Odderon search using the Bialas-Bzdak model

based on arXiv: 2005.14319 and other recent results

T. Csörgő[1,2] T. Novák[2], R. Pasechnik[3], A. Ster[1], I. Szanyi[1,4]

[1]Wigner RCP, Budapest, Hungary
[2]SZIE KRC, Gyöngyös, Hungary
[3]Lund University, Lund, Sweden
[4]ELTE, Budapest, Hungary

6th Day of Femtoscopy

29 October 2020, Gyöngyös, Hungary

Inelastic cross section in Bialas-Bzdak p=(q,d) model

$$\tilde{\sigma}_{in}(\vec{b}) = \int_{-\infty}^{+\infty} \dots \int_{-\infty}^{+\infty} d^2\vec{s}_q d^2\vec{s}'_q d^2\vec{s}_d d^2\vec{s}'_d \, D(\vec{s}_q,\vec{s}_d)\, D(\vec{s}'_q,\vec{s}'_d)\, \sigma(\vec{s}_q,\vec{s}_d;\vec{s}'_q,\vec{s}'_d;\vec{b})$$

- **quark-diquark distribution inside the proton:**

$$D(\vec{s}_q,\vec{s}_d) = \frac{1+\lambda^2}{R_{qd}^2\pi} e^{-\frac{s_q^2+s_d^2}{R_{qd}^2}} \delta^2(\vec{s}_q + \lambda\vec{s}_d)$$

$$\lambda = \frac{m_q}{m_d}$$

$$\vec{s}_d = -\lambda\vec{s}_q$$

$$\vec{s}'_d = -\lambda\vec{s}'_q$$

A. Bialas, A. Bzdak Acta Phys.Polon. B 38, 159-168 (2007)

- **interaction probability of the constituents:**

$$\sigma(\vec{s}_q,\vec{s}_d;\vec{s}'_q,\vec{s}'_d;\vec{b}) = 1 - \prod_a \prod_b [1 - \sigma_{ab}(\vec{b} + \vec{s}'_a - \vec{s}_b)]$$

$$\sigma_{ab}(\vec{s}) = A_{ab} e^{-s^2/S_{ab}^2}$$

$$S_{ab}^2 = R_a^2 + R_b^2$$

$$a, b \in \{q,d\}$$

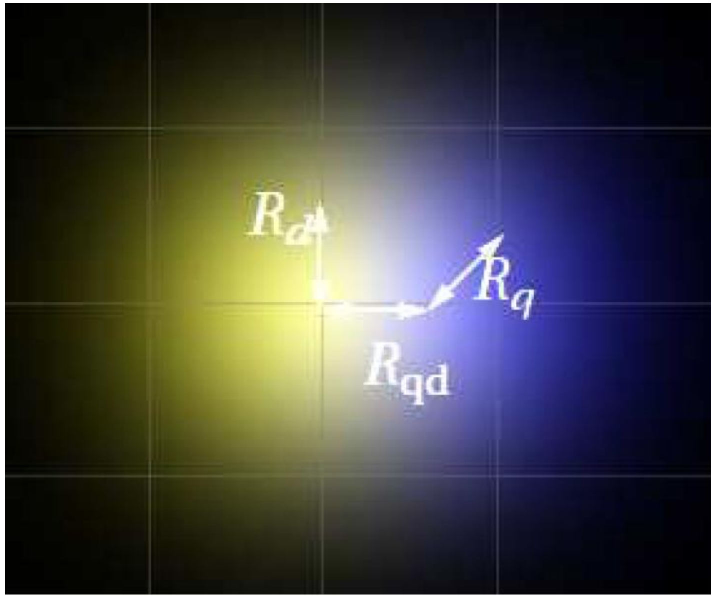
- **inelastic cross-sections of quark, diquark scatterings :**

$$\sigma_{ab,in} = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \sigma_{ab}(\vec{s})\, d^2\vec{s}$$

$$\sigma_{qq,in} : \sigma_{qd,in} : \sigma_{dd,in} = 1:2:4$$

- **free parameters:**

$A_{qq}, \lambda, R_q, R_d, R_{qd}$, $(A_{qq} = 1 \; and \; \lambda = 0.5 \; can \; be \; fixed)$



Proton-(anti)proton scattering in the quark-diquark model.

Unitarily extended Bialas-Bzdak model (reBB)

- **elastic scattering amplitude in the impact parameter space:**

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

arXiv:1505.01415

F. Nemes, T. Csörgő, M. Csanád, Int. J. Mod. Phys. A Vol. 30 (2015) 1550076

- **the opacity function:**

$$\Omega(s,\vec{b}) = Re\Omega(s,\vec{b}) + i\, Im\Omega(s,\vec{b})$$

$Im\Omega \neq 0$ as the real part of the amplitude is not negligibly small

$$Re\Omega(s,\vec{b}) = -\frac{1}{2} ln\left[1 - \tilde{\sigma}_{in}(s,\vec{b})\right]$$

$$Im\Omega(s,\vec{b}) = -\alpha\, \tilde{\sigma}_{in}(s,\vec{b})$$

NEW FREE PARAMETER

- **elastic scattering amplitude in momentum space:**

$$T(s,t) = 2\pi \int_0^{\infty} t_{el}(s,|\vec{b}|)\, J_0(|\vec{\Delta}||\vec{b}|)|\vec{b}|d|\vec{b}|$$

$$\sqrt{s} \to \infty\,, |\vec{\Delta}| \cong \sqrt{-t}$$

Measurable quantities

- **differential cross section:**

$$\frac{d\sigma}{dt}(s,t) = \frac{1}{4\pi}|T(s,t)|^2$$

- **total, elastic and inelastic cross sections:**

$$\sigma_{tot}(s) = 2ImT(s,t=0)$$

$$\sigma_{el}(s) = \int_{-\infty}^{0} \frac{d\sigma(s,t)}{dt} dt$$

$$\sigma_{in}(s) = \sigma_{tot}(s) - \sigma_{el}(s)$$

- **ratio ρ_0:**

$$\rho_0(s) = \frac{ReT(s,t=0)}{ImT(s,t=0)}$$

- **slope of dσ/dt:**

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

Fit method

- **least squares fitting with:**

$$\chi^2 = \left(\sum_{j=1}^{M} \left(\sum_{i=1}^{n_j} \frac{\left(d_{ij} + \epsilon_{bj}\tilde{\sigma}_{bij} + \epsilon_{cj} d_{ij}\sigma_{cj} - th_{ij}\right)^2}{\tilde{\sigma}_{ij}^2} \right) + \epsilon_{bj}^2 + \epsilon_{cj}^2 \right) + \left(\frac{d_{\sigma_{tot}} - th_{\sigma_{tot}}}{\delta\sigma_{tot}} \right)^2 + \left(\frac{d_{\rho_0} - th_{\rho_0}}{\delta\rho_0} \right)^2$$

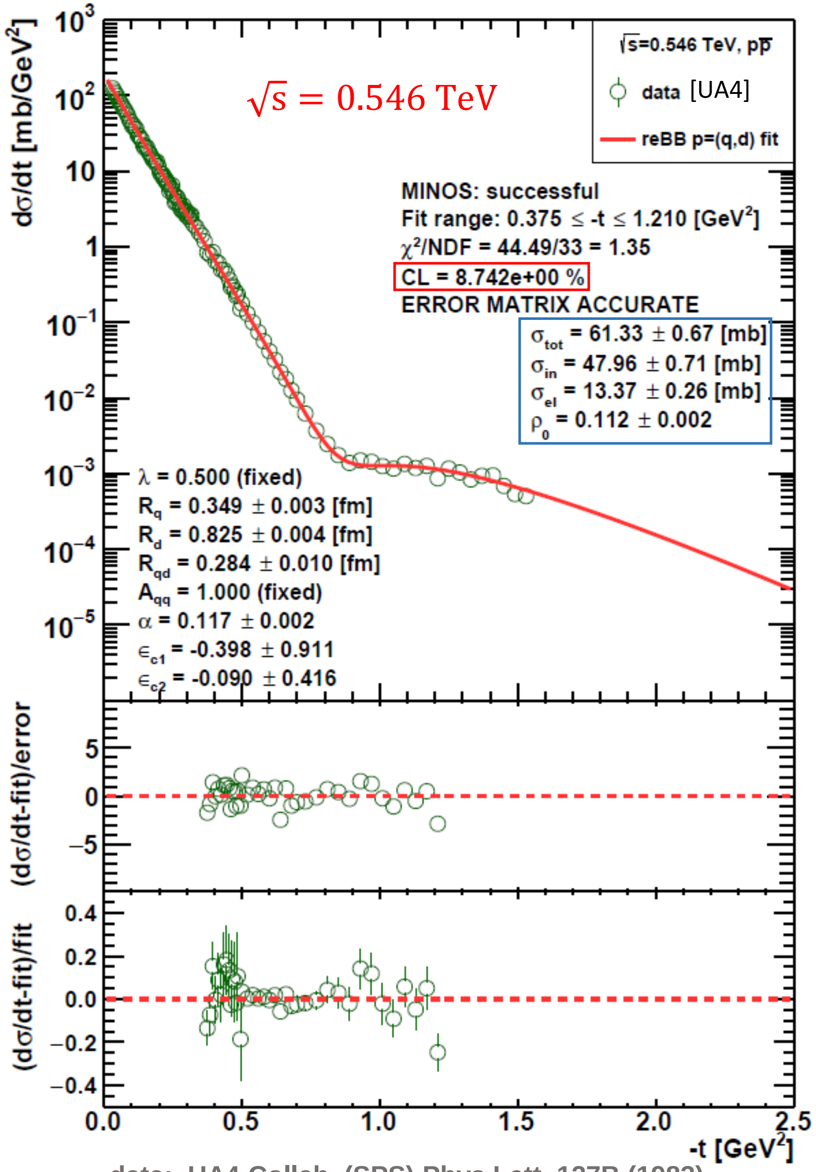
$$\tilde{\sigma}_{ij}^2 = \tilde{\sigma}_{aij} \left(\frac{d_{ij} + \epsilon_{bj}\tilde{\sigma}_{bij} + \epsilon_{cj} d_{ij}\sigma_{cj}}{d_{ij}} \right)$$

$$\tilde{\sigma}_{kij} = \sqrt{\sigma_{kij}^2 + (d'_{ij}\delta_k t_{ij})^2}, \qquad k \in \{a, b\}$$

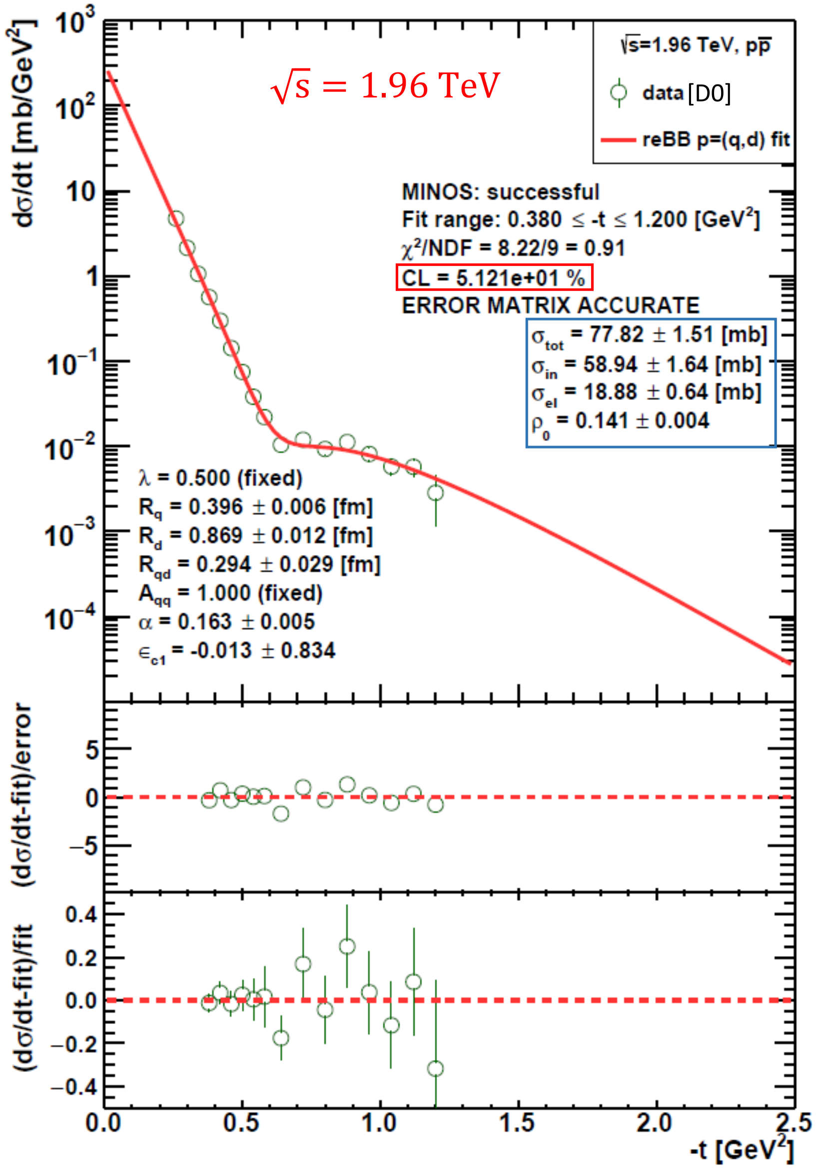
A. Adare *et al.* (PHENIX Collab.) Phys. Rev. C 77, 064907

- it takes into account (in M separately measured t ranges):
  - the t-dependent statistical (a) and systematic (b) errors (both vertical σ_k and horizontal $\delta_k t$) → ϵ_b parameters;
  - the t-independent σ_c normalization uncertainties → ϵ_c parameters;
  - the measured total cross-section $d_{\sigma_{tot}}$ and ratio d_{ρ_0} and their total uncertainties $\delta\sigma_{tot}$ and $\delta\rho_0$.
- **minimization with CERN Root MINUIT, parameter error estimation by MINOS.**

Satisfactory ReBB model fits for $p\bar{p}$ $d\sigma/dt$ data

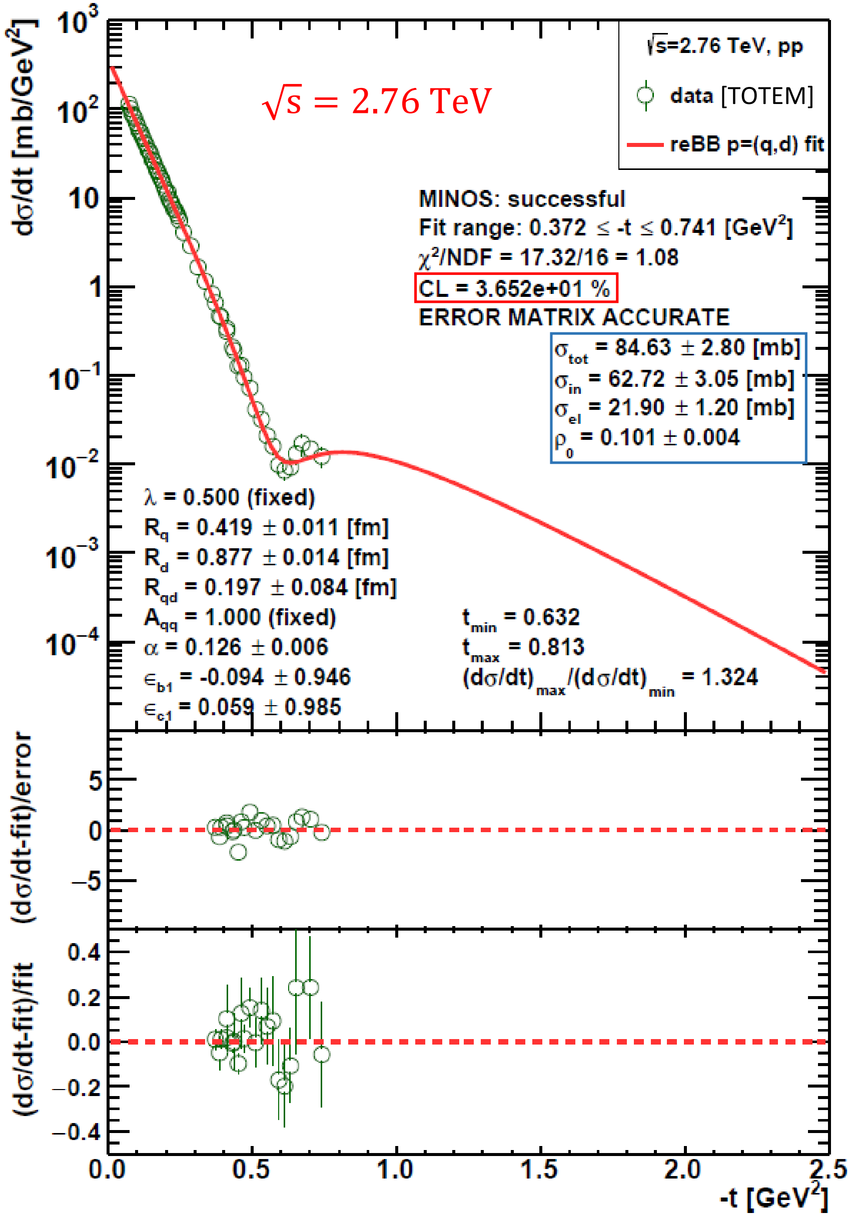


data: UA4 Collab. (SPS) Phys.Lett. 127B (1983)
UA4 Collab. (SPS) Phys.Lett. 155B (1985)

