PROCEEDINGS OF SCIENCE

CMS physics highlights in the LHC Run 1

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The main physics results obtained by the CMS experiment during the first three years of operation of the CERN Large Hadron Collider (2010–2013, aka. Run 1) are summarized. The advances in our understanding of the fundamental particles and their interactions are succinctly reviewed under the following physics topics: (i) Quantum Chromodynamics, (ii) Quark Gluon Plasma, (iii) Electroweak interaction, (iv) Top quark, (v) Higgs boson, (vi) Flavour, (vii) Supersymmetry, (viii) Dark Matter, and (ix) other searches of physics beyond the Standard Model.

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1. Introduction

Our theoretical understanding of particle physics is encoded in the Standard Model (SM), a renormalizable quantum field theory which –unifying quantum mechanics and special relativity– describes the fundamental interactions (except gravity) via a local $SU_c(3)\times SU_L(2)\times U_Y(1)$ gauge-symmetry group[1]. The three gauge-symmetry terms give rise to the strong, weak and electromagnetic forces, while the particles fall into different representations of these groups. The SM Lagrangian (without neutrino masses) contains 19 free parameters: 3 gauge couplings, 9 Higgs–fermion Yukawa couplings, 3 mixing-angles, 2 Charge-Parity (CP) phases, and 2 Higgs-boson couplings, to be determined experimentally. Despite the fact that the internal consistency and predictive power of the SM have been experimentally confirmed to great precision in the last 40 years, the theory is not complete and has several outstanding open questions, such as:

1. Mass generation problem: The generation of the elementary particles masses through the Brout-Englert-Higgs (BEH) mechanism [1] (as well as the unitarization of WW scattering below $\sim$1 TeV) required the existence of a new (Higgs) scalar boson which had eluded discovery for over 40 years (until 2012).

2. Flavour problem: The huge dominance of matter over antimatter in the Universe cannot be explained by the known sources of CP violation in the SM. More generally, the SM fails to explain the rationale behind the observed pattern of fermion families and flavour mixings.

3. Hierarchy / fine-tuning / naturalness problem: Even with the BEH scalar discovered, the running of its mass receives power-divergent quantum corrections up to the next known physics scale at Planck energies (10^{16} orders-of-magnitude above the electroweak scale), unless new particles/symmetries (e.g. Supersymmetry) provide compensating loop corrections.

4. Dark matter (DM) problem: The SM explains only $\sim$4% of the energy budget of the Universe, the rest being in the form of an unknown DM (plus dark energy), pointing to the existence of new weakly-interacting massive particles (SUSY partners, axions, heavy ν's,...).

5. Colour confinement: Colour-charged particles (quarks and gluons) are always confined inside $SU_c(3)$-invariant hadrons, yet no analytical proof exists that the theory of the strong interaction (QCD) should be confining. Interesting links of this problem exist with the conjectured (AdS/CFT) duality between strongly-interacting gauge and string theories [2].

Those open problems, among others, motivated the construction of CMS [3] (as well as other experiments) at the LHC [4], the ultimate particle collider in terms of center-of-mass (c.m.) energies ($\sqrt{s}$) and luminosity ($\mathscr{L}$). This paper succinctly summarizes the progress in our understanding of the SM and the searches for new physics based on data collected by the CMS experiment during the LHC Run 1 in p-p ($\mathscr{L}_{\rm int}$ = 25 fb^{-1} at $\sqrt{s}$ = 7, 8 TeV), p-Pb ($\mathscr{L}_{\rm int}$ = 34 nb^{-1} at $\sqrt{s_{_{NN}}}$ = 5. TeV), and Pb-Pb ($\mathscr{L}_{\rm int}$ = 170 μb^{-1} at $\sqrt{s_{_{NN}}}$ = 2.76 TeV) collisions.

[1] The subindices indicate the conserved colour, and weak (hyper)charge, and the action on left-handed fermions.

2. Quantum Chromodynamics (QCD)

The processes with the largest cross sections in hadronic collisions are mediated by the strong force between the colliding quarks and gluons, described by QCD –a quantum field theory with a very rich dynamical content (asymptotic freedom, infrared slavery, approximate chiral symmetry,...). Perturbative QCD (pQCD) calculations are able to accurately describe the production of jets (issuing from the hadronization of energetic partons) over an impressive 14 orders-of-magnitude range in their cross sections [5] (Fig. 1, left). In the chiral limit of massless quarks, QCD has a single parameter to be determined empirically: its coupling α_s, whose current uncertainty (around 0.6%) [6] makes of it the least precisely known of all fundamental interaction strengths in nature. Several CMS measurements –such as ratios of 2- to 3-jets, 3-jet masses, inclusive jet and top-quark cross sections [7]– have allowed us to measure α_s up to so-far unprobed scales $Q \approx 2$ TeV (Fig. 1, right). Our understanding of the unitarization of the pQCD cross sections in the $p_T \approx 1$–5 GeV range [8], dominated by "minijets" and multiparton interactions, has also progressed through different observables [9]. However, no clear deviation from the standard DGLAP parton evolution [10], due to BFKL- and/or parton saturation [11], has been observed yet. The most inclusive hadronic observable, the inelastic p-p cross section –including "peripheral" collisions dominated by diffractive interactions which cannot be computed from first-principles QCD– has been also measured [12]. This result, plus others on bulk hadron production [13, 14], have improved our knowledge of the highest-energy cosmic-rays observed on Earth through extended air showers [15].

