ODDERON EXCHANGE

OBSERVATION AND PROPERTIES

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

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[2] MATE KRC, Gyöngyös, Hungary
[3] University of Lund, Lund, Sweden
[4] Eötvös University, Budapest, Hungary

Intro to Odderon exchange
Model independent results:
Significance at least 6.26 σ
Model dependent results:
Significance at least 7.08 σ
New results at 8 TeV
1: H(x) scaling
2: ReBB Model vs ATLAS and TOTEM
Summary

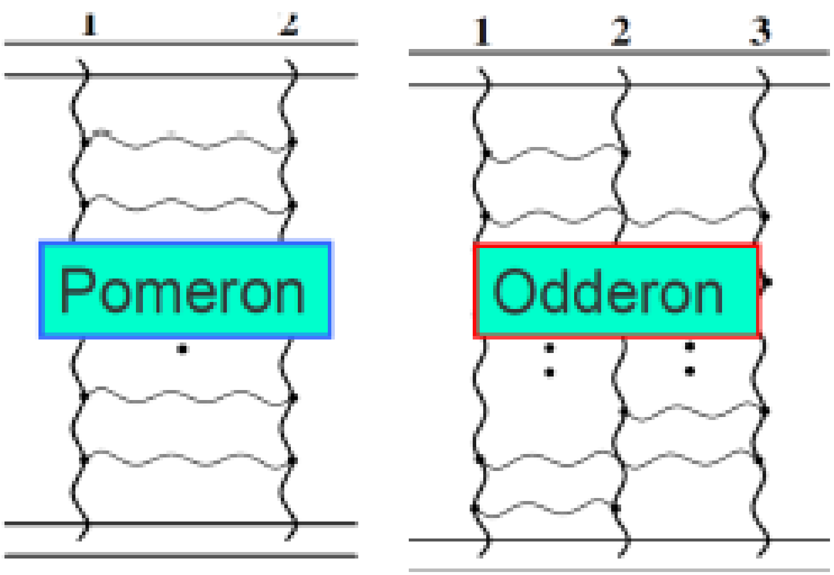
Universe **2024**, *10*(6),264;
https://doi.org/10.3390/universe10060264

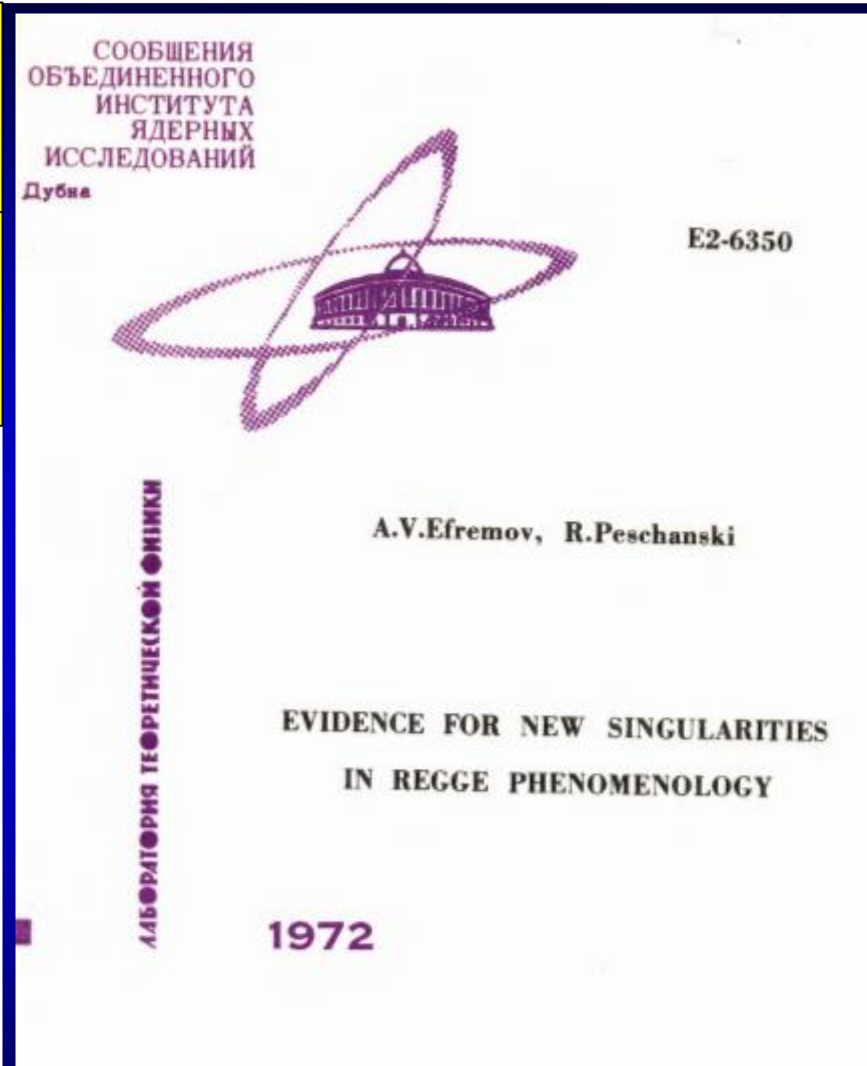
arXiv:2405.06733 [hep-ph]

Odderon: 48 years old scientific puzzle

Odderon: L. Lukaszuk, B. Nicolescu,
Lett. Nuovo Cim. 8, 405 (1973)
Received: **31 July 1973**

Odderon is an odd component of
elastic scattering:
Changes sign for crossing




СООБЩЕНИЯ
ОБЪЕДИНЕННОГО
ИНСТИТУТА
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ
Дубна

E2-6350

ЛАБОРАТОРИЯ ТЕОРЕТИЧЕСКОЙ ФИЗИКИ

A.V.Efremov, R.Peschanski

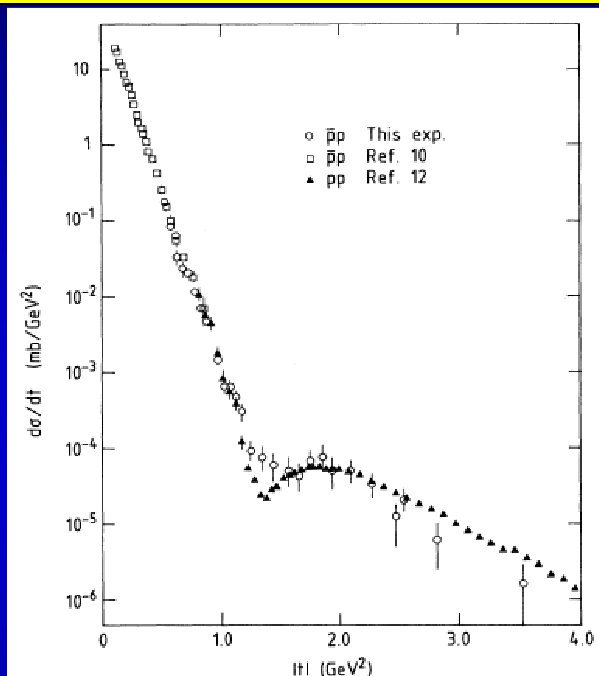
EVIDENCE FOR NEW SINGULARITIES
IN REGGE PHENOMENOLOGY

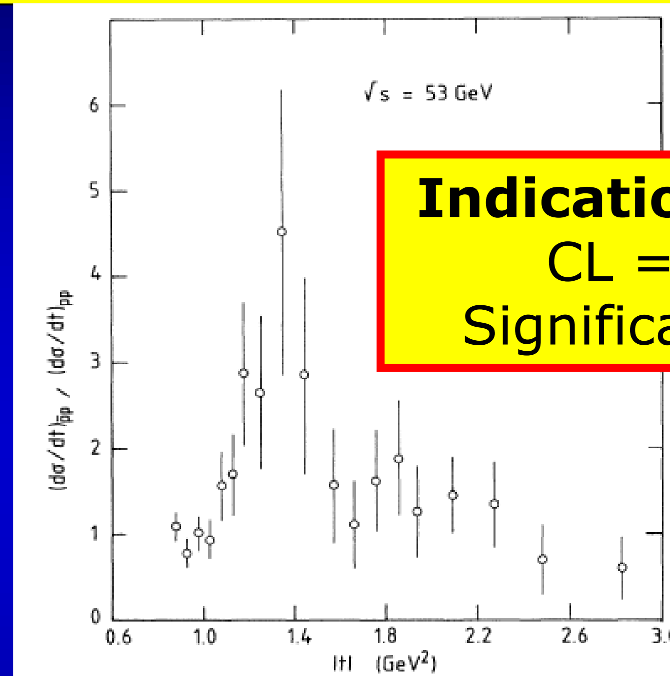
1972

Odderon name coined: D. Joynson, E. Leader, B. Nicolescu, C. Lopez,
Nuovo Cim. 30A, 345 (1975) - Well established in QCD by now !
Honorable mention: A. V. Efremov, R. Peschanski, JINR-E2-6350 (1972)

Odderon: elusive experimentally

Odderon search at ISR: indication but no conclusive result
Breakstone et al, Phys. Rev. Lett. 54, 2180 (**1985**): CL = 99.9 %





Indication of Odderon
CL = 99.9 %,
Significance: 3.35 σ

Terminology for **this** talk:
Agreement if statistical significance is < **3 σ**
Indication of signal if **3 σ** ≤ significance < **5 σ**
Evidence or observation of signal if **5 σ** ≤ significance
Discovery of signal if **5 σ** ≤ significance **for the first time**.
Accepted discovery if Clay Mathematical Institute (CMI) criteria satisfied.
Miscovery if CMI criteria for Millenium Prize Problems are **not** satisfied.

Odderon: first observation with > 5 σ

EPJ Web of Conf. (2020) **235**: 06005
https://doi.org/10.1051/epjconf/202023506002

Proton Holography -- Discovering Odderon from Scaling Properties of Elastic Scattering #4

T. Csorgo (Wigner RCP, Budapest and Eszterhazy Karoly U., Eger), T. Novak (EKU KRC, Gyongyos), R. Pasechnik (Lund U. and Rez, Nucl. Phys. Inst.), A. Ster (Wigner RCP, Budapest), I. Szanyi (Wigner RCP, Budapest and Eotvos U.) (Apr 15, 2020)

Published in: *EPJ Web Conf.* 235 (2020) 06002 • Contribution to: ISMD 2019 • e-Print: 2004.07095 [hep-ph]

pdf DOI cite 1 citation

First publication of an at least 5.0 σ (6.26 σ) odderon effect:
May 11, 2020,
EPJ Web of Conf. 235 (2020) 06002
in an **anonymously refereed / peer reviewed** conference proceedigs.
(Proc. ISMD 2019, Santa Fe, USA)

First journal publications, Odderon > 5 σ

Evidence of Odderon-exchange from scaling properties of elastic scattering at TeV energies #5

T. Csörgő (Wigner RCP, Budapest and CERN), T. Novak (Unlisted, HU), R. Pasechnik (Lund U., Dept. Theor. Phys.), A. Ster (Wigner RCP, Budapest), I. Szanyi (Wigner RCP, Budapest) (Dec 26, 2019)

Published in: *Eur.Phys.J.C* 81 (2021) 2, 180 • e-Print: 1912.11968 [hep-ph]

Online attention

- 26 tweeters
- 15 news outlets
- 3 Mendeley
- 4 blogs
- 4 Wikipedia page
- 2 Facebook pages

This article is in the 98th percentile (ranked 6,037th) of the 428,075 tracked articles of a similar age in all journals and the 99th percentile (ranked 1st) of the 231 tracked articles of a similar age in *The European Physical Journal C*

Hungarian-Swedish team:
Eur. Phys. J. C (2021) **81**: 180, Published: 23 February 2021
https://doi.org/10.1140/epjc/s10052-021-08867-6

... a real extended Bialas–Bzdak model study #2

... anyi (Eotvos U. and Wigner RCP, Budapest) (May 28, 2020)

Published in: *Eur.Phys.J.C* 81 (2021) 7, 611 • e-Print: 2005.14319 [hep-ph]

6 citations

Online attention

- 3 tweeters
- 1 Mendeley
- 1 Wikipedia page

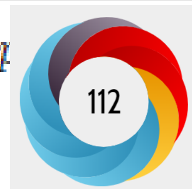
Hungarian team, model of Polish origin:
Eur. Phys. J. C (2021) **81**:611 , Published: 13 July 2021
https://doi.org/10.1140/epjc/s10052-021-09381-5

Odderon Exchange from Elastic Scattering Differences between *pp* ... from pp Forward Scattering Measurements

TOTEM and D0 Collaborations • V.M. Abazov (Dubna, JINR) et al. (Dec 7, 2020)

Published in: *Phys.Rev.Lett.* 127 (2021) 6, 062003 • e-Print: 20...

pdf links DOI cite



SUMMARY | News | Blogs | Twitter | Wikipedia | Dimensions citations

D0 and TOTEM Collaborations:
Phys. Rev. Lett. **127** (2021) 6, 062003, Published: 4 August 2021
https://doi.org/10.1103/PhysRevLett.127.062003

