

ODDERON AND SUBSTRUCTURES OF PROTON FROM A MODEL-INDEPENDENT LEVY IMAGING OF ELASTIC SCATTERING DATA

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Introduction to Diffraction

Lévy Expansion in a Nut-shell: a new imaging method

TOTEM p+p @ 7 and 13 TeV

p+p @ 23, 30, 45, 53, 62 GeV

Comparison of pp and p-antip

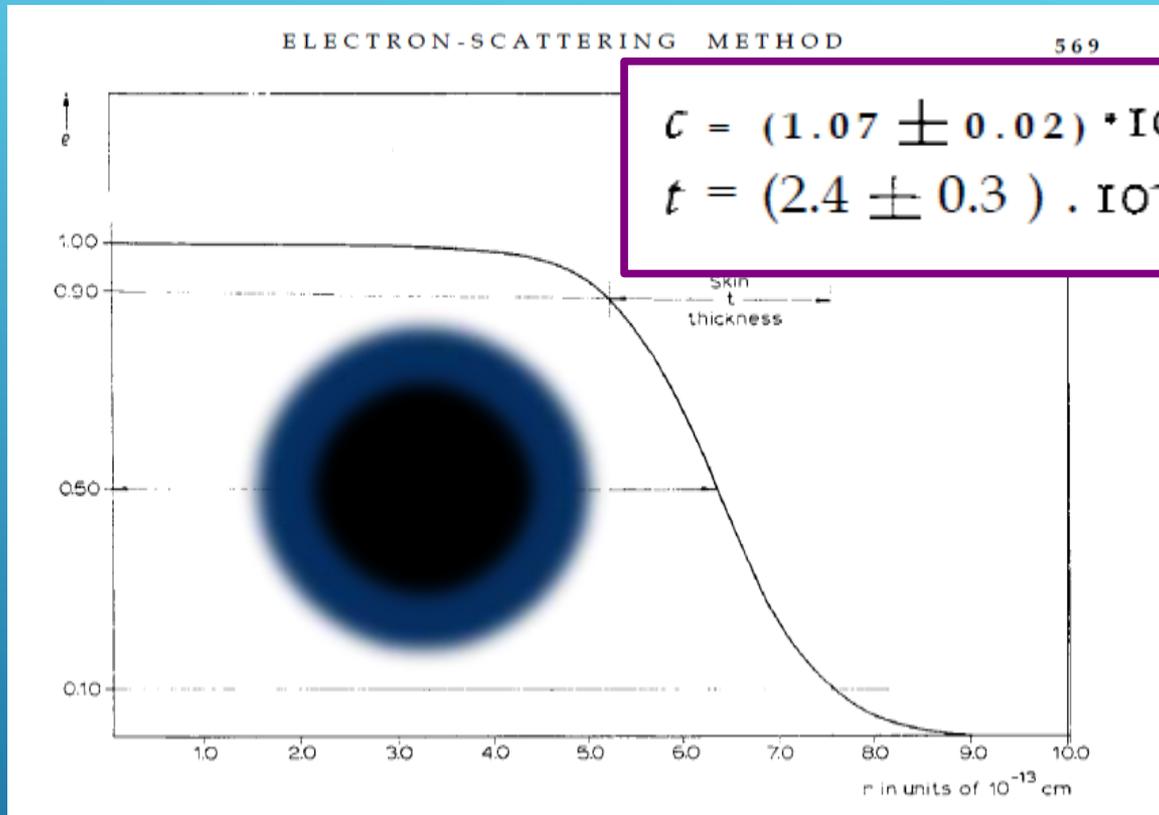
Odderon

Expect the unexpected: structures in protons

[arxiv:1807.02897](https://arxiv.org/abs/1807.02897) , [arXiv:1811.08913](https://arxiv.org/abs/1811.08913)

+ manuscript in preparation

DIFFRACTION: WHAT HAVE WE LEARNED?



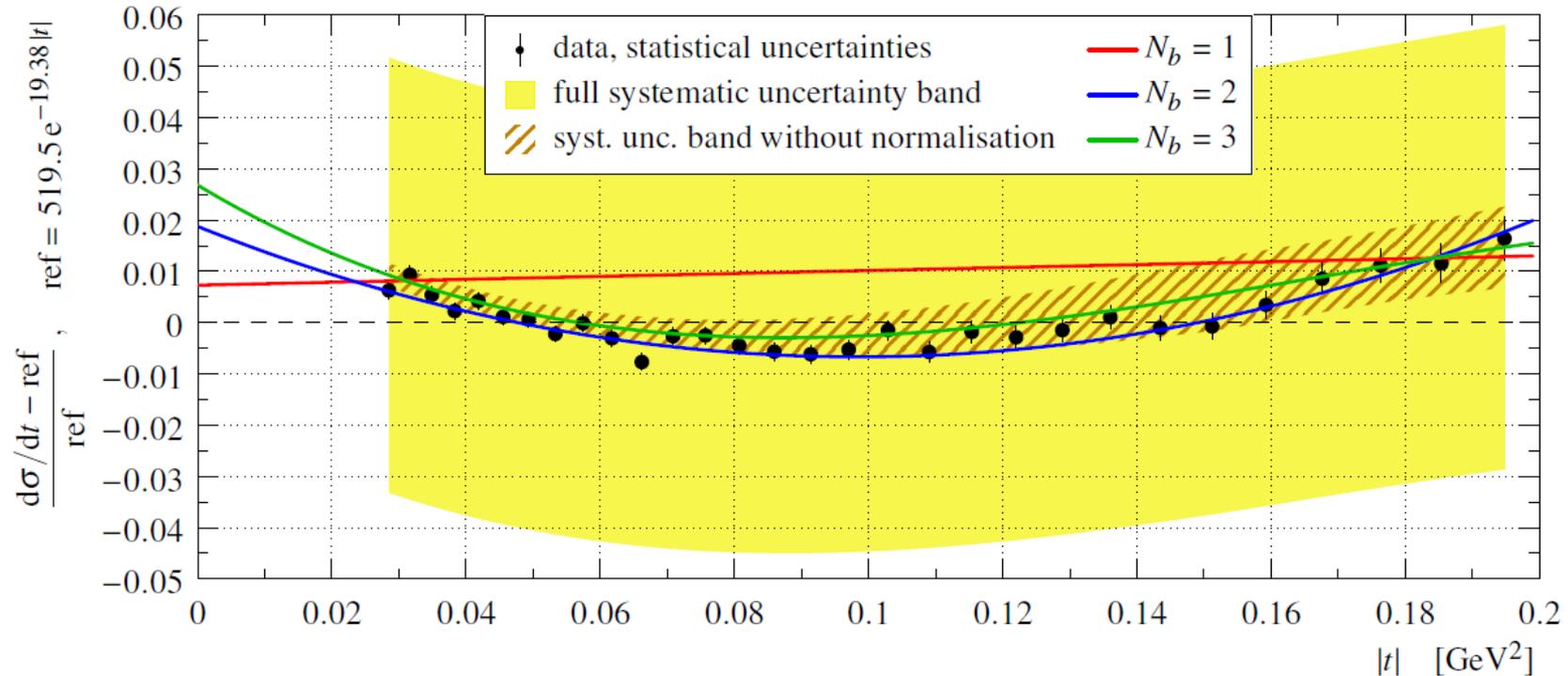
Volume V of spherical nuclei $\sim A$ (mass number)
Nuclear „skin-width“ is independent of A
→ Central density of big spherical nuclei is independent of A
R. Hofstadter, Nobel-lecture (1961)

TOTEM pp @ 8 TeV, arxiv:1503.08111

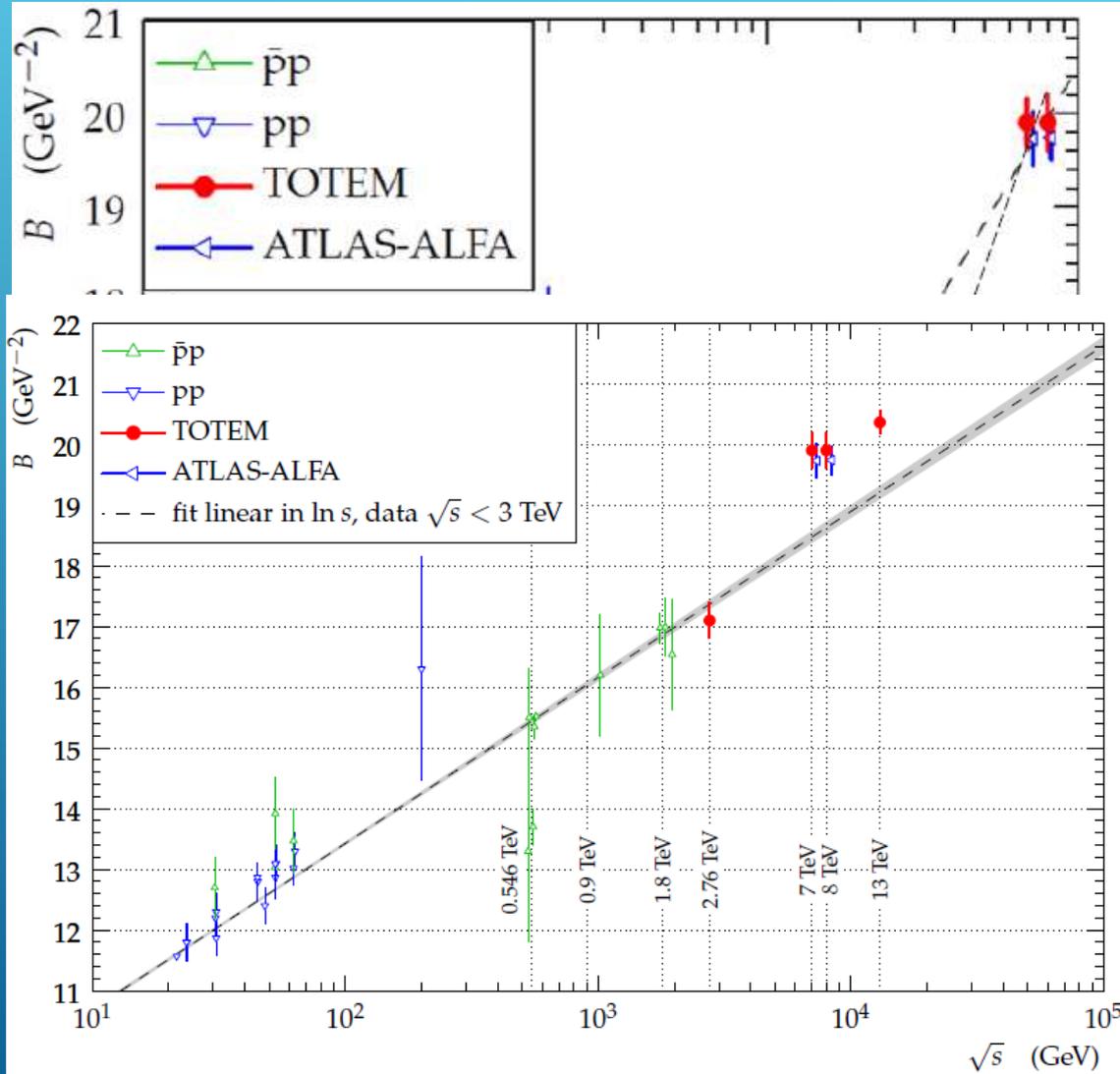
$d\sigma/dt$ non-exponential at low- t

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:

Change of low- $|t|$
trend at LHC

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**

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

$c_j = a_j + ib_j$, **idea: complete set of orthonormal functions, put NEB to the weight**

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

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

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

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

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

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

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

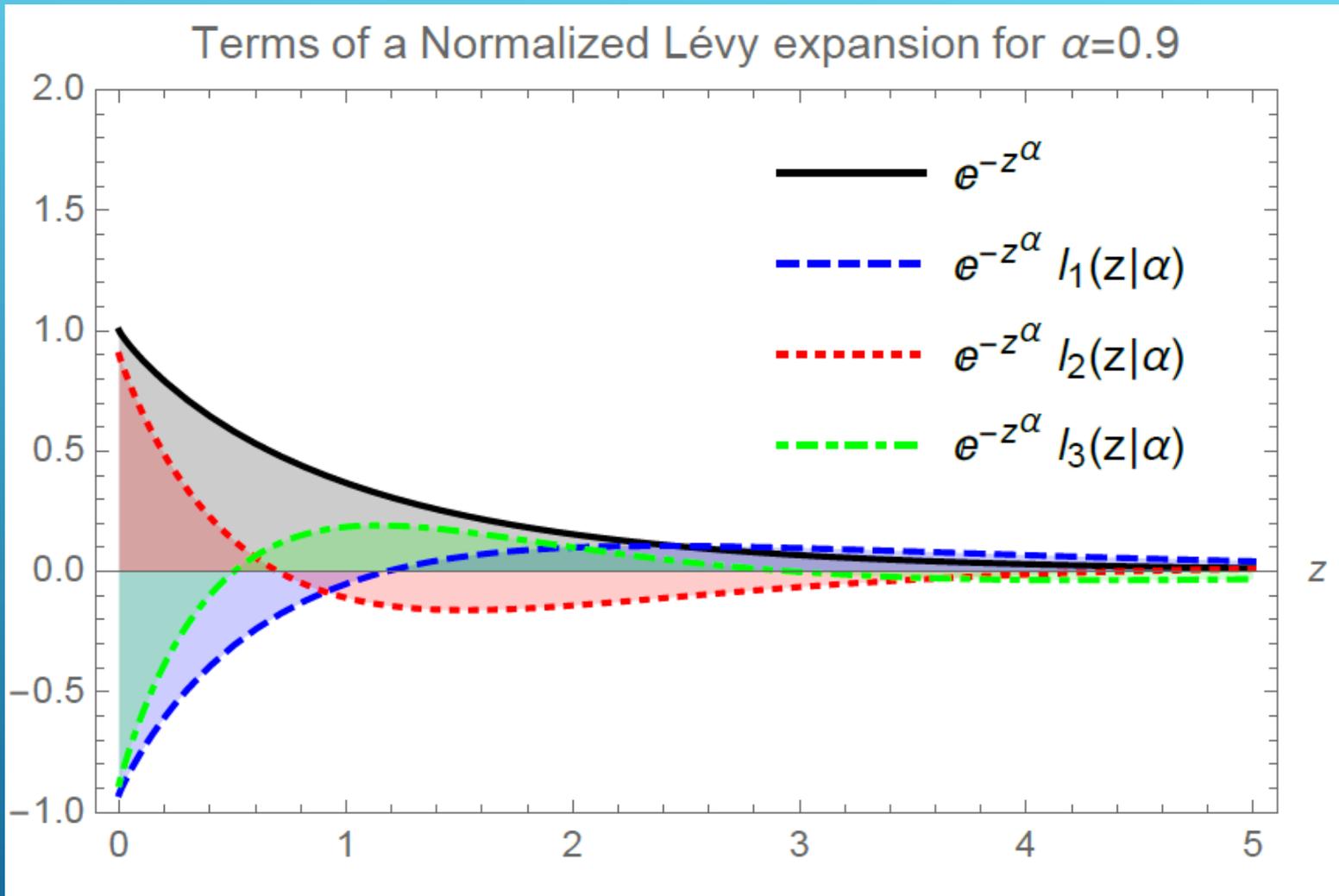
$$L_0(z|\alpha) = 1, \quad \text{T. Csörgő, R. Pasechnik, A. Ster, } \underline{\text{arxiv.org:1807.02897}}$$

