Current Status of the Odderon

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Odderon is the C-odd amplitude which does not die out (or die very slowly) with energy. We consider the constrains on the Odderon properties and the perturbative QCD odderon given at the lowest α_s order by the three gluon exchange. Then we dicsuss the experimental indications for the odderon contribution to high energy proton-proton elastic scattering and some other processes in which the odderon may reveal itself.

Plan

1. Theory

a) Unitarity constraints on Odderon amplitude
b) Odderon in pert.QCD

2. Odderon seen experimentally

a) Elastic scattering at $t \to 0$
b) Diffractive dip region

New results

3. Other processes

a) Exclusive C-even meson photoproduction
b) $K_L \to K_S$ regeneration

Conclusion

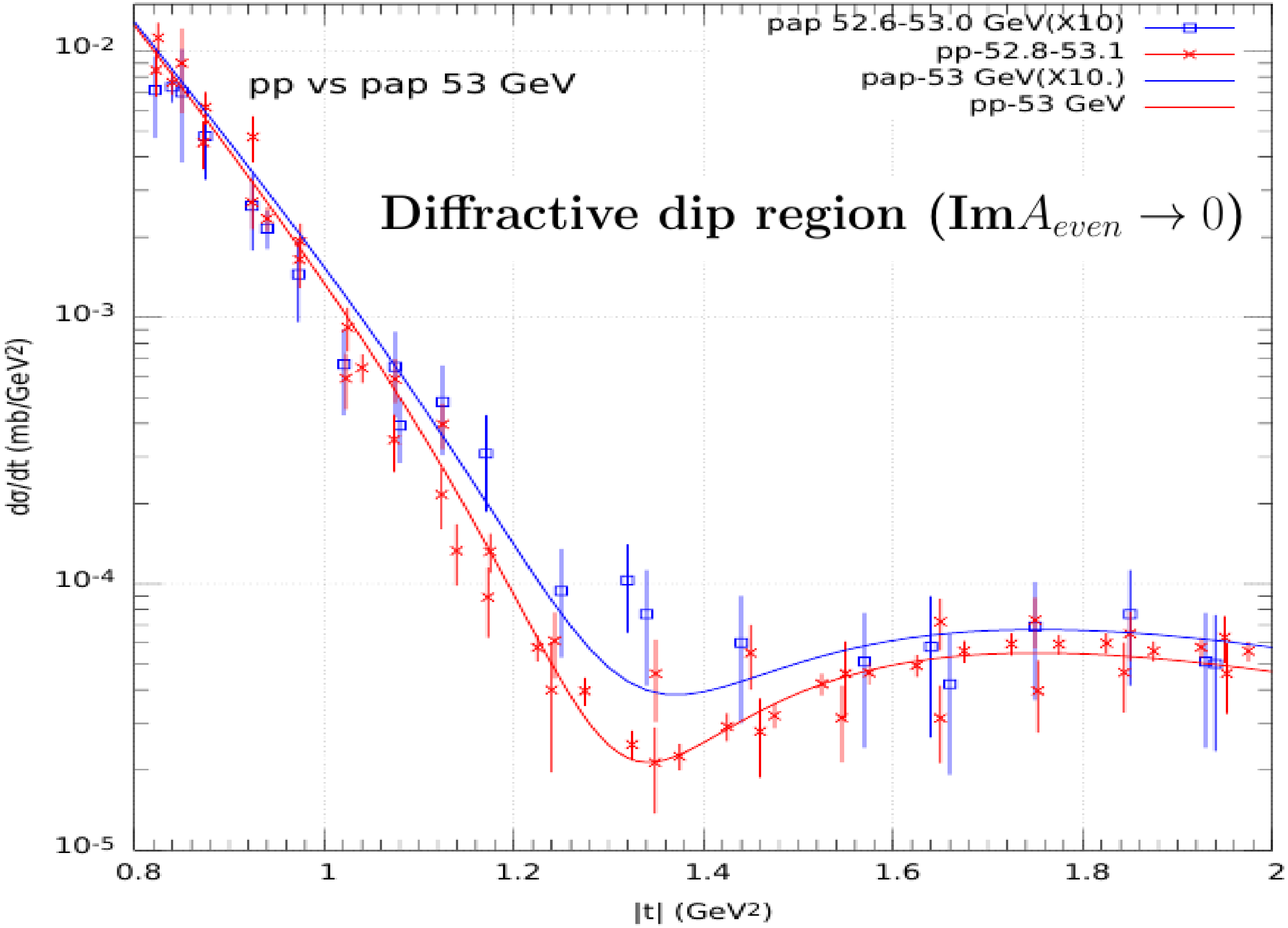


Fig. 6 pp and $\bar{p}p$ differential cross sections at $\sqrt{s} = 53$ GeV

Conclusion

- Odderon exists (i) in pert.QCD,
  (ii) in experiment but the coupling is small

- It was observed experimentally
  but number of σ=???

  (accuracy is limited by systematics and not by statistics)

- Odderon can be observed in elastic scattering at $t \to 0$ or in diffr. dip region

  to exclude systematics we have to measure pp and $\bar{p}p$ in the SAME experiment (LHC at 900 GeV)

- other possibilities
  C-even mesons, photoproduction
  $M = f_2, \eta, \eta_c,$
  (or exclusive $Pb + p \to Pb + M + p$ at the LHC)
  $K_L \to K_S$ regeneration

Theory

a) Constraints

At any impact parameter b

$$\mathrm{Im}A_{Odd}(s,b) \leq \mathrm{Im}A_{even}(s,b)$$

That is $\alpha_{Odd}(t=0) \leq \alpha_{even}(t=0)$ and $B_{Odd} \leq B_{even}$

b) pert. QCD

At the lowest α_s order (Born approx.)
Odderon = 3 gluon exchange

Properties: C-odd

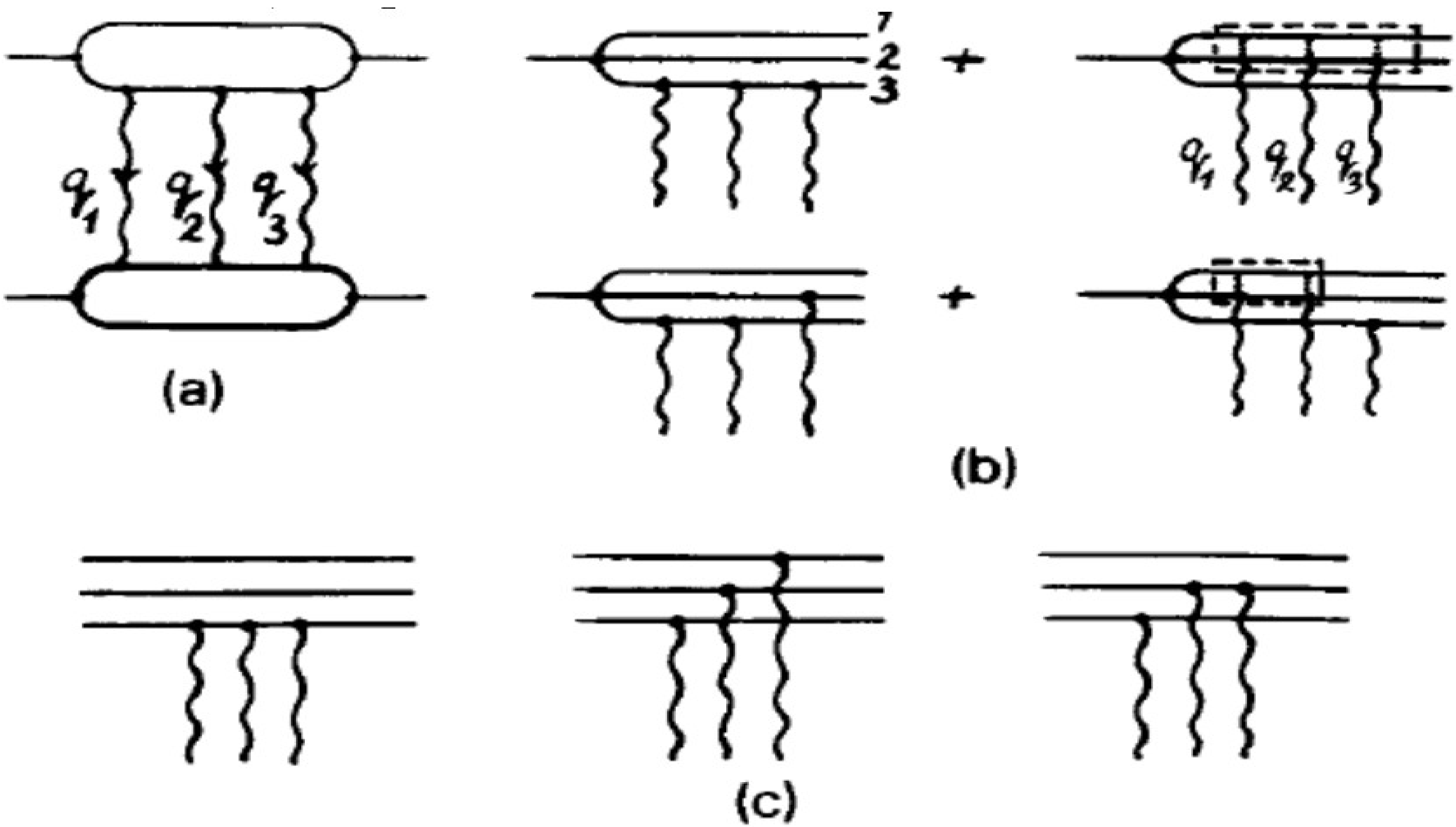
1. Odderon does not couple to pion/meson (due to C-parity)

