

# OBSERVATION OF ODDERON

## SCALING PROPERTIES OF ELASTIC SCATTERING

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**Motivation: Odderon**

**H(x) scaling at TeV**

**Model independent results:**

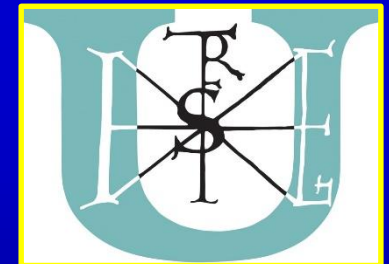
**Significance at least  $6.26 \sigma$**

**Model dependent results:**

**Significance at least  $7.08 \sigma$**

**Domain of validity**

**Conclusions**



# Formalism: elastic scattering

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

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

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

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

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

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

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

Basic problem:  $d\sigma/dt$  measures an amplitude, *modulus squared*.  
How to achieve amplitude level reconstruction? Phase info lost...

# Looking for Crossing-Odd(eron) effects

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

$$\begin{aligned}T_{el}^P(s, t) &= \frac{1}{2} (T_{el}^{pp}(s, t) + T_{el}^{p\bar{p}}(s, t)) \quad \text{for } \sqrt{s} \geq 1 \text{ TeV}, \\T_{el}^O(s, t) &= \frac{1}{2} (T_{el}^{pp}(s, t) - T_{el}^{p\bar{p}}(s, t)) \quad \text{for } \sqrt{s} \geq 1 \text{ TeV}.\end{aligned}$$

## Three simple consequences:

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

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

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

# Odderon search: a possible strategy

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

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

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

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

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

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

$$\frac{1}{B(s)\sigma_{el}(s)} \frac{d\sigma}{dt} = \exp [-tB(s)] \quad \text{versus} \quad x = -tB(s).$$

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

Advantages:

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

# H(x) scaling in greater x region

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

$$\text{Re exp} [-\Omega(s, b)] = 1 - r(s) E(\tilde{\mathbf{x}}),$$

$$\text{Im exp} [-\Omega(s, b)] = \rho_0 r(s) E(\tilde{\mathbf{x}}),$$

$$\tilde{\mathbf{x}} = \mathbf{b}/R(s),$$

$$R(s) = \sqrt{B(s)},$$

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

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

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

## 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.

# Model independent evidence for Odderon

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

T. Csorgo (Wigner RCP, Budapest and EKV KRC, Gyongyos), J. Szanyi (Eotvos U. and Wigner RCP, Budapest) (May 28, 2020)  
e-Print: 2005.14319 [hep-ph]

pdf cite

1 citation

## Proton Holography -- Discovering Odderon from Scaling Properties of Elastic Scattering #2

T. Csorgo (Wigner RCP, Budapest and Eszterhazy Karoly U., Eger), T. Növényi (EKU KRC, Gyongyos), R. Pasechnik (Lund U. and Rez, Nucl. Phys. Inst.), A. Szeir (Wigner RCP, Budapest), J. 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

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

T. Csörgő (Wigner RCP, Budapest and Eszterhazy Karoly U., Eger), T. Növényi (EKU KRC, Gyongyos), R. Pasechnik (Lund U., Dept. Theor. Phys.), A. Szeir (Wigner RCP, Budapest), J. Szanyi (Wigner RCP, Budapest and Eotvos U.) (Apr 15, 2020)  
e-Print: 2004.07318 [hep-ph]

pdf cite

3 citations

## Evidence of Odderon-exchange from scaling properties of elastic scattering at TeV energies #4

T. Csörgő (Wigner RCP, Budapest and CERN), T. Növényi (Unlisted, HU), R. Pasechnik (Lund U., Dept. Theor. Phys.), A. Szeir (Wigner RCP, Budapest), J. Szanyi (Wigner RCP, Budapest) (Dec 26, 2019)  
e-Print: 1912.11968 [hep-ph]

pdf cite

11 citations

4 manuscripts: 3 submitted for publication, detailed at DoF'2020  
1 published in EPJ Web of Conferences (Proc. ISMD 2019)