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

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

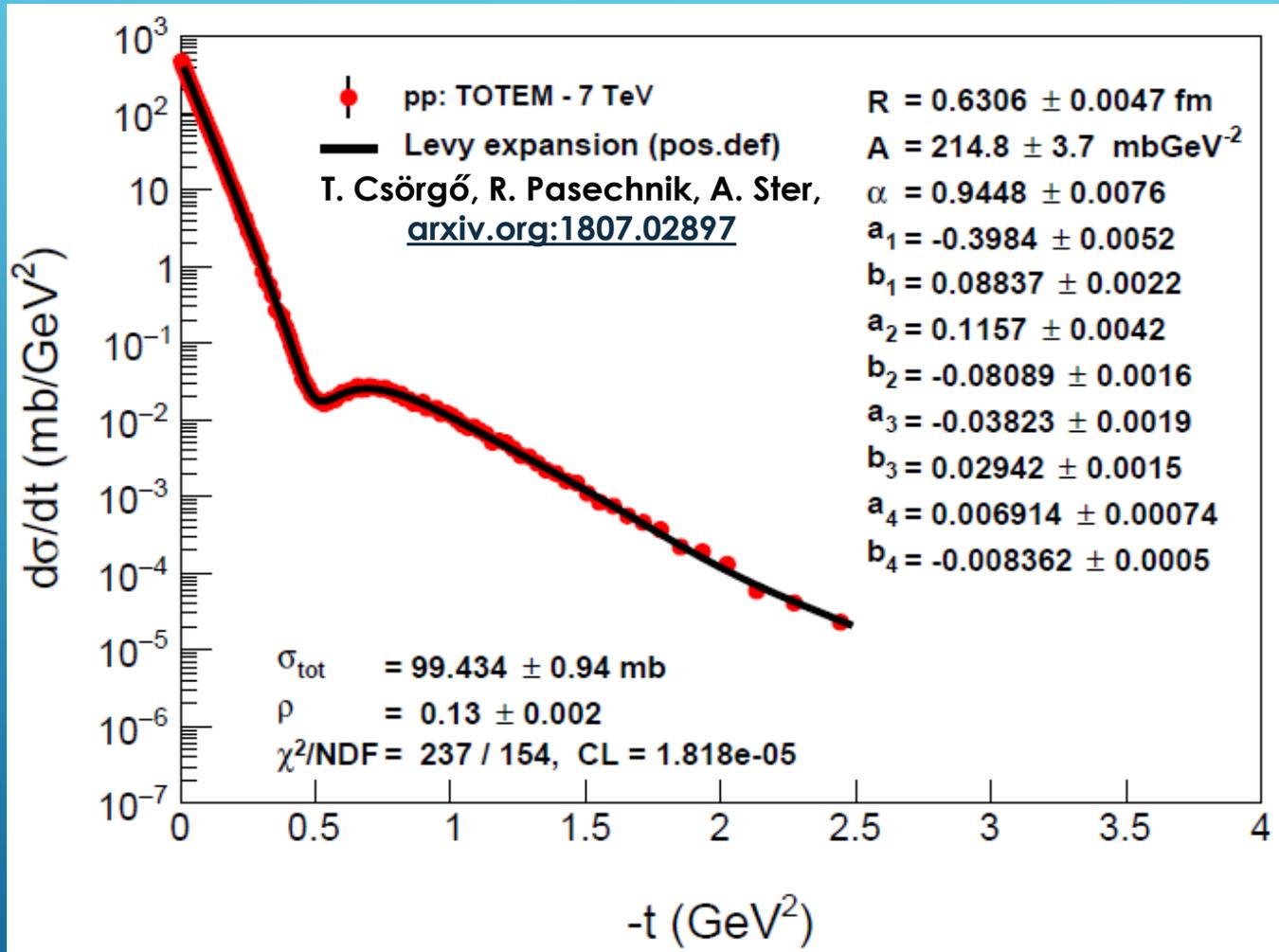
$$L_3(z|\alpha) = \det \begin{pmatrix} \mu_{0,\alpha} & \mu_{1,\alpha} & \mu_{2,\alpha} & \mu_{3,\alpha} \\ \mu_{1,\alpha} & \mu_{2,\alpha} & \mu_{3,\alpha} & \mu_{4,\alpha} \\ \mu_{2,\alpha} & \mu_{3,\alpha} & \mu_{4,\alpha} & \mu_{5,\alpha} \\ 1 & z & z^2 & z^3 \end{pmatrix},$$

MODEL INDEPENDENT LEVY EXPANSION



As $\alpha \rightarrow 1$, Lévy polynomials approach
Laguerre polynomials, orthonormal to $\exp(-t)$
T. Csörgő, T. Novák and A. Ster,
arXiv:1604.05513 [physics.data-an]

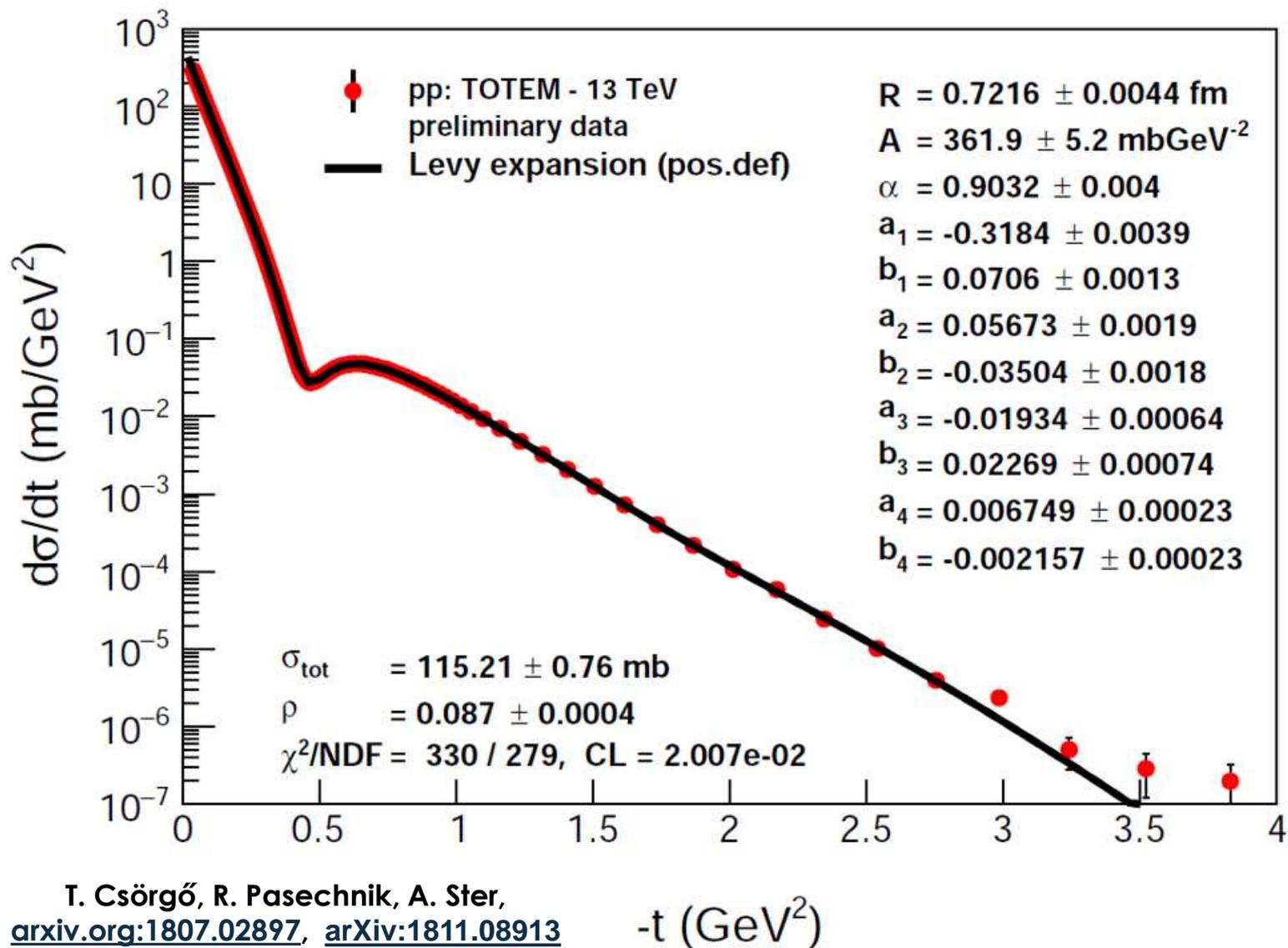
LEVY EXPANSION, 7 TeV



J. Chwastowski, Trento, 2016:
Model independent, but physics = ? 24

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

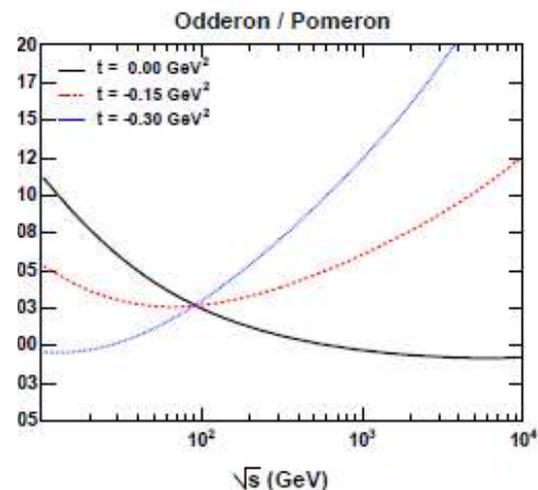
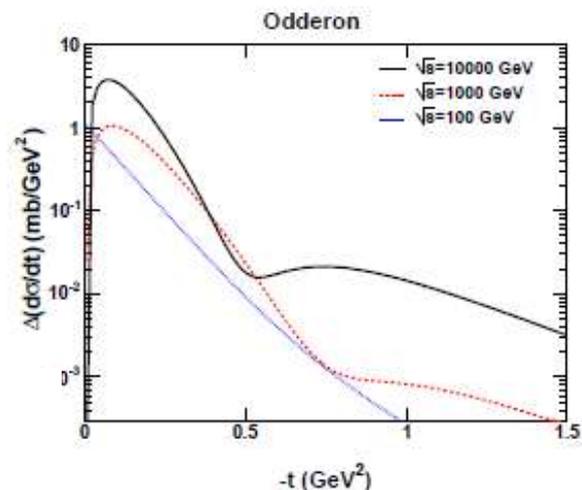
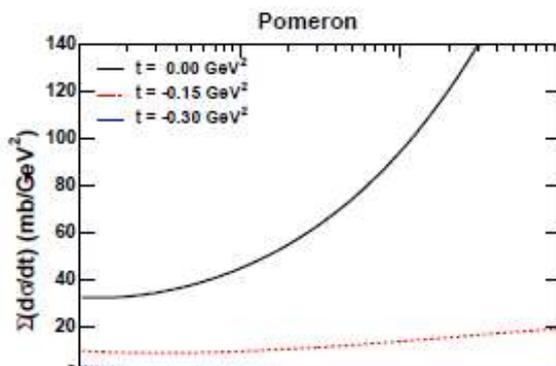
LEVY EXPANSION AT 13 TeV LHC



LOOKING FOR ODDERON EFFECTS

Odderon

Odderon
ppba
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].

