PROPERTIES OF ODDERON

FROM A META-ANALYSIS OF PUBLISHED DATA

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

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

Statistically Significant Observations of Odderon

Model independent results:

Significance ≥ 6.26 σ

Model dependent results:

Significance ≥ 7.08 σ

D0-TOTEM results:

Significance ≥ 5.2 σ

New: Model independently

Optimal Significance ≥ 6.36 σ

Domain of validity,

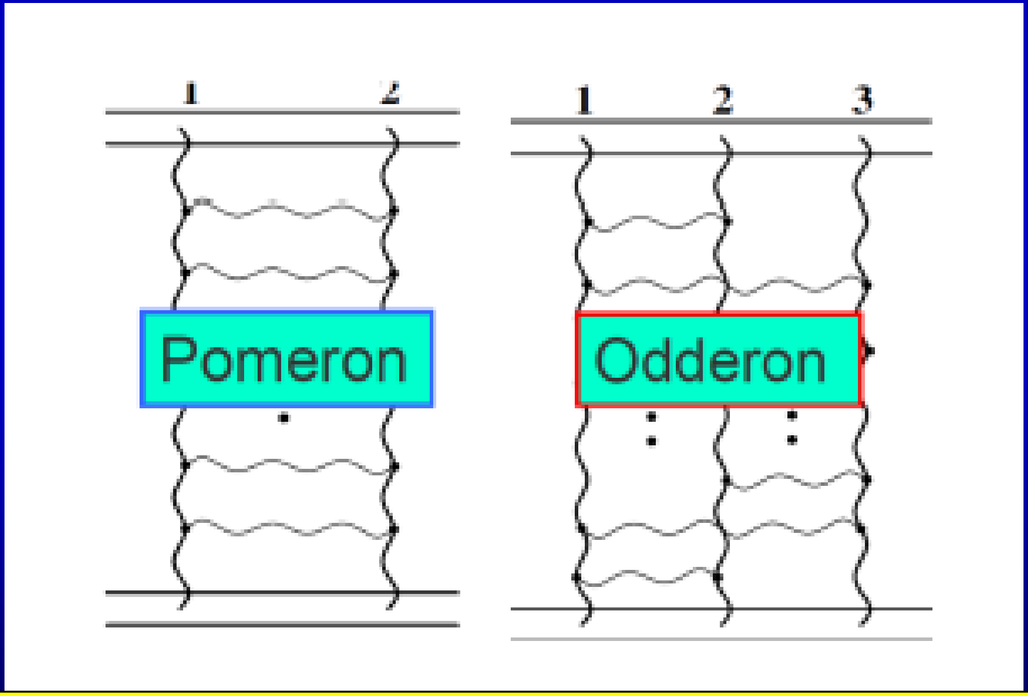
Sliding window, closing doors

First results on Odderon properties

Odderon: 48 years old scientific puzzle

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

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



Odderon name coined in: D. Joynson, E. Leader, <u>B. Nicolescu</u>, C. Lopez, Nuovo Cim. 30A, 345 (1975)
Well established in QCD by now !

Strategy of Odderon Search

and symmetry violation in elastic collisions

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

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

Four simple consequences:

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

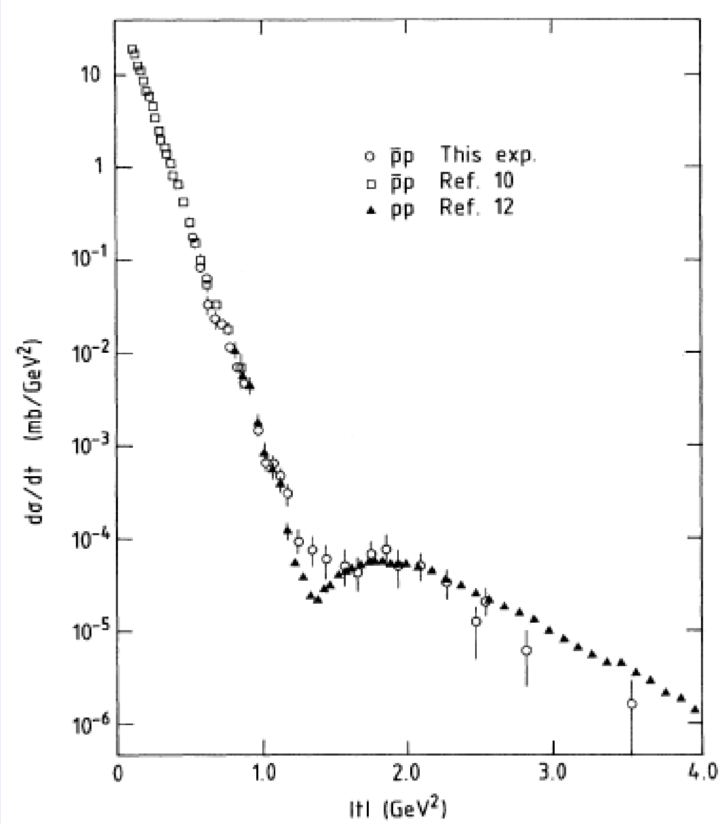
$$\frac{d\sigma^{pp}}{dt} \neq \frac{d\sigma^{p\bar{p}}}{dt} \quad \text{for } \sqrt{s} \geq 1\ \text{TeV} \implies T_{el}^{O}(s,t) \neq 0$$

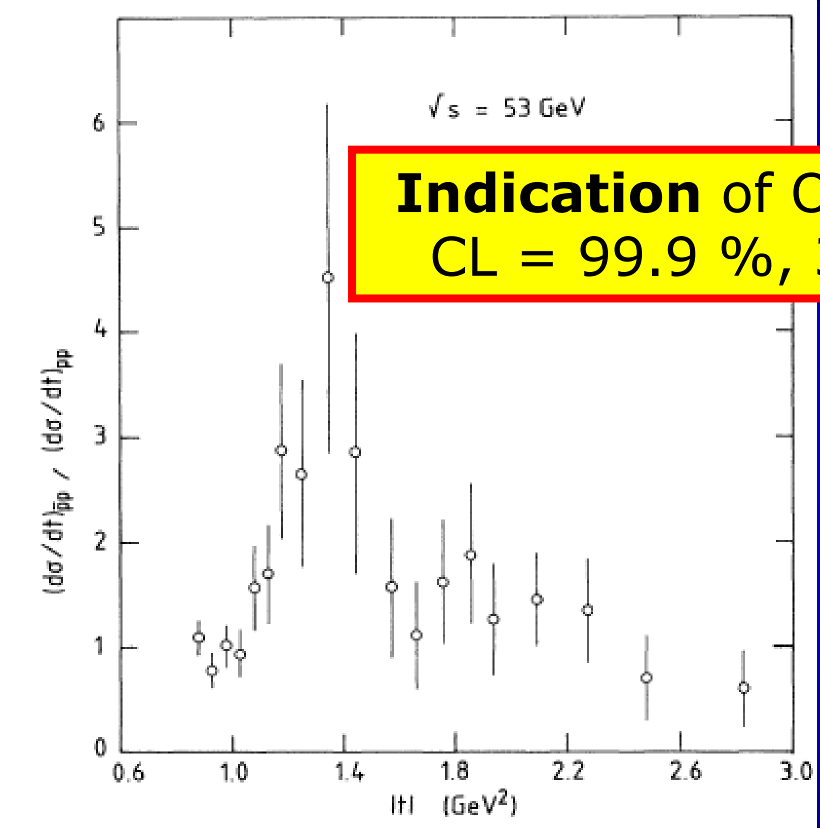
$$\rho_0^{pp}(s) \neq \rho_0^{p\bar{p}}(s) \quad \text{for } \sqrt{s} \geq 1\ \text{TeV} \implies T_{el}^{O}(s,t) \neq 0$$

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

Odderon: very 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 %, 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**.

Honorable mentions: Odderon, qualitatively

Proposal for LHC to hunt down the Odderon:

Extracting the Odderon from pp and $\bar{p}p$ scattering data #1

Andras Ster (Budapest, RMKI), Laszlo Jen
Budapest, RMKI) (Jan 15, 2015)

Published in: *Phys.Rev.D* 91 (2015) 7, 074

Searching for the odderon in $pp \to ppK^+K^-$ and $pp \to pp\mu^+\mu^-$ reactions in the $\phi(1020)$ resonance region at the LHC #2

Piotr Lebiedowicz (Cracow, INP), Otto Nachtmann (U. Heidelberg, ITP and Rzeszow U.), Antoni Szczurek (Cracow, INP) (Nov 5, 2019)

Published in: *Phys.Rev.D* 101 (2020) 9, 094012 • e-Print: 1911.01909 [hep-ph]

Qualitative Odderon signals: in t-dependence of B(s,t) and ρ(s,t)

Odderon and proton substructure from a model-independent Lévy imaging of elastic pp and $p\bar{p}$ collisions #6

T. Csörgő (Wigner RCP, Budape
Ster (Wigner RCP, Budapest) (J

Published in: *Eur.Phys.J.C* 79 (2

Analytical representation for amplitudes and differential cross section of pp elastic scattering at 13 TeV #1

E. Ferreira (Rio de Janeiro Federal U.), A.K. Kohara (SENAI/CETIQT, Rio de Janeiro), T. Kodama (Rio de Janeiro Federal U. and Niteroi, Fluminense U.) (Nov 26, 2020)

Published in: *Eur.Phys.J.C* 81 (2021) 4, 290 • e-Print: 2011.13335 [hep-ph]

Odderon effects in the

Evgenij Martynov (Kiev, INR), Basarab Nicolescu (Babes-Bolyai U.) (Au

Published in: *Eur.Phys.J.C* 79 (2019) 6, 461 • e-Print: 1808.08580 [hep-

Ratio $\rho^{pp}_{\bar{p}p}(s)$ in Froissaron and maximal odderon approach

E. Martynov (BITP, Kiev), G. Tersimonov (BITP, Kiev) (Nov 15, 2019)

Published in: *Phys.Rev.D* 100 (2019) 11, 114039 • e-Print: 1911.06873 [hep-ph]

New physics from TOTEM's recent measurements of e

István Szanyi (Uzhgorod Nat.

Published in: *J.Phys.G* 46 (201

Froissaron and Maximal Odderon with spin-flip in pp and $\bar{p}p$ high energy elastic scattering #1

N. Bence (Uzhgorod Nat. U.), A. Lengyel (Unlisted, UA), Z. Tarics (Unlisted, UA), E. Martynov (BITP, Kiev), G. Tersimonov (BITP, Kiev) (Sep 4, 2021)

Published in: *Eur.Phys.J.A* 57 (2021) 9, 265

Observations of Odderon with > 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]

pdf DOI cite 16 citations

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

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 (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]

pdf DOI cite 6 citations

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

Comparison of pp and $p\bar{p}$ differential elastic cross sections and observation of the exchange of a colorless C-odd gluonic compound #1

Odderon Exchange from Elastic Scattering Differences between pp and $p\bar{p}$ Data at 1.96 TeV and from pp Forward Scattering Measurements #1

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: 2012.03981 [hep-ex]

pdf links DOI ci 11 citations

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

Three Oldest Hungarian Universities

UP Story - 650 years

Home » University » UP Story 650 years

University of Pécs: 1367

The history of higher education in Pécs dates back to 1367, when Louis the Great initiated the establishment of a university in the episcopal city of Pécs. As a result of an integration process of several stages, the University of Pécs was founded, which has become one of the most famous, prestigious institutions having a leading role in regional education. It has ten faculties which cover the full spectrum of high-quality higher education.

1367

The University of Debrecen, the oldest institution of higher education in the country operated continuously in the same city, is one of the research universities of national excellence in Hungary offering the widest spectrum of educational programs in 14 faculties and 24 doctoral schools.

University of Debrecen: 1538

...ts of higher education in the city reach all the way back to the 16th century and the foundation ... Reformed College of Debrecen in 1538. The College played a central role in Hungarian education and culture for centuries. This is the date featured on the symbol of the university as well, the *gerundium*, a tool originally used by the students of the Reformed College to put out fires, showing respect for ancestors and traditions.

