

# Precision RENORM Tensor-Pomeron Cross Sections at LHC

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**Abstract.** Precision predictions of soft and hard diffraction, elastic scattering, and total proton-proton cross sections, based on a tensor-Pomeron implementation of the RENORM model, are compared to the latest experimental results at the LHC and cosmic-ray experiments, and extended to the planned SuperCollider energies.

## INTRODUCTION

In DIS-2015 (Spring 2015) we summarized [1] the pre-LHC predictions of the total, elastic and total-inelastic, as well as the single- and double-diffractive components of the proton-proton cross section at high energies, based on the RENORM/MBR model [2]. We compared the measurements of the SD and DD cross sections from the Tevatron and the LHC with the predictions of the model and found excellent agreement. Good agreement was also observed between the model predictions and the total, elastic, and total inelastic cross sections obtained at the Tevatron at  $\sqrt{s} = 1.8$  TeV, and at the LHC at  $\sqrt{s} = 7$  and 8 TeV.

The success of the predictions of the RENORM/MBR model for all the above cross sections at the Tevatron and LHC up to  $\sqrt{s} = 8$  TeV prompted an extrapolation to  $\sqrt{s} = 13$  TeV, the nominal foreseen colliding-beam energy at the LHC for Summer 2015. For  $\sigma_{\text{tot}}$ ,  $\sigma_{\text{el}}$  and  $\sigma_{\text{inel}}$ , we predicted 108 mb, 32 mb, and 77 mb, respectively, with uncertainties of  $\sim 11\%$ , mainly due to the uncertainty in the energy-squared scale parameter  $s_0$  of the model.

In Summer 2015 we updated the value of  $s_0$  to a more precise one based on a tensor glueball interpretation of the Axial Field Spectrometer (AFS) exclusive charged di-pion data [3, 4, 5]. This change in RENORM/MBR decreases the uncertainties in the predictions of the total, elastic, and total-inelastic cross sections to less than 2% from Tevatron to LHC energies, with little or no effect on the mean values. The predictions were compared with measurements by ATLAS at  $\sqrt{s} = 7$  TeV and by TOTEM at  $\sqrt{s} = 7$  and 8 TeV at Moriond QCD in March 2016 [6] and found to be in good agreement.

This is an update of the Moriond-QCD paper [6] that includes presented verbatim certain sections and describes new measurements of the total inelastic cross section at  $\sqrt{s} = 13$  TeV by ATLAS and CMS at DIS-2016 (April 2016) by Trzebinski (ATLAS) and Van Haevermaet [7] and in the summary talk by Sykora at ICHEP16 [8]. There are disagreements among the measurements themselves and the RENORM predictions at the  $\sim 2.5$  sigma level. In the present paper, we discuss these findings in an attempt to understand the origin of the observed discrepancies.

## RENORM CROSS SECTIONS

The total, elastic, and total-inelastic cross sections in the RENORM/MBR model depend on the value of the energy-squared scale parameter,  $s_0$ . Quoting verbatim from Ref. [1],

“The total cross section ( $\sigma_{\text{tot}}$ ) is expressed as [9]

