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The discovery of the odderon by the D0 and TOTEM collaborations

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We describe the recent discovery of the odderon by the D0 and TOTEM collaborations by comparing the pp and $p\bar{p}$ elastic $d\sigma/dt$ cross sections.

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PoS(LHCP2022)118

1. Introduction to the odderon

Elastic scattering was measured at high energies above a center-of-mass $\sqrt{s}$ of 1 TeV both in pp ($pp \to pp$) at the LHC and in $p\bar{p}$ ($p\bar{p} \to p\bar{p}$) interactions at the Tevatron following previous measurements that were performed at a lower center-of-mass energy $\sqrt{s}$. The signature is the existence of intact protons or proton-antiproton scattered at small angles that can be detected and measured in dedicated detectors close to the beam line called roman pots. The fact that the proton and anti-proton are intact after interaction indicates that a colorless exchange appeared. In the perturbative QCD language, this can be an even number of gluons (the pomeron) or an odd one (the odderon). The odderon is defined as a singularity in the complex plane, located at $J = 1$ when $t = 0$ and which contributes to the odd crossing amplitude [1, 2]. The colorless C-odd 3-gluon state, the odderon, predicts differences in elastic $d\sigma/dt$ for pp and $p\bar{p}$ interactions since it corresponds to different amplitudes and interferences. The D0 and TOTEM collaborations performed a detailed analysis of the potential differences between the Tevatron $p\bar{p}$ and LHC pp data with the difficulty that the data were taken at different $\sqrt{s}$. It is thus needed to extrapolate the LHC measurements at a $\sqrt{s}$ of 2.76, 7, 8 and 13 TeV down to the Tevatron energy of 1.96 TeV.

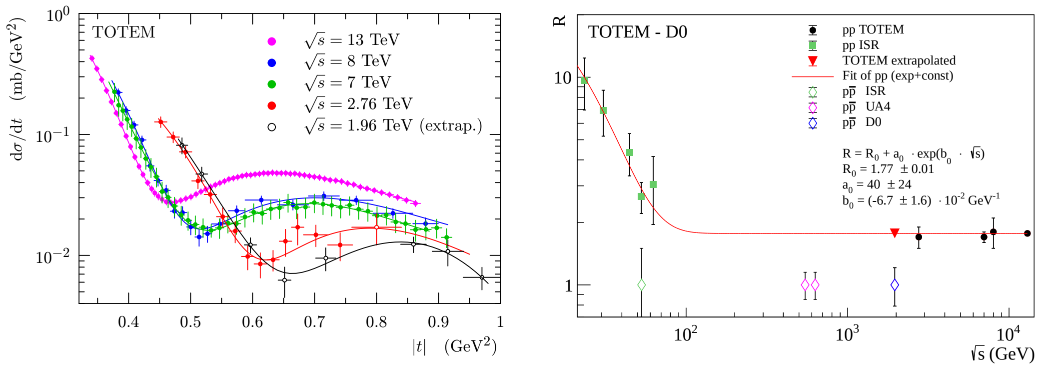

Figure 1: Left: TOTEM elastic pp $d\sigma/dt$ data at 2.76, 7, 8 and 13 TeV, and extrapolated to the Tevatron center-of-mass energy of 1.96 TeV. Right: bump over dip ratio as a function of $\sqrt{s}$ for pp and $p\bar{p}$ colliders.

2. Extrapolation of TOTEM data to the Tevatron $\sqrt{s}$ of 1.96 TeV

The advantage of the LHC machine is that it can run at different $\sqrt{s}$ and different values of β^* that allow to cover a large domain in $|t|$ (the momentum transfer square at the proton vertex) for the elastic pp $d\sigma/dt$ cross section measurement. The TOTEM collaboration measured elastic scattering at $\sqrt{s}$ of 2.76, 7, 8 and 13 TeV with high precision [3, 4, 5, 6] and the data are shown on Fig. 1, left. Data show always the same features, namely a fast exponentially decreasing cross section at low $|t|$, the existence of a maximum (the “bump") and a minimum (the “dip"), and a decreasing cross section at higher $|t|$. On the contrary, the D0 elastic $p\bar{p}$ $d\sigma/dt$ data [7] do not show the same features, a plateau appearing at medium $|t|$ but not the presence of a bump nor a dip.

