EVIDENCE FOR ODDERON AND SCALING PROPERTIES OF ELASTIC PP AND $\overline{\text{P}}$P SCATTERING

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Motivation

Long-time search for the hypothetical particle Odderon

Lukaszuk, Leszek; Nicolescu, Basarab (1973). "A possible interpretation of pp rising total cross-sections". *Lettere al Nuovo Cimento. 8 (7): 405-413*

First sign at ISR 53GeV (difference of pp and $\bar{p}$p at the dip)

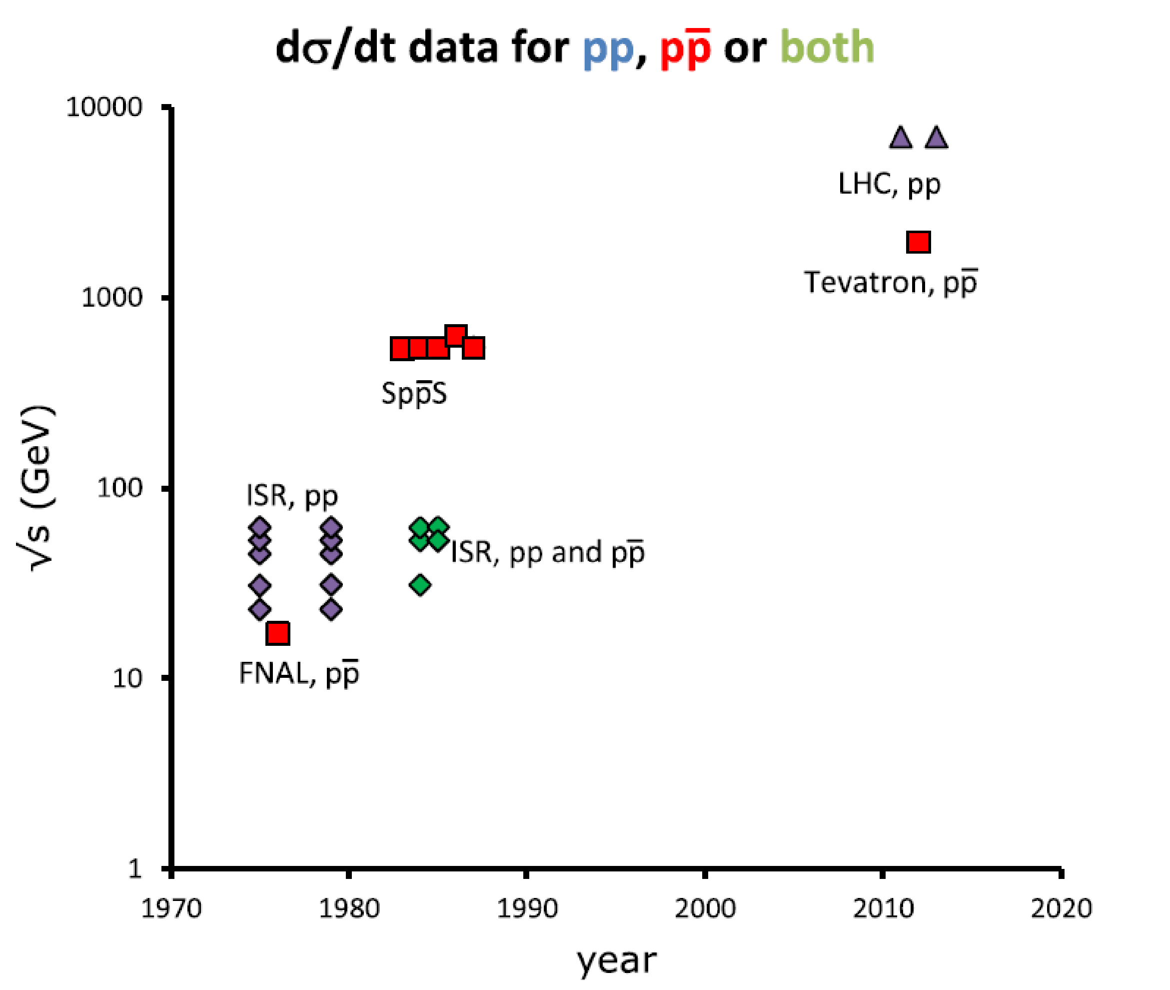
Indication at UA4 546 GeV (pp and $\bar{p}$p are different)

Strong indications by TOTEM and Niculescu at al.

Evgenij Martynov, Basarab Nicolescu:
Did TOTEM experiment discover the Odderon? PLB 778, 414 (2018)

TOTEM Coll., Elastic differential cross-section $d\sigma/dt$ at $\sqrt{s}$ =2.76 TeV and implications on the existence of a colourless 3-gluon bound state
arXiv:1812.08610; CERN-EP-2018-341; TOTEM-2018-002

Motivations



Problem:

No measurements at the same energies of pp and p$\bar{p}$ reactions at high enough (TeV) energies.

At LHC energies, a strong indication achieved by extrapolating to $\sqrt{s}$ = 1.96 TeV:

A. Ster, L. Jenkovszky, T. Csörgő: Extracting the Odderon from pp and pbarp scattering data. *Phys. Rev. D 91, 074018 (2015)*

History

Nuclear collisions ->

Scattering ->

Regge Theory (1959, Tullio Regge) ->

**Pomeron(1961, introduced by V. N. Gribov,
named after I. Pomeranchuk) ->**

Odderon(1973, B. Nicolescu and L. Lukaszuk) ->

Corrected amplitudes

Formalism: elastic scattering

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

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

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

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

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

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

$$\left. \frac{d\sigma(s)}{dt} \right|_{t \to 0} = \frac{1 + \rho_0^2(s)}{16\pi} \, \sigma_{\text{tot}}^2(s).$$

