EDS (Blois) 2017

Praha, June 26-30

ELASTIC & INELASTIC DIFFRACTION AT THE LHC

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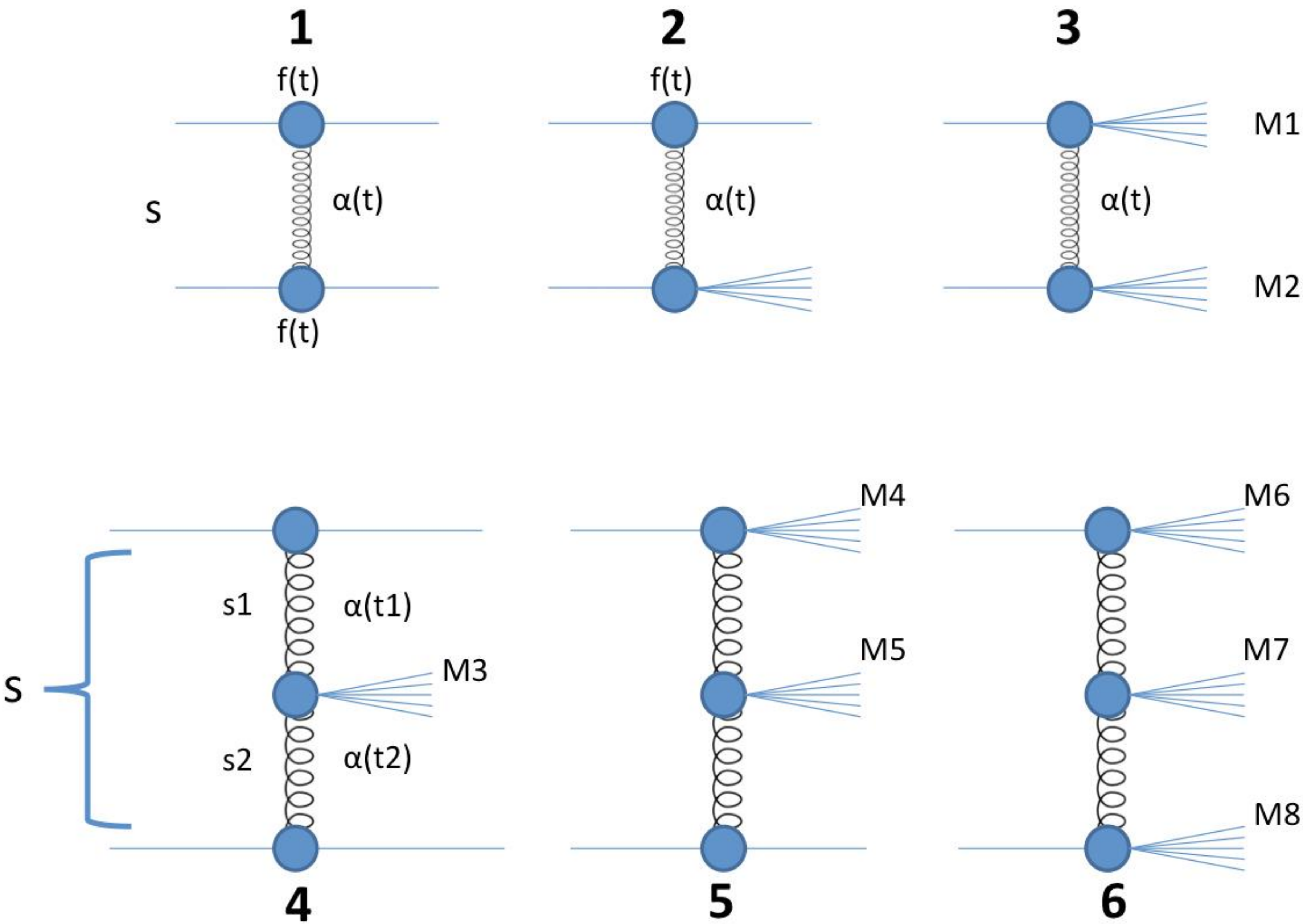
In collaboration with R. Fiore, R. Schicker, and I Szanyi

• Plan:

- Total cross section (slow-down, saturation?): Francesco Giovanni Celiberto, Laszlo Jenkovszky, Volodymyr Myronenko, **Saturation effects in low-x DIS structure functions and related hadronic total cross sections, Low-x 2016; arXiv:1608.04646;**
- Low-|t| elastic scattering (the "break"): László Jenkovszky, István Szanyi **Structures in the diffraction cone: the "break" and "dip" in high-energy proton-proton scattering,** Int'l J. Mod. Phys., in press, **arXiv:1701.01269, Fine structure of the diffraction cone: manifestation of t channel unitarity,** PEPAN Letters (Physics of Particles and Nuclei Letters), v. 14 (2017) N.5;
- **Single and double DD at low masses (resonances in M^2)** 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**;**
- Central production (Rainer Schicker's talk)

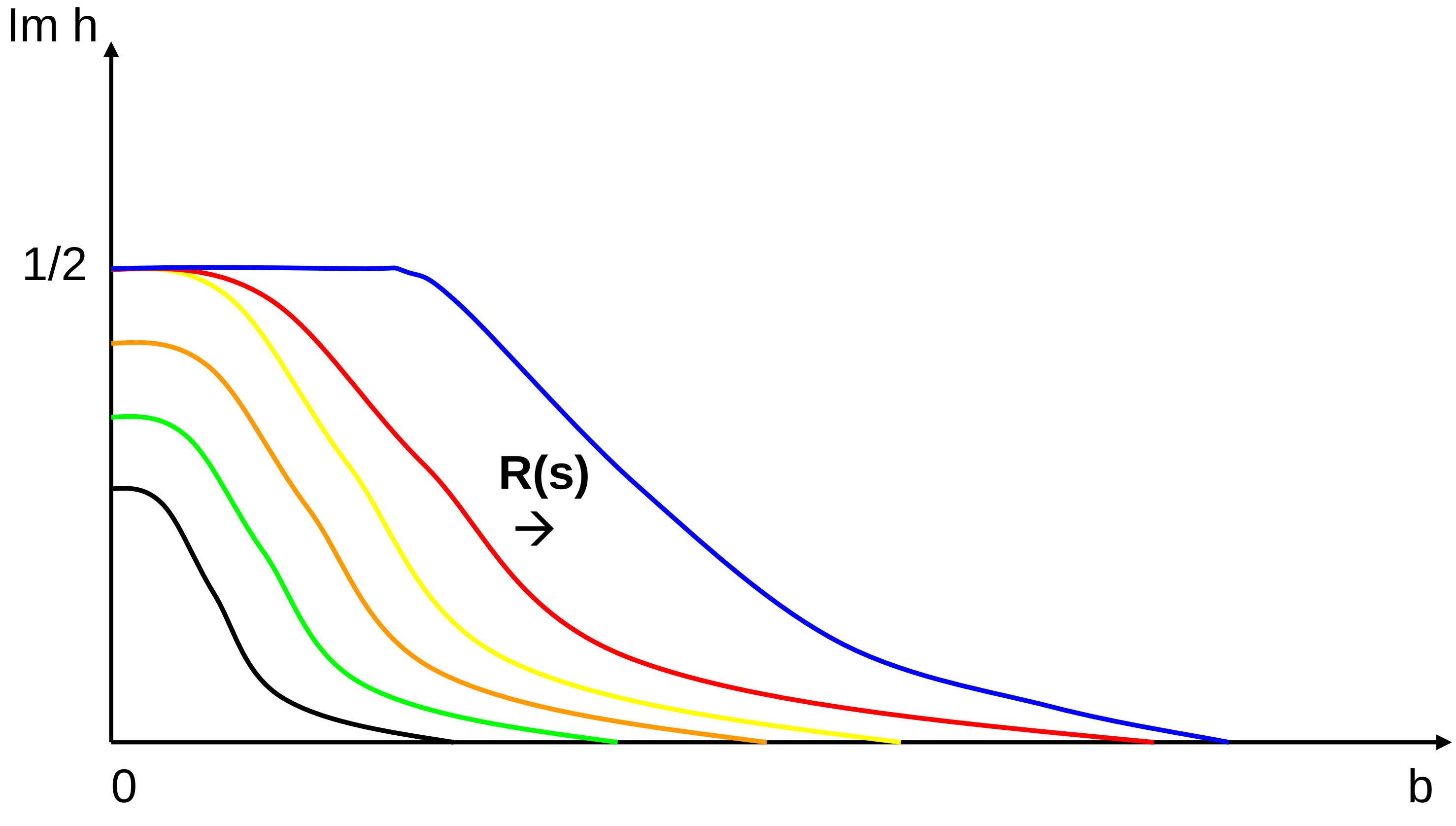


1
2
3
f(t)
f(t)
s
α(t)
α(t)
α(t)
M1
M2
f(t)
s1
α(t1)
M3
S
s2
α(t2)
M4
M5
M6
M7
M8
4
5
6

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)): $h(s,b) = \Im u(s,b)/[1 - iu(s,b))]$,


Im h
1/2
R(s)
→
0
b

Direct, s-channel point of view: additive quark model, single and multiple scattering of partons (Glauber).

Additive quark model relations (Levin-Frankfurt, 70-ies):

$$\sigma^t_{pp} = \sigma_0 n_A n_B. \tag{1}$$

While this simple rule is confirmed *e.g.* by the ratio 2/3 of meson-baryon to baryon-baryon scattering in a fairly wide range of intermediate energies, *e.g.* $\sigma^t_{\pi p}/\sigma^t_{pp} \approx 0.67$ at $\sqrt{s} \approx 10$ GeV, it is progressively violated as the energy increases. It was suggested in Ref. [2, 3] that while the constant components of the cross sections, obeying the above quark rule are determined by constituents quarks their rise comes from the increasing number of see quarks.

In Refs. [2, 3] the rise of hadronic total cross sections was related the proliferation of see quarks and gluons in colliding hadron, hence Eq. (1) modifies as

$$\sigma^t_{pp} = (n_v + n_s)^2, \tag{2}$$

where n_v and n_s is the number of valence and see quarks and gluons in the proton. The number of see quarks and gluons was related to the logarithmic scaling violation, resulting in

The fraction of momenta carried by quarks can be calculated from the integrals

$$\int_0^1 dx F_2^v(s, Q^2) = 0.423,$$

$$\int_0^1 dx F_2^s(s, Q^2) = 0.01 + 0.001 \ln(s/Q_0^2).$$

Consequently,

$$\sigma_{pp}^{tot} \approx \sigma_0 n_{v_1} n_{v_2} (1 + 0.016 \ln(s/Q_0^2).$$

We remind that $x \sim Q^2/s$.

$$\int_0^1 dx[F_2^V(x,Q^2) + F_2^S(x,Q^2)],$$

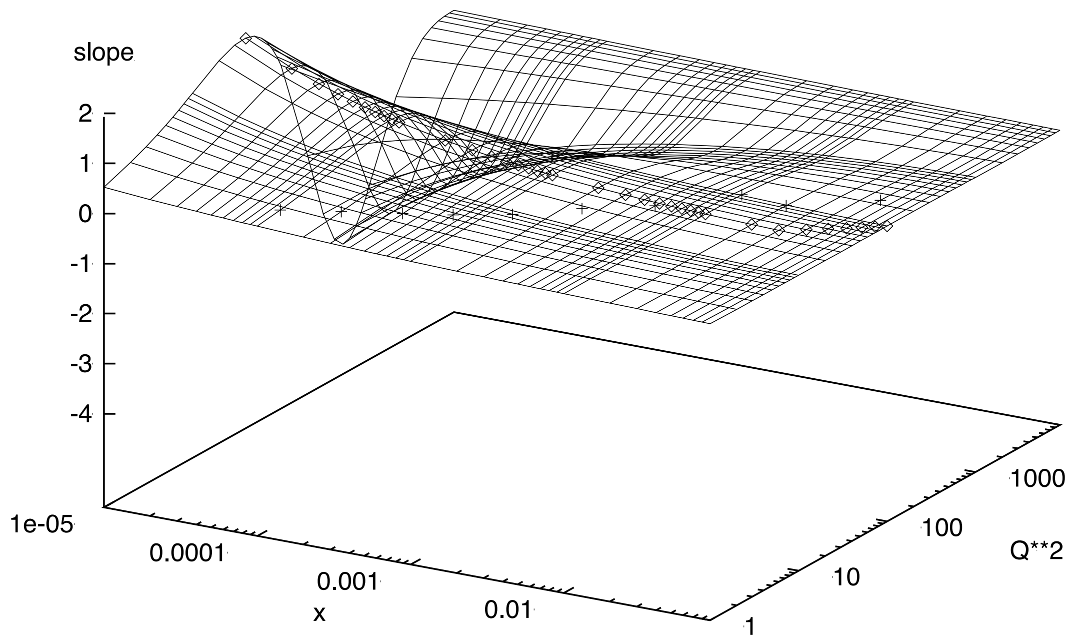
with typically logarithmic scaling violation parametrizations know at those times, e.g.

$$F_2^S(x) = F_2(x)\left[1 - \epsilon \ln\left(\frac{Q^2}{Q_0^2}\right) \ln\left(\frac{x}{x_0}\right)\right],$$

