Diffraction in high-energy hadron- and lepton-induced reactions

School on **New Trends in HEP and QCD**

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Plan

II. INTRODUCTORY

1. Historical introduction;
2. Definition: Diffraction= a) Pomeron exchange; b) Rapgap;
   How many Pomerons? One (but complicated!); The Odderon;
   amplitudes and measurables;
3. Regge poles (t-channel) and geometrical (s-channal) models;
4. Unitarity, impact parameter, eikonal, U-matrix, gap survival;

II. HADRON-INDUCED REACTIONS (FERMILAB, RHIC, LHC)

5. Elastic scattering, low=|t| structures, the dip-bump phenomenon, black disc limi
6. Resonance-Regge duality, the background, two-component duality;
7. SDD, DDD, CED, factorization relations;
8. The pPX vertex and DIS (HERA), triple Regge limit;
9. Duality and FMSR;
10. Diffraction at the LHC: Pomeron (>95%) dominance;

III. LEPTON-INDECED REACTIONS (HERA, JLAB,…)

11. Diffractive structure functions;
12. Diffractive vector meson production (VMP);

III. VMP at the LHC (ULTRA-PERIPHERA COLLISIONS)

Diffraction in optics and in HEP

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.

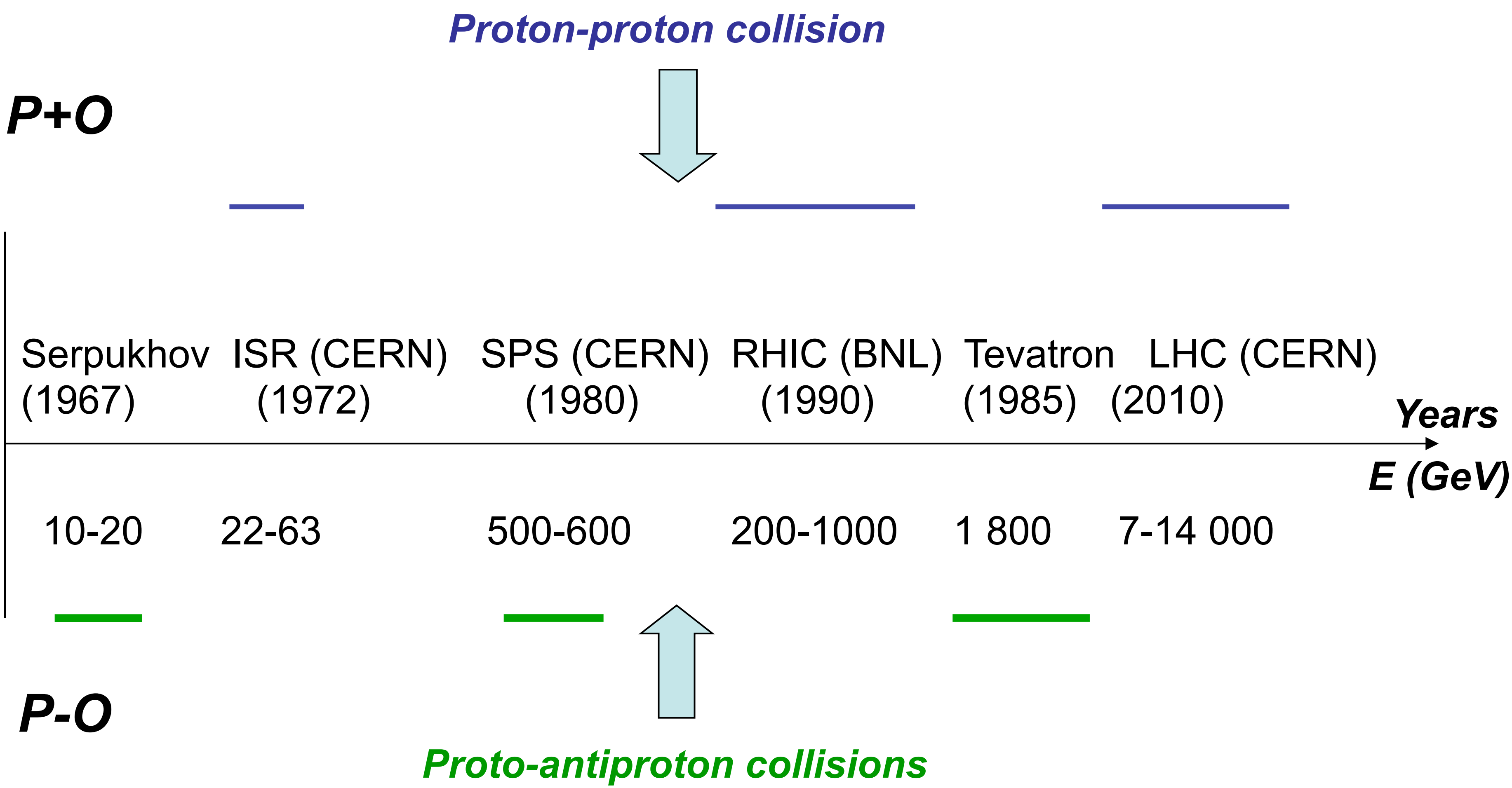
In high-energy, say, $> 1GeV$, experiments, *Fraunhofer* diffraction dominates: the obstacle, hole =detector is of $1Fm$, while the distance between the source and the detector is practically infinite. (N.B.: At tha LHC, however, Fresnel diffraction may occur in the Coulomb region.) At the LHC, $\sqrt{14}TeV$, $R \approx 1Fm$, $D\ 1cm$, 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 !

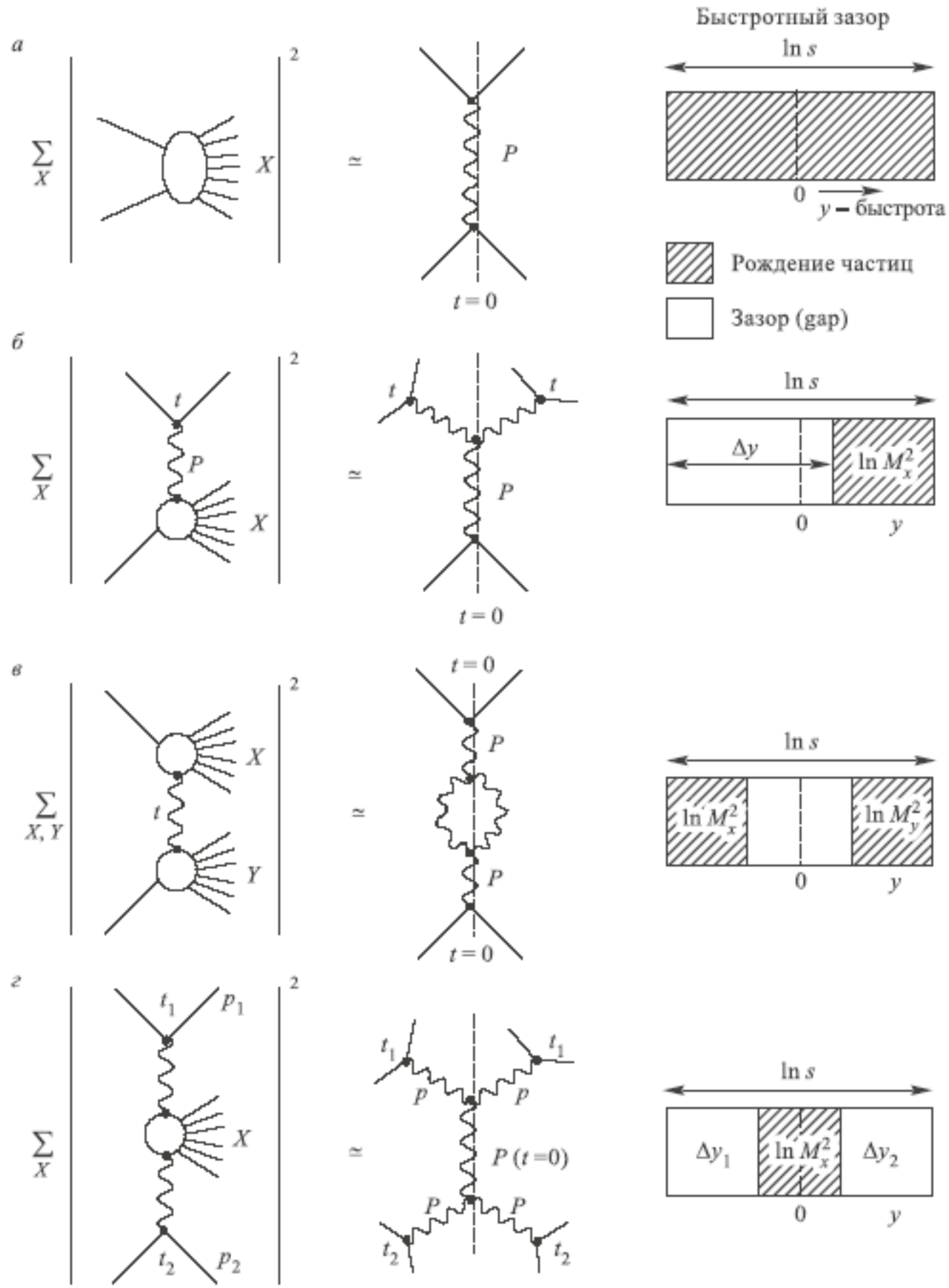
References

- P.D.B. Collins: *An introduction to Regge poles & HEP*, Cambridge Univ. Press, 1977;
- S. Donnachie, G. Dosch, P. Landshoff, and O. Nachtmann: *Pomeron physics and QCD*;
- V. Barone and E. Predazzi: High-energy particle diffraction
- L. Jenkovszky (below)

Accelerators, energy ranges, years (sketch)



P-Pomeron; O-odderon



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

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

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

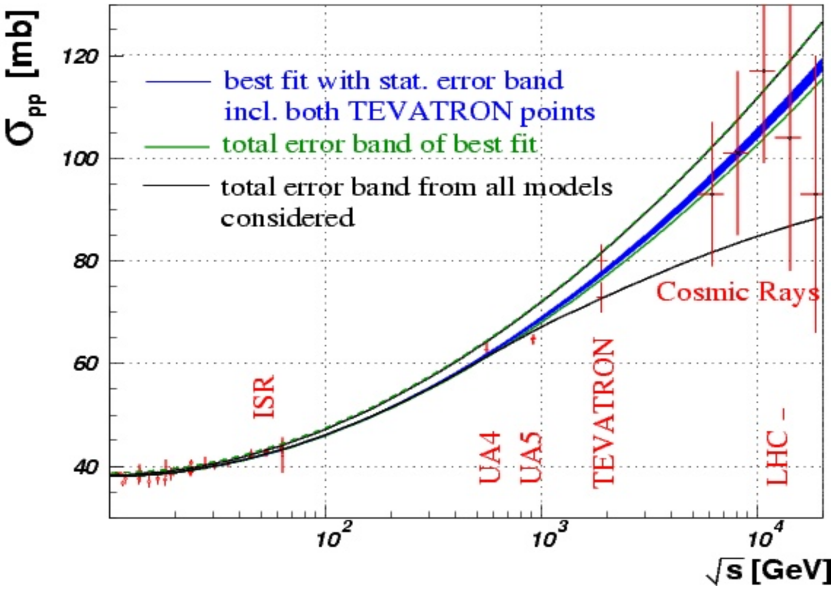
$$A_{pp}^{p\bar{p}}(s,t) = P(s,t) \pm O(s,t) + f(s,t) \pm \omega(s,t) \to_{LHC} \approx P(s,t) \pm O(s,t),$$

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

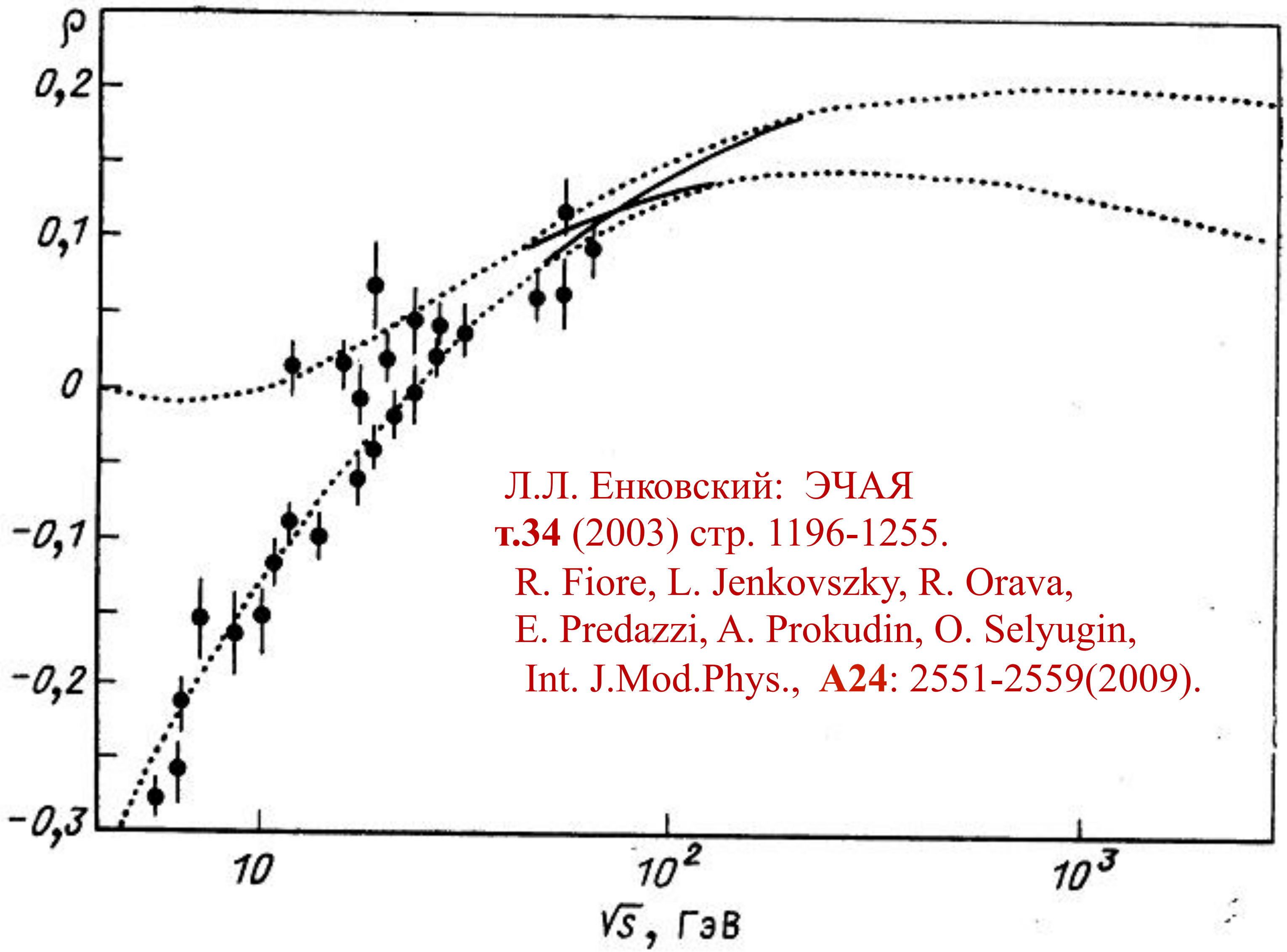
Inversely: $L\sigma_{tot} = N_{elastic} + N_{inelastic}$

(σ_{tot} + $dN/dt|_{t=0}$)
(L + $dN/dt|_{t=0}$)

→

($\Delta L/L$ > ~ 2 $\Delta\sigma_{tot}/\sigma_{tot}$)
($\Delta\sigma_{tot}/\sigma_{tot}$ > ~ $\frac{1}{2}$ $\Delta L/L$)

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

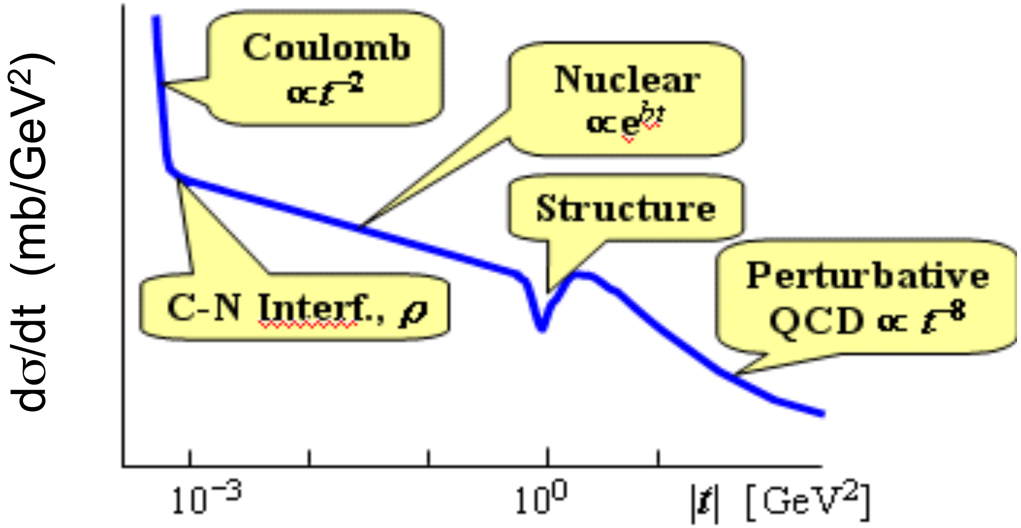


Л.Л. Енковский: ЭЧАЯ
т.34 (2003) стр. 1196-1255.

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

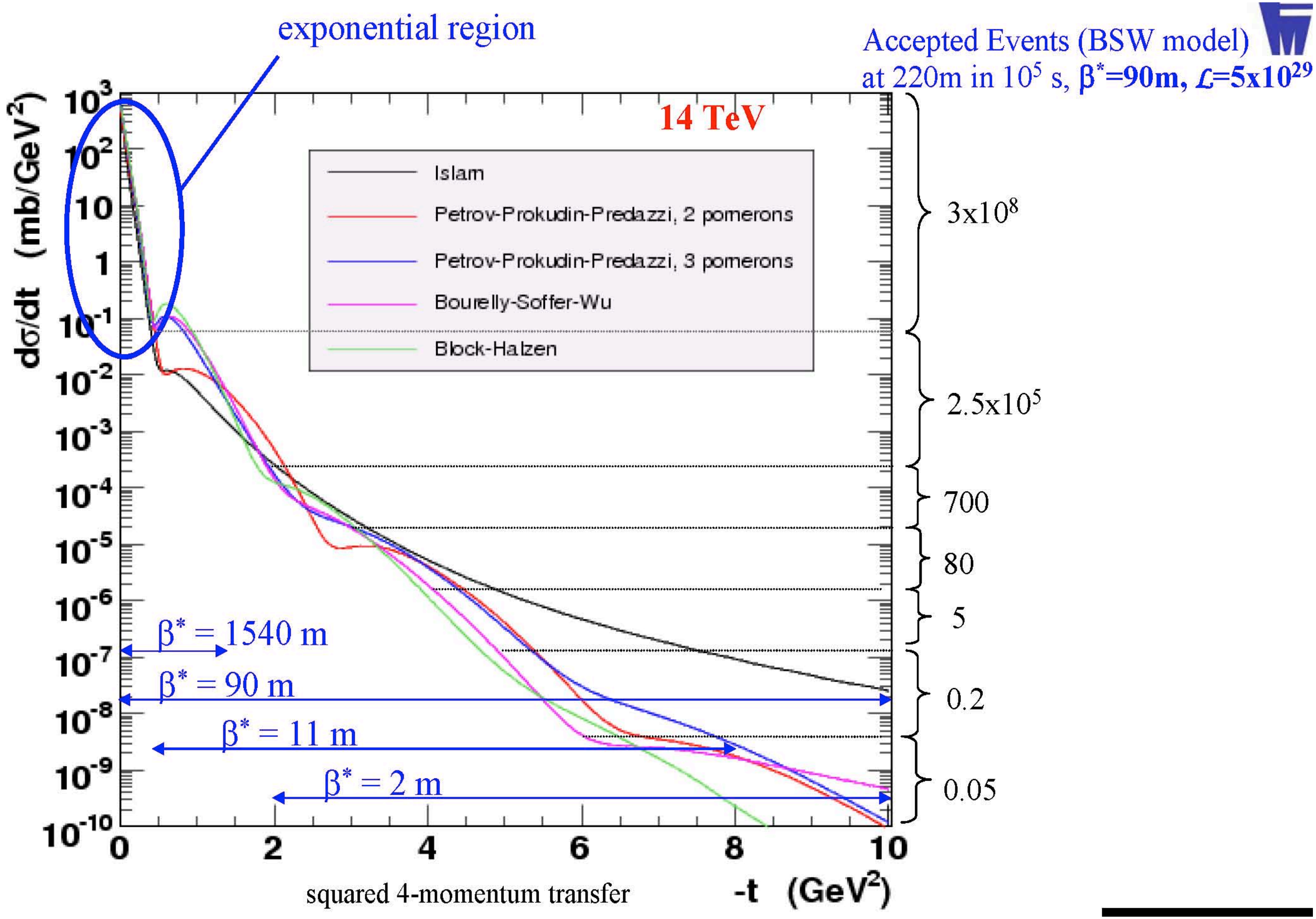
$$\rho = \left.\frac{\mathrm{Re}(f_{el}(t))}{\mathrm{Im}(f_{el}(t))}\right|_{t\to 0}$$

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

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

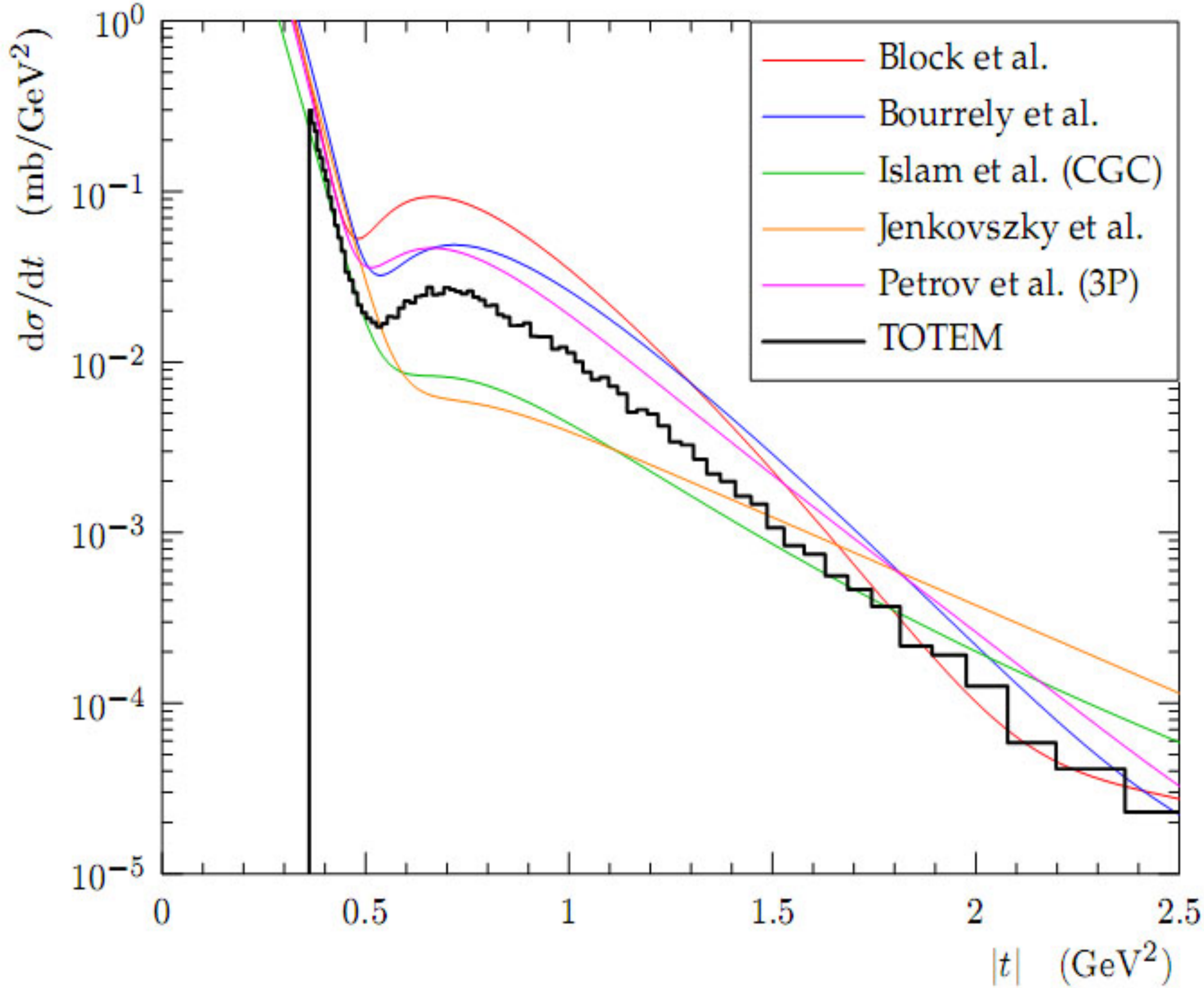
CNI region: $|f_C| \sim |f_N|$ → @ LHC: $-t \sim 6.5\ 10^{-4}$ GeV^2; $\theta_{min} \sim 3.4$ μrad

($\theta_{min} \sim 120$ μrad @ SPS)

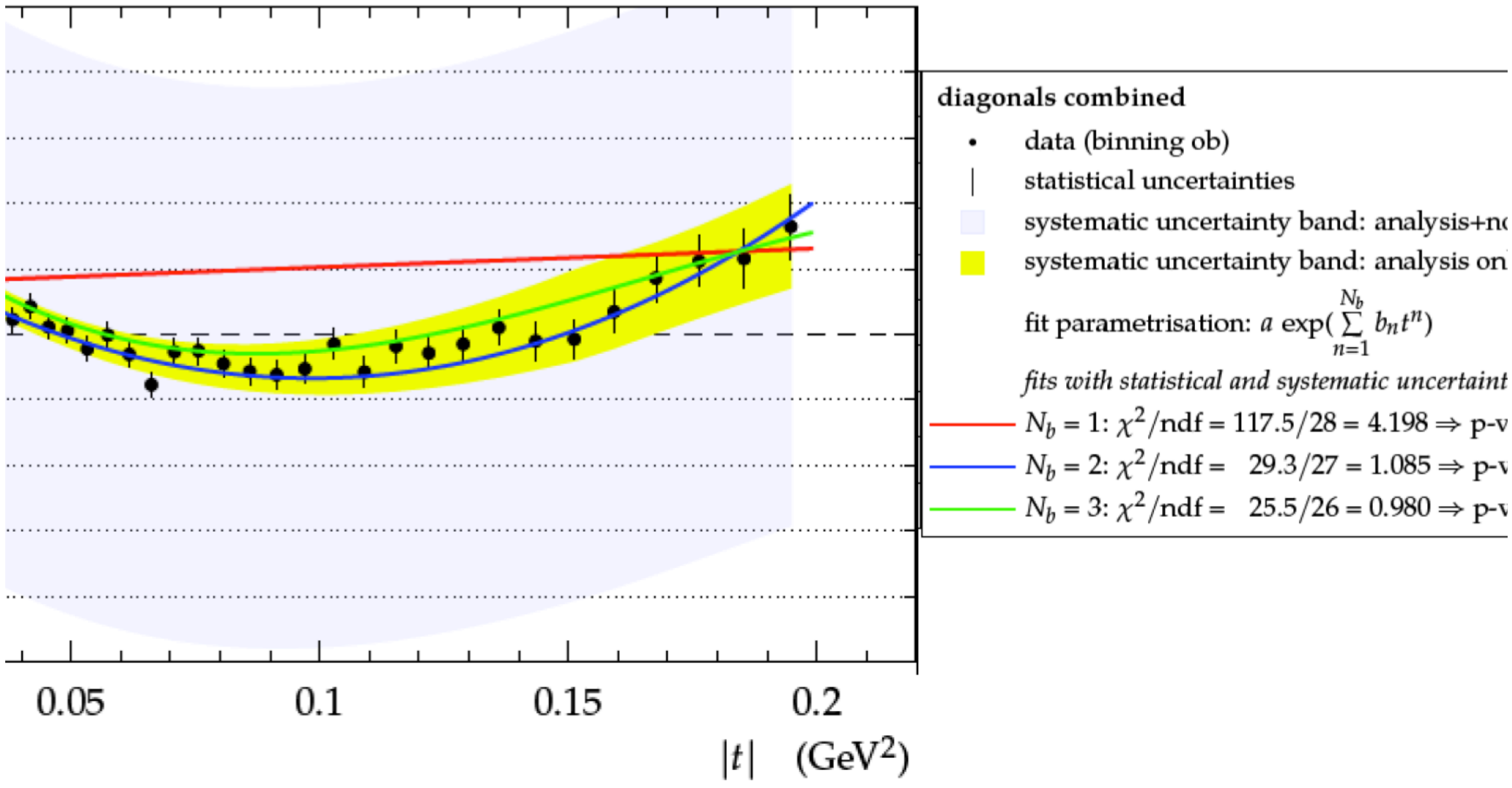


exponential region
Accepted Events (BSW model)
at 220m in 10^5 s, β*=90m, L=5x10^29
14 TeV
Islam
Petrov-Prokudin-Predazzi, 2 pomerons
Petrov-Prokudin-Predazzi, 3 pomerons
Bourelly-Soffer-Wu
Block-Halzen
dσ/dt (mb/GeV^2)
3x10^8
2.5x10^5
700
80
5
0.2
0.05
β* = 1540 m
β* = 90 m
β* = 11 m
β* = 2 m
squared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

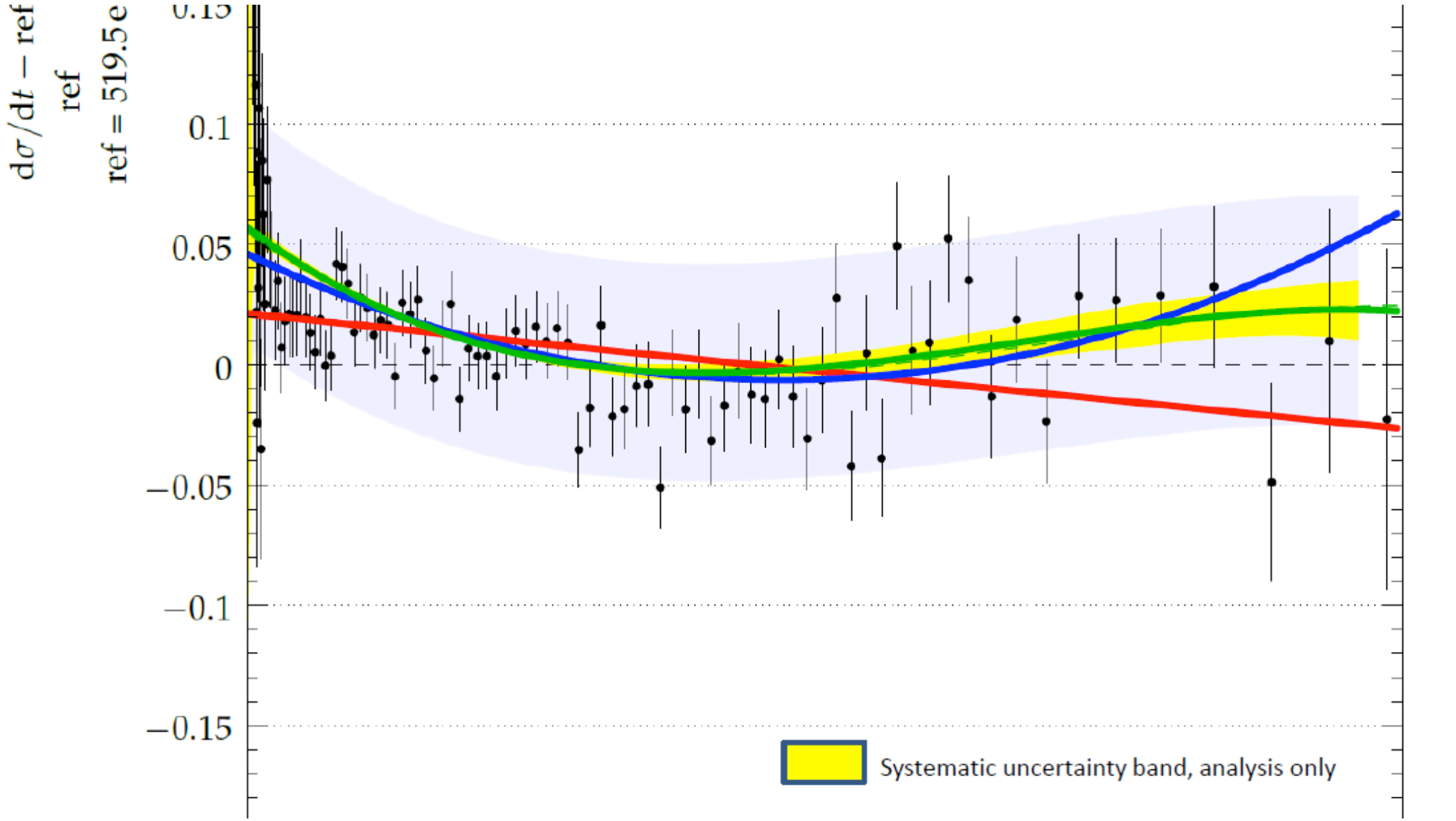
CERN LHC, TOTEM Collab., June 26, 2011:



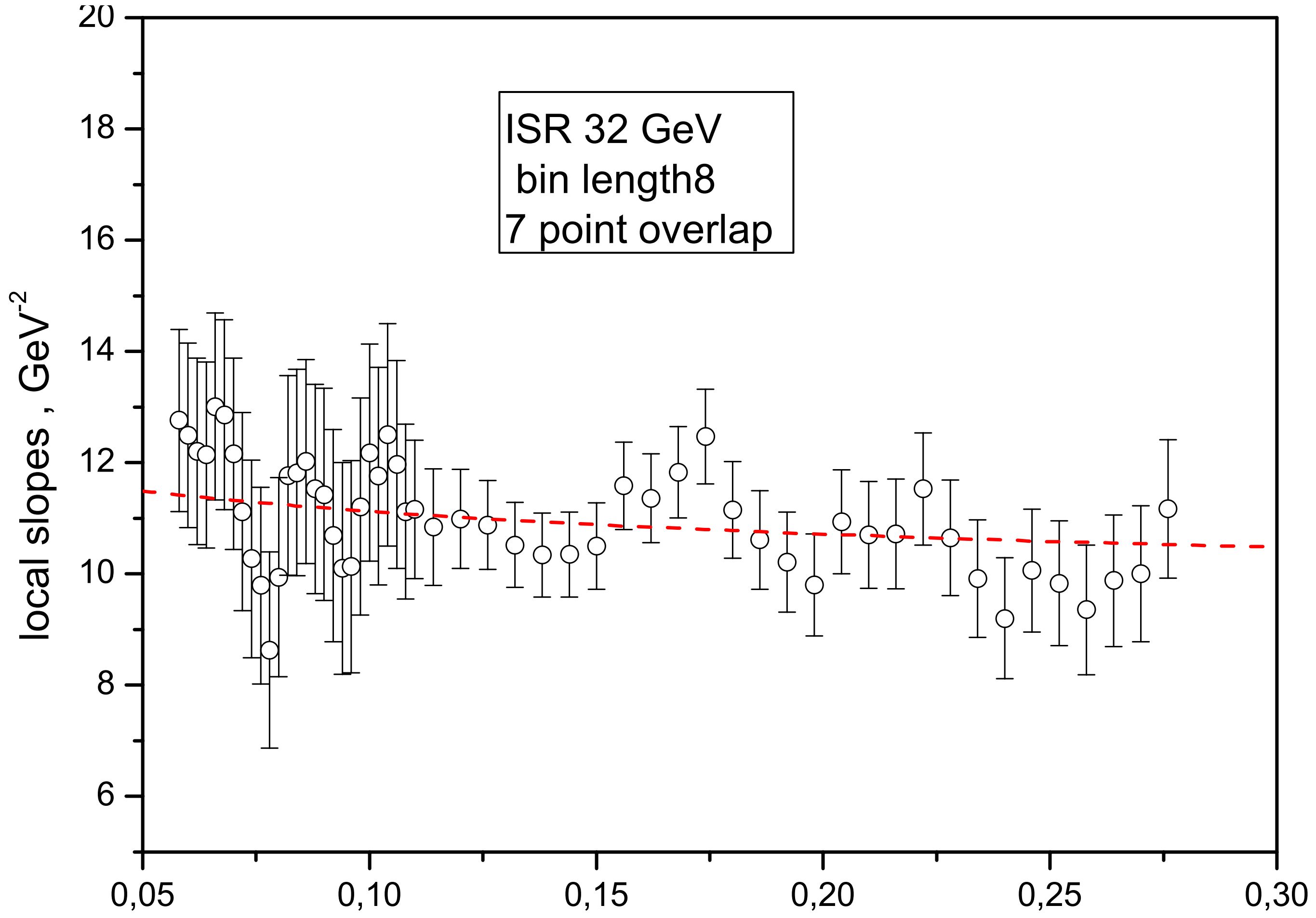
Fine structure of the Pomeron (at the LHC)



Fine structure of the Pomeron (TOTEM)



Tiny oscillations on the cone?

