Recent results from TOTEM

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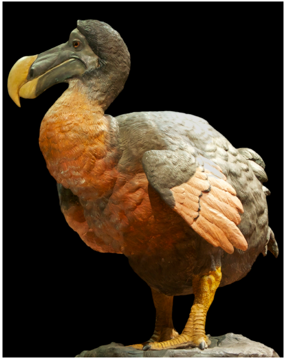
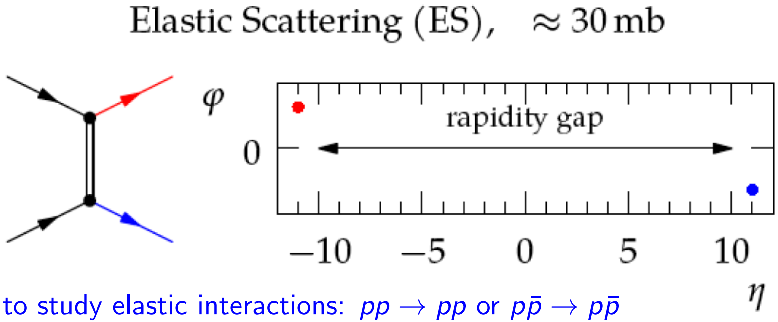


September 4-8 2022

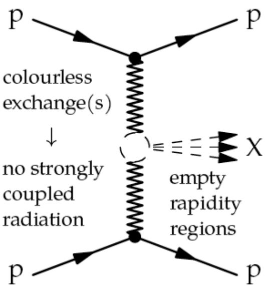
- Soft diffraction at the LHC
- Total cross section and elastic interactions
- Introduction to the Odderon
- D0 $p\bar{p}$ and TOTEM pp data
- The odderon discovery

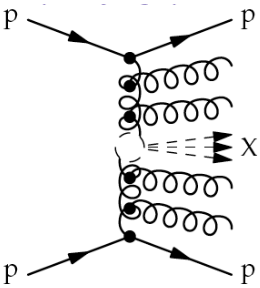
What do we want to study?



- We want to study elastic interactions: $pp \to pp$ or $p\bar{p} \to p\bar{p}$
- These are very clean events, where nothing is produced outside the two protons
- How to detect/measure these events? We need to detect the intact protons after interaction!
- Interactions explained by the exchange of a colorless object ($\geq$ 2 gluons, photon, etc...) between the two protons

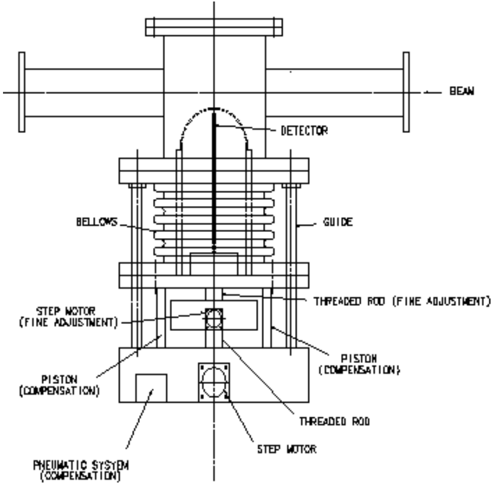
How to explain the fact that protons can be intact?





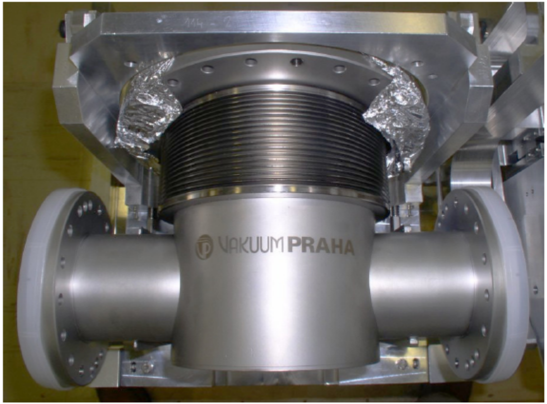
- Quarks/gluons radiate lots of gluons when one tries to separate them (confinement)
- Gluons exchange color, interact with other gluons in the proton and in that case protons are destroyed in the final state
- In order to explain how protons can remain intact: we need colorless exchanges, or at least 2 gluons to be exchanged

