Theory Summary of the Hadron Structure and QCD Workshop 2008 *

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This paper is the write-up version of the theory summary talk given at the HSQCD 2008 Workshop in Gatchina, Russia. Recent theoretical developments and results are summarized focusing on works that point out new perspectives, ranging from perturbative QCD, DGLAP and ERBL evolution, polarized and unpolarized parton distribution functions, small-x physics to nonperturbative QCD, lattice simulations, quark-gluon matter, hadron spectroscopy, and predictions for the LHC.

1 Introduction

The Workshop on the Hadron Structure and QCD 2008: From Low to High Energies continues the tradition of a series, started in 2004. This year’s meeting provided a

- balanced mixture of theoretical and experimental talks,
- high level of contributions,
- good mixture of experienced and young scientists,
- rich social program.

*Theory summary talk presented at International Workshop “Hadron Structure and QCD” (HSQCD’2008), June 30 - July 4, 2008, Gatchina, Russia
The aim of the workshop was to review the progress in hadronic physics, QCD, and the Standard Model and its generalizations, focusing on:

- perturbative QCD, BFKL- and DGLAP- evolution,
- polarized and unpolarized parton distribution functions,
- small-x physics,
- hard diffraction and Pomeron physics,
- heavy-ion collisions and quark-gluon matter,
- nonperturbative QCD, lattice computations, and chiral models of hadrons,
- hadron spectroscopy and exotic states,
- precision tests of the Standard Model,
- extensions of the Standard Model and predictions for the Large Hadron Collider (LHC) (and future colliders).

This theory summary is set in the broader context of hadronic physics and in the narrower context of QCD. Within this context, various theoretical papers—out of a total of fifty—have been selected for a more detailed presentation, weaving them into a theoretical frame in such a way as to convey the coherence of the underlying ideas and methods. The guide and motivation are the wide range of possible applications and their relevance in pursuing future developments in the advent of the LHC at CERN. These theoretical contributions are supplemented by thirty experimental talks, summarized by M. Sapozhnikov. However, it is outside the scope of this summary to provide rigorous and critical assessments on the pertinence and validity of the presented material. The theoretical contributions to follow are grouped by broad categories of concern: QCD Calculations (Sec. 2), Evolution Equations and Related Topics (Sec. 3), QCD and Higgs Physics (Sec. 4), Regge Physics and Diffraction (Sec. 5), Nonperturbative QCD and Low-energy Models (Sec. 6), Hadron Form Factors (Sec. 7), Quark Confinement (Sec. 8), and Mathematical and Other Analyses (Sec. 9). I hope that readers of these proceedings will find, whether or not they agree with particular arguments, that the presented contributions are in general competent and useful.
2 QCD Calculations

Parton distribution functions (PDF)s—unpolarized and polarized—give the probability to find partons (quarks and gluons) without and with spin in a hadron as a function of the longitudinal momentum fraction, \(x\), carried by the parton, and the hard scale \(Q^2\) (see [1] for an introduction). All other components of parton momentum are integrated over. These integrated PDFs have in the \(\overline{\text{MS}}\) scheme unambiguous gauge-invariant definitions in terms of matrix elements of operators and satisfy factorization theorems [2]—see, e.g., [3] for a review. When the integral over the parton’s transverse momentum is not carried out, one deals with unintegrated, or transverse-momentum dependent (TMD), PDFs whose gauge-invariant formulation is still an issue under scrutiny (see Stefanis’ talk).

The spin structure function \(g_1\) at low \(x\) and arbitrary \(Q^2\), as measured by the COMPASS Collaboration at CERN, was considered in Greco’s talk [4]. The hadronic tensor \(W_{\mu\nu}\) contains a symmetric part that does not depend on spin and an antisymmetric one, parameterized by two structure functions, viz., \(g_1\) and \(g_2\), which depend on \(Q^2\) and \(x = Q^2/2p \cdot q\) (0 < \(x\) < 1). These quantities involve both perturbative and nonperturbative QCD ingredients and are, therefore, model-dependent. On account of factorization, one can cast \(W_{\mu\nu}\) in the form of a convolution which separates out the nonperturbative content into the probabilities \(\Phi_{\text{quark}}\) and \(\Phi_{\text{gluon}}\). These functions (called the initial quark and gluon densities and denoted by \(\delta q\) and \(\delta g\)) cannot be calculated from first principles of QCD and have to be either modeled or fitted to experimental data at large \(x \sim 1\) and large \(Q^2\). Moreover, each structure function has both a non-singlet and a singlet component: \(g_1 = g_1^\text{NS} + g_1^\text{S}\) (analogously for \(g_2\)). Recall that there are various kinematical regions to cover in the \((1/x , Q^2)\) plane. For instance, one has for \(x \leq 1\) and \(Q^2 \gg \mu^2\) the DGLAP region, whereas for \(x \ll 1\) and \(Q^2 \leq \mu^2\) one probes the COMPASS region. Then, one can use the perturbative DGLAP \(Q^2\)-evolution equation—together with fits for the initial parton densities—to predict \(g_1^\text{NS}/\text{S}(x,Q^2)\).

