Scaling properties of elastic proton-proton scattering at LHC energies

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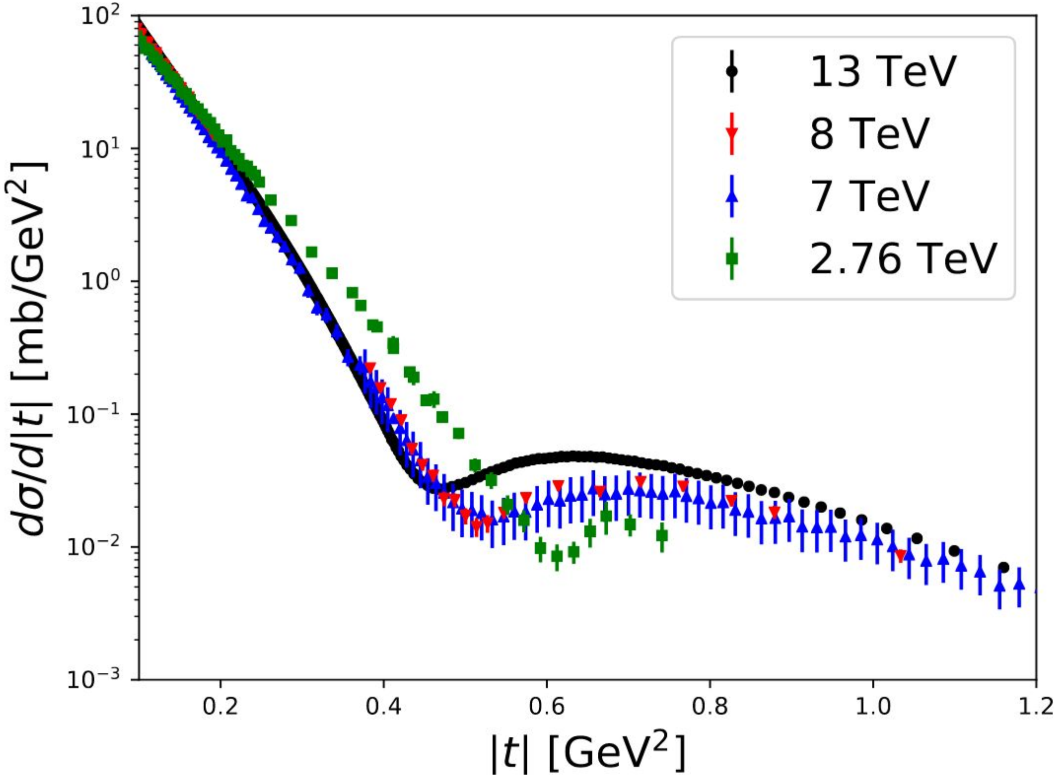
Elastic proton-proton scattering at the LHC

Precision measurements of differential cross section by the TOTEM experiment at the LHC at 2.76, 7, 8, and 13 TeV (Eur. Phys. J. C 80 (2020) 91, EPL 95 (2011) no. 41004; Nucl. Phys. B 899 (2015) 527; Eur. Phys. J. C79 (2019) 10, 861), and now more recently by ATLAS arXiv:2207.12246

dσ/d|t| points seem to evolve in a correlated way with √s, is there a simple rule that can be extracted from data?



Quality factor (QF) method to test scaling hypotheses

$$\mathrm{QF} = \left[\Sigma_i \frac{(v_{i+1} - v_i)^2 \times \Delta v_{i+1} \times \Delta v_i}{(u_{i+1} - u_i)^2 + \epsilon^2}\right]$$

where the Δv_i are the uncertainties on v_i and ϵ is a small constant to regularize divergences when $u_i+1 = u_i$ (v_i and u_i are the scaling variables under consideration).

QF measures the degree to which a set of data points can belong to a single continuous function, without any assumptions about such a functional form.

