Odderon observation by TOTEM and Do

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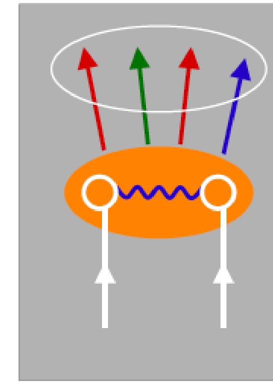
on behalf of Totem Collaboration

High energy particle diffraction

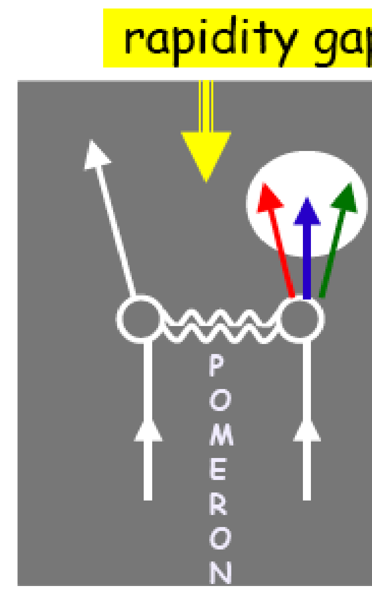
Non-diffractive hadron scattering

- Exchange of quantum numbers possible
- Rapidity gaps exponentially suppressed $\mathrm{d}N/\mathrm{d}\Delta\eta \sim e^{-\Delta\eta}$
- Incident hadrons acquire color and break apart



Diffractive hadron scattering

- No exchange of quantum number: no color exchange
- Rapidity gaps constant $\mathrm{d}N/\mathrm{d}\Delta\eta \sim const$
- One or both hadrons can survive the interaction (i.e. **elastic scattering**).
- At low |t| (soft diffraction) pQCD cannot be applied, but Regge phenomenological model can describe the data.
- Diffraction is modeled as an exchange of one or more ”objects” or ”trajectories” with vacuum quantum number. The leading trajectory is called Pomeron.



Notes on Regge framework

The Pomeron was first introduced during 60's in the Regge theory framework

$$A_{el}(s,t) \sim -\sum_{\xi=\pm1}\sum_i \beta_i(t)\frac{1+\xi e^{-i\pi\alpha_i(t)}}{\sin\pi\alpha_i(t)} s^{\alpha_i(t)}$$

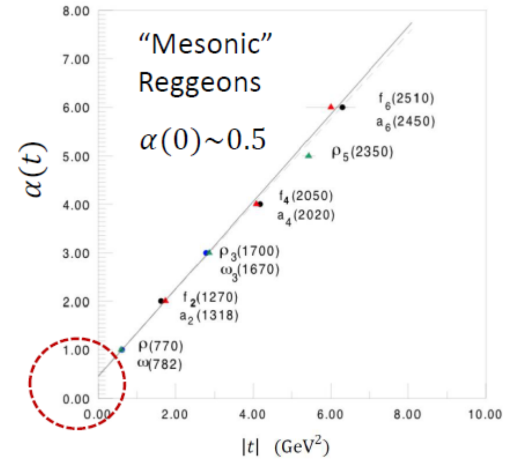
$\alpha_i(t)$ represents a trajectory (Reggeon) in the complex plane which interpolates the poles ($\alpha_i(t)$=j, j integer) of the scattering amplitude.

The poles identify resonances and bound state of increasing j --> A Reggeon is an exchange of a family of resonances with same quantum numbers.

In the high energy limit A_{el}(s,t) depends only on the leading pole $\alpha(t)$

Adding the Optical Theorem in the high energy limit:

$$\sigma_{tot} \cong \frac{1}{s} Im\, A_{el}(s,t=0) \quad \Rightarrow \quad \sigma_{tot} \sim s^{\alpha(0)-1}$$

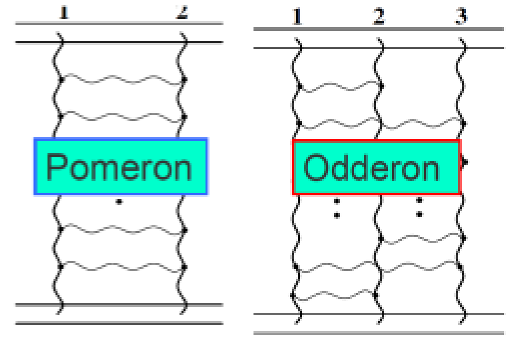


All Reggeons cooresponding to known mesons exchange have intercept below 1 --> Pomeron (C=P=1) introduced as the dominant trajectory with intercept above 1 to explain the observed increases with energy of hadronic cross sections

Fit on a large dataset of pp and $p\bar{p}$ gives a value for intercept α(0)~1.08 (Donnachie-Landshoff *)

* *Phys.Lett. B*, **296** (1992) 227-232

The Odderon



The Odderon is an interesting but elusive object. Its history goes back to 1973 when the possible contribution of a C-odd exchange in very high energy collisions was first studied.

Regge-like framework

Odderon: C-odd partner of the Pomeron, with intercept close to one.

In the limit of high energies and low t, the amplitude A_{el} is predominantly imaginary for the Pomeron and real for the Odderon.

QCD

Odderon existence is also a fundamental prediction of pQCD, where it is represented (in the most basic form) by the **exchange of a colourless 3-gluon bound state in the t-channel**. A $J^{PC}=1^{--}$ state predicted by lattice QCD with a mass of about 3 to 4 GeV (***vector glueball***).

Odderon effects are subdominant to the Pomeron (double gluon exchange in pQCD) -> need to investigate regions where Pomeron exchange contribution is small or where crossing-odd properties can emerge.

Odderon effect on ρ-σ_{tot} relation

More sensitive to the Odderon exchange than the cross section is the ρ parameter:

$$\rho = \left.\frac{\mathrm{Re}\,A(s,t)}{\mathrm{Im}\,A(s,t)}\right|_{t=0}$$

While Optical theorem relates Im$A(s,0)$ and σ_{tot}, general analyticity and crossing properties relate the real and the imaginary parts through dispersion relations.

It was demonstrated (Bronzan , Kane and Sukhatme *) that the crossing even part of ρ can be expressed as

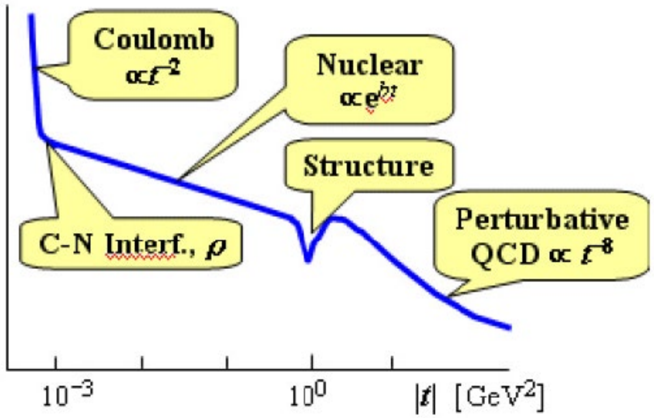
$$\rho^{+} \cong \frac{\pi}{2\sigma^{+}_{tot}} \frac{d\sigma^{+}_{tot}}{d\ln s} \qquad \rho_{pp} \sim \rho^{+} - \rho^{-}$$

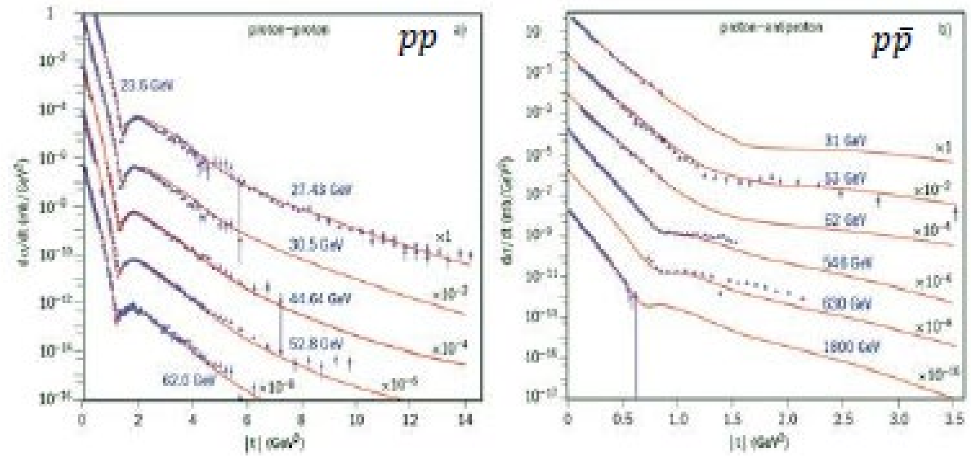
Deviation from this relation at LHC energy, where mesonic reggeon contributions are negligible, represents a hint for a non vanishing crossing odd contribution, the Odderon.

The contribution of the Odderon to the Re$A(s,t)$ generates a value of ρ deviating from predictions.

