Rudolf Haag’s legacy of Local Quantum Physics and reminiscences about a cherished teacher and friend

In memory of Rudolf Haag (1922-2016)

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Bert Schroer
permanent address: Institut für Theoretische Physik
FU-Berlin, Arnimallee 14, 14195 Berlin, Germany

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Abstract

After some personal recollections about Rudolf Haag and his thoughts which led him to “Local Quantum Physics”, the present work recalls his ideas about scattering theory, the relation between local observables and localized fields and his contributions to the physical aspects of modular operator theory which paved the way for an intrinsic understanding of quantum causal localization in which fields “coordinate” the local algebras.

The paper ends with the presentation of string-local fields whose construction and use in a new renormalization theory for higher spin fields is part of an ongoing reformulation of gauge theory in the conceptual setting of Haag’s LQP.

1 First encounter with Rudolf Haag

On his return from the Niels Bohr Institute in Copenhagen to the University of Munich Rudolf Haag passed through Hamburg to meet his colleague Harry Lehmann, at that time the newly appointed successor of Wilhelm Lenz who held the chair of theoretical physics since the 1920 foundation of the University of Hamburg. It was the year 1958 shortly after the decision to construct the DESY particle accelerator in Hamburg which created a lot of excitement. I had nearly completed my diploma thesis under Lehmann and begun to worry about my career.

Haag was about to accept an offer of a staff position at the University of Illinois in Urbana. He asked me whether I would be interested to continue my
career in the US as his collaborator. The prospect of a scientific career and the desire to change my somewhat precarious living conditions which I encountered after my 1953 flight from East Germany to Hamburg made such a prospect irresistible.

To better get to know each other Haag invited me to accompany him on a visit to Daniel Kastler who at that time was a recently appointed faculty member of the physics department of the University in Marseille. He had met Daniel a year before and both participated in an international conference in Lille/France where Rudolf for the first time presented his idea to base quantum field theory on spacetime-localized operator algebras at an international conference. Daniel was attracted by these new ideas and the purpose of Rudolf’s visit was to obtain Daniel’s help for the improvement of their at that time still shaky mathematical formulation. In this way Daniel and Rudolf became soulmates in the exploration of what was referred to as algebraic quantum field theory (AQFT) and later more appropriately named ”local quantum physics” which as a result of its frequent use will be abbreviated as LQP. With Rudolf’s acceptance of an offer from the University of Illinois and his impending move to the US their collaboration was delayed. Their first important joint publication appeared in 1962 [1].

The voyage to Marseille provided an opportunity to get to know each other before my planned but not yet approved move to the US. The journey by car through parts of Germany and across Switzerland and parts of southern France to Marseille was an unforgettable experience. Having fled communist East Germany and gone to Hamburg in 1953, it was my first travel outside the German borders. In particular the journey along the Côte d’Azur with its subtropical vegetation and its new scents and cultural impressions remains impressed in my memory.

After my return to Hamburg Rudolf’s offer to work with him in the position of a research associate took a concrete form; I bought boat tickets on the Holland America line for my family and the first birthday of our daughter was celebrated in the middle of the Atlantic.

Arriving at the University of Illinois in Urbana I encountered a formal problem. Even taking into account the shock from the 1957 launching of the Sputnik in 1957 which led to the creation of new positions for physicists and engineers, the offer of a research associate position to somebody without a Ph.D. was unusual. As I learned later from Rudolf he cleared this problem in a conversation with the department chairman Frederick Seitz.

Frederick Seitz, a renowned physicist with political influence on US science policies, was a former student of Wigner. This may have played a role in Wigner’s recommendation of Haag for a full professorship at the University of Illinois. Haag’s prior visiting position at the University of Princeton led to many scientific contacts with Wigner and Wightman. In his reminiscences [2] he gives credit to Wightman for having directed his attention to Wigner’s 1939 path-breaking work on the classification of all unitary representations of the Poincare group. It is hard to understand why this important work of Wigner’s remained unnoticed for more than a decade.

He also mentions contacts with other members of the Princeton university’s
physics faculty; in particular with Valja Bargmann, who extended Wigner’s work on representation theory, as well as with Marvin Goldberger and Sam Treiman, who at that time were working on the extension of the optical Kramers-Kronig dispersion relations to particle physics. During this time in Princeton Haag was the thesis adviser to Huzihiro Araki, a brilliant young student from Japan, Araki visited Urbana several times and some discussions even led to a joint publication [4].

Besides recalling personal events these notes present important ideas of Haag’s local quantum physics (LQP) in their historical context. In order to direct attention to its largely untapped innovative strength the last two sections include the beginnings of a LQP inspired positivity preserving string-local renormalization theory for interactions involving higher spin $s \geq 1$ fields whose aim to replace the ”gostly” BRST gauge theory by a LQP formulation which only uses physical degrees of freedom. For Haag this was one of LQP’s greatest challenges [2].

Frequently occurring scientific expressions will be abbreviated: quantum field theory (QFT), local quantum physics (LQP), point-like (pl), string-like (sl), string-local quantum field theory (SLFT), power-counting bound (pcb), spontaneous symmetry breaking (SSB), string theory (ST), the Becchi-Rouet-Stora-Tyutin gauge formalism (BRST).

2 With Haag in Urbana

After the resounding success of renormalization theory in quantum electrodynamics the main interest shifted to high energy nuclear interaction. It soon became clear that these methods of perturbative renormalization theory do not work for processes involving strong interactions (which in the field theoretic description at that time meant trilinear $\pi$-meson-nucleon couplings and $\pi$-selfinteractions).

Moreover doubts were increasing as to whether the locality, as formally contained in the relativistically covariant Lagrangian quantization, retains its validity in the new high energy domain of nuclear interactions. From earlier work on quantum optics it was well known that certain analytic relations, known as the aforementioned Kramers-Kronig dispersion relations, had a rather direct connection to relativistic causal propagation. The problem was to derive such analytic relations for the scattering amplitudes of strongly interacting particles.

That positivity of energy together with Einstein causality leads to analytic properties of spacetime correlation functions (vacuum expectation values) of fields was already well known. However fields in spacetime are not directly accessible to measurements; in experiments; one rather measures scattering amplitudes of particles in momentum space which have a large time asymptotic relation with fields. For those ”on-shell” amplitudes in momentum space the derivation of analytic consequences of causality posed a harder problem than that of ”off-shell” correlation functions in spacetime (Wightman functions).

For the confidence in the validity of causal locality at the higher energies of
a new generation of accelerators it was important to obtain a rigorous derivation from the causal localization properties of field operators (micro-causality of QFT). The form of the expected dispersion relation was known from the study of Feynman graphs; what was missing was a derivation from the spacelike (anti)commutation relations of quantum fields.

The joint effort of Harry Lehmann together with Res Jost as well as contributions from Freeman Dyson resulted in the derivation of dispersion relation from first principles. The subsequent experimental verification at the at that time highest energies at the Brookhaven accelerator brought the dispersion relation project to a successful close. The confidence in the validity of the causal locality principle in the new area of High Energy Physics was restored and the interest in nonlocal modifications of QFT subsided.

For Haag quantum causality is not fully accounted for by Einstein causality in the form of (anti)commutation of operators whose spacetime localization regions are spacelike separated. He expected that in his LQP formulation in terms of a net of causally related algebras the quantum counterpart of hyperbolic propagation of Cauchy data, although closely related to Einstein causality, can not be derived from it.

The relation of LQP to Wightman’s axiomatic formulation in terms of fields and their vacuum expectation values was from Haag’s LQP point of view analogous to the relation between the coordinate-independent presentation of modern geometry and its description in terms of coordinates. Decades later this analogy was made more precise by H.-J. Borchers who showed that the quantum fields form local equivalence classes and that the different members in one class (provided their matrixelements between the vacuum and one-particle states do not vanish) describe not only the same particles and their scattering matrix but also generate the same localized algebras [10] [32].

The necessarily singular nature as operator-valued Schwartz distributions (as a result of the omnipresence of vacuum polarization clouds) renders the relation between fields and operator algebras very intricate. The presence of these polarization clouds accounts for the fundamental difference of the intrinsic causal localization and the ”Born localization” in terms of an arbitrarily chosen quantum mechanical position operator. Haag expected that causality properties can be more natural described in his LQP setting.

In addition to Einstein causality there should also exist a time-like causality property which is the quantum analog of the hyperbolic propagation of classical waves. Classically the initial values within a sphere of radius $r$ at time $t = 0$ centered at the origin have a region of influence which is the forward and backward light cone emanating from the sphere. But they also lead to a compact double cone region $C = \{ x \mid - x^\mu x_\mu \leq r^2 \}$ inside which the radiation is completely determined in terms of the $t = 0$ Cauchy data in the sphere. Any classical field strength measured inside $C$ which cannot be accounted for in terms of these Cauchy data would be seen as a mysterious violation of causal propagation since according to Einstein’s causality requirement it could not have entered from the causal complement.

Apart from free quantum fields whose propagation properties can be directly
related to those of classical fields, it is not clear how to formulate this hyperbolic propagation property for interacting Wightman fields. Interestingly it turns out that this is much easier in Haag’s algebraic formulation of LQP. It amounts to an equality of two different localized (von Neumann) operator algebras

\[ \mathcal{A}(\mathcal{O}) = \mathcal{A}(\mathcal{O}^\prime) \]

where \( \mathcal{O} \) in the above illustration would correspond to a in time direction slightly thickened spatial sphere \[ \mathcal{O} \]. The causal complement \( \mathcal{O}^\prime \) consists of all points which are space-like with respect to \( \mathcal{O} \) and the causal completion (or causal shadow) is the complement taken twice which is generally larger than i.e. \( \mathcal{O} \subset \mathcal{O}^\prime \) with the equality defining the maximal extension which is consistent with Einstein causality (the causal completion).

Our joint effort was to look at the (at that time simpler appearing) problem of the time-slice property corresponding to the classical determination of the future field in terms of the global \( t = 0 \) Cauchy data. A global time slice can be patched together from infinitely many finite double cone \( \mathcal{O} \)'s since the additivity property of LQP relates a violation of the causal completeness with that of the time-slice property. Such a violation in a model which fulfills all other LQP requirements implies that causal completeness is not a consequence of Einstein causality.

In my recollection the start of my work on "local quantum physics" (LQP) with Rudolf is inexorably related with a beautiful summer on Wisconsin’s lake shores. Rudolf proposed to look for models which are Einstein causal but violate causal completeness. At the beginning I was somewhat discouraged because I considered my knowledge acquired under Lehmann as insufficient for the new work on LQP. But it then turned out that at least some of it was useful.

Rudolf’s heuristic idea was that too many degrees of freedom within a bounded spacetime region and a certain bound on their invariant energy content may (a kind of relativistic phase space) lead to violations of causal completeness. In such a case an observer would "see" more degrees of freedom in the double cone than his experimental friend had injected into the base region around \( t = 0 \). Such a "poltergeist" effect of increase of degrees of freedom apparently coming from nowhere (since according to Einstein causality they cannot come from space-like separated regions) is an unacceptable violation of causality and must be excluded and the LQP setting is the best way of formulating this.

Our simple counterexample was provided by so called generalized free fields with a sufficiently increasing mass distribution; so my modest contribution to a joint paper consisted in some calculation with generalized free fields with suitable chosen continuous mass distributions \( \rho(m) \). Rudolf’s intuition was vindicated

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1 Haag-Kastler nets of local operator algebras are localized in open spacetime. This is similar to interacting quantum fields which as a result of their singular short distance behavior have to be smeared with test functions supported in open regions.

2 The requirement that the operator algebra generated from the union of localized algebras with overlapping localization regions is equal to the algebra localized on the union of the localization regions.
by the result which showed that although all Wightman properties are satisfied, the time slice property is violated [3].

With the hindsight of later work one may view this illustration as a first indication of the importance of the notion of cardinality of degrees of freedom which in the decades to come received various refinements; first the Haag-Swieca ’compactness”, then the Buchholz-Wichmann ”nuclearity” [10] and the more recent ”modular nuclearity” which is used in existence proofs of certain \( d = 1+1 \) models of QFT (next section)

Together with the other postulates which already appeared in Haag’s contribution to the 1957 Lille conference [2] our work was a rather complete account of the ”axioms” which define the framework of LQP. Two years later it was superseded by a paper of Haag and Kastler [1] which contained a more detailed account of their mathematical structure and physical consequences. The H-K work is still considered to be the most authoritative reference for the algebraic approach to QFT.

The time slice property played no role in most presentations of LQP but it turned out to be important in recent formulations of QFT in curved spacetime.

For later reference it is helpful to collect the LQP causality requirements

\[ A(O) ' \subseteq A(O)'' \] Einstein causality, \( EC \)
\[ A(O) = A(O)' \] causal completion property, \( CC \)
\[ A(O)' = A(O)'' \] Haag duality, \( HD \)

Haag duality is an important special case of Einstein causality. The \( CC \) property is closely related to \( HD \). Einstein causality can be directly expressed in terms of covariant fields, whereas for \( HD \) and \( CC \) this is more subtle.

For a physical interpretation the \( EC \) and \( CC \) requirements are indispensable whereas violations of \( HD \) occur in the presence of massless \( s \geq 1 \) interaction for multiply connected spacetime regions (tori). The most prominent illustration is the operator of magnetic flux through a solid torus \( H(T) \) which belongs \( A(T)' \) but not to \( A(T) \) [6]. Interestingly the Aharonov-Bohm effect is related to this breakdown of Haag duality [3].

The causal completeness property also severely limits relations between LQPs in different spacetime dimensions (“extra dimensions”). This affects in particular the mathematical isomorphism between LQPs on \( n \) dimensional Anti de Sitter space (AdS) and \( n-1 \) dimensional conformal spacetime which share the same spacetime symmetry group. On heuristic grounds one expects that the AdS-CFT isomorphism leads to similar problems as the previous \( CC \) violation for certain generalized free fields with too many degrees of freedom.

This is precisely what happens on the lower spacetime dimensional conformal side [7]. In fact starting with a \( CC \) obeying AdS free field [8] one obtains an ”overpopulated” conformally invariant generalized free field [3], and this problem does not disappear in the presence of interactions. Conversely the LQP
double cone algebras on the \(AdS\) side obtained from a "healthy" conformal LQP are "anemic" in the sense that compact localized algebras do not contain any degrees of freedom and one has to pass to noncompact localization regions to encounter algebras which are not multiples of the identity. All those cases the algebraic isomorphism preserves \(EC\) but violates the with degrees of freedom connected \(CC\).

The Kaluza-Klein proposal of extra or lowered spacetime dimensions works for classical field theories as well as semi-classical approximations but it clashes with QFT. "Transplanting" the matter content between worlds of different spacetime dimensions preserves \(EC\) but fails on \(CC\).

The issue of causal localization sustaining quantum degrees of freedom is a very subtle one which is inexorably related with the role of vacuum polarization clouds in causal localization and has no counterpart in quantum mechanics or classical field theory. Using the standard formulation of QFT field coordinatizations one may easily overlook the breakdown of the causal completeness property as a result of an overpopulation of degrees of freedom resulting from resettling the degrees of freedom of a higher dimensional LQP into a lower dimensional spacetime vessel. This is precisely what happened when the AdS-CFT isomorphism and the idea of extra dimensions became a focal point of interests in the 90s which led to thousands of publications.

During the almost 3 years of my time in Urbana there were many interesting visitors. I remember that Gell-Mann on one of his visits asked us if we had a more intrinsic understanding of the relation between the partially conserved axial vector currents (PCAC) with the field of the \(\pi\)-meson. At that time gauge theoretic Lagrangian models with axial \(\rho\)-mesons as proposed by Sakurai enjoyed great popularity. At the end of the discussion Murray Gell-Mann joked: "you mean we can shoot Sakurai?" before he enjoyed looking at our somewhat helpless expressions.

Together with Haag I participated in a summer school in in Boulder, Colorado. My remembrances about the activities in physics are faint but I do recall having been impressed by the beautiful nature of the Rocky Mountains and a subsequent journey with my family through the Yellowstone National Park.

