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

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On behalf of D0 and TOTEM Collaborations

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# 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 Uncertatinties and normalization

4. Results

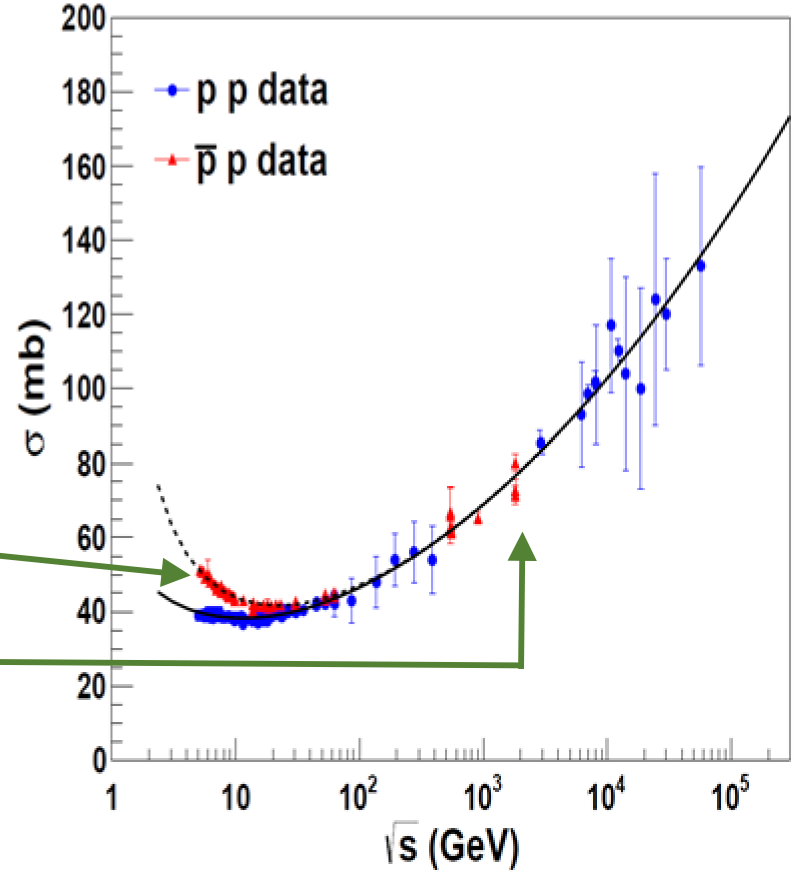
5. Concluding remarks

# The Odderon

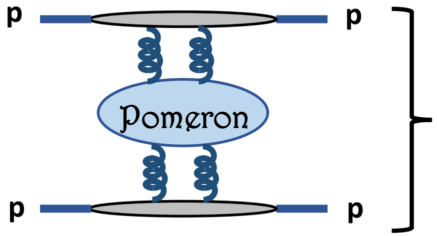
**Regge Theory:** doi.org/10.1140/epjc/s10052-016-4585-8

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

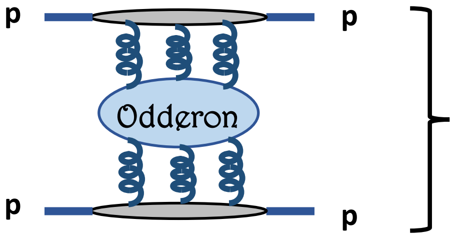
- Regge Trajectory: $\alpha_j(t) = \alpha_j(0) + \alpha_j' t$ ; $s_0 = 1\text{Gev}^2$
- Optical Theorem: $\sigma_{tot} = \frac{1}{s}\,\text{Im}(A(s,t=0)) \rightarrow \sigma_{tot} \sim (s/s_0)^{\alpha_j(0)-1}$
- $\rho, \omega, f$ Regge Trajectories: $\alpha(0) \approx 0.5 \rightarrow \sigma_{tot} \sim (s/s_0)^{-0.5}$
- 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 posible → **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.

See talk on glueballs by Prof. Felipe Llanes-Estrada

# Observables for Odderon effects

**At high energies:**

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

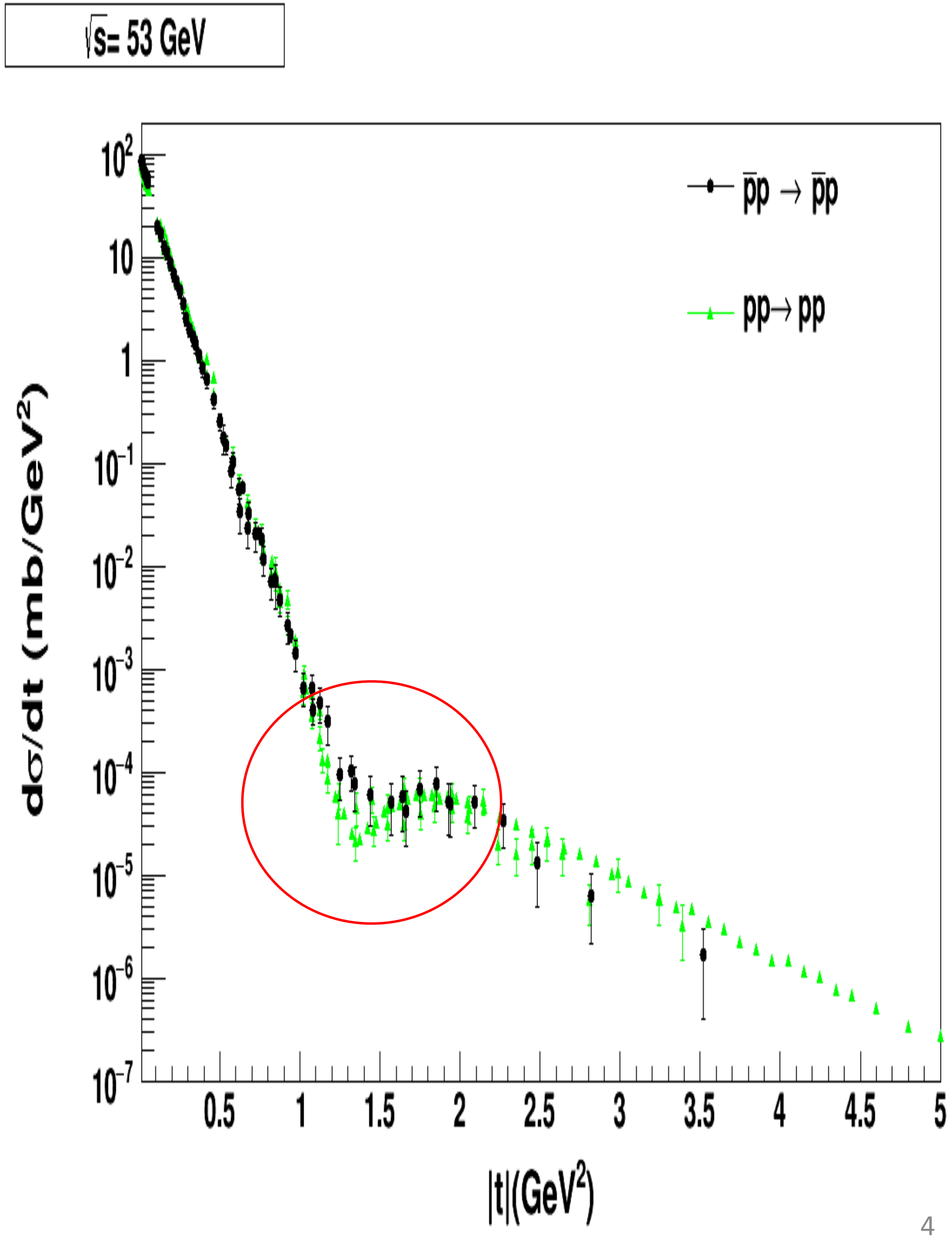
$$\frac{d\sigma_{p\bar{p}}}{dt} = |A_P(s,t) - A_O(s,t)|^2$$

- Differences in $pp$ and $p\bar{p}$ elastic $\frac{d\sigma}{dt}$ could become obervable when $A_P$ is small → around the diffraction minimum.

- Some differences in $pp$ and $p\bar{p}$ elastic $\frac{d\sigma}{dt}$, at $3\sigma$ 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.

