Comparison of pp and $p\bar{p}$ elastic differential cross sections of TOTEM and D0 experiments and Observation of Odderon exchange

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On behalf of D0 and TOTEM Collaborations

Low-x 2021 Workshop

TALK OUTLINE

1. Introduction

2. Brief description of D0 and TOTEM $\frac{d\sigma}{dt}$ measurements

3. Comparison of TOTEM $\frac{d\sigma^{pp}}{dt}$ and D0 $\frac{d\sigma^{p\bar{p}}}{dt}$:
   - 3.1 Bump to dip ratio
   - 3.2 Characteristic points
   - 3.3 Extrapolation
   - 3.4 Uncertainties and normalization

4. Results

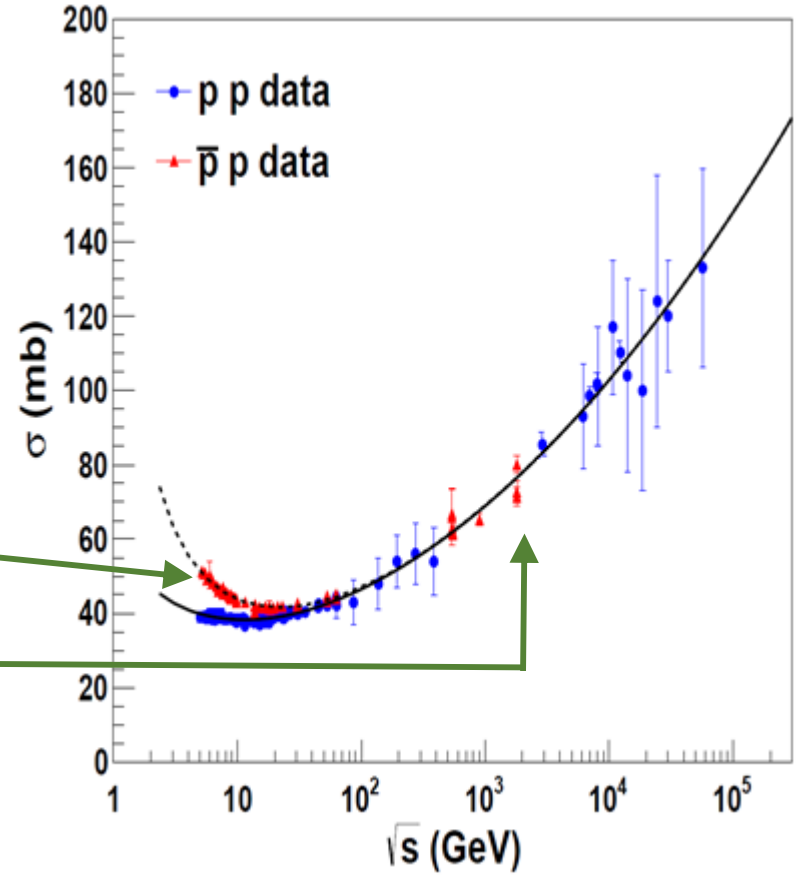
5. Concluding remarks

The Odderon

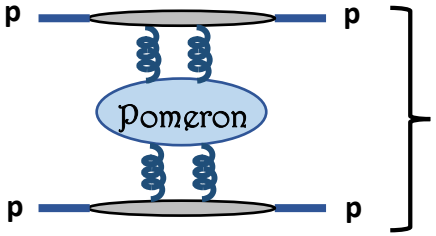
Regge Theory: Barone&Pedrazzi; Collins

At high energies, the poles in the complex angular momentum plane contribute to the scattering amplitude as $A_j(s,t) \sim (s/s_0)^{\alpha_j(t)}$

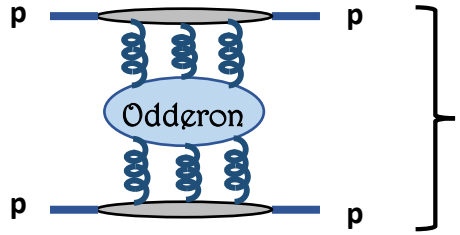
- Regge Trajectory: $\alpha_j(t) = \alpha_j(0) + \alpha_j' t$; $s_0 = 1\text{GeV}^2$
- Optical Theorem: $\sigma_{tot} = \frac{1}{s}\,\text{Im}(A(s,t=0)) \rightarrow \sigma_{tot} \sim (s/s_0)^{\alpha_j(0)-1}$
- ρ, ω, f Regge Trajectories: $\alpha(0) \approx 0.5 \rightarrow \sigma_{tot} \sim (s/s_0)^{-0.5}$
- A trajectory with $\alpha(0) = 1 + \varepsilon$ $(\varepsilon > 0)$ is needed to explain the rise of the total cross section → **Pomeron trajectory**, with C=+1 (contributes equally to pp and $p\bar{p}$ scattering).
- A trajectory with with $\alpha(0) \approx 1$ with C=-1 is also possible → **Odderon** (Lukaszuk&Nicolescu, 1973) (contributes oppositely to pp and $p\bar{p}$ scattering).



Non-perturbative QCD: /hep-ph/0306137.pdf



Pomeron = t-channel exchange of a colorless 2-gluon bound state (at leading order) .



Odderon = t-channel exchange of a colorless 3-gluon bound state (at leading order).

It is easier to make colorless 2-gluon states than colorless 3-gluon states

⇒ $|A_P| \gg |A_O|$

$\mathbb{P}, \mathbb{O}$ exchange in s-channel corresponds to glueballs of 2, 3 gluons, respectively.

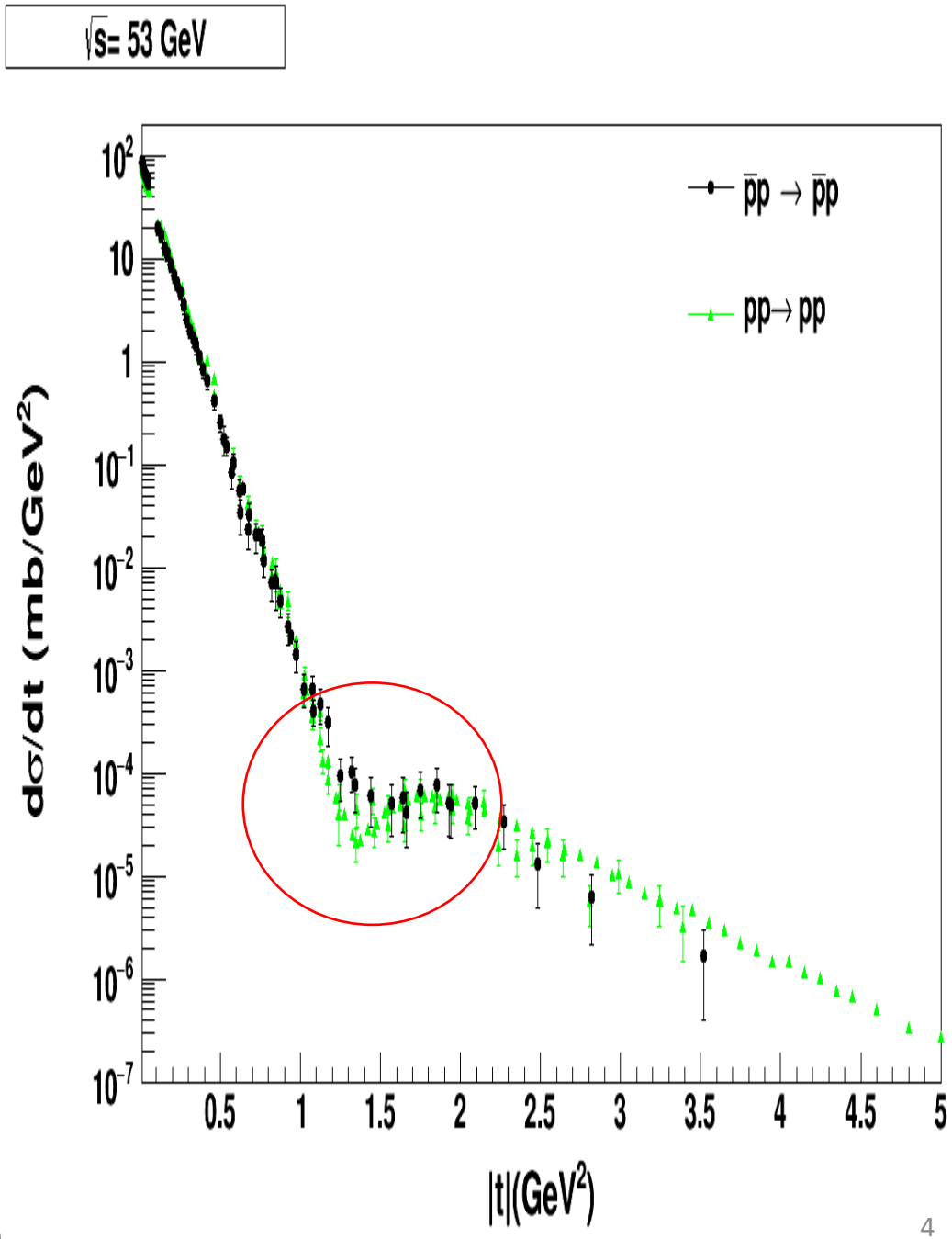
Observables for Odderon effects

At high energies:

$$\frac{d\sigma_{pp}}{dt} = |A_P(s,t) + A_O(s,t)|^2$$

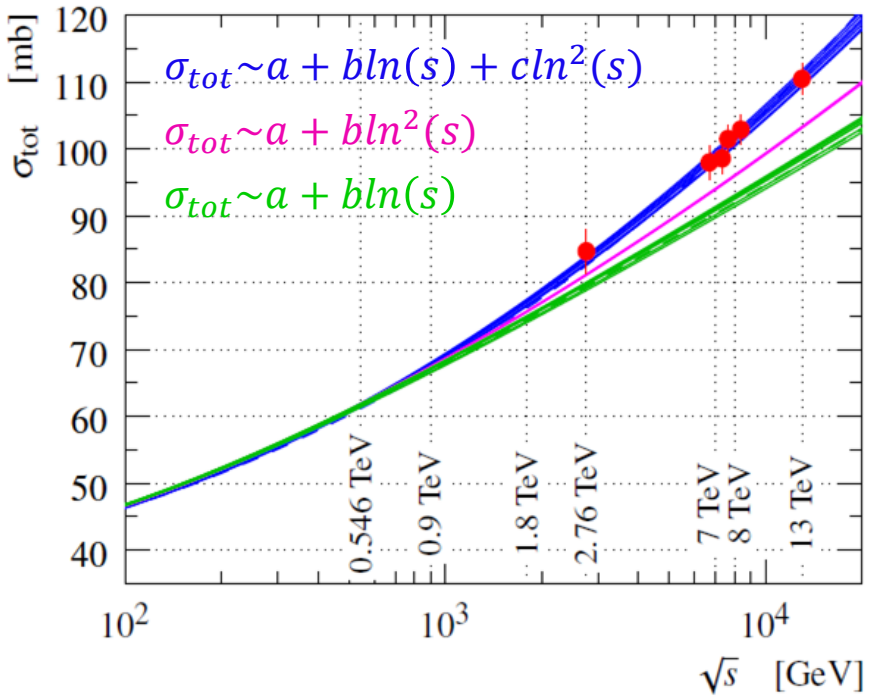
$$\frac{d\sigma_{p\bar{p}}}{dt} = |A_P(s,t) - A_O(s,t)|^2$$

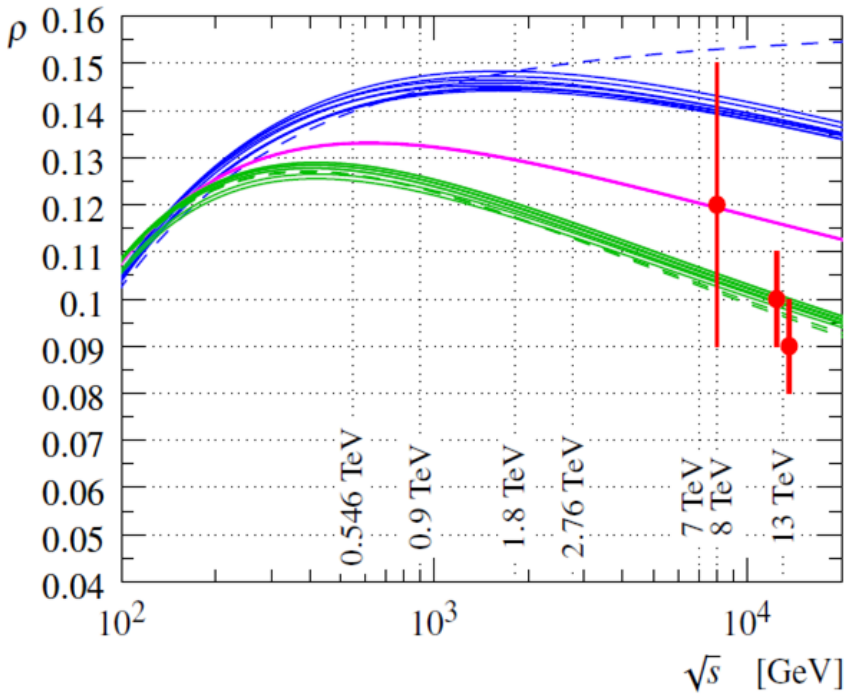
- A_P is mostly imaginary at low values of t, dominating σ_{tot} over A_O which is mostly real.
- Differences in pp and $p\bar{p}$ elastic $\frac{d\sigma}{dt}$ could become observable when A_P is small → around the diffraction minimum.
- Some differences in pp and $p\bar{p}$ elastic $\frac{d\sigma}{dt}$, at 3σ level, have been observed at $\sqrt{s}$ =53 GeV (Breakstone et al, 1985). Given the low CM energy, still there are non-negligible contributions from meson Regge trajectories, so any conclusion about existence of the Odderon cannot be made.
- The evolution of ρ and σ_{tot} with $\sqrt{s}$, $\rho = \frac{Re\{A(s,t=0\}}{Im\{A(s,t=0\}}$, is also useful to determine Odderon effects (TOTEM Collaboration,2019).



Evolution of ρ and σ_{tot} with energy

doi.org/10.1140/epjc/s10052-019-7223-4

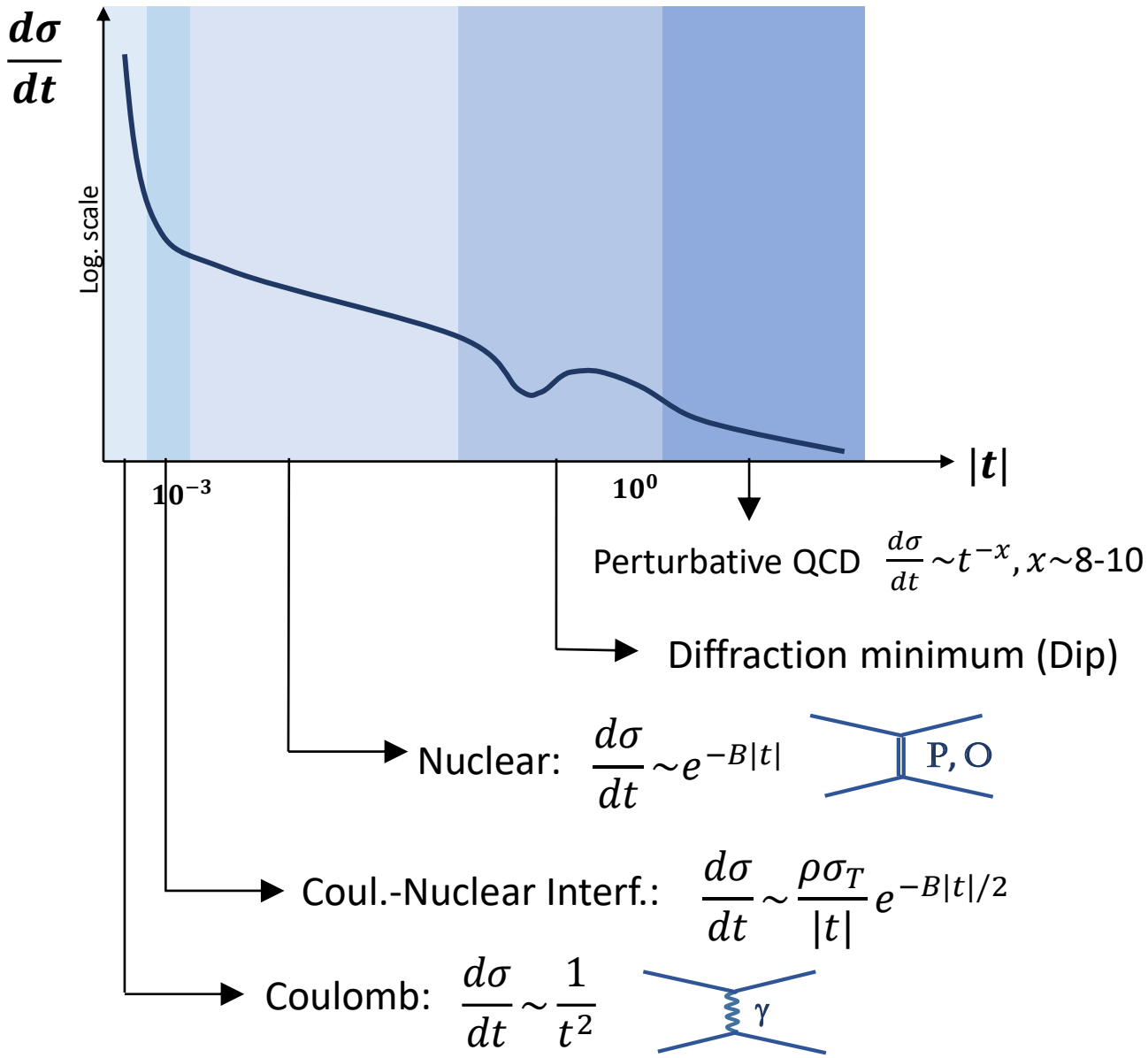




- With a high β optics (β= 2.5 km) at $\sqrt{s} = 13\ TeV$, TOTEM reached very low |t| values (|t|~8x10^{-4} GeV^2) that allowed a precise measurement of ρ: $\boldsymbol{\rho = 0.09 \pm 0.01}$.
- None of the 256 Pomeron-only models studied by the COMPETE Collaboration, nor Durham, nor Block-Halzen describe simultaneously the ensemble of σ_{tot} and ρ data measured by the TOTEM experiment.
- Additional C=-1 amplitude is needed to explain the evolution of σ_{tot} and ρ with $\sqrt{s}$, with a significance of 3.4 – 4.6σ for the range of models.

