The Moriond conference on QCD and High Energy Interactions has been a most exciting and interesting event once more. This year’s edition has been characterized by a very large amount of new results from the LHC experiments. However, also the experiments at other present or past accelerators are still giving extremely important input to our quest for the understanding of nature at shortest distance scales. In this review I will attempt to summarize the main experimental highlights of this conference.

1 Introduction

The focus of the Moriond “QCD and High Energy Interactions” conference series is on theoretical and experimental advances in our understanding of the Standard Model (SM), by studying processes up to the highest achievable energy scales, together with searching for physics beyond the SM. Particular attention is given to the many aspects of Quantum Chromodynamics (QCD), the theory of strong interactions. Phenomena ranging from strongly interacting matter at high energy densities, to scattering processes at highest energies and thus shortest distance scales, are being probed at unprecedented experimental precision and thus provide extremely valuable input to the theoretical community. Furthermore, the study of hadrons containing heavy quarks provides deep insights into phenomena related to the CP-violating sector of the SM.

This year’s conference has 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. Also the TEVATRON experiments continue to be an important player in the field, with new results appearing, which are based on the full Run II dataset of about 10 fb$^{-1}$. These being hadron (as well as heavy ion) colliders, obviously a deep understanding of QCD at many energy scales is necessary. The rich spectrum of LHC and TEVATRON physics is complemented by new results from past and present accelerators. Here an overview of the most recent developments will be given, which by the nature of the vast richness of the field cannot be complete. The author thus apologizes for any important omission.

The structure of this summary is the following. Our main tools, namely accelerators and detectors, are listed in Section 2. Section 3 is dedicated to Heavy Ion Physics, and in Section 4 we discuss new results on the proton structure and inelastic proton scattering. Heavy Flavour Physics is addressed in Section 5, followed by a summary of recent tests of perturbative QCD in Section 6. Top Physics is discussed in Section 7. Finally, searches for Physics beyond the SM and for the Higgs boson are summarized in Sections 8 and 9, respectively. Regarding the status of theoretical advances in the field, we refer to a dedicated review in these proceedings.
None of the results presented below would have been possible without the excellent performance of our tools, namely the accelerators and detectors. While at such conferences typically only the final results of long analysis chains are shown, it is easy to forget and praise all the immense work and ingenuity, which has gone into the design, construction, commissioning and operation of the various accelerators and the corresponding experiments.

Currently, the world’s spotlights are on the LHC and its experiments. As presented by Lamont[3], the LHC machine physicists and engineers had many special events to celebrate during the year 2011, because of several important milestones and even world records achieved, mostly in terms of beam intensities, instantaneous and integrated luminosities, both for the p-p and the heavy ion (HI) running. Overall, during the proton run the LHC has delivered about 12.5 fb$^{-1}$ to its experiments, with the largest fraction (about 5.5 fb$^{-1}$ each) to the two general purpose detectors ATLAS and CMS, and smaller amounts, because of luminosity leveling, to LHCb (1.2 fb$^{-1}$) and ALICE (0.005 fb$^{-1}$). This became possible thanks to an increase by a factor of 20 in the p-p peak luminosity, compared to the 2010 run. A similar factor of 20 increase has been achieved for the integrated luminosity of the HI run in 2011, compared to 2010, with 150 $\mu$b$^{-1}$ of Pb-Pb collisions delivered.

For the 2012 run it has been decided to increase the centre-of-mass energy to 8 TeV and to stay with 50 ns bunch spacing. Very tight collimator settings should allow for regularly running at a $\beta^*$ value of 0.6 m at the ATLAS and CMS interaction points. Combined with bunch intensities above the design value of $1.1 \times 10^{11}$ it is planned to attain peak luminosities of close to $7 \times 10^{33}$cm$^{-2}$s$^{-1}$. Taking the planned ~ 126 days of p-p running and the expected beam parameters above, integrated luminosities anywhere between 12 and 19 fb$^{-1}$ can be expected for ATLAS and CMS at the end of 2012. For LHCb and ALICE a larger $\beta^*$ value of 3 m is foreseen. Finally, at the end of the 2012 p-p run, currently some 22-24 days of p-Pb running are scheduled. It is worth noting that at the time of writing this review the LHC has already gone very close to the 2012 milestones in terms of peak luminosity, a fantastic achievement of the very short and smooth intensity ramp-up for this new 8 TeV run.

