PROCEEDINGS OF SCIENCE

Review of LHC results on proton-proton physics: present highlights and future

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This review summarises some of the most relevant recent results, obtained from proton-proton collisions registered by the LHC experiments. Emphasis is put on jet and vector boson production, on heavy flavour and top quark physics, the recent observation of a Higgs-like boson, and on searches for physics beyond the Standard Model. Finally, an outlook will be given.

Xth Quark Confinement and the Hadron Spectrum,
October 8-12, 2012
TUM Campus Garching, Munich, Germany

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PoS(Confinement X)011

1. Introduction

The last two years have been characterized by a most impressive amount of results presented by the LHC experiments. Most of these new measurements are based on the statistics collected during the 2011 LHC run, but first important results from the 2012 run at 8 TeV centre-of-mass energy have also been published, most notably the ATLAS and CMS observations of a new boson with mass of 125-126 GeV. Here an overview of some of the highlights will be given, with focus on hard scattering processes in proton-proton collisions, searches for new physics and searches for the Higgs boson. The plethora of results on soft, forward and diffractive physics can unfortunately not be covered here. More comprehensive recent reviews can, e.g., be found in Refs. [1, 2].

None of the results presented below would have been possible without the excellent performance of our tools, namely the accelerator and detectors. In 2012, the LHC has been operated at 8 TeV centre-of-mass energy, compared to 7 TeV in 2011. Several important milestones have been achieved, mostly in terms of beam intensities, instantaneous and integrated luminosities. At the time of this conference the LHC has already delivered about 16 fb^{-1} to ATLAS and CMS, and smaller amounts, because of luminosity levelling, to LHCb and ALICE. Peak values in instantaneous luminosity exceeding $7 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$ have been reached, which is not far from the original LHC design. These high luminosities come at the price of very large pile-up (simultaneous proton-proton collisions in a single bunch crossing). However, so far the experiments are coping well with these difficult conditions, and continue to collect data with very high efficiency (well above 90%) and good quality, i.e., by maintaining the performance in terms of selection efficiencies, momentum and energy resolutions of physics objects such as leptons, photons or jets.

2. The QCD/EWK sector: fermions and gauge bosons

Measurements of hard-scattering cross sections, with jets, photons or vector bosons in the final state, are interesting because of several reasons: (i) it allows probing higher-order predictions of perturbative QCD for the hard-scattering part of the overall process; (ii) parton distribution functions (PDFs) can be constrained; (iii) Standard Model (SM) predictions can be tested, in particular QCD calculations, as implemented in various codes and Monte Carlo (MC) generators, for processes which are important backgrounds for new physics searches. For a more extensive review of this subject we refer to, e.g. [3].

A central component of those measurements, which contain jets in the final state, is the excellent control of the systematic uncertainty due to the jet energy scale. This is essential because of the nature of the steeply falling cross sections as a function of the jet transverse momentum, p_T. By now the LHC experiments master this effect already at a remarkable level of precision [4, 5], e.g., around 2% or even better for central jets and a p_T range of about 50 to several hundred GeV.

Concerning jet production at the LHC, new results exist for inclusive jet production, dijet production as a function of dijet invariant mass and jet rapidity separation, as well as third-jet activities; see for example Ref. [8] for a recent review. In particular, new measurements have appeared on the inclusive jet cross section as a function of jet p_T by CMS [6], and dijet production by ATLAS [7], based on the full 2011 dataset, cf. Fig. 1. Overall, the agreement of next-to-leading order (NLO) QCD predictions with data over ~ 9 orders of magnitude is rather impressive. The inclusive jet cross section has been compared to predictions based on a large set of PDFs, showing in general good agreement within theoretical and experimental uncertainties. It is interesting to note that for central rapidities the experimental and theoretical uncertainties are of similar level (5-10%). For this region of rapidities the CT10 set gives a rather good description of the data, while PDFs based on data from deep inelastic scattering, such as from the HERA1.5 and ABKM09 sets, show larger discrepancies. The picture is somewhat inverted at large rapidities, where the low-x gluon becomes more important. In the dijet case, where the data have an impressive reach up to about 4 TeV in dijet mass, some discrepancies are found at very large masses and large dijet rapidity separation, a region where NLO predictions probably reach their limit of applicability.

