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Diffractive phenomena & Pomeron physics @ LHC

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

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

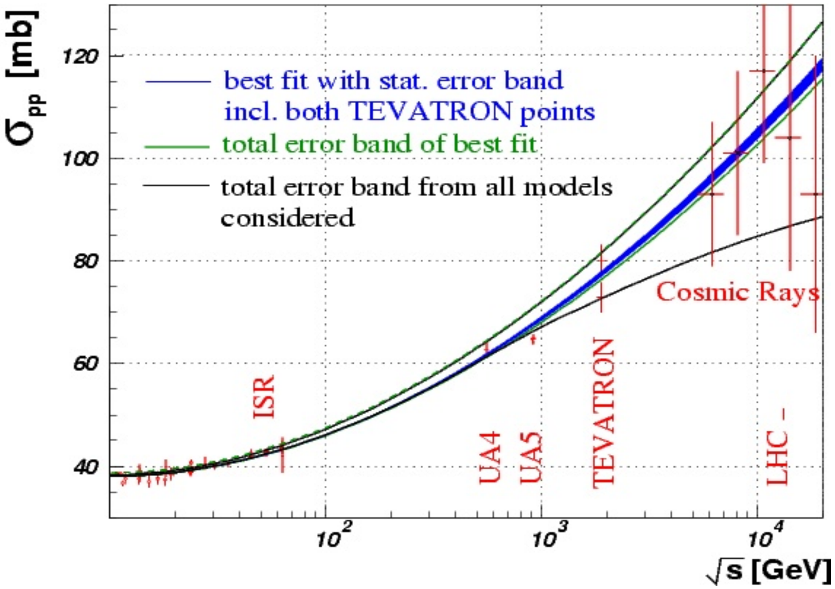
$$A_{pp}^{p\bar{p}}(s,t) = P(s,t) \pm O(s,t) + f(s,t) \pm \omega(s,t) \to_{LHC} \approx P(s,t) \pm O(s,t),$$

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

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

NB: The S-matrix theory (including Regge pole) is applicable to asymptotically free states only (not to quarks and gluons)!

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

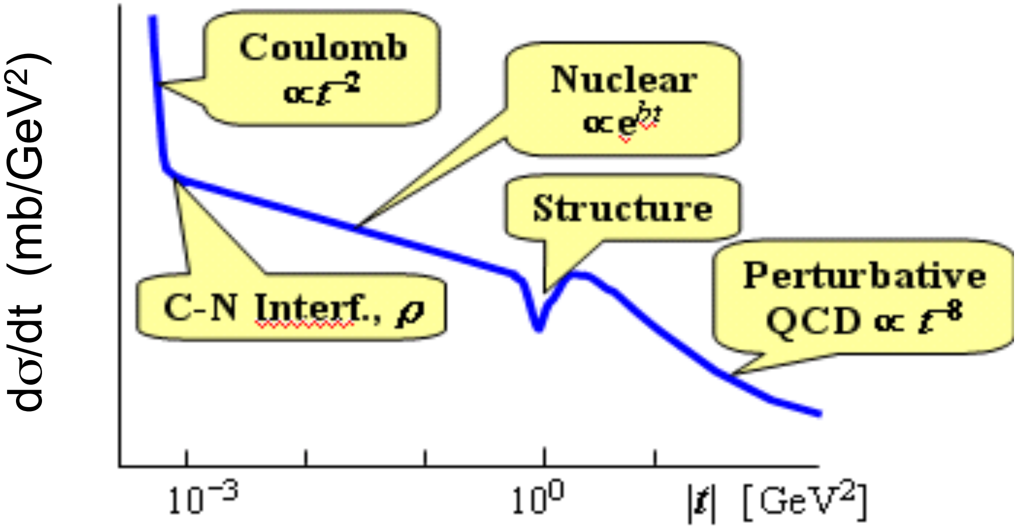
(σ_{tot} + $dN/dt|_{t=0}$) → ($\Delta L/L$ > ~ 2 $\Delta\sigma_{tot}/\sigma_{tot}$)

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

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

Elastic Scattering

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



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

θ = beam scattering angle

p = beam momentum

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

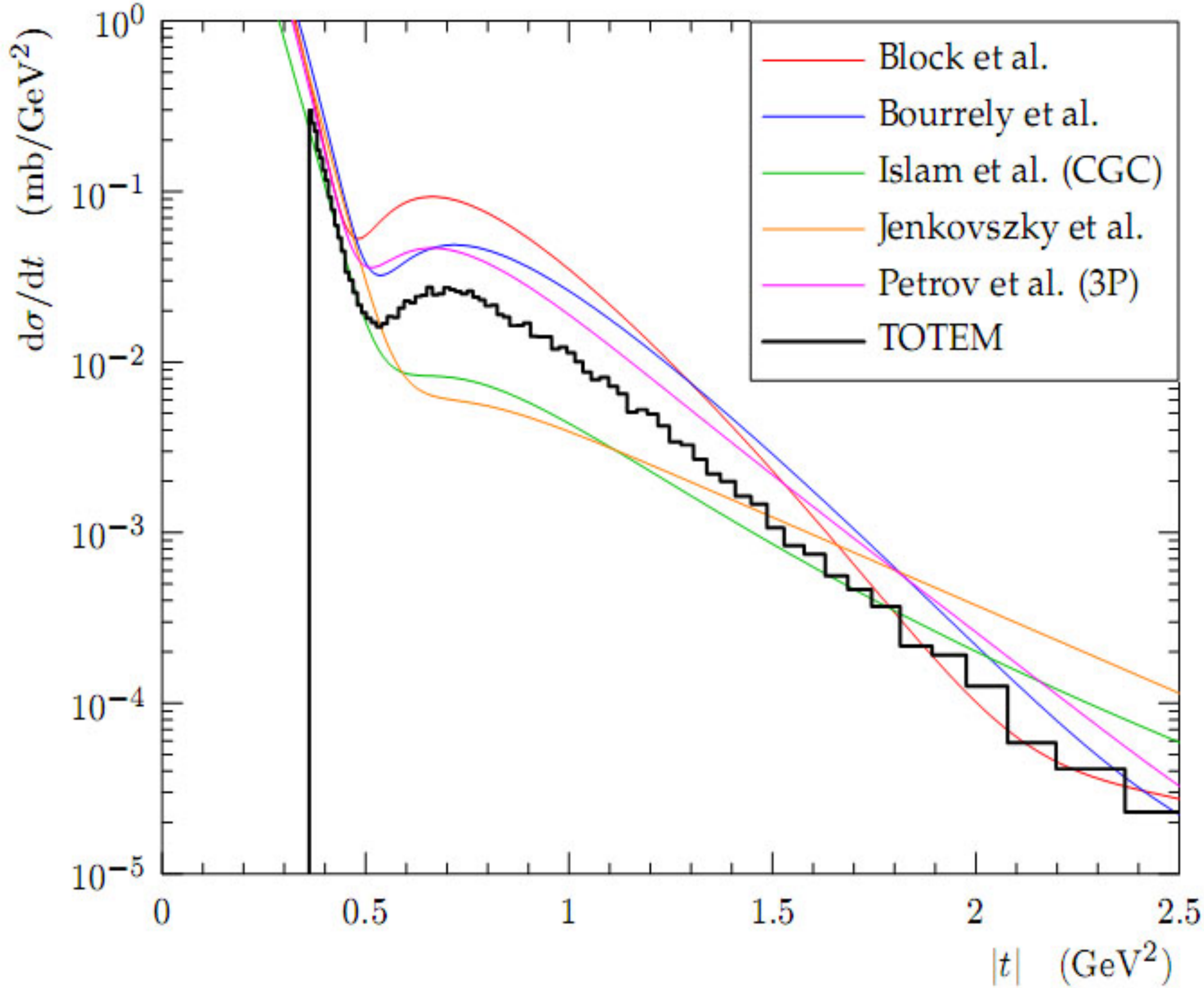
$$\left.\frac{dN}{dt}\right|_{t=CNI} = L\pi\left|f_C + f_N\right|^2 \approx L\pi\left|-\frac{2\alpha_{\mathrm{EM}}}{|t|} + \frac{\sigma_{\mathrm{tot}}}{4\pi}(i+\rho)e^{-\frac{b|t|}{2}}\right|^2$$

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

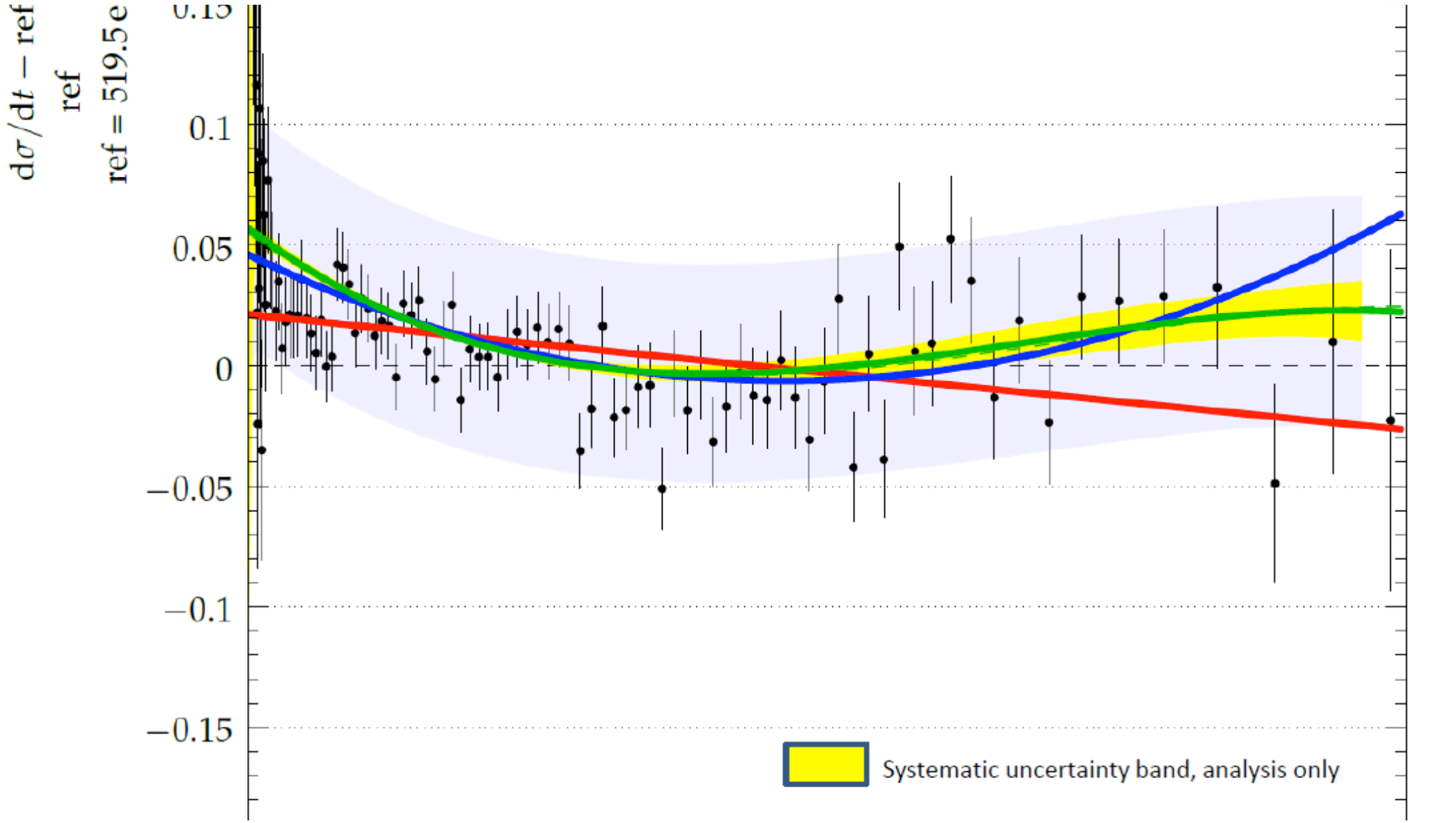
CNI region: $|f_C| \sim |f_N|$ → @ LHC: $-t \sim 6.5\ 10^{-4}$ GeV^2; $\theta_{min} \sim 3.4$ μrad

($\theta_{min} \sim 120$ μrad @ SPS)

