Ginzburg Centennial

ELASTIC & INELASTIC DIFFRACTION AT THE LHC

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Based on collaborative papers with R. Fiore, O. Kuprash, R.Orava, A. Salii, R. Schicker
and current research incorporating also V. Libov (Kiev-DESY), M. Mieskolainen (Helsinki), A. Potinenko (Odessa)

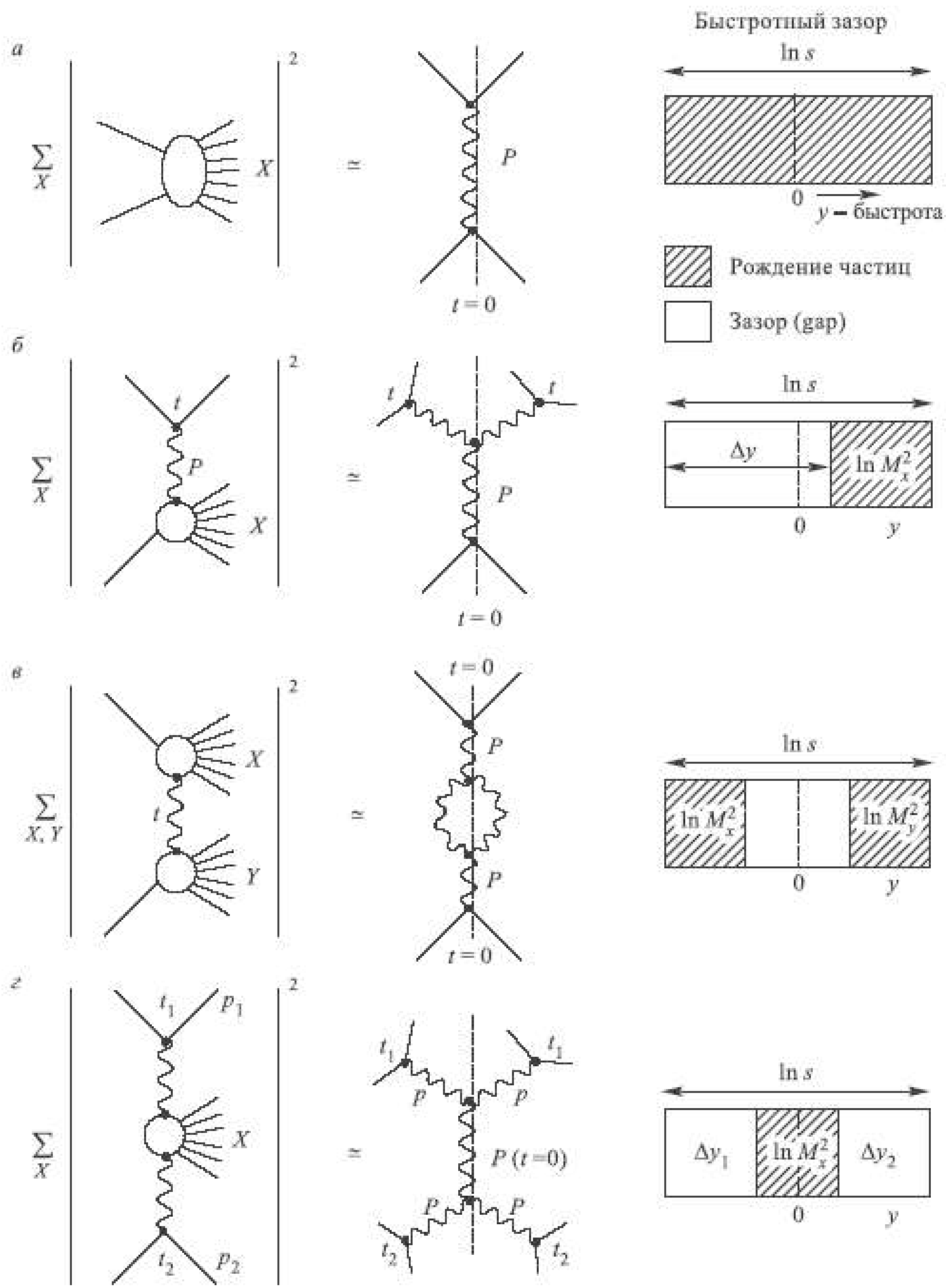
Abstract:

Salient feature of elastic and inelastic diffraction in proton-proton collisions with emphases on the recent LHC experimental data and future expectations are highlighted. These are:

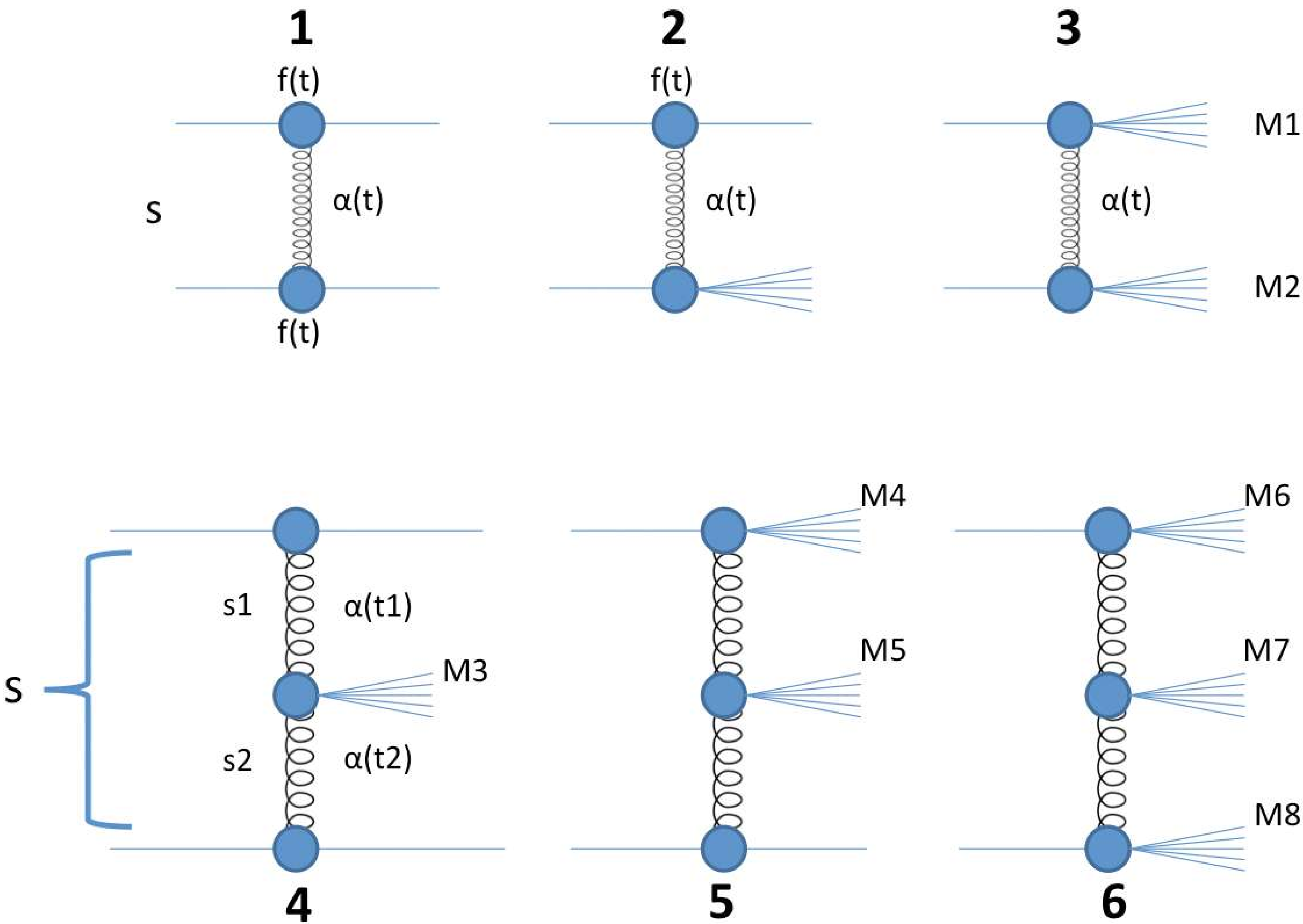
1. Rise with energy, unitarity, Dino's "flux renormalization" prescription;
2. Physics behind the non-exponential behavior of the elastic cone at low-$|t|$, observed both at the ISR and the LHC; will it be seen in diffraction dissociation? (Follow elastic!)
3. The dip-bump structure in elastic scattering and its possible appearance in diffraction dissociation (Follow elastic?)
4. Pomeron dominance at the LHC, Regge factorization and its breakdown;
5. Importance and open problems in the description of low missing mass, resonance structure in single- (SD) and double (DD) diffraction dissociation; misuse of the triple Regge limit; duality in the missing mass: finite mass sum rules (FMSR);
6. From differential to integrated cross sections: incompatibility caused by different integration limits used at the LHC;
7. Central exclusive production of glueballs and other meson resonances

Elastic and total pp and p-\bar p scattering, diffraction and the Pomeron; nucleon's "shape", the "black disc limit"

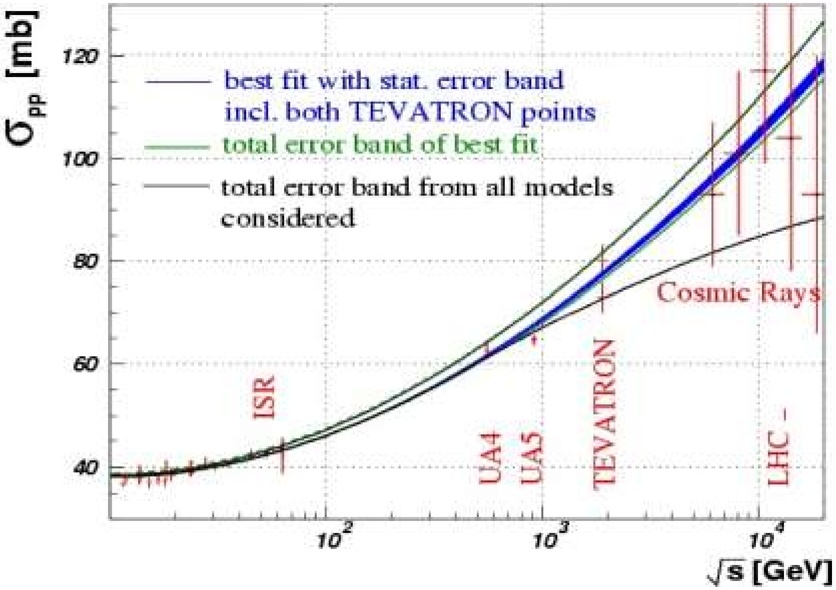
R. Fiore, L. Jenkovszky, R. Orava, E. Predazzi,
A. Prokudin, O. Selyugin, *Forward Physics at the LHC; Elastic Scattering*, Int. J.Mod.Phys., **A24**: 2551-2559 (2009).



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


1
2
3
f(t)
f(t)
α(t)
α(t)
α(t)
s
f(t)
M1
M2
M4
M6
s1
α(t1)
M5
M7
M3
S
s2
α(t2)
M8
4
5
6

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

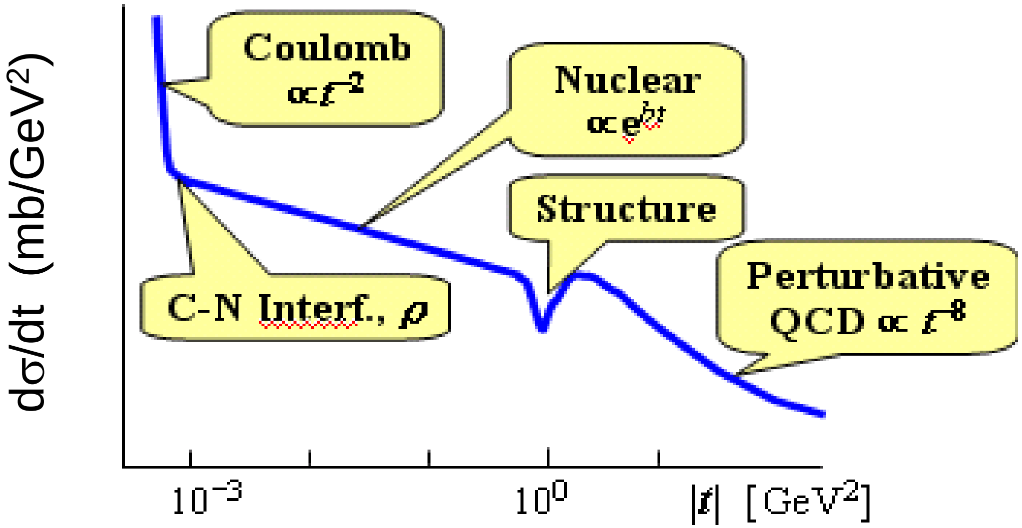
(σ_{tot} + $dN/dt|_{t=0}$) → ($\Delta L/L$ > ~ 2 $\Delta\sigma_{tot}/\sigma_{tot}$)

(L + $dN/dt|_{t=0}$) → ($\Delta\sigma_{tot}/\sigma_{tot}$ > ~ ½ $\Delta L/L$)

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

Elastic Scattering

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



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

θ = beam scattering angle

p = beam momentum

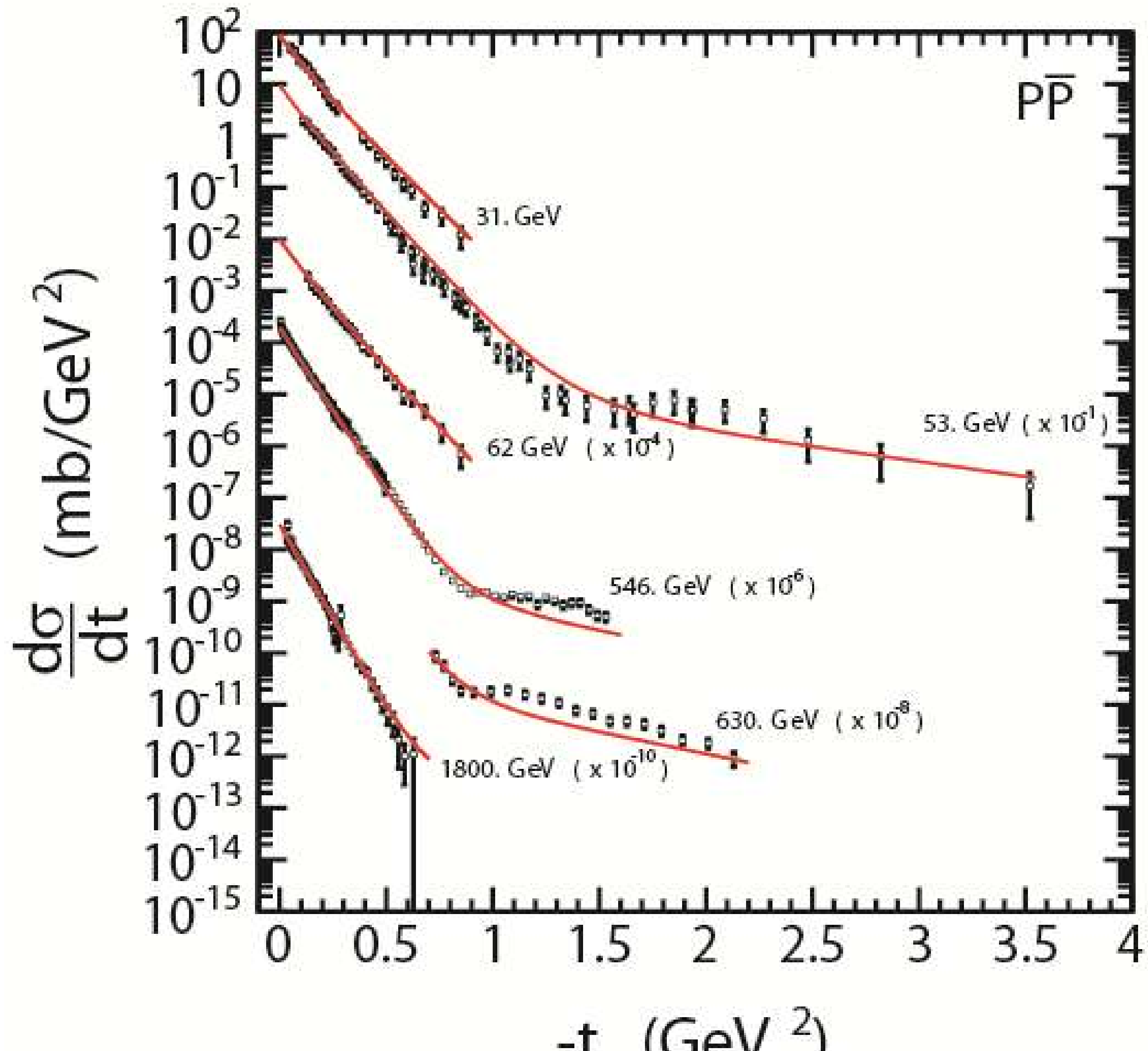
$$\rho = \left.\frac{\mathrm{Re}\left(f_{el}(t)\right)}{\mathrm{Im}\left(f_{el}(t)\right)}\right|_{t\to 0}$$

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

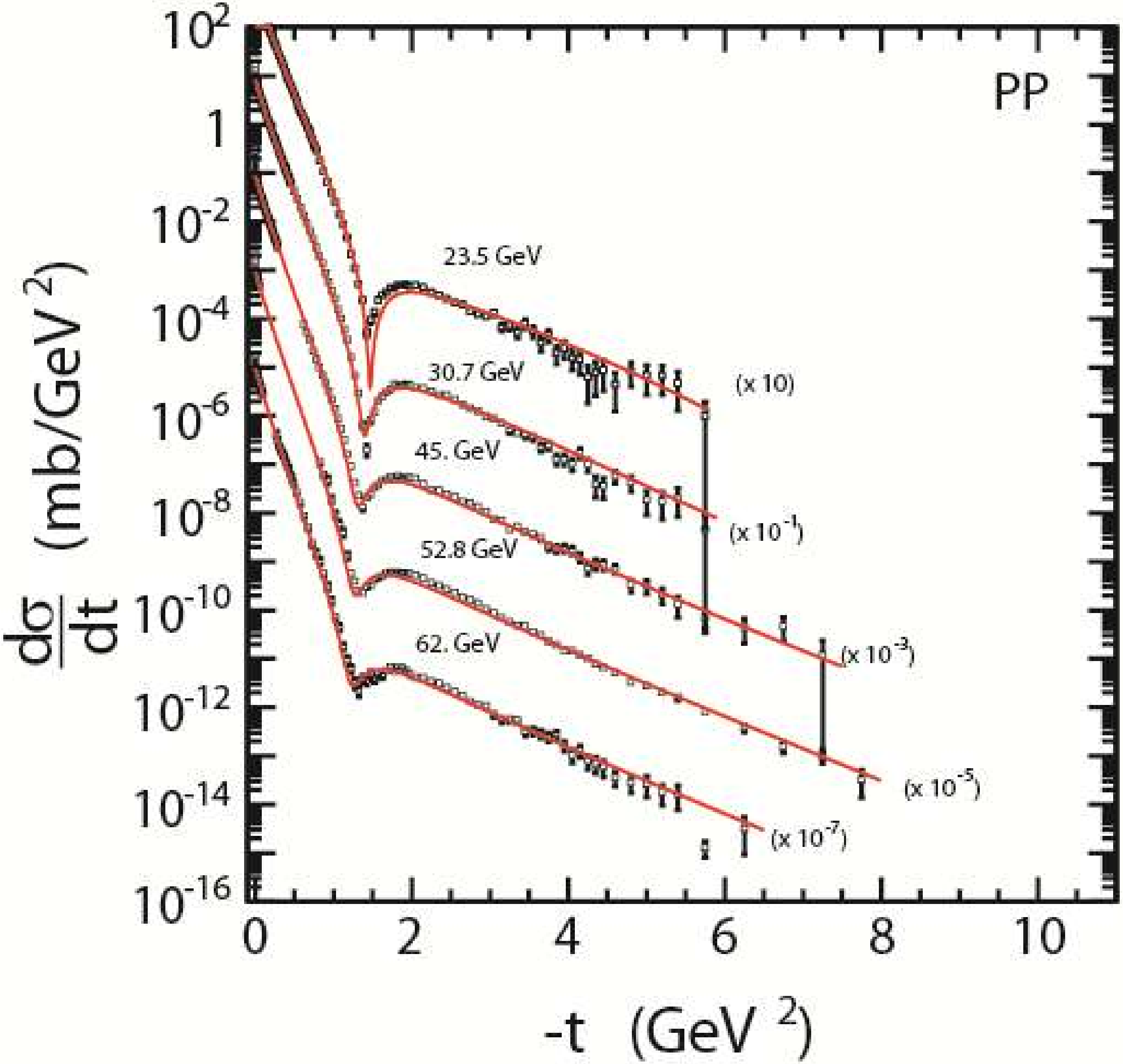
L, σ_{tot}, b, and ρ from FIT in CNI region (UA4)

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

(θ_{min}~120 μrad @ SPS)



PP̄
31. GeV
53. GeV (x 10⁻¹)
62 GeV (x 10⁴)
546. GeV (x 10⁻⁶)
630. GeV (x 10⁻⁸)
1800. GeV (x 10⁻¹⁰)
dσ/dt (mb/GeV 2)
-t (GeV 2)

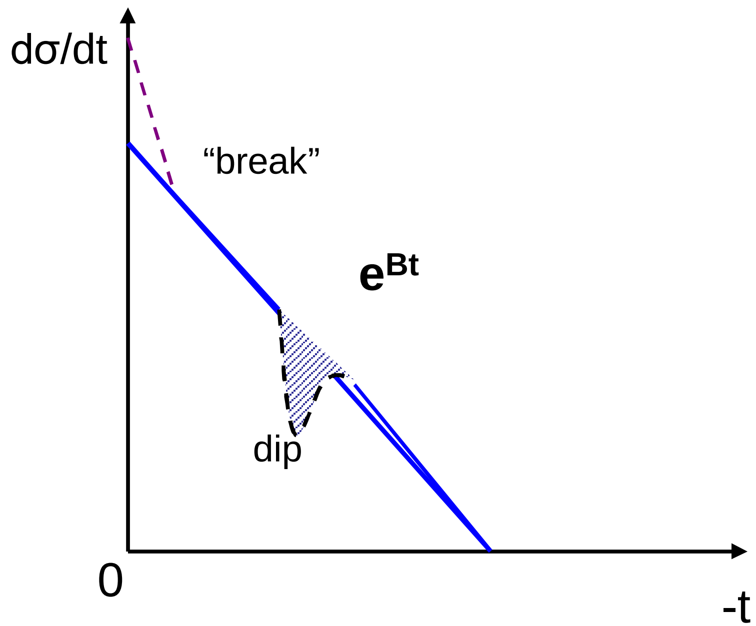

PP
23.5 GeV
30.7 GeV
45. GeV
52.8 GeV
62. GeV
(x 10)
(x 10^-1)
(x 10^-3)
(x 10^-5)
(x 10^-7)
dσ/dt (mb/GeV^2)
-t (GeV^2)

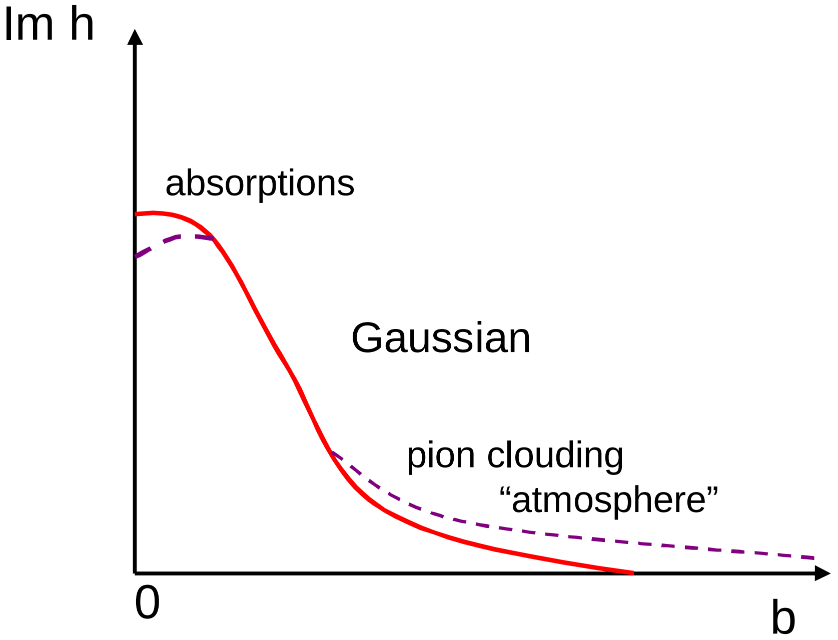
Geometrical scaling (GS), saturation and unitarity