2. $\alpha(0)_{Odd} = 0.96 \ - \ 1 \leq 1$

3. for $\alpha_{Odd} = 1$ C-odd amplitude A_{Odd} is real

Theory:

At the lowest α_s order (Born approx.)
Odderon = 3 gluon exchange



$$A_{Odd} \; = \; \beta_O^2(t) \left(\frac{s}{s_0} \right)^{\alpha_{Odd}(t)} \sim \frac{s}{s_0} \beta_O^2(t)$$

$\beta_O(t) \equiv 0$ for π (π is C-even)

for K-meson $\beta_O(t=0) = 0$ but $\beta_O(t \neq 0) \neq 0$

for proton $\beta_O \propto \; < r_{min}(\text{qq separation}) >$

in quark-diquark model (with point-like diquark)

$\beta_O(t=0) = 0$ as for K-meson

$$\sigma_{Odd} \sim \alpha^3{}_s \cdot < r^2_{min} > \sim \; 1\text{mb} \otimes \text{BKP}$$

$$\sigma_{Pom} \sim \alpha^2{}_s \cdot < r^2_{max} > \sim \; 40mb \otimes \text{BFKL}$$

Dispersion relation

$$\mathrm{Re}A(s,t=0) \;=\; \frac{1}{\pi}\int_{-\infty}^{0}\frac{ds'\mathrm{Im}A(s',t)}{s'-s} + \frac{1}{\pi}\int_{4m^2}^{\infty}\frac{ds'\mathrm{Im}A(s',t)}{s'-s}$$

$\mathrm{Im}A(s,0) = \sigma_{tot}$

$$\mathrm{Re}A(s,t=0) = \frac{1}{\pi}\int_{-\infty}^{0}\frac{ds'\sigma(p\bar{p})(-s'+4m^2)}{s'-s} + \frac{1}{\pi}\int_{4m^2}^{\infty}\frac{ds'\sigma(pp)(s')}{s'-s}$$

for $\alpha_{Odd} \simeq 1$

$\mathrm{Re}A_{Odd} \sim \ln s \cdot \mathrm{Im}A_{Odd}$ i.e. $\mathrm{Re}A_{Odd} >> \mathrm{Im}A_{Odd}$

$\mathrm{Re}A_{even} << \mathrm{Im}A_{even}$

$$\mathrm{Re}A_{even}(s,t=0) \;\simeq\; \frac{2s}{\pi}\int_{4m^2}^{\infty}\frac{ds'\sigma(pp)}{s'^2-s^2} \;\simeq\; \frac{\pi}{2}\frac{\partial\sigma(s)}{\partial \ln s}$$

TOTEM 13 TeV $\sigma_{tot} = 110.6 \pm 3.4$ **mb**

$(110.3 \pm 3.5)_{Coulomb} ==> 110.5 \pm 2.4$ **mb**

$\rho = Re/Im = 0.10 \pm 0.01_{N=3}\ (0.09 \pm 0.01_{N=1})$

arXiv: 1712.06153; 1812.04732

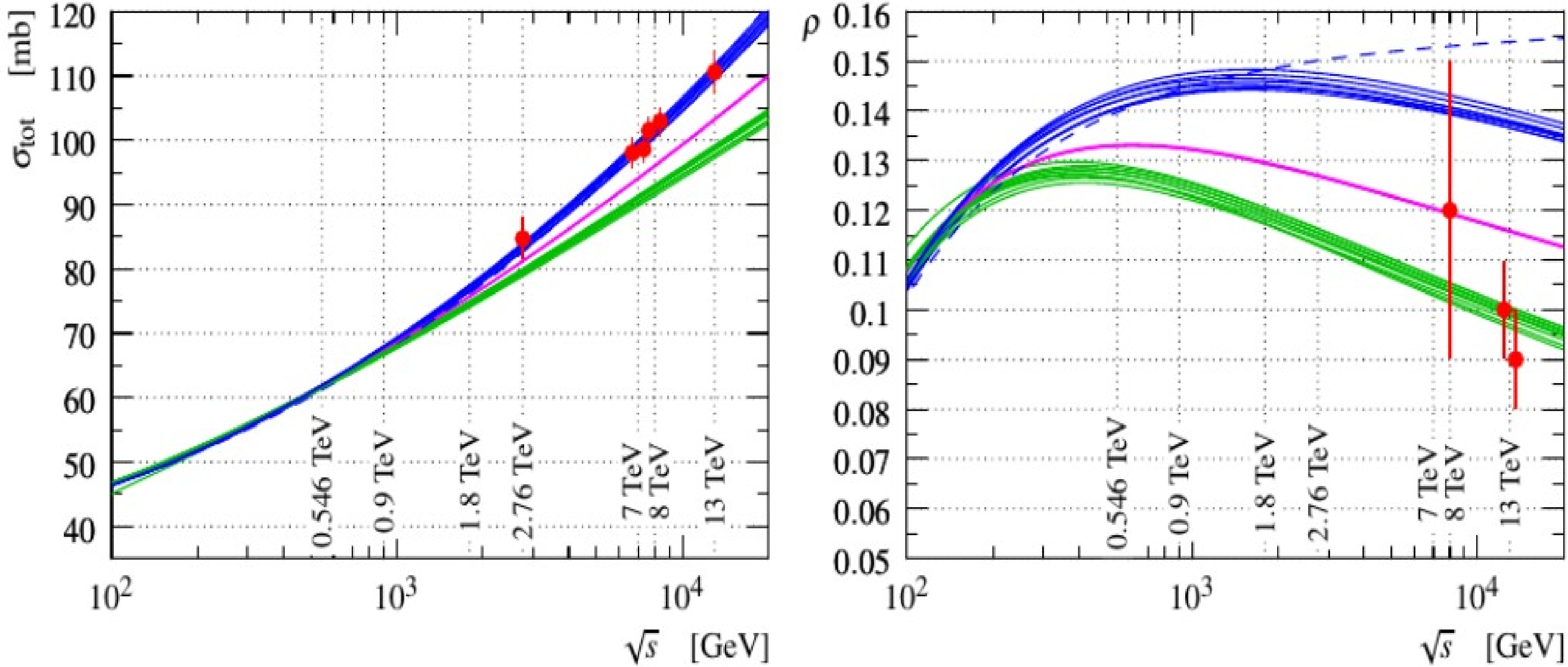


Fig. 18: Predictions of COMPETE models [32] for pp interactions. Each model is represented by one line (see

V.A. Petrov and N.P. Tkachenko, PRD 106, 054003 (2022) accounts for correlated errors and normalization factor

$\rho = 0.11 \pm 0.01$, $\sigma_{tot} = 107.6 \pm 1.7$ **mb**, $n = 0.92$

normalization to Coulomb

NEW **ATLAS/ALFA, EPJ C83, 441 (2023)**

$\sigma_{tot} = 104.7 \pm 1.1$ **mb**, $\rho = 0.10 \pm 0.01$

LRK fit E.G.S.Luna, M.G Ryskin, V.A.Khoze

2405.09385 $|t| < 0.1$ **GeV^2, 50 Gev**$< \sqrt{s} \leq$ **13 TeV**

Two channel eikonal $A_N(s,b) = i(1 - e^{i\Omega(s,b)/2})$

$\Omega = \Omega_{Pomeron} + \Omega_{Odd}$

$A(s,t) = A_N + e^{i\alpha\phi} A_C$

$$\mathcal{A}(s,t) = is \int_0^\infty b\, db\, J_0(bq) \left[1 - \frac{1}{4} e^{i(1+\gamma)^2 \Omega(s,b)/2} - \frac{1}{2} e^{i(1-\gamma^2)\Omega(s,b)/2} - \frac{1}{4} e^{i(1-\gamma)^2 \Omega(s,b)/2}\right]$$

TABLE I. Values of the parameters obtained in the global fits to Ensemble $A \oplus T$.

