LXXV International Conference «NUCLEUS – 2025. Nuclear physics, elementary particle physics and nuclear technologies

Санкт-Петербургский государственный университет

1-6 июля 2025

"…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

Properties of hadrons scattering at super-high (cosmic) energies

хотя асимптотия может быть очень далека, путь к ней лежит не через пустыню, а через цветущий регион захватывающей физики

O.V. Selyugin

(BLTPh, JINR)

$p\bar{p}$

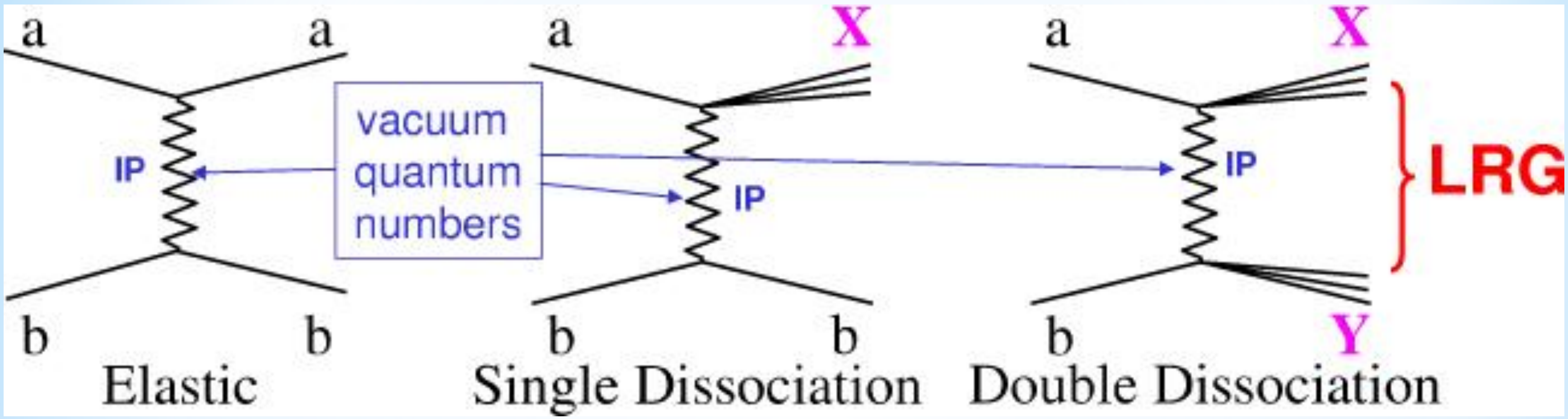
Hadron elastic scattering interactions.

There are some problems as confinement, hadron interaction at larger distances, non-perturbative hadron structure (parton distribution functions (PDFs), generalized parton distributions (GPDs) and others) that should be explored in the framework of the Standard Model.

These problems are connected with the hadron interaction at high and super-high energies and with the problem of energy dependence of the structure of the scattering amplitude and total cross sections.

Researches into the structure of the elastic hadron scattering amplitude at super-high energies and small momentum transfer – t outlines a connection between experimental knowledge and the fundamental asymptotic theorems, which are based on the first principles.

This reflects a tight connection of the main properties of elastic hadron scattering with the first principles of quantum field theory and the concept of the scattering amplitude as a unified analytic function of its kinematic variables which introduce by N.N. Bogolyubov


a
a
IP
vacuum quantum numbers
a
X
IP
a
X
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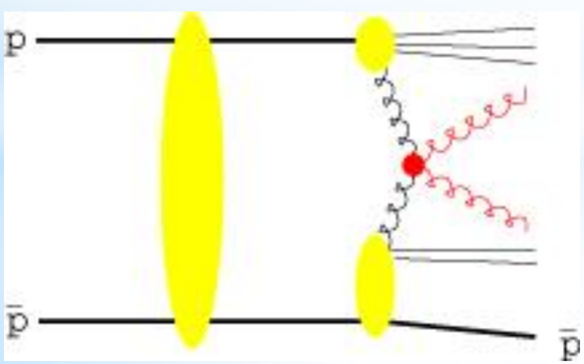
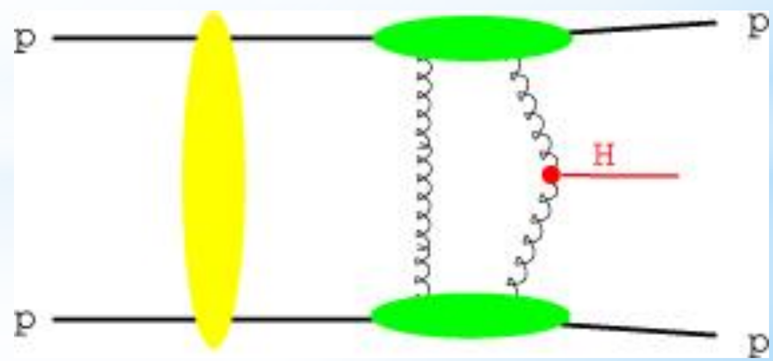
LRG
b
b
Elastic
b
b
Single Dissociation
b
Y
Double Dissociation


p
p̄
p̄


p
p
H
p
p

General properties associated with the phenomenon of diffraction:

1. $\sigma_{tot}(s) \sim (a_o + a_1 \ln s)^2$ Froissart – Martin bound

2. $\rho(s) \cong \dfrac{\pi\, a_1}{(a_o + a_1 \ln s)}$ Derivative dispersion relation

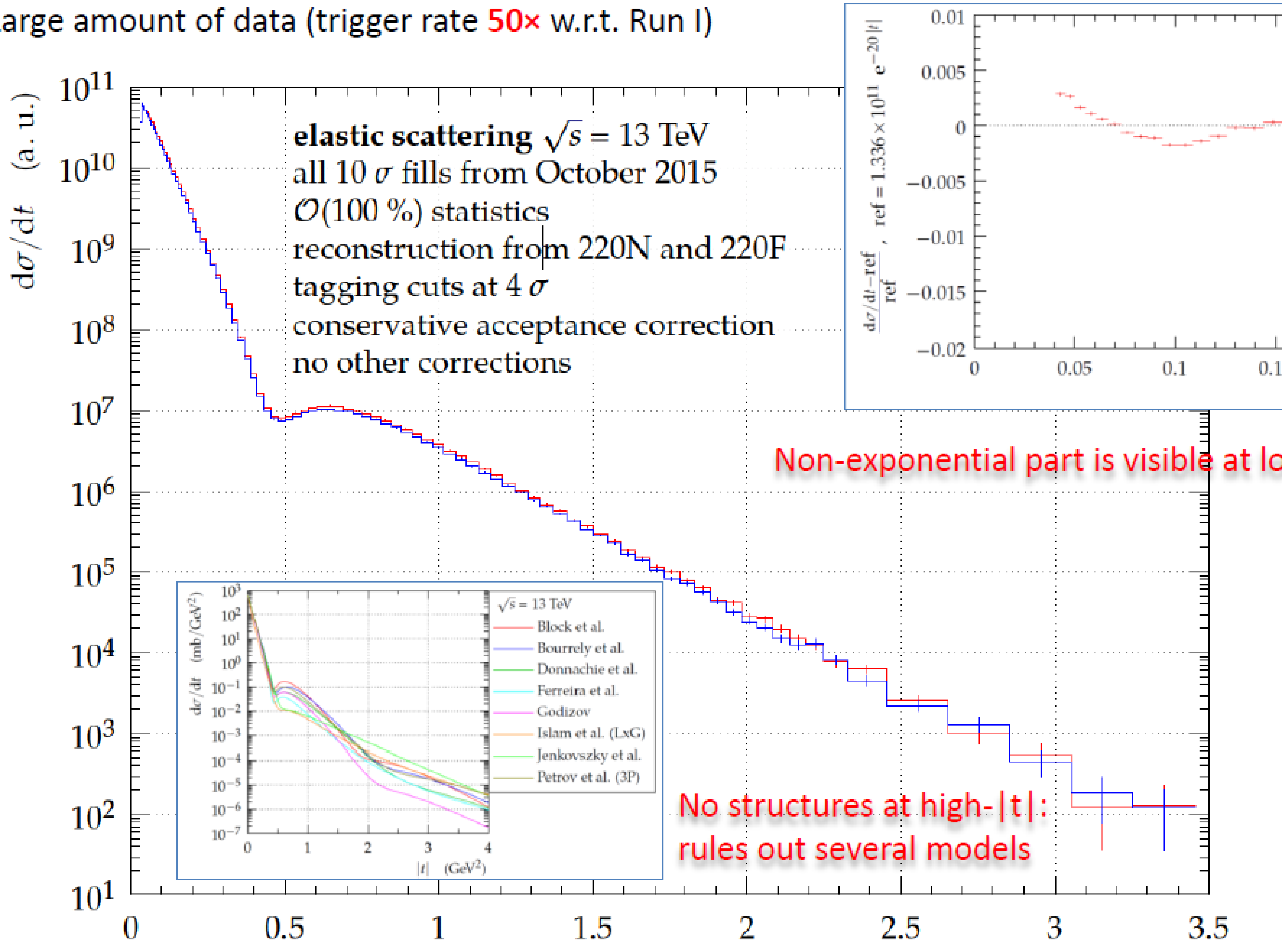
3. $T_D(s,t) \sim i\, s \ln^2 s\; f(|t| \ln^2 s)$ Auberson-Kinoshita-Martin scaling

4. $T_D^{\bar{p}p}(s,t) = T_D^{pp}(s,t)$ Crossing even

Frankfurt, Strickman, Weiss, and Zhalov (hep-ph/0412260)

Note:

- Large amount of data (trigger rate 50× w.r.t. Run I)



t = 0

Pomeron $\operatorname{Im} F_+(s,t=0) \sim s(\ln s)^2;\qquad \operatorname{Re} F_+(s,t=0) \sim s(\ln s);$

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

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

*

The Froissart bound

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

* The Very Low t Region

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

⇒INTERFERENCE

CNI = Coulomb – Nuclear Interference

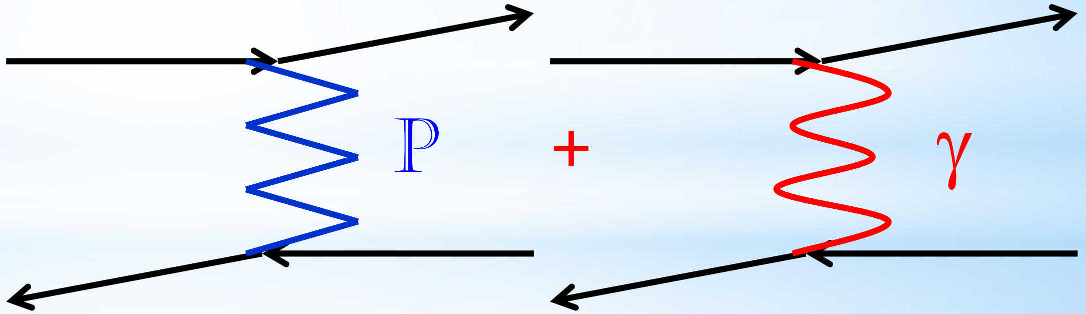
scattering amplitudes modified to include also electromagnetic contribution

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

hadronic interaction described in terms of Pomeron (Reggeon) exchange

electromagnetic single photon exchange

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



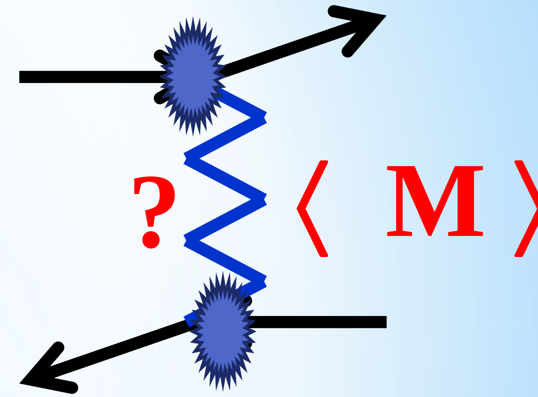
unpolarized ⇒ clearly visible in the cross section dσ/dt