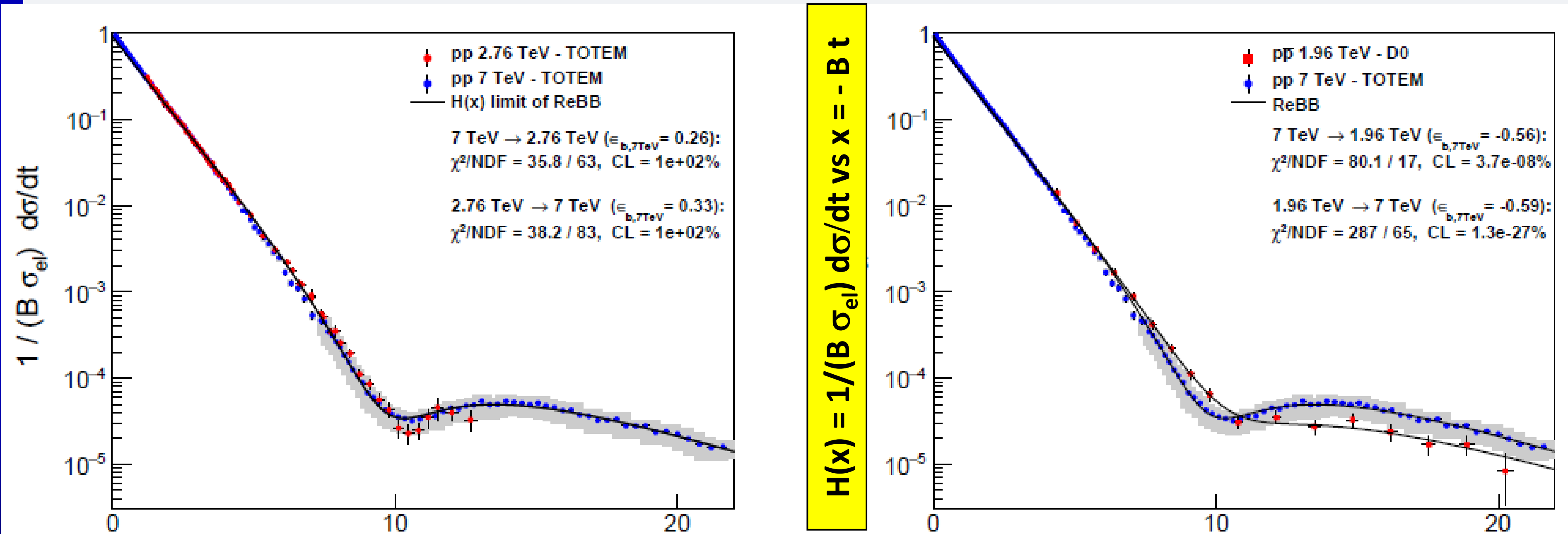
Hungarian-Swedish team, Odderon > 6.26 σ

Evidence of Odderon-exchange from scaling properties of elastic scattering at TeV energies #5

T. Csörgő (Wigner RCP, Budapest and CERN), T. Novak (Unlisted, HU), R. Pasechnik (Lund U., Dept. Theor. Phys.), A. Ster (Wigner RCP, Budapest), I. Szanyi (Wigner RCP, Budapest) (Dec 26, 2019)

Published in: *Eur.Phys.J.C* 81 (2021) 2, 180 • e-Print: 1912.11968 [hep-

Eur. Phys. J. C (2021) **81**: 180, published February 2021
https://doi.org/10.1140/epjc/s10052-021-08867-6



$B \equiv B_0(s)$ from now on

$x = -B\,t = -B_0(s)\,t$

S: Model independent Odderon significance ≥ 6.26 σ
C1: All D0 and TOTEM published data at 1.96, 2.76 and 7.0 TeV
C2: domain of validity is still determined **model dependently**.

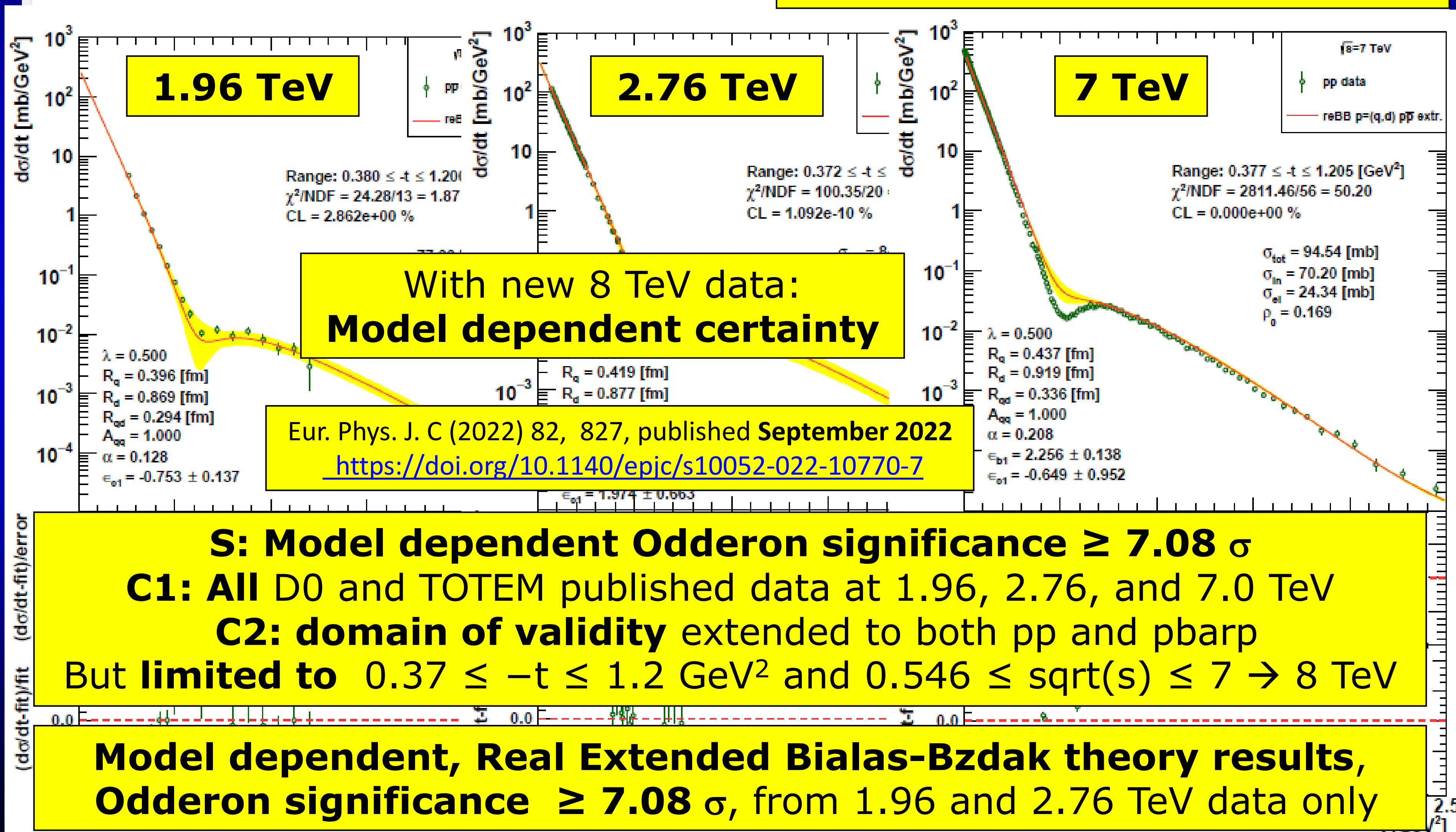
Hungarian team, Polish model, Odderon > 7.08 σ

Observation of Odderon Effects at LHC energies -- A Real Extended Bialas-Bzdak Model Study #2

T. Csorgo (Wigner RCP, Budapest and EKU KRC, Gyongyos), I. Szanyi (E

e-Print: 2005.14319 [hep-ph]

Eur. Phys. J. C (2021) **81**:611, published July 2021
https://doi.org/10.1140/epjc/s10052-021-09381-5



With new 8 TeV data:
Model dependent certainty

Eur. Phys. J. C (2022) 82, 827, published **September 2022**
https://doi.org/10.1140/epjc/s10052-022-10770-7

S: Model dependent Odderon significance ≥ 7.08 σ
C1: All D0 and TOTEM published data at 1.96, 2.76, and 7.0 TeV
C2: domain of validity extended to both pp and pbarp
But **limited to** $0.37 \leq -t \leq 1.2$ GeV² and $0.546 \leq \sqrt{s} \leq 7 \rightarrow 8$ TeV

Model dependent, Real Extended Bialas-Bzdak theory results,
Odderon significance ≥ 7.08 σ, from 1.96 and 2.76 TeV data only

2023-24: new O observations with > 5 σ

Model-independent Odderon Results Based on TOTEM data on Elastic Proton–Proton Scattering at 8 TeV #2

T. Csörgő (Wigner RCP, Budapest and Karoly Robert U. Coll.), T. Novák (Karoly Robert U. Coll.), R. Pasechnik (Lund U.), A. Ster (Wigner RCP, Budapest), I. Szanyi (Wigner RCP, Budapest and Karoly Robert U. Coll. and Eotvos U.) (Feb 9, 2023)

Published in: *Acta Phys.Polon.Supp.* 16 (2023) 5, 2 • Contribution to: Difflowx2022, 2, Difflowx2022 • e-Print: 2302.04930 [hep-ex]

Hungarian – Swedish team, new TOTEM data at 8 TeV:
Model-independent H(x) scaling method
Proc. Diffraction and Low-x 2022 by T. Csörgő
8 TeV data confirm and strengthen the Odderon signal

Model-independent Odderon results based on new TOTEM data on elastic pp collisions at 8 TeV #1

T. Csörgő (Budapest, RMKI and Karoly Robert U. Coll.), T. Novák (Karoly Robert U. Coll. and Budapest, Tech. U.), R. Pasechnik (Lund U.), A. Ster (Budapest, RMKI), I. Szanyi (Budapest, RMKI and Karoly Robert U. Coll. and Eotvos U.) (May 10, 2024)

Contribution to: ISMD23 • e-Print: 2405.06733 [hep-ph]

Hungarian – Swedish team, scaling method:
New TOTEM 8 TeV data vs H(x) scaling:
MDPI Universe (2024) 10(6), 264;
Detailed peer reviewed paper, see talk of A. Ster

Universe **2024**, *10*(6),264;
https://doi.org/10.3390/universe10060264

arXiv:2405.06733 [hep-ph]

What about domain of validity, model independently?
-- stay tuned… coming soon

Looking for Crossing-Odd(eron) effects

$$T_{\rm el}^{pp}(s,t) = T_{\rm el}^{+}(s,t) - T_{\rm el}^{-}(s,t),$$
$$T_{\rm el}^{p\overline{p}}(s,t) = T_{\rm el}^{+}(s,t) + T_{\rm el}^{-}(s,t),$$
$$T_{\rm el}^{+}(s,t) = T_{\rm el}^{P}(s,t) + T_{\rm el}^{f}(s,t),$$
$$T_{\rm el}^{-}(s,t) = T_{\rm el}^{O}(s,t) + T_{\rm el}^{\omega}(s,t).$$

$$T_{\rm el}^{P}(s,t) = \frac{1}{2}\left(T_{\rm el}^{pp}(s,t) + T_{\rm el}^{p\overline{p}}(s,t)\right)$$
$$T_{\rm el}^{O}(s,t) = \frac{1}{2}\left(T_{\rm el}^{p\overline{p}}(s,t) - T_{\rm el}^{pp}(s,t)\right)$$

$$\text{for } \sqrt{s} \geq 1 \text{ TeV},$$

Three simple consequences:

$$T_{el}^{O}(s,t) = 0 \implies \frac{d\sigma^{pp}}{dt} = \frac{d\sigma^{p\bar{p}}}{dt} \quad \text{for } \sqrt{s} \geq 1 \text{ TeV}$$

$$\frac{d\sigma^{pp}}{dt} = \frac{d\sigma^{p\bar{p}}}{dt} \quad \text{for } \sqrt{s} \geq 1 \text{ TeV} \;\not\Longrightarrow\; T_{el}^{O}(s,t) = 0.$$

$$\frac{d\sigma^{pp}}{dt} \neq \frac{d\sigma^{p\bar{p}}}{dt} \quad \text{for } \sqrt{s} \geq 1 \text{ TeV} \implies T_{el}^{O}(s,t) \neq 0$$

Odderon differential cross-section from pp and ppbar collisions, Reggeized Philips-Barger:
A. Ster, L. Jenkovszky, T. Cs., **arxiv:1501.03860,** *Phys.Rev.D* **91** (2015) 7, 074018

Scaling in the diffractive cone region

$$\frac{d\sigma}{dt} = A(s)\exp[B(s)t],$$

$$A(s) = B(s)\,\sigma_{\rm el}(s) = \frac{1+\rho_0^2(s)}{16\pi}\,\sigma_{\rm tot}^2(s),$$

$$\frac{1}{B(s)\sigma_{\rm el}(s)}\frac{d\sigma}{dt} = \exp[tB(s)]$$

$$H(x) \equiv \frac{1}{B(s)\sigma_{\rm el}(s)}\frac{d\sigma}{dt},$$
$$x = -tB(s).$$

Advantages:
1) H(x) ~ exp(-x) in the diffractive cone
2) Start from a place that you know
3) Measurable both for pp and pbarp