	Model I	**Model II**	**Model II**
$\beta_{\mathbb{P}}(0)$	2.247±0.013	2.259±0.016	2.307±0.022
ϵ	0.1173±0.0021	0.1180±0.0020	0.1134±0.0019
$\alpha'_{\mathbb{P}}$ (GeV^{-2})	0.124±0.024	0.128±0.022	0.133±0.023
A (GeV^{-2})	5.01±0.20	4.78±0.21	4.72±0.21
B (GeV^{-4})	6.61±0.99	6.7±1.1	6.9±1.2
C (GeV^{-6})	20.4±5.7	17.7±4.0	17.0±4.2
$\beta_{\mathbb{O}}(0)$	$(0.15 \times 10^{-4}) \pm 39$	0.90±0.18	0.88±0.18
N_{546}	0.941	0.933	0.958
$N_{1.8[E]}$	0.923	0.912	0.944
$N_{1.8[C]}$	1.087	1.070	1.109
$N_{7[A]}$	1.015	1.015	1.056
$N_{8[A]}$	1.003	1.003	1.045
$N_{13[A]}$	1.009	1.009	1.052
$N_{7[T]}$	1.077	1.077	1.121
$N_{8[T]}$	1.121	1.121	1.167
$N_{13[T]}$	1.150	1.150	1.200
$\rho^{pp}(\sqrt{s} = 13$ TeV)	0.114	0.111	0.109
$\rho^{\bar{p}p}(\sqrt{s} = 13$ TeV)	0.114	0.119	0.116
Allowed N_i interval	[0.85,1.15]	[0.85,1.15]	[0.80,1.20]
ν	504	504	504
χ^2/ν	1.44	1.11	1.03

$\chi^2 = 560$ **with Odderon**

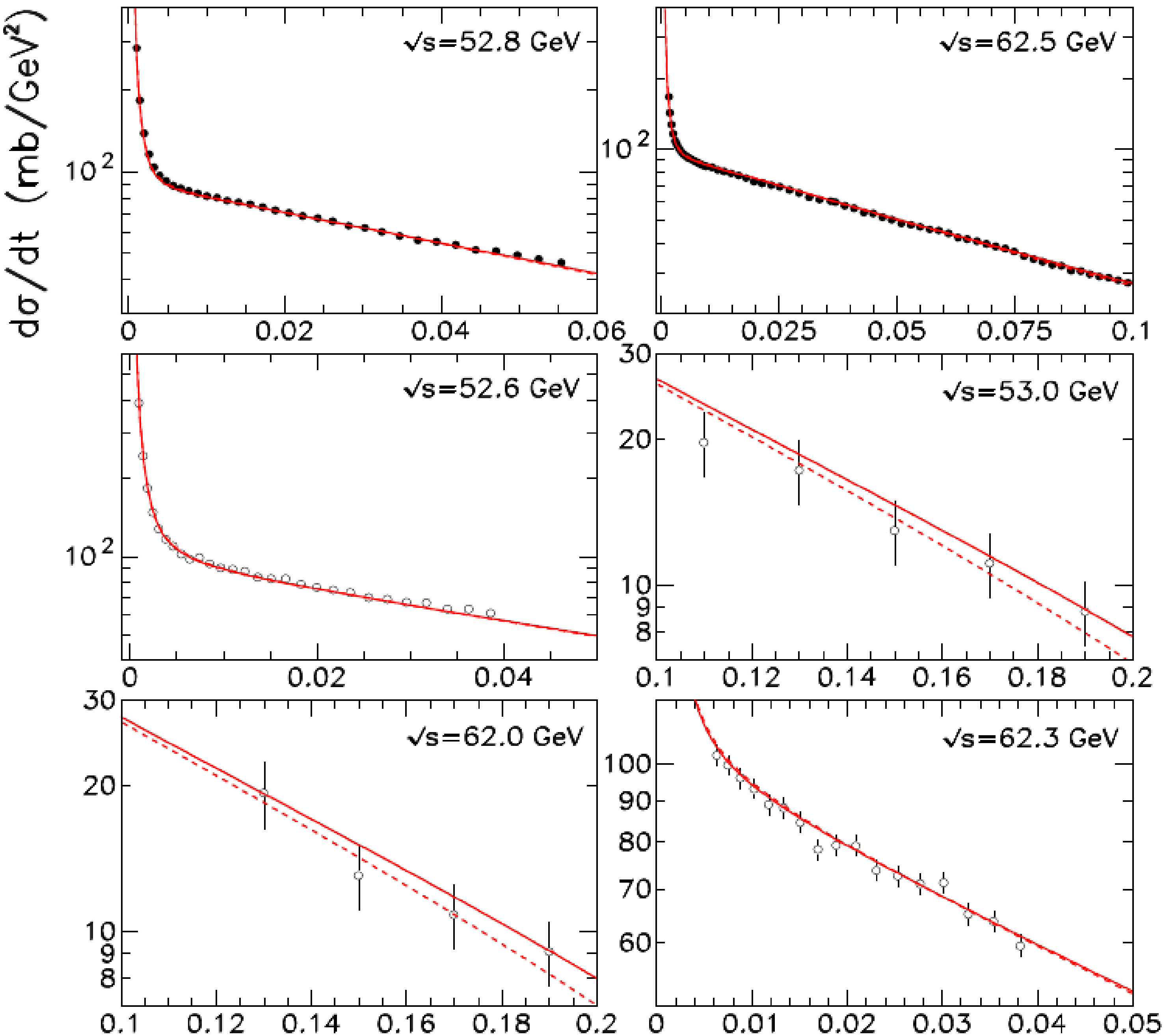
$\chi^2 = 726$ **without the Odderon**

TABLE II. Predictions for $\sigma_{tot}^{\bar{p}p,pp}$, $\sigma_{el}^{\bar{p}p,pp}$, and $\rho^{\bar{p}p,pp}$ using Models I and II. These results were derived for the scenario with $D = A/2$.