The first observable that shows the differences between pp and $p\bar{p}$ elastic interactions is the ratio of the elastic $d\sigma/dt$ cross sections at the bump and at the dip as shown in Fig. 1, right. The bump over dip ratio in pp elastic collisions decreases as a function of $\sqrt{s}$ up to $\sim$ 100 GeV [8] and is flat above. The D0 $p\bar{p}$ data show a ratio of 1.00±0.21 given the fact that no bump nor dip is observed in $p\bar{p}$ data within uncertainties that leads to a more than 3σ difference between pp and $p\bar{p}$ elastic data [9, 10] (assuming a flat behavior above $\sqrt{s} = 100 GeV$).

In order to extrapolate the D0 pp elastic $d\sigma/dt$ cross section measurements down to the Tevatron $\sqrt{s}$ of 1.96 TeV, we define eight reference points including the dip and the bump that represent the characteristic behavior of elastic pp $d\sigma/dt$ data as shown in Fig. 2, left. Fig. 2, middle and right, show how the values of $|t|$ and $d\sigma/dt$ of the reference points vary as a function of $\sqrt{s}$ allowing to predict their values at 1.96 TeV. It is remarkable that that the same $\sqrt{s}$ dependence is found for all reference points, namely $|t| = a\log(\sqrt{s}[\text{TeV}]) + b$ and $(d\sigma/dt) = c\sqrt{s}$ [TeV] $+ d$. Using these fits, we are able to predict the references points in $|t|$ and $d\sigma/dt$ for pp elastic scattering, extrapolating the TOTEM measurements. It is worth noting that having data at 2.76 TeV is crucial since the extrapolation is not that large between 2.76 TeV and 1.96 TeV, the Tevatron $\sqrt{s}$. It would be unfortunately impossible to perform the pp elastic $d\sigma/dt$ measurement at the LHC (and thus avoiding the extrapolation) since there is no acceptance in the bump and dip region with the present location of the TOTEM roman pots.

The fact that the $\sqrt{s}$ dependence is found to be the same for all reference points in the vicinity of the bump and dip region shows that the curves translate between each other in the $d\sigma/dt$ versus $|t|$ plane and this is the sign of the existence of a new scaling in elastic data at high energies. We found indeed that the elastic data fall onto a universal curve when they are mapped to the scaling variables $\text{d}\sigma/\text{d}t \times (s)^{-0.305}$ versus $s^{0.065}(t)^{0.72}$. In the impact parameter space, this could be interpreted a sign of having a large gluon density of inside colorless gluonic compounds that reach the black disc limit at small impact parameter [11].

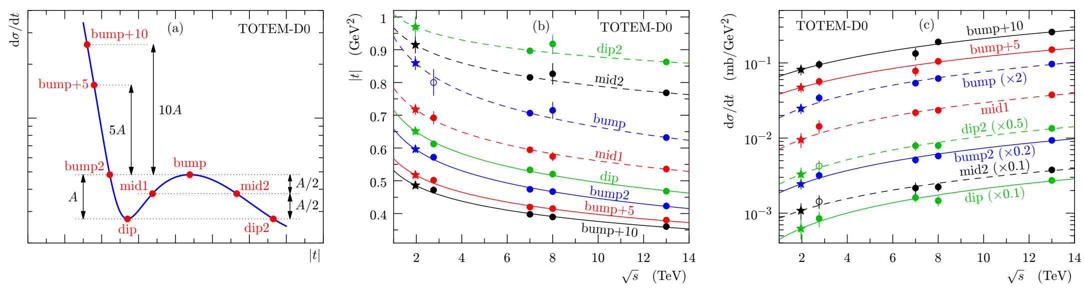

Figure 2: (a) Schematic definition of the characteristic points in the TOTEM differential cross section data. (b) and (c) Values of characteristic points in $|t|$ and $d\sigma/dt$ from TOTEM measurements at 2.76, 7, 8, and 13 TeV (circles) as a function of $\sqrt{s}$ extrapolated to Tevatron center-of-mass energy (stars).

