Observation of Odderon Effects at LHC energies

A Real Extended Bialas-Bzdak Model Study

based on T. Csörgő, I. Szanyi, *Eur. Phys. J. C* **81**, 611 (2021) and other recent results

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Day of Femtoscopy 2021

October 28, 2021, Gyöngyös, Hungary

Unitarity and the elastic amplitude

- **unitarity of the scattering matrix S:**

$$\boxed{SS^\dagger = I} \qquad \boxed{S = I + iT} \qquad \boxed{T - T^\dagger = iTT^\dagger}$$

- **unitarity equation in impact parameter b representation:**

$$\boxed{2\,\mathcal{I}m\, t_{el}(s,\vec{b}) = |t_{el}(s,\vec{b})|^2 + \tilde{\sigma}_{in}(s,\vec{b})}$$

(s is the squared CM energy)

- **the elastic amplitude can be written as a solution of the unitarity equation in terms of $\tilde{\sigma}_{in}$**

- $0 \le \tilde{\sigma}_{in}(s,\vec{b}) \le 1$ **and $\tilde{\sigma}_{in}$ can be calculated using the rules of the probability calculus based on Glauber's multiple scattering theory**

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:**

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

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

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

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

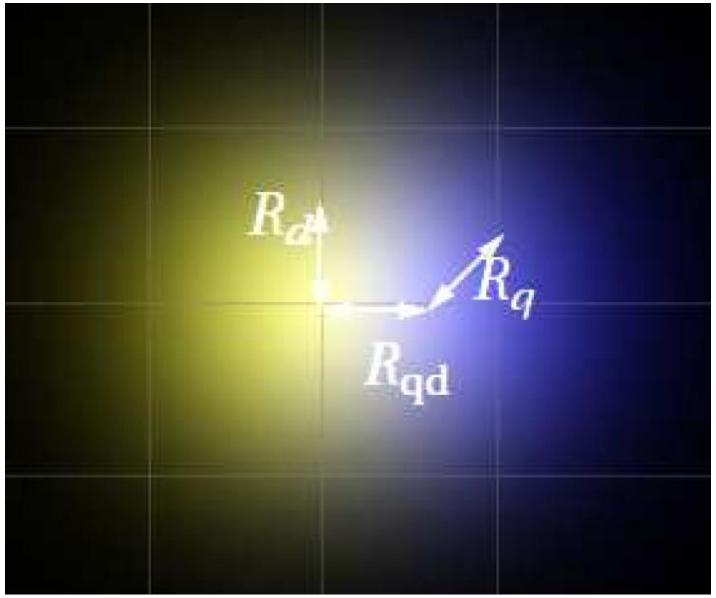
- **inelastic cross-sections of quark, diquark scatterings :**

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

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

- **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 Real Extended Bialas-Bzdak (ReBB) model

- **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:**

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

$$|\vec{\Delta}| \equiv \sqrt{-t} \quad as\ \sqrt{s} \to \infty$$

(t is the squared momentum transfer)

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:**

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

- **slope of dσ/dt:**

$$B_0(s) = \lim_{t\to 0} \mathrm{B}(s,\mathrm{t}) \equiv \frac{\mathrm{d}}{\mathrm{dt}}\left(\ln\frac{d\sigma}{\mathrm{dt}}(s,\mathrm{t})\right)\Bigg|_{t\to 0}$$

The pp and p$\bar{\text{p}}$ elastic scattering amplitude

- **according to the Regge formalism the strong scattering amplitude for pp and $p\bar{p}$ scattering can be written in terms of $C = +1$ and $C = -1$ exchange components**

$$\boxed{T^{pp}(s,t) = T^{+}(s,t) - T^{-}(s,t)} \qquad \boxed{T^{p\bar{p}}(s,t) = T^{+}(s,t) + T^{-}(s,t)}$$

- **for $\sqrt{s} \gtrsim 1\ \mathrm{TeV}$ the mesonic reggeon exchanges are negligible only the gluonic Pomeron and Odderon exchanges are present implying that**

$$\boxed{T^{+}(s,t) \equiv T^{P}(s,t)} \qquad \boxed{T^{-}(s,t) \equiv T^{O}(s,t)}$$

$$\Longrightarrow \quad \boxed{T^{P}(s,t) = \frac{1}{2}\left(T^{pp}(s,t) + T^{p\bar{p}}(s,t)\right)} \qquad \boxed{T^{O}(s,t) = \frac{1}{2}\left(T^{p\bar{p}}(s,t) - T^{pp}(s,t)\right)}$$

- **a simple and <u>model independent</u> consequence:**

$$\boxed{\text{if } \frac{d\sigma^{pp}}{dt}(s,t) \neq \frac{d\sigma^{p\bar{p}}}{dt}(s,t) \text{ for } \sqrt{s} \gtrsim 1\ \mathrm{TeV} \text{ then } T^{O}(s,t) \neq 0}$$

Fit method

- **least squares fitting with:**

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

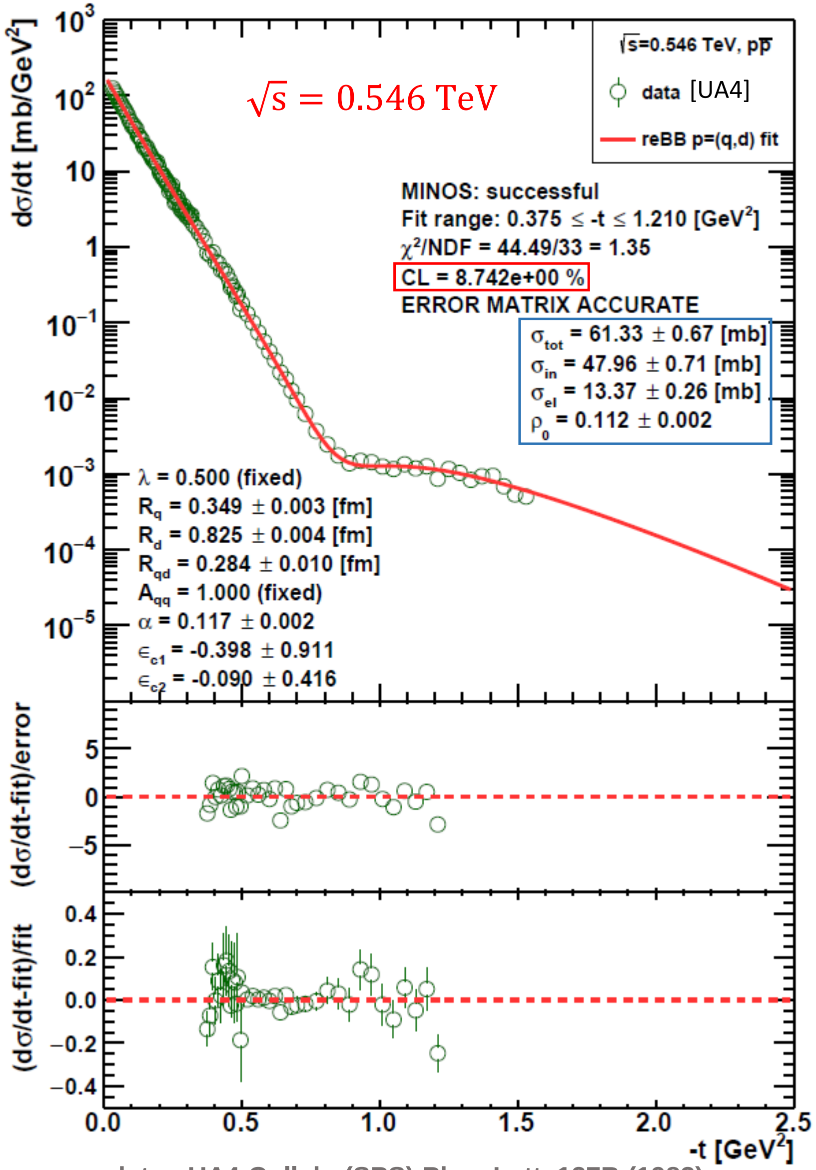
$$\tilde{\sigma}_{ij}^2 = \tilde{\sigma}_{aij}\left(\frac{d_{ij}+\epsilon_{bj}\tilde{\sigma}_{bij}+\epsilon_{cj}d_{ij}\sigma_{cj}}{d_{ij}}\right)$$

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

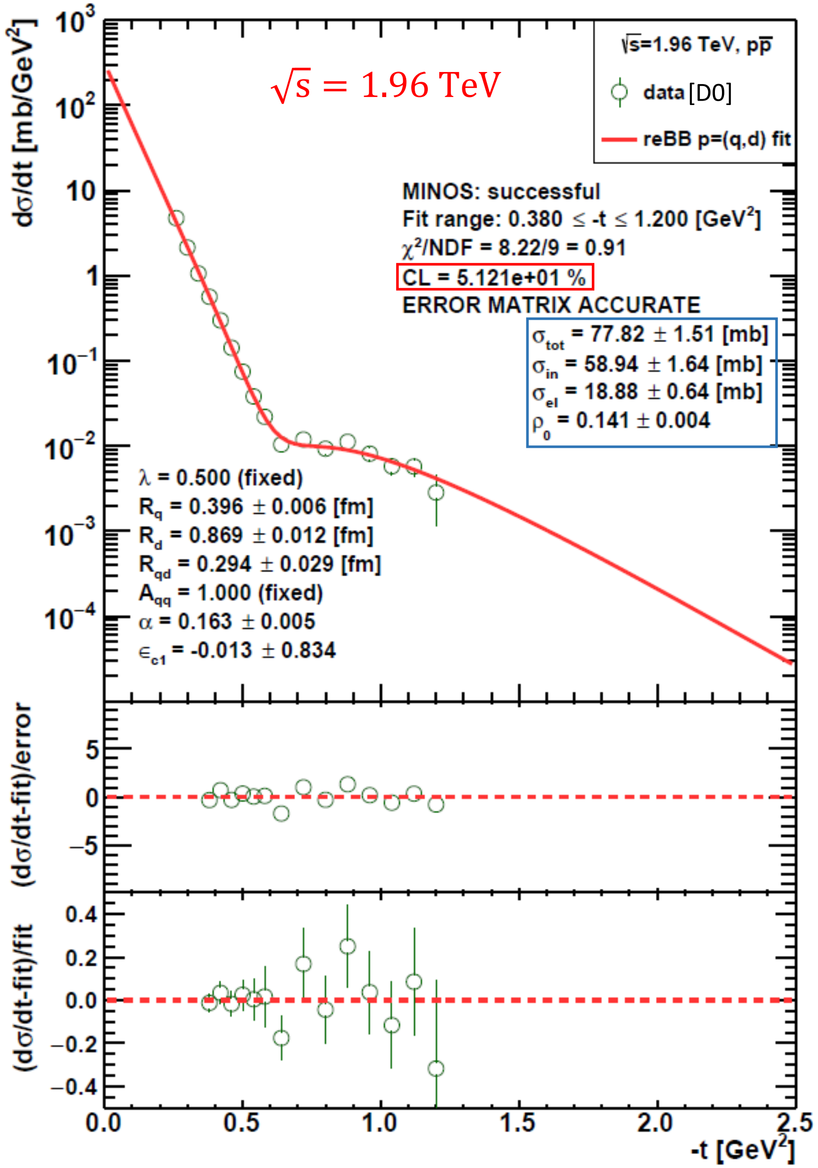
A. Adare *et al.* (PHENIX Collab.) Phys. Rev. C 77, 064907

