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Physics at the LHC: a short overview

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Abstract. The CERN Large Hadron Collider (LHC) started operation a few months ago. The machine will deliver proton-proton and nucleus-nucleus collisions at energies as high as $\sqrt{s} = 14$ TeV and luminosities up to $\mathcal{L} \sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, never reached before. The main open scientific questions that the seven LHC experiments – ATLAS, CMS, ALICE, LHCb, TOTEM, LHCf and MOEDAL – aim to solve in the coming years are succinctly reviewed.

1. Introduction

The LHC [1] is the ultimate particle collider in terms of centre-of-mass (c.m.) energies and luminosity. The machine together with its 7 international experiments at the CERN laboratory in Geneva, have been built to study the frontier of our knowledge about the particles, interactions, and space-time structure of the Universe. Their design goal addresses, in particular, at least 6 fundamental questions that still remain unsolved today in high-energy physics:

- (i) Mass generation problem: How do the elementary particles of the Standard Model (SM) acquire their bare masses? Is it via their coupling to the Higgs boson – the last predicted missing piece of the SM – or through other mechanisms?
- (ii) Hierarchy / fine-tuning problem: What mechanism stabilizes the Higgs boson mass up to the next known physics scale at Planck energies (10^{16} orders-of-magnitude above)? Supersymmetry (SUSY)? Higgs boson compositeness? new space dimensions?
- (iii) Dark matter (DM) problem: What weakly-interacting particle accounts for one fourth of the (invisible) content of the universe? Can the lightest sparticle or other new massive particles (lightest technihadron or Kaluza-Klein tower, axions, sterile ν 's, ...) explain DM?
- (iv) Flavour problem: Why do we observe a matter-antimatter asymmetry in the Universe? Why are there so many types of matter particles and they mix the way they do?
- (v) Strong interaction in non-perturbative regime: Why quarks are confined in hadrons? What is the energy evolution of the total hadronic cross sections? Can one experimentally test the conjectured duality between gauge and string theories (AdS/CFT)?
- (vi) Origin/Nature of the highest-energy cosmic-rays (CRs): What are the sources and type of particles constituting CRs at energies up to 10^{20} eV?

Of course, the solutions to these open problems need to be consistent, if not directly connected, among each other. The two large multipurpose detectors, ATLAS [2] and CMS [3], have the experimental capabilities to address the full set of questions. The two mid-size experiments, LHCb [4] and ALICE [5], are mostly optimised for problems (iv) and (v) respectively, although they can cover a subset of the rest of research topics. The smallest ones, TOTEM [6], LHCf [7] and MOEDAL [8], aim at studying particular aspects of questions (v), (vi) and (iii) respectively.

2. Preface: Rediscovering the Standard Model (SM)

The SM is a renormalizable quantum-field-theory which – unifying quantum mechanics and special relativity – explains the fundamental interactions (except gravity) among elementary particles via a local $SU_C(3) \times SU_L(2) \times U_Y(1)$ gauge-symmetry group¹. The three gauge-symmetry terms give rise to the strong, weak and electromagnetic interactions. The particles fall into different representations of these groups. The SM Lagrangian (without neutrino masses) contains 19 free parameters: 3 gauge couplings, 6 quark masses, 3 lepton masses, 3 mixing-angles, 2 CP phases, and 2 Higgs-boson couplings, to be determined experimentally. The SM (except the Higgs sector) has been verified to high precision in many measurements and the LHC will allow one to test it in a regime of energies up to 7 times higher than those probed before. Prior to looking for new physics signals one needs to confirm that we have a good experimental and theoretical control of processes which have been already measured at lower energies.