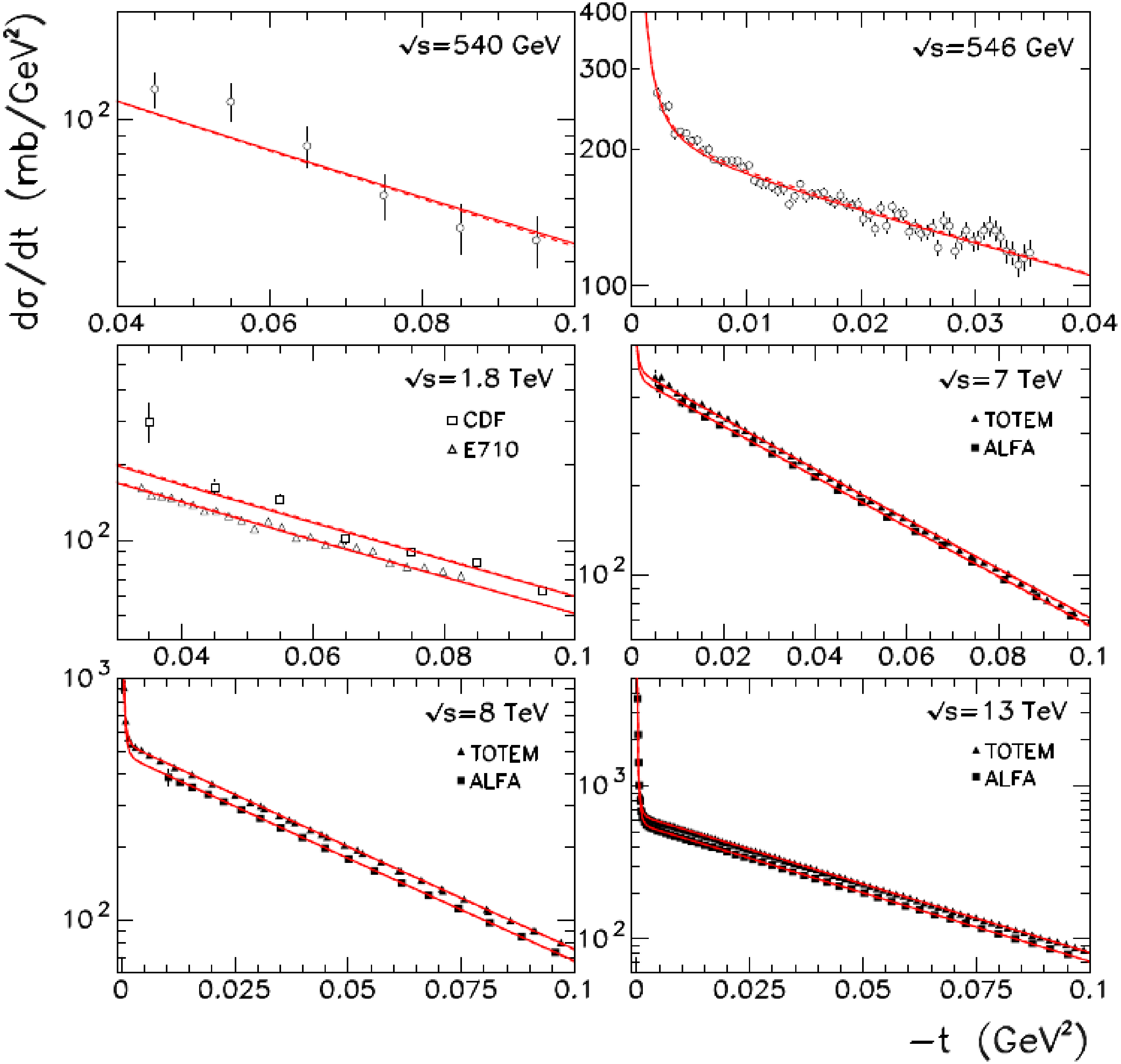
	Model I			Model II		
$\sqrt{s}$ (TeV)	σ_{tot}^{pp} | $\sigma_{tot}^{\bar{p}p}$ (mb)	σ_{el}^{pp} | $\sigma_{el}^{\bar{p}p}$ (mb)	ρ^{pp} | $\rho^{\bar{p}p}$	σ_{tot}^{pp} | $\sigma_{tot}^{\bar{p}p}$ (mb)	σ_{el}^{pp} | $\sigma_{el}^{\bar{p}p}$ (mb)	ρ^{pp} | $\rho^{\bar{p}p}$
0.541	64.2 | 64.2	13.2 | 13.2	0.130 | 0.130	63.8 | 64.1	13.3 | 13.5	0.117 | 0.144
1.8	78.0 | 78.0	17.6 | 17.6	0.124 | 0.124	77.6 | 77.8	17.7 | 17.9	0.116 | 0.133
7	95.9 | 95.9	23.9 | 23.9	0.117 | 0.117	95.7 | 95.9	24.0 | 24.2	0.113 | 0.123
8	97.9 | 97.9	24.5 | 24.5	0.116 | 0.116	97.6 | 97.8	24.7 | 24.8	0.113 | 0.122
13	105.1 | 105.1	27.2 | 27.2	0.114 | 0.114	104.9 | 105.1	27.3 | 27.4	0.111 | 0.119

	Ensemble $A \oplus T$				
D (GeV^{-2})	$0.1A$	$0.3A$	$0.5A$	$0.7A$	$0.9A$
$\beta_{\mathbb{O}}(0)$	1.09±0.24	0.95±0.19	0.90±0.18	0.86±0.17	0.83±0.16
$\beta_{\mathbb{P}}(0)$	2.235±0.023	2.257±0.016	2.259±0.016	2.258±0.016	2.258±0.017
ν	504	504	504	504	504
χ^2/ν	1.11	1.12	1.11	1.10	1.09
$\rho^{pp}(\sqrt{s} = 13$ TeV)	0.112	0.112	0.111	0.111	0.110
$\rho^{\bar{p}p}(\sqrt{s} = 13$ TeV)	0.119	0.118	0.119	0.119	0.120
$\sigma_{tot}^{pp}(\sqrt{s} = 13$ TeV) (mb)	104.9	104.9	104.9	104.9	104.9
$\sigma_{tot}^{\bar{p}p}(\sqrt{s} = 13$ TeV) (mb)	105.1	105.1	105.1	105.1	105.1

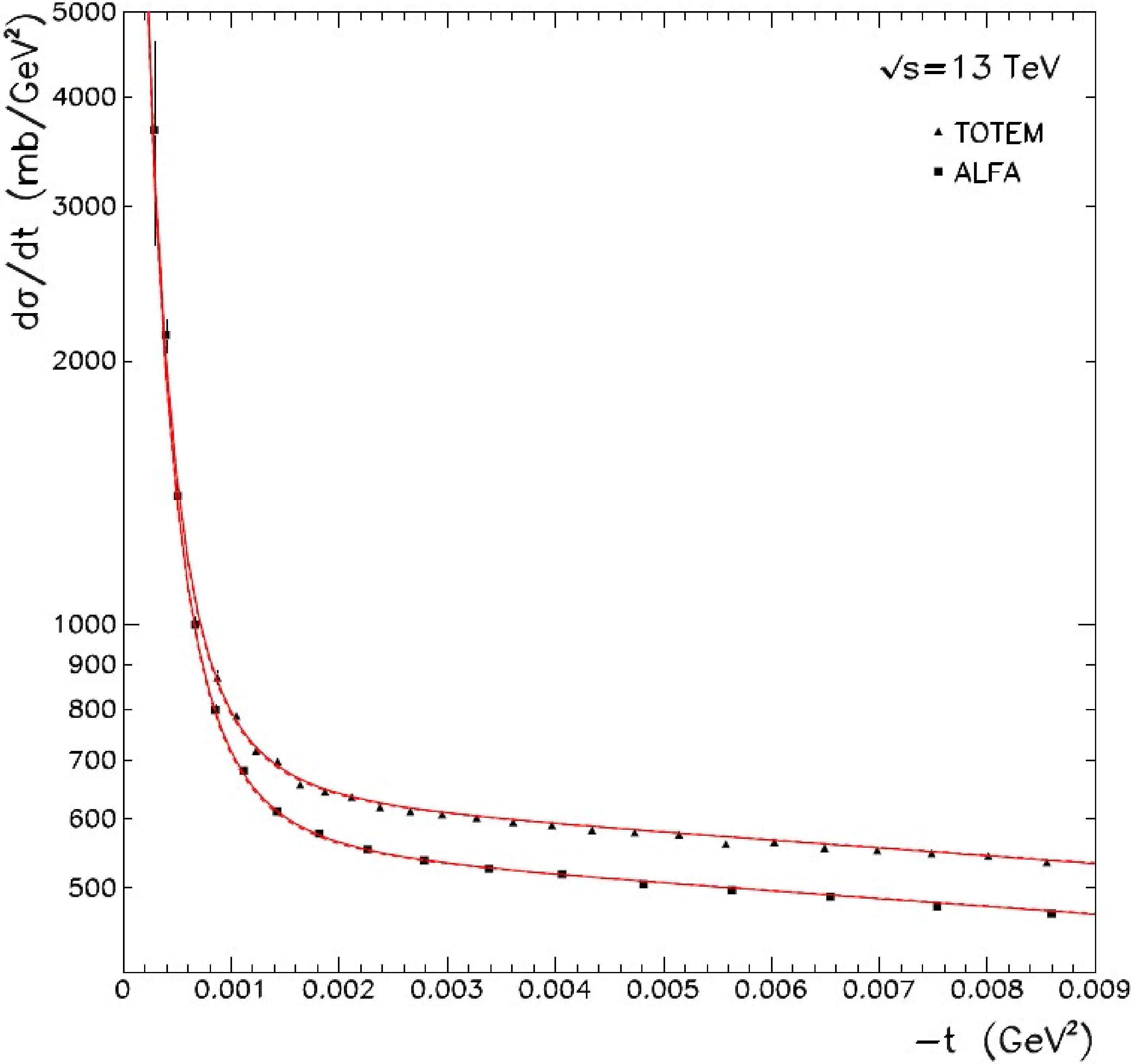
$$\beta_{\mathbb{O}}(t) = \beta_{\mathbb{O}}(0)e^{Dt/2} \qquad \beta_{\mathbb{P}}(t) = \beta_{\mathbb{P}}(0)e^{\left(At+Bt^2+Ct^3\right)/2}$$