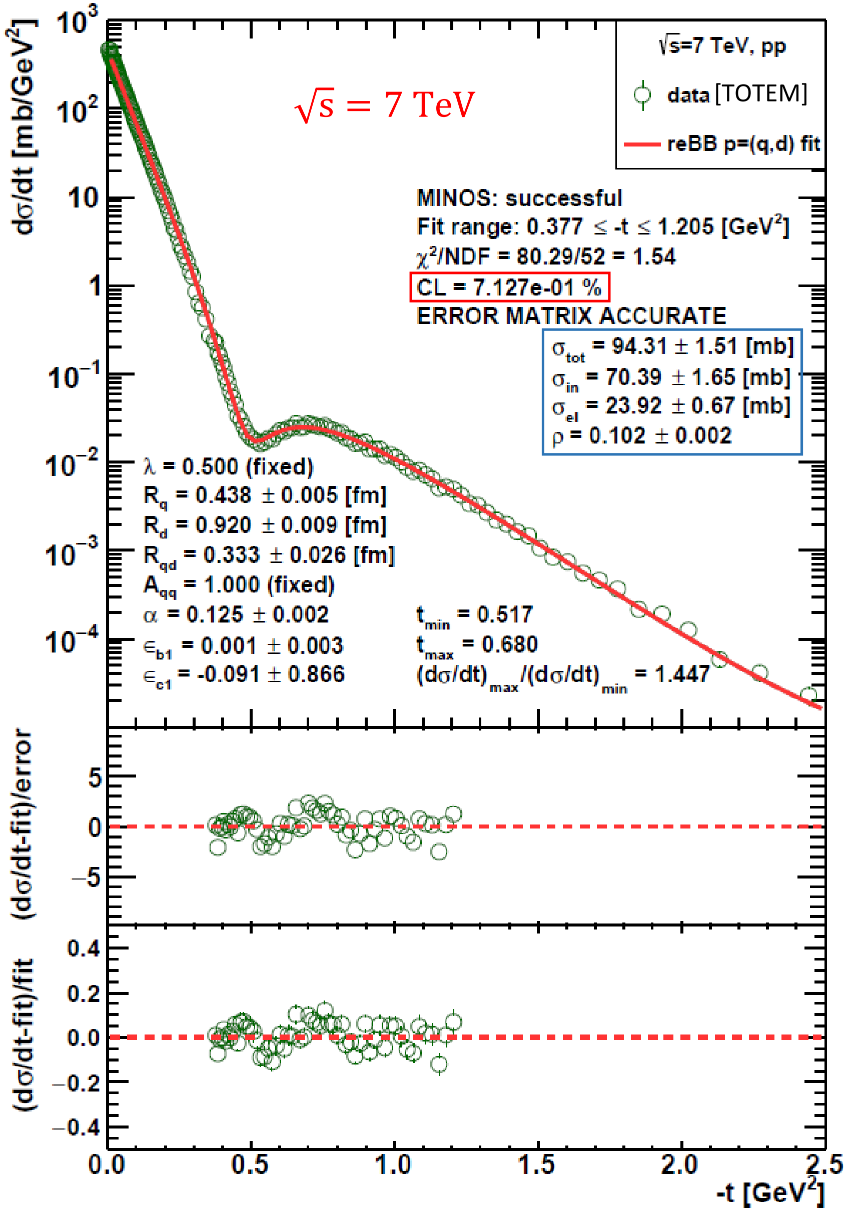


data: D0 Collab. (TEVATRON) Phys.Rev. D86 (2012)

Satisfactory ReBB model fits for pp dσ/dt data

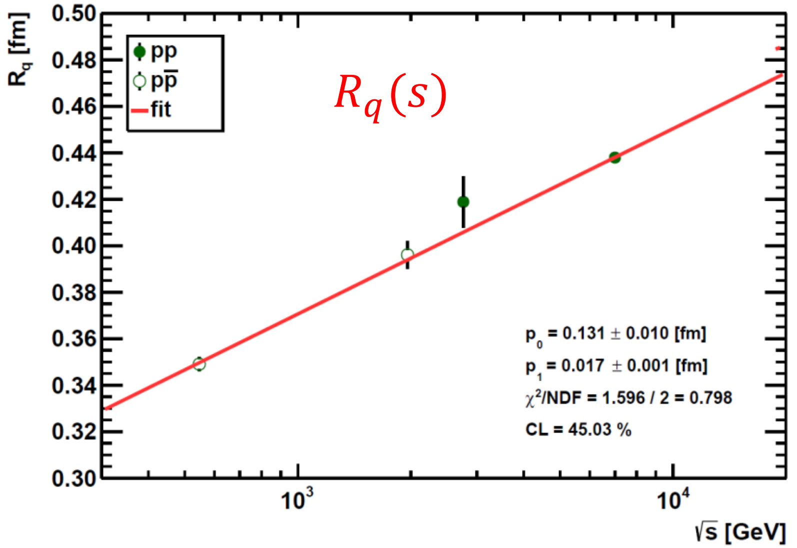


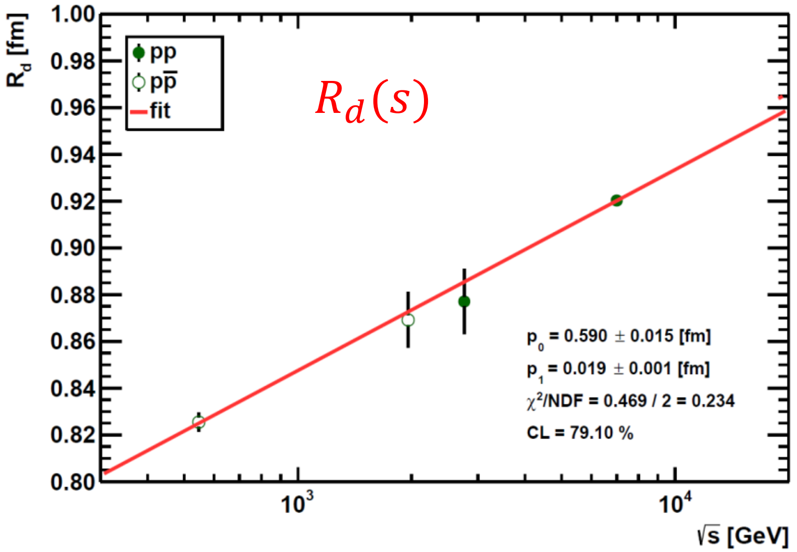
data: TOTEM Collab. (LHC) Eur. Phys. J. C 80 (2020) 91

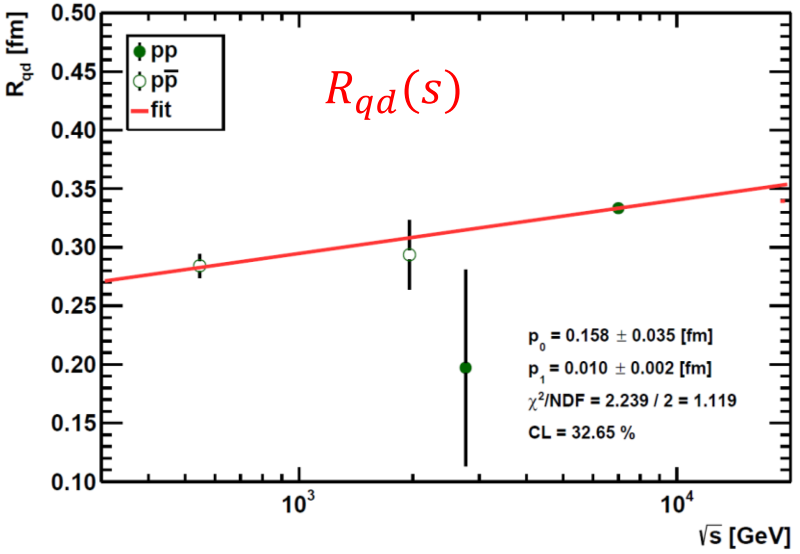


data: TOTEM Collab. (LHC) Europhys.Lett. 98 (2012)

Energy dependences of the scale parameters







The energy dependences of the scale parameters, R_q, R_d and R_{qd}, are the same for pp and $p\bar{p}$ processes!

$$P(s) = p_0 + p_1 ln(s/s_0)$$

$$P \in \{R_q, R_d, R_{qd}, \alpha\}$$

$$s_0 = 1\ GeV^2$$

Parameter	R_q $[fm]$	R_d $[fm]$	R_{qd} $[fm]$
χ^2/NDF	1.596/2	0.469/2	2.239/2
CL [%]	45.03	79.10	32.65
p_0	0.131 ± 0.010	0.590 ± 0.015	0.158 ± 0.035
p_1	0.017 ± 0.001	0.019 ± 0.001	0.010 ± 0.002

Parameters which define the energy dependence of the ReBB model scale parameters

New: proportionality between $\rho_0(s)$ and $\alpha(s)$

$$t_{el}(s,b) = i\left(1 - e^{i\,\alpha\,\tilde{\sigma}_{in}(s,b)}\sqrt{1-\tilde{\sigma}_{in}(s,b)}\right)$$

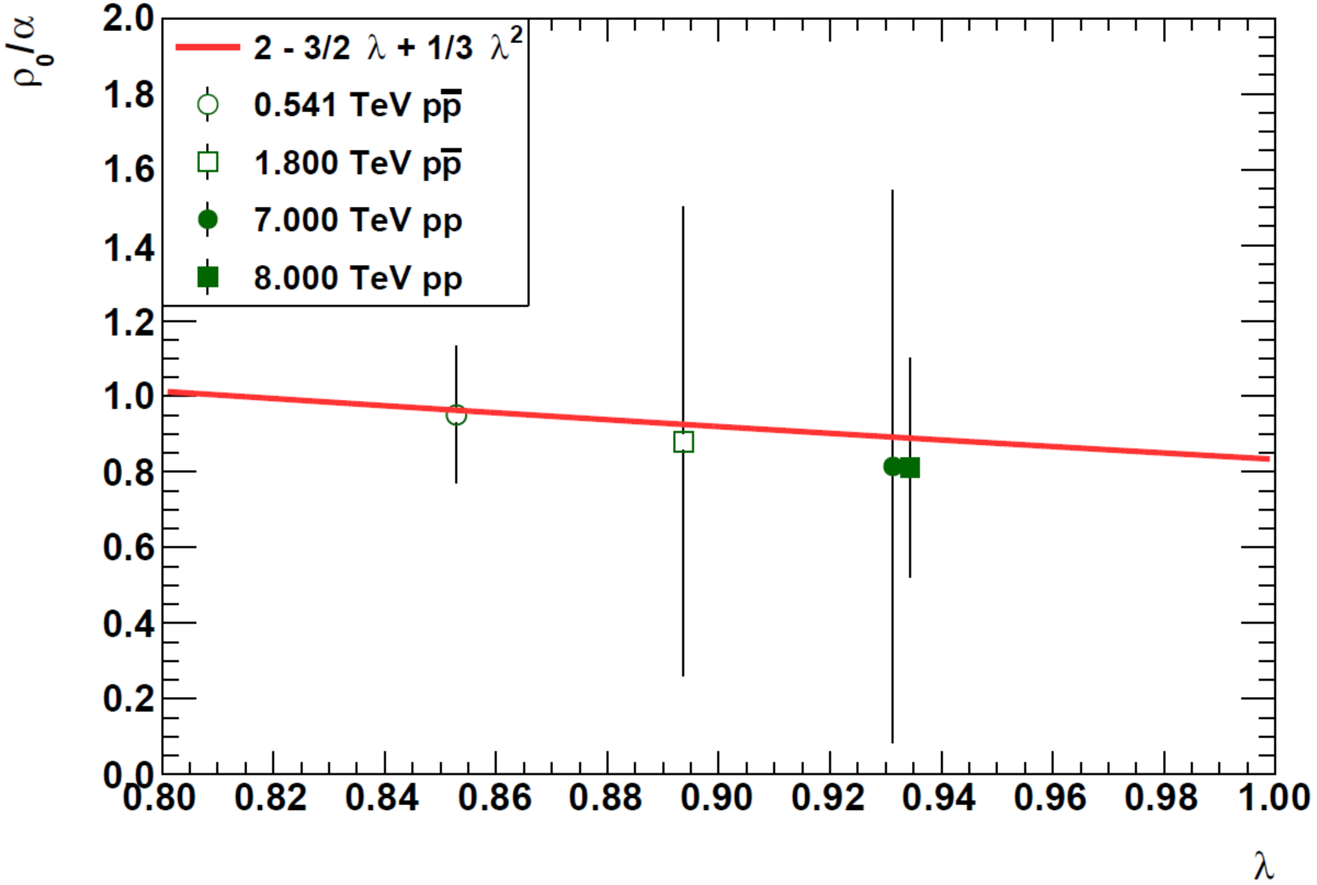
$$\alpha\tilde{\sigma}_{in} \ll 1$$

$$\mathrm{Im}\, t_{el}(s,b) \simeq \lambda(s)\exp\left(-\frac{b^2}{2R^2(s)}\right)$$

$$\rho_0(s) = \alpha(s)\left(2 - \frac{3}{2}\lambda(s) + \frac{1}{3}\lambda^2(s)\right)$$

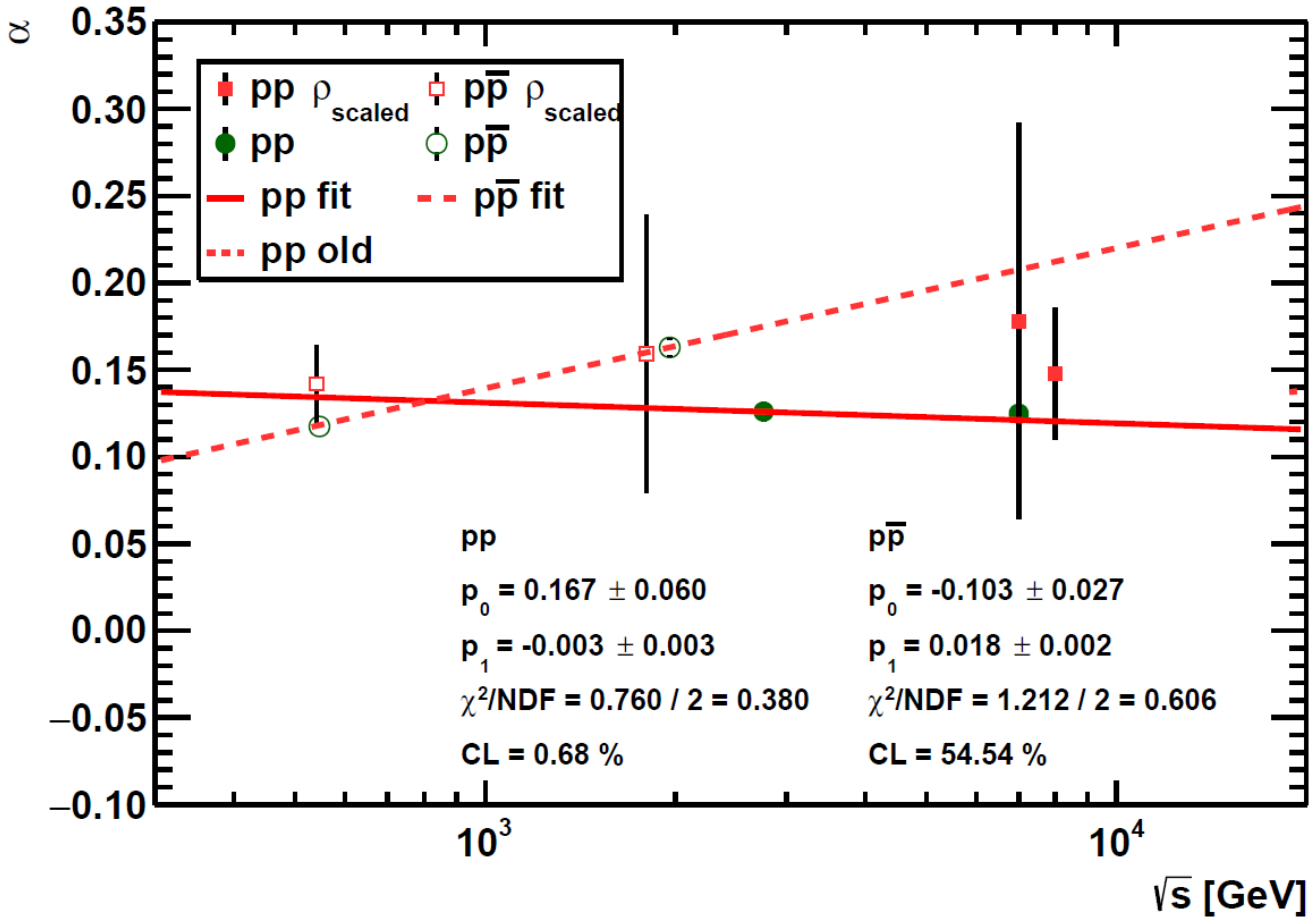
$$\lambda(s) = \mathrm{Im}\, t_{el}(s, b=0)$$

→ by rescaling one can get additional α parameter values at energies where ρ_0 is measured



The dependence of ρ_0/α on $\lambda = \mathrm{Im}\, t_{el}(s, b=0)$ in the TeV energy range. The data points are generated numerically by using the trends of the ReBB model scale parameters and the experimentally measured ρ-parameter values.

Energy dependence of the α parameter



$$P(s) = p_0 + p_1 ln(s/s_0)$$

$$P \in \{R_q, R_d, R_{qd}, \alpha\}$$

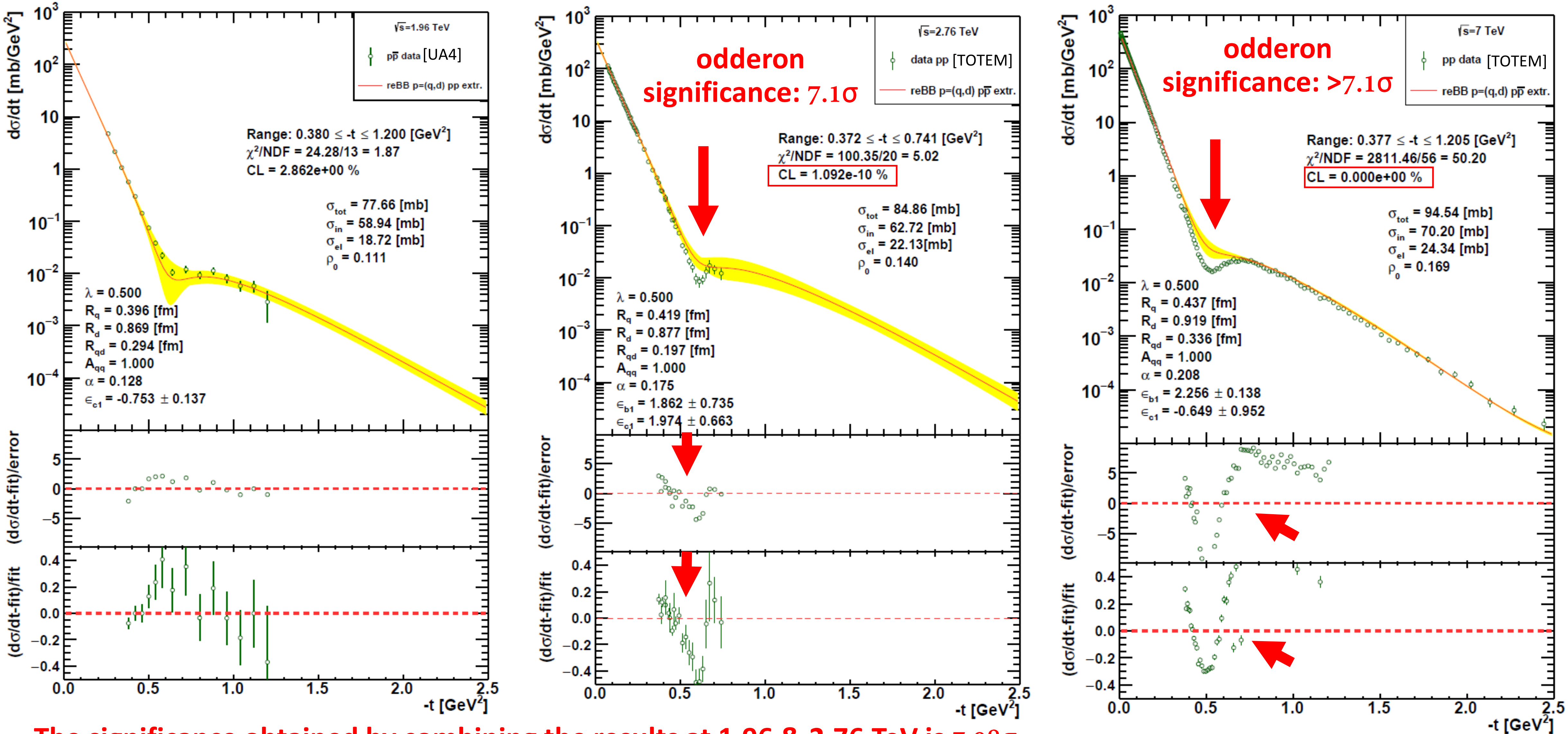
$$s_0 = 1\ GeV^2$$

Parameter	$\alpha\ (pp)$	$\alpha\ (p\bar{p})$
χ^2/NDF	$0.760/2$	$1.212/2$
CL [%]	0.68	54.54
p_0	0.167 ± 0.060	-0.103 ± 0.027
p_1	-0.003 ± 0.003	0.018 ± 0.002

Parameters which define the energy dependence of the ReBB model α parameters for pp and $p\bar{p}$

The energy dependence of the α parameter is not the same for pp and $p\bar{p}$ processes
→ the Odderon is characterized by a single parameter, α!

