

ODDERON AND SUBSTRUCTURES OF PROTON FROM A MODEL-INDEPENDENT LÉVY IMAGING OF ELASTIC PP COLLISIONS AT LHC

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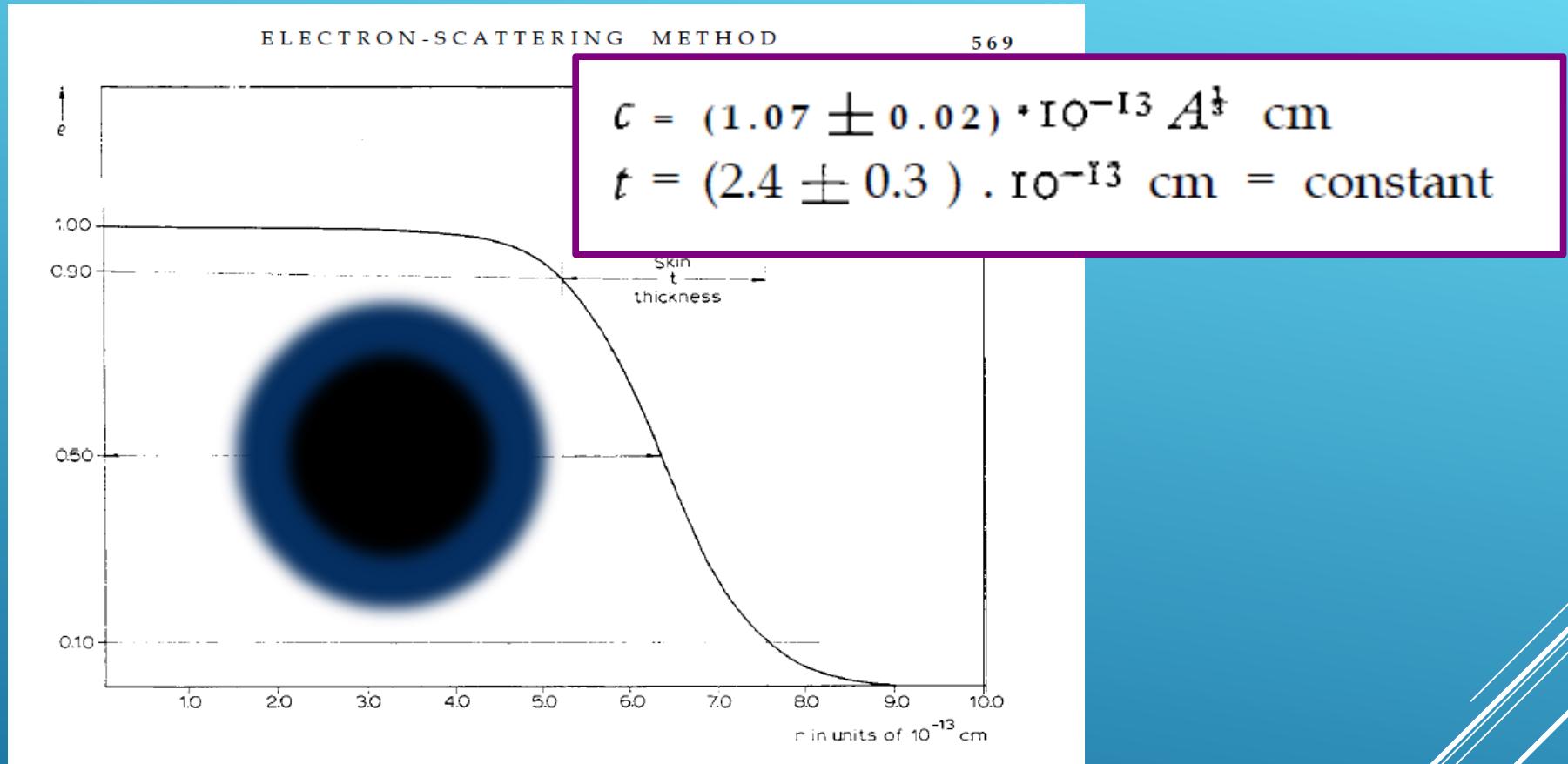
Introduction to Diffraction
Lévy Expansion in a Nut-shell: a new imaging method
TOTEM p+p @ 7 és 13 TeV
p+p @ 23, 30, 45, 53, 62 GeV
Comparison of pp and p-antip
Odderon

Expect the unexpected: structures in protons

[arxiv:1807.02897](https://arxiv.org/abs/1807.02897)

+ manuscript in preparation

DIFFRACTION: WHAT HAVE WE LEARNED?



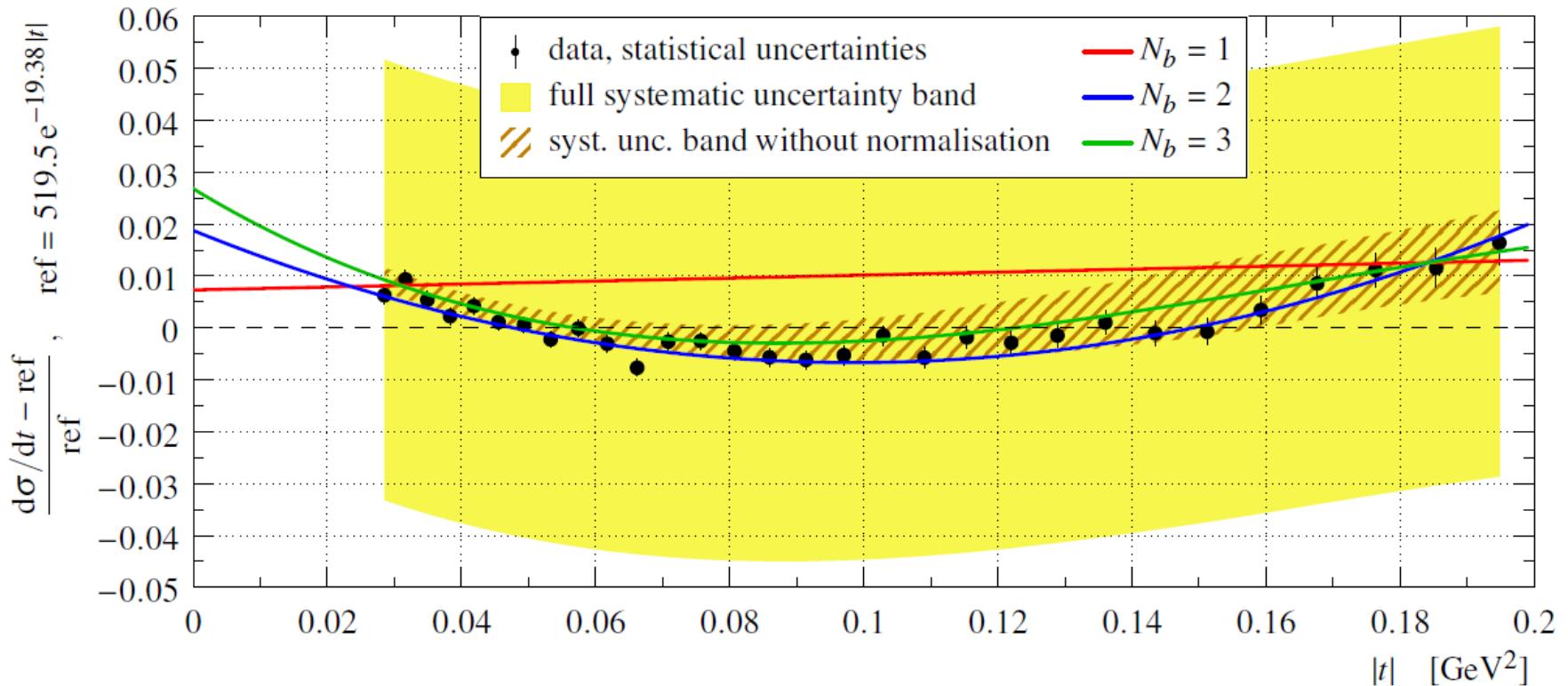
Volume V of spherical nuclei $\sim A$ (mass number)
Nuclear „skin-width“ is independent of A
→ Central density of big spherical nuclei is independent of A
R. Hofstadter, Nobel-lecture (1961)

TOTEM pp @ 8 TeV, arxiv:1503.08111

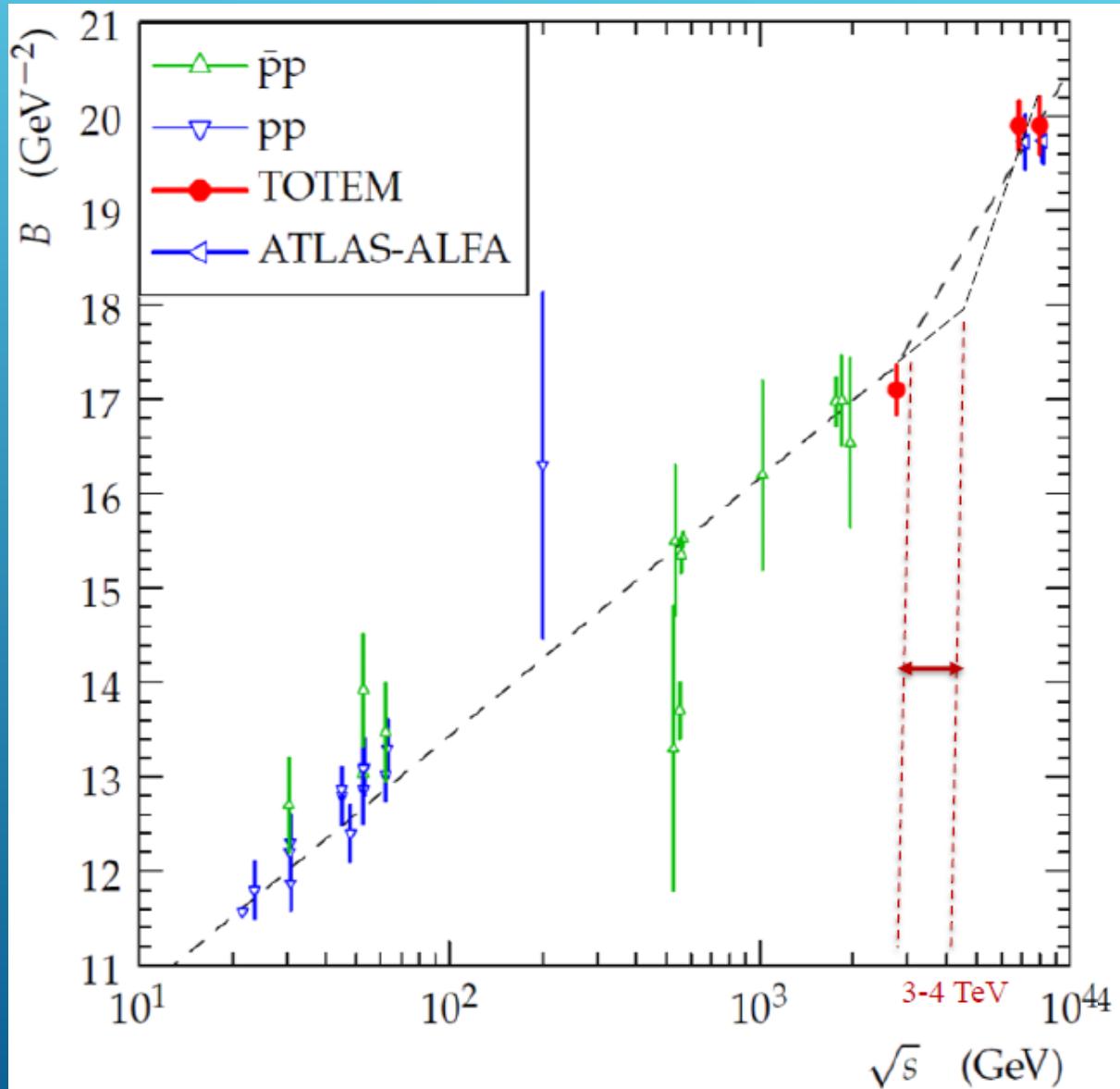
$d\sigma/dt$ non-exponential at low- t

Table 4: Fit quality measures for fits in Figure 11.

N_b	χ^2/ndf	p-value	significance
1	$117.5/28 = 4.20$	$6.1 \cdot 10^{-13}$	7.2σ
2	$29.3/27 = 1.09$	0.35	0.94σ
3	$25.5/26 = 0.98$	0.49	0.69σ



TOTEM preliminary at $\sqrt{s} = 13$ TeV



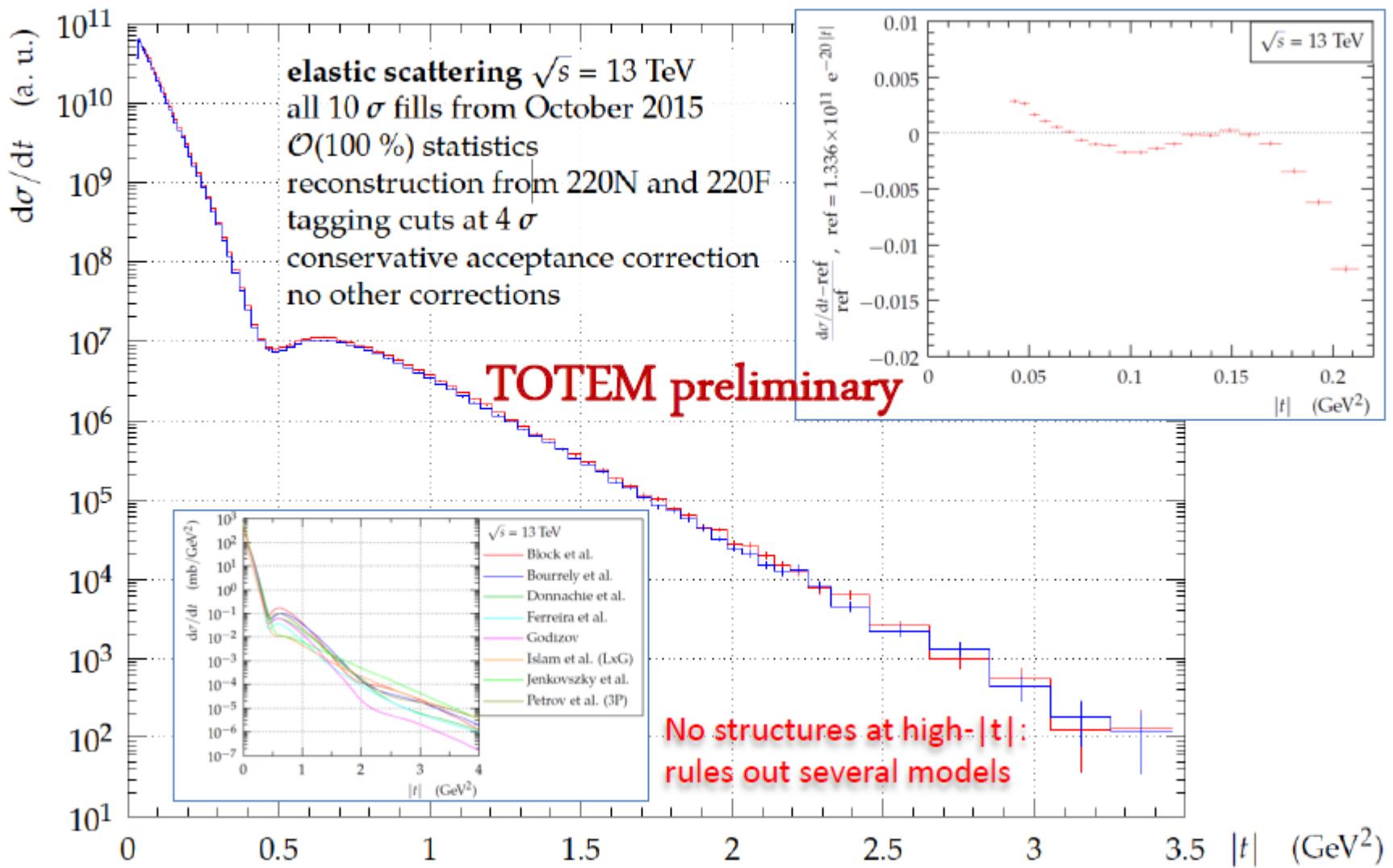
Growth of B: Universal properties of Pomeron

B(s) nearly jumps: Opening of an additional physics channel(?) from TOTEM preliminary 2.76 and 13 TeV

