Status of the Odderon search using the ReBB model

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

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

- **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 :**

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

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

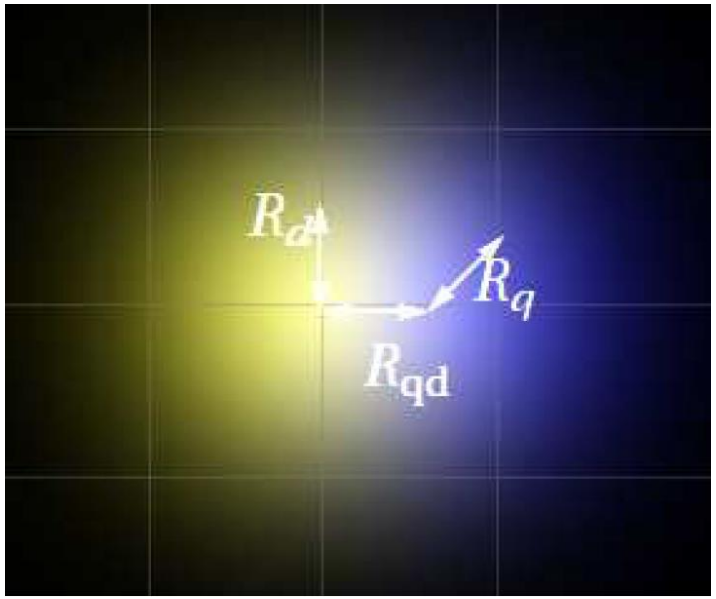
$$S_{ab}^2 = R_a^2 + R_b^2$$

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

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

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

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



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

- **Free parameters:**

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

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 :**

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

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

NEW FREE PARAMETER

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

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

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

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:**

$$\sigma_{\mathrm{tot}}(\mathrm{s}) = 2\mathrm{Im}T(\mathrm{s},\mathrm{t}=0)$$

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

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

- **Parameter ρ:**

$$\rho(\mathrm{s}) = \frac{\mathrm{Re}T(\mathrm{s},\mathrm{t}=0)}{\mathrm{Im}T(\mathrm{s},\mathrm{t}=0)}$$