(S,C) structure evident,
S: statement, valid if
C: condition is satisfied
See talk of R. Dardashti at ISMD21

Eötvös Loránd University: 1635

The predecessor of Eötvös Loránd University (ELTE) was founded in Nagyszombat in 1635 (sixteen thirty-five) by Archbishop of Esztergom, Péter Pázmány, and it is the oldest Hungarian university where the teaching has continued uninterrupted since its inception. More than sixty years

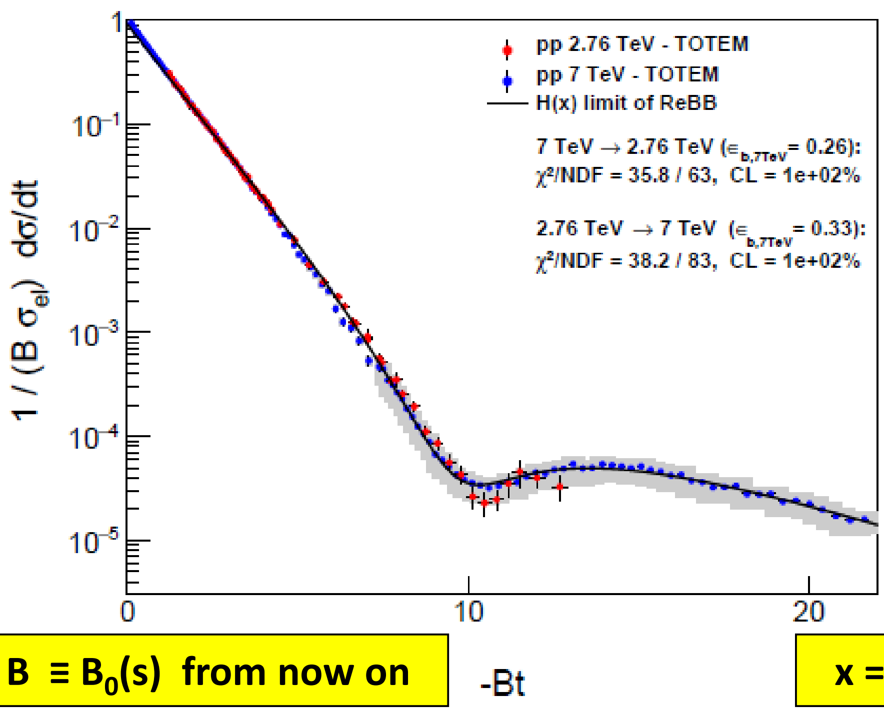
Model independent results since 2019

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

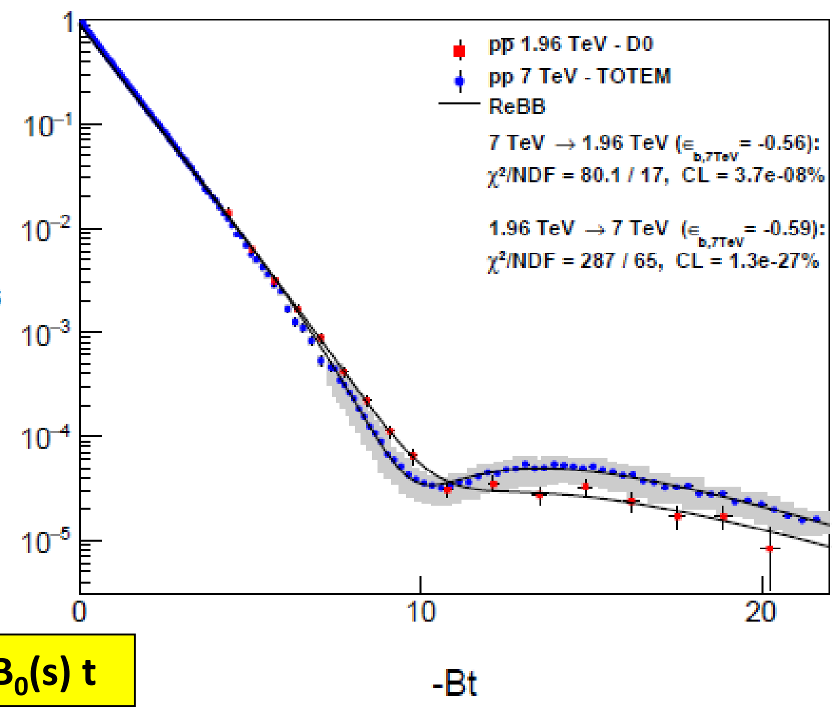
T. Csörgő (Wigner RCP, Budapest and CERN), T. Novak (Unlisted, HU), R. Pasechnik (Lund U., Dept. Theor. Phys.), A. Ster (Wigner RCP, Budapest), I. Szanyi (Wigner RCP, Budapest) (Dec 26, 2019)

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

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



H(x) = 1/(B σ$_{el}$) dσ/dt vs x = - B t



$B \equiv B_0(s)$ 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**.

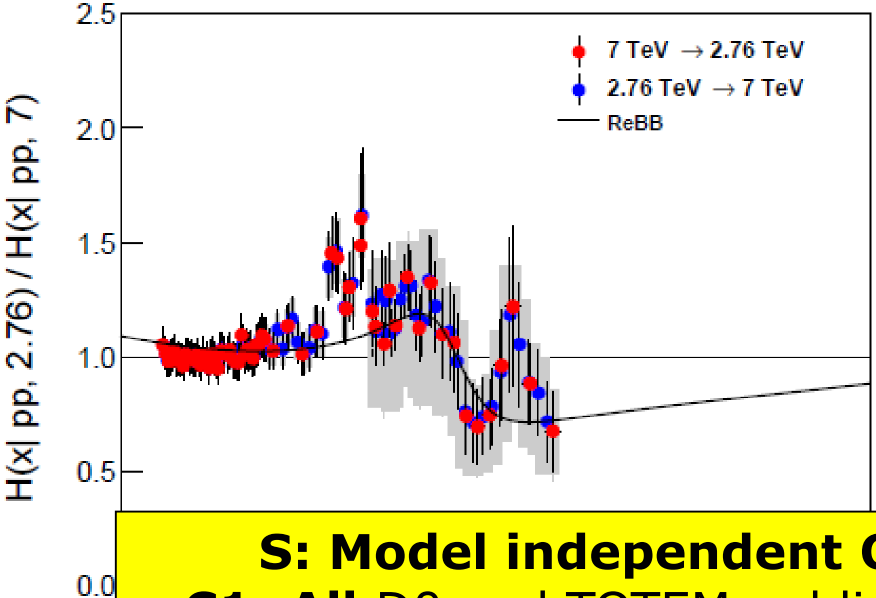
Model independent results (2)

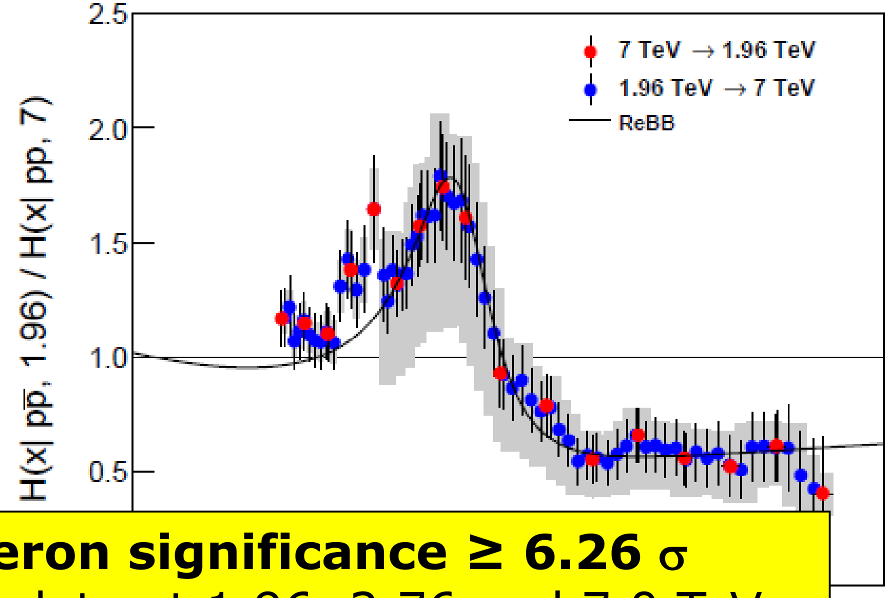
Scaling of high-energy elastic scattering and the observation of Odderon #1

T. Csörgő (Wigner RCP, Budapest and Eszterhazy Karoly U., Eger), T. Novák (EKU KRC, Gyongyos), R. Pasechnik (Lund U., Dept. Theor. Phys.), A. Ster (Wigner RCP, Budapest), I. Szanyi (Wigner RCP, Budapest and Eotvos U.) (Apr 15, 2020)

Published in: Gribov-90 Memorial Volume, pp. 69-80 (2021) (World Sc... and J. Nyiri) • e-Print: 2004.07318 [hep-ph]

Gribov’90 Memorial Volume, pp. 69-80 (2021)
https://doi.org/10.1142/9789811238406_0012





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**.

$H(x,s_1)/H(x,s_2)$ nearly 1 for pp with small violations. Peak for pbarp over pp.
Small violations under theoretical controll (next slide).
Model independent Odderon significance 6.26 σ
New result presented in this talk: domain of validity model independently

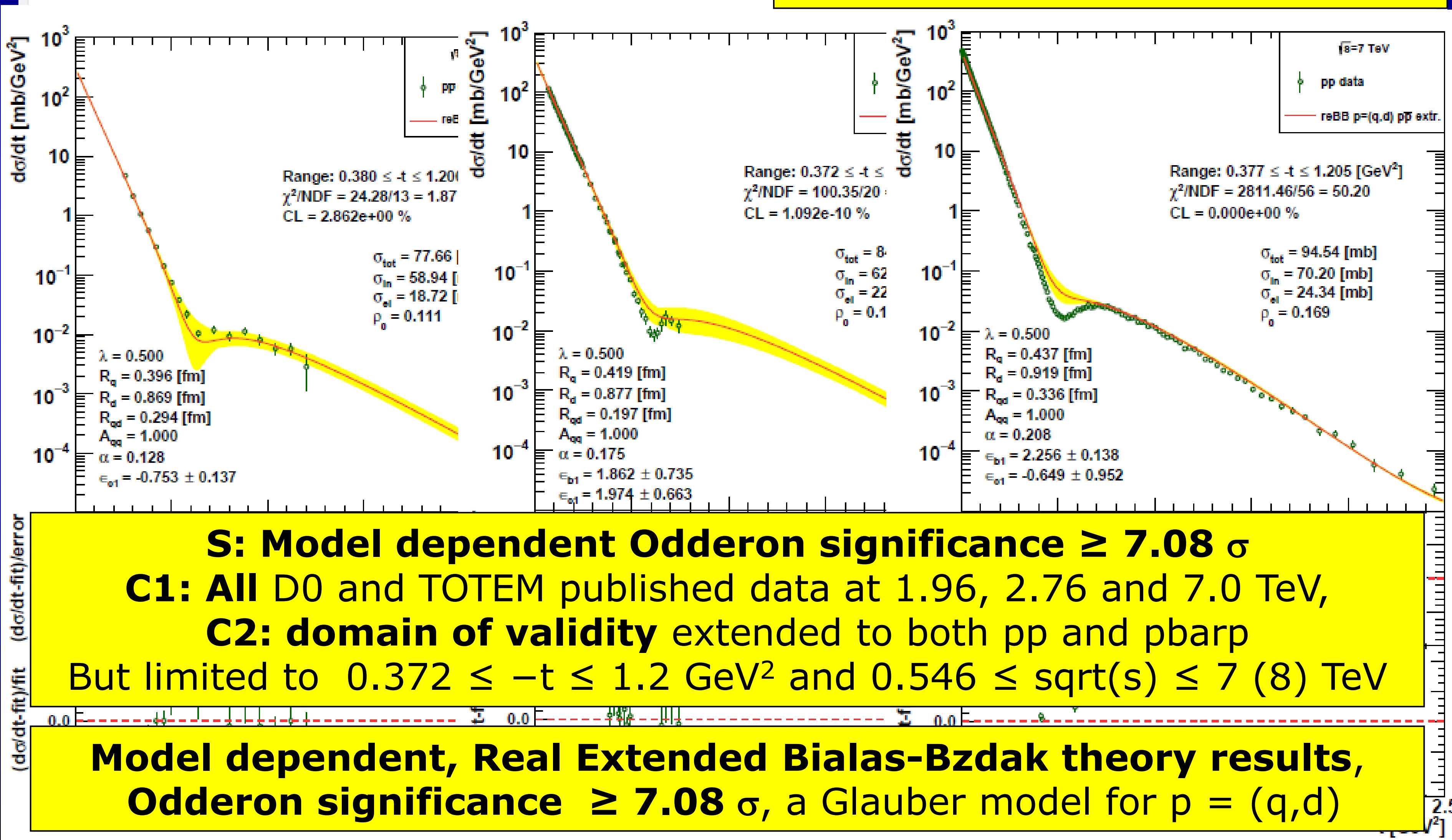
Model dependent evidence for Odderon

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, detailed by I. Szanyi
https://doi.org/10.1140/epjc/s10052-021-09381-5