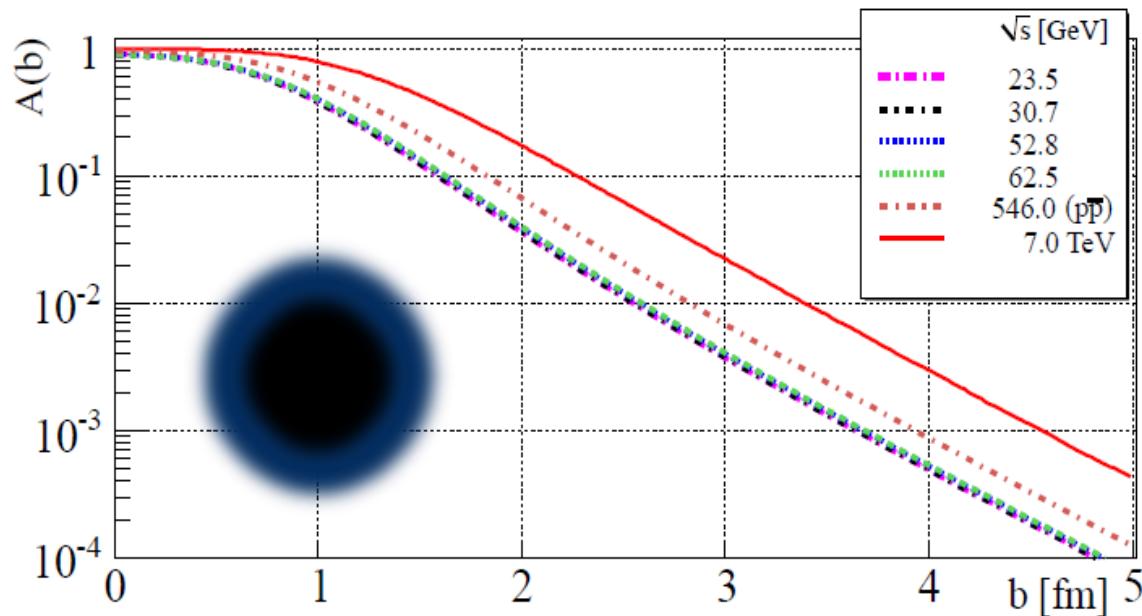
threshold \leq 3-4 TeV
followed by
very sharp growth:

TOTEM preliminary, $\sqrt{s} = 13$ TeV

- Large amount of data (trigger rate 50x w.r.t. Run I)



SATURATION FROM SHADOW PROFILES



at 7 TeV, proton

**Blacker, but
not Edgier,
and Larger**

BEL \rightarrow BnEL effect

[arxiv:1311.2308](https://arxiv.org/abs/1311.2308)

F. Nemes, T. Cs, M. Csanad

$$A(b) = 1 - |e^{-\Omega(b)}|^2$$

ISR and SppS:
R.J. Glauber and J. Velasco
Phys. Lett. B147 (1987) 380
 b_1, b_2 fixed

apparent saturation:
center of proton \sim black
at LHC, up to
 $r \sim 0.7$ fm

see also Lipari and Lusignoli,
[arXiv:1305.7216](https://arxiv.org/abs/1305.7216)

MODEL INDEPENDENT LEVY EXPANSION

$$\frac{d\sigma}{dt} = A w(z|\alpha) \left| 1 + \sum_{j=1}^{\infty} c_j l_j(z|\alpha) \right|^2,$$

$w(z|\alpha) = \exp(-z^\alpha)$, **non-exponential behavior (NEB) in a single parameter**

$$z = |t|R^2 \geq 0, \quad \alpha$$

idea: complete set of orthonormal functions, put NEB to the weight

$$l_j(z|\alpha) = D_j^{-\frac{1}{2}} D_{j+1}^{-\frac{1}{2}} L_j(z|\alpha),$$

$$D_0(\alpha) = 1,$$

$$D_1(\alpha) = \mu_{0,\alpha},$$

$$D_2(\alpha) = \det \begin{pmatrix} \mu_{0,\alpha} & \mu_{1,\alpha} \\ \mu_{1,\alpha} & \mu_{2,\alpha} \end{pmatrix},$$

$$D_3(\alpha) = \det \begin{pmatrix} \mu_{0,\alpha} & \mu_{1,\alpha} & \mu_{2,\alpha} \\ \mu_{1,\alpha} & \mu_{2,\alpha} & \mu_{3,\alpha} \\ \mu_{2,\alpha} & \mu_{3,\alpha} & \mu_{4,\alpha} \end{pmatrix},$$

$$\int_0^\infty dz \exp(-z^\alpha) l_n(z|\alpha) l_m(z|\alpha) = \delta_{n,m}$$

$$\mu_{n,\alpha} = \int_0^\infty dz z^n \exp(-z^\alpha) = \frac{1}{\alpha} \Gamma\left(\frac{n+1}{\alpha}\right)$$

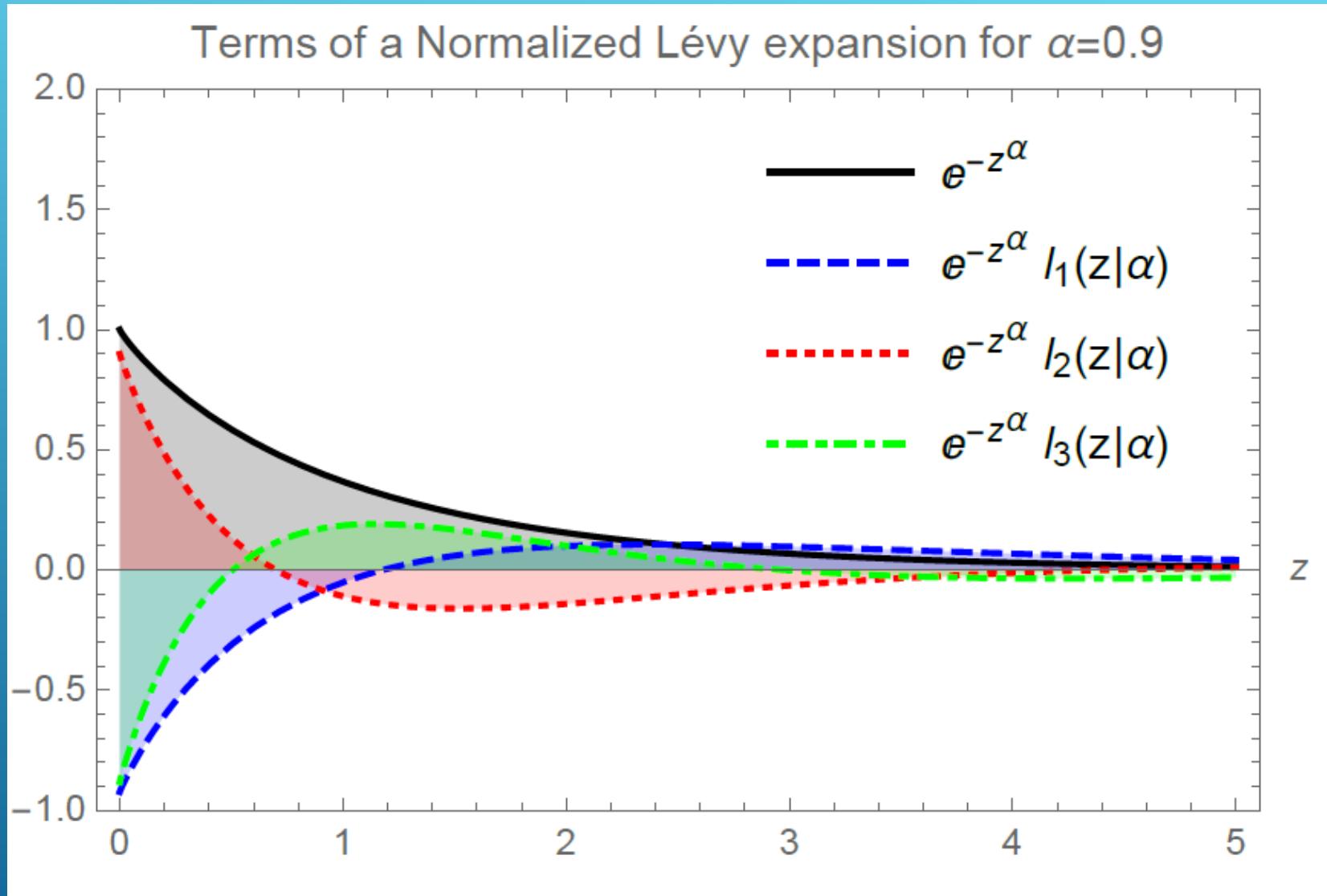
$L_0(z|\alpha) = 1$, **T. Csörgő, R. Pasechnik, A. Ster,
arxiv.org:1807.02897**

$$L_1(z|\alpha) = \det \begin{pmatrix} \mu_{0,\alpha} & \mu_{1,\alpha} \\ 1 & z \end{pmatrix},$$

$$L_2(z|\alpha) = \det \begin{pmatrix} \mu_{0,\alpha} & \mu_{1,\alpha} & \mu_{2,\alpha} \\ \mu_{1,\alpha} & \mu_{2,\alpha} & \mu_{3,\alpha} \\ 1 & z & z^2 \end{pmatrix},$$

$$L_3(z|\alpha) = \det \begin{pmatrix} \mu_{0,\alpha} & \mu_{1,\alpha} & \mu_{2,\alpha} & \mu_{3,\alpha} \\ \mu_{1,\alpha} & \mu_{2,\alpha} & \mu_{3,\alpha} & \mu_{4,\alpha} \\ \mu_{2,\alpha} & \mu_{3,\alpha} & \mu_{4,\alpha} & \mu_{5,\alpha} \\ 1 & z & z^2 & z^3 \end{pmatrix},$$

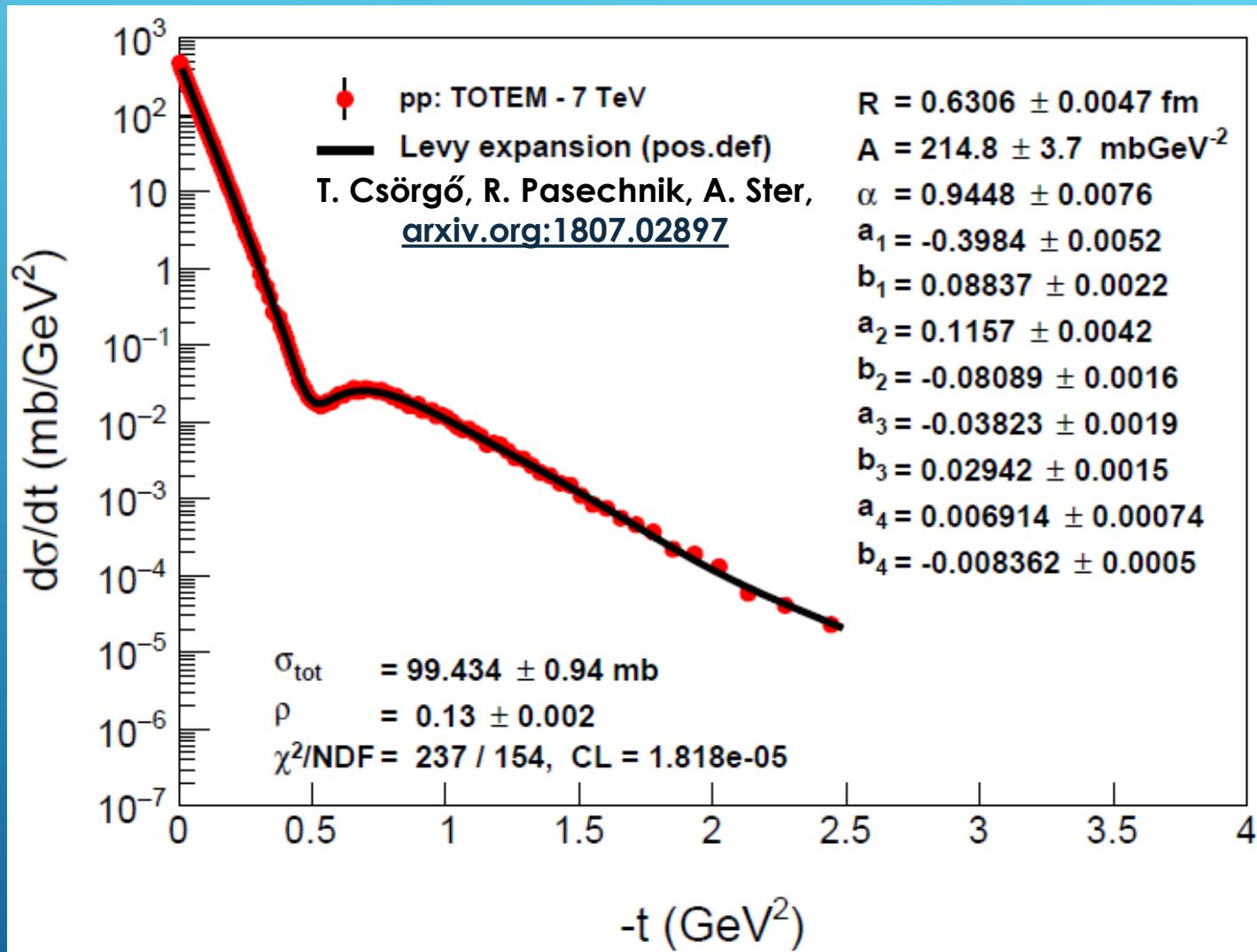
MODEL INDEPENDENT LEVY EXPANSION



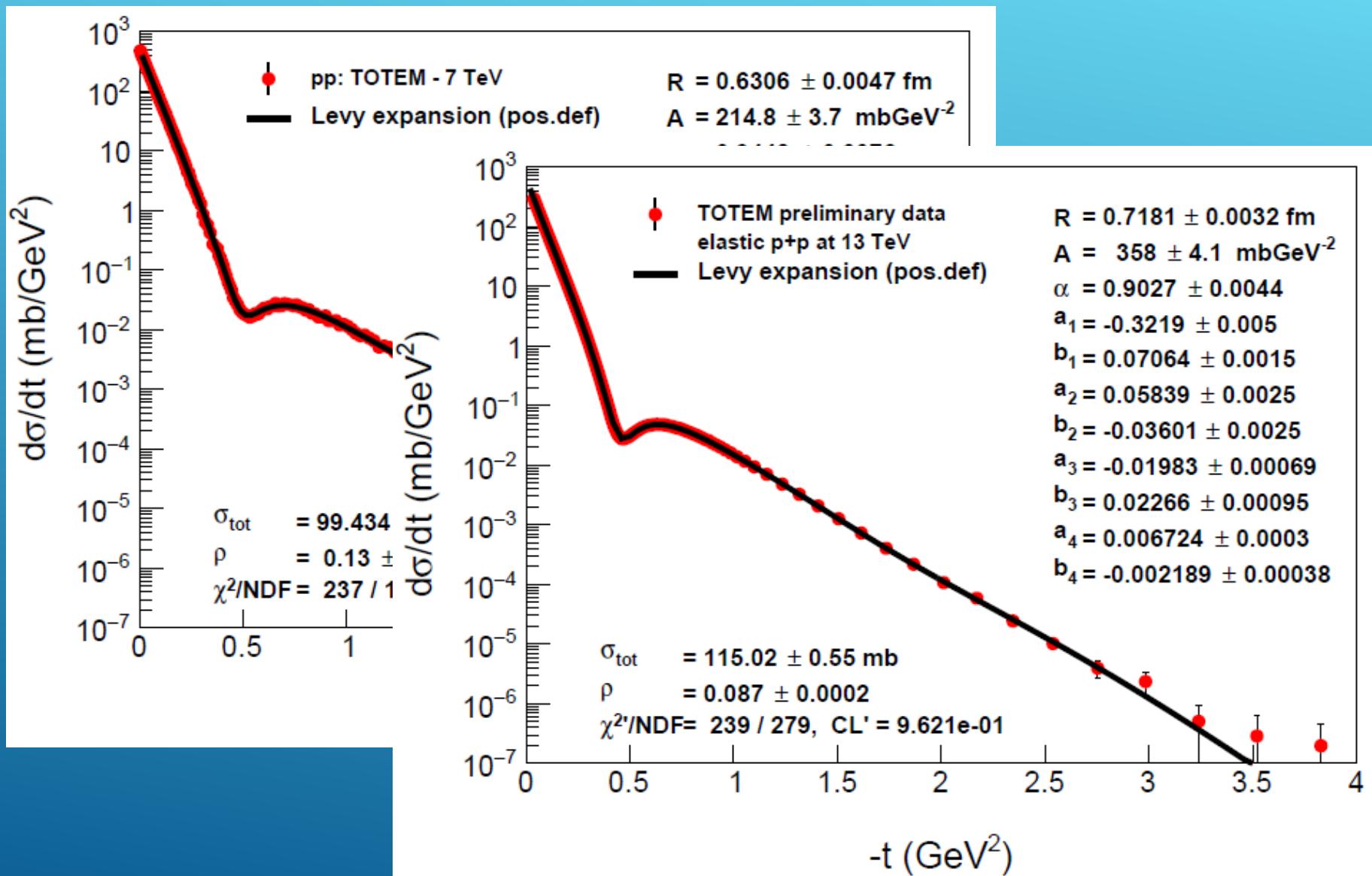
As $\alpha \rightarrow 1$, Levy polynomials approach Laguerre polynomials, orthonormal to $\exp(-t)$