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

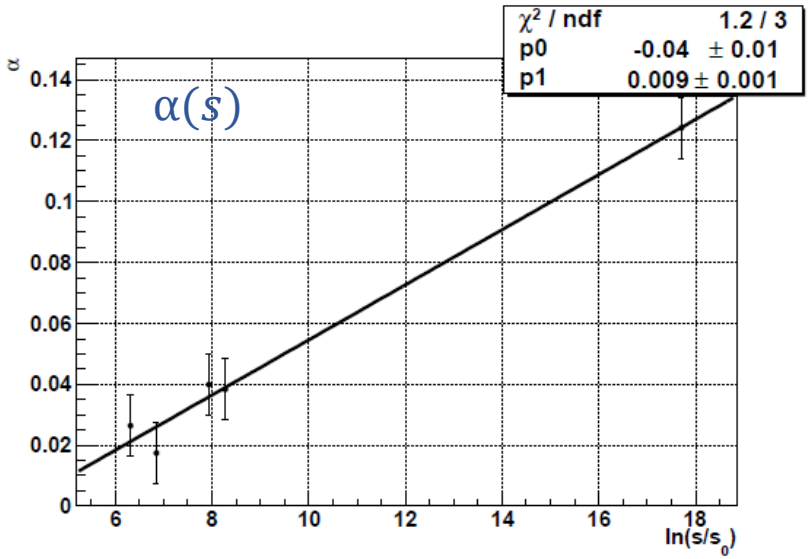
$$P(s) = p_0 + p_1 \cdot \ln(s/s_0)$$

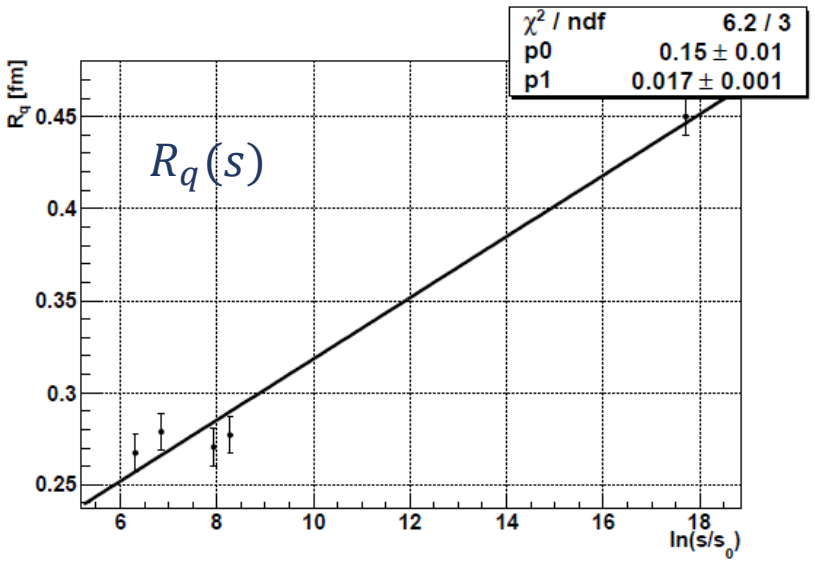
$$P \in \{R_q, R_d, R_{qd}, \alpha\}$$

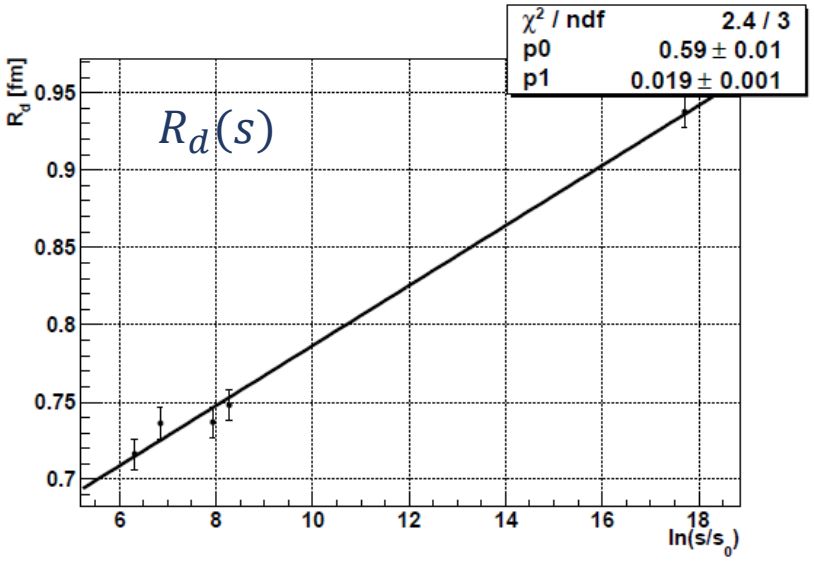