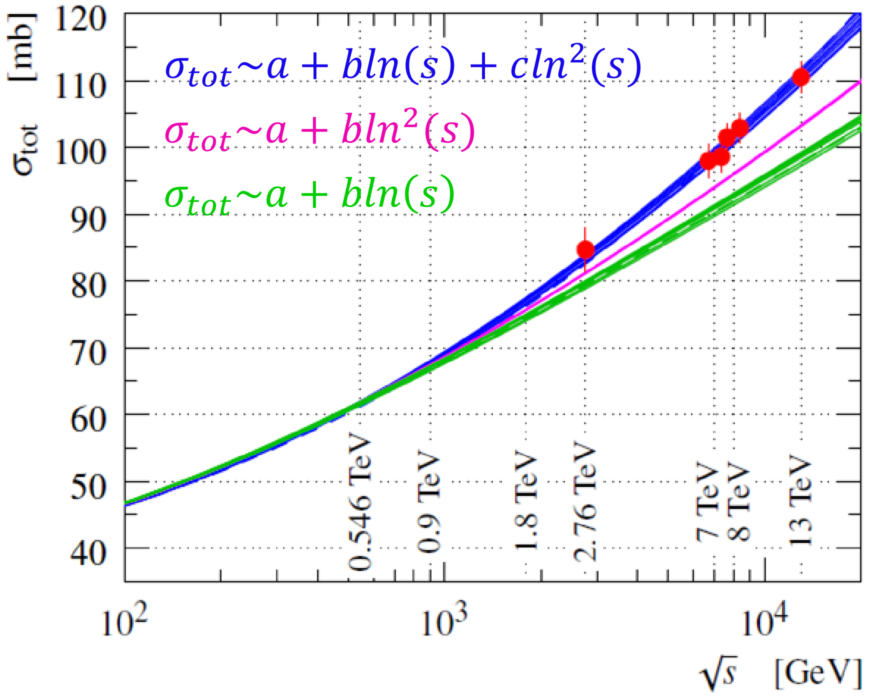
- $A_P$ is mostly imaginary at low values of t, dominating $\sigma_{tot}$ over $A_O$ which is mostly real.

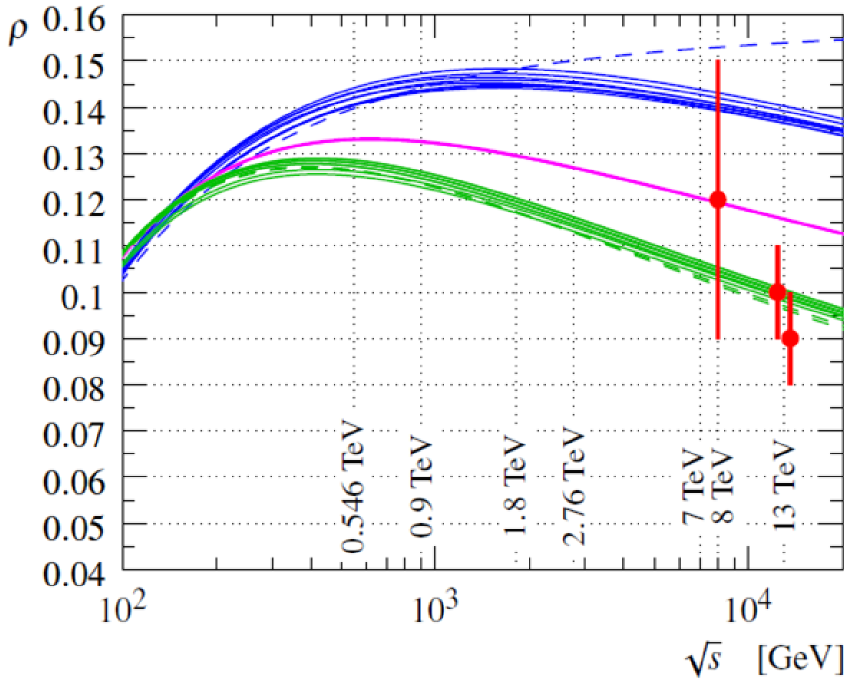
- The evolution of $\rho$ and $\sigma_{tot}$ with $\sqrt{s}$, $\rho = \frac{Re\{A(s,t=0\}}{Im\{A(s,t=0\}}$, is also useful to determine Odderon effects (TOTEM Collaboration,2019).



# Evolution of $\rho$ and $\sigma_{tot}$ with energy

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



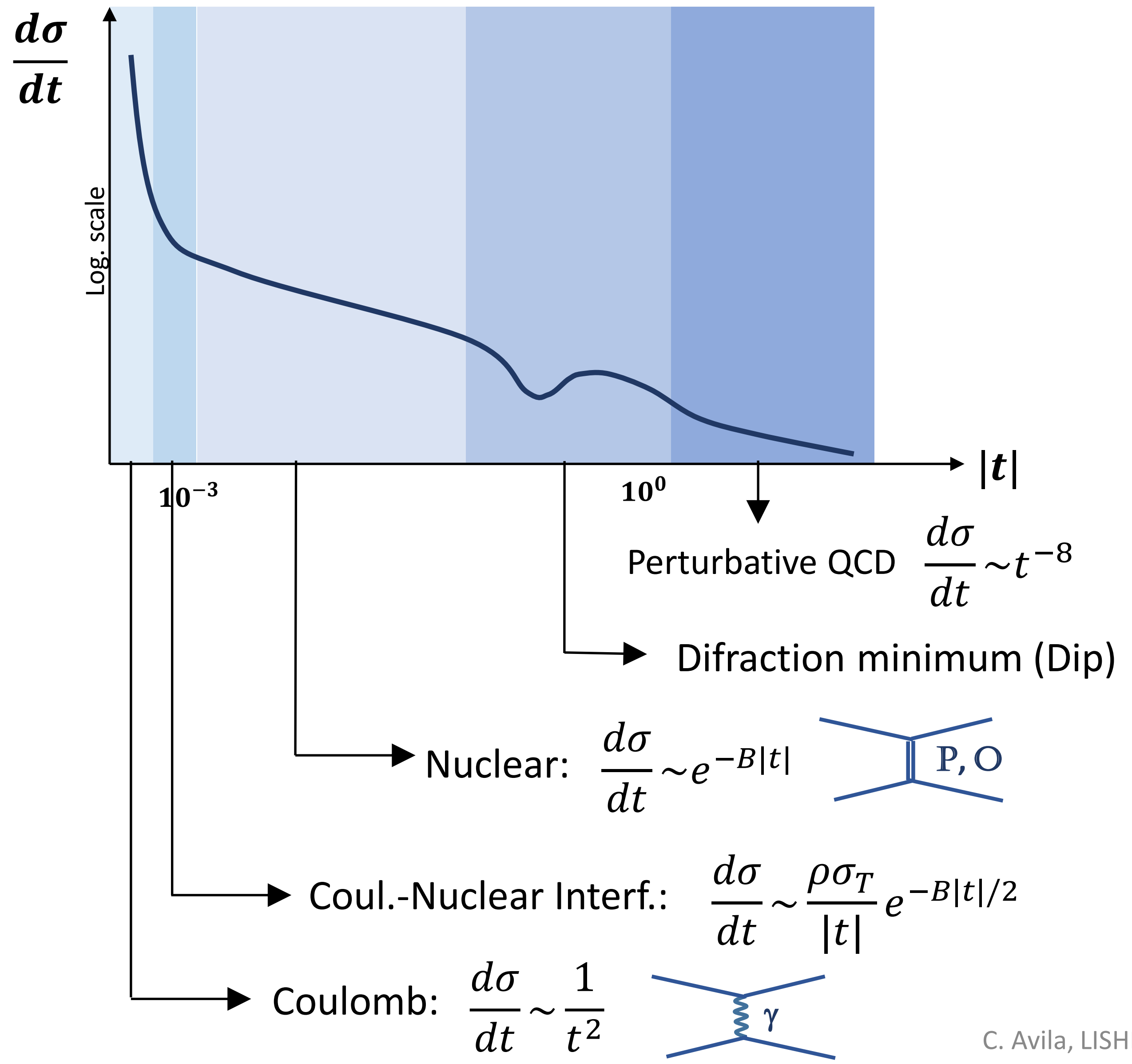

- With a high $\beta$ optics ($\beta$= 2.5 km) at $\sqrt{s} = 13\ TeV$, TOTEM reached very low |t| values (|t|~8x10$^{-4}$ GeV$^2$) that allowed a precise measurement of $\rho$: $\boldsymbol{\rho = 0.09 \pm 0.01.}$

- None of the 256 Pomeron-only models studied by the COMPETE Collaboration, nor Durham, nor Block-Halzen describe simultaneously the ensemble of $\sigma_{tot}$ and $\rho$ data measured by the TOTEM experiment.