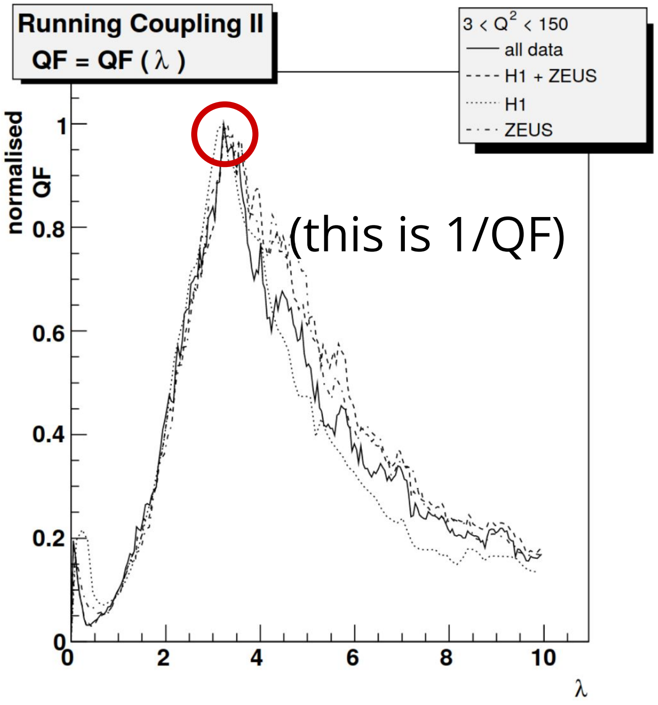
Scaling ⇒ smallest QF

Method previously used to examine scaling properties in DIS

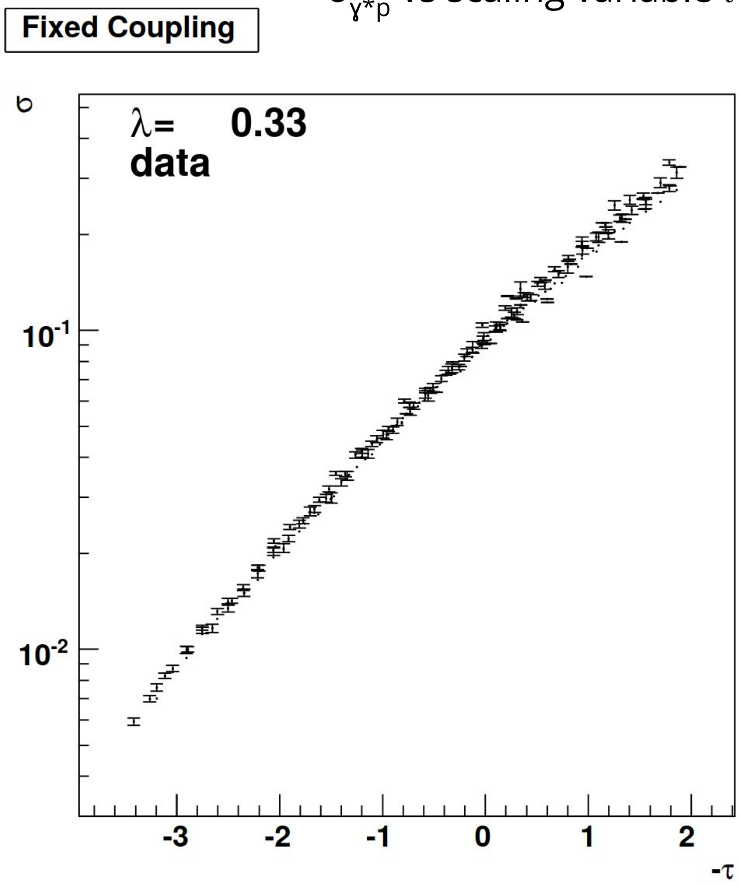
(C. Marquet and L. Schoeffel, PLB 639 (2006) 471; F. Gelis, R. B. Peschanski, G. Soyez, L. Schoeffel, PLB 647 (2007) 376; G. Beuf, R. Peschanski, C. Royon, and D. Salek, PRD 78 (2008) 074004)

Quality factor in DIS

G. Beuf, R. Peschanski, C. Royon, and D. Salek, PRD 78 (2008) 074004



σ_{γ^*p} vs scaling variable τ



$$\tau = \log Q^2 - \log Q_s^2(Y) = \log Q^2 - \lambda Y$$

Scaling ansatz

$d\sigma/dt^*$ scales with $t^{**} = t^*/s^B$

additional power of *s* is needed to describe translations of dip and bump with *s* in the fit