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

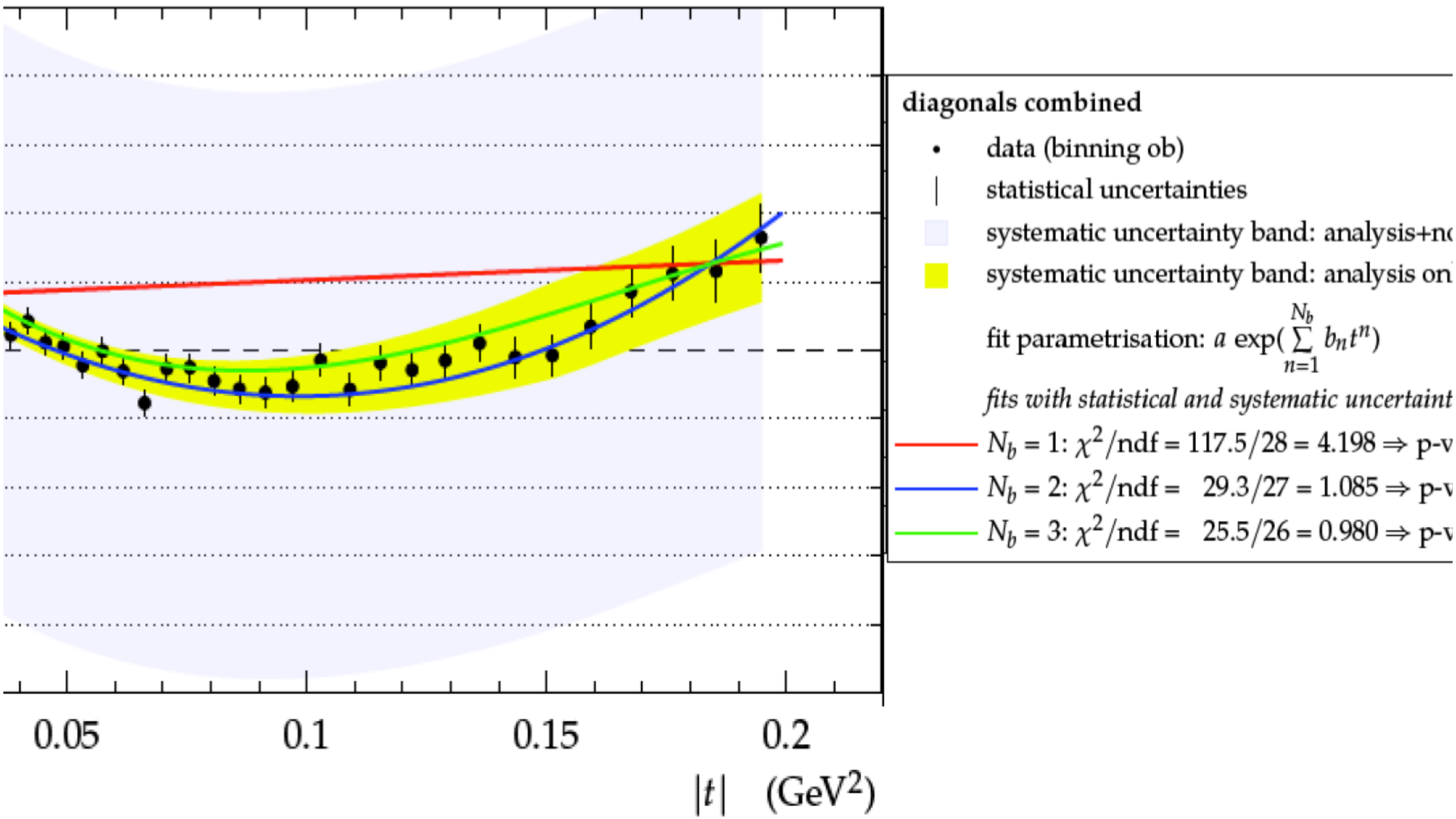


Fine structure of the Pomeron (TOTEM)

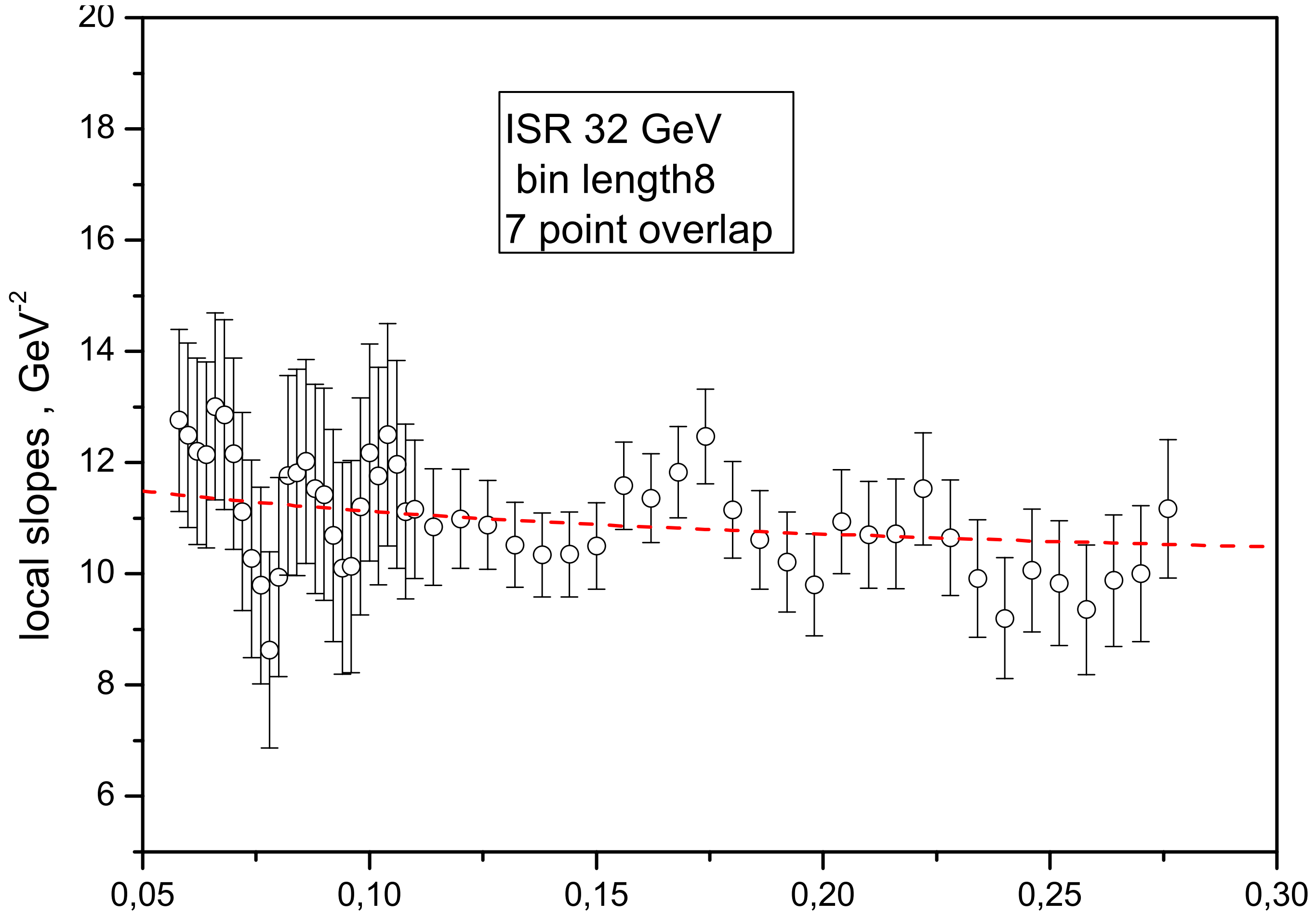


Low-|t|(fine-) structure of the cone (Pomeron?) the LHC:

L. Jenkovszky, A. Lengyel, Acta Phys. Pol. Acta Phys. Polonica B, **46** (2015) 863; arXiv:1410.4106; D. Fagundes et al., hep-ph/1509.02197.



Tiny oscillations on the cone?



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.

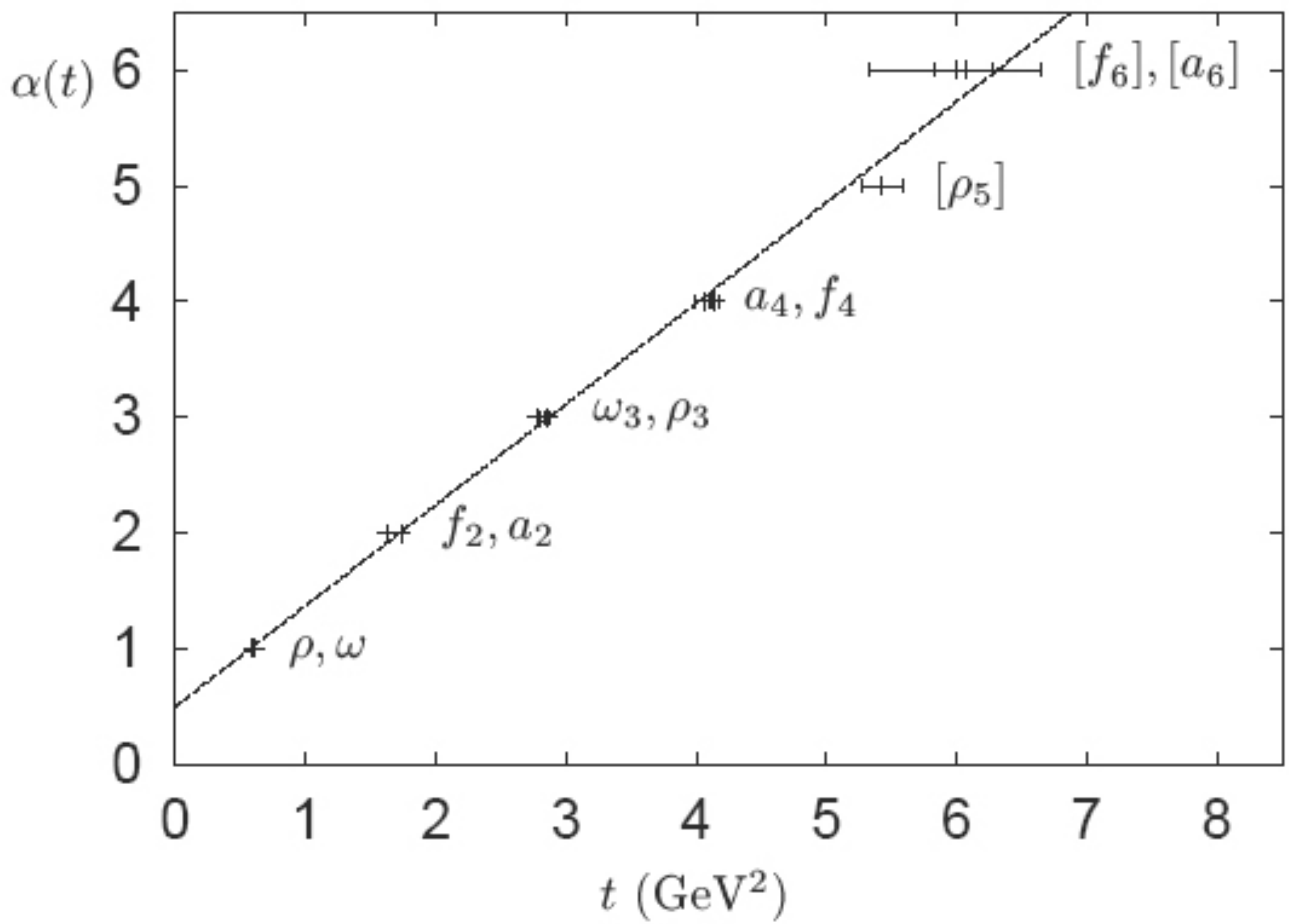
$$\alpha_P \equiv \alpha_P(t) = 1 + \delta_P + \alpha_{1P} t, \tag{TR.1}$$

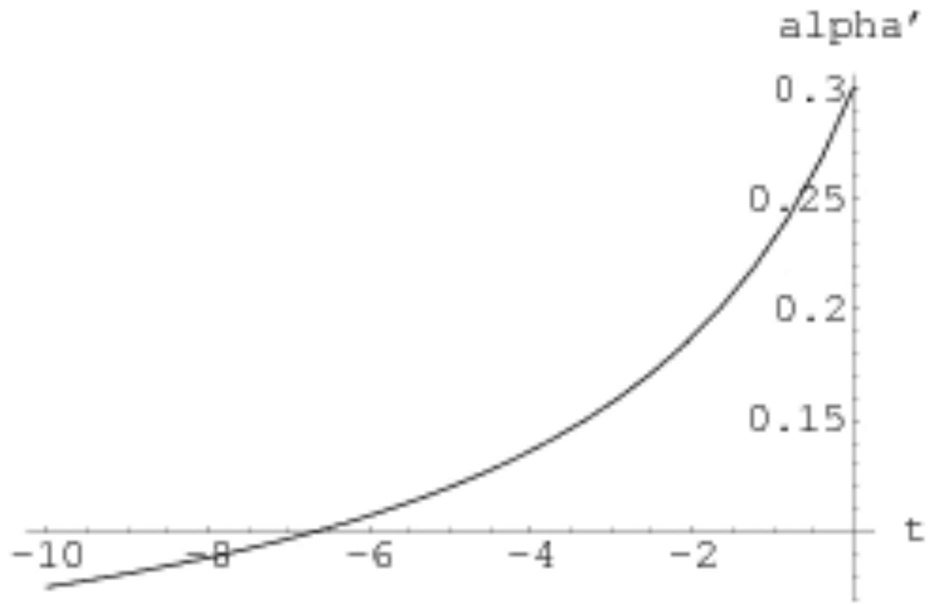
$$\alpha_P \equiv \alpha_P(t) = 1 + \delta_P + \alpha_{1P} t - \alpha_{2P} \left(\sqrt{4\alpha_{3P}^2 - t} - 2\alpha_{3P} \right), \tag{TR.2}$$

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

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).