Extrapolations → ODDERON



The significance obtained by combining the results at 1.96 & 2.76 TeV is 7.08σ.
Combining to them also the result at 7 TeV the significance becomes indeterminably high.

H(x) scaling of the ReBB model

- **conditions:**
  - energy independence for the α parameter (or ρ_0)

$$\alpha(s) = \alpha(s_0) \qquad (\text{or } \rho_0(s) = \rho_0(s_0))$$

  - the energy dependence of the scale parameters is determined by the same factorizable $b(s)$ scaling function

$$R_q(s) = b(s)R_q(s_0) \qquad R_d(s) = b(s)R_d(s_0) \qquad R_{qd}(s) = b(s)R_{qd}(s_0)$$

($\sqrt{s_0}$ is a reference energy to be chosen)

- **scaling of the measurables:**

$$\frac{d\sigma}{dt}(s,t) = b^2(s)\frac{d\sigma}{dt}\left(s_0, t_0 = \frac{t}{b^2(s)}\right) \qquad \sigma_{el}(s) = b^2(s)\sigma_{el}(s_0)$$

$$B_0(s) = b^2(s)B_0(s_0) \qquad \sigma_{tot}(s) = b^2(s)\sigma_{tot}(s_0)$$

b(s) scaling function

- **experimental determination of b(s):**

$$b(s) = \sqrt{\frac{\sigma_{el}(s)}{\sigma_{el}(s_0)}} \qquad b(s) = \sqrt{\frac{\sigma_{tot}(s)}{\sigma_{tot}(s_0)}}$$

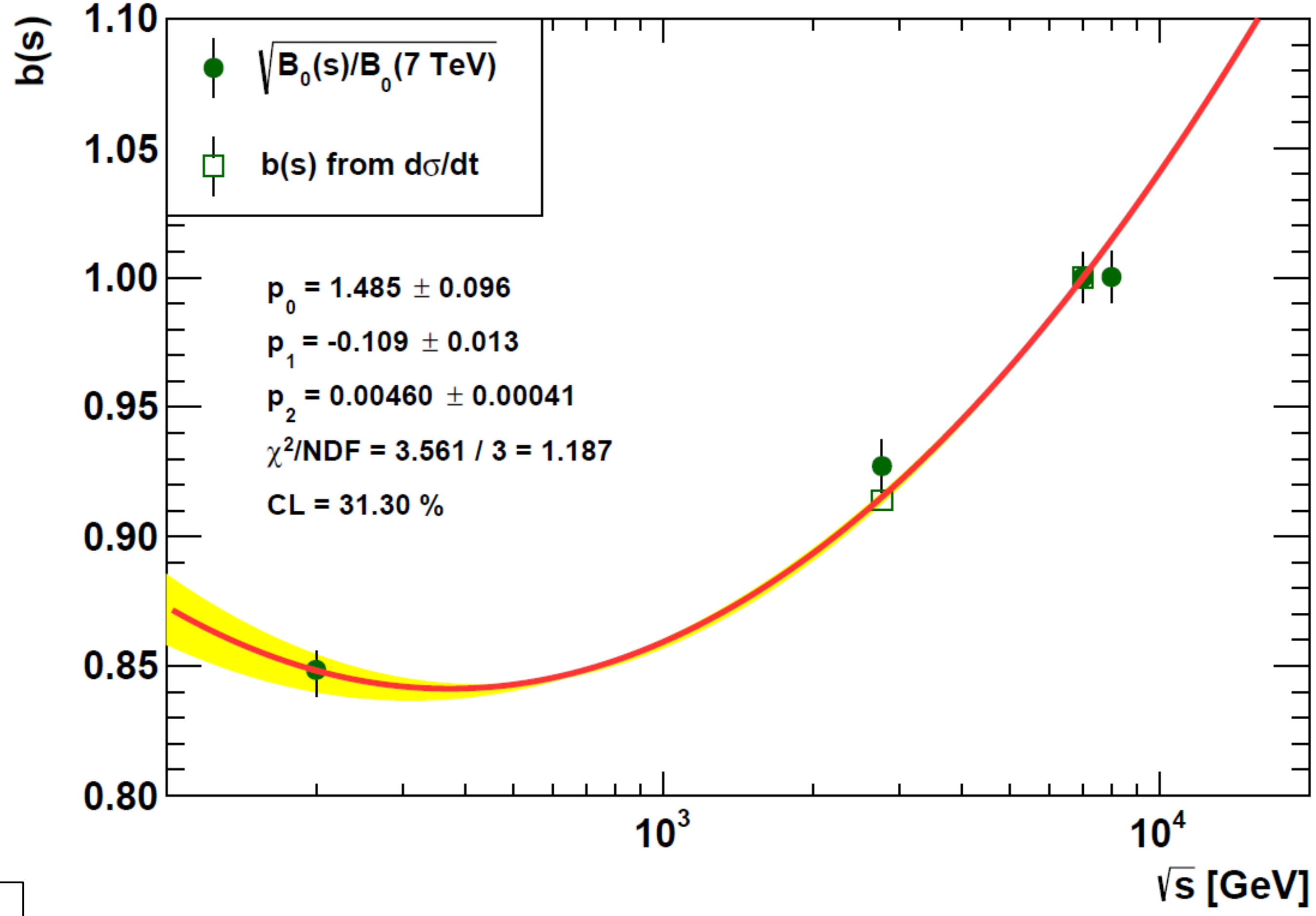
$$b(s) = \sqrt{\frac{B_0(s)}{B_0(s_0)}} \qquad b(s) = \sqrt{\frac{d\sigma/dt(s,t)}{d\sigma/dt\left(s_0, t_0 = t/b^2(s)\right)}}$$

  - the reference energy is chosen to be $\sqrt{s_0} = 7\ \mathrm{TeV}$

- **determination of the energy dependence:**

$$b(s) = p_0 + p_1 \ln(s/s_0) + p_2 \ln^2(s/s_0)$$

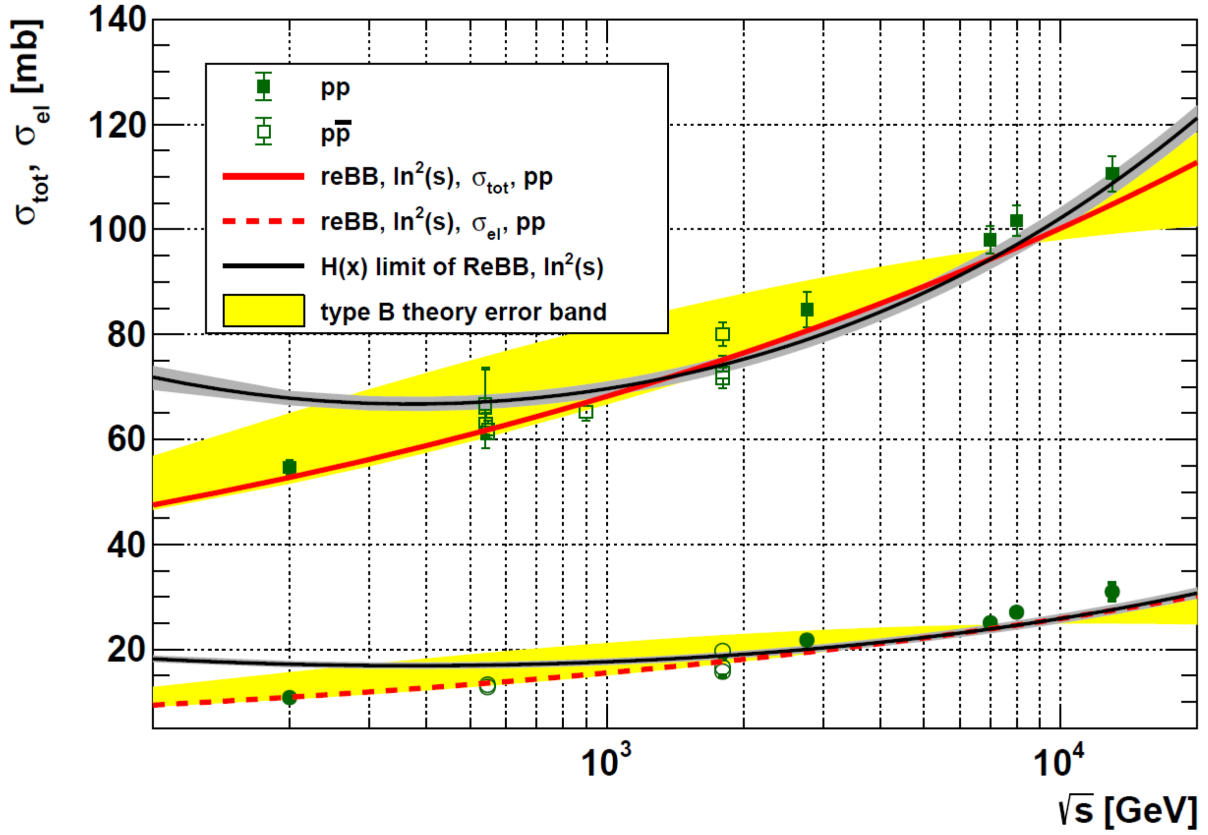
$$s_0 = 1\ GeV^2$$

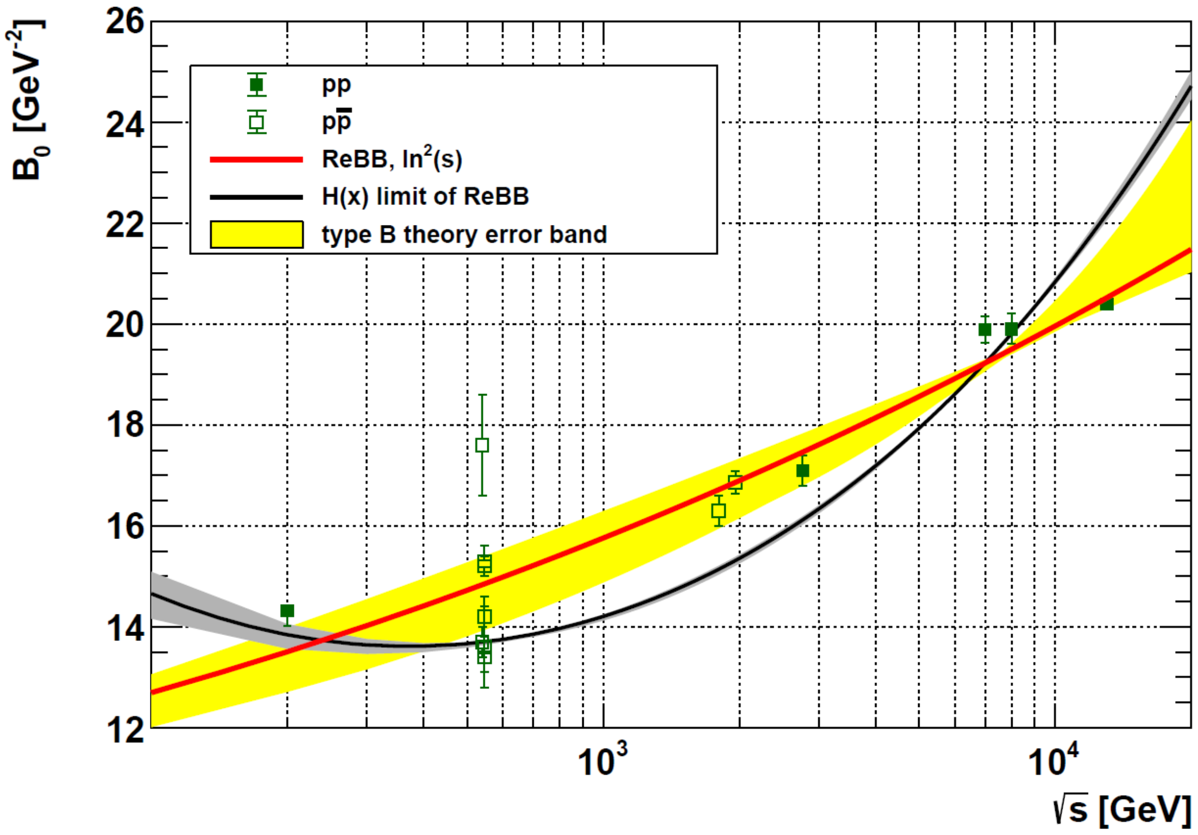


The energy dependence of the $b(s)$ scaling function utilizing the $B_0(s)$ and $d\sigma/dt(s,t)$ data and fitting with a squared logarithmic function.

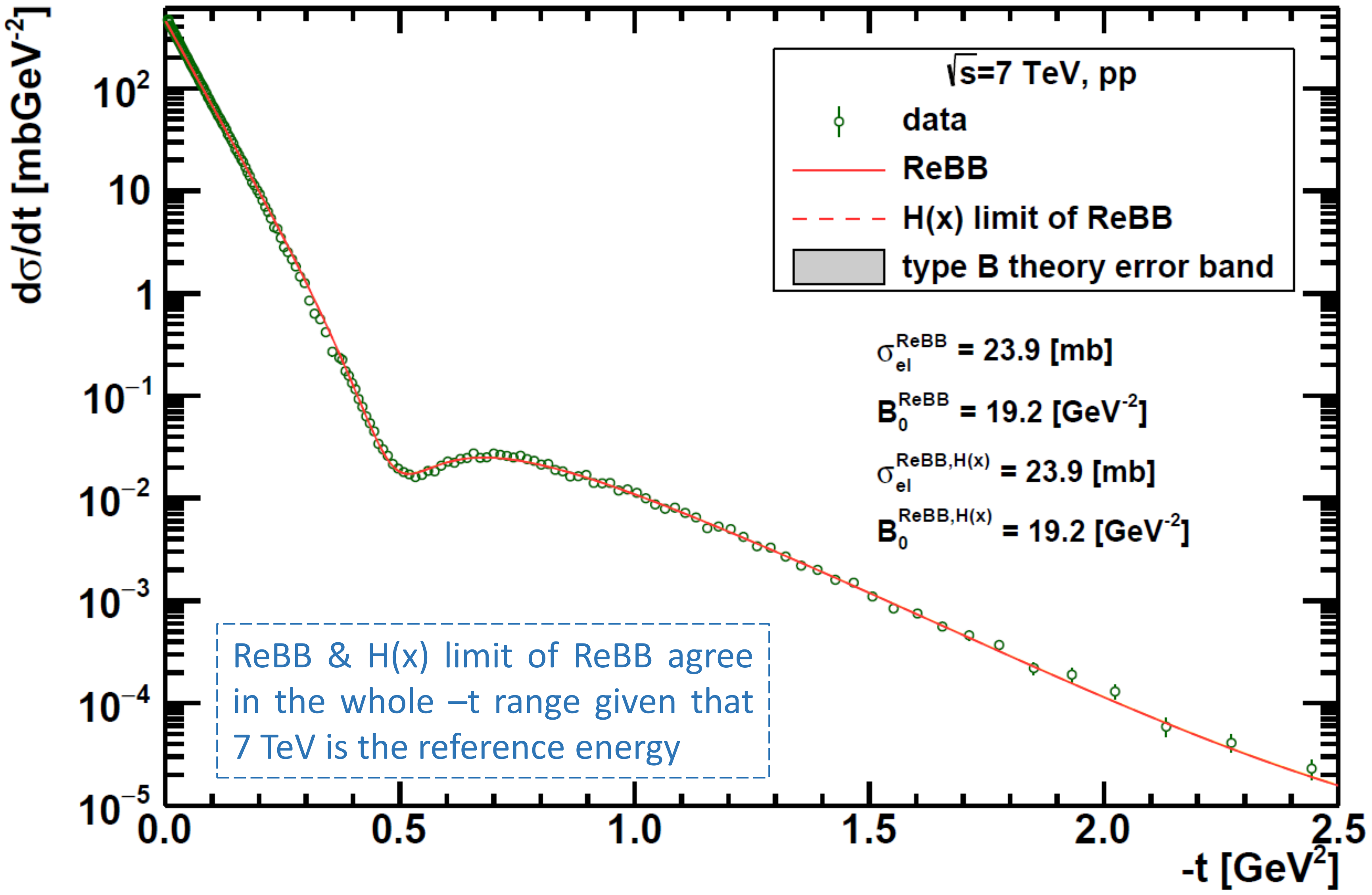
ReBB & H(x) limit of ReBB for pp $\sigma_{tot}(s)$, $\sigma_{el}(s)$, $B_0(s)$

- the ReBB & H(x) limit of ReBB curves, within the type B theory errors agree for $\sigma_{tot}(s)$ and $\sigma_{el}(s)$ down to about 300 GeV
- because of the problems with ReBB model at low $-t$ the results for $B_0(s)$ are not reliable (→ further improvement of the model is needed)