# Model independent results since DoF'19

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

#4

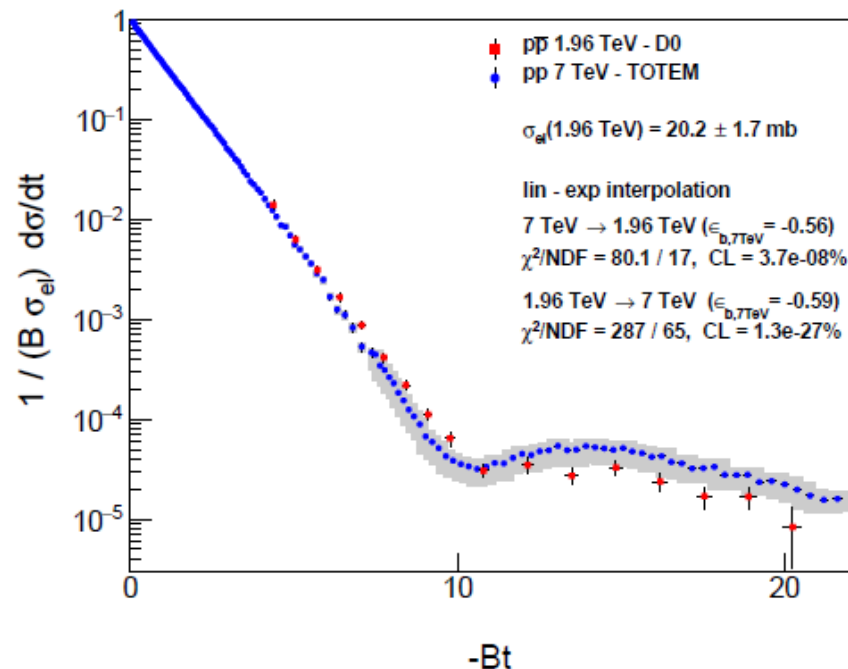
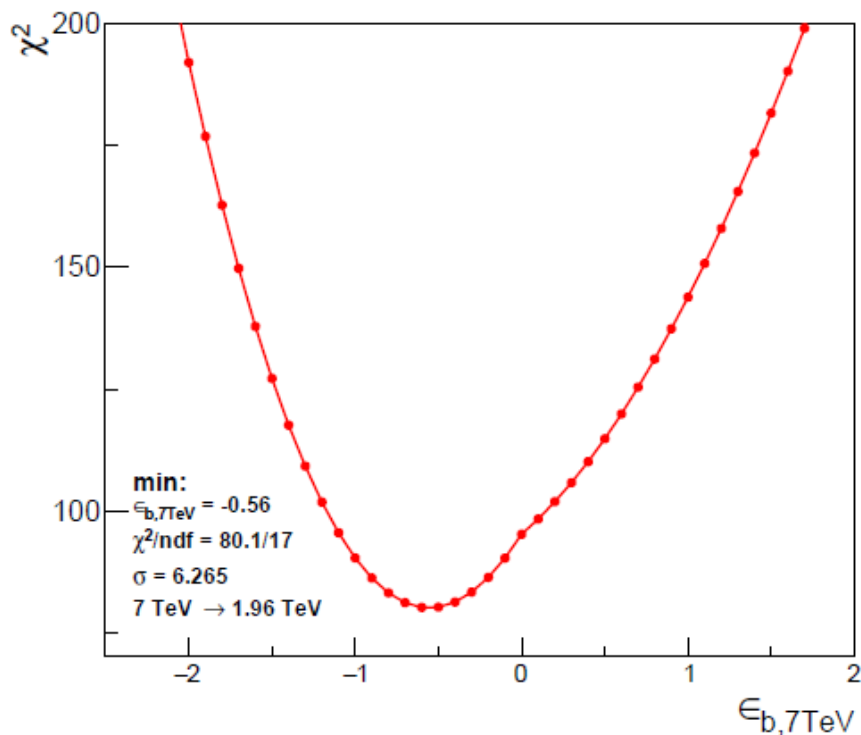