However, results shown at this conference were not only based on LHC data. Up to its end of operations in September 2011, the TEVATRON has delivered the impressive amount of 12 fb$^{-1}$ of p-$\bar{p}$ collisions, with 10 fb$^{-1}$ recorded and already analyzed to a large extent by the CDF and DØ experiments. New results are still arriving from the HERA experiments, as well as from the B-factories and DAPHNE. The BESIII e$^+e^-$ ring by now has delivered the world’s largest samples of $J/\psi$ and $\psi'$ mesons. The RHIC experiments have presented new results on HI collisions, and new measurements were presented based on data from the fixed-target SPS experiment COMPASS and even from the former JADE detector at PETRA.

3 Heavy Ion Physics

One of the main purposes of HI physics is to study the properties of a quark-gluon plasma (QGP), supposed to have existed during the initial stages of the Universe and to be created, under laboratory conditions, in HI collisions. More generally, the aim of HI experiments is to gain a better understanding of the many phases, which the strongly interacting matter undergoes from its initial creation in the HI collision to the freeze-out of colour-neutral hadrons. Having experiments at different centre-of-mass energies and with different colliding particles, such as at RHIC and LHC, gives additional handles for probing various areas in the phase diagram. Also, more and more (hard) probes are being studied, in particular at the LHC, where unprecedented measurements based on jets, photons, Z and W bosons have been made. Combining the information obtained by different probes and observables, the goal is to shed light on properties such
as the hydrodynamic behaviour of the hot and dense medium, jet quenching, quarkonia suppression and the medium’s “transparency” to colored partons or colour-neutral electromagnetically or weakly interacting particles.

An important class of measurements is given by the study of hydrodynamic flow. Starting from the simple fact that the initial state should exhibit a spatial anisotropy, due to non-central HI collisions, the pressure-driven expansion is expected to lead to an anisotropy in the distribution of final state momenta or correlations thereof. A standard approach to quantifying these anisotropies is by expanding such distributions in terms of a Fourier series in the angle w.r.t. the reaction plane. Whereas the 2nd order coefficient \(v_2\) captures the elliptic nature of the flow, and is well established since years, precise measurements of non-vanishing higher-order moments have become available only recently (see, e.g. Fig. 1, left), giving important insight. Indeed, the fact that such higher harmonics are non-zero gives strong support to the hydrodynamic picture of the QGP as a perfect liquid, whereas a finite viscosity of the medium would smear out any anisotropies due to fluctuations in the initial state and only lead to a finite \(v_2\) term. Quite a number of new results from flow studies have been shown by ATLAS, CMS, PHENIX, STAR and ALICE, with first measurements up to very high transverse momenta, flow distributions for identified hadrons and anti-particles, di-hadron correlations and first attempts to measure \(v_2\) with di-leptons, photons and D mesons. We refer to the dedicated HI contributions in these proceedings for further details.

![Figure 1: Left: Higher harmonics in flow measurements by ALICE, as a function of the centrality percentile; Right: \(R_{AA}\) measurements by CMS for charged particles, b-quarks, photons, W and Z bosons.](image)

As mentioned above, hard probes have become quite a unique tool for the LHC experiments. Here the main observable is the so-called nuclear modification factor \(R_{AA}\), a ratio of properly scaled A-A and p-p cross sections in order to account for the number of nucleon interactions in a single HI (A-A) collision. If a particular particle (probe) is not affected by the presence of the dense and hot medium, this ratio is expected to be unity. However, a strong suppression below 1 is expected and observed for hadrons, due to the influence of the medium on the colored constituents and thus on the hadron formation. Earlier RHIC measurements have been extended by the LHC experiments to \(p_T\) values up to 50 GeV or higher, where the initial strong rise of the modification factor between 10 and 20 GeV is observed to flatten out above \(\sim 40\) GeV. This behaviour is captured by a large number of models, however, the large spread of model predictions indicates the need of still a better understanding to be obtained. First measurements of \(R_{AA}\) for photons, Z and W bosons have been presented by ATLAS and CMS, cf. Fig. 1, right. As expected, \(R_{AA}\) values consistent with 1 within the still relatively large uncertainties are found. Interestingly, ATLAS has also measured the ratio for W and Z production, \(R_{W/Z} = 10.5 \pm 2.3\) and found it to be consistent with the SM expectation, within
the large uncertainty. Such types of measurements, with better statistics, should allow to obtain information on the parton distributions functions (pdfs) and their modifications in HI collisions. Concerning the observation of quarkonia suppression, it has been concluded that still a number of questions have to be clarified before firm statements can be made, in particular those related to the understanding of the initial conditions. Here dedicated RHIC studies at forward rapidity will give important input. Finally, the clear observation of jet quenching by ATLAS and CMS, reported after the 2010 run, has been confirmed and studied in more detail thanks to the large 2011 statistics. For example, CMS has found that an enhanced imbalance exists at all jet transverse momenta, while at the same time no angular decorrelation and no significant modification of the jet fragmentation function is observed.

