XXXIII International Conference

Protvino 08-12 November 2021

"…although asymptopia may be very far away indeed, the path to it is not through a desert but through a flourishing region of exciting Physics…"

-Elliot Leader in CERN Courier

Hadron potential at large distances and Fine structure of the diffraction peak at 13 TeV

09.11 2021

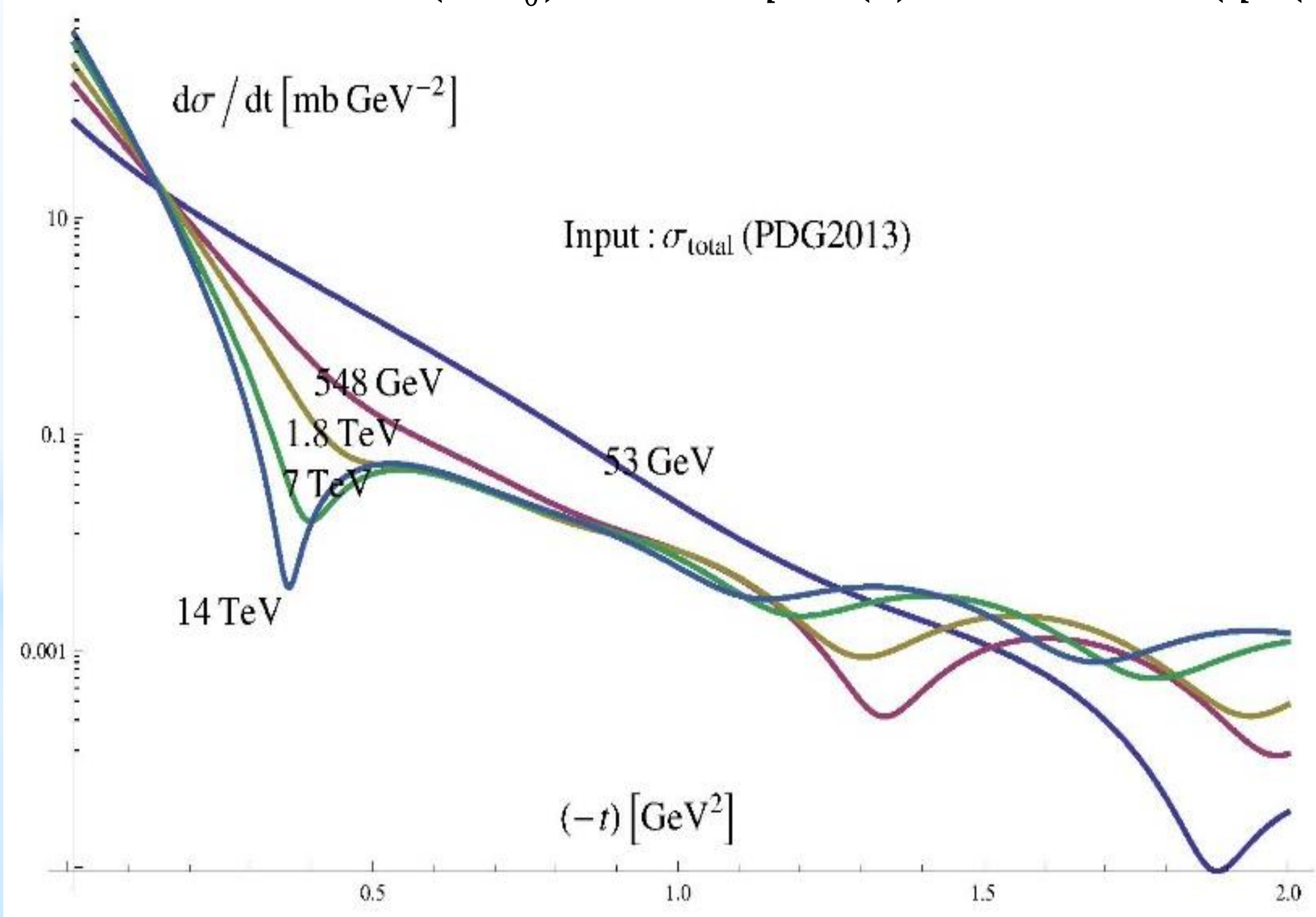
O.V. Selyugin

(JINR Dubna)

S.M. Roy
arXiv:1602.03627

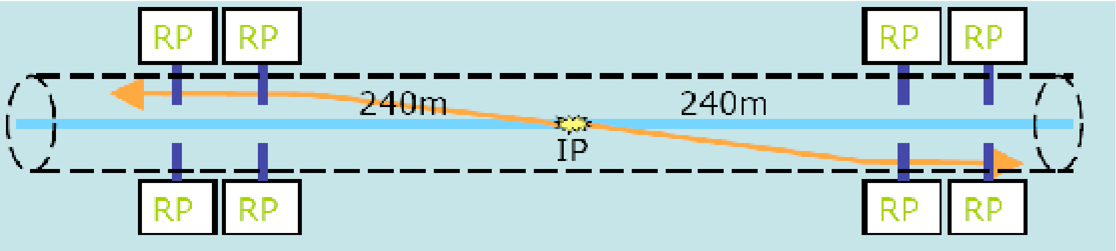
$$F_{(1)}(s,t)=\frac{k\sqrt{s}}{16\pi}\sigma_{tot1}(s)\exp[tb_P+t\alpha^{'}\ln(s)](i+t\pi\alpha^{'}/2)$$

$$F_{(2)}(s,t)=\frac{k\sqrt{s}}{16\pi}\sigma_{tot2}(s)[\frac{\pi}{\ln(s/s_0)}\frac{8J_2(qR(s)-16J_4(qR(s))}{q^2R^2(s)}+i\frac{48J_3(qR(s))}{(qR(s))^3}]$$

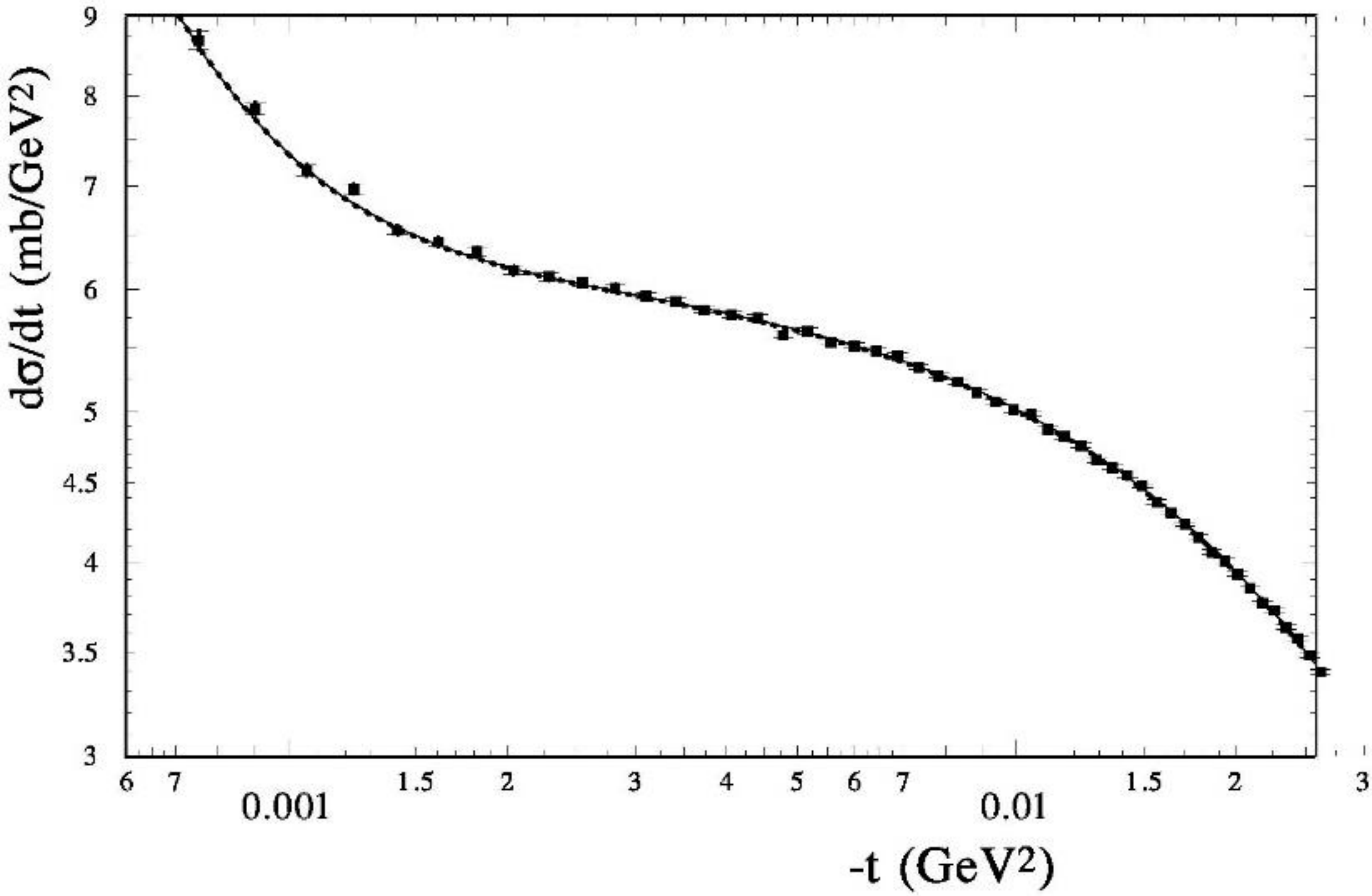


Elastic scattering in the Coulomb region: How technically?

- Goal: Understanding lumi with a precision better of 2-3%
- Measure elastic rate dN/dt in the Coulomb interference region: Necessity to go down to $t \sim 6.5\ 10^{-4}$ GeV^2, or $\theta \sim 3.5\ \mu$rad (when the strong amplitude equals the electromagnetic one)
- This requires:
  - Special high β^* beam optics
  - Detectors at $\sim$ 1.5 mm from LHC beam axis
  - Spatial resolution well below 100 μm
  - No significant inactive edge ($< 100 \mu$m)



TOTEM - 13 TeV



t = 0

Pomeron $\mathrm{Im}\, F_{+}(s,t=0) \to s(\ln s)^2; \quad \mathrm{Re}\, F_{+}(s,t=0) \to s(\ln s)$

Odderon $\mathrm{Re}\, F_{+}(s,t=0) \approx s(\ln s)^2; \quad \mathrm{Im}\, F_{+}(s,t=0) \approx s(\ln s);$

$$\rho_{\pm}(E)\,\sigma_{\pm}(E) = \frac{C}{P} + \frac{E}{\pi P}\int_m^{\infty} dE'\,P'\Big[\frac{\sigma_{\pm}(E')}{E'(E'-E)} - \frac{\sigma_{\mp}(E')}{E'(E'+E)}\Big].$$

The Froissart bound $\sigma_{tot}(s) \le a\,\log^2(s)$

$$\rho_{\pm}(E)\,\sigma_{\pm}(E) = \frac{C}{P} + \frac{E}{\pi P}\int_m^{\infty} dE'\,P'\Big[\frac{\sigma_{\pm}(E')}{E'(E'-E)} - \frac{\sigma_{\mp}(E')}{E'(E'+E)}\Big].$$

* The regions of very low *t and diffraction dip*

around $t \sim -10^{-3}\ (\text{GeV}/c)^2$ $A_{\text{hadronic}} \approx A_{\text{Coulomb}}$

⇒INTERFERENCE

CNI = Coulomb – Nuclear Interference

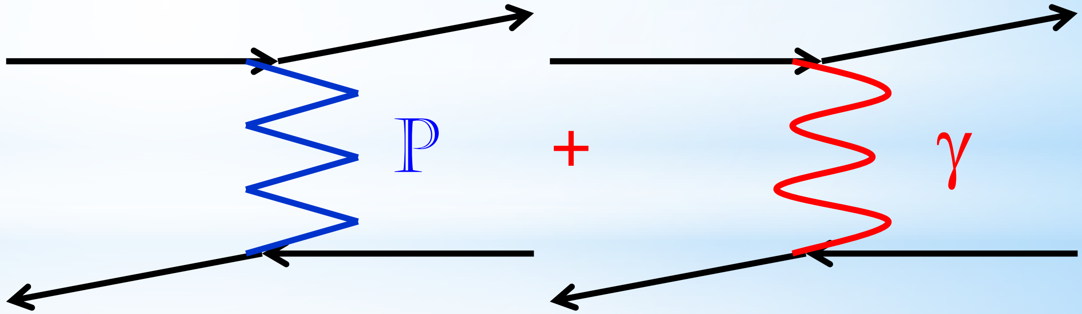
scattering amplitudes modified to include also electromagnetic contribution

$$\phi_i^{had} \rightarrow \phi_i^{had} + \phi_i^{em} e^{i\delta}$$

hadronic interaction described in terms of Pomeron (Reggion) exchange

electromagnetic single photon exchange

$$\sigma = |A_{\text{hadronic}} + A_{\text{Coulomb}}|^2$$



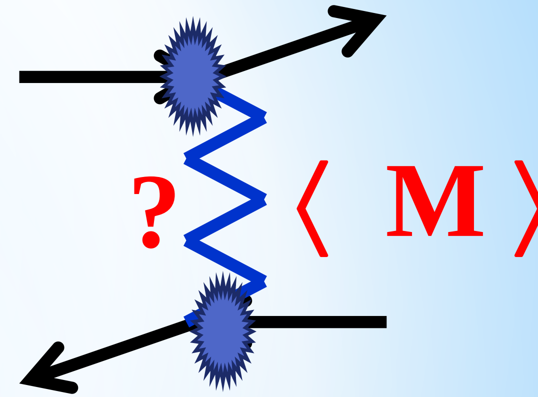
unpolarized ⇒ clearly visible in the cross section dσ/dt

polarized ⇒ “left – right” asymmetry A_N

Scattering process described in terms of Helicity Amplitudes ϕ_i

All dynamics contained in the Scattering Matrix M

(Spin) Cross Sections expressed in terms of



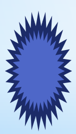
observables:

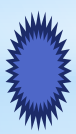
3 ×-sections

5 spin asymmetries

spin non–flip	$\phi_1(s,t) = \langle ++ \mid M \mid ++ \rangle$
double spin flip	$\phi_2(s,t) = \langle ++ \mid M \mid -- \rangle$
spin non–flip	$\phi_3(s,t) = \langle +- \mid M \mid +- \rangle$
double spin flip	$\phi_4(s,t) = \langle +- \mid M \mid -+ \rangle$
single spin flip	$\phi_5(s,t) = \langle ++ \mid M \mid +- \rangle = -\langle ++ \mid M \mid -+ \rangle$

identical spin ½ particles

 - GPDs → electromagnetic FF

 - GPDs → gravimagnetic FF

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

Generalized Parton Distributions -GPDs

Electromagnetic form factors (charge distribution)

Gravitomagnetic form factors (matter distribution)

$$F_1^D(t) = \frac{4M_p^2 - t\,\mu_p}{4M_p^2 - t} G_D(t);$$

$$G_D(t) = \frac{\Lambda^4}{(\Lambda^2 - t)^2};$$

$$G_A(t) = \frac{\Lambda_A^4}{(\Lambda_A^2 - t)^2};$$

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

$$9 \le \sqrt{s} \le 8000\, GeV; \qquad \hat{s} = s / s_0\, e^{-i\pi/2};$$

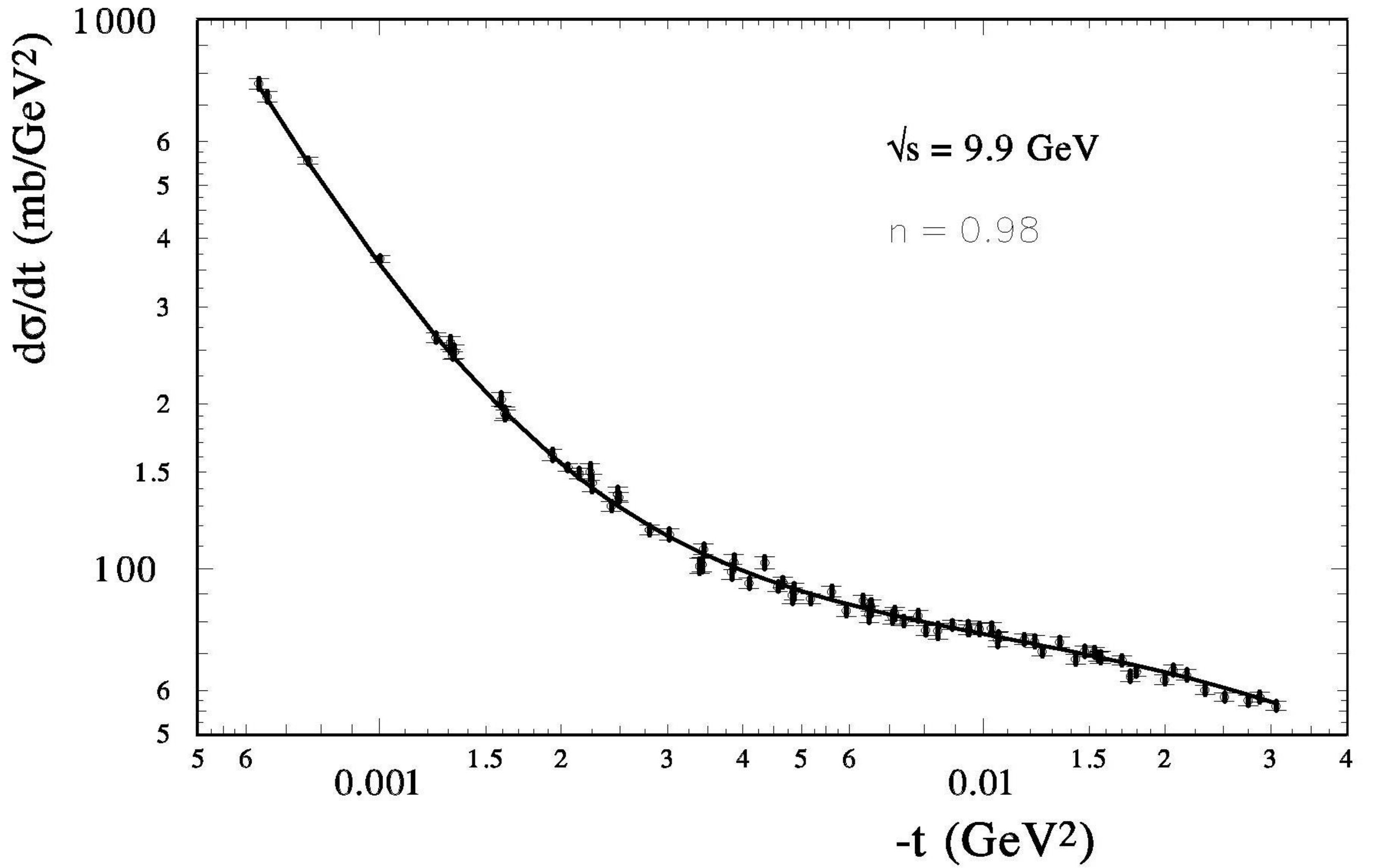
$$n = 980 \to 3416; \qquad 0.00037 < |t| < 15\ GeV^2; \qquad s_0 = 4m_p^2.$$

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

$$F^B(\hat{s},t) = F_1^B(\hat{s},t)(1 + R_1/\sqrt{\hat{s}}\ )] + F_3^B(\hat{s},t)(1 + R_2/\sqrt{\hat{s}}\ )]$$
$$+ F_{odd}^B(s,t);$$

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

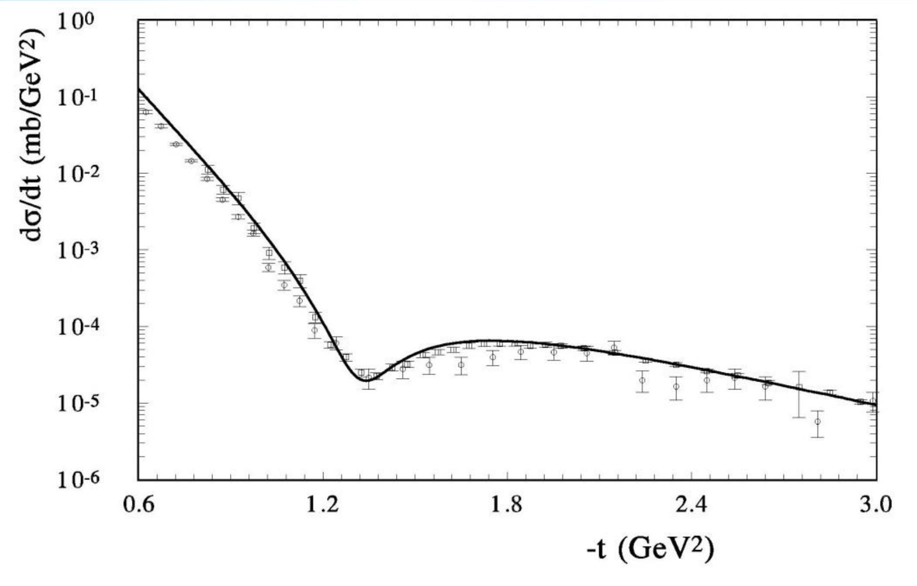
$$B(t) = (\alpha_1 + k_0\, q\, e^{k_0\, t\, ln\hat{s}}\ ) \ln \hat{s}.$$



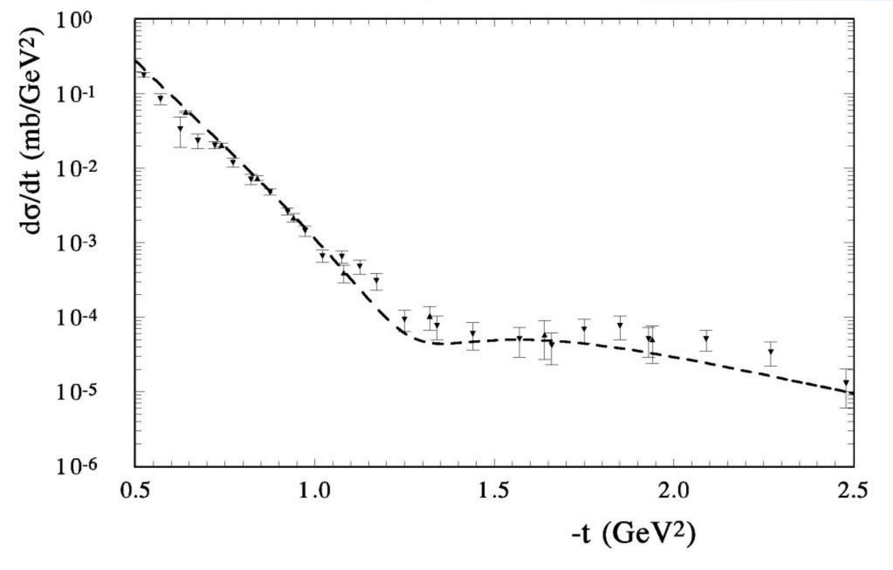
1000
6
5
4
3
2
1.5
100
6
5
dσ/dt (mb/GeV2)
√s = 9.9 GeV
n = 0.98
5
6
0.001
1.5
2
3
4
5
6
0.01
1.5
2
3
4
-t (GeV2)