- Additional C=-1 amplitude is needed to explain the evolution of $\sigma_{tot}$ and $\rho$ with $\sqrt{s}$, with a significance of 3.4 – 4.6$\sigma$ 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:

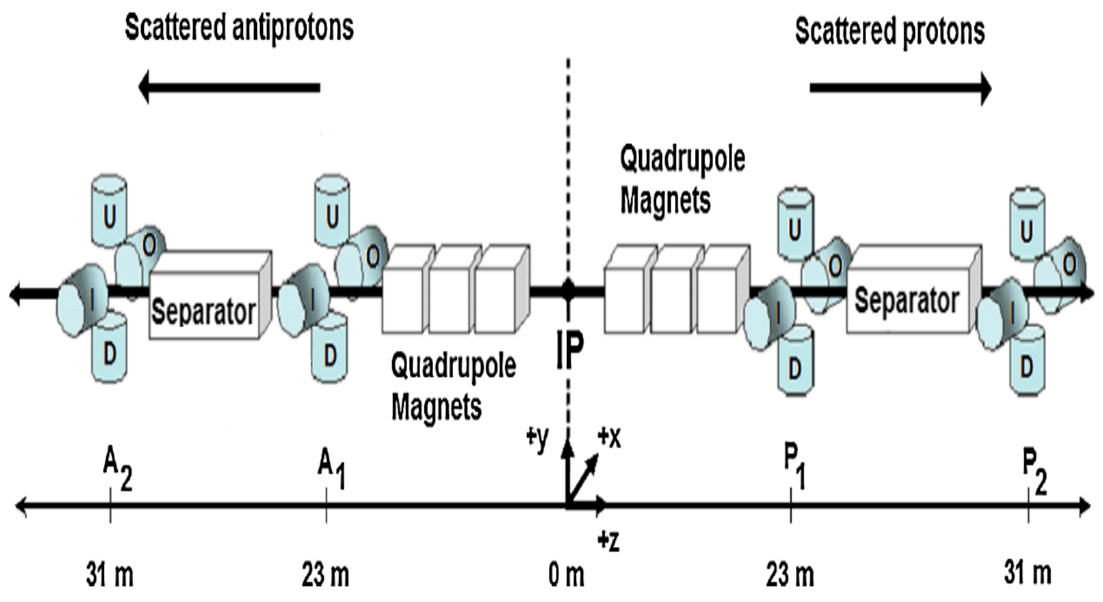
| $\sqrt{s}$ (TeV) | $\theta_{interf.}(\mu rad)$ |
|---|---|
| 1.96 | ~ 16 |
| 13.0 | ~ 2 |

- Need to locate detectors as far as posible to the interaction point and as close as posible 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 to obtain $d\sigma/dt$ .

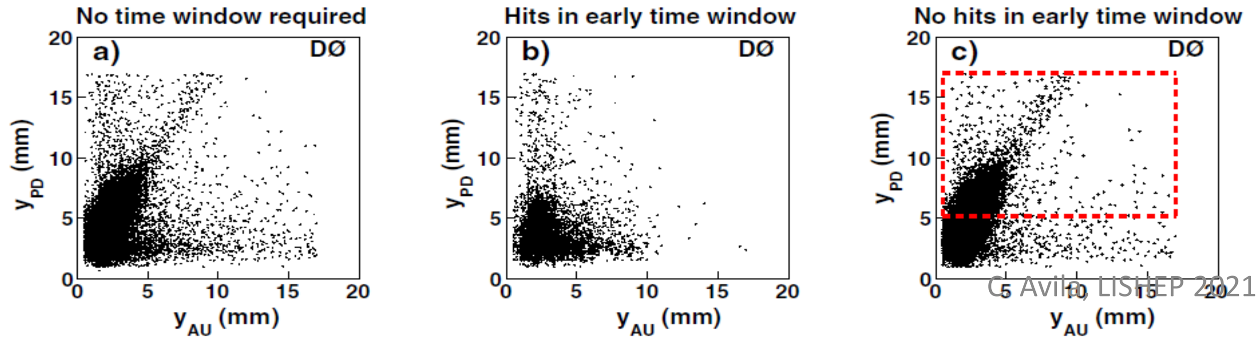
# Measurement of $p\bar{p}$ elastic $d\sigma/dt$ by D0 experiment



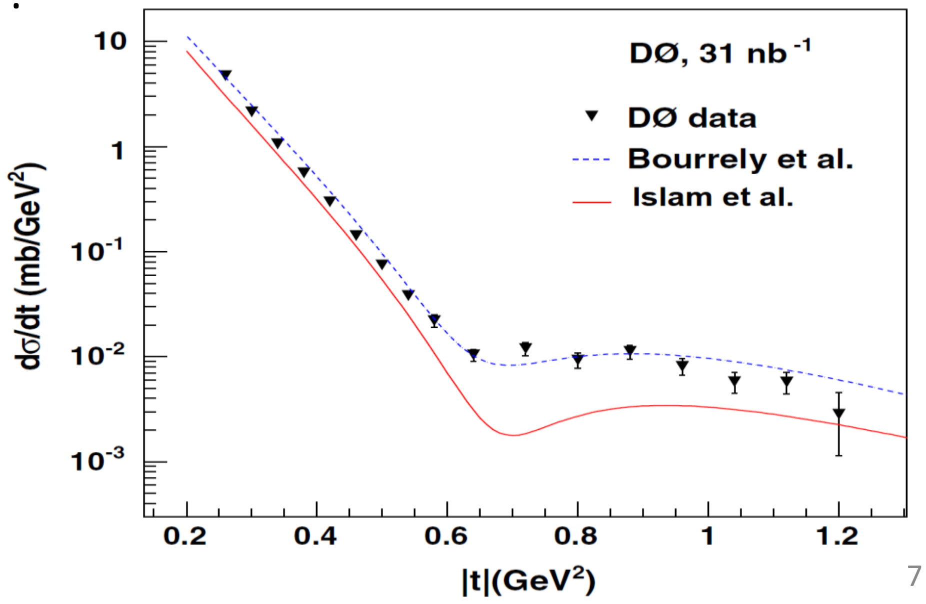

- Fiber scintillating detectors inside Roman pots (RP).
- Use vertical RP´s for measurement and horizontal RP´s for alignment.
- Integrated luminosity recorded = 31 $nb^{-1}$
- Data taken with a Tevatron injection lattice ($\beta^* = 1.6\ m$)
- |t| range covered: 0.26<|t|<|1.2| GeV/$c^2$.

A better name should be Brazilian pots, since they were designed and constructed in Brazil!

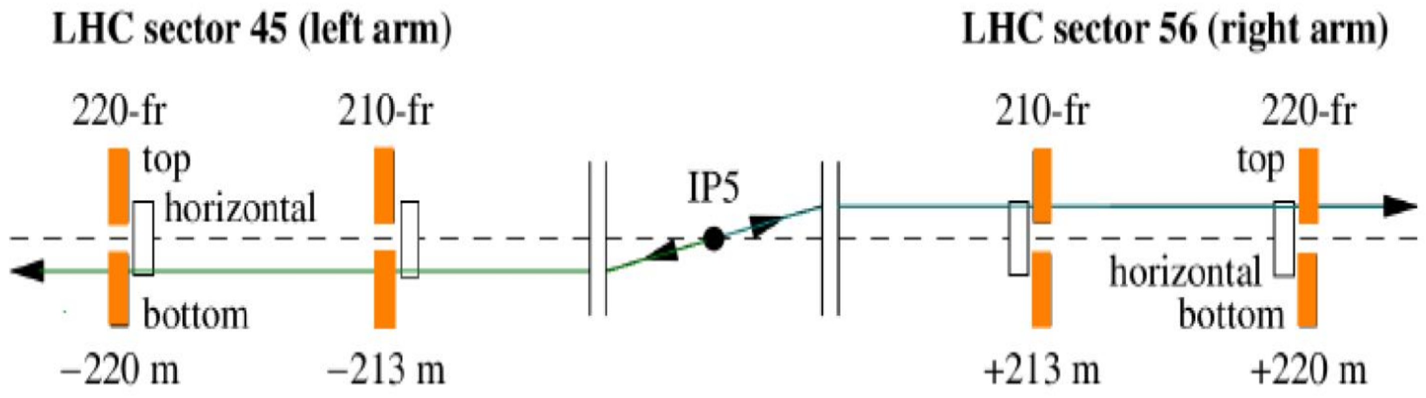
- Select elastic events with same $\theta$, opposite $\phi$ and consistent timing from IP.
- Estimate backgrounds from data with timing consistent with beam halo.
- Reconstruct $\theta$ from detector coordinates and beam transpor matrices.




