OPTIMIZING THE SIGNAL OF ODDERON

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Statistically Significant Observations of Odderon

Model independent results:

Significance ≥ 6.26 σ

Model dependent results:

Significance ≥ 7.08 σ

D0-TOTEM results:

Significance ≥ t 5.2 σ

New: Model independently

Optimal Significance ≥ 6.36 σ

Domain of validity

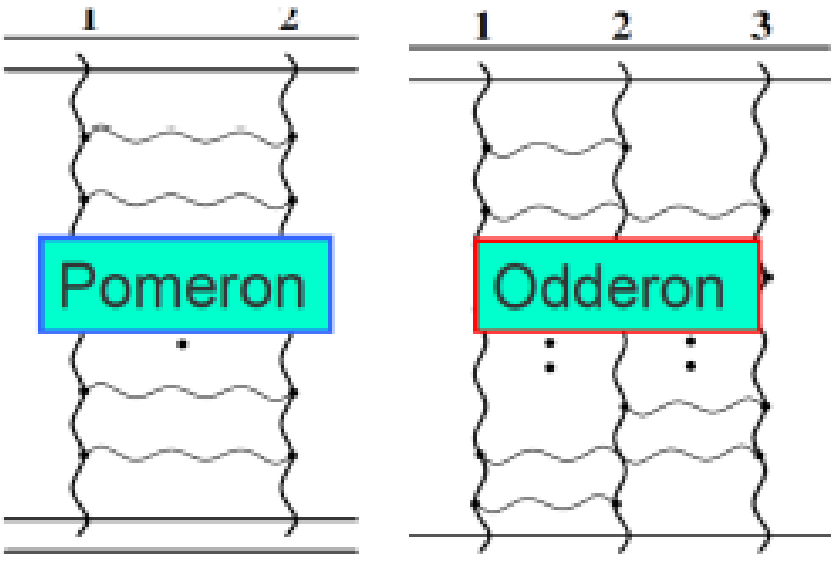
Sliding window, closing doors

Summary

Odderon: 48 years old scientific puzzle

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

At CERN LHC's TeV energy scale: Odderon is an odd component of elastic scattering: Changes sign for crossing



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 Elémentaires - 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

Odderon Search

and symmetry violation in elastic collisions

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

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

Two simple consequences:

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

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

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-

pdf DOI cite 15 citations

Eur. Phys. J. C (2021) **81**: 180
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)

e-Print: 2005.14319 [hep-ph]

pdf cite

Eur. Phys. J. C (2021) **81**:611
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

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

e-Print: 2012.03981 [hep-ex]

pdf links cite

Phys. Rev. Lett. (2021) **in press**
Accepted for a publication

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. [illegible]
Nucl. Phys. Inst.), A. Ster (Wigner RCP, Budapest), I. Szanyi (Wigner R[illegible]

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

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

pdf DOI cite 1 citation

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

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

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

pdf DOI cite 2 citations

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 ISMD'19

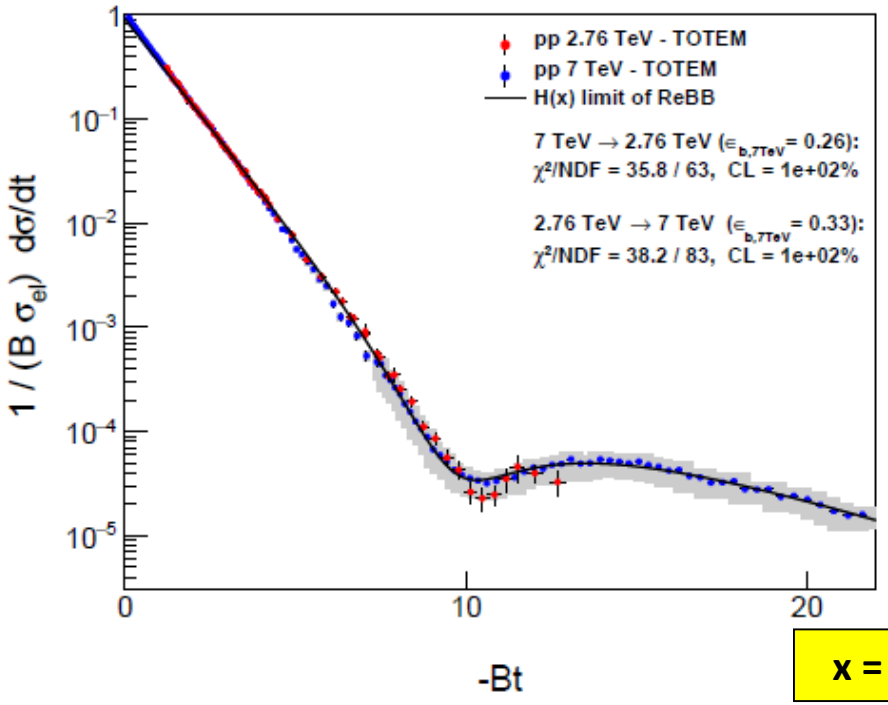
Evidence of Odderon-exchange from scaling properties of elastic scattering at TeV energies #5

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)

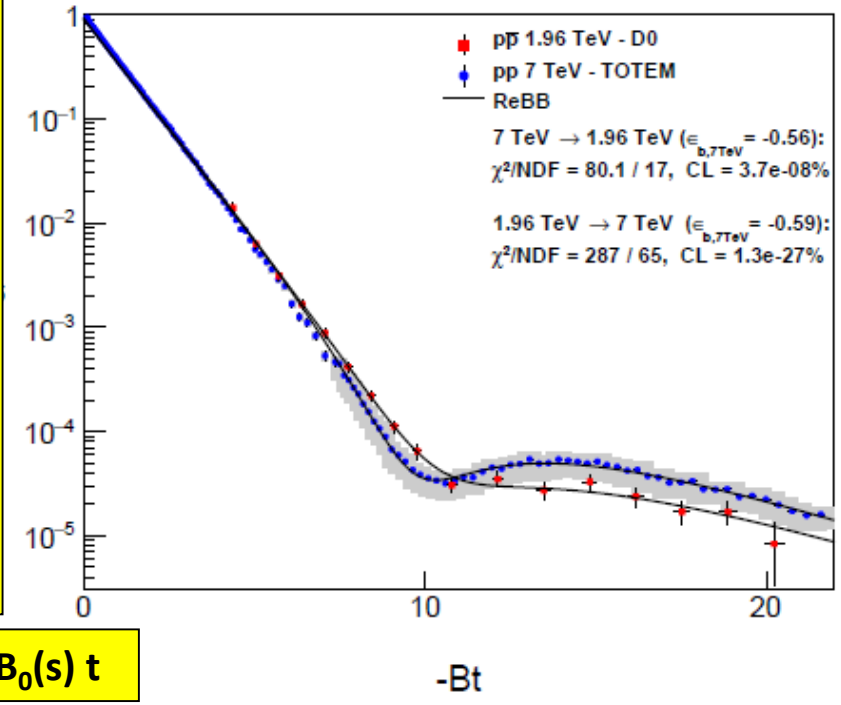
Published in: *Eur.Phys.J.C* 81 (2021) 2, 180 • e-Print: 1912.11968 [hep-

pdf DOI cite 15 citations

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



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**.

