

## QCD and Electroweak Physics at LHC

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First LHC data have been collected and collisions at a center-of-mass energy of 7 TeV are anticipated for the next months. The commissioning of the detectors and the re-establishment of the Standard Model in the new energy regime will be the main tasks for the experimental collaborations in the year to come. This report summarizes the measurement plans and performance expectations of the ATLAS and CMS experiments for a selected number of QCD and electroweak analyses with an emphasis on the early data taking phase. Some longer term prospects are pointed out.

*RADCOR 2009 - 9th International Symposium on Radiative Corrections (Applications of Quantum Field Theory to Phenomenology)  
October 25-30 2009  
Ascona, Switzerland*

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## 1. Introduction

In November 2009 the Large Hadron Collider (LHC) at CERN has been restarted and first collisions at the injection energy of  $\sqrt{s} = 900\text{ GeV}$  have been registered. On the 13th of December the proton beams could even be accelerated up to 1.18 TeV and achieved a record collision energy of 2.36 TeV dethroning the Tevatron at Fermilab as the most powerful particle accelerator in the world. A new era in particle physics has just started and even higher center-of-mass energies up to 7 TeV are anticipated for the next months.

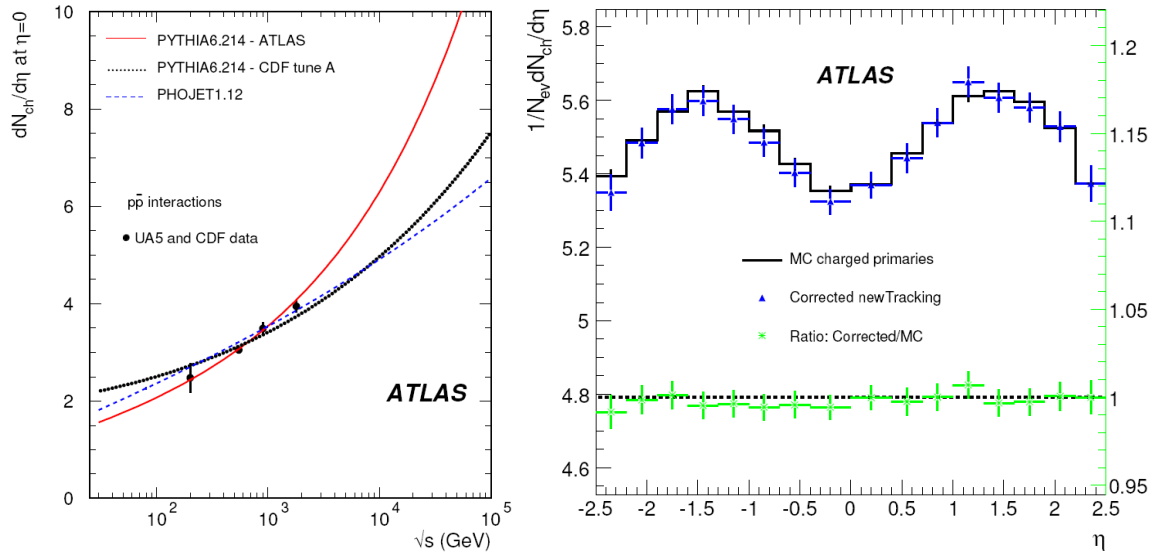
Reaching, however, the high level of understanding of the complex detectors and the accelerator that is required in order to perform measurements as accurate as reported here [1] from the Tevatron experiments CDF and D0 will take time. The commissioning of the detectors and the re-establishment of the Standard Model in the new energy regime will therefore be the main tasks for the experimental collaborations in the year to come. This report summarizes the measurement plans and performance expectations of the ATLAS and CMS experiments for a selected number of QCD and electroweak analyses with an emphasis on this early data taking phase. Some longer term prospects are pointed out. Detailed descriptions of the LHC and the four main experiments can be found elsewhere [2, 3, 4, 5, 6].