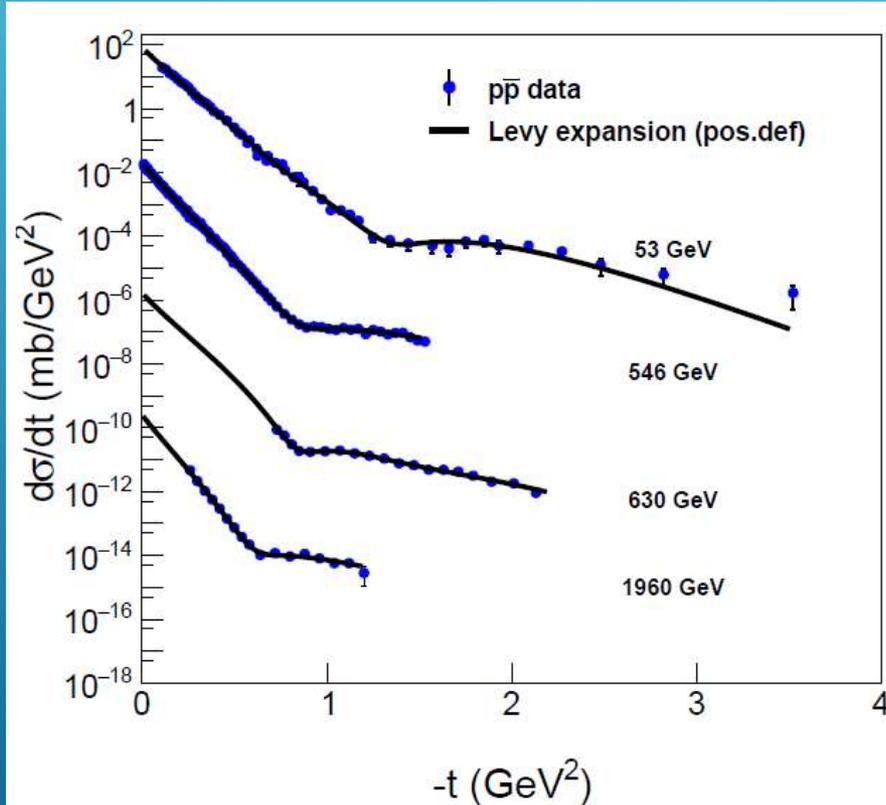
¹⁸I. M. Dremin, Universe **4**, no. 5, 65 (2018).

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

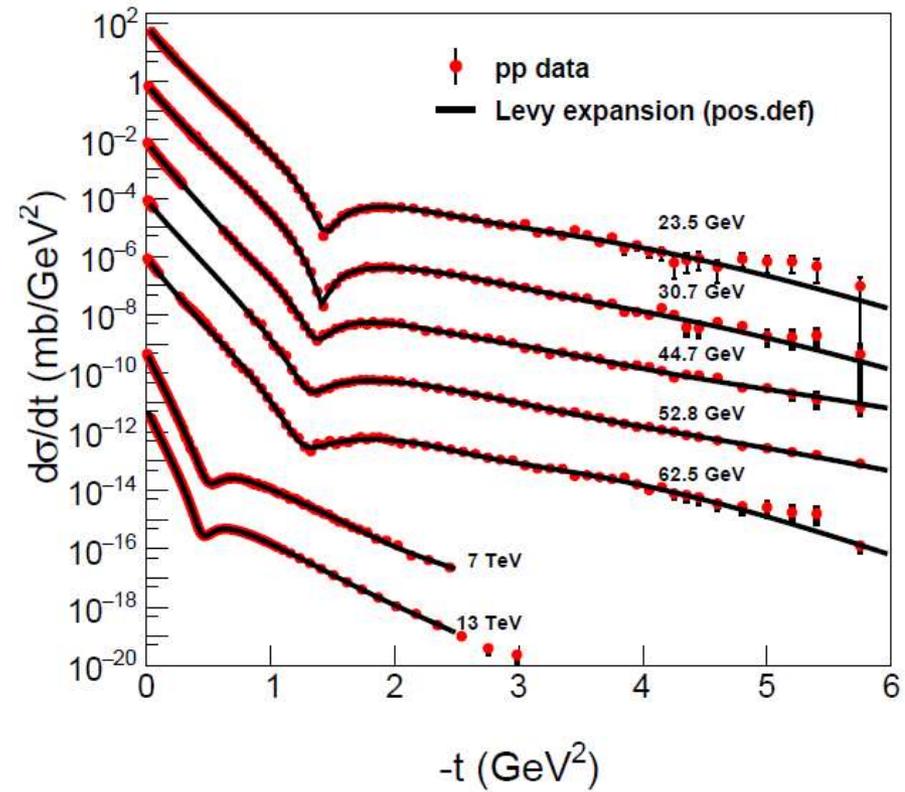
$$| \frac{d\sigma}{dt} |_{pp}^2 + | \mathcal{A} |_{pp}^2 = \Sigma_{Pom} \text{ fitted to the data.}$$

LEVY EXPANSION FOR ELASTIC PPBAR and PP

PPBAR: PROTON+ANTIPROTON

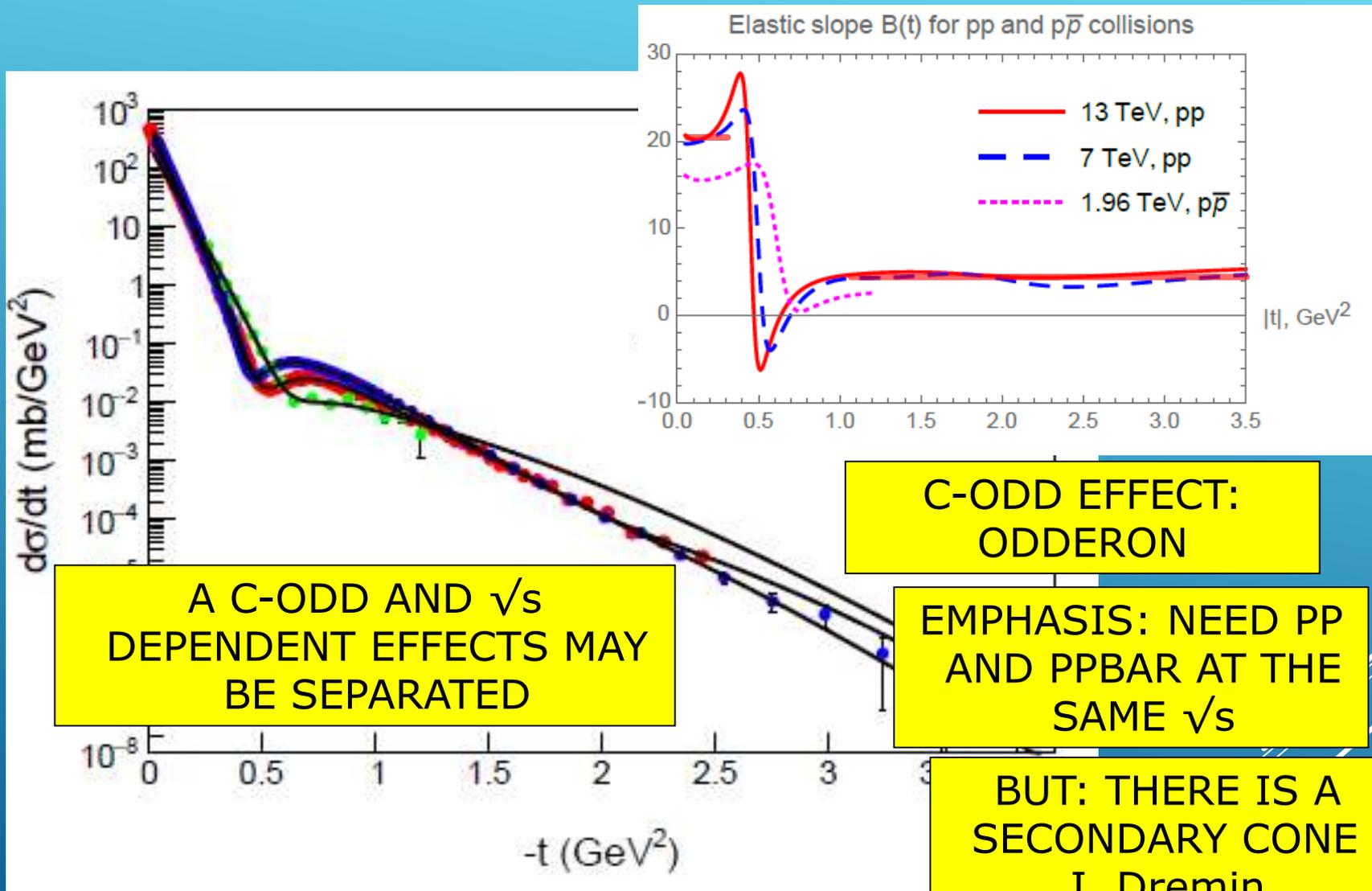


PP: PROTON+PROTON



T. Csörgő, R. Pasechnik, A. Ster, [arxiv.org:1807.02897](https://arxiv.org/abs/1807.02897)

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



IMAGING AT ISR AND AT LHC ENERGIES

PP: PROTON+PROTON

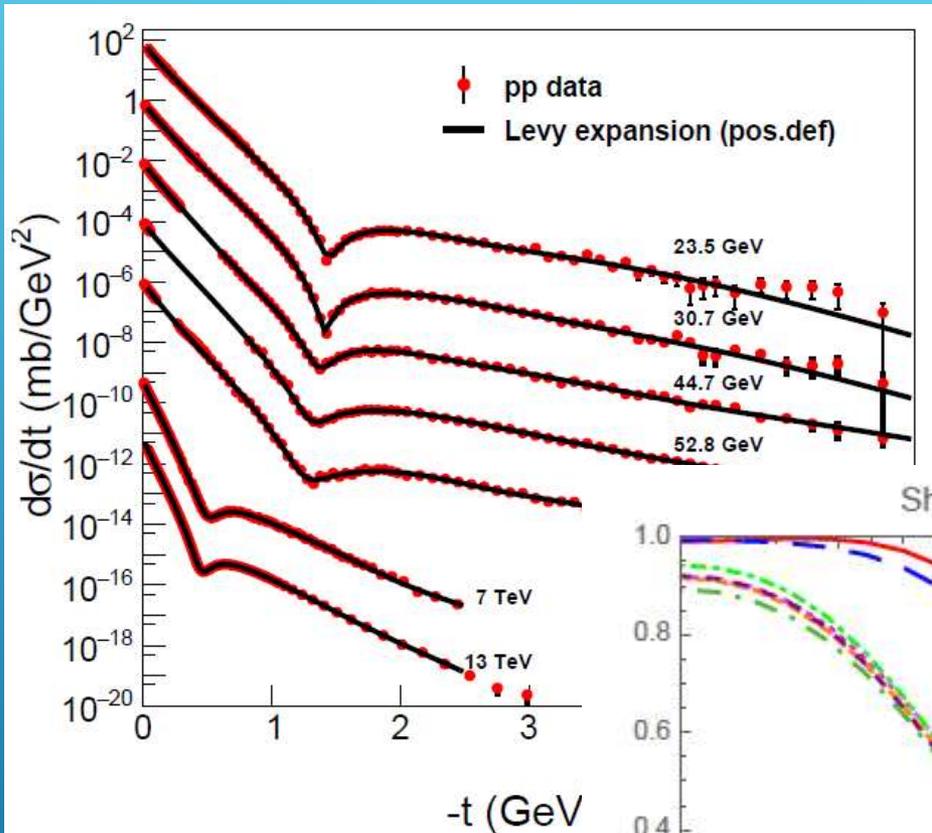
T. Csörgő, R. Pasechnik, A. Ster,

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

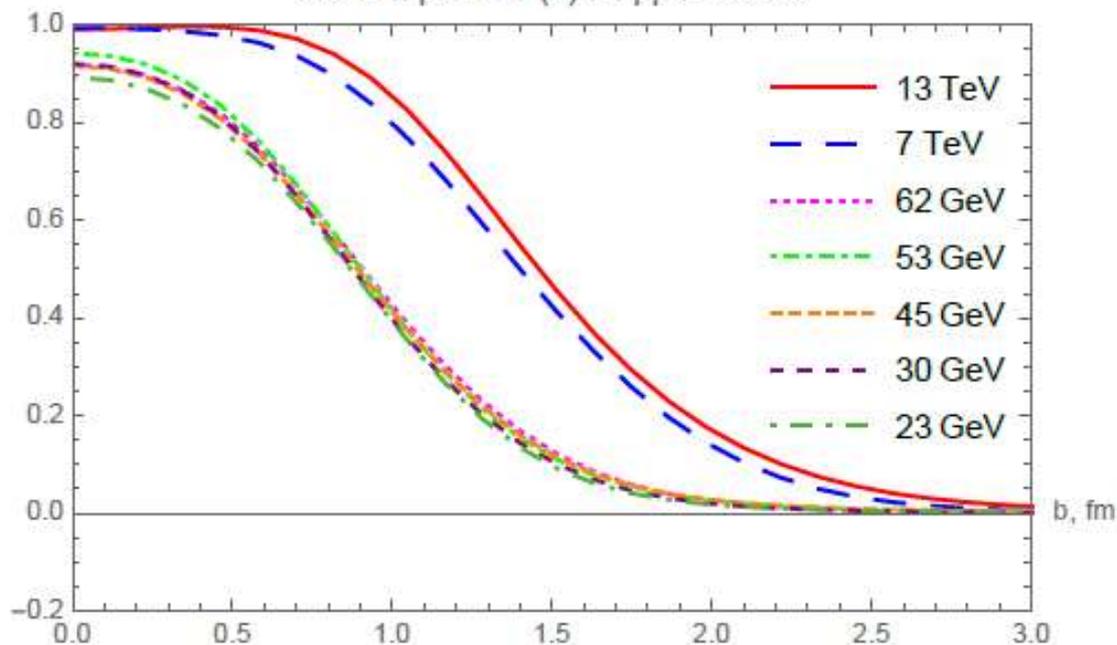
$$\frac{d\sigma}{dt} = \frac{1}{4\pi} |T_{el}(\Delta)|^2, \quad \Delta = \sqrt{-t},$$

$$T_{el}(\Delta) = i\sqrt{4\pi A} \exp\left(-\frac{1}{2}z^\alpha\right) \left[1 + \sum_{i=1}^{\infty} c_i l_i(z|\alpha)\right],$$

