Elastic *pp* scattering at the LHC from an empirical standpoint

Daniel A. Fagundes*

Universidade Estadual de Campinas - IFGW

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* in collaboration with A. Grau, S. Pacetti, G. Pancheri and Y.N. Srivastava

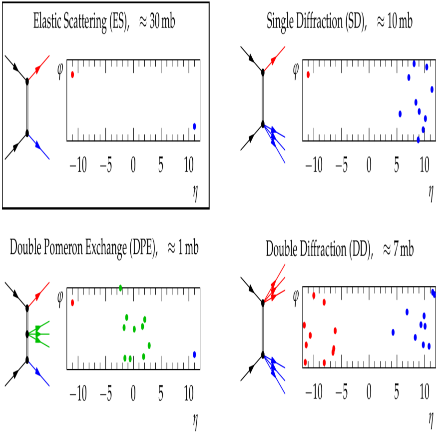
Outline

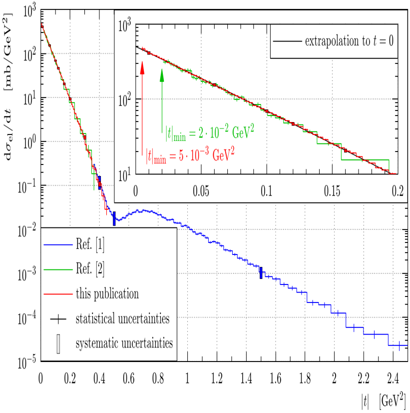
- Differential elastic cross section at LHC - data vs theory
- Barger-Phillips empirical amplitude
- Modified BP amplitudes - correcting the small t behaviour
- Model predictions for LHC8 and LHC14, asymptotic behaviour and geometric scaling

Elastic *pp* scattering at LHC

Differential elastic cross section at $\sqrt{s} = 7$ TeV*

Diffractive events measured by TOTEM





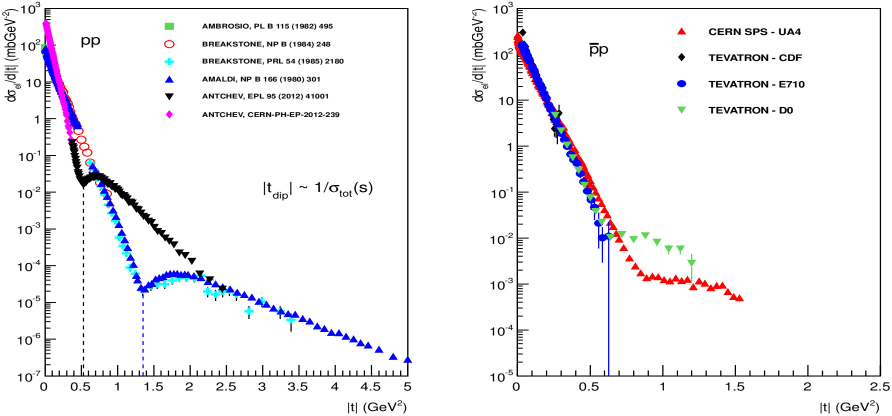
processes mediated by colorless exchange → quantum numbers preserved in the final state

* *Left*: G. Antchev, et al., Europhys.Lett. 101 (2013) 21002. *Right*: Jan Kaspar, Doctoral Thesis, CERN-Thesis-2011-214

Elastic *pp* scattering

from ISR to LHC

Diffractive pattern at high-energies revealed with scanned t

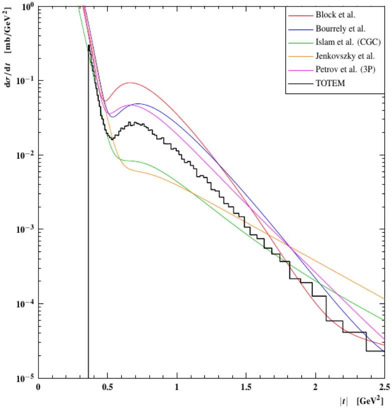


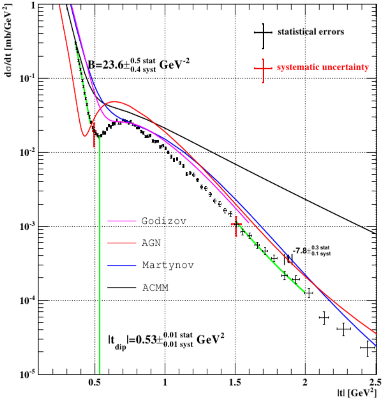
one *dip* present in the ***pp*** channel and a *shoulder* in $\bar{p}p$