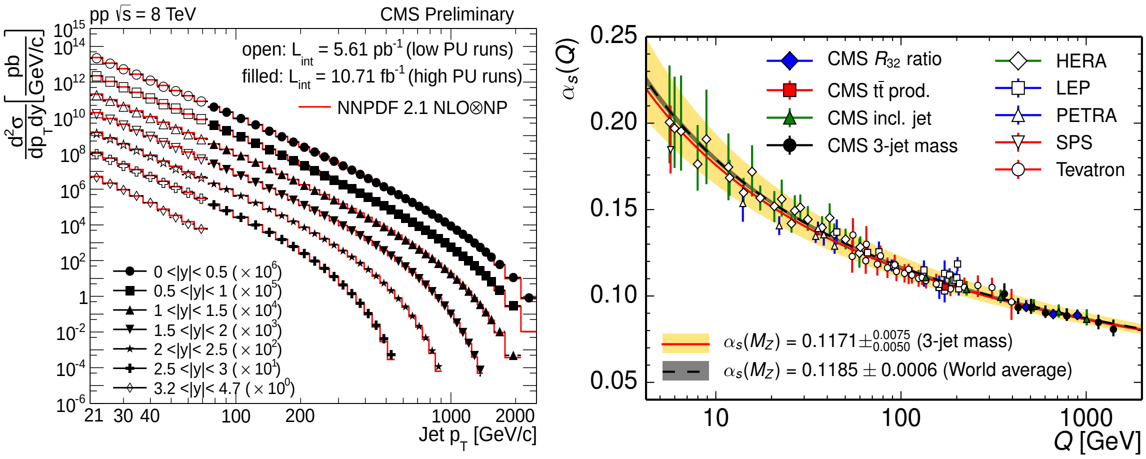


Figure 1: Compilation of CMS measurements of p_T-differential cross sections for jets in p-p at 8 TeV compared to NLO pQCD predictions [5] (left), and strong coupling α_s versus energy scale [7] (right).

3. Quark Gluon Plasma (QGP)

QCD is the only SM sector whose *collective* dynamics –phase diagram, (deconfinement and chiral) phase transitions, thermalization of fundamental fields– is accessible to scrutiny in the lab through the study of the hot and dense partonic medium produced in collisions of heavy nuclei. Interestingly, the large number of multiparton interactions in "central" collisions in the smaller p-p and p-Pb systems at the LHC produces also final states which share many characteristics of those found in heavy-ion collisions. One of the surprises of the first LHC run has been the observation of long-range near-side angular correlations (over $\Delta\eta \approx 8$ units of pseudorapidity) of hadrons produced in high-multiplicity p-p, p-Pb and Pb-Pb collisions (Fig. 2, left) [16], whose kinematical properties are consistent with the formation of a dense parton system (describable with the lattice QCD equation-of-state for a QGP) which expands hydrodynamically [17].

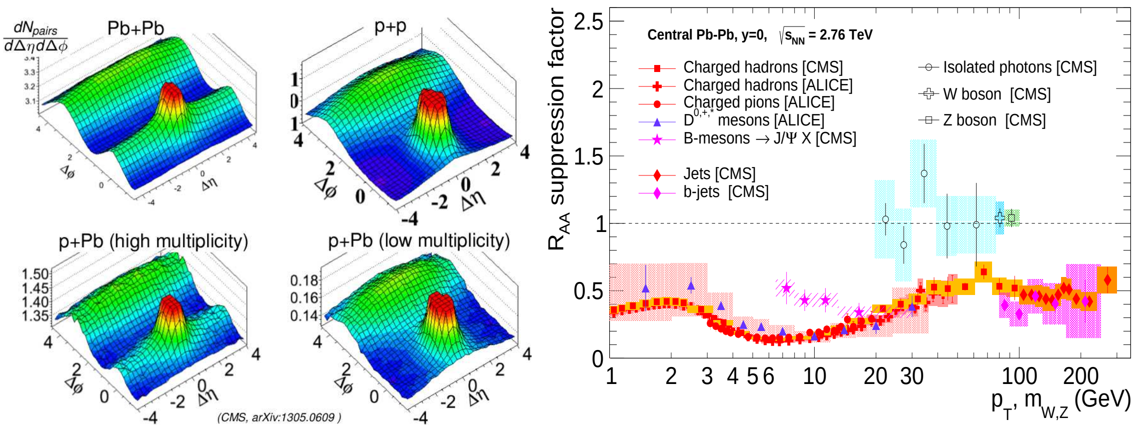


Figure 2: Left: Two-particle angular correlation strengths in $\Delta\eta$ vs. $\Delta\phi$ in p-p, p-Pb and Pb-Pb collisions. Right: Suppression factors for strongly-interacting particles (hadrons, heavy-quarks, jets) and weakly-interacting γ, W, Z bosons as a function of p_T (or mass, for the weak bosons) in central Pb-Pb collisions.

Among all heavy-ion observables, particles with large p_T and/or mass ("hard probes") are useful tomographic tools of the produced medium. In the absence of medium effects, their perturbative production should just be that from an incoherent superposition of independent p-p collisions, i.e. the ratio R_{AA} of Pb-Pb yields over p-p cross sections (normalized by the transverse overlap function of the collision) should be one. Experimentally, this is the behaviour observed for weakly-interacting probes (such as γ, W, Z bosons) [18, 19, 20], modulo small modifications due to nuclear PDFs, but not so for strongly-interacting particles (gluons, light and heavy quarks, and their fragmentation products) [21, 22, 23] which appear suppressed by up to a factor of seven (Fig. 2, right). The latter is a characteristic signature of large parton energy loss in the QGP formed in the collision. Intriguing yield suppressions have been also observed in the J/Ψ [24] and Υ [25] families, consistent with strong final-state interactions of $Q\bar{Q}$ bound states in the plasma.

