New scaling in elastic data

Christophe Royon, Cristian Baldenegro, Anna Stasto
University of Kansas, Lawrence, USA
ICHEP 2022, July 6-July 13 2022, Bologna, Italy

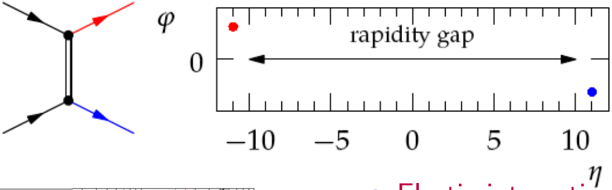
July 8 2022

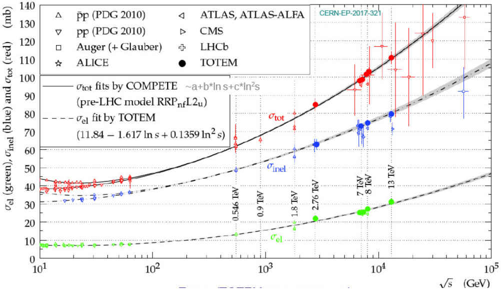
Contents

- Odderon discovery by D0 and TOTEM
- The starting point of a new scaling: elastic $d\sigma/dt$ measurements from TOTEM
- Definition of a new scaling variable
- Interpretation in the b-parameter space
- Phys. Lett.B 830 (2022) 137141, ArXiv 2204.08328

Elastic, inelastic, total cross section measurements (TOTEM/ATLAS)

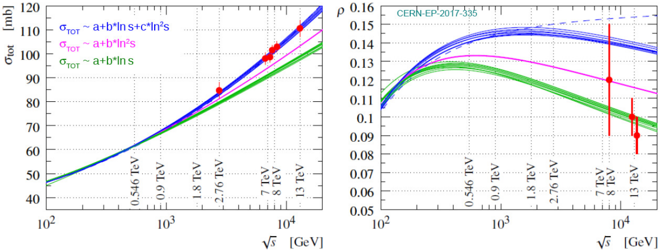
Elastic Scattering (ES), $\approx 30\,\text{mb}$

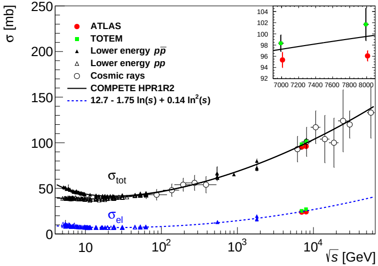




- Elastic interactions: $pp \to pp$: Detect the intact protons after interaction!
- High precision measurement of elastic, inelastic and total cross sections
- Measurements in agreement with cosmic-ray data
- ATLAS 1.9σ lower than TOTEM

ρ and σ_{tot} measurements as an indication for odderon



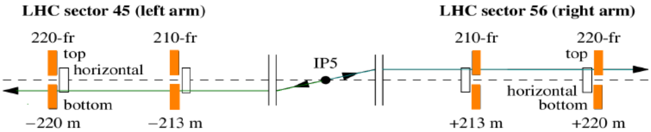


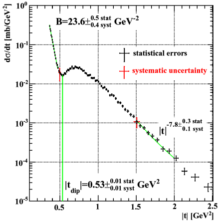
(a)

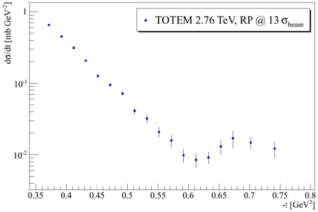
- Using low $|t|$ data in the Coulomb-nuclear interference region, measurement of ρ at 13 TeV ($\rho = \frac{Re(A^N(0))}{Im(A^N(0))}$) : $\rho = 0.09 \pm 0.01$ (EPJC 79 (2019) 785)
- Combination of the measured ρ and σ_{tot} values not compatible with any set of models without odderon exchange (COMPETE predictions above as an example) (TOTEM)
- Differences between σ_{tot} at 7 and 8 TeV between TOTEM and ATLAS (what about 13 TeV?)