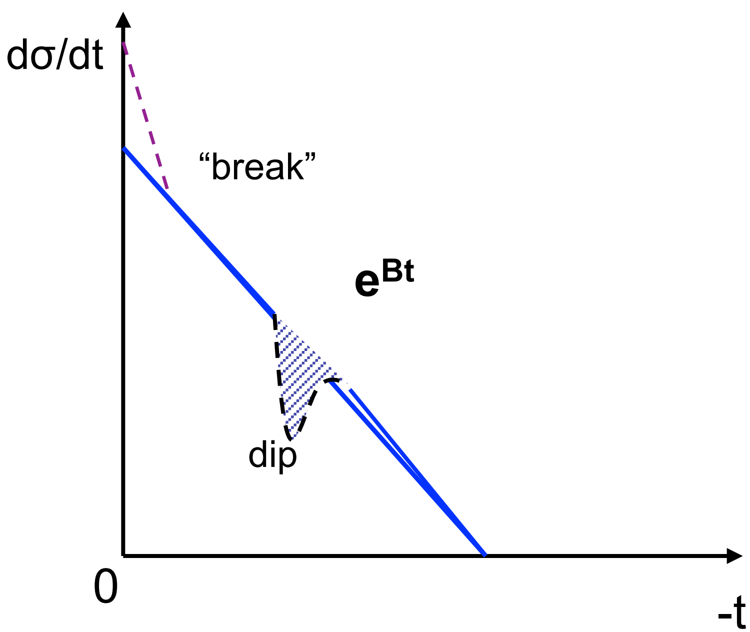


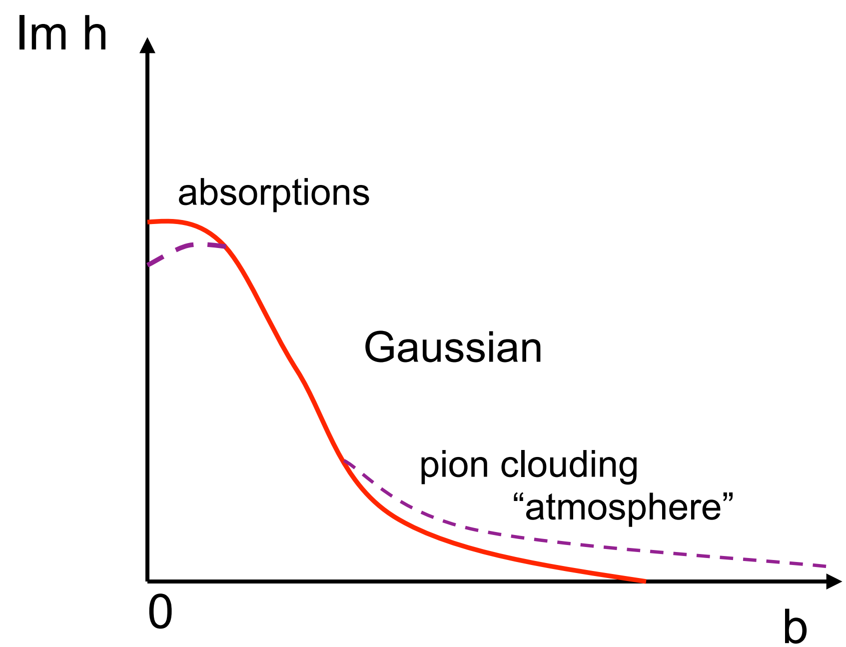
Geometrical scaling (GS), saturation and unitarity

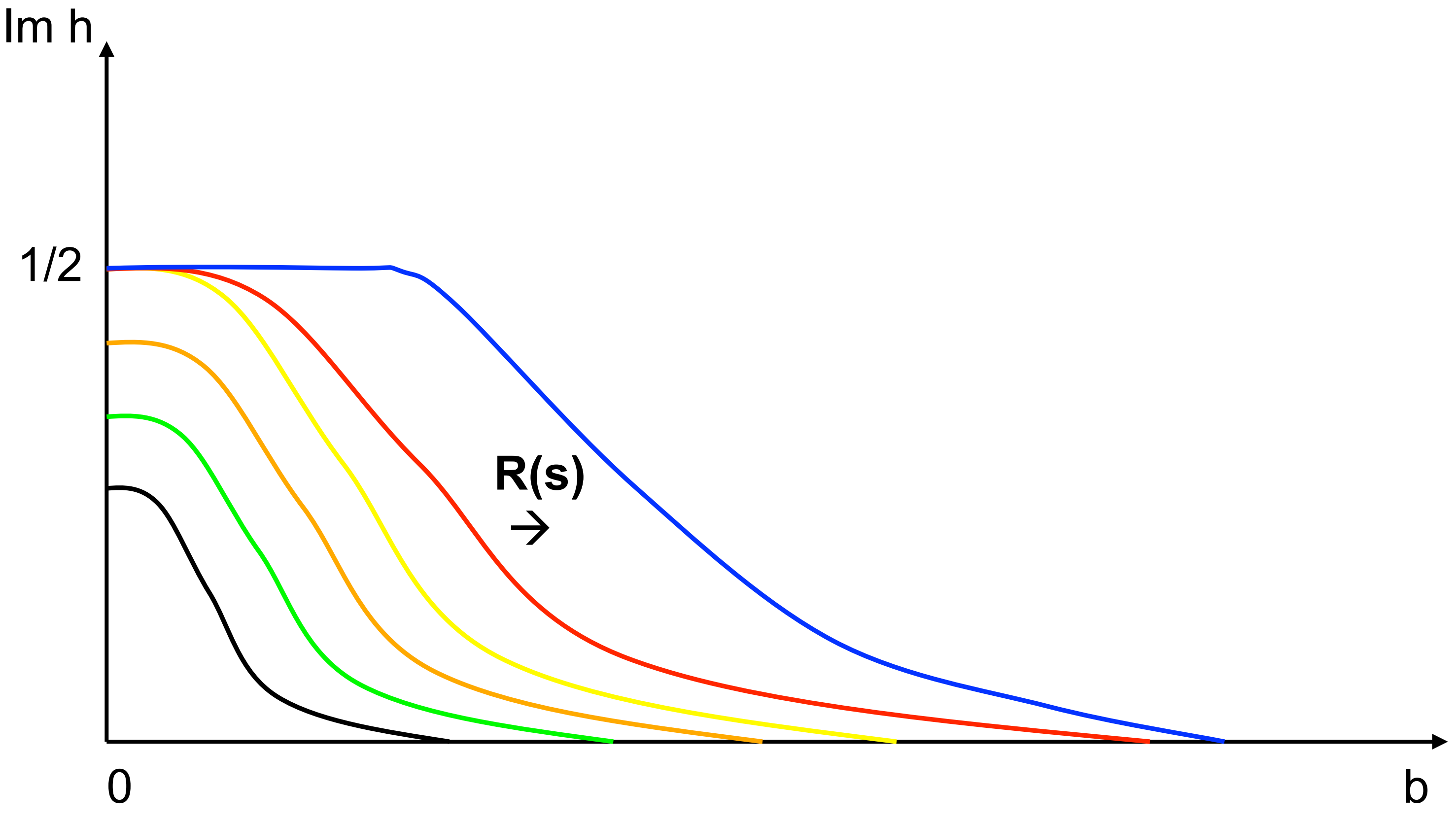
1. **On-shell (hadronic) reactions (s,t, Q^2=m^2);**

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

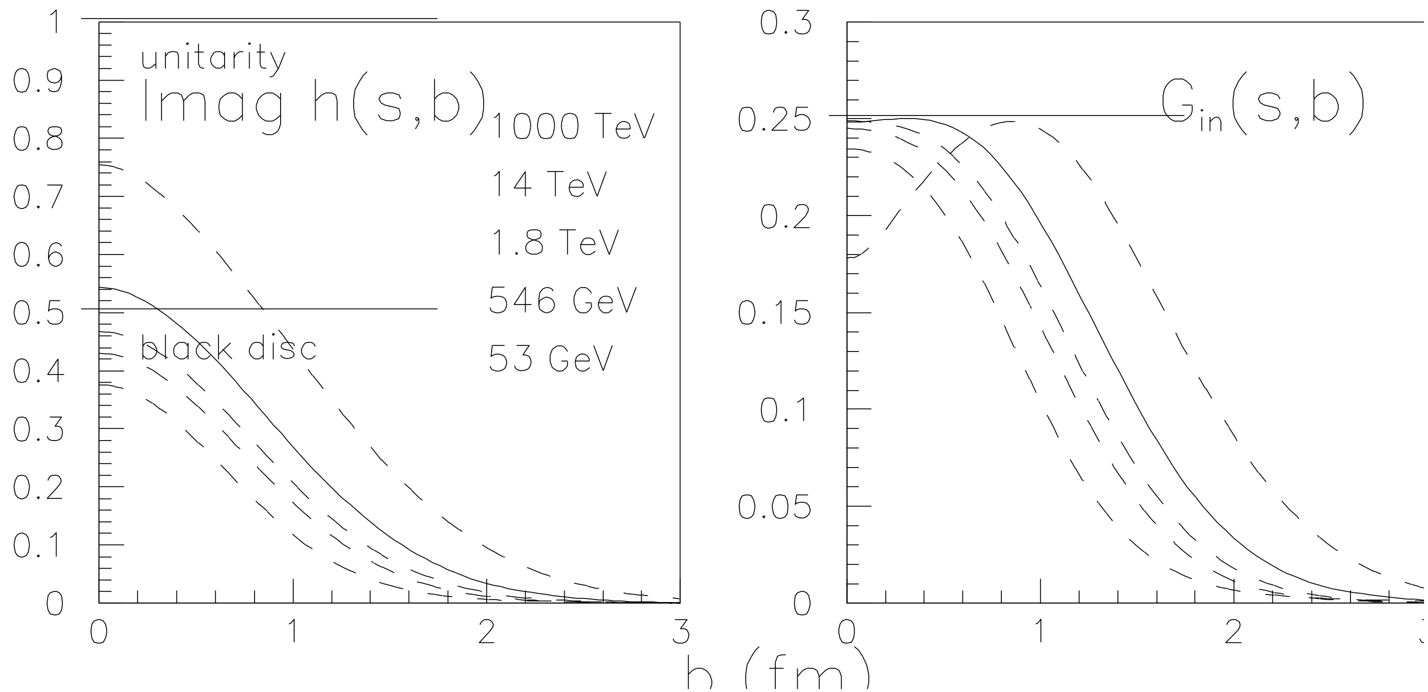
and dictionary:






Im h
1/2
R(s)
0
b

Black disc limit



P. Desgrolard, L.L. Jenkovszky and B.V. Struminsky, Z.Phys. C; Yad. Fizika, 1995.

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

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

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

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

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

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

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, 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.

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

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

The (s,t) term of a dual amplitude is

$$D(s,t) = c\int_0^1 dx\Big(\frac{x}{g_1}\Big)^{-\alpha(s')-1}\Big(\frac{1-x}{g_2}\Big)^{-\alpha(t')-1},$$

where s and t are the Mandelstam variables, and $g_1,\ g_2$ are parameters, $g_1, g_2 > 1$. For simplicity, we set $g_1 = g_2 = g_0$.

1. Regge behavior, $s \to \infty,\ \ t = const:\ D(s,t) \sim s^{\alpha(t)-1}$;

2. Thereshold behavior, $s \to s_0:\quad D(s,t) \sim \sqrt{s_0 - s}[const + \ln(1 - s_0/s)]$;

3. Direct-channel poles:

$$D(s,t)=\sum_{n=0}^{\infty} g^{n+1}\sum_{l=o}^{n}\frac{[-s\alpha'(s)]^l C_{n-l}(t)}{[n-\alpha(s)]^{l+1}}.$$

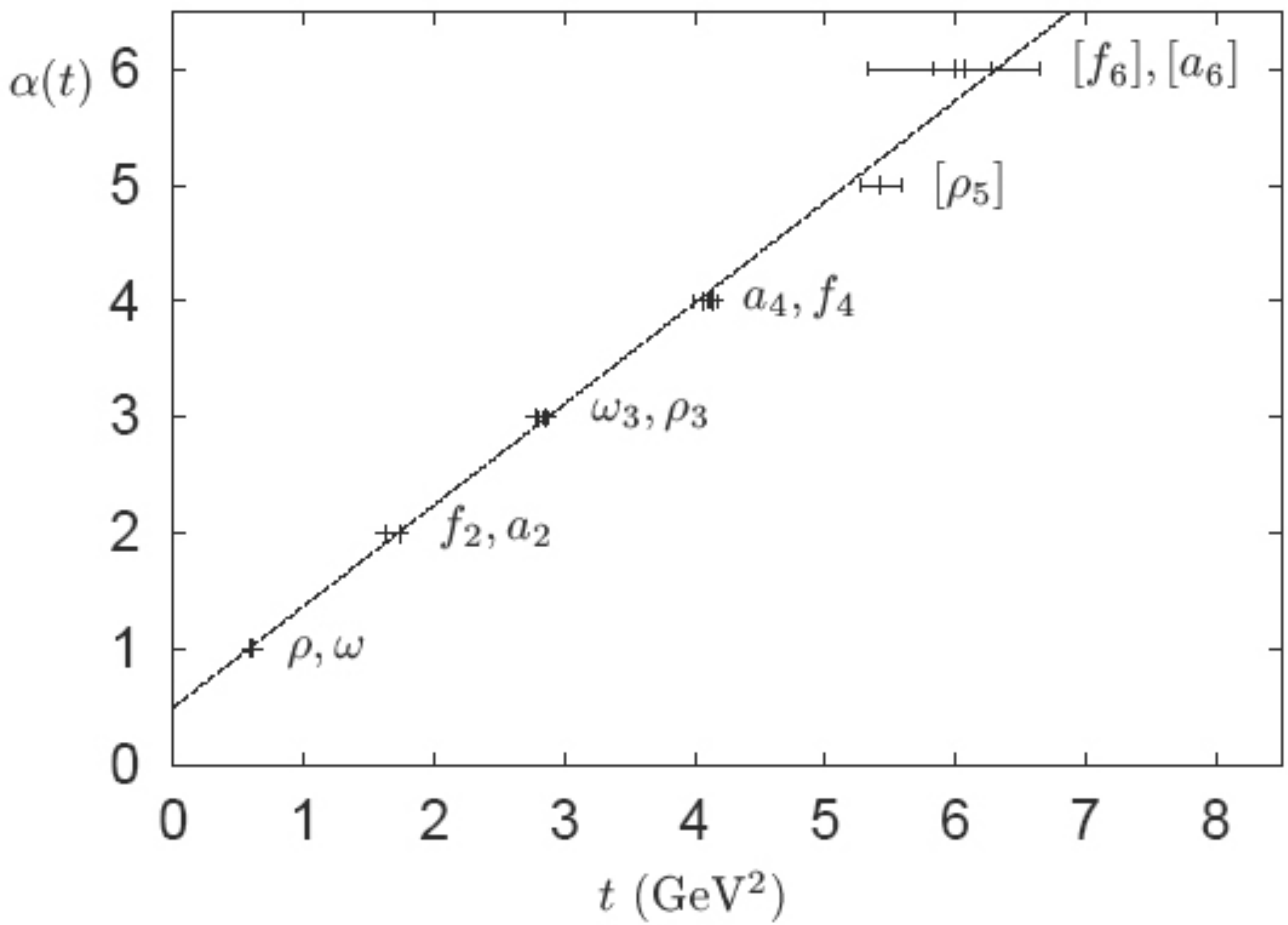
Exotic direct-channel trajectory: $\alpha(s)=\alpha(0)+\alpha_1(\sqrt{s}_0-\sqrt{s_0-s})$.

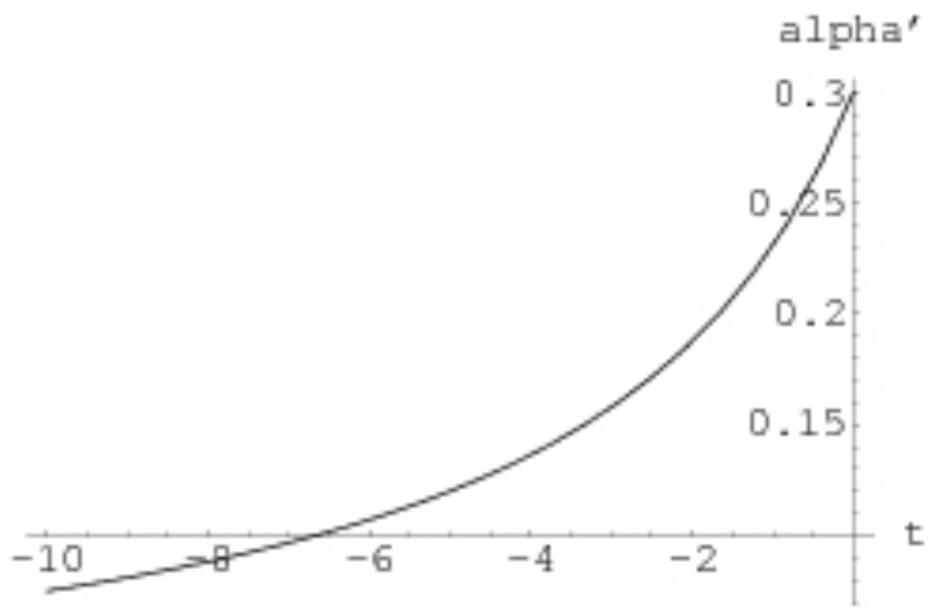
"GOLDEN" diffraction reaction: $J/\Psi p-$ scattering: By VMD, photoproduction is reduced to elastic hadron scattering:

$$D(\gamma p - Vp)=\sum \frac{e}{f_V} D(Vp-Vp).$$

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:

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

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.

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

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

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

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, 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.

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

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

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

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.

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

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

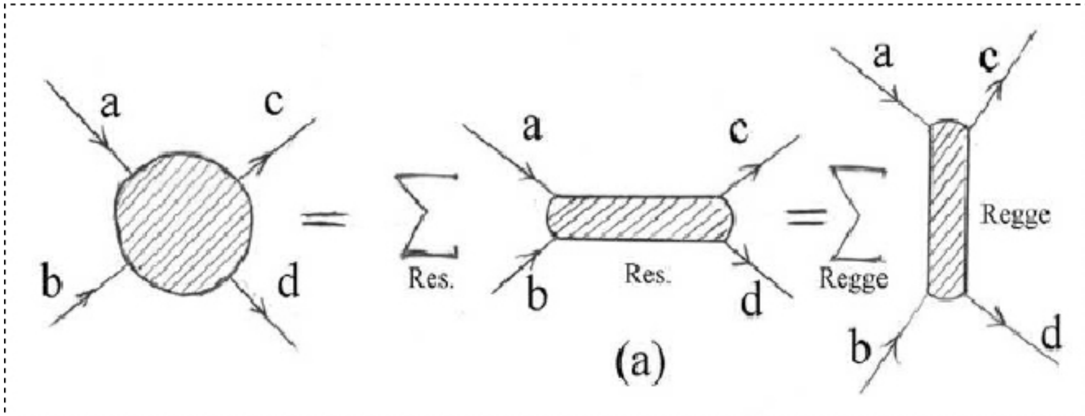
where $G(\alpha_P)$ is recovered by integration, and, as a consequence, the Pomeron amplitude can be rewritten in the following "geometrical" form

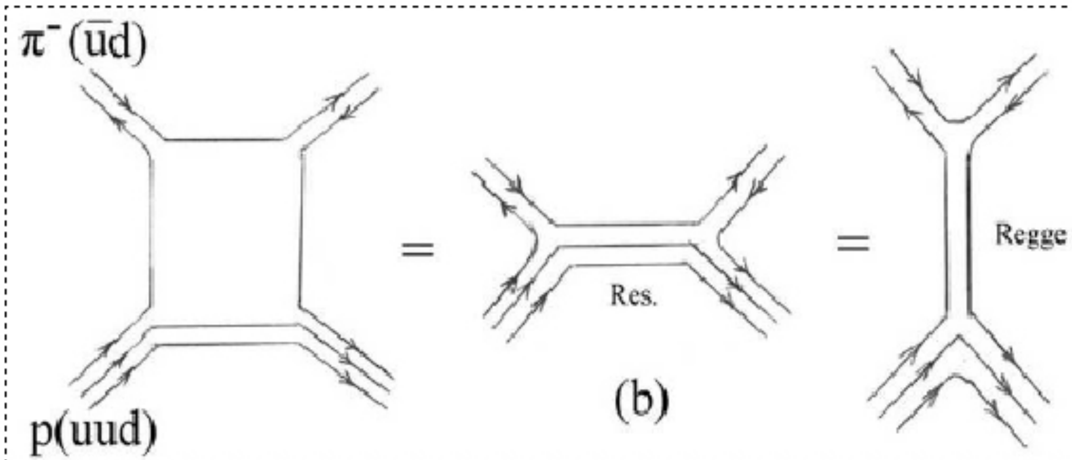
$$A_P(s,t) = i\frac{a_P\ \ s}{b_P\ \ s_0}[r_1^2(s)e^{r\ \ (s)[\alpha_P-1]} - \varepsilon_P r_2^2(s)e^{r\ \ (s)[\alpha_P-1]}], \tag{3}$$

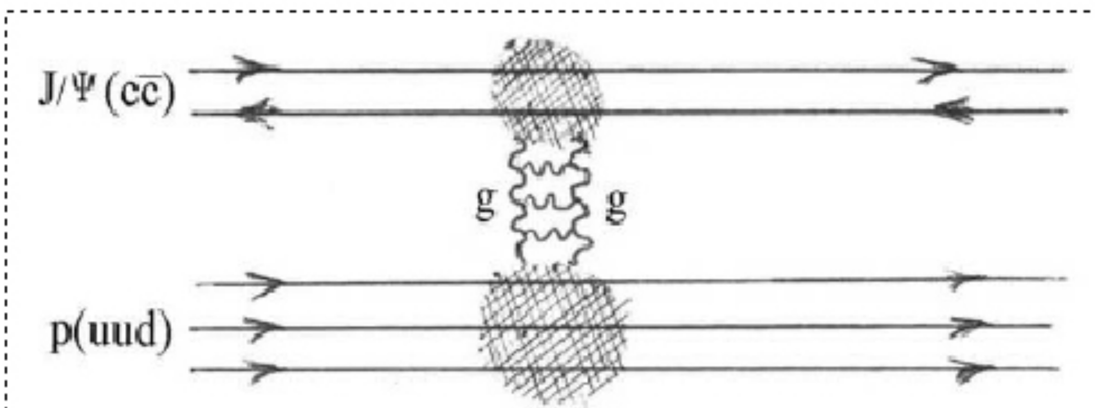
where $r_1^2(s) = b_P + L - i\pi/2, \quad r_2^2(s) = L - i\pi/2, \quad L \equiv \ln(s/s_0).$

TABLE I: Two-component duality

$\mathcal{I}mA(a+b\rightarrow c+d)=$	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	$s^{\alpha-1},\ \alpha<1$	$s^{\alpha-1},\ \alpha\geq 1$


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


π⁻ (ūd)
p(uud)
Res.
Regge
(b)

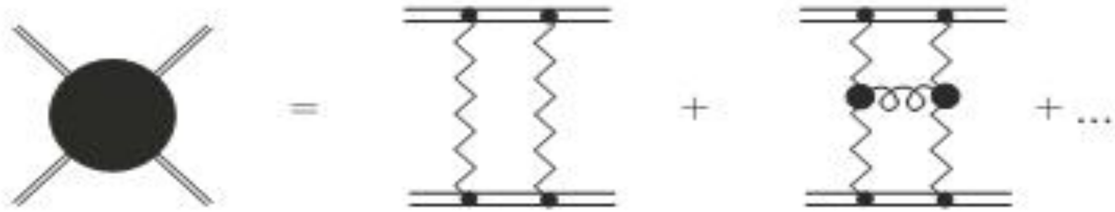

J/Ψ (cc̄)
g
g
p(uud)

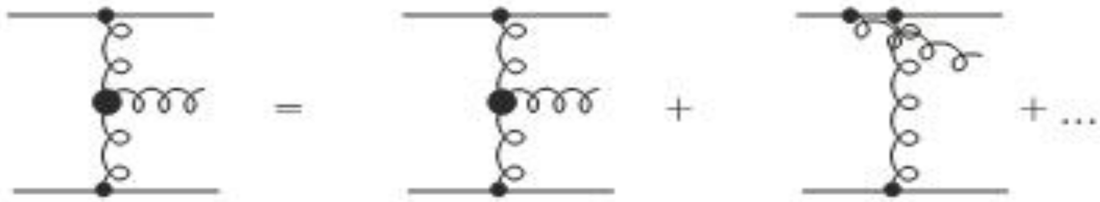
Does GS imply saturation? Not necessarily!

$ImH(s,b) = |h(s,b)|^2 + G_{in}(s,b)$, (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)): $h(s,b) = \Im u(s,b)/[1 - iu(s,b))]$,

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

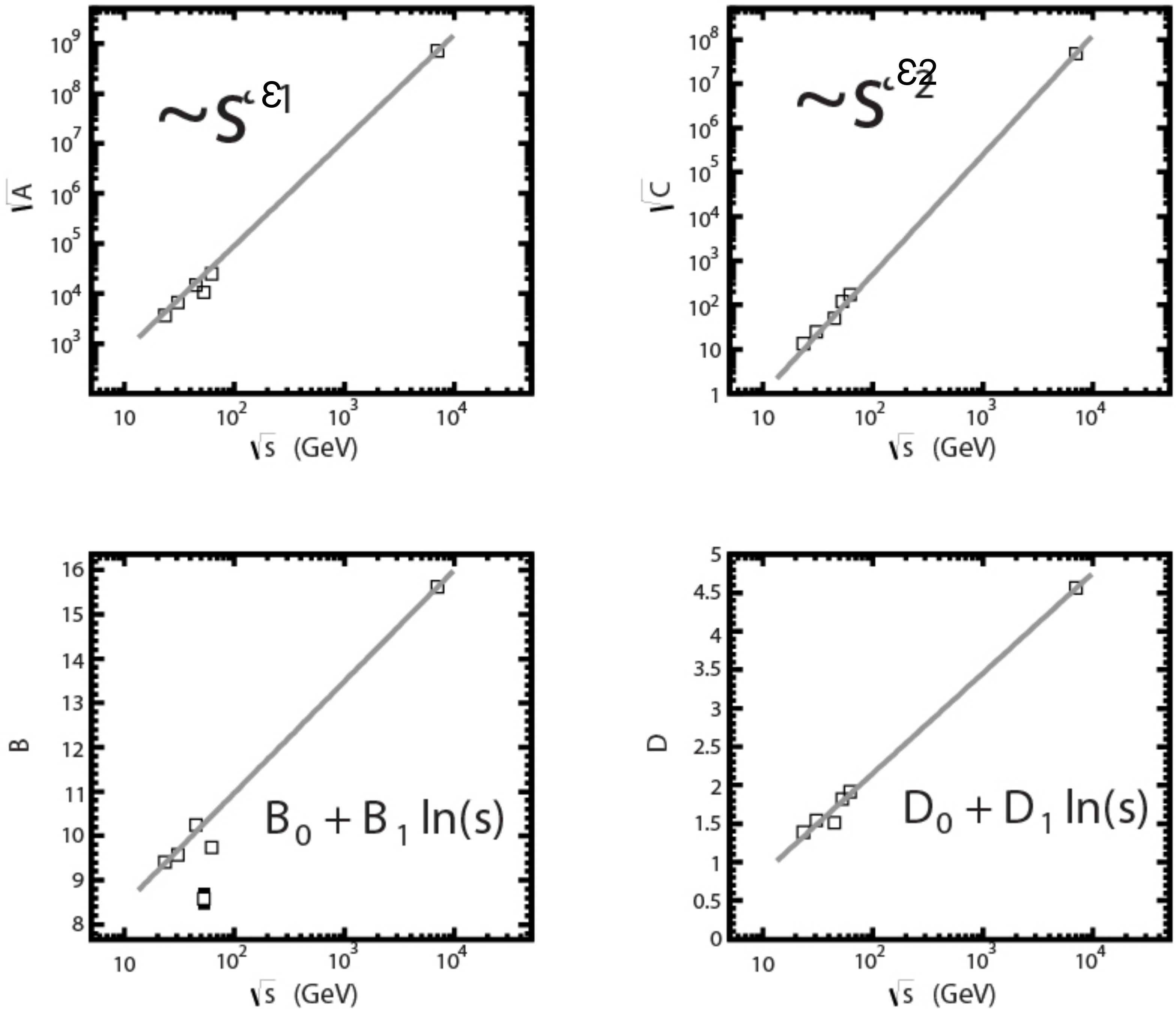
$$f_i = \sum_{j=0}^{i} a_{ij} L^j \; , \qquad (2)$$

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, International Journal of Modern Physics.