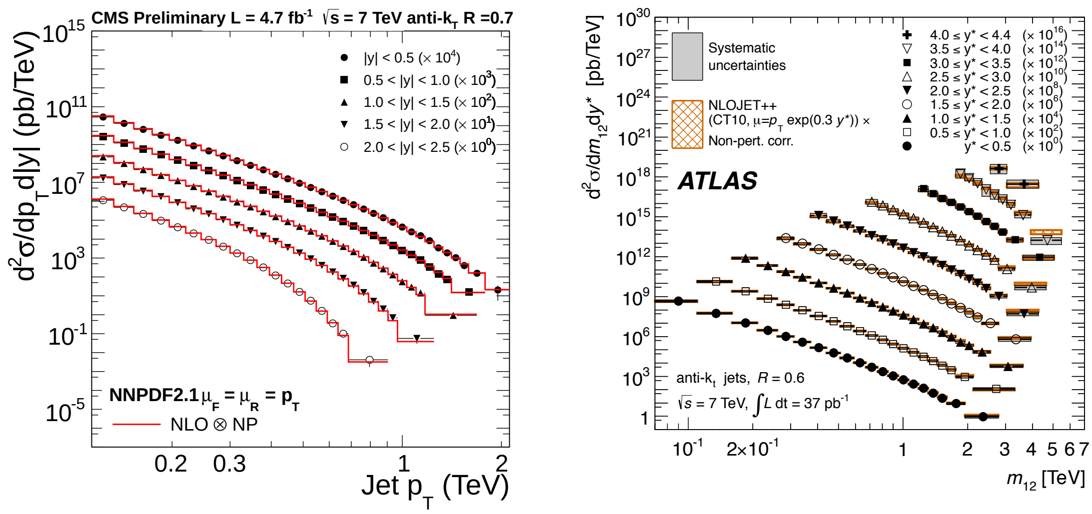

Figure 1: Left: Inclusive jet production, as a function of jet p_T and rapidity, measured by CMS [6]; Right: ATLAS data on dijet production [7].

A recent review of heavy flavour production results from the LHC [9] reveals that, overall, perturbative QCD gives a rather satisfactory description, with still some discrepancies seen for particular phase space regions of p_T and/or rapidity distributions. Indeed, such measurements have been carried out for inclusive open b production, B hadron production as well as b-jet production. Furthermore, angular correlations in events with two B-tags have shown some need for improvements in the Monte Carlo modelling of gluon splitting into b quarks. Recent highlights comprise new results from CMS on Λ_b production [10], showing a steeper p_T spectrum than observed for B mesons, the first particle discovered at the LHC, namely the $\chi_b(3P)$ state seen by ATLAS [11], and the observation of a new baryon (Ξ_b) by CMS [12], as well as new LHCb measurements [13] of χ_c, $\psi(2s)$ and double charm production. Interestingly, the latter represents a very stringent test for models of double parton scattering. Further new results for quarkonia production have appeared, such as a new measurement of the $\Upsilon(1S)$ cross section by ATLAS [14] with comparisons to colour-singlet and colour-octet models, and most importantly, the first LHC measurement of Upsilon polarisation (for the 1S,2S,3S states) by CMS [15], based on different reference systems and showing no evidence for any significant polarisation.

The top quark is given special attention because of several reasons: it is by far the heaviest of all quarks, and with a mass of the order of the electro-weak scale it is conceivable that the top plays a special role in electro-weak symmetry breaking. Furthermore, it is considered to be a possibly important gateway to new physics. A central test of SM predictions is the measurement of the inclusive top-pair production cross section. Lately, the LHC experiments have presented new results [16, 17] for a large number of channels (leptons+jets, dileptons, $\tau + \mu$, τ+jets, all hadronic), analyzing both 7 and 8 TeV data. Overall, excellent agreement is observed with the predictions. Here one should highlight that the experimental uncertainty has already reached a level of 5-6%, which is similar or smaller than the uncertainty on the theoretical predictions. Regarding the latter, significant improvements are just around the corner, with next-to-next-to-leading order (NNLO) calculations approaching completion. This should lead to an important reduction in the scale uncertainties, leaving the PDF uncertainties as dominant contributions. Thus it might become possible to use top production as an important PDF constraint.

What concerns the top mass, the TEVATRON is still leading, with the world's most precise measurement obtained from a TEVATRON combination of $m_t = 173.18 \pm 0.56(\text{stat}) \pm 0.75(\text{syst})$ GeV [18], noteworthy a quark mass measurement with a relative uncertainty of 0.54%. However, the LHC is catching up. For example, as summarized in [19], a preliminary combination of ATLAS and CMS measurements leads to $m_t = 173.3 \pm 0.5(\text{stat}) \pm 1.3(\text{syst})$ GeV, thus already achieving the same statistical precision as the TEVATRON experiments. A somewhat "disturbing" aspect of the direct top mass determinations from kinematic reconstruction is the not really well defined meaning of the finally extracted parameter. While it is supposed to be close to a definition according to a pole-mass scheme, currently a theoretically sound understanding is not available, which triggers the question if we really know this quark mass at the 0.5% accuracy level. On the other hand, a theoretically very well defined approach is given by the extraction of the top mass (typically in the form of a running mass) from a top cross section measurement. In view of the ever improving precision on the latter, this becomes more and more interesting. So far an accuracy of $\mathscr{O}(7 \text{ GeV})$ is attained, mostly dominated by PDF uncertainties.

