Structures in the diffraction cone: the "break" and "dip" in high-energy proton-proton scattering

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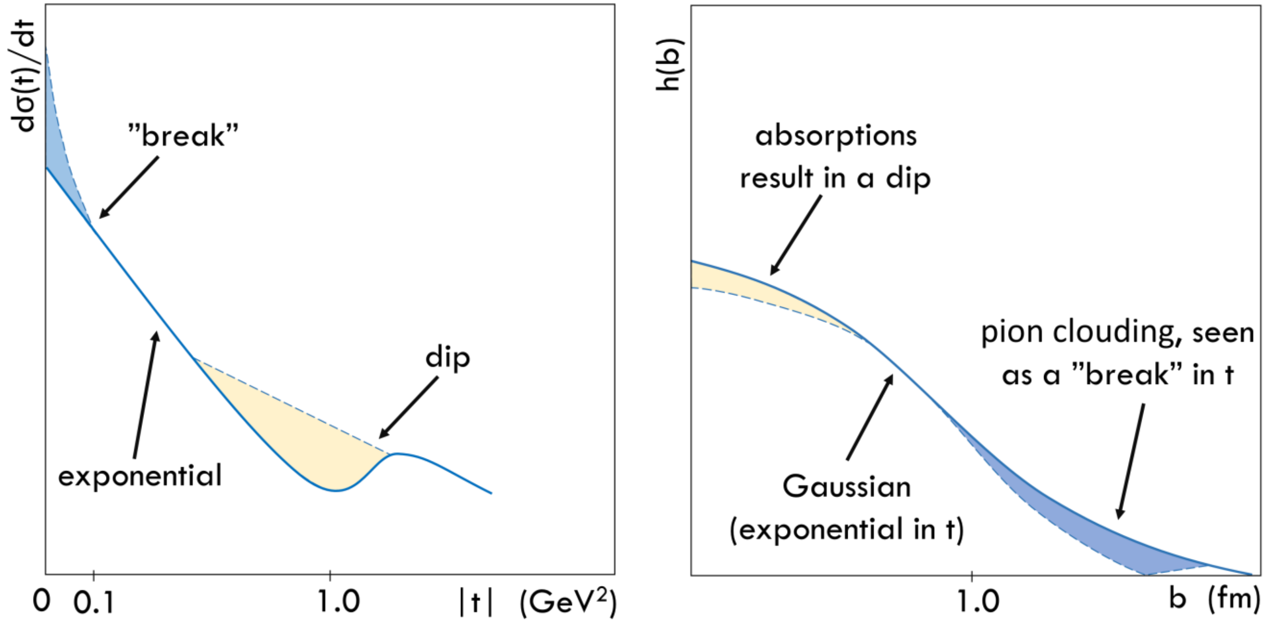
Outline

- Structures of high-energy pp diffraction cone:
    - “break”
    - “dip”
- Correlation between the ” break” and ”dip”
- The two-pion loop singularity
- A simple Regge-pole model for the “break” and its application
- A simple multipole (Pomeron and Odderon) model and its application

Structures of high-energy pp diffraction cone

- "break" – deviation from the purely exponential form of the diffraction cone near $|t| \approx 0.1\ \text{GeV}^2$ – i.e. it changes its slope;
- related to the two-pion exchange recquired by t-channel unitarity – corresponds to the nucleon "atmosphere";

- "dip" – diffraction minimum, moving slowly (logarithmically) with s towards smaller values of |t|;
- related to s-channel unitarity or absorption corrections to the scattering amplitude

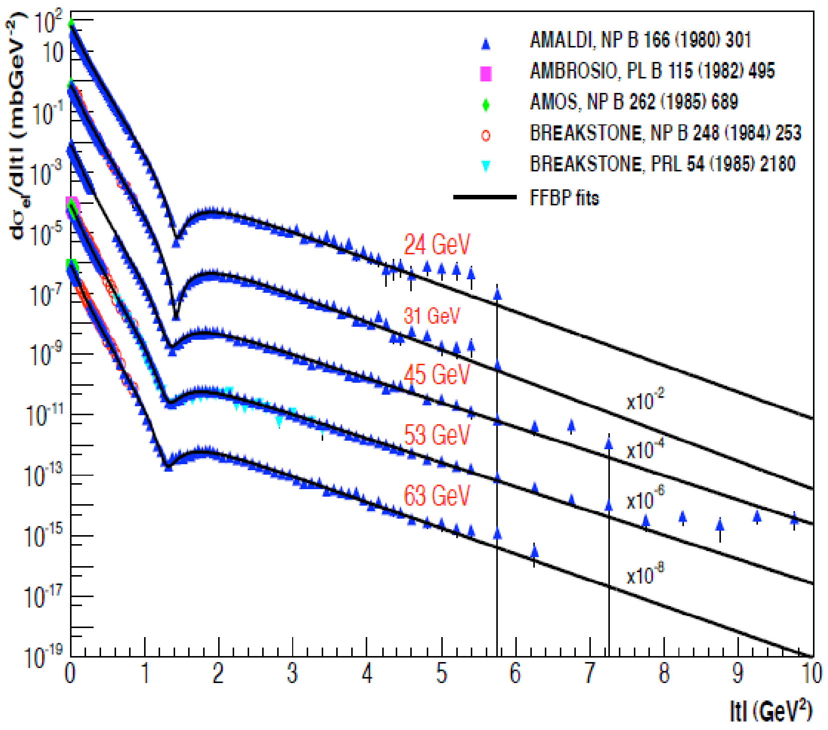


Shematic view of the pp elastic differential cross section in t and the impact parameter amplitude in b.