4. Electroweak physics

The electroweak sector of the SM describes processes involving the γ, W, Z (and Higgs, see later) bosons. Thanks to their precisely-known theoretical production cross sections, the differential distributions of W and Z bosons (aka. "standard candles") have improved our knowledge of the flavour dependence of the quark densities in the proton [26]. In addition, many other electroweak cross sections have been measured with good precision, down to the hundreds-of-fb scale, finding excellent agreement with next-to-leading (NLO) or next-to-NLO theoretical predictions (Fig. 3, left). Multiple first-ever measurements are worth to highlight: $W+t$ [27], $t\bar{t}$+γ [28], $t\bar{t}+Z$ [29], $\gamma\gamma \to WW$ [30], and vector-boson-fusion (VBF) Z boson production [31]. Particularly important are the processes where two or more bosons are produced, which provide also novel stringent limits on anomalous triple [32] and quartic [30, 33] gauge couplings (aQGC, Fig. 3, right).

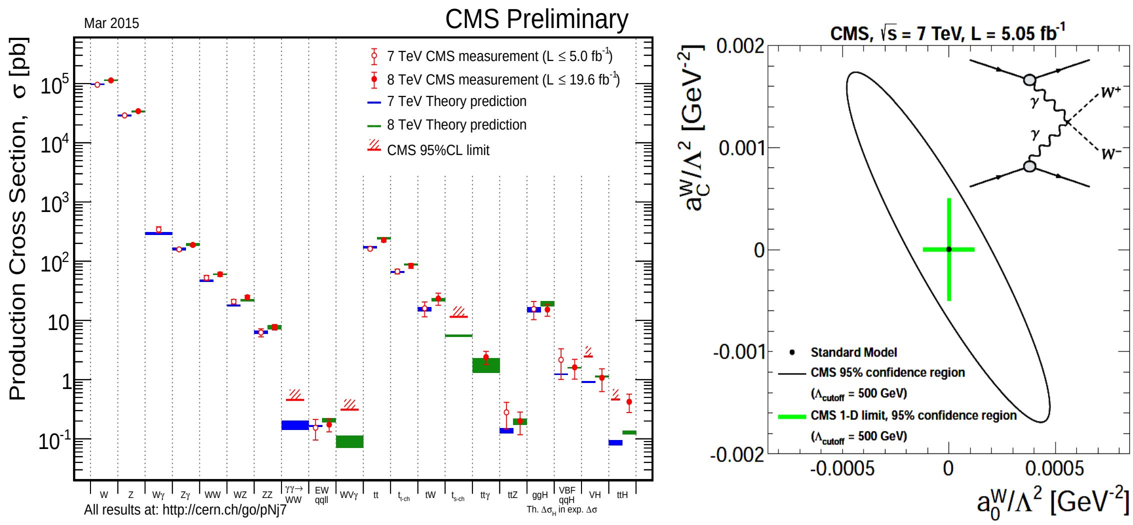


Figure 3: Left: Cross sections for various SM processes measured in p-p at 7, 8 TeV compared to the corresponding (N)NLO theoretical predictions. Right: Limits on aQGC from the $\gamma\gamma \to WW$ measurement [30].

5. Top quark physics

The top quark, being the heaviest elementary particle, features the strongest coupling to the Higgs field. Its mass is thus a fundamental SM parameter with far-reaching implications on naturalness, stability of the electroweak vacuum, SUSY predictions for $m_{\rm H}$, etc. The large top-pair production cross sections at the LHC provide large data samples to study its properties in vari-

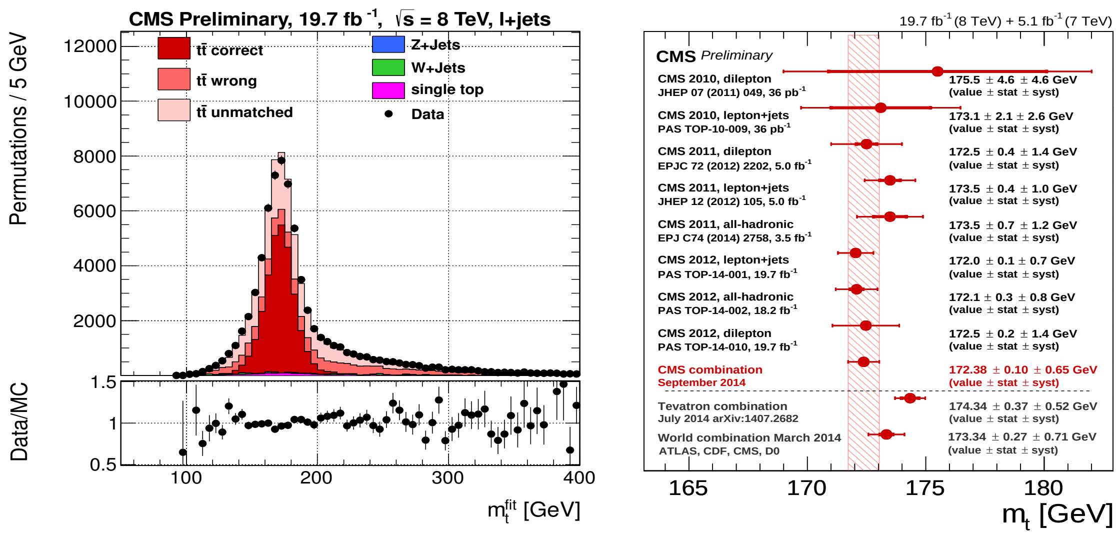


Figure 4: Left: $t\bar{t} \to (WWbb) \to \ell$+jets invariant mass distribution. Right: Combined $m_{\rm top}$ measurements.