$pp - p\bar{p}$ elastic scattering at TeV energies

General structure of elastic $\frac{d\sigma}{dt}$:



$$t = -4p^2 sin^2\left(\frac{\theta}{2}\right) \approx -p^2\theta^2$$

- Very small scattering angles have to be reached:

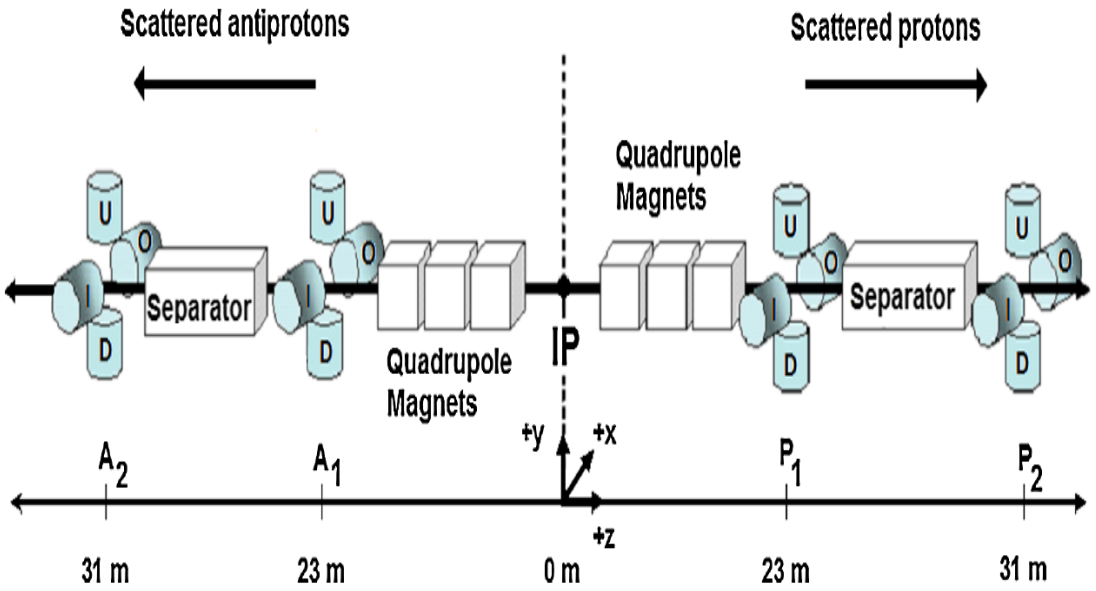
$\sqrt{s}$ (TeV)	$\theta_{interf.}(\mu rad)$
1.96	~ 16
13.0	~ 2

- Need to locate detectors as far as possible to the interaction point and as close as possible to the particle beam axis → Use Roman pots & special high β accelerator optics.

- Measured coordinates of scattered protons (or antiprotons) with respect to beam axis to reconstruct scattering angle and t (precise understanding of particle transport between IP and roman pots is crucial).

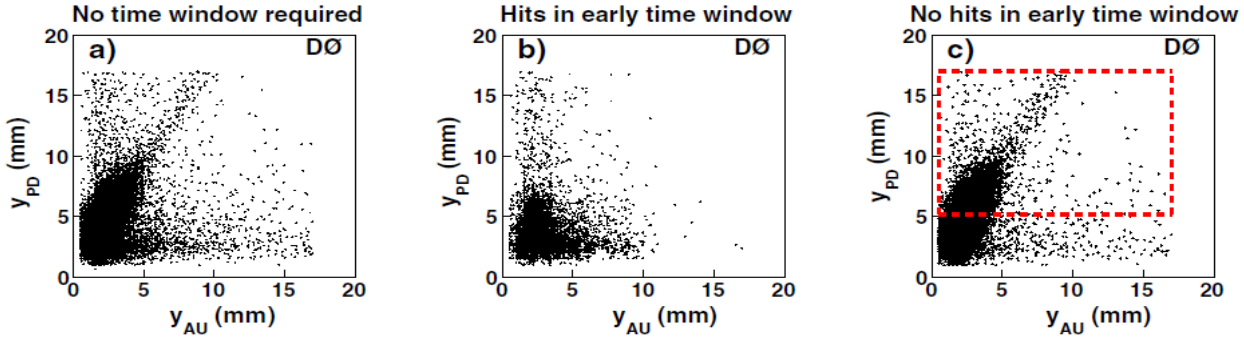
- Measure number of elastic pp ($p\bar{p}$) events as function of t, correcting for acceptance and efficiencies, and normalize to integrated luminosity or to a luminosity-independent σ_{tot} measurement to obtain $d\sigma/dt$.

Measurement of $p\bar{p}$ elastic $d\sigma/dt$ by D0 experiment

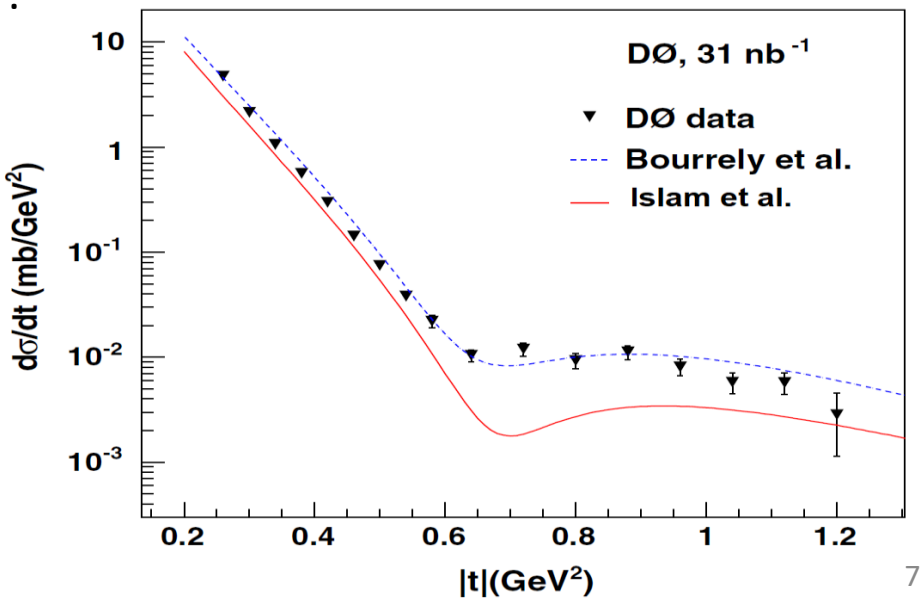


- Scintillating fiber detectors inside Roman pots (RP).
- Use vertical RP´s for measurement and horizontal RP´s for alignment.
- Integrated luminosity recorded = 31 nb^{-1}
- Data taken with a Tevatron injection lattice ($\beta^* = 1.6\ m$)
- |t| range covered: 0.26<|t|<|1.2| GeV/c^2.

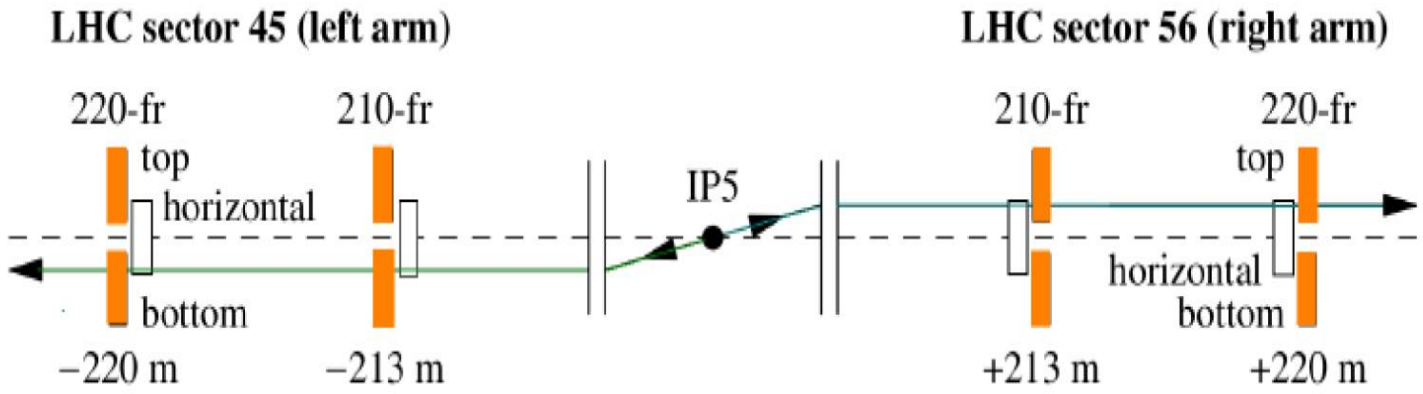
- Select elastic events with same θ, opposite ϕ and consistent timing from IP.
- Estimate backgrounds from data with timing consistent with beam halo.
- Reconstruct θ from detector coordinates and beam transport matrices.



doi/10.1103/PhysRevD.86.012009

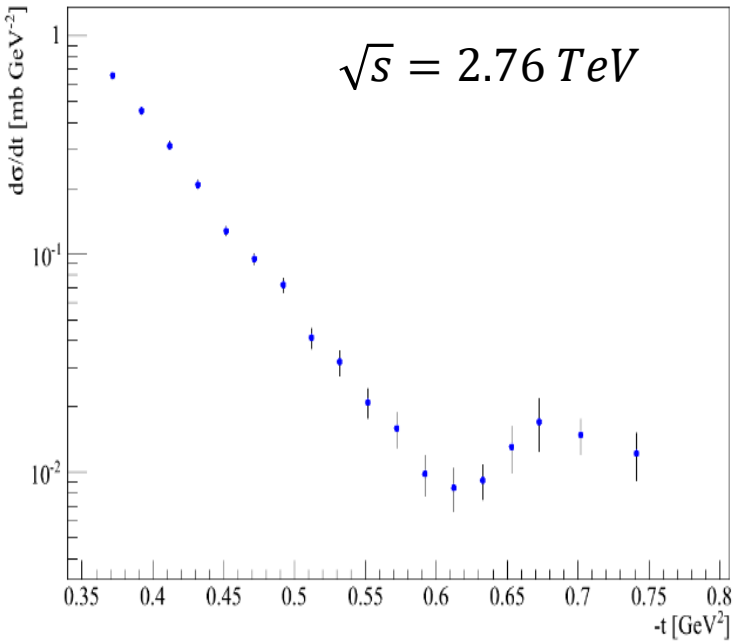


Measurements of pp elastic $d\sigma/dt$ by TOTEM experiment



- Silicon strip detectors inside Roman pots (RP).
- Precise measurements of pp elastic $d\sigma/dt$ at 4 CM energies: 2.76, 7.0, 8.0 and 13.0 TeV.
- Data taken in different high β^* optics runs (3.5m, 11m, 90m, 2500 m).