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



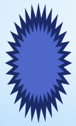
observables:

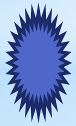
3 ×-sections

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

Regge-eikonal High Energy Generalized Structure (HEGS) model,

Generalized parton distributions;

electromagnetic and gravitomagnetic form factors,

differential cross sections ($-t = 10 - 15$ GeV)

and spin correlations $A_N(s, t)$

a feature of the differential cross sections at high energies;
hadron potential at large distance and

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

Обобщенные партонные распределения

Generalized Parton Distributions -GPDs

Electromagnetic
form factors
(charge
distribution)

Gravitomagnetic
form factors
(matter distribution)

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

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

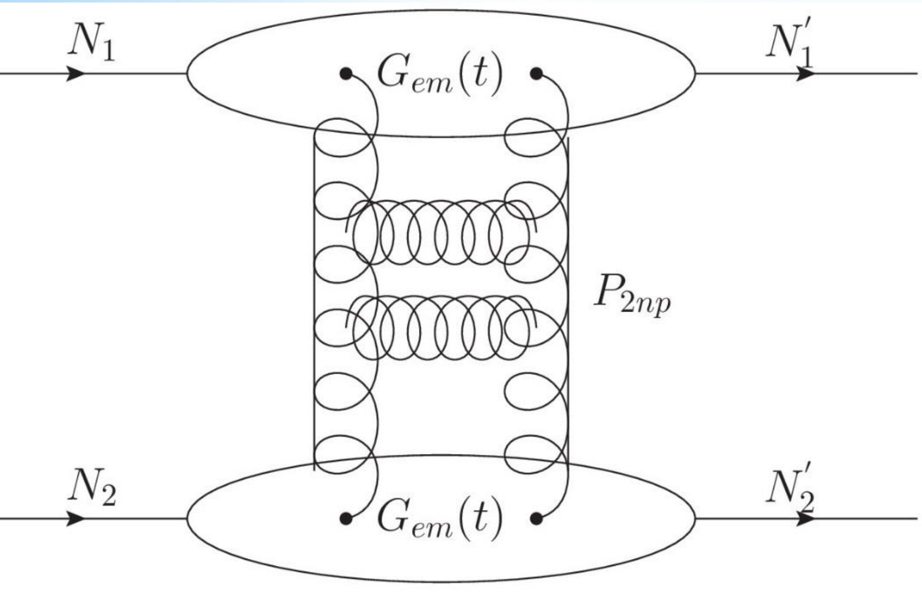
$$G_A(t) = \frac{\Lambda_A^4}{(\Lambda_A^2 - t)^2};$$

Gravimagnetic form factor

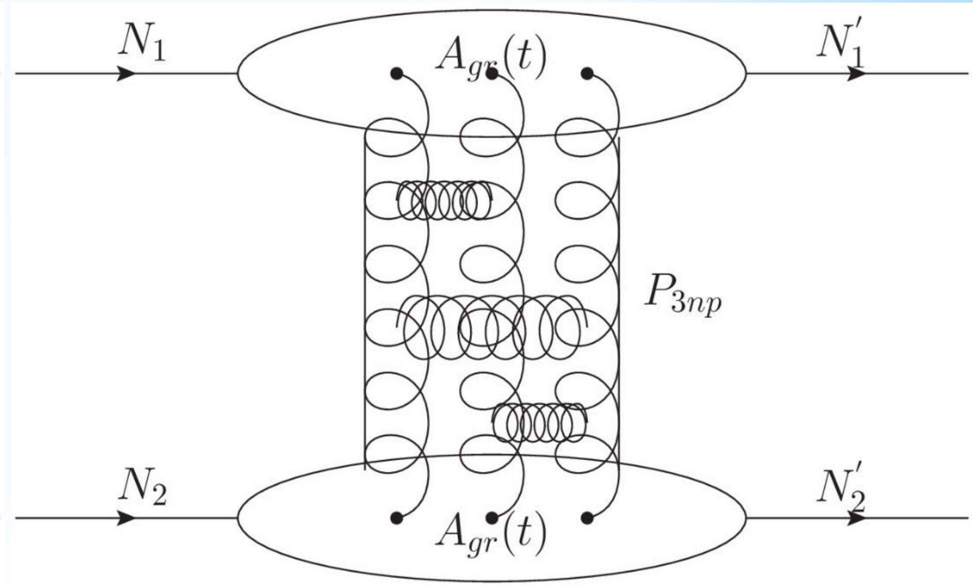
$$\int_{-1}^{1} dx \;\; x\,[\,H^{q}\left(x,\xi,t\right) + E^{q}\left(x,\xi,t\right)] = A_{q}(\Delta^{2}) + B_{q}(\Delta^{2})\,;$$

$$A^{q}(t) = \int_{0}^{1} dx \;\; x \;\; \mathcal{H}^{q}\left(x,t\right); \qquad B^{q}(t) = \int_{0}^{1} dx \;\; x \;\; \boldsymbol{\mathcal{E}}^{q}\left(x,t\right);$$

“Future studies using higher-statistics data will be crucial to justify or falsify model assumptions about the kinematic dependence of the GPDs.

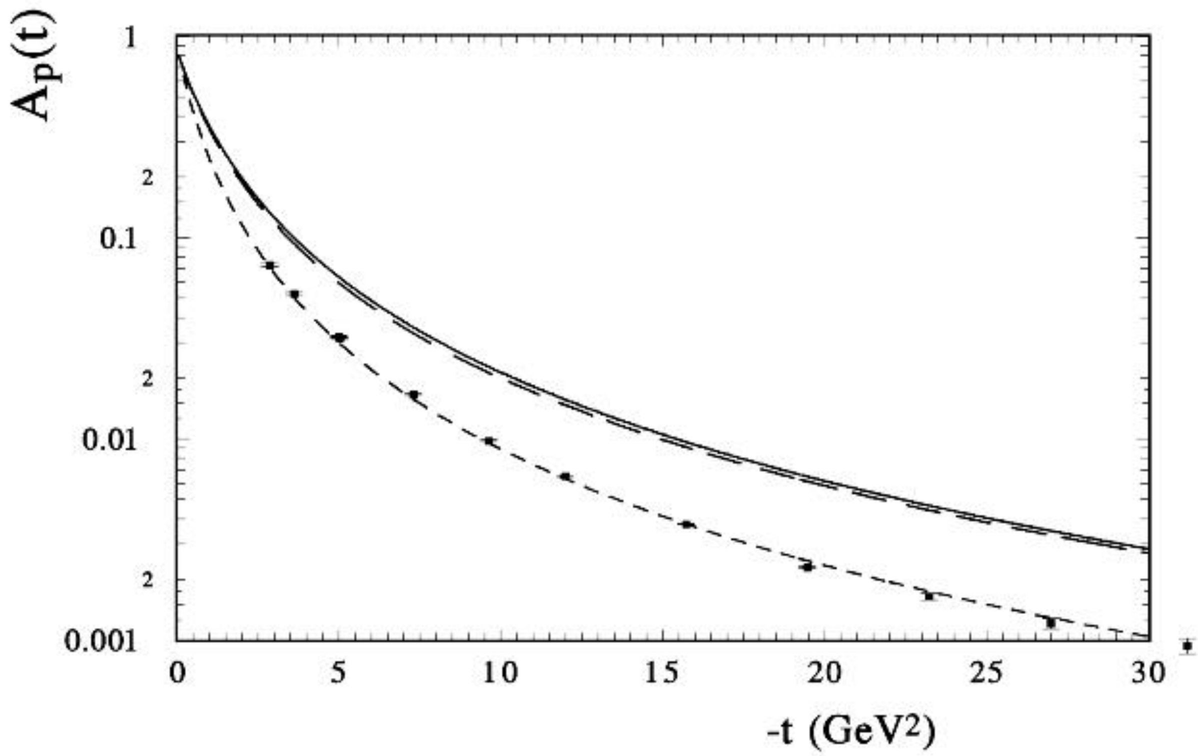


N_1
$G_{em}(t)$
N_1'
P_{2np}
N_2
$G_{em}(t)$
N_2'

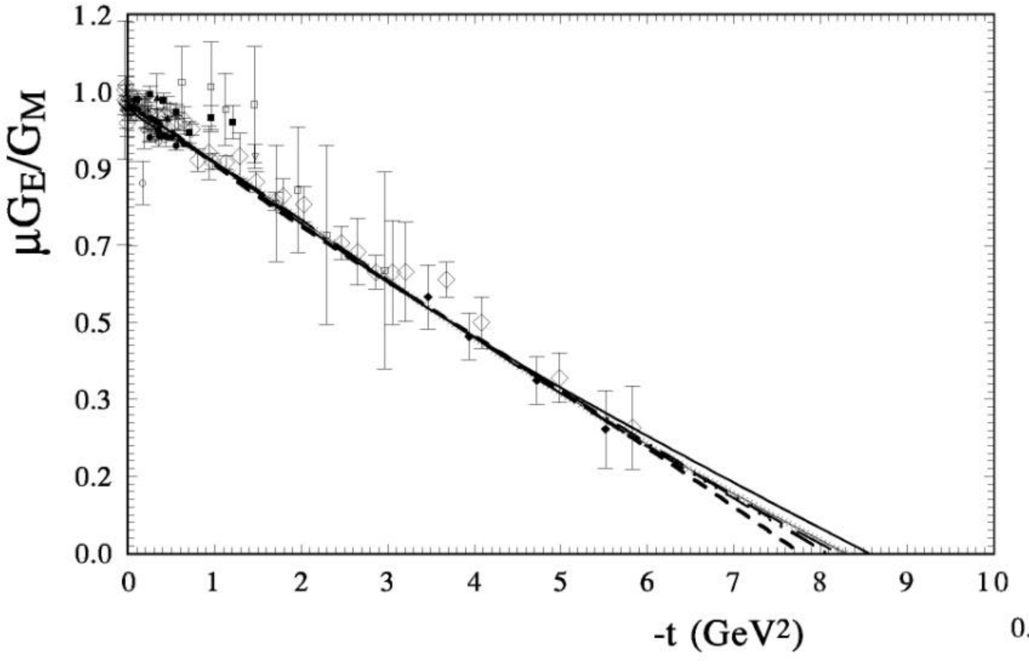


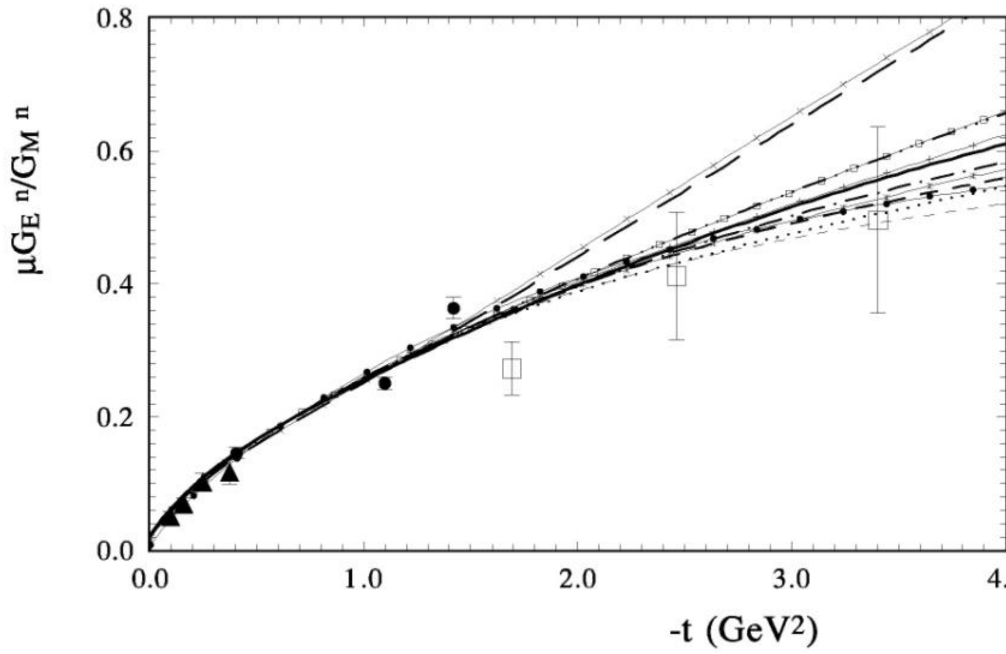
N_1
$A_{gr}(t)$
N_1'
P_{3np}
N_2
$A_{gr}(t)$
N_2'