T. Csörgő, T. Novák and A. Ster,
arXiv:1604.05513 [physics.data-an]

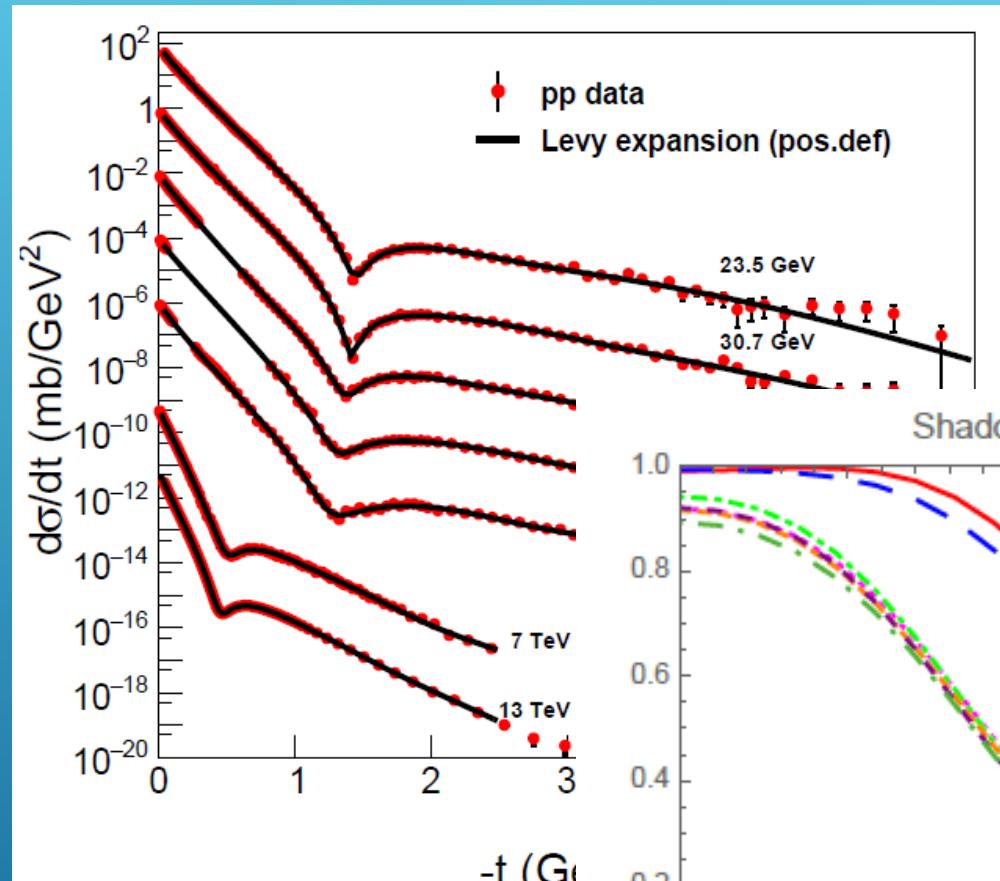
MODEL INDEPENDENT LEVY EXPANSION



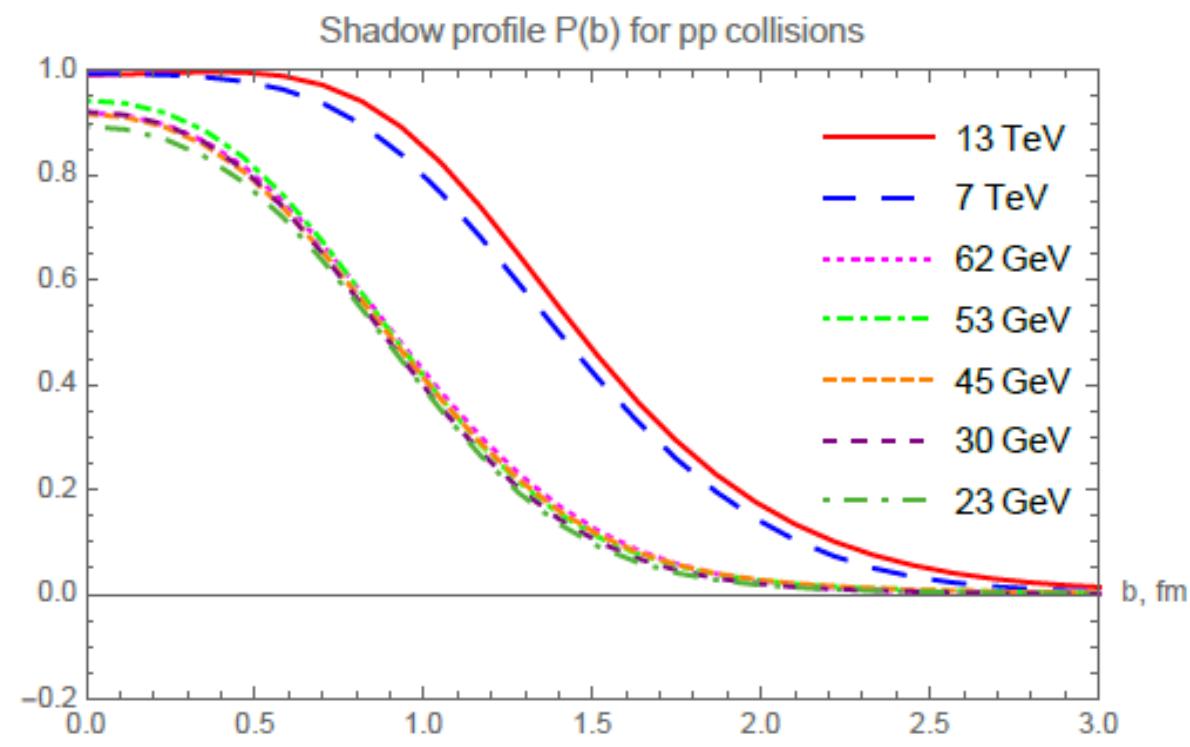
LEVY EXPANSION AT LHC ENERGIES



IMAGING AT ISR AND AT LHC ENERGIES



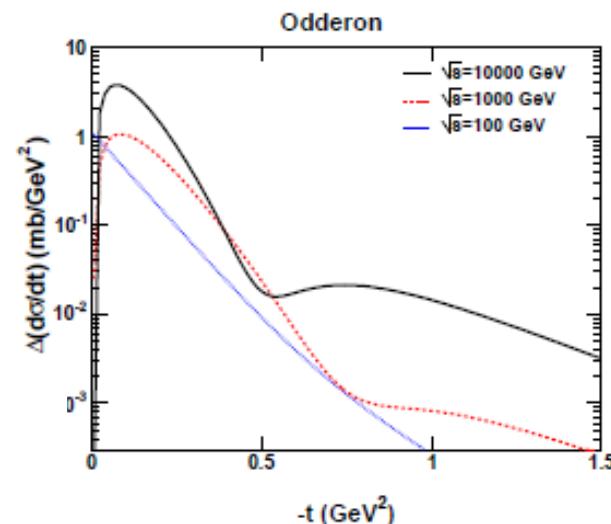
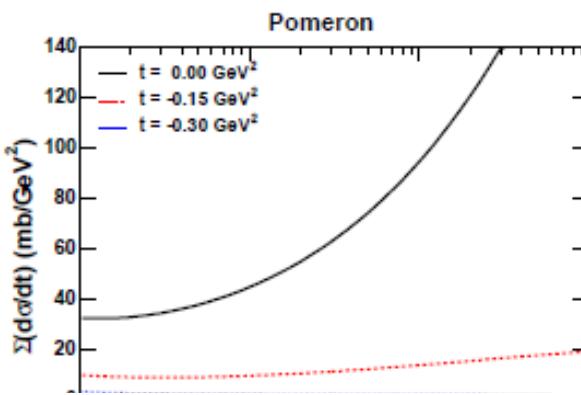
PP: PROTON+PROTON



LOOKING FOR ODDERON EFFECTS

Odderon

Odderon
ppbar
A. Ster,



⁷A. P. Samokhin and V. A. Petrov, Nucl. Phys. A **974**, 45 (2018) [arXiv:1708.02879 [hep-ph]].

⁸V. A. Khoze, A. D. Martin and M. G. Ryskin, Phys. Rev. D **97**, no. 3, 034019 (2018) [arXiv:1712.00325 [hep-ph]].

⁹V. A. Petrov, Eur. Phys. J. C **78**, no. 3, 221 (2018) Erratum: [Eur. Phys. J. C **78**, no. 5, 414 (2018)] [arXiv:1801.01815 [hep-ph]].

¹⁰V. A. Khoze, A. D. Martin and M. G. Ryskin, Phys. Lett. B **780**, 352 (2018) [arXiv:1801.07065 [hep-ph]].

¹¹V. P. Gonçalves and B. D. Moreira, Phys. Rev. D **97**, no. 9, 094009 (2018) [arXiv:1801.10501 [hep-ph]].

¹²Y. M. Shabelski and A. G. Shuvaev, Eur. Phys. J. C **78**, no. 6, 497 (2018) [arXiv:1802.02812 [hep-ph]].

¹³M. Broilo, E. G. S. Luna and M. J. Menon, arXiv:1803.06560 [hep-ph].

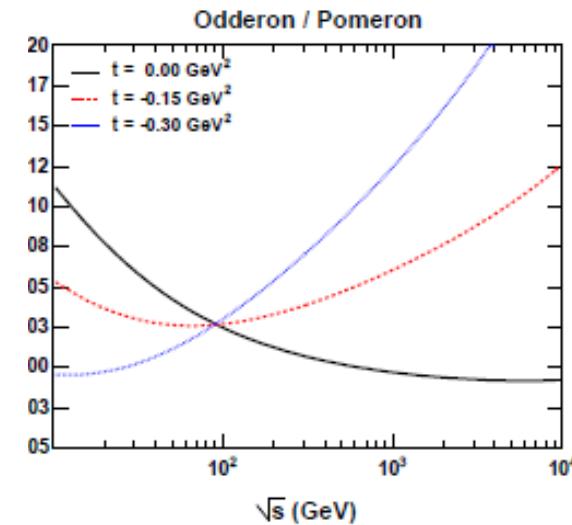
¹⁴M. Broilo, E. G. S. Luna and M. J. Menon, Phys. Lett. B **781**, 616 (2018) [arXiv:1803.07167 [hep-ph]].

¹⁵P. Lebiedowicz, O. Nachtmann and A. Szczurek, arXiv:1804.04706 [hep-ph].

¹⁶E. Martynov and B. Nicolescu, arXiv:1804.10139 [hep-ph].

¹⁷S. M. Troshin and N. E. Tyurin, arXiv:1805.05161 [hep-ph].

¹⁸I. M. Dremin, Universe **4**, no. 5, 65 (2018).