4 Proton Structure

The HERA and SPS experiments have presented some of their legacy measurements, in terms of unpolarized and polarized (spin-) structure functions and their interpretations. For example, a new and precise determination of HERA pdfs has been shown (HERAPDF1.7, cf. Fig. 2) based on combined inclusive HERA I + HERA II neutral and charged current data, HERA jet data, which reduce the strong correlation between the strong coupling $\alpha_s$ and the gluon pdf, and a combined $F^c_{2}$ measurement, which gives sensitivity to the gluon and charm content of the proton. It is worth highlighting that predictions, based on such proton pdfs extracted from $e^\pm p$ data alone, actually provide a good description of the LHC data.

Extensive account of the wealth of pioneering HERMES and COMPASS measurements in polarized $ep$ scattering has been given in the presentations by Riedl and Sozzi. Examples are inclusive spin structure functions, various amplitudes and asymmetries from exclusive samples of deeply virtual Compton scattering, and transverse spin asymmetries. The interpretation of such data is expected to lead to an improved understanding of the proton spin puzzle, of the related questions of orbital angular momentum carried by quarks and of the correlations among spin and transverse momentum, as well as between longitudinal momentum and transverse position, captured by transverse-momentum dependent or generalized parton distribution functions.

Figure 2: Left: Latest HERA pdf set, based on inclusive and charm structure functions and jet data; Right: Comparison of inelastic proton cross section data, from collider experiments and Auger, with various models.

Related to the basic understanding of the proton structure and of proton scattering cross sections are studies of the underlying event, multi-parton interactions, particle correlations and diffractive interactions. Recent measurements of this kind are important input to the tuning of Monte Carlo generators. A fundamental observable is the total inelastic proton-proton cross section, with several new measurements from ATLAS, CMS and TOTEM. Typically they are...
presented for the fiducial acceptance region and extrapolated to full phase space, as well as differential in the forward rapidity gap size. In this context, Garcia-Gamez[13] has shown a very interesting comparison of the LHC results with an interpretation of shower observables from Auger data, see Fig. 2, right.

5 Heavy Flavour Physics

Heavy flavour physics as discussed at this conference can be divided into the following classes: (i) studies of quarkonia systems, (ii) production of heavy flavors at colliders and (iii) studies of the CKM matrix, CP violation and indirect searches for new physics with heavy flavor hadrons.

Addressing the first class, we have seen a large amount of new studies of charmonium and bottomonium states, with data from BESIII, BELLE, BABAR and the LHC experiments[13-15]. In particular, most of the efforts are concentrating on understanding and deciphering the origin of already known or completely new resonant states, such as $X(1835)$, $X(1870)$, $X(2120)$, $X(2370)$, $X(3815)$, $X(3872)$, $X(3823)$ and $Y(5S)$. The main questions still to be answered in a satisfactory manner are if these (or some of these) are indeed tetra-quark states, and/or (loosely-bound) "molecules" of meson-meson pairs, e.g. $D - D^*$ or $B - B^*$.

A review of heavy flavour production results from the LHC[19][29] 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 modeling of gluon splitting into $b$ quarks. Highlights at this conference comprise new results from CMS on $\Lambda_b$ production, showing a steeper $p_T$ spectrum than observed for $B$ mesons, the first particle discovered at the LHC, namely the $\chi_b(3P)$ state, an observation by ATLAS now confirmed by DØ, as well as new LHCb measurements[21] of $\chi_c$, $\psi(2s)$ and double charm production. Interestingly, the latter represents a very stringent test for models of double parton scattering.

An excellent review on probing new physics with heavy flavours, and the current experimental status, was given by Schopper[22]. These efforts can be subdivided in (i) attempts to constrain the CKM parameters, (ii) measurements of direct or mixing-induced CP violation and (iii) the searches for very rare decays. Some of the most important new results or updates presented at the conference, concerning these areas, are LHCb studies of direct CP violation in hadronic $B$ decays[21][22] ($B \rightarrow hh'$), new results on CP violation in $B_s$ mixing[23], a large number of new results on rare decays[24][26][27] such as $B_s \rightarrow \mu^+\mu^-$ from LHCb, CMS, ATLAS and CDF, as well as $B \rightarrow K^*\mu^+\mu^-$ and further rare decays from LHCb, e.g. $B^+ \rightarrow \pi^+\mu^+\mu^-$ and $B \rightarrow 4\mu$. In the case of $B \rightarrow K^*\mu^+\mu^-$, LHCb has presented the world’s first measurement of the zero crossing point for the forward-backward asymmetry, giving nice agreement with the SM prediction. Finally, new results on the CP-asymmetry in charm have been presented[25], confirming values of this asymmetry around the $-1\%$ level and at $\sim 4\sigma$ from zero, thus indicating a larger value than expected from some of the currently available SM estimates.