doi/10.1103/PhysRevD.86.012009

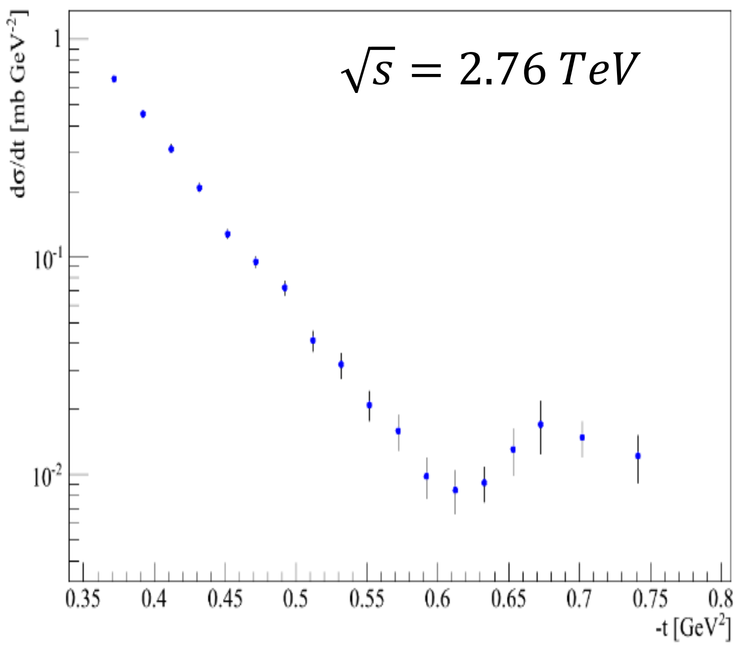


# Measurements of $pp$ elastic $d\sigma/dt$ by TOTEM experiment




- 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 $\beta^*$ optics runs (3.5m, 11m, 90m, 2500 m).

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

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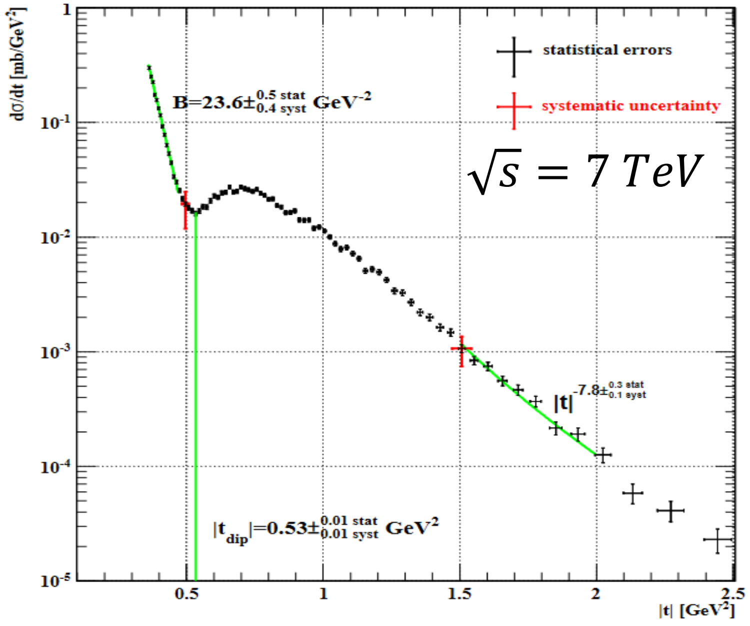


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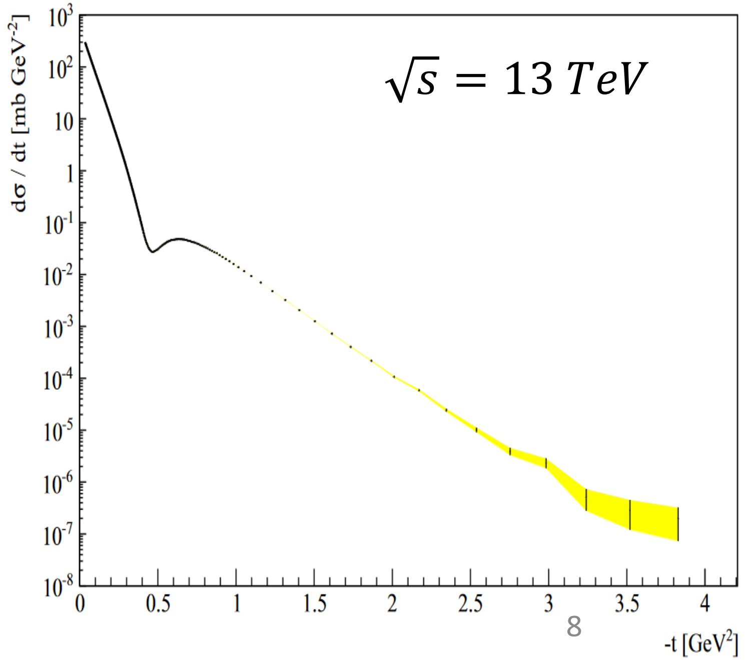
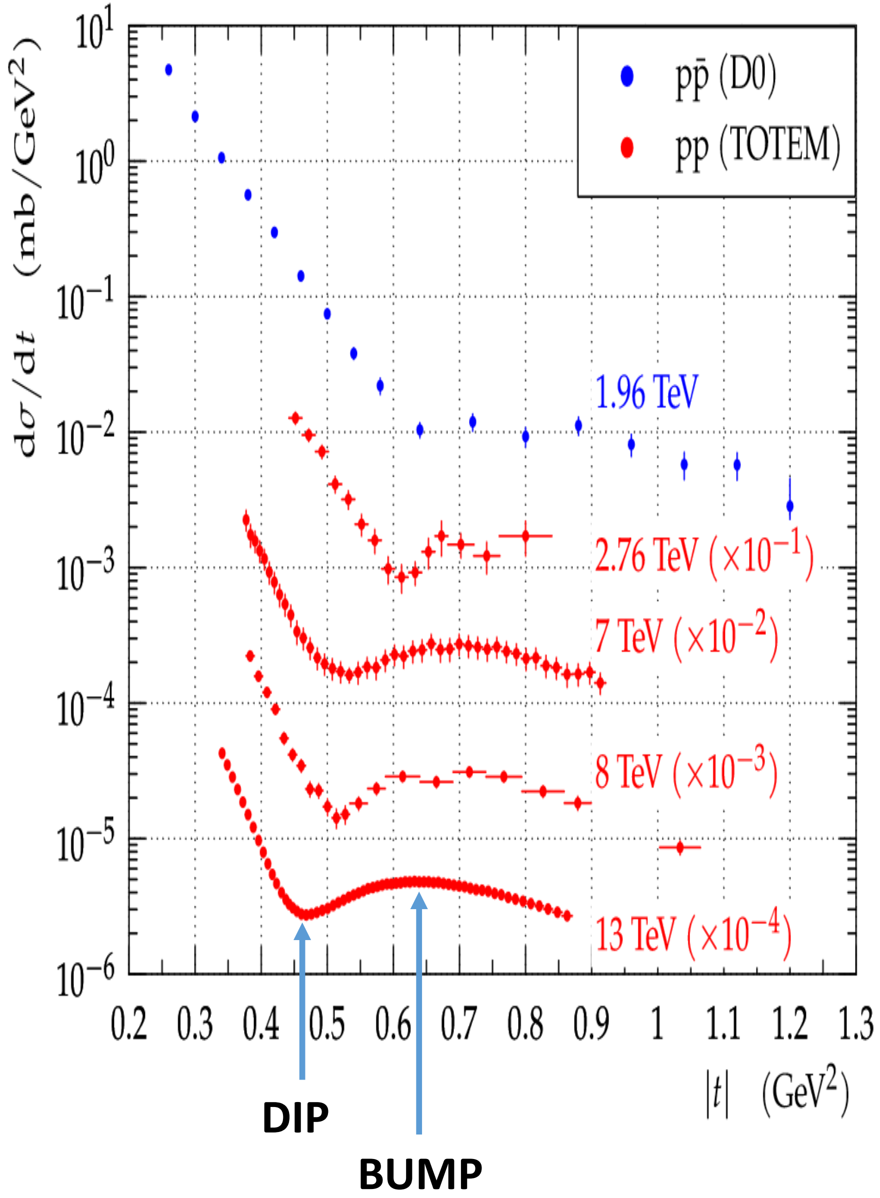


# Comparison of $pp$ and $p\bar{p}$ elastic $d\sigma/dt$ at TeV energies.

- 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.