Looking for Odderon effects

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

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

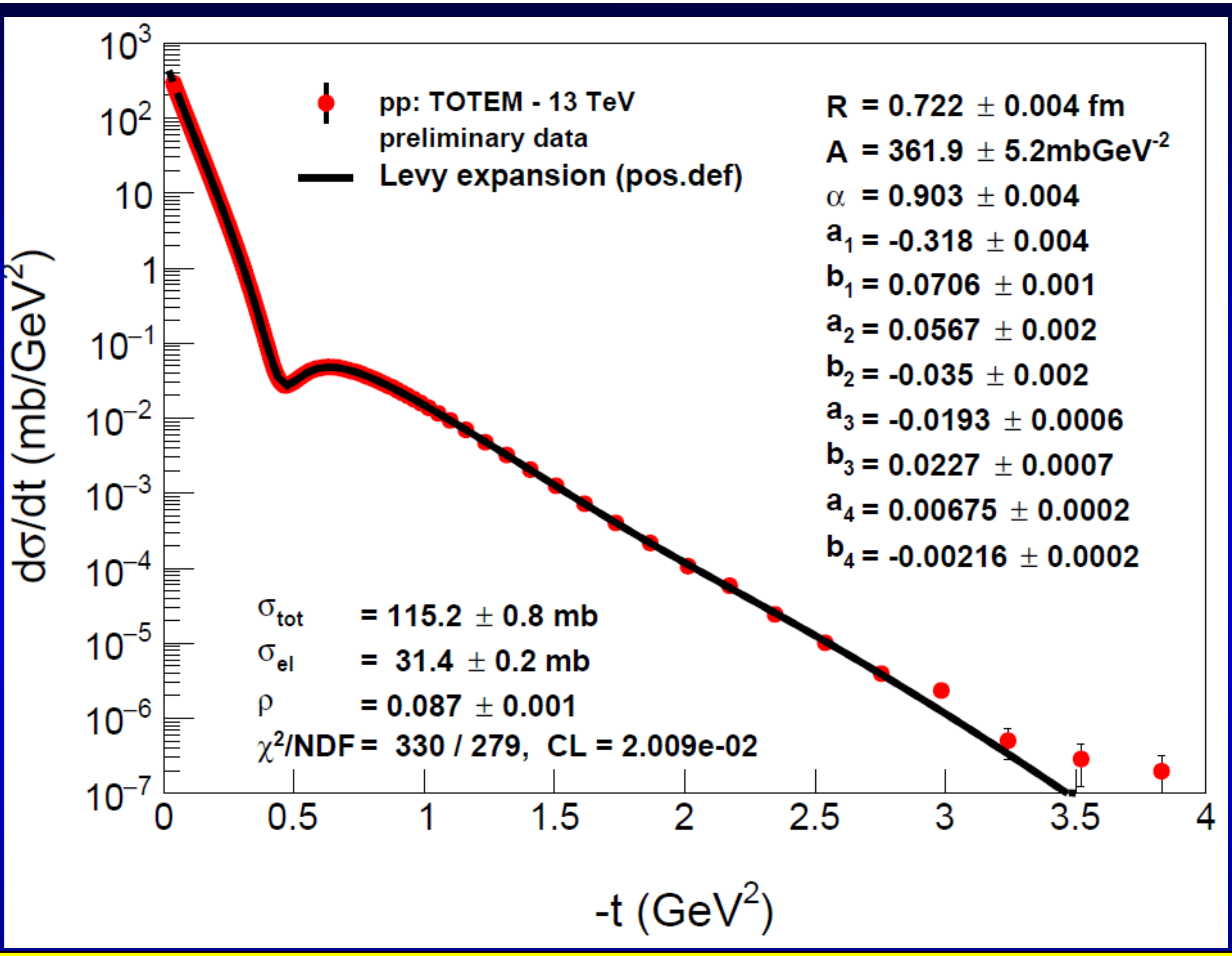
Three simple consequences:

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

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

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

Odderon search: a possible strategy #1



Extrapolation of Levy fit parameters via s dependence
to 1.96 TeV $\bar{p}p$ reactions
It is difficult: work in progress …
(preliminary results presented at DoF'2018)

Odderon search: a possible strategy #2

Our research strategy in this paper is to try to scale out the s-dependence of the differential cross-section by scaling out its dependencies on $\sigma_{tot}(s)$, $\sigma_{el}(s)$, $B(s)$ and $\rho(s)$. The residual scaling functions will be compared for proton-proton and proton-antiproton elastic scattering to see if any difference remains. Such residual difference is a clear as a signal for Odderon-exchange, if the differential cross-sections were measured at exactly the same energies. However, currently such data are lacking. So we may expect that after scaling out the trivial s-dependences, only small scaling violating terms remain that depends on s, which can be estimated by the scaling violations of differential cross-sections measured at various nearby energies. If we see larger differences between the scaling functions of proton-proton and proton-antiproton collisions as compared to the s-dependent scaling violating term, that will be an indication for the Odderon effect.

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

Scaling in the diffractive cone region

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

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

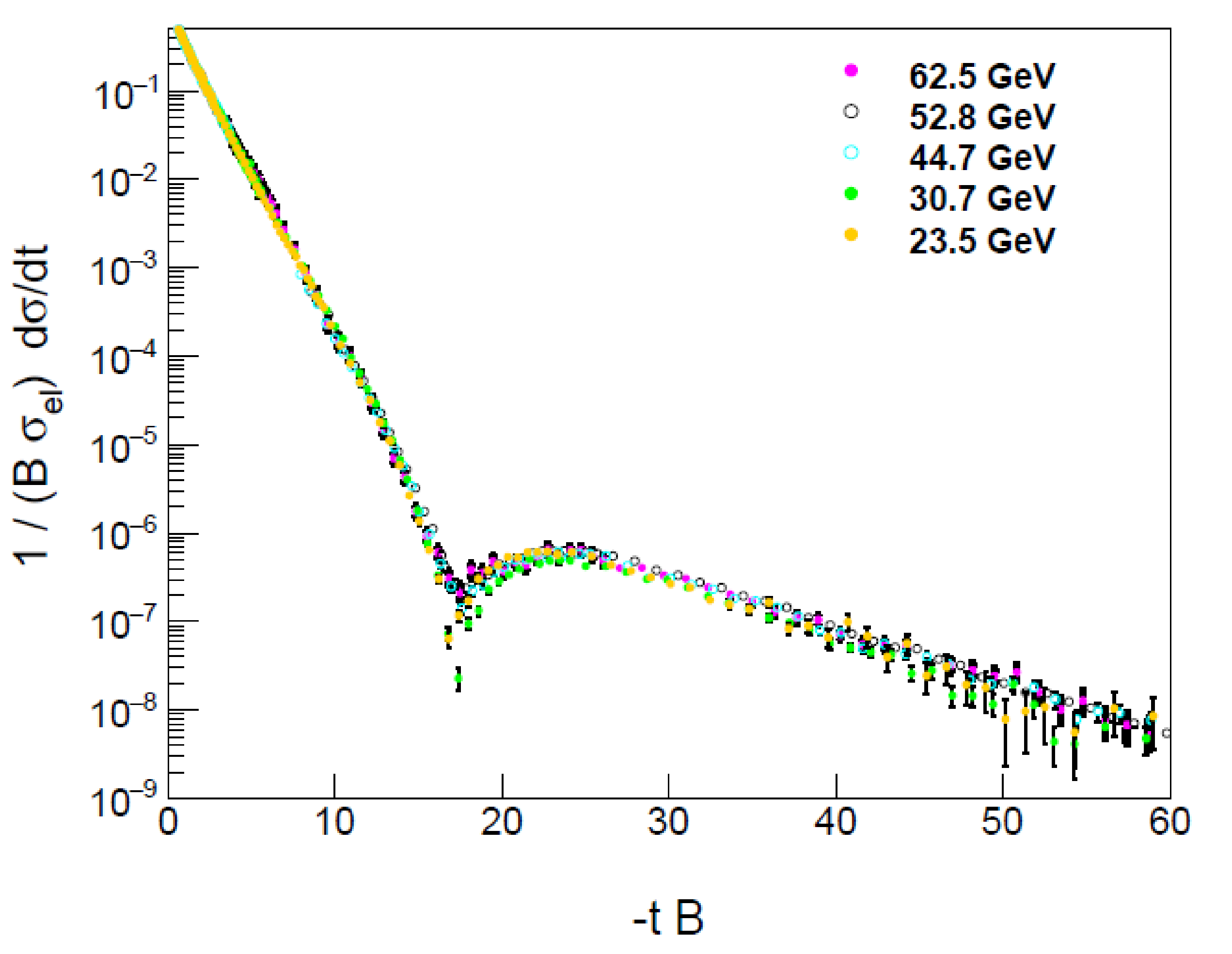
$$B(s) = \frac{1+\rho_0^2(s)}{16\,\pi}\,\frac{\sigma_{\rm tot}^2(s)}{\sigma_{\rm el}(s)}.$$

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

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

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

Test of the H(x) scaling on ISR data



Energy range: 23.5 – 62.5 GeV (nearly factor of 3)
H(x) works in the cone, shape ~ exp(-x)
H(x) scaling works also in the dip and bump region