doi.org/10.1140/epjc/s10052-020-7654-y



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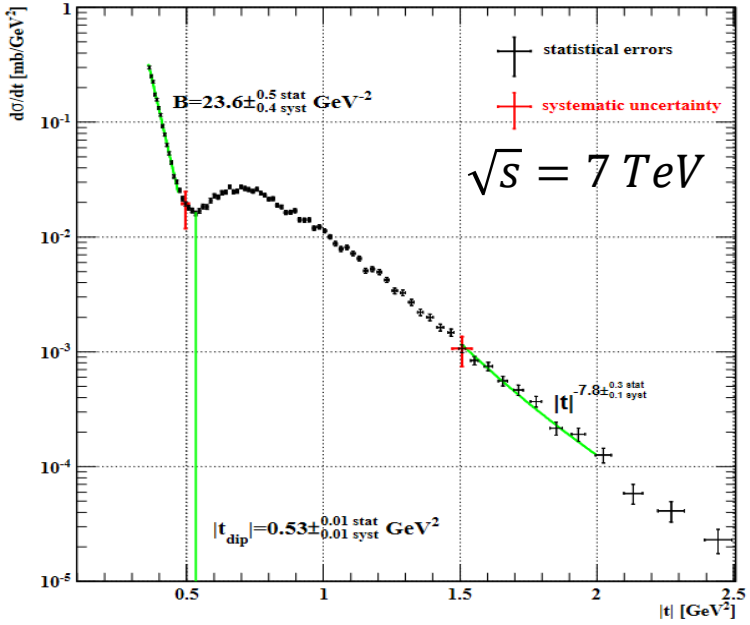

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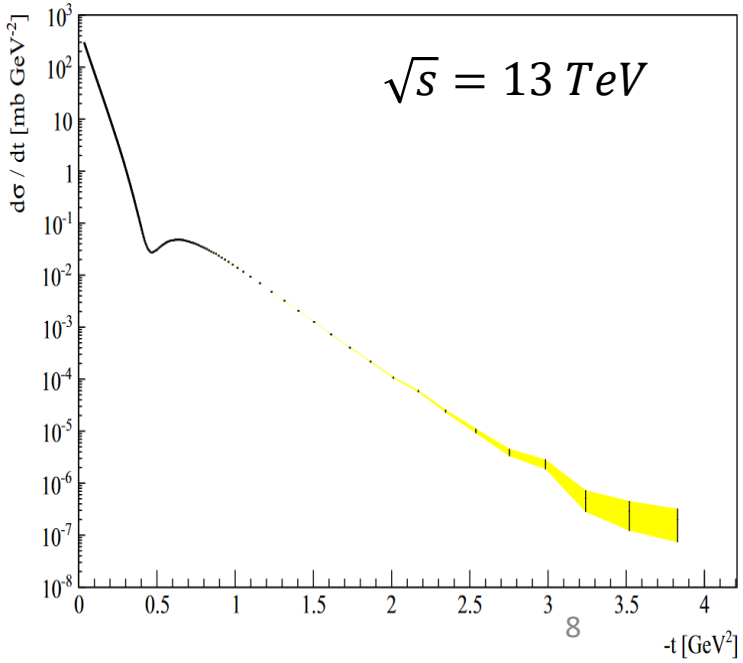
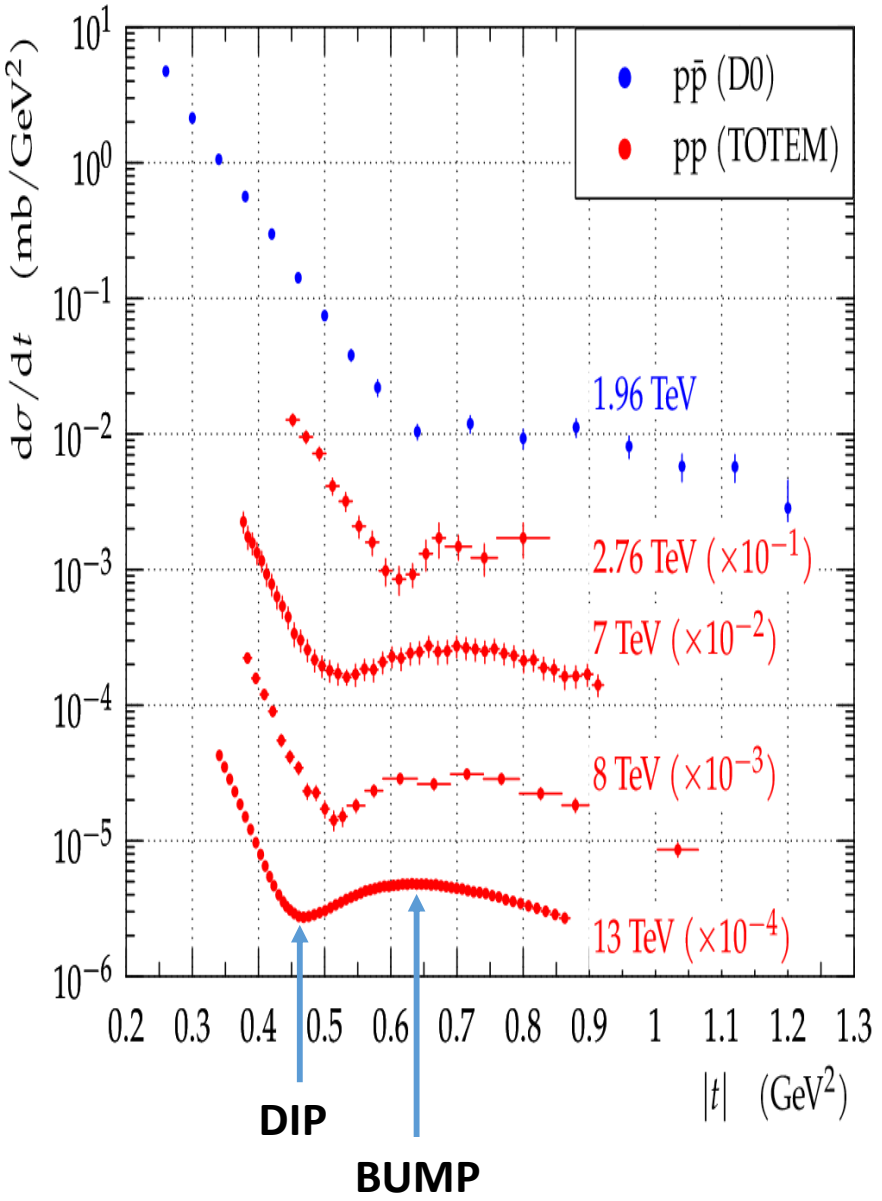


Comparison of pp and $p\bar{p}$ elastic $d\sigma/dt$ at TeV energies.

- TOTEM $d\sigma/dt$ data shows a diffractive mínimum (dip) and a second difraction maximum (bump), both moving towards lower |t| values as energy increases.

- D0 $d\sigma/dt$ data has an inflection point at $|t| \approx 0.65$ with no clear diffraction local minimum.

To perform a quantitative comparison between pp and $p\bar{p}$ cross sections, a direct extrapolation of TOTEM $\frac{d\sigma}{dt}$ data to 1.96 TeV is executed, as it is explained in the following slides.



Bump-over-dip ratio

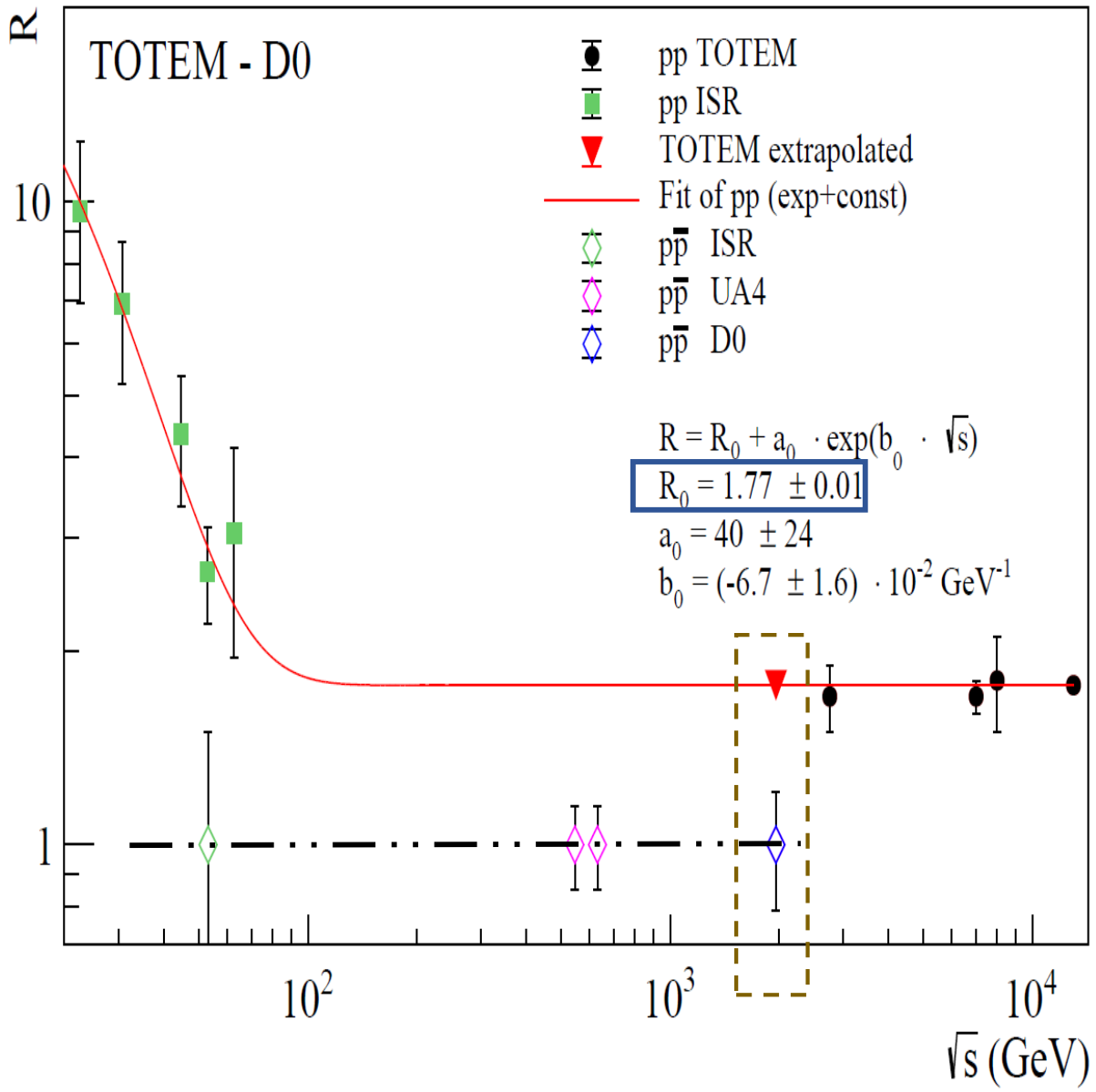
One simple way to quantify differences in pp and $p\bar{p}$ around the dip is by measuring the ratio:

$$R = \frac{\left.\frac{d\sigma}{dt}\right|_{t=t\_bump}}{\left.\frac{d\sigma}{dt}\right|_{t=t\_dip}}$$

- For pp collisions R decreases as a function of $\sqrt{s}$ up to about 100 GeV and then seems to flatten out.