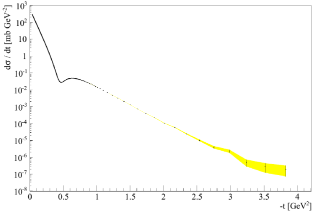
TOTEM elastic $pp\ d\sigma/dt$ cross section measurements

- Elastic $pp\ d\sigma/dt$ measurements: tag both intact protons in TOTEM Roman Pots 2.76, 7, 8 and 13 TeV
- Very precise measurements at 2.76, 7, 8 and 13 TeV: Eur. Phys. J. C 80 (2020) no.2, 91; EPL 95 (2011) no. 41004; Nucl. Phys. B 899 (2015) 527; Eur. Phys. J. C79 (2019) no.10, 861

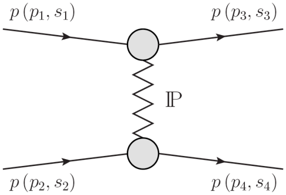








The odderon in a nutshell

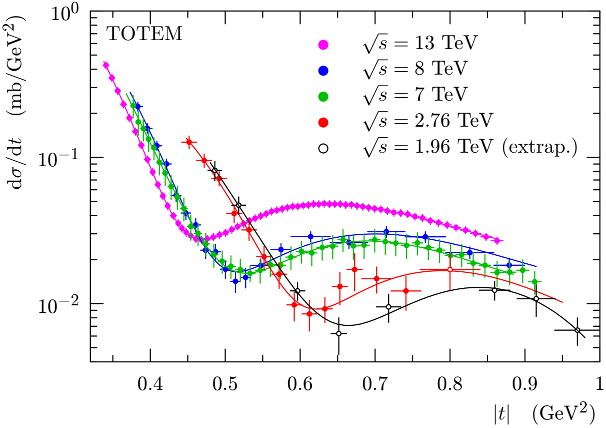


- Let us assume that elastic scattering can be due to exchange of colorless objects: Pomeron and Odderon
- Charge parity C: Charge conjugation changes the sign of all quantum charges
- Pomeron and Odderon correspond to positive and negative C parity: Pomeron is made of two gluons which leads to a $+1$ parity whereas the odderon is made of 3 gluons corresponding to a -1 parity
- Scattering amplitudes can be written as:

$$
\begin{aligned}
A_{pp} &= Even + Odd \\
A_{p\bar{p}} &= Even - Odd
\end{aligned}
$$

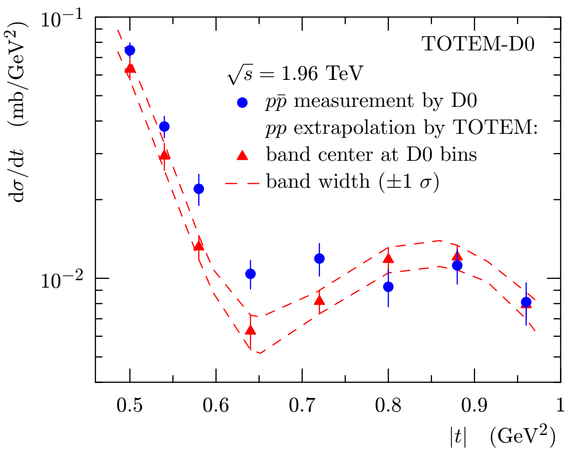
- From the equations above, it is clear that observing a difference between pp and $p\bar{p}$ interactions would be a clear way to observe the odderon

Strategy to compare *pp* and $p\bar{p}$ data sets



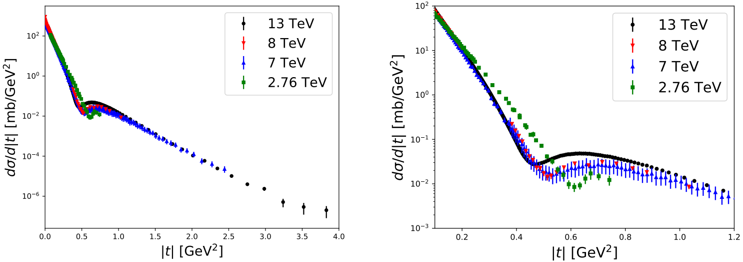
- In order to identify differences between *pp* and $p\bar{p}$ elastic $d\sigma/dt$ data, we need to compare TOTEM measurements at 2.76, 7, 8, 13 TeV and D0 measurements at 1.96 TeV
- All TOTEM $d\sigma/dt$ measurements show the same features, namely the presence of a dip and a bump in data, whereas D0 data do not show this feature