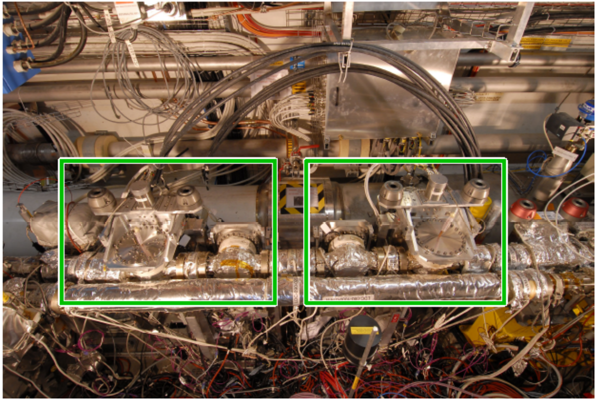
Which tools do we have? Roman Pot detectors

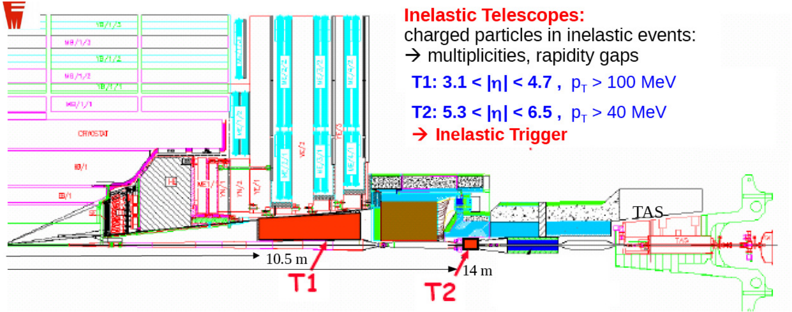


- We use special detectors to detect intact protons/ anti-protons called Roman Pots
- These detectors can move very close to the beam (up to 3σ) when beam are stable so that protons scattered at very small angles can be measured
- Roman pots installed on both sides of CMS at about 220 m from the interaction point

Roman Pot detectors at the LHC







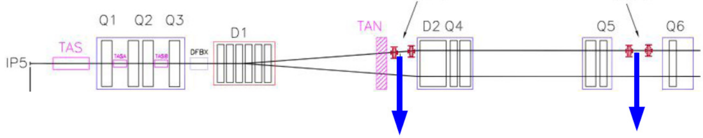
Inelastic Telescopes:
charged particles in inelastic events:
→ multiplicities, rapidity gaps

T1: $3.1 < |\eta| < 4.7$, $p_T > 100$ MeV

T2: $5.3 < |\eta| < 6.5$, $p_T > 40$ MeV

→ **Inelastic Trigger**

Roman Pots: elastic & diffractive protons close to outgoing beams → **Proton Trigger**

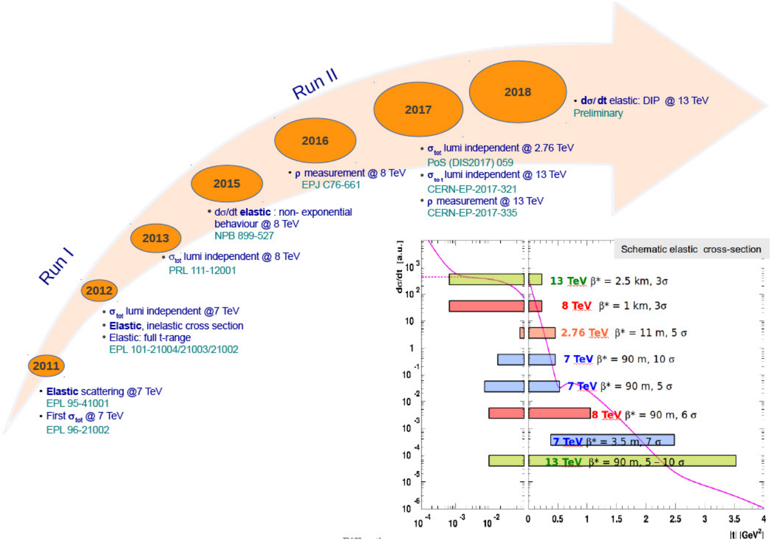


Roman Pot stations in the LHC tunnel (before LS1)