H(x) scaling in greater x region

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

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

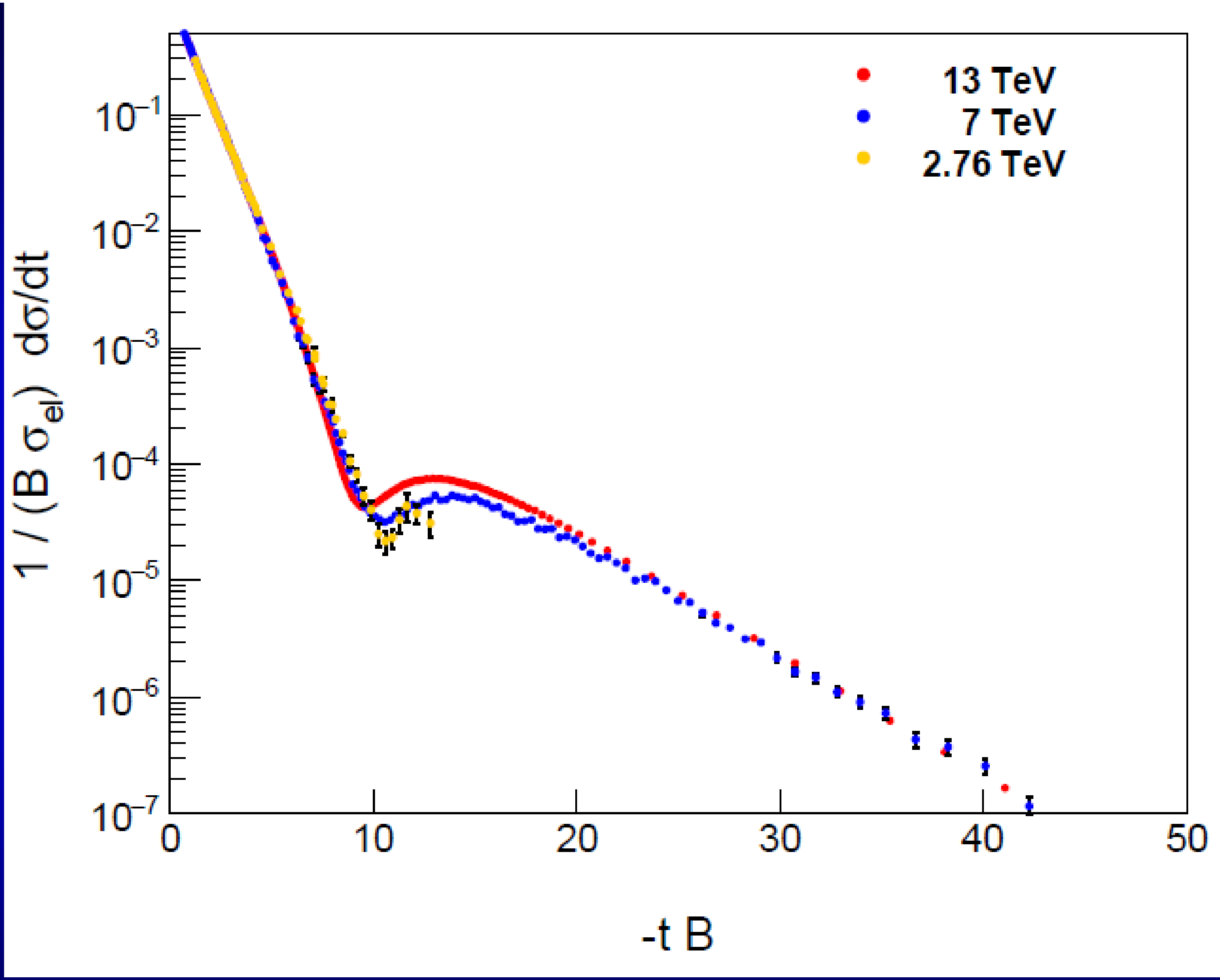
$$\frac{d\sigma}{dt} = \frac{1}{4\pi}|T_{el}(\Delta)|^2 = \frac{1+\rho_0^2}{4\pi} r^2(s) R^2(s) |\tilde{E}(R(s)\Delta)|^2$$

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

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

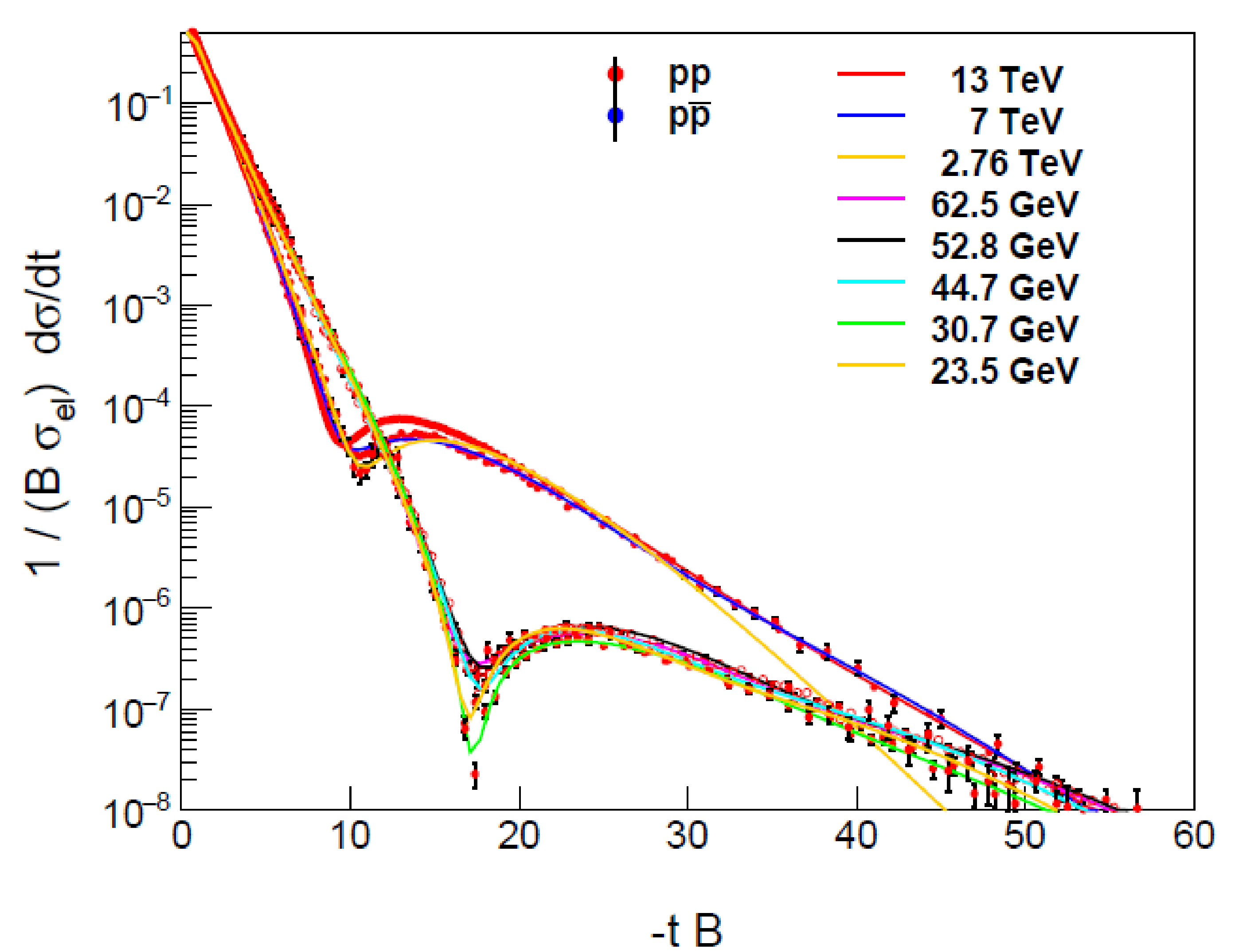
Advantages:
H(x) ≠ exp(-x) arbitrary positive def. in the dip-bump region
Measurable both for pp and $\overline{\mathrm{p}}$p