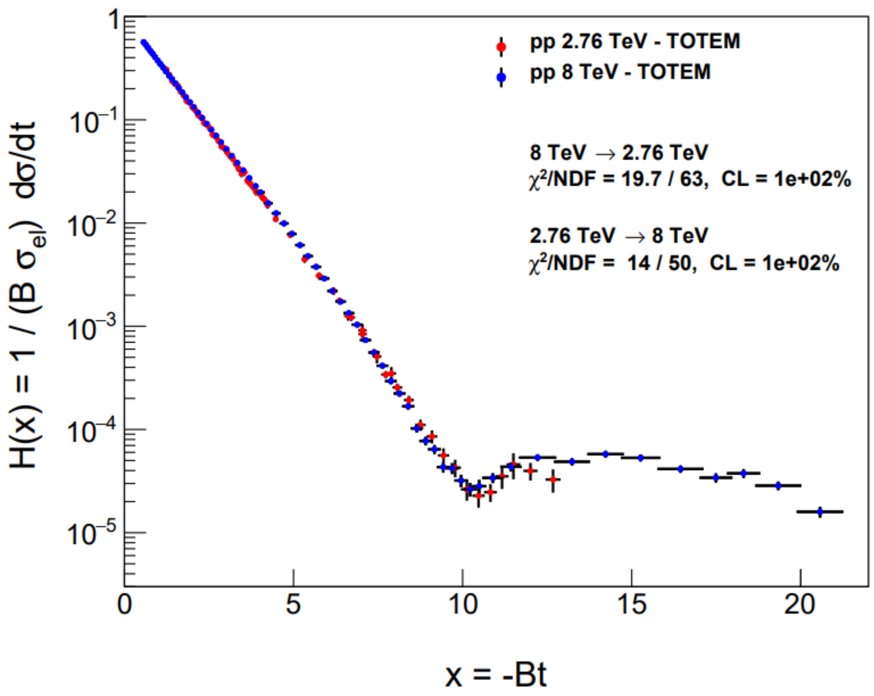
NEW RESULTS 1

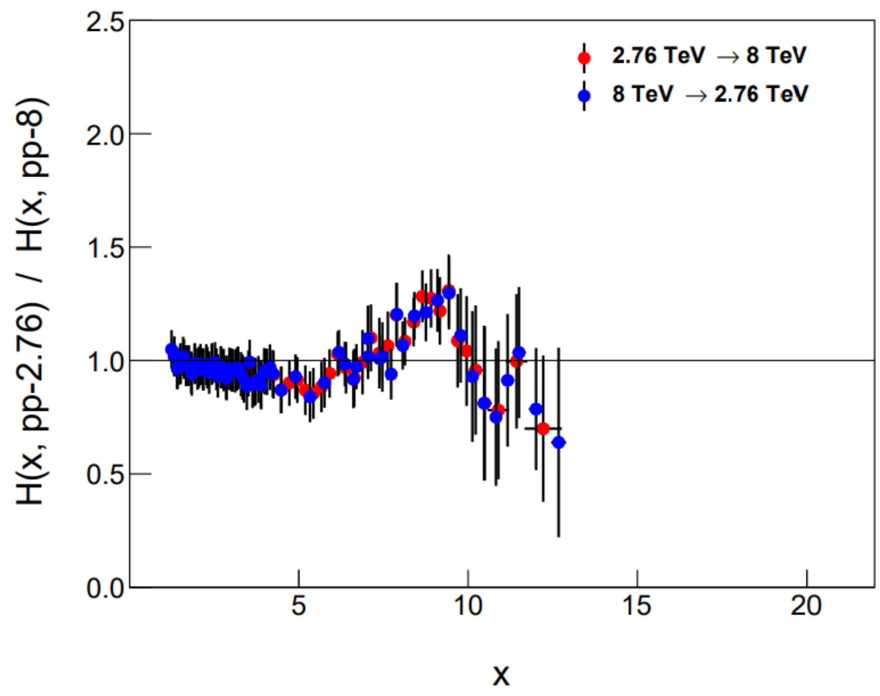
H(x) SCALING, USING 8 TeV

• 2405.06733
• 2405.06733 [hep-ph]

Test of H(x) scaling: 8 vs 2.76 TeV

$$H(x) \equiv \frac{1}{B(s)\sigma_{\rm el}(s)} \frac{d\sigma}{dt},$$
$$x = -tB(s).$$





Between 2.76 and 8 TeV, H(x) scaling observed!

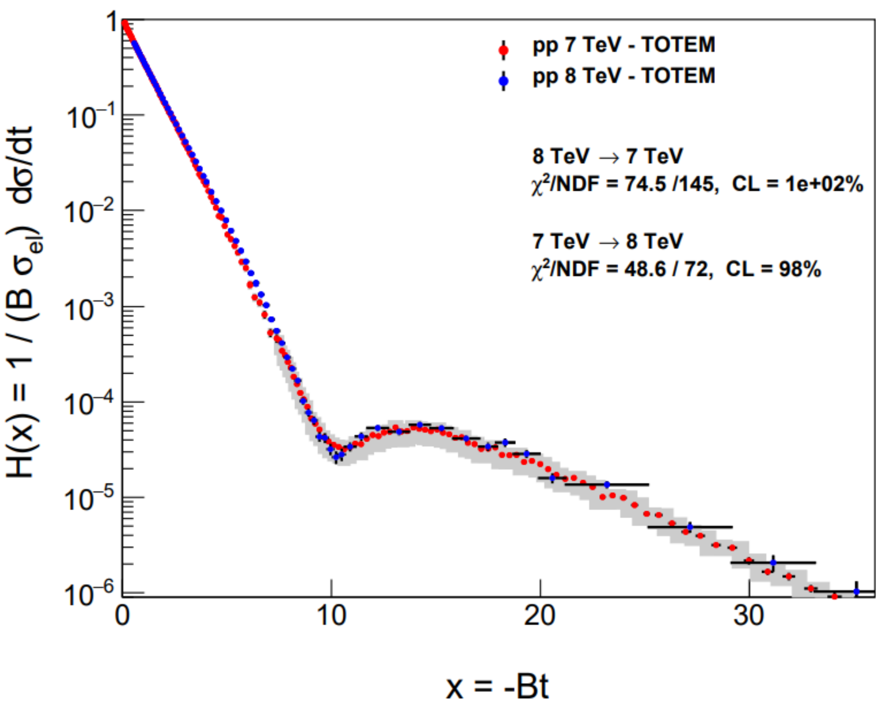
Hungarian-Swedish team, e-Print: 2405.06733 [hep-ph],

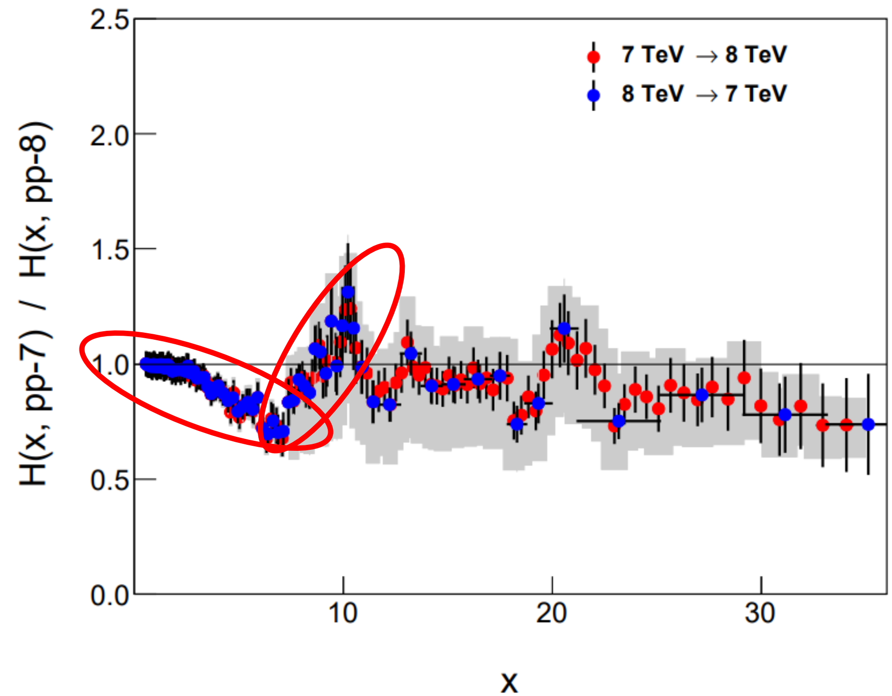
MDPI Universe **2024**, *10*(6), 264

•2405.06733
•2405.06733 [hep-ph]

Test of H(x) scaling: 8 vs 7 TeV TOTEM

$$H(x) \equiv \frac{1}{B(s)\sigma_{\rm el}(s)} \frac{d\sigma}{dt},$$
$$x = -tB(s).$$





Between 7 and 8 TeV, H(x) scaling observed, but …

Hungarian-Swedish team, e-Print: 2405.06733 [hep-ph],

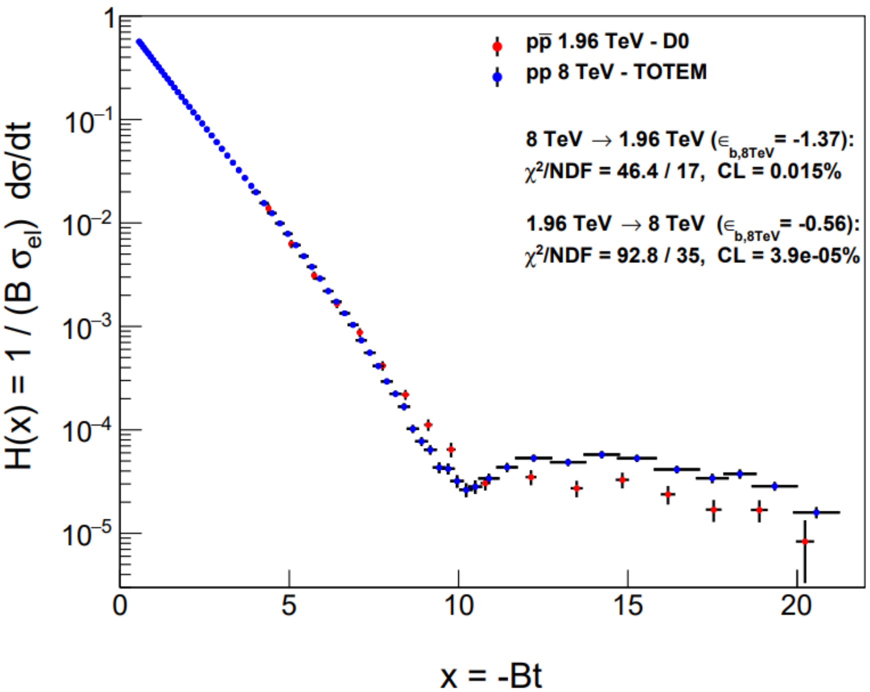
MDPI Universe **2024**, *10*(6), 264

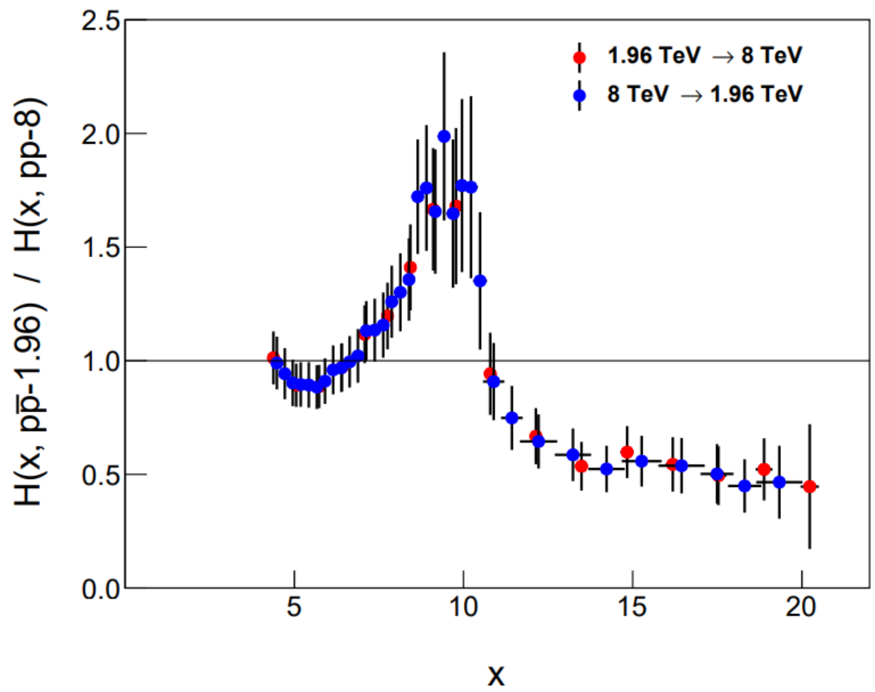
•2405.06733

•2405.06733 [hep-ph]

Odderon of H(x) scaling: 8 vs 1.96 TeV

$$H(x) \equiv \frac{1}{B(s)\sigma_{\rm el}(s)} \frac{d\sigma}{dt},$$
$$x = -tB(s).$$





Between 1.96 and 8 TeV, H(x|s,pp) and H(x|s,pbarp) are clearly different, with 3 < 3.79 < 5 σ

Hungarian-Swedish team, e-Print: 2405.06733 [hep-ph],

MDPI Universe **2024**, *10*(6), 264

•2405.06733

•2405.06733 [hep-ph]

Odderon significances from H(x) scaling

$\sqrt{s}$ (TeV)	χ^2	NDF	CL	significance (σ)
1.96 vs. 2.76	3.85	11	9.74×10^{-1}	0.03
1.96 vs. 7	80.1	17	3.681×10^{-10}	6.26
1.96 vs. 8	46.4	17	1.502×10^{-4}	3.79

$\sqrt{s}$ (TeV)	χ^2	NDF	CL	χ^2/NDF method	combined σ Stouffer's method
1.96 vs 2.76 & 8	50.25	28	6.064×10^{-3}	2.74	2.70
1.96 vs 2.76 & 7	83.95	28	1.698×10^{-7}	5.22	4.44
1.96 vs 2.76 & 7 & 8	130.35	45	2.935×10^{-10}	6.30	5.81
1.96 vs 7 & 8	126.5	34	1.415×10^{-12}	7.08	7.10

If 1.96, 2.76, 7 and 8 TeV data are combined, H(x) significances on all data results in 5 < 5.8 σ

If 1.96, 7 and 8 TeV data are combined, at least 7.08 σ.