For D0 $d\sigma/dt$, no bump/dip is observed within uncertainties → R = 1.0 ± 0.2, similar behavior is observed for lower energy $p\bar{p}$ data. For uncertainty, compute largest R in the neighborhood of the dip/bump locations expected for pp at 1.96 TeV.

- TOTEM extrapolated R value to $\sqrt{s} = 1.96$ TeV differs by more than 3σ with respect to D0 R value (assuming a flat behavior of R above $\sqrt{s}$= 100 GeV) .



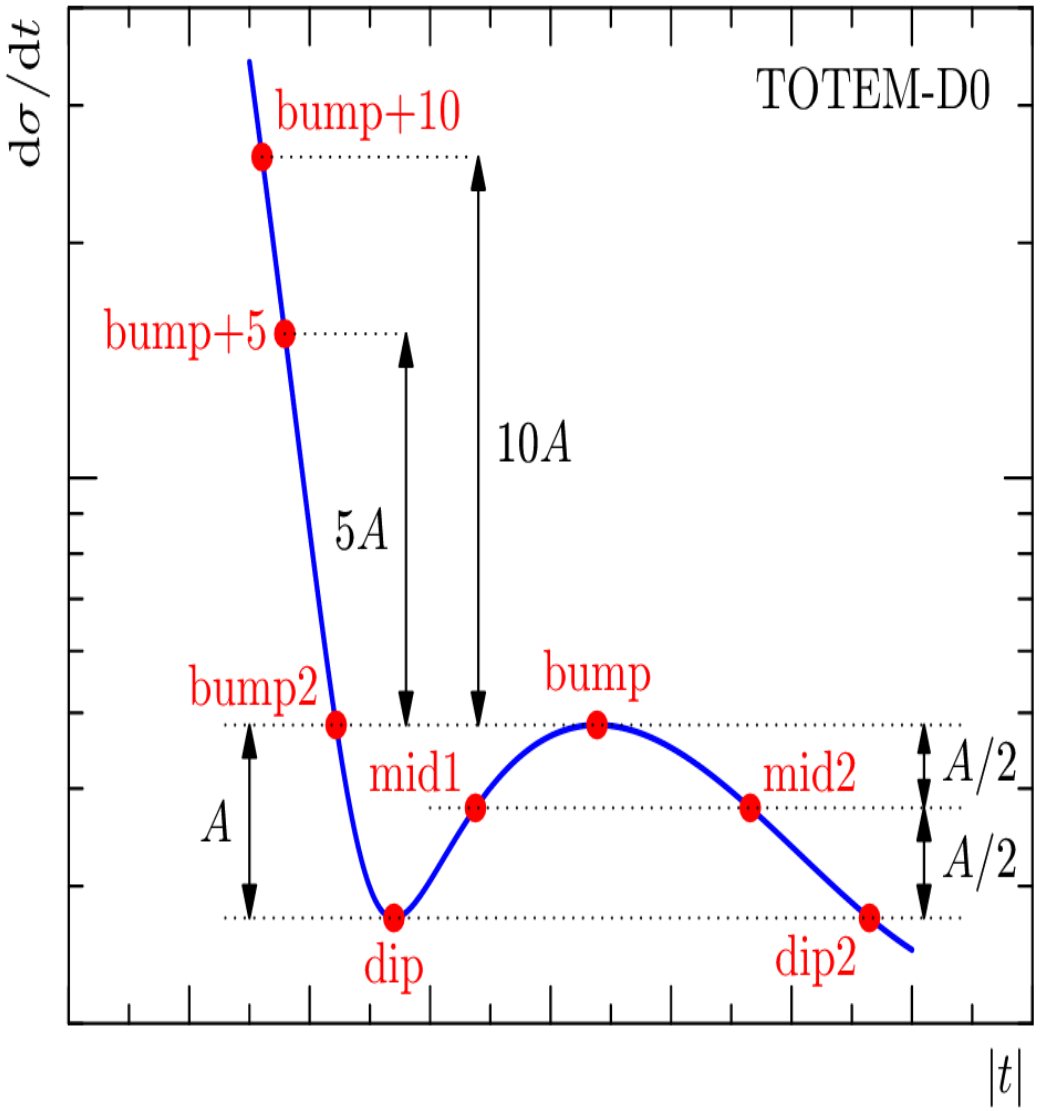
Characteristic points of pp $d\sigma/dt$

- A comparison of pp and $p\bar{p}$ $d\sigma/dt$ is restricted to the range $0.5<|t|<0.96$ GeV^2, where there are data at all 5 TeV energies.

- Define 8 characteristic points of TOTEM pp $d\sigma/dt$ data that describe the features around the dip-bump region.

- To avoid any model-dependency in the study, the $|t|$ and $d\sigma/dt$ values of the characteristic points are directly used to determine how they vary as $\sqrt{s}$ → data-driven comparison.

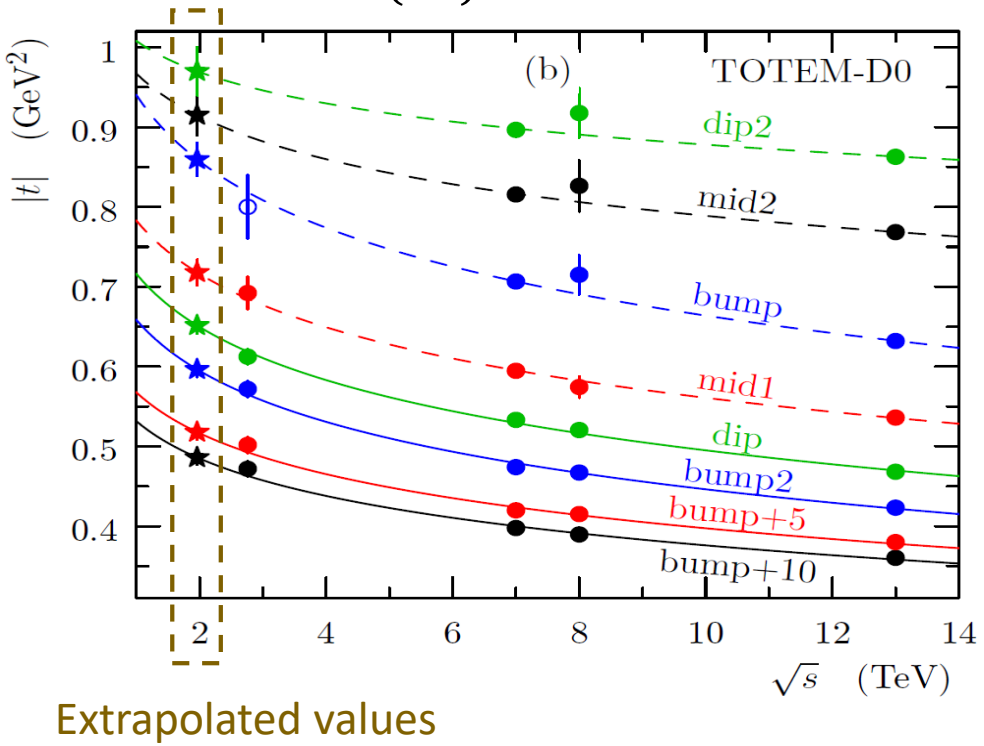
- Data bins are merged in case there are 2 adjacent $|t|$ bins with about same $d\sigma/dt$ value.



