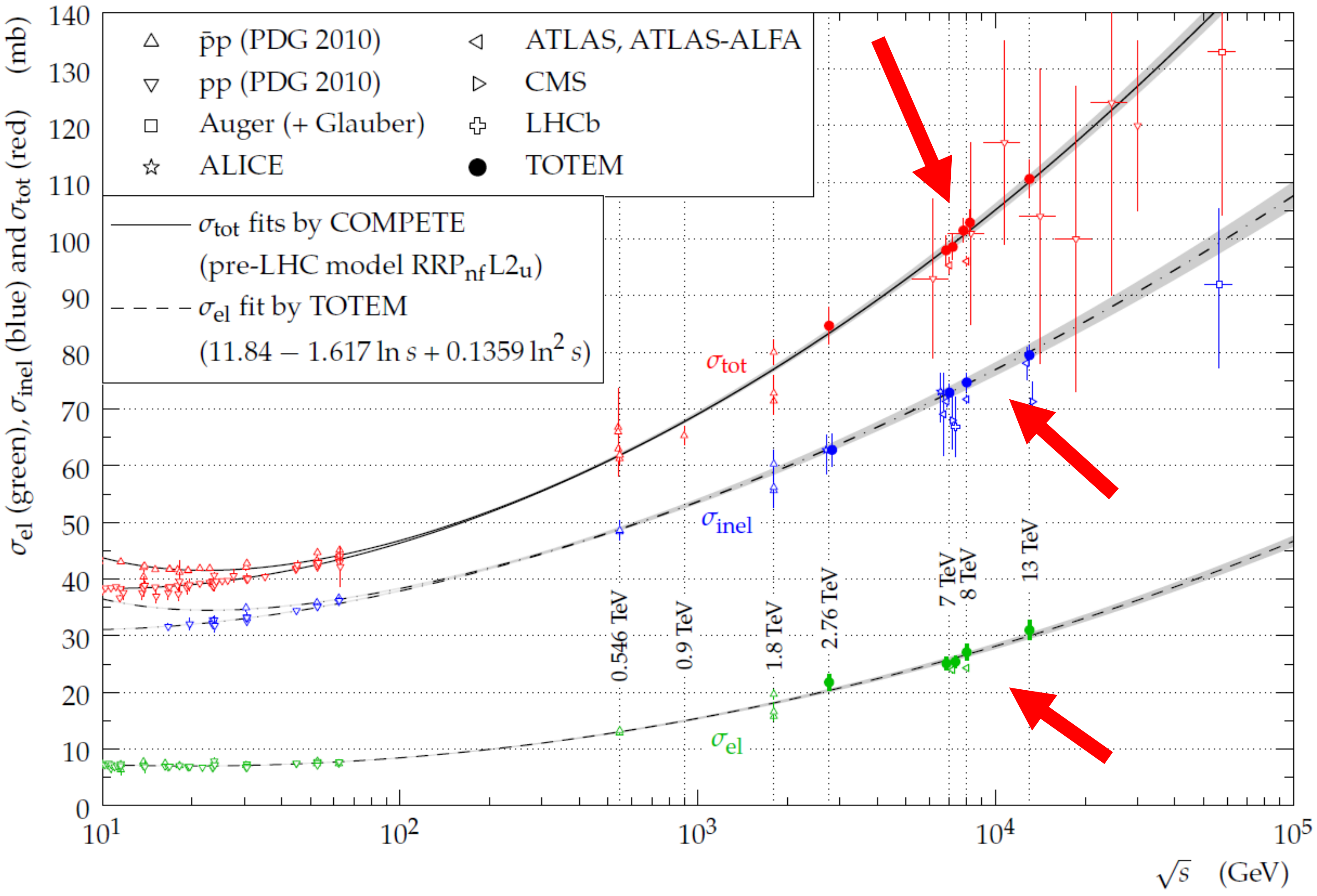
The shape of the interaction region of colliding protons in a Regge model

István Szanyi
in collaboration with László Jenkovszky
Eötvös Loránd University

New Trends in High-Energy Physics Conference
May 12 – 18, 2019, Odessa, Ukraine

Introduction

- Total, elastic and inelastic cross sections follow the expectations from lower energies.



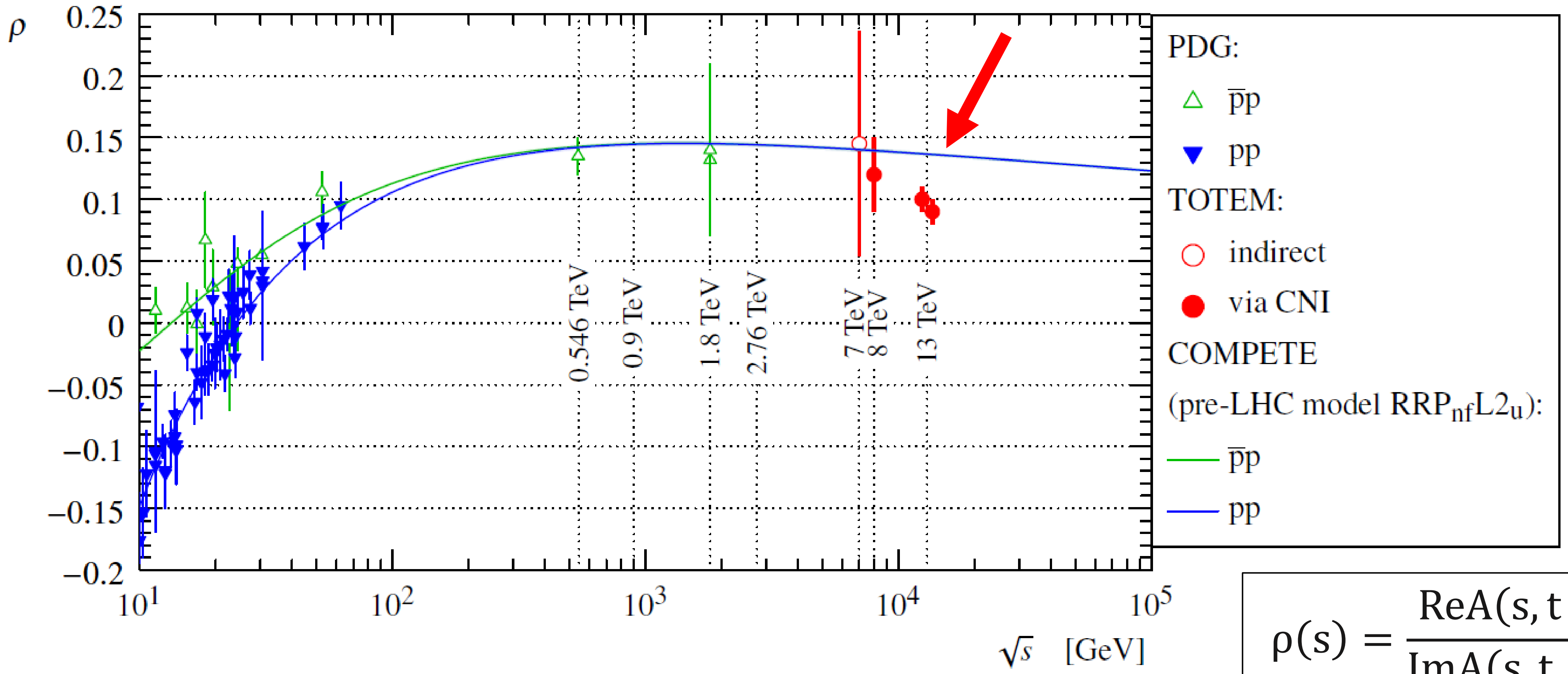
pp and $p\bar{p}$ total, elastic and inelastic cross sections measurements.

TOTEM Collab., Eur. Phys. J. C 79 (2019) 103

Introduction

- Very low value of the pp ρ-parameter at 13 TeV.

TOTEM Collab., CERN-EP-2017-335

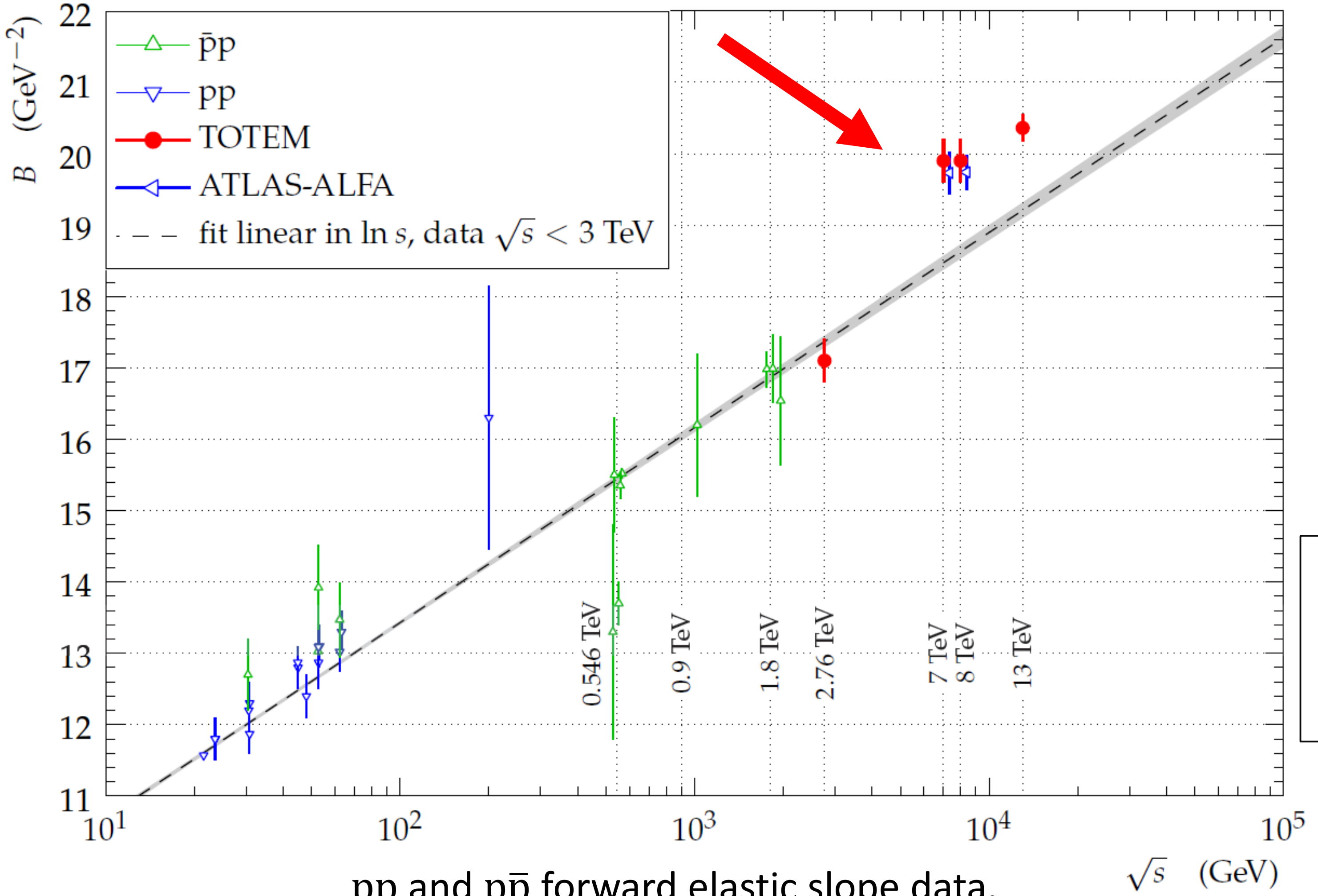


pp and pp̄ ρ-parameter measurements.

$$\rho(s) = \frac{\mathrm{Re}A(s, t = 0)}{\mathrm{Im}A(s, t = 0)}$$

Introduction

- Rapid rise of the pp forward slope from about 3 TeV.



pp and p$\bar{\text{p}}$ forward elastic slope data.