## 2. Minimum Bias and Underlying Event

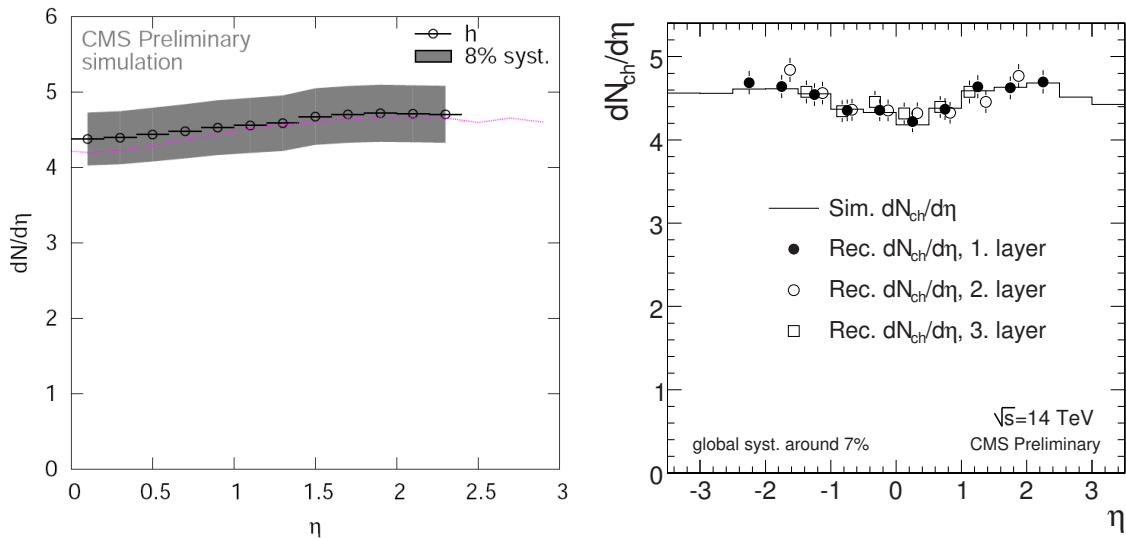
Charged-particle multiplicity distributions versus pseudorapidity  $\eta = -\ln \tan(\theta/2)$  (with  $\theta$  being the polar angle) and transverse momentum  $p_T$  have a long tradition in hadron-hadron collisions and have been measured e.g. in experiments at the ISR, SPS, Tevatron and RHIC colliders [7, 8, 9, 10]. Since in terms of theory only models are available, the predictions for higher energies vary significantly even though they have been tuned to describe currently available data. The expectations by the ATLAS Collaboration [11] from PYTHIA [12] and PHOJET [13] for the average charged-particle density at central rapidity versus the center-of-mass energy is presented in Figure 1 left. An example of the reconstruction of the charged-particle density  $dN_{ch}/d\eta$  using the ATLAS tracking for  $|\eta| < 2.5$  at 14 TeV is given in Figure 1 right [11].

Corresponding expectations by CMS for 14 GeV using full track reconstruction [14] or a pixel hit-counting technique [15], first developed by the PHOBOS experiment [16], are shown in Figure 2. Another method at 10 TeV is described by CMS in [17].

Since only a few thousand events are required for these measurements they can be performed already early after the turn-on of a new accelerator. In fact, the very first measurement on LHC data, albeit at only 900 GeV center-of-mass energy, has been published in the meantime by the ALICE collaboration [18]. Unsurprisingly, the new results are in line with previous measurements. Predicted differences between  $pp$  and  $p\bar{p}$  scattering at the order of some permille are well below the uncertainties and could not be observed. New publications from the LHC experiments including also the collision data at 2.36 GeV center-of-mass energy should be expected soon. In [19] also further preliminary observations with the first LHC data have been reported.



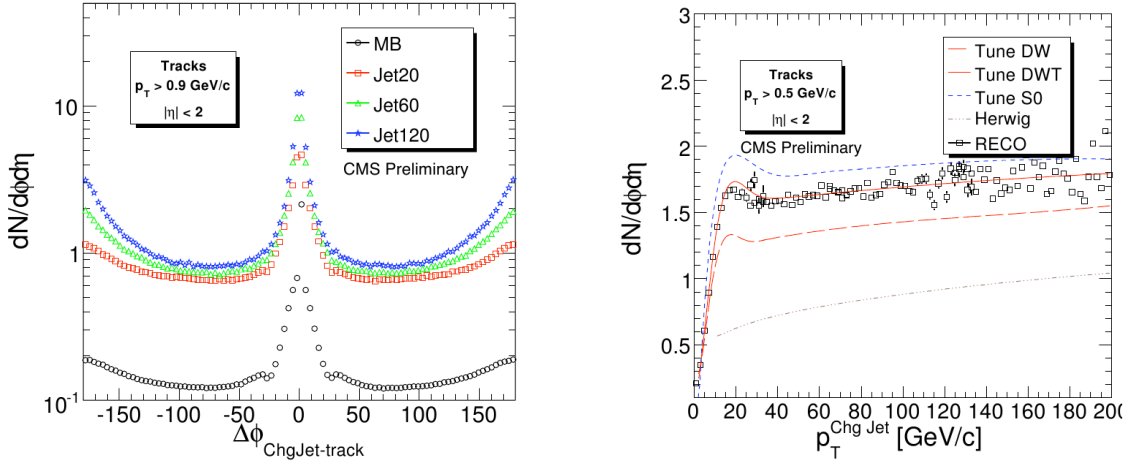
**Figure 1:** The average charged-particle density at central rapidity as a function of the center-of-mass energy is deduced from simulations with different tunes of the MC models PYTHIA and PHOJET on the left [11]. An example of the reconstruction of the charged-particle density using the ATLAS tracking for  $|\eta| < 2.5$  at 14 TeV is given on the right [11].