However, though DGLAP evolution resums all terms \(\sim (\alpha_s \ln(Q^2/\mu^2))^k\), it does not account for the resummation of logarithms of \(x\). For that reason, Greco and his coauthors have suggested another resummation procedure of the logarithms of \(1/x\) which employs an infrared cutoff in the transverse space \(k_\bot^2 > \mu^2\). This gives rise to the evolution of the structure functions with respect to the variable \(\mu^2\) (a method employed before by several authors, including Gribov, Lipatov, Kirschner, Bartels, Ermolaev, Manaenkov, and Ryskin). This Infra-Red Evolution Equations (IREE) assume for \(g_1^\text{NS}\) a form which is driven by an anomalous dimension summing up all double and some single logarithms...
of $x$. In contrast to DGLAP evolution which is reliable at large $x$, but fails at small $x$ lacking the total resummation of logarithms of $x$, the discussed approach is good at small $x$, turning bad at large $x$, because it neglects some contributions essential in this region. To merge both approaches, the authors involve an IR cutoff scale $\mu^2$ and shift $x \to \bar{x} = (Q^2 + \mu^2)/2p \cdot q$ already at the level of the involved Feynman graphs. This amounts to introducing a "mass" of virtual quarks and gluons to regulate IR singularities, i.e., $\int_{\mu^2}^{Q^2} \frac{dk_{\perp}^2}{k_{\perp}^2} \to \int_{0}^{Q^2} \frac{dk_{\perp}^2}{k_{\perp}^2 + \mu^2} = \ln \left( \frac{Q^2 + \mu^2}{\mu^2} \right)$. [We will encounter another IR protection within the framework of Fractional Analytic Perturbation Theory (FAPT) in Bakulev’s talk.] Using the scheme described, Greco et al. obtain the following results: (i) They predict that at small $Q^2$, $g_1$ is almost independent of $x$, even at $x \ll 1$, and depends only on $2p \cdot q = w$. (ii) They suggest that it would be interesting to study the $w$-dependence of $g_1$ at COMPASS. (iii) This would allow one to answer the question about the sign of the gluon density and fix the ratio $N_g/N_q$. (iv) The report concluded that using another target would allow to measure the non-singlet distribution $g_1$ and define $N_q$.

I presented this contribution in some technical and conceptual detail, because it contains several ingredients that appear also in other papers presented in this workshop.

Transverse-momentum dependent PDFs were considered also by Teryaev. He studied the relations between leading and higher twists in nonperturbative QCD in terms of matrix elements of quark/gluon operators as resummed towers of twists. In particular, he addressed the transverse moment of the Sivers function [5] in the context of Single-Spin Asymmetries (SSA) [6,7,8,9]. He pointed out that TMD PDFs of (naively) leading twist may turn into an infinite sum of higher twists. In the case of the Sivers function, this issue may be assessed by means of the T-invariance or, technically speaking, by considering the imaginary part of the (quark) density matrix. An important finding here is that the Sivers function appears to be related to the twist-3 gluonic poles.

In the talk of Stefanis the anomalous dimensions of fully gauge-invariant TMD PDFs [10,7] in the light-cone gauge were considered. It was shown in [11,12], and reported in these proceedings [13], that associating individual gauge contours of integration to the quark field operators in the quark-pair correlator describing the distribution of a quark in a quark, additional ultraviolet (UV) divergences appear. The origin of these UV divergences was found to be rooted in the renormalization effect on the junction point of Wilson lines, when they contain transverse segments extending to light-cone infinity. An explicit one-loop calculation in the light-cone gauge $A^+ = 0$ shows that the anomalous dimension ensuing from these divergences coincides with the one-loop expression of the universal cusp anomalous dimension [14]. To dispense with this anomalous-dimension
defect and obtain the same result for the renormalized TMD PDFs as in a covariant
gauge (say, the Feynman gauge), a modified definition of the TMD PDFs was proposed.
This contains a soft counter term in the sense of Collins and Hautmann [15] which is
a path-ordered exponential factor evaluated along a particular gauge contour with a
cusp. This integration contour stretches out to light-cone infinity and ventures off the
light cone in the transverse direction. The anomalous dimension associated with the
renormalization of this nonlocal operator compensates the anomalous-dimension artifact
and ensures that integrating over the parton transverse momentum, one finds a PDF
satisfying the DGLAP evolution equation. Moreover, the anomalous dimension of the
modified TMD PDF respects the Slavnov-Taylor identities and resembles the one-loop
expression one finds for a TMD PDF with a connector [16] (see also [17]) insertion,
i.e., the direct Wilson line between the two quark fields. The cusp-like junction point is
“concealed” by light-cone infinity, and reveals itself only after renormalization as a phase
entanglement [12] akin to the “intrinsic” Coulomb phase, found before in QED [18], and
being codified in the (one-loop) cusp anomalous dimension. The implications of a more
accurate definition of TMD PDFs are far reaching, ranging from more precise analyses of
various experimental data on hard-scattering cross sections to the development of more
accurate Monte Carlo event generators.

3 Evolution equations and related topics

Wilson lines were also on the focus of Balitsky’s presentation. He gave a status report
on the next-to-leading order (NLO) evolution of color dipoles (i.e., a two-Wilson-lines
operator), exploiting the NLO evolution kernel in detail [19]. This kernel consists of
three parts: (i) a running-coupling part proportional to the $\beta$ function, (ii) a conformal
part describing a $1 \to 3$ dipole transition, and (iii) a non-conformal part. The author
provided evidence that the result agrees with the forward NLO BFKL kernel up to a
term proportional to $\alpha_s^2 \zeta(3)$ (where $\zeta(s)$ is Riemann’s zeta function) times the original
dipole. Moreover, he argued that for the creation of dipoles in the small-$x$ evolution, the
argument of the coupling constant is determined by the size of the smallest dipole [19]. It
turns out that with a rigid $|\alpha_s| < \sigma$ cutoff, the NLO BK kernel in $N = 4$ supersymmetric
Yang-Mills (SYM) theory is (almost) conformally invariant in the transverse plane.