$\sqrt{s}$ dependency of the pp characteristic points

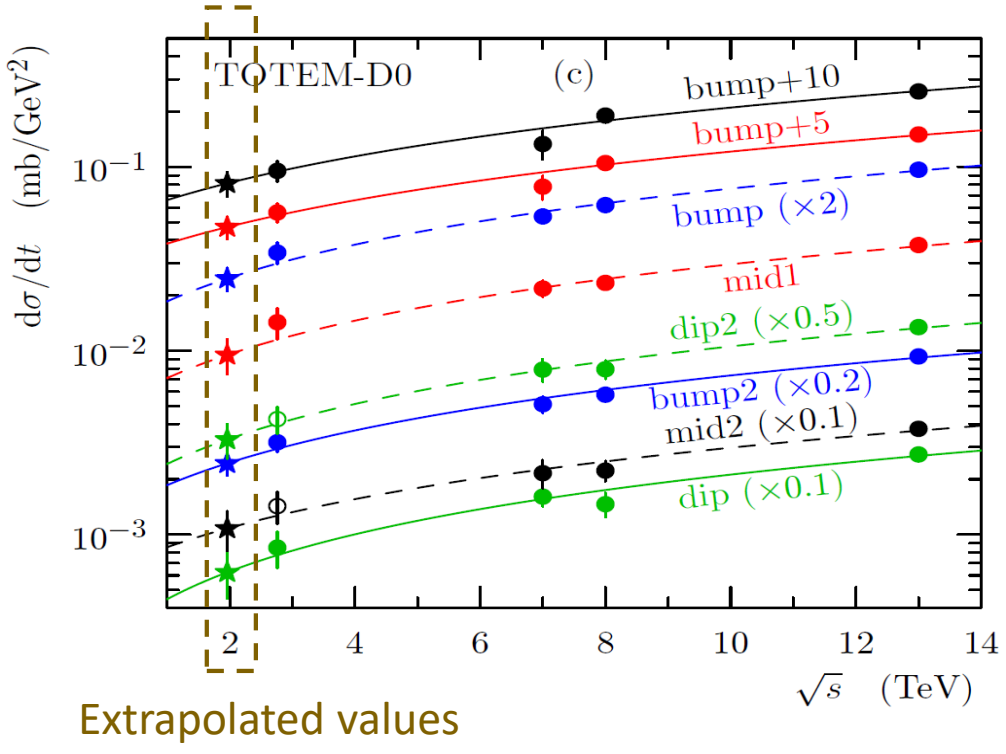
- TOTEM measurements for $\sqrt{s} = 2.76\ TeV$ only reached |t| values up to the bump. With 3 or 4 measured values we are restricted to a 2 parameter fit function:

$$|t| = \mathbf{a}\ \mathbf{ln}\left(\sqrt{s}\right) + \mathbf{b}$$



Extrapolated values

$$\frac{d\sigma}{dt} = c\sqrt{s} + d$$

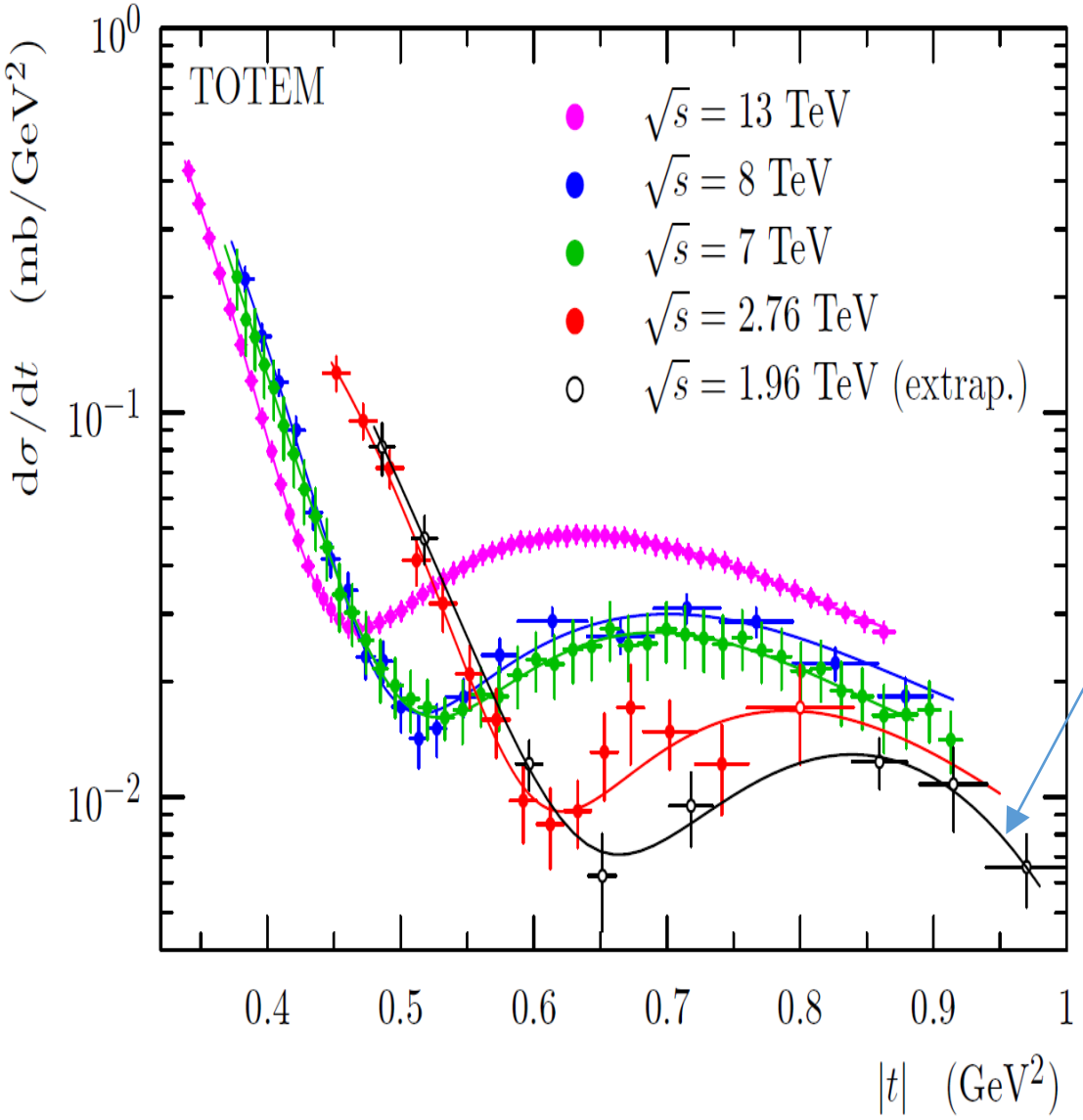


Extrapolated values

- Extrapolations to 1.96 TeV are small: Only 8% of the energy range where the measurements were performed.
- Alternate functions for extrapolating $|t|$ or $d\sigma/dt$ were tried with results well within fit errors.

Open symbols at $\sqrt{s} = 2.76\ TeV$ are from definitions of the characteristic points or small extrapolations.

Interpolation of pp characteristic points at $\sqrt{s}$=1.96 TeV



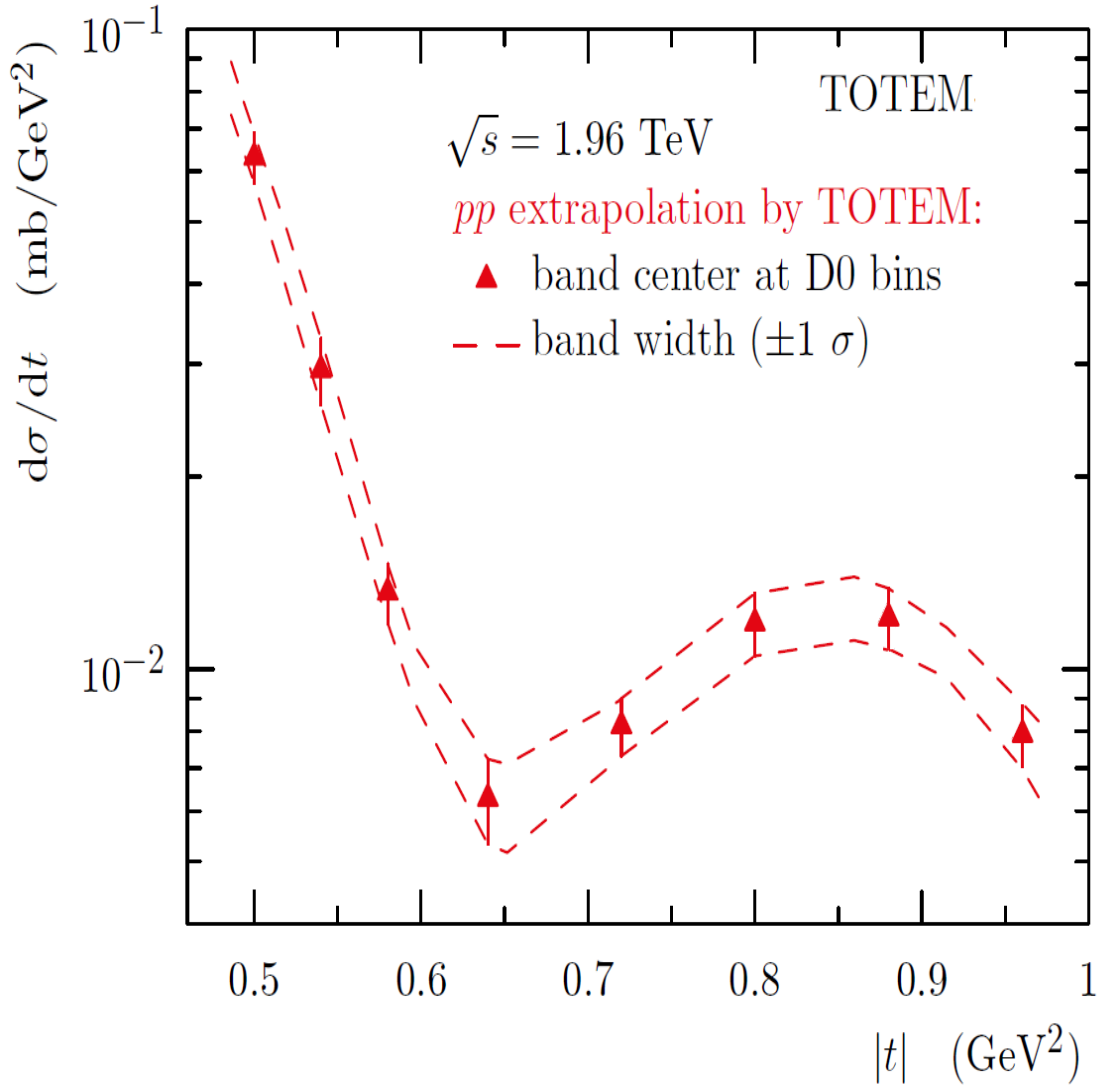
- The 8 extrapolated $d\sigma/dt$ vs $|t|$ characteristic pp points need to be compared to D0 $p\bar{p}$ data points, which are at different |t| values → An interpolation is needed.
- Use an empirical interpolation function (χ^2/dof= 0.63):

$$h(t) = \underbrace{a_1 e^{-(b_1|t|+c_1|t|^2)}}_{\text{Describes } d\sigma/dt \text{ up to the dip, then has a steep falloff}} + \underbrace{a_2 e^{-(b_2|t|+c_2|t|^2+c_3|t|^3)}}_{\text{Describes the bump and subsequent falloff}}$$

- $h(t)$ fits well all TOTEM data in the dip/bump region at 2.76, 7, 8 and 13 TeV.
- Due to the interpolation, the values of the extrapolated $d\sigma/dt$ at neighboring D0 |t| values are strongly correlated.