3. Comparison between D0 measurement and TOTEM extrapolated data and the odderon discovery

The last step is to predict the pp elastic cross sections at the same t values as the D0 measurement in order to make a direct comparison between pp and $p\bar{p}$ elastic scattering. We thus fit the reference points extrapolated to 1.96 TeV from the TOTEM measurements using a double

PoS(LHCP2022)118

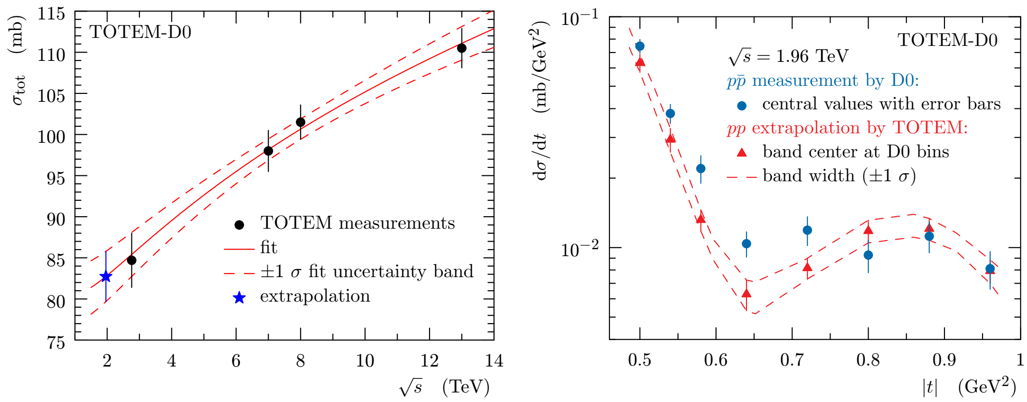

Figure 3: Left: Extrapolation of the pp total cross at 1.96 TeV from the TOTEM measurements at 1.96, 7, 8 and 13 TeV. Right: Comparison between the elastic $d\sigma/dt$ cross sections between $p\bar{p}$ and pp interactions corresponding respectively to the D0 measurement and to the extrapolation of TOTEM data to the Tevatron energy.

exponential fit that leads to a $\chi^2 = 0.63$ per dof

$$h(t) = a_1 e^{-b_1|t|^2 - c_1|t|} + d_1 e^{-f_1|t|^3 - g_1|t|^2 - h_1|t|}.$$

This function is chosen for fitting purposes only. The two exponential terms cross around the dip, one rapidly falling and becoming negligible in the high $|t|$-range where the other term rises above the dip. The systematic uncertainties are evaluated from an ensemble of MC experiments in which the cross section values of the eight reference points are varied within their Gaussian uncertainties. Let us note that such a formula leads also to a good description of TOTEM data in the dip and bump region at 2.76, 7, 8 and 13 TeV.

The differences in normalization are taken into account by adjusting TOTEM and D0 data sets to have the same cross sections at the optical point (OP) $d\sigma/dt(t=0)$ (OP cross sections are expected to be equal if there are only C-even exchanges, and a possible difference of maximum 3% is taken as an additional systematics due to odderon exchange). We first predict the pp total cross section from an extrapolated fit to the TOTEM measurements at 2.76, 7, 8 and 13 TeV as shown in Fig 3, left, with a χ^2 =0.27 using

$$\sigma_{tot} = a_2 \log^2 \sqrt{s}[\text{TeV}] + b_2 \tag{3.1}$$

Alternative parametrizations lead to similar results. It leads to an estimate of pp σ_{tot} of 82.7 ± 3.1 mb at 1.96 TeV.