I also recollect an extremely peculiar occurrence. When I looked as usual into the weekly Time Magazine I came across a story about two mathematicians at the University of Illinois which were engaged in classified work for the NSA before they defected via Cuba to the Soviet Union taking classified material with them. The name of one of them was the same as that of somebody who lived in an apartment in Urbana which I rented shortly before I went to Boulder. The apartment in a university housing project became too small for my family after the birth of my son. The former tenant whose name was Martin also sold his piano and some furniture to me before he moved out. There was a picture of the two mathematicians in Time Magazine, but the quality of printed photos in those times was so poor that I could not identify him. I brushed the incidence aside as a coincidence of names and enjoyed the rest of the stay.

Two agents of the CIA were already waiting for me. Apparently they found the check of my payment for the piano in a Washington deposit. They really
knew a lot about my past, in particular that in 1953 I fled from East Germany. Probably they obtained their knowledge from an archived protocolled hearing in a transit refugee camp, a former concentration camp near Hamburg where besides German officials also a US officer was present.

Rudolf assured me that this matter will be cleared up in a short time. Indeed after several meetings in a restaurant I succeeded to convince them that my involvement was coincidental and that I was not an East German spy.

Many years later when I mentioned the Martin-Mitchell spy story at an international physics conference to Ludvig Faddeev, he told me that a week before both of them applied for a position at the Steklov Institute in Leningrad. By that time they had Russian wives and families. How was this possible; did the communist ideology convert two homosexuals?

Before my position at the University of Illinois came to an end, I met Jorge Andre Swieca who, after having spent a year at the Werner Heisenberg Institute in Munich (one of the largest Max Planck Institutes for physics in Germany), passed through Urbana on his way to Brazil. The purpose of this visit was to introduce himself to Rudolf as his new Research Associate. After he defended his Ph.D thesis at the University of Sao Paulo (with Guettinger as his advisor) he returned to Urbana to start his work with Haag.

During my stay in Urbana I had obtained some results which were appropriate to be used for a Ph.D thesis. I returned 1963 to Hamburg where I submitted my thesis. The terminology "Infraparticles" in its title [9] referred to the conjecture that the infrared divergencies which appear in the scattering amplitudes of electrically charged particles are related to a modification of the Wigner particle structure. I was able to illustrate this in a two-dimensional model. The realistic case was taken up two decades later by Buchholz. The issue of infraparticles has remained a challenging topic of LQP [10].

After a one year at the IAS in Princeton, a short stay at the University of Hamburg and a visit to the Middle East University in Ankara at the invitation of Feza Gursey I returned to the US to take up my new position of associate professor at the University of Pittsburgh.

Shortly before I left Urbana I shared an office with Derek Robinson who became Haag’s second collaborator. During a visit by Kastler, Robinson Swieca and Kastler investigated the properties of conserved currents within the new algebraic Haag-Kastler setting of LQP. They found that the conservation law only secures the existence of a "partial" charge which secures the existence of a local symmetry within each finite spacetime localization regions but that the global charge may diverge i.e. the inverse of the quantum Noether theorem may be violated i.e. the current conservation may not secure the existence of a global "charge" (the infinitesimal generator of a unitary symmetry.

It was known from perturbative investigations of self-interacting scalar fields by Goldstone that the local current conservation may lead to a divergent global charge resulting from the contribution of a massless scalar ("Goldstone") boson which impedes the large distance convergence and in this way causes a situation which was appropriately referred to as spontaneous symmetry breaking (SSB).

Kastler, Swieca and Robinson showed that this cannot happen in the pres-
ence of a mass gap \cite{12}, and in a follow up paper (based on the use of the Jost-Lehmann-Dyson representation) Swieca together with Ezawa \cite{13} succeeded to prove the Goldstone theorem in a model- and perturbation-independent way.\footnote{The Goldstone theorem states that a Nöther symmetry in QFT is spontaneously broken precisely if a massless scalar "Goldstone boson" prevents the convergence of some of the global charge $Q = \int j_0 = \infty$.}

Goldstone constructed renormalizable SSB models of self-interacting scalar particles by applying the "shift in field space" prescription to formally symmetry-preserving "Mexican hat potentials".\footnote{Masses and mass ratios may appear in coupling strengths of induced higher order contributions.}

This quasiclassical prescription leads to a model-defining first order interaction density which maintains the conservation of the symmetry currents in all orders. There are symmetry-representing unitary operators for each finite spacetime region $O$ but the global charges $Q = \int j_0$ of same symmetry generating currents diverge. This is the definition of SSB whereas the shift in field space procedure is a way to prepare such a situation whenever SSB is possible.

For the later presentation of the Higgs model it is important to be aware of a fine point about SSB whose nonobservance led to a still lingering confusion. As soon as scalar self-interacting fields are coupled to $s = 1$ potentials the physical interpretation of the field shift manipulation on a Mexican hat potential as a SSB is incorrect; one obtains the Higgs model for the wrong physical reasons and misses the correct reasons why there can be no self-interacting massive vectormesons without the presence of a $H$-field. Although this can be described correctly in the gauge theoretic formulation, a better understanding is obtained in the positivity preserving string-local setting of LQP (see section 6)

QFT is not a theory which "creates" masses of model-defining fields. The masses of those free fields which define the first order interaction density) are, together with the coupling strengths, free parameters.\footnote{Masses and mass ratios may appear in coupling strengths of induced higher order contributions.} The only "dynamic" masses are those of bound states created by acting with interacting composite fields on the vacuum state but unfortunately there is no perturbative methods which describes bound states. space.

In a later paper Haag and Swieca investigated the cardinality of states contained in a finite spacetime region with limited energy content \cite{11}. In quantum mechanics this corresponds to the number of degrees of freedom per cell in phase space which is finite. They found that LQP leads to an infinite set whose cardinality cannot exceed that of a compact set.

### 3 The Brazilian connection

Shortly before I left in 1962 I met Jorge Andre Swieca for the first time when, on his return from the Max Planck Institute in Munich to the University of Sao Paulo (USP) he passed through Urbana for an interview with Haag. His thesis adviser was Werner Güttinger who, as several other German physicists, was invited to the in 1952 newly founded Instituto de Física Teórica (IFT) in
Sao Paulo. Güttinger recognized the potential of Andre Swieca and arranged a visiting position for him at the MPI in Munich. When I met Andre in Urbana he was on his way back to the USP in order to defend his thesis before taking up the research associate position with Haag in Urbana.

Güttinger is one of the few theoretical physicists who, shortly after Laurent Schwartz’s presentation of the theory of distributions, saw the relevance of that theory for the description of the singular nature of quantum fields. Before he obtained a permanent position at the University of Tübingen/Germany he spend some years in the second half of the 50s at the ITF. It is interesting to note that around 1952 Laurent Schwartz together with Alexander Grothendiek spend some time at the USP. On my first visit in 1968 there still existed traces of the legacy of Laurent Schwartz in the form of courses on distribution theory at the USP physics department which were presented by a young Brazilian lady who obtained her PhD with Laurent Schwartz.

My first chance to take a short leave of absence from the University of Pittsburgh to follow Andre Swieca’s invitation to the USP came in 1968. After his return from the collaboration with Haag in Urbana to Brazil at the end of 1966 Andre held the position of a junior professor at the USP. When I arrived he was surrounded by a group of enthusiastic young students of whom the most advanced (Jose Fernando Perez) was assigned the task to take care of me and to help me with the written version of my lectures on QFT. This was the beginning of what Haag in his reminiscences called the ”Brazilian connection” ([2] page 24).

During my visit Andre received the Moinho Santista prize for his quantum field theoretic work on symmetries and their spontaneous breaking. After Jaime Tiomno, one of the founders (together with Mario Schemberg and Jose Leite-Lopes) of theoretical physics in Brazil, Andre was its second recipient. After his collaboration with Kastler and Robinson in Urbana on the LQP formulation of symmetries and their conserved currents he had pursued this issue in more depth with particular attention for spontaneous symmetry breaking (SSB) for which the current remained conserved but the presence of a massless Goldstone boson one loses the symmetry generator since the global charge diverges. In a joint paper with H. Ezawa the Goldstone theorem, which previously only existed as a perturbative property of a special class of models, was derived in a model-independent way from the causal localization principles of QFT [13].

He lectured on his results in Erice [14] and up to date I know no clearer model-independent presentation of Goldstone’s SSB theorem about SSB as a consequence of the causality and spectral properties principle of QFT than that in his notes. This is particularly important in times in which SSB became somewhat misleadingly synonymous with a shift in field space on a Mexican hat potential (see remarks in previous section).

At the time of my visits during the 60s and 70s Brazil was ruled by a military junta which took power in 1964 coup. At the start of my visit in 1968 I hardly noticed the presence of a military dictatorship, but the situation changed abruptly in May 1968 when at the time of intensification of the Vietnam war there were student demonstrations in Paris and Berlin and other places. I lis-
tended to the news on my short wave radio but soon became aware that there was an increasing number of demonstrations against the military dictatorship whose only connection with the Vietnam war was that those who started the war were the same who supported the military regime in Brazil.

Many years after Swieca’s premature death in 1980 somebody asked me whether I knew something about a rumor that after having received the Santista prize he was approached by the military government to explore the possibility to offer the post of a scientific/cultural attaché to Israel. I did not, but I was sure that if this really happened Andre would have declined an offer of representing a military dictatorship in a democratic country. Sometimes I saw military police entering the USP campus and later I learned that one of my colleagues Ernesto Hamburger was taken into custody and his wife was tortured.

Andre told me a saddening story about an occurrence which happened shortly before to one his professors from whom he took his first physics courses. Plinio Susskind had a very strong personal contact with his students, after the lectures he joint them to continue discussions about matters of physics and daily events in nearby cafes and bars. He had a collection of books which included the work of Marx and others which after the military coup were considered subversive. When the military police searched his apartment they found a copy of Sergei Eisenstein’s “Couracado Potemkin” (Battleship Potemkin). He was taken into custody and after having been released he lost his university position.

He was not internationally known and had no chance to continue working outside Brazil. He fell into poverty and Andre and some of his former fellow students supported him for many years. The worst aspect of a military regime is that it encouraged denunciations which in some people used to settle accounts. Two of the founders of theoretical physics in Brazil as Jaime Tiomno and Leite-Lopes who felt threatened by the regime accepted positions in the US or France.

For more than a decade, starting from the beginning of the 70s up to the return of democracy in 1985, the catholic university of Rio de Janeiro (PUC) became a refuge for many Brazilian scientists including Jorge Andre Swieca who worked there for several years.

On this first visit to Brazil there was little time and peace of mind to talk about how to use our shared knowledge acquired as collaborators of Haag for establishing a joint project. We postponed the discussions of topics of joint interests to future visits.

One week after my return to Pittsburgh I received a notice that military tanks entered the USP at dawn and took positions around the CRUSP housing and took everybody into custody. Apparently was released on the same day; not because he was particularly cooperative but rather as the result of taking notice that his fiancé was the daughter of a high ranking military; an occurrence which is easily understood for those who experienced the Brazilian “jeitinho” which survived any system up to date.

When back in Pittsburgh I obtained informations about the worsening political situation in Brazil I found myself in an unusual schizophrenic situation; here I was living peacefully in a democratic country whose government supported military dictatorships in other countries under which my colleagues suffered.
Less than two years later Andre visited me at the University of Pittsburgh
where the QFT group was meanwhile strengthened by Ruedi Seiler, a mathema-
tical physicist who received his PhD shortly before from the ETH in Zurich.
Looking for a topic on which one could start a short time collaboration we found
it worthwhile to investigate to what extend Einstein causality and the causal
shadow property retain their validity for interactions of quantum fields with
external (classical) fields.

Using functional analytic methods it was possible to show with the help of
the energy norm that these causality properties hold for models of low spin quan-
tum fields coupled to time-dependent asymptotically vanishing classical fields
and for $s > 1$ interactions we extended previous observations about acausalities
\[15\]. In case of strong stationary external fields we were able to improve the
understanding about an inconsistency of the Klein Gordon field in a strong poten-
tial made thirty years before \[16\]. The result was that there are two ways of
quantizing bound states with negative $E^2$ namely either by using indefinite met-
ric or by abandoning the vacuum postulate and accepting repulsive (inverted)
oscillator degrees of freedom associated to such bound states.

This led me to take another look at "tachyons" described by fields with
$m^2 \rightarrow -m^2$. As the name suggests these fields were thought of as being associ-
ated to fields describing "superluminal stuff". But how can this be in view of
the fact that a classical tachyon field has a perfectly causal propagation? The
answer was that in limiting oneself to real spacelike momenta one has left out
imaginary values $-m^2 + \vec{p}^2 < 0$ whose momenta lead to inverted oscillators
which in quantum theory requires to substitute the vacuum state by a contin-
um of negative energy "jelly" states. Such a situation without bottom becomes
chaotically unstable in the presence of interactions; this is reminiscent of Dirac’s
hole theory except that in the tachyon case there is no "filling", with arbitray
large negative energies They correspond to those inverted oscillators which in
the problem of strong external potentials prevent the existence of a lowest en-
ergy vacuum state. In the tachyon problem they require the introduction of a
continuum of negative energy "jelly states" whose presence is indispen-
sable for maintaining causal propagation. Although the free theory exists, any perturba-
tion will cause a similar instability as the Dirac sea before filling it, except that
for tachyons such filling is not possible \[17\].

This instability argument was later used in the quasiclassical preparation
of spontaneous symmetry breaking (SSB), which is a mild form of symmetry
breaking in which there still exists a conserved current but its charge (the gen-
erator of the symmetry) diverges due to the presence of a massless scalar boson
(the Goldstone boson). Since it is somewhat tedious to prepare a first order
interaction density with this property one starts from a symmetric Mexican hat
kind of selfinteraction of a multiplett of particles and uses the quasiclassical
trick of a shift in field space which brings an apparently tachyonic situation of
a Mexican hat potential into a less symmetric one with a vacuum.

The test whether the quasiclassical shift in field space on a selfinteracting
multiplet with a tachyonic mass term which preserves the current conservation
of the multiplett leads really to a SSB is decided in terms of $Q = \infty$. This and

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not the manipulation is the definition of SSB. In the absence of couplings to $s \geq 1$ fields this is the case but it fails in models in which the scalar matter couples to a vector potential. As will be demonstrated in the last two sections the "fattening of the photon" does not require the presence of a Higgs field; it is rather related to the appearance of an escort field which in turn is the unavoidable consequence of maintaining positivity in the presence of massless vector potential.

As far as one knows Nature provides no realization of exact internal symmetries or SSB in particle physics beyond the particle-antiparticle symmetry; the application remains in the hands of phenomenologists. But there can be no doubt that Nature supports the existence of a Higgs particle without which there can be no self-interacting massive vector mesons.

Shortly after my 1968 visit of the USP John Lowenstein, Haag’s last PhD student before he left Urbana and moved to the University of Hamburg, joined Andre as a post-doc. Their joint work on QED in two dimensions impressed me as a thorough application of mathematical ideas and concepts from LQP. For private reasons John wanted to return to the US and I was able to be helpful in obtaining a position at the University of Pittsburgh. This was the start of a fruitful collaboration on perturbative renormalization theory to all orders, in particular to gauge theory and its axial anomalies, which continued after my move to Berlin in 1971.

The collaboration with Andre and his research group continued during the 70ies; he came twice to Berlin and I met him 3 times, twice at the PUC in Rio and a third time after he moved to the USP in Sao Carlos. We wrote several papers on models with conformal symmetry in particular on global operator expansions and one of my collaborators (A. Voelkel) had a short time visiting position at the PUC.

In the middle 70ies a class of two-dimensional models with factorizing S-matrices became the focus of attention. These integrable models were of particular interest since perturbative constructions did not permit to establish the existence of nontrivial models so that QFT was the only area of theoretical physics for which the existence of interacting models within its conceptual framework (causality, Hilbert space positivity) remained widely open.

The discovery of these $d = 1 + 1$ integrable models led to a close collaboration between group of research associates at the FU Berlin (Berg, Karowski, Thun, Truong and Weisz) with a group around Swieca (Köberle, Kurak, Marino, Rothe) with my self representing the link between the two. Swieca’ death at the end of 1980 also marks the end of what Haag in his reminiscences called “the Brazilian connection”.