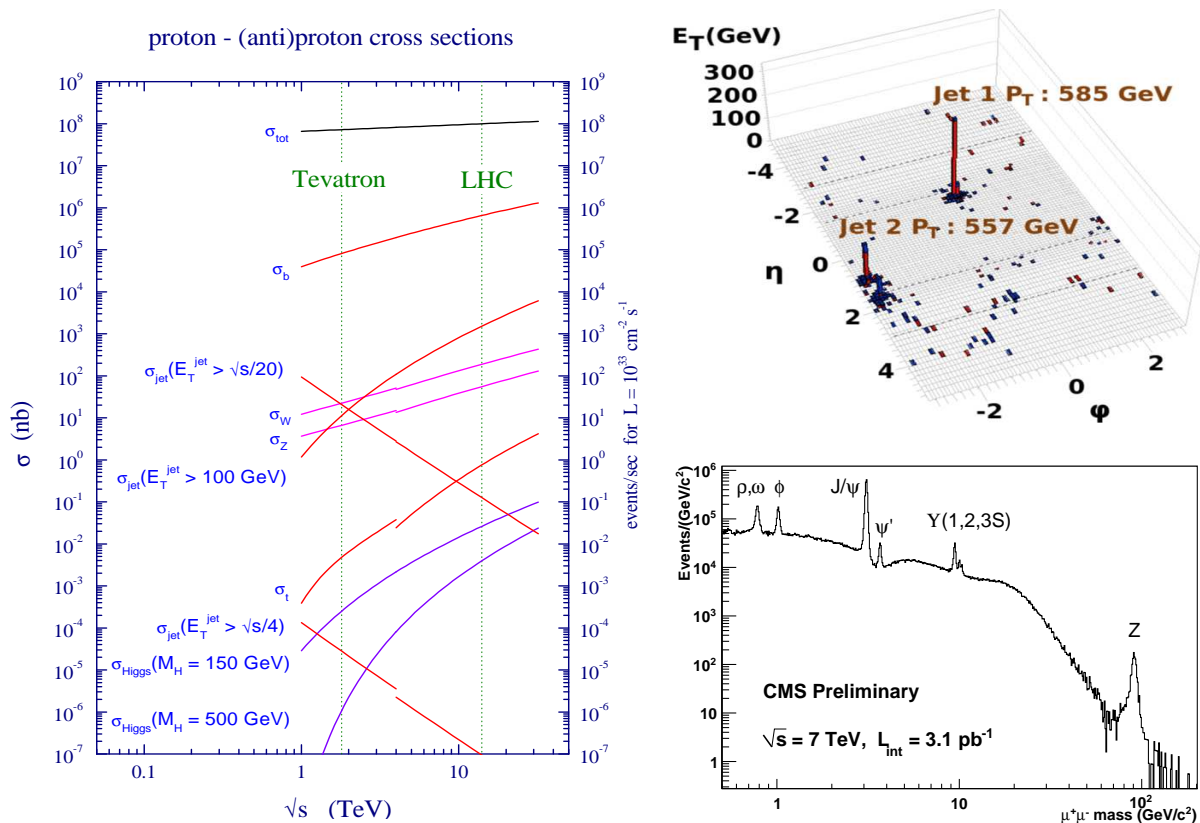


Figure 1. Left: Cross sections (and rates for $\mathcal{L} = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$) as a function of \sqrt{s} for various SM processes in p - p (p - \bar{p}) collisions [9]. Right: First measurements in p - p at 7 TeV: dijet event with $m_{jj} = 2.13 \text{ TeV}/c^2$ (top), and mass spectrum of all known dimuon resonances (bottom) [10].

The processes with the largest cross sections in hadronic collisions are mediated by the strong force (upper curves in Fig. 1, left) and thus the first LHC measurements in p - p at $\sqrt{s} = 7 \text{ TeV}$ are linked to QCD observables such as those shown in Fig. 1 right. Perturbative QCD calculations agree well with preliminary data such as high- p_T hadrons, jets, and heavy-flavours measured by ATLAS [11], CMS [10], ALICE [12] and LHCb [13]. Next in importance in terms of cross sections are the electroweak processes: the first W and Z bosons (highest-mass dimuon peak in Fig. 1 right) have been detected with the first hundred nb^{-1} integrated by CMS and ATLAS.

¹ The subindices indicate the conserved color and weak-hypercharge and the action on left-handed fermions.

3. Problem I: Mass generation problem – the Higgs boson

The LHC together with the ATLAS and CMS experiments have been designed primarily to be able to solve the last missing element of the SM: the mechanism of generation of the elementary particle masses. Indeed, the electroweak (EWK) sector of the theory suffers from two problems:

- The $SU_L(2) \times U_Y(1)$ symmetry imposes zero-masses for the gauge bosons and fermions in striking contradiction, in particular, with the large observed masses for W and Z.
- Without a mechanism to generate the vector-boson masses, the longitudinal WW scattering cross sections grow quadratically with energy and break unitarity at energies $\mathcal{O}(1 \text{ TeV})$.