The recent progress towards identification of rare decays attracts most of the current attention. Figure 3 (left) gives a summary of the most recent upper limits obtained on the branching ratio for $B_s \rightarrow \mu^+\mu^-$, which is very sensitive to contributions from new physics such as SUSY and predicted by the SM to be $(3.2 \pm 0.2) \times 10^{-9}$. The current world’s best limit, obtained by LHCb from their 1 fb$^{-1}$ dataset, is $BR(B_s \rightarrow \mu^+\mu^-) < 4.5 \times 10^{-9}$, closely followed by CMS which finds $BR(B_s \rightarrow \mu^+\mu^-) < 7.1 \times 10^{-9}$ from their full 2011 dataset (5 fb$^{-1}$). Also ATLAS has presented a first limit from an analysis of a 2.4 fb$^{-1}$ data sample, and CDF has shown an update based on their full RunII statistics. Their new result does not further enhance, but rather reduce, a slight excess found in their 7 fb$^{-1}$ sample. The strong power of this observable...
is nicely illustrated by Fig. 3 (right) and further discussed in Sec. 8 below, showing that these recent results exclude a very large portion of parameter space for SUSY models.

![Figure 3: Left: Summary of upper limits on the branching ratio for $B_s \rightarrow \mu^+\mu^-$; Right: Impact of these limits on the parameter space of SUSY models (from D. Straub, Moriond EWK 2012).]

In conclusion, the results on heavy flavour physics presented at this conference could be summarized by naming LHCb as an "anomaly terminator". This is because (i) earlier indications of a large phase $\Phi_s$ in $B_s$ mixing have not been confirmed, the current results showing nice agreement with SM expectations; (ii) the measured forward-backward asymmetry and derived parameters in the $B \rightarrow K^*\mu^+\mu^-$ decay also agree with the SM, and thus do not confirm earlier hopes of possible signs of new physics in this decay; (iii) and finally the limit on the $B_s \rightarrow \mu^+\mu^-$ branching ratio is approaching the SM value, with a first measurement to be expected later in 2012. Nevertheless, for those believing in new physics showing up in heavy flavour systems, there is now some new hope due to the large CP-asymmetry found in charm. However, care should be taken here, since SM predictions in this area suffer from large long-distance (non-perturbative) QCD effects, thus are notoriously difficult to predict, i.e. in the end it could simply turn out that the observed large asymmetry could be ascribed to such QCD effects. Overall, the phenomenologists are more and more given a fantastic set of data and experimental constraints, which allow putting strong limits on new physics, in particular when combined with other observables, such as direct searches at colliders (see below).

6 Tests of perturbative QCD

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 can be constrained; (iii) SM predictions can be tested, in particular QCD calculations, as implemented in various codes and MC generators, for processes which are important backgrounds for new physics searches. At this conference a large number of new results in these directions have been presented, in general showing a remarkable agreement of theory and data. We note in passing that a more extensive review of this subject has been published recently.

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 $p_T$. By now the LHC experiments master this effect already at a remarkable level of precision, 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 have been presented for inclusive jet production, dijet production as a function of dijet invariant mass and jet rapidity separation, as
well as third-jet activities. In particular, new measurements have appeared on the inclusive jet cross section as a function of jet $p_T$ by CMS, and dijet production by ATLAS, based on the full 2011 dataset, cf. Fig. 4. Overall, the agreement of next-to-leading order (NLO) QCD predictions with data over many 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. 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. A similar observation is made by a dedicated CMS analysis, which studied central jet production with the additional requirement of a second jet in the forward region. They found some significant disagreements among data and MC models. Finally, ATLAS has presented a measurement of the $D^*$ fragmentation function, showing a sizable discrepancy, with MC clearly underestimating the yield in the data. This might point to a problem with the simulations for gluon splitting to charm, similarly to the observations for the b-quark case in an earlier CMS measurement of $B\bar{B}$ angular correlations.

