Results of the Odderon search with the Real Extended Bialas-Bzdak model

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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:**

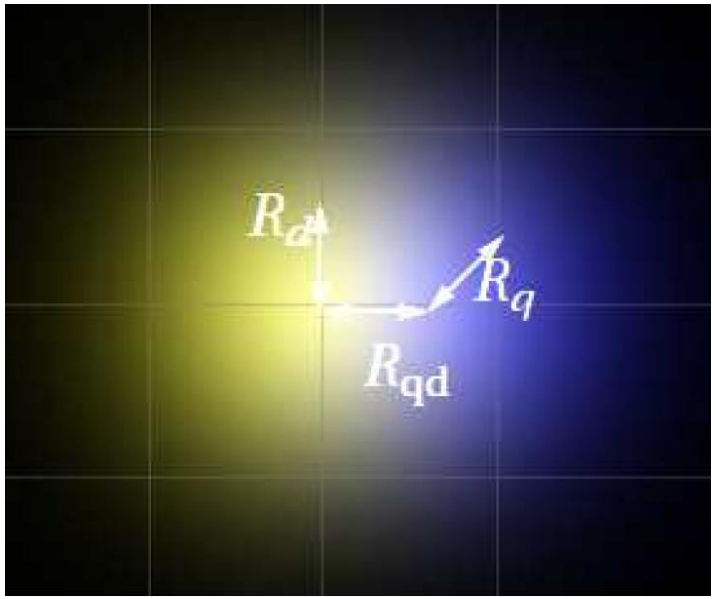
$$\sigma(\vec{s}_q, \vec{s}_d; \vec{s}'_q, \vec{s}'_d; \vec{b}) = 1 - \prod_a \prod_b \left[1 - \sigma_{ab}(\vec{b} + \vec{s}'_a - \vec{s}_b)\right]$$

$$\sigma_{ab}(\vec{s}) = A_{ab} e^{-s^2/S_{ab}^2} \qquad S_{ab}^2 = R_a^2 + R_b^2 \qquad a, b \in \{q, d\}$$

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

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

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



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

- **free parameters:**

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

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:**

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

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

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

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:**

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

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

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

- **parameter ρ:**

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

Earlier results

$A_{qq} = 1$ (fixed), $\lambda = 0.5$ (fixed)

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

$\sqrt{s}$ [GeV]	23.5	30.7	52.8	62.5	7000	
$\|t\|$ [GeV^2]	$(0, 2.5)$				$(0, \|t_{sep}\|)$	$(\|t_{sep}\|, 2.5)$
χ^2/NDF	124.7/101	95.6/46	96.1/47	76.2/46	109.9/81	120.4/73
CL [%]	5.5	2×10^{-3}	3×10^{-3}	0.3	1.8	4×10^{-2}
R_q $[fm]$	0.27±0.01	0.28±0.01	0.28±0.01	0.28±0.01	0.45±0.01	0.43±0.01
R_d $[fm]$	0.72±0.01	0.74±0.01	0.74±0.01	0.75±0.01	0.94±0.01	0.91±0.01
R_{qd} $[fm]$	0.30±0.01	0.29±0.01	0.31±0.01	0.32±0.01	0.32±0.05	0.37±0.02
α	0.03±0.01	0.02±0.01	0.04±0.01	0.04±0.01	0.11±0.04	0.12±0.01

Table 1: The values of the fitted ReBB model parameters from ISR to LHC energies. At the 7 TeV LHC energy, the pp elastic $d\sigma/dt$ data measured by the TOTEM experiment is a composition of two subsequent measurements, which are separated at $t_{sep} = -0.375$ GeV^2. The errors and the values are rounded up to two valuable decimal digits.