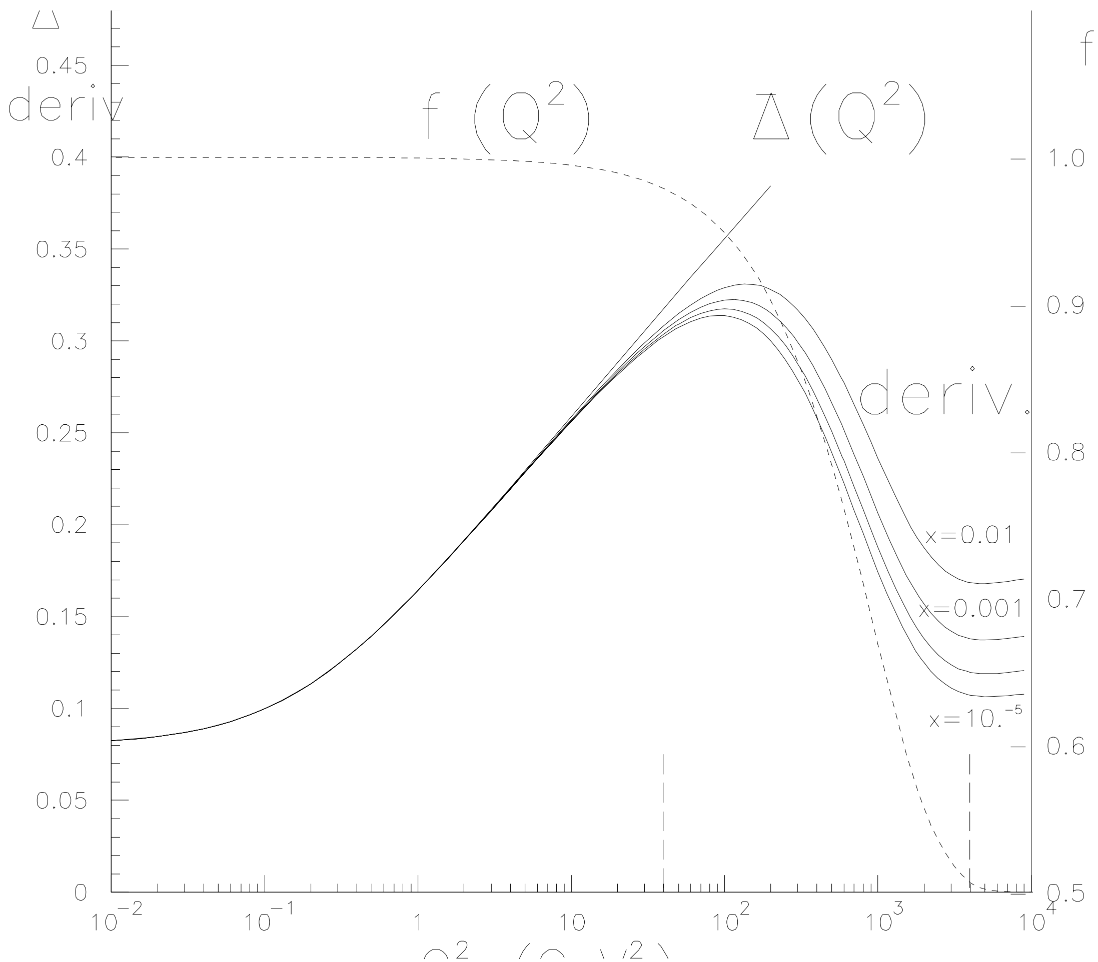
or

$$F_2^S(x) = F_2(x)\left[1 + \epsilon\left(\frac{Q^2}{Q_0^2}\right)^{f(x)}\right], \quad f(x) = x_0 - x,$$

with the following values of the parameters: $a = 0.25,\ b = 1.35,\ c = 0.2,\ \epsilon = 0.05$ and $q_0^2 = 3\ \mathrm{GeV}^2$,



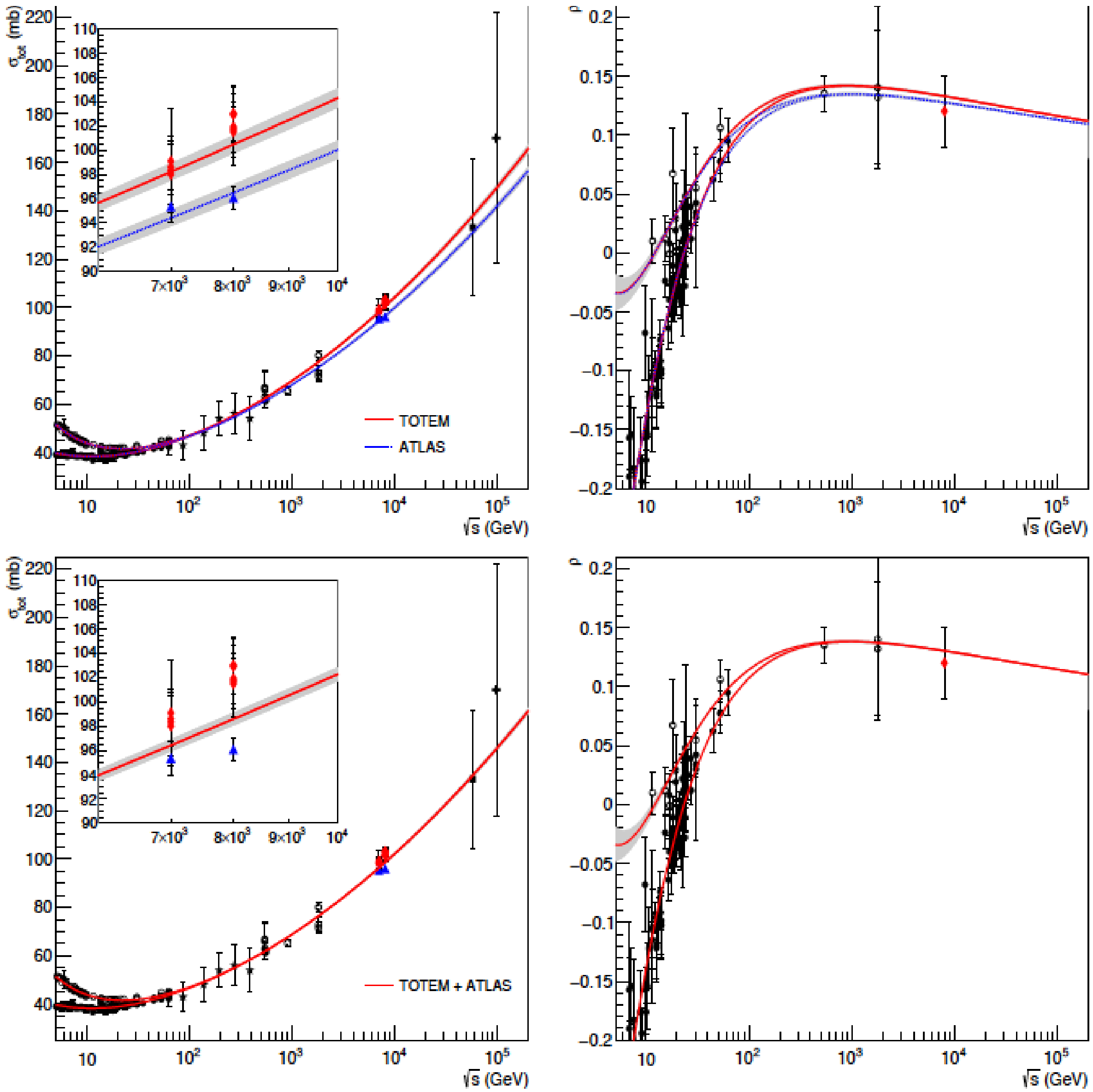
slope
2
1
0
-1
-2
-3
-4
1e-05
0.0001
0.001
x
0.01
1
10
100
1000
Q**2



Δ
deriv
f (Q²)
Δ(Q²)
f
deriv.
x=0.01
x=0.001
x=10.⁻⁵
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1.0
0.9
0.8
0.7
0.6
0.5
10⁻²
10⁻¹
1
10
10²
10³
10⁴

Bounds on the rise of total cross section from LHC7 and LHC8 data

D. A. Fagundes[a], M. J. Menon[b], P. V. R. G. Silva[b]

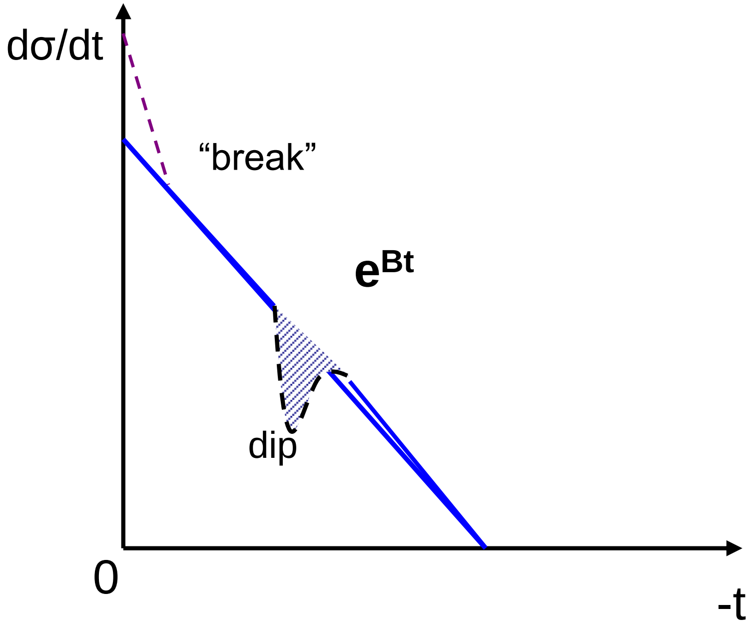


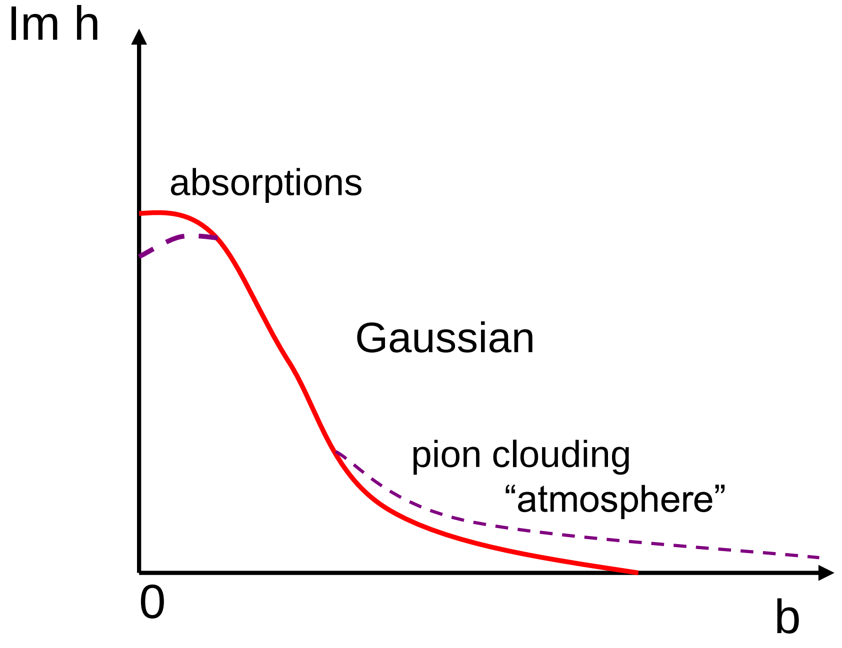
1703.07486

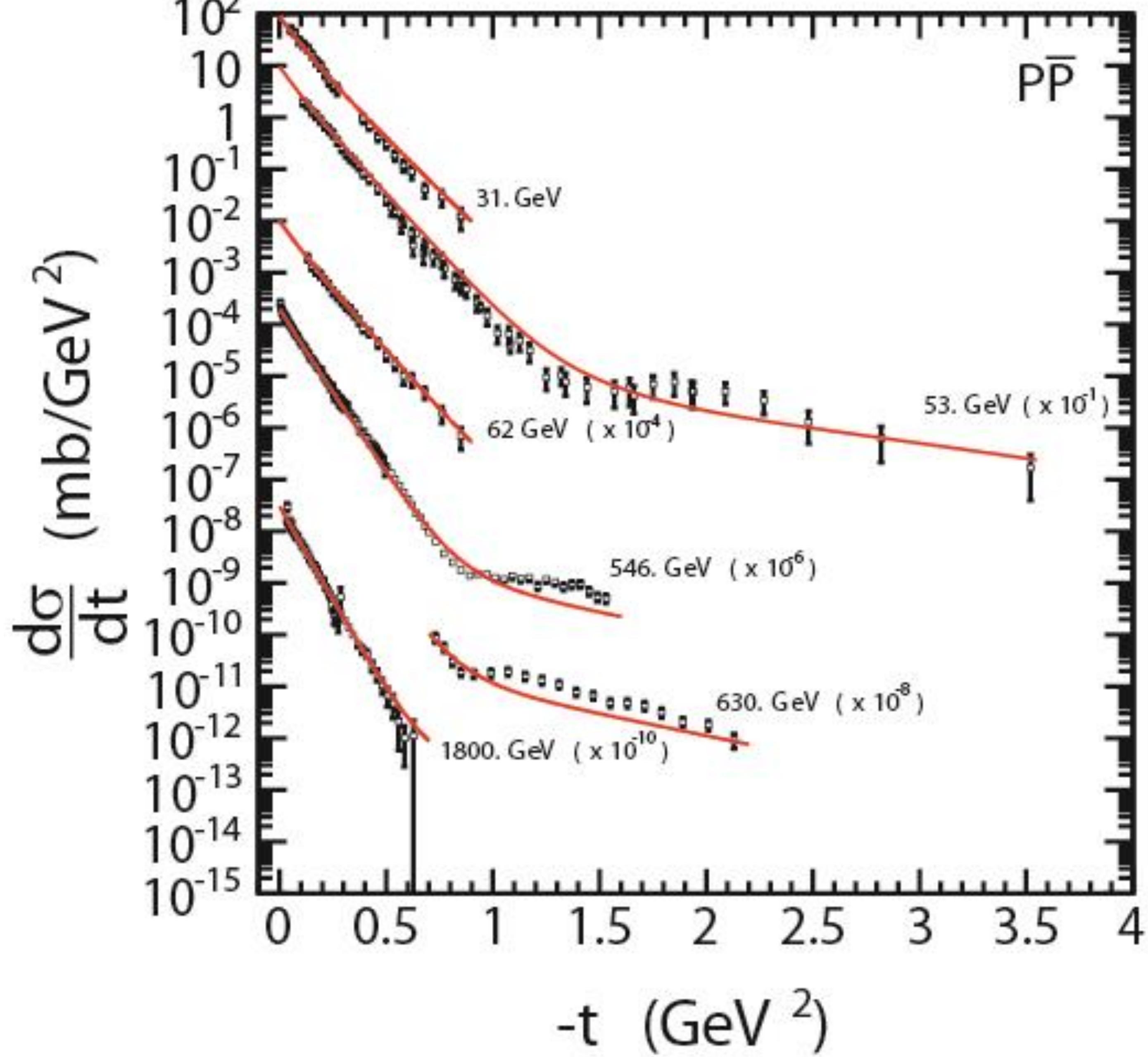
Figure 1: Fit results with the L2 model to ensembles T and A (above) and T+A (below).

