

PRAHA -2017

EDS-2017

« Elastic and Difractive Scattering »

The structure and analytic properties of the scattering amplitude at LHC energies

O.V. Selyugin

BLTPh, JINR

in collaboration with **J.-R. CUDELL**

FAGO, Univ. Liege

Contents

* Introduction
* Elastic hadron scattering – new data LHC
* Comparing the data with High Energy Generalized structure model (HEGS)
* The structure of the scattering amplitude in t and b - representation
* Simultaneously fit with the simplest phenomenological model
* Results and Summery

Predictions

$$\sqrt{s} = 14 TeV$$

Model	$\sigma_{\tau o \tau}$	$\sigma_{el}/\sigma_{\tau o \tau}$	❒☎t =0)	B ☎t=0)
COMPET	111		0.11	
Marseilles	103	0.28	0.12	19
Dubna	128	0.33	0.19	21.
Pomer.(s+h)	150	0.29	0.24	21.4
Serpukhov	230	0.67		

Total cross sections

TOTEM **ATLAS**

$$\sigma_{tot} = (98.3 \pm 2.8)\, mb;$$
$$(98.6 \pm 2.2)\, mb;$$
$$(99.1 \pm 4.3)\, mb;$$
$$(98.0 \pm 2.5)\, mb;$$

$$\sqrt{s} = 7000\, GeV;$$

$$\sigma_{tot} = (98.5 \pm 2.9)\, mb$$

$$\sigma_{tot} = (95.35 \pm 2.0)\, mb$$

$$\Delta = 3.15\ mb;$$

$$\sqrt{s} = 8000\, GeV;$$

$$\sigma_{tot} = (101.7 \pm 2.9)\, mb$$
$$\sigma_{tot} = (102.0 \pm 2.2)\, mb$$
$$\sigma_{tot} = (102.3 \pm 2.3)\, mb$$

$$\sigma_{tot} = (96.07 \pm 1.34)\, mb$$

$$\Delta = 5.93\ mb;$$

$$F_1^{em}(t) = \alpha f_1^2(t)\frac{s-2m^2}{t}; \quad F_3^{em}(t) = F_1^{em};$$

and for spin-flip amplitudes:

$$F_2^{em}(t) = \alpha \frac{f_2^2(t)}{4m^2} s; \quad F_4^{em}(t) = -F_2^{em}(t),$$

$$F_5^{em}(t) = \alpha \frac{s}{2m\sqrt{|t|}} f_1(t)\ f_2(t),$$

where the form factors are:

$$f_1(t) = \frac{4m_p^2 - (1+k)\ t}{4m_p^2 - \ t}\ G_d(t);$$

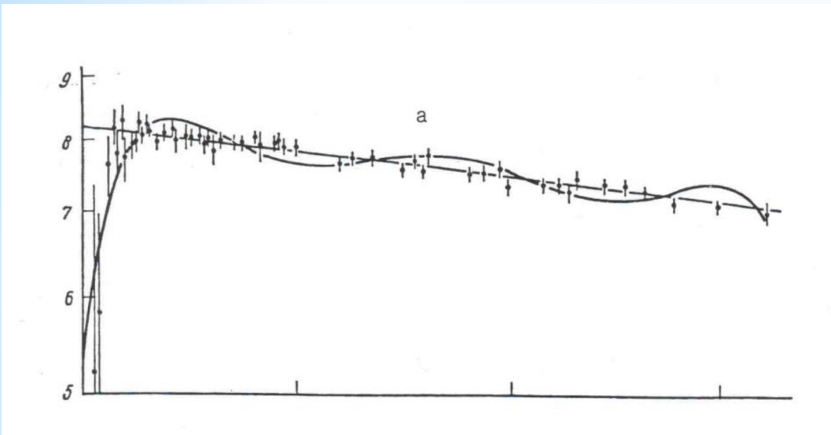
$$f_2(t) = \frac{4m_p^2\ k}{4m_p^2 - \ t}\ G_d(t);$$

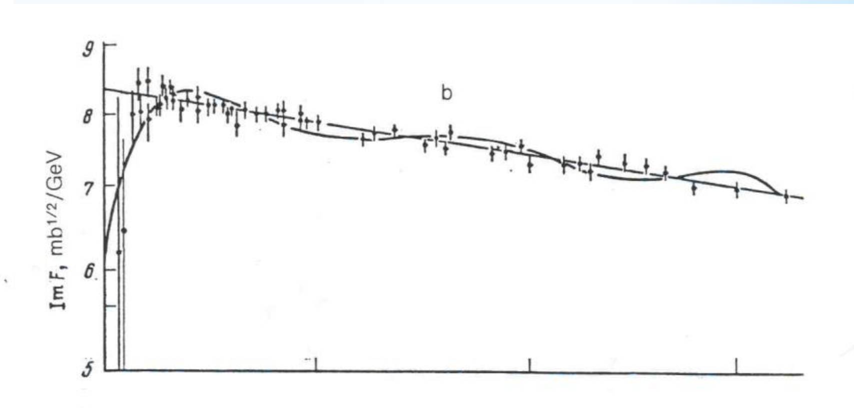
$$\frac{dN}{dt} = \mathcal{L}\left[\frac{4\pi\alpha^2}{|t|^2}G^4(t) - \frac{2\alpha\left(\rho(s,t)+\phi_{CN}(s,t)\right)\sigma_{tot}G^2(t)e^{-\frac{B(s,t)|t|}{2}}}{|t|} + \frac{\sigma_{tot}^2(1+\rho(s,t)^2)e^{-B(s,t)|t|}}{16\pi}\right]$$

Proton-proton $\sqrt{s} = 27.4\,GeV;$

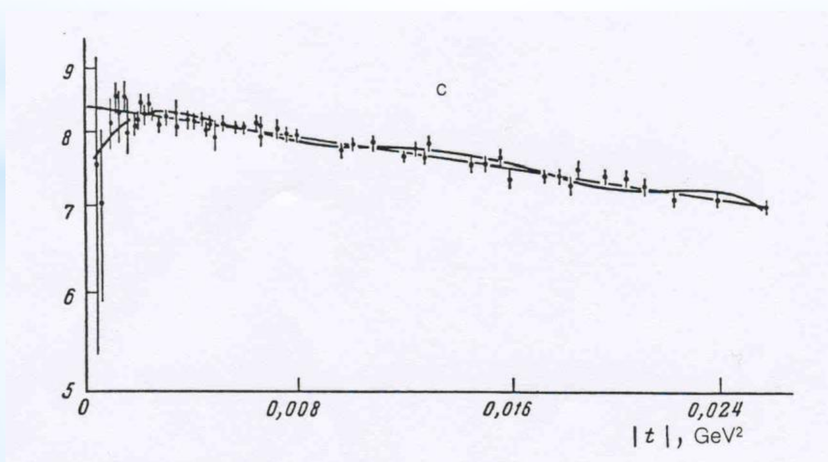
Exp.: $\rho = 0.012,\ B = 11.95\,GeV^{-2},\ \sigma_{tot} = 40.65\,mb;$

fit: $\rho = 0.033,\ B = 14.5\,GeV^{-2},\ \sigma_{tot} = 40.9\,mb;$



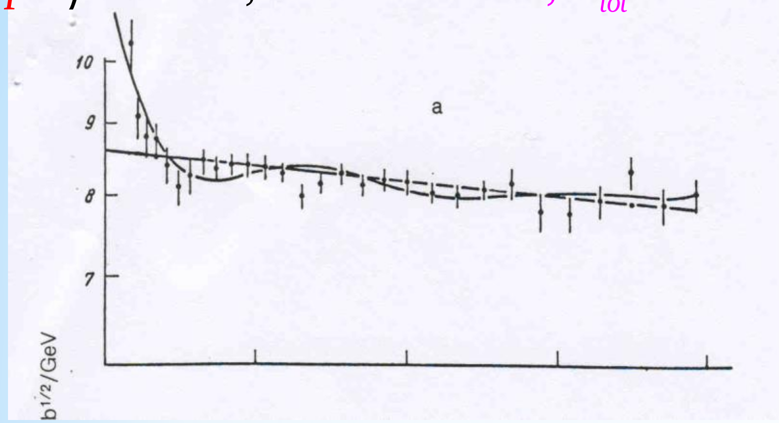


fit: $\rho = 0.02,\ B = 13.8\,GeV^{-2},\ \sigma_{tot} = 41.34\,mb,\ n = 1.02;$

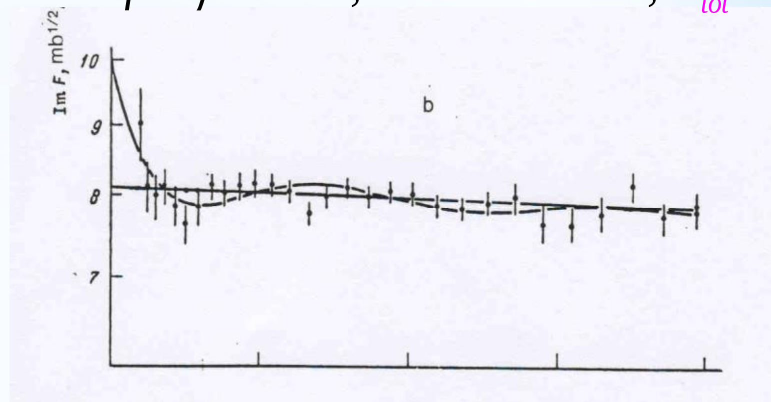


Proton-antiproton $\sqrt{s} = 30.4\,GeV;$

$Exp.: \rho = 0.055,\ B = 12.7\,GeV^{-2},\ \sigma_{tot} = 42.13\,mb;$



$fit: \rho = 0.12,\ B = 14.1\,GeV^{-2},\ \sigma_{tot} = 39.65\,mb;$



$fit: \rho = -0.01,\ B = 11.75\,GeV^{-2},\ \sigma_{tot} = 40.22\,mb,\ n = 0.9;$

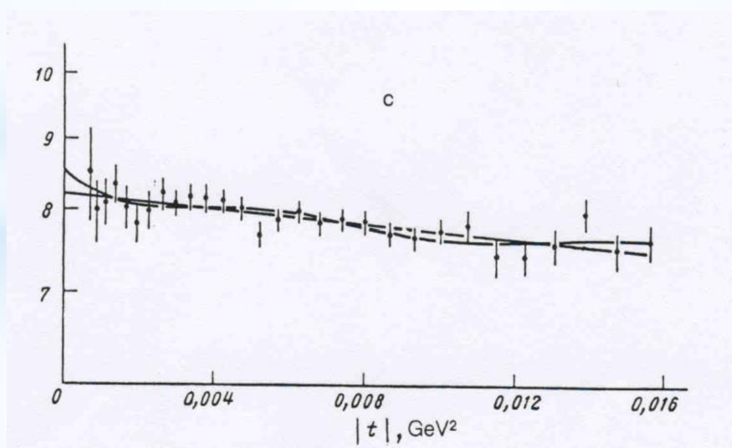


Table 4: Fit results with $N_b = 1$. Each column corresponds to a fit with different interference formula and/or nuclear phase.