* A(t) Gravitational form factor A and proton Dirac F_1



O.V.S., Phys. Rev., D 89, 093007-22, 2014





“TOMOGRAPHY” of NUCLEONS

M.Burkardt Phys.Rev, D74(2004)

$$\rho_0^N(\vec{b}) = \frac{1}{2\pi}\int_0^\infty\int_0^1 dx\, qdq\, J_0(qb)\, H(q,x)$$

$$q_y(x,\vec{b}_T) = \frac{1}{2M}\frac{\partial}{\partial b_y}\int_0^\infty d^2\vec{\Delta}_T\, e^{i\vec{b}_T\vec{\Delta}_T}\; E_q(x,0,-\vec{\Delta}_T),$$

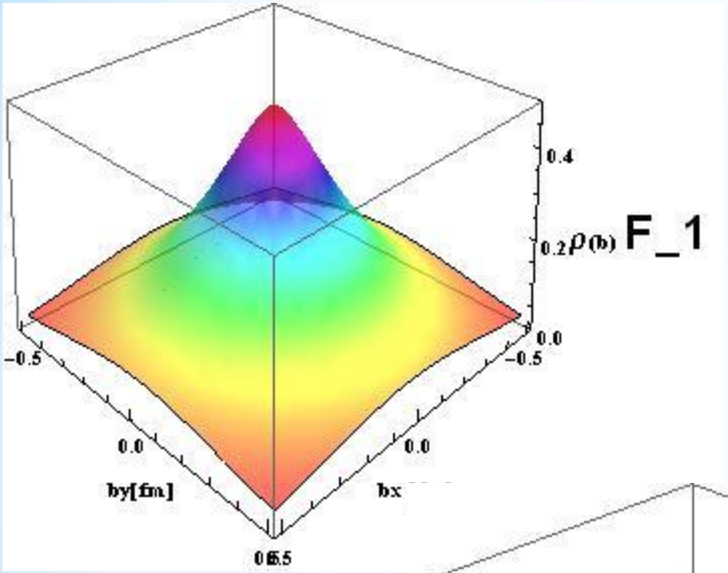
C.Carlson, M. Vanderhaeghen

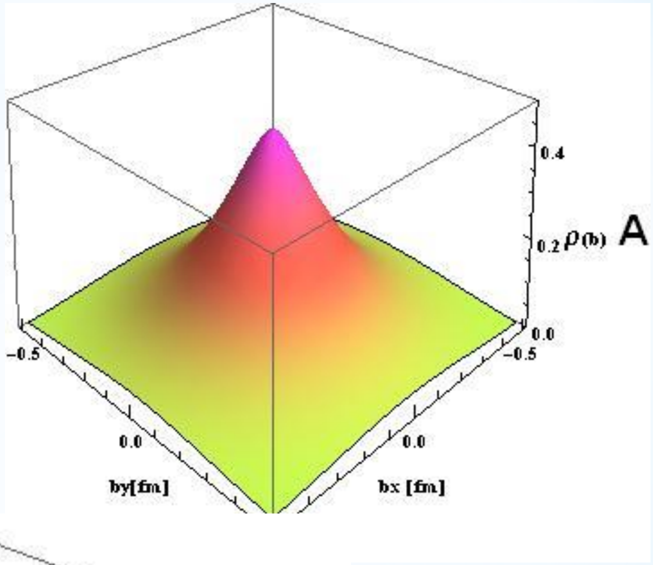
Phys.Rev.Lett., 100,(2008)

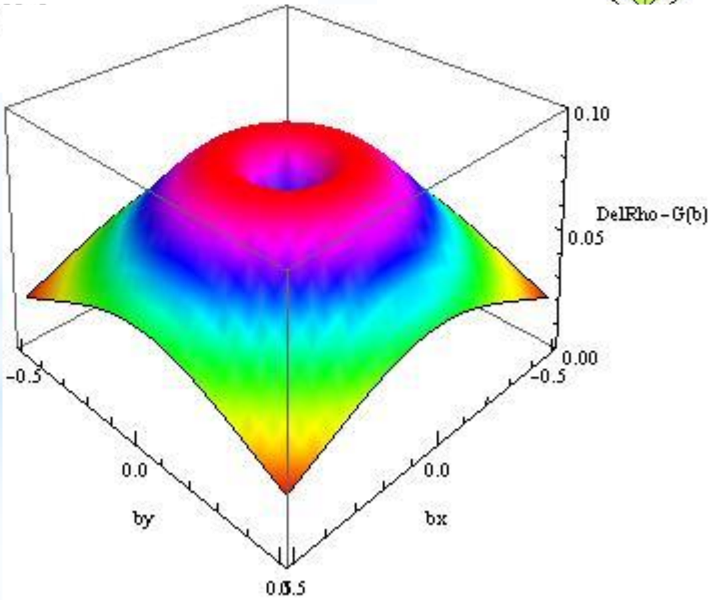
$$\vec{b} = b[\cos(\varphi_b\widehat{e}_x) + \sin(\varphi_b\widehat{e}_y)]$$

$$\rho_T^N(\vec{b}) = \rho_0^N(\vec{b}) - \sin(\varphi_b)\frac{1}{2\pi}\int_0^\infty\int_0^1 dx\,\frac{q^2}{2M_N}dq\, J_1(qb)\, E(q,x)$$

Proton - Del = (F1_em – A_gr)







Extending of model (HEGS2) – O.V. S. Phys.Rev. D 91, (2015) 113003
O.V. S., Phys. At. Nucl. V. 87, **(2024)**

$$3.6 \leq \sqrt{s} \leq 13000\, GeV; \quad 0.000003 < |t| < 14\ GeV^2; \qquad \hat{s} = s / s_0\, e^{-i\pi/2};$$

$$n = 4326 + 526; \quad 90\ sets\ of\ \exp eriments. \qquad s_0 = 4m_p^2.$$

$$F_2^B(s,t) = h_2 G_{em}(t)\ (\hat{s})^{\Delta_1} e^{\alpha_1 t \ln(\hat{s})}; \ \ F_3^B(s,t) = h_3 G_A(t)^2\ (\hat{s})^{\Delta_1} e^{\alpha_1/4 t \ln(\hat{s})};$$

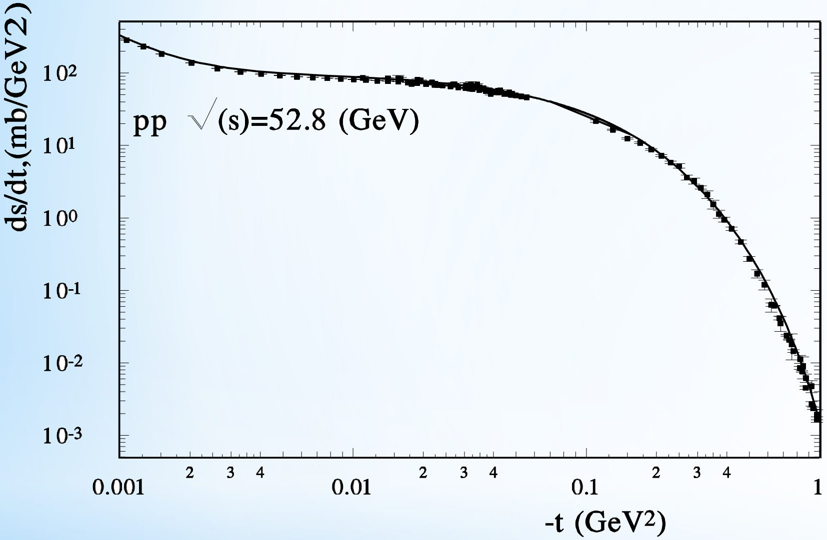
$$F^B(\hat{s},t) = F_2^B(\hat{s},t)(1 + R_1/\sqrt{\hat{s}}\ )] + F_3^B(\hat{s},t) + F_{odd}^B(s,t);$$

$$F_{Odd}^B(s,t) = h_{Odd}\ G_A(t)^2\ (\hat{s})^{\Delta_1}(h_{as} + r_2/(\sqrt{s}\ )^{0.75})\ \frac{t}{1 - r_o^2 t} e^{\alpha_1/4 t \ln(\hat{s})};$$

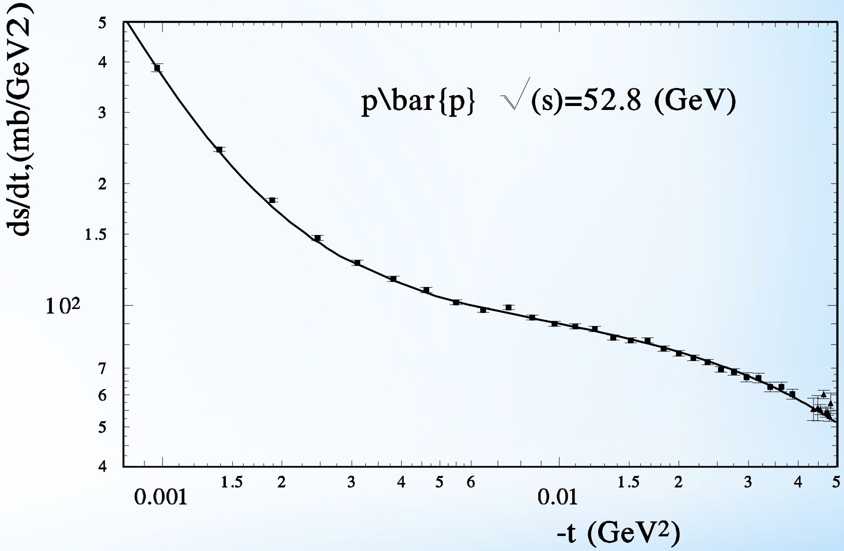
$$B(t) = (\alpha_1 + k_0\, q\, e^{k_0\, t\, ln\hat{s}}\ ) \ln \hat{s}.$$

TABLE I. The simultaneously fit of the sum of all sets of different reactions from $\sqrt{s}$ = 3.6 GeV up to $\sqrt{s}$ = 13 TeV

Reac.	N_exp.	$\sqrt{s}$ *min* GeV	$\sqrt{s}$ max GeV	$-t$, min GeV^2	$-t$, max GeV^2	$\sum \chi_j^2$;	$\sum \chi_{tot}^2$;
pp	3170	6.4	13000	0.00029	14	3579	
$p\bar{p}$	921	3.52	1960	0.001	3	947	
$A_N(s,t)$;	235	3.6	23.5	0.01	3	263	
$\sum \chi_{ij}^2$;	4326	3.6	13000	3 10^(-4)	14		4789
pn	536	4.6	27.4	10^(-6)	1.8	601	
$\pi^{\pm} p$	2009	7.8	23.5	0.014	10	2415	