Besides production cross sections and mass, an amazing amount of further top properties have been studied, see e.g. [20] for a review earlier this year. These comprise spin correlations, W helicity and polarization in top decays, extractions of $|V_{tb}|$, $m_t - m_{\bar{t}}$, the electric charge of the top, the charge asymmetry, searches for anomalous couplings and flavour-changing neutral currents, as well as a first study of jet veto effects in top-pair production. Basically for all these properties and observables agreement is found among data and SM predictions. After the inclusive single top and top pair cross sections, the new frontier attacked by the LHC experiments is the measurement of differential cross sections [21] (eg. Fig. 2, left), of top production in association with jets [22] or photons [23], or the very first evidence of top pair production in association with a W or Z boson [24] (Fig. 2, right). These measurements will become more and more important, also in view of future Higgs searches in exclusive channels, such as $t\bar{t}H$ production. Finally, CMS has presented the very first and rather precise determination of the strong coupling constant [25] using the top-pair cross section, following a similar approach as for the indirect top mass measurement.

Turning to the inclusive production of W and Z bosons, excellent agreement of the 7 and 8 TeV data with NNLO QCD predictions is found, as eg. documented in [26]. Here it is worth highlighting that the experimental precision has approached the 1% level, in particular for ratio observables such as the W^+ over W^- cross section ratio. In addition to these inclusive observables, many differential distributions are under scrutiny, such as the lepton charge asymmetry from central up

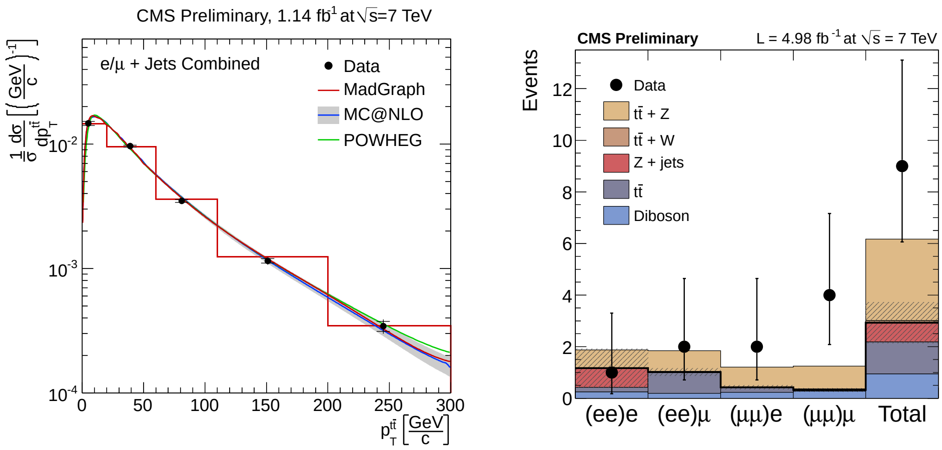

Figure 2: Left: Top production cross section as function of the top-pair transverse momentum, measured by CMS [21]; Right: Number of trilepton events measured by CMS [24], giving evidence for the associated production of top quark pairs with W and Z bosons.

to large rapidities (see e.g. [27]), which is an important handle for constraining PDFs. Indeed, the LHC data have a great potential for further improving our PDF knowledge, by including them in the global fits or by dedicated studies such as in Ref. [28], where ratios of jet cross sections at 2.76 TeV and 7 TeV centre-of-mass energy have been analyzed in order to test their sensitivity to the gluon PDF. In fact, ratios of cross sections at different centre-of-mass energies, for different processes or for the same process in different phase space regions should turn out to be very important tools for either constraining PDFs over a large Bjorken-x range, or for obtaining precise SM predictions (at the % level or better) with small PDF uncertainties, e.g. for background estimations in new physics searches. An interesting study in this direction, looking at top-pair and jet production, can be found in Ref. [29].

Another highly relevant class of measurements is related to vector boson plus jet production. These processes are extremely important backgrounds for searches of supersymmetry and the Higgs, especially for associated Higgs production in the low mass region. Furthermore, such measurements allow for testing different approaches to the implementation of perturbative QCD calculations into MC codes, such as at fixed order (NLO) or based on the matching of leading order matrix elements with parton showers, for example in MADGRAPH, ALPGEN or SHERPA. Thanks to important recent advances, NLO calculations are now available up to high jet multiplicities (see [30] for a recent overview). Concerning jet multiplicities and jet momenta in W (or Z) plus jet production (Fig. 3, left), as well as angular correlations among the jets, overall a very good agreement with the NLO and matched calculations is found. Also dijet masses and the H_T distribution (scalar sum of jet momenta) are well modelled over large regions of phase space, where the various calculations are applicable. Going lower in production cross section for electro-weak particles, the most relevant and often studied processes are di-boson production ($W\gamma, Z\gamma, WW, WZ, ZZ$), for various decay channels of the vector bosons. The picture arising (Fig. 3, right) is that all the aforementioned processes, measured at 7 and 8 TeV, are in agreement with the predictions, which represents another most impressive confirmation of the SM at the highest available energies.