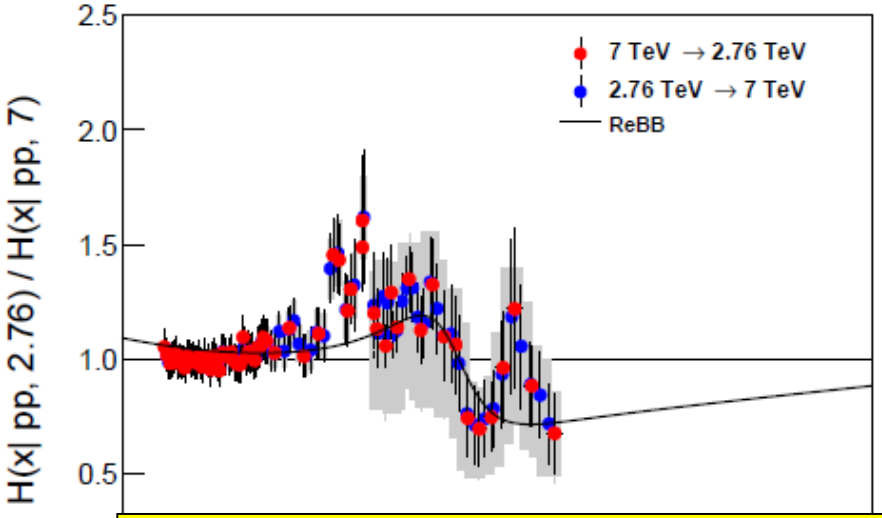
Model independent results since ISMD'19

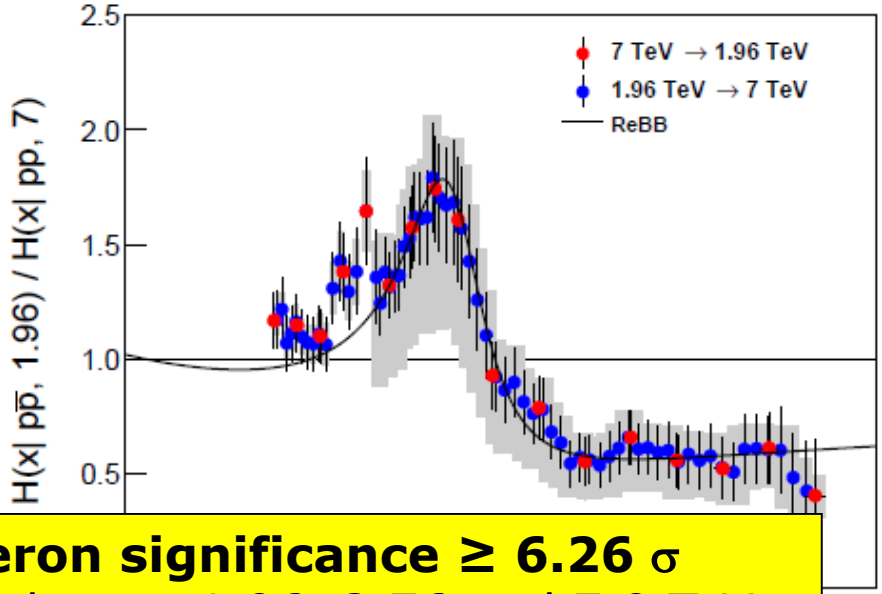
Scaling of high-energy elastic scattering and the observation of Odderon #1

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.
Model independent Odderon significance 6.26 σ
Small violations under theoretical controll (next slide).
New result presented in this talk: domain of validity model independently

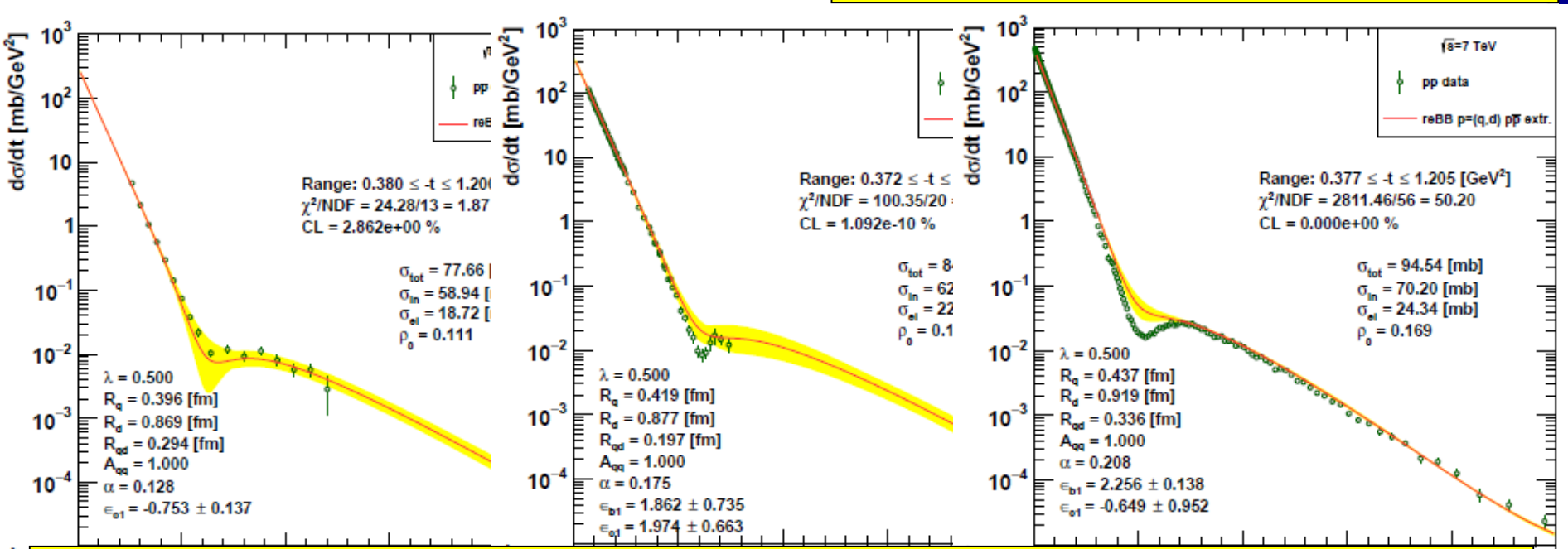
Model dependent evidence for Odderon

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
https://doi.org/10.1140/epjc/s10052-021-09381-5



S: Model independent 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 $0.372 \leq -t \leq 1.2$ GeV^2 and $0.546 \leq \sqrt{s} \leq 7$ (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

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

#1

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

e-Print: 2012.03981 [hep-ex]