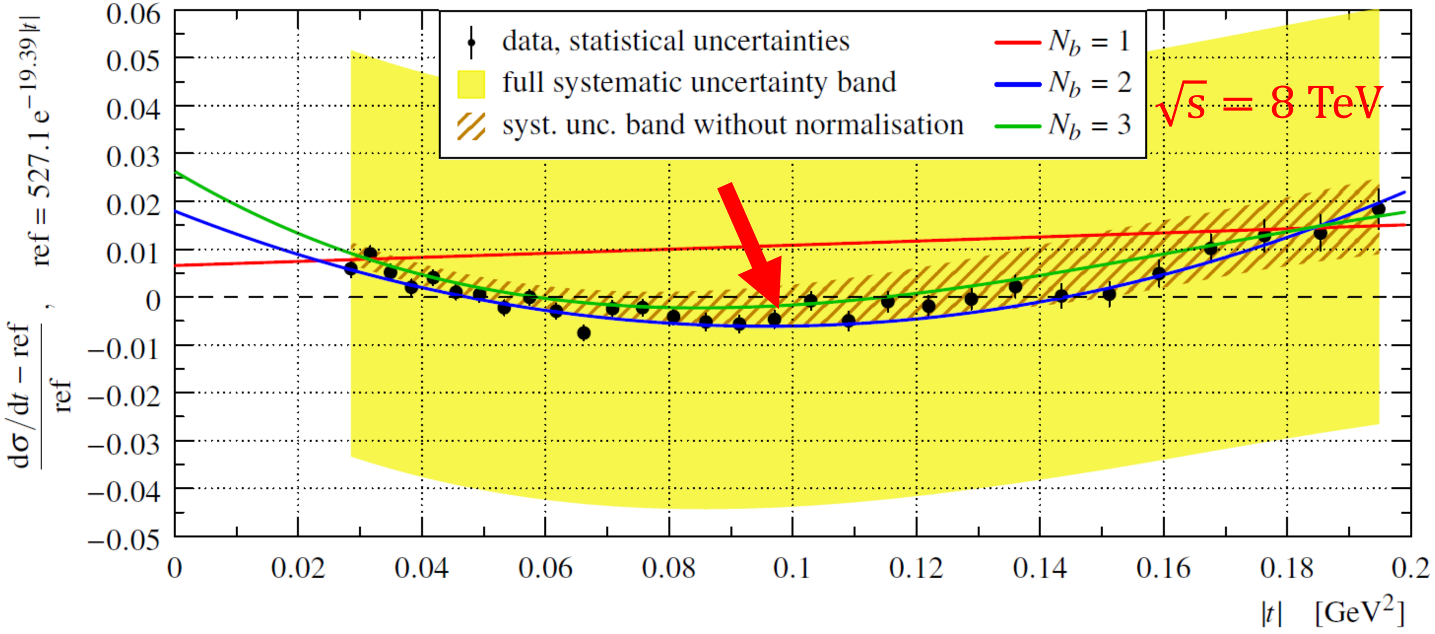
[TOTEM Collab., Eur. Phys. J. C 79 (2019) 103]

$$B(s) = \frac{d}{dt}\left(\ln \frac{d\sigma_{el}}{dt}(s,t)\right)\Bigg|_{t=0}$$

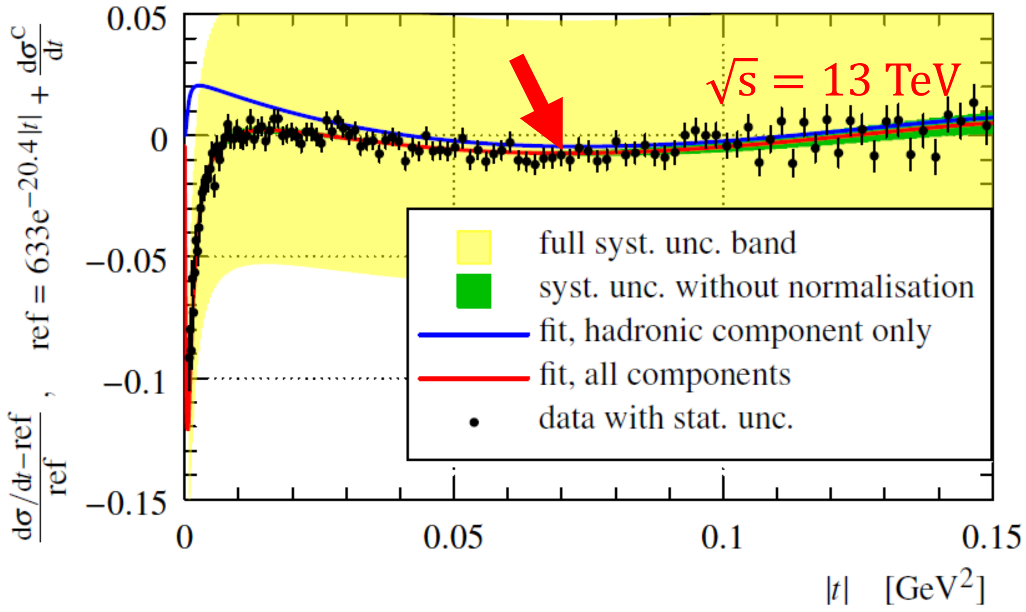
Introduction

- Low-|t| structure in the pp differential cross section (the so called "break").

TOTEM Collab., Nucl. Phys. B 899 (2015) 527-546



TOTEM Collab., CERN-EP-2017-335



Normalized form of the elastic pp low-|t|differential cross section data measured by TOTEM at 8 and 13 TeV.

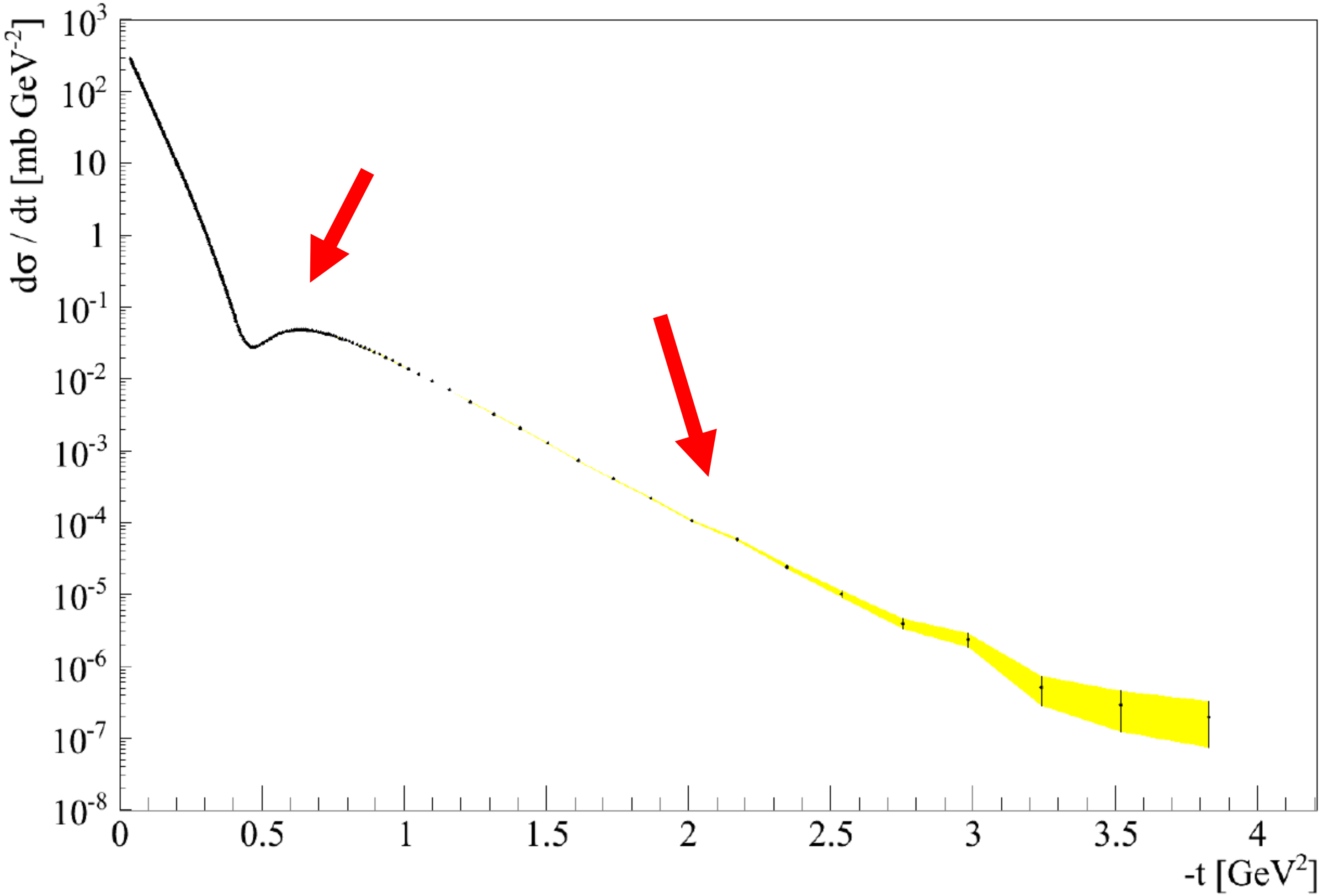
L. Jenkovszky, I. Szanyi, Phys. Part. Nuclei Lett., 14 (2017) 687

L. Jenkovszky, I. Szanyi, Mod. Phys. Lett. A 32, 1750116 (2017)

L. Jenkovszky, I. Szanyi, CI. Tan, Eur. Phys. J. A 54: 116 (2018)

Introduction

- Absence of secondary dips and bumps in the pp differential cross section.



Elastic pp differential cross section preliminary data measured by TOTEM at 13 TeV.