A simple and elegant solution to these problems, was proposed by Englert-Brout-Higgs-Guralnik-Hagen-Kibble [14] who demonstrated that the W and Z bosons can acquire a mass while preserving the $SU_L(2) \times U_Y(1)$ symmetry of the EWK Lagrangian, if the vacuum is filled with a field with a non-zero expectation value which couples to the (massless) vector-bosons. The electroweak symmetry is preserved in the Lagrangian but it is broken spontaneously by the ground-state actually realized in nature. Such a mechanism involves adding new terms, an extra scalar-doublet and associated couplings, to the SM Lagrangian. Three of the four degrees of freedom of this extra field mix with the W,Z bosons to provide them with mass, while the other one becomes the Higgs boson, a new scalar particle. In a similar manner, Higgs bosons “lurking virtually” in the vacuum drag on all fermions to give them mass. The quadratic rise of the WW,ZZ cross sections is thus damped by new diagrams involving Higgs boson exchange.

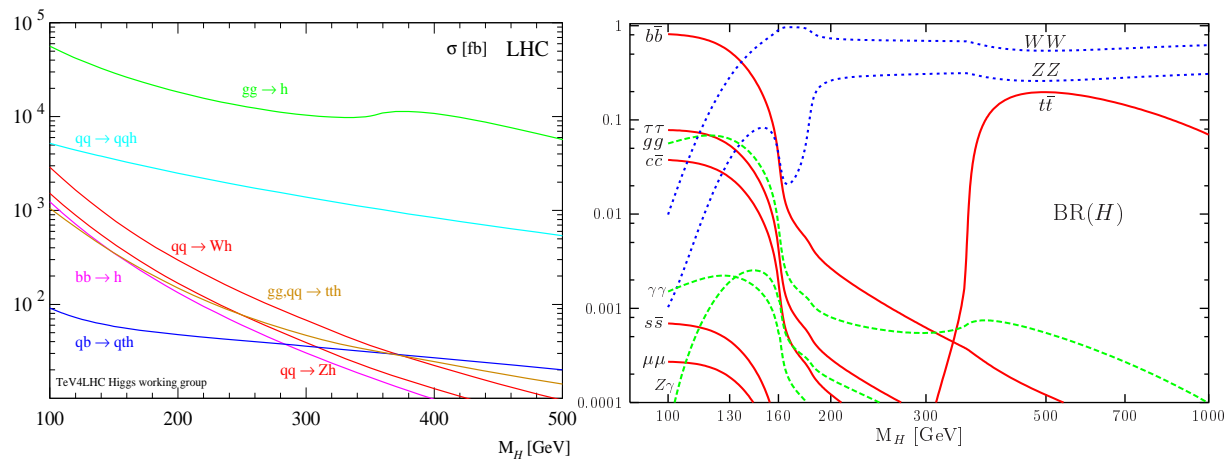


Figure 2. SM Higgs boson: LHC production channels (left) [15] and branching ratios (right) [16].

The mass of the Higgs boson is a free parameter of the SM. Direct searches at LEP [17] and Tevatron [18] have constrained its value at 95% confidence level (CL) to the range $114.4 - 158 \text{ GeV}/c^2$ and $m_H > 175 \text{ GeV}/c^2$, whereas indirect constraints from global fits to precision EWK data (accounting for virtual Higgs contributions e.g. to the W and top-quark masses) exclude $m_H > 185 \text{ GeV}/c^2$ at 95% CL [19]. At the LHC, several Higgs production processes and decay channels are accessible (Fig. 2). Depending on its mass, different production/decay modes can be exploited for a 5σ -discovery integrating a few tens of fb^{-1} in p - p at 14-TeV [2, 3]:

- For $m_H < 135 \text{ GeV}/c^2$, the preferred channels involve $\gamma\gamma$ and $\tau\tau$ decays, in particular in vector-boson-fusion production processes accompanied by forward-backward jets.
- For $m_H > 135 \text{ GeV}/c^2$, the $H \rightarrow WW^{(*)}, ZZ^{(*)}$ modes, characterized by four (two) high- p_T electrons or (and) muons in the final-state, provide a relatively clean signal.

The determination of the Higgs couplings to all SM particles and its quantum numbers will likely require a more precise e^+e^- collider or resort to other more suppressed production channels [20].