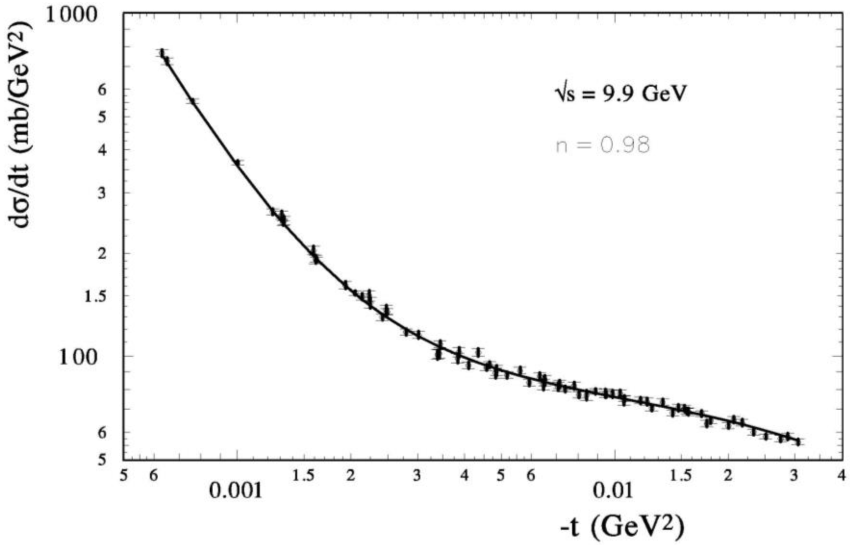


ds/dt,(mb/GeV2)
pp √(s)=52.8 (GeV)
10^2
10^1
10^0
10^-1
10^-2
10^-3
0.001
0.01
0.1
1
-t (GeV2)

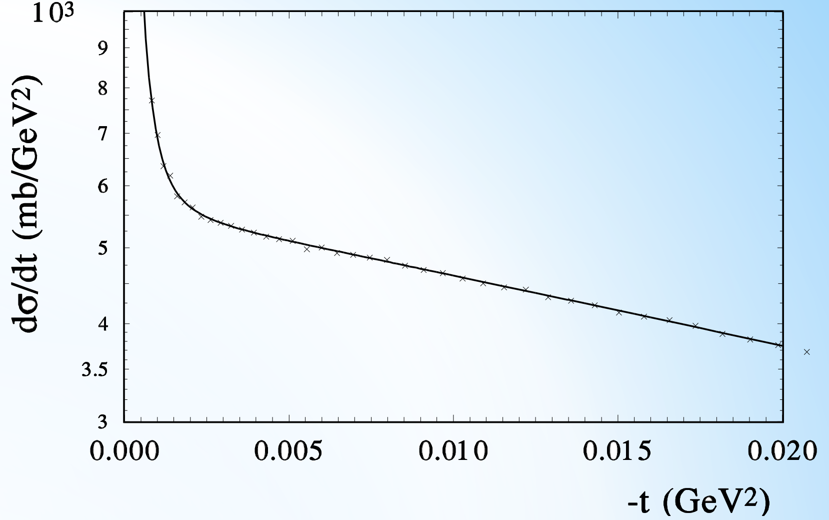


ds/dt,(mb/GeV2)
p\bar{p} √(s)=52.8 (GeV)
10^2
0.001
0.01
-t (GeV2)

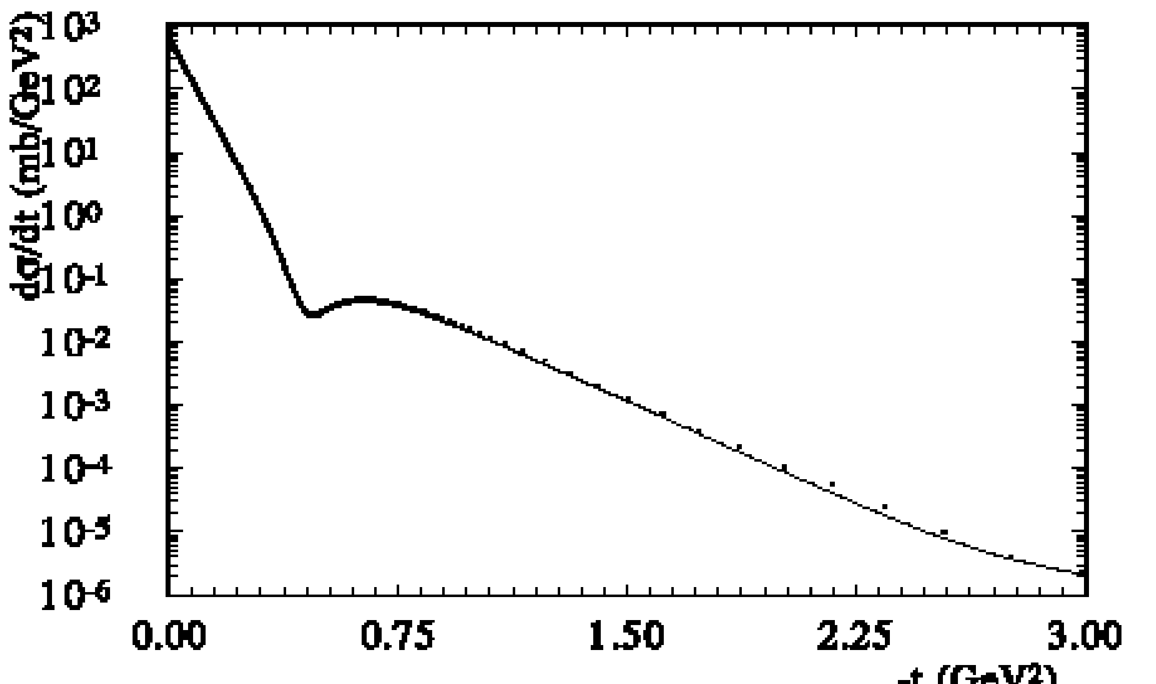
Ch-III



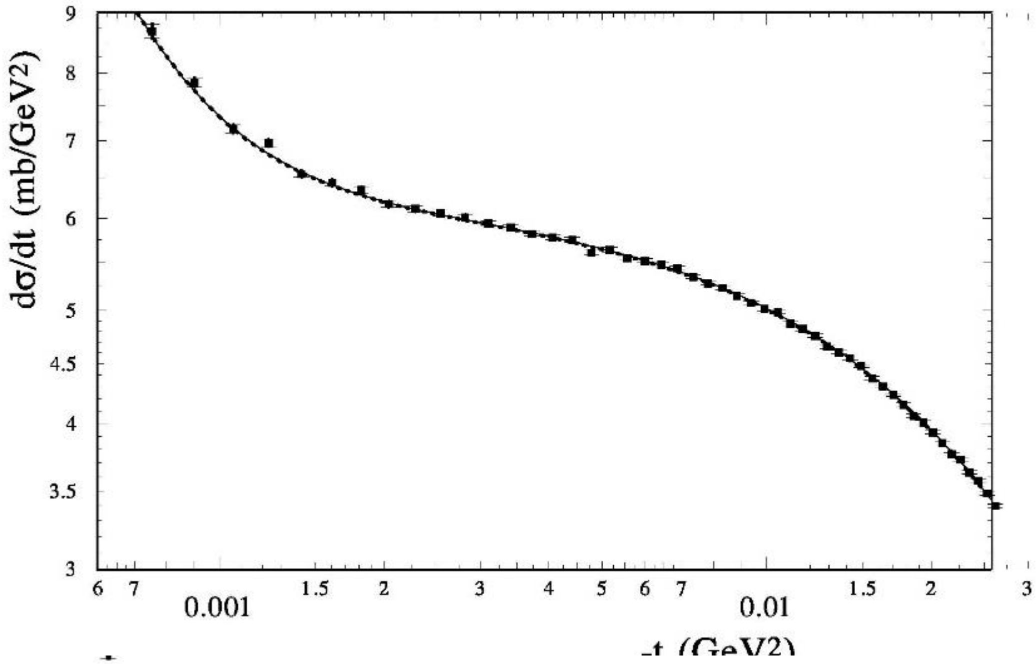
1000
100
dσ/dt (mb/GeV2)
√s = 9.9 GeV
n = 0.98
0.001
0.01
-t (GeV2)

