Physics potential of precision measurements of the LHC luminosity

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Abstract

A precision measurement of the LHC luminosity is a key ingredient for its physics program. In this contribution first of all we review the theoretical accuracy in the computation of LHC benchmark processes. Then we discuss the impact of available and future LHC data in global analysis of parton distributions, with emphasis on the treatment of luminosity uncertainties. Finally we present some suggestions for the physics opportunities that can become available by measuring ratios of cross sections between the 8 TeV and 7 TeV runs.

THEORETICAL ACCURACY OF LHC STANDARD CANDLES

An accurate determination of the luminosity uncertainty is specially important when comparing data and theory for the total rates of relevant processes like top quark or electroweak boson production, for which the theoretical predictions are very accurate. For top quark pair production the theoretical accuracy is NLO+NNLL. An up–to–date comparison between theoretical predictions and experimental data for top quark pair cross sections has been presented in Ref. [1]. The comparison of these updated predictions with the most recent ATLAS and CMS data is show in Fig. 1. The current accuracy in the theoretical computation of the cross section is about 18 pb (10%) from higher orders and PDF uncertainties. It is reasonable to expect that this theory error will decrease down to 3-5 pb once the full NNLO calculation and more updated PDFs with LHC data become available. This would allow stringent tests of new physics scenarios by comparing to the LHC data, provided that luminosity uncertainties can be reduced down to a similar level.

Another very important cross sections are the $W$ and $Z$ cross sections. In particular, the $Z$ cross section has been used as a cross check of the calibration of the absolute luminosity. The NNLO corrections for this processes are know since a long time, and have recently been implemented in fully differential programs like FEWZ [2] or DYNNLO [3] that allow to apply exactly the same cuts as in the experimental analysis. In Fig. 2 we show the comparison of the recent ATLAS and CMS data on the $W^+$ and $W^−$ total cross sections with predictions from different PDF sets. The comparison between data and theory for these observables is now limited by normalization uncertainties, so it is clear that more stringent comparisons would be possible with an more accurate determination of the LHC luminosity. This source of uncertainty can be eliminated taking suitable ratios of cross sections, like the $W^+/W^−$ ratio, but this way useful information about the normalizations of the distributions is lost.

$W$, $Z$ and top production are two of the best standard candles at the LHC, but many other cross sections have been measured with good accuracy to begin to challenge theory, and is clear that at the level of an accuracy of 5-10%, the luminosity uncertainties begin to play a role. In Fig. 3 we show a recent compilation of CMS electroweak

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Figure 1: Comparison of the most updated theoretical predictions for top quark pair production with ATLAS and CMS data. Figure taken from [1].

Figure 2: Comparison of the recent ATLAS and CMS data on the $W^+$ and $W^−$ total cross sections with predictions from different PDF sets. Figure taken from [4].
measurements compared to theory predictions. One might expect that the accuracy of other processes like \( W W \) or \( Z \gamma \) to improve in the near future up to the point in which they would benefit from a more accurate luminosity measurement. Eventually, even processes like \( W \) in association with one jet could be measured precisely enough so that the comparison with theory is limited by luminosity uncertainties.

![Figure 3: Comparison of a variety of electroweak processes between theory and the CMS measurements from the 2010 and 2011 data. The luminosity uncertainty of 4% is also shown](image)

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All in all, there is a strong physics motivation to obtain accurate determinations of the LHC luminosity to optimize the comparisons between data and theory for several standard candle processes. Now we turn to discuss the impact of normalization errors and LHC data in the context of global PDF analysis.

**IMPACT OF LHC DATA INTO PDFS**

The precise knowledge of parton distributions functions is an important requirement for the LHC physics program. Just to mention two examples: accurate PDFs, and in particular the gluon, are crucial to determine the theoretical precision of the Higgs cross section in gluon fusion \([5, 6]\), and PDFs are now the dominant systematic error in the very precise CDF determination of \( M_W \) \([7]\), which imposes tight constraints on SM Higgs and new physics from indirect EW fits. In both cases LHC data is known to improve the accuracy of the theoretical predictions from the PDF side (see for example \([8]\) for the \( M_W \) case.)

PDFs are determined from a wide variety of different data like deep–inelastic scattering, Drell-Yan and jet production. With the advent of the LHC, the emphasis is moving towards using as much as possible solid and robust LHC data. There are many processes that have been measured at the LHC that can be used as an input to global PDF analyses, and many others that will be measured in the future. A necessarily incomplete list is the following:

- Electroweak boson production, both inclusive and in association with jets and heavy quarks
- Inclusive jet and dijet production
- Isolated photon and photon-jet production
- Top quark pair production distributions and single top production
- Heavy flavor production

The kinematical coverage in the \( x, Q^2 \) plane of the different experiments included in the NNPDF2.1 analysis \([9]\), supplemented with that of some recent LHC measurements, is shown in Fig. 4. LHC measurements have already been used to constrain PDFs in public sets: for example, the NNPDF2.2 set \([10]\) already includes the \( W \) asymmetry data obtained from 36 pb\(^{-1}\) by ATLAS and CMS.