ous $t\bar{t} \to WWbb$ final states depending on the decays of the two W bosons (fully-hadronic, lepton+jets, or fully-leptonic). The most precise $m_{\rm top}$ single measurement to date is that obtained from a kinematic fit of $t\bar{t}$ events decaying into a lepton plus at least four jets (Fig. 4, left) [34]. The simultaneous data fit with an overall jet energy scale factor (JSF), constrained by the known mass of the W boson in $q\bar{q}$ decays, yields $m_{\rm top}$ = 172.04$\pm$0.19 (stat+JSF) $\pm$0.75 (syst) GeV. The combined CMS measurements yield a top mass with a 0.4% uncertainty, $m_{\rm top}$ = 172.38 $\pm$ 0.67 GeV (Fig. 4, right). Such a value is about 2σ higher than the $m_{\rm top} \lesssim 171$ GeV required for the stability of the electroweak vacuum given by the evolution of the Higgs quartic coupling (in the absence of new physics up to the Planck scale) for $m_{\rm H}$ = 125 GeV, and $\alpha_s = 0.1184$ [35], indicating that the current Universe is in a metastable state. It is interesting to note that this result hinges partly on our limited understanding of a non-pQCD phenomenon –the modelling of the colour reconnection among the decay partons of the top-quarks and the partons from the rest of the p-p event– which constitutes one of the leading theoretical uncertainties on $m_{\rm top}$. Beyond $t\bar{t}$, single-top cross sections have been measured in the $W+t$ associated production [27] and in the t-channel [36] allowing the extraction (via $\sigma_{\rm single-t} \propto |V_{\rm tb}|^2$) of the Cabibbo-Kobayashi-Maskawa (CKM) t-b element, $|V_{\rm tb}| = 0.998 \pm 0.038 \pm 0.016$, independently of assumptions on the number of quark generations and unitarity of the CKM matrix.

6. Higgs boson physics

The main driving force for the construction of the LHC was to close the last missing piece of the SM: the generation the W,Z bosons (as well as fermions') masses through the spontaneous breaking of the $\mathrm{SU_L(2)}\times\mathrm{U_Y(1)}$ symmetry of the Lagrangian by the presence of a new (Higgs) scalar doublet. Higgs boson searches at the LHC involve a large combination of production chan-

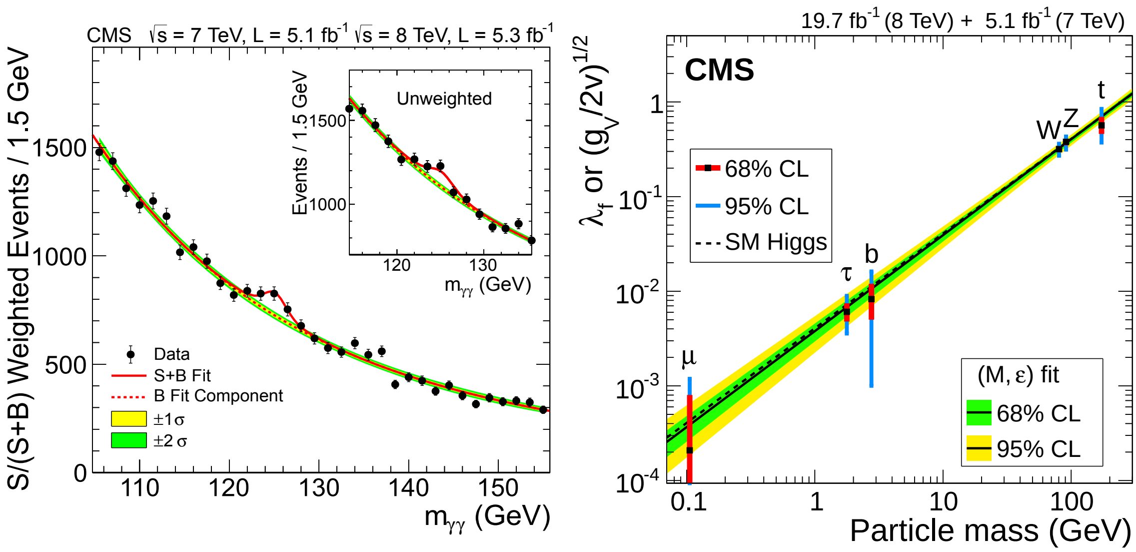


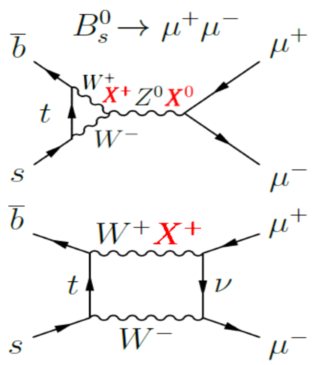
Figure 5: Left: Diphoton invariant mass distribution with the Higgs signal over the continuum background [38]. Right: Higgs boson couplings to fermions and bosons as a function of the particle mass [42].

nels: g-g fusion, VBF fusion, and associated with W,Z,top; and decay modes: $\gamma\gamma$ and $ZZ^\star \to 4\ell$

providing the "cleanest" signal, and $WW^\star, b\bar{b}, \tau\tau$ the largest cross sections. The scalar boson was first observed in the H$\to \gamma\gamma, ZZ^\star(4\ell)$ modes [37] as a resonance over smooth continuum backgrounds (Fig. 5, left), and then as broader (2–4)σ excesses in the $WW^\star$ [39] and 3rd-family fermion ($b\bar{b}, \tau\tau$) [40, 41] decays. The combination of many production and decay channels confirm that the new resonance couples proportionally to the (Yukawa) fermions' masses as well as to the square of the weak-boson masses (Fig. 5, right) [42]. Its mass, $m_{_\mathrm{H}} = 125.09 \pm 0.21 \pm 0.11$ GeV, obtained combining the high-resolution CMS+ATLAS channels, is known already with an impressive uncertainty below 0.2% [43]. Its width has been constrained through the ratio of the on- and off-shell $ZZ^\star(4\ell)$ decays, and found to be smaller than 5.4 times the SM prediction: $\Gamma_{_\mathrm{H}} < 22$ MeV (95% CL) [44]. Its quantum numbers ($J^{PC} = 0^{++}$), determined mostly through the kinematical distributions of the $ZZ^\star$ decay leptons, are those expected for a SM Higgs boson [45]. Taken together, all measured properties show no deviation so-far from the expectations for the SM Higgs boson.