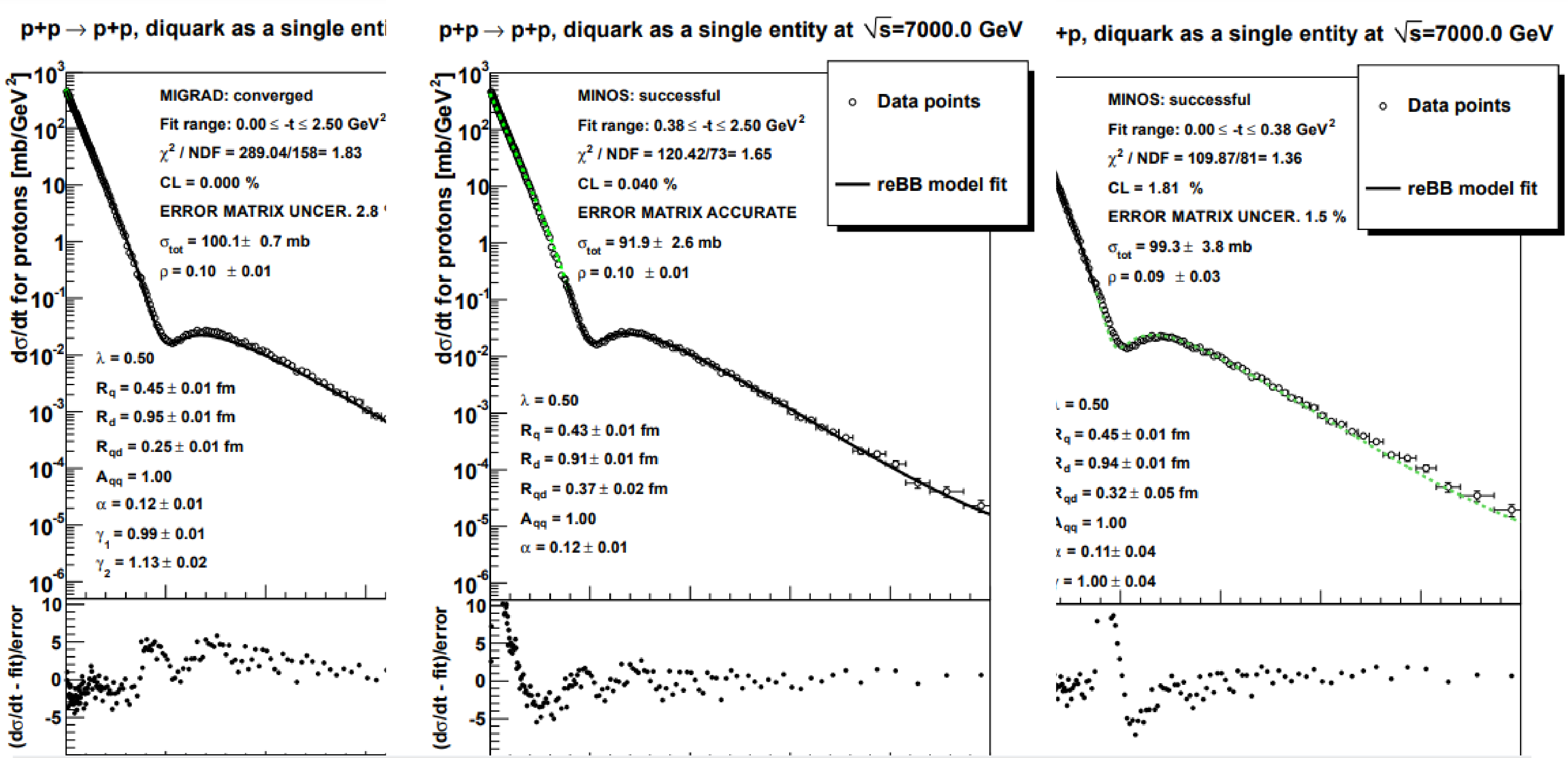
Hungarian-Swedish team, e-Print: 2405.06733 [hep-ph],

MDPI Universe **2024**, *10*(6), 264

NEW RESULTS 2

Low-t extension of ReBB
7 and 8 TeV pp
(cross-check, without Levy)

Statement of the problem, with old chi2



Excitation function of elastic pp scattering from a unitarily extended Bialas–Bzdak model #1

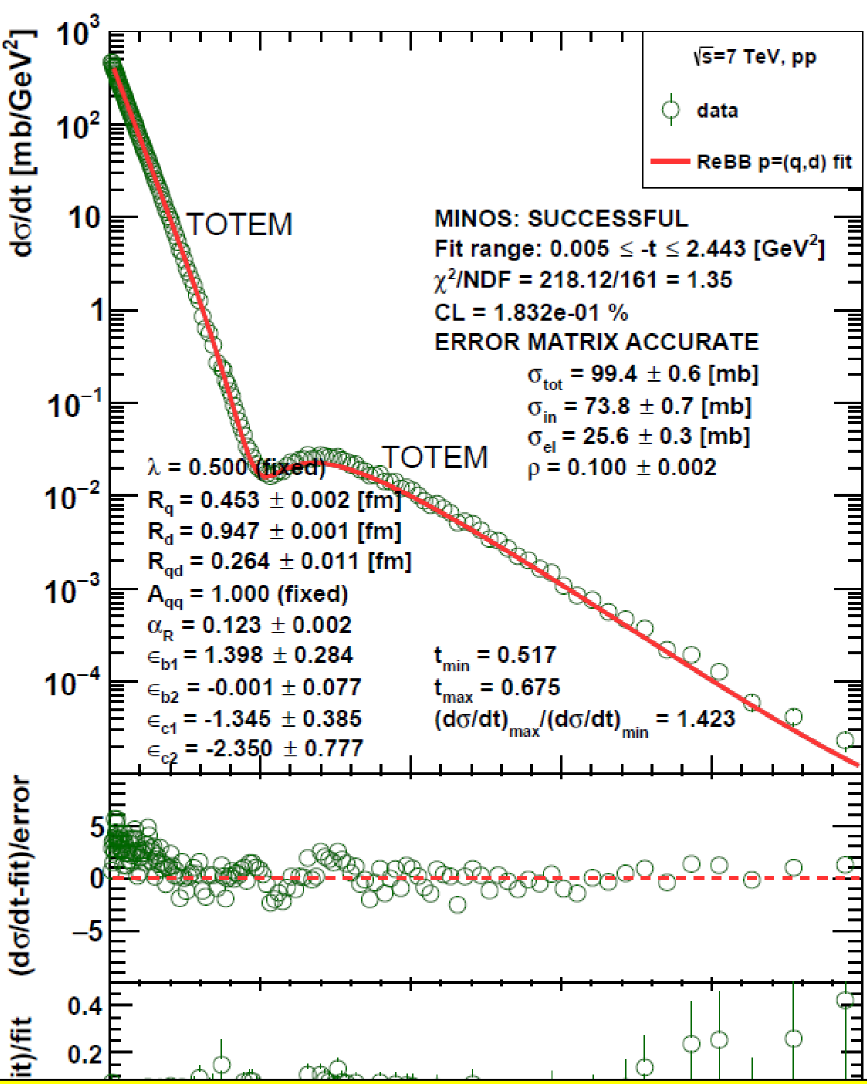
F. Nemes (CERN and Wigner RCP, Budapest), T. Csörgő (Wigner RCP, Budapest and Unlisted, HU), M. Csanád (Eotvos U.) (Apr 16, 2015)

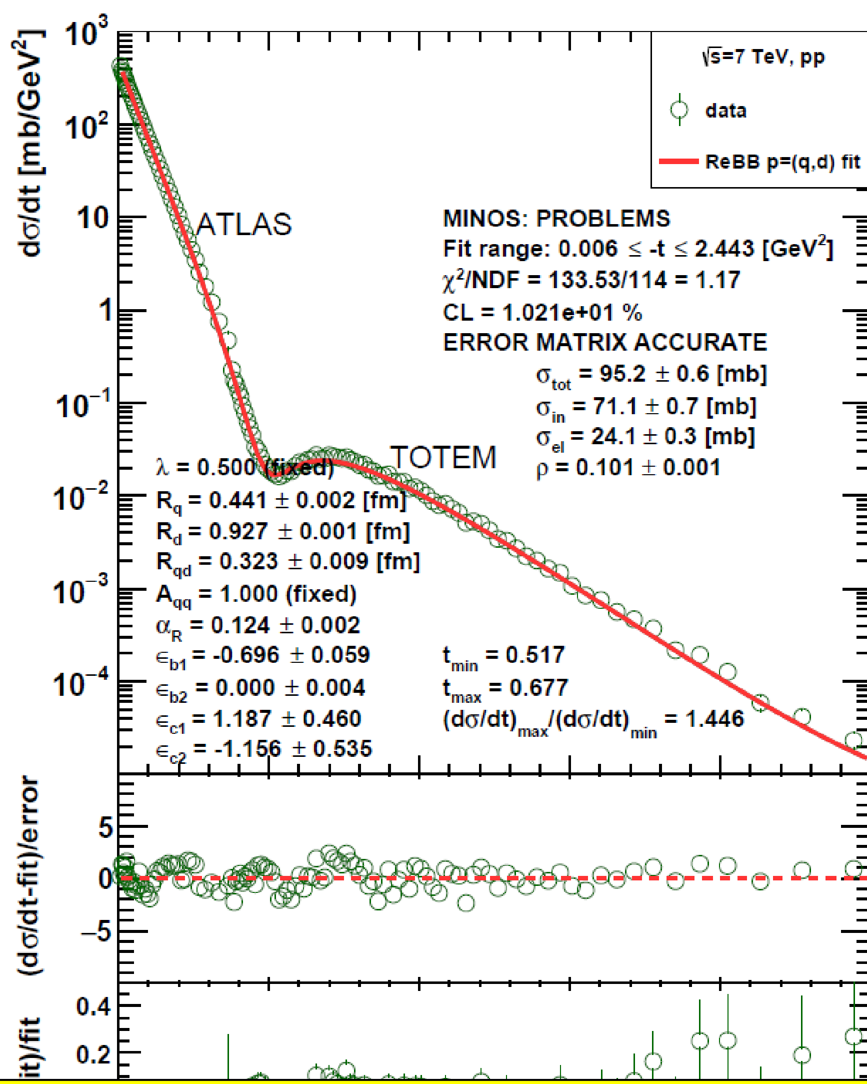
Published in: *Int.J.Mod.Phys.A* 30 (2015) 14, 1550076 • e-Print: 1505.01415 [hep-ph]

TOTEM low-t vs TOTEM-large-t fit acceptable at 7 TeV, but

The two datasets could not be ReBB fitted without a PHENIX method !

