Study of $\mathbf{pp}$ and $\mathbf{p\bar{p}}$ scattering at LHC energies using an extended Bialas-Bzdak model

T. Csörgő[1,2] and I. Szanyi[1,3]

[1]Wigner RCP, Budapest, Hungary
[2]EKE KRC, Gyöngyös, Hungary
[3]ELTE, Budapest, Hungary

18th Zimányi School, Budapest, Hungary

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

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

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

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

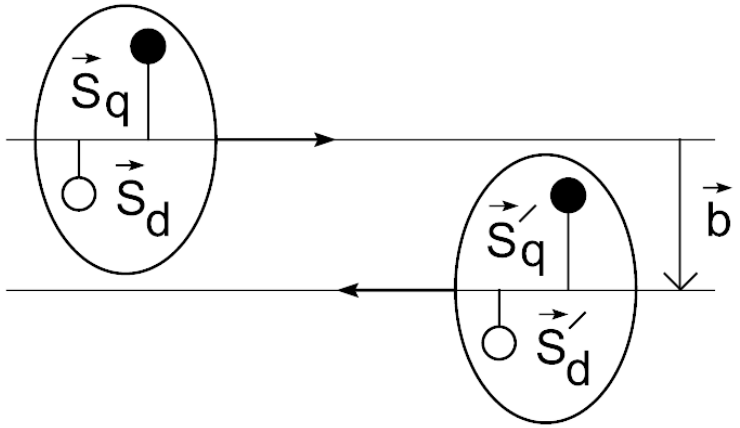
A. Bialas, A. Bzdak Acta Phys.Polon. B 38, 159-168 (2007)

arXiv:0612038

- **Interaction probability of the constituents:**

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

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



Proton-proton scattering in the quark-diquark model.

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

$$\sigma_{ab,\mathrm{inel}} = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \sigma_{ab}\left(\vec{s}\right) \mathrm{d}^2 s$$

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

- **Free parameters:**

$$R_q,\ R_d,\ R_{qd},\ A_{qq},\ \lambda$$

Unitarily extended Bialas-Bzdak model (reBB)

- **Elastic amplitude in the impact parameter space:**

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

arXiv:1505.01415

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

- **The opacity or eikonal function:**

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

$$\mathrm{Im}\,\Omega(s,b) = -\alpha \cdot \tilde{\sigma}_{inel}(s,b)$$

- **Elastic amplitude in the momentum space:**

$$T(s,\Delta) = 2\pi \int_0^\infty J_0\left(\Delta \cdot b\right) t_{el}(s,b) b\,\mathrm{d}b$$