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

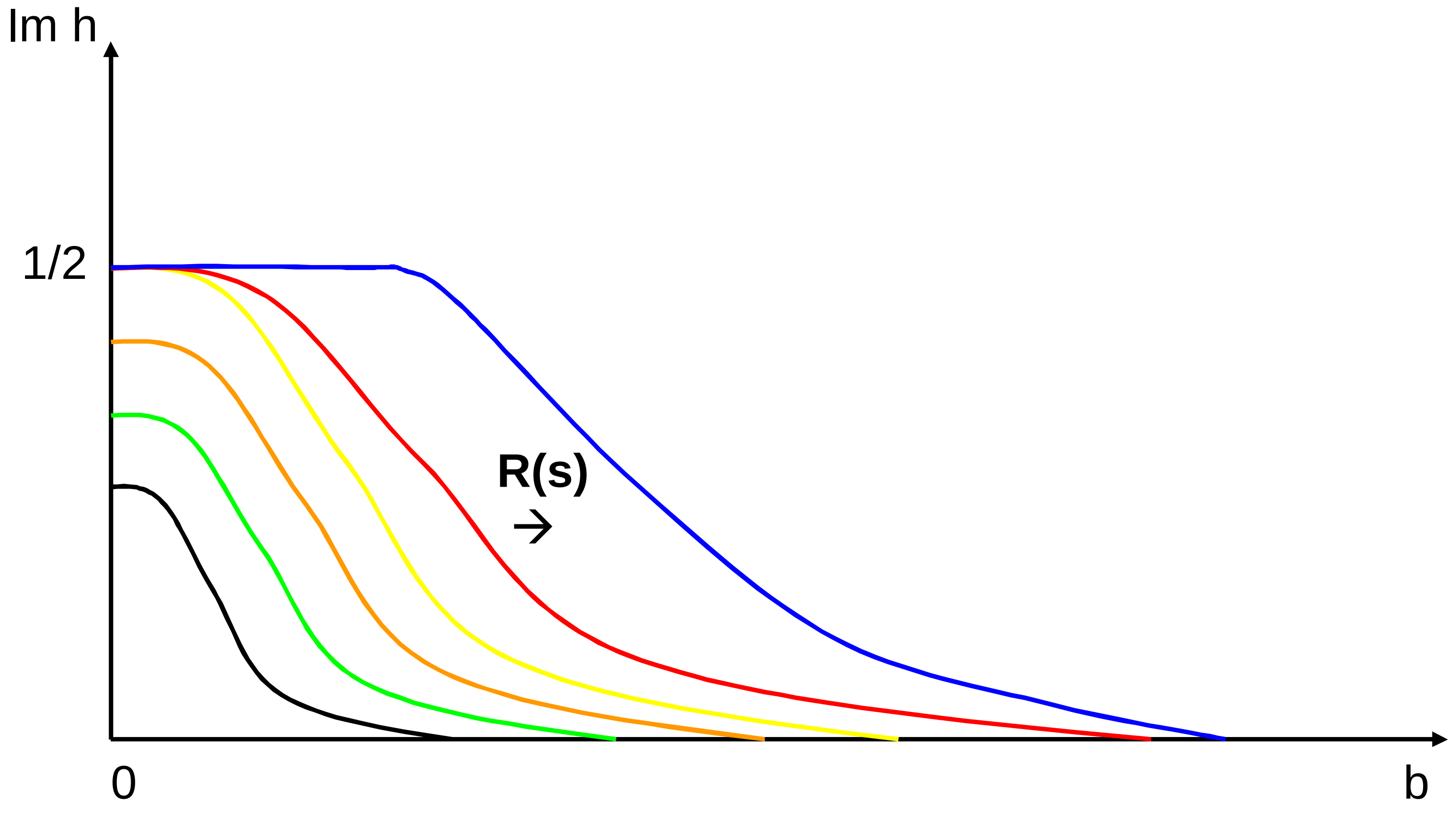
$t \leftarrow\rightarrow b$ **transformation:** $h(s,b)=\int_0^\infty d\sqrt{-t}\sqrt{-t}A(s,t)$

and dictionary:





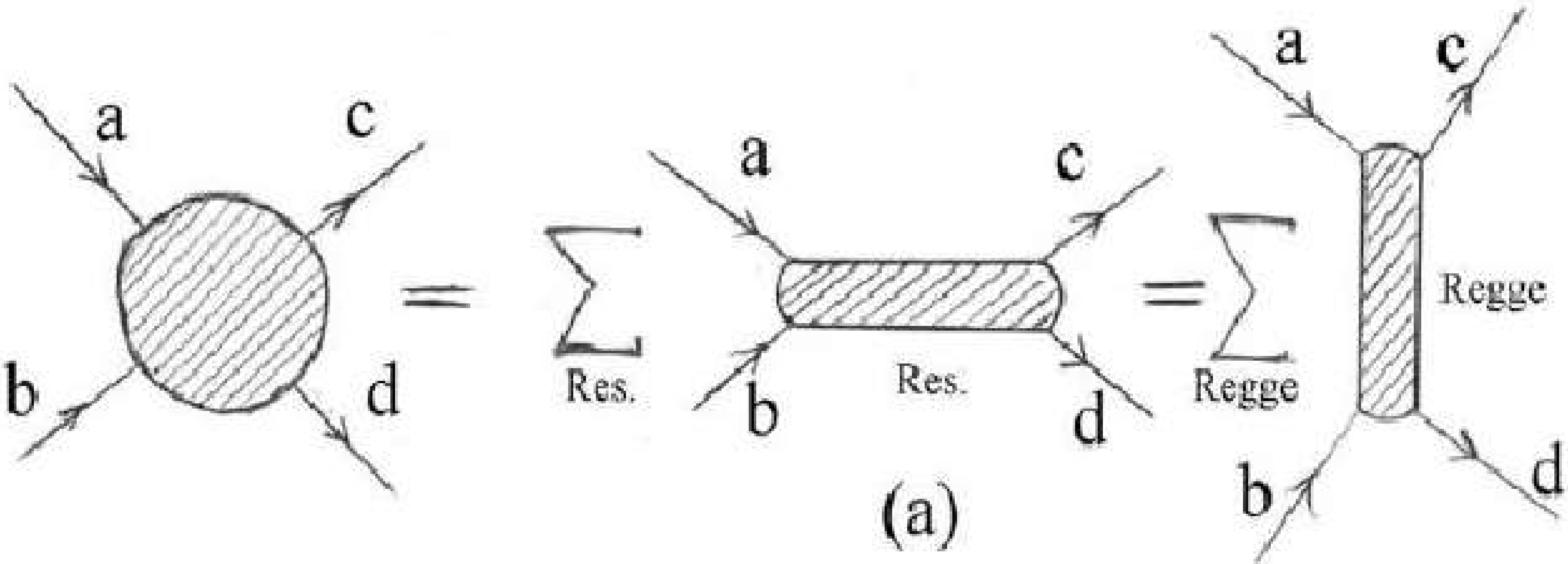
П.Дегрола, Л.Л. енковский, Б.В. Струминский, ЯФ



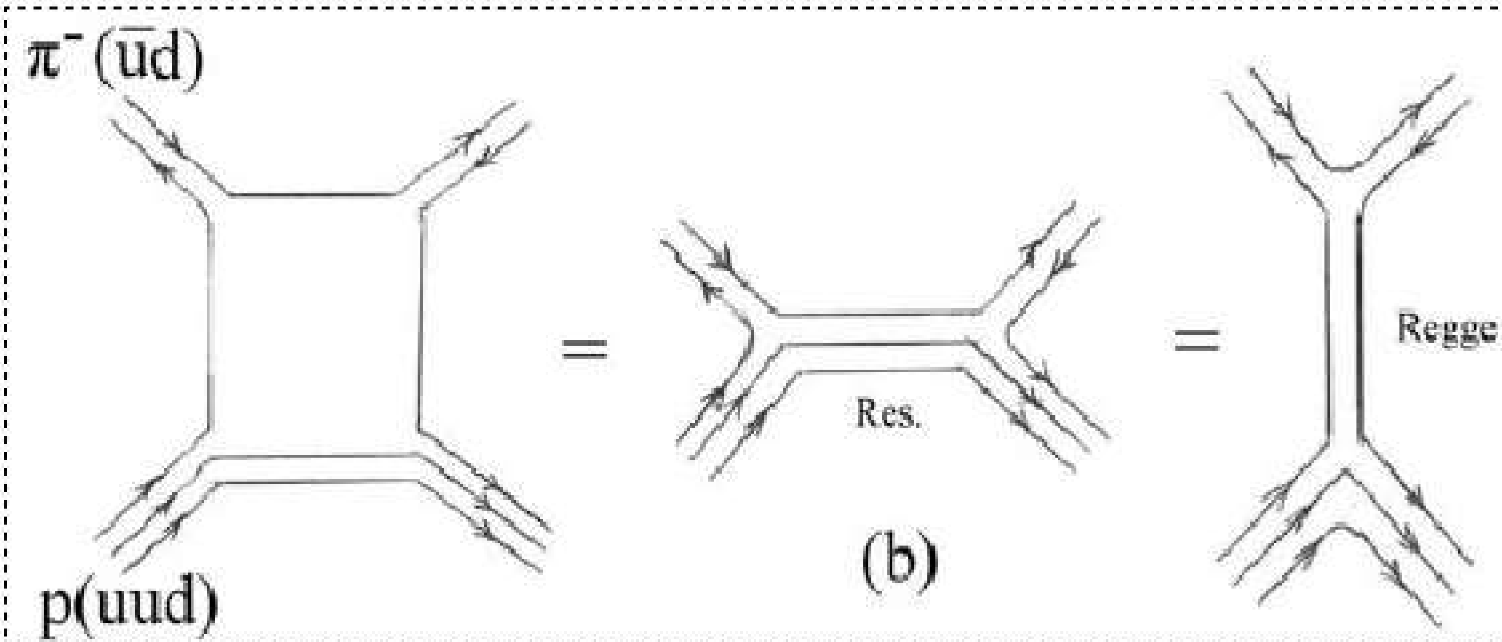
Does GS imply saturation? Not necessarily!

$ImH(s,b) = |h(s,b)|^2 + G_{in}(s,b)$, (h is associaed with the "opacity), Here from: $0 \leq |h(s,b)|^2 \leq \Im h(s,b)) \leq 1$. 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)): $h(s,b) = \Im u(s,b)/[1 - iu(s,b))]$,



(a)



$\pi^-(\bar{u}d)$
p(uud)
=
Res.
=
Regge
(b)

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

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

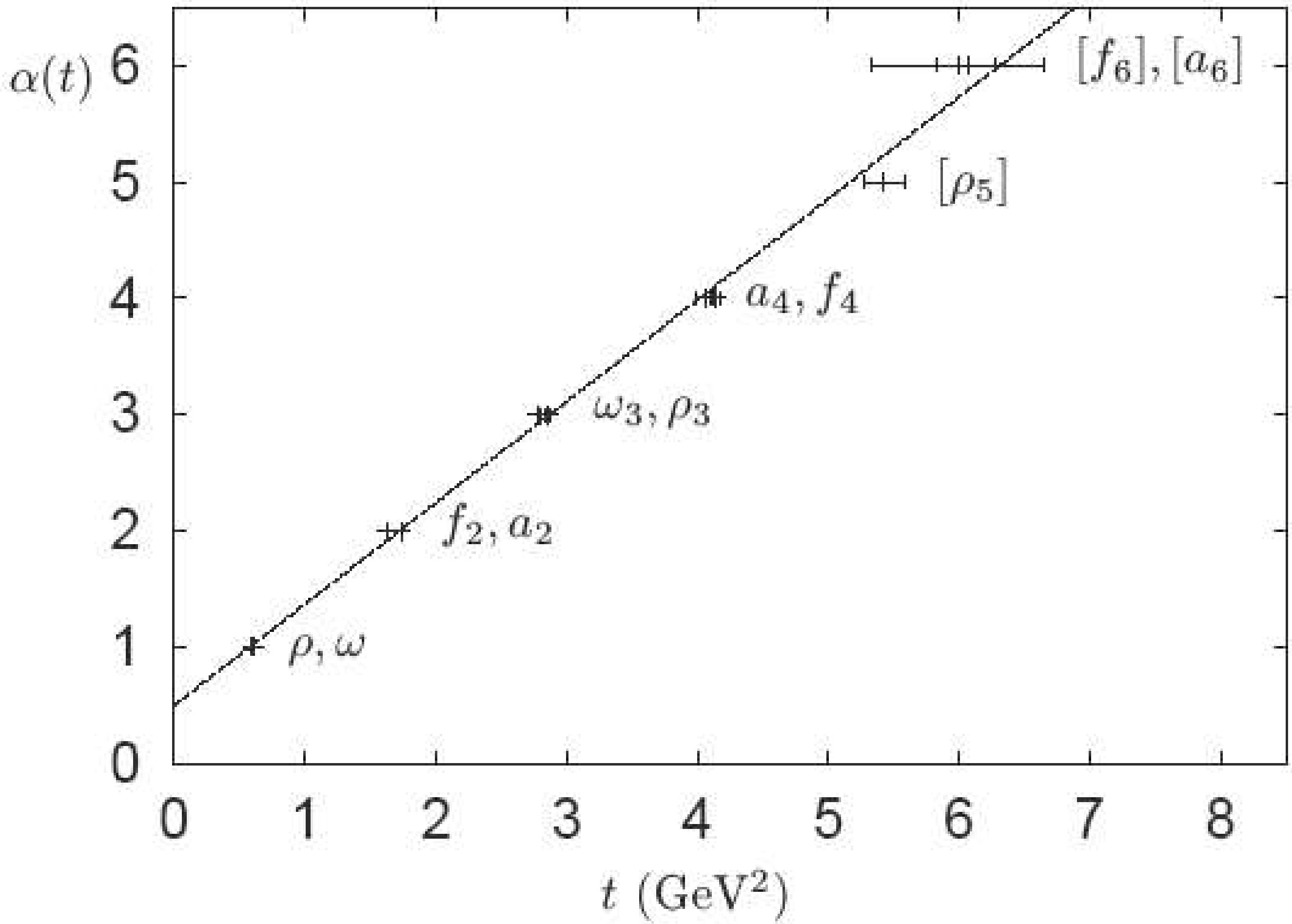
$$A_{pp}^{p\bar{p}}(s,t) = P(s,t) \pm O(s,t) + f(s,t) \pm \omega(s,t) \rightarrow_{LHC} \approx P(s,t) \pm O(s,t),$$

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

α(0)\C	+	-
1	**P**	**O**
1/2	**f**	**ω**

Linear particle trajectories

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



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

TOTEM 2011-01
22 June 2011

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

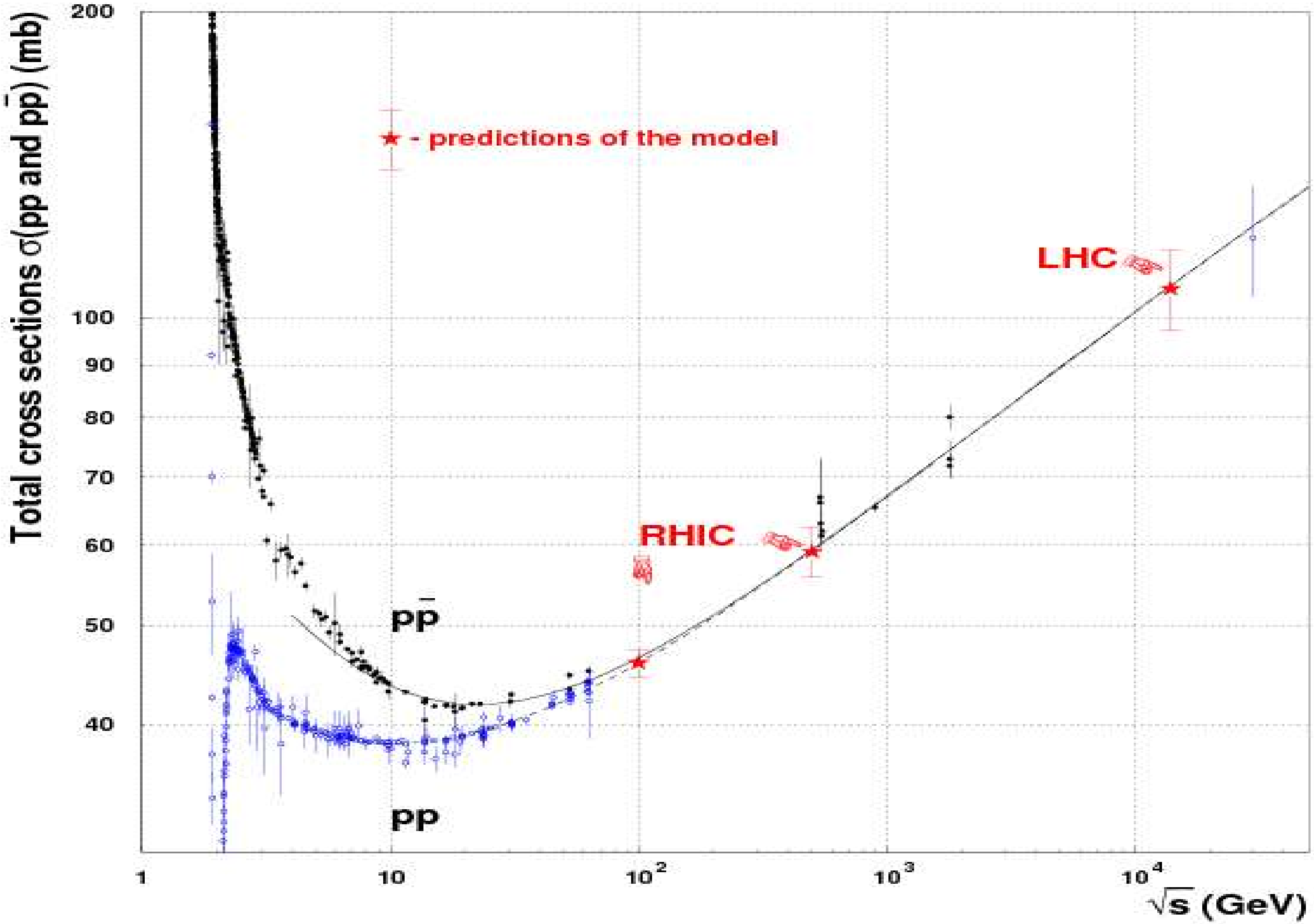
Elastic pp Scattering at the LHC at $\sqrt{s} = 7$ TeV.

The TOTEM Collaboration

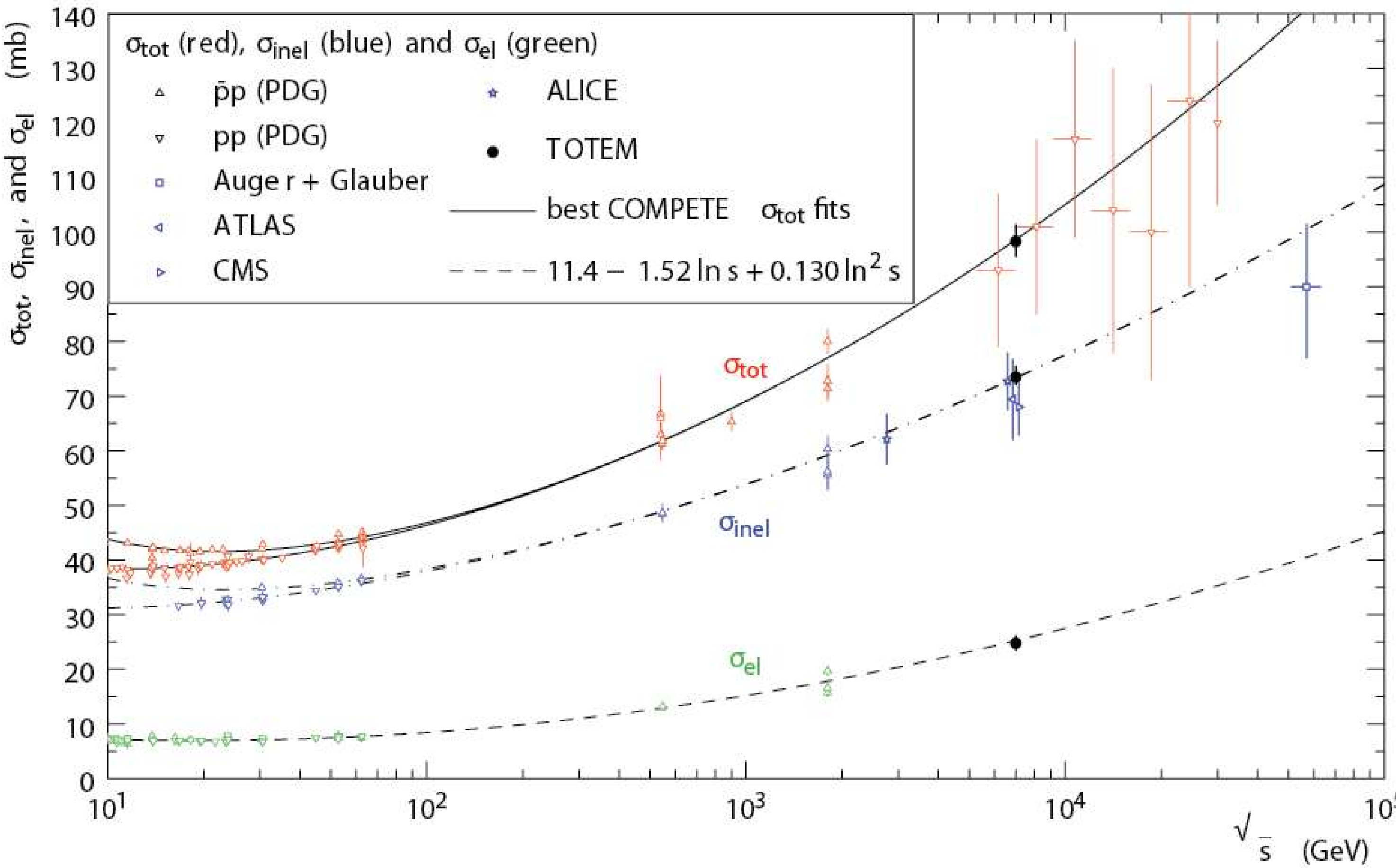
G. Antchev[*], P. Aspell[8], I. Atanassov[8,*], V. Avati[8], J. Baechler[8], V. Berardi[5b,5a], M. Berretti[7b], M. Bozzo[6b,6a], E. Brücken[3a,3b], A. Buzzo[6a], F. Cafagna[5a], M. Calicchio[5b,5a], M. G. Catanesi[5a], C. Covault[9], M. Csanád[4†], T. Csörgő[4], M. Deile[8], E. Dimovasili[8], M. Doubek[1b], 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].

P. Aspell et. al. (TOTEM Collaboaration), *Proton-proton elastic scattering at the LHC energy 7 TeV*, Europhys. Lett. **95** (2011) 41001; arXiv:1110.1385.

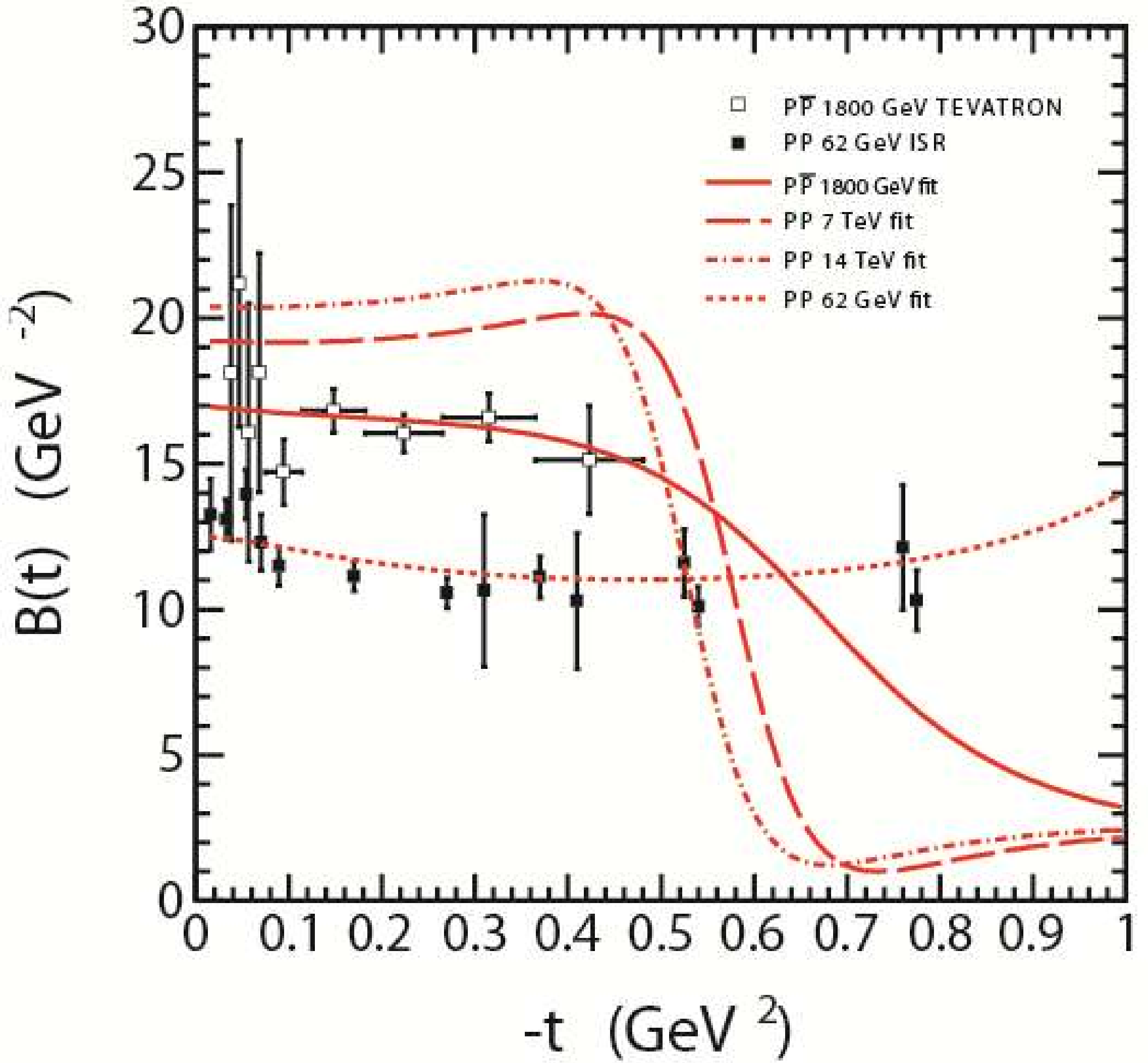
G. Antchev et al. (TOTEM Collab.*), First measurement of the total proton-proton cross section at the LHC energy of 7 TeV*, EPL; arXiv:1110.1395.



