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Deliverable:

Physics at the LHC: Report covering main findings at the LHC with relevance for future energy frontier accelerator projects.

Executive summary:

We briefly review the overall status of physics at the LHC, with a view to their potential impact on future hadron colliders.

Status of Physics at the LHC

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We briefly review the overall status of physics at the LHC, with a view to their potential impact on future hadron collider projects.[1]

1 Introduction - The LHC and its Experiments

The Large Hadron Collider (LHC) has been taking data since 2009, its luminosity production meeting or even surpassing the expectations (see Fig. 1). The altogether seven LHC experiments (in alphabetic order: ALICE, ATLAS, CMS, MoEDAL, LHCb, LHCf, TOTEM) have been extremely productive — ATLAS [1] and CMS [2] have each produced over 700 scientific publications, the most remarkable ones probably being the papers on the discovery of the Higgs boson in 2012 [3, 4]. The physics portfolio of these two general-purpose experiments is extremely broad — it ranges from standard model (SM) measurements in the electroweak and QCD sectors over the physics of heavy quarks and especially the top quark to Higgs physics and searches for new physics, especially for supersymmetry.

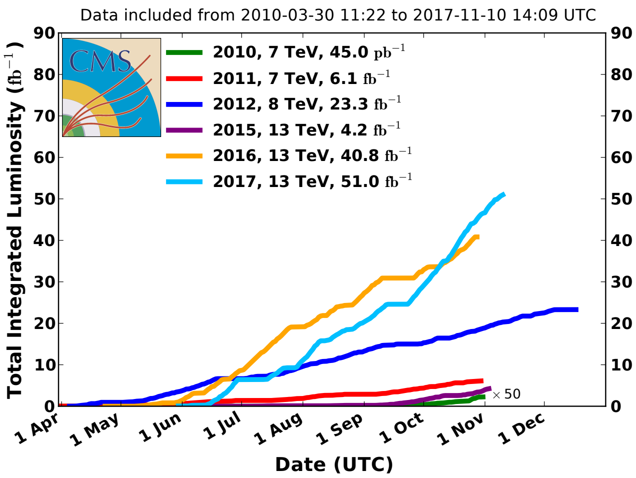

Figure 1: The luminosity integrated by the CMS experiment since 2010. Source: `https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults`.

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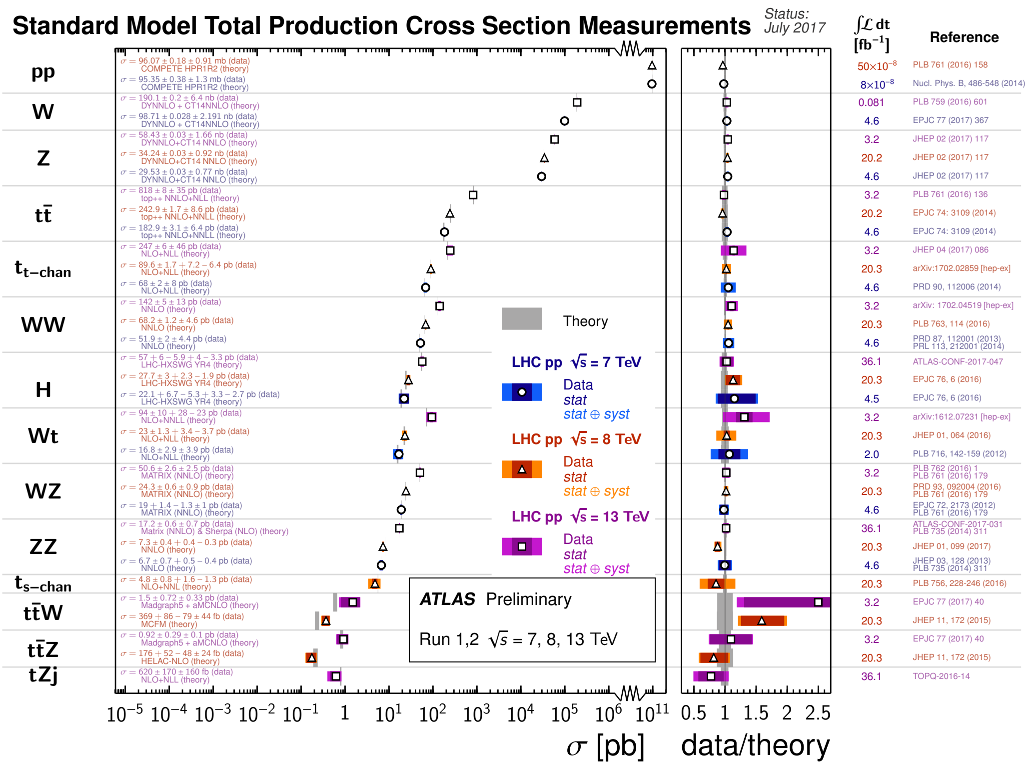

Figure 2: Summary of several standard model total production cross section measurements, corrected for leptonic branching fractions, compared to the corresponding theoretical expectations. The dark-color error bar represents the statistical uncertainty. The lighter-color error bar represents the full uncertainty, including systematics and luminosity uncertainties. Source: `https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/ATLAS_c_SMSummary_TotalXsect_rotated/history.html`.