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:

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

where the symbols P, f, O, ω 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.

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

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

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

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

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

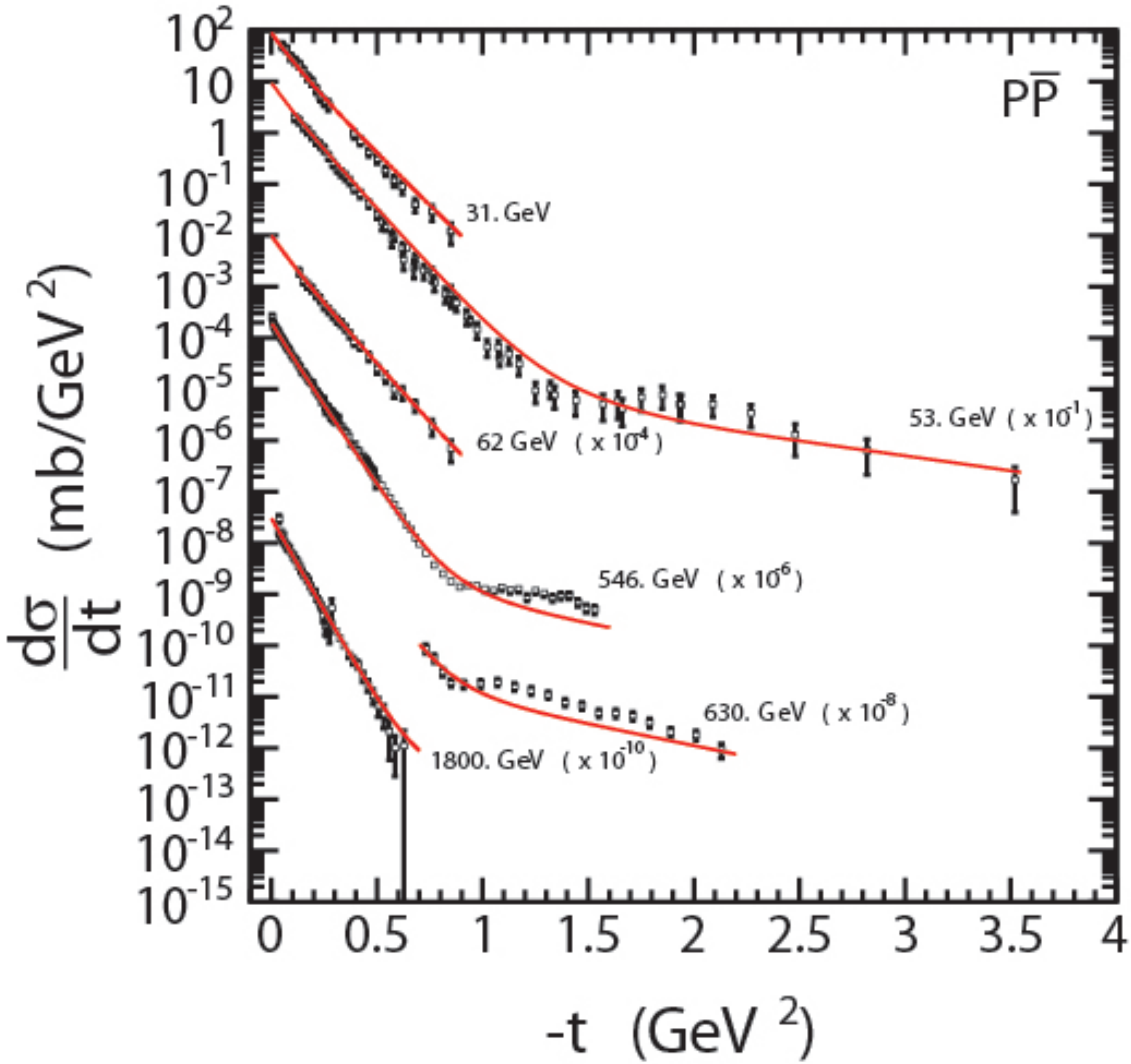
Since the first term in squared brackets determines the shape of the cone, one fixes

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

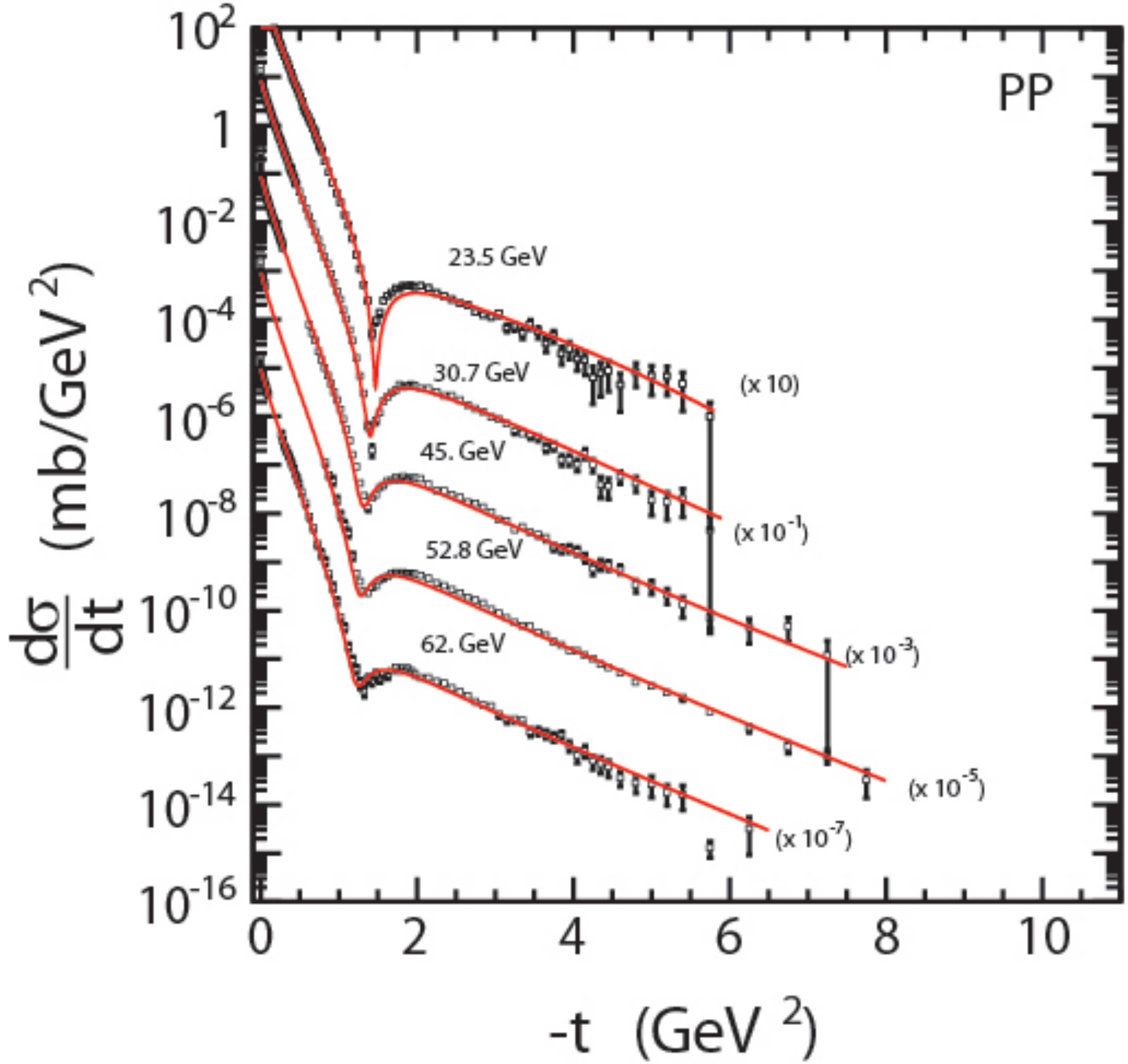
where $G(\alpha_P)$ is recovered by integration, and, as a consequence, the Pomeron amplitude can be rewritten in the following "geometrical" form

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

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



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/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)

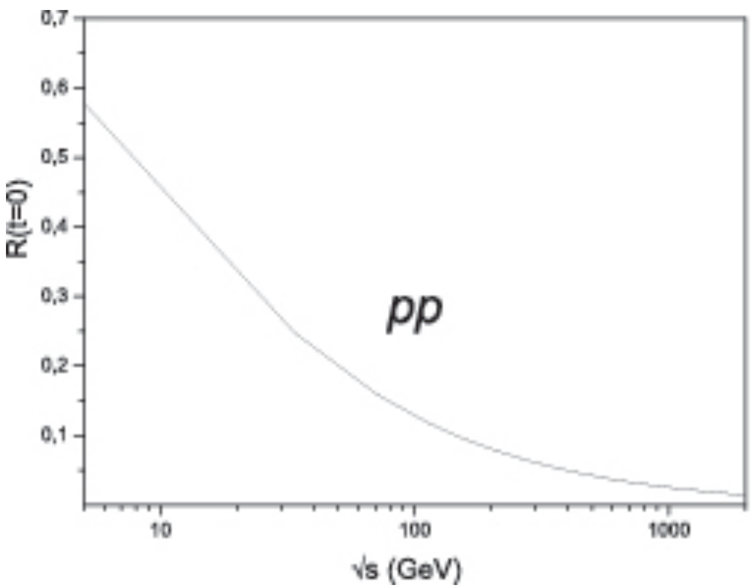
Energy variation of the relative importance of the Pomeron with respect to contributions from the secondary trajectories and the Odderon:

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

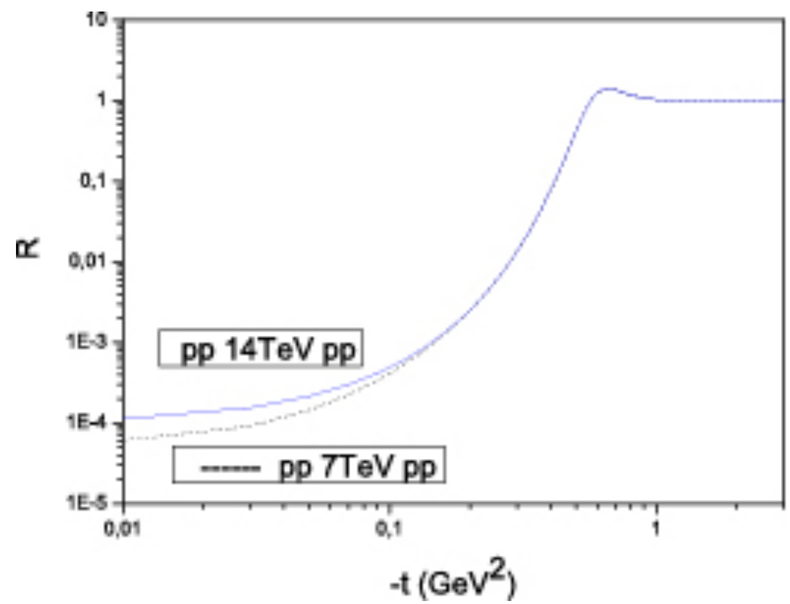
where the total scattering amplitude A includes the Pomeron contribution A_P plus the contribution from the secondary Reggeons and the Odderon.