* *Phys. Lett. B*, **49** (1974) 3, pp.272-276

Elastic scattering dσ/dt





Main features of the elastic differential cross section:

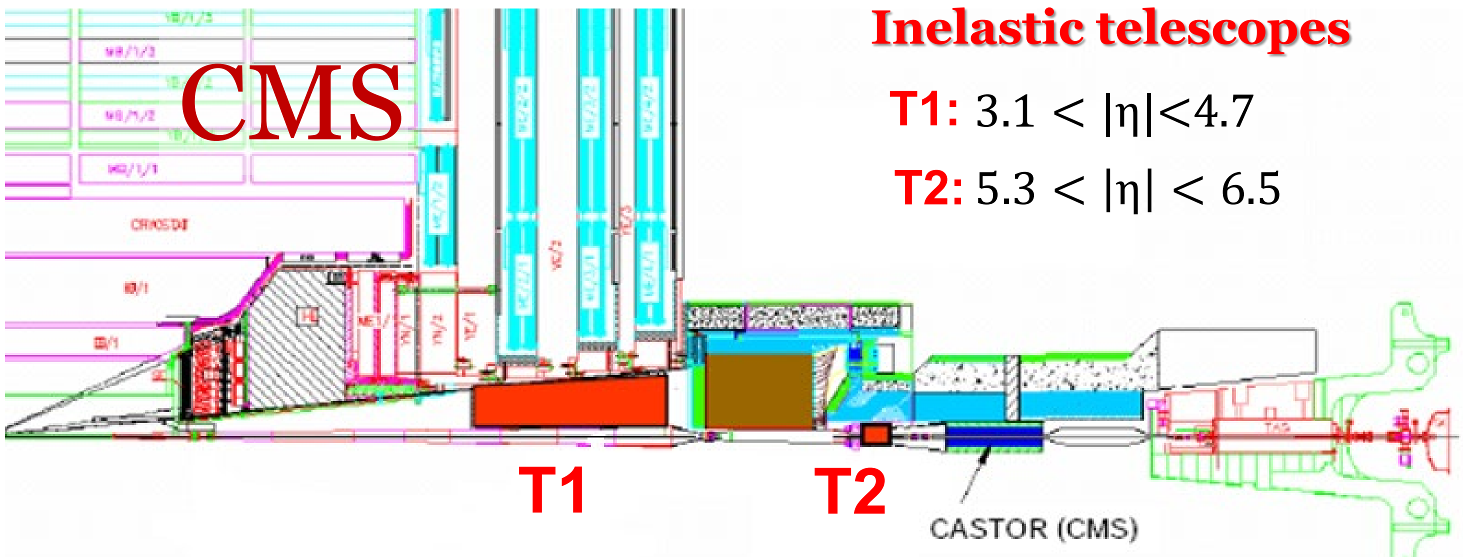
- Forward peak with exponential behavior (at first approximation)
- Shrinkage of the forward peak with energy, well described by Regge theory with no analogies in optical diffraction
- Dip and bump structure (pp) or shoulder ($p\bar{p}$)
- $\sim|t|^{-8}$ beahviour at larger |t| (as per pQCD prediction dominated by the exchange of 3 free gluons)

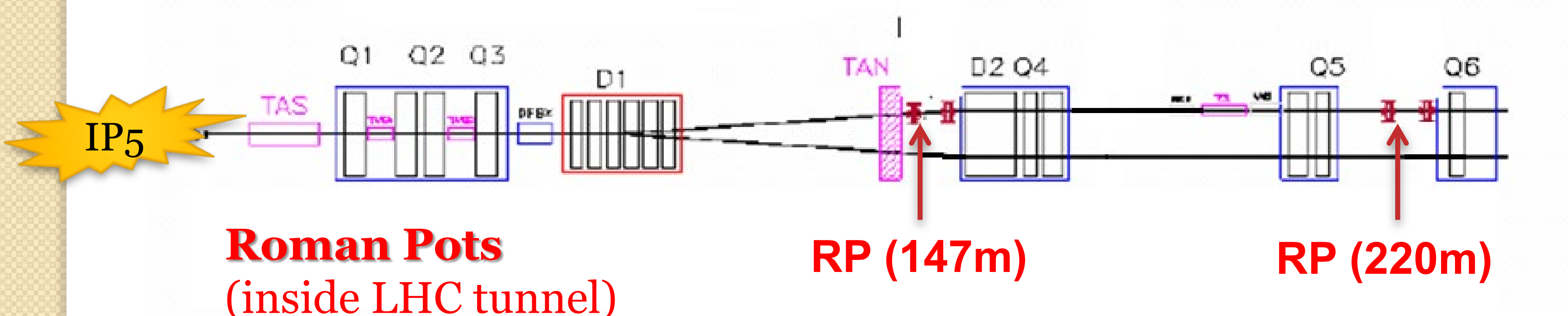
The dip can be described as the |t|-range where $\text{Im}\,A(s,t)$ is crossing zero, dσ/dt is thus dominated by the real part of the amplitude to which a 3-gluon exchange contributes.

- The cross-odd behaviour of the Odderon leads to a different dip-bump structure in pp and $p\bar{p}$ data.
- At lower (ISR) energies the difference can be due to the mesonic Reggeons contributions

The experiments: TOTEM at LHC

- Inelastic telescopes and proton tagging detectors



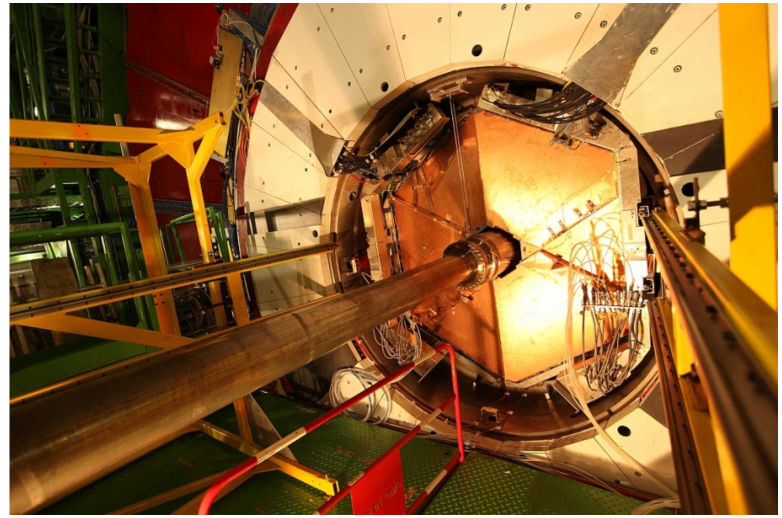


TOTEM inelastic telescopes

- Inelastic event counting, charged multiplicity, rapidity gaps

T1

- 5 CSC planes
- $3.1<|\eta|<4.7$
- $\Delta\phi = 2\pi$

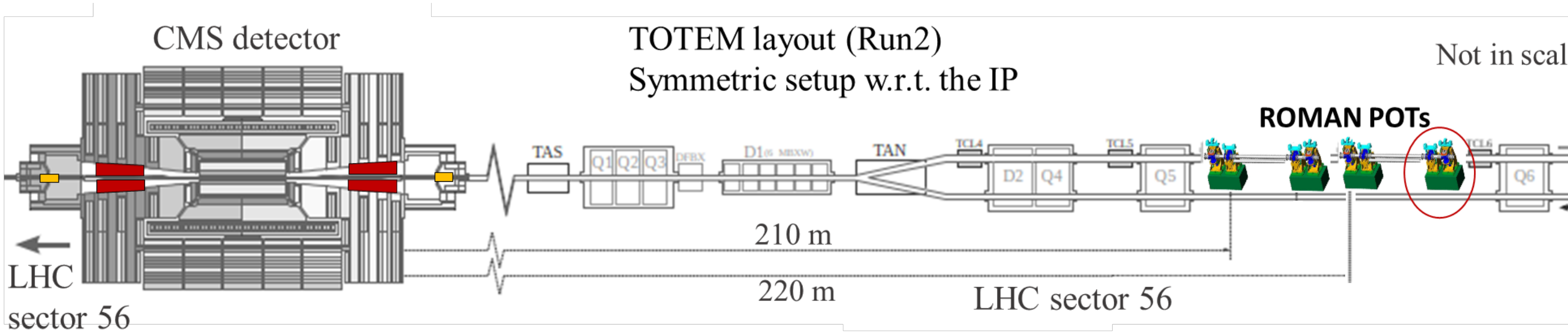


Designed, built and operated by INFN - Genova

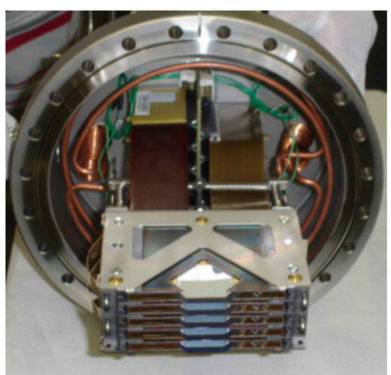
T2

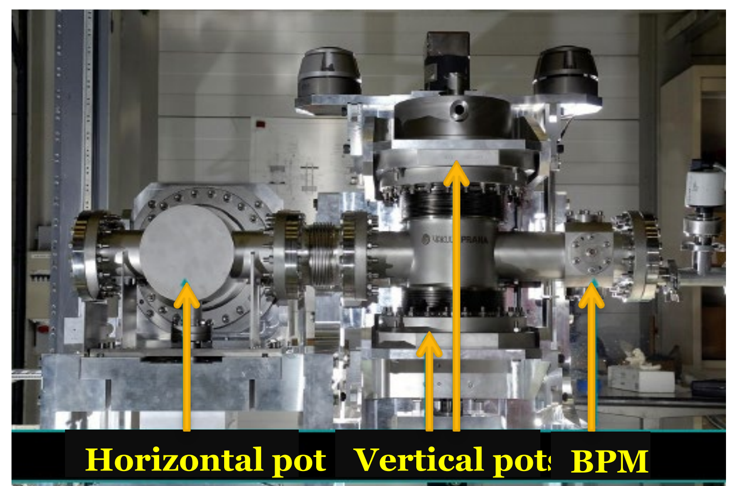
- 10 GEM planes
- $5.3<|\eta|<6.5$
- $\Delta\phi = 2\pi$

