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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Unitarity and the elastic amplitude

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

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

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

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

(s is the squared CM energy)

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

- $0 \leq \tilde{\sigma}_{in}(s,\vec{b}) \leq 1$ **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:**

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

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

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

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

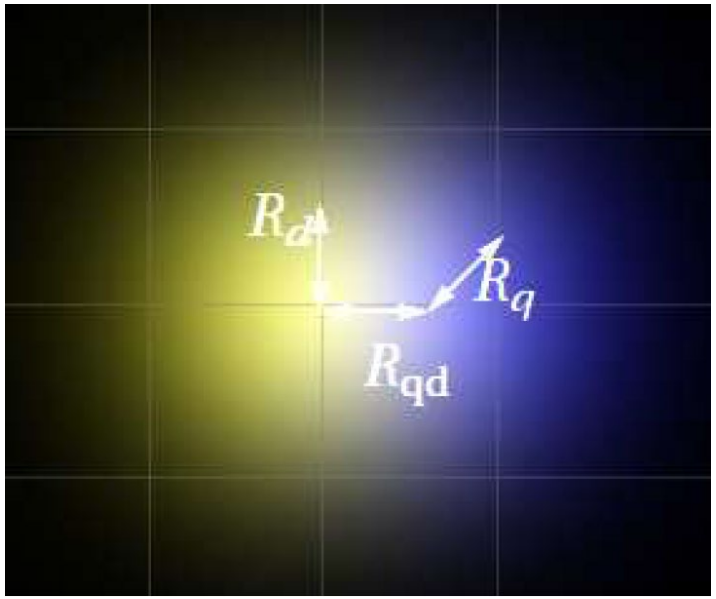
- **inelastic cross-sections of quark, diquark scatterings :**

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

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

- **free parameters:**

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



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:**

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

The pp and $p\bar{p}$ 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**

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

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

$$T^{+}(s,t) \equiv T^{P}(s,t)$$

$$T^{-}(s,t) \equiv T^{O}(s,t)$$

$$T^{P}(s,t) = \frac{1}{2}\left(T^{pp}(s,t) + T^{p\bar{p}}(s,t)\right)$$

$$T^{O}(s,t) = \frac{1}{2}\left(T^{p\bar{p}}(s,t) - T^{pp}(s,t)\right)$$

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

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

Fit method

- **least squares fitting with:**

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

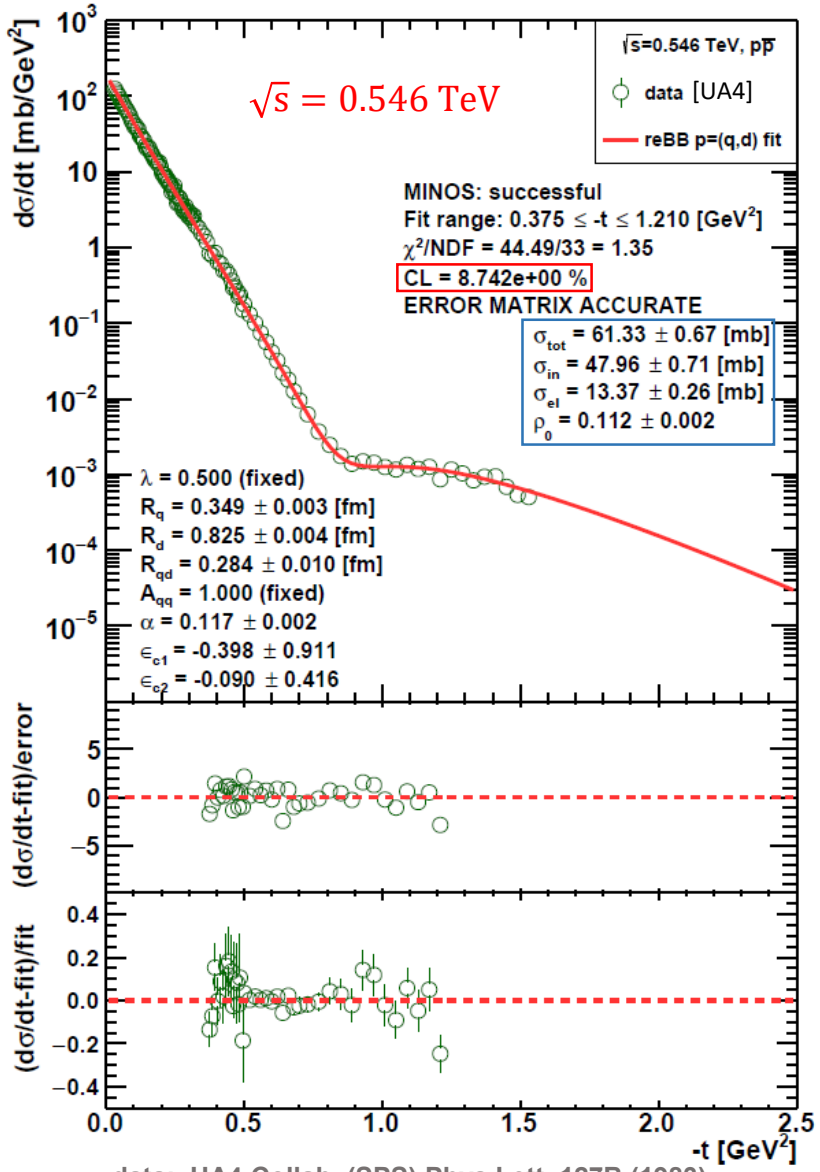
$$\tilde{\sigma}_{ij}^2 = \tilde{\sigma}_{aij} \left(\frac{d_{ij} + \epsilon_{bj}\tilde{\sigma}_{bij} + \epsilon_{cj} d_{ij}\sigma_{cj}}{d_{ij}} \right)$$

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

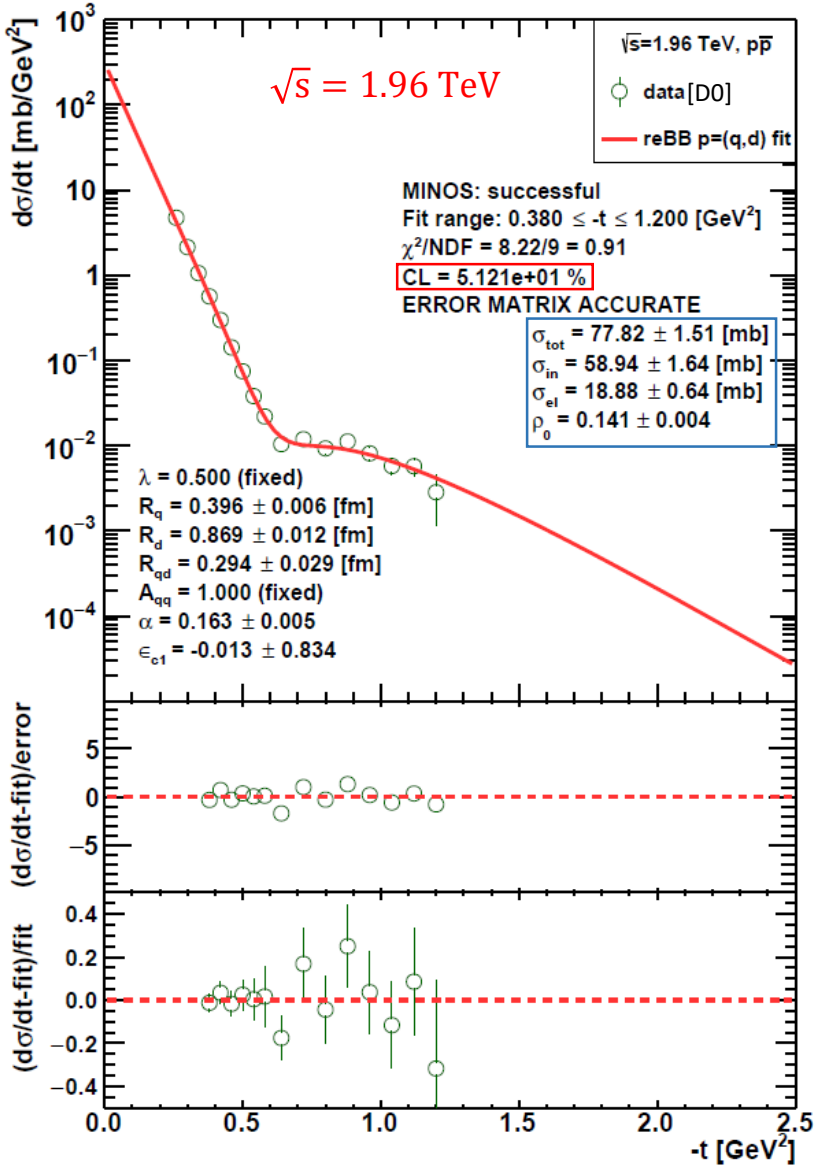
A. Adare *et al.* (PHENIX Collab.) Phys. Rev. C 77, 064907

- 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 $p\bar{p}$ dσ/dt data

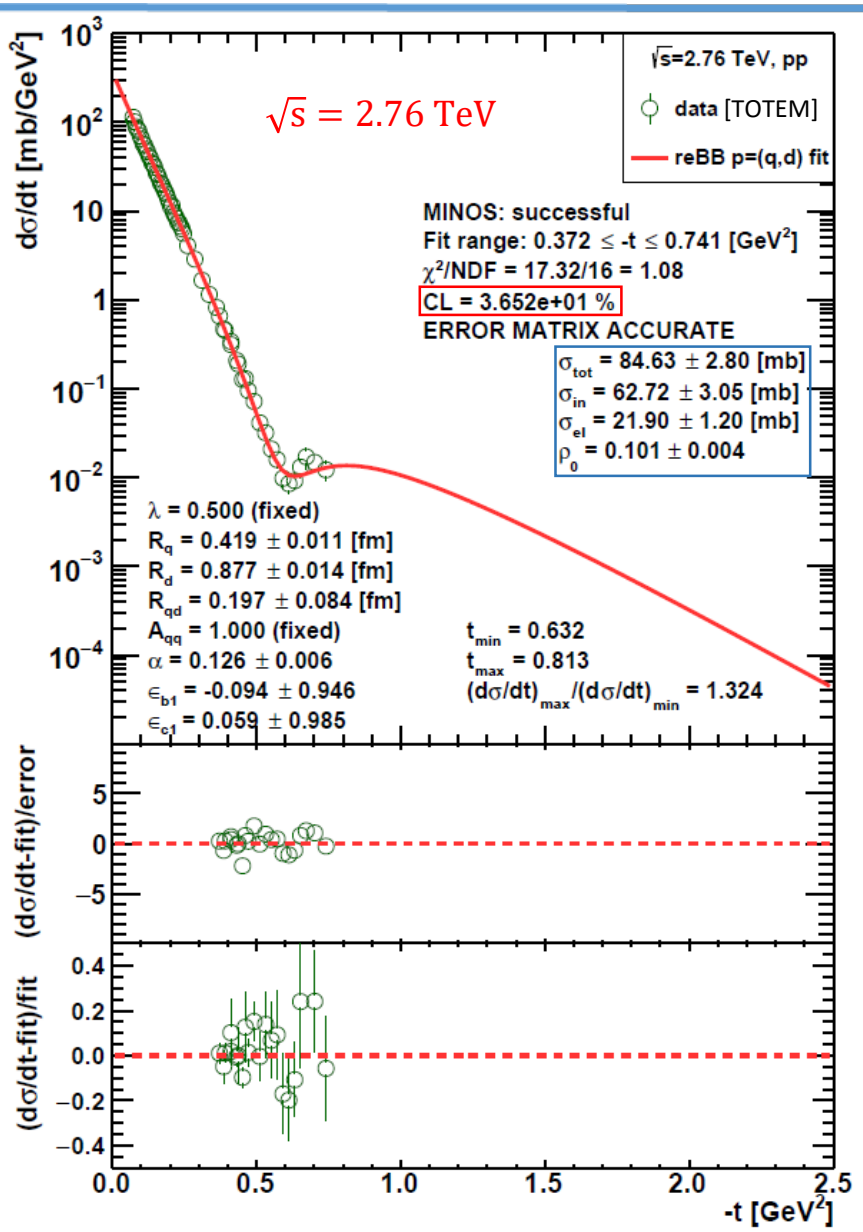


data: UA4 Collab. (SPS) Phys.Lett. 127B (1983)
UA4 Collab. (SPS) Phys.Lett. 155B (1985)