1. **On-shell (hadronic) reactions (s,t, Q^2=m^2);**
   t ←→ b **transformation dictionary:**

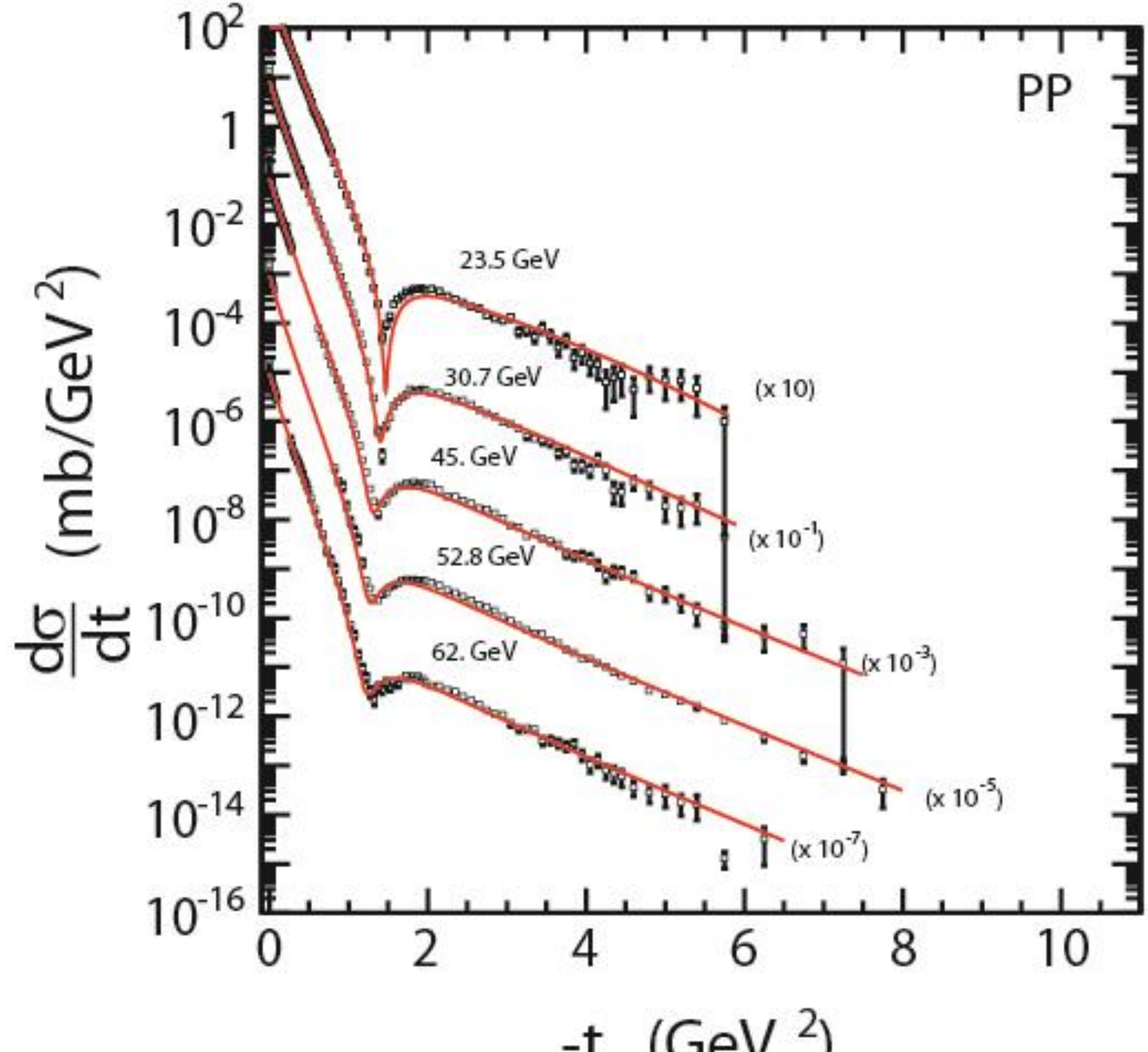
$$h(s,b) = \int_0^\infty d\sqrt{-t}\sqrt{-t}A(s,t)$$





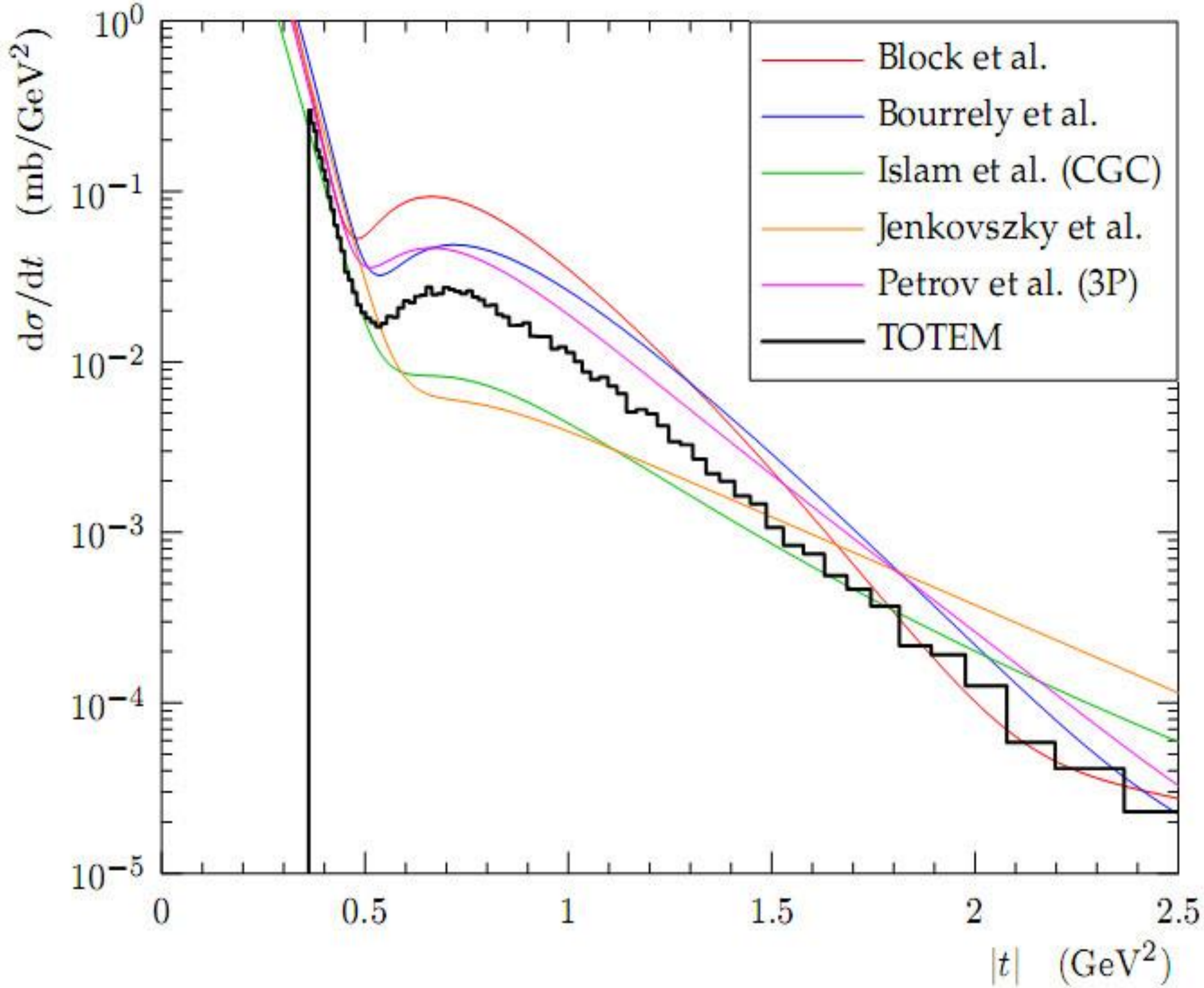


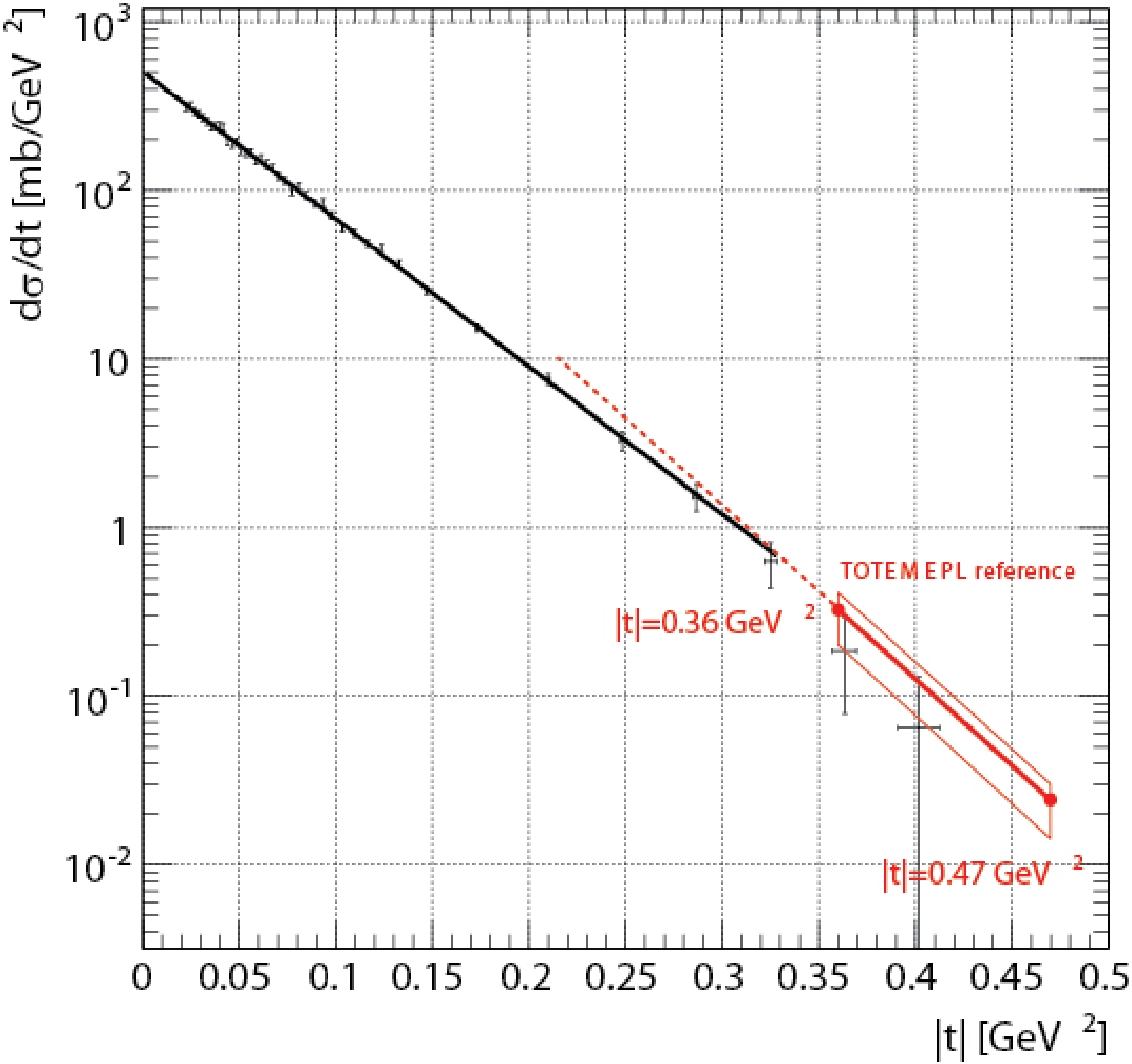
PP̄
31. GeV
53. GeV (x 10⁻¹)
62 GeV (x 10⁻⁴)
546. GeV (x 10⁻⁶)
630. GeV (x 10⁻⁸)
1800. GeV (x 10⁻¹⁰)
dσ/dt (mb/GeV²)
-t (GeV²)



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)

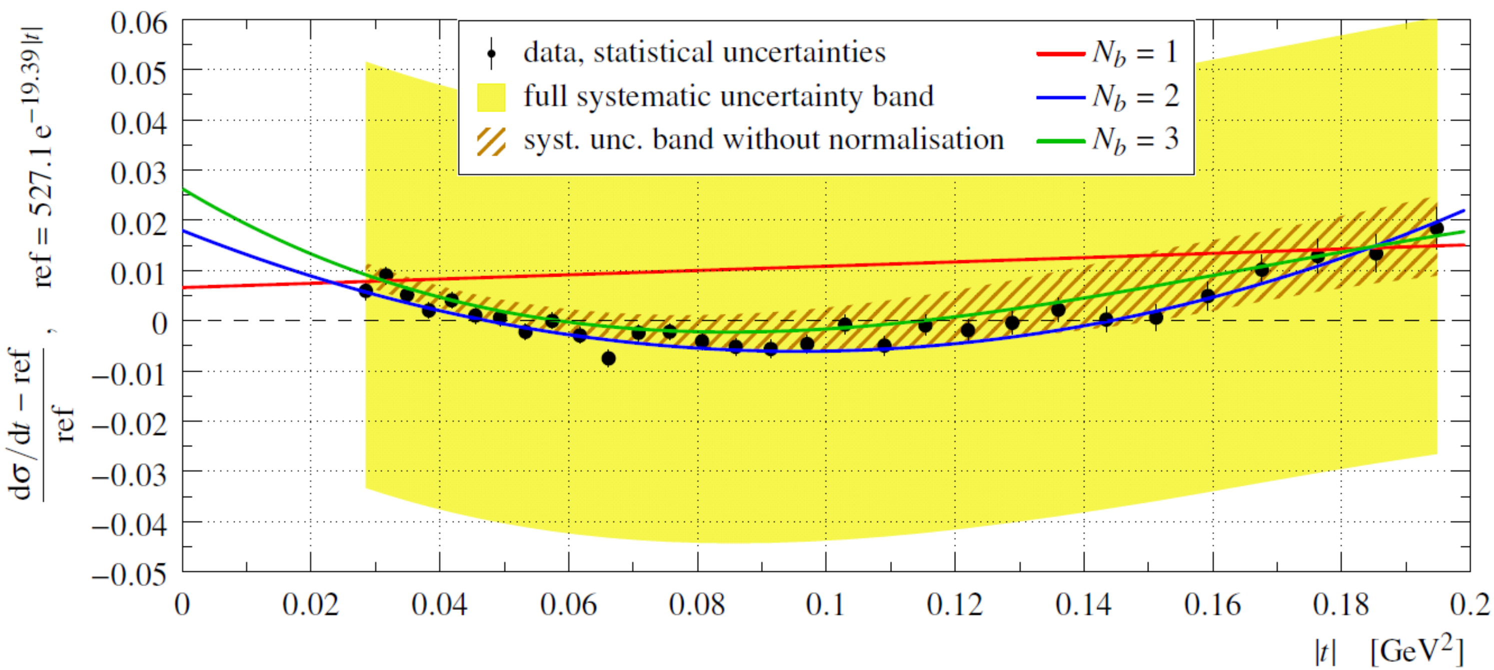
CERN LHC, TOTEM Collab., June 26, 2011:





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

Elastic scattering: non-exponentiality at low |t|



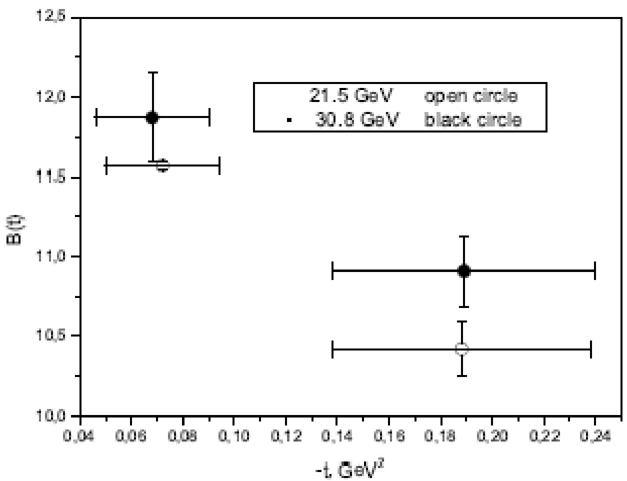
$$\frac{d\sigma}{dt}(t) = \left.\frac{d\sigma}{dt}\right|_{t=0} \exp\left(\sum_{i=1}^{N_b} b_i\, t^i\right)$$

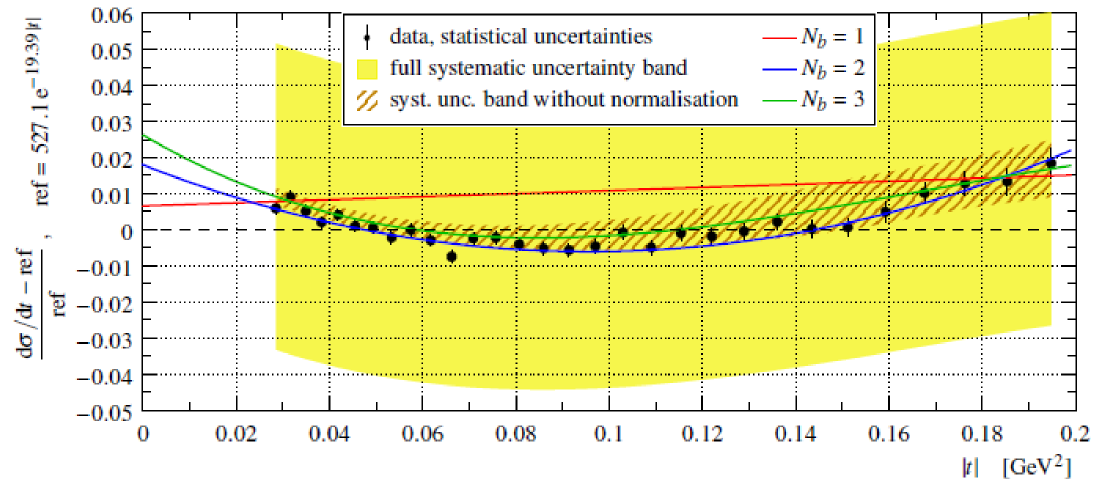
N_b = 1 excluded with 7σ significance!

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

Nuclear Physics B 899 (2015) 527–546

“break”





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

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

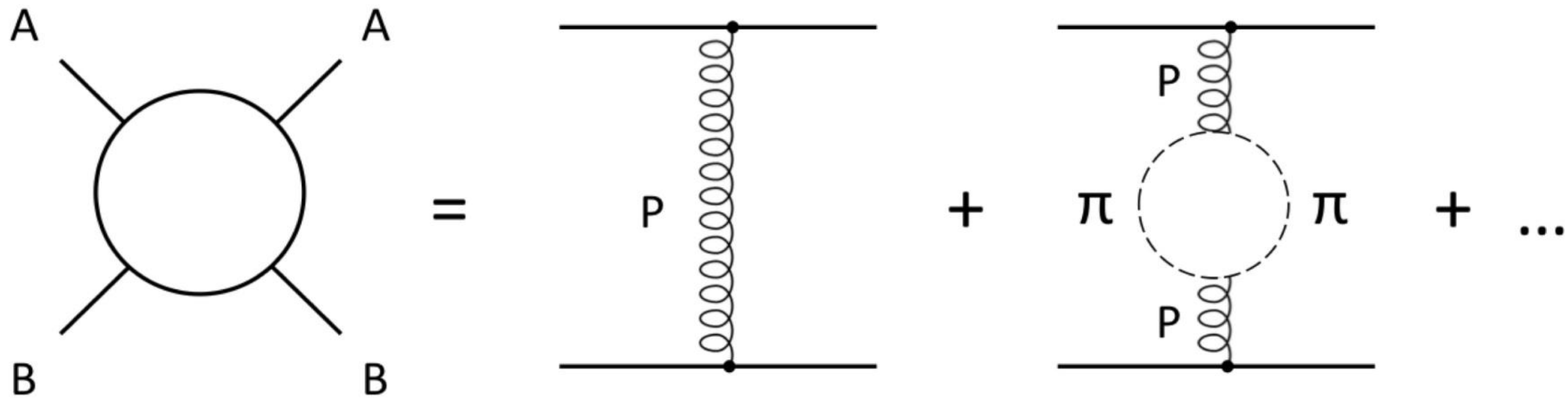
R(t) calculated for low-|t| 8 TeV data.

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

$$ref = Ae^{Bt}$$

arXiv:1410.4106
G. Barbiellini et al., Phys. Lett. B 39 (1972) 663

arXiv:1503.08111



Experimentalists usually quantify the departure from the linear exponential by replacing

$$|A^N| = a\exp(Bt) \rightarrow a\exp(b_1 t + b_2 t^2 + b_3 t^3 + ...) \tag{1}$$

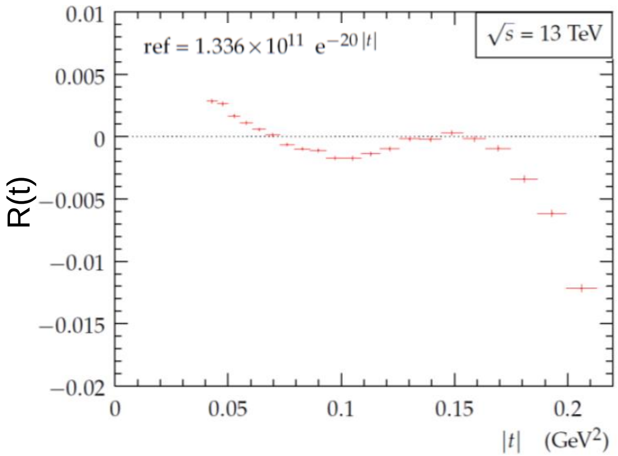
with coefficients b_i fitted to the data.

Two-pion loop contributes in the t channel through Regge trajectories, that are non-linear complex functions,

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

where t_0 is the lightest threshold, $4m_\pi^2$ in the case of the vacuum quantum numbers (Pomeron or f meson). Since $Re\alpha(4m_\pi^2)$ is small, a square-root threshold is a reasonable approximation to the above constrain.

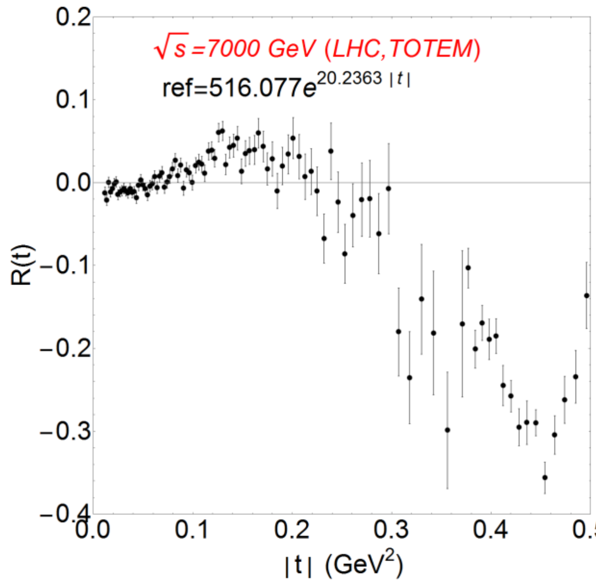
Correlation between the “break” and “dip”



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

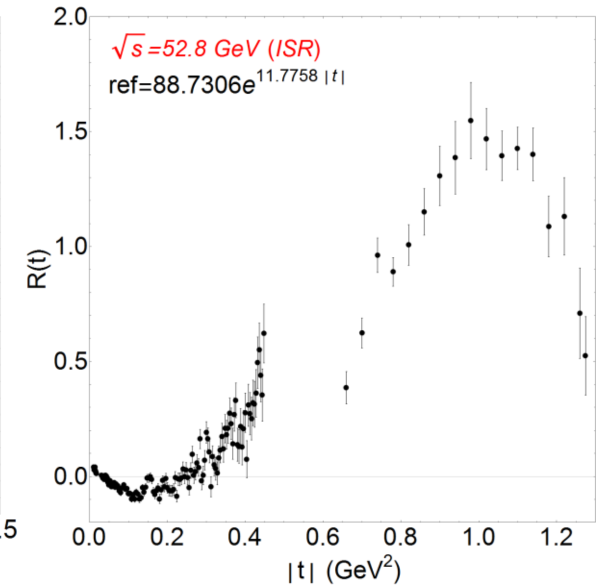
$$R(t) = \frac{d\sigma(t)/dt - ref}{ref}$$

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)

Pomeron's relative contribution

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

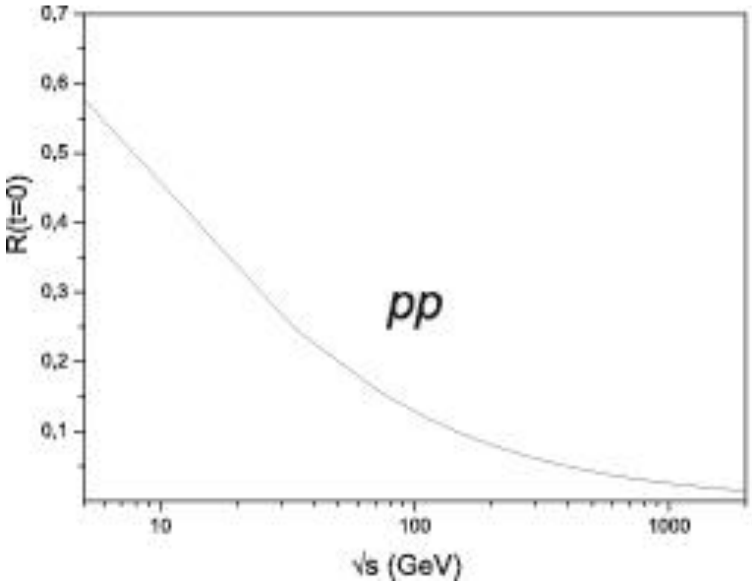
$$R(s,t=0) = \frac{\Im m(A(s,t) - A_P(s,t))}{\Im A(s,t)}, \tag{1}$$

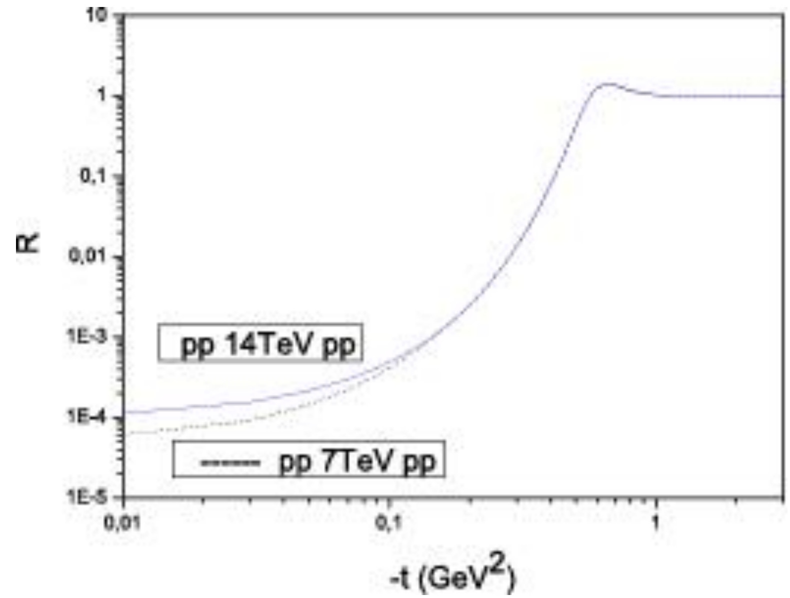
where the total scattering amplitude A includes the Pomeron contribution A_P plus the contribution from the secondary Reggeons and the Odderon.

