Il Colle di Galileo

Prospects and Precision at the Large Hadron Collider at 14 TeV

GGI, Florence, September 1st - October 24th, 2014
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Abstract. The Workshop gathered world experts in precision predictions in QCD and in the electroweak theory for physics at the LHC. Both discovery and precision physics, as well as their interaction, were addressed. Areas where theoretical improvement is needed were clearly identified in view of the forthcoming Run II of the LHC. Workshop activity opened with the fifth edition of the HP2 conference, bringing together the leading world experts in precision Standard Model calculations. After a central week of lectures addressed to young fellows, the last few days of the workshop hosted a topical meeting on the precision measurement of W boson mass at the LHC, attended by experimentalists and theorists directly involved in the subject.

Keywords. LHC, QCD, Electroweak theory, Higgs and New Physics, precision calculations, Monte Carlo generators

Scientific motivation

The primary goal of the Large Hadron Collider (LHC) is to understand the mechanism of electroweak symmetry breaking (EWSB) and the search for physics beyond the Standard Model (SM). On July 4th 2012 the ATLAS and CMS experiments at the LHC announced the discovery of a new scalar particle compatible with a SM Higgs boson of a mass of about 125 GeV. This discovery was followed by impressive experimental progress, which provided detailed information on the properties of the new boson and its interactions with the other SM particles.

These achievements were made possible by a very good machine performance in the runs during 2010-2012 at a center-of-mass energy for the colliding protons of 7 and 8 TeV. After a shutdown of three years, the LHC is now ready for the second run with higher energy and luminosity, expected to start during summer 2015.

On the theory side, the successful search for the Higgs and the studies of the EWSB mechanism have received great support and have been provided with the-

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oretical predictions of an unprecedented precision. To exploit the high quality of the collected data, equally accurate computations of SM cross sections are indispensable. This in turn requires a quantitative understanding of the SM at the per cent level, including radiative corrections in the gauge theory of the strong interactions, Quantum Chromodynamics (QCD), as well as in the electroweak (EW) sector of the SM. Dedicated analyses of well-known standard-candle processes along with the simultaneous determination of non-perturbative parameters such as the strong coupling constant α_s, masses of heavy quarks and Parton Distribution Functions (PDFs) have laid the foundations for searches for the Higgs particle and new physics phenomena at the LHC, with signals expected as a small excess of events over a large SM background.

In particular, with the Higgs boson found at the LHC, the comparison of its measured mass with the SM indirect determination obtained through the fits to electroweak data will be a test of the model at the quantum level or alternatively a possible indication of new physics. In this scenario, the role played by precise measurements of the top-quark and W -boson mass will be crucial, emphasizing the importance of the legacy of LEP/Tevatron and of a cross-fertilization between discovery and precision physics.

This situation was very demanding for theorists even during the LHC runs at 7 and 8 TeV center-of-mass energy. It will pose a real challenge in the anticipated operation at the design collision energy of 14 TeV, in view of the increase in the available phase space for the production of new particles with large masses or high transverse momentum. At the same time, tests of the quantum numbers of the SM Higgs boson will require stringent cuts during event selection, so that in all cases high-level control of all competing SM processes is mandatory.

As emphasized during the workshop, with the first data analyses at 14 TeV center-of-mass energy, the accuracy of the available theoretical predictions can be judged, enabling a rapid and cohesive response from the theoretical community.

The HP2 conference

The Workshop began with the fifth edition of the conference "HP2: High Precision for Hard Processes", held from September 3rd to September 5th, addressing the most recent advances in the field of QCD and EW higher-order predictions for both Standard Model and Beyond Standard Model processes at hadron colliders. The conference, attended by about 60 scientists, set the stage for all the different aspects of precision physics, discussed in detail over the following weeks of the workshop.

The main highlights presented and discussed during the HP2 conference were the challenging calculation of the Higgs production cross-section in gluon-gluon fusion at N3LO (Next to Next to Next to Leading Order) accuracy in QCD, the

recent progress in automated tools for NLO computations, important developments in the field of event generators with NLO + Parton Shower accuracy, new results in resummation and in NLO/NNLO QCD predictions to phenomenologically relevant processes.

The slides of the talks given at the conference are all available on the workshop website.

The Workshop

As observed during the HP2 conference, NLO QCD predictions are strictly required and routinely applied in the analyses of scattering reactions with multiple particles (and jets) with large transverse momentum in the final state at the LHC. Even NNLO QCD corrections are mandatory and used for a large variety of processes and the first N3LO QCD corrected predictions for Higgs production have just been calculated.

The interplay between the strong and EW interactions has also become important, and in some cases unavoidable, at the LHC because of the large center-of-mass energy compared to the masses of the weak bosons, as well as because of the high precision achieved in a number of experimental measurements.

One of the successful achievements of the workshop was to bring together the world experts in precision predictions in QCD and in EW theory. This made it possible to identify areas where theoretical improvements, based on the combination of QCD and EW corrections, are definitely needed in view of the Run II of the LHC, such as EW physics in single vector boson and diboson production, Higgs and top quark studies and searches for New Physics in extreme kinematical regions.

The discussions benefited greatly from the presence of key experimentalists, who gave review talks on prominent topics at the beginning of each week of the workshop. Moreover, the format of the workshop was characterized by lively collaboration among the participants, with several informal seminars during each week. Particular attention was paid to allowing young fellows to present the results of their own research work.