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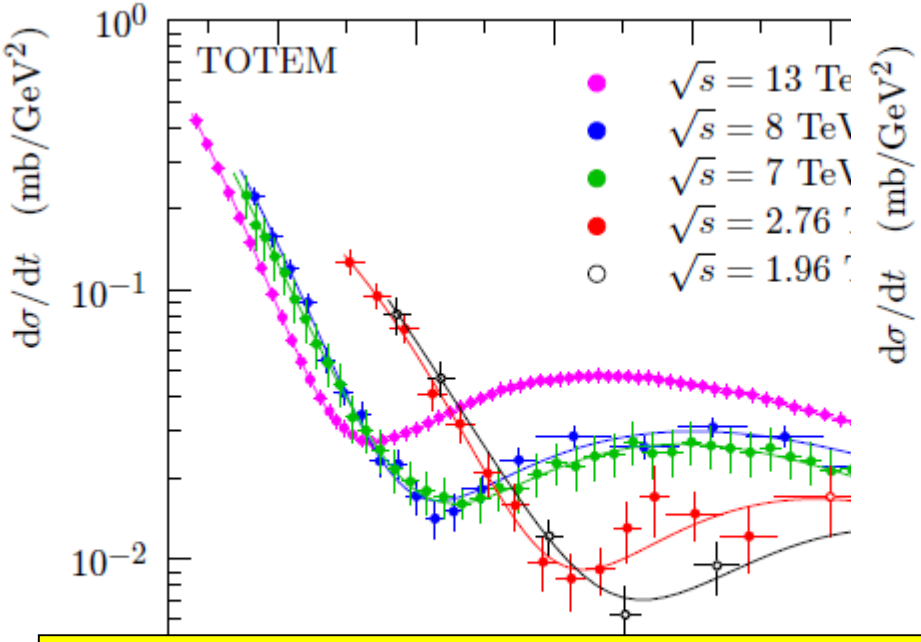
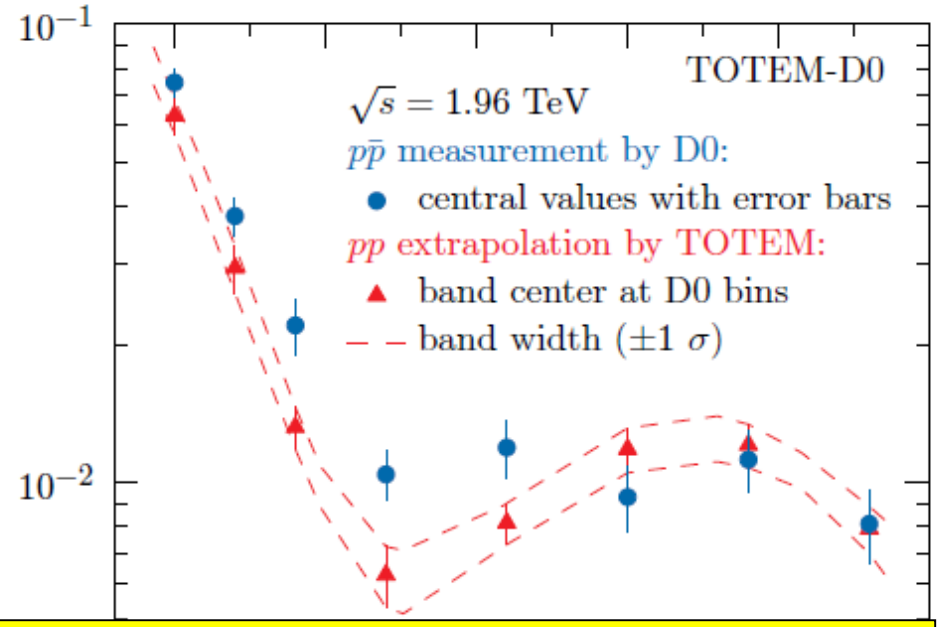
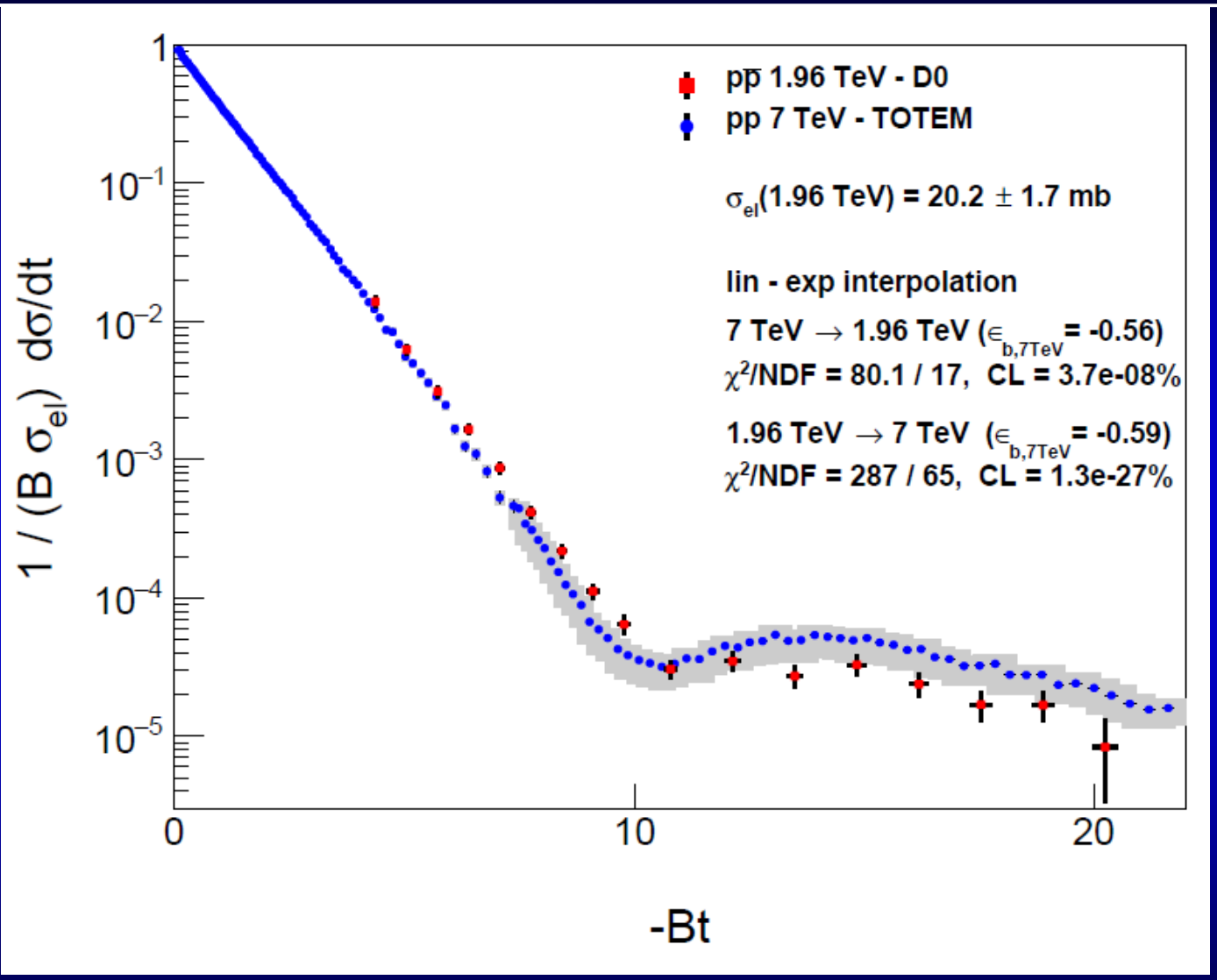