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 $0.372 \le -t \le 1.2$ GeV² and $0.546 \le \sqrt{s} \le 7$ (8) TeV

Model dependent, Real Extended Bialas-Bzdak theory results,
Odderon significance ≥ 7.08 σ, a Glauber model for p = (q,d)

Evidence for Odderon, new D0-TOTEM

Odderon Exchange from Elastic Scattering Differences between pp and $p\bar{p}$ Data at 1.96 TeV and from pp Forward Scattering Measurements #1

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: 2012.03981 [hep-ex]

pdf links DOI

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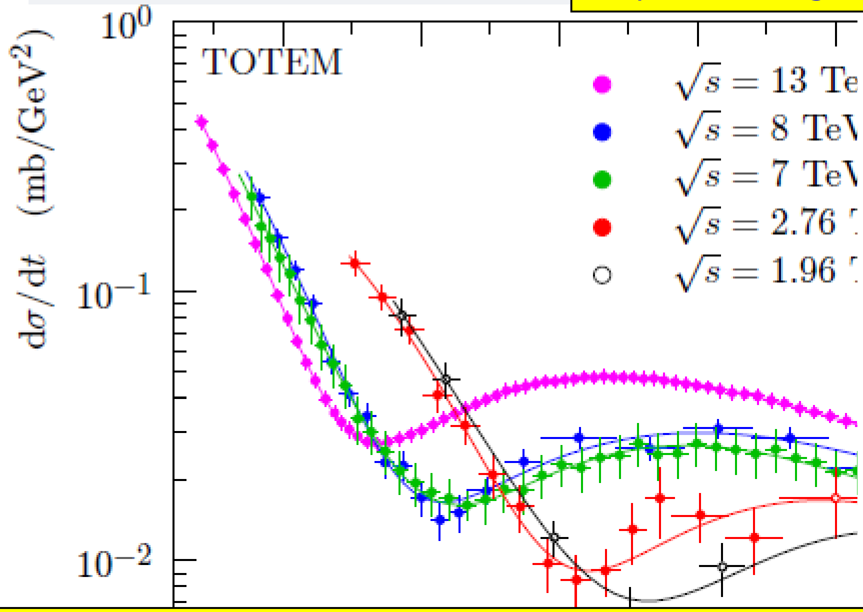
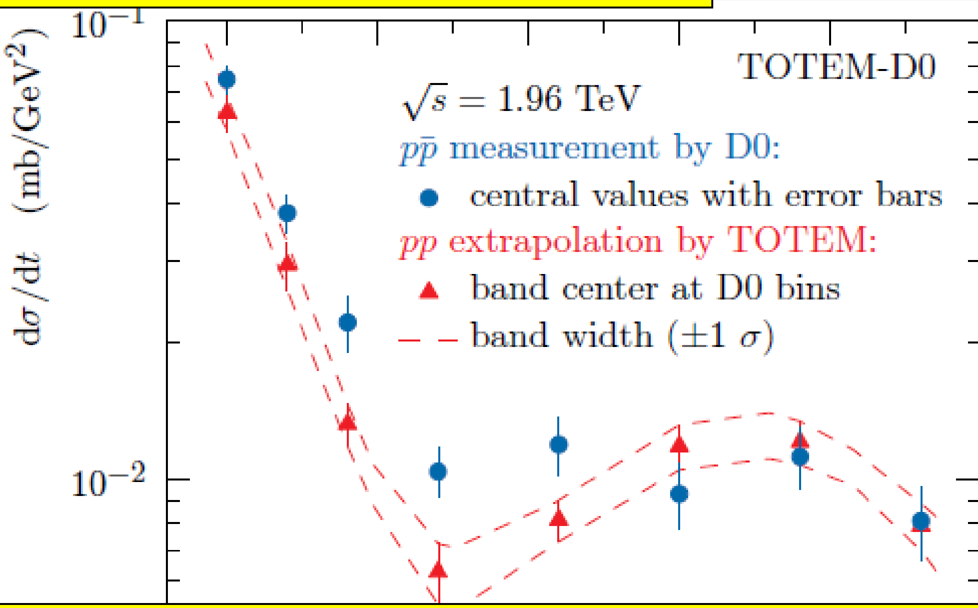




S: Odderon significance $\geq$ 5.2 σ, IF

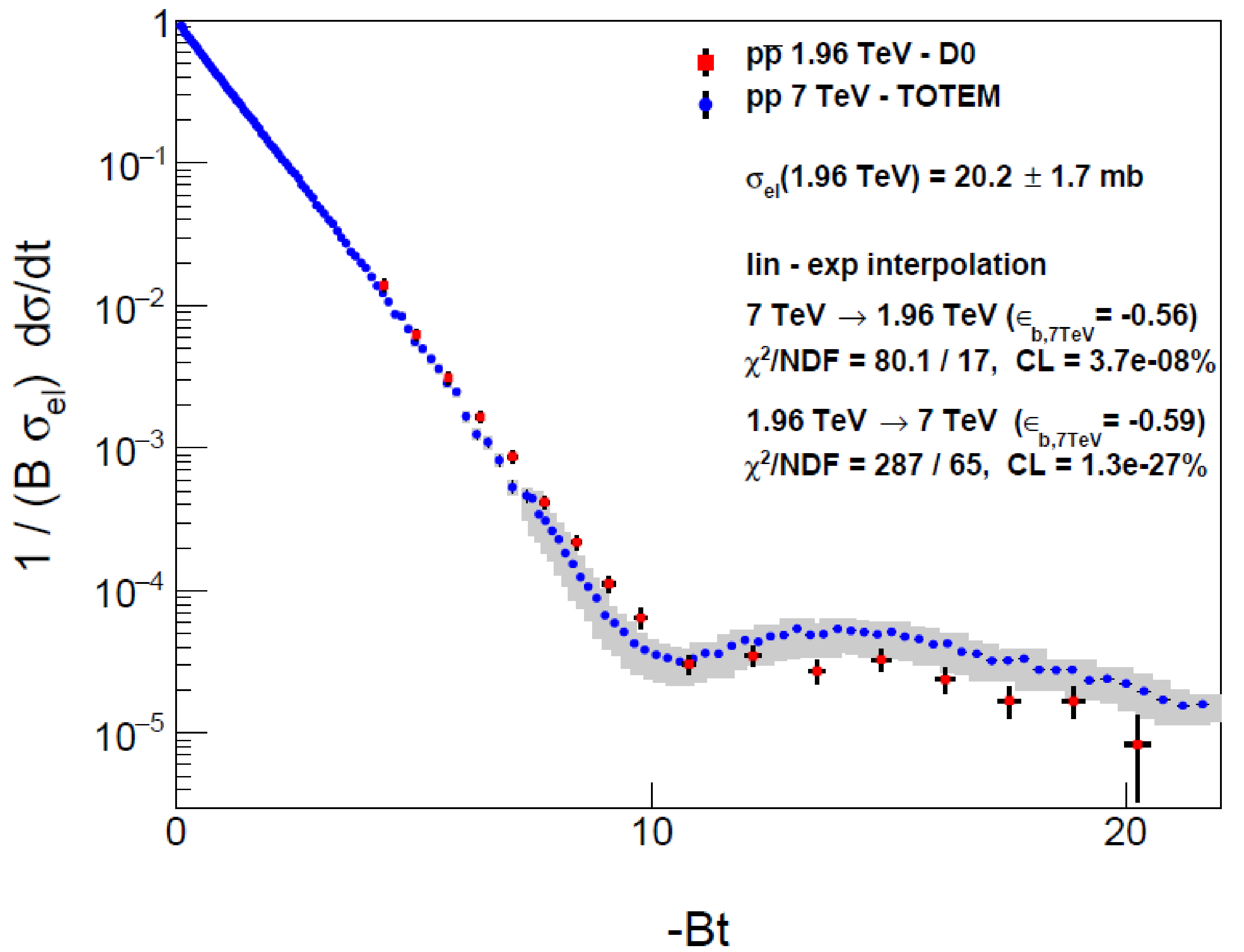
C1: if combined with 13 TeV σ_{tot} and ρ_0

C2: using a **new pp dataset** at 8 TeV and **a new data point** at 2.76 TeV,

C3: **if only 8 out of the 17 D0 points is used**

C4: if D0 pbarp data and TOTEM pp extrap.data **equal at t=0** (Optical Point)

Back to Scaling: Model independently



H(x|pp)
s-independent:
2.76 – 7(8) TeV

H(x|pp, 7 TeV)
≠
H(x|pbarp, 1.96)

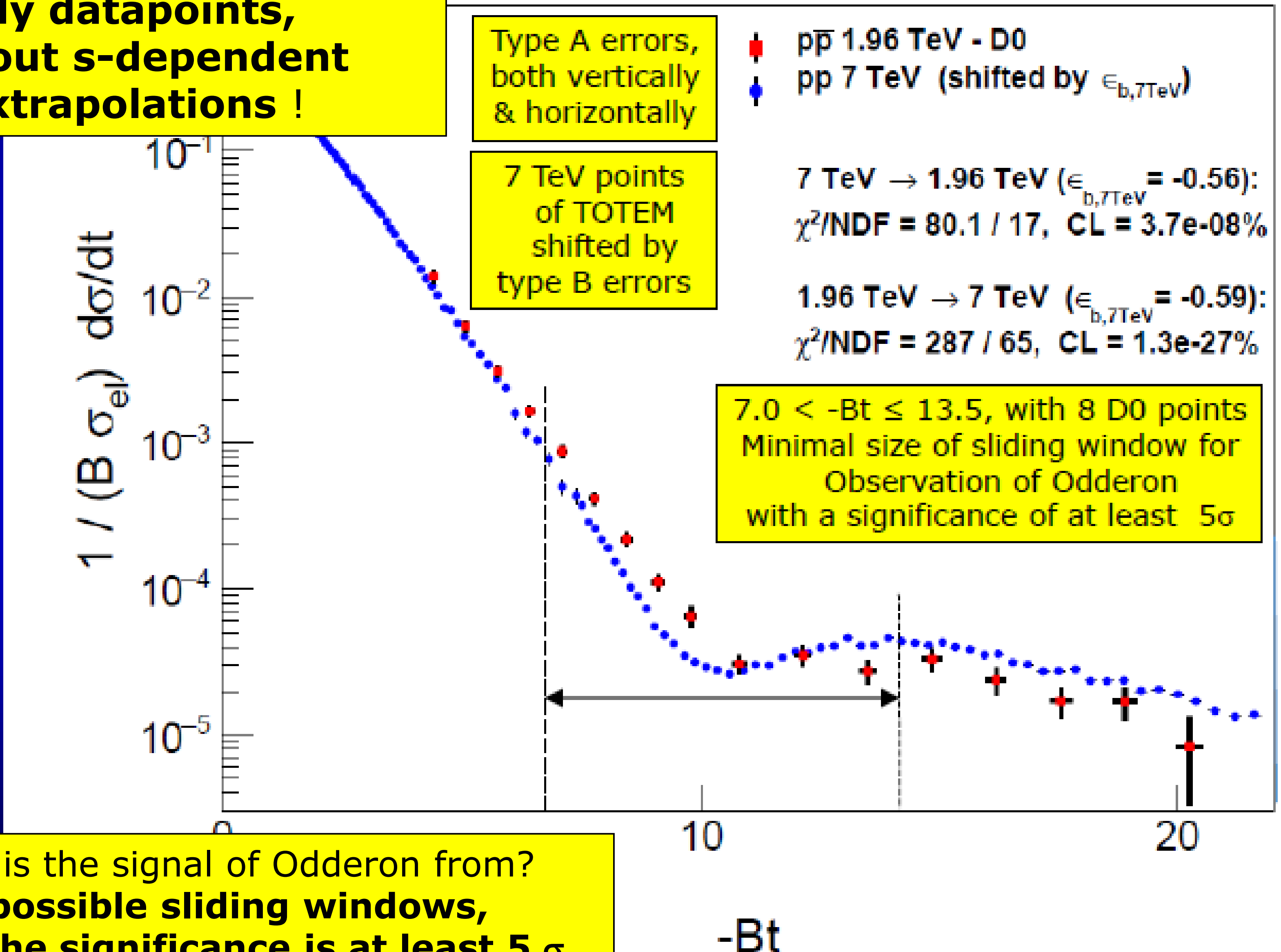
Odderon,
IF scaling holds in pp down to 1.96 TeV

6.26 σ Odderon effect

Energy range: tested **both** model independently and with modelling.
Modelling is useful, but model independent tests more important!