- **Elastic differential cross section:**

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

$$\sqrt{s} \to \infty,\ \Delta(t) \simeq \sqrt{-t}$$

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

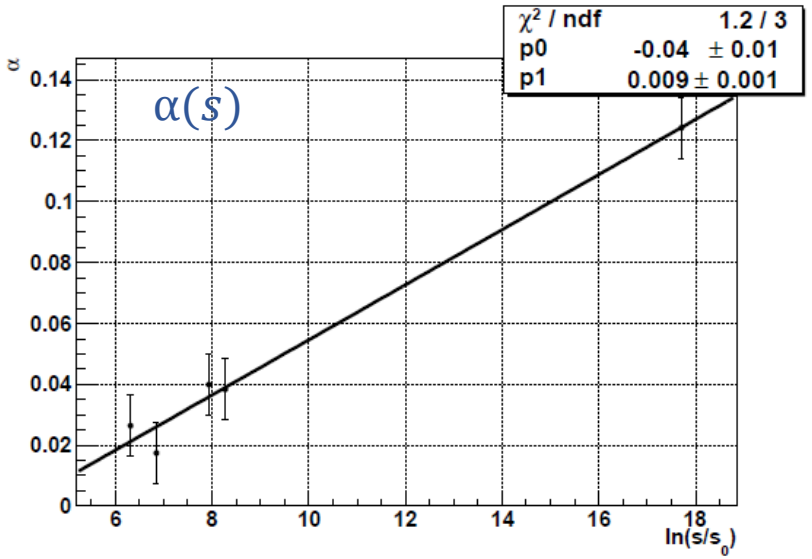
$$P(s) = p_0 + p_1 \cdot \ln(s/s_0)$$

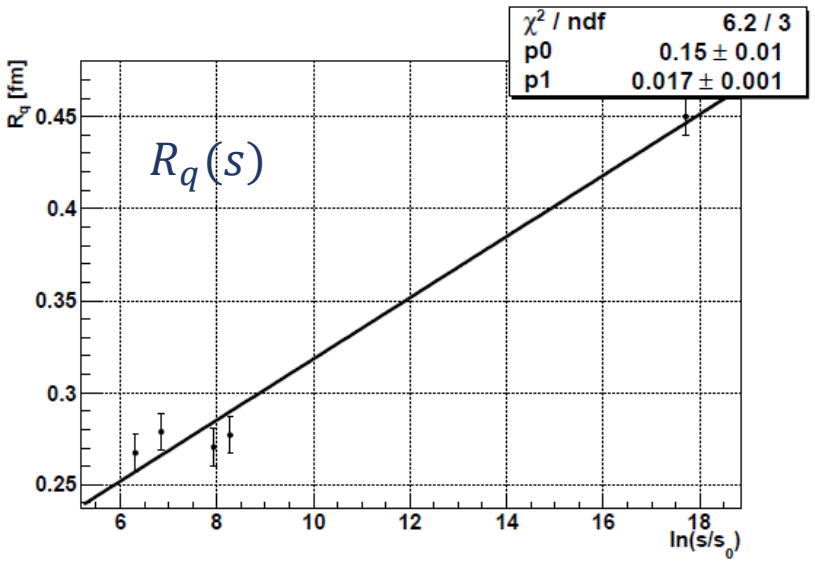
$$P \in \{R_q, R_d, R_{qd}, \alpha\}$$

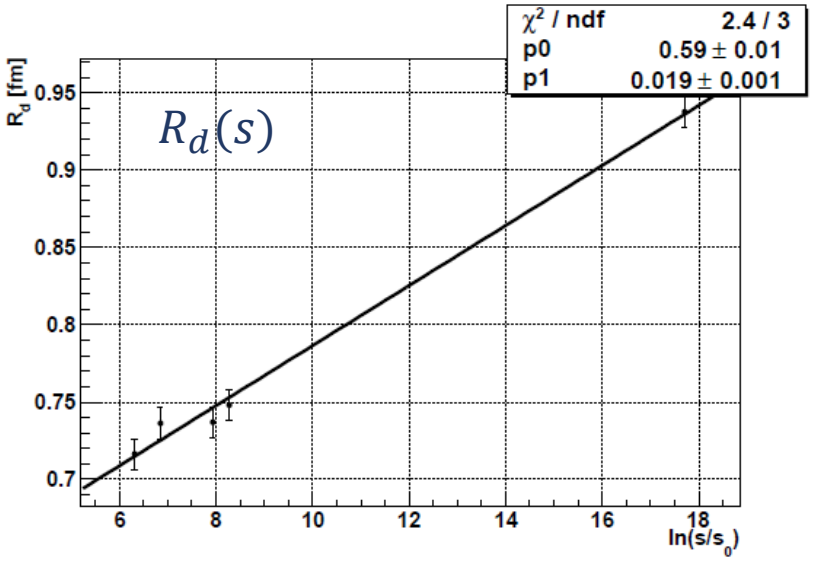
$$s_0 = 1\ \mathrm{GeV}^2$$

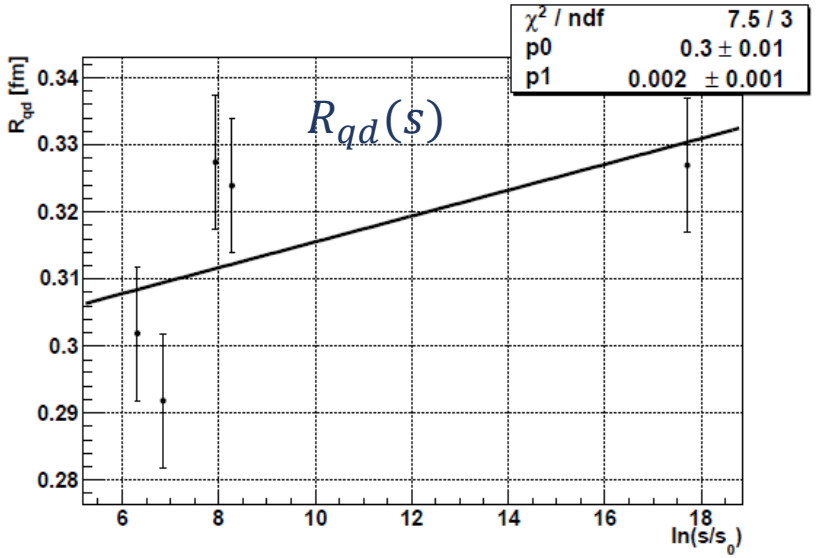
arXiv:1505.01415

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