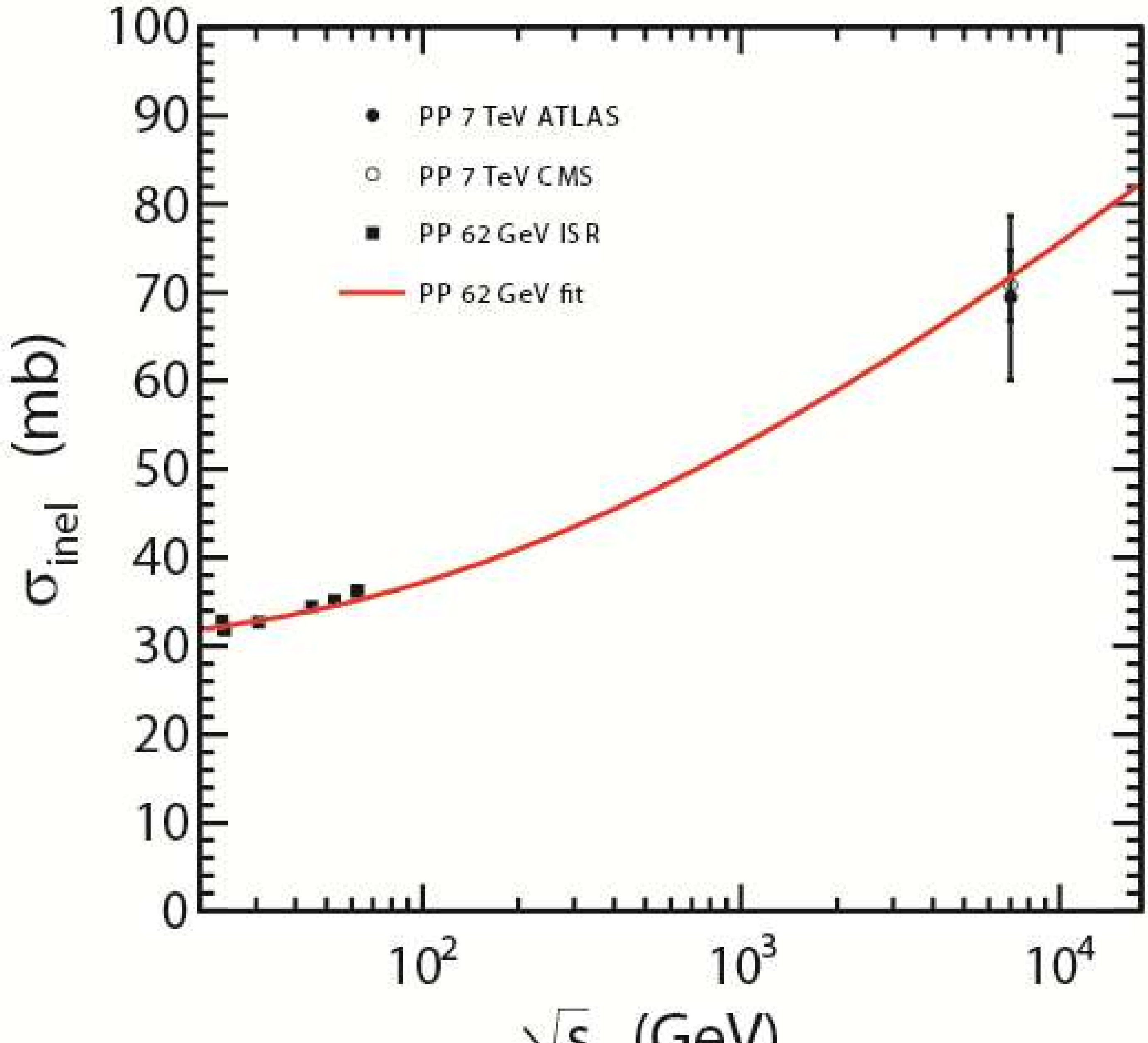
Total cross sections σ(pp and pp̄) (mb)
200
100
90
80
70
60
50
40
★ - predictions of the model
LHC
RHIC
pp̄
pp
1
10
10^2
10^3
10^4
√s (GeV)



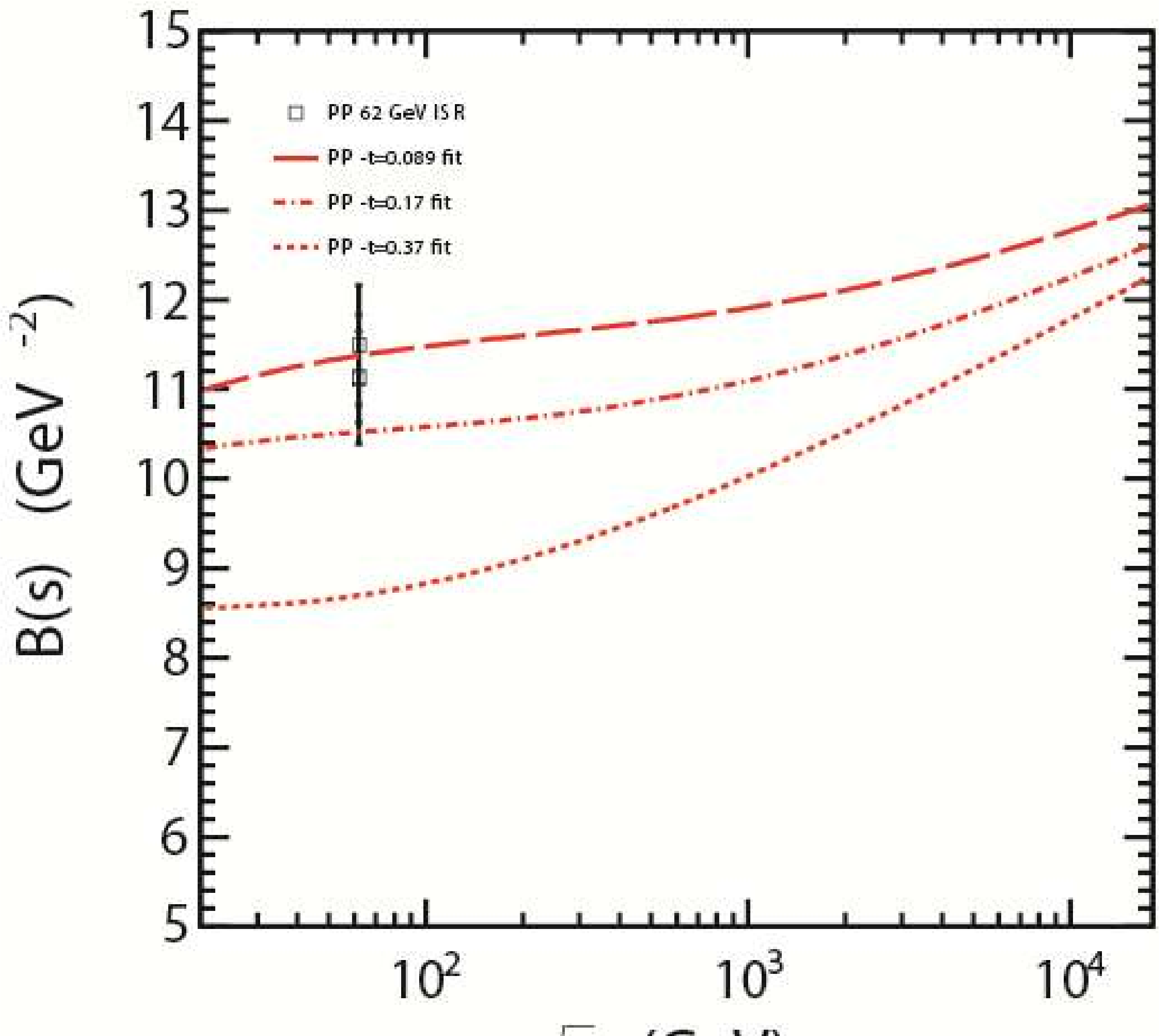
σtot (red), σinel (blue) and σel (green)
p̄p (PDG)
pp (PDG)
Auger r + Glauber
ATLAS
CMS
ALICE
TOTEM
best COMPETE σtot fits
11.4 − 1.52 ln s + 0.130 ln² s
σtot
σinel
σel
σtot, σinel, and σel (mb)
√s (GeV)



PP̄ 1800 GeV TEVATRON
PP 62 GeV ISR
PP̄ 1800 GeV fit
PP 7 TeV fit
PP 14 TeV fit
PP 62 GeV fit
B(t) (GeV $^{-2}$)
-t (GeV ^{2})
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



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



PP 62 GeV ISR
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

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

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

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.

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

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

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

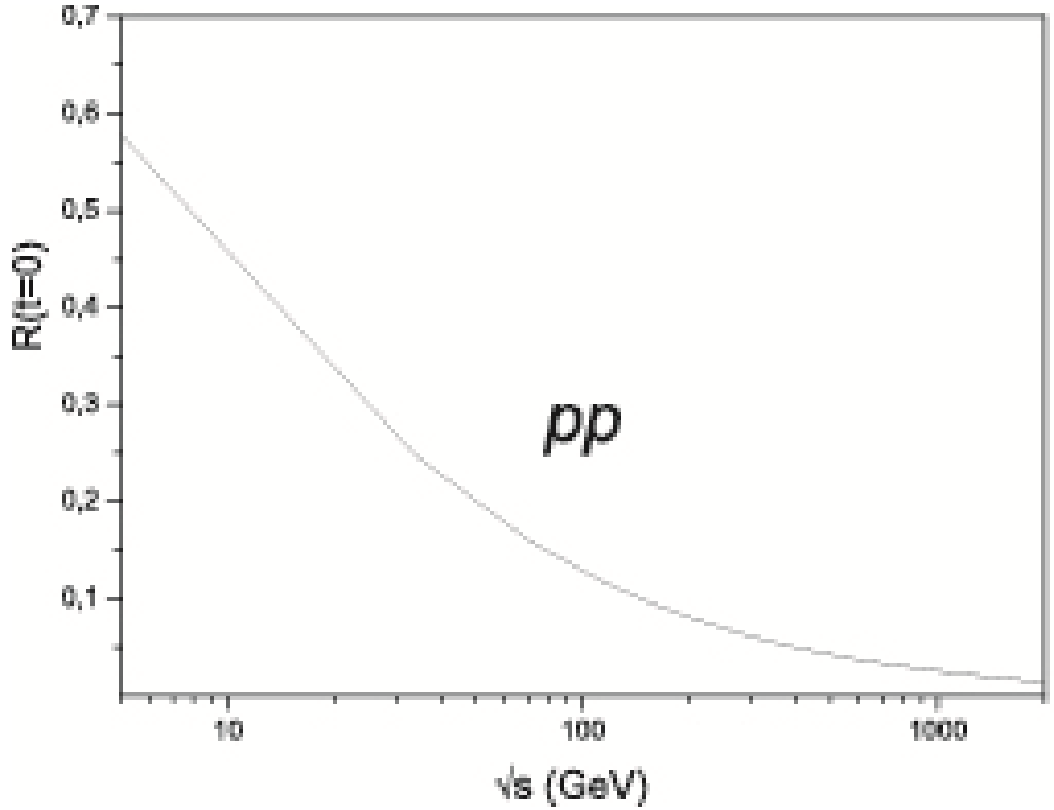
Since the first term in squared brackets determines the shape of the cone, one fixes

$$G'(\alpha_P) = -a_P e^{b_P[\alpha_P - 1]}, \tag{2}$$

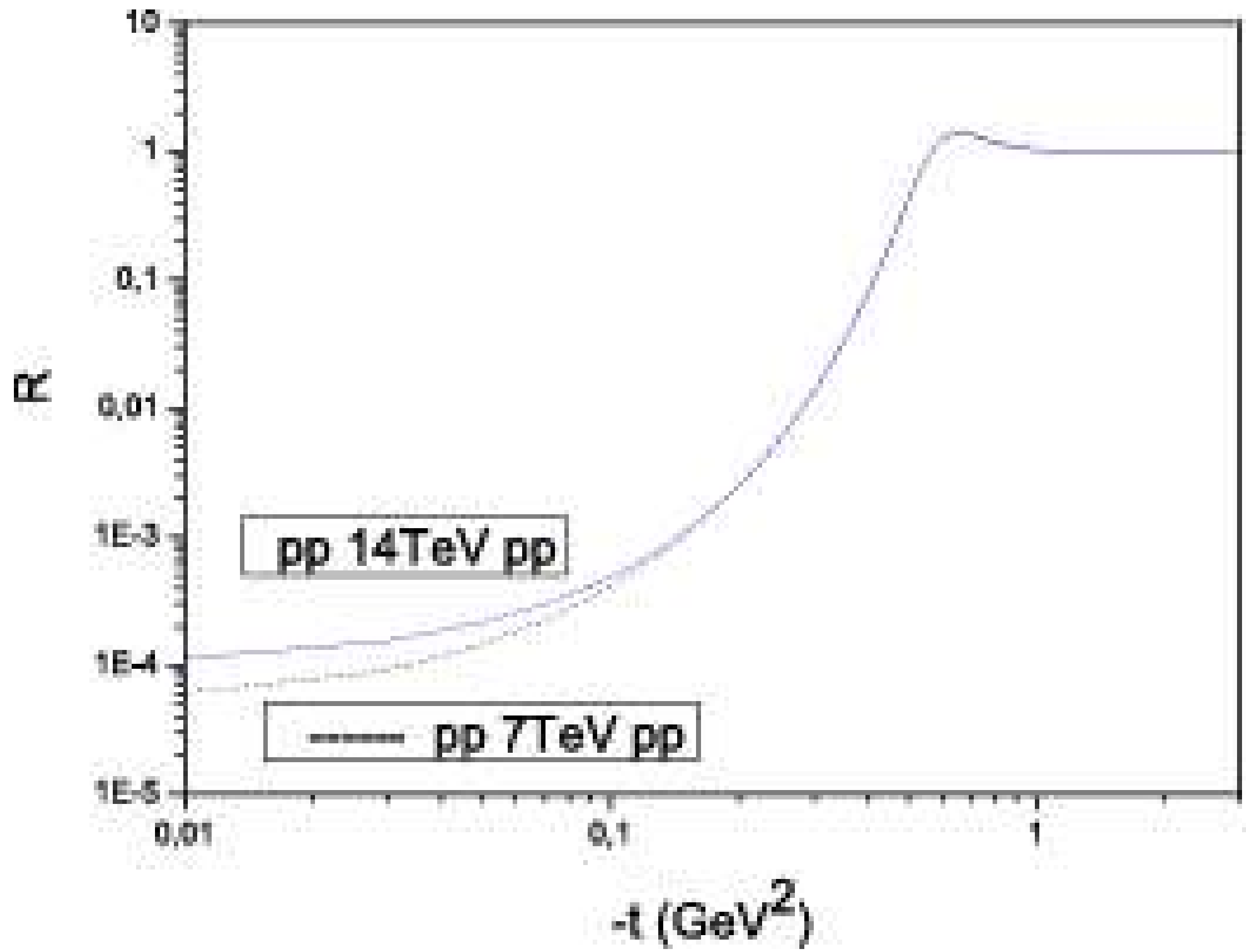
where $G(\alpha_P)$ is recovered by integration, and, as a consequence, the Pomeron amplitude can be rewritten in the following "geometrical" form

$$A_P(s,t) = i\frac{a_P\ s}{b_P\ s_0}\big[r_1^2(s)e^{r\ \ (s)[\alpha_P-1]} - \varepsilon_P r_2^2(s)e^{r\ \ (s)[\alpha_P-1]}\big], \tag{3}$$

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



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
0,01
0,1
1
-t (GeV^2)
pp 14TeV pp
pp 7TeV pp

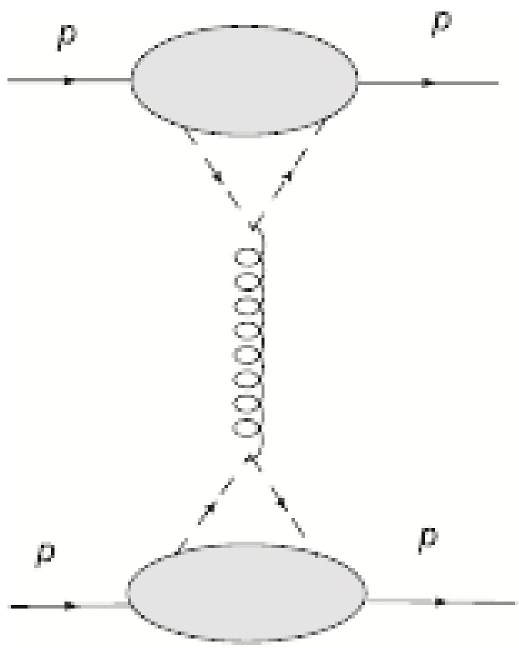
Low-mass diffraction dissociation at the LHC

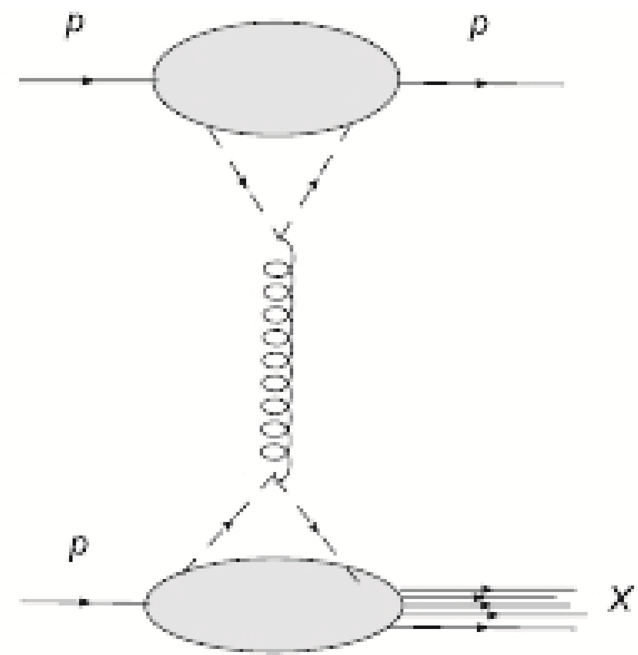
L. Jenkovszky, O. Kuprash, J. Lamsa, V. Magas, and R,. Orava:
Dual-Regge approach to high-energy, low-mass DD at the LHC,
Phys. Rev. D83(2011)0566014; hep-ph/1-11.0664.
L. Jenkovszky, O. Kuprash, J. Lamsa and R. Orava: hep-ph/11063299,
Mod. Phys. Letters A. **26**(2011) 1-9, August 2011.

Experimentally, diffraction dissociation in proton-proton scattering was intensively studied in the '70-ies at the Fermilab and the CERN ISR. In particular, double differential cross section $\frac{d\sigma}{dtdM_X^2}$ was measured in the region $0.024 < -t < 0.234$ $(\mathrm{GeV/c})^2$, $0 < M^2 < 0.12s$, and $(105 < s < 752)$ GeV^2, and a single peak in M_X^2 was identified.

Low-mass single diffraction dissociation (SDD) of protons, $pp \to pX$ as well as their double diffraction dissociation (DDD) are among the priorities at the LHC. For the CMS Collaboration, the SDD mass coverage is presently limited to some 10 GeV. With the Zero Degree Calorimeter (ZDS), this could be reduced to smaller masses, in case the SDD system produces very forward neutrals, i.e. like a N^* decaying into a fast leading neutron. Together with the T2 detectors of TOTEM, SDD masses down to 4 GeV could be covered.

While high-mass diffraction dissociation receives much attention, mainly due to its relatively easy theoretical treatment within the triple Reggeon formalism and successful reproduction of the data, this is not the case for low-masses, which are beyond the range of perturbative quantum chromodynamics (QCD). The forthcoming measurements at the LHC urge a relevant theoretical understanding and treatment of low mass DD, which essentially has both spectroscopic and dynamic aspects. The low-mass, M_X spectrum is rich of nucleon resonances. Their discrimination is a difficult experimental task, and theoretical predictions of the appearance of the resonances depending on s, t and M is also very difficult since, as mentioned, perturbative QCD, or asymptotic Regge pole formula are of no use here. Below we concentrate on single diffraction dissociation; generalization to DDD is straightforward.


p
p
p
p


p
p
p
X

The pp scattering amplitude

$$A(s,t)_P = \\ -\beta^2[f^u(t)+f^d(t)]^2\left(\frac{s}{s_0}\right)^{\alpha_P(t)-1}\frac{1+e^{-i\pi\alpha_P(t)}}{\sin\pi\alpha_P(t)}, \tag{1}$$

where $f^u(t)$ and $f^d(t)$ are the amplitudes for the emission of u and d valence quarks by the nucleon, β is the quark-Pomeron coupling, to be determined below; $\alpha_P(t)$ is a vacuum Regge trajectory. It is assumed that the Pomeron couples to the proton via quarks like a scalar photon.

A single-Pomeron exchange is valid at the LHC energies, however at lower energies (e.g. those of the ISR or the SPS) the contribution of non-leading Regge exchanges should be accounted for as well.

Thus, the unpolarized elastic pp differential cross section is

$$\frac{d\sigma}{dt} = \frac{[3\beta F^p(t)]^4}{4\pi\sin^2[\pi\alpha_P(t)/2]}(s/s_0)^{2\alpha_P(t)-2}. \tag{2}$$

Similar to the case of elastic scattering, the double differential cross section for the SDD reaction, by Regge factorization, can be written as

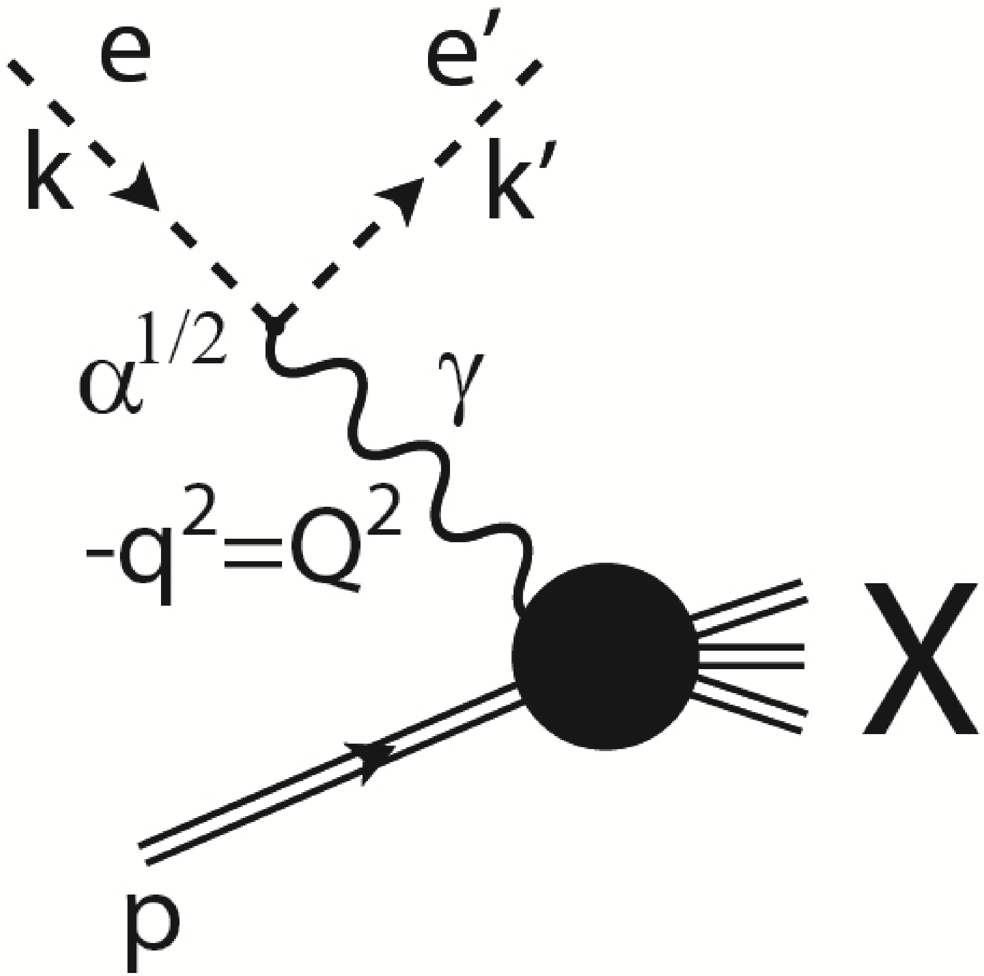
$$\frac{d^2\sigma}{dtdM_X^2} = \frac{9\beta^4[F^p(t)]^2}{4\pi\sin^2[\pi\alpha_P(t)/2]}(s/M_X^2)^{2\alpha_P(t)-2}\times \\ \left[\frac{W_2}{2m}\left(1-M_X^2/s\right) - mW_1(t+2m^2)/s^2\right], \tag{1}$$

where $W_i, \quad i=1,2$ are related to the structure functions of the nucleon and $W_2 \gg W_1$. For high M_X^2, the $W_{1,2}$ are Regge-behaved, while for small M_X^2 their behavior is dominated by nucleon resonances. The knowledge of the inelastic form factors (or transition amplitudes) is crucial for the calculation of low-mass diffraction dissociation.