Fig. 13 Left panel indicates that as a function of  $\epsilon_{b,7 \text{ TeV}}$ , the  $\chi^2 \equiv \tilde{\chi}_{21}^2$  distribution has a unique minimum and nearly quadratic minimum. The minimum value is  $\chi^2/\text{NDF} = 80.1/17$ , corresponding to a statistically significant difference between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

[arXiv:1912.11968](https://arxiv.org/abs/1912.11968), detailed by R. Pasechnik

Model independent Odderon significance at least  $6.26 \sigma$

34 pages, 13 figures, 7 tables, submitted for publication (final round)



# Model independent results since DoF'19

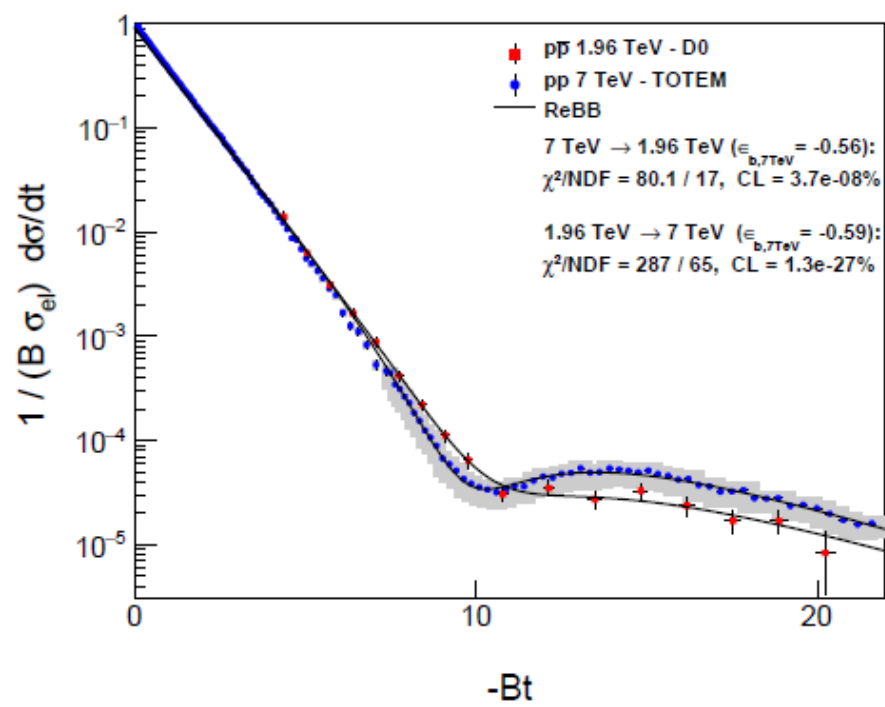
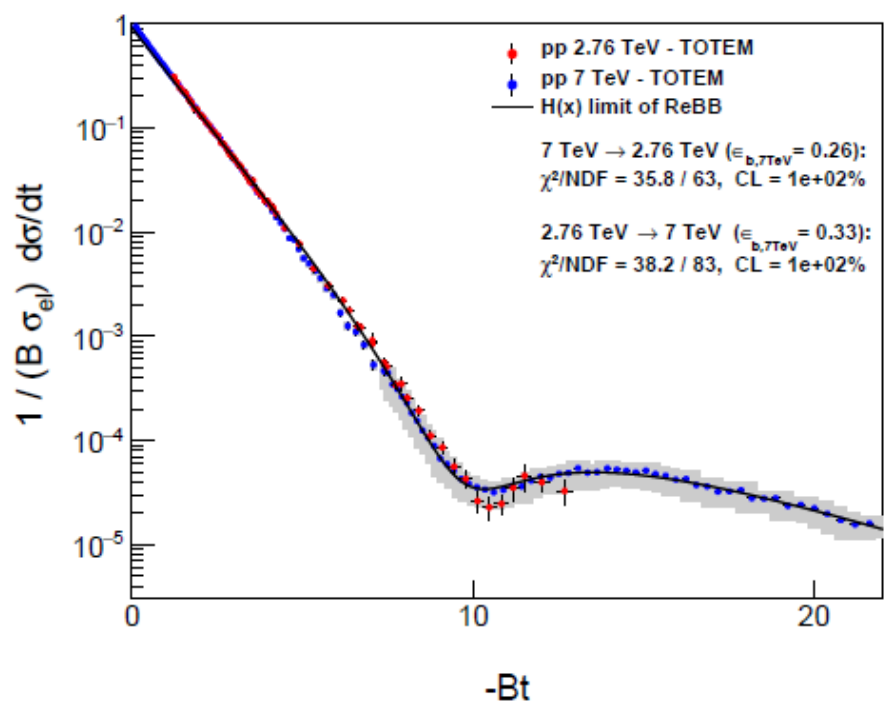
## Scaling of high-energy elastic scattering and the observation of Odderon #3