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





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

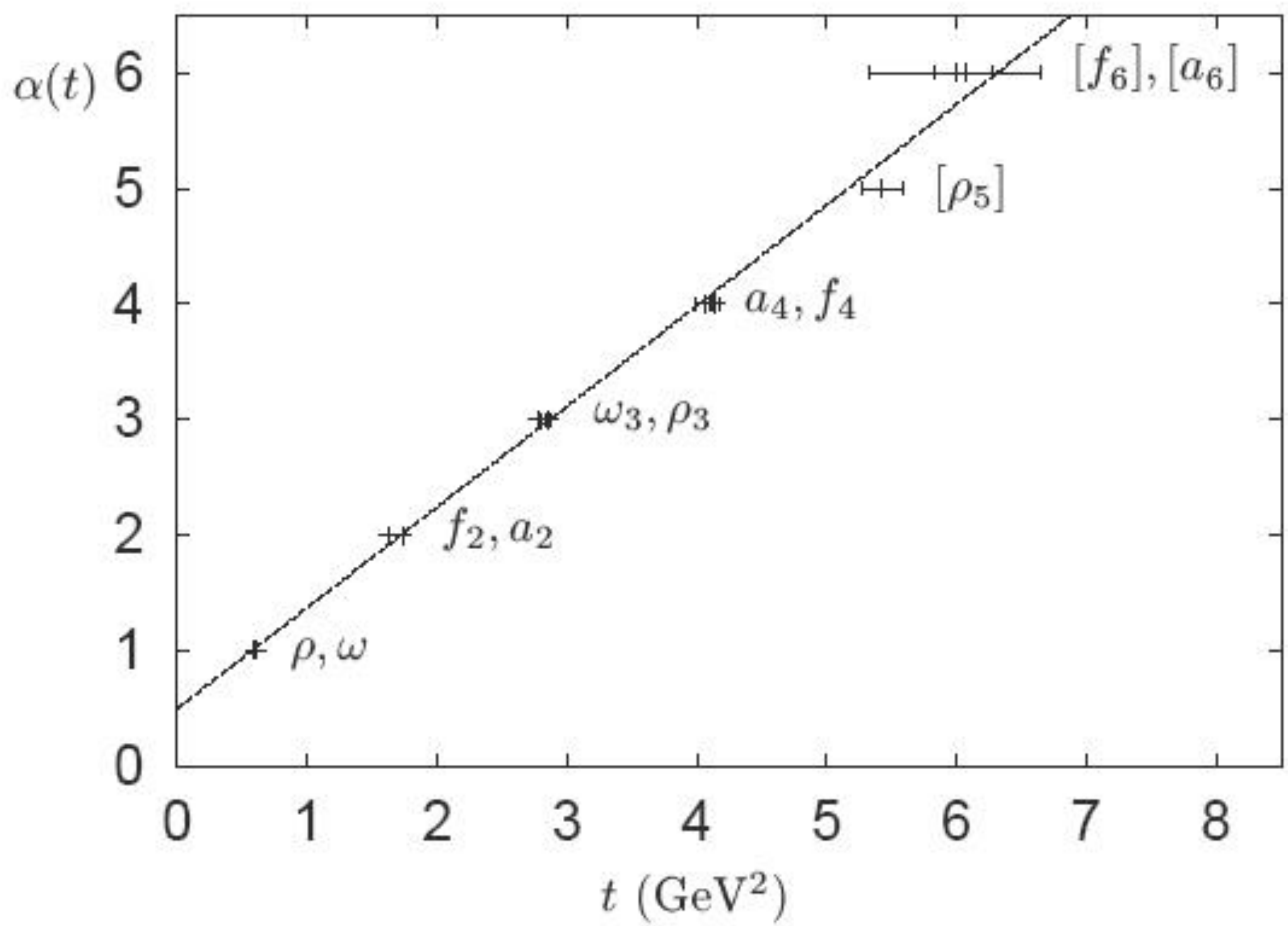
$$\Im\alpha(t) \sim (t-t_0)^{\Re\alpha(t_0)+1/2}, \quad t \to t_0,$$

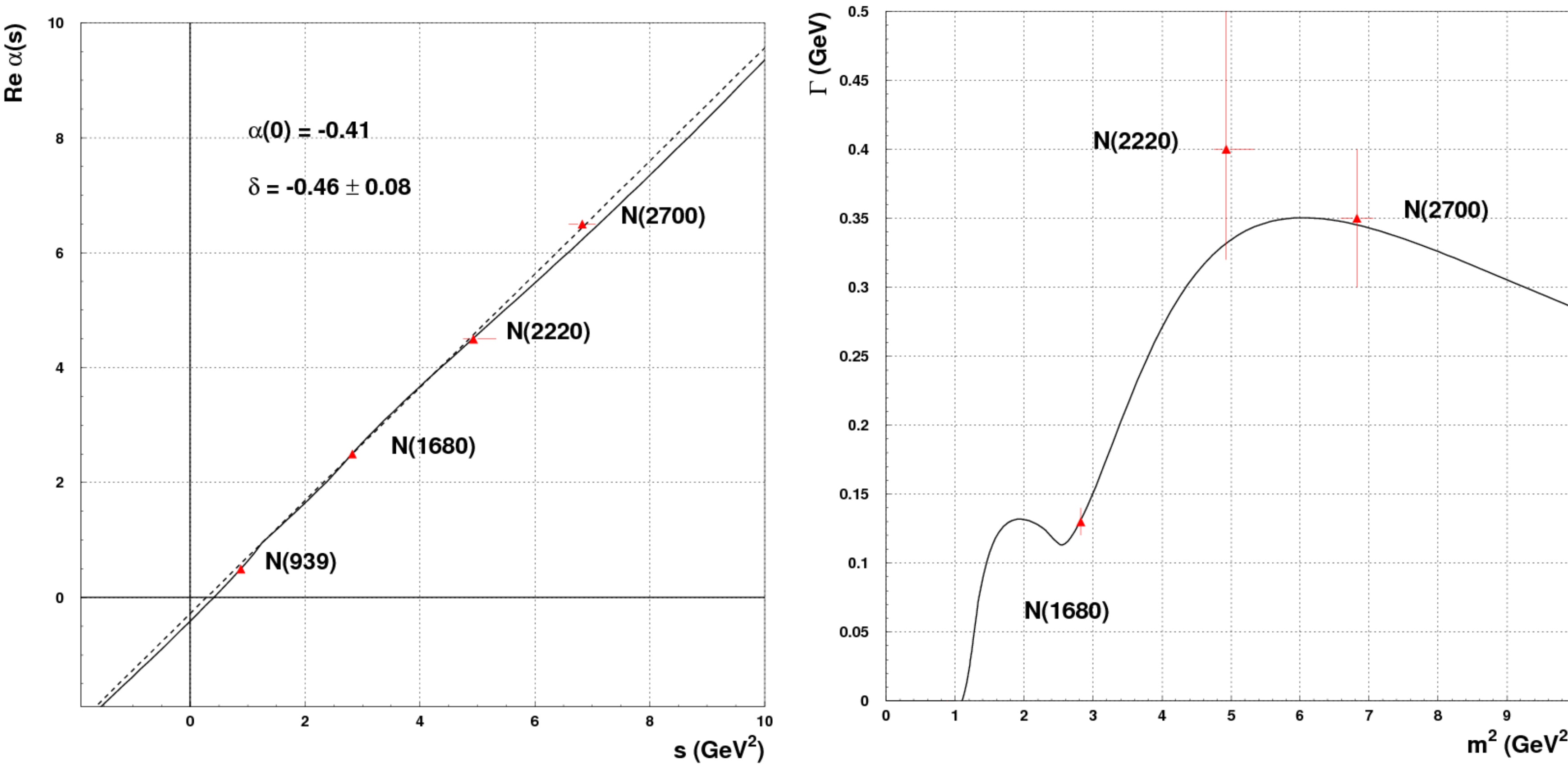
where t_0 is the lightest threshold. For the Pomeron trajectory it is $t_0 = 4m_\pi^2$, and near the threshold:

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

Linear particle trajectories

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

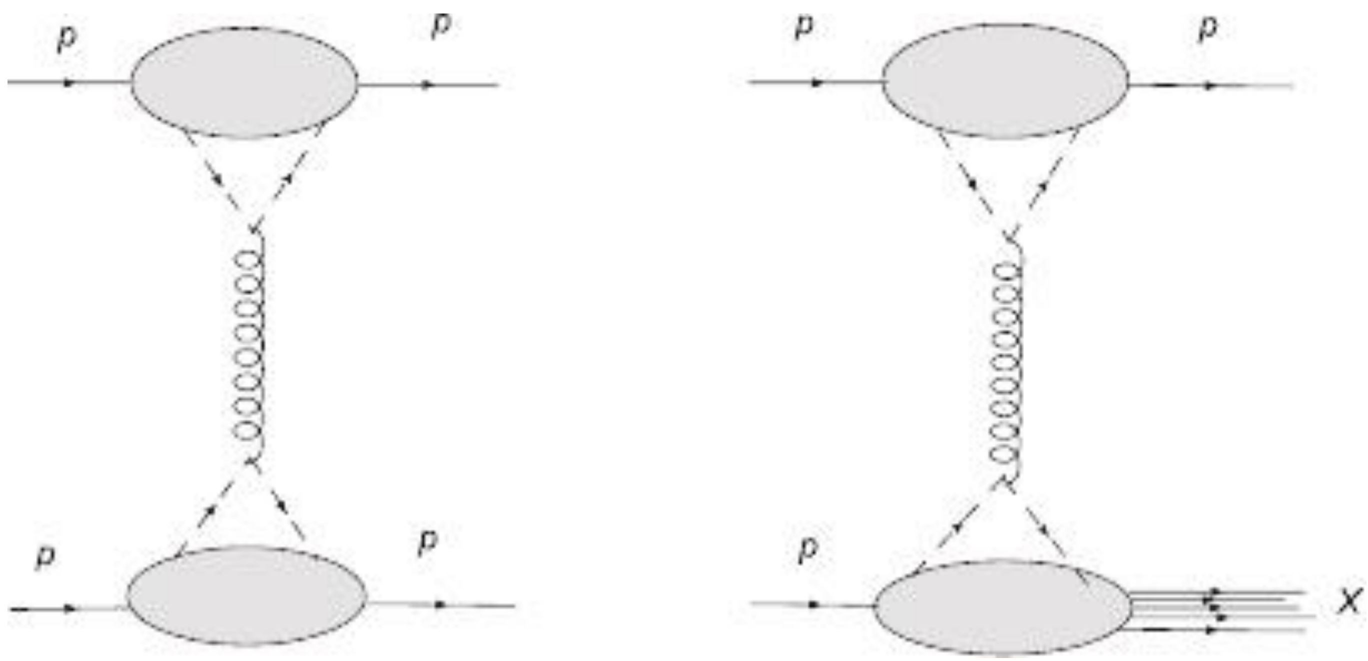


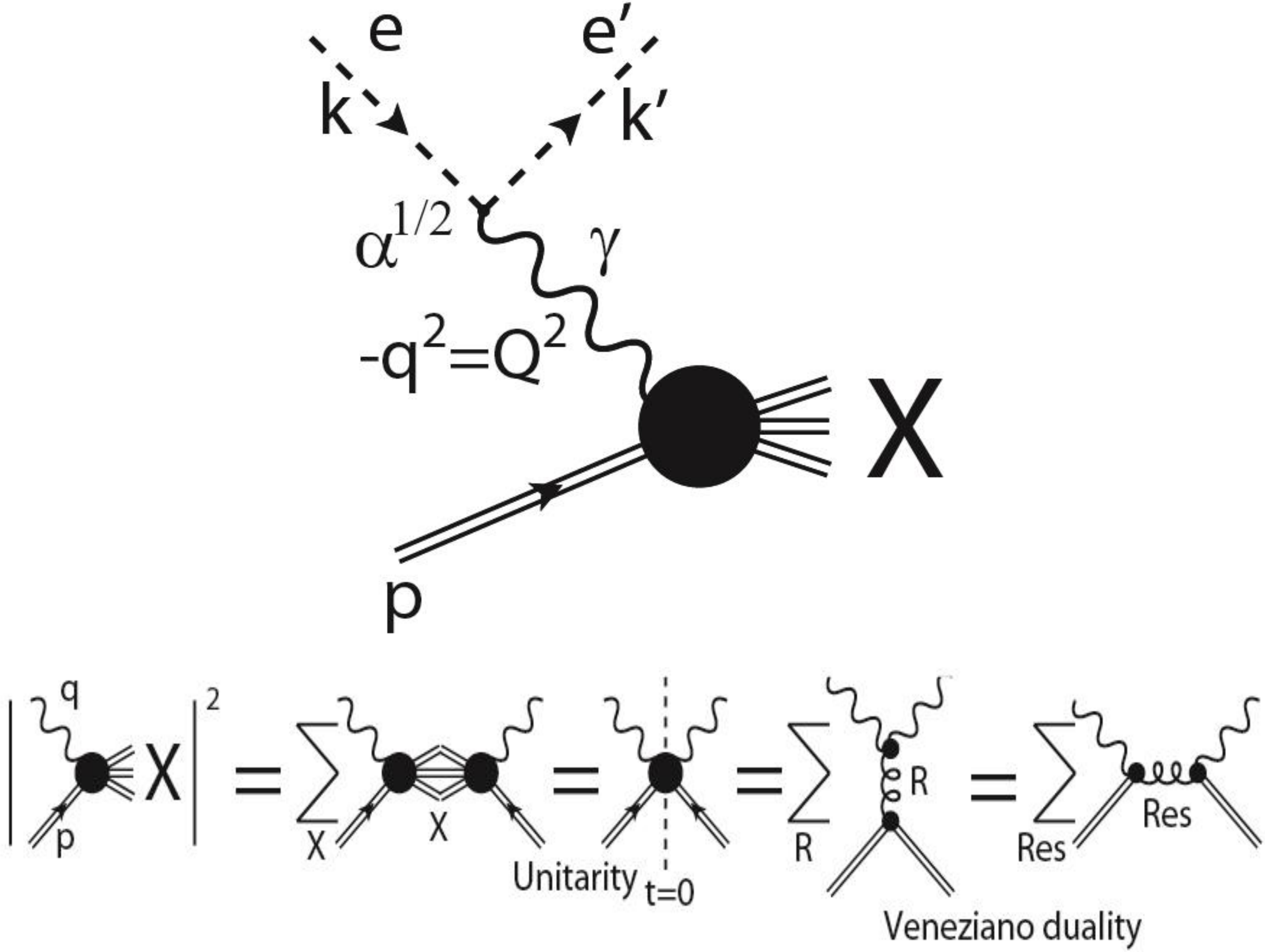


The imaginary part of the trajectory can be written in the following way:

$$\mathcal{I}m\,\alpha(s) = s^{\delta} \sum_n c_n \left(\frac{s - s_n}{s} \right)^{\lambda_n} \cdot \theta(s - s_n)\,, \tag{1}$$