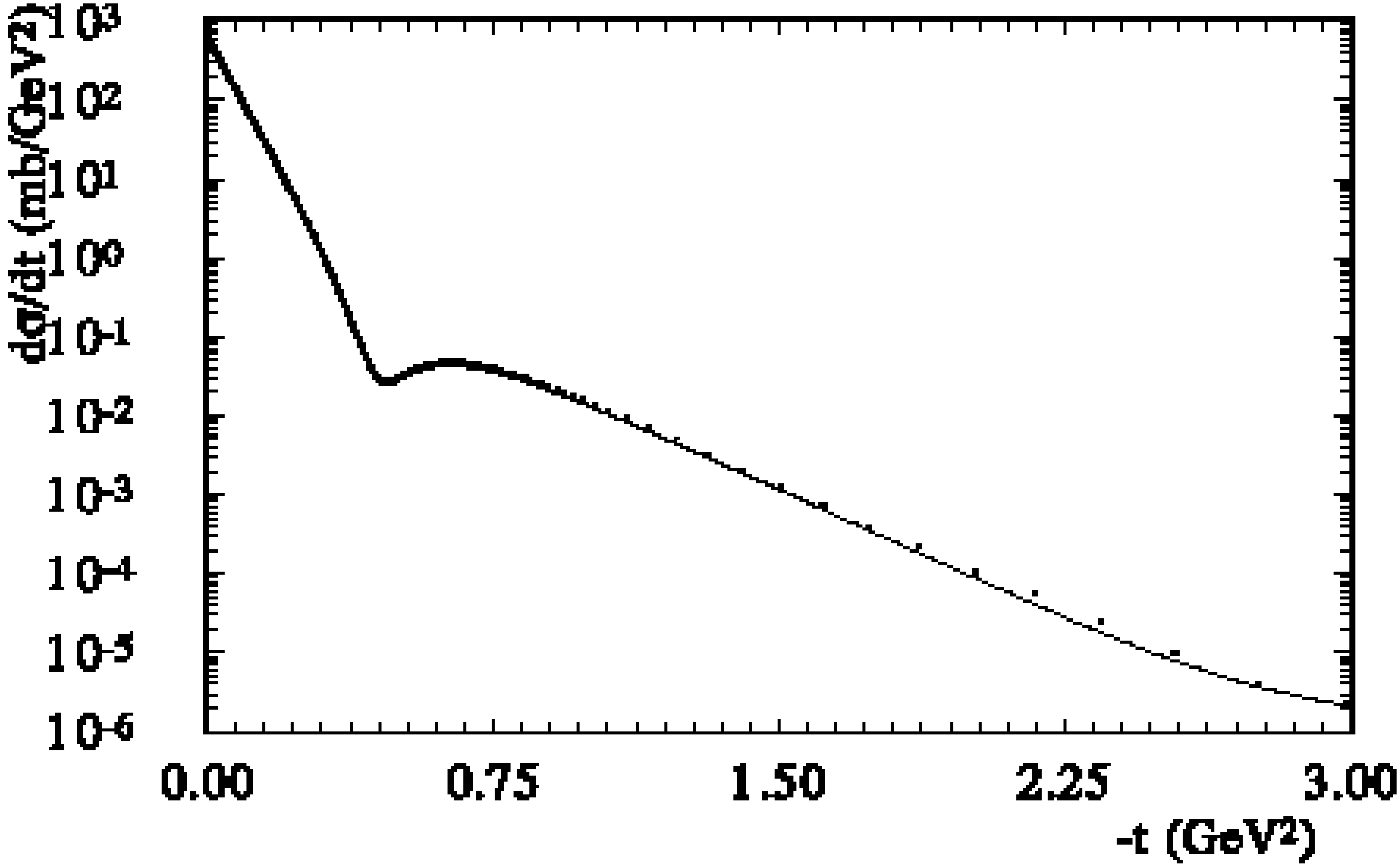
$$\sqrt{s} = 52.8\ \ GeV$$

$pp \rightarrow pp$



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





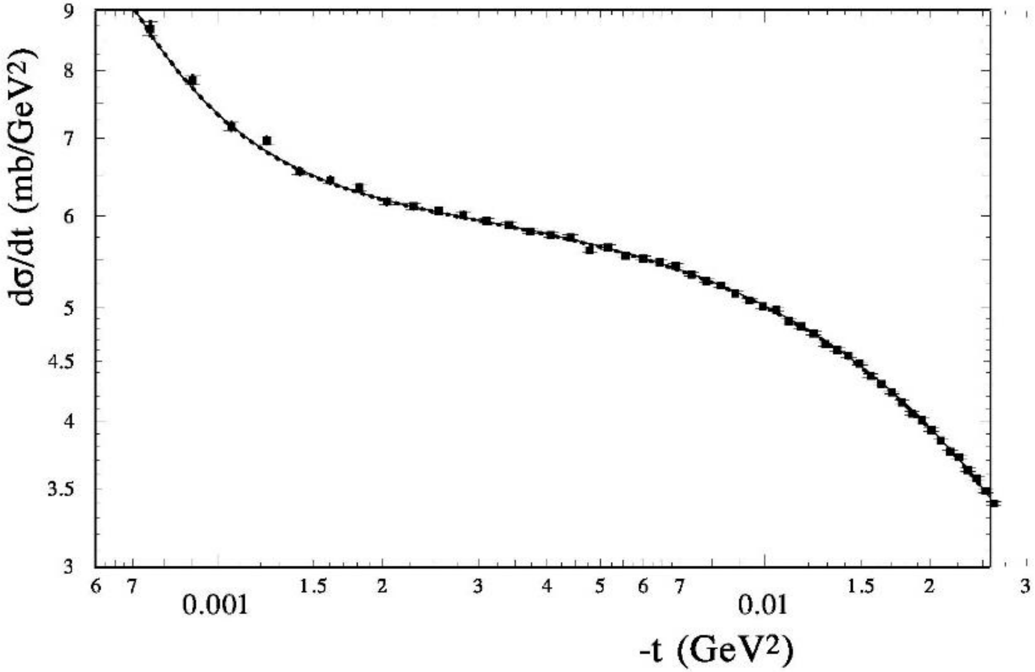
dσ/dt (mb/GeV2)
10-6
10-5
10-4
10-3
10-2
10-1
100
101
102
103
0.00
0.75
1.50
2.25
3.00
-t (GeV2)

$$\chi^2 = \sum_{i=1}^{k} \frac{(d\sigma^{\exp}/dt(t=t_i) - d\sigma^{th}/dt(t=t_i))^2}{\Delta^2_{\exp,i}}$$

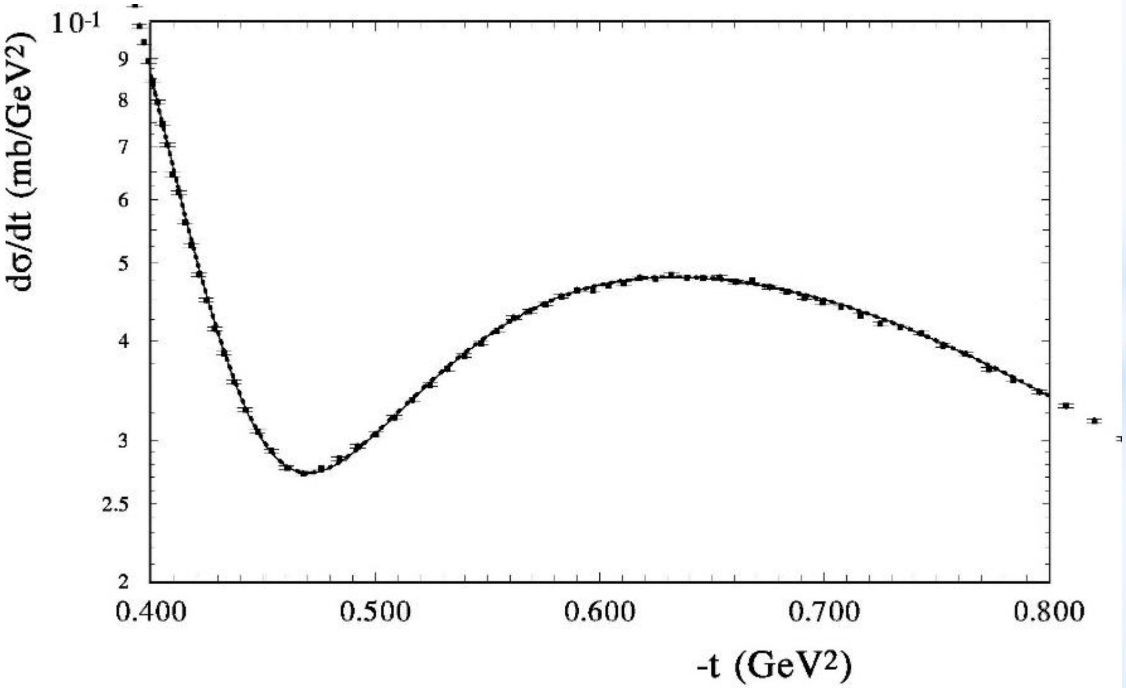
$$\Delta^2_{\exp,i} = \sigma^2_{st.} + \sigma^2_{syst.}$$

$$\chi^2 = \sum_{j}^{N} \sum_{i=1}^{k_j} \frac{(d\sigma^{\exp}/dt(t=t_i) - k_j\, d\sigma^{th}/dt(t=t_i))^2}{\sigma^2_{st,j,i}} + \sum_{j}^{N} \frac{(k_j - 1)^2}{\sigma^2_{sys,j}}$$

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

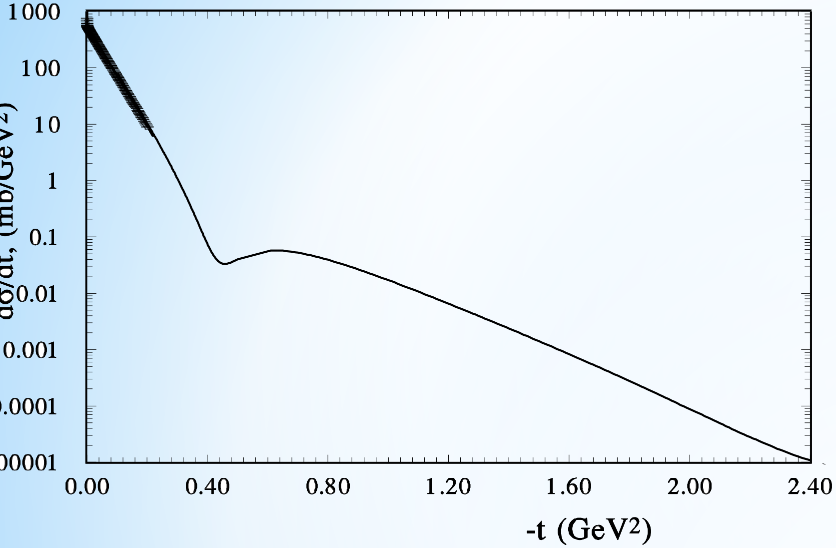


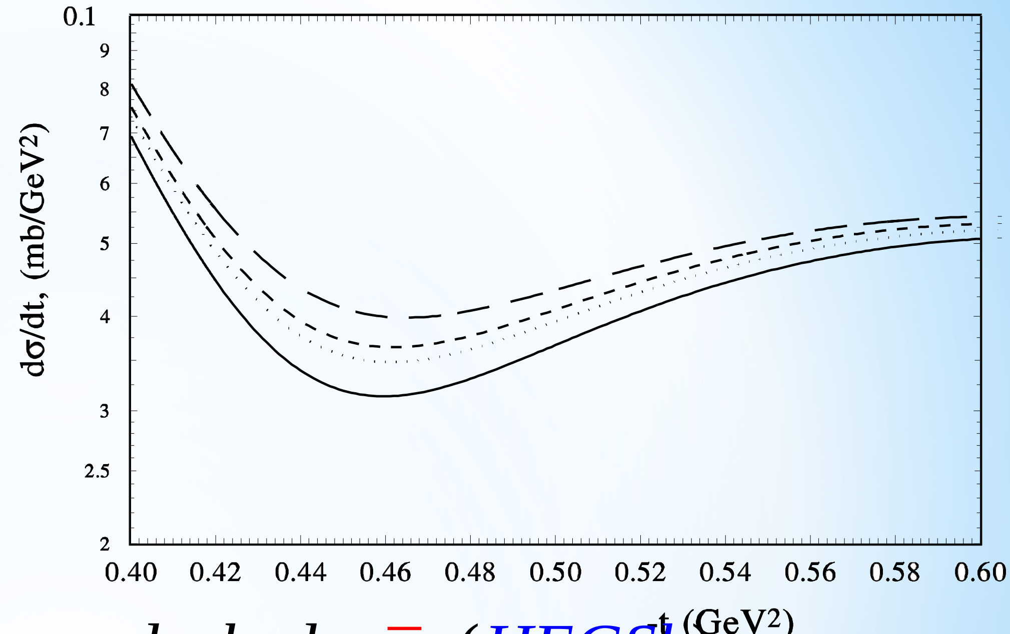
dσ/dt (mb/GeV2)
9
8
7
6
5
4.5
4
3.5
3
6 7 1.5 2 3 4 5 6 7 1.5 2 3
0.001
0.01
-t (GeV2)



dσ/dt (mb/GeV2)
10-1
9
8
7
6
5
4
3
2.5
2
0.400
0.500
0.600
0.700
0.800
-t (GeV2)

Diffraction (2018) Odderon and LHC data





$$hard\ line\ \ pp;\ long\ \ dushed\ \ p\bar{p}\ \ (HEGSh);$$

$$short-dashed\ \ pp;\ dotted-\ \ p\bar{p}\ \ (without\ \ Odderon);$$

$$HEGSh\ \rightarrow -t_{\min}=0.46\,GeV^{2};\ -t_{\max}=0.62\,GeV^{2};\ R=1.78;$$

$$TOTEM\ \rightarrow -t_{\min}=0.47\,GeV^{2};\ -t_{\max}=0.638\,GeV^{2};\ R=1.78;$$

Nemez, talk on workshop , May 28 (2018)

O.S. - New methods for calculating parameters of the diffraction scattering amplitude, "VI Intern. Conf. On Diffraction...", Blois, France,(1995).

O.S. “Additional ways to determination of structure of high energy elastic scattering amplitude” arxiv.org:[hep-ph/0104295]

P. Gauron, B. Nicolescu, O.S. “A New Method for the Determination of the Real Part of the Hadron Elastic Scattering Amplitude at Small Angles and High Energies” Phys.Lett. B629 (2005) 83-92

$$\Delta_R(t) = [\mathrm{Re}\,F^h(t) + \mathrm{Re}\,F^C(t)]^2 = [\frac{d\sigma}{dt}|_{\mathrm{exp.}} - k\pi\,(\mathrm{Im}\,F^h(t) + \mathrm{Im}\,F^C(t)]^2 / (k\pi)$$

“Gedanken” experiment – 2006 y.