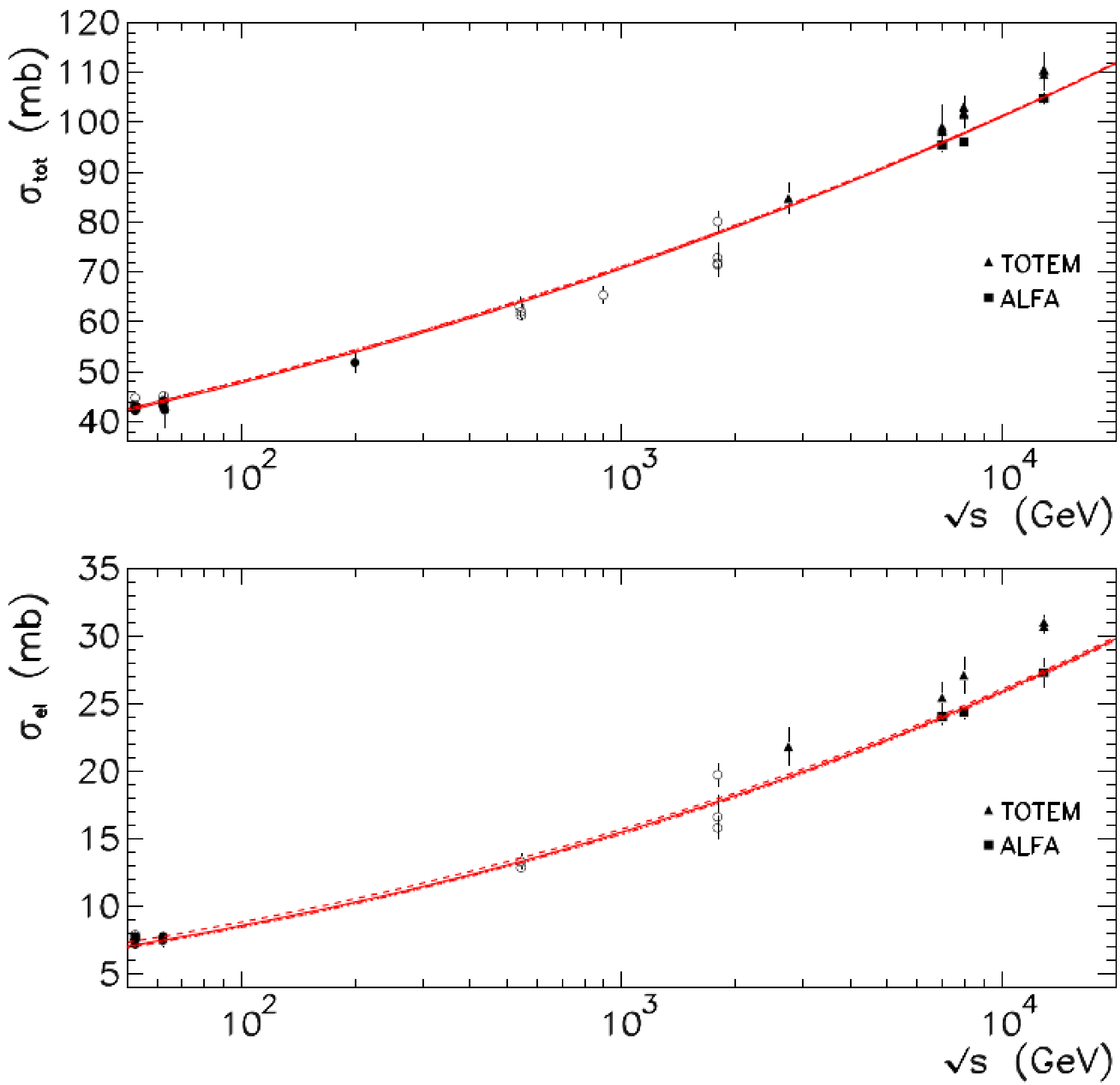
dσ/dt (mb/GeV²)
√s=52.8 GeV
√s=62.5 GeV
√s=52.6 GeV
√s=53.0 GeV
√s=62.0 GeV
√s=62.3 GeV



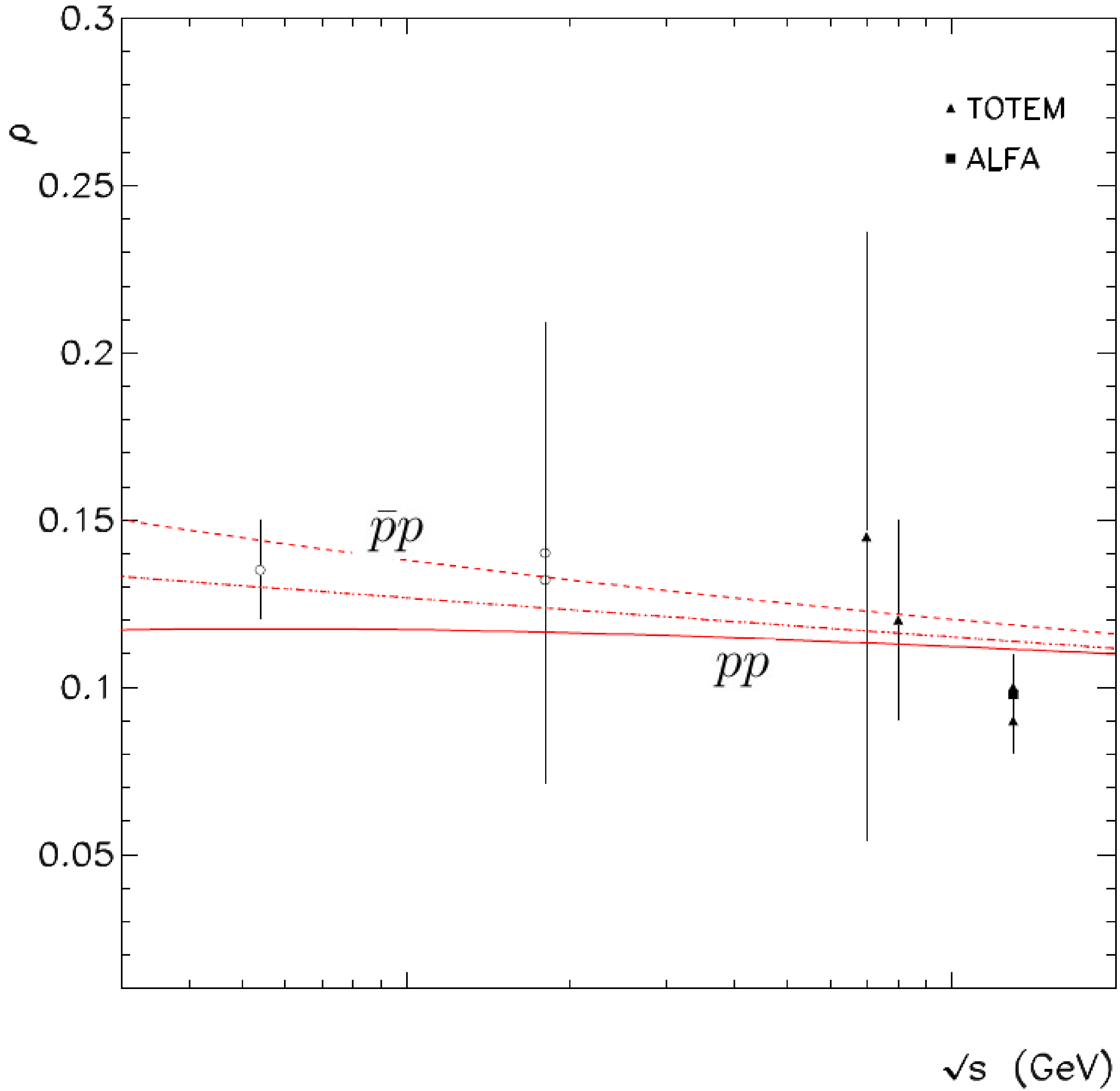
dσ/dt (mb/GeV²)
√s=540 GeV
√s=546 GeV
√s=1.8 TeV
CDF
E710
√s=7 TeV
TOTEM
ALFA
√s=8 TeV
TOTEM
ALFA
√s=13 TeV
TOTEM
ALFA
−t (GeV²)