TOTEM proton detectors

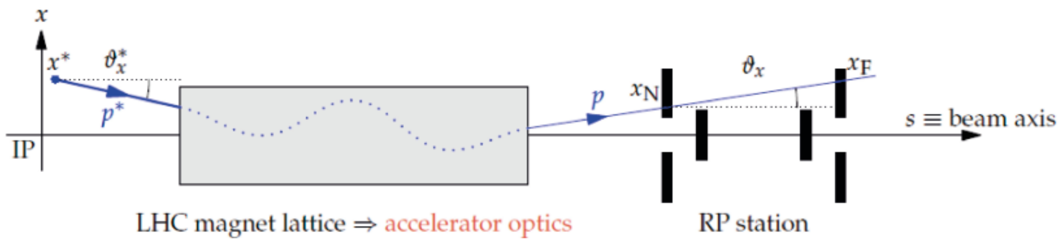


- **Detection of the leading protons**
- Roman pot stations in the LHC tunnel at 147m and 220m from IP (both sides)
- 10 edgeless (<50μm) Si micro strip detectors per pot
- Resolution ~15μm





Proton reconstruction and beam optics



- (x^*, y^*): vertex position
- (θ_x^*, θ_y^*): emission angle: $t \approx -p^2(\theta_x^{*2} + \theta_y^{*2})$
- $\xi = \Delta p/p$: momentum loss (elastic case: $\xi = 0$)

Measured in RP

$$\begin{pmatrix} x \\ \Theta_x \\ y \\ \Theta_y \\ \Delta p/p \end{pmatrix}_{RP} = \begin{pmatrix} v_x & L_x & 0 & 0 & D_x \\ v'_x & L'_x & 0 & 0 & D'_x \\ 0 & 0 & v_y & L_y & 0 \\ 0 & 0 & v'_y & L'_y & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x^* \\ \Theta_x^* \\ y^* \\ \Theta_y^* \\ \Delta p/p \end{pmatrix}_{IP5}$$

Values at IP5 to be reconstructed

Product of all lattice element matrices

$$x_{RP} = L_x \Theta_x^* + v_x x^* + D_x \xi$$

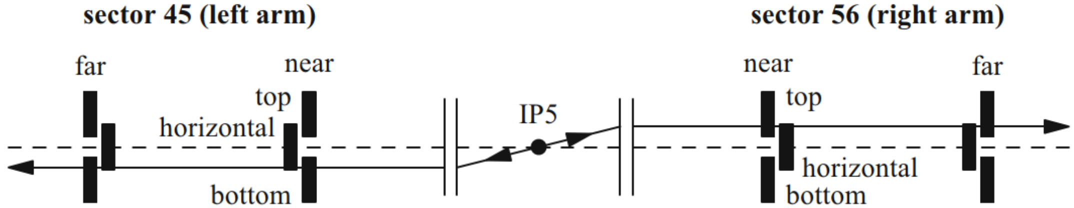
$$y_{RP} = L_y \Theta_y^* + v_y y^*$$

- L_x, L_y: effective lengths (sensitivity to scattering angle)
- v_x, v_y: magnifications (sensitivity to vertex position)
- D_x : dispersion (sensitivity to momentum loss); $D_y \sim 0$:

Reconstruction of proton kinematics inverting the transport equation

Excellent beam optics understanding needed

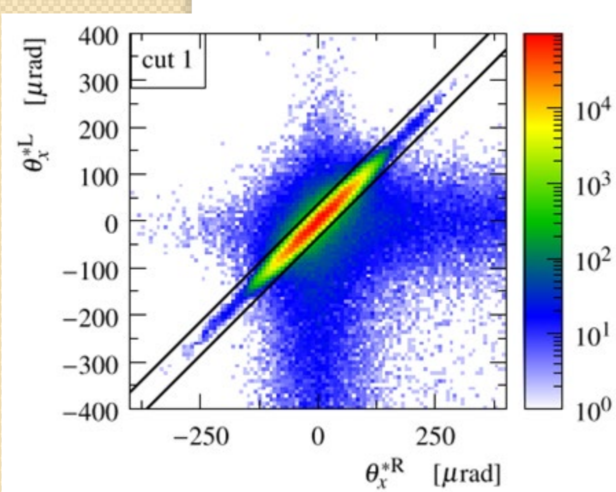
Elastic event selection



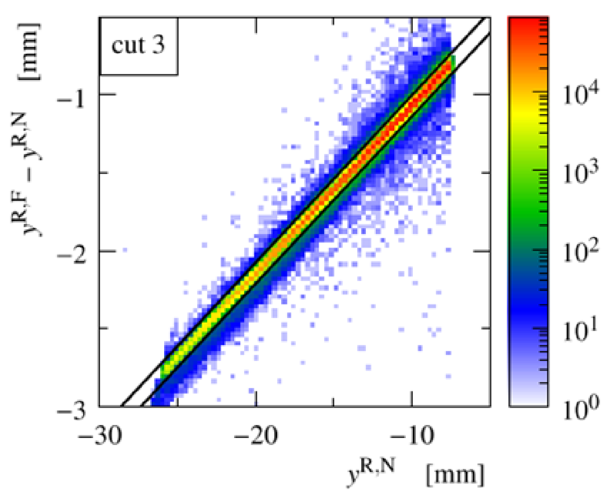
+ opposite configuration

Further elastic selection is performed with the application of selection cuts, tuned with the data.