$$z = \Delta^2 R^2 = |t|R^2.$$



Shadow profile P(b) for pp collisions

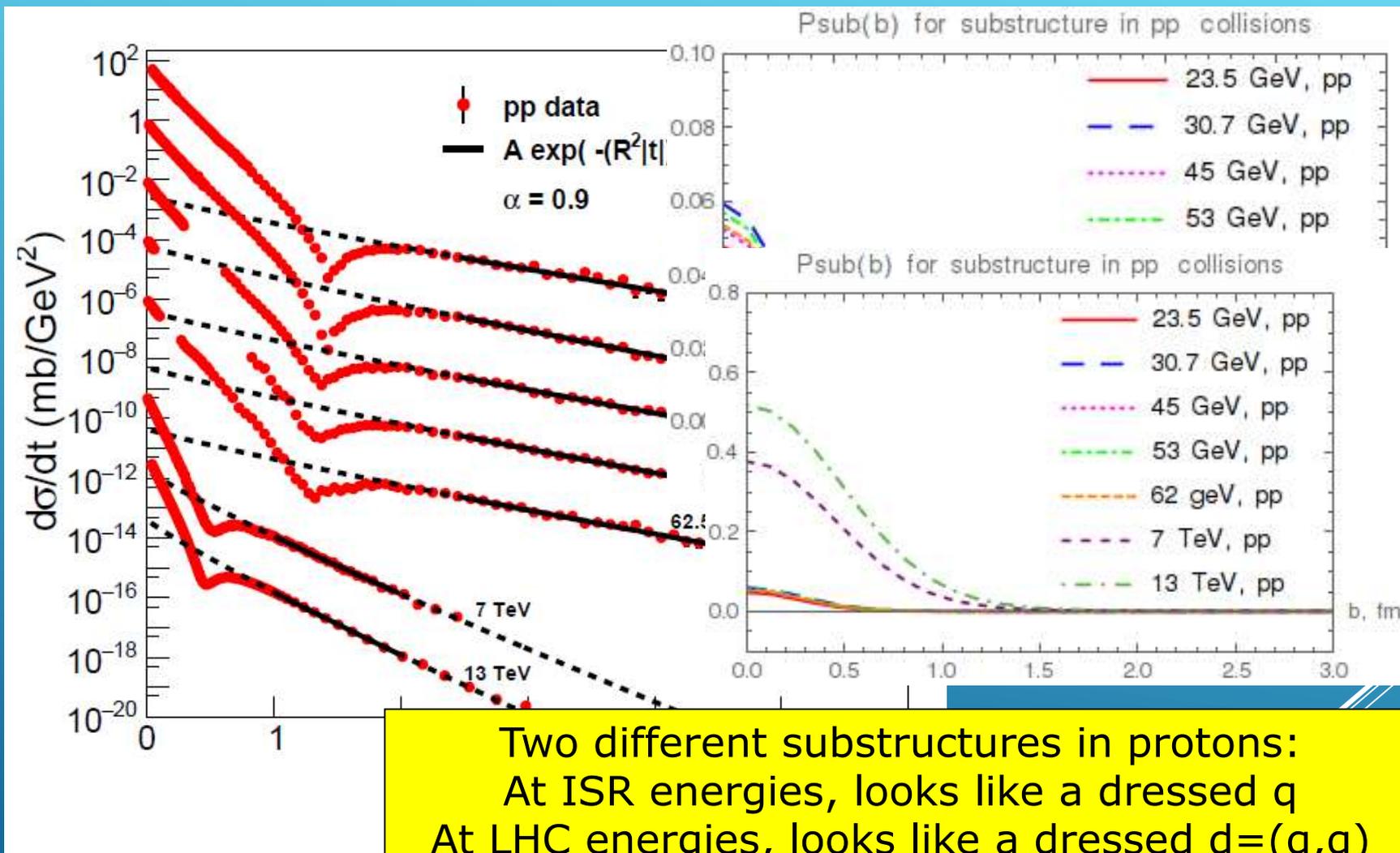


$$t_{el}(b) = \int \frac{d^2\vec{\Delta}}{(2\pi)^2} e^{-i\vec{\Delta}\vec{b}} T_{el}(\Delta)$$

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

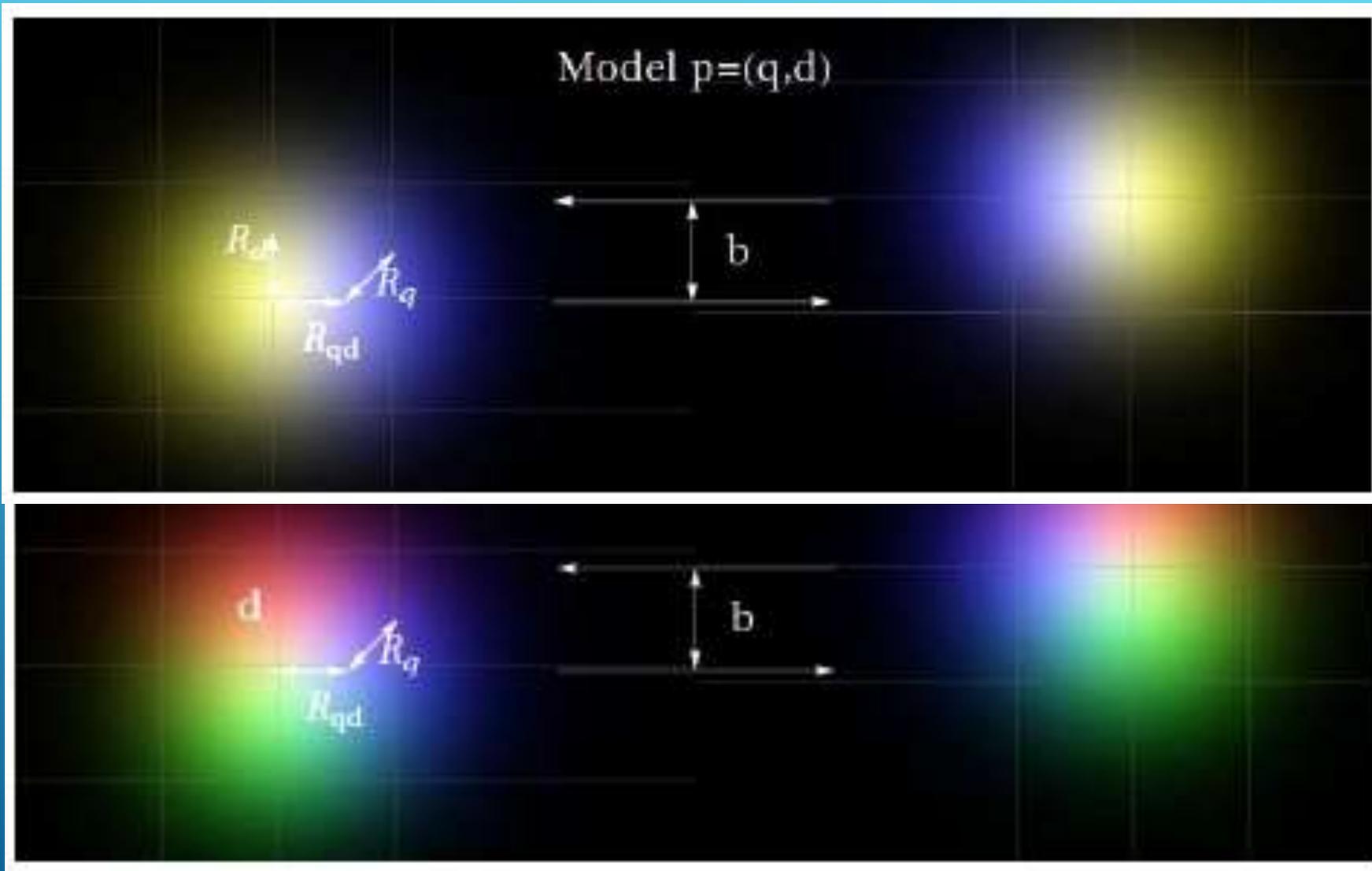
$$P(b) = 1 - |e^{-\Omega(b)}|^2$$

LEVY FITS TO LARGE $-t$: SUBSTRUCTURES

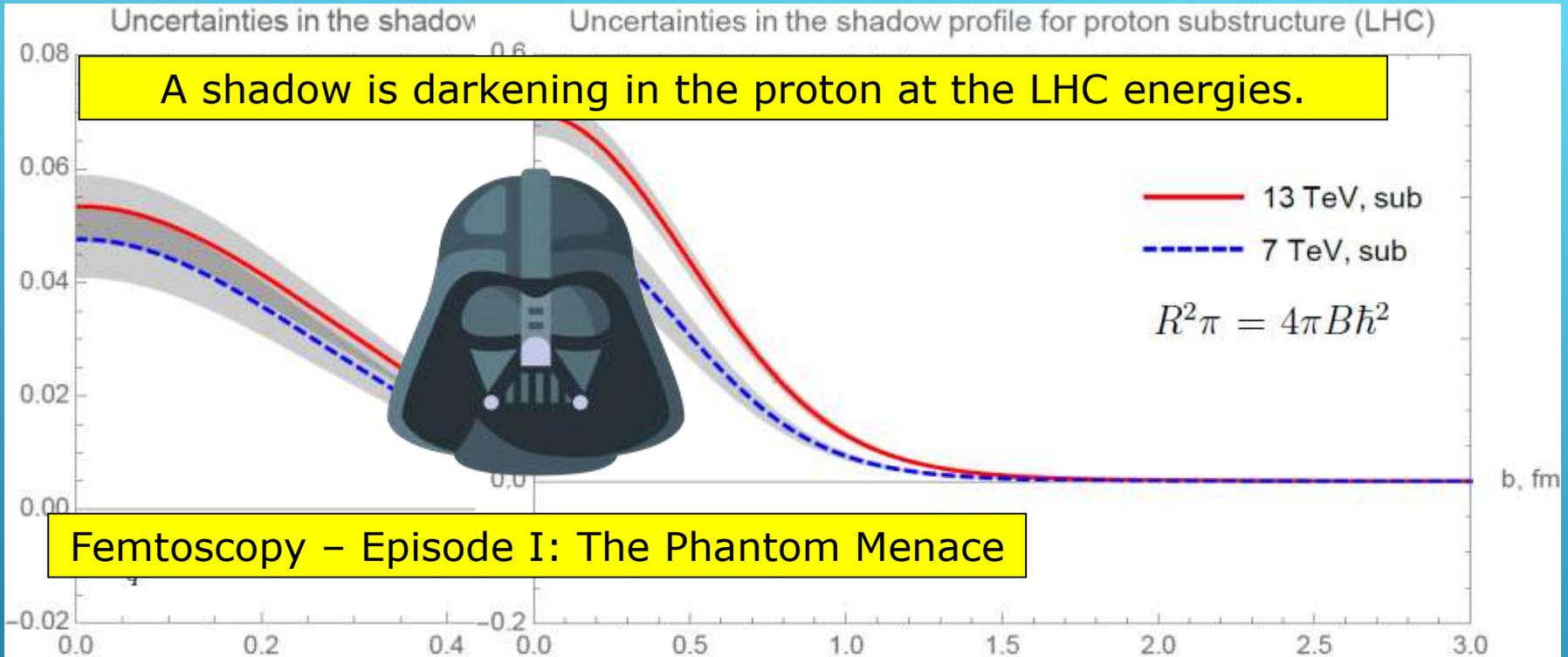


Two different substructures in protons:
 At ISR energies, looks like a dressed q
 At LHC energies, looks like a dressed $d=(q,q)$

LEVY FITS TO LARGE -t: SUBSTRUCTURES



Systematic uncertainties

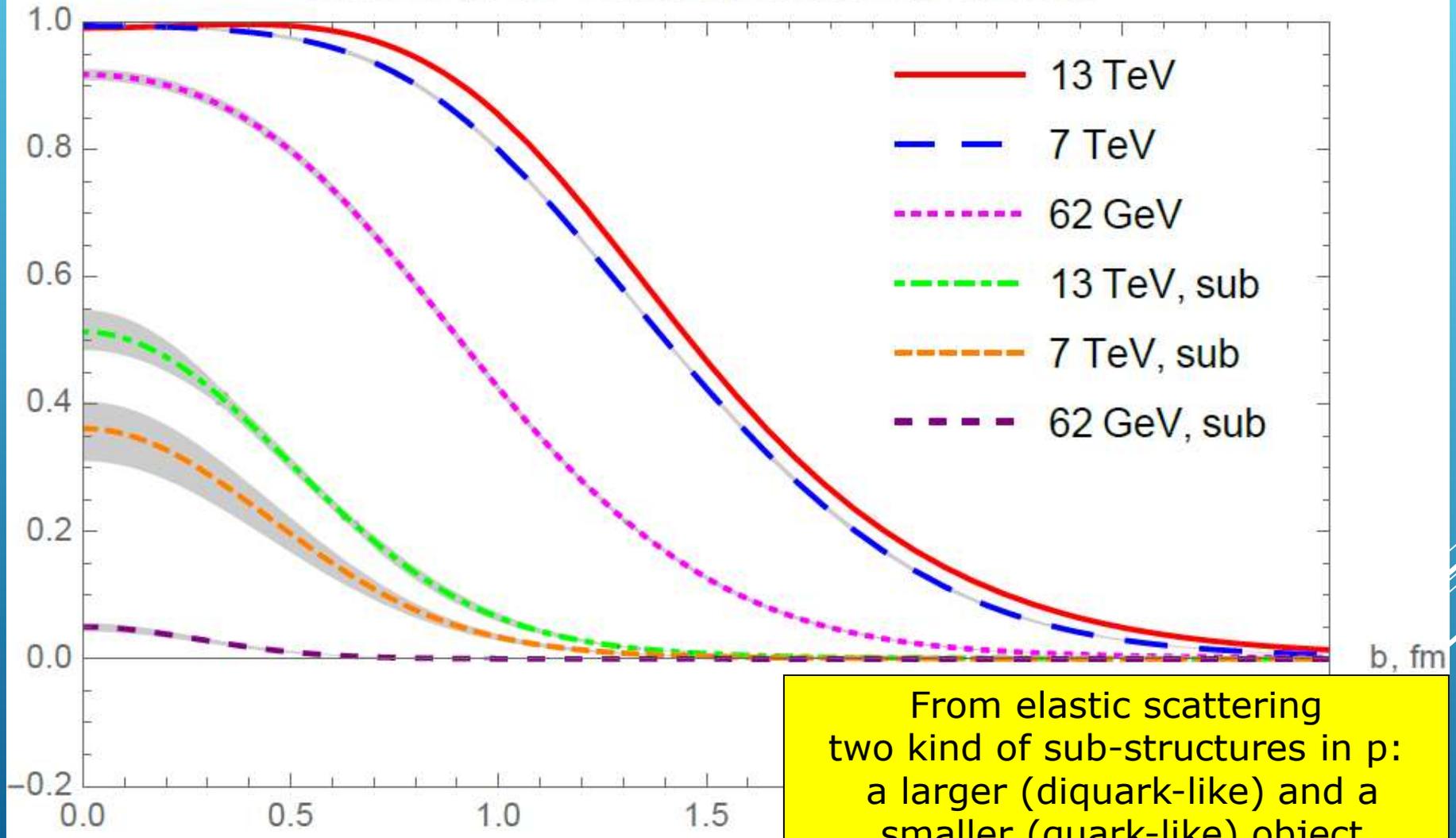


The shadow profile for the substructures in the proton are within errors the same from 23 to 62 GeV at ISR: the same object is seen, within errors.