$$s_0 = 1\ \mathrm{GeV}^2$$

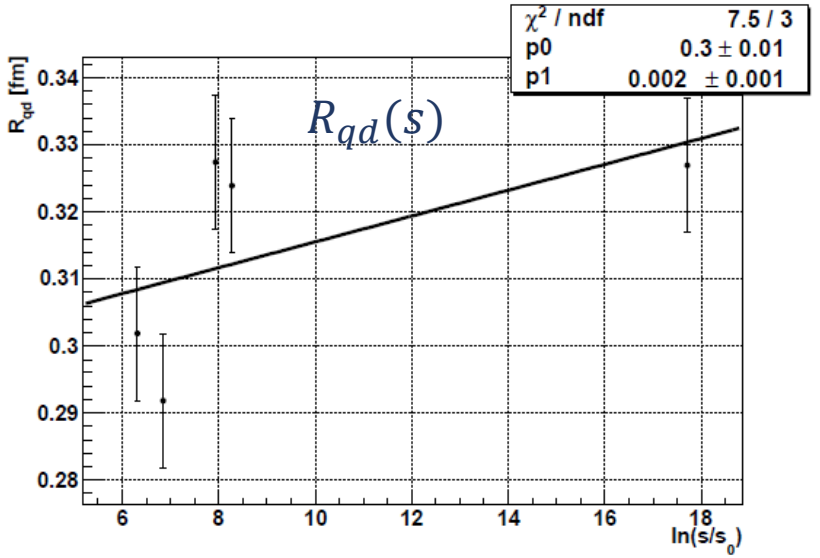
arXiv:1505.01415

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









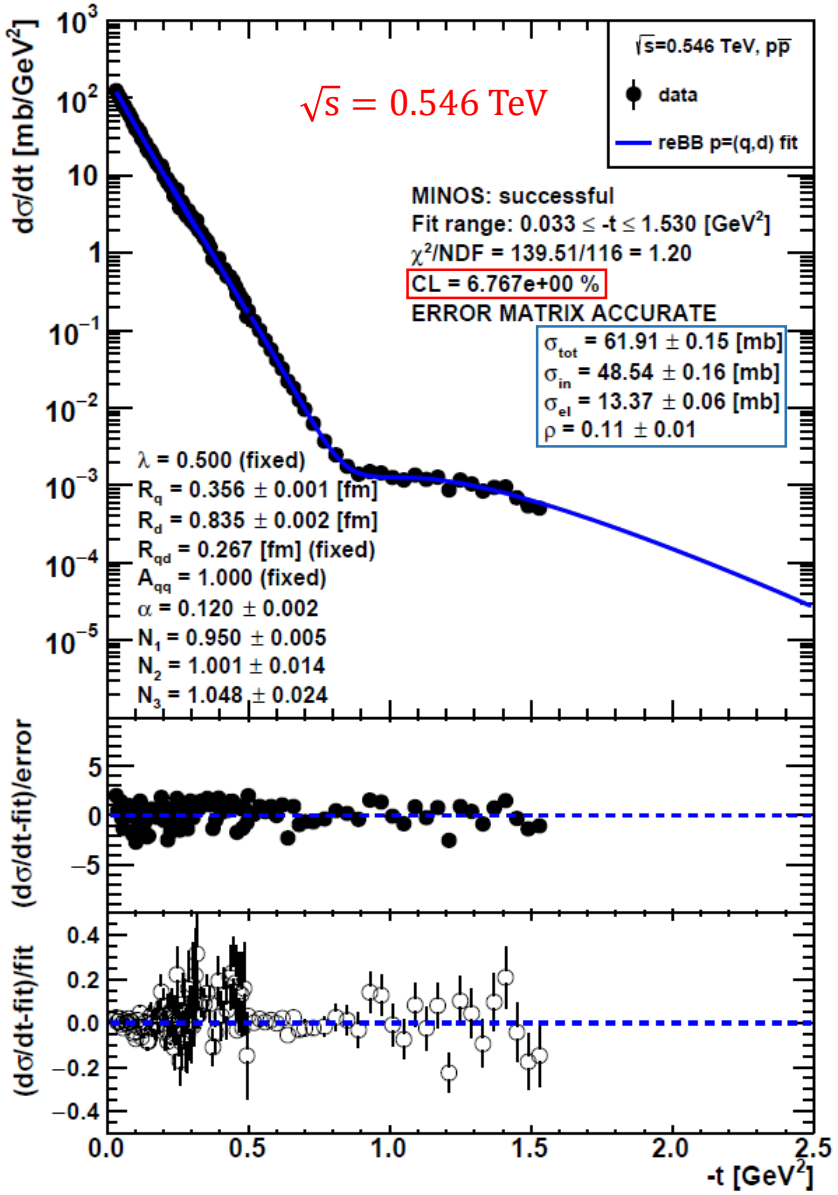
Fit method

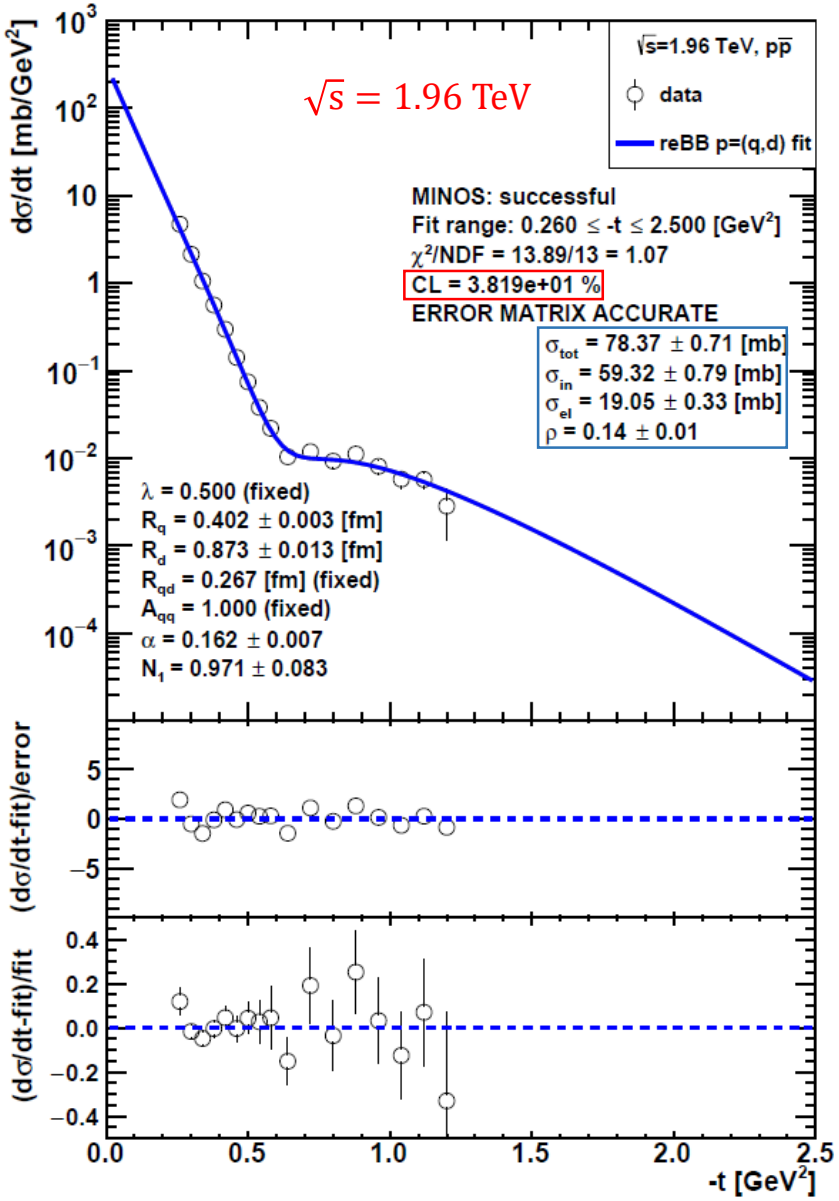
- Least squares fitting with:

$$\chi^2 = \sum_{j=1}^{M}\sum_{i=1}^{n_j}\frac{(d_i - N_j th_i)^2}{e_i^2 + s_i^2} + \sum_{j=1}^{M}\frac{(N_j - 1)^2}{\delta N_j^2} + \frac{(\sigma_{tot} - \sqrt{N_1}\sigma_{tot,th})^2}{\delta^2 \sigma_{tot}}$$

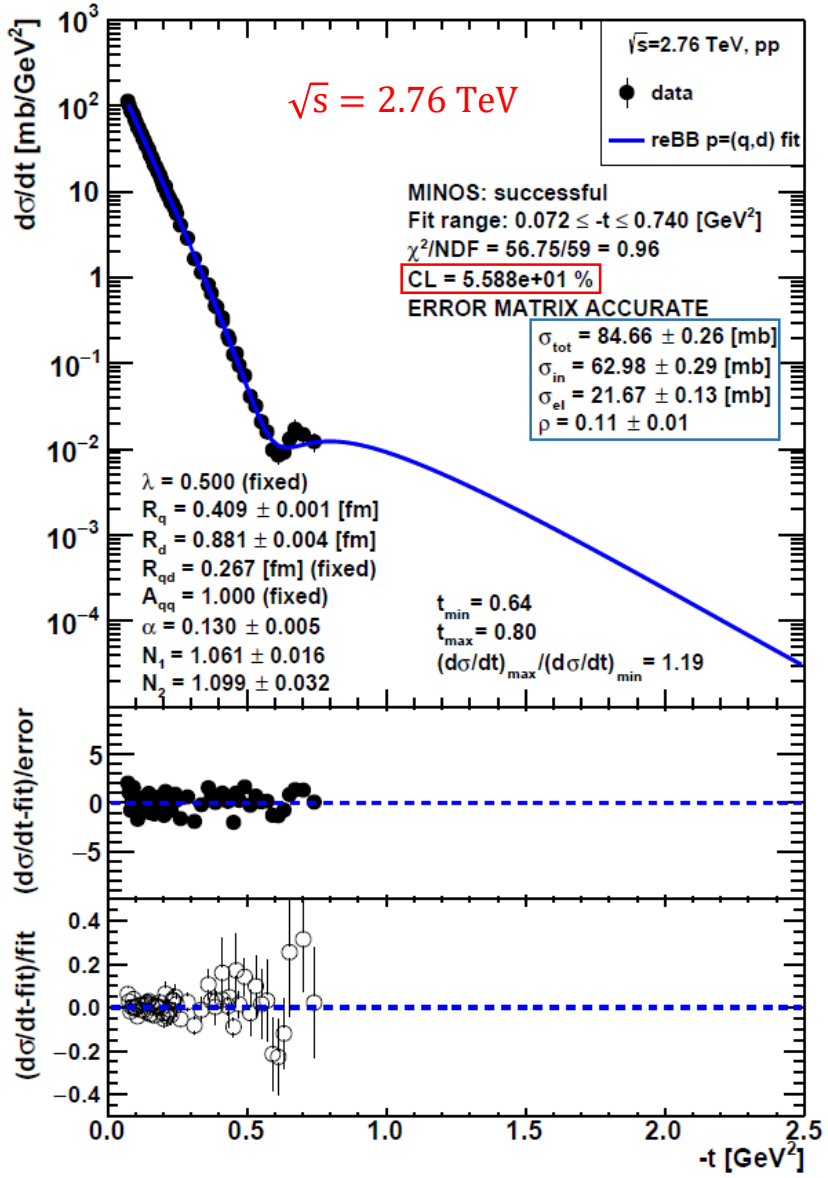
- It takes into account:
  - the t-dependent statistical and systematic errors;
  - the normalization uncertainties → N_j parameters;
  - the measured total cross-section and its total uncertainty .
- What is missing:
  - covariance matrix analysis
  - better handling of the asymmetric, t-dependent systematic errors (7 TeV)
- Minimization with CERN Root MINUIT; parameter error estimation by MINOS.