S: Odderon significance ≥ 5.2 σ,
C1: if combined with 13 TeV σ_{tot} and ρ_0
C2: if **new pp data** at 13, 8 TeV and 1 new point at 2.76 TeV is added,
C3: **if only 8 out of the 17 D0 points is used**

Model independent result



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

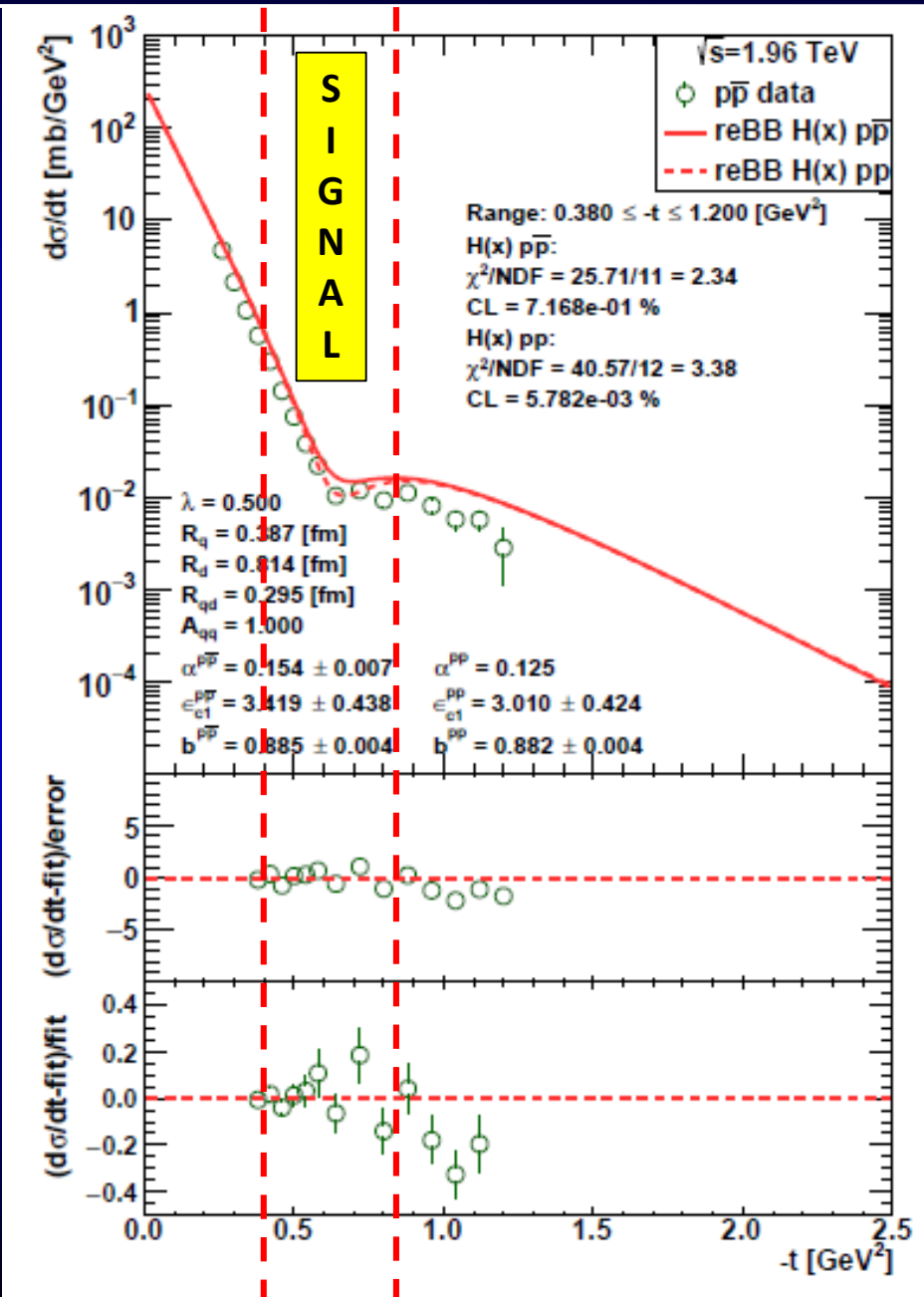
H(x|pp, 7 TeV) ≠ H(x|pantip, 1.96 TeV)

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!

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)

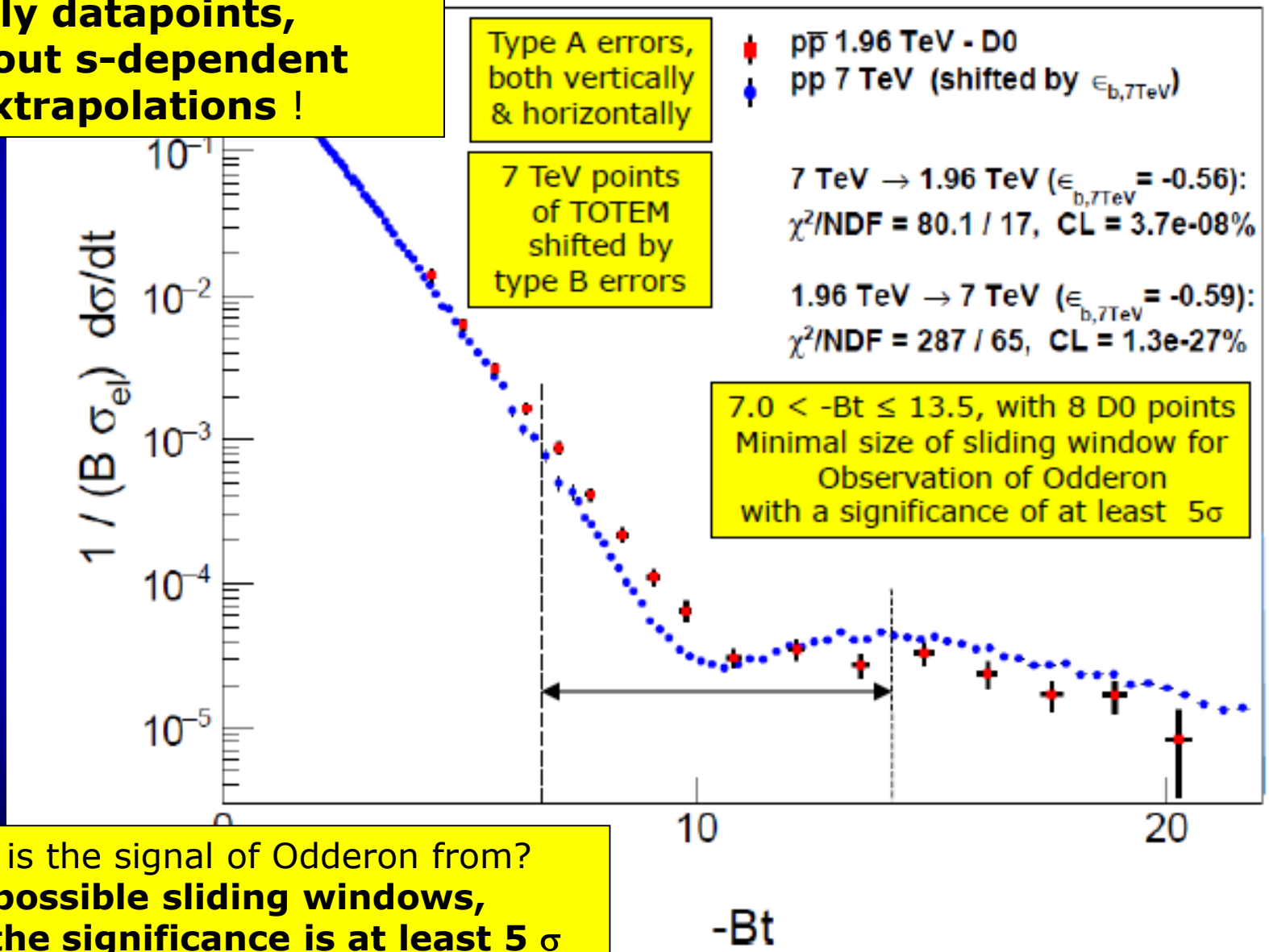
Pull plots:
(data-fit)/error
(data-fit)/fit

