CRIMEA - 2011

On the FIRST TOTEM RESULTS on ELASTIC *pp* SCATTERING: the FATE of the *DIP*

László L. Jenkovszky,
jenk@bitp.kiev.ua

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

TOTEM 2011-01
22 June 2011

CERN-PH-EP-2011-101
26 June 2011

Elastic pp Scattering at the LHC at $\sqrt{s} = 7$ TeV.

The TOTEM Collaboration
G. Antchev[*], P. Aspell[8], I. Atanassov[8,*], V. Avati[8], J. Baechler[8], V. Berardi[5b,5a], M. Berretti[7b], M. Bozzo[6b,6a], E. Brücken[3a,3b], A. Buzzo[6a], F. Cafagna[5a], M. Calicchio[5b,5a], M. G. Catanesi[5a], C. Covault[9], M. Csanád[4†] , T. Csörgö[4], M. Deile[8], E. Dimovasili[8], M. Doubek[1b], K. Eggert[9], V.Eremin[‡], F. Ferro[6a], A. Fiergolski[§], F. Garcia[3a], S. Giani[8], V. Greco[7b,8], L. Grzanka[8,¶], J. Heino[3a], T. Hilden[3a,3b], M. Janda[1b], J. Kašpar[1a,8], J. Kopal[1a,8], V. Kundrát[1a], K. Kurvinen[3a], S. Lami[7a], G. Latino[7b], R. Lauhakangas[3a], T. Leszko[§] E. Lippmaa[2], M. Lokajíček[1a], M. Lo Vetere[6b,6a], F. Lucas Rodríguez[8], M. Macrí[6a], L. Magaletti[5b,5a], G. Magazzù[7a], A. Mercadante[5b,5a], M. Meucci[7b], S. Minutoli[6a], F. Nemes[4,†] H. Niewiadomski[8], E. Noschis[8], T. Novak[4,‖], E. Oliveri[7b], F. Oljemark[3a,3b], R. Orava[3a,3b], M. Oriunno[8**], K. Österberg[3a,3b], A.-L. Perrot[8], P. Palazzi[8], E. Pedreschi[7a], J. Petäjäjärvi[3a], J. Procházka[1a], M. Quinto[5a], E. Radermacher[8], E. Radicioni[5a], F. Ravotti[8], E. Robutti[6a], L. Ropelewski[8], G. Ruggiero[8], H. Saarikko[3a,3b], A. Santroni[6b,6a], A. Scribano[7b], G. Sette[6b,6a], W. Snoeys[8], F. Spinella[7a], J. Sziklai[4], C. Taylor[9], N. Turini[7b], V. Vacek[1b], J. Welti[3a,b], M. Vítek[1b], J. Whitmore[10].

Definitions

Necessary condition for **diffraction** (deviation from geometrical optics):

$kR^2 >> 1$, where $k = 2\pi/\lambda$, λ is the wave length and R is the size of the obstacle (or hole) is

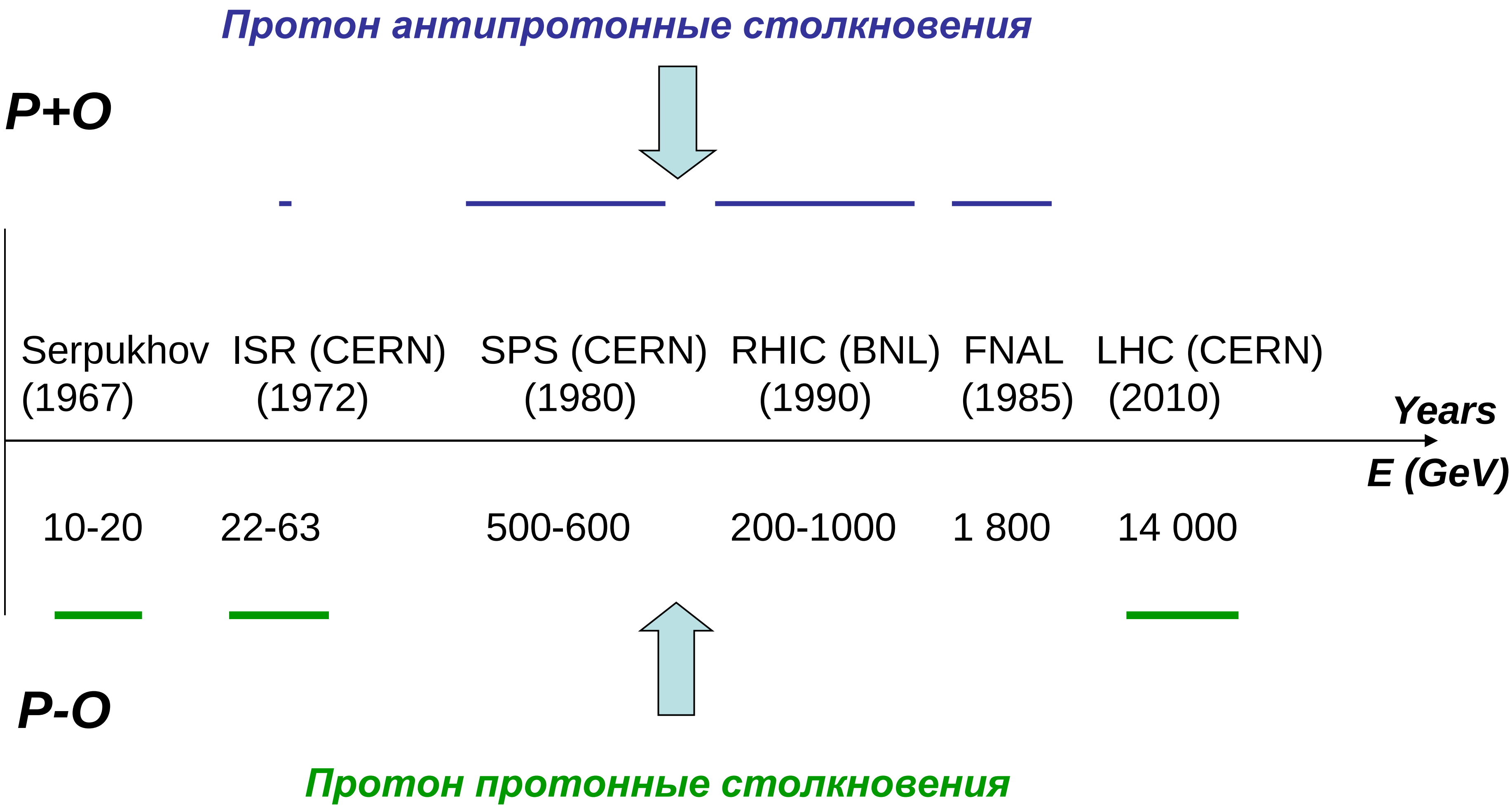
Fraunhofer diffr.: $kR^2/D << 1$,

Frenel diffr.: $kR^2/D \approx 1$, where D is the distance between the source and the detector. The case $kR^2/D >> 1$ corresponds to linear optics.

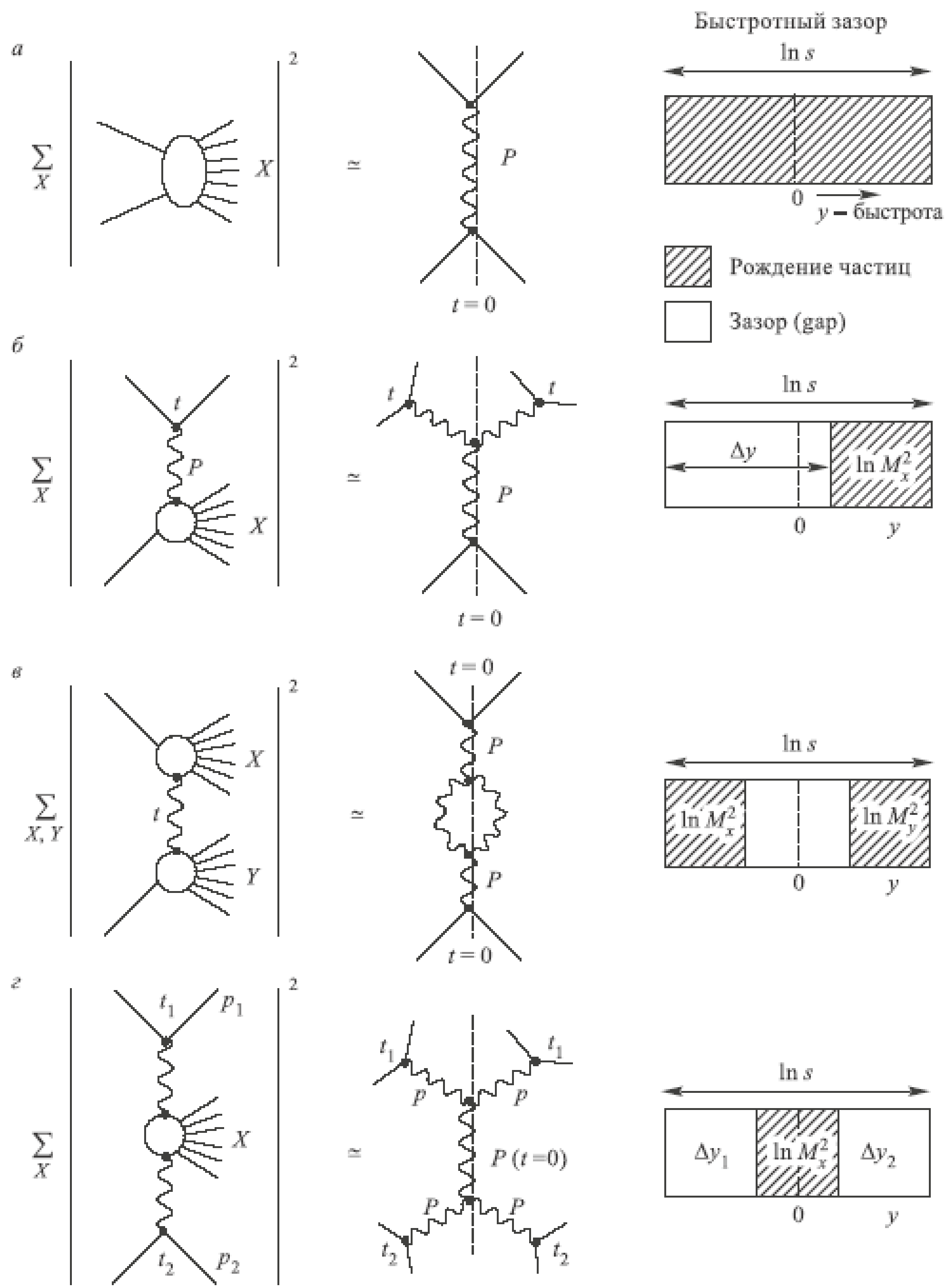
In high-energy, say, $> 1GeV$, experiments, *Fraunhofer* diffraction dominates: the obstacle, hole =detector is of $1Fm$, while the distance between the source and the detector is practically infinite. (N.B.: At tha LHC, however, Fresnel diffraction may occur in the Coulomb region.) At the LHC, $\sqrt{14}TeV$, $R \approx 1Fm$, D $1cm$, hence $kR^2/D \approx 10^{-6}$, (compared with $\sqrt{5}0GeV, \rightarrow kR^2/D \approx 10^{-9}$ at the ISR (CERN).

Diffraction extends in a huge span of wavelengths !

Ускорители протонов, антипротонов и ядер



P-померон; O-оддерон


Быстротный зазор
а
ln s
X
P
0
y – быстрота
t = 0
Рождение частиц
Зазор (gap)
б
t
P
X
Δy
ln M_x^2
y
t = 0
в
t = 0
X
t
Y
P
ln M_x^2
ln M_y^2
X, Y
г
t_1
p_1
t_2
p_2
P (t = 0)
Δy_1
Δy_2

$$\sigma_t(s) = \frac{4\pi}{s} Im A(s, t = 0); \quad \frac{d\sigma}{dt} = \frac{\pi}{s^2}|A(s,t)|^2; \quad \boldsymbol{n(s)};$$

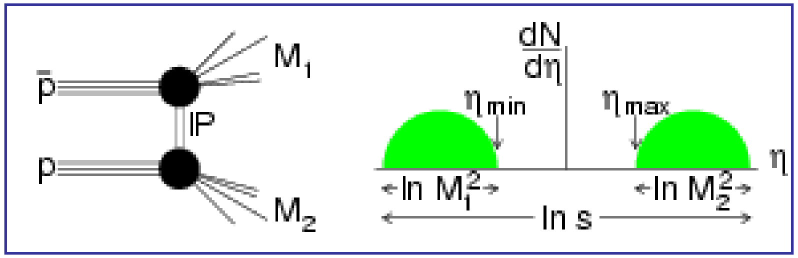
$$\sigma_{el} = \int_{t_{min \approx -s/2 \approx \infty}}^{t_{thr. \approx 0}} \frac{d\sigma}{dt}; \quad \sigma_{in} = \sigma_t - \sigma_{el}; \quad B(s,t) = \frac{d}{dt} \ln\left(\frac{d\sigma}{dt}\right);$$

$$A_{pp}^{p\bar{p}}(s,t) = P(s,t) \pm O(s,t) + f(s,t) \pm \omega(s,t) \to_{LHC} \approx P(s,t) \pm O(s,t),$$

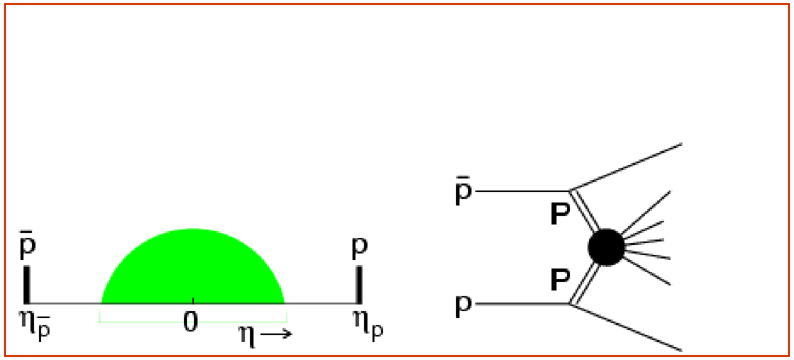
where P, O, f. ω are the Pomeron, odderon and non-leading Reggeon contributions.