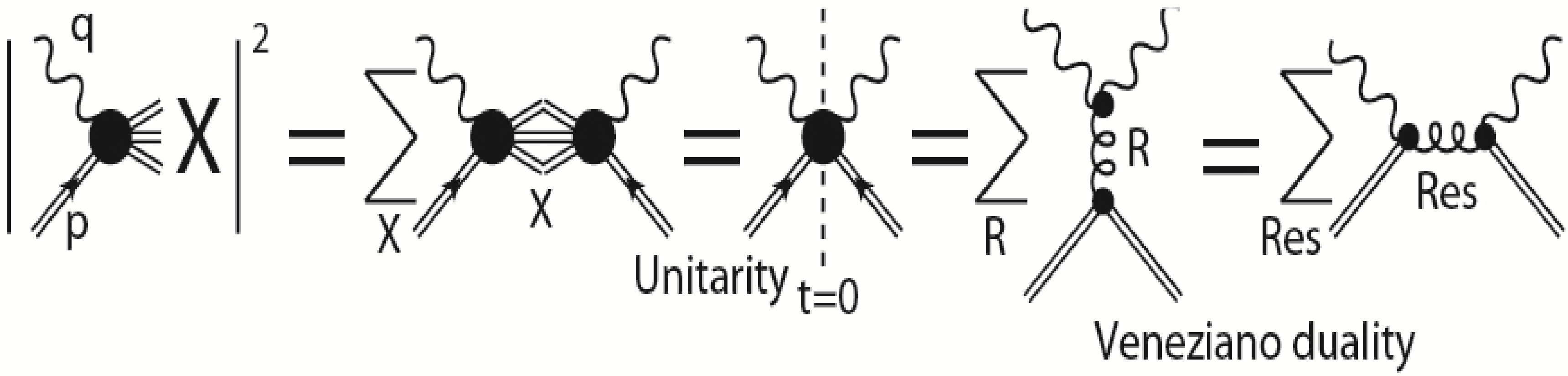
In the LHC energy region it simplifies to:

$$\frac{d^2\sigma}{dtdM_X^2} \approx \frac{9\beta^4[F^p(t)]^2}{4\pi}(s/M_X^2)^{2\alpha_P(t)-2}\frac{W_2}{2m}\,. \tag{1}$$

These expressions for SDD do not contain the elastic scattering limit because the inelastic form factor $W_2(M_X, t)$ has no elastic form factor limit $F(t)$ as $M_X \to m$. This problem is similar to the $x \to 1$ limit of the deep inelastic structure function $F_2(x, Q^2)$. The elastic contribution to SDD should be added separately.



e
e′
k
k′
α^{1/2}
γ
-q^2=Q^2
X
p


q
p
X
2
X
X
Unitarity
t=0
R
R
Veneziano duality
Res
Res

The final expression for the double differential cross section reads:

$$\frac{d^2\sigma}{dtdM_X^2} =$$
$$A_0 \left(\frac{s}{M_X^2}\right)^{2\alpha_P(t)-2} \frac{x(1-x)^2\ [F^p(t)]^2}{(M_x^2 - m^2)\left(1 + \frac{4m^2x^2}{-t}\right)^{3/2}} \times \tag{1}$$
$$\sum_{n=1,3} \frac{[f(t)]^{2(n+1)}\, Im\, \alpha(M_X^2)}{(2n + 0.5 - Re\, \alpha(M_X^2))^2 + (Im\, \alpha(M_X^2))^2}\,.$$

Pomerons (diffraction's) fraction

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

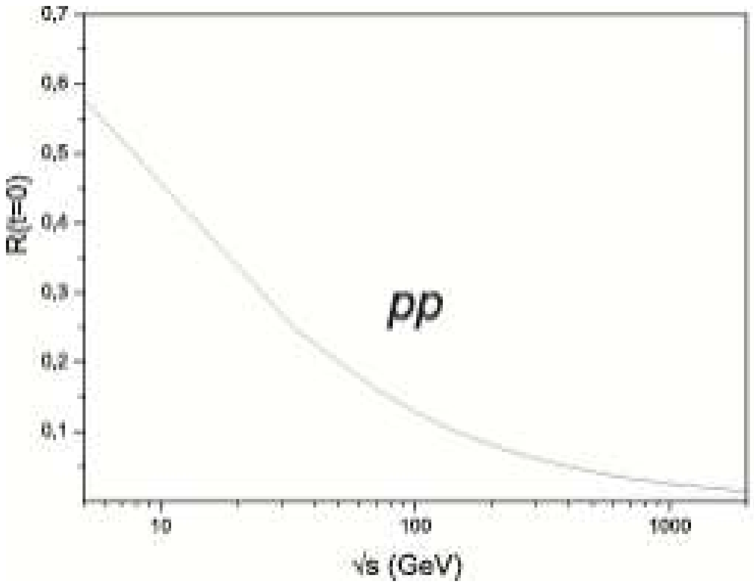
$$R(s, t = 0) = \frac{\Im m(A(s,t) - A_P(s,t))}{\Im A(s,t)}, \tag{1}$$

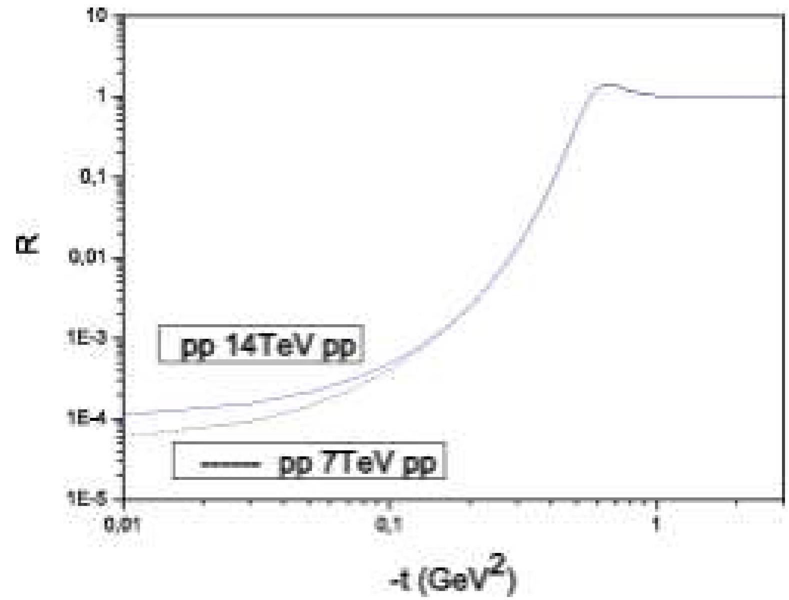
where the total scattering amplitude A includes the Pomeron contribution A_P plus the contribution from the secondary Reggeons and the Odderon.

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.

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

Pomeron dominance at the LHC





Factorization (nearly perfect at the LHC!)

$$(g_1 g_2)^2 = \frac{(g_1 f_1)^2 (f_1 g_2)^2}{(f_1 f_2)^2}.$$

Hence

$$\frac{d^3\sigma}{dt dM_1^2 dM_2^2} = \frac{d^2\sigma_1}{dt dM_1^2} \frac{d^2\sigma_2}{dt dM_2^2} \frac{d\sigma_{el}}{dt}.$$

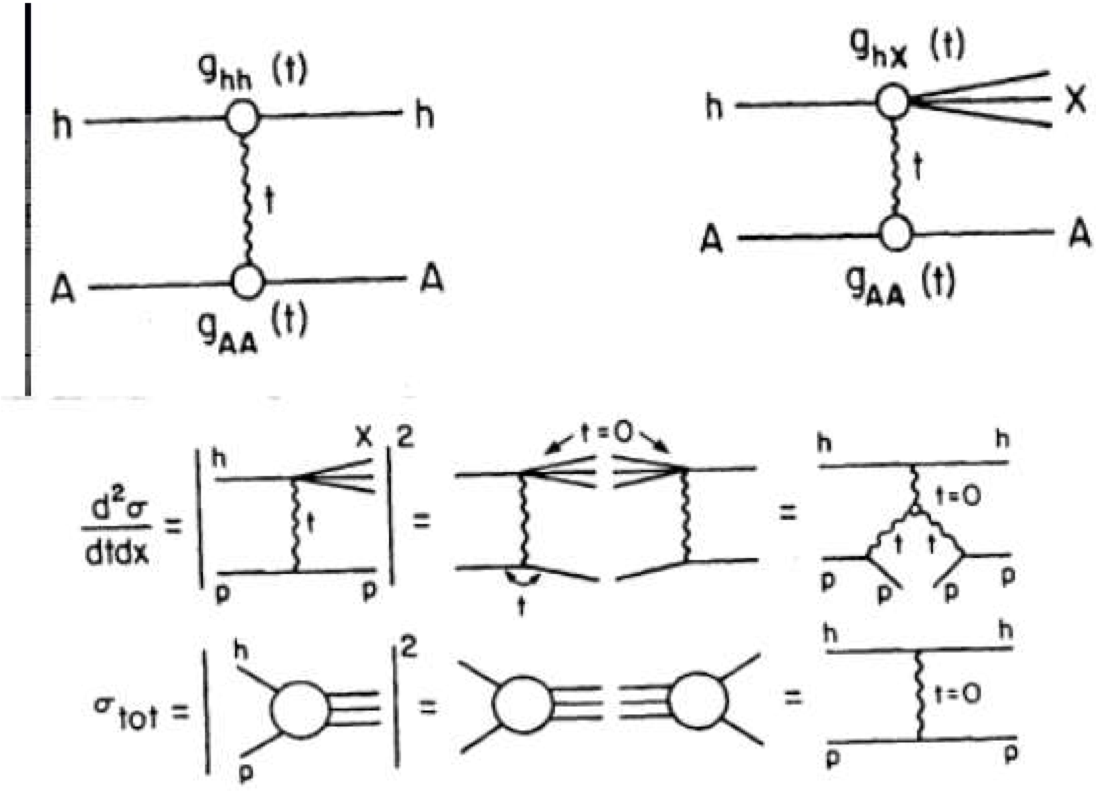
Assuming exponential cone, t^{bt} and integrating in t, one gets

$$\frac{d^2\sigma_{DD}}{dM_1^2 dM_2^2} = k \frac{1}{\sigma_{el}} \frac{d\sigma_1}{dM_1^2} \frac{d\sigma_2}{dM_2^2},$$

where $k = r^2/(2r-1)$, $r = b_{SD}/b_{el}$.

Further integration in M^2 yelds $\sigma_{DD} = k\frac{\sigma_{SD}^2}{\sigma_{el}}$.

The optical (general optical – Müller) theorem and triple-Regge limit



The differential cross section for $1 + 2 \to X$ is

$$\frac{d^2\sigma}{dt dM^2} = \frac{G(t)}{16\pi^2 s_0^2}\left(\frac{s}{s_0}\right)^{2\alpha(t)-2}\left(\frac{M^2}{s_0}\right)^{\alpha(0)-2\alpha(t)}, \tag{1}$$

where $G(t)$ is the triple Pomeron vertex, $G(t) = Ge^{at}$ for simplicity, and $\alpha(t) = \alpha^0 + \alpha'(t)$ is the (linear for the moment) Pomeron trajectory.

For a critical Pomeron, $\alpha^0 = 1$, one can use the formula

$$\int \frac{dx}{x \ln x} = \ln(\ln x)) \tag{2}$$

to get

$$\sigma^{SD}(s) \sim (2\alpha')^{-1} \ln\left(1 + \frac{2\alpha'}{a} \ln s\right) \sim \ln(\ln s)), \tag{3}$$

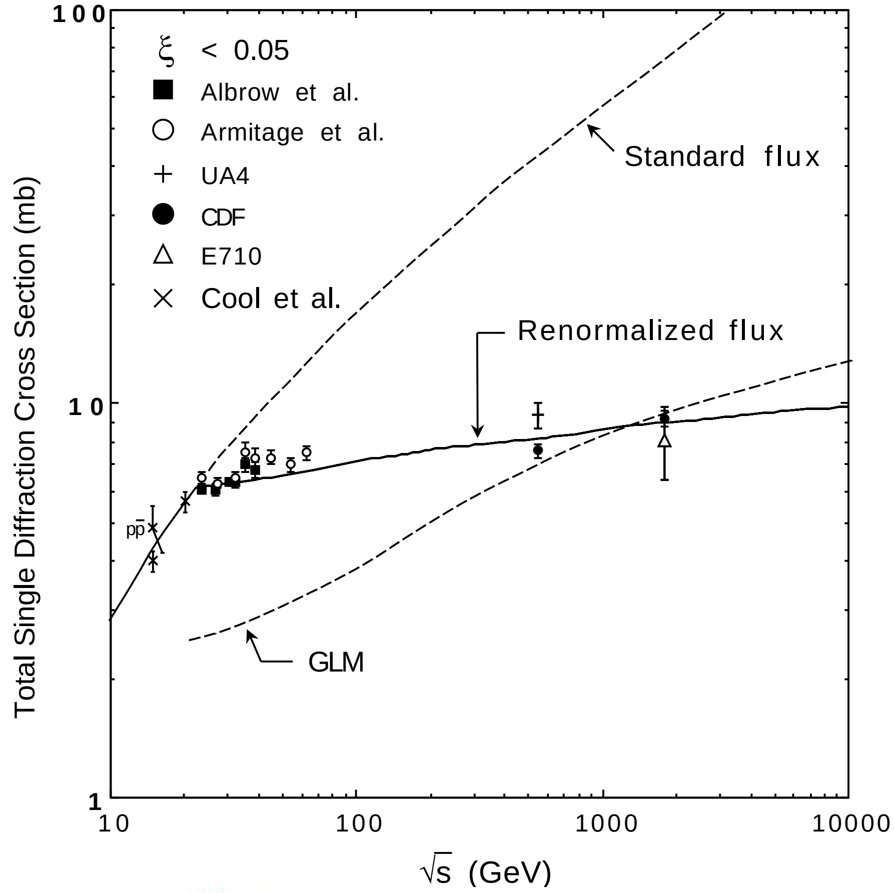
while the total cross section

$$\sigma^{tot}(s) \to const. \tag{4}$$

It contradicts unitarity since e.g. for critical Pomeron, $\alpha^0 = 1$, the partial (SD) cross section overshoots the total cross section $\sigma^{SD} > \sigma^{tot}$.

A trivial trick to avoid violation of unitarity is to assume the triple Pomeron vertex $G(t)$ vanishing at $t = 0$. Huge literature (Kaidalov, Brower, Ganguli, Kopeliovich,...) exists reflecting the efforts along this direction. The main conclusion is that decoupling (vanishing of the triple Pomeron vertex at $t = 0$) is incompatible with the data.

To remedy this difficulty, Dino Goulianos suggested a renormalization procedure, by which the Pomeron flux is multiplied by a factor $N(s)$ moderating the rise of inelastic diffraction starting from a certain threshold. The appearance of a threshold, however may violate analyticity.

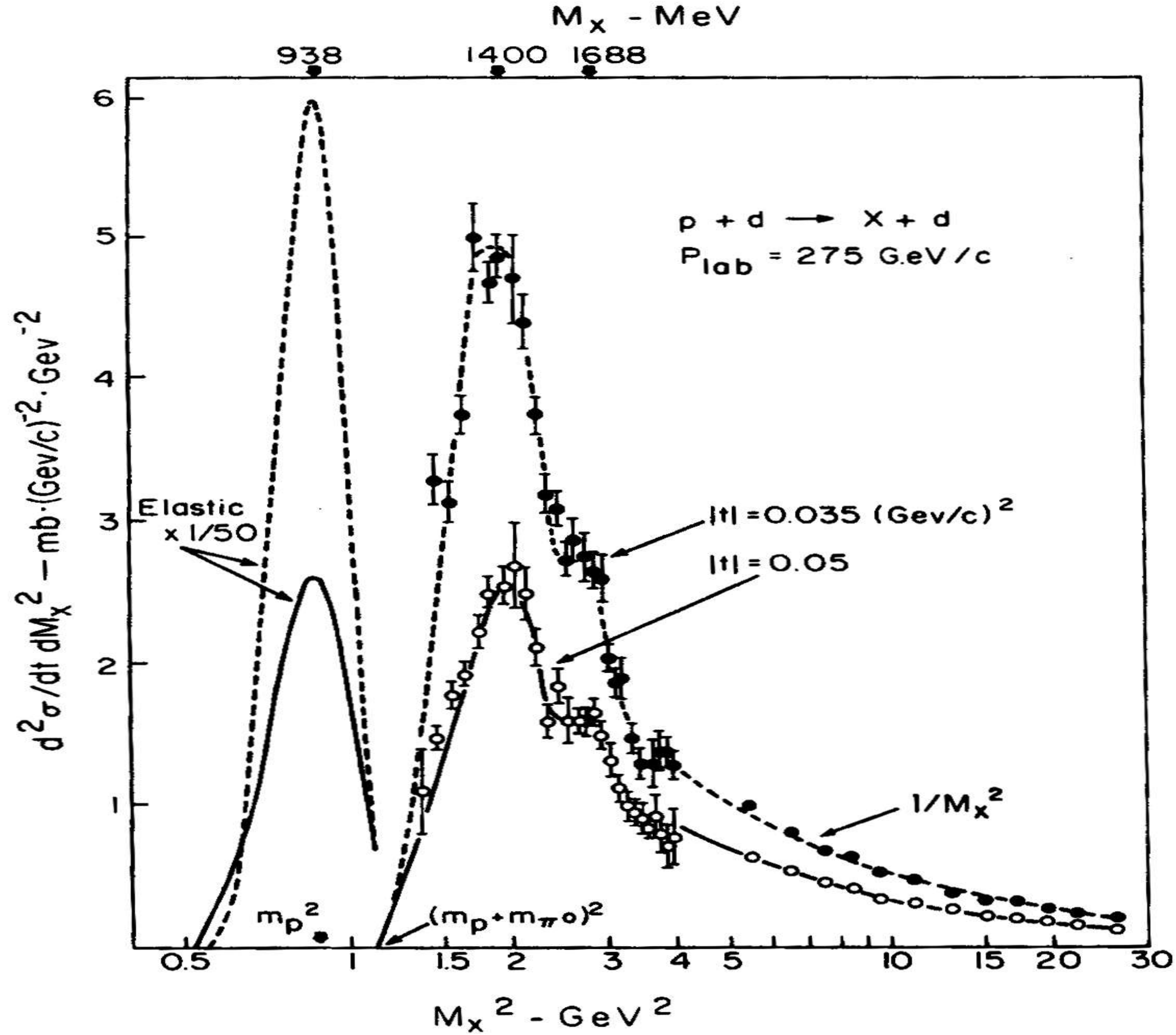


The function $N(s)$ is the so-called renormalization factor, introduced by K. Goulianos,

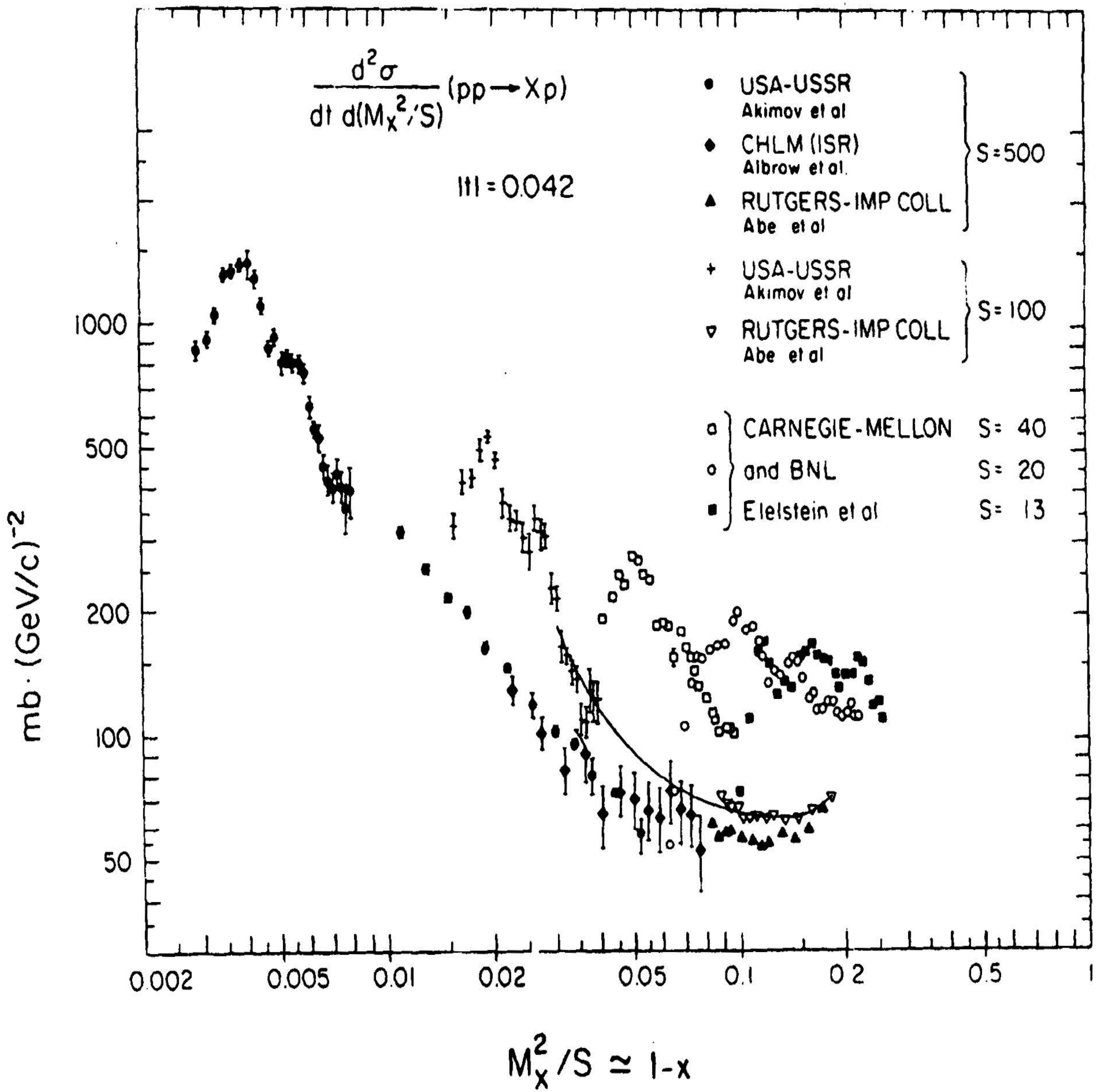
$$N_s \equiv \int_{\xi(min)}^{\xi(max)} \int_{t=0}^{-\infty} dt f_{P/p}(\xi, t) \sim s^{2\epsilon},$$

where $\xi(min) = 1.4/s$ and $\xi(max) = 0.1$. This factor secures unitarity.