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.

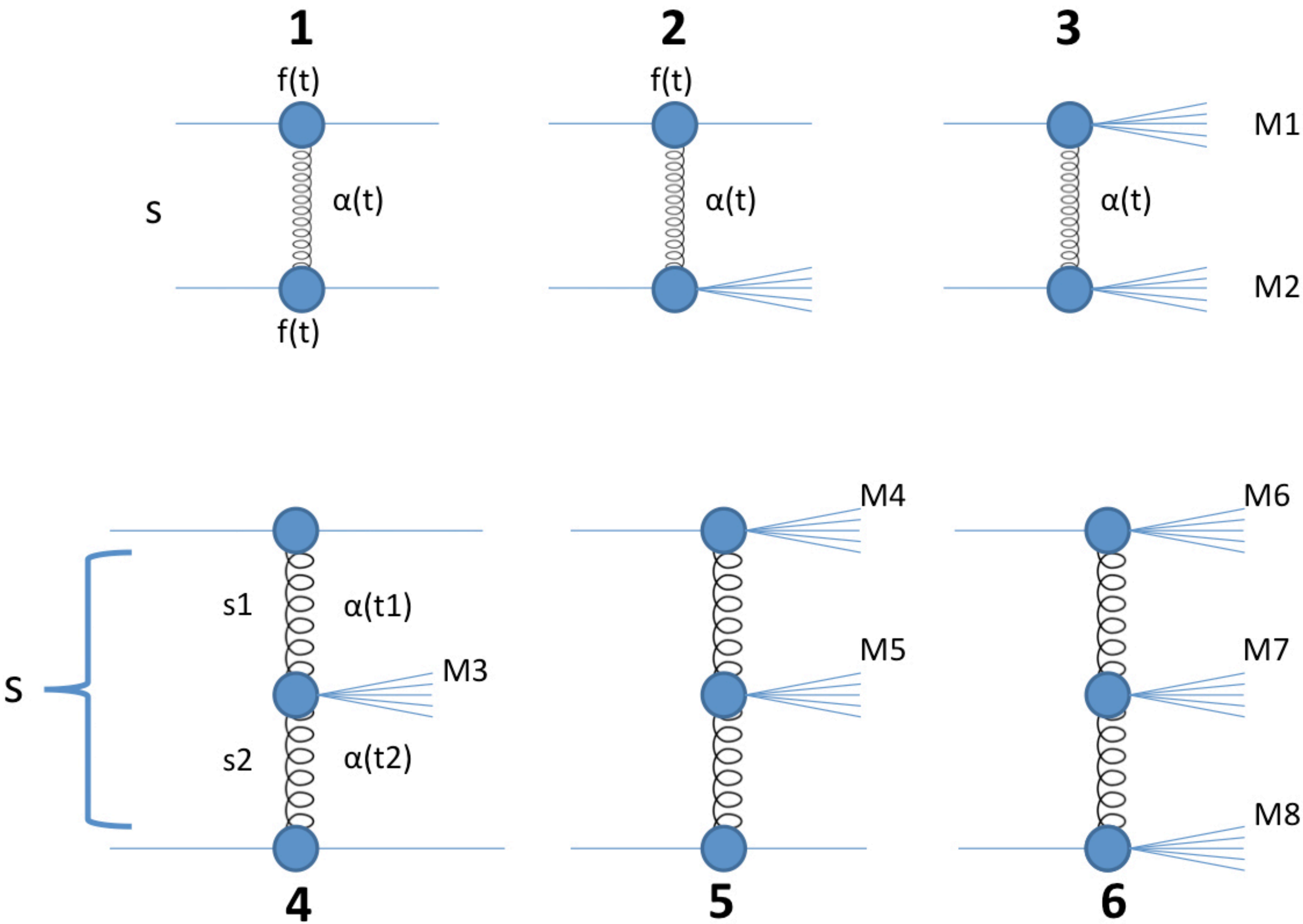
$$R(s,t)=\frac{|(A(s,t)-A_P(s,t)|^2}{|A(s,t)|^2}. \tag{2}$$



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



R
10
1
0,1
0,01
1E-3
1E-4
1E-5
0,01
0,1
1
-t (GeV^2)
pp 14TeV pp
pp 7TeV pp



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

Factorization (nearly perfect at the LHC!)

$$(g_1g_2)^2 = \frac{(g_1f_1)^2(f_1g_2)^2}{(f_1f_2)^2}.$$

Hence

$$\frac{d^3\sigma}{dtdM_1^2dM_2^2} = \frac{d^2\sigma_1}{dtdM_1^2}\frac{d^2\sigma_2}{dtdM_2^2}\frac{d\sigma_{el}}{dt}.$$

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

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

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

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

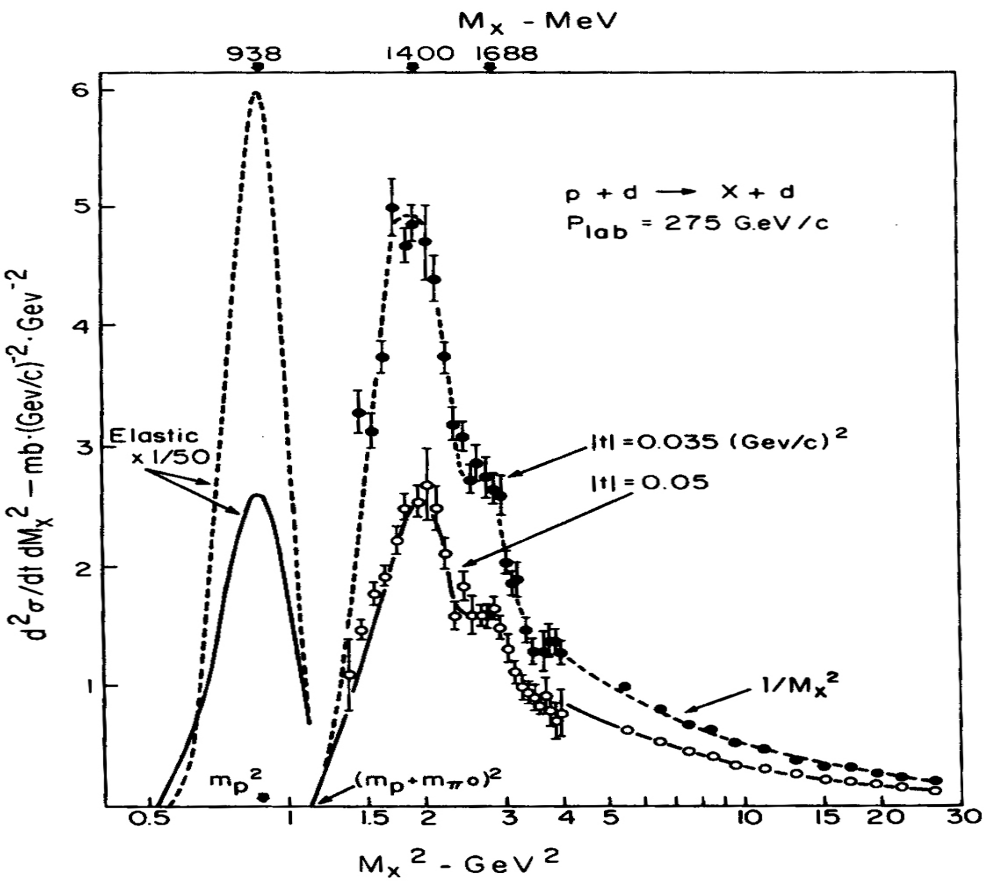
Low-mass diffraction dissociation at the LHC

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

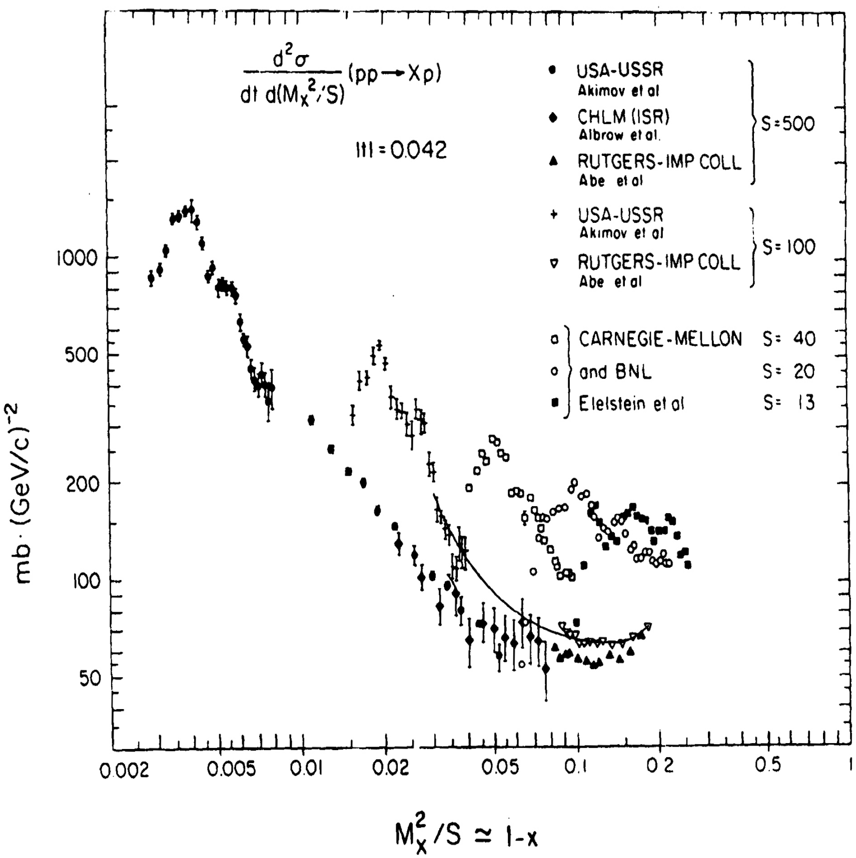
Experimentally, diffraction dissociation in proton-proton scattering was intensively studied in the '70-ies at the Fermilab and the CERN ISR. In particular, double differential cross section $\frac{d\sigma}{dtdM_X^2}$ was measured in the region $0.024 < -t < 0.234$ $(\mathrm{GeV/c})^2$, $0 < M^2 < 0.12s$,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

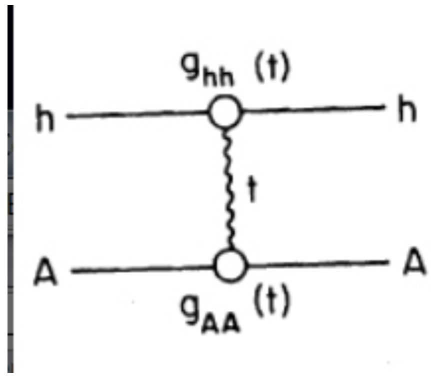
FNAL



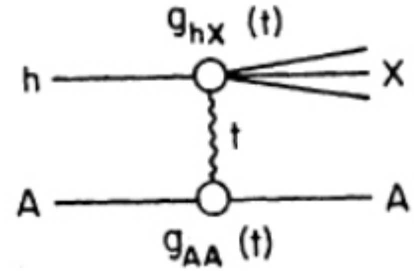
M_X - MeV
938
1400
1688
p + d → X + d
P_lab = 275 GeV/c
Elastic x 1/50
|t| = 0.035 (GeV/c)²
|t| = 0.05
1/M_X²
m_p²
(m_p + m_π0)²
d²σ/dt dM_X² — mb·(GeV/c)⁻²·GeV⁻²
M_X² - GeV²