New results on inclusive photon, di-photon and photon plus jet production at the TEVATRON and the LHC have been presented by Dittmann and Gascon-Shotkin. Among the highlights of this year, there is a new calculation at next-to-NLO (NNLO) level for di-photon production, which finally brings the theory into agreement with data in the region of small azimuthal separation (Fig. 5, left). In that region of phase space the previously available NLO calculation is effectively a leading order approximation, which underestimates the data obtained for this distribution both at the LHC and the TEVATRON. Thus here we have a spectacular example for the need of NNLO calculations, for the description of particular variables in specific regions of phase space, not only because of radiative corrections, but also because of the appearance of new partonic channels in the initial state only at a certain order of perturbation theory. Also worth mentioning is the first LHC measurement on photon plus jet production by ATLAS, as a function of several kinematic variables and differential in the photon-jet angular separation. This is a classical study for hadron colliders, in particular because of the sensitivity to the gluon pdf. The data are in good agreement with NLO predictions (Fig. 5, right), besides some deviations seen for photon $p_T$ below 50 GeV. A similar observation had been made for inclusive photon production. Also worth mentioning is a measurement of angular decorrelations.

Figure 4: Left: Inclusive jet production, as a function of jet $p_T$ and rapidity, measured by CMS; Right: ATLAS data on dijet production.
in photon plus 2 or 3 jets final states by DØ, showing nice evidence for the need to include double parton scattering contributions into the theoretical predictions.

Figure 5: Left: Comparison of CMS data and QCD predictions for the di-photon azimuthal separation; Right: photon plus jet production cross section from ATLAS.

Whereas the excellent agreement of data with NNLO QCD predictions, for the inclusive production of $W$ and $Z$ bosons, had already been shown and discussed at earlier conferences, this year special focus has been put on the study of 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. Concerning such jet multiplicities in $W$ (or $Z$) plus jet production, 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 modeled 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. An interesting new measurement of $VZ(\rightarrow bb)$ production at the TEVATRON is further discussed in section 9 below. The large and by now rather complete set of LHC results is summarized in more detail in Ref. The picture arising is that all the aforementioned processes, measured with statistics up to 5 fb$^{-1}$, are in agreement with NLO QCD predictions, which then allows to put stringent constraints on anomalous trilinear gauge couplings. It has been remarked that the measured $WW$ cross section appears to be slightly higher (however, not at a statistically significant level) both in ATLAS and CMS, compared to the NLO predictions. Since this process is particularly relevant for the understanding of
electro-weak symmetry breaking, it will be interesting to follow up on future results in this area. In the past, a bump in the dijet mass distribution for \( W + 2 \text{ jets} \) production, observed by CDF, had caused a certain amount of excitement. However, at this conference both DØ and CMS presented results, which do not confirm that finding. Finally, an interesting new LHC measurement, related to the \( ZZ \) and \( H \rightarrow ZZ \) processes, has been put forward by CMS, namely the first observation at a hadron collider of \( Z \rightarrow 4 \ell \). While interesting in itself, this process will turn out to be an extremely useful standard candle for controlling the absolute mass scale, the mass resolution and the reconstruction efficiencies for the Higgs search in the four-leptons channel.

We close this section on tests of perturbative QCD by mentioning a nice re-analysis of JADE data for the 3-jet rate, used to precisely determine the strong coupling constant at NNLO+NLLA approximation\(^{39}\). Indeed, it is shown that this measurement has an uncertainty due to higher order QCD corrections below the 1\% level, and is dominated by hadronization model systematics. Similarly, new recent results were also shown on jet production and \( \alpha_s \) determinations based on HERA data\(^{40}\).

7 Physics of the Top Quark

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. Until recently the TEVATRON has been the only player in the field. However, the LHC has quickly risen to the status of a ”top factory” and the LHC experiments start to play the leading role more and more. A central test of SM predictions is the measurement of the top-pair production cross section. The LHC experiments have presented new results\(^{41}\) for a large number of channels (leptons+jets, dileptons, \( \tau + \mu, \tau + \text{jets} \), all hadronic), analyzing data sets between 0.7 and 4.7 fb\(^{-1}\). The currently combined best cross section values found by ATLAS and CMS are \( \sigma_{tt} = 177 \pm 3(\text{stat}) \pm 2(\text{syst}) \pm 7(\text{lumi}) \text{ pb} \) and \( \sigma_{tt} = 165.8 \pm 2.2(\text{stat}) \pm 10.6(\text{syst}) \pm 7.8(\text{lumi}) \text{ pb} \), respectively. Here one should highlight that the experimental uncertainty has already achieved a level of 6\%, which is smaller than the uncertainty on the
theoretical predictions. It would be interesting to see an ATLAS-CMS combination, also in light of the very slight tension which appears from these two experimental results and the fact that most likely part of the systematic uncertainties are correlated. Nevertheless, both results are in agreement with expectations from perturbative QCD, and one should start considering the possible impact of this cross section on pdf determinations.