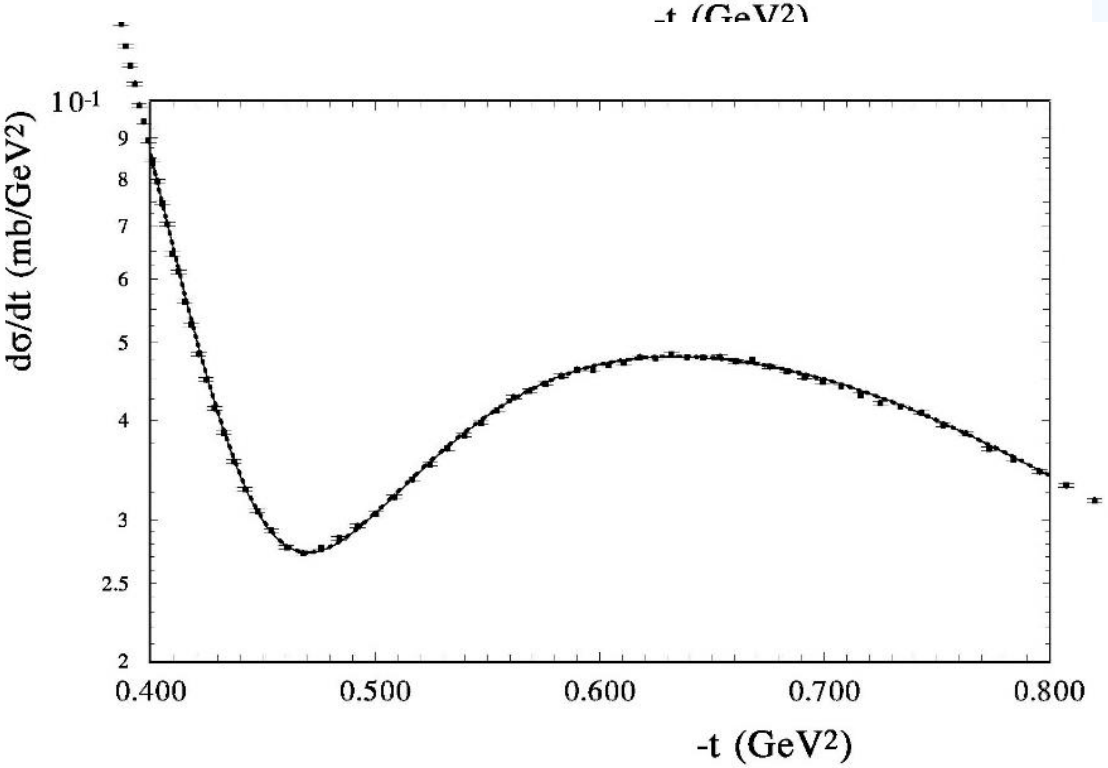


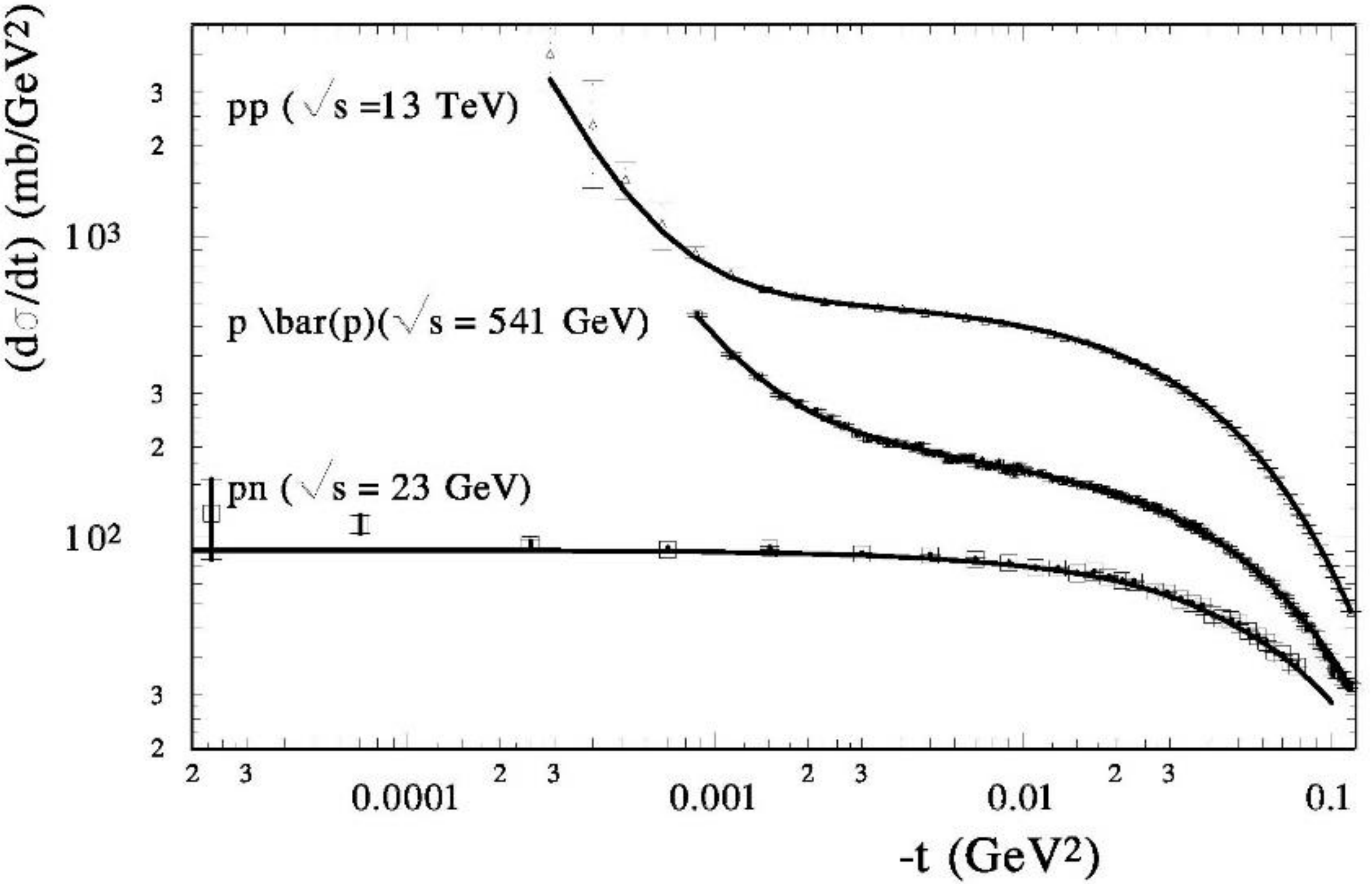
103
dσ/dt (mb/GeV2)
0.000
0.005
0.010
0.015
0.020
-t (GeV2)



dσ/dt (mb/GeV2)
0.00
0.75
1.50
2.25
3.00

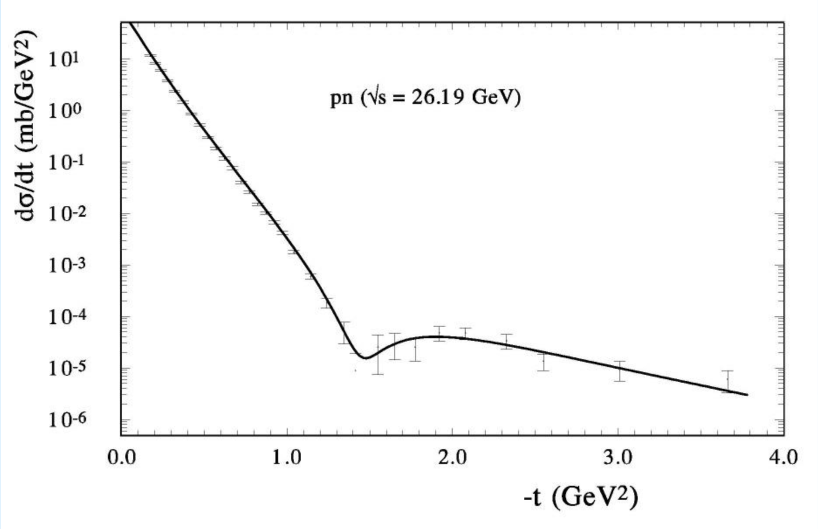

dσ/dt (mb/GeV2)
-t (GeV2)
0.001
0.01

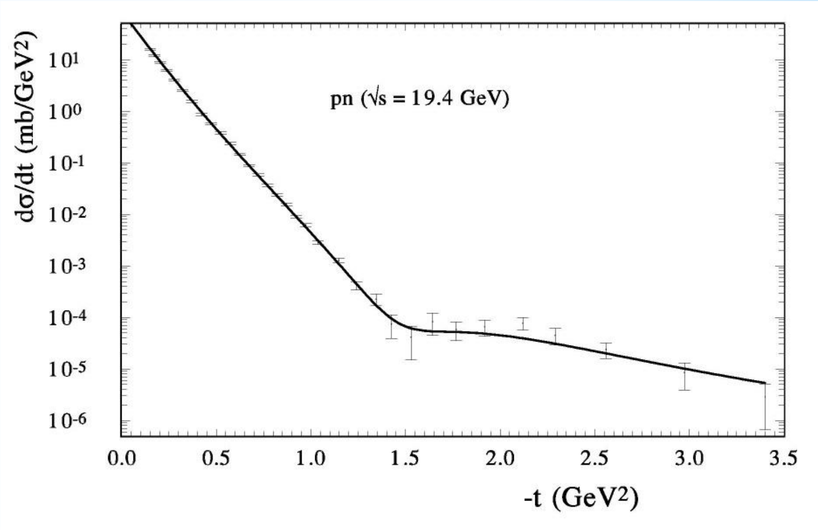

dσ/dt (mb/GeV2)
10-1
0.400
0.500
0.600
0.700
0.800
-t (GeV2)

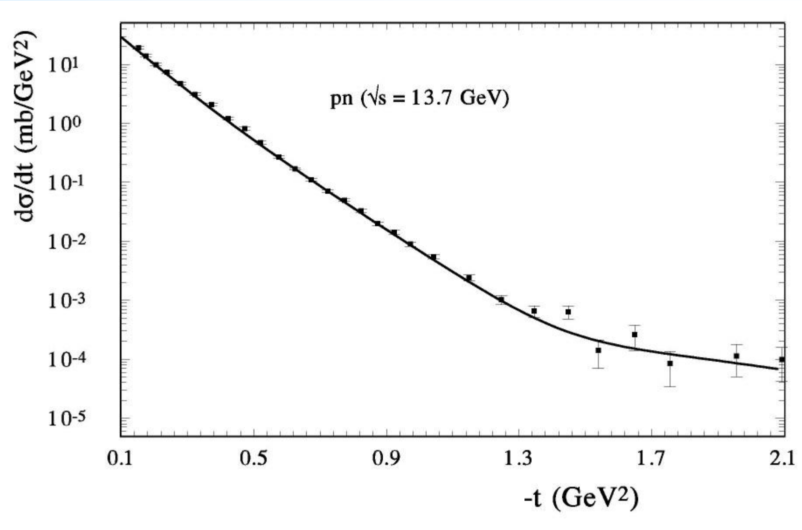


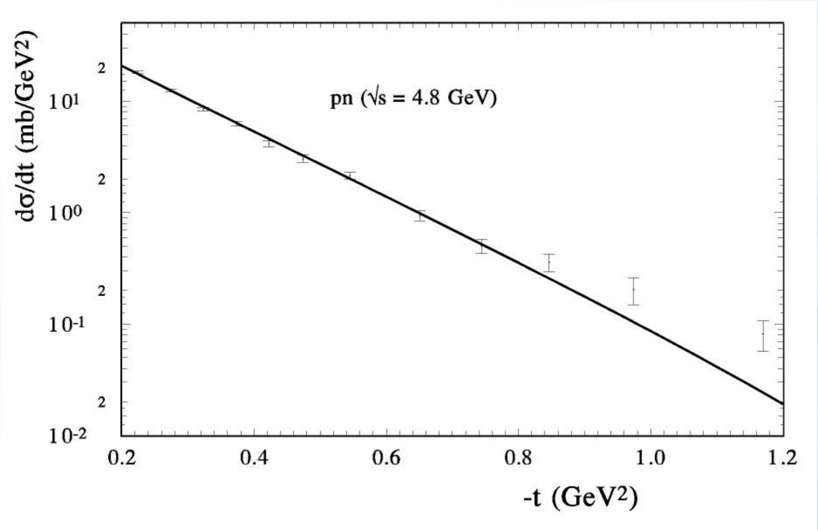
(dσ/dt) (mb/GeV2)
pp (√s =13 TeV)
p \bar(p)(√s = 541 GeV)
pn (√s = 23 GeV)
10^3
10^2
0.0001
0.001
0.01
0.1
-t (GeV2)