From Lipatov’s talk we learned about new calculations of scattering amplitudes in
$N = 4$ SYM theory with BFKL kernels at the two-loop order. In this approach, the
Pomeron is a composite state of Reggeized gluons, for which an effective action was de-
rived. The integrability of the equations for the multi-gluon states was proved and it was shown that the BFKL dynamics is integrable in Leading Logarithmic Approximation (LLA). A supplementary analysis was presented by Hentschinski. He reported on the computation of longitudinal loop integrals in a gauge-invariant effective action for high-energy QCD [20]. He described how longitudinal integrations up to two t-channel gluons should be performed using the effective action. Finally, he demonstrated that the obtained result for the elastic and the production amplitude reproduces correctly the leading logarithmic contribution and the energy discontinuities.

Saleev’s talk (see also Shipilova’s talk) was devoted to an investigation of DIS and the prompt photon production in the Regge limit of QCD in terms of Reggeized high-energy amplitudes (or, equivalently, of Reggeized quarks and gluons) and effective vertices. Using the QMRK (quasi-multi-Regge kinematics) approach—developed by teams from St. Petersburg and Novosibirsk—and the Reggeized quark ansatz, explicit analytic expressions for $F_2(x_B,Q^2)$ and $F_L(x_B,Q^2)$ were obtained. Recall in this context that in the case of Reggeized gluons, Feynman rules for the effective theory have been derived on the basis of Lipatov’s non-Abelian gauge-invariant action [21]. More recently, Antonov, Kuraev, Lipatov, and Cherednikov [22], derived the Feynman rules directly from the effective Reggeon-particle action and computed explicit expressions for some important effective vertices. Saleev and collaborators obtained predictions for $F_2$, $F_L$ by employing LO quasi-multi-Regge kinematics and Kimber-Martin-Ryskin quark (and gluon) unintegrated PDFs [23]. They found that these functions are consistent with the prompt-photon production data measured at the Tevatron. In particular, agreement with the DØ and the CDF data for prompt photons was found by considering $Q\bar{Q} \rightarrow \gamma$ as the main production mechanism. Using the QMRK approach, Shipilova and Saleev investigated the D-meson production, measured at the Tevatron and at HERA. Shipilova presented in her talk calculations of the $p_T$-spectra of the D-meson photoproduction at HERA and found satisfactory agreement at high $p_T$ between their predictions for the production (via LO QMRK) of the subprocess $\gamma^*Q \rightarrow q$ (where $Q$ denotes the Reggeized quark) and the experimental data. Remarkably, the calculated $p_T$-spectra of the D-meson production at the Tevatron via two LO QMRK processes also show agreement with the experimental data. In view of this outcome, she concluded that the unintegrated c-quark and gluon distribution functions in the proton seem to be correct, given that they yield good agreement between theory and the data for different reactions.

In Ermolaev’s contribution (in collaboration with Troyan) the parametrization of the QCD coupling in evolution equations—including DGLAP—was studied [24,25], with
particular attention payed to the appropriate scale setting for the argument of the QCD coupling. The presented analysis of the parametrization of $\alpha_s$ pertains to a wide group of evolution equations of the Bethe–Salpeter type, including BFKL and DGLAP, where one virtual gluon is factorized out of the blob. Such a gluon can propagate either in the $s$-channel or in the crossing channels and the parametrization of $\alpha_s(\mu^2)$ depends on the considered channel. In the $s$-channel, an effective coupling was derived that incorporates $\pi^2$-terms due to the analytic continuation from the Euclidean to the Minkowski region (cf. Bakulev’s presentation). For large values of $\mu^2$, these contributions can be neglected and one recovers the standard DGLAP $\alpha_s$-parametrization.

4 QCD and Higgs physics

While the QCD strong coupling at high momenta (energies) is small—thanks to asymptotic freedom—its low-momentum behavior cannot be controlled by perturbation theory. In fact, at Euclidean momenta $Q^2 \sim \Lambda^2_{\text{QCD}}$, the one-loop $\alpha_s(Q^2)$ exhibits a Landau pole which is purely unphysical. As a result, the analytic continuation of the standard strong coupling to Minkowski space fails. Various proposals have been suggested over the past three decades how to avert the Landau singularity of $\alpha_s$ at one as well as at higher loops in the spacelike as well as how to define it in the timelike region. A crucial step forwards represents the so-called analytic perturbation theory (APT), initiated by Shirkov and Solovtsov [26] and recently reviewed in [27]. Underlying this approach is the spectral representation of the strong coupling in the Euclidean region in terms of a universal spectral density which allows to define—under the proviso of renormalization-group invariance—an analytic coupling simultaneously in the Euclidean and in the Minkowski space. Also applications to the ultra-low momentum region have been carried out recently [28], and alternative formulations of the strong coupling below the Landau ghost singularities have been proposed with the goal to include nonperturbative input [29, 30].