Elastic differential cross section

at LHC7 and model predictions

Failure of representative models†





Transition from soft to (semi) hard domain unclear

† *Left*: G. Antchev *et al.*, Europhys.Lett. 95 (2011) 41001. *Right*: A.A. Godizov, PoS (IHEP-LHC-2011) 005.

Physics of the 'dip-shoulder' region

delicate cancelation between $C = \pm 1$ amplitudes

The *dip/shoulder* occur through cancellations in elastic amplitude due to $t-$channel processes:

$$A^{pp,\bar{p}p}(s,t) = \frac{A^{+}(s,t) \pm A^{-}(s,t)}{2}$$

$A^{\pm}(s,t)$ are even/odd amplitudes corresponding to $C = \pm 1$ exchanges in the t-channel. In *Regge Phenomenology*, they are called "Pomeron" and "Odderon" terms, which can be translated into QCD (LO) language as $2g$-exchange[‡] and $3g$-exchange[§]. Eventually, the nonleading contribution of secondary *Reggeons* and *Pomeron cuts* make their relative phase $\phi \neq \pi$.

[‡] F.E. Low, *Phys.Rev. D12 (1975) 163* and S. Nussinov, *Phys.Rev.Lett. 34 (1975) 1286*

[§] A. Donnachie and P.V. Landshoff, *Z.Phys. C2 (1979) 55*

Parametrizing the elastic differential cross-section

Barger-Phillips amplitude and observables

$$\mathcal{A}_{el}^{BP}(s,t) = \mathrm{i}[\underbrace{\sqrt{A(s)}e^{B(s)t/2}}_{leading\ :\ C=+1} + \underbrace{e^{\mathrm{i}\phi(s)}\sqrt{C(s)}e^{D(s)t/2}}_{non-leading\ :\ C=\pm 1}]$$

$\downarrow$ at $t = 0$

$$\sigma_{tot}(s) = 4\sqrt{\pi}(\sqrt{A(s)} + \sqrt{C(s)}\cos\phi)$$

$$\sigma_{el}(s) = \frac{A(s)}{B(s)} + \frac{C(s)}{D(s)} + 4\frac{\sqrt{A(s)C(s)}}{B(s)+D(s)}\cos\phi$$

$$\left.\frac{d\sigma_{el}}{dt}\right|_{t=0} = A(s) + C(s) + 2\sqrt{A(s)C(s)}\cos\phi$$

$\downarrow$ at $t \leqslant 0$

$$\frac{d\sigma_{el}}{dt} = A(s)e^{B(s)t} + C(s)e^{D(s)t} + 2\sqrt{A(s)C(s)}e^{(B(s)+D(s))t/2}\cos\phi$$

A simple Regge-model for the non-leading term

for constant average ϕ

A standard $C=+1$ state contribution to the elastic amplitude follows

$$\mathcal{A}_R^{(+)}(s,t) = iC_+(\frac{1}{s})[(\frac{se^{-i\pi/2}}{s_o})]^{\alpha_+(t)},$$

with $\alpha_+(t)$ is the positive signature trajectory and for a $C=-1$ state,

$$\mathcal{A}_R^{(-)}(s,t) = C_-(\frac{1}{s})[(\frac{se^{-i\pi/2}}{s_o})]^{\alpha_-(t)},$$

with $\alpha_-(t)$ a negative signature trajectory. Having $\alpha_+(t)=\alpha_-(t)$, degenerate trajectories, linear and assuming that $\alpha_\pm(0)=1$ - the critical Pomeron - their total contribution follows