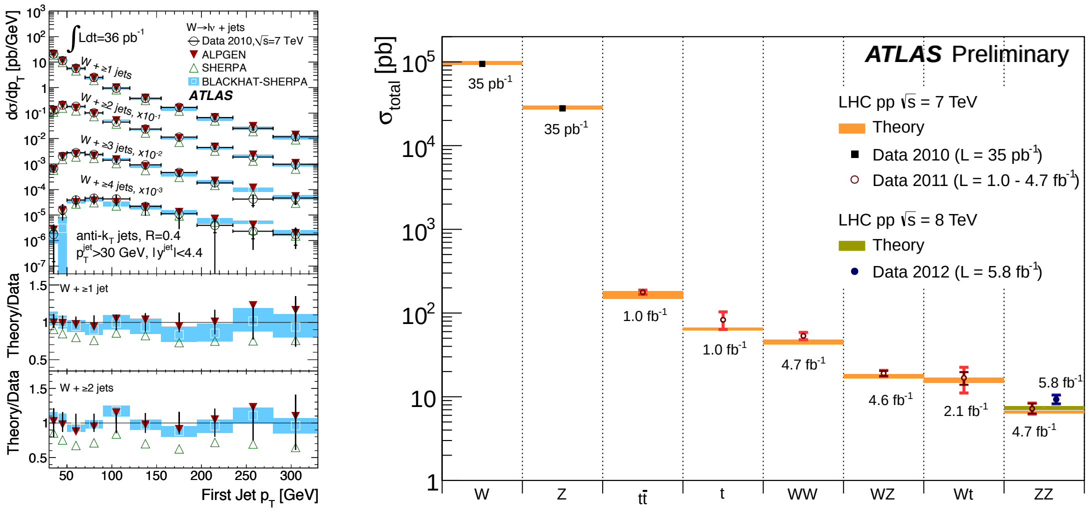

Figure 3: Left: Transverse momentum distribution for the leading jet in W+jet production, measured by ATLAS [31]; Right: Overview of ATLAS cross section measurements at 7 and 8 TeV centre-of-mass energy [32].

3. The Higgs sector

A traditional approach to testing the electroweak sector of the SM has been by looking at the overall consistency among direct measurements of the W and top quark masses, previous limits on the Higgs mass m_H, and the SM relationship among m_W, m_t and m_H. A recent version of this test has been summarized in Ref. [33], showing consistency, at the 1 sigma level, among these mass measurements and a possible existence of a SM Higgs with mass around 125 GeV. A central ingredient to this test is an improved measurement of m_W at the TEVATRON. The latest, and the world's most precise, determination of the W mass has been obtained by CDF [34], with a total uncertainty of 19 MeV, leading to an uncertainty on the latest TEVATRON combination (world average) of 16 MeV (15 MeV) [35].

However, the name of the game has changed, with a major milestone reached in July 2012, when ATLAS [36] and CMS [37] announced the independent observation of a new boson with mass around 125-126 GeV and Higgs-like properties in terms of signal strength. While the direct observation of such a boson at a mass as expected from the electro-weak fits can be viewed as yet another triumph of the SM at the loop level, the real focus is now on studying this newly discovered particle, in order to verify if indeed all its properties are consistent with the expectation of a SM Higgs boson, or if deviations can be found, thus indicating the additional existence of a new physics sector. Possibilities in this direction are obviously supersymmetric models or, e.g., new strongly interacting sectors which could lead to the Higgs boson being a composite state.

In terms of production of a SM Higgs, the channels with the strongest sensitivity so far at the LHC are the gluon-fusion and the vector-boson fusion channels, whereas the most promising decay processes are the di-photon, the ZZ to four leptons and the leptonic WW channels. The former two do not have the largest branching fraction for a Higgs with mass around 125 GeV (where rather the $b\bar{b}$ channel dominates), but allow the reconstruction of an invariant mass peak over a smoothly

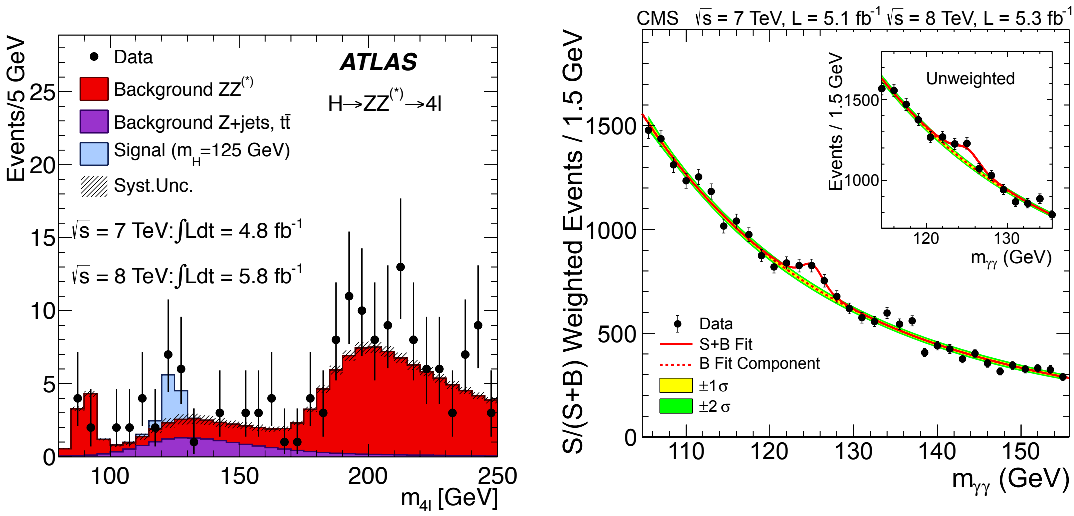

Figure 4: Left: Invariant mass distribution in the ZZ to four leptons channel of the ATLAS Higgs search [36]; Right: Invariant mass distribution in the di-photon channel of the CMS Higgs search [37].