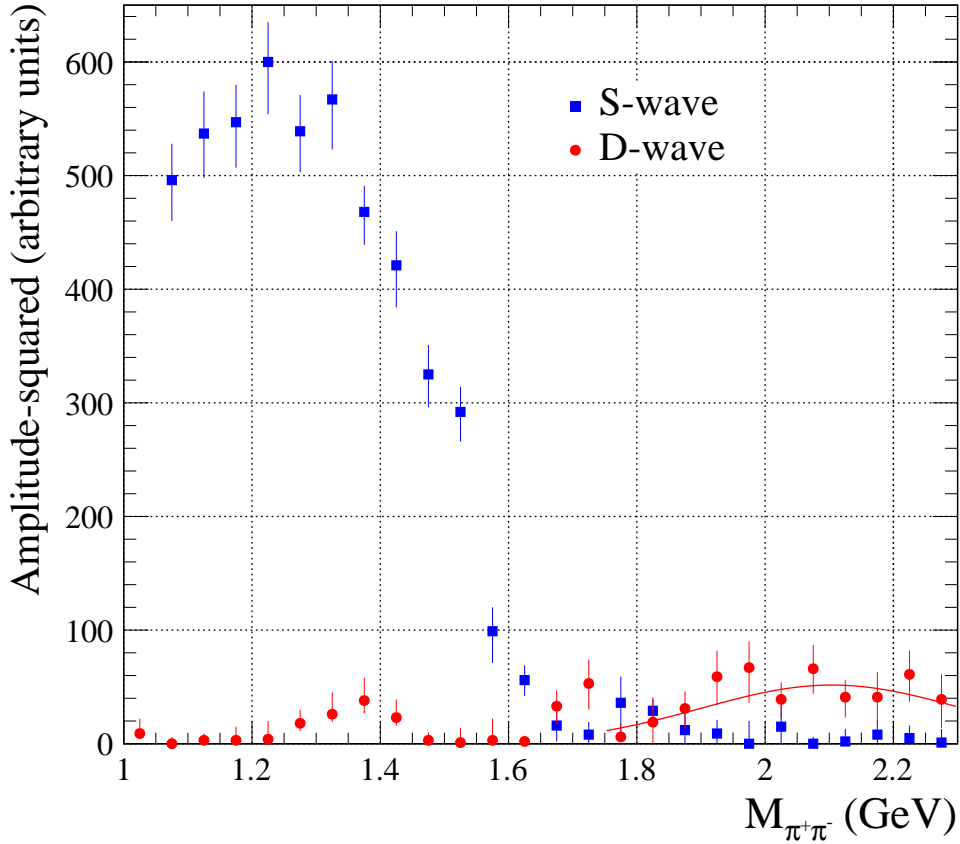
$$\sigma_{\text{tot}}^{p^+p} = 16.79s^{0.104} + 60.81s^{-0.32} \mp 31.68s^{-0.54} \quad \text{for } \sqrt{s} \leq 1.8 \text{ tev}, \quad (1)$$

$$\sigma_{\text{tot}}^{p^+p} = \sigma_{\text{tot}}^{\text{cdf}} + \frac{\pi}{s_0} \left[ \left( \ln \frac{s}{s_f} \right)^2 - \left( \ln \frac{s^{\text{cdf}}}{s_f} \right)^2 \right] \quad \text{for } \sqrt{s} \geq 1.8 \text{ tev}, \quad (2)$$

where  $s_0$  and  $s_f$  are the energy and (Pomeron flux) saturation scales,  $s_0 = 3.7 \pm 1.5 \text{ GeV}^2$  and  $\sqrt{s_f} = 22 \text{ GeV}$ , respectively. For  $\sqrt{s} \leq 1.8 \text{ TeV}$ , where there are Reggeon contributions, we use the global fit expression [10], while for  $\sqrt{s} \geq 1.8 \text{ TeV}$ , where Reggeon contributions are negligible, we employ the Froissart-Martin formula [11, 12, 13]. The two expressions are smoothly matched at  $\sqrt{s} \approx 1.8 \text{ TeV}$ . The  $\sigma_{\text{el}}$  for  $\sqrt{s} \leq 1.8 \text{ TeV}$  is obtained from the global fit [10], while for  $1.8 < \sqrt{s} \leq 50 \text{ TeV}$  we use an extrapolation of the global-fit ratio of  $\sigma_{\text{el}}/\sigma_{\text{tot}}$ , which is slowly varying with  $\sqrt{s}$ , multiplied by  $\sigma_{\text{tot}}$ . The total non-diffractive cross section is given by  $\sigma_{\text{nd}} = (\sigma_{\text{tot}} - \sigma_{\text{el}}) - (2\sigma_{\text{sd}} + \sigma_{\text{dd}} + \sigma_{\text{cd}})$ .

### Tensor-Pomeron predictions

The partial wave analysis of the AFS exclusive  $\pi^\pm$  data [5], performed in terms of a fit with a model with S-wave and D-wave amplitudes as a function of the di-pion mass up to 2.3 GeV, leads to the results presented in Figure 1.