[TOTEM Collab., CERN-EP-2018-338]

The $d\sigma(t)/dt$ and the $\mathrm{Im}\, h(b)$

$$\frac{d\sigma_{el}}{dt}(s,t) = \frac{\pi}{s^2}|A(s,t)|^2 \quad \longleftrightarrow \quad h(s,b) = \frac{1}{s}\int_0^{\infty} A(s,t) J_0\left(b\sqrt{-t}\right)\sqrt{-t}\, d\sqrt{-t}$$

- **"break":** deviation from an exponential form near $-t = 0.1\ \mathrm{GeV}^2$

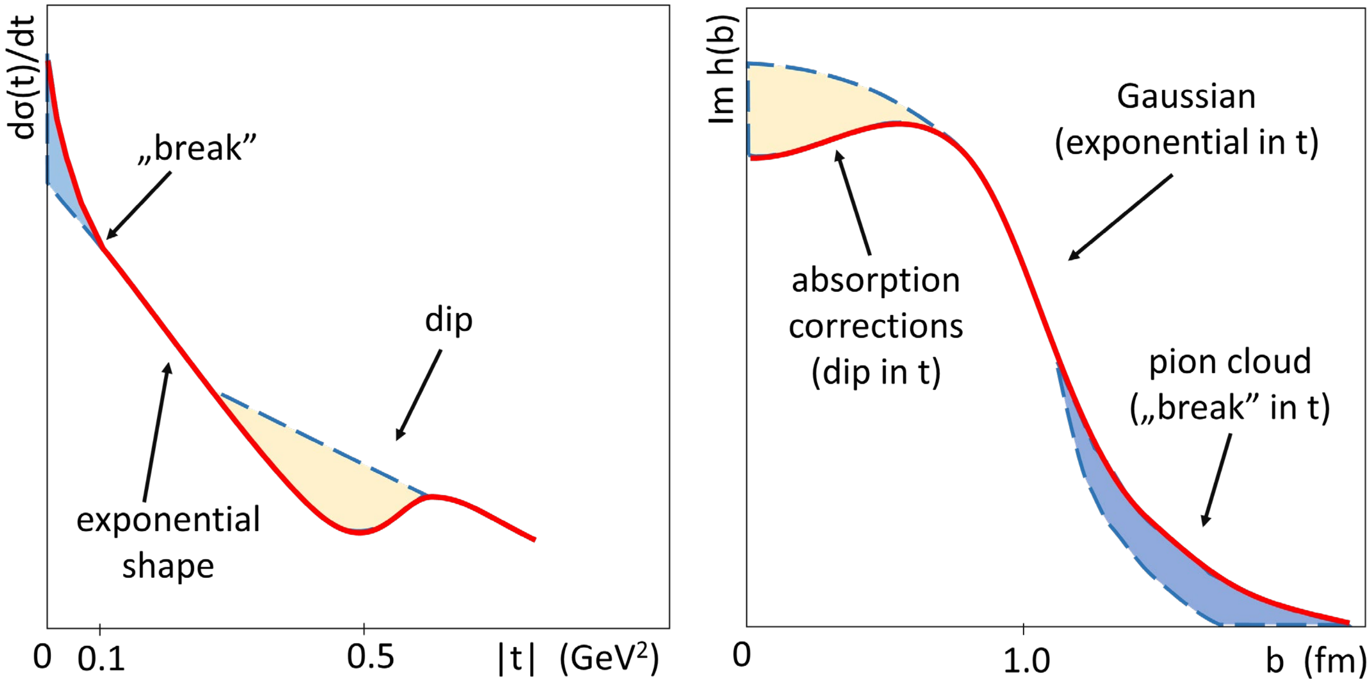
  → related to the two-pion exchange (t-channel unitarity)

  → pion cloud of the proton

- **dip:** diffraction minimum with energy dependent location

→ related to absorption corrections (s-channel unitarity)

→ decrease in $\mathrm{Im}\, h(b)$ at small b



Connection between the elastic pp differential cross section and the imaginary part of the impact parameter amplitude (schematic view).

Scattering amplitude: dipole Regge model

$$\boxed{A(s,t)_{pp}^{\bar{p}p} = \mathbf{A_P(s,t)} \pm \mathbf{A_O(s,t)} + A_f(s,t) \pm A_\omega(s,t) + \ \ldots}$$

- **Dipole pomeron and odderon:**

I. Szanyi, N. Bence, L. Jenkovszky: J. Phys. G 46, 055002 (2019)

$$\boxed{\mathbf{A_P}(s,t) = i\frac{a_P s}{b_P s_{0P}}\left[r_{1P}^2(s) e^{r_{1P}^2(s)[\alpha_P - 1]} - \varepsilon_P r_{2P}^2(s) e^{r_{2P}^2(s)[\alpha_P - 1]}\right]}$$

$$\boxed{\mathbf{A_O}(s,t) = -i\mathbf{A_P}(s,t)}$$

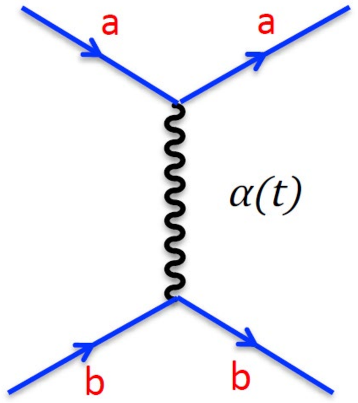
(with free parameters labeld by "**O**")

$$\boxed{r_{1P}^2(s) = b_P + L_P - i\pi/2} \quad \boxed{r_{2P}^2(s) = L_P - i\pi/2} \quad \boxed{L_P \equiv \ln(s/s_{0P})}$$

- **Pomeron and odderon trajectories:**

$$\boxed{\alpha_P \equiv \ \alpha_P(t) = 1 + \delta_P + \alpha_{1P} t - \alpha_{2P}\left(\sqrt{4m_\pi^2 - t} - 2m_\pi\right)}$$

$$\boxed{\alpha_O \equiv \ \alpha_O(t) = 1 + \delta_O + \alpha_{1O} t - \alpha_{2O}\left(\sqrt{9m_\pi^2 - t} - 3m_\pi\right)}$$



Exchange of a Regge trajectory in the t-channel.

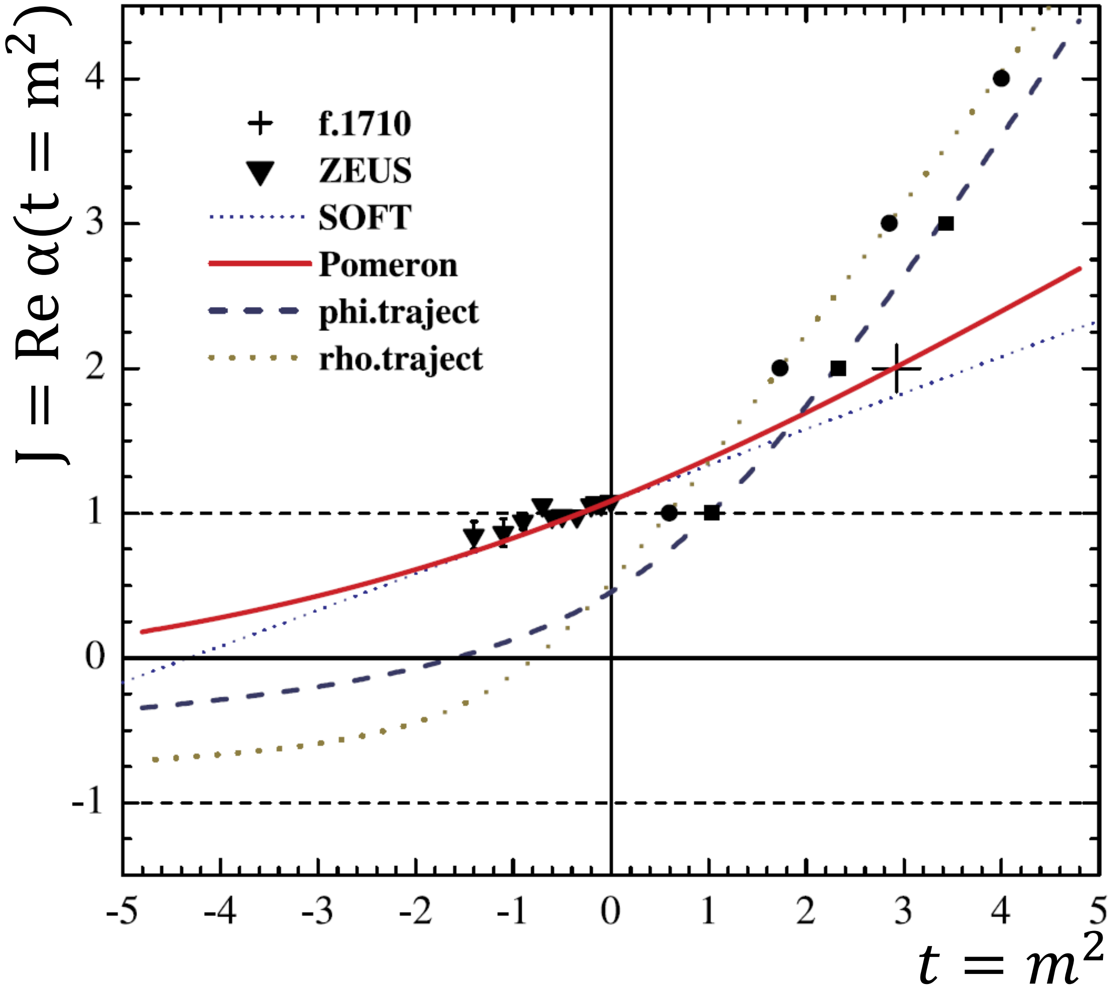
Regge trajectories

- Reggeon (in general):

  → virtual particle with continuously varying spin $(J = \mathrm{Re}\,\alpha(t))$ and virtuality $(t = m^2)$ lying on the relevant trajectory (scattering at $-t$)
  → at certain values of virtuality there are real particles (spectroscopy at $+t$)

- Secondary reggeons (f, ω, ρ, ϕ …) → mesonic exchanges and meson spectra

- Pomeron (P) and odderon (O) → gluonic exchanges and glueball spectra



The Chew–Frautschi plots of the leading ρ, φ and P complex Regge trajectories
M.N. Sergeenko, Eur. Phys. J. C (2012) 72:2128