4. Problem II: Hierarchy/fine-tuning – New symmetries at high energies ?

The hierarchy problem of the SM is related to the “uncontrollable” running of the Higgs boson mass with energy. Indeed, (i) the m_H value is not predicted by the theory, nor protected by any internal SM symmetry; and (ii) being a scalar field, the loop radiative corrections make m_H increase *quadratically*² up to next physics scale known today, where gravity becomes as strong as the gauge interactions. Thus, if m_H is imposed from a symmetry at the Planck scale, then its value has to be fine-tuned to 1 part in $m_{EW}/m_{Planck} \approx G_F^{-1/2}/G_N^{-1/2} \approx 10^{16}$!

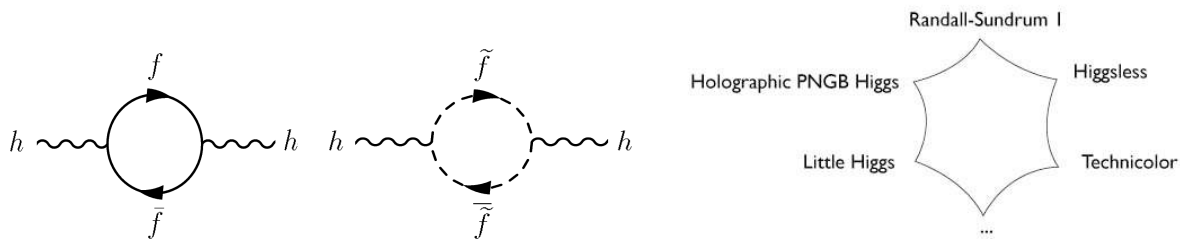


Figure 3. Left: Virtual contributions to the Higgs mass from SM fermions and SUSY sfermions. Right: Alternative (non-SUSY) models beyond the SM [21].

There are three general theoretical solutions to the hierarchy problem. All of them imply physics beyond the Standard Model (BSM), and the existence of new symmetries and associated new particles at the TeV scale:

- (i) SUSY: The existence of new SUSY partners, differing by 1/2 unit of spin, for every SM particle provides a simple way to stabilize the Higgs potential, as their amplitude in the quantum corrections come with opposite sign and cancel the SM contributions (Fig. 3, left).
- (ii) Non-Standard “Higgs” models: The W and Z masses can also be generated *dynamically* via a Goldstone boson corresponding to a spontaneously broken global symmetry of a new strongly-interacting (QCD-like) sector at some higher mass scale Λ , as done e.g. in Technicolour [22] or little-Higgs models. In the previous case, the Higgs boson is not an elementary scalar but a condensate of techni-fermions. In the latter, the Higgs is a pseudo-Goldstone boson and its mass is protected from acquiring quadratically-divergent loop corrections by the contributions of new particles (heavy-top, W' , Z' , ...).
- (iii) Low-energy quantum gravity: The huge hierarchy between the EWK and Planck scales can be solved if one considers that the apparent relative weakness of gravitation is not real but only due to the fact that it expands over extra (hidden) spatial dimensions, whereas the other interactions are confined to our visible 3-D space. Theories with extra dimensions (flat as in ADD [23] or warped as in RS [24] models) predict also new particles at the TeV-scale (Kaluza-Klein towers, radion, mini-blackholes, ...).

5. Problem III: Dark matter – New heavy particles ?

The existence of dark matter (DM), accounting for one-fourth of the content of the Universe has been confirmed by several experimental evidences such as (i) the fact that the galactic rotation speed curves do not follow the expected Copernican fall-off with distance from the center, (ii) the structure of the power spectrum of the temperature fluctuations of the cosmic microwave background, (iii) the separation in the distribution of matter observed by gravitational-lensing and by radiation in the collision of two clusters of galaxies. The current DM signatures favour

² In contrast, the radiative corrections for the fermion masses are only logarithmic with energy.

a Weakly-Interacting Massive Particle (WIMP) which is sensitive only to the weak-interaction and gravitation, and which is a stable heavy relic from the early Universe. All BSM theories mentioned in the previous section naturally contain DM candidates such as:

- (i) the lightest SUSY Particle (LSP), such as neutralinos or gravitinos;
- (ii) the lightest technibaryon in technicolor models;
- (iii) the lightest Kaluza-Klein tower (resonances arising from quantized waves in the extra dimension), gravitons from adjacent branes, or radions; in ADD or RS approaches.

In addition, axions or heavy right-handed (sterile) neutrinos, among others have also been proposed as DM particle candidates.