Comparison between D0 measurement and extrapolated TOTEM data: the odderon discovery



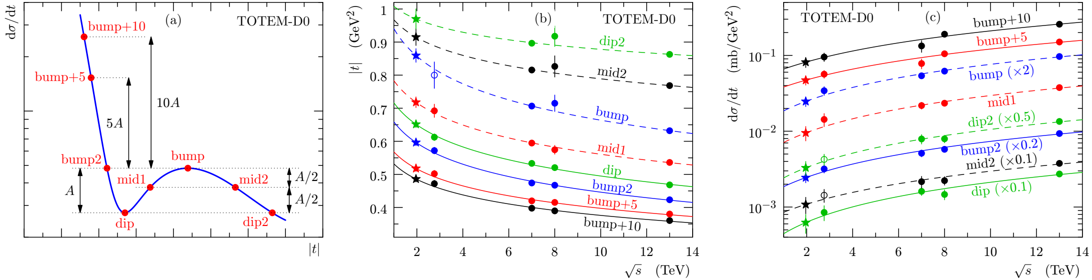
- Comparison between extrapolated TOTEM data at 1.96 TeV (Tevatron energy) and D0 measurement in the dip/bump region where there is a common domain of measurement in t
- p-value of 0.00061, corresponding to a significance of 3.4σ
- Combined significance with the ρ measurement ranges from **5.3 to 5.7σ depending on the model** (PRL 127 (2021) 6, 062003)
- Models without colorless C-odd gluonic compound are excluded

The starting point of new scaling: elastic $d\sigma/dt$ measurements from TOTEM



- The TOTEM collaboration measured elastic pp $d\sigma/dt$ differential cross sections as a function of t for different center-of-mass energies of 2.76, 7, 8, and 13 TeV
- We see that the data points vary together especially in the dip/bump region

The starting point: elastic $d\sigma/dt$ measurements from TOTEM



- Extrapolation of TOTEM data at 2.76, 7, 8, 13 TeV down to the Tevatron energy of 1.96 TeV to compare between pp and $p\bar{p}$ elastic energies
- 8 reference points were identified on TOTEM elastic pp $d\sigma/dt$ and their variation of the t and $d\sigma/dt$ as a function of $\sqrt{s}$
- Striking observation: the same $\sqrt{s}$ dependence for all characteristic points, namely $|t| = a\log(\sqrt{s}) + b$ and $d\sigma/dt = c\sqrt{s} + d$ in the dip/bump region
- It means that all points vary together and are not independent, curves are “parallel”

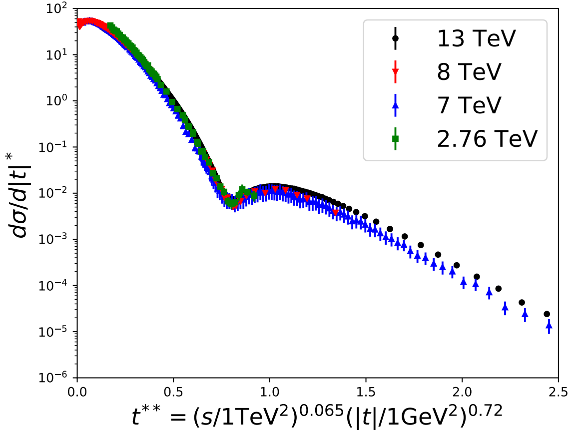
A new scaling in data

- 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
- We use the Quality Factor method to fit α

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

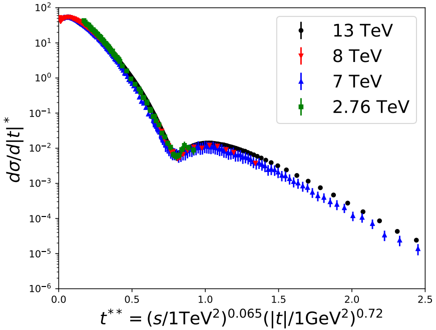
where the Δv_i are the uncertainties on v_i and ϵ is a small constant to regularize divergences when $u_{i+1} = u_i$.