proton – neutron elastic scattering

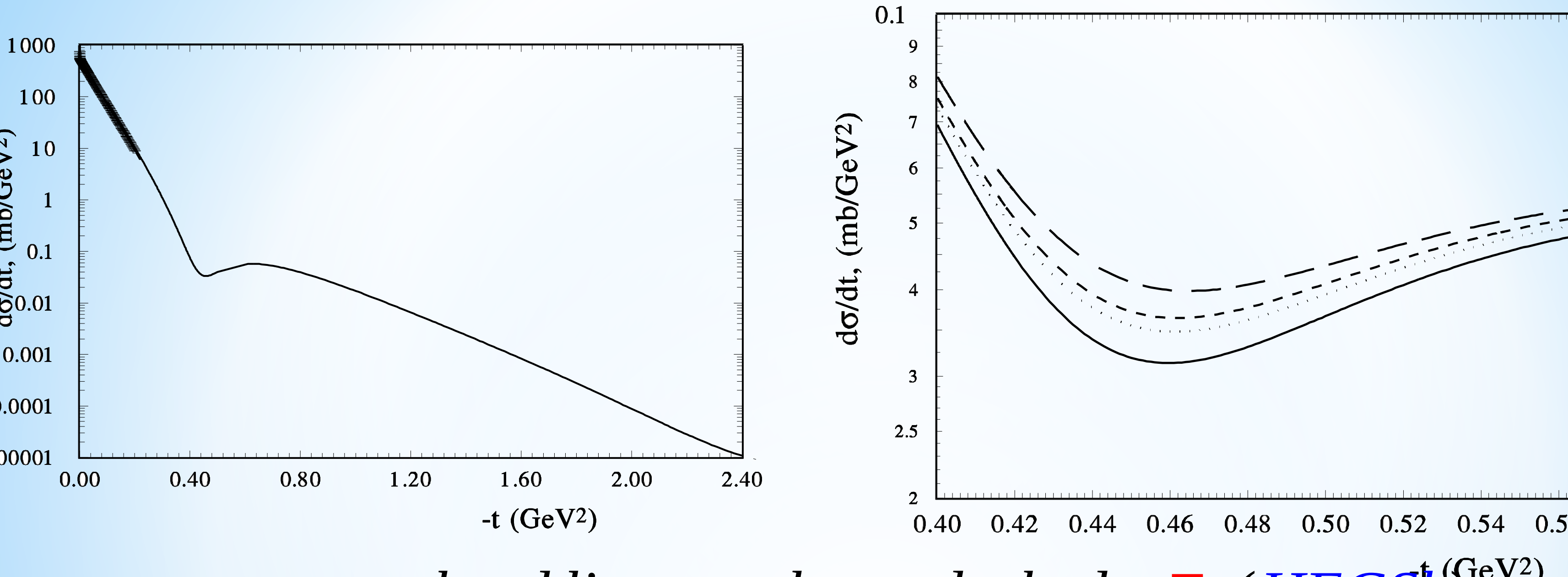








Diffraction (2018) Odderon and LHC data



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

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

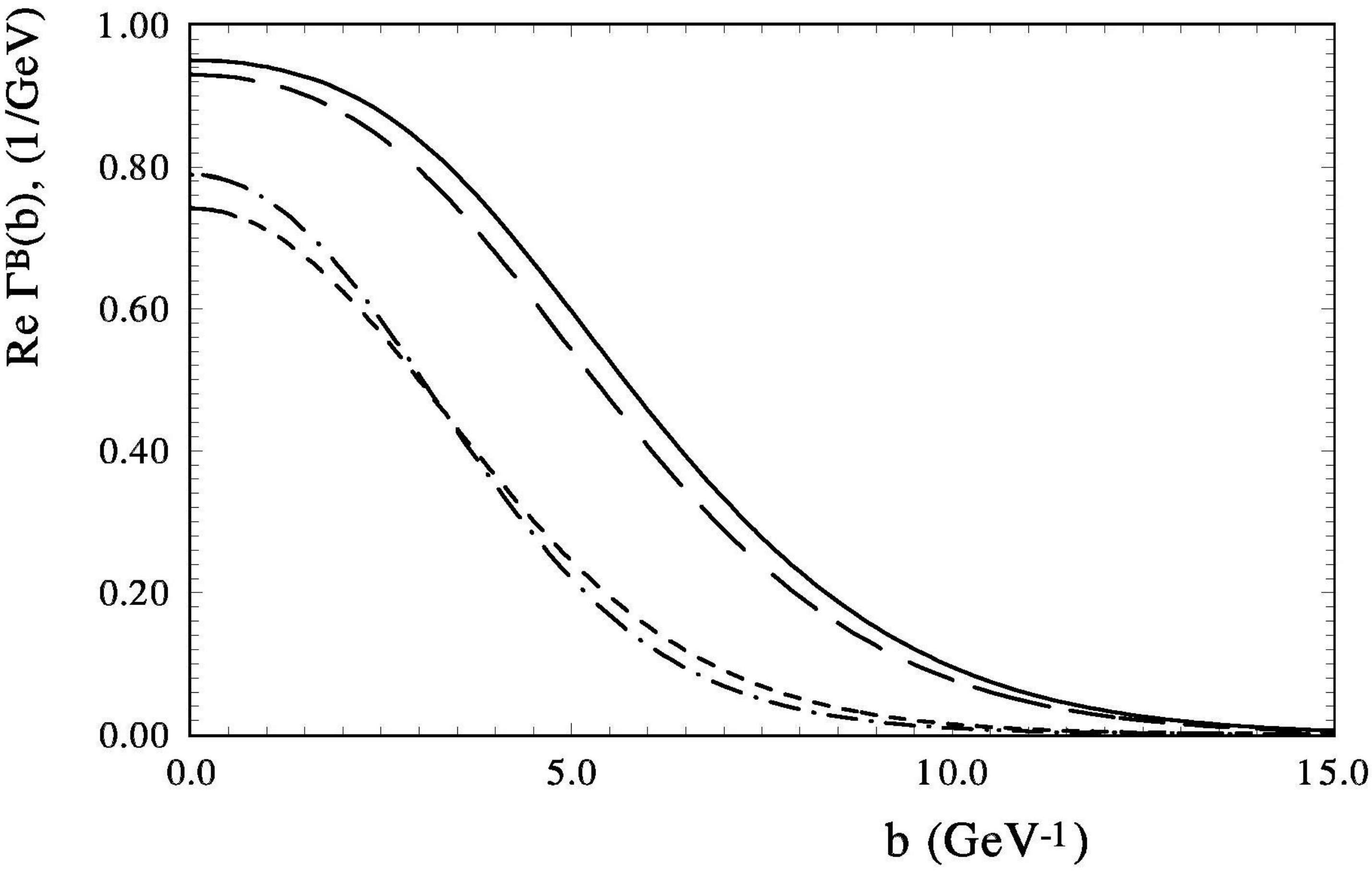
$$HEGSh\ \rightarrow -t_{\min} = 0.46\,GeV^2;\ -t_{\max} = 0.62\,GeV^2;\ R = 1.78;$$

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

Nemez, talk on workshop , May 28 (2018)

$$F(s,t) = \frac{i}{2\pi}\int_0^\infty b\, e^{i\vec{q}\vec{b}}\, J_0(b\,q)\ \Gamma(s,b)\, db$$

$$\Gamma(s,b) = [1 - e^{-\chi(s,b)}]$$



$\sqrt{s} = 14\ TeV$

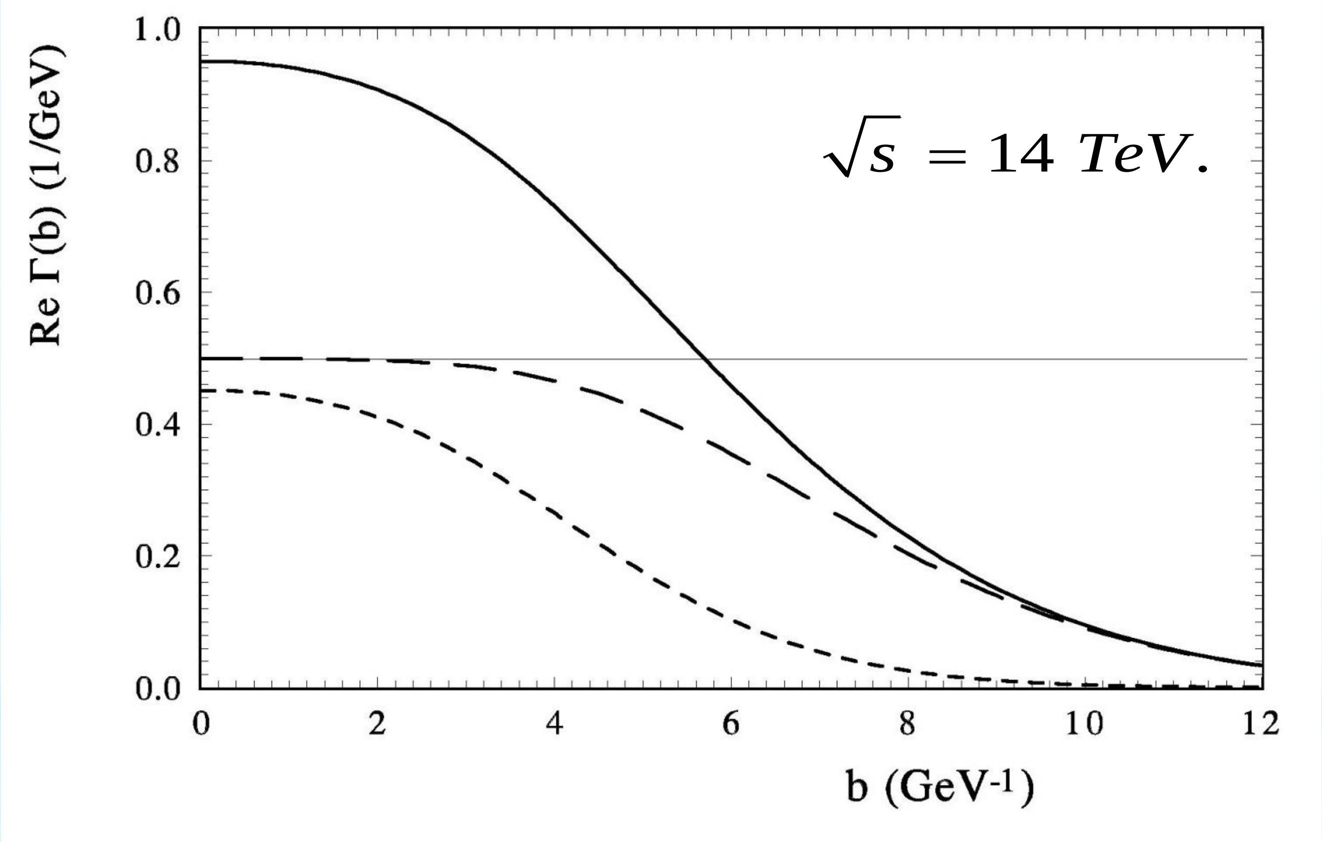
$\sqrt{s} = 7\ TeV$

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

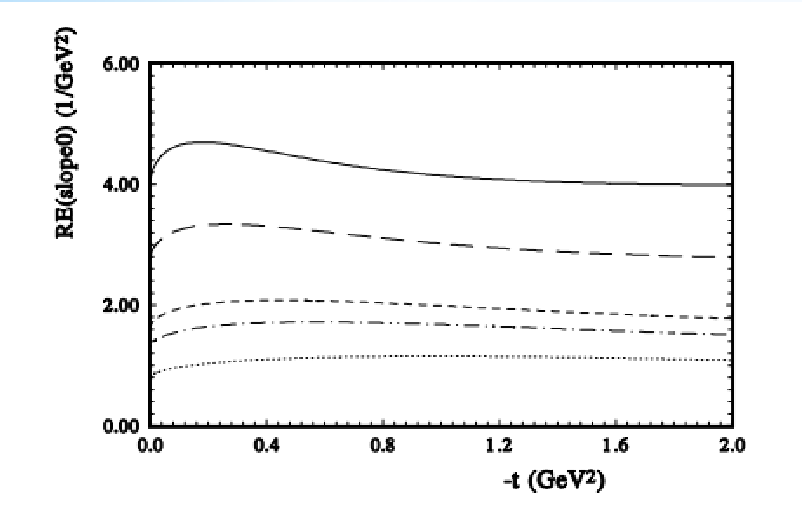
$\sqrt{s} = 9.8\, GeV$

$$\Gamma_{tot}(s,b) = [1 - e^{-\chi(s,b)}]$$

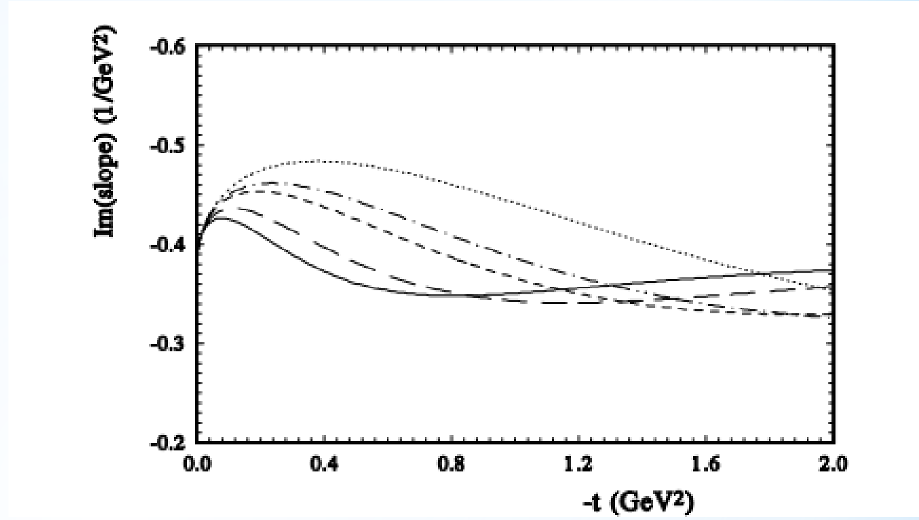
$$\Gamma_{el}(s,b) = [1 - e^{-\chi(s,b)}]^2; \; \Gamma_{inel}(s,b) = [1 - e^{-2\chi(s,b)}]$$