7. Flavour physics

The known differences between particles and antiparticles in the SM, induced by the CP-violation of the electroweak interaction, are way too small to explain the observed matter-antimatter imbalance and new particles and/or CP-phases are needed in order to explain how baryon dominance, $(n_{_\mathrm{B}} - n_{_{\bar{\mathrm{B}}}})/n_{_\gamma} \approx 10^{-9}$, appeared in the Universe (baryogenesis). Precision flavour studies at the LHC involve indirect searches of new virtual particles contributing to higher-order loops (Penguin or box, see Fig. 6, left), in particular in flavour-changing neutral current (FCNC) processes involving B-mesons (e.g. $b \to s$ transitions) which are less constrained by lower-energy experiments. The very-rare $B^0_s, B^0 \to \mu^+\mu^-$ decays, with branching ratios BR $\approx 10^{-8.5,-10}$, have been



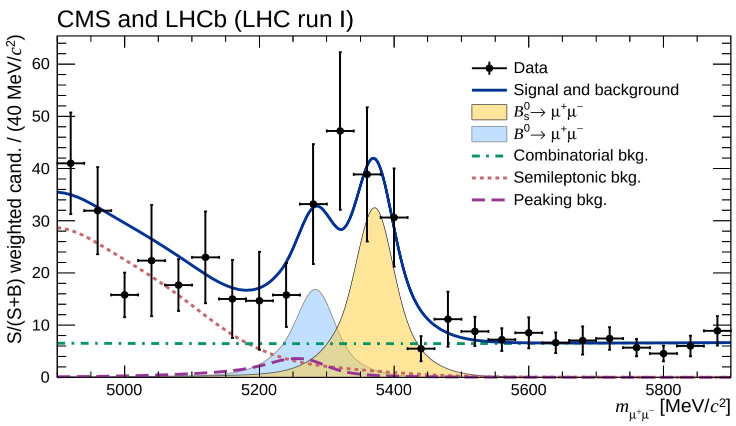


Figure 6: Left: Higher-order FCNC diagrams for the SM B^0_s decay (and in SM extensions with new particles $X^{0,\pm}$ altering the decay rate). Right: Measured invariant dimuon mass in the B^0_s, B^0 decay range [46].

for years considered as "golden channels" to look for deviations from the SM due to new virtual contributions. The combined measurement of the CMS and LHCb experiments (Fig. 6, right) has established conclusively the existence of $B^0_s \to \mu^+\mu^-$ with a 6.2σ statistical significance (as well as a 3σ-evidence for the B^0 decay) with a BR fully compatible with the SM prediction [46]. Such a result imposes novel constraints on the flavour-changing sector of any viable theoretical extension of the SM.

8. Supersymmetry (SUSY)

SUSY has been for decades a leading candidate theory for the extension of the SM due to various reasons: (i) it solves the hierarchy problem by providing new spartners, differing by 1/2 spin-unit for every SM particle, whose quantum corrections stabilize the running of the Higgs mass, (ii) it provides viable dark matter candidates (in R-parity-conserving SUSY) in the form of stable lightest SUSY Particles (LSP, such as neutralinos or gravitinos), (iii) it leads to the high-energy unification of the three interaction couplings, plus (iv) it has various theoretically-appealing features (simplest extension of the Poincaré space-time symmetry, fermion-boson symmetry required by string theory,...). Most of the SUSY searches are based on the assumption of R-parity conservation (leading to sparticle pair-production which decay into other sparticles plus any number of SM particles) with final states characterized by large missing transverse energy ($\not{E}_T$) from the invisible LSP ($\tilde{\chi}^0$) at the end of a decay chain, plus multi-jets,γ and/or same-sign leptons from intermediate sparticle decays. Any final excess (or lack thereof) is then interpreted phenomeno-