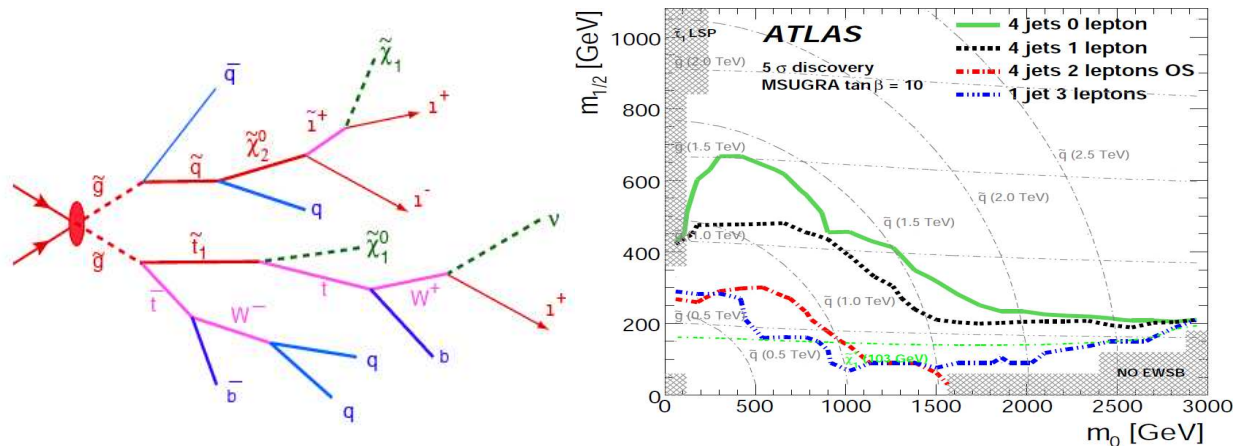


Figure 4. Left: Cascade decay of a pair of gluinos in a p - p collision. Right: mSUGRA discovery contours in jets+leptons+ \cancel{E}_T channels (p - p 14 TeV, 1 fb^{-1}) as a function of m_0 and $m_{1/2}$ [2].

By its own characteristics, any heavy WIMP produced at the LHC will appear as (large) missing transverse energy in a p - p event. In the SUSY case³ the LSP – e.g. the neutralino (a neutral-charge mixture of superpartners of the SM gauge bosons) or the gravitino – is a paradigmatic stable heavy candidate for DM. LSPs are produced in events whose experimental event topologies (Fig. 4, left) are characterized by:

- missing transverse energy (\cancel{E}_T) from the invisible WIMP at the end of a decay cascade,
- multi-jets: from intermediate sparticle decays into heavy SM particles (top, W, Z),
- same-sign leptons/multi-photons: from decay of the intermediate sparticles.

An example of the discovery potential of a particular class of SUSY models (mSUGRA, $\tan\beta = 10$) based on such experimental signatures, is shown in Fig. 4 (right) as a function of two of the free parameters of the theory (the common scalar m_0 and fermion $m_{1/2}$ masses).

In addition, in many BSM approaches the next-to-lightest new particle is metastable (long-lived) and has a mass/charge ratio which makes it a highly ionizing particle when interacting with normal matter⁴. The MOEDAL experiment [8] (sharing the interaction point with LHCb) aims at measuring such highly-ionizing tracks in large plastic detectors.

³ The LSP is stable, as it cannot decay anymore, if SUSY conserves R-parity (i.e. sparticles are produced in pairs and decay into another SUSY particle plus any number of normal particles).

⁴ Typical SUSY highly-ionizing particles are NLSPs such as staus as well as R-hadrons (gluino-parton bound-states).

6. Problem IV: Matter-antimatter asymmetry – new virtual particles ?

The process of changing a quark flavour into another is controlled by the (charged-current) weak interaction. The observation that kaons and B-mesons can transform into their anti-particles with different probabilities in each direction and that they can decay into a state with different Charge-Parity (CP) quantum numbers, implies that the weak force is not invariant under C- (particles and antiparticles exchange) and P- (changing a particle by its mirror image) transformations. In the SM, weak interactions involving W exchange act exclusively on left-(right-)handed (anti)particles, and the coupling among quarks is done in terms of mixed-flavour objects which do not correspond to the quark mass-eigenstates (to which QCD and QED couple) but to a superposition of them. The relationship between the mass- and weak- eigenstates is implemented via the Cabibbo-Kobayashi-Maskawa (CKM) matrix V_{ij} , which describes how quarks mix/decay among each others. CP violation is then incorporated via a CKM matrix complex phase, constrained by the condition $V_{ud}V_{ub} + V_{cd}V_{cb} + V_{td}V_{tb} = 0$, which is often displayed as a unitarity triangle with angles $\alpha = f(V_{td,tb}, V_{ud,ub})$, $\beta = f(V_{cd,cb}, V_{td,tb})$ and $\gamma = f(V_{ud,ub}, V_{cd,cb})$ obtained from kaon and B-meson measurements (Fig. 5, left).

