OBSERVATION OF ODDERON

SCALING PROPERTIES OF ELASTIC SCATTERING

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Motivation: Odderon
H(x) scaling at TeV
Model independent results:
Significance at least 6.26 σ
Model dependent results:
Significance at least 7.08 σ
Domain of validity
Conclusions

Formalism: elastic scattering

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

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

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

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

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

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

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

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

Formalism 2: elastic scattering in b space

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

$$t_{\rm el}(s,b) = \int \frac{d^2\boldsymbol{\Delta}}{(2\pi)^2} e^{-i\boldsymbol{\Delta}\boldsymbol{b}} T_{\rm el}(s,\Delta) =$$
$$= \frac{1}{2\pi}\int J_0(\Delta\, b)\, T_{\rm el}(s,\Delta)\,\Delta\, d\Delta\,,$$
$$\Delta \equiv |\boldsymbol{\Delta}|, \quad b \equiv |\boldsymbol{b}|.$$

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

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

Impact parameter or b space:
elastic scattering *interferes with no collisions*.
Complex opacity function Ω(s,b) (eikonal, from unitarity)
P(s,b): shadow profile function = probability of inelastic scattering

Looking for Crossing-Odd(eron) effects

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

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

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

Odderon search: a possible strategy

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

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

Scaling in the diffractive cone region

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

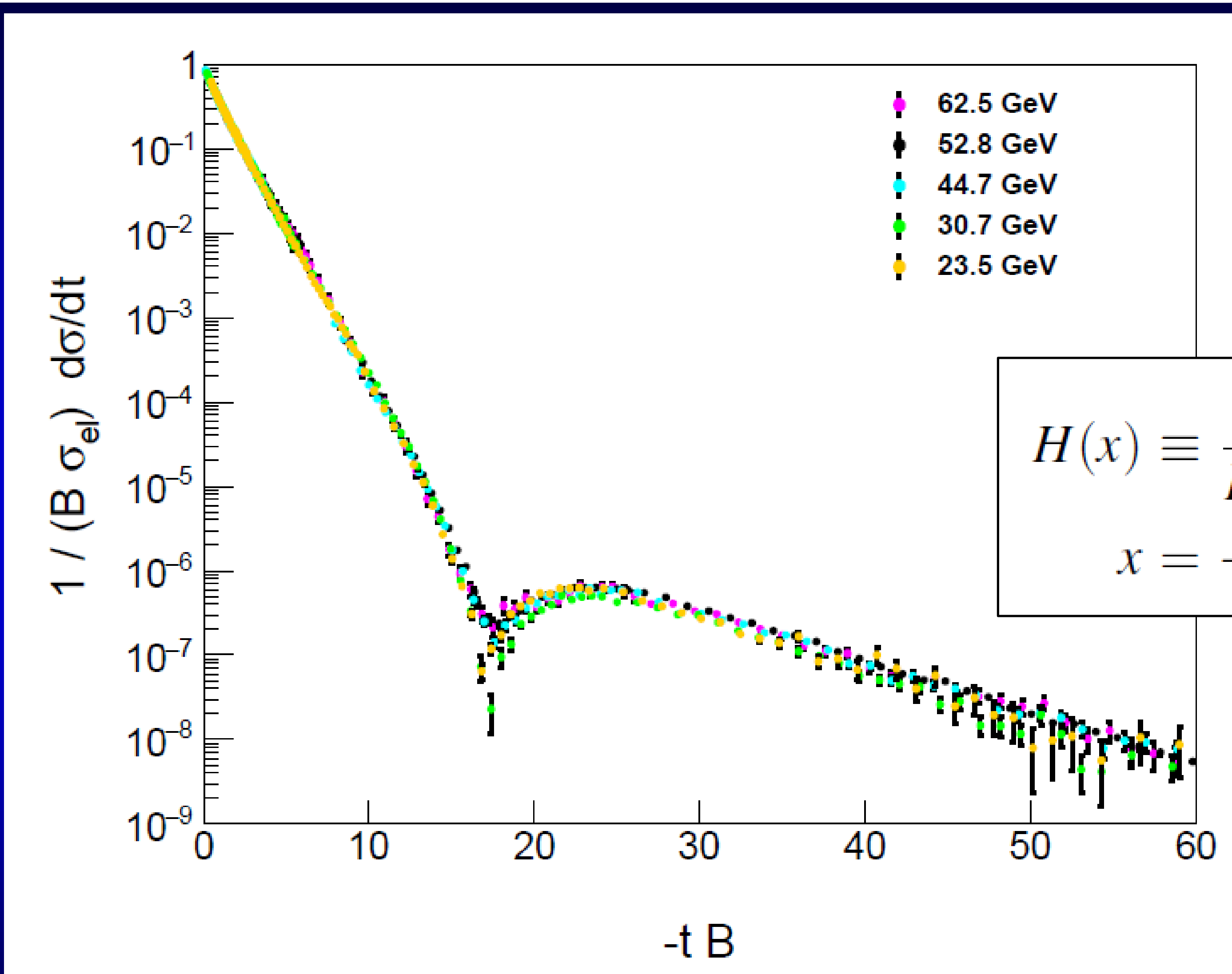
$$A(s) = B(s)\,\sigma_{\rm el}(s) = \frac{1+\rho_0^2(s)}{16\pi}\,\sigma_{\rm tot}^2(s),$$

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

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

Advantages:
H(x) = exp(-x) in the cone
Measurable both for pp and p-antip

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!

H(x) scaling in greater x region

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

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

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

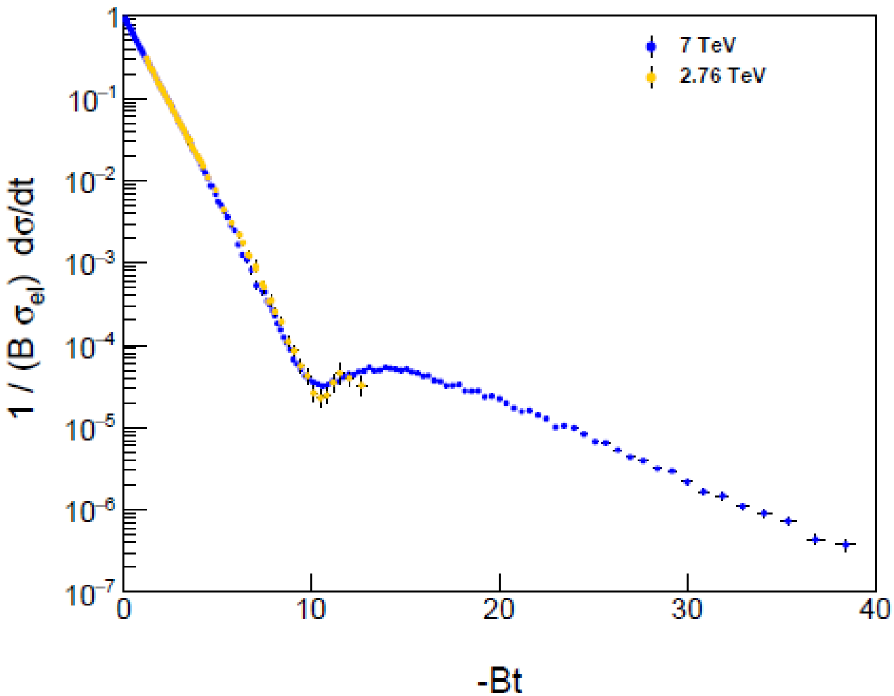
$$A = \left.\frac{d\sigma}{dt}\right|_{t=0} = \frac{1+\rho_0^2}{4\pi} r^2(s) R^2(s) |\tilde{E}(0)|^2,$$

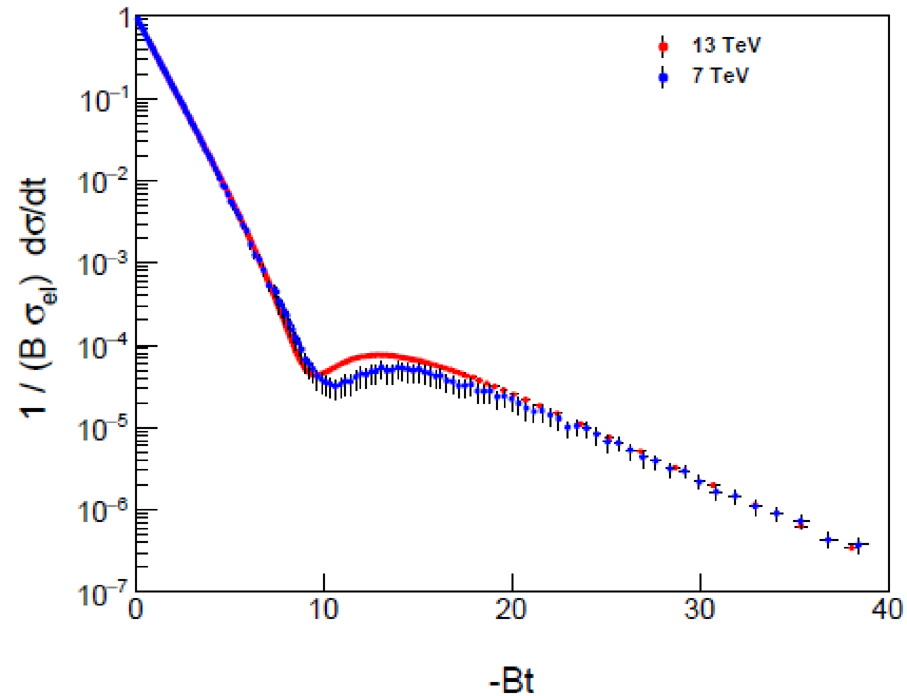
$$\frac{1}{A}\frac{d\sigma}{dt} = \frac{|\tilde{E}(\sqrt{x})|^2}{|\tilde{E}(x=0)|^2} = H(x),$$

Advantages:
H(x) ≠ exp(-x) arbitrary positive def. in the dip-bump region
Measurable both for pp and p-antip. Normalized as H(0) = 1.