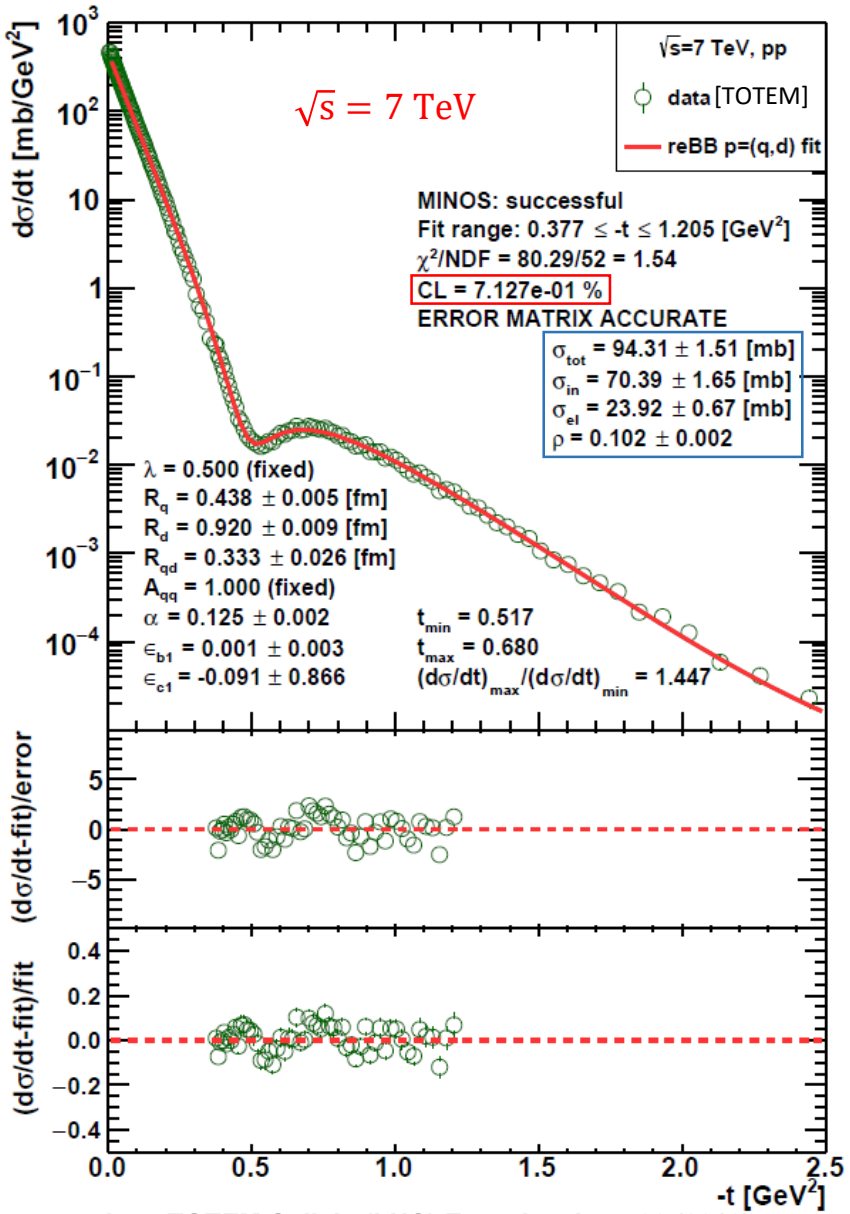


data: D0 Collab. (TEVATRON) Phys.Rev. D86 (2012)

Satisfactory ReBB model fits for pp dσ/dt data

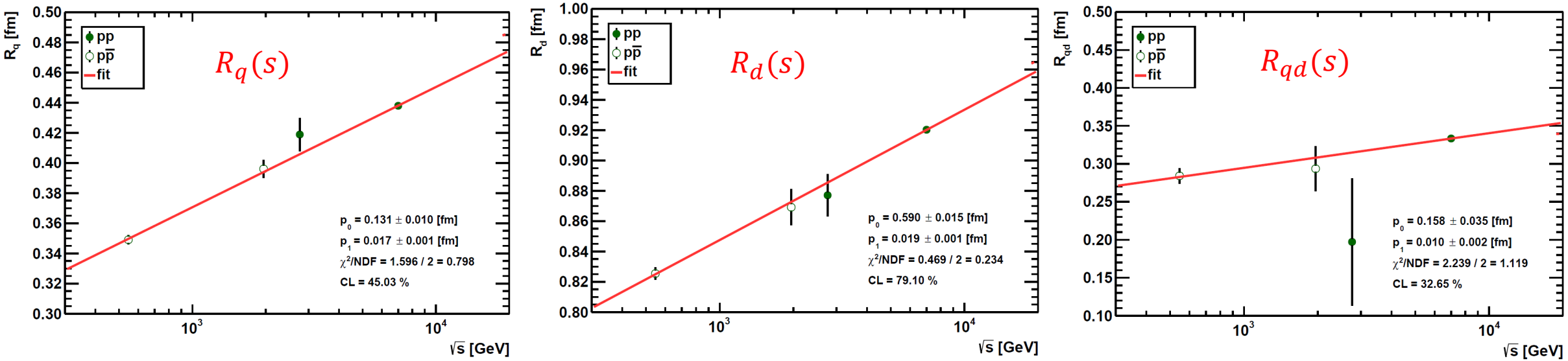


data: TOTEM Collab. (LHC) Eur. Phys. J. C 80 (2020) 91



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 $\alpha(s)$

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

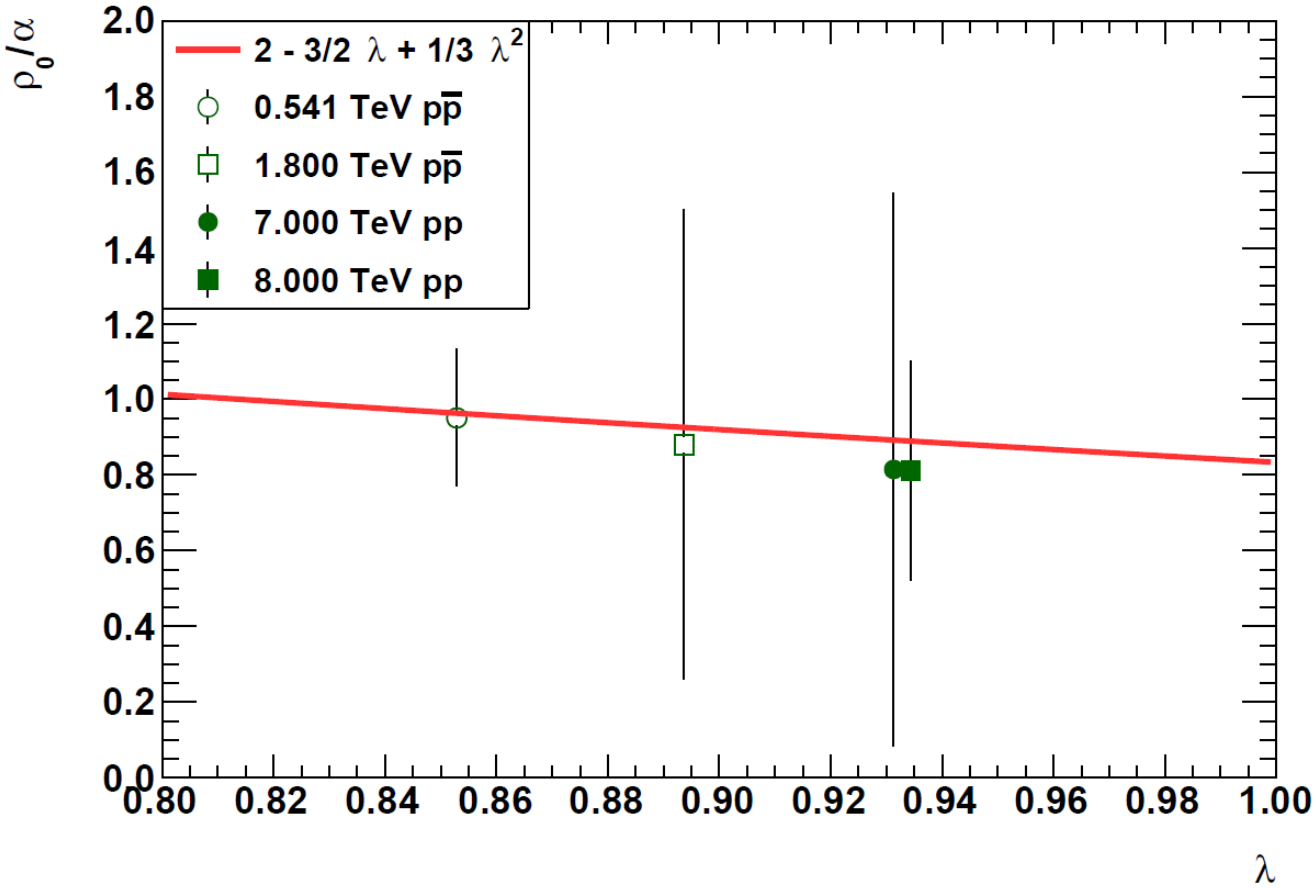
$$\alpha\tilde{\sigma}_{in} \ll 1$$

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

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

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

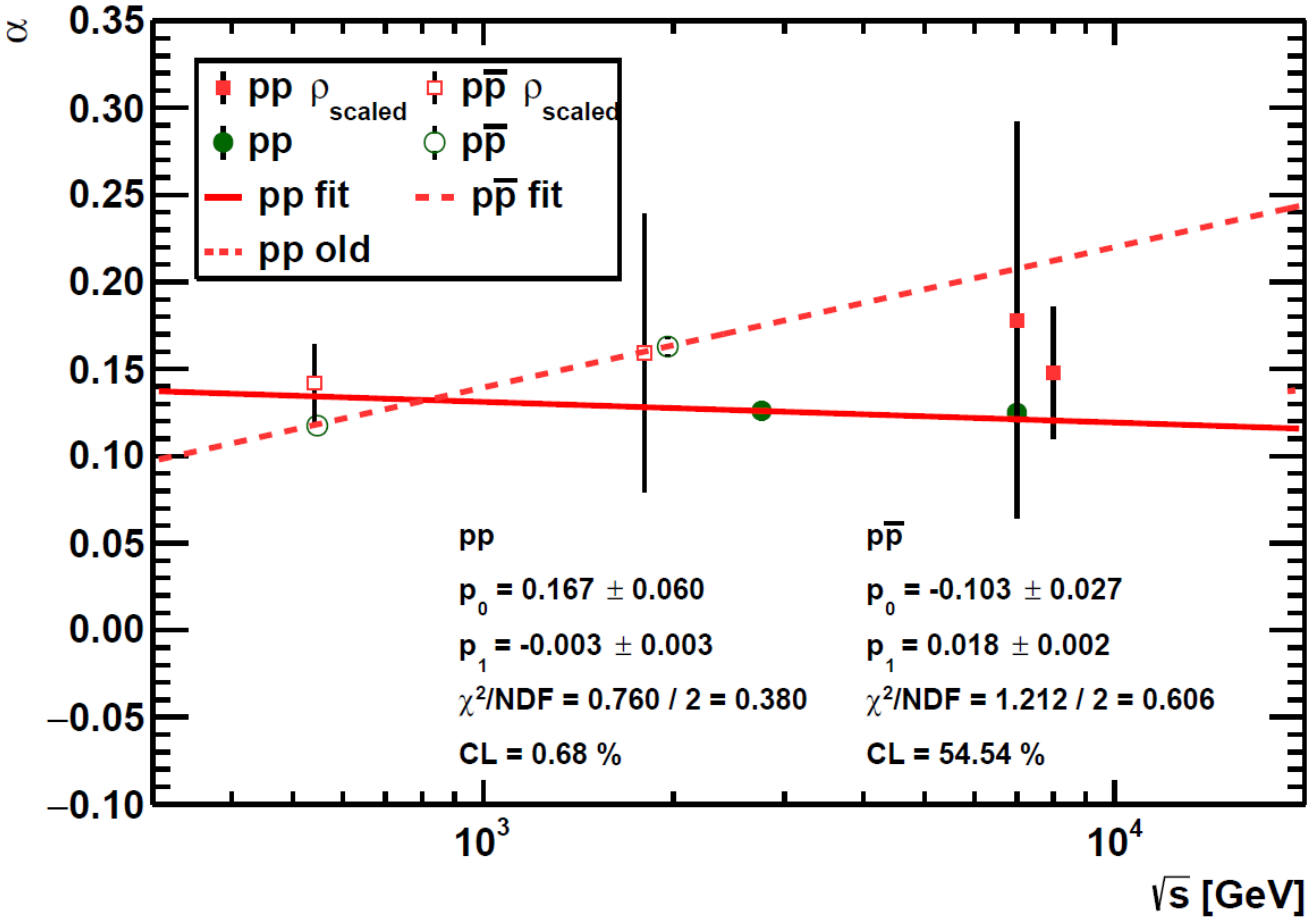
→ by rescaling one can get additional α parameter values at energies where ρ_0 is measured



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.