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

→ x_{max}(1.96 TeV, pp) > 20

SLIDING WINDOW for 5 σ

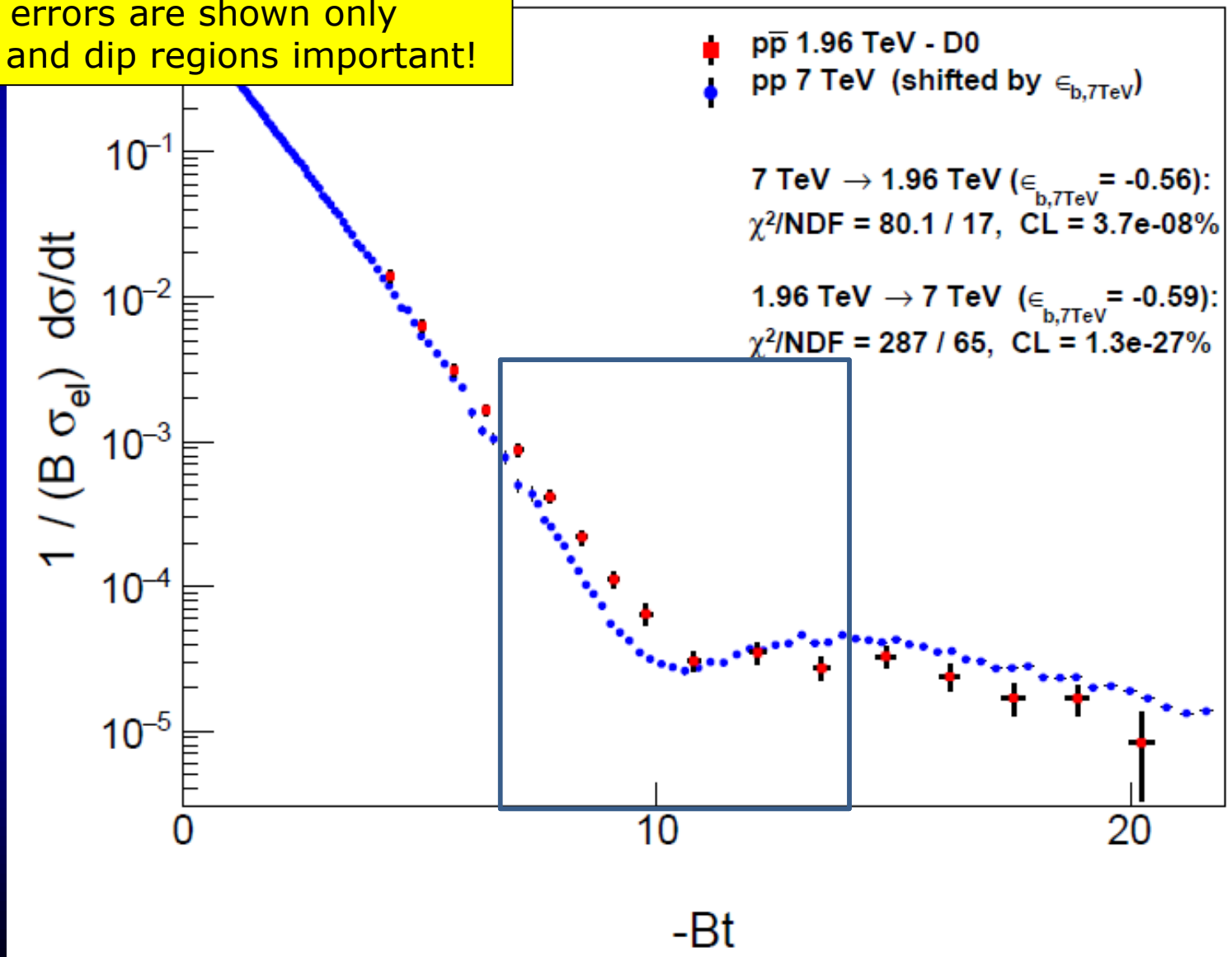
Model independent results: only datapoints, without s-dependent extrapolations !