α(0)\C	+	-
1	P	O
1/2	f	ω

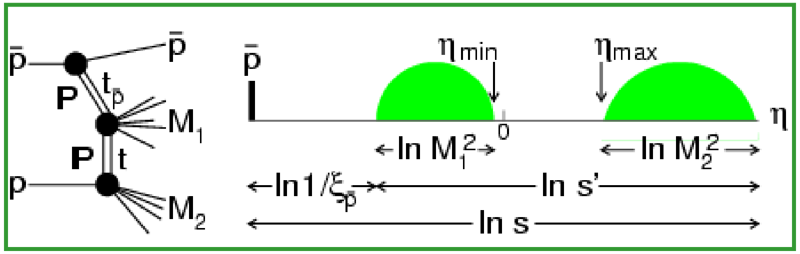
Central and Multigap Diffraction



- **Double Diffraction Dissociation**
  - **One central gap**



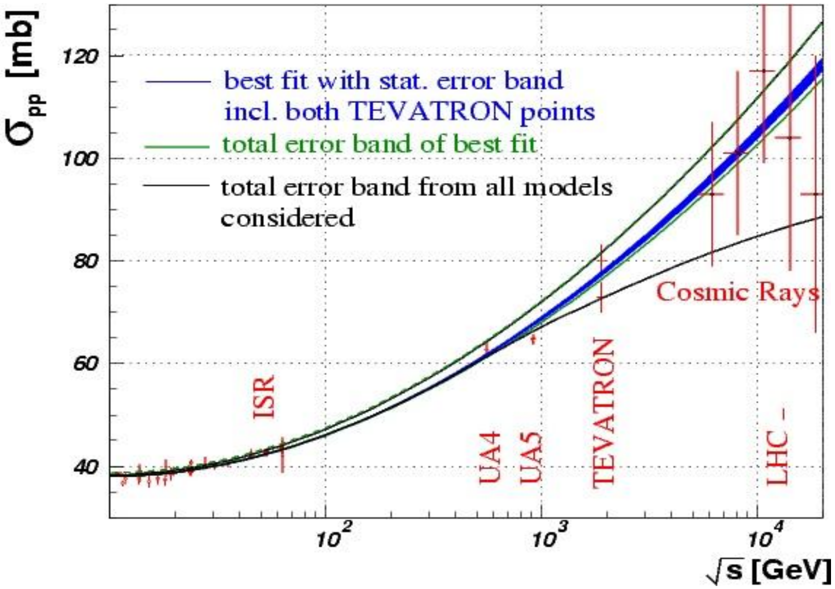
- **Double Pomeron Exchange**
  - **Two forward gaps**



- **SDD: Single+Double Diffraction**
  - **One forward gap+ one central gap**

Rate for second diffractive gap is not suppressed!

Total Cross-Section



$$\sigma_{tot} = \frac{16\pi}{1+\rho^2} \times \frac{(dN/dt)|_{t=0}}{N_{el} + N_{inel}}$$

Luminosity-independent measurement via optical-theorem → simultaneous evaluation of forward elastic and inelastic rate (TOTEM)

$\sigma_{tot} \propto (\log s)^{\gamma}$

- σ_{tot} (LHC) ~ 110 mb (γ=2; best-fit)
- σ_{tot} (LHC) ~ 95 mb (γ=1)

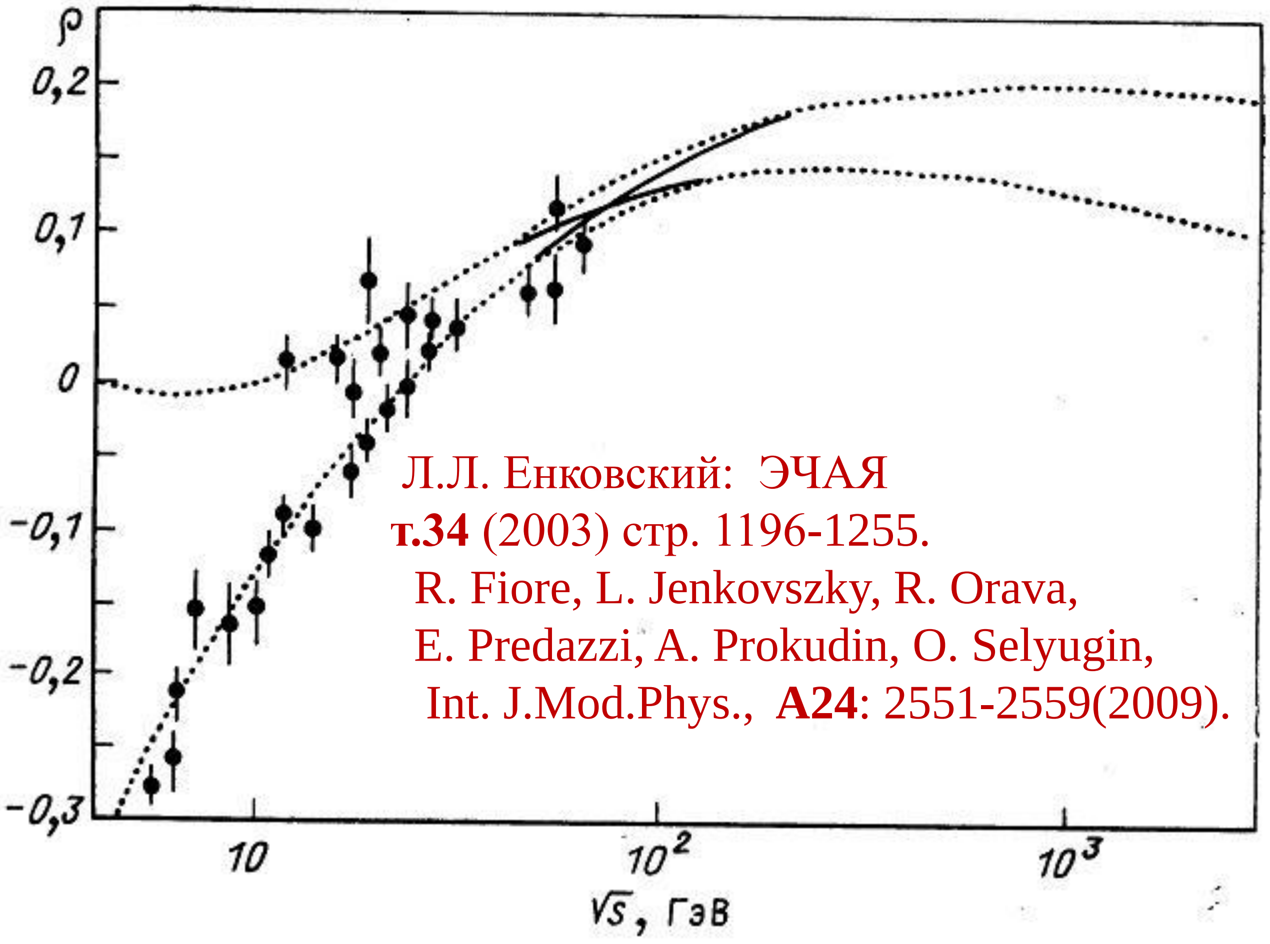
- elastic rate down to $|t|=10^{-3}$ GeV^2 to keep extrapolation error small (1-2%)
- Sufficient η coverage to access Nel+Ninel

Inversely: $$L\sigma_{tot} = N_{elastic} + N_{inelastic}$$

(σ_{tot} + $dN/dt|_{t=0}$) ➡ ($\Delta L/L$ > ~ 2 $\Delta\sigma_{tot}/\sigma_{tot}$)

(L + $dN/dt|_{t=0}$) ➡ ($\Delta\sigma_{tot}/\sigma_{tot}$ > ~ $\frac{1}{2}$ $\Delta L/L$)

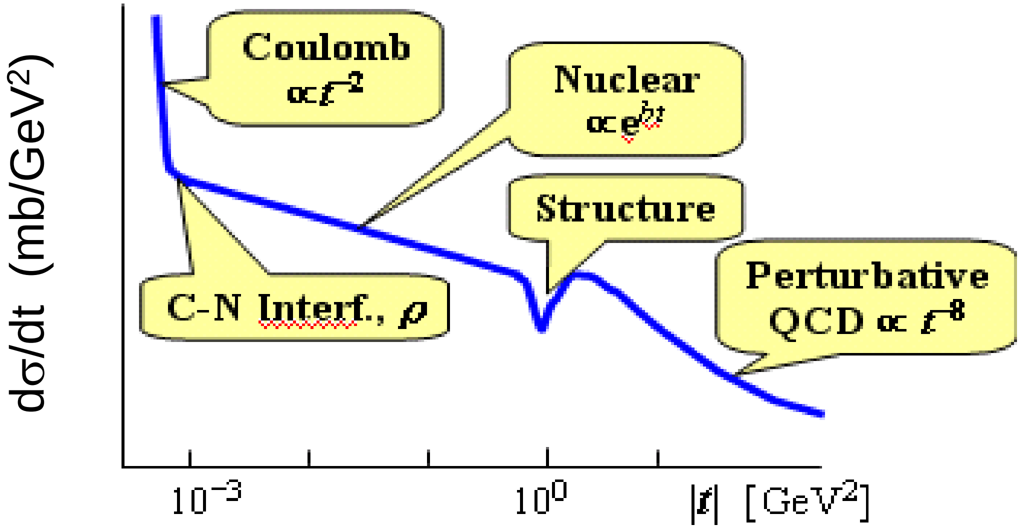
$$L\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2} \times \left.\frac{dN}{dt}\right|_{t=0}$$



Л.Л. Енковский: ЭЧАЯ
т.34 (2003) стр. 1196-1255.
R. Fiore, L. Jenkovszky, R. Orava,
E. Predazzi, A. Prokudin, O. Selyugin,
Int. J.Mod.Phys., **A24**: 2551-2559(2009).