$$\mathcal{A}_R(s,t) = i\frac{C_+ - iC_-}{s_o}e^{t\alpha'(ln(s/s_o)-i\pi/2)}.$$

Defining

$$C_+ = s_o C cos\phi; \;\; C_- = -s_o C sin\phi,$$

one gets

$$\mathcal{A}_R(s,t) = iCe^{t\alpha'(ln(s/s_o)-i\pi/2)}e^{i\phi}.$$

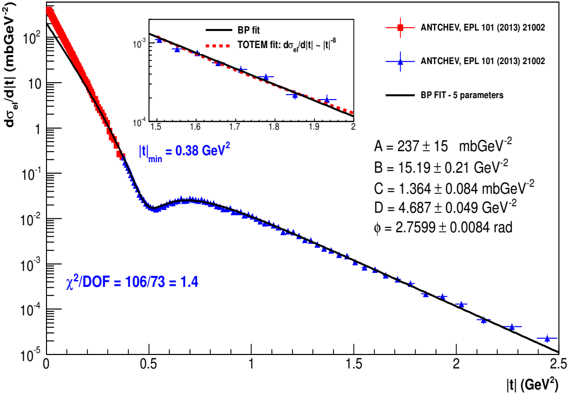
Apart from the “extra” phase $e^{-it\alpha'\pi/2}$, this corresponds to the second term of the Barger-Phillips amplitude - the “C-term” - with $D(s)=2\alpha' ln(s/s_o)$. Notice that this phase is present in any Regge amplitude.

Parametrizing the elastic differential cross-section

the original Barger-Phillips model[¶]

We have applied the old Barger-Phillips parametrization to LHC7 data

$$\mathcal{A}_{el}^{BP}(s,t) = i[\sqrt{A(s)}e^{-B(s)|t|/2} + \sqrt{C(s)}e^{i\phi(s)}e^{-D(s)|t|/2}]$$



excellent description for $|t| > 0.4$ GeV^2 $\rightarrow$ need to correct small $-t$ behaviour

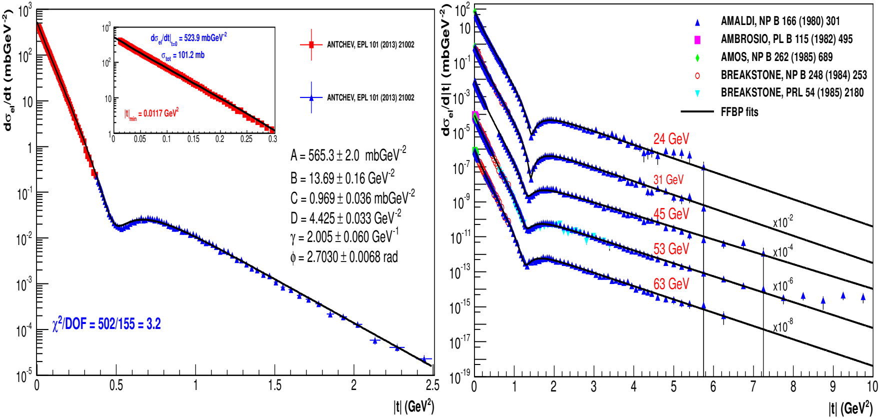
¶ Phillips and Barger, *Phys.Lett. B46 (1973) 412*; Grau et al., *Phys.Lett. B714 (2012) 70*

Parametrizing the elastic differential cross-section

modified BP model - *mBP1*

Our first attempt - introduction of a square root threshold at small $|t|$ (normalized)[‖]:

$$\mathcal{A}_{el}^{mBP1}(s,t) = i[\sqrt{A(s)}e^{-B(s)|t|/2}e^{-\gamma(s)(\sqrt{4m_\pi^2+|t|}-2m_\pi)} + \sqrt{C(s)}e^{i\phi(s)}e^{-D(s)|t|/2}]$$



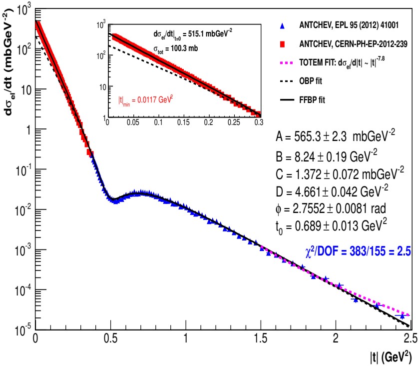
‖ the *two − pion loop* insertion in the Pomeron trajectory: A.A. Anselm and V.N. Gribov, *Phys.Lett. B* 40 (1972); Fiore et al. *Int.J.Mod.Phys. A24 (2009) 2551*