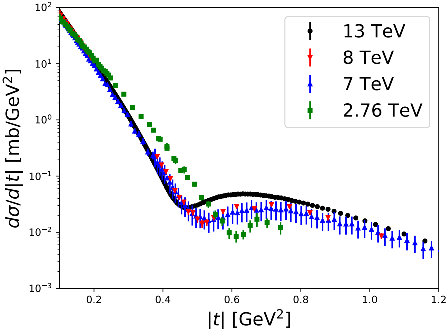
- The u_i and v_i are respectively: $\ln(t^{**})$ and $\ln[(s^{-\alpha} d\sigma/dt]$
- The QF method is well adapted when there is no analytic expression for $\ln[(s^{-\alpha} d\sigma/dt]$: fit α so that there is a continuous description of data



- We introduce the variable $t^* = (s/|t|)^A \times |t|$ which is inspired by geometric scaling in terms of saturation models which is natural since we look for a new scaling in data
- $t^{**} = t^*/s^B$, A and B being parameters to be fitted to data
- We definitely observe that $d\sigma/dt^*$ shows scaling as a function of t^{**}

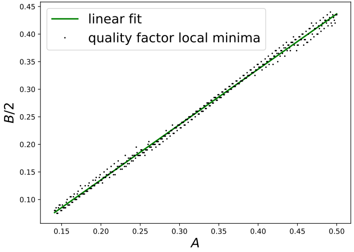
The first approach of a new scaling in data: zoom in the dip/bump region

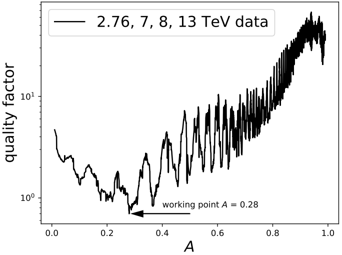




- Left: $d\sigma/dt^*$ as a function of t^{**} in the bump/dip region: scaling
- Right: $d\sigma/dt$ as a function of $|t|$ in the bump/dip region: no scaling

A and B parameters are not independent





- We noticed that we have a full valley of parameters that are possible for A and B ($t^{**} = (s/|t|)^A \times t/s^B$)
- A and B correlation: $B = A - 0.065$ obtained by fitting the B value that leads to a minimum of QF for a given A value (QF are found to be similar)
- It means that we can have a 1-parameter fit only

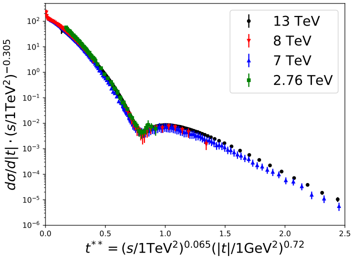
A new scaling in data

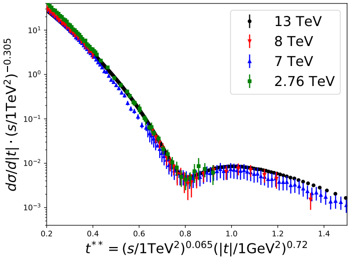
- We learned from data that $d\sigma/dt^*$ scales as a function of $t^{**} = s^{0.065} \times |t|^{1-A}$ where $t^* = (s/|t|)^A \times |t|$
- We have

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

- Since $d\sigma/dt^*$ scales, it does not depend on s, which means the s dependence on $d\sigma/dt$ is imposed by scaling
- $s^{-\alpha}d\sigma/dt$ should not depend on s or scales by definition with $\alpha = \frac{-A(A-1.065)}{1-A}$

Scaling in TOTEM elastic data





- We use the QF method to fit the A parameter (using all data from TOTEM at 2.76, 7.8 and 13 TeV): $A = 0.28$
- $s^{-0.305} d\sigma/dt$ scales as a function of t^{**} ($0.305 = \frac{-A(A-1.065)}{1-A}$ and $t^{**} = s^{0.065} \times |t|^{1-A}$)
- All data shown or zoomed into the dip and bump region where scaling is supposed to be valid (low $|t|$ corresponds to the QED Coulomb region and high $|t|$ the perturbative QCD domain)

Going to the b-parameter space

- Relation between the profile function Γ and the amplitude A:

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

and

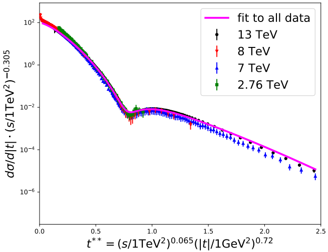
$$\frac{\mathrm{d}\sigma}{\mathrm{d}|t|} = \frac{1}{16\pi s^2}|A(s,t)|^2 = |\mathcal{A}(s,t)|^2$$

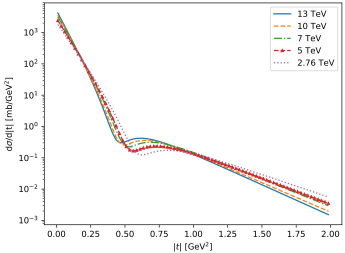
- We fit the amplitude to TOTEM data using the formula

$$\begin{aligned}
\mathcal{A}(s,t) &= i\big(\mathcal{A}_1(s,t) + \mathcal{A}_2(s,t)\big)e^{i\theta} \\
\mathcal{A}_1(s,t) &= N_1(s)e^{-B_1(s)|t|} \\
\mathcal{A}_2(s,t) &= N_2(s)e^{-B_2(s)|t|}e^{i\phi}
\end{aligned}$$

where $N_1(s) = N_1^0(s/1\ \mathrm{TeV}^2)^{\alpha/2}$, $N_2(s) = N_2^0(s/1\ \mathrm{TeV}^2)^{\alpha/2}$, $B_1(s) = B_1^0(s/1\ \mathrm{TeV}^2)^{\gamma/2}$ and $B_2(s) = B_2^0(s/1\ \mathrm{TeV}^2)^{\gamma/2}$

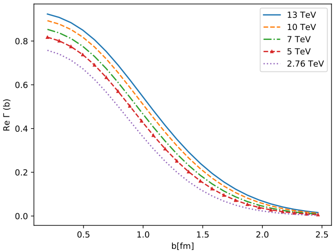
Fit to TOTEM elastic data

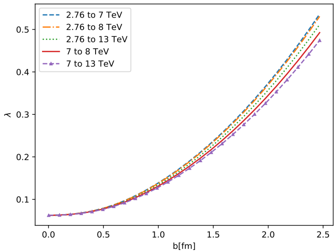




- $\alpha = 0.305$ and $\gamma/2 \equiv 0.065/(1-A) = 0.065/0.72 \approx 0.09$ are fixed by scaling
- six free parameters in the fit to $\mathcal{A}(s,t)$: N_1^0, N_2^0, B_1^0, B_2^0, ϕ, and θ, and predictions of $d\sigma/dt$ for different s from the fits
- Fit quality: χ^2/dof =1.08 for $0.2 < t^{**} < 1.5$ in the dip-bump region (476 data points) that avoid very low $|t|$ (Coulomb QED region) and high $|t|$, perturbative QCD domain (χ^2/dof =8.7 for the full domain in $|t|$, 599 data points)

The profile function





- Use top formula to compute the profile function (see previous slide)
- We define λ as

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

- $\lambda = (\alpha - \gamma)/2+$term vanishing when $b \to 0$, $\lambda = 0.06$ which means that scaling predicts a universal behavior of λ at small b

Possible interpretation of a new scaling and conclusion

- Values of λ at small b (0.06) are compatible with expectations from a dense object, such as a black disc
- Values of λ 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 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 in the “hot spot” is smaller and in principle describable by BFKL dynamics
- In this sense, we can interpret our results as the presence of hot spots in the proton at high energy. The density of these hot spots in the proton can be small, but the density of the gluons inside these hot spots can be large

Conclusion

- TOTEM measured very precisely the elastic $d\sigma/dt$ at high energy at the LHC (2.76, 7, 8, and 13 TeV)
- It seems that the points on the $d\sigma/dt$ do not vary independently from each other, but rather in a correlated way
- We analyzed the behavior of the differential cross section 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 $d\sigma/dt \to d\sigma/dt(s)^{-0.305}$ and $|t| \to (s)^{0.065}|t|^{0.72}$
- This might be related to the presence of hot spots in the proton at high energy. While the density of these hot spots in the proton can be small, the density of the gluons inside these hot spots can be large