**Figure 2:** Pseudorapidity dependence of the charged-particle multiplicity at 14 TeV by full track reconstruction [14] as well as by applying a pixel hit-counting method to PYTHIA events simulated for the CMS detector [15].

Another related topic exploits the fact that the transverse region of  $60^\circ < |\Delta\phi| < 120^\circ$  with respect to the leading jet in an event is most sensitive to the Underlying Event, i.e. every collision product not coming directly from the hard scatter [20, 21]. Extrapolations of the UE contributions to events at LHC energies vary widely such that an early determination of its size and the tuning of the MC generators is an important start-up measurement.

Figure 3 presents the composition of the total charged-particle distribution in  $\Delta\phi$  collected with Minimum Bias and jet triggers with different jet  $p_T$  thresholds on the left and the resulting  $p_T$  dependence of the charged-particle density in the transverse plane on the right [22] as reconstructed from CMS simulations with PYTHIA tune DWT. For comparison the MC predictions of PYTHIA with various tunes and from HERWIG without model for multiple parton interactions are shown as well. Already with the assumed  $10\text{pb}^{-1}$  of integrated luminosity at  $\sqrt{s} = 14\text{TeV}$  it will be possible to differentiate between the extrapolations of some models to LHC energies. Note that in Figure 3 right tracks with a lower limit of  $p_T > 500\text{MeV}$  have been chosen to further increase the sensitivity.



**Figure 3:** Composition of the total charged-particle distribution in  $\Delta\phi$  for all trigger streams (left) and the resulting  $p_T$  dependence of the reconstructed charged-particle density in the transverse plane together with predictions of various PYTHIA tunes and from HERWIG assuming  $10\text{pb}^{-1}$  of integrated luminosity at  $\sqrt{s} = 14\text{TeV}$  [22].

### 3. Jet Measurements

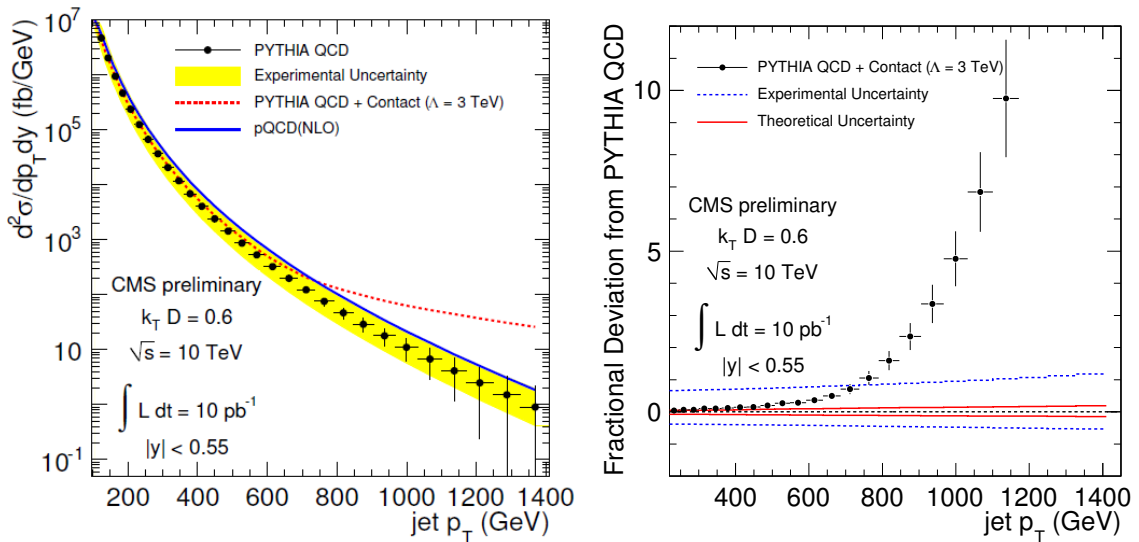
In order to establish a closer connection to the hard process which is described theoretically in terms of partons, i.e. quarks, anti-quarks and gluons, jet algorithms are employed. Although it is impossible to unambiguously assign bunches of observed hadrons to the originating partons, one can define a distance measure between objects and uniquely determine which of them are sufficiently close to each other to be considered to belong to the same jet or respectively to have a common origin.