- 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

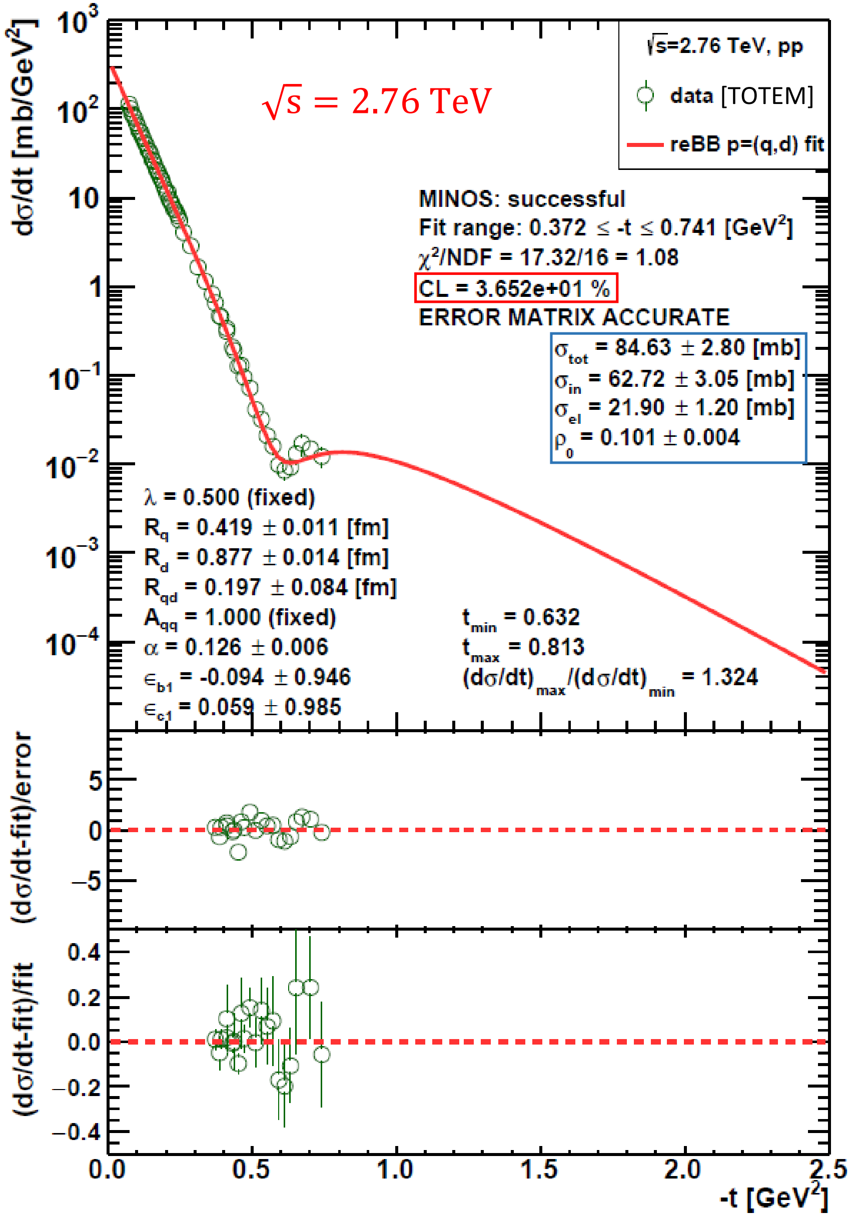


data: UA4 Collab. (SPS) Phys.Lett. 127B (1983)
UA4 Collab. (SPS) Phys.Lett. 155B (1985)

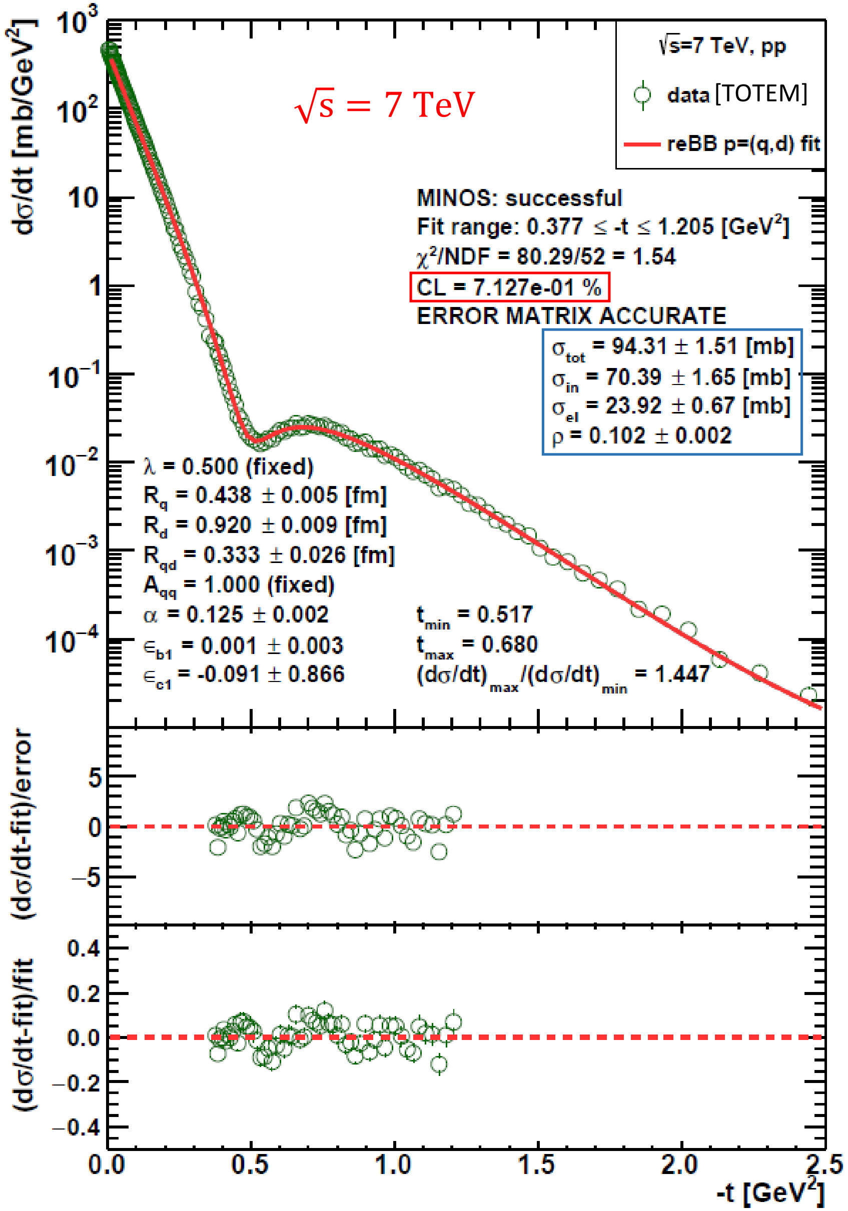


data: D0 Collab. (TEVATRON) Phys.Rev. D86 (2012)

Satisfactory ReBB model fits for pp dσ/dt data

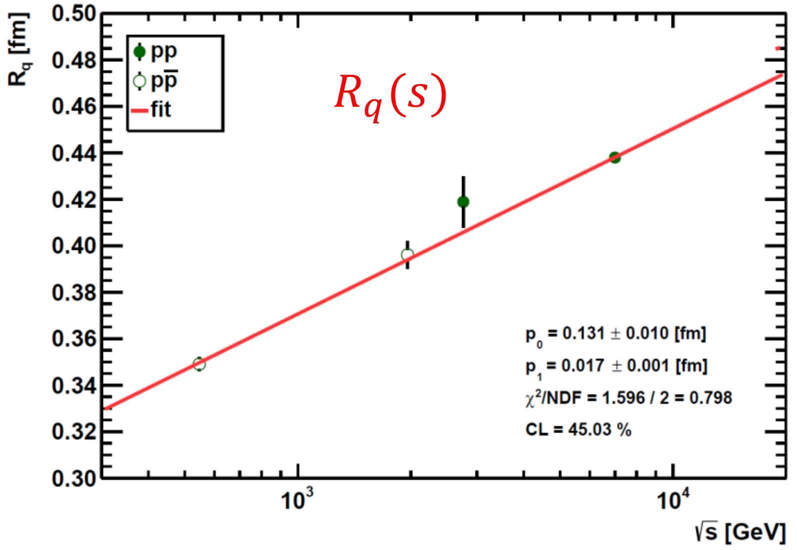


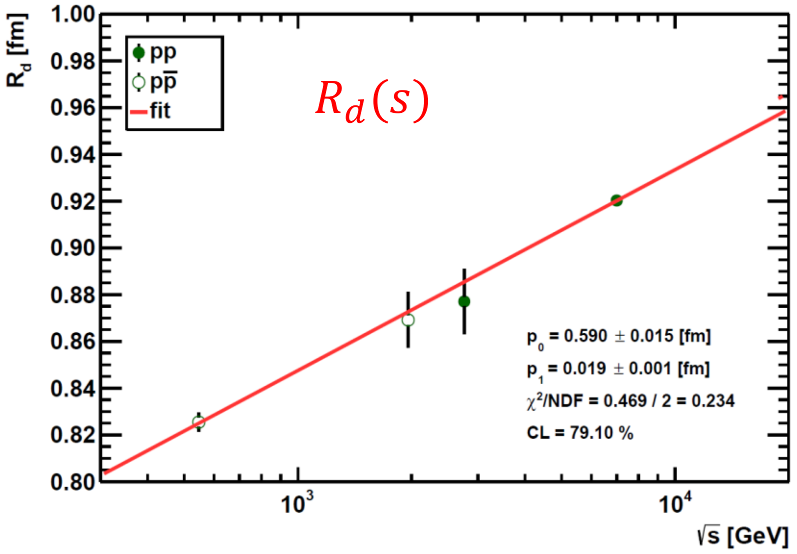
data: TOTEM Collab. (LHC) Eur. Phys. J. C 80 (2020) 91

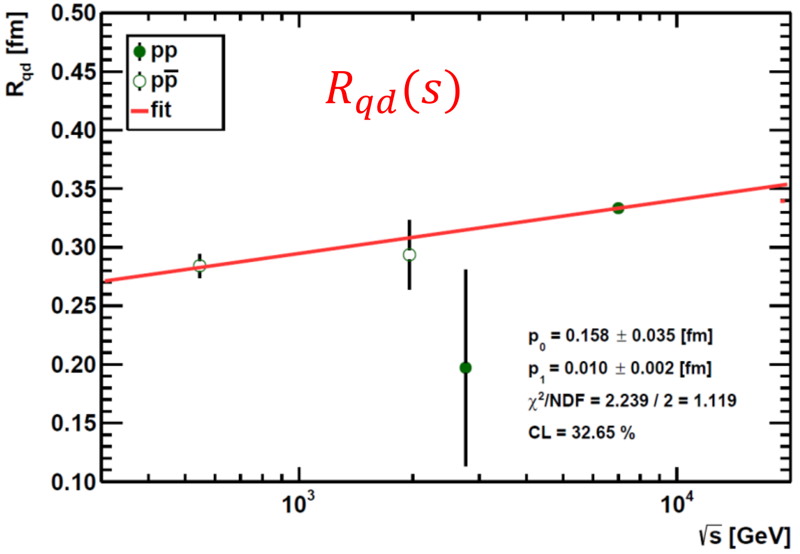


data: TOTEM Collab. (LHC) Europhys.Lett. 98 (2012)

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$\bar{\text{p}}$ 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 $\alpha(s)$