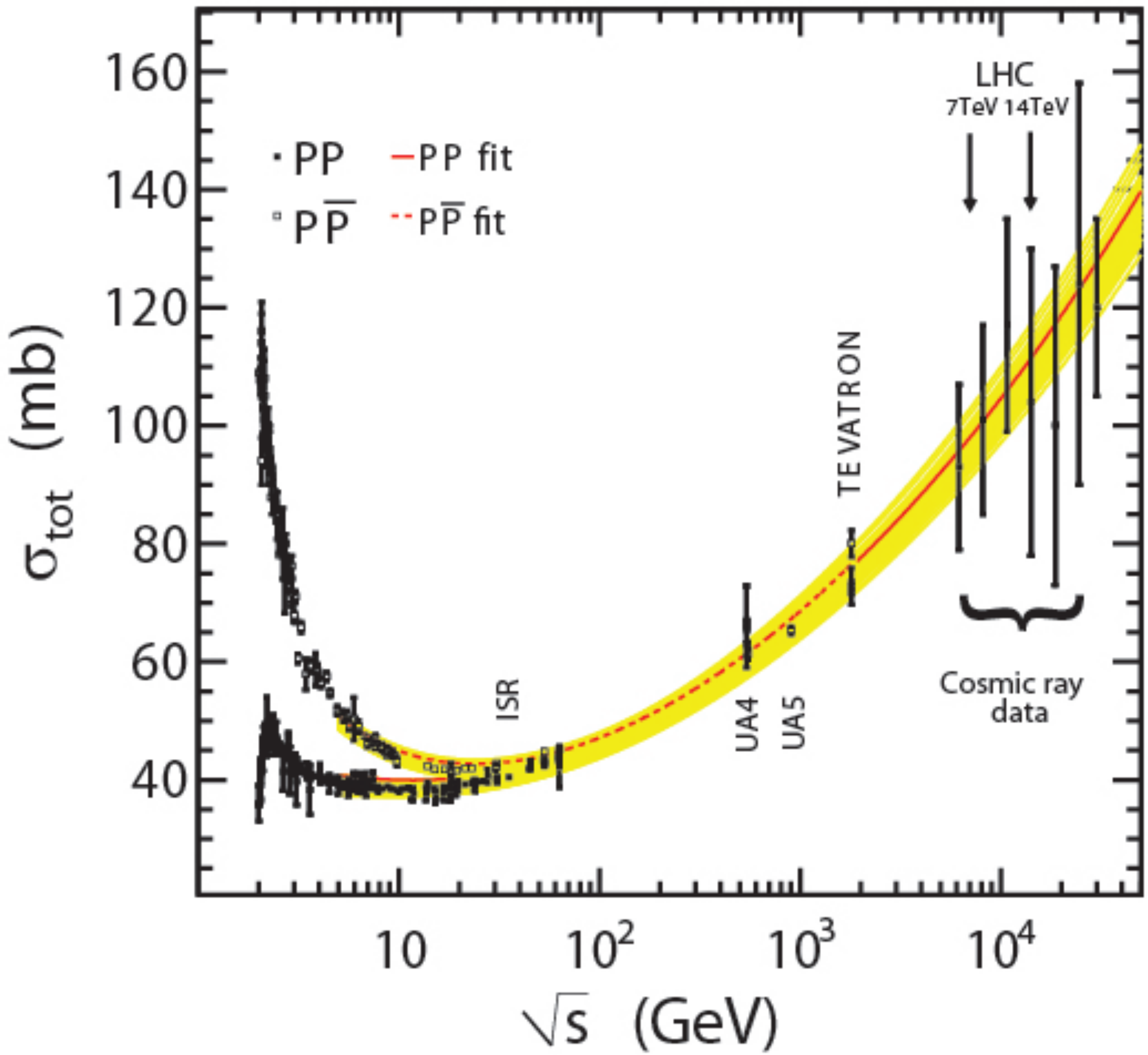


~S^ε1
~S^ε2
√A
√C
B
D
√s (GeV)
B0 + B1 ln(s)
D0 + D1 ln(s)

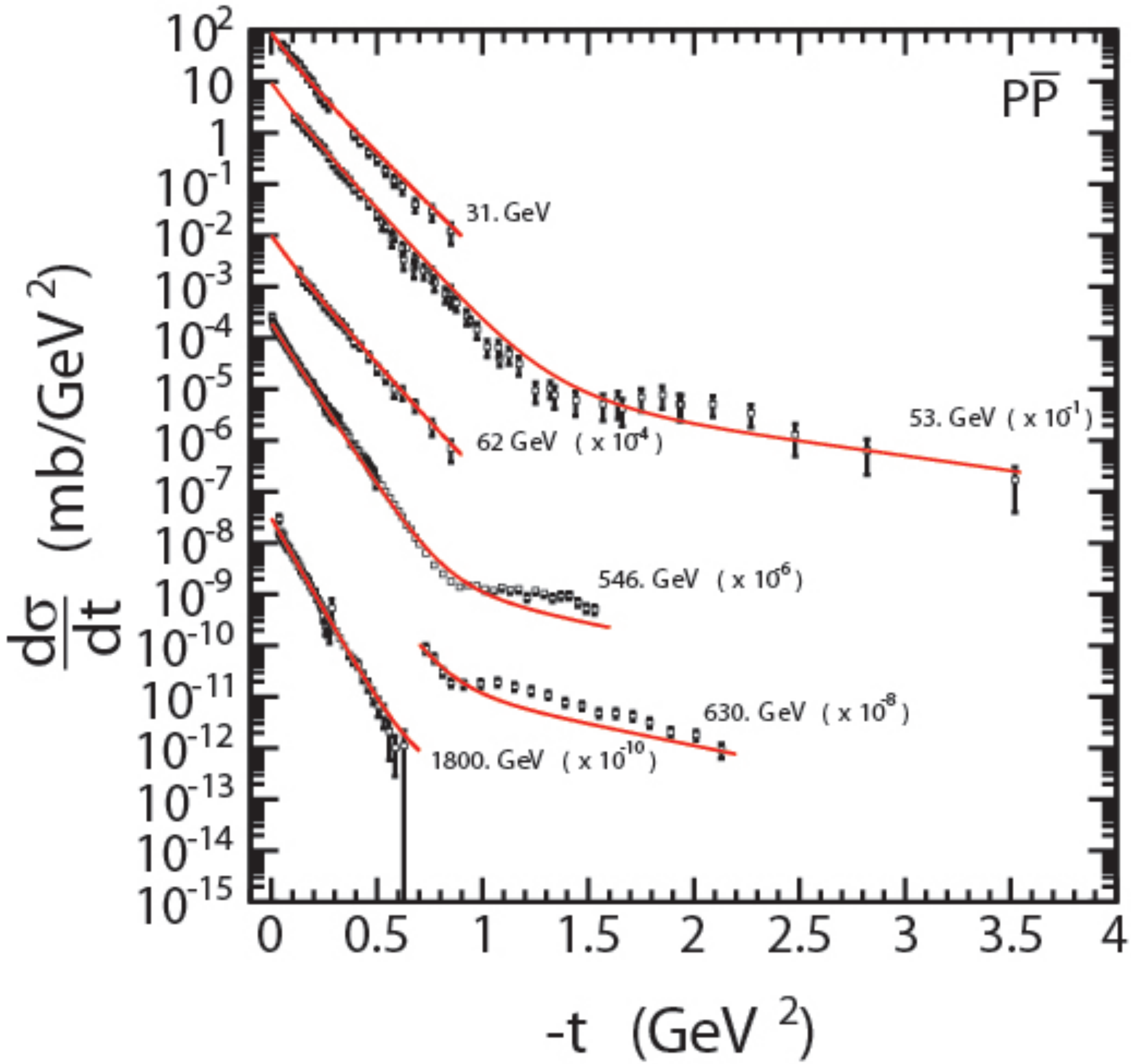
L. Jenkovszky and D. Lontkovskiy: In the Proc. of the Crimean (2011) Conference; also presented at the Russian-Spanish Dual Meeting in Barcelona, November, 2011:

Parameter name	Value	Uncertainty
	χ^2/NDF	4.60434
$\sqrt{A}$	+2.214549e+001	+2.344779e-001
B_0	+1.391529e+000	+7.408365e-003
B_1	+3.032435e-001	+1.525472e-003
$\sqrt{C}$	+6.952456e+003	+1.596950e+001
D_0	+9.766352e+000	+1.234181e-002
D_1	+4.648188e-001	+9.965043e-003
ϵ_1	+1.358585e+000	+1.243930e-003
ϵ_2	+1.057306e+000	+1.830864e-003
ϕ	+3.511842e+000	+3.713867e-003

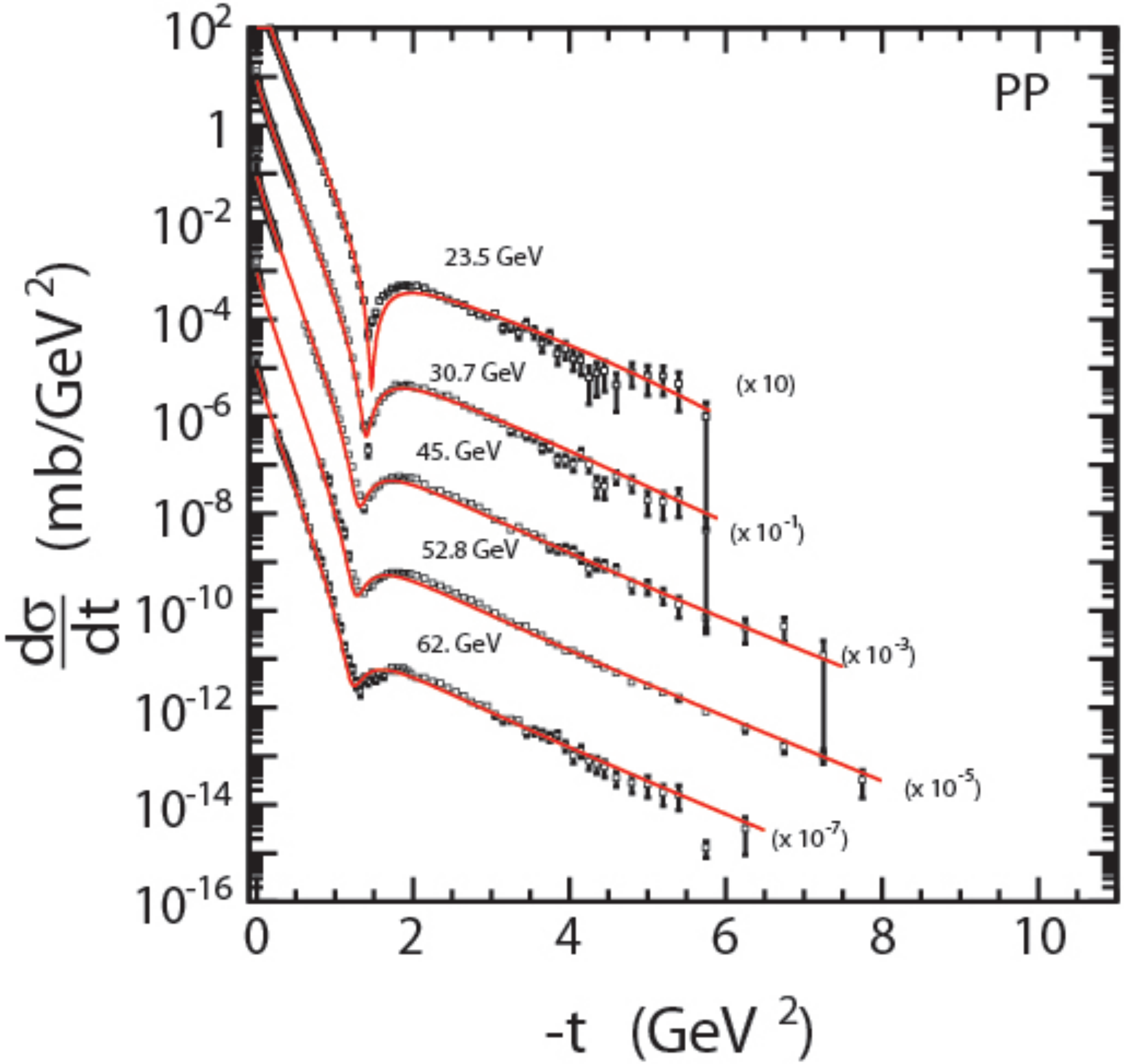
Table 2: Parameters obtained from the fit to the pp data



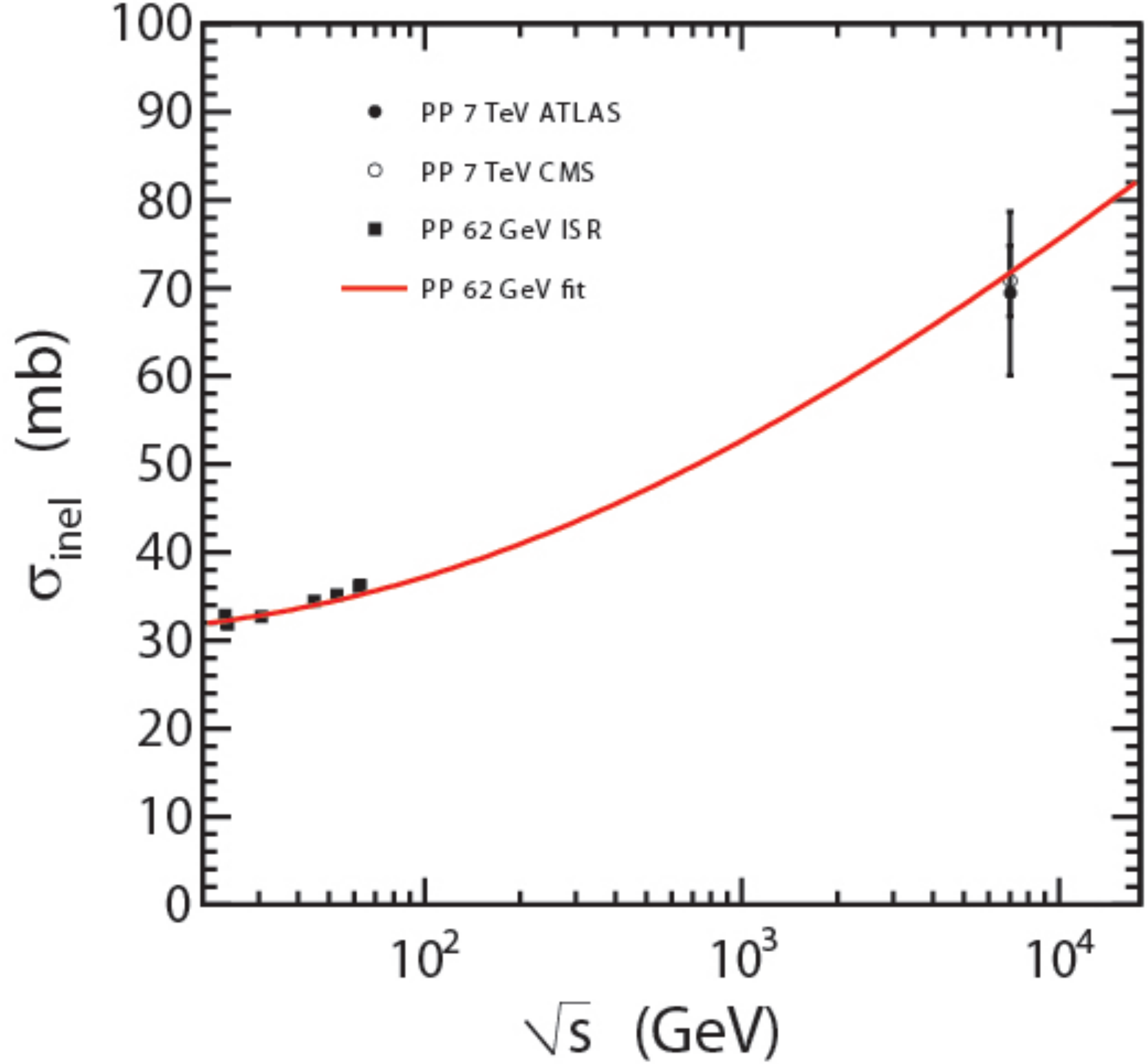
160
140
120
100
80
60
40
σtot (mb)
10
10^2
10^3
10^4
√s (GeV)
PP
P P̄
PP fit
PP̄ fit
LHC
7TeV 14TeV
ISR
UA4
UA5
TEVATRON
Cosmic ray data



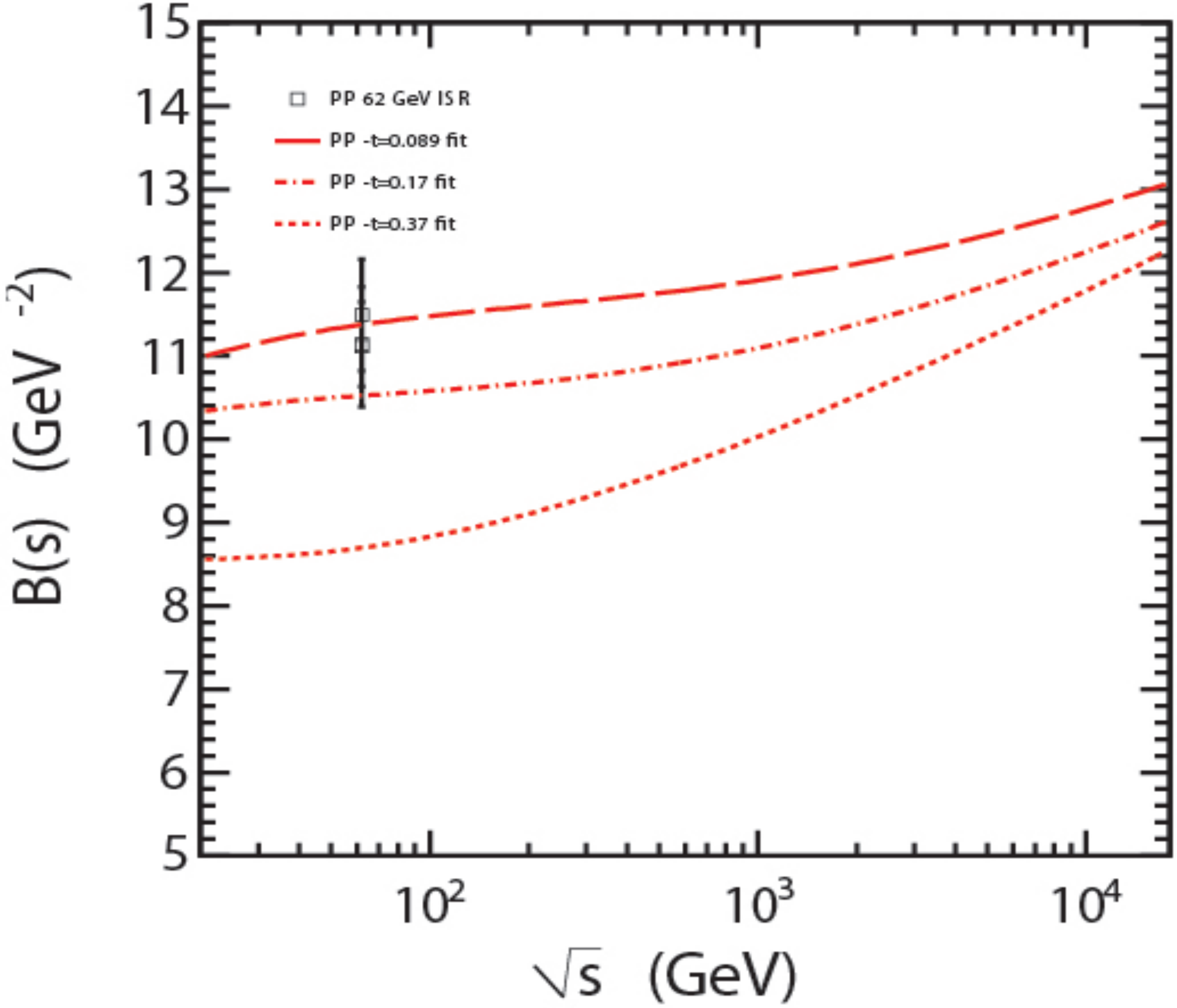
$\frac{d\sigma}{dt}$ (mb/GeV^2)
-t (GeV ^{2})
$P\bar{P}$
31. GeV
53. GeV (x 10^{-1})
62 GeV (x 10^{-4})
546. GeV (x 10^{-6})
630. GeV (x 10^{-8})
1800. GeV (x 10^{-10})



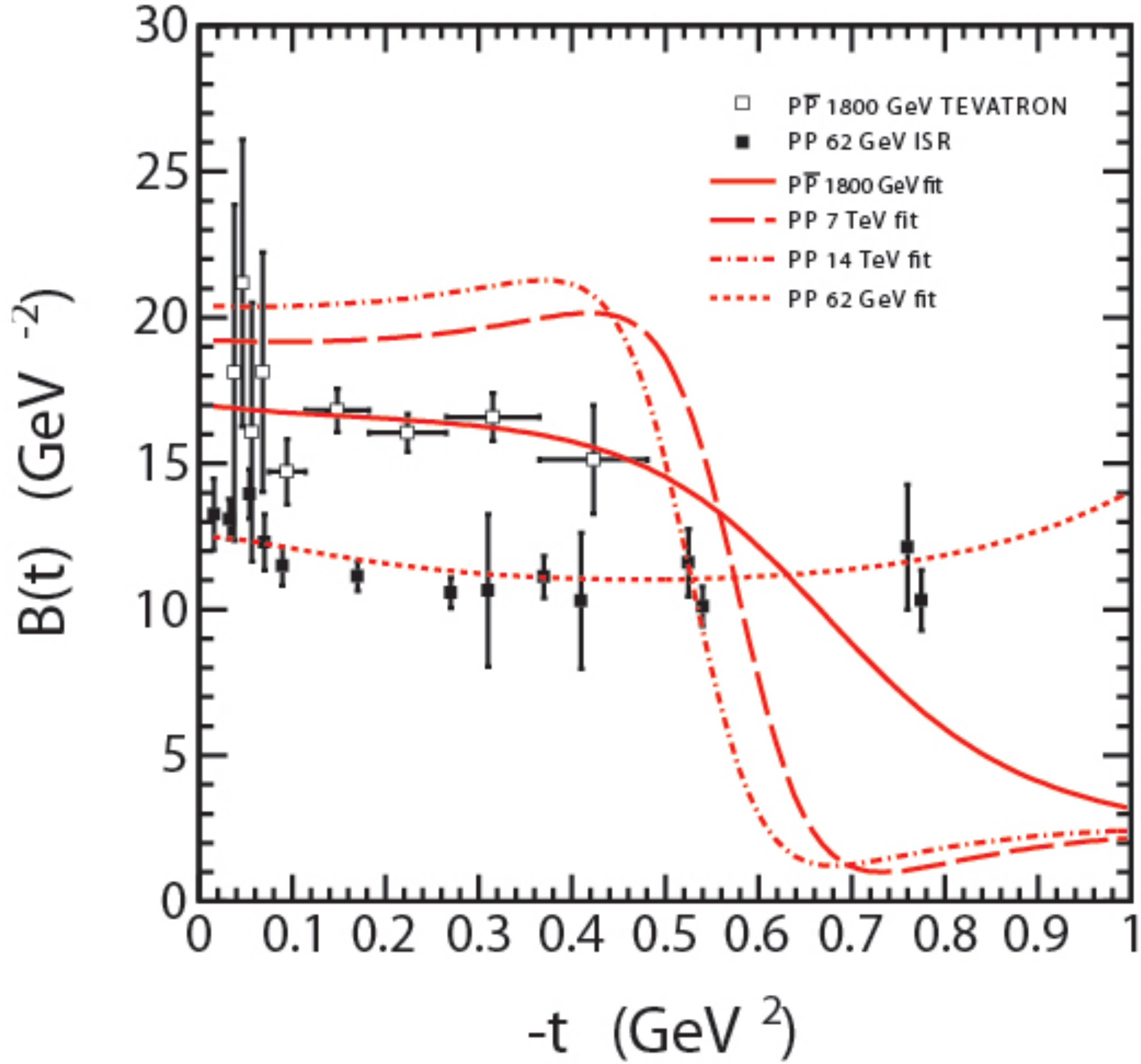
PP
23.5 GeV
30.7 GeV
45. GeV
52.8 GeV
62. GeV
(x 10)
(x 10^{-1})
(x 10^{-3})
(x 10^{-5})
(x 10^{-7})
$\frac{d\sigma}{dt}$ (mb/GeV^2)
-t (GeV^2)



PP 7 TeV ATLAS
PP 7 TeV CMS
PP 62 GeV ISR
PP 62 GeV fit
σ_inel (mb)
√s (GeV)



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

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, 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.

Extracting the Odderon:

Odd=A(p,bar p)-A(pp)

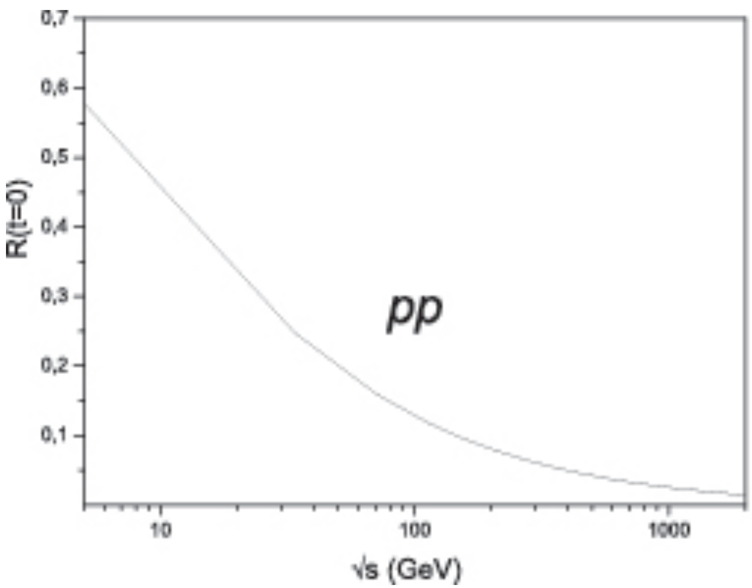
Energy variation of the relative importance of the Pomeron with respect to contributions from the secondary trajectories and the Odderon:

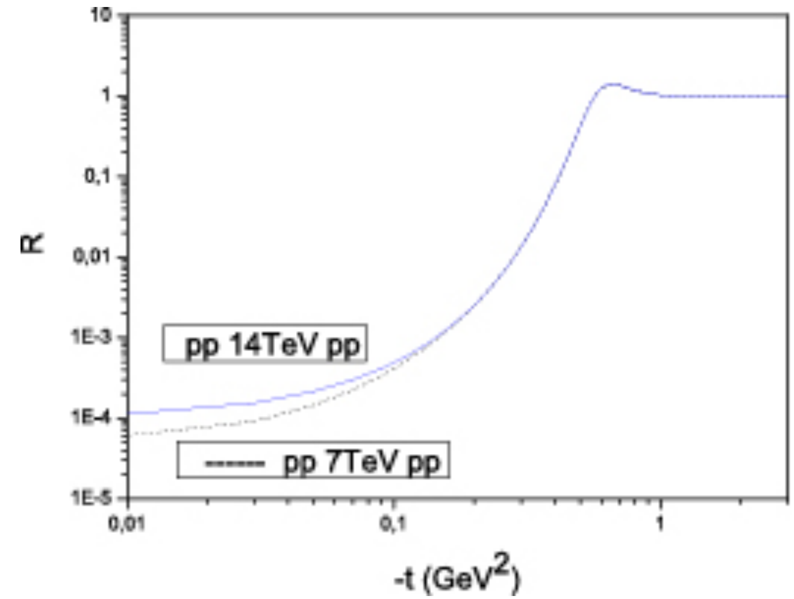
$$R(s,t=0) = \frac{\Im m(A(s,t) - A_P(s,t))}{\Im A(s,t)}, \tag{1}$$

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)

Regge→EoS→Inflation of the Universe

$$A_P(s,t) = -\beta_P(t)(-is)^{\alpha_P(t)},$$

$$\beta_P(t) = \beta_P e^{b_P t}, \quad \alpha_P(t) = \alpha(0) + \alpha' t,$$

$$\alpha(0) \approx 1.1, \quad \alpha' \approx 0.3.$$

$$P_2^P(T) = \frac{\beta_P^2 \alpha'_P T^6}{8(2\pi)^4 (b_P + 2\alpha'_P \ln T)^2}.$$

L.L. Jenkovszky and A.A. Trushevsky (Nuovo Cim. **34A** *(1976) 369)* saturated the scattering amplitude with a Pomeron exchange in the t channel, resulting in:

$$p(T) \sim k(\sigma_t, \alpha')T^6, \quad T \gg m, \quad p = \epsilon/5.$$

This *heretic* result resides on two basic and firm properties of the strong interaction, namely the existence of the forward cone in the differential cross section and the non-decreasing total cross sections.

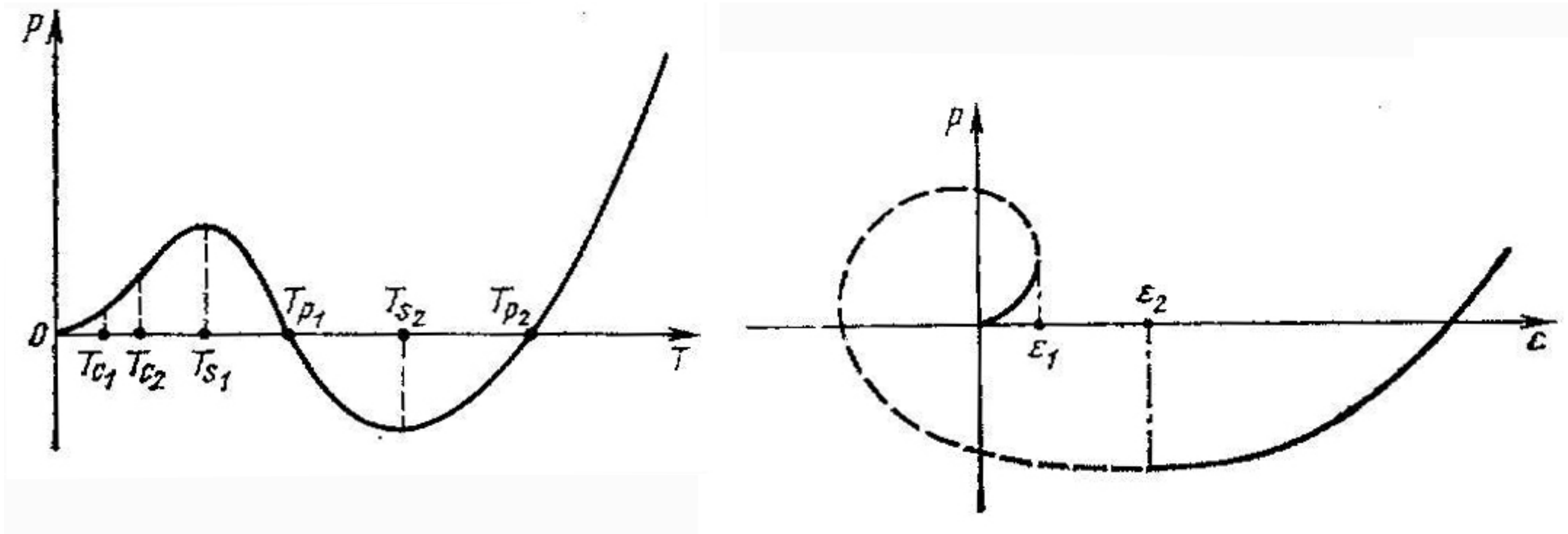
By duality the sum of direct channel resonances is dual to Regge exchanges (L.L. Jekovszky, P. Fre and L. Sertorio, Lett. Nuovo Cim. **15** *(1976) 365.)*

The non-asymptotic behavior of the EOS $p(T)$ was studied by *A.B. Bugrij and A.A. Trushevsky (ZHETP,* **73** *(1977) 3)*, who included in the scattering amplitude non-leading (secondary) trajectories (f, ω etc) with the following (surprising) result:

$$p(T) = AT^4 - BT^5 + CT^6,$$

where the coefficients A, B and C are determined by fits to the data on hadronic (e.g. pp, $\bar{p}p$) scattering data (see: *L.L. Jenkovszky and A.N. Shelkovenko, Nuovo Cim. A* **101** *((1989) 137).*

Remarcably, this EOS exhibits a local maximum and minimum at negative temperature



EOS from the S matrix (scattering amplitude)
Bugrij, Jenkovszky, Trushevsky

The quark bag model:

$$p_q(T) = a_q T^4 - B, \quad p_h(T) = a_h T^4;$$

$$\epsilon_q = 3a_q T^4 + B, \quad \epsilon_h = 3a_h T^4;$$

$$s_q(T) = 4a_q T^3, \quad s_h(T) = 4a_h T^3,$$

where $a_q = g_q \pi^2/90$, $a_h = g_h \pi^2/90$, $B = (a_q - a_h)T_c^4$ and g_q, g_h are the quark and hadronic degreed of freedom.

A generalization of the bag EOS: $B \to B(T)$ (C.G. Källman, Phys. Lett. B **134** (1984) 363).

$$p_q((T) = a_q T^4 - AT, \quad p_h(T) = a_h T^4;$$

$$\epsilon_q = 3a_q T^4, \quad \epsilon_h = 3a_h T^4;$$

$$s_q(T) = 4a_q T^3 - A, \quad s_h(T) = 4a_h T^3,$$

where $A = (a_q - a_h)T_c^3$.