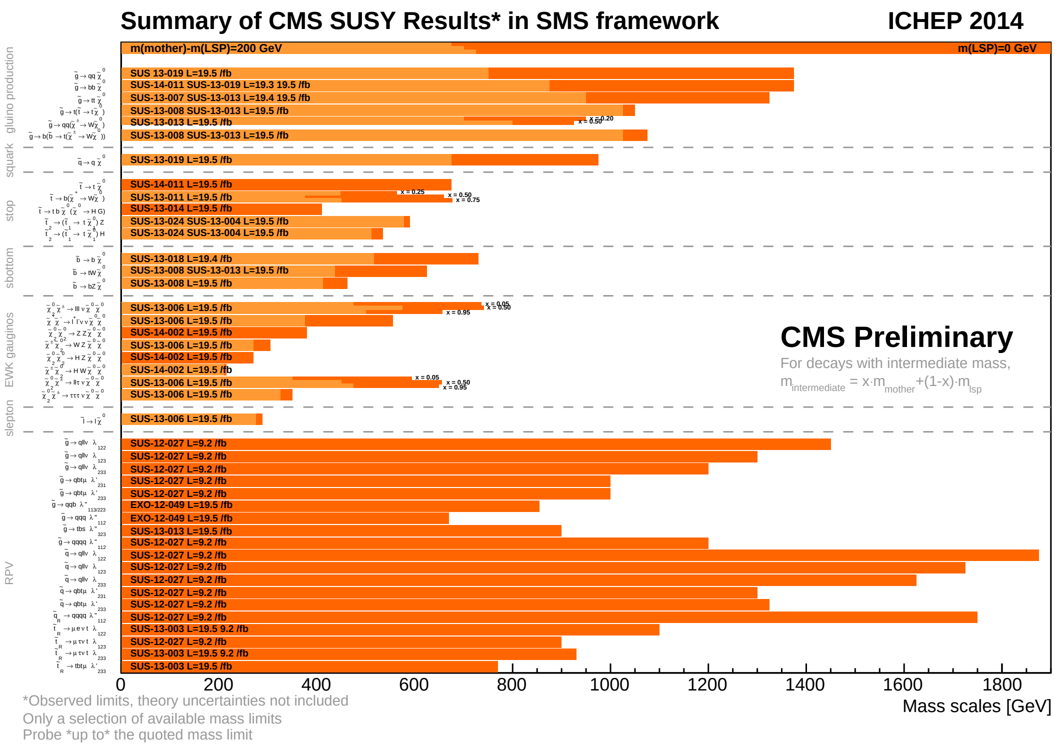


Figure 7: Summary of exclusion limits on (SMS) SUSY particles masses in different CMS searches.

logically in terms of simplified model space (SMS) SUSY realizations with a few free parameters (e.g. within constrained-MSSM or mSUGRA with $\tan\beta$, A, sign(μ) plus common scalar m_0 and fermion masses $m_{1/2}$ defined at the GUT scale and evolved down in energy). Figure 7 summarizes the current exclusion limits on spartners masses: strongly-interacting gluinos and squarks are pushed above ≈1 TeV, stops and sbottoms above ≈0.5 TeV, and electroweak gauginos and sleptons above ≈0.3 TeV. Such masses, increasingly away from the electroweak scale, render SUSY less and less "natural" (i.e. relevant for the resolution of the SM fine-tuning problem).

9. Dark matter (DM)

The existence of dark matter, accounting for about 27% of the Universe energy budget [47], has been confirmed by many observations: (i) non-Keplerian star (galaxies) orbits in galaxies (clusters), (ii) offset in the distribution of matter observed via gravitational-lensing and via radiation in colliding clusters of galaxies, (iii) pattern of the power spectrum of the temperature fluctuations of the cosmic microwave background, and (iv) simulations of the large-scale structure of the cosmos, among others. All we know of DM is that is sensitive to gravitation, stable, and an early-Universe relic. The preferred candidate is a Weakly-Interacting Massive Particle (WIMP) of mass $m_\chi \approx$ 10–1000 GeV with electroweak-like DM-SM interaction strength, so that its early-Universe annihilation cross sections ($\sigma_{\rm anni} \propto g^4_{\rm ewk}/m_\chi$) are compatible with the current DM density. Many SM extensions include DM candidates such as the LSP in SUSY, the lightest Kaluza-Klein tower in extra dimension models, heavy R-handed (sterile) neutrinos, axions, or particles from a new hidden sector (e.g. moduli fields from string/M-theory compactifications). The null $\not{E}_T$ excesses observed in the Run-1 searches (see previous Section) seem to exclude the simplest LSP candidates from R-parity-conserving SUSY. The most generic DM search at colliders involves an unbalanced

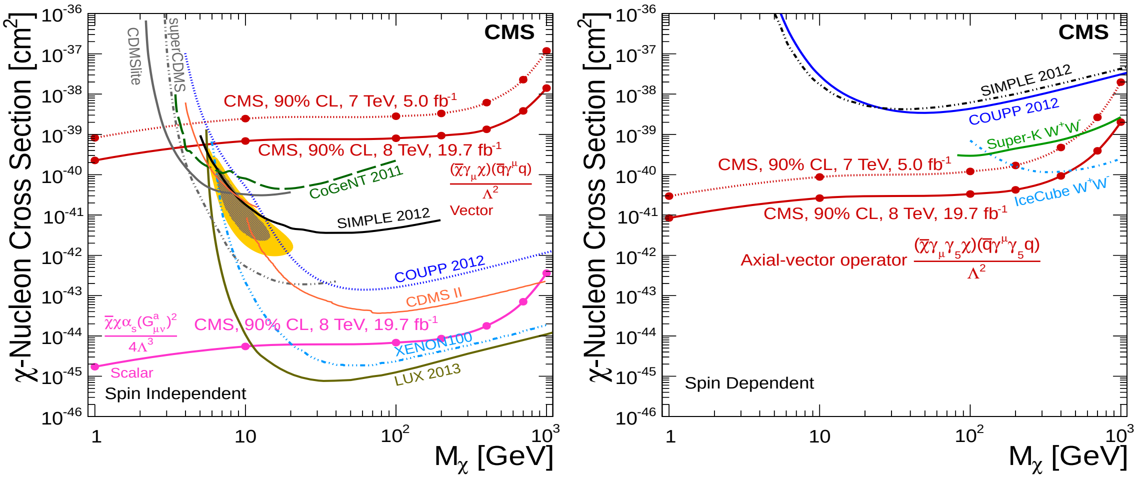


Figure 8: Upper limits (90% CL) on the DM-nucleon cross section vs. DM mass (CMS and direct DM searches) for vector and scalar (left) and axial-vector (right) operators [48].