T. Csörgő, I. Szanyi, *Eur. Phys. J. C* **81**, 611 (2021)

Energy dependence of the α parameter



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

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

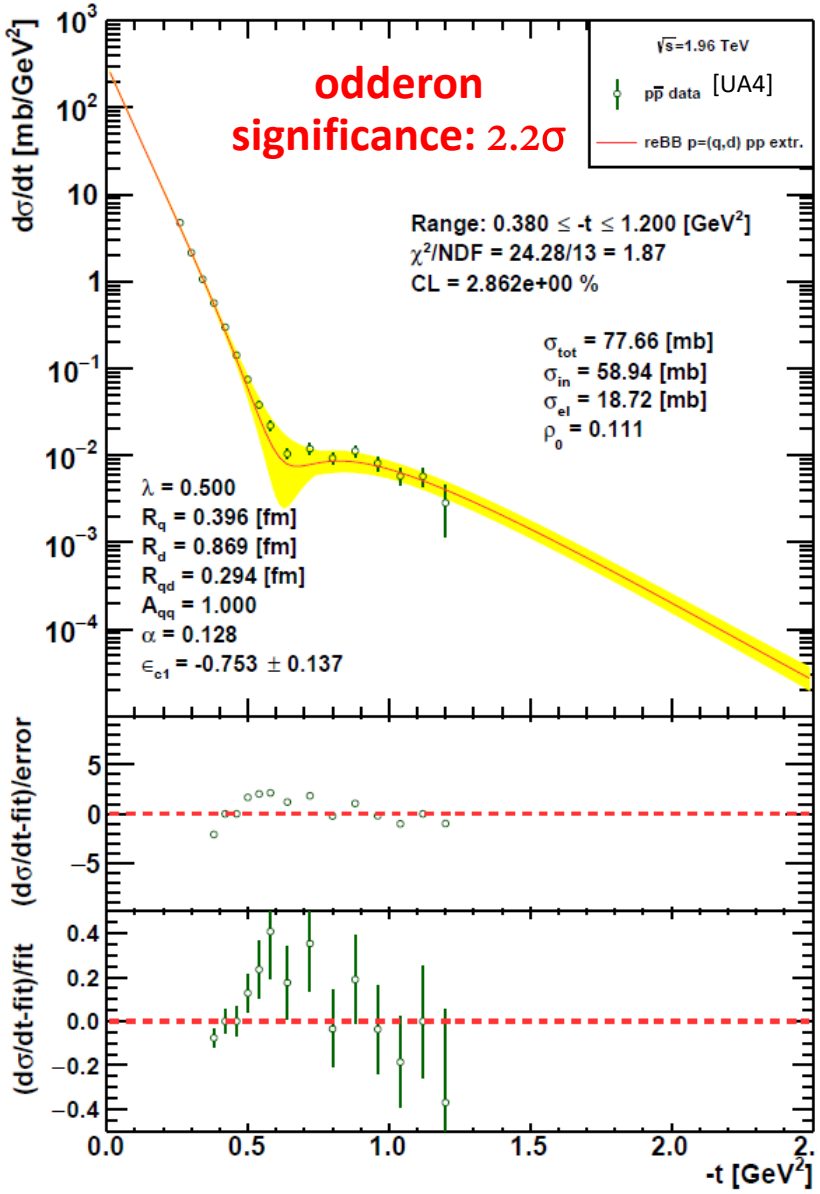
$$s_0 = 1\ GeV^2$$

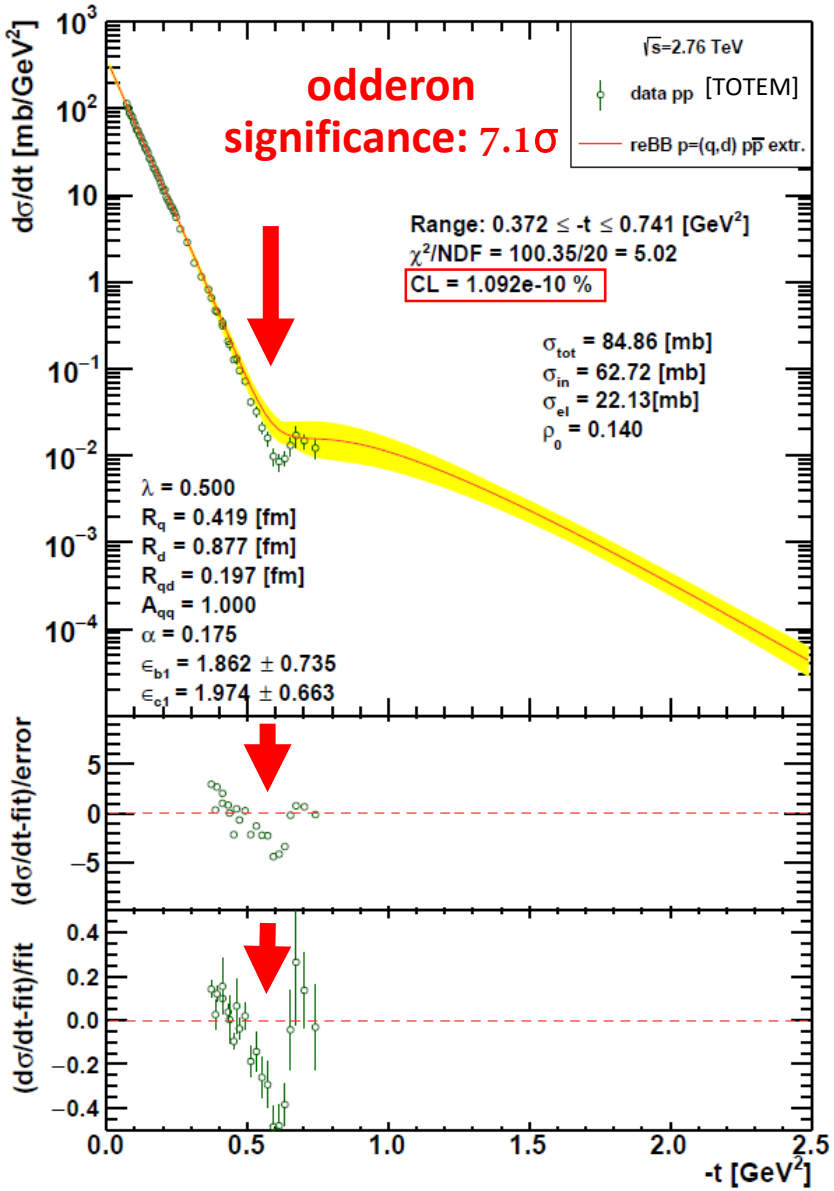
Parameter	$\alpha\ (pp)$	$\alpha\ (p\bar{p})$
χ^2/NDF	$0.760/2$	$1.212/2$
CL [%]	0.68	54.54
p_0	0.167 ± 0.060	-0.103 ± 0.027
p_1	-0.003 ± 0.003	0.018 ± 0.002

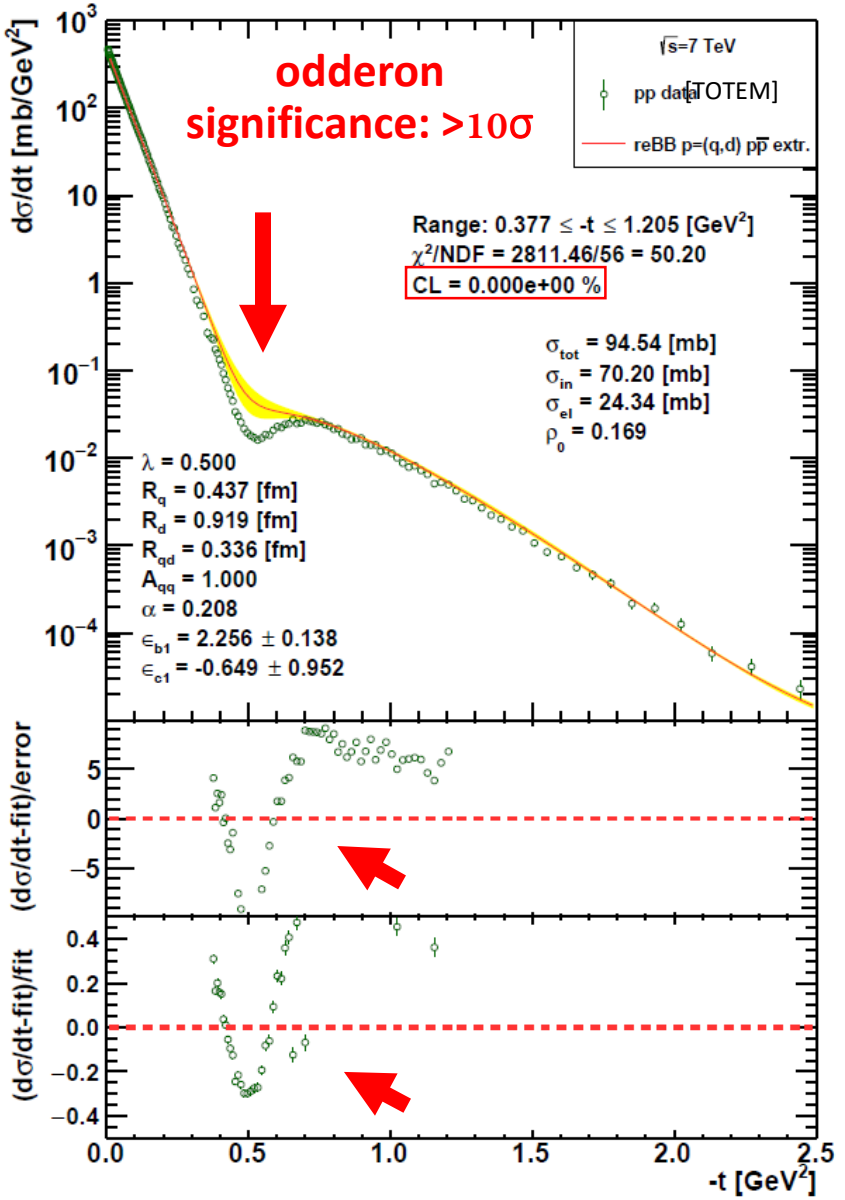
Parameters which define the energy dependence of the ReBB model α parameters for pp and p$\bar{p}$

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!