Different strategies can be followed for a quantitative comparison :

1. **Make a direct comparison of 2.76 TeV $pp$ data to 1.96 TeV $p\bar{p}$ data. →** Difficult to asses systematic uncertainties because the difference in energy.
2. **Fit TOTEM $d\sigma/dt$ measurements with a function inspired by a theory model and extrapolate parameters to 1.96 TeV. →** Difficult to quantify unknown uncertainties related to the model chosen.
3. **Perform a direct extrapolation of TOTEM $d\sigma/dt$ data to 1.96 TeV. →** There is a systematic uncertainty due to the extrapolation but allows for a more model-independent result.




**We followed a variant of strategy 3.**

# Bump-over-dip ratio

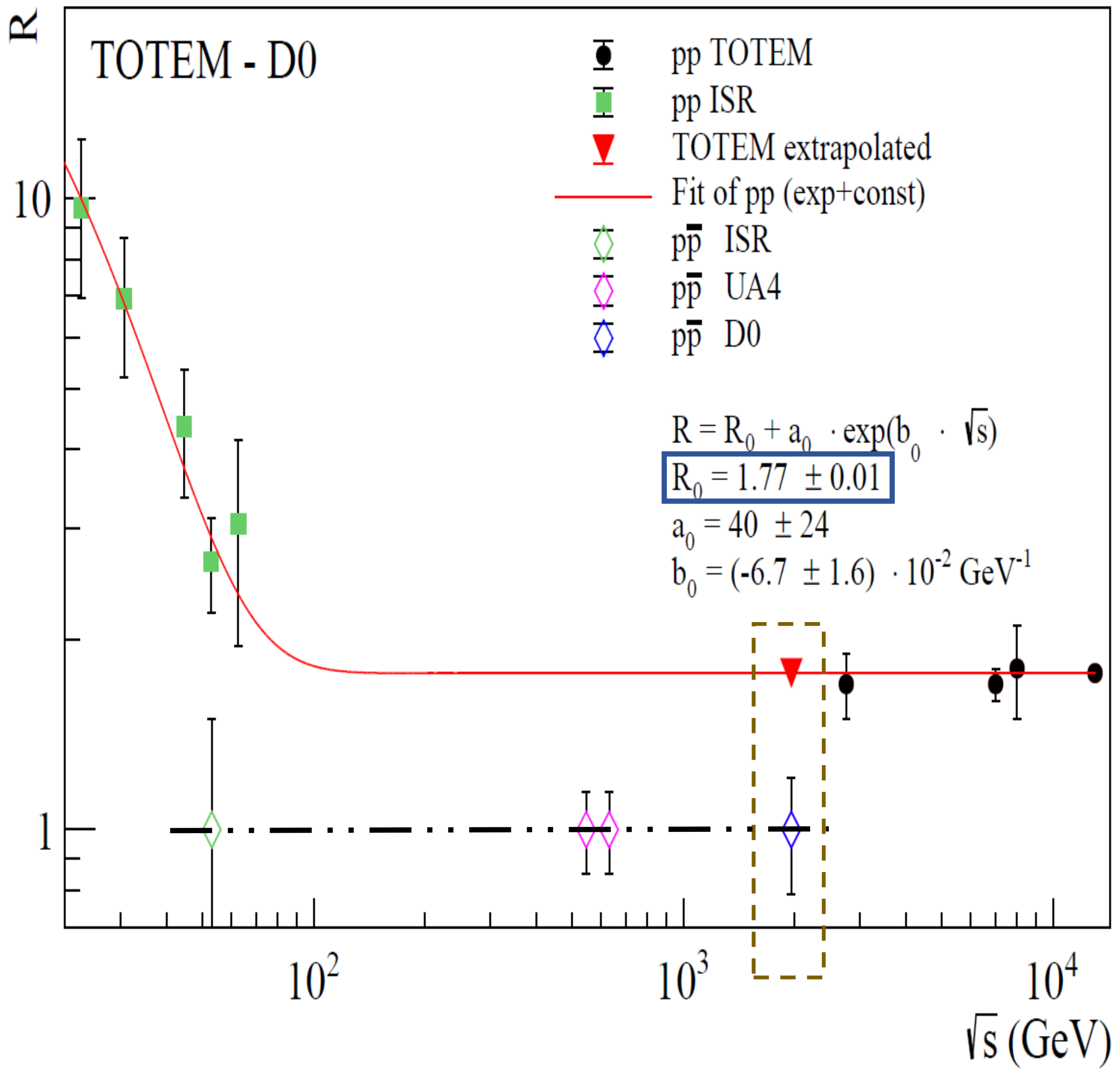
One simple way to quantify differences in $pp$ and $p\bar{p}$ around the dip is by measuring the ratio:

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

- 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, 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 $3\sigma$ with respect to D0 R value (assuming a flat behavior of R above $\sqrt{s}$= 100 GeV) .



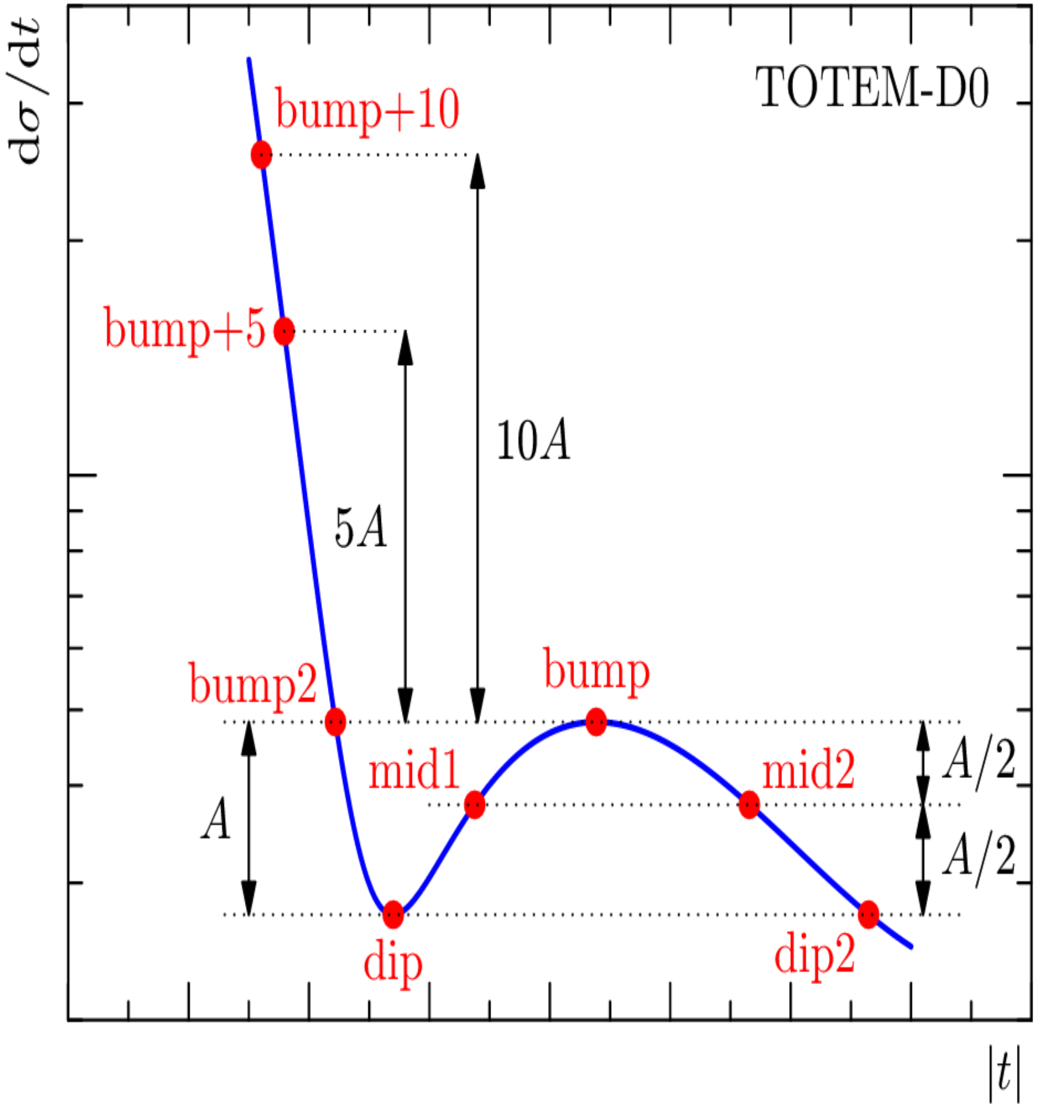
# Characteristic points of pp $d\sigma/dt$

- 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.