In total six different jet algorithms with jet sizes  $R$  (or  $D$ ) ranging from 0.4 to 0.7 are in use by the ATLAS and CMS collaborations out of which two Iterative Cone algorithms (ICone-PR, ICone-SM, see [23]) are not safe with respect to comparisons with theory calculations in perturbative

QCD and therefore are not considered further. The remaining four are the Seedless Infrared-Safe Cone algorithm (SIS Cone) [24] and three algorithms of the sequential recombination type: The  $k_T$  [25, 26, 27], the Cambridge/Aachen [28] and the anti- $k_T$  algorithm [23].

The standard jet measurement performed at all previous colliders so far is the differential inclusive jet production cross section. Unfortunately, it is affected by practically all the dominant experimental uncertainties due to the jet energy calibration (JEC), the luminosity determination, the jet energy resolution (JER), trigger efficiencies, and, less important, the spatial resolutions in azimuthal angle and pseudorapidity.

The reach in jet transverse momentum, however, is beyond any previous collider experiment [29, 30, 31] already with  $10\text{pb}^{-1}$  of integrated luminosity at a center-of-mass energy of  $\sqrt{s} = 10\text{TeV}$ . Indications of new physics like from contact interactions would clearly be observable as demonstrated by CMS in [32]. Figure 4 compares the inclusive jet cross section in such a contact interaction scenario for a compositeness scale of  $\Lambda^+ = 3\text{TeV}$  with the pure QCD prediction including estimates of all relevant experimental and theoretical uncertainties.



**Figure 4:** Measured inclusive jet spectrum (K factors times PYTHIA with CMS simulation) with experimental systematic uncertainty compared with theory (NLO times non-perturbative corrections) and PYTHIA QCD+3 TeV contact interaction term (left). Fractional difference of the QCD+contact interaction term and pure PYTHIA QCD is shown in comparison to the experimental and theoretical uncertainties (right).

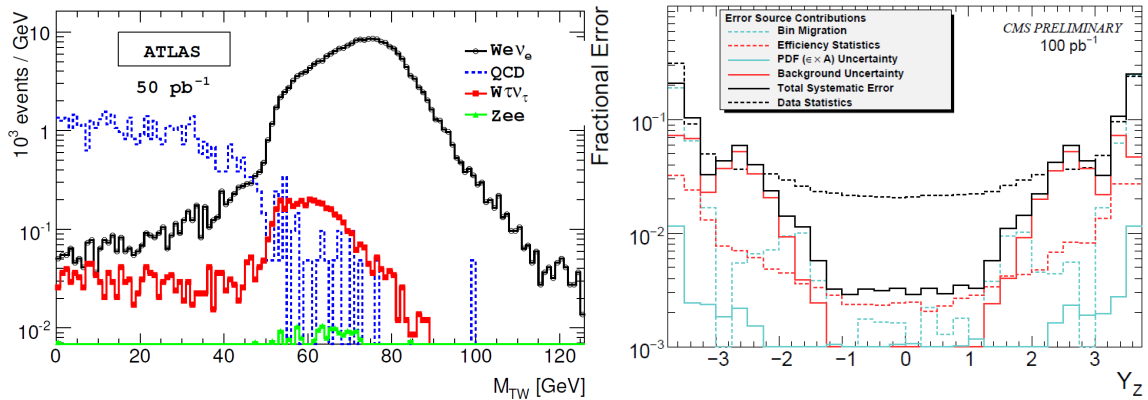
Examples for jet observables less sensitive to experimental uncertainties are angle-related and/or normalized like dijet azimuthal decorrelations and event shapes or cross-section ratios like the dijet production ratio in pseudorapidity and 3-jet to all-jet ratios. Here, the luminosity uncertainty is eliminated and the uncertainty due to the JEC is largely reduced. Expectations for LHC with this type of analyses can be found for example in the references [33, 34, 35].