falling (di-photon) or small and flattish (ZZ) background. In any case, both channels rely on the best possible efficiency and energy/momentum resolution for the reconstruction of photons and leptons. The leptonic WW channel is the dominant process for a Higgs around 160 GeV, with decreasing importance towards lower masses, but still maintaining important sensitivity. In addition, the LHC experiments have also analysed the $b\bar{b}$ (in associated Higgs production with a vector boson) and the $\tau^+\tau^-$ channels, which are or will become highly important for a light Higgs. The data analysed comprised the full 2011 statistics (of order 4.8 fb^{-1} at 7 TeV) as well as more than 5 fb^{-1} at 8 TeV collected up to summer 2012. Both experiments obtained the most significant deviations from the background-only hypotheses in the ZZ and di-photon channels, as can be seen from the excess found in the invariant mass distributions of four leptons and two photons (Fig. 4), as well as from the distribution of the local p-value as a function of the hypothetical Higgs mass (Fig. 5). This p-value indicates the probability, under the background-only hypothesis, to observe an excess equal or larger than the actual observed one. If this value reaches the 5σ (or equivalently 10^{-7}) level, then the convention is to talk about a discovery. As evident from Fig. 5, both experiments reach or exceed this level when combining all their individual search channels for a Higgs mass hypothesis of 125-126 GeV. Also, the p-values are consistent (within uncertainties) with what would be expected for a Higgs boson at that mass, as indicated by the dashed line in the plots. It is worth noting that besides this excess at low mass, the experiments by now exclude a SM Higgs boson at or above the 95% confidence level for higher masses, up to 600 GeV where the searches end. As an example for a recent and more detailed discussion of these results, see e.g. Ref. [38].

After the observation, the immediate next step is the scrutiny of the newly found object. The list of questions includes: (i) what is the exact mass? (ii) what is its spin and parity? (iii) is it a CP-even or CP-odd state, or an admixture of both? (iv) are the couplings to the vector bosons as expected from the SM, is this boson indeed related to electro-weak symmetry breaking and how much does it contribute to restoring unitarity in the scattering of longitudinally polarised W

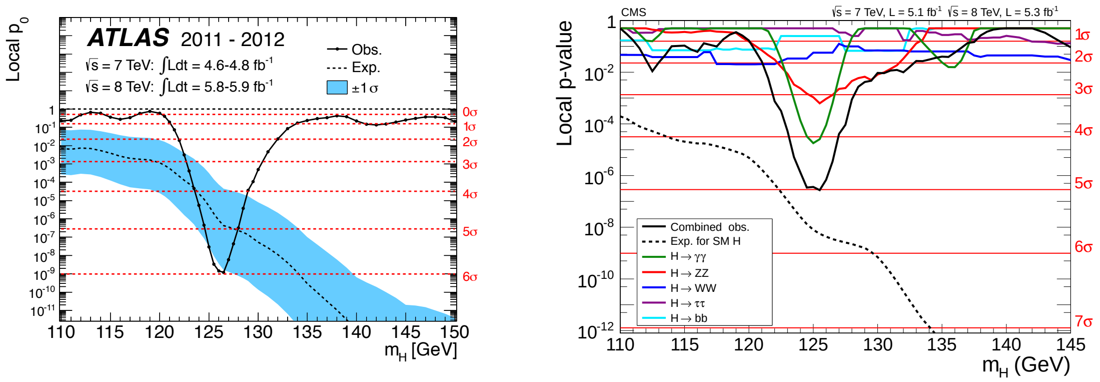

Figure 5: Local p-values in the ATLAS (left) and CMS (right) Higgs searches. The full black line gives the observed combination of all individual channels, whereas the dashed line shows the expected distribution for a Higgs boson at the corresponding mass.

bosons? (v) what are its couplings to fermions, is Yukawa interaction really at work, is the coupling proportional to the mass, what is the contribution to unitarity restoring? (vi) is there only one such state or are there more of them? (vii) is it elementary or composite? (viii) what is its self-interaction?