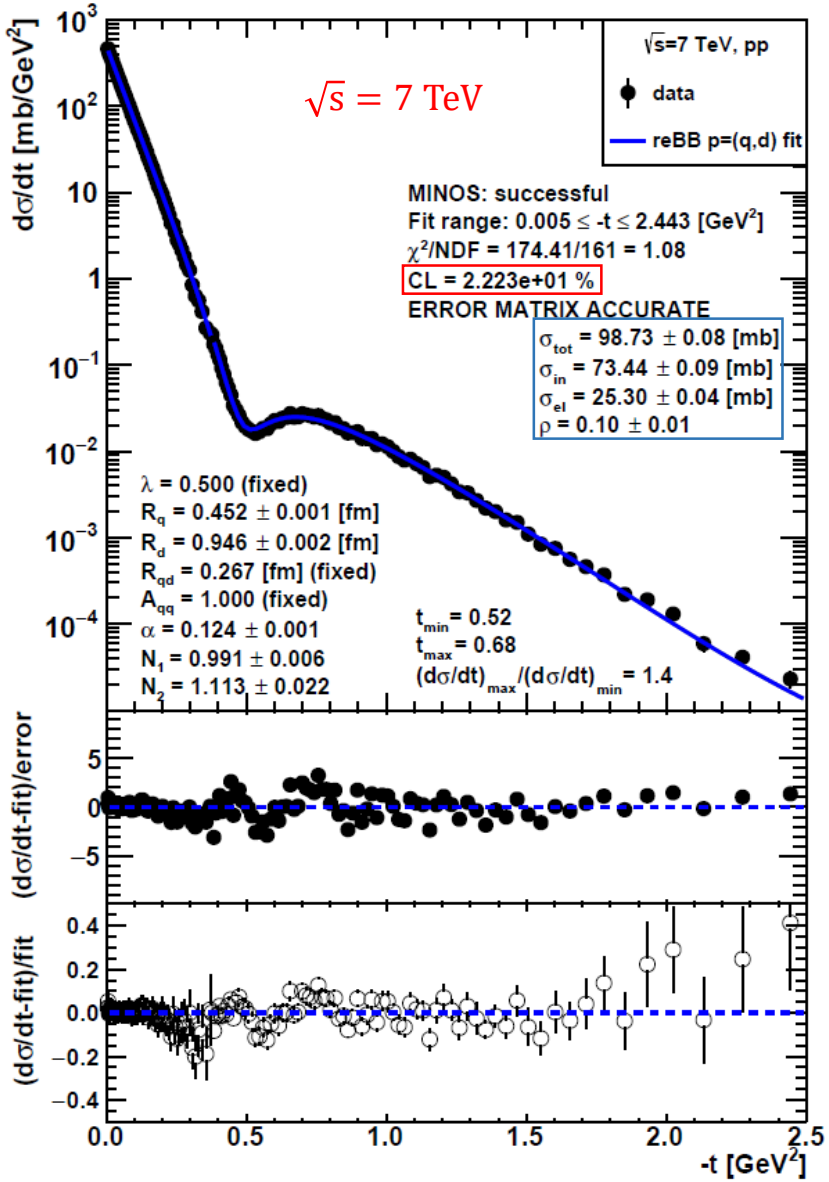
New ReBB fits to $p\bar{p}$ dσ/dt data

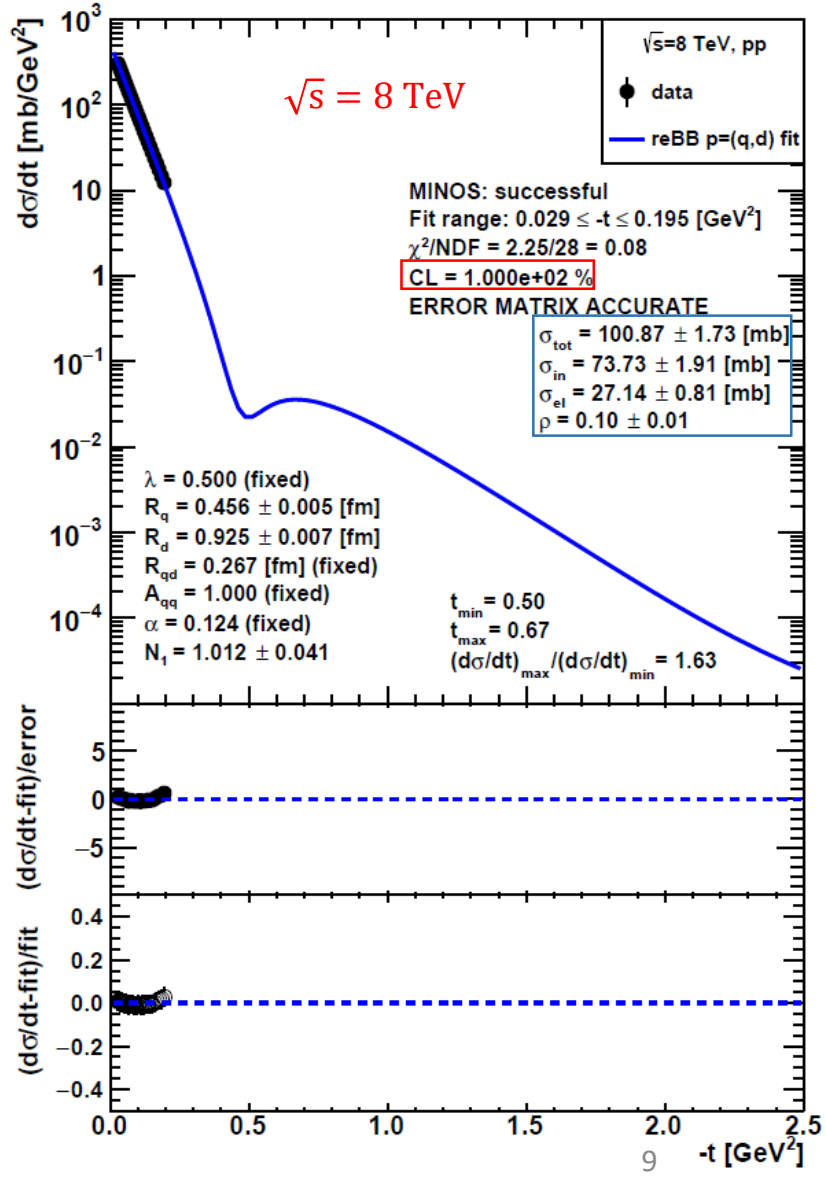




New ReBB fits for the TOTEM pp dσ/dt data







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)	7 (pp)	8 (pp)
$\|t\|$ [GeV^2]	(0.033, 1.530)	(0.260, 1.200)	(0.072, 0.740)	(0.005, 2.443)	(0.029, 0.195)
χ^2/NDF	139.51/116	13.89/13	56.75/59	174.41/161	2.25/28
CL [%]	6.77	38.19	55.88	22.23	100
R_q $[fm]$	0.356± 0.001	0.402 ± 0.003	0.409 ± 0.001	0.452 ± 0.001	0.456 ± 0.005