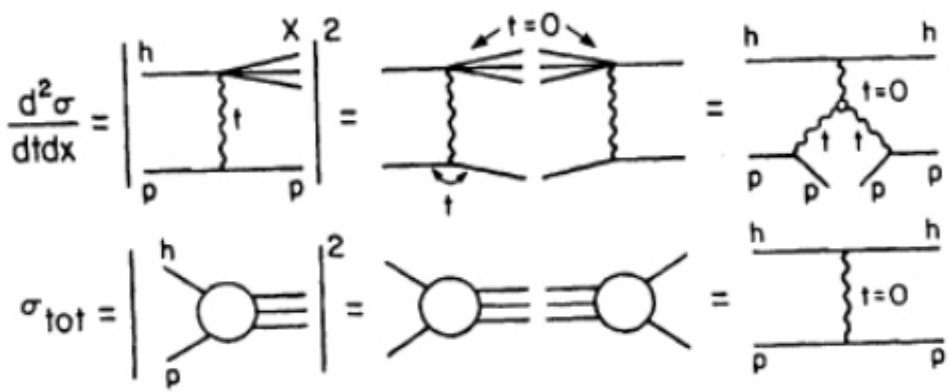
d²σ/dt d(M_X²/S) (pp → Xp)
|t| = 0.042
USA-USSR Akimov et al
CHLM (ISR) Albrow et al.
RUTGERS-IMP COLL Abe et al
S=500
USA-USSR Akimov et al
RUTGERS-IMP COLL Abe et al
S=100
CARNEGIE-MELLON S= 40
and BNL S= 20
Edelstein et al S= 13
mb·(GeV/c)⁻²
M_X²/S ≃ 1-x



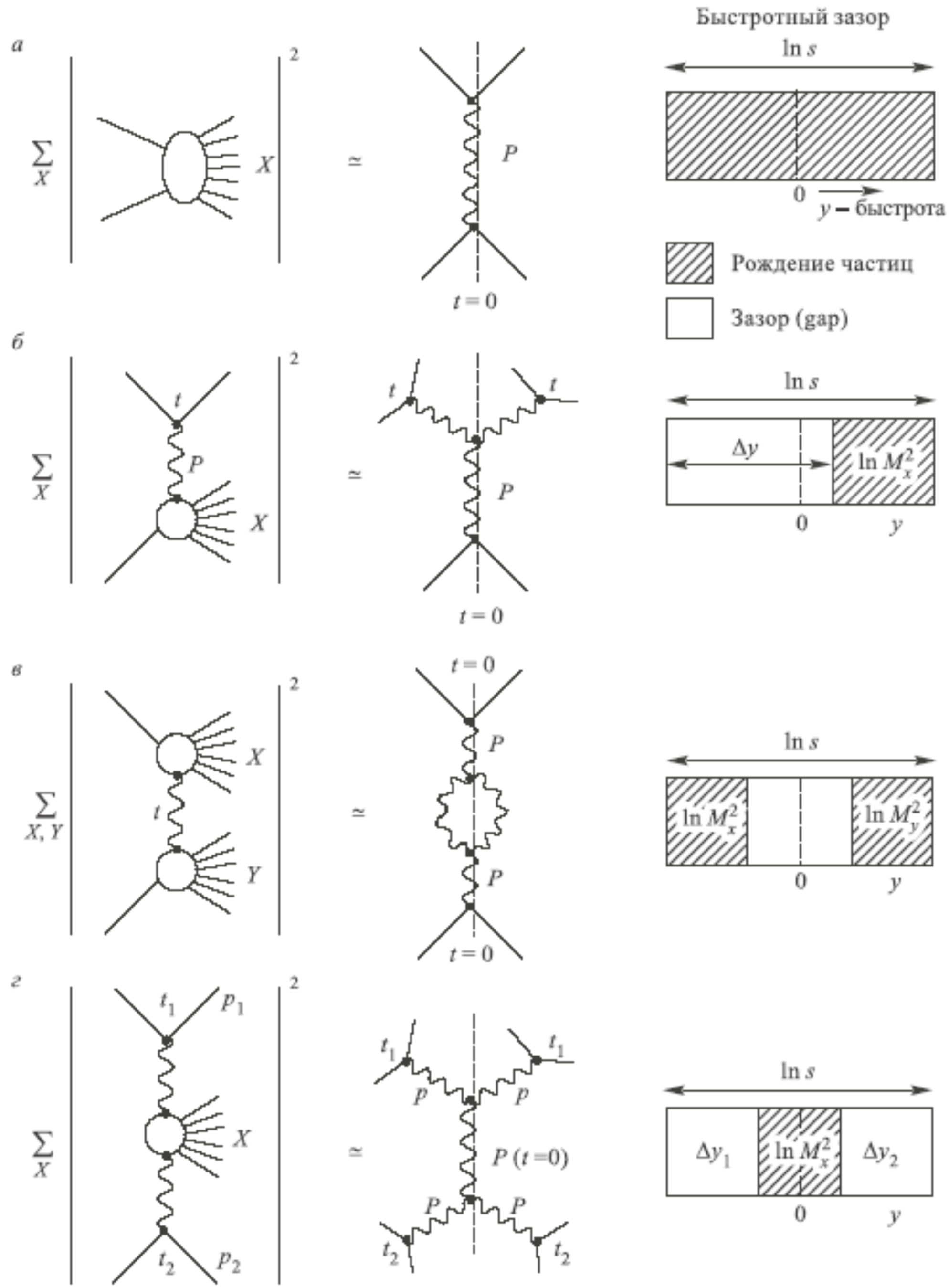
g_hh (t)
h
h
t
A
A
g_AA (t)



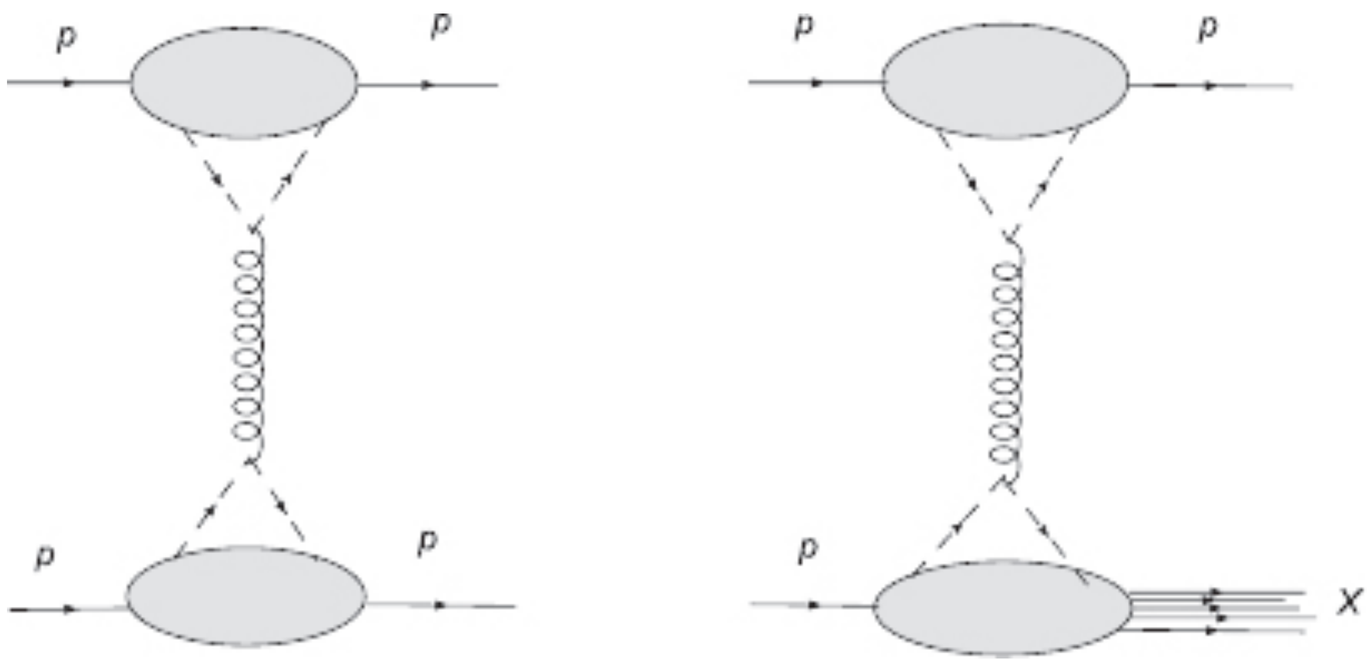
g_hX (t)
h
X
t
A
A
g_AA (t)

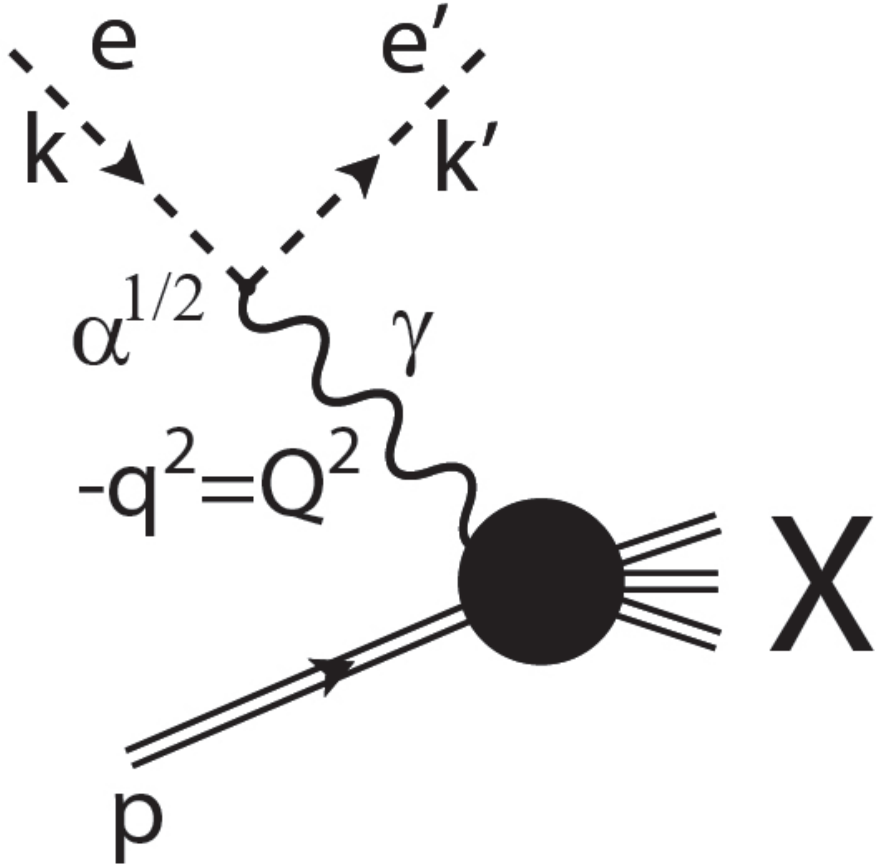


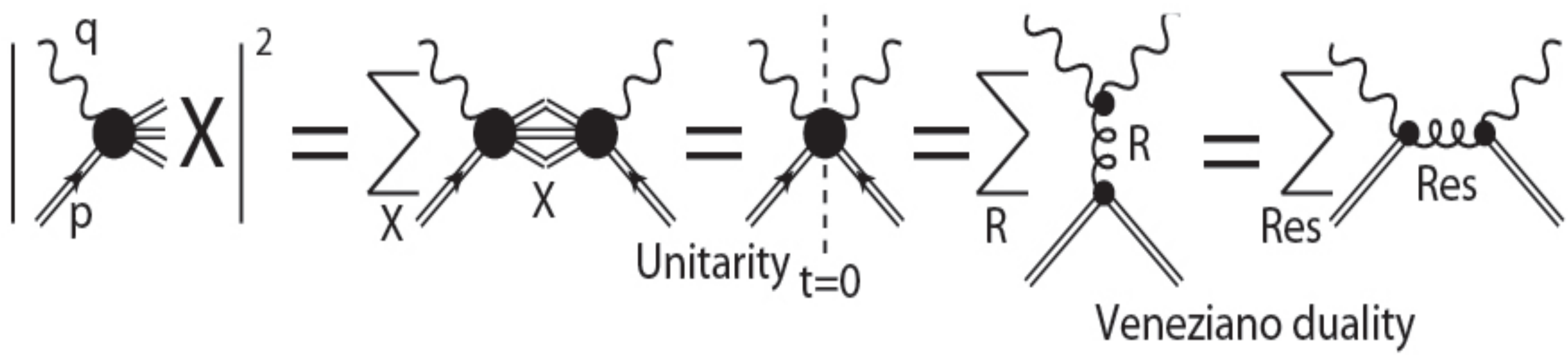
d²σ/dtdx =
h
X
2
t
p
p
=
t=0
t
=
h
h
t=0
t
t
p
p
p
p
σ_tot =
h
2
p
=
=
h
h
t=0
p
p



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


p
p
p
p
p
p
p
X


e
k
e′
k′
α^{1/2}
γ
-q^2=Q^2
X
p


q
p
X
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

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

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.