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

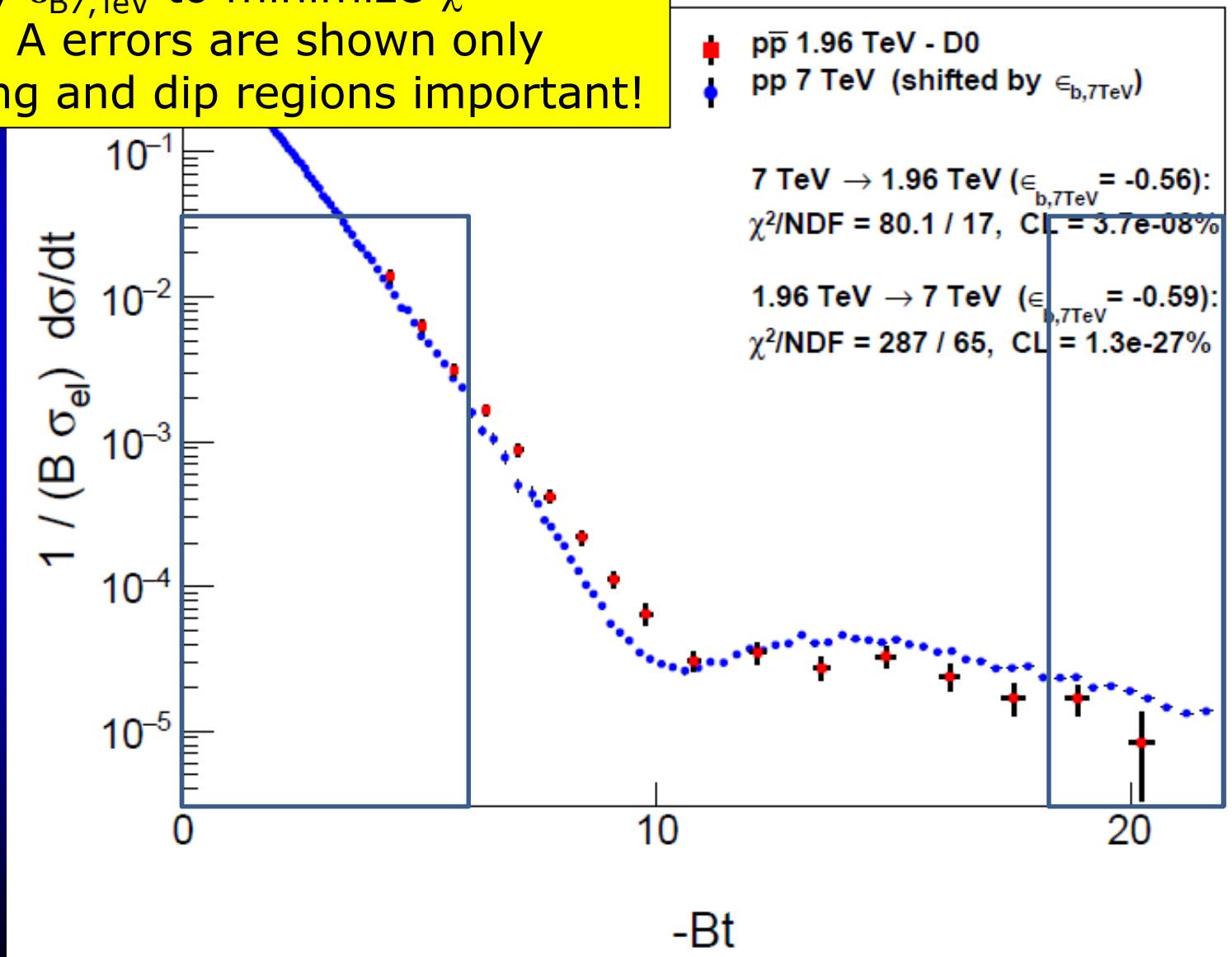
SLIDING WINDOWS

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



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:
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:
Best background: pp and pbarp agree within 1.7 σ

SUMMARY: AT LEAST 6.36 σ ODDERON

An at least 6.36 σ Odderon effect

Odderon first discovered in three papers
2 published
1 accepted for publication, but
under three different conditions