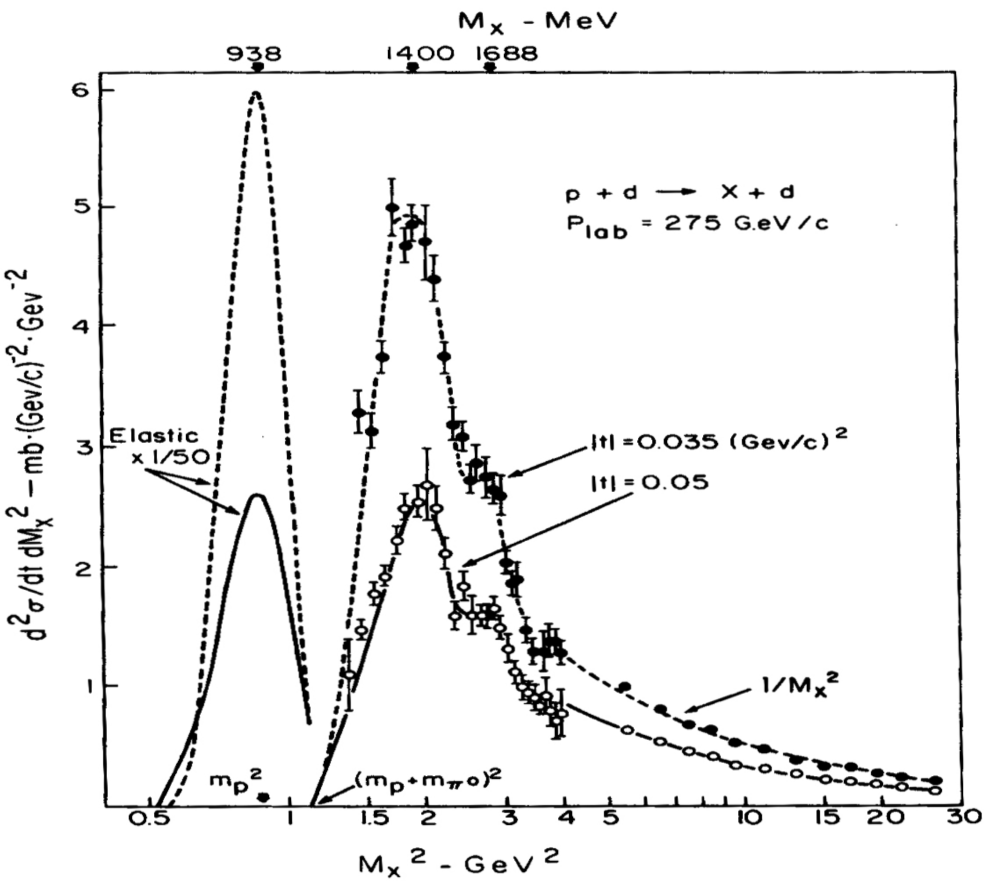
where $\lambda_n = \mathcal{R}e\ \alpha(s_n)$.


p
p
p
p
p
p
p
X

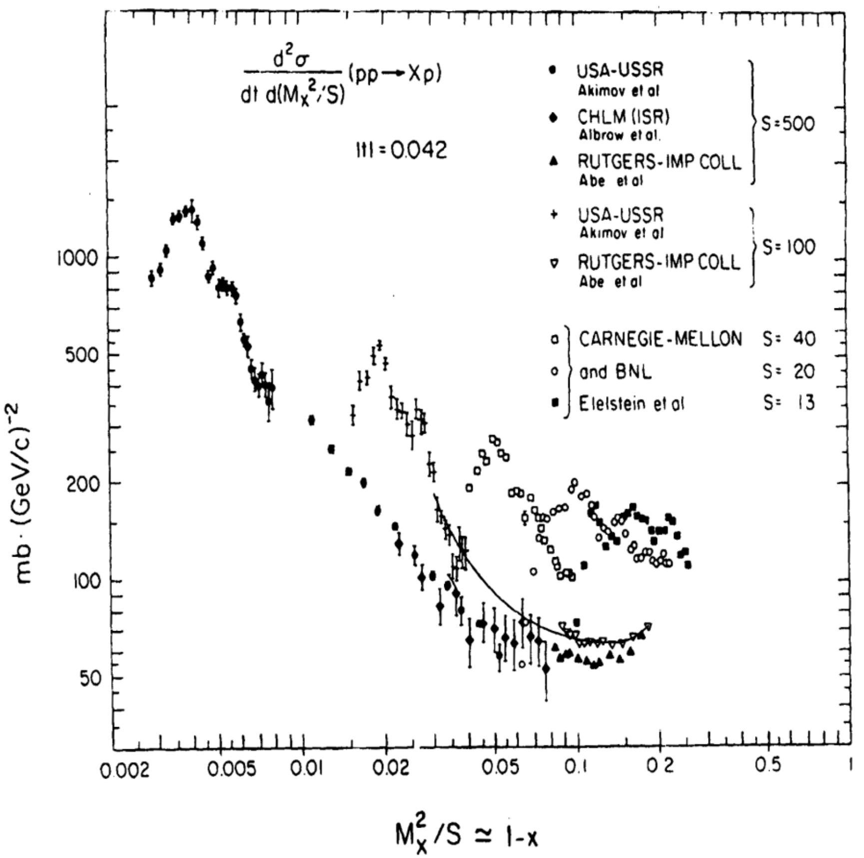


e
e′
k
k′
α^{1/2}
γ
-q²=Q²
X
p
q
p
X
X
X
Unitarity
t=0
R
R
Res
Res
Veneziano duality

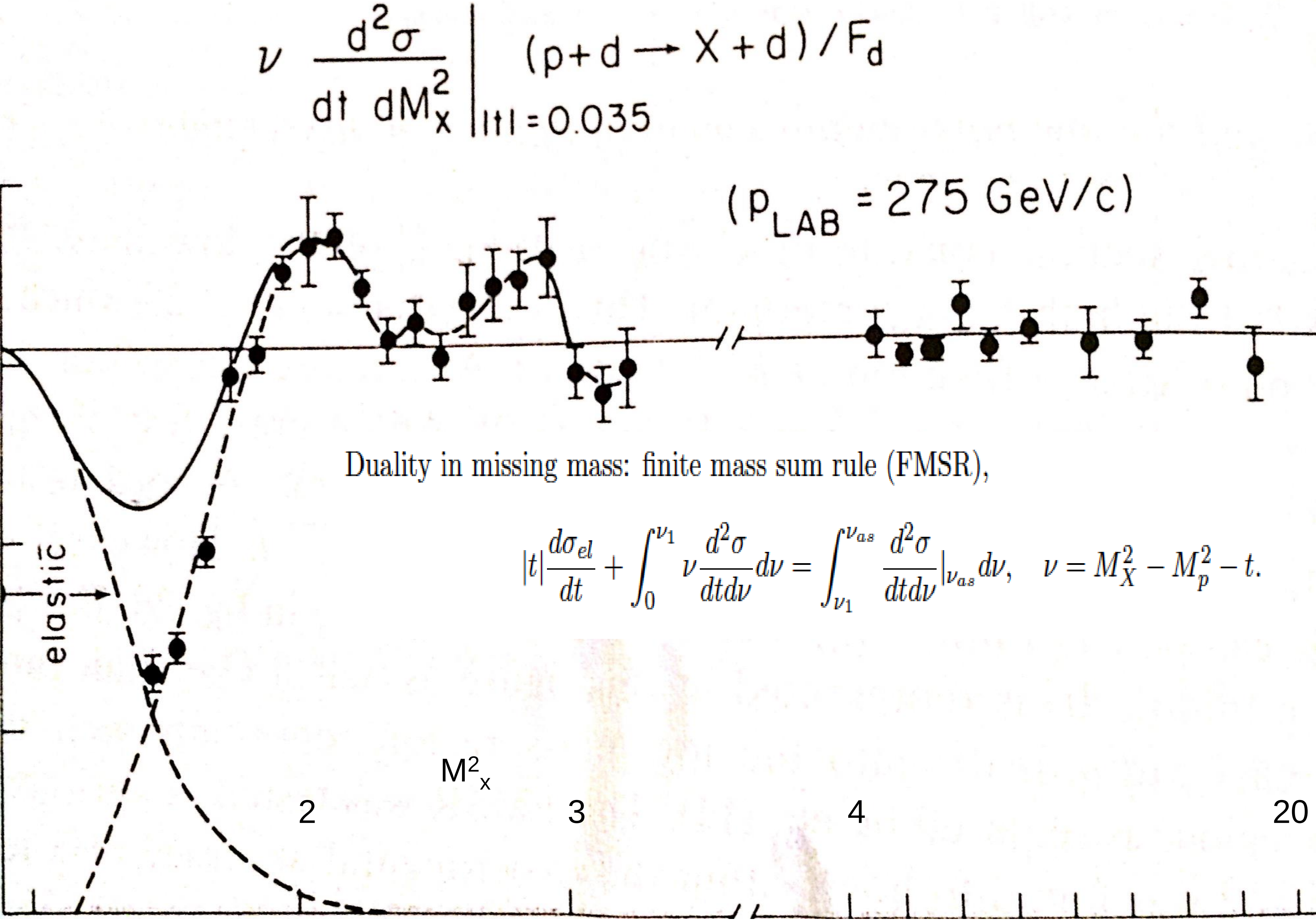
FNAL



M_x - MeV
938
1400
1688
p + d → 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 S = 40
and BNL S = 20
Eleistein et al S = 13
mb·(GeV/c)$^{-2}$
$M_X^2/S \simeq 1-x$



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

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

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.

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.

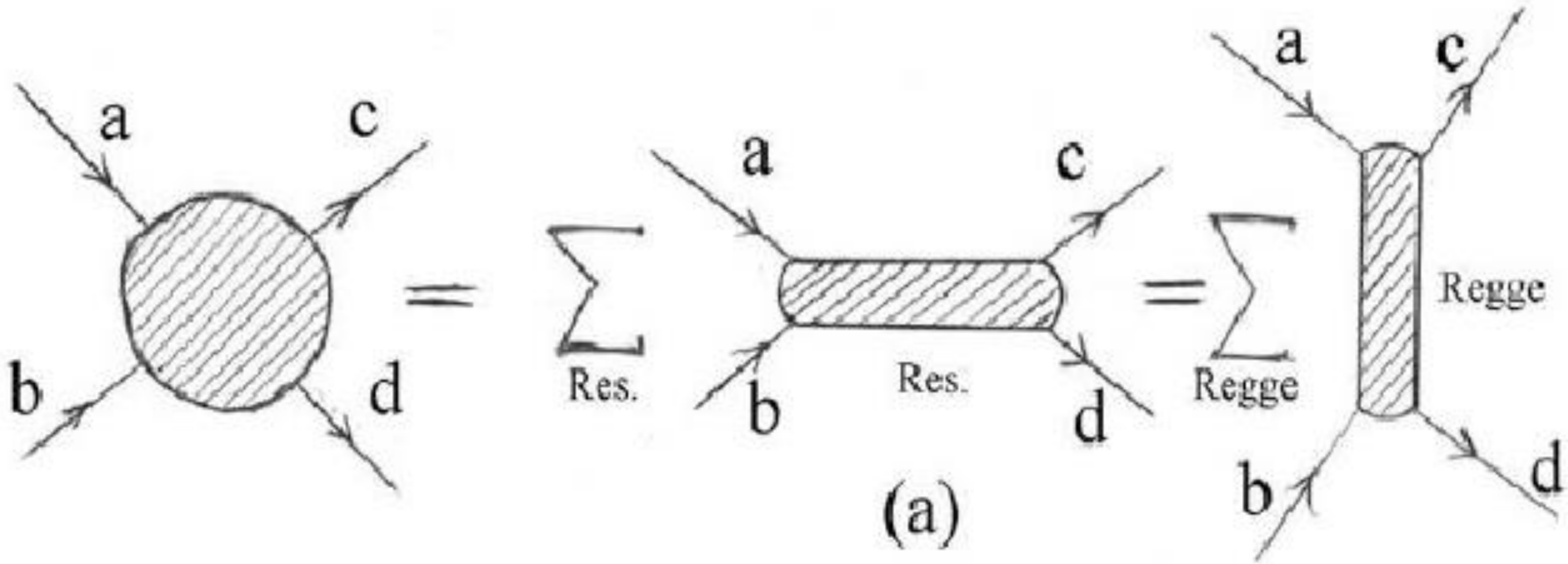
A single-Pomeron exchange is valid at the LHC energies, however at lower energies (e.g. those of the ISR or the SPS) the contribution of non-leading Regge exchanges should be accounted for as well.

