Challenges for precision measurements at the LHC

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Challenges for precision measurements at the LHC are discussed and a proposal how to move forward to overcome the LHC-specific precision brick-walls is presented.

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1 What I mean by precision measurements

In the presented contribution the “precision measurements” are those which test the Standard Model (SM) with a better precision with respect to what has so far been achieved. We shall not discuss here the measurements for which the statistical errors are the dominant ones (e.g. the measurements of rare decay modes of the of heavy flavours), but focus our attention only on those of the measurements for which the precision is limited by the systematic measurement errors or by the Monte-Carlo modeling uncertainties. The latter may include both the uncertainties in the modeling of the parton distribution functions (PDFs) and the uncertainties inherent to the theoretical framework, used in the unfolding procedures (the order of the perturbative expansion, the presence, or lack, of the higher twist (HT) effects, etc.).

Up to now the LHC has not contributed significantly to the domain of precision measurements. The questions we shall try to answer in this contribution are: (1) Why? and (2) What could be the way forward for the LHC precision measurement programme to be competitive?

2 Challenges for precision physics at the LHC

The hadronic colliders are optimal for generic exploration of interactions of a large variety of the Standard Model point-like particles, over a large momentum range, which extends up to the momentum of the colliding hadrons. Their merits are complementary to those of electron–positron colliders, which employ better controlled, but less luminous beams of the point-like particles, colliding in a cleaner environment.
It is obvious to everyone that the hadronic colliders can hardly compete with the leptonic ones in the measurement precision for those of the SM processes for which the systematic errors dominate over the statistical ones. What, however, often escapes attention, and is a focus point of this contribution, is that the LHC proton–proton collision scheme is by far more challenging than the proton–antiproton collision one.

At the LHC the symmetry relations (specific to the proton–antiproton colliders) are no longer at work. We thus need to understand the charge and polarisation asymmetries in the $W$ and $Z$ boson production processes to a much higher precision than at the Tevatron. As a consequence, the relative strength of the valence and sea contributions to the proton wave function must be understood to a much higher precision at the LHC than at the Tevatron.

The LHC beams are accelerated to a much higher energy than at the Tevatron ones. The heavy flavour excitations of the proton become thus significant and we shall have to understand the heavy flavour content of the proton wave function to a much better precision than that required for the Tevatron measurements.

The $W$ and $Z$ bosons are produced at the LHC by the low-$x$ partons. We thus need to precisely understand not only the $x$ dependence of their distributions and their momentum, flavour and spin correlations but, in addition, their flavour-dependent transverse momentum distributions.

Last but not the least, the gain in the collected luminosity at the LHC with respect to the Tevatron is achieved at the cost of a large $pp$ collision pile-up.

In view of all the LHC-specific problems the following question may be asked: Can the LHC experiments improve the measurement precision achieved at the previous colliders?

The departure point of this contribution is the following statement: If the Monte Carlo tools and the measurement procedures developed for the Tevatron programme are used at the LHC, and if no LHC-specific effort is undertaken, then the precision of a large majority of the SM measurements will not be improved at the LHC – no matter what level of understanding of the LHC machine and detectors performance will eventually be achieved.

The goal of this contribution is to introduce several ideas how to move forward to overcome these LHC-specific measurement precision brick-walls. These ideas were developed and quantitatively evaluated in the series of papers which are recalled in the next section of this contribution.

3 How to move forward

3.1 Use of flexibilities of operation modes of the LHC

The following operation modes of the LHC, most of them not feasible at the Tevatron, could be used to significantly improve the precision of the LHC measurements:

- running at several, suitably chosen, centre-of-mass energies to reduce the impact of systematic experimental errors (e.g. the jet energy scale), and the modeling errors (e.g. missing higher order QCD corrections) on the measured quantities – proposed and discussed in ref.\(^1\), ref.\(^2\) and more recently in ref.\(^3\);

- running, for a fraction of the LHC operation time, the proton–ion collisions for a precision investigation of the electroweak vacuum properties – proposed and discussed in ref.\(^4\);