RP (147 m)

RP (220m)

TOTEM cross section measurements



Analysis methods in TOTEM: total cross section

- N_{inel} measured using T_1 and T_2 telescopes, and N_{el} from the roman pots
- Known equations (Optical theorem) (ρ: ratio of real/Imaginary part of cross section)

$$L\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2}(dN_{el}/dt)_{t=0}$$
$$L\sigma_{tot} = N_{el} + N_{inel}$$

- Different methods to measure the total cross section
  - Lumi independent measurement

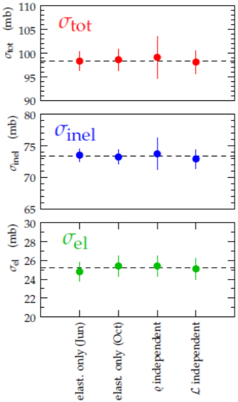
$$\sigma_{tot} = \frac{16\pi}{(1+\rho^2)}\frac{(dN_{el}/dt)_{t=0}}{(N_{el}+N_{inel})}$$

  - Lumi dependent measurement (elastic only)

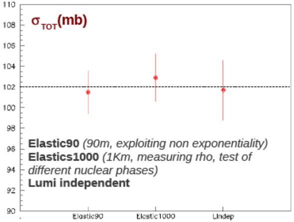
$$\sigma_{tot}^2 = \frac{16\pi}{(1+\rho^2)}\frac{1}{L}(dN_{el}/dt)_{t=0}$$

  - ρ independent measurement $\sigma_{tot} = \sigma_{el} + \sigma_{inel}$

Elastic, Inelastic and Total cross section at 7, 8 and 13 TeV



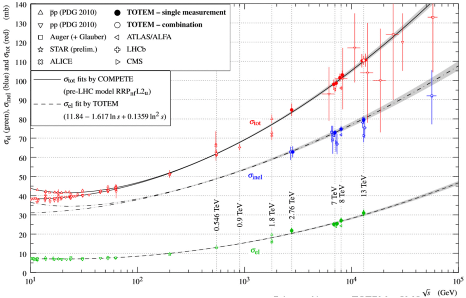
7 TeV, several methods
Same beam conditions

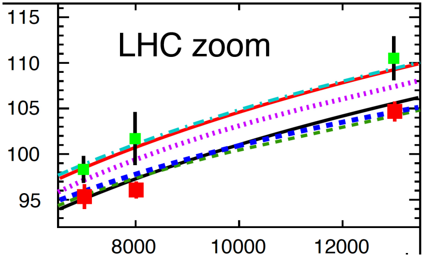


8 TeV, several methods
Different beam conditions

- Independent methods with different precision/systematics lead to similar results on elastic, inelastic and total cross sections
- In addition, at 13 TeV, total cross section using lumi independent method for $\beta^* = 90m$:
  $\sigma_{tot} = 110.6 \pm 3.4$mb,
  $\sigma_{el} = 31.0 \pm 1.7$mb,
  $\sigma_{inel} = 79.5 \pm 1.8$mb
- ρ measurement using $\beta^* = 2500m$ data

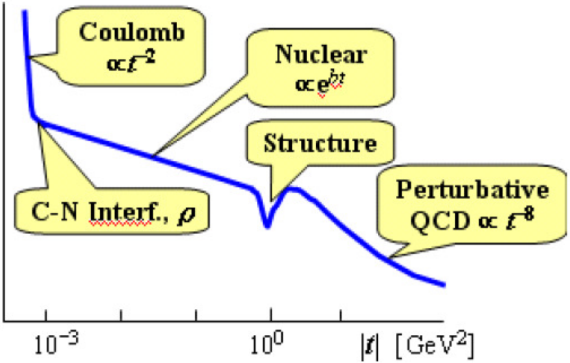
Elastic, inelastic, total cross section measurements