L. Jenkovszky, R. Schicker and I. Szanyi. Int. J. Mod. Phys. E 27, 1830005 (2018)

Unitarity and overlap functions

- **Unitarity of the S-matrix,** $SS^{+} = 1$ → relation between the elastic scattering amplitude and the inelastic processes.
- The **unitarity constraint in impact parameter representation**:

$$\boxed{2\mathrm{Im}h(s,b) = |h(s,b)|^{2} + G_{in}(s,b)}$$

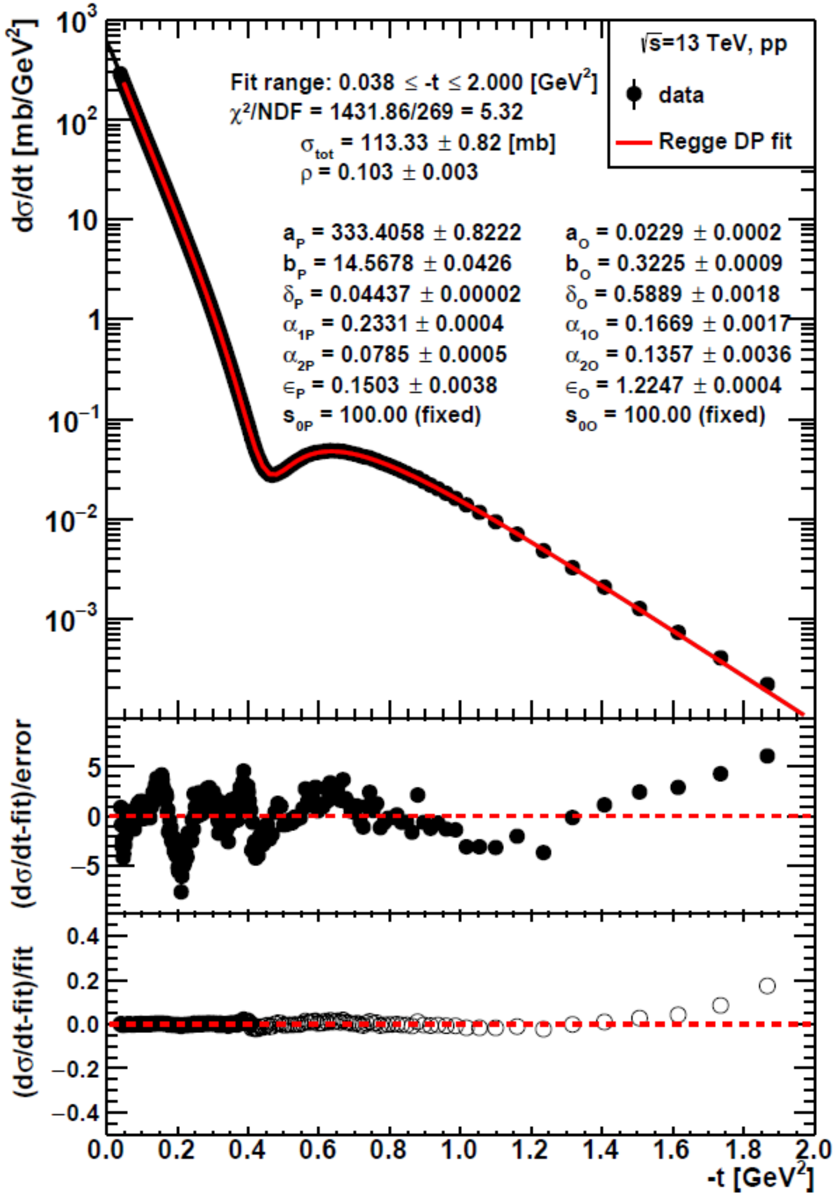
- The **total, elastic and inelastic cross sections**:

$$\boxed{\sigma_{tot}(s) = 2\int d^{2}b\, \mathrm{Im}h(s,b)} \quad \boxed{\sigma_{el}(s) = \int d^{2}b\, |h(s,b)|^{2}} \quad \boxed{\sigma_{in}(s) = \int d^{2}b\, G_{in}(s,b)}$$

- The **inelastic overlap function G_{in}** → probability of absorption associated to a given b value → gives the shape of the interaction region:

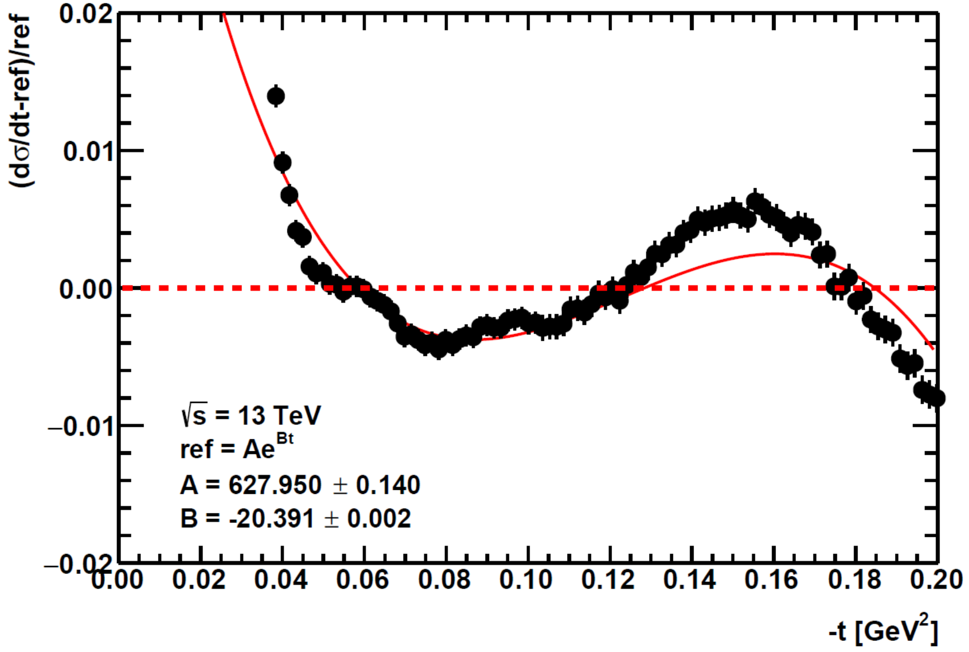
$$\boxed{G_{in}(s,b) = 2\mathrm{Im}h(s,b) - |h(s,b)|^{2}} \quad \text{with} \quad \boxed{0 \leq G_{in}(s,b) \leq 1}$$

Fit of $d\sigma(t)/dt$ @ 13 TeV



$$R(t) = \frac{d\sigma/dt - \mathrm{ref}}{\mathrm{ref}}$$

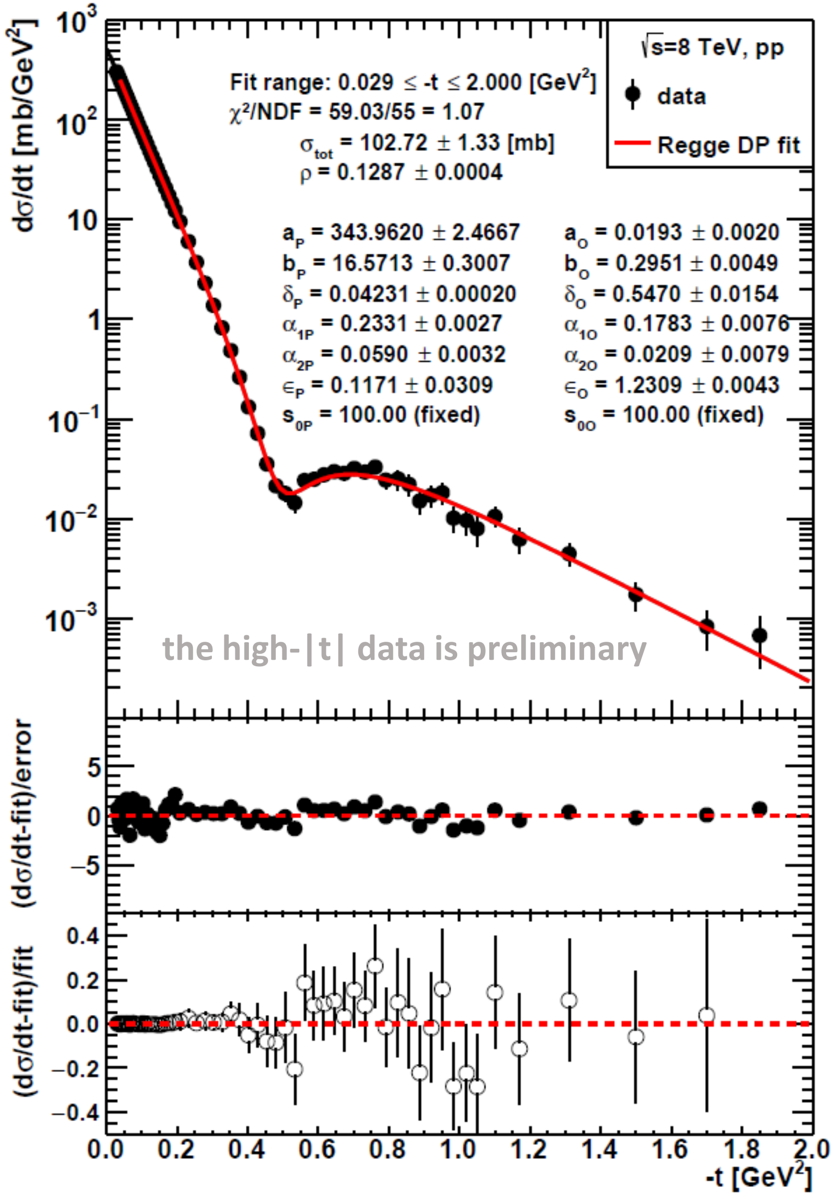
$$\mathrm{ref} = Ae^{Bt}$$

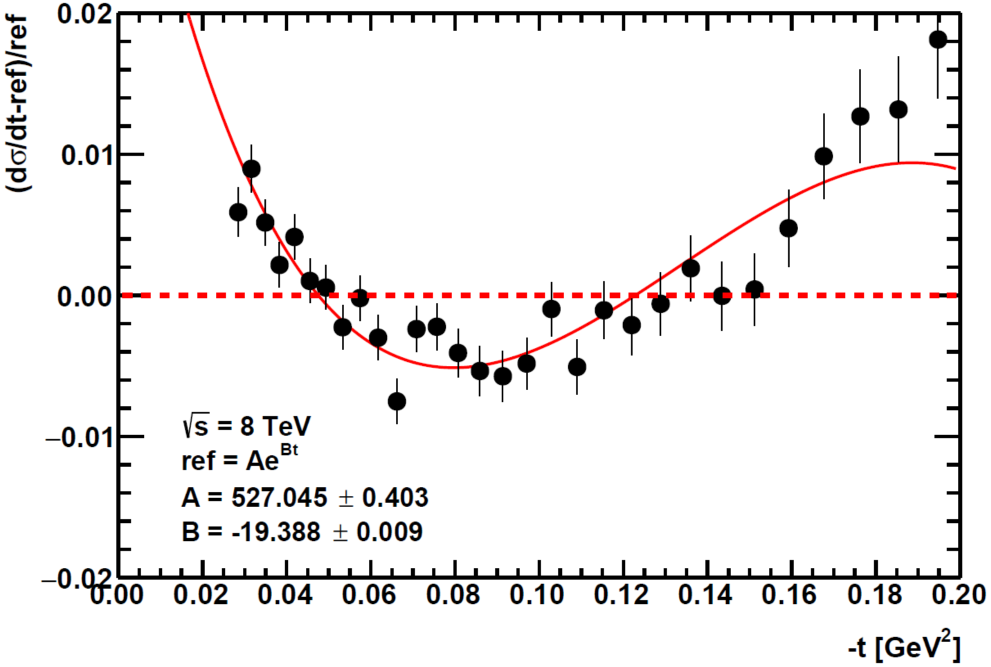


Normalized form of the differential cross section showing the low-|t| "break"