#### 4. Weak Boson Cross-Sections, $W$ Mass

In contrast to the previously presented reactions the production rates for the weak bosons are orders of magnitudes smaller than for Minimum Bias or jet events (depending on  $p_T$ ). Nevertheless

approximate rates of 10/s resp. 3/s for  $W$  resp.  $Z$  bosons and theoretical uncertainties smaller than 1% allow for precision measurements that stringently test the Standard Model in a new energy regime. Experimental uncertainties are well under control as long as the leptonic decay modes into muons and electrons are concerned. For selections of isolated leptons plus missing transverse momentum or unlike-sign lepton pairs within  $|\eta_l| < 2.5$  and for  $p_T > 15\text{--}25\text{ GeV}$  an accuracy of the  $W$  and  $Z$  production cross sections of about 5% for  $W$ 's and 3% for  $Z$ 's is expected by ATLAS for an integrated luminosity of  $50\text{ pb}^{-1}$  at 14 TeV [11]. With  $1\text{ fb}^{-1}$  of data irreducible uncertainties of about 1–2% are anticipated. Corresponding estimations by CMS can be found in [36, 37].

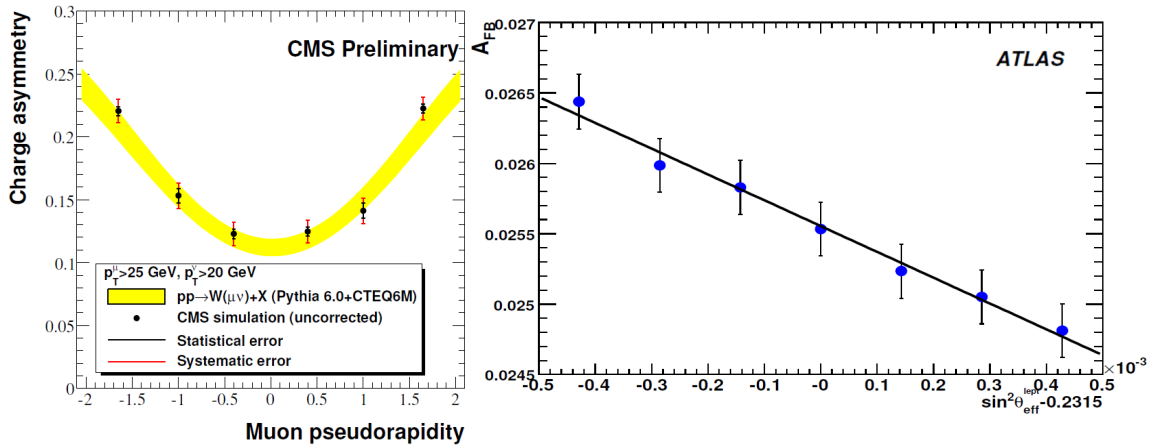
Improving on the  $W$  mass is more difficult, especially considering the reduced uncertainty of  $\Delta M_W = 31\text{ MeV}$  from CDF and D0 presented at this conference [1]. Compared to the PDG Review 2009 [38] with  $\Delta M_W = 40\text{ MeV}$  from Tevatron and 25 MeV as world combination this is a remarkable progress. On a longer timescale ATLAS predicts an achievable precision of  $\mathcal{O}(< 10\text{ MeV})$  for  $10\text{ fb}^{-1}$  of integrated luminosity at 14 TeV provided radiative corrections are under control on the theory side [39, 40]. An example for a  $W$  transverse mass distribution in the  $W \rightarrow e\nu_e$  channel for  $50\text{ pb}^{-1}$  at 14 TeV is displayed in Figure 5 left.



**Figure 5:**  $W$  transverse mass distribution in the  $W \rightarrow e\nu_e$  channel (left) [11] and fractional uncertainties of a  $Z$  rapidity measurement (right) [41].