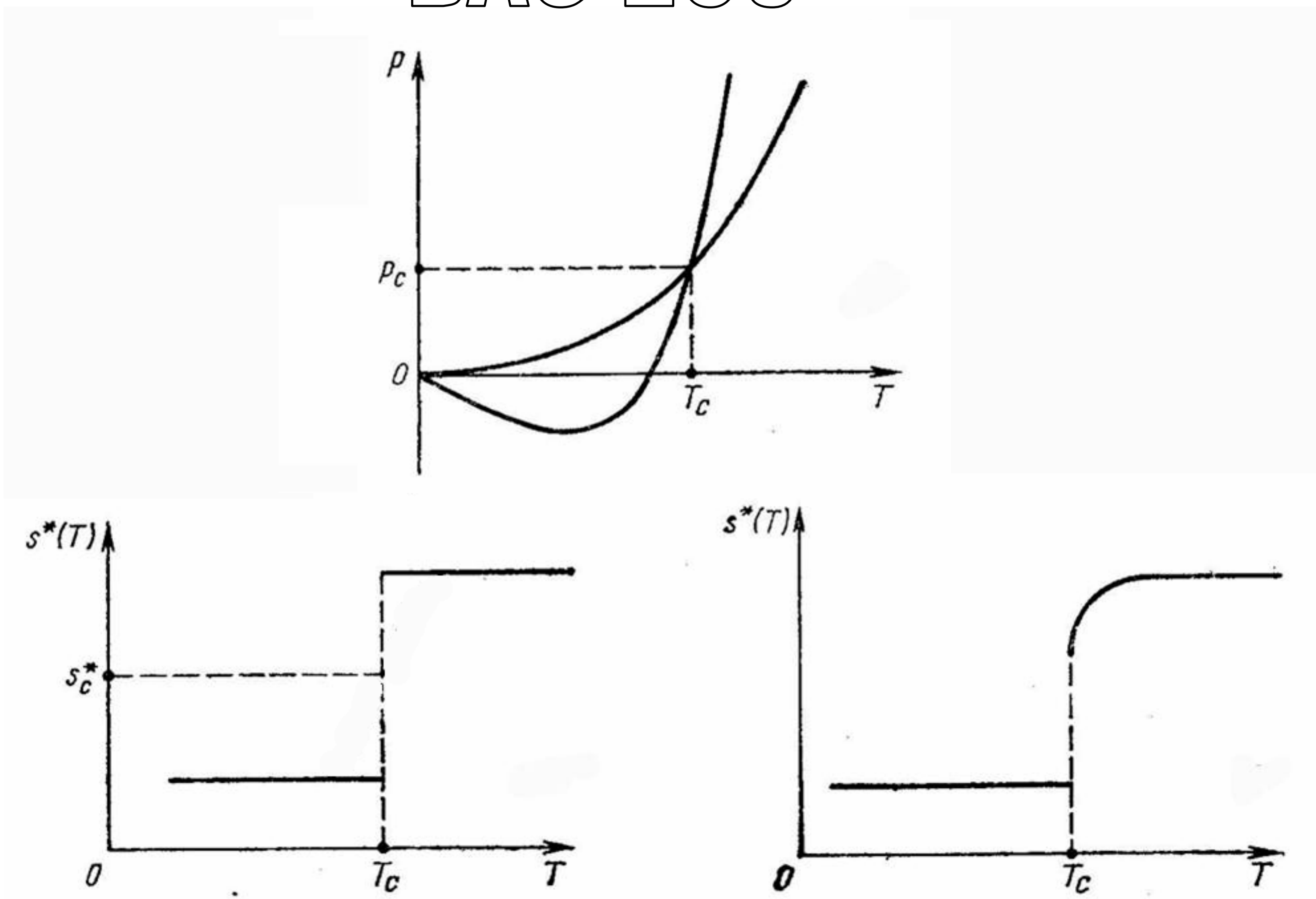
This system of bag equations of state can be written in one line:

$$s(T) = p'(T) = \frac{2}{45}\pi^2 T^3 \Big(g_h (1 - \Theta(T - T_c)) + g_q \Theta(T - T_c) \Big).$$

Blaizot and Ollitrault (Phys. Lett. B **191** (1987) 21):

$$\Theta(x) \to (1/2)[1 + th(\frac{x}{\Delta T})],$$

BAG EOS



Blaizot and Ollitrault (Phys. Lett. B **191** *(1987) 21)*:

$$\Theta(x) \to (1/2)[1 + th(\frac{x}{\Delta T})],$$

where ΔT is a smearing parameter, charactarizing the smoothness of the transition. Consequently, the EOS can be rewritten as

$$\frac{(T - T_C)}{\Delta T} = arth(\Gamma \Delta s^*)$$

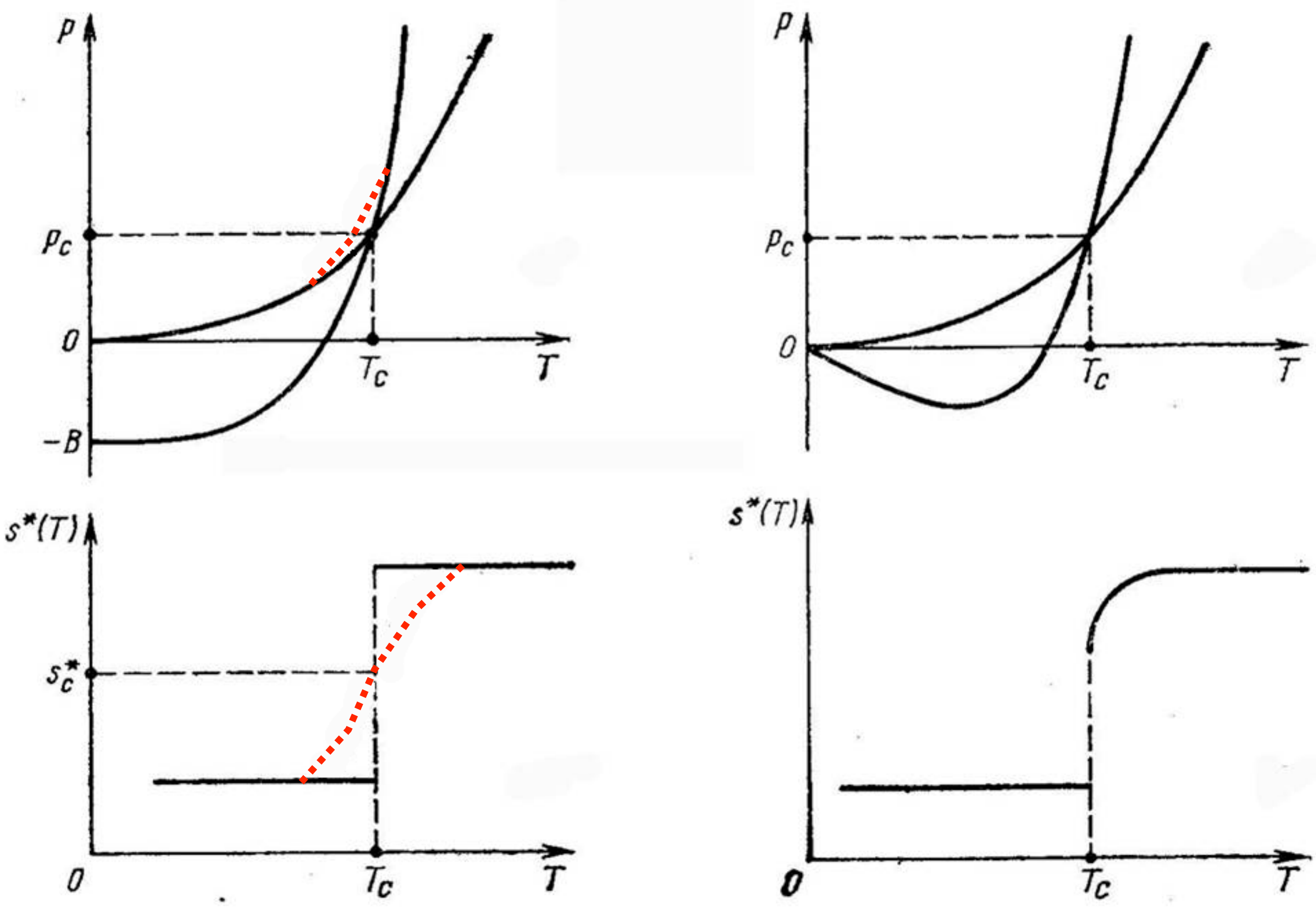
with $\Gamma = 45/[\pi^2(g_q - g_h)], \quad \Delta s^* = s^* - s^*_C.$

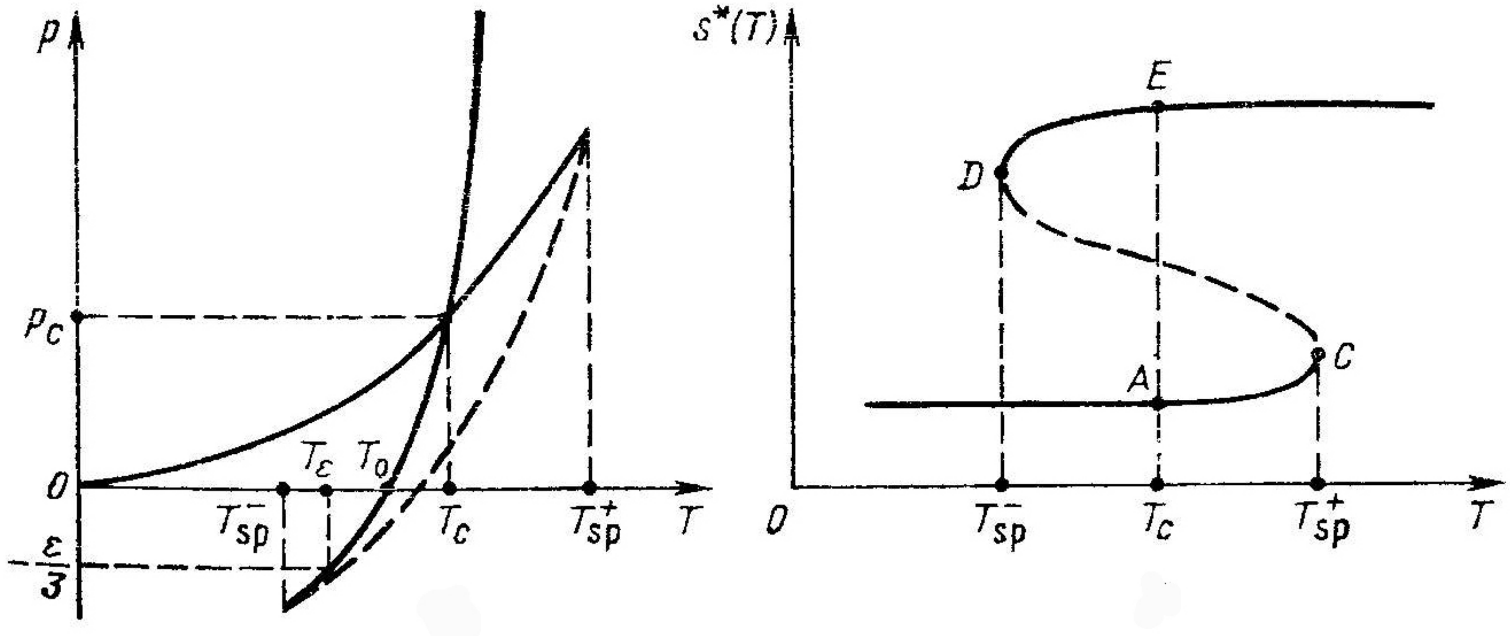
Metastable states (e.g. with $T < o0$) will appear in a further modification of the bag EOS, suggested by *V.G. Boyko, L.L. Jenkovszky and V.M. Sysoev (XVII Hirschegg Workshop, 1989; Yad.FIz.* **50** *(1989) 1747; Z.Phys. C* **45** *(1990) 607)*:

$$\frac{(T - T_C)}{\Delta T} = arth(\Gamma \Delta s^*) - \gamma \Delta s^*,$$

where γ is the **"metastabiity parameter"**. For $\Gamma - \gamma > 0$ the EOS has the same feature

Modified bag EOS





Metastability in the bag EOS (Jenkovszky, Kaemfer, Sysosev)

An application: *L.L. Jenkovszky, B. Kämpfer, V.M. Sysoev: Inflating Metastable Quark-Gluon Plasma Universe, ITP-90-2E preprint, Kiev, 1990*. The Friedman equation (isotopic, homogeneous and flat universe):

$$\dot{R} - GR\sqrt{\epsilon} = 0;$$

$$\epsilon + 3\dot{(}\dot{R}/R(\epsilon + p) = 0,$$

where $G = \sqrt{8\pi/3}/M_p, \quad M_p = 1.2 * 10^{19}\text{GeV}$, hence

$$\ddot{R} = -G^2 R(\epsilon + 3p)/2.$$

We remind that $\epsilon = p'(T)T - p(T), \quad \mu = 0$.

The necessary condition of inflation is $3p+\epsilon<0$, and the sufficient one is $\epsilon=-p$.

From the Friedman equations,

$$t=\int\frac{dR}{R\sqrt{G^2\epsilon}},\quad \ln R=-\int\frac{d\epsilon}{p+\epsilon}.$$

By integration, $R^3=const/p'(T)$, where from

$$t=1/3\int_T^\infty\frac{p''(T)dT}{p'(T)G\sqrt{\epsilon(T)}}.$$

By expanding $p'(T)$ around $T=T_m,\quad p'(T)\sim T-T_v$, we get the exponential expansion of the universe.

Low-mass diffraction dissociation at the LHC

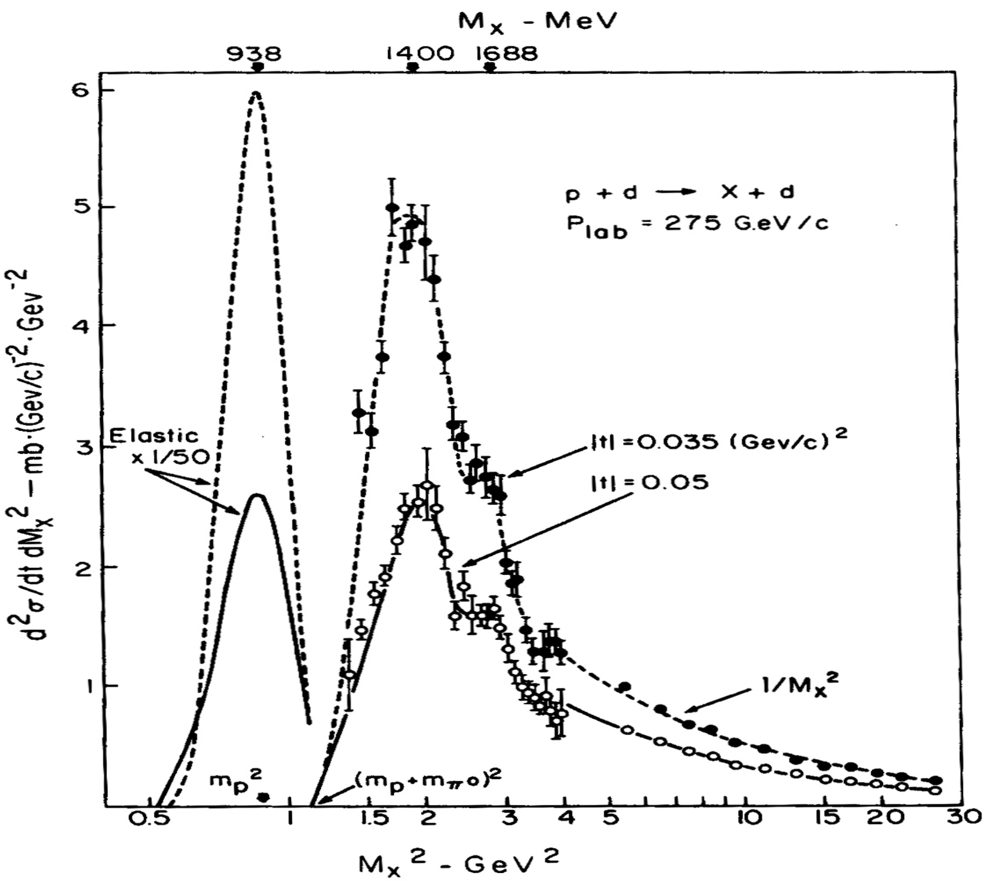
L. Jenkovszky, O. Kuprash, J. Lamsa, V. Magas, and R,. Orava:
Dual-Regge approach to high-energy, low-mass DD at the LHC,
Phys. Rev. D83(2011)0566014; hep-ph/1-11.0664.
L. Jenkovszky, O. Kuprash, J. Lamsa and R. Orava: hep-ph/11063299,
Mod. Phys. Letters A. **26**(2011) 1-9, August 2011;
L. Jenkovszky, 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 $\frac{d\sigma}{dt dM_X^2}$ 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.

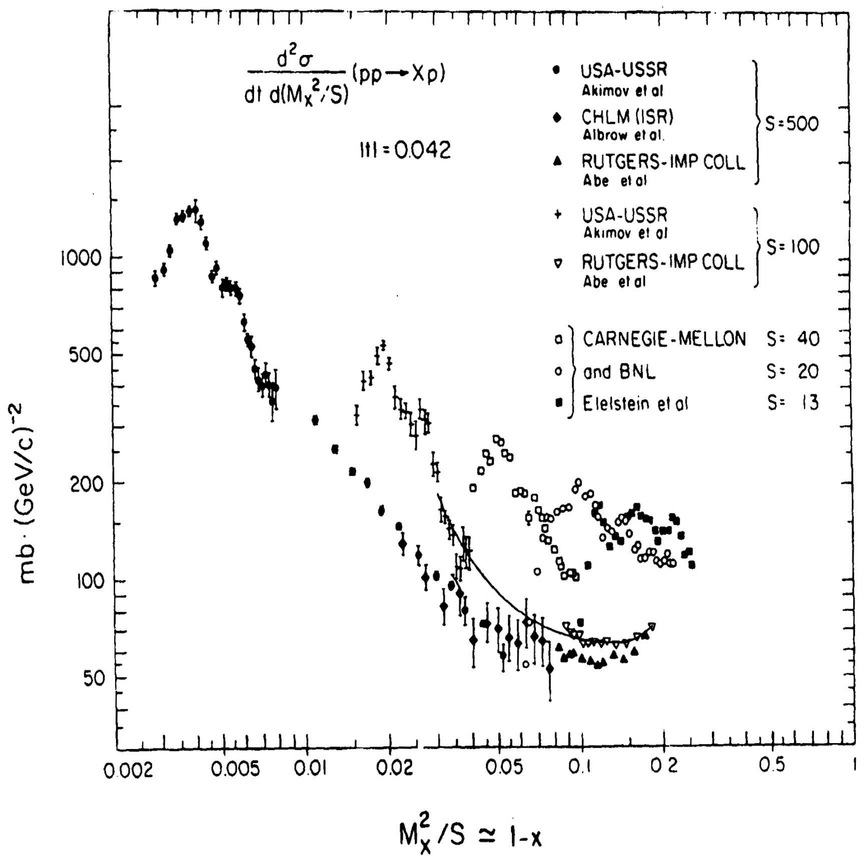
Low-mass single diffraction dissociation (SDD) of protons, $pp \to pX$ as well as their double diffraction dissociation (DDD) are among the priorities at the LHC. For the CMS Collaboration, the SDD mass coverage is presently limited to some 10 GeV. With the Zero Degree Calorimeter (ZDS), this could be 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.

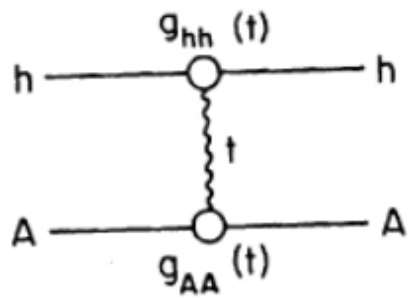
FNAL

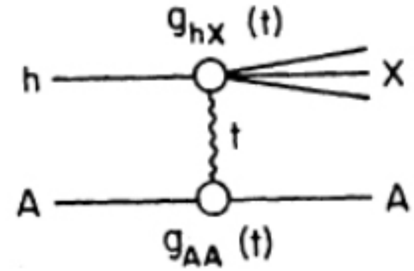


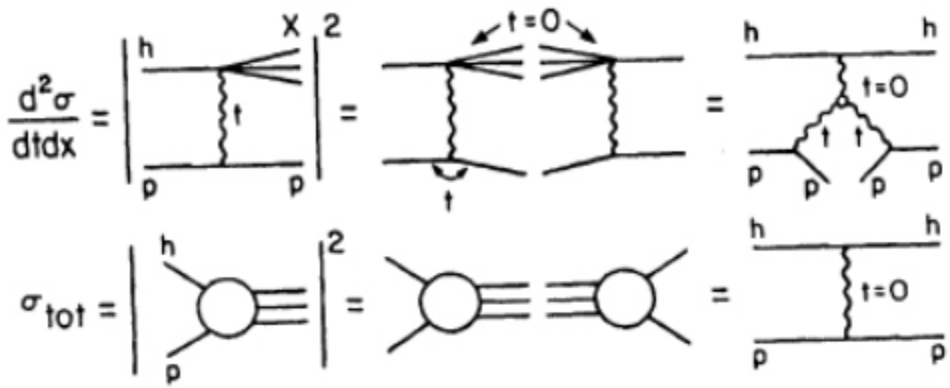
M_X - MeV
938
1400
1688
$p + d \rightarrow X + d$
P_{lab} = 275 GeV/c
Elastic x 1/50
|t| = 0.035 (GeV/c)^2
|t| = 0.05
$1/M_X^2$
m_p^2
$(m_p + m_{\pi^0})^2$
$d^2\sigma/dt\,dM_X^2$ – mb·(GeV/c)$^{-2}$·GeV^{-2}
M_X^2 - GeV^2

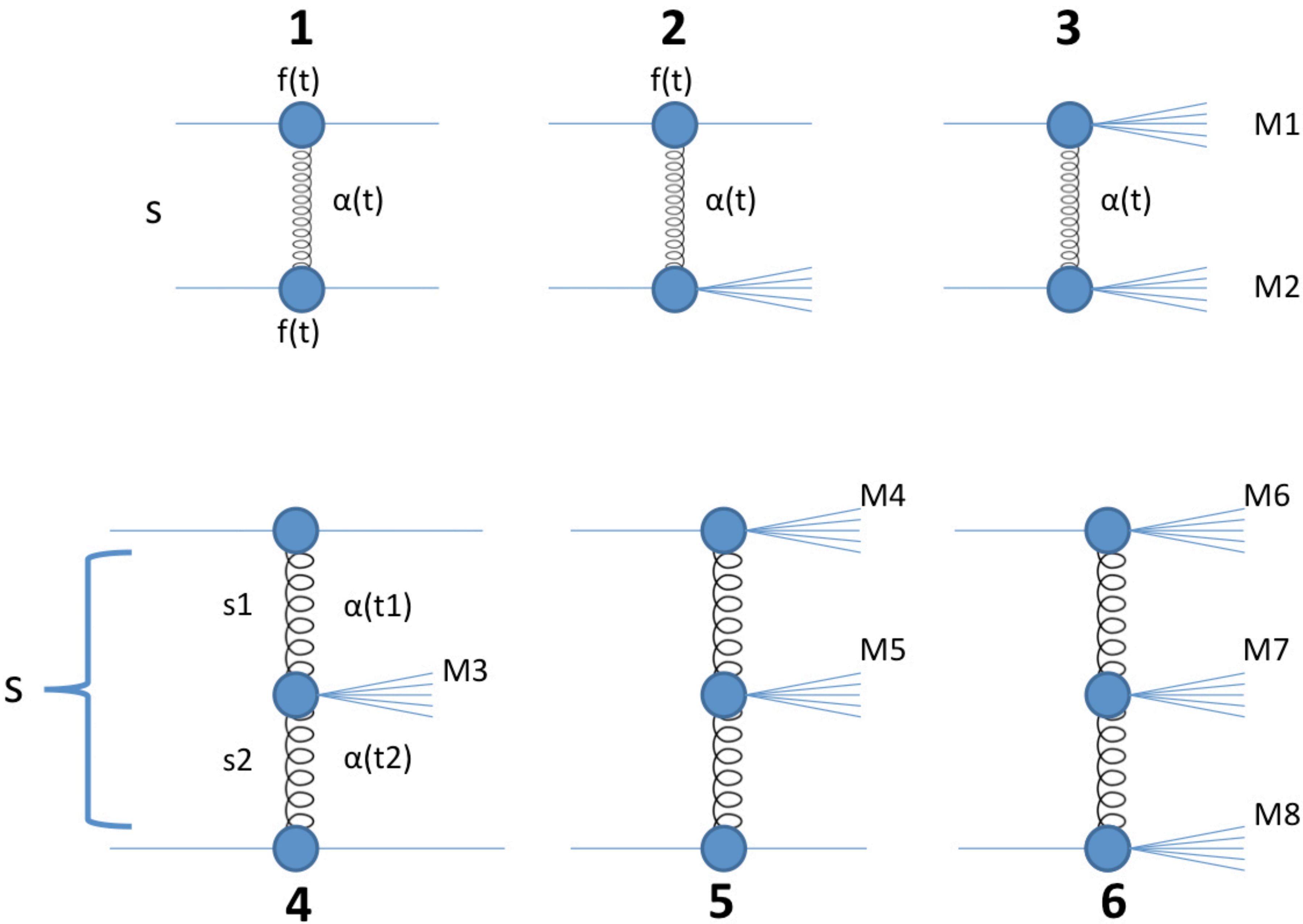


$\frac{d^2\sigma}{dt\,d(M_X^2/S)}$ (pp → Xp)
|t| = 0.042
USA-USSR Akimov et al
CHLM (ISR) Albrow et al.
RUTGERS-IMP COLL Abe et al
S=500
USA-USSR Akimov et al
RUTGERS-IMP COLL Abe et al
S=100
CARNEGIE-MELLON S= 40
and BNL S= 20
Ellelstein et al S= 13
mb·(GeV/c)$^{-2}$
$M_X^2/S \simeq 1-x$


$g_{hh}(t)$
h
h
t
A
A
$g_{AA}(t)$


$g_{hX}(t)$
h
X
t
A
A
$g_{AA}(t)$


$\frac{d^2\sigma}{dtdx}$ =
h
X
2
t
p
p
=
t=0
t
=
h
h
t=0
t t
p
p
p
p
σ_{tot} =
h
p
2
=
=
h
h
t=0
p
p


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

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

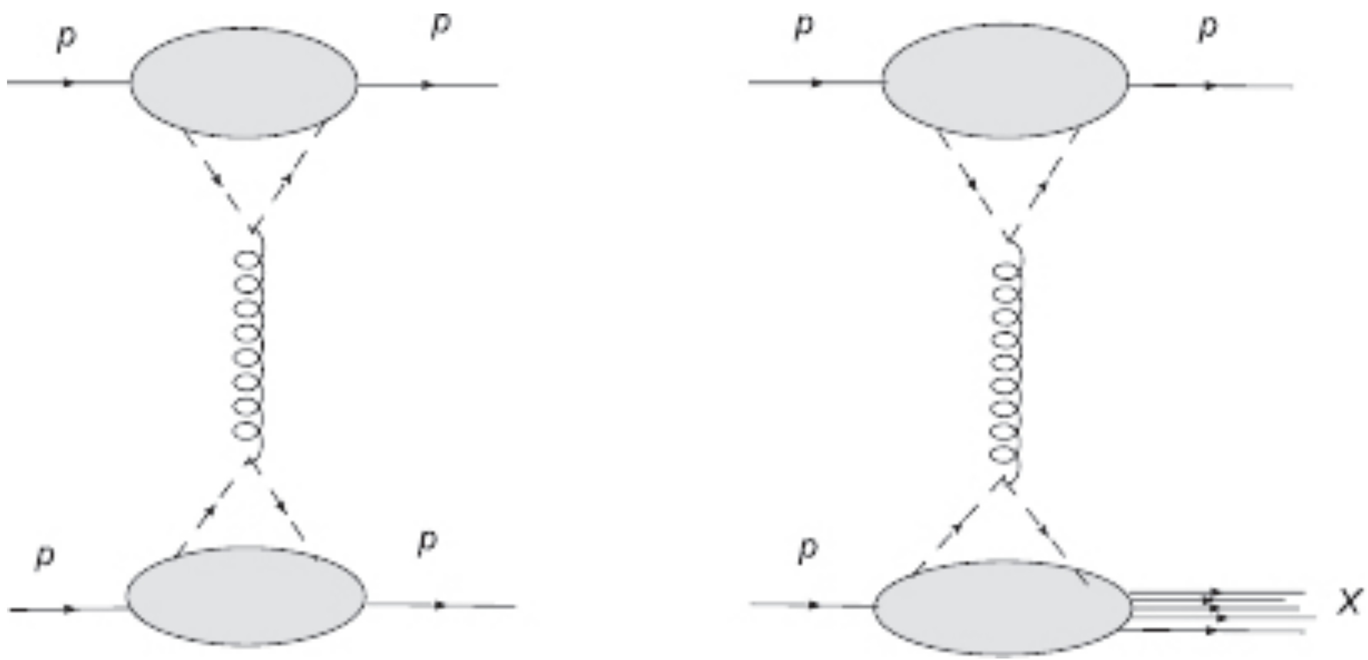
$$\frac{d^3\sigma}{dt dM_1^2 dM_2^2} = \frac{d^2\sigma_1}{dt dM_1^2} \frac{d^2\sigma_2}{dt dM_2^2} \frac{d\sigma_{el}}{dt}.$$

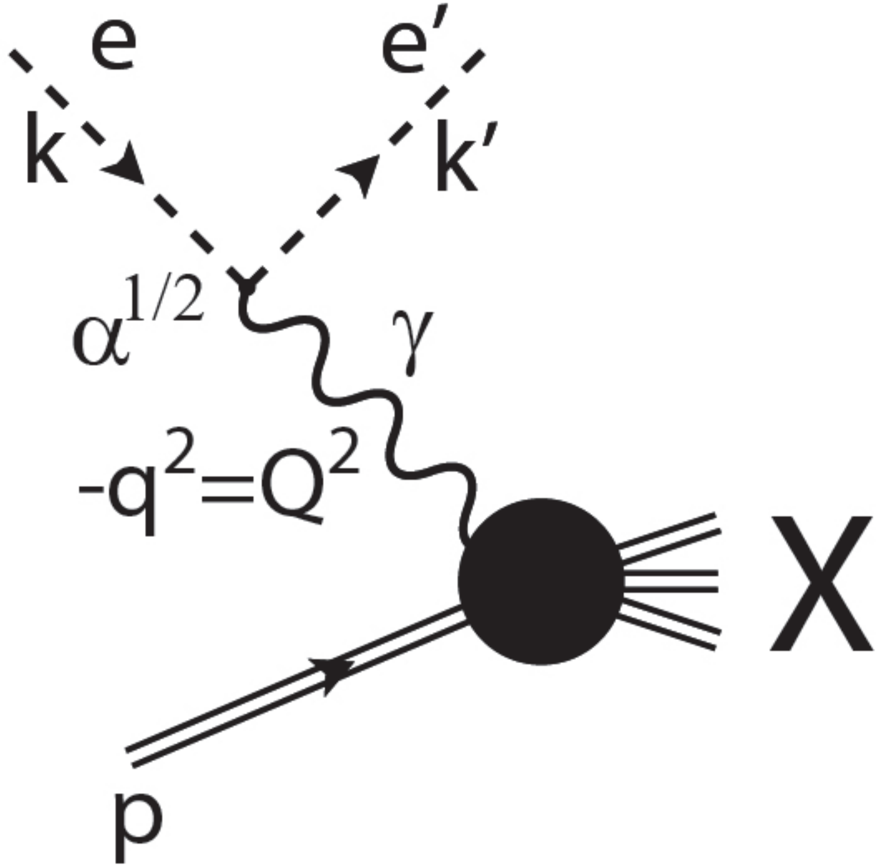
Assuming exponential cone, t^{bt} and integrating in t, one gets

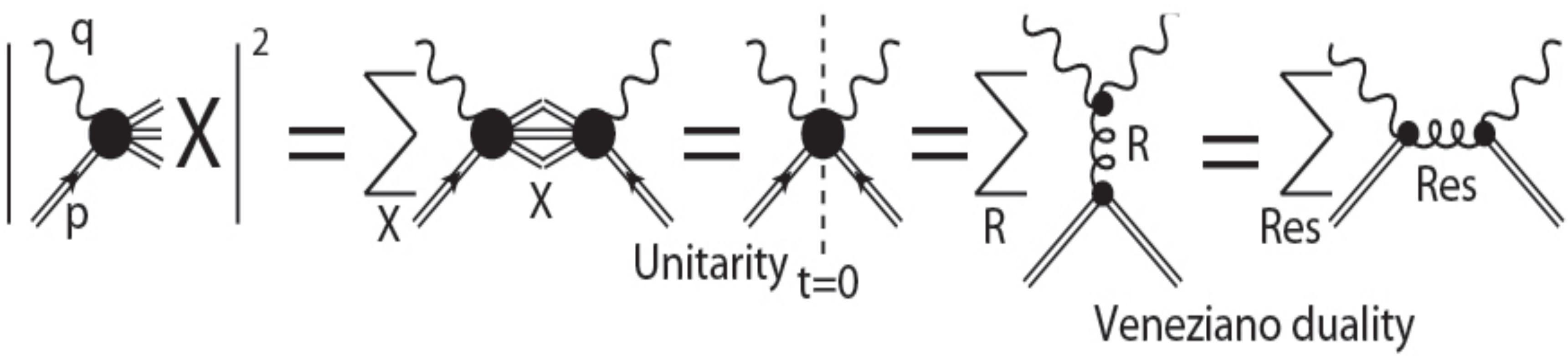
$$\frac{d^2\sigma_{DD}}{dM_1^2 dM_2^2} = k \frac{1}{\sigma_{el}} \frac{d\sigma_1}{dM_1^2} \frac{d\sigma_2}{dM_2^2},$$

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

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


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
2
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, $i=1,2$ 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:

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

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:

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

SD and DD cross sections

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

$$\frac{d^3\sigma_{DD}}{dt dM_1^2 dM_2^2} = C_n F^2(x_B, t) \frac{\sigma_T^{Pp}(M_1^2, t)}{2m_p} \frac{\sigma_T^{Pp}(M_2^2, t)}{2m_p} \times \left(\frac{s}{(M_1 + M_2)^2}\right)^{2(\alpha(t)-1)} \ln\left(\frac{s}{(M_1 + M_2)^2}\right)$$

“Reggeized (dual) Breit-Wigner” formula:

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

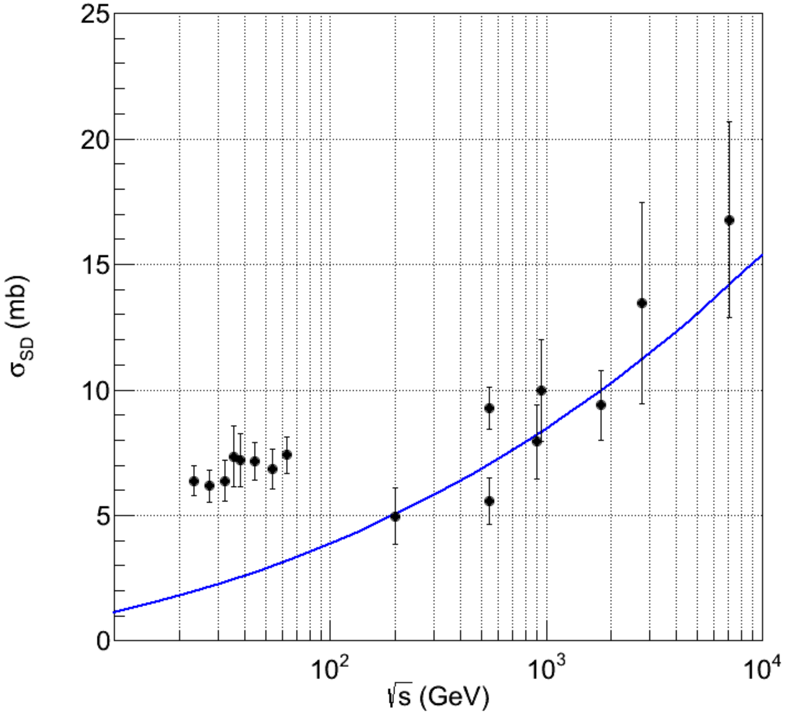
$$= A_n \sum_{n=0,1,\ldots} \frac{[f(t)]^{2(n+1)}\,Im\,\alpha(M_x^2)}{(2n+0.5-Re\,\alpha(M_x^2))^2 + (Im\,\alpha(M_x^2))^2} + B_n e^{b_{in}^{bg}t}\left(M_x^2 - M_{p+\pi}^2\right)^{\epsilon}$$

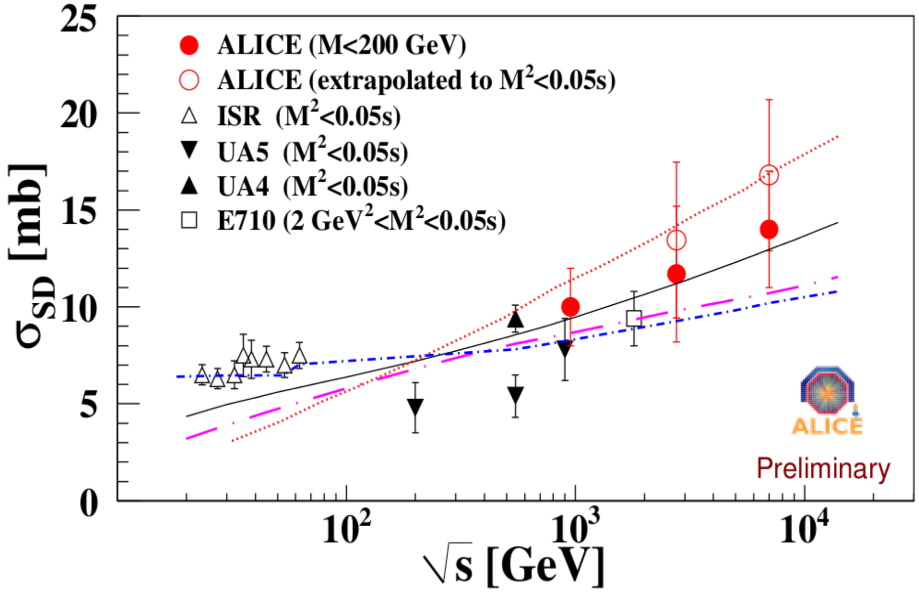
$$F(x_B,t) = \frac{x_B(1-x_B)}{\left(M_x^2 - m_p^2\right)\left(1 + 4m_p^2 x_B^2/(-t)\right)^{3/2}}, \quad x_B = \frac{-t}{M_x^2 - m_p^2 - t}$$

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

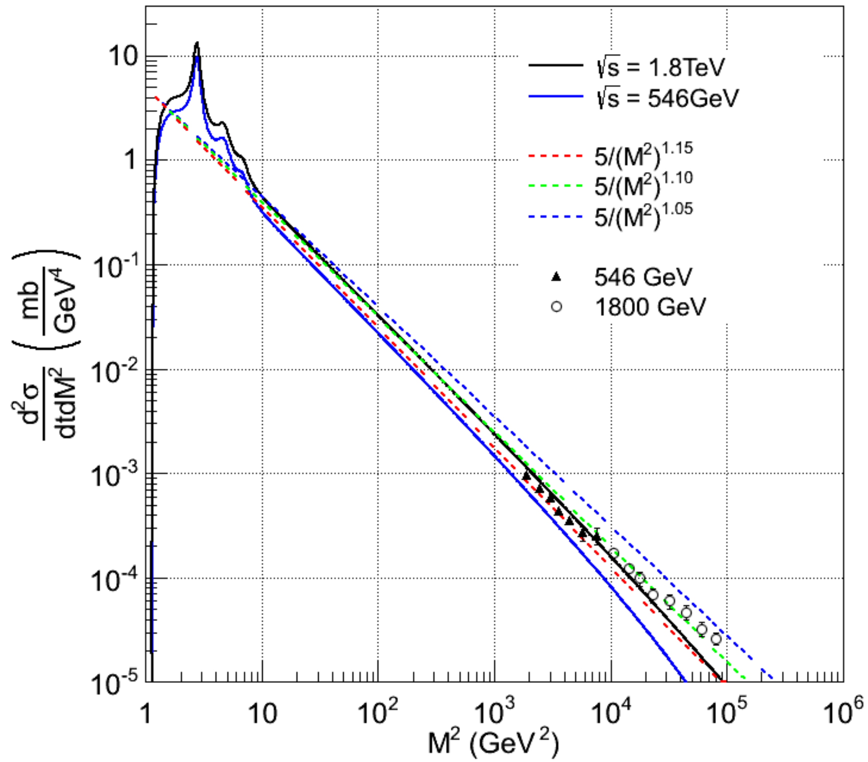
$$\alpha(t) = \alpha(0) + \alpha' t = 1.04 + 0.25t$$

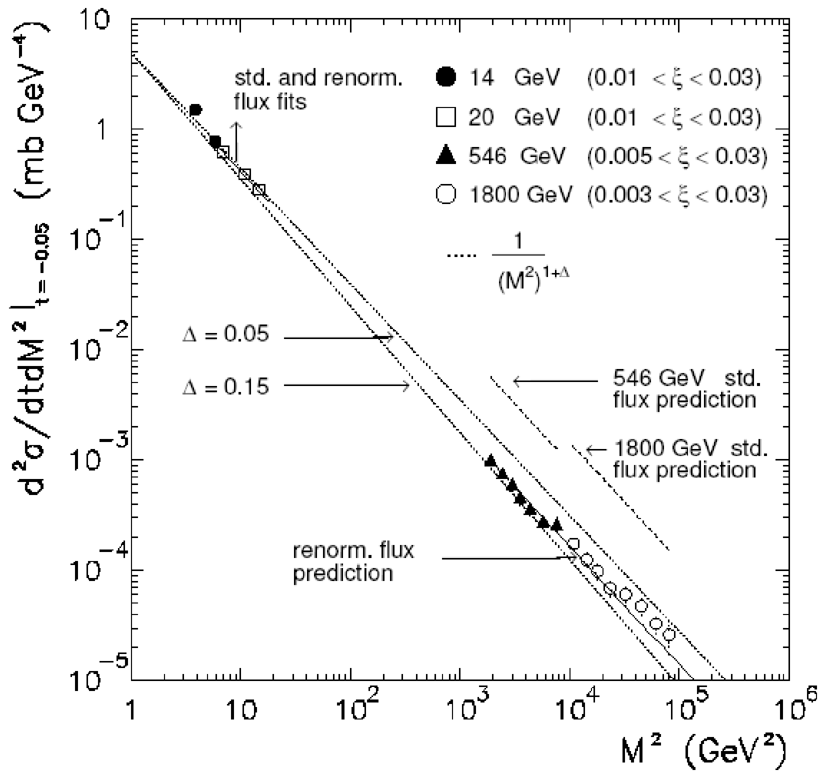
SDD cross sections vs. energy.



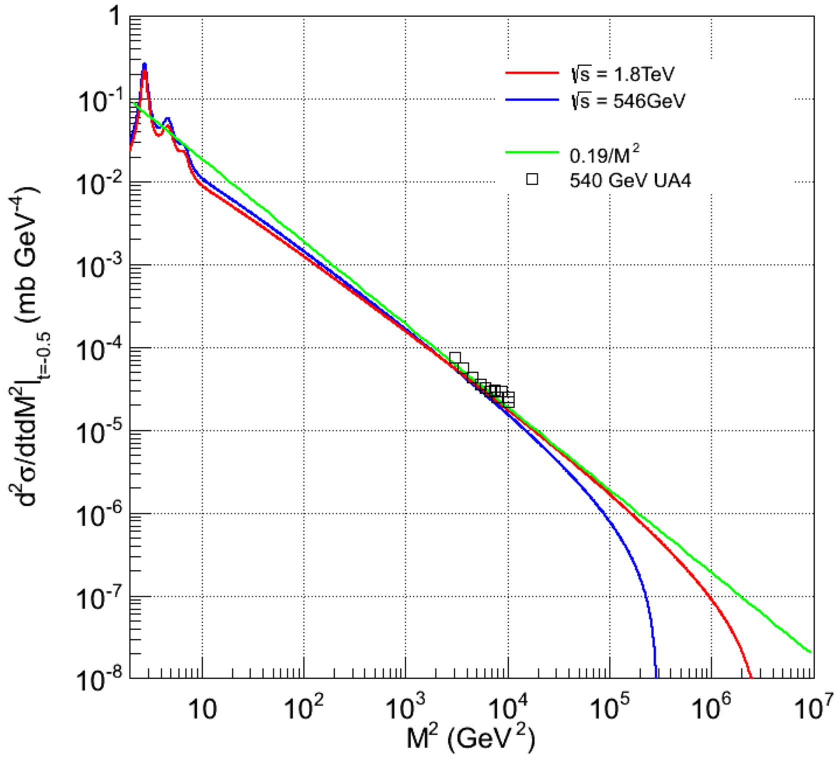


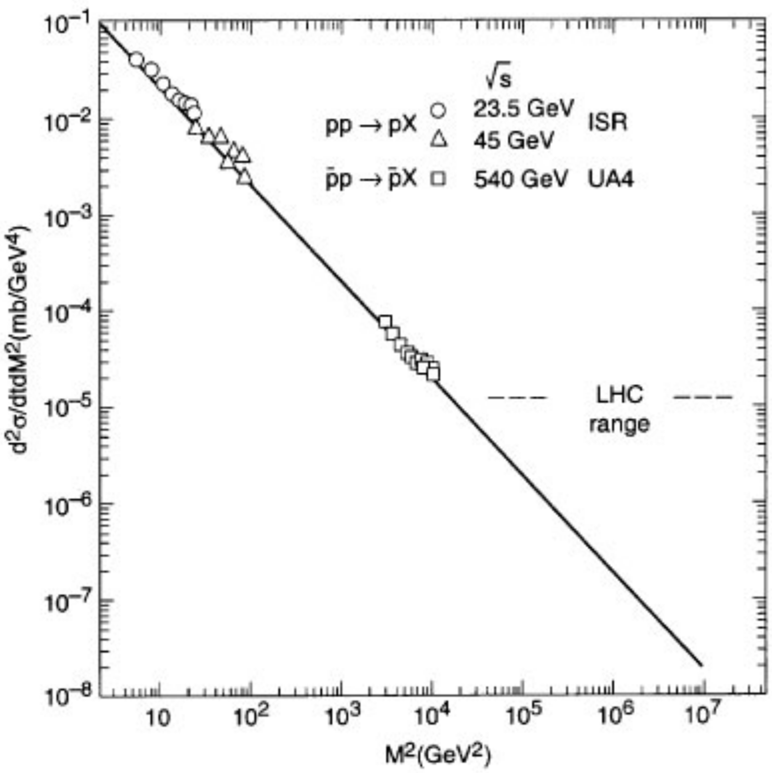
Approximation of background to reference points (t=-0.05)



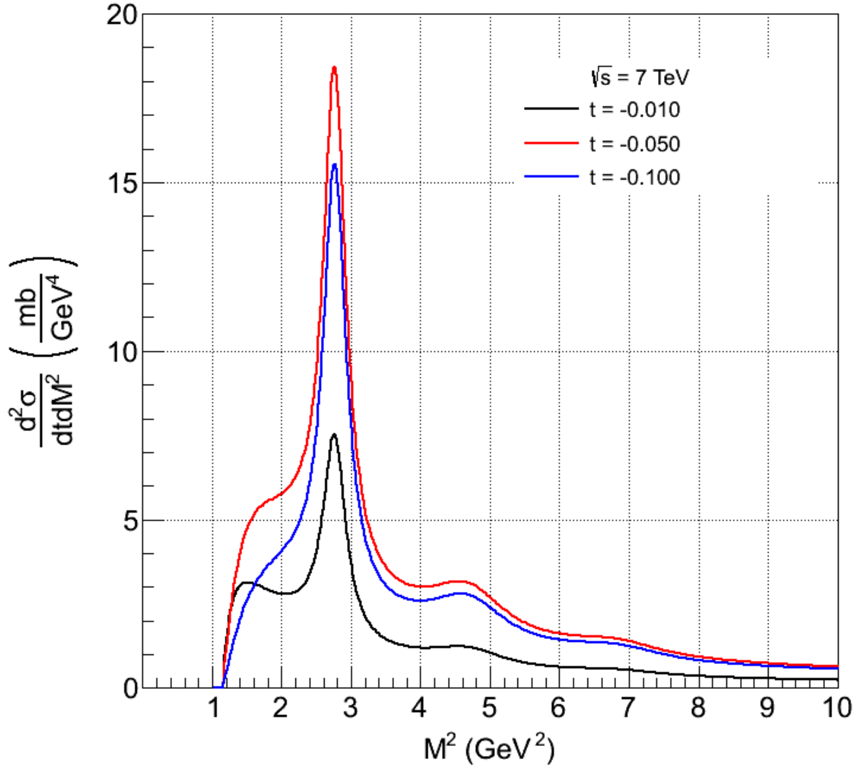


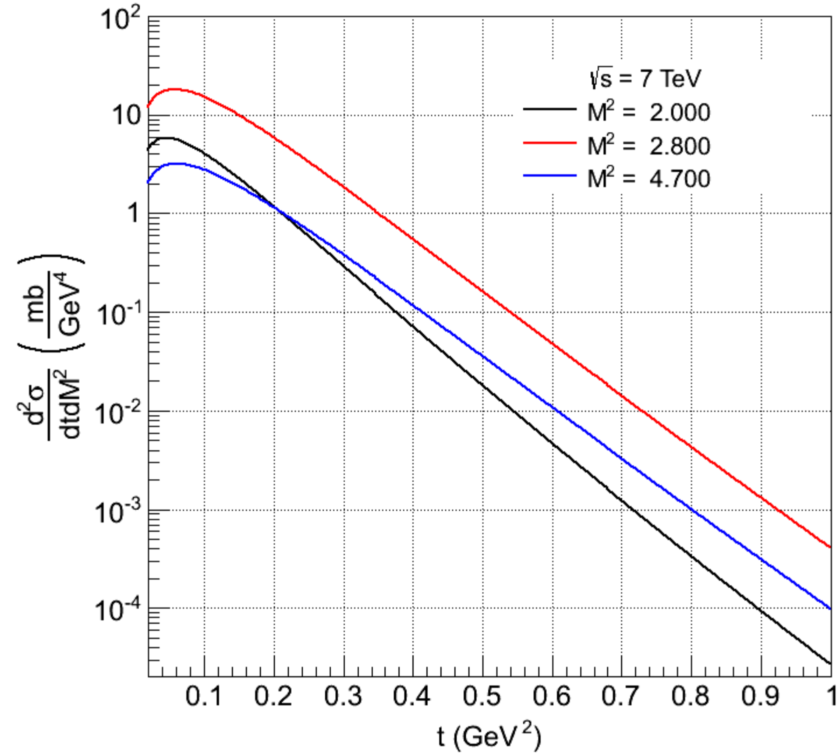
Approximation of background to reference points (t=-0.5)



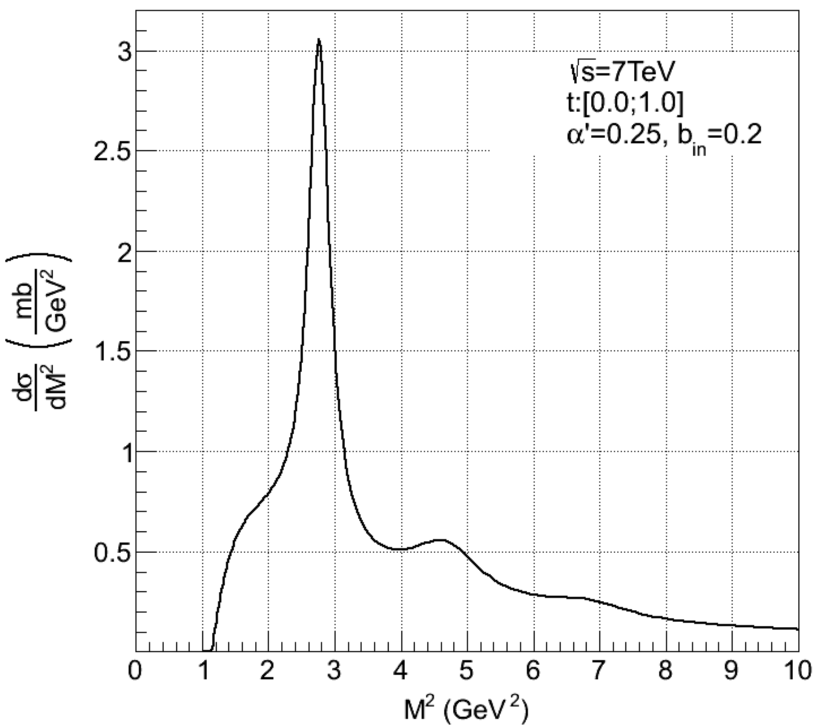


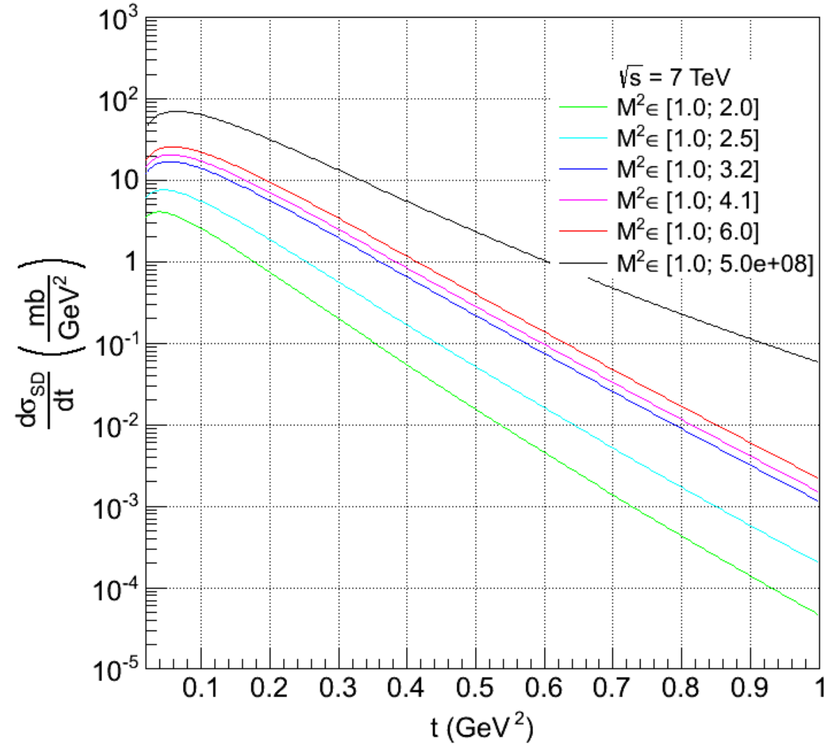
Double differential SD cross sections



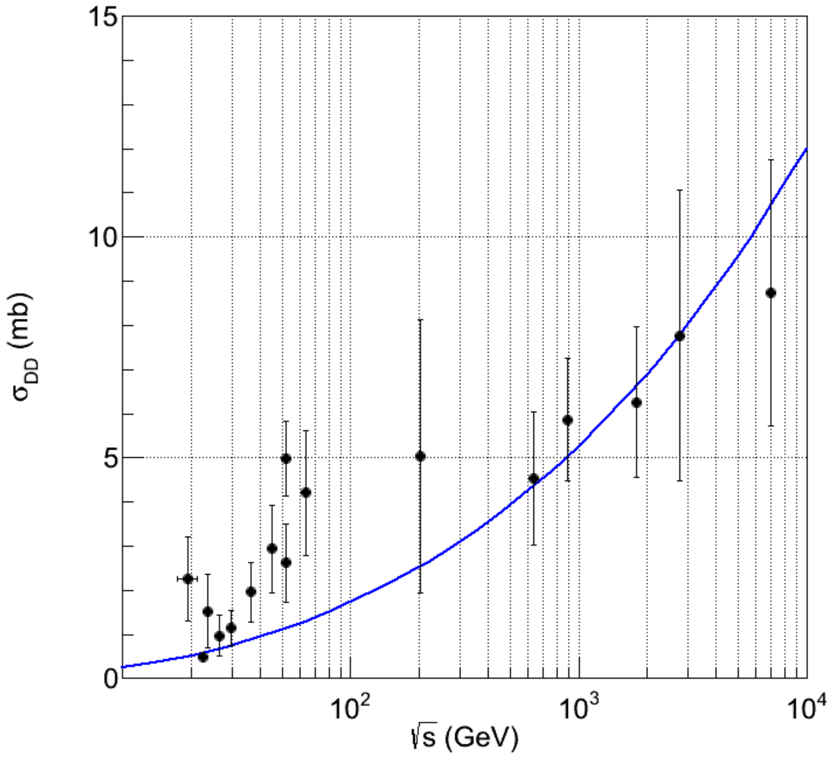


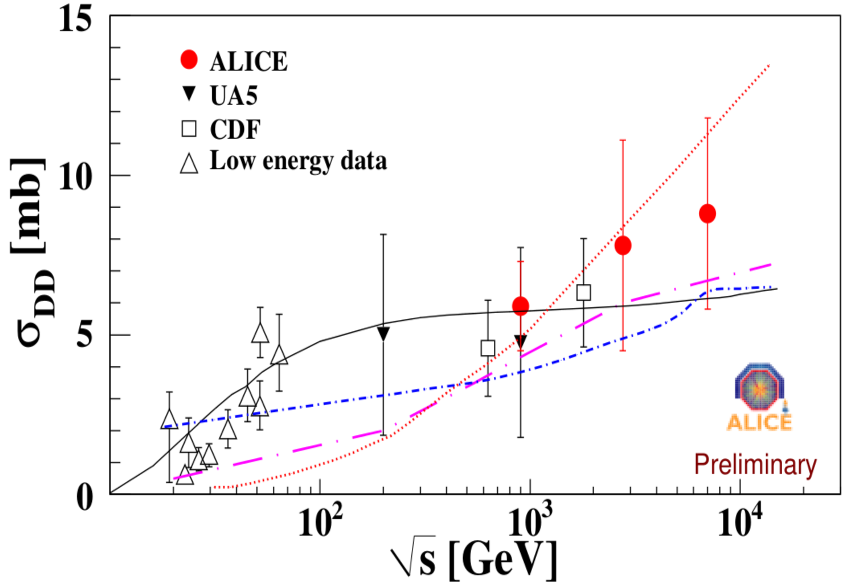
Single differential integrated SD cross sections



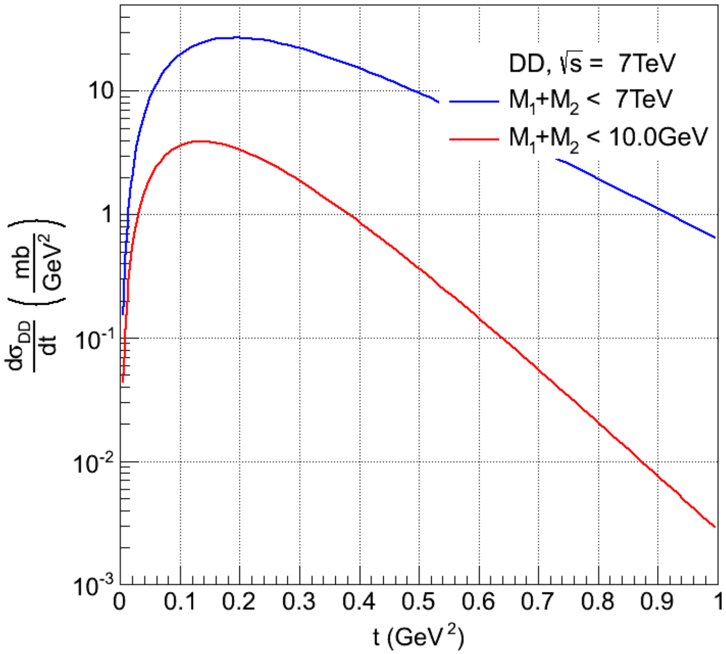


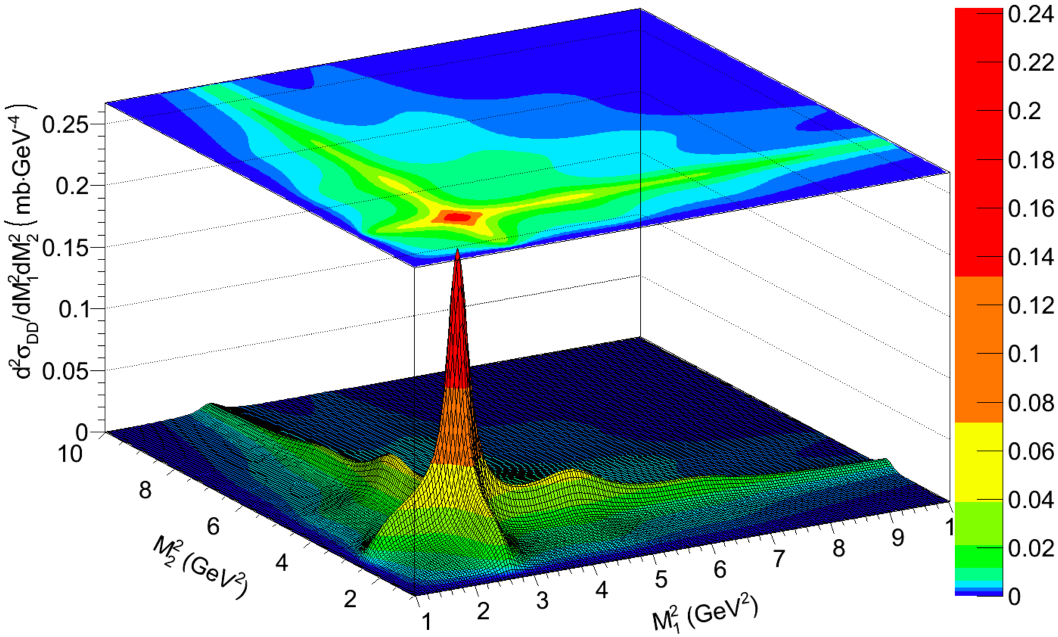
DDD cross sections vs. energy.



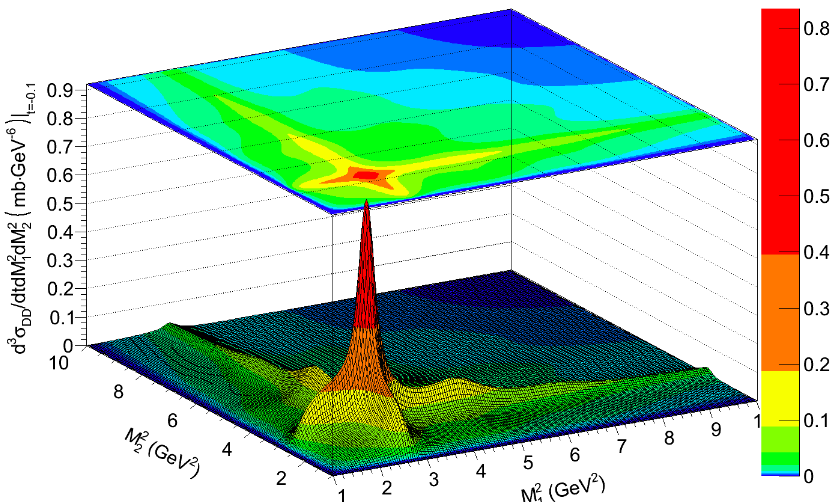


Integrated DD cross sections

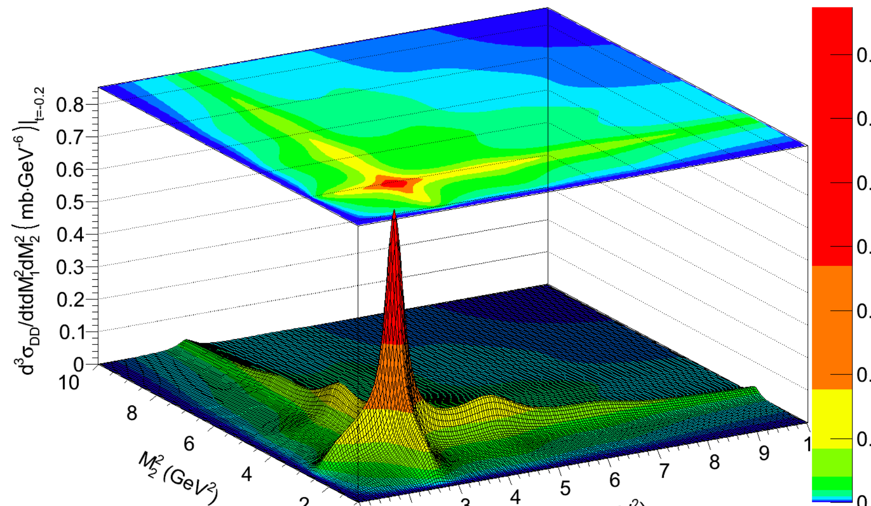




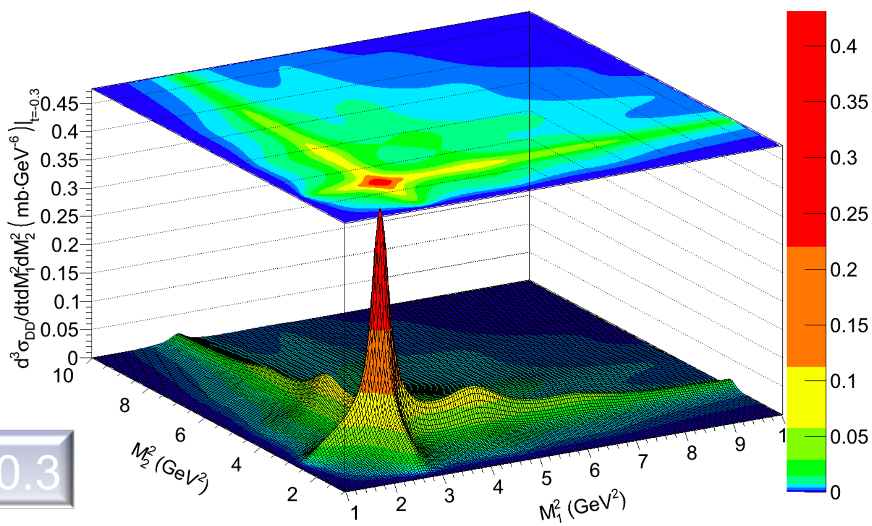
Triple differential DD cross sections



t = - 0.1



t = - 0.2



t = - 0.3

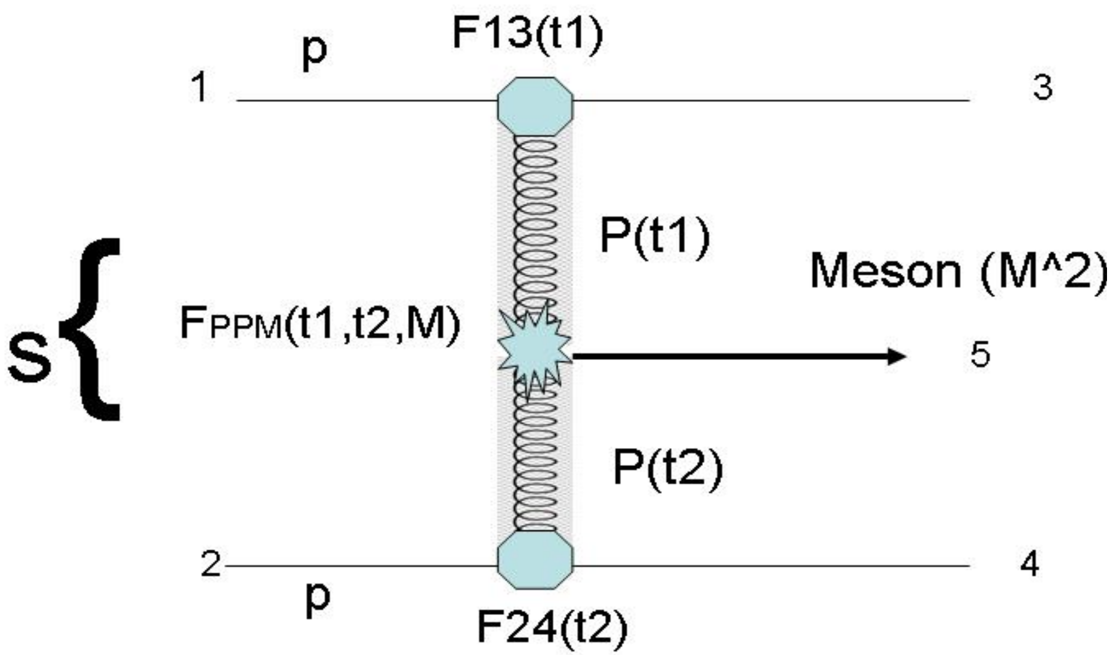
The parameters and results

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
$\sigma_{SD}(M < 3.5 GeV)$ (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