In the following few pages, we will briefly go through all of these fields and summarise the status of measurements giving a few highlights. At the end of this report, an outlook to the High-Luminosity LHC (HL-LHC) and its physics potential is given.

2 QCD and Electroweak Measurements

Precision SM measurements in the strong and electroweak interaction sectors form the backbone of data analysis at the LHC, as they allow for detailed tests of theoretical predictions (and thus of our understanding of the SM) and for the extraction of fundamental parameters like, e.g., the strong coupling α_S. It is also important to understand SM processes to a great level of detail because they form the backgrounds for searches for new physics. Finally, new physics might also show up in tiny deviations between measurements and SM predictions. Figure 2 (from the ATLAS collaboration) shows an overview of SM production cross section measurements.

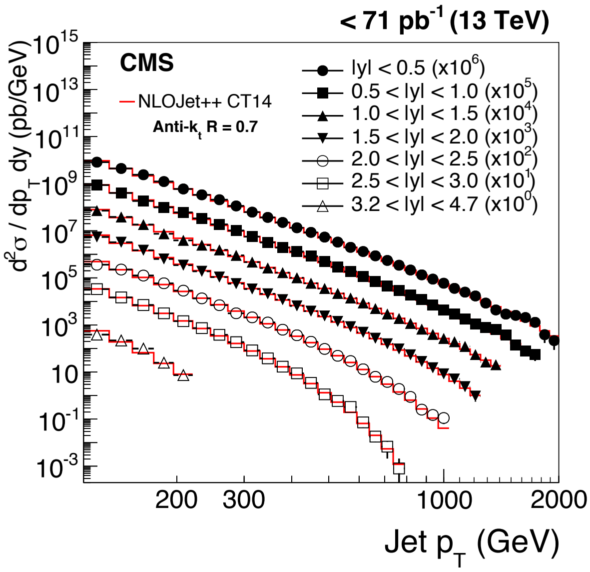

Figure 3: The double-differential inclusive jet cross section as a function of the jet transverse momentum, as measured by CMS [5]. The data are compared to NLO QCD calculations.

No significant deviations between measurement and theory are observed, and an overall good understanding of the involved processes is demonstrated. It should be noted that the measured cross sections span close to twelve orders of magnitude — and that typical predicted cross sections for processes of new physics are still much smaller than the measured SM cross sections!

The most prominent feature of strong interactions at the LHC is the production of hard jets. As an example, Fig. 3 shows the double-differential jet cross section as measured by CMS [5]. Here, and generally for all kinds of jet observables, the data can be well reproduced by the theory predictions — pQCD works very well. So well in fact that jet data from the LHC serve as an important source of α_S determinations. At the LHC, this fundamental QCD parameter has been determined for scales up to almost 2 TeV e.g. using inclusive jet cross sections, the ratio of three-jet to two-jet cross sections, top-antitop quark pair production cross sections, and others. A further and more detailed scrutiny of our picture of strong interactions — e.g. studying QCD at higher scales — requires higher collision energies as well as more statistics. Especially higher energies would also facilitate an increased reach in exotics searches in the dijet channel (see below). It should be noted that theory is also progressing at a significant pace: The past few years brought about, for instance, pQCD predictions for jet physics at NNLO, which promise smaller theory uncertainties and yet more refined comparisons of data with predictions.

In the field of electroweak measurements, massive samples of $W^\pm$ and Z^0 bosons have been collected, allowing for very detailed studies. Cross sections for the production of weak bosons have been determined at all LHC centre-of-mass energies, and a measurement precision of few percent has been achieved. The measurements can be compared to NNLO predictions, and very good overall agreement is observed. As an example, Fig. 4 from Ref. [6] shows the integrated fiducial cross sections times leptonic branching ratios of $W^\pm$ production versus Z^0

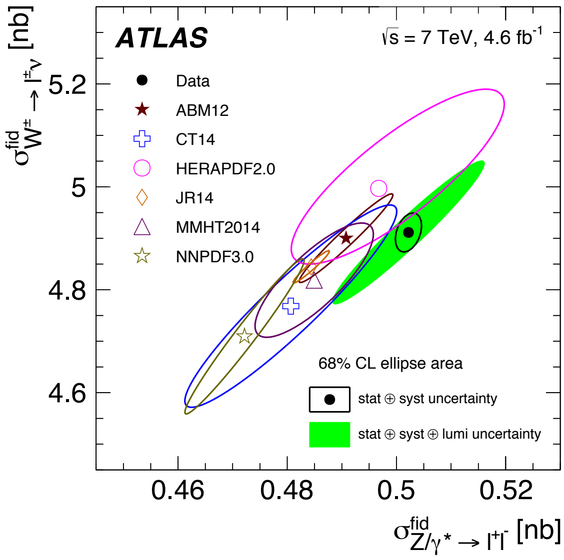

Figure 4: Integrated fiducial cross section times branching ratio for $W^{\pm}$ production versus that of Z^0 production [6].

production. Good agreement between measurement and predictions is observed in this low-energy measurement (centre-of-mass energy 7 TeV), and also for corresponding measurements at higher energies and for more complex processes like the production of vector bosons together with jets or with heavy flavour, and also multi-boson production (see also again Fig. 2).