Test of the H(x) scaling with TOTEM@LHC

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

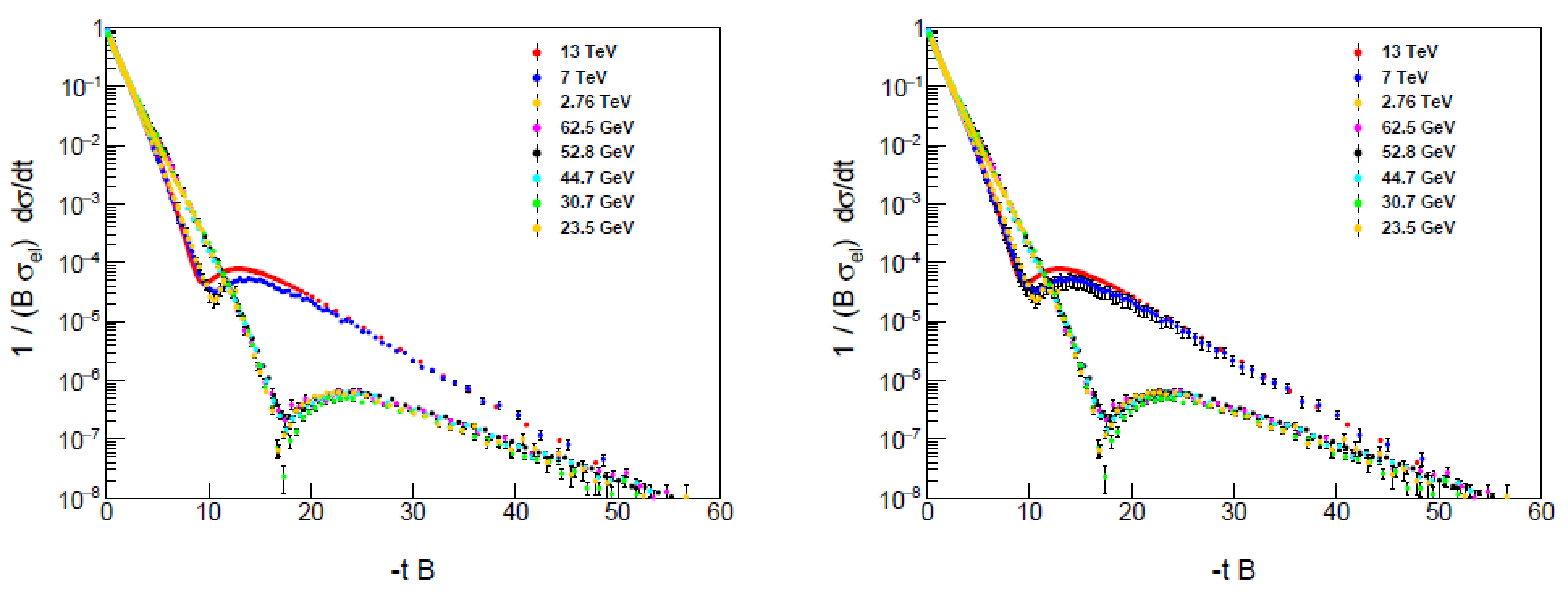




Between 2.76 and 7 TeV, even with stat errors only, valid in the bump/tail region!
Between 7 and 13 TeV, scaling in the cone,
Violations beyond stat+syst errors in the dip/dump/tail region

H(x) scaling from ISR to LHC

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



Left: stat errors only, Right: stat + syst errors in quadrature
Scaling approximate, valid in the cone, violations important
if √s changes from 23.5 GeV to 13 TeV!

Model independent evidence for Odderon

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)

e-Print: 2004.07318 [hep-ph]

pdf cite 4 citations

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 1 citation

Evidence of Odderon-exchange from scaling properties of elastic scattering at TeV energies #3

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)

e-Print: 1912.11968 [hep-ph]

pdf cite 12 citations

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

Convergence properties of Lévy expansions: implications for Odderon and proton structure #4

T. Csörgő (Wigner RCP, Budapest and CERN), R. Pasechnik (Lund U., Dept. Theor. Phys.), A. Ster (Wigner RCP, Budapest) (Mar 19, 2019)

Published in: *EPJ Web Conf.* 206 (2019) 06007 • Contribution to: ISMD 2018 • e-Print: 1903.08235 [hep-ph]

pdf DOI cite 2 citations

1 paper published, 2 submitted for publication, Zimányi 2019 and 2020
1 refereed proceedings EPJ Web of Conferences (Proc. ISMD 2019)

Model independent results since ISMD'19

Evidence of Odderon-exchange from scaling properties of elastic scattering at TeV energies #3

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

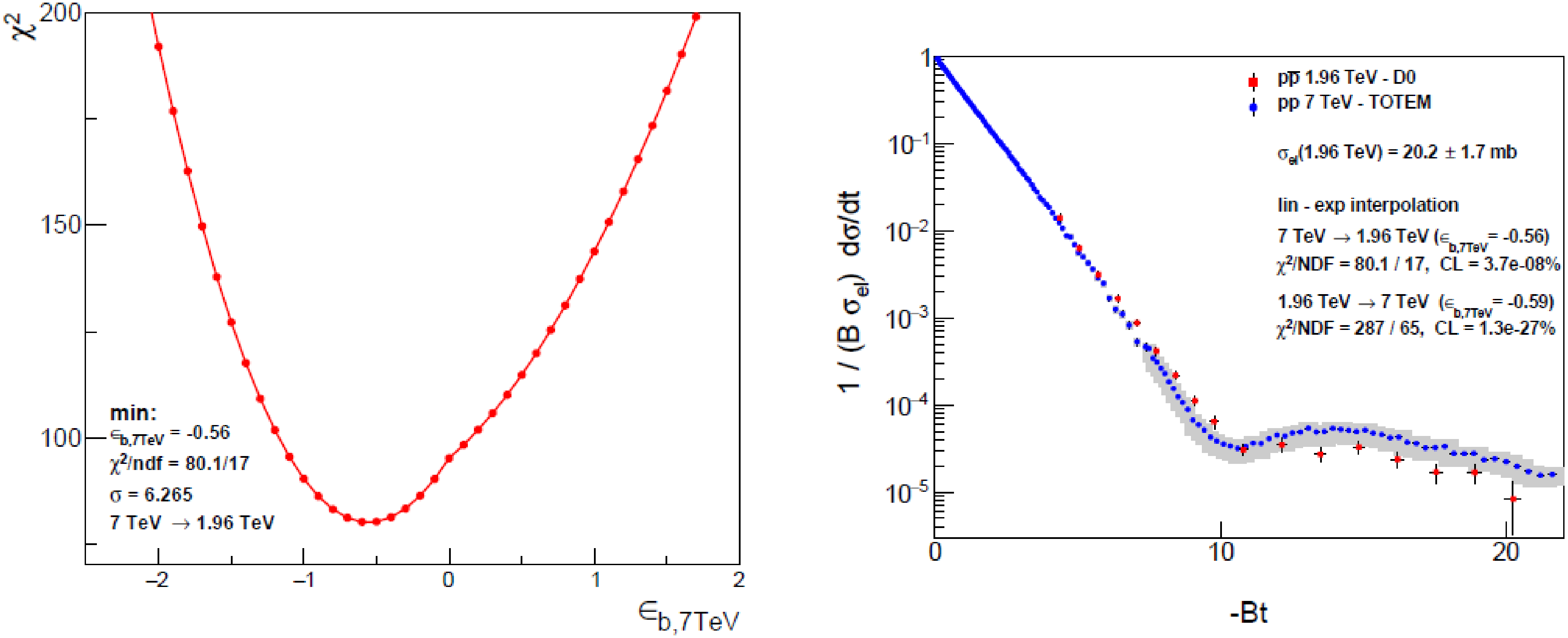


Fig. 13 Left panel indicates that as a function of $\varepsilon_{b,7\ \mathrm{TeV}}$, the $\chi^2 \equiv \tilde{\chi}^2_{21}$ distribution has a unique minimum and nearly quadratic minimum. The minimum value is $\chi^2/\mathrm{NDF} = 80.1/17$, corresponding to a statistically significant difference between the pp and $p\bar{p}$ $H(x)$ scaling functions. at the level of 6.26σ. The right panel shows the comparison of the $H(x)$ data using the values of $\varepsilon_{b,7\ \mathrm{TeV}}$ corresponding to such a minimum, both for the case of the $7 \rightarrow 1.96$ TeV and for the case of $1.96 \rightarrow 7$ TeV projections.

