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Predictions of Diffractive and Total Cross Sections at LHC Confirmed by Measurements

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Predictions of diffractive proton-proton cross sections at LHC, and of the total and total-inelastic proton-proton cross sections based on the RENORM unitarization model, also referred to as the MBR (minimum-bias-Rockefeller) model implemented in PYTHIA8-MBR, are confirmed by recent LHC measurements. Several other available diffraction models are discussed, highlighting differences among them and PYTHIA8-MBR regarding rapidity-gap and final-state distributions.

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1. Introduction

This is an update of the paper on soft cross-section predictions at the LHC contributed to the DIS-2013 proceedings [1], confirming that the RENORM / NBR model describes well all diffractive and total cross-section results with the same set of parameters, determined from pre-LHC experimental measurements. While focusing on a comparison of predictions among various diffractive and total cross section models, for the convenience of the reader and completeness we include verbatim a large portion of the 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 physics models, and that it is not possible to reliably predict all such processes, or even all aspects of a given process, using a single model [2]. In the CDF studies of diffraction at the Tevatron, all processes are well modeled by the MBR (Minimum Bias Rockefeller) MC simulation, which is a stand-alone simulation based on a unitarized Regge-theory model, RENORM [3], employing 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 PYTHIA8 since version PYTHIA8.165 [5], to be referred hereforth as PYTHIA8-MBR. In this paper, we briefly review the cross sections [6] implemented in this option of PYTHIA8 and compare them with LHC measurements.

The PYTHIA8-MBR option of PYTHIA8 includes a full simulation of the hadronization of the implemented diffractive processes: single, double, and central diffraction. In the original MBR simulation used in 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 produced in the final state, with multiplicities obeying a statistical model of a modified Gamma distribution that provided good fits to experimental data [7]. This model could not be used to predict specific-particle final states.

In the PYTHIA8-MBR implementation, hadronization is performed by PYTHIA8 tuned to reproduce final-state particle distributions in agreement with MBR's, with the hadronization implemented in the PYTHIA8 framework. Thus, all final-state particles are now automatically produced, greatly enhancing the horizon of applicability of this simulation.

2. Cross sections

The following diffractive processes are considered in PYTHIA8-MBR:

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

The RENORM predictions are expressed as unitarized Regge-theory formulas, in which the unitarization is achieved by a renormalization scheme where the Pomeron ($I\!P$) flux is interpreted as the probability for forming a diffractive (non-exponentially suppressed) rapidity gap and thereby its integral over all phase space saturates when it reaches unity. Differential cross sections are expressed in terms of the $I\!P$-trajectory, $\alpha(t) = 1+\varepsilon+\alpha' t = 1.104+0.25\ (\mathrm{GeV}^{-2})\cdot t$, the $I\!P$-p coupling, $\beta(t)$, and the ratio of the triple-$I\!P$ to the $I\!P$-p couplings, $\kappa \equiv g(t)/\beta(0)$. 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 Pomerons in the DPE event, $\Delta y = \Delta y_1 + \Delta y_2$ is the total rapidity gap (sum of two gaps) in the event, and y_c is the center in η of the centrally-produced hadronic system.

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 energy and (Pomeron flux) saturation scales, 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 $\sqrt{s} \geq 1.8$ TeV.

The elastic cross section is obtained from the global fit [8] for $\sqrt{s} \leq 1.8$ TeV, 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 then calculated as $\sigma_{\rm ND} = (\sigma_{\rm tot} - \sigma_{\rm el}) - (2\sigma_{\rm SD} + \sigma_{\rm DD} + \sigma_{\rm CD})$.

3. Results

In this section, we present as examples of the predictive power of RENORM some results reported by the TOTEM, CMS, and ALICE collaborations for pp collisions at $\sqrt{s} = 7$ TeV, which can be directly compared with RENORM formulas without using the PYTHIA8-MBR simulation.

Figure 1 (left) shows a comparison of the TOTEM total, elastic, and total-inelastic cross sections, along with results from other experiments, fitted by the COMPETE collaboration [12].The RENORM predictions, displayed as filled (green) squares, are in excellent agreement with the TOTEM results. Similarly, in Fig. 1 (right), good agreement is observed between inelastic cross-section measurements at $\sqrt{s} = 7$ TeV and the corresponding PYTHIA8-MBR predictions [14].