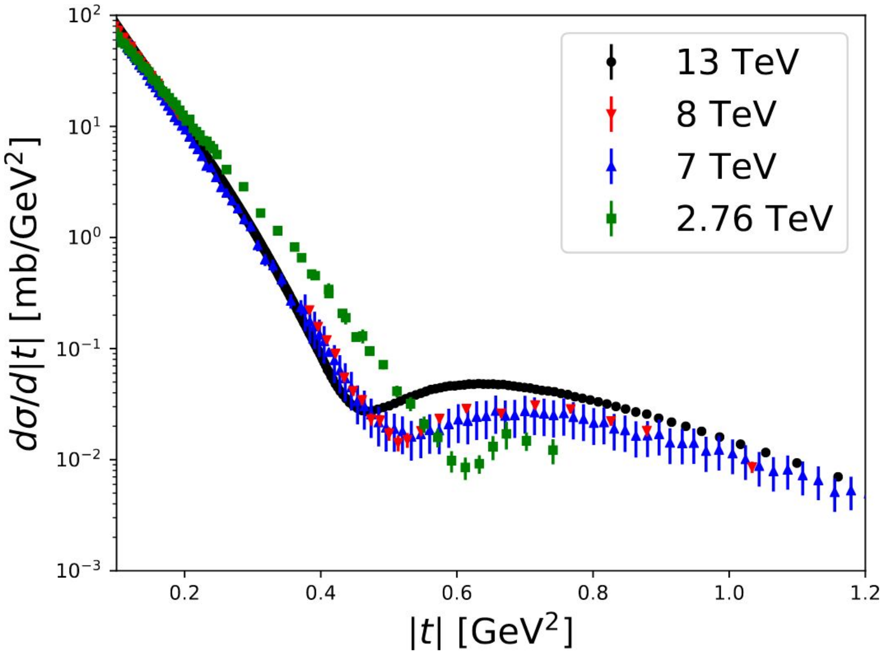
$t^* = (s/|t|)^A \times |t|$

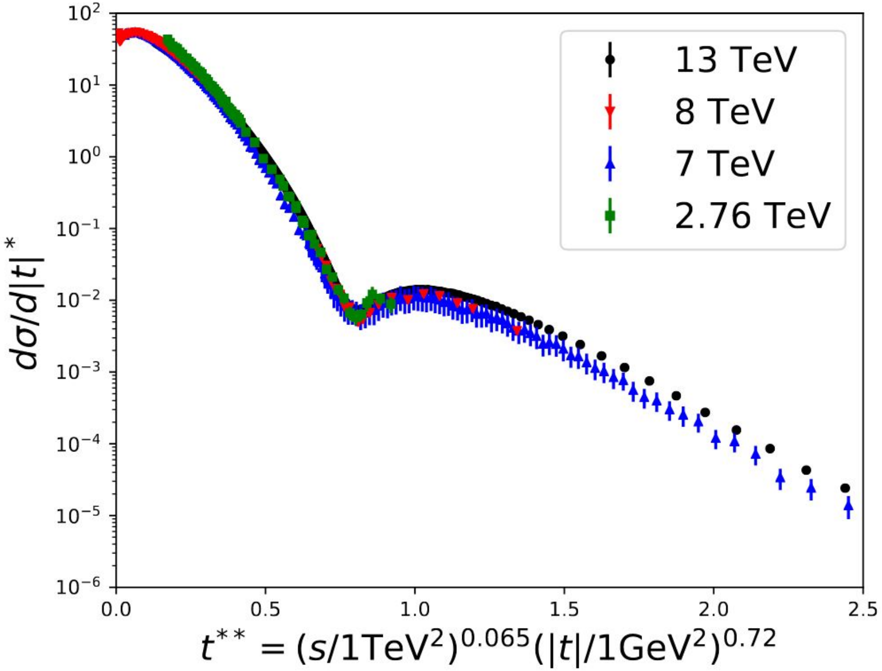
inspired on geometric scaling expected from saturation models

(as observed in particle spectra measurements e.g. L. McLerran and M. Praszalowicz PLB, 741 (2015) 246, M. Praszalowicz and A. Francuz, PRD 92 (2015) 074036)

A and *B* are scaling constants to be fit to data.

W/ quality factor method, A = 0.28 and B = 0.215



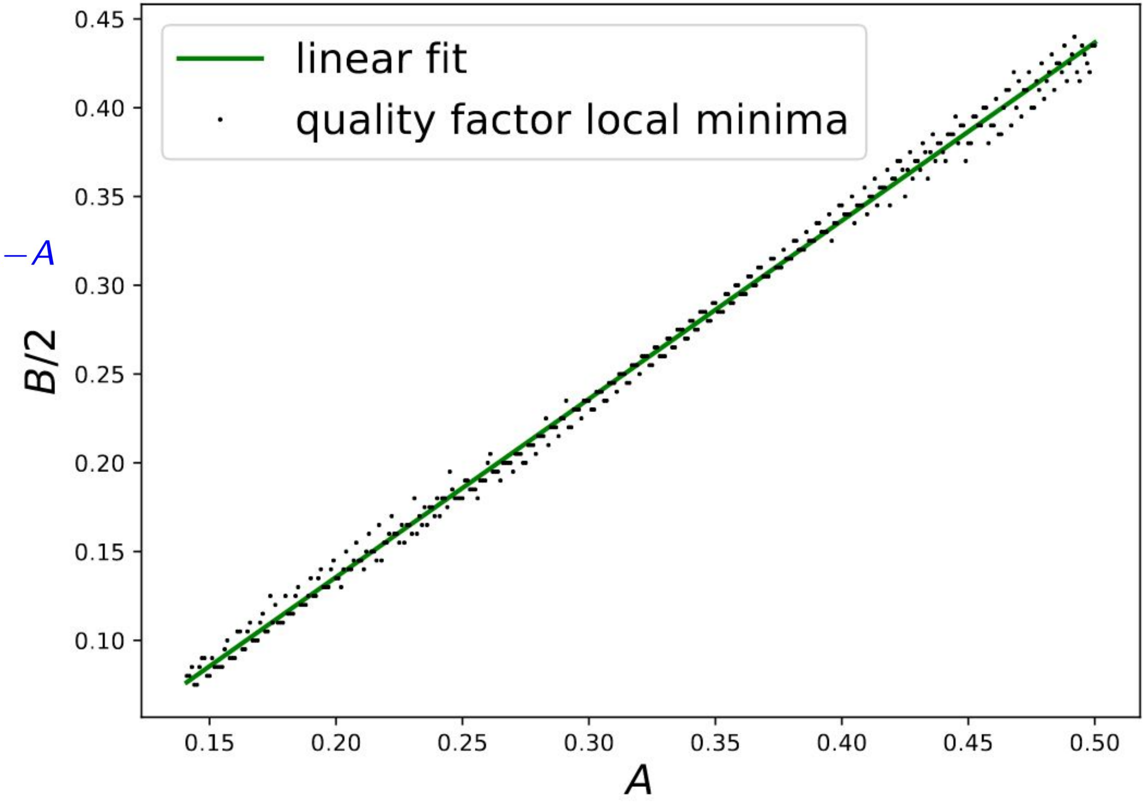


Strong correlation between *A* and *B* constants

We find that $B = A - 0.065$

This implies with $t^{**} = s^{0.065} \times |t|^{1-A}$

Analysis can be reduced to one-parameter fit.