T. Cs, R. Pasechnik, T. Novák, A. Ster, I. Szanyi, Eur. Phys. J. C (2021) **81**: 180
https://doi.org/10.1140/epjc/s10052-021-08867-6 , 1912.11968 [hep-ph]

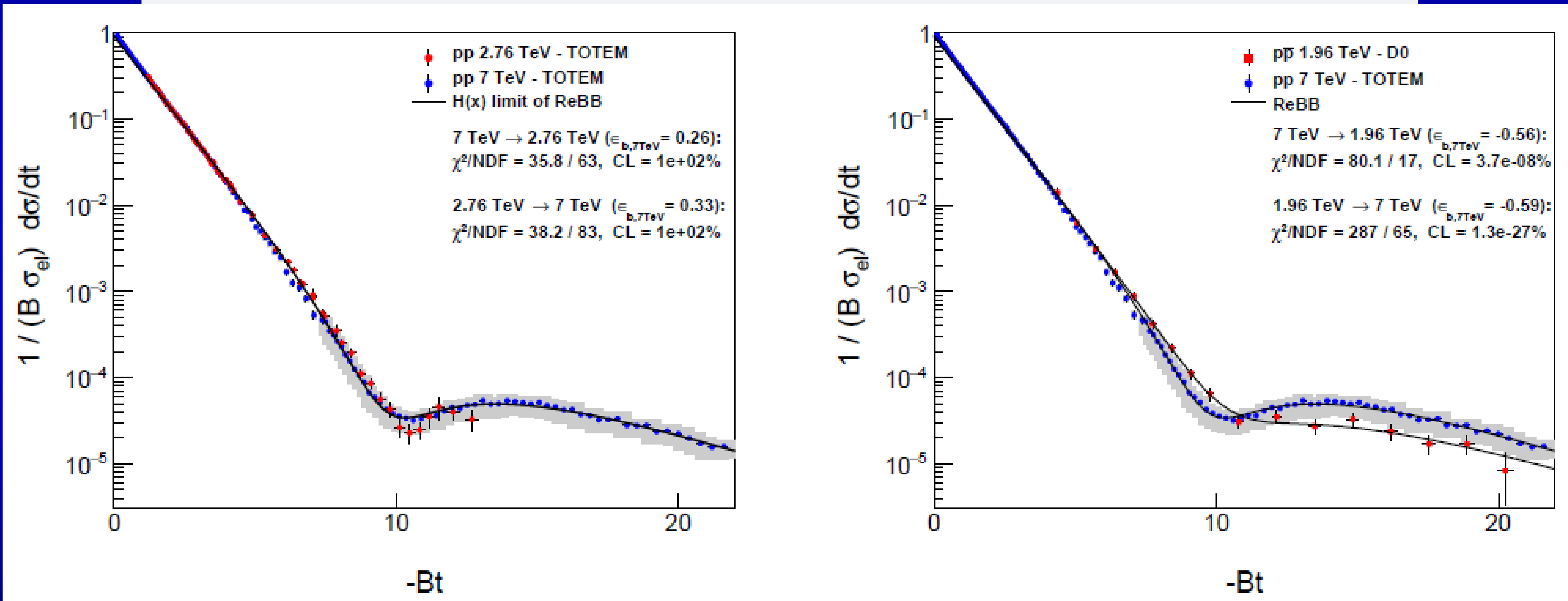
Model independent results since ISMD'19

Scaling of high-energy elastic scattering and the observation of Odderon #3

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)

e-Print: 2004.07318 [hep-ph]

pdf cite 3 citations



arXiv:2004.07318v2

Model independent Odderon significance 6.26 σ

11 pages, 2 figures, submitted for publication,

detailed at DoF'2020 and Zimányi'2020 by T. Novák and A. Ster

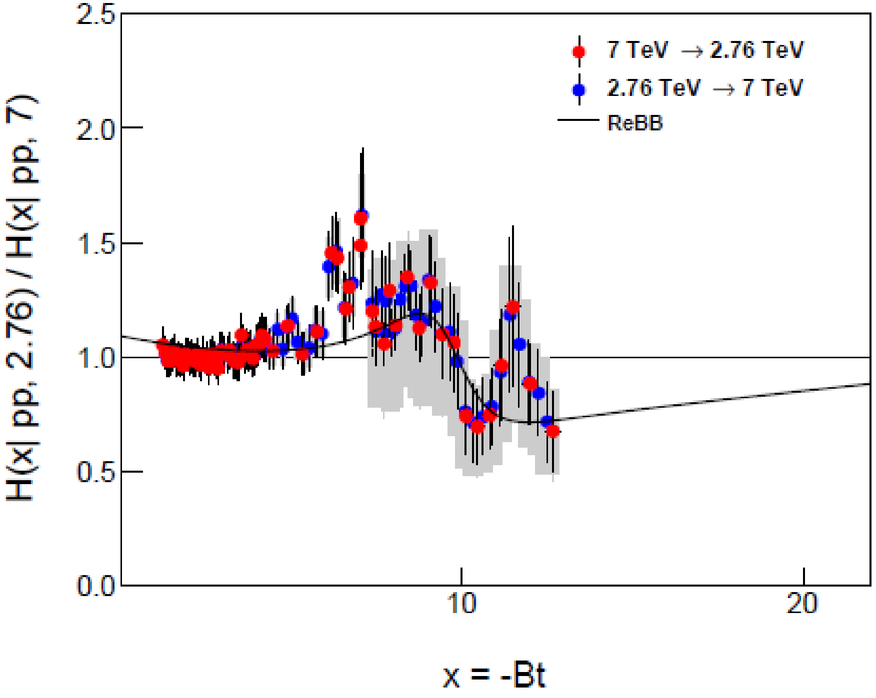
Model independent results since ISMD'19

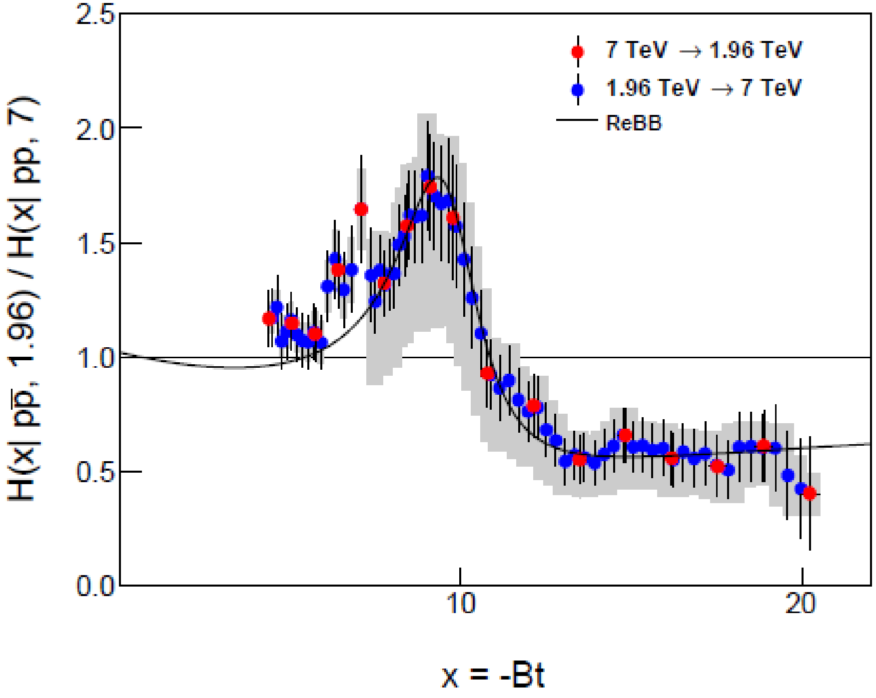
Scaling of high-energy elastic scattering and the observation of Odderon

#3

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)

e-Print: 2004.07318 [hep-ph]





arXiv:2004.07318v2

Model independent Odderon significance 6.26 σ

11 pages, 2 figures, submitted for publication,

detailed at DoF'20 and Zimányi'20 by T. Novák and A. Ster

Model dependent evidence for Odderon

Observation of Odderon Effects at LHC energies -- A Real Extended Bialas-Bzdak Model Study #1

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

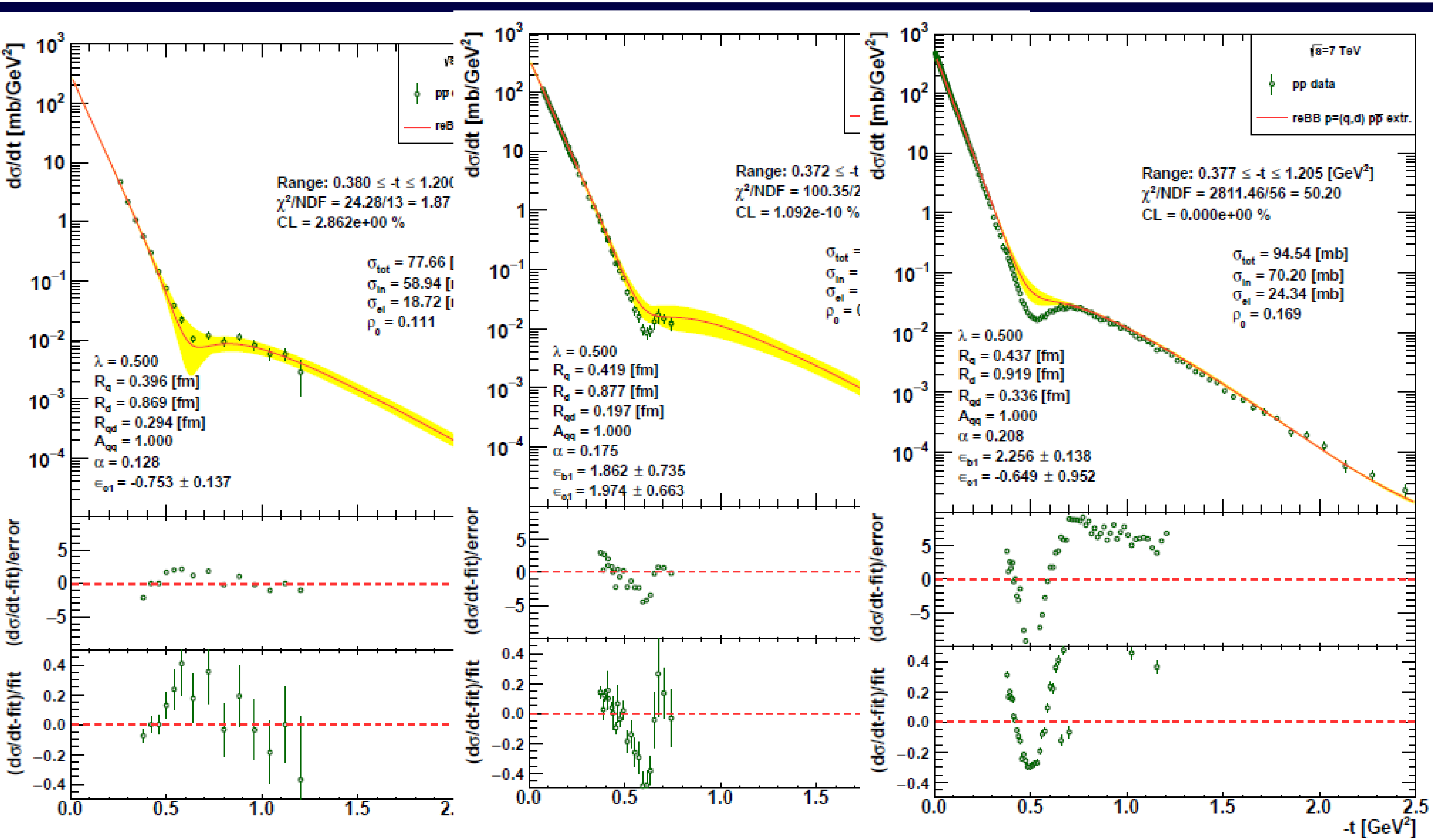
e-Print: 2005.14319 [hep-ph]