A generalization and conceptual extension of APT was developed in a series of works during the last decade, starting with applications to the calculation of the factorizable part of the pion’s electromagnetic form factor in QCD [31] which typifies exclusive processes. This study was continued and refined in [32]. In the year 2001 Karanikas and Stefanis generalized the analyticity imperative by demanding that all terms in a QCD amplitude that can affect the discontinuity across the cut along the negative real axis $-\infty < Q^2 < 0$, and hence contribute to the spectral density, have to be included into the analytization procedure, i.e., into the dispersion relation [33, 34]. This work paved the
way for further extending the whole analytic approach beyond the level of integer powers of the coupling and find analytic images of any real power in both the Euclidean [35] and in the Minkowski region [36], finally culminating into the creation of Fractional Analytic Perturbation Theory. Using again the spacelike electromagnetic form factor as a “theoretical laboratory”, it was shown in [37] (see also [38, 39, 40]) that FAPT provides a diminished sensitivity of the predictions on all perturbative scales—the renormalization as well as the factorization scale—while reducing significantly also the dependence on the renormalization-scale setting procedure (and scheme) used. In the Minkowski region, where Landau ghosts are absent, the application of FAPT [36] to the decay of a scalar Higgs into a \( b\bar{b} \) pair at the four-loop level has provided expressions that incorporate all \( \pi^2 \) terms induced by analytic continuation.

Using the FAPT methodology, Bakulev raised in his talk the important question as to what order of the perturbative expansion one has to go in order to find an estimate, say, for the Higgs boson decay, with an acceptable precision (to parallel experimental results). In fact, Bakulev showed that both APT and FAPT produce finite resummed answers for perturbative quantities, provided one knows the generating function for the coefficients of the perturbative-series expansion. Recall that within the analytic approach one deals not with a power series, but with functional non-power-series expansions. Using a simple model for the generating function [41] pertaining to the Higgs-boson decay \( H \rightarrow b\bar{b} \), it was concluded that at the N\(^3\)LO the obtained accuracy of the truncation is of the order of 1\%. On the other hand, for the Adler function \( D(Q^2) \), an accuracy of the order of as high as 0.1\% was reached already at N\(^2\)LO (for more details, see [42]). These are encouraging results for further applications, given the extreme complexity and computational amount of work in computing high-order corrections in standard QCD perturbation theory.

Staying within the same subject, let us continue with Kim’s talk which considered the calculation of the main Higgs-boson decay width into bottom quarks, and the role of higher-order QCD corrections and their resummation. Different methods for treating the results of higher-order perturbative QCD calculations of this quantity were examined and their outcomes compared. Special attention was paid to the analysis of the dependence of the decay width on the Higgs mass in the cases when the \( b \)-quark mass is defined as the running parameter in the \( \overline{\text{MS}} \) scheme and as the quark pole. An important observation was that the results obtained with different methods yield effects of \( O(\alpha_s) \)-corrections that are consistent to each other. This applies in particular to the estimated theoretical precision of these results with respect to \( \Gamma_{H \rightarrow \tau_0} \). Furthermore, Kim discussed a means of verifying the stability of the results against the inclusion of higher-order effects up to \( \alpha_s^4 \),
calculated in [43]. He pointed out that the obtained predictions match those extracted from FAPT without [36, 39] and with the use of resummation techniques [41].

Higgs production was also the subject of Strikman’s talk. He considered hard processes in high-energy pp scattering as an important tool in the search for new heavy particles—in particular of the Higgs at LHC—via a diffractive process in which the produced heavy particle is separated from the projectile fragments by large rapidity gaps [44]. A gap survival in the mean field approximation (i.e., when there is no correlation between hard and soft interactions in the impact parameter) was considered with a possible strong suppression of this effect due to the onset of the so-called black disk regime. [The name derives from the fact that at high energies, strong interactions enter a regime in which cross sections are comparable to the “geometric size” of the hadrons and unitarity becomes an essential feature of the dynamics.] A crucial observation here is that the transverse area occupied by partons with $x > 0.05$ is much smaller than the transverse area associated with the proton in soft interactions. This is, because of color fluctuations in fast nucleons and the slow space-time evolution of their wave function. Strikman provided evidence that the gap survival probability at the LHC should be much smaller ($< 0.01$)—owing to the onset of the black disk regime (or regime of high gluon field)—as compared to models which neglect correlations of partons in the transverse plane. A safe contribution was found to come from the region with $b > 1.2$ fm, leading to $S^2 \geq 0.004$. Hence, the $t$-dependence may provide a critical test in distinguishing different mechanisms for the rapidity-gap suppression.

Another exciting application of Higgs physics was discussed by Khoze, referring to a recent published work [45]. In his talk he assessed the Higgs sector beyond the Standard Model (SM), suggesting forward proton tagging at the LHC. His main aim was to demonstrate that the Central Exclusive Diffractive Production can provide unique advantages for probing the non-SM Higgs sector. Indeed, the Forward Proton Tagging (FPT) would significantly extend the physics reach of the ATLAS and CMS detectors by giving access to a wide range of various channels pertaining to new physics effects. Khoze underlined that FPT has the unique potential to enable such measurements at the LHC—even being able to challenge those at the International Linear Collider (ILC). It turns out that for certain non-Standard-Model scenarios, FPT may become the Higgs discovery channel at all, remarked Khoze, offering a sensitive probe of the CP structure of the Higgs sector.