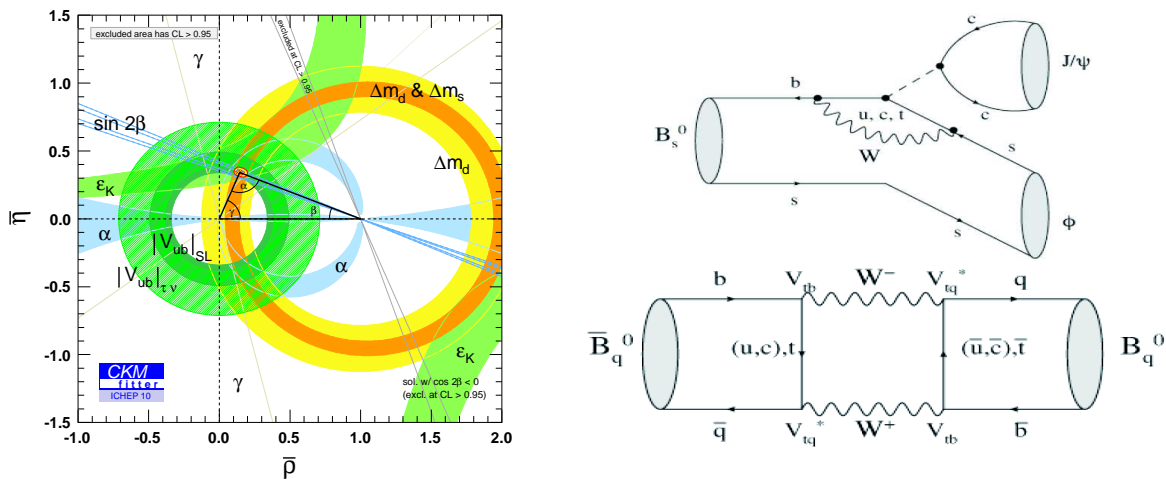


Figure 5. Left: Unitarity triangle fit [25]. Right: Examples of penguin (top) and box (bottom) diagrams for B-meson decay and oscillations in the SM.

The currently known differences between particles and antiparticles (i.e. the amount CP-violation in the SM) are however way too small to explain the matter-antimatter imbalance observed today, $(n_B - n_{\bar{B}})/n_\gamma \approx 10^{-9}$, and new particles/CP-phases are needed to explain how baryon dominance appeared in the Universe (baryogenesis). CP-violation studies at the LHC involve indirect searches of new virtual particles contributing to higher-order (Penguin or box) loops in flavour-changing neutral current processes (Fig. 5, right). The LHCb experiment [4] focuses on measurements in the bottom sector (e.g. $b \rightarrow s$ transitions) which are less constrained by current data and can access higher energy scales than the kaon system, such as:

- (i) detailed B-meson studies of rare decay rates, branching ratios, decays asymmetries, oscillation frequencies, and lifetimes;
- (ii) over-constraints of the unitarity triangle via improved precision of CKM angles and sides, and cross-checks of the same quantity via various measurements.

In all cases, any possibly found inconsistency (in the phases of the couplings, their absolute values, and/or their Lorentz structure) can be a sign of new physics.

7. Problem V: Strongly-interacting matter – QGP, CGC, AdS/CFT, σ_{tot}

The strong interaction among quarks and gluons is described by QCD, a quantum field theory with a very rich dynamical content including asymptotic freedom, infrared slavery, (approximate) chiral symmetry, non trivial vacuum topology (instantons), strong CP problem, $U_A(1)$ axial-vector anomaly, ... All these properties translate into a diverse many-body phenomenology at various limits (Fig. 6, left). Interestingly, QCD is the only SM sector whose full *collective* behaviour – phase diagram, (deconfinement and chiral) phase transitions, thermalization of fundamental fields – is accessible to scrutiny in the laboratory, via high-energy heavy-ion collisions. The study of strongly-interacting matter in extreme conditions of temperature, density and small parton momentum fraction (low- x) can be carried out by measuring different observables in nucleus-nucleus (A-A) collisions which are sensitive to the underlying QCD medium properties (Fig. 6, right) [26].