pdf cite 1 citation

Structure: Introduction,
Fits with CL > 0.1 % to published pp and pbarp data function
In the dip/bump region (large –t fits)
Linear excitation function in TeV energy range: $p_0 + p_1 \ln(s/s_0)$
Sanity tests: Validation of the trends
Extrapolations both for pp and pbarp data
Odderon significance from pp and pbarp comparisions
From combined 1.96 and 2.76 TeV analysis: Odderon seen at 7.08 σ
Cross-checks (quadratic trend, ISR data)

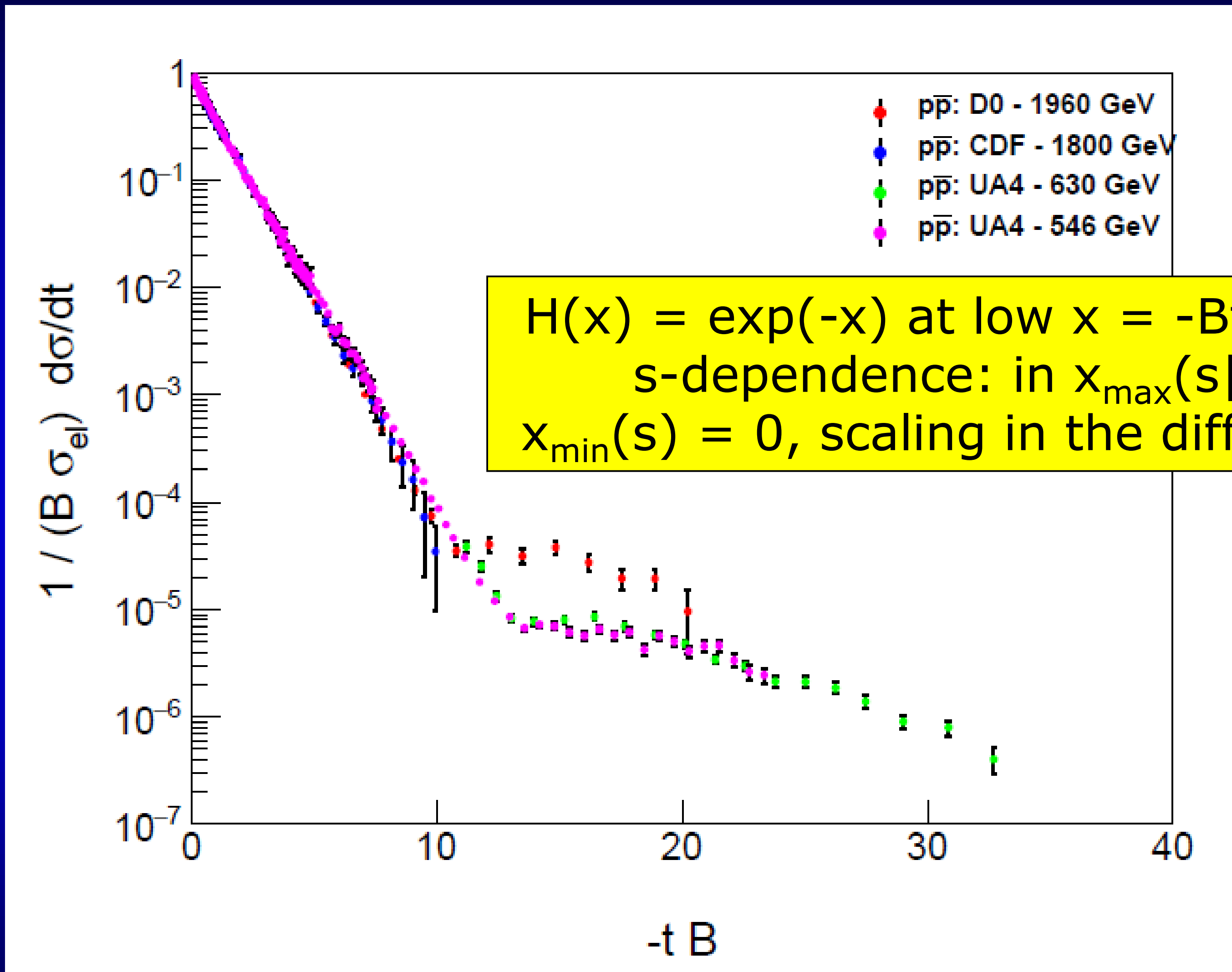
82 pages, 31 figures, model dependent Odderon significance 7.1 σ,
submitted for publication, Zimányi’2020, see next talk by I. Szanyi

Model dependent evidence for Odderon



82 pages, 31 figures, model dependent Odderon significance ≥ 7.08 σ, submitted for publication, presented at Zimányi'19 and '20 by I. Szanyi

H(x) scaling for p antip scattering

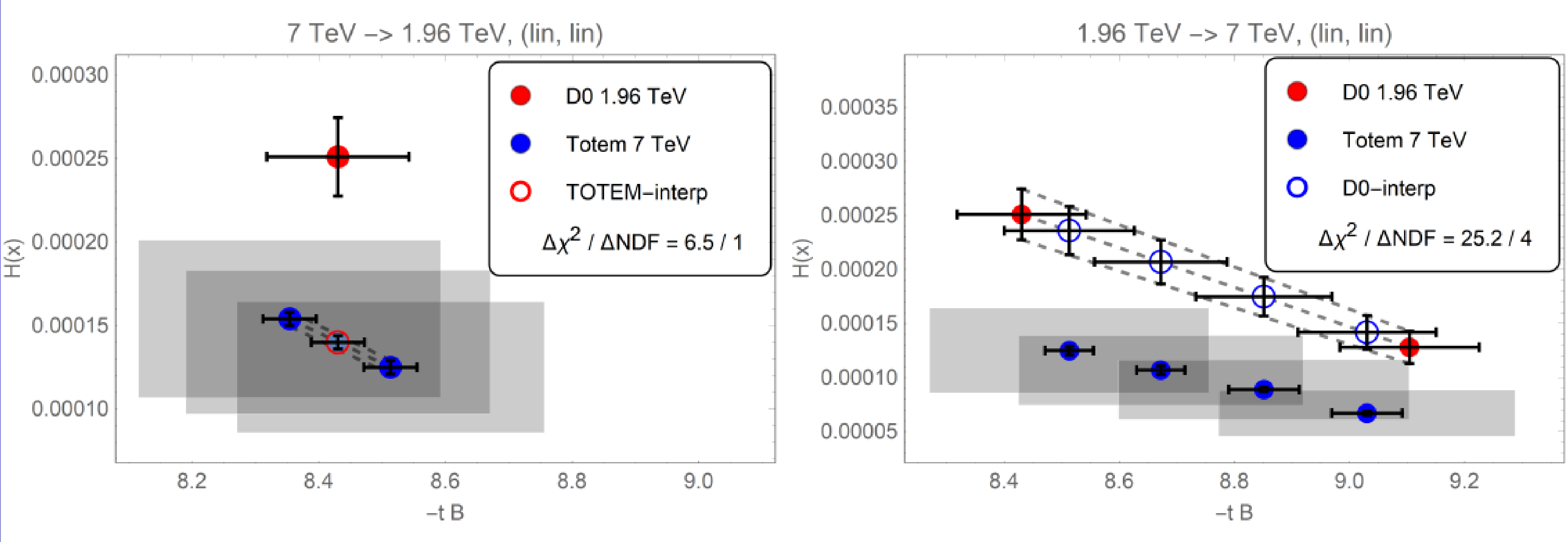


H(x) = exp(-x) at low x = -Bt at ~ every s
s-dependence: in x_{max}(s|p+antip)
x_{min}(s) = 0, scaling in the diffractive cone !