$$B(s,t) \ = (\alpha_1 + kqe^{-kq^2 Ln(\hat{s}\ t)})Ln(\hat{s}).$$



The real part of $B(s,t)$

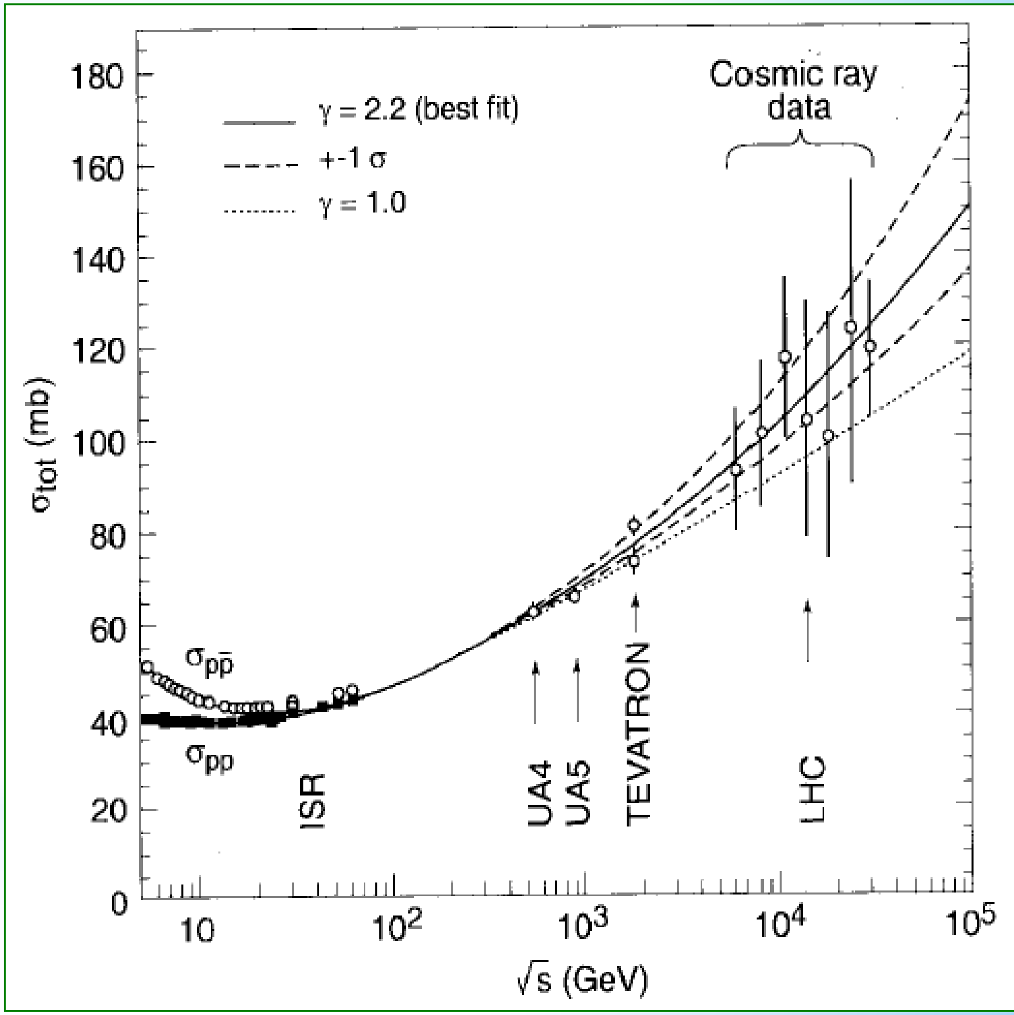


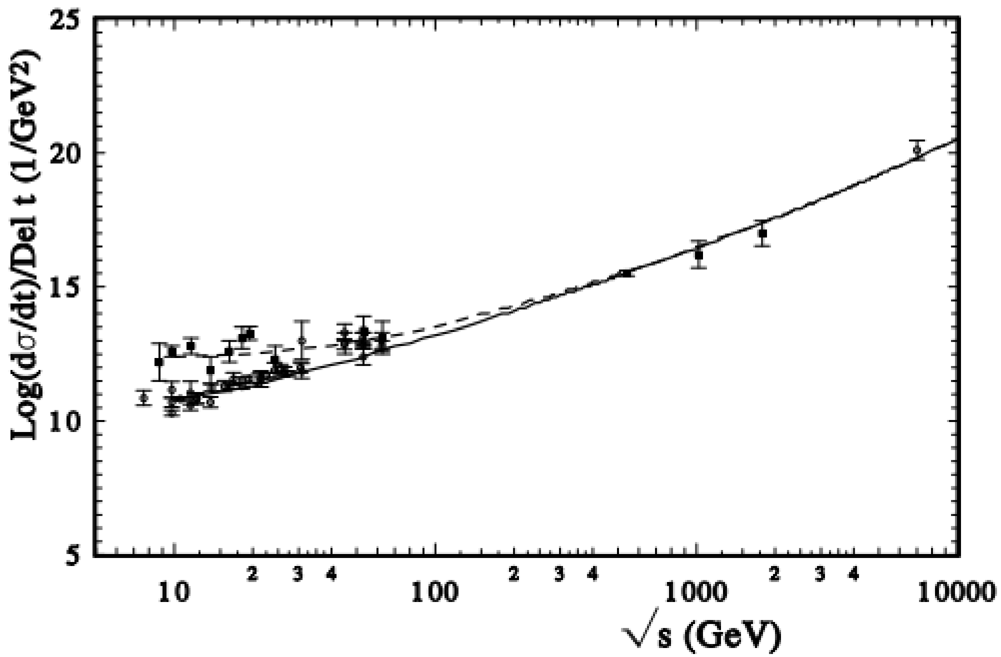
the imaginary parts of $B(,t)$

the the pp elastic scattering amplitudes at $\sqrt{s} = 7$ TeV (solid line), $\sqrt{s} = 541$ GeV (long-dashed line), $\sqrt{s} = 52.8$ GeV (dashed line), $\sqrt{s} = 27.4$ GeV (dashed-dotted line), $\sqrt{s} = 9.8$ GeV (dotted line).

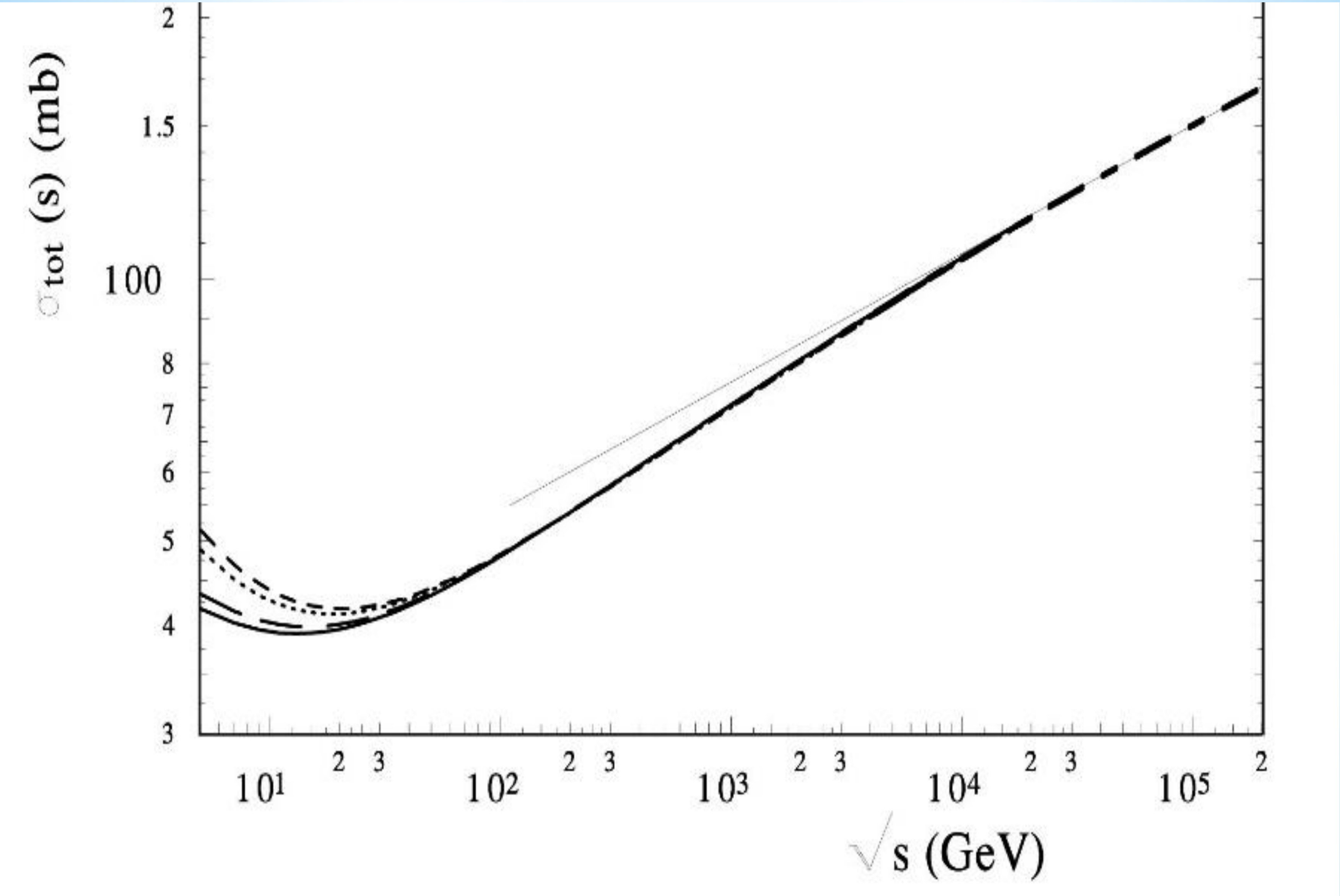
Total cross-section

- Understand the asymptotic behavior of σ_{tot}





The energy dependence of the forward elastic slope compared to the existing experimental data for pp (hard line and open circles) and $p\bar{p}$ (dashed line and squares) scattering.



σtot (s) (mb)
2
1.5
100
8
7
6
5
4
3
10¹
2
3
10²
2
3
10³
2
3
10⁴
2
3
10⁵
2
√s (GeV)

Non-exponential behavior (origins)

1. Non-linear Regge trajectory

   a) Contributions of the meson cloud (J.Pumplin, G.L. Kane; O.V.S.)

   b) Pion loops (Anselm, Gribov, Khoze, Martin; Jenkovski et al.)

2. Different slopes of the other contributions
   (real part, odderon, spin-flip amplitude)

3. Unitarization

arXiv: 2009.10129 [hep-ph, hep-ex] (2020).
(accepted in Mod.Phys.Lett. A)

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

$$F_d(t) = i\, h_d Ln(\hat{s}/s_0)[1 + h_{d1} Ln(\hat{s}/s_0)]/k\, e^{-\alpha_d (|t| + (2t)^2)\, Ln(\hat{s}/s_0)};$$

The parameters of the additional term are well defined
$h_d = 1.07 \pm 0.02$; $\alpha_d = 0.516 \pm 0.018$;

K. Chadan, A. Martin: "Scattering theory and dispersion relations for a class of long-range oscillating potentials", CERN (1979)

$$V(r) \sim \sin[\exp(\mu r)]/(1+r^2)^2;$$

2. a) Van-der-Waals potential $V_{ad} \sim h/r^4$

b) F. Ferrer, M. Nowakowski (1998)
(Golstoun boson – long range forces) $V_{ad} \sim h/r^3$

3. S-L interaction

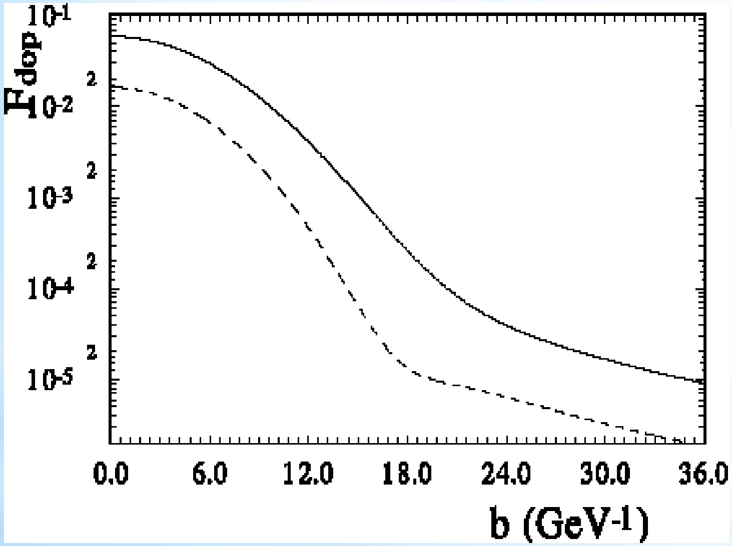
$$F_C(s,t) + F_{ad}(s,t) = is\int_0^\infty b\,db\,J_0(bq)[(1-e^{\chi_c(s,b)}) + \chi_{LS}^2(s,b)]$$

