PROCEEDINGS OF SCIENCE

New scaling in elastic data at high energies at the LHC

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Using the recently published elastic pp differential cross section $d\sigma/dt$ at $\sqrt{s} = 2.76$, 7, 8, and 13 TeV by the TOTEM collaboration, we find that the data fall onto a universal curve when they are mapped to the scaling variables $\mathrm{d}\sigma/\mathrm{d}|t| \times (s/TeV^2)^{-0.305}$ versus $(s/TeV^2)^{0.065}(t/GeV^2)^{0.72}$. We also discuss the possible implications in the impact parameter space.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

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PoS(ICHEP2022)762

1. Introduction

The TOTEM collaboration recently measured the pp elastic $d\sigma/dt$ cross sections at a center-of-mass $\sqrt{s}$ of 2.76 [1], 7 [2], 8 [3] and 13 [4] TeV as illustrated in Fig 1. We note the same features for all data sets, namely the presence of a minimum, the dip, and a maximum, the bump, for all elastic pp data. The position in $|t|$ and $d\sigma/dt$ for eight reference points, characteristic of the shape of the elastic $d\sigma/dt$, were measured as a function of $\sqrt{s}$ [5]. The same $\sqrt{s}$ dependence was found for all reference points in the dip and bump region, showing that all $d\sigma/dt$ curves for different energies were found to be parallel as shown in Fig. 1. This was clearly an indication of the existence of a new scaling in elastic data at high energies [6]. It also led to the recent discovery of the odderon by the D0 and TOTEM collaborations [5, 7] by comparing the elastic $d\sigma/dt$ cross sections in $p\bar{p}$ and in pp collisions at $\sqrt{s}$ =1.96 TeV, respectively measured by the D0 collaboration and extrapolated from the TOTEM measurements at $\sqrt{s}$ =1.96, 7, 8, and 13 TeV as shown in Fig. 1, right. Both data sets disagree with a p-value of 0.00061, corresponding to a significance of 3.4σ. The combined significance with the previous ρ measurement [8] from the TOTEM collaboration ranges from 5.3 to 5.7σ depending on the model and models without colorless C-odd gluonic compound or the odderon are excluded by more than 5σ.

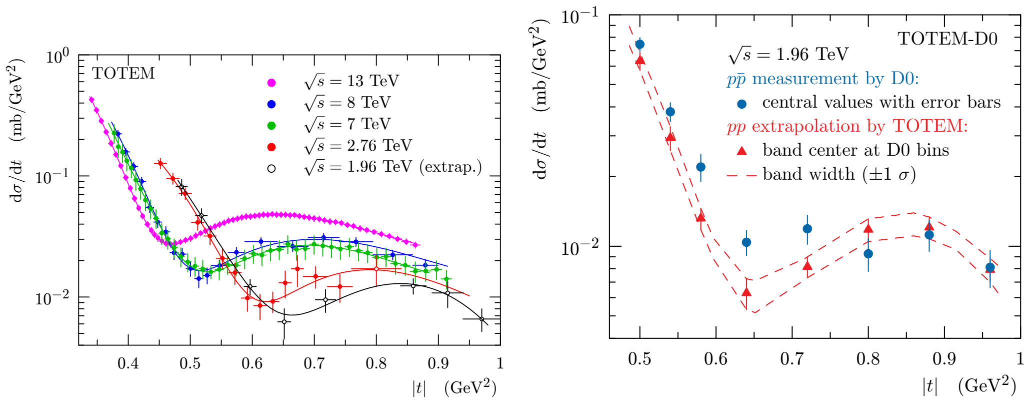

Figure 1: Left: TOTEM elastic pp $d\sigma/dt$ data at 2.76, 7, 8 and 13 TeV, and extrapolated to the Tevatron center-of-mass energy of 1.96 TeV. Right: Comparison between the elastic $d\sigma/dt$ cross sections in $p\bar{p}$ and in pp collisions at $\sqrt{s}$ =1.96 TeV, respectively measured by the D0 collaboration and extrapolated from the TOTEM measurements at $\sqrt{s}$ =1.96, 7, 8, and 13 TeV [5].