Energy range: 546 GeV – 1.96 TeV
Qualitatively different from pp: scaling in the cone only for p+antip

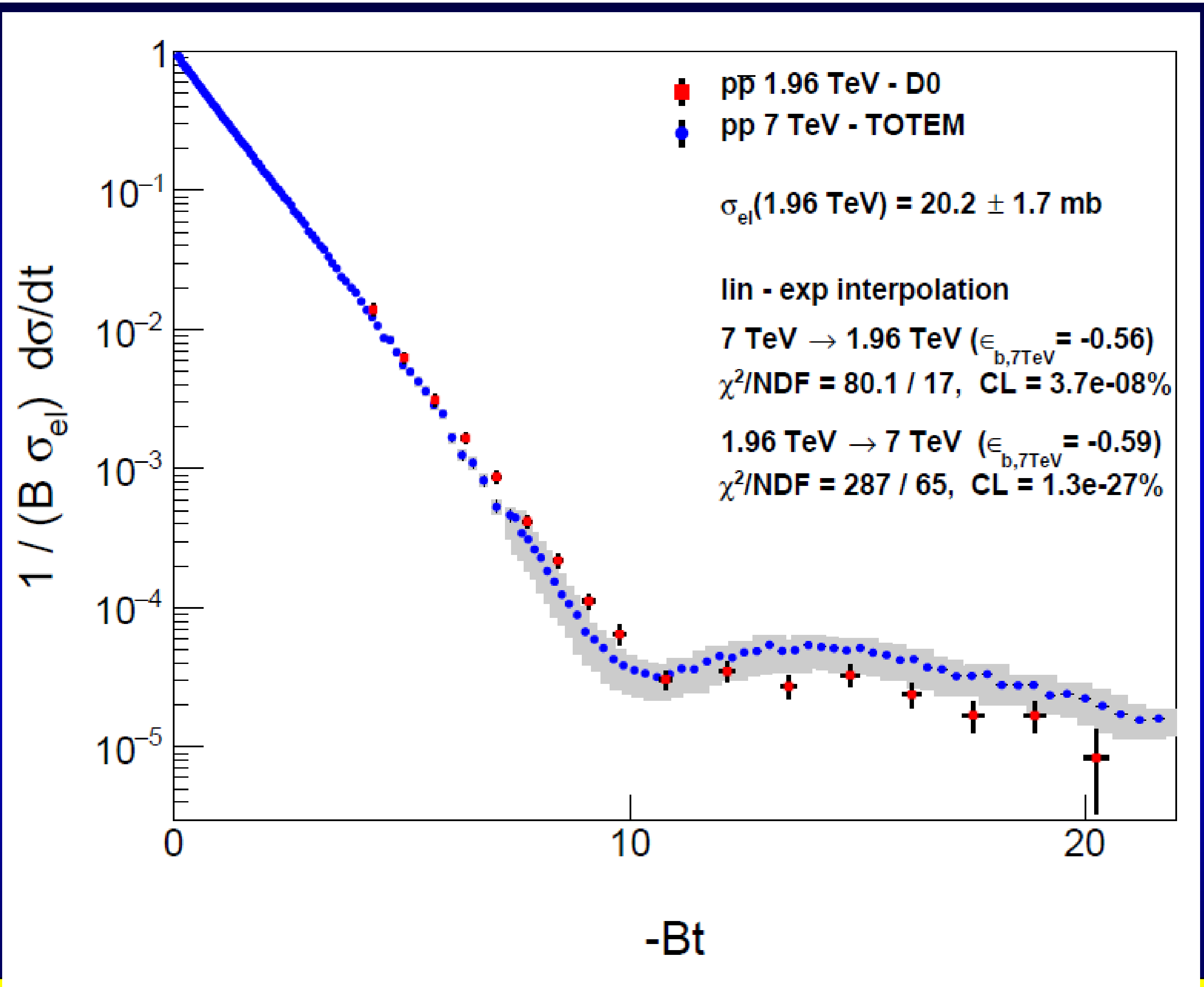
H(x) scaling for p antip scattering

Need for a comparison of different data sets measured at different values of x: Linear interpolation to the same x



Errors: both vertical AND horizontal, type A, B, C
type A: point-to-point fluctuating error
type B: point-to-point 100 % correlated error
type C: point independent overall correlated error

Main result of quantification



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 effect

Energy range: HAS to be tested
Modelling useful, but also model independent tests possible

Asymmetry parameter for C-violation

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

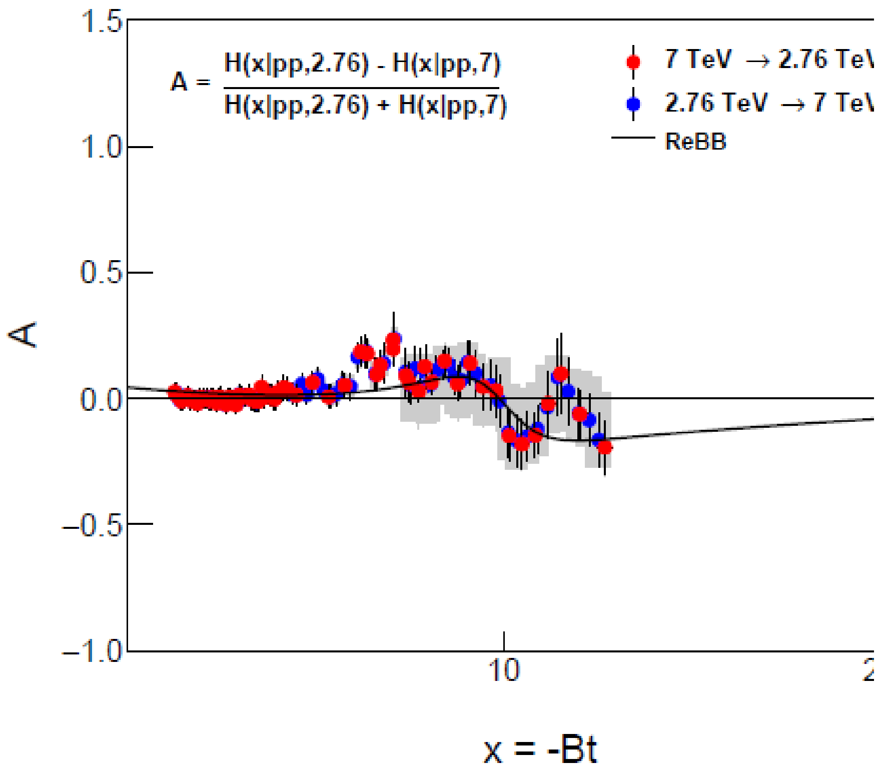
$$A(x|pp,s_1|pp,s_2) = \frac{H(x|pp,s_1) - H(x|pp,s_2)}{H(x|pp,s_1) + H(x|pp,s_2)}.$$

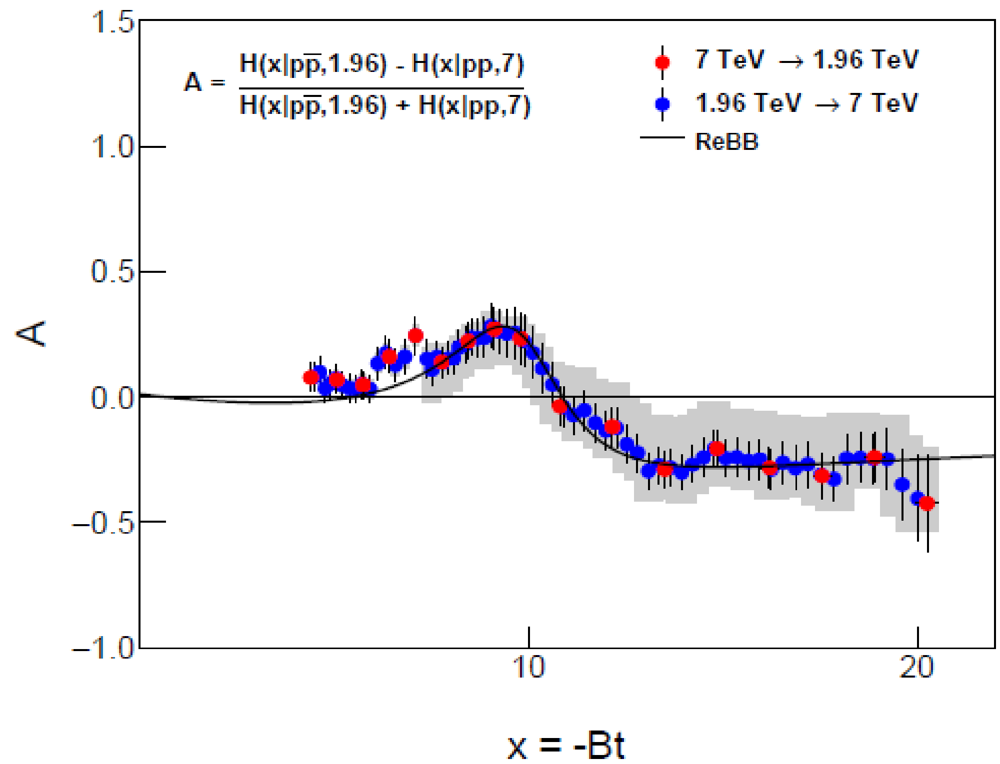
A(x|pbarp,s_1|pp,s_2)
does NOT vanish
for a C-symmetry violation AND

