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TOWARDS PRECISION MEASUREMENTS AT THE LHC

ANDRE GEORG HOLZNER
Institut für Teilchenphysik, ETH Hönggerberg
CH-8093 Zürich, Switzerland
E-mail: Andre.Georg.Holzner@cern.ch

This article discusses some basic aspects of cross section measurements at the future Large Hadron Collider (LHC) at CERN.

1 Cross section measurements

One basic physics problem in collider experiments is to measure cross sections, thus to count the number of observed events after a given selection. The selected event sample is not background-free in most cases, so one has to perform some kind of background subtraction:

$$N_{\text{signal}}^{\text{corrected}} = \frac{N_{\text{signal}}^{\text{observed}}}{\varepsilon_{\text{signal}}} = \frac{N_{\text{observed}} - N_{\text{background}}}{\varepsilon_{\text{signal}}} \tag{1}$$

Where $N_{\text{signal}}^{\text{corrected}}$ is the estimate of the number of events coming from the process of interest ('signal') produced in the detector. $N_{\text{signal}}^{\text{observed}}$ is the number of 'observed signal events', $N_{\text{background}}$ is the number of background events (expected or measured) and $\varepsilon_{\text{signal}}$ is the efficiency of the overall selection (trigger and off-line selection efficiency, detector acceptance etc.) for the signal process. Usually, one wants to compare $N_{\text{signal}}^{\text{observed}}$ to the expected number $N_{\text{signal}}^{\text{expected}}$:

$$N_{\text{signal}}^{\text{expected}} = \sigma_{\text{partons}\to\text{signal}} \otimes PDF(x_1, x_2, Q^2) \times L_{\text{pp}} \times \varepsilon_{\text{signal}} \tag{2}$$

where and $\otimes$ is in fact a convolution of the parton distribution functions (PDFs) and the hard cross section. L_{pp} is the proton-proton luminosity, which can be measured as:

$$L_{\text{pp}} = \frac{N_{\text{pp}\to\text{pp}(+\text{X})}}{\varepsilon_{\text{pp}\to\text{pp}(+\text{X})}\sigma_{\text{pp}\to\text{pp}(+\text{X})}} \tag{3}$$

i.e. by counting the number of (quasi) elastic proton-proton collisions.

The problem with the proton-proton luminosity however is that it is difficult to measure and to calculate accurately. In fact, the ATLAS and CMS collaborations, currently estimate to achieve about 5% uncertainty on L_{pp} [1]. This would mean that absolute cross sections can not be measured with an accuracy better than 5%.

2 Luminosity measurements

The question arises whether this limitation of the proton-proton luminosity is actually important. In fact, considering that for all calculations (free) partons collide with each other at LHC energies (as opposed to protons), one should be looking for a precise determination of the *parton luminosity* [2]. In other words, use a 'hard' process (instead of quasi elastic proton-proton scattering) to normalize the cross sections to. Such a process must fulfill the following conditions:

1. It must have a high rate
2. It must have a clean signature with small background, and last but not least,
3. Precise calculations for the (differential) cross section must exist.

Single W and Z production clearly fulfill condition 1. and 2. and their couplings to fermions have been measured at LEP to an accuracy of 1% or better. More precise calculations are becoming available [3].

Let us consider an example: The number of W pair and single Z events is given by:

$$\begin{aligned} N^{\text{expected}}_{\text{pp}\to\text{WW}} &= \sigma_{\text{pp}\to\text{WW}} \otimes PDF(x'_1, x'_2, Q'^2) \times L_{\text{pp}} \times \varepsilon_{\text{pp}\to\text{WW}} \\ N^{\text{observed}}_{\text{pp}\to\text{Z}} &= \sigma_{\text{pp}\to\text{Z}} \quad \otimes PDF(x_1, x_2, Q^2) \ \times L_{\text{pp}} \times \varepsilon_{\text{pp}\to\text{Z}} \end{aligned} \tag{4}$$

Dividing the first equation by the second, one obtains:

$$N^{\text{expected}}_{\text{pp}\to\text{WW}} = N^{\text{observed}}_{\text{pp}\to\text{Z}} \times \frac{\sigma_{\text{pp}\to\text{WW}}}{\sigma_{\text{pp}\to\text{Z}}} \times \frac{\varepsilon_{\text{pp}\to\text{WW}}}{\varepsilon_{\text{pp}\to\text{Z}}} \otimes \frac{PDF(x'_1, x'_2, Q'^2)}{PDF(x_1, x_2, Q^2)} \tag{5}$$

i.e. the number of expected W pair events is expressed in terms of the number of observed single Z events, the cross section ratios and a PDF ratio. The proton-proton luminosity cancels out. The systematic uncertainties which are left come from the selection efficiencies, the theoretical cross section predictions and the PDF uncertainties.