A collection of Swieca’s publications appeared later as "obras colligidas" to which I wrote a long introduction with the title "From the Principles of Quantum Field Theory towards New Dynamical Intuition from Studies of Models". This marked the end of a decade lasting collaboration to explore and illustrate the content of Haag’s LQP in concrete models of QFT. Our last joint project to detach operator product expansion from conformal QFT and in this way obtain a nonperturbative construction remained an unfulfilled project.
Recently there has been significant progress on this old problem \cite{20}.

When I revisited Brazil 20 years later, some of Andre’s closest colleagues had retired or died (Jose Giambiagi) and his former younger collaborators were working on different problems.

The old project received a new impulse when Karowski and Weiss extended it to what nowadays is referred to as the ”formfactor program” which consists in the explicit nonperturbative construction of matrixelements of fields between particle states. Besides presenting new insights into nonperturbative QFT its aim is to construct a QFT in terms of vacuum expectation values of quantum fields which can be formally represented as infinite sums over product of form-factors. As in perturbation theory there is presently no control of such sums.

Meanwhile a different approach has led to the first existence proofs for integrable models in the absence of bound states. It does not use individual fields but rather directly Haag’s LQP setting in terms of net of local algebras. It is a top-to-bottom approach which starts from the observation that the modular localization theory (see next section) connects the algebraic structure of wedge-localized algebras with the S-matrix and uses the fact that for factorizing S-matrices without bound states there exist simple generating operators for wedge algebras whose Fourier transforms fulfill the Zamolodchikov-Faddeev algebra relations.

Knowing the structure of the wedge algebra the next step is to show the existence of nontrivial algebras associated to compact spacetime regions resulting from intersection of wedges. This is the real hard part where estimates about degrees of freedom in the form of ”nuclear modularity” enter \cite{46}. The terminology top-to-bottom refers to obtain algebras of compact spacetime regions by intersection of wedge algebras. Covariant fields which generate these algebras would appear only in a later stage of this (”top-to-bottom”) construction. Since the physical consequences can be directly extracted from the algebras they are not needed. The protagonists of these ideas believe that future existence proofs of interacting QFTs in $d = 1+3$ will be based on such top-to-bottom constructions.

The remainder contains some remarks which bear no relation to physics but which form part of my personal ”Brazilian connection”

During the collaboration with Andre the weight of the past was always present. Andre was born in 1938 in Warsaw/Poland. His family had the good luck to escape from the murderous anti-semitism of the Nazis to that part of Poland which in 1939 according to the Hitler-Stalin pact was occupied by the Soviet from Union. Before Hitler’s assault of the Soviet Union and the Nazi occupation of the rest of Poland, the Swiecas fled to the Soviet Union from where they succeeded to reach Vladivostoc on the transsiberian railroad from there they got by boat to Yokohama and finally to South America.

They had some relatives in Rio de Janeiro but Getulio Vargas’s anti-semitic police chief Filinto Müller created problems which forced them to remain for some months in Buenos Aires. In the 70s Müller was the senator of the states of Mato Grosso and leader of the Arena party which was created by the military.

I was invited several times to the house of Andre’s parents and on one of these visits I sensed a mood of commotion. It was the day on which Filinto Müller
died in a plain from Rio to Paris. In those days the seats in many airplanes contained a material (polyvinyl chloride) which, if ignited by a cigarette, could lead to a smoldering fire. This happened on Müller’s flight; the captain made an emergency landing but all the passengers and those of the crew who did not succeed to enter the captain’s cabin perished in the toxic fumes.

Andre and his parents were not religious, yet there was a feeling of higher form of justice since Filinto Müller was responsible for the deportation of Olga Benario-Prestes on a Spanish ship via Franco’s Spain and her extradition to Nazi-Germany [21]. Olga, a German communist, together with the Brazilian tenant Luis Carlos Prestes were in opposition to the dictatorship of Getulio Vargas. Their attempt to initiate a revolt within the Brazilian military failed and both were jailed. Müller deported Olga on a Spanish ship and the Franco extradited her to Nazi-Germany. Being of Jewish descent this was like a death penalty. Her deportation caused national and international protests in particular since such an extradition in a state of advanced pregnancy was against the Brazilian law. Olga gave birth to her daughter Anita Leocadia Prestes in a Berlin prison clinic. Using her connections to the Itamaraty (the Brazilian Foreign Office) Prestes mother succeeded to take the baby to Brazil. Nowadays she is a professor of history at the Federal University of Rio de Janeiro.

Olga was taken to the Ravensbrück concentration camp and killed by gas in the Bernburg Euthanasia Centre which the Nazis created years before as part of their euthanasia program for mentally ill people. When after protests from part of the Catholic Church this clandestine murderous program was halted, the installation was used to kill prisoners from those near by concentration camps which, as the women’s camp at Ravensbrück, had no extermination facilities.

The fate of Filinto Müller, who died the same way as Olga Benario, is remarkable even for those who do not believe in higher justice and destiny.

The fact that I spent my childhood in Bernburg, and that I remembered my mother whispering with neighbors about busses with painted windows arriving at the mental hospital, constitutes an encounter with my past in a manner which I could never have imagined. In this way this became an inexorable part of my "Brazilian connection".

4 Local Quantum Physics and Modular Localization

One of the meetings between mathematical physicists and mathematicians which I attended in the 60s was a 1967 conference in Baton Rouge, Luisiana. In the center of attention was the work of Yuji Tomita, an elderly Japanese mathematician who appeared with a thick still unpublished manuscript. Its title contained the word "modular", indicating that he wanted his new results on operator algebras to be viewed as a kind of noncommutative generalization of measure theory. I understood very little of these new mathematical results.

Richard Kadison, an authority on operator algebras who chaired the confer-
ence, had doubts about some of Tomita’s arguments. He encouraged Tomita’s compatriot Takesaki to review the arguments and rework the presentation of the results together with Tomita. This led to the still authoritative first book on Tomita’s theory which became known as *the Tomita-Takesaki modular theory* [23].

Tomita’s ideas led to a new formulation in which the unitary modular group was associated with operator algebras satisfying certain conditions. This seemed to be connected in some way to new formulation (statistical mechanics of open systems) of equilibrium statistical mechanics directly in the infinite volume limit (without using Gibbs trace formula) proposed by Haag, Hugenholtz and Winnink [22]. Their results were also presented at this conference. What these authors referred to as the KMS property had its much more general operator-algebraic counterpart in Tomita’s work.

The KMS property appeared first in previous work by Kubo, Martin and Schwinger (the historic origin of the terminology). In the work of these authors it was merely a computational trick which converted the calculation of traces in the Gibbs formula into more manageable analytic properties involving analytic continuations. But in the new context it acquired a foundational meaning far beyond a mere computational device.

This terminology and also some of its physical content was afterwards adopted by the operator algebraists: Alain Connes and Uffe Haagerup used it in his impressive classification of the type III von Neumann factor algebras. Whereas the mathematical concepts of quantum mechanics, such as the Hilbert space and operators acting on it, existed before its discovery, the foundations of modular theory are the result of a joint effort between mathematicians and mathematical physicists. More details about the path-breaking Baton Rouge conference can be found in Haag’s reminiscences [2] and an authoritative account about its impact on mathematical physics including an important interrelation with causal localization is contained in a seminal article by H.-J. Borchers [24].

A decade later the work of Bisognano and Wichmann [25] revealed that causal localization and the KMS thermal aspects are inexorably interconnected; subsequently Geoffrey Sewell pointed out that this interrelation plays a fundamental role in the understanding of Hawking’s black hole radiation and the Unruh effect [26]. An account of the Hawking radiation from the viewpoint of LQP can be found in [27].

The interest in the application of LQP to problems in curved spacetime is reflected in an increasing number of publications starting in the 90s. A recent review with references to earlier work can be found in [29].

In this context it is also interesting to note that modular localization sheds some new light on a fascinating but for a long time incompletely understood controversy between Einstein and Jordan (the Einstein-Jordan ”conundrum”) which led Jordan to the first model of a field theory (the model of conserved current in $d = 1 + 1$).

Haag’s view of localized quantum matter as a net of causally localized operator algebras acting in a joint Hilbert space received important support from the modular theory of operator algebras [28]. A particularly fruitful concep-
tual enrichment came from the application of modular localization to integrable models\footnote{For a recent account containing a rather complete list of references to previous work see \cite{46}.} and to the use of Wigner’s representation theory of the Poincare group for the construction of noninteracting nets of operator algebras \cite{30}. Since this concept plays an important role in the later sections an at least rudimentary understanding will be helpful.

There exists a weaker version of the T-T modular theory which does not refer to operator algebras but uses the concept of a so-called standard subspace $K$ of a Hilbert space $H$. This is a closed real subspace $K \subset H$ whose complexification is dense in $H$ i.e. $\overline{K+iK} = H$ and $K \cap iK = \{0\}$ where the bar refers to the closure. The Tomita $S$ operator is then defined as $S(\zeta + i\eta) = \zeta - i\eta$; conversely $K$ can be represented in terms of a Tomita operator $K = \ker(S - 1)$. As in the algebraic Tomita-Takesaki setting the $S$ has a polar decomposition $S = J\Delta^{1/2}$ where $\Delta$ is an automorphism of $K$ and the antiunitary $J$ transforms $K$ into its symplectic complement (symplectic orthogonal) of $K$ within $H$ which is defined in terms of the symplectic product $i \text{Im}(f,g)$.

The simple physical illustration of the connection of causal localization with the T-T modular theory is provided by the 2-point function of a scalar free field

$$ (f, g) = \langle \varphi(f)\Omega, \varphi(g)\Omega \rangle, \varphi(f) = \int \varphi(x)f(x)d^4x $$

defines a scalar product between the forward mass-shell restriction of the Schwartz test functions. The Hilbert space $\mathcal{H}$ is the space of Wigner wave functions $\mathcal{H}$ of a scalar particle which is obtained from the closure of the forward mass-shell restriction of the Fourier transformed test functions.

The closed subspace $\mathcal{K}(\mathcal{O})$ of $\mathcal{H}$ obtained by the closure of real test functions localized in $\mathcal{O}$ turns out to be standard in the above sense; this follows from the one particle projection of the cyclic and the separating property of quantum fields known as the Reeh-Schlieder property \cite{10} (or can be shown directly). Since $i \text{Im}(f,g)$ can be written in terms of the vacuum expectation of the commutator

$$ i \text{Im}(f,g) := \langle \Omega [\varphi(f)^*, \varphi(g)] \Omega \rangle $$

the aforementioned symplectic orthogonality receives a physical interpretation in terms of Einstein causality.

More interesting and important is the inversion of this relation i.e. the construction of a net of causally localized subspaces $\mathcal{K}(\mathcal{O}) \subset \mathcal{H}_{\text{Wig}}$ of the Wigner’s representation space using his representation theory of the Poincare group. The key for this construction is the Bisognano-Wichmann property i.e. the physical identification of the Tomita operator $S_W$ for a wedge region e.g. $W = \{x_3 > |x_0|\}$. In this situation these authors showed (under mild technical assumptions in a Wightman setting \cite{25}) that the antilinear $S$-operator associated to the dense set of states obtained by applying a wedge-localized operator algebra to the vacuum can be expressed in terms of physical data. Whereas
the unitary modular group $\Delta^t$ associated to the radial part of its polar decomposition $S = J\Delta^{1/2}$ is the $W$-preserving boost $\Delta^t = U(\Lambda_W(-2\pi t))$, the antunitary angular part $J$ is, apart from a $\pi$-rotation in the plane of the edge, the TCP operator which plays a fundamental role in QFT.

With this physical identification one obtains the modular subspace $\mathcal{K}(W)$, and by covariance also all its Poincare transforms. Subspaces $\mathcal{K}(\mathcal{O})$ for general localization regions $\mathcal{O}$ are obtained in terms of intersections, their modular groups have no geometric interpretation (except in the presence of conformal covariance); although they preserve the localization region their action inside is "fuzzy" i.e. cannot be visualized in terms of geometric transformations inside $\mathcal{O}$. Using the functorial relation between real one-particle subspaces and operator subalgebras, which is defined in terms of Weyl operators, one finally arrives at an explicit construction of Haag's net of local algebras in the absence of interactions [30].

This functorial relation which maps localized real subspaces into local von Neumann algebras in such a way that subregions correspond to subalgebras and Einstein causality holds permits a generalization to all positive energy Wigner representations. The fact that it is tied to the energy positivity shows (perhaps somewhat unexpected) close connection between geometric with spectral properties of the translation operators (stability properties).

This relation breaks down in the presence of interactions. In this case one may start from the Wigner-Fock space which in the presence of a gap is provided by (LSZ or Haag Ruelle [10]) scattering theory. It has been known for a long time that in this case the TCP operator differs from that of a free incoming fields by the scattering matrix $S_{\text{scat}}$ so that one obtains $J = S_{\text{scat}}J_0$ where $J_0$ refers to the free fields associated to the Wigner-Fock space.

An explicit construction of modular localized subspace in the presence of interactions is possible for integrable models with known factorizing S-matrix. An important supporting property is the existence of so called vacuum polarization free generators (PFG) i.e. operators in an interacting theory whose application to the vacuum creates a polarization-free one-particle vector. Their existence is based on the relation between the tightness of causal localization and the strength of interaction-caused vacuum polarization clouds. It is well-known that the singular nature of states created by interacting quantum fields is related to the strength of vacuum polarization clouds; the larger the space-time localization region conceded to the clouds, the easier to find less singular operators.

It had been known for a long time that covariant point-local fields which create a polarization-free one particle state from the vacuum must be free fields (the J-S theorem [32]). The more general concept of vacuum polarization free generators (PFG) leads to theorem that for compact localized spacetime regions such PFGs do not exist in interacting theories. The tightest noncompact region for which (under certain weak condition) PFGs exist are (arbitrarily narrow) space-like cones [33]. The fact that they are always available in wedge regions [34] makes the latter an ideal point of departure for existence proofs.

In the case of integrable models such PFGs are provided by the Fourier trans-
forms of the creation/annihilation operators which obey the Zamolodchikov-Faddeev algebra \[35\] whose commutation structure is given in terms of the known elastic part of the factorizing S-matrix. This observation is the starting point of an LQP-based construction project starting from the PFG-generated \( \mathcal{A}(W) \) operator algebra. A highly intricate part of the construction is the demonstration of nontriviality of double cone intersections of wedge algebras \[46\]. Here concepts of cardinality of degrees of freedom in the form of modular nuclearity play an important role.

The obtained results are complementary to those of the form factor program for integrable models. Whereas the latter lead to concrete closed-form expressions for formfactors of point-local fields (but without control of the convergence of the resulting infinite series expressions for the correlation functions), the LQP construction starts from the generators of the wedge algebra and establishes the existence of a nontrivial double cone intersection of arbitrary small diameter (but falls short of constructing the generating point-local fields).

Interacting models in dimensions \( d > 1 + 1 \) are not integrable and hence possess no closed form (analytically representable) solutions. Whether the extension of ideas based on modular localization to \( d = 1 + 3 \) dimensional interacting models will lead to a nonperturbative control remains a dream of the future. Different from all other areas of theoretical physics QFT remains an enigmatic project.

QFT earned its standing as the most comprehensive description of Nature’s physical properties from the observational success of its perturbative formulation. The predictive success of the Standard Model is based on low order perturbation theory complemented by phenomenologically supported proposals.

Contrary to a widespread misconception renormalized perturbation theory does not depend on any quantization parallelism with classical field theory. As shown in \[31\] covariant point-local (pl) free fields are constructed from Wigner’s theory of unitary positive energy representations of the Poincaré group; the corresponding spaces of particle wave functions bear no relation to actions of classical point-local particles (section 5).