Uncertainties of extrapolated pp $d\sigma/dt$

- **The extrapolated pp cross-section uncertainties are determined from MC ensembles:**
  - The extrapolated cross-sections of the 8 characteristic points are varied within their gaussian uncertainties.
  - Each MC varied distribution is fitted to the interpolation $h(t)$ function.
  - The gaussian spread obtained at each D0 |t| value corresponds to the uncertainty in pp $d\sigma/dt$.

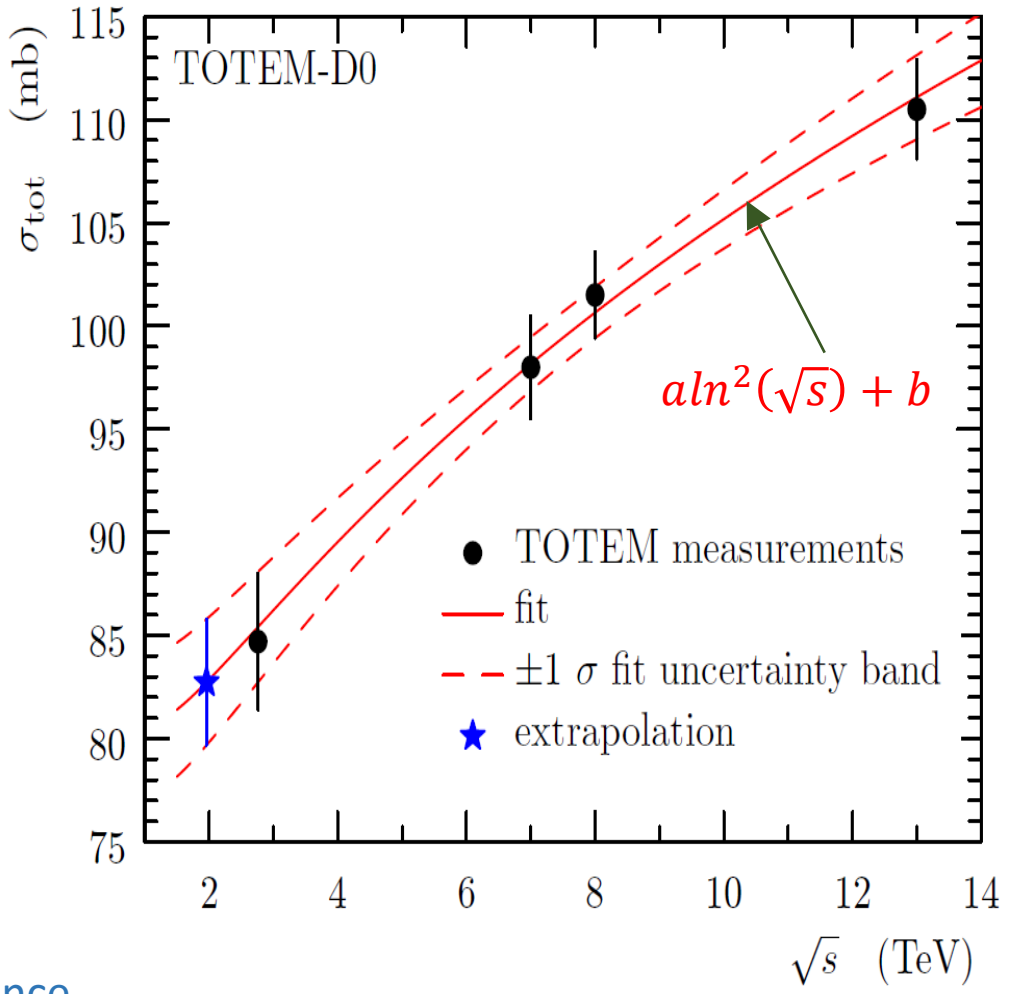


Normalization of $d\sigma/dt$

- **We want a common normalization to make a direct $d\sigma/dt$ comparison, so we scale the TOTEM $d\sigma/dt(t=0)$ (optical point, OP) to agree with D0.**
  - D0 $d\sigma/dt$, before the dip, is fitted to $Ae^{-B|t|}$ → A=341±49 mb/GeV^2
  - A small extrapolation of the TOTEM σ_{tot} data to $1.96\ TeV$ is performed
  - The optical theorem is then used to get $d\sigma/dt(t=0)$ (using $\rho = 0.145$):

$$\sigma_{tot}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2}\left(\frac{d\sigma}{dt}\right)_{t=0} \Rightarrow \left(\frac{d\sigma}{dt}\right)_{t=0} = 357\pm26\ \text{mb/GeV}^2$$

  - Then, the extrapolated $pp\ d\sigma/dt$ is normalized by a factor of 0.954±0.071



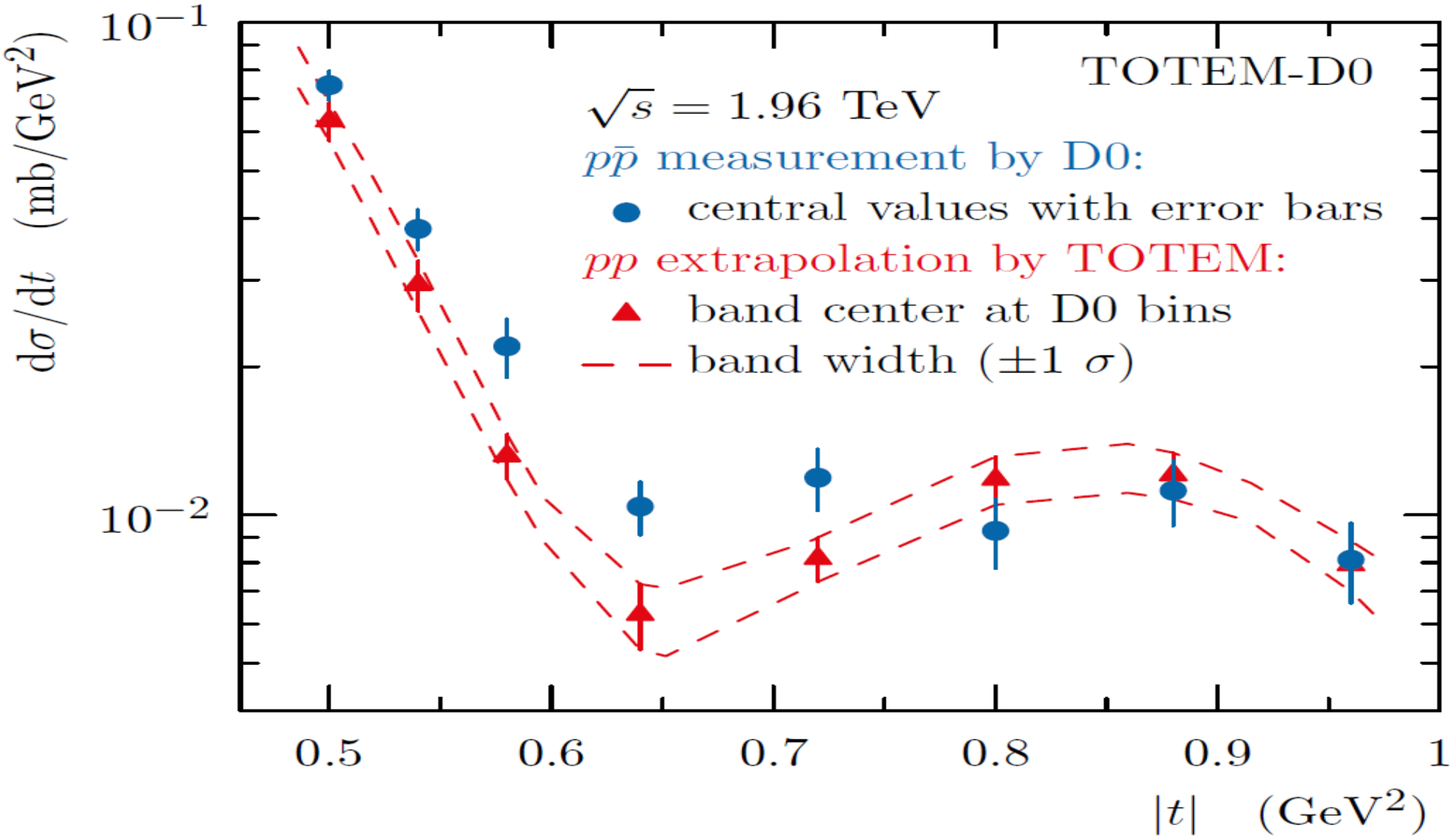
OP´s are expected to be equal for C-even only exchanges. The largest difference by theoretical Odderon models (2.9%) is taken as a systematic uncertainty.

Uncertainties due to differences in ρ_{pp} and $\rho_{p\bar{p}}$, departures from pure exponential slopes at small t, and effects of subdominant Regge exchanges are negligible.

Extrapolated pp σ_{tot} at $\sqrt{s} = 1.96\ TeV$:

$$\sigma_{tot}^{pp} = 82.7 \pm 3.1\ mb$$

Extrapolated pp $\frac{d\sigma}{dt}$ and measured $p\bar{p}$ $\frac{d\sigma}{dt}$ at $\sqrt{s} = 1.96\ TeV$



Statistical comparison of extrapolated pp $\frac{d\sigma}{dt}$ to measured $p\bar{p}$ $\frac{d\sigma}{dt}$ at $\sqrt{s} = 1.96\ TeV$.