More specifically, the topics addressed during the weeks of workshop were:

1. new methods for the computation of higher-order corrections to multiparticle final state hard scattering cross sections at NLO and NNLO accuracy;
2. phenomenological importance of electroweak corrections for discovery physics at the LHC, e.g. for precision studies of the Higgs sector (see Fig. 1, left panel) and for background evaluation of new physics searches at the highest energy scale;
3. combination of electroweak and QCD corrections for precision measurements at the LHC, such as the W mass, top mass and the weak mixing angle;

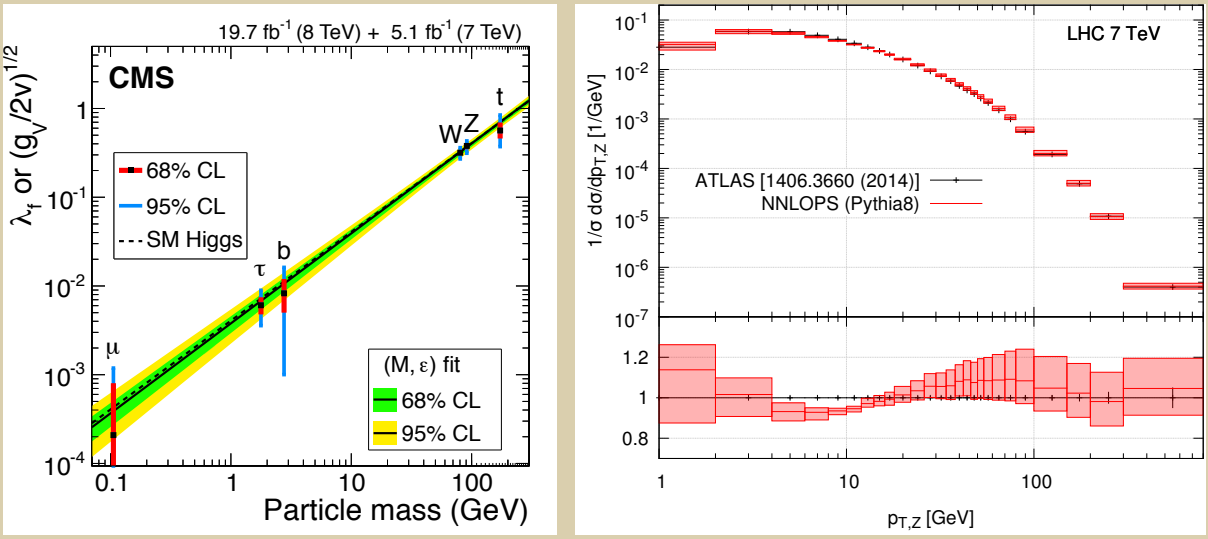

Figure 1. Left panel: Yukawa couplings of fermions and weak bosons to the Higgs particle, as measured by the CMS Collaboration, in comparison to the SM expectations. From V. Khachatryan et al., CMS Collaboration, arXiv:1412.8662. Right panel: Comparison between the transverse momentum of the Z boson as measured by ATLAS Collaboration, and NNLO+Parton Shower predictions. From A. Karlberg et al. JHEP 1409 (2014) 134.

4. studies of jet dynamics, minimum bias and underlying event at the LHC @ 14 TeV;
5. studies of multiparton interactions at 14 TeV and multiple proton-proton interactions at high luminosity;
6. new developments in all order resummation and Monte Carlo generators (see Fig. 1, right panel);
7. improved determination of parton distributions and αs;
8. inclusion of electroweak contributions into PDFs and into QCD NLO + Parton Shower generators.

The workshop was attended by over 100 scientists from different institutions all over the world, with an average number of more than 30 people per week present at GGI. A significant proportion (about 40%) are members of the Italian particle physics community, partly thanks to the financial support provided by the INFN Structures (Local Units and Laboratories). It is interesting to note that several participants were young fellows, including PhD students, partially supported by the EU network LHCPhenoNet, funded by the European Commission between 2011 and 2014. Seven students were supported by the GGI funding scheme for young researchers.

The Training Week

From September 29th to October 3rd the Workshop hosted a Training Week, primarily devoted to lectures addressed to PhD students and early-stage researchers. The Training Week program benefited from lectures given by keynote senior researchers in particle physics phenomenology, as detailed below:
A. Djouadi: Higgs physics in the Standard Model and Supersymmetric Theories (4 h) Y. Dokshitzer: Introduction to Multiple Parton Interactions (2 h)
E. Laenen: QCD hard scattering processes at the LHC (pQCD and resummation) (4 h) P. Nason: Monte Carlo generators for physics at the LHC (4 h)
A. Romanino: Physics beyond the Standard Model: Supersymmetry and composite Higgs (4 h) M. Strikman: Transverse geometry of hard and soft p p collisions at the LHC (2 h)
D. Wackeroth: Electroweak precision predictions in the LHC era (4 h)
S. Weinzierl: New computational methods for NLO and NNLO calculations in QCD (4 h)

Near the end of the Workshop, the first joint ATLAS-CMS-Theory topical meeting on the W mass measurement at the LHC took place from October 20th to October 21st. The meeting was attended by about 30 experts working in the field, including both experimentalists and theorists.

The aim of the meeting was to assess the level of precision attainable by the experiments, and on the theoretical side, in the determination the W -boson mass at the LHC, also relying on the experience of the Tevatron. The precise measurement of MW represents one of the main goals of the precision physics program at the LHC, since the comparison between the direct measurement and the indirect determination, via quantum loops, of MW yields clues to the possible existence of New Physics beyond the SM. The list of talks given at the meeting is available on the workshop website.

The meeting at GGI was characterized by lively and useful discussions and highlighted the importance of ongoing synergy between experimental and theoretical efforts for a precise MW measurement at the LHC. It was the first one of a series which is ongoing at CERN, as part of the LPCC activities. A second meeting already took place at CERN on 23-24 February 2015, as a result of the fruitful experience acquired at GGI.