![Figure 4: Kinematical coverage in the \( x, Q^2 \) plane of the different experiments included in the NNPDF2.1 analyses, supplemented with that of some recent LHC measurements.](image)

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Each of the LHC processes listed above provides a handle on different parton combinations and on different \( x \)-regions. For example, the light quarks and antiquarks, including the strange PDFs, can be determined from electroweak boson production. ATLAS has presented a measurement of the 2010 data for the \( W^+, W^- \) and \( Z \) lepton distributions with full covariance matrix \([11]\), that can be used to impose tight constraints on the medium and small-\( x \) quarks and antiquarks. For this dataset the luminosity uncertainties are the dominant experimental error. In Fig. 5 we show how the NNPDF2.1 NNLO prediction are modified by the inclusion of these ATLAS data, where the theoretical NNLO predictions have been computed with DYNNLO. Related constraints are provided by the CMS and LHCb \( W \) asymmetry measurements \([12]\), as well by off–shell Drell–Yan collider data.

Another interesting process is the associated production of a charm quark together with a \( W \) boson: this process provides a unique direct handle on the strange quark PDF \([13]\), which is the worse known of all light quark
PDFs. In Fig. 6 we show preliminary results of a study of the impact of $W^+ c$ LHC pseudo-data into the NNPDF2.1 NNLO collider only PDFs: it is clear that the $W^+ c$ process will allow a direct determination of the strangeness content of the proton, without the need to resort to low energy neutrino DIS data, which are less reliable because of large theoretical corrections, ambiguities of the heavy quark treatment and nuclear corrections. The inclusive $W$ and $Z$ data should also provide constraints on the strange sea. A recent ATLAS analysis [14] suggest that their inclusive measurements are accurate enough to pin down strangeness with good precision, although the analysis is based on a restrictive parametrization of the input strange PDF.

Other measurements from the LHC are sensitive to the gluon PDF. Inclusive jets are known to provide an important handle to constrain the large-$x$ gluon. For example, the D0 and CDF Tevatron Run II measurements are necessary to stabilize the gluon PDF (as well as the strong coupling [15]) in the region relevant for Higgs boson production via gluon fusion at the LHC [16]. ATLAS [17] and CMS [18] have presented their results for inclusive jets and dijets with the 2010 datasets, however only ATLAS provides the full covariance matrix of the measurement. Preliminary results for the CMS inclusive jets and dijets from the 2011 data, which span a much wider kinematical range, are also available.

Another process directly sensitive to the gluon PDF at leading order is direct photon production. Indeed, prompt photon data was also used until the 90s to constrain the gluon in PDF fits, but a discrepancy with some fixed target experiments lead to abandon it. A recent reanalysis shows a remarkable agreement between NLO QCD and collider isolated photon data from all scales from 200 GeV up to 7 TeV [19], finding also that the LHC isolated photon data is accurate enough to provide moderate constraints in the gluon PDF at intermediate values of $x$, see Fig. 7 and in the associated Higgs cross sections in gluon fusion.

A careful and consistent treatment of normalization uncertainties between datasets is crucial in the context of a global PDF analysis. Ref. [20] reviews the different statistical approaches currently used to include multiplicative normalization errors into recent PDF analysis. As an illustration, it is clear that it is important to consistently take common normalizations between different datasets: two 2010 ATLAS measurements like inclusive jets and $W/Z$ production, both available with the full covariance matrix, have a common single normalization uncertainty coming from the luminosity calibration, and this is important for a more accurate PDF analysis. A similar point was emphasized in Ref. [16], where it is argued that the consistent treatment of the normalizations of the Tevatron inclusive jet data and Z rapidity distributions was very important, since the latter fixed the normalization shift and improved the constraints on the PDFs coming from the former.

In general, to optimize experimental data combination in a global theoretical analysis, we need to quantify as accurately as possible the possible information:

- The correlation of the systematic errors, including luminosity, between two datasets in the same experi-
The correlation of the systematic errors, including luminosity, between two datasets of different experiments, say $W, Z$ from ATLAS and CMS.

- The correlation of the systematic errors, including luminosity, between two datasets of the same experiment from two different runs, say CMS $W, Z$ between the 2012 and 2011 data.

Of course, this is a very optimistic program – but even if it can be achieved only in a limited way, it will be very beneficial for the LHC precision physics studies. Moreover any eventual combination of LHC data will require to understand this cross-correlations between different experiments, just as understanding the correlations between the H1 and ZEUS data lead to the very precise combined HERA–I dataset [21].

### CROSS SECTION RATIOS AT 8 TeV

The 8 TeV 2012 LHC run offers a wide new range of physics possibilities that go beyond the expanded center of mass energy. One interesting study would be to measure ratios of cross sections between the 2012 and 2011 data. Such ratios of cross sections are important because they can be measured very precisely thanks to a strong cancellation of systematic uncertainties and partly of normalization uncertainties as well. Thus in principle one can expect to obtain useful information by selecting suitable observables.