Source of the data:
TOTEM Collab., CERN-EP-2018-338

Fit of dσ(t)/dt @ 8 TeV

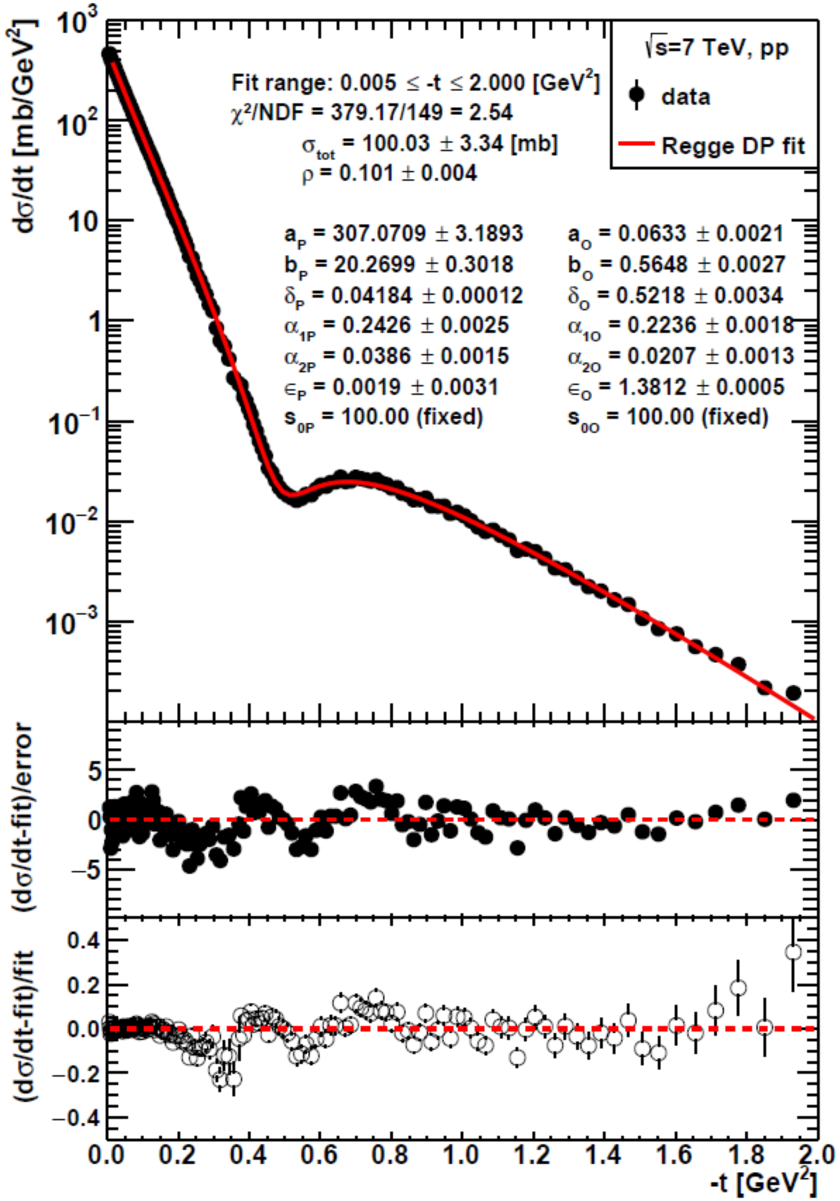


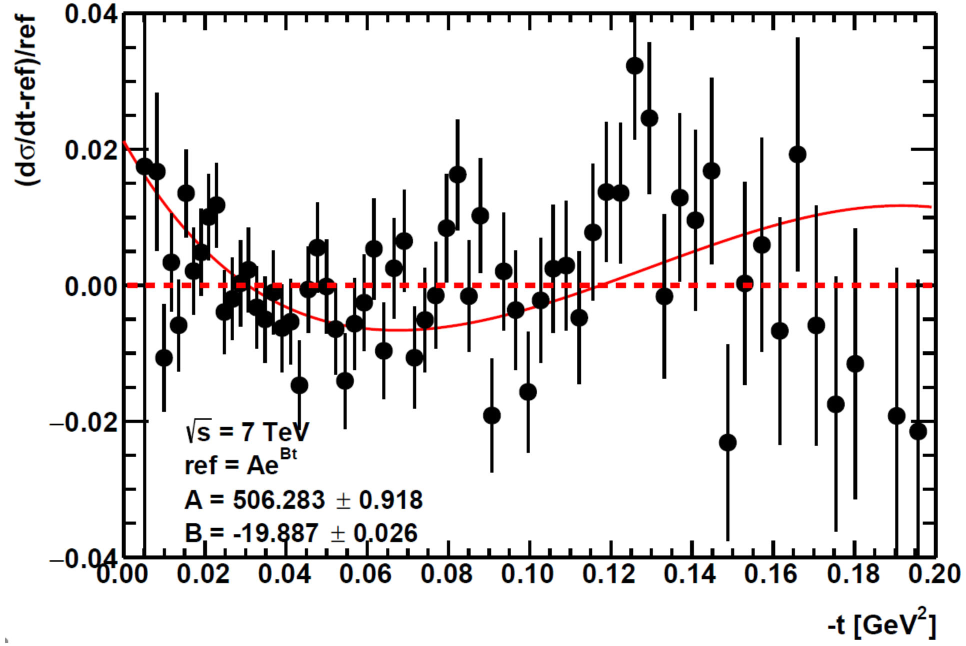


Normalized form of the differential cross section showing the low-|t| "break"

Source of the data:
TOTEM Collab., Nucl. Phys. B 899 (2015) 527-546
J. Kaspar, ISMD2017, Tlaxcala, Mexico (2017).

Fit of dσ(t)/dt @ 7 TeV

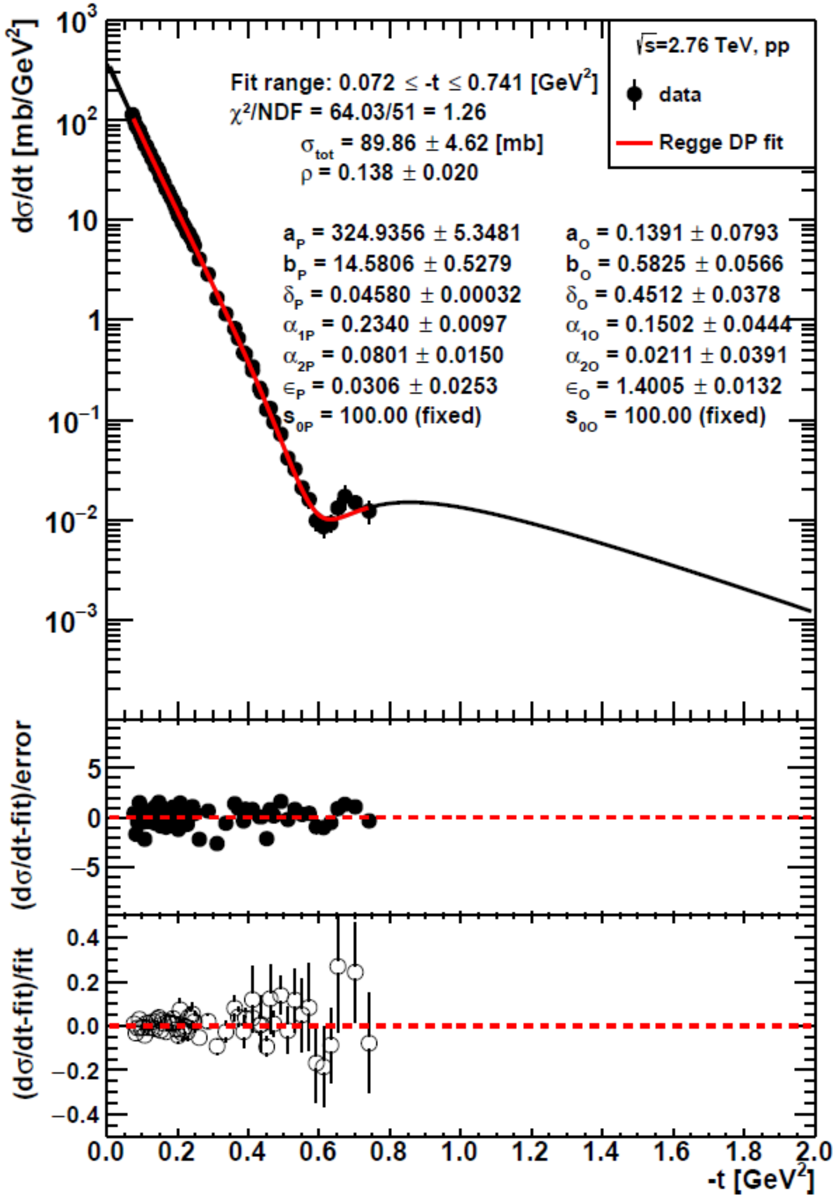


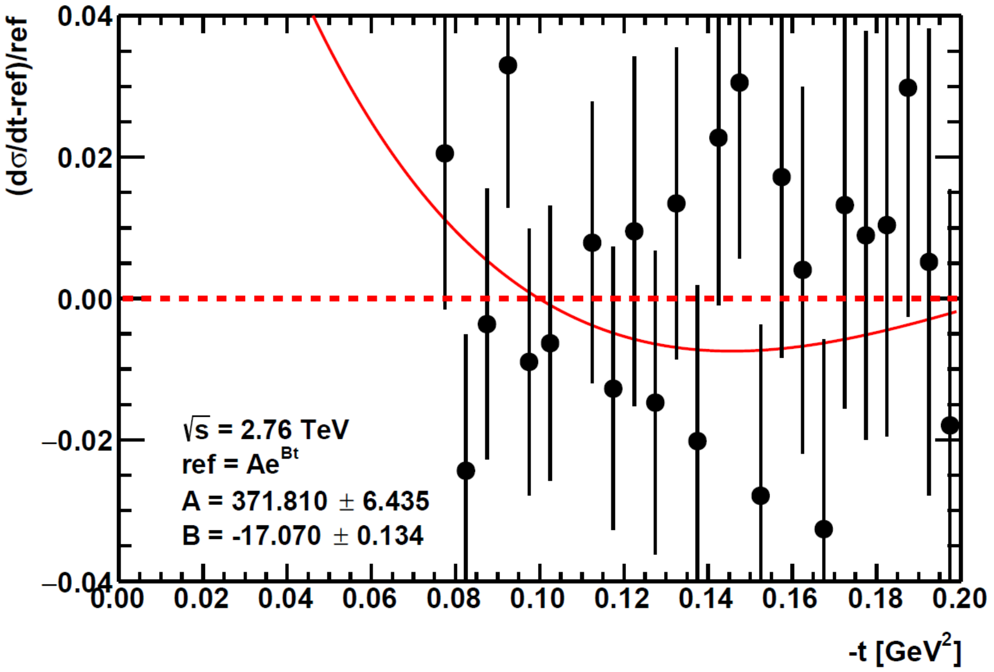


Normalized form of the differential cross section showing the low-|t| ”break”