- High precision measurement of elastic, inelastic and total cross sections
- Measurements in agreement with cosmic-ray data (large error bars though)
- ATLAS $\sim 2\,\sigma$ lower than TOTEM at 8 and 13 TeV: differences due to luminosity measurements?

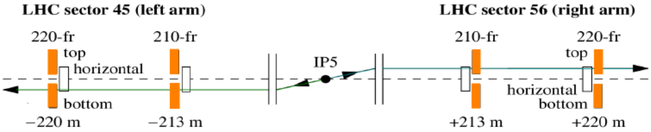
Measurement of elastic scattering at Tevatron and LHC

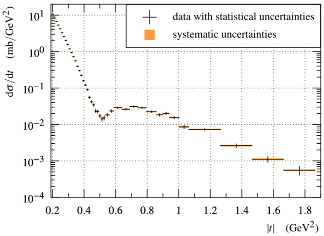


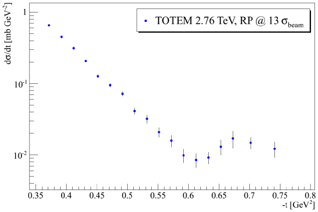
- Study of elastic $pp \to pp$ reaction: exchange of momentum between the two protons which remain intact
- Measure intact protons scattered close to the beam using Roman Pots installed both by D0 and TOTEM collaborations
- From counting the number of events as a function of $|t|$ (4-momentum transferred square at the proton vertex measured by tracking the protons), we get $d\sigma/dt$

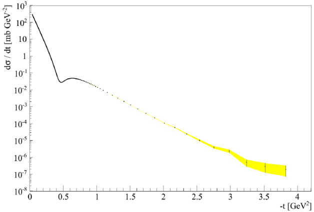
TOTEM elastic $pp\ d\sigma/dt$ cross section measurements

- 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

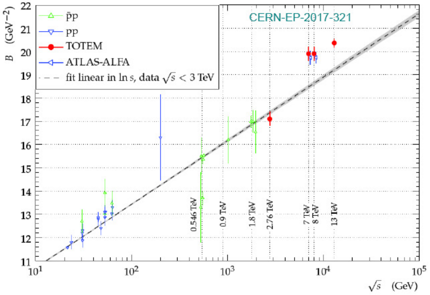


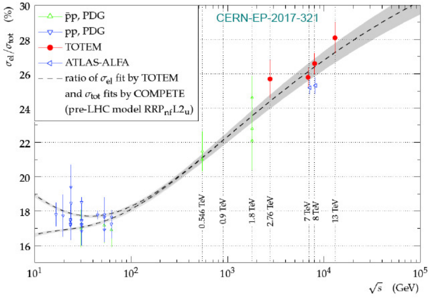






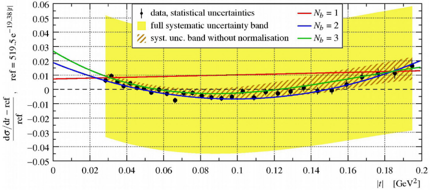
Implication of elastic cross section measurements: B slope at 13 TeV

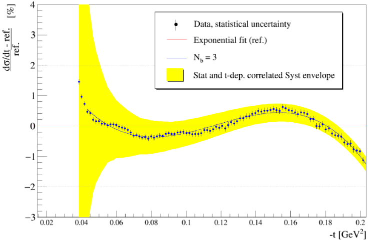




- B slope of $d\sigma/dt$: larger slope at 13 TeV
- Linear behavior ($\ln s$) compatible for $\sqrt{s} < 3$ TeV, incompatible at higher energy
- The increase of σ_{el}/σ_{tot} with energy is confirmed at LHC