mono-X final-state where the colliding quarks or gluons emit an object X=jet,photon,W,... prior to their annihilation into a pair of DM particles (indirectly observed via $\not{E}_T$). A third DM search approach at the LHC (for $m_\chi < m_{\rm H}/2$) involves looking for invisible Higgs decays [49]. The lack (so far) of mono-jet,photon excesses above the SM backgrounds (most notably $Z(\nu\nu)$+jet,γ) can be interpreted within an effective field theory (EFT) for the SM-DM interaction –characterized by an effective scale $\Lambda = m_{\rm med}\sqrt{g_\chi\, g_{q,q}}$ (where $m_{\rm med}$ is the mediator mass and $g_{\chi,q,g}$ its couplings to DM and SM particles), and m_χ. Corresponding limits in the plane of DM-nucleon cross section $\sigma(\chi N)$ vs. m_χ can be set and compared to direct underground searches (Fig. 8). The current LHC limits, $\sigma(\chi$-N$) \lesssim 10^{-40}$ cm^2 (for spin-independent interactions, left) and 10^{-41} cm^2 (for spin-dependent ones, right) are particularly competitive at low DM masses ($m_\chi \lesssim$ 10 GeV) where the tiny recoil energy of nuclei in direct underground searches is not visible, but the collider $\not{E}_T$ searches benefit from potentially large Lorentz boosts.

10. Other searches of physics beyond the Standard Model (BSM)

Apart from the aforementioned dedicated SUSY and dark matter studies, almost a hundred other BSM searches have been carried out in p-p collisions at 7,8 TeV looking for excesses over the SM predictions, mostly in the high invariant-mass tails of the distributions of pairs of objects (jets, leptons, photons,...). Figure 9 summarizes the latest (95% CL) limits on the mass of new

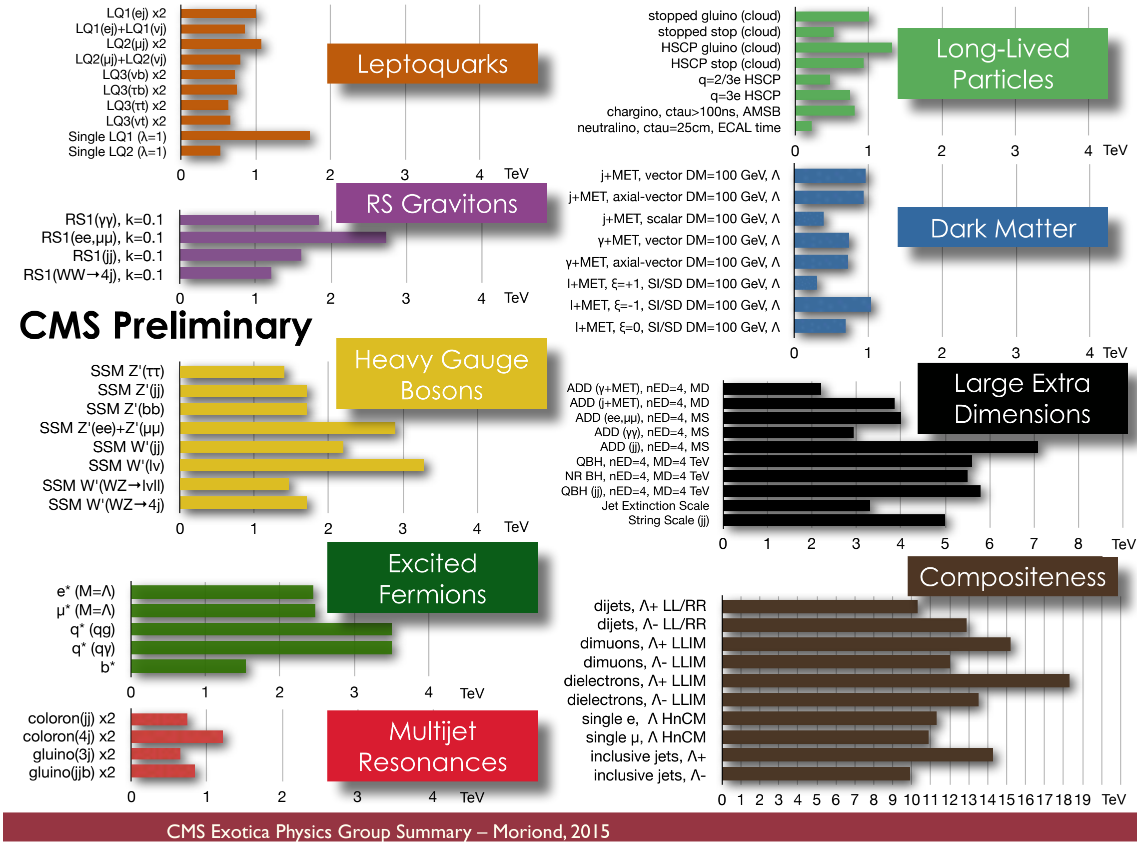


Figure 9: Summary of CMS limits on new physics particle-masses/scales in different BSM searches.

particles (m_X) or the scale of new physics (Λ). The highest scales probed ($\Lambda \gtrsim 15$ TeV) correspond to searches of quark compositeness (contact interactions) [50], followed by $\Lambda \gtrsim 5$–7 TeV for virtual graviton exchanges [51] based on the Arkani-Hamed–Dimopoulos–Dvali (ADD) model of large extra spatial dimensions [52]. Heavy gauge bosons (Z', W') [53] –from new U(1), SU(2) gauge symmetries at high energies– or new excited fermions ($\ell^\star$, $q^\star$) [54] are excluded below masses $m_X \approx 1.5$–3.5 TeV (depending on their decay channels). The scale for the onset of quantum gravity, in Randall-Sundrum (RS) warped extra-dimension scenarios [55], is pushed above the $\Lambda \approx 2.5$ TeV range [56], whereas leptoquarks [57], long-lived particles [58] (e.g. from R-parity-violating SUSY), and fourth-generation b',t' quark partners [59] are excluded for masses below $m_X \approx 0.6$ TeV.