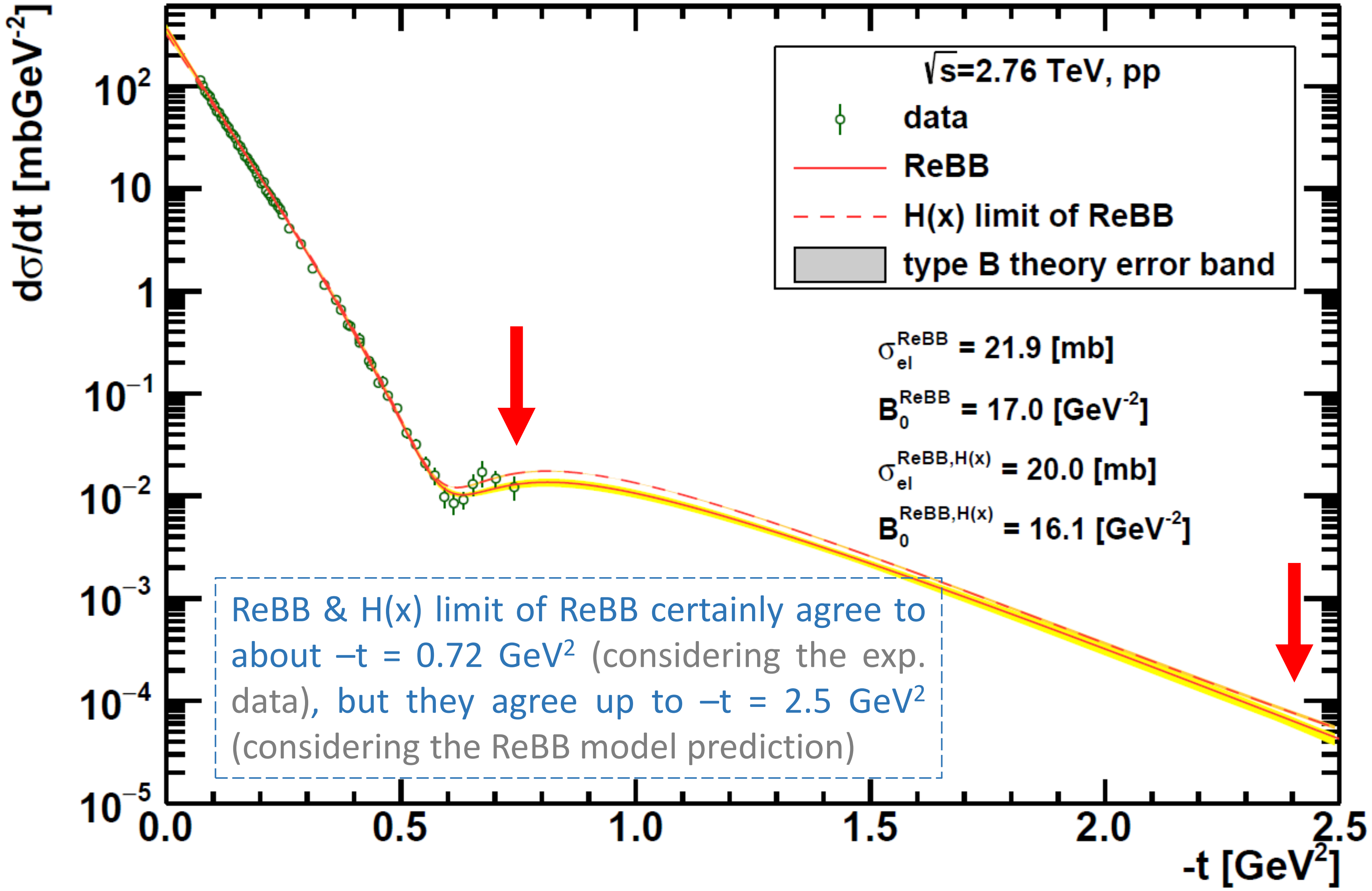


ReBB & H(x) limit of ReBB for pp $d\sigma/dt$ @ 7 TeV



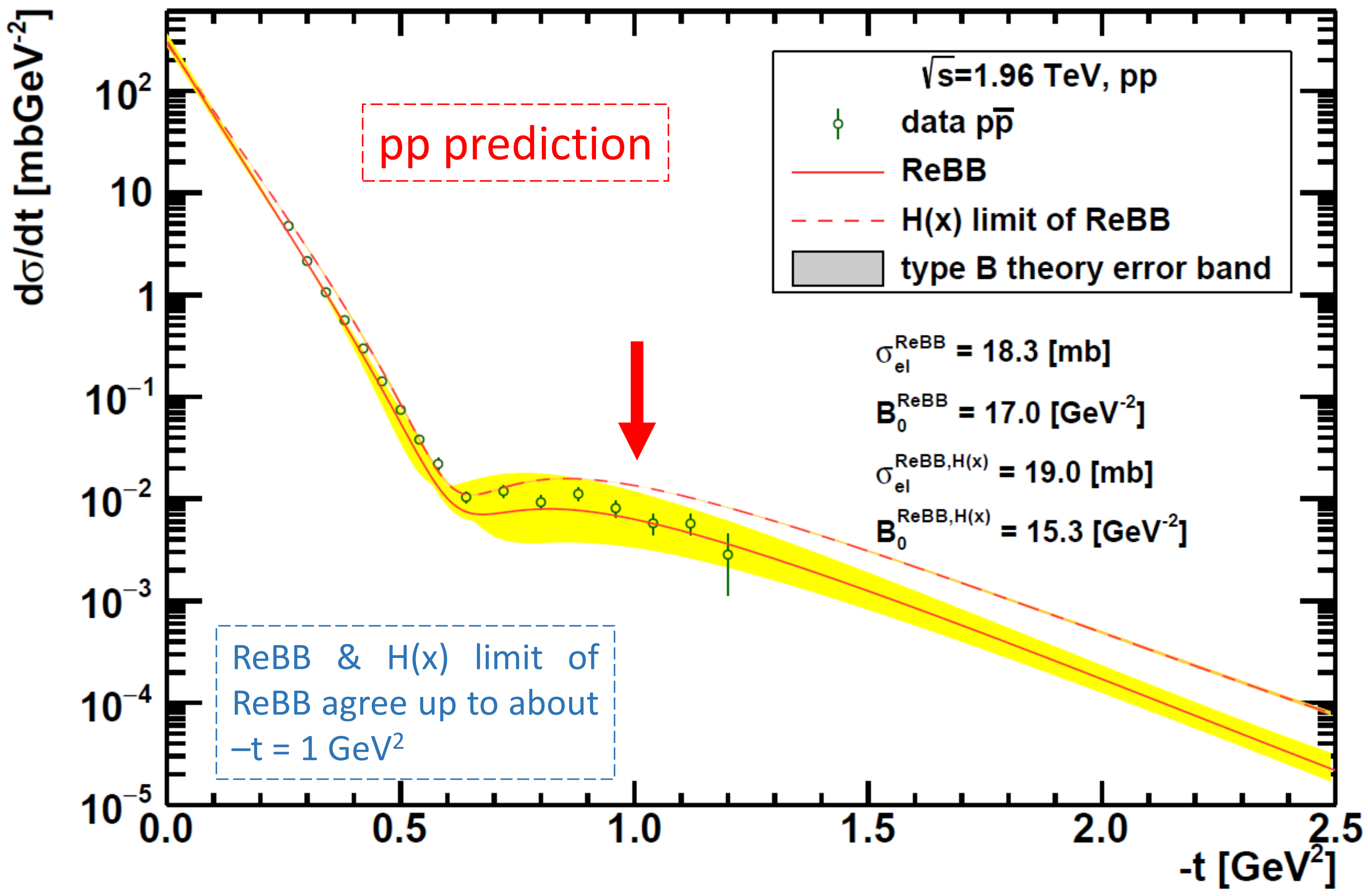
ReBB & H(x) limit of ReBB agree in the whole –t range given that 7 TeV is the reference energy

ReBB & H(x) limit of ReBB for pp $d\sigma/dt$ @ 2.76 TeV

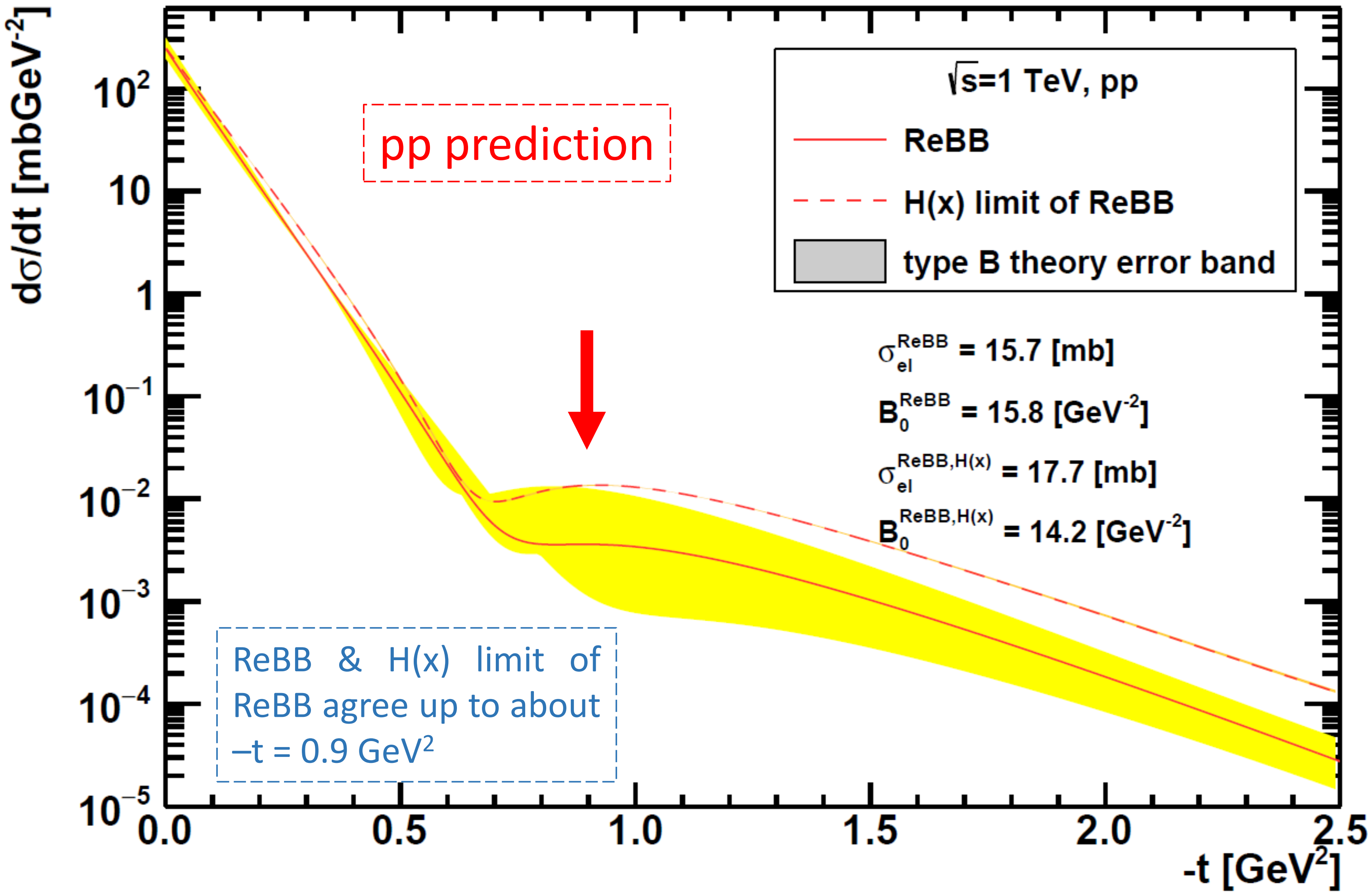


ReBB & H(x) limit of ReBB certainly agree to about $-t$ = 0.72 GeV^2 (considering the exp. data), but they agree up to $-t$ = 2.5 GeV^2 (considering the ReBB model prediction)

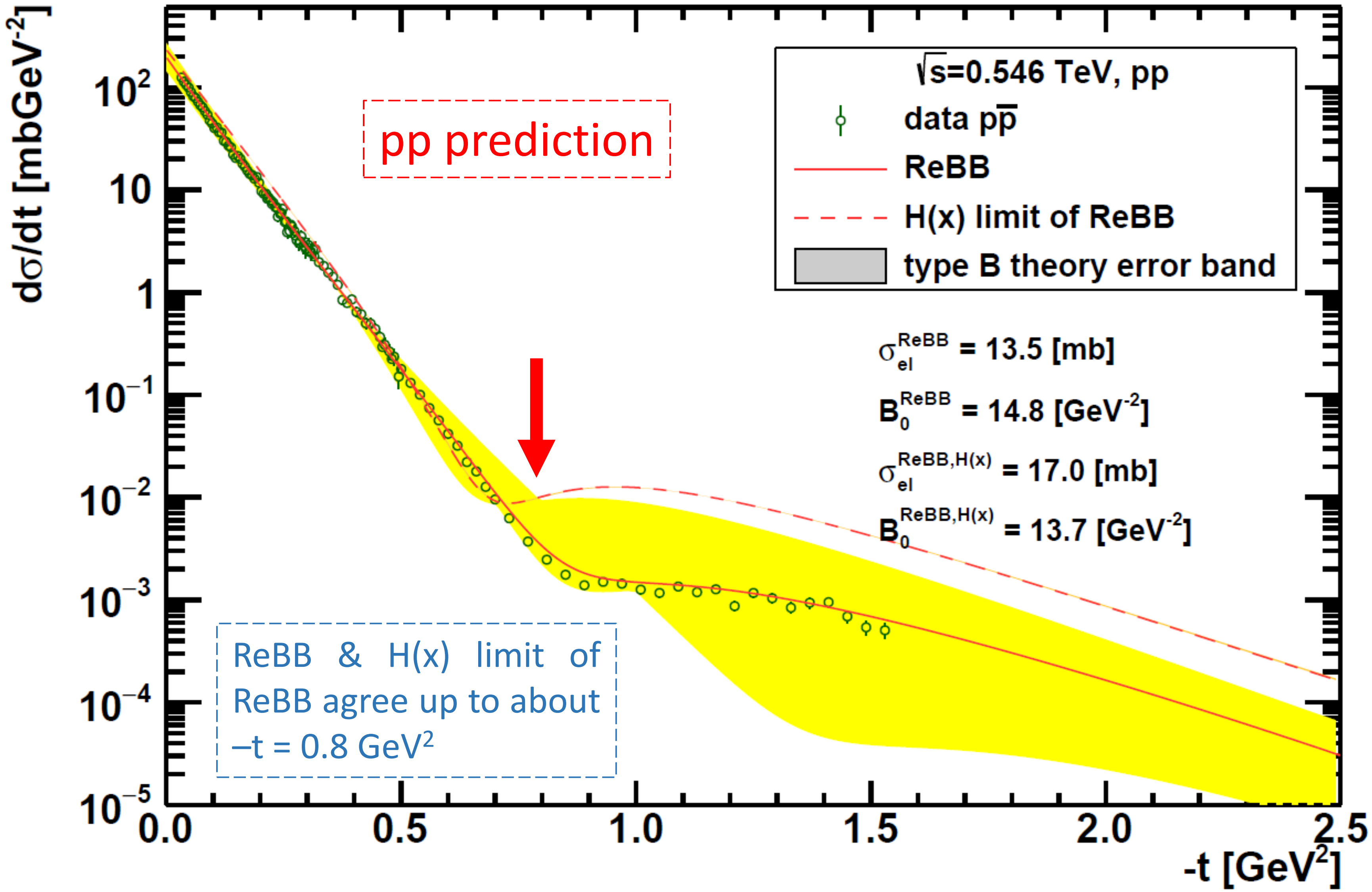
ReBB & H(x) limit of ReBB for pp $d\sigma/dt$ @ 1.96 TeV



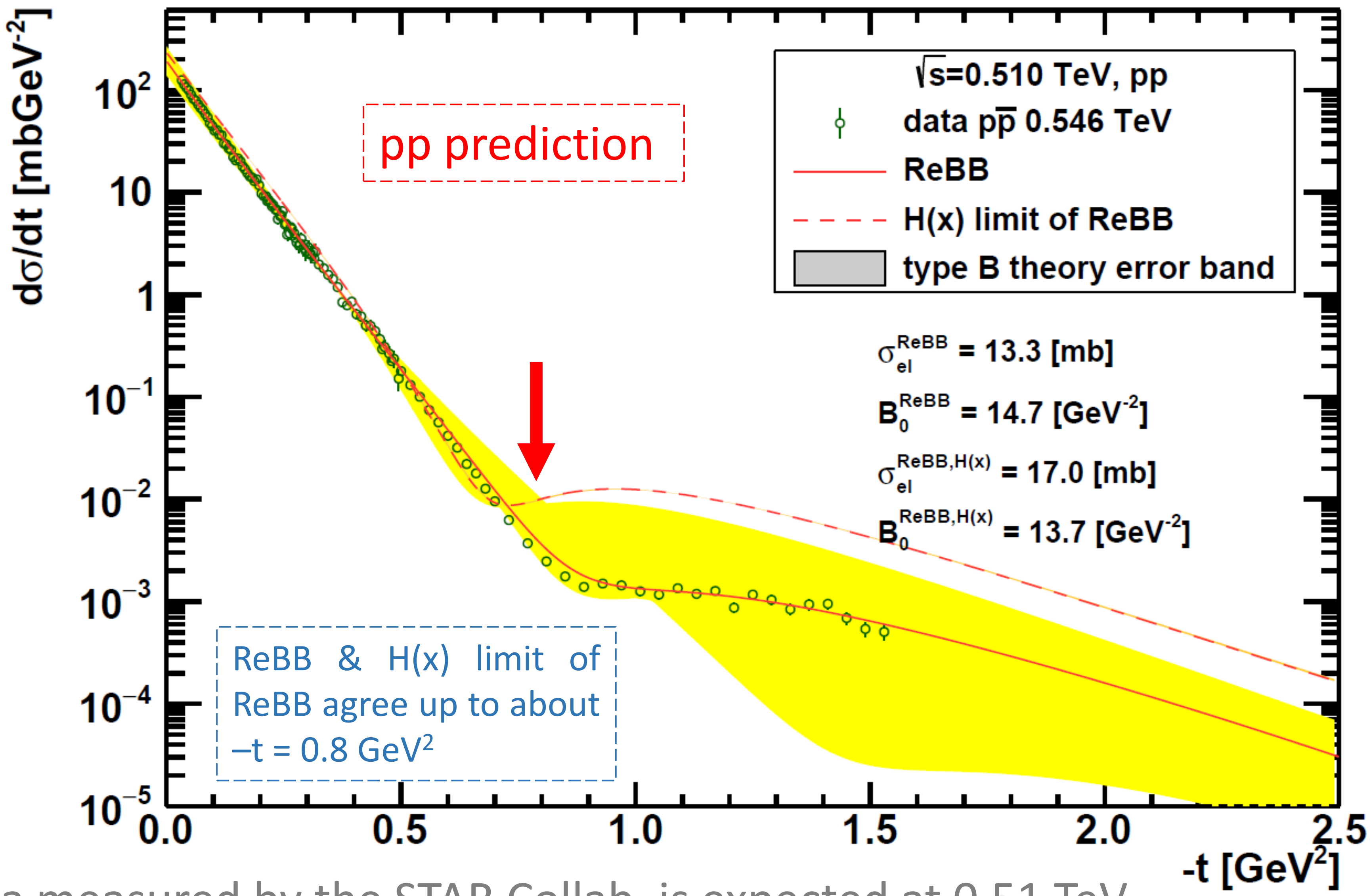
ReBB & H(x) limit of ReBB for pp $d\sigma/dt$ @ 1 TeV