**FIGURE 1.** Extraction of tensor-Pomeron parameters from a Gaussian fit to the exclusive  $\pi^\pm$  Axial Field Spectrometer data: mean mass value  $\langle m_{\pi^+\pi^-} \rangle = 2.10 \text{ GeV}$  and width  $\delta = \pm 0.68 \text{ GeV}$ .

The D-wave dominates at masses above  $\sim 2 \text{ GeV}$ , and according to the presumed interpretation in Ref. [5] it corresponds to a spin-2 tensor glueball of mass  $M_{\text{tgb}}$ . A Gaussian fit to this enhancement yields  $M_{\text{tgb}} = 2.10 \pm 0.68 \text{ GeV}$ . Identifying  $M_{\text{tgb}}^2$  with the saturated glueball-like enhancement of the MBR-model parameter  $s_0$  (see Equation 2) yields  $s_0 = 4.42 \pm 0.34 \text{ GeV}^2$ . Using this value in Equation 2, we predicted for  $\sigma_{\text{tot}}$ ,  $\sigma_{\text{el}}$ , and  $\sigma_{\text{inel}}$  at 13 TeV cross sections of  $103.7 \pm 1.9 \text{ mb}$ ,  $30.2 \pm 0.8 \text{ mb}$ , and  $73.5 \pm 1.3 \text{ mb}$ , respectively. The ATLAS- and TOTEM-measured cross sections at  $\sqrt{s} = 7$  and  $8 \text{ TeV}$  [14]–2015, [15]–2013, and [16]–2013 are shown in Table 1 along with the MBR predictions. The measurements are in good agreement with the predictions. Also shown is a measurement of the total inelastic cross section by ATLAS at  $\sqrt{s} = 13 \text{ TeV}$  [17] (Aspen Winter Conference 2016),  $\sigma_{\text{inel}} = 73.1 \pm 0.9 \text{ (exp)} \pm 3.8 \text{ (extr)} \pm 6.6 \text{ (lumi)} \text{ mb}$ , which, apart from the extrapolation and luminosity uncertainties, is in excellent agreement with MBR.

It should be emphasized that the tensor-Pomeron hypothesis predicts directly only the total cross section. As discussed above, the elastic cross section for  $\sqrt{s} \leq 1.8$  TeV is obtained from the global fit [10], while for  $1.8 < \sqrt{s} \leq 13$  TeV we use an extrapolation of the global-fit ratio of  $\sigma_{el}/\sigma_{tot}$ , which is slowly varying with  $\sqrt{s}$ , multiplied by  $\sigma_{tot}$ .

The total inelastic cross section is calculated as the difference between the total and the elastic cross sections. Thus, a measured lower  $\sigma_{el}$  would result in a higher  $\sigma_{inel}$ . Table 1 displays MBR-predicted versus measured cross sections. The MBR  $\sigma_{el}$  is larger than the TOTEM and CMS measurements by  $\sim 2.5$  mb at both  $\sqrt{s}=7$  and 8 TeV, which would imply a higher MBR prediction for  $\sigma_{inel}$  at 13 TeV by  $\sim 2.5$  mb as well. At Moriond 2016, we underscored that this interplay between  $\sigma_{el}$  and  $\sigma_{inel}$  should be carefully taken into consideration as further results with reduced luminosity and extrapolation uncertainties of both  $\sigma_{el}$  and  $\sigma_{tot}$  at  $\sqrt{s} = 8$  TeV and  $\sqrt{s} = 13$  TeV became available.

New results were presented at ICHEP16 by ATLAS (ALFA\_fit) and CMS [8] (see reference ‘‘h’’ in Table 1). The new ATLAS  $\sigma_{tot}$  at  $\sqrt{s} = 8$  TeV agrees with that of TOTEM, but the  $\sigma_{el}$  is  $\sim 2.5$  mb lower. At  $\sqrt{s} = 13$  TeV, ATLAS measures a  $\sigma_{inel}$  larger than the previous value by  $\sim 6 \pm 3$  mb, while the CMS  $\sigma_{inel}$  is unchanged. The uncertainty in both experiments is dominated by the extrapolation to the unmeasured low-mass region.