Summary

The main physics results of the CMS experiment during the LHC Run 1 –obtained in about 500 different measurements carried out in p-p, p-Pb and Pb-Pb collisions at c.m. energies $\sqrt{s}$ = 2.76–8 TeV– have been summarized. They can be succinctly categorized under the following topics:

Quantum Chromodynamics: In the hard sector, jet distributions are found to be in excellent agreement with NLO pQCD over 14 decades in cross sections, and the strong coupling has been determined up to so-far unprobed scales $Q \approx 2$ TeV. Upcoming NNLO jet calculations will highly profit from such measurements to better constrain the proton PDFs and α_s. In the semihard sector, the prominent role of multiparton interactions has been confirmed, but no "beyond DGLAP" (BFKL, saturation) QCD radiation has been observed. The bulk hadron production properties have helped improve the MCs for high-energy cosmic-rays physics.

Quark Gluon Plasma: Signs of parton collectivity ("ridge"-like angular correlations) have been observed in "central" collisions of small systems (p-p, p-Pb) with high particle multiplicities. In central Pb-Pb collisions, the yields of weakly-interacting probes (γ, W, Z) are found to be unaffected by the QGP (and have helped constrain the nuclear PDFs), but those of strongly-interacting particles (jets, b-jets, quarkonia, high-p_T hadrons) are found to be largely suppressed due to final-state interactions in the produced hot and dense QCD medium.

Electroweak: The high-statistics differential distributions of W and Z bosons have improved our knowledge of the quark densities in the proton, while many other electroweak cross sections, down to the hundreds-of-fb scale, have been found in excellent agreement with (N)NLO predictions. First-ever electroweak measurements include: $W+t$, $t\bar{t}$+γ, $t\bar{t}+Z$, VBF production of the Z boson, and $\gamma\gamma \to WW$. Multiboson processes have imposed stringent limits on anomalous triple and quartic gauge couplings.

Top quark: Top-pair cross sections agree well with NNLO pQCD predictions and furnish a new competitive extraction of α_s. A very precise measurement of the top mass, a key SM parameter chiefly connected to the electroweak vacuum stability, has been obtained by combining many different $t\bar{t}$ final states: $m_{\rm top}$ = 172.38 $\pm$ 0.67 GeV (0.4% uncertainty). Single-top cross sections provide also novel independent constraints on the $|V_{\rm tb}|$ CKM element.

Higgs boson: The last missing piece of the SM, the scalar BEH boson, was observed in 2012 in the high-resolution $\gamma\gamma$ and $ZZ^\star(4\ell)$ decay channels. Its mass, $m_{\rm H}$ = 125.09 $\pm$ 0.21 $\pm$ 0.11 GeV, is known with an impressive uncertainty below 0.2%. Its width has been constrained through the ratio of the on- and off-shell $ZZ^\star(4\ell)$ decays, and found to be smaller than 5.4 times the SM prediction: $\Gamma_{\rm H} < 22$ MeV (95% CL). Its quantum numbers ($J^{PC} = 0^{++}$), determined mostly through the kinematical distributions of the $ZZ^\star$ decay mode, are those expected for a SM Higgs boson. The Higgs couplings to the W, Z bosons as well as to the fermions (τ, b quark, and indirectly t quark) are found to be proportional to their masses (squared for W, Z) as expected.

Flavour: The very-rare $B_s^0 \to \mu^+\mu^-$ decay with SM branching ratio BR $\approx 10^{-8.5}$, considered as a "golden channel" for searches of SM deviations thanks to its sensitivity to virtual contributions from new heavy particles, has been observed with the expected BR with a statistical significance of 6.2σ, imposing novel flavour-changing constraints in the parameter space of models beyond the SM.

Supersymmetry: All searches of spartners in p-p final-states with excesses of $\not\!\!E_T$, same-sign leptons, multi-jets,γ,... have been unsuccessful so far. Such searches, mostly interpreted in terms of minimal SUSY implementations with a few parameters, push the spartner masses increasingly away from the electroweak scale, and render the theory less and less "natural" (i.e. relevant for the resolution of the SM fine-tuning problem at least).

Dark matter: Mono-jet,photon searches at the LHC provide the best limits on DM searches at low masses ($m_\chi \lesssim 10$ GeV) by exploiting boosts present in the annihilation of two partons into a DM pair. The derived nucleon-DM interaction cross sections limits, $\sigma(\chi\text{-N}) \lesssim 10^{-40}, 10^{-41}$ cm^2 for spin-independent and spin-dependent interactions respectively, cover a range of DM masses not accessible via nuclear recoils in direct underground searches.

Other beyond the SM searches: No evidence of new resonances or particles connected to new symmetries at the TeV scale has been observed so far by looking for excesses over the SM mostly in the high invariant-mass tails of the distributions of pairs of jets, leptons, photons,... Stringent limits on new-physics scenarios have been imposed: $\Lambda \gtrsim 15$ TeV for quark compositeness (contact interactions); $\Lambda \gtrsim 5$–7 TeV for ADD gravitons; m$_X \gtrsim 1.5$–3.5 TeV for W', Z' bosons; $\Lambda \gtrsim 2.5$ TeV for RS extra-dimensions; and m$_X \gtrsim 0.6$ TeV for leptoquarks, new long-lived particles, or heavy-quark partners,...

The lack of evidence for deviations in the data from the SM expectations is puzzling given that, apart from the Higgs boson confirmation, the fundamental physics problems that motivated the construction of the LHC (listed in the Introduction) remain still unsolved today. The upcoming Run-2 of the LHC, with collisions at center-of-masses reaching the nominal 14-TeV and hundreds of fb^{-1} integrated luminosities, will bring us back to discovery mode and hopefully to the direct (or indirect, via precision tests) observation of new particles/symmetries at the TeV scale.

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