ReBB & H(x) limit of ReBB for pp $d\sigma/dt$ @ 0.546 TeV

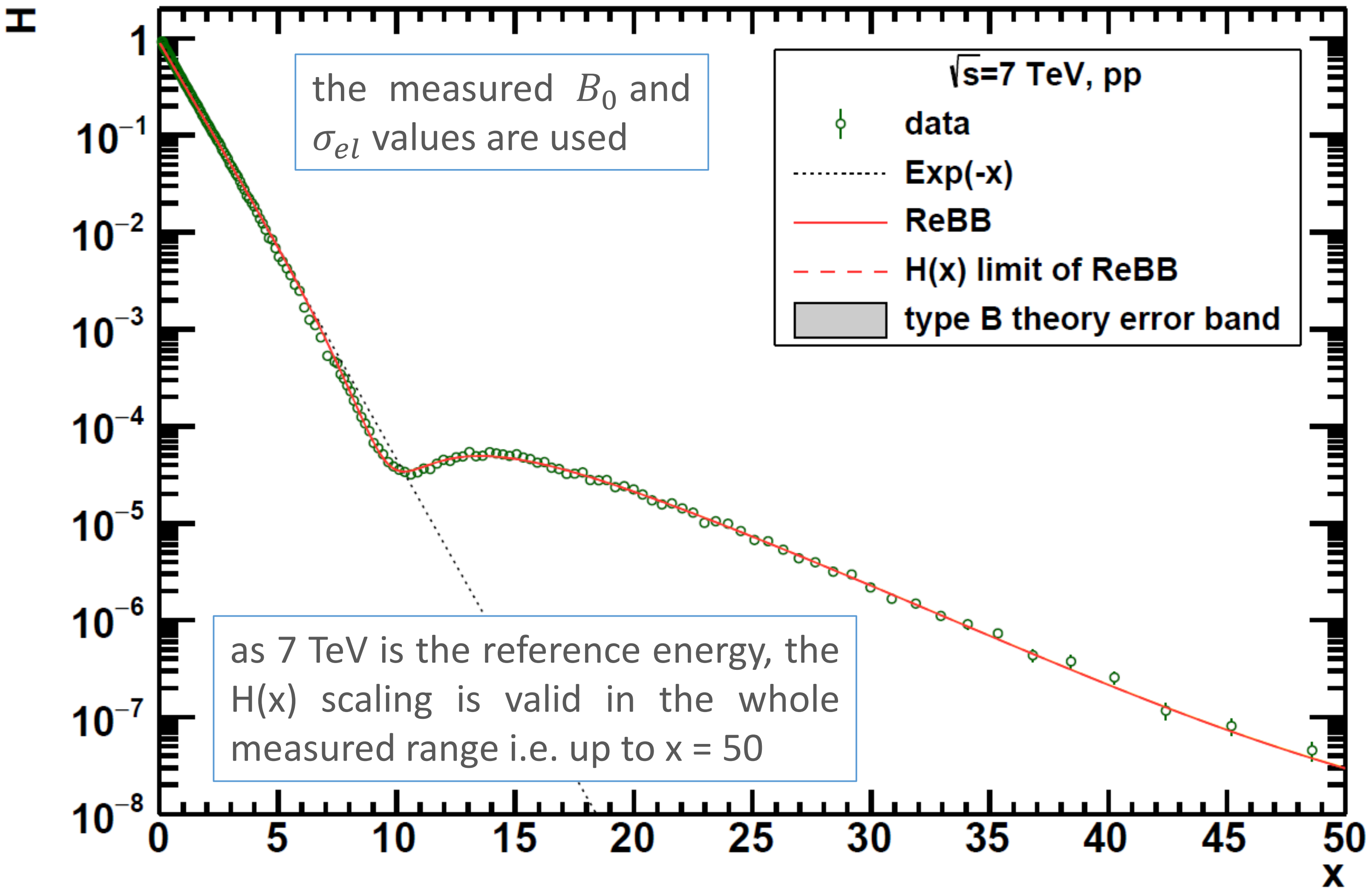


ReBB & H(x) limit of ReBB for pp $d\sigma/dt$ @ 0.51 TeV



- pp data measured by the STAR Collab. is expected at 0.51 TeV

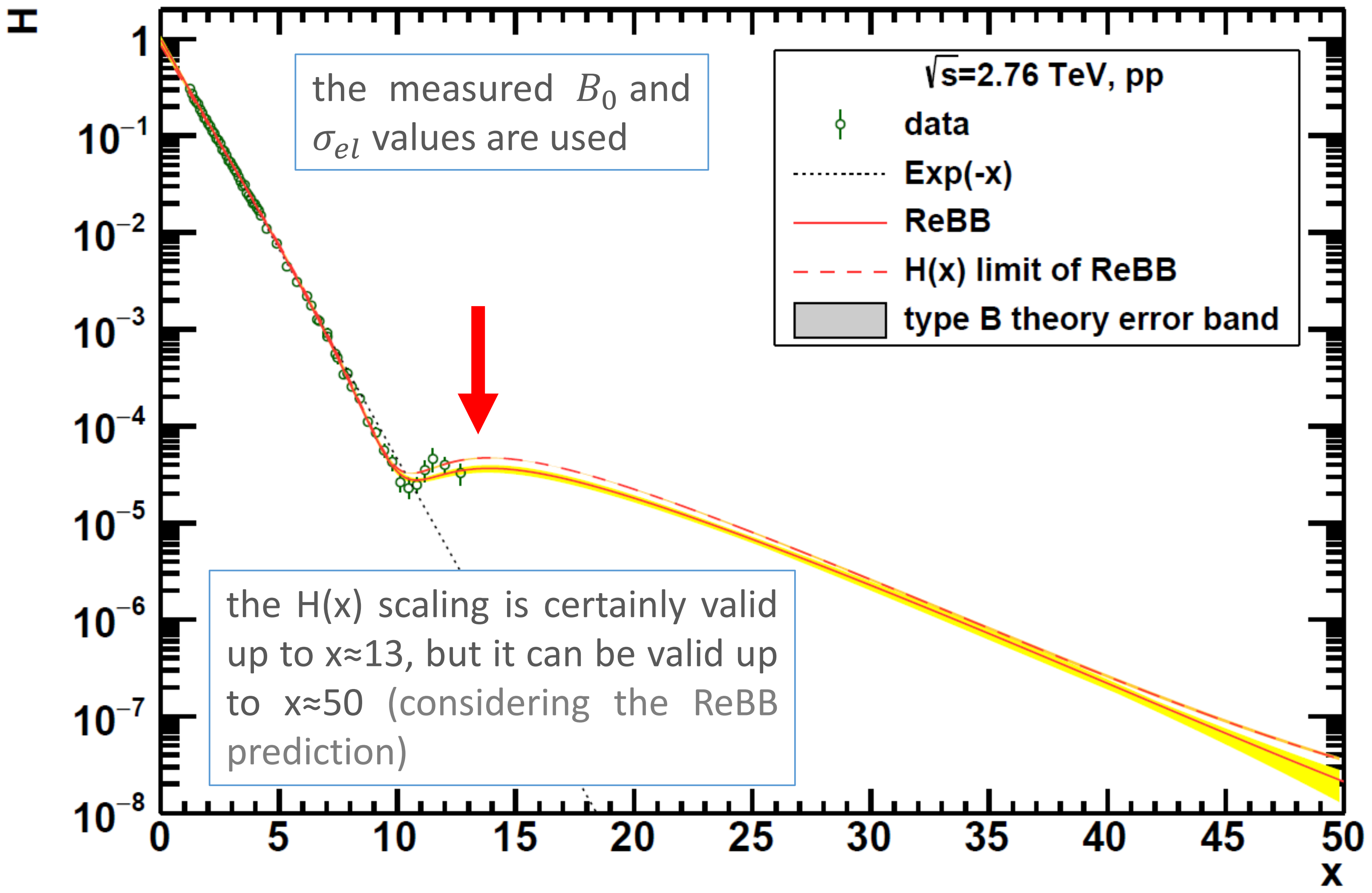
ReBB & H(x) limit of ReBB for pp $\mathrm{H}(\mathrm{x})$ @ 7 TeV



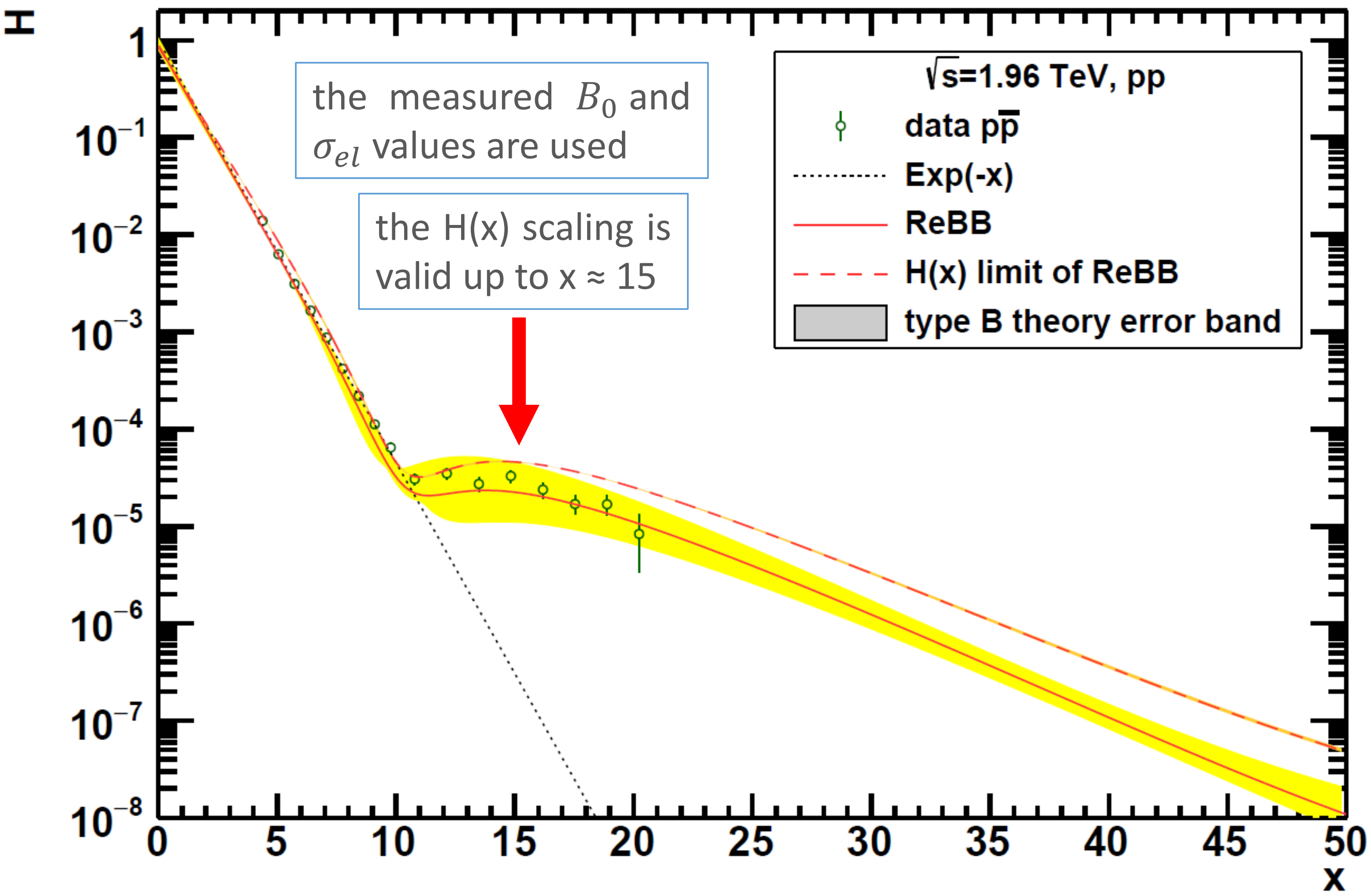
the measured B_0 and σ_{el} values are used

as 7 TeV is the reference energy, the H(x) scaling is valid in the whole measured range i.e. up to x = 50

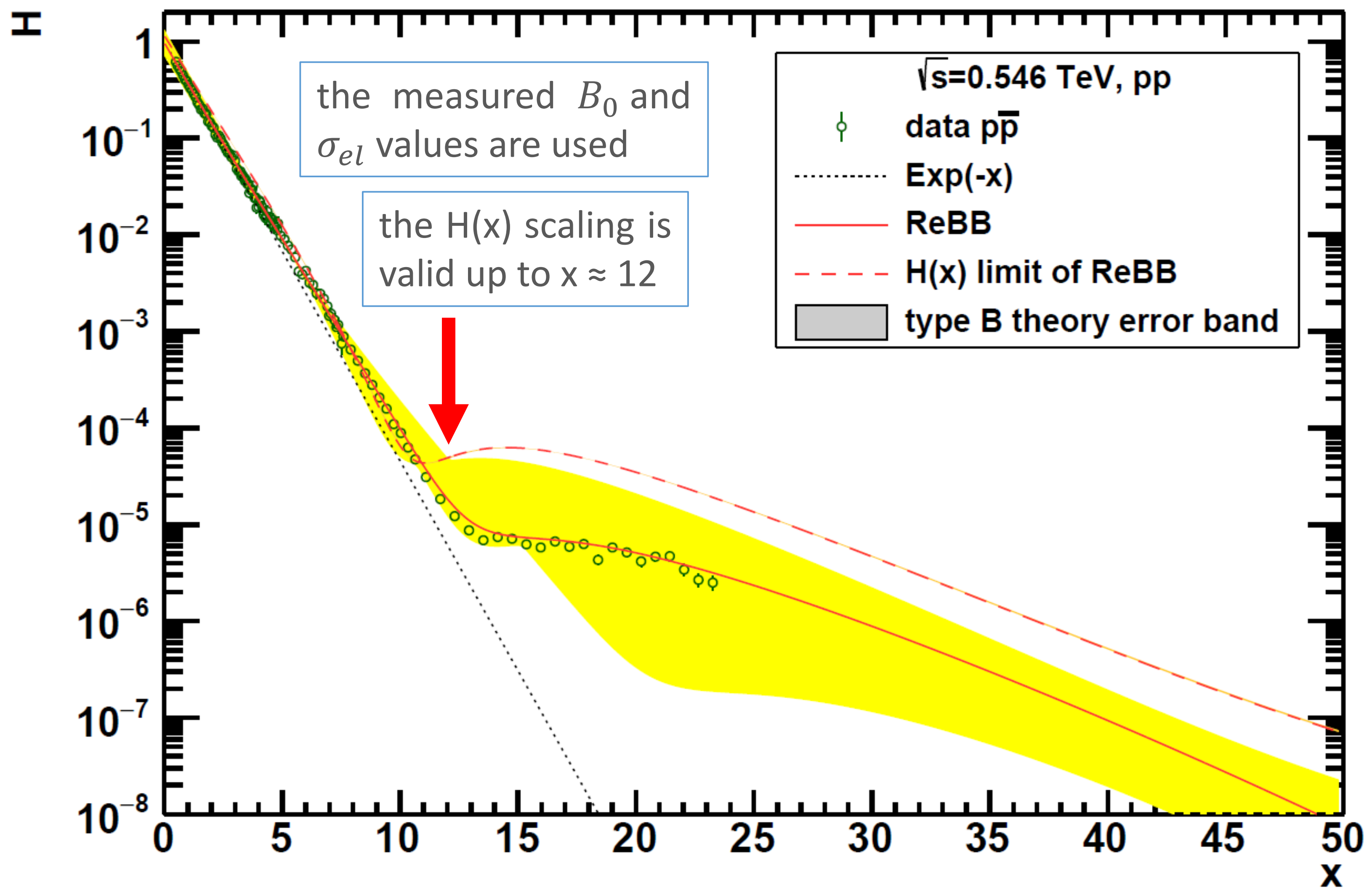
ReBB & H(x) limit of ReBB for pp H(x) @ 2.76 TeV



ReBB & H(x) limit of ReBB for pp H(x) @ 1.96 TeV



ReBB & H(x) limit of ReBB for pp H(x) @ 0.546 TeV

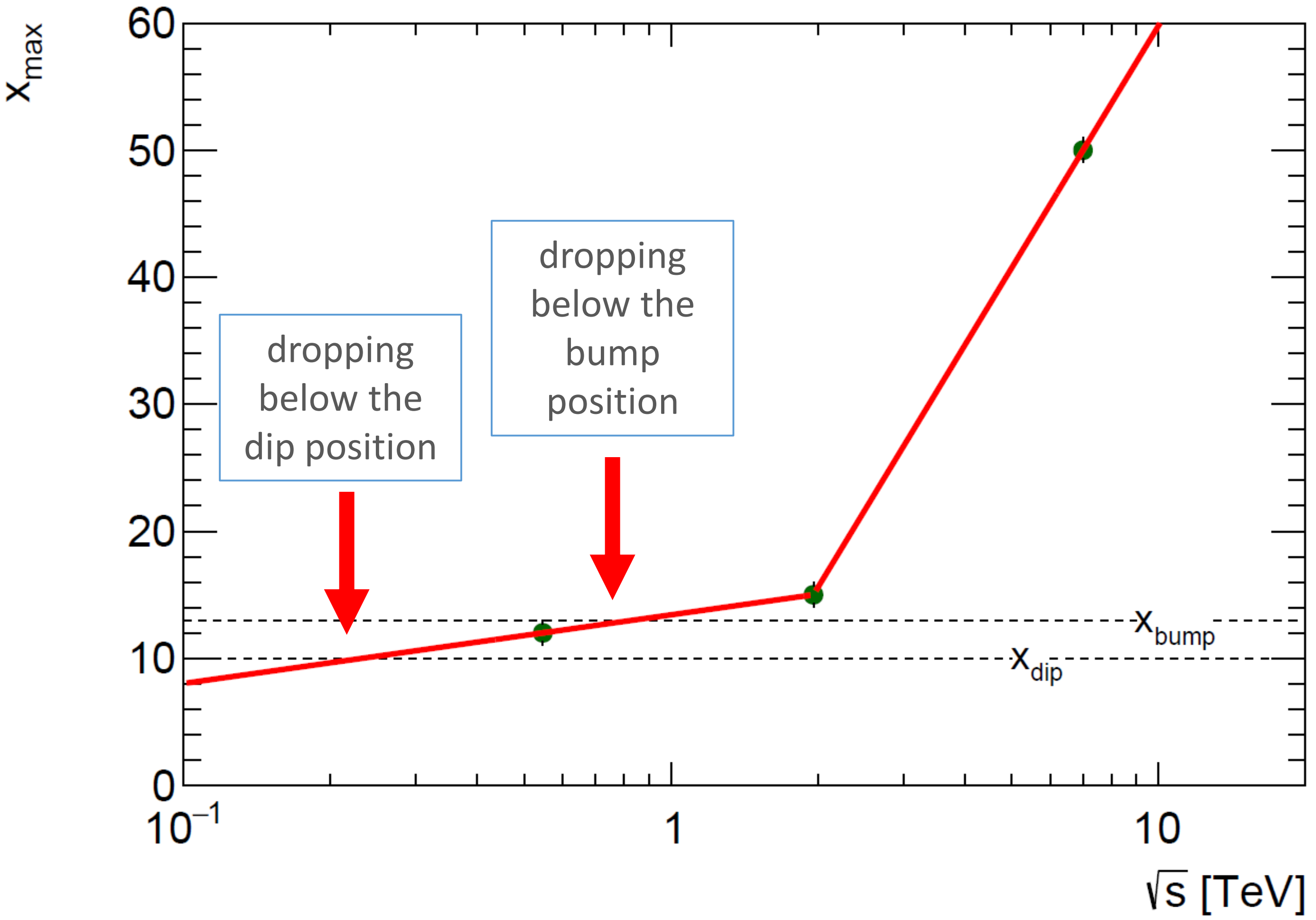


Validity of the H(x) scaling in x as a function of $\sqrt{s}$

- problems with ReBB model at low $-t$
  → only those energies are included where experimental data on $B_0(s)$ and $\sigma_{el}(s)$ are available