	SWY, constant	KL, constant	KL, peripheral
step 1: χ^2/ndf	$48.0/27 = 1.78$	$48.1/27 = 1.78$	$27.7/27 = 1.03$
step 2: χ^2/ndf	$180.8/58 = 3.12$	$181.2/58 = 3.12$	$64.3/58 = 1.11$
a [mb/GeV^2]	533 ± 23	533 ± 23	551 ± 23
b_1 [GeV^{-2}]	19.42 ± 0.05	19.42 ± 0.05	19.74 ± 0.05
ρ	0.05 ± 0.02	0.05 ± 0.02	0.10 ± 0.02
ζ_1			800
κ			2.311
ν [GeV^{-2}]			8.161
σ_{tot} [mb]	102.0 ± 2.2	102.0 ± 2.2	103.4 ± 2.3

In each case, the fit results are used to calculate the total cross-section via the optical theorem:

$$\sigma_{\text{tot}}^2 = \frac{16\pi\,(\hbar c)^2}{1+\rho^2}\,a\,. \tag{27}$$

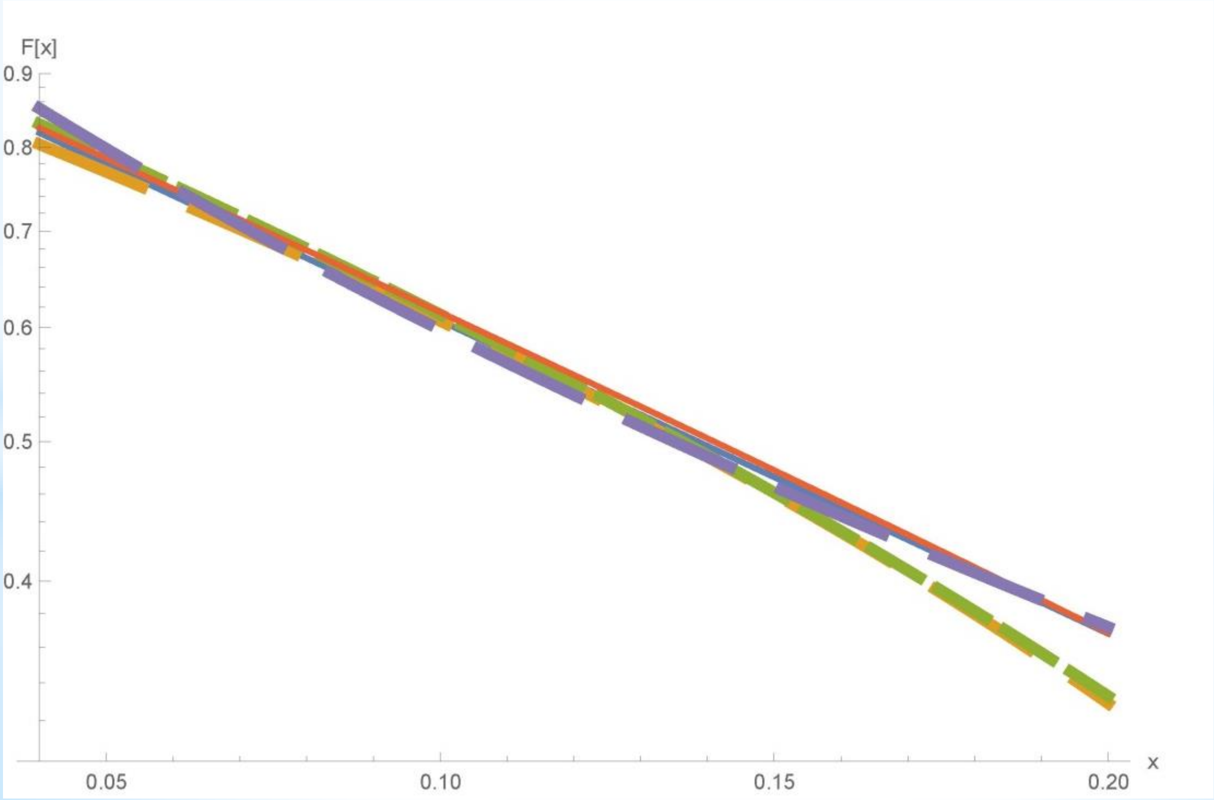
$$\Gamma(b) = e^{-b^2/R^2}; \quad \rightarrow \quad F_1(t) \,\square\, e^{5t};$$

$$\Gamma(b) = \delta(R_0); \quad \rightarrow \quad F_1(t) \,\square\, J_0(R\sqrt{|t|});$$

$$\Gamma(b) = e^{-(b-R_0)\wedge 2/R_0^2}; \rightarrow \quad F_1(t) \,\square\, e^{2.8t} J_0(2.8\sqrt{|t|});$$

$$\Gamma(b) = C(0 - R_0); \quad \rightarrow \quad F_1(t) \,\square\, J_1(R_0\sqrt{|t|}) / R_0\sqrt{|t|};$$

$$\Gamma(b) = e^{-\mu(\sqrt{4R_o^2 - t})}; \quad \rightarrow \quad F_1(t) \,\square\, e^{-5R_0(\sqrt{\mu^2 - t})};$$



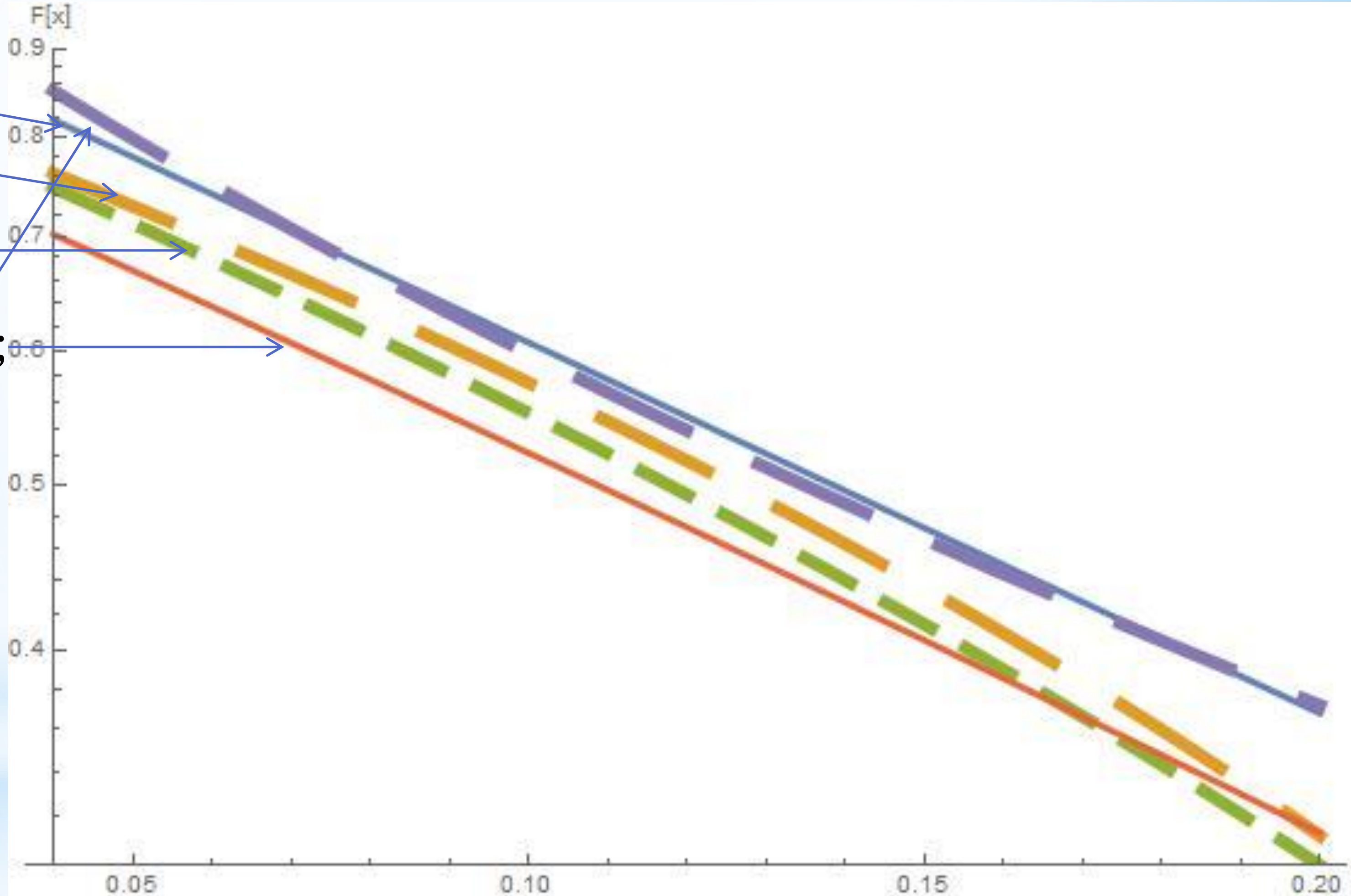
$$e^{5t};$$

$$J_0(4\sqrt{|t|});$$

$$e^{2.8t} J_0(2.8\sqrt{|t|});$$

$$J_1(6\sqrt{|t|}) / 6\sqrt{|t|};$$

$$e^{4.5 R_0(\sqrt{\mu^2 - t})};$$



BSW_1 - C. Bourrely, J. Soffer, T.T. Wu - ( )

BSW_2 - C. Bourrely, J. Soffer, T.T. Wu - ( )

$HEGS_0$ – O.V.S. -

$HEGS_1$ – O.V.S. -

	BSW_1	BSW_2	$HEGS_0$	$HEGS_1$
N_{exp}	369	955	980	3416
N_{par}	7+Regge	11+Regge	3+2	5+4
$\sqrt{s}$, GeV	24 ÷ 630	13.4 ÷ 1800	52 ÷ 1800	9 ÷ 8000
Δt, GeV^2	0.1 ÷ 2.6	0.1 ÷ 5	$8.7\cdot10^{-4}$ ÷ 10	$3.7\cdot10^{-4}$ ÷ 15
$(\Sigma x^2)/N$	4.45	1.95	1.8	1.28