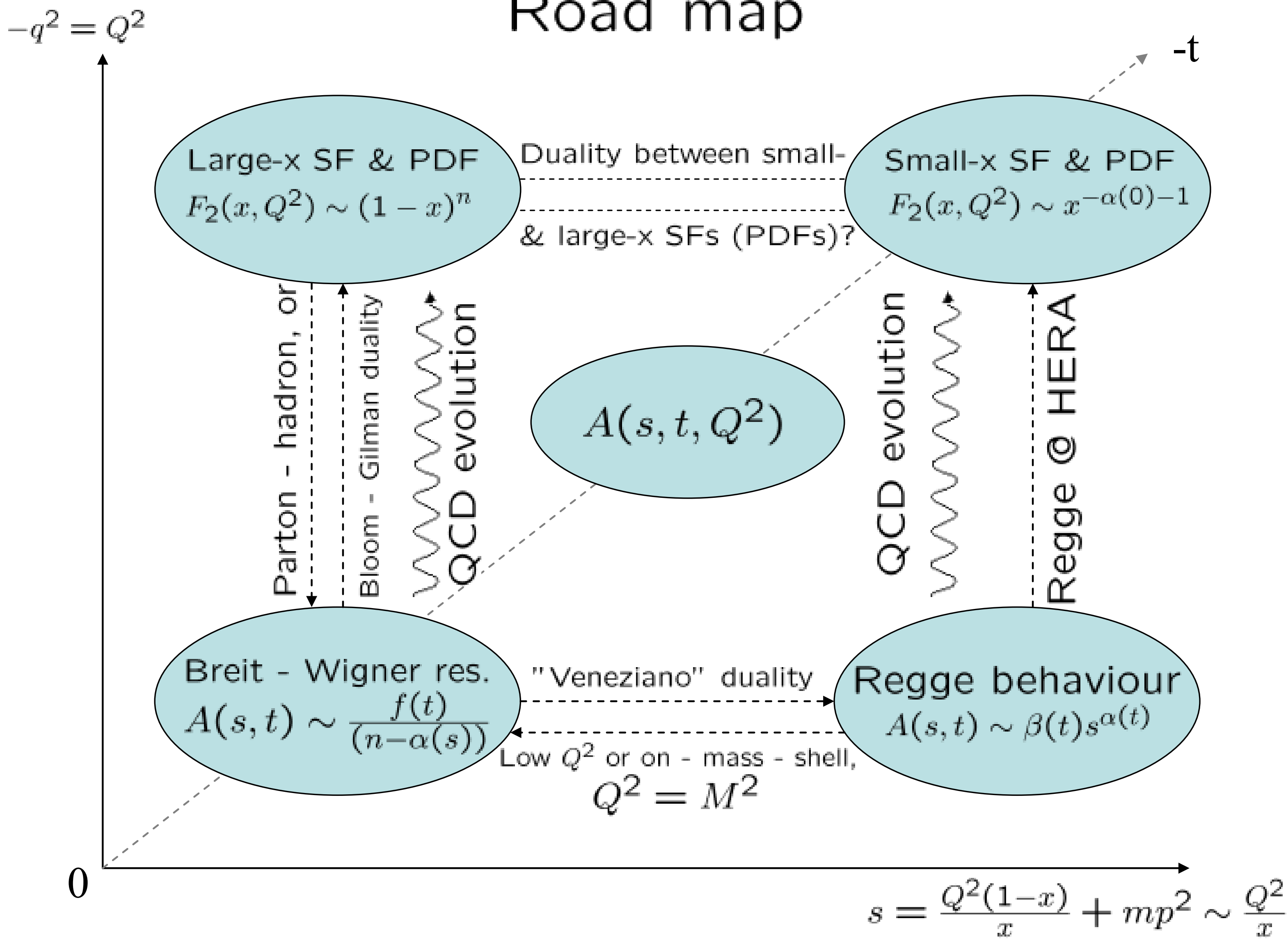
Prospects (future plans):

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)

Road map



$-q^2 = Q^2$
-t
Large-x SF & PDF
$F_2(x, Q^2) \sim (1-x)^n$
Duality between small-
& large-x SFs (PDFs)?
Small-x SF & PDF
$F_2(x, Q^2) \sim x^{-\alpha(0)-1}$
Parton - hadron, or
Bloom - Gilman duality
QCD evolution
$A(s, t, Q^2)$
QCD evolution
Regge @ HERA
Breit - Wigner res.
$A(s,t) \sim \frac{f(t)}{(n-\alpha(s))}$
"Veneziano" duality
Regge behaviour
$A(s,t) \sim \beta(t) s^{\alpha(t)}$
Low Q^2 or on - mass - shell,
$Q^2 = M^2$
0
$s = \frac{Q^2(1-x)}{x} + mp^2 \sim \frac{Q^2}{x}$

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).

DIS &
Vector meson production at HERA and at the LHC

In collaboration with R. Fiore,

V. Libov, M. Machado and A. Salii

Objectives

1 Reactions: DVCS: $\gamma^* p \to \gamma p$ (NB: elastic Compton, $\gamma p \to \gamma p$, is less known!), exclusive (diffractive) VMP $\gamma^* p \to V p$ (at HERA) and elastic (diffractive) hadron scattering (*e.g.* $pp \to pp$ at ISR-LHC).

2. Measurables (observables): differential x-ion $d\sigma/dt$, integrated in t σ_{el}, slope $B(s,t,Q^2)$ total x-ion σ_t (for elastic scattering only!).

3. Fitting strategy:

a) in DVCS and VMP: $d\sigma/dt$, vs. σ_{el} - which one is the "primitive" ?

b) weighting the data point? (the number of data points in pp is by an order of magnitude larger and better than in lepton-induced reactions!

c) simultaneous (multidimensional) vs. "sequent" (sequently in each variable and/or reaction)?

d) experientally measured bins and "symmetrization" (in DVCS and VMP).

e) the "soft" and "hard" components.

The basic object of the theory

$$A(s,t,Q^2) \to A(s,t,Q^2=m^2) \text{ (on mass shell)}$$

$$A(s,t,Q^2) \to \Im m A(s,t=0,Q^2) \sim F_2 \quad \text{DIS}$$

Reconstruction of the DVCS amplitude from DIS

$$F_2 \sim \Im m A(\gamma^* p \to \gamma^* p)\big|_{t=0} \to \Im m A(\gamma^* p \to \gamma p)\big|_{t=0}$$

$$\to A(\gamma^* p \to \gamma p)\big|_{t=0} \to A(\gamma^* p \to \gamma p)$$

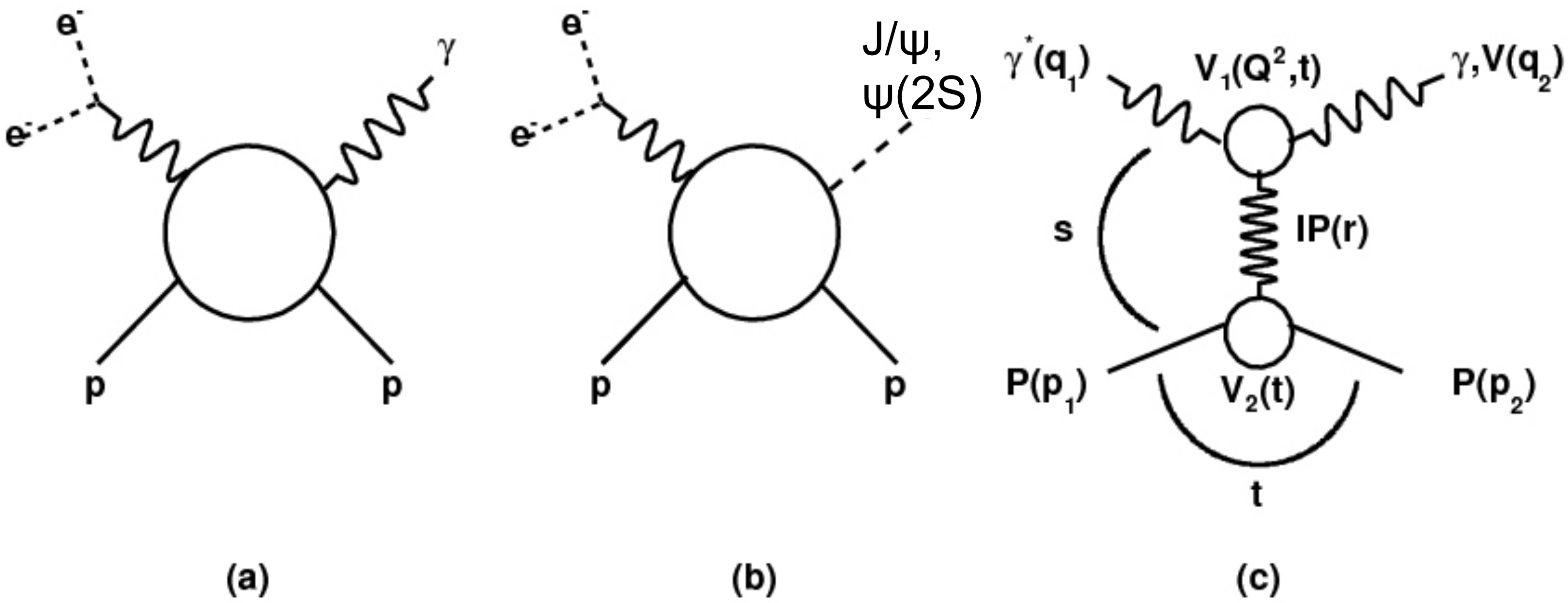
or

$$\Im m A(\gamma^* p \to \gamma^* p)\big|_{t=0} \sim F_2(x_B,Q^2) = x_B q(x_B,Q^2)$$

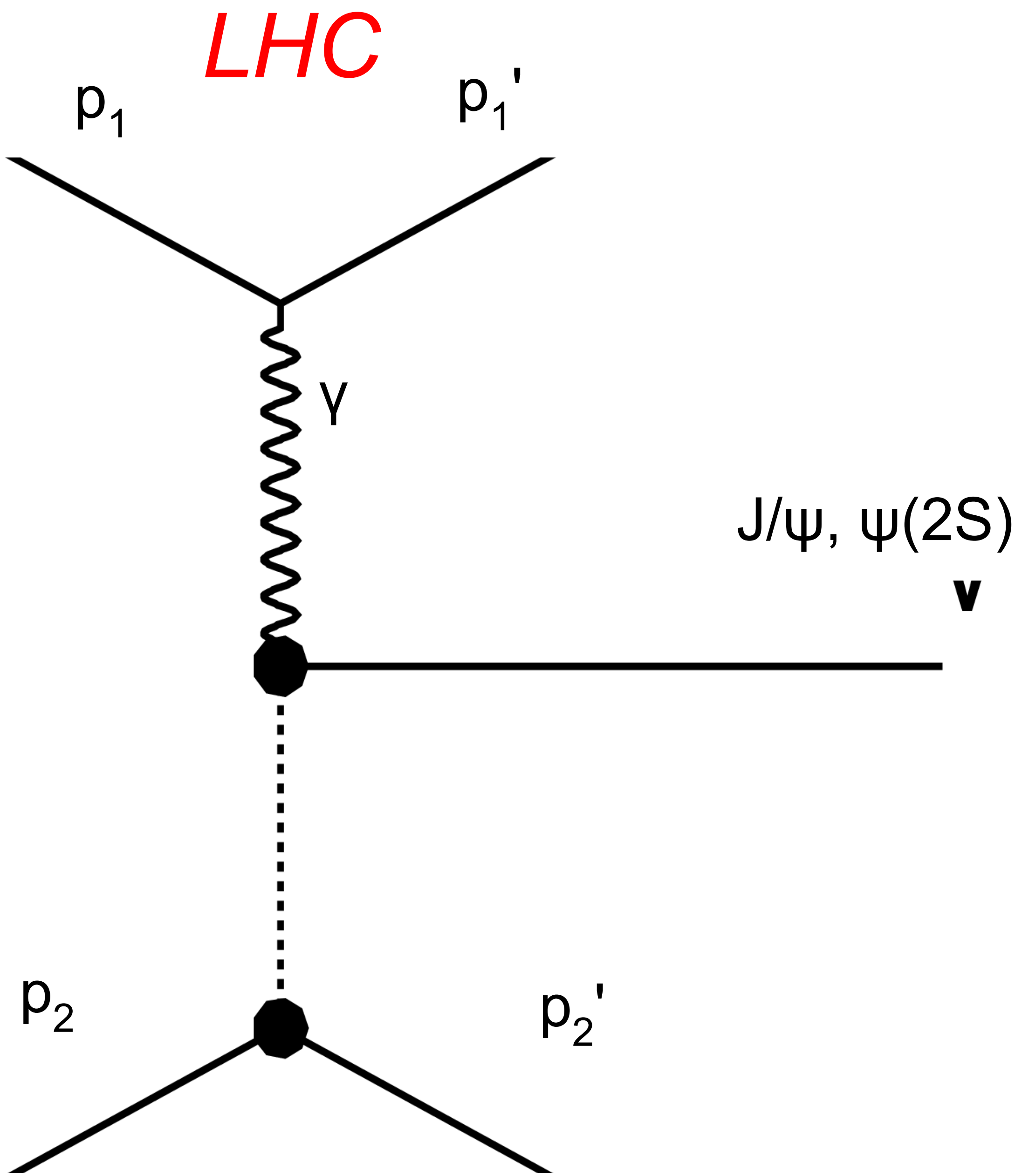
$$q(x_B,Q^2) \to q(\xi,\eta,t,x_B,Q^2) \to$$

$$\to \xi q(\xi,\eta,t,x_B,Q^2) \overset{?}{=} GPD(\xi,\eta,t,x_B,Q^2)$$

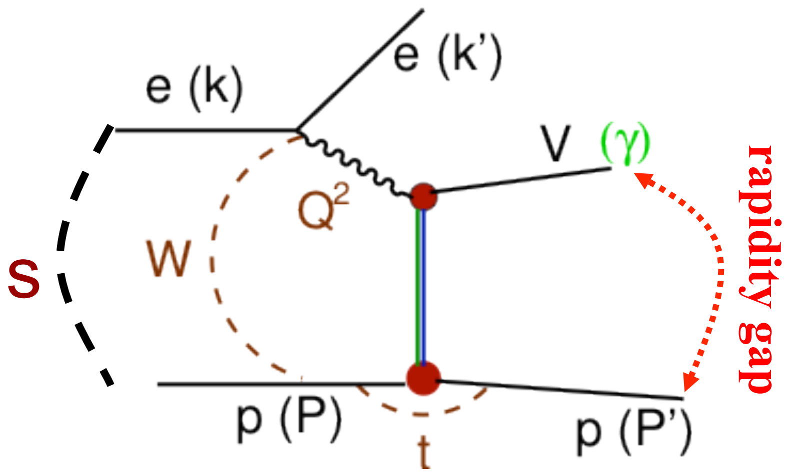
HERA



Diagrams of DVCS (a) and VMP (b) amplitudes
and their Regge-factorized form (c)


LHC
p1
p1'
γ
J/ψ, ψ(2S)
p2
p2'

Exclusive diffraction



Main kinematic variables

electron-proton centre-of-mass energy:

$$s = (k+p)^2 \approx 4E_e E_p$$

photon virtuality:

$$Q^2 = -q^2 = -(k-k')^2 \approx 4E_e E'_e \sin^2\frac{\theta}{2}$$

photon-proton centre-of-mass energy:

$$W^2 = (q+p)^2, \text{ where: } m_p < W < \sqrt{s}$$

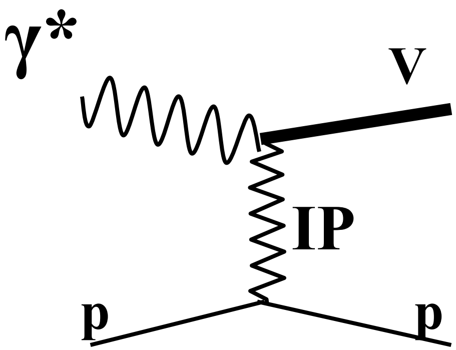
square 4-momentum at the *p* vertex:

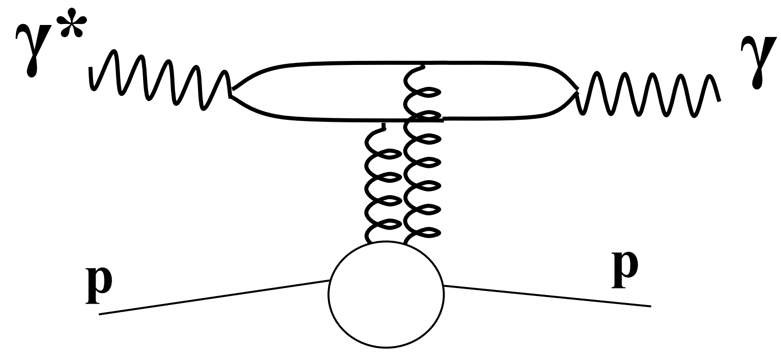
$$t = (p' - p)^2$$

- **Vector Mesons production in diffraction**
- **Deeply Virtual Compton Scattering**

Deeply Virtual Compton Scattering

VM (ρ, ω, φ, J/ψ, Y) — DVCS (γ)

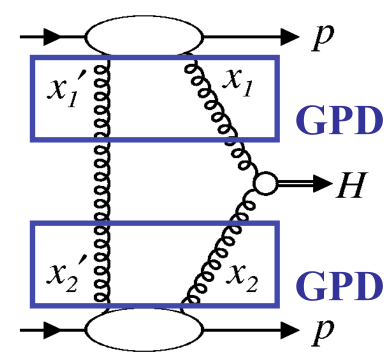




Scale: $Q^2 + M^2$ ⟷ Q^2

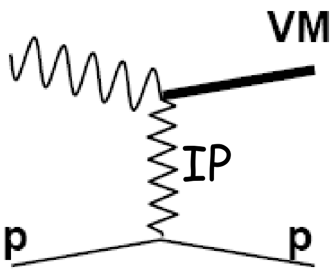
DVCS properties:

- **Similar to VM production, but γ instead of VM in the final state**
- **No VM wave-function involved**
- **Important to determine Generalized Parton Distributions sensible to the correlations in the proton**
- **GPD$_s$ are an ingredient for estimating diffractive cross sections at the LHC**



Diffraction: soft -> hard

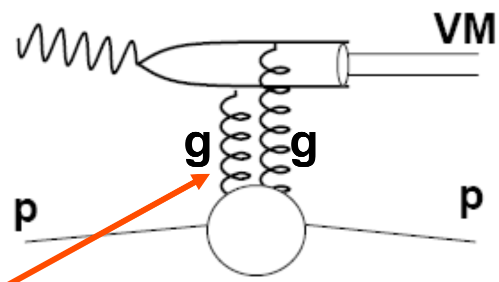
Vector Meson production (ρ, ϕ, J/ψ, Υ, γ)



'soft'

$$Q^2 + M_V^2$$

2-gluon exchange
(pQCD)



'hard'

Gluon density in the proton

Cross section proportional to probability of finding 2 gluons in the proton

$$\begin{cases} \sigma \propto [x\, g(x,\mu^2)]^2 \\ \mu^2 \propto (Q^2 + M_V^2) \end{cases}$$

$$\sigma(W) \propto W^{\delta}$$

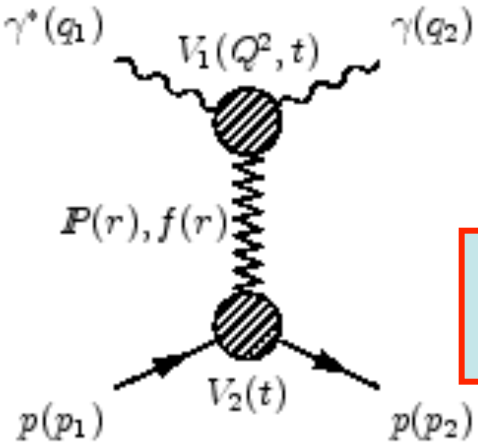
δ increases from soft (~0.2, "soft Pomeron") to hard (~0.8, "hard Pomeron")

$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$

b decreases from soft (~10 GeV^{-2}) to hard (~4-5 GeV^{-2})

Regge-type DVCS amplitude

M. Capua, S. F., R. Fiore, L. L. Jenkovszky, and F Paccanoni
Published in: Physics Letters B645 (Feb. 2007) 161-166



$$V_1 = e^{b\beta(z)}$$

$$V_2 = e^{b\alpha(t)}$$

A new variable is introduced: $z = t - Q^2$

Applications for the model can be:

- Study of various regimes of the scattering amplitude vs *Q2, W, t* (perturbative –> unperturbative QCD)
- Study of GPD_s

DVCS amplitude: $$A(s,t,Q^2)_{\gamma^* p \to \gamma p} = -A_0 V_1(t,Q^2) V_2(t) (-is/s_0)^{\alpha(t)}$$

the *t* dependence at the vertex *pIPp* is introduced by: $$\alpha(t) = \alpha(0) - \alpha_1 \ln(1 - \alpha_2 t)$$

the vertex *γ*IPγ* is introduced by the trajectory: $$\beta(z) = \beta(0) - \beta_1 \ln(1 - \beta_2 z)$$

indicating with: $L = \ln(-is/s_0)$ **the DVCS amplitude can be written as:**

$$A(s,t,Q^2)_{\gamma^* p \to \gamma p} = -A_0 e^{b\alpha(t)} e^{b\beta(z)} (-is/s_0)^{\alpha(t)} = -A_0 e^{(b+L)\alpha(t) + b\beta(z)}$$

Basic ideas of the Kiev-Calabria-Padova Collab.: M. Capua, R. Fiore, L. J., F. Paccanoni, A.Papa "*A DVCS Amplitude*"", Phys. Lett. **B645** (2007) 161-166; hep-ph/0605319; S. Fazio, R. Fiore et al., "Unifying "soft" and "hard…", PR **D**90(2014)016007, arXiv 1312.5683.

Reggeometry=Regge+geometry (play on words = *pun*)

How to combine s, t and Q^2 dependencies in a binary reaction?

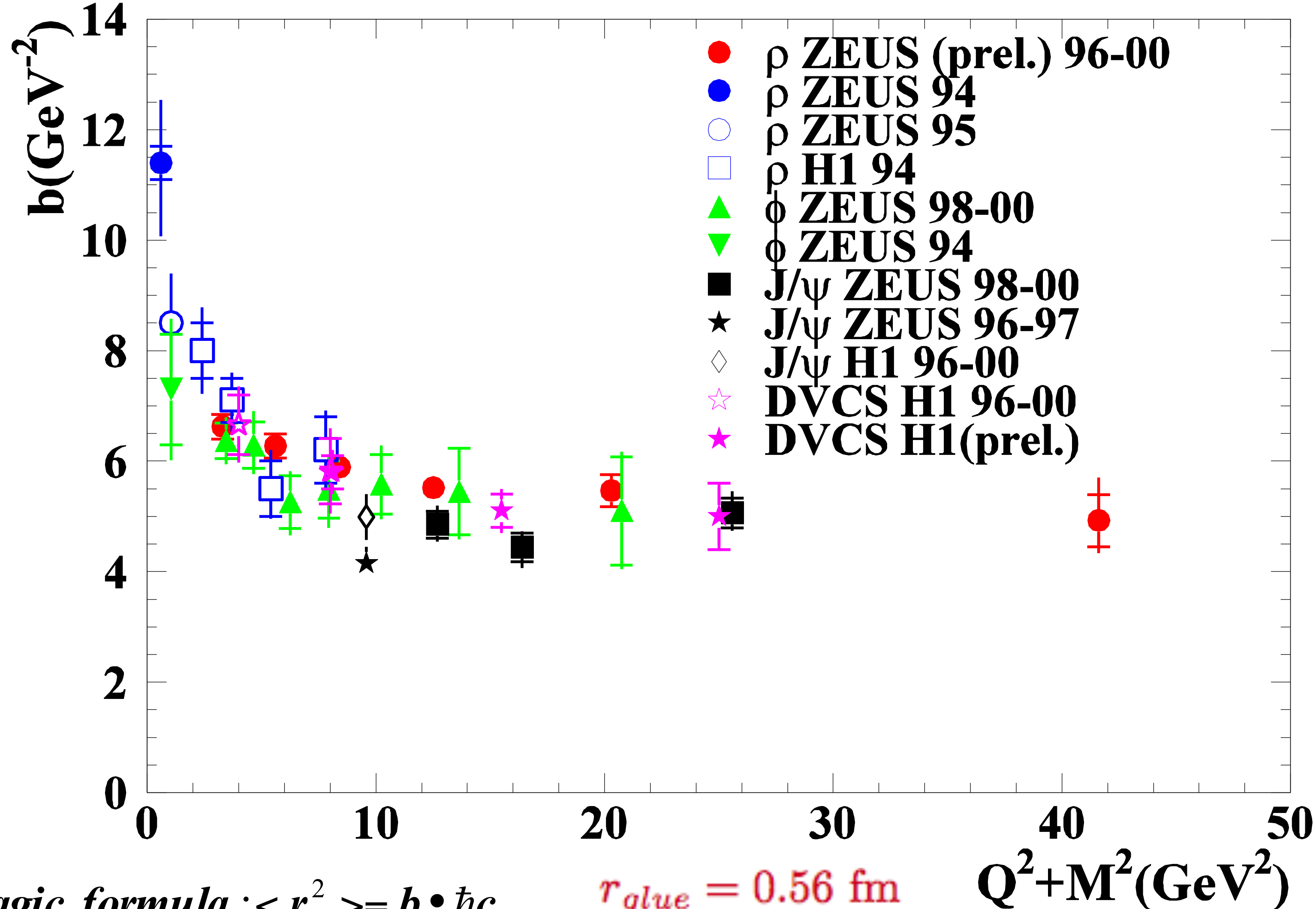
1. The t and $\tilde{Q}^2$ depedences are combined by "geometry":
A rough estimates (to be fine-tuned!) yields

$$\beta(t, M, Q^2) = \exp\Big[4\Big(\frac{1}{M_V^2 + Q^2} + \frac{1}{2m_N^2}\Big)t\Big].$$

2. The s and t behavior are related by the Regge-pole model;

3. There is only one, universal, Pomeron, but it has two components - soft and hard, their relative weights depending on $\tilde{Q}^2$.

$b(Q^2+M^2)$ - VM



Magic formula : $<r^2> = b \bullet \hbar c$

$r_{glue} = 0.56$ fm

$r_{proton} = 0.8$ fm

Pomeron Trajectory

Regge-type: $$\frac{d\sigma}{dt}(W) = \exp(b_0 t) \cdot W^{2[2\alpha_{IP}(t)+2]}$$

First measured in h-h scattering

Linear Pomeron trajectory

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

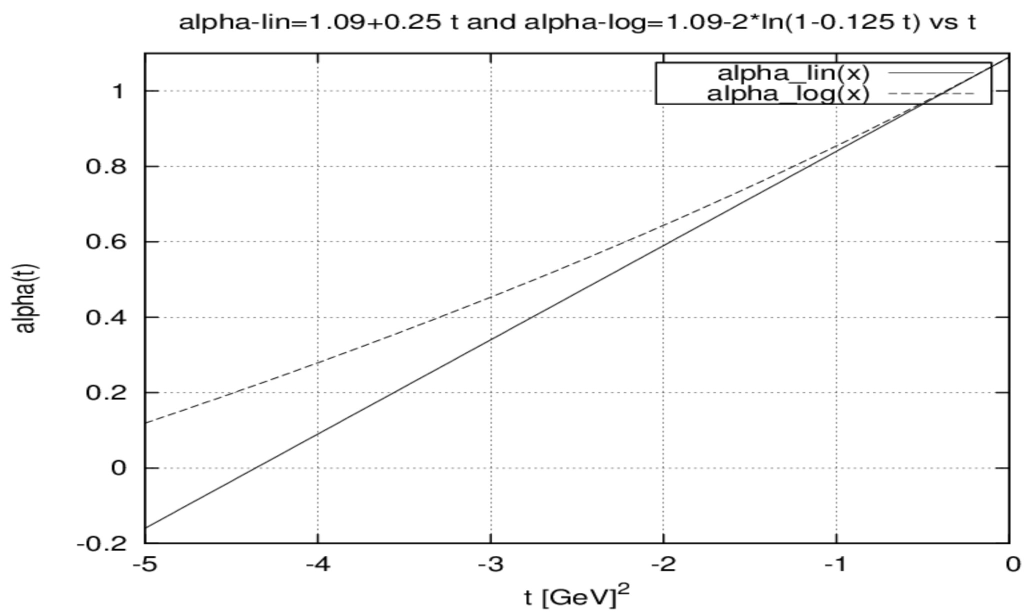
$\alpha(0)$ and α' are foundamental parameters to represent the basic features of strong interactions

Soft Pomeron values
$\alpha(0) \approx 1.09$
$\alpha' \approx 0.25$

$\alpha(0)$: determines the energy dependence of the diff. Cross section

$$\frac{d\sigma}{dt} \propto \exp(b_0 t) \cdot W^{4\alpha(t)-4} = W^{4\alpha(0)-4} \cdot \exp(bt); \qquad b = b_0 + 4\alpha' \ln(W)$$

α': determines the energy dependence of the transverse extention system


alpha-lin=1.09+0.25 t and alpha-log=1.09-2*ln(1-0.125 t) vs t
alpha_lin(x)
alpha_log(x)
alpha(t)
t [GeV]2
1
0.8
0.6
0.4
0.2
0
-0.2
-5
-4
-3
-2
-1
0

Unique Pomeron with two ("soft" and "hard") components
R. Fiore et al. Phys. Rev. PR **D**90(2014)016007, arXiv 1312.5683

$$A(s,t,Q^2,{M_v}^2) = \frac{\tilde{A}_s}{\left(1+\frac{\widetilde{Q^2}}{\widetilde{Q_s^2}}\right)^{n_s}} e^{-i\frac{\pi}{2}\alpha_s(t)} \left(\frac{s}{s_{0s}}\right)^{\alpha_s(t)} e^{2\left(\frac{a_s}{\widetilde{Q^2}}+\frac{b_s}{2m_p^2}\right)t}$$

$$+\frac{\tilde{A}_h\left(\frac{\widetilde{Q^2}}{\widetilde{Q_h^2}}\right)}{\left(1+\frac{\widetilde{Q^2}}{\widetilde{Q_h^2}}\right)^{n_h+1}} e^{-i\frac{\pi}{2}\alpha_h(t)} \left(\frac{s}{s_{0h}}\right)^{\alpha_h(t)} e^{2\left(\frac{a_h}{\widetilde{Q^2}}+\frac{b_h}{2m_p^2}\right)t}$$

$$\frac{d\sigma_{el}}{d|t|} = H_s^2 e^{2L_s(\alpha_s(t)-1)+g_s t} + H_h^2 e^{2L_h(\alpha_h(t)-1)+g_h t}$$

$$+2H_s H_h e^{L_s(\alpha_s(t)-1)+L_h(\alpha_h(t)-1)+(g_s+g_h)t} \cos\left(\frac{\pi}{2}(\alpha_s(t) - \alpha_h(t))\right)$$

$$H_s = \frac{A_s}{\left(1+\frac{\widetilde{Q^2}}{\widetilde{Q_s^2}}\right)^{n_s}} \quad H_h = \frac{A_h\left(\frac{\widetilde{Q^2}}{\tilde{Q}_h^2}\right)}{\left(1+\frac{\widetilde{Q^2}}{\widetilde{Q_h^2}}\right)^{n_h+1}}$$

$$L_s = \ln\left(\frac{s}{s_{0s}}\right) \quad g_s = 2\left(\frac{a_s}{\widetilde{Q^2}} + \frac{b_s}{2m_p^2}\right) \quad \alpha_s(t) = \alpha_{0s} + \alpha'_s t$$

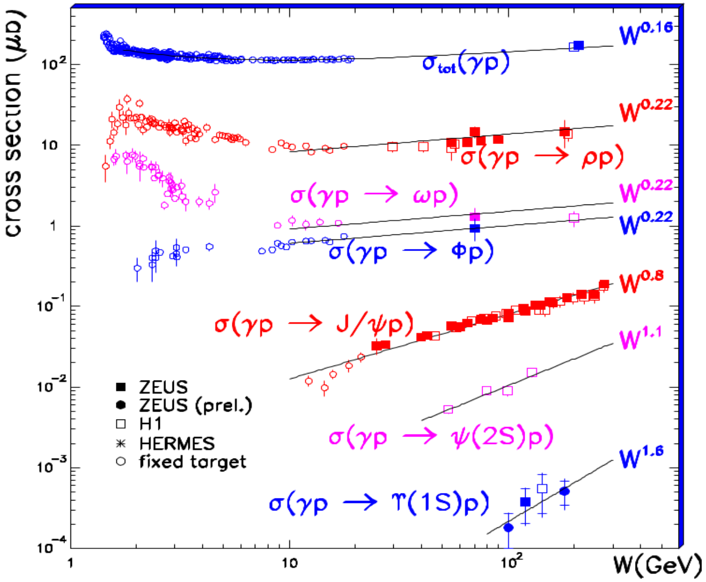
$$L_h = \ln\left(\frac{s}{s_{0h}}\right) \quad g_h = 2\left(\frac{a_h}{\widetilde{Q^2}} + \frac{b_h}{2m_p^2}\right) \quad \alpha_h(t) = \alpha_{0h} + \alpha'_h t$$

	A_s	$\widetilde{Q_s^2}$	n_s	α_{0s}	α'_s	a_s	b_s	$\tilde{\chi}^2$
pp	5.9 ± 5.7	$***$	0.00	1.05 ± 0.14	0.276 ± 0.474	2.877 ± 2.837	0.00	1.52
ρ^0	59.5 ± 29.3	1.33	1.35 ± 0.05	1.15 ± 0.06	0.15	-0.22	1.69	6.56
ϕ	31.8 ± 35.3	1.30	1.32 ± 0.10	1.14 ± 0.12	0.15	-0.85 ± 1.60	2.51 ± 2.67	3.81
J/ψ	34.2 ± 19.0	1.4 ± 0.7	1.39 ± 0.13	1.21 ± 0.05	0.09	1.90	1.03	4.50
$\Upsilon(1S)$	37 ± 101	0.9 ± 1.7	1.53 ± 0.55	1.29 ± 0.26	0.01 ± 0.6	1.90	1.03	1.28
$DVCS$	9.7 ± 9.0	0.45 ± 0.5	0.94 ± 0.24	1.19 ± 0.09	-0.007 ± 0.3	1.94 ± 4.65	1.74 ± 2.28	1.75

Table 1. Fitting results

	δ	α_{0s}	$\alpha_{0s}(fit)$	α'_s
pp		1.08(DL)	1.05 ± 0.14	0.276 ± 0.474
ρ^0	0.22	1.055	1.15 ± 0.06	0.15
ϕ	0.22	1.055	1.14 ± 0.12	0.15
J/ψ	0.8	1.2	1.21 ± 0.05	0.09
$\Upsilon(1S)$	1.6	1.4	1.29 ± 0.26	0.01 ± 0.6
$DVCS$	0.54	1.135	1.19 ± 0.09	-0.007 ± 0.3

Table 2. α(0), α'

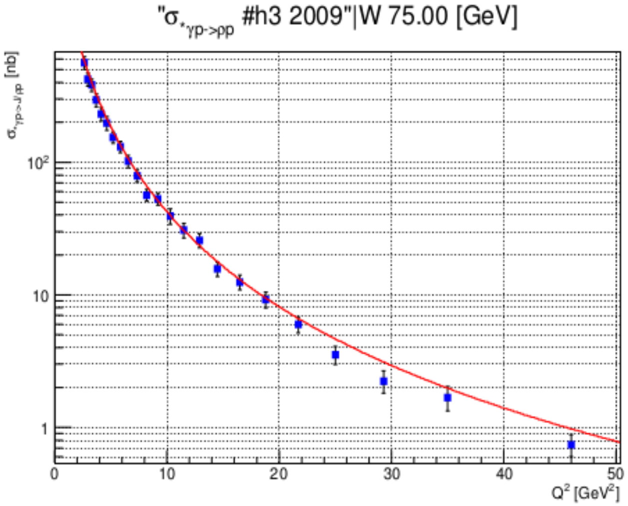


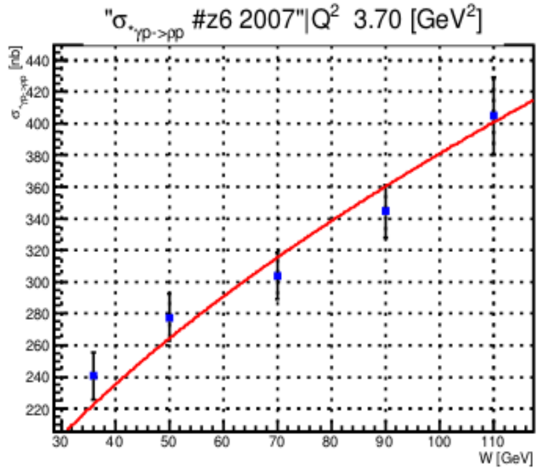
(a) The W dependence of the cross section for exclusive VM photoproduction together with the total photoproduction cross section. Lines are the result of a W^δ fit to the data at high W-energy values.