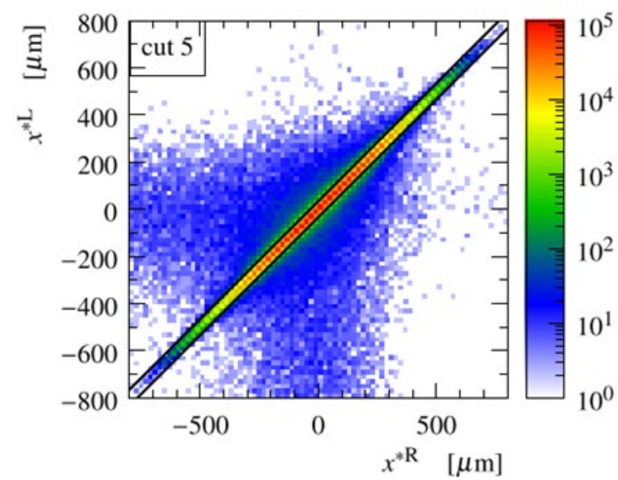
Collinearity



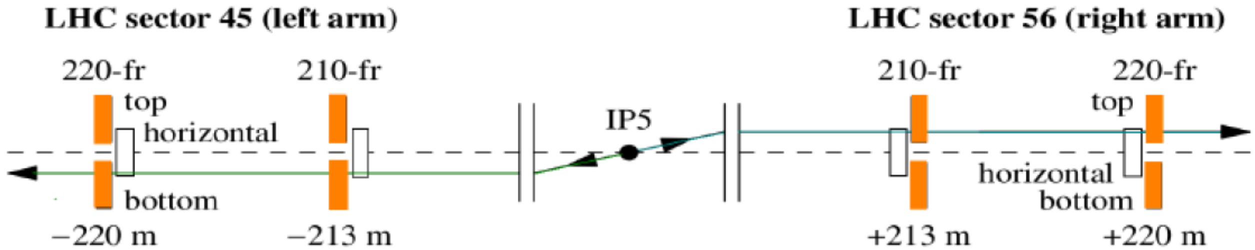
Angle/position correlation

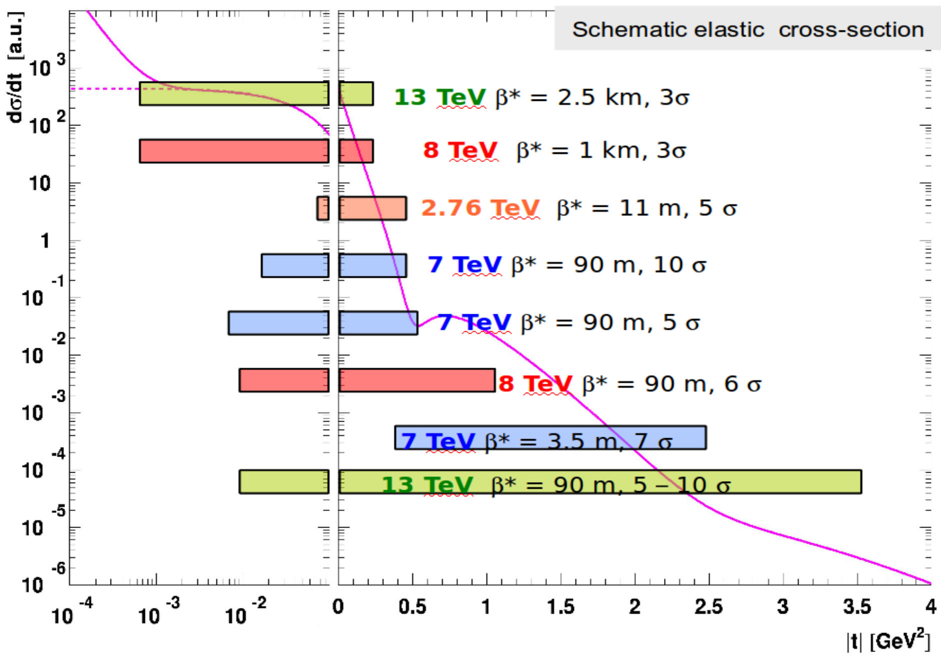


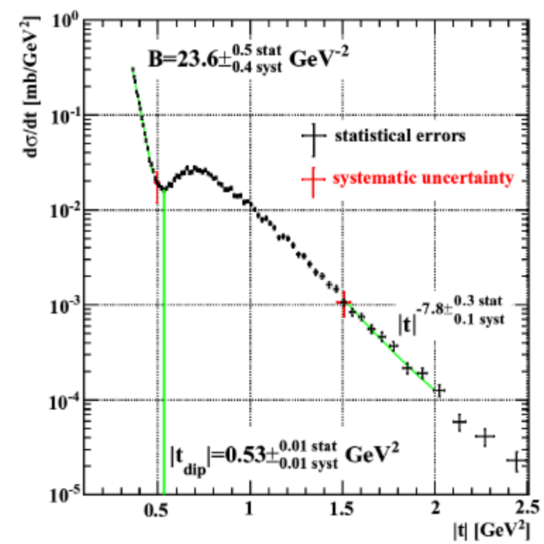
Vertex compatibility



Elastic scattering at TOTEM







- Elastic pp dσ/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*

pp total cross section measurements

- $dN_{el}/dt|_{t=0}$
- $\sigma_{el} \leftarrow dN_{el}/dt$ integr.
- Luminosity (from CMS)
- N_{inel} (from T1 & T2)
- ρ from COMPETE

elastic observation only
(through Optical theorem)

$$\sigma_{tot}^{2} = \frac{16\pi}{1+\rho^2}\frac{1}{\mathcal{L}}\frac{dN_{el}}{dt}\bigg|_{t=0}$$

σ_{tot}

ρ independent

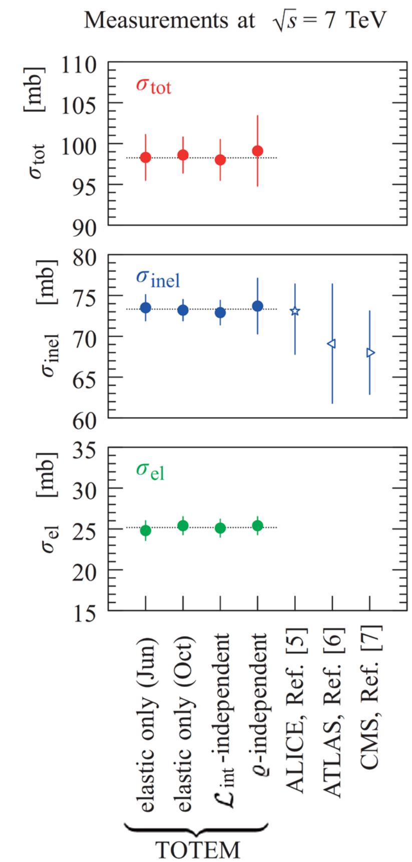
$$\sigma_{tot} = \frac{1}{\mathcal{L}}\left(N_{el} + N_{inel}\right)$$

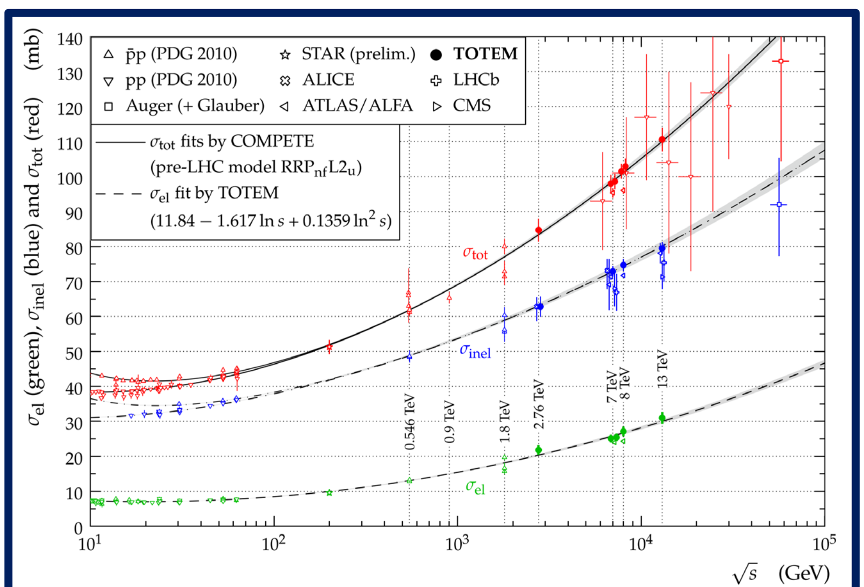
From T1 & T2 data σ_{inel} can be directly measured

luminosity independent

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

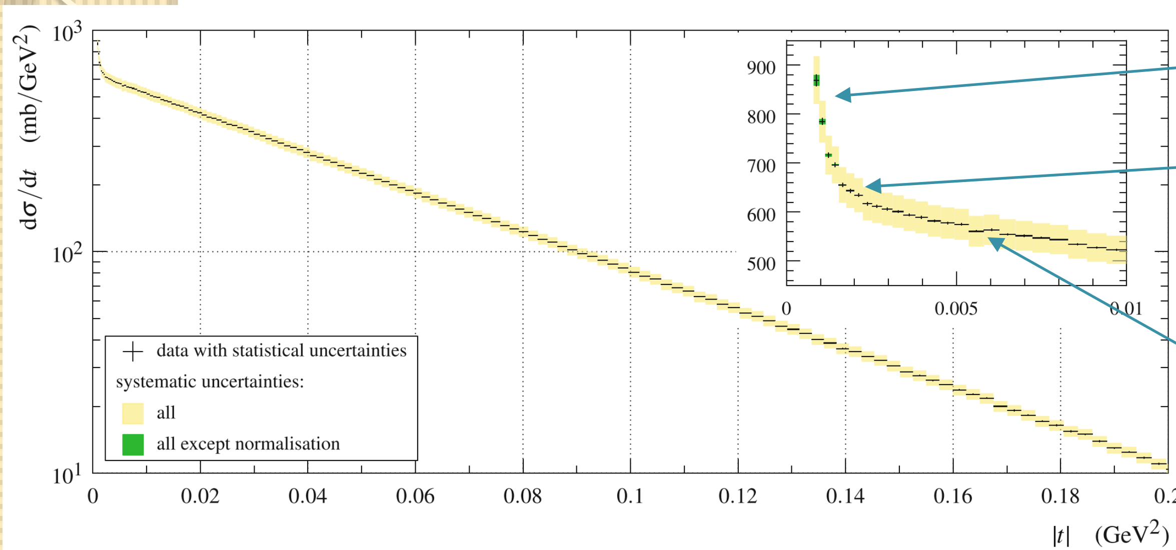
Preferred method due to the large uncertainty on $\mathcal{L}$

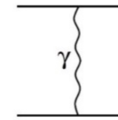




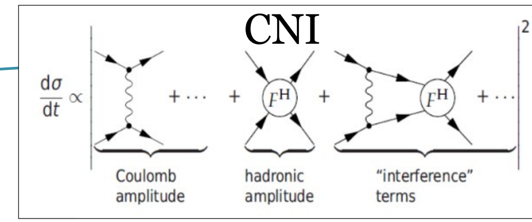
pp elastic scattering at very low-t

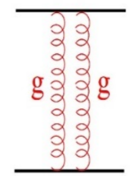
At small enough |t| the pp scattering is also affected by the Coulomb interaction. Need investigation of very low-t region ($|t| < 10^{-3}\ \mathrm{GeV}^2$).





Coulomb

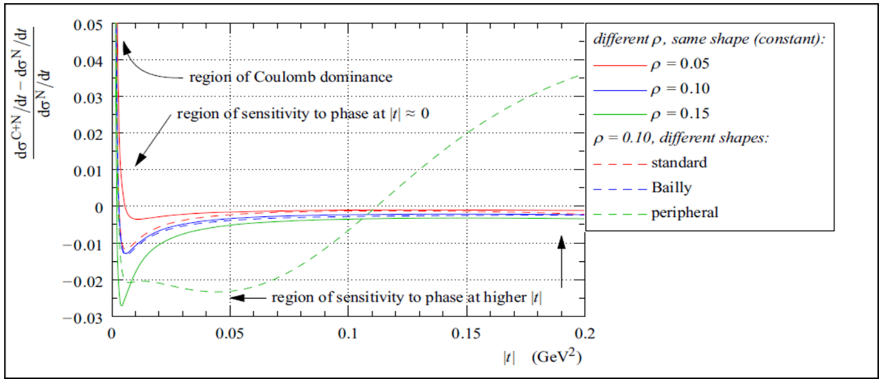


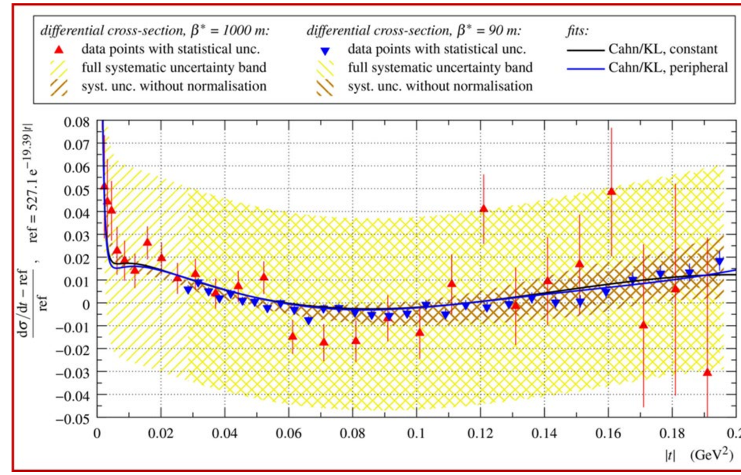


Nuclear (Pomeron)