SLIDING WINDOW for 5 σ

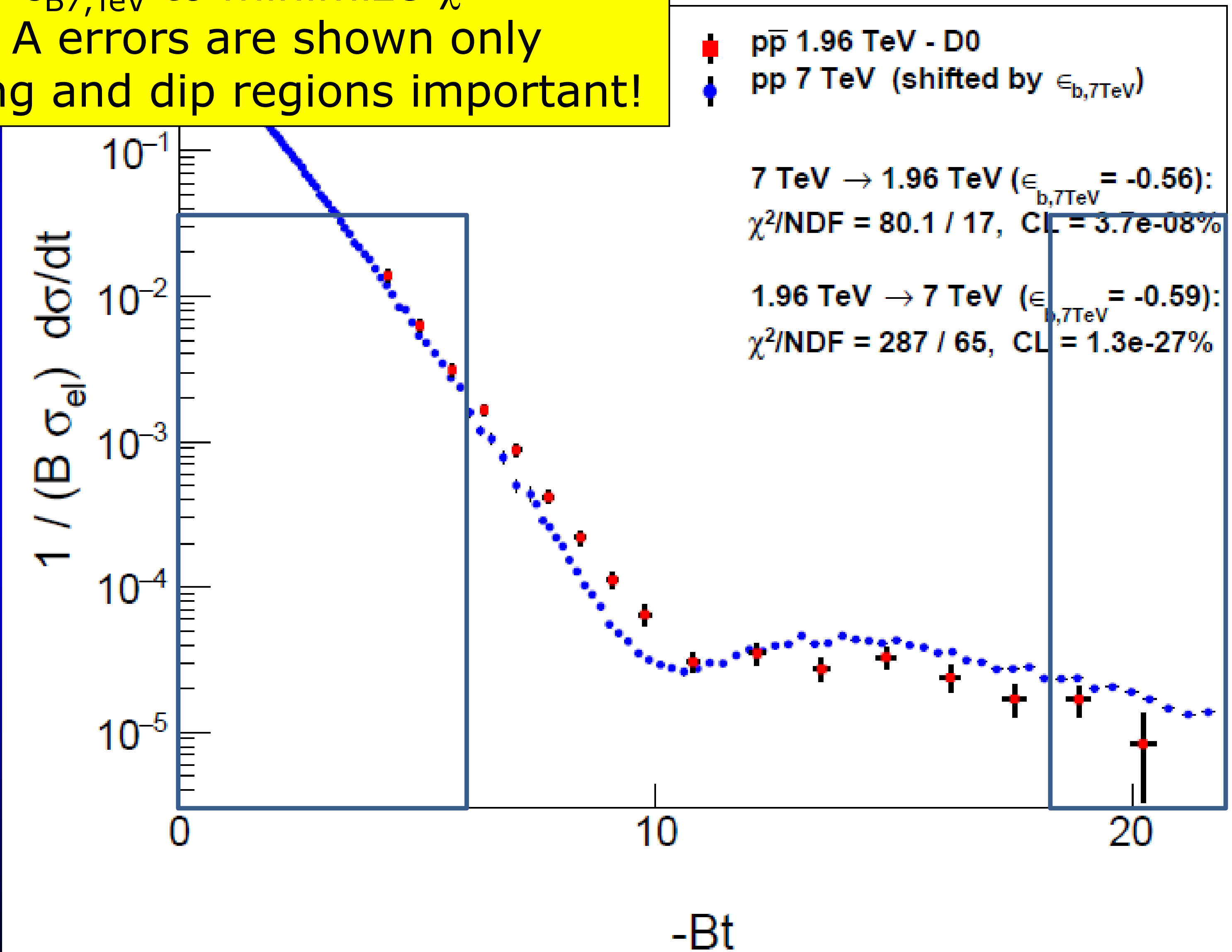
Model independent results: only datapoints, without s-dependent extrapolations !



Where is the signal of Odderon from?
All possible sliding windows, where the significance is at least 5 σ

CLOSING DOORS/GATES

7 TeV data shifted
by $\varepsilon_{B7,TeV}$ to minimize χ^2
Type A errors are shown only
Both swing and dip regions important!



RESULTS FOR CLOSING GATES

Two sliding gates of size n and size m:
(n,m): Leaving out the first n and last m D0 point

Sliding door technique with two wings (n,m) Left door excludes the first n, right door excludes the last m D0 points			
n	m	Odderon signal	Background
2	2	6.27 σ	1.68 σ
3	2	6.33 σ	1.70 σ
4	2	6.21 σ	2.37 σ

New MODEL INDEPENT RESULT:
In best window, optimized Odderon signal is 6.33 σ

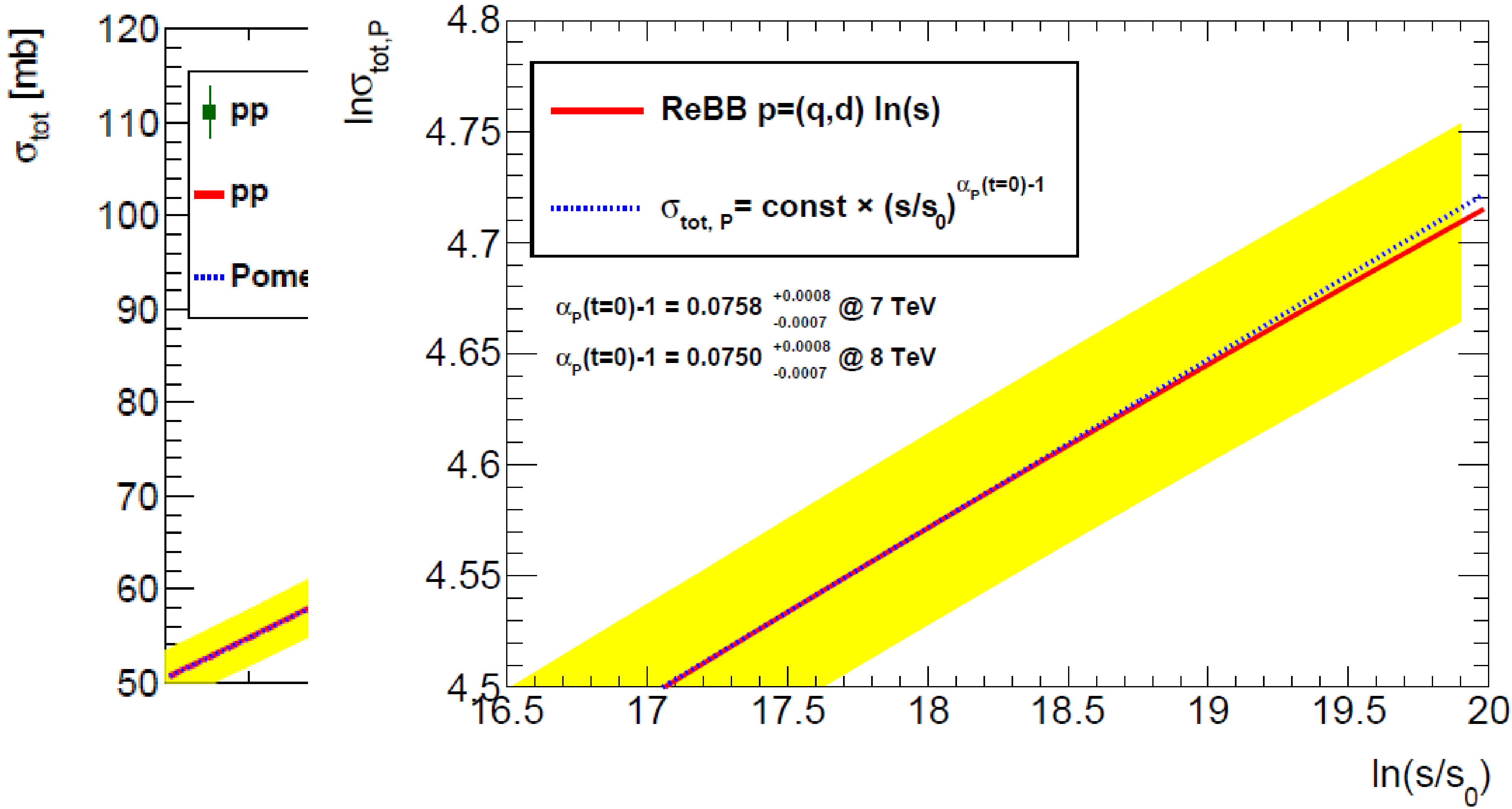
New MODEL INDEPENT RESULT 2:
Best window: leaving out first 3 and last 2 D0 point

New MODEL INDEPENT RESULT 3:
Outside the best window:
pp and pbarp backgrounds agree within 1.7 σ

POMERON PROPERTIES

MODEL RESULT BASED ON EPJC 81 (2021) 7, 611

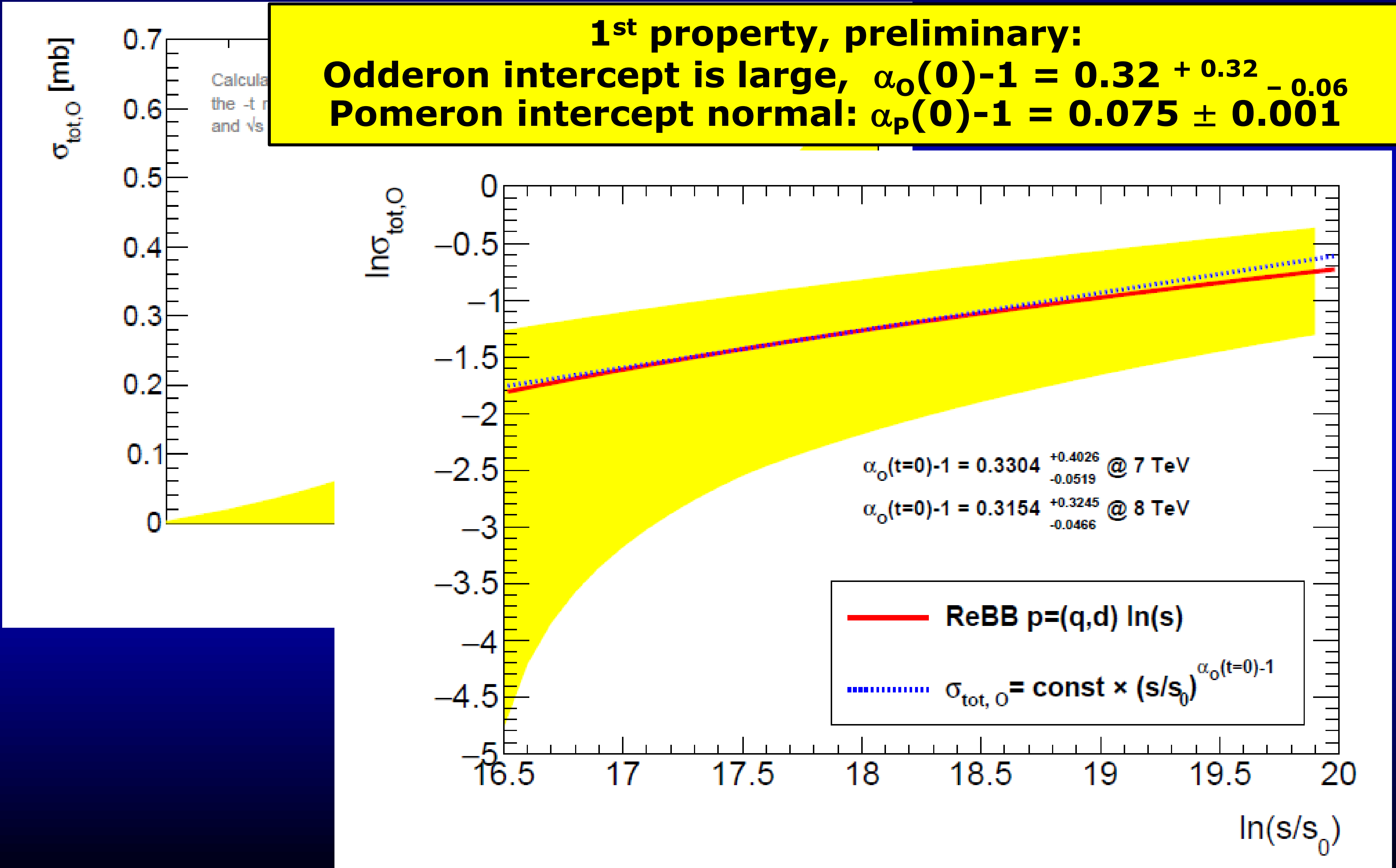
1st property, preliminary:
Pomeron intercept normal: $\alpha_P(0)-1 = 0.075 \pm 0.001$