The current answers by the experiments to the first question are mass values with uncertainties of order 600 MeV, measured by fitting the signal strength (the observed cross section normalised to the expected cross section for a SM Higgs boson) as a function of the mass in the two most sensitive channels (four leptons and di-photons). In this fit the signal strength is allowed to float independently in each channel in order to reduce the model dependence. This results in $126.0 \pm 0.4 \pm 0.4$ GeV quoted by ATLAS and $125.3 \pm 0.4 \pm 0.5$ GeV quoted by CMS. What concerns spin and parity, from the Landau-Yang theorem it can already be concluded that it is not a spin-1 state, since it decays to two photons. Further information on spin-parity is obtained by studying angular correlations in the ZZ, WW and $\gamma\gamma$ channels, and it is expected that a $\sim 4\sigma$ separation between the hypotheses 0^+ vs 0^- and 0^+ vs. 2^+ can be achieved after collection of the full 2012 statistics, see e.g. Ref. [39]. Concerning the combined and channel-per-channel signal strengths, so far consistency is found between the measurements and the SM expectations (Fig. 6). The most striking feature of these results is the somewhat high rate in the di-photon channel, observed by both experiments and at both centre-of-mass energies. Yet, statistics are still too small for making strong conclusions. Also, it will be interesting to follow the development in the fermonic sector, where the current data sample does not yet have enough sensitivity. Indeed, the further measurements of these signal strengths, and the corresponding extraction of Higgs couplings will be a central theme of the short and long-term activities of the LHC experiments. For example, with the full 8 TeV statistics we can expect to reach $\sim 15\%$ accuracy for the total signal strength, individual 5σ observations in the ZZ and $\gamma\gamma$ channels and about 3σ in the $WW, b\bar{b}$ and $\tau^+\tau^-$ channels. On the longer term, with a statistics of about 300 fb^{-1} at 14 TeV, a precision of 5-10% for the various coupling scale factors should be achievable, as e.g. reported in some of the contributions to [40].

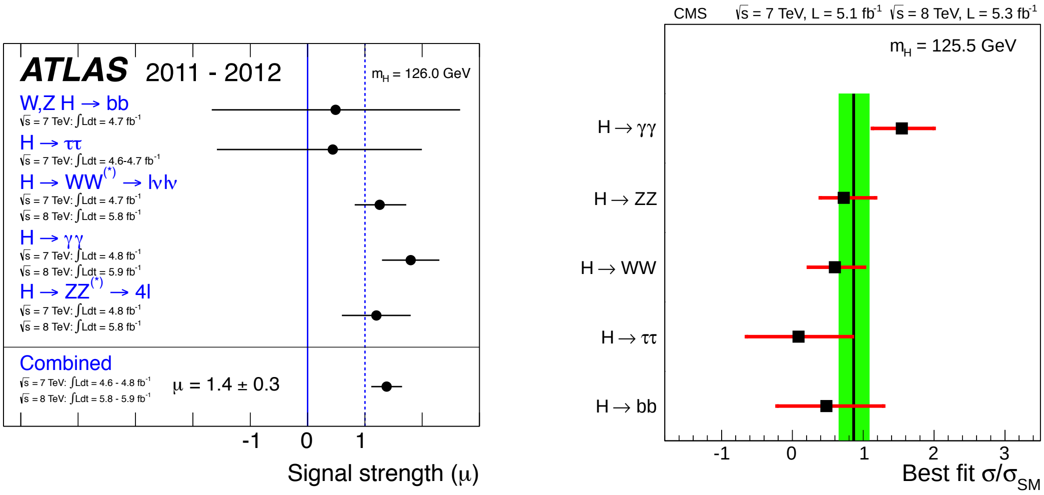

Figure 6: Individual (per channel) and combined signal strengths observed by the ATLAS (left) and CMS (right) Higgs searches.

4. Searches for New Phenomena

The searches for new physics, now dominated by the LHC results, can be roughly classified into two large sectors, namely (i) those concentrating on signatures of SUSY particles, and (ii) the large class of searches for other particles and interactions beyond the SM. The sheer amount of SUSY exclusion plots published so far is testimony of the enormous efforts invested at the collider experiments, in order to get any hint of SUSY components in the data. Typical classifications of the analyses follow topological considerations, such as looking for events with large missing transverse energy (MET), due to the possible production of weakly interacting massive SUSY particles, accompanied by high-p_T jets, one or two opposite or same-sign leptons, more than two leptons or photons. Particular effort has been put in obtaining SM background estimations using control regions in the data themselves, thus reducing as much as possible the dependence on Monte Carlo predictions. The interpretation of the, so far unsuccessful, searches of any deviation from the SM predictions is carried out in various manners; either in the context of since long established specific SUSY incarnations, with very constrained parameter sets, such as mSUGRA or cMSSM, or in a more general approach as implemented in so-called Simplified Models (see e.g. Ref.[41]). In this case basic properties of particle cascades, arising from the decays of heavy particles such as pair-produced gluinos, are explored.

In 2012 results were presented based either on the full 2011 statistics or on first 8 TeV data, showing the potential for big advances in terms of excluded parameter space, see e.g. Fig. 7. In simple terms, the current results of ”generic” squark and gluino searches, in the topologies as mentioned before, allow setting limits at the level of 1.2-1.4 TeV, or even up to 1.5 TeV under the assumption of equal squark and gluino masses, if interpreted in scenarios such as the cMSSM. The rather inclusive searches typically target a phase space with large visible momenta and MET and large mass splitting between the heavy SUSY partners at the beginning of the decay chain and the stable lightest supersymmetric particle (LSP). Nevertheless, these searches keep having sensitivity even for LSP masses up to a few hundred GeV, until trigger constraints start to be important. More recently, the LHC experiments have also started to target scenarios with compressed spectra and/or high jet multiplicities.

