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Review of RENORM Diffractive Predictions for LHC up to 8 TeV and Extension to 13 TeV

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Predictions for diffractive, total, and total-inelastic cross sections at the LHC, based on the pre-LHC renormalization model of diffraction RENORM, are compared with the latest experimental results and the predictions of other models. RENORM is found to be in reasonable agreement with all the results, and is extended to include predictions for the upcoming LHC run at 13 TeV.

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1. Introduction

The predictions for the diffractive and total cross sections at the LHC presented at DIS-2014 [1], which were based on the RENORM /MBR (Minimum Bias Rockefeller) model, described well all available diffractive and total cross section results using a single set of fixed parameters determined from pre-LHC experimental measurements. In this paper, we compare the RENORM /NBR predictions with those from various other diffractive and total cross section models and experimental results from the LHC at $\sqrt{s} = 7$ and 8 TeV, and extend them to $\sqrt{s} = 13$ TeV. For the convenience of the reader, we include verbatim some of the introductory material presented in [1].

Measurements at the LHC have shown that there are sizable disagreements among Monte Carlo (MC) implementations of "soft" processes based on cross sections proposed by various models. Reliably predicting all such processes, or even all aspects of a given process using a single model has been a challenging task [1]. In the CDF studies of diffraction at the Tevatron (see [2]), all processes are well modeled by the stand-alone MBR MC simulation, based on the unitarized Regge-theory model RENORM [3] that employs inclusive nucleon parton distribution functions (PDF's) and QCD color factors. The RENORM model was updated in a presentation at EDS-2009 [4] to include a unique unitarization prescription for predicting the total pp cross section at high energies, and that update has been included as an MBR option for simulating diffractive processes in PYTHIA 8.165 [5], referred to hereforth as PYTHIA 8 MBR. Below, we briefly review the cross sections implemented in PYTHIA 8 MBR [6] and compare them with recent LHC measurements.

PYTHIA 8 MBR includes a full simulation of the hadronization of the three implemented diffractive processes: single, double, and central diffraction. In the original simulation used at CDF, the hadronization of the final state(s) was based on a data-driven phenomenological model of multiplicities and p_t distributions calibrated using S$\bar{p}p$S and Fermilab fixed target results. Later, the model was successfully tested against Tevatron MB and diffraction data. However, only $\pi^{\pm}$ and π^0 particles were assumed to be produced in the final state, with multiplicities obeying a statistical model of a modified Gamma distribution that provided good fits to experimental data [7]. While useful for trigger studies, this model could not be used to predict specific-particle final states.

In the PYTHIA 8 MBR MC implementation, hadronization is performed by PYTHIA 8 tuned to reproduce final state particle distributions in agreement with MBR's. Thus, all final state particles are now automatically produced, greatly enhancing the horizon of applicability of the simulation.

2. Cross sections

The following diffractive processes are implemented in PYTHIA 8 MBR:

$$
\begin{aligned}
&\text{SD} \quad pp \to Xp \quad \text{Single Diffraction (or Single Dissociation)}, && (2.1)\\
&\text{or} \quad pp \to pY && \\
&\text{DD} \quad pp \to XY \quad \text{Double Diffraction (or Double Dissociation)}, && (2.2)\\
&\text{CD (or DPE)} \quad pp \to pXp \quad \text{Central Diffraction (or Double Pomeron Exchange)}. && (2.3)
\end{aligned}
$$

The RENORM predictions are expressed as unitarized Regge-theory formulas, in which unitarization is enforced by interpreting the Pomeron ($I\!P$) flux as the probability for forming a diffractive (non-exponentially suppressed) rapidity gap and demanding that its integral over all phase space saturates when it reaches unity. Differential cross sections are expressed in terms of the $I\!P$-trajectory, $\alpha(t) = 1+\varepsilon+\alpha' t$, the $I\!P$-p coupling, $\beta(t)$, and the ratio κ of the triple-$I\!P$ coupling, $g(t)$, to $\beta(0)$, namely $\kappa \equiv g(t)/\beta(0)$. For large rapidity gaps, $\Delta y \geq 3$, for which $I\!P$-exchange dominates, the cross sections may be written as

$$\frac{d^2\sigma_{SD}}{dt d\Delta y} = \frac{1}{N_{\rm gap}(s)} \left[\frac{\beta^2(t)}{16\pi} e^{2[\alpha(t)-1]\Delta y}\right] \cdot \left\{\kappa\beta^2(0)\left(\frac{s'}{s_0}\right)^{\varepsilon}\right\}, \tag{2.4}$$

