OBSERVATION OF ODDERON

SCALING PROPERTIES OF ELASTIC SCATTERING

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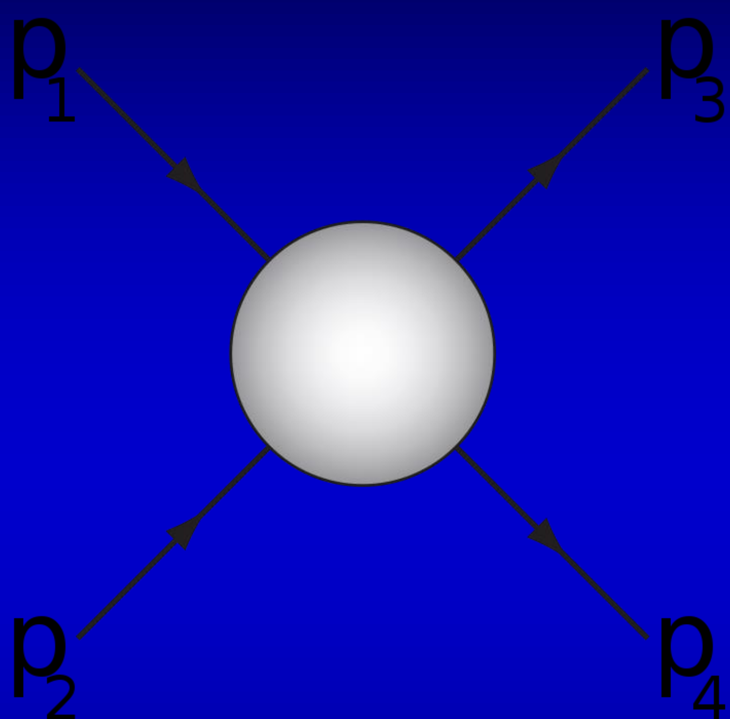
Intro to elastic scattering
Motivation: Odderon
H(x) scaling at TeV
Model independent results:
Significance at least 6.26 σ
Model dependent results:
Significance at least 7.08 σ
Domain of validity
Conclusions
Appendix

Mandelstam variables



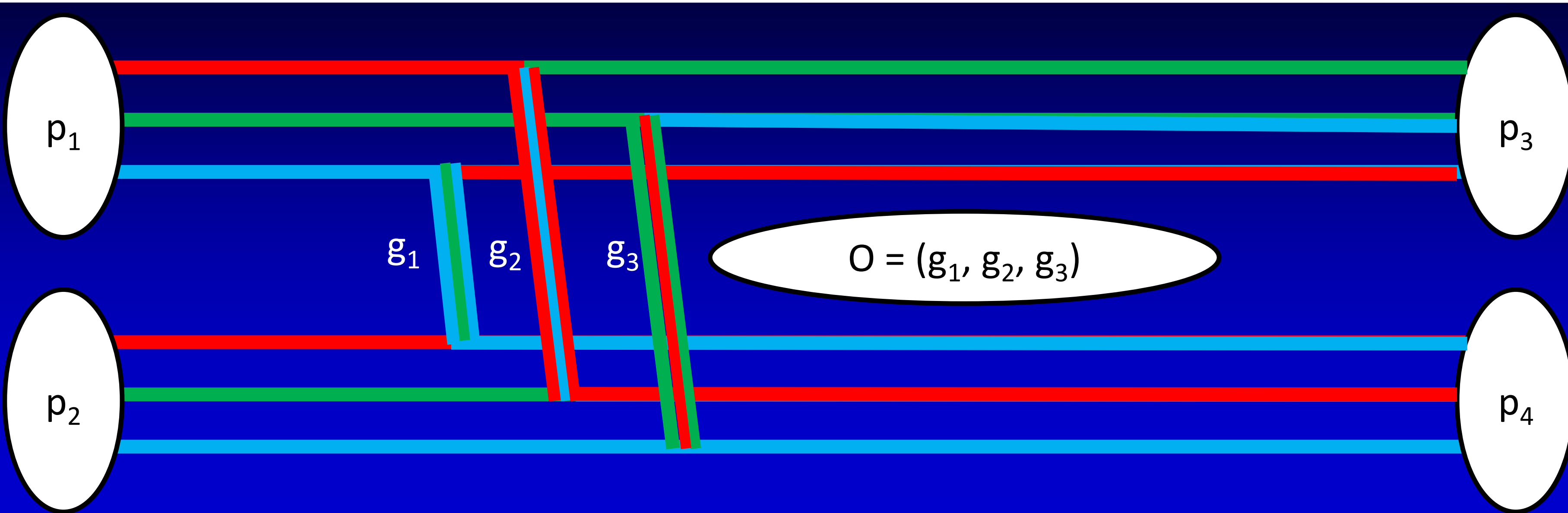
$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$
$$t = (p_1 - p_3)^2 = (p_4 - p_2)^2$$
$$u = (p_1 - p_4)^2 = (p_3 - p_2)^2$$

p_1,p_2: four-momenta before elastic scattering

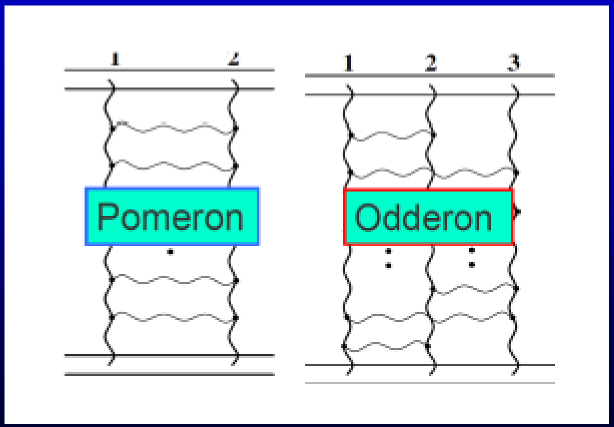
p_3,p_4: four-momenta after elastic scattering

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

Odderon and quantum chromodynamics



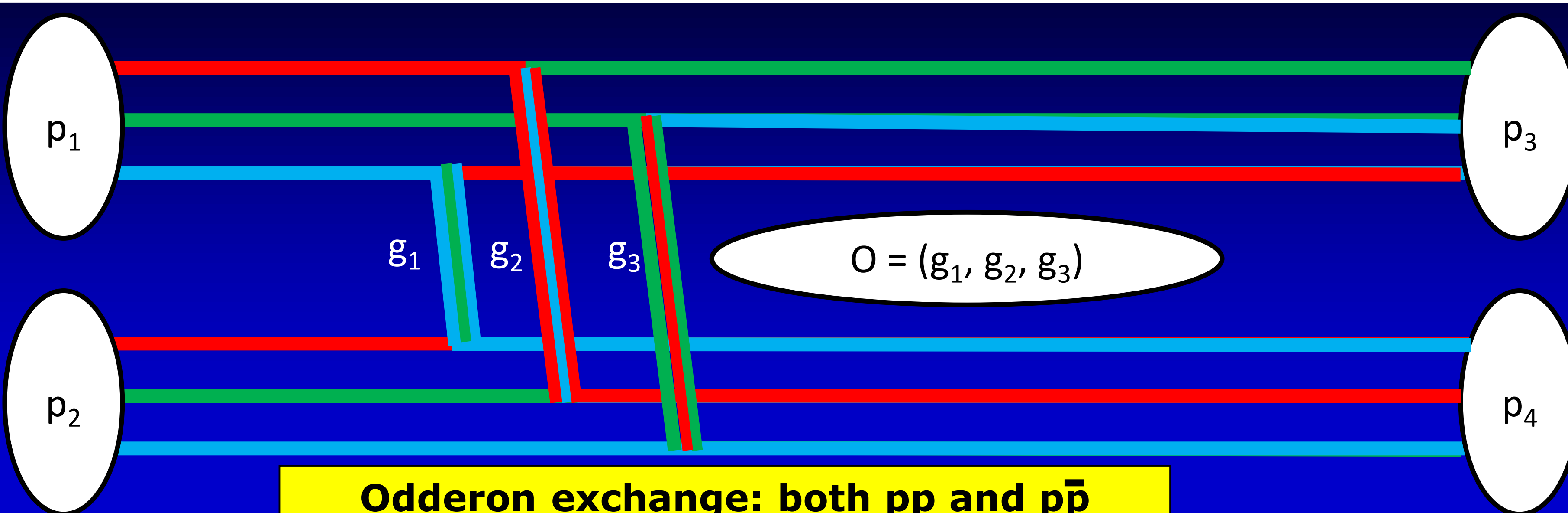
$g_1 = B\overline{R}+R\overline{B}$ $g_2 = R\overline{G}+G\overline{R}$ $g_3 = G\overline{B}+B\overline{G}$



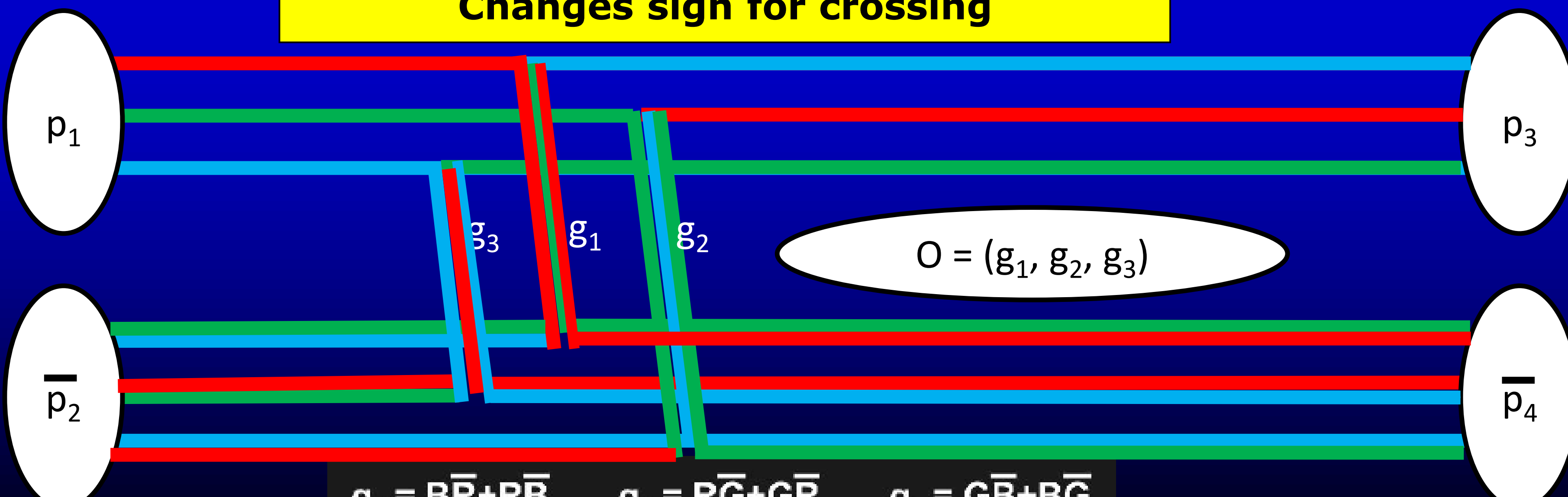
Pomeron (2+4+…) gluon in pp:
(RGB)+(RGB) → (GRB)+(GRB)

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

Odderon and elastic collisions



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



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

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 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,** *Phys.Rev.D* **91** (2015) 7, 074018