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.

$$P = (q, d)$$

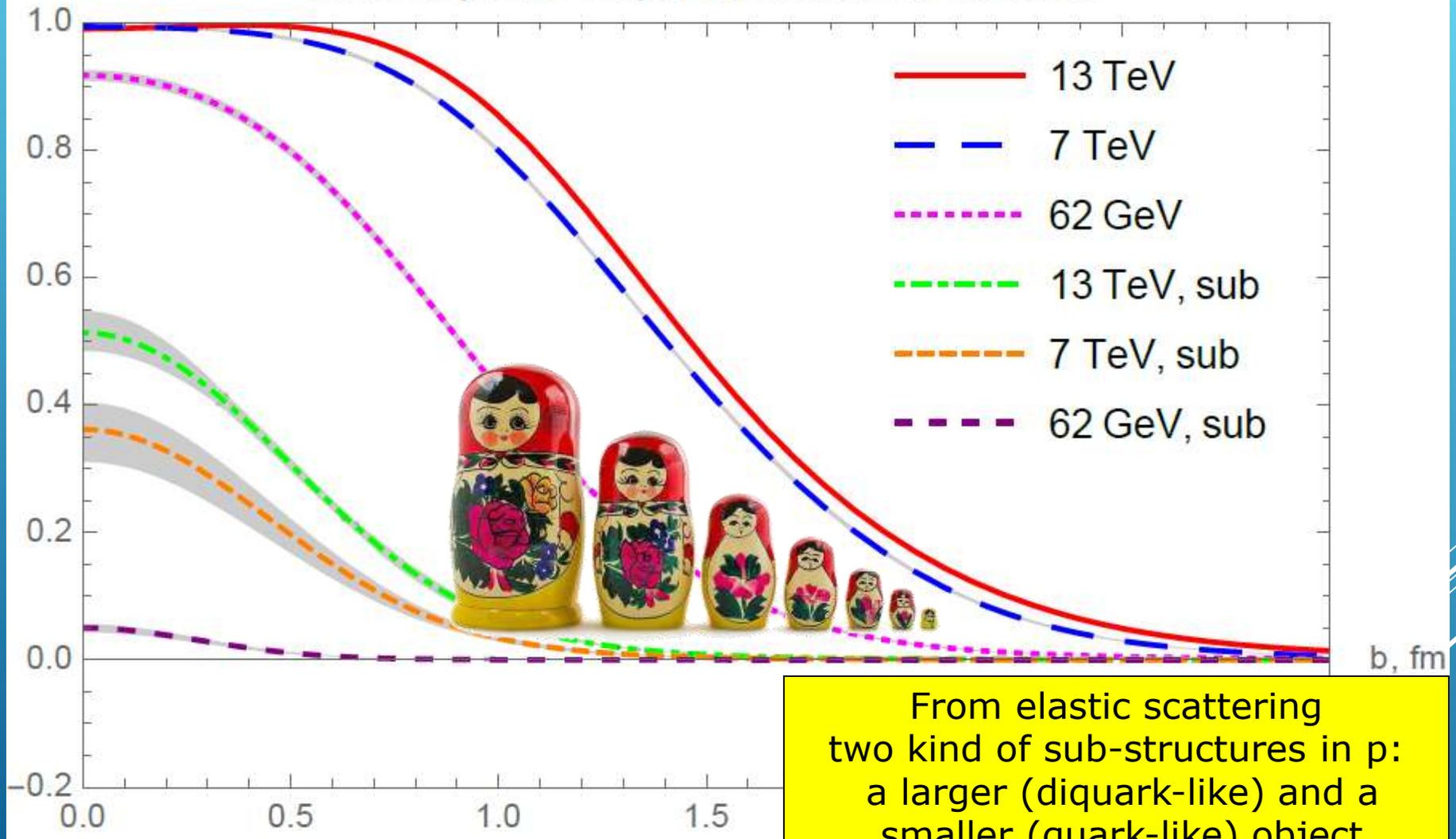
Shadow profile for proton and its substructure



From elastic scattering
two kind of sub-structures in p:
a larger (diquark-like) and a
smaller (quark-like) object.
Grey bands: systematic errors!

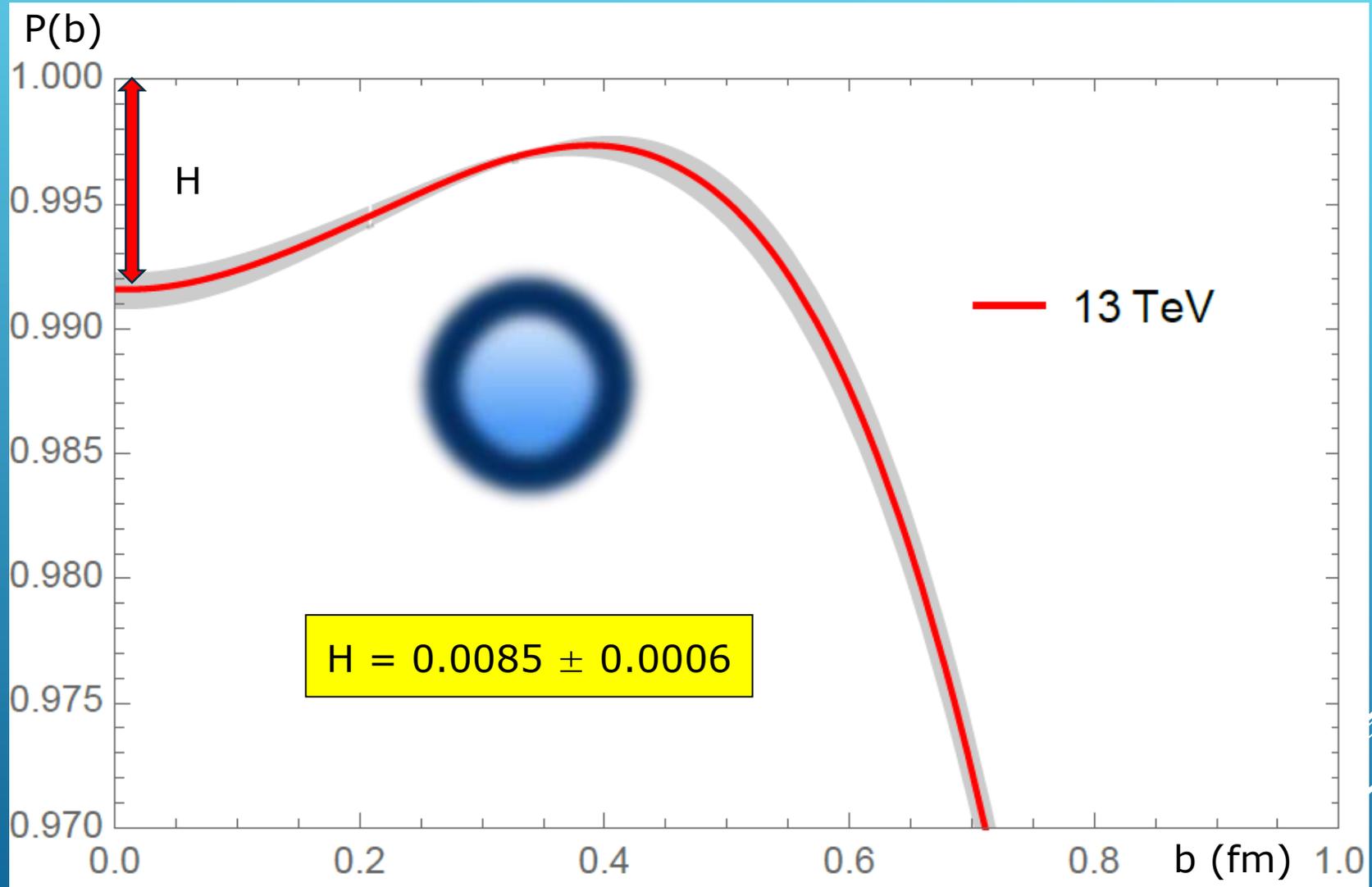
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Shadow profile for proton and its substructure



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What about hollowness?



I. Dremin, [arXiv:1610.07937](https://arxiv.org/abs/1610.07937) also in *Universe* 4 (2018) no.5, 65
W. Broniowski et al, [arXiv:1806.04756](https://arxiv.org/abs/1806.04756)
V. A. Petrov and A. Samokhin, [arXiv:1801.038](https://arxiv.org/abs/1801.038)

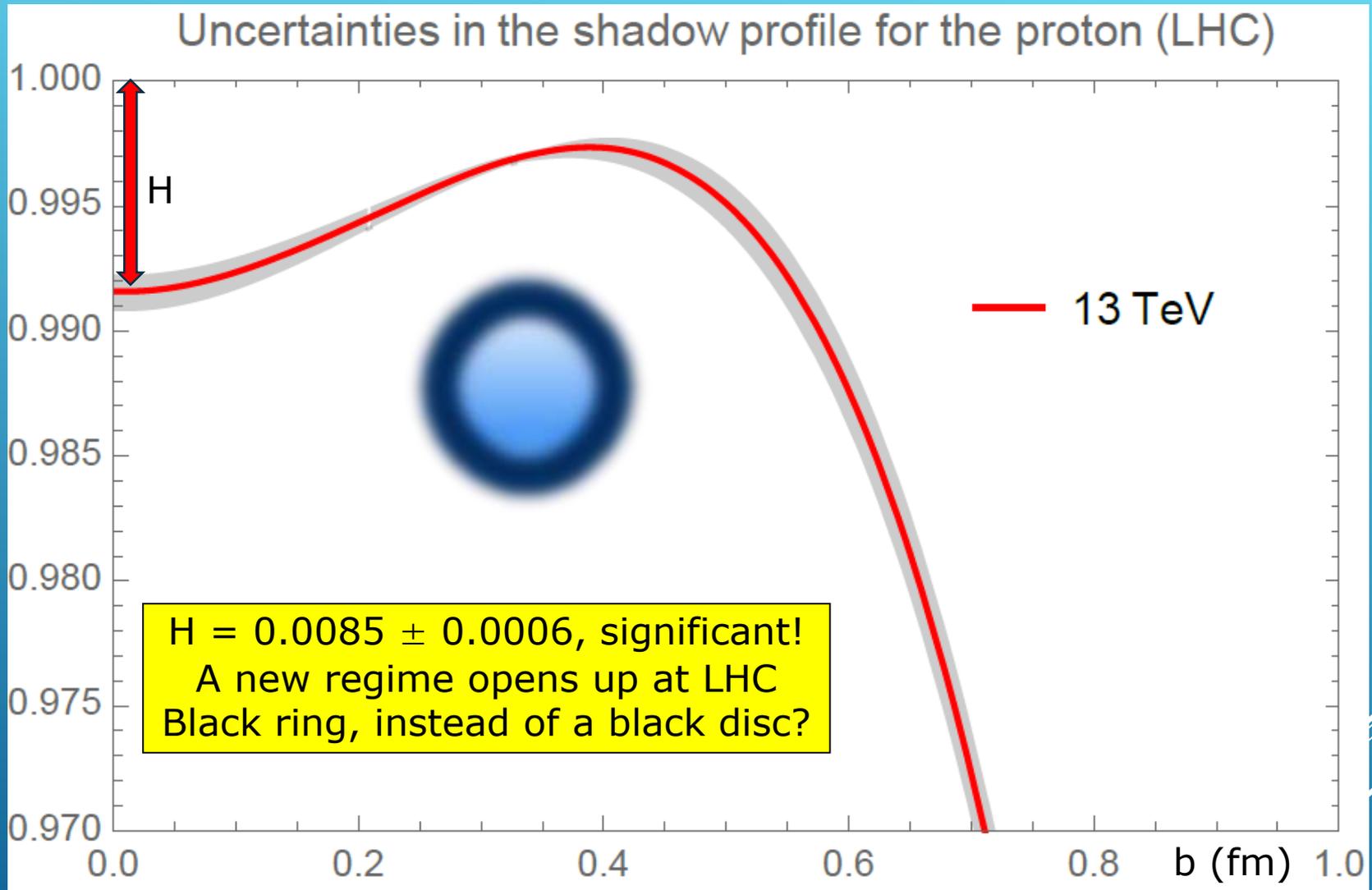
35

Alkin et al, [arXiv:1807.06471](https://arxiv.org/abs/1807.06471)

Significance:

T. Csörgő, R. Pasechnik, A. Ster, in preparation

What about hollowness?