$$\frac{d^3\sigma_{DD}}{dt d\Delta y dy_0} = \frac{1}{N_{\rm gap}(s)} \left[\frac{\kappa\beta^2(0)}{16\pi} e^{2[\alpha(t)-1]\Delta y}\right] \cdot \left\{\kappa\beta^2(0)\left(\frac{s'}{s_0}\right)^{\varepsilon}\right\}, \tag{2.5}$$

$$\frac{d^4\sigma_{DPE}}{dt_1 dt_2 d\Delta y dy_c} = \frac{1}{N_{\rm gap}(s)} \left[\Pi_i \left[\frac{\beta^2(t_i)}{16\pi} e^{2[\alpha(t_i)-1]\Delta y_i}\right]\right] \cdot \kappa \left\{\kappa\beta^2(0)\left(\frac{s'}{s_0}\right)^{\varepsilon}\right\}, \tag{2.6}$$

where t is the 4-momentum-transfer squared at the proton vertex, Δy the rapidity-gap width, and y_0 the center of the rapidity gap. In Eq. (2.6), the subscript $i=1,2$ enumerates Pomeron exchanges in the DPE event, $\Delta y \equiv \Delta y_1 + \Delta y_2$ is the total rapidity gap (sum of two gaps), y_c is the center in η of the centrally-produced hadronic system, and s_0 is an energy-squared scalling parameter.

The total cross section ($\sigma_{\rm tot}$) is expressed as [6]

$$\sigma_{\rm tot}^{p^\pm p} = 16.79 s^{0.104} + 60.81 s^{-0.32} \mp 31.68 s^{-0.54} \quad \text{for } \sqrt{s} \leq 1.8 \text{ TeV}, \tag{2.7}$$

$$\sigma_{\rm tot}^{p^\pm p} = \sigma_{\rm tot}^{\rm CDF} + \frac{\pi}{s_0}\left[\left(\ln\frac{s}{s_F}\right)^2 - \left(\ln\frac{s^{\rm CDF}}{s_F}\right)^2\right] \quad \text{for } \sqrt{s} \geq 1.8 \text{ TeV}, \tag{2.8}$$

where s_0 and s_F are the energy and (Pomeron flux) saturation scales, $s_0 = 3.7 \pm 1.5$ GeV^2 and $\sqrt{s_F} = 22$ GeV, respectively. For $\sqrt{s} \leq 1.8$ TeV, where there are Reggeon contributions, we use the global fit expression [8], while for $\sqrt{s} \geq 1.8$ TeV, where Reggeon contributions are negligible, we employ the Froissart-Martin formula [9, 10, 11]. The two expressions are smoothly matched at $\sqrt{s} \approx 1.8$ TeV.

The $\sigma_{\rm el}$ for $\sqrt{s} \leq 1.8$ TeV is obtained from the global fit [8], while for $1.8 < \sqrt{s} \leq 50$ TeV we use an extrapolation of the global-fit ratio of $\sigma_{\rm el}/\sigma_{\rm tot}$, which is slowly varying with $\sqrt{s}$, multiplied by σ_{tot}. The total non-diffractive cross section is given by $\sigma_{\rm ND} = (\sigma_{\rm tot} - \sigma_{\rm el}) - (2\sigma_{\rm SD} + \sigma_{\rm DD} + \sigma_{\rm CD})$.

3. Updated results and predictions of cross sections

Updated results on integrated SD and DD cross sections for $\xi < 0.05$ are compared in Fig. 1 with MBR predictions based on $I\!P$-trajectory parameters $\varepsilon = 0.08$ and $\alpha' = 0.25$ GeV^{-2} [12]. A downward scaling adjustment implemented on the DD cross section in MBR improves the agreement with the 7 TeV DD data while preserving compatibility with the CDF DD results within the CDF uncertainties. The adjusted MBR predictions are in good agreement with all the measurements of the SD and DD cross sections in the region of $\sqrt{s} \geq 100$ GeV (see details in [12]).