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

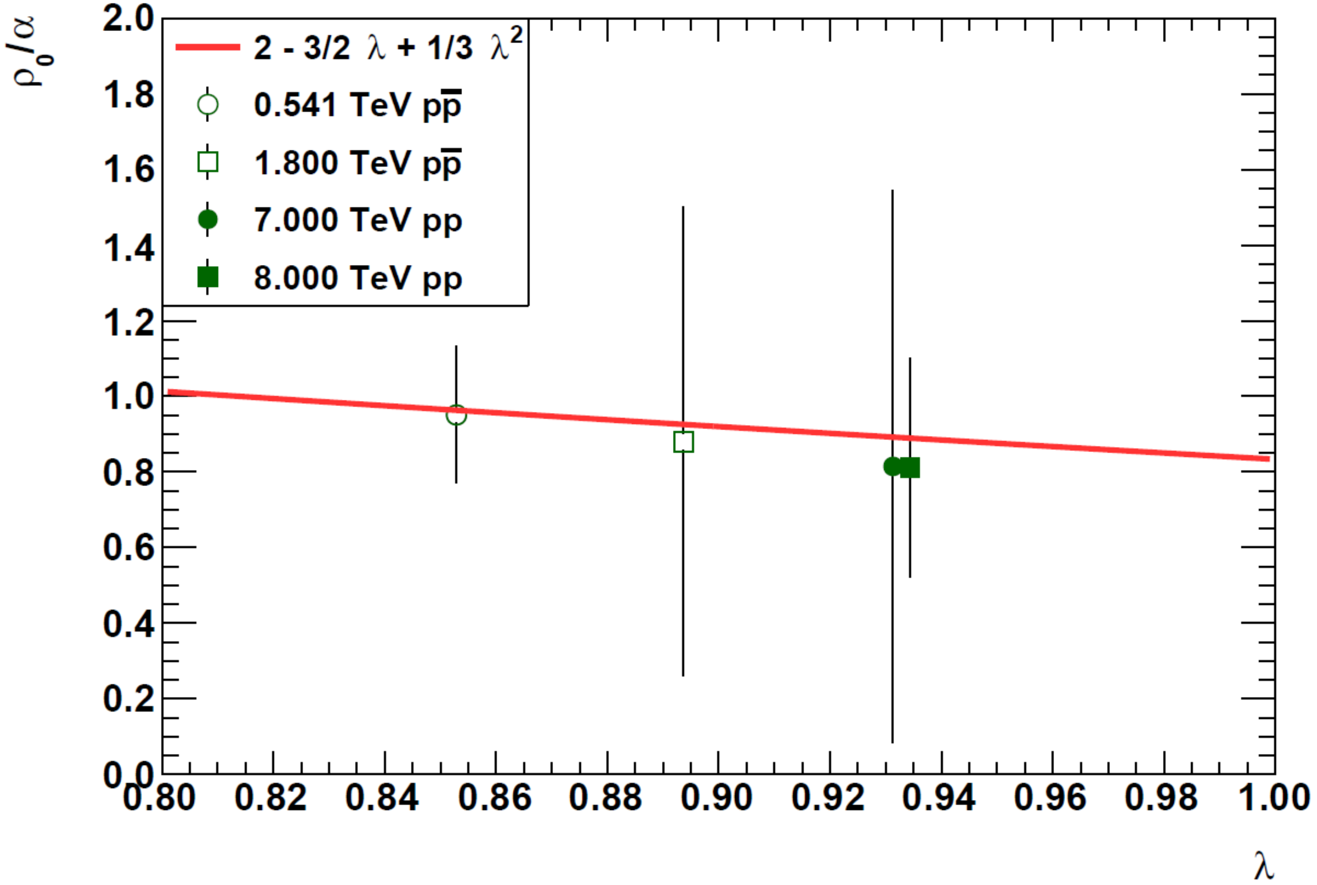
$$\alpha\tilde{\sigma}_{in} \ll 1$$

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

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

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

→ 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.

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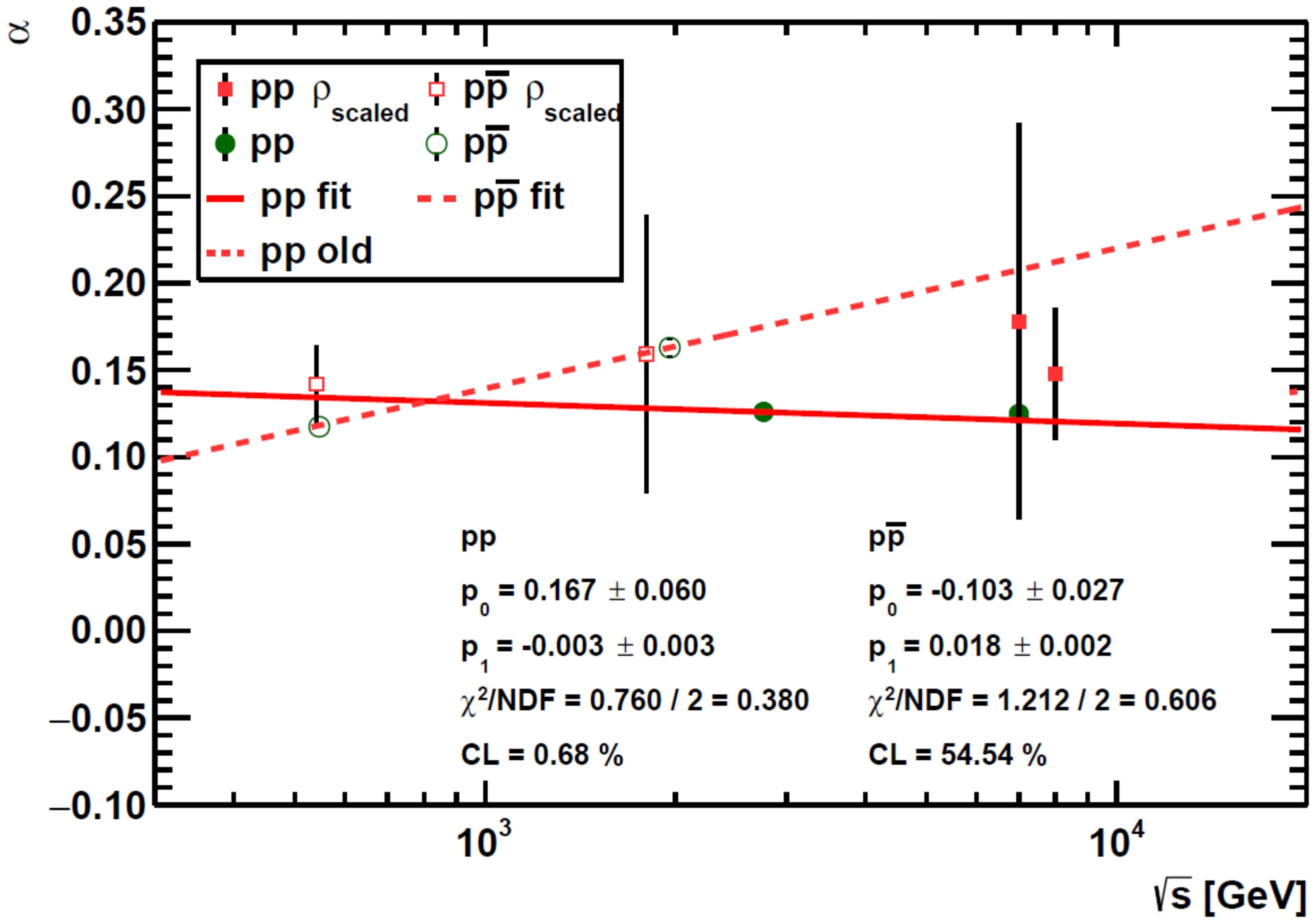
Energy dependence of the α parameter



$$\boxed{P(s) = p_0 + p_1 ln(s/s_0)}$$

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

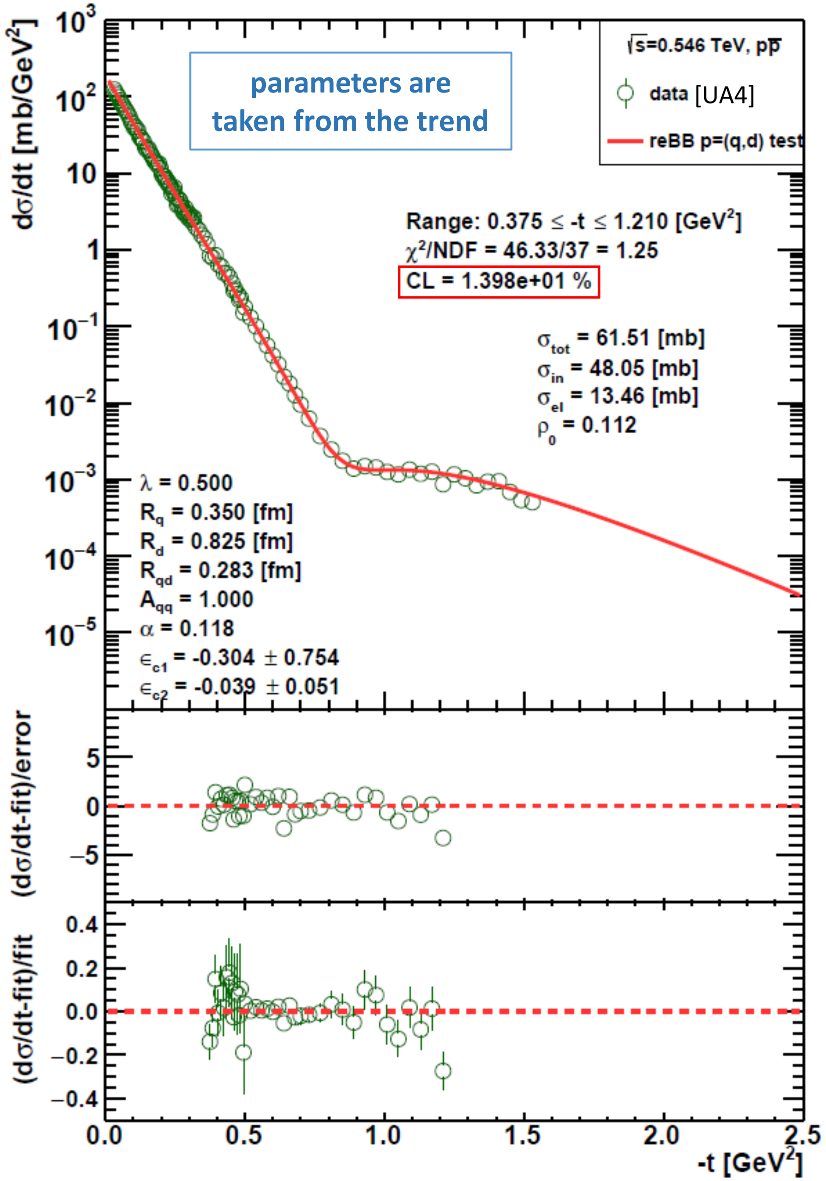
$$\boxed{s_0 = 1\ GeV^2}$$

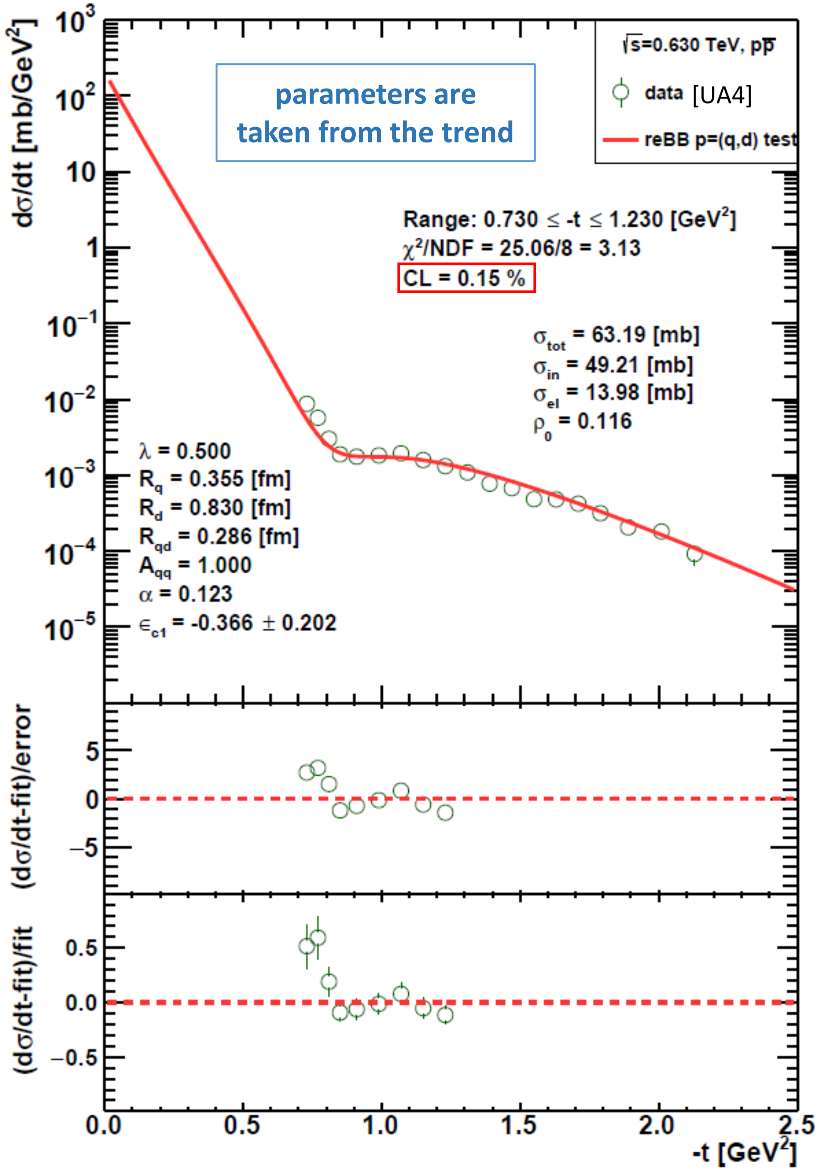
Parameter	$\alpha\ (pp)$	$\alpha\ (p\bar{p})$
χ^2/NDF	$0.760/2$	$1.212/2$
CL [%]	0.68	54.54
p_0	0.167 ± 0.060	-0.103 ± 0.027
p_1	-0.003 ± 0.003	0.018 ± 0.002

Parameters which define the energy dependence of the ReBB model α parameters for pp and pp̄

The energy dependence of the α parameter is not the same for pp and pp̄ processes
→ the Odderon is characterized by a single parameter, α!