2. A new scaling in TOTEM elastic data at high energies

The idea is to find a new variable, which we call t^{**}, for which $s^{-\alpha} d\sigma/dt$ as a function of t^{**} does no longer depend on $\sqrt{s}$, where α is a constant to be fitted to data. The method is to use the Quality Factor method [9] to fit α and to check the quality of the new scaling

$$\mathrm{QF} = \left[\Sigma_i \frac{(v_{i+1} - v_i)^2 \times \Delta v_{i+1} \times \Delta v_i}{(u_{i+1} - u_i)^2 + \varepsilon^2} \right]$$

where the Δv_i are the uncertainties on v_i and ε is a small constant to regularize divergences when $u_{i+1} = u_i$. The u_i and v_i are respectively $\ln(t^{**})$ and $\ln[s^{-\alpha} d\sigma/dt]$. The QF method is well adapted

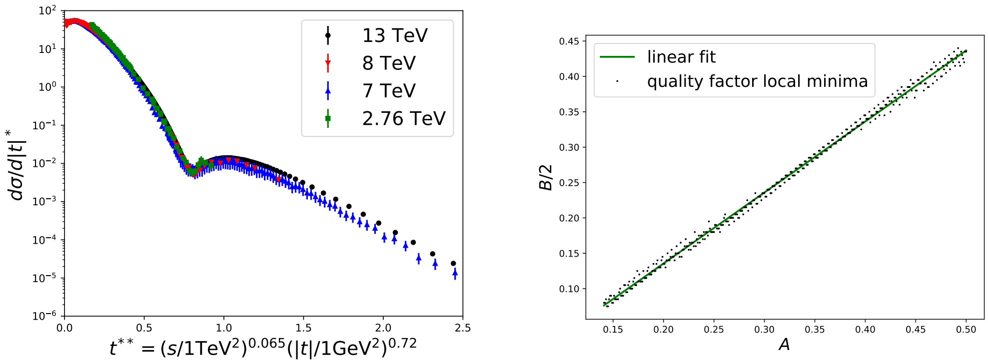

Figure 2: Left: $d\sigma/dt^*$ as a function of t^{**} showing the scaling of all TOTEM elastic scattering data at $\sqrt{s} =$ 2.76, 7, 8 and 13 TeV. Right: Correlation between the A and B scaling constants that lead to a minimum QF.

when there is no analytic expression for $\ln[s^{-\alpha}d\sigma/dt]$ and α is fitted so that the data description can be as smooth as possible. Let us now define this new scaling variable t^{**} [6].

We first introduce an intermediary variable $t^* = (s/|t|)^A \times |t|$ which is inspired by geometric scaling in terms of saturation models which is somehow natural. Phenomenologically, we thus look for a scaling variable t^{**} defined as $t^{**} = t^*/s^B$, A and B being parameters to be fitted to data. The result is shown in Fig. 2, left, where we display $d\sigma/dt^*$ as a function of t^{**} with $A = 0.28$ and $B = 0.215$. In addition, we noticed that we have a full valley of parameters that are possible for A and B, which means that A and B are correlated. As shown in Fig. 2, right, we see that $B = A - 0.065$, as obtained by fitting the B value that leads to a minimum of QF for a given A value (all QFs are found to be of similar value in a wide range of A values). This means that we can perform a fit with one parameter only.

Let us now express the consequences of scaling on $d\sigma/dt$. We know that

$$\frac{d\sigma}{dt^*} = \frac{d\sigma}{dt}\frac{dt}{dt^*} = \frac{d\sigma}{dt} \times s^{A\frac{A-1.065}{1-A}} \times f(t^{**}) = (s)^{-\alpha}\frac{d\sigma}{dt} f(t^{**}). \quad (2.1)$$