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

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

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

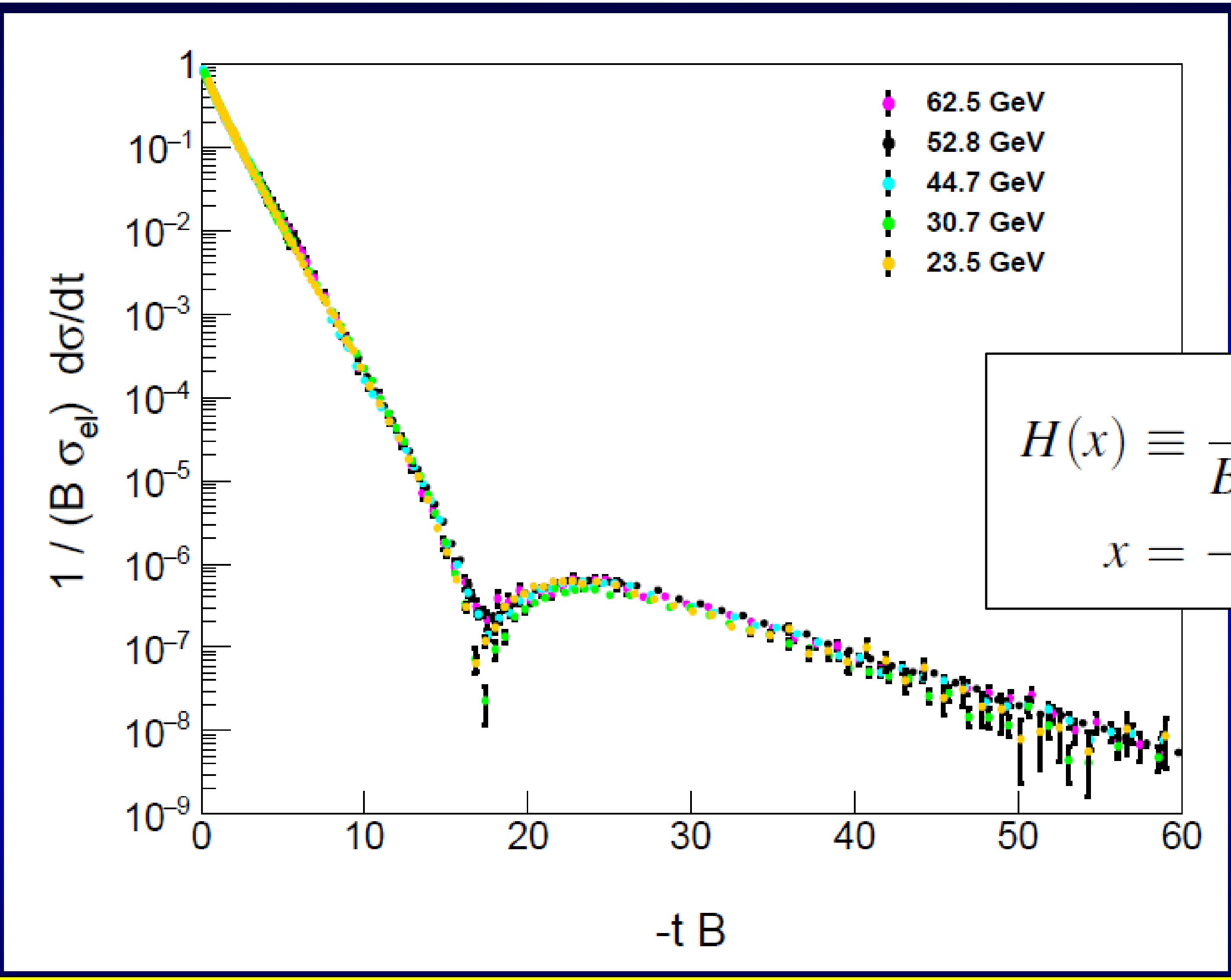
$$\frac{1}{B(s)\sigma_{\rm el}(s)}\frac{d\sigma}{dt} = \exp\left[tB(s)\right]$$

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

$$x = -tB(s).$$

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

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

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

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

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

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

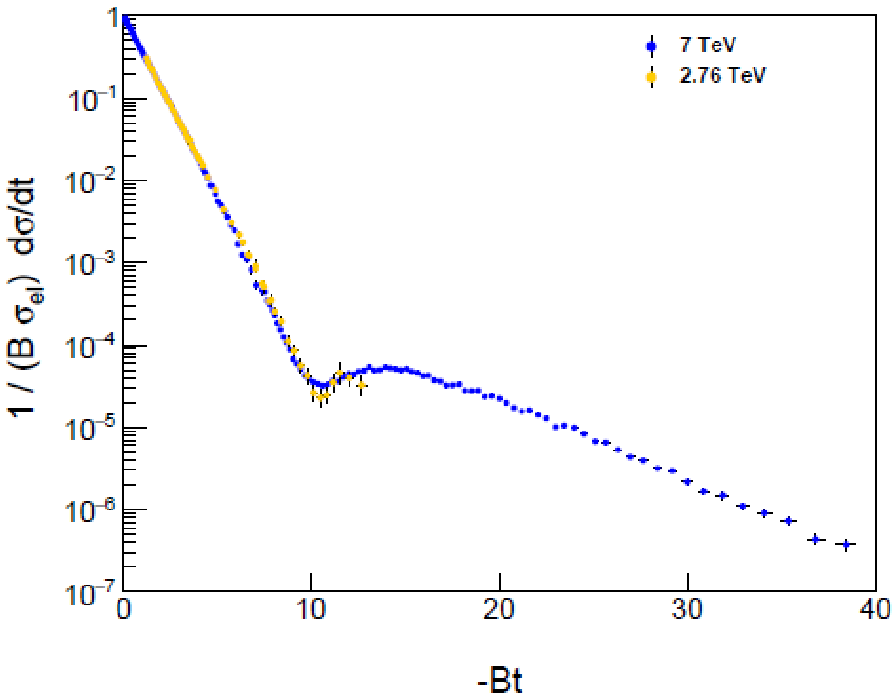
Advantages:

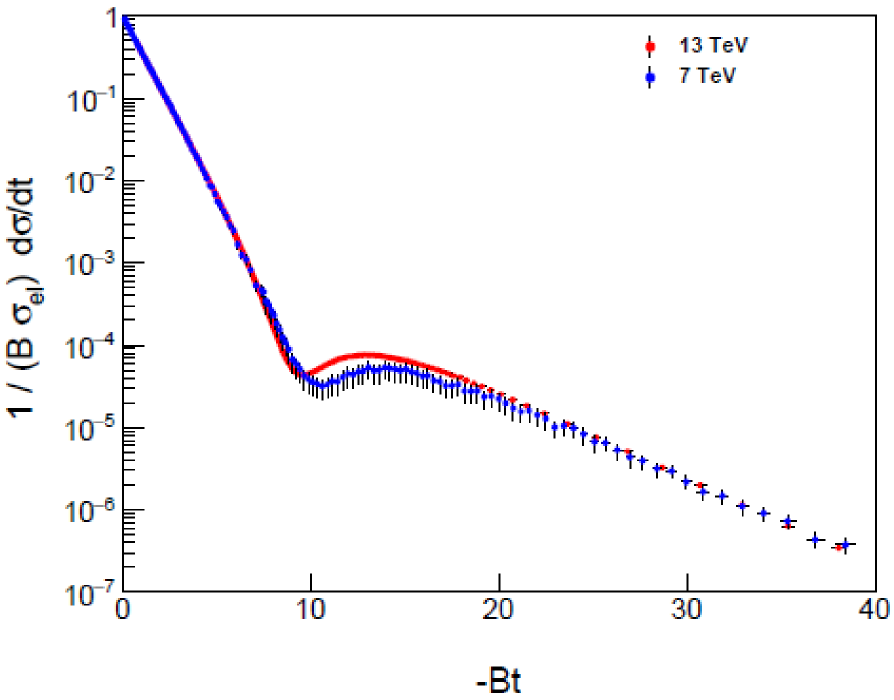
H(x) ≠ exp(-x) arbitrary positive def. in the dip-bump region

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

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

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





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

Odderon discovery model-independently

Evidence of Odderon-exchange from scaling properties of elastic scattering at TeV energies #1

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

pdf DOI cite

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

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

Proton Holography -- Discovering Odderon from Scaling

T. Csorgo (Wigner RCP, Budapest and Eszterhazy Karoly U., Eger), T. Novak

Nucl. Phys. Inst.), A. Ster (Wigner RCP, Budapest), I. Szanyi (Wigner RCP, Bu

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

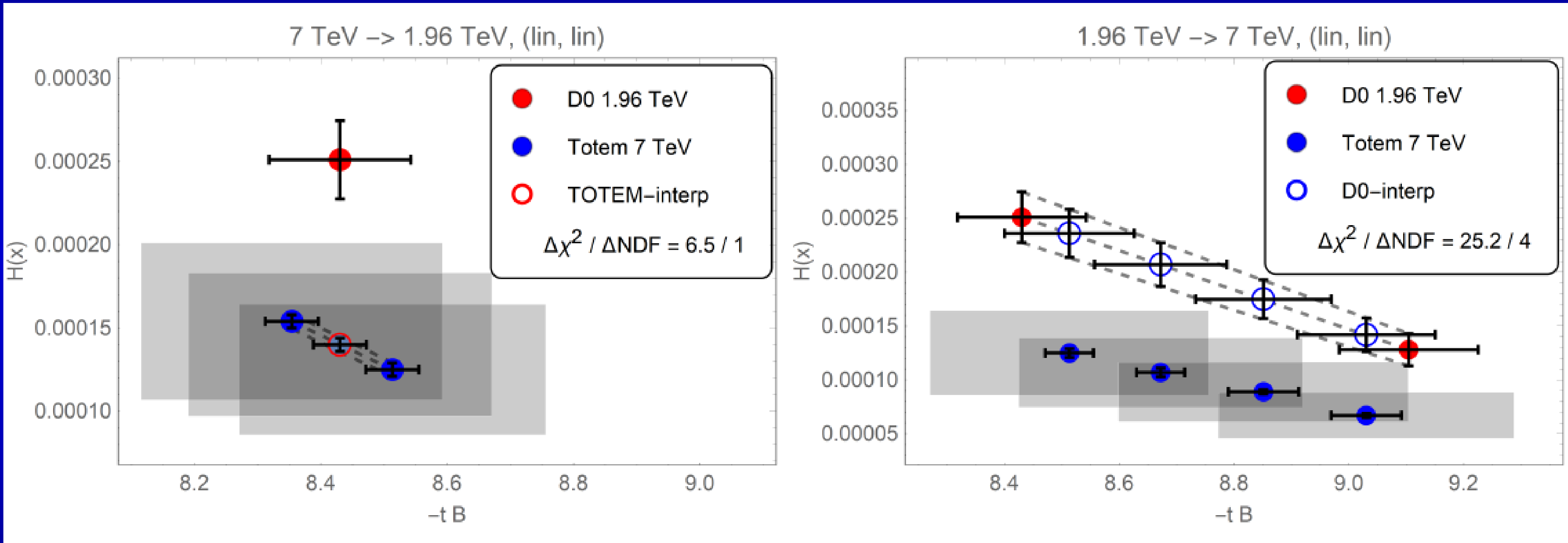
Published in: *EPJ Web Conf.* 235 (2020) 06002 • Contribution to: ISMD 2019 • e-Print: 2004.07095 [hep-ph]

pdf DOI cite

1 paper published in EPJ C, 2 manuscripts submitted for a publication, +<u>1 refereed conference proceedigs</u> (ISMD 2019, Santa Fe, USA) so far

H(x) rebin: linear interpolations in x

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



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

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, Budapest), I. Szanyi (Wigner RCP, Budapest) (Dec 26, 2019)

e-Print: 1912.11968 [hep-ph]