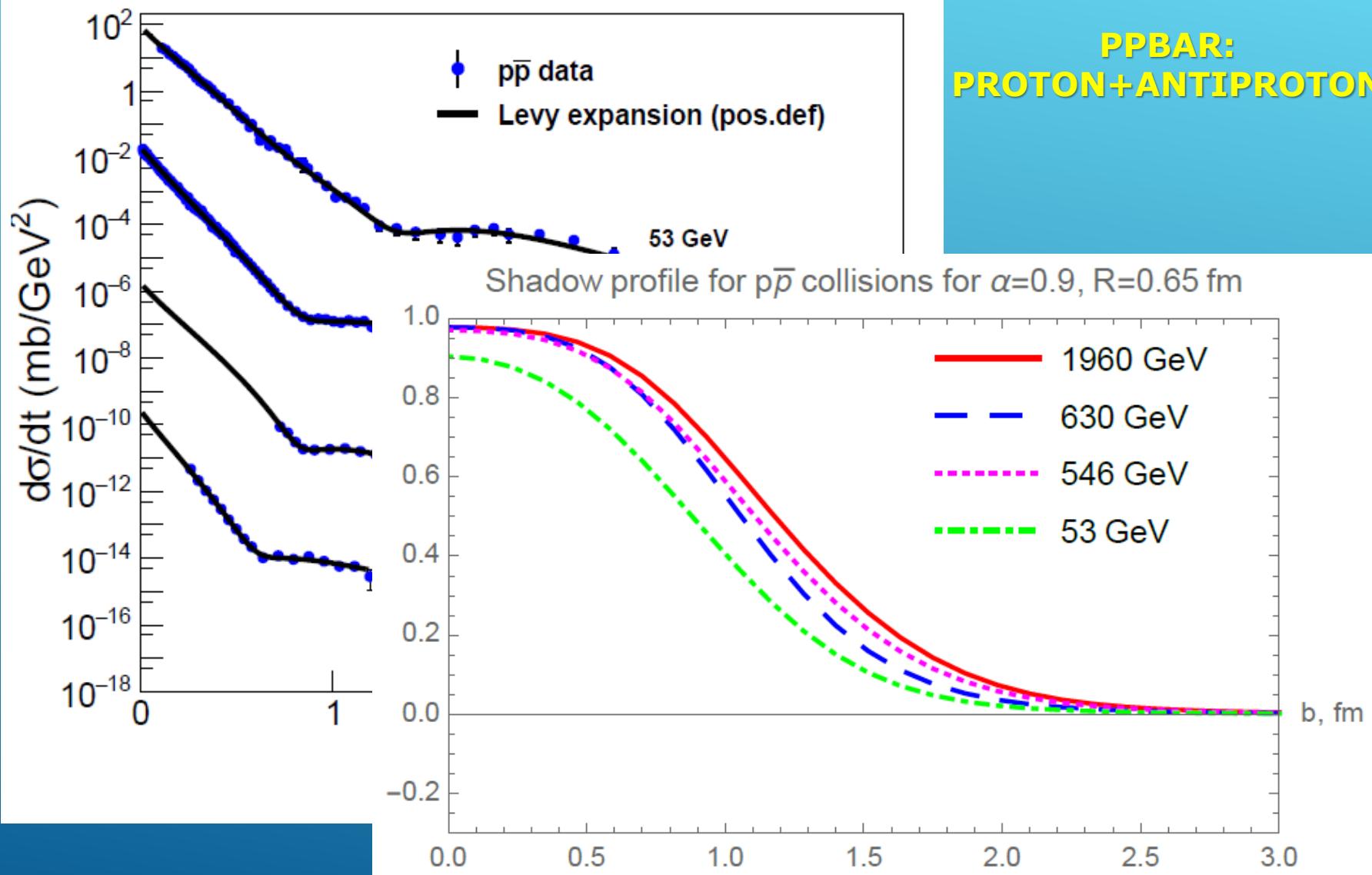


f the $d\sigma/dt$ cross sections calculated from the

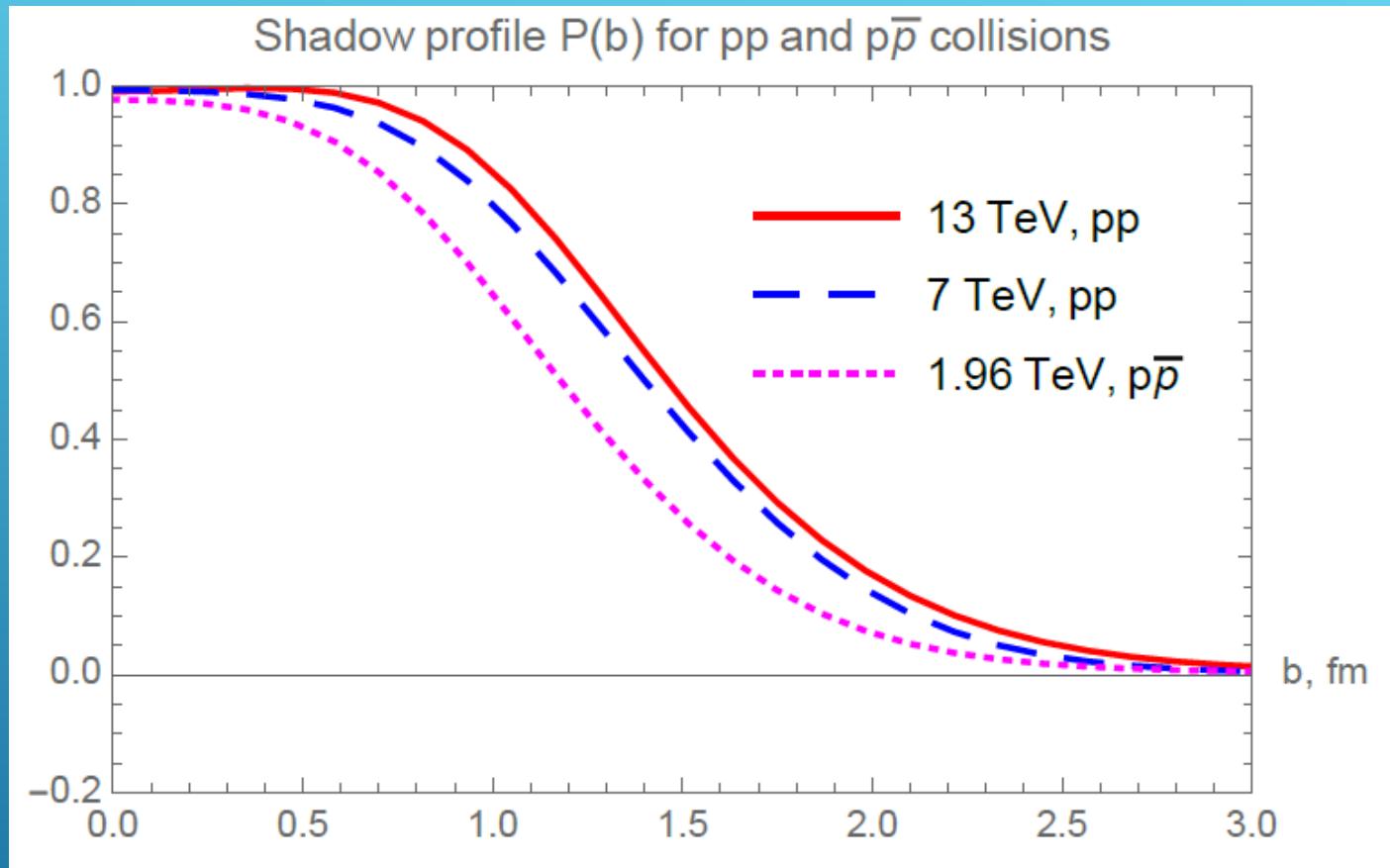
$\| \mathcal{A}_{pp}^2 + |\mathcal{A}|_{pp}^2 = \Sigma_{Pom}$ fitted to the data.

LEVY EXPANSION FOR ELASTIC PPBAR

PPBAR:
PROTON+ANTIPROTON

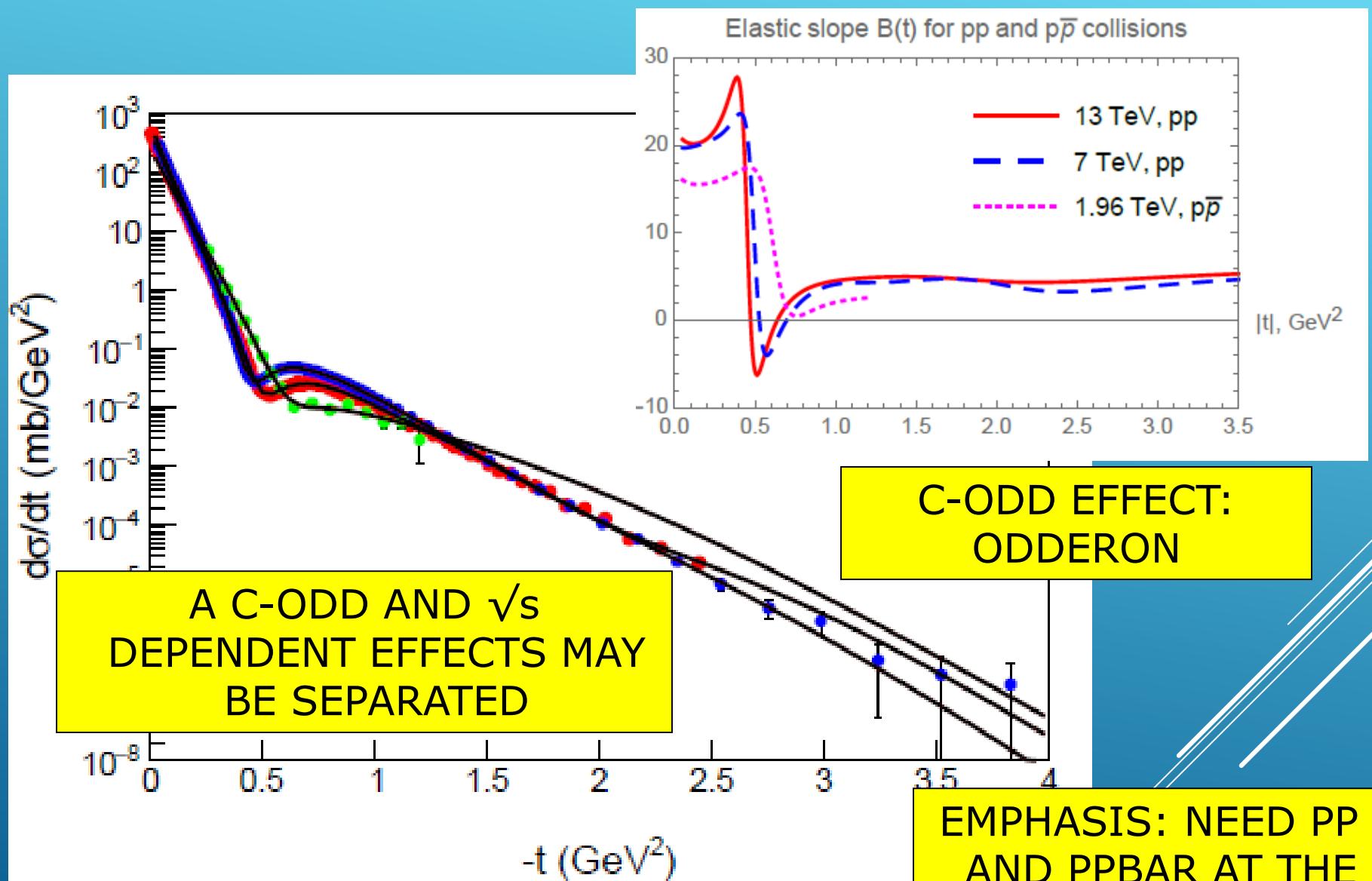


COMPARISON : (P,P) vs (P,ANTIP)

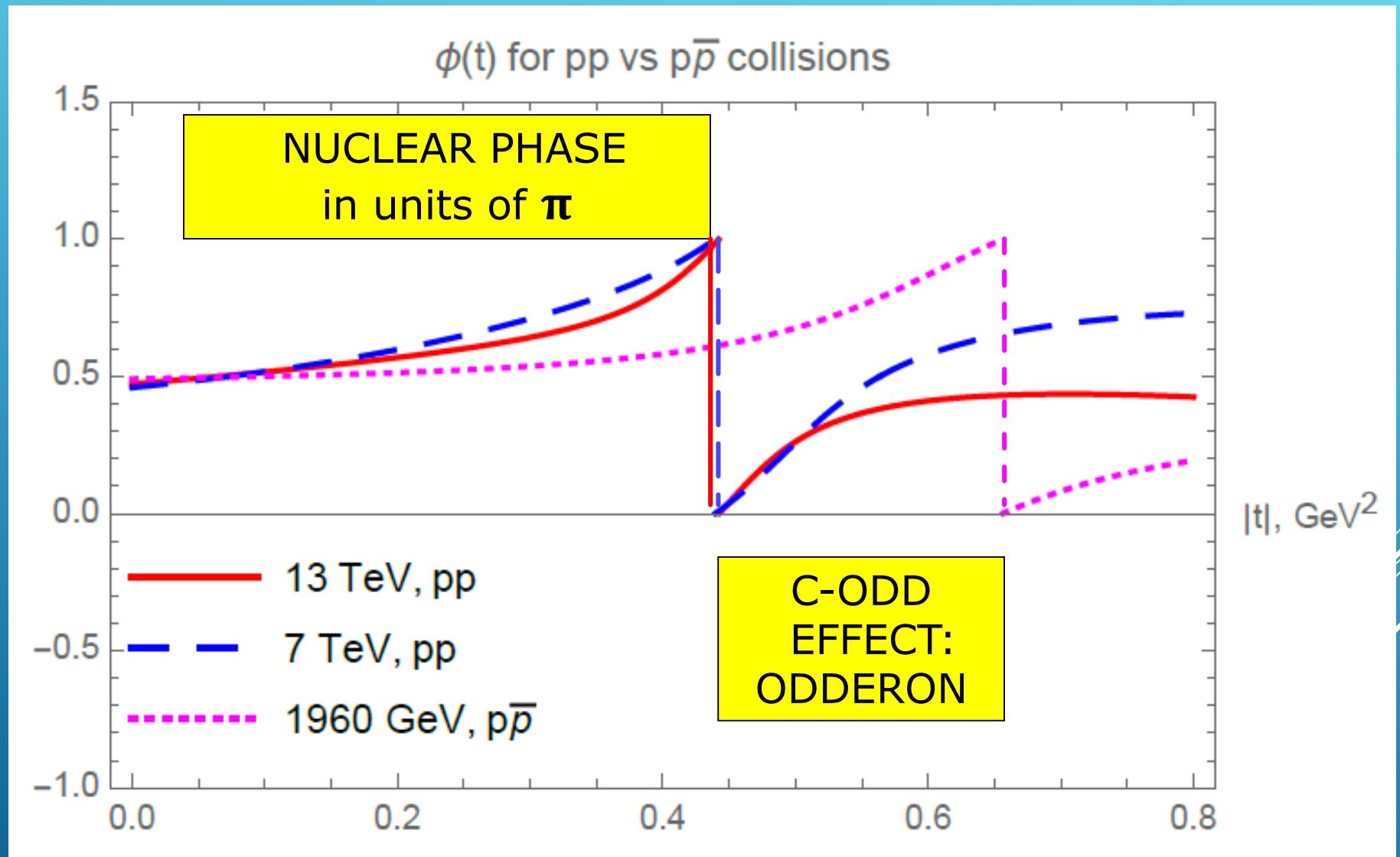


SHADOW PROFILES:
C-ODD AND ENERGY DEPENDENT
EFFECTS MAY BE MIXED
TOGETHER

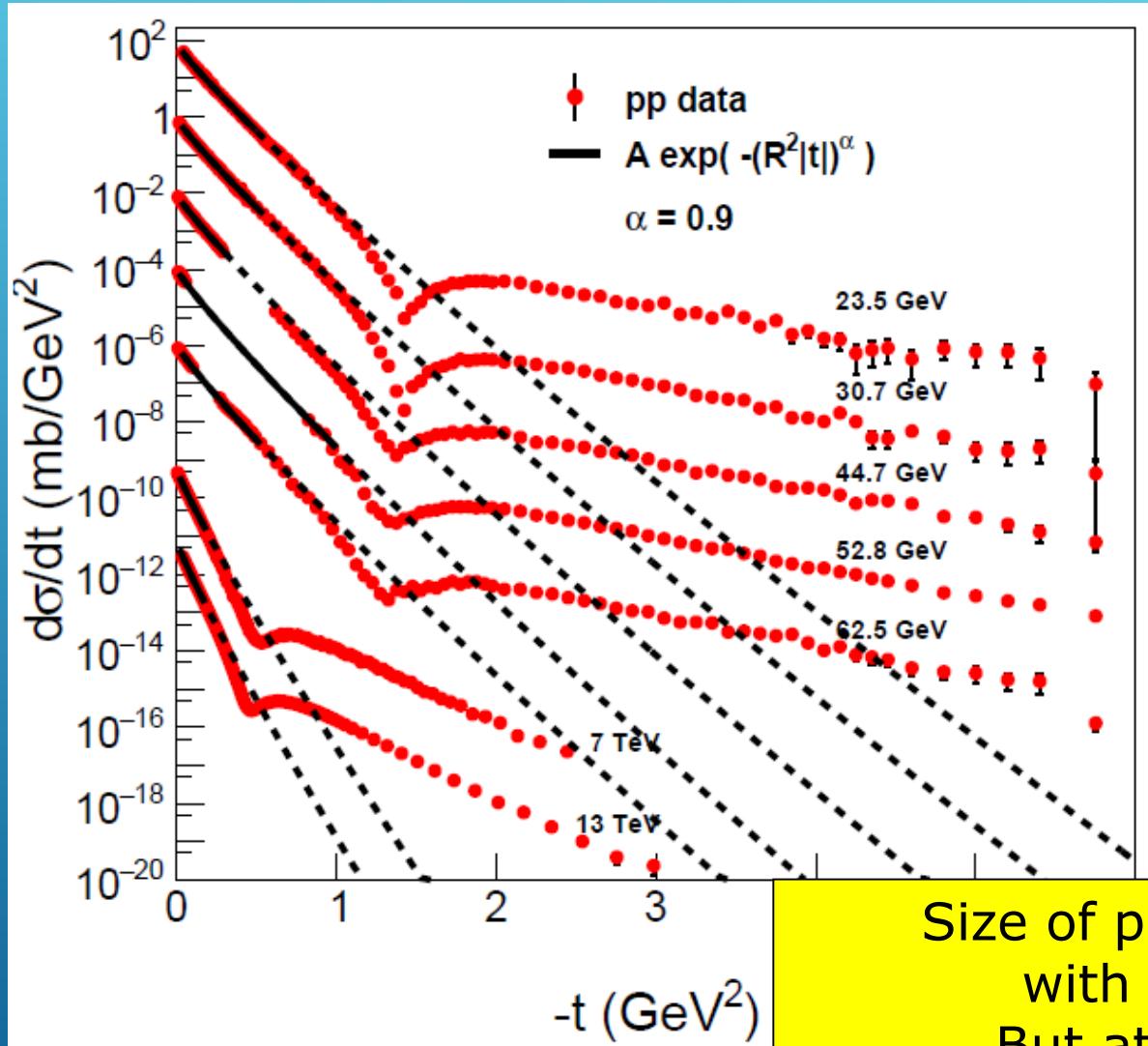
COMPARISON: (P,P) vs (P,ANTIP)



COMPARISON : (P,P) vs (P,ANTIP)