The studies of single top production are steadily progressing, both at the TEVATRON and the LHC. Thanks to the considerably enhanced cross section at the LHC compared to the TEVATRON, ATLAS and CMS have already reached an accuracy of ~ 20% in the measurement of $t$-channel production (Fig. 7, left). A clear wish has been expressed at the conference for harmonizing, among the LHC experiments, the treatment of theoretical uncertainties in this class of measurements. CMS has interpreted the cross section measurement in terms of $|V_{tb}|$ and extracted a measurement at the 10% accuracy level. Besides this production channel, a considerable effort is spent by all experiments, in order to close in on the $tW$ and $s$ channels.

What concerns the top mass, the TEVATRON is still leading, with the world’s most precise measurement, from a TEVATRON combination, presented to be $m_t = 173.2 \pm 0.6({\text{stat}}) \pm 0.8({\text{syst}})$ GeV, noteworthy a quark mass measurement with a relative uncertainty of 0.54%. Further improvements are still expected until the final analysis of the full Run II dataset. However, the LHC is catching up. For example, CMS has come up with their latest best result of $m_t = 172.6 \pm 0.6({\text{stat}}) \pm 1.2({\text{syst}})$ GeV, thus already achieving the same statistical precision as the TEVATRON experiments. However, it was noted that this determination does not yet consider some systematic uncertainties, such as color reconnection and underlying event effects. There is certainly an interest in obtaining an LHC, and ultimately an LHC-TEVATRON, combination for this important parameter. Such an effort should then also help in synchronizing the treatment of systematic effects by the different experiments. A further observation made at the conference was that all experiments use the $W$ mass as a kinematic constraint in their analyses, meaning that there is some correlation between the top and $W$ mass measurements. On the other hand, in the electro-weak precision tests, where the consistency among $m_t, m_W, m_H$ is tested (see also below), such a correlation is not taken into account. However, because of the largely different levels of precision achieved for these mass determinations, in the end this is not a serious issue, most likely. 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 some experts to 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 (see above), this becomes more and more interesting. So far an accuracy of $\mathcal{O}(7 \text{ GeV})$ is attained, mostly dominated by pdf uncertainties, and achieving a 5 GeV error seems to be viable.

Besides production cross sections and mass, an amazing amount of further top properties have been studied by the TEVATRON and LHC experiments. These comprise spin correlations, $W$ helicity and polarization in top decays, extractions of $|V_{tb}|$, the top width, $m_t - m_\bar{t}$, 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, besides the well-known discrepancy found for the forward-backward asymmetry ($A_{FB}$) at the TEVATRON. CDF has presented a differential study of $A_{FB}$ as a function of the invariant mass of the $t\bar{t}$ system, showing a steeper slope in data compared to theory. Probably further improved understanding, eg., of non-perturbative effects when correcting from particle to parton level, as well as from higher-order QCD, is needed before establishing this as a signif-
icant hint for new physics. This cautious approach appears to be supported by an interesting interpretation by ATLAS of their latest measurement of the top charge asymmetry, $A_C$. When comparing their measurement, as well as CDF’s $A_{FB}$ result, to predictions for $m_{t\bar{t}} > 450$ GeV, there appears to arise some tension, Fig. 7, right. For example, while some physics beyond the SM, such as a heavy Z boson, would still be consistent with the CDF measurement, its effect would lead to a larger $A_C$ than observed by ATLAS.

8 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 shown at this conference 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. 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. 50). In this case basic properties of particle cascades, arising from the decays of heavy particles such as pair-produced gluinos, are explored. At the conference first results were presented based on the full 2011 statistics, showing the potential for big advances in terms of excluded parameter space. In simple terms, the current results of ”generic” squark and gluino searches, in the topologies as mentioned before, allow setting limits around the TeV scale, if interpreted in scenarios such as the cMSSM49. Thus, with the first two years of LHC data this 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 with much more vigor in 2012, regarding the searches for third generation squarks. So far limits in those cases are not too strong, roughly around 300 GeV. 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 could turn out to be rather difficult, in particular if the mass separation between the top and third-generation spartners is not too large. Related to these SUSY searches, there are two further aspects worth mentioning: (i) when looking at the enormous amount of analyses, in the end always condensed into a few exclusion plots, one easily forgets to appreciate the large ingenuity and the many new ideas, which are at the basis of those results. In particular, during these last years a large set of new observables, which are differently sensitive to SM backgrounds and to the appearance of new heavy particles, have been established, as well as many clever, so-called data-driven, methods have been developed, in order to estimate SM background contributions to the search regions. In this context, also observables are studied, such as the ratio of \( Z^+ \text{jet} \) over \( \gamma^+ \text{jet} \) production as a function of \( H_T \) and/or jet multiplicity, which are interesting in itself from a SM point of view.

