EPJ Web of Conferences **49**, 16001 (2013)
DOI: 10.1051/epjconf/20134916001

Diffractive and exclusive production at HERA and LHC

Elisabetta Gallo[1,2,a]

[1] *INFN Firenze, Italy*
[2] *On behalf of the H1, ZEUS, CMS and ATLAS Collaborations*

Abstract. A review of the most recent results on diffraction and exclusive production at HERA and LHC is presented. These include the combination of the cross section results with a leading proton at HERA, the measurement of the inelastic cross section at ATLAS and CMS and diffractive dijets and exclusive processes at CMS.

1 Introduction

Diffraction has been extensively studied at the ep collider HERA and plays an important role in the understanding of the proton structure at low Bjorken x. In deep inelastic scattering (DIS) processes, the proton emits a colourless object, and either remains intact or dissociates in a small mass sytem (Fig. 1). The virtual photon probes the partonic structure of the colour-singlet and the so-called diffractive parton density functions (dPDFs) can be extracted from the measured cross sections. These dPDFs can in principle be used to predict hard diffraction at the hadron colliders. The system X observed in the detector is separated from the leading proton by a large rapidity gap (LRG), due to the lack of colour flow between the p-beam and X. The presence of a LRG is widely used to select diffraction at HERA and LHC, or in alternative the requirement of a leading proton, *i.e.* with energy very close to the beam momentum.

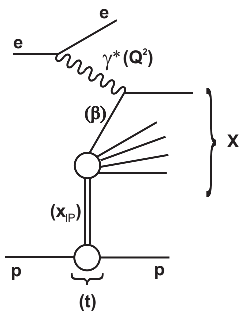

Figure 1. Diagram of a DIS diffractive interaction at HERA.

2 Combined leading proton results at HERA

Recently the H1 and ZEUS Collaborations have published [1] a combination of their inclusive diffractive cross section results at $\sqrt{s}$ = 318 GeV, where the events were selected by the requirement of a leading proton detected in dedicated spectrometers along the beam line. The measurement is in terms of the reduced cross section $\sigma_r{}^D(3)$, defined as:

$$\frac{d^3\sigma}{d\beta dQ^2 dx_{\boldsymbol{P}}} = \frac{4\pi\alpha^2}{\beta Q^4}[1 - y + y^2/2]\sigma_r{}^D(3)(\beta, Q^2, x_{\boldsymbol{P}}),$$

determined for $0.00035 < x_{\boldsymbol{P}} < 0.09$ and in the common |t| range 0.09-0.55 GeV^2.

Here $x_{\boldsymbol{P}}$ is the fraction of proton momentum carried by the colour-singlet object, β is the analougous of Bjorken x in diffraction, Q^2 is the photon virtuality, y is the inelasticity and t is the four-momentum transferred at the proton vertex. The combination method, which is the same used for the extraction of the HERA PDFs [2], takes into account the correlation of systematic uncertainties.

Few significant bins are shown in Fig. 2. The figure shows the strong scaling violations of $\sigma_r{}^D(3)$ as a function of Q^2, which persist also at relatively high values of β, a sign of the high gluonic content of the colourless object. The combined HERA data are plotted overlayed to the individual H1 and ZEUS points, showing their much improved precision. In the combination, a cross calibration effect of each experiment to the other one reduces by up to a factor 2 correlated systematic uncertainties, like those due to the hadronic energy scale and the normalization in the leading proton selection. At low $x_{\boldsymbol{P}}$ these combined data provide the most precise absolute normalization, with an uncertainty of 4%, and in general the most precise points have an uncertainty of 6%.

[a] e-mail: gallo@fi.infn.it

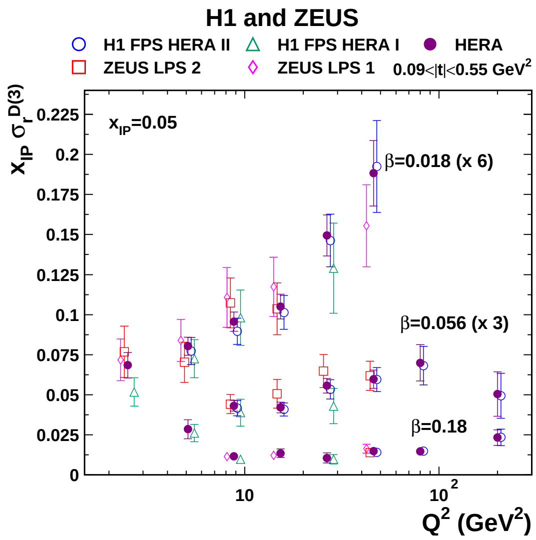

Figure 2. Reduced diffractive cross section for the H1, ZEUS and combined HERA data as a function of Q^2 and in three bins in β at $x_{\boldsymbol{P}} = 0.05$. The cross section is here integrated over t and multiplied by $x_{\boldsymbol{P}}$ for better visibility.