Energy dependence of the parameters for **pp**

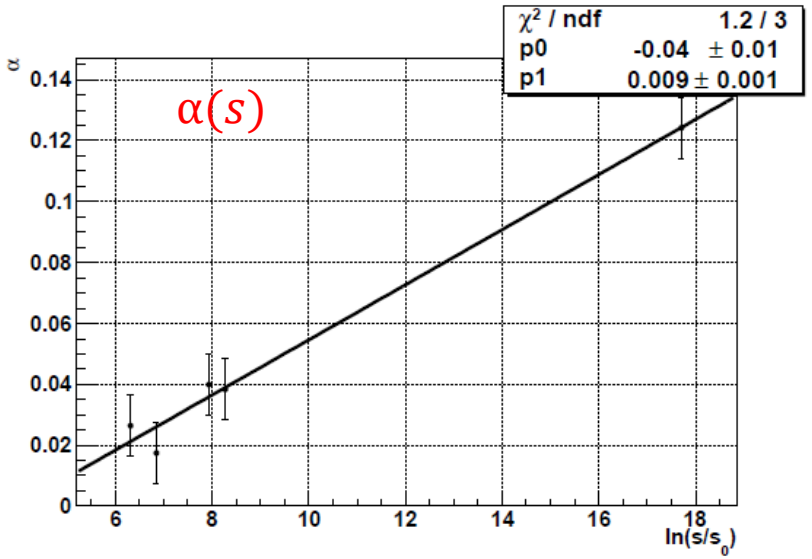
$$P(s) = p_0 + p_1 ln(s/s_0)$$

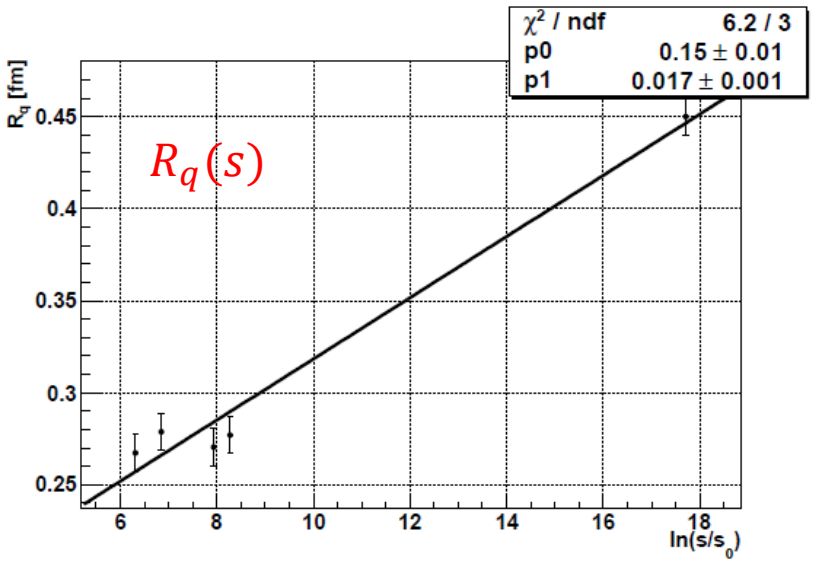
$$P \in \{R_q, R_d, R_{qd}, \alpha\}$$

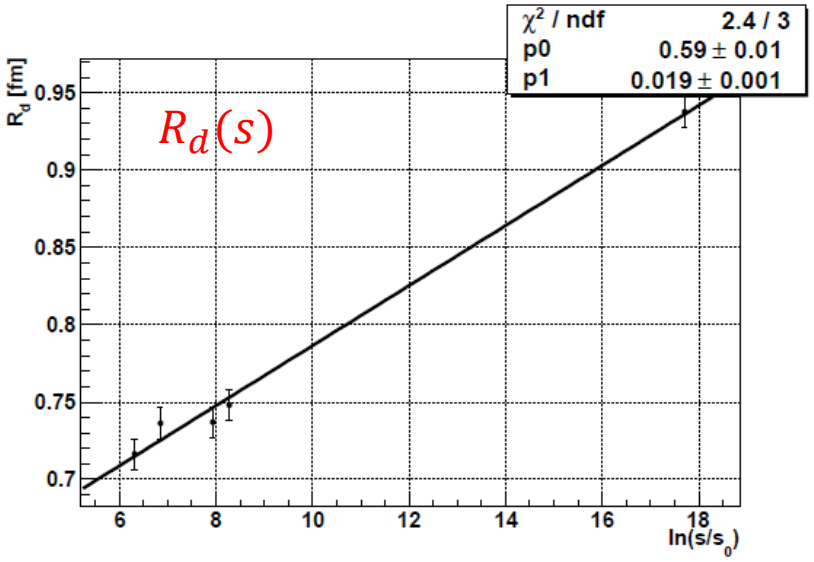
$$s_0 = 1\ GeV^2$$

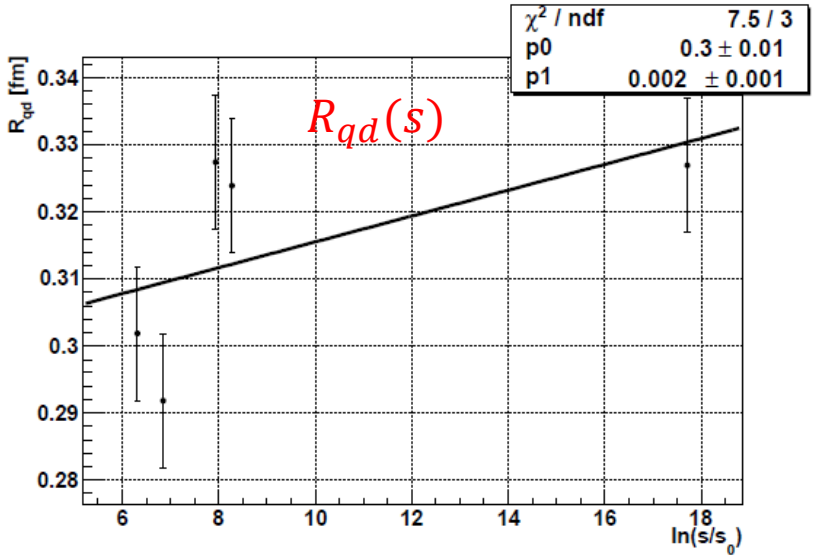
arXiv:1505.01415

Parameter	$R_q\ [fm]$	$R_d\ [fm]$	$R_{qd}\ [fm]$	α
χ^2/NDF	6.2/3	2.4/3	7.5/3	1.2/3
CL [%]	10.2	49.4	5.8	75.3
p_0	0.15 ± 0.01	0.59 ± 0.01	0.30 ± 0.01	-0.04 ± 0.01
p_1	0.017 ± 0.001	0.019 ± 0.001	0.002 ± 0.001	0.009 ± 0.001









New fit method

- **least squares fitting with:**

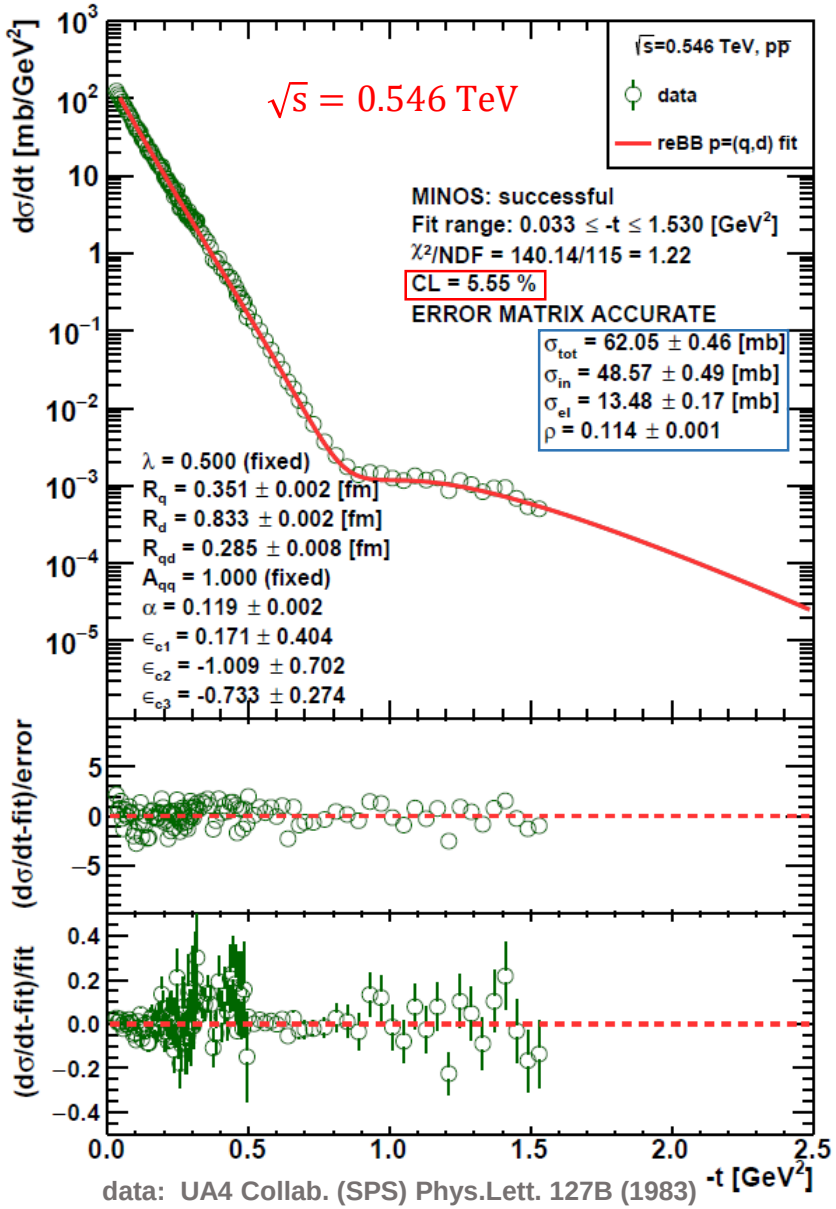
$$\chi^2 = \sum_{j=1}^{M} \sum_{i=1}^{n_j} \frac{\left(d_i + \epsilon_{bj}\sigma_{bji} + \epsilon_{cj} d_i \sigma_{cj} - th_i\right)^2}{\tilde{\sigma}_{ji}^2} + \epsilon_{bj}^2 + \epsilon_{cj}^2 + \left(\frac{d_{\sigma_{tot}} - th_{\sigma_{tot}}}{\delta\sigma_{tot}}\right)^2$$

$$\tilde{\sigma}_{ji}^2 = \sigma_{aji}\left(\frac{d_i + \epsilon_{bj}\sigma_{bji} + \epsilon_{cj} d_i \sigma_{cj}}{d_i}\right)$$

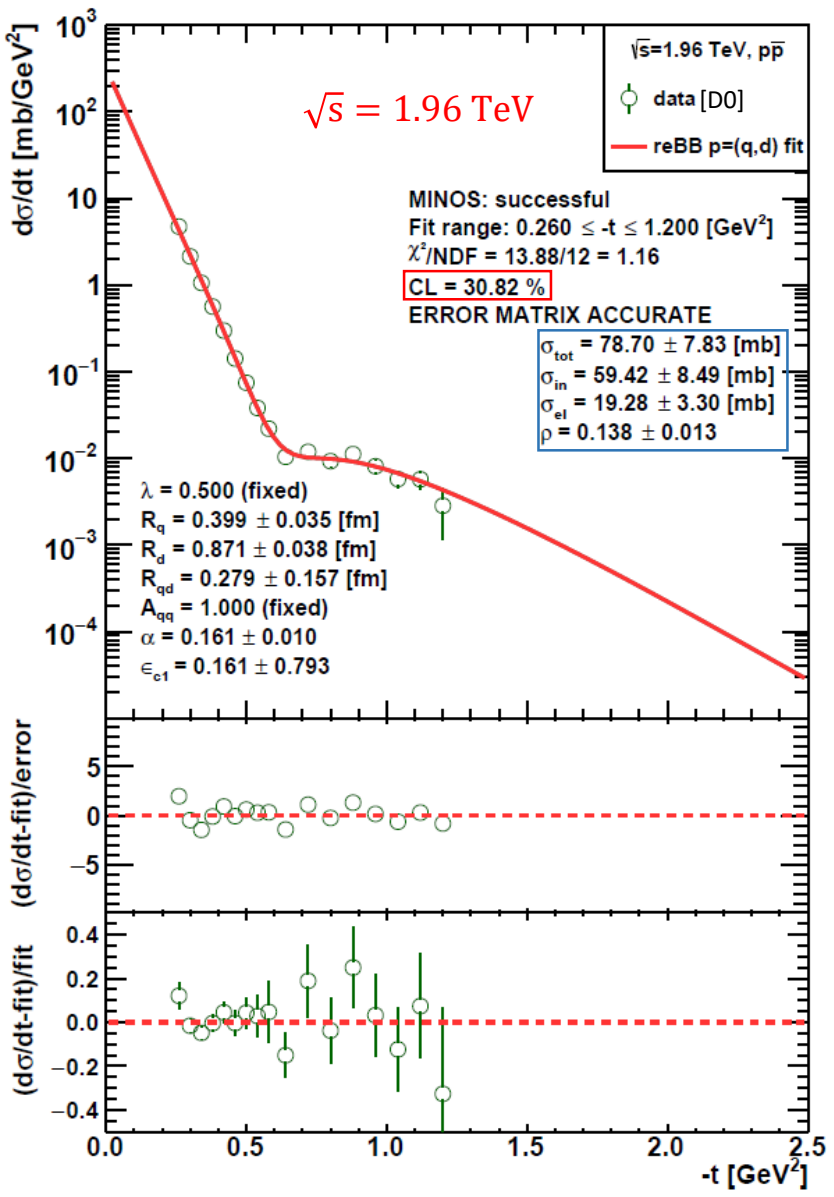
A. Adare *et al.* (PHENIX Collab.) Phys. Rev. C 77, 064907