One example is provided by the fact that one can measure ratios of cross sections between 8 and 7 TeV to constrain the large-$x$ PDFs. Indeed, large-$x$ PDFs are poorly constrained by available data: as can be seen Fig. 8 the gluon-gluon parton luminosity when the invariant mass of the produced final state is large has very substantial uncertainties. This in turn affects the sensitivity for searches and eventual characterization of new physics produced close to threshold, like heavy supersymmetric particles or new resonances.

However, it can be seen that large-$x$ PDFs can be studied by measuring ratios of cross sections at high final state invariant masses. Indeed, if one can take the ratio of PDF luminosities between 8 TeV and 7 TeV, for example, the gluon-gluon luminosity defined as

$$ R_{gg} \equiv \frac{\int_{r_{7}}^{r_{8}} \frac{dx}{x_1} g (x_1, M_{X}^2) g (r_{7}/x_1, M_{X}^2)}{\int_{r_{7}}^{r_{8}} \frac{dx}{x_1} g (x_1, M_{X}^2) g (r_{7}/x_1, M_{X}^2)}, $$

where $r_{7} = M_{X}^2/s_{7}$, $\sqrt{s_{7}} = 7$ TeV and likewise for 8 TeV. Then one can see that producing a final state partonic system with invariant mass $M_{X}$ probes the very large-$x$ PDFs for large $M_{X}$. In Fig. 9 we have computed the PDF uncertainty in the ratio of parton luminosities between 8 TeV and 7 TeV, Eq. 1 obtained with the NNPDF2.1 NNLO PDFs [22] for different partonic subchannels. Is clear that as soon as the mass of the final state object raises above 1 TeV, the PDF uncertainties on the ratio of luminosities grows up very fast, up to larger than 100 %. Thus any measurement at this scales would provide a major constraint on large-$x$ PDFs.

As an illustration of the physics potential of such cross section ratios measurements, we show in Fig. 10 the ratio of production cross sections between 8 and 7 TeV of a new heavy quark with mass $m_{Q}$ at the TeV scale. The band represents the PDF uncertainties only. The cross section has been computed with the HATHOR code [23] and the NNPDF2.1 NNLO PDFs. While PDF uncertainties in the cross section ratio are small below $m_{Q} = 1$ TeV, above they increase significantly until they blow up: this is so because of the cancellation of parton luminosities in Eq. 1 fails when the approach the kinematical production threshold. Therefore, a measurement of a generic cross section ratio with similar gluon initiated kinematics (like dijet
production) would provide stringent constraints on large-\(x\) PDFs even if the experimental uncertainties are only moderate.

![Graph](image)

Figure 10: The ratio of production cross sections between 8 and 7 TeV of a new heavy quark boson with mass \(m_Q\) at the TeV scale. The band represents the PDF uncertainties only. The cross section has been computed with the HATHOR code and the NNPDF2.1 NNLO PDFs.

This is just a particular example of how to use cross section ratios to perform interesting physics studies, and that can be easily generalized to many other processes like electroweak production in association with jets, photon or dijet production. It is anyway clear that ratios of cross sections and distributions between 8 and 7 TeV data have a very interesting physics potential for PDFs, that should be explored systematically. Many other topics not necessarily related to PDFs can also be investigated, using the reduced experimental uncertainties of ratios of cross sections between different collider energies.

Of course, the effectiveness of cross section ratios data heavily relies on the possibility to cancel systematic and luminosity uncertainties in these ratios. The extent to which is possible still needs to be investigated.

**SUMMARY AND OUTLOOK**

A precision measurement of the LHC luminosity is very important for its physics program. In this contribution we have reviewed the impact of accurate LHC luminosity determination for the data/theory comparison of important standard candles and then we have discussed the impact of available and future LHC data in global analysis of parton distributions, with emphasis on the treatment of luminosity uncertainties. Finally we have present some possible new physics opportunities by measuring ratios of cross sections between th 8 TeV and 7 TeV run, with the particular example of the determination of large-\(x\) parton distributions.

It is clear that understanding to which extent normalization uncertainties (as well as in general systematic errors) between datasets, experiments and runs are correlated is important to optimize the potential of the LHC data. In other contributions to these proceedings these various issues are discussed in more detail. One of the outcomes of this workshop was that quantifying the correlations of the luminosity uncertainty between the 2010 and 2011 data was difficult and that probably they were mostly uncorrelated, however, even if the correlation is small it will anyway be useful to quantify it.

To conclude, let us mention that it was suggested during the workshop to determine the relative luminosity between ATLAS and CMS by measuring the same process, say the \(Z\) cross section, within the same fiducial volume. This is a process for which the dominant error is by far the normalization uncertainty. Therefore, it would allow a determination with high accuracy of the relative luminosity difference between the two experiments, something which would be an important input to subsequent theoretical analysis that combine the information from the ATLAS and CMS data. These kind of studies are very relevant for the LHC precision program, and we expect that this particular one and related analysis are carried out in the near future.

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