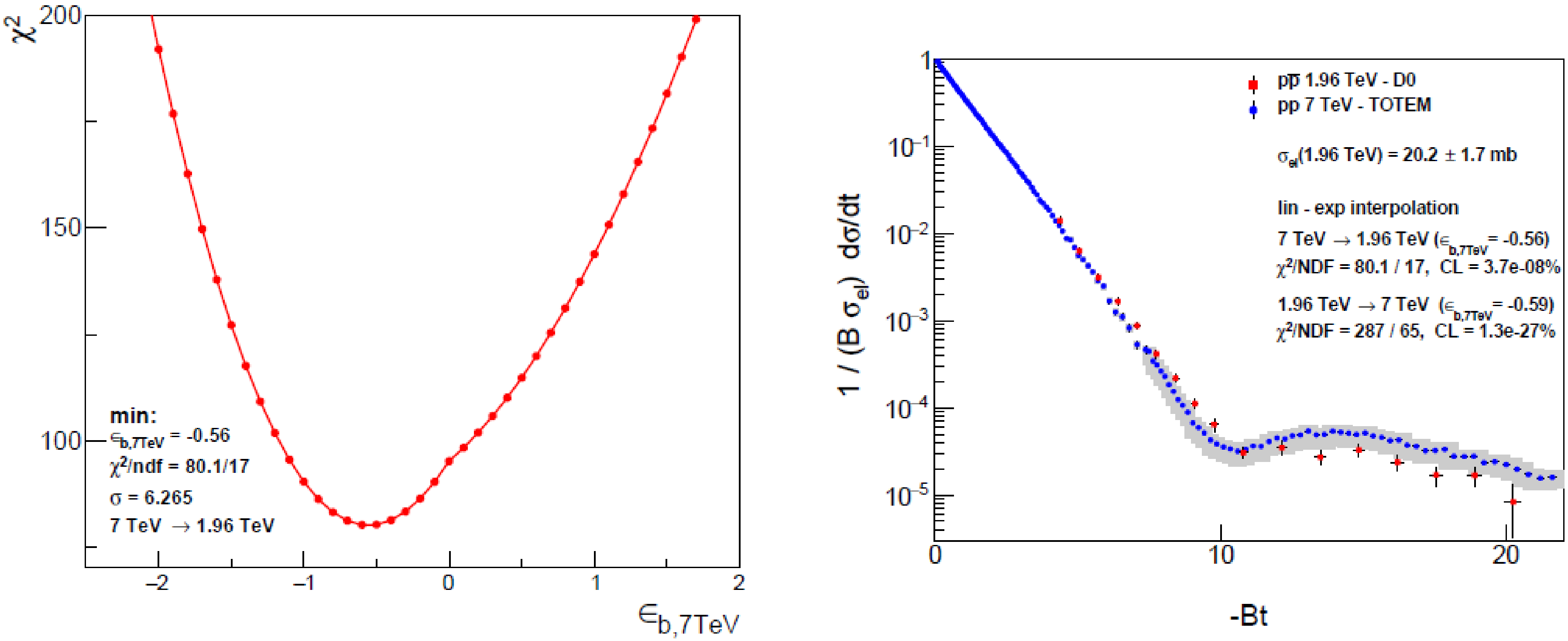


Fig. 13 Left panel indicates that as a function of $\epsilon_{b,7\ \mathrm{TeV}}$, the $\chi^2 \equiv \tilde{\chi}^2_{21}$ distribution has a unique minimum and nearly quadratic minimum. The minimum value is $\chi^2/\mathrm{NDF} = 80.1/17$, corresponding to a statistically significant difference between 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 $\epsilon_{b,7\ \mathrm{TeV}}$ corresponding to such a minimum, both for the case of the $7 \to 1.96$ TeV and for the case of $1.96 \to 7$ 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]

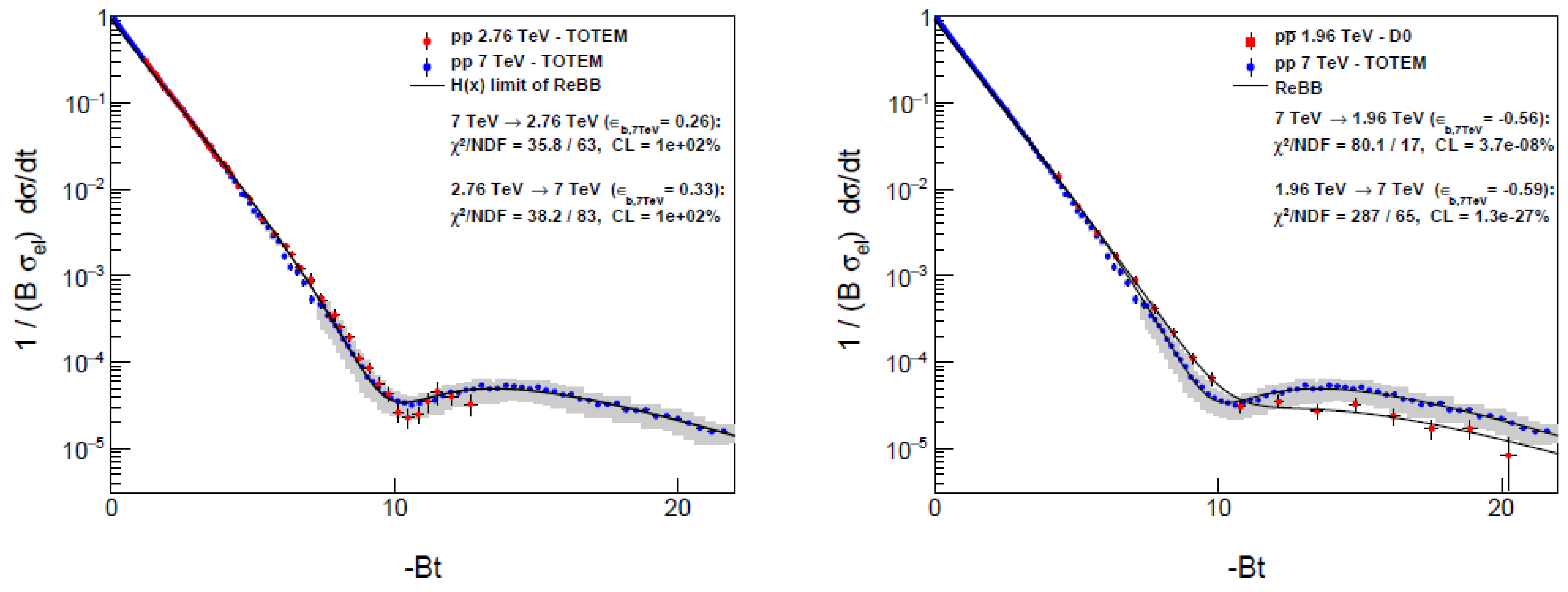
Model independent results since ISMD’19

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

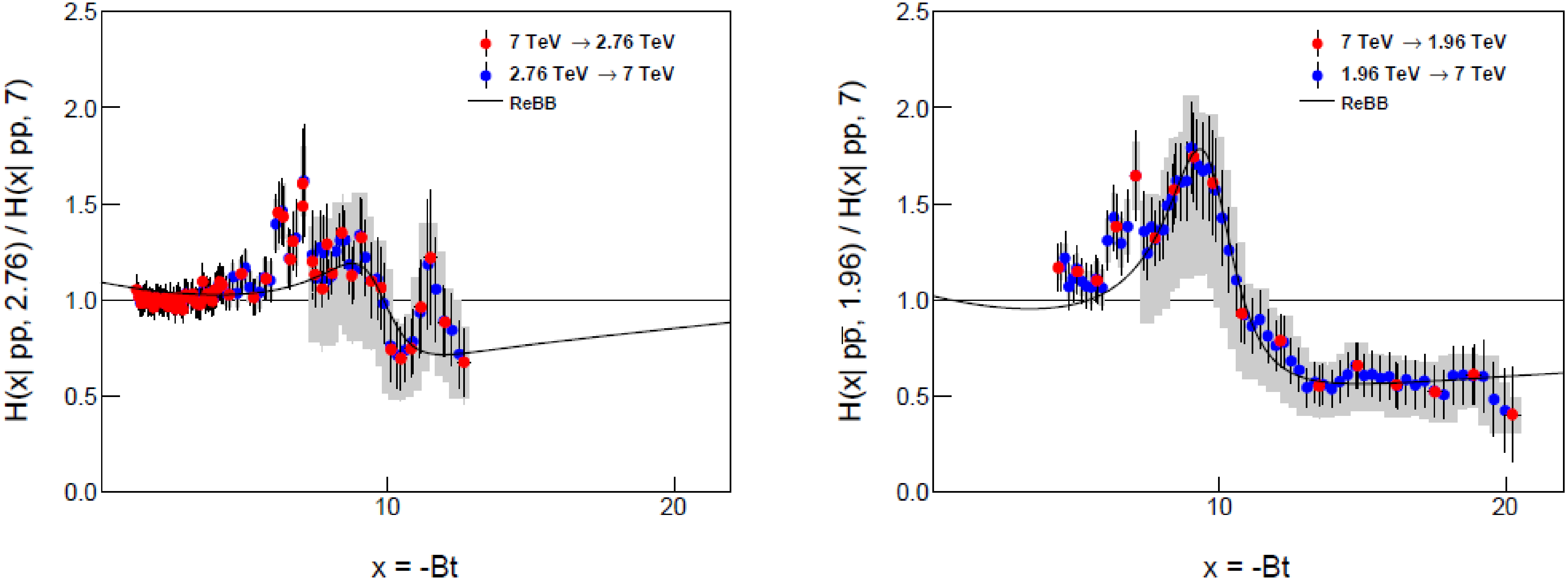
11 pages, 2 figures, synthesis of data analysis and theory results

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]