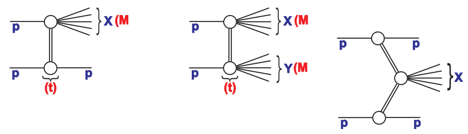

Figure 3. Illustration of single-diffractive (left), double-diffractive (center) and central diffractive (right) processes at the LHC. By convention the system X is the one with higher mass M_X.

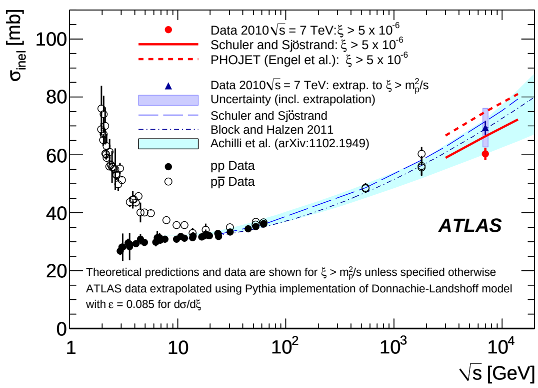

Figure 4. Inelastic cross section versus $\sqrt{s}$ for ATLAS and various lower energy experiments, with several predictions overlayed.

3 Inelastic cross section at the LHC

At the LHC, the total pp cross section can be written as the sum of the elastic and inelastic cross section, where the latter has the contributions from non-diffractive (ND), single-diffractive (SD), double-diffractive (DD) and central diffractive (CD) (Fig. 3). Measurements of diffraction at the LHC requires low pileup and in generally low-threshold or dedicated triggers, for this reason they are mainly performed with the early low-luminosity data in 2010.

The first measurement of the inelastic cross section was performed by ATLAS using 20 μb^{-1} of data collected at $\sqrt{s}$ = 7 TeV in 2010 [3]. Inelastic processes are selected counting events with hits in the minimum-bias trigger scintillators (MBTS), counters positioned in the forward regions of the ATLAS detector, at pseudorapidity values of $2.1 < |\eta| < 3.8$. Due to the MBTS acceptance, the measurement is restricted to the range $\xi > 5 \times 10^{-6}$, where $\xi = M_X^2/s$ is the fractional momentum loss of the proton, and is later extrapolated to the elastic limit of $\xi = m_p^2/s$ for comparison with other experiments, using Monte Carlo (MC) calculations. The result, $\sigma_{\text{inel}}(\xi > 5 \times 10^{-6}) = 60.3 \pm 0.05(\text{stat.}) \pm 0.5(\text{syst.}) \pm 2.1(\text{lumi})$, is shown as the red full circle in Fig. 4, where it can be seen that it is significantly lower than the prediction of the Schüler and Sjöstrand model, used by Pythia6 and Pythia8, and of the Phojet MC. After the extrapolation (blue triangle) which adds a large uncertainty, the ATLAS data agree with predictions based on lower energy data with both a power law dependence or a logarithmic rise with energy.

A more recent measurement is performed in terms of a differential cross section as a function of $\Delta\eta^F$, the larger of the two forward rapidity gaps [4]. Here the foward rapidity gap is defined as the interval in pseudorapidity between the first track with transverse momentum greater than 200-800 MeV in $|\eta| < 2.5$, or the first CAL activity above noise, and the detector edge at $|\eta| < 4.9$. The differential cross section, corrected at hadron level, is shown in Fig. 5. The plot shows an exponential decrease at low $\Delta\eta_F$, which corresponds to non-diffractive interactions, and a plateau at large values of $\Delta\eta^F$, which is characteristic of diffraction. Several models (Phojet, Pythia6 and Pythia8 with different tunes) reproduce roughly the general trend of the data, but none of them gives a full description. Integrating over the diffractive region $5 < \Delta\eta^F < 8$, a cross section of 3.05 ± 0.23 mb is obtained, corresponding to approximately 1 mb per unit of gap size. This is a quite precise measurement of the single+double diffractive cross section at the LHC.

A measurement of the inelastic cross section was also performed by CMS using two independent methodolgies [5]. The first method relies on counting the number of events in the hadron forward calorimeters (HF), situated on opposite sides of the central detector in the pseudorapidity intervals $3.0 < |\eta| < 5.2$. The requirement to have an energy $E_{\text{HF}} > 5$ GeV corresponds to ξ

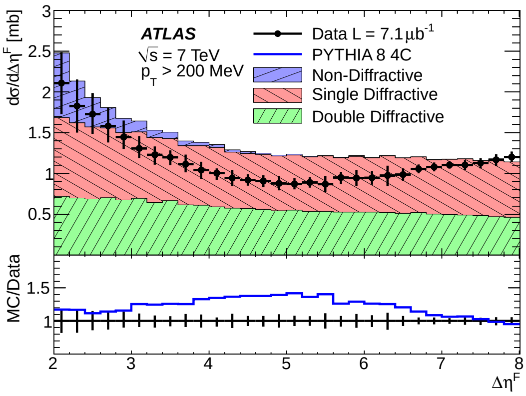

Figure 5. ATLAS inelastic cross section versus $\Delta\eta^F$, compared to one of the models. The predicted non-, single- and double-diffractive contributions are shown in different colours.