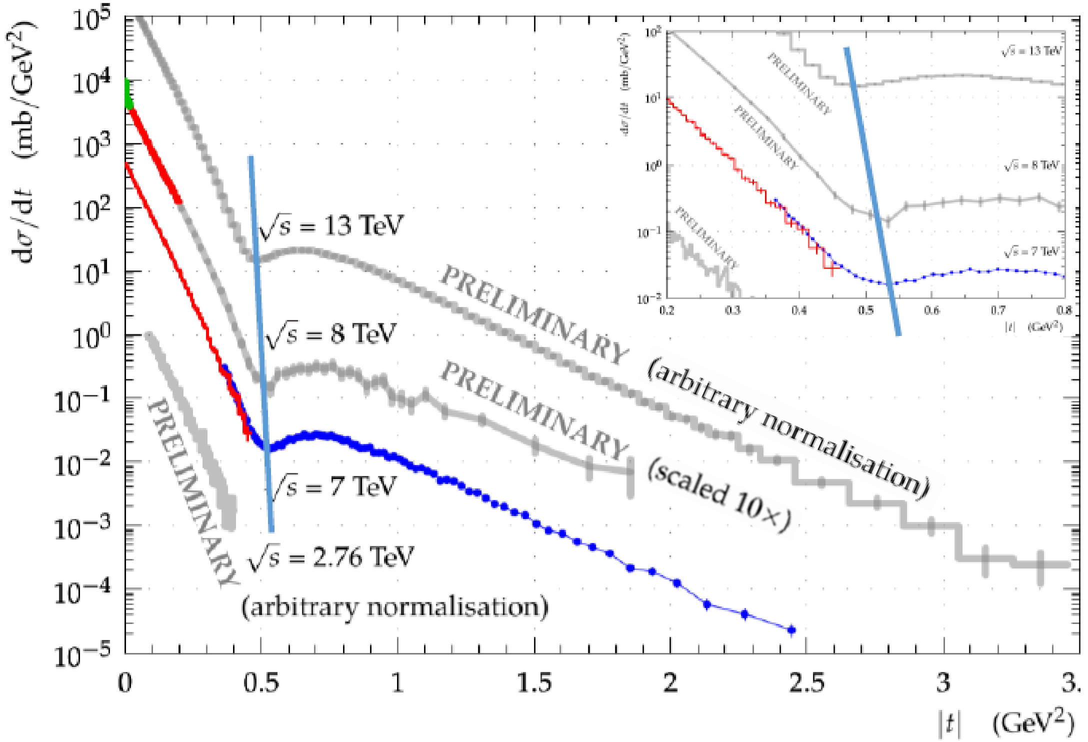
L. Jenkovszky: Phenomenology of Elastic Hadron Diffraction. Fortschritte der Physik, 84 (1986) 791.

$$\frac{d\sigma(s,t)}{dt} = \frac{\pi}{s^2}|A(s,t)|^2 \quad \leftrightarrow \quad h(s,b) = \frac{1}{s}\int_0^\infty A(s,t) J_0(b,\sqrt{-t})\sqrt{-t}\,d\sqrt{-t}$$

“dip”



ISR elastic pp differential cross section measurements



LHC TOTEM elastic pp differential cross section measurements

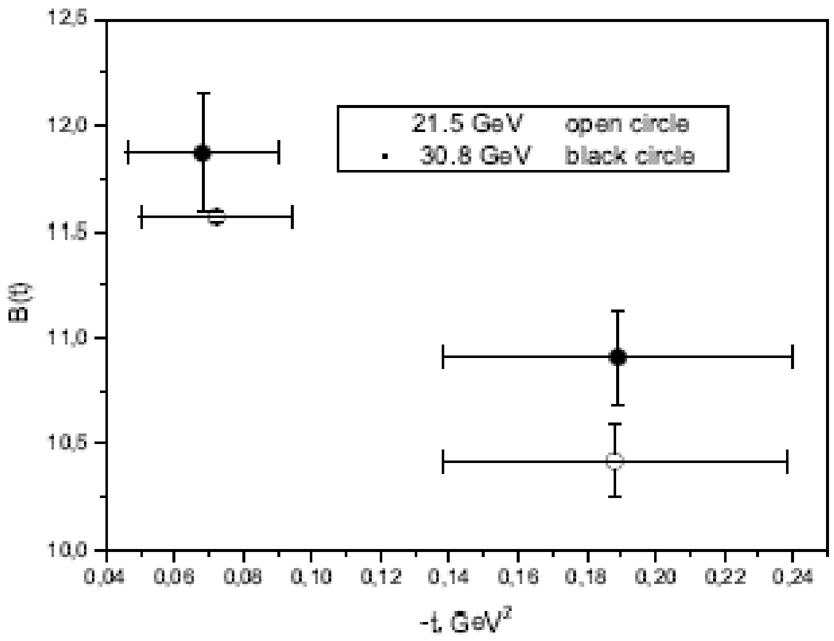
ISR: $|t_{dip}| \approx 1.4\ \mathrm{GeV}^2$