Test of H(x) scaling on LHC pp data



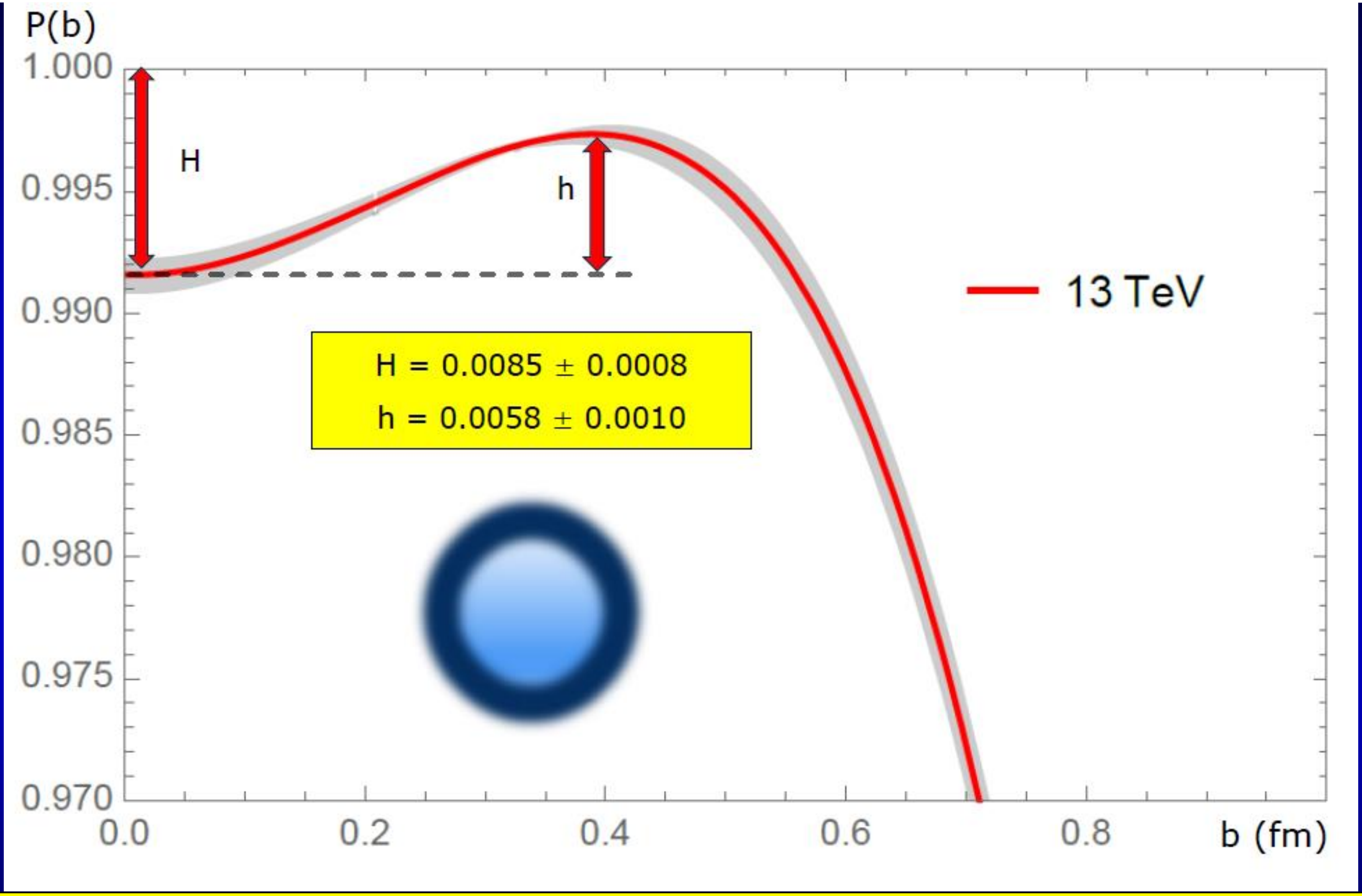
Energy range: 2.76 – 13 TeV (nearly factor of 4) in pp
H(x) scaling nearly works up to 7 TeV, scaling violations at 13 TeV

H(x) scaling vs LHC + ISR pp data



Energy range: 23.5 GeV – 13 TeV (nearly factor of 100)
scaling violating terms are large, Levy fits guide the eye

H(x) scaling vs LHC + ISR pp data



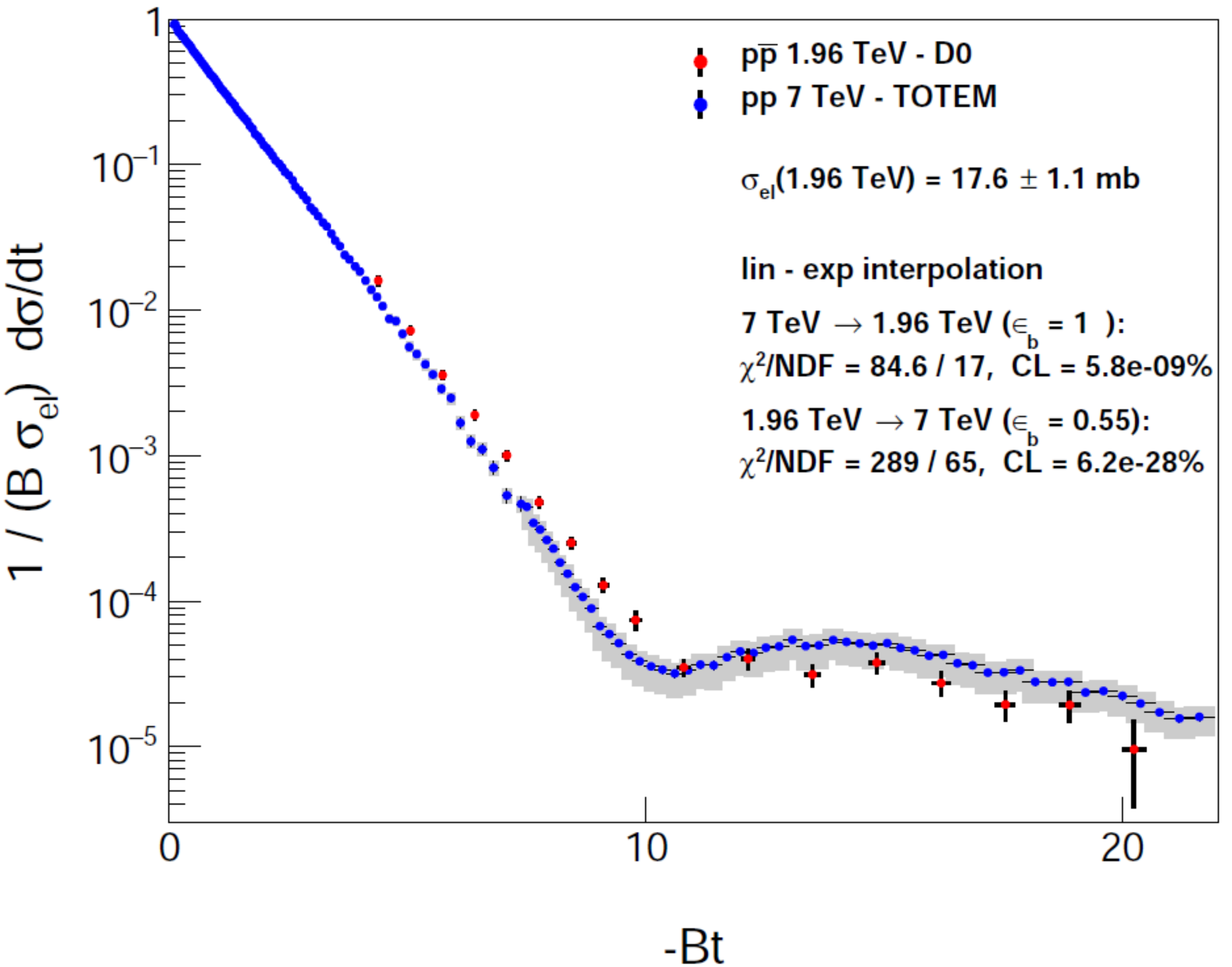
Violation of H(x) scaling at 13 TeV
New domain of QCD: saturation, hollowness, arxiv.org:1910.08817