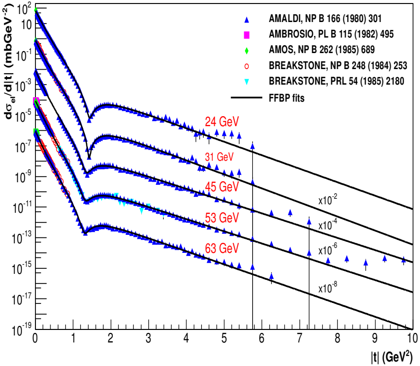
Parametrizing the elastic differential cross-section

modified BP model - *mBP2*

We correct the small $-t$ behaviour with the proton's FF at the BP amplitude **

$$\mathcal{A}_{el}^{mBP2}(s,t) = i\left[\sqrt{A(s)}e^{-B(s)|t|/2}\frac{1}{\left(1+\frac{|t|}{t_0}\right)^4} + \sqrt{C(s)}e^{i\phi(s)}e^{-D(s)|t|/2}\right]^{\dagger\dagger}$$





$F_p(t)$ to account for elastic rescatterings as $|t|$ increases $\leftrightarrow$ proton does not break up

** D.A. Fagundes et al., *Phys.Rev. D88 (2013) 094019*

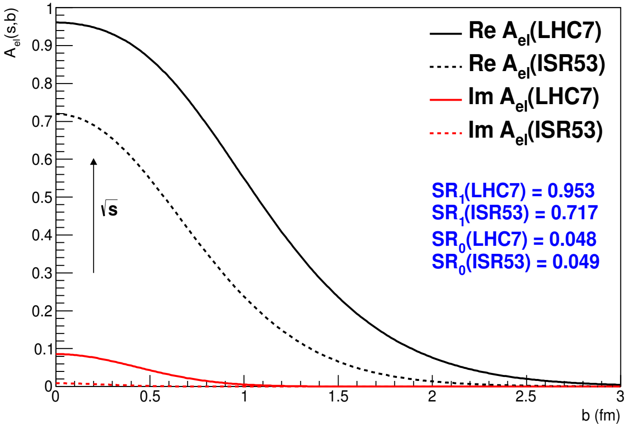
†† for $\sqrt{s} > 7$TeV we make the ansatz $t_0 \to 0.71$ GeV^2 (the EM FF scale)

Asymptotic sum rules

and impact parameter structure

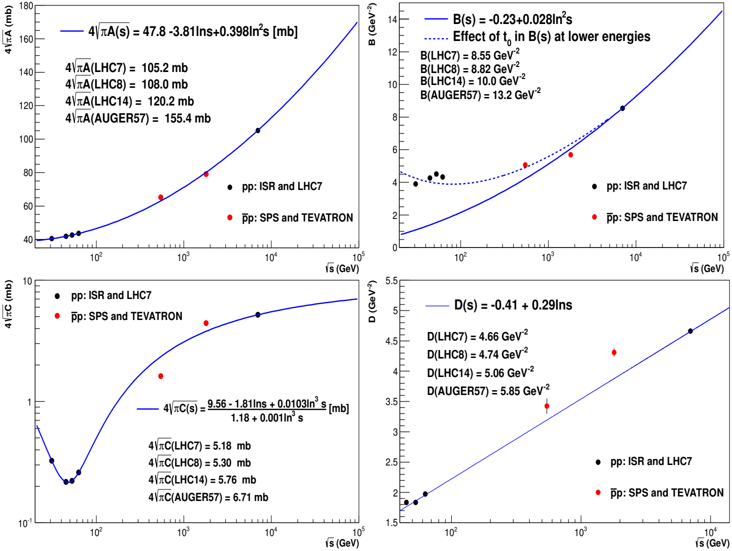
Asymptotic sum rules - total absorption of partial waves ($\eta(s,b) \to 0$)

$$SR_1 = \frac{1}{2\sqrt{\pi}} \int_{-\infty}^{0} dt \mathcal{A}^I_{el}(s,t) \to 1 \qquad SR_0 = \frac{1}{2\sqrt{\pi}} \int_{-\infty}^{0} dt \mathcal{A}^R_{el}(s,t) \to 0$$