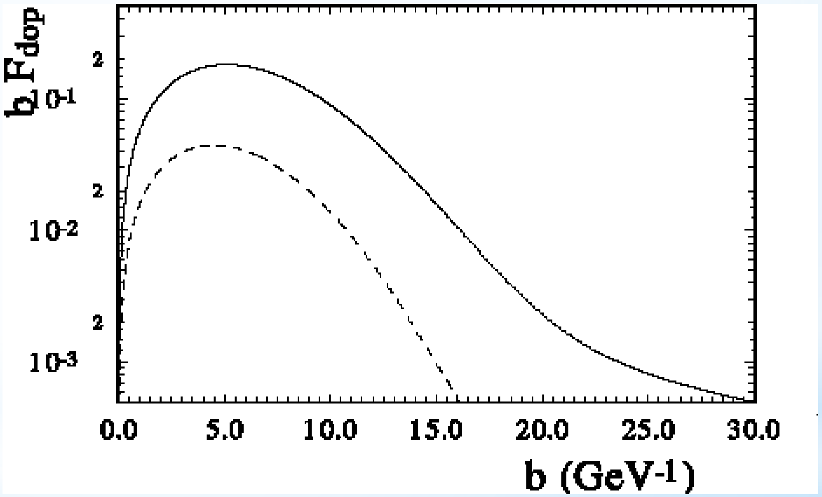
4. N-dimensional gravipotential (ADD-model)
Oscillations"- I. Aref'eva [1007.4777:arXiv-hep-ph]

$$F_{ad}(s,t) \sim \frac{s}{M_d^2};$$

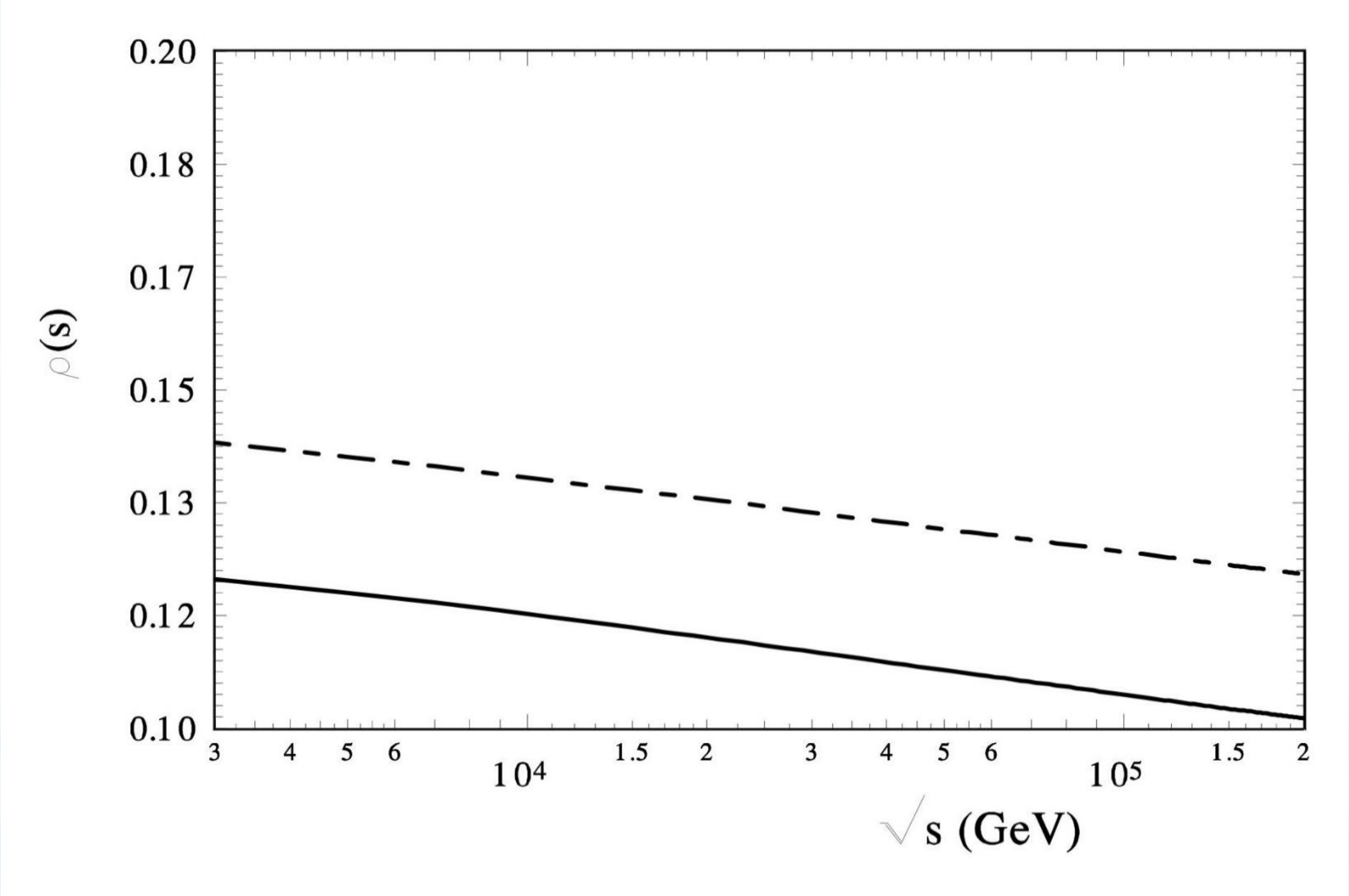
Universal scenario?

The amplitude F_dop(b) in the impact parameter representation



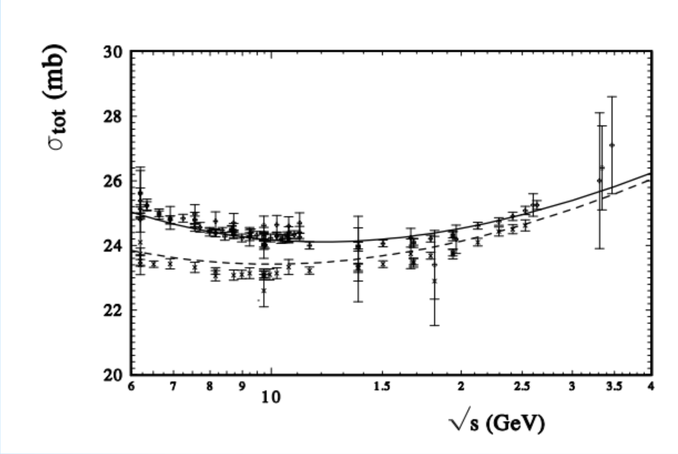


hard line – the real part; dashed line – the imaginary part

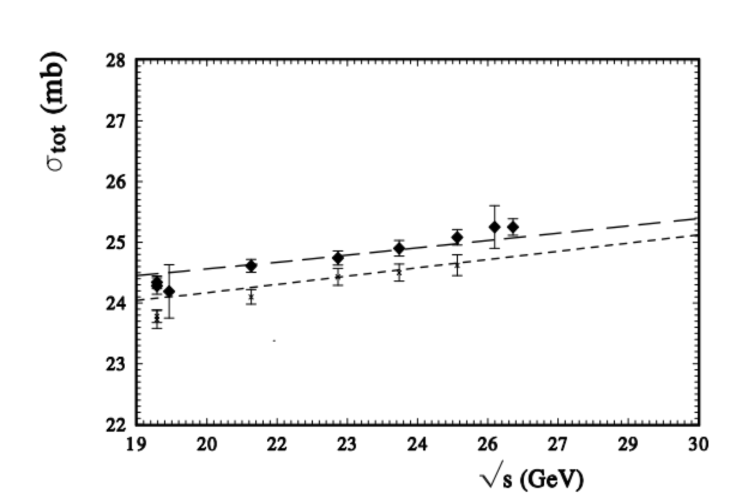


0.20
0.18
0.17
0.15
0.13
0.12
0.10
ρ(s)
3
4
5
6
10^4
1.5
2
3
4
5
6
10^5
1.5
2
√s (GeV)

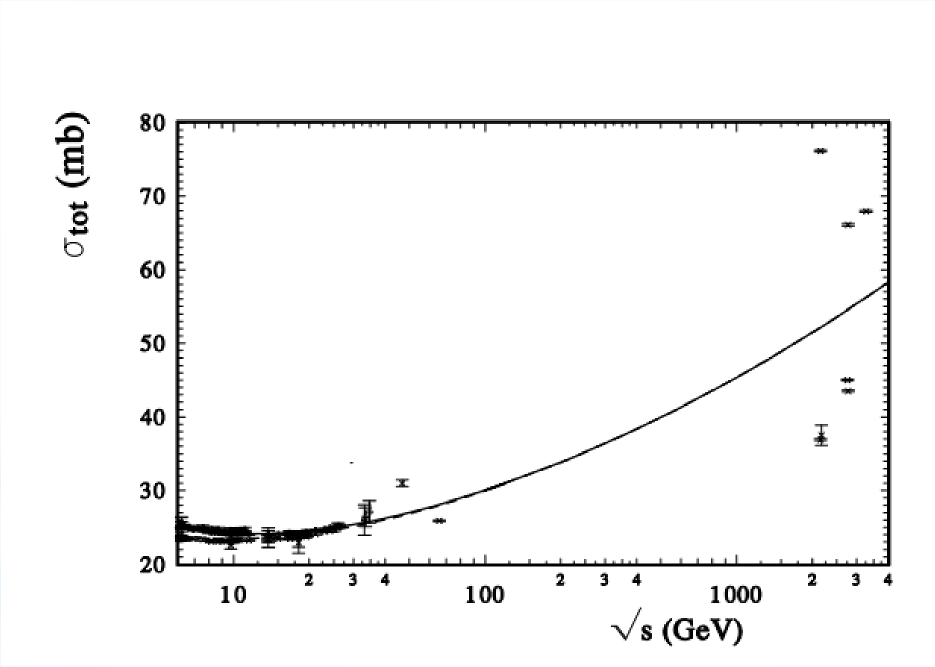
√s GeV	$\sigma_{tot}(s)\ mb$	EXP $\sigma_{tot}(s)\ mb$	$\rho(s, t=0)$
3TeV	86.6		0.122
7 TeV	99.8		0.1186
13 TeV	110.3		0.115
25 TeV	122.3		0.112
50 TeV	136		0.108
100 TeV	152		0.105
150 TeV	160		0.102
200 TeV	166.4		0.101



σtot (mb)
30
28
26
24
22
20
6
7
8
9
10
1.5
2
2.5
3
3.5
4
√s (GeV)



σtot (mb)
28
27
26
25
24
23
22
19
20
22
23
24
26
27
29
30
√s (GeV)



σtot (mb)
80
70
60
50
40
30
20
10
2
3
4
100
2
3
4
1000
2
3
4
√s (GeV)

outcome

The new Regge-eikonal model of hadron interaction based on the analyticity of the scattering amplitude with taking into account the hadron structure.

The main features of the model are:

a unique energy dependence of the basic asymptotic terms of the Born amplitude (all Born terms have one fixed intercept) and fixed slopes;

the real part of the hadronic elastic scattering amplitude is determined only through the complex Mandelstam variable $\hat{s}$, satisfying the dispersion relations;

The elastic scattering reflects the generalized structure of the hadron. The model use of two fixed forms of factors determined by different momenta of the same Generalized Parton Distribution (GPDs).

The model used in fitting **procedure only statistical** errors, the systematical errors used as additional normalization coefficient which is the same for experimental data of one set.

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

- The experimental data show some periodical structure in the Coulomb-hadron interference region of t and in a wide energy region.1

The small period of the "oscillation" is related with the long hadron screening potential at large distances

The non-fitting (statistical) method can show the existence of some oscillations in the differential cross sections and help to check the values of B, ρ ,

In the framework of the model the contribution of the hard pomeron do not feeling.

$\sigma_{tot}(s)\ mb$

The extending variant of the model shows the contribution of the "maximal" odderon with specific kinematic properties. Its contribution is important at 13 TeV.

Спасибо за внимание

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XXV Intern. Baldin Seminar on HE Phys. Relativistic Nuclear Physics and QCD, Dubna, RF (2023);
XIXth Workshop on High Energy Spin Physics dedicated to 90th anniversary of A.V. Efremov birth, Dubna, Russia (2023);
XXXiV Intern. Workshop on HE Phys.: ”Hard Problems of Hadron Physics: Non-Perturbative QCD”, Protvino, RF (2024);