H(x) scaling for TOTEM + D0 data

The method for quantifying the Odderon: $\sigma_{\rm odd}$

1) Calculate χ^2 between the two data sets with all the possible stat and −t dependent sys errors. Stat and sys errors need to be treated differently. (Diagonalize the covariance matrix by a PHENIX method)
2) Use only published data, B and total $\sigma_{\rm el}$.
3) Interpolate between data points by (linear,linear) and (linear, exponential).
4) Propagate all the errors to H(x), including that of −t, dσ/dt, B and $\sigma_{\rm el}$.

H(x) scaling for TOTEM + D0 data



σ_{el} (1.96) = 17.6 mb,

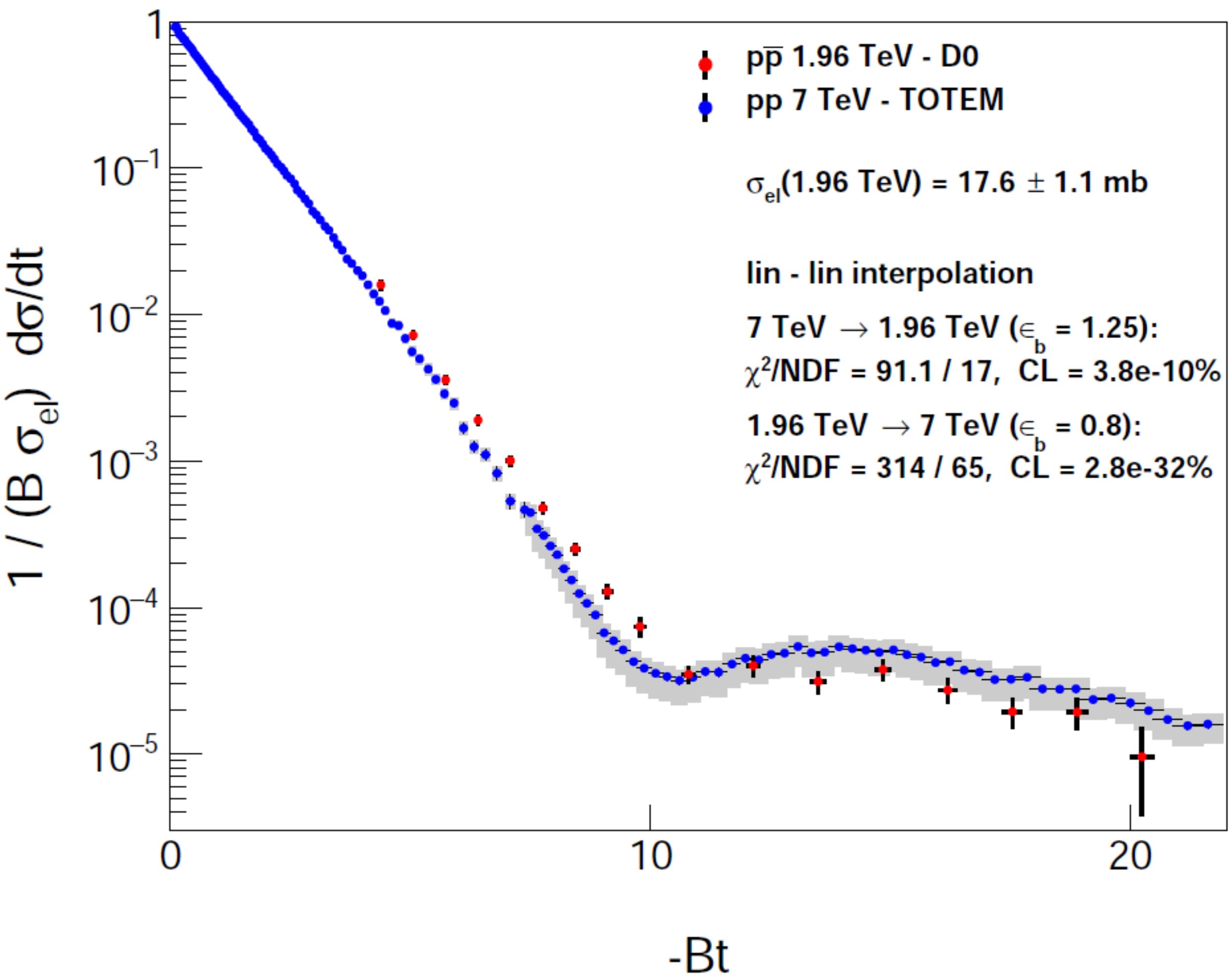
with (linear, exp) interpolation

Significance of Odderon:

$\sigma_{odd} \geq 6.549$

Energy range: 1.96 – 7 TeV (factor of 3.5)
H(x|pp) ≠ H(x|$\bar{p}$p) : a significant, at least 6.549 σ Odderon effect