R_d $[fm]$	0.835 ± 0.002	0.873 ± 0.012	0.881 ± 0.004	0.946 ± 0.002	0.925 ± 0.007
R_{qd} $[fm]$	0.267 (fixed)				
α	0.120 ± 0.002	0.162 ± 0.007	0.130 ± 0.005	0.124 ± 0.001	0.124 (fixed)
N_1	0.950 ± 0.005	0.976 ± 0.076	1.061 ± 0.016	0.991 ± 0.006	1.012 ± 0.041
N_2	1.001 ± 0.014	–	1.099 ± 0.032	1.113 ± 0.022	–
N_3	1.048 ± 0.024	–	–	–	–

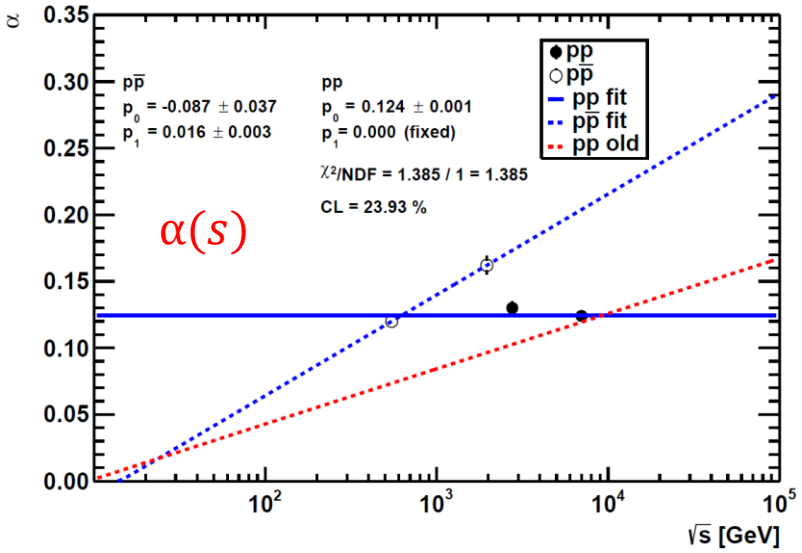
Fitted parameters of the ReBB model for proton-proton and proton-antiproton scattering.
The parameters and their errors are rounded up to three valuable decimal digits.