Thus, the unpolarized elastic pp differential cross section is

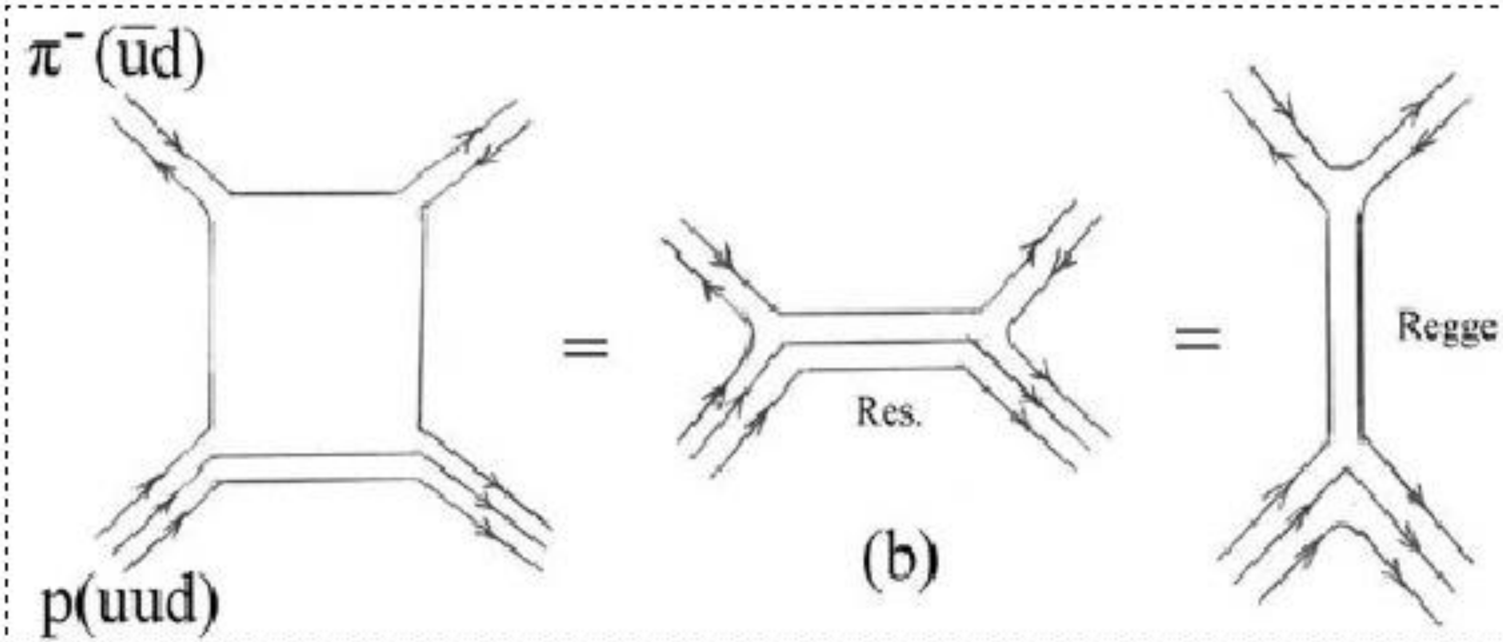
$$\frac{d\sigma}{dt} = \frac{[3\beta F^p(t)]^4}{4\pi\sin^2[\pi\alpha_P(t)/2]}(s/s_0)^{2\alpha_P(t)-2}. \tag{2}$$

The final expression for the double differential cross section reads:

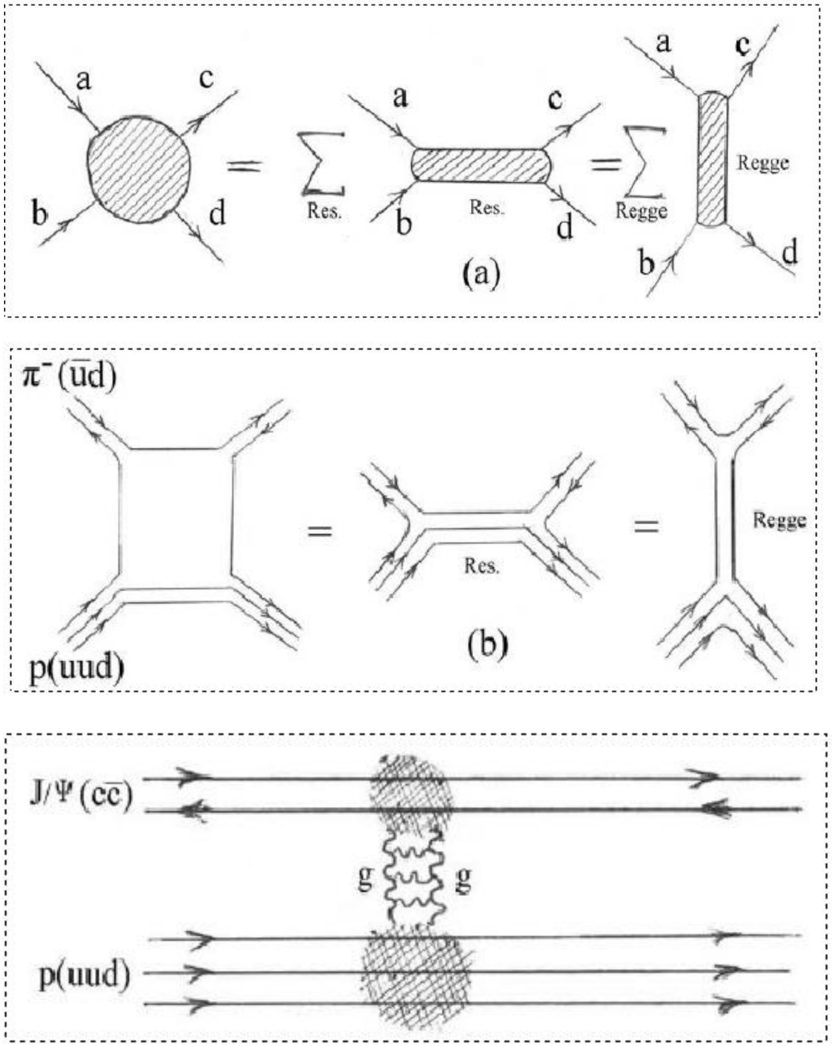
$$\frac{d^2\sigma}{dtdM_X^2} =$$
$$A_0 \left(\frac{s}{M_X^2}\right)^{2\alpha_P(t)-2} \frac{x(1-x)^2\ [F^p(t)]^2}{(M_x^2-m^2)\left(1+\frac{4m^2x^2}{-t}\right)^{3/2}} \times$$
$$\sum_{n=1,3} \frac{[f(t)]^{2(n+1)}\, Im\,\alpha(M_X^2)}{(2n+0.5-Re\,\alpha(M_X^2))^2+(Im\,\alpha(M_X^2))^2}\,. \tag{1}$$



(a)



(b)


a
c
b
d
Res.
a
c
b
Res.
d
(a)
Regge
a
c
Regge
b
d
π⁻ (ūd)
p(uud)
Res.
(b)
Regge
J/Ψ (cc̄)
g
g
p(uud)

“Reggeized (dual) Breit-Wigner” formula:

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

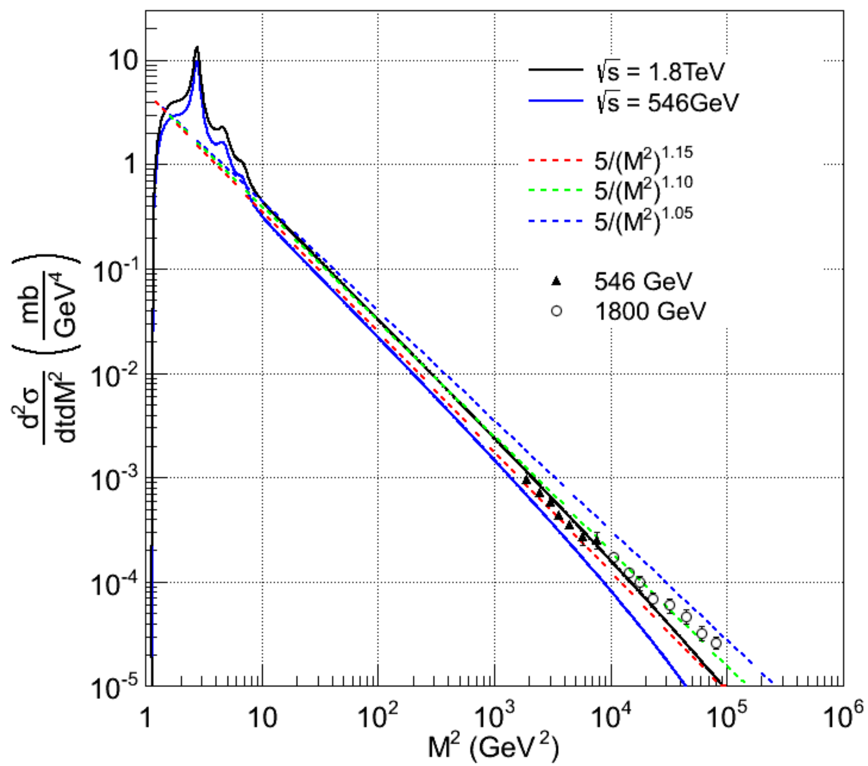
$$= A_n \sum_{n=0,1,\ldots} \frac{[f(t)]^{2(n+1)} Im\, \alpha(M_x^2)}{(2n + 0.5 - Re\, \alpha(M_x^2))^2 + (Im\, \alpha(M_x^2))^2} + B_n e^{b_{in}^{bg} t} \left(M_x^2 - M_{p+\pi}^2\right)^{\epsilon}$$

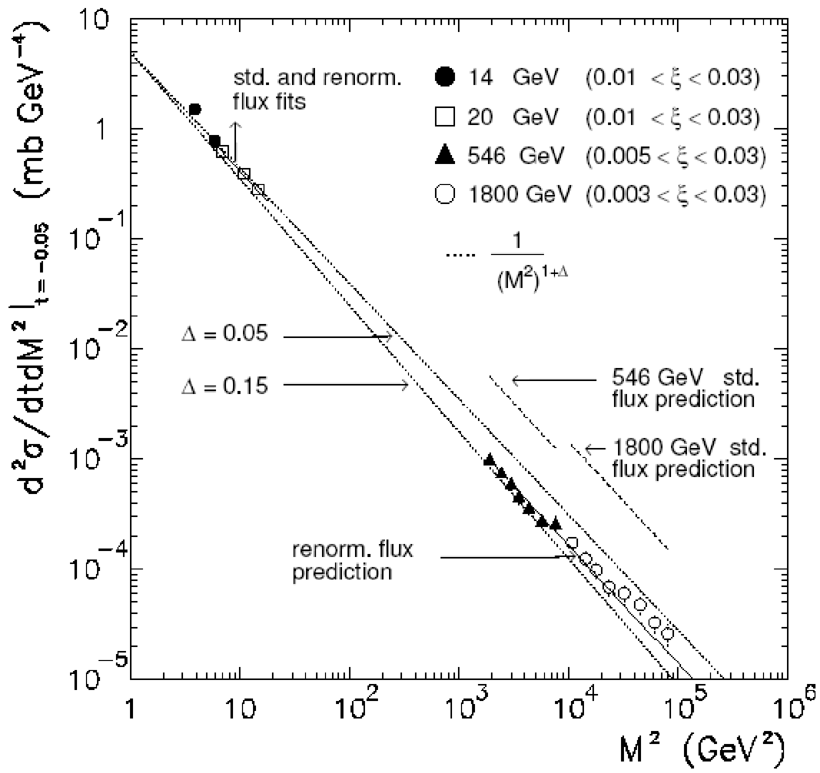
$$F(x_B, t) = \frac{x_B(1 - x_B)}{\left(M_x^2 - m_p^2\right)\left(1 + 4m_p^2 x_B^2/(-t)\right)^{3/2}}, \quad x_B = \frac{-t}{M_x^2 - m_p^2 - t}$$

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

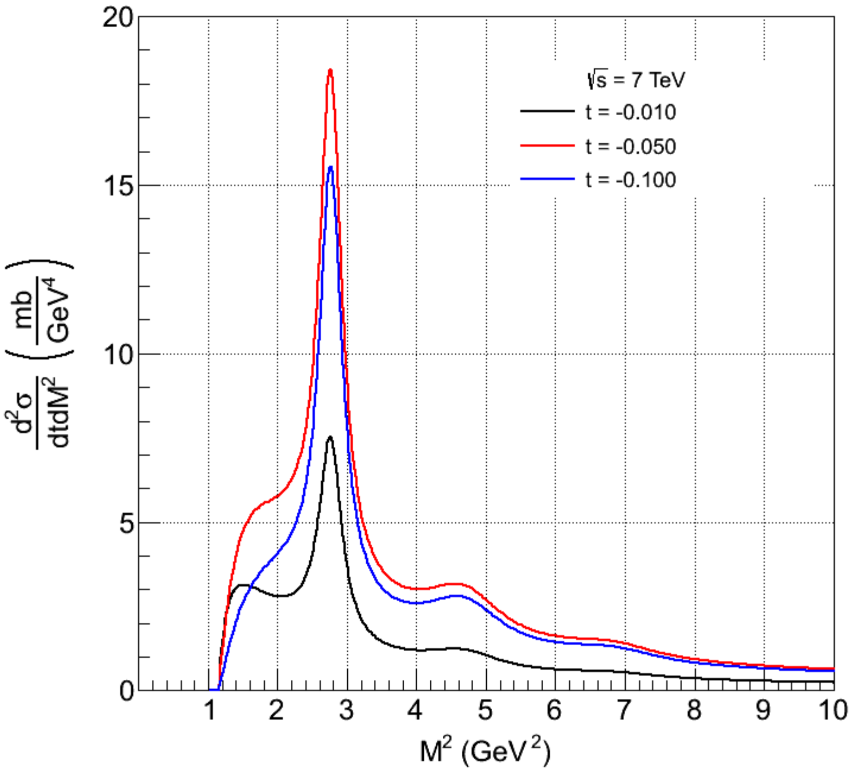
$$\alpha(t) = \alpha(0) + \alpha' t = 1.04 + 0.25t$$

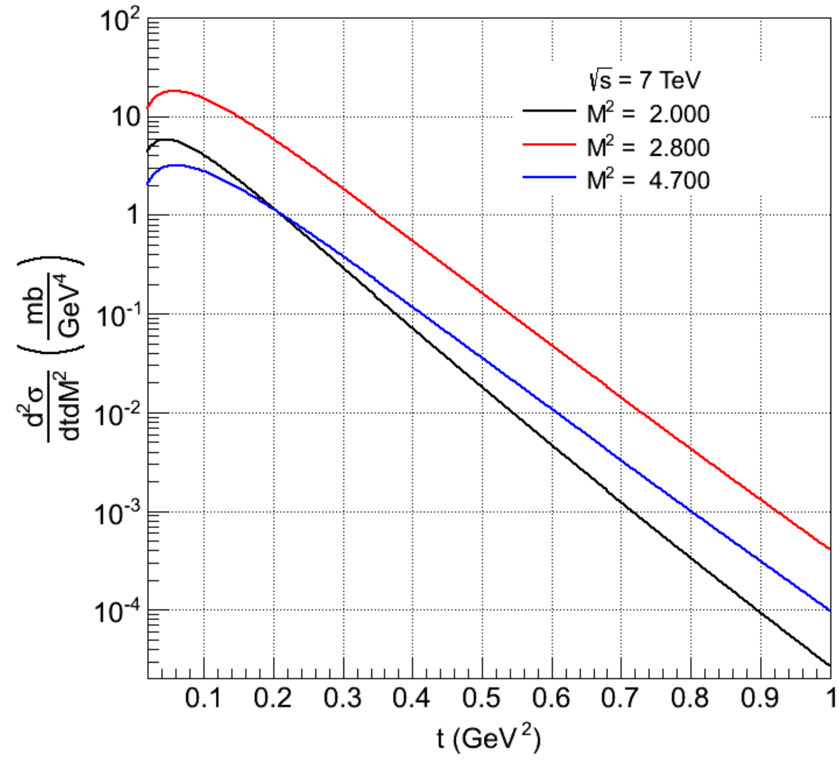
Approximation of background to reference points (t=-0.05)