Figure 2 shows the $\xi_X (\approx M_X^2/s)$ dependence of the SD cross section for the PYTHIA8 4C, PYTHIA6 Z2*, PHOJET [14, 15], QGSJET-II-03 [16], QGSJET-II-04 [16], and EPOS [17] simulations. The ξ_X distributions are compared to the nominal PYTHIA8 MBR simulation predictions for two regions of ξ_X, $-5.5 < \log_{10}\xi_X < -2.5$ (yellow) and $\xi_X < 0.05$ (khaki). The PYTHIA8 MBR predictions with α' and ε changed from their nominal values to $\alpha' = 0.125$ GeV^{-2}, $\varepsilon = 0.104$, and

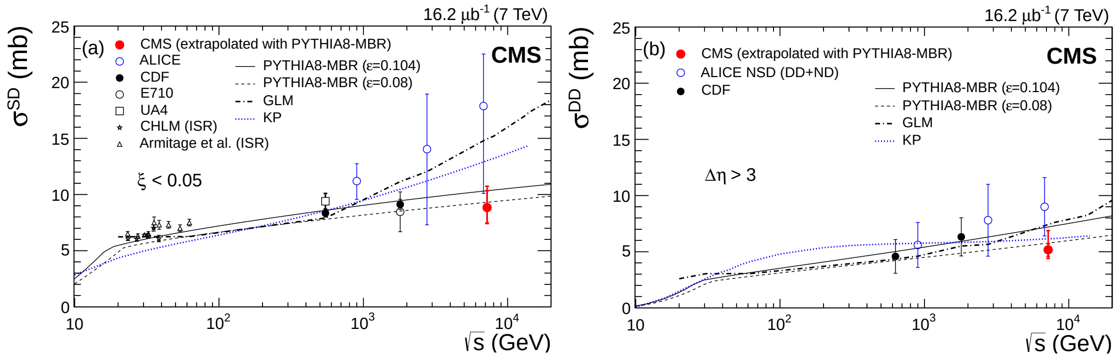

Figure 1: Measured SD (left) and DD (right) cross sections for $\xi < 0.05$ compared with theoretical predictions. The model embedded in PYTHIA8-MBR provides a good description of all data.

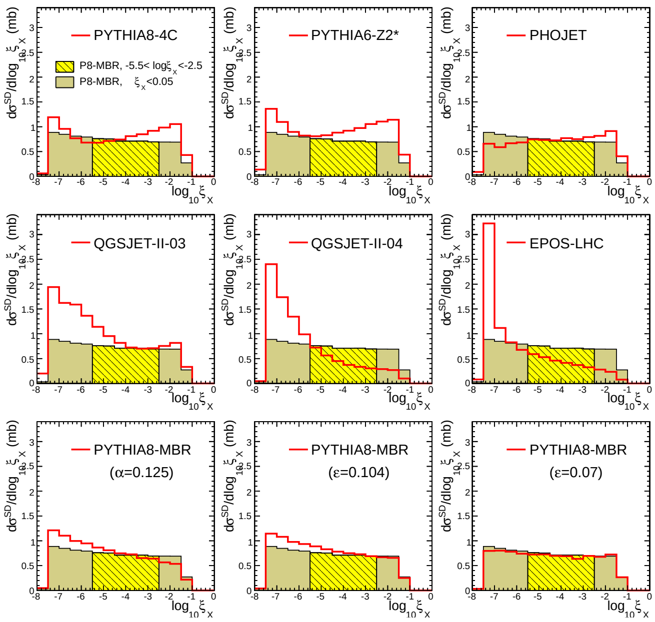

Figure 2: Generator-level SD cross sections as a function of $\xi_X(\equiv M_X^2/s)$ for PYTHIA8-4C, PYTHIA6-Z2*, PHOJET, QGSJET-II-03, QGSJET-II-04, EPOS, and PYTHIA8-MBR, with the parameters of the Pomeron trajectory changed from the nominal values ($\alpha' = 0.25$ GeV^{-2}, $\varepsilon = 0.08$) to $\alpha' = 0.125$ GeV^{-2} , $\varepsilon = 0.104$, and $\varepsilon = 0.07$ (changing one parameter at a time). The nominal PYTHIA8-MBR simulation is presented in each plot for the regions of ξ_X, $-5.5 < \log_{10}\xi_X < -2.5$ (dashed yellow) and $\xi_X < 0.05$ (solid khaki), used to extrapolate the measured SD cross section (from the dashed/yellow to the solid/khaki regions).

$\varepsilon = 0.07$ (one parameter changed at a time) are also included, to provide a scale for their effect on the cross sections. The changes in the values of α' and ε are chosen to cover a wide range of model predictions. The PYTHIA8 4C, PYTHIA6 Z2*, and PHOJET simulations do not predict correctly the ξ_X dependence of the SD cross section, while QGSJET-II-04 and EPOS underestimate it in the region of the CMS measurement. The RENORM model describes all aspects of the measurements in both shape and normalization and is therefore used for the extrapolation of the measured cross sections to the regions where there is no detector coverage.