Energy dependendence of fit parameters

amplitudes and slopes with $t_0 \to 0.71$ GeV^2

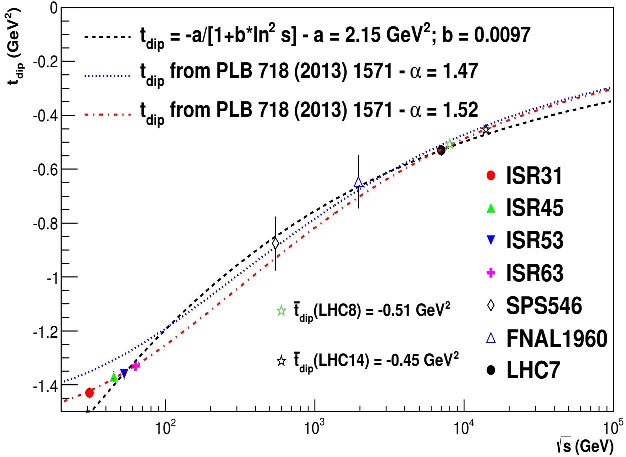


Energy evolution of the dip position

using Geometric Scaling (GS)

We assume GS is valid asymptotically, thus

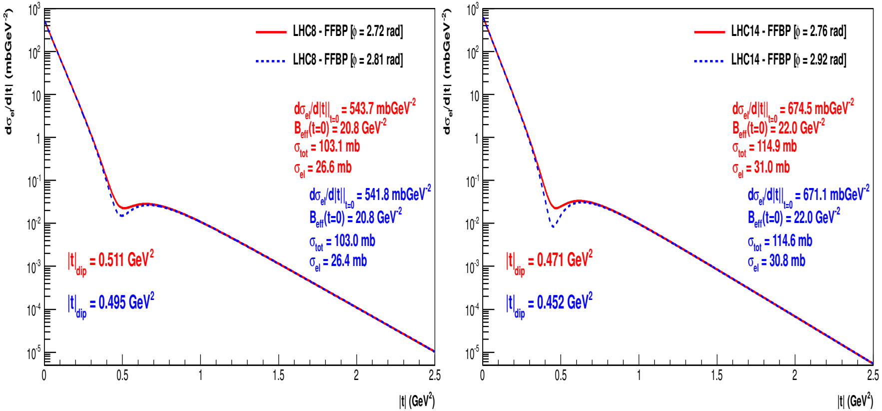
$$-t_{dip}\sigma_{tot} \sim constant \longrightarrow t_{dip} \simeq -\frac{a}{1 + b\ln^2 s}$$



This model predictions

for LHC8 and LHC14

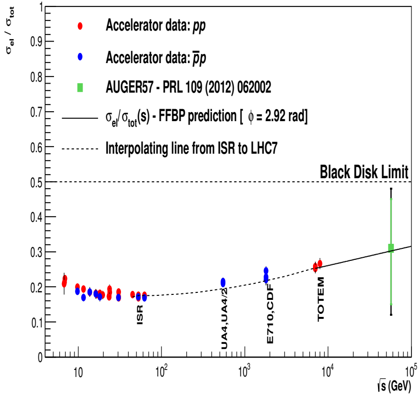
Asymptotic SR dictate the energy behaviour of fit parameters, allowing to make predictions