Proton-proton elastic scattering at LHC

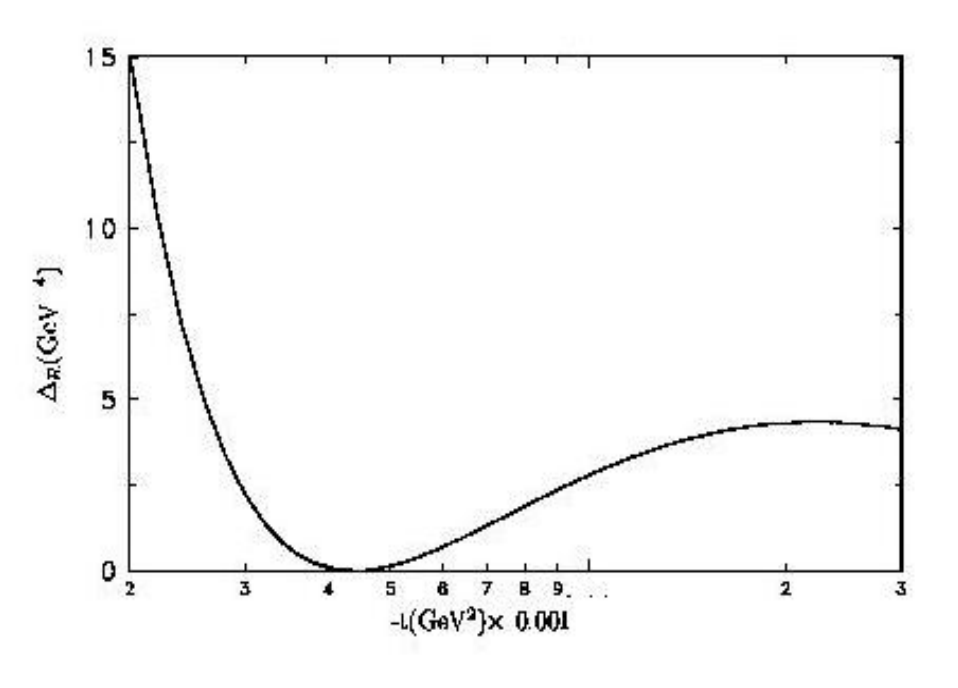
COMPETE values

$B = 22\ GeV^{-2}$ $\sigma_{tot} = 111.5\ mb$

$\mathrm{Im}\, F_N(s,t) = \sigma_{tot} / (0.389 \cdot 4\pi)\ e^{Bt/2}$

$$\rho(s,t) = \frac{\mathrm{Re}\, F_N(s,t)}{\mathrm{Im}\, F_N(s,t)} = 0.15$$

$t_{\min}^{pp} = -0.0044\ GeV^2$

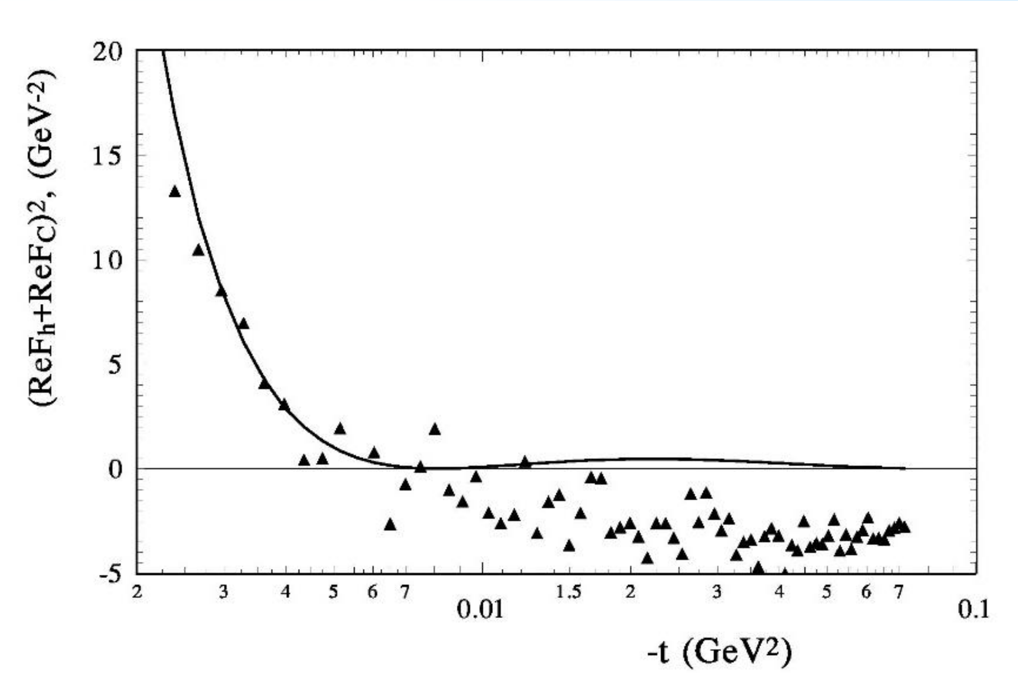


TOTEM 1 slope

$\sigma_{tot} = 111.9\ mb$

$B = 10.39\ GeV^{-2}$

$\rho(s,t) = 0.09$



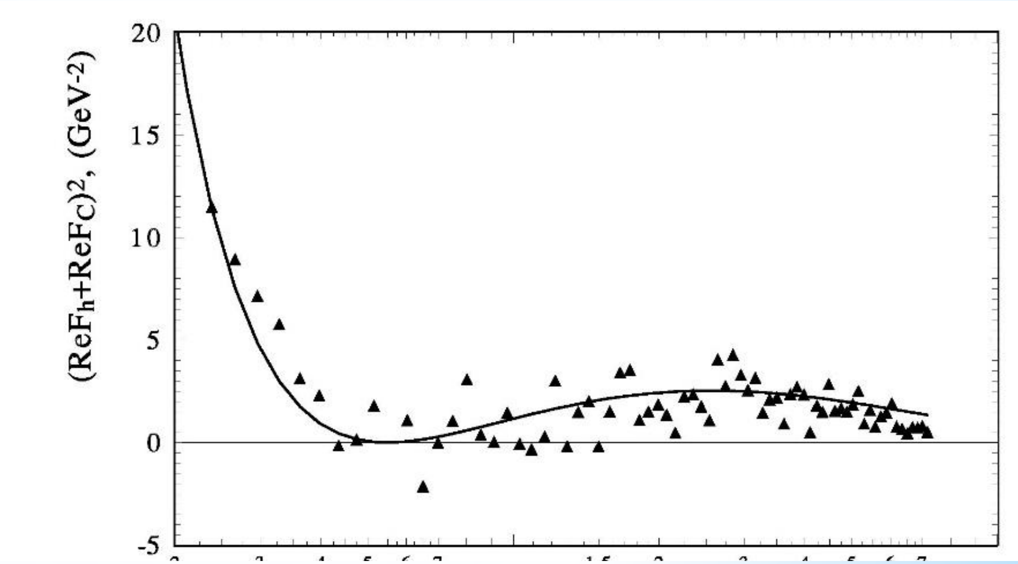
TOTEM 3 slope

$\sigma_{tot} = 112.1\ mb$

$B = 10.74\ GeV^{-2}$

But take

$\rho(s,t) = 0.12$



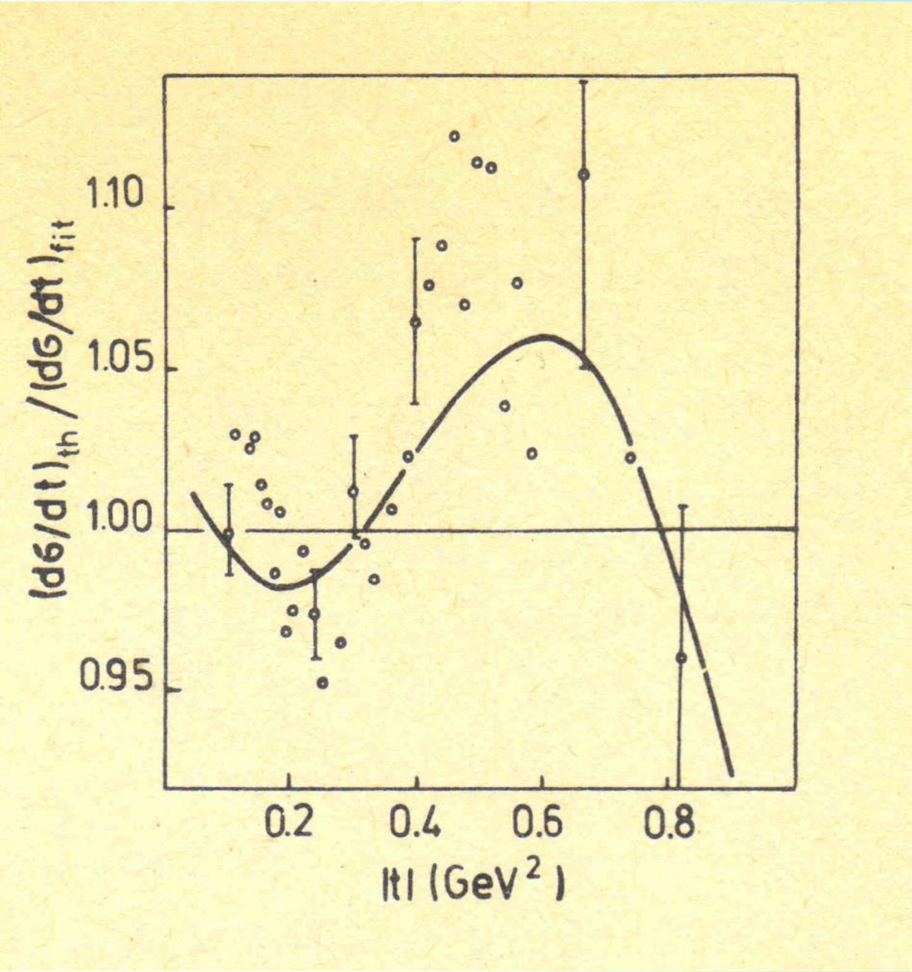
Yu.M. Antipov et al.,

Preprint IHEP (Protvino) 76-95 (1976)

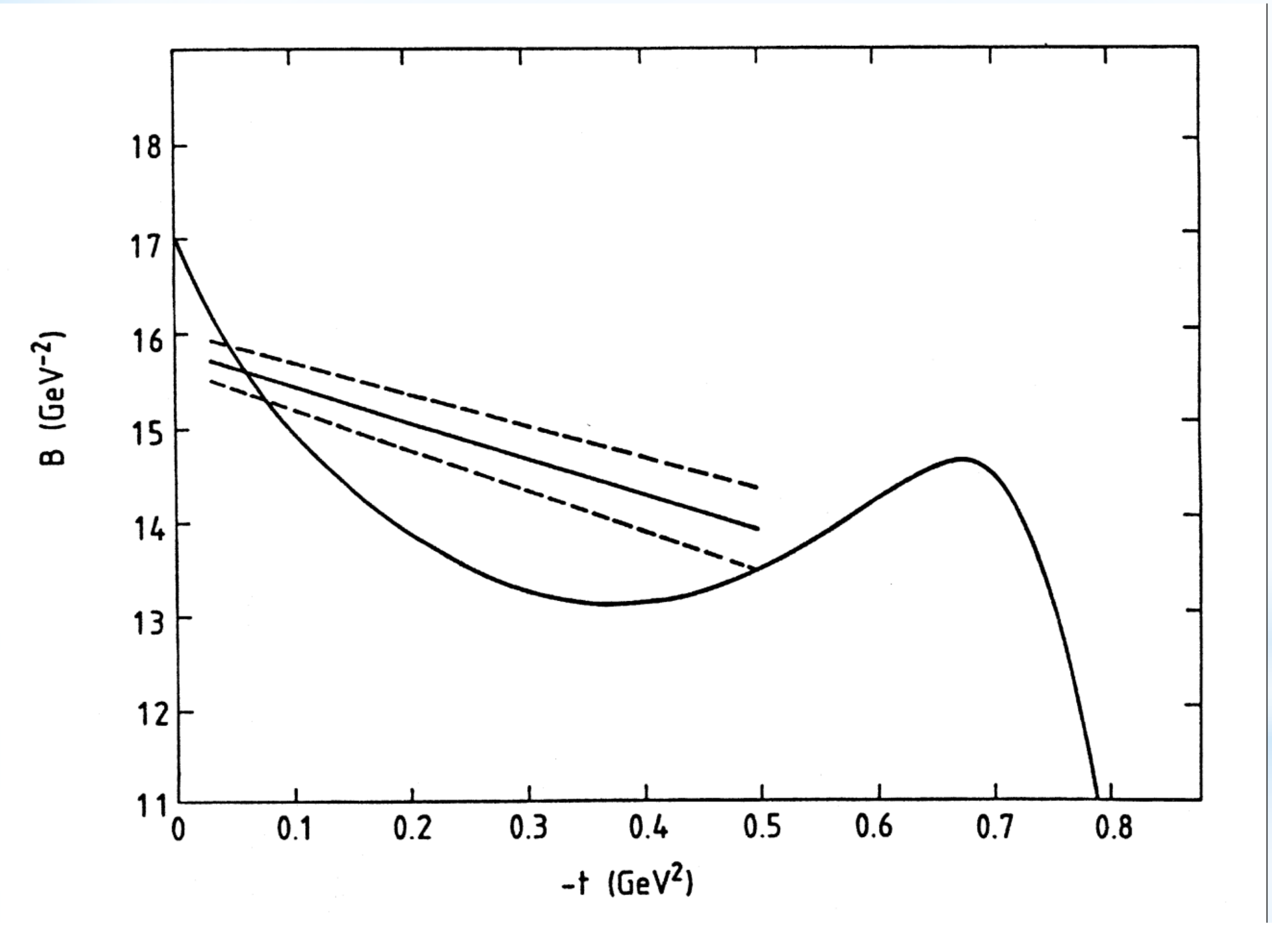
Problem:

Compare non-exponential and exponential forms

O.V. Selyugin
Int.workshop, Protvino
(1982)



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



V.A. Tzarev   Model of complex Regge poles

Preprint NAL-Pub-74/17, 1974; DAN-USSR, v.95 (1977)

$$T_k^{Pol}(s,t) = (^{-1}_{\ i})2\pi\sqrt{\alpha^{'}}F(t)e^{\lambda(\alpha_0+r_0^2)}(-\alpha^{'}t)^{k+1/2}\frac{1}{\alpha_I}\times$$

$$\times\{ish\frac{\pi\alpha_I}{2}cos(\vartheta(t)+\alpha_I(t)\log s)-ch\frac{\pi}{\alpha_I}\sin(\vartheta(t)+\alpha_I(t)\log s)];$$

$$\alpha_I = -\frac{1}{2}\alpha^{'}F\sqrt{-(F^2+4t)};\ \ \vartheta = arctg\frac{\alpha_I}{r_0^2};\ \ r_0^2 = \alpha^{'}(t+F/2)^{-1}.$$

$$\frac{d\sigma}{dt} \simeq (\frac{d\sigma}{dt})_{midl}[1+C\,cos(\vartheta(t)+\mathrm{Im}\,\alpha(t)\log s)];$$

$$If\ \ \ \mathrm{Im}\,\alpha(t) = \alpha(0)(1-t/t_0),\ \ \ \vartheta(t) = \vartheta(0) = 0$$

$$oscillations\ \ \ with\ \ \ \Delta t = \frac{2\pi t_0}{\mathrm{Im}\,\alpha(0)\ln s}$$

O.V. Selyugin

Potential of rigid string

Fit over (q)

Ukr.J. Phys., v.41 (1996)

$$T_{osc}(s,t) = is\int_0^\infty b\,db\,J_0(bq)\ \chi_{osc}(s,b)\exp[-\chi(s,b)])$$

$$F_N^{ad} = h_{ad}\sin[\omega q + \varphi(s)]/[\omega q + \varphi(s)];$$

$$For\ \sqrt{s} = 19,4;\ 27.4;\ 541(GeV)$$

$$one\,obtains\quad \omega = 324.7(GeV^{-1})$$

$$correspounding\quad to\ one\,half\ \ of\ the\ period$$

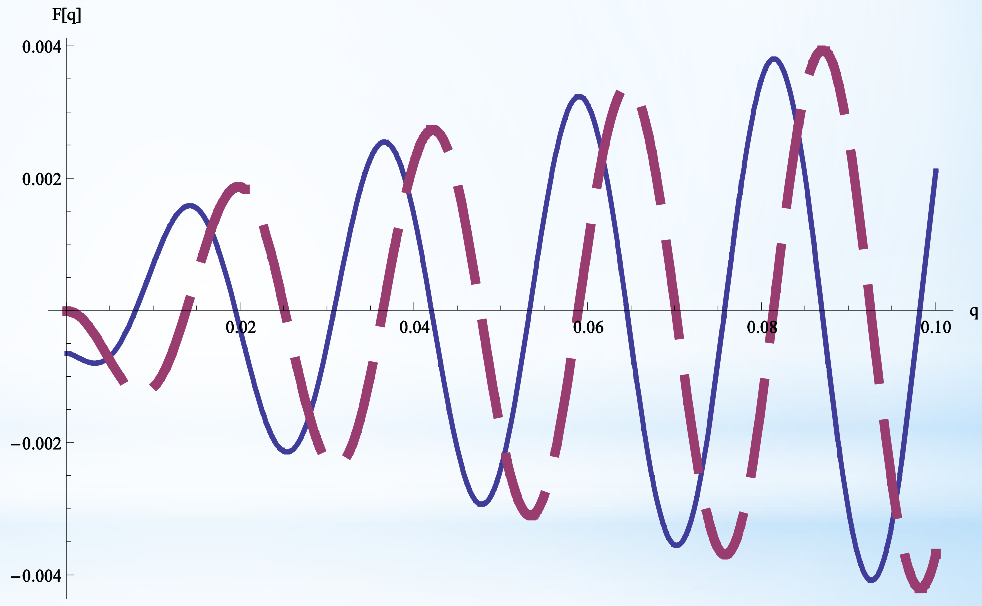
$$\Delta q \approx 0.01(GeV)$$

Screening long range potential

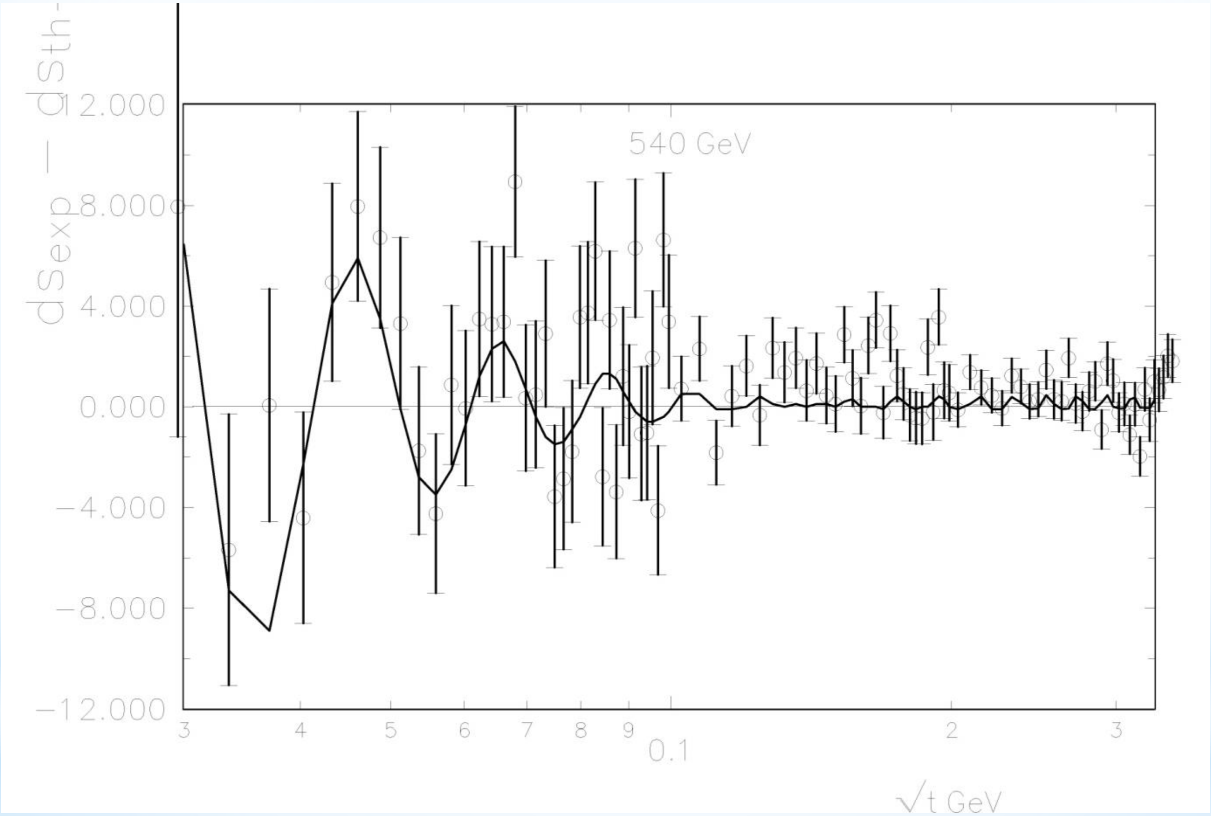
$$T_{osc}(s,t) = is\int_0^\infty b\,db\,J_0(bq)\;\chi_{osc}(s,b)\exp[-\chi(s,b)])$$

$$\chi_{osc}(s,b)=\frac{h_{osc}(s)}{(r_{scr}^2-b^2)^2};\qquad \chi_{osc}(s,b)=[1-e^{-h/(b^2-r_{scr}^2)}];$$

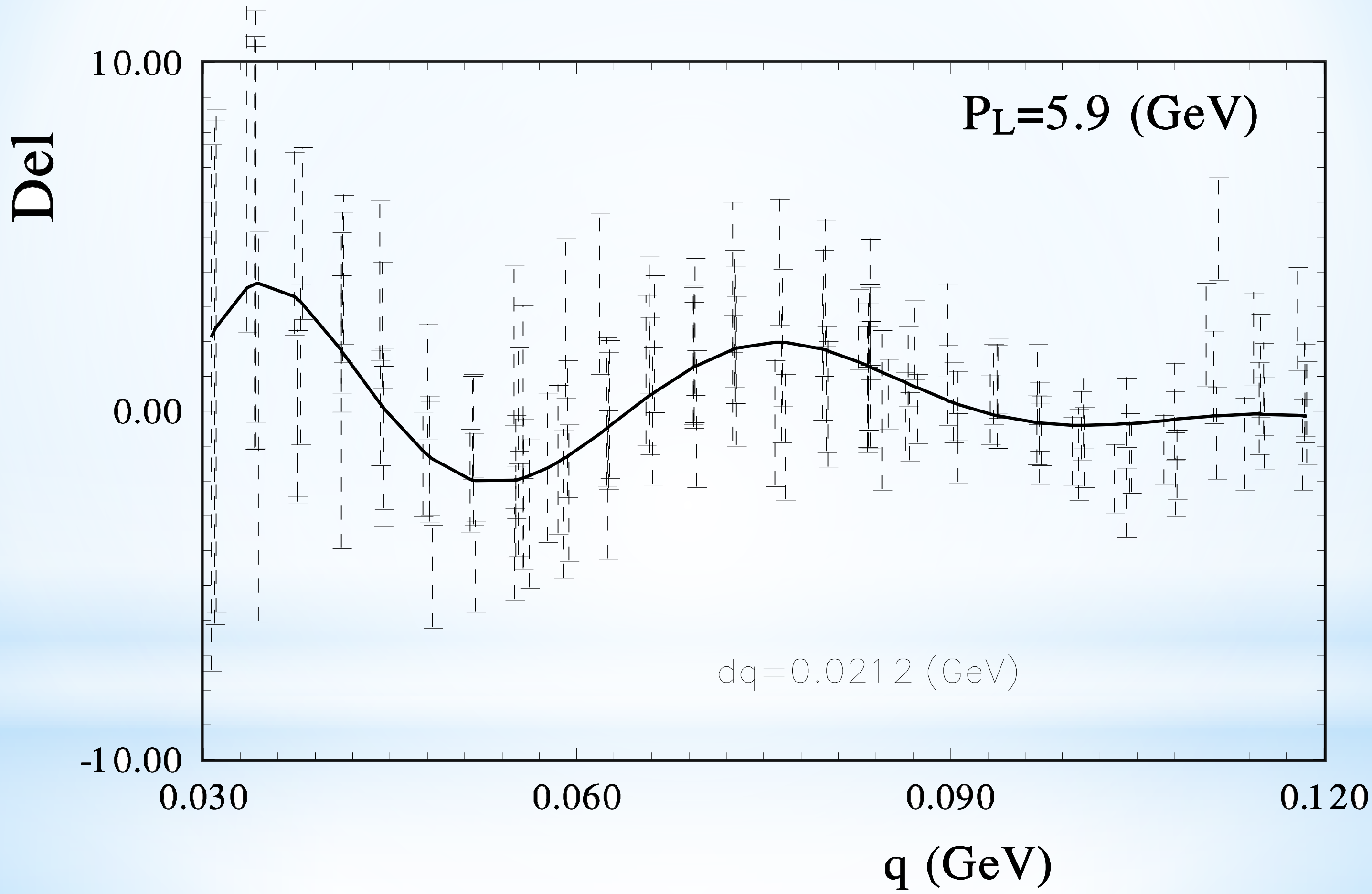
$$T_{osc}(s,t)=\frac{1}{2}\frac{iq}{r_{scr}}K_1(i\,r_{scr}q);$$



* Experimental data UA4/2



Proton-antiproton scattering



NEW EFFECT

Fitting procedure:

$$F_N(s,t) = H_N(i+\rho)e^{Bt/2} + F_N^{ad}(s,t)\, G_d^2(t)$$

$$F_N^{ad}(s,t) = h_{ad}\sin[\pi(q+\varphi(s))/q_0]; \quad \{J_0;\ J_1\}$$

$$\delta\chi^2(q_0) = \frac{\sum_i \chi_i^2 - \sum_i \chi_i^2(q_0)_{with\,oscil.}}{\sum_i \chi_i^2};$$