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

Energy range: HAS to be tested

Main result of A



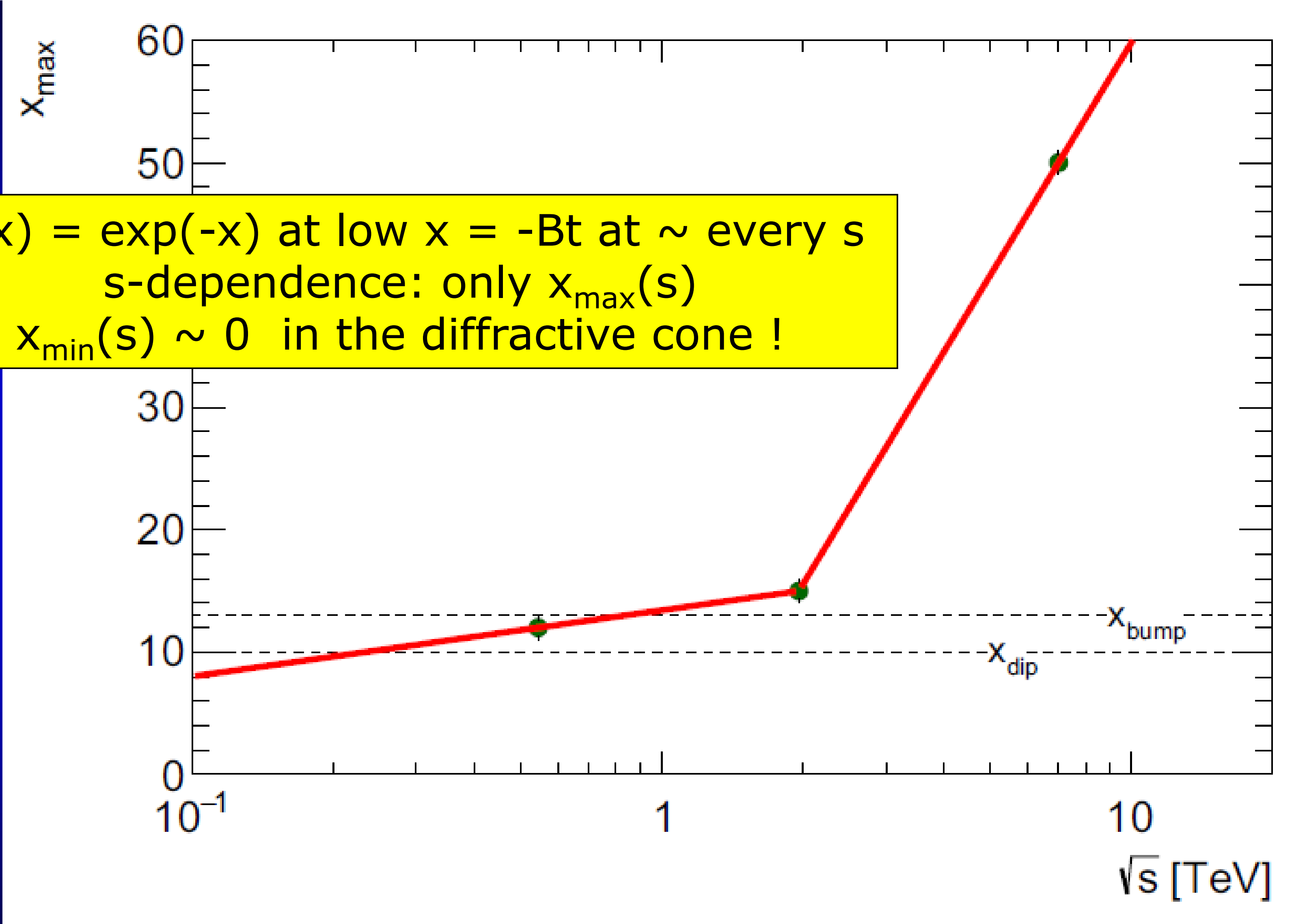


$A(x|pp,s_1|pp,s_2)$
vanishes if
H(x) scaling valid

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

Scaling violations: under theoretical control:
Model calculations by solid line, see I. Szanyi's talk

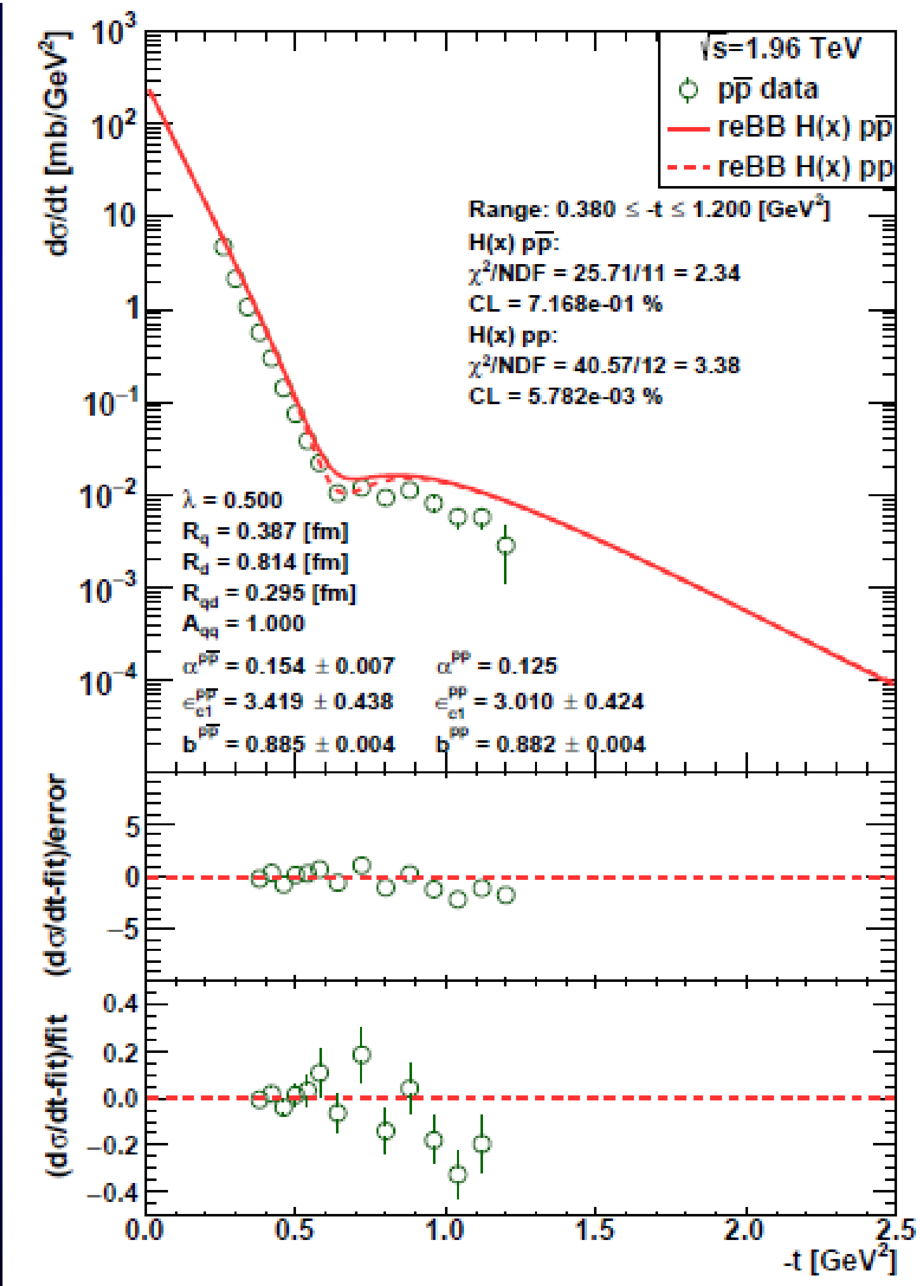
pp: model dependent limit on H(x)



H(x) = exp(-x) at low x = -Bt at ~ every s
s-dependence: only x_{max}(s)
x_{min}(s) ~ 0 in the diffractive cone !

Energy range: 200 GeV – 8 TeV (nearly factor of 40)
With decreasing s, the x = -Bt range for H(x) scaling decreases

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



1.96 TeV
Highest energy where p+antip data are avaialble

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

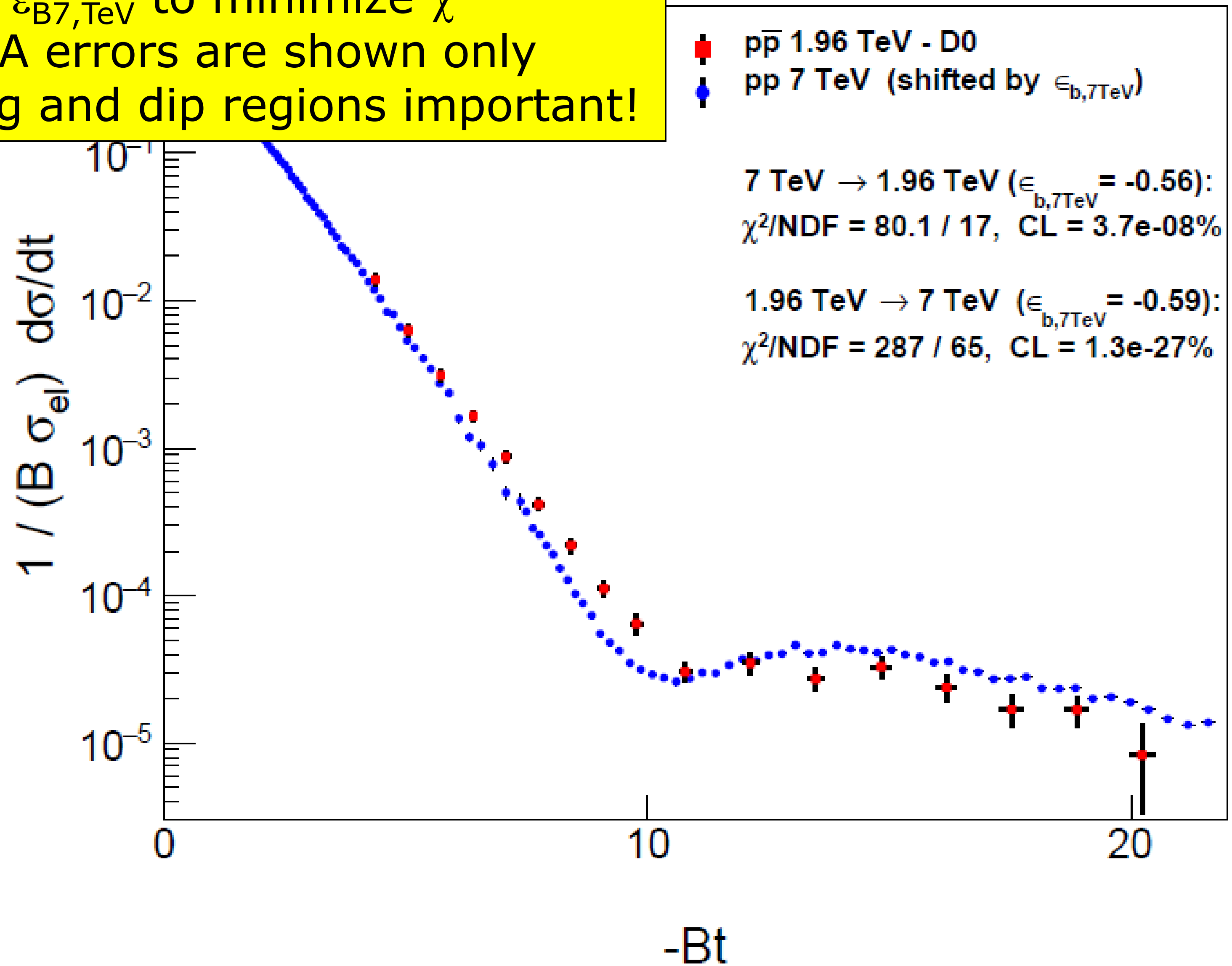
Fits pantip data up to largest -t
(red line, dashed line: pp)