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. Szapuj (Wigner RCP, Budapest and Eotvos U.) (Apr 15, 2020)

e-Print: 2004.07318 [hep-ph]

pdf cite

3 citations



[arXiv:2004.07318v2](https://arxiv.org/abs/2004.07318v2)

Model independent Odderon significance  $6.26 \sigma$   
11 pages, 2 figures, submitted for publication,  
detailed at DoF'20 by T. Novák and A. Ster

# Model independent results since DoF'19

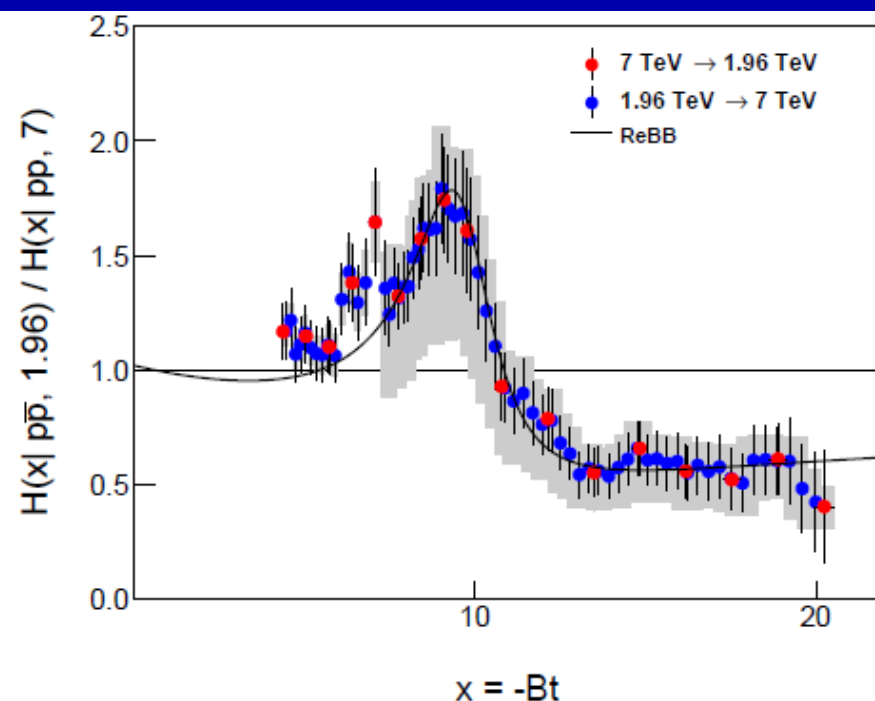
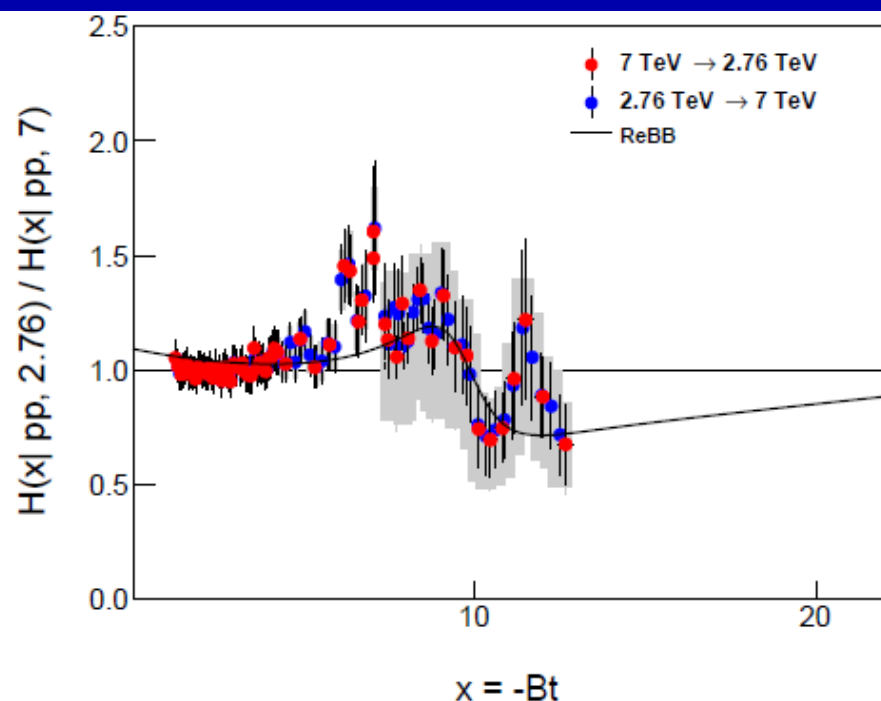
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T. Csörgő (Wigner RCP, Budapest and Eszterhazy Karoly U., Eger), T. Novák (EKU KRC, Gyongyos), R. Pasechnik (Lund U., Dept. Theor. Phys.), A. Šter (Wigner RCP, Budapest), I. Szapnyj (Wigner RCP, Budapest and Eotvos U.) (Apr 15, 2020)

e-Print: 2004.07318 [hep-ph]

pdf cite

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# 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 EKV KRC, Gyongyos), I. Szanyi (Eotvos U. and Wigner RCP, Budapest) (May 28, 2020)

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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