In terms of the creation/annihilation operators \( a^\#(p, s, s_3) \) for massive particles and their anti-particles \( b^\#(p, s, s_3) \) which act in a Wigner Fock space, the pl covariant free fields are of the form

\[
\psi^{A, B}(x) = \frac{1}{(2\pi)^{d/2}} \int \sum_{s_3 = -s}^s (e^{ipx} u^{A, B}(p, s, s_3) a^*(p, s_3) + e^{-ipx} v^{A, B}(p, s_3) b(p)) \frac{d^3p}{2p_0}
\]

(5)

where the intertwiner functions \( u^{A, B}(p, s, s_3) \) and their charge-conjugate counterpart are \((2A + 1)(2B + 1)\) component which intertwine between the unitary \((2s + 1)\)-component Wigner representation and the covariant \((2A + 1)(2B + 1)\) dimensional spinorial representation labeled by the semi-integer \( A, B \) which characterize the finite dimensional representations of the covering of the Lorentz group \( SL(2, C) \). The intertwiner functions are determined in terms of group theoretic properties; the use of modular localization is not necessary.
There is one annoying loophole in this construction in that the important massless vector potential and more generally tensor potentials do not exist in a point-local form since they violate positivity. In that case the way out has been to quantize classical gauge theory. The problem with this is that Hilbert space positivity, which is classically irrelevant but indispensable for the probabilistic properties of quantum theory, is violated in the quantized result. It can be recovered only for the gauge invariant part of the theory which excludes the important matter fields but includes the local observables in the form of gauge invariant fields. There exist no perturbative approach based on point-local fields which is able to avoid the use of unphysical fields. This requires the introduction of additional indefinite metric degrees of freedom and ghost fields which have no counterpart in the classical theory but are necessary to implement the operator gauge transformations; the latter bear no relation with physical symmetries but are nevertheless needed in order to extract the physical quantities from an unphysical setting.

The physical reason for being forced to take recourse to quantum gauge theory is that there is a clash between positivity and localization of which the problem with massless pl free vector potentials is only the tip of an iceberg. It also manifests itself in the nonexistence of massless conserved pl currents for $s \geq 1$ as well as that of massless energy-momentum tensors for $s \geq 2$. In the presence of interactions its manifestation affects even massive QFTs in that it is the cause of the nonexistence of positivity preserving renormalizable interactions involving $s \geq 1$ fields. Instead of combatting this phenomenon by short distance improvement resulting from compensations of part of the positive probability with negative metric contributions the positivity preserving way of improving short distance scale dimensions of fields is a relaxation on tightness of causal localization by passing from pl to sl free fields.

## 5 String-localized fields

Point-local free fields for spin $s$ or helicity $h$ are uniquely determined in terms of their covariance. Massive tensor fields of spin $s$ have short distance dimension $d_{sd} = s + 1$. Interaction densities $L$ are defined in terms of Lorentz-invariant Wick-ordered products of free fields and according to the power counting bound of renormalizability $d_{sd}(L) \leq 4$ there are no renormalizable interactions with $s \geq 1$. Positivity obeying massless point-local tensor fields of helicity $h \geq 1$ and tensor degree $h$ do not exist; this is a consequence of the absence of intertwiners from massless helicity $h$ unitary Wigner representations to $(h/2, h/2)$ covariant tensor fields.

Both problems are related to the positivity of pl fields which is in turn a consequence of the unitarity of Wigner’s representation theory. For $s = 1$ this problem is formally solved by replacing the Hilbert space by a positivity-violating indefinite metric Krein space which lowers the $d_{sd}$ of the Proca field from 2 to 1. The indispensable positivity property is then recovered for the

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7A similar problem exists for massless fermionic fields for $s \geq 3/2$. 

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subtheory of local observables (which includes field strengths) whereas the important charge-carrying fields, which relate the causality principle with particles, remain outside gauge theory. Hence gauge theory, although in its classical form a complete theory with local gauge invariance, is an incomplete QFT in which gauge symmetry plays the role of a formal device whose only purpose is to filter the physical subtheory from an unphysical (negative probabilities containing) description.

The new string local field theory (SLFT) is a complete QFT whose construction is based on the observation that the culprit for the indefinite metric and the resulting lack of positivity of probabilities is the use of covariant pl fields. As soon as one uses their covariant sl siblings in a way which is consistent with their weaker localization one is led to the beginnings of a new renormalization theory in which \( s = 1 \) (and more generally \( s > 1 \)) fields have a spin-independent short distance dimension \( d_{sd}(\text{bosons}) = 1, \ d_{sd}(\text{fermion}) = 3/2 \) and thus permit the formation of tri- or quadri-linear interaction densities \( L \) with the power counting bound (pcb) \( d_{sd}(L) \leq 4 \).

The "naturalness" of sl fields follows from a theorem in LQP \[10\] which states that in the presence of a mass gap there exists for each particle type an interpolating sl field\[9\]. From SLFT one knows that interactions containing \( s \geq 1 \) fields lead (apart from pl observables) to sl interacting fields. The terminology QFT and in particular LQP always refers to positivity maintaining descriptions; indefinite metric descriptions will be referred to as gauge theory (GT).

The Wightman setting of QFT and Haag’s LQP cannot dispense with positivity; its absence does not only affect the probability interpretation but gauge dependent fields also fail to describe the correct causal localization. In order to solve the positivity problem it is important to understand the relation between tightness of localization and short distance dimensions in more detail. Starting from a massive \( d_{sd} = 2 \) Proca vector potential \( A^\mu \) it is easy to see that the covariant string-local solution of the operator-valued differential 2-form \( F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \) results in \( A_\mu(x,e) = \int_0^\infty F_{\mu\nu}(x + \lambda e)e^\nu d\lambda, \ e^2 = -1 \) (6)

Here the linear form of the space-like string and the Lorentz transformation of \( e \) in the covariant secures the covariance of sl fields and the integration to infinity insures the lowering of the dimension from \( d_{sd} = 2 \) to 1.

By starting from a massive general spin \( s \) tensor field and forming the field strength which corresponds to a 2s-form the s-fold repetition of the line integration results in a \( d_{sd} = 1 \) \( e \)-dependent string-local counterpart while their iterative application to the pl degree \( s \) tensor potential define the \( s \) tensorial escorts of maximal degree \( s - 1 \) \[36\]. A similar idea applied to the point-local spinor-tensor potential of half-integer spin \( s \) (one spinor- and \( s - 1/2 \) tensor indices) leads to a similar situation in which the resulting string-local spin \( s \) field

\[8\]In the algebraic setting of LQP this corresponds to an interpolating operator which belongs to an algebra of an arbitrary narrow space-like cone (whose core is a space-like string).
has the same dimension as a \( s = 1/2 \) Dirac field namely \( d_{sd} = 3/2 \), independent of \( s \). By taking a more general integration measure \( d\lambda \to \kappa(\lambda)d\lambda \) one can vary the \( d_{sd} \) continuously down to zero.

Only the so constructed massive sl tensor potentials have smooth massless limit\(^9\). This does not only lead to the sl replacement of the missing pl massless potential but it also defuses a No-Go theorem by Weinberg and Witten claiming that massless energy-momentum tensors do not exist for \( s \geq 2 \)\(^{37} \). The correct statement is that \textit{pl conserved massless E-M tensors do not exist}; they have to be replaced by \textit{sl E-M tensors which are different as densities but lead to the same global charges} (generators of the Poincare group).

One may think that the use of sl instead of pl fields which converts pcb violating pl interaction densities into pcb obeying sl ones renders a model renormalizable. But as often in QFT, trying to patch up a problem creates another problem at an unexpected place. Without the fulfillment of an additional condition, which prevents the total delocalization at higher orders, the validity of the pcb is insufficient to guaranty consistency. This additional requirement will be addressed in section 6.

Covariant sl fields can be constructed in a rather elementary way from their pl counterparts without referring to the more foundational LQP. But overlooked simple constructions arise sometimes in a roundabout way. The study of sl fields did not start in the above form but rather developed in the aftermath of solving the foundational problem, more than 7 decades old, of the causal localization of Wigner’s infinite spin matter for which it was essential to use modular localization theory.

In \cite{30} it was shown that all positive energy representations are localizable in arbitrary narrow (noncompact) space-like cones. Since it is well known that the massive and finite helicity zero mass class is pl generated and that the generating fields of the infinite spin representations cannot be pl Wightman fields \cite{38} it seemed likely that their generating fields are localized on the semi-infinite string-like cores of a space-like cones. Using the modular localization of the LQP setting it was possible to construct the intertwiner functions \( u(p,e) \) which relate the momentum space Wigner creation/annihilation operators with covariant sl fields \cite{39}. Previous attempts in terms of Weinberg’s group theoretic method based on covariance had failed.

Meanwhile there appeared a rather sophisticated direct proof which excludes the existence of nontrivial compact modular localized Wigner-Fock subspaces \cite{41}. It uses the spatial version of modular localization (the \( K \)-spaces) sketched in the previous section. This raises the question about possible physical properties of those fields. The new setting of sl perturbative renormalization theory strongly suggests that this infinite spin matter is inert with respect to interaction with normal matter. Matter which only exists in the form of free fields and, through the use of its energy momentum tensor in Einstein-Hilbert equations,

\(^9\)What is meant is that the 2-point massive correlation functions converge to those of the massless helicity fields but the representations of the operators of course remain unitarily inequivalent.
may lead to backreactions on the gravitational field, is an interesting candidate for dark matter since its "coldness" is natural \[42\].

The same method of modular localization applied to Wigner’s unitary representations of ordinary matter led to the rather large class of massive and finite helicity massless spin fields which also can be directly constructed in terms of semi-infinite line integrals over pl fields.

The next section addresses the question of interest for many readers are string-localized fields related to ST theory?.

6 21st century physics, or, the new phlogiston?

The naturalness of string-localization in LQP and its generic appearance in all positivity preserving renormalizable interactions involving $s \geq 1$ particles begs the question of its relation to string theory (ST).

To understand how particle physicists arrived at ST it is helpful to recall its historical roots which can be traced back to ideas about an autonomous S-matrix theory. This refers to attempts to formulate a theory of scattering amplitudes without the use of its large time asymptotic relation with QFT. The problem of such a project is that causal localization principles of QFT are not available in such a direct construction of global on-shell objects.

A possible way out was to look for analyticity properties which generalize those of the dispersion relations. The most conspicuous model-independent property of on-shell restrictions of Feynman diagrams is the analytic crossing property. In order to separate this property from its (for strong interactions useless) perturbative context Mandelstam proposed a representation for the elastic scattering amplitude which incorporates such a property.

The historical origin of ST cannot be understood without Veneziano’s subsequent Dual Model which replaces Mandelstam’s representation by a concrete crossing symmetric meromorphic functions which substitutes the elastic scattering continuum by a trajectory of particle poles.

ST started by viewing such on-shell particle mass trajectories as manifestations of strings in spacetime in analogy with the energy spectrum of a chain of quantum mechanical oscillators. This new spacetime interpretation implied a return to an off-shell description based on the quantization of actions of world sheets traced out by strings in spacetime. The interaction between such strings was assumed to be described in terms of splitting and recombining tubes representing world sheets.

The positivity requirement on this quantization selected one model in which the spacetime was the target space of a certain $d = 1 + 1$ conformal field theory associated to a 10-component supersymmetric current. Our 4-dimensional world was to result from a Kaluza-Klein dimensional reduction.

Since Haag’s LQP comprises all models which fulfill the causal localization principles in a (positivity obeying!) Hilbert space setting and ST falls according its protagonists into this category, the obvious question is whether the objects of ST describe, as string theorists claim, string-localized objects in the sense of
causal localization in Minkowski space. If localization in ST really means what the terminology suggests, two string operators should commute if the strings are spacelike separated (the quantum version of Einstein-causalit y); there is no other physical meaning which one can attribute to quantum strings localized in spacetime.

Freed from a quantization parallelism to classical physics, the LQP formulation is synonymous with a realization of causal localization principles in the context of quantum theory which means in particular that string-local operators are defined as objects in spacetime which are causally localized i.e. two string operators commute if they are relatively spacelike separated.

Causal localization is inexorably connected to vacuum polarization and the strength of the vacuum polarization clouds depend on the tightness of localization. This affect in particular the short distance scale dimensions of pl fields. If the alleged ”stringy” objects of ST bear any relation to spacetime strings they must be related to the sl fields of LQP even if they had been constructed in a different way from that of sl fields. The main point of contention is whether the objects of ST are really string-local in any with relativistic causality compatible sense.

In order to understand that string theorists use the terminology ”string” for something which bears no relation with localized quantum objects in spacetime it is helpful to look at what they are doing and understand why they think they are addressing propertie of quantum localization. Before add ressing the quantization of the Nambu-Goto action or constructing their 10 dimensional ”superstring model” from the action of a particular 10 component supersymmetric $d = 1 + 1$ conformal current model string theorists it is helpful to take a critical look at their view of the quantum theoretical counterpart of particle world lines [43].

The model is defined in terms of the relativistic action $\sqrt{-ds^2}$ but the resulting covariant classical world line has no quantized counterpart since particle operators $\vec{q}(t)$ only exist in (nonrelativistic) quantum mechanics (the nonintrinsic ”Born localization”) and the quantum theoretical description of a single relativistic particle uses Wigner representation theory. From the latter one can construct free fields which and the point-local free fields can be reformulated in terms of a relativistic action. There is simply no access to wave functions of relativistic particles in terms a quantization of actions describing relativistic world lines and hence this construction turns out to be a squib load.

The theory which describes relativistic particles is Wigner’s construction of unitary representations of the Poincaré group which cannot be accessed by quantization of classical actions; in fact his 1939 unitary representation theory was the first successful intrinsic quantum construction of a relativistic particle theory. As we know nowadays this theory already contains the germ of causal localization\[\text{10}\] in the form of modular localization of positive energy states which

\[\text{10}\]Wigner tried ito find a representation theoretical signal of causal localization and became disappointed when he realized that the ”Newton-Wigner localization” did not solve the problem \[2\]. The conceptual prerequisites for the later ”modular localization did not exist at that time.
is closely related to the causal localization of fields.

Only on this level of causal localization of fields can one make contact with the quantization of pl fields (section 3). The more generic and important covariant sl fields cannot be accessed in this way (section 4). They are objects which are pure quantum in that the umbilical cord of an alleged quantization parallelism has been cut. This is our main motivation for giving much space to causal localization in an article dedicated to the memory of the protagonist of LQP which places causally localized operator algebras into the center stage.

This leaves the question of what remains of ST if it is not a theory of quantum strings in spacetime. An authoritative answer from somebody who has spent a good part of his professional life to understand the physical content of the Nambu-Goto action is that it describes an infinite set of conserved charges as one finds in \( d = 1 + 1 \) integrable QFTs. But different from integrable \( d=1+1 \) QFT there is no trace of any spacetime localization in N-G models \[44\].

The fusion and splitting of world sheets as a description of spacetime strings in analogy to the interpretation of perturbative Feynman graphs as coalescing and splitting of point-like particles represents an attempt of string theorists to create localized interactions in terms of classical metaphors. On the other hand the fact that this is based on misunderstandings of quantum causal localization does not invalidate the mathematical use of such constructions as an inspiration for interesting topological, algebraic and geometric constructions. ST also led to some new computational techniques which are useful in other areas of particle theory. If it did not prevent careers by occupying many research positions and distract many from problems of particle theory it would be easier for physicists to appreciate its mathematical contributions.

One reliable result which was obtained by string theorists, although not related to string localization, is a theorem by Brower \[45\]. It states that the irreducible superstring algebra, defined in terms of the aforementioned supersymmetric 10 component conformal field theory, carries a positive energy Wigner representation which decomposes into an infinite direct sum of irreducible \((m > 0, s)\) and \((m = 0, h)\) Wigner representations.

This has an interesting connection with an old project by Majorana. In analogy to the description of the discrete spectrum of the hydrogen atom in terms of a \( O(4, 2) \) representation, Majorana’s idea was to construct a group algebras of a higher dimensional group which contain a tower of particle wave function spaces. This idea underwent a revival in the 60s in the form of ”dynamical groups” leading to a discrete spectrum of particles. Apart from the fact that the irreducible superstring algebra associated to the conformal field theory is not a group algebra, Brower’s theorem is similar in that it refers to a particular particle spectrum which originates from the action of the Poincaré group on an irreducible algebra.