I. Dremin, [arXiv:1610.07937](https://arxiv.org/abs/1610.07937) also in *Universe* 4 (2018) no.5, 65
W. Broniowski et al, [arXiv:1806.04756](https://arxiv.org/abs/1806.04756)
V. A. Petrov and A. Samokhin, [arXiv:1801.038](https://arxiv.org/abs/1801.038)

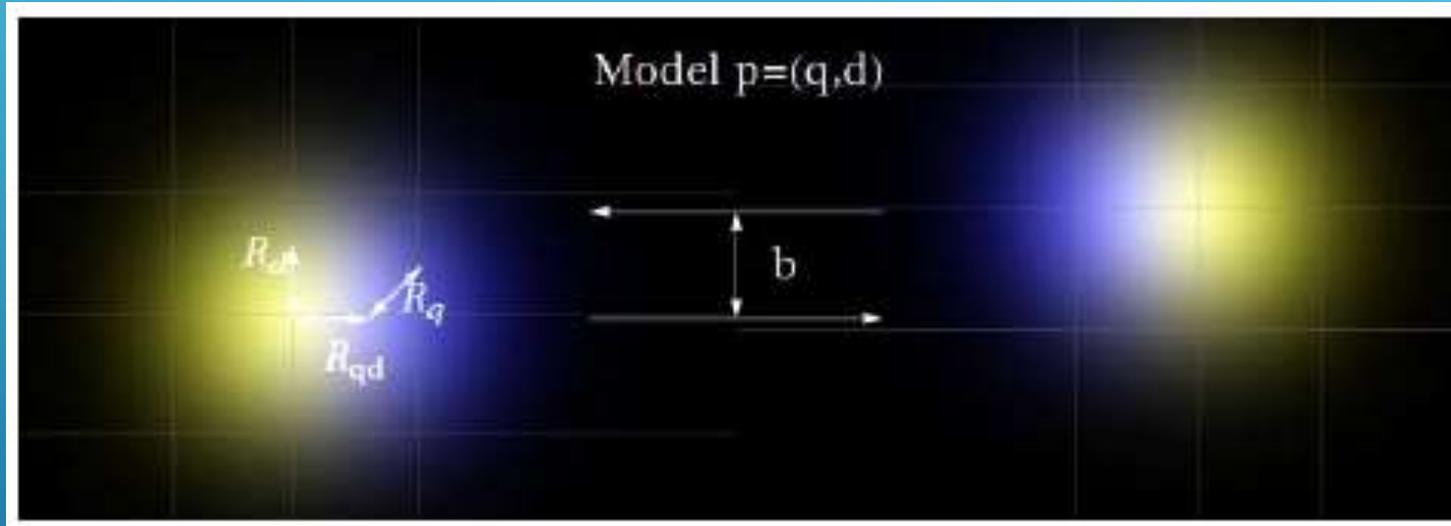
36

Alkin et al, [arXiv:1807.06471](https://arxiv.org/abs/1807.06471)

Significance:

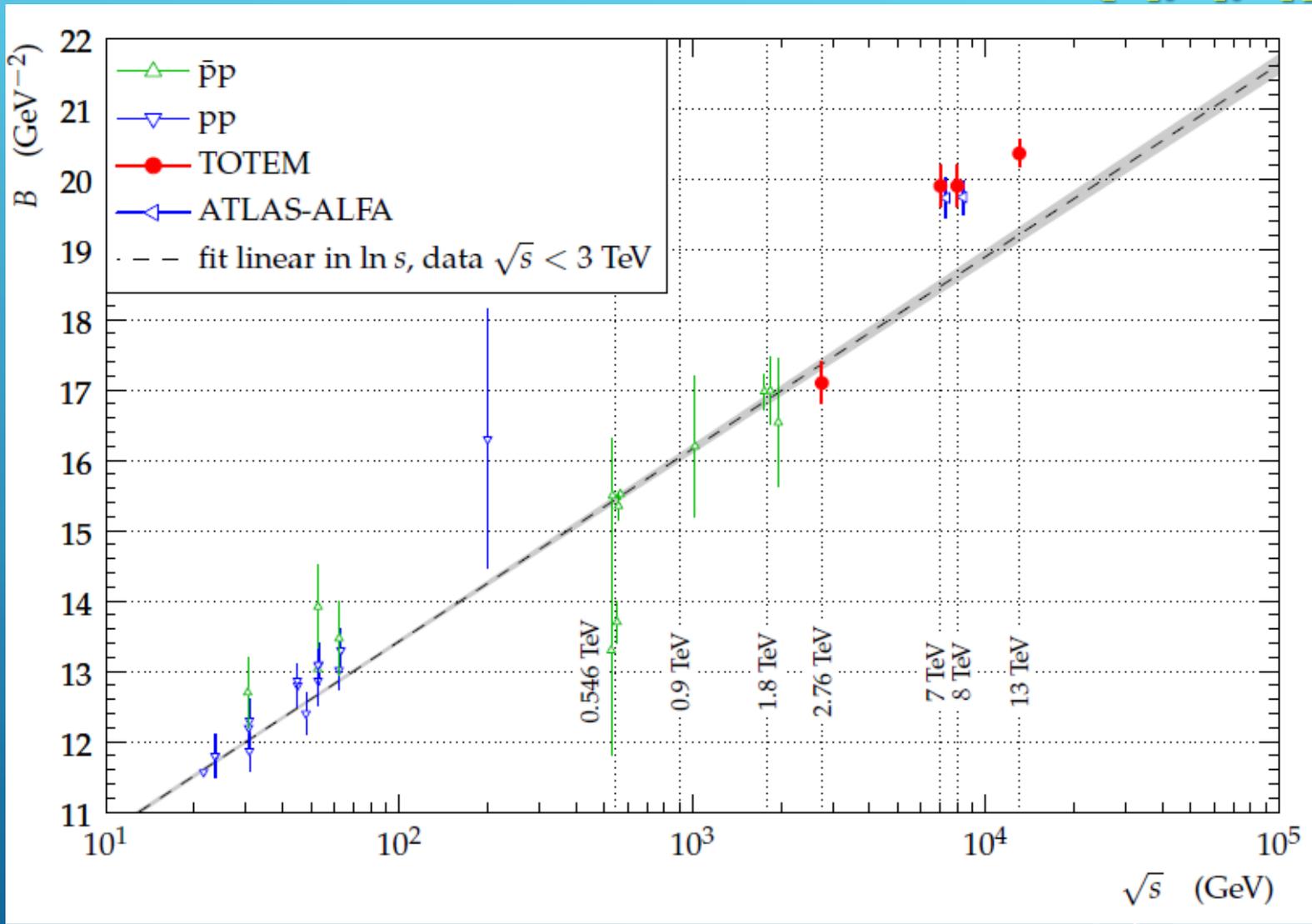
T. Csörgő, R. Pasechnik, A. Ster, in preparation

SUMMARY



Thank you for your attention!
Questions?

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

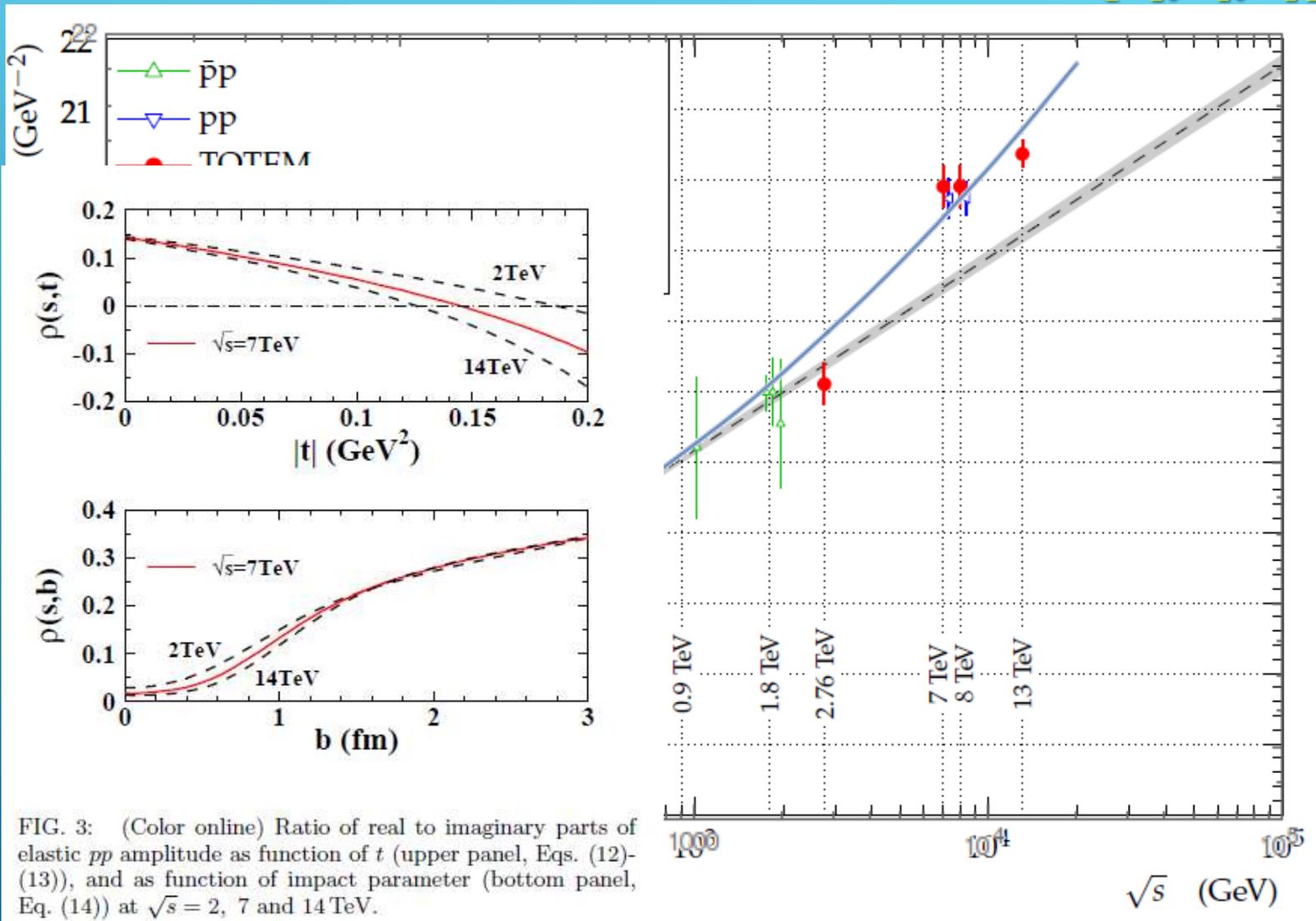


FIG. 3: (Color online) Ratio of real to imaginary parts of elastic pp amplitude as function of t (upper panel, Eqs. (12)-(13)), and as function of impact parameter (bottom panel, Eq. (14)) at $\sqrt{s} = 2, 7$ and 14 TeV.

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

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

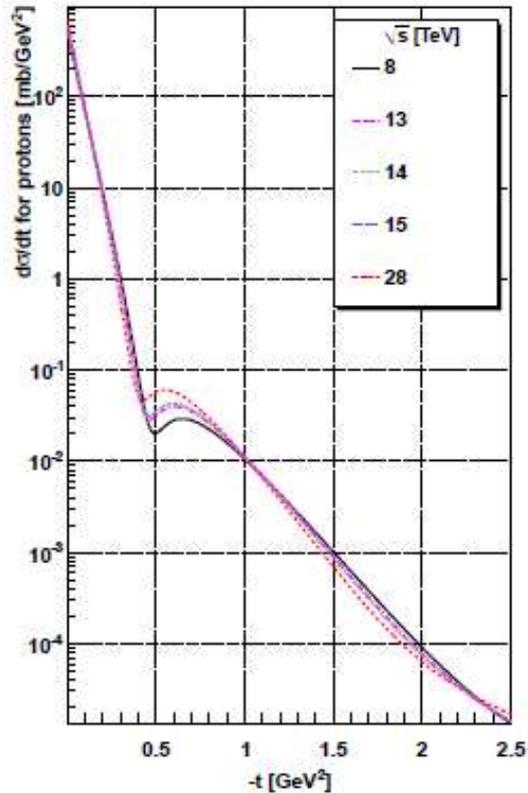


Figure 8: The pp elastic differential cross-section is extrapolated to 8 TeV as well as to future LHC energies and beyond.