The possibility of soft diffraction at the LHC was addressed by Ryskin (these Pro-

\footnote{Taka Yasuda reported about Higgs searches at the Tevatron on behalf of the DØ and CDF collaborations at Fermilab.}
ceedings [46] and [47, 48]). Two recent global analyses of available soft data, taken at the CERN-ISR (Intersecting Storage Ring) up to the Tevatron energy range, could be reproduced. Ryskin stressed that the large bare triple-Pomeron (denoted below by the label $P$) coupling regime, described by $g_{3P} \sim 0.25g_N$ (where $g_N$ is the nucleon-Pomeron coupling) and $\Delta = \alpha_P(0) - 1 \sim 0.3$ (with $\alpha_P(0)$ being the ‘bare Pomeron’ intercept), could predict $\sigma_{tot} \sim 90$ mb at LHC by taking recourse to screening effects due to the soft ↔ hard Pomeron transition. The exclusive central diffractive production, $pp \rightarrow p + A + p$, has great advantages for studying the Higgs sector at the LHC, because it would allow to measure the mass of the Higgs boson with a very high resolution [48]. However, the expected number of events in the SM case is expected to be rather small. Extending the study to SUSY Higgs bosons, there are regions of the SUSY parameter space, where the signal could be enhanced by a factor of 10 or more, while the background remains unaltered. This opens up the possibility to discover new physics at the Tevatron (as well as at the LHC).

An important question in the context of the exclusive central diffractive production of the $b\bar{b}$ cross section at the LHC concerns the size of QCD radiative corrections. An in-depth analysis of this issue was presented by Shuvaev, who reported about a recent work published in [49]. The amplitude for the $gg \rightarrow b\bar{b}$ production amplitude was calculated for a color-singlet $J_z = 0$ digluon state at $O(\alpha_s^2)$. It turns out that the radiative QCD (one-loop) corrections were found to suppress the exclusive $b\bar{b}$ background by a factor $\sim 2$ (or more for larger $b\bar{b}$-masses) for the central exclusive diffractive Higgs production, in comparison with calculations using the Born $gg \rightarrow b\bar{b}$ amplitude.

5 Regge Physics and Diffraction

Nikolaev reported on an extensive study [50, 51] of multi-Pomeron vertices in QCD using nonlinear $k_\perp$ factorization. He made the following observations: (i) The concept of a coherent (collective) nuclear glue proves extremely useful for the formulation of the Reggeon field theory vertices of multi-Pomeron-cut and uncut-couplings to particles and between themselves. (ii) The concept of the collective nuclear glue as a coherent state of the in-vacuum (Reggeized) gluons provides a useful tool, with the nuclear collective glue defining an observable by coherent diffraction. (iii) Nonlinear $k_\perp$-factorization quadratures for hard scattering off nuclei with a fixed multiplicity of color-excited nucleons could be derived and an expansion of nuclear unintegrated glue in terms of the collective glue of overlapping nucleons and coherent nuclear gluons could be performed. (iv) It
was demonstrated how the coupled-channel non-Abelian intranuclear evolution of color dipoles, inherent in perturbative QCD, gives rise to the Reggeon field theory diagrams for the final states. (v) Remarkably, the coherent diffraction does not factorize into the photon impact factor and the triple-Pomeron vertex.

It is clear from the previous report that $k_\perp$-factorization is a powerful theoretical tool that can be used to analyze various processes. In Schäfer’s talk [52] unitarity cutting rules for hard processes on nuclear targets were discussed [50] and some applications for DIS off heavy nuclei were studied [53]. It was found that topological cross-sections follow directly from the nonlinear $k_\perp$-factorization for the inclusive cross-sections. A novel property of the QCD unitarity cutting rules is that it gives rise to two kinds of cut Pomerons. It turns out that the topological cross-sections in DIS are substantially different from the naive application of the Glauber–Abramovsky, Gribov, and Kancheli (AGK) [54] approach for color dipoles.

6 Non-perturbative QCD and Low-Energy Models

Recent experimental measurements of the anomalous magnetic moment of the muon, $a_\mu = (g_\mu - 2)/2$, by the E821 experiment at the Brookhaven National Laboratory have provided the value $a_{\text{exp}} = 11659208.0(6.3) \cdot 10^{-10}$. This unprecedented accuracy poses a challenge to theory within the SM and asks for a theoretical uncertainty lower than the uncertainties for the nearest-future experiments (at BNL, JPARC, and FNAL) in order to be able to reveal effects of contributions beyond the SM. Within the SM, one has $a_{\mu}^{\text{SM}} = a_{\mu}^{\text{QED}} + a_{\mu}^{\text{EW}} + a_{\mu}^{\text{Hadr}} = 11659178.5(6.3) \cdot 10^{-10}$, a prediction $3.4\sigma$ below the experimental value. Because both $a_{\mu}^{\text{QED}}$ and $a_{\mu}^{\text{EW}}$ are known with a high accuracy, the only source of uncertainty (within the SM) is the hadronic part, encoded in $a_{\mu}^{\text{Hadr}}$. The analysis [55] presented by Dorokhov is devoted to the calculation of the pion-pole contribution of the hadronic light-by-light (LbL) scattering to $a_\mu$ within the nonlocal chiral quark model (N$\chi$QM) [56, 57]—motivated by the instanton model of the QCD vacuum [58, 59, 60]. The benchmarks of the work include a new estimate $a_{\mu}^{\text{LbL}, \pi} = 6.5 \cdot 10^{-10}$ which agrees with previous ones based on the usage of the CLEO data on the pion-photon transition form factor. Moreover, the QCD constraints suggested by Melnikov and Vainshtein [61] are satisfied within this model calculation. The more demanding calculational task of including the scalar, axial-vector, and the $\eta, \eta'$ meson exchanges, as well as taking into account the quark and meson box diagrams, is still in progress.\footnote{See also Eric Bartos’ talk on the pion-pole contributions to the LbL part of $(g - 2)_\mu$ [62].} Hence, it remains to
be seen whether the SM can fully explain the measured value of $a_\nu$, or if there is room for new physics.