## 5. Differential Weak Boson Measurements

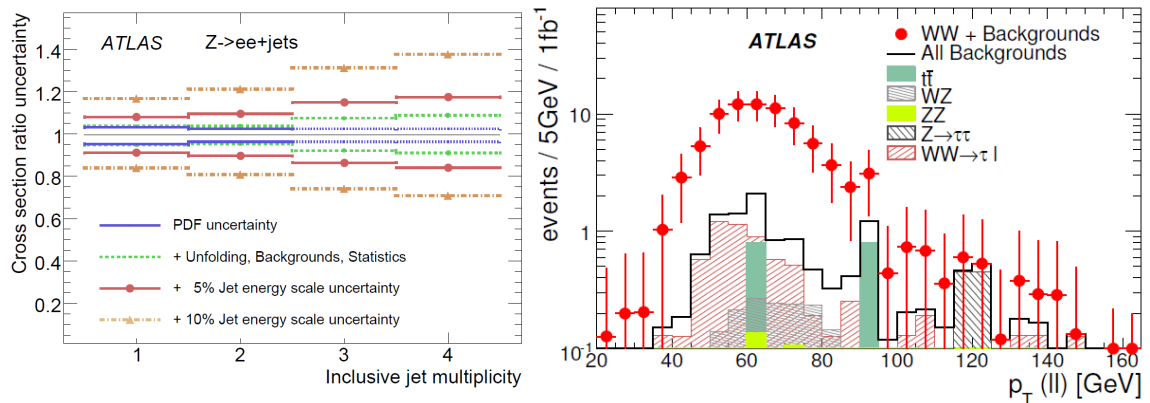
With somewhat more integrated luminosity the differential distributions of the weak bosons, in particular for the  $Z$ , can be exploited where the  $Z$  transverse momentum provides even more constraints on QCD, especially on non-perturbative effects of initial parton emissions, while the rapidity distribution directly probes the parton density functions (PDFs) of the proton. Estimates on the fractional uncertainties for the  $Z$  rapidity distribution from CMS [41] are displayed in Figure 5 right. Equally, the  $W$  charge asymmetry shown in Figure 6 left can start constraining the PDFs with only  $50\text{ pb}^{-1}$  of data [42]. On a much longer timescale, once, about  $100\text{ fb}^{-1}$  of integrated luminosity at highest LHC energies have been accumulated, the weak mixing angle comes in reach for improving its accuracy. This has been studied by ATLAS in [11]. The lever arm for this is pictured in Figure 6 right.



**Figure 6:** The reconstructed  $W$  charge asymmetry including estimated statistical and systematic uncertainties for  $100\text{pb}^{-1}$  of simulated luminosity at  $10\text{TeV}$  from CMS (left) [42] and the forward backward asymmetry  $A_{FB}$  versus the weak mixing angle  $\sin^2 \theta_{\text{eff}}^{\text{lept}}$  at the  $Z$  pole for  $100\text{fb}^{-1}$  of integrated luminosity at  $14\text{GeV}$  from ATLAS (right) [11].

## 6. Boson plus Jet and Di-Boson Production

Finally, the much higher center-of-mass energy at the LHC allows for more precise studies than ever before of multiple boson or of boson plus jet production. Figure 7 shows an estimate on the fractional uncertainties for the  $Z$ -jet cross sections in the  $Z \rightarrow ee$  channel (left) [43] as well as the  $p_T$  distribution of candidate lepton pairs for  $WW$  di-boson events together with backgrounds (right) [11] both from ATLAS for  $1\text{fb}^{-1}$  of integrated luminosity at  $14\text{TeV}$ . A study by CMS on  $Z$ -jet production can be found in [44]. The CMS potential for measuring  $WW$  production with  $100\text{pb}^{-1}$  at  $10\text{TeV}$  is reported in [45].



**Figure 7:** Relative uncertainties on a data-theory comparison of the  $Z$ -jet multiplicity cross sections in the  $Z \rightarrow ee$  channel (left) [43] and the  $p_T$  distribution of lepton pairs for simulated  $WW$  candidate events (right) [11] both for  $1\text{fb}^{-1}$  of integrated luminosity at  $14\text{TeV}$ .



## 7. Outlook

The first LHC collision data have been registered up to a center-of-mass energy of 2.36 TeV and the LHC experiments are in full swing of commissioning their detectors and publishing first physics results. Even higher energies will be reached in the very near future opening up a window to an unprecedented multitude of physics analyses involving multiple jet and boson production studies that were not possible before. The rich program of new physics measurements not only re-establishes the Standard Model but also sets the scene for searches for new phenomena. This year marks the beginning of a new era of particle physics.

## Acknowledgments

I would like to thank the organizers for the kind invitation to participate in this conference.

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