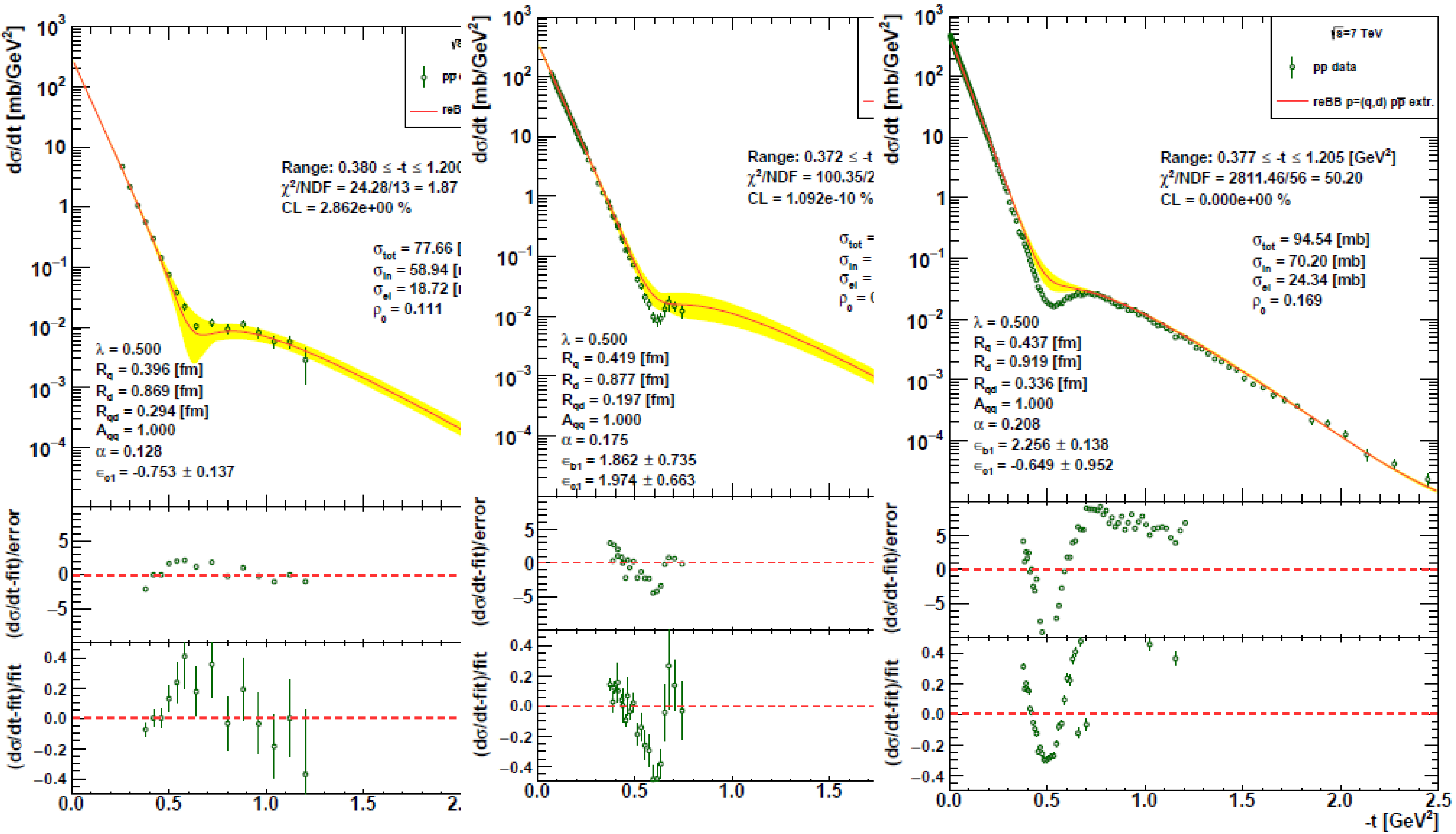


arXiv:2004.07318v2

Model independent Odderon significance 6.26 σ

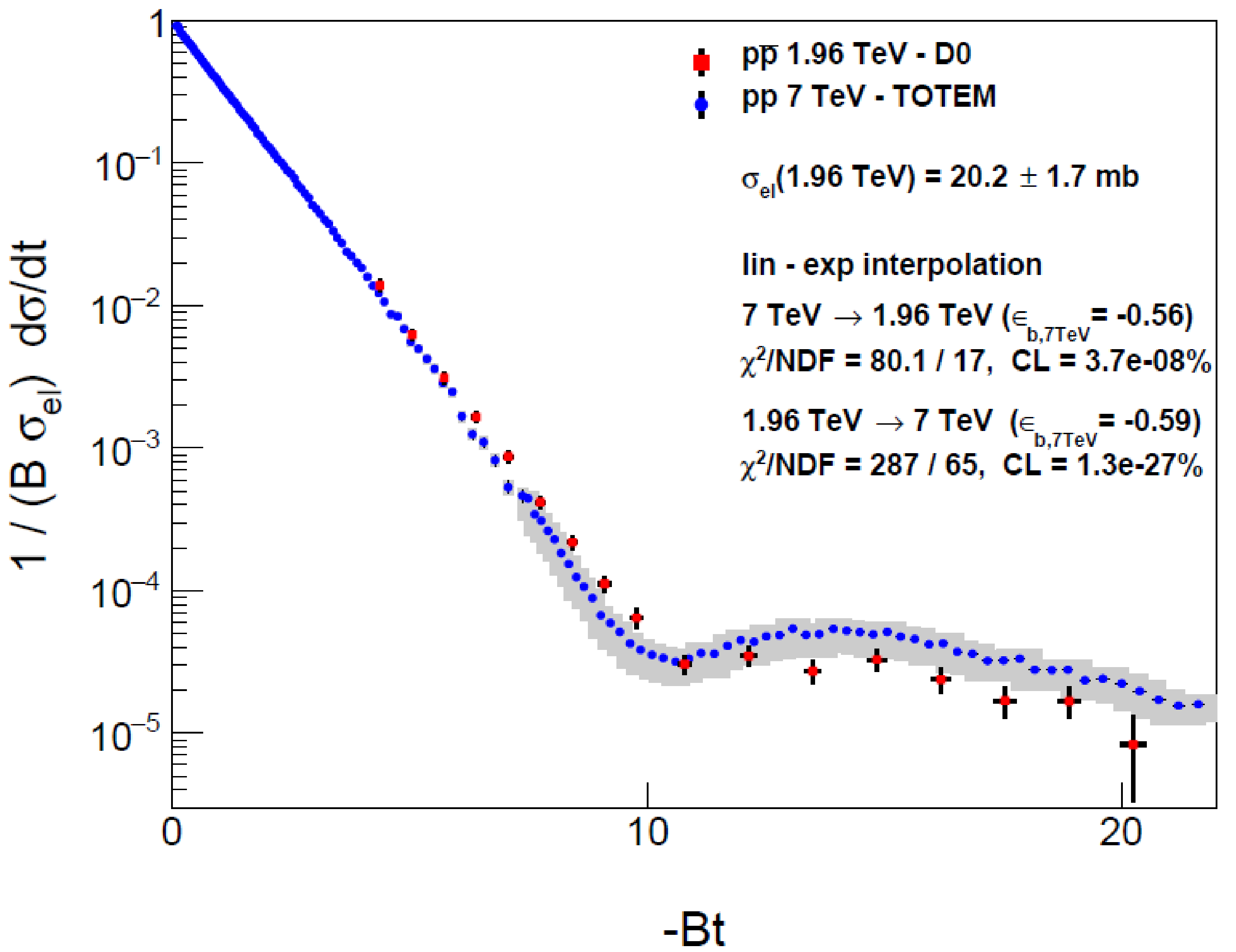
11 pages, 2 figures , synthesis of data analysis and theory results

Model dependent evidence for Odderon



82 pages, 31 figures, **model dependent theory results**,
Odderon significance ≥ 7.08 σ, see e-Print: [2005.14319] [hep-ph]

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!

Asymmetry parameter for C-violation

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

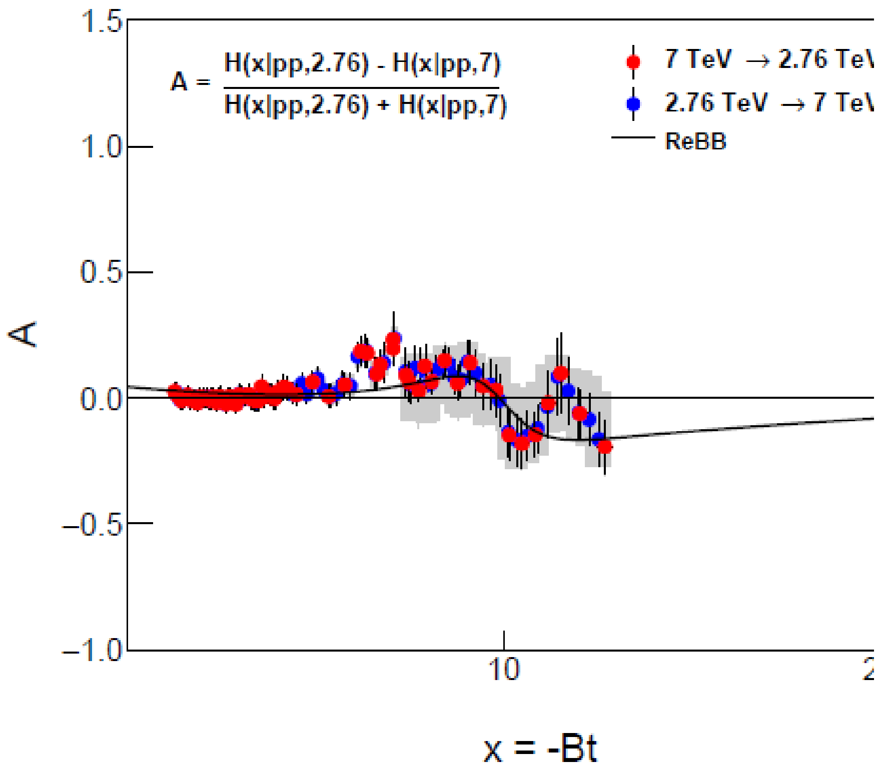
$$A(x|pp,s_1|pp,s_2) = \frac{H(x|pp,s_1) - H(x|pp,s_2)}{H(x|pp,s_1) + H(x|pp,s_2)}.$$

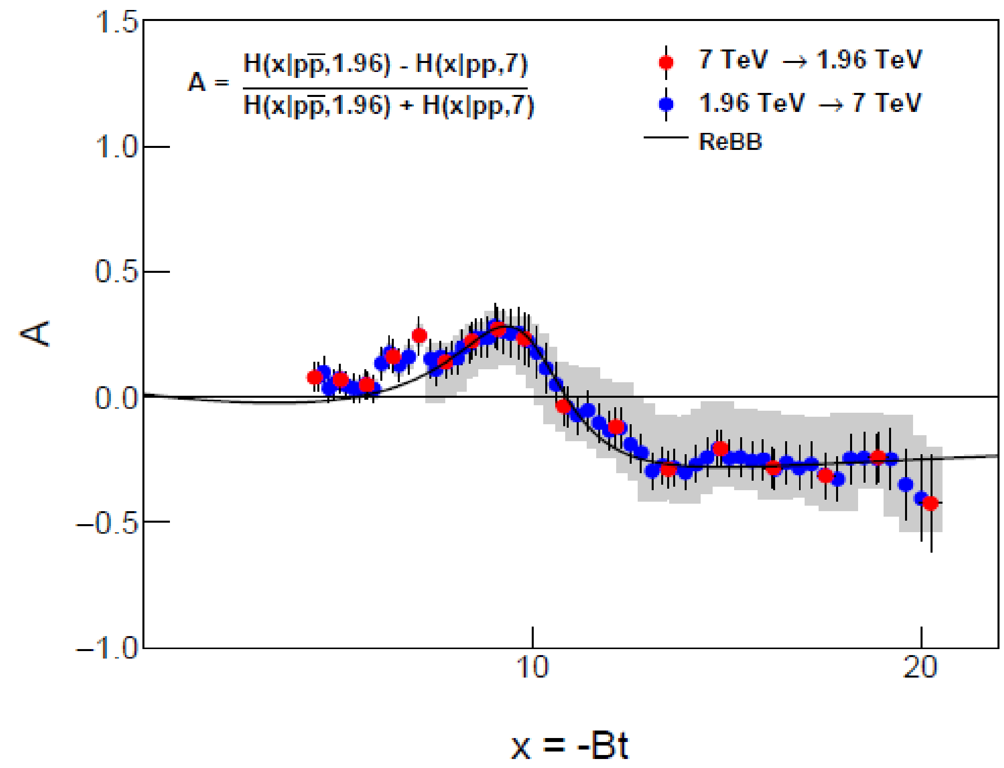
$A(x|pbarp,s_1|pp,s_2)$
does NOT vanish
for a C-symmetry violation AND