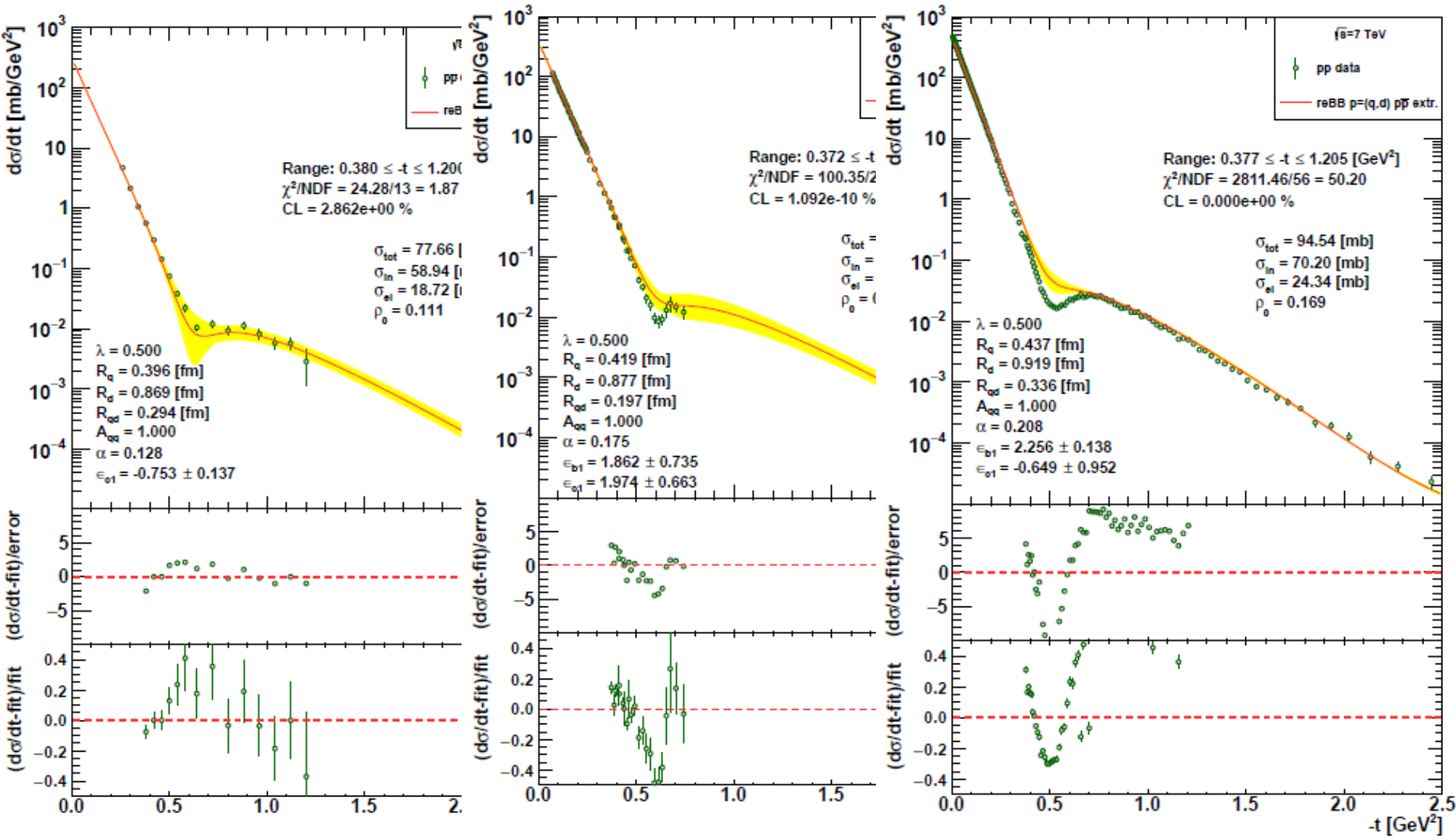
Odderon significance from pp and pbarp comparisons

From combined 1.96 and 2.76 TeV analysis: Odderon seen at  $7.08 \sigma$

Cross-checks (quadratic trend, ISR data)