H(x) scaling for TOTEM + D0 data



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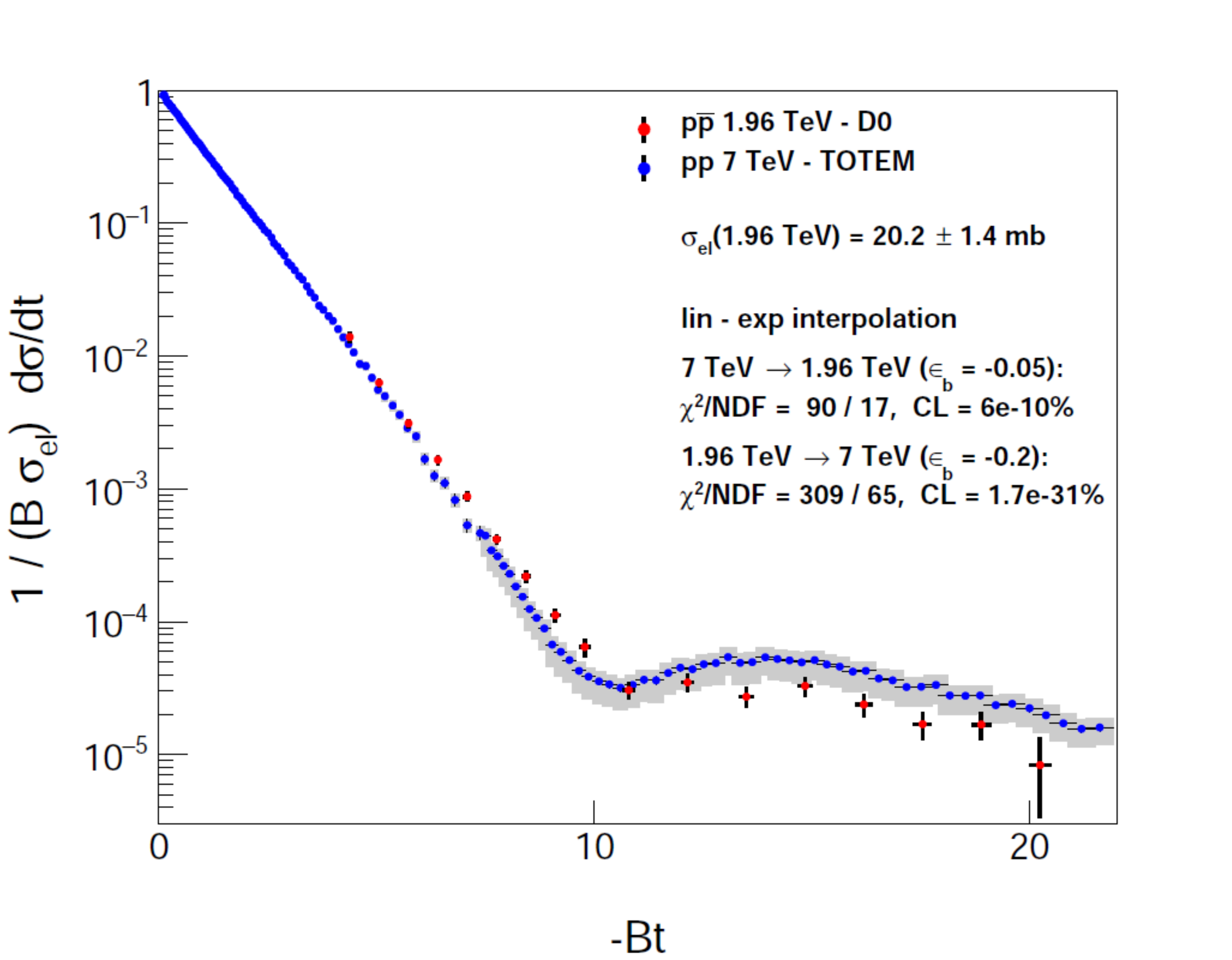
Significance of Odderon:

σ_{odd} > 7.0

Energy range: 1.96 – 7 TeV (factor of 3.5)
$H(x|pp) \neq H(x|\bar{p}p)$: a significant, at least 6.549 σ Odderon effect

H(x) scaling for TOTEM + D0 data



σ_{el} (1.96) = 20.2 mb,

with (linear, exp) interpolation

Significance of Odderon:

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Energy range: 1.96 – 7 TeV (factor of 3.5)
H(x|pp) ≠ H(x|p$\bar{p}$) : a significant, at least 6.549 σ Odderon effect

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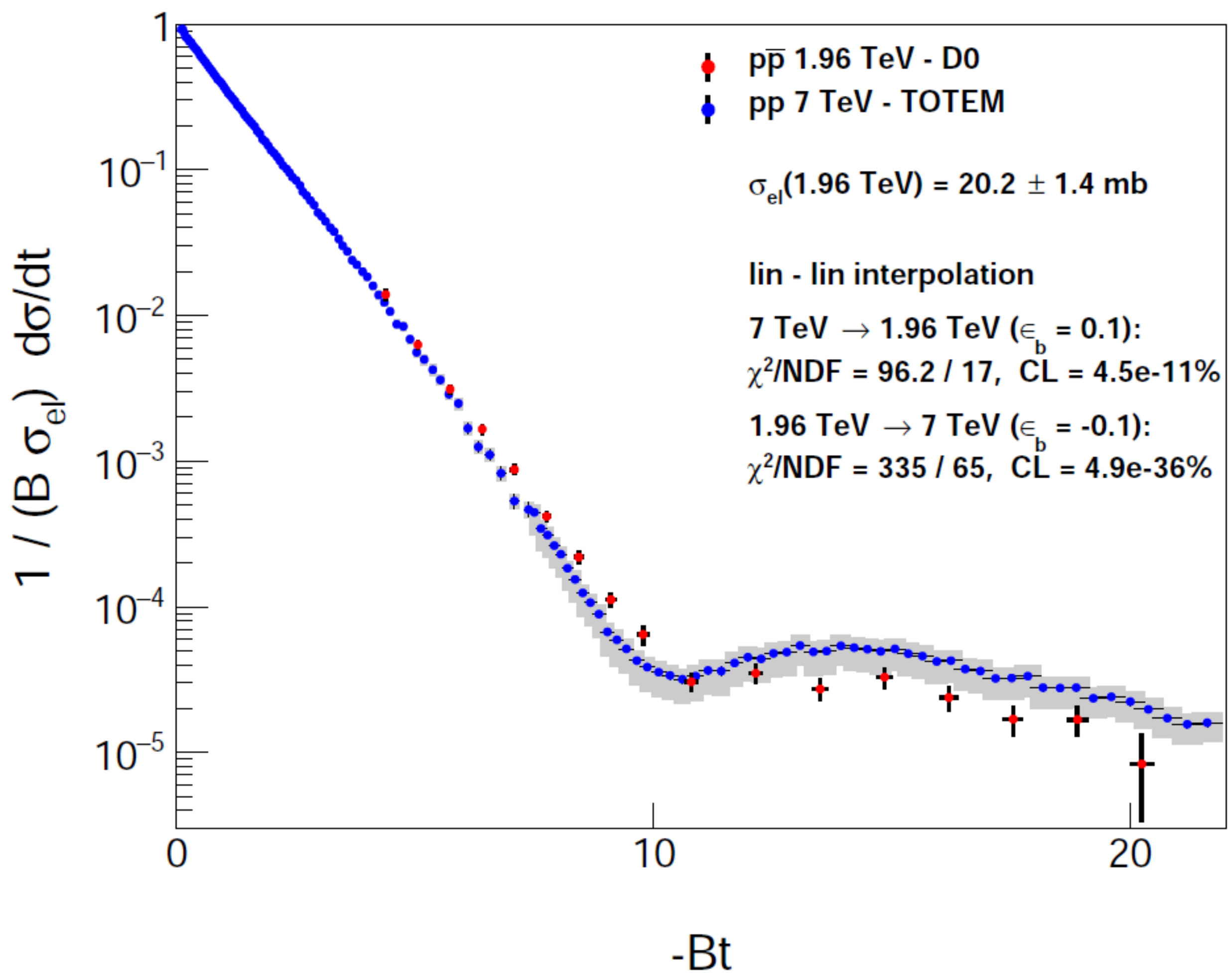

