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

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

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

- Very low value of the \( pp \rho \)-parameter at 13 TeV.

\[ \rho(s) = \frac{\text{Re}A(s, t = 0)}{\text{Im}A(s, t = 0)} \]

\( \rho \) and \( p\bar{p} \) \( \rho \)-parameter measurements.

Introduction

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

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

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

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

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

\[
\frac{d\sigma_{\text{el}}}{dt}(s, t) = \frac{\pi}{s^2} |A(s, t)|^2
\]

- "break": deviation from an exponential form near $-t = 0.1 \text{ GeV}^2$
  → 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 $\text{Im} h(b)$ at small $b$

\[
h(s, b) = \frac{1}{s} \int_0^\infty A(s, t) J_0(b\sqrt{-t}) \sqrt{-t}d\sqrt{-t}
\]
Scattering amplitude: dipole Regge model

\[ A(s, t)_{pp} = A_P(s, t) \pm A_0(s, t) + A_f(s, t) \pm A_\omega(s, t) + \ldots \]

- **Dipole pomeron and odderon:**

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

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

- **Pomeron and odderon trajectories:**

\[ \alpha_P \equiv \alpha_P(t) = 1 + \delta_P + \alpha_{1P} t - \alpha_{2P} \left( \sqrt{4m^2_{\pi^2}} - t - 2m_{\pi} \right) \]

\[ \alpha_0 \equiv \alpha_0(t) = 1 + \delta_0 + \alpha_{10} t - \alpha_{20} \left( \sqrt{9m^2_{\pi^2}} - t - 3m_{\pi} \right) \]


(With free parameters labeled by "O")

Exchange of a Regge trajectory in the t-channel.
Regge trajectories

- Reggeon (in general):
  - virtual particle with continuously varying spin \( J = \text{Re} \alpha(t) \) 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, \(\omega\), \(\rho\), \(\phi\) ...) \(\rightarrow\) mesonic exchanges and meson spectra

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

\[
\alpha(t = m^2) = \text{Re} \alpha(t) \]

\[
\begin{align*}
J &= \text{Re} \alpha(t = m^2) \\
n &\approx 0.048 \\
\end{align*}
\]

- L. Jenkovszky, R. Schicker and I. Szanyi.

The Chew–Frautschi plots of the leading \(\rho\), \(\varphi\) and \(P\) complex Regge trajectories

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**: 
  \[
  2\text{Im}h(s, b) = |h(s, b)|^2 + G_{\text{in}}(s, b)
  \]

- The **total, elastic and inelastic cross sections**:
  \[
  \sigma_{\text{tot}}(s) = 2 \int d^2b \, \text{Im}h(s, b) \\
  \sigma_{\text{el}}(s) = \int d^2b \, |h(s, b)|^2 \\
  \sigma_{\text{in}}(s) = \int d^2b \, G_{\text{in}}(s, b)
  \]

- The **inelastic overlap function** \(G_{\text{in}}\) → probability of absorption associated to a given \(b\) value → gives the shape of the interaction region:
  \[
  G_{\text{in}}(s, b) = 2\text{Im}h(s, b) - |h(s, b)|^2 \\
  \text{with} \quad 0 \leq G_{\text{in}}(s, b) \leq 1
  \]
Fit of $d\sigma(t)/dt$ @ 13 TeV

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

Source of the data:
Fit of $d\sigma(t)/dt$ @ 8 TeV

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

Source of the data:

the high- $|t|$ data is preliminary
Fit of $d\sigma(t)/dt$ @ 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 $d\sigma(t)/dt$ @ 2.76 TeV

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

Source of the data:
Inelastic overlap function @ 13 TeV

Calculated $G_{\text{in}}(b)$.  

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

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

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

Inelastic overlap function @ 8 TeV

Calculated $G_{\text{in}}(b)$. $G_{\text{in}}(b)$ with logarithmic vertical axis. $G_{\text{in}}(b)$ enlarged for low $b$ values.
Inelastic overlap function @ 7 TeV

Calculated $G_{\text{in}}(b)$.  

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

$G_{\text{in}}(b)$ enlarged for low $b$ values.
Inelastic overlap function @ 2.76 TeV

Calculated $G_{\text{in}}(b)$.  

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

$G_{\text{in}}(b)$ enlarged for low $b$ values.
Comparison of $G_{in}(b)$ at 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 $G_{in}$ 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!

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