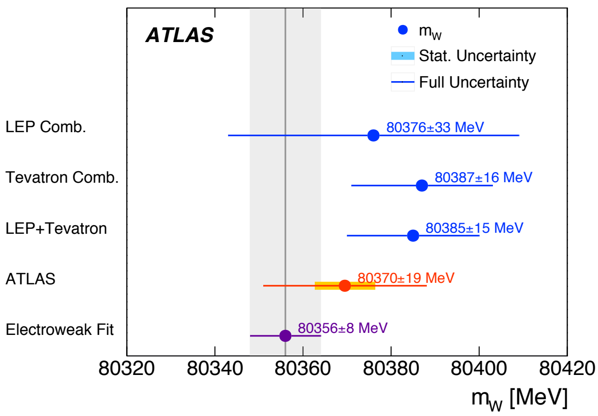

Figure 5: ATLAS determination of the W-boson mass at 7 TeV [7]. The ATLAS result is compared to various other determinations.

Another prime example of electroweak measurements is the determination of the mass of

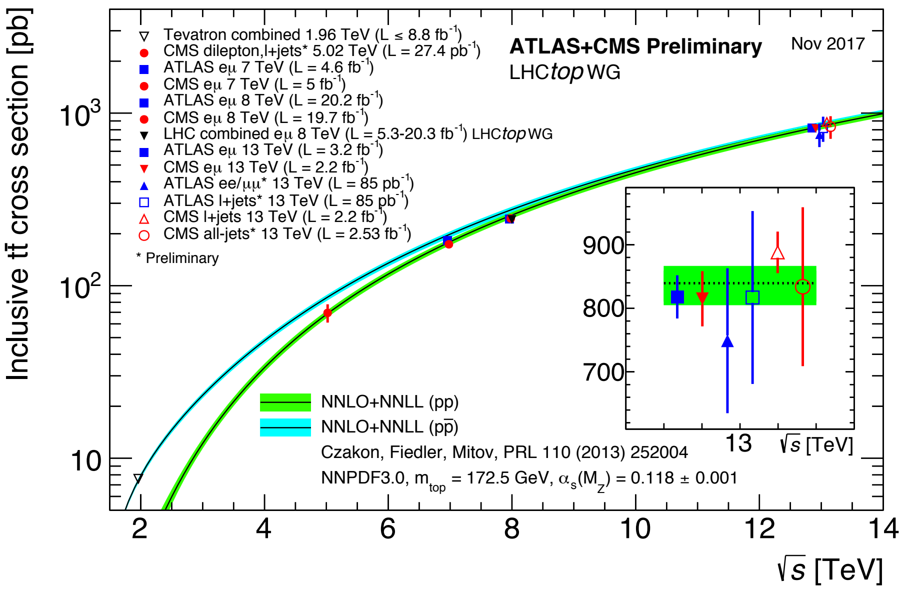

Figure 6: Summary of LHC and Tevatron measurements of the top-pair production cross-section as a function of the centre-of-mass energy compared to the NNLO QCD calculation complemented with NNLL resummation. Source: LHC top WG (`https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TopPairCrossectionSqrtsHistory`).

the W boson, the precision of which is slowly approaching the level previously achieved at the Tevatron (see Fig. 5). In the ATLAS case shown in the figure, the measurement is done using the distributions of transverse momentum and transverse mass, separately for positively and negatively charged W bosons and in different bins of pseudo-rapidity. The result has an uncertainty of 19 MeV.

Electroweak physics, like the QCD measurements discussed above, also offers sensitivity to manifestations of new physics. One example is vector boson scattering to final states with two Z^0 bosons and jets, as recently measured by CMS [8], a process sensitive to anomalous gauge couplings that would indicate new physics. And here, as in the QCD case and in many SM measurements, one would significantly profit from higher collision energies. Another example for such a channel sensitive to new physics via modified gauge couplings and the sensitivity to the production of doubly charged Higgs bosons is the production of two same-sign W bosons, as recently observed by CMS [9].

In summary, SM measurements at all LHC centre-of-mass energies show no surprises. Clearly higher scales and more data are required to increase the sensitivity of the data — a clear argument for the HL-LHC programme and for future hadron colliders at increased centre-of-mass energies!