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:

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

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:

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

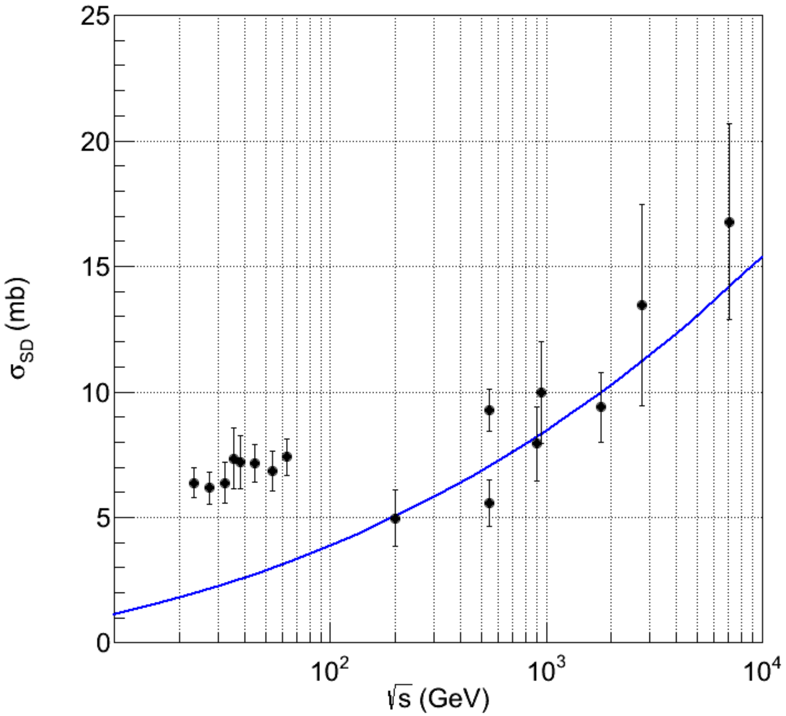
$$= A_n \sum_{n=0,1,\ldots} \frac{[f(t)]^{2(n+1)}\, Im\, \alpha(M_x^2)}{(2n + 0.5 - Re\, \alpha(M_x^2))^2 + (Im\, \alpha(M_x^2))^2} + B_n e^{b_{in}^{bg} t} \left(M_x^2 - M_{p+\pi}^2\right)^\epsilon$$

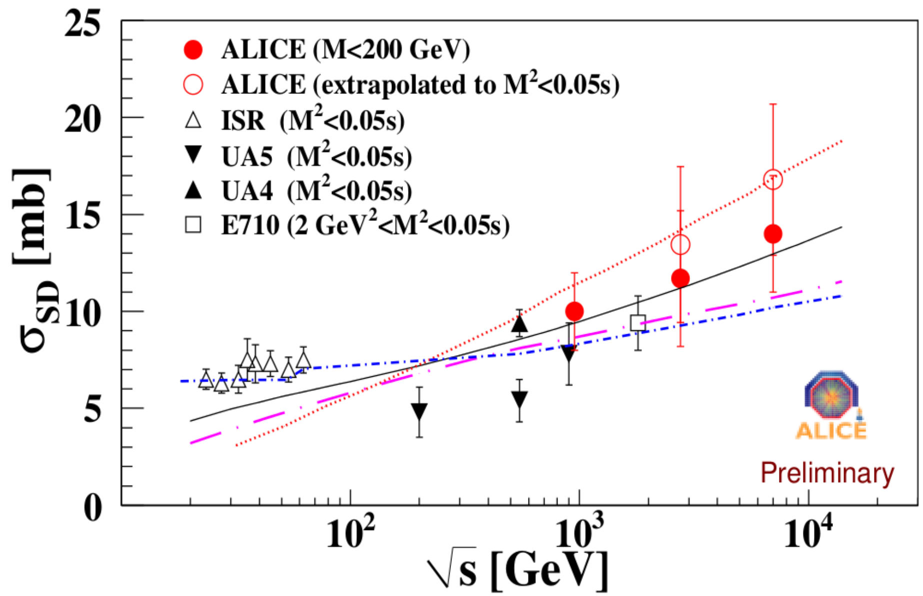
$$F(x_B, t) = \frac{x_B(1 - x_B)}{\left(M_x^2 - m_p^2\right)\left(1 + 4m_p^2 x_B^2/(-t)\right)^{3/2}}, \quad x_B = \frac{-t}{M_x^2 - m_p^2 - t}$$

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

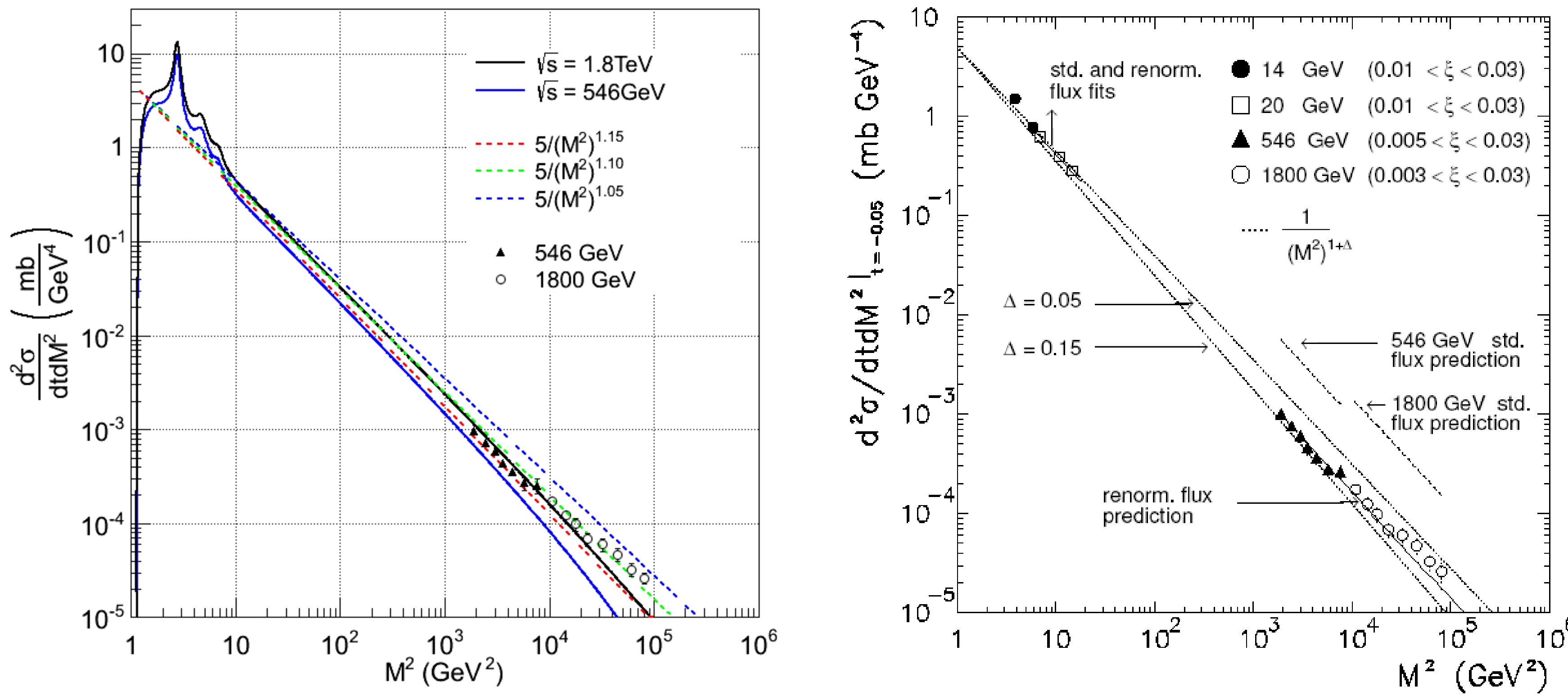
$$\alpha(t) = \alpha(0) + \alpha' t = 1.04 + 0.25t$$

SDD cross sections vs. energy.

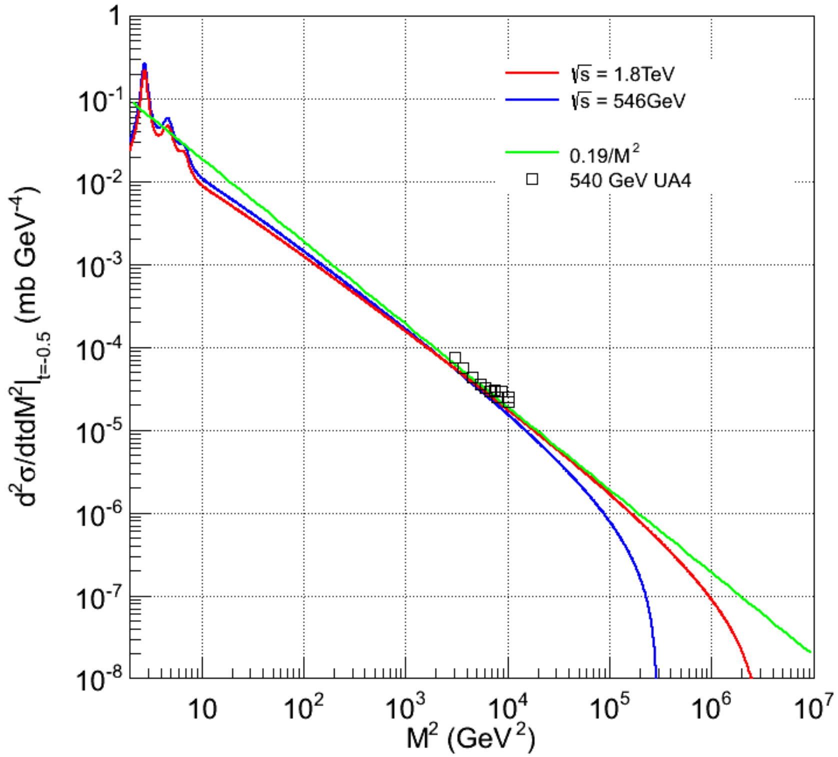


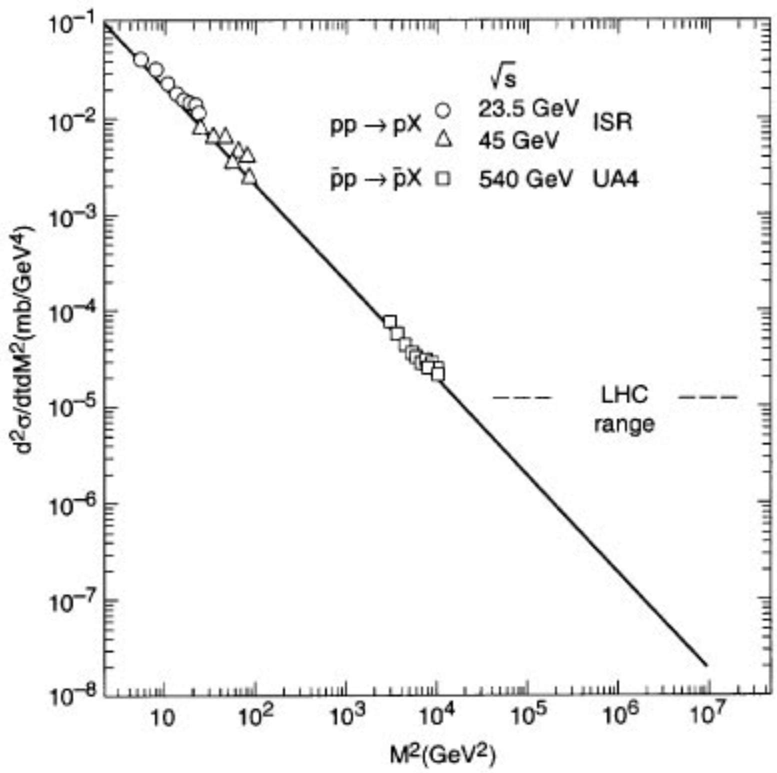


Approximation of background to reference points (t=-0.05)