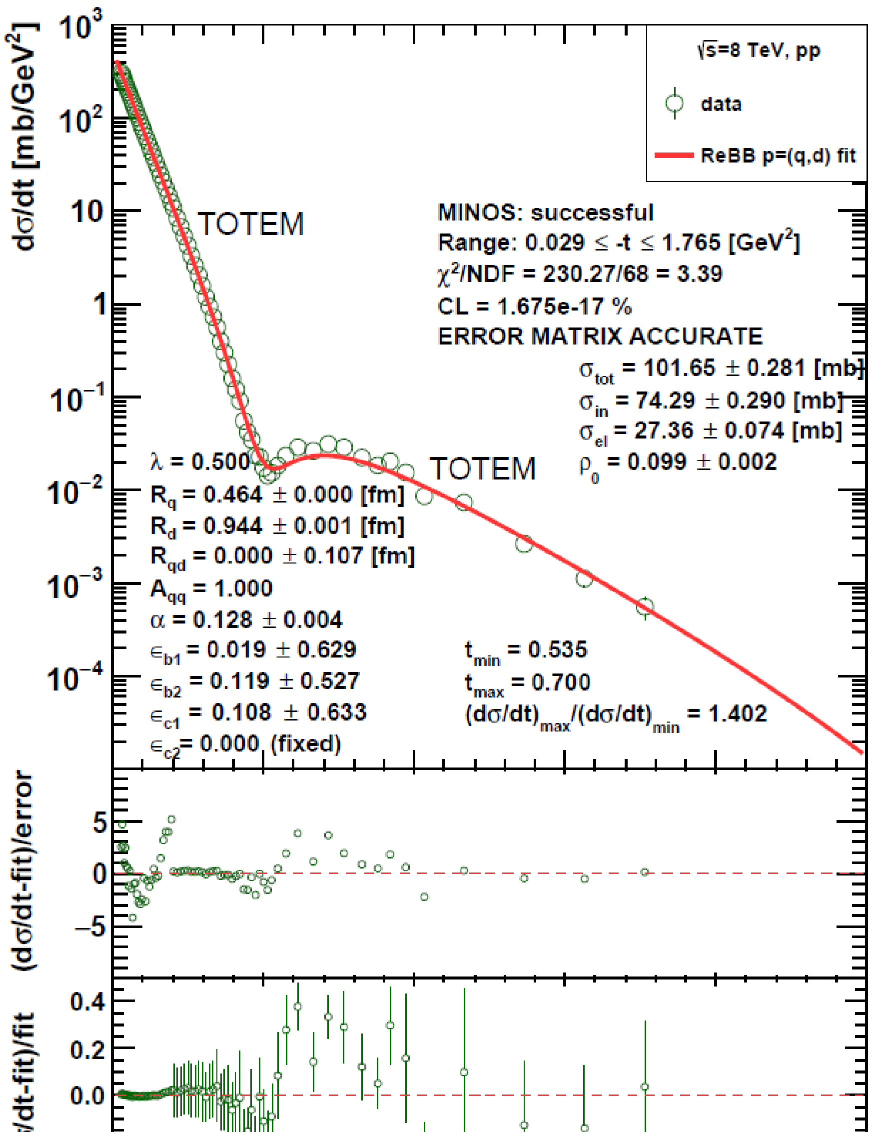
ReBB model extension to low –t, 7 TeV

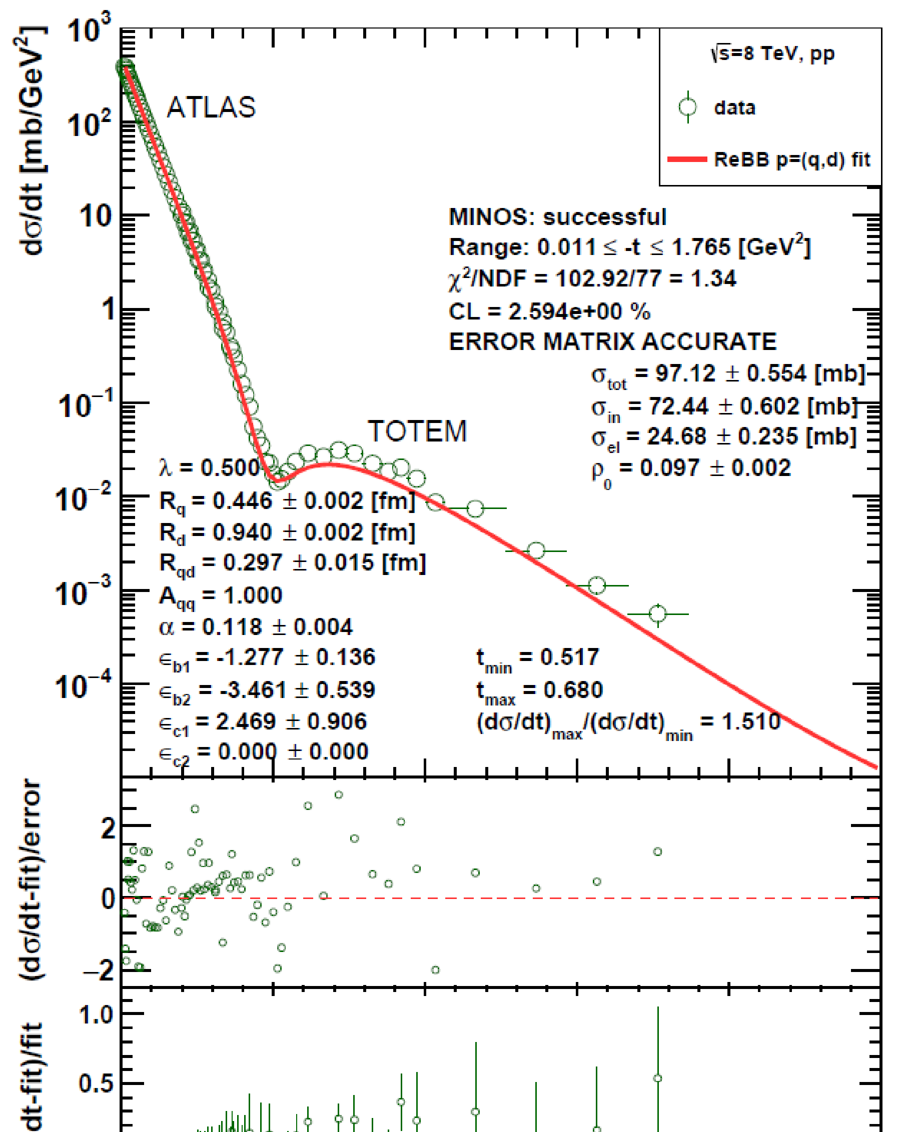




TOTEM low-t vs TOTEM-large-t fit acceptable at 7 TeV, using using PHENIX method of covariance diagonalization, but ... ATLAS low-t vs TOTEM-large-t fit successful at 7 TeV !

ReBB model extension to low −t, 8 TeV



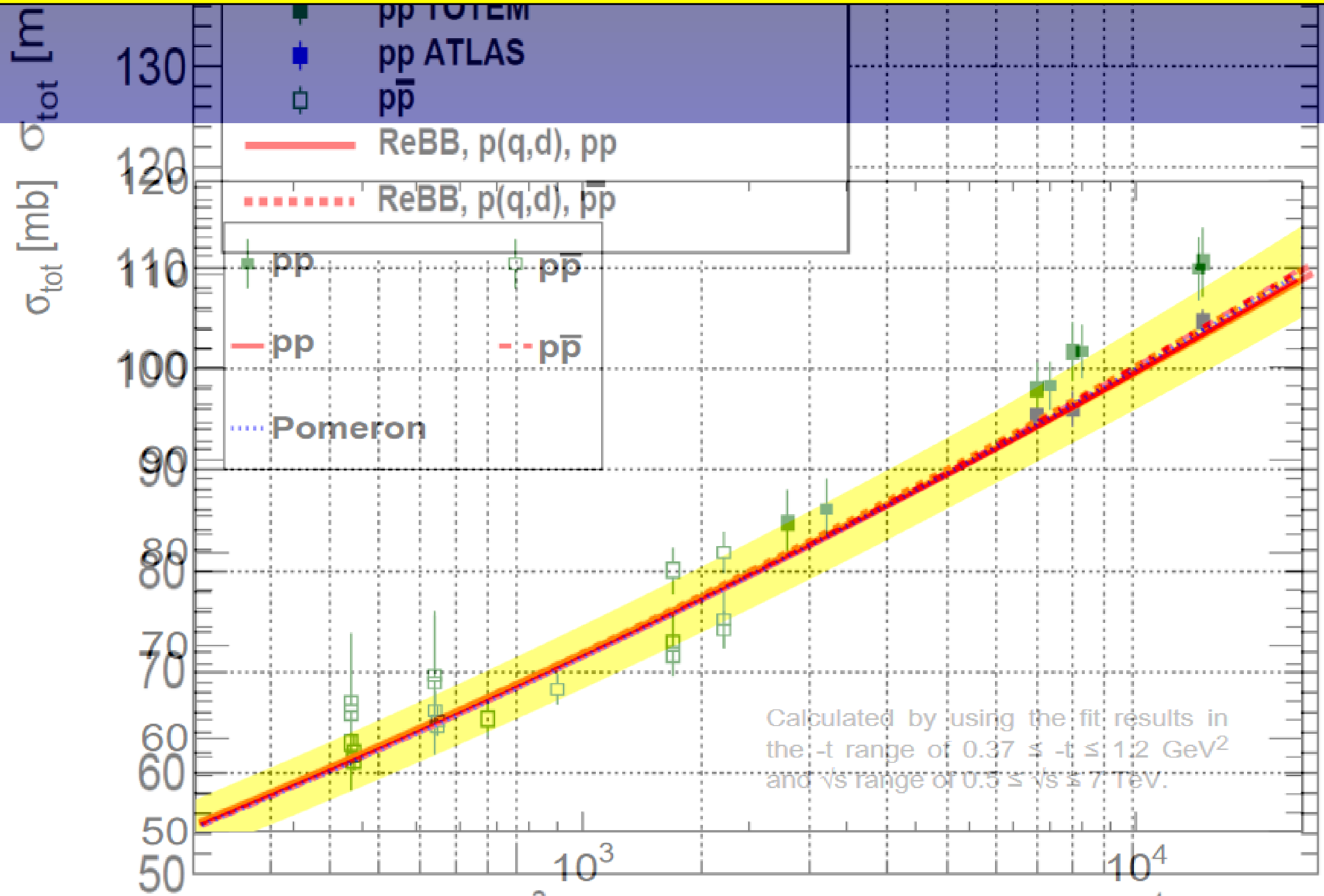


TOTEM low-t vs TOTEM-large-t fit FAILS at 8 TeV, but …

ATLAS low-t vs TOTEM-large-t fit SUCCESSFUL at 8 TeV !

ReBB at low –t vs ATLAS and TOTEM σ_{tot}

ReBB prediction vs ATLAS and TOTEM data at low -t:



T. Csörgő and I. Szanyi, *Eur.Phys.J.C* 81 (2021) 7, 611 •e-Print: [2005.14319] [hep-ph]

Fig. 27 Excitation function of the total cross-section for elastic pp, $p\bar{p}$ collisions and for the amplitude of Pomeron exchange, as evaluated from the log-linear excitation functions of the opacity parameters $\alpha^{pp}(s)$ and $\alpha^{p\bar{p}}(s)$ as well as that of the scale parameters, $R_q(s)$, $R_d(s)$, $R_{qd}(s)$, corresponding to Table 2. The yellow band indicates our conservative estimates on the systematic errors of the total cross-section of the Pomeron exchange.

Detailed Summary and Conclusions

New 8 TeV TOTEM data strenghten
Odderon signal using H(x) scaling method

New 8 TeV TOTEM data strenghten
Odderon signal using ReBB model

ReBB fit range can be extended to low –t at 8 TeV, if ATLAS data
are used instead of TOTEM low –t data

THANK YOU !

QUESTIONS?

2022 observations of Odderon with > 5 σ

Characterisation of the dip-bump structure observed in proton–proton elastic scattering at $\sqrt{s}$ = 8 TeV #1

TOTEM Collaboration • G. Antchev (Pilsen U.) et al. (Nov 23, 2021)

Published in: *Eur.Phys.J.C* 82 (2022) 3, 263 • e-Print: 2111.11991 [hep-ex]

Online attention

1

1 tweeters

This article is in the 1st percentile (ranked 279,419th) of the 343,918 tracked articles of a similar age in all journals and the 1st percentile (ranked 73rd) of the 114 tracked articles of a similar age in *The European Physical Journal C*

TOTEM Collaboration:
8 TeV: EPJ C (2022) 82, 263 (2022). Published: March 26, 2022
https://doi.org/10.1140/epjc/s10052-022-10065-x
Publishes final data for D0-TOTEM PRL published in 2021

The ReBB model and its H(x) scaling version at 8 TeV: Odderon exchange is a certainty #1

I. Szanyi (Eotvos U. and Wigner RCP, Budapest and Karoly Robert U. Coll.), T. Csörgő (Wigner RCP, Budapest and Karoly Robert U. Coll.) (Apr 21, 2022)

Published in: *Eur.Phys.J.C* 82 (2022) 9, 827, *Eur.Phys.J.C* 82 (2022) 827 • e-Print: 2204.10094 [hep-ph]

Online attention

3

1 Wikipedia page

This article is in the 64th percentile (ranked 57,525th) of the 166,532 tracked articles of a similar age in all journals and the 99th percentile (ranked 1st) of the 1 tracked articles of a similar age in *The European Physical Journal C*

Hungarian team, model of Polish origin:
New TOTEM 8 TeV data vs ReBB model predictions:
EPJ C 82 (2022) 9, 827. Published: Sept 19, 2022
In the ReBB model, Odderon exchange is a certainty
Presented at Zimányi'22 by I. Szanyi

What about model independent results?

NEW RESULTS 3

Simple Levy fits at small –t

(For details, see talk of I. Szanyi)

Review: Elastic scattering at small –t

$$\frac{d\sigma}{dt}(s,t) \simeq A(s)\exp(tB(s))$$

$$\sigma_{el}(s) = \int_0^\infty d|t| \frac{d\sigma(s)}{dt}$$

$$A(s) = \frac{1}{16\pi}(1+\rho_0^2(s))\sigma_{tot}^2(s)$$

$$\sigma_{\mathbf{el}}(s) = \frac{1}{16\pi}(1+\rho_0^2(s))\frac{\sigma_{tot}^2(s)}{B_0(s)}$$

If Odderon exists: signals possible both at t = 0 and at –t > 0.
Where the significance of the signal is coming from?

