Beyond the Standard Model

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The well-founded cornerstones of our discussion are the classical (Einstein) theory of gravity, local relativistic quantum field theory (QFT), and elementary particle physics, today described so impressively by its so-called “Standard Model” (SM). “Well-founded” does not just imply mathematical elegance but most importantly a solid fundament of observational/experimental findings – the relevance of black holes and of the standard cosmological model confirmed by astrophysical observations; the spectacular successes of quantum electrodynamics (QED), e.g. for anomalous magnetic moments; non-abelian gauge theories and the three-quark-lepton generation structure in the SM explaining a huge body of data (“Rosenfeld table”). The big question remains how to raise a building with these cornerstones: are there further essential pieces still missing? Will it be one unifying building as suggested by the only theory ansatz with this claim – superstring theory?

This involves questions rather far away from our present experimental/observational possibilities. The Planck scale $M_{PL} \sim 10^{18}$ GeV of gravity, important in quantum gravity, and related scales in string theory are far, far above the “high energy” scale of present accelerators, being above, but still in the range of the electroweak scale $\sim 10^{2}$ GeV. Even the highest observed scale of cosmic rays $\sim 10^{10}$ GeV still is intermediate on the way to $M_{PL}$.

A century ago there was a similar problem how to connect microscopic and macroscopic physics. Its solution was one of the great successes of mankind. A deep understanding on one side was based on experimental access to microscopic physics – molecules, crystal lattices, nuclei, ..., on the other side on theoretical methods to develop “effective theories” for the macroscopic world, – gases, fluids, solid states. The appropriate language of the discussion raised above, today, is “Wilsonian” renormalization leading to “effective field theories” designed for a certain scale of observation. The description of a physical system in such a language changes if one considers the same system with varying resolution. Going to a weaker resolution, “to the infrared” (IR), finer details of the object are “integrated out”. Perturbation theory in such effective theories is finite since Feynman loop integrals are cut off in momentum/energy
above the fixed scale of the theory. Adding non-renormalizable terms at very small distances (large momenta) is harmless since they vanish going to the IR region interesting for us. This explains the importance of renormalizable theories in the SM and why we can work quite successfully in this well-known area of QFT (well-known only if infrared properties like confinement are dealt with numerically; there still appear questions concerning its precise nature, and progress, e.g. using supersymmetric variants of quantum chromodynamics (QCD), is slow). The process of renormalization “group” by integrating out physics can strictly speaking not be inverted going to small distances – the “ultraviolet” (UV). Still in QCD the postulate that there is a simple asymptotic freedom behavior at small distances is consistent. All this can be made very concise in the path integral formulation (“sum over fields”) of QFT and can be discussed even quantitatively in numerical studies of discretized theories (“lattice (gauge) theory”).

Let us inspect questions of elementary particle physics which cannot be answered within the SM: certainly most prominent is the unification of the strong and electroweak gauge forces. Indeed continuing the “running” (effective) gauge couplings based on the particle content of the SM towards the UV, one observes some convergence to a common value at a scale of about $10^{14}$ GeV. Going to the minimal supersymmetric extension of the SM (MSSM) this is much improved resulting in a common value of about $M_{GU} \approx 10^{16}$ GeV. Postulating a grand unified gauge symmetry corresponding to a semisimple gauge group ($SU(5), SO(10)$) quarks and leptons are in common representations and related by gauge interactions. For a spontaneous breaking to the SM one has to introduce eventually further Higgs fields (or some non-local Wilson-loop operators) all in representations of these groups. This clearly leads beyond the SM. Massive neutrinos, now well established in experiments, can be considered still partly in the range of the SM, but their small mass naturally induces new scales $M_M \approx 10^7 - 10^{14}$ GeV via $m_\nu \sim m_D^2 / M_M$ (where $m_D$ is a typical charged lepton mass), the so-called “see-saw mechanism”. The scale $M_{GU} \approx 10^{16}$ GeV is still two orders of magnitude below the Planck scale $M_{PL}$ of gravity but big enough to suppress the decay of protons and neutrons of our universe within its age of $\approx 10^{10}$ years.

Supersymmetry (SUSY) is essential in most of these model buildings. This is a symmetry between bosons and fermions, e.g. between a photon and a photino, an electron and its bosonic partner (“selectron”). In its gauged (“local”) form it also changes gravity to supergravity (SUGRA). Supersymmetry is the only possible enlargement of the Ponicare group. In more practical terms it allows to continue the successful way to do calculations in the SM. The main point here is its ability to tame UV-divergences requiring an artificial fine tuning in the SM in order to preserve hierarchies between vastly different scales. This is why it allows to continue the successful calculations of the SM and why it is so popular now in phenomenologically minded circles though being a genuinely theoretical concept not confirmed in experiments up to now (but hopefully soon). Since there are certainly no observed super-partners