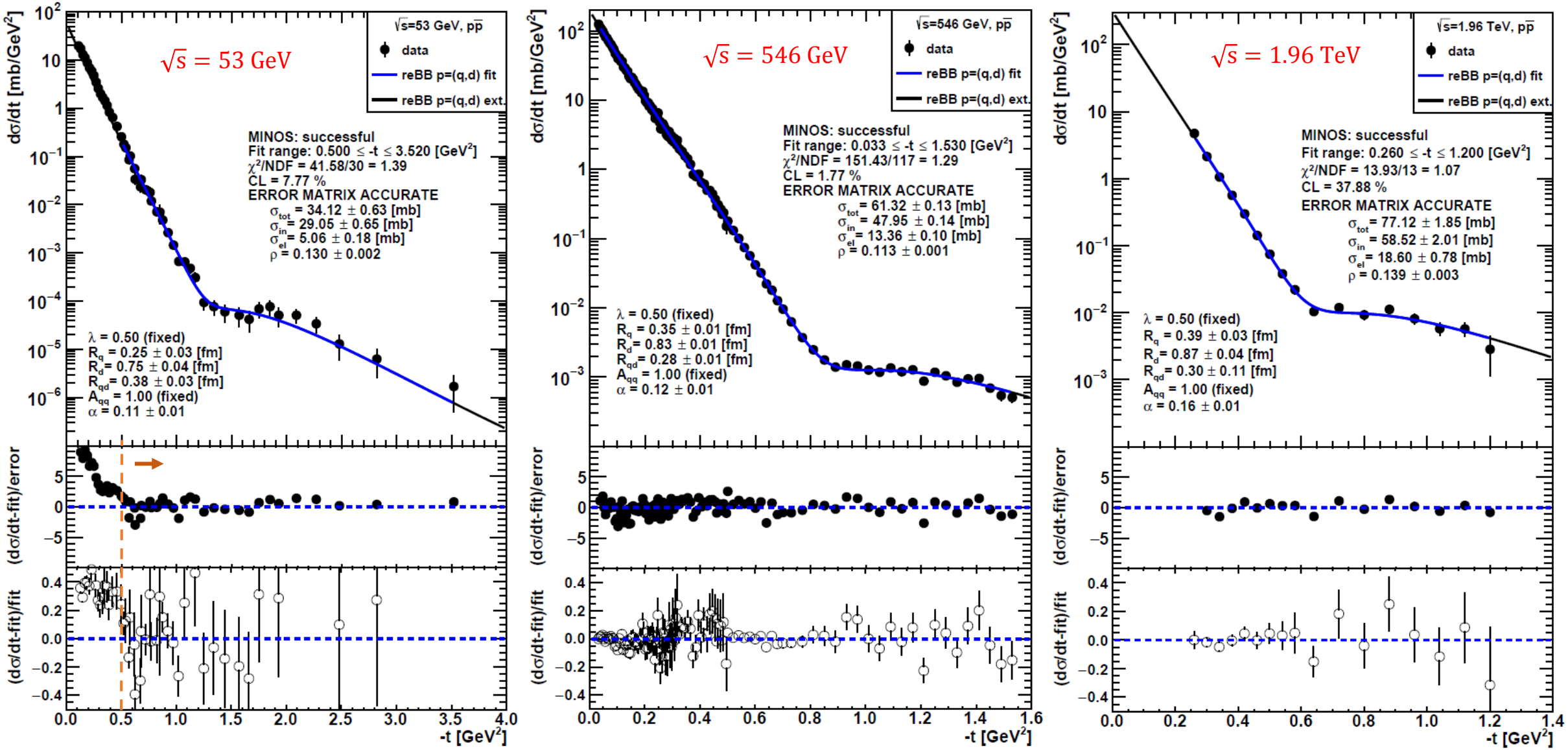








New results: ReBB fits to $p\bar{p}$ dσ/dt data



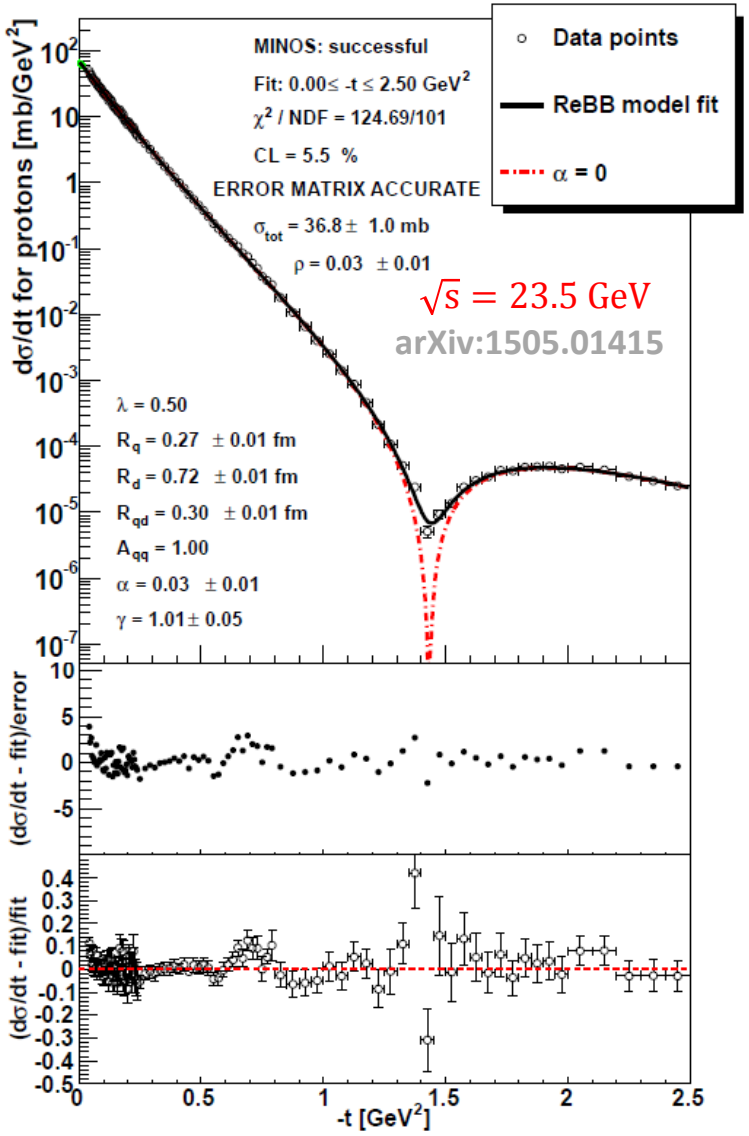
New results

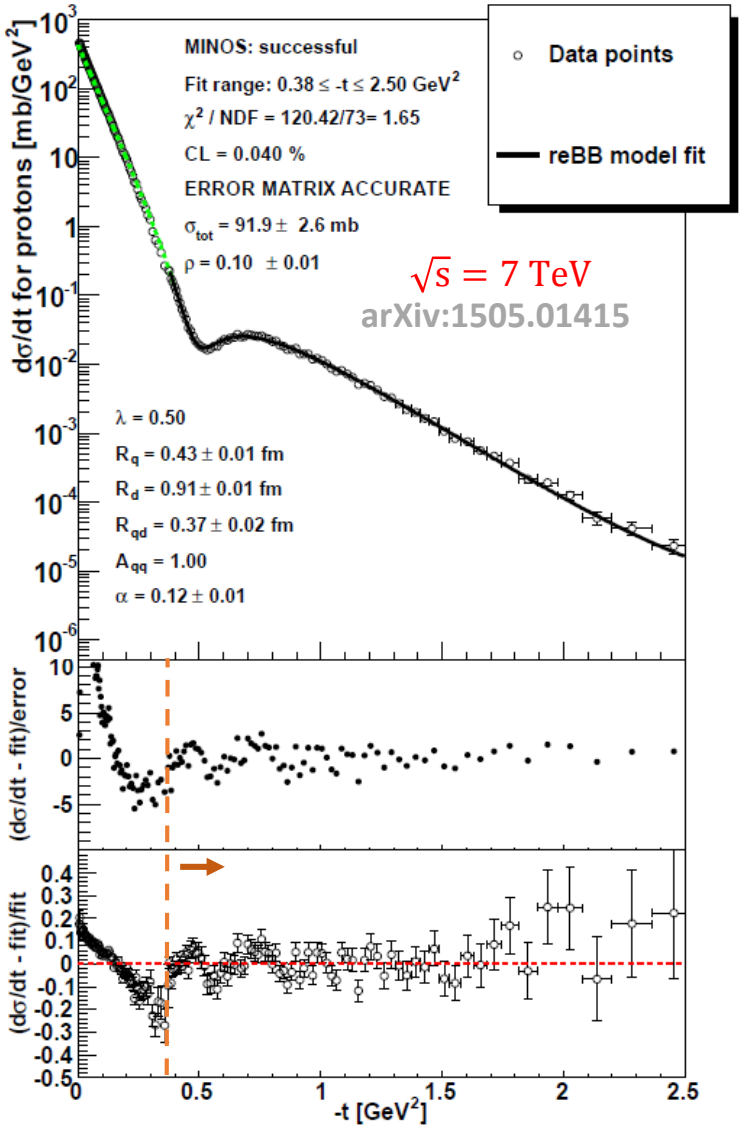
$A_{qq} = 1$ (fixed), $\lambda = 0.5$ (fixed)

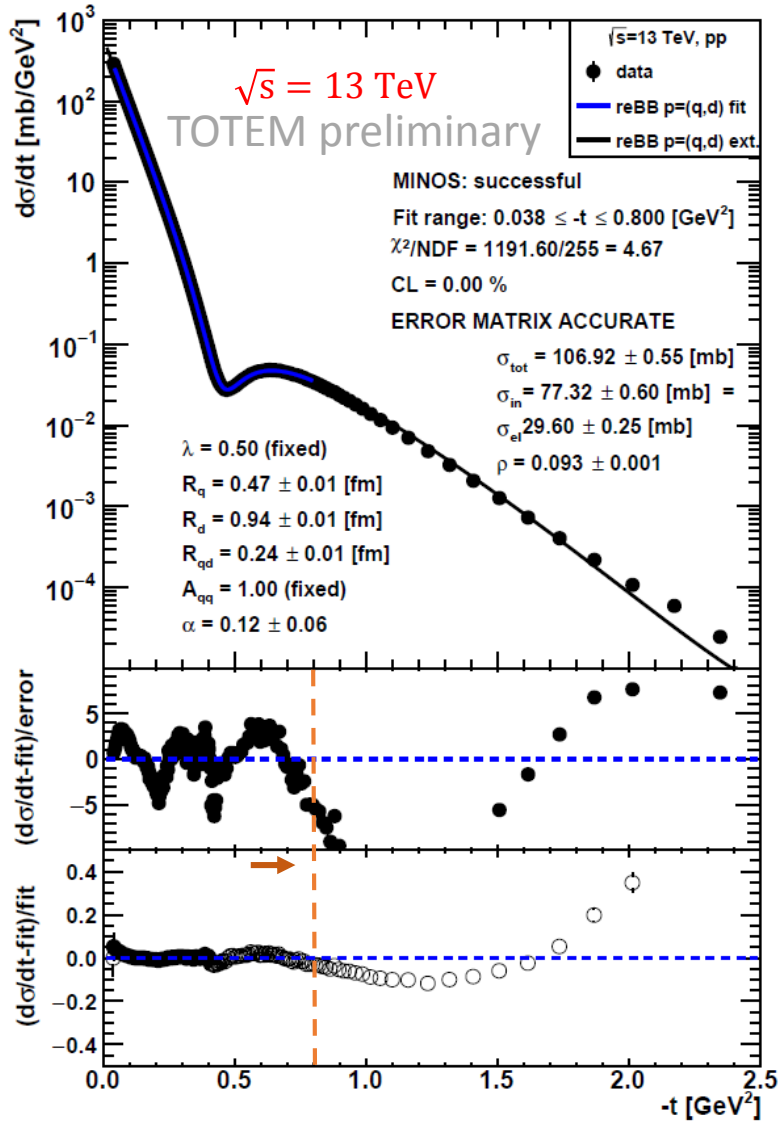
$\sqrt{s}$ [GeV]	31	53	62	546	1800	1960	13000
$\lvert t\rvert$ [GeV^2]	(0.05,0.85)	(0.5,3.52)	(0.13,0.85)	(0.033,1.53)	(0.034,0.62)	(0.26,1.2)	(0.038,0.8)
χ^2/NDF	17.34/18	41.58/30	14.30/19	151.43/117	29.18/47	13.93/13	1191.6/255
CL [%]	49.99	7.77	76.59	1.77	98.07	37.88	0.00
R_q $[fm]$	0.28±0.01	0.25±0.03	0.27±0.01	0.35±0.01	0.38±0.01	0.39±0.03	0.47±0.01
R_d $[fm]$	0.75±0.01	0.75±0.04	0.72±0.05	0.83±0.01	0.87±0.02	0.87±0.04	0.94±0.01
R_{qd} $[fm]$	0.36±0.06	0.38±0.03	0.39±0.07	0.28±0.01	0.33±0.04	0.30±0.11	0.24±0.06
α	0.27±0.08	0.11±0.01	0.19±0.09	0.12±0.01	0.14±0.04	0.16±0.01	0.12±0.01

Table 2: The values of the fitted ReBB model parameters for $p\bar{p}$ scattering at ISR, SPS and TEVATRON (D0) energies and for pp scattering at 13 TeV (LHC TOTEM). The errors and the values are rounded up to two valuable decimal digits.