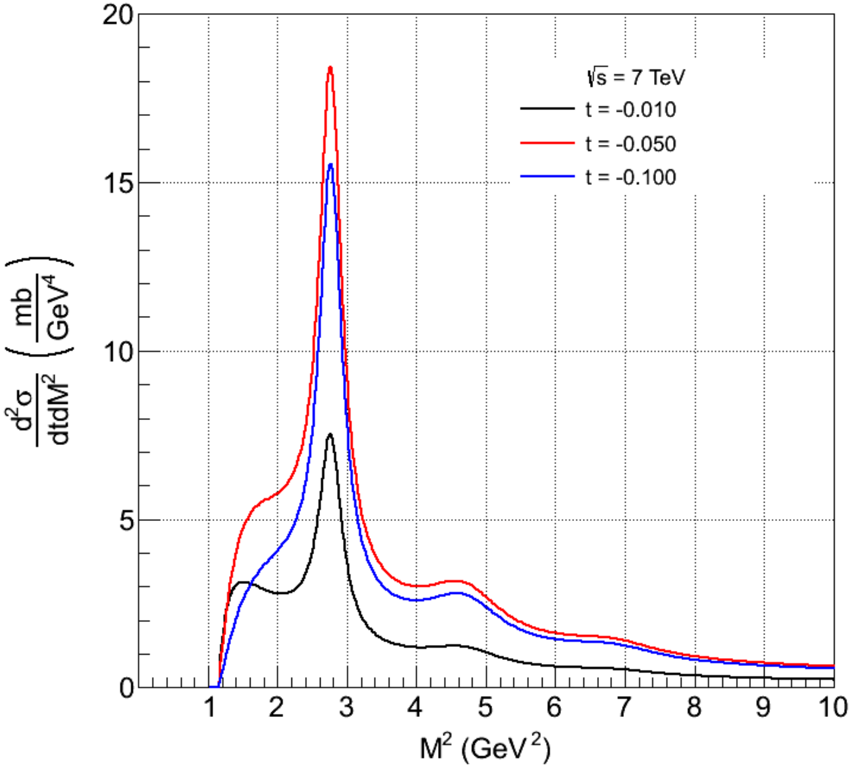


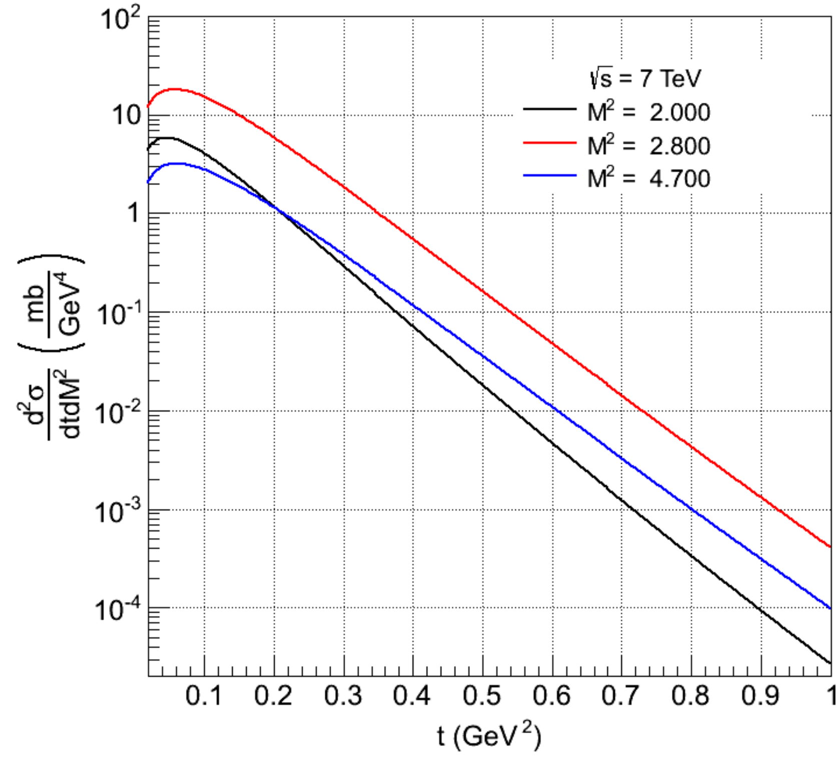
Approximation of background to reference points (t=-0.5)



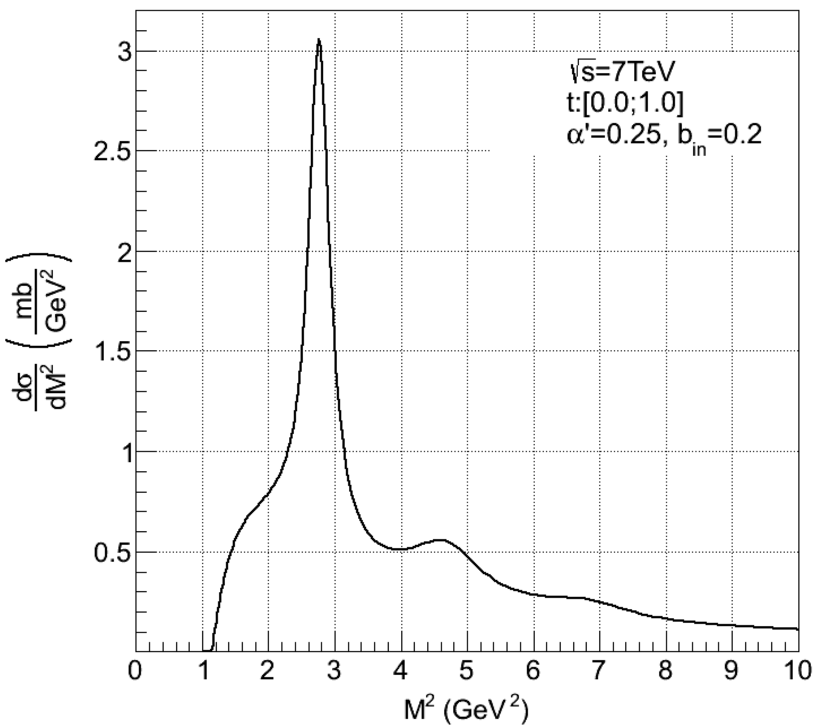


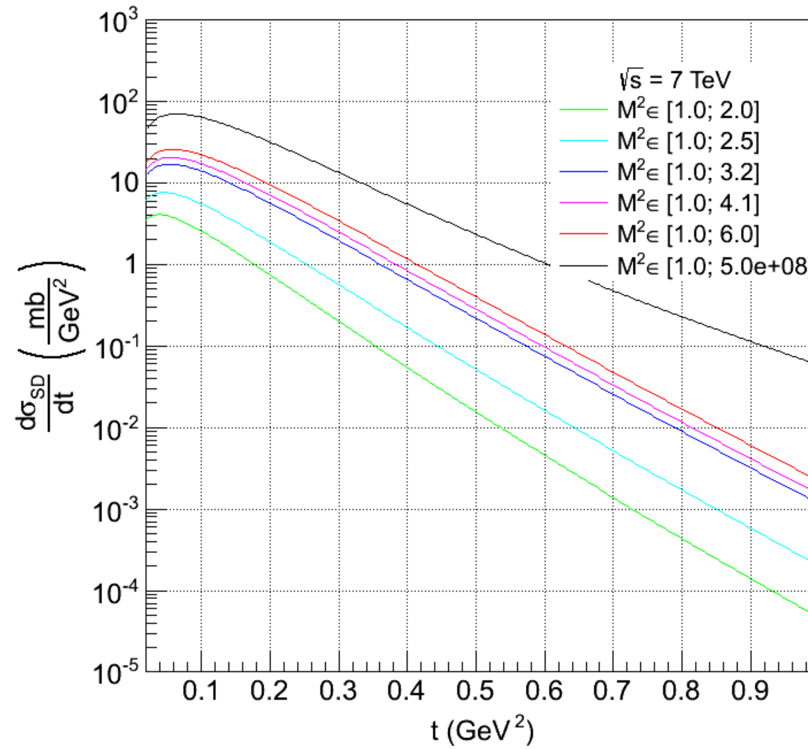
Double differential SD cross sections



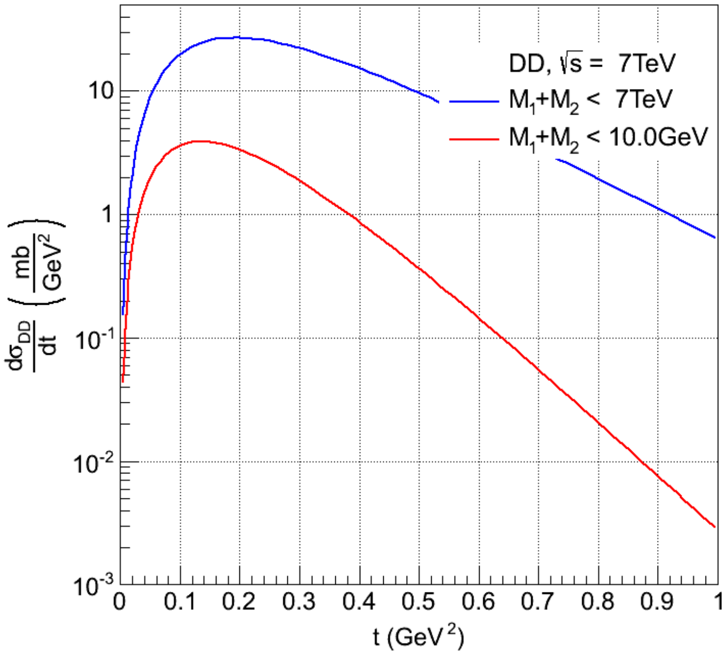


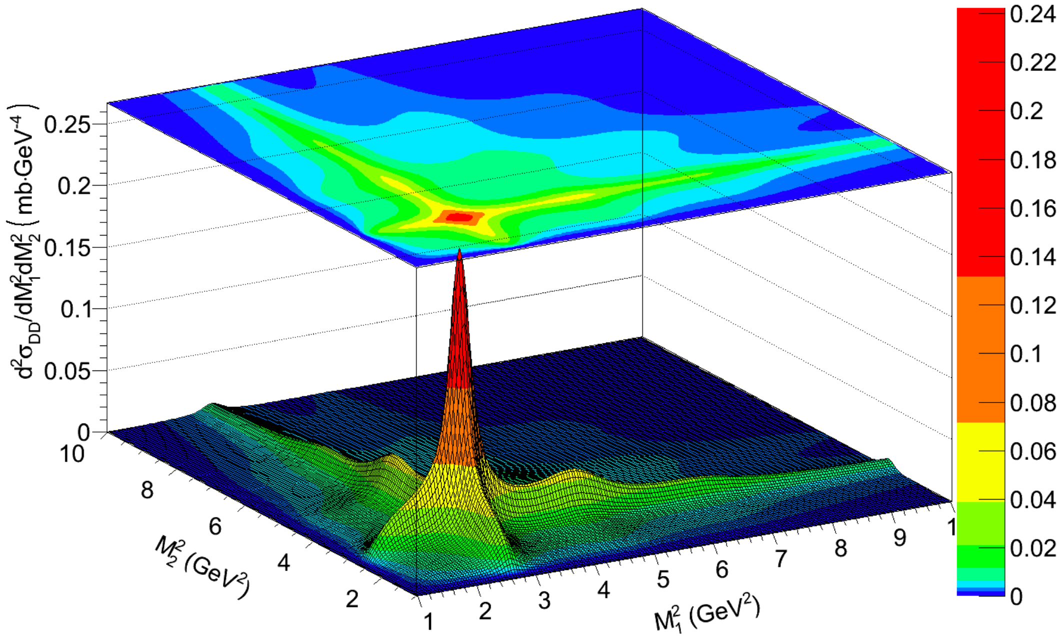
Single differential integrated SD cross sections