Two statistical independent choices

$$\mathbf{x}'_{\mathbf{n_1}} \quad \text{and} \quad \mathbf{x}''_{\mathbf{n_2}}$$

of values of the quantity X distributed around a definitely value of A with

the standard error equal to 1, The arithmetic mean of these choices

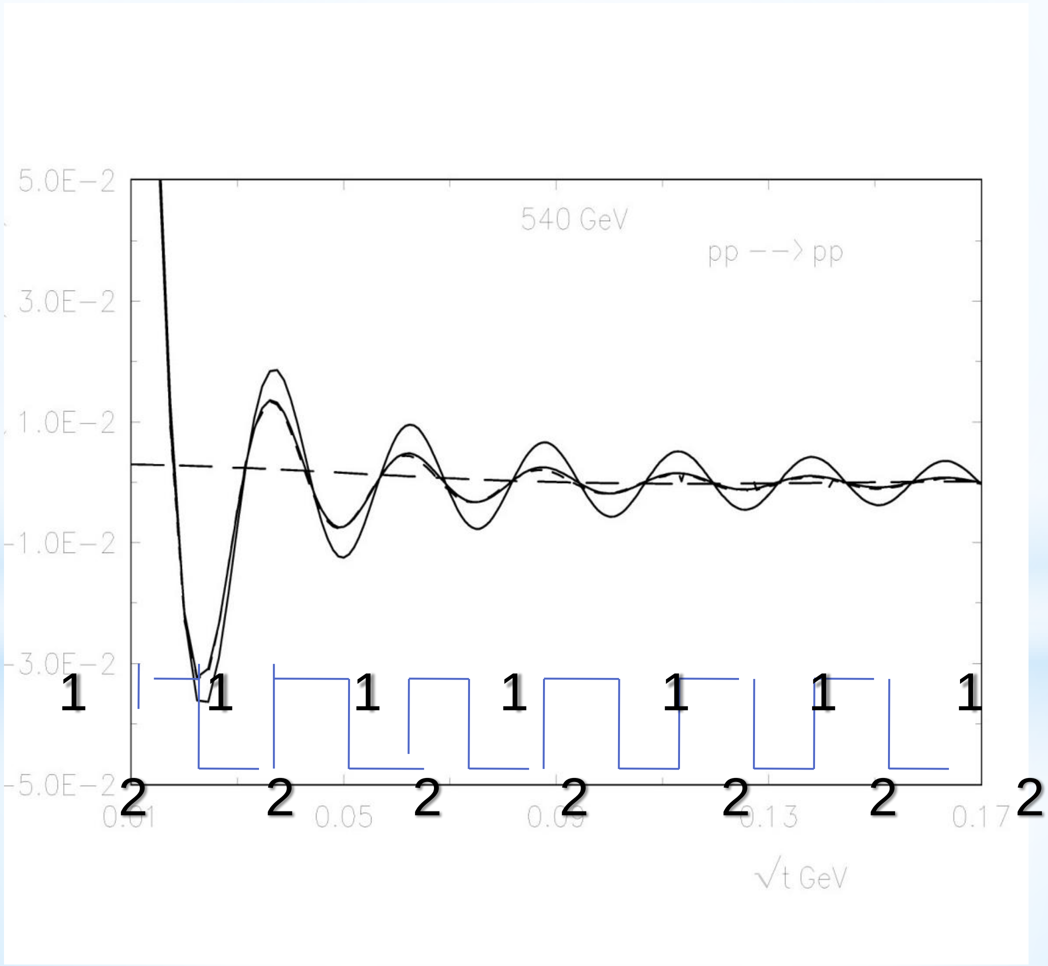
$$\Delta \mathbf{X} = (\mathbf{x}'_1 + \mathbf{x}'_2 + \ldots \mathbf{x}'_{n1})/\mathbf{n}_1 - (\mathbf{x}''_1 + \mathbf{x}''_2 + \ldots \mathbf{x}''_{n2})/\mathbf{n}_2 = \overline{\mathbf{x}'_{\mathbf{n_1}}} - \overline{\mathbf{x}''_{\mathbf{n_2}}}.$$

The standard deviation

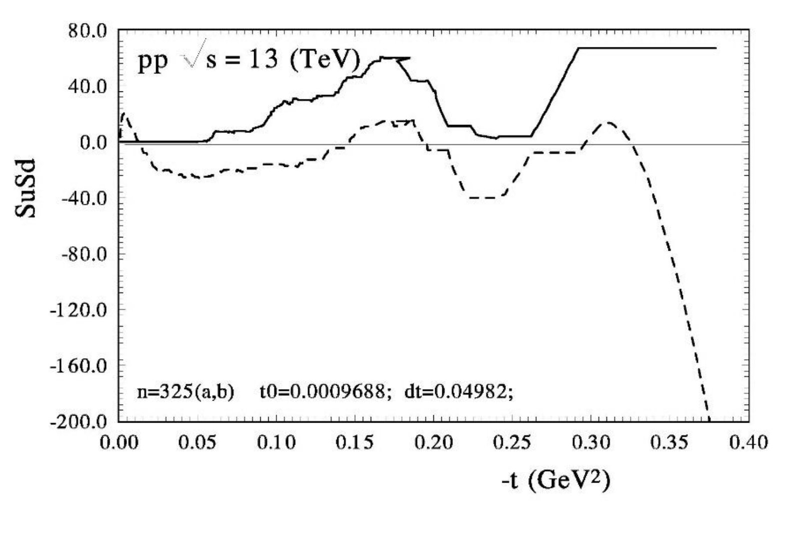
$$\delta_{\overline{\mathbf{x}}} = [\mathbf{1}/\mathbf{n}_1 + \mathbf{1}/\mathbf{n}_2]^{1/2}$$

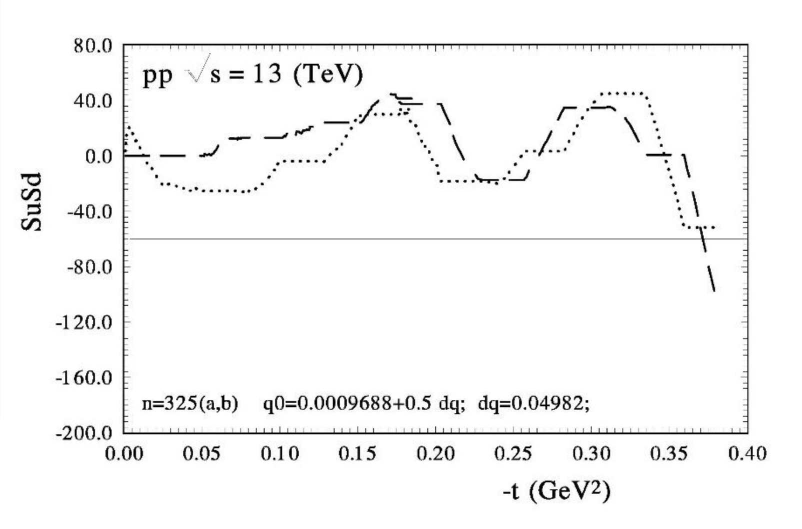
If $\Delta \mathbf{X}/\delta_{\overline{\mathbf{x}}}$ is large than 3

that the difference between these two choices has with the 99% probability


5.0E−2
3.0E−2
1.0E−2
−1.0E−2
−3.0E−2
−5.0E−2
540 GeV
pp −−> pp
0.01
0.05
0.09
0.13
0.17
√t GeV
1
1
1
1
1
1
1
2
2
2
2
2
2
2

O.V. Selyugin, Phys.Lett. B 797, 134870 (2019).





$$r = \frac{\overline{\Delta S}}{\overline{\delta S}} = \frac{\overline{S_{up}} - \overline{S_{dn}}}{(1/[1/n_1 + 1/n_2]^{1/2})} = \frac{1.7 + 0.5}{0.53} = 4.15;$$

HEGS model analysis

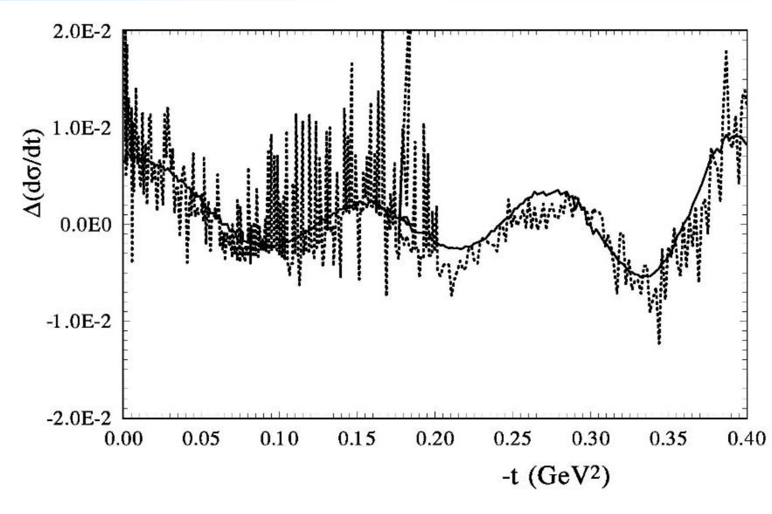
$$F_N^{ad}(s,t) = F_{HEGS\,0}(s,t) + F_{osc}^{ad}(s,t);$$

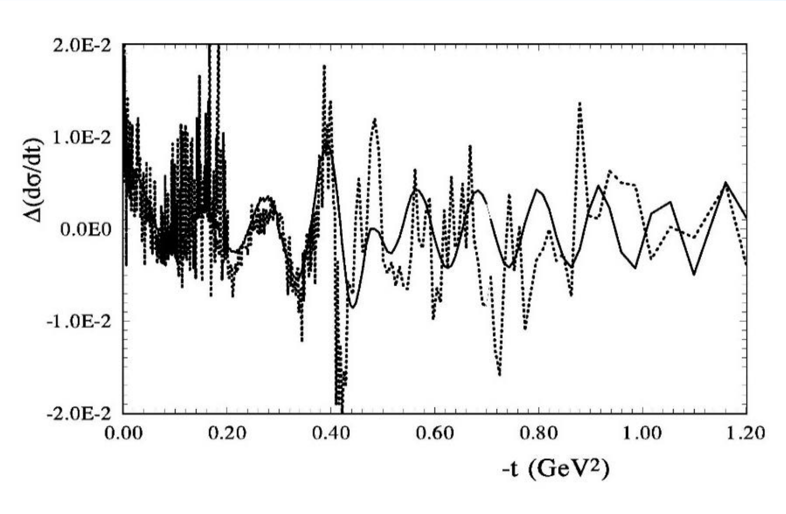
$$F_{osc}^{ad}(s,t) = h_{osc}\; J_1[\tau]/\tau; \quad \tau = \pi(\varphi_0 - t/t_0);$$

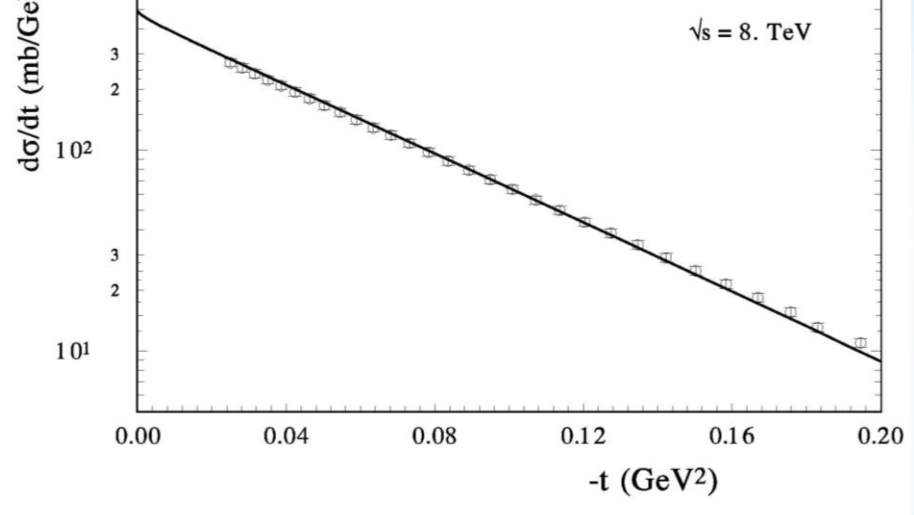
Results:
with F(osc) $\chi^2_{dof} = 1.24$;

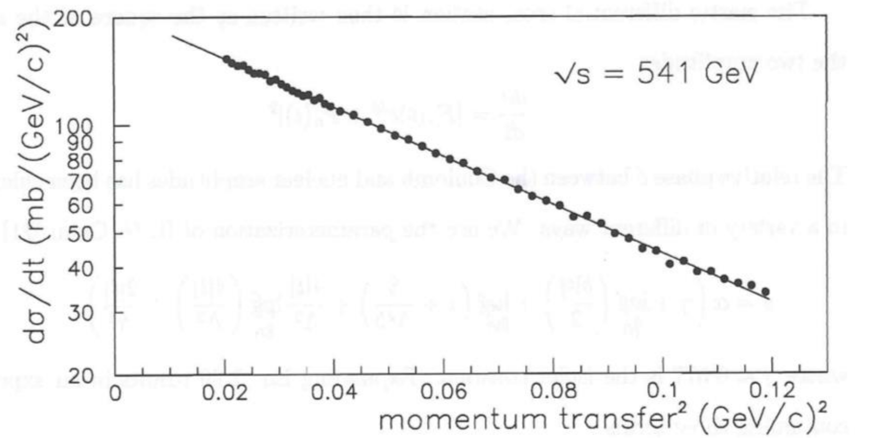
$$R_i\Delta_{th} = [(d\sigma/dt)_{th+osc} - (d\sigma/dt)_{th0}] \; / \; (d\sigma/dt)_{th0}; \quad -- \; line$$