ReBB fits to pp dσ/dt data at several energies







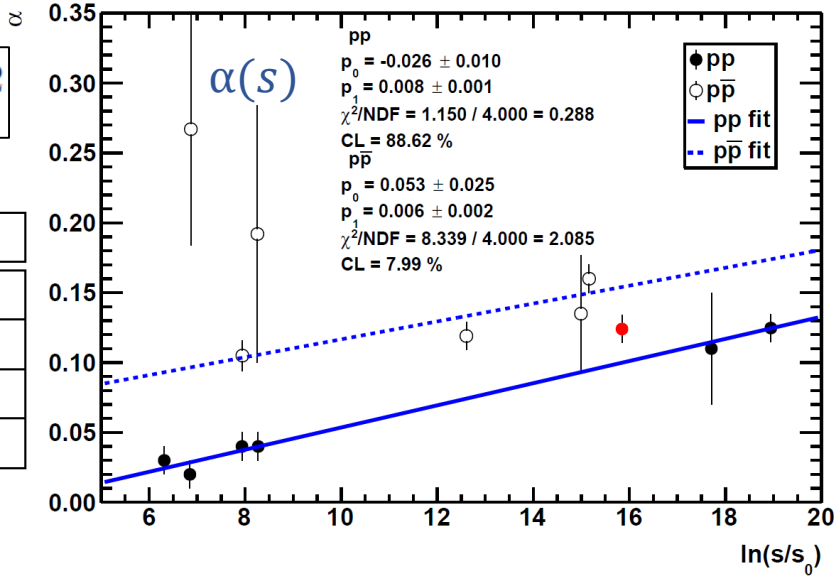
Energy dependence of the parameters for pp & $p\bar{p}$