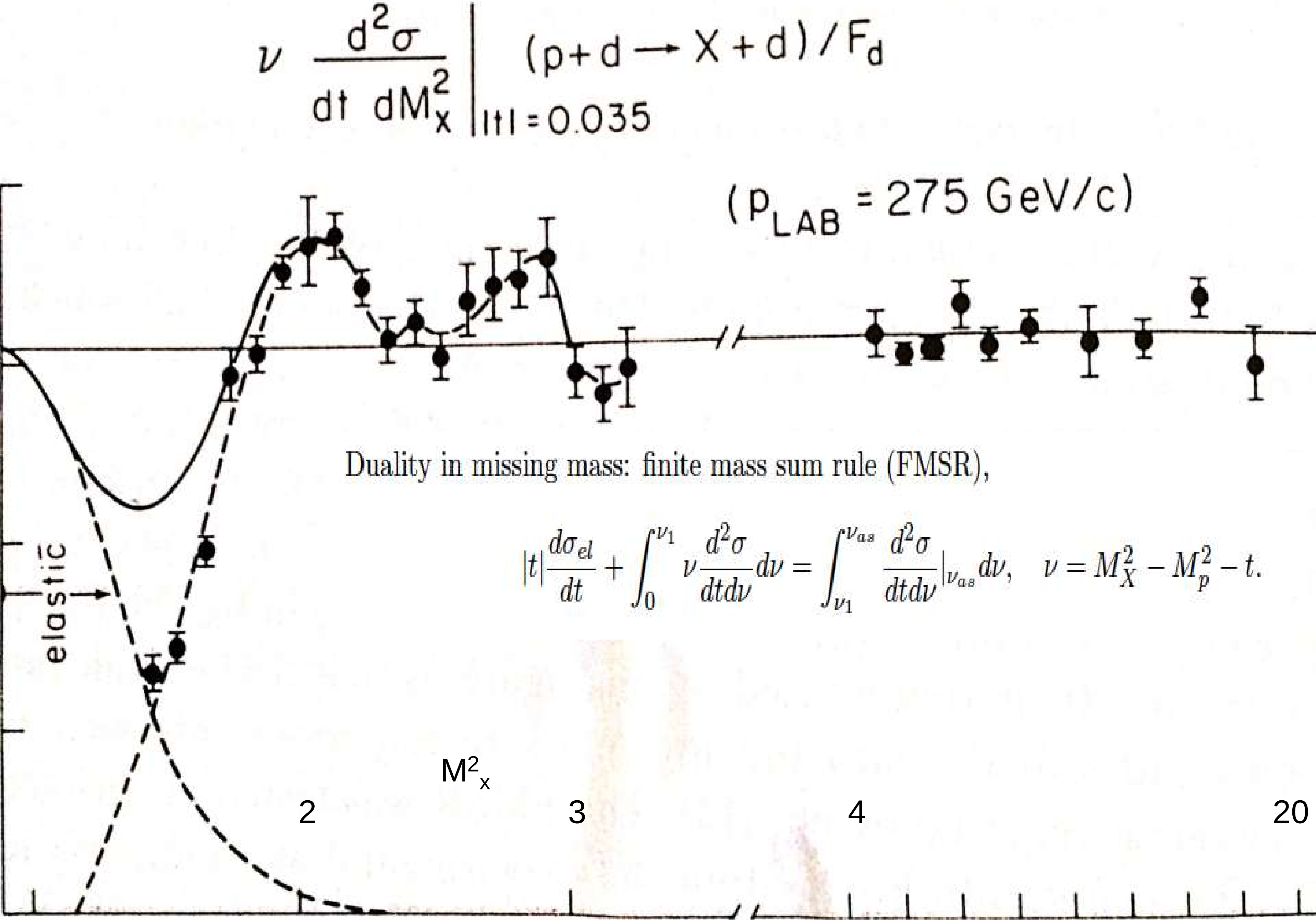
FNAL



M_X - MeV
938
1400
1688
$p + d \longrightarrow X + d$
P_{lab} = 275 GeV/c
Elastic x 1/50
$|t| = 0.035\ (GeV/c)^2$
$|t| = 0.05$
$1/M_X^2$
m_p^2
$(m_p + m_{\pi^0})^2$
$d^2\sigma/dt\,dM_X^2$ — mb·(Gev/c)$^{-2}$·Gev^{-2}
M_X^2 - GeV^2



$\frac{d^2\sigma}{dt\, d(M_X^2/S)}$ (pp → Xp)
|t| = 0.042
USA-USSR
Akimov et al
CHLM (ISR)
Albrow et al.
RUTGERS-IMP COLL
Abe et al
S=500
USA-USSR
Akimov et al
RUTGERS-IMP COLL
Abe et al
S=100
CARNEGIE-MELLON
and BNL
Elelstein et al
S= 40
S= 20
S= 13
mb · (GeV/c)$^{-2}$
1000
500
200
100
50
0.002
0.005
0.01
0.02
0.05
0.1
0.2
0.5
1
$M_X^2/S \simeq 1-x$



Duality in missing mass: finite mass sum rule (FMSR),

$$|t|\frac{d\sigma_{el}}{dt} + \int_0^{\nu_1} \nu \frac{d^2\sigma}{dtd\nu} d\nu = \int_{\nu_1}^{\nu_{as}} \frac{d^2\sigma}{dtd\nu}|_{\nu_{as}} d\nu, \quad \nu = M_X^2 - M_p^2 - t.$$

Low-mass diffraction dissociation at the LHC

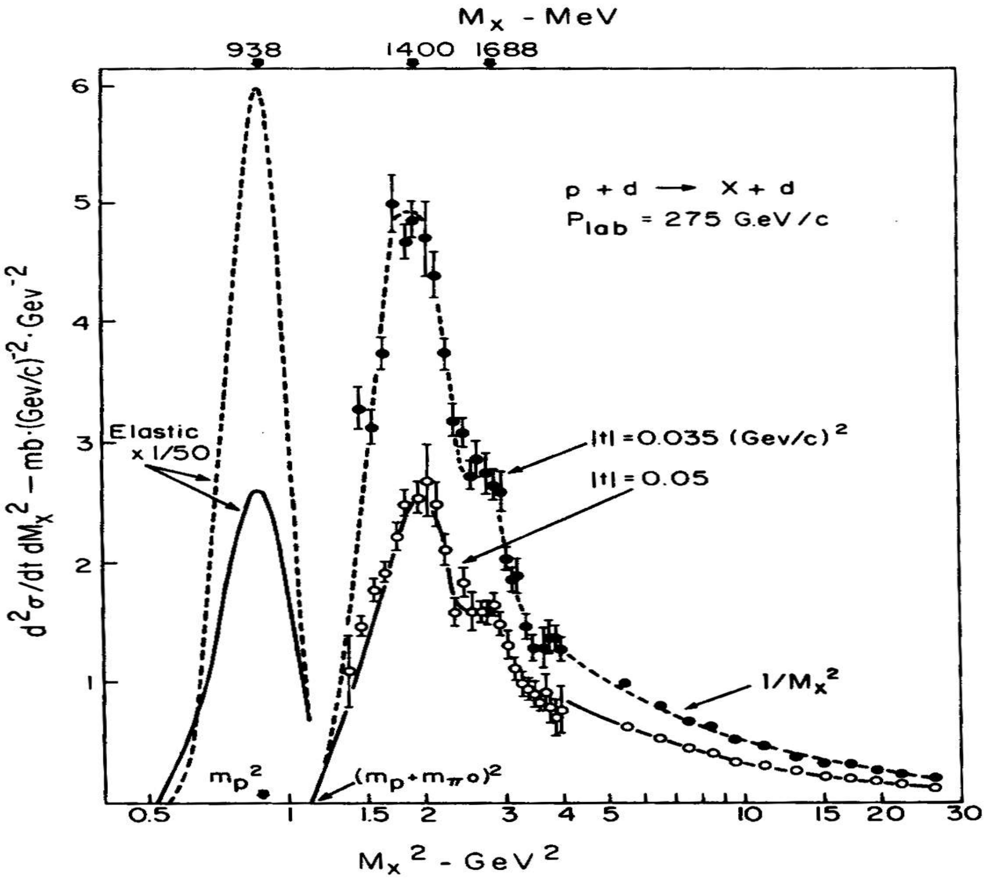
L. Jenkovszky, O. Kuprash, J. Lamsa, V. Magas, and R,. Orava:
Dual-Regge approach to high-energy, low-mass DD at the LHC,
Phys. Rev. D83(2011)0566014; hep-ph/1-11.0664.
L. Jenkovszky, O. Kuprash, J. Lamsa and R. Orava: hep-ph/11063299,
Mod. Phys. Letters A. **26**(2011) 1-9, August 2011;
L. Jenkovszky, O. Kuprash, Risto Orava, A. Salii, arXi**v:1211.584,**
Low missing mass, single- and double diffraction dissociation at the LHC

Experimentally, diffraction dissociation in proton-proton scattering was intensively studied in the '70-ies at the Fermilab and the CERN ISR. In particular, double differential cross section $\frac{d\sigma}{dtdM_X^2}$ was measured in the region $0.024 < -t < 0.234$ (GeV/c)^2, $0 < M^2 < 0.12s$, and $(105 < s < 752)$ GeV^2, and a single peak in M_X^2 was identified.

Low-mass single diffraction dissociation (SDD) of protons, $pp \to pX$ as well as their double diffraction dissociation (DDD) are among the priorities at the LHC. For the CMS Collaboration, the SDD mass coverage is presently limited to some 10 GeV. With the Zero Degree Calorimeter (ZDS), this could be reduced to smaller masses, in case the SDD system produces very forward neutrals, i.e. like a N^* decaying into a fast leading neutron. Together with the T2 detectors of TOTEM, SDD masses down to 4 GeV could be covered.

While high-mass diffraction dissociation receives much attention, mainly due to its relatively easy theoretical treatment within the triple Reggeon formalism and successful reproduction of the data, this is not the case for low-masses, which are beyond the range of perturbative quantum chromodynamics (QCD). The forthcoming measurements at the LHC urge a relevant theoretical understanding and treatment of low mass DD, which essentially has both spectroscopic and dynamic aspects. The low-mass, M_X spectrum is rich of nucleon resonances. Their discrimination is a difficult experimental task, and theoretical predictions of the appearance of the resonances depending on s, t and M is also very difficult since, as mentioned, perturbative QCD, or asymptotic Regge pole formula are of no use here. Below we concentrate on single diffraction dissociation; generalization to DDD is straightforward.

FNAL



M_X - MeV
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1688
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P_{lab} = 275 GeV/c
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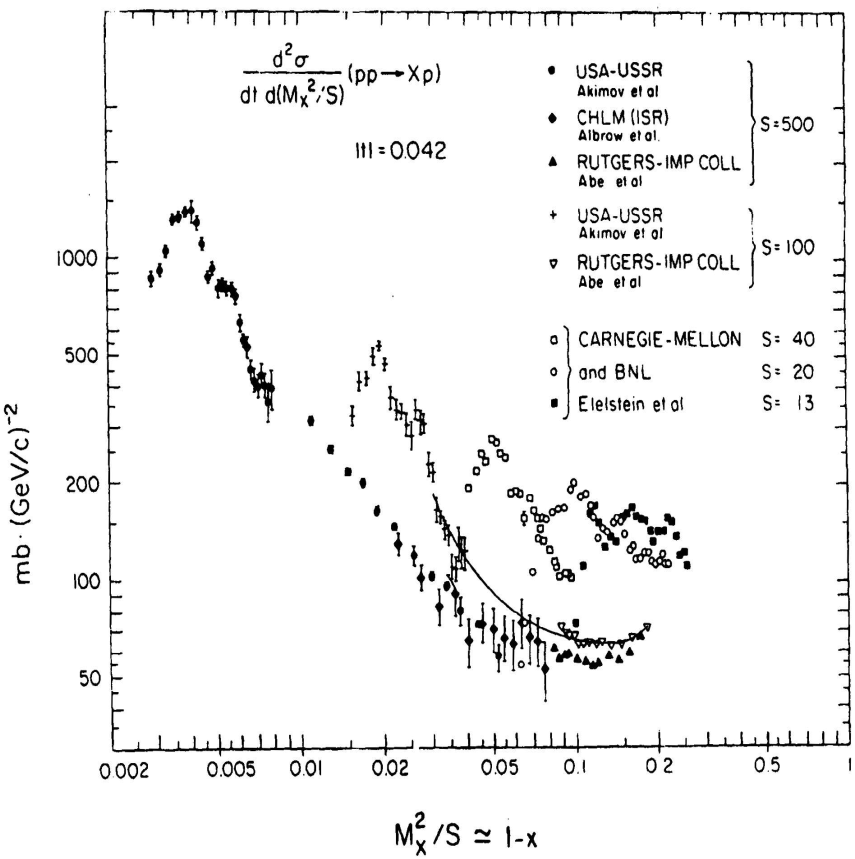
|t| = 0.035 (GeV/c)^2
|t| = 0.05
$1/M_X^2$
m_p^2
$(m_p+m_{\pi^0})^2$
$d^2\sigma/dt\,dM_X^2$ — mb·(GeV/c)$^{-2}$·GeV^{-2}
M_X^2 - GeV^2



$\frac{d^2\sigma}{dt\,d(M_X^2/S)}$ (pp→Xp)
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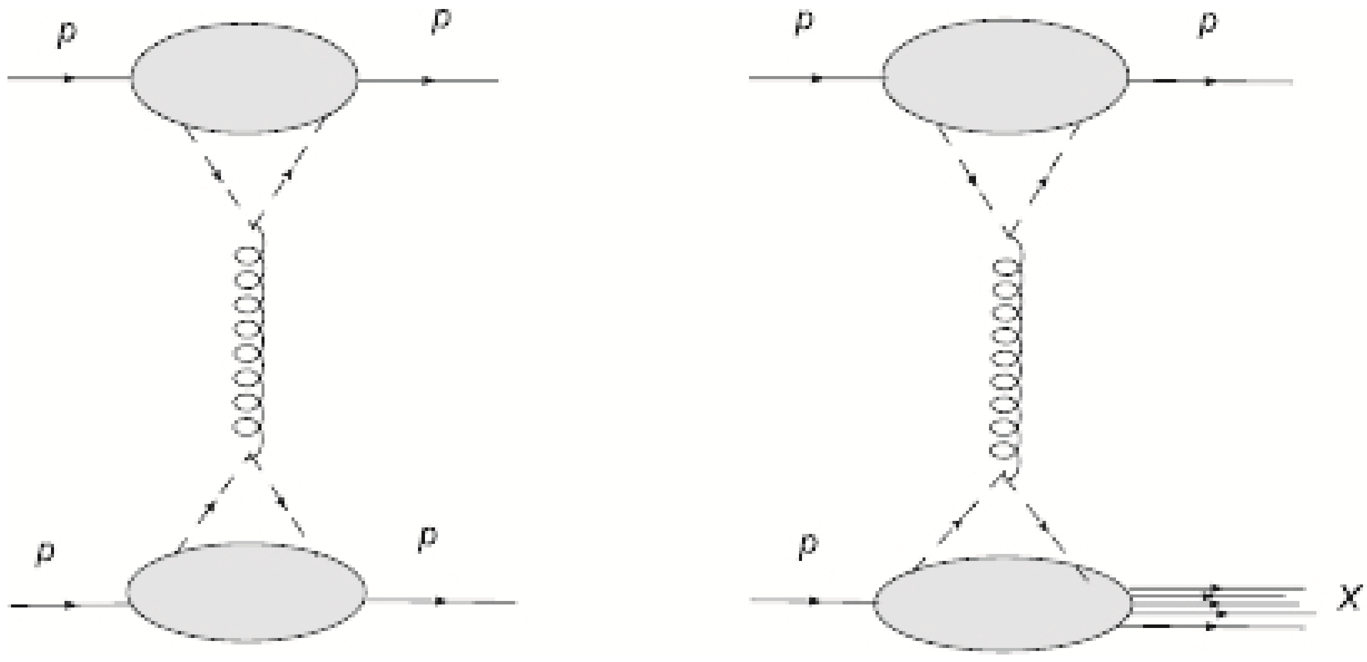
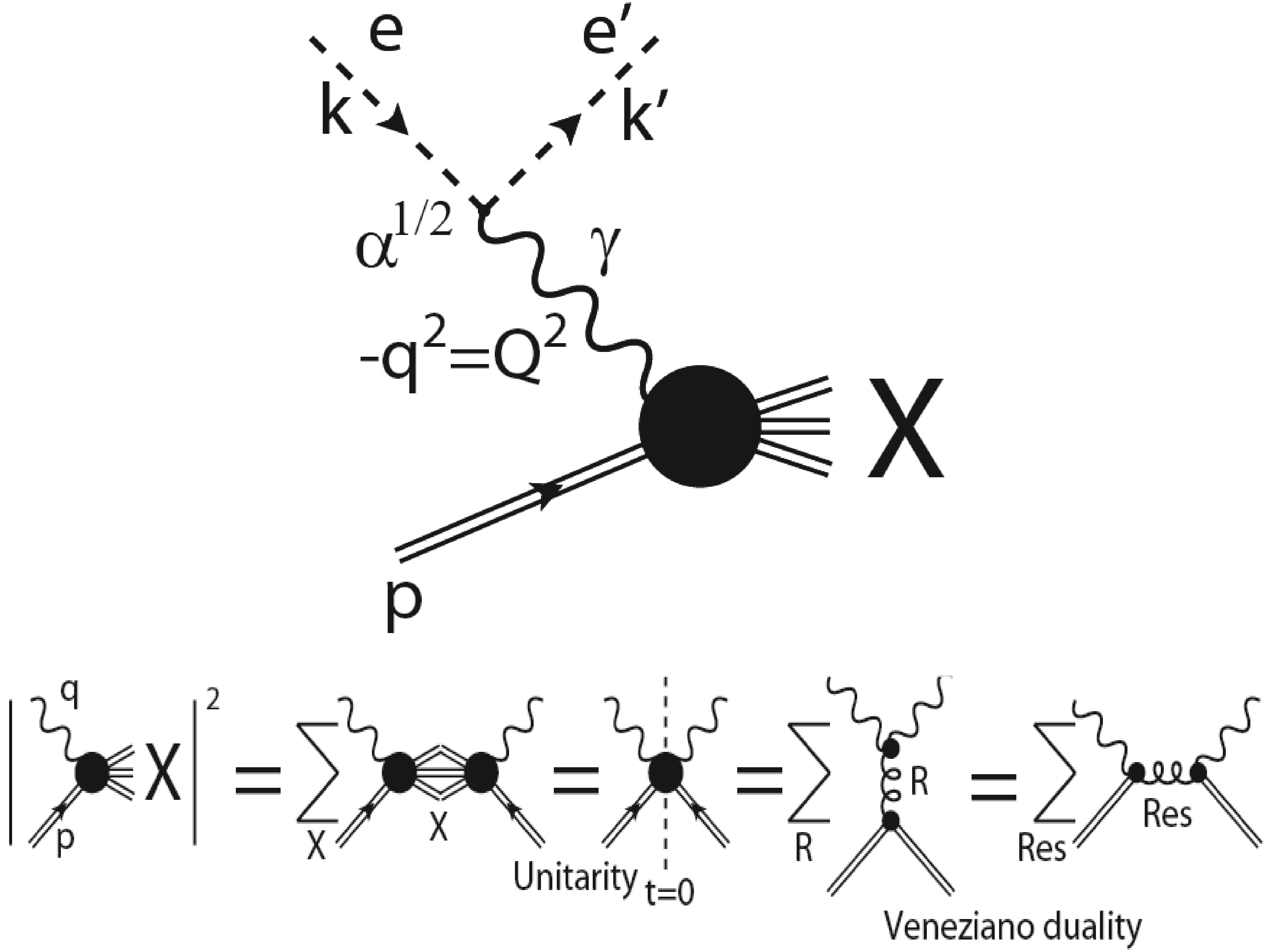
mb·(GeV/c)$^{-2}$
$M_X^2/S \simeq 1-x$



p
p
p
p
p
p
p
X



e
e′
k
k′
α^{1/2}
γ
-q^2=Q^2
X
p
q
X
p
X
X
Unitarity
t=0
R
R
Res
Res
Veneziano duality

Similar to the case of elastic scattering, the double differential cross section for the SDD reaction, by Regge factorization, can be written as

$$\begin{aligned} \frac{d^2\sigma}{dt dM_X^2} = \frac{9\beta^4[F^p(t)]^2}{4\pi\sin^2[\pi\alpha_P(t)/2]}(s/M_X^2)^{2\alpha_P(t)-2}\times \\ \left[\frac{W_2}{2m}\left(1-M_X^2/s\right)-mW_1(t+2m^2)/s^2\right], \end{aligned} \tag{1}$$

where $W_i, \quad i=1,2$ are related to the structure functions of the nucleon and $W_2 \gg W_1$. For high M_X^2, the $W_{1,2}$ are Regge-behaved, while for small M_X^2 their behavior is dominated by nucleon resonances. The knowledge of the inelastic form factors (or transition amplitudes) is crucial for the calculation of low-mass diffraction dissociation.

The pp scattering amplitude

$$A(s,t)_P = \\ -\beta^2[f^u(t)+f^d(t)]^2\left(\frac{s}{s_0}\right)^{\alpha_P(t)-1}\frac{1+e^{-i\pi\alpha_P(t)}}{\sin\pi\alpha_P(t)}, \tag{1}$$

where $f^u(t)$ and $f^d(t)$ are the amplitudes for the emission of u and d valence quarks by the nucleon, β is the quark-Pomeron coupling, to be determined below; $\alpha_P(t)$ is a vacuum Regge trajectory. It is assumed that the Pomeron couples to the proton via quarks like a scalar photon.

A single-Pomeron exchange is valid at the LHC energies, however at lower energies (e.g. those of the ISR or the SPS) the contribution of non-leading Regge exchanges should be accounted for as well.

Thus, the unpolarized elastic pp differential cross section is

$$\frac{d\sigma}{dt} = \frac{[3\beta F^p(t)]^4}{4\pi\sin^2[\pi\alpha_P(t)/2]}(s/s_0)^{2\alpha_P(t)-2}. \tag{2}$$

The final expression for the double differential cross section reads:

$$\frac{d^2\sigma}{dtdM_X^2} =$$
$$A_0 \left(\frac{s}{M_X^2}\right)^{2\alpha_P(t)-2} \frac{x(1-x)^2\ [F^p(t)]^2}{(M_x^2-m^2)\left(1+\frac{4m^2x^2}{-t}\right)^{3/2}} \times \tag{1}$$
$$\sum_{n=1,3} \frac{[f(t)]^{2(n+1)}\, Im\,\alpha(M_X^2)}{(2n+0.5-Re\,\alpha(M_X^2))^2+(Im\,\alpha(M_X^2))^2}\,.$$

SD and DD cross sections

$$\frac{d^2\sigma_{SD}}{dtdM_x^2} = {F_p}^2(t)F(x_B,t)\frac{\sigma_T^{Pp}(M_x^2,t)}{2m_p}\left(\frac{s}{M_x^2}\right)^{2(\alpha(t)-1)}\ln\left(\frac{s}{M_x^2}\right)$$

$$\frac{d^3\sigma_{DD}}{dtdM_1^2dM_2^2} = C_nF^2(x_B,t)\frac{\sigma_T^{Pp}(M_1^2,t)}{2m_p}\frac{\sigma_T^{Pp}(M_2^2,t)}{2m_p}$$

$$\times\left(\frac{s}{(M_1+M_2)^2}\right)^{2(\alpha(t)-1)}\ln\left(\frac{s}{(M_1+M_2)^2}\right)$$

“Reggeized (dual) Breit-Wigner” formula:

$$\sigma_T^{Pp}(M_x^2,t) = Im\,A(M_x^2,t) = \frac{A_{N^*}}{\sum_n n-\alpha_{N^*}(M_x^2)} + Bg(t,M_x^2) =$$

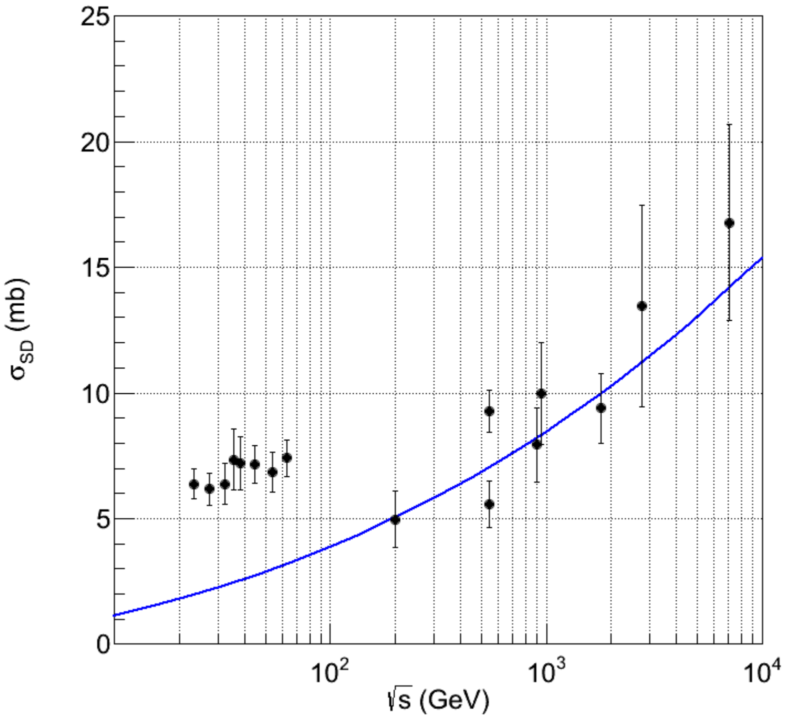
$$= A_n \sum_{n=0,1,\dots} \frac{[f(t)]^{2(n+1)}\,Im\,\alpha(M_x^2)}{(2n+0.5-Re\,\alpha(M_x^2))^2+(Im\,\alpha(M_x^2))^2} + B_n e^{b_{in}^{bg}t}\left(M_x^2-M_{p+\pi}^2\right)^{\epsilon}$$

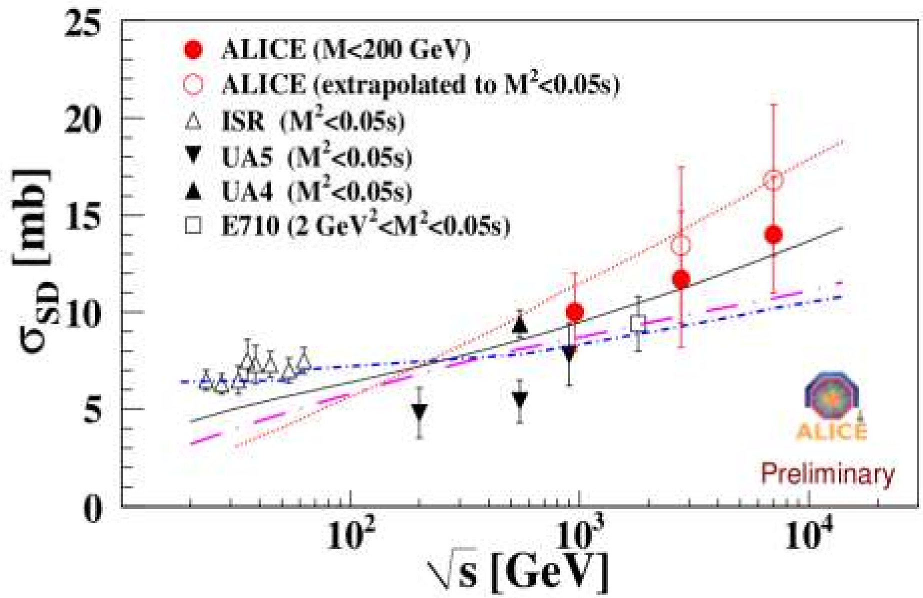
$$F(x_B,t) = \frac{x_B(1-x_B)}{\left(M_x^2-m_p^2\right)\left(1+4m_p^2x_B^2/(-t)\right)^{3/2}}, \quad x_B = \frac{-t}{M_x^2-m_p^2-t}$$

$$F_p(t) = \frac{1}{1-\frac{t}{0.71}}, \quad f(t) = e^{b_{in}t}$$

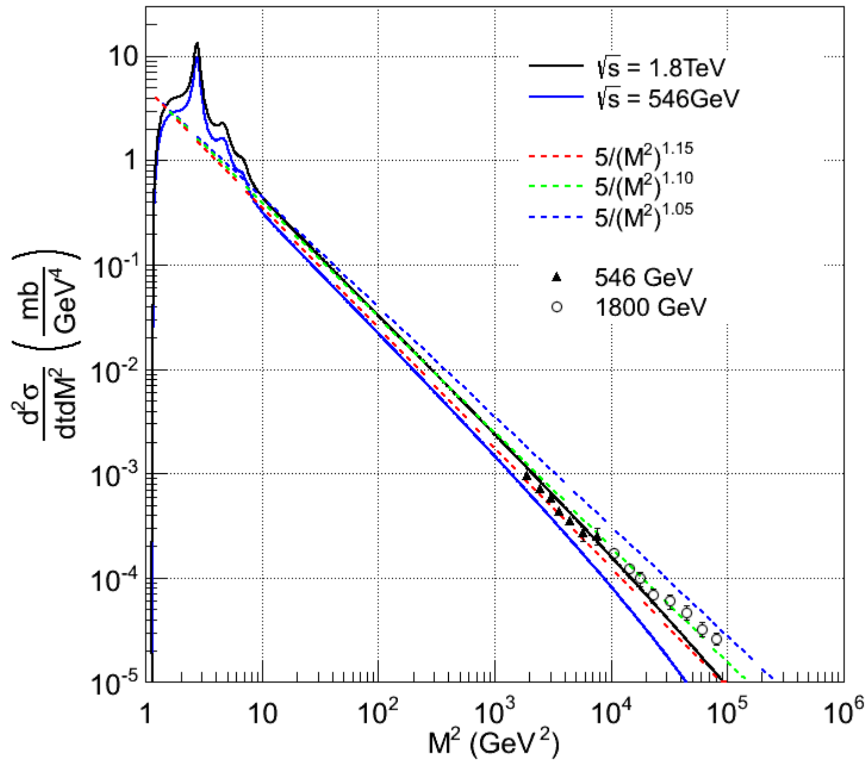
$$\alpha(t) = \alpha(0)+\alpha' t = 1.04+0.25t$$

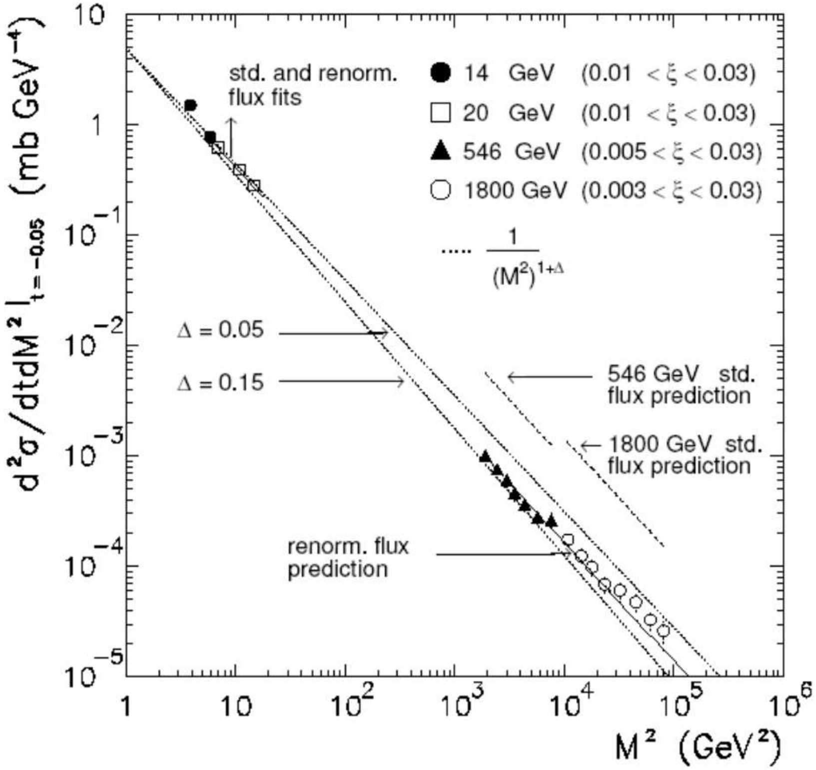
SDD cross sections vs. energy.