A χ^2 comparison between the scaled TOTEM and D0 $\frac{d\sigma}{dt}$'s is performed as:

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

Where: $T_i = \left(\frac{d\sigma}{dt}\right)_i^{TOTEM}$; $D_i = \left(\frac{d\sigma}{dt}\right)_i^{D0}$; $C_{i,j}$= (i,j) element of the cov. matrix.

Two constraints are applied (Therefore 6 d.o.f):

1) The OP match between pp and $p\bar{p}$.

2) We constraint the pp and $p\bar{p}$ nuclear slopes to their measured values, which agree within statistics (to good approximation $B(pp) = B(p\bar{p})$). This constraint is also consistent with the Cornille-Martin Theorem : the ratio of the pp and $p\bar{p}$ integrated elastic cross sections tends to unity as $s \to \infty$.

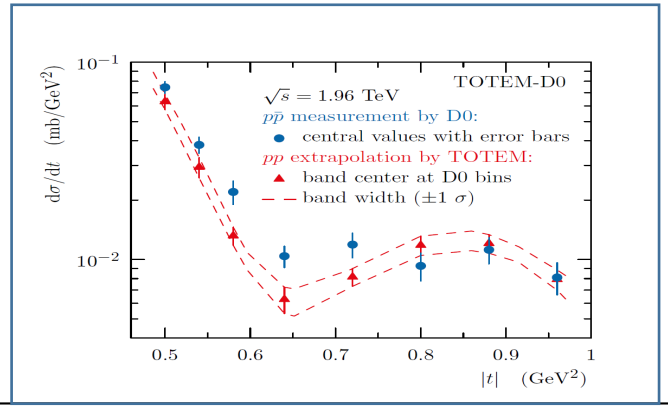
We obtain: χ^2 = 23.64, equivalent to a p-value of 6.1x10^{-4} for 6 dof, with a corresponding significance of 3.4 σ

A cross check was done with a modified K-S test, including correlations, we get a consistent p-value with that of the χ^2test.

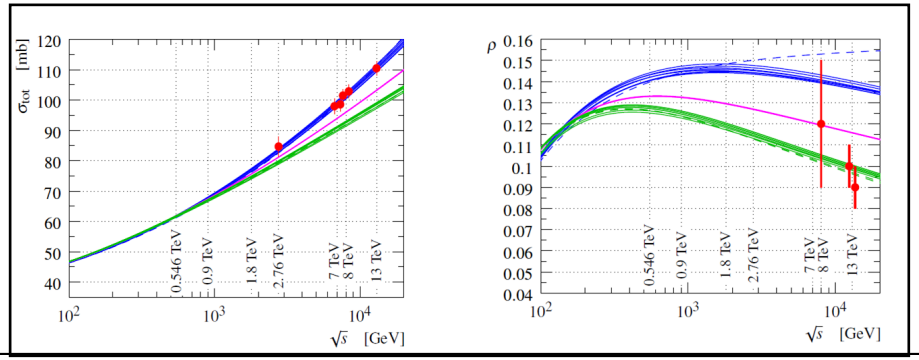
We interpret this difference in pp and $p\bar{p}$ elastic $d\sigma/dt$ at TeV energies as evidence of an Odderon amplitude contributing to the scattering process, in addition to the Pomeron amplitude.

Combining evidence of Odderon Exchange from ρ, σ_{tot} and elastic $d\sigma/dt$ data

Measurements were obtained with different detectors and in different |t| regions→ Fully independent



Evidence from the D0 -TOTEM elastic $d\sigma/dt$ difference at 3.4σ level



256 models studied by the COMPETE Collaboration, Durham, and Block-Halzen with no-Odderon contribution are ruled out by TOTEM σ_{tot} and ρ measurements, at the level of 3.4 to 4.6σ

pp vs $p\bar{p}$ cross-section and $\rho - \sigma_{tot}$ significances are combined using the Stouffer method.

Overall significance ranging between 5.2 to 5.7 σ, depending on the model.

Concluding remarks

1. A thorough data-driven comparison between the TOTEM pp (at 2.76, 7, 8 , 13 TeV) and the D0 $p\bar{p}$ (at 1.96 TeV) elastic $d\sigma/dt$ was carried out.

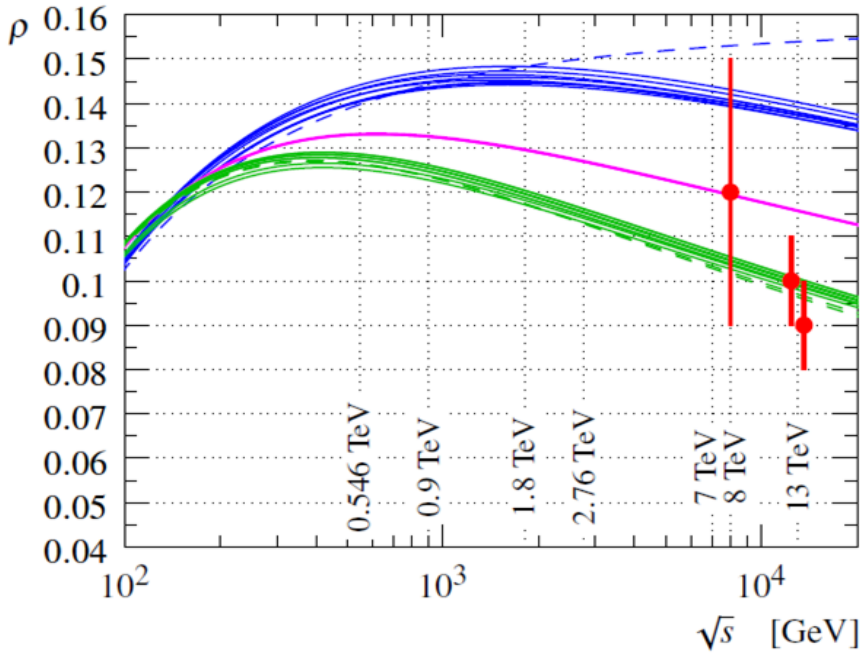
2. The extrapolated $\frac{d\sigma_{pp}}{dt}$ differs from the measured $\frac{d\sigma_{p\bar{p}}}{dt}$ (at 1.96 TeV) at the level of 3.4σ, which is interpreted as evidence of a contribution of an Odderon amplitude.

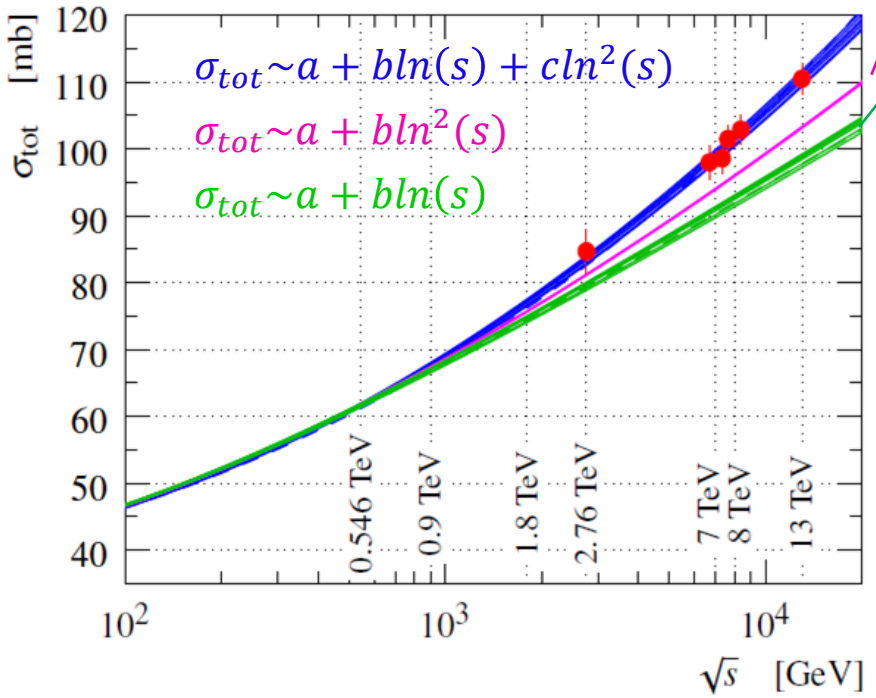
3. The evidence of the difference of the elastic $d\sigma/dt$ combined with the evidence from the values of σ_{tot} and ρ at the TeV energies, constitutes the **first experimental observation of the Odderon.**

For more details please see the publication of the present study: https://link.aps.org/doi/10.1103/PhysRevLett.127.062003

Thank you
for your attention

BACKUP SLIDES





- Excluded at **4.6σ** level with $\rho(13\ TeV) = 0.09$
- Excluded at **5.7σ** level when combining significance from ρ and from difference in pp and $p\bar{p}$ $\frac{d\sigma}{dt}$.

- Excluded at **4.0σ** level with TOTEM $\rho +\ \sigma_{tot}$ data.
- Excluded at **5.3σ** level when combining significance from TOTEM $\rho +\ \sigma_{tot}$ data and from difference in pp and $p\bar{p}$ $\frac{d\sigma}{dt}$.

- Excluded at **4.6σ** level with TOTEM $\rho +\ \sigma_{tot}$ data.
- Excluded at **5.7σ** level when combining significance from TOTEM $\rho +\ \sigma_{tot}$ data and from difference in pp and $p\bar{p}$ $\frac{d\sigma}{dt}$.

Durham Model:

- Excluded at **3.4σ** level with TOTEM $\rho +\ \sigma_{tot}$ data.
- Excluded at **5.2σ** level when combining significance from TOTEM $\rho +\ \sigma_{tot}$ data and from Durham prediction for D0 $p\bar{p}$ $\frac{d\sigma}{dt}$.

Block-Halzen Model:

- Excluded at **3.9σ** level with TOTEM ρ data.
- Excluded at **5.2σ** level when combining significance from TOTEM ρ data and and from difference in pp and $p\bar{p}$ $\frac{d\sigma}{dt}$.