The discussions of SUSY searches have focused on two further highly-interesting aspects. Tait\(^{51}\) highlighted the important complementarity of searches for dark matter (DM) candidates (in particular Weakly Interacting Massive Particles, WIMPs), as carried out at colliders, with direct DM searches. Whereas at colliders we probe the parton-DM couplings, in direct DM searches one explores the coherent nucleon-DM scattering. An advantage of collider searches is their reach towards very small DM masses, by e.g. looking for monojet signatures induced by direct DM pair-production and a jet from initial state radiation\(^{52}\). This complementarity is nicely expressed in exclusion plots as shown in Fig. 8 left. Another example of complementarity was underlined by Mahmoudi\(^{53}\), who analyzed the constraining power, in terms of SUSY models, arising from heavy flavor physics, such as rare decays (\( B \rightarrow K^* \mu^+ \mu^- \), \( B_s \rightarrow \mu^+ \mu^- \)) mentioned above, or from searches for (supersymmetric) Higgs bosons. In simple terms, the direct searches push the masses of (first generation) particles higher and higher, and rare decays such as \( B_s \rightarrow \mu^+ \mu^- \) strongly constrain \( \tan \beta \) to lower values, therefore creating tension with other observables such as the muon \( g - 2 \) result. Though, concerning the latter, participants at the conference highlighted the need for a still better understanding of the theory uncertainties, before taking this tension too seriously. Finally, if the current exclusion limits for a very light Higgs below about 120 GeV are taken at face value, particular implementations of SUSY breaking, such as gauge mediation (GMSB), can be considered to be ruled out.

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. Many new LHC results have been presented\(^{52}\), which show that exclusion limits for heavy objects, such as heavy vector bosons

\[ \text{FIG. 11: Spin independent coupling assuming both down and up type coupling such that the neutron to proton coupling ratio is } -0.7. \]
($Z'$, $W'$) or excited quarks, have reached the few-TeV range. Even higher scales are excluded in the context of certain large extra dimension models or the searches for miniature black holes. Typical exclusion limits for heavy fermions, such as 4th generation partners, are around half a TeV. A number of spectacular events, discovered by such analyses, have been shown at the conference (cf. Fig. 8, right). For sure, the philosophy of not leaving any stone unturned, will be pursued at the new 8 TeV LHC run, where the higher centre-of-mass energy leads to a significant increase of effective luminosity, in particular when searching for very heavy objects.

9 Searches for the Higgs Boson

A traditional approach to testing the electroweak sector of the SM is by looking at the overall consistency among direct measurements of the $W$ and top quark masses, current limits on the Higgs mass $m_H$, and the SM relationship among $m_W$, $m_t$ and $m_H$. The latest version of this test has been shown at this conference, Fig. 9, and can be considered as one of the real highlights. Indeed, we see that there is consistency, at the 1 sigma level, among these mass measurements and a possible existence of a SM Higgs with mass around 125 GeV. The two most important new ingredients to this test are an improved measurement of $m_W$ at the TEVATRON and the strong Higgs exclusion limits, as discussed below. The latest, and the world’s most precise, determination of the $W$ mass has been obtained by CDF, with an astonishing total uncertainty of 19 MeV, leading to an uncertainty on the latest TEVATRON combination (world average) of 17 MeV (15 MeV). An important contribution to the uncertainty of the final TEVATRON result, related to the knowledge of parton distribution functions, was estimated to be about 10 MeV. However, this error and its possible further reduction in the future, has been questioned by some of the theorists present.