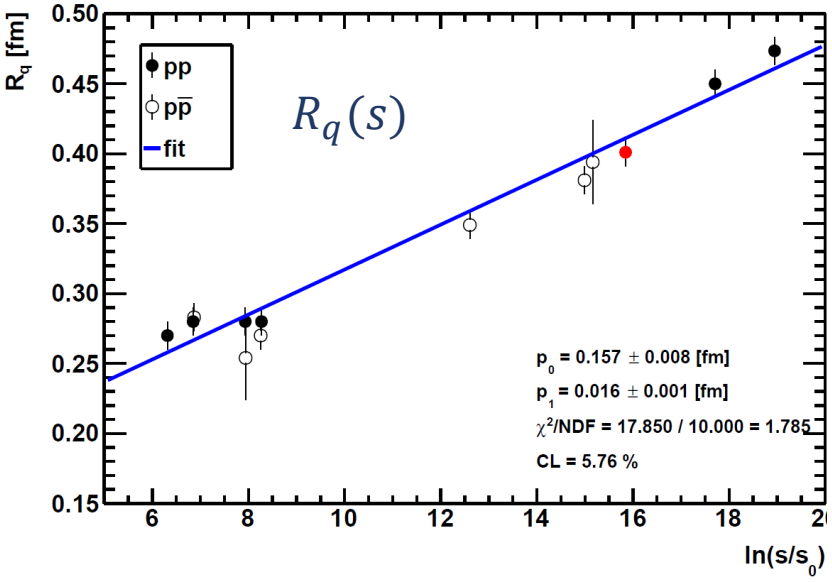
$$P(s) = p_0 + p_1 \cdot \ln(s/s_0)$$

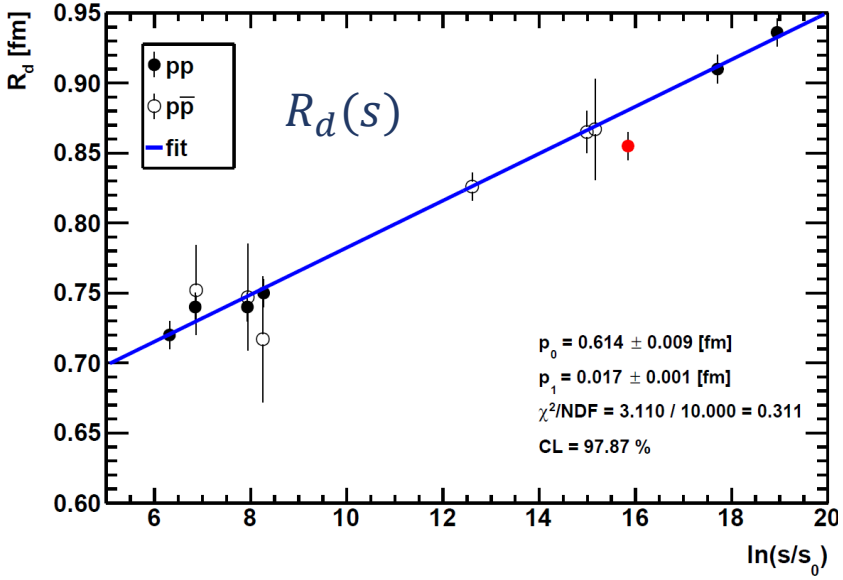
$$P \in \{R_q, R_d, R_{qd}, \alpha\}$$

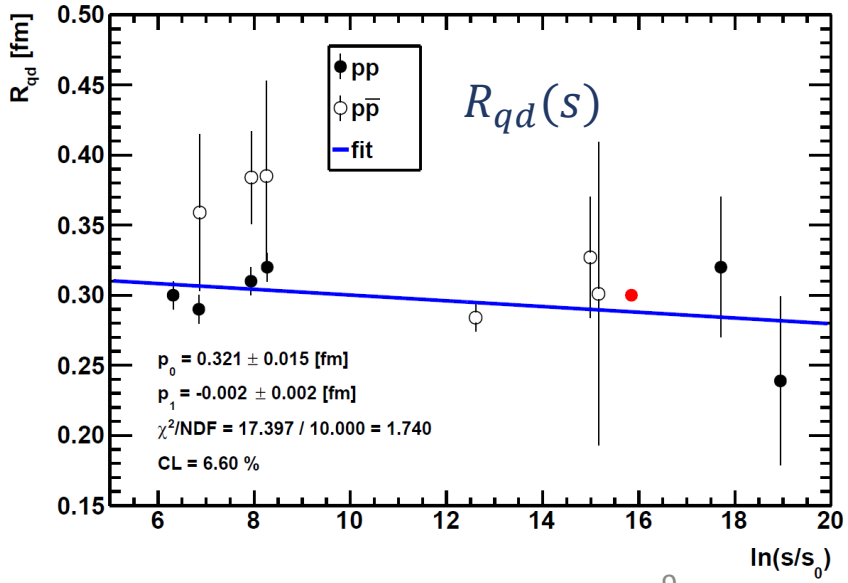
$$s_0 = 1\ \mathrm{GeV}^2$$

Parameter	$R_q\ [fm]$	$R_d\ [fm]$	$R_{qd}\ [fm]$	$\alpha\ (for\ pp)$	$\alpha\ (for\ p\bar{p})$
χ^2/NDF	17.850/10	3.110/10	17.397/10	1.150/4	8.339/4
CL [%]	5.76	97.87	6.60	88.62	7.99
p_0	0.157 ± 0.008	0.614 ± 0.009	0.321 ± 0.015	-0.026 ± 0.01	0.053 ± 0.025
p_1	0.016 ± 0.001	0.017 ± 0.001	-0.002 ± 0.002	0.008 ± 0.001	0.006 ± 0.002