3 PDF uncertainties

Fig. 1 shows the regions in the x vs. Q^2 plane covered by past and present experiments. It can be seen clearly that a large fraction of the region accessible at LHC is uncovered by today's experiments and thus one has to rely on extrapolations of today's experiments (at lower Q^2) to LHC scales. For example, to produce a W boson at rapidity 0, both partons have a x of 0.006. If one goes to non-zero rapidities, one of the partons must have a smaller x.

The uncertainties are significantly larger for $x < 0.005$ (e.g. in the MRST PDFs) than for $x > 0.005$. This due to inconsistencies in the data points fitted, which affects a wide kinematic region of interest at the LHC. These uncertainties are expected to be reduced by including higher order (full NNLO) calculations, theoretical corrections for extremely small and large x as well as corrections at low Q^2 [4].

One approach to estimate the consequences of such uncertainties at LHC scales is to calculate cross sections with different PDFs and compare the values obtained. Since recently, several PDF functions provided by the fitting groups now also include an uncertainty (e.g. [5]).

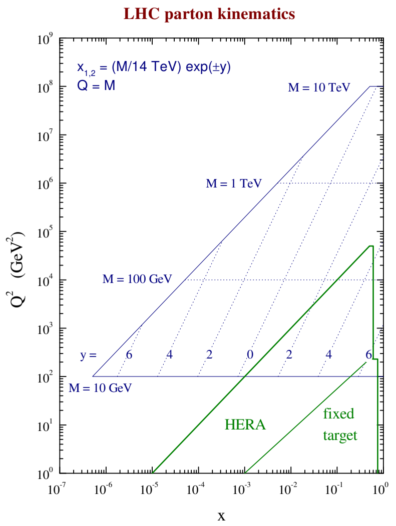

Figure 1. Relation between rapidity y, the scale of the hard interaction Q (here set to the mass) and the momentum fraction of the initial-state parton in heavy particle production at LHC [6]. The graph shows the regions measured by the HERA experiments and the region important at LHC.

4 Constraining PDFs at LHC

When LHC becomes operational, the PDFs can be constrained further from the data itself instead of solely relying on the extrapolations based on today's measurements.

4.1 Quarks

Single W and Z production are perfect processes to constrain the relative quark densities at the LHC (e.g. the ratio of the up- to the down-quark density). For a fixed interaction scale Q (i.e. particle mass), the product $x_1 x_2$ of the two momentum fractions of the colliding partons is fixed (in leading order). The rapidity of the particle is then determined by the ratio x_1/x_2 (see Fig. 1). Thus, different rapidities of heavy particles are sensitive to different ranges of x values. An example of the ratio of the number of charged leptons produced in single $W^{\pm}$ events in different pseudorapidity bins of the charged lepton is shown in Fig. 2. The PDFs shown differ only in their sea quark distributions which is either symmetric (MRS(A)) or not (MRS(H)). Although they are not the latest sets of PDFs, they nicely illustrate that only a very small amount of data is needed to distinguish between very similar PDFs. The statistical uncertainty is about 1% in each bin for data corresponding to roughly one day in the low-luminosity phase of LHC.

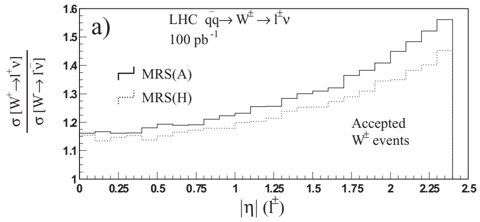

Figure 2. Ratio $\sigma(\mathrm{pp} \to \mathrm{W}^+ \to \ell^+\nu)/\sigma(\mathrm{pp} \to \mathrm{W}^- \to \ell^-\bar{\nu})$ as function of the charged lepton pseudorapidity for two very similar PDFs [2].