Focusing on  $\sqrt{s} = 13$  TeV, there is significant disagreement between the new ATLAS and CMS  $\sigma_{inel}$ . Lowering  $\sigma_{el}^{MBR}$  by 2.5 mb, which is within its systematic uncertainty, would increase  $\sigma_{inel}^{MBR}$  to  $75.5 \pm 1.3$  mb, placing it comfortably between ATLAS and CMS as we await for the two experimental results to coalesce to the same value.

**TABLE 1.** Measured total, elastic, and total inelastic cross sections at 7, 8, and 13 TeV by ATLAS, TOTEM, and CMS at the LHC compared to RENORM/MBR predictions. Data uncertainties include systematics combined in quadrature unless explicitly stated.

$\sqrt{s}$ (TeV)	Input source	Reference*	$\sigma_{tot}$ (mb)	$\sigma_{el}$ (mb)	$\sigma_{inel}$ (mb)
7	MBR	a	$95.4 \pm 1.2$	$26.4 \pm 0.3$	$69.0 \pm 1.0$
	ATLAS	b	$95.35 \pm 1.36$	$24.00 \pm 0.60$	$71.34 \pm 0.90$
	TOTEM	c	$101.7 \pm 1.36$	$27.1 \pm 1.4$	$74.7 \pm 1.7$
	TOTEM_Lum_ind	d	$98.0 \pm 2.5$	$24.00 \pm 0.60$	$72.9 \pm 1.5$
8	MBR	a	$97.1 \pm 1.4$	$27.2 \pm 0.4$	$69.9 \pm 1.0$
	TOTEM	e	$101.7 \pm 2.9$	$27.1 \pm 1.4$	$74.8 \pm 1.7$
	ATLAS_ALFA_fit	(h) ICHEP16	$96.1 \pm 0.9$	$24.3 \pm 0.4$	xxx
13	MBR	a	$103.7 \pm 1.9$	$30.2 \pm 0.8$	$73.5 \pm 1.3$
	ATLAS	f&g	xxx	xxx	$73.1 \pm 0.9(\text{exp}) \pm 3.8(\text{extr}) \pm 6.6(\text{lumi})$
	ATLAS_ALFA_fit	(h) ICHEP16	xxx	xxx	$79.3 \pm 0.6(\text{exp}) \pm 2.5(\text{extr}) \pm 1.3(\text{lumi})$
	CMS	(h) ICHEP16	xxx	xxx	$71.3 \pm 0.6(\text{exp}) \pm 2.7(\text{extr}) \pm 0.1(\text{lumi})$

\*Reference:

(a) <http://arxiv.org/abs/1205.1446>

(b) <http://arxiv.org/abs/1408.5778>

(c) <http://arxiv.org/abs/1204.5689>

(d) <http://iopscience.iop.org/article/10.1209/0295-5075/101/21004>

(e) <http://dx.doi.org/10.1103/PhysRevLett.111.012001>

(f) M. Trzebinski (ATLAS), DIS-2016 [7]-(a)

(g) H. Van Haevermaet (CMS), DIS-2016 [7]-(b)

(h) T. Sykora, *Cross sections summary*, ICHEP16 [8]

## SUMMARY AND CONCLUSIONS

We present the predictions of the total, elastic scattering, and total-inelastic proton-proton cross sections at  $\sqrt{s} = 7, 8,$  and 13 TeV of the MBR model, based on a Regge-theory inspired tensor-Pomeron implementation of the RENORM model for hadronic diffraction, and compare them with experimental results by the TOTEM, ATLAS, and CMS Collaborations. All measured cross sections are in good agreement within the experimental uncertainties of the data and the theoretical uncertainties of the model, reaching down to the  $\sim 1\%$  level.

However, we emphasize that the tensor-Pomeron prediction applies only to the total cross section, while the predicted  $\sigma_{el}$  is calculated by an extrapolation of the global-fit ratio of  $\sigma_{el}/\sigma_{tot}$  multiplied by the tensor-Pomeron  $\sigma_{tot}$ , and therefore carries the larger uncertainties of this ratio. Future measurements of both  $\sigma_{el}$  and  $\sigma_{tot}$  at  $\sqrt{s} = 8$  TeV and  $\sqrt{s} = 13$  TeV with reduced luminosity and extrapolation uncertainties are needed to clarify the experimental status.

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