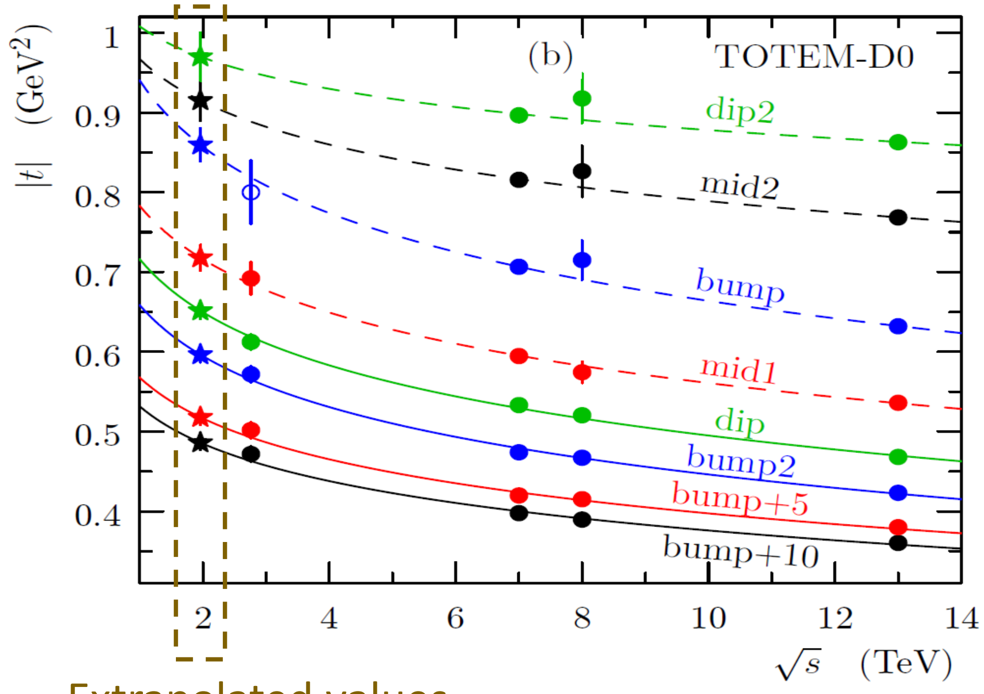


# $\sqrt{s}$ dependency of the pp characteristic points

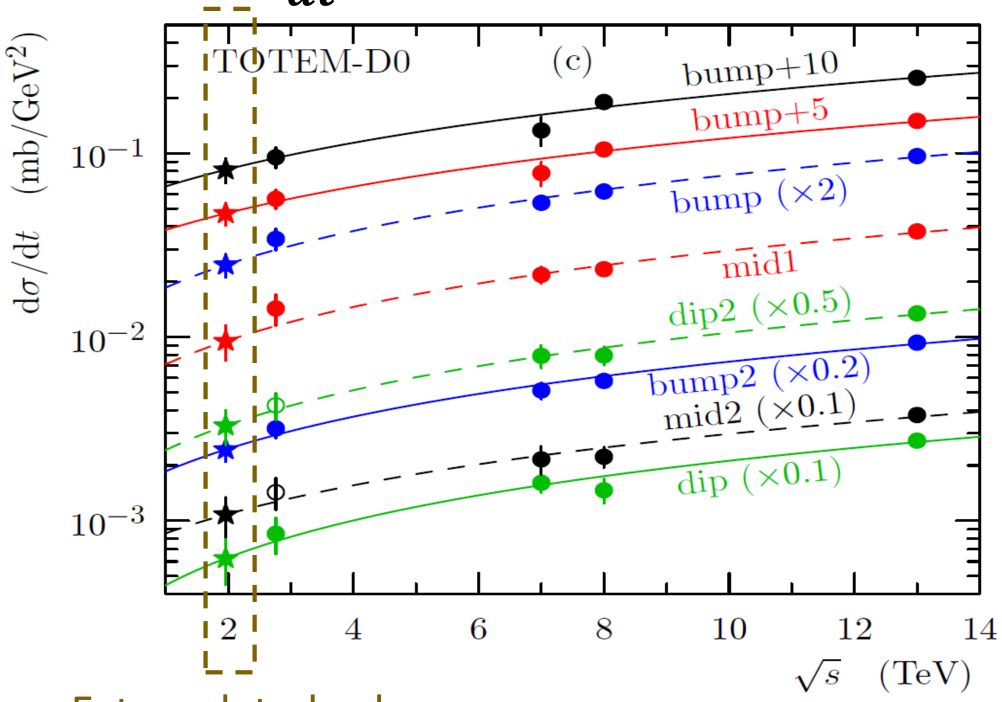
- TOTEM measurements for $\sqrt{s} = 2.76\ TeV$ only reached |t| values up to the bump. With 3 or 4 measured values we are restricted to a 2 parameter fit function:

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

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




Extrapolated values

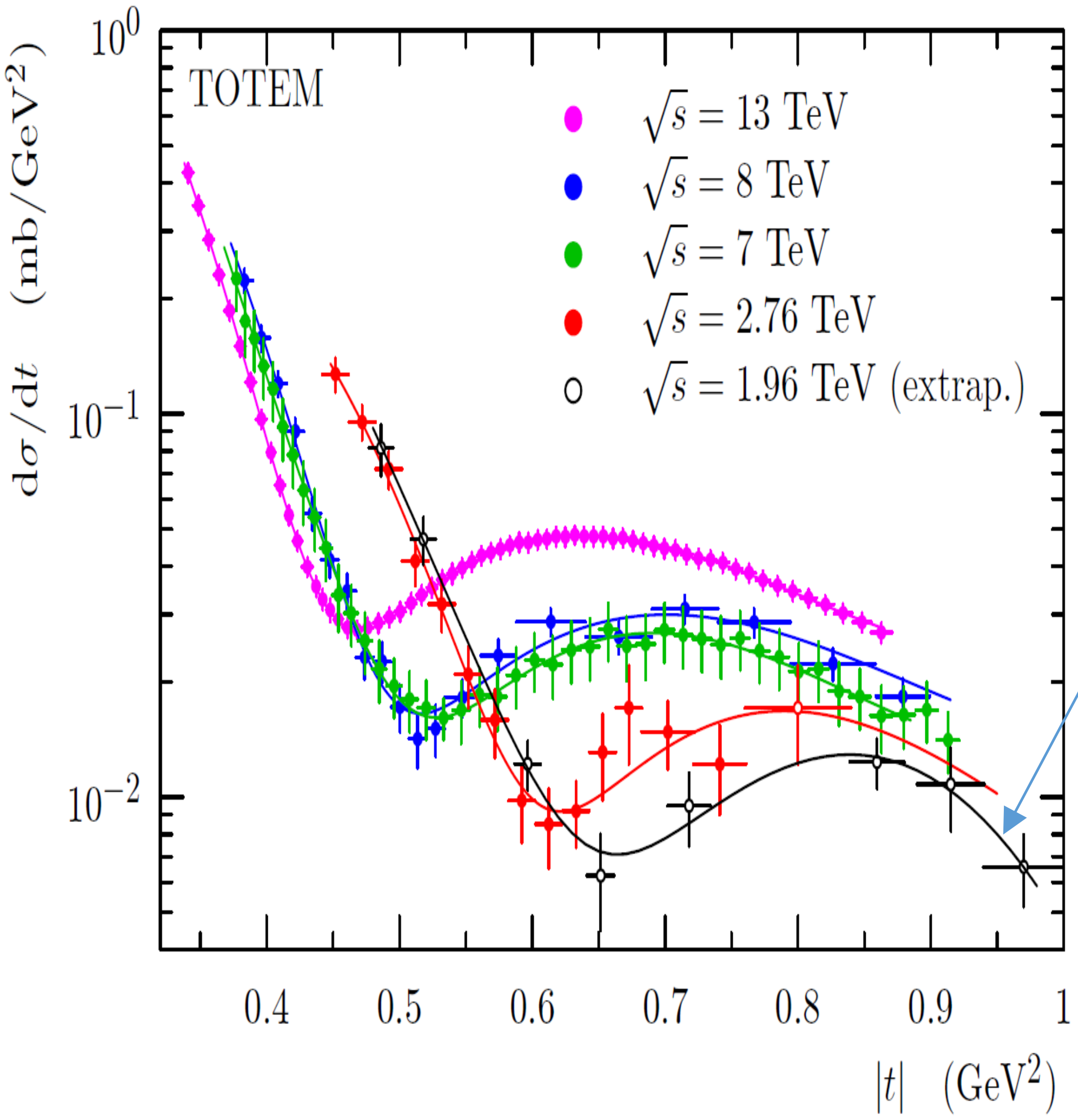



Extrapolated values

- Extrapolations to 1.96 TeV are small: Only 8% of the energy range where the measurements were performed