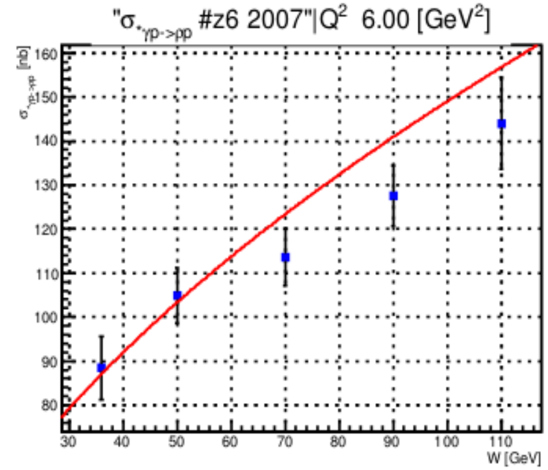
Parameter s_{0s} for simplicity is also fixed $s_{0s} = 1$.

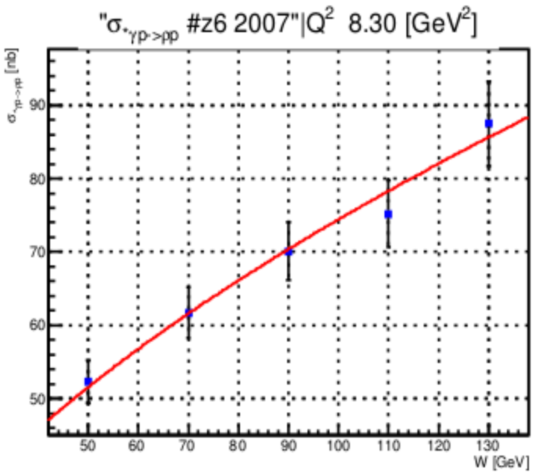
$*$ Parameters that doesn't have errors in table[1] were fixed at fitting stage.

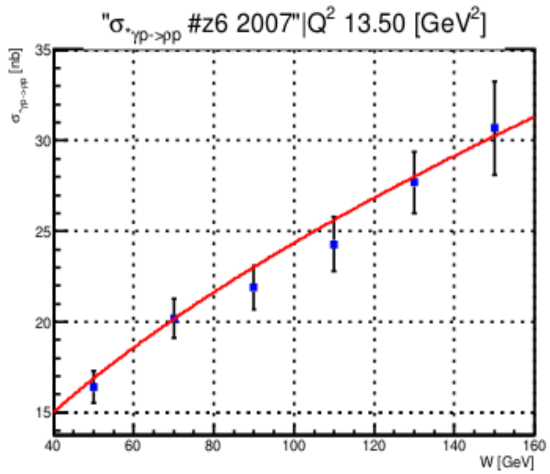
rho0(1)

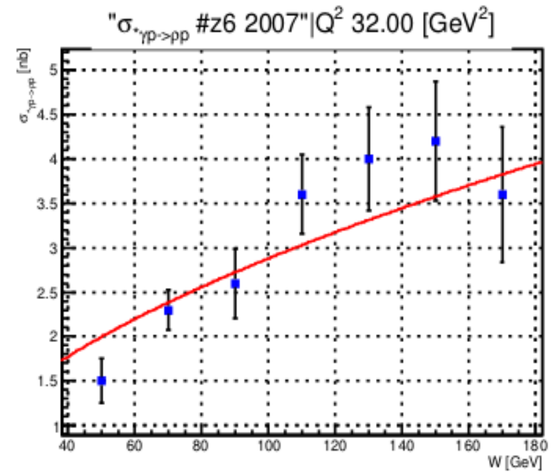

"σ*γp->J/ψp #h3 2009"|W 75.00 [GeV]
σ*γp->J/ψp [nb]
Q² [GeV²]


"σ*γp->ρp #z6 2007"|Q² 3.70 [GeV²]
σ*γp->ρp [nb]
W [GeV]

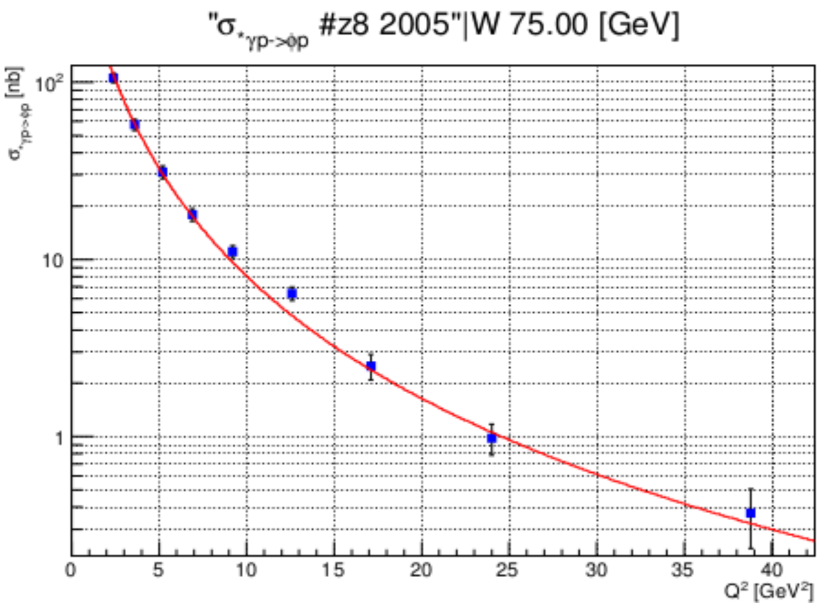

"σ*γp->ρp #z6 2007"|Q² 6.00 [GeV²]
σ*γp->ρp [nb]
W [GeV]

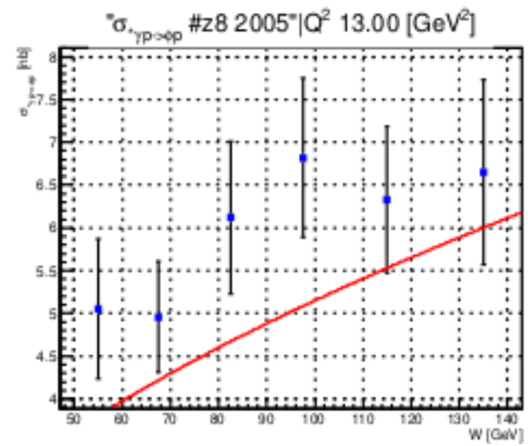

"σ*γp->ρp #z6 2007"|Q² 8.30 [GeV²]
σ*γp->ρp [nb]
W [GeV]

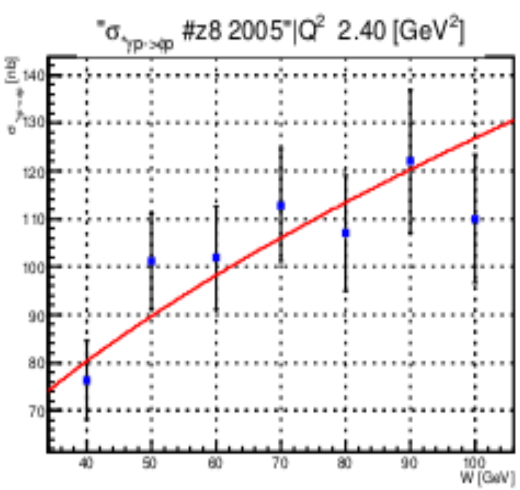

"σ*γp->ρp #z6 2007"|Q² 13.50 [GeV²]
σ*γp->ρp [nb]
W [GeV]

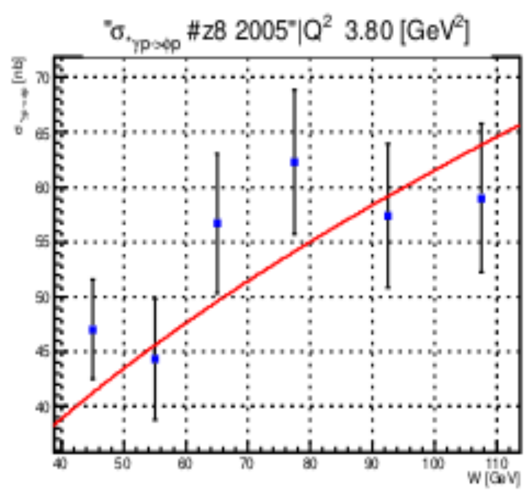

"σ*γp->ρp #z6 2007"|Q² 32.00 [GeV²]
σ*γp->ρp [nb]
W [GeV]

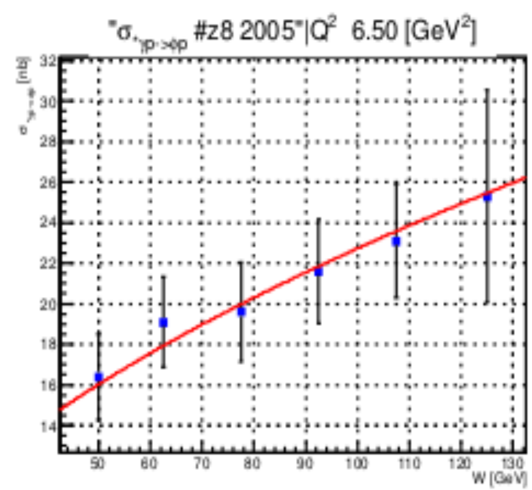
phi (1)


"σ*γp->φp #z8 2005"|W 75.00 [GeV]
σ*γp->φp [nb]
Q² [GeV²]

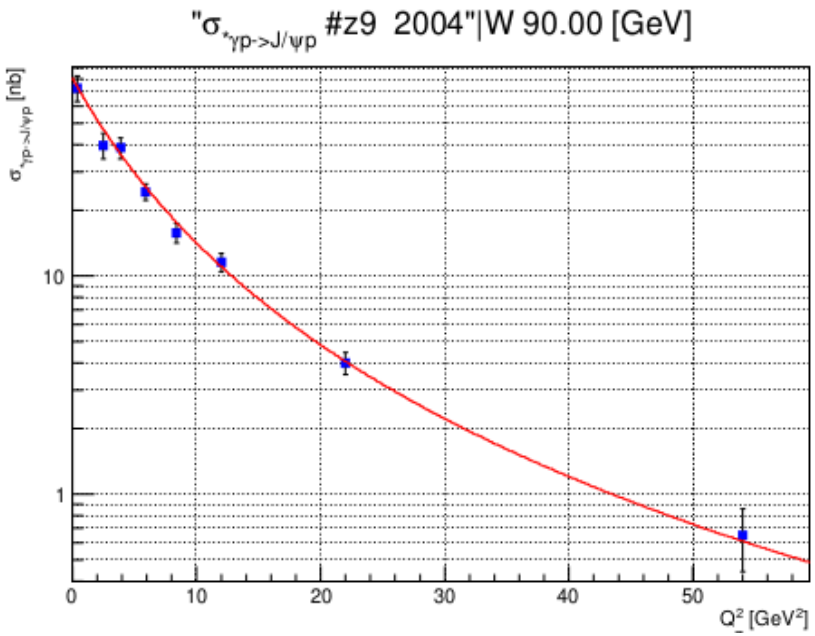

"σ*γp->φp #z8 2005"|Q² 13.00 [GeV²]
W [GeV]

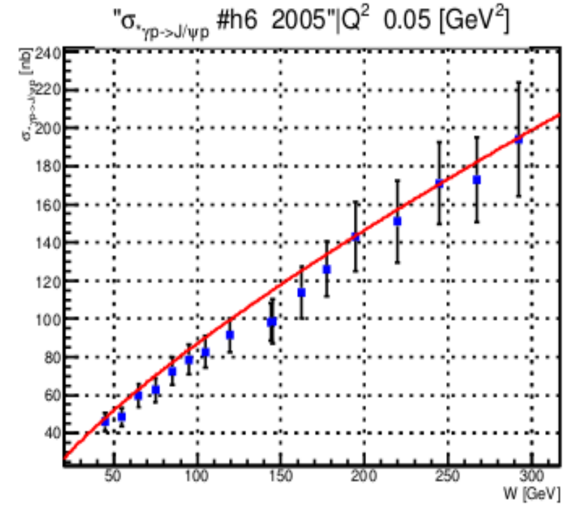

"σ*γp->φp #z8 2005"|Q² 2.40 [GeV²]
W [GeV]

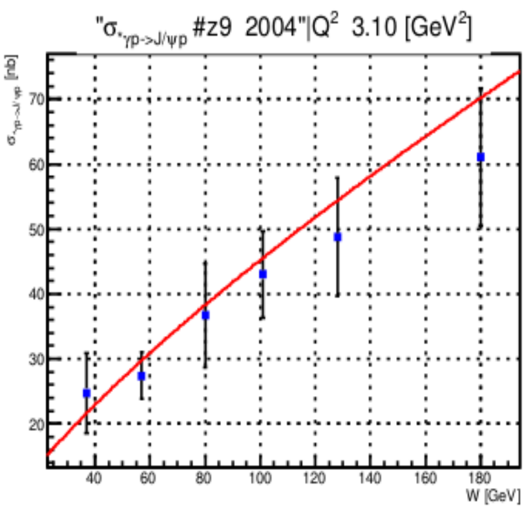

"σ*γp->φp #z8 2005"|Q² 3.80 [GeV²]
W [GeV]

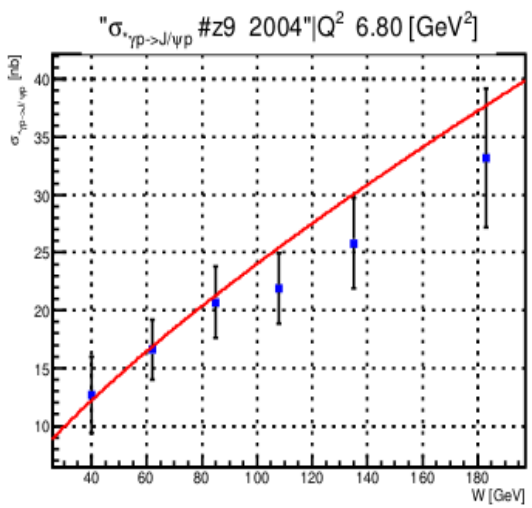

"σ*γp->φp #z8 2005"|Q² 6.50 [GeV²]
W [GeV]

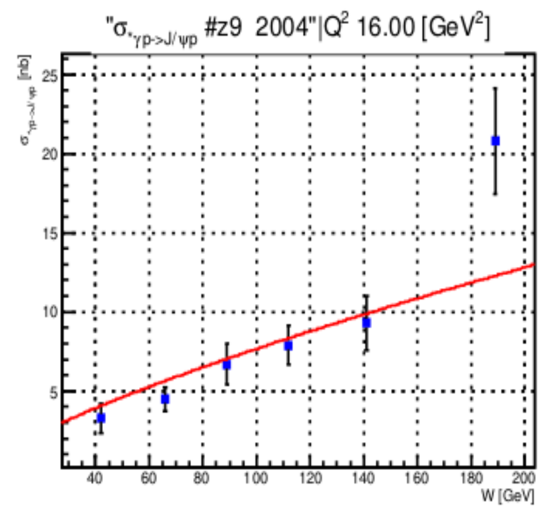
J/psi (1)


"σ*γp->J/ψp #z9 2004"|W 90.00 [GeV]
σ*γp->J/ψp [nb]
Q2 [GeV2]
10
1
0
10
20
30
40
50

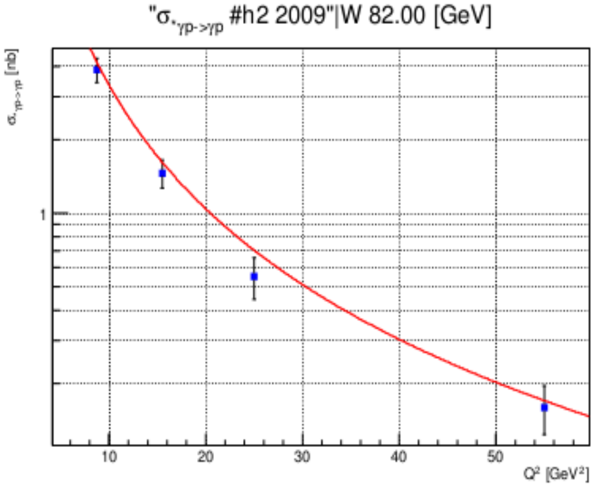

"σ*γp->J/ψp #h6 2005"|Q2 0.05 [GeV2]
σ*γp->J/ψp [nb]
W [GeV]
40
60
80
100
120
140
160
180
200
220
240
50
100
150
200
250
300

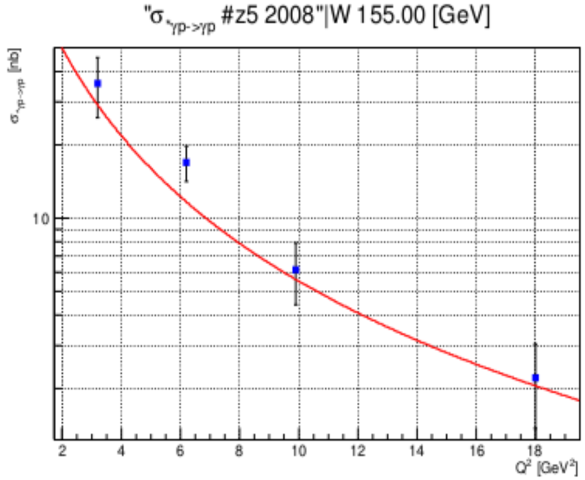

"σ*γp->J/ψp #z9 2004"|Q2 3.10 [GeV2]
σ*γp->J/ψp [nb]
W [GeV]
20
30
40
50
60
70
40
60
80
100
120
140
160
180

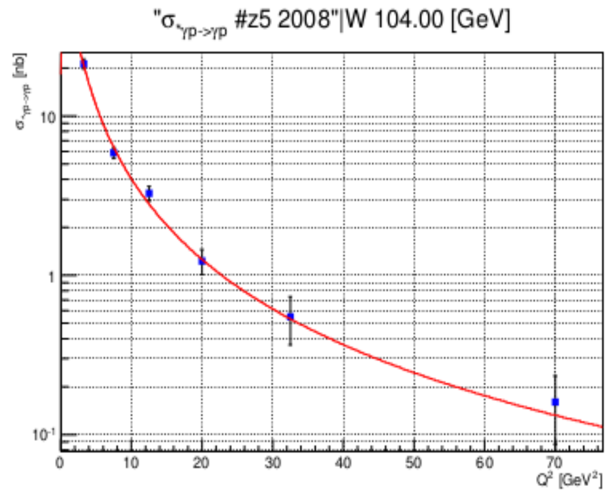

"σ*γp->J/ψp #z9 2004"|Q2 6.80 [GeV2]
σ*γp->J/ψp [nb]
W [GeV]
10
15
20
25
30
35
40
40
60
80
100
120
140
160
180

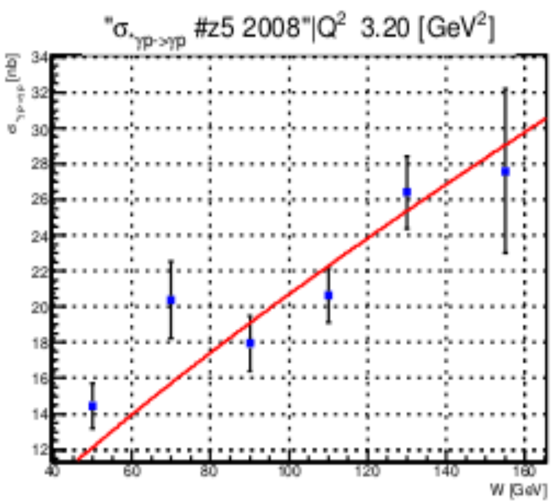

"σ*γp->J/ψp #z9 2004"|Q2 16.00 [GeV2]
σ*γp->J/ψp [nb]
W [GeV]
5
10
15
20
25
40
60
80
100
120
140
160
180
200

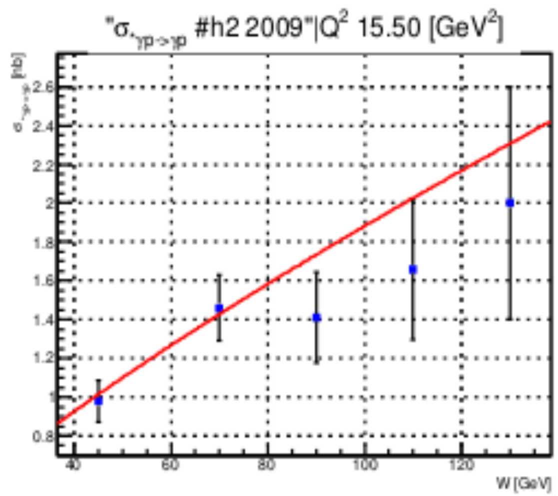
DVCS (1)

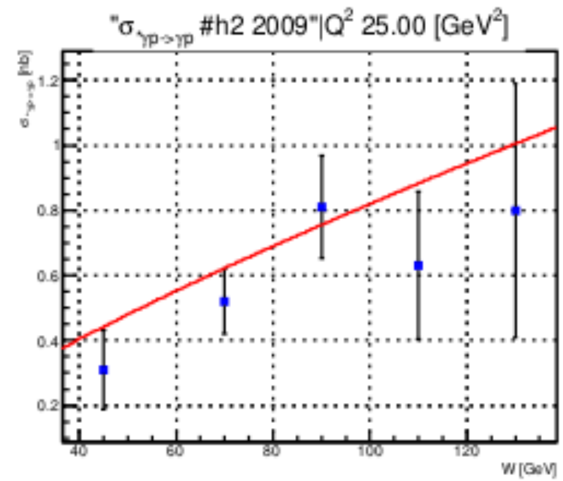

"σ*γp->γp #h2 2009"|W 82.00 [GeV]
σ*γp->γp [nb]
Q² [GeV²]

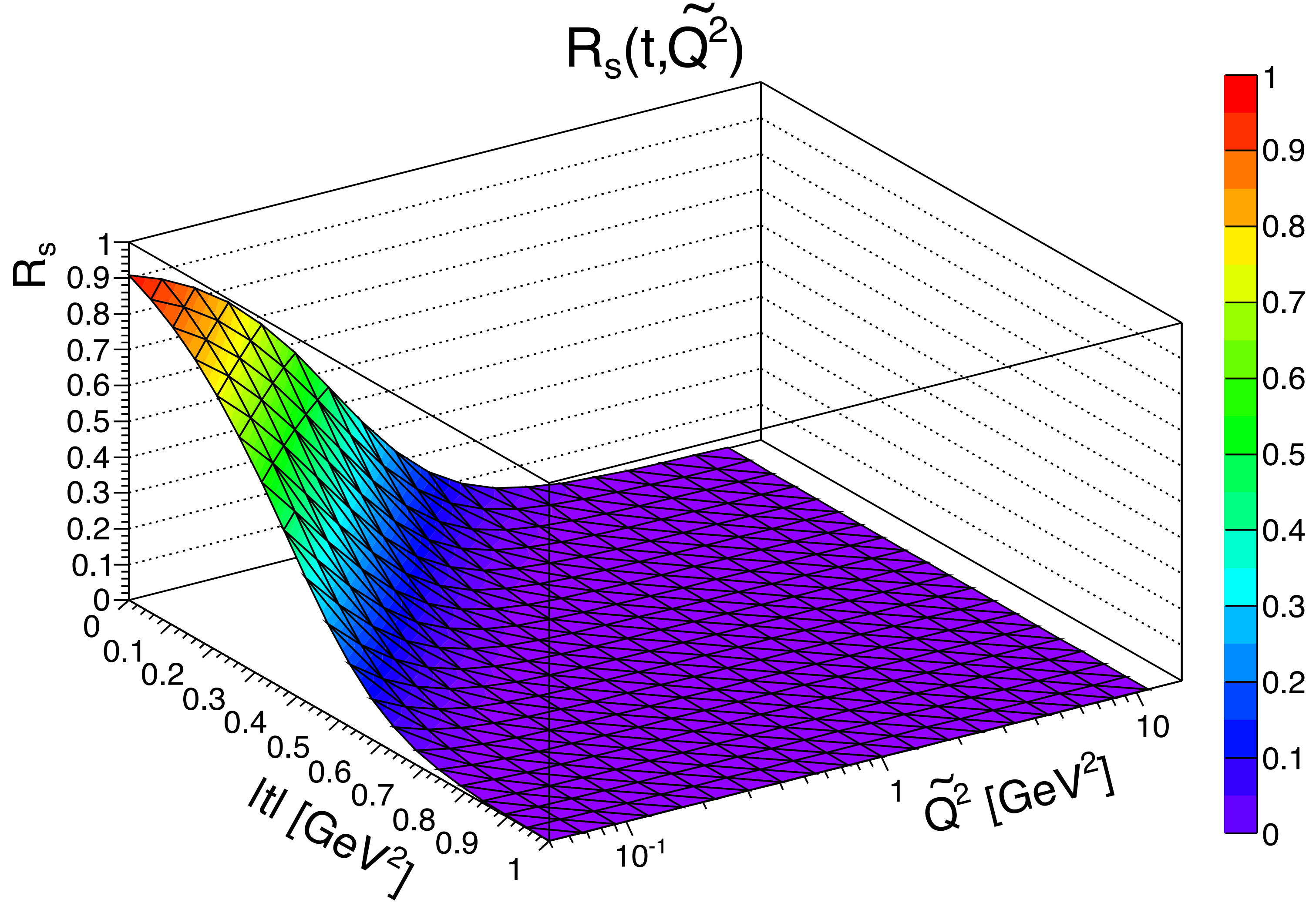

"σ*γp->γp #z5 2008"|W 155.00 [GeV]
σ*γp->γp [nb]
Q² [GeV²]


"σ*γp->γp #z5 2008"|W 104.00 [GeV]
σ*γp->γp [nb]
Q² [GeV²]


"σ*γp->γp #z5 2008"|Q² 3.20 [GeV²]
σ*γp->γp [nb]
W [GeV]

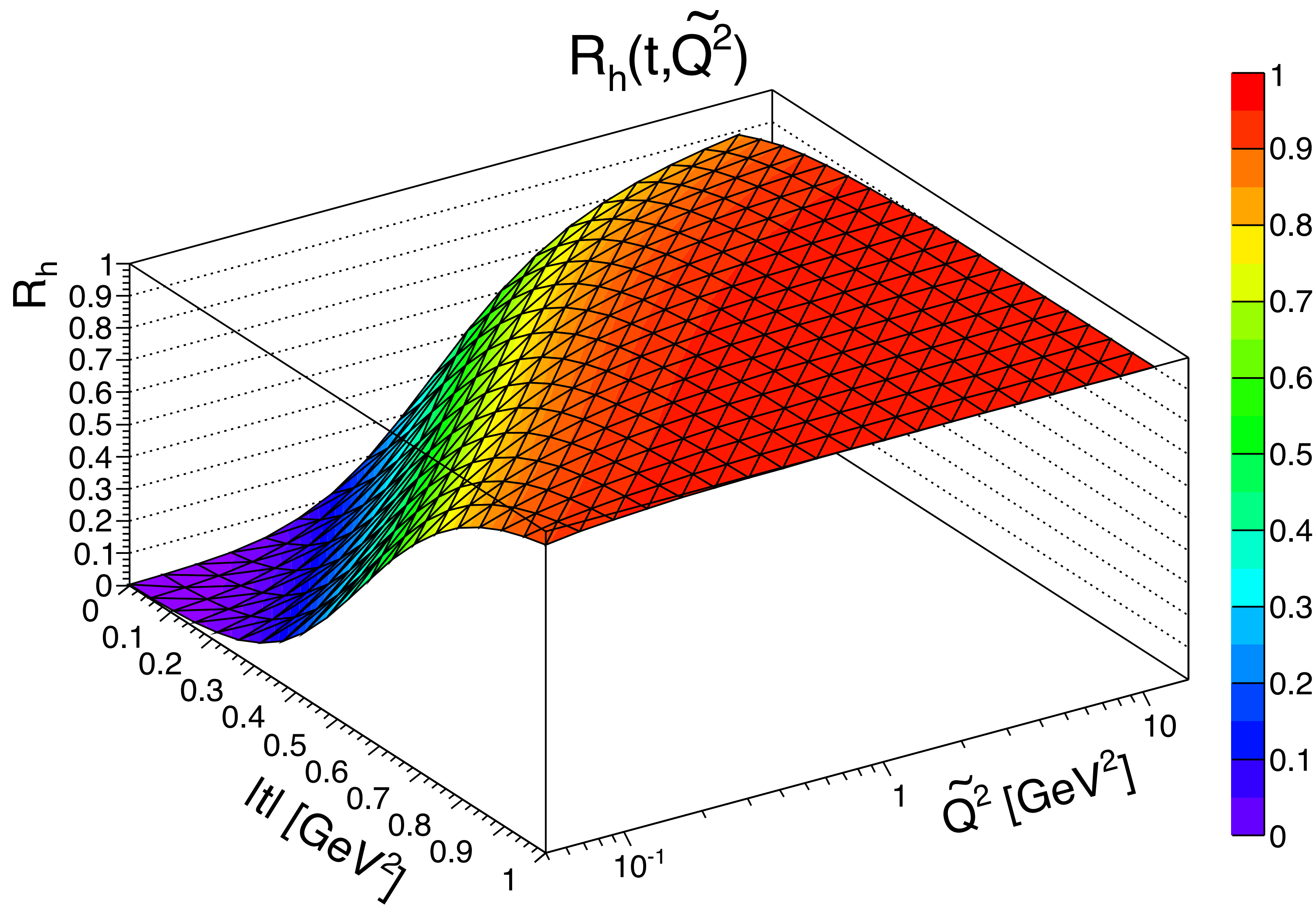

"σ*γp->γp #h2 2009"|Q² 15.50 [GeV²]
σ*γp->γp [nb]
W [GeV]