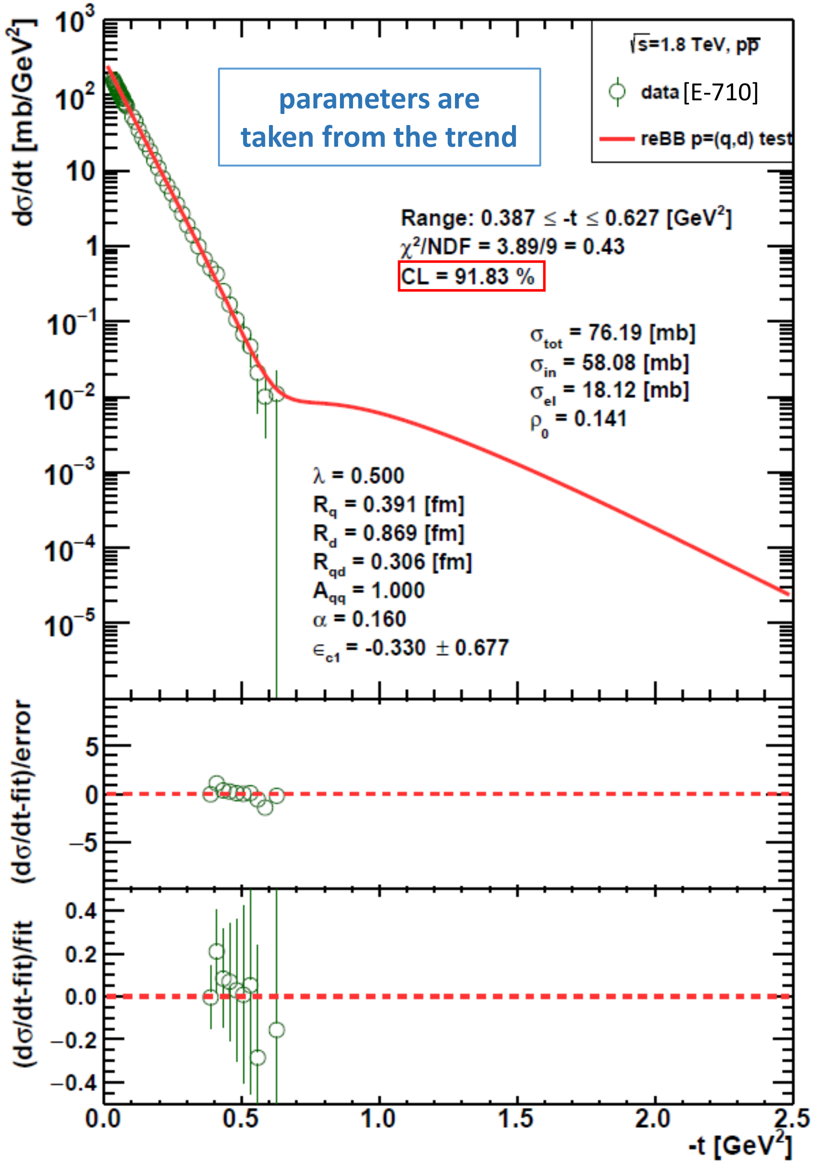
Tests @ 0.546 & 0.630 TeV ✓

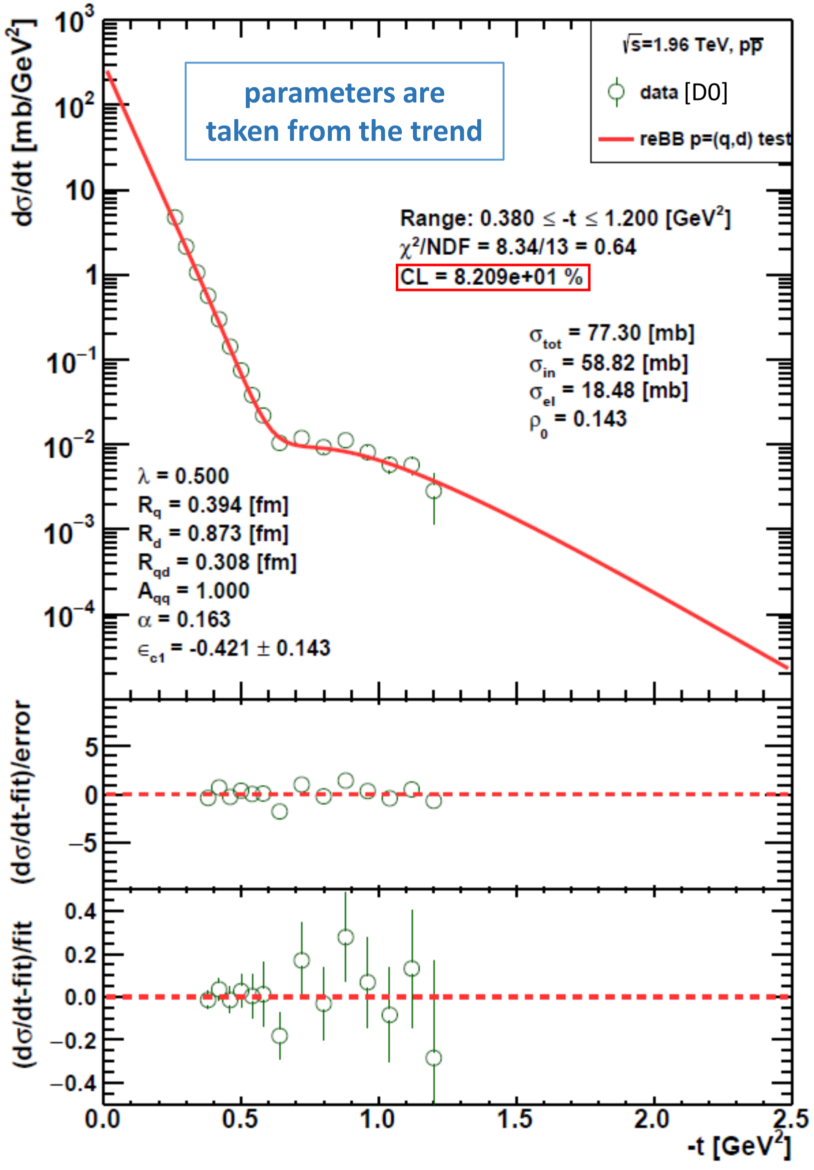




data: UA4 Collab. (SPS) Phys.Lett. B171 (1986)