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

Energy range: HAS to be tested

Main result of A





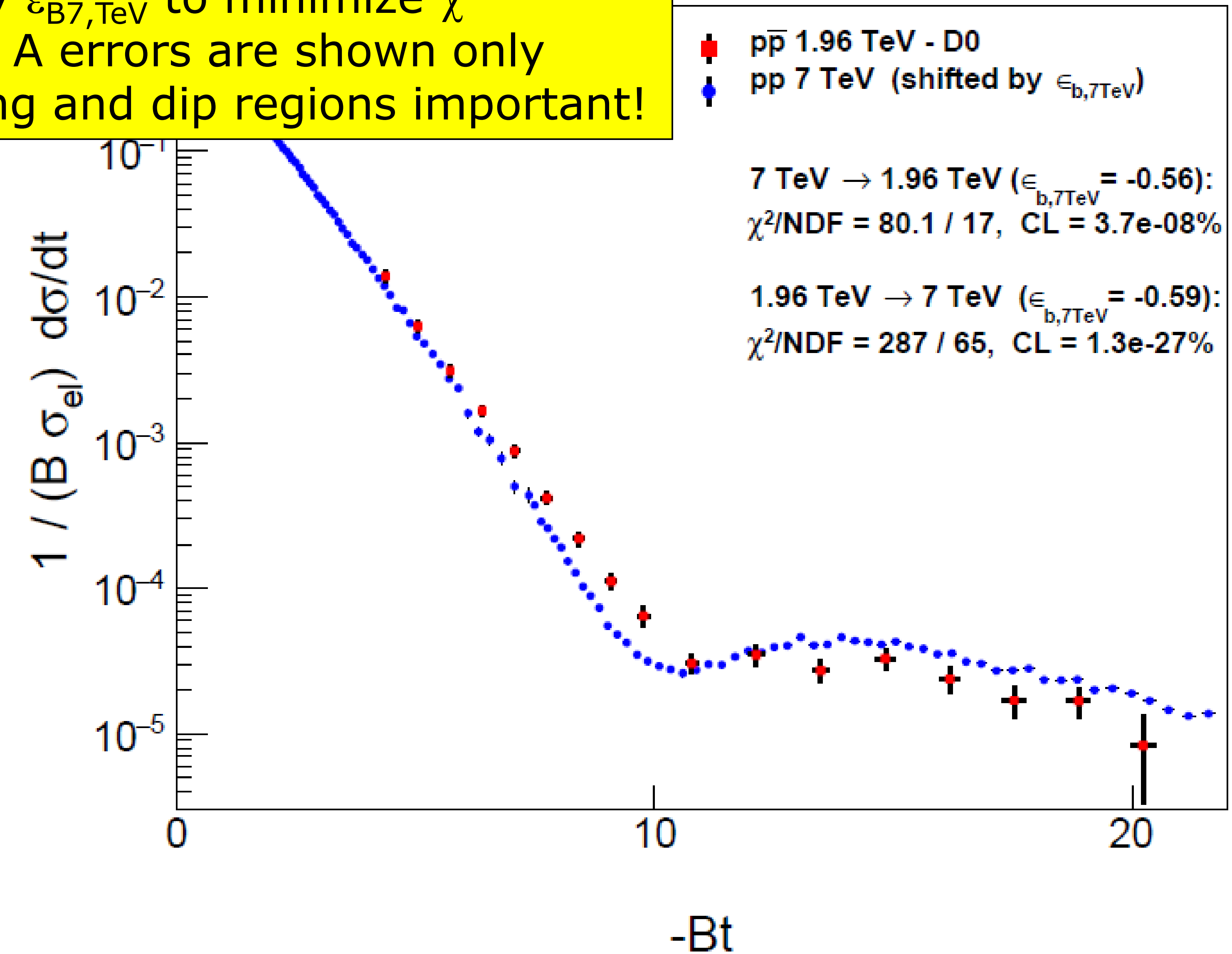
$A(x|pp,s_1|pp,s_2)$
vanishes if
H(x) scaling valid

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

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

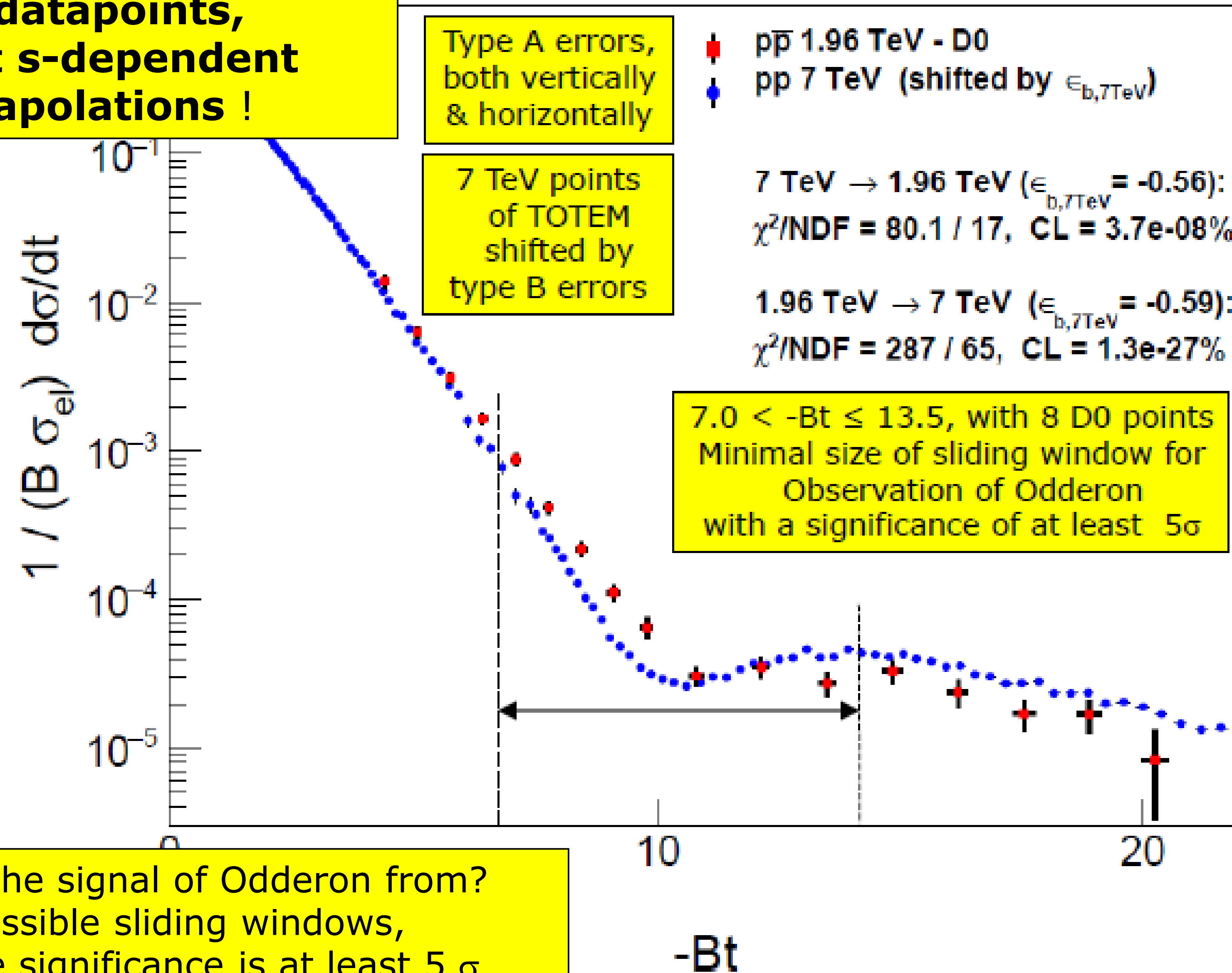
OBSERVATION OF ODDERON

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



SLIDING WINDOW for 5 σ

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



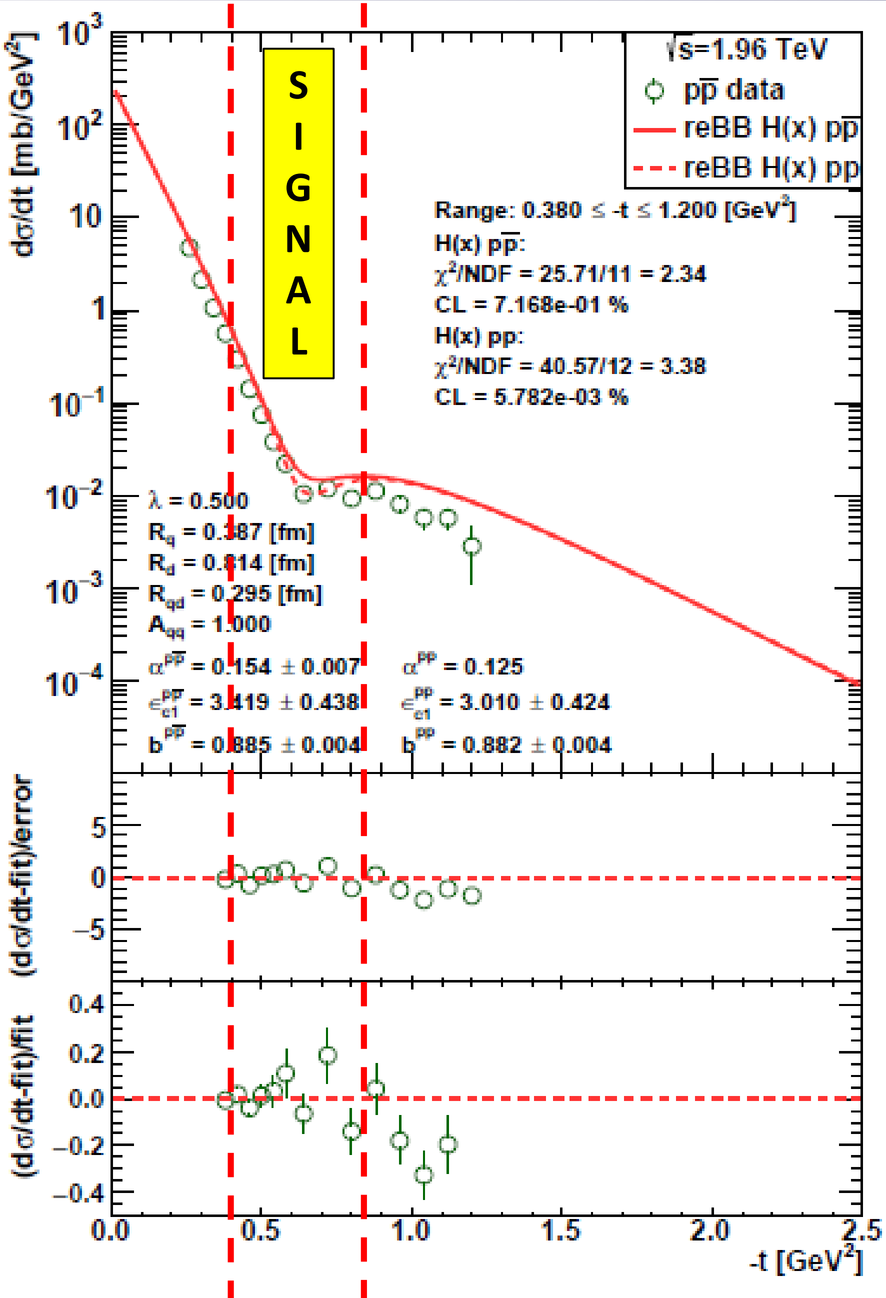
Where is the signal of Odderon from?
All possible sliding windows,
where the significance is at least 5 σ

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

MODEL INDEPENDENTLY:
In the background of the Odderon signal,
defined as $x \leq 7.0 \cup x > 13.5$
H(x|pp,7 TeV) ~ H(x|pbarp, 1.96 TeV)
within a significance of 2.39 σ

Results for the background: $x \leq 7.0$ in union with $x > 13.5$ for $\varepsilon_{B21}(7\ \text{TeV}) = -1.1$ that minimizes signal in the background				
x_{max}	ε_{B21} of min[χ^2(background)]	$\Delta\chi^2$(background)	NDF(background)	σ (background)
20.2	-1.10	20.20	9	2.39

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



MODEL DEPENDENT answer:
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)

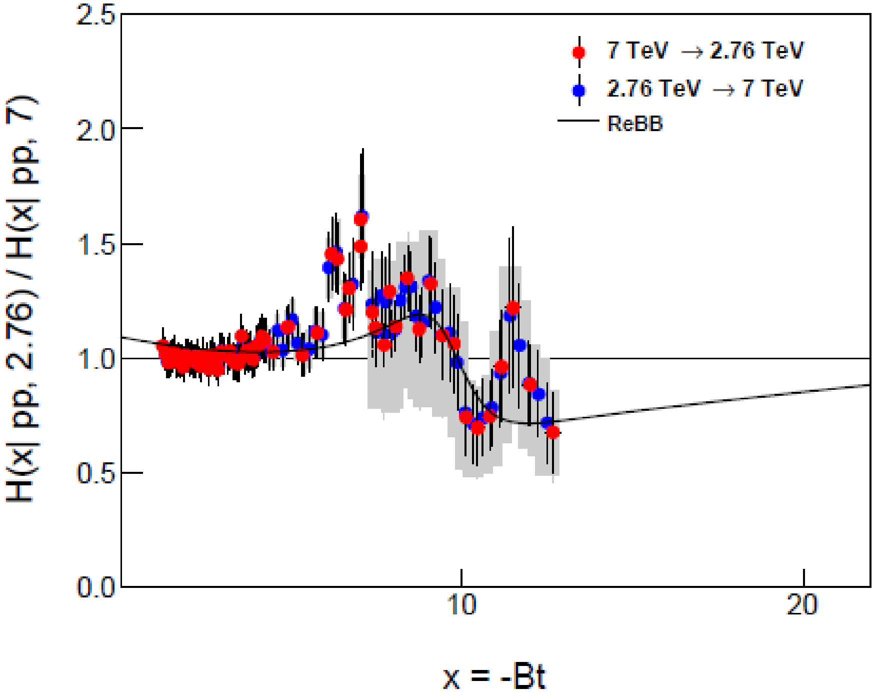
Pull plots:
(data-fit)/error
(data-fit)/fit