4.2 Gluons

About half of the proton's momentum is carried by gluons. Furthermore, the gluon distributions are often determined only indirectly in deep inelastic scattering experiments. It is therefore important to determine the gluon distribution directly at the LHC. This can be done using processes like $\mathrm{g} + \mathrm{q} \to \mathrm{q} + (\gamma/\mathrm{W}/\mathrm{Z})$ which correspond to the experimental signature jet + photon / W / Z. For example photons can be measured very precisely with the ATLAS and CMS detectors. Fig. 3 shows the photon pseudorapidity distribution after a cut on the photon energy and the jet pseudorapidity for two different PDFs [7]. The main background are events with a leading π^0 looking like single isolated photon in the detector. The absolute scale has an uncertainty of about 10% which comes from the choice of the QCD renormalization scale.

5 Higher Order Calculations

Most of the parton shower Monte Carlo generators available today are based on leading order (LO) calculations. Higher order calculations are often available for the total cross section. A widely used procedure to study how well a certain physics process can be observed or measured at LHC is to use a leading order parton shower Monte Carlo generator and scale the distributions of the observables such that the cross section calculated by the generator matches analytical higher order results (the scaling factor is commonly known as 'K-Factor'). In practice, one is however obliged to apply some cuts on the transverse momentum (e.g. due to the trigger threshold) or the pseudorapidity of the particles produced (due to limited detector coverage). An example of a differential cross section obtained with PYTHIA [8] and from analytical higher order calculations is shown in Fig. 4. The simply scaled

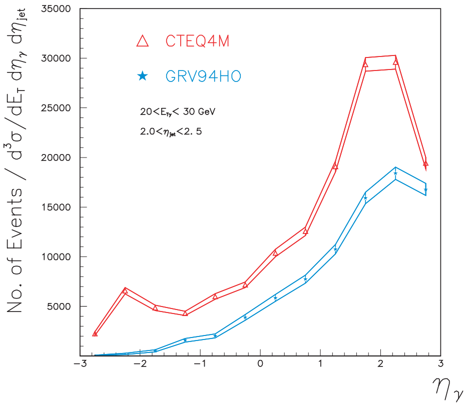

Figure 3. Photon pseudorapidity for a photon + jets selection for two different PDFs [7]. The number of events shown correspond to 10 days of luminosity of $10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

LO distribution does not match the higher order analytical calculation and thus introduces a large uncertainty of the selection efficiency. However, a reweighting method allows perfect matching.

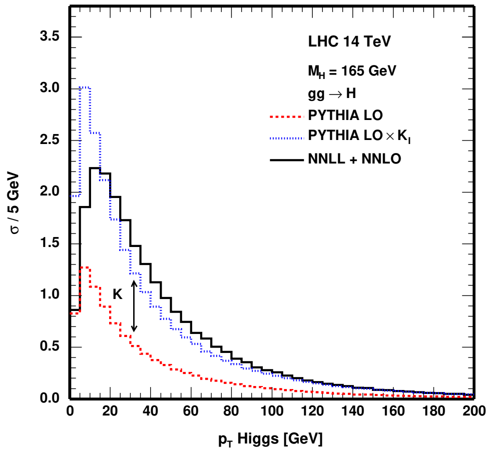

Figure 4. This plot illustrates the need for a differential higher order cross section calculation [9]: The leading order differential cross section scaled by the K factor does not reproduce the NNLL + NNLO calculation. Thresholds on the transverse energies of the trigger will preferably select high transverse momentum Higgs events, whose fraction is underestimated by the LO × K-factor distribution.

6 Summary

Todays uncertainties of PDFs are about 4% [4]. Uncertainties on single W and Z cross sections due to the experimental uncertainty in the PDFs amount to 3%, ratio measurements can be better, e.g. 0.5%.

While today we can only extrapolate the PDFs from measurements performed e.g. by HERA to the LHC scale, the latter will be able to constrain them further in the kinematic region of interest. Single W and Z production are a useful tool to constrain the quark distributions while jet + photon events give a handle on the gluon distribution.

An optimistic estimate of the experimental precision achievable for single W and Z measurements is 1%, which can be used reduce the uncertainty on the recorded luminosity to values significantly smaller than the 5% previously foreseen.

NNLO calculations will be necessary wherever a quantity can be measured to better than 10% accuracy experimentally if the theoretical error should be of the order of the experimental error.

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