Elastic Scattering

$\sqrt{s}$ = 14 TeV prediction of BSW model



momentum transfer $-t \sim (p\theta)^2$

θ = beam scattering angle

p = beam momentum

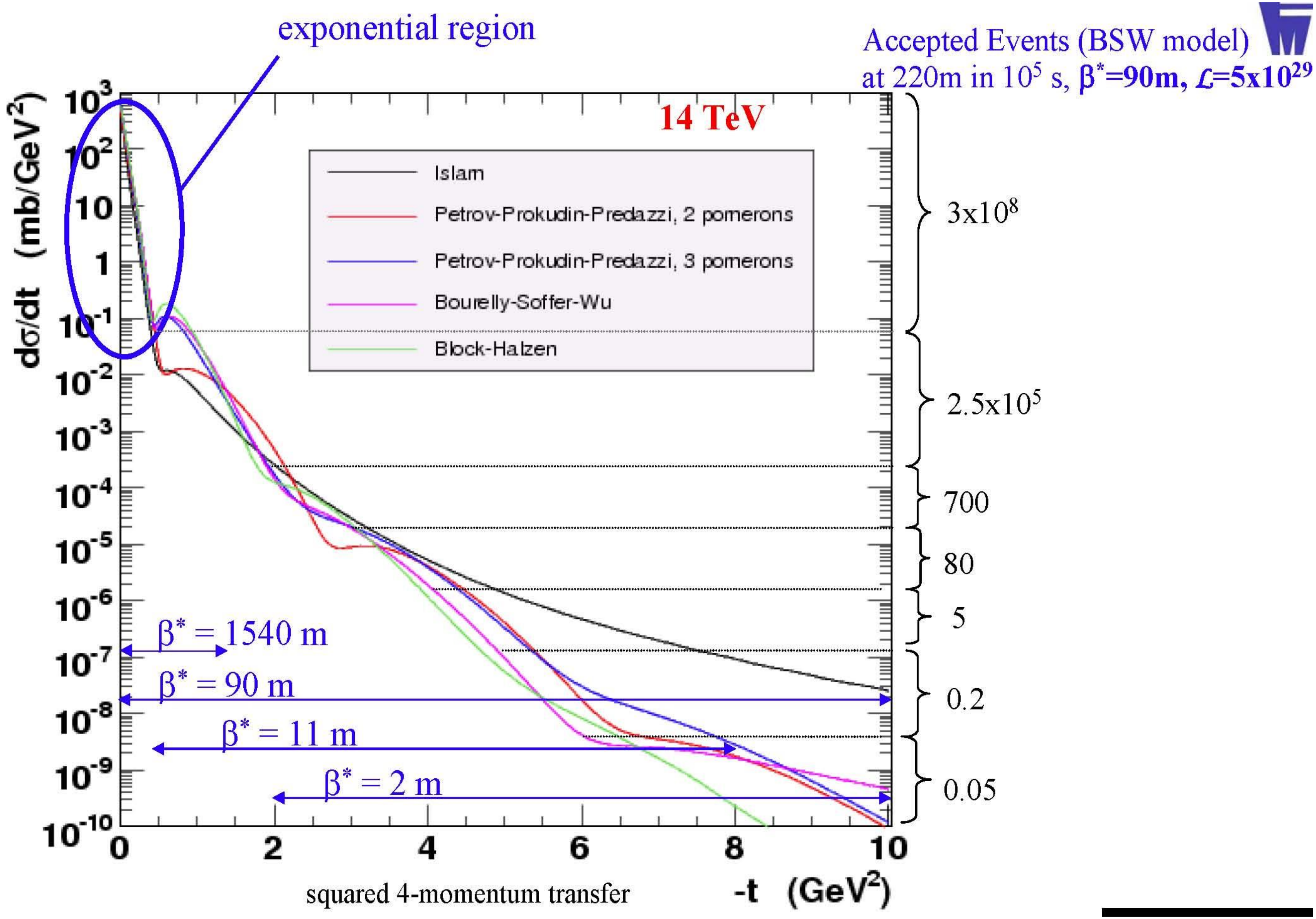
$$\rho = \frac{\mathrm{Re}\left(f_{el}(t)\right)}{\mathrm{Im}\left(f_{el}(t)\right)}\bigg|_{t\to 0}$$

$$\frac{dN}{dt}\bigg|_{t=CNI} = L\pi\left|f_C + f_N\right|^2 \approx L\pi\left|-\frac{2\alpha_{\mathrm{EM}}}{|t|} + \frac{\sigma_{\mathrm{tot}}}{4\pi}(i+\rho)e^{-\frac{b|t|}{2}}\right|^2$$

L, σ_{tot}, **b**, and ρ from FIT in CNI region (UA4)

CNI region: $|f_C| \sim |f_N|$ → @ LHC: $-t \sim 6.5\ 10^{-4}$ GeV^2; $\theta_{min} \sim 3.4$ μrad

($\theta_{min} \sim 120$ μrad @ SPS)



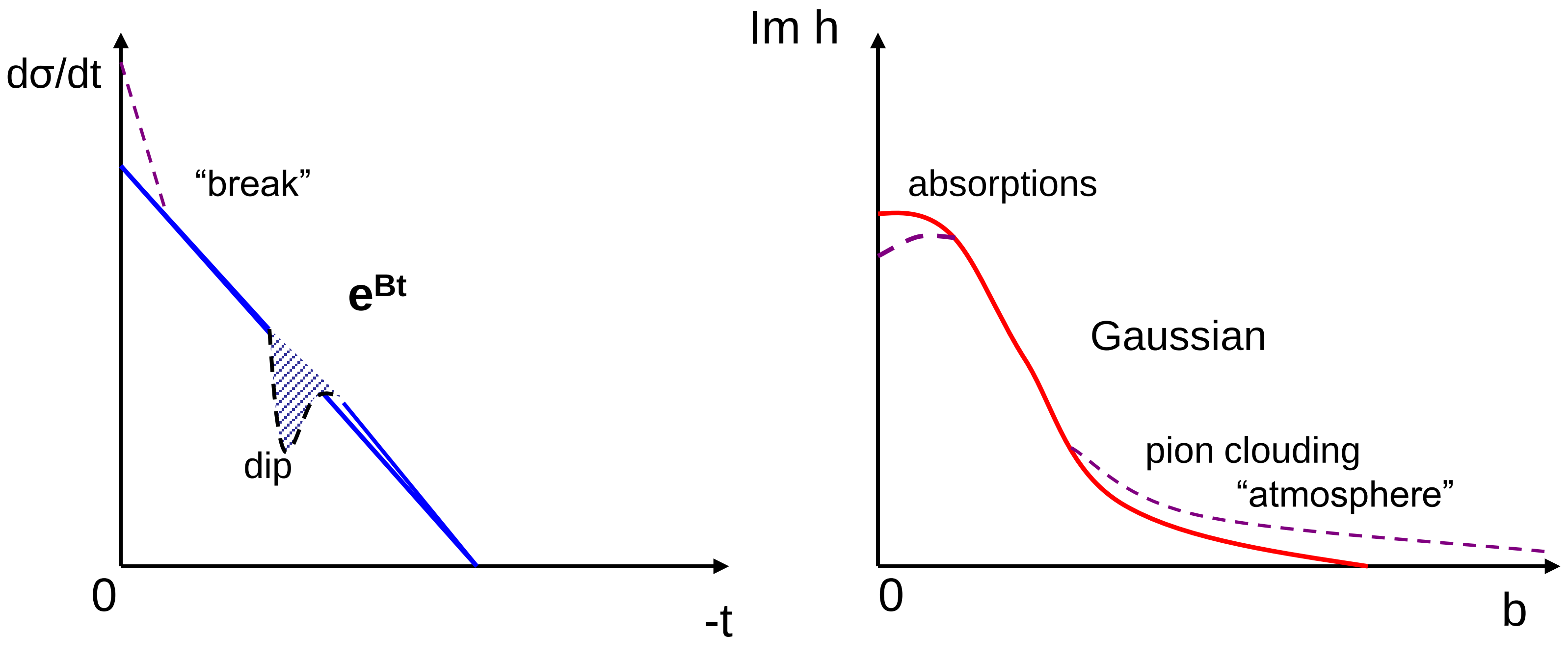
exponential region
Accepted Events (BSW model)
at 220m in 10^5 s, β*=90m, L=5x10^29
14 TeV
Islam
Petrov-Prokudin-Predazzi, 2 pomerons
Petrov-Prokudin-Predazzi, 3 pomerons
Bourelly-Soffer-Wu
Block-Halzen
3x10^8
2.5x10^5
700
80
5
0.2
0.05
β* = 1540 m
β* = 90 m
β* = 11 m
β* = 2 m
dσ/dt (mb/GeV^2)
squared 4-momentum transfer
-t (GeV^2)

Geometrical scaling (GS), saturation and unitarity

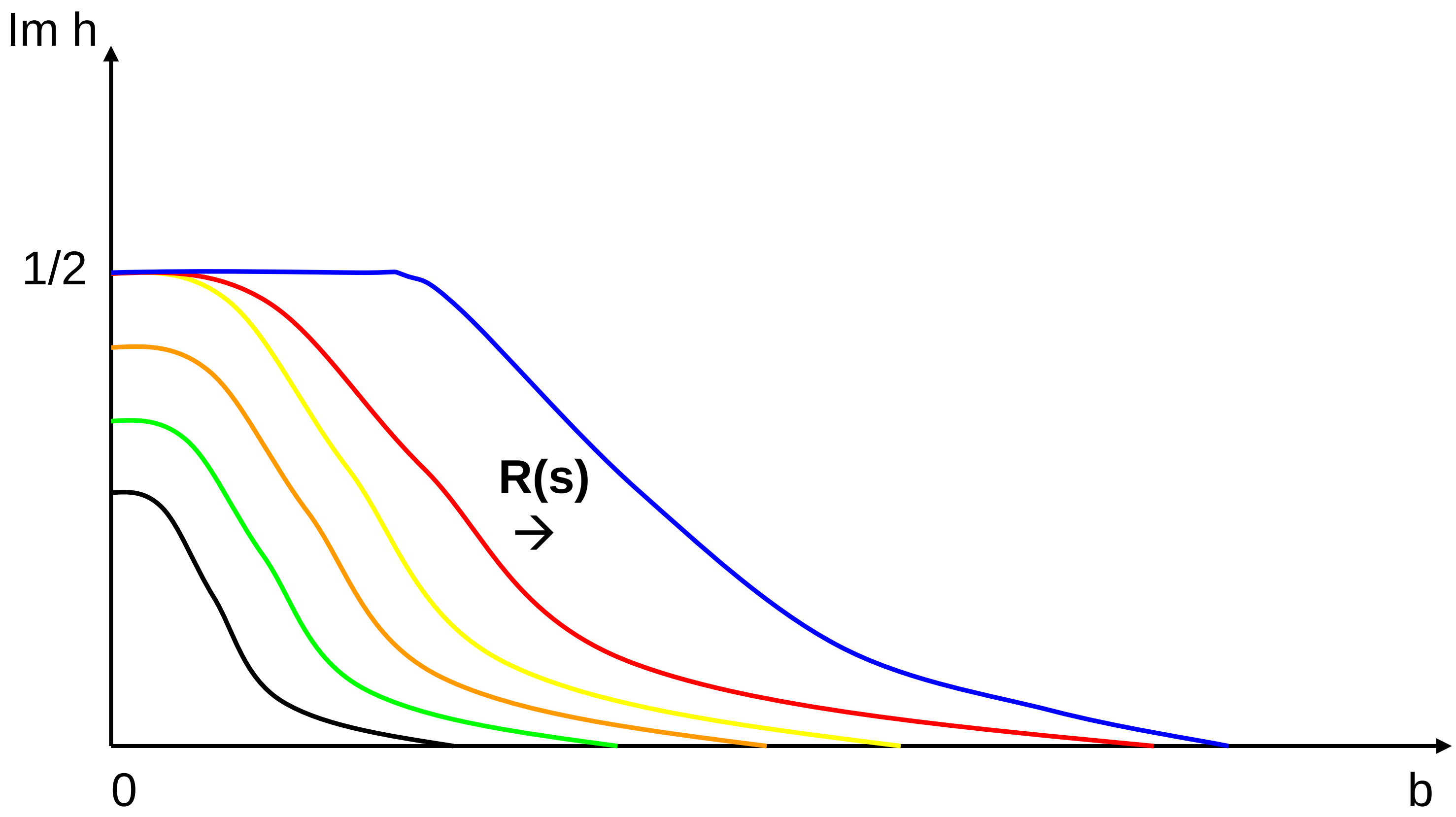
1. On-shell (hadronic) reactions (s,t, Q^2=m^2);

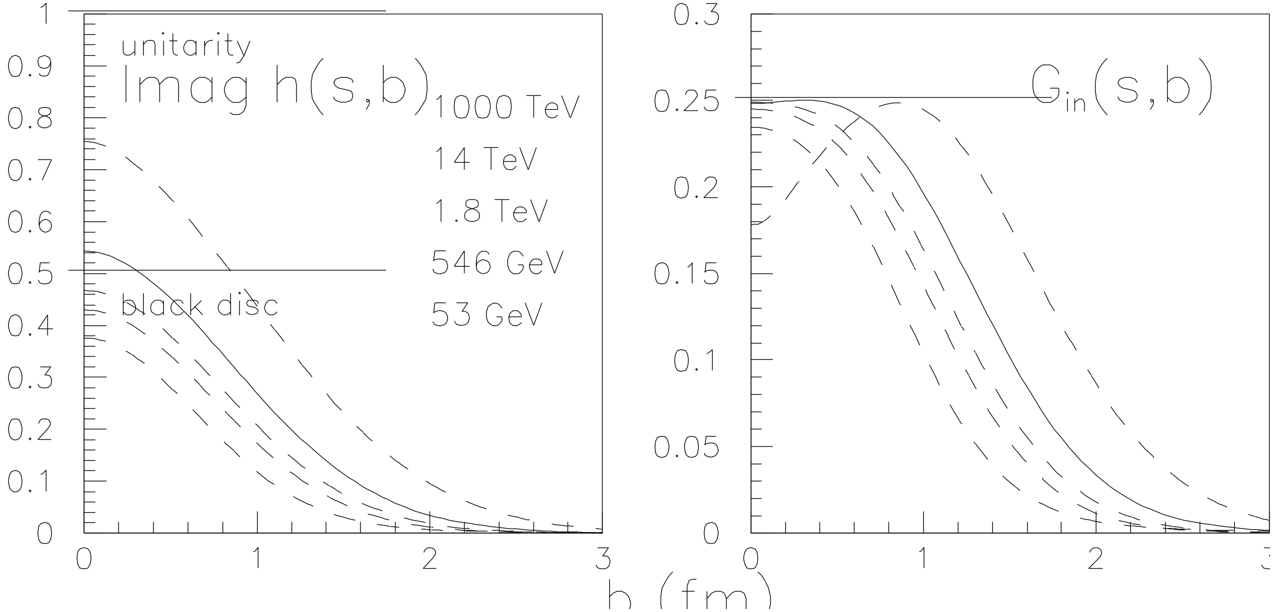
t ←→ *b* **transformation:** $h(s,b) = \int_0^\infty d\sqrt{-t}\sqrt{-t}A(s,t)$

and dictionary:



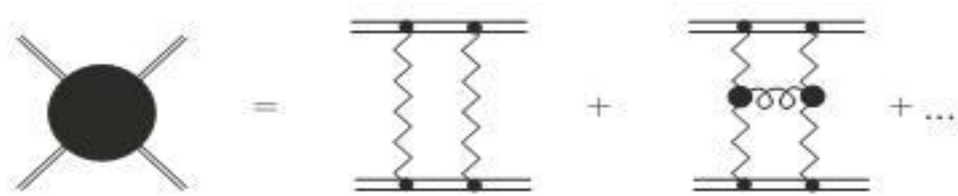
П.Дегрола, Л.Л. енковский, Б.В. Струминский, ЯФ

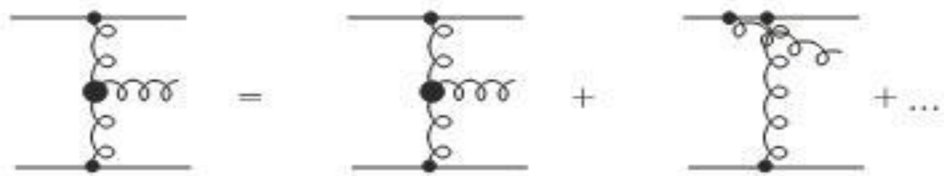




P. Desgrolard, L.L. Jenkovszky and B.V. Struminsky,

R. Fiore, L.L. Jenkovszky, E.A. Kuraev, A.I. Lengyel, and Z.Z. Tarics, ***Predictions for high-energy pp and \bar pp scattering from a finite sum of gluon ladders,*** **Phys. Rev. D81, #5 (2010) 056005; arXiv0911.2094/hep-ph**

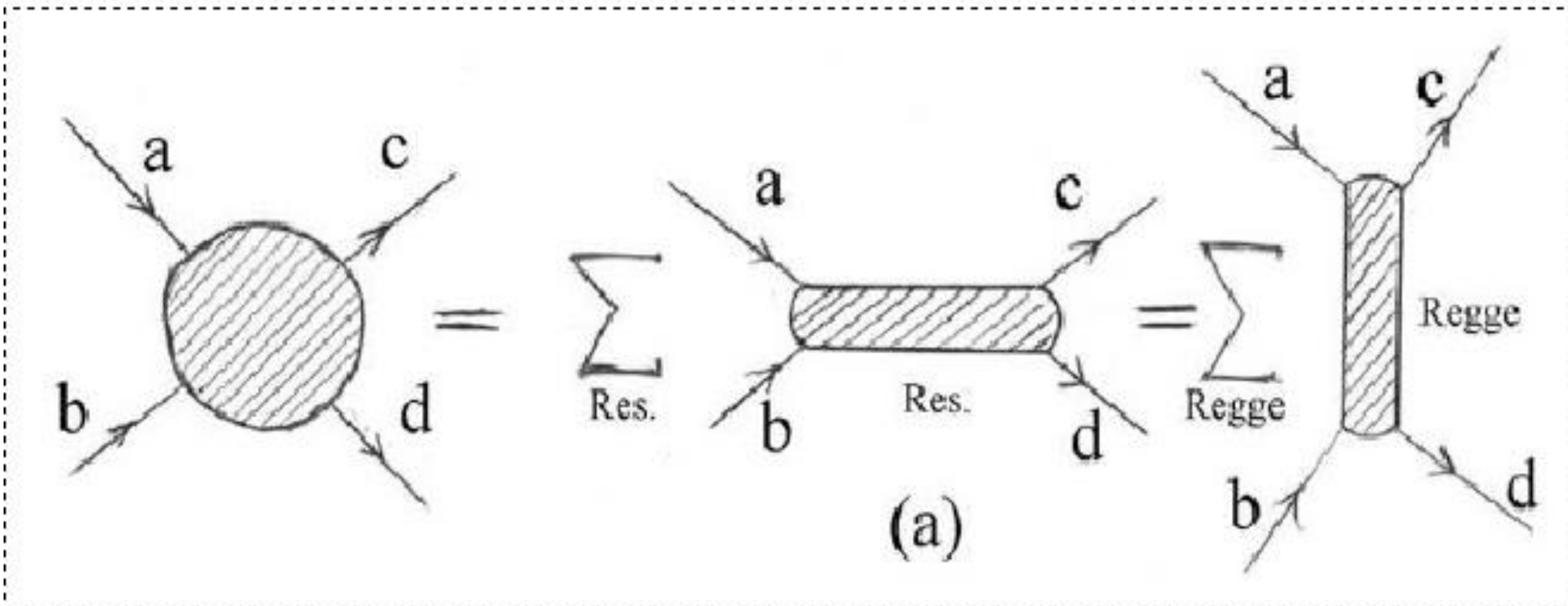




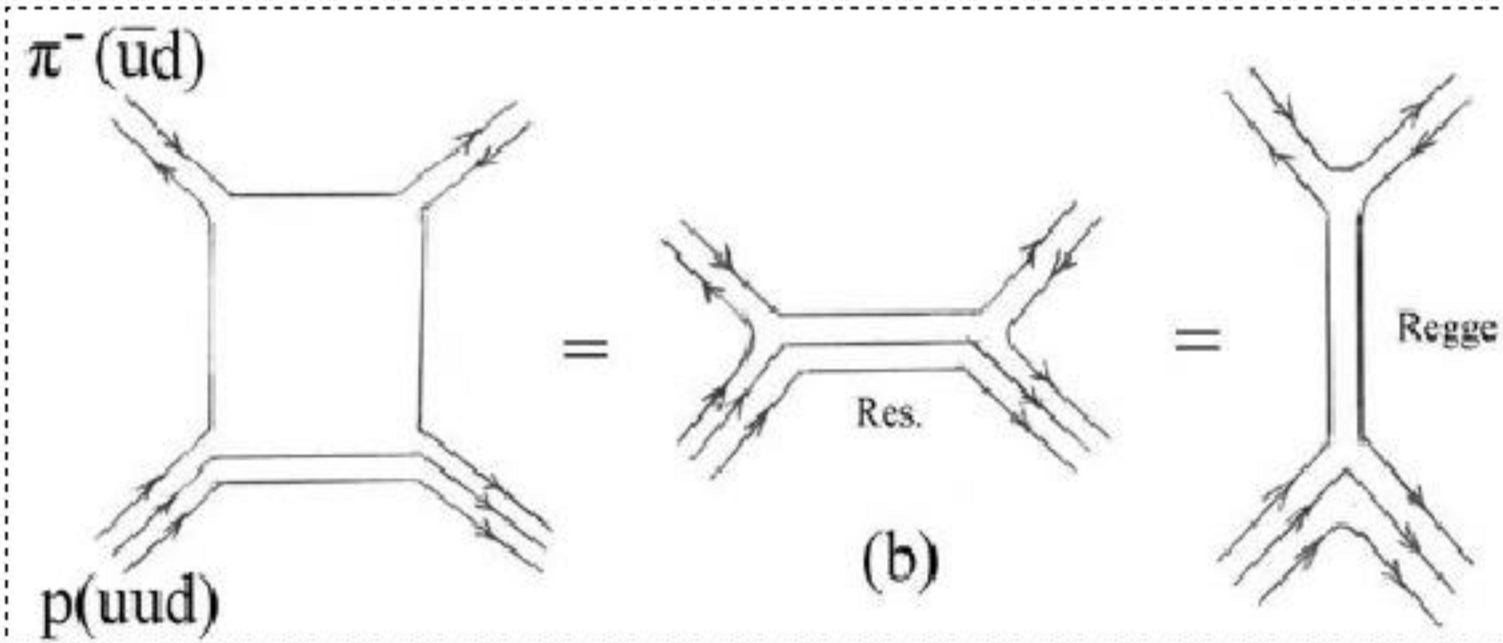
$$\sigma_t^{(P)}(s) = \sum_{i=0}^{N} f_i\,\theta(s - s_0^i)\,\theta(s_0^{i+1} - s)\ , \qquad (1)$$

where

$$f_i = \sum_{j=0}^{i} a_{ij} L^j\ , \qquad (2)$$



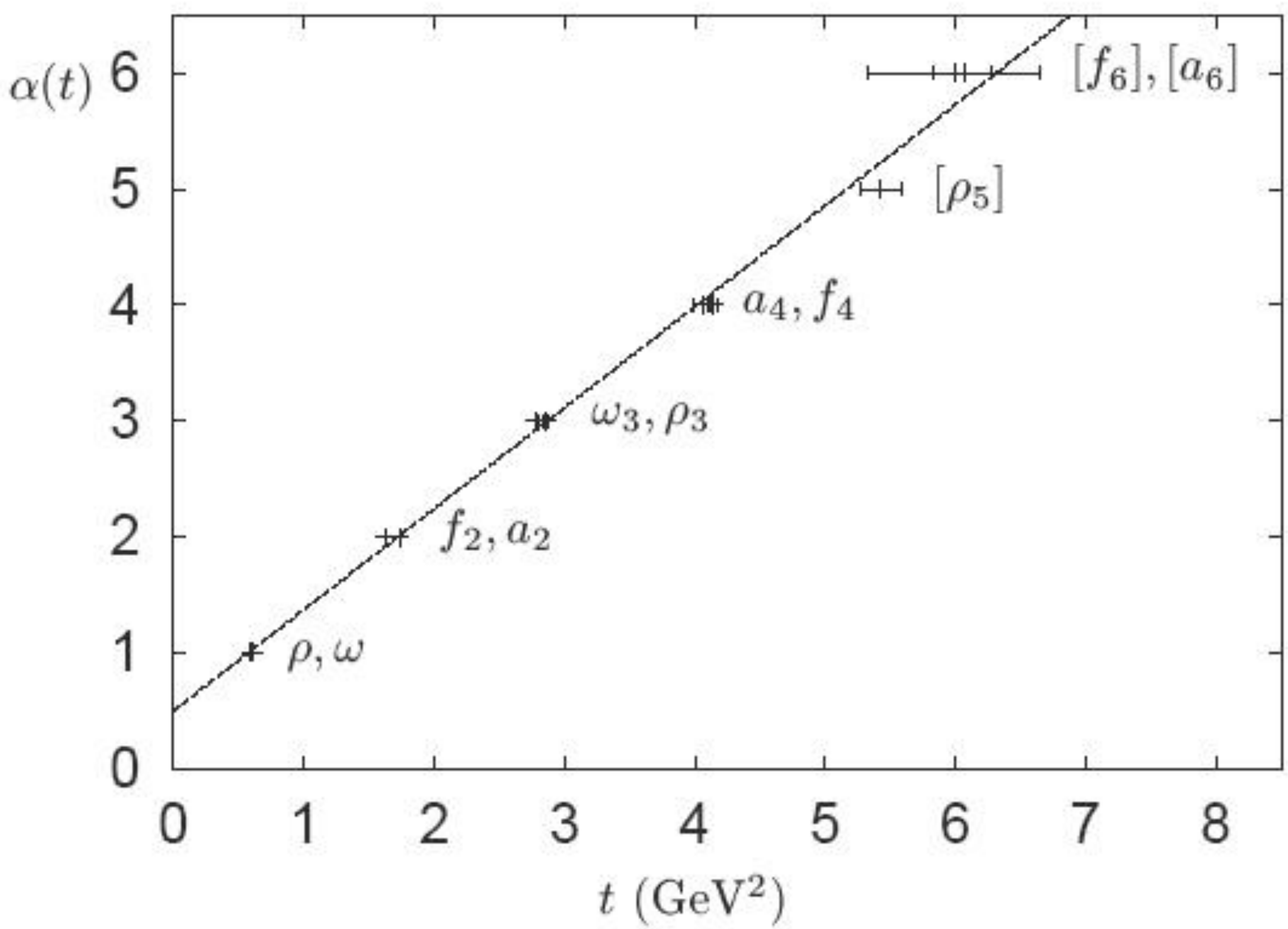
a
b
c
d
Res.
a
b
c
d
Res.
Regge
a
b
c
d
Regge
(a)

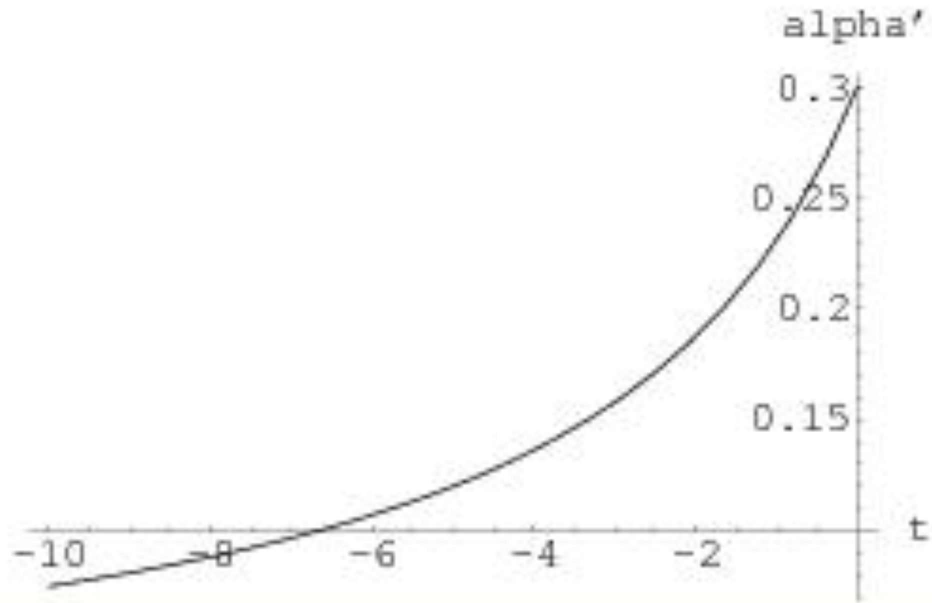


(b)

Linear particle trajectories

Plot of spins of families of particles against their squared masses:





The slope of the cone for a single pole is: $B(s,t) \sim \alpha'(t) \ln s$. The Regge residue $e^{b\alpha(t)}$ with a logarithmic trajectory $\alpha(t) = \alpha(0) - \gamma \ln(1 - \beta t)$, is identical to a form factor (geometrical model).