- it takes into account (in M different t ranges):
  - the t-dependent σ_{aj} statistical and σ_{bj} systematic errors → ϵ_{bj} parameters;
  - the t-independent σ_{cj} normalization uncertainties → ϵ_{cj} parameters;
  - the measured total cross-section $d_{\sigma_{tot}}$ and its total uncertainty $\delta\sigma_{tot}$.
- **minimization with CERN Root MINUIT;**
- **parameter error estimation by MINOS.**

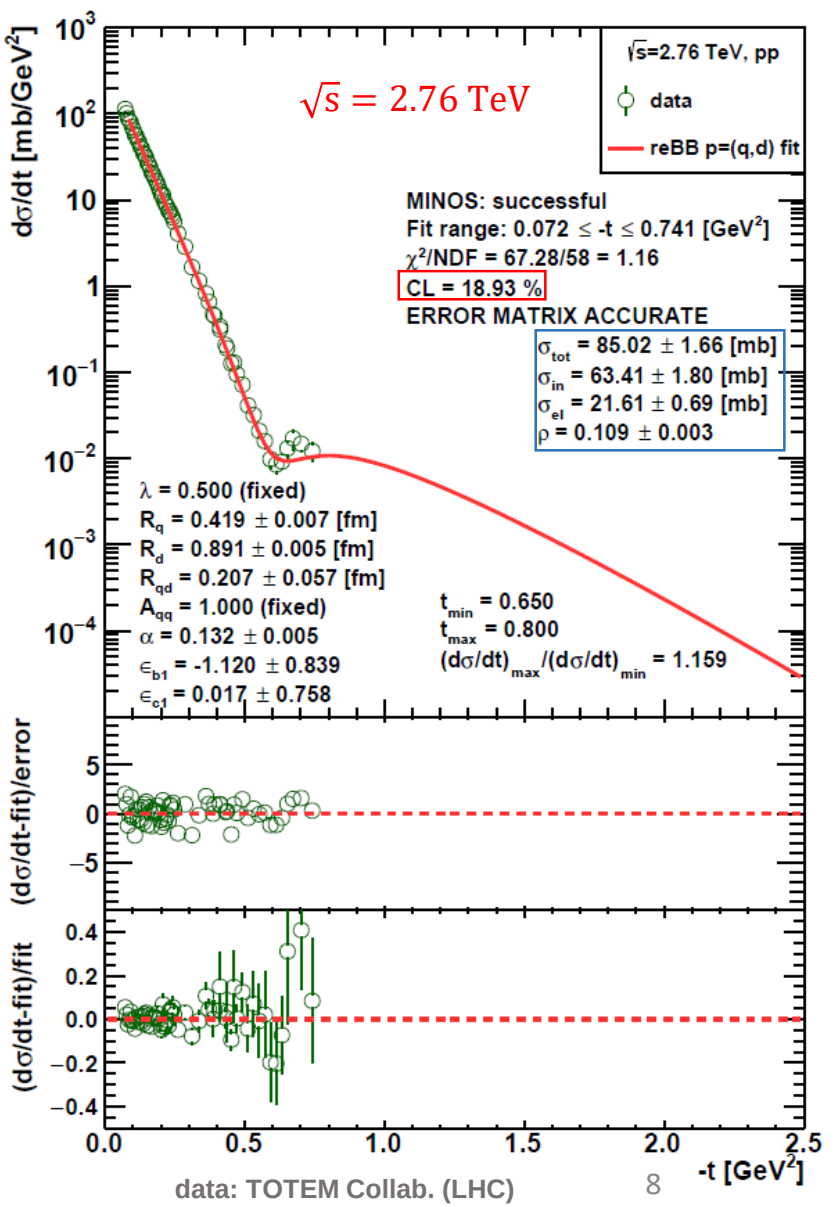
New (satisfactory) ReBB fits for $\mathbf{pp}$ & $\mathbf{p\bar{p}}$ dσ/dt data



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

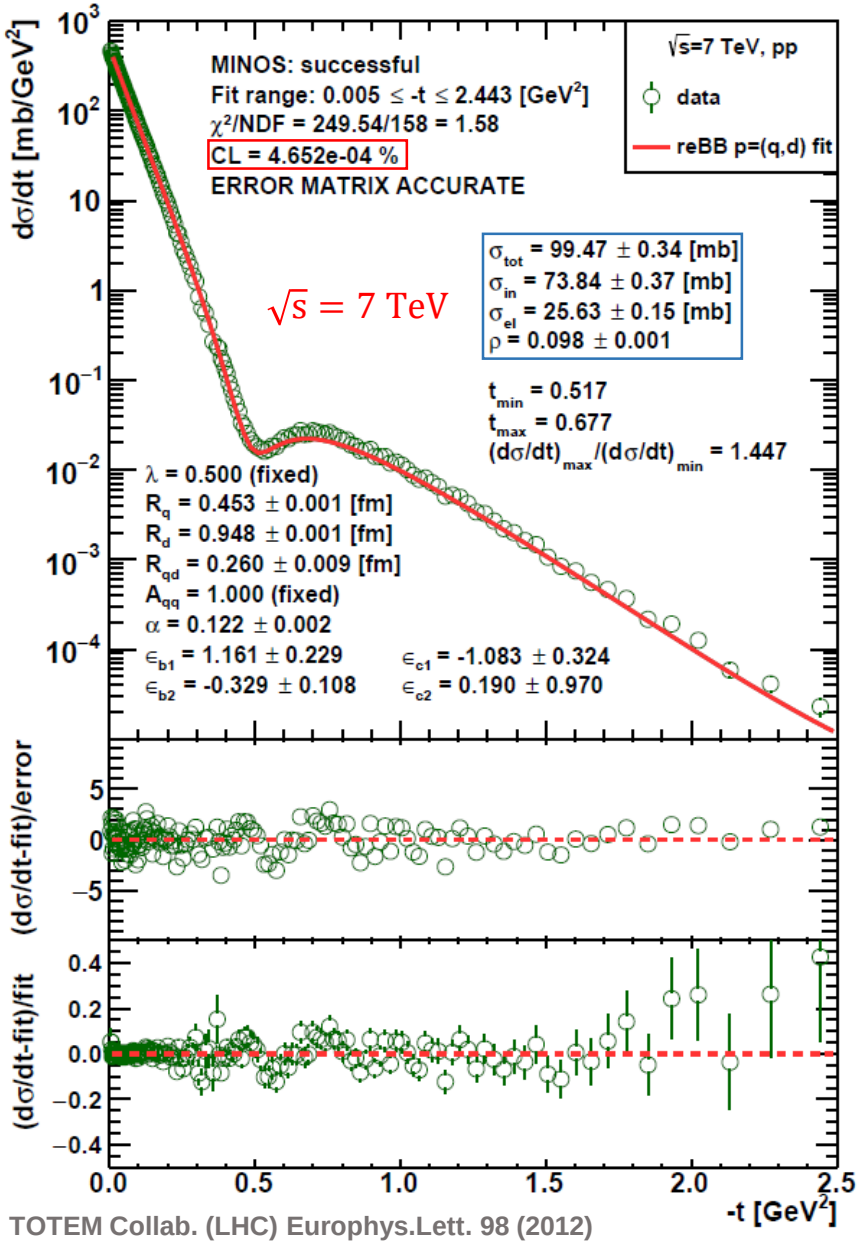


data: D0 Collab. (TEVATRON) Phys.Rev. D86 (2012)