dσ/dt (mb/GeV²)
5000
4000
3000
2000
1000
900
800
700
600
500
√s=13 TeV
TOTEM
ALFA
0
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009
−t (GeV²)



σ_tot (mb)
120
110
100
90
80
70
60
50
40
TOTEM
ALFA
10^2
10^3
10^4
√s (GeV)
σ_el (mb)
35
30
25
20
15
10
5
TOTEM
ALFA
10^2
10^3
10^4
√s (GeV)



0.3
0.25
0.2
0.15
0.1
0.05
ρ
TOTEM
ALFA
$\bar{p}p$
pp
√s (GeV)

The main lessons about the Odderon **at low** $|t|$

- The description using the Odderon improves the fit (the χ^2/ν is the lowest one).

- The sign of the Odderon amplitude needed to describe the very low $|t|$ data is opposite to that predicted by the perturbative QCD three-gluon exchange contribution **for "quark-diquark" proton** $\beta_O(t=0)=0$

  then at $t=0$ **Pomeron-Odderon cut dominate**

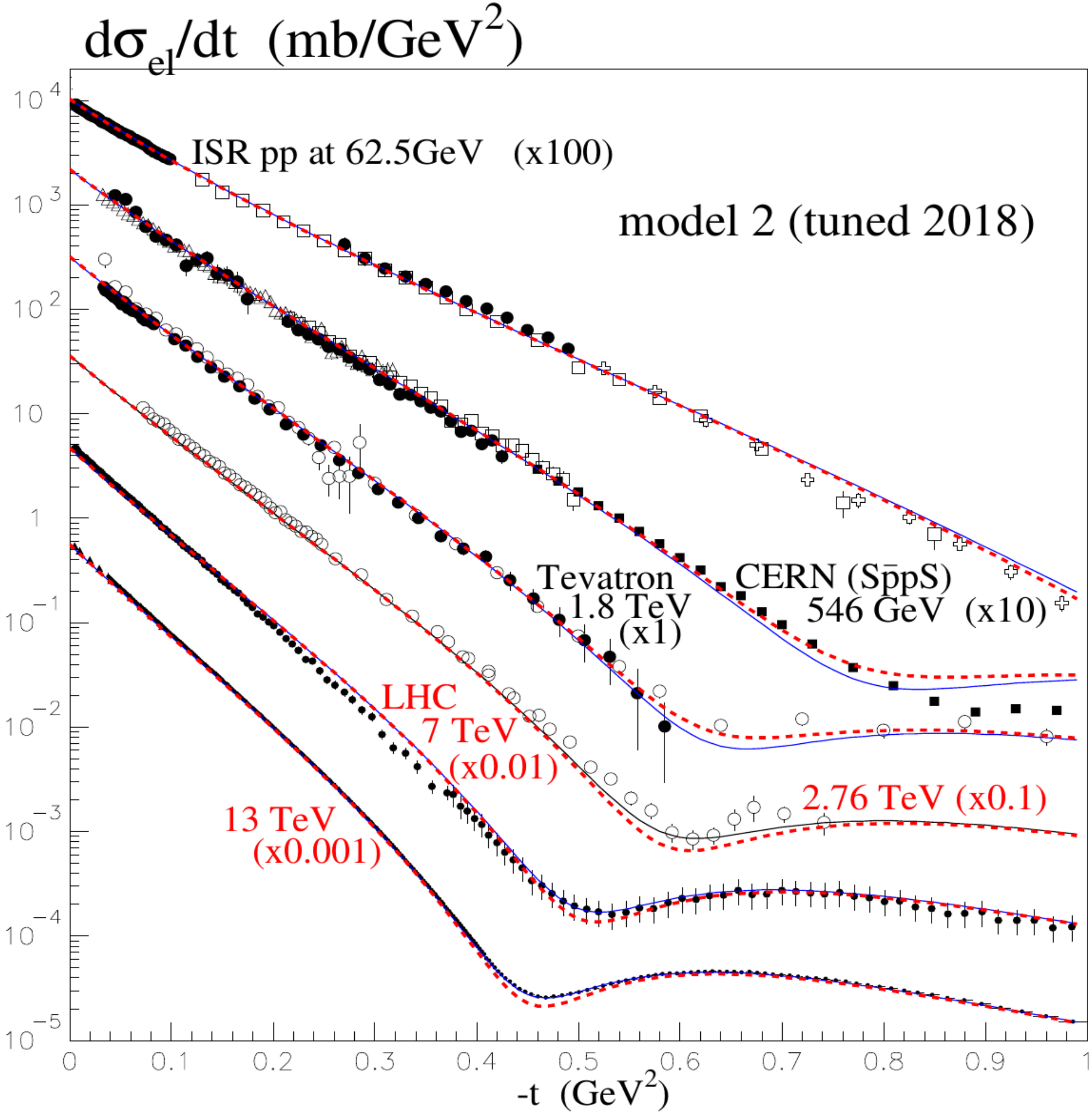
  leading to

  negative sign

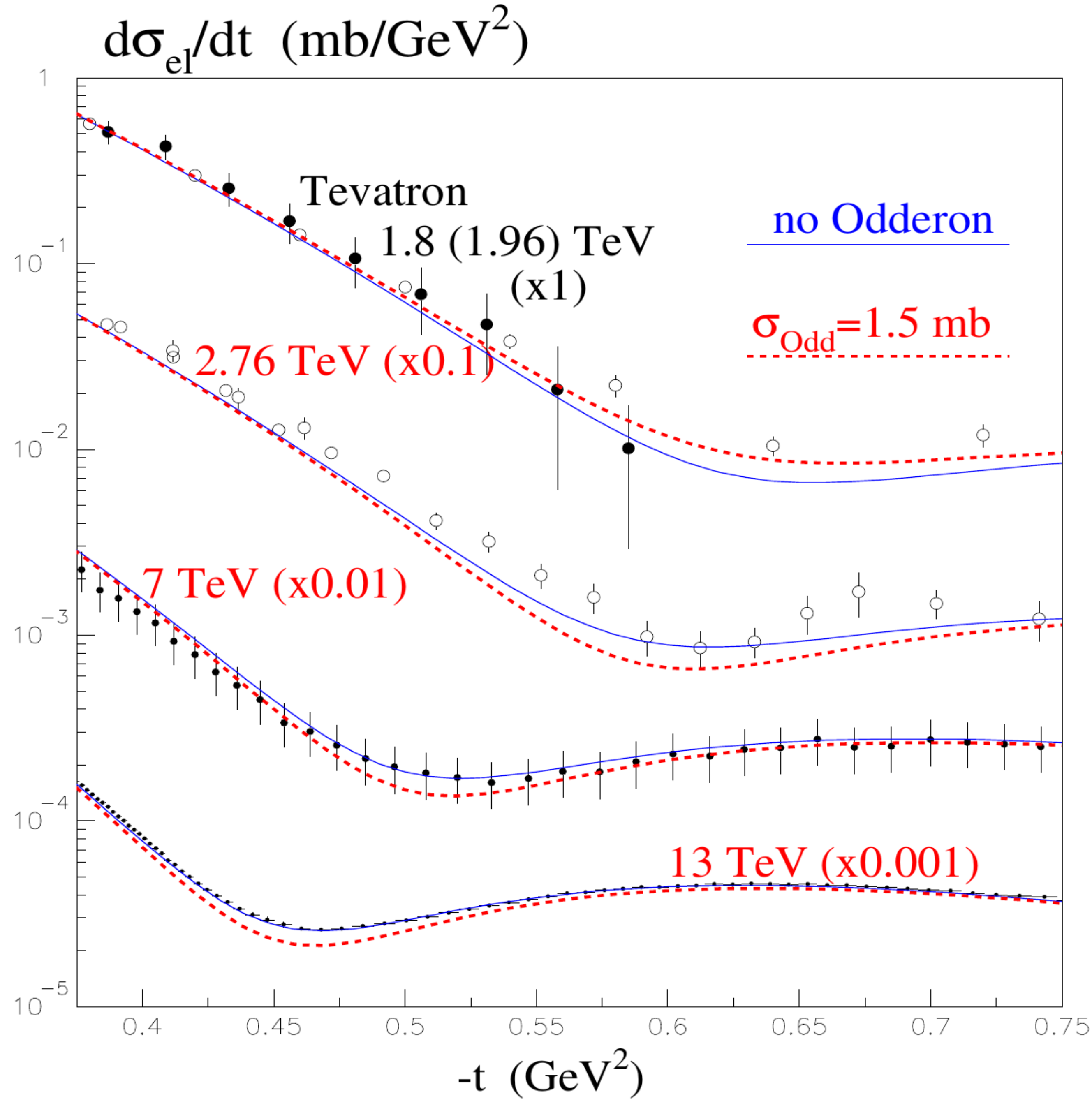
- The quality of the description weakly depends on the Odderon t-slope, D