- at 2.76 TeV the measured x range is not extended enough to determine reasonably well the validity of the H(x) scaling
  → no 2.76 TeV point included

- at energies $\lesssim$ 800 GeV the validity range of the H(x) scaling drops below the bump position while at energies $\lesssim$ 200 GeV below the dip position



Approximate energy dependence of the maximum x value up to which the H(x) scaling is valid

Summary

- **ReBB model fits to pp and $p\bar{p}$ dσ/dt data**

→ satisfactory description in the energy range of $0.546 \leq \sqrt{s} \leq 7$ TeV and squared momentum transfer range of $0.37 \leq -t \leq 1.2$ GeV^2

- **determination of the energy dependence of the parameters & extrapolations to accomplish comparative study between pp and $p\bar{p}$ dσ/dt**

→ **model-dependent evidence for Odderon (colourless 3-gluon bound state) exchange with a significance of at least 7.08σ**

- **determination of the H(x) scaling limit of the ReBB model & model-dependent determination of the lower limit of the validity of the H(x) scaling**

→ for $\sigma_{tot}(s)$ and $\sigma_{el}(s)$ the scaling is valid down to $\sqrt{s} \approx 0.3\ \mathrm{TeV}$ (with $\sqrt{s_0} = 7\ \mathrm{TeV}$)

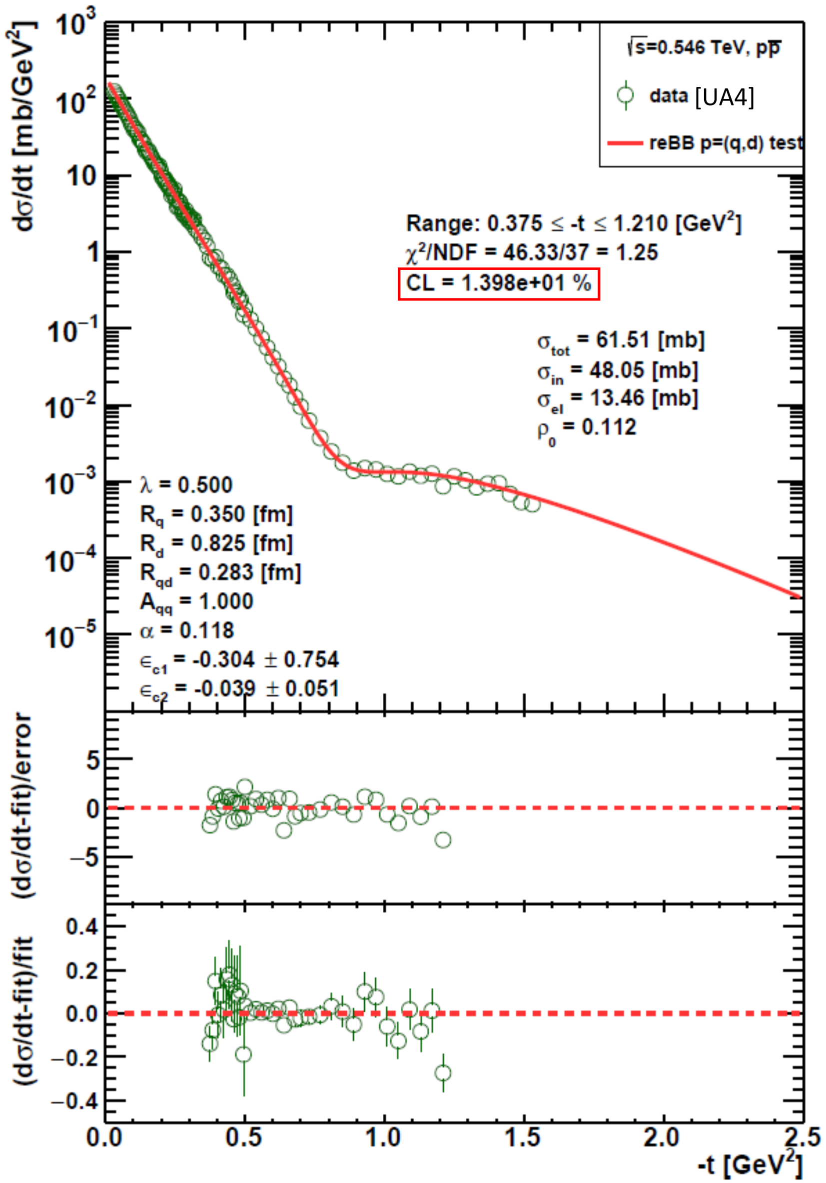
→ to determine the validity limit for $B_0(s)$ further improvement of the model is needed

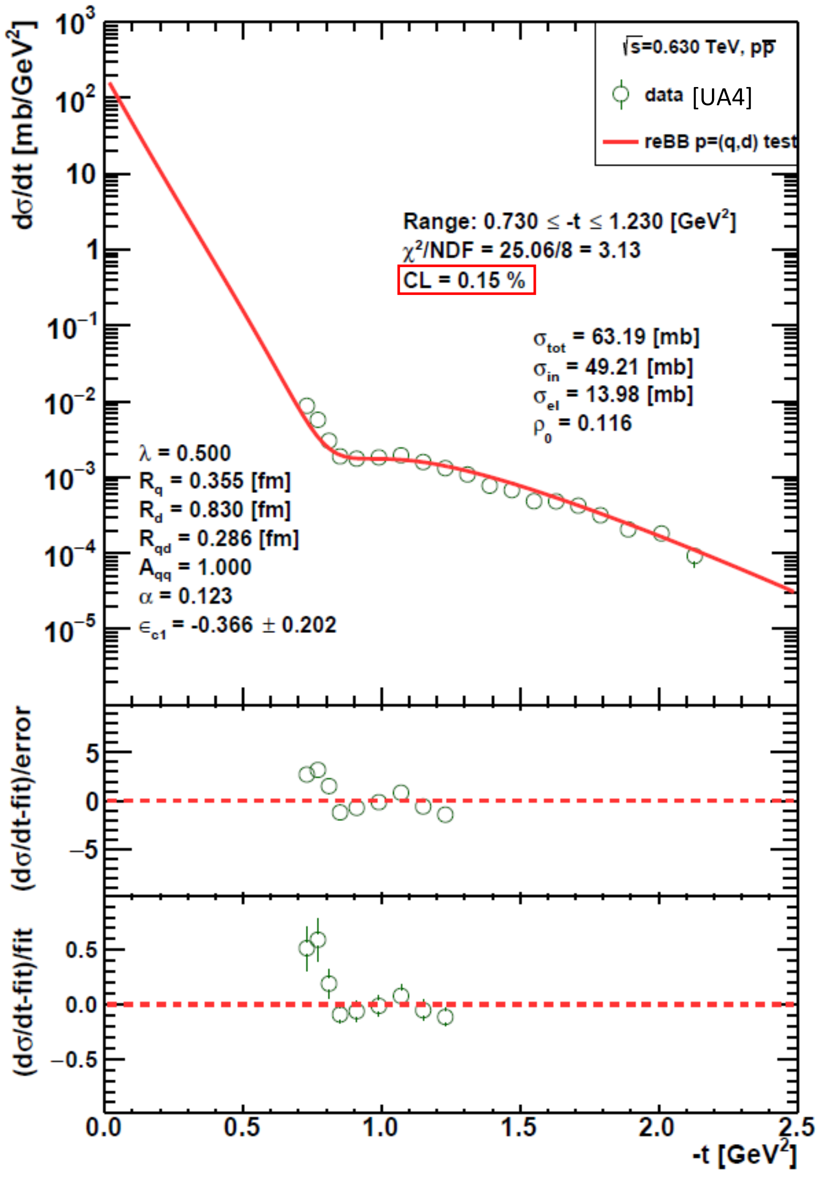
→ for $\mathrm{d}\sigma/\mathrm{dt}$ the maximum of the validity limit in x drops as the energy decreases: at $\sqrt{s_0} \lesssim 800\ \mathrm{GeV}$ below the bump position, at $\sqrt{s_0} \lesssim 200\ \mathrm{GeV}$ below the dip position

Thank you for your attention!

Backup slides

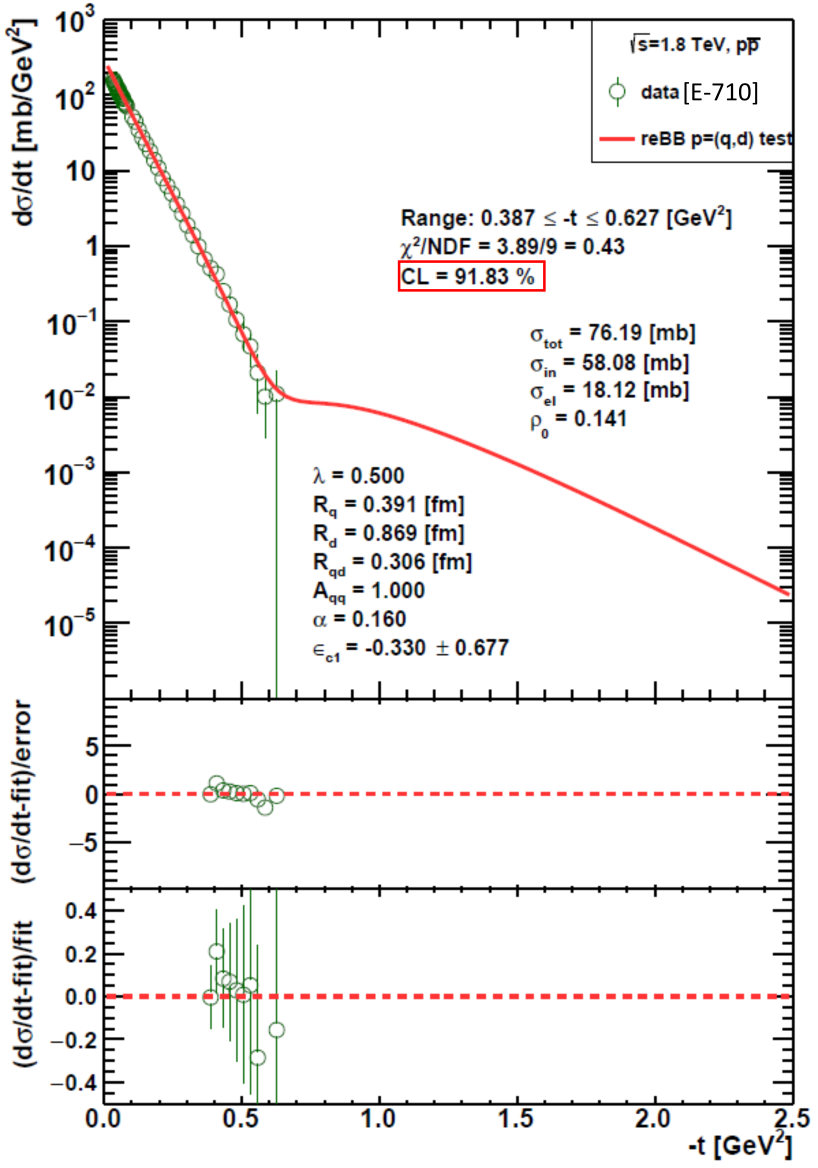
Tests @ 0.546 & 0.630 TeV ✓

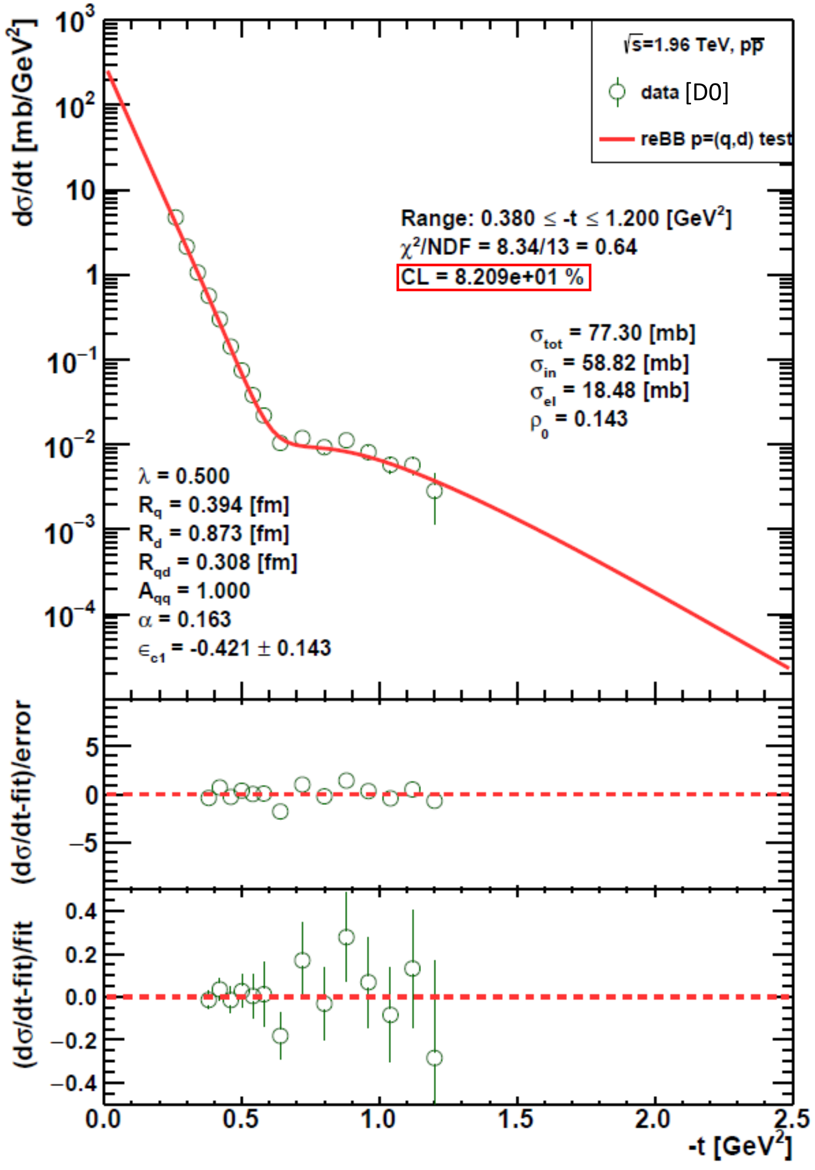




data: UA4 Collab. (SPS) Phys.Lett. B171 (1986)