A new application [63] of Chiral Perturbation Theory (ChPT) to pion polarizabilities was reported by Ivanov. More specifically, he discussed a chiral expansion applied to the $\gamma\gamma \to \pi\pi$ amplitude at the Compton threshold and found that the outcome converges quite rapidly. The obtained two-loop result for the charged pion polarizabilities ($\alpha - \beta$)$_\pi$ shows agreement with well-known low-energy theorems. However, a discrepancy of almost a factor of 2 between this result and several experiments remains, he said, so that more efforts are required here. In this respect, data from the COMPASS Collaboration at CERN may be useful before further model-dependent interpretation is possible.

Hadron light-cone distribution amplitudes (LCDA) are the chief ingredients of factorization formulae in QCD because they are (i) process independent, i.e., universal, and (ii) they encode in terms of appropriate expansion coefficients the nonperturbative dynamics of confinement [64, 65], while their evolution is controlled order-by-order by renormalization-group type equations within QCD perturbation theory. Evidently, their calculation/derivation is of paramount importance for various phenomenological applications. Several methods and models have been proposed over the years with varying degree of precision and/or inherent theoretical uncertainties. The interested reader may consult for further reading the reviews in Refs. [66, 67, 68].

One of the most applied and most serious analytic approaches to extract quantitative information on the hadron DAs is the method of QCD Sum Rules—see [66]. Pivovarov addressed in his talk the extraction of the kaon LCDA using the QCD sum rule approach [69] and including NNLO perturbative corrections. He outlined that these perturbative corrections to the original nonperturbative QCD sum rule are numerically important because they change the relative magnitude of the $d = 2$ loop diagrams and the $d = 4, 6$ condensate terms in the Operator Product Expansion. As a result, the first Gegenbauer moment $a_{1K}^K$ of the corresponding leading-twist kaon DA at a low scale $\mu \sim 1$ GeV amounts to $a_{1K}^K(1$ GeV$) = 0.10 \pm 0.04$, while the previous (average) result reads $a_{1K}^K(1$ GeV$) = 0.06 \pm 0.03$. There is, however, a rather large uncertainty in the determination of $a_{1K}^K$ owing to the poor precision of the light quark masses—with $m_s$ directly entering the QCD sum rule—, whereas $m_{u(d)}$ determine the quark-condensate densities via the Gell-Mann–Oakes–Renner relation. The comparison of the result for $a_{1K}^K$ is also in disagreement with very recent computations of this quantity on the lattice by the QCDSF/UHQCD [70] and the UKQCD Collaboration [71]. They found, respectively, $a_{1K}^K(2$ GeV$) = 0.0453 \pm 0.0009 \pm 0.0029$ and $a_{1K}^K(2$ GeV$) = 0.048 \pm 0.003$. Two-loop
evolution of Pivovarov’s QCD sum-rule result to the lattice scale $\mu_{lat} = 2$ GeV gives $a_1^K(2\text{GeV}) = 0.08 \pm 0.04$, which is—within the quoted uncertainties—only in marginal agreement with the lattice estimates. Clearly, here more work has to be done in order to understand the roots of the observed discrepancy and achieve agreement between QCD sum-rule calculations and lattice simulations.

The method of QCD sum rules underlies also the analysis of the moments of the heavy-quark parton distribution function, reported by Oganesian [72]. The method was developed in [73] and is outlined in the first entry of Ref. [72]. The reliability of the heavy-quark mass limit of the sum rule (in the description of the heavy-quark fragmentation functions), expressed in terms of moments (calculated with QCD sum rules) of heavy-quark parton distribution functions, was studied. It was shown that in the case of the bottom quark, the heavy-mass limit (of the expansion in the heavy-quark mass) is reliable, provided the second $O(1/m^2)$ term is included. In the case of the charm quark, the heavy-mass limit is not reliable and, hence, the moments are far from the exact answer. This implies, concluded Oganesian, that the heavy-quark limit is not a reliable approximation for the parton distributions and fragmentation functions of the $c$-quark.