Odderon Search at small –t

$$T_{\rm el}^{O}(s,t) = \frac{1}{2}\left(T_{\rm el}^{p\overline{p}}(s,t) - T_{\rm el}^{pp}(s,t)\right)$$

valid for $\sqrt{s} \geq 1\ \mathrm{TeV},$

Some simple consequences at small –t, Gaussian sources:

$$\frac{d\sigma}{dt}(s,t) \simeq A(s)\exp(tB(s))$$

If any of

$$\begin{aligned} A^{pp}(s) &\neq A^{p\bar{p}}(s), \\ B^{pp}(s) &\neq B^{p\bar{p}}(s). \end{aligned}$$

$$\begin{aligned} \rho_0^{pp}(s) &\neq \rho_0^{p\bar{p}}(s), \\ \sigma_{el}^{pp}(s) &\neq \sigma_{el}^{p\bar{p}}(s), \\ \sigma_{tot}^{pp}(s) &\neq \sigma_{tot}^{p\bar{p}}(s). \end{aligned}$$

is statistically significant

$$\text{for } \sqrt{s} \geq 1\,\mathrm{TeV} \implies T_{el}^{O}(s,0) \neq 0$$

Odderon Search at small –t

$$T_{\rm el}^{O}(s,t) = \frac{1}{2}\left(T_{\rm el}^{p\bar{p}}(s,t) - T_{\rm el}^{pp}(s,t)\right)$$

valid for $\sqrt{s} \geq 1\ \mathrm{TeV},$

Some simple consequences at small –t, Levy sources:

If any of

$$\begin{aligned} a^{pp}(s) &\neq a^{p\bar{p}}(s), \\ b^{pp}(s) &\neq b^{p\bar{p}}(s), \\ \alpha_L^{pp} &\neq \alpha_L^{p\bar{p}}, \end{aligned}$$

$$\begin{aligned} \rho_0^{pp}(s) &\neq \rho_0^{p\bar{p}}(s), \\ \sigma_{el}^{pp}(s) &\neq \sigma_{el}^{p\bar{p}}(s), \\ \sigma_{tot}^{pp}(s) &\neq \sigma_{tot}^{p\bar{p}}(s). \end{aligned}$$

$$\frac{d\sigma}{dt}(s,t) \simeq a(s)\exp\left[-(tb(s))^{\alpha_L/2}\right]$$

is statistically significant

$$\text{for } \sqrt{s} \geq 1\,\mathrm{TeV} \implies T_{el}^{O}(s,0) \neq 0$$

Lévy α-Stable Model for the Non-Exponential Low-|t| Proton–Proton Differential Cross-Section #1

Tamás Csörgő (Karoly Robert U. Coll. and Budapest, RMKI), Sándor Hegyi (Budapest, RMKI), István Szanyi (Karoly Robert U. Coll. and Budapest, RMKI and Eotvos U., Dept. Atomic Phys.) (Aug 3, 2023)

Published in: *Universe* 9 (2023) 8, 361, *Universe* 9 (2023) 361 • e-Print: 2308.05000 [hep-ph]

Levy generalized Bialas-Bzdak Model

Simple results at small -t:

$$a(s) = \frac{81}{16}\pi \left(2R_q^{\alpha_L(s)}(s)\right)^{4/\alpha_L} \left(1 + 4\alpha_R^2(s)\right)$$

$$b(s) = \frac{1}{36}\left(\frac{4}{3}\right)^{2/\alpha_L(s)} \left(\left(2 + 2^{\alpha_L(s)}\right)R_{qd}^{\alpha_L(s)}(s) + 3^{\alpha_L(s)}\left(2R_d^{\alpha_L(s)}(s) + R_q^{\alpha_L(s)}(s)\right)\right)^{2/\alpha_L(s)}$$

$$\rho_0(s) = 2\alpha_R(s)$$

$$\sigma_{tot}(s) = 9\pi \left(2R_q^{\alpha_L(s)}(s)\right)^{2/\alpha_L(s)}$$

$$\sigma_{el}(s) = \frac{a(s)}{b(s)}\Gamma\left(\frac{2 + \alpha_L(s)}{\alpha_L(s)}\right)$$

From data fits: R_q, R_d, R_{qd}, α_L is same in pp and pbarb

But!

$$\rho_0^{pp}(s) \neq \rho_0^{p\bar{p}}(s),$$

Lévy α-stable model for the non-exponential low-$|t|$ proton-proton differential cross section #1

Click a bar to select papers. Click the bar again to reset your selection.

T. Csörgő (Karoly Robert U. Coll. and Budapest, RMKI), S. Hegyi, I. Szanyi (Karoly Robert U. Coll. and Budapest, RMKI and Eotvos U., Dept. Atomic Phys.) (Aug 9, 2023)

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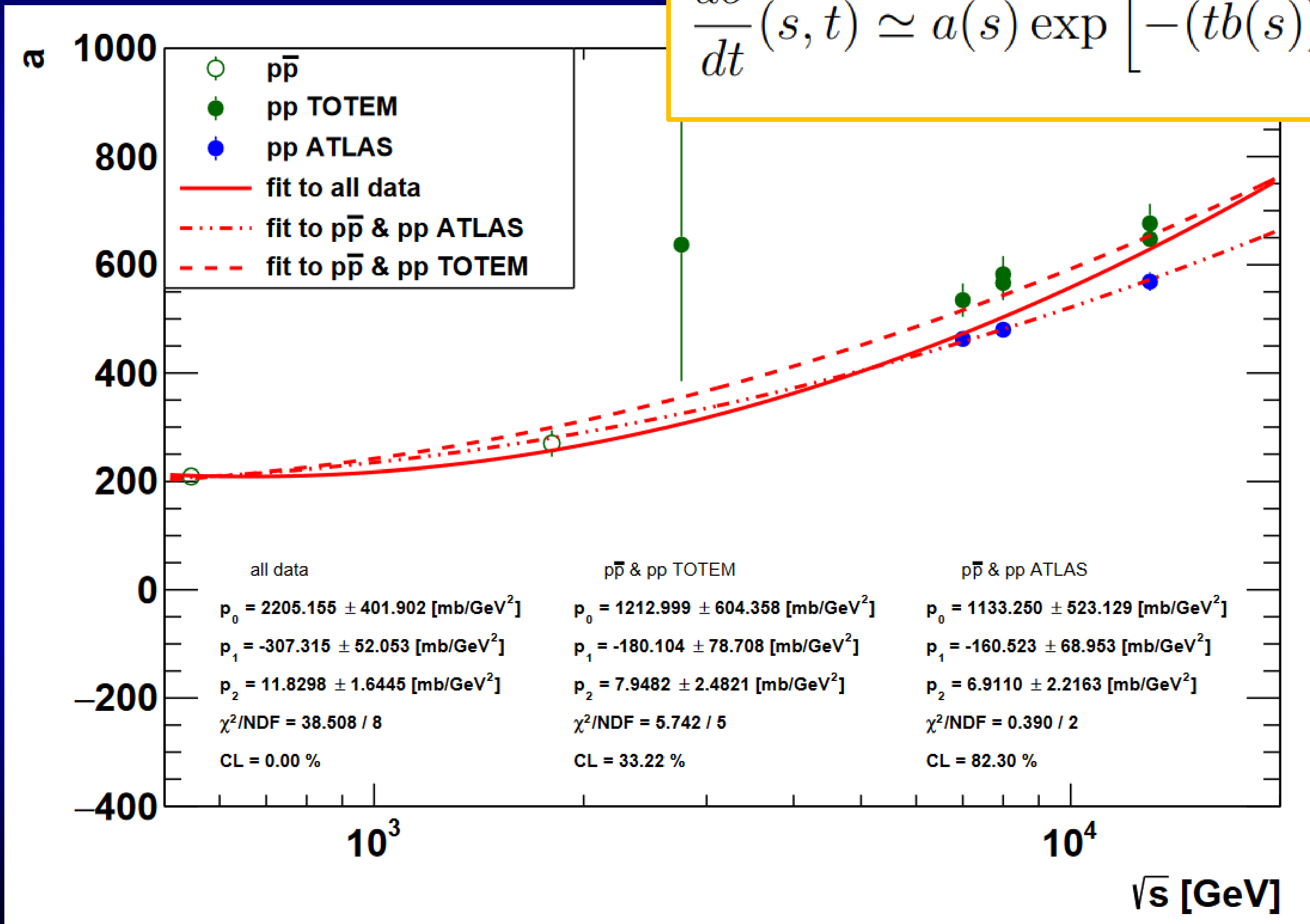
$$\frac{d\sigma}{dt}(s,t) \simeq a(s) \exp\left[-(tb(s))^{\alpha_L/2}\right]$$



#1

Lévy α-stable model for the non-exponential low-$|t|$ proton-proton differential cross section

Click a bar to select papers. Click the bar again to reset your selection.

T. Csörgő (Karoly Robert U. Coll. and Budapest, RMKI), S. Hegyi, I. Szanyi (Karoly Robert U. Coll. and Budapest, RMKI and Eotvos U., Dept. Atomic Phys.) (Aug 9, 2023)

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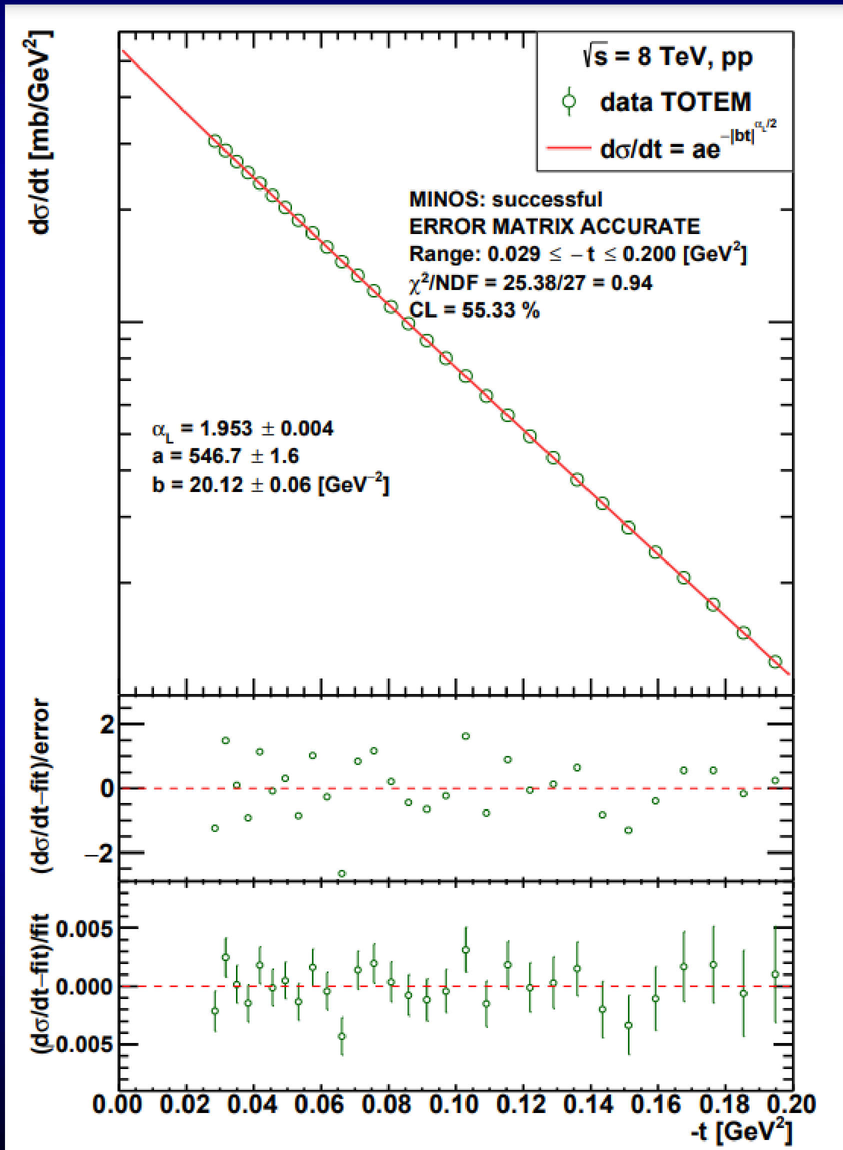
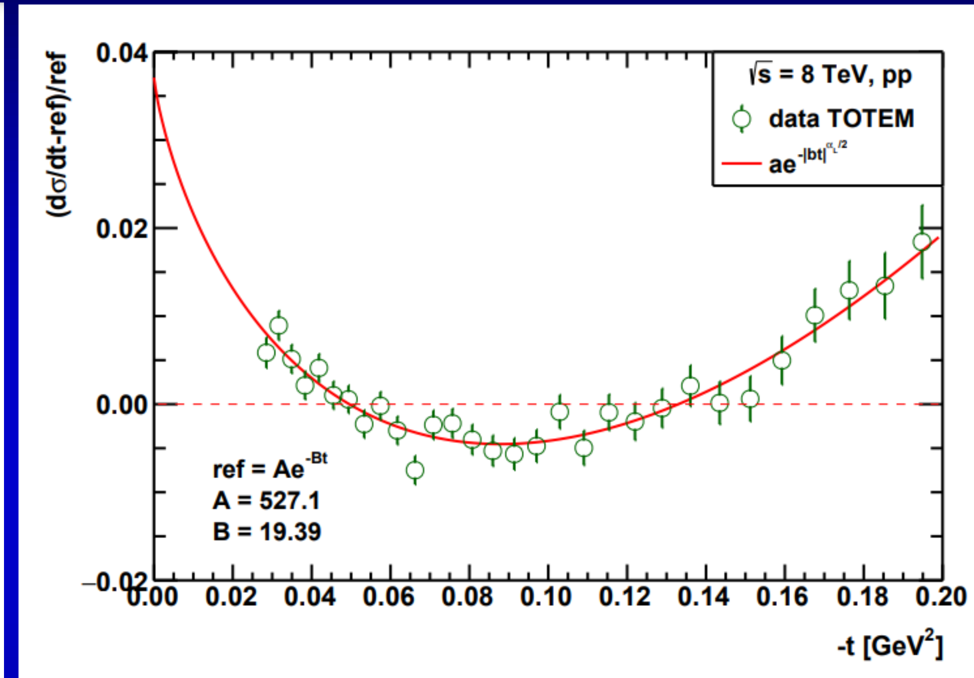
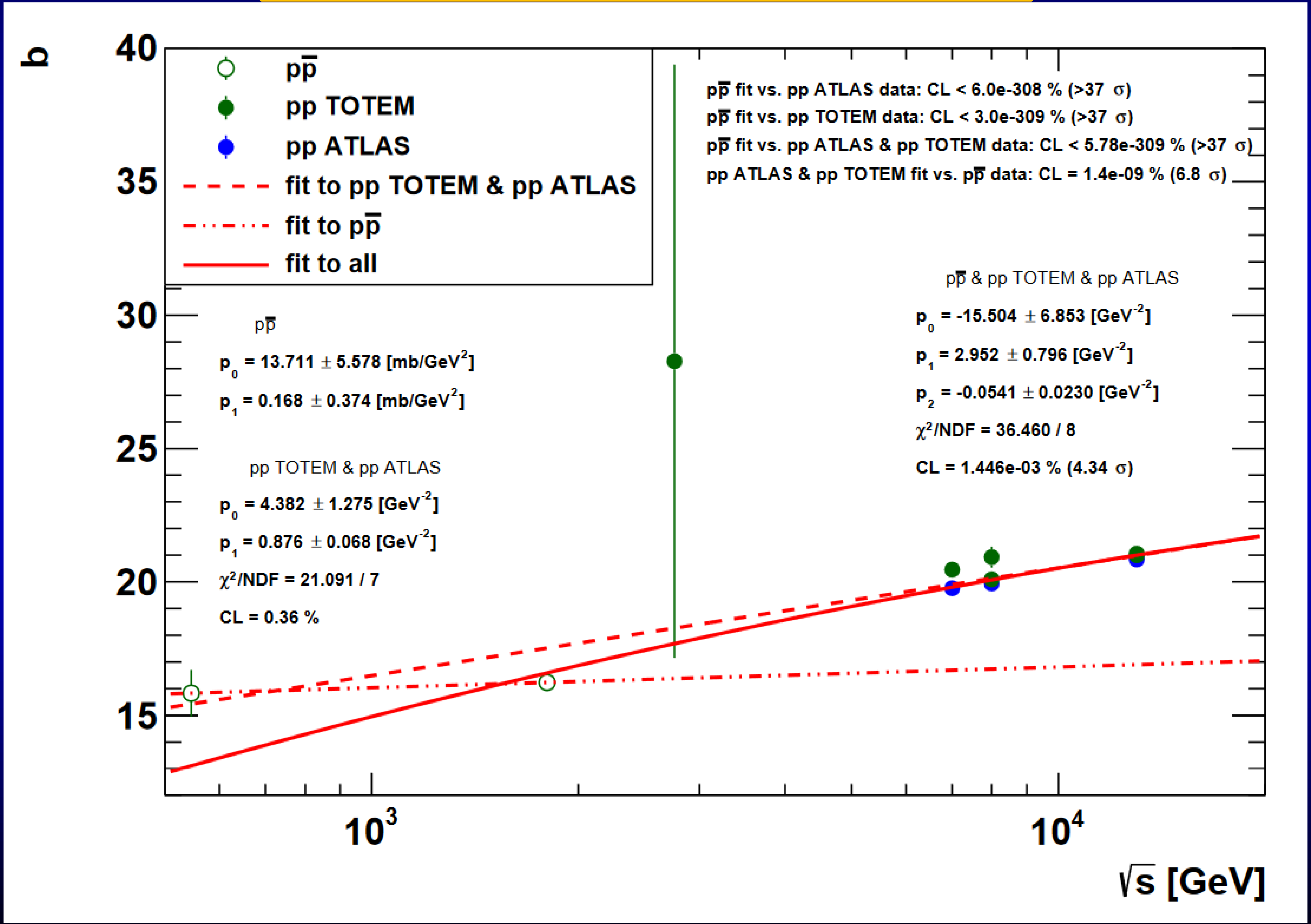