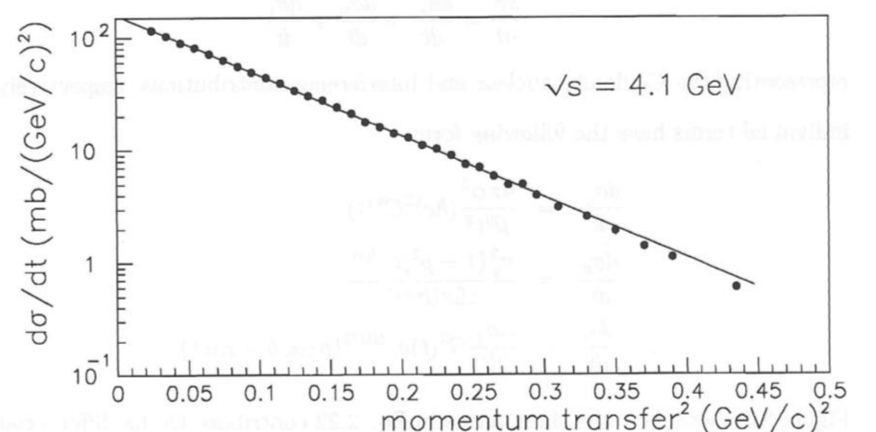
$$R_i\Delta_{EXP} = [(d\sigma/dt)_{EXP} - (d\sigma/dt)_{th0}] \; / \; (d\sigma/dt)_{th0}; \quad by\, experiment \; data$$






√s = 8. TeV
dσ/dt (mb/Ge
-t (GeV2)
0.00
0.04
0.08
0.12
0.16
0.20
10²
10¹


√s = 541 GeV
dσ/dt (mb/(GeV/c)²)
momentum transfer² (GeV/c)²
0
0.02
0.04
0.06
0.08
0.1
0.12
200
100
20


√s = 4.1 GeV
dσ/dt (mb/(GeV/c)²)
momentum transfer² (GeV/c)²
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
10²
10
1
10⁻¹

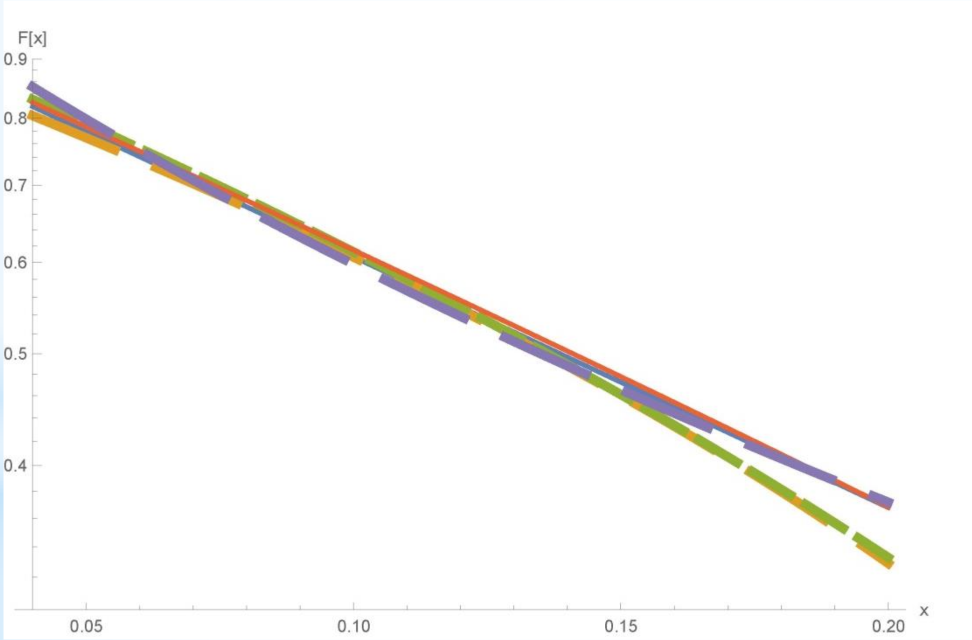
$$\Gamma(b) = e^{-b^2/R^2}; \quad \rightarrow \quad F_1(t) \approx e^{5t};$$

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

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

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

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



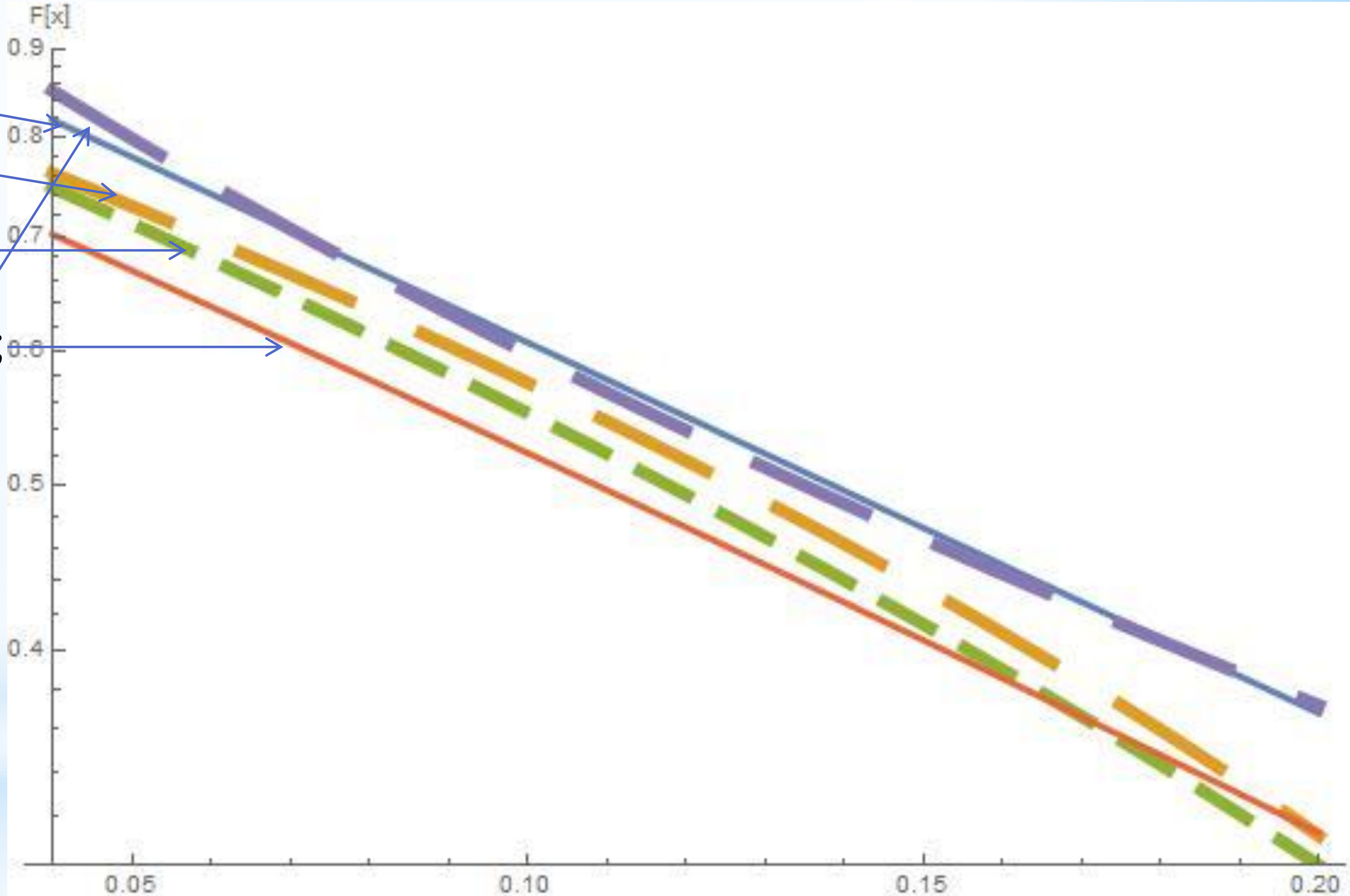
e^{5t};

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

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

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

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



Modern Physics Letters A, V. 36, No. 18 (2021) 2150148.

The result was obtained with a sufficiently large addition coefficient of the normalization $n = 1/k = 1.135$. It can be for a large momentum transfer, but unusual for the small region of t.

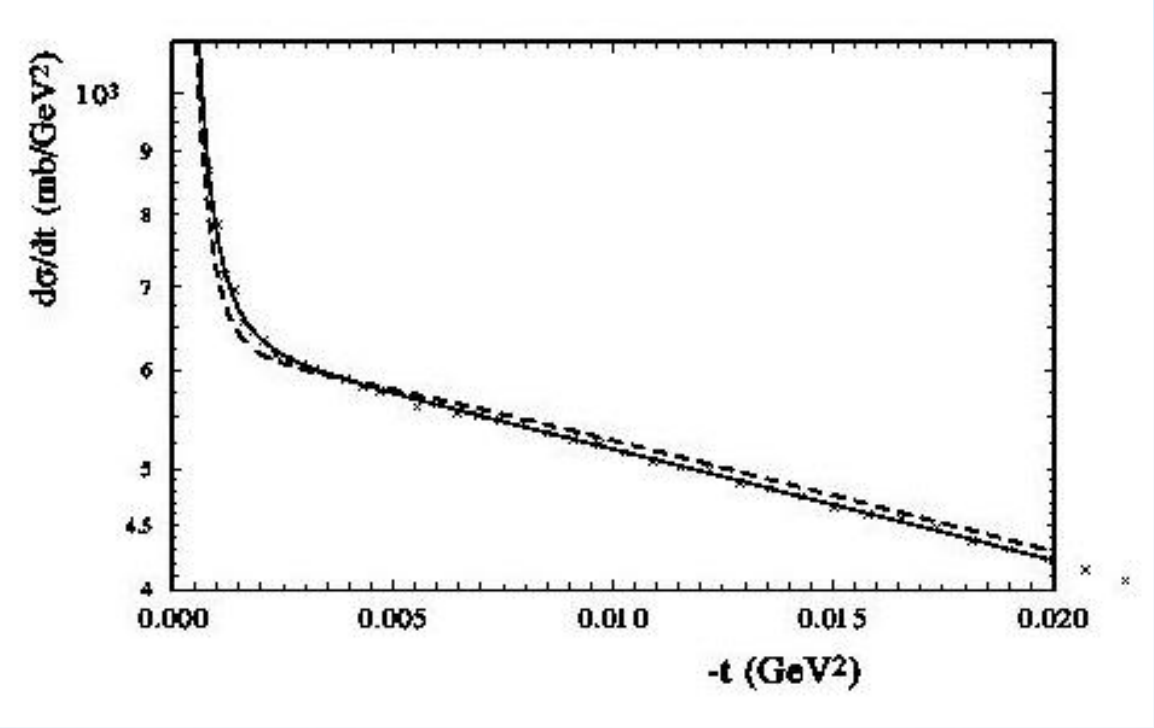
Let us put the additional **normalization coefficient to unity and continue to take into account in our fitting procedure** only statistical errors.