The Pomeron trajectory

The Pomeron trajectory has threshold singularities, the lowest one being due to the two-pion exchange, required by the $t-$channel unitarity. There is a constrain (Barut, Zwanziger; Gribov) from the $t-$ channel unitarity, by which

$$\Im\alpha(t) \sim (t-t_0)^{\Re\alpha(t_0)+1/2}, \quad t \to t_0,$$

where t_0 is the lightest threshold. For the Pomeron trajectory it is $t_0 = 4m_\pi^2$, and near the threshold:

$$\alpha(t) \sim \sqrt{4m_\pi^2 - t}. \tag{1}$$

Representative examples of the Pomeron trajectories: 1) Linear; 2) With a square-root threshold, required by $t-$channel unitarity and accounting for the small-t "break" as well as the possible "Orear", $e^{\sqrt{-t}}$ behavior in the second cone; and 3) A logarithmic one, anticipating possible "hard effects" at large $|t|$ $|t| < 8$ GeV^2.

$$\alpha_P \equiv \alpha_P(t) = 1 + \delta_P + \alpha_{1P}t, \quad \text{(TR.1)}$$

$$\alpha_P \equiv \alpha_P(t) = 1 + \delta_P + \alpha_{1P}t - \alpha_{2P}\left(\sqrt{4\alpha_{3P}^2 - t} - 2\alpha_{3P}\right), \quad \text{(TR.2)}$$

$$\alpha_P \equiv \alpha_P(t) = 1 + \delta_P - \alpha_{1P}\ln\left(1 - \alpha_{2P}t\right). \quad \text{(TR.3)}$$

$$A_{pp}^{p\bar{p}}(s,t) = P(s,t) \pm O(s,t) + f(s,t) \pm \omega(s,t) \to_{LHC} P(s,t) \pm O(s,t),$$

where P is the Pomeron contribution and O is that of the Odderon.

$$P(s,t) = i\frac{as}{bs_0}\left(r_1^2(s)e^{r_1^2(s)[\alpha_P(t)-1]} - \epsilon r_2^2(s)e^{r_2^2(s)[\alpha_P(t)-1]}\right),$$

where $r_1^2(s) = b + L - \frac{i\pi}{2}, \quad r_2^2(s) = L - \frac{i\pi}{2}$ with $L \equiv \ln\frac{s}{s_0}$; $\alpha_P(t)$ is the Pomeron trajectory and a, b, s_0 and ϵ are free parameters.

Does GS imply saturation? Not necessarily!

$ImH(s,b) = |h(s,b)|^2 + G_{in}(s,b)$, (h is associaed with the "opacity), Here from: $0 \le |h(s,b)|^2 \le \Im h(s,b)) \le 1$. The Black Disc Limit (BDL) corresponds to $\Im h(s,b) = 1/2$, provided $h(s,b) = i(1 - \exp[i\omega(s,b)]/2$, with an imaginary eikonal $\omega(s,b) = i\Omega(s,b)$.

There is an alternative solution, that with the "minus" sign in $h(s,b) = [1 \pm \sqrt{1 - 4G_{in}(s,b)}]/2$, giving (S.Troshin and N.Tyurin (Protvino)): $h(s,b) = \Im u(s,b)/[1 - iu(s,b))]$,

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Phillips and Barger in 1973 [ ], right after its first observation at the ISR. Their formula reads

$$\frac{d\sigma}{dt} = |\sqrt{A}\exp(Bt/2) + \sqrt{C}\exp(Dt/2 + i\phi)|^2, \tag{1}$$

where A, B, C, D and ϕ are determined independently at each energy.

L.Jenkovszky, A. Lengyel, D. Lontkovskyi:
The Pomeron and Odderon in elastic, inelastic and total cross-sections,
hep-ph/056014.

P and f (second column) have positive C-parity, thus entering in the scattering amplitude with the same sign in pp and $\bar{p}p$ scattering, while the Odderon and ω (third column) have negative C-parity, thus entering pp and $\bar{p}p$ scattering with opposite signs, as shown below:

$$A\left(s,t\right)_{pp}^{\bar{p}p} = A_P\left(s,t\right) + A_f\left(s,t\right) \pm \left[A_\omega\left(s,t\right) + A_O\left(s,t\right)\right], \tag{1}$$

where the symbols $P,\ f,\ O,\ \omega$ stand for the relevant Regge-pole amplitudes and the super(sub)script, evidently, indicate $\bar{p}p(pp)$ scattering with the relevant choice of the signs in the sum.

$$A_P(s,t) = \frac{d}{d\alpha_P}\left[e^{-i\pi\alpha_P/2}G(\alpha_P)\left(s/s_0\right)^{\alpha_P}\right] = \tag{1}$$

$$e^{-i\pi\alpha_P(t)/2}\left(s/s_0\right)^{\alpha_P(t)}\left[G'(\alpha_P) + \left(L - i\pi/2\right)G(\alpha_P)\right].$$

The Pomeron is a dipole in the $j-$plane

$$A_P(s,t)=\frac{d}{d\alpha_P}\Big[e^{-i\pi\alpha_P/2}G(\alpha_P)\Big(s/s_0\Big)^{\alpha_P}\Big]= \qquad (1)$$

$$e^{-i\pi\alpha_P(t)/2}\Big(s/s_0\Big)^{\alpha_P(t)}\Big[G'(\alpha_P)+\Big(L-i\pi/2\Big)G(\alpha_P)\Big].$$

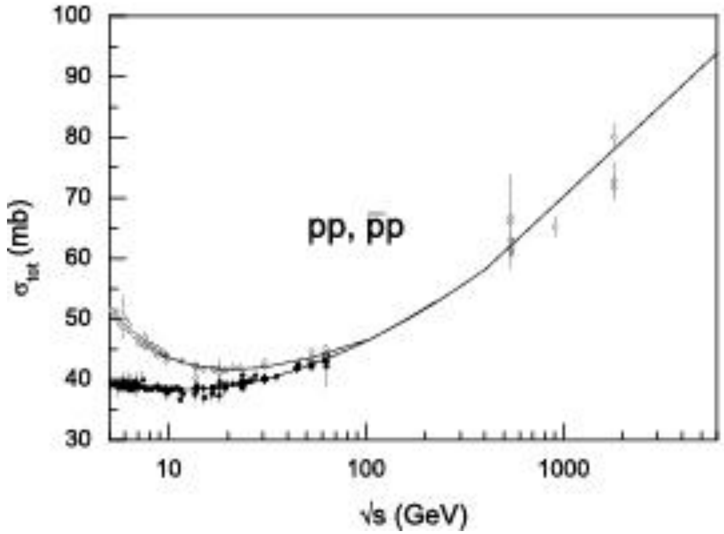
Since the first term in squared brackets determines the shape of the cone, one fixes

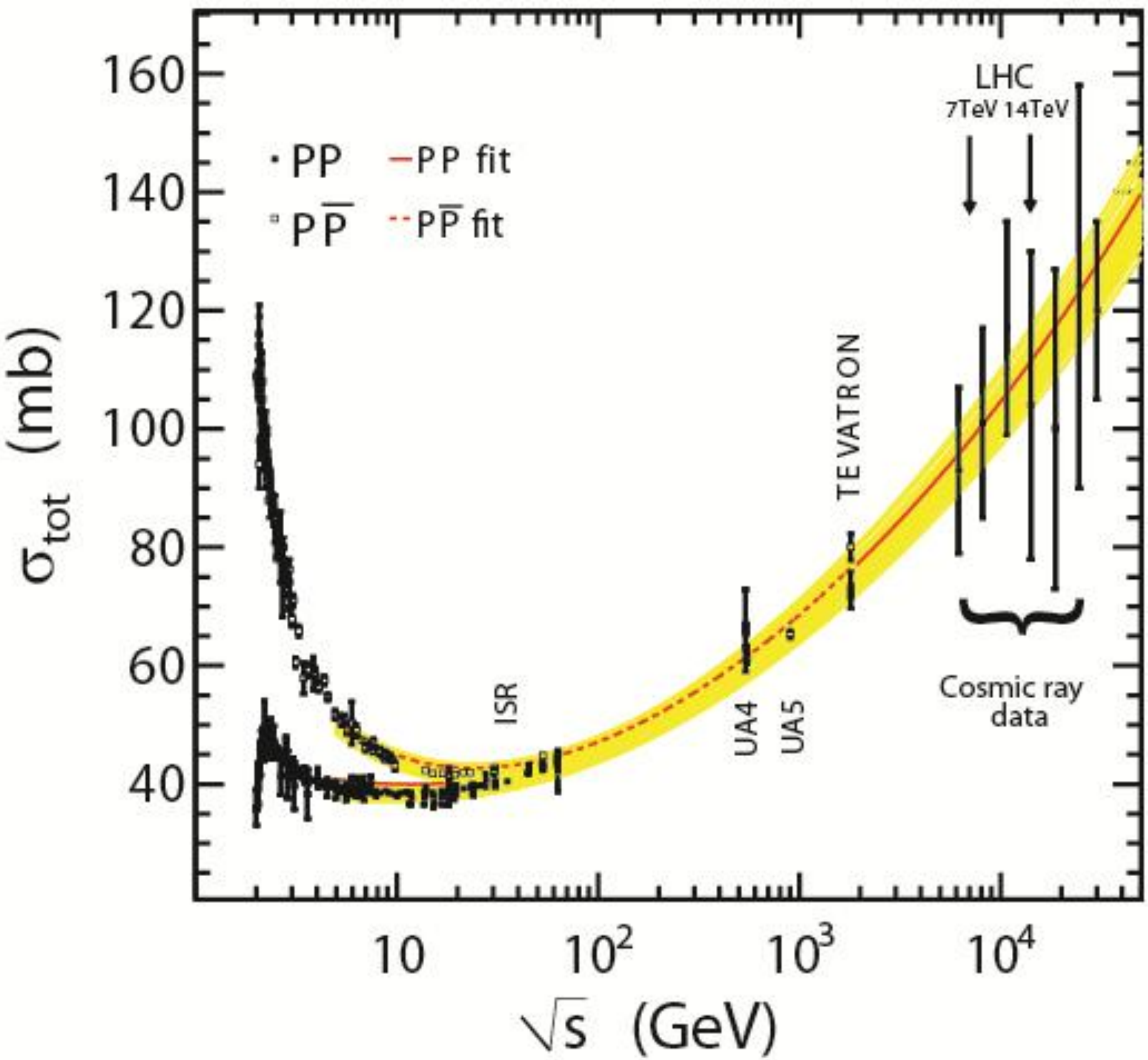
$$G'(\alpha_P)=-a_Pe^{b_P[\alpha_P-1]}, \qquad (2)$$

where $G(\alpha_P)$ is recovered by integration, and, as a consequence, the Pomeron amplitude can be rewritten in the following "geometrical" form