"σ*γp->γp #h2 2009"|Q² 25.00 [GeV²]
σ*γp->γp [nb]
W [GeV]



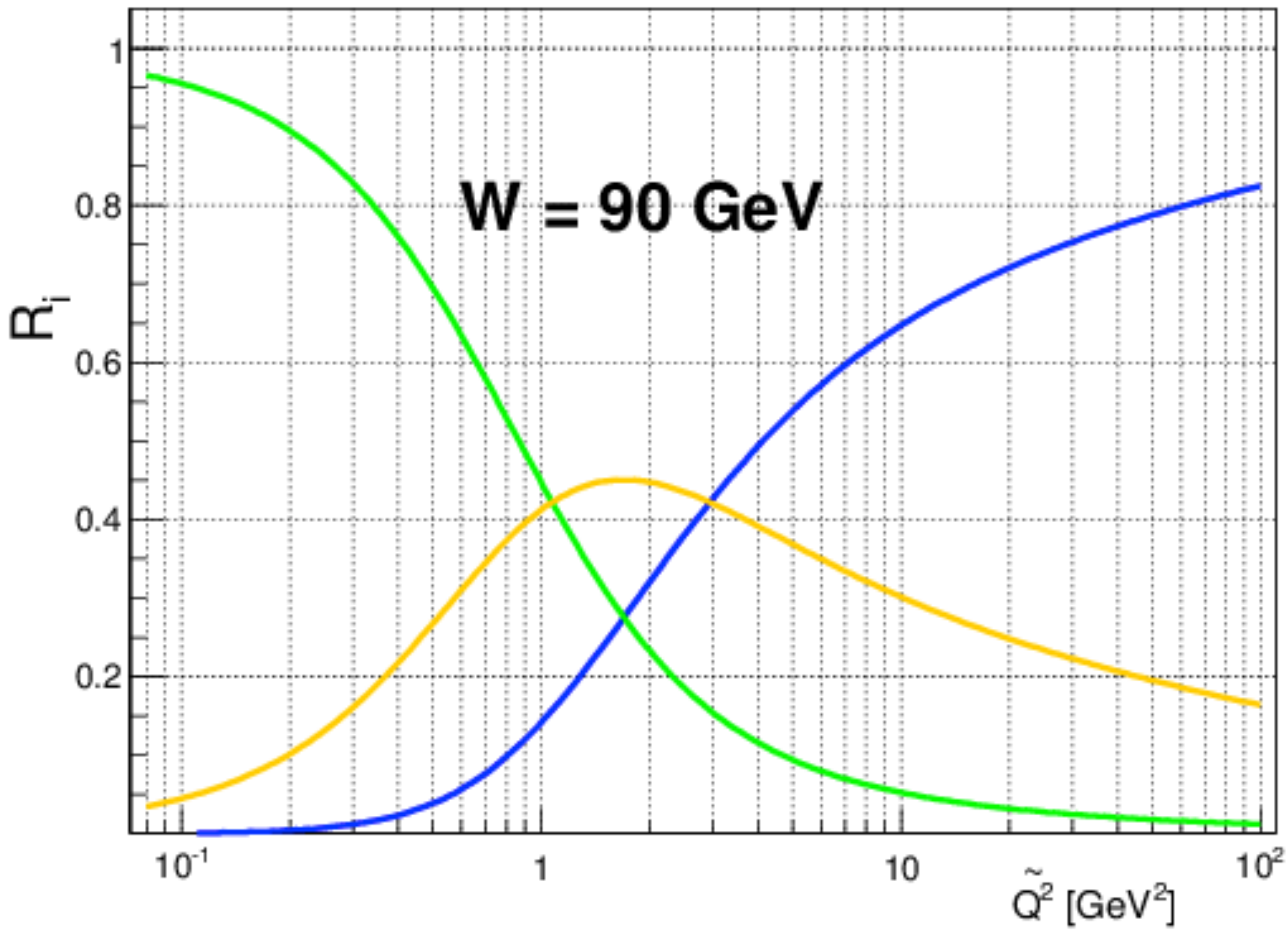
$R_s(t,\tilde{Q}^2)$
R_s
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
|t| [GeV^2]
10^{-1}
1
10
$\tilde{Q}^2$ [GeV^2]

04.09.14



$R_h(t,\tilde{Q}^2)$
R_h
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
|t| [GeV^2]
10^{-1}
1
10
$\tilde{Q}^2$ [GeV^2]

04.09.14



W = 90 GeV
R_i
1
0.8
0.6
0.4
0.2
10^-1
1
10
10^2
Q̃^2 [GeV^2]

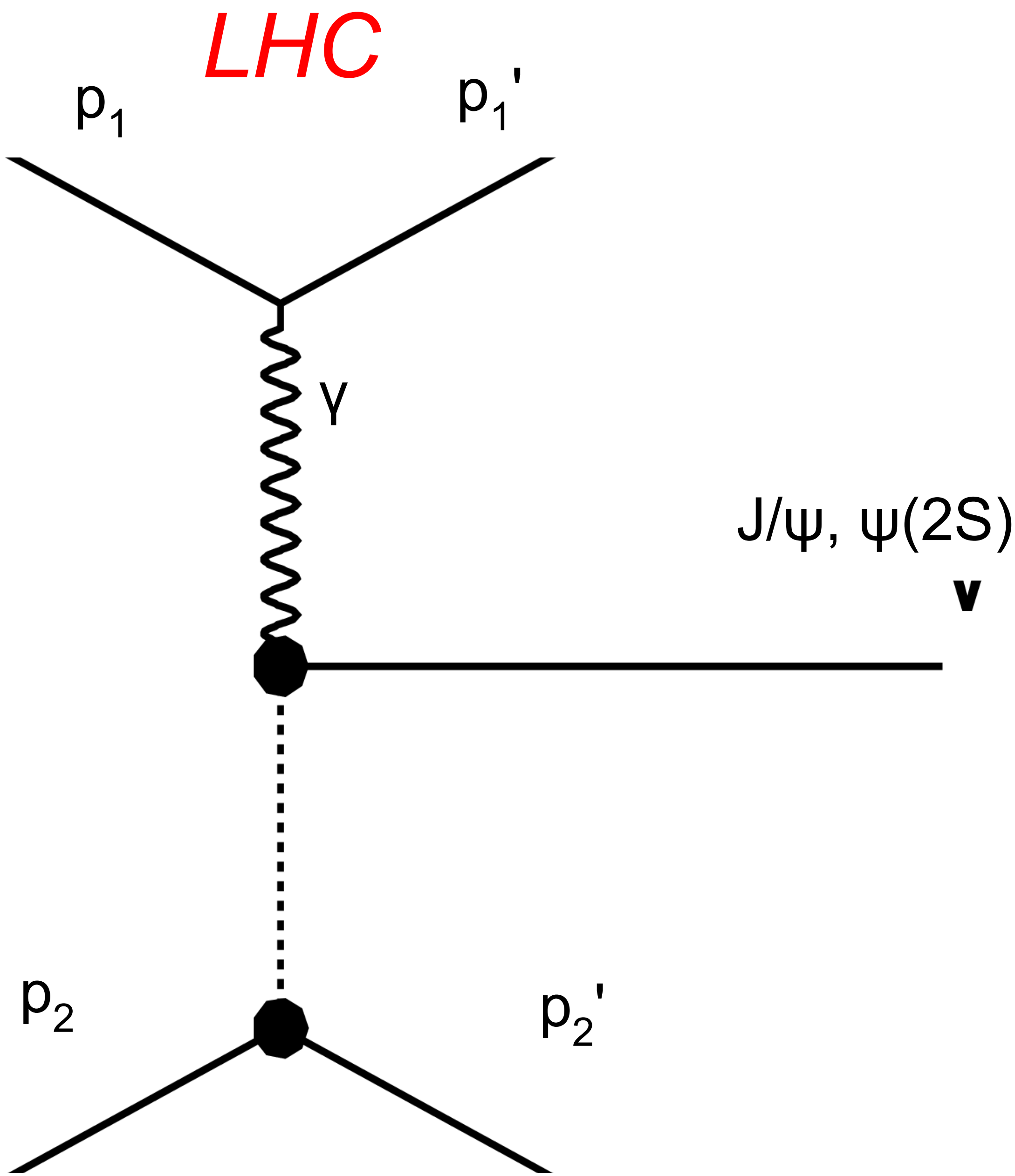
Summary and prospects for **ep** collisions:

I. Problems:

1) unifying DVCS and VMP (the photon “mass”);
2) balancing between “soft” and “hard”, QCD?
3) extension to low energies (non-diffractive component, secondary Reggeons) ;
4) saturation effects, unitarity (gap survival);
5) Is BFKL Regge behaved?

Prospects: application to the new ZEUS data.

II. Moving from HERA to the LHC: ultraperipheral **pp, pA and AA** collisions: R. Fiore, L. J., V. Libov, and M. Machado, arXiv, 2014, to be publ. in: Teor. and Math. Physics. Predecessors: Joakim Nystrand, A. Szczurek et al, L. Motyka, G. Watt; Brazilian group…). Contrary to ep, no Q^2 or t dependence here.



LHC
p1
p1'
γ
J/ψ, ψ(2S)
p2
p2'

The differential cross section reads:

$$\frac{d\sigma(h_1 + h_2 \to h_1 + V + h_2)}{dY}$$

$$= \omega_+ \frac{dN_{\gamma/h_1}(\omega_+)}{d\omega}\sigma_{\gamma h_2 \to V h_2}(\omega_+) + \omega_- \frac{dN_{\gamma/h_2}(\omega_-)}{d\omega}\sigma_{\gamma h_1 \to V h_1}(\omega_-),$$

where $\frac{dN_{\gamma/h}(\omega)}{d\omega}$ is the "equivalent" photon flux $\frac{dN_{\gamma/h}(\omega)}{d\omega} = \frac{\alpha_{em}}{2\pi\omega}[1+(1-\frac{2\omega}{\sqrt{s}})^2](\ln\Omega - \frac{11}{6} + \frac{3}{\Omega} - \frac{3}{2\Omega^2} + \frac{1}{3\Omega^3})$ and $\sigma_{\gamma p \to Vp}(\omega)$ is the total cross section of the vector meson photoproduction subprocess. ω is the photon energy, $\omega = W_{\gamma p}^2/2\sqrt{s}_{pp}$ with $\omega_{min} = M_V^2/(4\gamma_L m_p)$, where $\gamma_L = \sqrt{s}/(2m_p)$ is the Lorentz factor, e.g., for pp at the LHC for $\sqrt{s} = 7$ TeV, $\gamma_L = 3731$.

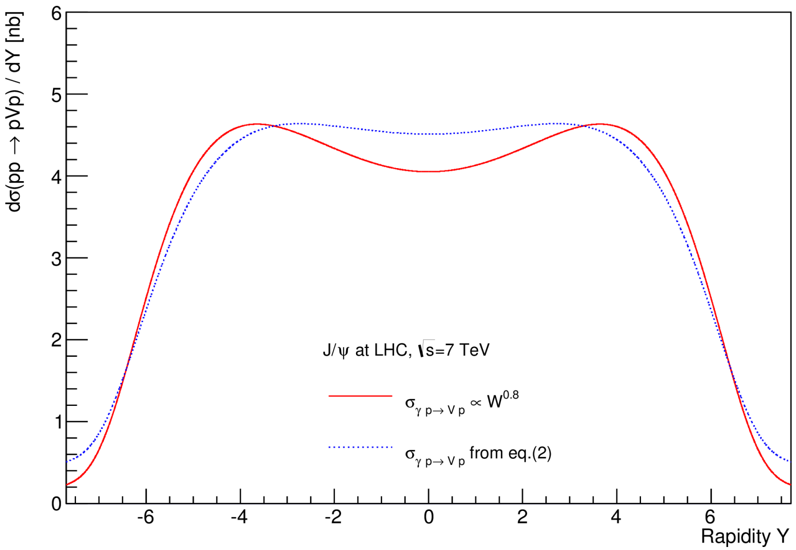
Photon flux: V.M. Budnev et al., Phys. Rep., 1975; G. Baur et al., ibid, 1988.

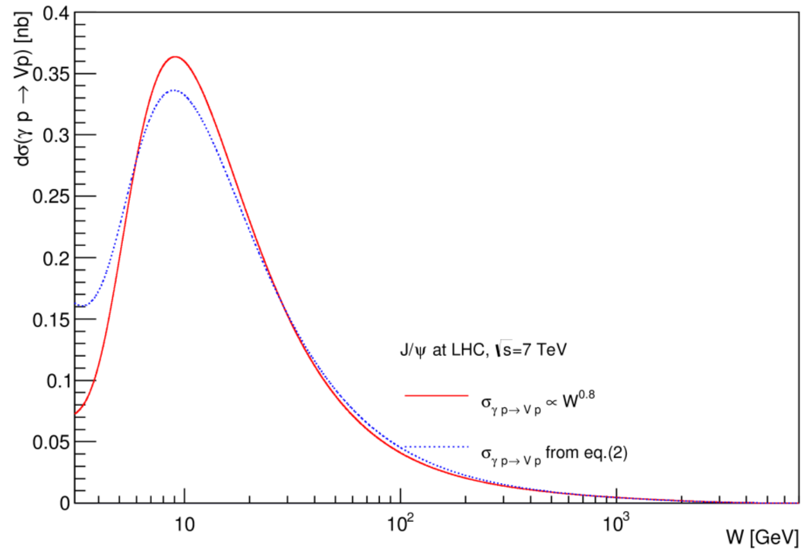
Unique Pomeron with two ("soft" and "hard") components in pp (AA) collisions: R. Fiore, L.L., V. Libov, M. Machado, arXiv: 1408.0530, Theor. and Math. Physics, in press.

$$A(s,t,Q^2,{M_v}^2) = \frac{\tilde{A}_s}{\left(1+\frac{\widetilde{Q^2}}{\widetilde{Q_s^2}}\right)^{n_s}} e^{-i\frac{\pi}{2}\alpha_s(t)} \left(\frac{s}{s_{0s}}\right)^{\alpha_s(t)} e^{2\left(\frac{a_s}{\widetilde{Q^2}}+\frac{b_s}{2m_p^2}\right)t}$$

$$+\frac{\tilde{A}_h\left(\frac{\widetilde{Q^2}}{\widetilde{Q_h^2}}\right)}{\left(1+\frac{\widetilde{Q^2}}{\widetilde{Q_h^2}}\right)^{n_h+1}} e^{-i\frac{\pi}{2}\alpha_h(t)} \left(\frac{s}{s_{0h}}\right)^{\alpha_h(t)} e^{2\left(\frac{a_h}{\widetilde{Q^2}}+\frac{b_h}{2m_p^2}\right)t}$$

Power law vs geometric model at LHC

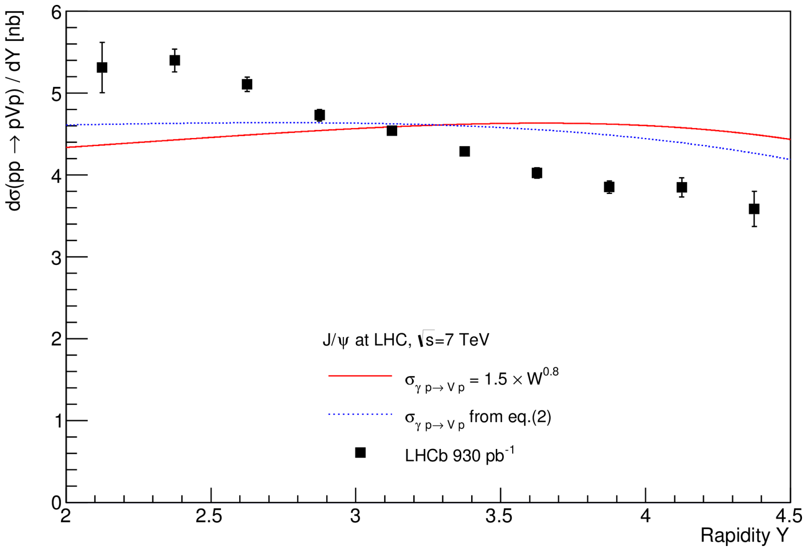


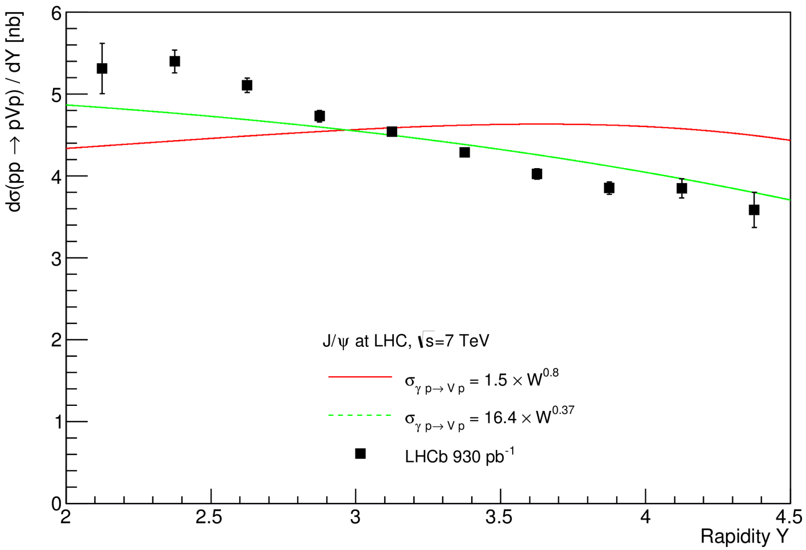


Generally similar behaviour

Power law is somewhat steeper in W → a more distinct bell-like structure in y

Adding LHCb rapidity cross section

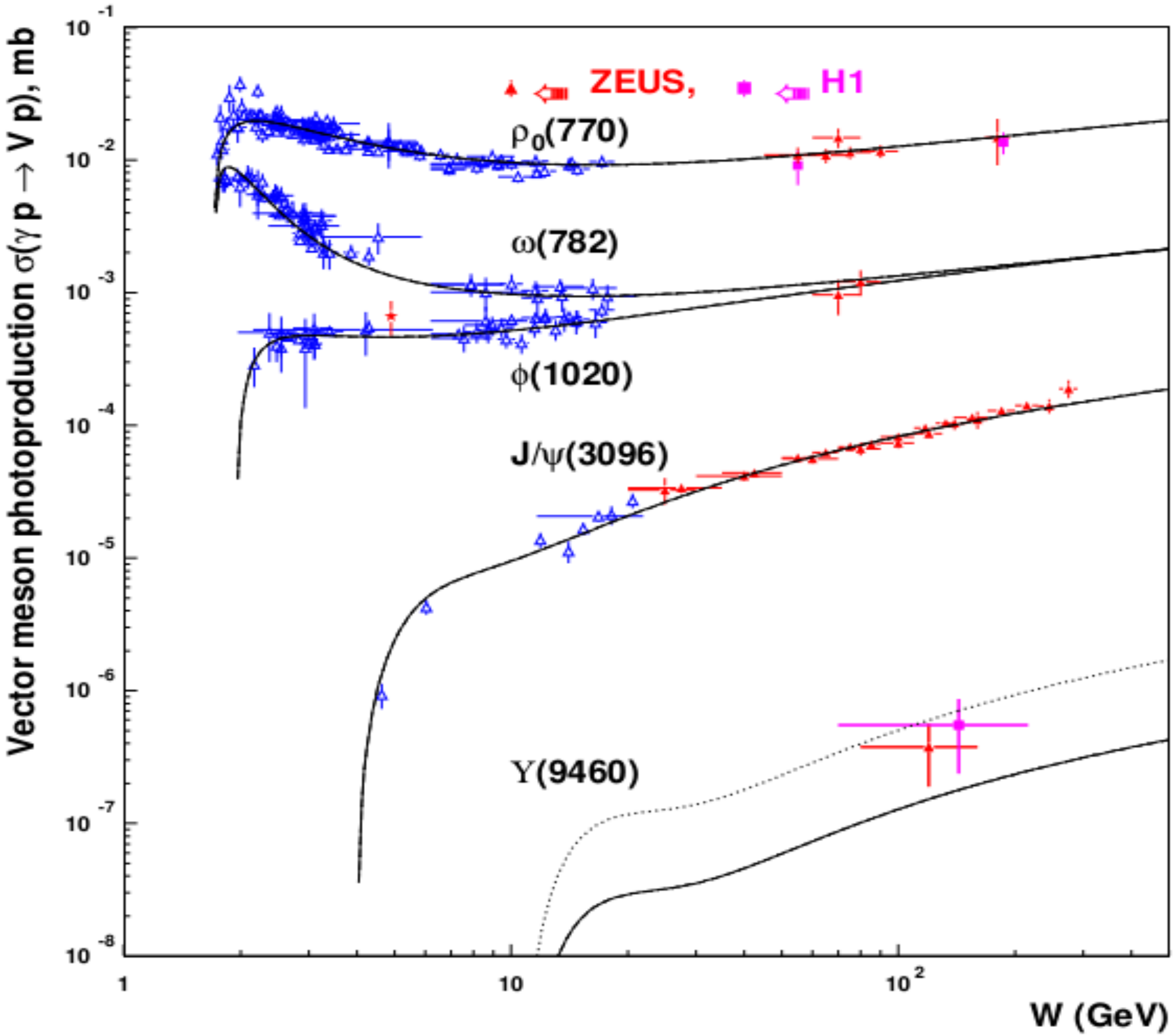


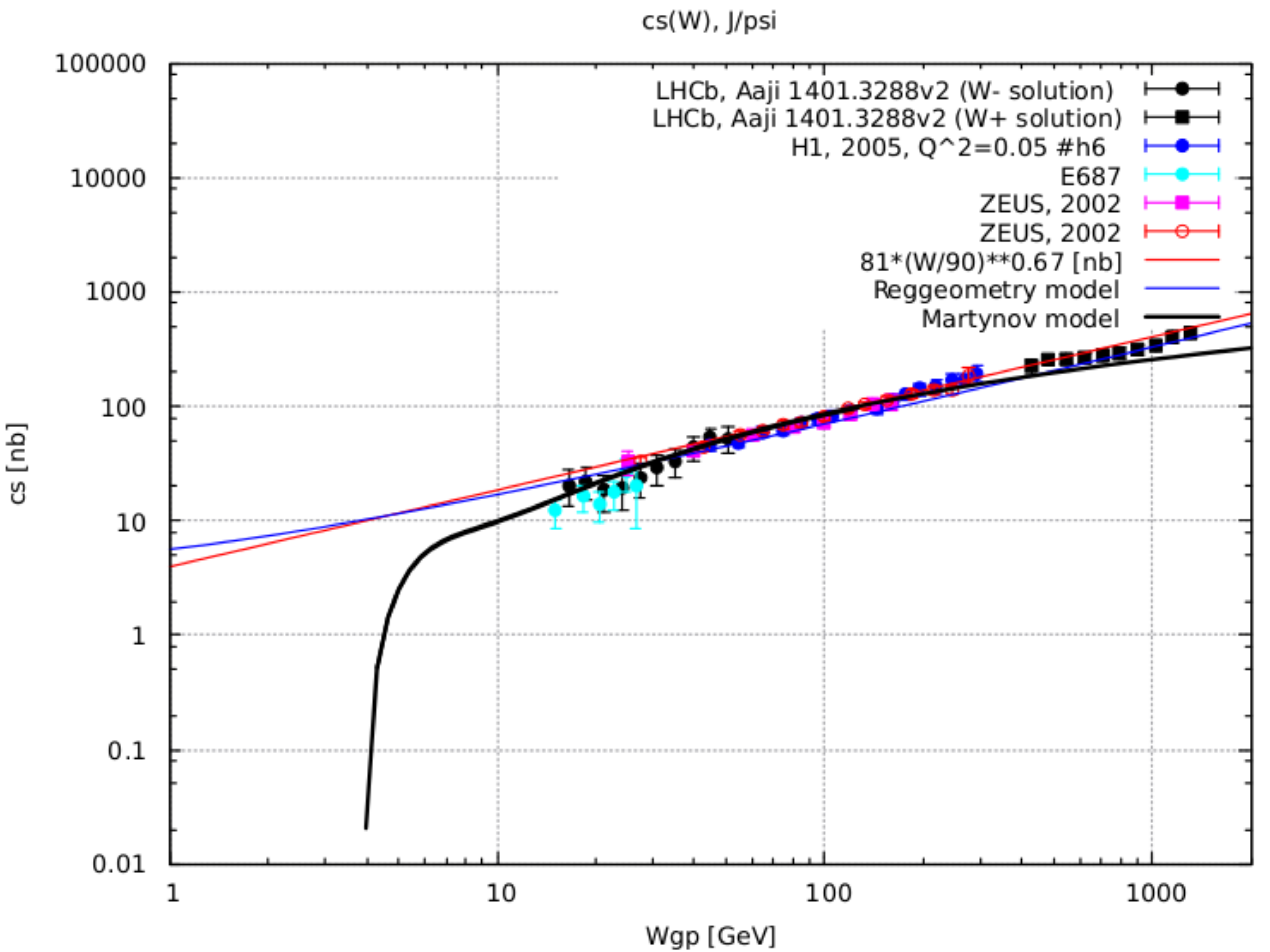


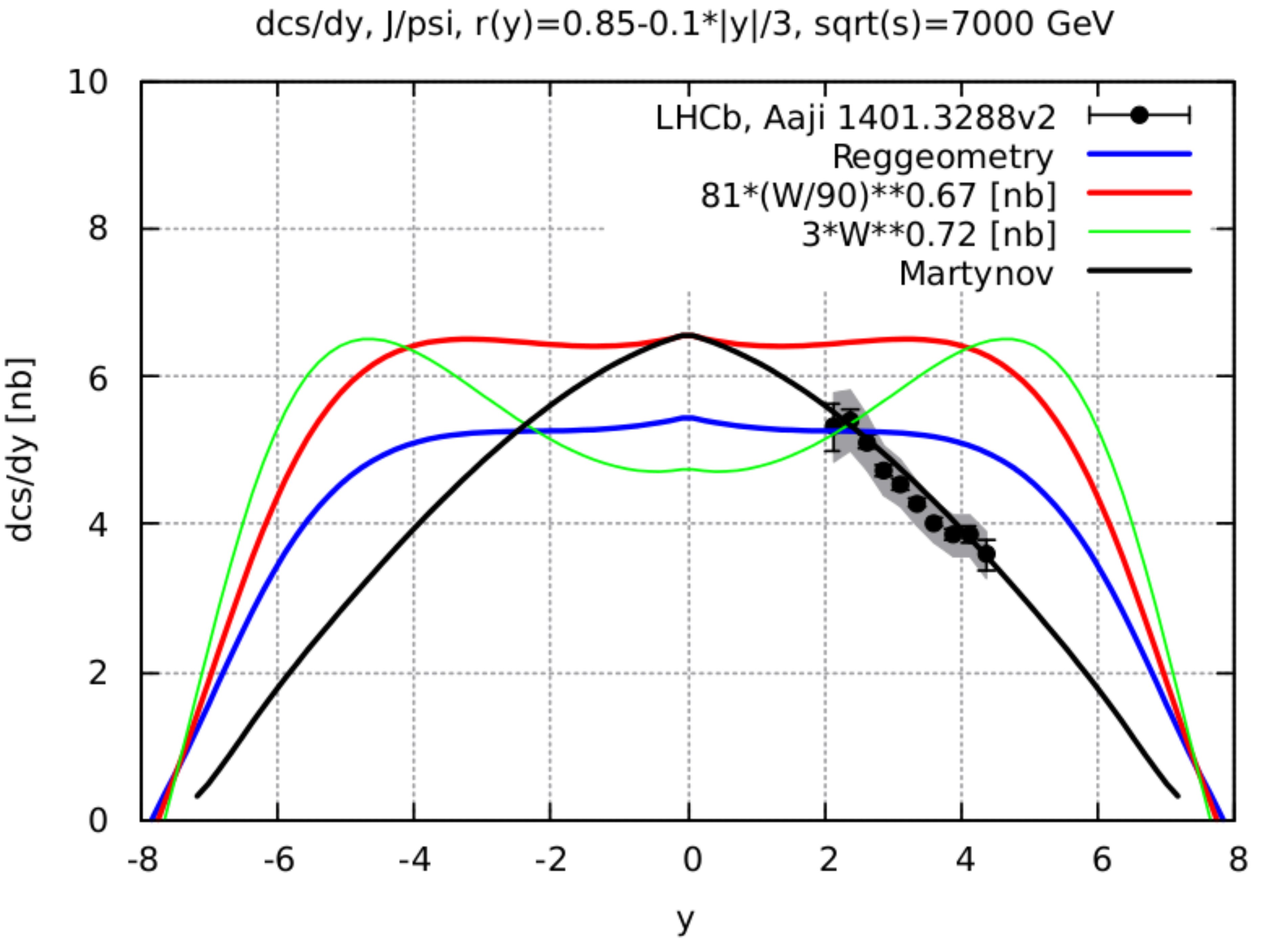
Both power law and geometric model are much flatter than the data

By fitting the power (and normalization) a much better description of data can be obtained (green curve)
However, power tends to be very small (δ=0.37) which contradicts HERA (page 4)

Low-energy extrapolation

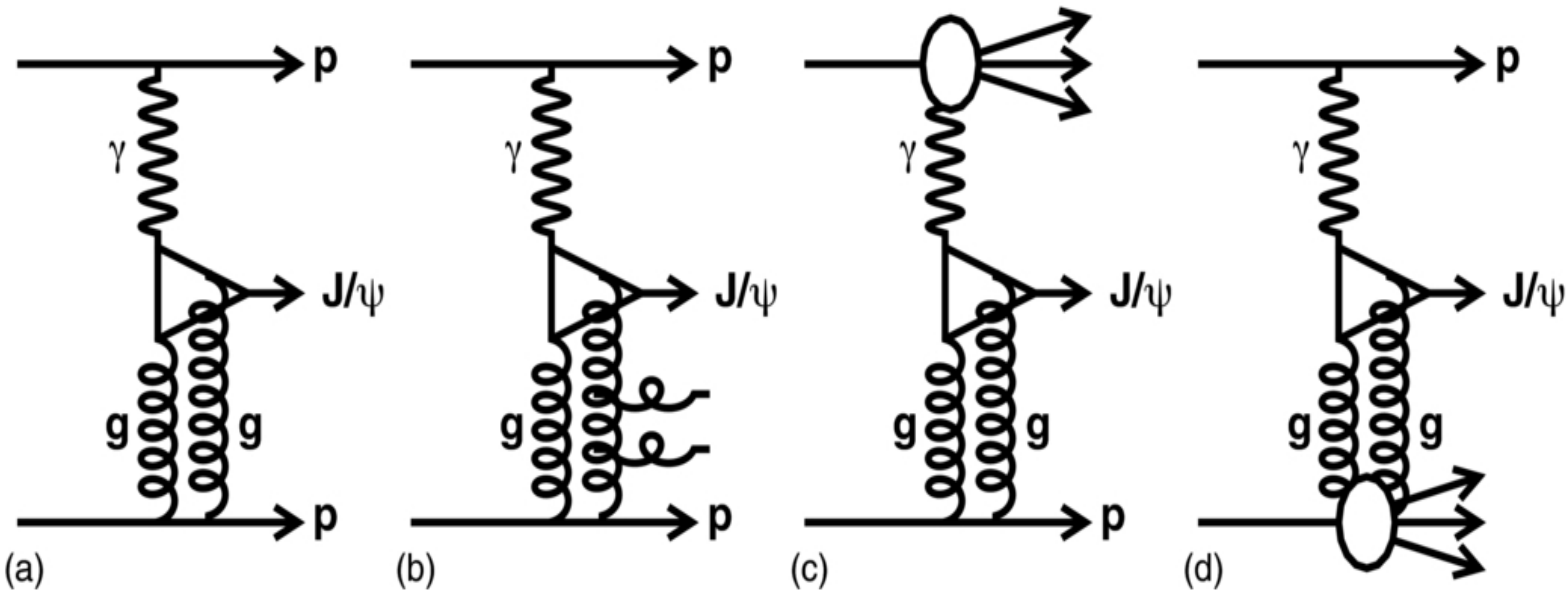



cs(W), J/psi
LHCb, Aaji 1401.3288v2 (W- solution)
LHCb, Aaji 1401.3288v2 (W+ solution)
H1, 2005, Q^2=0.05 #h6
E687
ZEUS, 2002
ZEUS, 2002
81*(W/90)**0.67 [nb]
Reggeometry model
Martynov model
cs [nb]
Wgp [GeV]
100000
10000
1000
100
10
1
0.1
0.01
1
10
100
1000



dcs/dy, J/psi, r(y)=0.85-0.1*|y|/3, sqrt(s)=7000 GeV
LHCb, Aaji 1401.3288v2
Reggeometry
81*(W/90)**0.67 [nb]
3*W**0.72 [nb]
Martynov
dcs/dy [nb]
y
0
2
4
6
8
10
-8
-6
-4
-2
0
2
4
6
8

Prospects:



From nucleons to nuclei

$$\sigma_{hA} = A\sigma_{hN}(1 - A^{1/3}(A-1)/A\sigma_{hN}/(8\pi R^2) + ...) \approx A\sigma_{hN}.$$

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