GPDs

$$\lim it \;\; Q_{\gamma}^{2} = 0, \;\; and \;\; \xi = 0$$

X.Ji Sum Rules (1997)

$$\Phi_{\xi=0}(x;t) = \Phi(x;t)$$

$$F_1^{q}(t) = \int_{-1}^{1} dx \;\; H^{q}\left(x, \xi, t\right);$$

$$F_2^{q}(t) = \int_{-1}^{1} dx \;\; E^{q}\left(x, \xi, t\right);$$

$$H^{q}(x;t) = H^{q}(x,0,t) + H^{q}(-x,0,t)$$

$$E^{q}(x;t) = E^{q}(x,0,t) + E^{q}(-x,0,t)$$

$$F_1^{q}(t) = \int_{0}^{1} dx \;\; \square^{q}\left(x, \xi, t\right);$$

$$F_2^{q}(t) = \int_{0}^{1} dx \;\; \boldsymbol{\mathcal{E}}^{q}\left(x, \xi, t\right);$$

$$\int_{-1}^{1} dx \;\; x\left[H^{q}\left(x, \xi, t\right) + E^{q}\left(x, \xi, t\right)\right] = A_q(\Delta^2) + B_q(\Delta^2);$$

High Energy General Structure (HEGS) model O.V.S. - Eur. Phys. J. C (2012) 72:2073

Extending of model (HEGS1) – O.V. S. Phys.Rev. D 91, (2015) 113003

$$\hat{s} = s / s_0 \, e^{-i\pi/2}; \qquad s_0 = 4m_p^2.$$

$$F_1^B(s,t) = h_2 G_{em}(t) \, (\hat{s})^{\Delta_1} e^{\alpha_1 t \ln(\hat{s})}; \; F_3^B(s,t) = h_3 G_A(t)^2 \, (\hat{s})^{\Delta_1} e^{\alpha_1/4 t \ln(\hat{s})};$$

$$^B(\hat{s},t) = F_2^B(\hat{s},t)(1 + R_1 / \sqrt{\hat{s}} \;)] \; + F_3^B(\hat{s},t)(1 + R_2 / \sqrt{\hat{s}} \;)] + F_{odd}^B(s,t);$$

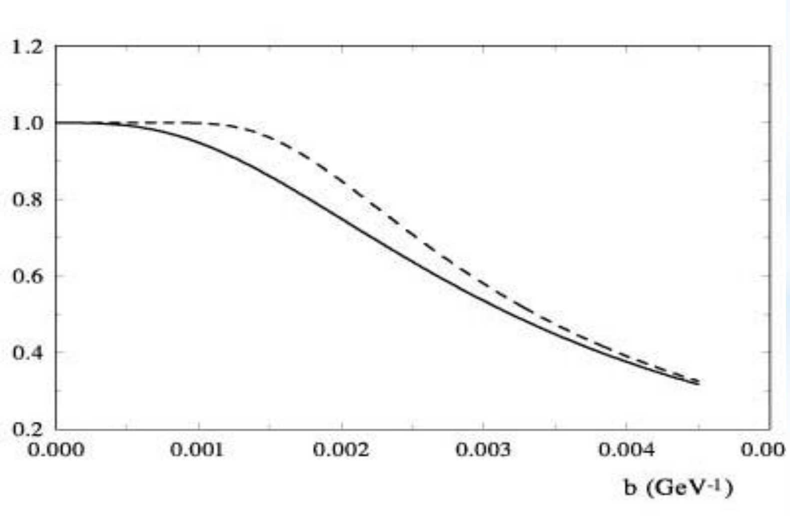
$$F_{Odd}^B(s,t) = h_{Odd} \; G_A(t)^2 \; (\hat{s})^{\Delta_1} \; \frac{t}{1 - r_o^2 t} e^{\alpha_1/4 t \ln(\hat{s})};$$

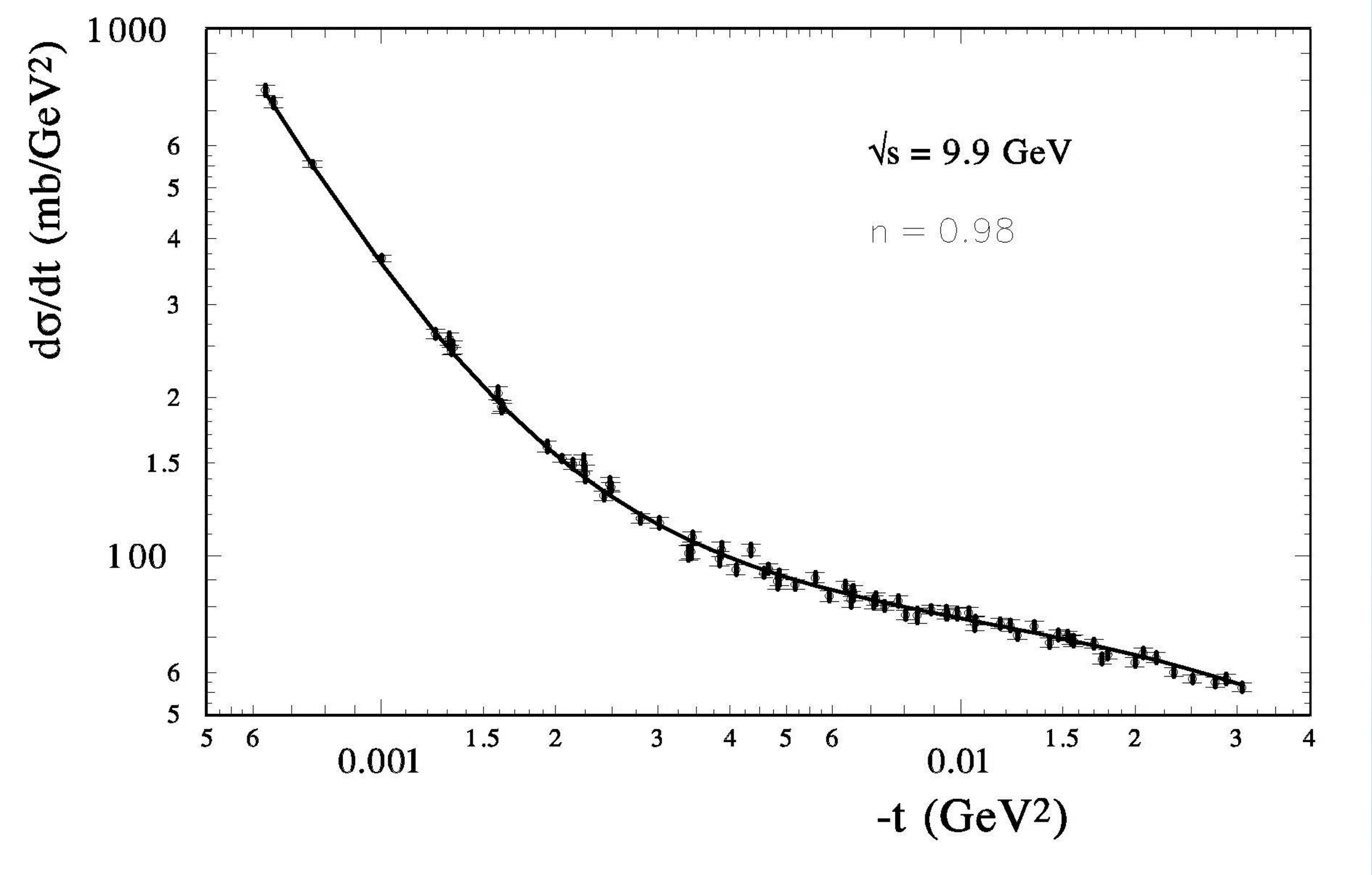
UNITARIZATION → eikonal representation

$$\chi(s,b) = 2\pi \int_0^\infty q\ J_0(bq)\ F_B^h(s,q)\, dq$$

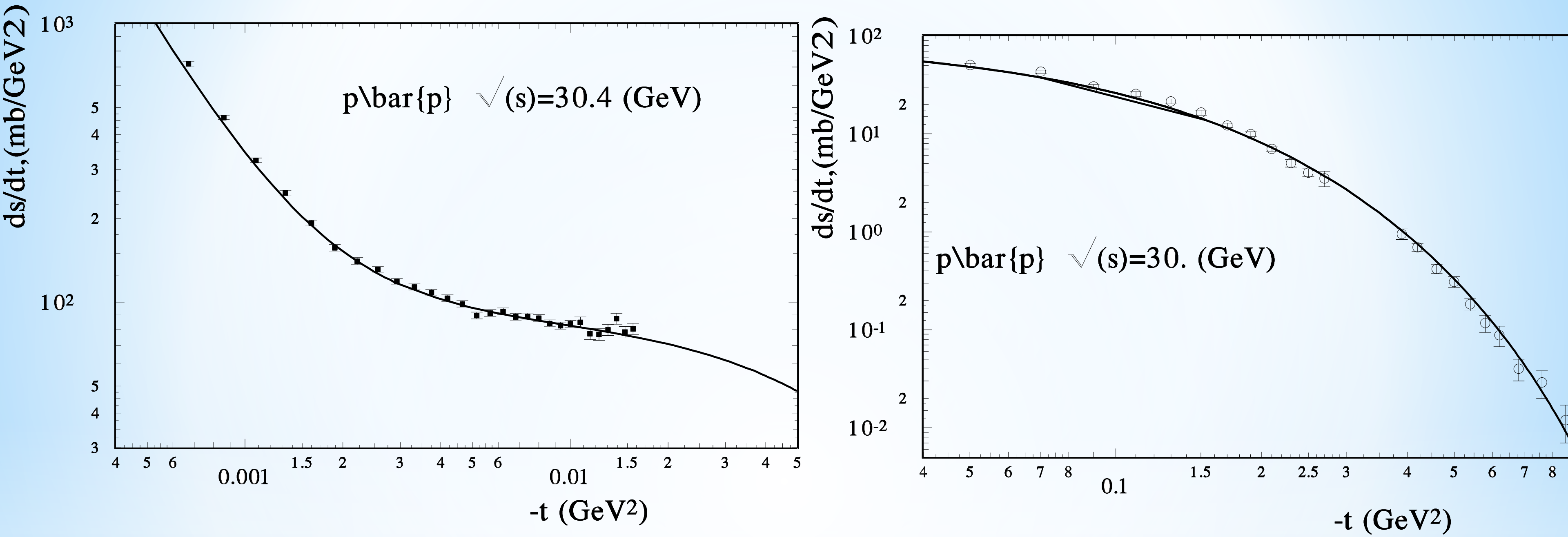
$$\chi(s,b) = -\frac{1}{2k} \int_{-\infty}^{\infty} dz V[\sqrt{z^2 + b^2}]$$

$$F^h(s,t) = \frac{1}{2\pi} \int_0^\infty b\ J_0(bq)\ [1 - e^{-\chi(s,b)}]\, db$$