![Figure 9: Left: Summary of recent measurements of the $W$ mass; Right: Consistency check among the $m_W$, $m_t$ measurements, the limits on the Higgs mass, and their relation in the context of the SM.](image)

The LHC and TEVATRON experiments have presented the latest combinations of their Higgs searches leading to the following executive summary: (i) ATLAS excludes, at 95% C.L., the mass ranges 110-117.5, 118.5-122.5 and 129-539 GeV, (ii) CMS excludes the range 127.5-600 GeV, and (iii) the TEVATRON has a 95% exclusion limit for $100 < m_H < 106$ and $147 < m_H < 179$ GeV. Very interestingly, all these combined results indicate a slight excess in the mass range of roughly 122-128 GeV, with the individual significances of those excesses somewhat above the 2 sigma level (cf. Figs. 10 and 11). When looking more closely at the updates presented at this conference, the following observations can be made:
• at the CERN seminar on Dec. 13, 2011, CMS had presented already a complete set of Higgs searches in the various channels, based on the full 2011 statistics. In the meantime, they have performed a new, alternative analysis of the $H \rightarrow \gamma \gamma$ channel now based on an event classification derived from a multi-variate approach to the measurement of photon properties. This leads to a \( \sim 20\% \) improvement in the expected limit, leaving the overall conclusions from the observation on real data unchanged, compared to their earlier analysis. Furthermore, they have presented first results for the $WH \rightarrow WWWW \rightarrow 3\ell 3\nu$ channel and for two new channels in the $H \rightarrow \tau \tau$ search.

• in contrast to CMS, previously ATLAS had shown full-2011 statistics results only for the $H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$ channels, which are most sensitive in the low-$m_H$ region and characterized by their excellent mass resolution. Now, at this conference ATLAS has complemented those analyses with a full suite of analyses based on the full 2011 data sample, covering basically all relevant channels and mass regions;

• interestingly, when comparing all those ATLAS and CMS analyses, it is evident that currently both experiments have very similar sensitivity in basically all the channels.

• the most important recent changes at the TEVATRON come from the $VH(\rightarrow b\bar{b})$ channel, in particular thanks to a considerable improvement in the CDF $b$-tagging performance. An interesting application of the improved tools, and at the same time an important "cal-
ibration” channel for the low-mass Higgs search, is their latest measurement of $WZ(\rightarrow b\bar{b})$ production, Fig. 11 showing excellent agreement with the SM prediction. When analyzing further the recently observed excess in the TEVATRON data, one finds that this excess is driven by the $H\rightarrow bb$ search in CDF and by a contribution from DØ in the $H\rightarrow WW$ channel. The most significant channel for the CDF excess is $Z(\rightarrow e^+e^-)H(\rightarrow bb)$.

- A closer look at the LHC results reveals that there are downward fluctuations in the measurement of the signal strength modifier (Fig. 12, left) at the lower end of the search region, which should probably looked at with the same attention as the upward fluctuations around 125 GeV, since they tell us something about the (relatively little) statistics still involved. Furthermore, it was noted that the updated ATLAS result for the $H\rightarrow WW$ channel does not really confirm the excess in the di-photon and four-lepton channel, as for example seen in the distribution of the background-only probability, Fig. 12, right. However, obviously all these observations correspond to $\sim 2$ sigma effects only, thus should be taken with the appropriate grain of salt.

In conclusion, it is simply impressive to see what the LHC and TEVATRON experiments have delivered, in terms of Higgs results, over such a short time scale between the end of data taking in 2011 and the winter conferences in 2012. A rather solid conclusion appears to be that a SM Higgs boson is excluded, to very high level of confidence, for masses above $\sim 130$ GeV up to about 600 GeV, where the current searches stop. As mentioned above, all experiments observe some excess in the region around 125 GeV, which may be called tantalizing at this stage. However, we should not forget the still limited statistics available, correspondingly the still not overwhelming significance of these observations, and therefore try not to be carried away. Luckily, new data at 8 TeV start pouring in, the hope being that the increased statistics expected in 2012 will allow to make concluding statements on the existence (or exclusion) of a SM Higgs boson. The challenge is with the analyzers, who will have to avoid, at all costs, the (psychological) bias, which undeniably exists after having seen the 2011 results. Finally, it is also worth mentioning that a number of non-SM Higgs searches have been presented, eg. in the context of fermiophobic, (N)MSSM or doubly-charged Higgs scenarios, without any significant hints for a signal.
10 Conclusions

Following the 93 (!) presentations of this conference has been most interesting and allowed obtaining an excellent and rather complete overview of the present theoretical and experimental status in the field of QCD and high energy interactions. The wealth of new data, in particular arriving from the LHC experiments, is overwhelming and exciting at the same time. So far, the Standard Model appears to be as healthy as ever, with no really significant indication for a deviation from its predictions observed, and with the final missing building block, the Higgs boson, probably on the horizon. In a year from now, our big puzzle called "particle physics up to the TeV scale" will be even more complete than already seen this year, and we might know then if there is any space left for some missing piece of the puzzle, entitled "new physics".

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