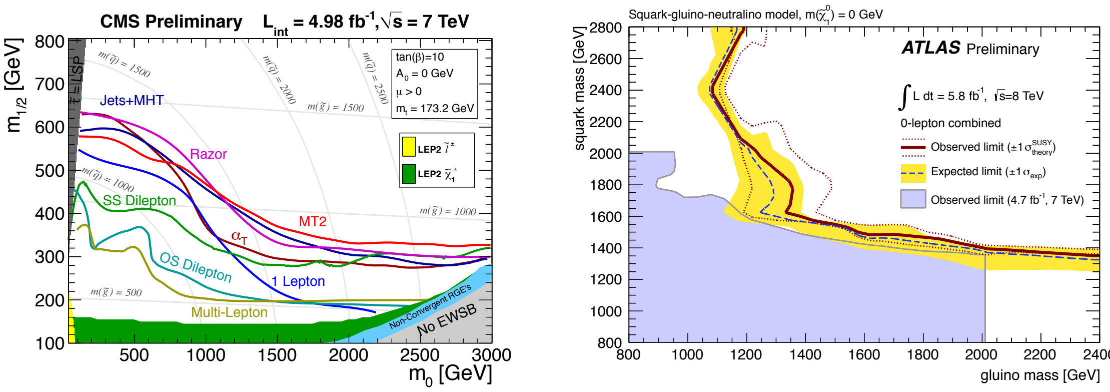

Figure 7: Left: Summary of CMS SUSY searches, when interpreted in the context of the cMSSM parameter space [42]; Right: Limits obtained by ATLAS with SUSY searches in events with jets and MET, and interpreted in a simplified scenario [43].

Thus, with the first years of LHC data the SUSY mass scale is pushed rather high, such that some start to consider giving up (at least to some extent) naturalness arguments. On the other hand, first attempts have already started, and will be pursued further, regarding the searches for third generation squarks. So far limits in those cases are not too strong, roughly around a few hundred GeV up to $\sim$ 0.5 TeV, and strongly depending on the assumptions such as the LSP mass. Such efforts are, e.g., motivated by models where the first generation squarks are pushed to very high mass scales, whereas only the third generation is kept light, around the electroweak scale, arguing that after all naturalness can be maintained if the effects from top loops, which dominate radiative corrections to the Higgs mass, are controlled by contributions from particles such as stops. These searches can turn out to be rather difficult, in particular if the mass separation between the top and third-generation spartners is not too large. In view of the large excluded mass range for squarks and gluinos, another new frontier is the search for direct 'EWK-ino' (charginos, neutralinos) or slepton production, with cross sections starting to become relevant. Again, the given exclusion ranges strongly depend on the assumptions made, such as the LSP mass or the masses of intermediate states in cascades. A similar warning in this direction has to be made in view of limits obtained when using simplified models, since again a considerable number of assumptions and simplifications (such as branching ratios) are underlying such limits. Finally, the long list of SUSY searches is complemented with dedicated analyses looking for long-lived particles or addressing scenarios without R-parity conservation. As an example, a rather comprehensive overview of recent limits can be found at [44].

Similarly to the SUSY searches, also other attempts to look for new physics are so numerous by now that a comprehensive summary is basically impossible. The basic philosophy of the large class of so-called 'exotica' searches is to leave no stone unturned, i.e., to address as many topologies and new physics scenarios as possible. Prominent examples are the searches for single or pair production of heavy objects, such as heavy vector bosons (Z', W') or excited quarks (Fig. 8). The limits on the masses of Z' or W' bosons, assuming SM-like couplings, are in the range of 2.5 - 3 TeV, whereas excited quarks are already excluded for masses below $\sim$ 3.5 TeV and contact interaction scales up to 8 TeV have been probed. Another example is the search for resonances in the invariant mass spectrum of top-pair events, which by now extends up to 3 TeV (see e.g. Ref. [47]) and can be interpreted in terms of exclusion limits on new physics, such as Kaluza-Klein gluons with mass below 1.5 TeV. It is worth mentioning that such searches start to exploit modern tools for resolving jet substructure or reconstructing boosted top quark decays. A grand overview of exclusion limits for a large list of new physics models can be found, e.g., at [48].