Scaling ansatz can be further simplified

$$\frac{d\sigma}{dt^*} = \frac{d\sigma}{dt}\frac{dt}{dt^*} = \frac{d\sigma}{dt} \times s^{A\frac{A-1.065}{1-A}} \times f(t^{**}) = (s)^{-\alpha}\frac{d\sigma}{dt}f(t^{**})$$

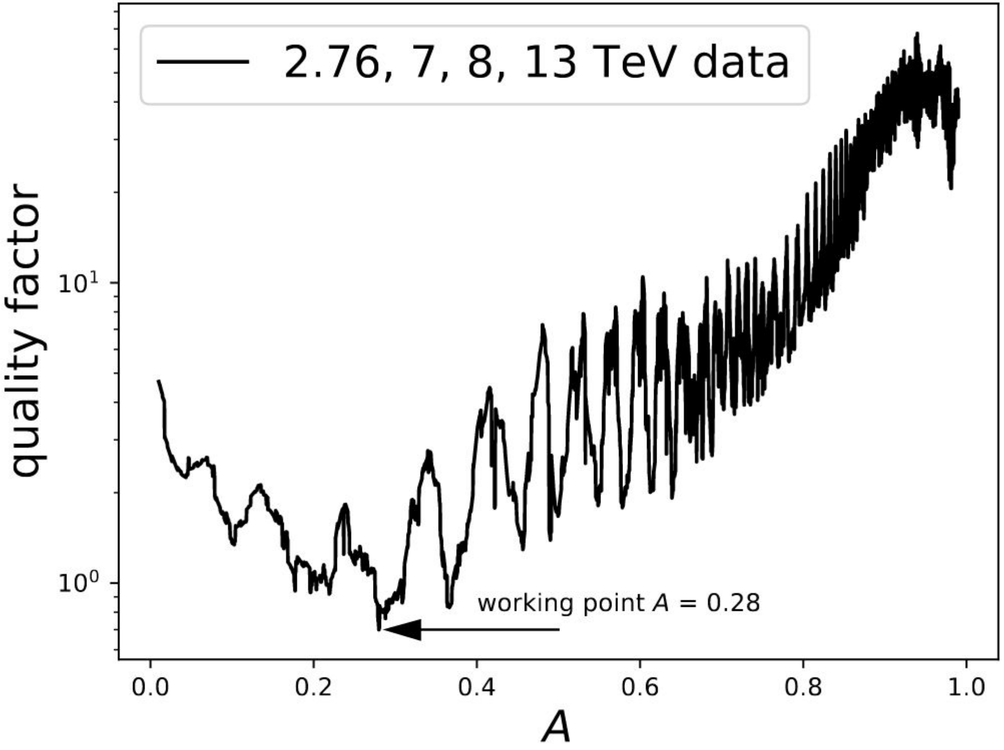
f(t^{**}) carries the dependence on t^{**} and $\alpha = \frac{-A(A-1.065)}{1-A}$

If dσ/dt* scales with *s* , then s^{α}dσ/dt must scale with s too.

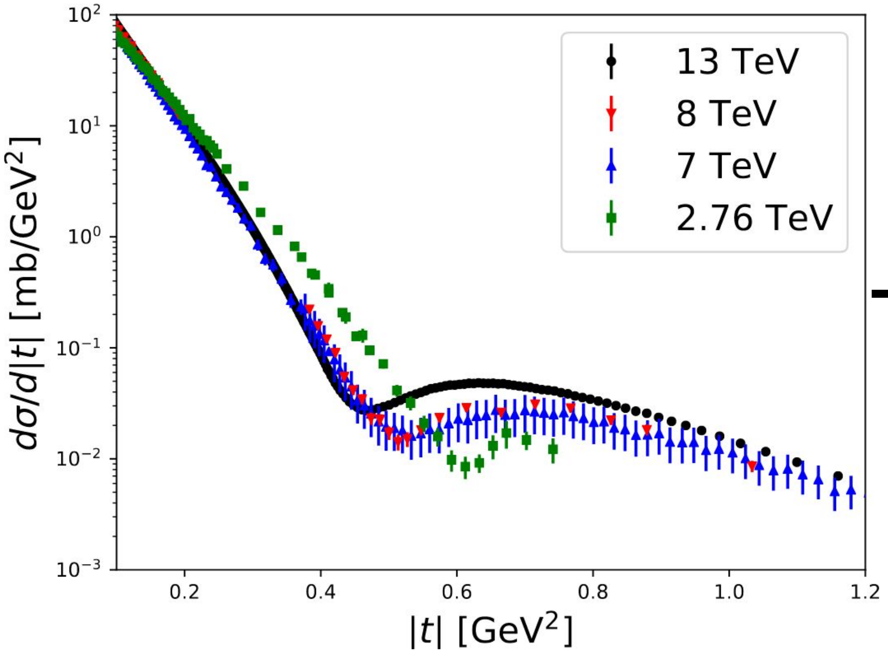
One-parameter scan quality factor

We pick the absolute minimum A = 0.28 as a working point.