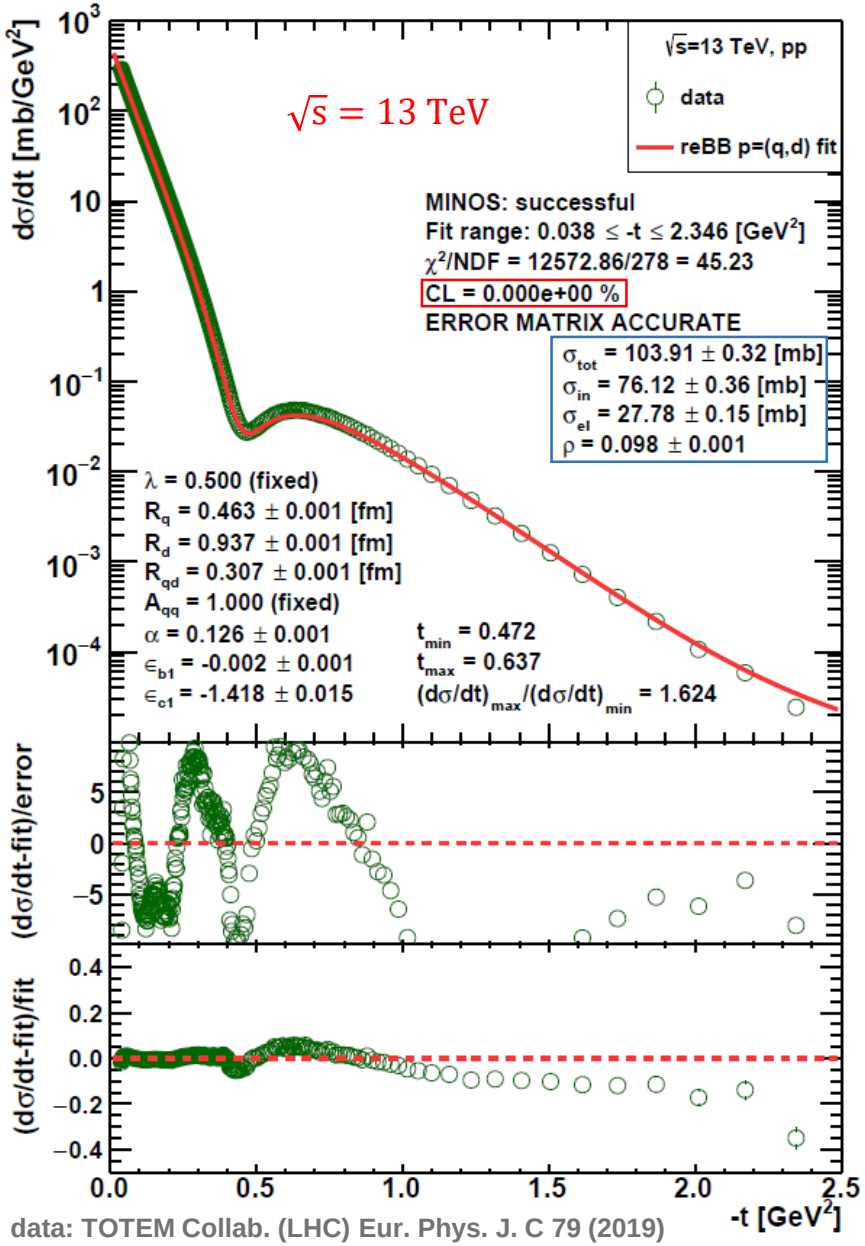


data: TOTEM Collab. (LHC)
CERN-EP-2018-341 arXiv:1812.08610

New (unsatisfactory) ReBB fits for **pp** dσ/dt data



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



data: TOTEM Collab. (LHC) Eur. Phys. J. C 79 (2019)

Fitted parameters of the ReBB model

$$A_{qq} = 1\ (fixed), \qquad \lambda = 0.5\ (fixed)$$

$\sqrt{s}$ [TeV]	0.546 $(p\bar{p})$	1.96 $(p\bar{p})$	2.76 (pp)
$\lvert t\rvert$ [GeV^2]	(0.033, 1.530)	(0.260, 1.200)	(0.072, 0.740)
χ^2/NDF	140.14/115	13.88/12	67.28/58
CL [%]	5.55	30.82	18.93
R_q $[fm]$	0.351 ± 0.002	0.399 ± 0.035	0.419 ± 0.007
R_d $[fm]$	0.833 ± 0.002	0.871 ± 0.038	0.891 ± 0.005
R_{qd} $[fm]$	0.285 ± 0.008	0.279 ± 0.157	0.207 ± 0.057
α	0.119 ± 0.002	0.161 ± 0.010	0.132 ± 0.005
ϵ_{b1}	–	–	-1.120 ± 0.839
ϵ_{c1}	0.171 ± 0.404	0.161 ± 0.793	0.017 ± 0.758
ϵ_{c2}	-1.009 ± 0.702	–	–
ϵ_{c3}	0.733 ± 0.274	–	–

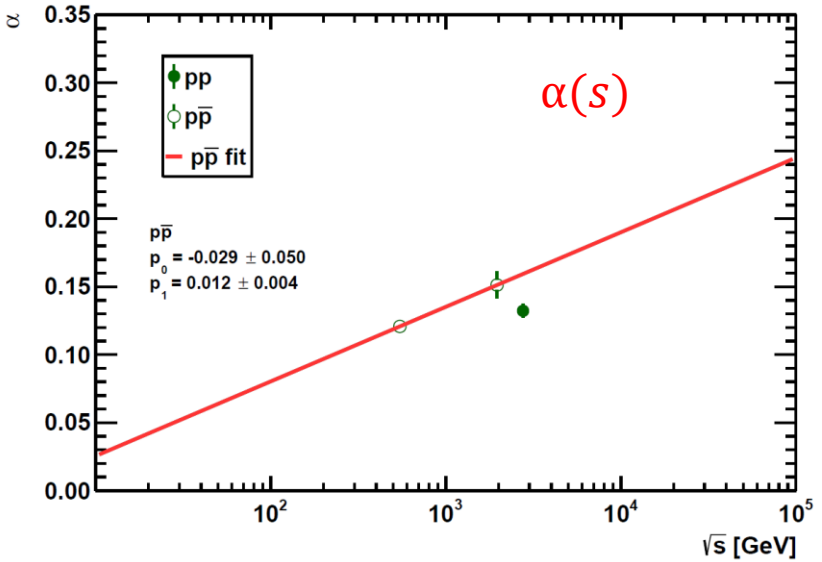
Fitted parameters of the ReBB model for proton-proton and proton-antiproton scattering. The parameters and their errors are rounded up to three valuable decimal digits.

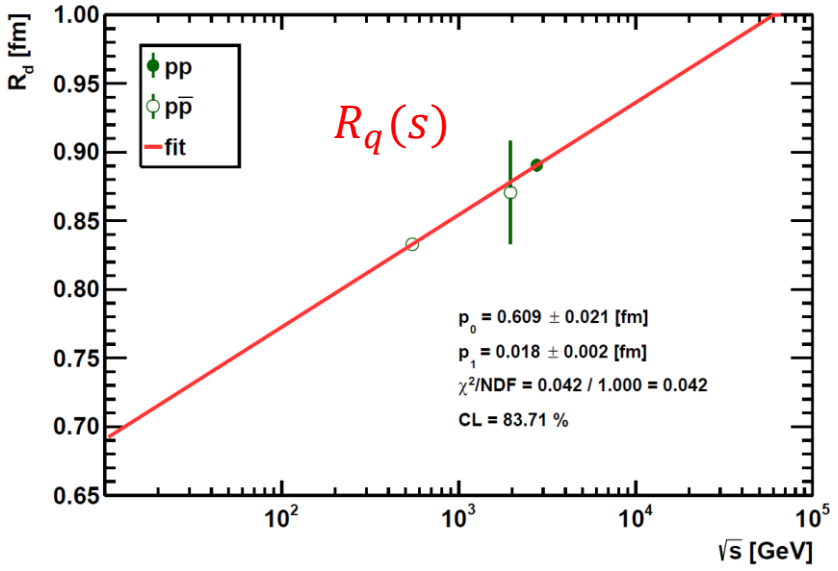
Energy dependence of the parameters

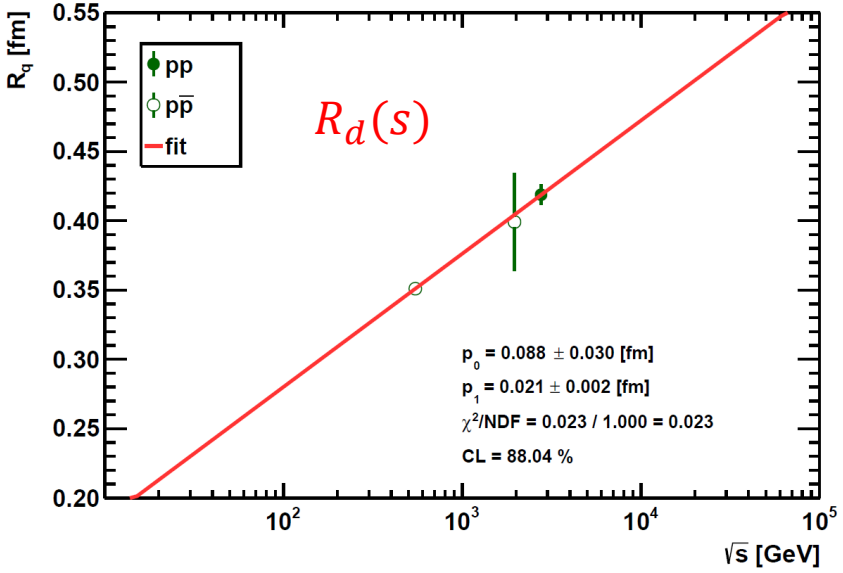
$P(s) = p_0 + p_1 ln(s/s_0)$ $P \in \{R_q, R_d, R_{qd}, \alpha\}$ $s_0 = 1\ GeV^2$