- Coulomb amplitude well known from QED
- Different phenomenological parametrizations for the other regimes:
    - Hadronic modulus
    - Hadronic phase
    - Interference formula → Contains explicit dependence from ρ

ρ extrapolation in pp

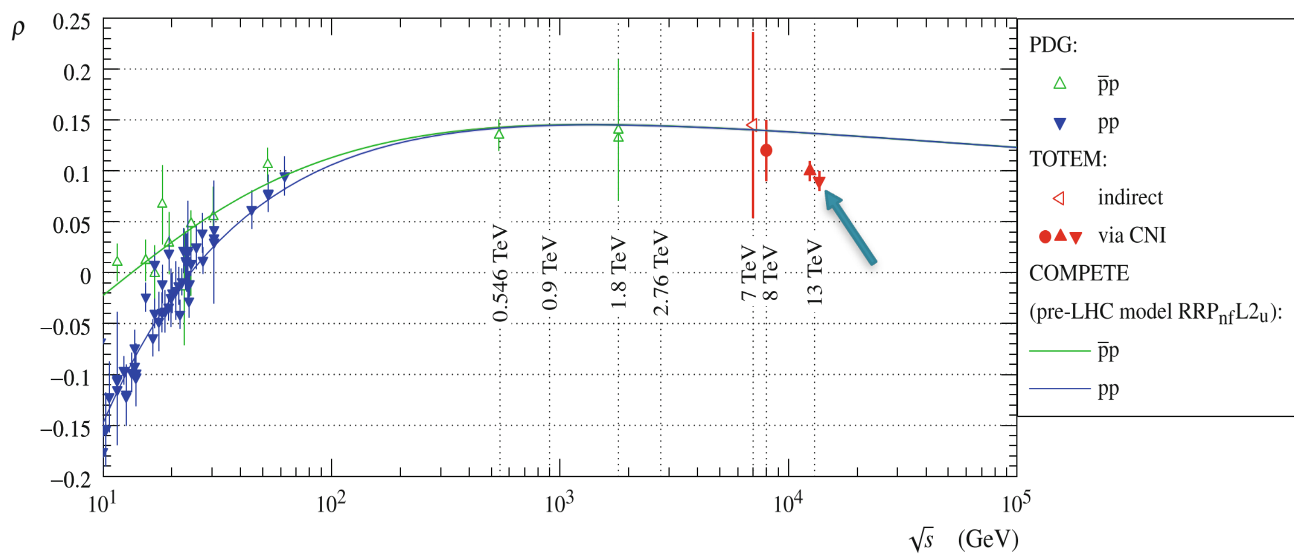




Fit of data in the low-t range allows to determine ρ

Normalization uncertainty introduces an overall scaling factor. Modification to the distribution shape and to the ρ value negligible. Included in systematics.

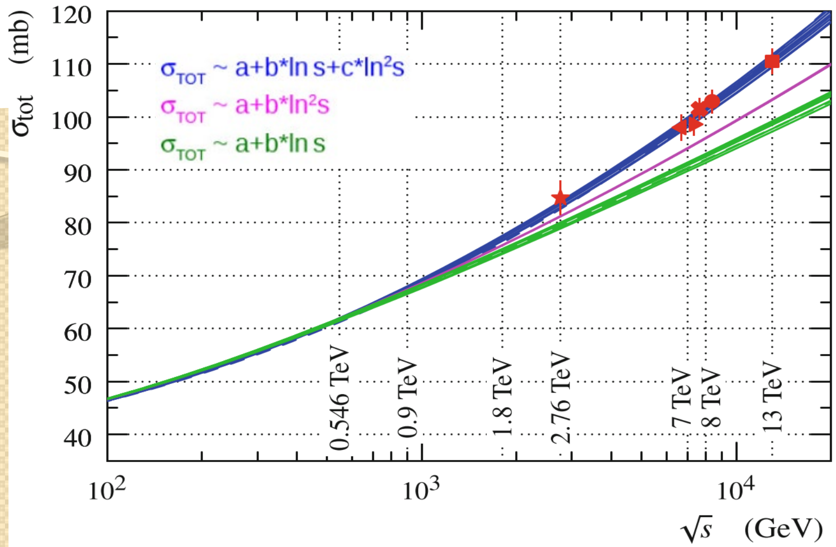
$$\rho = 0.12 \pm 0.3 \; at \; 8 \; TeV$$

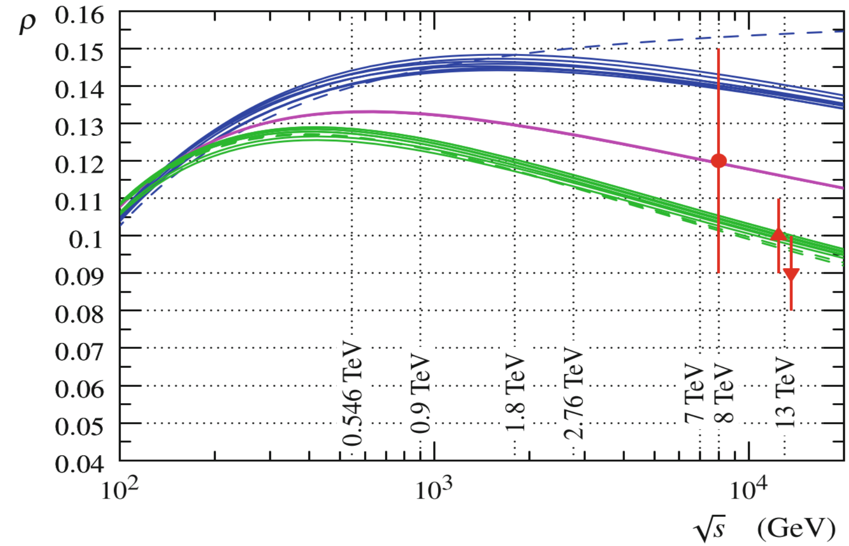


Eur. Phys. J. C 79, (2019) 785

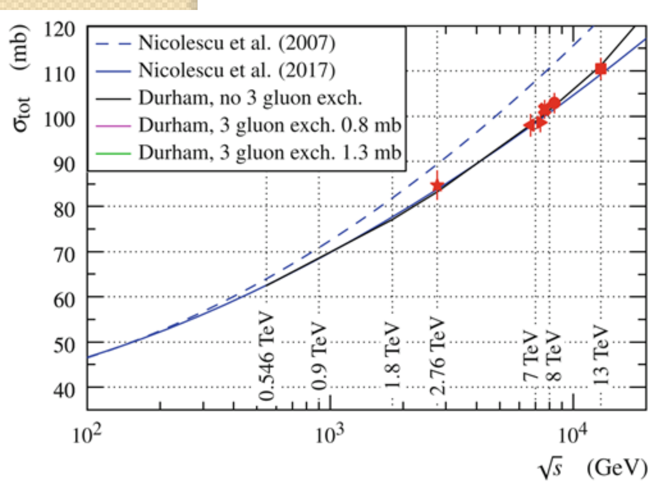
Comparison with models

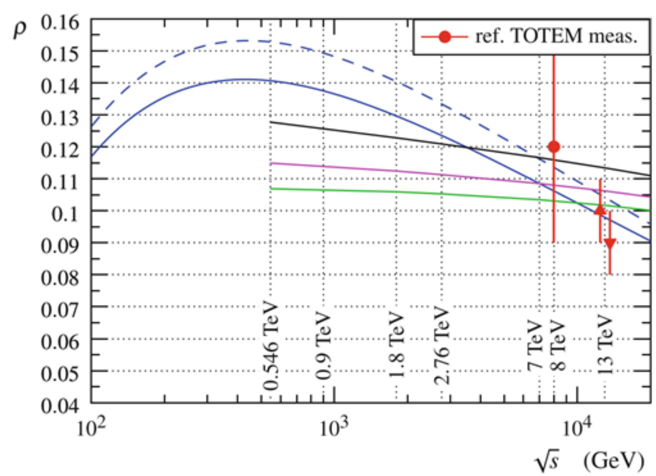
An evidence of Odderon





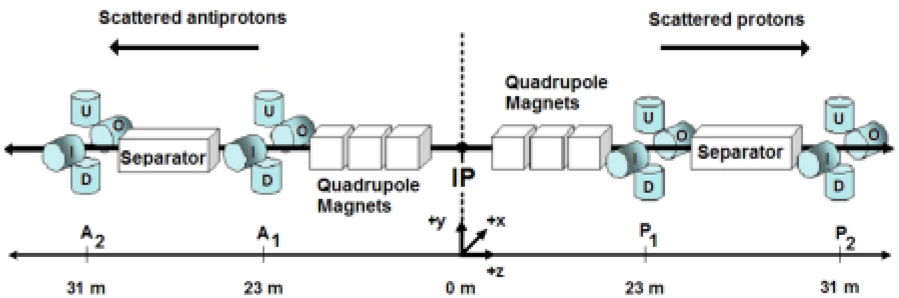
No COMPETE model (where C-odd component not included) able to describe TOTEM σ_{tot} & ρ measurements. Preferred model incompatibility 4.6σ