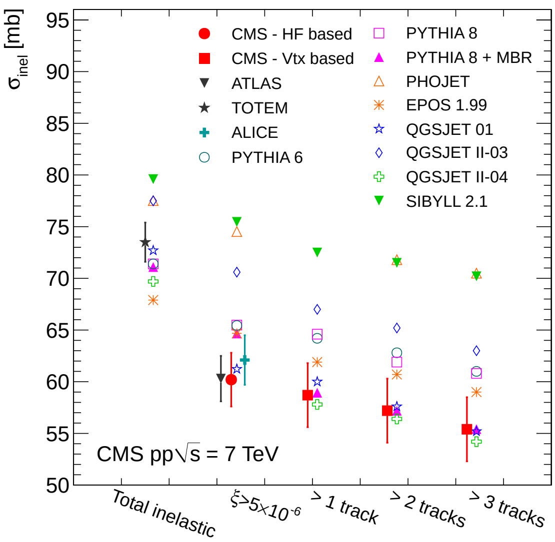

Figure 6. CMS inelastic cross section at $\sqrt{s}$ = 7 TeV, measured with the HF, via pileup event counting, and compared to other measurements and model predictions.

values as those of ATLAS, $\xi > 5 \times 10^{-6}$. The inelastic cross section is found to be $\sigma_{\rm inel}(\xi > 5 \times 10^{-6}) = 60.2 \pm 0.2({\rm stat.}) \pm 1.1({\rm syst.}) \pm 2.4({\rm lumi})$, shown as the red full circle in Fig. 6. The measured cross section is in good agreement with the results from ATLAS, Alice and TOTEM.

The second method assumes that the number of collisions per trigger follows a Poisson distribution with $P(i, \lambda) = \lambda^i e^{-\lambda}/i!$, where i is the number of simultaneous collisions (pileup), λ is the mean number of interactions and is related to the inelastic cross section by $\lambda = L \cdot \sigma_{\rm inel}$, where L is the istantaneous bunch luminosity. The probability of having i inelastic pp interactions, each producing a vertex with > 1, > 2, > 3 charged particles for i between 0 and 8, is measured at different luminosities to determine $\sigma_{\rm inel}$. This method is more sensitive to centrally-produced events and complements the method based on the HF, which is sensitive to systems that produce forward energy and have a small mass M_X. The results are shown as the red full squares in Fig. 6. The CMS data are compared also to various MC models, Pythia6 and Pythia8 with different tunes, and MC generators like Phojet, Qgsjet 01, QGsjet02, Sybill and Epos, the four latter ones commonly used in cosmic-rays physics. Qgsjet 01 and Qgsjet II-04 are the models that agree best with the data, inside one standard deviation.

4 Hard diffraction at CMS

The CMS experiment has studied events with two high transverse momentum (p_T) jets as a function of the ξ variable defined above. Diffractive hard interactions are particularly interesting to test perturbative QCD and QCD factorisation in diffraction. The cross section for this process can be written as:

$$\frac{d^2\sigma}{d\xi dt} = \sum \int dx_1 dx_2 d\hat{t} f(\xi, t) f_{\boldsymbol{P}}(x_1, \mu) f_p(x_2, \mu) \frac{d\hat{\sigma}(\hat{s}, \hat{t})}{d\hat{t}},$$

where f_p is the proton structure function, the product $f \cdot f_{\boldsymbol{P}}$ is the diffractive PDF, which in Regge factorisation can be factorised in a flux f and a partonic structure function $f_{\boldsymbol{P}}$. The cross section $\hat{\sigma}$ is the hard parton-parton scattering cross section, calculable in perturbative QCD, where one parton from the proton and one from the colourless object interact to give the two jets in the final state. If QCD factorisation would hold, the dPDFs extracted from HERA data could be applied to predict hard cross sections in hadron-hadron collisions. However soft scattering interactions between the spectator partons lead to a suppression of the predicted cross section, suppression called *rapidity gap survival probability*. This is a non-perturbative quantity, determined already at Tevatron, and it is therefore interesting to measure it at the LHC energies.