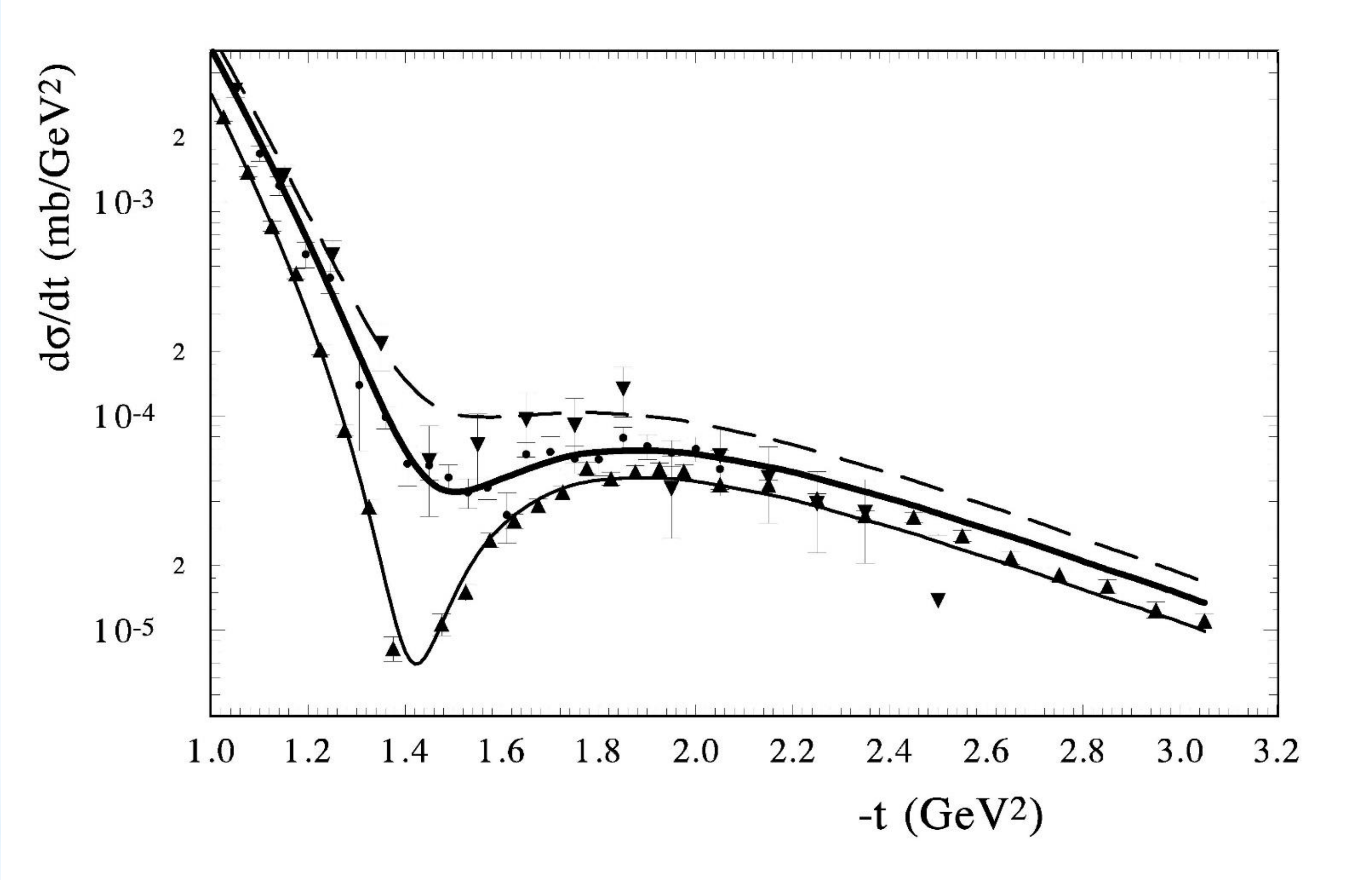




1000
6
5
4
3
2
1.5
100
6
5
dσ/dt (mb/GeV2)
√s = 9.9 GeV
n = 0.98
5
6
0.001
1.5
2
3
4
5
6
0.01
1.5
2
3
4
-t (GeV2)



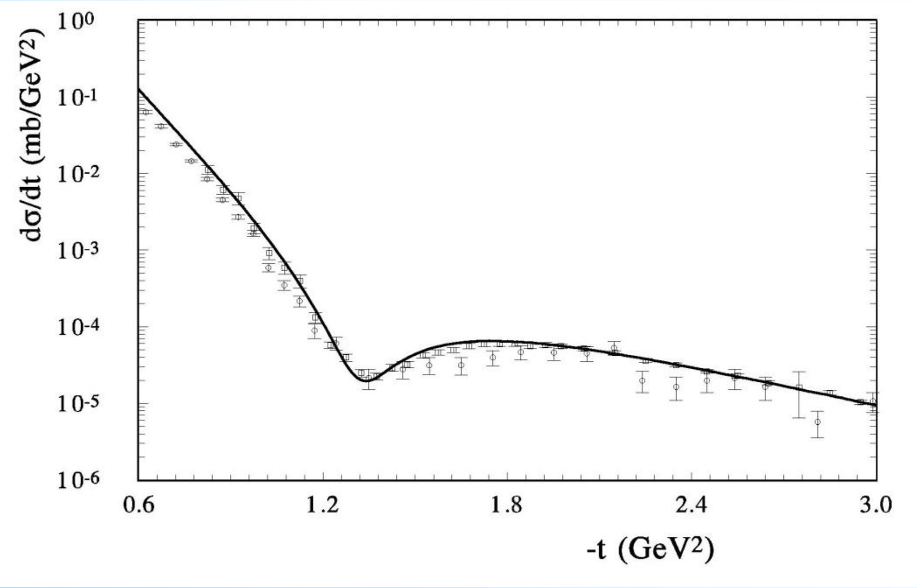
ds/dt,(mb/GeV2)
p\bar{p} √(s)=30.4 (GeV)
-t (GeV2)
0.001
0.01
ds/dt,(mb/GeV2)
p\bar{p} √(s)=30. (GeV)
-t (GeV2)
0.1



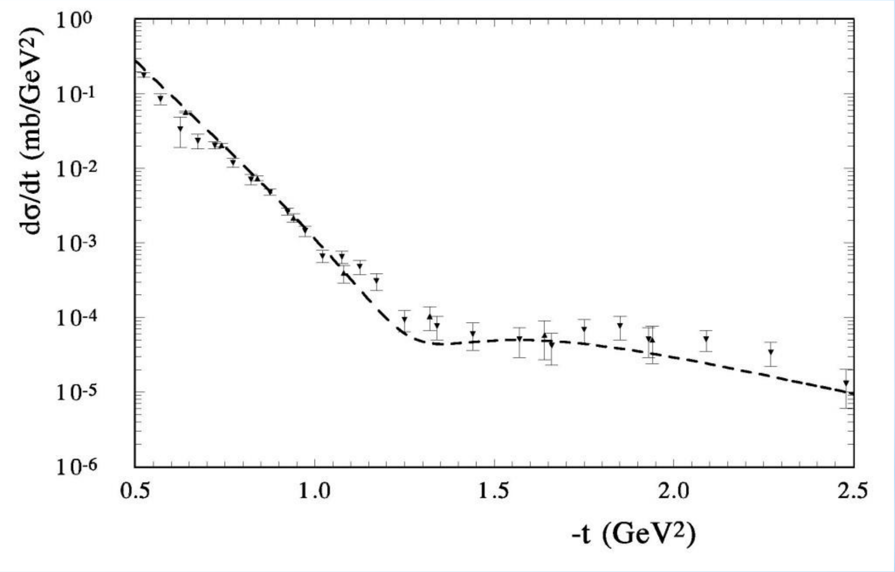
dσ/dt (mb/GeV2)
2
10-3
2
10-4
2
10-5
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
-t (GeV2)