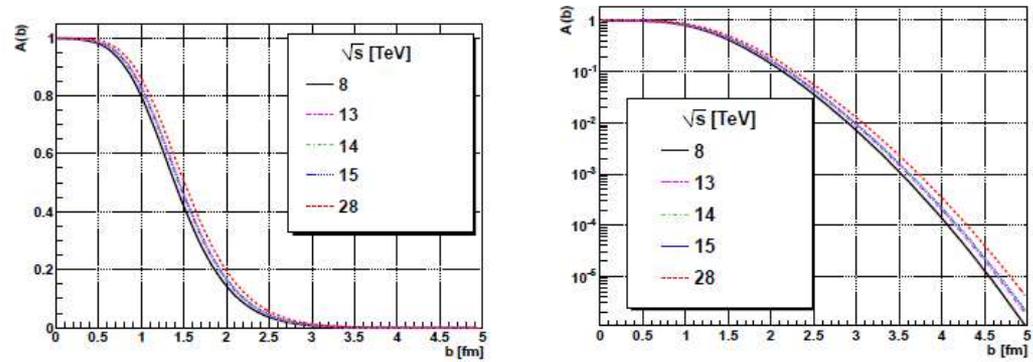
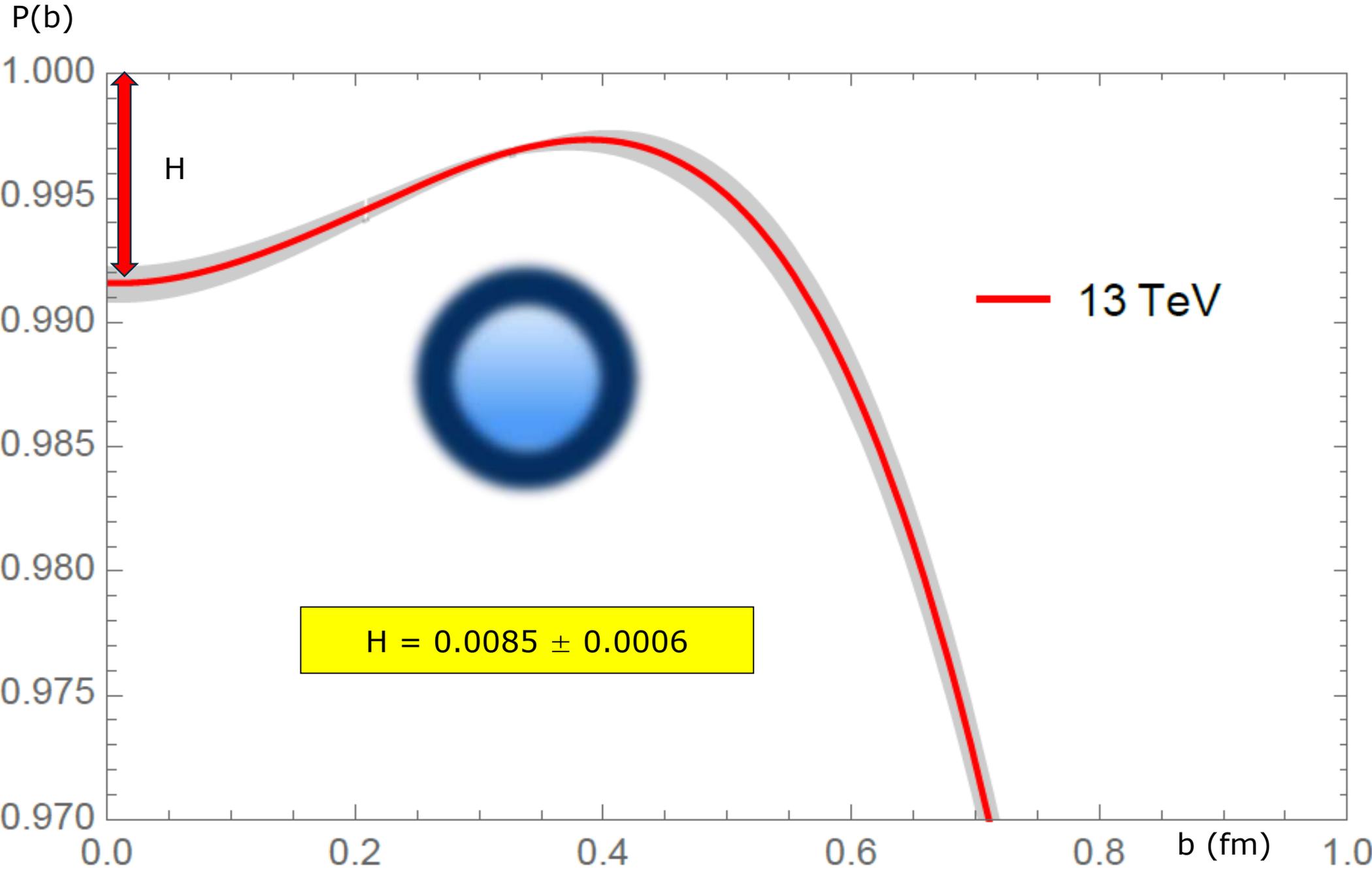


Figure 9: The shadow profile function at the extrapolated energies \sqrt{s} . The results show the increase of the proton interaction radius with increasing \sqrt{s} energies. Also note that the “edge” of the distributions remains of approximately constant width and shape.

\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 refined.
 $P = (q,(q,q))$ variation gave too many oscillations in $d\sigma/dt$ at large $-t$.

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



(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 coefficients 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 existence 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.

T. Cs, R. Pasechnik, A. Ster, [arxiv.org:1807.02897](https://arxiv.org/abs/1807.02897)

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

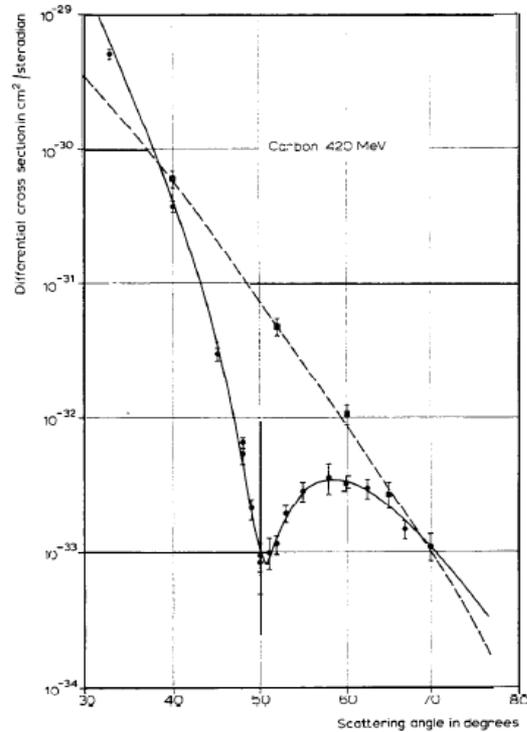
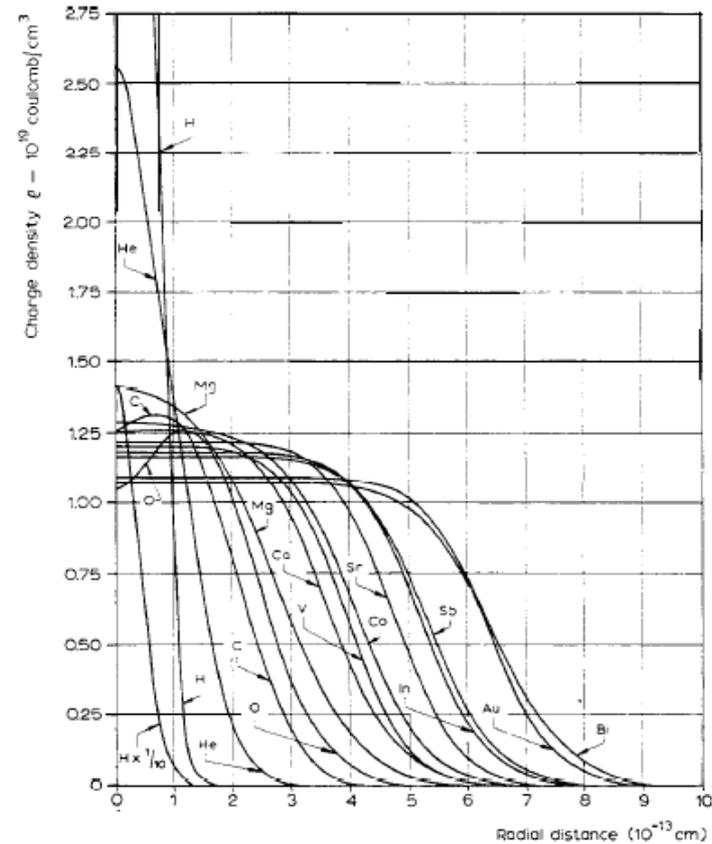


Fig. 5. This figure shows the elastic and inelastic curves corresponding to the scattering of 420-MeV electrons by ^{12}C . The *solid circles*, representing experimental points, show the elastic-scattering behavior while the *solid squares* show the inelastic-scattering curve for the 4.43-MeV level 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.

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1961 R. HOFSTADTER



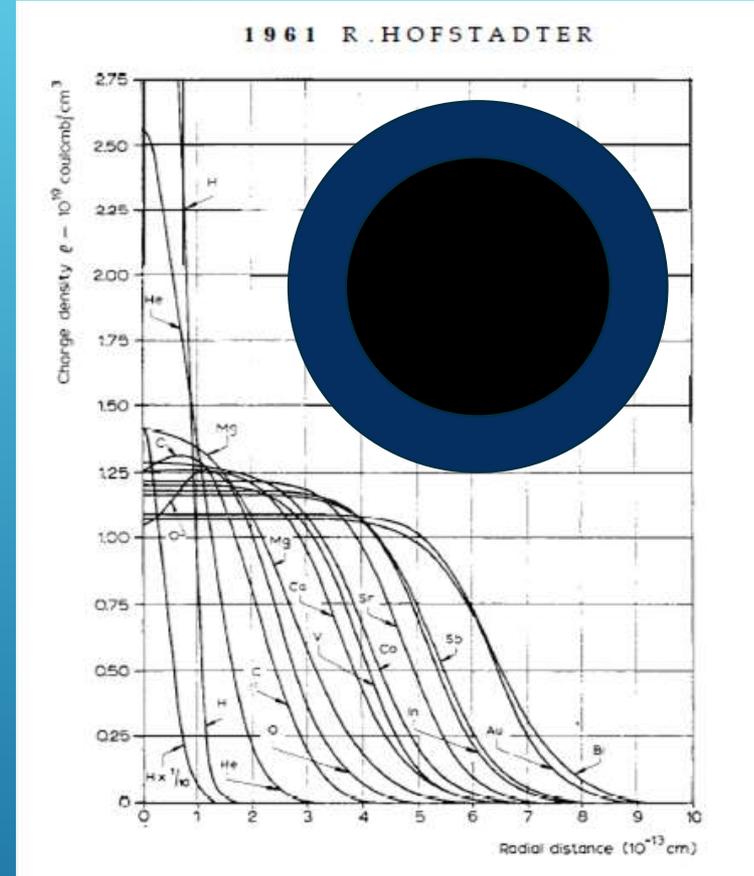
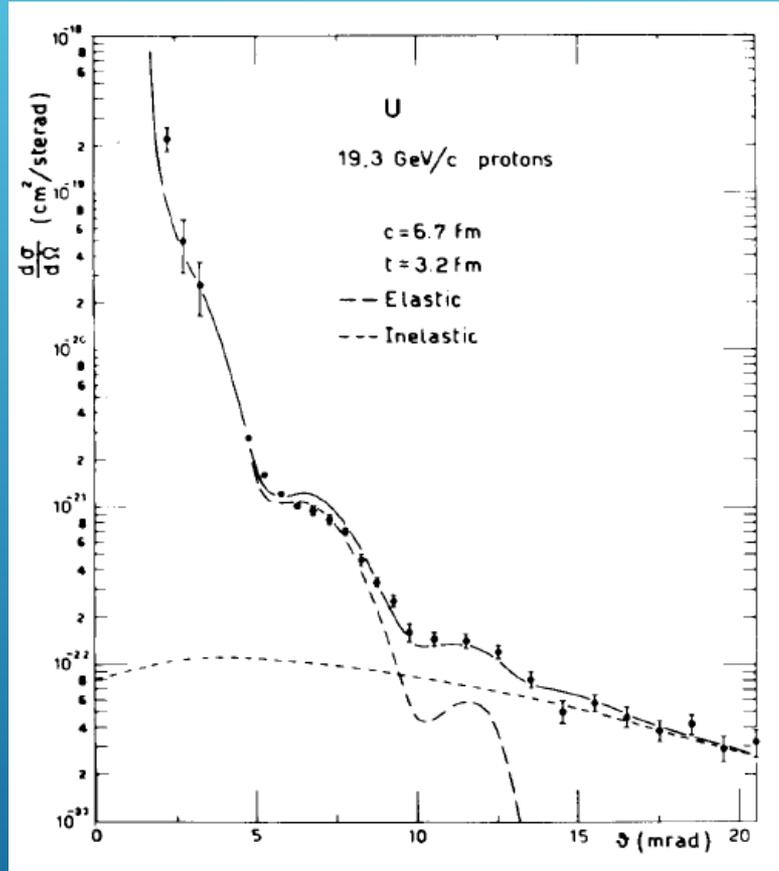
e+A: elastic electron-nucleus scattering