LHC: $|t_{dip}| \approx 0.5\ \mathrm{GeV}^2$

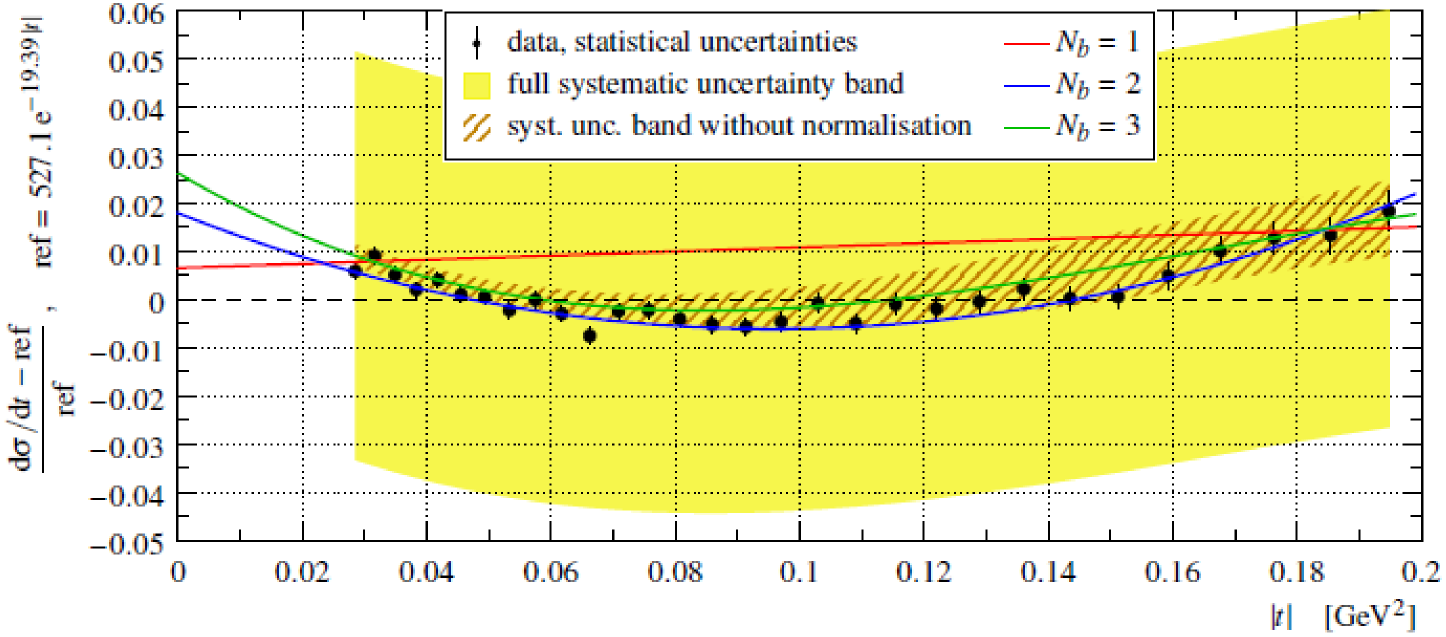
arXiv:1306.0452

T. Sýkora: Total, elastic and inelastic p-p cross sections at the LHC. ICHEP 2016 (2016, Chicago)

“break”



Local slopes B(t) calculated for low-|t| ISR data.



R(t) calculated for LHC TOTEM low-|t| 8 TeV data.

$$B(t) = \frac{d}{dt} ln \frac{d\sigma(t)}{dt}$$

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

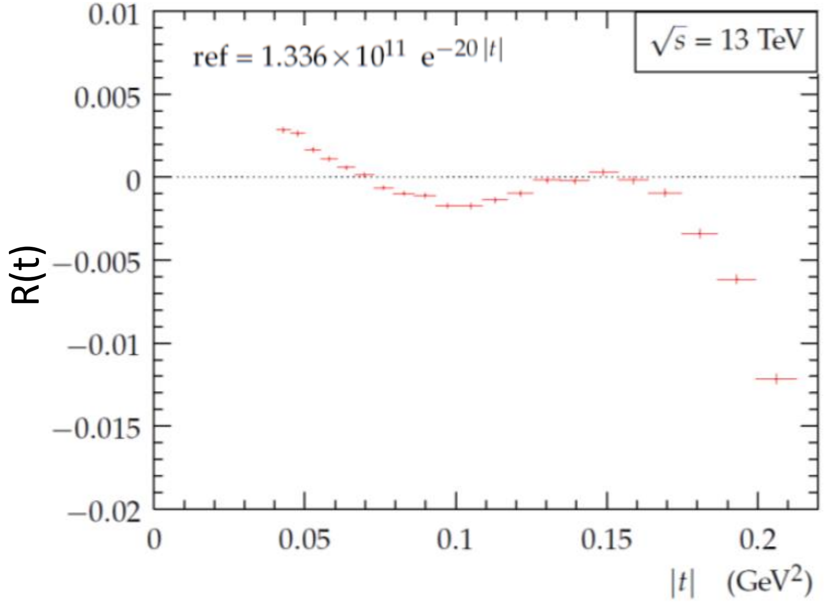
$$ref = Ae^{Bt}$$

arXiv:1410.4106

G. Barbiellini et al., Phys. Lett. B 39 (1972) 663

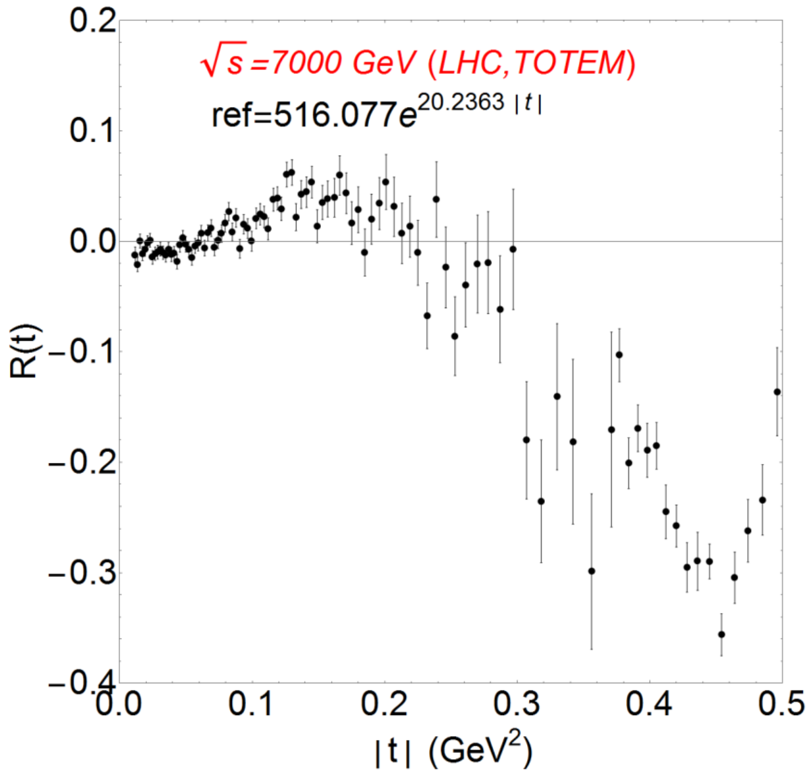
arXiv:1503.08111

Correlation between the "break" and "dip"