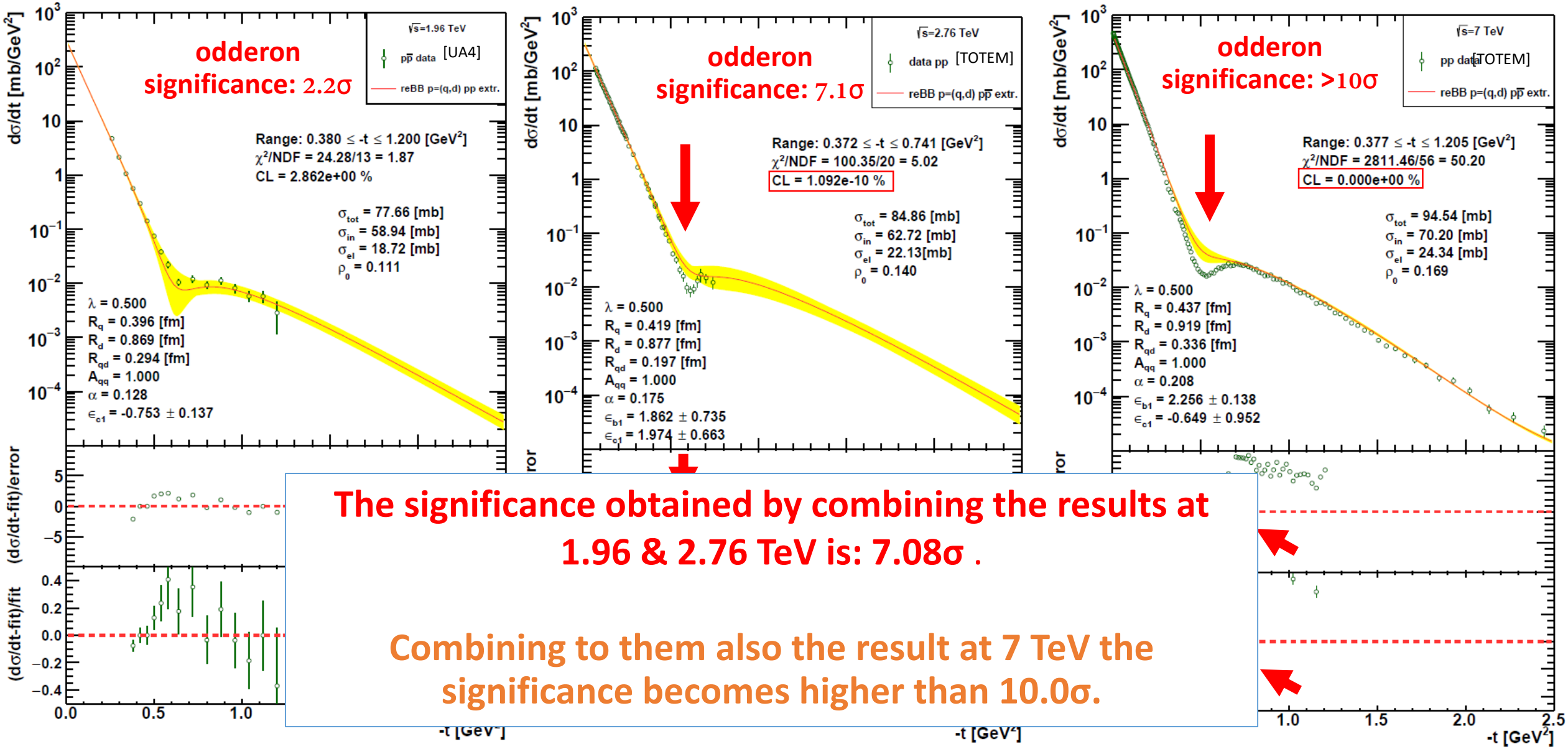
Extrapolations → ODDERON







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.

Summary

- **ReBB model fits to $\mathbf{pp}$ and $\mathbf{p\bar{p}}$ 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**

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

- lack of pp and $p\bar{p}$ 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**

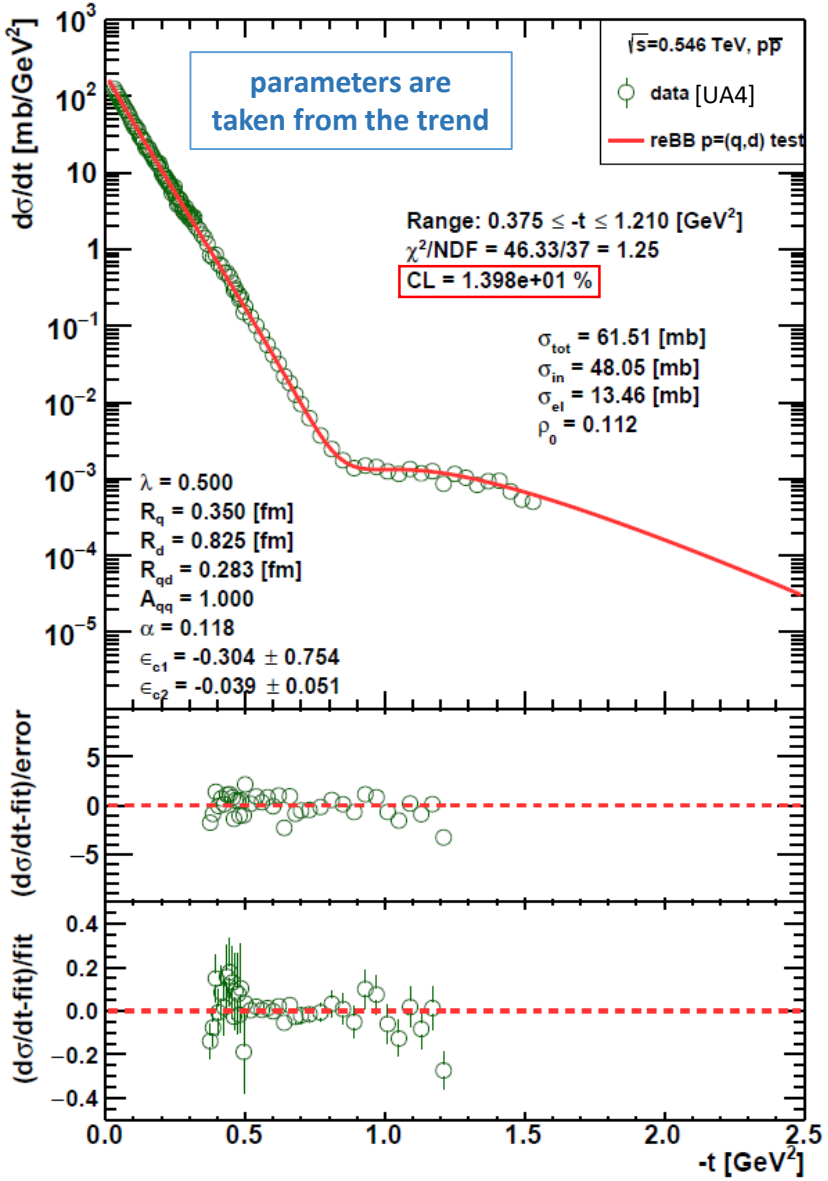
→ **difference between $\mathbf{pp}$ and $\mathbf{p\bar{p}}$ dσ/dt** in the dip region

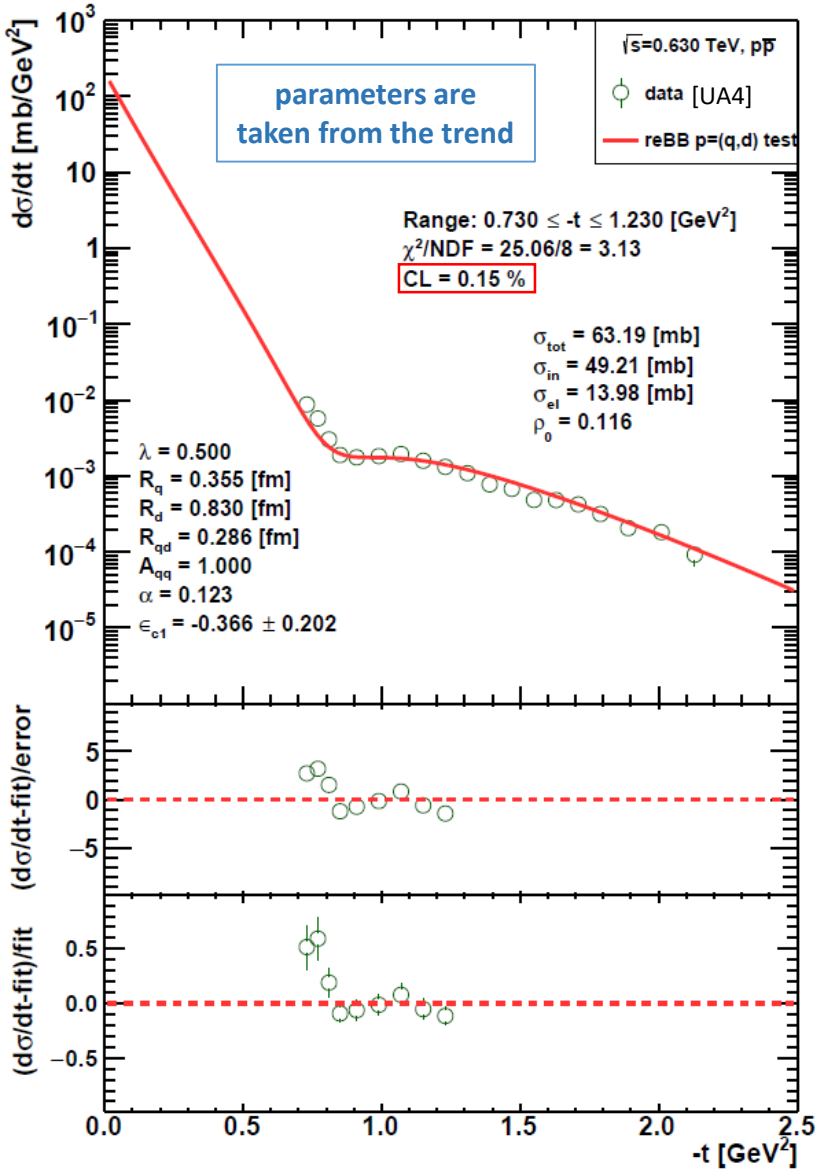
→ **model-dependent evidence for Odderon exchange in t-channel at $\sqrt{s} \gtrsim 1$ TeV with a significance of at least 7.08σ**

Thank you for your attention!