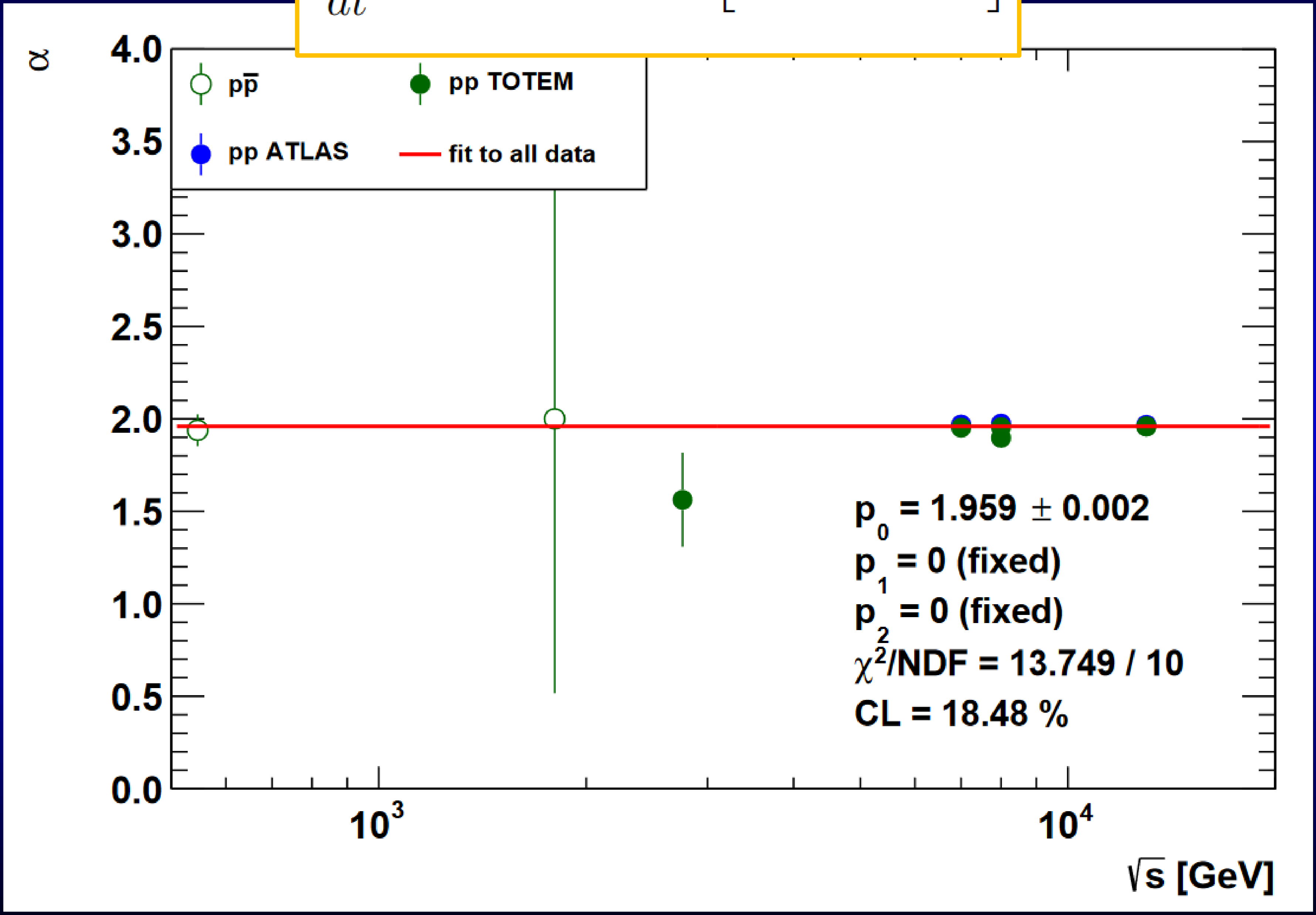
$$\frac{d\sigma}{dt}(s,t) \simeq a(s)\exp\left[-(tb(s))^{\alpha_L/2}\right]$$

From Glauber's theory, p=(q,d)
Good quality fits at 8 TeV and also
at every low –t dataset for pp, pbarp

$$\frac{d\sigma}{dt}(s,t) \simeq a(s)\exp\left[-(tb(s))^{\alpha_L/2}\right]$$



$$\frac{d\sigma}{dt}(s,t) \simeq a(s)\exp\left[-(tb(s))^{\alpha_L/2}\right]$$

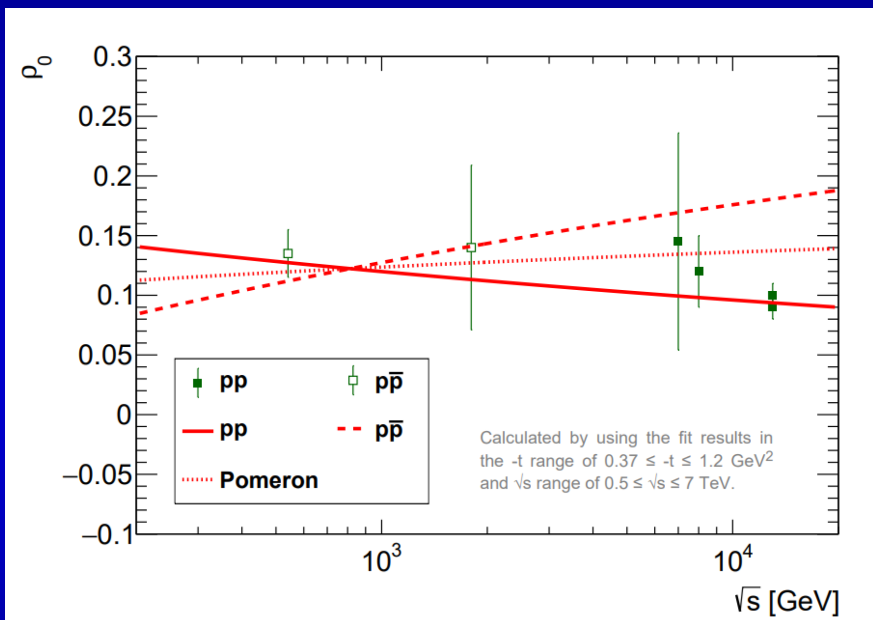


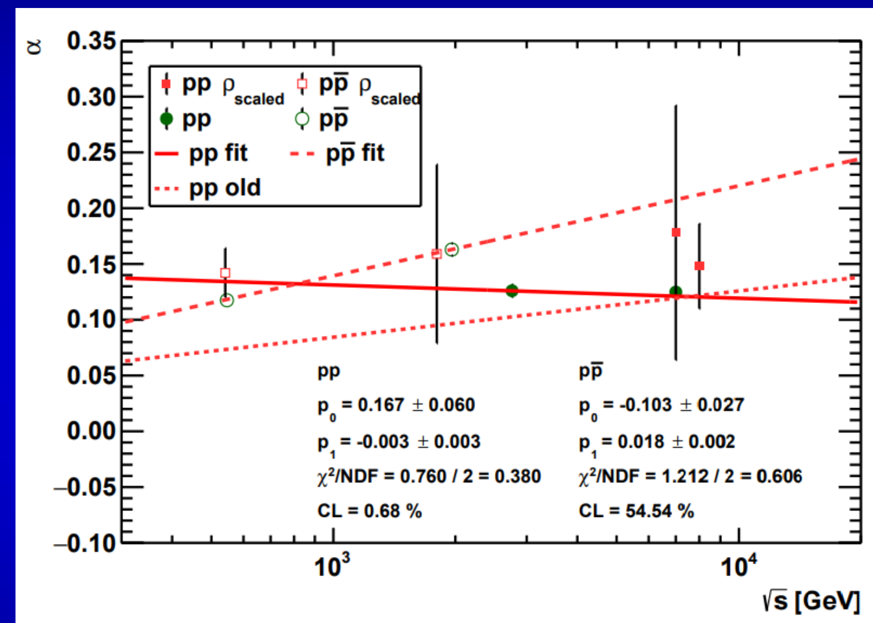
ρ_0 from fits to data

Observation of Odderon effects at LHC energies: a real extended Bialas–Bzdak model study

T. Csorgo (Wigner RCP, Budapest and EKU KRC, Gyongyos), I. Szanyi (Eotvos U. and Wigner RCP, Budapest) (May 28, 2020)

Published in: *Eur.Phys.J.C* 81 (2021) 7, 611 • e-Print: 2005.14319 [hep-ph]





From data fits: R_q, R_d, R_{qd} is the same, but $\alpha \sim \rho$ (opacity) is not the same in pp and pbarb

$$\rho_0^{pp}(s) \neq \rho_0^{p\bar{p}}(s),$$

Levy + Bialas-Bzdak at small t

Lévy α-Stable Model for the Non-Exponential Low-|t| Proton–Proton Differential Cross-Section #1

Tamás Csörgő (Karoly Robert U. Coll. and Budapest, RMKI), Sándor Hegyi (Budapest, RMKI), István Szanyi (Karoly Robert U. Coll. and Budapest, RMKI and Eotvos U., Dept. Atomic Phys.) (Aug 3, 2023)

Published in: *Universe* 9 (2023) 8, 361, *Universe* 9 (2023) 361 • e-Print: 2308.05000 [hep-ph]

Easy to fit model, with dramatic consequences

$$
\begin{aligned}
b^{pp}(s) &= b^{p\bar{p}}(s), \\
\sigma^{pp}_{tot}(s) &= \sigma^{p\bar{p}}_{tot}(s).
\end{aligned}
$$

Strong form of Pomeranchuk theorem,
with small signals of odderon exchange in optical point, ρ and elastic cross-section! Tests are needed…

$$
\begin{aligned}
a^{pp}(s) &\neq a^{p\bar{p}}(s), \\
\rho_0^{pp}(s) &\neq \rho_0^{p\bar{p}}(s), \\
\sigma^{pp}_{el}(s) &\neq \sigma^{p\bar{p}}_{el}(s),
\end{aligned}
$$

Formalism: elastic scattering

$$\frac{d\sigma(s)}{dt} = \frac{1}{4\pi}|T_{el}(s,\Delta)|^2, \qquad \Delta = \sqrt{|t|}.$$

$$\sigma_{el}(s) = \int_0^\infty d|t| \frac{d\sigma(s)}{dt}$$

$$A(s) = \lim_{t\to 0} \frac{d\sigma}{dt}(s,t)$$

$$A(s) = \frac{1}{16\pi}(1+\rho_0^2(s))\sigma_{tot}^2(s)$$

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

$$\rho(s,t) \equiv \frac{\mathrm{Re}\, T_{el}(s,\Delta)}{\mathrm{Im}\, T_{el}(s,\Delta)}$$

$$B(s) \equiv B_0(s) = \lim_{t\to 0} B(s,t),$$

$$\rho(s) \equiv \rho_0(s) = \lim_{t\to 0} \rho(s,t)$$

$$\sigma_{\mathrm{tot}}(s) \equiv 2\,\mathrm{Im}\, T_{el}(\Delta = 0, s)$$

Basic problem: dσ/dt measures an amplitude, *modulus squared*.
If Odderon exists: signals in elastic scattering at t = 0 and at –t > 0.