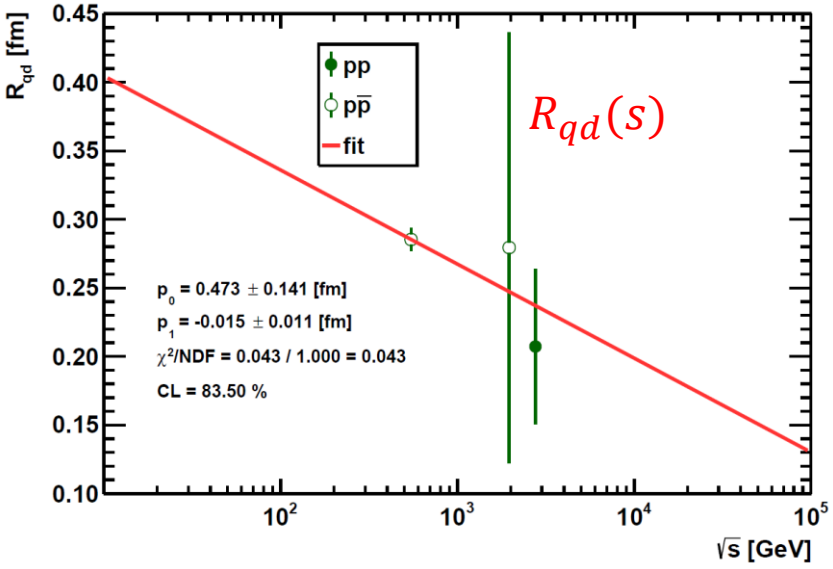
Parameter	R_q $[fm]$	R_d $[fm]$	R_{qd} $[fm]$	α $(p\bar{p})$
χ^2/NDF	0.023 / 1	0.042 / 1	0.043 / 1	–
CL [%]	88.04	83.71	83.50	–
p_0	0.088 ± 0.030	0.609 ± 0.021	0.473 ± 0.141	-0.029 ± 0.050
p_1	0.021 ± 0.002	0.018 ± 0.002	-0.015 ± 0.011	0.012 ± 0.004

Parameters which define the energy dependence of the ReBB model parameters

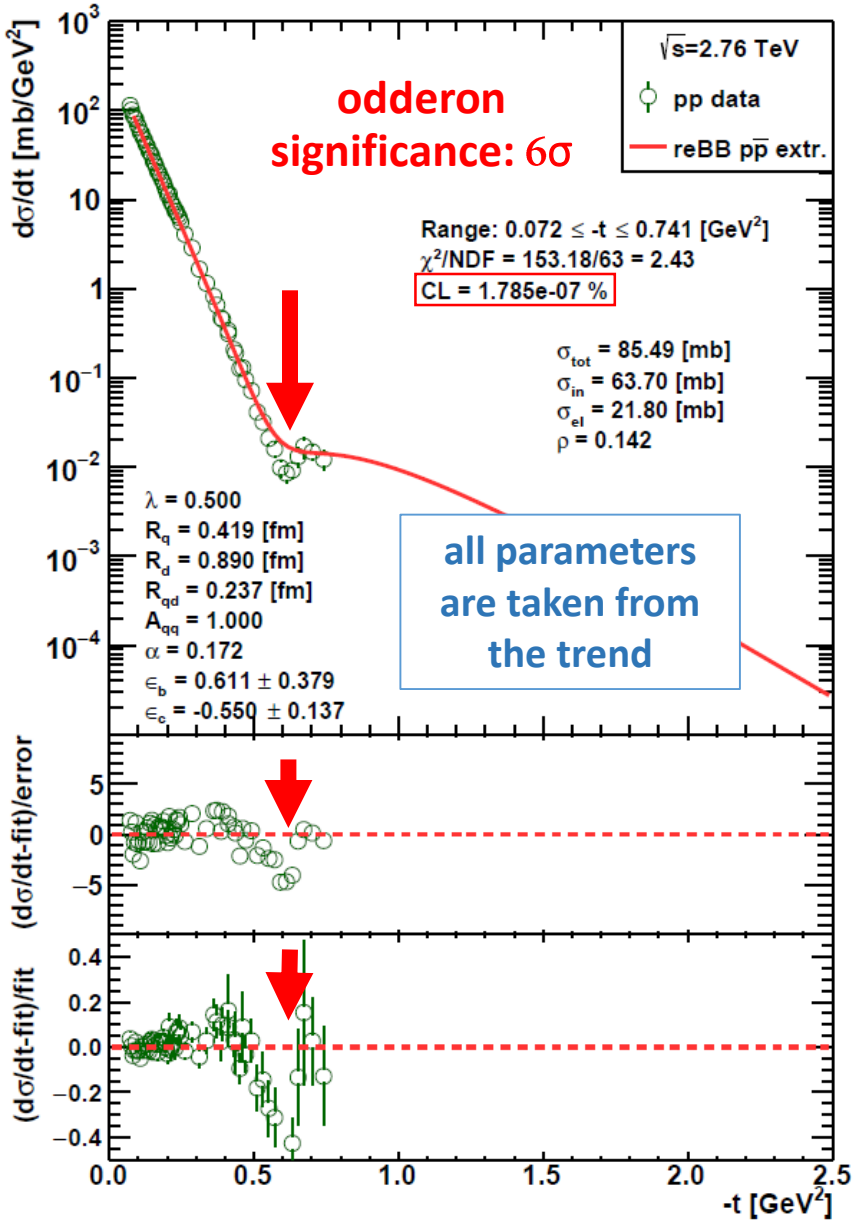


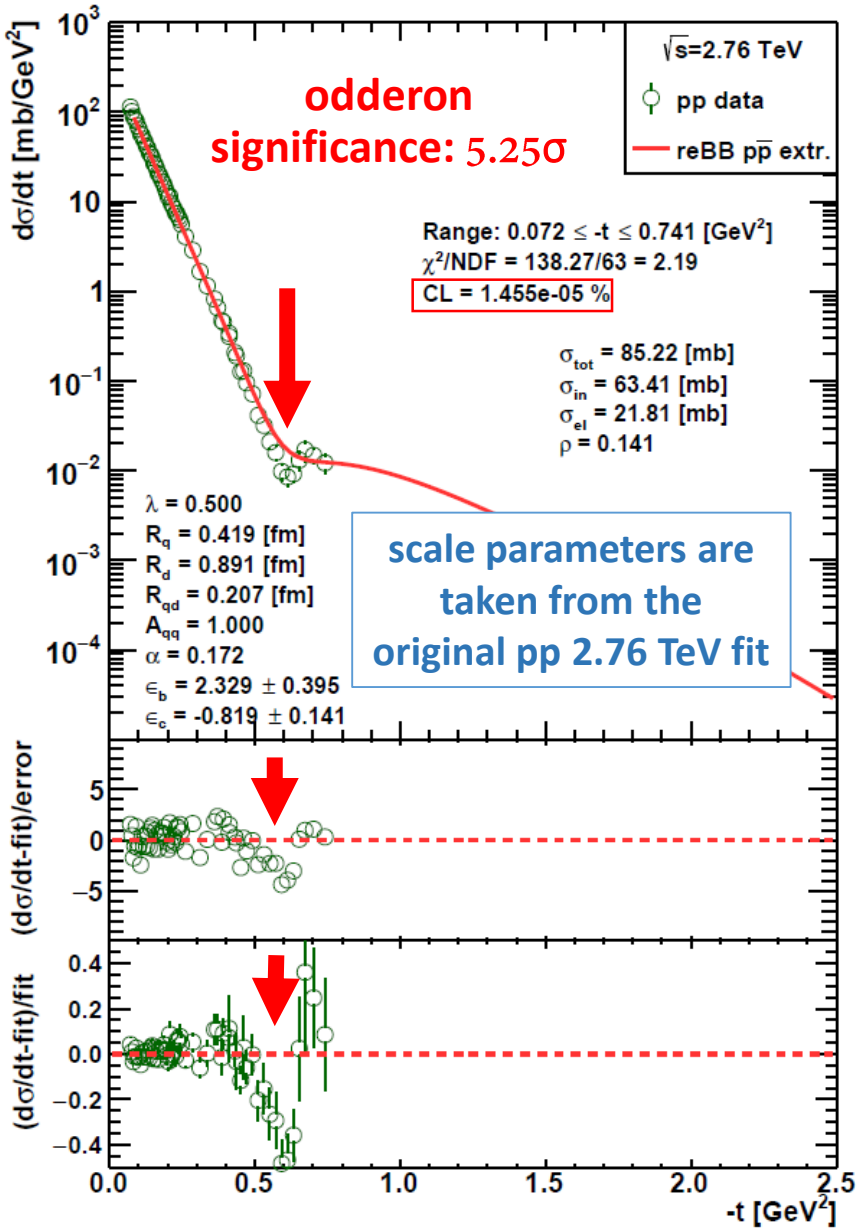






Extrapolation for $p\bar{p}$ dσ/dt @ 2.76 TeV → ODDERON





Summary

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

→ acceptable description in the energy range $0.546 \leq \sqrt{s} \leq 2.76$ TeV

- **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** at 2.76 TeV in the dip region