Backup slides

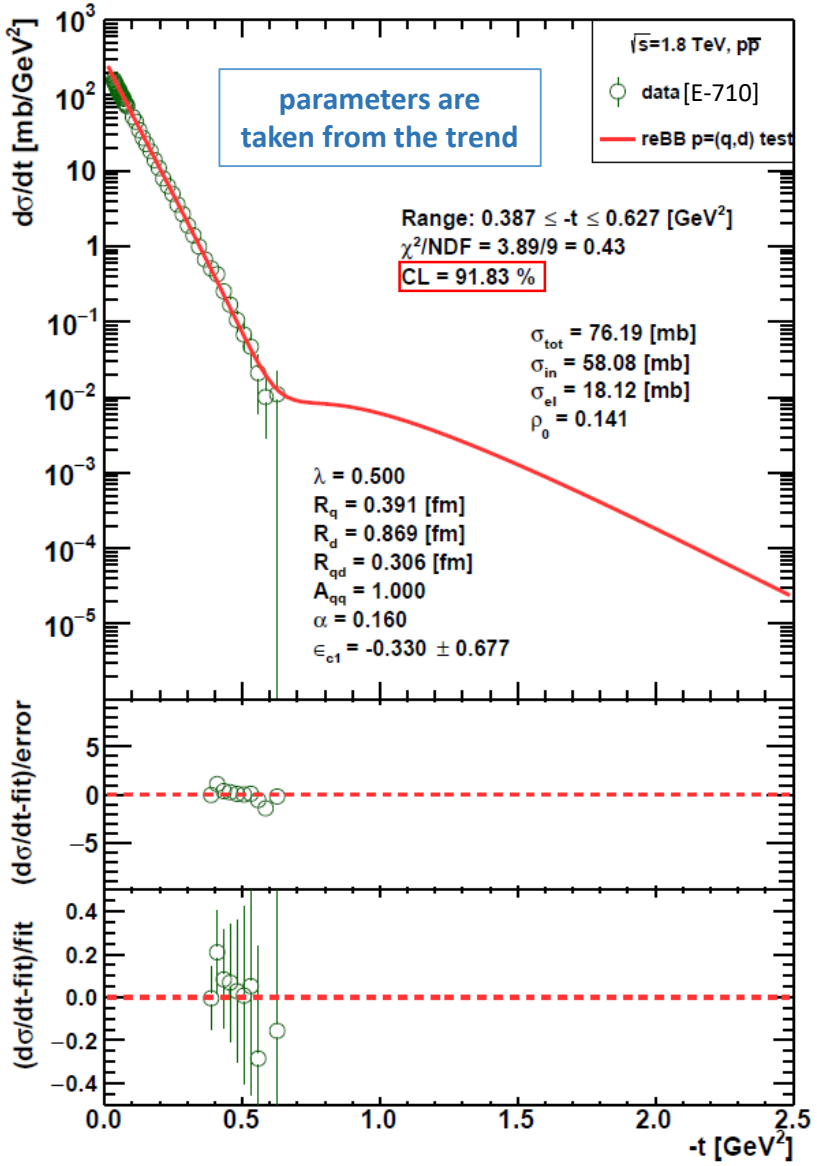
Tests @ 0.546 & 0.630 TeV ✓

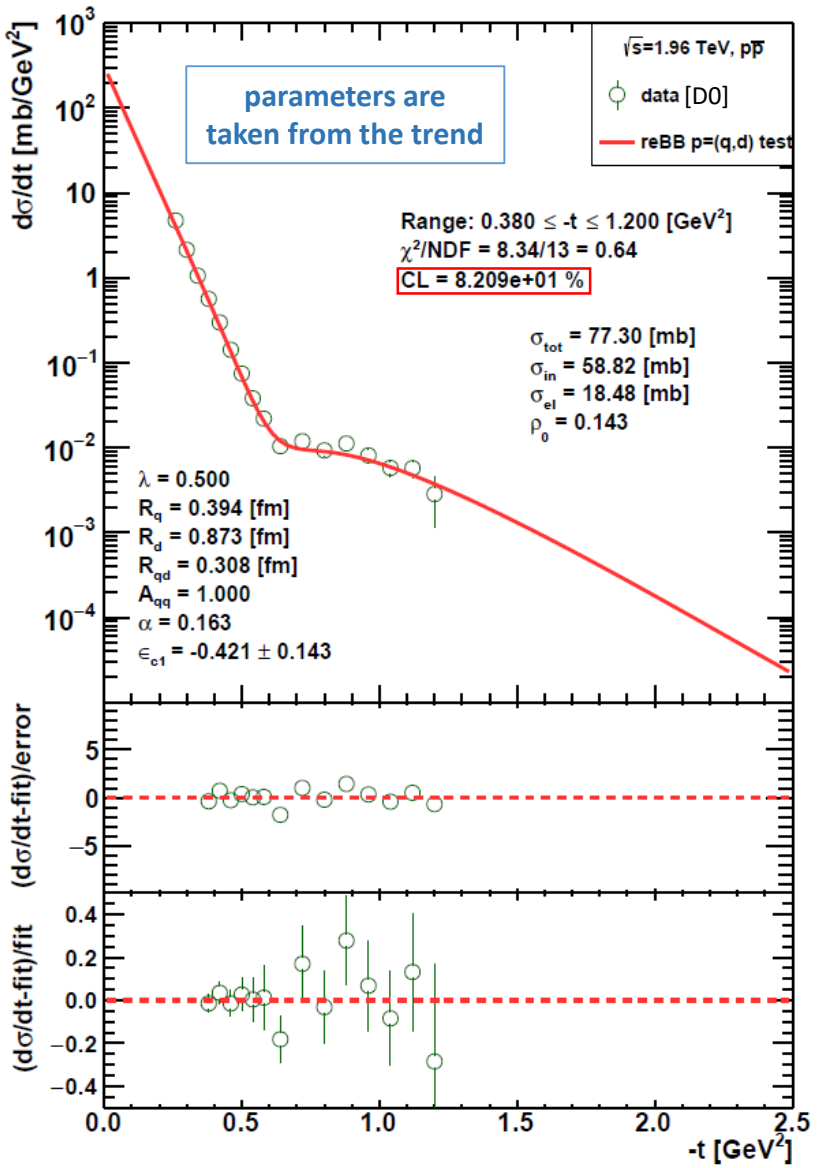




data: UA4 Collab. (SPS) Phys.Lett. B171 (1986)