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

OBSERVATION OF ODDERON

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



Where is the Odderon signal from?

Swing, interference, tail regions
Interference region is dominant

Partial significances from the swing, interference, tail and all regions, characterized by $x_{min} < x \leq x_{max}$					
x_{min}	x_{max}	ε_{B21} of min $\Delta\chi^2$ in $x_{min} < x \leq x_{max}$	$\Delta\chi^2$ in $x_{min} < x \leq x_{max}$	NDF in $x_{min} < x \leq x_{max}$	σ in $x_{min} < x \leq x_{max}$
5.1	8.4	1.90	4.19	5	0.64
8.4	13.5	-0.49	25.31	5	3.84
13.5	20.2	-1.39	1.79	5	0.15
5.1	13.5	0.28	48.27	10	5.01
8.4	20.2	-0.96	35.79	10	3.91
5.1	20.2	-0.60	75.41	15	6.23

Safely above the 5 σ threshold

Role of the H(x) scaling violations
Do they decrease the signal or not?

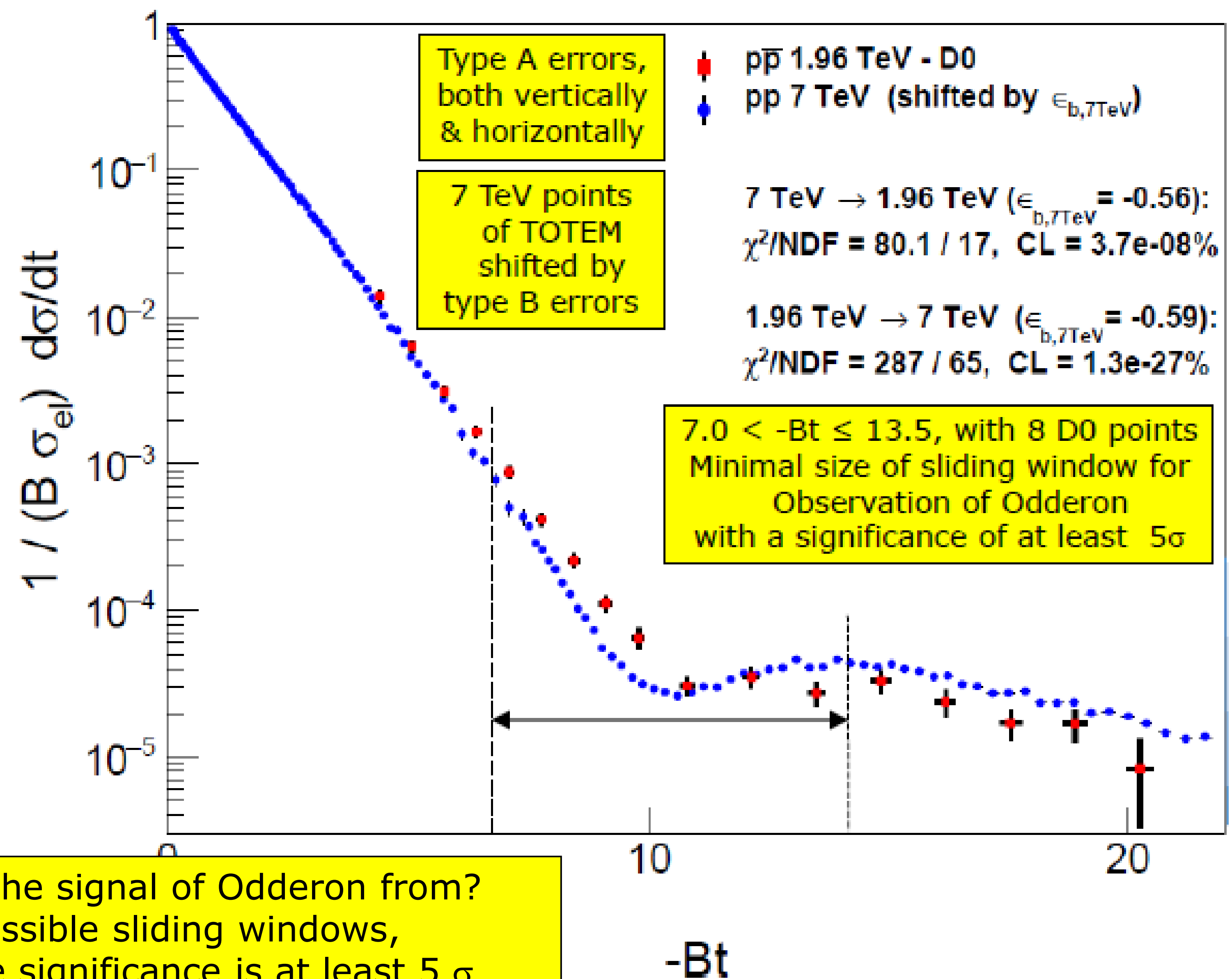
√s (TeV)	χ^2	NDF (ReBB)	σ (ReBB)
1.96	24.28	13	2.19
2.76	100.35	20	7.12
1.96 and 2.76	124.63	33	7.08

H(x) scaling: allows to project pp data ONLY
Scaling violations decrease significance at 1.96 TeV
BUT
Also allow to evaluate pbarp data at 2.76 TeV

Trade-off effect!

Odderon significance increases
From 6.26 to 7.08 σ .

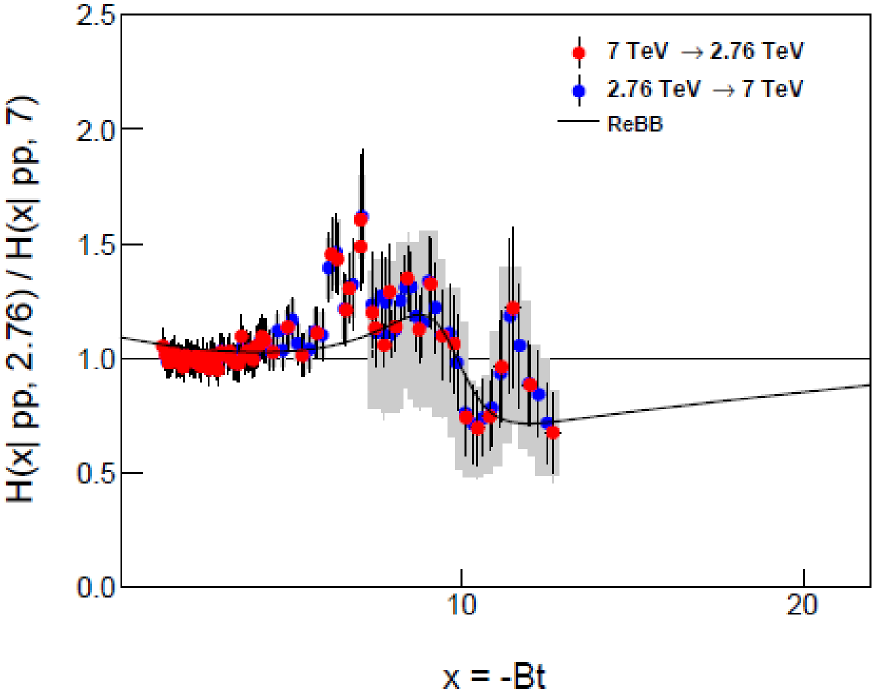
SLIDING WINDOW for 5 σ

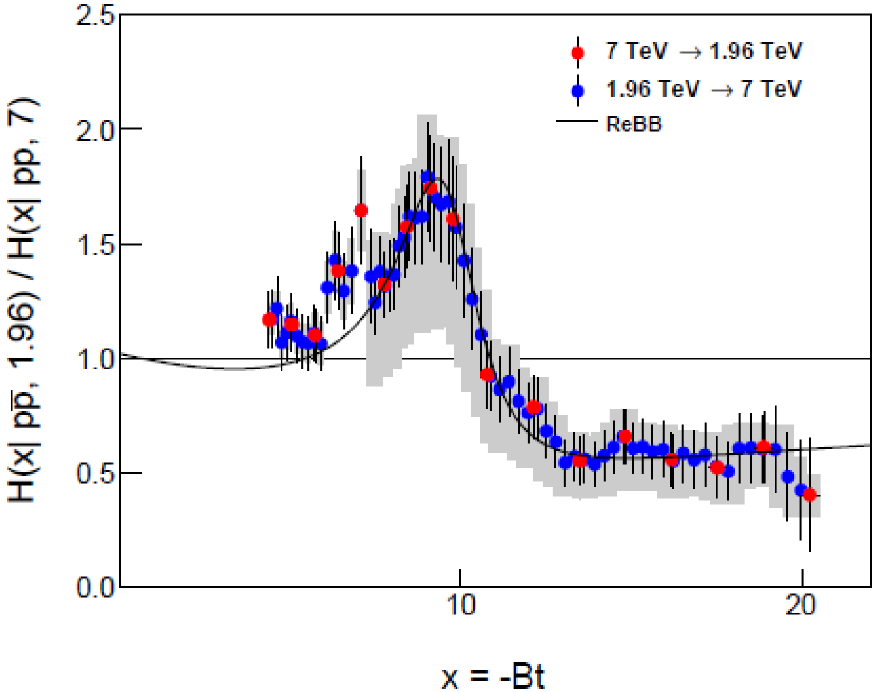


Where is the signal of Odderon from?
All possible sliding windows,
where the significance is at least 5 σ