→ **model-dependent evidence for Odderon (colourless 3-gluon bound state) exchange with an estimated significance higher than 5σ.**

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

Thank you for your attention!

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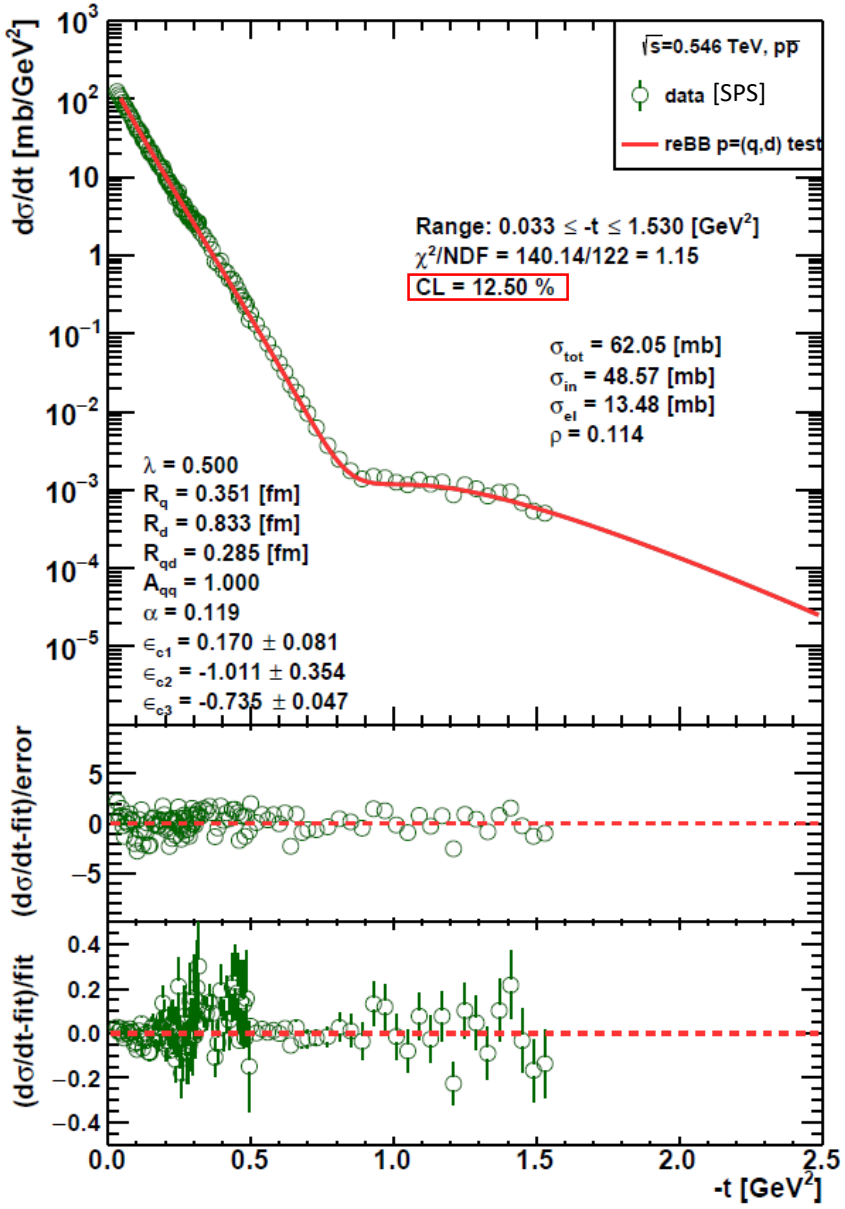
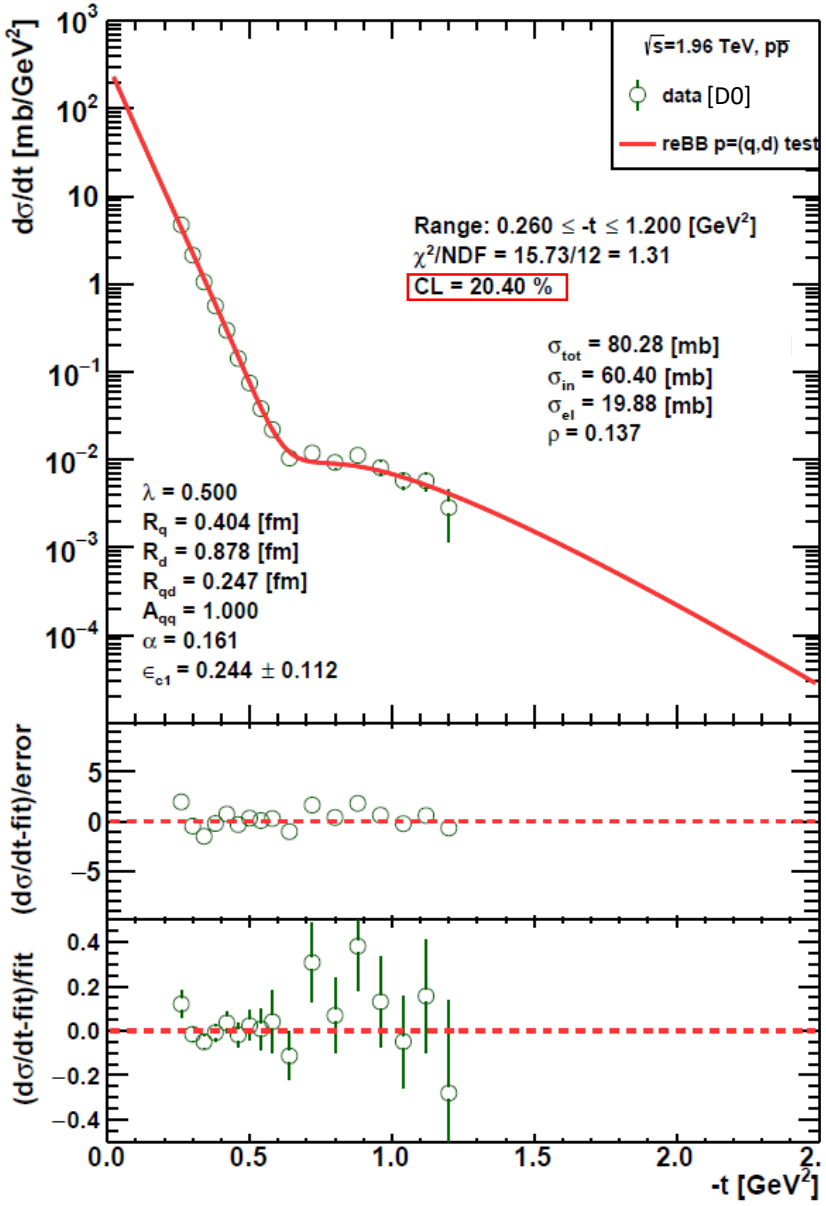
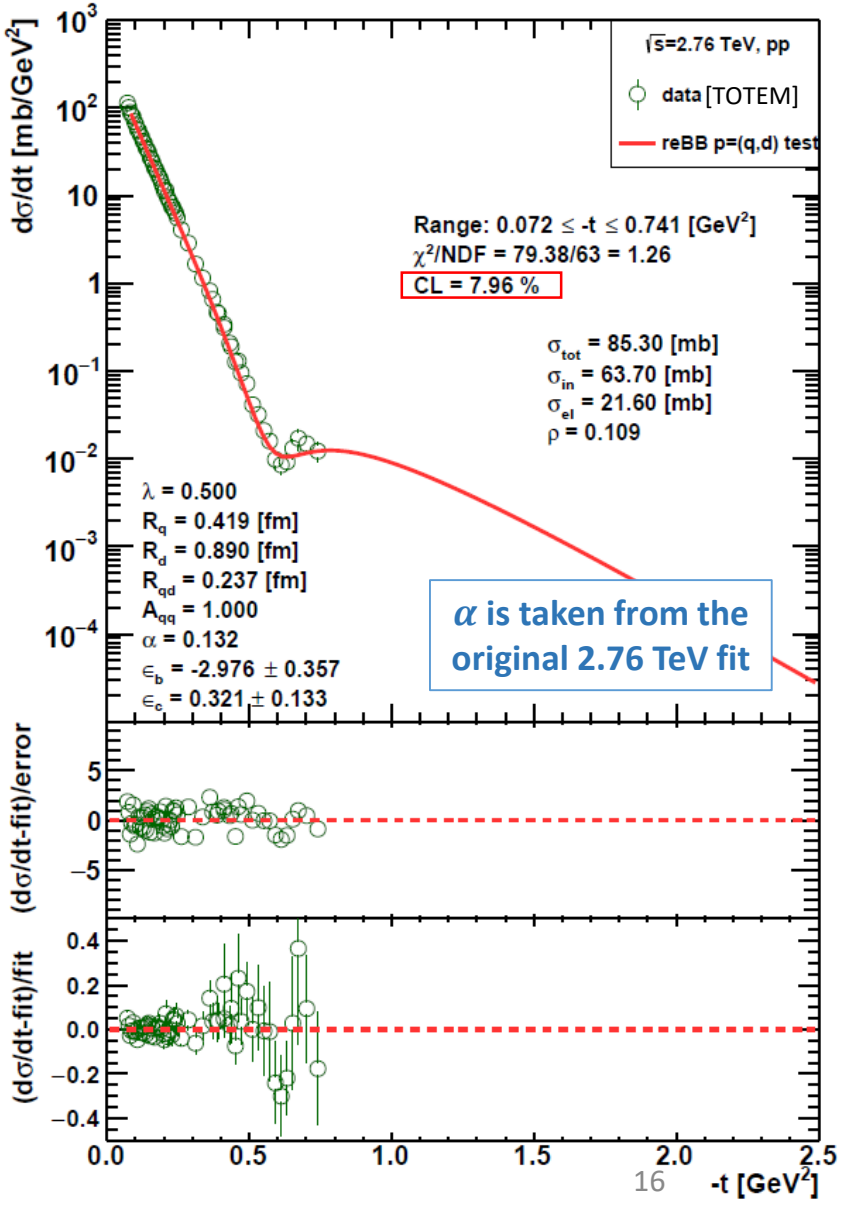
- Circles of Knowledge Club, Hungary