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

OBSERVATION OF ODDERON

2020 → 2020

THANK YOU FOR YOUR ATTENTION

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

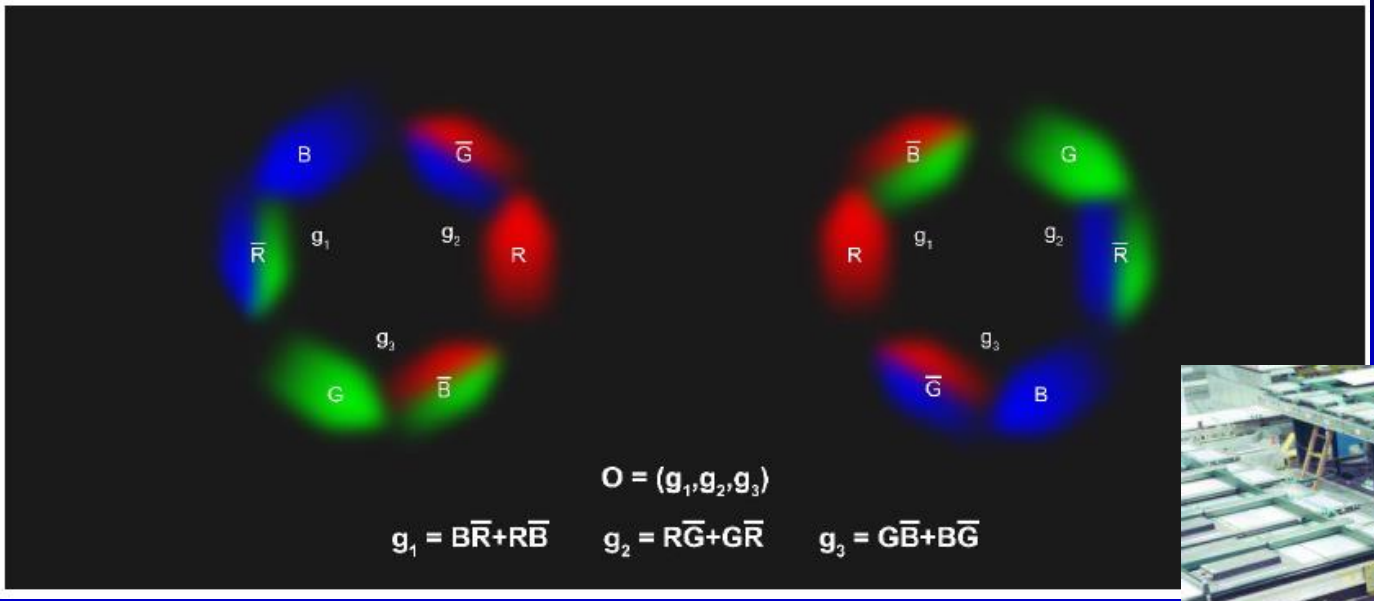
OBERON POETRY MAGAZINE

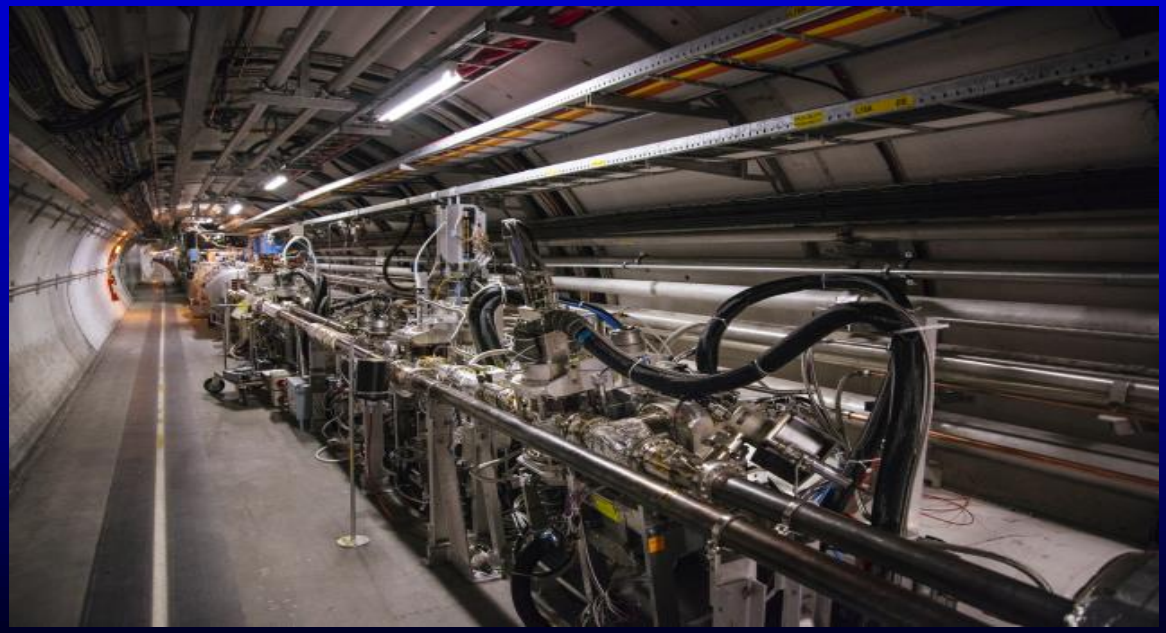
So happy together,
with love for science and research:
Happiness and pleasure
must not slow down the search!

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

BACKUP SLIDES





Asymmetry parameter for C-violation

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

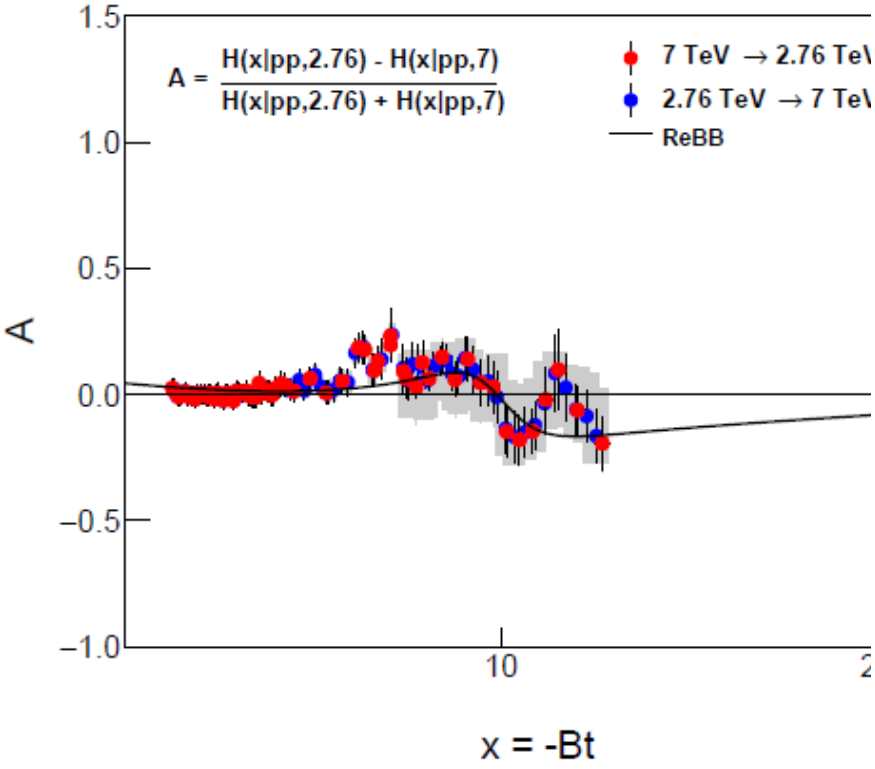
$$A(x|pp,s_1|pp,s_2) = \frac{H(x|pp,s_1) - H(x|pp,s_2)}{H(x|pp,s_1) + H(x|pp,s_2)}.$$

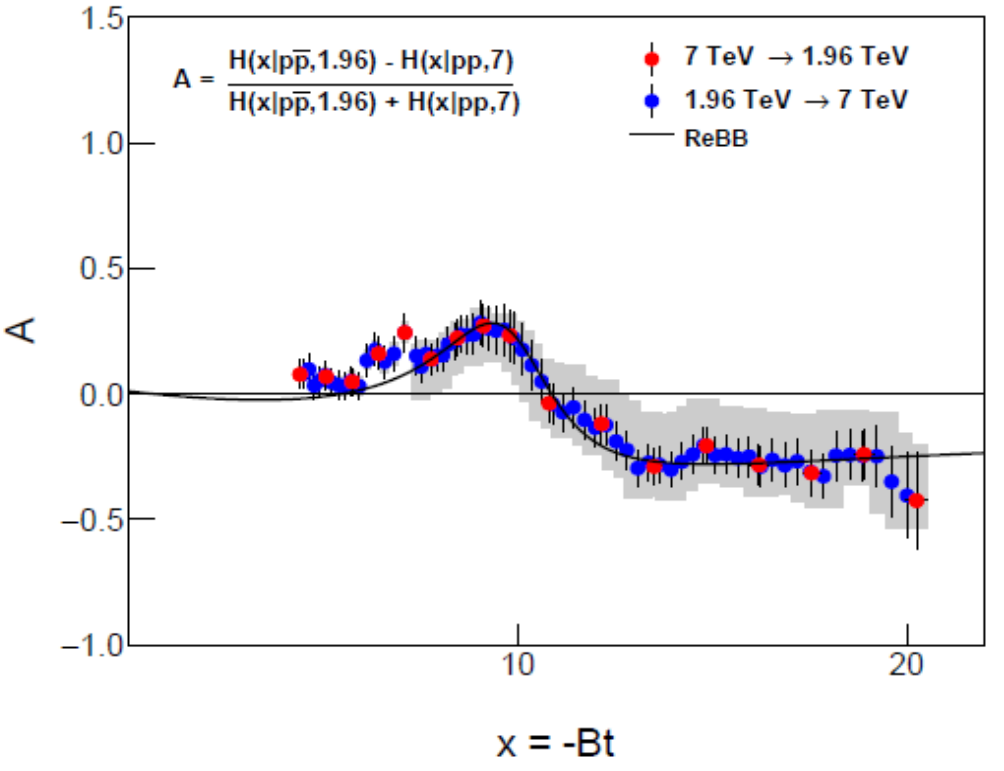
$A(x|\text{pbarp},s_1|\text{pp},s_2)$
does NOT vanish
for a C-symmetry violation AND

$A(x|\text{pp},s_1|\text{pp},s_2)$
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]