Another example of the predictive power of RENORM is shown in Fig. 2, which displays the total SD (left) and DD (right) cross sections for $\xi < 0.05$, after extrapolation into the low mass region from the measured CMS cross sections at higher mass regions(see [15]) using RENORM.

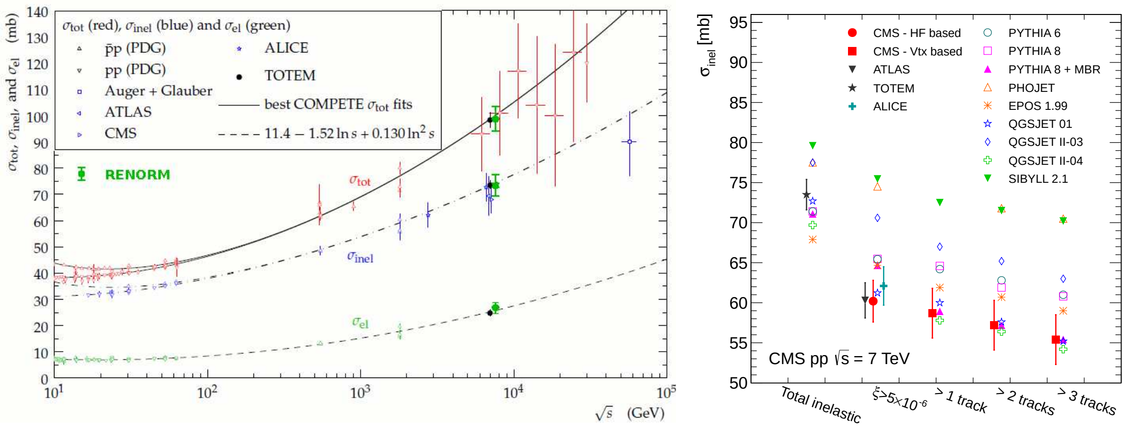
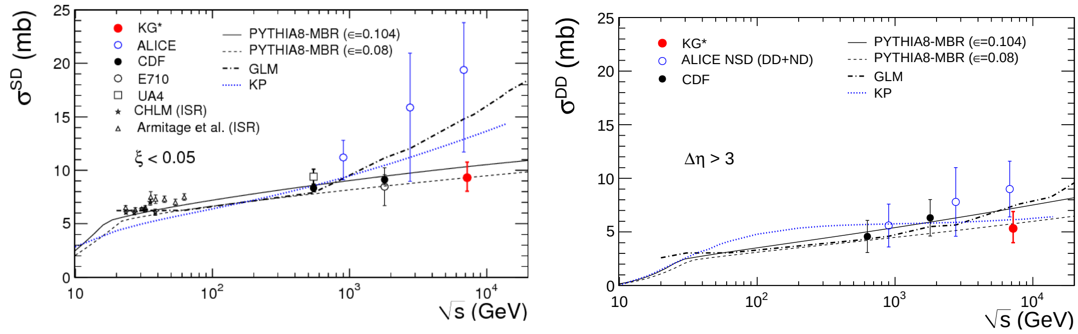


Figure 1: (left) TOTEM measurements of the total, total-inelastic, and elastic pp cross sections at $\sqrt{s} = 7$ TeV shown with best COMPETE fits [12] and RENORM predictions; (right) inelastic cross-section measurements at $\sqrt{s}$ =7 TeV are in good agreement with RENORM / PYTHIA8-MBR predictions [14]).



KG*: this "data" point was obtained after extrapolation into the unmeasured low mass region(s) from the measured CMS cross sections [15] using the MBR model.

Figure 2: 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 3 shows the $\xi_X = M_X^2/s$ dependence of the SD cross section for the PYTHIA8-4C, PYTHIA6-D6T, PHOJET [16, 17], QGSJET-II-03(LHC) [18], QGSJET-II-04(LHC) [18], and EPOS-LHC [19] simulations, compared to the nominal PYTHIA8-MBR simulation, 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 values of α' and ε changed to $\alpha' = 0.125$ GeV^{-2}, $\varepsilon = 0.104$, and $\varepsilon = 0.07$ (one parameter changed at a time) are also included in order to provide a scale for their effect on the cross sections.