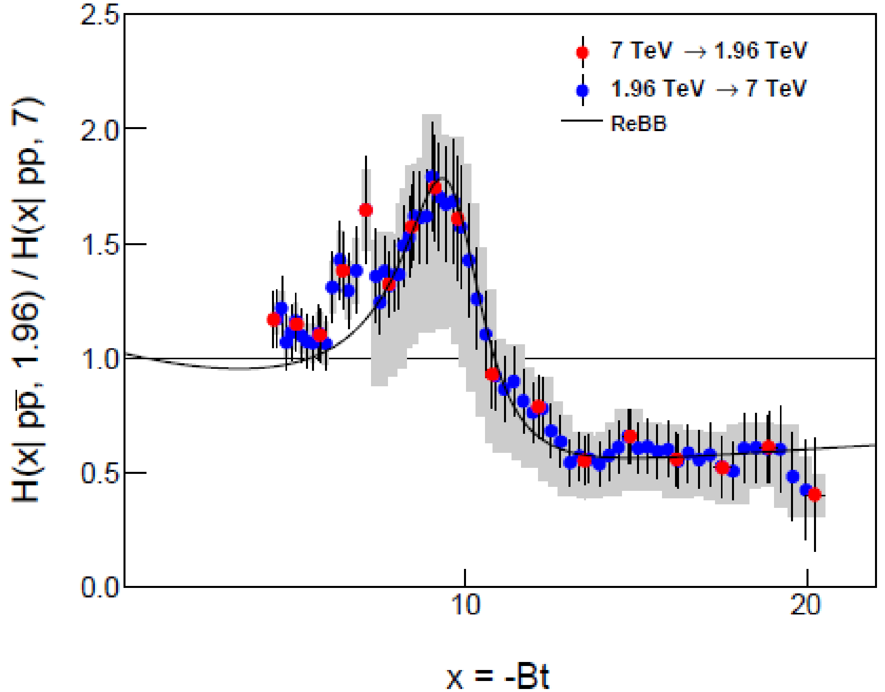
t_{max}(1.96 TeV, pp) > 1.2 GeV^2

→ x_{max}(1.96 TeV, pp) > 20

SUMMARY: AT LEAST 6.26 σ ODDERON

An at least 6.26 σ Odderon effect





A discovery level, **model independent** Odderon effect at TeV scale.
Published: Eur. Phys. J. C **81**, 180 (2021).
https://doi.org/10.1140/epjc/s10052-021-08867-6

Domain of validity of H(x) scaling:
full x =-tB range of D0 at 1.96 TeV, model INDEPENDENTLY !
Model dependent results, using the ReBB model
Significance ≥ 7.08 σ , see e-Print: 2005.14319 [hep-ph]

OBSERVATION OF ODDERON

2020 → 2O2O

THANK YOU FOR YOUR ATTENTION

Recent results from D0/TOTEM

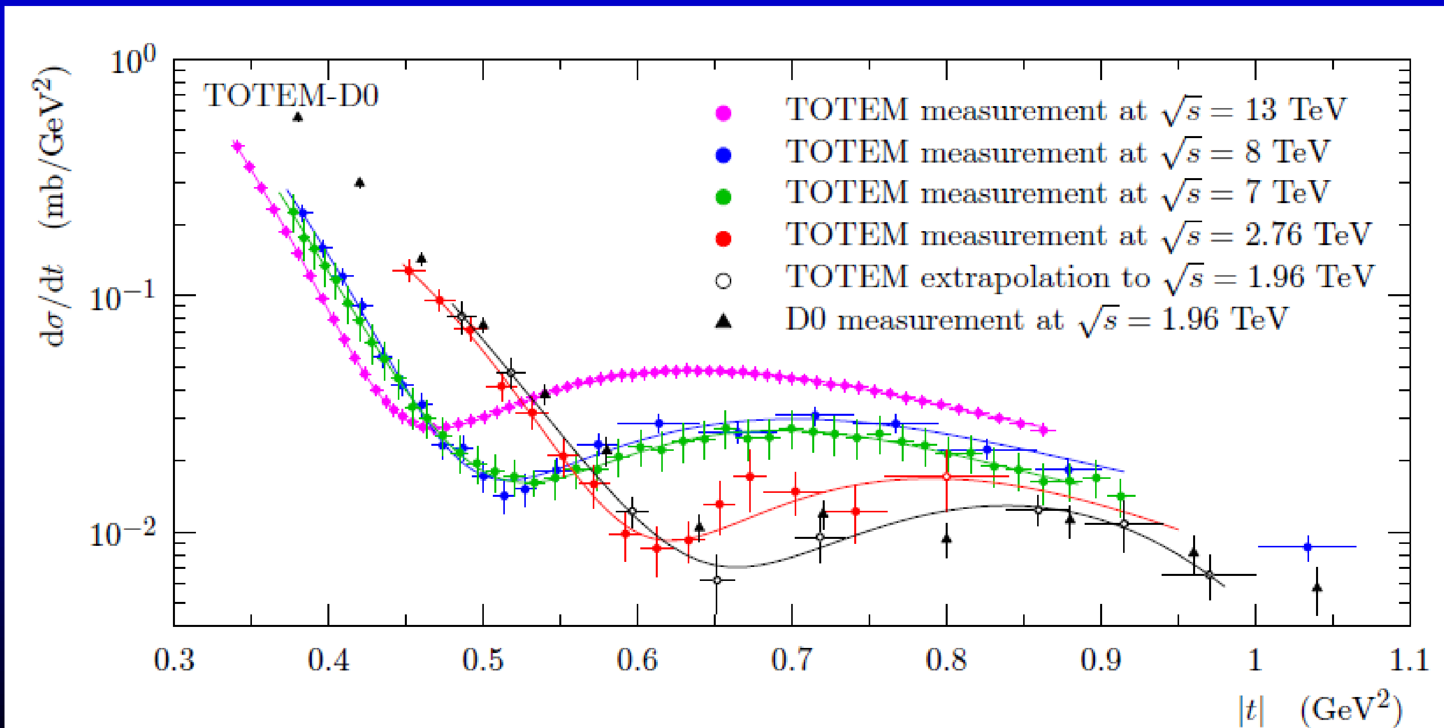
including our contributions

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

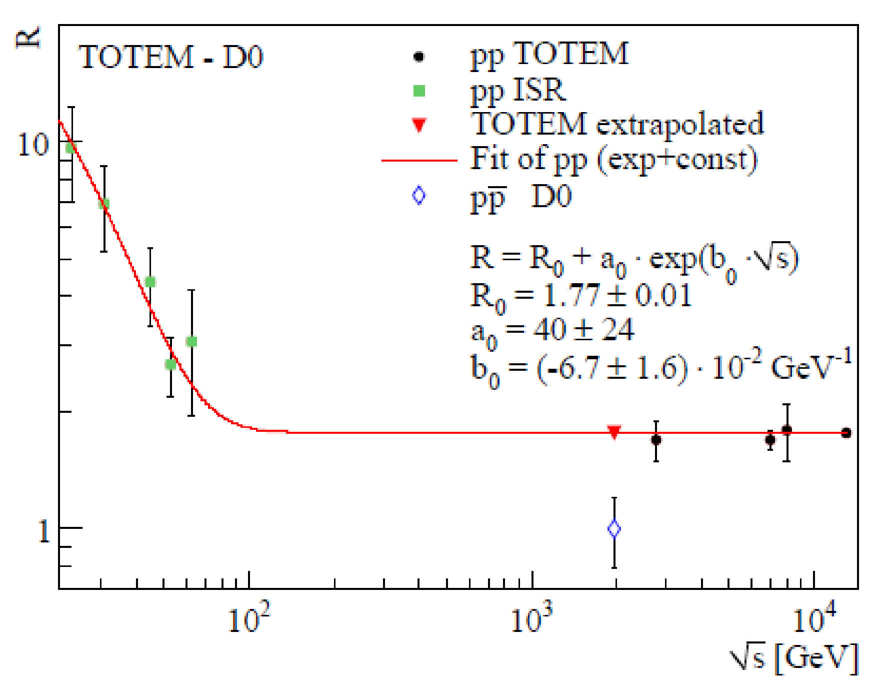
D0 and TOTEM Collaborations • V.M. Abazov (Dubna, JINR) et al. (Dec 7, 2020)

e-Print: 2012.03981 [hep-ex]

Submitted to PRL in December 2020.
Uses *13, 8*, 7 and 2.76 TeV TOTEM data,
limited in -t to the dip-bump structure.



APPENDIX: D0/TOTEM Fig. 2 OK



Our cross-test of Fig. 2 of arxiv:2012.03981:
Fits ISR and LHC data with *separate* lines

$p_1^{LHC} = 0.034 \pm 0.050$

Consistent with 0 → fix it to 0!

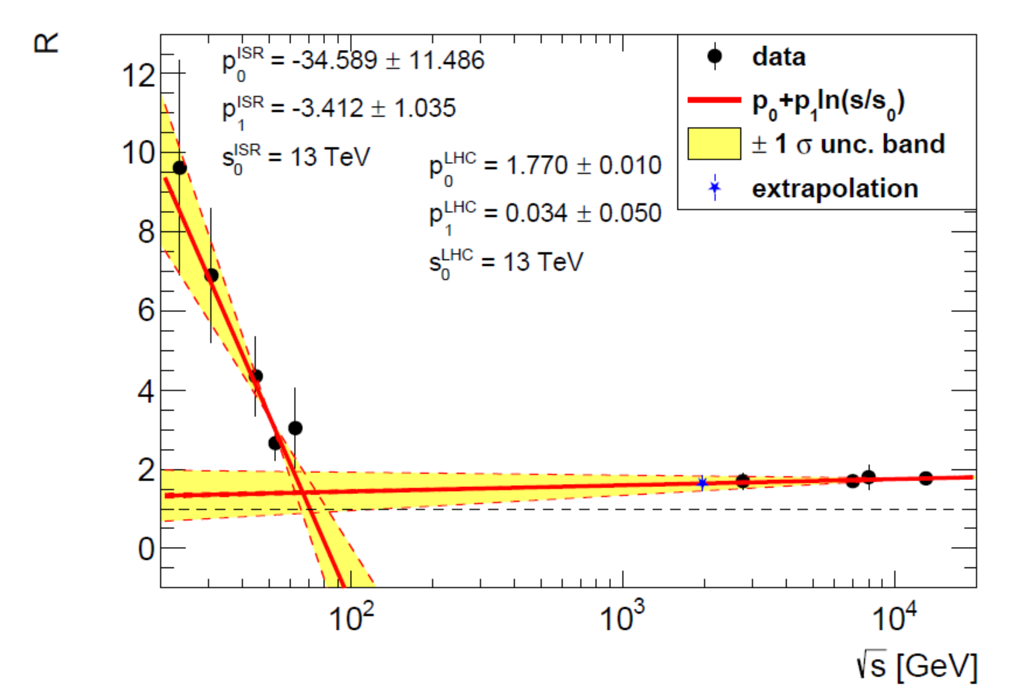
R(pp) = 1.77 ± 0.01 @ 1.96 TeV

→ Reggeon effects negiligble @ 1.96 TeV, OK.

Fig. 2 of arxiv:2012.03981:
Fits ISR and LHC data with *same* curve

R(pp) = 1.77 ± 0.01 @ 1.96 TeV

Reggeon effects from ISR? Test this!