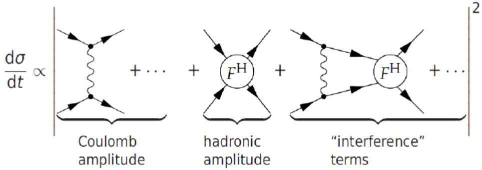
Non-exponential dependence of TOTEM elastic data





- Attempt of a usual simple exponential fit to $d\sigma/dt$ at low t
- Exponential fit: $d\sigma/dt = A\exp(-B(t)|t|)$
- Different polynomial fits of $B(t)$:
  - $N_b = 1$ $B = b_1$, reference
  - $N_b = 2$, $B = b_1 + b_2 t$
  - $N_b = 3$, $B = b_1 + b_2 t + b_3 t^2$
- Pure simple exponential form ($N_b = 1$, $B = cte$) excluded at 7.2 σ with 8 TeV data, similar results using 13 TeV data

Analysis methods in TOTEM: ρ measurement

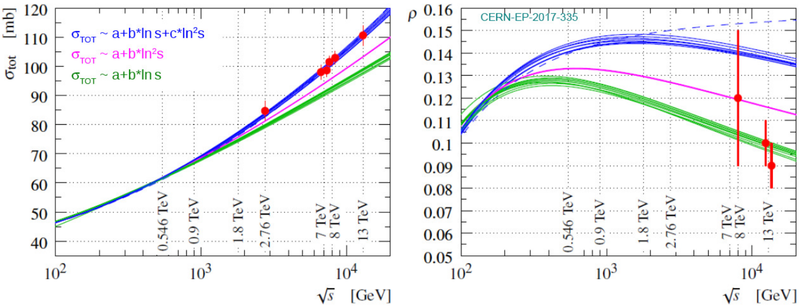


- Measure elastic scattering at very low t: Coulomb-Nuclear interference region

$$\frac{d\sigma}{dt} \sim |A^C + A^N(1 - \alpha G(t))|^2$$

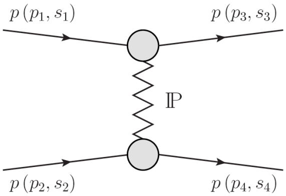
- The differential cross section is sensitive to the phase of the nuclear amplitude
- In the CNI region, both the modulus and the phase of the nuclear amplitude can be used to determine $\rho = \frac{Re(A^N(0))}{Im(A^N(0))}$ where the modulus is constrained by the measurement in the hadronic region and the phase by the t dependence

ρ measurement at 13 TeV



- ρ is the ratio of the imaginary and real part of the total cross section
- Using low $|t|$ data, measurement of ρ at 13 TeV: $\rho = 0.09 \pm 0.01$
- ρ value at 13 TeV clearly below expectations (COMPETE fits as an example)
- This result can be explained by the exchange of the Odderon in addition to the Pomeron at high energies

The odderon in a nutshell

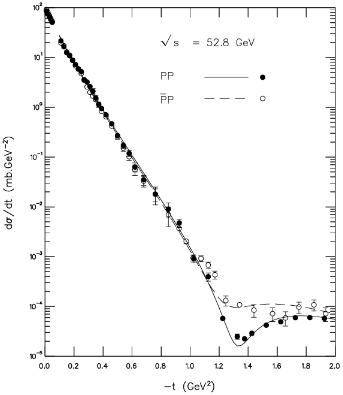


- Let us assume that elastic scattering can be due to exchange of colorless objects: Pomeron and Odderon
- Charge parity C: Charge conjugation changes the sign of all quantum charges
- Pomeron and Odderon correspond to positive and negative C parity: Pomeron is made of two gluons which leads to a $+1$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

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

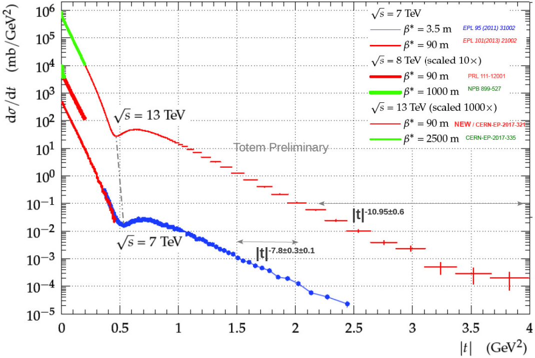
- From the equations above, it is clear that observing a difference between pp and $p\bar{p}$ interactions would be a clear way to observe the odderon

Why has the odderon not been observed yet? Why is it so elusive?