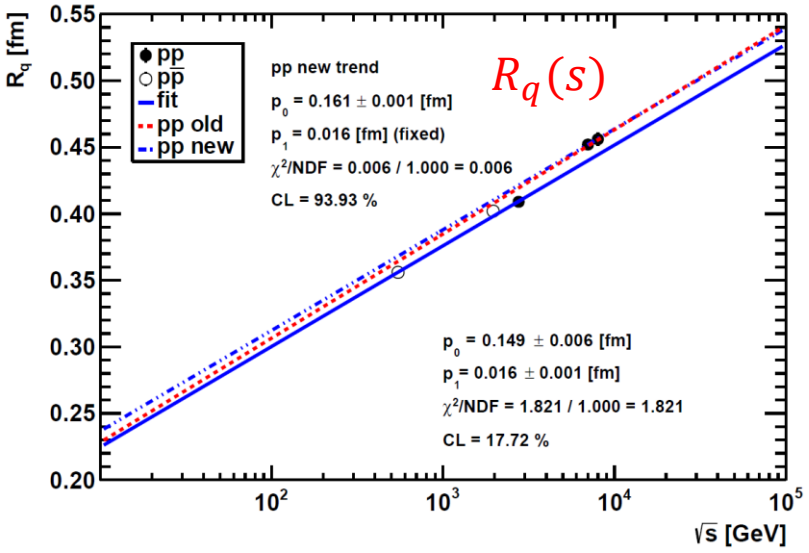
Energy dependence of the parameters

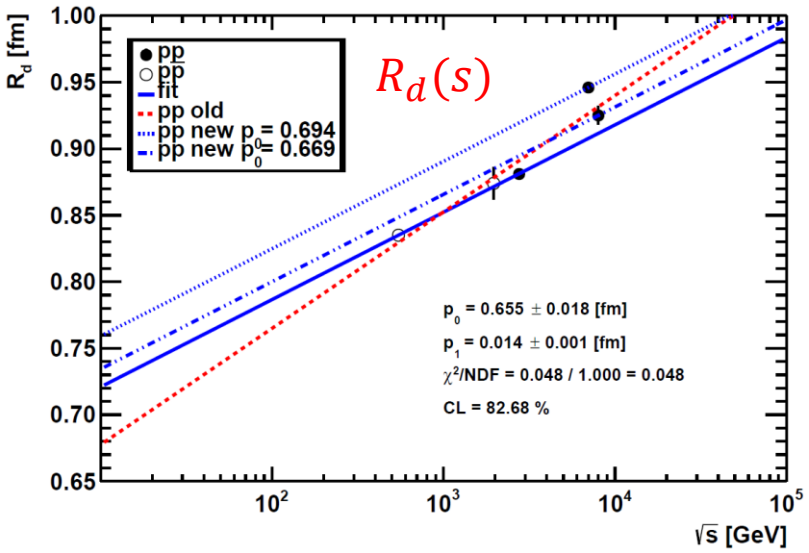
$$P(s) = p_0 + p_1 ln(s/s_0) \qquad P \in \{R_q, R_d, R_{qd}, \alpha\} \qquad s_0 = 1\ GeV^2$$

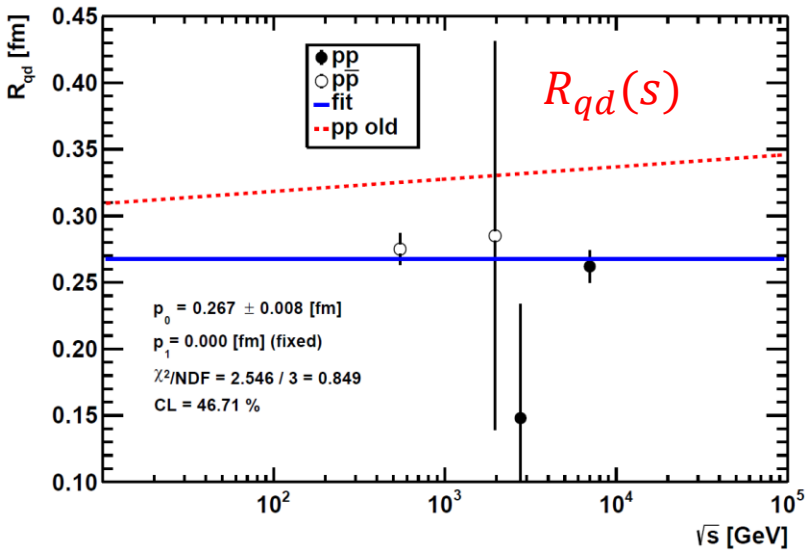
Parameter	$R_q\ [fm]$	$R_d\ [fm]$	$R_{qd}\ [fm]$	$\alpha\ (p\bar{p})$	$\alpha\ (pp)$
χ^2/NDF	$1.821/1$	$0.048/1$	$2.546/3$	–	$1.385/1$
CL [%]	17.72	82.68	46.71	–	23.93
p_0	0.149 ± 0.006	0.655 ± 0.018	0.267 ± 0.008	-0.087 ± 0.037	0.124 ± 0.001
p_1	0.016 ± 0.001	0.014 ± 0.001	$0.000\ (fixed)$	0.016 ± 0.003	$0.000\ (fixed)$

Parameters which define the energy dependence of the ReBB model parameters (correspond to solid (pp) and dashed ($p\bar{p}$) blue lines in the figures)