In DIFFRACTION 2014, the ATLAS Collaboration updated the $\sqrt{7}$ TeV results on $\sigma_{\rm tot}$, $\sigma_{\rm el}$, and $\sigma_{\rm inel}$ to $\sigma_{\rm tot} = 95.35 \pm 1.36$ mb, $\sigma_{\rm el} = 24.00 \pm 0.60$ mb, and $\sigma_{\rm inel} = 71.34 \pm = 0.90$ mb [18]. These results are in agreement within the errors with the 2013 $\sqrt{7}$ TeV TOTEM results of (a) $\sigma_{\rm tot} = 98.6 \pm 2.2$ mb, $\sigma_{\rm el} = 25.4 \pm 1.1$ mb and $\sigma_{\rm inel} \equiv \sigma_{\rm tot} - \sigma_{\rm el} = 73.2 \pm = 1.6$ mb (Roman pots), (b) $\sigma_{\rm tot} = 98.0 \pm 2.5$ mb and $\sigma_{\rm el} = 25.1 \pm 1.1$ mb (luminosity independent method), and (c) $\sigma_{\rm inel} = 73.7 \pm = 3.4$ mb ($\beta* = 90$ m) [19]. The mean values of the default RENORM /MBR predictions at $\sqrt{s} = 7$ TeV, $\sigma_{\rm tot} = 98.3 \pm 8.1$ mb, $\sigma_{\rm el} = 27.2 \pm 1.6$ mb, and $\sigma_{\rm inel} = 71.1 \pm 4.8$ mb [6] agree with the ATLAS and TOTEM results. The errors in the MBR cross sections can be reduced by about a factor of four by determining s_O more precisely from the measurements on exclusive $\pi^{\pm}$ production with the Axial Field Spectrometer (AFS) at the CERN Intersecting Storage Rings (see [20], Sec. 4.2).

The TOTEM 2013 measurement at $\sqrt{s} = 8$ TeV, using the luminosity independent method, yielded $\sigma_{\rm tot} = 101.7 \pm 2.9$ mb, $\sigma_{\rm el} = 27.1 \pm 1.4$ mb, and $\sigma_{\rm inel} = 74.7 \pm 1.7$ mb [21]. The default RENORM /MBR predictions for $\sqrt{s} = 8$ TeV are $\sigma_{\rm tot} = 100 \pm 8.3$ mb, $\sigma_{\rm el} = 28.1 \pm 1.8$ mb, and $\sigma_{\rm inel} = 72.3 \pm 4.9$ mb. Good agreement on the mean values between the data and MC predictions is observed. Again, as in the 7 TeV case, a reduction of the MBR uncertainties by a factor of ~ 4 can be accomplished by using AFS results without affecting the mean values of the cross sections.

The default cross-section predictions of RENORM /MBR at 13 TeV for $\sigma_{\rm tot}$, $\sigma_{\rm el}$, and $\sigma_{\rm inel}$ are 108, 32, and 77 mb, respectively, with uncertainties of $\sim 11\%$ mainly due to that in s_0. Similarly as for the 7 and 8 TeV predictions, the uncertainties can be reduced by a factor of ~ 4 using AFS data to better determine the uncertainty in s_o.

4. Conclusion

We summarize the pre-LHC predictions of the total, elastic, total-inelastic, and diffractive components of the proton-proton cross section at high energies, which are based on the special parton-model approach to diffraction RENORM / MBR, updating the summary presented in DIS-2014 [1]. We compare measurements of the SD and DD cross sections at the Tevatron and the LHC with the RENORM / MBR predictions and find excellent agreement. Using RENORM / MBR as a reference model, we compare its predictions for SD with those of various Monte Carlo models: PYTHIA8-4C, PYTHIA6-Z2*, PHOJET, QGSJET-II-03, and QGSJET-II-04, EPOS. We find that the RENORM/MBR model describes well all aspects of the data and is used to extrapolate to the total SD cross section.

The RENORM/MBR model also describes well the measured total, elasic, and total inelastic cross sections at the Tevatron at 0.63 and 1.8 TeV and at the LHC at 7 and 8 TeV.

Based on its success in describing data at the Tevatron and LHC, we use RENORM/MBR to extrapolate cross sections to 13 TeV at the LHC.

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