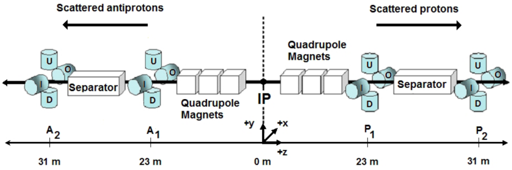
- The situation is not that simple: elastic scattering at low energies can be due to exchanges of additional particles to pomeron/odderon: ρ, ω, ϕ, reggeons...
- How to distinguish between all these exchanges? Not easy...
- At ISR energies, there was already some indication of a possible difference between pp and $p\bar{p}$ interactions, differences of about 3σ between pp and $p\bar{p}$ interactions but this was not considered to be a clean proof of the odderon because of these additional reggeon, meson exchanges at low $\sqrt{s}$

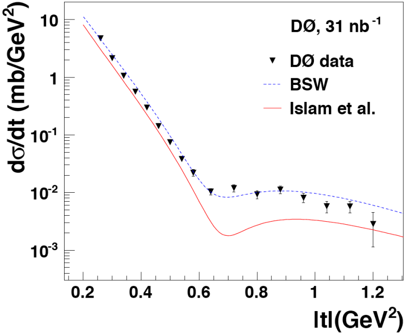
Are we in the asymptotic regime at the LHC?



- Contrary to what some models expected before LHC, the elastic cross section is smooth: we do not see reggeons, mesons...!
- Effects of reggeon, meson exchanges are negligible at LHC energies: we can concentrate on pomeron/odderon studies!
- We can directly look for the existence of the odderon by comparing pp and $p\bar{p}$ elastic cross sections at very high energies: 1.96 TeV (Tevatron), 2.76, 7, 8, 13 (LHC)

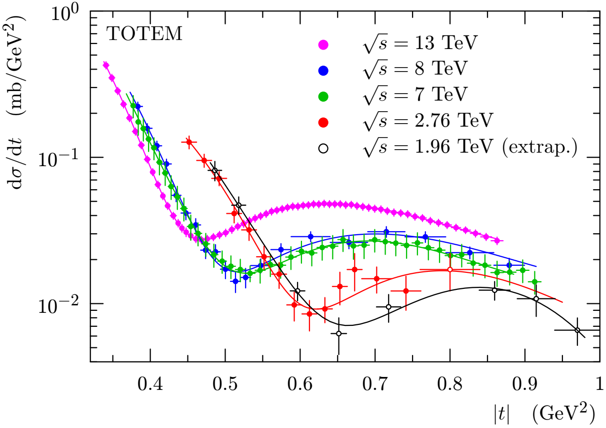
D0 elastic $p\bar{p}$ $d\sigma/dt$ cross section measurements





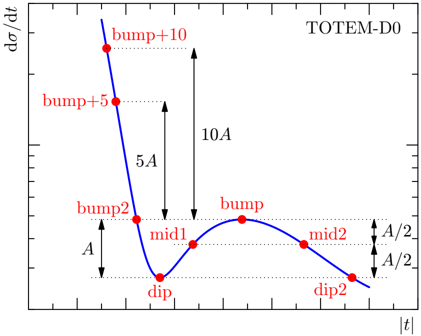
- D0 collected elastic $p\bar{p}$ data with intact p and $\bar{p}$ detected in the Forward Proton Detector with 31 nb^{-1} Phys. Rev. D 86 (2012) 012009
- Measurement of elastic $p\bar{p}$ $d\sigma/dt$ at 1.96 TeV for $0.26 < |t| < 1.2$ GeV^2