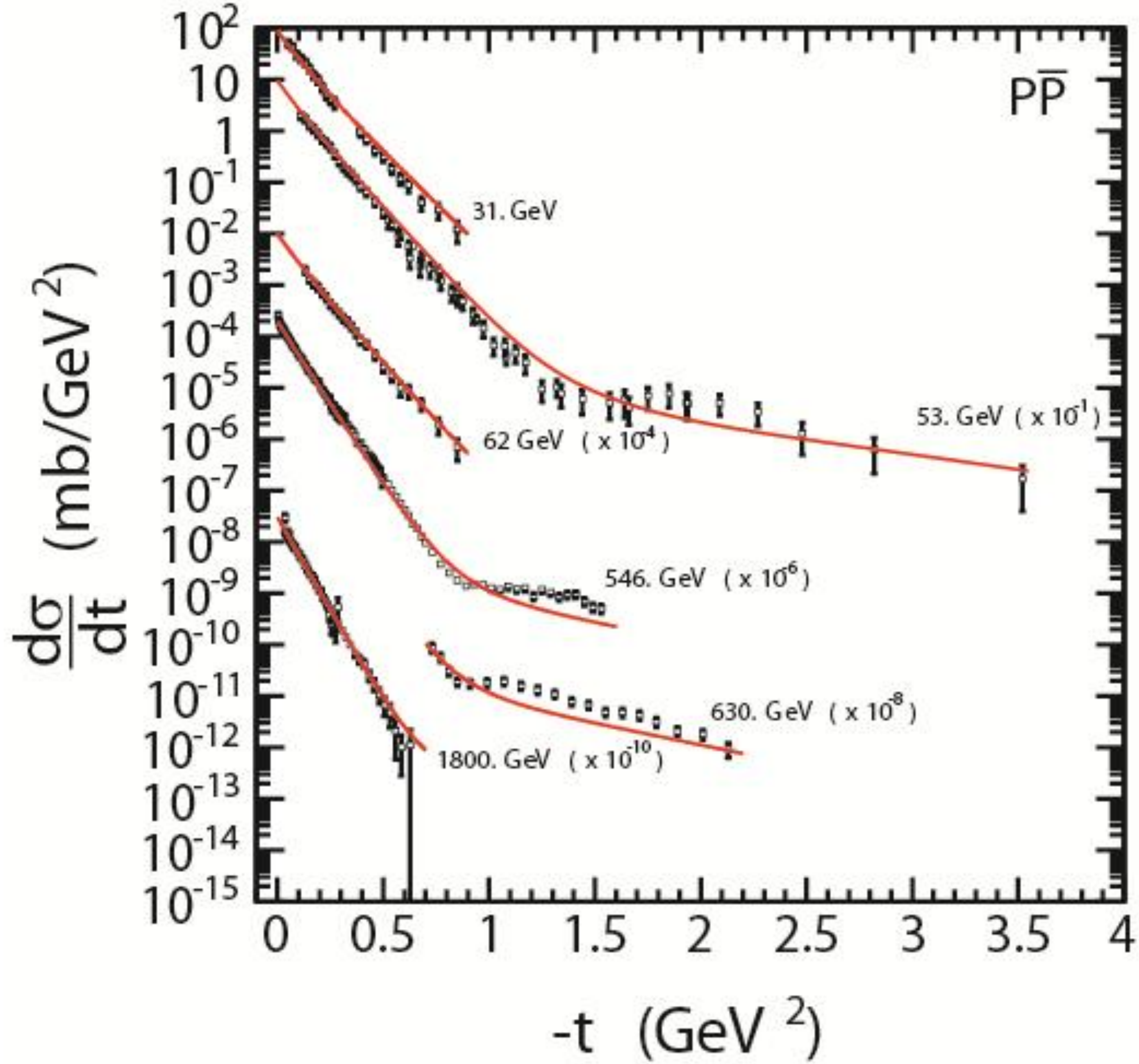
$$A_P(s,t)=i\frac{a_P\ s}{b_P\ s_0}[r_1^2(s)e^{r\ \ (s)[\alpha_P-1]}-\varepsilon_Pr_2^2(s)e^{r\ \ (s)[\alpha_P-1]}], \qquad (3)$$

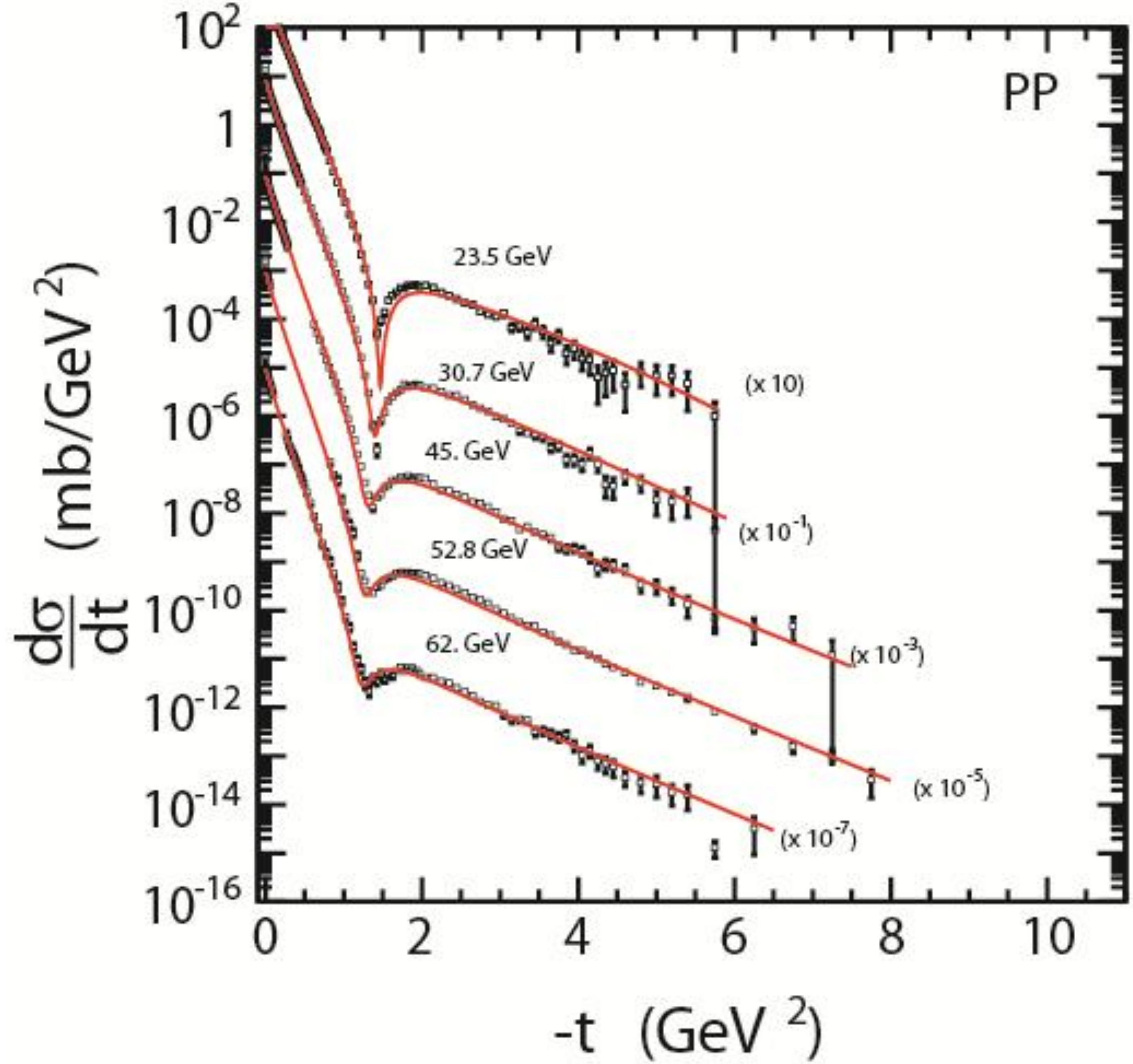
where $r_1^2(s)=b_P+L-i\pi/2,\ \ r_2^2(s)=L-i\pi/2,\ \ L\equiv\ln(s/s_0)$.


100
90
80
70
60
50
40
30
σ_{tot} (mb)
pp, $\bar{p}$p
10
100
1000
√s (GeV)

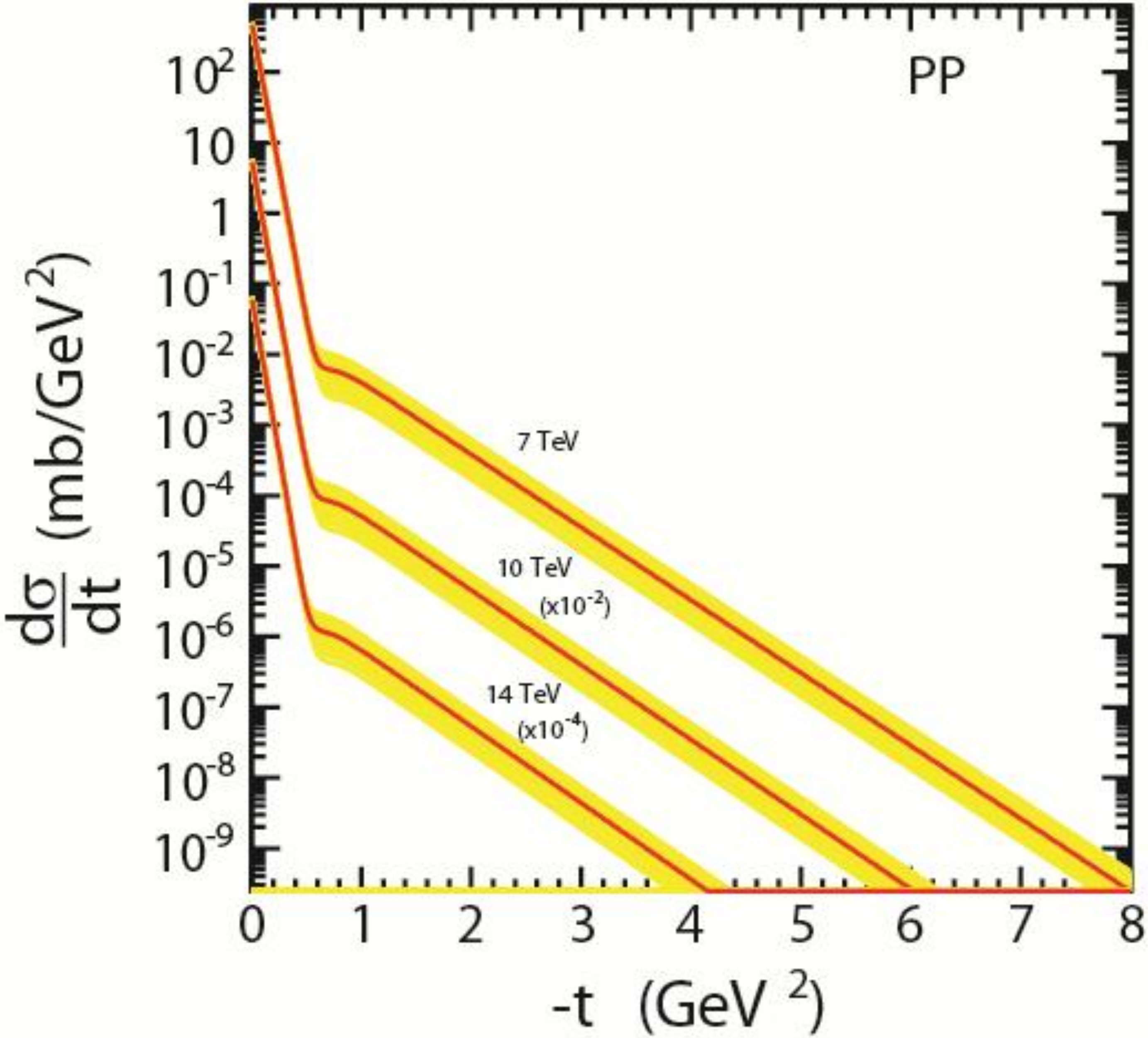


LHC
7TeV 14TeV
PP
PP fit
P$\overline{P}$
P$\overline{P}$ fit
ISR
UA4
UA5
TEVATRON
Cosmic ray data
160
140
120
100
80
60
40
σ_{tot} (mb)
10
10^2
10^3
10^4
$\sqrt{s}$ (GeV)


PP̄
31. GeV
62 GeV (x 10^4)
53. GeV (x 10^-1)
546. GeV (x 10^-6)
630. GeV (x 10^-8)
1800. GeV (x 10^-10)
dσ/dt (mb/GeV^2)
-t (GeV^2)