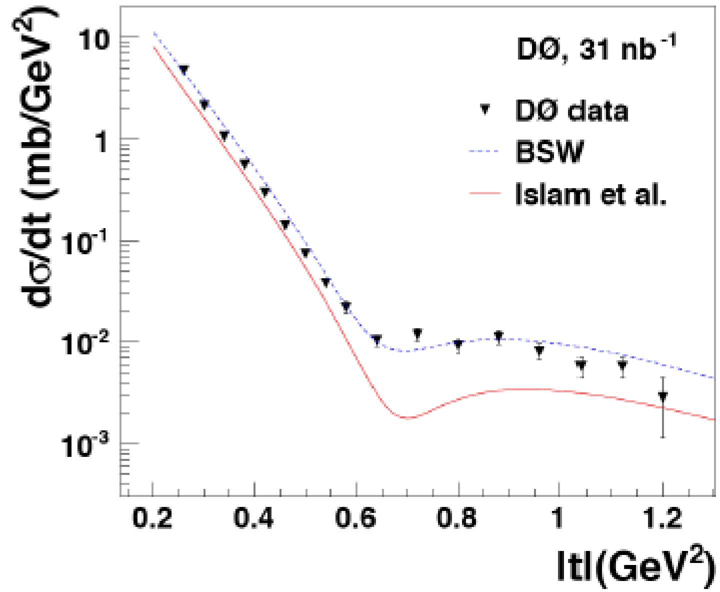


Models with C-odd exchange can describe the data

Elastic scattering at D0



- The FPD detectors used for the analysis consists of spectrometers on both the scattered proton and scattered antiproton sides, two vertical and two horizontal.
- Each spectrometer is composed of two scintillating fiber detectors, located at about 23 and 31 m from the IP.



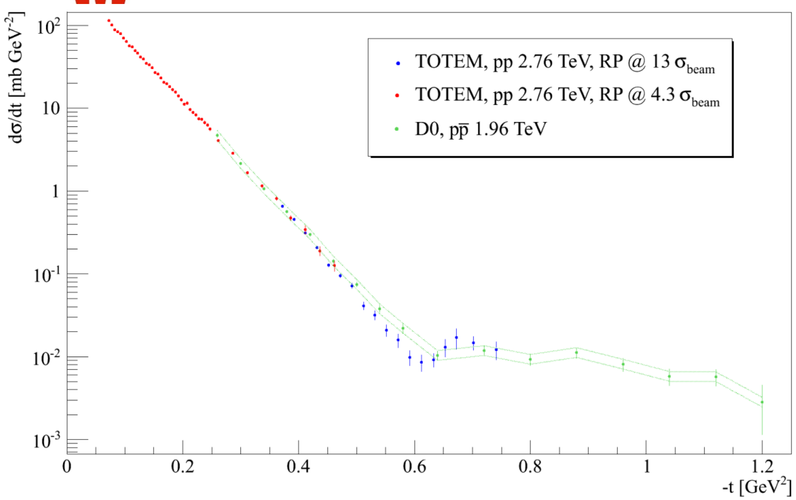
Proton detectors are hosted in Roman Pot like in the TOTEM setup.
Proton kinematics reconstruction procedure similar to the one already discussed

- 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) 12009)
- Measurement of elastic $p\bar{p}$ $d\sigma/dt$ at 1.96 TeV for $0.26 < |t| < 1.2$ GeV^2

Probing dip/bump structure

Data collected by TOTEM at 2.76 TeV are close in energy to D0 result of $p\bar{p}$ measured at 1.96 TeV.

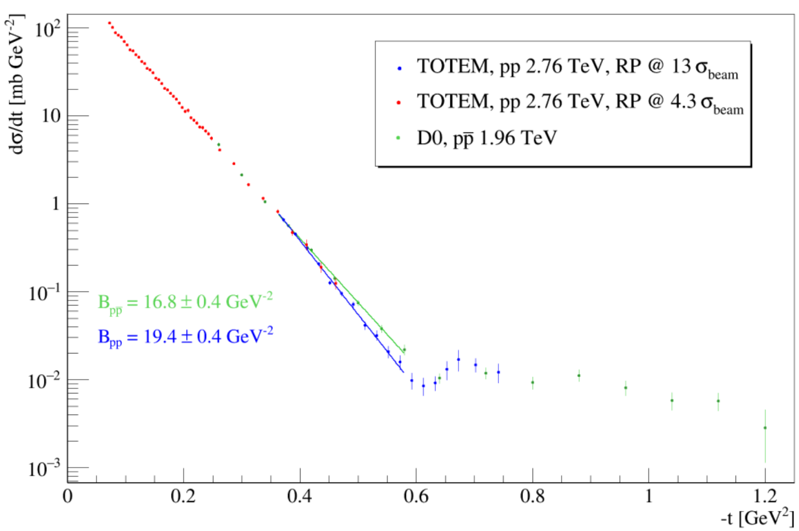
Low-|t| region used for normalization and total cross section measurement



Dip-bump structure compared with the D0 published results. Main parameters:

- $R = \left.\frac{d\sigma}{dt}\right|_{t_{bump}} \Big/ \left.\frac{d\sigma}{dt}\right|_{t_{dip}}$ (dip-bump ratio)

- B slope in the region close to the dip ($0.36 < |t| < 0.54\ \mathrm{GeV}^2$)



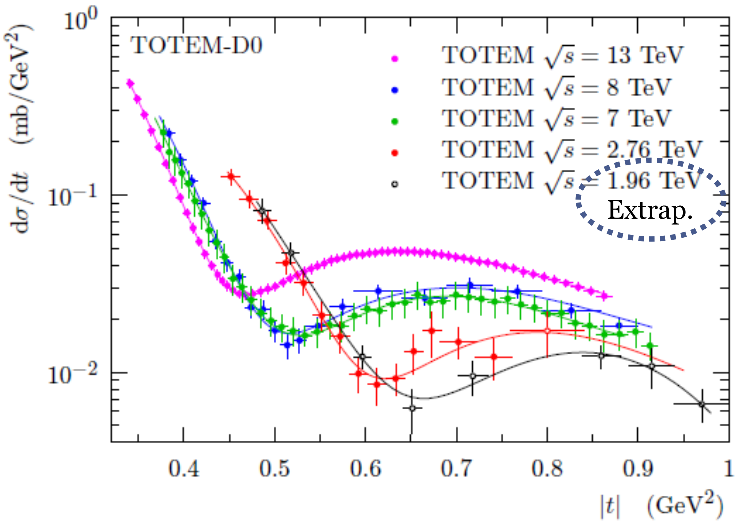
$R_{pp} = 1.7 \pm 0.2$; $R_{p\bar{p}} = 1.0 \pm 0.1$

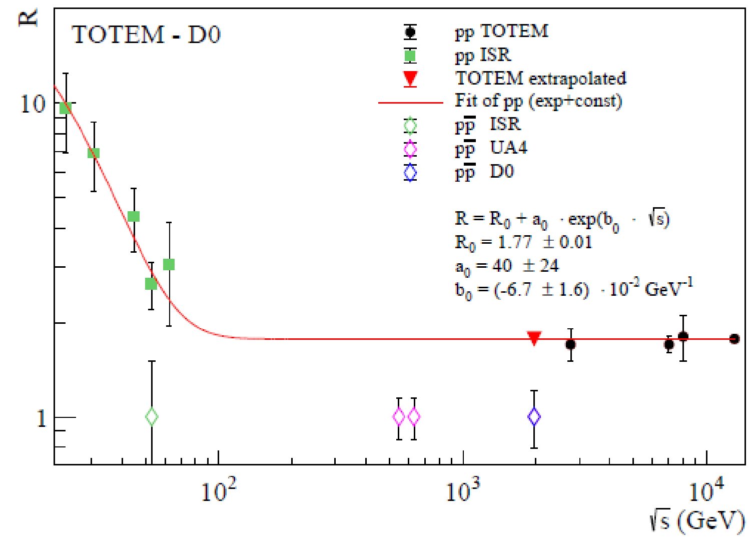
$B_{pp} = 19.4 \pm 0.4\ \mathrm{GeV}^2$; $B_{p\bar{p}} = 16.8 \pm 0.4\ \mathrm{GeV}^2$

Significant incompatibility $\sim 3\sigma$ for R, $\sim 4\sigma$ for B

Still due to 800 GeV difference?