Backup slides

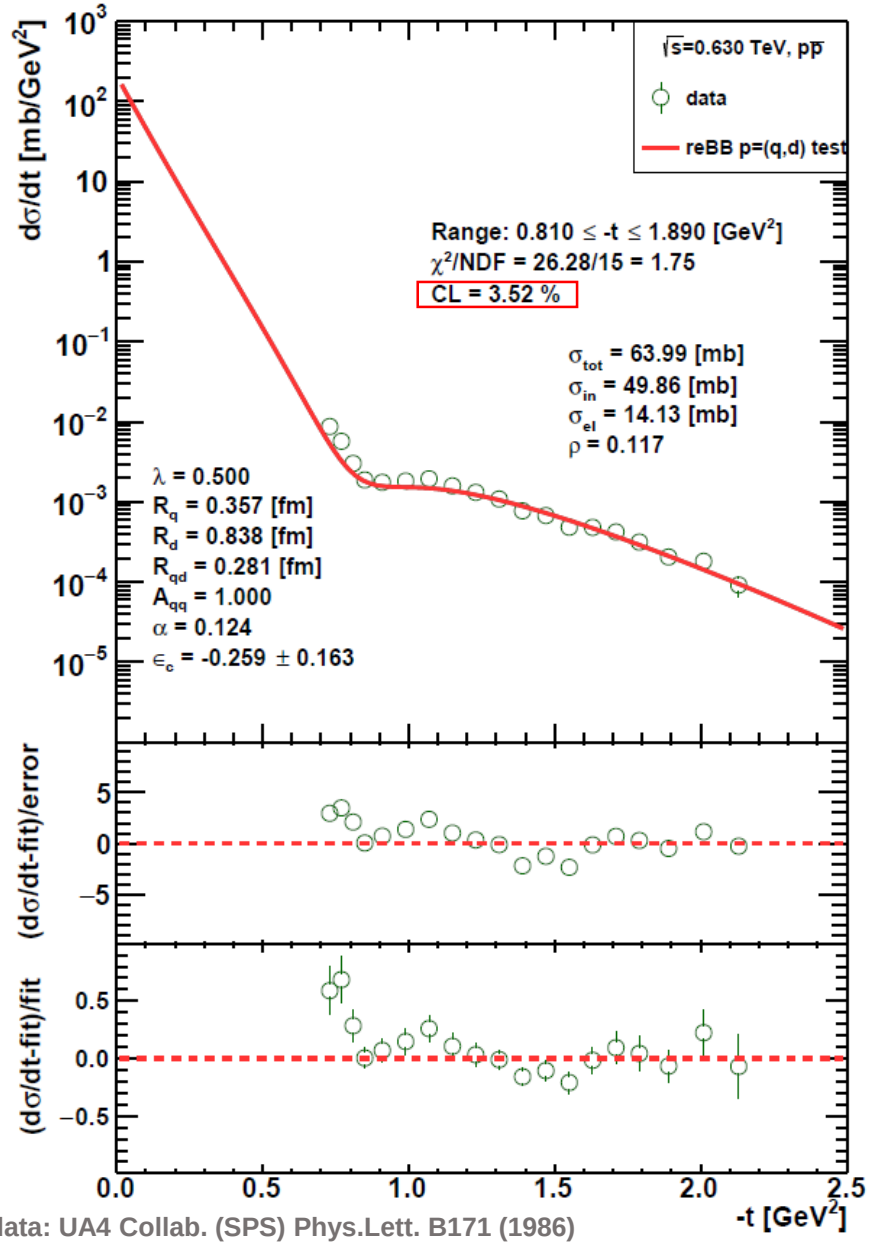
Cross-checks @ 0.546, 1.96 & 2.76 TeV ✓







Tests @ 0.63 & 1.8 TeV ✓



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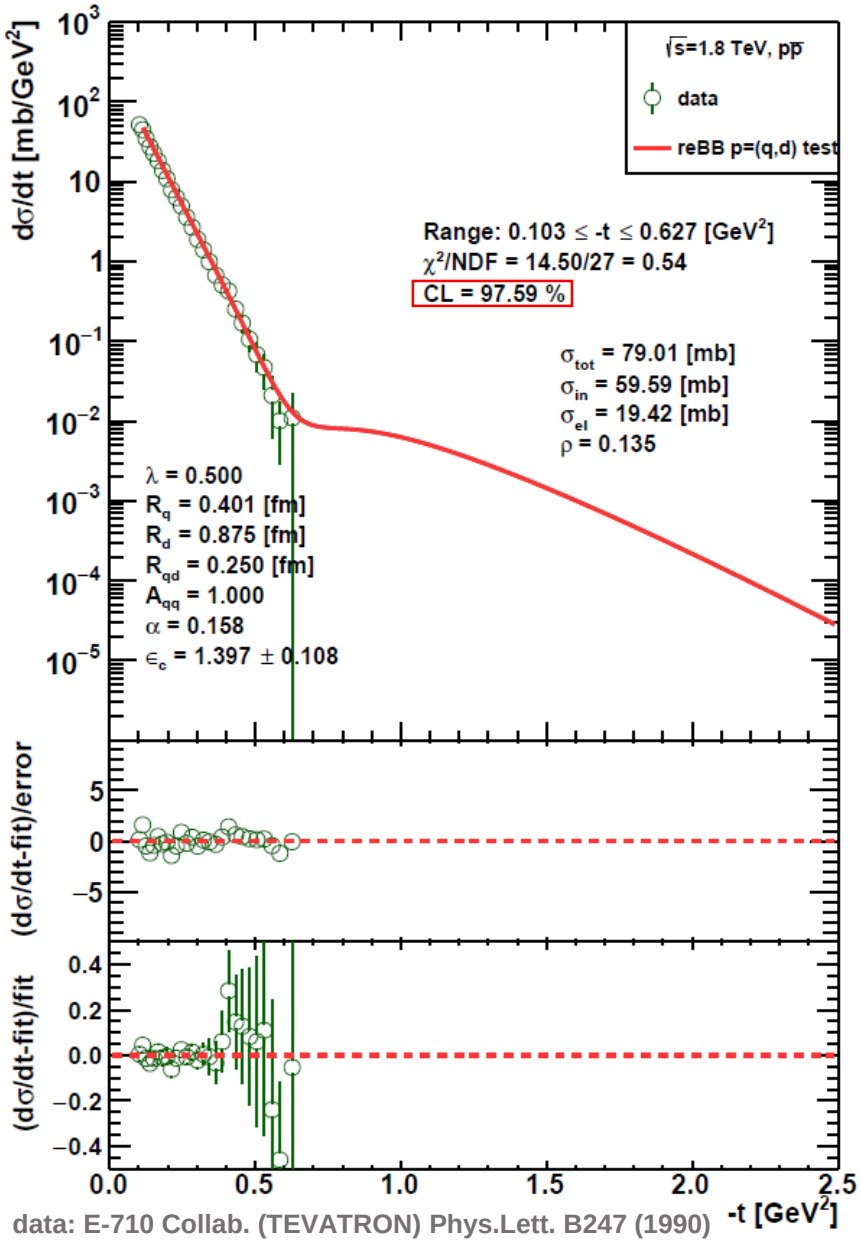
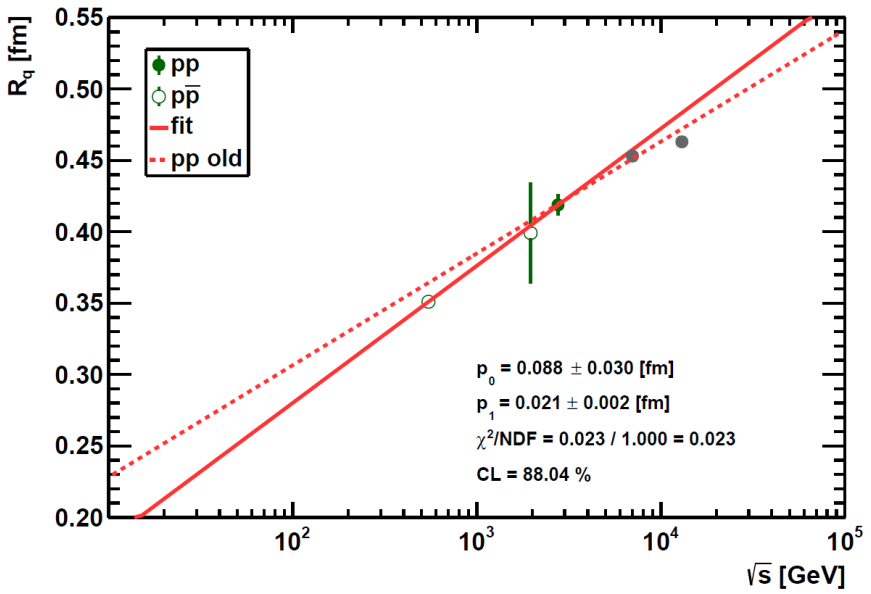