- The Odderon-proton coupling, $\beta_{\mathbb{O}}$, is smaller than that for the Pomeron, $\beta_{\mathbb{P}}$. For $D=A/2$ we get $\beta_{\mathbb{O}}/\beta_{\mathbb{P}}=0.40$, however after accounting for screening by the Pomeron the final C-odd contribution to ρ at 13 TeV becomes quite small,

$$\delta\rho=(\rho^{\bar{p}p}-\rho^{pp})/2\leq 0.004$$



dσ_el/dt (mb/GeV^2)
ISR pp at 62.5GeV (x100)
model 2 (tuned 2018)
Tevatron
1.8 TeV
(x1)
CERN (Sp̄pS)
546 GeV (x10)
LHC
7 TeV
(x0.01)
2.76 TeV (x0.1)
13 TeV
(x0.001)
-t (GeV^2)

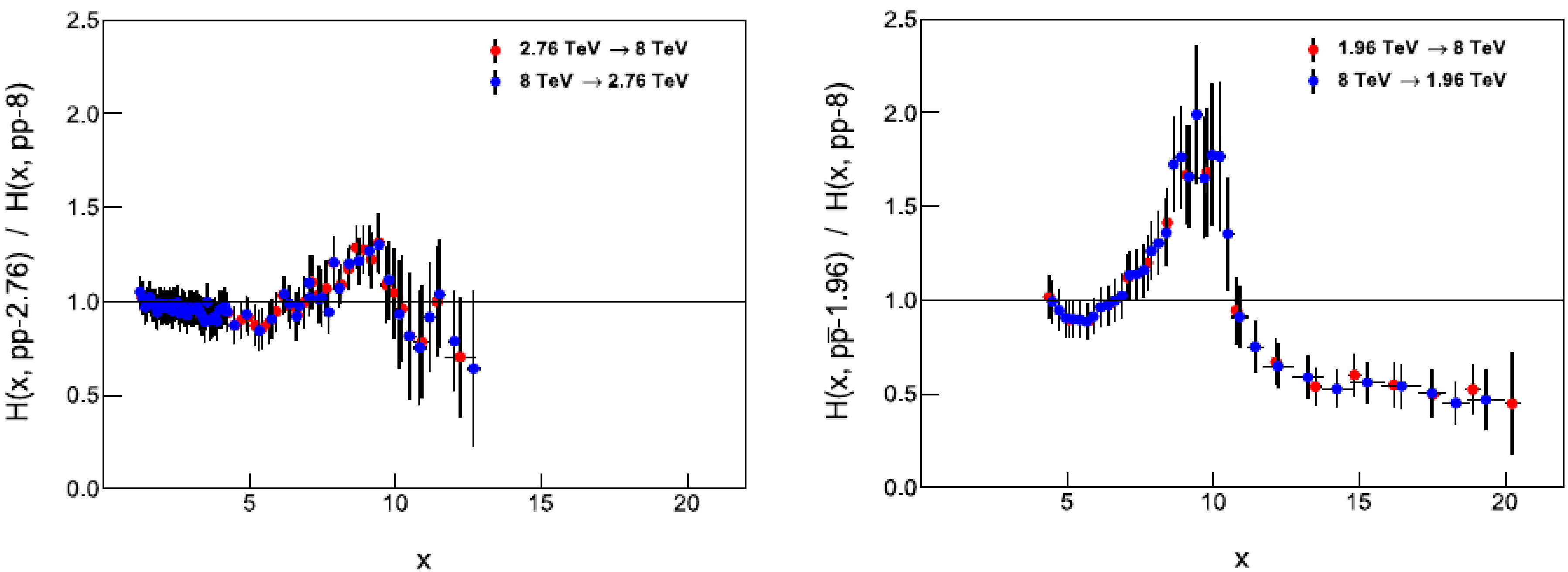


dσel/dt (mb/GeV²)
Tevatron
1.8 (1.96) TeV
(x1)
no Odderon
σOdd=1.5 mb
2.76 TeV (x0.1)
7 TeV (x0.01)
13 TeV (x0.001)
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
-t (GeV²)

T. Csörgő[1,2], T. Novák[2,3], R. Pasechnik[4], A. Ster[1], I. Szanyi[1,2,5]

Evaluating the $H(x, s|pp)$ scaling function of elastic proton-proton (pp) collisions from recent TOTEM data at $\sqrt{s} = 8$ TeV and comparing it with the same function of elastic proton-antiproton ($p\bar{p}$) data of the D0 collaboration at $\sqrt{s} = 1.96$ TeV, we find, signal of Odderon exchange.

$$H(x, s|pp) = \frac{1}{B\sigma_{\rm el}^{pp}} \frac{d\sigma^{pp}}{dt}, \quad x = -tB$$



C-even meson photoproduction

$$\sigma(\gamma p \to \pi^0 p) \sim 300 \textbf{ nb} \quad (< 39\textbf{nb - HERA})$$

(Rueter, Dosch, Nachtmann Ph.Rev. D59 (1999) 014018)

C-even meson (M)	Odderon Signal		Backgrounds		
	Upper Limit	QCD Prediction	$\gamma\gamma$	Pomeron-Pomeron	$V \to M + \gamma$
π^0	7.4	0.1 - 1	0.044	–	30
$f_2(1270)$	3	0.05 - 0.5	0.020	3 - 4.5	0.02
$\eta(548)$	3.4	0.05 - 0.5	0.042	negligible	3
η_c	–	$(0.1 - 0.5) \cdot 10^{-3}$	0.0025	$\sim 10^{-5}$	0.012

Table 3: The expected cross sections ($d\sigma/dY_M$ at $Y_M = 0$ in μb) of the Odderon signal and backgrounds in the CEP* ultraperipheral production of C-even mesons (M) in high-energy proton-lead collisions ($Pb + p \to Pb + M + p$) integrated over the interval $0.2 < p_\perp < 1$ GeV. In the η_c case a total branching ratio of 0.05 has been applied, i.e. summing over the channels discussed in