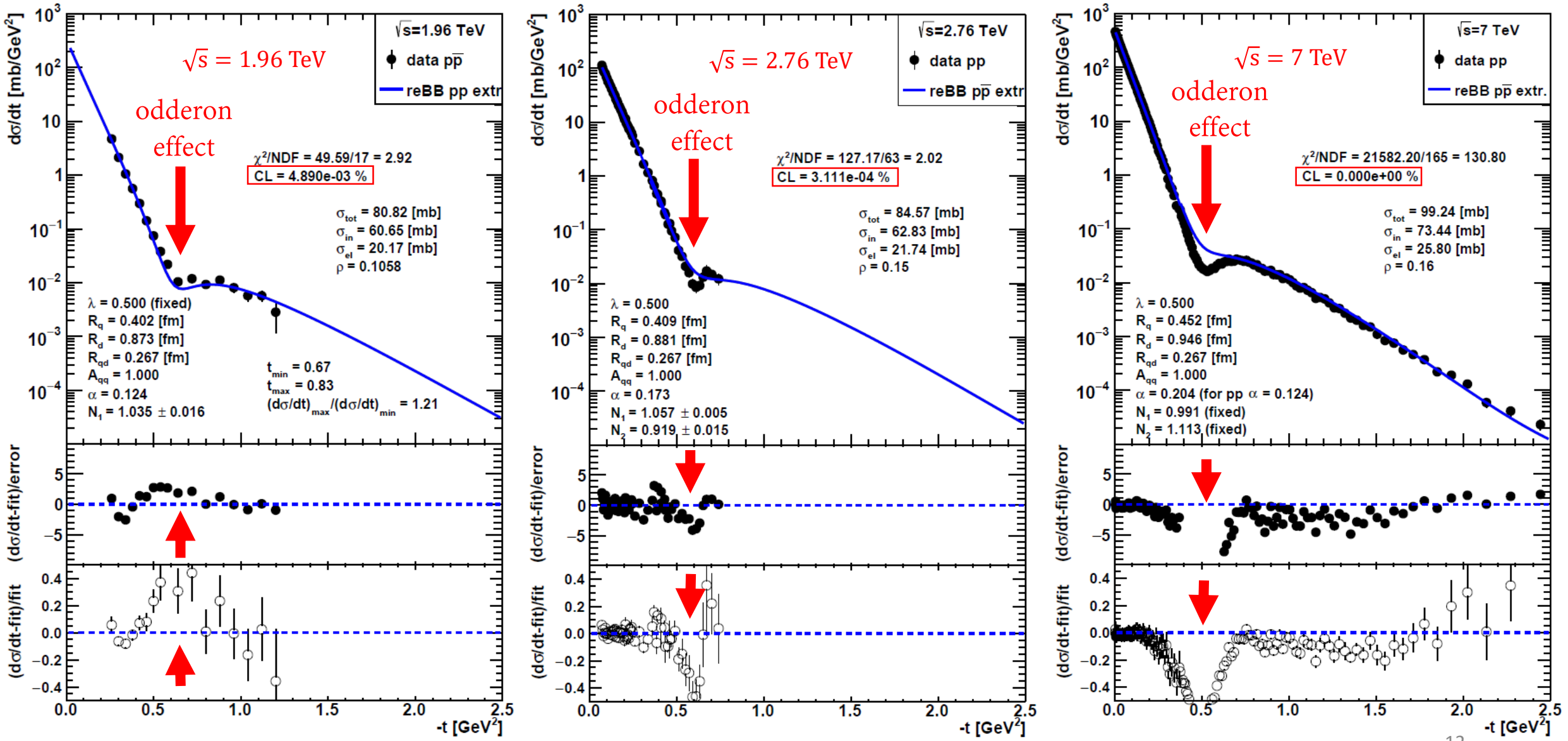








Extrapolations: evidence for Odderon exchange



Ster, Jenkovszky, Csörgő: Phys. Rev. D 91, 074018 (2015) – earlier similar study

Summary: Odderon

- **ReBB model fits to $\mathbf{pp}$ and $\mathbf{p\bar{p}}$ dσ/dt data →** acceptable description in the energy range $0.546 \leq \sqrt{s} \leq 8$ TeV
- **Determination of the energy dependence of the parameters**

→ new channel between 2.76 and 7 TeV: jump in the energy dependence
→ $R_q(s)$, $R_d(s)$ 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**
- **Significant difference between $\mathbf{pp}$ and $\mathbf{p\bar{p}}$ dσ/dt** in the dip region **→ Odderon** (P=C=-1 colorless bound states of odd number of gluons) **exchnage** with high probability**:**

P = 0.99995381 (1.96 TeV) **P = 0.99999689** (2.76 TeV) **P = 1.0** (7 TeV)

Thank you for your attention!

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