The CMS collaboration has measured [6] the inclusive production of dijets with p_T>20 GeV and $|\eta| < 4.4$ as a function of the variable $\tilde{\xi}$, an approximation of ξ. Figure 7 shows the result in three $\tilde{\xi}$ bins, where the data are represented by the full circles. Comparing to non-diffractive models like Pythia6 and Pythia8, shown as the red lines, one can clearly see an excess of the data in the lowest $\tilde{\xi}$ bin, $0.0003 < \tilde{\xi} < 0.002$. This is the bin where diffraction is expected to dominate, showing evidence for hard diffraction.

The data are also compared to diffractive models, like Pomwig and Pompyt, represented by the blue lines. However one can see that these models predict more events than are observed, by a factor of about 5 in the lowest $\tilde{\xi}$ bin. This factor can be used to estimate the rapidity gap survival rapidity, S^2. A correction has to be made for the proton-dissociation background in the CMS data and in the dPDF extracted from the H1 data at HERA. After this correction, $S^2 = 0.12 \pm 0.05$ when comparing to the leading-order Pompyt MC and $S^2 = 0.08 \pm 0.04$ when comparing to the next-to-leading-order Powheg calculation. These values are close to what found at the Tevatron, however the

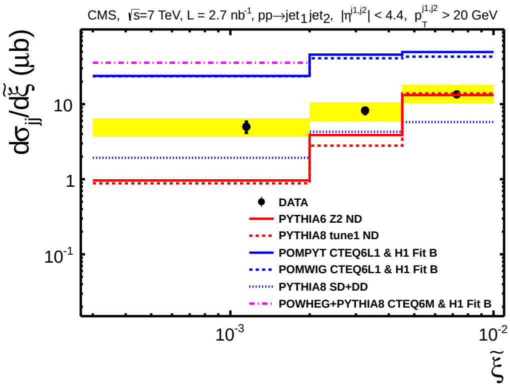

Figure 7. CMS inclusive dijet cross section as a function of $\tilde{\xi}$.

Table 1. Observed and expected yields for central exclusive dielectron production at CMS.

Observed in data	17
Expected from QED (LPAIR)	16.3 ± 1.3
Background	0.85 ± 0.28

CDF data cover a higher range of ξ and cannot be directly compared, as S^2 is expected to increase with decreasing ξ.

5 Exclusive production at CMS

The CMS Collaboration has recently published [7] an analysis of central exclusive diphoton and dielectron production at $\sqrt{s}$ = 7 TeV. In this process, pp→p+X+p, the colliding protons emerge intact and carry a small transverse momentum, transferring all their energies to a colour-singlet system, that produce a diphoton or dielectron final state at central rapidities. No other particle is produced and large LRG regions are present in the detector. The exclusive diphoton production, which proceeds from gg→ $\gamma\gamma$, with an additional screening gluon to cancel the colour of the interacting gluons, is closely related to exclusive Higgs production at the LHC and can therefore shed light on this process.

Candidate diphoton and dielectron events are selected in the kinematic region E_T > 5.5 GeV for each electron or photon and $|\eta| < 2.5$. No other particle in the region $|\eta| < 5.2$ is required.

No diphoton events survive the selection criteria, and an upper limit on the cross section $\sigma(E_T(\gamma) > 5.5\text{ GeV}, |\eta(\gamma)| < 2.5) < 1.8$ pb is derived. In the dielectron channel, 17 events are observed, in agreement with the prediction from a QED Monte Carlo (LPAIR) and the expected background (Table 1). The prediction includes the elastic-elastic, inelastic-elastic and inelastic-inelastic contributions, where the first two dominate. Also kinematic distributions show agreement with this QED model.

6 Summary

Diffraction has been extensively studied at HERA, recently combined results with the forward proton spectrometers from H1 and ZEUS provide new precise diffractive cross section points. Diffraction has also been observed at the LHC. The inelastic cross section and the single+double diffractive cross sections have been measured in pp collisions at $\sqrt{s}$ = 7 TeV. There is evidence for hard diffraction and a suppression of the dijet cross section has been observed, as expected from QCD factorization breaking in diffractive hadron-hadron collisions. Exclusive central production gives new important inputs to theoretical predictions, also of related processes. More results are expected soon.

References

[1] H1 and ZEUS Collaborations, Eur. Phys. J. **C72**, 2175 (2012).

[2] H1 and ZEUS Collaborations, JHEP **01** 1 (2010).

[3] ATLAS Collaboration, Nature Comm. **2** 463 (2011).

[4] ATLAS Collaboration, Eur. Phys. J. **C72** 1926 (2012).

[5] CMS Collaboration, CMS paper FWD-11-001, arXiv:1210.6718, submitted to Phys. Lett. B.

[6] CMS Collaboration, CMS paper FWD-10-004, arXiv:1209.1805, submitted to Phys. Rev D.

[7] CMS Collaboration, CMS paper FWD-11-004, arXiv:1209.1666, accepted by JHEP.