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



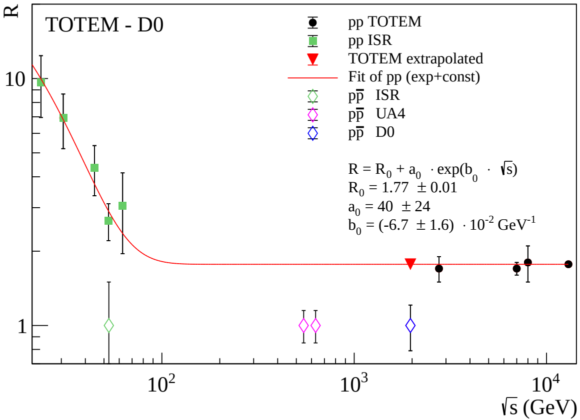
- In order to identify differences between pp and $p\bar{p}$ elastic $d\sigma/dt$ data, we need to compare TOTEM measurements at 2.76, 7, 8, 13 TeV and D0 measurements at 1.96 TeV
- All TOTEM $d\sigma/dt$ measurements show the same features, namely the presence of a dip and a bump in data, whereas D0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

Reference points of elastic $d\sigma/dt$



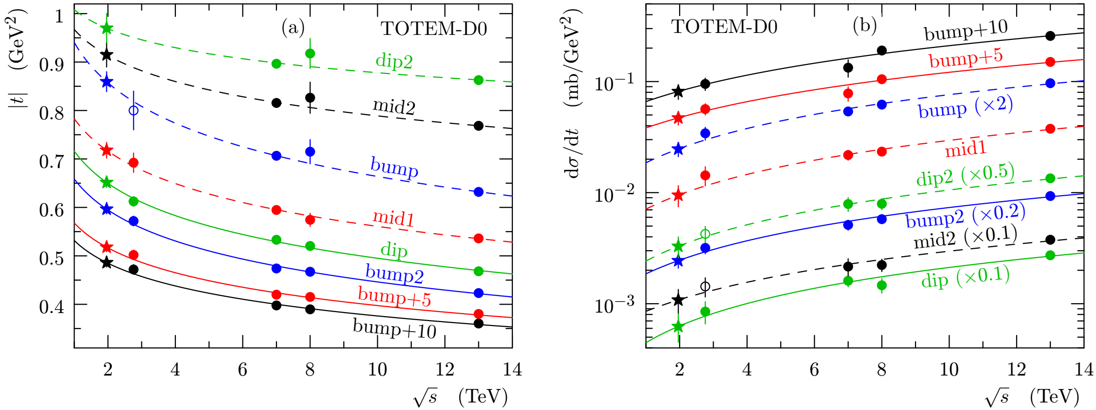
- Define 8 characteristic points of elastic *pp* $d\sigma/dt$ cross sections (dip, bump...) that are feature of elastic *pp* interactions
- Determine how the values of $|t|$ and $d\sigma/dt$ of characteristic points vary as a function of $\sqrt{s}$ in order to predict their values at 1.96 TeV
- We use data points closest to those characteristic points (avoiding model-dependent fits)
- Data bins are merged in case there are two adjacent dip or bump points of about equal value
- This gives a distribution of t and $d\sigma/dt$ values as a function of $\sqrt{s}$ for all characteristic points

Bump over dip ratio



- Bump over dip ratio measured for pp interactions at ISR and LHC energies
- Bump over dip ratio in pp elastic collisions: decreasing as a function of $\sqrt{s}$ up to $\sim$ 100 GeV and flat above
- D0 $p\bar{p}$ shows a ratio of 1.00$\pm$0.21 given the fact that no bump/dip is observed in $p\bar{p}$ data within uncertainties: **more than 3σ difference between pp and $p\bar{p}$ elastic data** (assuming flat behavior above $\sqrt{s} = 100 GeV$)