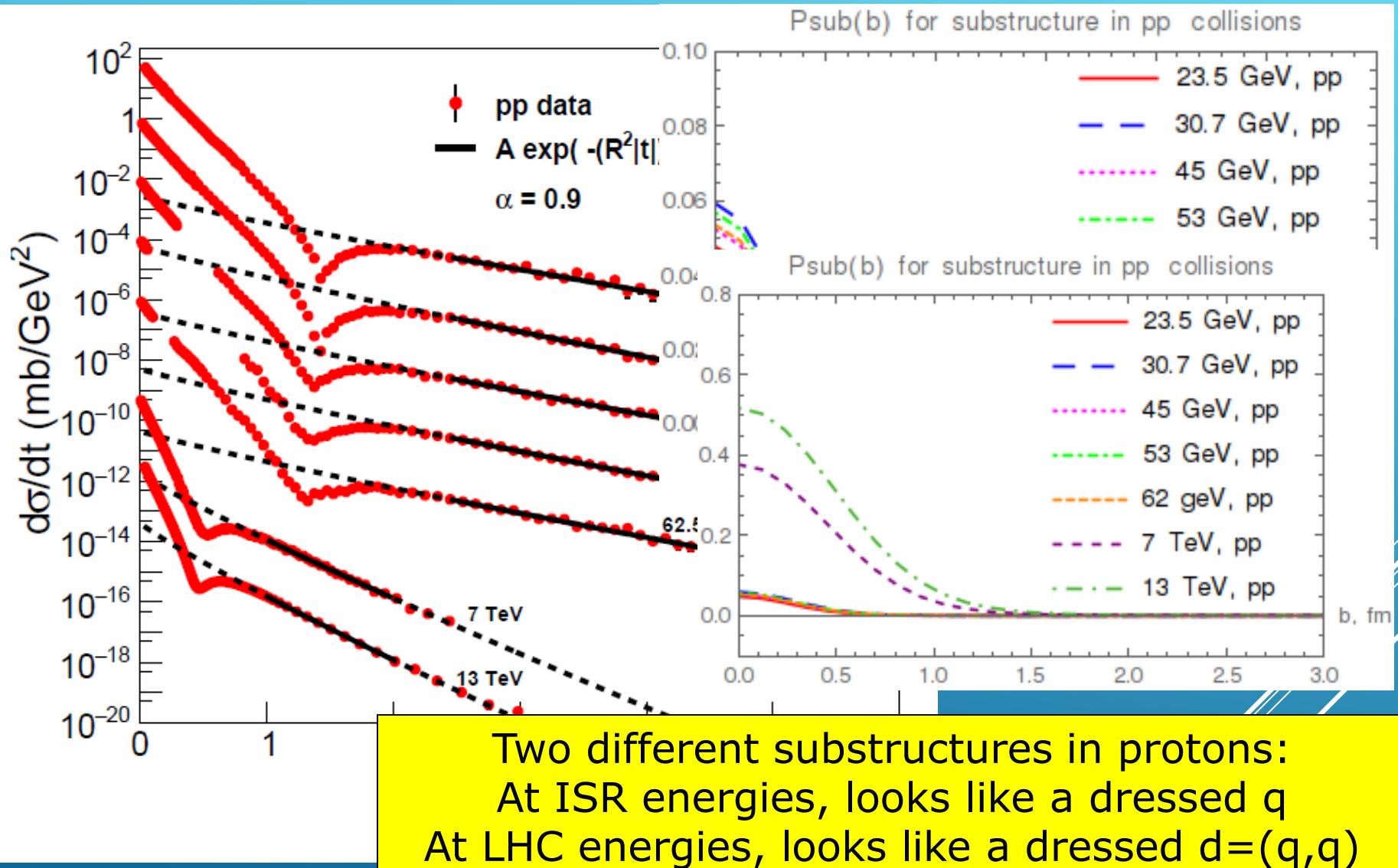


LEVY FITS: APPROXIMATE STRUCTURE



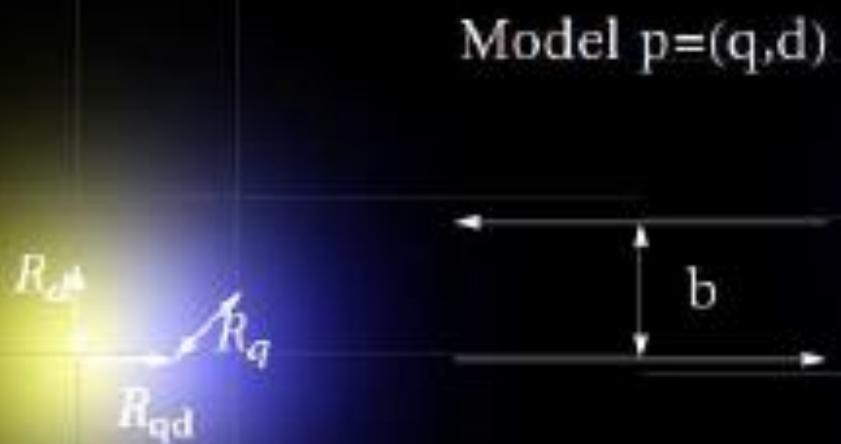
Size of proton is increasing
with increasing \sqrt{s} :
But at LHC energies,
the shape of proton changes too!

LEVY FITS TO LARGE $-t$: SUBSTRUCTURES

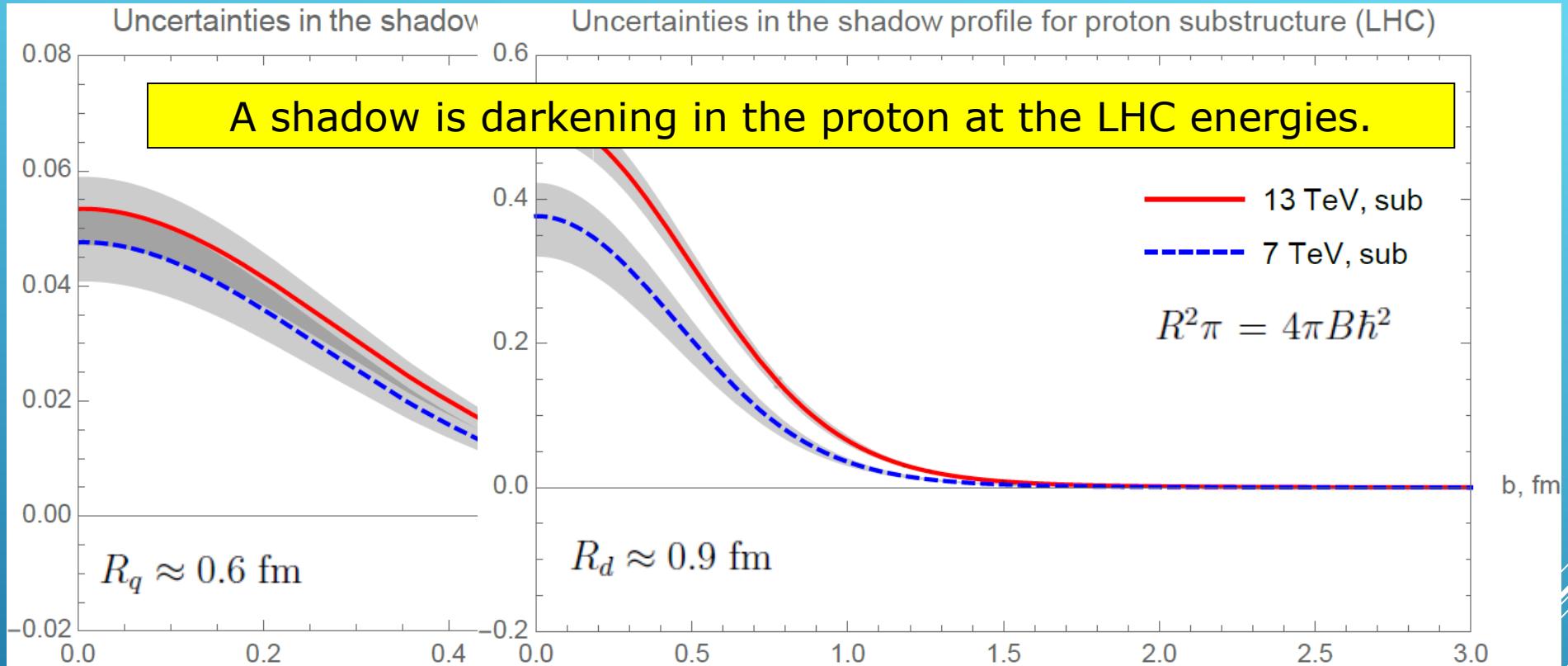


First suggested by I. M. Dremin,
Universe 4 (2018) no.5, 65

LEVY FITS TO LARGE -t: SUBSTRUCTURES



Systematic uncertainties

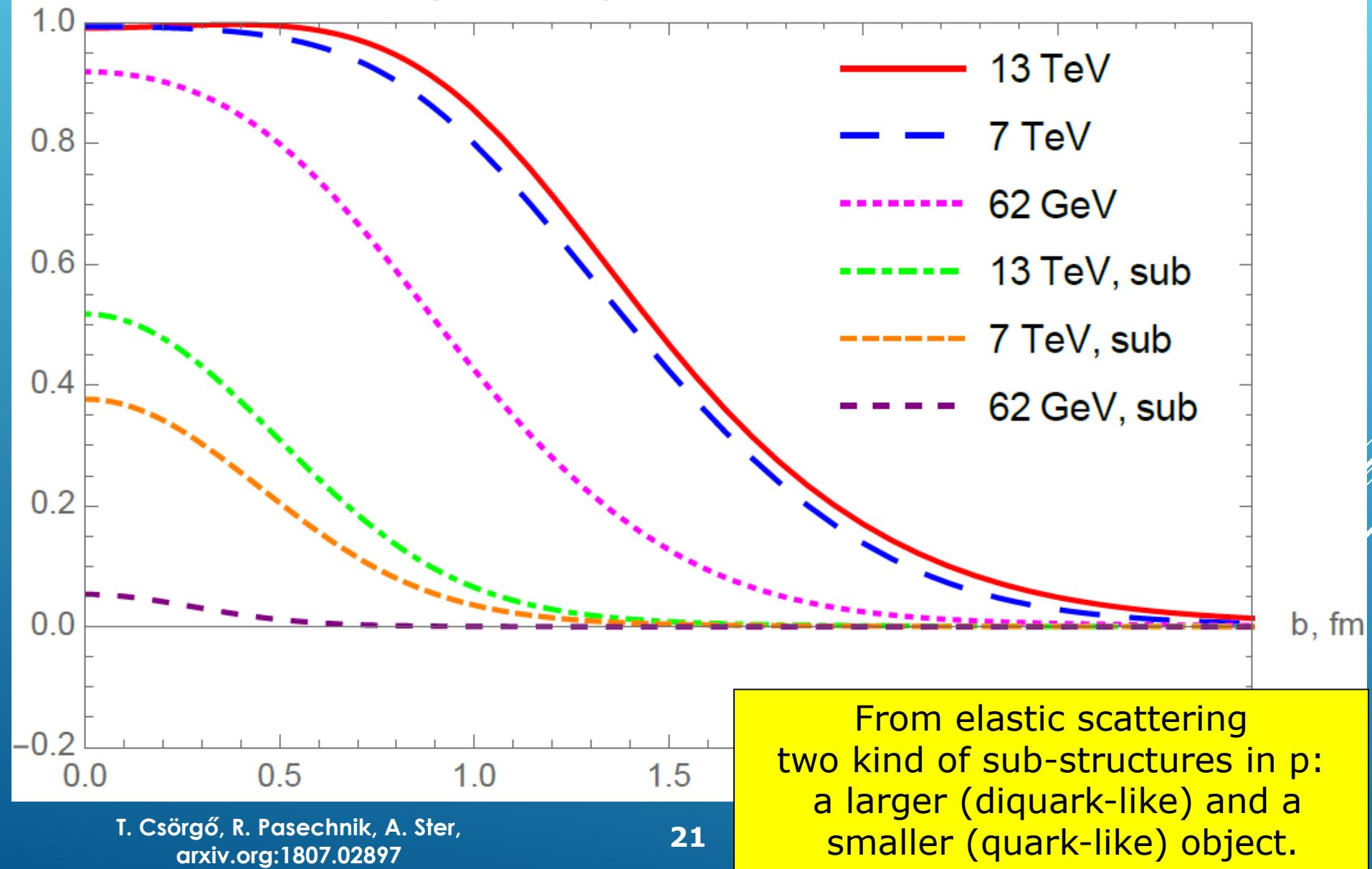


The shadow profile for the substructures in the proton are within errors the same from 23 to 62 GeV at ISR: the same object is seen, within errors.

The shadow profile for the substructures in the proton are within errors DIFFERENT from 7 to 13 TeV at LHC: the same size, but its shadow is getting darker.

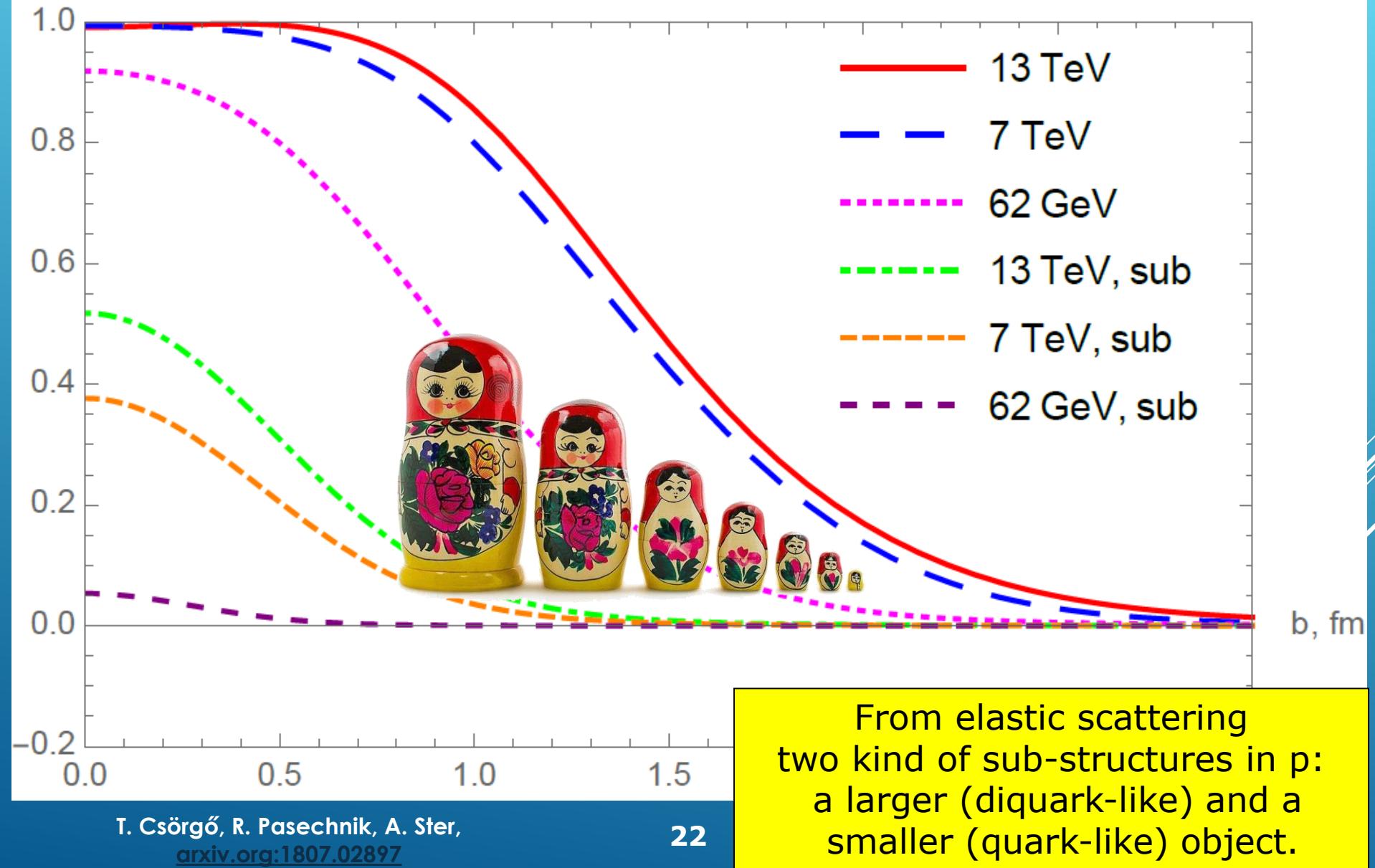
$P = (q, d)$

Shadow profile for proton and its substructure



$P = (q, d)$

Shadow profile for proton and its substructure



SUMMARY

At LHC energies the proton becomes
Blacker, but not Edgier, and Larger: BnEL effect
p not only grows with \sqrt{s} , but its shape also changes

Looking for possible Odderon effects ...
**We identified two model-independent
ODDERON signals in TOTEM data**

Bonus extra: evidence for substructures inside proton
strikingly similar to dressed quark and diquarks

$$\mathbf{P}=(\mathbf{q},\mathbf{d})$$

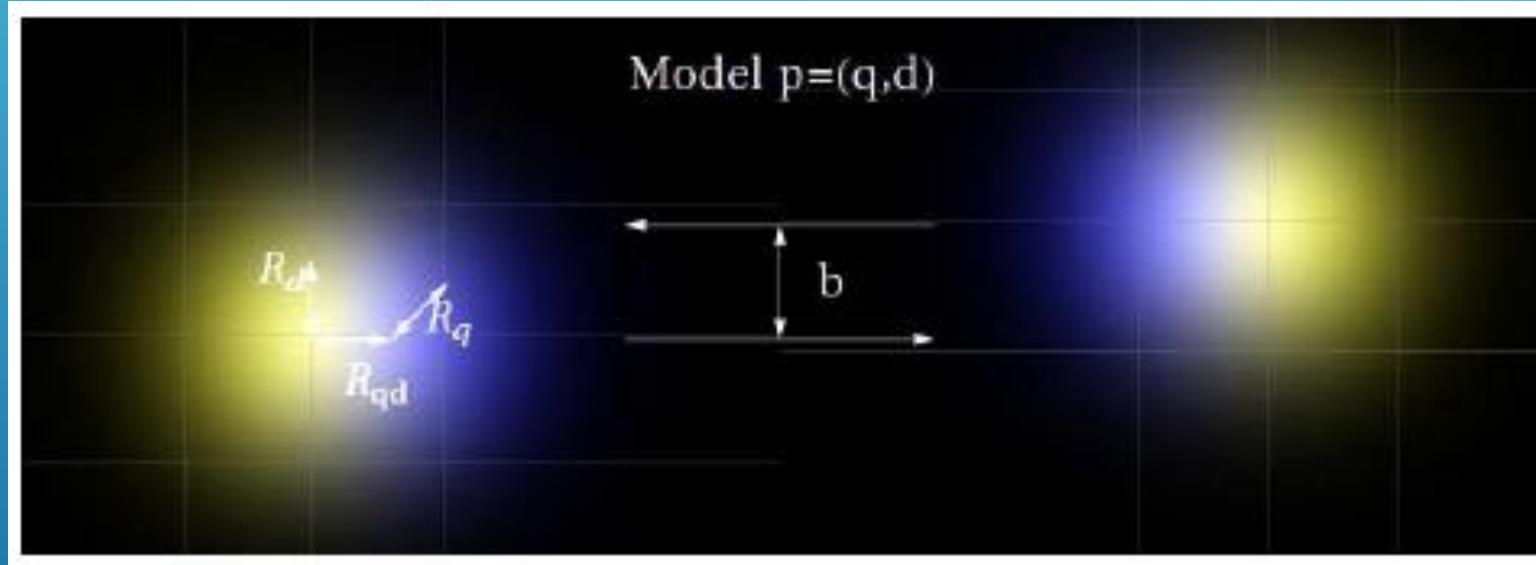
We measured two substructure **sizes**,

$$R_{\text{sub}}(\text{ISR}) < R_{\text{sub}}(\text{LHC})$$

If these are **different substructures**, **B(s) may jump !**

If these are the **same**: growig gluon cloud, **B(s) may be smooth**

THANK YOU FOR YOUR ATTENTION!