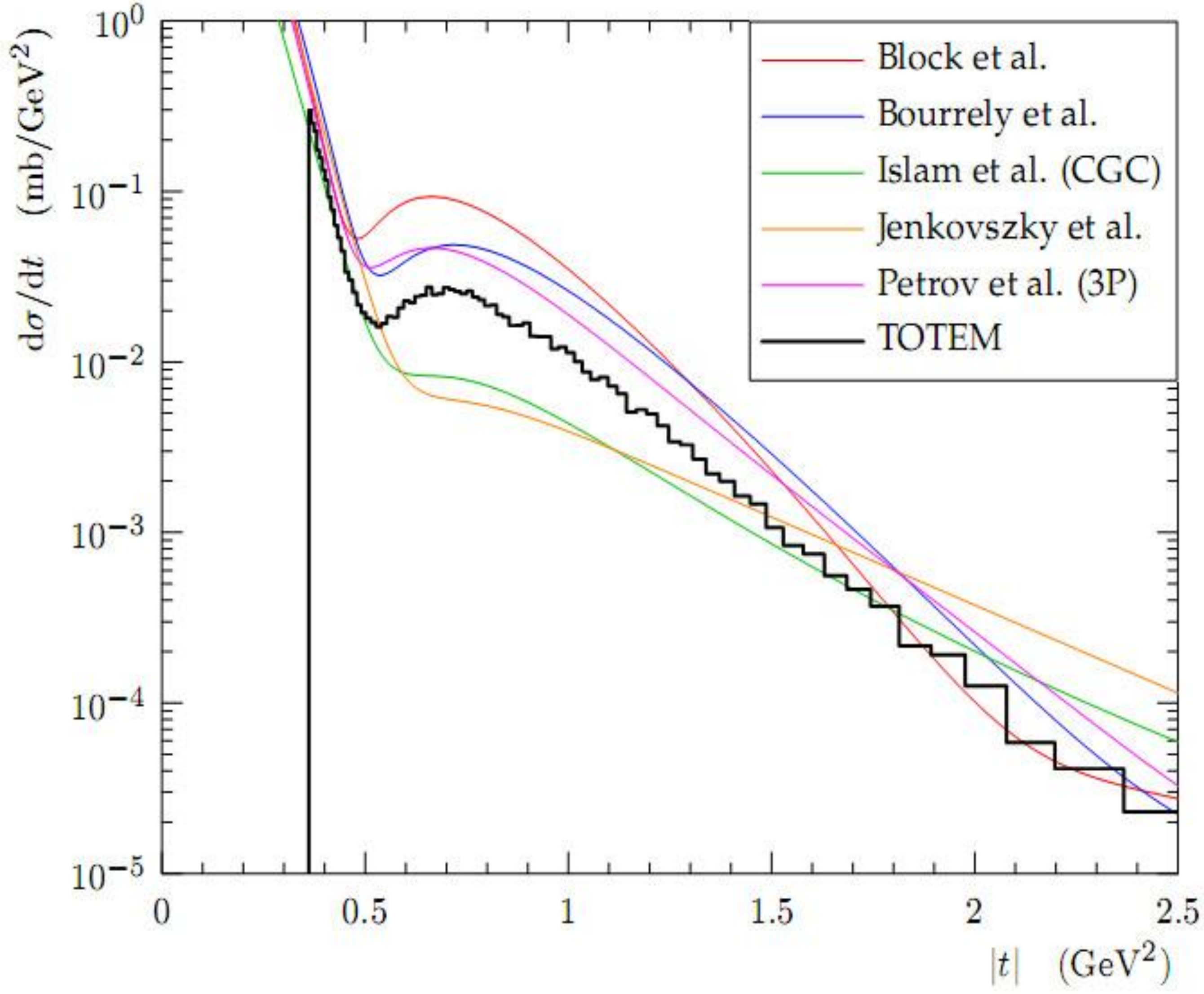


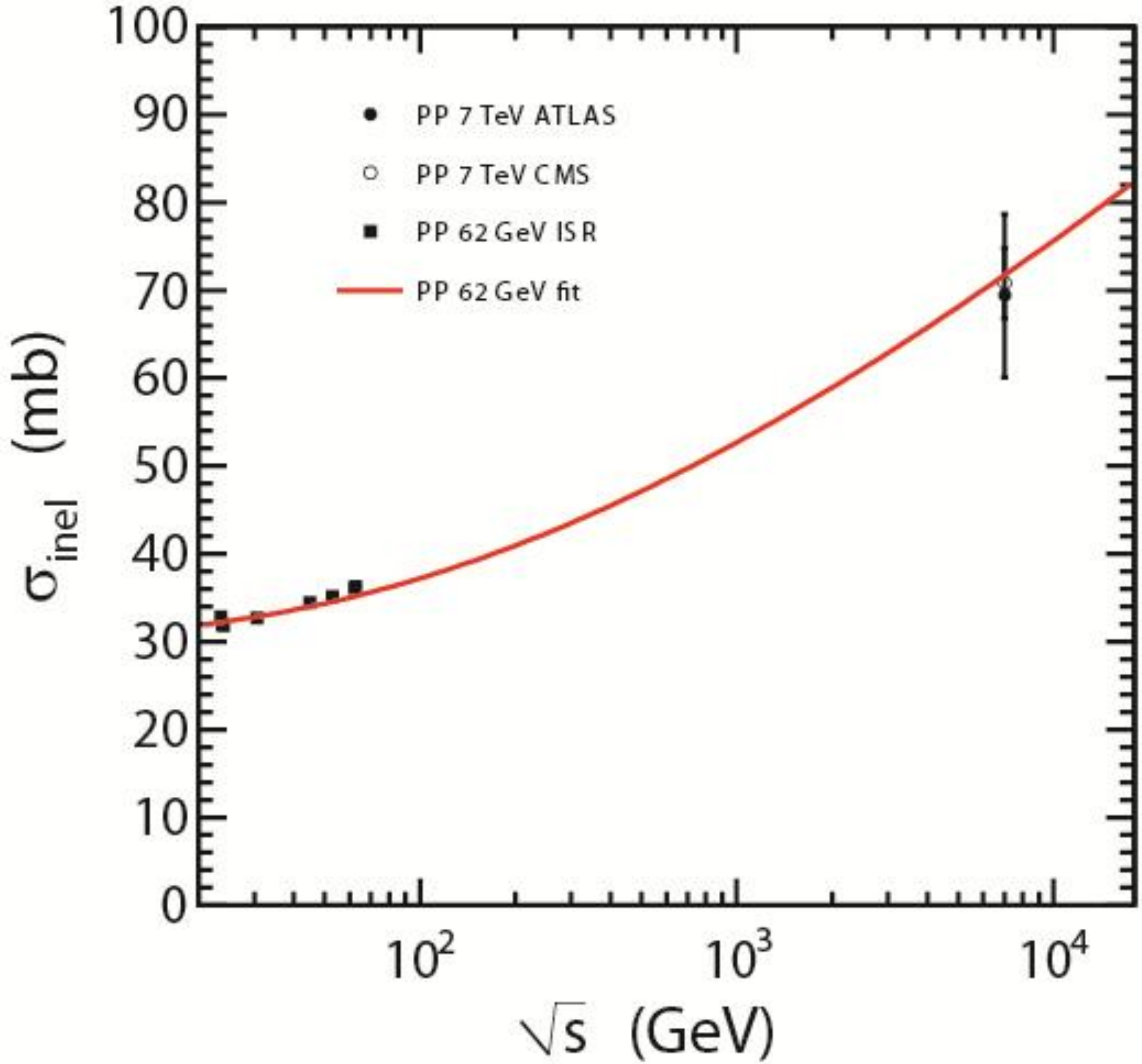
PP
23.5 GeV
30.7 GeV
45. GeV
52.8 GeV
62. GeV
(x 10)
(x 10^{-1})
(x 10^{-3})
(x 10^{-5})
(x 10^{-7})
$\frac{d\sigma}{dt}$ (mb/GeV^2)
-t (GeV^2)



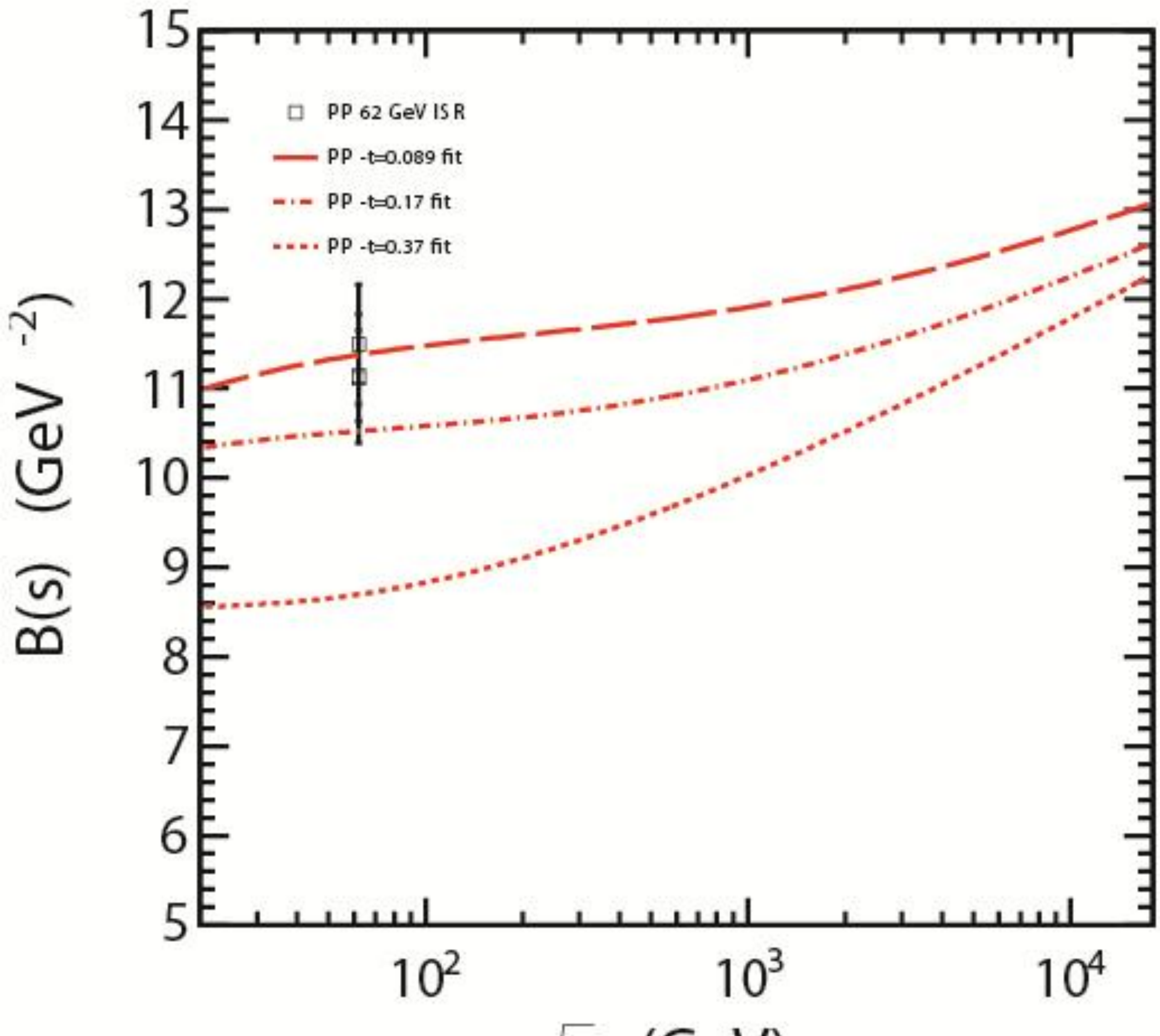
PP
7 TeV
10 TeV
(x10^-2)
14 TeV
(x10^-4)
dσ/dt (mb/GeV^2)
-t (GeV^2)
10^2
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
0
1
2
3
4
5
6
7
8

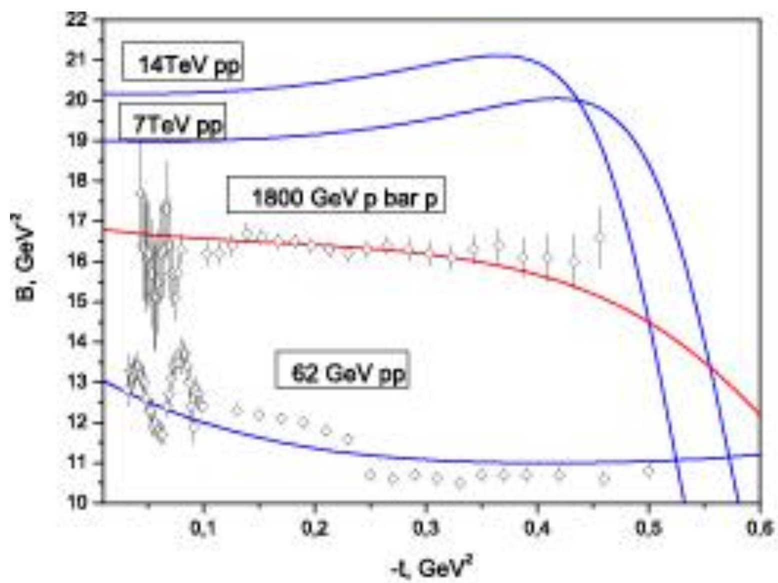
CERN LHC, TOTEM Collab., June 26, 2011:



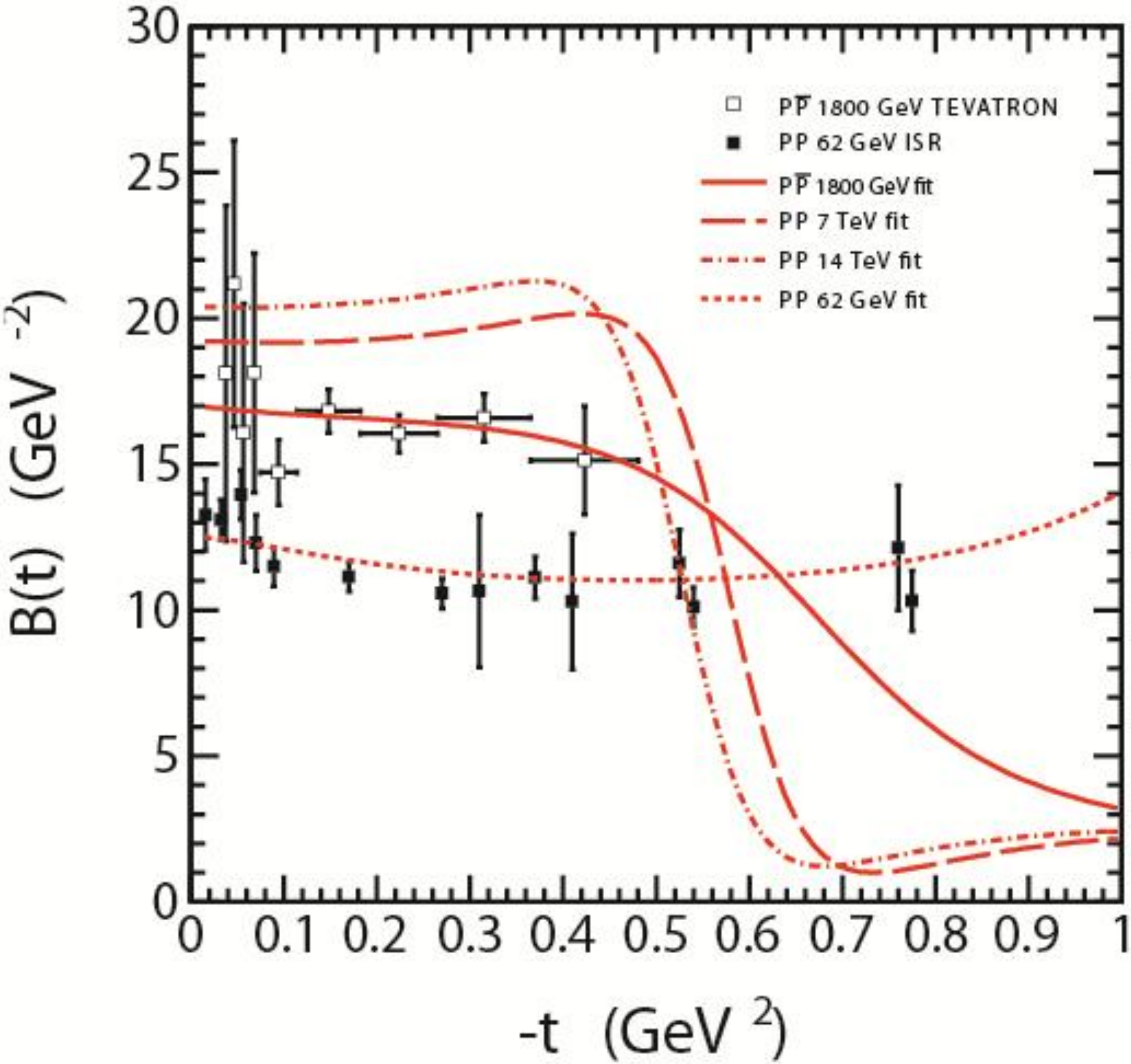


100
90
80
70
60
50
40
30
20
10
0
σ_{inel} (mb)
PP 7 TeV ATLAS
PP 7 TeV CMS
PP 62 GeV ISR
PP 62 GeV fit
10^2
10^3
10^4
$\sqrt{s}$ (GeV)


PP 62 GeV IS R
PP -t=0.089 fit
PP -t=0.17 fit
PP -t=0.37 fit
B(s) (GeV -2)
15
14
13
12
11
10
9
8
7
6
5
10^2
10^3
10^4



14TeV pp
7TeV pp
1800 GeV p bar p
62 GeV pp
B, GeV^-2
-t, GeV^2
22
21
20
19
18
17
16
15
14
13
12
11
10
0,1
0,2
0,3
0,4
0,5
0,6



B(t) (GeV $^{-2}$)
-t (GeV ^{2})
PP̄ 1800 GeV TEVATRON
PP 62 GeV ISR
PP̄ 1800 GeV fit
PP 7 TeV fit
PP 14 TeV fit
PP 62 GeV fit
0
5
10
15
20
25
30
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

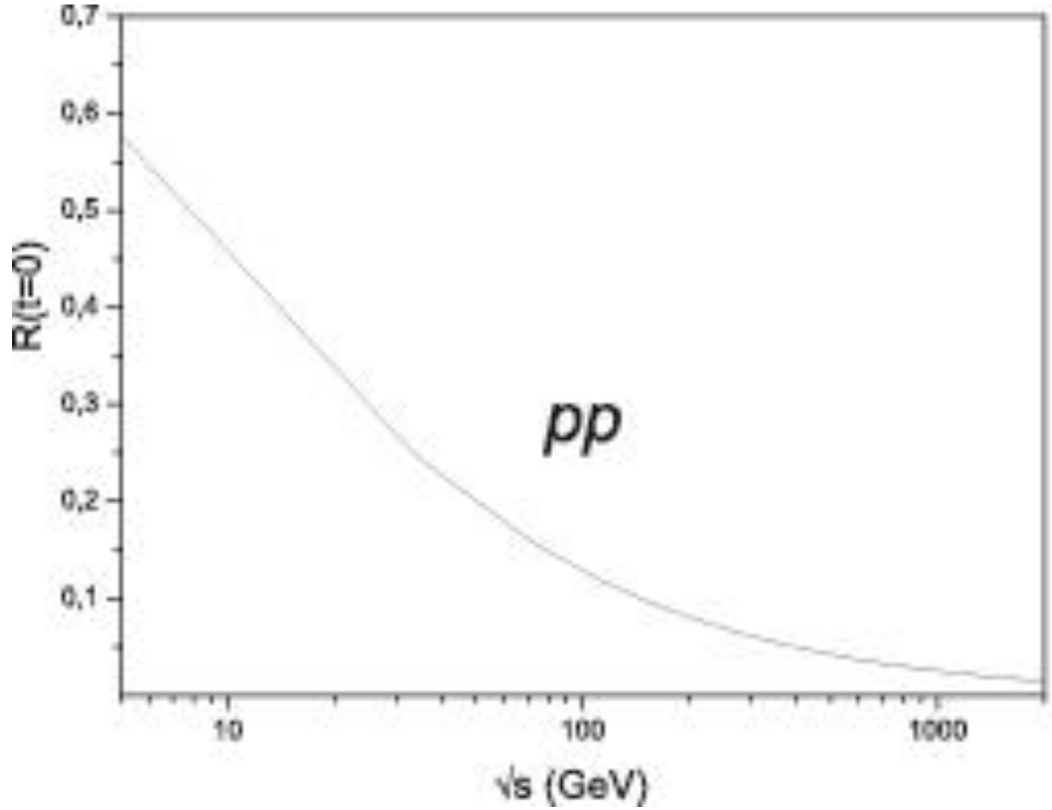
Energy variation of the relative importance of the Pomeron with respect to contributions from the secondary trajectories and the Odderon:

$$R(s,t=0) = \frac{\Im m(A(s,t) - A_P(s,t))}{\Im A(s,t)}, \tag{1}$$

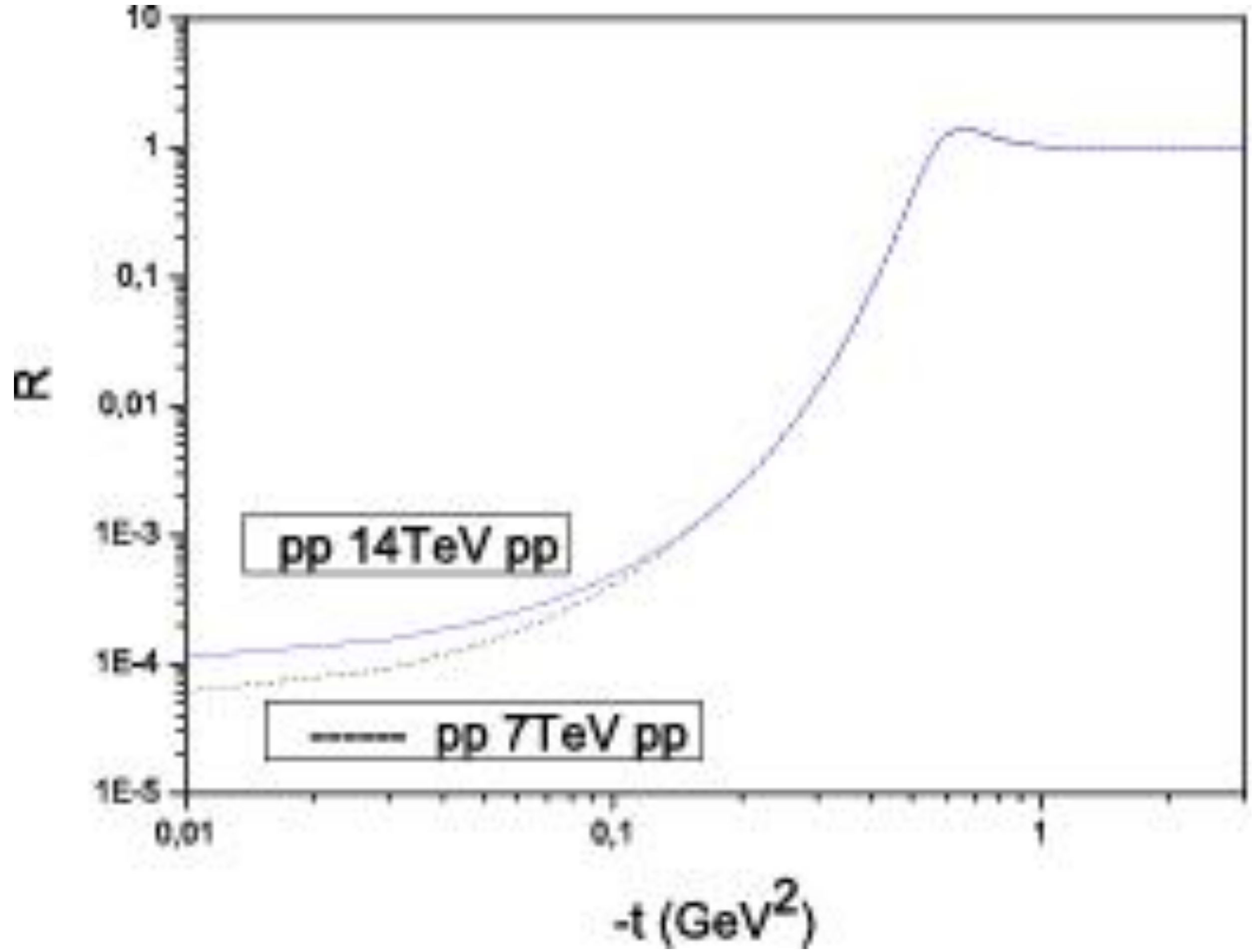
where the total scattering amplitude A includes the Pomeron contribution A_P plus the contribution from the secondary Reggeons and the Odderon.

Starting from the Tevatron energy region, the relative contribution of the non-Pomeron terms to the total cross-section becomes smaller than the experimental uncertainty and hence at higher energies they may be completely neglected, irrespective of the model used.

$$R(s,t) = \frac{|(A(s,t) - A_P(s,t)|^2}{|A(s,t)|^2}. \tag{2}$$



0,7
0,6
0,5
0,4
0,3
0,2
0,1
R(t=0)
pp
10
100
1000
√s (GeV)



10
1
0,1
0,01
1E-3
1E-4
1E-5
R
pp 14TeV pp
pp 7TeV pp
0,01
0,1
1
-t (GeV2)

Review papers:

А.Н. Валл, Л.Л. Енковский, Б.В. Струминский: *Взаимодействие адронов при высоких энергиях*, Физика элементарных частиц и атомного ядра (ЭЧАЯ) **т.19** (1988) стр. 181-223.

Л.Л. Енковский: Дифракция *в адрон-адронных и лептон-адронных процессах при высоких энергиях*, ЭЧАЯ **т.34** (2003) стр. 1196-1255.

R. Fiore, L. Jenkovszky, R. Orava, E. Predazzi, A. Prokudin, O. Selyugin, *Forward Physics at the LHC; Elastic Scattering*, Int. J.Mod.Phys., **A24**: 2551-2559 (2009).

Спасибо !