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 ($\chi^2/dof$= 0.63):

$$h(t) = \boldsymbol{a_1 e^{-(b_1|t|+c_1|t|^2)}} + \boldsymbol{a_2 e^{-(b_2|t|+c_2|t|^2+c_3|t|^3)}}$$

Describes $d\sigma/dt$ up to the dip, then has a steep falloff

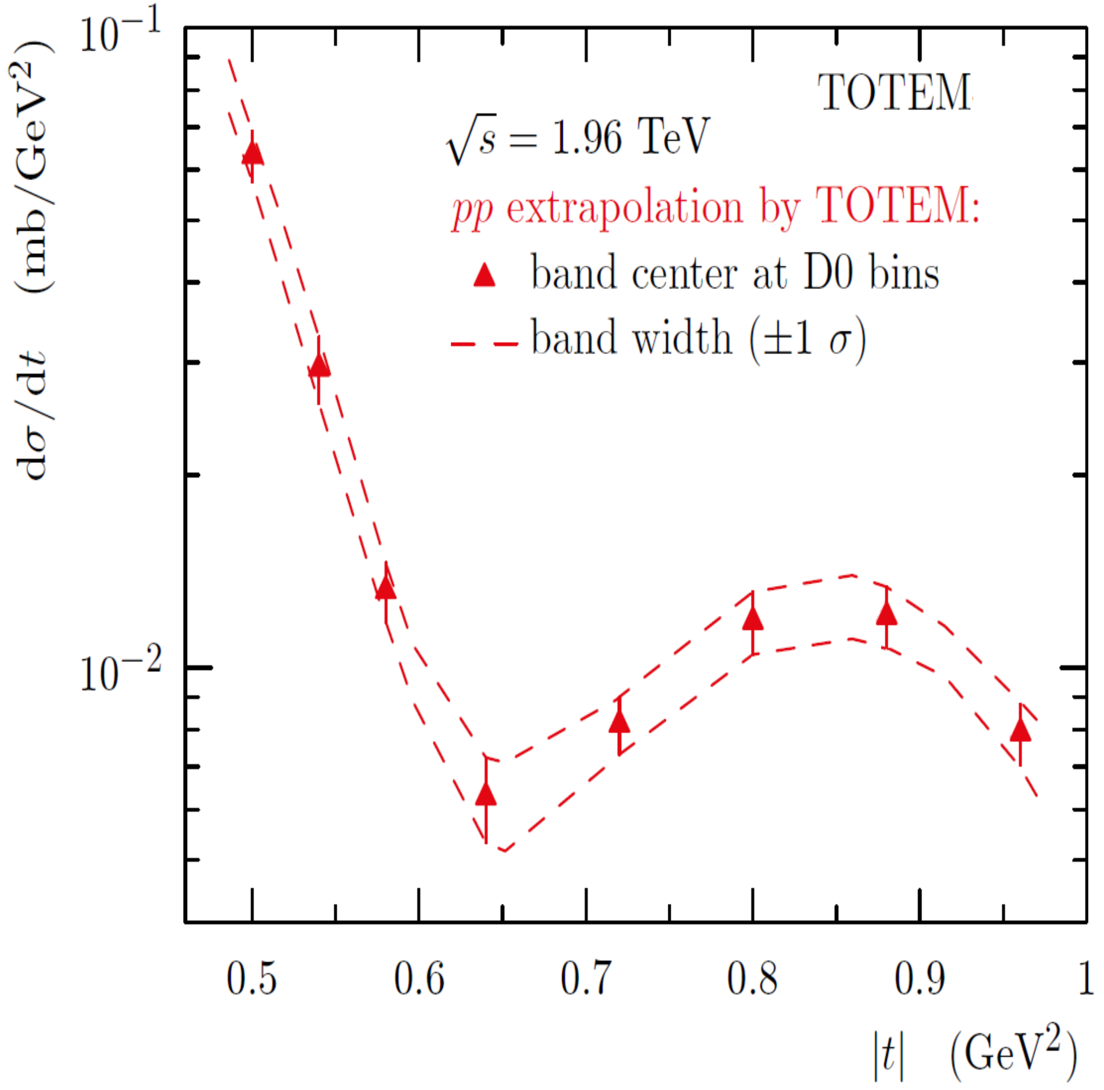
Describes the bump and subsequent falloff

- $h(t)$ 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 $d\sigma/dt$ at neighboring |t| values are correlated.

# Uncertainties of extrapolated pp $d\sigma/dt$

- **The pp extrapolation uncertainties are determined from MC ensembles:**
  - The extrapolated x-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 $pp \;\; d\sigma/dt$.



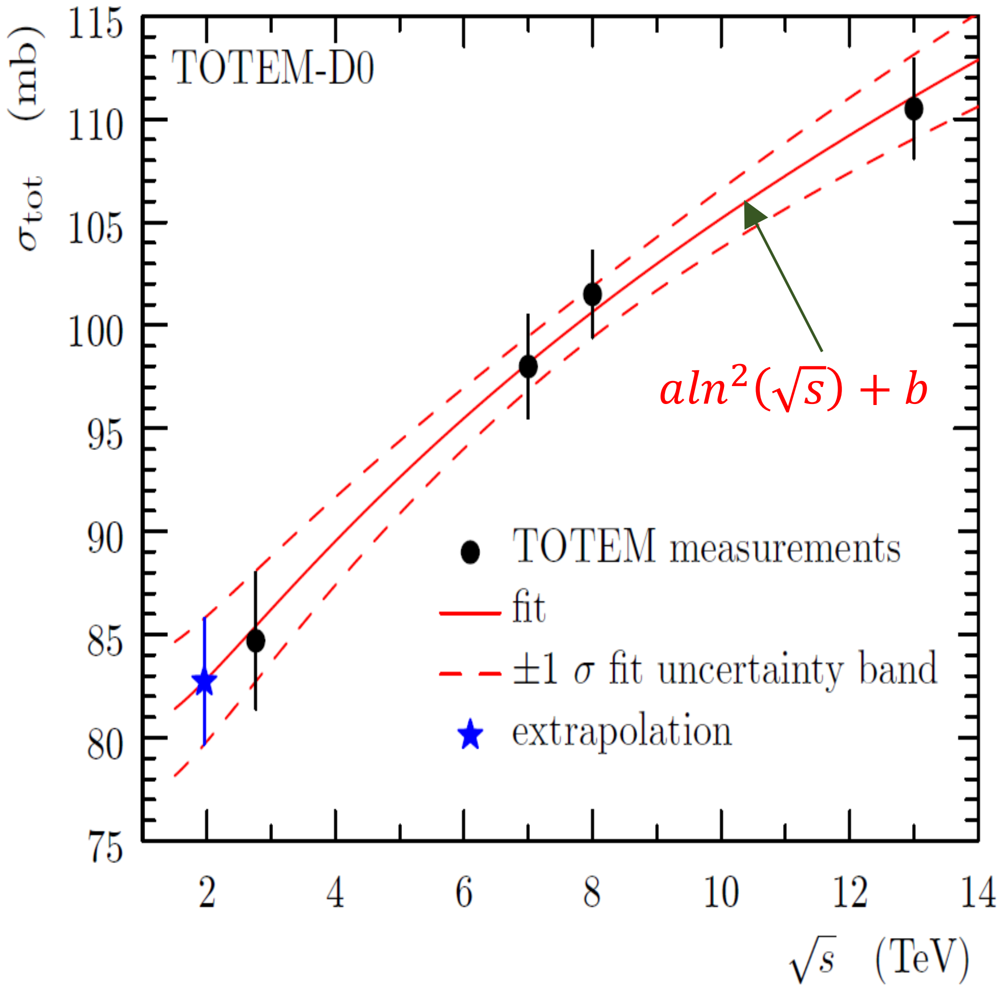
# Normalization of $d\sigma/dt$

- **We want a common normalization to compare the $d\sigma/dt$ shapes, 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 $\sigma_{tot}$ data to 1.96 $TeV$ is performed
  - The optical theorem is then used to get $d\sigma/dt(t=0)$ (using $\rho = 0.145$):

$$\sigma_{tot}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2}\left(\frac{d\sigma}{dt}\right)_{t=0} \Rightarrow \left(\frac{d\sigma}{dt}\right)_{t=0} = 357 \pm 26 \text{ mb/GeV}^2$$