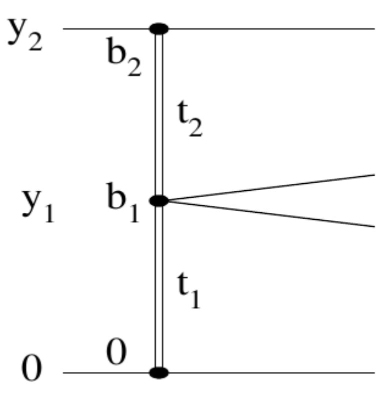
Conclusion

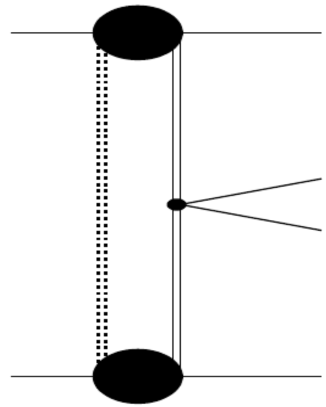
- Odderon exists (i) in pert.QCD,
  (ii) in experiment but the coupling is small
- It was observed experimentally
  but number of σ=???
  (accuracy is limited by systematics and not by statistics)
- Odderon can be observed in elastic
  scattering at $t \to 0$ or in diffr. dip region
  to exclude systematics we have to measure pp and $\bar{p}p$ in the
  SAME experiment (LHC at 900 GeV)
- other possibilities
  C-even mesons, photoproduction
  $M = f_2, \eta, \eta_c$,
  (or exclusive $Pb + p \to Pb + M + p$ at the LHC)
  $K_L \to K_S$ regeneration

The goal is not to proof that the Odderon exists (no reason to have *No* Odderon) but to *measure* the Odderon exchange amplitude.

Maximum odderon ($A_{Odd} \propto \ln^2 s$) is another story.
Max. Odderon contradicts unitarity
(taking s- and t- unit. together)

THANK YOU





$$S(b) = 1 + iA_{el}(b) \to 0!$$

Max. Odderon screens himself to zero

Maximal Odderon **Violates unitarity**

$$2\mathbf{Im}A_{el}(b) = |A_{el}(b)|^2 + G_{inel}(b) \text{ (s-unit.)}$$

Solution: $A_{el}(b) = i(1 - e^{2i\delta(b)})$

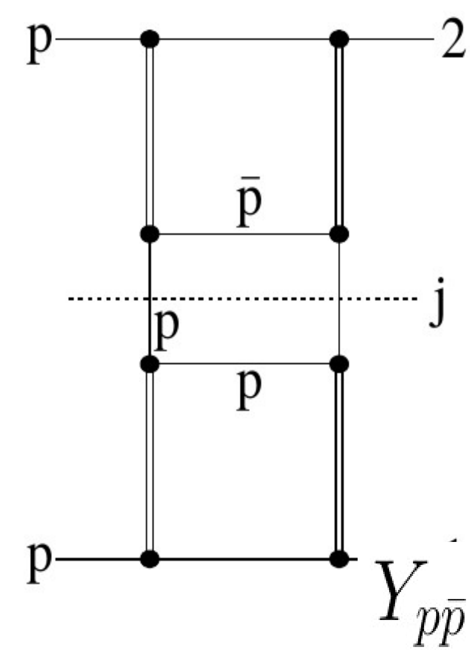
$$l = b\sqrt{s}/2$$

$$\delta(b) = \delta_{even} + \delta_{Odd} \quad \mathbf{Im}\delta_{even}(b) > 0$$

Max.Odd. assume $A_{Odd} = a\theta(c \ln s - b)$

Then $\sigma(pp \to p + p\bar{p} + p)(b) \geq c' \ln s$

i.e. $\mathbf{Im}\delta_{even}(b) \propto \ln s ==> A_{el} = i$



Bethe phase $\phi = \ln \frac{B|t|}{2} + \gamma + const$

ρ **depends on const.** **For** $\phi = 0$

Kohara-Ferreira-Rangel (Ph.Lett. B789, p.1)

got $\rho = 0.131$ **with** $\chi^2/ndf = 0.94$

$\rho = 0.112 \pm 0.005$ **for const=2** $(\chi^2/ndf = 0.96)$

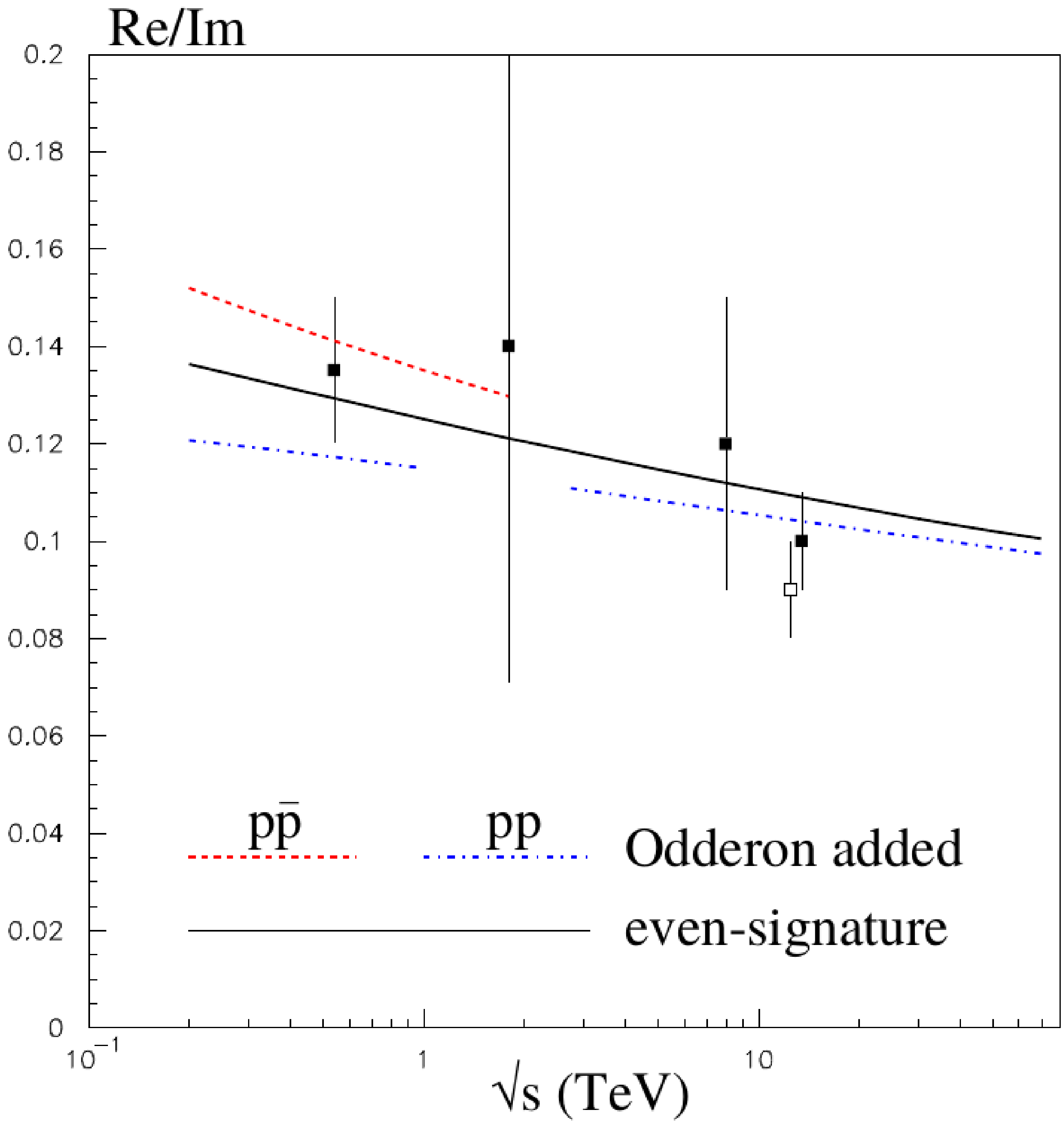
Cudell-Selyugin (1901.05863) accounts for correlated errors and normalization factor n**.**

They got (const=0):

$\sigma_{tot} = 106.4 \pm 2.2$ **mb,** $\rho = 0.098 \pm 0.008$,

$n = 0.91 \pm 0.04 \quad (\chi^2/ndf = 0.81)$

(79 points $0.0008 < |t| < 0.07$ **GeV**^{2}**)**


Re/Im
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
10^{-1}
1
10
$\sqrt{s}$ (TeV)
$p\bar{p}$
pp
Odderon added
even-signature