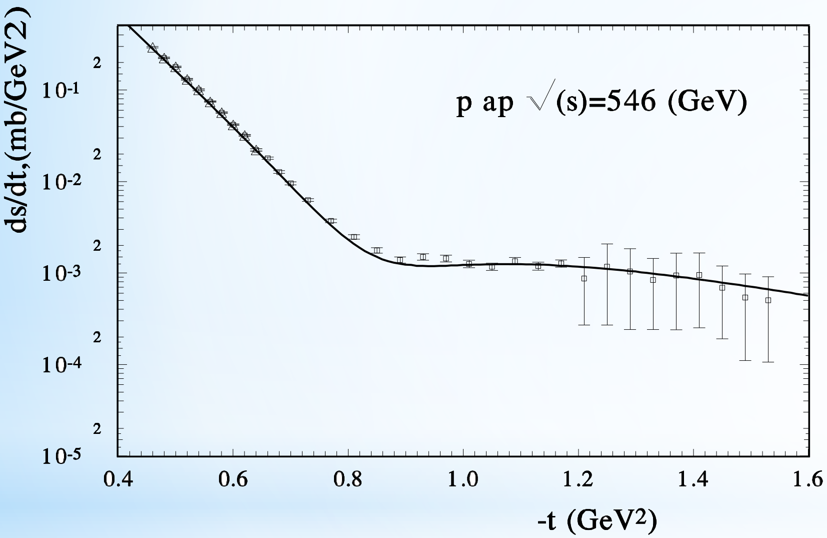
$$\sqrt{s} = 52.8 \ GeV$$

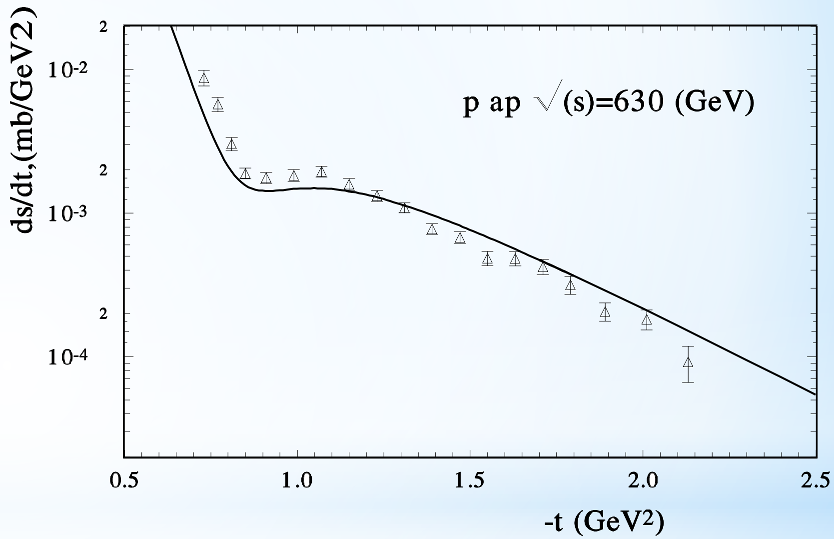
$pp \rightarrow pp$



$p\bar{p} \rightarrow p\bar{p}$



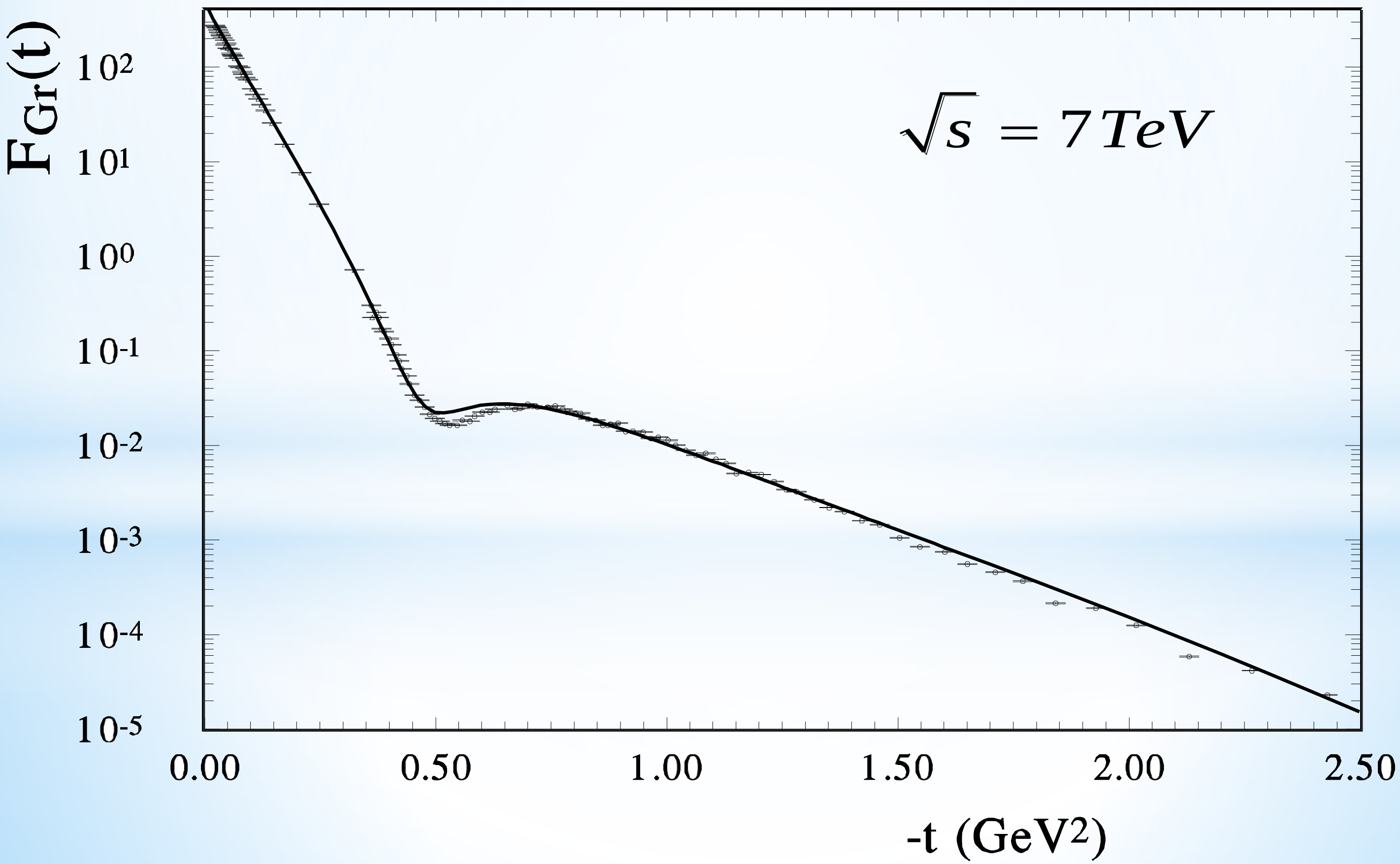

ds/dt,(mb/GeV2)
p ap √(s)=546 (GeV)
10-1
10-2
10-3
10-4
10-5
0.4
0.6
0.8
1.0
1.2
1.4
1.6
-t (GeV2)


ds/dt,(mb/GeV2)
p ap √(s)=630 (GeV)
10-2
10-3
10-4
0.5
1.0
1.5
2.0
2.5
-t (GeV2)

$$52.8\,GeV <= \sqrt{s} <= 1.8\,TeV$$

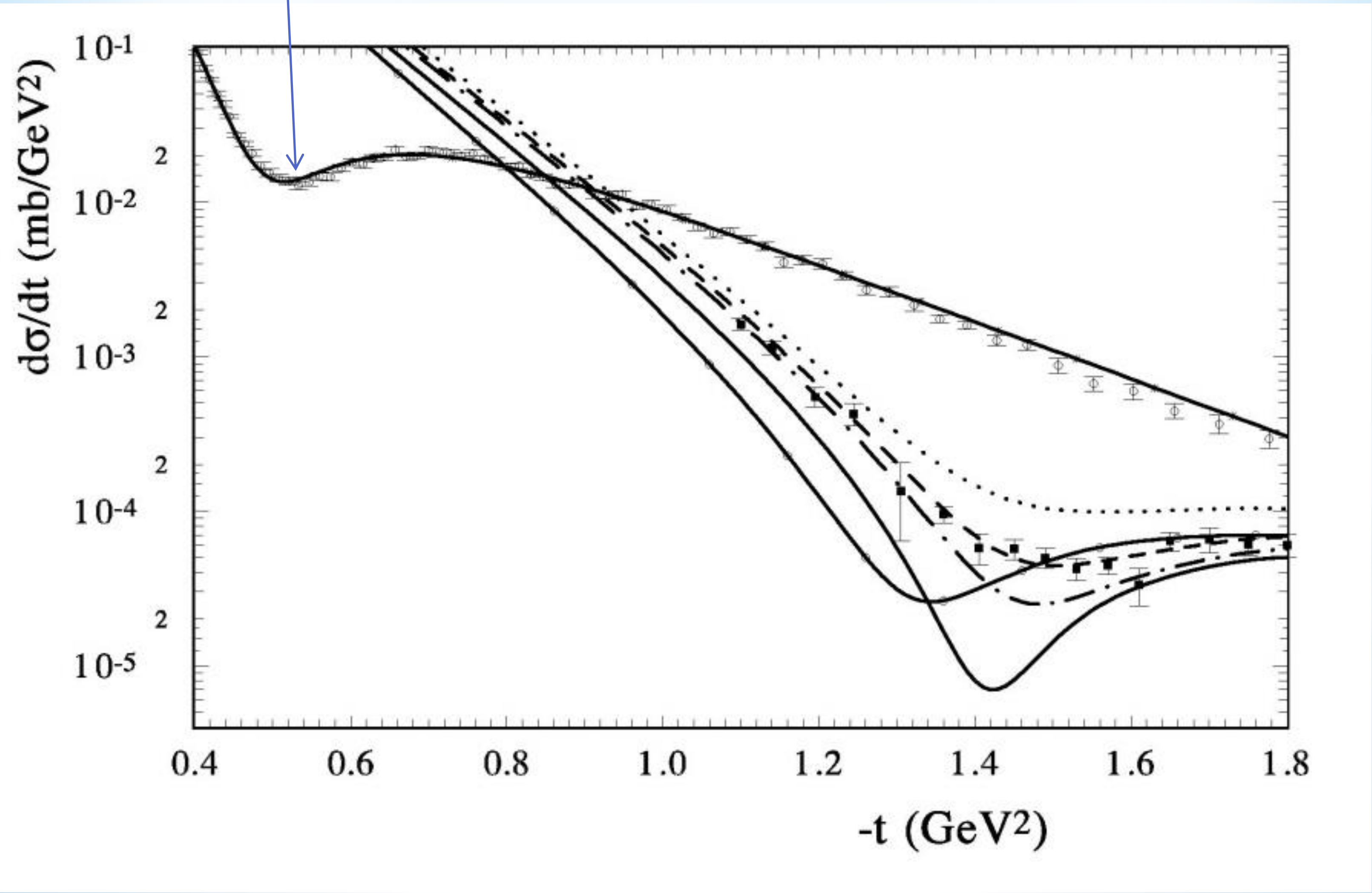
O.V.S. Eur. Phys. J. C (2012) 72:2073(2012);