ODDERON PROPERTIES

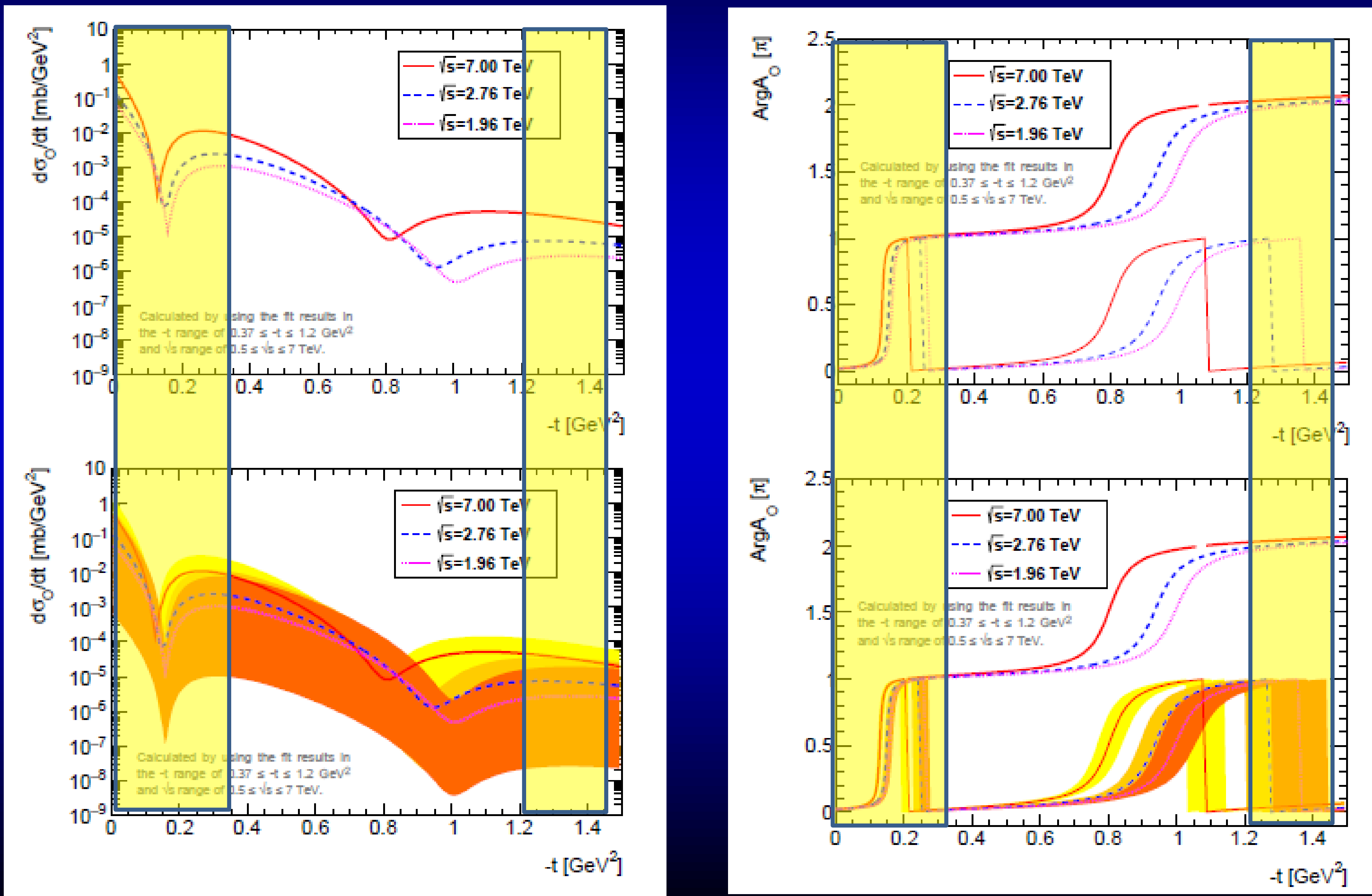
MODEL RESULT BASED ON EPJC 81 (2021) 7, 611

1st property, preliminary:
Odderon intercept is large, $\alpha_O(0)-1 = 0.32^{+0.32}_{-0.06}$
Pomeron intercept normal: $\alpha_P(0)-1 = 0.075 \pm 0.001$



ODDERON dσ/dt and Phase(s,t)

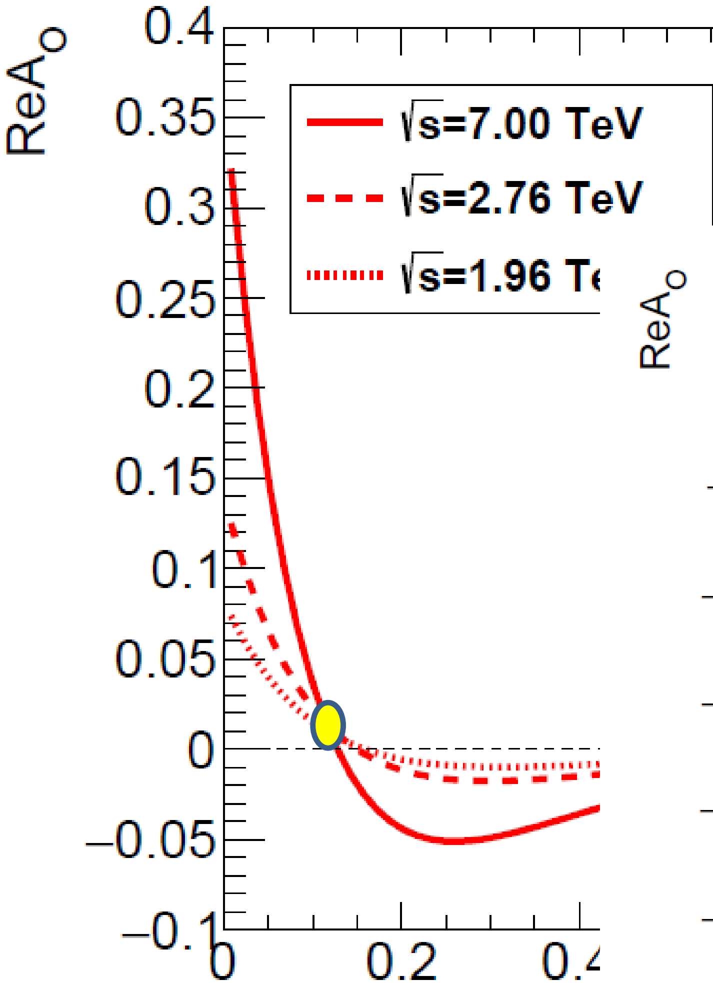
ReBB MODEL RESULT FROM EPJC 81 (2021) 7, 611

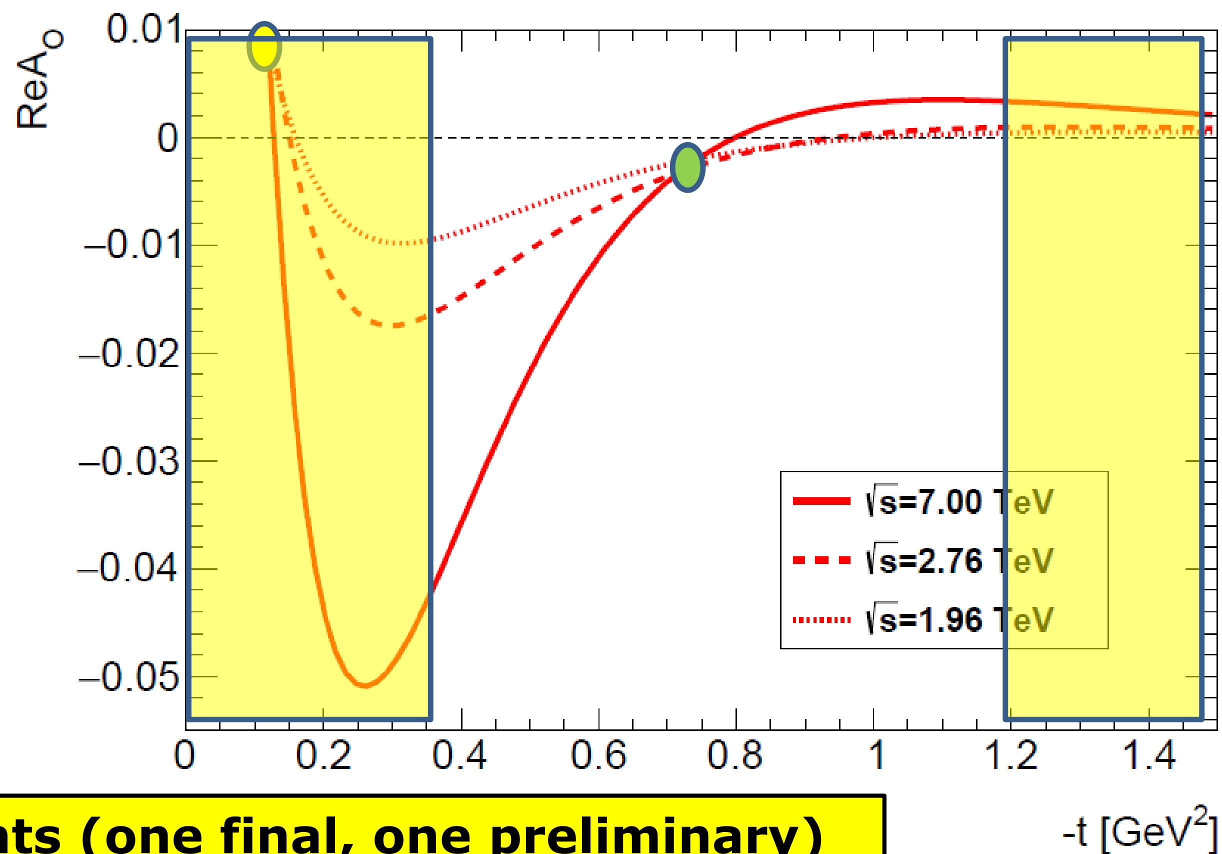


Re OF ODDERON AMPLITUDE

BASED ON ReBB MODEL OF EPJC 81 (2021) 7, 611

2nd property:
Zeros of Odderon amplitude
Re $T_O(s,t)$ has two zeros: expected



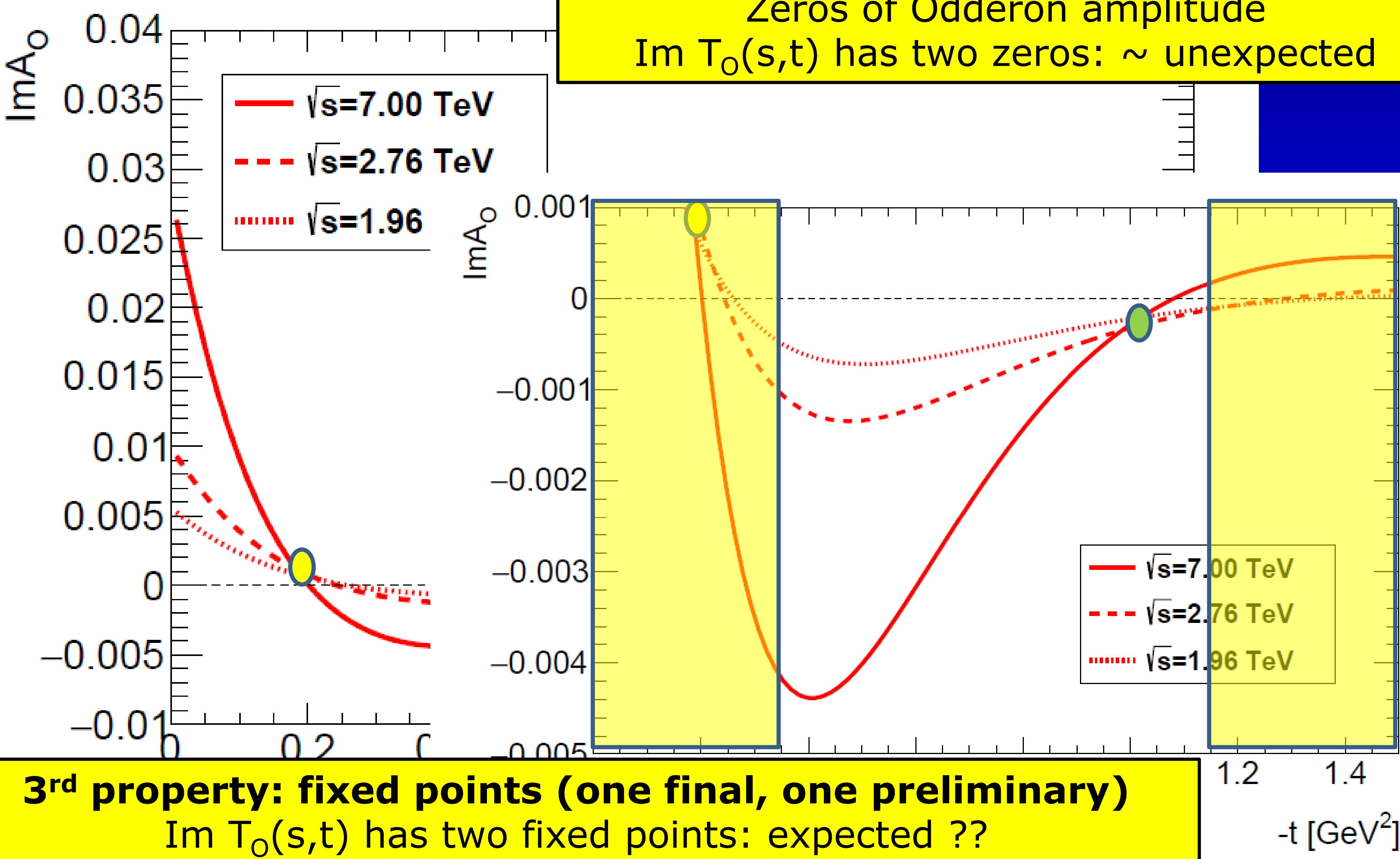


3rd property: fixed points (one final, one preliminary)
Re $T_O(s,t)$ has two fixed points: expected ??