Formalism in b space

$$\frac{d\sigma(s)}{dt} = \frac{1}{4\pi}|T_{el}(s,\Delta)|^2, \qquad \Delta = \sqrt{|t|}.$$

$$t_{\rm el}(s,b) = \int \frac{d^2\boldsymbol{\Delta}}{(2\pi)^2} e^{-i\boldsymbol{\Delta b}} T_{\rm el}(s,\Delta) =$$

$$= \frac{1}{2\pi}\int J_0(\Delta\, b)\, T_{\rm el}(s,\Delta)\,\Delta\, d\Delta\,,$$

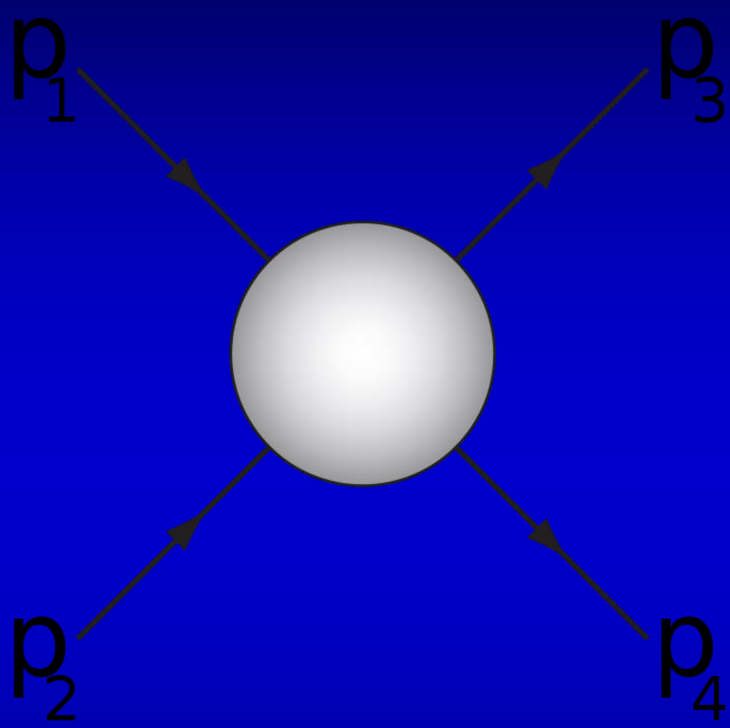
$$\Delta \equiv |\boldsymbol{\Delta}|, \quad b \equiv |\boldsymbol{b}|.$$

$$t_{\rm el}(s,b) = i\left[1 - e^{-\Omega(s,b)}\right]$$

$$P(s,b) = 1 - \left|e^{-\Omega(s,b)}\right|^2$$

Impact parameter or b space:
elastic scattering interferes with propagation w/o collisions: Genuine quantum physics.
Complex opacity function Ω(s,b) (eikonal, from unitarity)
$0 \le P(s,b) \le 1$: *inelastic* scattering has a probabilistic interpretation

Mandelstam variables



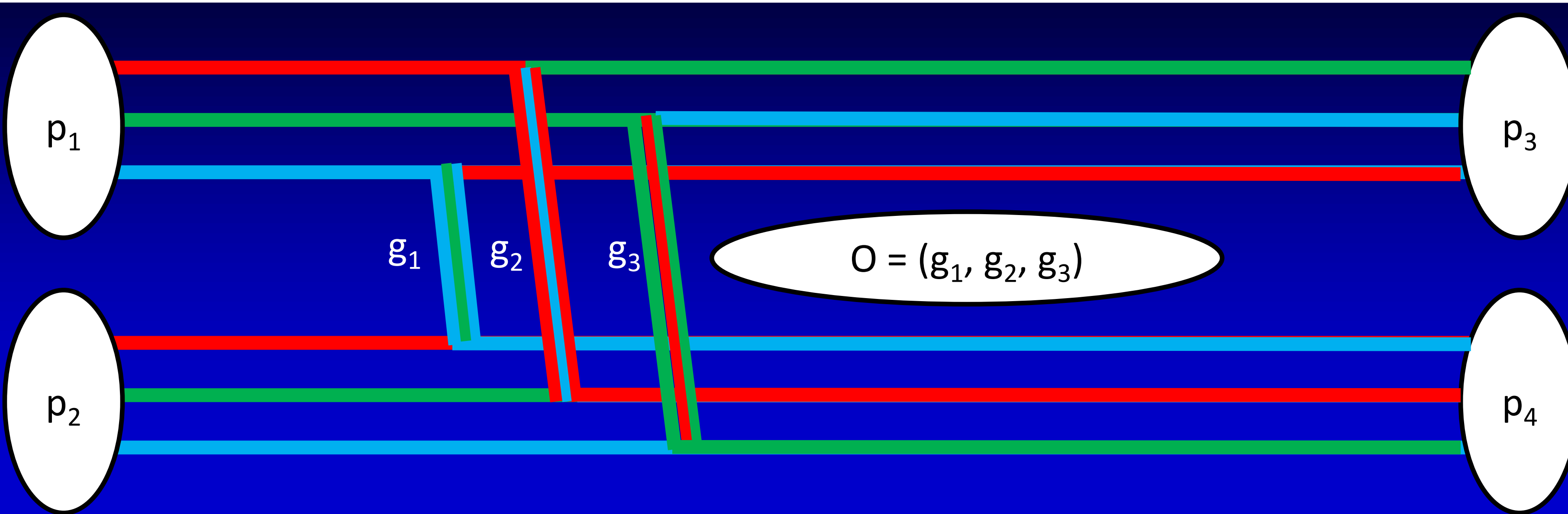
$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$
$$t = (p_1 - p_3)^2 = (p_4 - p_2)^2$$
$$u = (p_1 - p_4)^2 = (p_3 - p_2)^2$$

p_1,p_2: four-momenta before elastic scattering

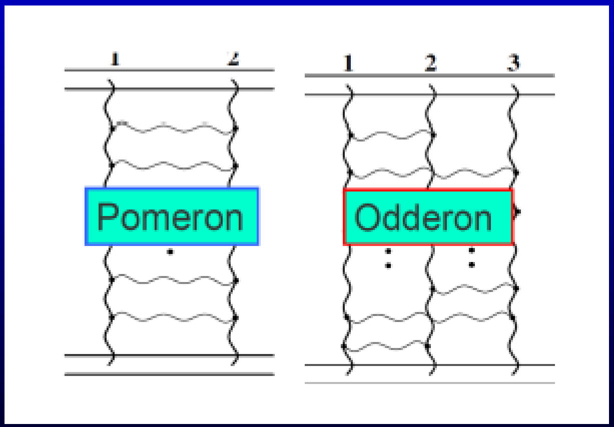
p_3,p_4: four-momenta after elastic scattering

s: square of the cms energy
t: square of four-momentum transfer

Odderon and QCD in Laymen's Terms



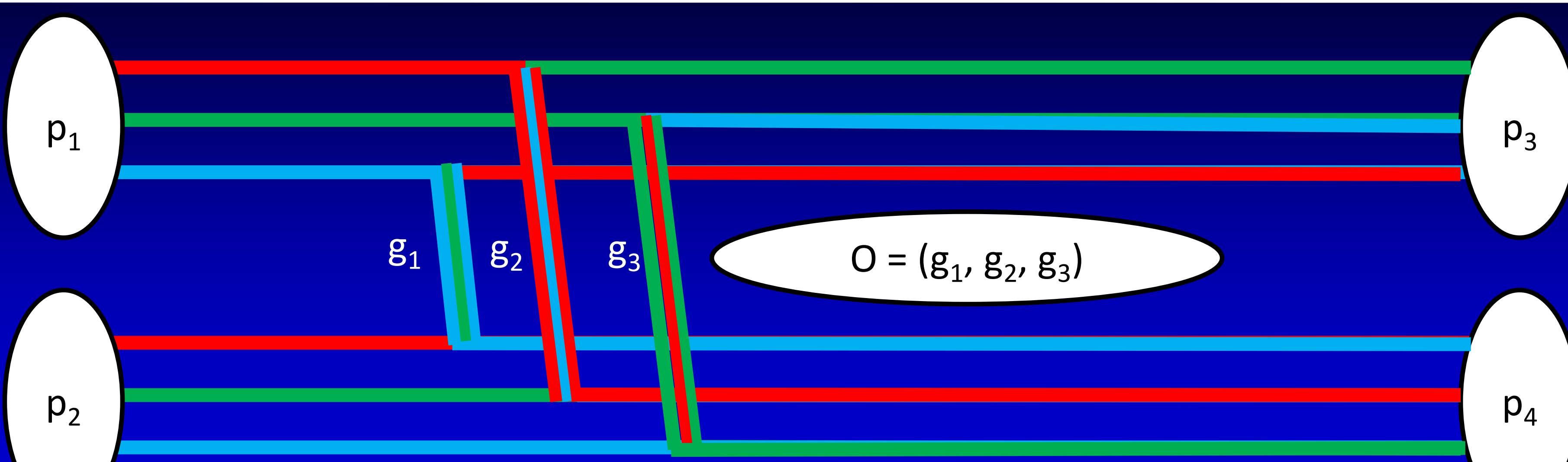
$g_1 = B\bar{R}+R\bar{B}$ $g_2 = R\bar{G}+G\bar{R}$ $g_3 = G\bar{B}+B\bar{G}$



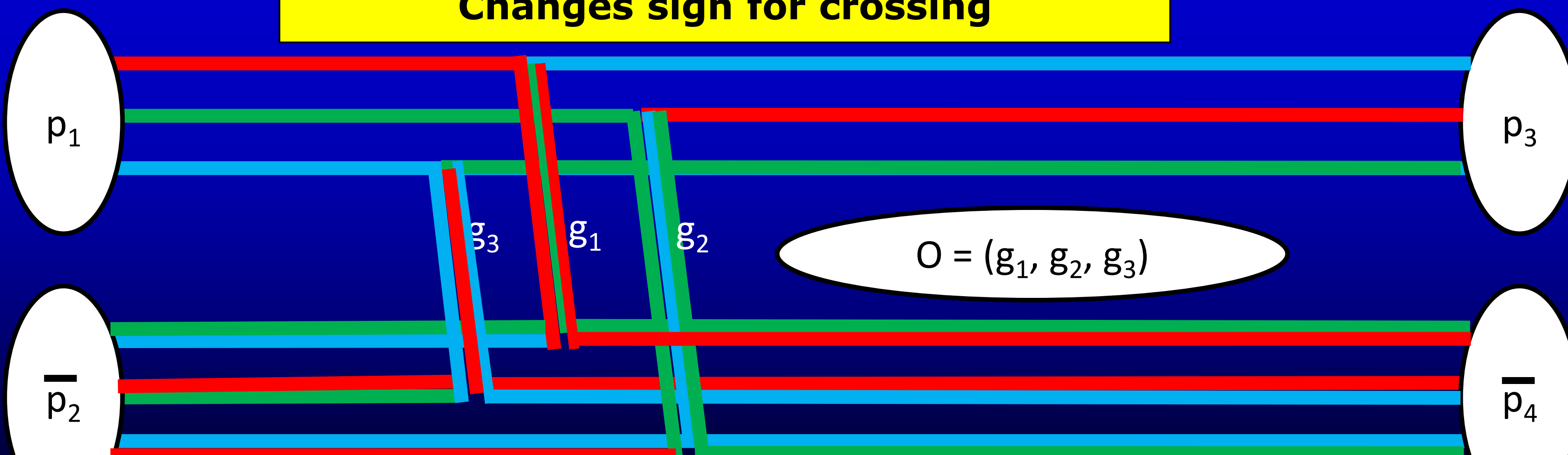
Pomeron (2+4+…) gluon in pp:
(RGB)+(RGB) → (GRB)+(GRB)

Odderon (3+5+… gluon) in pp:
(RGB)+(RGB) → (GBR)+(BRG)
Well established in QCD

Odderon and elastic collisions



Odderon exchange: both pp and $p\bar{p}$
$(RGB)+(\bar{R}\bar{B}\bar{G}) \rightarrow (BRG)+(\bar{B}\bar{G}\bar{R})$
Changes sign for crossing



$g_1 = B\bar{R}+R\bar{B}$ $g_2 = R\bar{G}+G\bar{R}$ $g_3 = G\bar{B}+B\bar{G}$