Questions?

POSSIBLE ALTERNATIVES: $P = (q, q, q)$?

$$d\sigma/dt \text{ (mb)}/(\text{GeV})^2$$

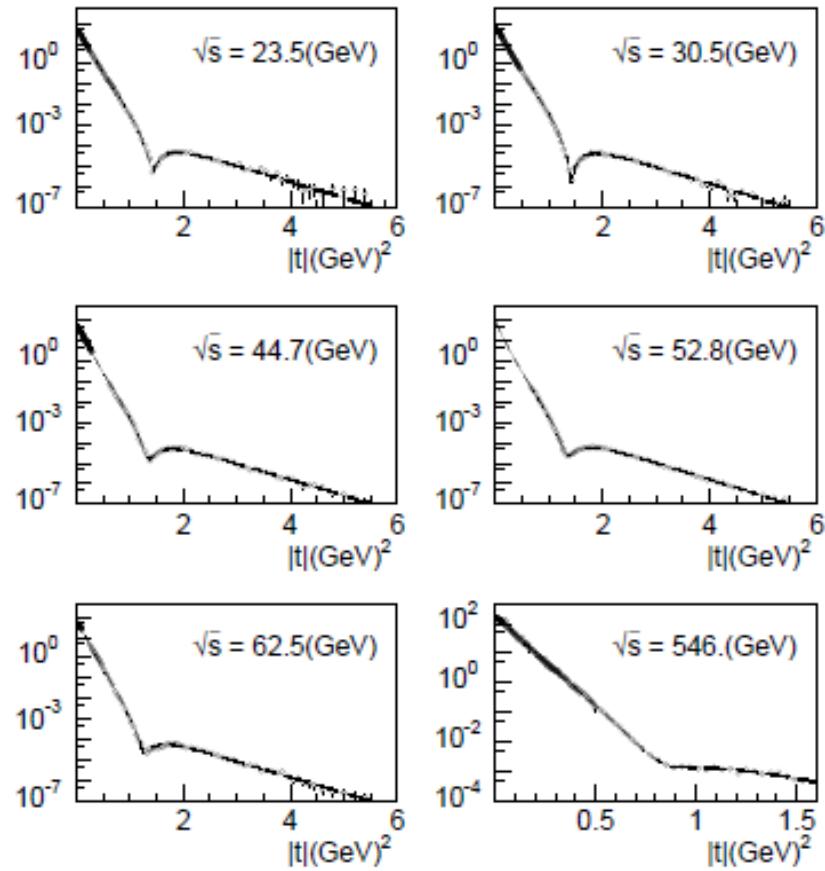


Figure 6: The differential cross sections of elastic pp and $p\bar{p}$ scattering at different energies. The first five panels show the pp data from ISR [29], the last one the pp data [45] from SppS. The curves show our fit Eqs. (27)-(29) in variant I.

Is this $p = (q, q, q)$ picture consistent with data at LHC?
Structures and oscillations in $d\sigma/dt$, jump in $B(s)$??

TABLE I: Predictions of Refs. 3-4 for the cross sections and elastic slopes at $\sqrt{s} = 7, 8$ and 14 TeV. Two values of the slope correspond to $t = 0$ and $t = -0.1 \text{ GeV}^2$ (in parentheses).

\sqrt{s}	$\sigma_{tot}^{pp} \text{ (mb)}$	$\sigma_{el}^{pp} \text{ (mb)}$	$B_{el} \text{ (GeV}^{-2})$
7 TeV	98.00	25.63	19.44 (19.82)
8 TeV	100.41	26.50	19.70 (20.19)
14 TeV	111.07	30.39	20.84 (21.92)

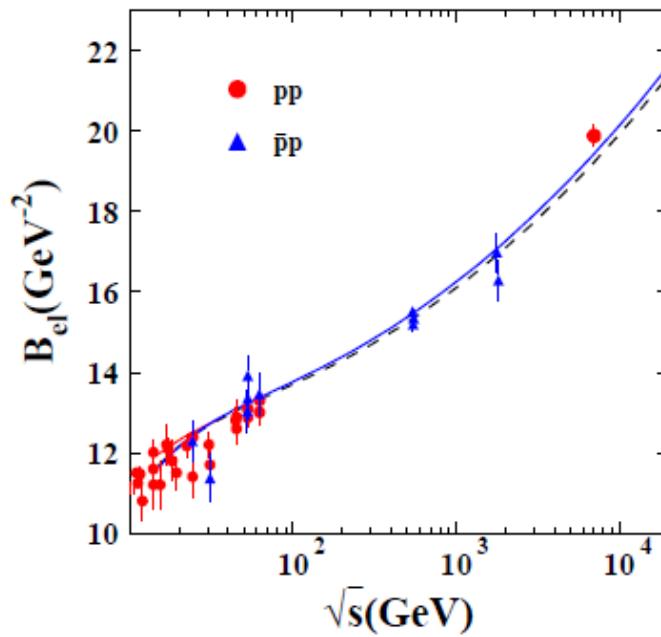
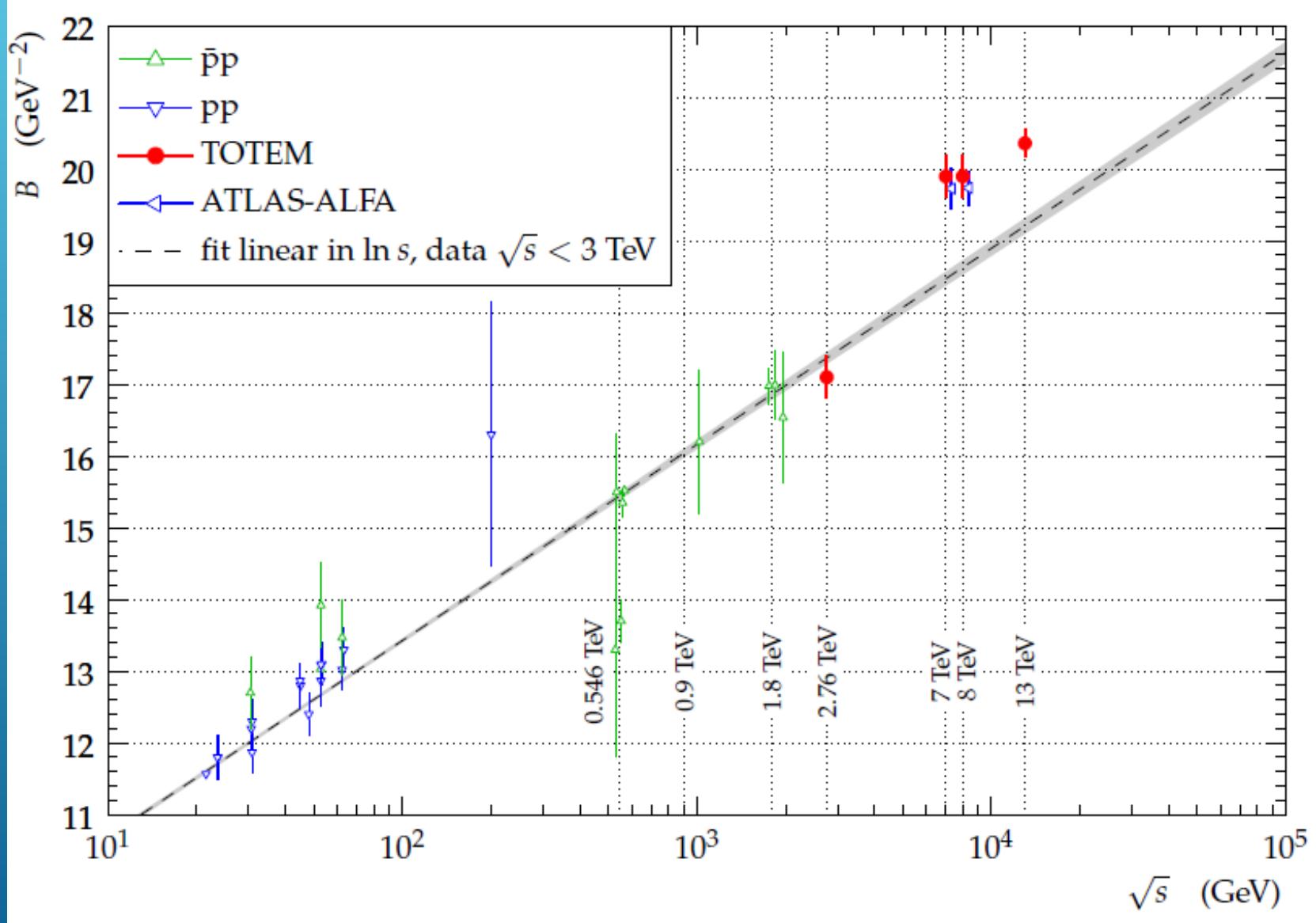


FIG. 5: (Color online) Elastic slope predicted at $t = 0$ in [3, 4] and measured by TOTEM [1, 2]. Dashed and solid curves show B_{el} , calculated excluding or including the real part of the amplitude, respectively.

POSSIBLE ALTERNATIVES: $P = (q,q,q)$?



Is this $p = (q,q,q)$ picture consistent with data at LHC?
Structures and oscillations in $d\sigma/dt$, jump in $B(s)$??

POSSIBLE ALTERNATIVES: $P = (q, q, q)$?

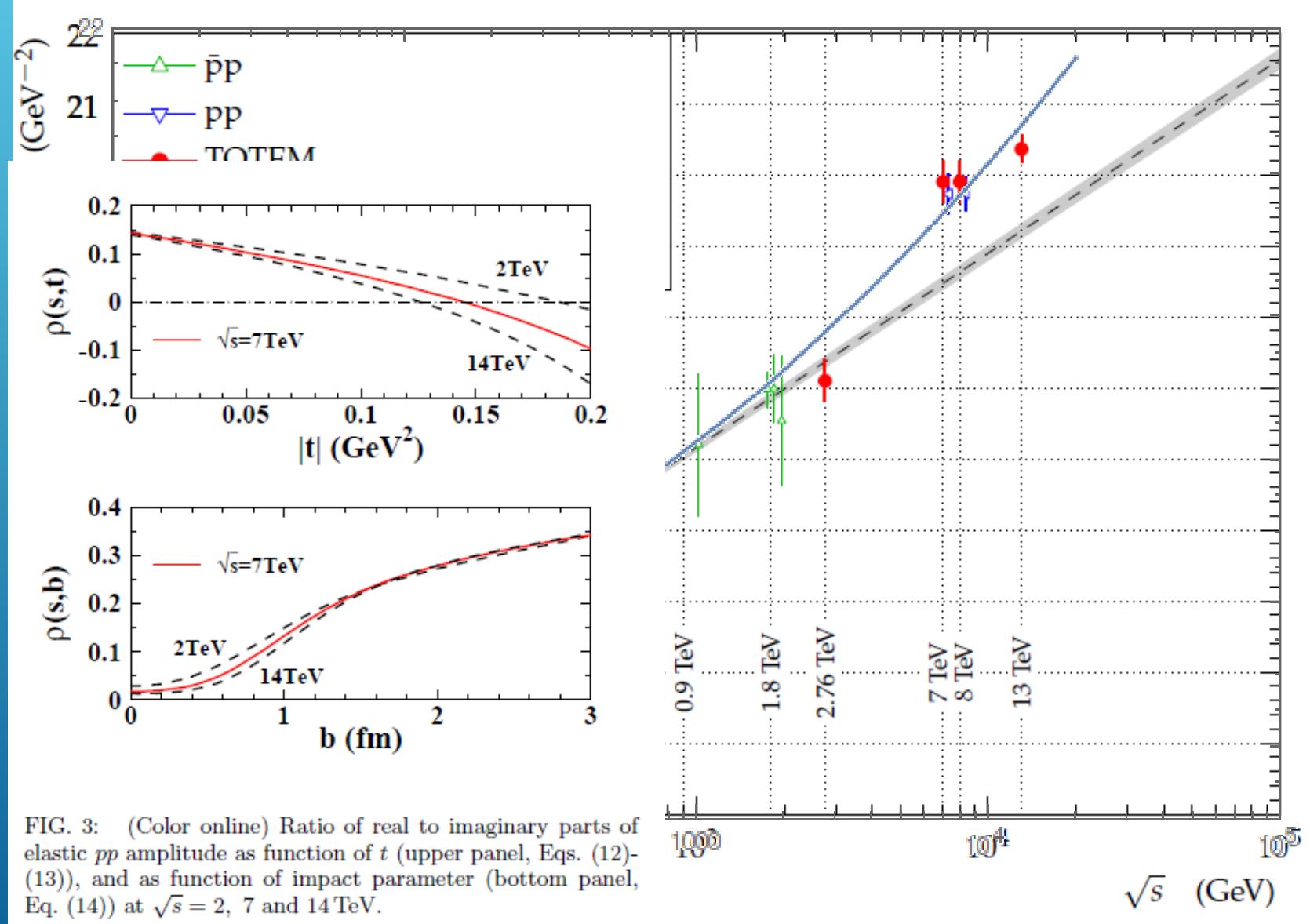


FIG. 3: (Color online) Ratio of real to imaginary parts of elastic pp amplitude as function of t (upper panel, Eqs. (12)-(13)), and as function of impact parameter (bottom panel, Eq. (14)) at $\sqrt{s} = 2, 7$ and 14 TeV.

Is this $p = (q, q, q)$ picture consistent with data at LHC?
 Structures and oscillations in $d\sigma/dt$, jump in $B(s)$??
 $B(2.76 \text{ TeV})$ overestimated (by 3 σ) BUT $\rho(13 \text{ TeV})$ by 6 σ

POSSIBLE ALTERNATIVES: $P = (q,d)$?

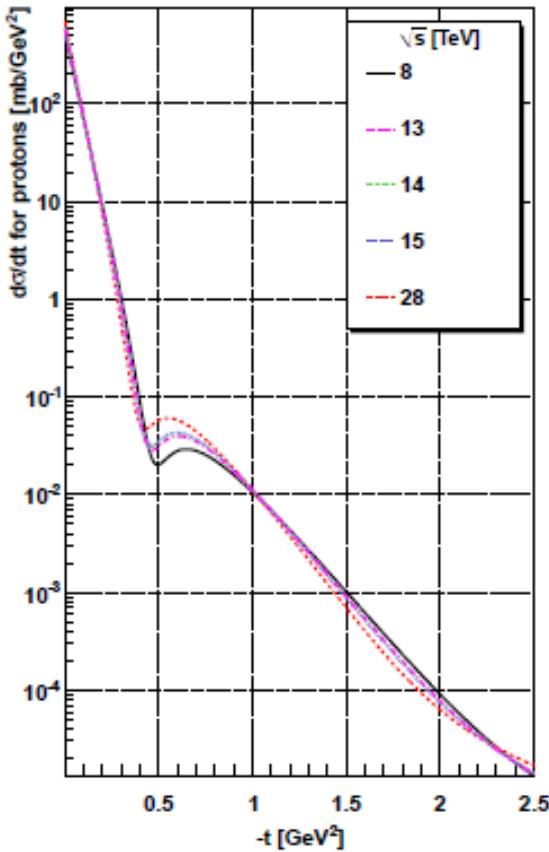


Figure 8: The pp elastic differential cross-section is extrapolated to 8 TeV as well as to future LHC energies and beyond.