Let us close this section by considering the study of the photon DA and the role played by the magnetic susceptibility of the QCD vacuum within the context of QCD sum rules with nonlocal condensates [74, 75], presented by Pimikov. The final goal of his analysis is the extraction of the photon DA and the vacuum magnetic susceptibility $\chi$ at $Q^2 = 0$ and $\mu^2 = 1$ GeV$^2$ including the NLO perturbative corrections. This task has not yet been accomplished. Hence, Pimikov restricted his report on the obtained results at the LO level of the sum rules and concentrated on a nondiagonal correlator to extract the photon DA and $\chi(0)$. His main results are: (i) A phenomenological estimate of $\chi^{Ph}(0) = 4.05 \pm 0.33$ GeV$^{-2}$. (ii) The LO values $\chi^{LO}(0) = 4.5 \pm 0.5$ GeV$^{-2}$ and $\phi_2^{LO}(x) = 1$ (with the exception of the endpoints). He argued that the NLO magnetic susceptibility should be smaller, i.e., $\chi^{NLO}(0) = 4.0 \pm 0.5$ GeV$^{-2}$, and emphasized that the NLO terms should play a crucial role in the determination of the photon DA in the endpoint regions.

7 Hadron form factors

Form factors constitute a powerful and effective tool in analyzing the inner structure of hadrons and compare theoretical predictions with experimental data with respect to charge and magnetic properties. Coupled with QCD, hadron form factors provide a
basic understanding of the quark-gluon dynamics at the amplitude level. Even more important, exclusive processes, naturally described in terms of form factors, depend in detail on the composition of the hadron wave functions themselves. These are, as we have discussed earlier, the basic nonperturbative ingredients in QCD calculations. In view of the complexity of the QCD binding effects, it is not possible to derive form factors from first principles of QCD. Therefore, one attempts to model them as close to QCD as possible, paying particular attention to factorization, causality, and renormalization. At low-momentum transfer, where hadronization effects become dominant, form factors are combined with Vector Meson Dominance (VMD) constraints in order to account for hadronic degrees of freedom. In this way, it becomes possible to explore a wide region of $Q^2$ both in the spacelike as well as in the timelike regime.

Naturally, the form factors of the nucleon are attracting much interest both theoretically and phenomenologically. From the theoretical point of view, one is keen to use them at large $Q^2 = -q^2$, where factorization applies, for different shapes of the nucleon wave functions [68] and test whether they can provide the correct sign, normalization, and scaling behavior as compared to the data. But also phenomenological approaches which combine the perturbative QCD asymptotics with VMD at low $Q^2$ are indispensable in analyzing the various existing data from SLAC and JLab, measuring the differential cross section and polarization observables.

Tomasi-Gustafsson gave an overview on electromagnetic hadron form factors, notably of the nucleon and the deuteron in the space- and the timelike regions in terms of selected nucleon models (see [76, 77, 78]). She also presented model-independent features that are connecting scattering (in Euclidean space) and annihilation (in Minkowski space) channels, thus providing a deeper insight into the underlying physics. Polarization experiments are especially crucial for the timelike form factors as these are complex quantities. In the presented work, parametrizations for the nucleon (and the deuteron) form factors were used which work well in the spacelike region, the motivation being provided by the fact that one can use the abundance of the existing precise experimental data to constrain the model parameters. These parametrizations are then analytically continued to the timelike region [79]. A particular role is played here by the ratio $F_2/F_1$ of the Pauli over the Dirac form factor and its analytic continuation from the spacelike to the timelike region. Predictions were extracted for the magnetic and electric form factors of the proton and the neutron in the Sacs parametrization and compared in detail with experimental data from JLab [8]. An extension to spin-1 particles (and to the

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3For the deuteron form factors, see also Adamuśćin's contribution in the Proceedings and Dubnička's
axial form factor of the proton) was performed with the help of the VDM. Predictions were presented for the differential cross section and for polarization observables for the following processes: \( e^+e^- \rightarrow d + 7 \), \( e^+e^- \rightarrow \rho + 4\pi \), and \( e^+e^- \rightarrow a_1 + \pi \rightarrow 4\pi \). An important observation in the presented analysis is that the asymptotic regime defined by the prescriptions of the considered models and the asymptotic properties derived from the analyticity of the form factors act at a different level. In other words, the asymptotics of the total cross section for the \( NN \) and \( NN \) interactions and the QCD asymptotics are connected to each other in a non-trivial way.

In Dubnicka’s talk, based on original work published in [79, 80], the size of the two-photon contribution to the elastic electron-deuteron scattering was estimated. The new JLab proton polarization data on \( \mu_p G_{Ep}(t)/G_{Mp}(t) \) [81] were analyzed together with all existing nucleon data on the electromagnetic nucleon form factor in both the spacelike and the timelike region (see [79] for further references). A ten-resonance unitary and analytic model was designed and used in order to capture the key features of the electromagnetic structure of the nucleon. As a result, a non-dipole behavior of \( G_{Ep}(t) \) in the spacelike region with a zero around \( t = -13 \text{ GeV}^2 \) was revealed. The difference in the deuteron elastic structure functions \( A(t) \) and \( B(t) \) between the non-dipole behavior of \( G_{Ep}(t) \) and the Rosenbluth dipole behavior found to be negligible. This outcome was interpreted as indicating that the two-photon-exchange contribution to the unpolarized elastic \( ed \)-scattering is of less importance relative to the one-photon exchange part.