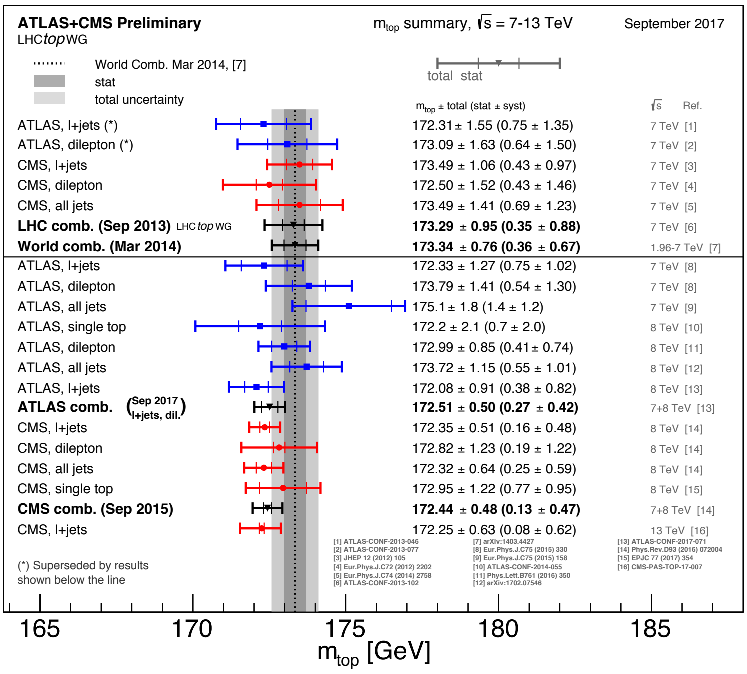

Figure 7: Summary of the ATLAS and CMS direct measurements of the top-quark mass. The results are compared with the LHC and Tevatron+LHC mtop combinations. Source: LHC top WG (`https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TopMassHistory`).

3 Top Physics

The top quark is the heaviest known elementary particle, with a mass of roughly 173 GeV. Its high mass and the fact that its coupling to the Higgs boson is approx. unity raise the question whether the top might play a very special role in electroweak symmetry breaking and could, as a window to the world beyond the SM, provide insights into new physics. The top is copiously produced at the LHC — in 2016 alone, roughly 30 million top-antitop pairs were produced — a fact that enables numerous detailed studies of top production and decay modes and of top-quark properties: Besides the "simple" things like mass, lifetime, charge, width and polarisation, also more complex observables like spin correlations or the charge asymmetry and many others can be investigated. Top-quark production has been studied at all LHC collision energies so far, and Fig. 6 shows the measured production cross section compared to NNLO+NNLL theory. A very good agreement between data and predictions is observed, as is the case for basically all top-quark distributions.

Figure 7 shows the current status of top-quark mass measurements. The precision is now well below half a percent, and more progress is expected from a new ATLAS+CMS combination of measurements.

All in all, all measurements in the top-quark sector are in good agreement with the SM predictions, and no hints for new physics beyond the standard model have been observed. Again, more statistics and higher energy would aid many measurements and increase the sensitivity

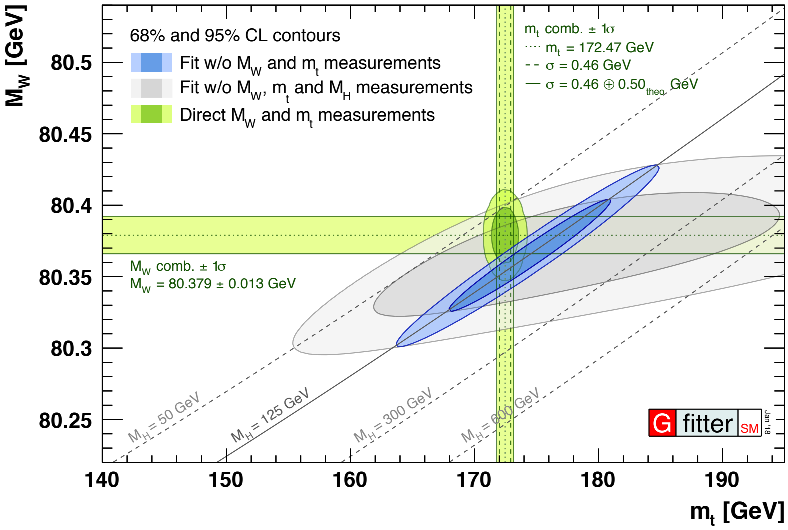

Figure 8: Contours of 68% and 95% confidence level obtained from scans of fits with fixed variable pairs of the W-boson mass versus the top-quark mass [10]. The narrower blue and larger grey allowed regions are the results of the fit including and excluding the Higgs-boson mass measurements, respectively.

for effects of new physics in the top "portal". And together, QCD, electroweak and top measurements give a consistent picture of the standard model, as is indicated by global electroweak fits performed e.g. by the LEP electroweak working group or the Gfitter group (Fig. 8 shows the latest global overview of the masses of top quark, W boson and Higgs boson in the context of the Gfitter electroweak fit [10]).

4 Flavour Physics

In contrast to the fields discussed so far, progress and success in flavour physics is not depending on the very high collision energies provided by the LHC or a potential successor machine — and there are hints for exciting developments on which the LHC might very well shed light already in the near future (together with the Belle II experiment at Japan's KEK).

Recent years have been full of discoveries of new heavy resonances and of detailed heavy-flavour measurements. As an example, Fig. 9 shows a recent CMS measurement [11] of quarkonium production in the 13 TeV data — or more precisely of the three $\Upsilon(nS)$ $(n = 1, 2, 3)$ states reconstructed in the two-muon channel. Differential cross sections are measured as function of the quarkonium transverse momentum, and the cross sections are well described by theory.