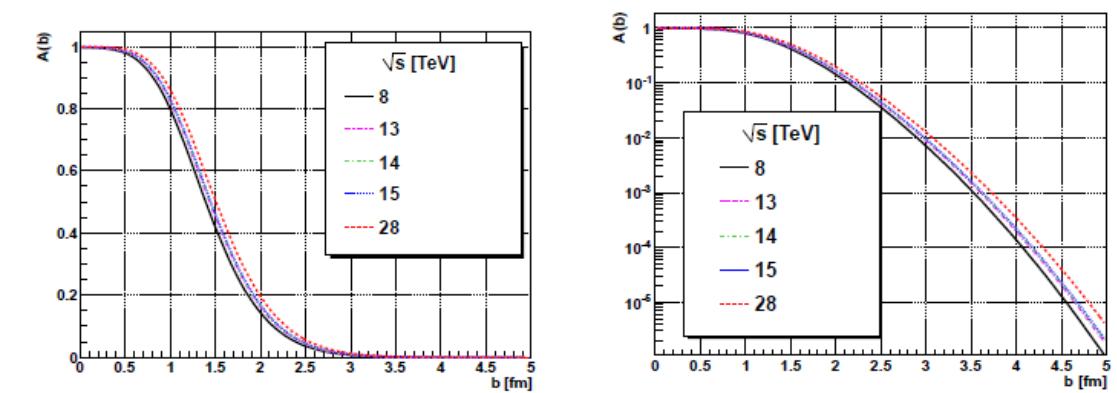


Figure 9: The shadow profile function at the extrapolated energies \sqrt{s} . The results show the increase of the proton interaction radius with increasing \sqrt{s} energies. Also note that the “edge” of the distributions remains of approximately constant width and shape.

\sqrt{s} [TeV]	σ_{tot} [mb]	$ t_{dip} $ [GeV 2]	ρ	$ t_{dip} \cdot \sigma_{tot}$ [mb GeV 2]
8	99.6	0.494	0.103	49.20
13	106.4	0.465	0.108	49.48
14	107.5	0.461	0.108	49.56
15	108.5	0.457	0.109	49.58
28	117.7	0.426	0.114	50.14

The unitarized bialas-Bzdak mmodel, $p = (q,d)$ picture
 Reasonably good prediction for $\sqrt{s} = 13$ TeV, but needs to be retuned.
 $P = (q,(q,q))$ variation gave too many oscillations in $d\sigma/dt$ at large $-t$.

From F. Nemes, M. Csanad and T. Cs, [arXiv:1505.01415](https://arxiv.org/abs/1505.01415)

SELF-CONSISTENCY OF TOTEM σ_{tot} DATA

inelastic independent

$$\sigma_{\text{tot}}^2 = \frac{16\pi}{(1 + \rho^2)} \frac{1}{\mathcal{L}} \left(\frac{dN_{el}}{dt} \right)_{t=0}$$

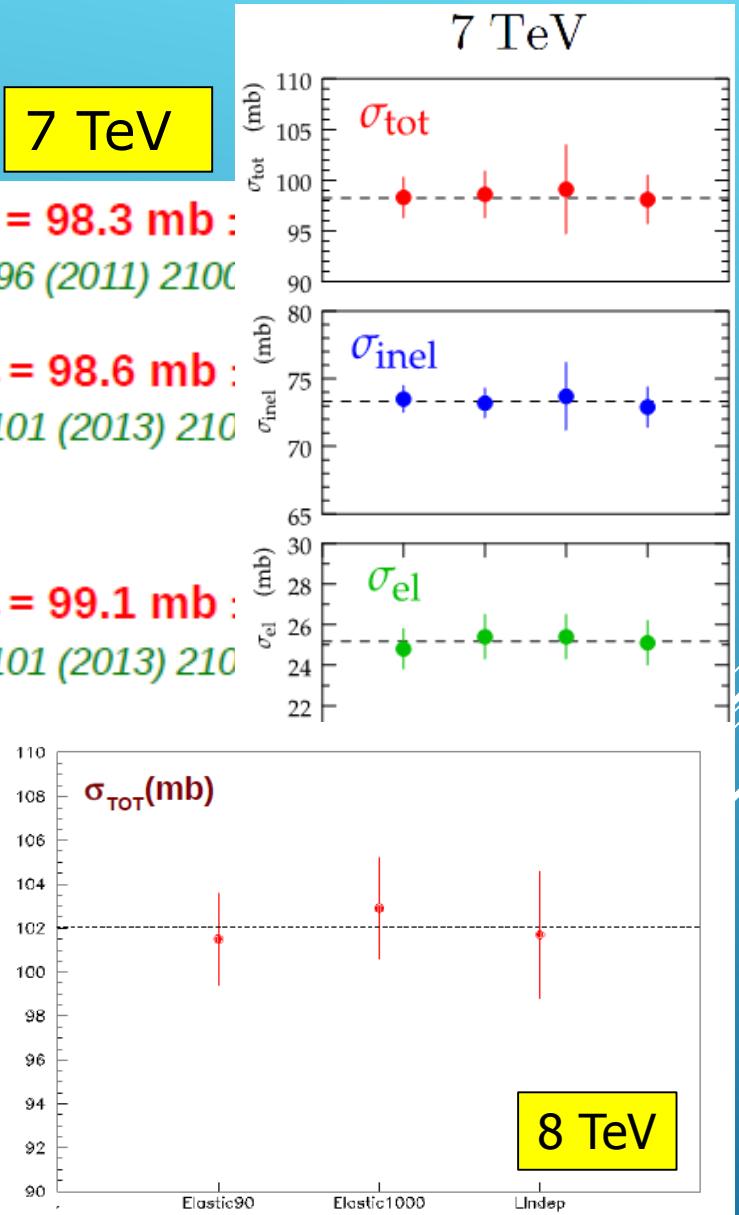
ρ independent

$$\sigma_{\text{tot}} = \sigma_{el} + \sigma_{inel}$$

\mathcal{L} independent

$$\sigma_{\text{tot}} = \frac{16\pi}{(1 + \rho^2)} \frac{(dN_{el}/dt)_{t=0}}{(N_{el} + N_{inel})}$$

Excellent agreements between
 - different methods (7 TeV)
 - different beam conditions (8 TeV)



(IM)POSSIBLE ALTERNATIVES

Thus we feel strongly motivated to warn the astute reader against the over-interpretation of model results that indicate certain features of the elastic scattering data correctly only on the qualitative level, but fail miserably on a confidence level test. Actually, the Odderon effects that we discuss in detail below are due to some robust and model independent features of the data, but we have investigated other more subtle effects too that we do not emphasize

Nevertheless, we may warn the careful readers that descriptions of possible Odderon effects or the lack of them, based on data analysis with zero confidence levels might have apparently been over-interpreted recently: the significance of the interpretation of fits that do not describe the data in a statistically acceptable manner is not particularly well defined.

We recommend extreme care before drawing big conclusions, given that we see the sensitivity of some of the details like $\phi(t)$ at large $|t|$ for tiny details in the data and in changing some of the higher order coefficinets of the fits. Possibly these tiny details differ in some papers that may apparently draw big, but contradicting, and not particularly well founded conclusions about the exitence or the non-existence of the Odderon effects.

POSSIBLE IMPLICATIONS

Finally, based on our experience with precision description of the differential cross-sections of elastic proton-proton and proton-antiproton collisions let us warn the careful readers against over-interpreting fit results when the fitted function does not represent the data with a statistically not unacceptable confidence level.

May we hope that this data analysis method of Lévy series expansion, detailed for the first time in this manuscript for a positive definite function, may find several important applications in the future, in a broad range of quantitative sciences. Essentially this method is able to characterize the deviations from Fourier-transformed and symmetric Lévy stable source distributions. Given the ubiquity of Lévy distributions in Nature, we hope that our new method will be relevant in several areas of human knowledge, that extend far beyond the science of physics.

Diffraction: R. Hofstadter, Nobel-prize (1961)

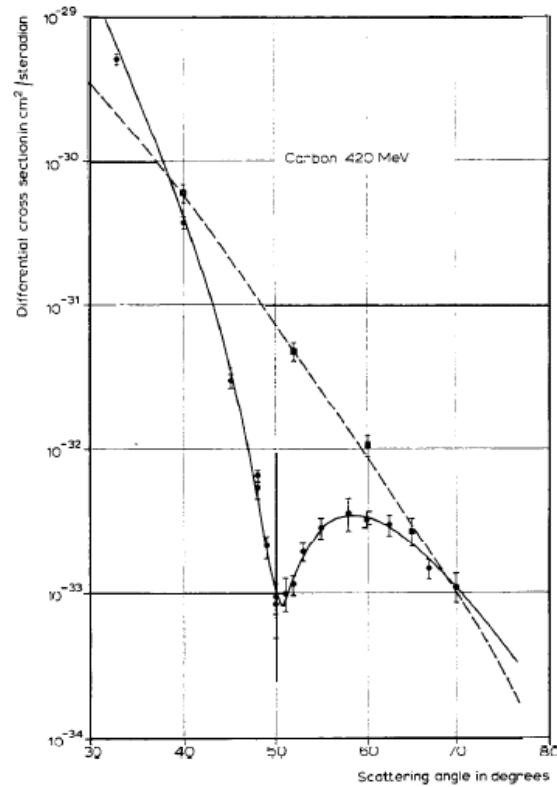
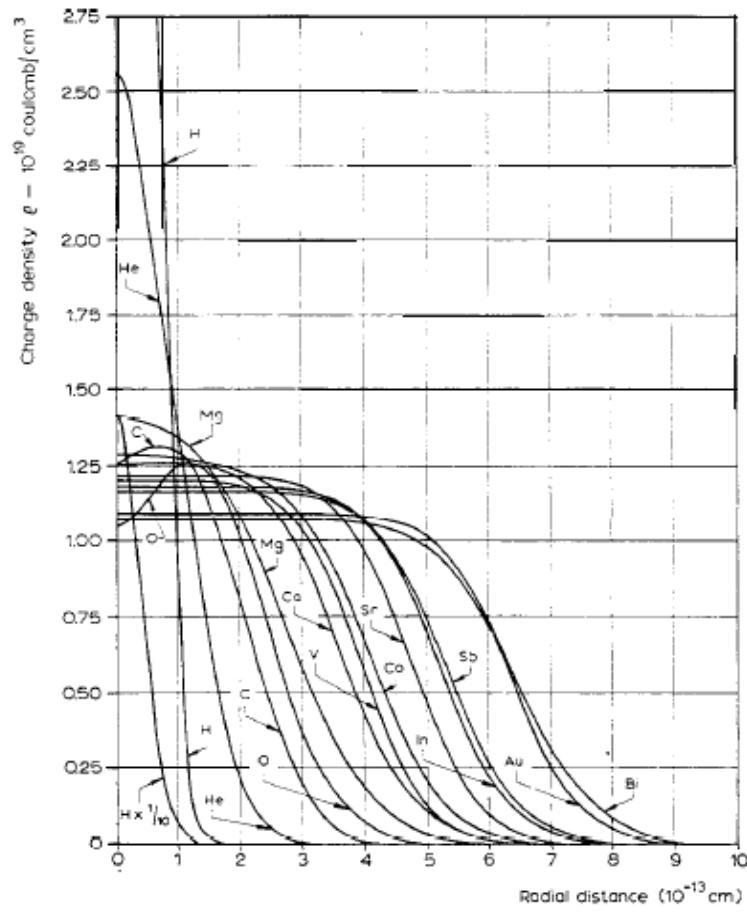


Fig. 5. This figure shows the elastic and inelastic curves corresponding to the scattering of 420-MeV electrons by ^{12}C . The solid circles, representing experimental points, show the elastic-scattering behavior while the solid squares show the inelastic-scattering curve for the 4.43-MeV level in carbon. The solid line through the elastic data shows the type of fit that can be calculated by phase-shift theory for the model of carbon shown in Fig. 8.

1961 R. HOFSTADTER

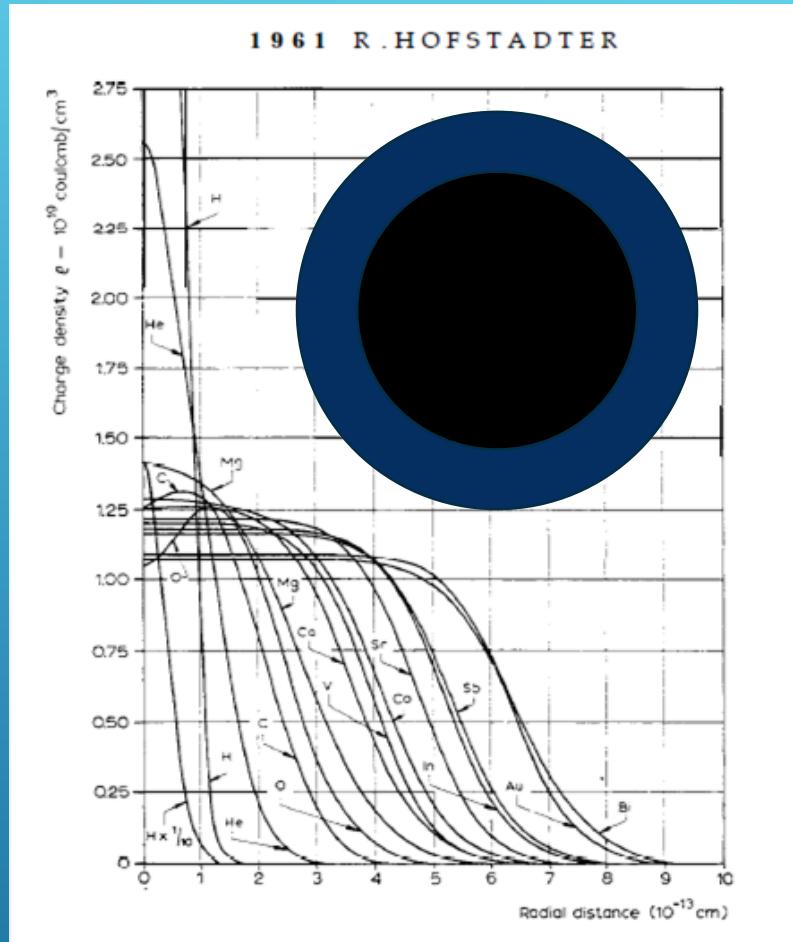
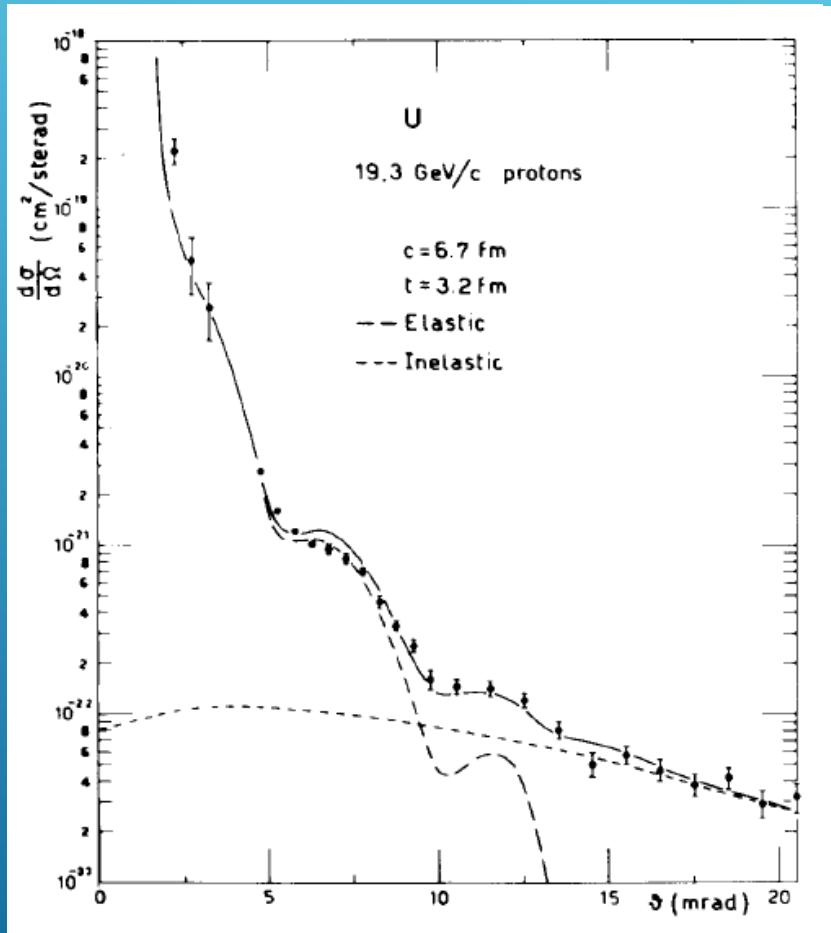