- running, for a fraction of the LHC operation time, iso-scalar ion beams, such as the deuterium or helium ones, to restore the strong isospin symmetry of the light valence and sea quarks and, as a consequence, to get rid of the corresponding PDF modeling uncertainties – proposed in ref.\(^5\);
• running, for a small fraction of time, partially stripped ion beams at the LHC to deliver the monochromatic electron beam to the interaction points of the LHC experiments (e.g. for precision calibration of the detector response to jets) – see ref. 6 for the feasibility studies of such a running mode;

• using, for the experimental control of the pile-up effects, the “precision oriented” LHC bunch-filling scheme in which the first two 3-batch bunch trains, injected from the SPS to the LHC, have a reduced number of protons to assure, on the average, one collision per bunch crossing (the remaining bunches injected in the same LHC fill are stored at their nominal proton density) – such a LHC filling scheme was proposed in ref. 7.

3.2 Creation of precision support LHC-auxiliary exp. programme

There are several measurements (e.g. the precision measurement of the $W$-boson mass) where the ultimate precision will be limited by the accuracy of the LHC-external input which is necessary to derive the values of the SM parameters from the LHC measurements. Two initiatives can be mentioned here: (1) the letter of intent for the dedicated SPS fixed target experiment 8, having as a main goal a high-precision understanding of the $W$ and $Z$ polarisation at the LHC, and (2) the initial proposal of the iCHEEPx project 9 to collide electrons coming from the 2.45 GeV Energy Recovery Linac, with 6 recirculation passes in the arcs, providing the electron beams of: 5.5, 10.4, 15.3, 20.2, 25.1 and 30.0 GeV with the SPS proton and ion beams (over their full momentum range). The principal target of the latter initiative is to understand the QCD processes at the femto-meter distance scale.

3.3 Switching to a new operation mode of the LHC experiments

The present configuration of the trigger, online event selection, and event reconstruction framework, which the LHC experiments inherited from the previous large scale HEP experiments, may turn out to be inadequate for the precision measurement phase of the LHC. The present configuration gives too a little freedom for the physics groups to implement their, specific task oriented, data selection, reconstruction and analysis methods. The Gauge Model of the Trigger, Data Acquisition and the Data Analysis for the LHC experiments proposed in ref. 10 defines an alternative configuration. In such a configuration physics groups may implement their own on-line and off-line data handling schemes which may run concurrently in a mutually transparent way.

3.4 Precision oriented upgrade the LHC detectors

One of the most important upgrade task for the LHC experiments to increase the accuracy of their measurements is to construct and implement a dedicated detector capable to cross-normalize:

• the cross sections at different centre-of-mass energies,

• the cross sections measured in runs with different beam species,

• the cross sections measured at the LHC and at the Tevatron,

with a LEP-like per-mille precision. A per-mille cross-normalisation of the cross-sections is of primordial importance for e.g. the filtering out the Primakoff processes, Higgs sector and Quark-Gluon-Plasma measurements. The detector design and the corresponding measurement strategy capable to achieve the requisite precision has been proposed and evaluated in ref. 11, ref. 12 and ref. 13.
3.5 Define new observables and new precision measurement strategies

The observables measured at the LHC are sensitive not only to the underlying physics mechanisms, but also to the detector systematic effects and to the approximations present in the models which are used both to interpret the measurements and to unfold the “truth” distributions. The goal of introducing new observables and new measured strategies is to try maximize their sensitivity to the physics effects, while minimizing the effects of the systematic error sources. The concrete examples of the new measurement strategies and of the new observables can be found in ref. 1, ref. 2, ref. 14 and ref. 5. They exploit the flexibility of the detector and the machine running modes to minimize the impact of the dominant sources of the systematic and modeling errors on the precision of the measurement of the SM parameters such as: \( M_W \), \( \Gamma_W \), their charge asymmetries, \( \sin \theta_W \), and \( \alpha_s \).

4 Conclusions

The measurements at the LHC require already a substantial effort to reach the precision limits of the LHC detectors and to reach the requisite precision of the event generators. The basic message of this contribution is that such an initial effort is necessary but, unfortunately, not sufficient. In order to be competitive, new measurement strategies exploiting fully the flexibilities of the LHC collider and its detectors (e.g. such as sketched in this talk) must be incorporated. The precision measurement programme is worth an effort, not only for the textbook measurements, but also as a complementary approach to searches for new physics phenomena at the precision frontier of particle physics.

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