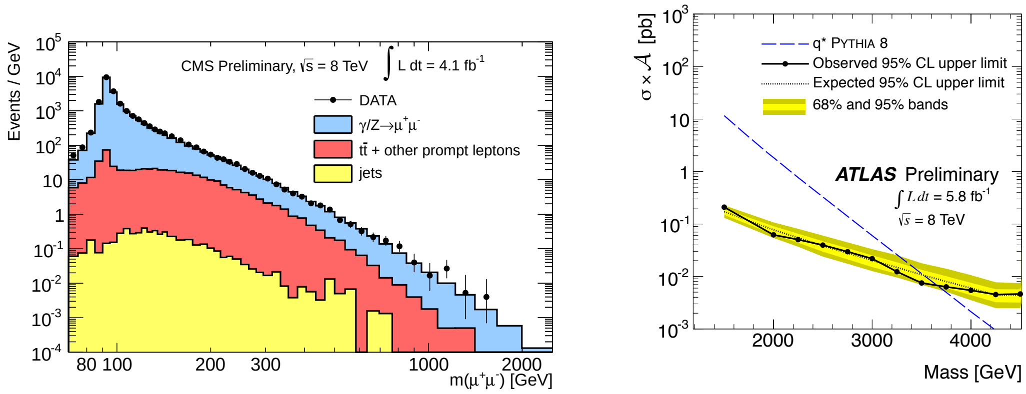

Figure 8: Left: Di-muon invariant mass spectrum measured by CMS in Drell-Yan events, where a heavy Z' boson would show up as resonance at high invariant mass [45]; Right: Limits on the mass of excited quarks obtained by ATLAS in the study of high-mass dijet events [46].

5. Outlook

The current planning for the LHC and injector chain foresees a series of three long shutdowns, designated LS1, LS2, and LS3. The repair and consolidation work during LS1 (in the period 2013-2014) should allow increasing the centre-of-mass energy to 13 or 14 TeV, when LHC running will be resumed in 2015. In the period throughout LS2 (2018), the injector chain will be upgraded to deliver very bright bunches (high intensity and low emittance) to the LHC. Finally, in LS3 (2022), the LHC itself will be upgraded with new low-beta triplets and crab-cavities in order to optimize the bunch overlap at the interaction region. The original performance goal for the LHC to operate at an instantaneous luminosity of 1×10^{34} cm^{-2}s^{-1}, with 25 ns bunch spacing, is likely to be achieved soon after LS1. Based on the excellent LHC performance to date, and the upgrade plans for the accelerators, it is anticipated that the peak luminosity will be close to 2×10^{34} cm^{-2}s^{-1} before LS2, and perhaps significantly higher after LS2. The total integrated luminosity prior to LS2 should reach a value of order 200 fb^{-1}, with 500 fb^{-1} achieved by LS3. The preliminary goal for the High Luminosity LHC program is to deliver a further $\sim$ 3000 fb^{-1} beyond LS3.

These anticipated much larger energies and integrated luminosities will open a huge unexplored phase/parameter space for the searches of new physics, as well as deliver large amounts of data for precision studies of the newly found boson. The impact of the higher centre-of-mass energy can be best appreciated by studying ratios of parton luminosities at different centre-of-mass energies, as can be found, e.g., at [49]. These ratios are typically calculated as a function of a fixed (large) mass scale, such as the mass of a singly produced heavy object, and start to increase steeply towards the largest accessible mass scale. This increase can be understood from the steep fall-off of the parton luminosity at the lower centre-of-mass energy at large Bjorken-x (corresponding to the large mass scale). For example, assuming the production of an object of 2 TeV mass in gluon-gluon fusion, the parton luminosity ratio for 14 TeV vs. 7 TeV reaches values of up to 40 or 50. Multiplying this with an expected proton-proton luminosity of order 300 fb^{-1} during the first years of high-energy running, it immediately becomes clear how much more statistics we can expect for the study of such high-mass objects. As for example summarized in the documents submitted to the European strategy meeting in Krakow in Sep 2012 [40], the LHC experiments expect to push the limits (in case of non-observation) for stops and sbottoms up to the TeV scale, and those for squarks and gluinos up to ~ 3 TeV. Similarly, limits on heavy vector bosons could reach up to about 7 TeV. Furthermore, the High Luminosity LHC program will allow to address small coupling scenarios. However, going much further in mass scale would clearly require a new machine at much higher centre-of-mass energy.

6. Conclusions

The excellent operation of the LHC accelerator and its experiments during the first three years of proton-proton running have already led to an enormous number of results, summarised in several hundred physics publications. In short, the following main conclusions can be drawn at this stage: (i) The SM, in terms of its QCD and electro-weak parts, works perfectly well, up to the % level, at the highest energies probed so far (7 and 8 TeV); (ii) we have very advanced theory tools at hand, giving us precise predictions and Monte Carlo simulations of the relevant physics processes; (iii) there is a new boson of mass around 125 GeV, with properties consistent with the SM Higgs boson, within the current uncertainties. More data are needed to ascertain the exact nature of this particle; (iv) so far, no indications of physics beyond the SM have been obtained from direct searches at the high-energy frontier. Coloured SUSY particles of the first generations are ruled out for masses below ~ 1 TeV, assuming a light LSP, 'natural' SUSY scenarios are being probed at the level of several hundred GeV for the masses of 3rd generation sparticles, exotic heavy objects such as heavy vector bosons have been ruled out up to masses of 2-3 TeV, but there is still a lot of phase/parameter space to be explored, especially at the future high-energy LHC running; (v) currently very few anomalies exist in the world-wide data from the high-energy frontier, but (vi) it should be appreciated that we are just at the beginning of the exploration of this frontier. Thus exciting times are ahead of us.

Acknowledgments

My sincere thanks go to the organisers of this excellent conference, for their kind invitation to give this presentation.

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