predictions



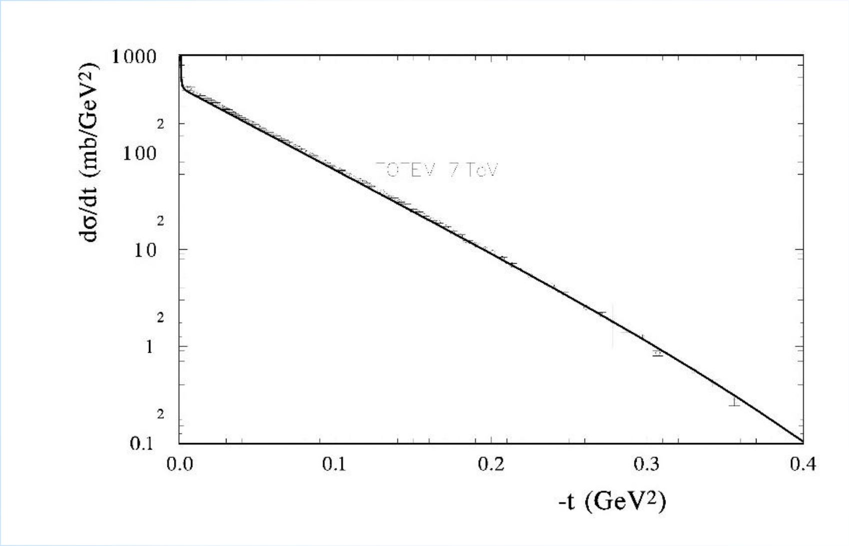
O.V. S. Phys.Rev. D 91, (2015) 113003

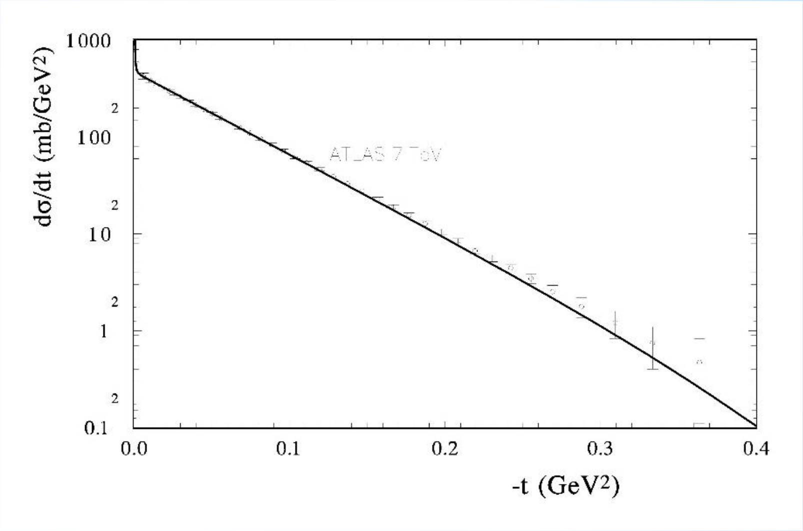
TOTEM data – 7 TeV



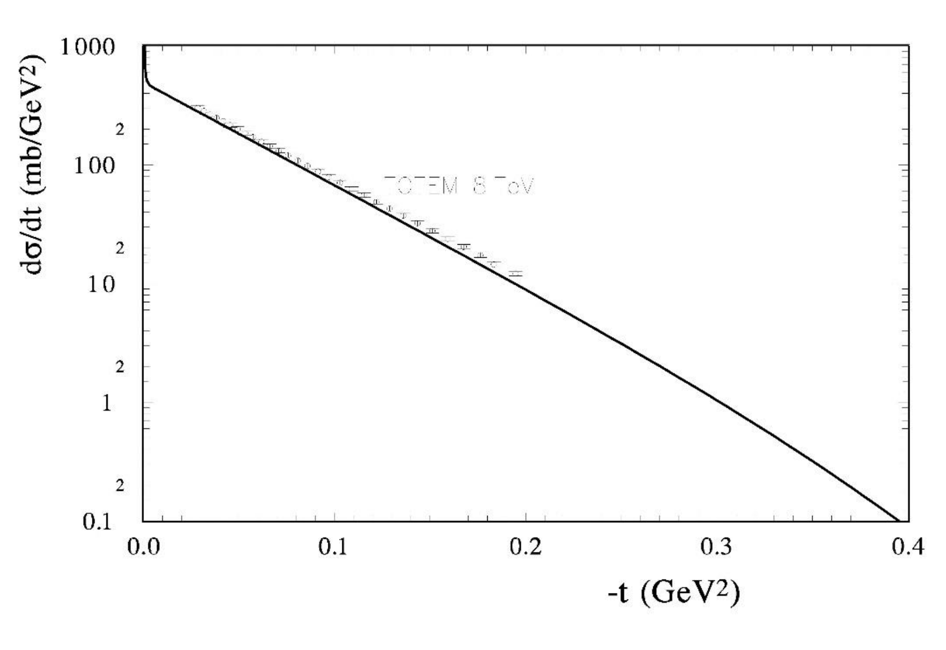
7 TeV (TOTEM) - t [0.00515 – 0.371]
n = 0.94