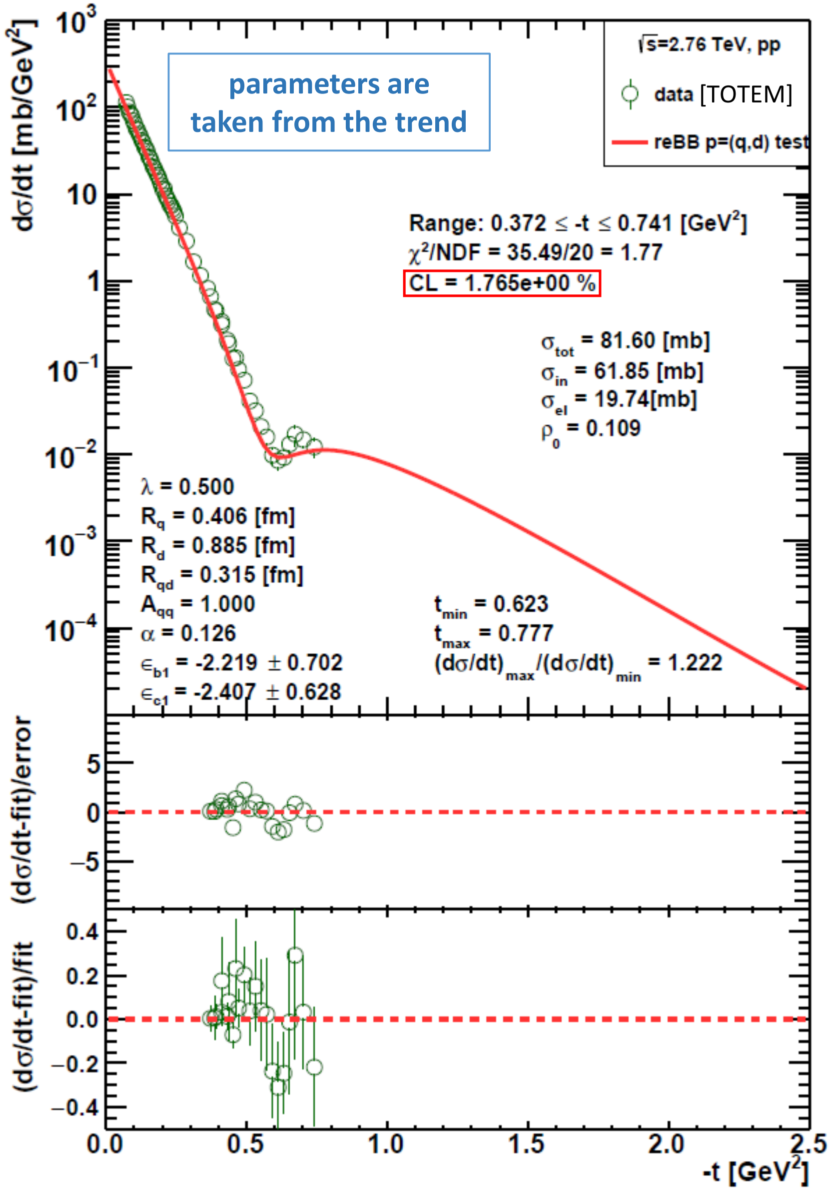
Tests @ 1.8 & 1.96 TeV ✓

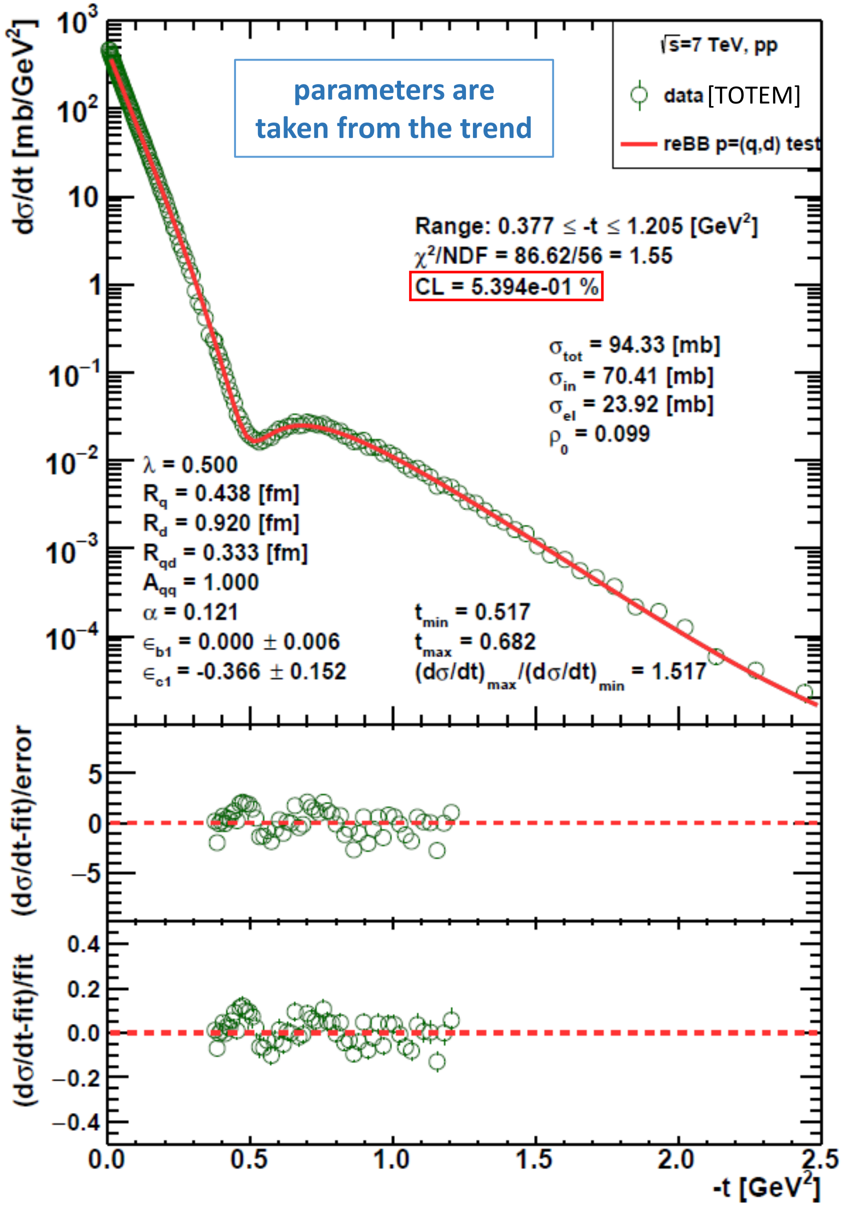




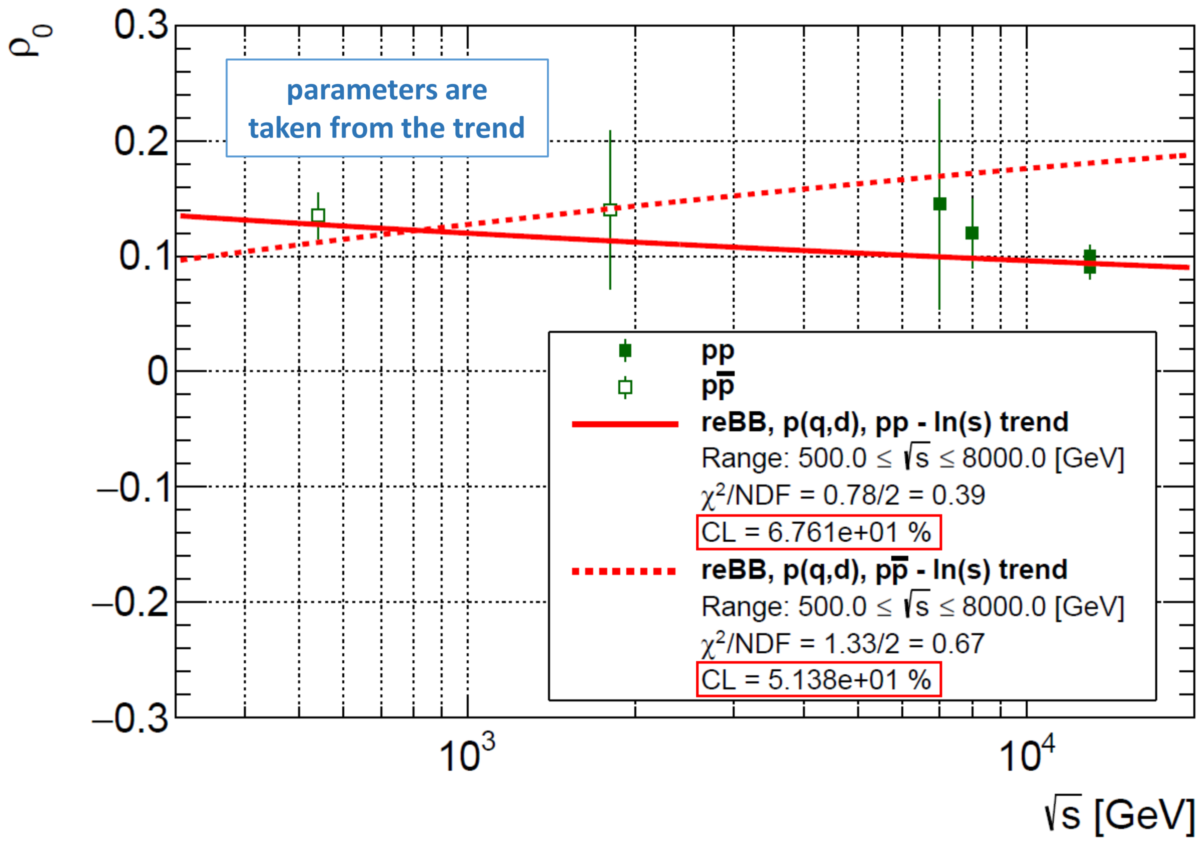
data: E-710 Collab. (TEVATRON) Phys.Lett. B247 (1990)