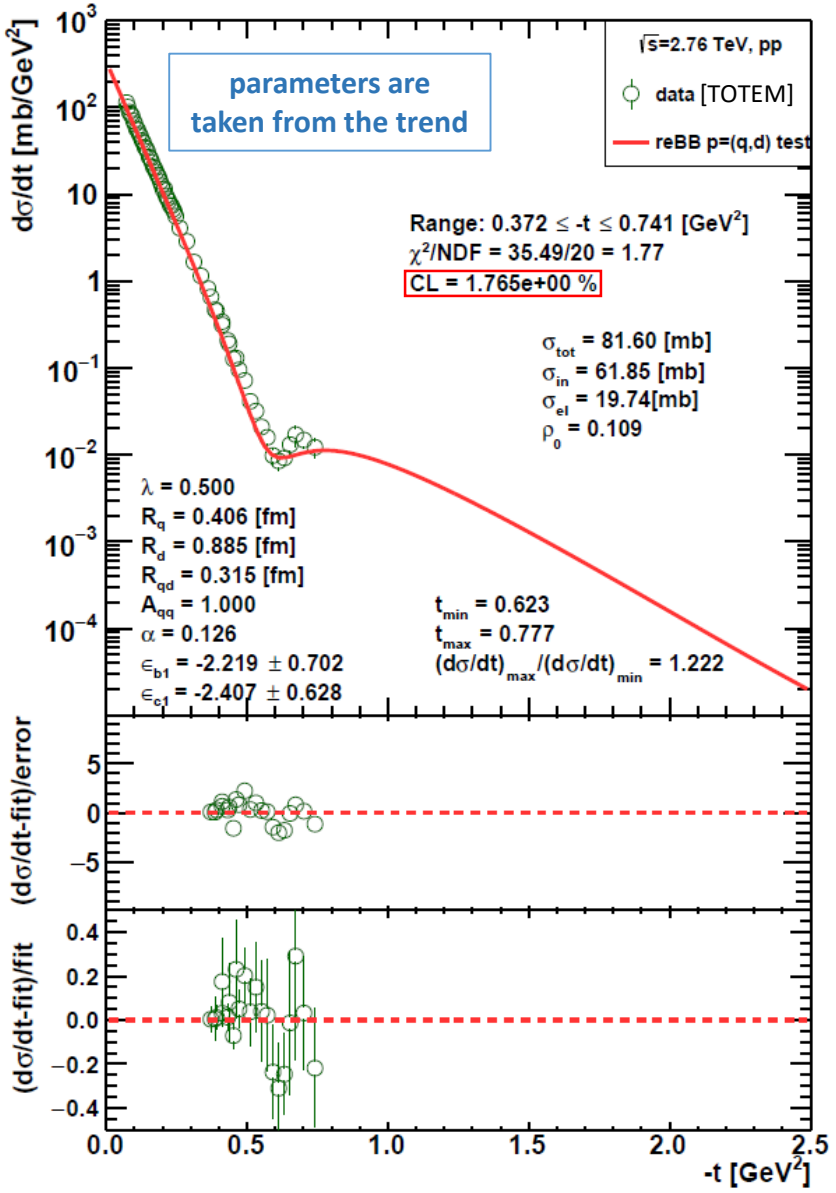
Tests @ 1.8 & 1.96 TeV ✓

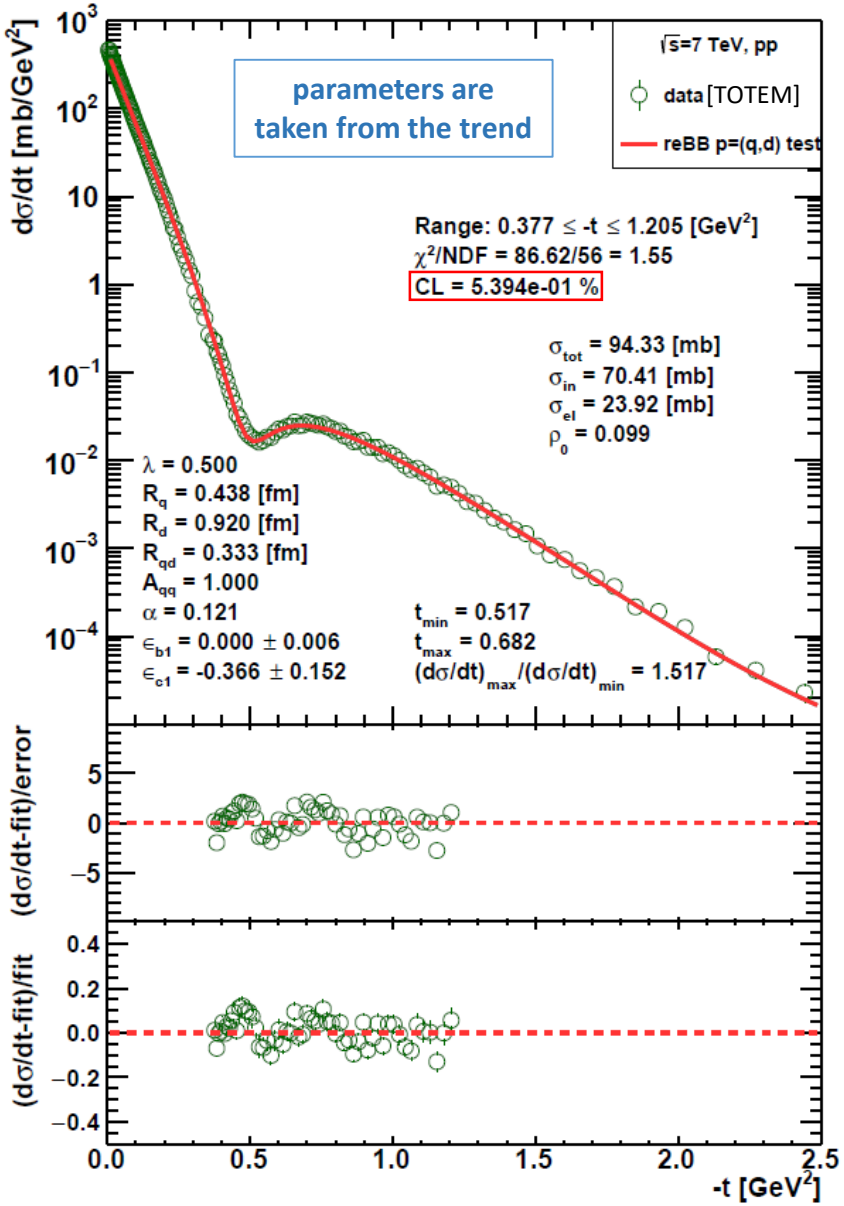




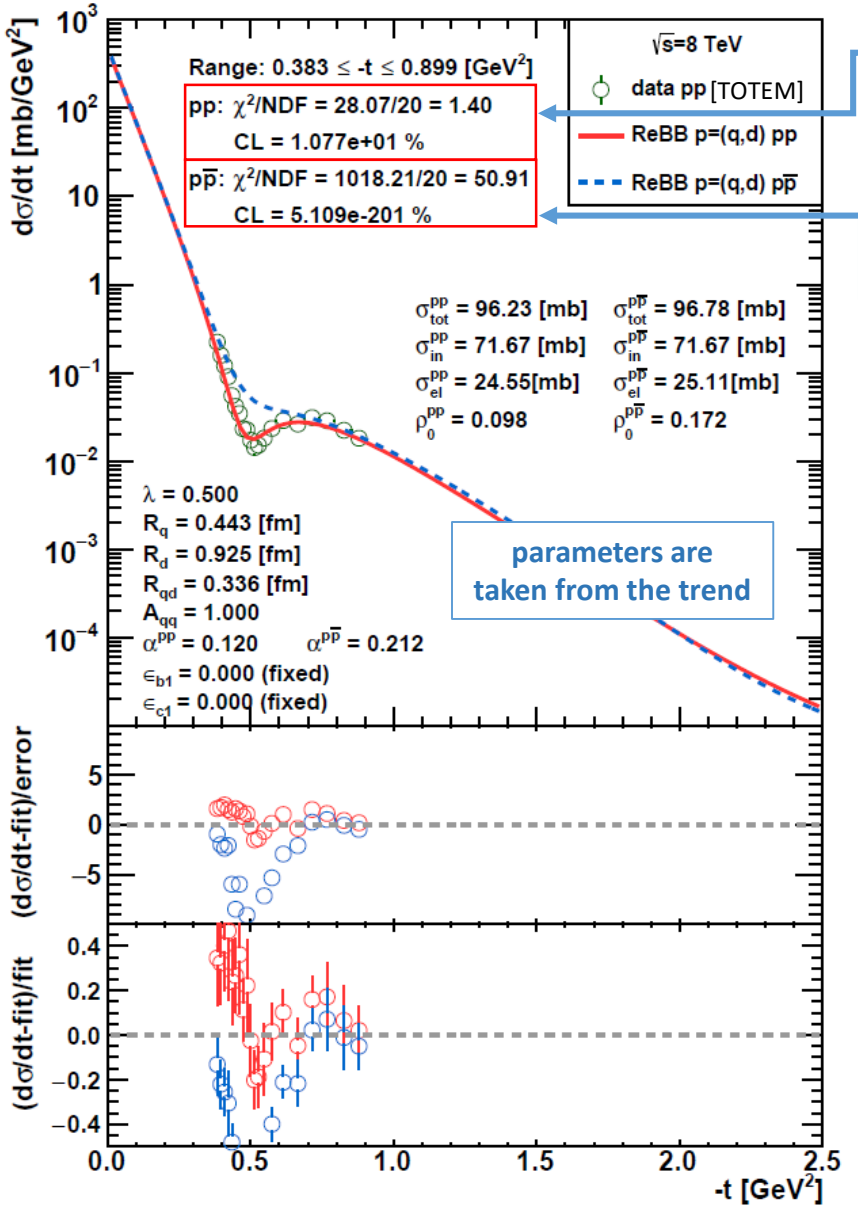
data: E-710 Collab. (TEVATRON) Phys.Lett. B247 (1990)

Tests @ 2.76 & 7.0 TeV ✓





pp test and $p\bar{p}$ extrapolation @ 8.0 TeV

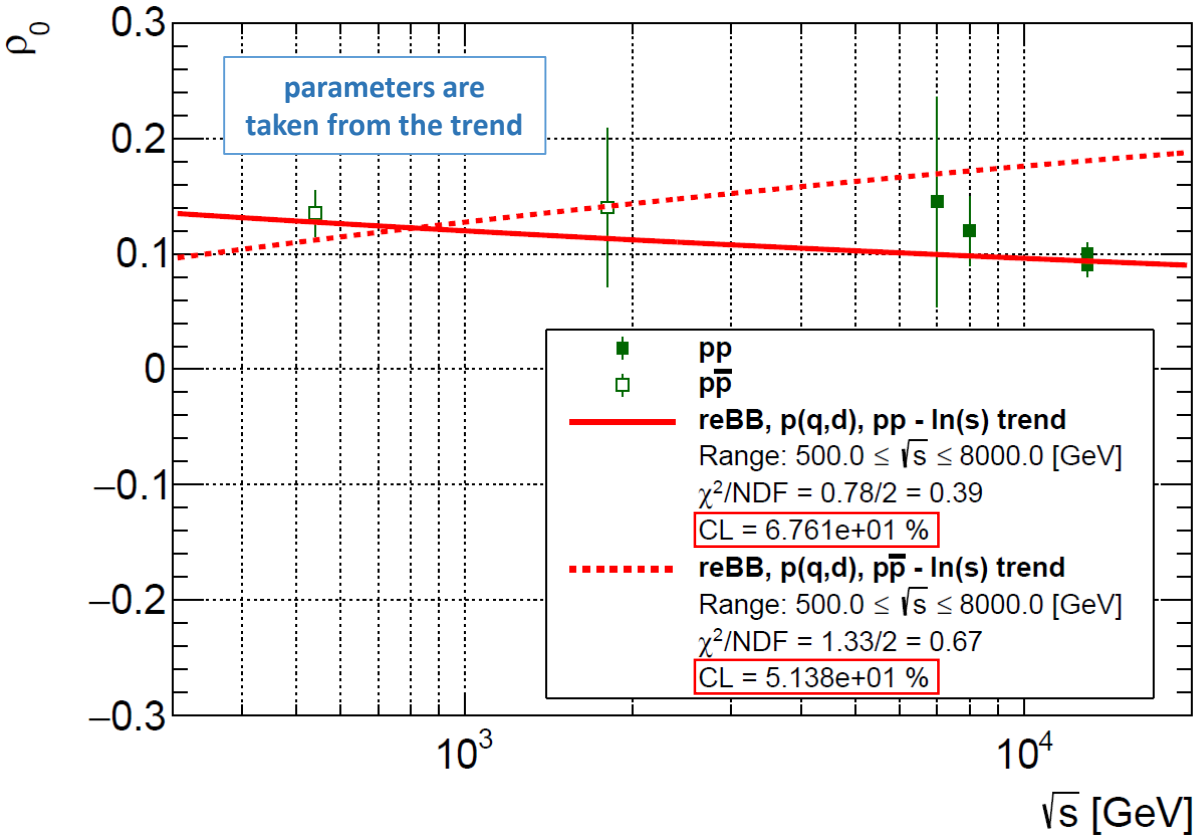


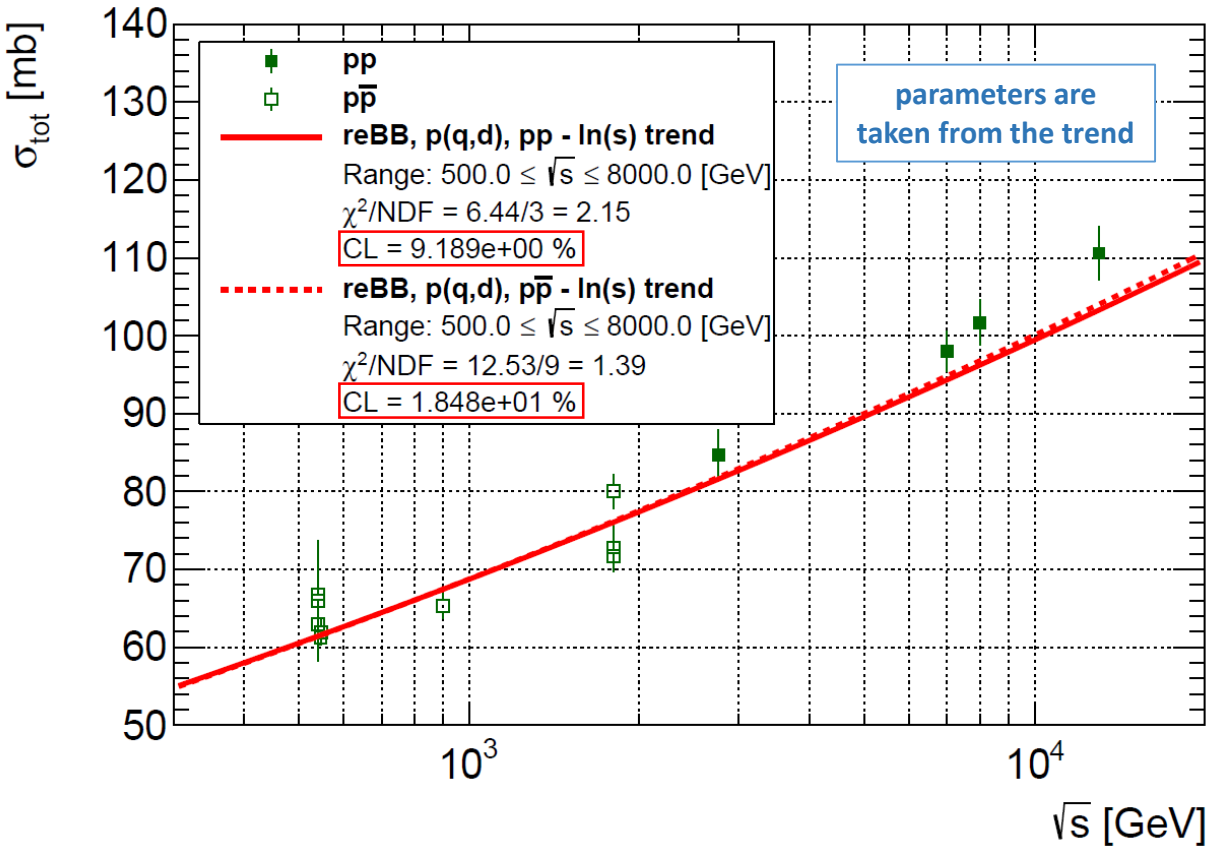
pp-pp agreement ✓

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

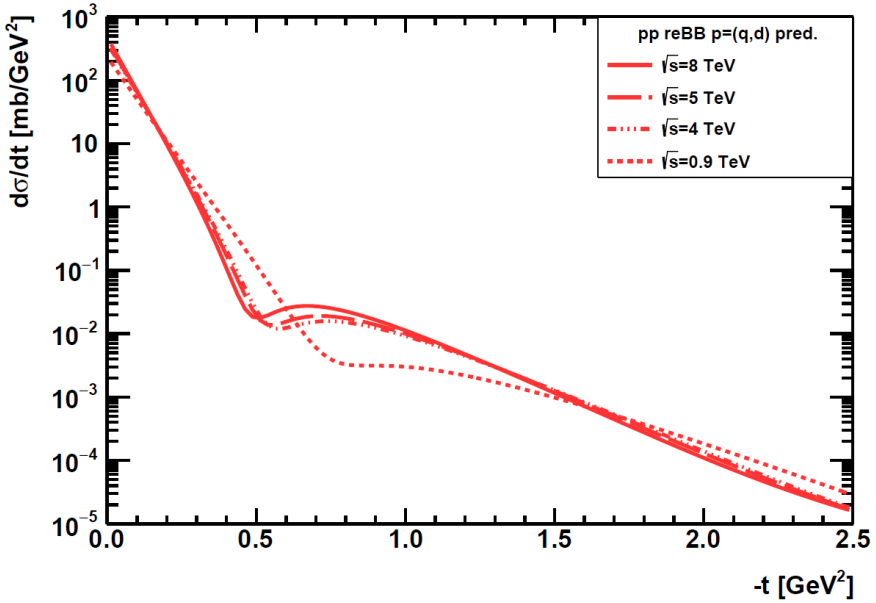
data: TOTEM&D0 Collab. (LHC) Phys. Rev. Lett. 127 (2021)