7 TeV (ATLAS) - t [0.0062 – 0.3636]
n=1.0

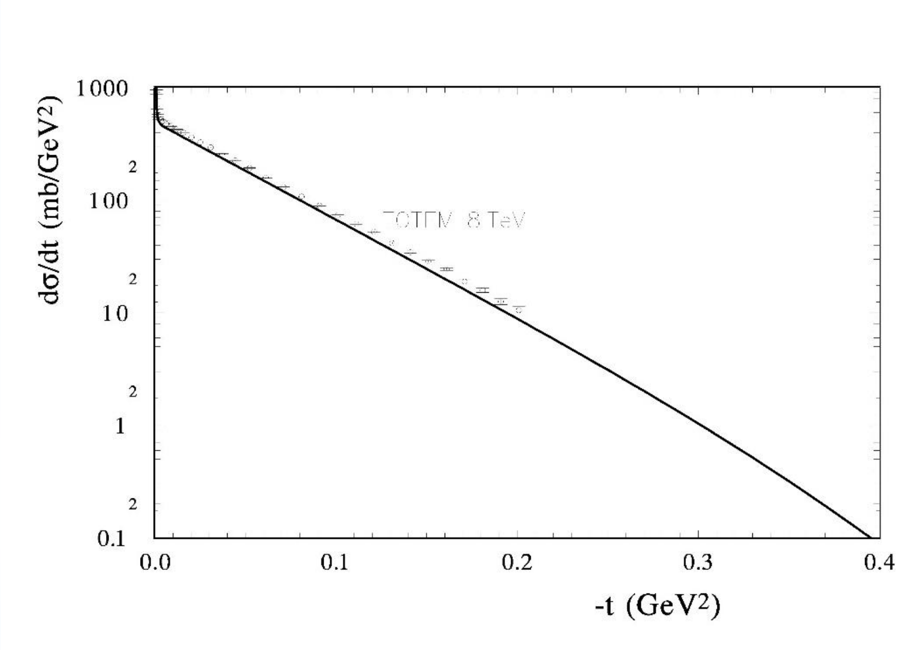




8 TeV (TOTEM) - t [0.0285 – 0.1947]
n=0.9

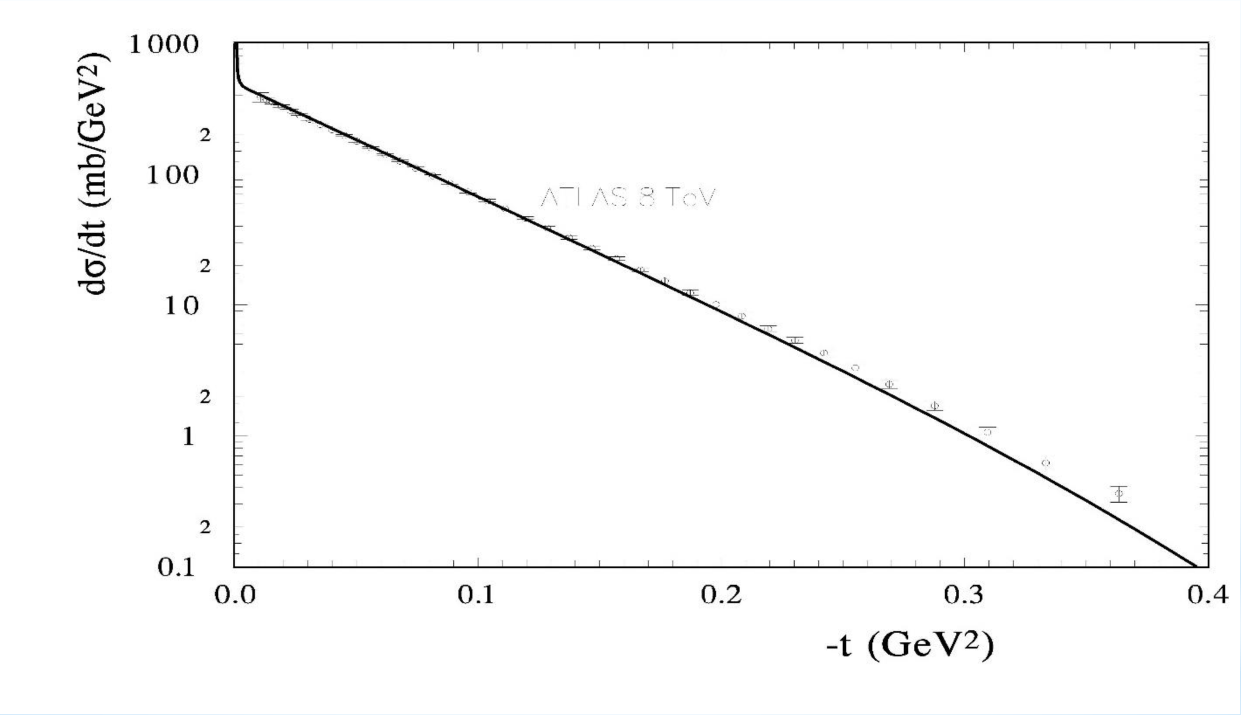


8 TeV (TOTEM) - t [0.000741 – 0.201]
n=0.9

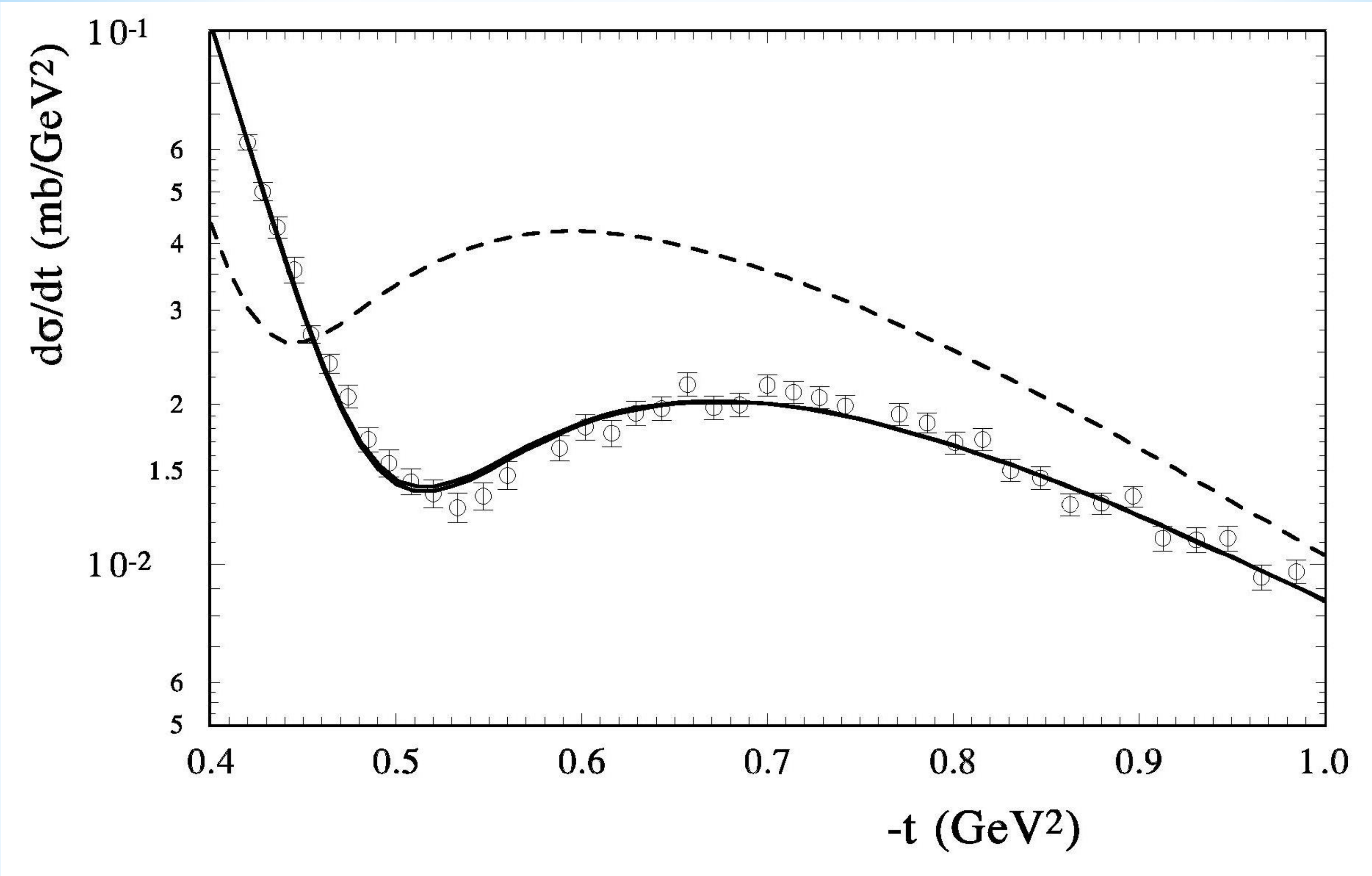


8 TeV (ATLAS) - t [0.01050 – 0.3635]

n=1.0

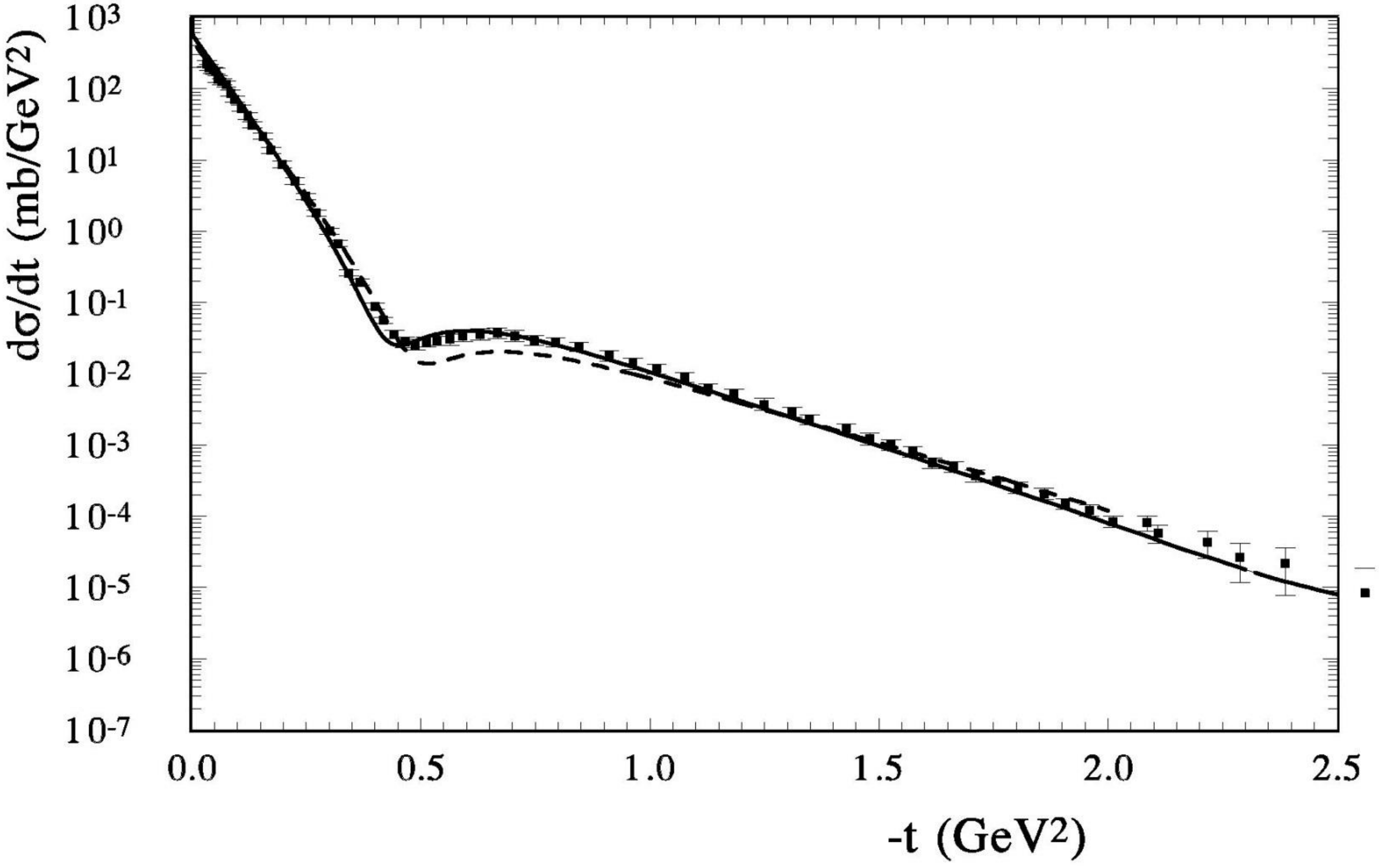


$$\sqrt{s} = 7\ \ TeV; \quad 14\ TeV.$$



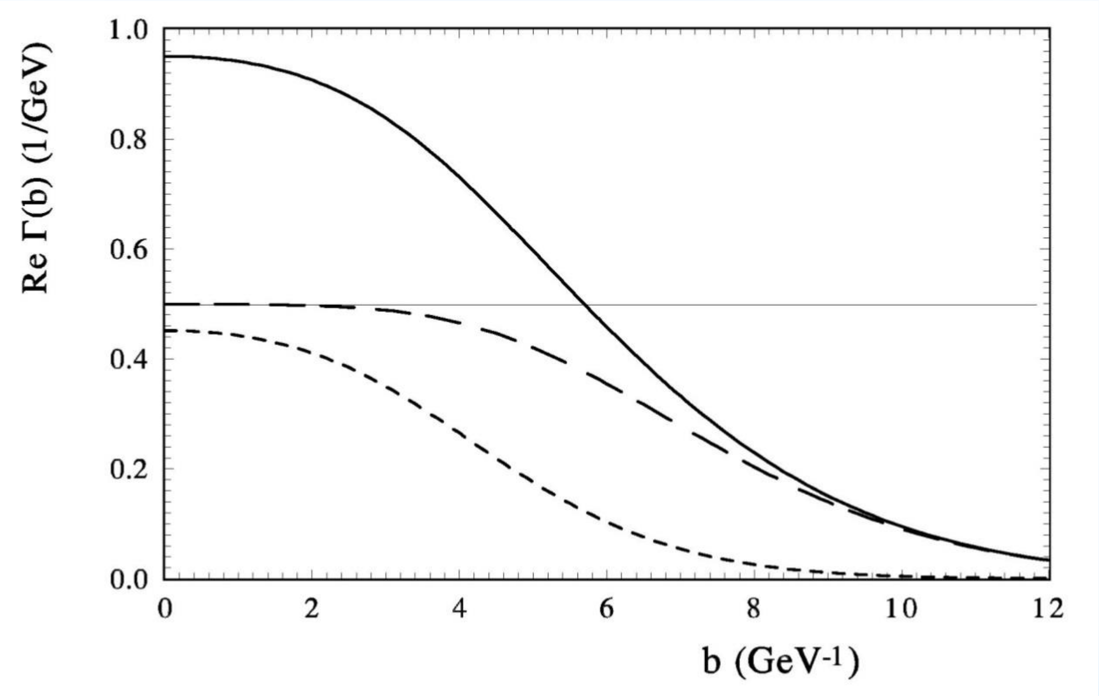
O.V. S. Nucl.Phys. A,959 (2017); arxiv: 1609.08847

13 TeV (line and points) and 7 TeV – dashed line



(The normalization of the 13 TeV data on the model calculations)