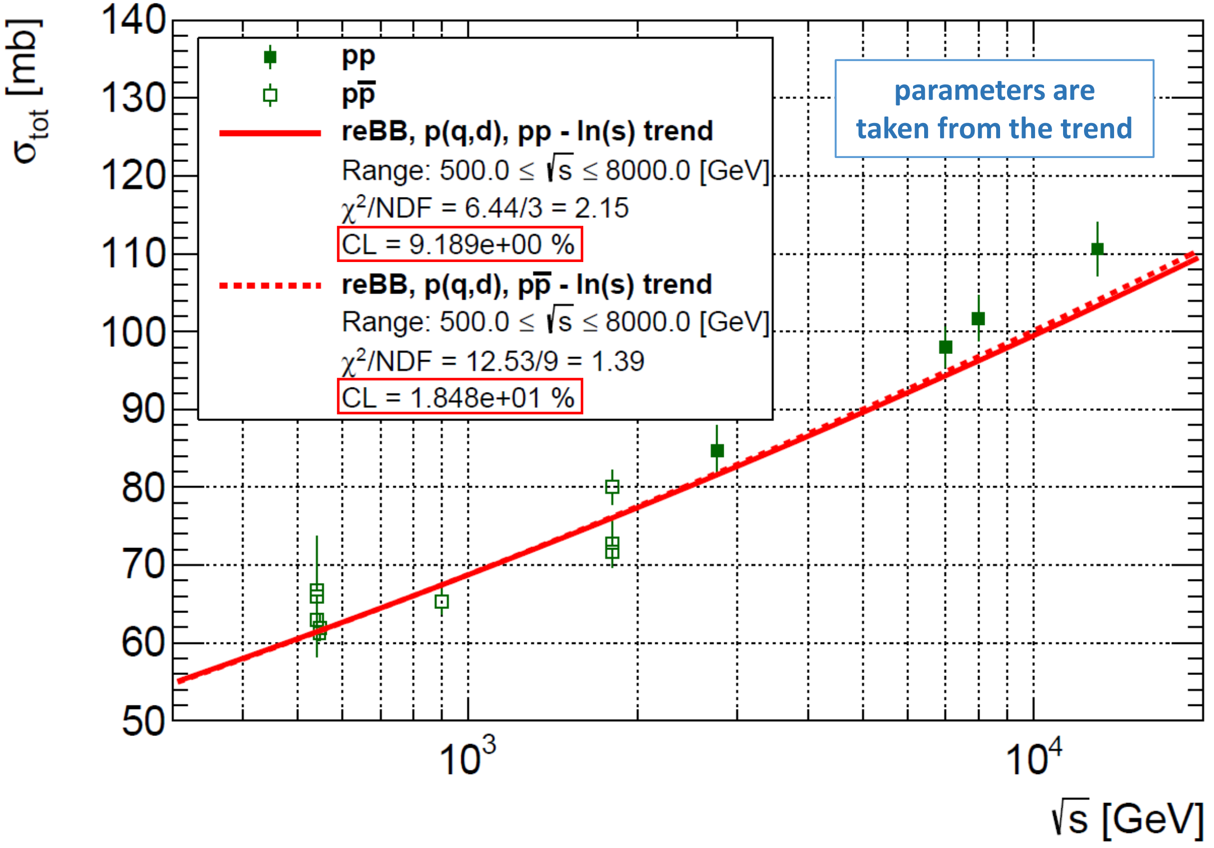
Tests @ 2.76 & 7.0 TeV ✓



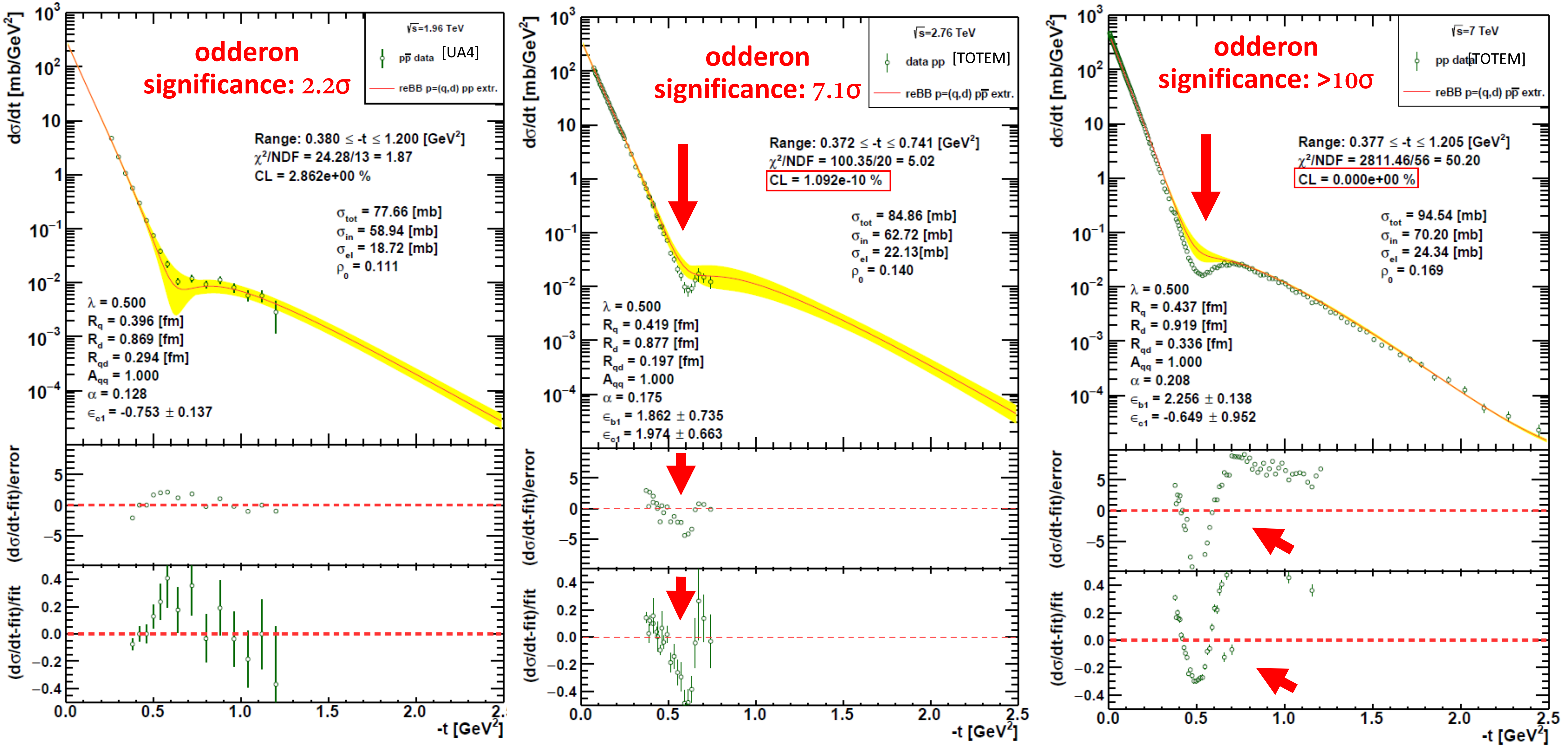


Tests for σ_{tot} and ρ_0 ✓

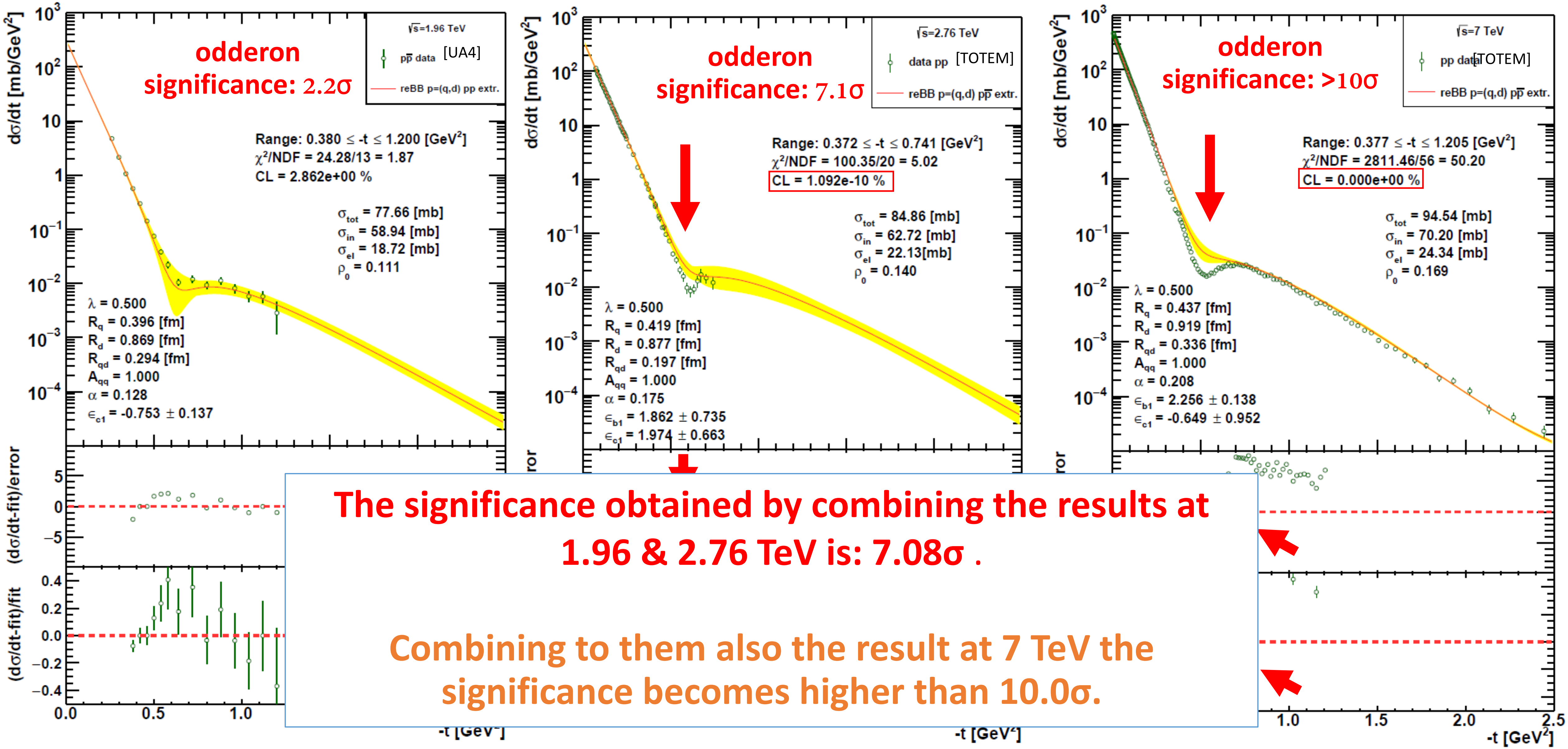




Extrapolations → ODDERON



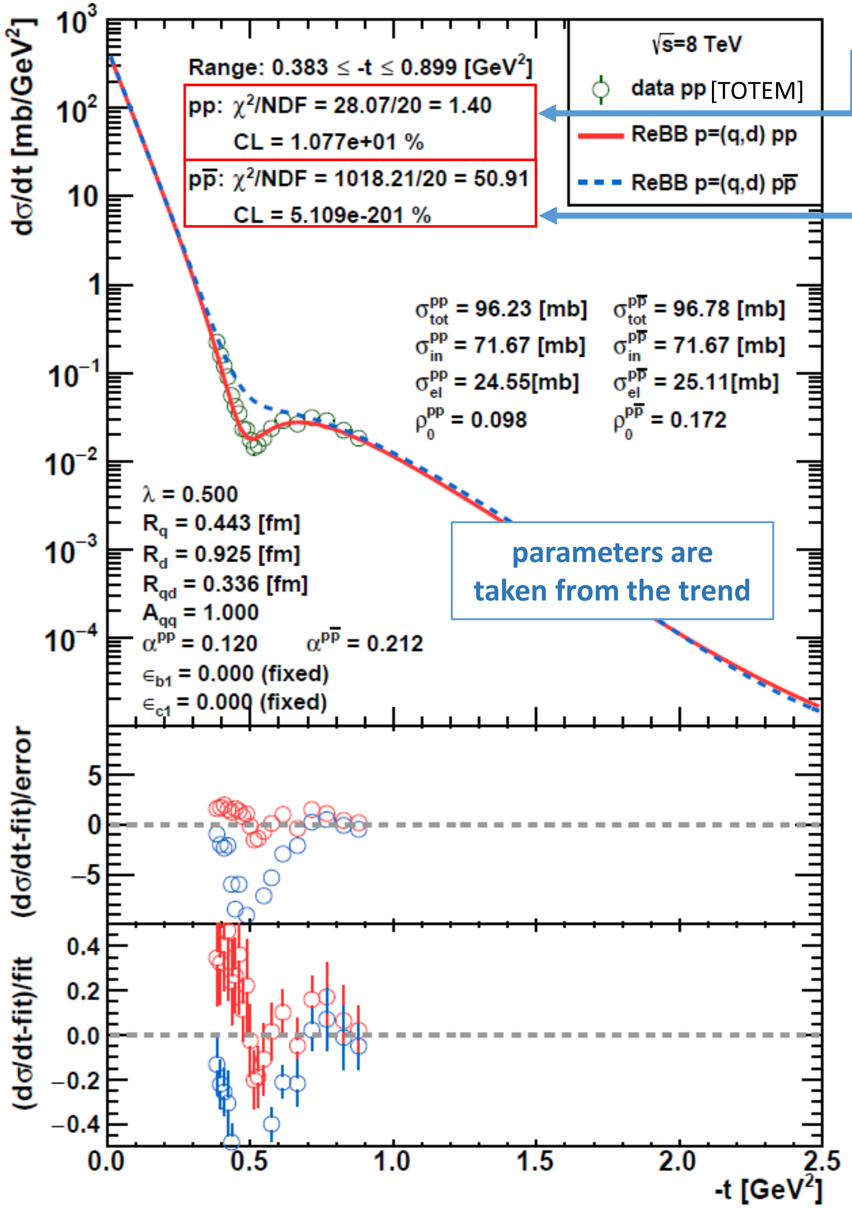
Extrapolations → ODDERON



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 higher than 10.0σ.

Confirmation @ 8.0 TeV

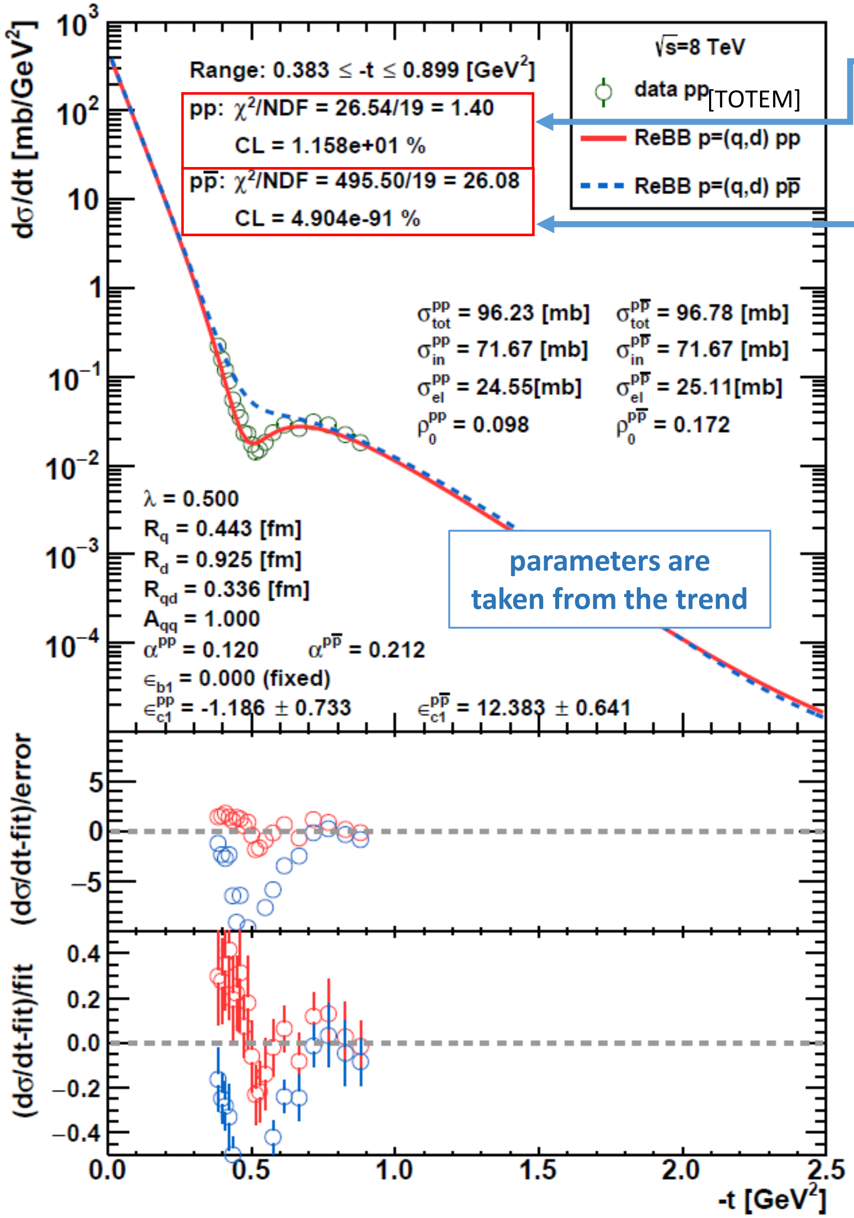


pp-pp agreement ✓

pp-pp̄ inagreement:
Odderon

data: TOTEM&D0 Collab. (LHC) Phys. Rev. Lett. 127 (2021)

Confirmation @ 8.0 TeV (with 3% C-type error)



data: TOTEM&D0 Collab. (LHC) Phys. Rev. Lett. 127 (2021)

pp-pp agreement ✓

pp-p$\bar{p}$ inagreement: **Odderon**

Summary

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

→ satisfactory description in the energy range of $0.546 \leq \sqrt{s} \leq 7(8)$ TeV and squared momentum transfer range of $0.37 \leq -t \leq 1.2$ GeV^2

- **determination of the energy dependence of the parameters**

→ $R_q(s)$, $R_d(s)$ and $R_{qd}(s)$ are the same for pp and p$\bar{\text{p}}$ processes, $\alpha(s)$ is not
→ **Odderon effect**

- lack of pp and p$\bar{\text{p}}$ dσ/dt measured data at the same energies at the TeV energy region

- **extrapolations to accomplish comparative study and obtain a significance for the Odderon effect**