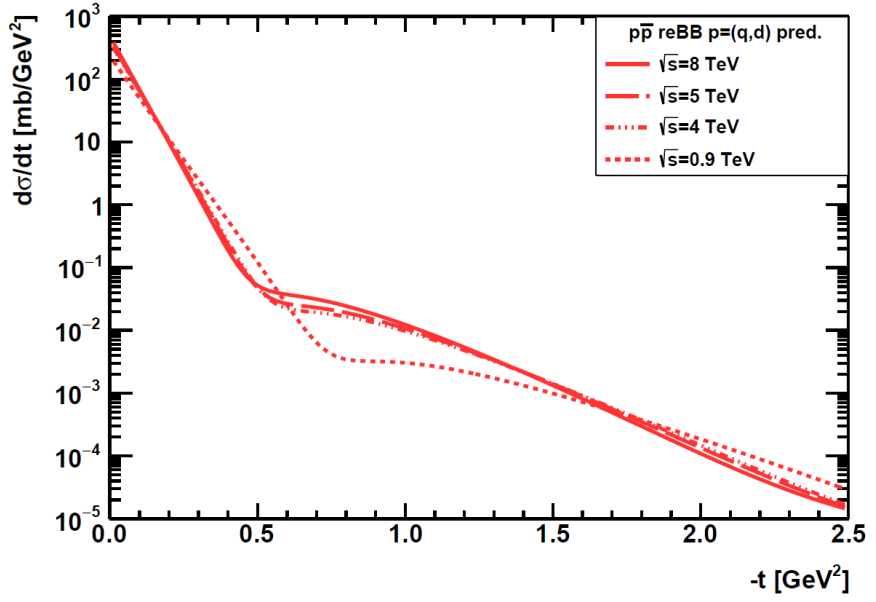
Tests for σ_{tot} and ρ_0 ✓

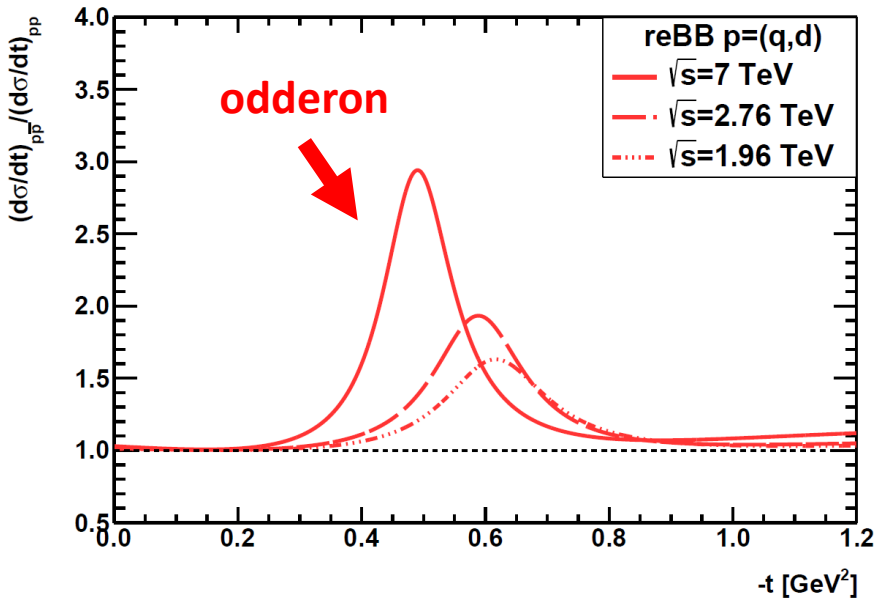


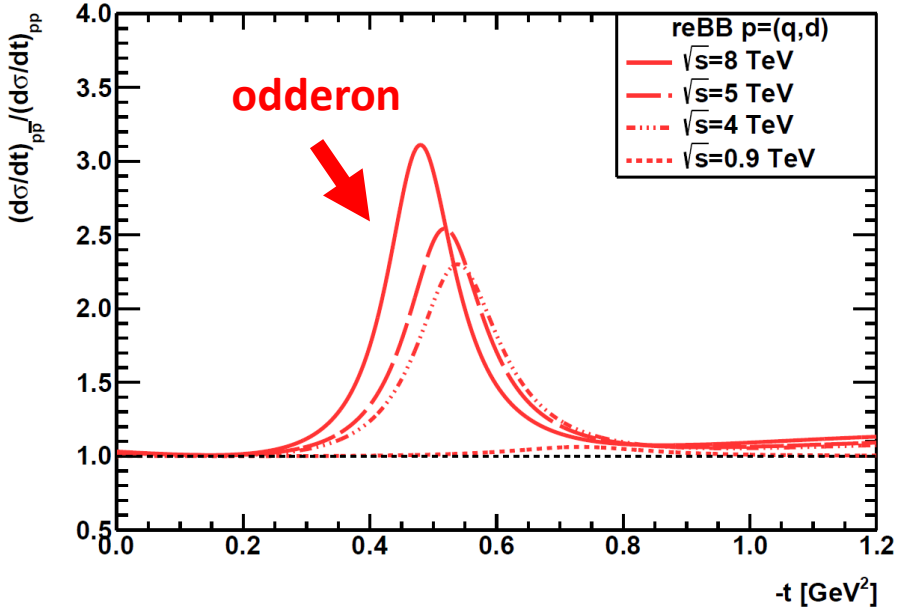


Predictions for pp and $p\bar{p}$ dσ/dt and their ratios

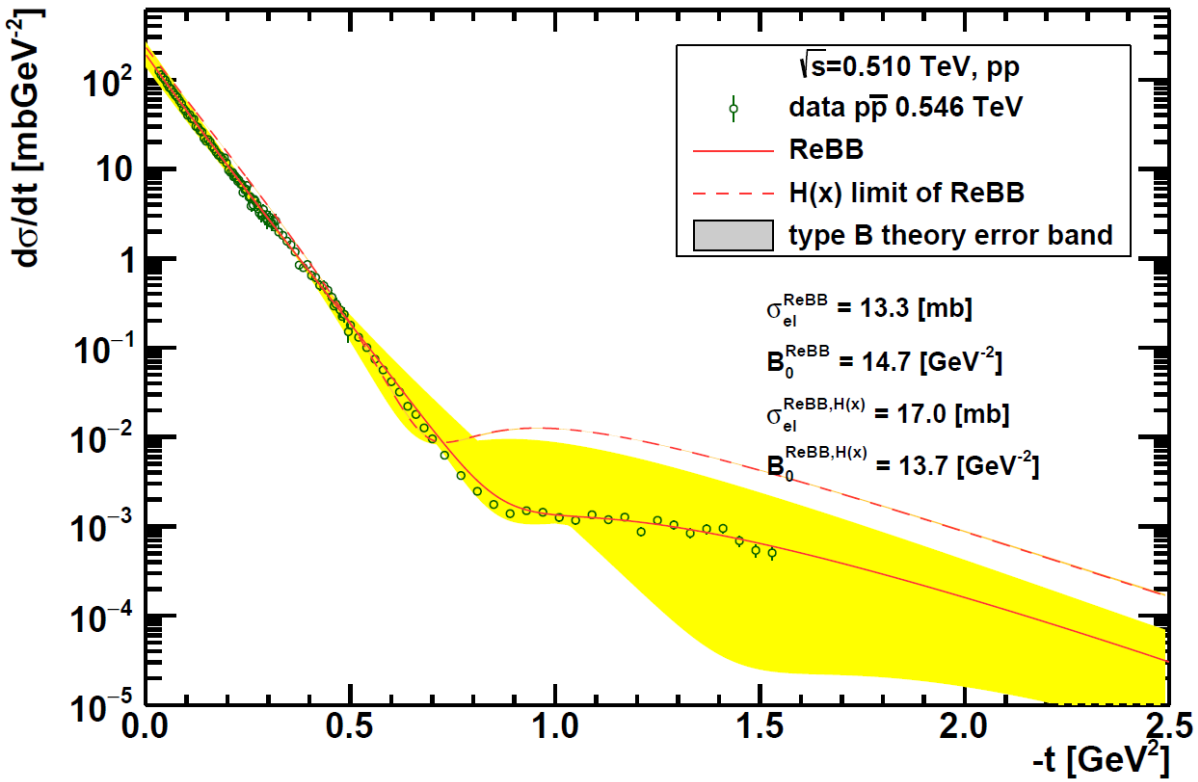


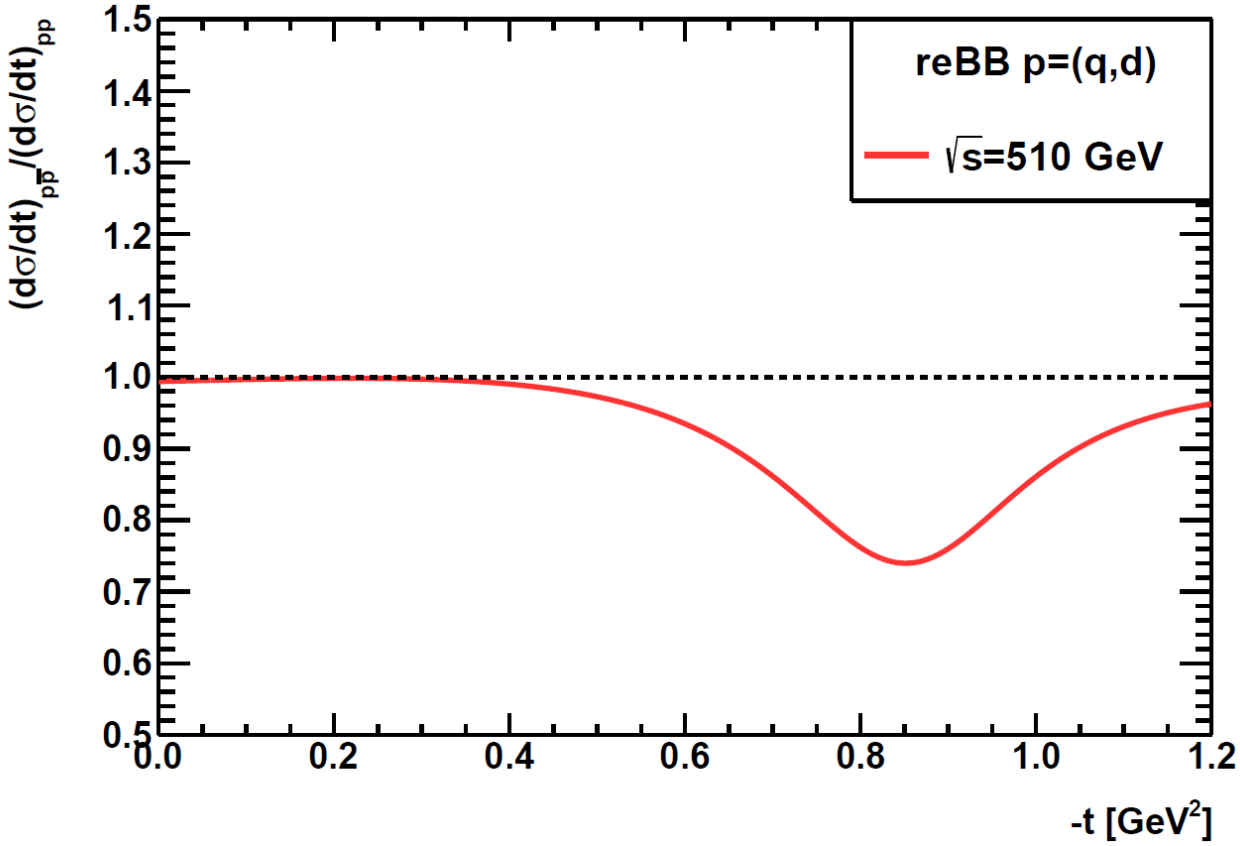






ReBB prediction for pp dσ/dt @ 0.51 TeV

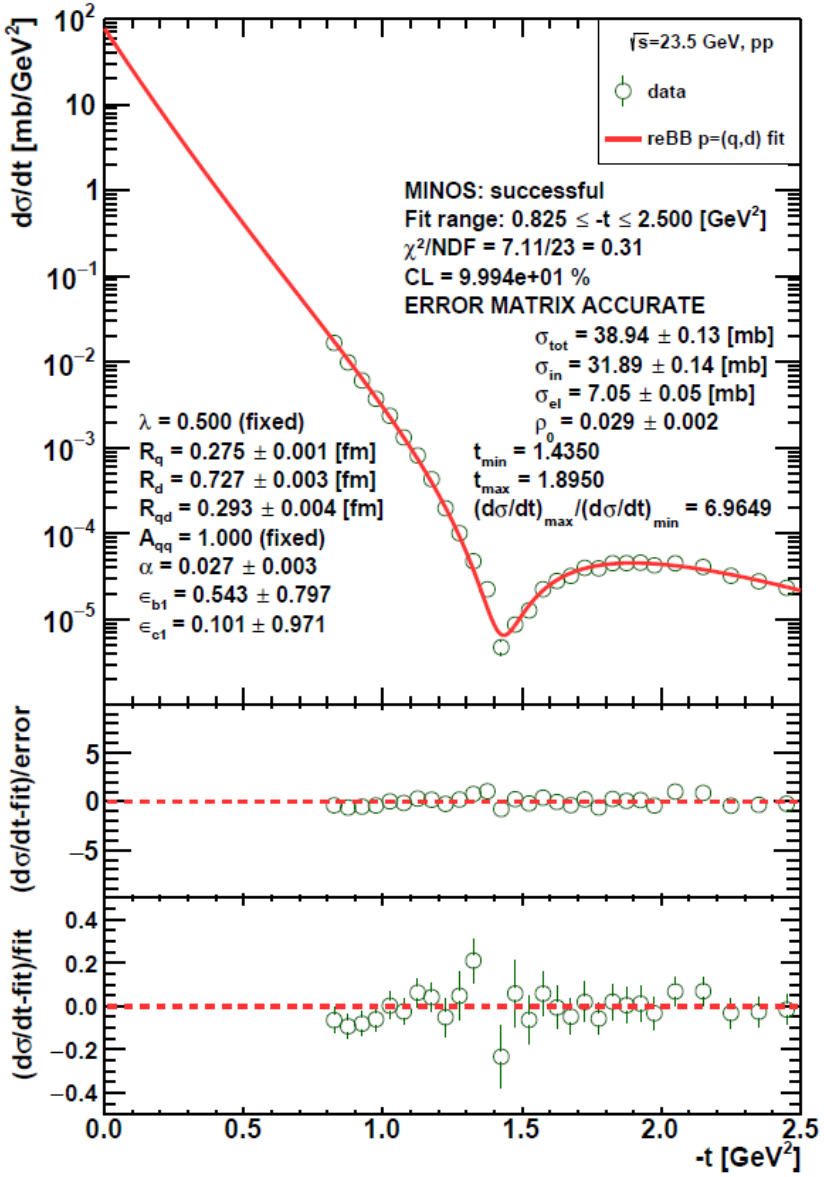


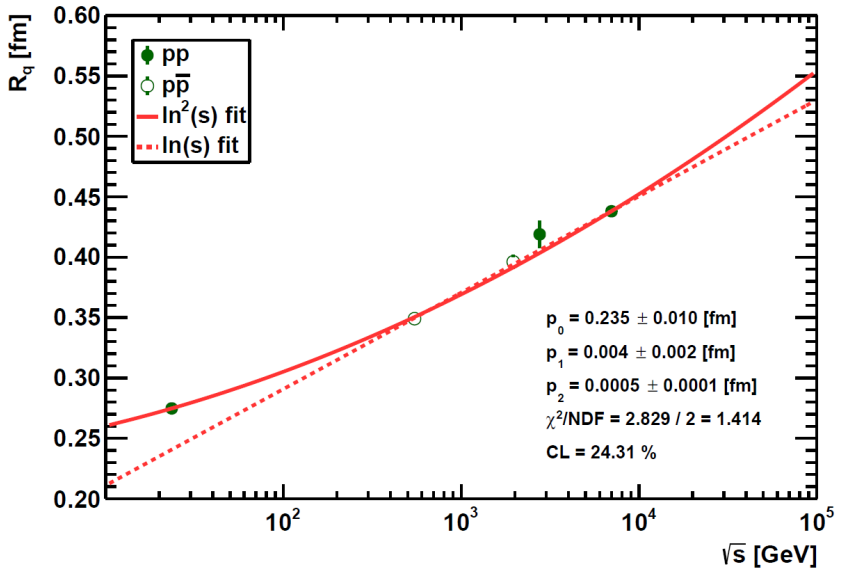