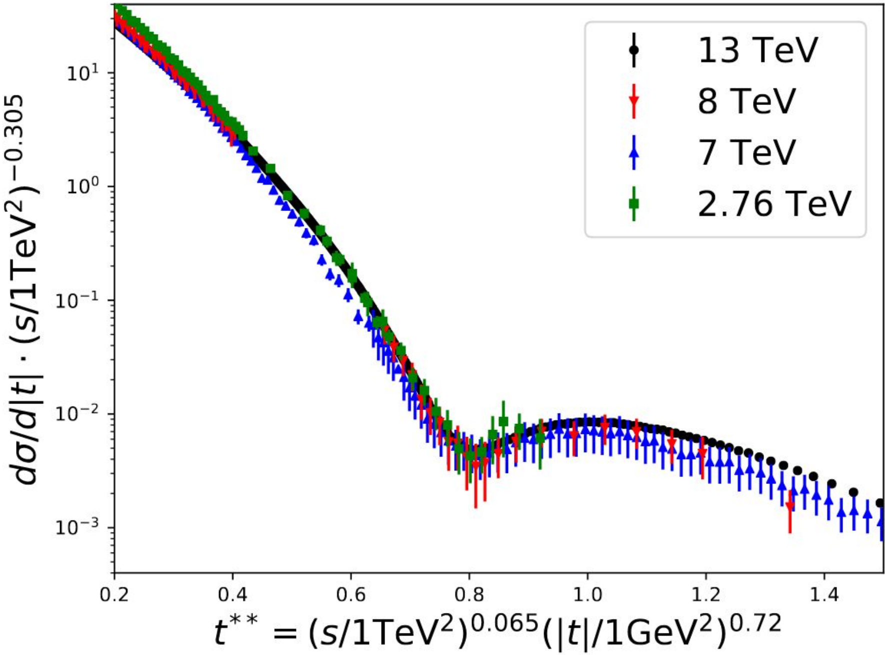
"noise" is due to Moiré pattern effect (smooth variations of fit constants yield different overlaps between the data sets).



TOTEM data in (*s*,*t*)-space



TOTEM data mapped to scaling variables



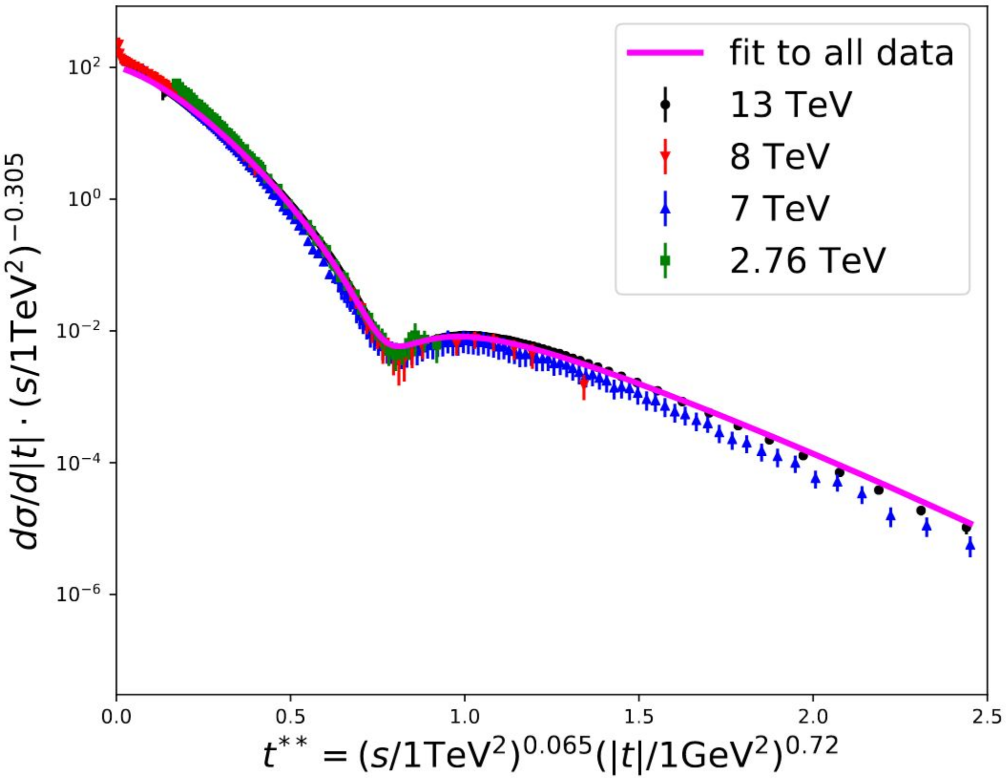
We find $\alpha = 0.305$

Fit to all data*

$$\frac{d\sigma}{d|t|} = \frac{1}{16\pi s^2}|A(s,t)|^2 = |\mathcal{A}(s,t)|^2$$

Double-exponential parametrization** of the cross section (six free parameters):

$$\begin{aligned}\mathcal{A}(s,t) &= i\big(\mathcal{A}_1(s,t) + \mathcal{A}_2(s,t)\big)e^{i\theta}\\ \mathcal{A}_1(s,t) &= N_1(s)e^{-B_1(s)|t|}\\ \mathcal{A}_2(s,t) &= N_2(s)e^{-B_2(s)|t|}e^{i\phi}\end{aligned}$$