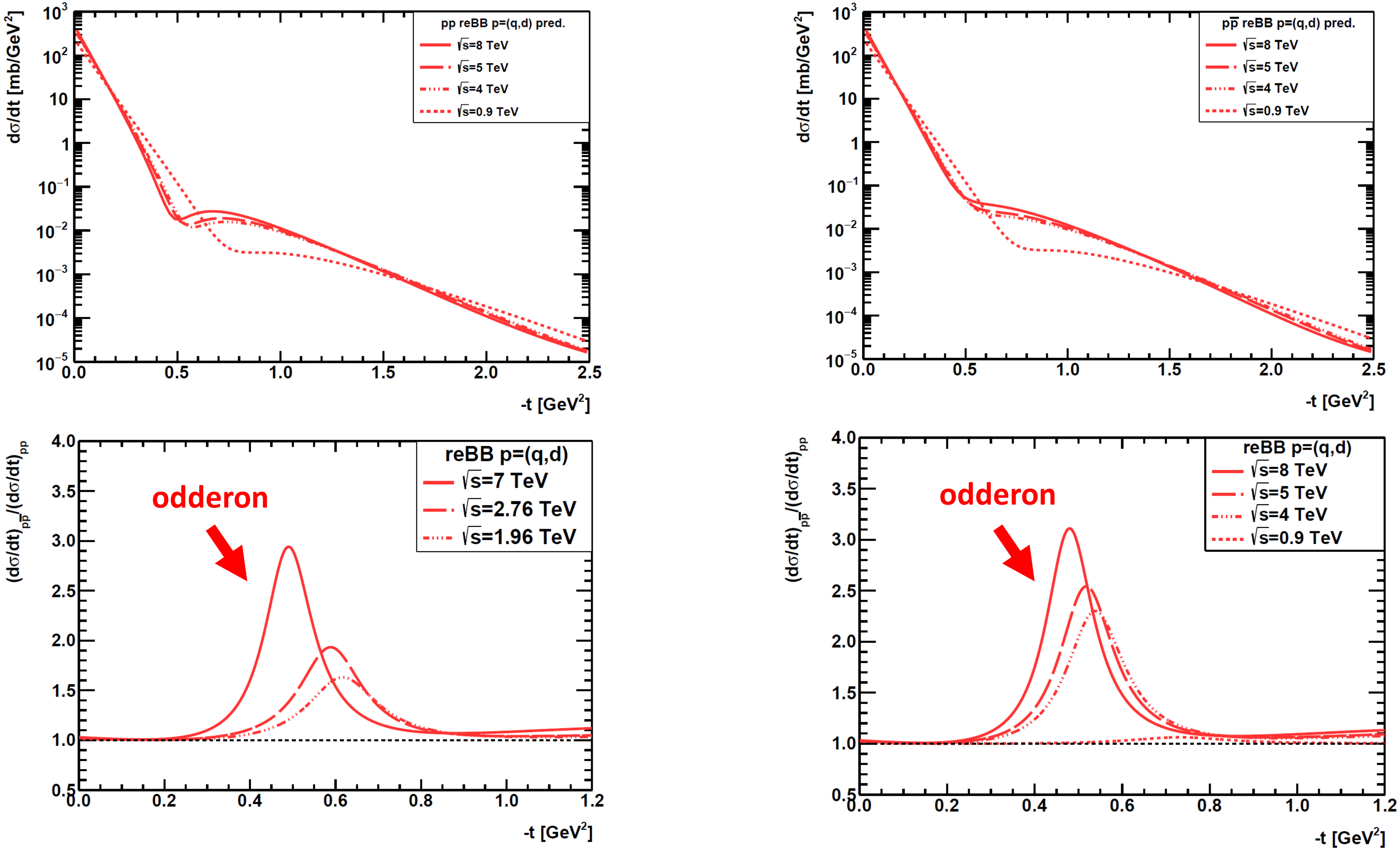
→ **difference between pp and p$\bar{\text{p}}$ dσ/dt** in the dip region

→ **model-dependent evidence for Odderon exchange in t-channel at $\sqrt{s} \gtrsim 1$ TeV with a significance of at least 7.08σ**

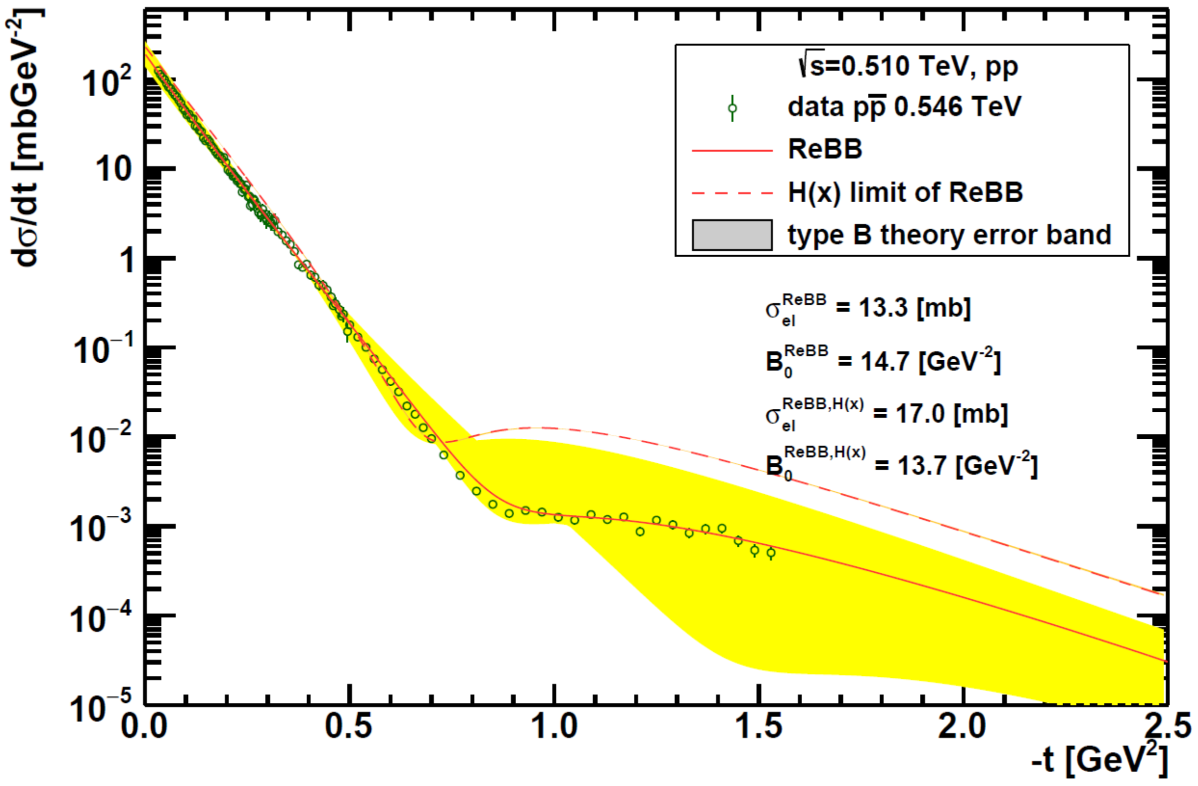
Thank you for your attention!