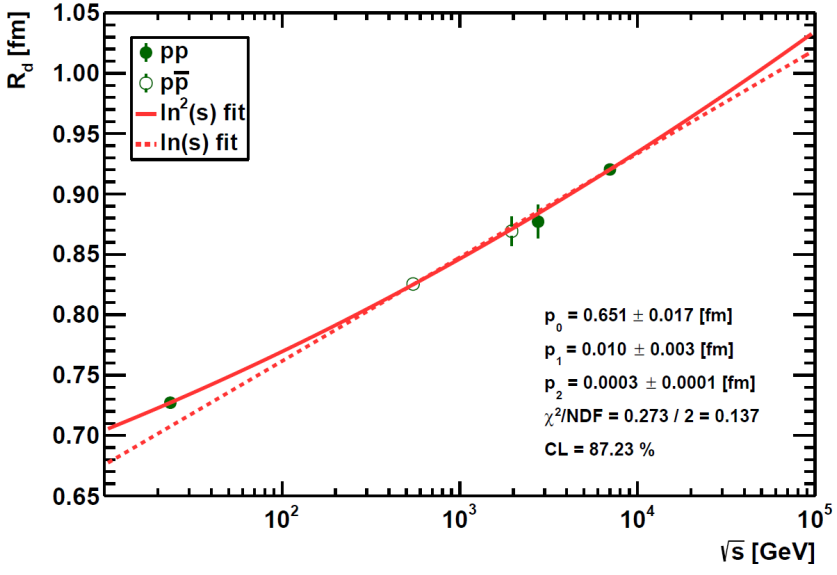
- pp data measured by the STAR Collab. is expected at 0.51 TeV

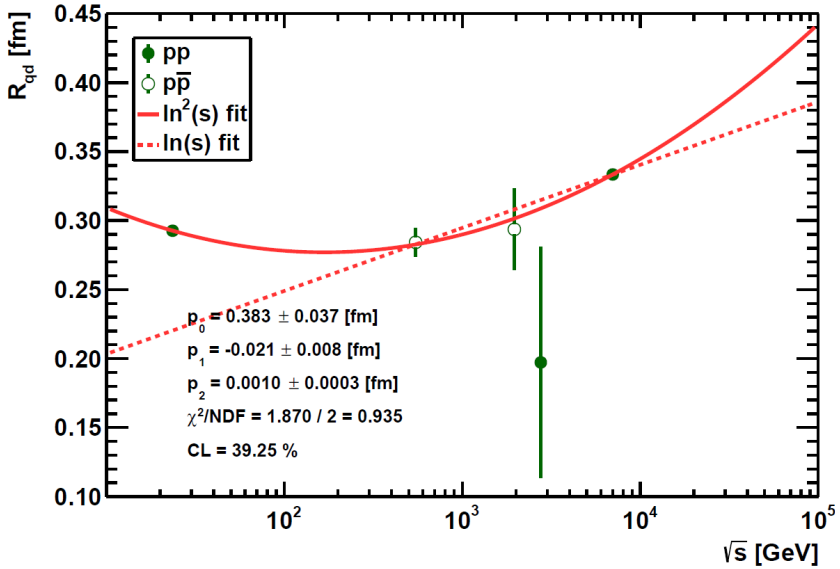
Fit at pp 23.5 GeV & $\ln^2(s)$ energy dependence

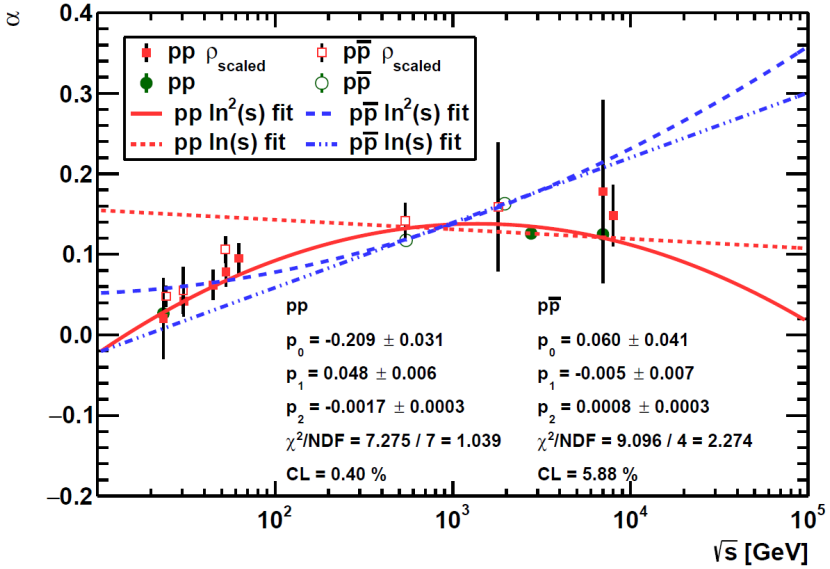
$$P(s) = p_0 + p_1 \ln(s/s_0) + p_2 \ln^2(s/s_0) \qquad s_0 = 1\ GeV^2$$



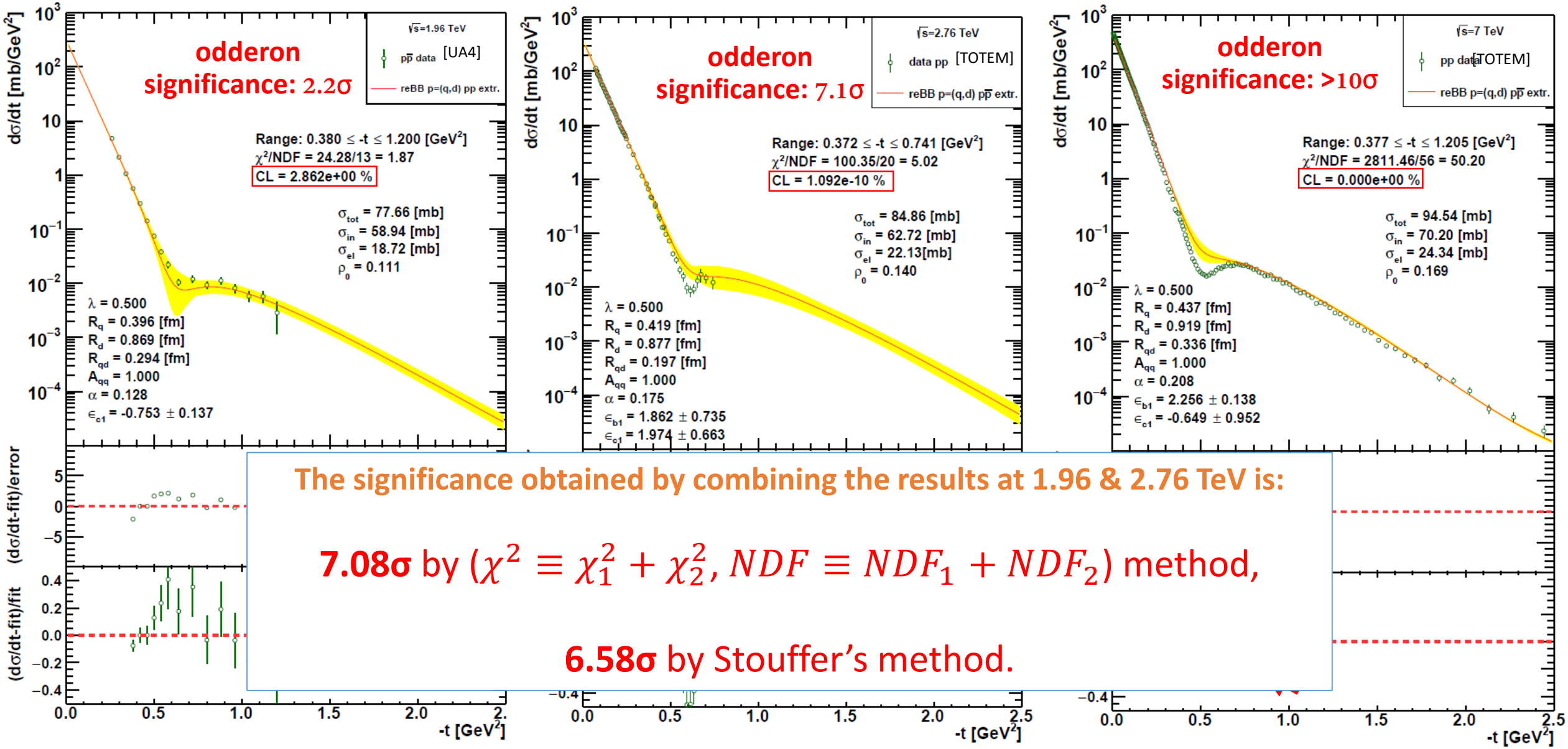








Various significance combinations



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.