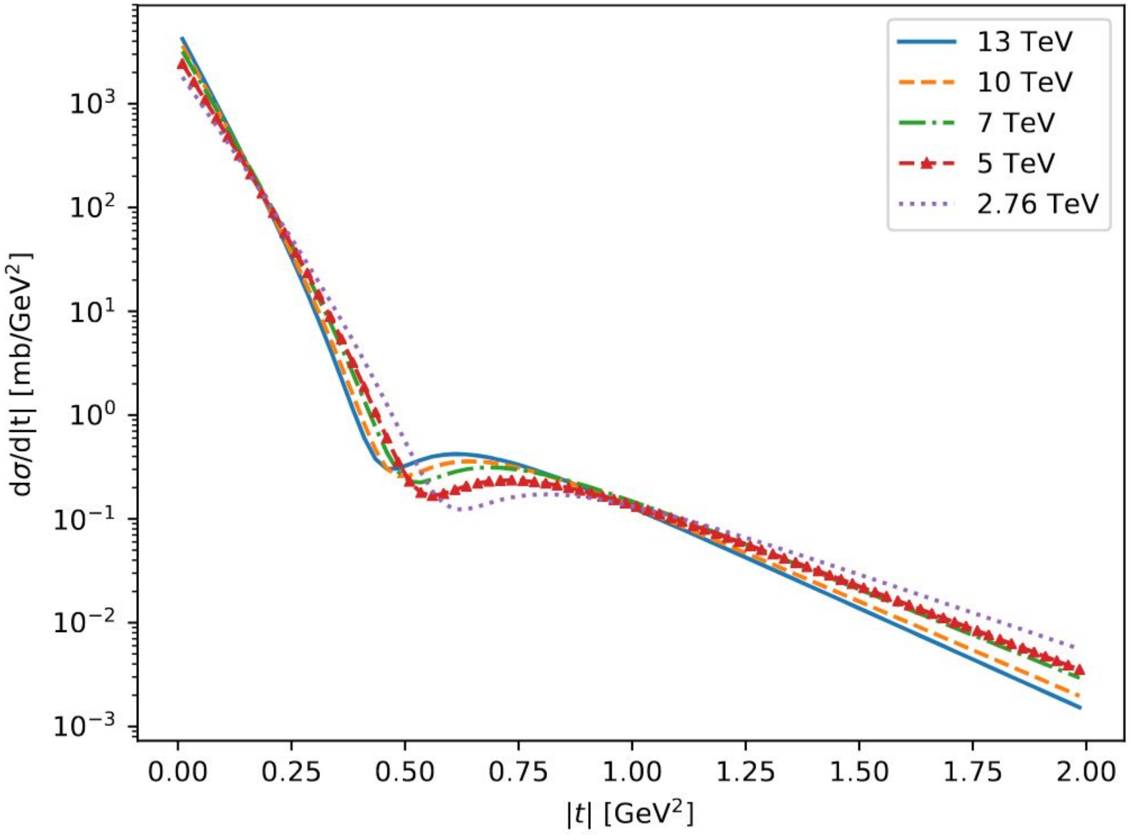
where $N_1(s) = N_1^0(s/1\text{ TeV}^2)^{\alpha/2}$, $N_2(s) = N_2^0(s/1\text{ TeV}^2)^{\alpha/2}$, $B_1(s) = B_1^0(s/1\text{ TeV}^2)^{\gamma/2}$ and $B_2(s) = B_2^0(s/1\text{ TeV}^2)^{\gamma/2}$

α = 0.305 and $\gamma \equiv \gamma(\alpha)$ = 0.09 are fixed by scaling

*assumed uncorrelated uncertainties for fits

**R. J. N. Phillips and V. D. Barger, PLB, 46 (1973) 412

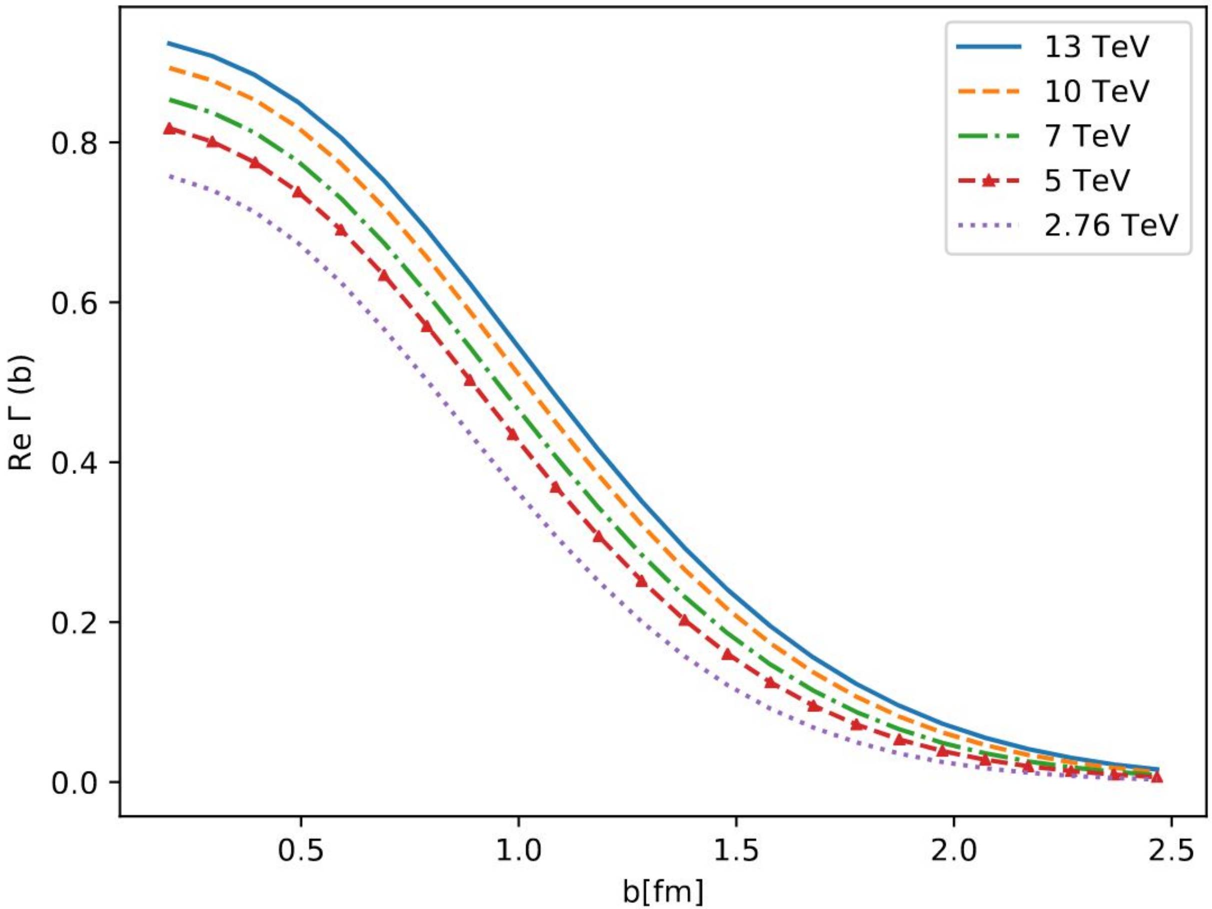
"Predictions" for dσ/d|t| based on fits to all data in scaling plane