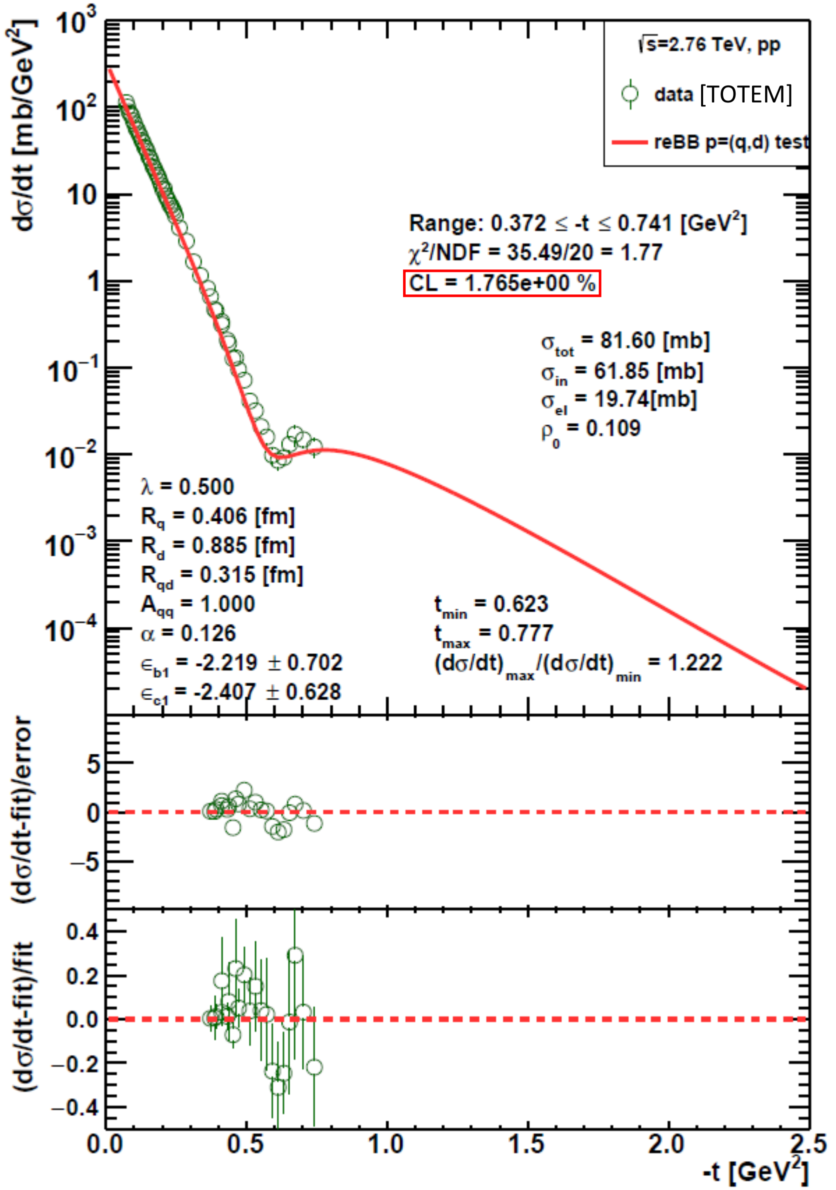
Tests @ 1.8 & 1.96 TeV ✓

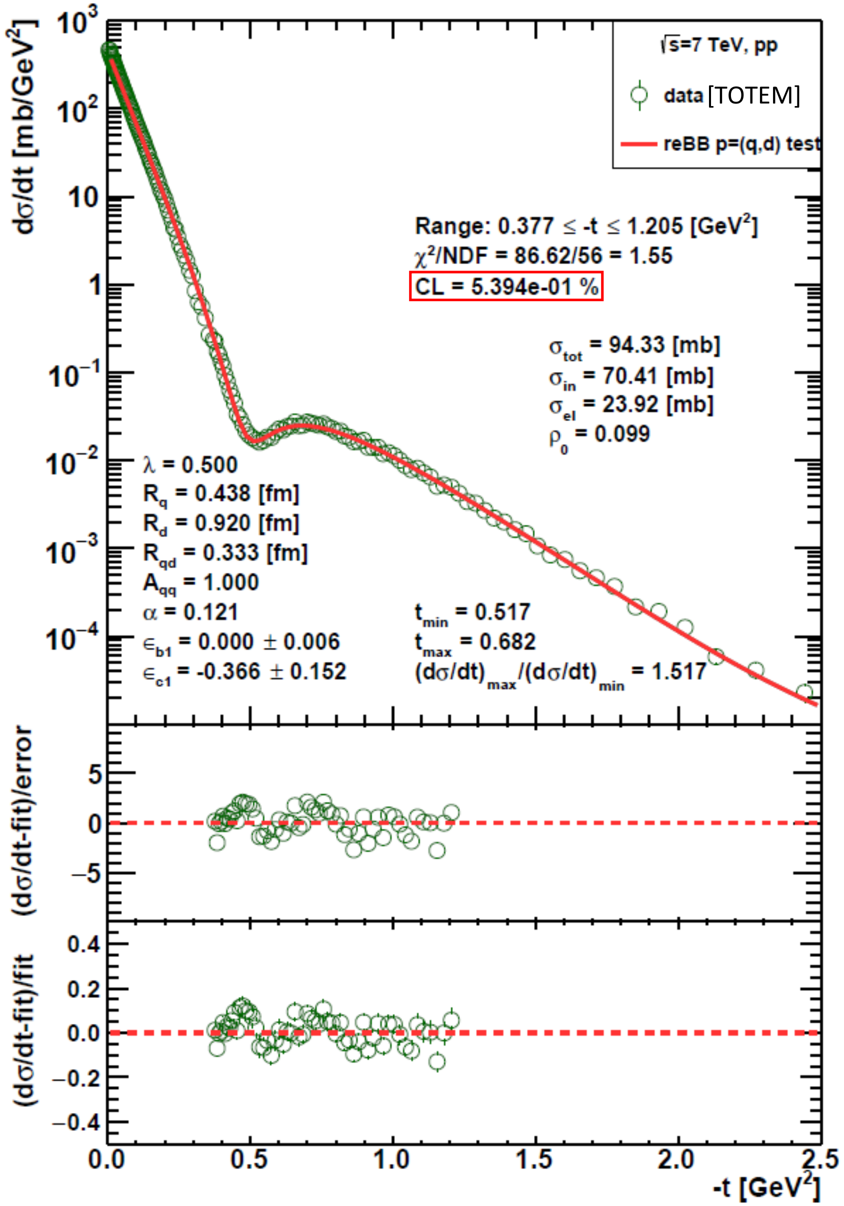




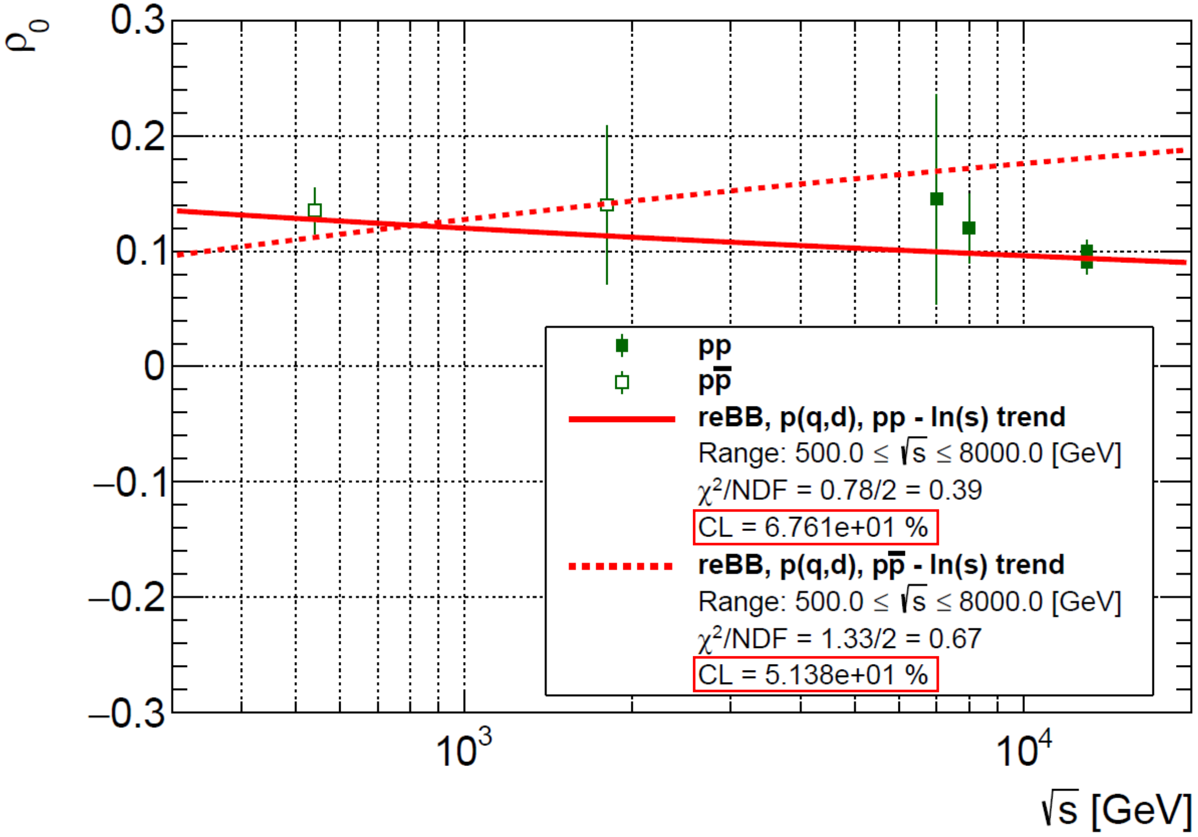
data: E-710 Collab. (TEVATRON) Phys.Lett. B247 (1990)