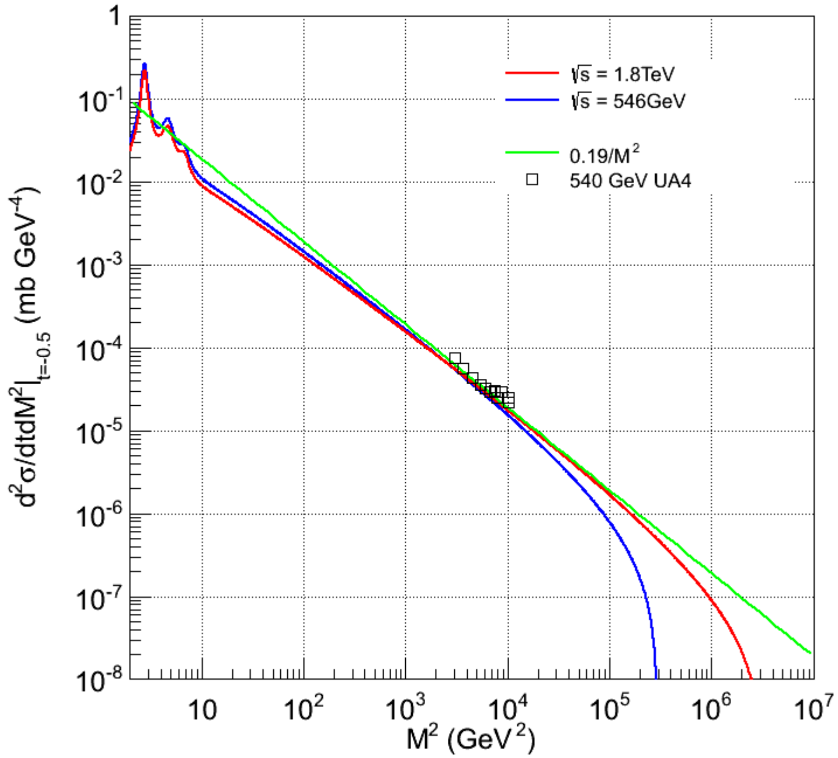


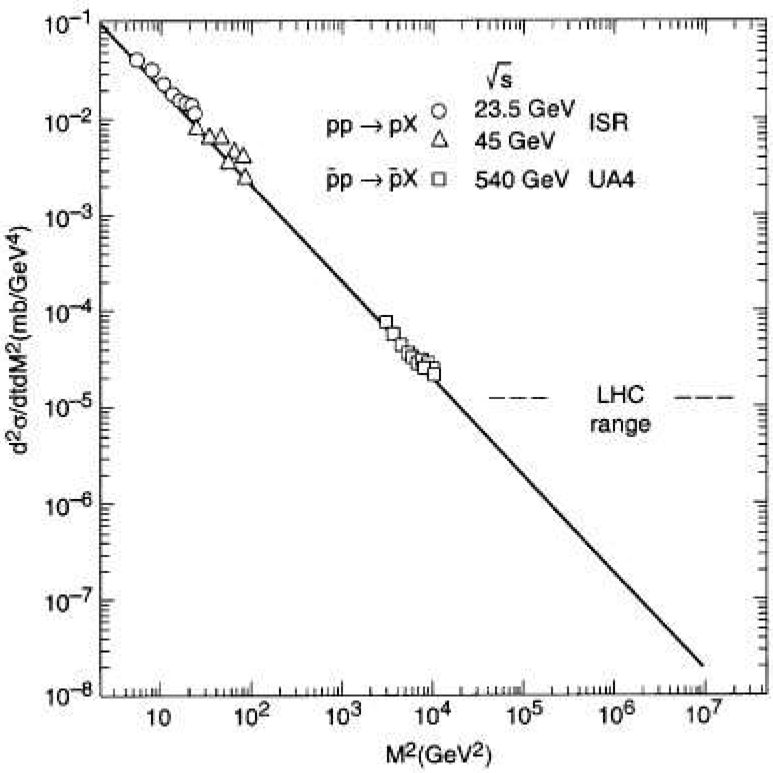
Approximation of background to reference points (t=-0.05)



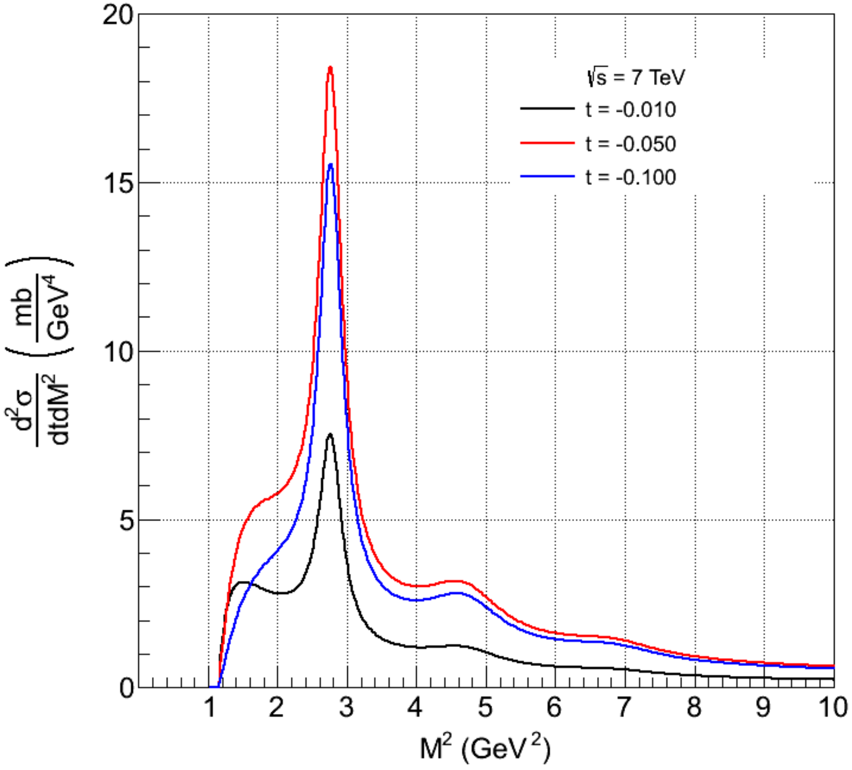


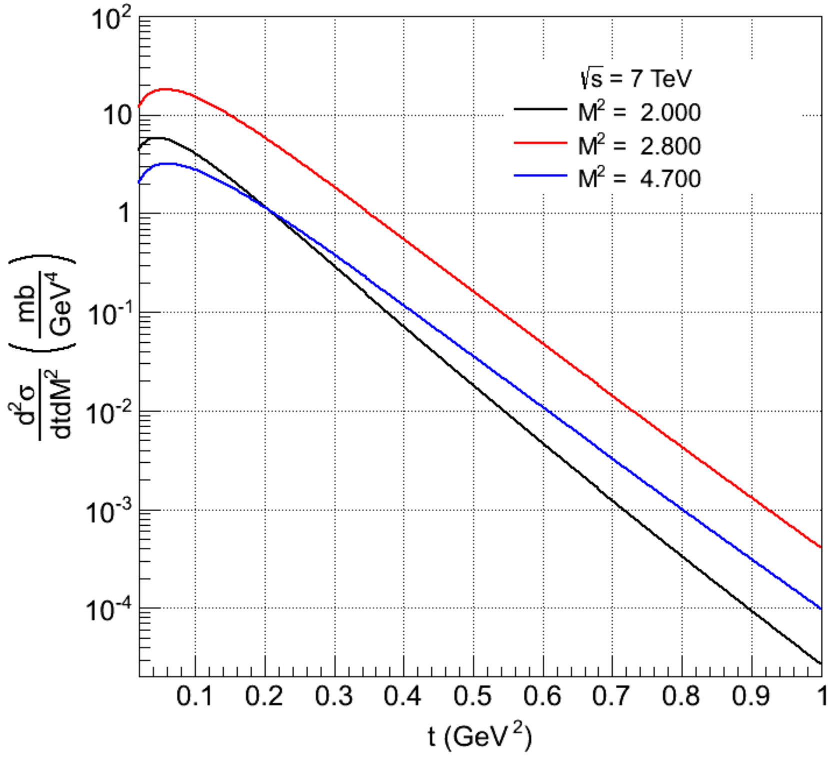
Approximation of background to reference points (t=-0.5)



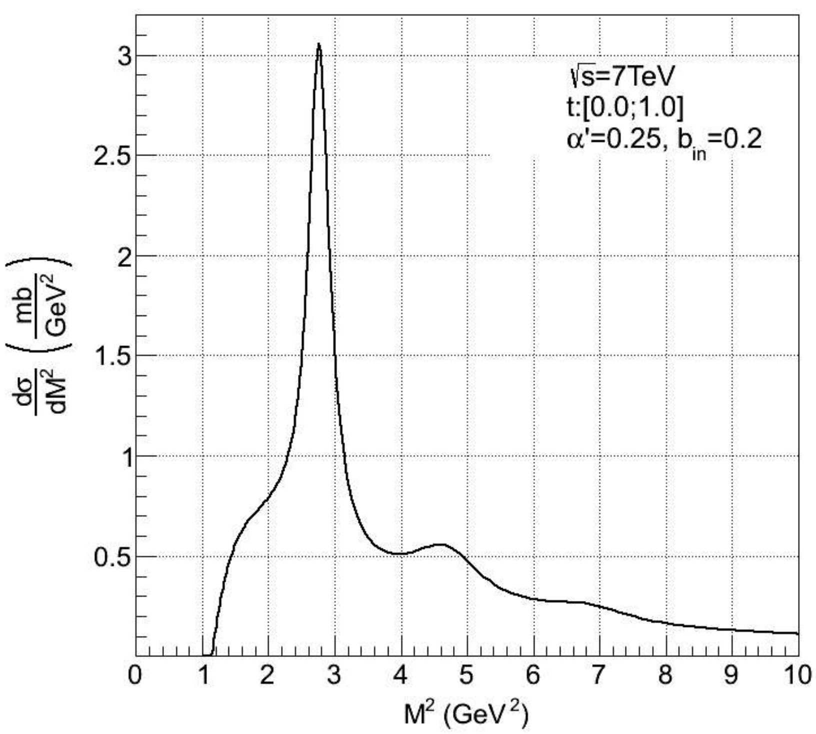


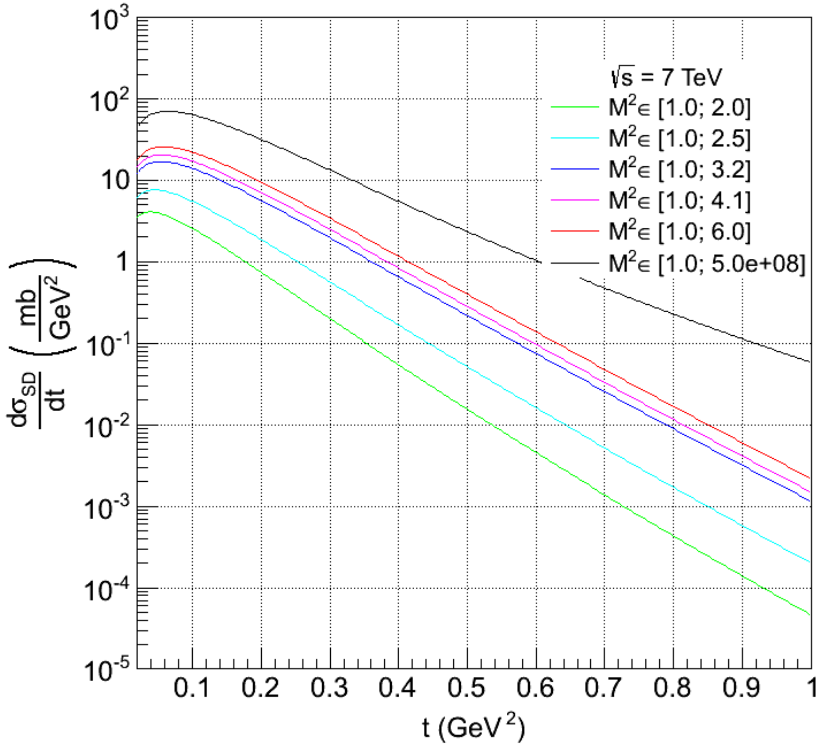
Double differential SD cross sections



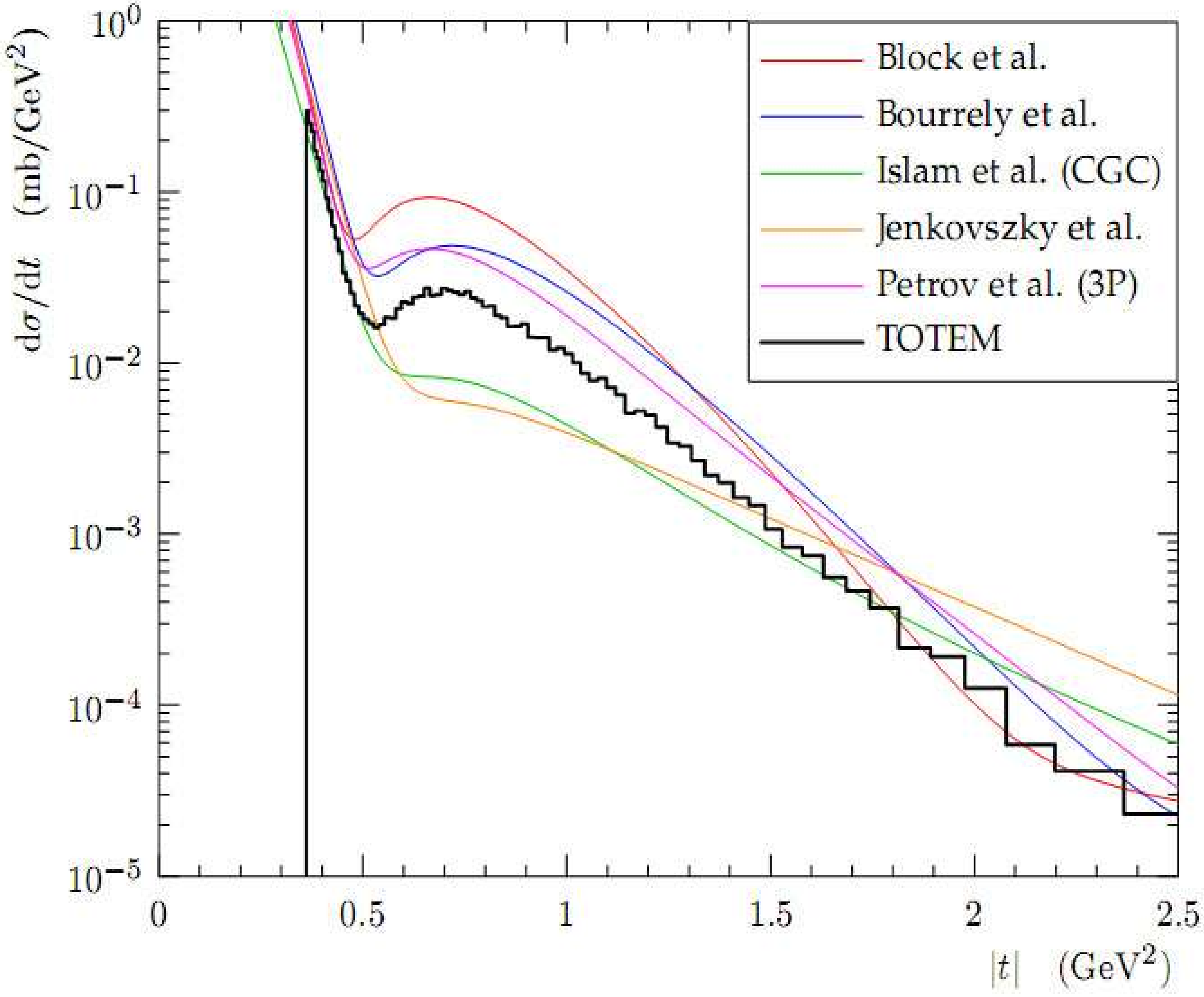


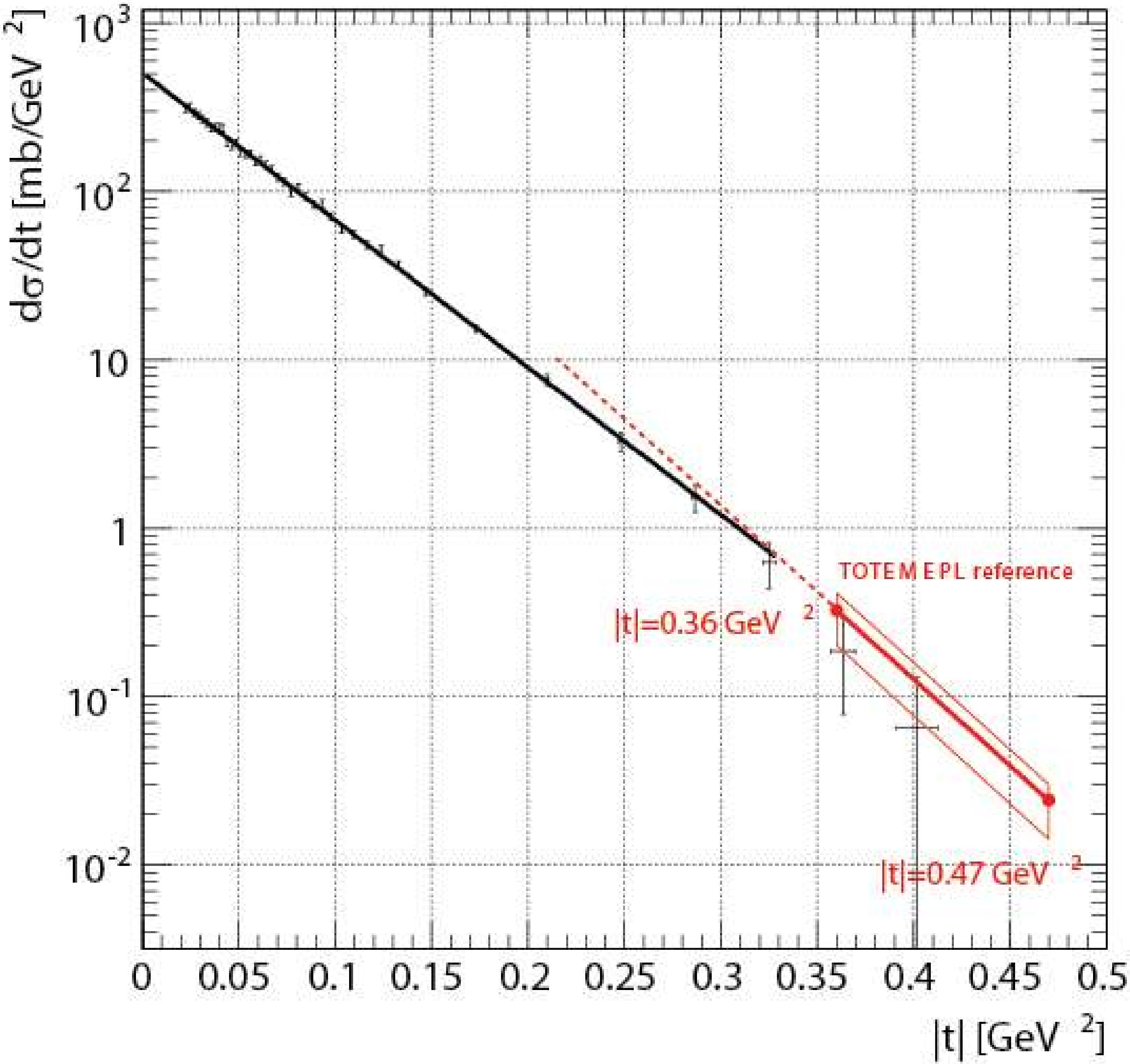
Single differential integrated SD cross sections





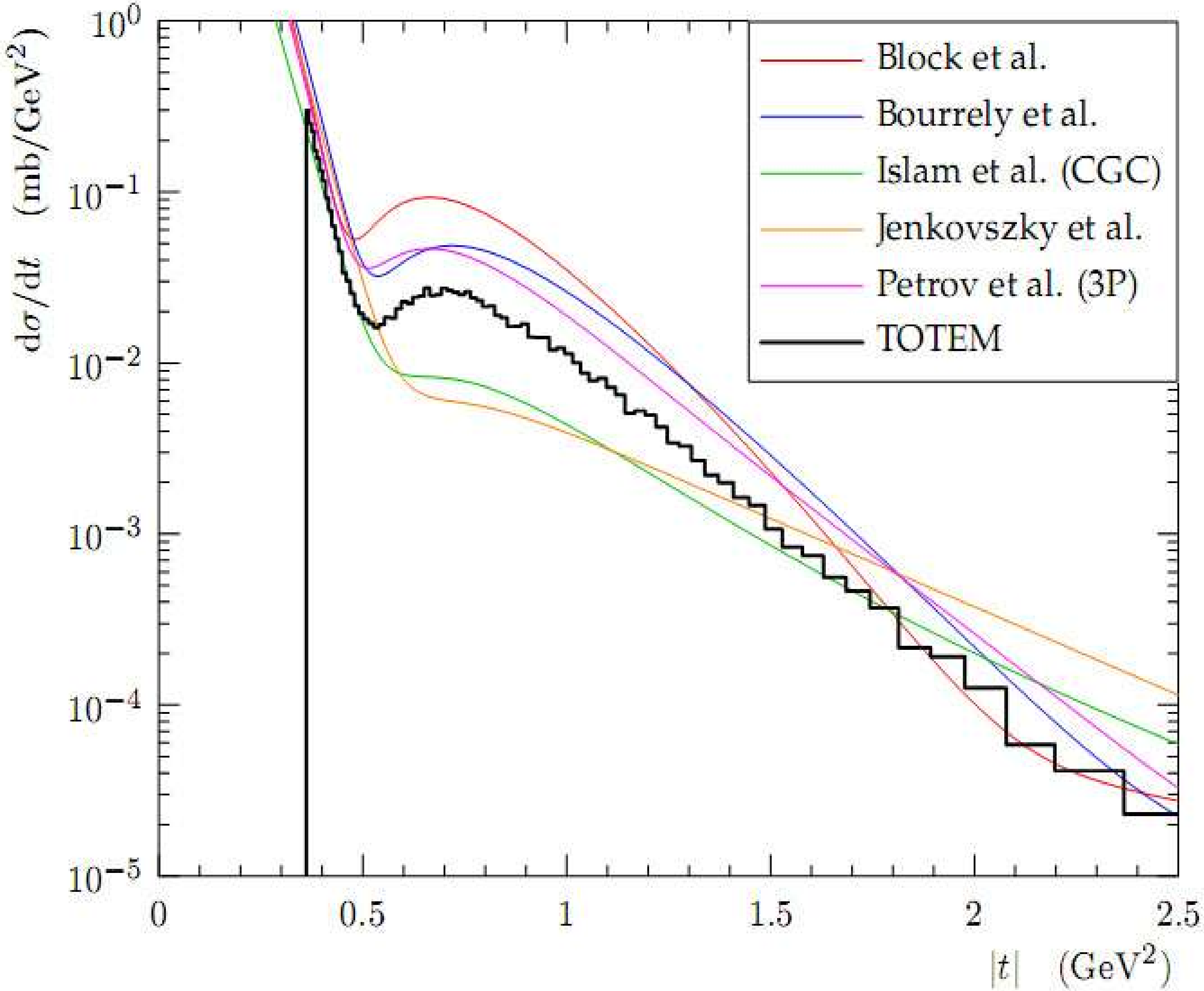
CERN LHC, TOTEM Collab., June 26, 2011:

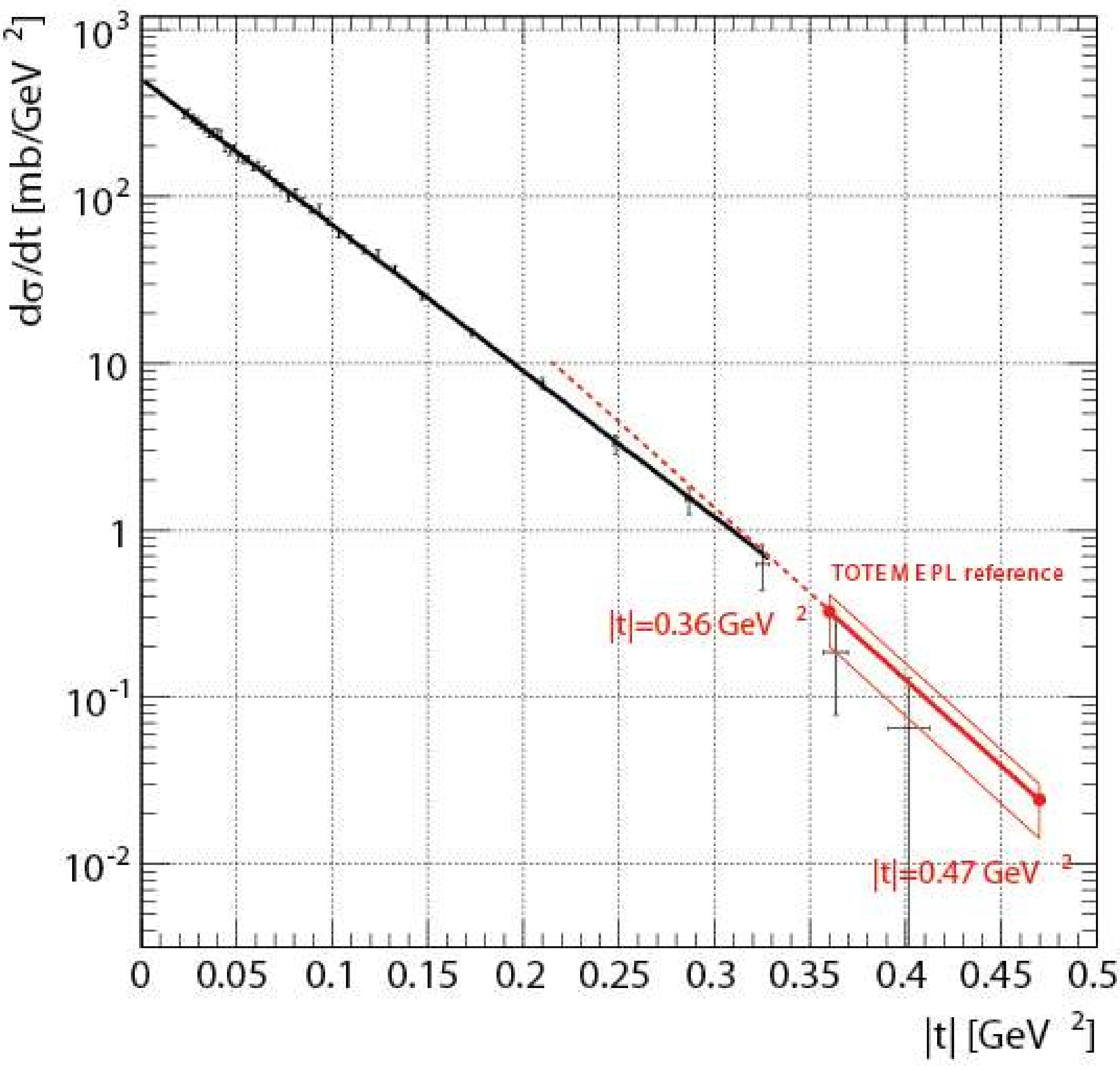




dσ/dt [mb/GeV 2]
10³
10²
10
1
10⁻¹
10⁻²
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
|t| [GeV 2]
TOTEM EPL reference
|t|=0.36 GeV 2
|t|=0.47 GeV 2

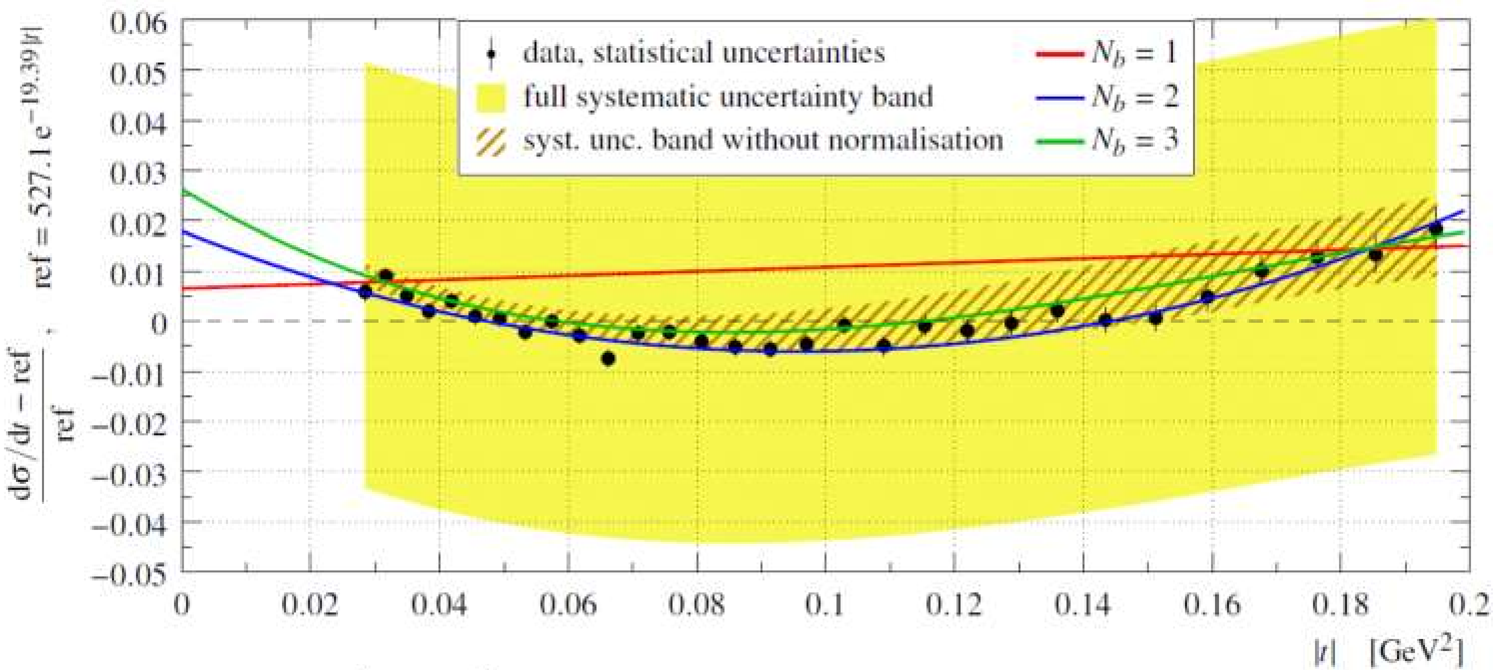
CERN LHC, TOTEM Collab., June 26, 2011:





dσ/dt [mb/GeV 2]
|t| [GeV 2]
TOTEM EPL reference
|t|=0.36 GeV 2
|t|=0.47 GeV 2

Elastic scattering: non-exponentiality at low |t|



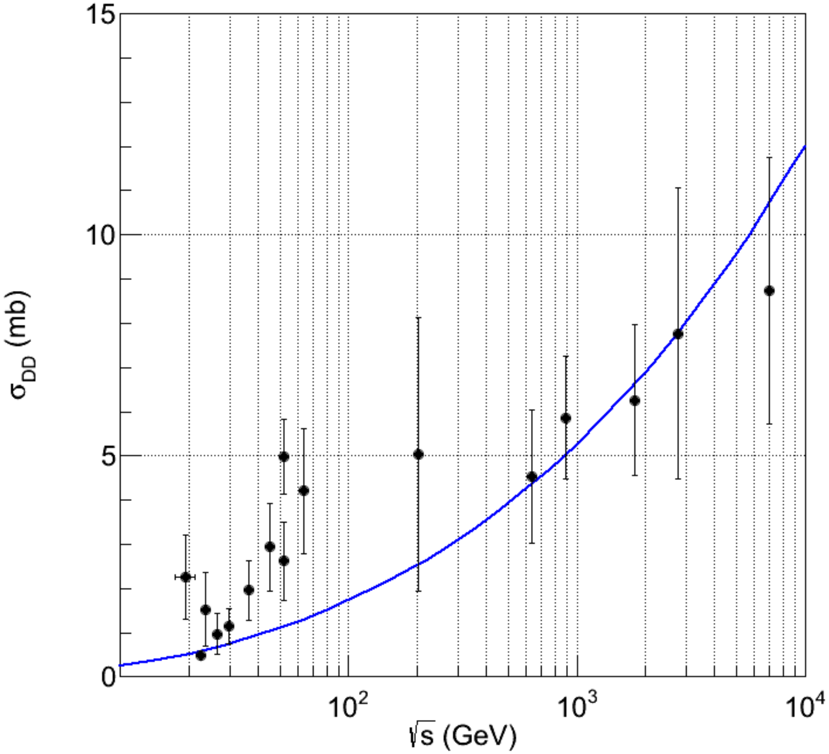
$$\frac{d\sigma}{dt}(t) = \left.\frac{d\sigma}{dt}\right|_{t=0} \exp\left(\sum_{i=1}^{N_b} b_i t^i\right)$$

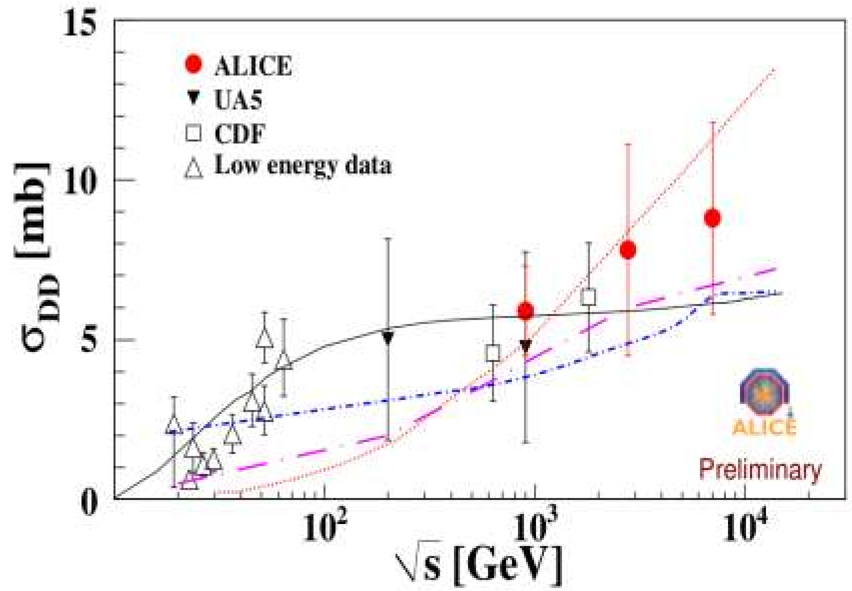
$N_b = 1$ excluded with 7σ significance!

$N_b = 2$: σ_{tot} = (101.5 ± 2.1) mb
$N_b = 3$: σ_{tot} = (101.9 ± 2.1) mb

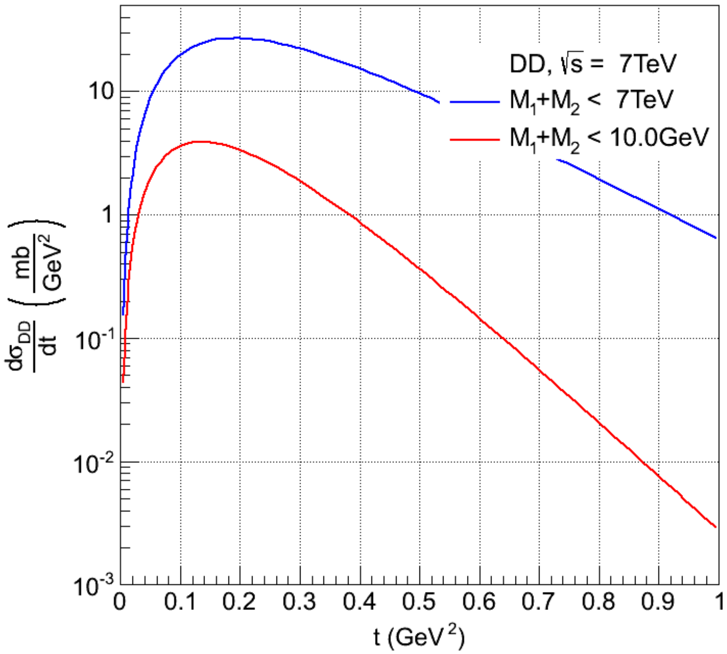
Nuclear Physics B 899 (2015) 527–546

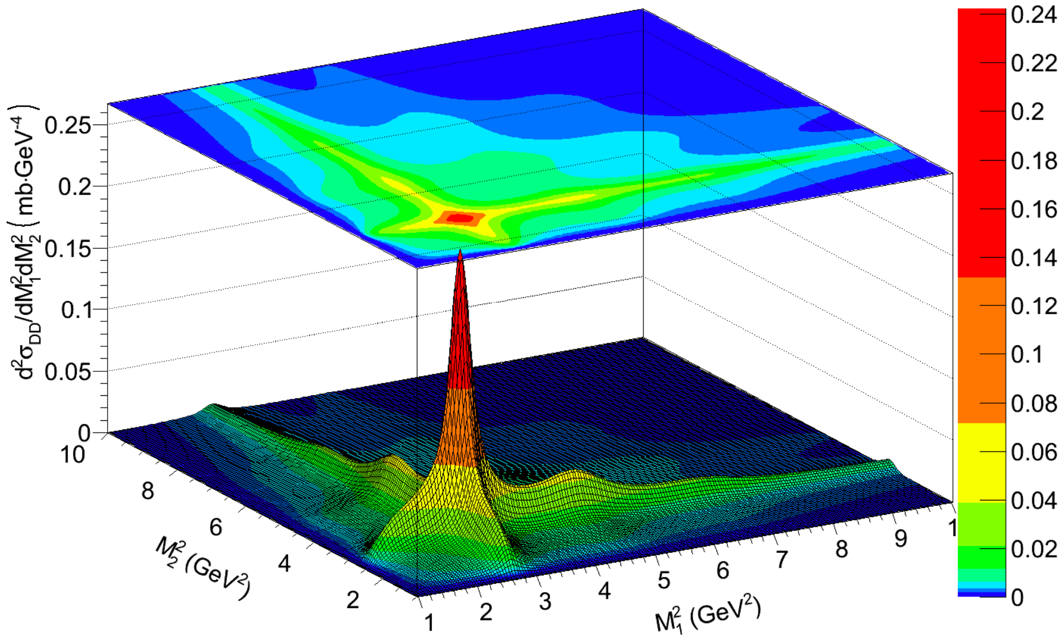
DDD cross sections vs. energy.



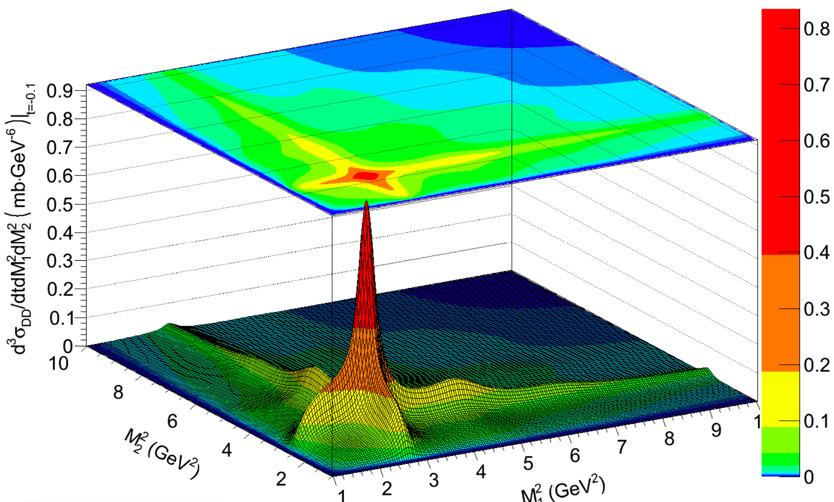


Integrated DD cross sections

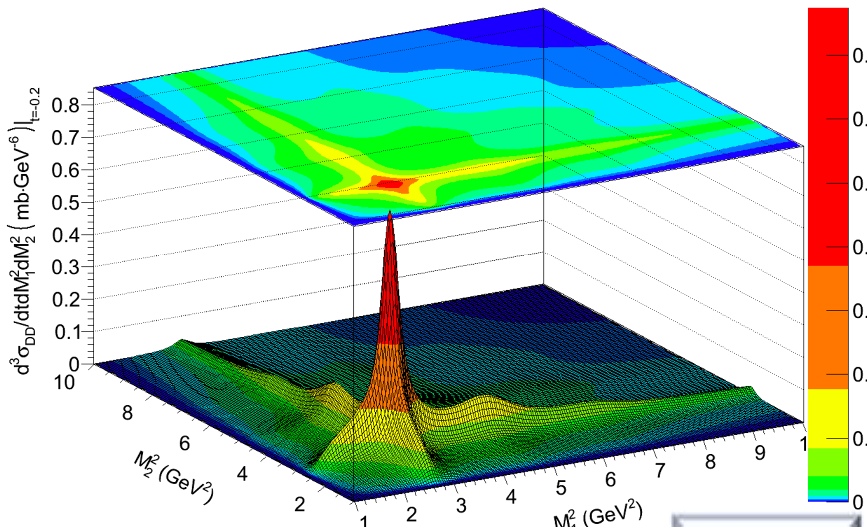




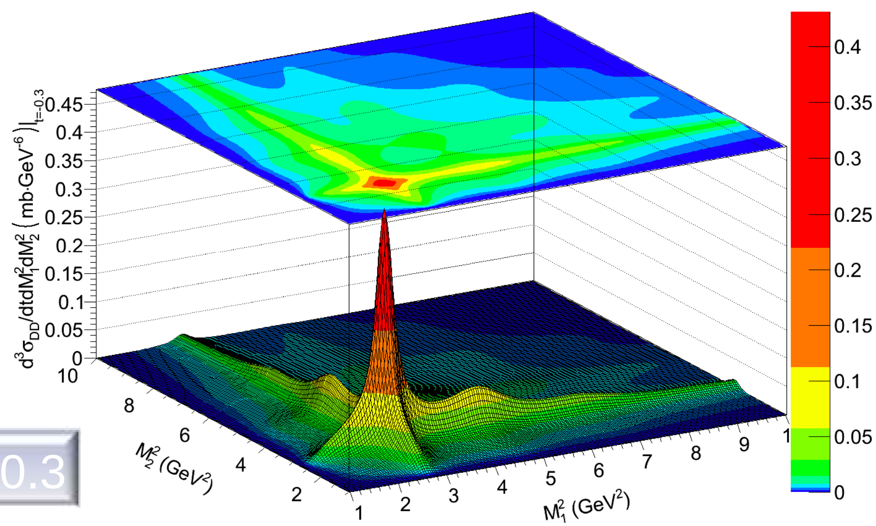
Triple differential DD cross sections



t = - 0.1



t = - 0.2



t = - 0.3

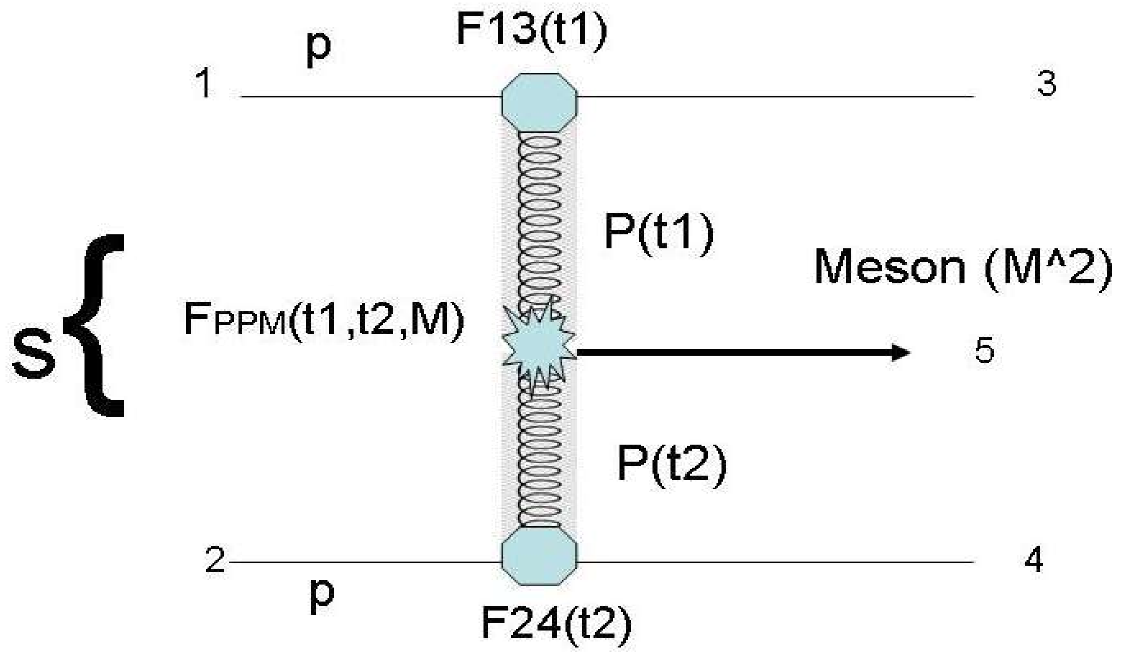
The parameters and results

b_{in} (GeV^{-2})	0.2
b_{in}^{bg} (GeV^{-2})	3
α' (GeV^{-2})	0.25
$\alpha(0)$	1.04
ϵ	1.03
A_n	18.7
B_n	8.8
C_n	3.79e-2

σ_{SD} (mb)	14.13
$\sigma_{SD}(M < 3.5GeV)$ (mb)	4.68
$\sigma_{SD}(M > 3.5GeV)$ (mb)	9.45
σ_{Res}^{SD} (mb)	2.48
σ_{Bg}^{SD} (mb)	9.45
σ_{DD} (mb)	10.68
$\sigma_{DD}(M < 10GeV)$ (mb)	1.05
$\sigma_{DD}(M > 10GeV)$ (mb)	9.63

Prospects (future plans):

1. Central diffractive meson production (double Pomeron exchange);



2. Charge exchange reactions at the LHC (single Reggeon exchnge), e.g. pp→nΔ (in collaboration with Oleg Kuprash and Rainer Schicker)

Open problems:

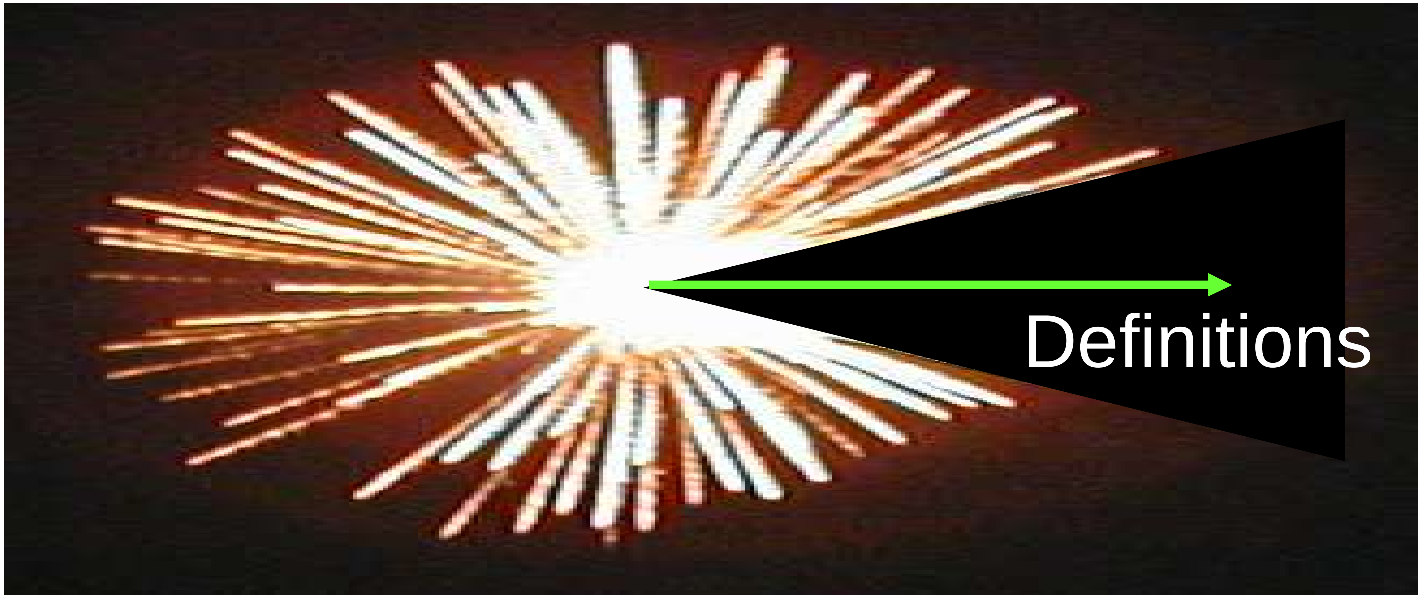
1. Interpolation in energy: from the Fermilab and ISR to the LHC; (Inclusion of non-leading contributions);
3. Deviation from a simple Pomeron pole model and breakdown of Regge-factorization;
4. Experimental studies of the exclusive channels (p+**π,…)** produced from the decay of resonances (N*, Roper?,,,) in the nearly forward direction.
5. Turn down of the cross section towards t=o?!
6. Need for a bank of models. Open an international PROJECT