More excitingly, perhaps, is the recent observation of the rare decay $B_s^0 \to \mu^+\mu^-$— only three B_s^0 in a billion will follow this decay path! The decay has been searched for for close to three decades, and now has been seen by ATLAS [12], CMS [13] (in a common publication with LHCb) and already earlier by LHCb alone [14]. The results, at the current level of measurement precision, are consistent with the theoretical predictions (see Fig. 10, which shows the best fit

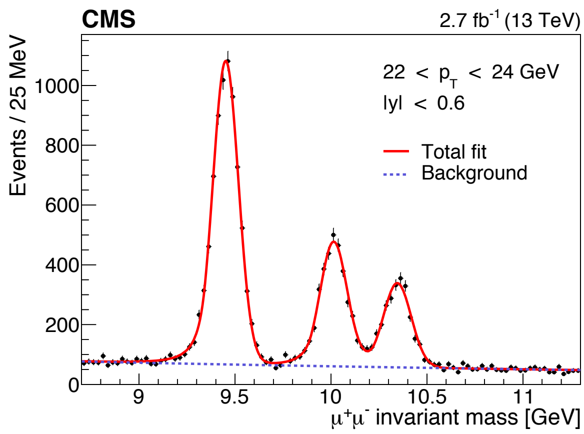

Figure 9: Fit of the two-muon invariant mass distribution for the $\Upsilon(nS)$ candidate events [11]. The results from the total fit and for the background component are shown.

results for ATLAS and for the CMS+LHCb result in the plane of the branching ratios of $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$).

The interesting part is that new physics is expected to modify significantly the branching ratios of the processes $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$, so that deviations from SM predictions might easily become visible. With more data and thus higher precision expected from future LHC runs and especially from the HL-LHC, these decays might well deliver the new physics signatures eagerly awaited. This ties in nicely with the findings, by LHCb and Belle, of possible signs of lepton flavour universality violation (see below).

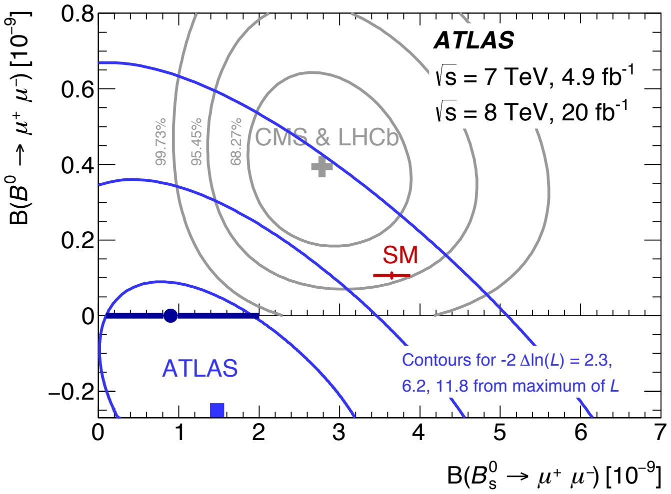

Figure 10: Contours in the plane $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$, $\mathcal{B}(B^0 \to \mu^+\mu^-)$ for intervals of $-2\Delta\ln(L)$ equal to 2.3, 6.2 and 11.8 relative to the absolute maximum of the likelihood [12].

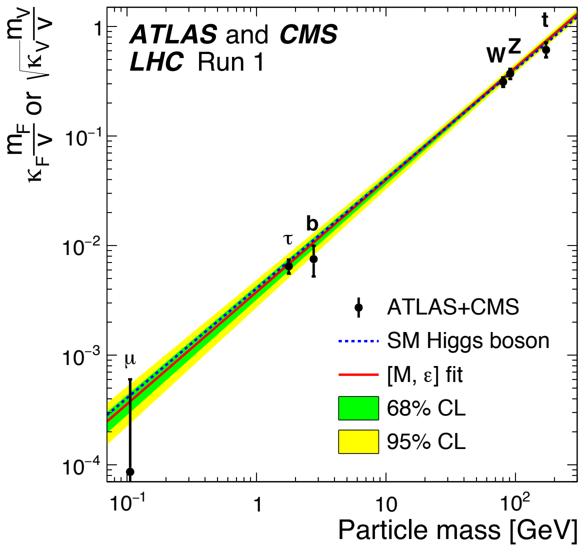

Figure 11: Best fit values of the couplings of the Higgs boson with known bosons and fermions as a function of particle mass for the combination of ATLAS and CMS data [15].

5 Higgs Physics

The Higgs boson discovered in 2012 has been scrutinised in great detail in LHC Run 1, and basically its SM-like behaviour has been established. As an example, Fig. 11 summarises the Run 1 status of the combined ATLAS+CMS coupling measurements of the new particle [15]. Nevertheless, the LHC experiments are eagerly continuing to look for deviations from the expected SM behaviour.