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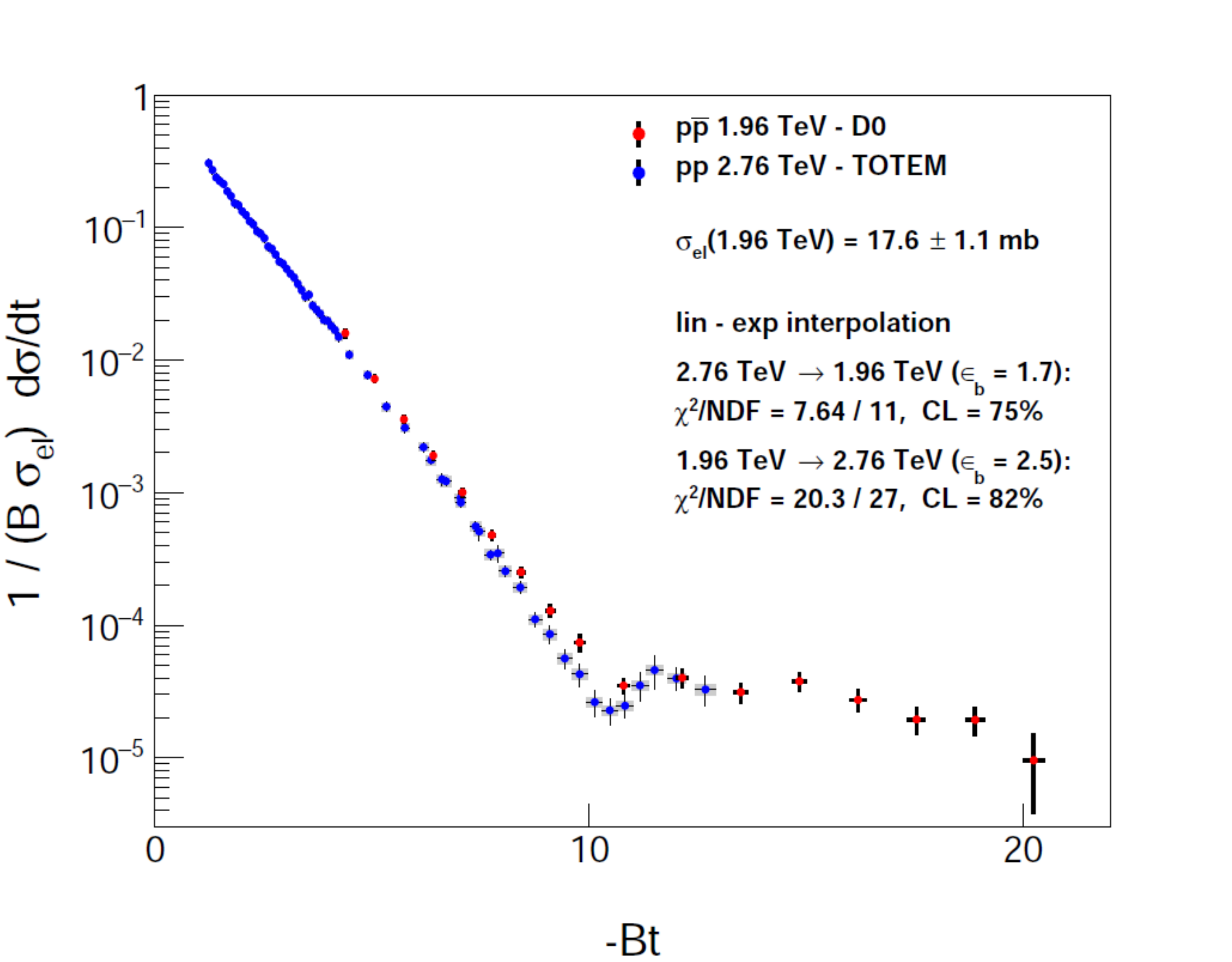

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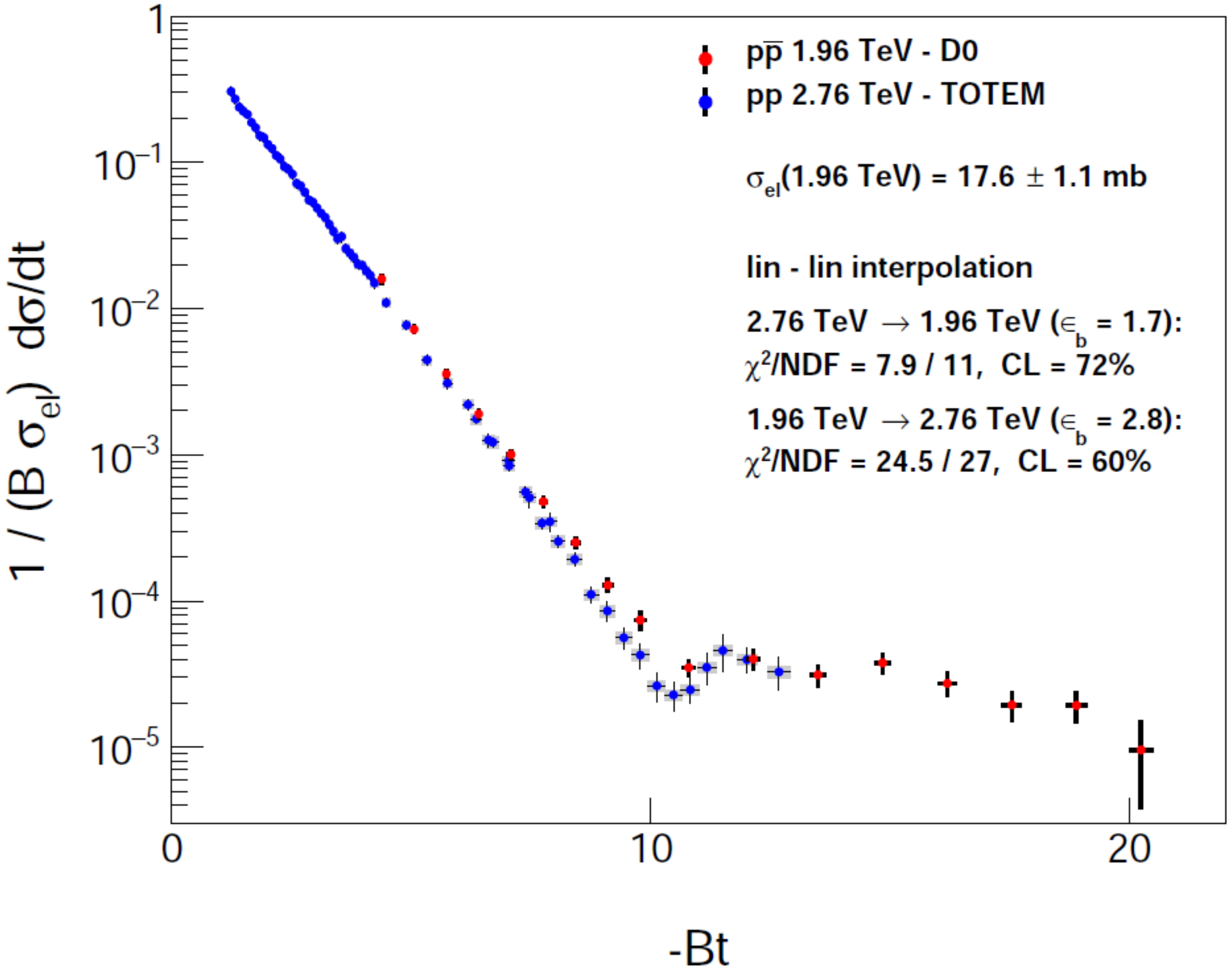
In H(x), lack of significant Odderon effect: Limitations in acceptance and Statistics at 2.76

Energy range: 1.96 TeV – 2.76 TeV (factor of 1.5), but we find no significant difference between H(x|pp,2.76) and H(x|$\bar{p}$p,1.96)