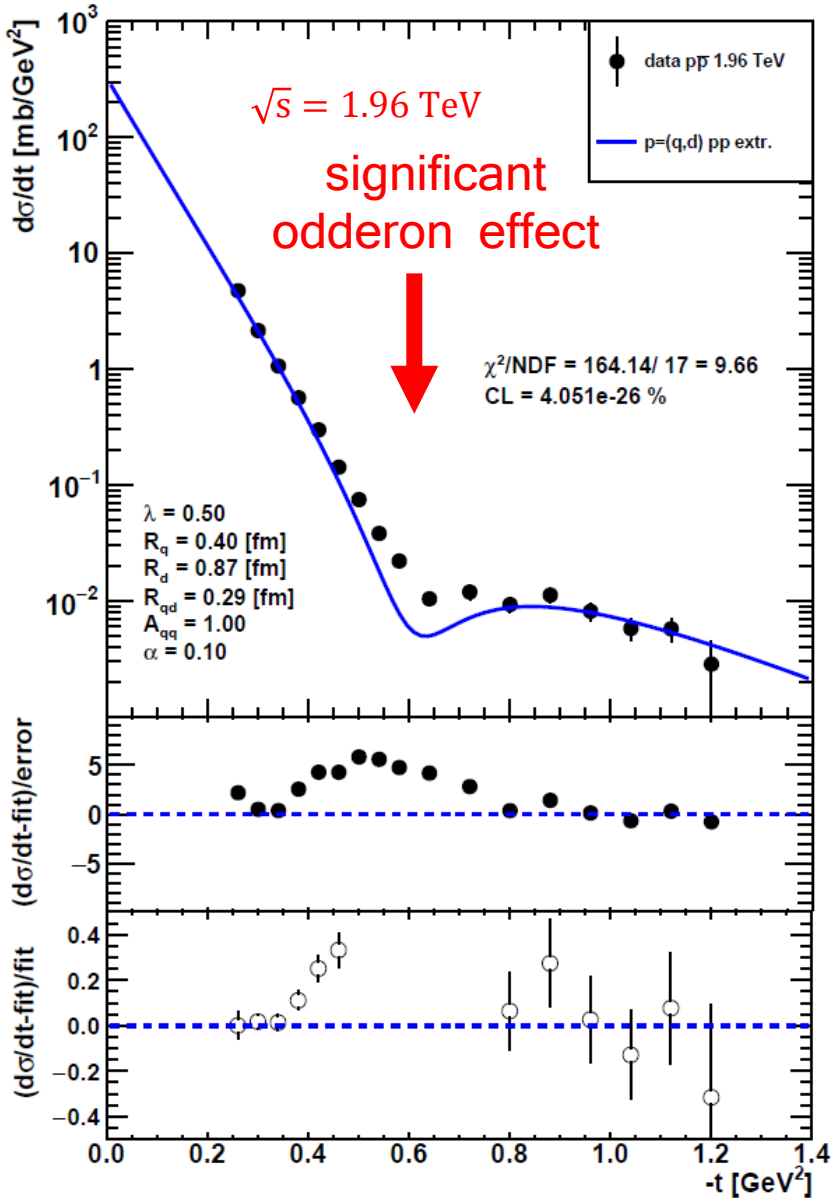


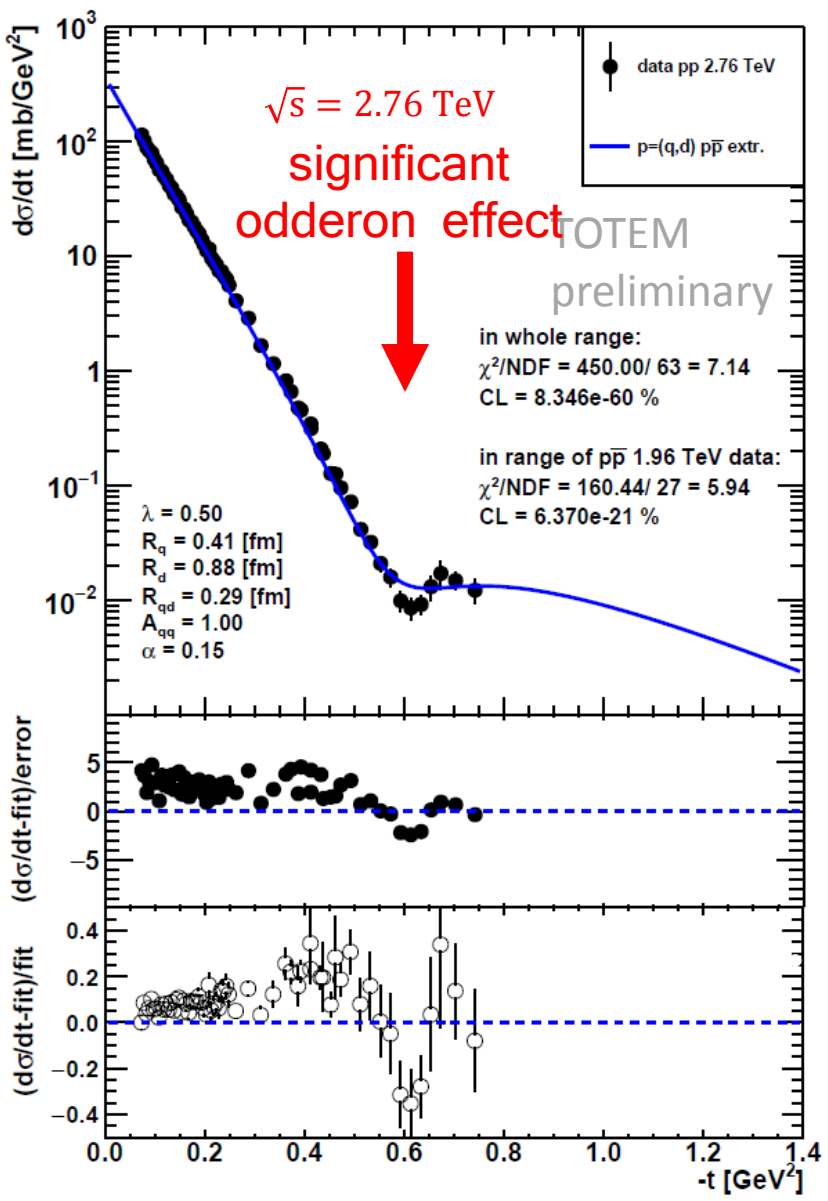




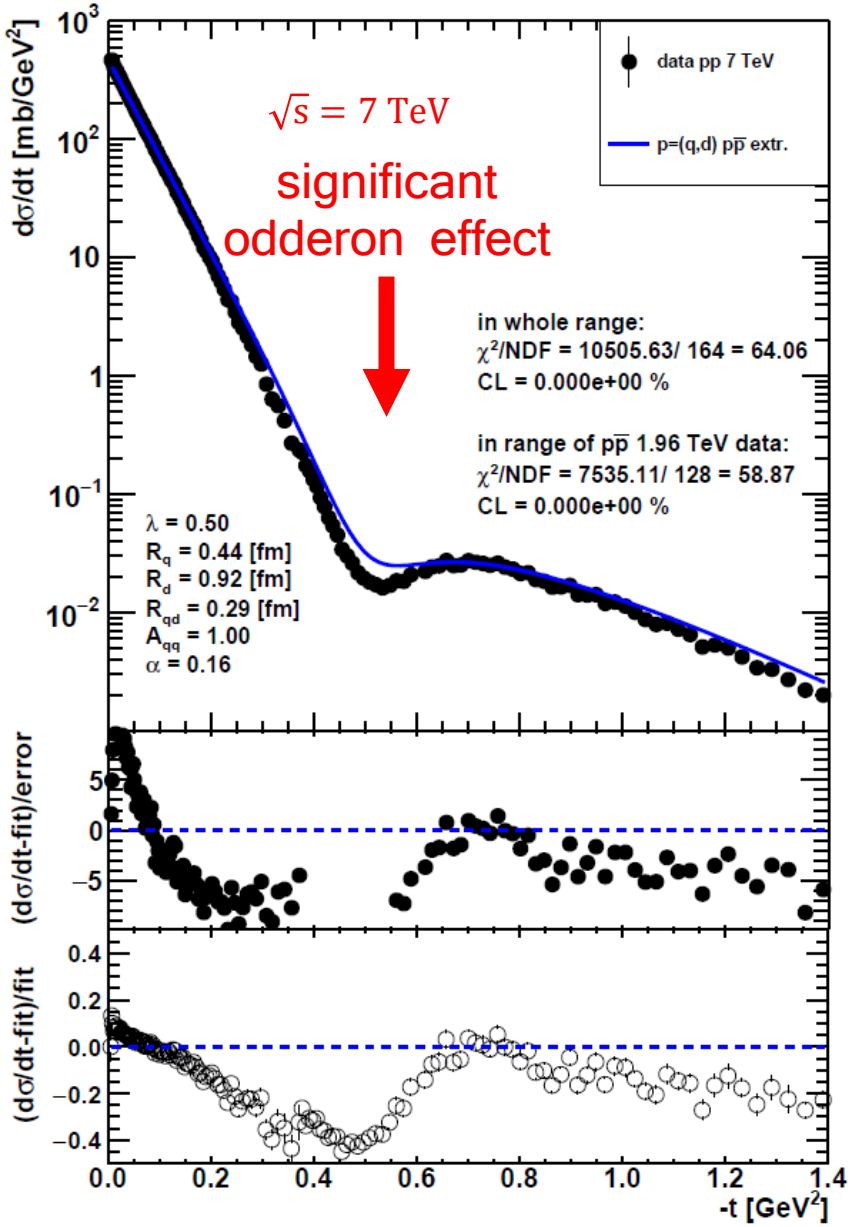


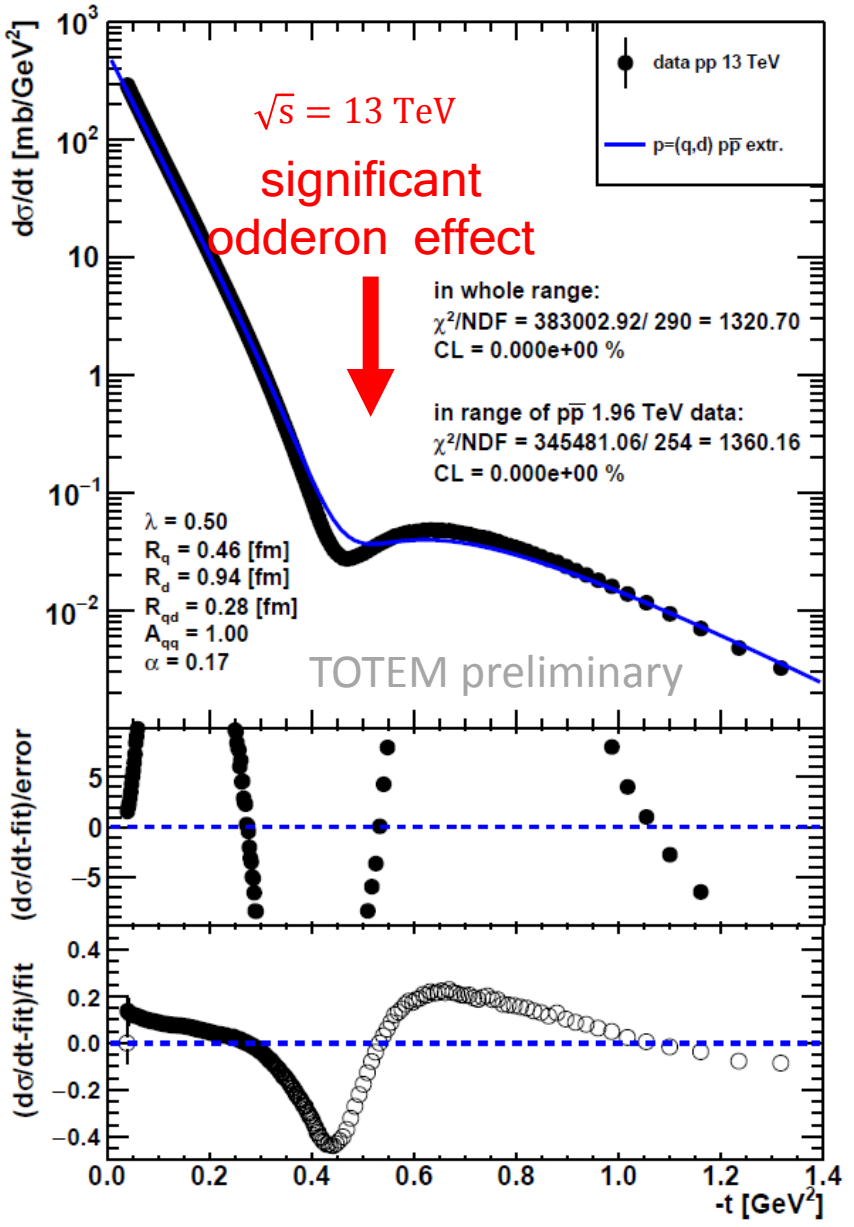
Extrapolation for pp @ 1.96 TeV & $p\bar{p}$ at 2.76 TeV





Extrapolation for $p\bar{p}$ at 7 & 13 TeV





Summary and conclusions

- ReBB model fits for pp and $\mathrm{p\bar{p}}$ dσ/dt datasets from ISR to LHC energies.
- Determined energy dependence of the fitted parameters for pp and $\mathrm{p\bar{p}}$ scattering.
- $R_q(s)$, $R_d(s)$ and $R_{qd}(s)$ are same for pp and $\mathrm{p\bar{p}}$ processes while $\alpha(s)$ is different.
- Extrapolations for pp and $\mathrm{p\bar{p}}$ dσ/dt at same energies in the TeV region.
- Significant difference between the pp and $\mathrm{p\bar{p}}$ dσ/dt: violation of crossing symmetry.
- Possible interpretation: odderon exchange between protons and antiprotons.
- Further plans: improvement of the model and statistically acceptable generalized descriptions for the available data.

Thank you for your attention!

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