In the eyes of string theorists the map of the two-dimensional conformal space into the 10 dimensional target space describes what they call a string in form of a world sheet defined in terms of a map from the two-dimensional conformal space into the 10-dimensional ”target” spacetime. Without these ”string glasses” one only sees a discrete direct sum of unitary Wigner representation (but no target
space localization) whose conversion into covariant free fields leaves the choice of pl or sl. As for any unitary positive energy Wigner representation which carries a modular localization structure it is the interaction which decides about the localization: renormalizable interactions of $s < 1$ require the use of pl fields whereas renormalizability and positivity in the presence of $s \geq 1$ fields can only be maintained in terms of string-localization.

The problem of localization of fields has nothing to do with that particles; the latter remain what they always were: states described by in time dissipating Wigner wave function which, as a result of their positive energy content, do not admit a causal pl or sl localization. What may be idealized as a pl event is the registering in a counter; the difference whether the fields whose application to the vacuum create these states were sl or pl only manifests itself in a more spacetime spread out region of clicks. It is important to have a clear view of the relation between fields and particles in order to understand Haag’s stomach ache with string theorists view of strings and particles (see below).

The heuristic picture of ST in terms of splitting and recombining world sheets has led, particularly in the hands of Ed Witten, to highly interesting new ideas and results in geometry and topology but this has not helped to its physical use. Concepts as that of modular localization which are the raison d’être for local quantum physics have remained outside ST and its derivations (extra-dimensions, AdS-CFT).

The promise to address the issue of string-localization (which is the origin of the terminology ST) has remained unfulfilled and there is no way in which this can change. It is simply not possible to create a new theory without a foundational dispute with the in every aspect successful and comprehensive QFT. Mathematical enrichments cannot hide the fact that the physical contributions of ST to particle theory has remained smaller than any preassigned epsilon.

Historian of physics who would seriously attempt to take stock of viable theoretical physics concepts which originated within 50 years of ST will presumably have a hard time to account for what had been achieved. Haag’s reaction to the present situation in this respect is quite interesting.

On the occasion of presenting a seminar talk more than three decades after having held a visiting position at the university of Princeton, he was hard pressed by Ed Witten to join the ST community. Haag’s recollection of this situation can be found in his published reminiscenses [2]. He writes:

"I visited Princeton in the early 90ies. At that time Sam Treiman was head of the physics department at the university. I had known him since 1958 and highly appreciated his sober judgement. So I asked him about his assessment of the future of string theory. He said that he had not occupied himself with it but that he was supporting it without reservation because the people who worked on it were very very good. He meant primarily Ed Witten who was now the spearhead of this approach. I had been asked to give a physics colloquium talk about my views on quantum gravity and hoped to have some discussion with Ed Witten. Next morning he greeted me by saying: “Your talk was very interesting but I would really advise you to work on string theory”. When he saw the somewhat incredulous look on my face he added “I really mean..."
it. I shall send you the manuscript of the first chapters of our book”. This
ended our discussion. Back in Hamburg I received the manuscript but it did
not convert me to string theory. I remained a heathen to this day and regret
that meanwhile most physics departments believe that they must have a string
theory group and have filled their vacant positions with string theorists. To be
precise: It is good that people with vision like Ed Witten spend time trying to
develop a revolutionary theory. But it is not healthy if a whole generation of
young theorists is engaged in speculative work with only superficial grounding
in traditional knowledge.”

Haag’s critical comments should be seen in the context of his conduct of
research which is distinguished by self-reliance and a self-critical scrutinizing.
This may have had its origin in the circumstances in which his interest in the-
oretical physics arose. As a teen ager he was on a private visit to his sister
who lived in the UK when in 1939 the war started and he could not return to
his mother in Stuttgart and finish high school (in 1939 his age was 17). As a
German citizen he was shipped to Canada where he spend the years of war in
a detention center. There he managed to get hold of a book on physics which
he used for self-studies.

Returning at the end of the war from the Canadian camp to Stuttgart he
found himself in a war-devastated city without a functioning academic teach-
ing program. In such a situation self-reliance and intellectual autonomy were
important.

To find his former strongly independent minded colleague from Princeton
Sam Treiman three decades later in a state of dependence on authorities con-
cerning a subject which he considered of prime importance was apparent-
ly somewhat unexpected for Rudolf Haag.

The reaction of Haag to both Witten and Treiman can be best commented
in form of a metaphor: it is not enough to believe to have discovered the Lapis
Philosophorum, one must also have the charisma to convince sufficiently many
prestigious persons to share this belief.

Haag was hardly impressed by mathematical work whose motivation did not
originate from fundamental physical problems. The situation of QFT after the
discovery of perturbative QED, in which different prescriptions of “exorcising
infinities” amazingly led to mutually compatible results, certainly motivated
him to look for a more coherent description which finally culminated in his
framework of what he later referred to as local quantum physics (LQP). He was
convinced that all properties of causally localized quantum matter was encoded
in the relation between observable algebras $\mathcal{A}(\mathcal{O})$ labeled by their spacetime
localization region $\mathcal{O}$. His innovative strength resulted from his ability to find
the appropriate mathematical setting for his physical ideas. For more detailed
mathematical knowledge he relied often on mathematically more knowledgeable
collaborators.

The mere fact that ST did not arrive at any observationally testable proposal
throughout its 50 years of existence (which is its common critique) was of not
much concern to Haag. One can assume that both he and Witten shared the
belief that foundational ideas should have all the time they need to evolve.
He would however have expected that the exploration of a foundational idea should lead to a steady increase of knowledge about important theoretical problems of particle physics. His LQP led to a profound understanding of why the local structure of QFT is much more powerful than its classical counterpart. Together with his collaborators Sergio Doplicher and John Roberts he derived a classification of internal symmetries and the absence of parastatistics as consequences of properties of superselection rules which in turn were obtained from localization structure of local observables. Theorems in Wightman’s formulation of QFT \cite{32} have their counterpart in LQP and some properties (including the causal completion property and Haag duality) permit no natural formulation in Wightman’s field theoretic setting. Most of the results were obtained by a few researchers; the number of people working on foundational problems of QFT in the 80s was rather small compared with that in ST.

On the other hand ST led to ”hot topics” which produced thousands of publications and provided university positions to their authors who in many cases obtained their positions because they were working on such a fashionable topic.

The formation of such transient fashions is reminiscent of bubbles in the financial market but it is presently not clear to me whether this is the consequence of the increasing dominance of financial capitalism in all areas of life or whether this has its more specific explanation in the seducing charisma of the protagonists of ST; probably it is the result of a Zrizgeist in which both interplay.

An example of such a bubble in the wake of ST is the physical use of the mathematically correct AdS-CFT isomorphism. Fronsdal observed already in the 60s that the spacetime symmetry group of the so-called anti-de Sitter spacetime is isomorphic to the symmetry group of a one dimensional lower conformally invariant spacetime. As a result of a presumed connection between five-dimensional gravity with gauge theories in four spacetime dimensions the problem of a possible QFT isomorphism behind the AdS-CFT group theoretical relation returned in the late 90s.

Since the mismatch between degrees of freedoms in comparing QFTs in different spacetime dimensions renders the use of fields unsuitable, the existence of a AdS-CFT isomorphism was finally rigorously established within the algebraic LQP setting \cite{7}. The proof showed that the mismatch of the cardinality of degrees of freedom between isomorphically related QFTs in different spacetime dimension only affects the causal completeness property, which is the quantum counterpart of the hyperbolic propagation of classical Cauchy data.

As mentioned before (section 2) this problem is not limited to this particular isomorphism but it affects all problems related to ”transplanting” quantum matter between spacetimes of different dimensions; metaphorically speaking the resettling from higher to lower dimensions suffers from overpopulation whereas in the opposite direction it causes ”anemia” in that there are not enough degrees of freedom to sustain AdS fields. The most appropriate way is to express the isomorphism in terms of localized operator algebras \cite{7}.

Methods based on quantization of actions are not suitable for the study of
such isomorphisms because the notion of cardinality of degrees of freedom has no counterpart in classical or semiclassical field theory and therefore tends to be overlooked. This mismatch of cardinality of degrees of freedom removes the rug from underneath the idea of *extra dimensions*.

This situation reveals a dilemma of present foundational theoretical research. The increasing number of researchers in particle theory does not seem to lead to a broadening of topics and an increase of critical knowledge: it rather tends to favor monocultures and a loss of past knowledge and wisdom.

It is interesting to compare the present situation with that which Haag met in the 50s during his stay at the Niels Bohr Institute in Copenhagen ([2] page 269) and which still dominated the scientific discourse during the 60s. This was the high time of the ”European Streitkultur” in which different views about problems and the elimination of incorrect or misunderstood ideas as well as what new directions to take was hammered out in often heated and sometimes even polemic disputes between equals.

After the discovery of quantum theory in Europe different universities often represented different schools of thought (”the Copenhagen interpretation”) which led to rivalries and sometimes even to polemics between the protagonists of these schools. When the political situation worsened many of the leading scientist left for the US and this rivalry spread to the US. In the 50’s and 60’s the discourse was dominated by individuals as Pauli, Jost, Kallen, Landau, Lehmann, Feynman, Schwinger to name just a few.

A positive effect of this often somewhat rough way of communicating was that futile or erroneous ideas (the S-matrix bootstrap, peratization, Heisenberg’s spinor theory, Reggeology, SO(6),...) could not survive for more than a decade. In highly speculative research as particle theory the occurrence of wrong turns is inevitable and therefore the existence of a lively ”Streitkultur” is important. In such a climate the survival of theory bases on misunderstood or even for more with a Nearly all our important theoretical results and computational tools, which later became household goods, originated in those times.

Compare this with the legacy of 5 decades of ST; apart from some new calculational techniques and an enrichment of certain ares of mathematics it is hard to find any remaining contribution to particle theory. ST and its legacy appears increasingly as a gigantic bubble in particle theory which has led to extra dimensions, branes, M-theory,...which contradict basic properties of QFT. The more damaging legacy of this bubble is the incorrect view of the field-particle relation which ignores previously gained wisdom.

It is interesting to quote Haag on this matter [2]. ”In many popularized presentations the starting point of string theory is explained as the replacement of the fundamental notion of ”particles” with its classical picture of a point in space or a world line in spacetime by a string in space respectively a sheet in spacetime. This, I think, is a misunderstanding of existing wisdom. First of all, paraphrasing Heisenberg , one may say ”Particles are the roof of the theory, not its foundation.” Secondly points in space cannot be defined as the position of particles in a relativistic theory.”

The understanding of the relation between fields and particles is one of the
most important and subtle achievements of the 50’s and 60’s. Quantum fields are the carriers of the foundational causal localization principles and are generally not objects of direct observation.\footnote{However their quasiclassical approximations (usually expectation values in coherent states) are measurable in QED (the massless photons are important).}

In particular the correct formulation of string-like localization of fields does not imply that particles become ”stringy”. Covariant free fields exist in pl as well in a sl form; applied to the vacuum pl and sl fields create states in the same Wigner representation. Their difference only shows up in interactions; in particular renormalizability requires to use sl $s \geq 1$ fields in the interaction density (section 6) and higher order interactions transfers this sl localization to the originally (in lowest order) pl $s < 1$ fields.

There naturalness of sl localization is supported by a theorem (\cite{10} section IV.3) which states that in models with a mass gap and local observables the asymptotic particles and their scattering matrix can be described in terms of the large time asymptotic behavior of operators which are localized in arbitrary narrow spacelike cones whose cores are spacelike strings. Taking this theorem from its algebraic LQP setting to that of QFT formulated in terms of covariant fields it states that in such a theory the Wigner particles can be described in terms of interpolating covariant sl fields.

What was not known at the time when Haag wrote his reminiscences was that positivity violating local gauge theory can be reformulated in terms of a positivity obeying sl theory and that the idea of positivity preservation requires the use of sl $s \geq 1$ fields in all interactions involving such fields. Viewing local gauge theory as a prick in the flesh of QFT he certainly would have appreciated this recent insight. It strongly suggests that sl is the standard situation and interacting pl fields are limited to $s < 1$ interactions.

The state space generated by charge-carrying fields coupled to photons has a more complicated particle structure ("infraparticles") than a Wigner-Fock particle space and its description remains essentially unknown, although there exist efficient momentum space descriptions for photon-inclusive cross sections (Bloch-Nordsiek, Yenny-Frautschi-Suura \cite{61}). The loss of foundational knowledge on the road to a ”theory of everything” bodes ill for the future of particle theory.

Research at the frontiers of particle theory is an intrinsically highly speculative intellectual activity. According to one of Feynman’s allegorical comments it is sometimes necessary ”to dive into the blue yonder” but, as he continues to point out, such jumps should be only undertaken from a platform of solid knowledge of QFT, so that one can return and try other directions instead of getting lost for the rest of one’s life in a hopeless project. In his last years of his life he saw the problems originating from the popularization of ST but he was unable to influence its course.

For the first three decades of post-renormalization QFT it was possible to make important discoveries without deep conceptual investments. With some basic knowledge about computational techniques of QFT and a heuristic under-
standing of the field-particle relation one could make important discoveries "by pulling up one's sleeves" and starting a calculation and, if necessary, correcting it or trying other directions.

It was not important whether a consistent and interesting-looking result was derived from a fully correct theory since there was always the possibility to consider incomplete or faulty theoretical ideas which led to important discoveries as a temporary placeholder and hope for a future more appropriate understanding. In this way Dirac discovered antiparticles within the less than correct hole theory.

This way of conducting research was exhausted at the end of the 70s. ST and its derivates are the result of attempts which tried to extend this success without making new conceptual investments. According to Phil Anderson the overwhelming success of particle theory in its first decades of existence had created a kind of intellectual arrogance about Nature. It was easier to speculate about how to go beyond QFT and claim to arrive at a theory of everything than to do the hard work necessary for the understanding of the deeper conceptual layers of our most successful and comprehensive theory of the material nature of the world. The superficial image of QFT which the leading influential representatives of ST painted and transmitted was that of "old QFT" being replaced by ST.

The title of this section contains the term "phlogiston" which in pre-oxygen times represented a substance which allegedly escapes in the process of burning. The phlogiston theory only disappeared when Lavoisier at the time of the French revolution discovered oxygen and its role in combustion. ST cannot disappear in this way because unlike phlogiston it has no observables consequences. As long as there are renown scientists (including bearers of Nobel prizes) among its protagonists it will persist. The times in which it was possible to clarify issues in disputes between equals as in the old European Streitkultur are long gone.

7 String-local perturbation theory

In the absence of interactions massive pl fields and their sl counterparts are two physically equivalent ways of coordinatizing a free LQP model; in particular the sl fields maintain the asymptotic relation between fields and particles which is the basis of time dependent (LSZ, Haag-Ruelle) scattering theory. The Wigner-Fock particle structure breaks down in case the interaction involves massless fields.

Haag’s LQP and in particular the concept of modular localization played an important role in raising awareness about the important role of covariant sl fields and led to their first constructions \[39\]. It turned out that, apart from fields associated to Wigner’s infinite spin representation class, all covariant sl free fields can be directly constructed in terms of pl free.weighted line integrals over pl fields.

Perturbative constructions involving sl fields are very much in their infancy, and if the following simple illustrations encourage other particle theoreticians to
engage in the exploration of this extremely rich area of research this section will have accomplished its purpose. The only perturbative interactions which have been considered up to date are couplings of massive $s = 1$ vector potentials to lower spin ($s = 1, 1/2$) matter fields.

In order to pass from a nonrenormalizable pl interaction density to its less singular sl counterpart one needs a linear relation between the $s \geq 1$ pl fields and their less singular sl counterparts. For massive vector potentials this relation reads

$$A_\mu(x,e) = A_\mu^p(x) + \partial_\mu \phi(x,e), \quad \phi(x,e) = \int d\lambda e^{\nu} A_\nu^p(x + \lambda e)$$

(7)

$$A_\mu(x,e) = \int d\lambda e^{\nu} F_{\mu\nu}(x + \lambda e), \quad F_{\mu\nu}(x) = \partial_\mu A_\nu^p - \partial_\nu A_\mu^p$$

It involves an additional scalar sl field.