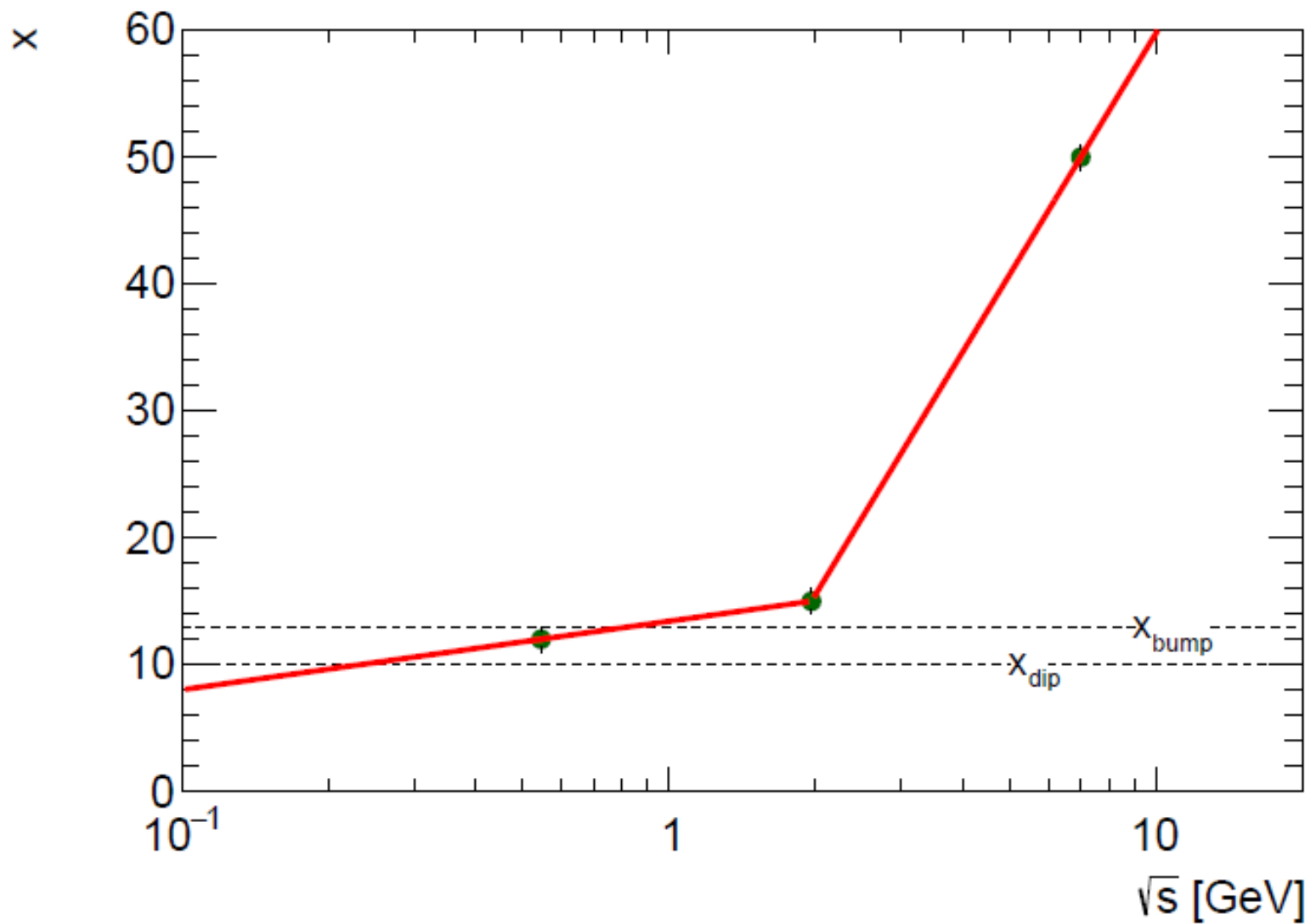
82 pages, 31 figures, model dependent Odderon significance  $7.1 \sigma$ ,  
submitted for publication, detailed at DoF'2020 by I. Szanyi

# Model dependent evidence for Odderon



82 pages, 31 figures, model dependent Odderon significance  $7.1 \sigma$ , submitted for publication, detailed at DoF'2020 by I. Szanyi