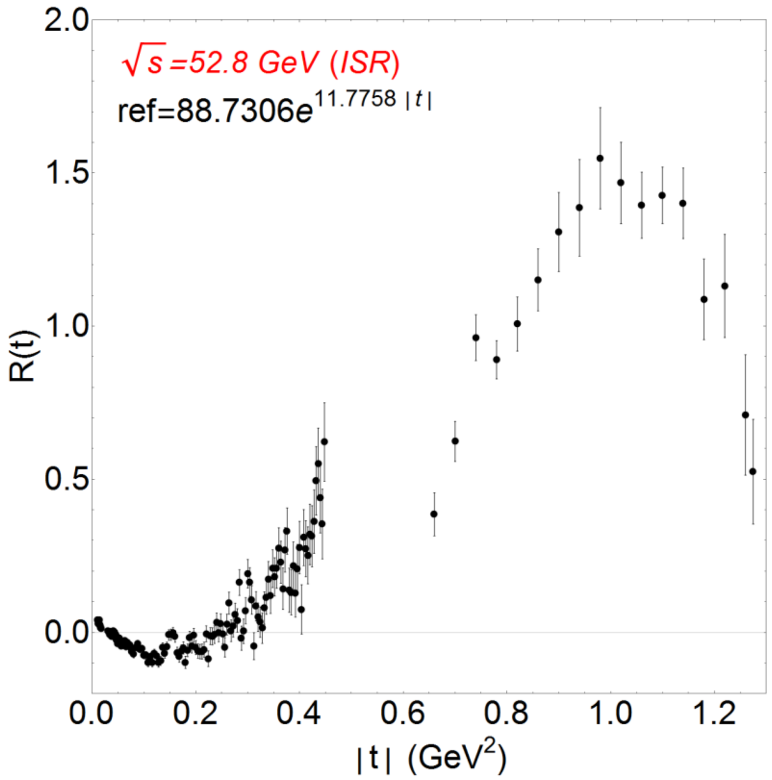
R(t) calculated for low-|t| 13 TeV TOTEM preliminary data.

F. Nemes: The results of the TOTEM experiment. Proceedings of the Diffraction 2016 conference, (2016, Acireale).



R(t) calculated for low-|t| 7 TeV TOTEM data.

TOTEM Collab. EPL 101 21002 (2013).



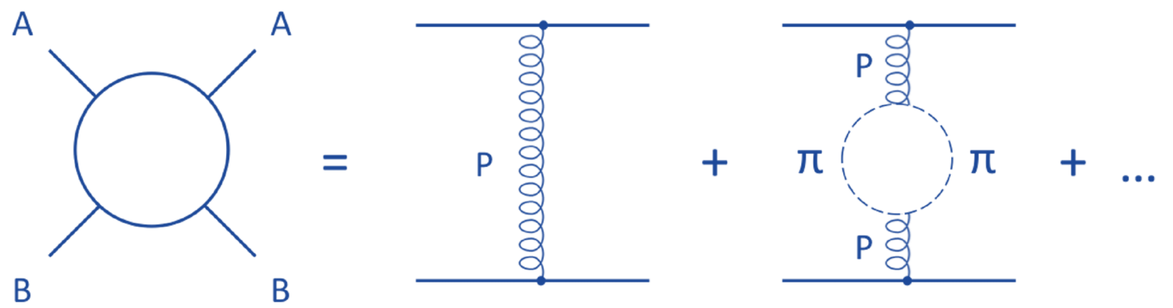
R(t) calculated for low-|t| ISR 52.8 GeV data.

Amaldi, U. , Schubert, Klaus R. Nucl.Phys. B166 (1980)

L. Jenkovszky, I. Szanyi: Structures in the diffraction cone: the "break" and "dip" in high-energy proton-proton scattering (International Journal of Modern Physics A (2017), in press) - arXiv:1705.04880

The description of the “break”

- introduction of a two-pion loop contribution to the t-channel through Regge trajectories



Feynman diagram for elastic scattering with a t-channel exchange containing a branch point at t = $4m_\pi^2$.

- the lowest threshold singularity of the scattering amplitude due to the two-pion (loop) exchange, recquired by t-channel unitarity: $t_0 = 4m_\pi^2 \approx 0.08\, GeV^2$ (m_π – pion mass)

- the Regge-trajectories near the threshold:

$$\alpha(t) \sim \alpha_1 \sqrt{t_0 - t}$$

- the threshold singularity is at positive $t_0 = 4m_\pi^2$, while the "break" is at negative t, ("symmetric" to $4m_\pi^2$) - this reflection is the analytic property of scattering amplitude.

A. O. Barut and D. E. Zwanziger Phys. Rev. 127, 974 arXiv:1410.4106

A simple Regge-pole model

- Scattering amplitude:

$$A(s,t) = A_P(s,t) + A_f(s,t)$$

Pomeron term:

$$A_P(s,t) = -a_P e^{b_P \alpha_P(t)} e^{-\frac{i\pi\alpha_P(t)}{2}} (s/s_{0P})^{\alpha_P(t)}$$

Effective-reggeon term:

$$A_f(s,t) = -a_f e^{b_f \alpha_f(t)} e^{-\frac{i\pi\alpha_f(t)}{2}} (s/s_{0f})^{\alpha_f(t)}$$

- Regge trajectories:

Pomeron trajectory:

$$\alpha_P(t) = \alpha_{0P} + \alpha'_P t - \alpha_{1P}\left(\sqrt{4m_\pi^2 - t} - 2m_\pi\right)$$

Effective-reggeon trajectory:

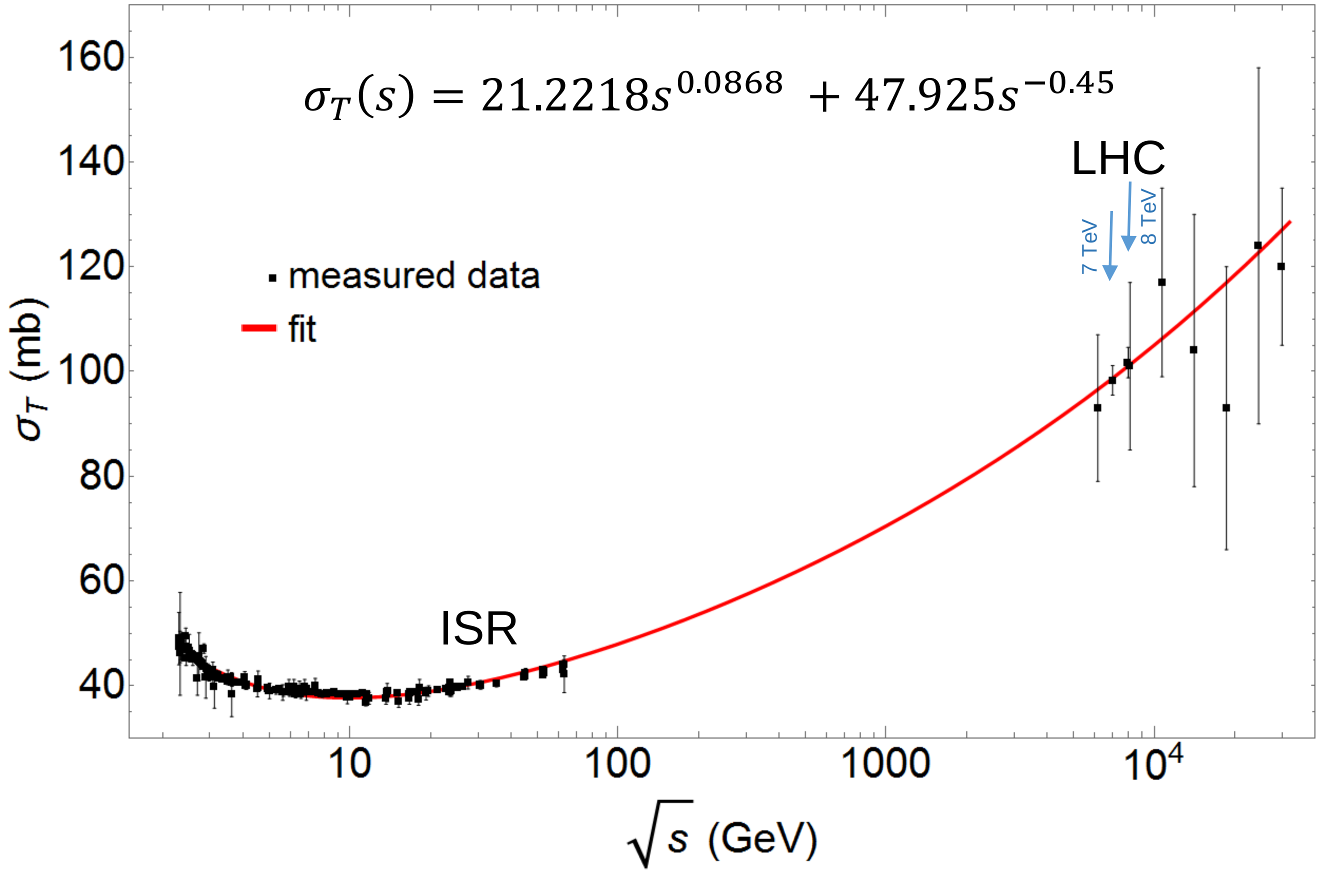
$$\alpha_f(t) = \alpha_{0f} + \alpha'_f t - \alpha_{1f}\left(\sqrt{4m_\pi^2 - t} - 2m_\pi\right)$$

- Free parameters:

$$a_P(\sqrt{\text{mbGeV}^2}),\ b_P,\ \alpha_{0P},\ \alpha'_P t\ (\text{GeV}^{-2}),\ \alpha_{1P}\ (\text{GeV}^{-1}),\ s_{0P}\ (\text{GeV}^2),$$
$$a_f\ (\sqrt{\text{mbGeV}^2}),\ b_f,\ \alpha_{0f},\ \alpha'_f t\ (\text{GeV}^{-2}),\ \alpha_{1f}\ (\text{GeV}^{-1}),\ s_{0f}\ (\text{GeV}^2)$$

L. Jenkovszky, I. Szanyi. Fine structure of the diffraction cone: manifestation of t-channel unitarity. (Physics of Particles and Nuclei Letters **14** (2017), in press) - arXiv:1701.01269

Fit of the total pp cross section



Result of fit of the simple Regge-pole model to the total pp coross section data.

$$\sigma_T = \frac{4\pi}{s} ImA(s, t=0)$$

Used range: $2.3 \leq \sqrt{s} \leq 30000$ GeV

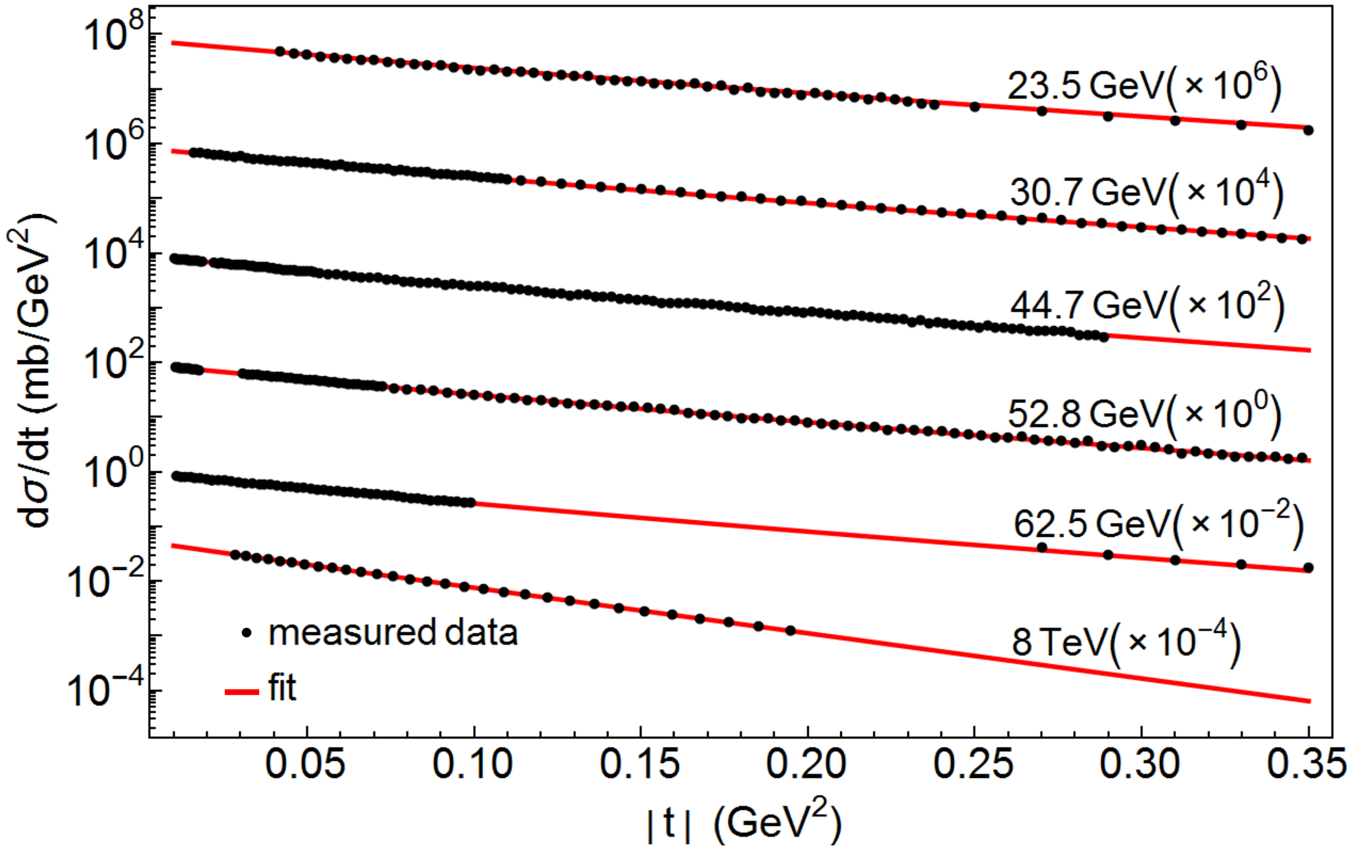
α_{0P}	1.0868 (fixed)	α_{0f}	0.55 (fixed)
a_P	2.07009	a_f	10.4546
b_P	1.96559	b_f	2.90172
s_{0P}	1 (fixed)	s_{0f}	1 (fixed)