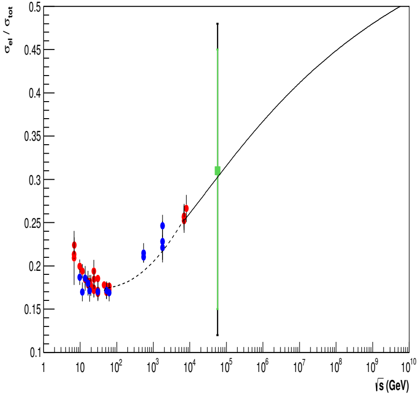


Uncertainty in ϕ specifies the band of predictions

This model predictions

from ISR to AUGER and asymptotia



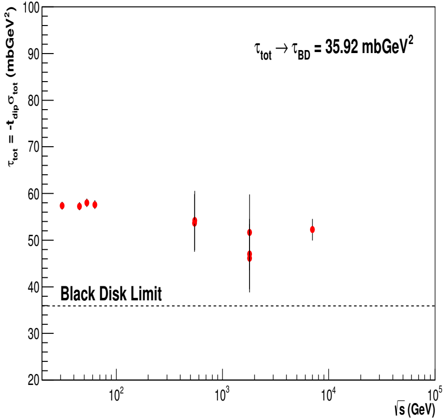


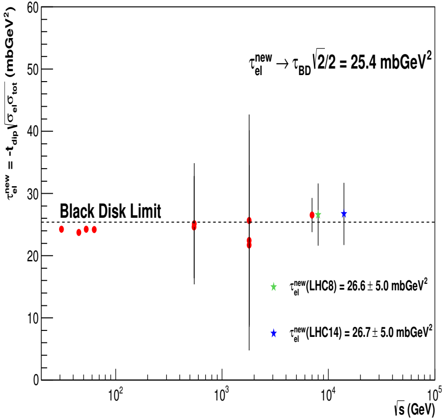
$$\frac{\sigma_{el}}{\sigma_{tot}} \longrightarrow 1/2 \quad \text{at} \quad \sqrt{s} \simeq 10^{10}\mathrm{GeV} \quad (E_{lab} \sim 10^{20}\mathrm{GeV})$$

Dip position, the Black Disk limit and Geometrical scaling

two scales at non-asymptotic energy

No scaling with $\sigma_{tot}(s)$ and central opacity, $R_{el} = \sigma_{el}/\sigma_{tot}$, plays a role in GS at LHC energies





$R_{el} \neq 1/2$ at present energies $\Rightarrow$ influence of two scales with different energy behaviour, $\sigma_{el}(s)$ and $\sigma_{tot}(s)$, through the geometric average cross section $\bar{\sigma} = \sqrt{\sigma_{el}(s)\sigma_{tot}(s)}$

Summary

What have we learned from this simple model?

1. the Barger-Phillips amplitude dissects the differential cross section in building blocks: diff. peak, dip region and tail
2. when augmented by the proton FF, the BP amplitude reproduce data from ISR to LHC $\rightarrow$ giving $\sigma_{tot}(s), \sigma_{el}(s), B_{el}(s)$
3. the dip structure arising from the interference of two terms with a relative phase (mixing of $C = \pm 1$ processes)
4. the first term (leading) is well understood, $A(s)$ giving $\sigma_{tot}(s)$ and $B(s)+t_0(s)$ giving the forward slope;
5. the second term (nonleading) carries an energy dependece through the slope $D(s)$, which requires deeper understanding
6. sum rules in impact parameter space and asymptotic theorems $\rightarrow$ hints towards energy dependence of parameters $\rightarrow$ predictions for LHC8 and LHC14
7. Geometric scaling with σ_{tot} achieved at asymptotic energies and at LHC two scales, σ_{el} and σ_{tot} still present

Acknowledgements

FAPESP

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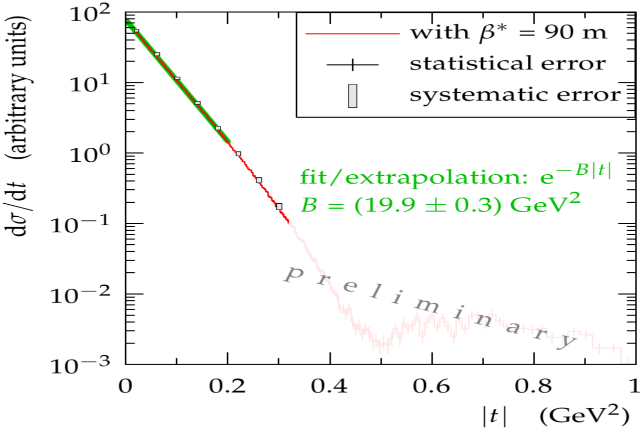
THANK YOU!!!