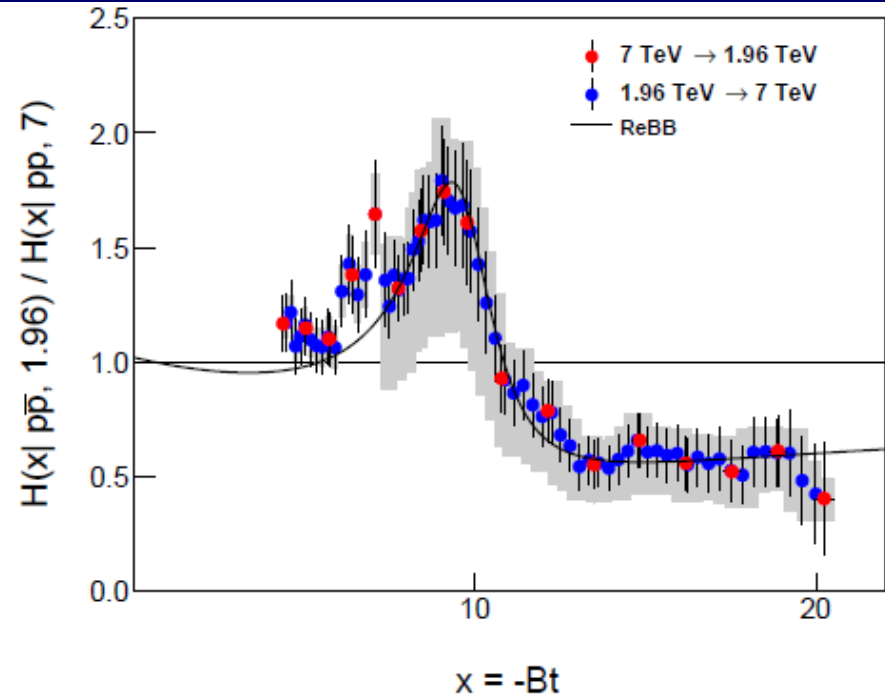
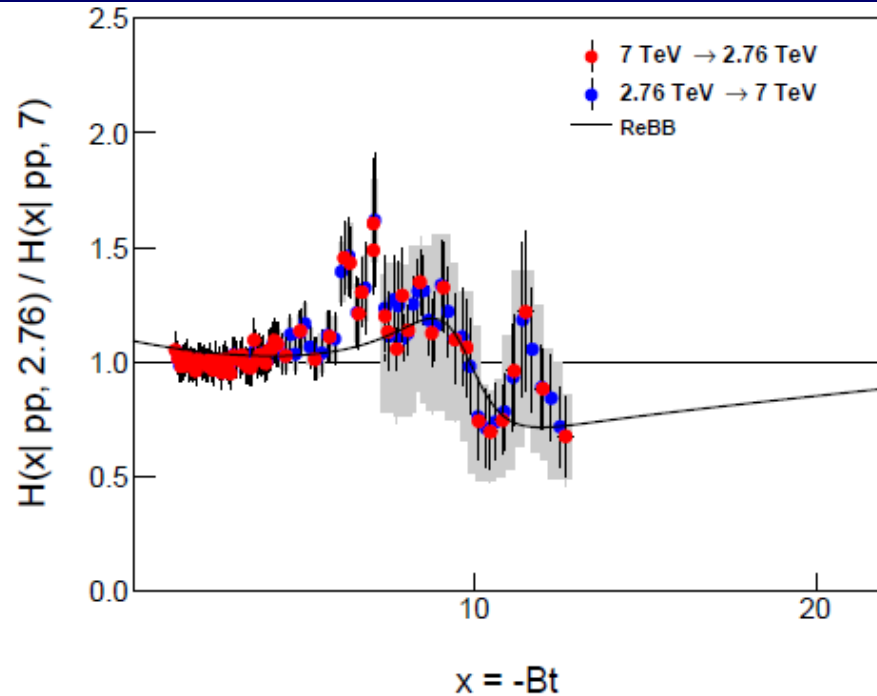
# New: model dependent limit on $H(x)$



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

# SUMMARY: AT LEAST 6.26 $\sigma$ ODDERON

A 6.26  $\sigma$  Odderon effect



Significance  $\geq 6.26 \sigma$  :

a **significant** and model independent Odderon effect.  
For details, see talks of R. Pasechnik, T. Novák, A. Ster  
Model dependent results, using the ReBB model  
Significance  $\geq 7.08 \sigma$ , see the talk of I. Szanyi