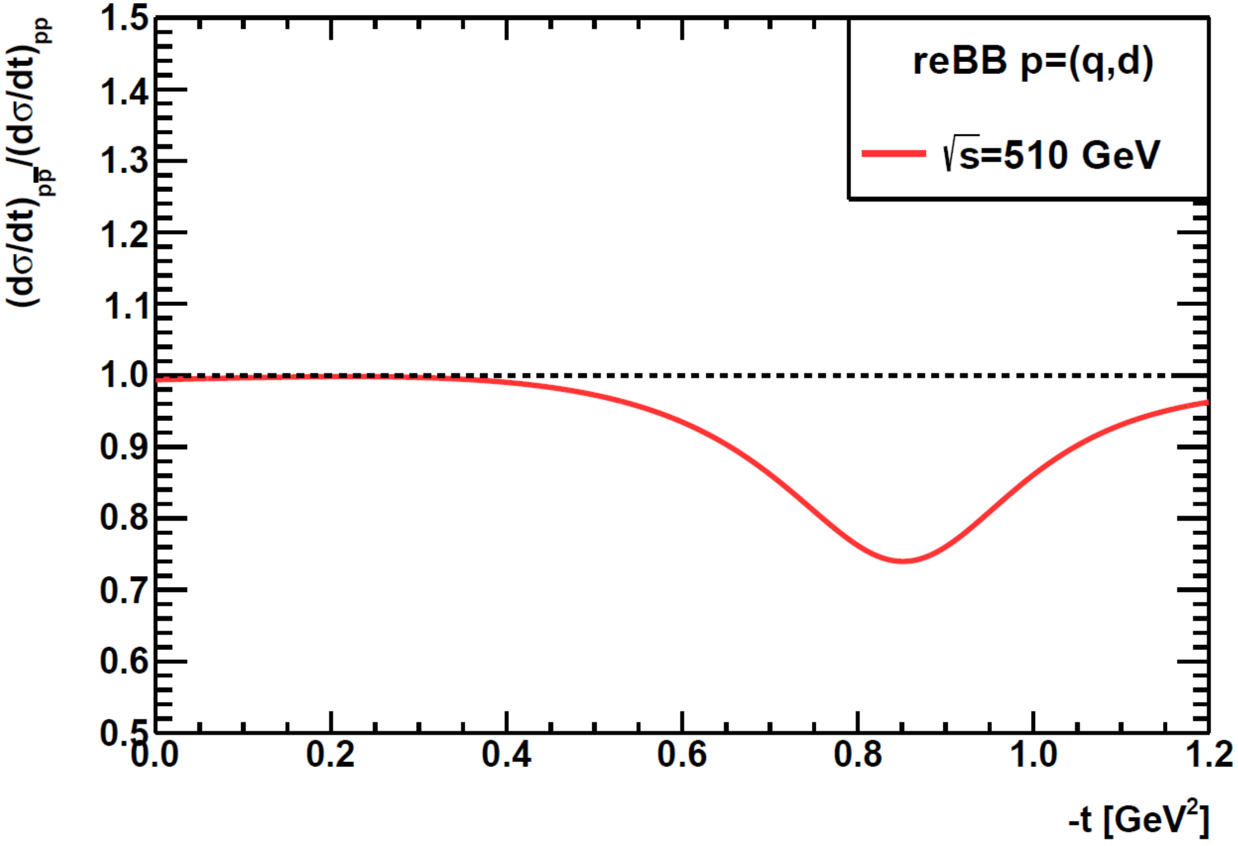
Backup slides

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



ReBB prediction for pp $d\sigma/dt$ @ 0.51 TeV



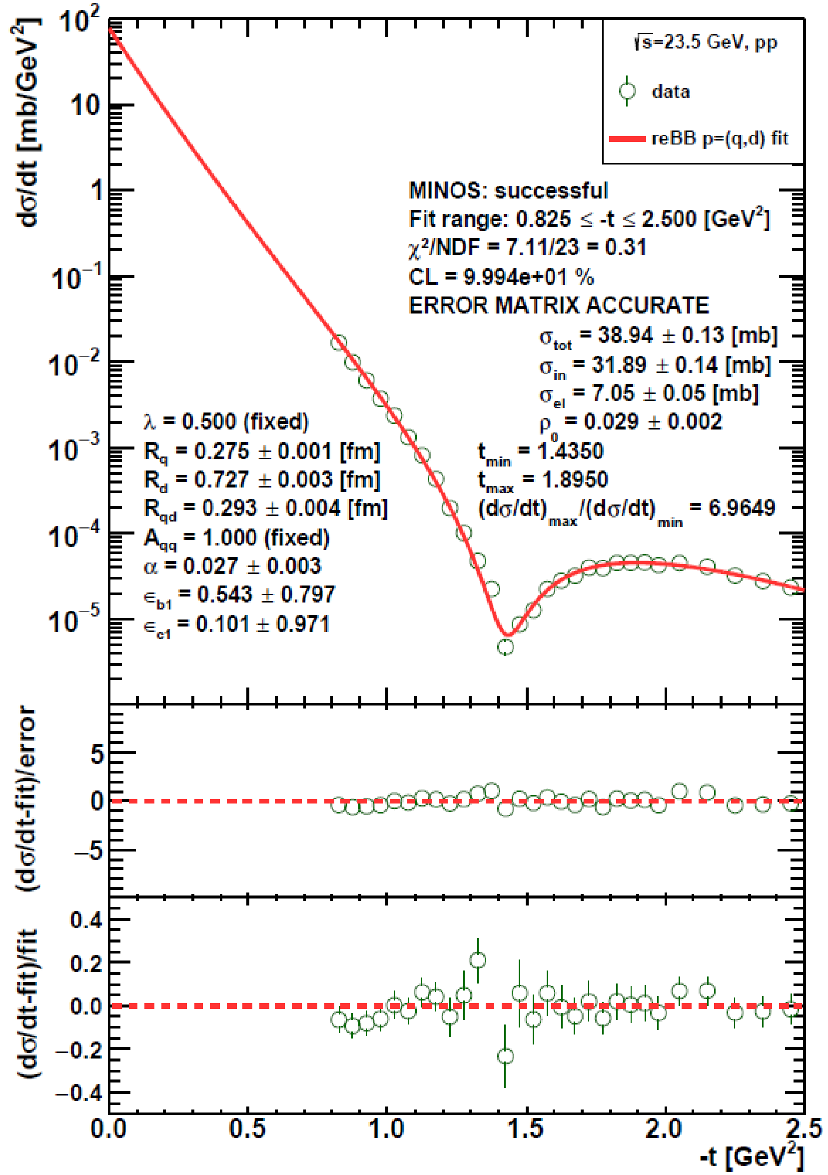


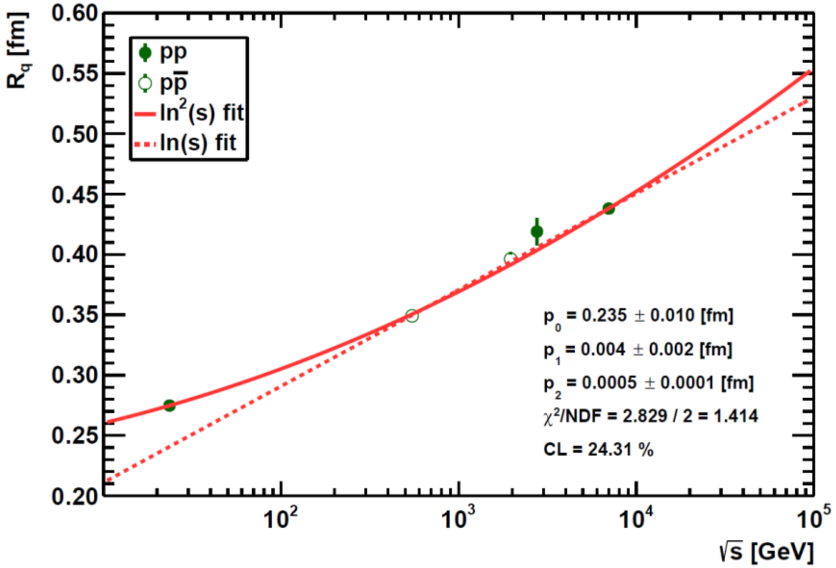
- pp data measured by the STAR Collab. is expected at 0.51 TeV

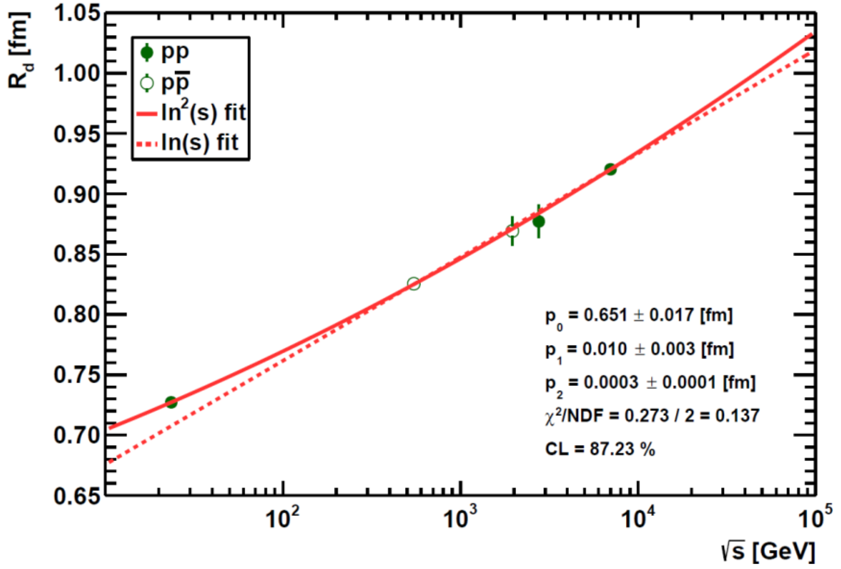
Fit at pp 23.5 GeV & $\ln^2(s)$ energy dependence

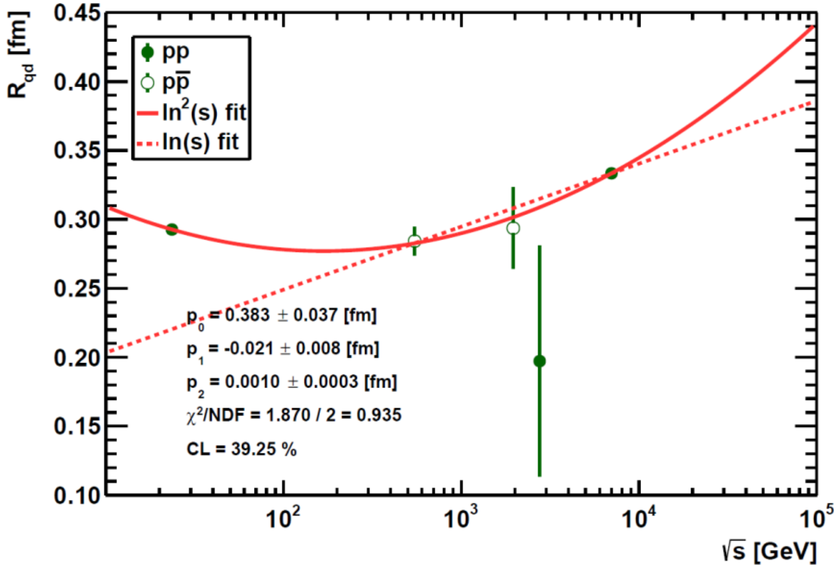
$$P(s) = p_0 + p_1 \ln(s/s_0) + p_2 \ln^2(s/s_0)$$

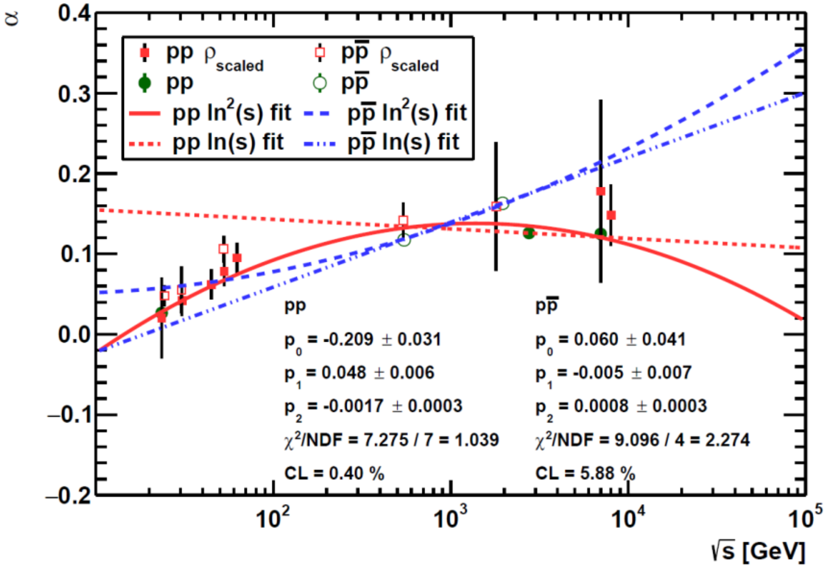
$$s_0 = 1\ GeV^2$$



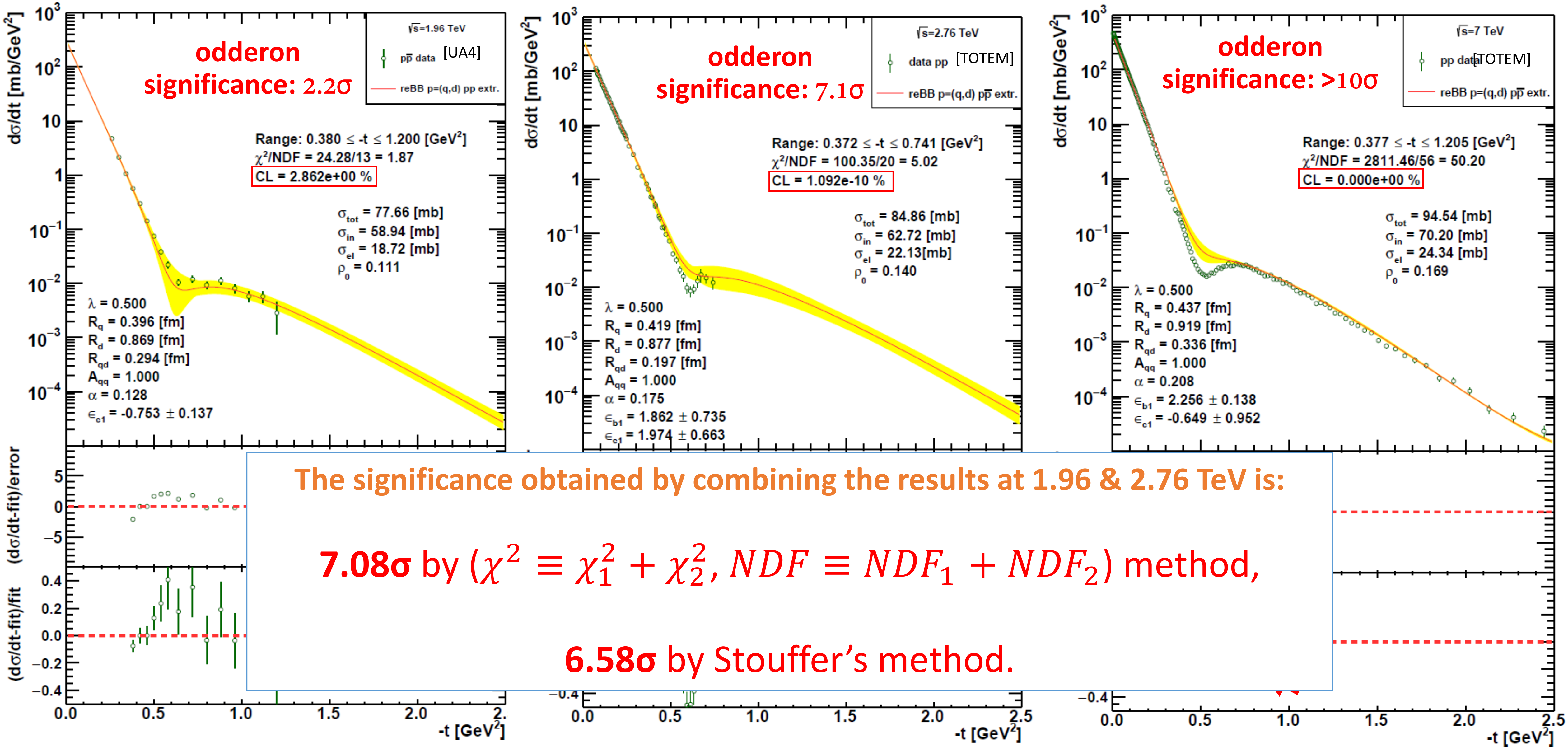








Various significance combinations



The significance obtained by combining the results at 1.96 & 2.76 TeV is:

7.08σ by ($\chi^2 \equiv \chi_1^2 + \chi_2^2, NDF \equiv NDF_1 + NDF_2$) method,

6.58σ by Stouffer's method.