Scalar covariant sl fields for any integer spin have been first constructed in [39]: their semi-integer fermionic counterparts are sl Dirac fields for any half-integer spin. They violate the connection between physical spin and the covariant transformation property of their pl counterparts. It turns out that only those sl fields which appear in a linear relation between covariant pl fields and their sl counterparts as in (7) play an important role in the new SLFT renormalization theory. On a purely formal level their appearance in the form of a gauge transformation is reminiscent of scalar negative metric Stueckelberg fields which appear in the operator gauge transformation between the Feynman gauge and its unitary counterpart; they convert the renormalizable but unphysical matter fields into their formally physical but very singular counterparts [50].

The conceptual and mathematical situation in (7) is very different. The three linearly related fields live on the same Wigner Fock space of $s = 1$ particles and belong to the same sl localization class (i.e. they are relatively Einstein-causal in the sense of string-localization). The sl setting avoids the introduction of additional (unphysical) degrees of freedom and in this respect may be viewed as the result of the "application of Ockham’s razor to gauge theory" [36]. It is not a gauge theory because the local operator gauge transformations (different from the global U(1) transformations) cannot be defined without the presence of additional (indefinite metric) degrees of freedom.

The computational tests and the conceptual coherence of the new SLFT setting leave no doubt that after more than 70 years one finally arrived at a new setting which reunites the $s < 1$ renormalizable interactions with those of $s \geq 1$ under the same conceptual roof of causally localized and positivity obeying (quantum probability preserving) genuine quantum theories.

The sl scalar $\phi$-fields will be referred to as an "escort" of the pl Proca potential. Only the correlation functions of the sl potential permits a massless limit whose reconstructed Wightman field [32] is the vector potential of Wigner’s $h = 1$ helicity representation [13]. The purpose of this care about massless limits, 

\footnote{They are not polynomially bounded and hence they cannot be Wightman fields.}

\footnote{Since massless Wigner representations are unitarily inequivalent to massive ones, the smooth behavior refers to the expectation values and not to the operators.}
which in the present context appears pedantic, is to raise awareness about the reconstruction problem of a physical Hilbert space which corresponds to the Wigner Fock space provided by scattering theory in the presence of a mass gap. One knows very little about a particle-like description of this limit (the problem of “infraparticles” and confinement).

The linear relation (7) between $A^P, A$ and the escort $\phi$ is really a linear relation between their intertwiners. Computing the intertwiners $u_{\mu,s_3}(p,e)$ of $A_\mu(x,e)$ and $u_{s_3}(p,e)$ of $\phi(x,e)$ in terms of the intertwiner $u_{\mu,s_3}(p)$ of $A^P$

$$A^P_\mu(x) = \frac{1}{(2\pi)^{3/2}} \int \sum_{s_3} e^{ipx} u_{\mu,s_3}(p) a^*(p, s_3) + h.c.$$  

using their definition in (7), one verifies the linear relation [14] for general spin the corresponding formula contains $s$ escorts [36] [5]. A more geometric interpretation views the escort field in the context of the Poincare lemma applied to the differential 2-form $F_{\mu\nu}$.

It is interesting to note that the massless limit preserves the number of degrees of freedom: 2 are accounted for by $h = 1$ and one is carried by the massless limit of the pl scalar field $\phi^P(x) = \lim_{m \to 0} m\phi(x,e).$ This prevails for spin $s$ tensor fields for which the linear relation (7) contains $s$ tensorial escort fields.

Starting from the 2-point function of the unique positivity-obeying long-range massless vector potential and ”switching on” the mass one cannot return to the short range 2-point function of the Proca potential without the escort $\phi$ plying its 14. The difference from the Higgs’s mechanism is that escort fields do not introduce new degrees of freedom; so whenever the presence of an additional Higgs field is necessary it must be for other reasons.

The important property of the sl vector potential $A_\mu(x,e)$ can be seen in its 2-point function 15

$$\langle A_\mu(x,e) A_\nu(x',e') \rangle = \frac{1}{(2\pi)^{3/2}} \int e^{-i(x-x')p} M_{\mu\nu}(p;e,e') \frac{d^3p}{2p_0}$$

where the $\pm$ signs refer to the distributional boundary values $\lim_{\varepsilon \to 0} 1/(pe \pm i\varepsilon)$ from the Fourier transforms of the Heaviside function of the semi-infinite linear string.

The gauge theoretic Feynman 2-point function (without the additional rational $p$-dependent contributions) looks much simpler but contains longitudinal positivity-violating unphysical degrees of freedom which in the presence of interactions ”infect” the matter degrees of freedom and account for the physical

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[14] The Fourier transforms of the Heaviside functions $\theta(x)$ account for denominators $1/pe$.

[15] All pl fields have polynomial two-point functions in $p.$
limitations of local gauge theory which, as a result of the positivity-localization interrelation also affects causal localization.\footnote{The interacting positivity-obeying electric charge carrying covariant field of is necessary sl, even so the particle counter events can be well localized.}

In contrast to the Proca 2-point functions

\[ M^P_{\mu\nu}(p) = -g_{\mu\nu} + \frac{p_\mu p_\nu}{m^2} \]  

which has a quadratic mass divergence the sl 2-point function \( \langle A \phi \rangle \) admits a well-defined massless limit in that it passes smoothly to its sl helicity \( h = 1 \) counterpart (the mass only enters the \( p_0 \)).

The price for having used Ockham’s razor is the appearance of nondiagonal 2-point functions of free fields, e.g. mixed 2-point function \( \langle A \phi \rangle \). This is not surprising since both \( A \) and \( \phi \) are linear combinations of the same Wigner creation/annihilation operators. This leads to a slightly more involved perturbation theory. But it is very worthwhile to pay this increase computational expenditure since the new formalism does not only maintain the quantum probability but secures also the physical localization.

Already for the free sl potentials this implies a slightly more refined interpretation of the Aharonov-Bohm effect. It can be shown that Wilson loops keep a topological memory of the string dependence \footnote{This is the origin of the quirky feeling about causality which makes the A-B effect a subject of public interest.} which leads to a violation of the Haag duality. The latter is slightly stronger than Einstein causality (= instead of \( \subset \)) which is intuitively often identified with the latter \footnote{Haag’s presentation of Cooper pairs is particularly close to the spirit of LQP \cite{10}.}. The violation of Haag duality is a feature of all massless physical \( s \geq 1 \) fields which only exist in the form of positivity preserving sl fields.

The conversion of \( d_{sd} = s + 1 \) potentials into their \( d_{sd} = 1 \) sl counterparts is a general phenomenon \footnote{Among other things they account for the change of long-range classical Maxwell vector potentials into their short-range counterparts inside a superconductor (F. London’s screening).} and has an extension to Fermions. For instance for the massive \( s = 3/2 \) Rarita-Schwinger potential the corresponding escort shares the \( d_{sd} = 1 \) with the above scalar escort but reveals its Fermi statistics through the presence of gamma matrices in the propagator. The claim that there exist gamma independent \( d_{sd} = 1, s = 1/2 \) ”Elko fields” is based on a misunderstanding of the relation of free fields with Wigner’s representation theory \cite{51}.

New physical properties arising from the reorganization of already existing degrees of freedom into new fields represent a quite common phenomenon in quantum mechanical many body problems. For example the Cooper pairs in superconductivity are the result of such regrouping of electrons into bosonic bound pairs at low temperature\footnote{Among other things they account for the change of long-range classical Maxwell vector potentials into their short-range counterparts inside a superconductor (F. London’s screening).}.

In fact this analogy between escorts \( \phi \) and Cooper pairs goes much further. It clears the head from the tale about ”fattening” of photons by ”swallowing” massless Goldstones and facilitates the correct understanding why massive...
neutral Hermitian $H$ fields are really needed to save the second order renormalizability of self-interacting massive vector mesons through short distance compensations. This is similar to what what was expected to be a fringe benefit of supersymmetry but in the present case it is the raison d’être for the $H$ field (more details below).

By analogy the long range vector potentials of photons cannot be converted into their massive Proca counterparts by just "switching on" a mass; one also needs the intervention of the $\phi$ escort field. QFT. Such escort fields do not appear in renormalizable lower spin $s < 1$ interactions or in the $s = 1$ indefinite metric local gauge theory\(^{19}\), but their presence turns out to be an indispensable aspect of renormalizable positivity preserving LQP interactions involving $s \geq 1$ particles. The conversion of $d_{sd} = s+1$ spin $s$ pl fields into their better behaved $d_{sd} = 1$ sl counterparts requires the introduction of $s$ (for half-integer spin $s - 1/2$) escort fields.

Before addressing the dynamic use of sl vector potentials it is interesting to note a relation of the massless sl potential with the $d_{sd} = 1$ radiation potential. The angular integration of the sl potential over the directions emanating from the point $x$ in a equal time hypersurface leads to the radiation potential. Both the non-covariant radiation potential and the covariant sl potential live in the same Hilbert space and remain infrared convergent in the massless limit.

It has been known for a long time that the radiation (Coulomb) potential (in contrast to vector potentials in gauge theory) lives in the Hilbert space of the $h = 1$ Wigner representation. This is the reason why investigations of long distance (infrared) properties of charged particles have been preferably discussed in the "Coulomb gauge"\(^{[52]}\). But the radiation potential is not a gauge in the sense in which we have used the word gauge theory and gauge transformation in the present work since any gauge theory needs additional (generally indefinite metric) degrees of freedom to implement operator gauge transformation for passing from one gauge to another.

The main reason for using the gauge theoretic setting in QED is that the lack of covariance makes the Coulomb potential unsuitable for renormalization. The new renormalization theory based on covariant sl fields permits to compute the renormalized Coulomb equivalent of any operator by angular averaging over all string directions. This shows in particular the equality of $e$-independent operators (local observables, S-matrix) in both descriptions.

The guiding idea of the new sl renormalization theory is the conversion of the power-counting bound (pcb) violating first order pl interaction density $L^P$ with $d_{sd}^{int} > 4$ into a $d_{sd}^{int} \leq 4$ renormalizable sl density $L$. In this way one maintains the heuristic physical content while improving the short distance properties. This passing from pl to sl does not affect the Hilbert space positivity (unlike gauge theory which achieves this by a brute force compensations of part of the positive with negative metric contributions in a Krein space setting.

Let us take a brief look at how this is done. Using the linear relation\(^{[7]}\) one

\(^{19}\)This is the reason why they played no role in the more than 80 years history of QFT.
finds

\[ L^P(x) = A_\mu^P j_\mu = L - \partial^\mu V_\mu \]  
\[ L := A^\mu(x,e) j_\mu, \ V_\mu := \phi(x,e) j_\mu \]

\[ S^{(1)} = \int L^P = \int L \]  

In this way the \( d_{\text{int}} = 5 \) (3 from the \( j_\mu \), 2 from \( A^\mu \)) of \( L^P \) is lowered to \( d_{\text{int}} = 4 \) of \( L \) at the expense of \( d_{\text{int}} (\partial V) = 5 \) of the divergence term. But in models with a mass gap this term does not contribute to the first order S-matrix in the adiabatic limit.

The problem is whether the use of the renormalizable \( L \) in the adiabatic limit extends to the higher order S-matrix and whether this idea of adiabatic equivalence also works for the construction of correlation functions of sl fields. Formally speaking this corresponds to the independence from internal \( e' s \) in suitable sums of Feynman graphs after having integrated over inner \( x' s \). For the S-matrix (i.e. in the absence of external lines) this is reminiscent of gauge theory except that covariant gauge fixing parameters are spacetime independent unphysical object which bear no relation with the independently fluctuating \( e \)-directions in inner propagators.

The LQP localization theorem \[59\] does not specify for which models one needs sl instead of pl fields; here one has to appeal to the pcb of perturbative renormalizability criterion which reveals that there are no positivity obeying interaction densities within the pcb limitation \( d_{\text{pcb}} = 4 \) which involve \( d_{\text{sd}} = s+1 \) pl \( s \geq 1 \) fields. PCB violating pl interactions exist only for \( s < 1 \).

It is convenient to formulate the adiabatic equivalence in terms of the differential form calculus of the 2 + 1 de Sitter space of spacelike directions \( e^2 = -1 \)

\[ d_e (L - \partial V) = 0 \]  

here shortly referred to as the " \( L, V_\mu \) pair condition"; it states that the zero form \( L - \partial V \) is in fact exact. Its second (and correspondingly also higher) order extension \[53\] \[36\]

\[ (d_e + d_{e'}) (TLL' - \partial^\mu TV_\mu L' - \partial^\mu TLV_\mu' + \partial^\mu \partial^\nu TV_\mu V_\nu) = 0 \]  
\[ TLL^P L^P = (d_e + d_{e'}) (TLL' - \partial^\mu TV_\mu L' - \partial^\mu TLV_\mu' + \partial^\mu \partial^\nu TV_\mu V_\nu) \]

would be a trivial consequence of (13) if the time-ordered products would not be distribution valued. It is in fact a normalization condition on the time-ordering which extends the \( e \)-independence to a singular set of intersecting strings, in particular (which include coinciding end points \( x \) which carry the strongest singularities).

The higher order \( L, V_\mu \) pair condition can be seen as a round about way to define time ordered products of \( T \)-products of pl interaction densities whose direct calculation in the pl renormalization setting would lead to a with the number of \( L^P \) growing number of undetermined parameters (second line). A higher order
implementation of this formalism requires an extension of the Epstein-Glaser renormalization theory \cite{56} to sl crossings.

The pair condition \cite{[12]} is a requirement on interaction densities. Whereas there is no problem to satisfy the pcq condition for tri- and quadri-linear interaction densities $L$ involving $s \geq 1$ sl fields, to construct an $L, V$ pair for a specified field content (including the escorts) imposes restrictions on $L$ and is not always possible. But without it the higher order perturbation would cause a total delocalization and such a first order $L$ would not define a perturbative model of LQP.

There exists a simpler version of the pair condition which replaces the $V_\mu$ by $Q_\mu = d_\nu V$

\begin{align}
  d_\nu L &= \partial^\mu Q_\mu, \quad Q_\mu = d_\mu V, \quad u := d_\nu \phi \\
  (d_\mu + d_\nu) T L L' &= \partial^\mu T Q_\mu L' + \partial^\mu T L Q'_\mu
\end{align}

Assuming asymptotic completeness (no problem in perturbation theory) the Hilbert space in the presence of massive vector mesons is the Wigner-Fock tensor product space of massive vector mesons with that of the $s < 1$ matter particles. The loss of the Wigner-Fock structure in the limit of massless vector potentials presages itself in the form of infrared divergences of the perturbative scattering amplitudes.

The application of the pair formalism up to second order leads to interesting new phenomena as well as new views of old phenomena. In the following we will report on the results for four different models

- **Massive spinor QED**

  The simplest model is massive spinor QED with $j_\mu = \bar{\psi} \gamma_\mu \psi$; In that case the use of the standard kinematic time-ordered propagator \cite{47} yields the tree contribution to the 2-particle scattering contribution to which we restrict our presentation. It is important to note that the $\epsilon, \epsilon'$ dependence is only lost in the on-shell S-matrix. Using $\epsilon = \epsilon'$ in off-shell relations leads to infinite fluctuations. Since the $\epsilon'$s can be pictures as points on $d=1+2$ de Sitter space these fluctuations are similar to those of coincident points in $x$-space. Although these $\epsilon$-fluctuations have no counterpart in the spacetime independent gauge fixing parameters of gauge theory the SLF formalism shares with gauge theory the $\epsilon$-respectively gauge-independence of scattering amplitudes \cite{5}. Off shell correlation functions are independent of inner $\epsilon'$s but depend on the (fluctuating) $\epsilon'$s of the fields in the vacuum expectation values. Second order off-shell calculations have been started in \cite{47}.

  One expects that their leading short distance behavior is shared with that of gauge theory but anticipates significant differences in the long distance regime where the incorrect localization of gauge theory has its incorrect localization properties of gauge dependent fields have their strongest ramifications. In the

\footnote{obtained by the replacement $\frac{d^3 p}{p^2} \rightarrow \frac{d^4 p}{p^2 - m^2}$}
massless QED limit these expected changes even affect the particle structure (infraparticles) of the Hilbert space in a way which has not been fully understood. From a physical viewpoint the terminology ”local gauge symmetry” is misleading since behind this more local looking ”symmetry” is the result of the presence of unphysical degrees of freedom. The physical localization properties are only correctly described in a positivity-respecting setting.