Source of the data:
TOTEM Collab., EPL 101 (2013) 21002

Fit of dσ(t)/dt @ 2.76 TeV

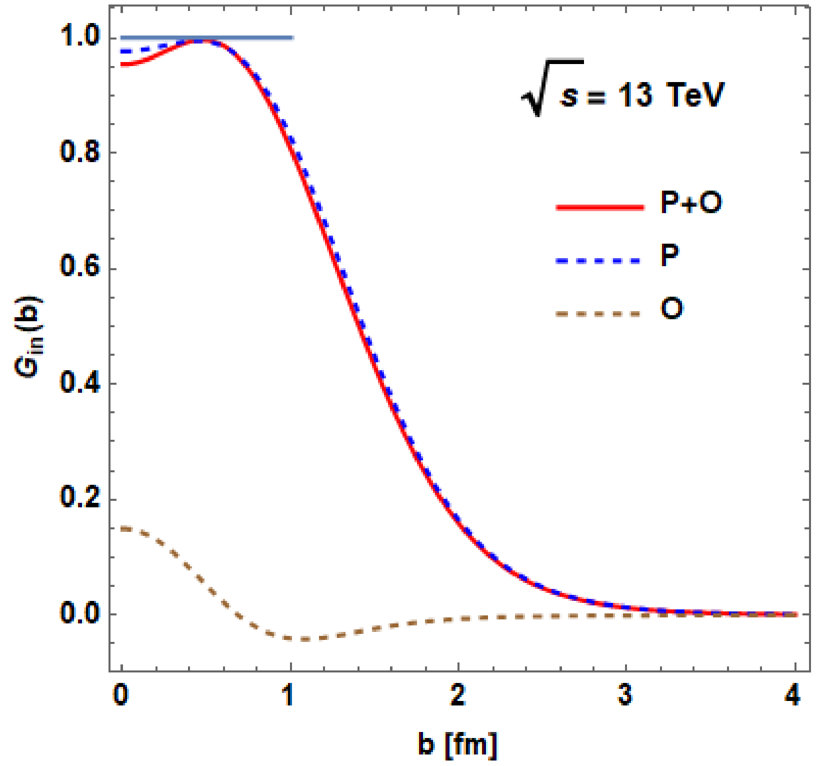




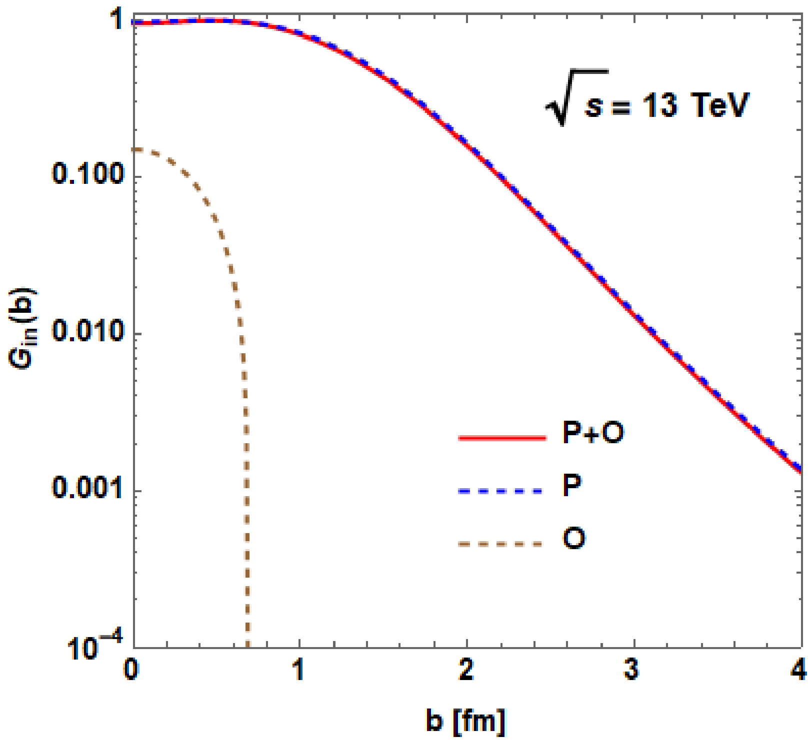
Normalized form of the differential cross section showing the low-|t| ”break”

Source of the data:
TOTEM Collab., CERN-EP-2018-341

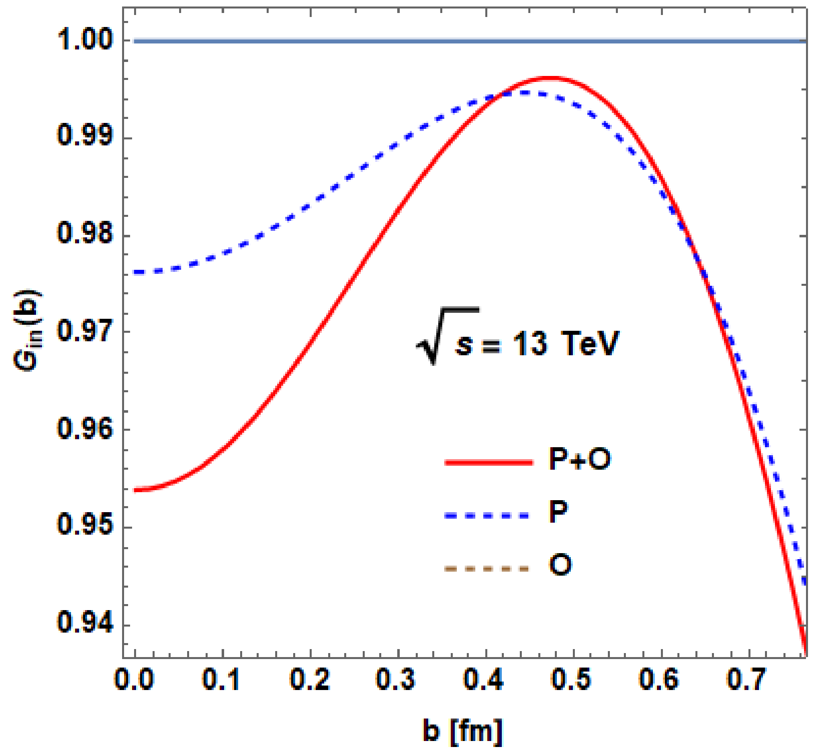
Inelastic overlap function @ 13 TeV



Calculated $G_{in}(b)$.



$G_{in}(b)$ with logarithmic vertical axis.

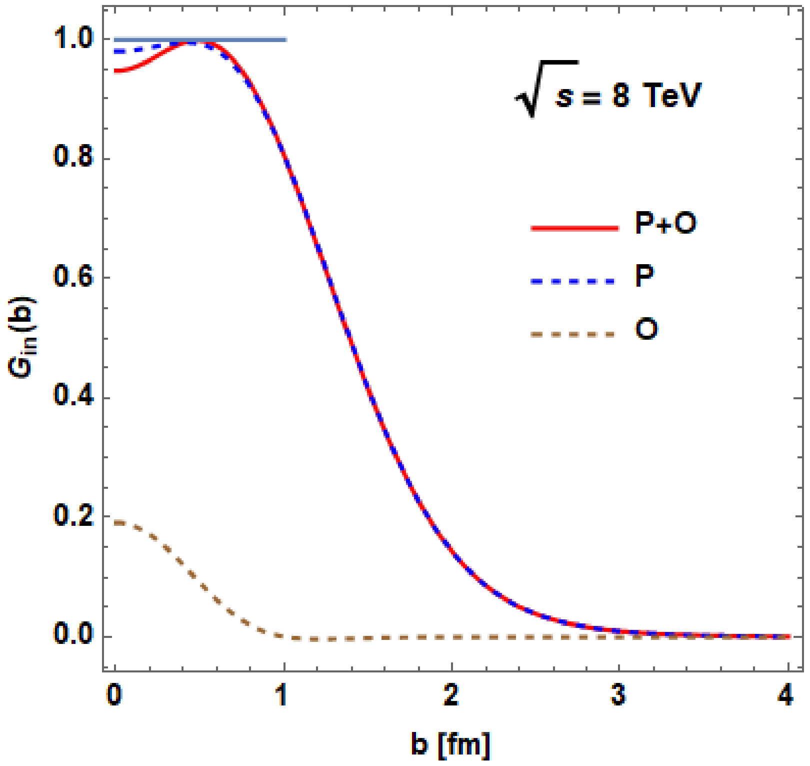


$G_{in}(b)$ enlarged for low b values.

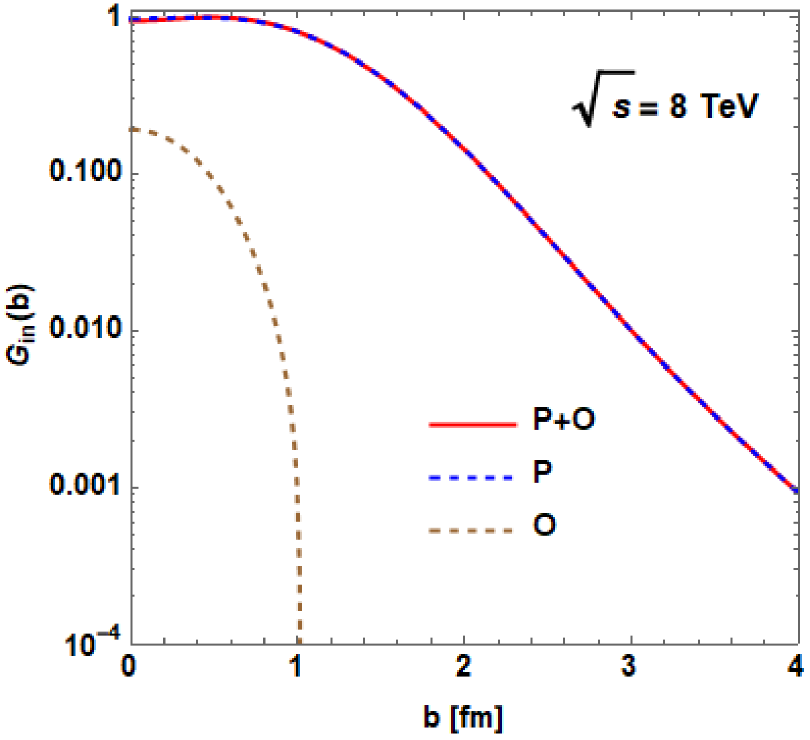
Similar results concerning the low-b G_{in}:

- I.M. Dremin, Physics 1 (2019) 33-39.
- T. Csörgő, R. Pasechnik, A. Ster, arXiv:1902.00109.
- W. Broniowski, L. Jenkovszky, E. Ruiz Arriola, I. Szanyi, Phys. Rev. D 98, 074012 (2018).