Backup

Differential elastic cross section at $\sqrt{s} = 8$ TeV[‡‡]

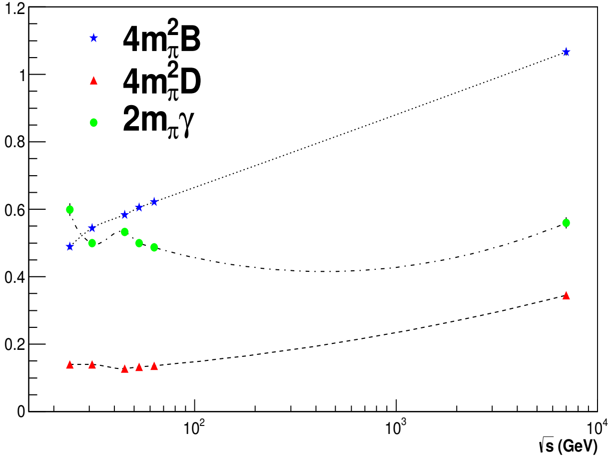


[‡‡] from Jan Kašpar talk *"Total, elastic and diffractive cross sections with TOTEM"*, CERN, December 4th, 2012

Backup

parameters of the modified BP model *mBP*1

However, the new term does not behave as expected, with $\gamma(s) \sim \ln s$...

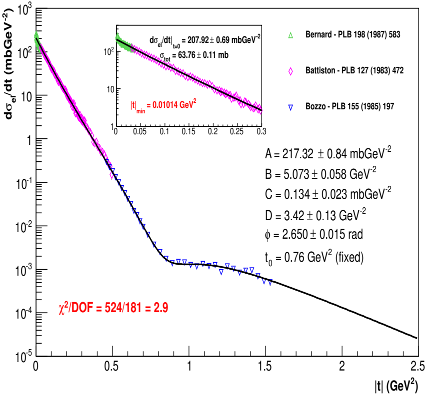


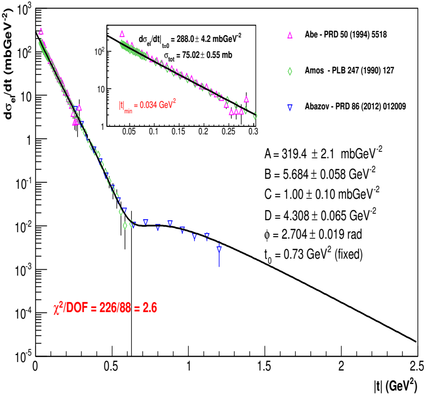
...instead it 'swings' with increasing c.m. energy → interpretation fails

Backup

modified BP model $mBP2$ applied to $\bar{p}p$ data

As an <u>empirical</u> formula, it can be applied for the crossed channel just as well

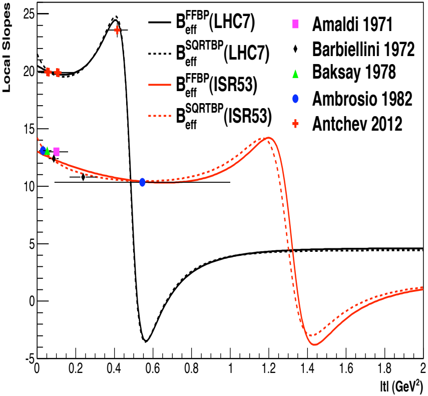


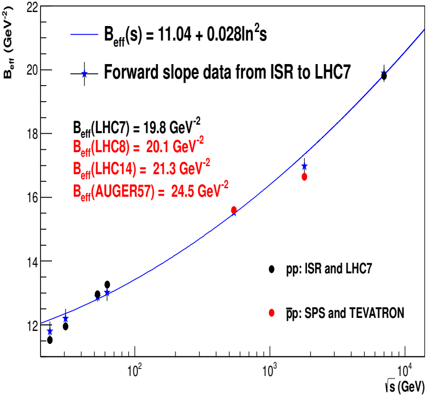


Backup

local and forward slopess

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





interaction radius “speed up” at LHC - $B_{eff}(s) \sim \ln^2 s$