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

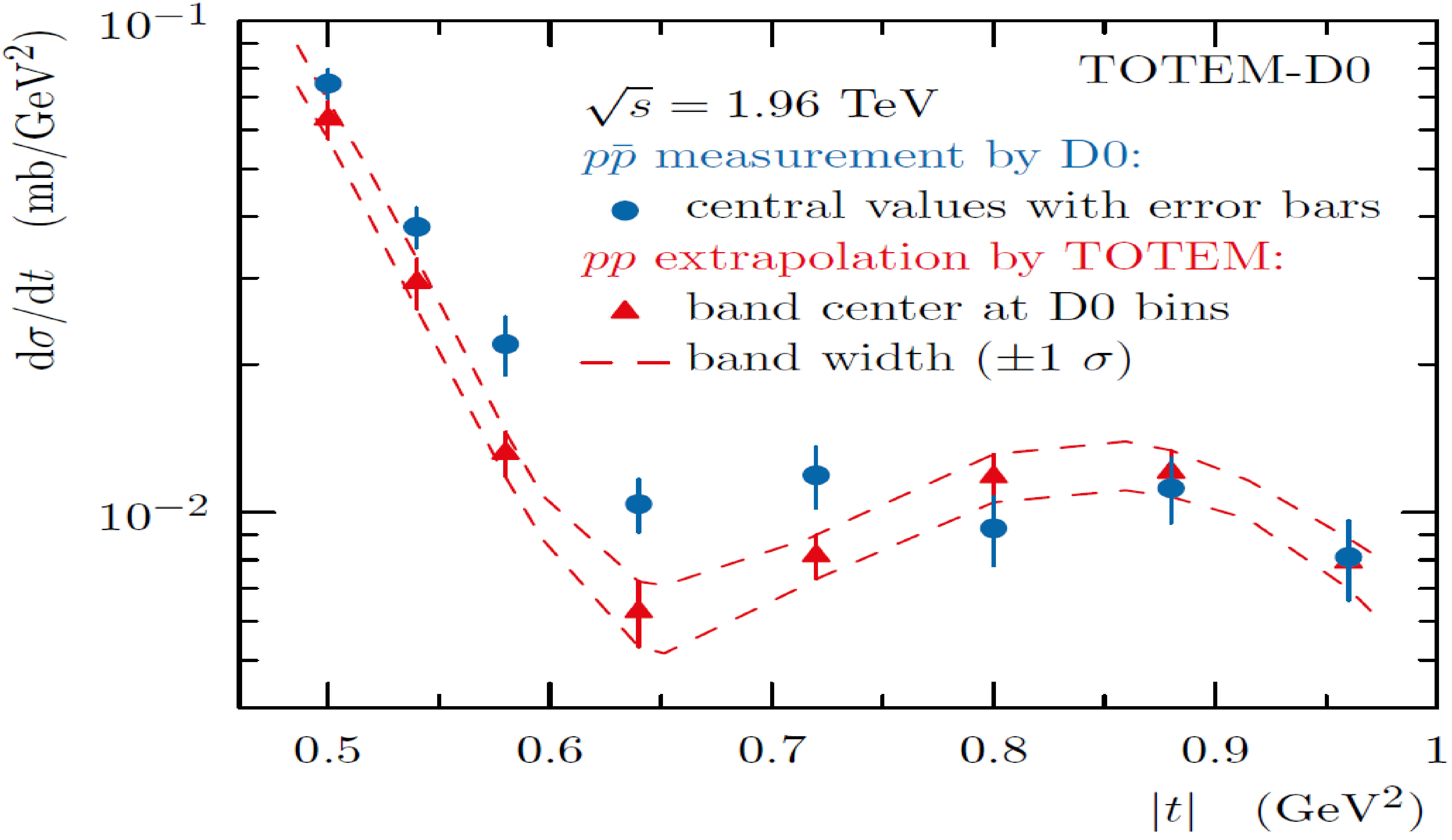
OP´s are expected to be equal for C-even only exchanges. The largest difference by theoretical Odderon models (2.9%) is taken as a systematic uncertainty.




Extrapolated $pp$ $\sigma_{tot}$ 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 $\chi^2$ 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 to the Cornille-Martin Theorem : the ratio of the $pp$ and $p\bar{p}$ integrated elastic cross sections tends to unity as $s \to \infty$.

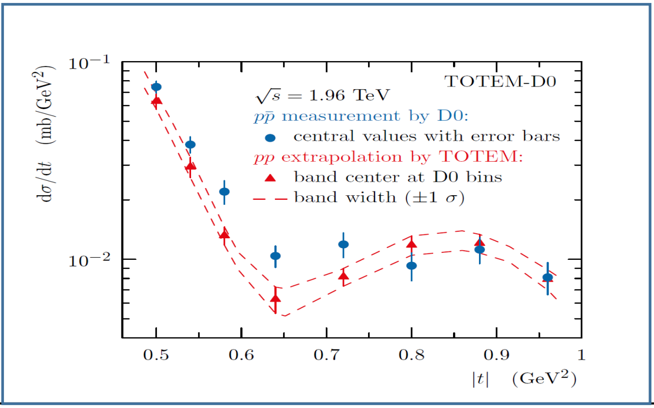
**We obtain: $\chi^2$ = 23.64, equivalent to a p-value of 6.1x10$^{-4}$ for 6 dof, with a corresponding significance of 3.4 $\sigma$**

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

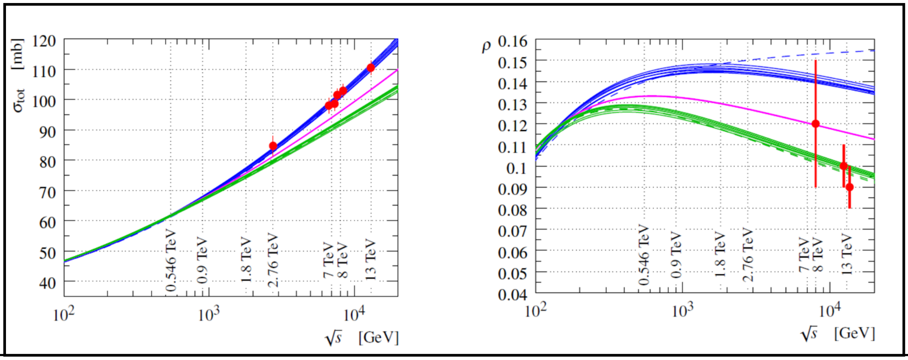
**We interpret this difference in $pp$ and $p\bar{p}$ elastic $d\sigma/dt$ at TeV energies as evidence of an Odderon amplitude contributing to the scattering process, in adddition to the Pomeron amplitude.**

# Combining evidence of Odderon Exchange from $\rho, \sigma_{tot}$ 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 3.4$\sigma$ level




256 models studied by the COMPETE Collaboration, and Durham, and Block-Halzen, with no-Odderon contribution are ruled out by TOTEM $\sigma_{tot}$ and $\rho$ measurements, at the level of 3.4 to 4.6$\sigma$

$\chi^2$

**Overall significance ranging between 5.3 to 5.7 $\sigma$,**
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 in shape from the measured $\frac{d\sigma_{p\bar{p}}}{dt}$ (at 1.96 TeV) at the level of $3.4\sigma$, which is interpreted as evidence of a contribution of an Odderon amplitude.

3. The evidence of the difference in shapes of the elastic $d\sigma/dt$ combined to the evidence from the values of $\sigma_{tot}$ and $\rho$ at the TeV energies, constitutes the **first experimental observation of the Odderon.**

Accepted for publication: https://journals.aps.org/prl/accepted/a307cY4eM5e1436c84761f33fc483a78ffc2cf0e7

# Thank you
# for your attention