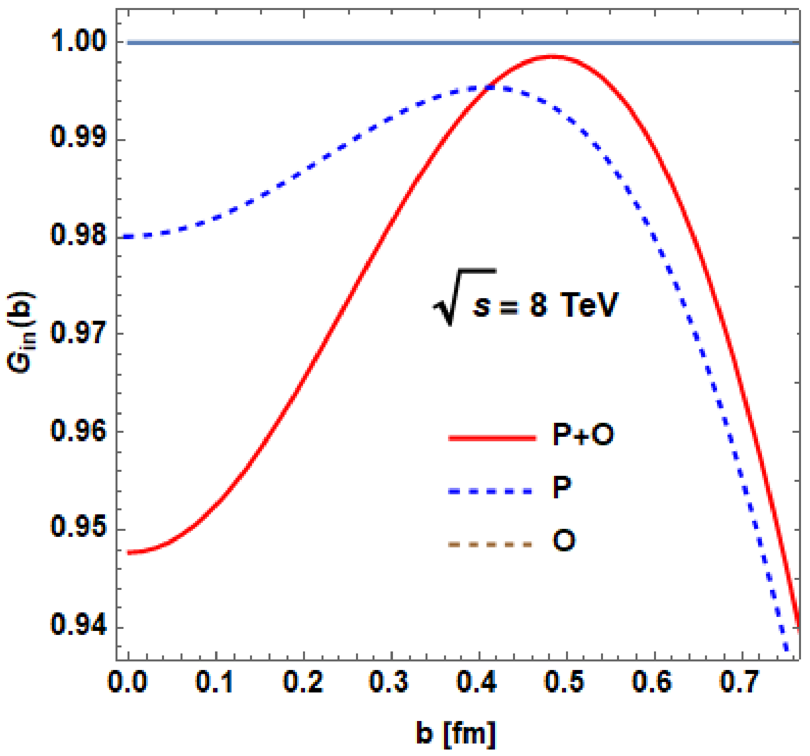
Inelastic overlap function @ 8 TeV



Calculated $G_{in}(b)$.

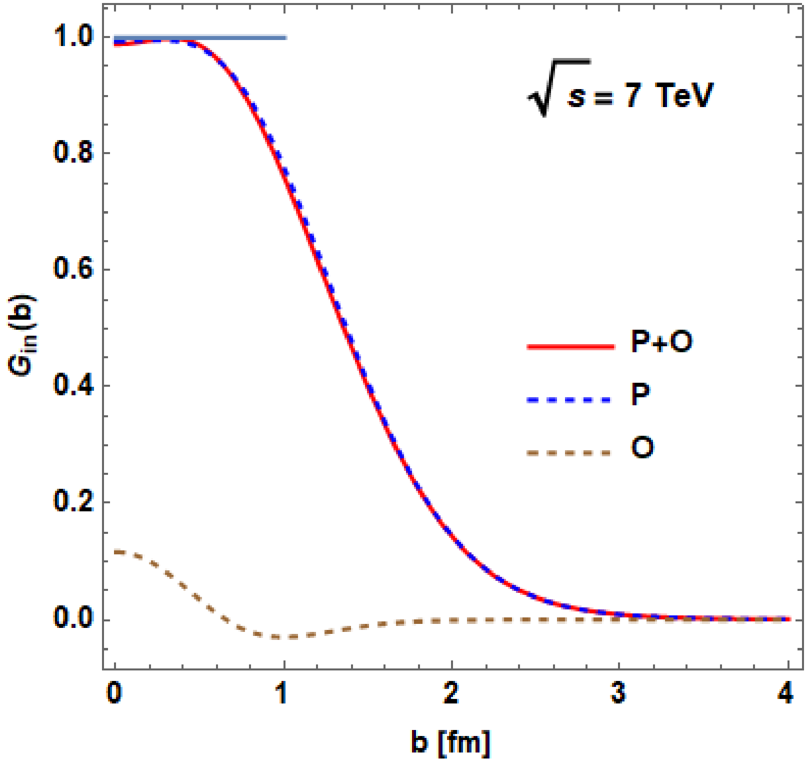


$G_{in}(b)$ with logarithmic vertical axis.

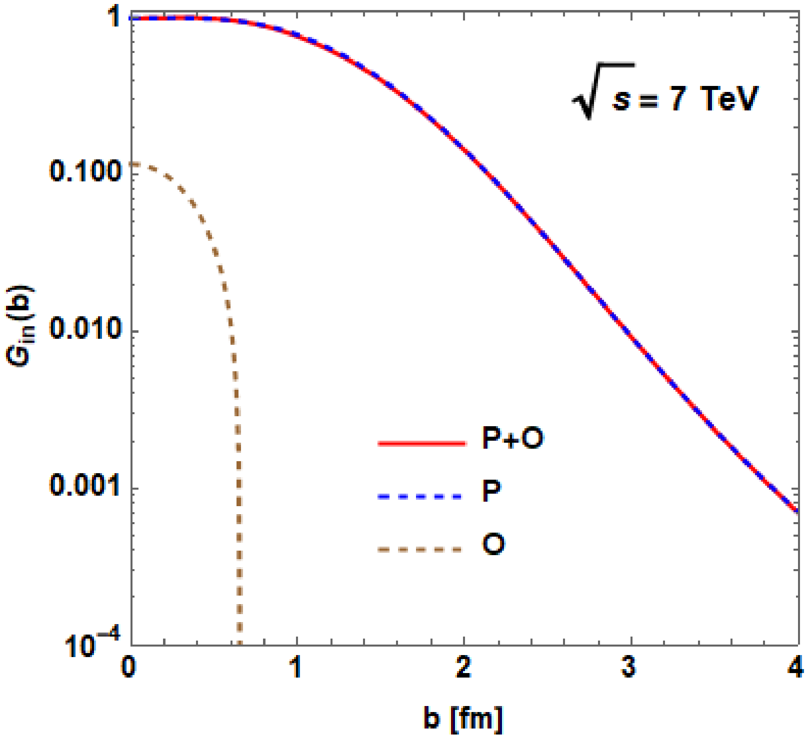


$G_{in}(b)$ enlarged for low b values.

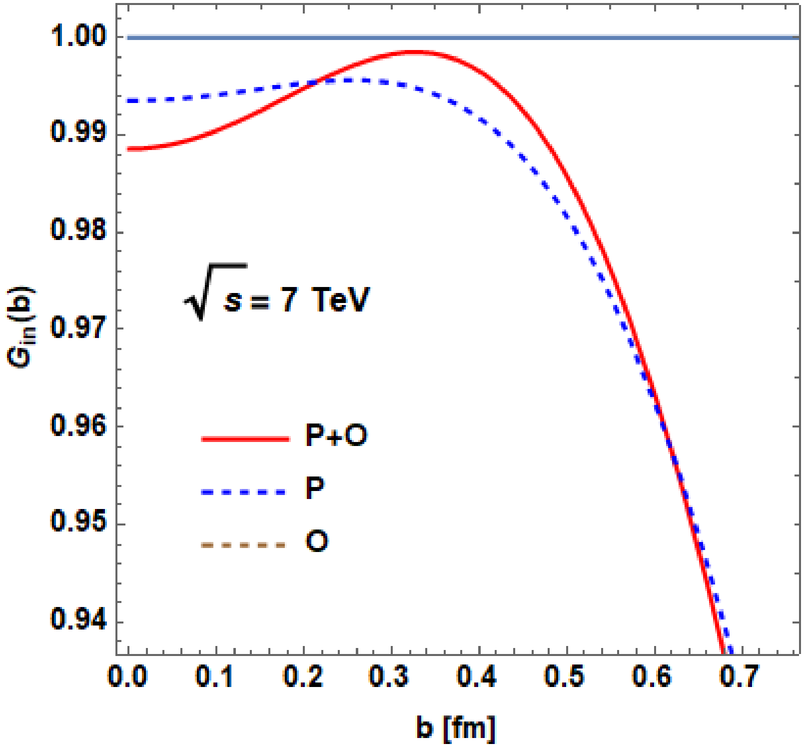
Inelastic overlap function @ 7 TeV



Calculated $G_{in}(b)$.

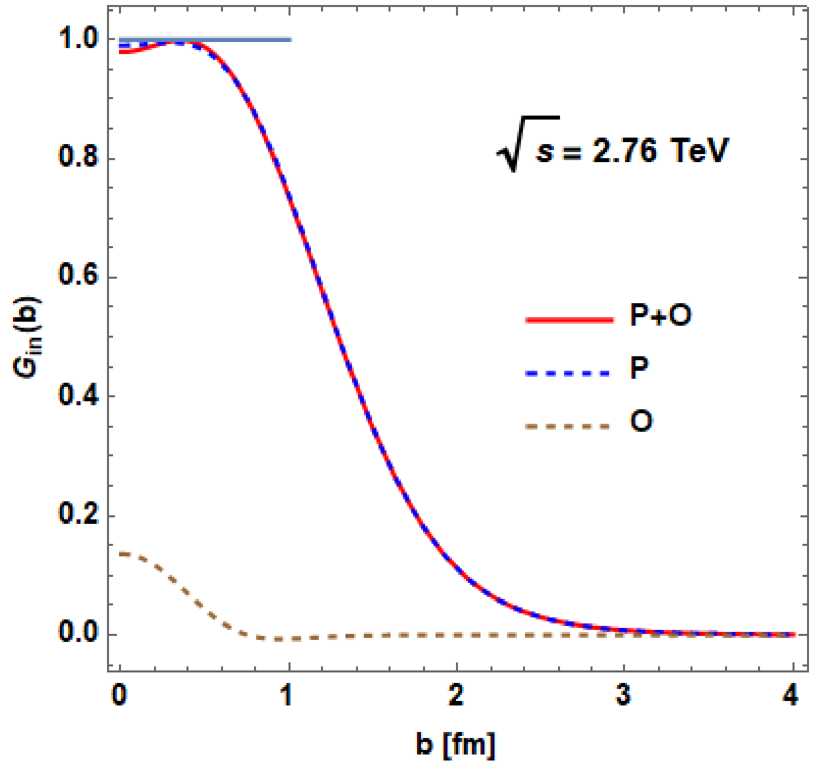


$G_{in}(b)$ with logarithmic vertical axis.