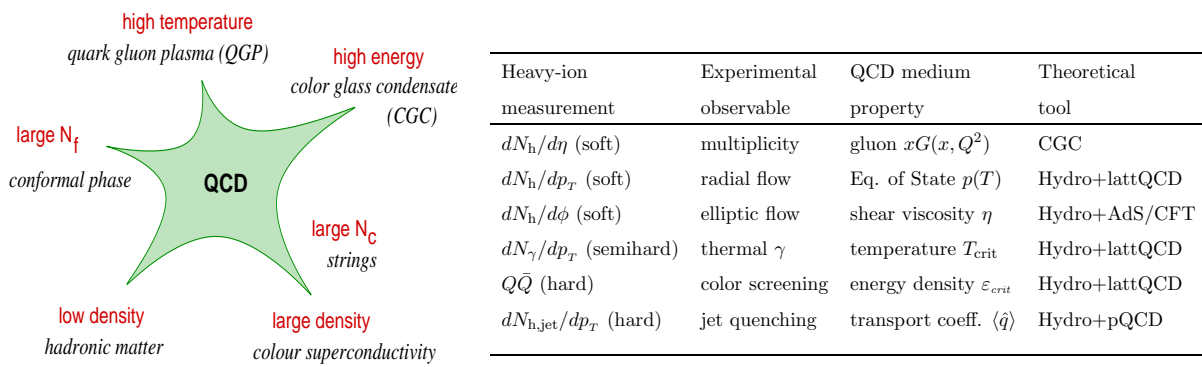


Figure 6. Left: Many-body QCD at various limits [27]. Right: Experimental and theoretical tools in high-energy A-A collisions (dN_h stands for differential hadron distributions).

The collisions of lead nuclei at the LHC ($\sqrt{s_{NN}} = 5.5$ TeV, 30 times higher than those attained previously) will allow one to study quark-gluon matter at unprecedented values of energy density ($\varepsilon_{\text{Bjorken}} \approx 10$ GeV/fm³ at times $\tau_0 = 1$ fm/c) using pQCD probes produced with cross sections 10 to 10^4 higher than at the Relativistic Heavy-Ion Collider. The fractional momenta of the colliding partons will be as low as $x \approx p_T/\sqrt{s_{NN}} \exp(-\eta) = \mathcal{O}(10^{-5})$, where gluon saturation effects, as described in the Color-Glass-Condensate (CGC) approach [28], are expected to dominate the parton dynamics. A part from the standard searches of the formation of a deconfined and chirally-symmetric Quark-Gluon-Plasma (QGP) via quarkonia suppression or jet quenching, one of the important measurements will be that of the azimuthal anisotropies of bulk hadron production with respect to the reaction plane. Such “explosive” anisotropies, known under the name of “elliptic flow”, have been found to be very sensitive to the viscosity/entropy ratio of the produced medium, according to advanced relativistic fluid-dynamics calculations [29] including the QCD equation-of-state computed in the lattice. The field of heavy-ion physics has attracted lots of theoretical interest as testbed for the application of the Anti-de-Sitter/Conformal-Field-Theory (AdS/CFT) duality between weakly-coupled gravity and strongly-coupled gauge theories [30]. Applications of such a formalism have led to the determination of transport properties such as the viscosity [31] of Supersymmetric-Yang-Mills (SYM) plasmas, from simpler black-hole thermodynamics calculations. The large differences between SYM theory and QCD (extra SUSY degrees of freedom, no running-coupling, no confinement, ...) seem to “wash out” at finite temperature [32].

The measurements of the total and elastic p - p cross sections are also part of the LHC physics programme, providing a valuable test of fundamental quantum mechanics relations such as

the Froissart bound $\sigma_{tot} < Const \ln^2 s$, the optical theorem $\sigma_{tot} \sim \text{Im} f_{el}(t=0)$, and dispersion relations $\text{Re} f_{el}(t=0) \sim \text{Im} f_{el}(t=0)$ [33]. The current extrapolations of the total p - p cross section at the LHC ($\sigma_{tot} = 90 - 140$ mb), of which the elastic contribution accounts for about one fourth, suffer from large uncertainties due to disagreeing measurements at the Tevatron and uncertain extractions from cosmic-ray collisions with air nuclei (Fig. 7, left). The main goal of the TOTEM experiment [6] is to obtain a measurement of the total and elastic p - p cross sections, with an uncertainty of about 1%, over a large range of 4-momentum transfers from $-t \approx 2 \cdot 10^{-3} \text{ GeV}^2$ to 8 GeV^2 . TOTEM Roman-pots detectors will measure the elastically scattered protons inside the LHC tunnel area adjacent to the CMS collision point.