Im OF ODDERON AMPLITUDE

BASED ON ReBB MODEL OF EPJC 81 (2021) 7, 611

2nd property:
Zeros of Odderon amplitude
Im $T_O(s,t)$ has two zeros: ~ unexpected



3rd property: fixed points (one final, one preliminary)
Im $T_O(s,t)$ has two fixed points: expected ??

SUMMARY: ODDERON PROPERTIES

An at least 6.36 σ Odderon effect

Odderon first discovered in three published papers:
three different analysis, each with a statistical significance > 5 σ

(S,C) structure evident,
S: scientific statement, valid if
C: condition is satisfied

0th property:
Odderon exist in Nature: confirmed by public and new D0-TOTEM data

1st property:
Odderon intercept is large, $\alpha_O(0)-1 = 0.32^{+0.32}_{-0.06}$
Pomeron intercept normal: $\alpha_P(0)-1 = 0.075 \pm 0.001$

2nd property: Odderon amplitude has zeros
Re $T_O(s,t)$ has two zeros: expected
Im $T_O(s,t)$ has two zeros: unexpected

3rd property: Odderon amplitude has fixed points
Re $T_O(s,t)$ and Im $T_O(s,t)$ have two fixed points: unexpected

Detailed investigation of conditions and (S,C) structure at DoF'21

ODE TO ODDERON → OBERON

Ode to Odderon

Let's be truly happy,
for what we've come upon:
We have just discovered
the elusive odderon!

For forty-eight years,
forging a ring of colors white:
Odd number of gluons
has been hiding in plain sight!

``Discovery consists of seeing what everybody has seen,
and thinking what nobody has thought."
Albert Szent-Györgyi

OBERON POETRY MAGAZINE

So happy together,
with love for science and research:
Happiness and pleasure
must not slow down the search!

Let's live in harmony,
and in equanimity:
Let's make light of the fight,
gloom is our true enemy!

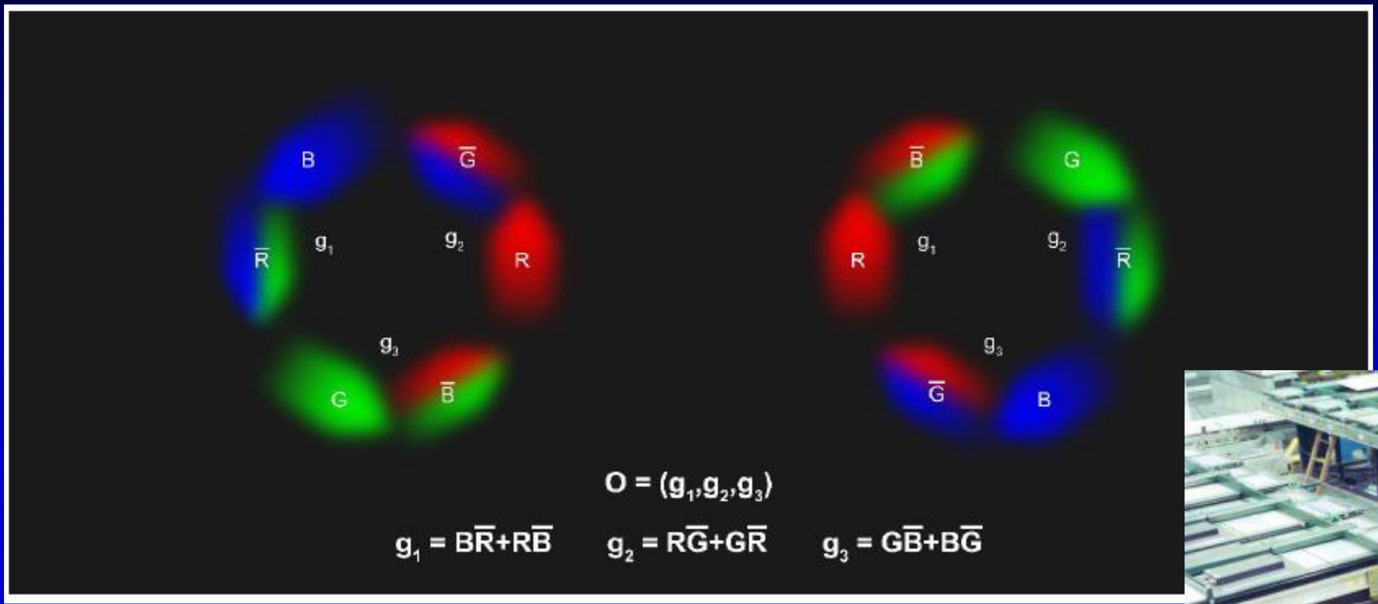
© by Tamás Csörgő
Gyöngyös, Hungary, March 11 – April 11, 2021

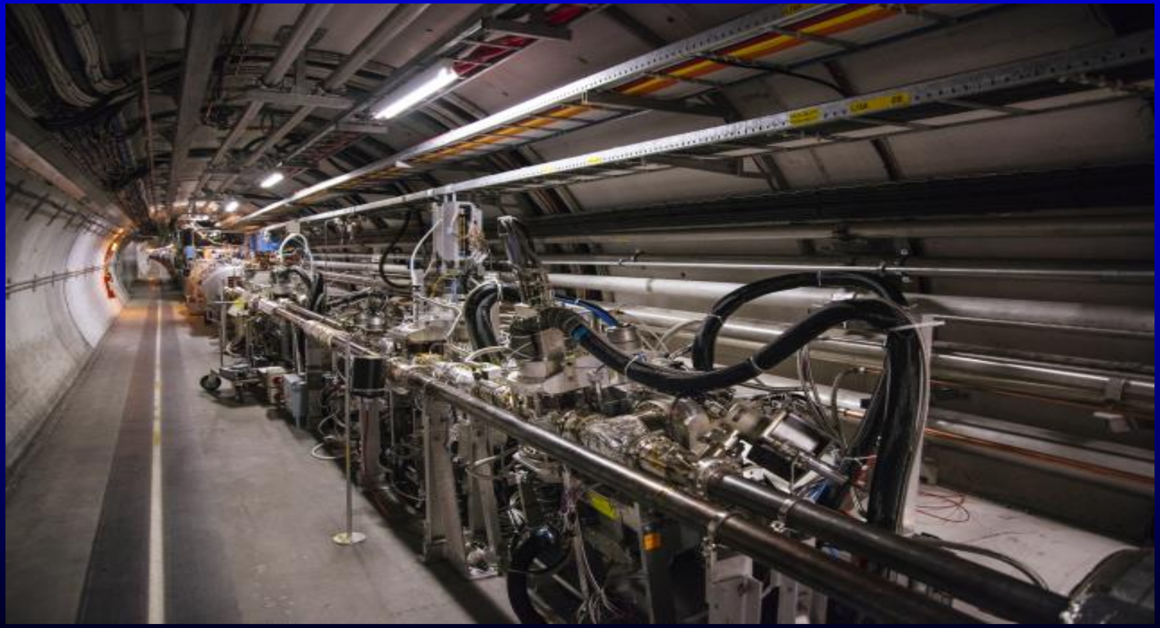
OBSERVATION OF ODDERON

2020 → 2O2O

THANK YOU FOR YOUR ATTENTION

BACKUP SLIDES





BACKUP SLIDES

cordis.europa.eu/article/id/429667-particle-physics-milestone-achieved-at-cern

Alkalmazások CERN ET Wigner Conf Stabil-Invest Kft. Szanyi István

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English EN

For most of us, physics terms such as odderon are – and will always remain – firmly lodged in the science fiction realm. Not so for the scientific community, whose determined members spent nearly half a century searching (without much success) for this mythical particle.

Now, a research team including physicists from Hungary and Sweden has discovered the odderon by analysing experimental data from the Large Hadron Collider (LHC) at Switzerland's European Organization for Nuclear Research, better known as CERN. Supported by the EU-funded MorePheno project, the physicists have published a paper describing their findings in the 'The European Physical Journal C'.

DE

Particle physics milestone achieved at CERN

After 50 years of research, physicists have found evidence that the elusive subatomic quasiparticle called odderon actually exists.

BACKUP SLIDES

Nature Reviews Physics | https://doi.org/10.1038/s42254-021-00375-6 | Published online: 02 September 2021

IN RETROSPECT

Discovery of the odderon

In the 1950s, experimental data on the total cross-section for proton–proton collisions (σ_{pp}) suggested that σ_{pp} was initially decreasing as the collision energy increased and then flattening out to a constant value. Isaak Pomeranchuk hypothesized a 'crossing even' mechanism to explain this behaviour, which involved an equal contribution to the cross-section for proton–antiproton collisions ($\sigma_{p\bar{p}}$). This became known as pomeron exchange. Since beams of antiprotons are very difficult to produce, data on $\sigma_{p\bar{p}}$ were scarce, but did seem to fit the idea of pomeron exchange.

In the 1970s, *pp* collisions at the much higher total centre of mass energy (E_{CM} = 53 GeV) at the Intersecting Storage Rings (ISR) collider at CERN showed that σ_{pp} was actually growing as the energy increased, begging the question of what is the theoretical maximal permitted rate of growth. Marcel Froissart answered that it should be $\sigma_{pp} \sim [\log(E_{CM})]^2$. Like the pomeron exchange, this mechanism was crossing even, so that at sufficiently high energies one would find similar growth with the same factor for *pp* and $p\bar{p}$ cross-sections and thus, eventually, at high enough energies the difference between σ_{pp} and $\sigma_{p\bar{p}}$ would go to zero.

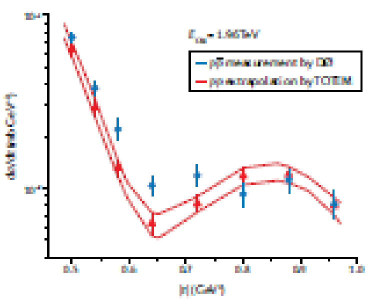
In 1973, Leszek Lukaszuk and Basarab Nicolescu argued that there could, in principle, also exist a 'crossing odd' mechanism: one that contributes to σ_{pp} and $\sigma_{p\bar{p}}$ with opposite signs, and which could also grow like $[\log(E_{CM})]^2$, a mechanism known as odderon exchange.

The main implication of odderon exchange was that σ_{pp} and $\sigma_{p\bar{p}}$ would not become equal as the energy increased. It also implied that the real parts of the *pp* and $p\bar{p}$ elastic scattering amplitudes would not become equal and the shapes of their differential cross-sections would differ.

Literally during the last week of operation of the ISR in 1985, data were obtained showing that the shapes of the differential cross-sections for *pp* and $p\bar{p}$ at E_{CM} = 53 GeV were indeed different, but the general feeling in the community was that this was not sufficient to confirm the existence of the odderon.

On the theoretical side, many later papers based on quantum chromodynamics showed that abstract mechanisms such as the pomeron and odderon exchange could emerge in reality as a result of the forces produced by the exchange of an even or an odd number of gluons in the scattering process.