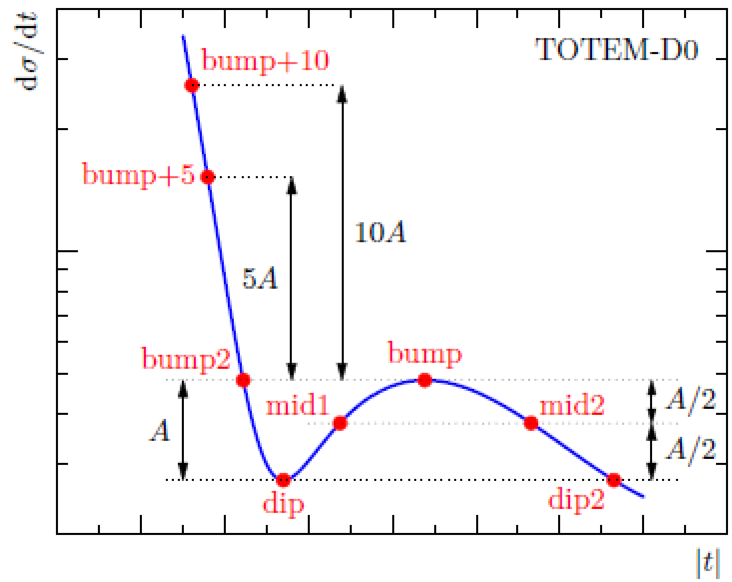
Strategy to compare pp and $p\bar{p}$





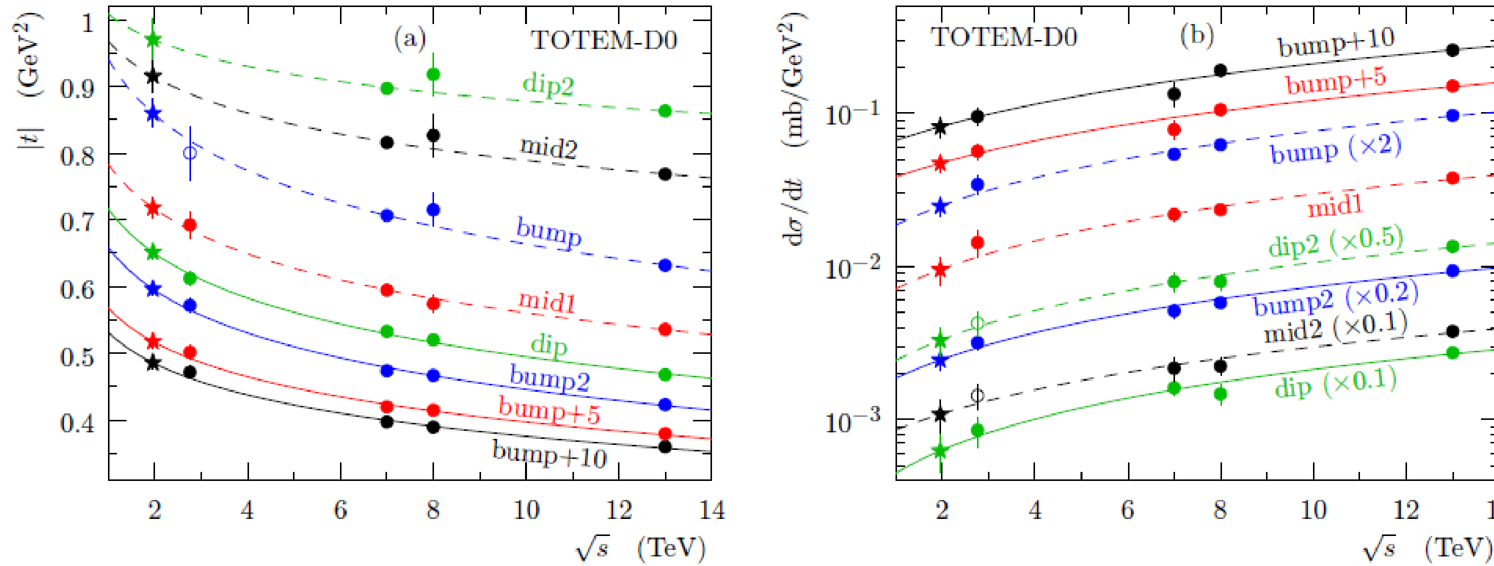
- In order to identify differences between pp and $p\bar{p}$ elastic $d\sigma/dt$ data, we need to compare TOTEM measurements at 2.76, 7, 8, 13 TeV and D0 measurements at 1.96 TeV
- All TOTEM $d\sigma/dt$ measurements show the same features, namely the presence of a dip and a bump in data, whereas D0 data do not show this feature
- Bump over dip ratio in pp elastic collisions: decreasing as a function of $\sqrt{s}$ up to ~100 GeV and flat above
- D0 $p\bar{p}$ shows a ratio of 1.00±0.21 given the fact that no bump-dip structure 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 $\sqrt{s}$ = 100GeV)

Reference points in dσ/dt



- Define 8 characteristic points of elastic pp dσ/dt cross sections (dip, bump...) that are feature of elastic pp interactions
- Determine how the values of |t| and dσ/dt of characteristic points vary as a function of √s in order to predict their values at 1.96 TeV
- 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 dσ/dt values as a function of √s for all characteristic points comparison

Extrapolation of characteristic points for pp data

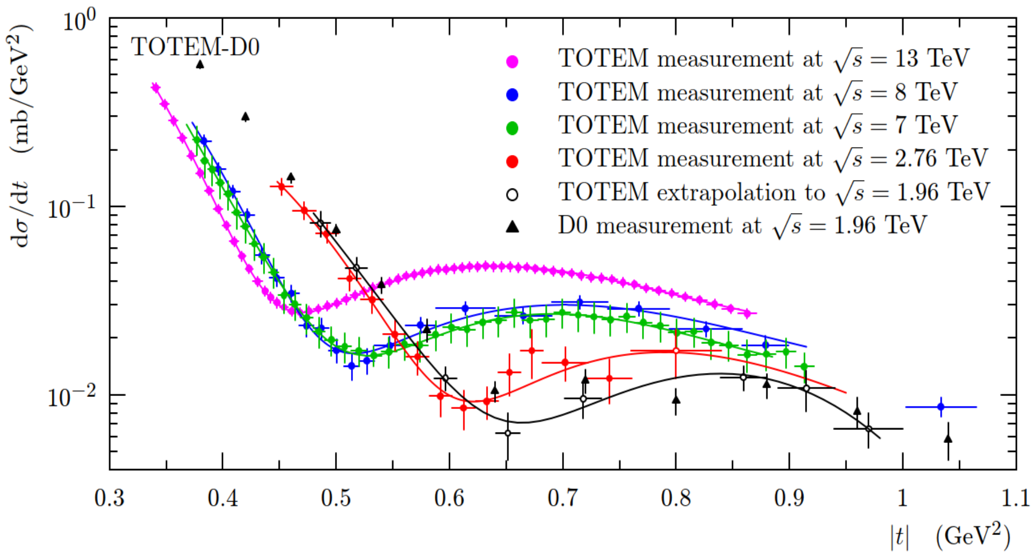


- Fit of all reference points using the following formulae:

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

- The same form is used for the 8 reference points (this is an assumption and works to describe all characteristic points): this simple form is chosen since at most 4 points are fitted, corresponding to $\sqrt{s}$ = 2.76, 7, 8 and 13 TeV
- Alternate parametrizations leading to compatible results within uncertainties
- Leads to very good χ^2 per dof, better than 1 for most of the fits
- Extrapolation of the fits leads to predictions on |t| and dσ/dt at 1.96 TeV for each characteristic point

Fits of TOTEM extrapolated characteristic points at 1.96 TeV

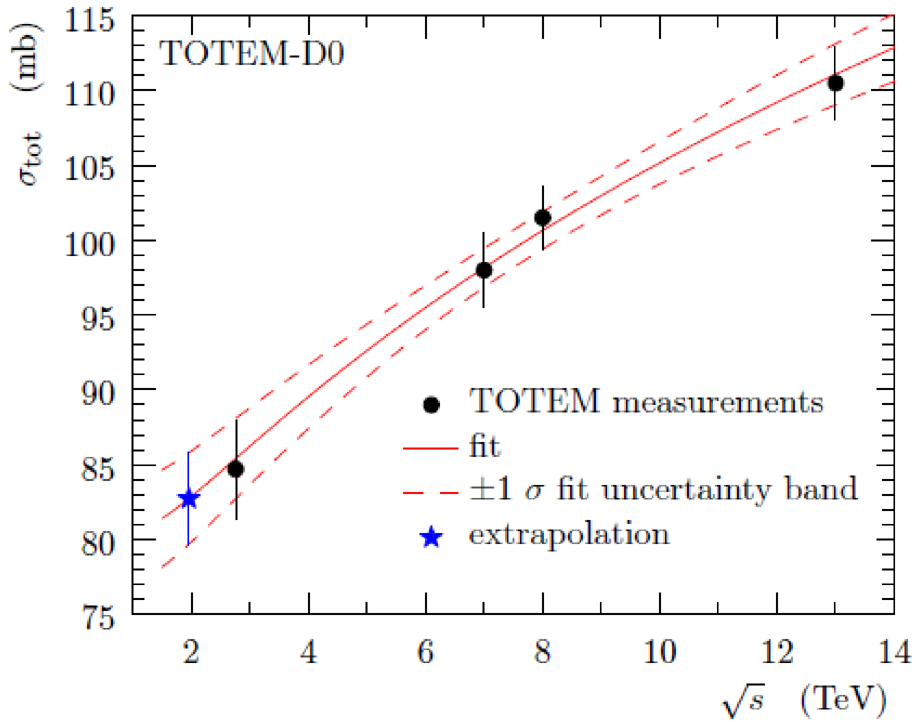


- Predict the pp elastic cross sections at the same t values as measured by D0 in order to make a direct comparison
- Fit the reference points extrapolated to 1.96 TeV from TOTEM measurements using a double exponential fit ($\chi^2 = 0.63$ per dof):