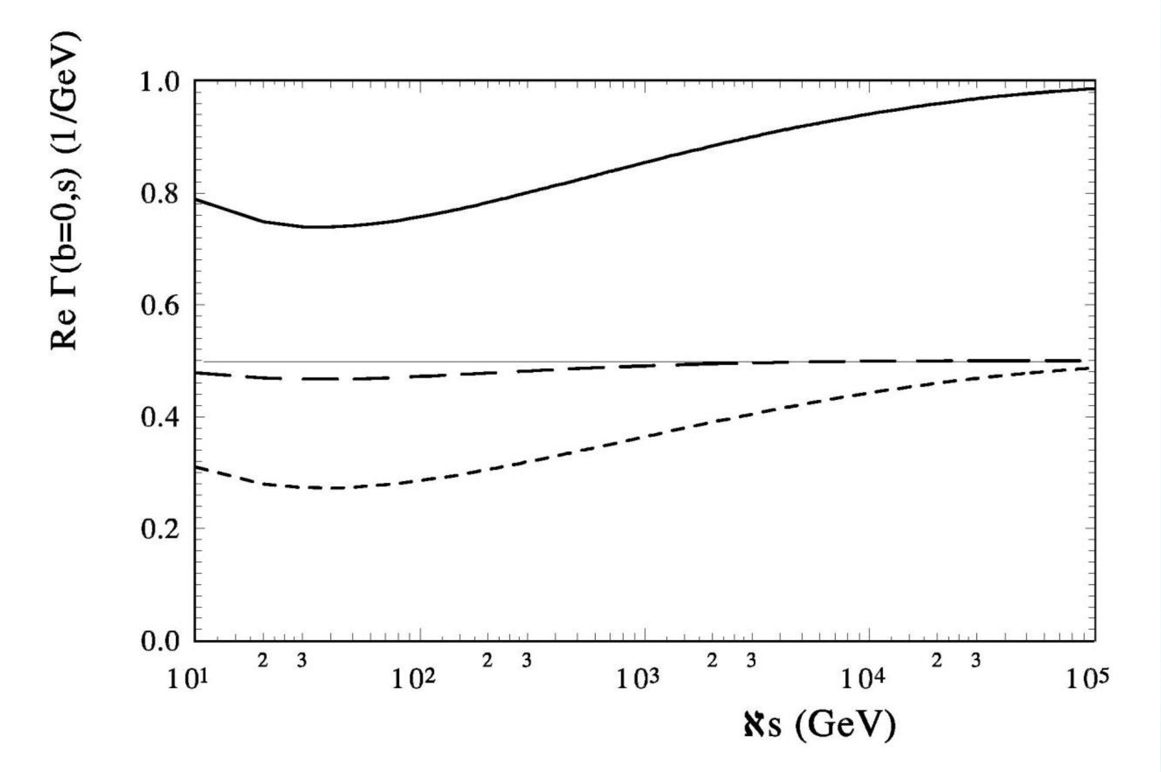
$$\sqrt{s} = 14 TeV$$



$\Gamma(s,b)_{tot}$ (hard line)

$\Gamma(s,b)_{elast.}$ (dashed line); $\Gamma(s,b)_{inel.}$ (long dashed line)

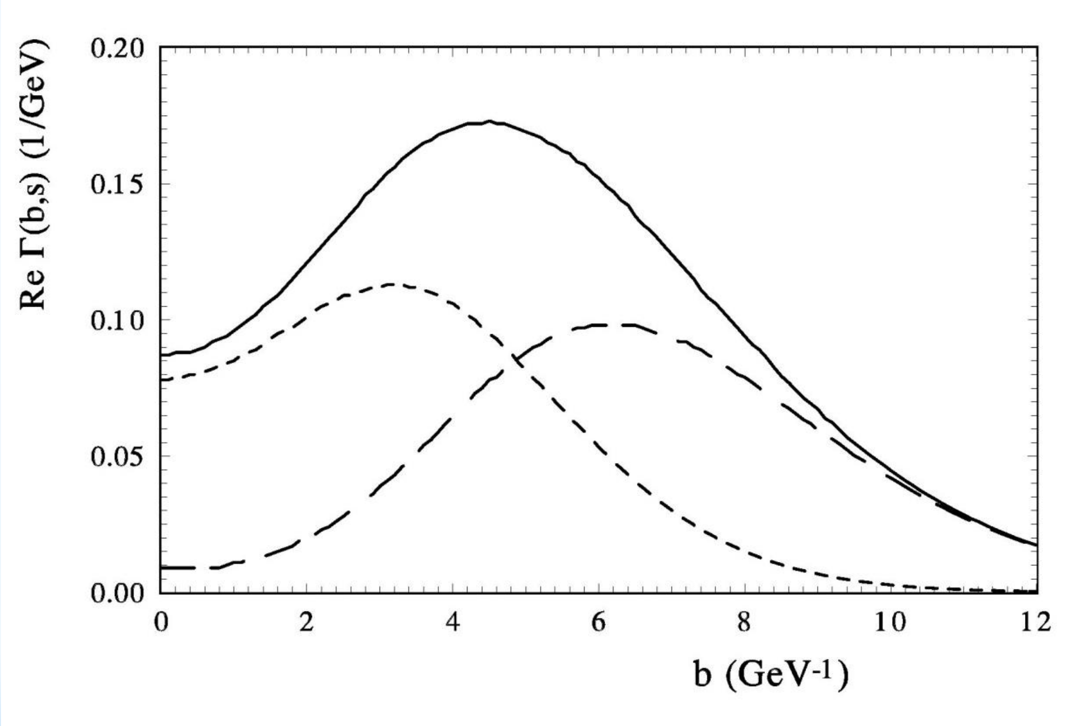
The energy dependence of



$\Gamma(s,b=0)_{tot}$ (hard line)

$\Gamma(s,b=0)_{elast.}$ (dashed line); $\Gamma(s,b=0)_{inel.}$ (long dashed line)

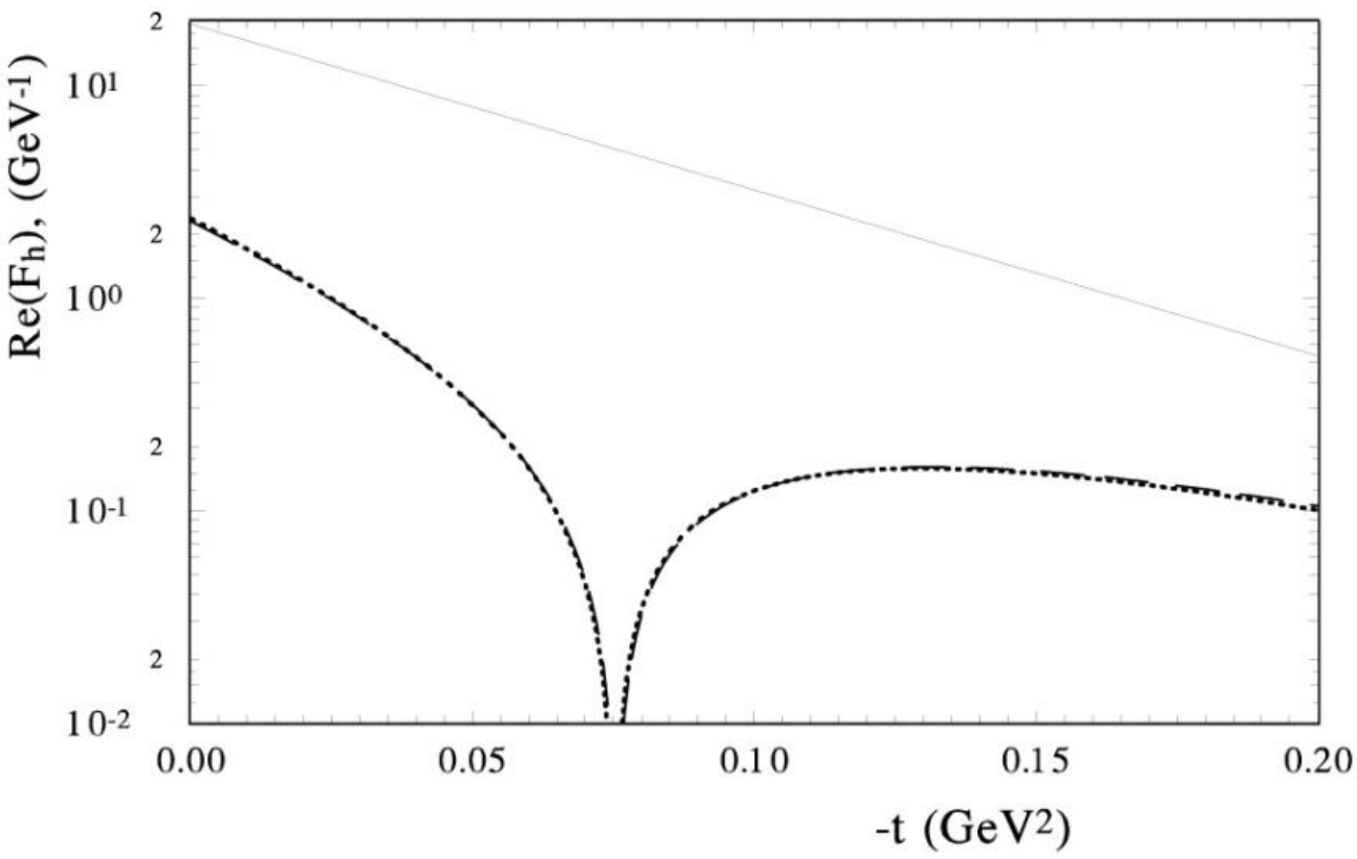
The difference between $\sqrt{s} = 14 TeV$ and $\sqrt{s} = 7 TeV$



$\Gamma(s,b)_{tot}$ (hard line)

$\Gamma(s,b)_{elast.}$(dashed line); $\Gamma(s,b)_{inel.}$ (long dashed line)

$$\operatorname{Im} F(s,t) = (C + a\ln(s)^2)\, e^{-Bt\ln(s)};$$



The description of the differential cross sections at LHC energies

$$F_h(s,t) = ihln(s)^2(1. - i\rho)e^{B_1/2t + B_2/2t^2}G^2(t);$$

with the form factor

$$G(t) = \frac{4m_p^2 - \mu t}{4m_p^2 - t}\frac{\Lambda^2}{(\Lambda - t)^2}.$$

with m_p being the proton mass, $\Lambda = 0.71$ GeV^2 and $\mu = 2.79$.

The description of the differential cross sections at LHC energies

$\sum_N \chi^2$; (err.)	h	B_1	B_2	ρ	σ_{tot} 7TeV/8TeV	n_i T;A;—T;T;A
48337 ($\sigma^2_{st.}$)	0.30	0.55	-0.39	$0._b$	95.3/98.2	1.; 1.; |1.; 1.; 1.
421 ($\sigma^2_{st.+syst.}$)	0.30	0.55	-0.45	$0._b$	95.1/98.0	1.; 1.; |1.; 1.; 1.
1812 (7 TeV) ($\sigma^2_{st.}$) (8TeV)	0.31	0.58	-0.26	$0._b$	96.7 99.7	1.03; 0.98.; | 1.06; 1.06; 0.94

LHC

* The new data bounded essentially the limits of the models.

The elastic scattering reflects the generalized structure of the hadron

and the scattering amplitude is satisfied the basic analytic properties.

GPDs open the new way to connections of the elastic and inelastic interactions

The standard eikonal approximation works perfectly from Sqrt(s}=9 GeV up to 8 TeV.

But: where is the hard Pomeron?; t and s dependence of the Odderon? Unitarization – eikonal?

* The problems of the determination of $\rho(s,t)$ and $\sigma_{tot}(s)$

- The thin structure of the slope - B(s,t),
- (non-exponential, oscillations)

Asymptotic of the scattering amplitude - wide region

Wait the high precision of the new data at small t and 13 TeV

TOTEM; ATLAS

THANKS

FOR YOUR ATTENTION

END