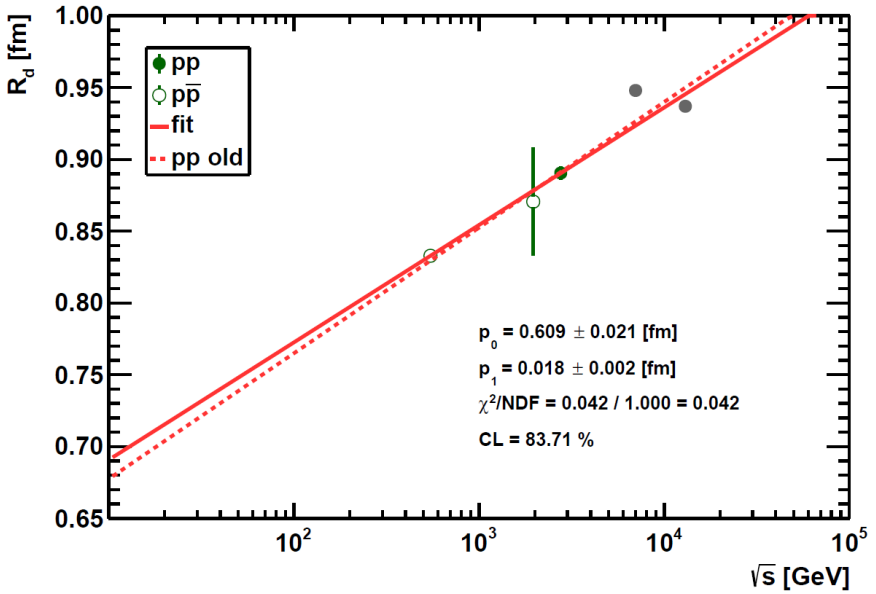
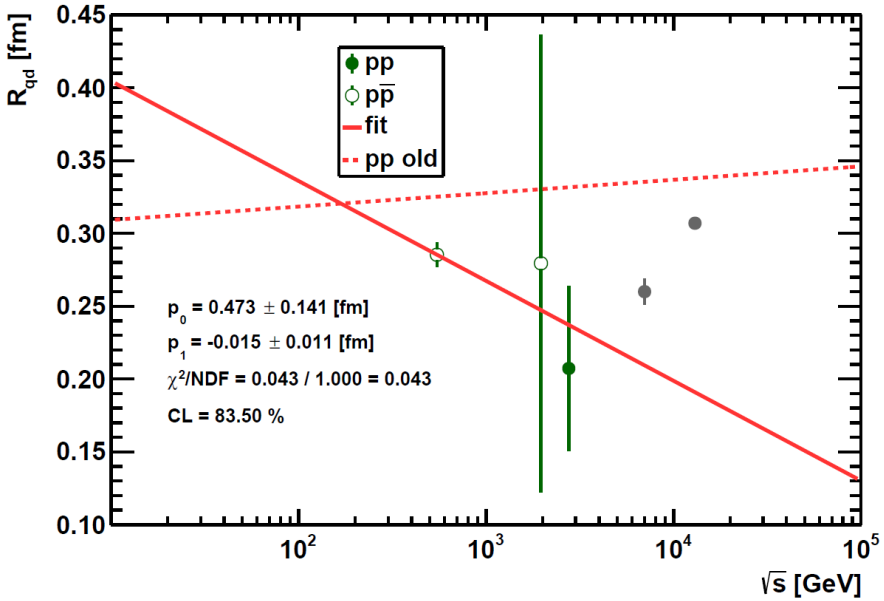


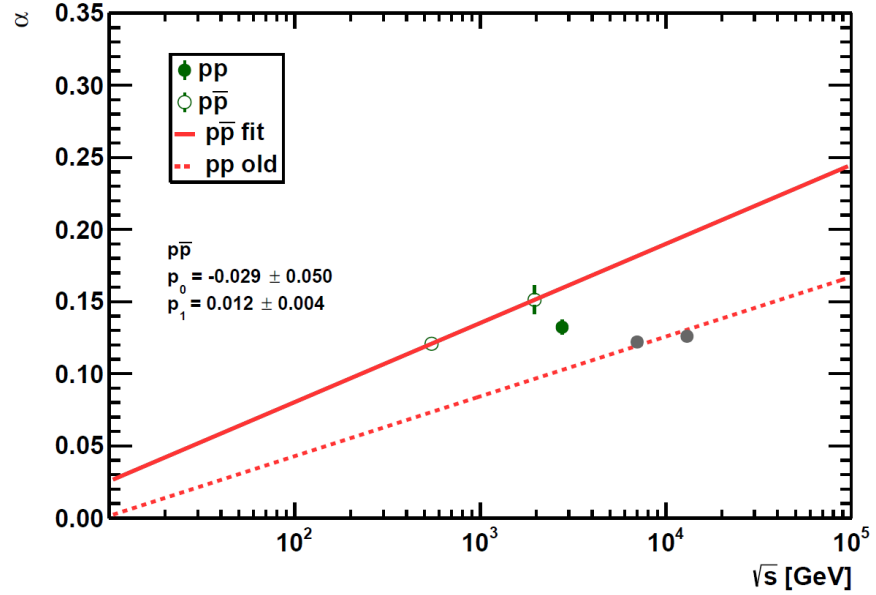
data: E-710 Collab. (TEVATRON) Phys.Lett. B247 (1990)

Comparison of the new and old (only pp) trends









Fits for 7 TeV pp data with modified stat. errors