In Dubnicková’s talk a compatibility check of the new spacelike-region pion’s form-factor data with \( \sigma_{tot}(e^+e^- \rightarrow \text{hadrons}) \), obtained by radiative return, was outlined. To this end, the new high-precision JLab data on the pion form factor in the spacelike region [82] were investigated as regards their compatibility with the very precise data on the total cross-section of the \( e^+e^- \)-annihilation process obtained via radiative return by the KLOE Collaboration [83] and the CMD-2 Collaboration [84]. Technically speaking, this means to express the pion form factor in the form of a dispersion relation and take into account its QCD asymptotic properties. Exploiting the analytic behavior of the pion form factor the way just described, the compatibility of the two different experimental-data sets was established.

report to follow.
8 Quark confinement

As mentioned earlier in this summary, a systematic treatment of QCD is possible only within perturbation theory in the region of large momenta, where the strong coupling is a small parameter of the expansion. In contrast, the region of low momenta, where quark and gluon degrees of freedom start to hadronize into mesons and baryons, is not accessible to perturbation theory and one has to rely upon effective QCD-inspired models. The deeper reason behind this failure, is the fact the there is no any \textit{ab initio} understanding of the mechanism that transforms colored partons into colorless hadrons. The technical name of this phenomenon is quark confinement and is still the most puzzling issue (and stumbling block) of QCD as a quantized Yang-Mills (YM) theory with local color gauge invariance. Of course, one may hope that with increasing computer power, lattice theory will provide a complete understanding of how quarks interact with each other at large distances, revealing this way the confinement mechanism (we have already some clues about this in terms of the string tension). However, one may strive to get an analytic understanding of confinement and work out the crucial criteria for this in an unbroken YM theory, like QCD.

Diakonov and Petrov dedicated strong efforts \cite{85, 86} to understand quark confinement in terms of dyons which are (anti-)self dual solutions of the equations of motion of the pure YM theory. In this work, presented by Petrov, two scenarios for confinement at $T \neq 0$ were addressed using a model based on dyons. One scenario assumes that $\langle P \rangle = 0$ appears as the result of strong fluctuations and the vacuum is essentially quantum. The other option considers the state with $\langle P \rangle = 0$ to be the most favorable one and emerging due to nonperturbative effects. Fluctuations above this state are small and the situation is semi-classical. Skipping here technical details, let us concentrate on the main findings of the presented approach: (i) The semiclassical vacuum built of dyons has many features expected for the confining pure YM theory. (ii) It turns out that the minimum of the free energy for the dyon ensemble lies exactly at the holonomy corresponding to the zero Polyakov line $\langle P \rangle = 0$. (iii) The dyon model reproduces all qualitative features of pure gluon-dynamics known from lattice simulations. (iv) Ideologically, it completely follows the t'Hooft–Polyakov scenario of confinement and despite the fact that it is quite crude, it appears to be numerically successful.
9 Mathematical and other analyses

At the fundamental level, theorists are considering various ideas to reveal the mechanism of the electroweak symmetry breaking. In recent work [87], Faddeev and collaborators worked out a version of the electroweak Lagrangian in terms of manifestly gauge-invariant variables, which are the analogs of the Meißner supercurrent that appears in the BCS superconductor. These non-Abelian supercurrents remove all undesired gauge dependence from the electroweak Lagrangian by a mere change of variables and without any gauge fixing. Then, as Faddeev pointed out, any issues with Elitzur’s theorem become obsolete. Moreover, he showed that the ensuing Lagrangian describes the electromagnetic interactions of the $SU_L(2) \times U_Y(1)$ gauge-invariant $W$ and $Z$ bosons and (overlooking topological structures) it coincides with the original Lagrangian in the unitary gauge. Within this context, the Lagrangian acquires a generally covariant form and the vector bosons receive their masses with no reference to any symmetry breaking by a Higgs potential, provided the Higgs field is interpreted as a dilaton that determines the conformal scale in a locally conformally flat spacetime.

Let us complete this summary report by listing some more interesting approaches that cannot be discussed here in detail, but may inspire the interest of the readers. Tkachev made a comment on the LLA method, the $k_T$ jet algorithm and the BFKL theory. Colferai studied a matrix formulation for the small-$x$ renormalization-group improved evolution [88]. Krokhotin discussed BFKL effects in the jet production and a Monte Carlo generator with BFKL evolution. Was gave a comprehensive review of exact phase-space and spin amplitudes and its applications in QCD NLO Monte Carlo programs. Kojo addressed QCD Sum Rules and the $1/N_c$ expansion in connection with dynamical studies of bare $2q$ and $4q$ poles in the $\sigma$ meson [89]. Korchin presented a study of decays with light scalar mesons in Resonance Chiral Perturbation Theory. The electromagnetic form factors of kaons were computed [90] and compared with the data. Buividovich reported on the entanglement entropy of gauge theories and the holography for electric strings, worked out together with Polikarpov [91]. Ktorides considered the AdS/CFT correspondence using Cartan’s theory of spinors. Pajas analyzed rapidity long-range correlations, the color glass condensate, and the percolation of strings [92, 93]. Kudryavtsev presented a composite superstring model for hadrons, employing the extended Virasoro superconformal symmetry [94]. I apologize to those speakers whose contributions have been omitted.
10 Conclusions

This conference took place just a couple of months before the start-up of the LHC. Many of the studies presented here may increase the precision of theoretical calculations to the level relevant for the physics to be probed at the LHC in the years to come. To attain this goal, several issues, still at stake, have to be clarified and improved techniques have to be further developed, like the simultaneous resummation of QED and QCD large infrared effects. Many speakers and authors of the papers presented here have given efforts in advancing our understanding of these and other momentous topics pertaining to a deeper understanding of QCD and its applications.

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