- **Massive scalar QED**

For scalar massive QED with $j_\mu = \varphi^\dagger \overleftarrow{\partial}_\mu \varphi$ the appearance of a derivative leads to the well known second order quadratic in $A$ contribution

$$\delta(c - x')A_\mu(x,e)\varphi^\dagger(x)A^\mu(x',e')\varphi(x') + h.c$$

This comes about because the undetermined parameter $c$ of the Epstein-Glaser renormalization formalism which modifies the kinematic time-ordering by adding a delta function term

$$\langle T\partial_\mu \varphi \partial_\nu \varphi \rangle = \langle T\partial_\mu \varphi \partial_\nu \varphi \rangle + cg_{\mu\nu}\delta(x - x')$$

is fixed by the requirement (13) to $c = 1$. This insures that the in $A$ quadratic contribution does not introduce a new counterterm parameter. In the classical gauge theory this results from the substitution $\partial_\mu \rightarrow D_\mu = \partial_\mu - igA_\mu$ required by the differential geometry of fibre bundles whereas in SLFT it follows from the causal localization property which leads to he independence of particles and the S-matrix on string directions. We will refer to renormalization terms whose parameters are fixed by the locality principle as *induced interaction terms*. As in the previous case the fluctuations in the $e'$s become $e$-independent on-shell after adding all contributions to a particular second order scattering process.

- **The abelian Higgs model**

In this case the $L$ in the $L, V_\mu$ pair conditions depends explicitly on the scalar escort \( \phi \)

\[
L^P = mA^P \cdot A^P H = L - \partial V
\]

\[
L = m(A \cdot AH + A \cdot \phi \overleftarrow{\partial} H - \frac{m^2_H}{2} \phi^2 H)
\]

\[
V^\mu = m(A^\mu \phi H + \frac{1}{2} \phi^2 \overleftarrow{\partial}^\mu H), \quad Q_\mu = m(A^\mu uH + u\phi \overleftarrow{\partial}_\mu H)
\]

Here the vector meson mass $m$ factor in front accounts for the correct mass dimension $d_{sd} = 4$ of the interaction density\(^{21}\). The requirement of second and third order preservation of the pair property in the tree approximation comes with a surprise: in addition to the expected delta contributions $\delta(x - x')A \cdot A\phi^2$ and $\delta(x - x')A \cdot AH^2$ which can be encoded into a $T_0 \rightarrow T$ change of

\(^{21}\)Note that according to its definition the escort $\phi$ has mass dimension $d_{ms} = 0$. 

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time-ordering, there is a second order induced potential of the form of a linear combination of $H^3, H^4, \phi^2 H^2, \phi^4$\footnote{As pointed out before the $e$-independence of the S-matrix is not a postulate but rather the consequence of the LSZ scattering formalism in the presence of a mass gap \cite{59}.} There is a formal similarity with the gauge theoretic calculations in \cite{48}.

This similarity should however not be permitted to obscure the significant conceptual difference: whereas the induction in the SLFT setting is a direct consequence of the perturbative implementation of the causal localization principles, the BRST gauge theory results from the imposition of a formal symmetry which rescues a perturbative subtheory (local observables, the perturbative S-matrix) from a positivity- and causal localization-violating point-like description\footnote{The $Q_\mu$ formalism is somewhat easier to handle and maintains a formal similarity with the CGI gauge formulation \cite{43}.}. That SLFT contains only physical degrees of freedom would certainly have pleased Rudolf Haag (section 5).

SSB applies to internal symmetries of interacting $s < 1$ matter for which the same field content can perfectly exist in the form of SSB or less symmetry (independent coupling parameters and masses and a reduced number of conserved currents). For $s \geq 1$ the causal localization principle leads to the new phenomenon of a fibre bundle-like structure.

Some of these differences were suspected by Rudolf Haag and his LQP school when they realized that their classification of superselection sectors led to inner symmetries and the exclusion of parastatistics but confronts serious conceptual problems in attempts to construct field algebra which extends the local observables of gauge theory \cite{54} \cite{55}. The perturbative SLFT adds the new viewpoint of a causal localization caused intrinsic quantum fibre-bundle structure in $s \geq 1$ interacting theories. The suggestion of perturbative SLFT is that interpolating fields for particles in interacting models involving $s \geq 1$ fields exist only in the form of sl Wightman fields.

The arguments in this subsection are a good preparation for understanding the true physical reasons why Higgs fields are needed in the presence of self-interacting massive vector mesons which will be addressed below.

- **Self-interacting massive vector mesons**

An even bigger surprise arises in the presence of self-interacting massive vector mesons. In this case the pair condition and its second order iteration leads to two quite remarkable observations. On the one hand the second order restriction requires the first order $f_{abc}$ coupling strengths in the general ansatz for a self-interacting vector potential

\[
L = \sum_{abc} f_{abc} F^\mu_\alpha A_{\mu,b} A_{\nu,c} + \ldots A, \phi \text{ contr.}
\] (19)

to fulfill the Lie algebra relations of a reductive Lie group; to find this Lie algebra structure one has to implement the $L, Q_\mu$ pair condition\footnote{The $Q_\mu$ formalism is somewhat easier to handle and maintains a formal similarity with the CGI gauge formulation \cite{43}.} up to second order. In the BRST gauge setting this has been known for a long time \cite{45}.
but this is hardly surprising since this BRST formalism resulted from achieving formal compatibility between Lagrangian quantization of classical gauge theory (where this relation follows from the fibre bundle requirements) with the algebraic structure of QFT.

But in the new sl setting the Lie algebra structure follows from the \( s \geq 1 \) causal localization principles in the form of the \( L, Q_\mu \) pair requirement; the calculation is in this regard formally similar to that based on the BRST gauge formalism \[48\].

Another important observation is that the second order leads to \( d_{sd} = 5 \) delta contribution which, if left uncompensated, would destroy the renormalizability and hence the perturbative existence of the model. It is saved as a renormalizable QFT by extending the field content and adding a nonabelian \( A \cdot AH \) interaction of the massive vector mesons with a \( H \)-field whose second order contribution contains (after adjusting its coupling strength) compensating \( d_{sd} = 5 \) second order terms generates such a second order compensating. This is reminiscent of short distance compensations between different spin components in supermultiplets except that in the present case it is not an epiphenomenon of an extended symmetry but rather the raison d’être for the \( H \)-particle.

- **Added comments**

The new string local quantum field theory (SLFT) shows many formal similarities with the prior causal gauge invariance (CGI) reformulation of BRST in the Epstein-Glaser operator setting \[57\]. It has the advantage of clearly distinguishing between properties which holds only on-shell such as the BRST invariance \( sS = 0 \) of the S-matrix and off-shell properties as SSB

SLFT does not disqualify gauge theory, it rather shows its physical limitations. Before commenting on this it is interesting to recall what Haag said about the BRST formulation. In his reminiscences [10] one finds the following remarks "this elegant scheme is generally accepted today as the adequate formulation of the local gauge principle in perturbation theory. But it bears no resemblance to the conceptually simple picture in classical theory with its continuous group acting on the fibres of a bundle."

He goes on to expresses his problem with the ghost degrees of freedom which at the end of the day have to be removed with the help of BRST gauge invariance. This is necessary in order to recover the most important property of any quantum theory namely the positivity which secures the quantum theoretical probability interpretation. Indeed the problem with pl \( s \geq 1 \) interactions reveal a deep clash between pl localization and positivity. Either one permits negative contributions in sums over intermediate states as in the Krein space setting of local gauge theory, or one saves positivity and uses the more natural SLF formulation in terms of \( L, V_\mu \) pairs.\[25\]

\[24\]Contrary to its abelian counterpart for which a corresponding second order \( d_{sd} = 5 \) term vanishes on the \( e = e' \) diagonal, the nonabelian contribution provides precisely the necessary compensating contribution.

\[25\]The physically preferred choice is supported by the B-F theorem \[69\] which states that
In philosophical terms one may say that SLFT is the result of applying Ockham’s razor to the "ghostly" BRST Krein space setting. This leads to the concept of sl escort fields which depend on the same degrees of freedom as those already contained in the fields which they are escorting. Such free fields have necessarily mixed two-point functions i.e. all nondiagonal contributions \( \langle A^P \phi \rangle \), \( \langle A^P u \rangle \)...of the linear sl (Borchers) equivalence class are nonvanishing. This makes perturbative sl calculations somewhat more involved than those in the pl Krein space renormalization theory.

Interactions which involve \( s = 1 \) fields are subject to additional requirements; In the CGI gauge setting this is the BRST invariance of the S-matrix \( sS = 0 \), whereas in the SLFT formulation the causal localization requirement demands the independence of the S-matrix from the fluctuating string directions which in \( n^{th} \) order reads
\[
d_{\epsilon}^{(n)} S^{(n)} = 0, \quad d_{\epsilon}^{(n)} := \sum_{i=1}^{n} d_{\epsilon_i}
\]
In the SLFT setting this requirement on the S-matrix follows directly from the causal localization principle whereas in the CGI setting it is part of the BRST formalism (whose spacetime interpretation is restricted to gauge invariant observables).

For the implementation one uses the \( L, Q_{\mu} \) pair property and its higher order extension. The main difference between couplings of vector potentials to complex and Hermitian matter is that in the latter case one obtains a richer set of second order induced terms including selfinteractions of the \( H \) and the \( \phi \) escort fields. The fact that these induced contributions have the appearance of a field-shifted Mexican hat potential does not mean that the result bears a relation to the physics of SSB.

A renormalized interaction density is uniquely fixed in terms of its field content (including their masses and internal symmetries). The interpretation of a renormalized model of QFT cannot be described by the calculating theoretician, it is uniquely determined by intrinsic properties; \( Q_{sc} = 0 \), \( Q_{sym} < \infty \), \( Q_{SSB} = \infty \) represent the 3 different mutually exclusive realizations of the causal localization principles, they correspond to screening, inner symmetry and SSB.

As mentioned in the previous subsection selfinteracting vector mesons lead to two new phenomena. Such models are subject to the SLFT renormalization theory based on the \( L, V_{\mu} \) pair condition. This requires the \( f_{abc} \) selfcouplings to obey a fibre-bundle like structure \([19]\) which, in contrast to gauge theory, is not imposed but by quantum adjustments to classical fibre bundles but rather a consequence of the causal localization principles. For massive self-interacting vector-mesons there is the additional phenomenon of second order violation renormalizability violation which requires the compensatory presence of \( H \) fields in order to save the Standard Model.

It is interesting to note that apart from the particle-antiparticle symmetry Nature has no use of the concept of inner symmetries and their SSB (apart from

in the presence of a mass gap one needs no weaker localized interpolating fields than sl fields (i.e. no need for "branes" in LQP)
phenomenological applications by theorists). As the success of the Standard Model shows Nature prefers the fibre-bundle like structure of \( s \geq 1 \) selfinteractions and renormalizability-saving compensations (the raison d’être for the \( H \)).

The next and final section contains remarks about possible extensions to higher spins \( s \geq 2 \) and the challenge their perturbative verification would pose to LQP.

8 New challenges to Local Quantum Physics

The new perturbative SLFT originated from modular localization theory within Haag’s LQP; in particular the observation that Wigner’s infinite spin representations does not permit compact localization and requires the construction of sl fields \[39\] played an important catalyzing role. This begs the question whether the extension of perturbation theory could also lead to an enrichment of LQP.

One challenging question is if the sl nature of interpolating fields in the presence of \( s \geq 1 \) massive particles is a general (perturbation-independent) structural property of LQP. The naturalness of sl localization\[26\] suggest that this is the case. Part of the problem of proving such a conjecture is that one has no intrinsic nonperturbative spacetime local (off-shell) understanding of ”interaction”; the reference to the nontriviality of the global (on-shell) S-matrix is too far removed from properties of causal localization. The reformulation of ”axiomatic” QFT in the sense of Wightman \[32\] in terms of sl Wightman fields is expected to be straightforward apart from the sl replacement of the pl extended tube analyticity (since the representation of sl fields in terms of line integrals over pl fields is limited to free fields).

An important part of such a reformulation is a better understanding of problems which are outside the physical range of gauge theory, as e.g. the construction of electrical charge-carrying fields in terms of properties of local observables \[10\]. The use of the Gauss law in the LQP setting shows that such fields are necessarily string-local in a very strong sense \[60\]. In fact a physical description of the Hilbert space of QED (which is not a Wigner-Fock space !) and the operators acting in it is still outstanding.

The particle structure of the Hilbert space is synonymous with the existence of the S-matrix i.e. with the large time behavior of the charge-carrying fields. Observationally important momentum space prescriptions for photon-inclusive cross sections are no during replacement for a spacetime understanding of infrared aspects. Since the gauge theoretic indefinite metric destroys the physical localization, the correct spacetime properties require the use of the positivity preserving sl localization; in fact the correct analogy of quantum mechanical long range (Coulomb) interactions are rigid (i.e. consistent with the Gauss law)

\[26\]Weaker localization on e.g. spacelike branes is not needed (\[10\] section IV,3).
\[27\]As a result of photonic vacuum polarization clouds along the space-like string direction the strings are “rigid” and, different from massive vector mesons, cause a spontaneous symmetry breaking of the Lorentz symmetry.
string-local quantum fields.

The proposed physical spacetime explanation for the appearance of the logarithmic divergencies is that the coupling to massless photons changes the mass-shell delta functions of the charge-carrying massive particles into a milder coupling strength dependent singularity which leads to vanishing spacetime scattering amplitudes. The logarithmic divergencies are the result of an illegitimate expansion of the ”softened” mass shell singularity into a power-series in the coupling strength accounts. In [61] one finds rather convincing arguments that the introduction of an infrared cutoff parameter and taking the limit of its vanishing after summing over the leading logarithms to all orders indeed leads to a vanishing amplitudes of photonless collisions of charge-carrying particles.

The correct spacetime scattering theory is expected to be a description in terms of a large time behavior of expectation values (probabilities). This is outside the range of gauge theory and can only be achieved within a positivity preserving sl setting.

Another ambitious project outside the range of gauge theory is a LQP understanding of confinement. Different from the on-shell infrared phenomenon whose cause is a change of the mass-shell properties of charged particles (which leads to the vanishing of the large time limits of fields but has no direct effect on fields and their vacuum expectation values), confinement is a more radical phenomenon in which correlation functions containing self-interacting massive vector mesons (massive Yang-Mills fields) coupled to spinor or scalar quarks and the fields disappear in the massless gluon limit and only leave their composite hadron-, gluonium- and quark-antiquark string-bridged fields behind.

In analogy with the vanishing scattering amplitudes for photonless charged particle collisions one expects that all correlation functions which contain in addition to hadron and gluonium fields as well as string-bridged \( q\bar{q} \) fields also gluon or quark fields vanish, so that only those which contain no gluon and quark operators are nontrivial. The only known way to describe theories in which the basic model-defining fields leave only their ”composite shadows” behind in our present perturbative setting is in the form of zero mass limits of the conceptually much clearer situation of selfinteracting between massive vector mesons.

Do the perturbative correlation function show such a behavior? A systematic construction of massless correlation functions of nonabelian gauge theories can be found in [62] and the for the present purpose relevant result is that there are no infrared divergent correlation functions in covariant gauges apart from the expected on-shell logarithmic divergencies which are already present in the abelian case. This had to be expected in view of the fact that gauge dependent fields, although possibly revealing the correct short distance behavior in the sense of having the physically correct beta-function will be maximally incorrect for long distances where the string-localization plays an important role.

In the presence of SLFT perturbative self-interacting gluons one however

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28In the SLFT formulation one would preserve covariance by viewing QED as a massless limit of a vector mesons.