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

  - 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 off the dip
- Systematic uncertainties evaluated from an ensemble of MC experiments in which the cross-section values of the eight characteristic points are varied within their Gaussian uncertainties.
- Such formula leads also to a good description of TOTEM data in the dip/bump region at 2.76, 7, 8 and 13 TeV

Relative normalization



- Differences in normalization taken into account by adjusting TOTEM and D0 data sets to have the same cross sections at the optical point dσ/dt(t = 0)
  - NB: OP cross sections expected to be equal if there are only C-even exchanges (included in systematics)
- Predict the pp total cross section from extrapolated t to TOTEM data (χ^2=0.27)

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

- Leads to an estimate of pp total cross-section at 1.96 TeV of σ_{tot} =82.7±3.1 mb

Rescaling TOTEM data

- Adjust 1.96 TeV dσ/dt(t = 0) from extrapolated TOTEM data to D0 measurement
- From TOTEM pp σ_{tot}, obtain dσ/dt(t = 0) :

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

- Assuming ρ = 0.145, the ratio of the imaginary and the real part of the elastic nuclear amplitude, as taken from COMPETE extrapolation
- This leads to a TOTEM dσ/dt(t = 0) at the OP of 357.1±26.4 mb/GeV^2
- D0 measured the optical point dσ/dt at small t: 341±48 mb/GeV^2
- TOTEM data rescaled by 0.954 ± 0.071
- *NB: No claim of performing a measurement of dσ/dt at the OP (t = 0) since it would require additional measurements closer to t = 0. The two extrapolations simply used to obtain a common and somewhat arbitrary normalization point*

Extrapolate total cross section from TOTEM measurements to 1.96 TeV

$(\sigma_{tot} = b_1 \log^2(\sqrt{s}/1\text{TeV}) + b_2)$

σ_{tot}= 82.7±3.1 mb

→

Compute optical point inverting optical theorem (ρ= 0.145 from COMPETE)

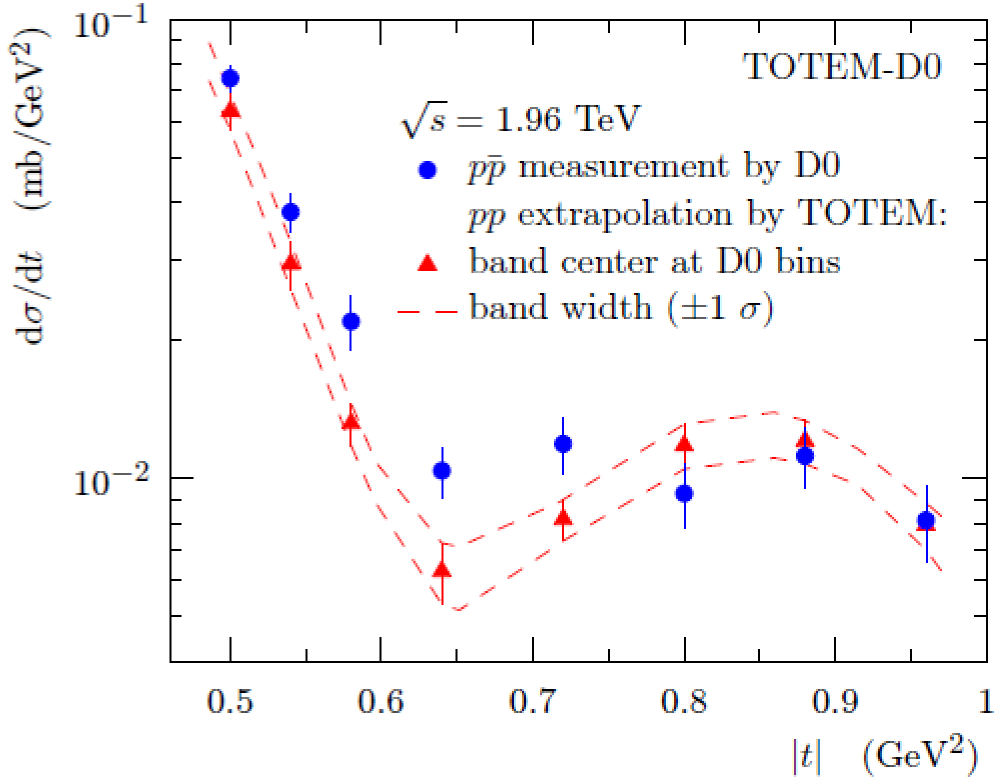
$\left.\frac{d\sigma}{dt}\right|_{t=0}$ = 357 ± 26 mb/GeV^2

→

Calcute OP normalization factor as the ratio of TOTEM and D0 (341 ± 48 mb/GeV^2)

Scale factor = 0.954 ± 0.071

TOTEM-Do comparison at 1.96 TeV

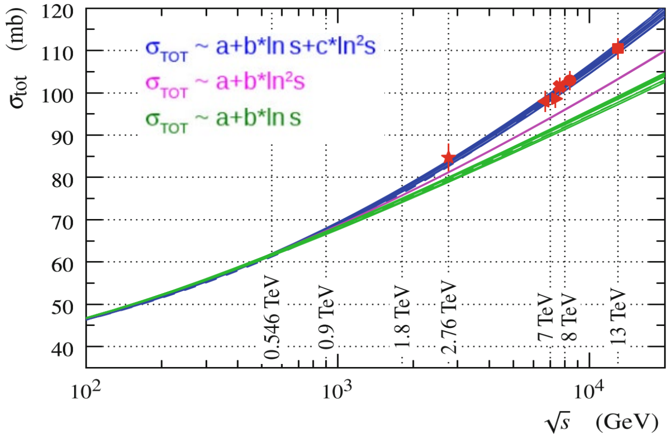


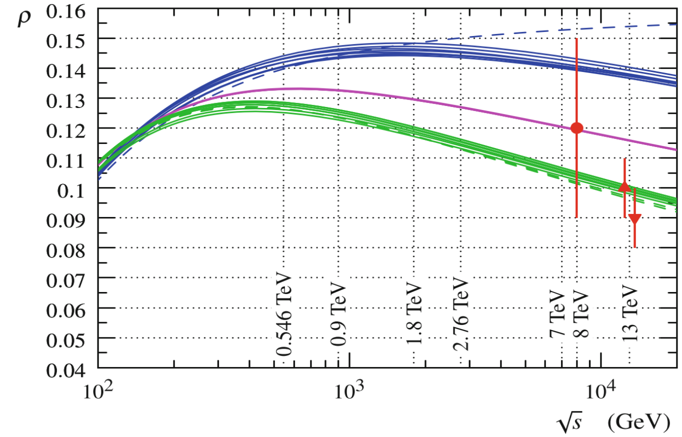
χ^2 test to examine the probability for the Do and TOTEM differential elastic cross sections to agree.

The test use the difference of the integrated cross section in the examined |t|-range with its fully correlated uncertainty, and the experimental and extrapolated points with their covariance matrices

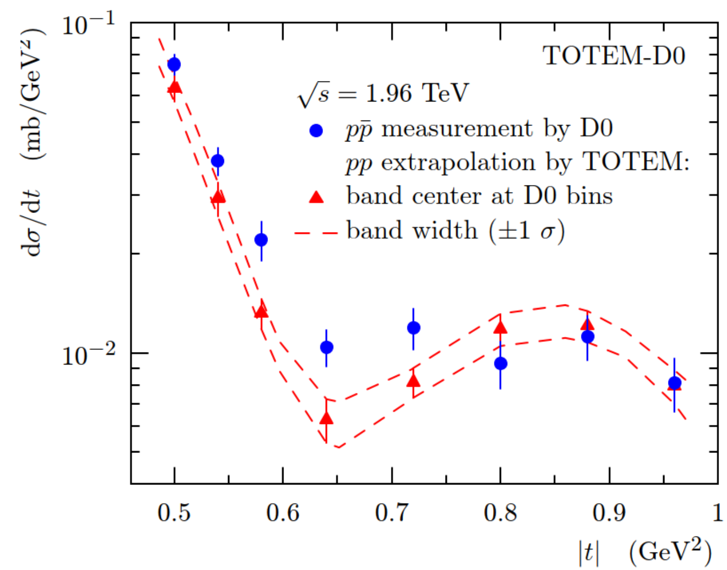
Given the constraints on the OP normalization of the elastic cross sections, the χ^2 test with six degrees of freedom yields the p-value of 0.00061, corresponding to a significance of 3.4σ

Combined significance





Cross section and ρ measurements in completely different t-range w.r.t the pp/p$\bar{\text{p}}$ comparison.



Combined significance (Stouffer method) for t-channel exchange of a colorless C-odd gluonic compound :

- 5.7 σ if preferred COMPETE model is used
- 5.2 to 5.7 σ depending on the model, including model uncertainties

Conclusions

- Detailed comparison between $p\bar{p}$ (1.96 TeV from D0) and pp (2.76, 7, 8, 13 TeV from TOTEM) elastic dσ/dt data - *FERMILAB-PUB-20-568-E; CERN-EP-2020-236*
- R ratio of bump/dip shows a difference of more than 3σ between D0 (R=1.0±0.21), and TOTEM (assuming flat behavior above $\sqrt{s}$ = 100 GeV)
- Fits of 8 *characteristic* points of elastic pp dσ/dt data such as dip, bump, etc. as a function of $\sqrt{s}$ in order to predict pp data 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 provides evidence that the Colorless C-odd gluonic compound (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 5.2 to 5.7 σ and thus constitutes the first experimental observation of the Odderon.