The most direct way to demonstrate the existence of the odderon is to compare σ_{pp} and $\sigma_{p\bar{p}}$ at equal and sufficiently high energies, where it is safe to ignore contributions from the known mechanisms that contribute at lower energies. Data from the Tevatron $p\bar{p}$ collider at Fermilab, and from the Relativistic Heavy Ion Collider *pp* collider at Brookhaven National Laboratory, were in agreement regarding a $\sim[\log(E_{CM})]^2$ growth, and this was confirmed for the *pp* case at the high energies (between 2.76 TeV and 13 TeV) reached at the Large Hadron Collider (LHC) at CERN. Unfortunately, the highest energy reached for the $p\bar{p}$ case, at the Tevatron, was E_{CM} = 1.96 TeV, slightly below the minimum energy at which the LHC operates, so an absolute direct comparison of σ_{pp} and $\sigma_{p\bar{p}}$ at identical ultra-high energies was not possible. To make matters worse, two different measurements at Fermilab disagreed with each other significantly. Nonetheless, in a recent article in *Physical Review Letters* the CERN TOTEM and the Fermilab D0 collaborations reported the discovery of the odderon. This result is based mainly on an almost model-independent extrapolation down in the energy of the *pp* differential cross-sections measured at the LHC and a comparison with the $p\bar{p}$ differential cross-section measured at the Tevatron. The significant difference in the shape of differential cross-sections (pictured) at this ultra-high energy is at last convincing evidence for the existence of the odderon.



Credit: CERN, for the D0 and TOTEM collaborations, under a Creative Commons License CC BY 4.0

Elliot Leader
Imperial College London, London, UK.
e-mail: e.leader@bbk.ac.uk

Competing interests
The author declares no competing interests.

ORIGINAL ARTICLE Lukaszuk, L. & Nicolescu, B. A possible interpretation of pp rising total cross-sections. *Lett. Nuovo Cimento* **8**, 405–413 (1973)
RELATED ARTICLE Abazov, V. M. et al. Odderon exchange from elastic scattering differences between pp and $p\bar{p}$ data at 1.96 TeV and from pp forward scattering measurements. *Phys. Rev. Lett.* **127**, 062003 (2021)

Essentially, Odderon

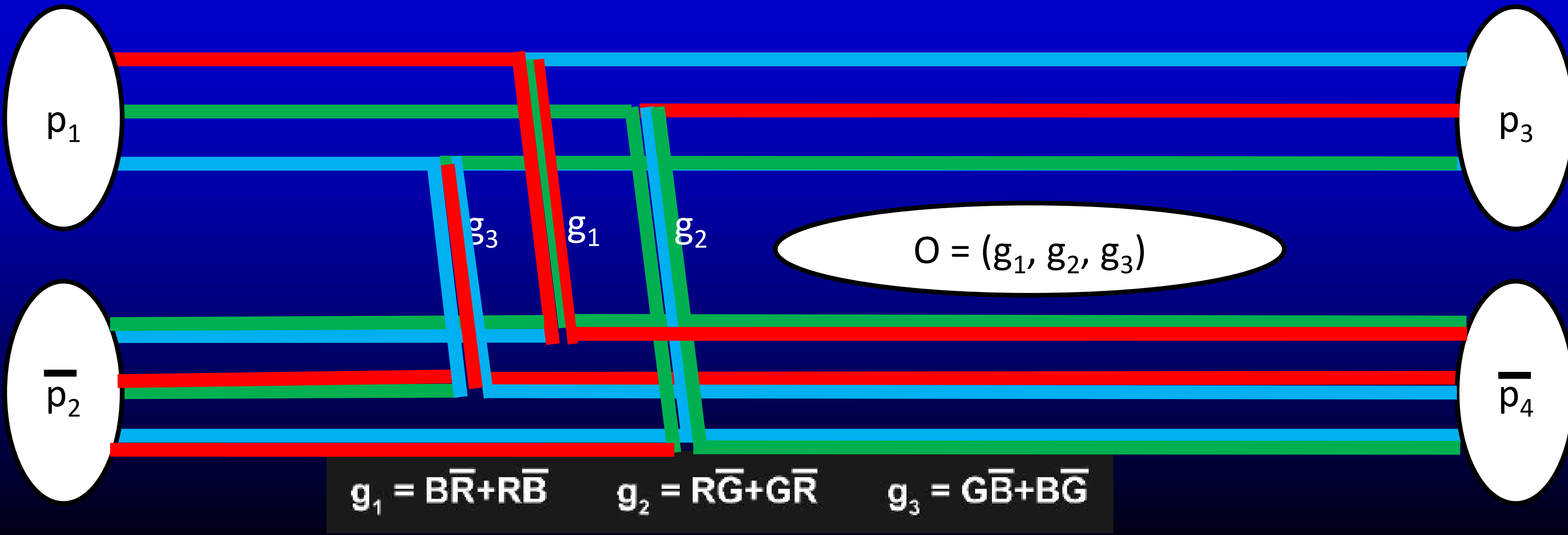
$p+p \rightarrow p+p$

$(RGB) + (RGB) \rightarrow (GBR) + (GBR)$

-

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

$(RGB) + (\bar{R}\bar{B}\bar{G}) \rightarrow (BRG) + (\bar{B}\bar{G}\bar{R})$



Odderon: origin of its name

Odderon name coined in 1975:
D. Joynson, E. Leader, B. Nicolescu, C. Lopez
Nuovo Cim. 30A, 345 (1975)

IL NUOVO CIMENTO Vol. 30 A, N. 3 1 Dicembre 1975

Non-Regge and Hyper-Regge Effects in Pion-Nucleon Charge Exchange Scattering at High Energies.

D. Joynson (*), E. Leader (**) and B. Nicolescu

Division de Physique Théorique (***), *Institut de Physique Nucléaire* (*.*) - *Paris*
Laboratoire de Physique Théorique des Particules Élémentaires - Paris (*.*)

C. Lopez (*.*)

Laboratoire de Physique Théorique et Hautes Energies - Paris (*.*)

(ricevuto il 24 Giugno 1975)

Odderon: well established in QCD

Odderon proposed in Regge phenomenology:
L. Lukaszuk, B. Nicolescu, Lett. Nuovo Cim. 8, 405 (1973)

Three Gluon Integral Equation and Odd c Singlet Regge Singularities in QCD
J. Kwiecinski, M. Praszalowicz, Phys.Lett.B 94 (1980) 413-416

A new Odderon intercept from QCD:
R. A. Janik, J. Wosiek, Phys. Rev. Lett. 82 (1999) 1092

Odderon in QCD:
J. Bartels, L.N. Lipatov, G. P. Vacca: Phys. Lett. B (2000) 178

Odderon in QCD with running coupling:
J. Bartels, C. Contreras, G. P. Vacca, *JHEP* 04 (2020) 183

For an excellent theory intro/review, see Yu. Kovchegov's CTEQ Webinar, April 28, 2021
http://youtu.be/yHBO3zcB3V4

Three Odderon Proceedings with > 5 σ

Scaling of high-energy elastic scattering and the observation of Odderon

#1

T. Csörgő (Wigner RCP, Budapest and Eszterhazy Karoly U., Eger), T. Novák (EKU KRC, Gyongyos), R. Pasechnik (Lund U., Dept. Theor. Phys.), A. Ster (Wigner RCP, Budapest), I. Szanyi (Wigner RCP, Budapest and Eotvos U.) (Apr 15, 2020)

Published in: Gribov-90 Memorial Volume, pp. 69-80 (2021) (World Scientific, Singapore, ed. Yu. Dokshitzer, P. L\'evai, \'A. Luk\'acs and J. Nyiri) • e-Print: 2004.07318 [hep-ph]

pdf DOI cite

Gribov'90 Memorial Volume, pp. 69-80 (2021)
https://doi.org/10.1142/9789811238406_0012

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

#2

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

EPJ Web Conf. 235 (2020) 06002, proc. **ISMD 2019**
https://doi.org/10.1051/epjconf/202023506002

Comparison of differential elastic cross sections in pp and $p\bar{p}$ collisions as evidence of the existence of the colourless C-odd three-gluon state

#1

D0 and Totem Collaborations • Christophe Royon (Kansas U.) for the collaborations. (Dec 5, 2020)

Published in: *PoS* ICHEP2020 (2021) 496 • Contribution to: ICHEP2020, 496 • e-Print: 2012.03150 [hep-ex]

pdf DOI cite

PoS **ICHEP 2020** (2021)
https://doi.org/10.22323/1.390.0496

Formalism: elastic scattering

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

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

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

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

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

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

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

Basic problem: dσ/dt measures an amplitude, *modulus squared*.
How to achieve amplitude level reconstruction? Phase info lost…

Formalism in b space

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

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

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

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

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

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

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 ≤ P(s,b) ≤ 1 : *inelastic* scattering has a probabilistic interpretation

Looking for Crossing-Odd(eron) effects

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

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

for $\sqrt{s} \geq 1$ 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

Odderon search: strategy with scaling

Known trivial s-dependences in
$\sigma_{tot}(s)$, $\sigma_{el}(s)$, $B(s)$, $\rho(s)$

Try to scale this out
Look for data collapsing (scaling)

Look for scaling violations

In the TeV energy range:
Odderon is equivalent with
a crossing-odd component
Look for violations of C-symmetry

Close the energy gap with scaling

Scaling in the diffractive cone region

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

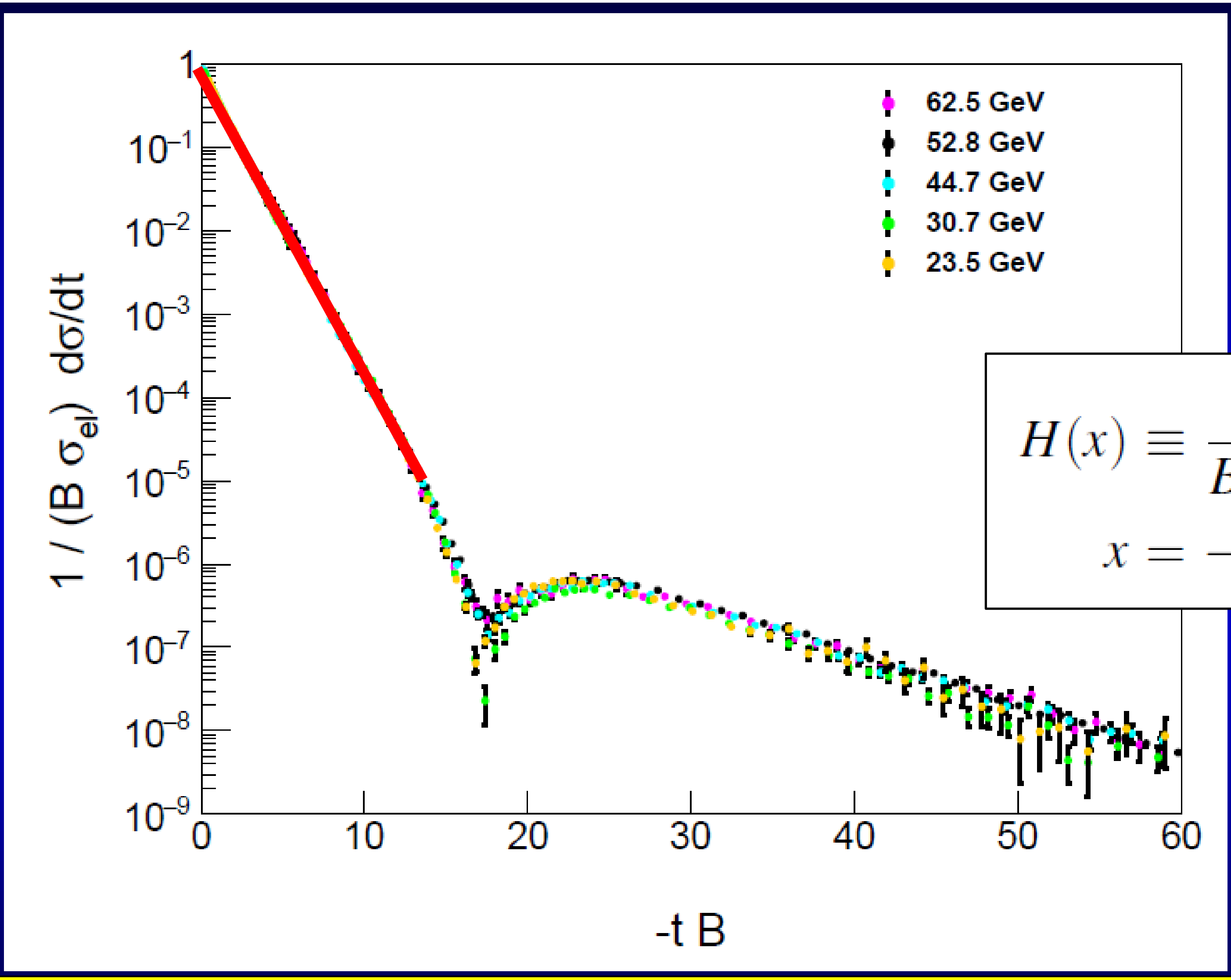
$$A(s) = B(s)\,\sigma_{\rm el}(s) = \frac{1+\rho_0^2(s)}{16\pi}\,\sigma_{\rm tot}^2(s),$$

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

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

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

Test of the H(x) scaling at ISR



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

H(x) = exp(-x) in the cone
Works better than expected, even in the bump/tail region!