Recent developments in the scrutiny of the Higgs boson comprise, among others, the observation of Higgs-boson decays to τ leptons [16] and evidence for the decay to bottom quarks [17], as well as searches for decays into charm quarks or muons. On the production side, several results deal with the production of a Higgs boson in conjunction with a top-antitop pair, addressing the question of the top–Higgs Yukawa coupling. Also detailed studies of the very clean decay channels to two photons or two Z^0 bosons (which subsequently decay to four leptons) have been carried out that are sensitive to higher-order QCD corrections, to the Higgs boson's spin and CP quantum numbers, and to potential anomalous couplings of the Higgs boson.

Many of the Higgs measurements have been or are being done in the much larger Run 2 data sample, and the future months will see several new publications. In general, the Higgs boson as seen in the combined Run 1 and 2 data still behaves very much like the SM Higgs boson, and hopes are high that future data taking in Run 3 or at the HL-LHC will lead to deviations between measurements and SM predictions or even to additional Higgs states (see below). For this to happen, increased luminosity and increased collision energy are prerequisites.

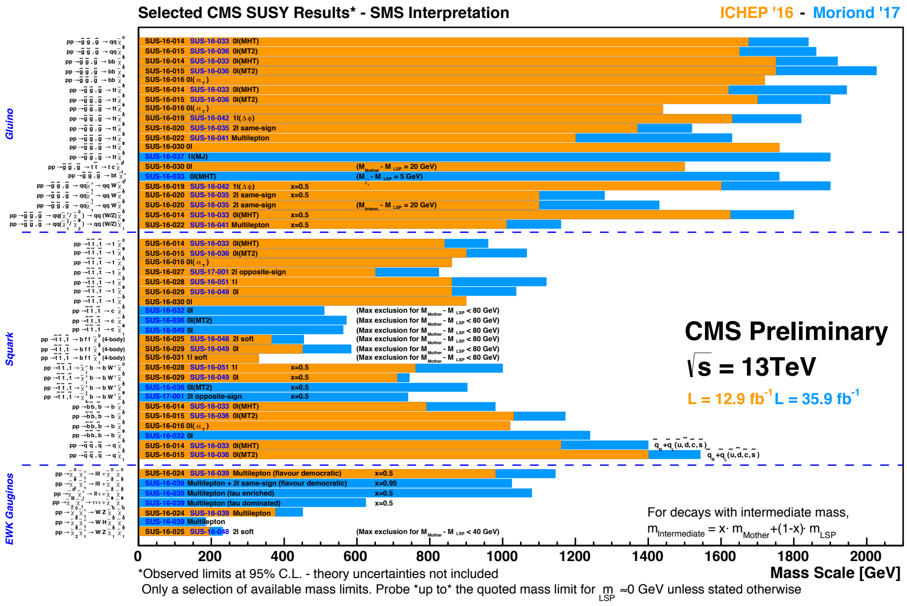

Figure 12: Reach of selected CMS SUSY searches. Source: `https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS`.

6 Searches for Supersymmetry

Supersymmetry (SUSY) is still considered the most promising candidate for extensions of the standard model. Given the rich nature of SUSY, a multitude of different analyses has been performed in all kinds of channels. Recent examples of SUSY searches performed in the 13 TeV data set are a CMS search for SUSY in the channel with high transverse-momentum Higgs bosons together with missing transverse energy [18], an ATLAS search for top quark pair production in one lepton, jets, and missing transverse energy [19], a CMS search for R-parity violating SUSY with one lepton and bottom-quark jets [20], or an ATLAS search for squarks and gluinos with jets, zero leptons and missing transverse energy [21].

Figure 12 from the CMS experiment shows a selection of limits on SUSY particles ("sparticles"), in the SMS interpretation. With more than 35 fb^{-1} collected at 13 TeV, mass limits on strongly interacting sparticles can be set between around 500 GeV to 1 TeV (for squarks) and 1–2 TeV (for gluinos); electroweak gauginos also have limits of up to 1 TeV.

An overview and interpretation of all SUSY results from the LHC and elsewhere shows that constrained SUSY models are basically ruled out. The recent focus of analysis and interpretation efforts was very much on natural models, i.e. models with, e.g. relatively light SUSY partners of the top quark that avoid fine-tuning problems. However, as can be seen from Fig. 12, also these models have come under considerable pressure from the LHC data. This can also be seen in Fig. 13, which shows, as vertical bars, the one-dimensional projection of the fraction of model points excluded, with colour coding representing the fraction of model points excluded for each sparticle.

It is therefore fair to say that the possibilities are becoming more and more reduced for

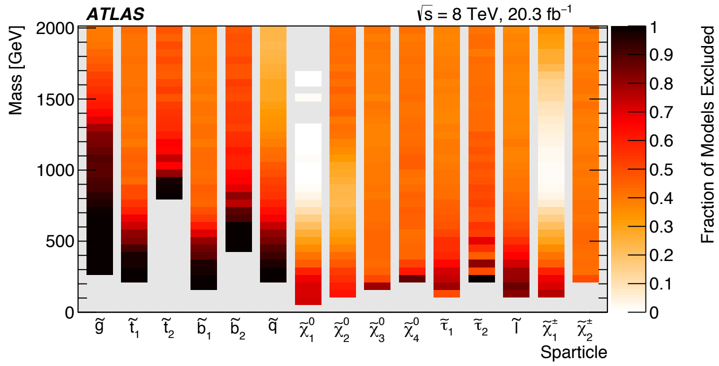

Figure 13: SUSY model exclusion by the ATLAS experiment. Source: `https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults`.