29The Callen-Symanzik equation and in particular the beta function may turn out to be be independent of \( e \).
expects such logarithmic divergences. SLFT corresponds to the noncovariant axial gauge which has been abandoned since it generates an entangled mix of incurable ultraviolet and infrared divergencies. But the role of $e$ in SLFT is very different from that of a gauge fixing parameter. In contrast to a global gauge parameter the $e$ in SLFT is as $x$ a spacetime variable in which each field fluctuates independently in such a way that on-shell objects as particles and the S-matrix as well as pl local observables remain $e$-independent, but fields and their composites depend on $e$ and transform covariant as linear spacelike strings $S = x + \mathbb{R}_+ e$, $e^2 = -1$. A low order calculation of two-point correlations correlation functions for self-interacting massless vector mesons which could reveal whether SLFT contains a signal of confinement is more elaborate but feasible.

The SLFT renormalization theory enlarges the number of renormalizable positivity maintaining interactions. There are two requirements which a prescribed field content containing $s \geq 1$ fields must fulfill in order to define a positivity maintaining renormalizable SLFT. There must exist a $L, V_\mu$ pair with $d_{sd}(L) \leq 4$ which fulfills the pair requirement $d_{s}L - \partial^\mu V_\mu = 0$ and it must be possible to compensate induced higher order anomaly terms with $d_{sd} \geq 5$ by extending the field content of $L$.

The first requirement is a lowest order consistency condition which prevents the short-distance improving string-localization of fields to destroy the large time field-particle relation and maintains on-shell objects as the S-matrix $e$-independent. Its preservation in higher orders is a normalization condition which leads to induced higher order contributions. In contrast to renormalization counterterms which enlarge the number of coupling parameters, higher order induced terms preserve them. They are similar to the second order induced $A \cdot A |\varphi|^2$ term in scalar QED except that in SLFT they do not originate from quantization of classical fibre bundle structures but are an autonomous consequence of the positivity maintaining causal localization principle of QFT. This applies also to the Lie-algebra structure of self-interacting vector potentials. It shows that QFT does not need "quantization crutches" but can perfectly stand on its own feet.

The second requirement maintains renormalizability to all orders. It has no counterpart in $s < 1$ pl interactions for which first order renormalizability $d_{sd}(L) \leq 4$ guarantees renormalizability to all orders (no "induction"). It is a new phenomenon for interactions involving $s \geq 1$ fields (unless one wants to view it as an analog of the alleged renormalizability-improving role of compensation between different spin components within a supermultiplet).

Interactions of abelian vector mesons with spinor-, complex scalar- or real (Higgs)- matter do not require the compensatory extension of the field content; the implementation of the pair condition suffices in those models. The need for a compensatory enlargement in order to preserve second order renormalizability leads to the Higgs field in the presence of massive self-interacting vector potentials. Both requirements have their counterpart in the CGI operator setting of BRST gauge theory where the causality implementing pair requirement corresponds to the BRST invariance of the S-matrix.
The SLFT renormalization theory is still in its infancy. For \( s > 1 \) there are as yet no SLFT results apart from the qualitative observation that higher spin fields will enhance the short distance dimension of \( Q_\mu \) which in turn may lead to renormalizability violating induced higher order delta terms whose compensation requires the enlargement of the field content. The most plausible scenario in analogy to the compensatory role of the Higgs field is that the highest spin \( s \) requires the presence of all lower spin fields (e.g. for \( s = 2 \) the presence of \( s = 1 \) and \( s = 0 \)).

Fields belonging to the zero mass infinite spin Wigner class fail on the \( L, Q_\mu \) pair requirement; they exist only in the form of sl free fields [42]. We will refer to such matter as *non-reactive or inert* in the sense of SLFT perturbation theory. Hence the problem posed by the two requirements is the question: *up to what spin does matter remain reactive?*

Since a further lessening of the tightness of localization beyond sl as a localization on spacelike hypersurfaces ("branes") brings no gain for renormalizability, it is not unreasonable to expect that a field content which permits no renormalizable perturbative interaction in the SLFT formulation has also no counterpart outside perturbation theory. This belief is based on the naturalness of string-localization i.e. the fact that particles in LQP always admit sl interpolating fields with pl being a special case of sl [59].

This does not require the convergence of the perturbative series; the singular nature of fields due to the omnipresence of vacuum polarization clouds limits their use in mathematical existence proofs. But a field of spin \( s > 1 \) which allows no renormalizable interactions with itself and lower spin fields is also believed to be inert par excellence.

All positive energy matter can be shown to admit a conserved energy-momentum tensor; the No-Go theorem in [37] for *massless* higher spin matter refers to pl fields, whereas conserved weaker localized sl E-M tensors whose global charges are identical to those of their pl siblings exist and have a well-defined massless limit. Hence also inert matter which only exists in the form of free fields couples to gravity and leads to gravitational backreaction, which makes it interesting as candidates for dark matter. Intrinsically sl infinite spin matter is inert [42] but as a result of its fleeting nature resulting from its masslessness it does not seem to be compatible with the halo like accumulation of dark matter around galaxies.

This is the content of a structural theorem of LQP which states that in order to describe particles one does not need weaker than string localized interpolating fields. Hence one expects that interactions which fail on both previous properties do not exist as the result of lack of reactivity of the highest spin component.

The string-localization of matter fields in interactions involving sl \( s \geq 1 \) potentials in SLFT renormalized perturbation theory begs the question to what extend its occurrence can be understood in the nonperturbative LQP setting. The problem is that there is no nonperturbative localization-based intrinsic definition of "interaction"; the existence of a nontrivial S-matrix is too remote from the spacetime properties of interacting fields. A proof would amount to a theorem stating that a particle spectrum with mass gaps which includes \( s \geq 1 \)
particles is either a free field theory or an model whose interacting fields are sl Wightman fields. The adjustment of Wightman’s axiomatic framework to sl fields would then be the lesser problem.

Perturbative SLFT also directs attention to a new problem of formal symmetries which are not inner symmetries in the sense of the DHR superselection theory. As mentioned before such a problem is posed by the perturbative Lie algebra structure of self-interacting vector mesons. Such a situation can not be subsumed under inner symmetry since the latter always permit interactions with the same field content but less or no symmetry. There is as yet no natural conceptual place in LQP.

In the BRST gauge formulation this is less surprising since that formalism is the result of a repair job which is necessary to control the indefinite metric aspects of a formulation obtained from adjusting a classical fibre bundle setting to the exigencies of a quantum theory which is only possible at the price of indefinite metric and ghosts. In a somewhat metaphoric sense result from the quantization (of a classical theory which has no use for ”positivity”). Why does Nature not present particle multiplets associated to internal symmetries (or Goldstone particles of an exact SSB)? Why does she prefers the Lie algebra structure of self-interacting vector mesons (the Standard Model)?

LQP is still far from its ultimate goal of establishing the mathematical existence of nontrivial models and finding mathematically controlled approximation procedures. However there are good reasons to expect that the pursuit of this goal will lead to important more new insights. Rudolf Haag’s general LQP view of QFT as causally localized quantum matter [2] remains a valuable compass which helps to avoid a cul-de-sac as that mentioned in section 5.

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References

[1] R. Haag and D. Kastler, *An algebraic approach to quantum field theory*, J. Math. Phys 5, 848 (1964)

[2] R. Haag, *Some people and some problems met in half a century of commitment to mathematical physics*, Eur. Phys. J. H 35, 263–307 (2010)

[3] R. Haag and B. Schroer, *Postulates of quantum field theory*, J. Math. Phys. 3, 248 (1962)

[4] H. Araki, R. Haag and B. Schroer, The Determination of a Local or Almost Local Field from a Given Current, Nuovo Cimento 19, 90 (1961)

[5] B. Schroer, *Beyond gauge theory; positivity and causal localization in the presence of vector mesons*, Eu. Phys. J. C 76 (2016)
[6] P. Leyland, J. Roberts and D. Testard, Duality for Quantum Free Fields (Centre de Physique Théorique, CNRS Marseille, 1978)

[7] K-H. Rehren, Local Quantum observables in the Anti-deSitter-Conformal QFT Correspondence, Phys. Lett. B493, 883 (2000)

[8] M. Duetsch and K-H. Rehren, A comment on the dual field in the AdS-CFT correspondence, Lett. Math. Phys. 62, 171 (2002)

[9] B. Schroer, Infrateilchen in der Quantenfeldtheorie, Fortschr. Phys. 173, 1527 (1963)

[10] R. Haag, Local Quantum Physics, Fields, Particles, Algebras, Springer-Verlag 1992

[11] R. Haag and J.A. Swieca, When does a quantum field theory describe particles?, Commun. Math. Phys. 1, 308 (1965)

[12] D. Kastler, D.W. Robinson and J.A. Swieca, Conserved currents and associate symmetries; Goldstone’s theorem, Commun. Math. Phys. 2, 108 (1966).

[13] H. Ezawa and J.A. Swieca, Spontaneous breakdown of symmetries and zero-mass states, Comm. Mat. Phys. 5, 330 (1967).

[14] J. A. Swieca, Goldstone’s Theorem and Related Topics, Cargese Lecture Notes in Physics, Vol. 4, 215, (1970)

[15] B. Schroer, R. Seiler and J.A. Swieca, Problems of Stability for Quantum Fields in External Time-Dependent Potentials, Phys. Rev. D, 2 2927 (1970)

[16] B. Schroer and J.A. Swieca, Indefinite Metric and Stationary External Interactions of Quantized Fields, Phys. Rev. D 2, 2938 (1970)

[17] B. Schroer, Quantization of m0 Field Equations, Phys.Rev. D3, 1764 (1971).

[18] J. H. Lowenstein and J.A. Swieca, Quantum Electrodynamics in Two Dimensions, Annals of Physics 68, 172 (1971)

[19] Jorge André Swieca, Obras Collogidas, Projeto Galileo Galilei, CNPq, Brasilia 1981

[20] J. Holland and S. Hollands, Recursive construction of operator product expansion coefficients, Commun.Math. Phys. 336, 1555 (2015)

[21] Olga, by Fernando Morais, published by Companhia das Letras 1985

[22] R. Haag, N. Hugenholtz and M. Winnink, On the equilibrium states in quantum statistical mechanics, Commun. Mat. Phys. 5, 215 (1967)
[23] M. Takesaki, *Tomita’s Theory of Modular Hilbert Algebras and its Applications*, Springer, Berlin 1970

[24] H.-J. Borchers, *On revolutionizing quantum field theory with Tomita’s modular theory*, J. Math. Phys. 3604 (2000)

[25] J.J. Bisognano and E. H. Wichmann, *On the duality-condition for quantum fields*, J. Math. Phys. 17, 303 (1976)

[26] G. Sewell, *Relativity of temperature and the Hawking effect*, Phys. Rev. Lett. 79A, 23 (1980)

[27] K. Fredenhagen and R. Haag, *On the derivation of Hawking radiation associated with the formation of a black hole*, Commun. Math. Phys. 127, 273 (1990)

[28] K. Fredenhagen, *On the modular structure of local algebras of observables*, Commun. Math. Phys. 97, 79 (1985)

[29] K. Fredenhagen and K. Rejzner, *QFT on curved spacetime; axiomatic framework and examples*, J. Math. Phys 57, 031101 (2016)

[30] R. Brunetti, D. Guido and R. Longo, *Modular localization and Wigner particles*, Rev. Math. Phys. 14, (2002) 759

[31] S. Weinberg, *The Quantum Theory of Fields I*, Cambridge University Press 1991

[32] R. S. Streater and A. S. Wightman, *PCT, Spin and Statistics and all that*, New York: Benjamin 1964

[33] J. Mund, *An Algebraic Jost-Schroer Theorem for Massive Theories*, Commun. Math. Phys. 315, 445 (2012)

[34] H-J Borchers, D. Buchholz and B. Schroer, *Polarisation-Free Generators and the S-Matrix*, Commun. Math. Phys. 219, 125 (2001)

[35] B. Schroer, *Modular Wedge Localization and the bootstrap Formfactor Program*, Ann. Phys. 275, 190 (1999)

[36] J. Mund and Erichardson T. de Oliveira, *String-localized free vector and tensor potentials for massive particles with any spin; 1. Bosons*, arXiv:1609.01667

[37] S. Weinberg and E. Witten, *Limits on massless particles*, Phys. Lett. B 96 (1-2) (1980) 59

[38] J. Yngvason, *Zero-mass infinite spin representations of the Poincar´e group and quantum field theory*, Commun. Math. Phys. 18 (1970), 195–203.

[39] J. Mund, B. Schroer and J. Yngvason, *String-localized Quantum Fields and Modular Localization*, CMP 268 (2006) 621, math-ph/0511042
[40] J. Mund, *String-localized quantum fields and modular localization*, Commun. Math. Phys. 268, (2006) 621

[41] R. Longo, V. Morinelli and K.-H. Rehren, *Where Infinite Spin Particles Are Localizable*, Commun. Math. Phys. 345 (2016) 587, [arXiv:1505.01759](http://arxiv.org/abs/1505.01759)

[42] B. Schroer, *Can the inert matter corresponding to Wigner’s infinite spin representations be dark matter?*, submitted to EPJC

[43] J. Polchinski, *String theory, Vol I*, Cambridge University Press 1998

[44] C. Meusburger and K.-H. Rehren, *Algebraic quantization of the closed bosonic string*, Commun.Math.Phys.237 (2003) 69

[45] R. Brower, *Spectrum-generating algebra and no-ghost theorem in the dual model*, Phys. Rev. D6, 1655 (1972)

[46] S. Alazzawi and G. Lechner, *Inverse Scattering and Locality in Integrable Quantum Field Theories*, [arXiv:1608.02359](http://arxiv.org/abs/1608.02359)

[47] F. Pedrosa and J. Mund, *String-local Dirac fields in massive QED*, in preparation

[48] G. Scharf, *Quantum Gauge Theory, A True Ghost Story*, John Wiley & Sons, Inc. New York 2001

[49] H. Ruegg and M. Ruiz-Altaba, *The Stueckelberg field*, Int.J.Mod.Phys A19, 3265 (2003)

[50] J. Lowenstein and B. Schroer, *Gauge Invariance and Ward Identities in a Massive Vector-Meson Model*, Phys Rev D6, 1553 (1972)

[51] D. V. Ahluwalia, *A story of phases, duals, and adjoints for a local Lorentz covariant theory of mass dimension one fermions*, arXiv:160103188

[52] G. Morchio and F. Strocchi, *The infrared problem in QED: A lesson from a model with Coulomb interaction and realistic photon emission*, [arXiv:1410.7289](http://arxiv.org/abs/1410.7289)

[53] B. Schroer, *Peculiarities of massive vector mesons and their zero mass limits*, E.P.J.C. 75 (2015)

[54] D. Buchholz and J.E. Roberts, *New Light on Infrared Problems: Sectors, Statistics, Symmetries and Spectrum*, [arXiv:1304.2794](http://arxiv.org/abs/1304.2794)

[55] D. Buchholz, F. Ciolli, G.Ruzzi and E. Vasselli, *The universal C*-algebra of the electromagnetic field*, [arXiv:1506.06603](http://arxiv.org/abs/1506.06603)

[56] H. Epstein and V. Glaser, *The role of locality in perturbation theory*, Ann. Henri Poincaré Phys. Theor. A 19, 311 (1973)
[57] M. Duetsch, J. M. Gracia-Bondia, F. Scheck, J. C. Varilly, *Quantum gauge models without classical Higgs mechanism*, Eur. Phys. J. **C89**, (2012) 599, [arXiv:1001.0932](http://arxiv.org/abs/1001.0932)

[58] R. Jost, *The General Theory of Quantized Fields*, American Mathematical Society 1965

[59] D. Buchholz and K. Fredenhagen, *Locality and the structure of particle states*, Commun. Math. Phys. **84**, (1982) 1

[60] D. Buchholz, The physical state space of quantum electrodynamics, Commun. Math. Phys. **85**, (1982) 40

[61] D. Yenni, S. Frautschi and H. Suura, *The infrared phenomena and high energy processes*, Ann. of Phys. 13, (1961) 370

[62] S. Hollands, *Renormalized Quantum Yang-Mills Fields in Curved Spacetime*, Rev. Math. Phys. **20**, (2008) 1033, [arXiv:0705.3340](http://arxiv.org/abs/0705.3340)