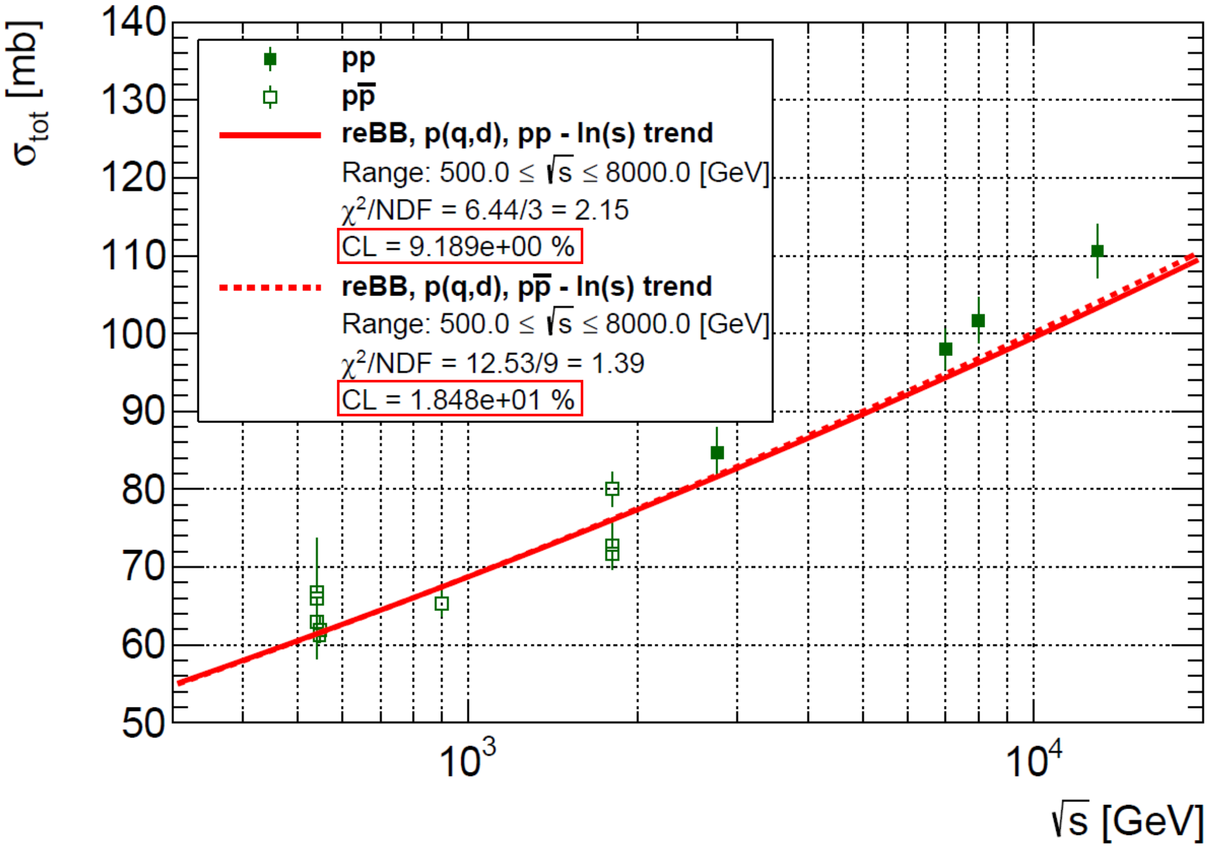
Tests @ 2.76 & 7.0 TeV ✓



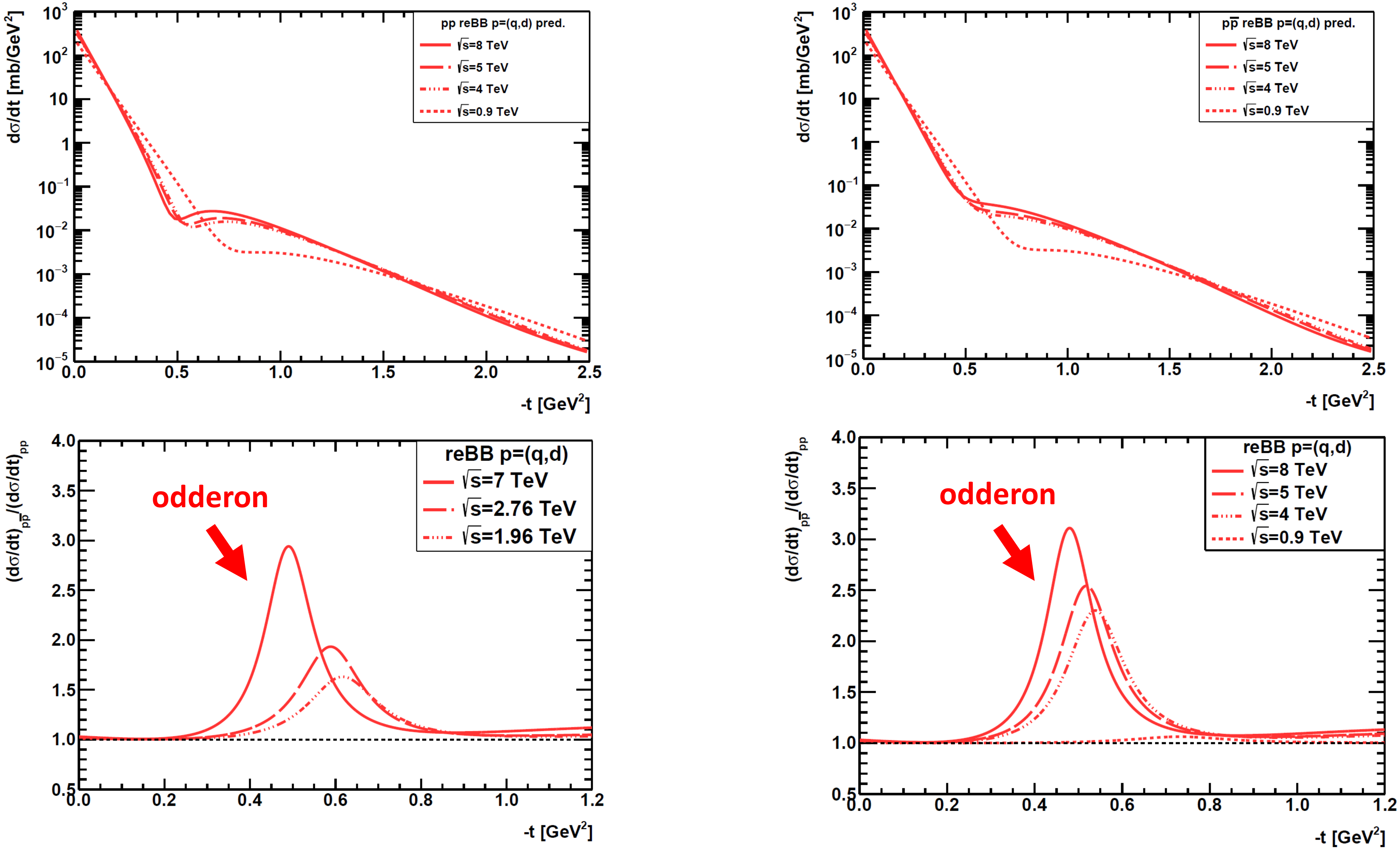


Tests for σ_{tot} and ρ_0 ✓

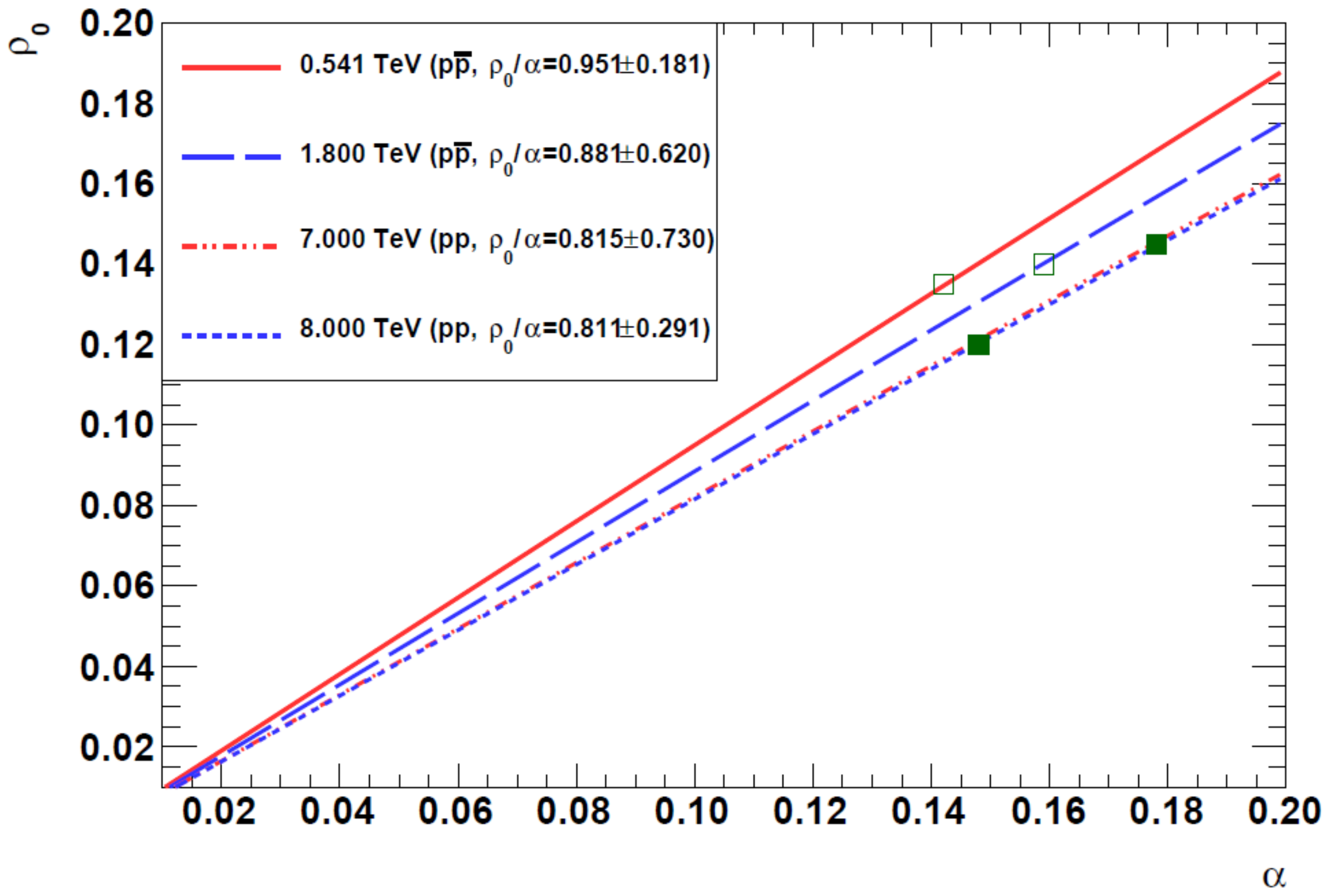




Predictions for pp and $p\bar{p}$ dσ/dt and their ratios



Connection between ρ_0 and the ReBB α parameter

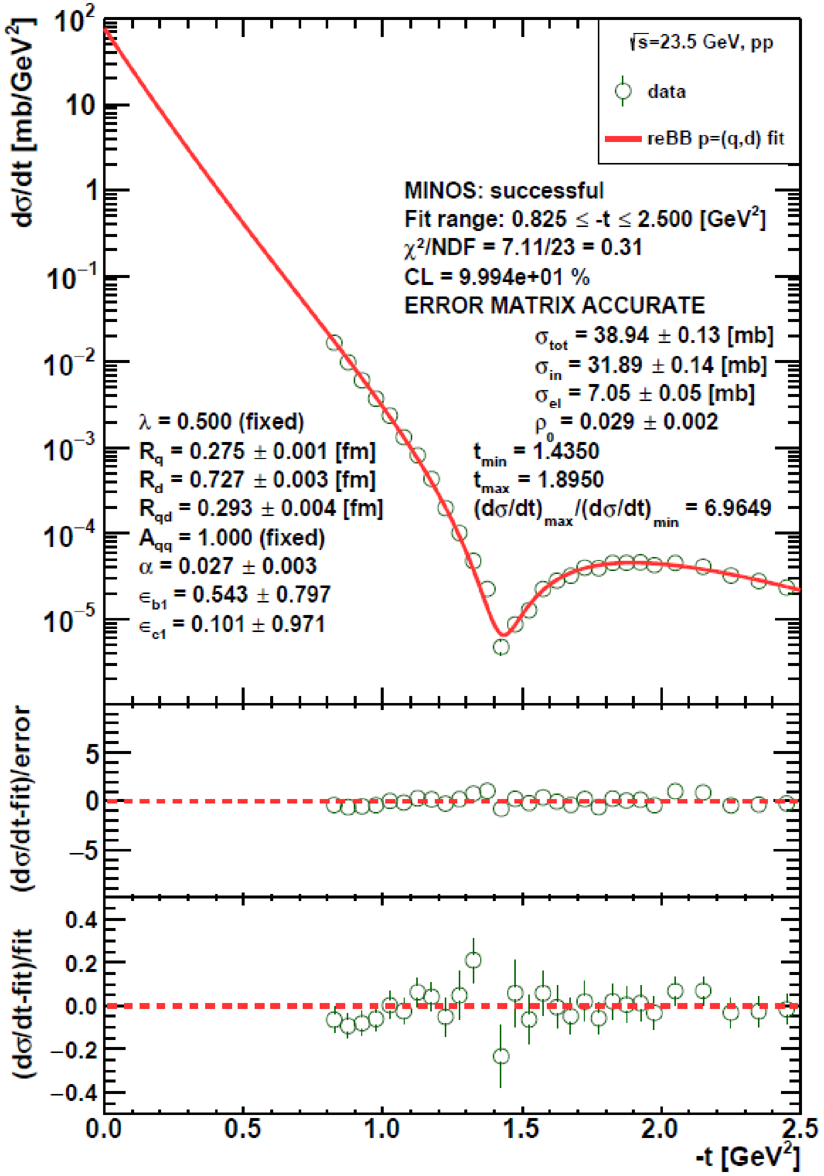


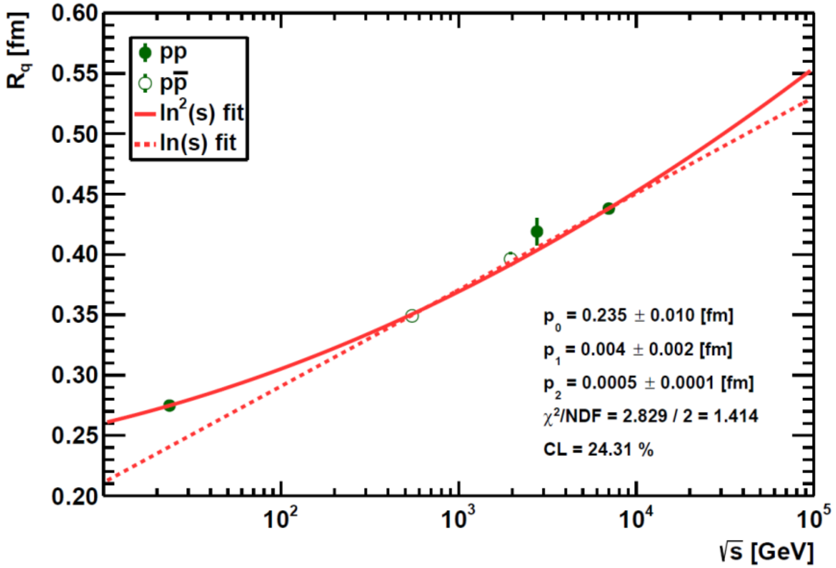
Connection between the ratio ρ_0 and the α parameter of the ReBB model in the TeV energy region calculated from the trends of the scale parameters, R_q, R_d, R_{qd}. If an experimentally measured ρ_0 parameter value is available at a particular energy, the corresponding α parameter value can be determined. The square shaped markers in the figure are positioned to the experimentally measured ρ_0 values.

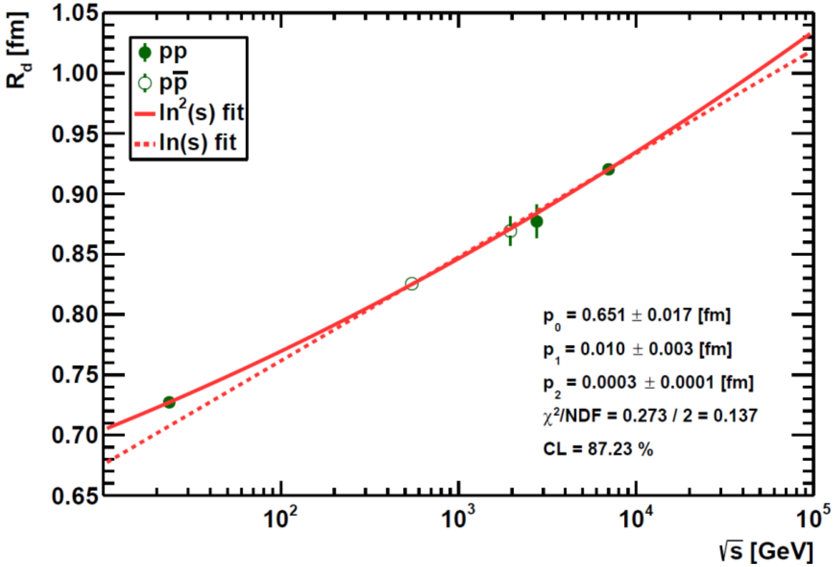
Fit at pp 23.5 GeV & $\ln^2(s)$ energy dependence

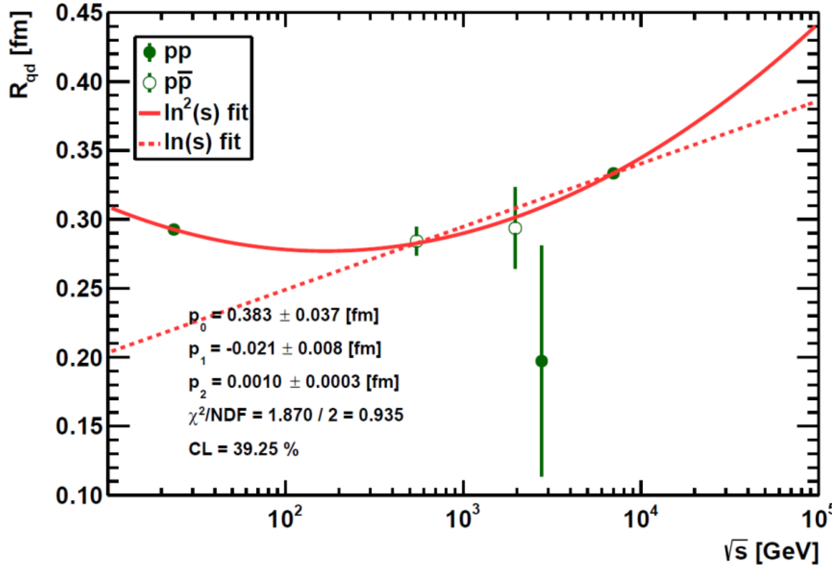
$$P(s) = p_0 + p_1 \ln(s/s_0) + p_2 \ln^2(s/s_0)$$

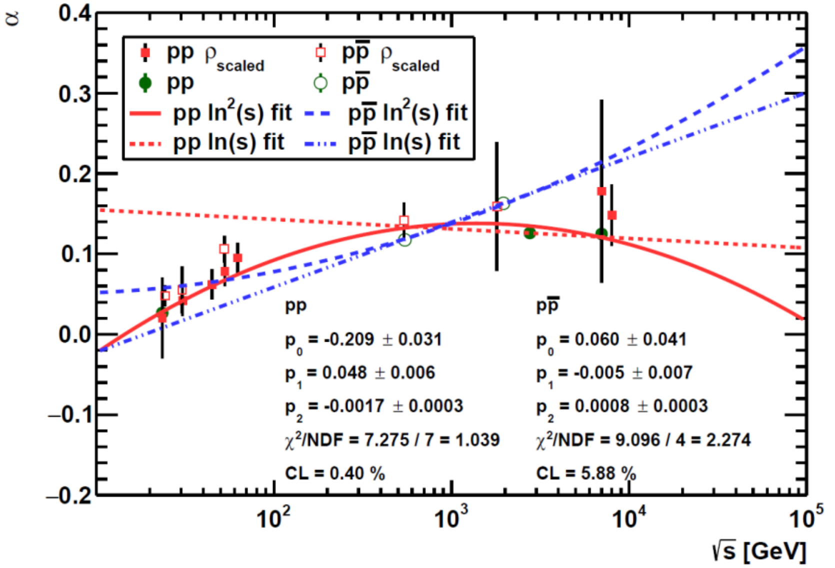
$$s_0 = 1\ GeV^2$$



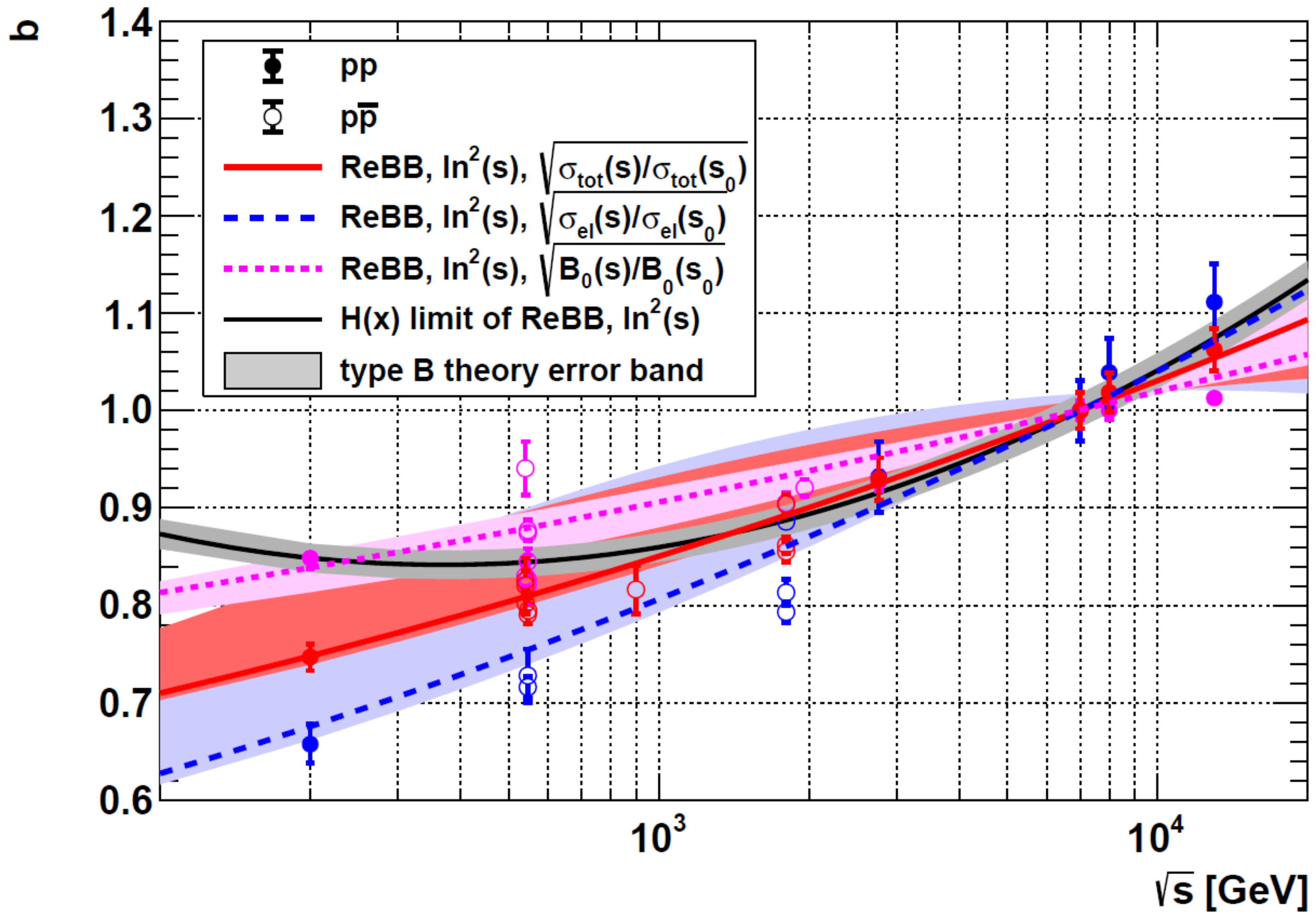








b(s) scaling function

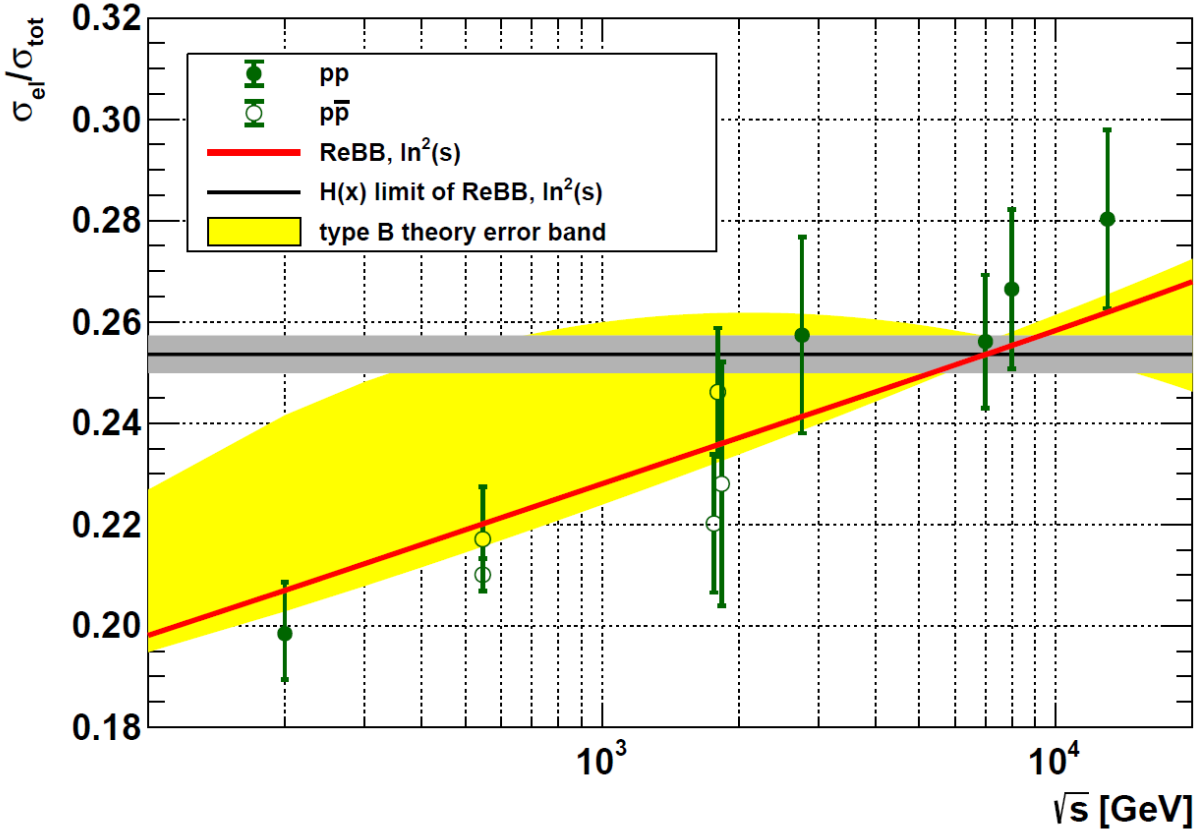


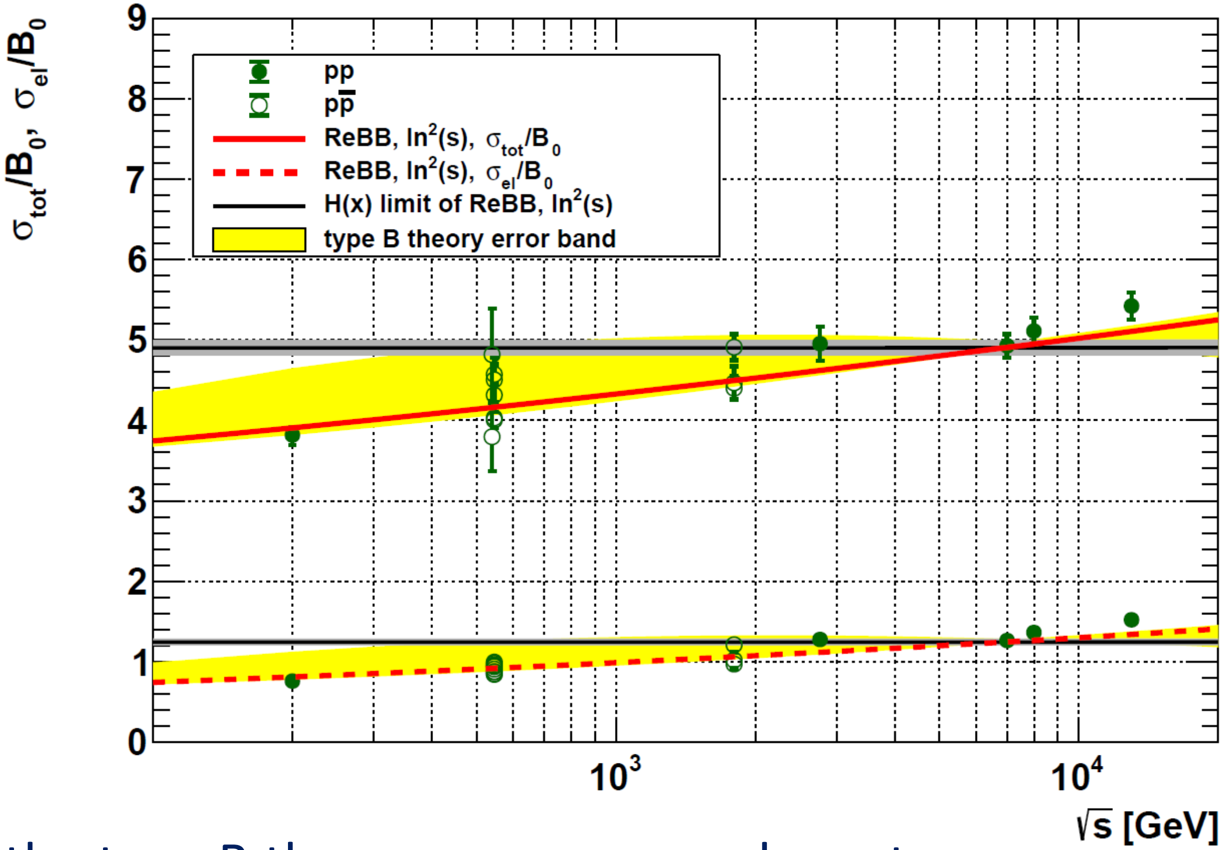
The energy dependence of the $b(s)$ scaling function determined from the experimental data and compared to the original ReBB model as well as its H(x) scaling version

H(x) scaling in the ReBB model

- **consequences of the H(x) scaling:**

$$\frac{\sigma_{el}(s)}{\sigma_{tot}(s)} = const \qquad \frac{\sigma_{tot}(s)}{B_0(s)} = const \qquad \frac{\sigma_{el}(s)}{B_0(s)} = const$$





→ the ReBB & H(x) limit of ReBB curves, within the type B theory errors agree down to about 400 GeV

ReBB vs. H(x) limit of ReBB H(x) @ 1 and 0.51 TeV

the used B_0 and σ_{el} values are the ones calculated from the ReBB model