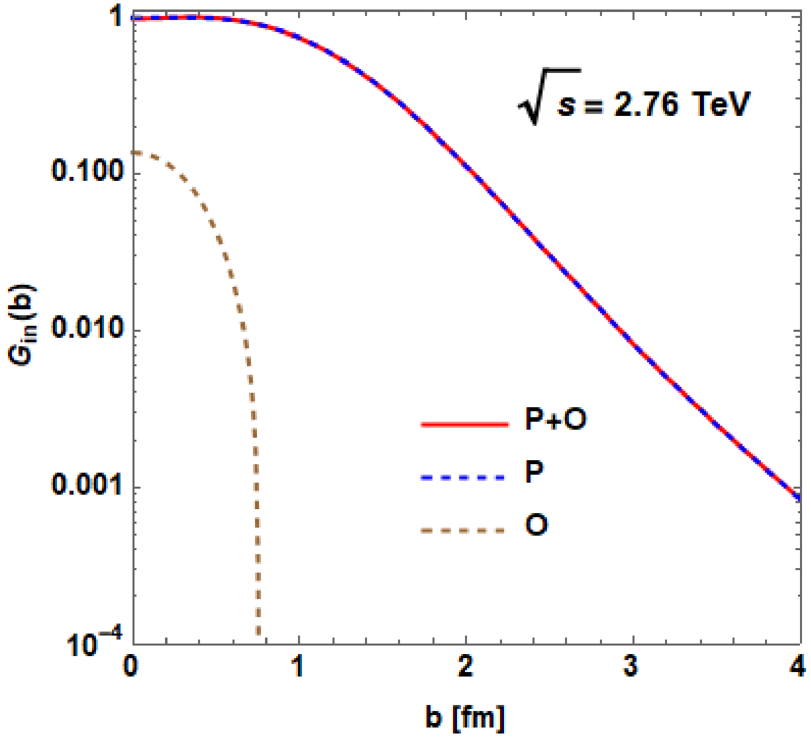


$G_{in}(b)$ enlarged for low b values.

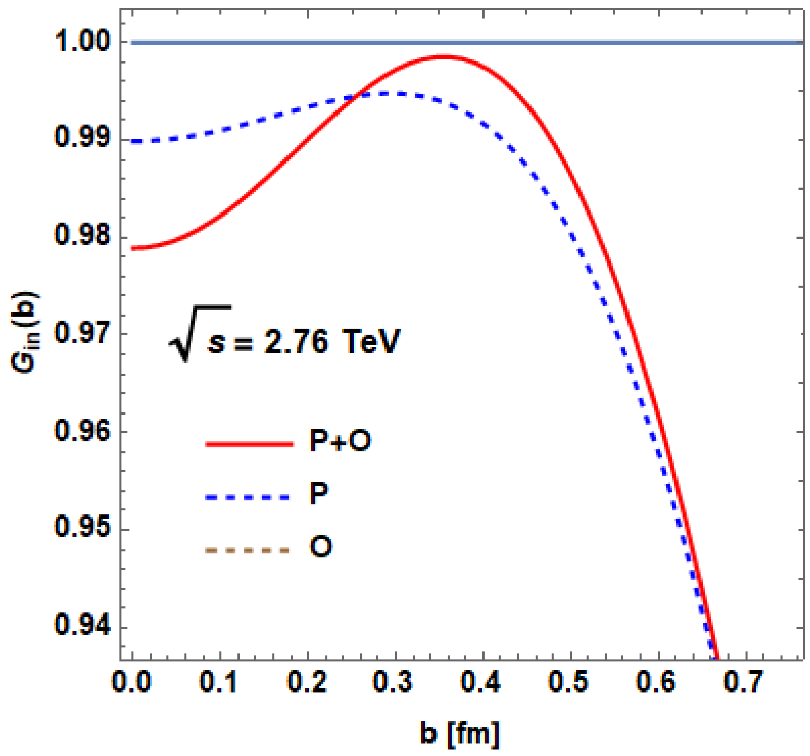
Inelastic overlap function @ 2.76 TeV



Calculated $G_{in}(b)$.

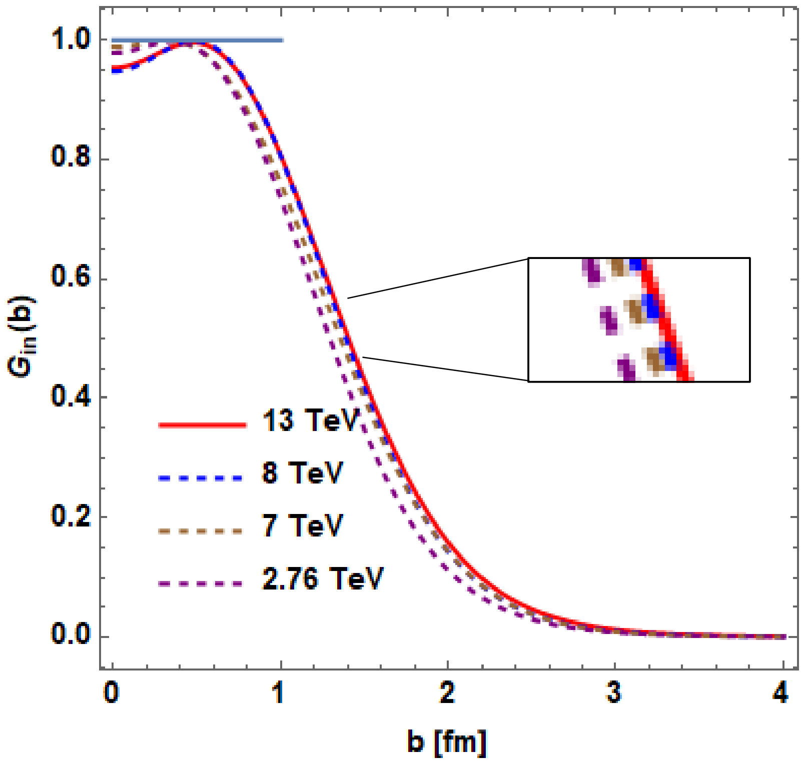


$G_{in}(b)$ with logarithmic vertical axis.

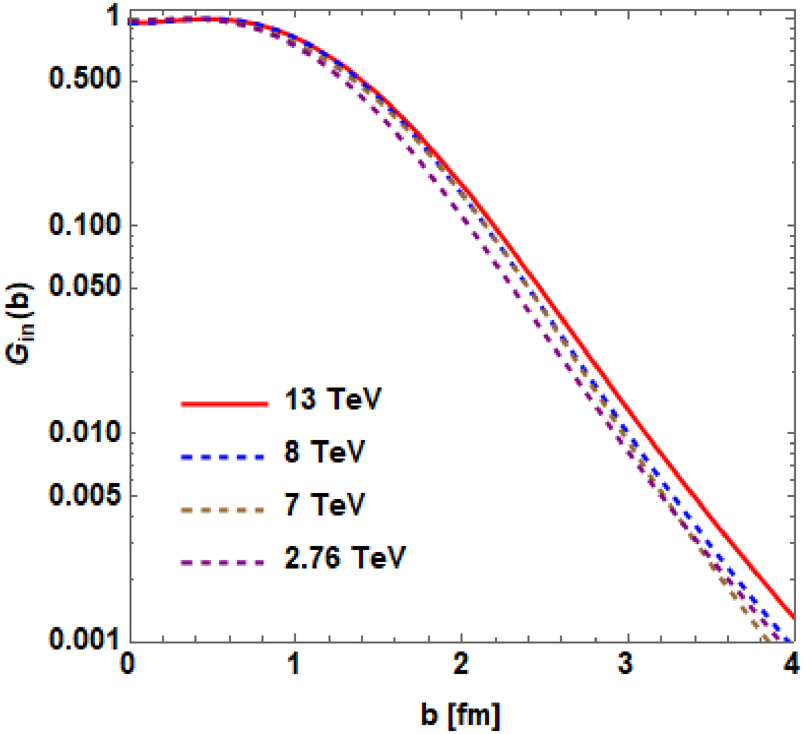


$G_{in}(b)$ enlarged for low b values.

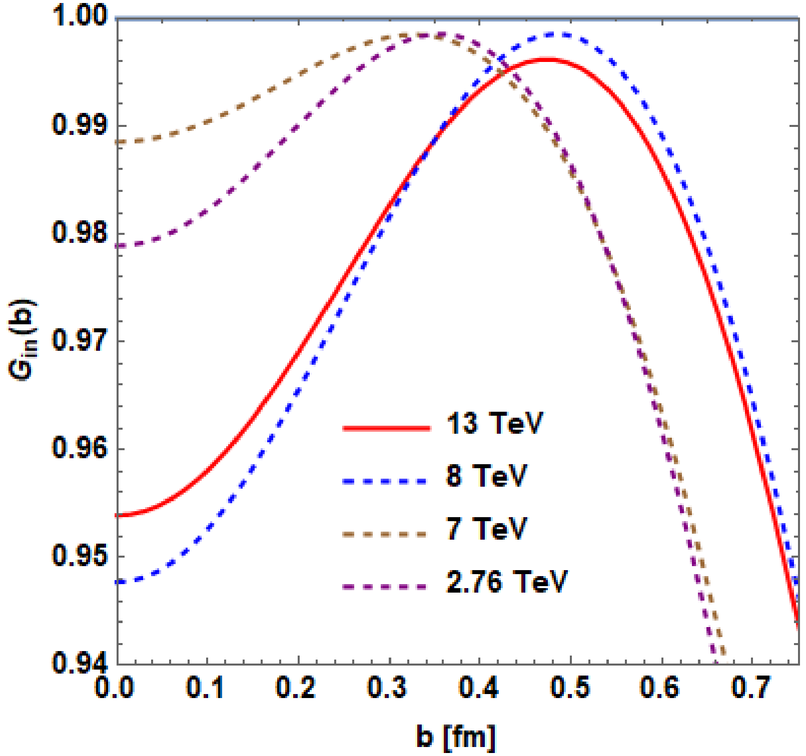
Comparison of $G_{in}(b)$ @ different energies



$G_{in}(b)$ calculated at different energies.



$G_{in}(b)$ calculated at different energies and illustrated with logarithmic vertical axis.



$G_{in}(b)$ calculated at different energies and enlarged for small b values.

Summary and conclusions

- Fits for the newest TOTEM proton-proton differential cross section data using a Regge model with dipole pomeron and odderon.
- Determination of the impact parameter amplitude.
- Calculation of inelastic overlap functions.
- Conclusions for the investigated energy range in the framework of the used model:
  - the proton is surrounded by pion cloud and its effective size is growing with energy
  - the interaction region of the colliding protons has a toroid-like shape (hollowness)
  - this shape is dominantly determined by the pomeron component of the amplitude to which the odderon gives a smaller contribution
  - the energy dependence of the minimum and the maximum of the $\mathrm{G_{in}}$ does not show a regularity
  - problems may arise from the fact that the exact t-dependent phase cannot be recovered from the experimental data

Thank you for your attention!

THE RESEARCH WAS SUPPORTED BY THE ''MÁRTON ÁRON SZAKKOLLÉGIUM'' PROGRAM

THE CONFERENCE PARTICIPATION WAS PARTLY SUBSIDISED BY THE TALENT SUPPORT COUNCIL OF EÖTVÖS LORÁND UNIVERSITY, BUDAPEST