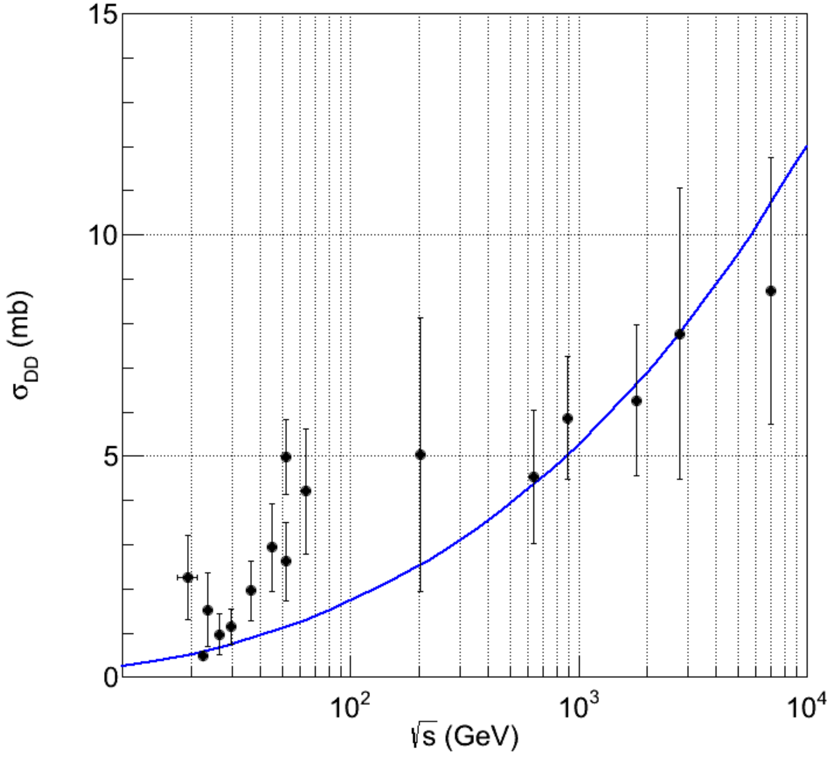


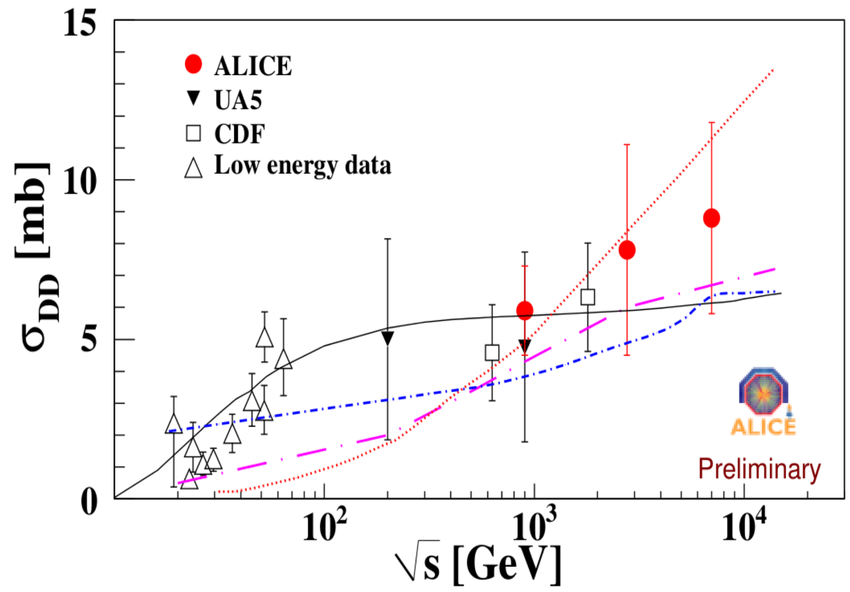
Double differential SD cross sections



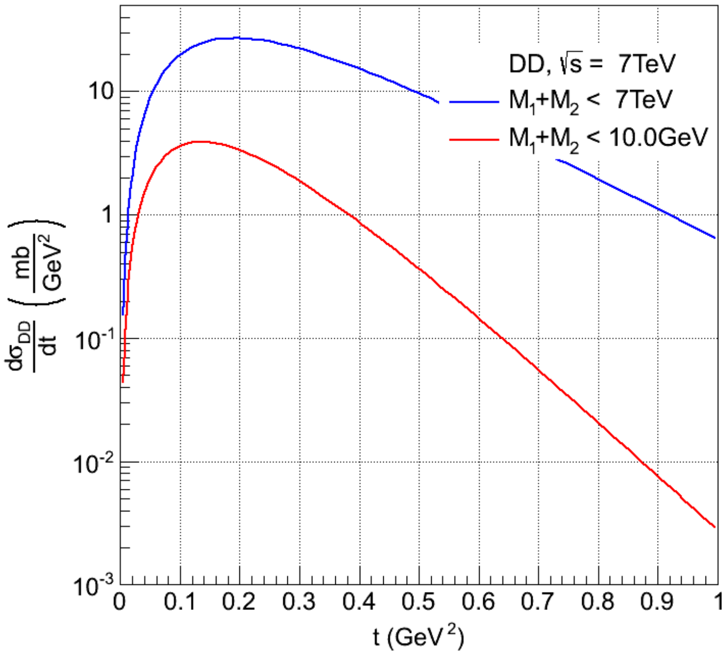


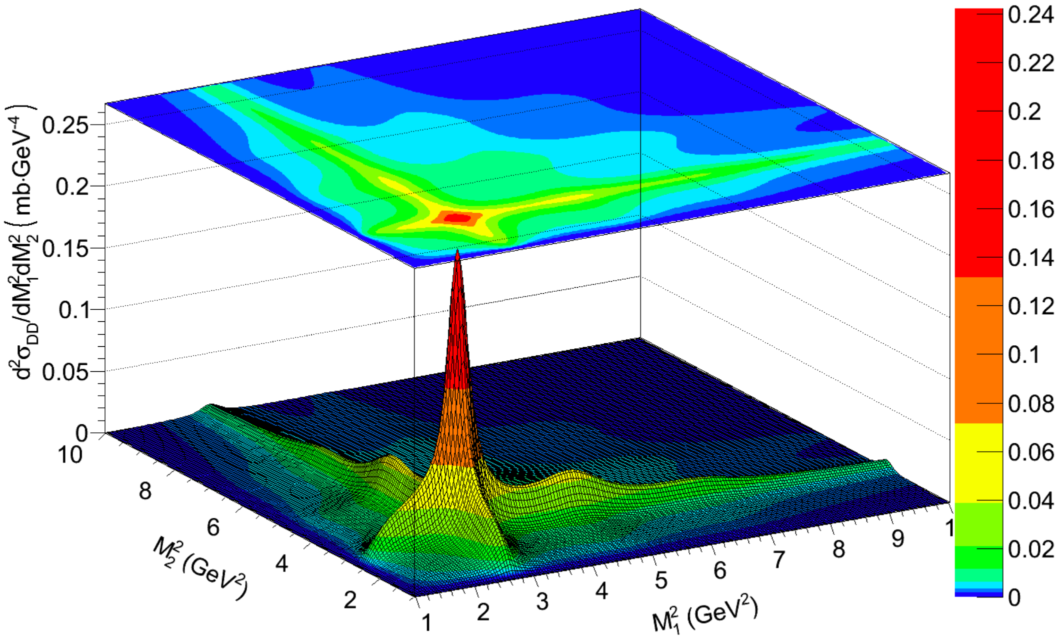
DDD cross sections vs. energy.



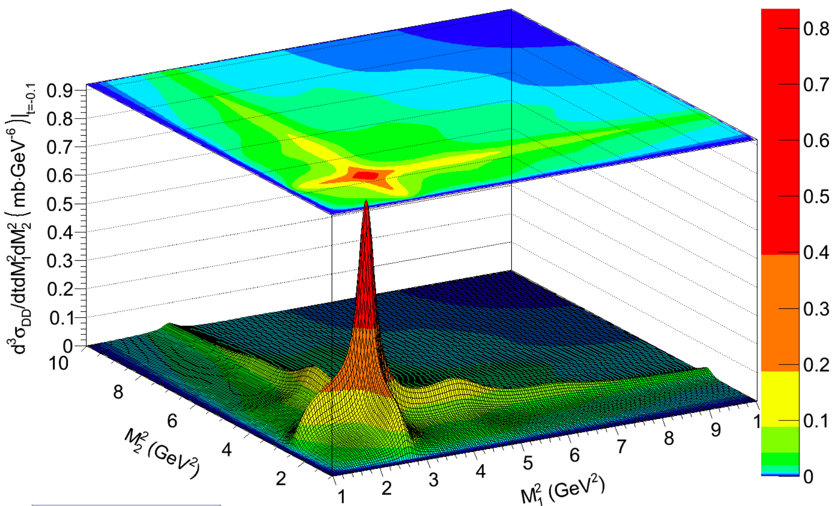


Integrated DD cross sections

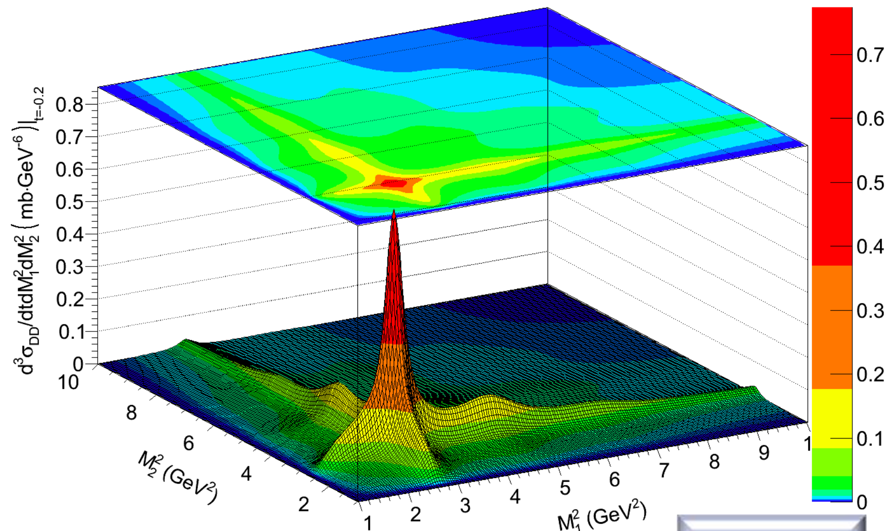




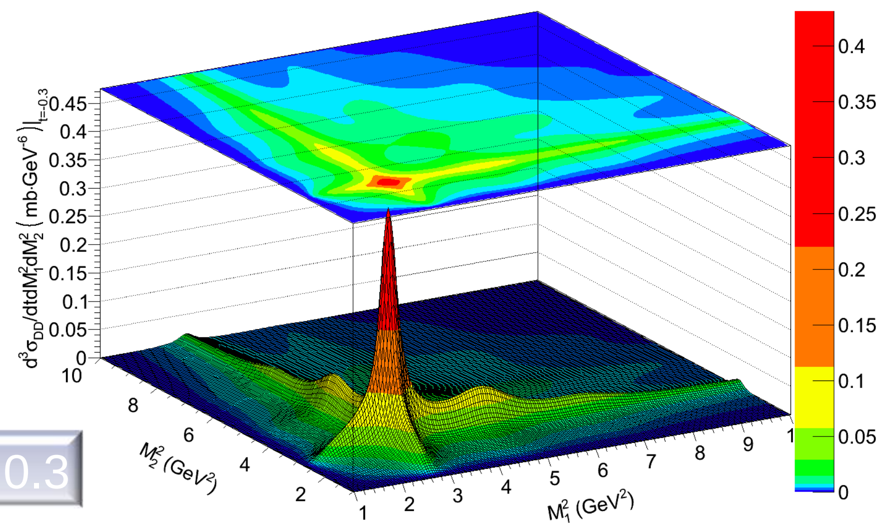
Triple differential DD cross sections



t = - 0.1

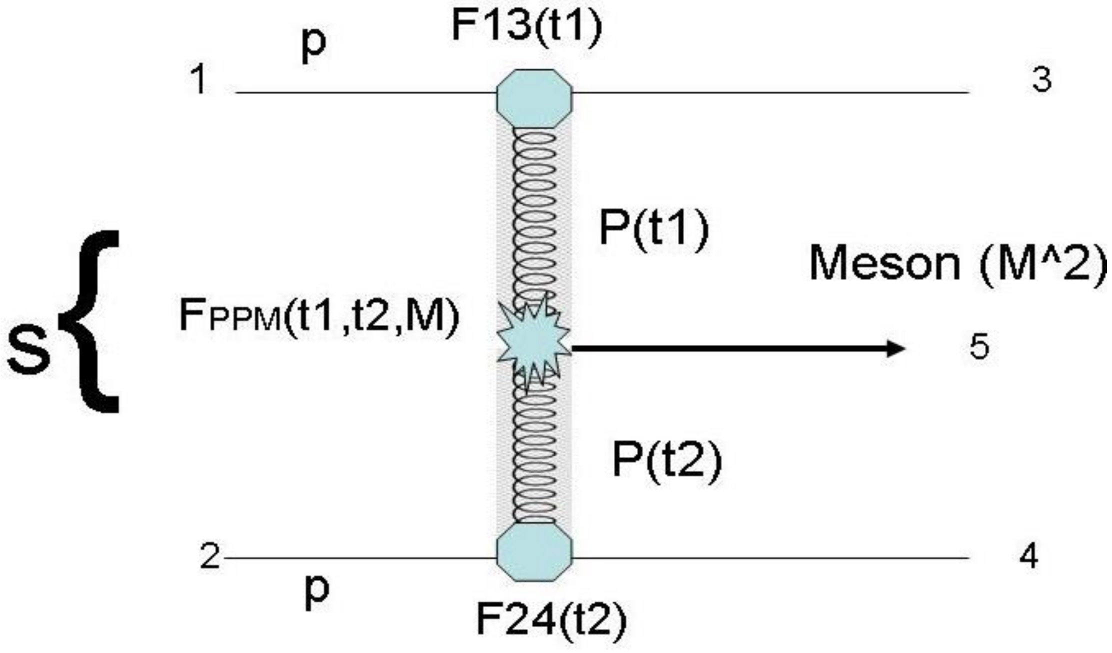


t = - 0.2



t = - 0.3

Central diffractive meson production (double Pomeron exchange), R. Schicker's talk;



Thank you !