The idea is then to adjust the 1.96 TeV $d\sigma/dt(t=0)$ from the extrapolated TOTEM data to the D0 measurement. From the TOTEM pp σ_{tot} at 1.96 TeV, we obtain the value of $d\sigma/dt(t=0)$ using the optical theorem

$$\sigma_{tot}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2} \left(\frac{d\sigma}{dt}\right)_{t=0} \tag{3.2}$$

Assuming $\rho = 0.145$, the ratio of the imaginary and the real part of the elastic amplitude, as taken from the COMPETE parametrization [12], this leads to a TOTEM $d\sigma/dt(t=0)$ at the OP of 357.1

± 26.4 mb/GeV^2. D0 measured the optical point of $d\sigma/dt$ at small t as 341±48 mb/GeV^2. The TOTEM data are thus rescaled by 0.954 ± 0.071. Of course, we do not claim that we performed a measurement of $d\sigma/dt$ at the OP at $t = 0$ (it would require additional measurements closer to $t = 0$), but we use the two extrapolations simply in order to obtain a common and somewhat arbitrary normalization point between both data sets.

The comparison between the extrapolated pp TOTEM measurements and the $p\bar{p}$ D0 data at 1.96 TeV is shown in Fig. 3, right. We see a clear discrepancy in the bump and dip region between the two data sets. We perform a χ^2 test to examine the probability for the D0 and TOTEM $d\sigma/dt$ to agree

$$\chi^2 = \Sigma_{i,j}[(T_i - D_i)C_{ij}^{-1}(T_j - D_j)] + \frac{(A - A_0)^2}{\sigma_A^2} + \frac{(B - B_0)^2}{\sigma_B^2} \tag{3.3}$$

where T_j and D_j are the j^{th} $d\sigma/dt$ values for TOTEM and D0, C_{ij} the covariance matrix, A (B) being the nuisance parameters for scale (slope) with A_0 (B_0) their nominal values. Given the constraints on the OP normalization and logarithmic slopes of the elastic cross sections, the χ^2 test with six degrees of freedom yields a p-value of 0.00061, corresponding to a significance of 3.4σ.

Using independent data sets at very low $|t|$, the TOTEM collaboration measured the value of σ_{tot} and of the ρ parameter [13] to be $\rho = 0.09 \pm 0.01$ at 13 TeV. The combination of the measured ρ and σ_{tot} values are found not to be compatible with any set of models without odderon exchange and this result can be considered as an independent evidence for the odderon. The significance is of 3.4 to 4.6σ depending on the models, to be combined with the previous D0 and TOTEM result since it is performed using independent data sets. The combined significance ranges from 5.3 to 5.7σ depending on the model and models without colorless C-odd gluonic compound are excluded by more than 5σ.

4. Conclusion

We performed a detailed comparison between $p\bar{p}$ ($\sqrt{s}$ =1.96 TeV from D0) and pp ($\sqrt{s}$ =2.76, 7, 8, 13 TeV from TOTEM) elastic $d\sigma/dt$ data. The R ratio of the elastic $d\sigma/dt$ cross section at the bump and at the dip shows a difference of more than 3σ between D0 (R=1.0±0.21), and TOTEM. Fits of eight “reference" points of elastic pp $d\sigma/dt$ data such as the dip, the bump, etc, were performed as a function of $\sqrt{s}$ in order to predict the pp elastic reference points at 1.96 TeV. pp and $p\bar{p}$ cross sections differ with a significance of 3.4σ in a model-independent way and thus provide evidence that the Colorless C-odd gluonic compound i.e. the odderon is needed to explain elastic scattering at high energies. When combined with the ρ and total cross section result at 13 TeV, the significance is in the range 5.3 to 5.7σ and thus constitutes the first experimental observation of the odderon.

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