We also learned that $d\sigma/dt^*$ scales as a function of $t^{**} = s^{0.065} \times |t|^{1-A}$ where $t^* = (s/|t|)^A \times |t|$. This implies that $d\sigma/dt^*$ does not depend on s, which means that the s dependence on $d\sigma/dt$ is imposed by scaling. In other words, $s^{-\alpha}d\sigma/dt$ does not depend on s (or scales) by definition with $\alpha = \frac{-A(A-1.065)}{1-A}$. If we use the QF method to fit the A parameter (using all data from TOTEM at 2.76, 7, 8 and 13 TeV), we obtain $A = 0.28$. The conclusion is that $s^{-0.305}d\sigma/dt$ scales as a function of t^{**} ($\alpha = 0.305 = \frac{-A(A-1.065)}{1-A}$ and $t^{**} = s^{0.065} \times |t|^{1-A}$). The results are shown in Fig. 3, left where $(s^{-0.305}d\sigma/dt)$ is displayed as a function of t^{**} showing the scaling of all TOTEM data. The scaling is quite good in the dip and bump region. Scaling is not supposed to work perfectly at low $|t|$ that corresponds to the QED Coulomb region and at high $|t|$ in the perturbative QCD domain. The prediction of $d\sigma/dt$ from scaling at different $\sqrt{s}$ is shown in Fig. 3, right.

3. Interpretation in the impact parameter space

In order to compute the profile function Γ in the impact b-parameter space, we use the follow-

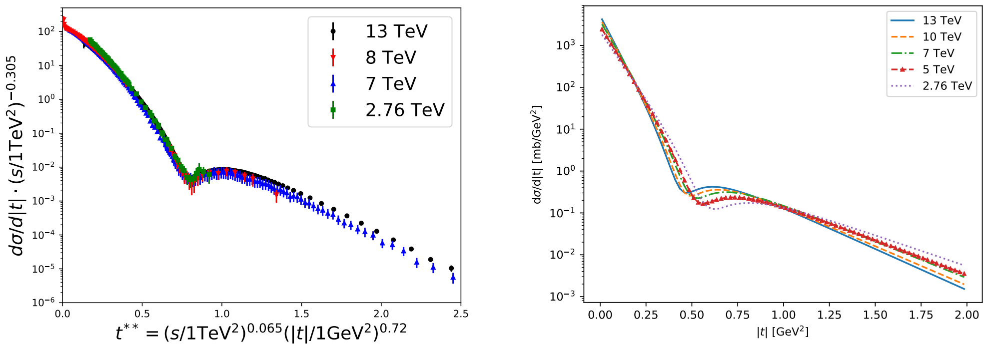

Figure 3: Left: $(s/\text{TeV}^2)^{-0.305} d\sigma/d|t|$ as a function of t^{**} showing the scaling of all TOTEM $d\sigma/d|t|$ data in these variables. Right: Prediction of $\mathrm{d}\sigma/\mathrm{d}t$ from the scaling fit at different $\sqrt{s}$

ing relation between Γ and the amplitude A

$$\mathrm{Re}(\Gamma(s,b)) = \frac{1}{4\pi i s}\int_0^\infty dq\, q\, J_0(qb) A(s,t=-q^2) \tag{3.1}$$

and

$$\frac{\mathrm{d}\sigma}{\mathrm{d}|t|} = \frac{1}{16\pi s^2}|A(s,t)|^2 = |\mathscr{A}(s,t)|^2. \tag{3.2}$$

To compute Γ, we need to fit the amplitude to TOTEM data using the formulae

$$\mathscr{A}(s,t) = i\big(\mathscr{A}_1(s,t)+\mathscr{A}_2(s,t)\big)e^{i\theta} \tag{3.3}$$
$$\mathscr{A}_1(s,t) = N_1(s)e^{-B_1(s)|t|}$$
$$\mathscr{A}_2(s,t) = N_2(s)e^{-B_2(s)|t|}e^{i\phi} \tag{3.4}$$

where $N_1(s) = N_1^0 s^{\alpha/2}$, $N_2(s) = N_2^0 s^{\alpha/2}$, $B_1(s) = B_1^0 s^{\gamma/2}$ and $B_2(s) = B_2^0 s^{\gamma/2}$. There are six free parameters in the fit to $\mathscr{A}(s,t)$, namely N_1^0, N_2^0, B_1^0, B_2^0, ϕ, and θ. $\alpha = 0.305$ and $\gamma/2 \equiv 0.065/(1-A) = 0.065/0.72 \approx 0.09$ are fixed by scaling. The fit quality is quite good with a χ^2/dof =1.08 for $0.2 < t^{**} < 1.5$ in the dip-bump region for 476 data points that avoids very low $|t|$ (Coulomb QED region) and high $|t|$ (perturbative QCD domain). The χ^2/dof =8.7 for the full domain in $|t|$ with 599 data points.