Variation of t and $d\sigma/dt$ values for reference points

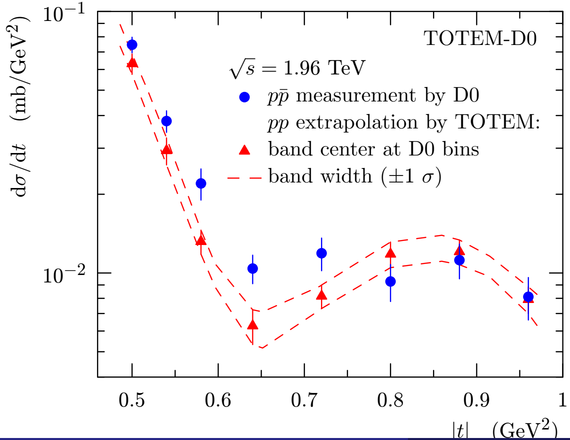


$$|t| = a\log(\sqrt{s}[\mathrm{TeV}]) + b \qquad (d\sigma/dt) = c\sqrt{s}\ [\mathrm{TeV}] + d$$

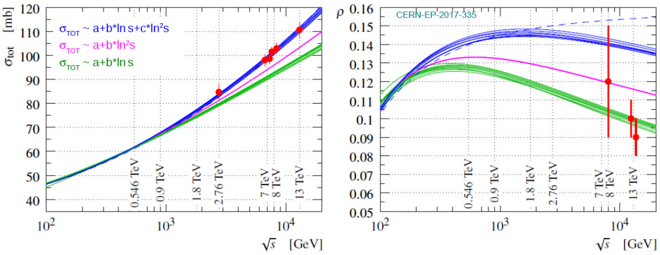
Fits of TOTEM extrapolated characteristic points at 1.96 TeV

- The last step is to predict the *pp* elastic cross sections at the same t values as measured by D0 in order to make a direct comparison
- Fit the reference points extrapolated to 1.96 TeV from TOTEM measurements using a double exponential fit ($\chi^2 = 0.63$ 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
  - Low-t diffractive cone (1st function) and asymmetric structure of bump/dip (2nd function)
  - 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
- Differences in normalization taken into account by adjusting TOTEM and D0 data sets to have the same cross sections at the optical point $d\sigma/dt(t=0)$ (NB: OP cross sections expected to be equal if there are only C-even exchanges)

- Reference points at 1.96 TeV (extrapolating TOTEM data) and 1σ uncertainty band
- Comparison with D0 data: the χ^2 test with six degrees of freedom yields the ***p*-value of 0.00061, corresponding to a significance of 3.4σ**



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



- Using low $|t|$ data in the Coulomb-nuclear interference region, measurement of ρ at 13 TeV: $\rho = 0.09 \pm 0.01$ (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)
- This result can be explained by the exchange of the Odderon in addition to the Pomeron

Comparison between D0 measurement and extrapolated TOTEM data

- Combination with the independent evidence of the odderon found by the TOTEM Collaboration using ρ and total cross section measurements at low t in a completely different kinematical domain
- For the models included in COMPETE, the TOTEM ρ measurement at 13 TeV provided a 3.4 to 4.6σ significance, to be combined with the D0/TOTEM result
- The combined significance ranges from **5.3 to 5.7σ depending on the model**
- Models without colorless C-odd gluonic compound are excluded including the Durham model and different sets of COMPETE models (blue, magenta and green bands on the previous slide)

Conclusion

- Total and elastic cross sections measured by the TOTEM collaboration at 2.76, 7, 8 and 13 TeV: non-exponential behavior of $d\sigma/dt$
- Detailed comparison between $p\bar{p}$ (1.96 TeV from D0) and pp (2.76, 7, 8, 13 TeV from TOTEM) elastic $d\sigma/dt$ data - FERMILAB-PUB-20-568-E; CERN-EP-2020-236, accepted in PRL
- **pp and $p\bar{p}$ cross sections differ with a significance of 3.4σ in a model-independent way and thus provides 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: Major discovery at CERN/Tevatron**