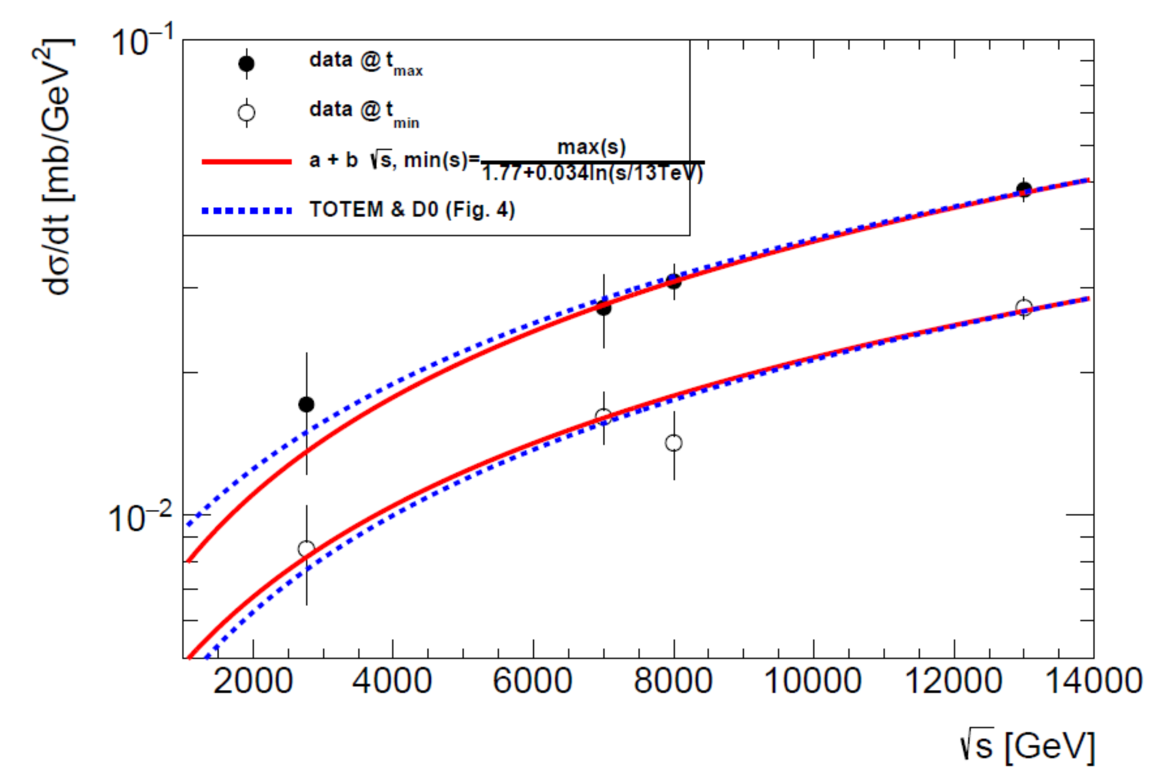
APPENDIX: D0/TOTEM FIG. 3 OK

Our cross-test of
Fig. 3 of arxiv:2012.03981:
Fits to max(s) and min(s) neglect the constraint of Fig. 2:

R(s|pp) = max(s|pp)/min(s|pp)

measured to be 1.77 ±0.01 !

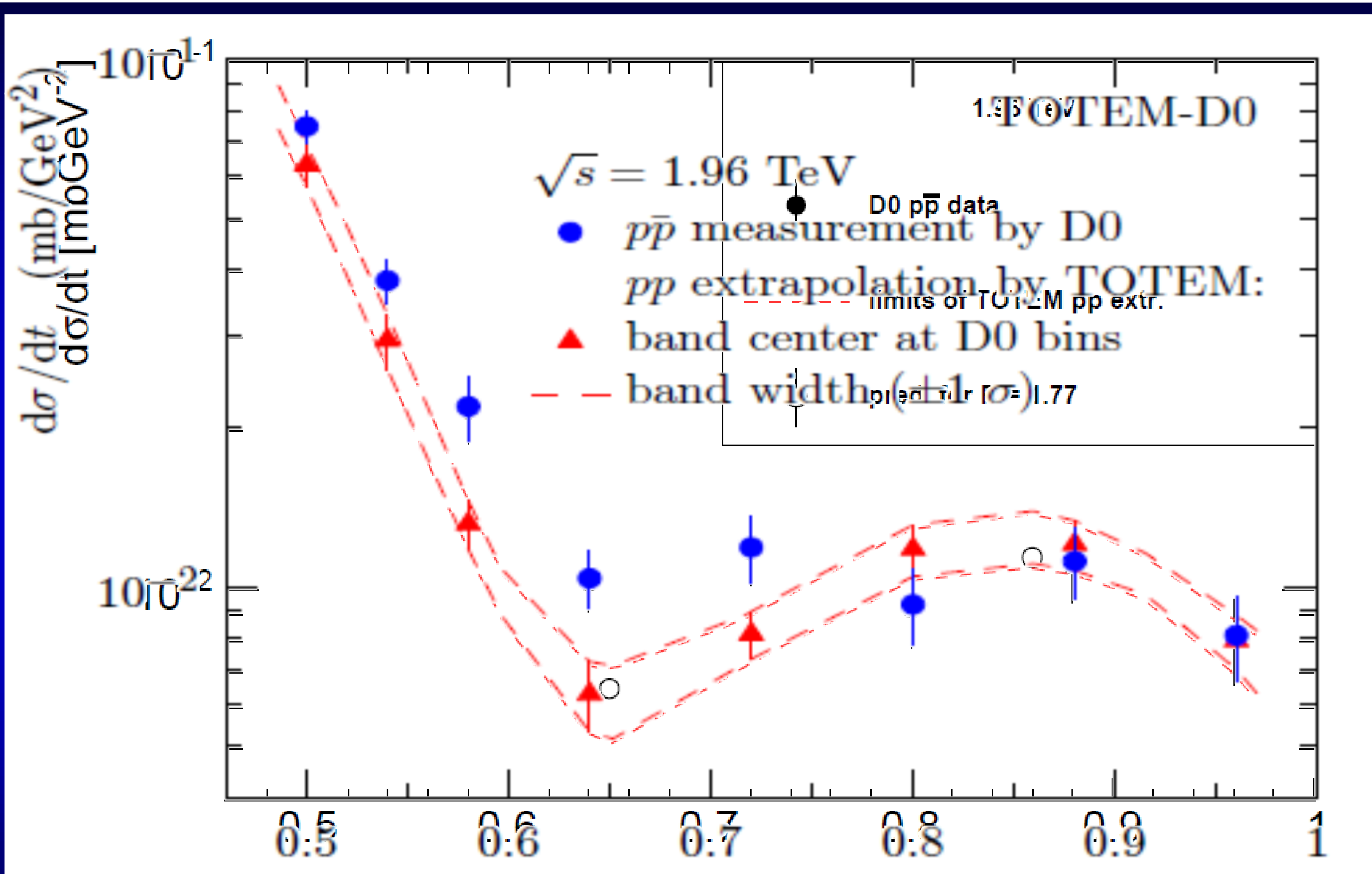
What about constrained fits?



Only two out of three quantities can be fitted independently :
max(s), min(s) and R(s) = max(s) / min(s)
Red lines: min(s|pp) = max(s|pp)/R(s|pp) <u>constrained fits</u>