Profile function

$$\mathrm{Re}(\Gamma(s,b)) = \frac{1}{4\pi i s}\int_0^\infty dq\, q\, J_0(qb)\, A(s, t=-q^2)$$

Use scaling to predict *A*(s, t) at any √s, calculate real part of profile function to explore implications in parameter space dependence.



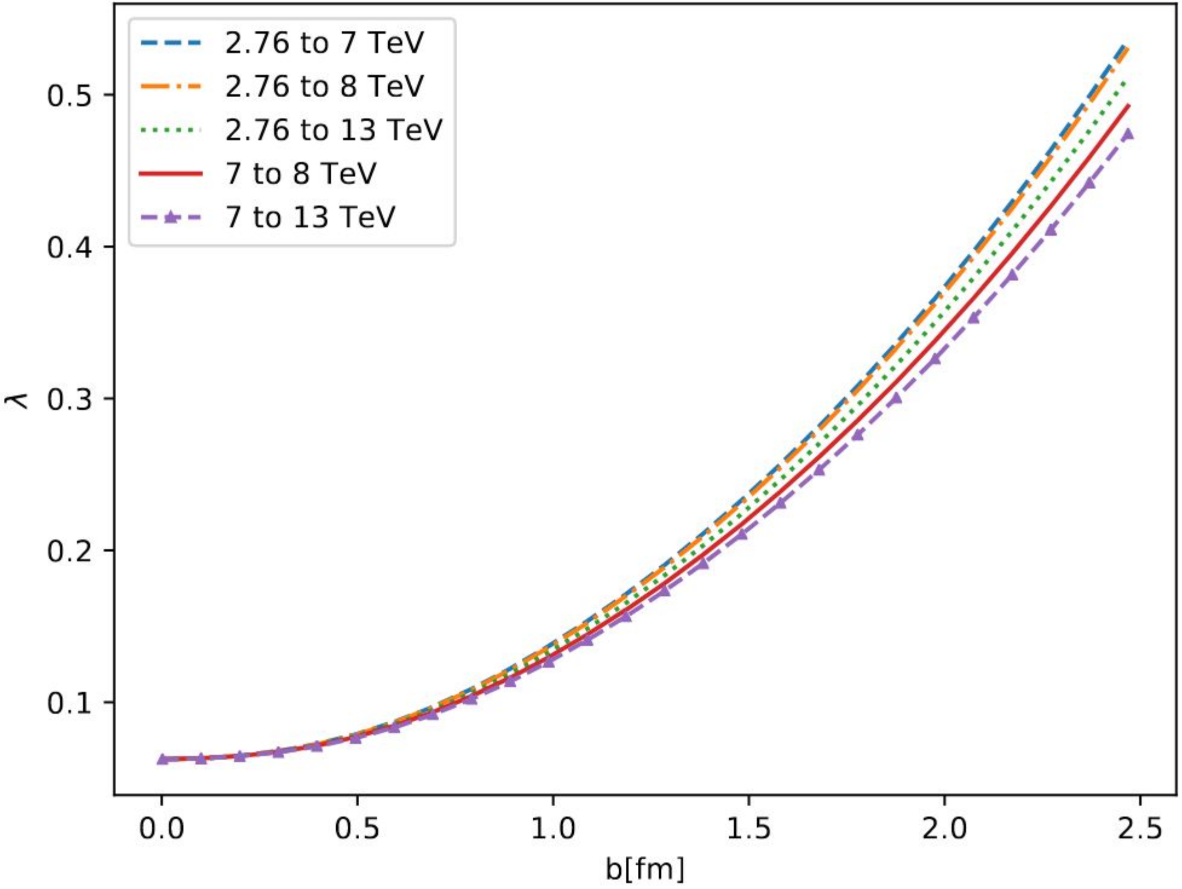
Power exponent in impact parameter space

$$\lambda = \frac{1}{\ln(s_1/s_2)} \ln\left(\frac{\mathrm{Re}\Gamma(s_1, b)}{\mathrm{Re}\Gamma(s_2, b)}\right)$$

Quadratic dependence on *b*.
Power-exponent is (weakly) dependent on reference energies.