SUSY models to be studied within the reach of the LHC, and the higher luminosity and — potentially in the farther future — the higher centre-of-mass energy of future hadron colliders are the only way to progress further in the hunt for SUSY (note that the sensitivity to new physics at high masses scales directly with the centre-of-mass energy).

7 Exotics Searches

SUSY is not the only potential answer to the open questions of the standard model. At the LHC experiments, searches for other phenomena that might, for example, deliver dark matter candidate particles run under the name of "exotics". Since this is a vast field — limited only by the ingenuity of theorists and model builders — only a very coarse overview can be given here.

Clearly dark matter is one of the drivers of the field, and numerous searches address this phenomenon that most likely can be explained by a new, as yet undetected, heavy particle. One prominent search strategy is that for "mono-X" objects — mono-jets, mono-bosons, mono-tops etc. — produced together with missing transverse energy stemming from the escaping pair-produced dark matter particles. However, none of the mono signatures have shown any positive result so far, and only limits could be placed in various models.

Similarly negative conclusions hold for the search for extra spatial dimensions — where a limit on the "new" Planck scale (reduced from its originally high value of around 10^{19} GeV by the extra dimensions) can be set somewhere around 6–10 GeV — and for the search for microscopic black holes, which can be excluded below approximately 8 TeV. Also searches for light vector resonances, for dilepton states or for vector-like quarks did not have any success.

A conceptually simple search strategy is that for dijets stemming from the decay of heavy resonances. Figure 14 shows the recent ATLAS search for such objects, which in the 13 TeV from 2016 — depending on the model — leads to limits of the order of 2–8 TeV. Dijet events at high invariant masses also have an additional use in the search for exotic phenomena: The angular correlations of the two jets can be used for searches for contact interactions, extra dimensions, black holes etc.; however, also these searches have not brought any signal of new physics, and limits on certain new phenomena of up to 17 TeV could be set.

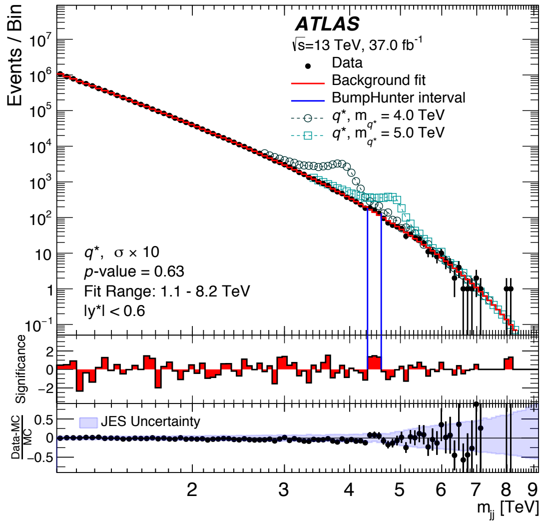

Figure 14: The reconstructed dijet mass distribution (filled points) is shown for events with transverse energies above 440 (60) GeV for the leading (subleading) jet [22].

Three more exotic search topics need to be mentioned: The two-photon channel, due to its cleanliness, is always good for surprises, and after the discovery of the Higgs boson at two-photon masses of around 125 GeV and after the excitement about a potential signal at around 750 GeV in summer 2016, now again a small excess of about 2.8 σ has occurred at CMS in the 8 and 13 TeV data sets at approx. 95 GeV [23]. While leaving much room for interpretation, this excess still needs to be confirmed in larger CMS data sets and also by the ATLAS experiment.

Another interesting field is that of the search for very exotic particles: Examples are long-

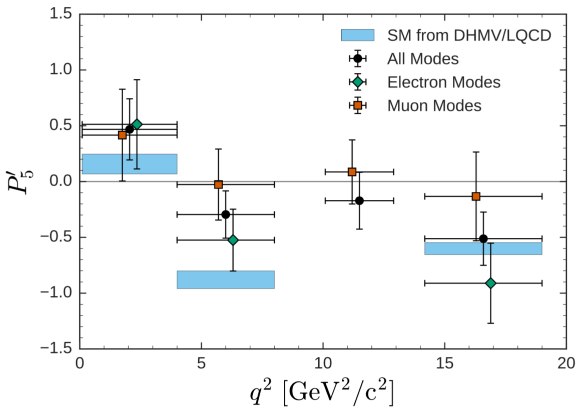

Figure 15: P_5' observable for combined, electron and muon modes for the decay $b \to s\ell^+\ell^-$ [25]. The SM predictions are displayed as boxes for the muon modes only.