Values of fitted parameters of the simple Regge-pole model to the pp total cross section data.

arXiv:1602.06207

K.A. Olive *et al.* (PDG), Chin. Phys. C, **38**, 090001 (2014)

Fit of the pp elastic differential cross section



Result of fit of the simple Regge-pole model to the elastic differential pp coross section ISR and LHC TOTEM 8 TeV data.

Amaldi, U. , Schubert, Klaus R.
Nucl.Phys. B166 (1980)

arXiv:1503.08111

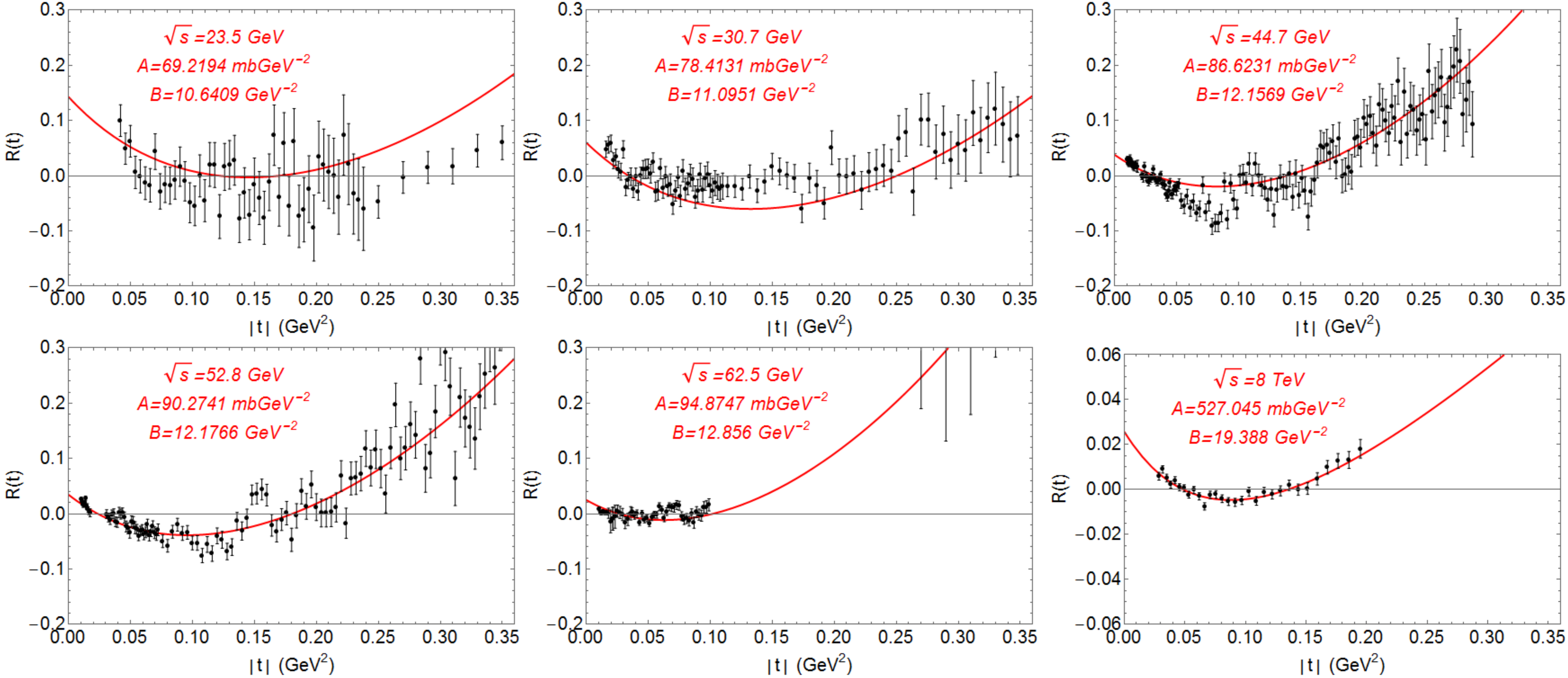
$$\frac{d\sigma}{dt} = \frac{\pi}{s^2}|A(s,t)|^2$$

Used range: $0.01 \leq |t| \leq 0.35\ GeV^2$

α_{0P}	1.11412	α_{0f}	0.909389
α'_P	0.443138	α'_f	0.885668
α_{1P}	0.00322277	α_{1f}	0.0800739
a_P	0.0658733	a_f	0.189486
b_P	3.2934	b_f	3.60252
s_{0P}	1 (fixed)	s_{0f}	1 (fixed)
dof	466	χ^2/dof	2.2