As $b \to 0$, λ = λ(α) = 0.06; the power exponent is fixed by scaling, no dependence on double exponential fit parameters.

Would be interesting to see if physics models expect such behavior.



Possible refinements for future studies

- Explore other unassuming optimization methods.

- Explore other scaling variables, preferably based on physics grounds.

- Simultaneous fit together with total cross section.

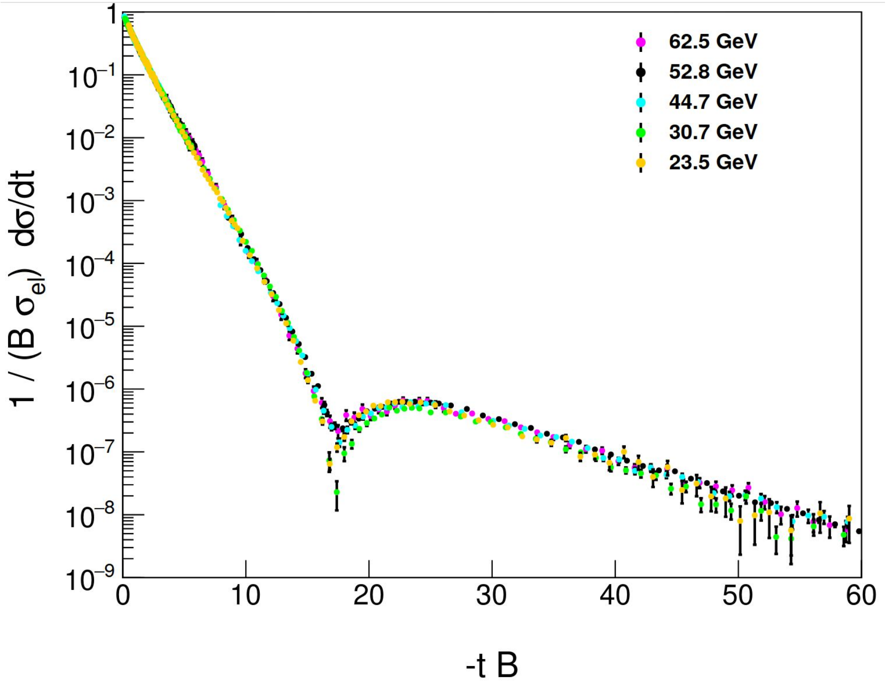
- Use full covariance matrices for all data sets to account for bin-to-bin correlations in the fits when public.

- Include recent $d\sigma/d|t|$ measurement by ATLAS at 13 TeV, try to conceal also with lower $\sqrt{s}$.

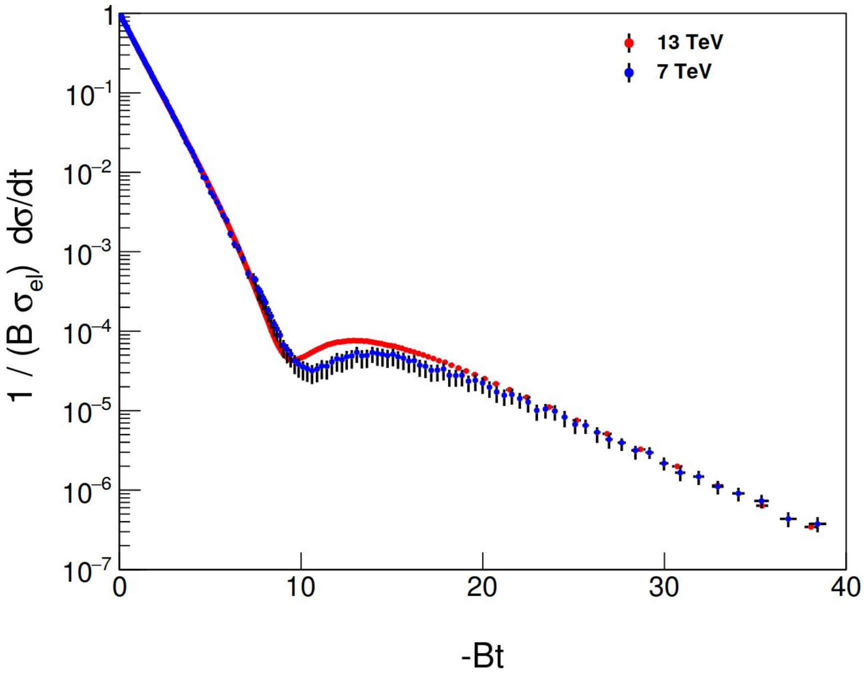
What about lower √s data?

Study by T. Csorgo, T. Novak, R. Pasechnik, A. Ster, I. Szanyi, Eur. Phys. J. C (2021) 81: 180

Scaling found at lower √s



Same scaling breaks down at higher √s



Summary and outlook

- Precision measurements by TOTEM at the LHC exhibit a smooth evolution with collision energy.

- An (approximate) scaling law is found in elastic pp scattering at LHC energies, namely:

$$s^{-0.305}\, d\sigma/d|t| \text{ scales with } t^{**} = s^{0.065}\, t^{0.72}$$

- Scaling violations present at low-t and high-t, room for improved studies.