H(x) scaling for TOTEM + D0 data



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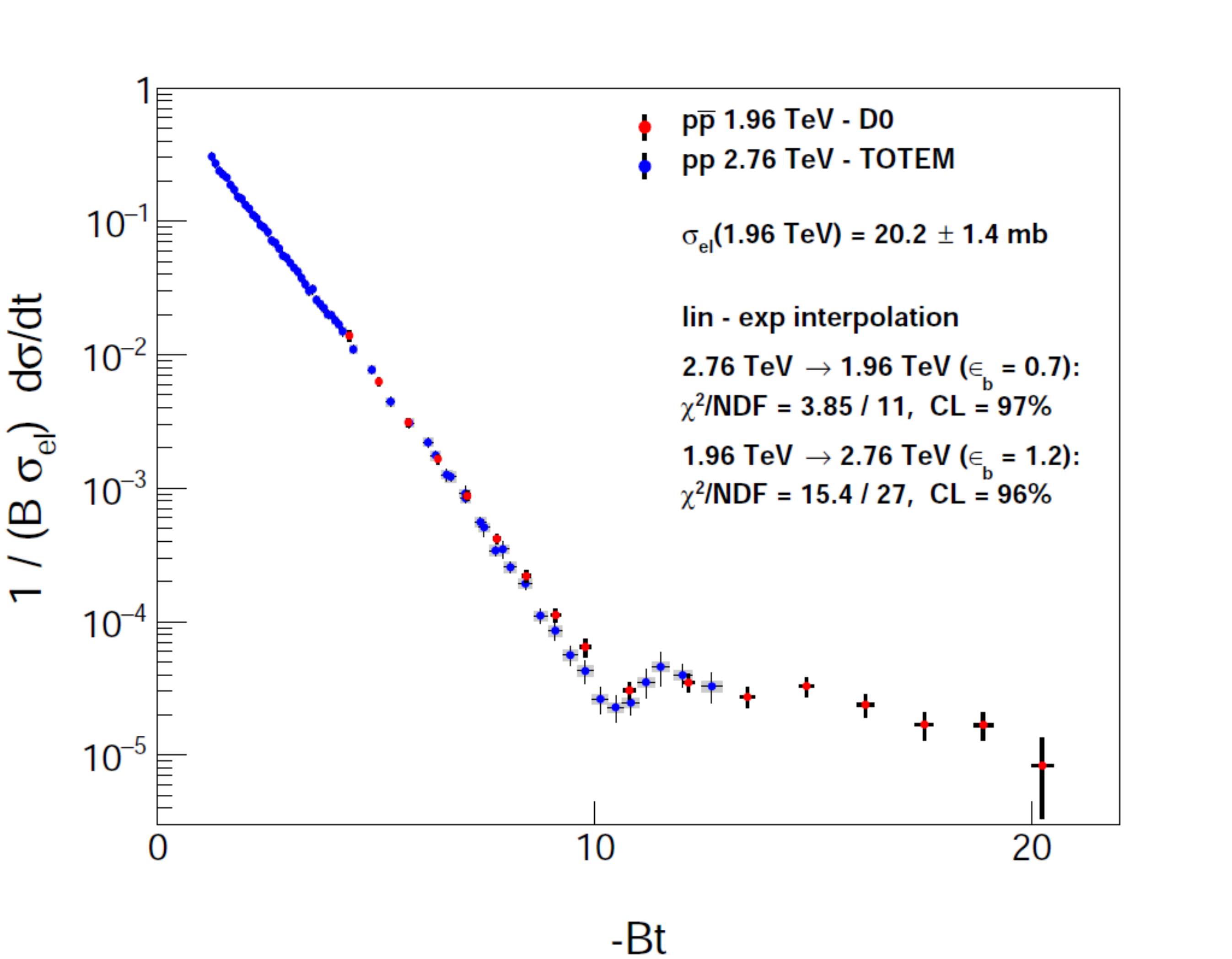

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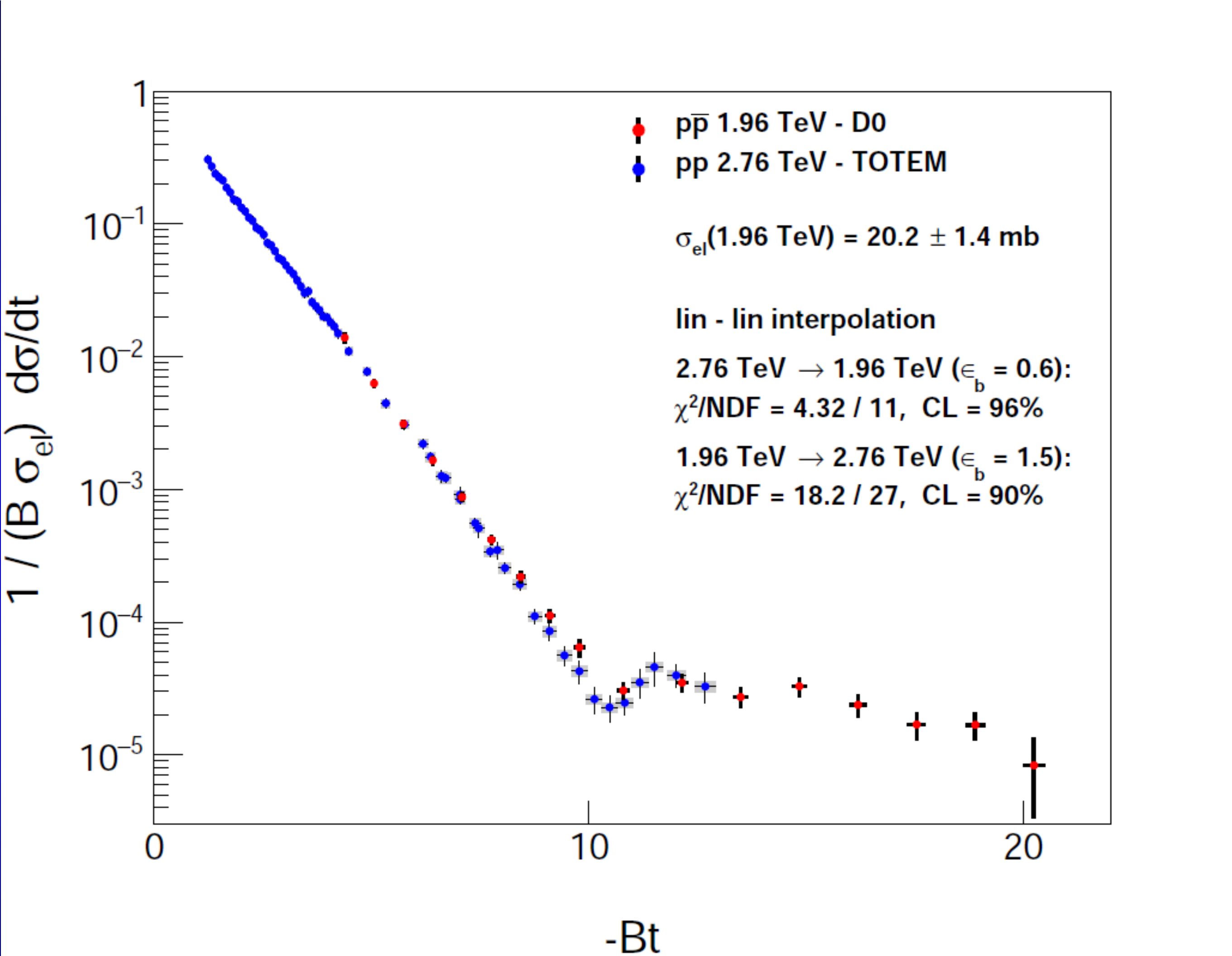

σ_{el} (1.96) = 20.2 mb,

with (linear, linear) interpolation

In H(x), lack of significant Odderon effect: Limitations in acceptance and statistics

Energy range: 1.96 TeV – 2.76 TeV (factor of 1.5), but we find no significant difference between H(x|pp,2.76) and H(x|$\bar{p}$p,1.96)

Summary and conclusions

Strong and model independent Odderon effect is discovered in the scaled differential cross-sections, H(x) when comparing 7 TeV pp data of TOTEM with 1.96 TeV $\bar{p}p$ data of D0.

The significance of the Odderon was calculated from the (χ^2,NDF) of the comparison of 7 TeV $\bar{p}p$ and 1.96 TeV pp data.

The significance of the Odderon effect is at least **6.549** σ.

These model independent results are being written up, manuscript to be released as soon as reasonably possible.