A simple derivation of H(x) scaling for all x
Data suggest scaling well beyond the x < 1 cone

$$t_{el}(s, \mathrm{b}) = (i + \rho_0)\, r(s) E(\tilde{\mathrm{x}}).$$

$$\begin{aligned}
\mathrm{Re}\, \exp\left[-\Omega(s,b)\right] &= 1 - r(s)E(\tilde{\mathrm{x}}), \\
\mathrm{Im}\, \exp\left[-\Omega(s,b)\right] &= \rho_0\, r(s)E(\tilde{\mathrm{x}}), \\
\tilde{\mathrm{x}} &= \mathrm{b}/R(s), \\
R(s) &= \sqrt{B(s)},
\end{aligned}$$

$$\frac{d\sigma}{dt} = \frac{1}{4\pi}|T_{el}(\Delta)|^2 = \frac{1+\rho_0^2}{4\pi} r^2(s) R^2(s) |\tilde{E}(R(s)\Delta)|^2$$

$$A = \left.\frac{d\sigma}{dt}\right|_{t=0} = \frac{1+\rho_0^2}{4\pi} r^2(s) R^2(s) |\tilde{E}(0)|^2,$$

$$\frac{1}{A}\frac{d\sigma}{dt} = \frac{|\tilde{E}(\sqrt{x})|^2}{|\tilde{E}(x=0)|^2} = H(x),$$

Advantages:

$H(x) \neq \exp(-x)$ arbitrary positive def. in the dip-bump region

Measurable both for pp and p-antip. Normalized as $H(0) = 1$.

More general derivations published, e.g. in the ReBB model

Asymmetry parameter for C-violation

$$A(x|p\bar{p},s_1|pp,s_2) = \frac{H(x|p\bar{p},s_1) - H(x|pp,s_2)}{H(x|p\bar{p},s_1) + H(x|pp,s_2)},$$

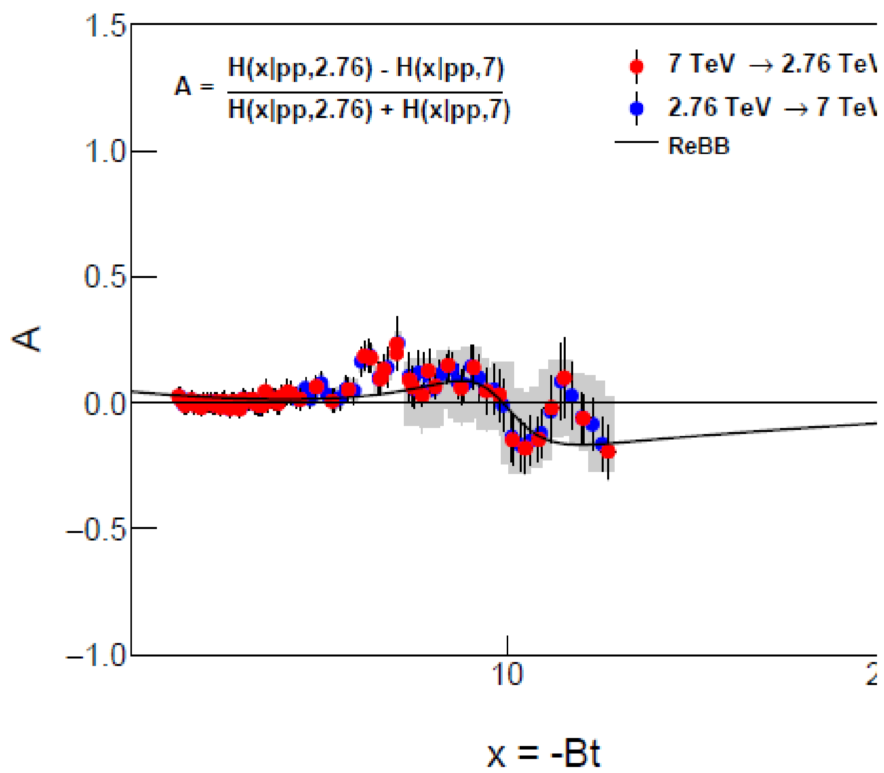
$$A(x|pp,s_1|pp,s_2) = \frac{H(x|pp,s_1) - H(x|pp,s_2)}{H(x|pp,s_1) + H(x|pp,s_2)}.$$

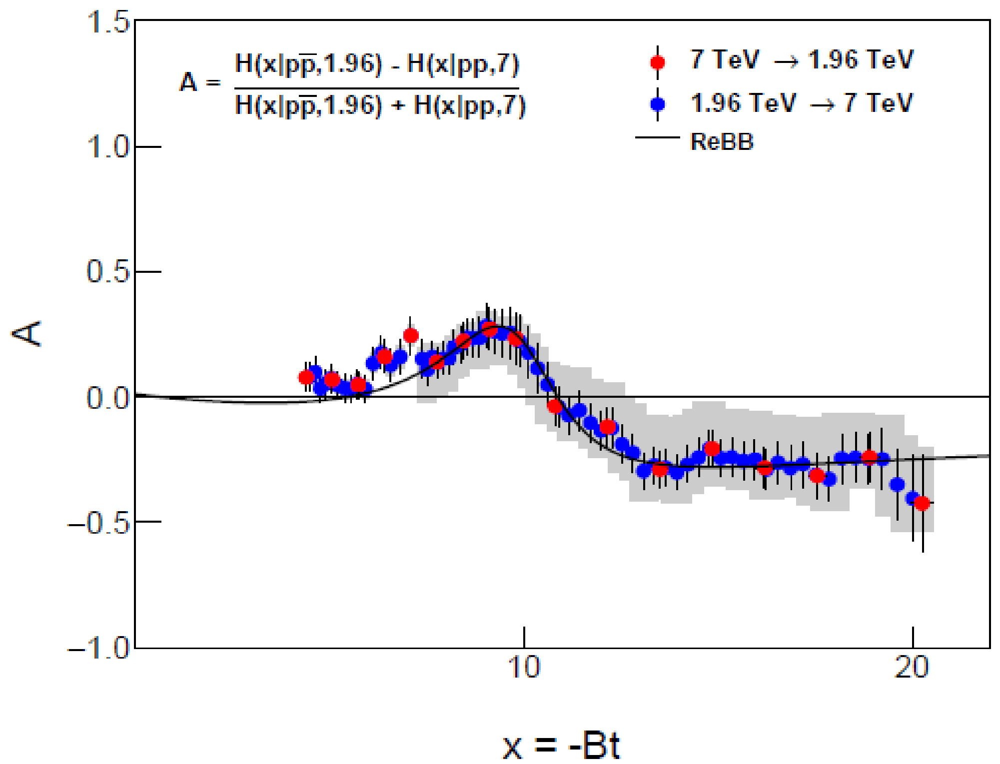
$A(x|pbarp,s_1|pp,s_2)$
does NOT vanish
for a C-symmetry violation AND

$A(x|pp,s_1|pp,s_2)$
vanishes if
H(x) scaling valid

Energy range: HAS to be tested carefully

Main result of A



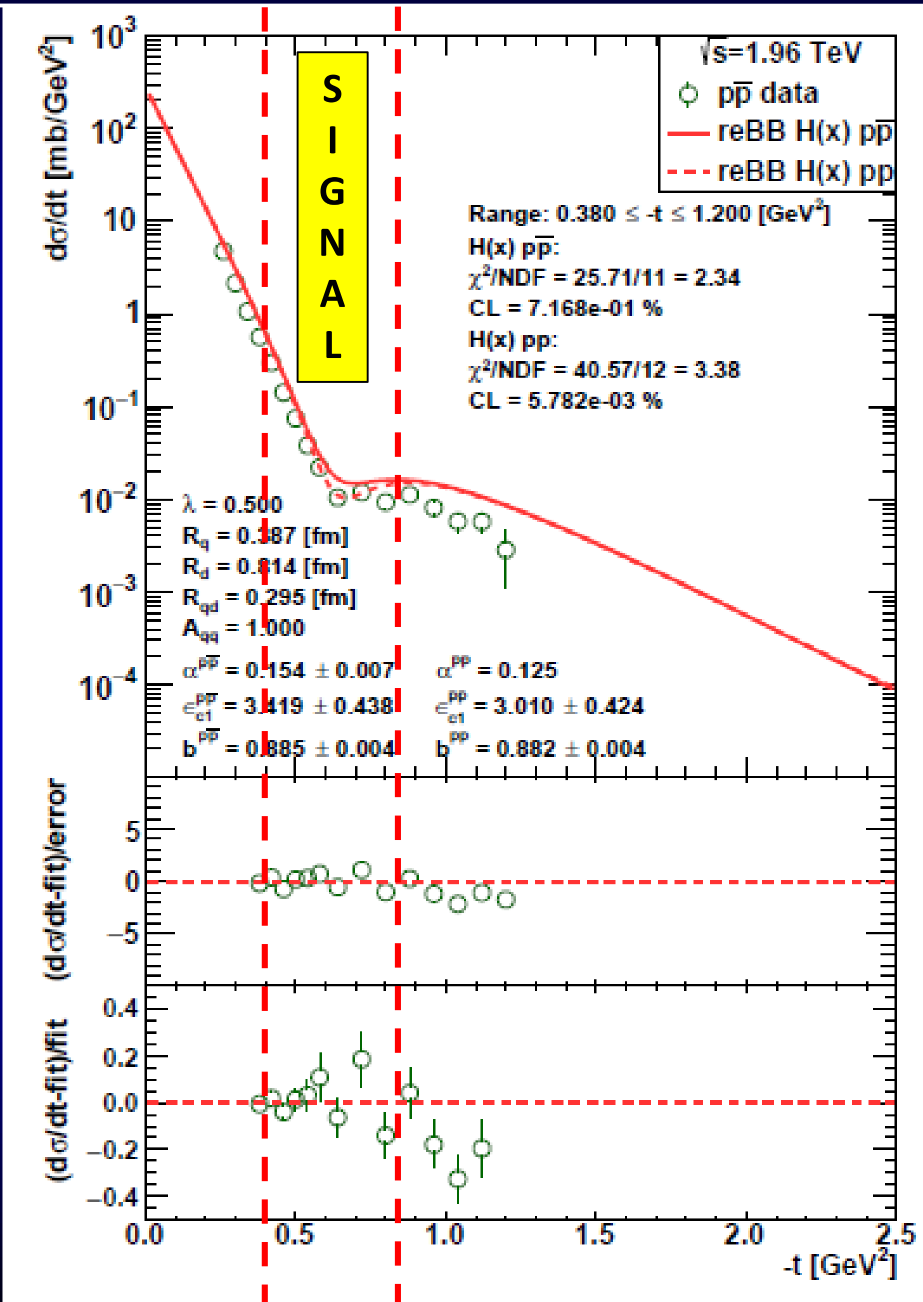


$A(x|pp,s_1|pp,s_2) \sim 0$
vanishes if
H(x) scaling valid

$A(x|pbarp,s_1|pp,s_2) \neq 0$
does NOT vanish
if Odderon term is present

Scaling violations: under theoretical control:
Model calculations by solid line, see e-Print: 2005.14319 [hep-ph]

Is H(x,s) = H(x) at 1.96 TeV?



MODEL DEPENDENTLY: Yes
1.96 TeV
Highest energy where p+antip data are available

H(x) scaling limit:
in the Bialas-Bzdak model

Fits pbarp data up to largest -t
(red line, dashed line: pp)

Pull plots:
(data-fit)/error
(data-fit)/fit

t_{max}(1.96 TeV, pp) > 1.2 GeV^2

→ x_{max}(1.96 TeV, pp) > 20

SLIDING WINDOWS

7 TeV data shifted
by $\varepsilon_{B7,TeV}$ to minimize χ^2
Type A errors are shown only
Both swing and dip regions important!