AT LEAST 6.26 σ ODDERON

A 6.26 σ Odderon effect seen on H(x|pbarp)/H(x|pp)

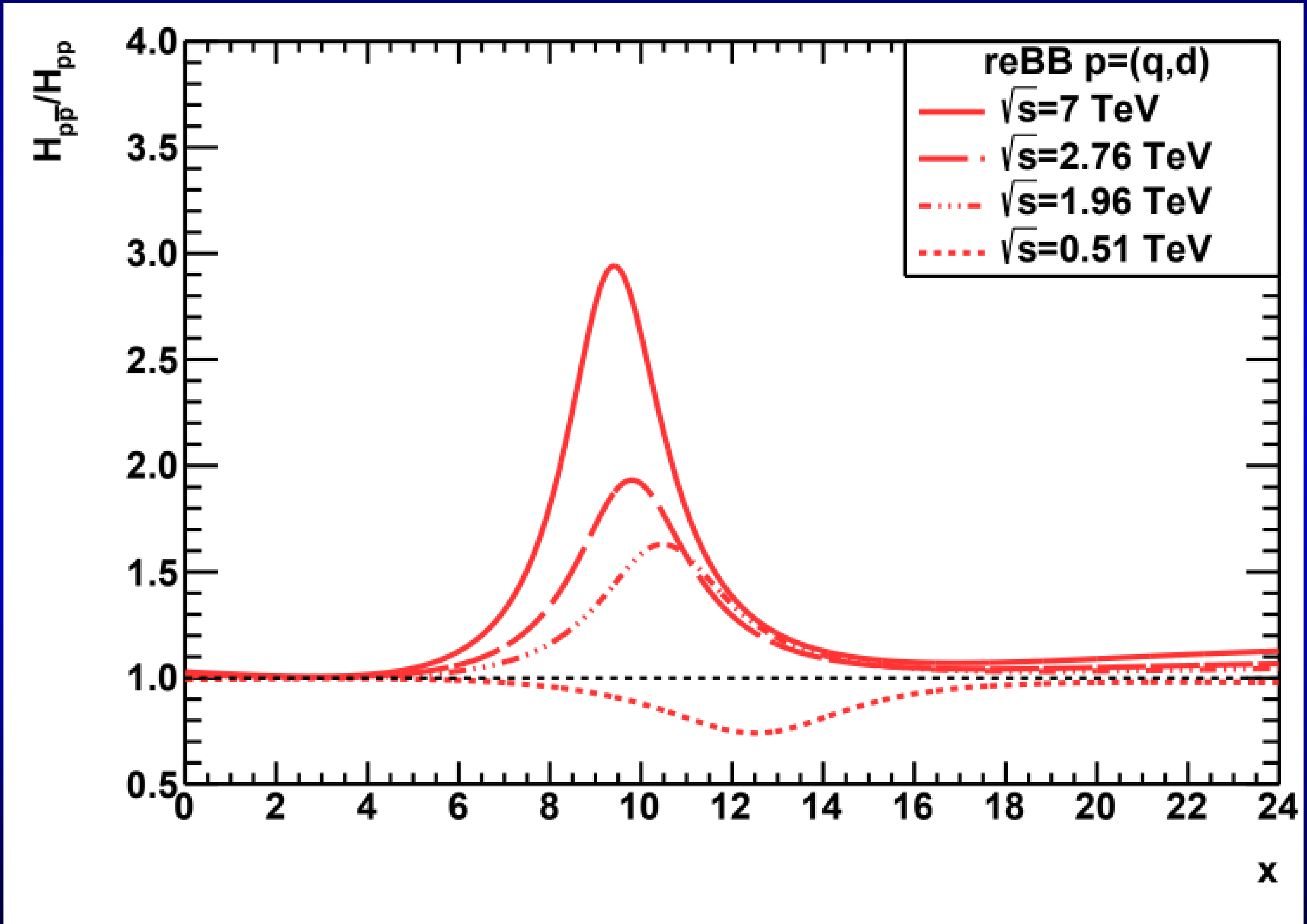




Significance ≥ 6.26 σ :
a **significant** and **model independent** Odderon effect at TeV scale.
For details, see talks of A. Ster, T. Novák, I. Szanyi, Zimányi 2020
Model dependent results, using the ReBB model
Significance ≥ 7.08 σ , see the talk of I. Szanyi

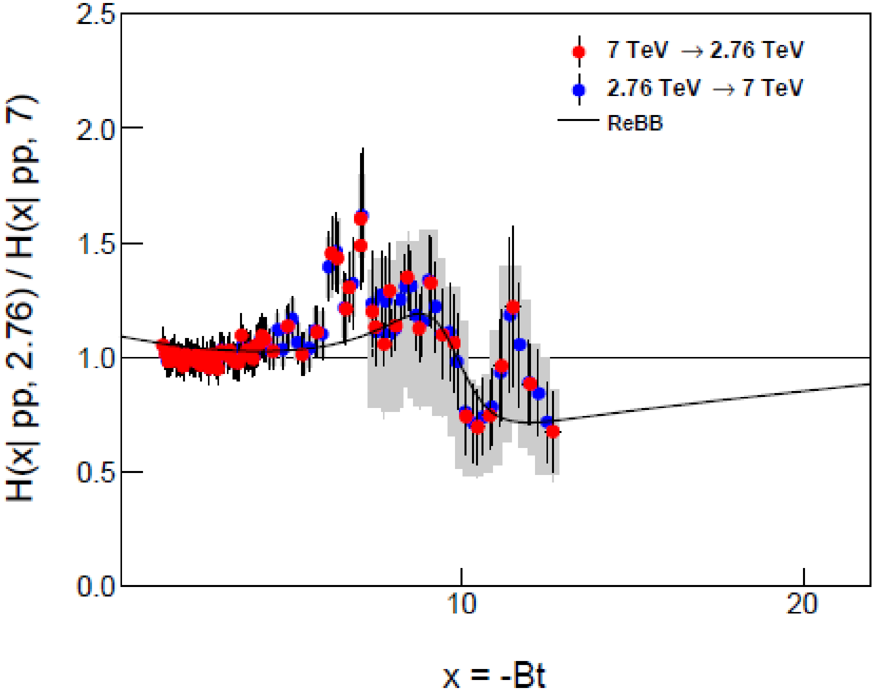
OBSERVATION OF ODDERON

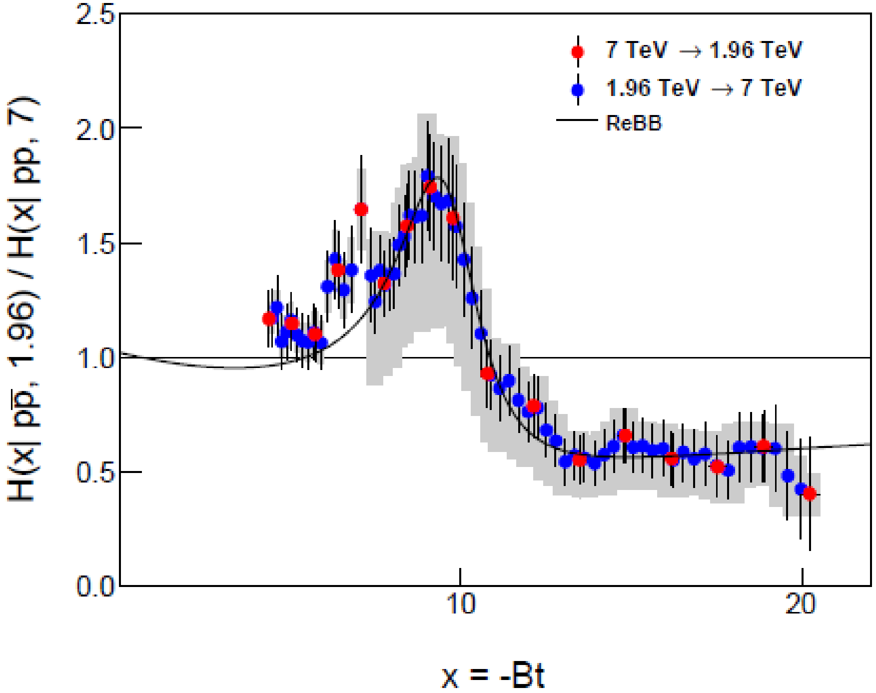
2020 → 2O2O



SUMMARY: AT LEAST 6.26 σ ODDERON

A 6.26 σ Odderon effect





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OBSERVATION OF ODDERON

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THANK YOU FOR YOUR ATTENTION

OBSERVATION OF ODDERON

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