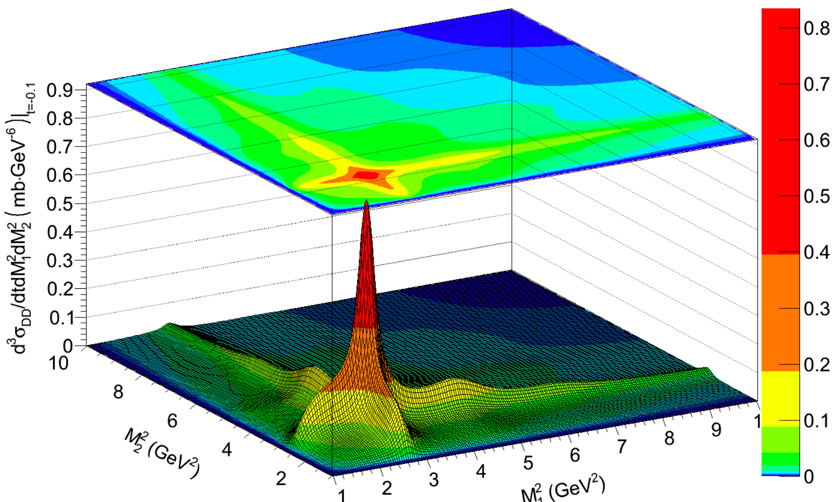


Integrated DD cross sections

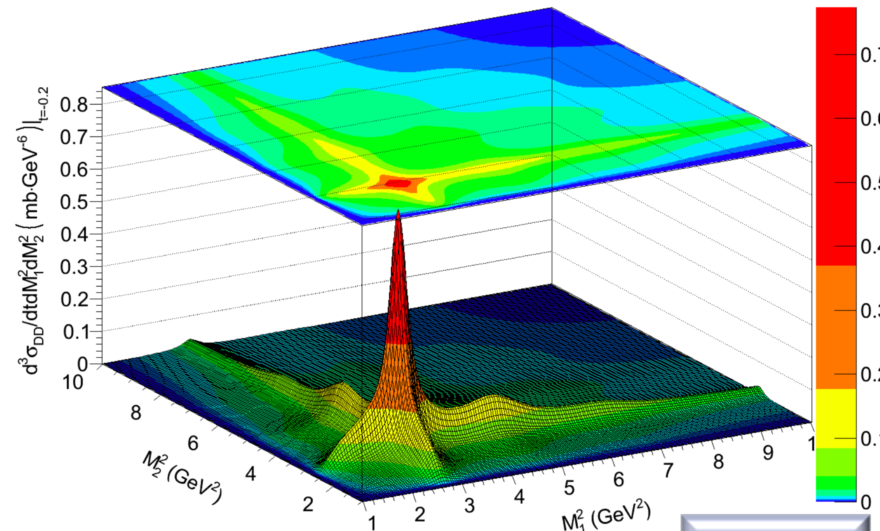




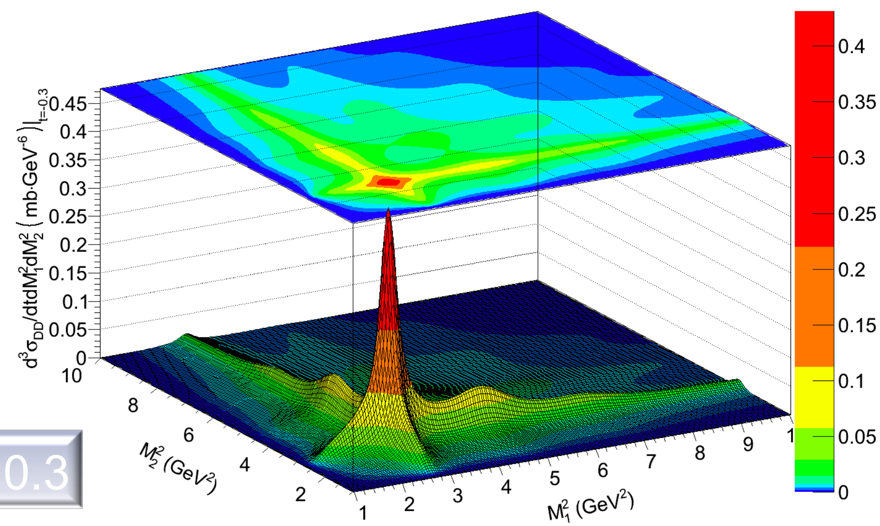
Triple differential DD cross sections



t = - 0.1



t = - 0.2



t = - 0.3

The parameters and results

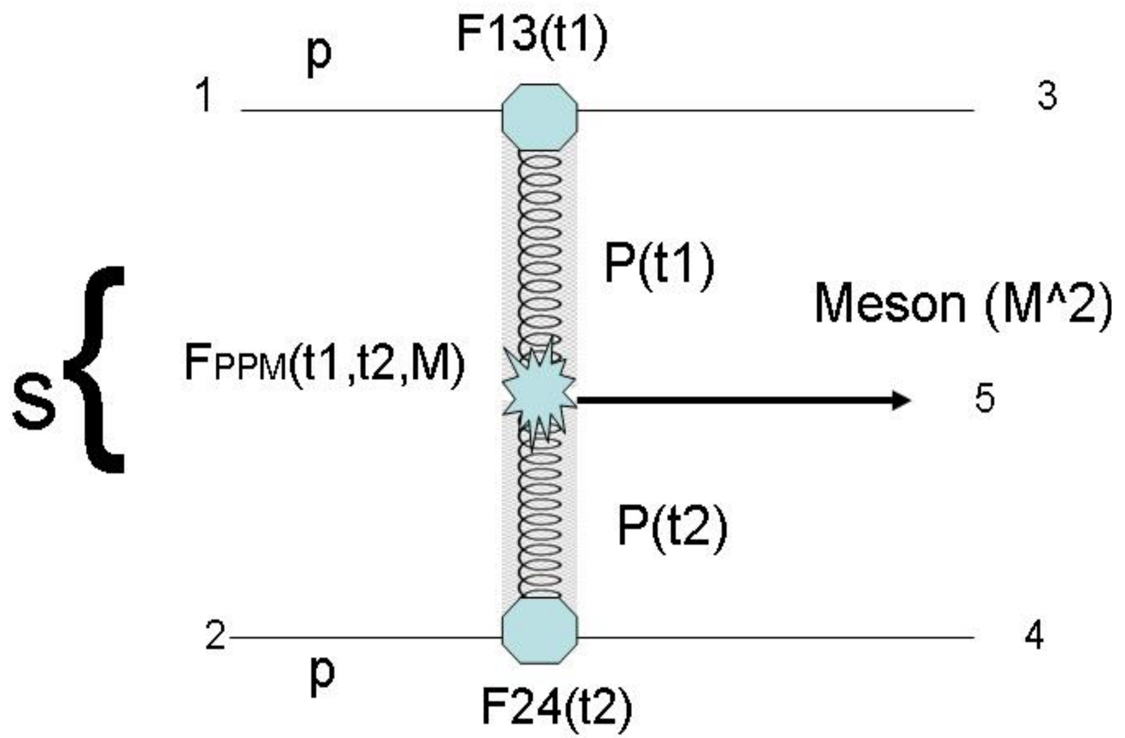
b_{in} (GeV^{-2})	0.2
b_{in}^{bg} (GeV^{-2})	3
α' (GeV^{-2})	0.25
$\alpha(0)$	1.04
ϵ	1.03
A_n	18.7
B_n	8.8
C_n	3.79e-2

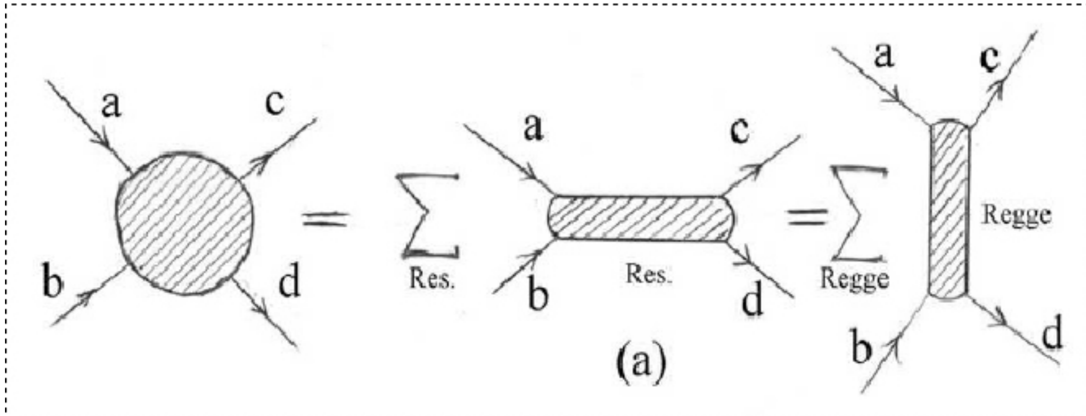
σ_{SD} (mb)	14.13
$\sigma_{SD}(M < 3.5 GeV)$ (mb)	4.68
$\sigma_{SD}(M > 3.5 GeV)$ (mb)	9.45
σ_{Res}^{SD} (mb)	2.48
σ_{Bg}^{SD} (mb)	9.45
σ_{DD} (mb)	10.68
$\sigma_{DD}(M < 10 GeV)$ (mb)	1.05
$\sigma_{DD}(M > 10 GeV)$ (mb)	9.63

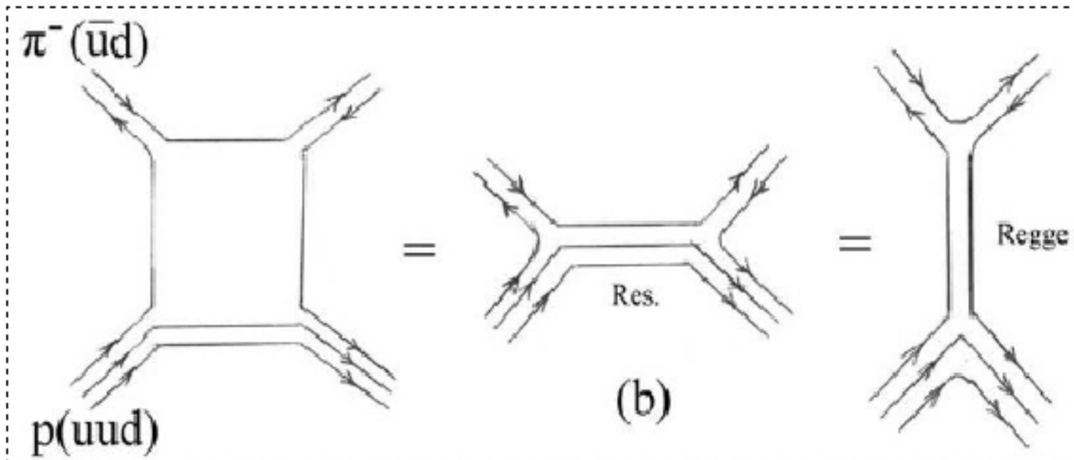
Prospects:

Central diffractive meson production (double Pomeron exchange);

Antoni Szczurek et al., talk at this Symposium




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


π⁻ (ūd)
p(uud)
Res.
Regge
(b)

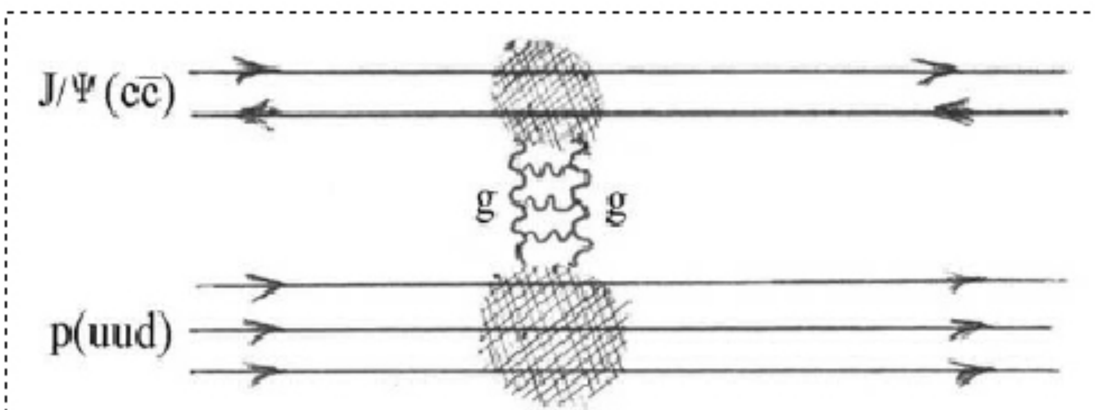

J/Ψ (cc̄)
g
g
p(uud)

TABLE I: Two-component duality

$\mathcal{I}mA(a+b\to c+d) =$	R	Pomeron
$s-$channel	$\sum A_{Res}$	Non-resonant background
$t-$channel	$\sum A_{Regge}$	Pomeron $(I=S=B=0;\ C=+1)$
Duality quark diagram	Fig. 1b	Fig. 2
High energy dependence	$s^{\alpha-1},\ \alpha<1$	$s^{\alpha-1},\ \alpha\geq 1$

Thank you!

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