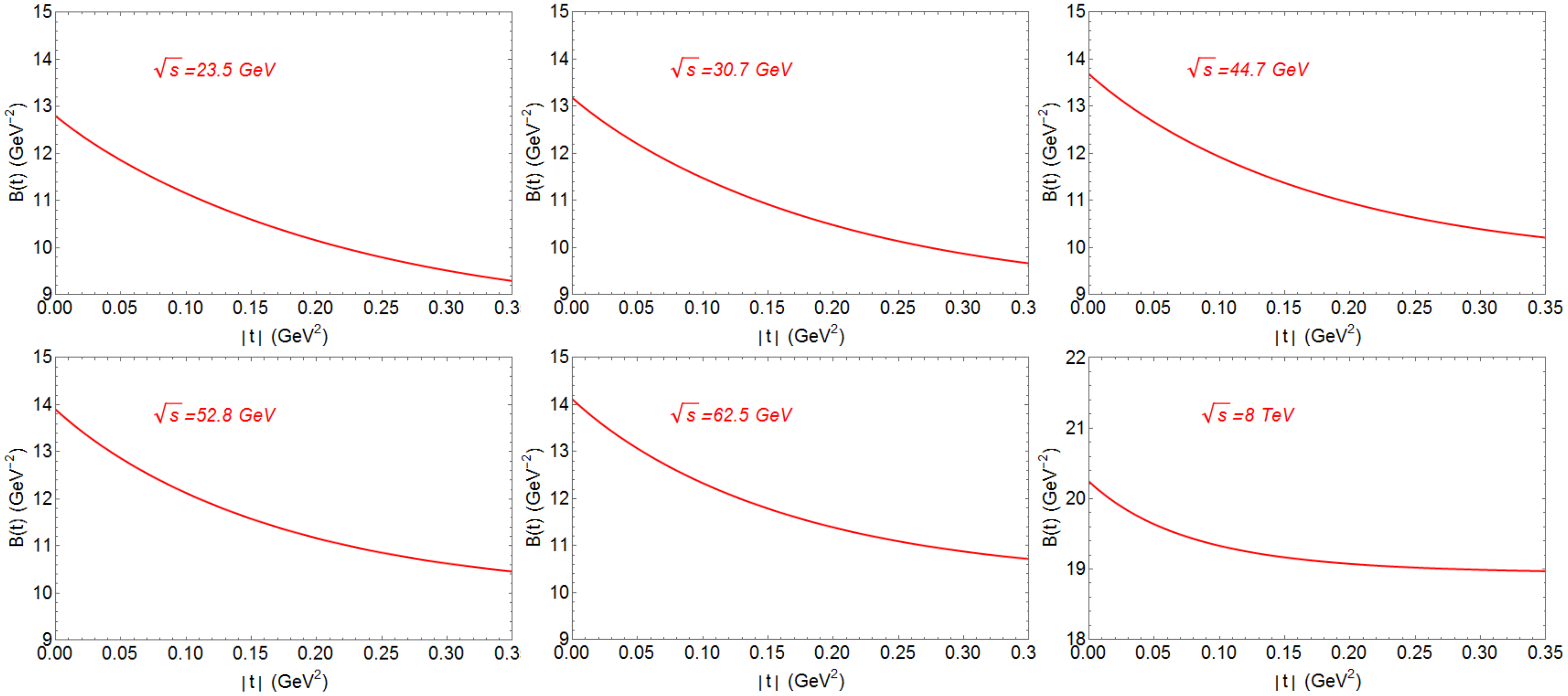
Values of fitted parameters of the simple Regge-pole model to the elastic pp differential cross section data.

R(t) ratios



R(t) ratios calculated for the ISR and LHC TOTEM 8 TeV data.

Local slopes



Local slopes calculated for the ISR and LHC TOTEM 8 TeV data.

A simple multipole – Pomeron and Odderon – model

- Scattering amplitude:

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

Pomeron term:

$$A_P(s,t) = i\frac{a_P s}{b_P s_0}\left[r_1^2(s)e^{r_1^2(s)[\alpha_P - 1]} - \varepsilon_P r_2^2(s)e^{r_2^2(s)[\alpha_P - 1]}\right]$$

where

$$r_1^2(s) = b_P + L - i\pi/2 \qquad r_2^2(s) = L - i\pi/2 \qquad L \equiv \ln(s/s_0)$$

Pomeron trajectory:

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

Odderon term:

$$A_O(s,t) = \frac{a_O s}{b_O s_0}\left[r_{1O}^2(s)e^{r_{1O}^2(s)[\alpha_O - 1]} - \varepsilon_O r_{2O}^2(s)e^{r_{2O}^2(s)[\alpha_O - 1]}\right]$$

Reggeon term:

$$A_R(s,t) = a_R e^{b_R t} e^{-\frac{i\pi\alpha_R(t)}{2}}(s/s_0)^{\alpha_R(t)}$$

Reggeon trajectories:

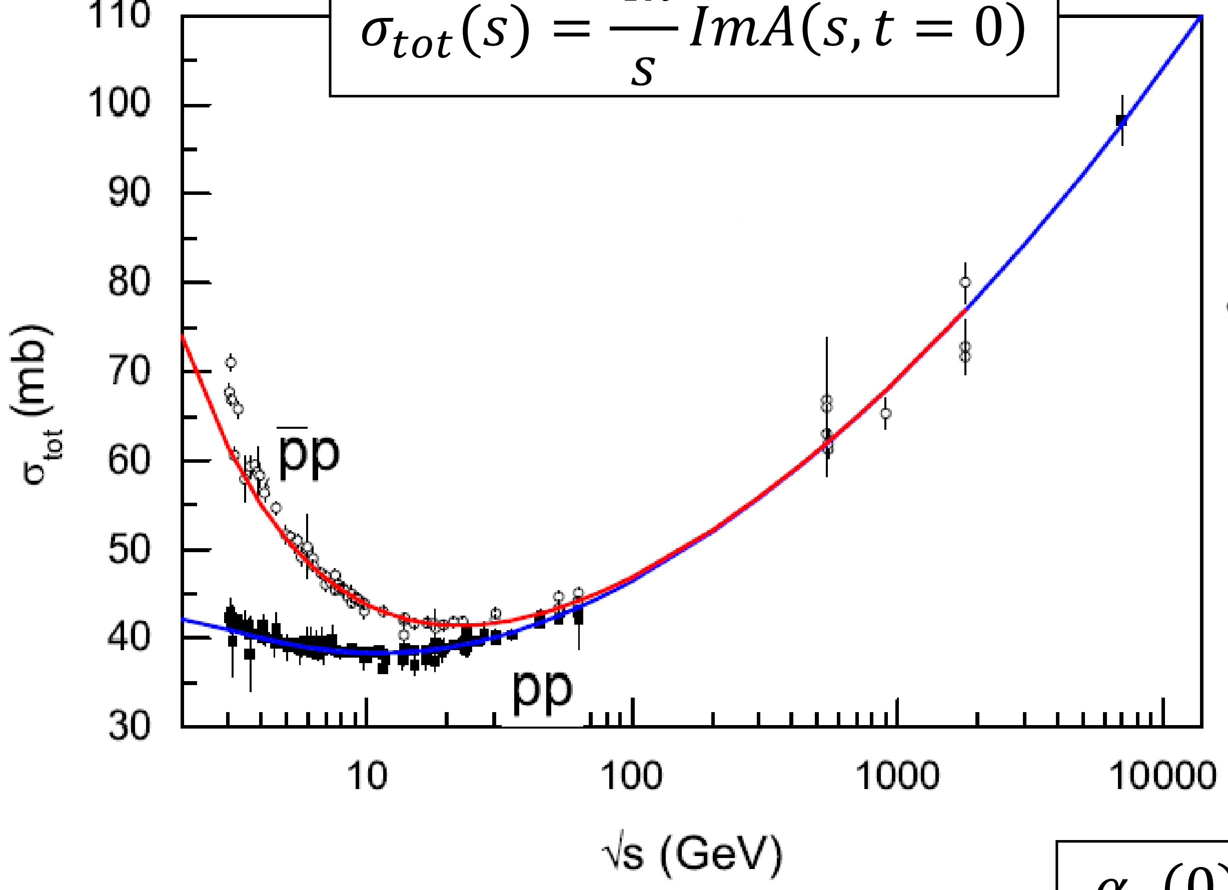
$$\alpha_f(t) = 0.79 + 0.84t$$

$$\alpha_\omega(t) = 0.47 + 0.93t$$

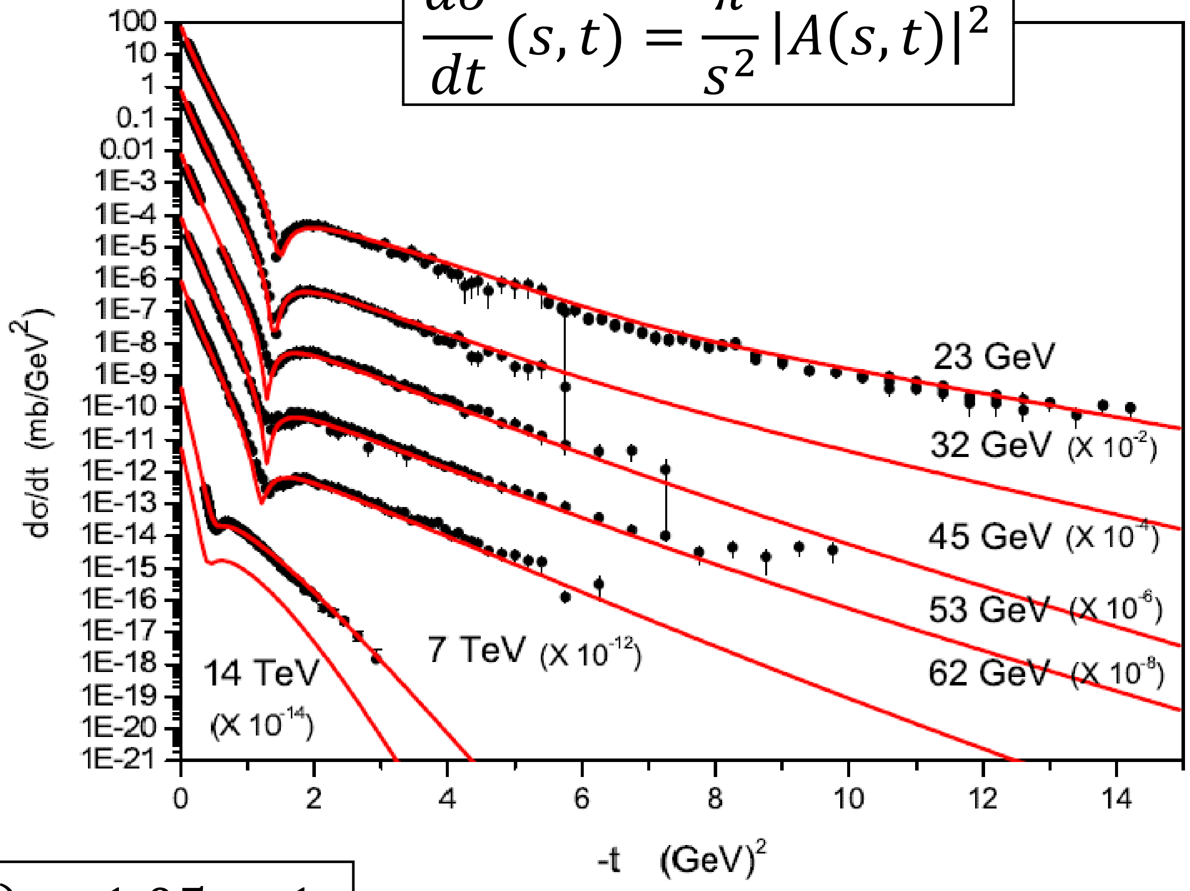
arXiv:1206.5837

Results of fitting with the multipole model

$$\sigma_{tot}(s) = \frac{4\pi}{s} ImA(s, t = 0)$$



$$\frac{d\sigma}{dt}(s,t) = \frac{\pi}{s^2}|A(s,t)|^2$$



$$\alpha_P(0) \approx 1.05 > 1$$

Multipole model fitted to the pp total and differential cross sections.

arXiv:1206.5837

Summary and conclusions

- Structures of the pp diffraction cone with quite different origin and physical meaning:
  - "break" – deviation from the purely exponential form of the diffraction cone near $|t| \approx 0.1\ \mathrm{GeV}^2$ and related to the two-pion exchange recquired by t-channel unirarity ;
  - "dip" – diffraction minimum, moving slowly with the energy towards smaller values of $|t|$ and related to s-channel unitarity or absorption corrections to the scattering amplitude;
- Movement of the"dip" with its "vortex" behaviour affects for the parametrization and identification of the "break" at the LHC ;
- Successful fits to the pp total and elastic differential cross sections (mapping the t-dependence through the energy) shows the efficiency of the Regge theory in reproducing the energy dependence allowing to obtain a unified explanation for the structures at different energies.
- Improvement of the theory as a result of new measurements.

Thank you for your attention!