Essentially, Odderon

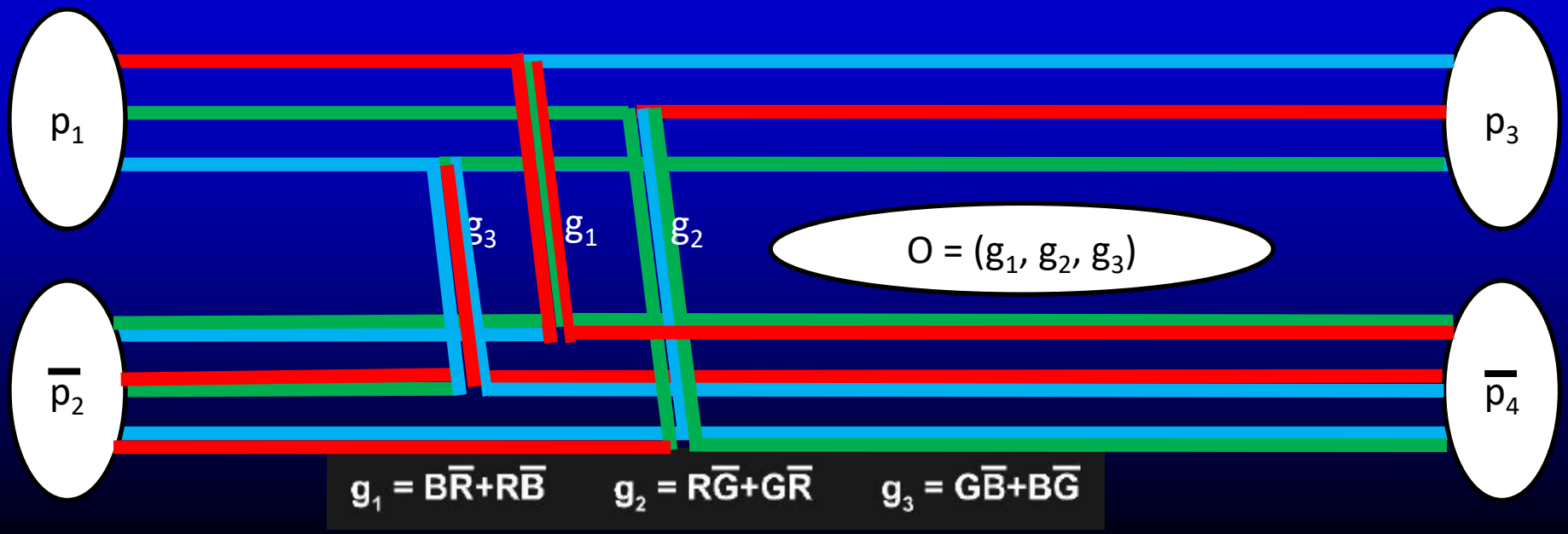
$p+p \rightarrow p+p$

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

-

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

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



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

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

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

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

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

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

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

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

Odderon search: a possible strategy

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

Try to scale this out
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

Looking for Crossing-Odd(eron) effects

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

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

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

Scaling in the diffractive cone region

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

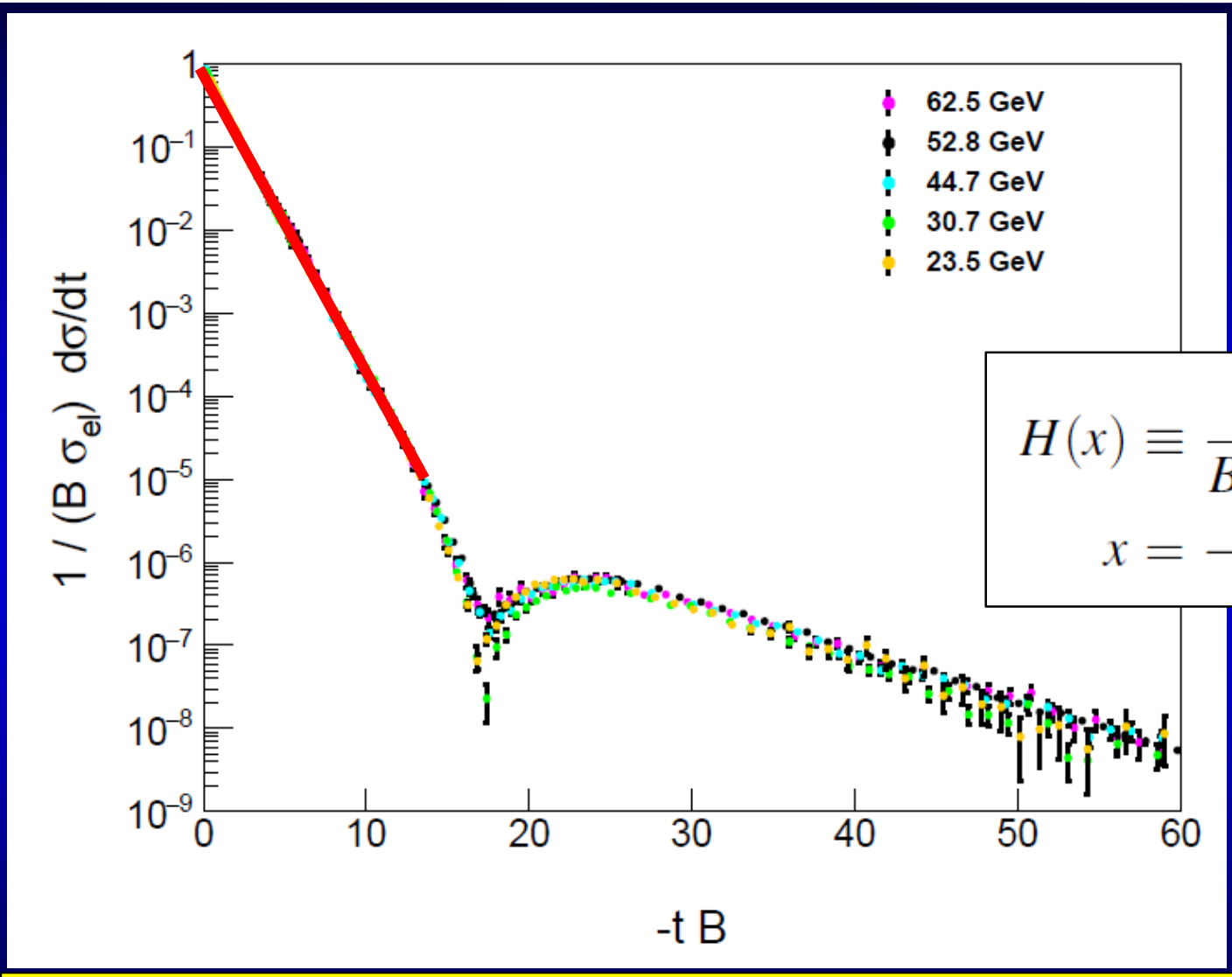
$$A(s) = B(s)\,\sigma_{\mathrm{el}}(s) = \frac{1+\rho_0^2(s)}{16\,\pi}\,\sigma_{\mathrm{tot}}^2(s),$$

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

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

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



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

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

Derivation of H(x) scaling for all x

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

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

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

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

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

Advantages:

H(x) ≠ exp(-x) arbitrary positive def. in the dip-bump region

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