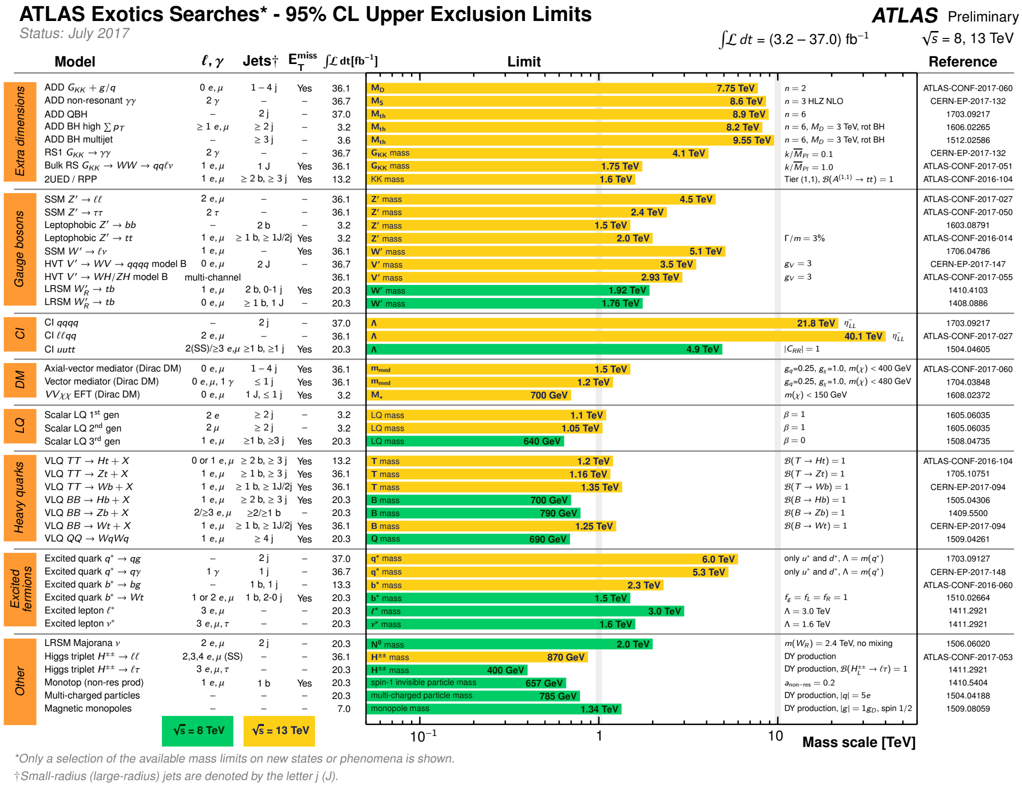

Figure 16: Reach of selected ATLAS searches for new phenomena other than supersymmetry. Source: `https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/ATLAS_Exotics_Summary/history.html`.

lived particles that are trapped in the detector or in the cavern material and that decay after significant time (seconds to months) or also heavy stable particles, etc. Such particles occur in many different models of new physics (split SUSY, neutral naturalness, GMSB, AMSB, etc.) and can have very specific signatures: high ionisation losses, out-of-time decays, displaced vertices, disappearing tracks, ... Their search poses particular challenges to the detector, e.g. to the time-of-flight systems, to tracking, to the trigger etc. So far, no signal has been found, and limits on various models have been set. At the LHC, a specific working group focusing on these particles has been set up between ATLAS, CMS and LHCb and is currently preparing a white paper to be published in early 2018 that, among other things, will suggest new dedicated experiments [24].

The LHCb and Belle experiments have published evidence for the violation of lepton flavour universality (LFU) in the rare decay $b \to s\ell^+\ell^-$ [25], see Fig. 15, and recently also CMS has looked into this process [26]. In global heavy-flavour fits considering more than 150 measurements by LHCb, Belle, ATLAS and CMS, evidence of non-SM contributions to this rare decay at the level of 5 σ is observed. Only future experiments — be it at the LHC or with the Belle II experiment at KEK going into operation in 2018 — can confirm or dispell this finding. In many models, LFU violation also comes with lepton flavour violation, and corresponding analyses are being planned.

Figure 16 from the ATLAS collaboration summarises, for a few selected models of "exotic" physics at the LHC. As can be seen, most analyses have already been performed in the 13 TeV data, and limits for the models investigated are typically well above 1 TeV. The current LHC is slowly "running out of steam", and significantly more data (as promised by the HL-LHC) or even better higher centre-of-mass energy (as envisaged for the HE-LHC or FCC) are mandatory for progress in the wide field of exotic physics, as are improvements to the detectors, the analysis strategies, and to theory.

8 Conclusions and Outlook

The LHC experiments have each collected around 100 fb^{-1} of integrated luminosity, and a factor 2.5 more is envisaged until the beginning of the HL-LHC upgrade. The next big step in reach for new physics is expected only from the HL-LHC — which will increase the luminosity by a factor of 10 and run at even higher centre-of-mass energies of 14 TeV. This is very promising for numerous search channels that are slowly reaching their limits at the LHC. The physics case for the HL-LHC is sound — see e.g. the ECFA HL-LHC 2016 workshop for detailed discussions of HL-LHC projections [27] — and a CERN yellow report documenting this is under preparation (see the web pages of the HL/HE-LHC Physics Workshop [28].

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