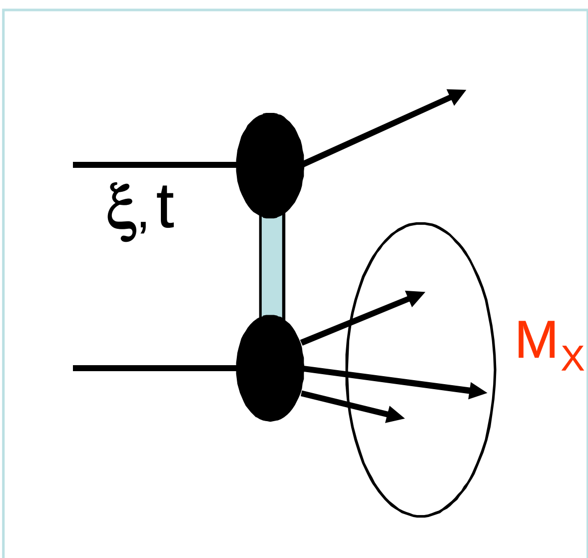
Elastic and total scattering, diffraction in hadron- and lepton-induced reactions:

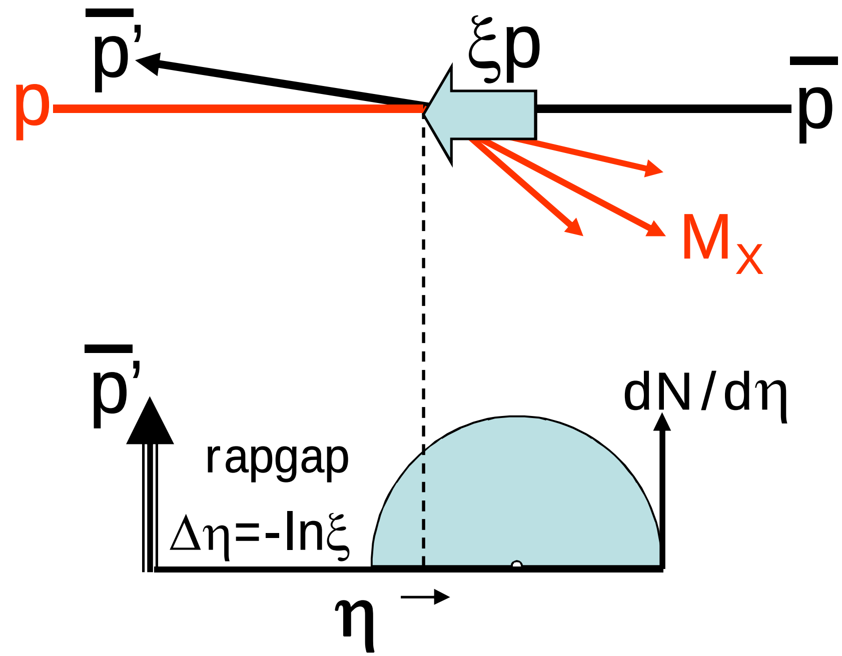
А.Н. Валл, Л.Л. Енковский, Б.В. Струминский: *Взаимодействие адронов при высоких энергиях*, Физика элементарных частиц и атомного ядра (ЭЧАЯ – Particles and Nuclei) **т.19** (1988) стр. 181-223.

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

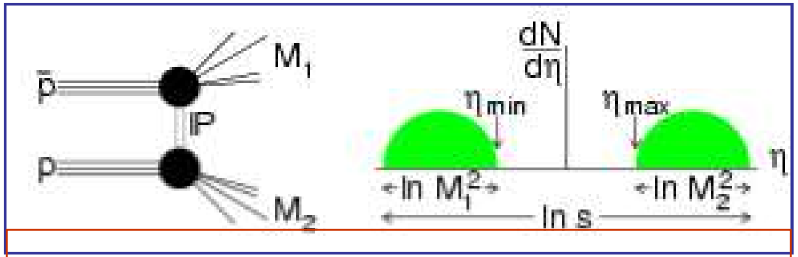
R. Fiore, L. Jenkovszky, R. Orava, E. Predazzi, A. Prokudin, O. Selyugin, *Forward Physics at the LHC; Elastic Scattering*, Int. J.Mod.Phys., **A24**: 2551-2559 (2009).


Definitions

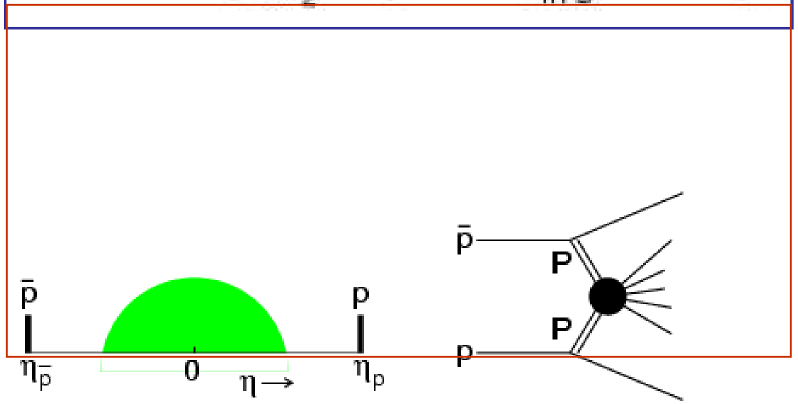

ξ, t
M_X


$\bar{p}'$
ξp
p
$\bar{p}$
M_X
$\bar{p}'$
rapgap
$\Delta\eta = -\ln\xi$
dN / dη
η

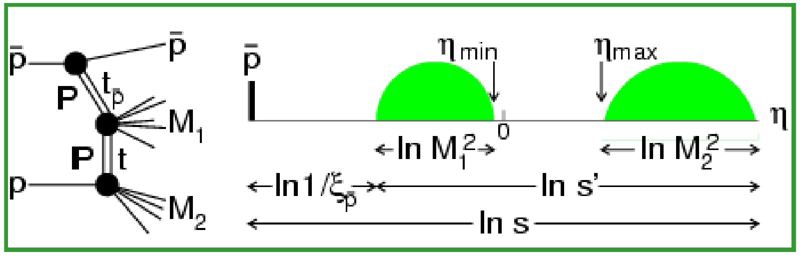
Central and Multigap Diffraction



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

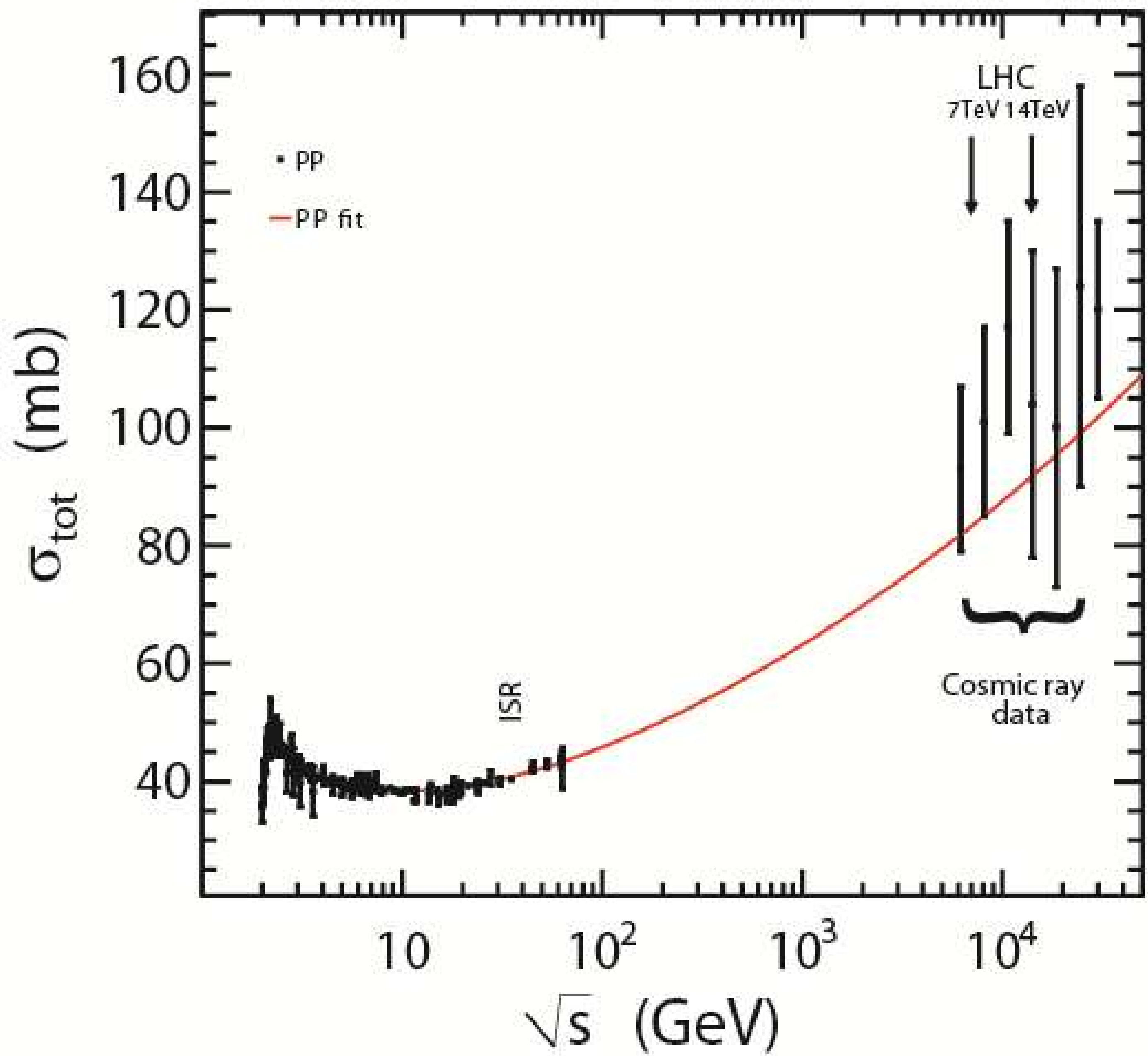


- **Double Pomeron Exchange**
  - **Two forward gaps**

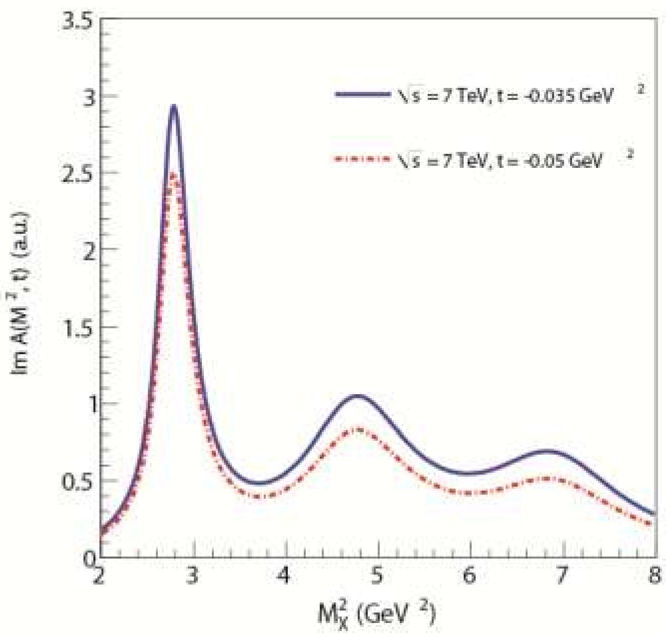


- **SDD: Single+Double Diffraction**
  - **One forward gap+ one central gap**

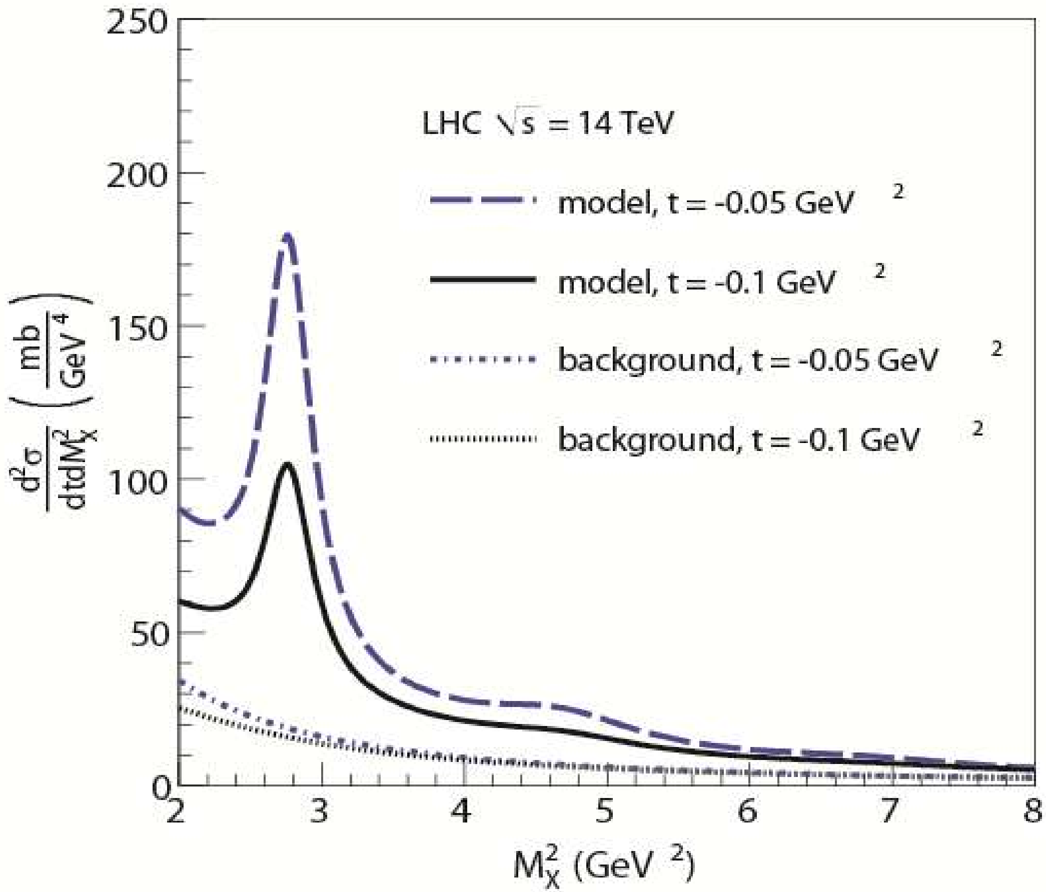
Rate for second diffractive gap is not suppressed!

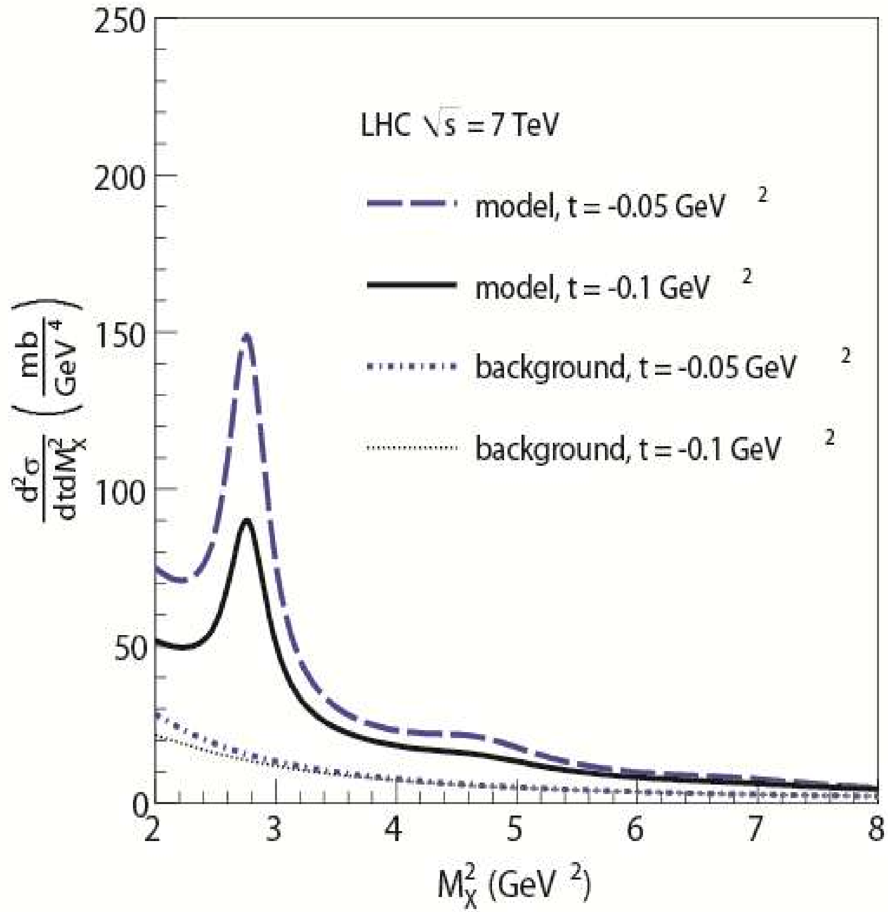


σ_tot (mb)
160
140
120
100
80
60
40
• PP
PP fit
ISR
LHC
7TeV 14TeV
Cosmic ray data
10
10^2
10^3
10^4
√s (GeV)

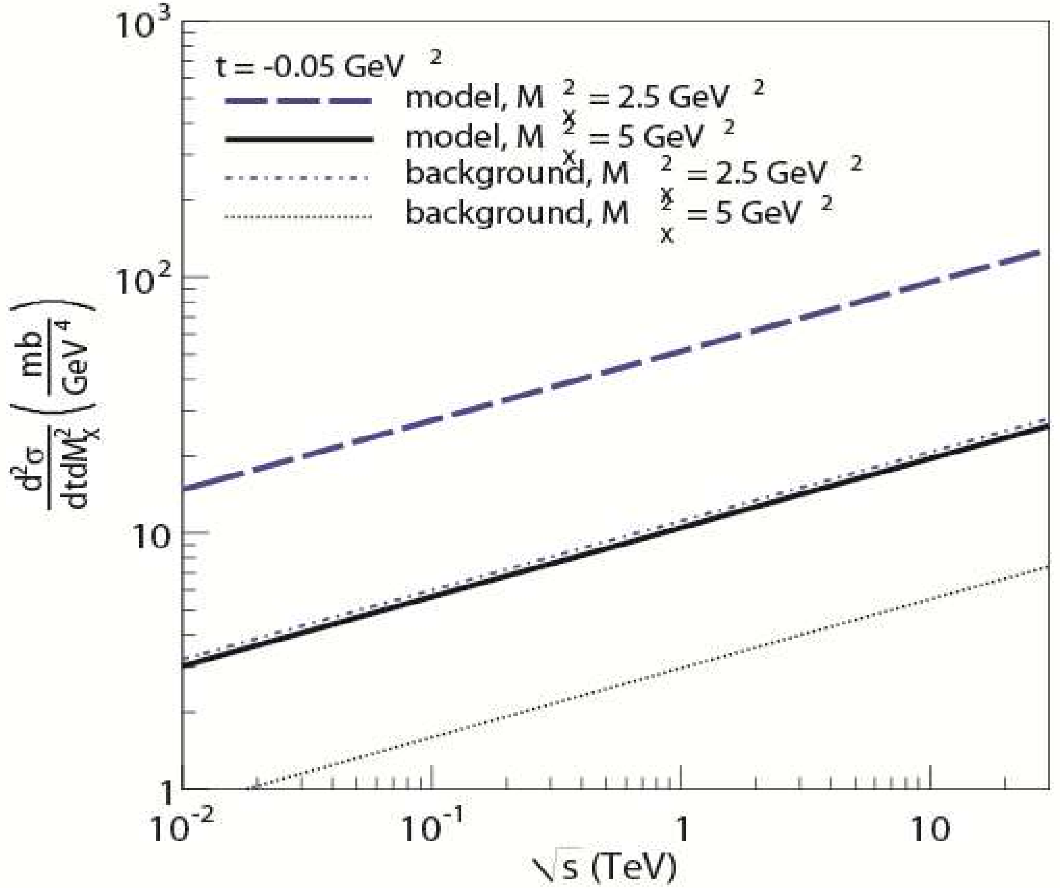


√s = 7 TeV, t = -0.035 GeV 2
√s = 7 TeV, t = -0.05 GeV 2
Im A(M 2 , t) (a.u.)
M2X (GeV 2)

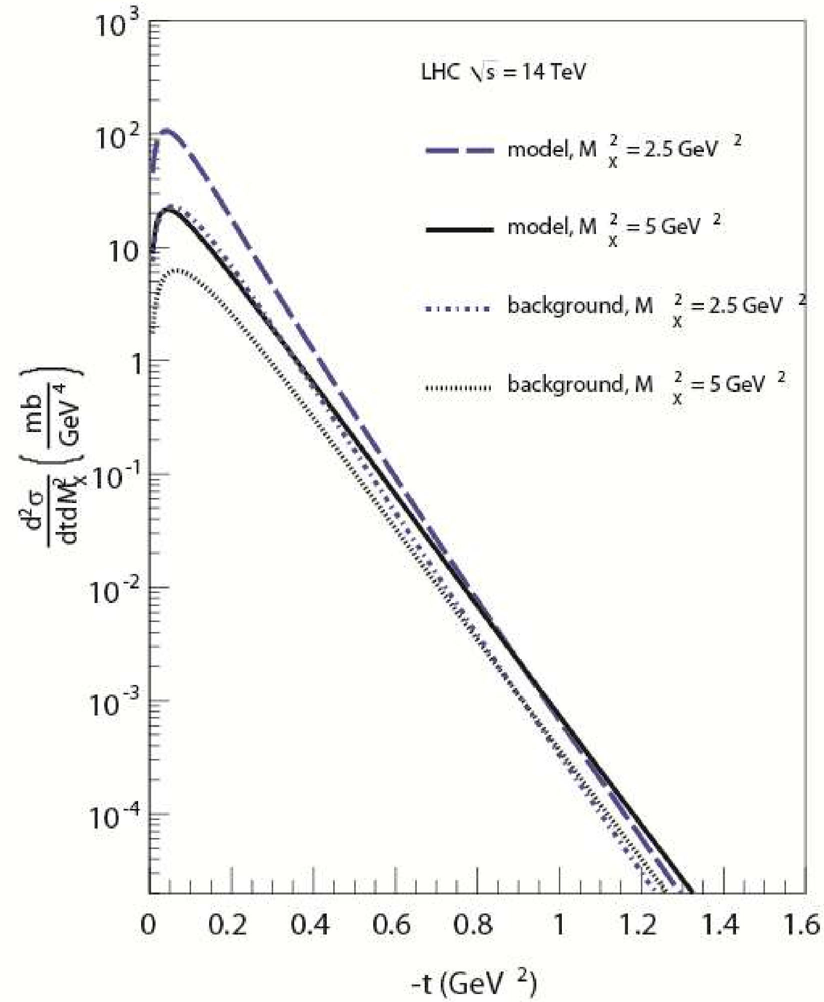

LHC $\sqrt{s}$ = 14 TeV
model, t = -0.05 GeV ^{2}
model, t = -0.1 GeV ^{2}
background, t = -0.05 GeV ^{2}
background, t = -0.1 GeV ^{2}
$\frac{d^2\sigma}{dtdM_X^2}\left(\frac{mb}{GeV^4}\right)$
M_X^2 (GeV ^{2})
0
50
100
150
200
250
2
3
4
5
6
7
8



LHC $\sqrt{s}$ = 7 TeV
model, t = -0.05 GeV ^{2}
model, t = -0.1 GeV ^{2}
background, t = -0.05 GeV ^{2}
background, t = -0.1 GeV ^{2}
$\frac{d^2\sigma}{dtdM_X^2}\left(\frac{mb}{GeV^4}\right)$
M_X^2 (GeV ^{2})
0
50
100
150
200
250
2
3
4
5
6
7
8



t = -0.05 GeV 2
model, M x 2 = 2.5 GeV 2
model, M x 2 = 5 GeV 2
background, M x 2 = 2.5 GeV 2
background, M x 2 = 5 GeV 2
$\frac{d^2\sigma}{dtdM_X^2}\left(\frac{mb}{GeV^4}\right)$
10^3
10^2
10
1
10^{-2}
10^{-1}
1
10
$\sqrt{s}$ (TeV)



LHC $\sqrt{s}$ = 14 TeV
model, M_X^2 = 2.5 GeV ^{2}
model, M_X^2 = 5 GeV ^{2}
background, M_X^2 = 2.5 GeV ^{2}
background, M_X^2 = 5 GeV ^{2}
$\frac{d^2\sigma}{dt dM_X^2}\left(\frac{mb}{GeV^4}\right)$
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
-t (GeV ^{2})