We examined two different forms. One is the simple exponential form

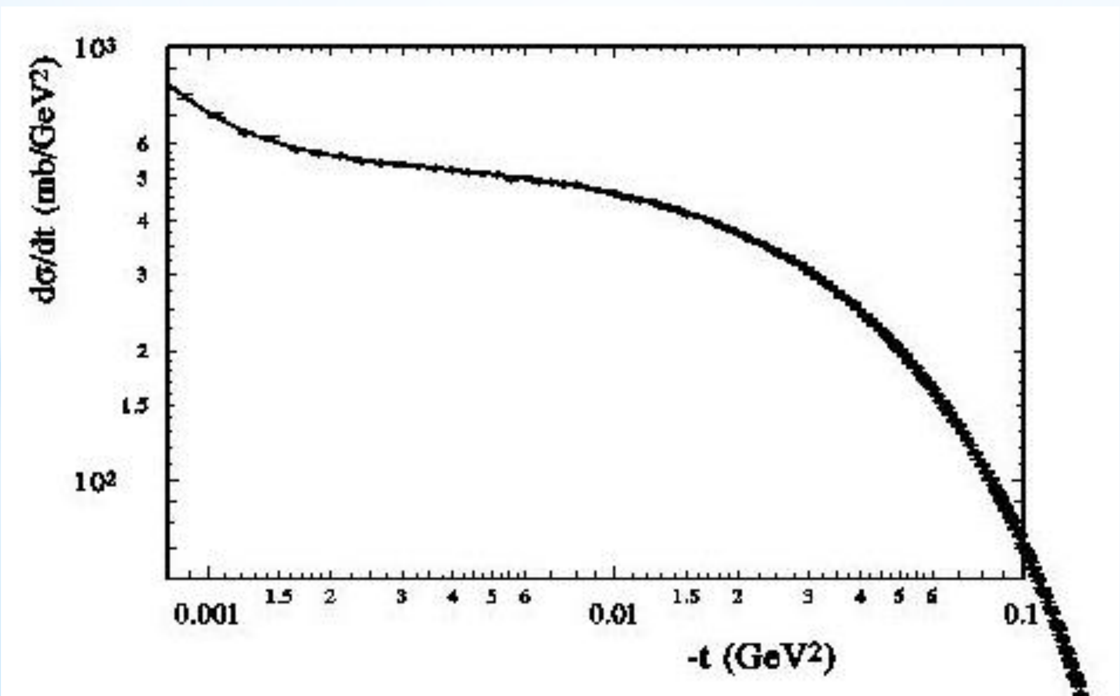
$$F_d(t) = h_d(i+\rho)\, e^{B_d\, t^d\ Ln(s)};$$

The parameters of the additional term are well defined

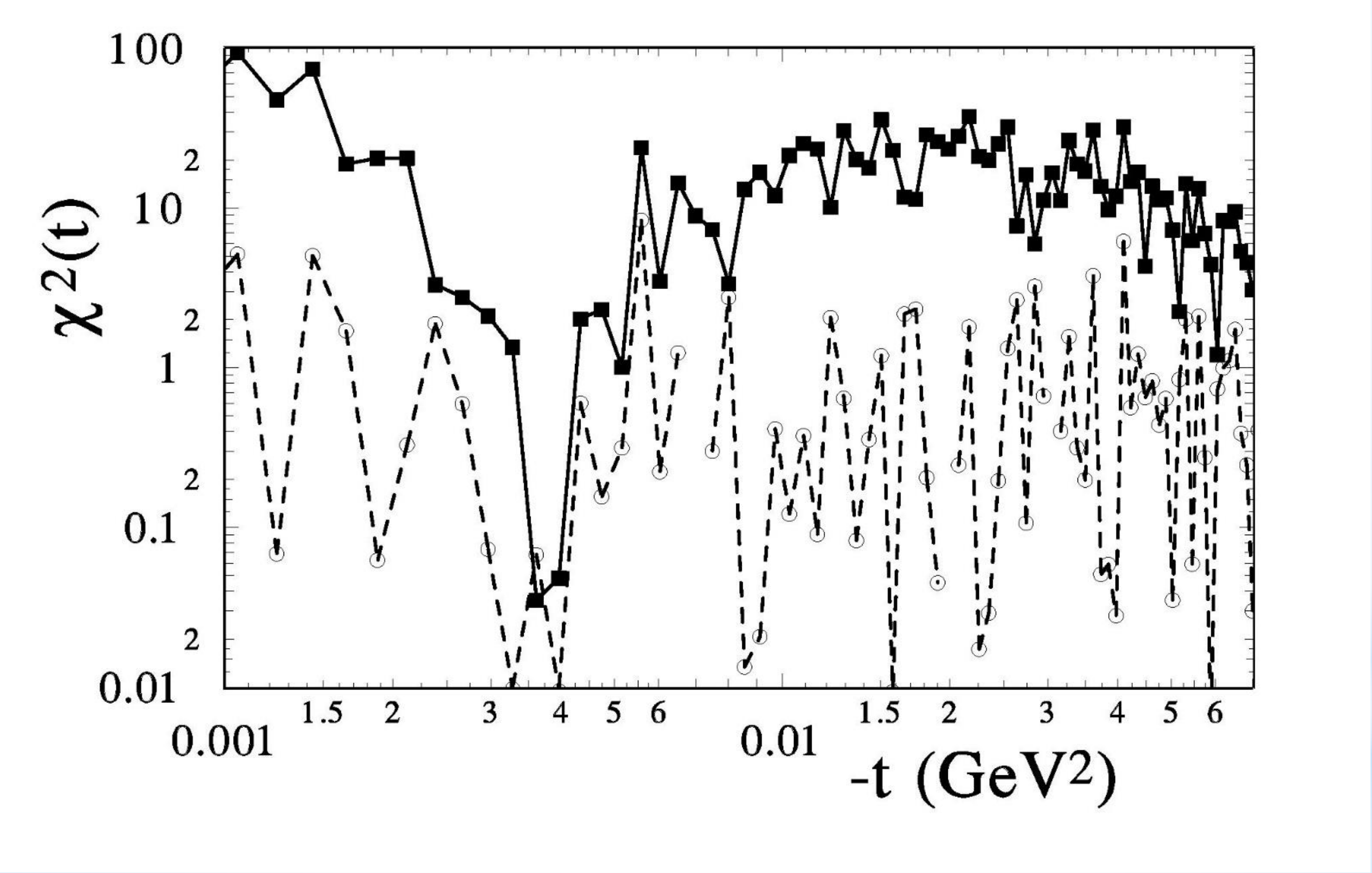
$h_d = 1.7 \pm 0.01$; $\rho_d = -0.45 \pm 0.06$; $B_d = 0.616 \pm 0.026$; $d = 1.119 \pm 0.024$.



dσ/dt (mb/GeV2)
10³
9
8
7
6
5
4.5
4
0.000
0.005
0.010
0.015
0.020
-t (GeV2)



dσ/dt (mb/GeV2)
10³
6
5
4
3
2
1.5
10²
0.001
1.5
2
3
4
5
6
0.01
1.5
2
3
4
5
6
0.1
-t (GeV2)



100
10
1
0.1
0.01
2
2
2
2
$\chi^2(t)$
0.001
1.5
2
3
4
5
6
0.01
1.5
2
3
4
5
6
-t (GeV^2)

$\sigma_{tot}(mb)[TOTEM] = 110.6 \pm 3.4\ mb; \quad \rho(t=0) = 0.1 \pm 0.01.$

$\rho(t=0) = 0.09 \pm 0.01.$

k(d)	model	$\sum \chi^2$	$\sigma_{tot}(mb)$	$\rho(t=0)$
0.87		525/415	106.1	0.146
0.87	Fd=0	515/425	106.2	0.142
0.87		527/425	106.2	0.148
1	Fd(rd)	539/425	113.2	0.109
1	Fd (rd)	549/425	113.2	0.113
1	Fd(exp)	550/425	112.6	0.115

Analysis of the all LHC data (878 experimental points)

$$\sqrt{s} \leq 13\,TeV; \quad (TOTEM - 2\ sets\ \ (independent));$$
$$\sqrt{s} \leq 8\,TeV; \quad (TOTEM - 2\ sets;\ ATLAS - 1 set)$$
$$\sqrt{s} \leq 7\,TeV; \quad (TOTEM - 2\ sets;\ ATLAS - 1 set)$$

$$N = 666; \ \sum_{i,j}^{N,n} \chi^2_{i,j} = 884; \quad \chi^2_{dof} = 1.35$$

$$F_d(\hat{s},t) = i\, h_d\, Ln(\hat{s})^2 G^2_{em}(t)\ \ e^{-(B_d|t| + C_d t^2)\ln(\hat{s})};$$
$$h_d = 2.4 \pm 0.1;$$
$$h^{pp}_{osc} = 0.18 \pm 0.007; \quad h^{pp}_{osc} \approx h^{p\bar{p}}_{osc};$$

* Summary

- The experimental data show some periodical structure in the Coulomb-hadron interference region of t and in a wide energy region.

- The small period of the “oscillation” is related with the long hadron screening potential at large distances.

An additional term with large slope is require
for the quantitatively description of the experimental data
in the case of the standard normalization of 13 TeV data

Such term leads to the increasing
the size of $\rho(s,t=0)$
and decreasing the size of $\sigma_{tot}(s)\ mb$

Preliminary analysis of whole sets of high energy experimental data support the existence such anomalous term.

- More experimental data in the Coulomb-hadron interference region are needed. [NICA (low energy) and LHC(high energy)]

- It is crucial that the experiments measure – $\rho(s,t=0)$ and $\sigma_{tot}(s)\ mb$ simultaneously.

THANKS FOR YOUR ATTENTION

Спасибо за внимание

	BSW_1	BSW_2	AGN	MN	HESG0	HESG1
N_exp.	369	955	1728+238	2600+300	980	3090
n_par.	7+Regge	11	36	36+7	3+2	6+3
$\sqrt{s}\ GeV$	23.4-630	13.4 - 1800	9.3-1800	5-1800	52-1800	9-7000
$\Delta t\ GeV^2$		0.1 - 5	0,1-2.6	0.1-16	0.000875-10	0.00037-15
$\sum \chi_i^2 / N$	4.45	1.95	1.16	1.23	2.	1.28

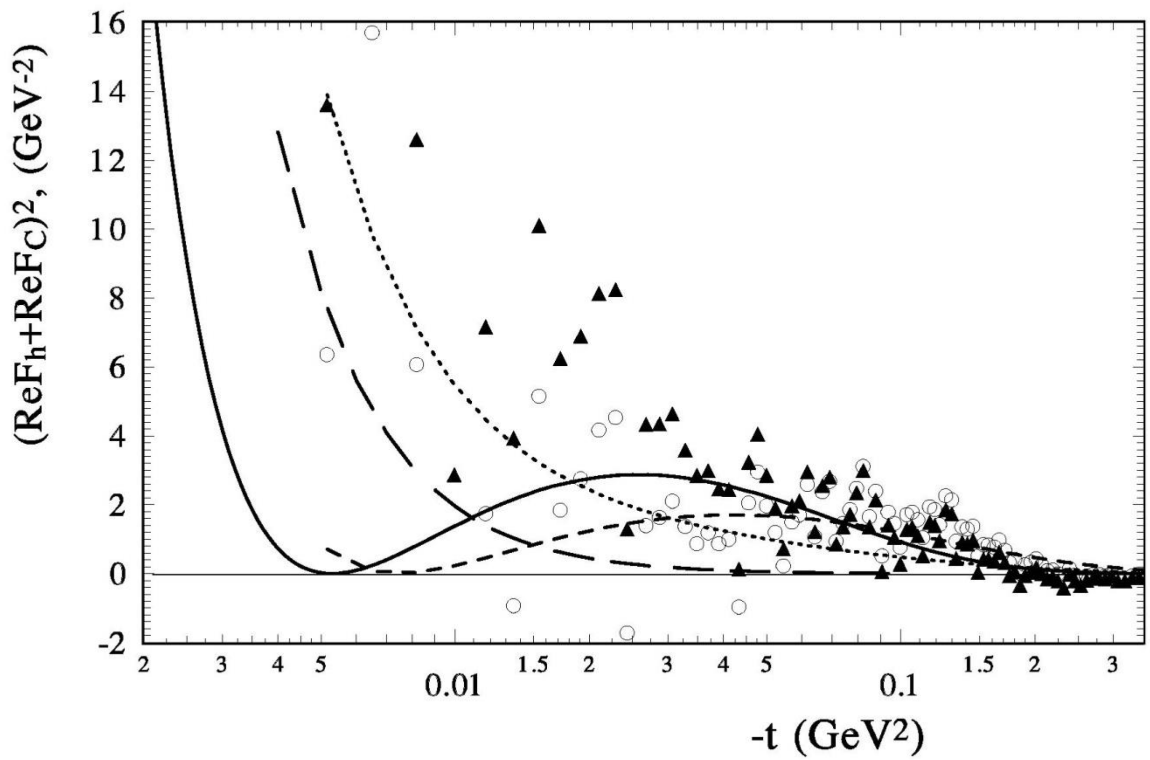
O.S. – J. Nucl.Phys. (Yad.Phys.) v.55 (1992)

$$ReF^h(t) = \quad -ReF_c(t) \qquad (9)$$
$$+ \quad [[\frac{d\sigma}{dt}|_{exp.} - k\pi * (ImF_c + ImF_h)^2]/(k\pi)]^{1/2}.$$

let us take the imaginary part of the hadron scattering amplitude in the simple exponential form with the parameters obtained by the TOTEM Collaboration

$$ImF^h(t) = \sigma_{tot}/(4k\pi)e^{Bt/2}, \qquad (10)$$

O.S. Nucl.Phys. A 922 (2014)



pp - 7 TeV
(TOTEM)

- TOTEM parameters

⬩♉♦◻♦=96.4 mb B=20.3 GeV-2; C=-0.05; n=1.08

TOTEM parameters; ❒=0.141

- - - - ; ⬩tot=96.4 mb; B=19.9 GeV-2; ❒=0.1

— — — — - ❒= 0

. . . . ⬩tot=96.4 mb; B=19.9 GeV-2; ❒= -0.05 ;

Total cross sections

TOTEM **ATLAS**

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

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

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

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

$$\Delta = 3.15\ mb;$$

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

$$\sigma_{tot} = (101.7 \pm 2.9)\, mb$$

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

$$\Delta = 5.63\ mb;$$