8. Problem VI: Origin and nature of the highest-energy cosmic-rays

The origin and nature of cosmic rays (CRs) with energies between 10^{15} eV and the Greisen-Zatsepin-Kuzmin (GZK) cutoff at about 10^{20} eV, measured by the HiRes [34] and recently confirmed by the Auger [35] experiments (Fig. 7, right), remains a central open question in high-energy astrophysics. One key to solving this question is the determination of the elemental composition of cosmic rays in this energy range. The candidate particles, ranging from protons to Fe ions, are measured with surface detectors that detect the “extended air-showers” (EAS) generated in the CR interactions with air nuclei when entering the Earth’s atmosphere [36].

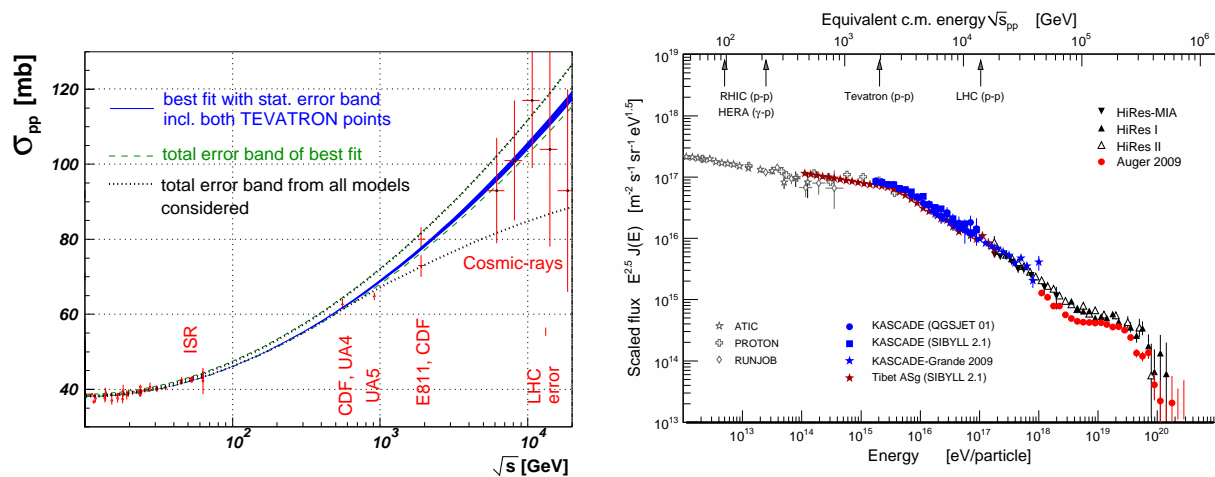


Figure 7. Left: COMPETE fits [37] of σ_{tot} as a function of \sqrt{s} . Right: Measured (scaled) cosmic ray flux as a function of E_{lab} (the equivalent \sqrt{s} of different colliders is also shown) [36].

The determination of the primary energy and mass relies on hadronic Monte Carlo (MC) codes which describe the interactions of the primary cosmic-ray with air nuclei (N, O). The bulk of the primary particle production is dominated by forward and soft QCD interactions, modeled commonly in Regge-Gribov+pQCD approaches with parameters tuned to reproduce the pre-LHC collider data ($E_{lab} \lesssim 10^{15}$ eV). When extrapolated to energies around the GZK-cutoff, the current MCs predict energy and multiplicity flows differing by factors as large as three with significant inconsistencies in the forward region. The LHCf experiment [7] has installed scintillator/silicon calorimeters inside the tunnel area 140 m away of the ATLAS interaction point to detect neutral particles (photons, π^0 , neutrons) close to the beam-rapidity ($|\eta| \gtrsim 8.3$). Measurement of forward particle production in p - p , p -Pb, and Pb-Pb collisions at LHC energies ($E_{lab} \approx 10^{17}$ eV) will provide strong constraints on these models and allow for more reliable determinations of the CR energy and composition at the highest energies.

Acknowledgments

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