From the fit of the amplitude, we can compute the profile function Γ using formula 3.1. The real part of the profile function $\Gamma(b)$ as a function of the impact parameter b is displayed for different $\sqrt{s}$ values in Fig. 4, left. We then define λ as a function of the ratio of two values of Γ for two values of $\sqrt{s}$ as

$$\lambda = \frac{1}{\ln(s_1/s_2)} \ln\left(\frac{\mathrm{Re}\Gamma(s_1,b)}{\mathrm{Re}\Gamma(s_2,b)}\right). \tag{3.5}$$

The values of λ as a function of b for different $\sqrt{s}$ are shown in Fig. 4, right. $\lambda = (\alpha-\gamma)/2 = 0.06$ when $b \to 0$ as predicted by scaling. This means that scaling predicts a universal behavior of λ at small b. Values of λ at small b are compatible with expectations from a dense object, such

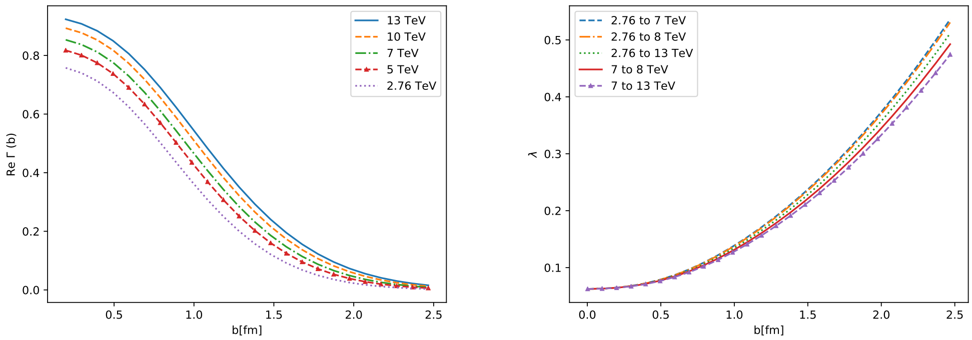

Figure 4: Left: The real part of the profile function $\Gamma(b)$ as a function of the impact parameter (b) at different $\sqrt{s}$. Right: Power growth exponent λ as a function of b for various reference $\sqrt{s}$ pairs.

as a black disc, and reach higher values around 0.3 for $b = 1$ fm, which is reminiscent of the power-law exponent in the small-x limit of QCD, described by the perturbative BFKL evolution equation [10, 11] at next-to-leading logarithmic accuracy. Scaling, together with the value of λ at low b, could be interpreted as having a large density of gluons inside colorless gluonic compounds (responsible for diffraction) that reach the black disc limit at small b. At higher b, the density of gluons is smaller and in principle describable by BFKL dynamics. In this sense, we can interpret our results as the presence of dense gluonic objects in the proton at high energy. The density of these objects in the proton can be small, but the density of the gluons inside can be large.

4. Conclusion

We analyzed the behavior of the recently published by TOTEM differential cross sections of proton-proton elastic scattering as a function of t and s at LHC energies and found that $d\sigma/dt$ at $\sqrt{s}$ =2.76, 7, 8, and 13 TeV exhibits scaling. The data fall onto a universal curve after mapping them with $d\sigma/dt \rightarrow d\sigma/dt(s/TeV^2)^{-0.305}$ and $|t| \rightarrow (s/TeV^2)^{0.065}(|t|/GeV^2)^{0.72}$. Results could be interpreted as having a large density of gluons inside colorless gluonic compounds that reach the black disc limit at small b.

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