→ Fig. 3. of D0/TOTEM OK within 1 σ

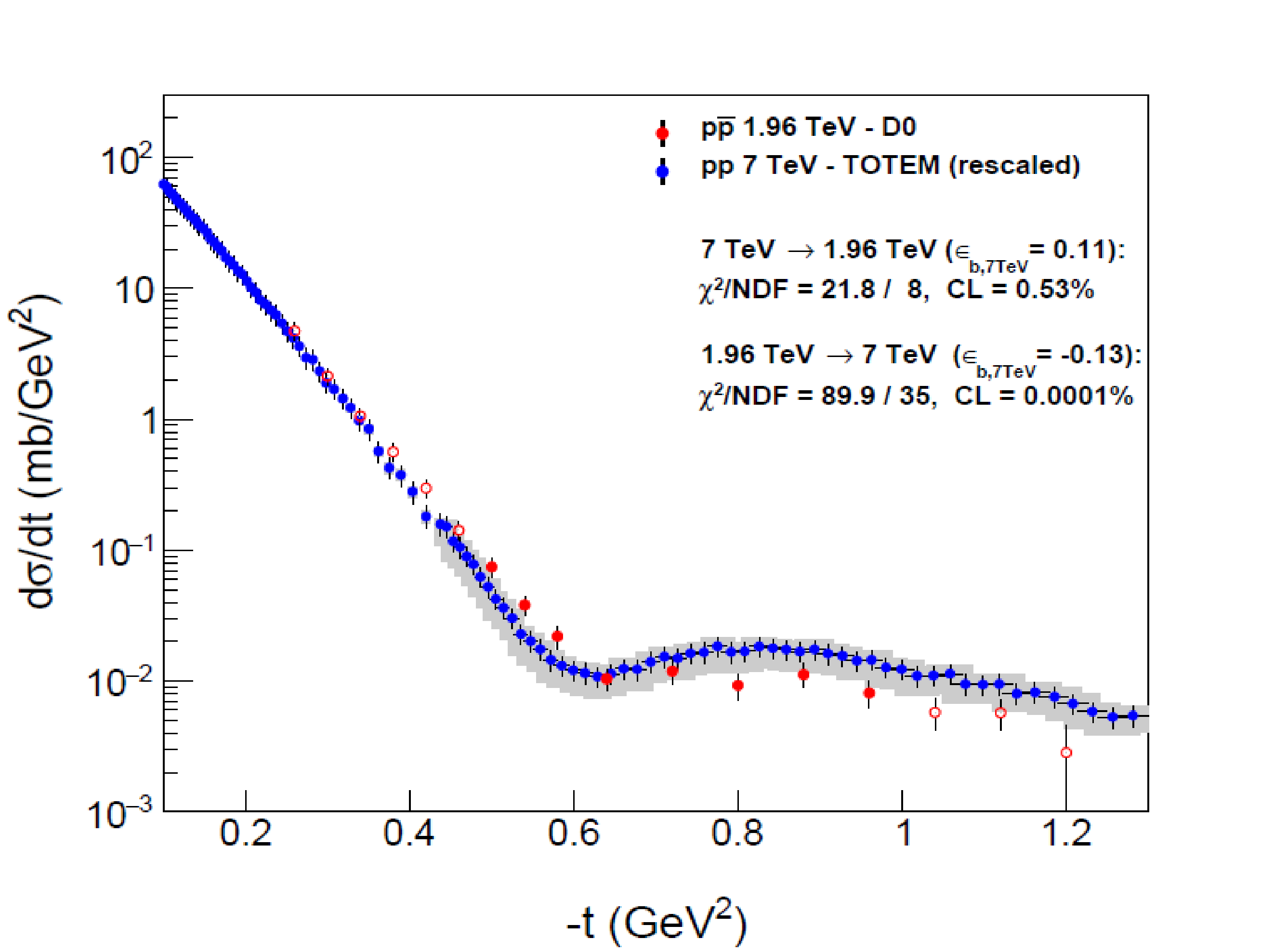
CROSS-CHECK OF D0/TOTEM FIG. 5



Empty circles from min(s|pp) = max(s|pp)/R(s|pp) <u>constrained fits</u>

→ Fig. 5. of D0/TOTEM OK within 1 σ

D0/TOTEM FIRMS UP OUR RESULTS



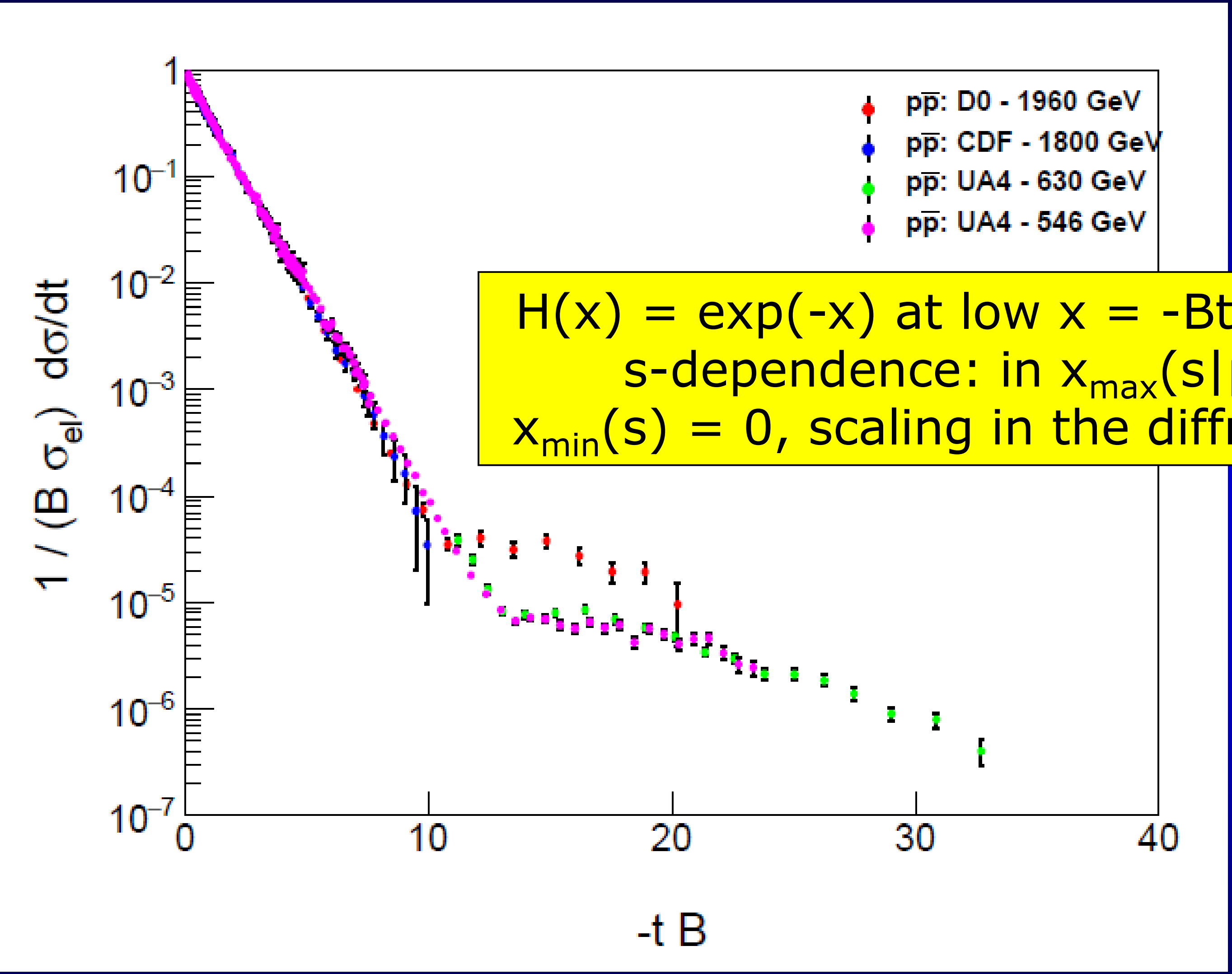
If we study dσ/dt and limit **our analysis to the same range as D0/TOTEM:** Significance reduces to **5.01 σ effect,** due to leaving out 9 D0 points

If we add D0's 14.4 % overall correlated error to fluctuating errors, for all D0 data: Our *published* value is **3.27 σ**

If we conservatively optimize coefficient $\varepsilon_{B,7TeV}$ of point-to-point correlated errors: **2.79 σ**
Significance of D0/TOTEM for dσ/dt: **3.4 σ**

BACKUP SLIDES

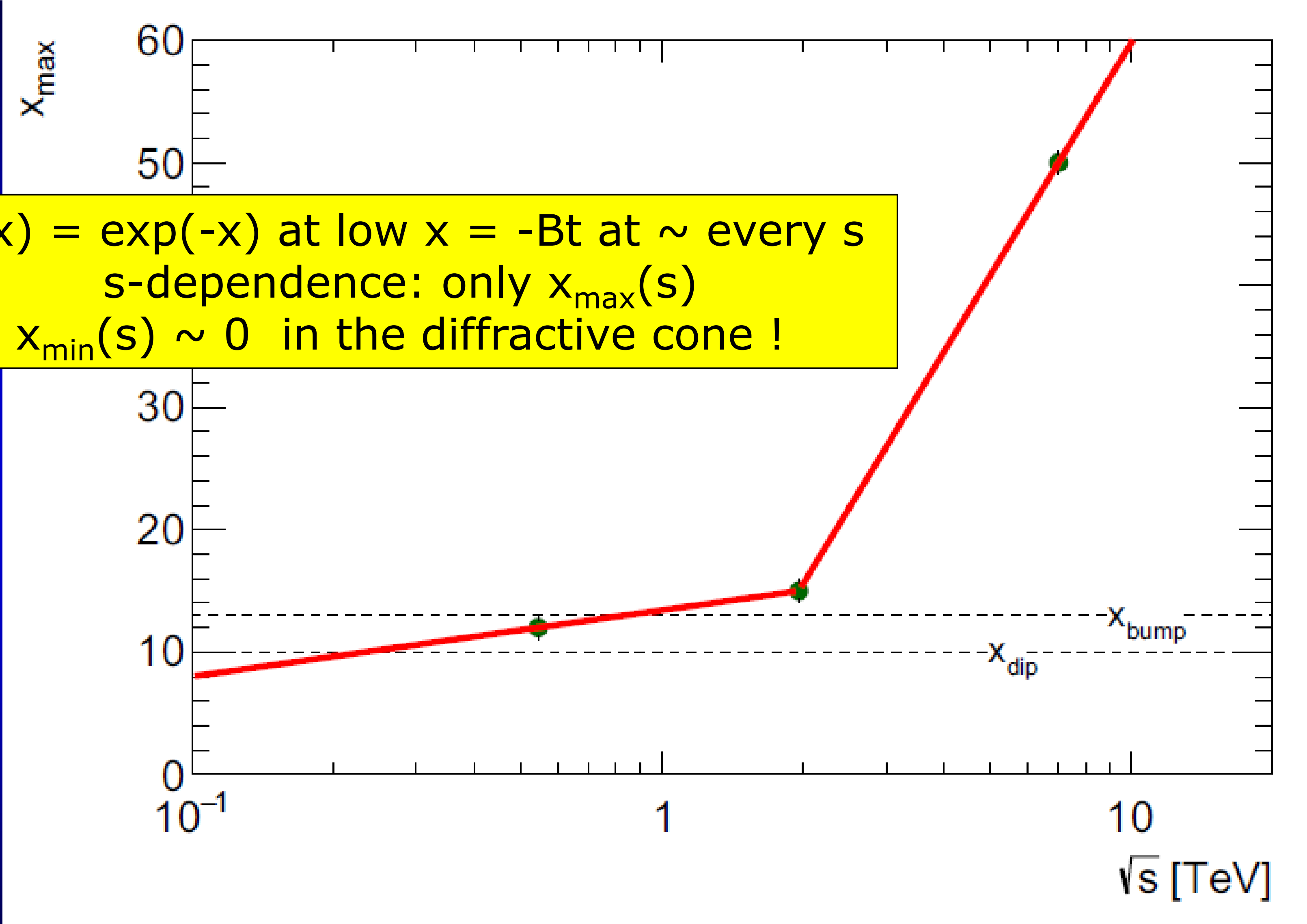
H(x) scaling for p antip scattering



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

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

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

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 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, see also talk by I. Szanyi @ Zimányi'2020

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

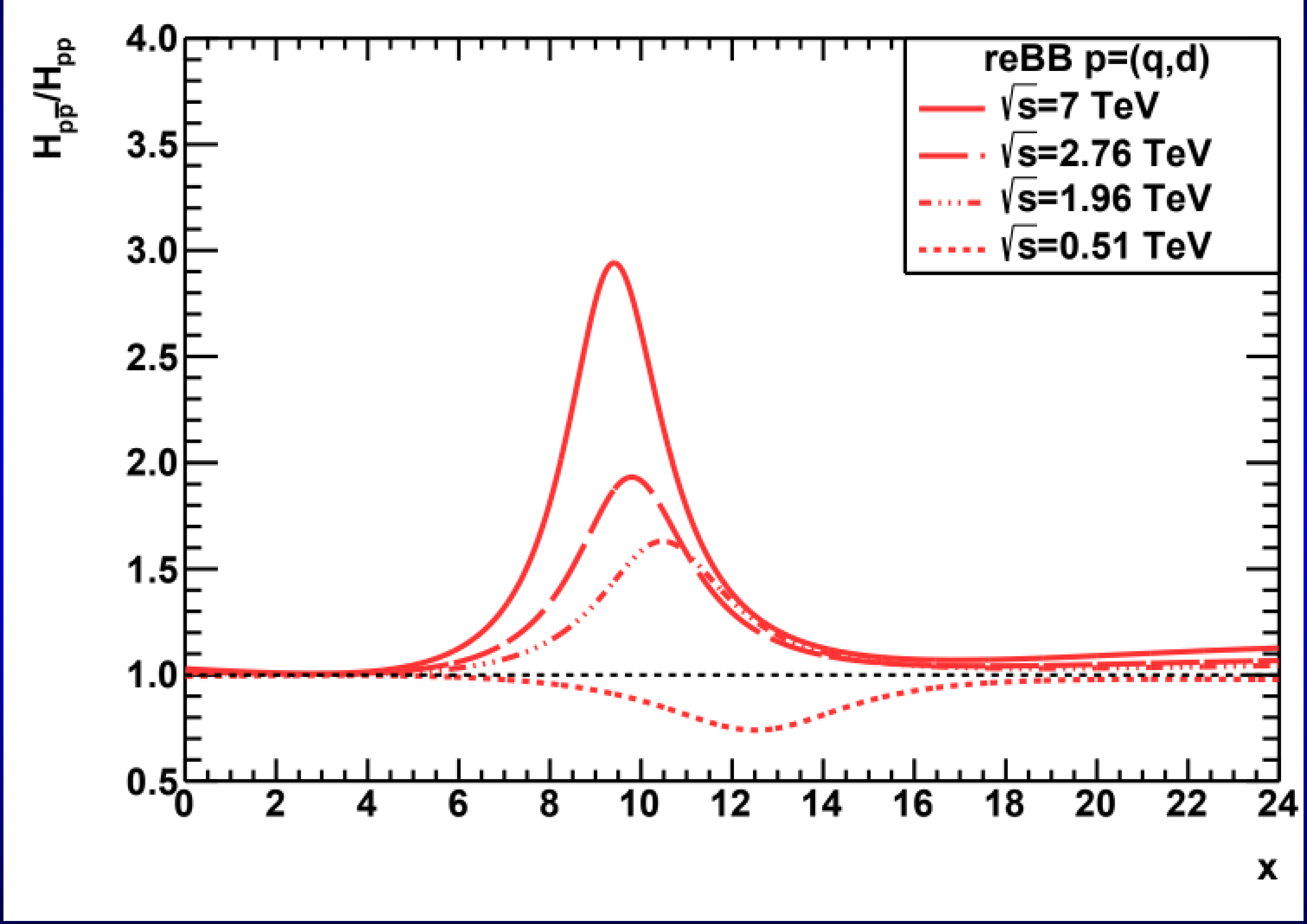
H(x) scaling: allows to project pp data ONLY
Scaling violations decrease significance at 1.96 TeV
BUT
Also allow to evaluate pbarp data at 2.76 TeV

Trade-off effect!

Odderon significance increases
From 6.26 to 7.08 σ .

OBSERVATION OF ODDERON

2020 → 2O2O



Prediction for 510 GeV pp @ RHIC: scaling violations