Note that PYTHIA8-4C, PYTHIA6-D6T, and PHOJET do not predict correctly the ξ_X dependence of the SD cross section, while QGSJET-II-04(LHC) and EPOS-LHC underestimate it in the region of the CMS measurement. Therefore, the RENORM / NBR model, which describes well all aspects of the measurements presented above in both shape and normalization, is used for the extrapolation of the measured cross sections to the regions where there is no detector coverage.

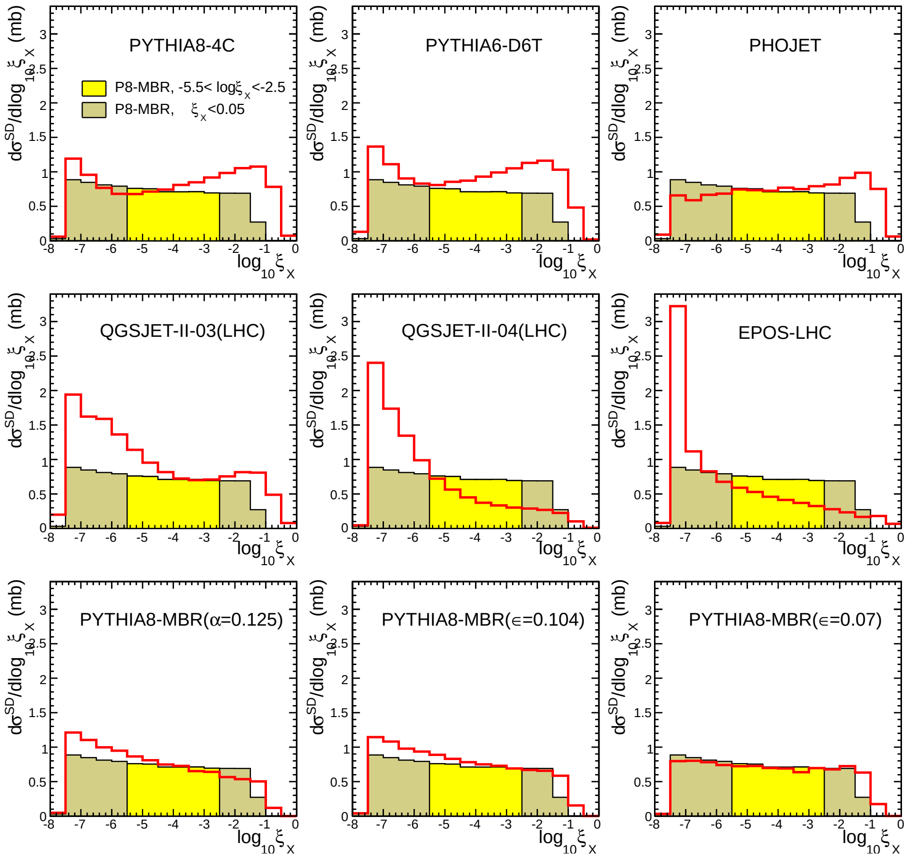


Figure 3: The generator-level SD cross section as a function of $\xi_X = M_X^2/s$, shown for PYTHIA8-4C, PYTHIA6-D6T, PHOJET, QGSJET-II-03(LHC), QGSJET-II-04(LHC), EPOS-LHC, and PYTHIA8-MBR with the parameters of Pomeron trajectory changed from the nominal values ($\alpha' = 0.25$ GeV^{-2}, $\varepsilon = 0.08$) to $\alpha' = 0.125$ GeV^{-2}, $\varepsilon = 0.104$, and $\varepsilon = 0.07$ (one parameter changed at a time). The nominal PYTHIA8-MBR simulation is presented in each plot for the two regions of ξ_X, $-5.5 < \log_{10}\xi_X < -2.5$ (yellow) and $\xi_X < 0.05$ (khaki), used to extrapolate the measured SD cross section (from yellow to khaki).

4. Summary

We summarize our pre-LHC predictions for the total, elastic, total-inelastic, and diffractive components of the proton-proton cross section at high energies, based on our special parton-model approach to diffraction, RENORM / NBR, as discussed in DIS-2013 [1], and present a comparison of the single diffractive differential cross-section predictions among various Monte Carlo models: PYTHIA8-4C, PYTHIA6-D6T, PHOJET, QGSJET-II-03(LHC), QGSJET-II-04(LHC), EPOS-LHC, and PYTHIA8-MBR. We find that the RENORM / NBR model describes well all aspects of the data.

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