e+A: elastic electron-nucleus scattering

Imaging: electric charge distribution of spherical nuclei

$p+A \rightarrow p+A$

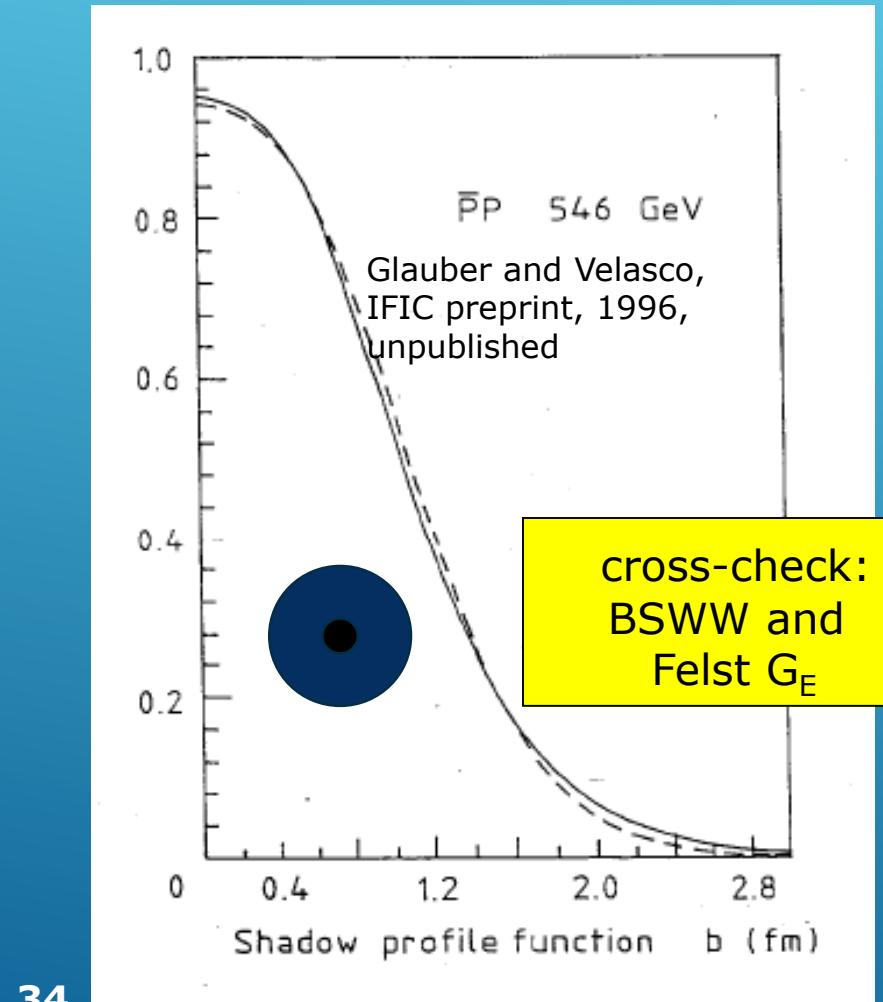
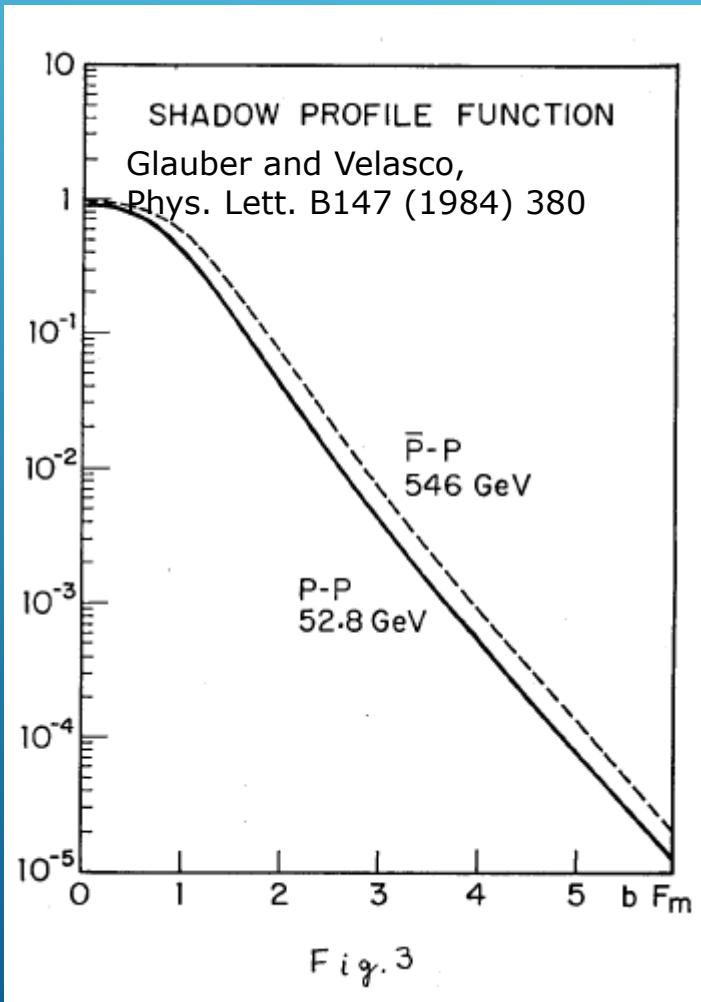
Glauber and Matthiae, NPB21 (1970) 135



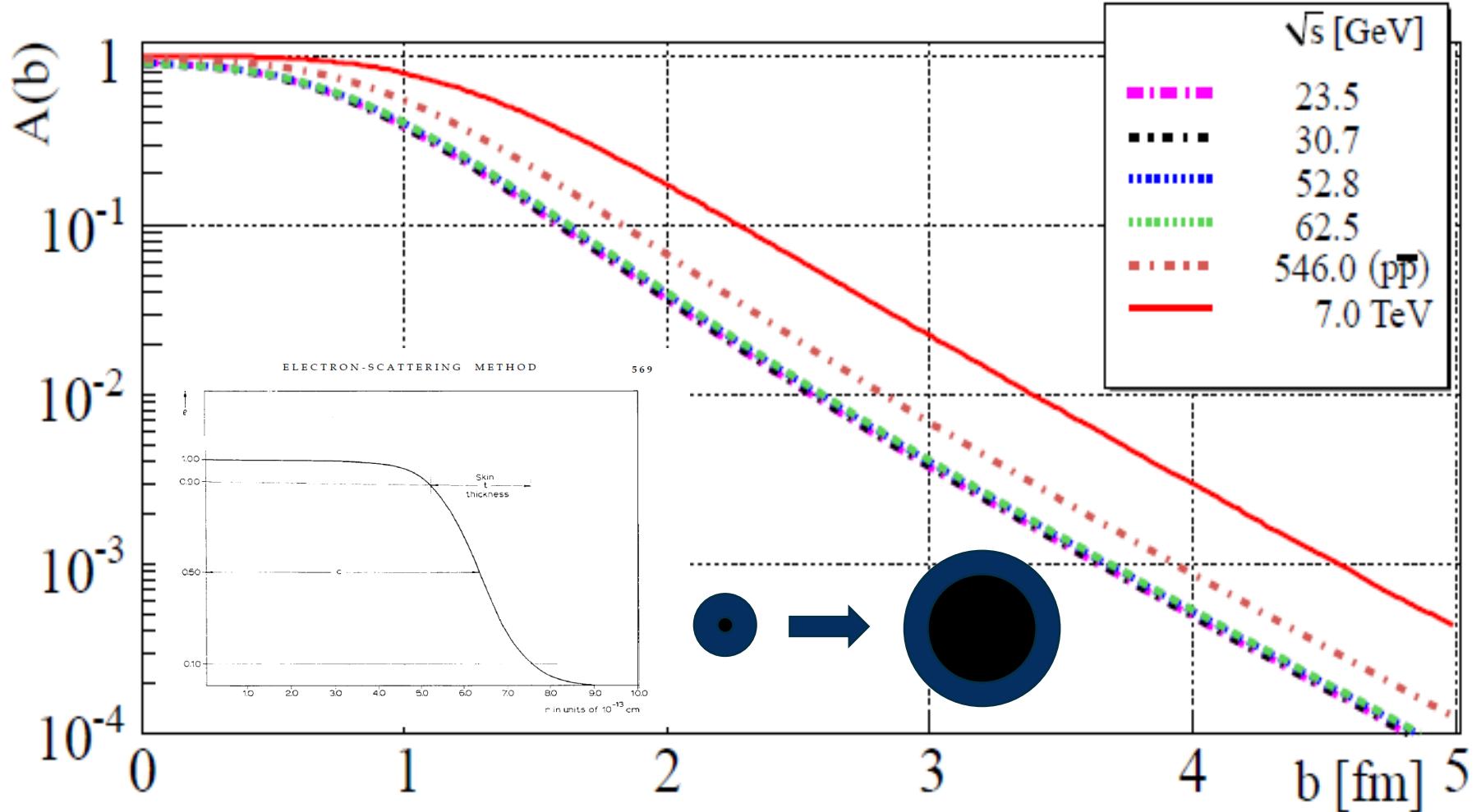
The distribution of the nucleons (p+n)
~ the distribution of electric charge (p) in atomic nuclei.

Imaging with shadow profile

$$A(b) = 1 - |e^{-\Omega(b)}|^2$$



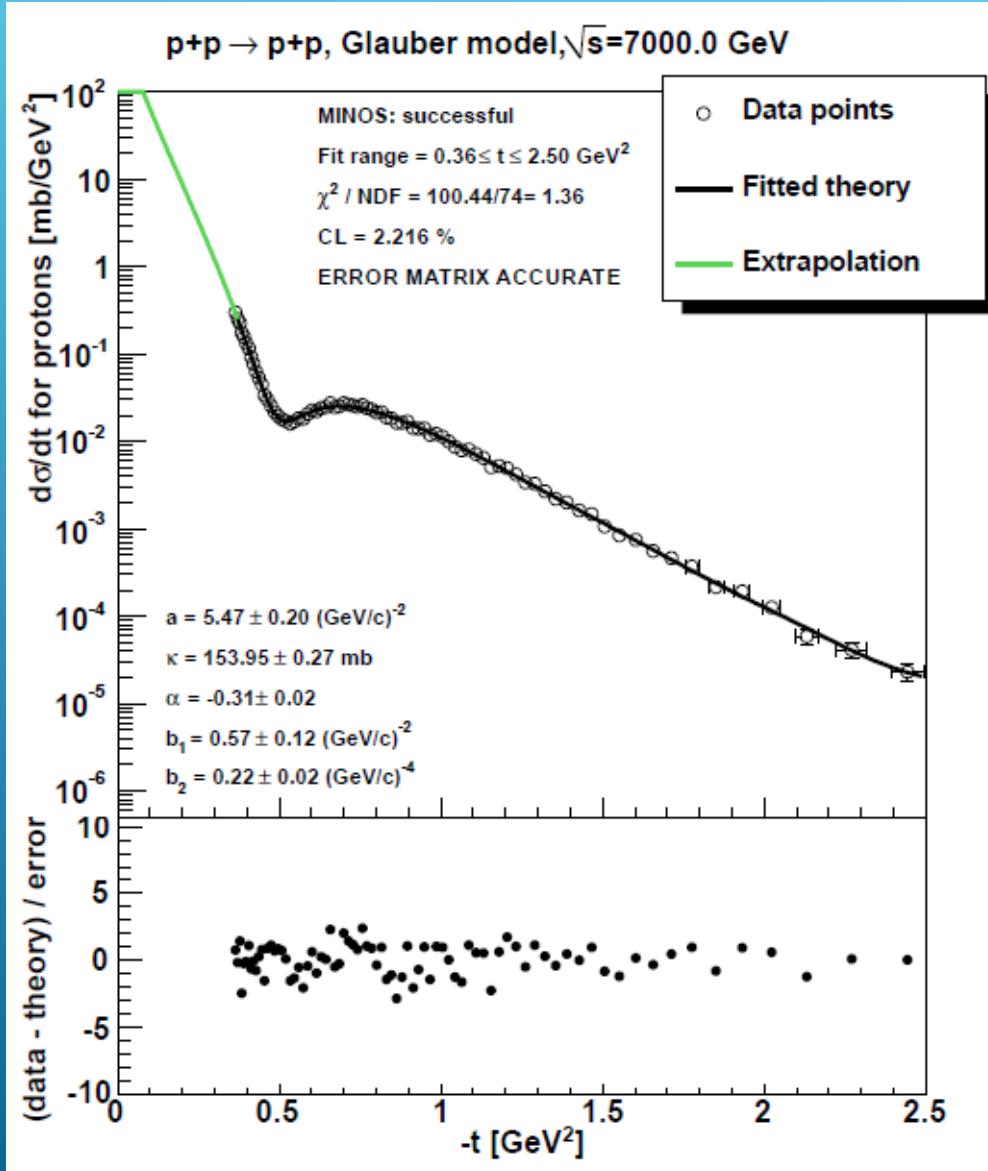
Shadow imaging in p+p at LHC



The **BnEL** effect.

Can it explain TOTEM data,
new trends of B at LHC?

First results @ Low-X 2013: GV works for $d\sigma/dt$ dip



Glauber-Velasco (GV)
(original)

describes $d\sigma/dt$ data
Both at ISR and
TOTEM@LHC
in the dip region

[arxiv:1311.2308](https://arxiv.org/abs/1311.2308)

Note: at low-t
GV is \sim exponential

Really?
Lower energies?

Non-exponential $\bar{p}p$ in GV model

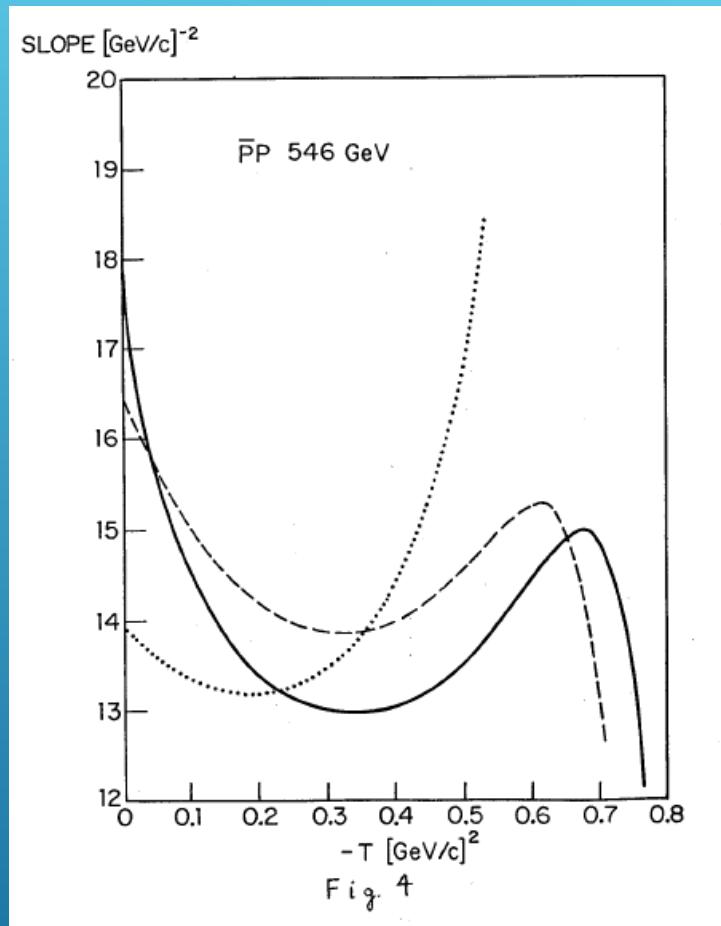


Figure 4 from
Glauber-Velasco
PLB 147 (1984) 380
Slope is not quite
exponential:

A non-Gaussian behaviour
of proton scattering
in coordinate space

Fig. 4: Logarithmic slopes of the $\bar{p} - p$ differential cross-section at 546 GeV calculated according to: the *BSWW* form factor, which is accurate at small momentum transfers (solid wave), the *Felst* form factor, which accounts only for the data at larger momentum transfers (dashed curve) and the dipole form factor together with the *Chou-yang* scattering amplitude (dotted curve).