Imaging: electric charge distribution of spherical nuclei

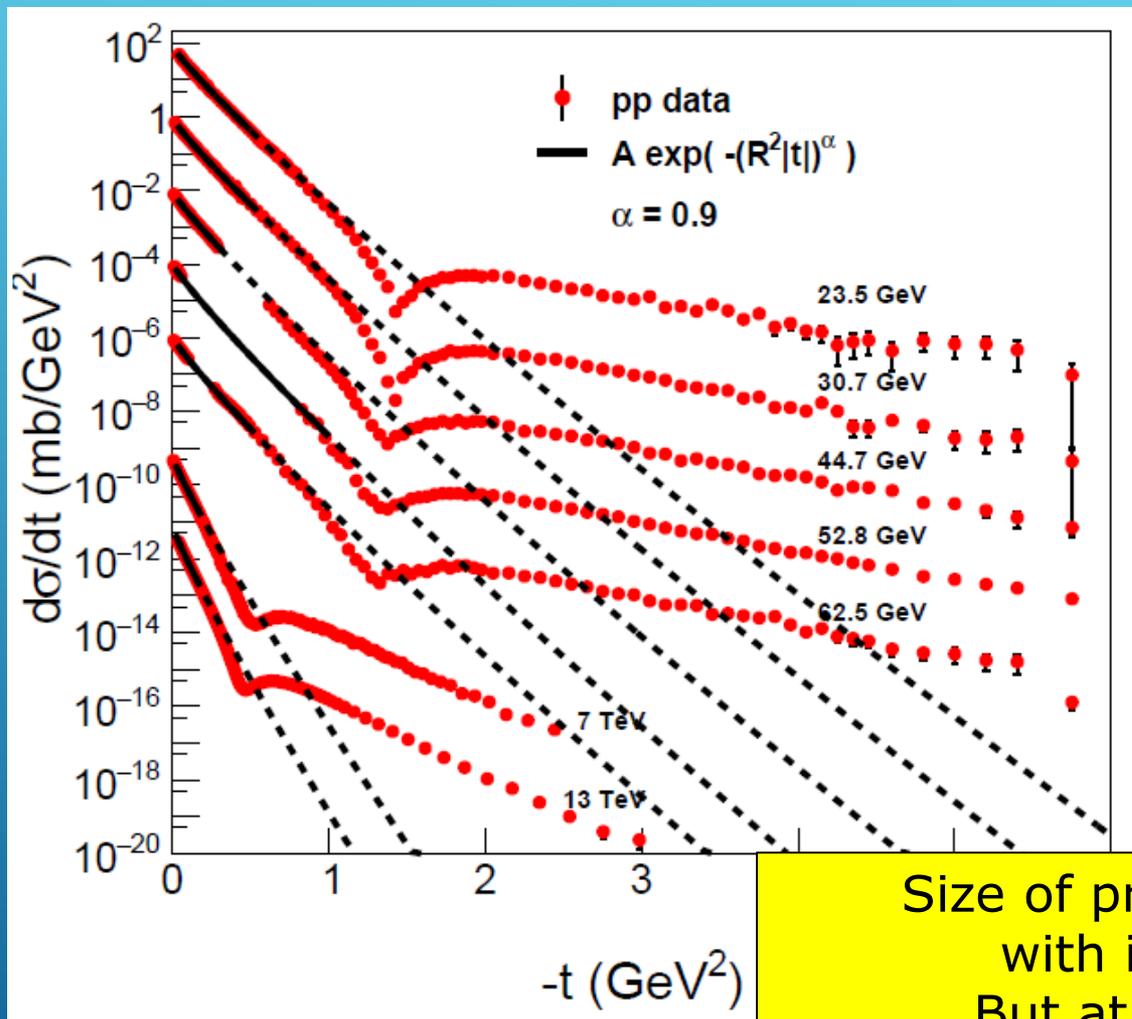
p+A → p+A

Glauber and Matthiae, NPB21 (1970) 135



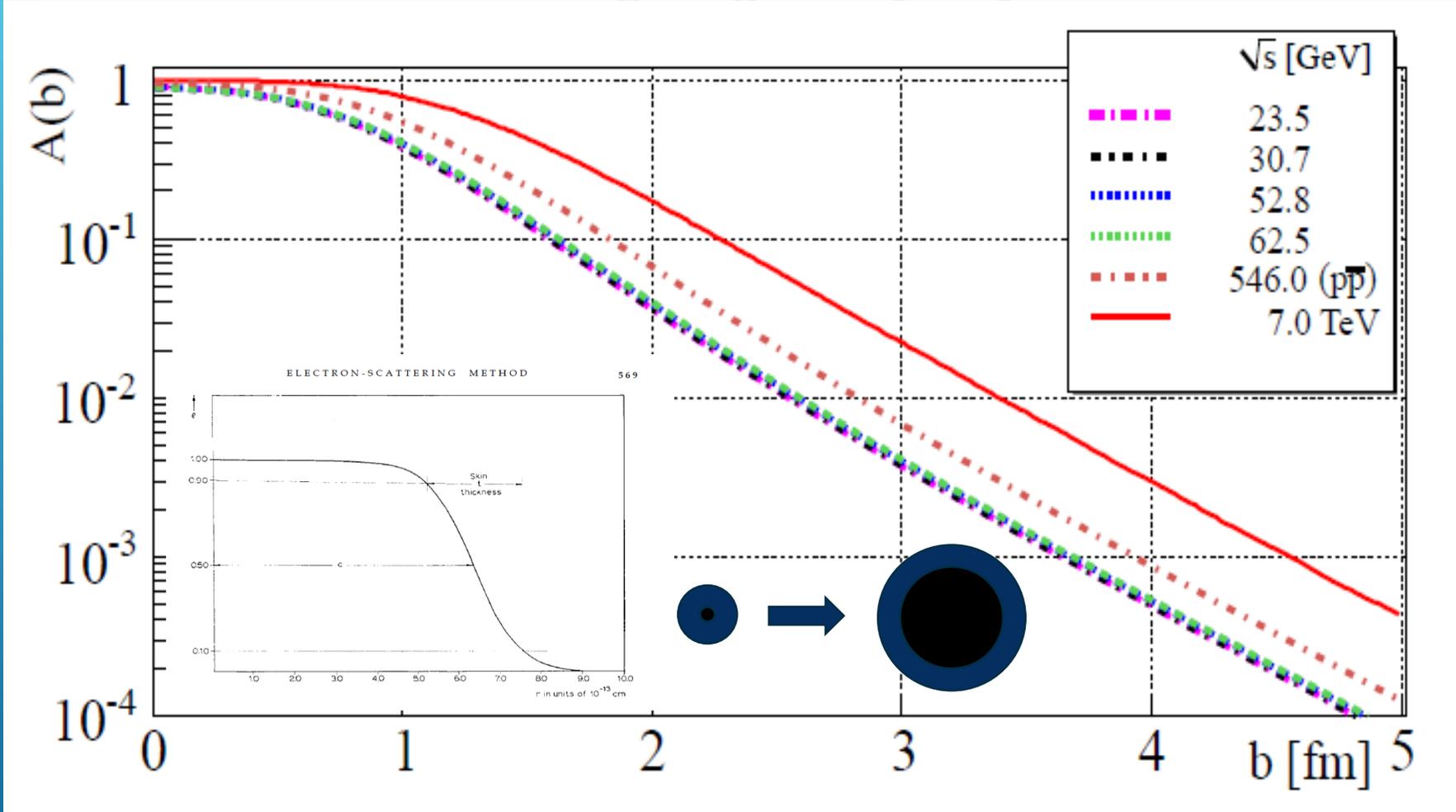
The distribution of the nucleons (p+n)
 \sim the distribution of electric charge (p) in atomic nuclei.

LEVY FITS: APPROXIMATE STRUCTURE



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

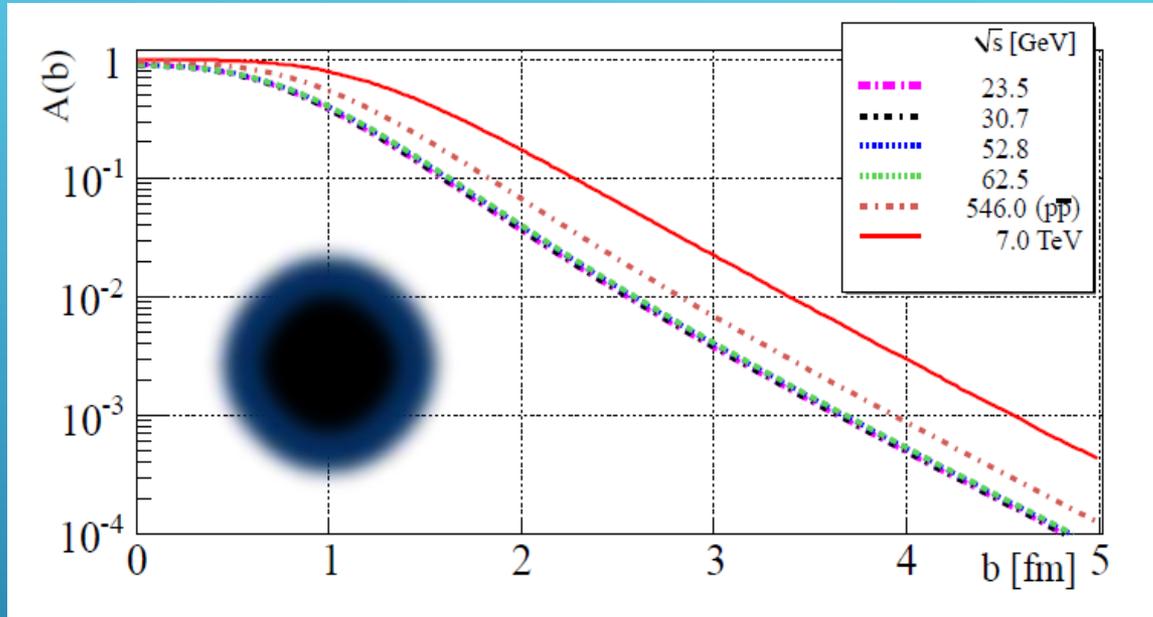
Shadow imaging in p+p at LHC



The **BnEL** effect.

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

SATURATION FROM SHADOW PROFILES



at 7 TeV, proton

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

BEL → **BnEL** effect
[arxiv:1311.2308](https://arxiv.org/abs/1311.2308)
F. Nemes, T. Cs, M. Csanád

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

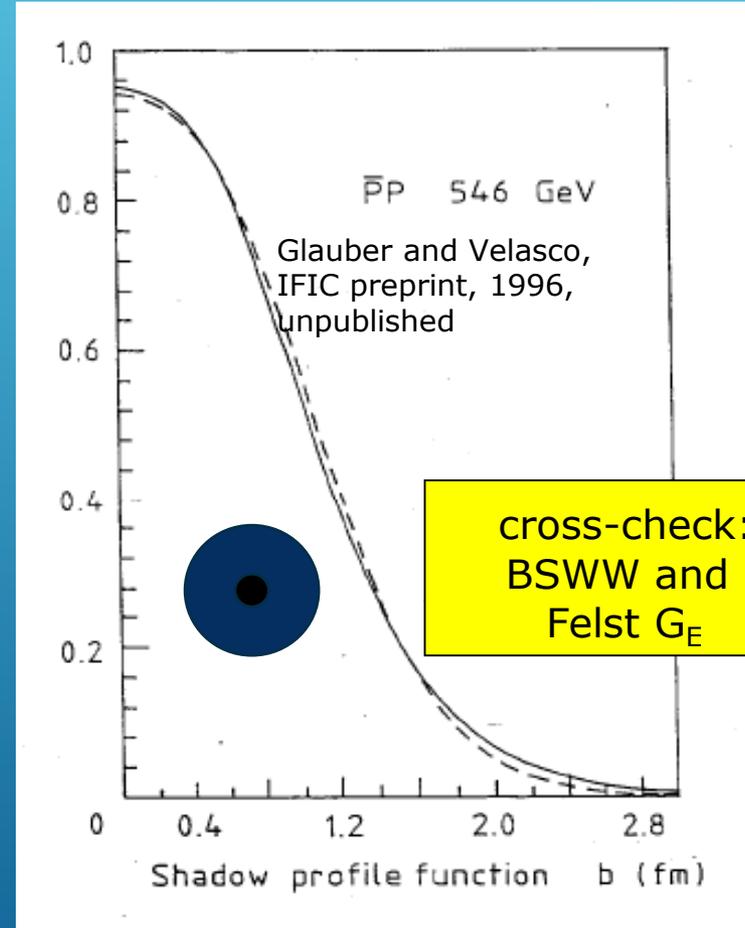
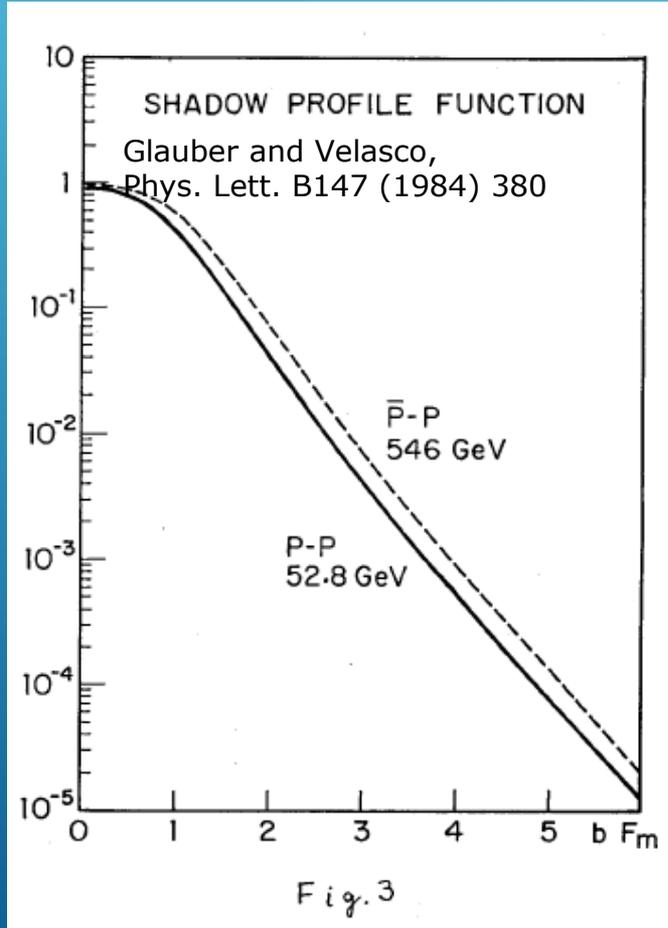
ISR and SppS:
R.J. Glauber and J.Velasco
Phys. Lett. B147 (1987) 380
 b_1, b_2 fixed

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

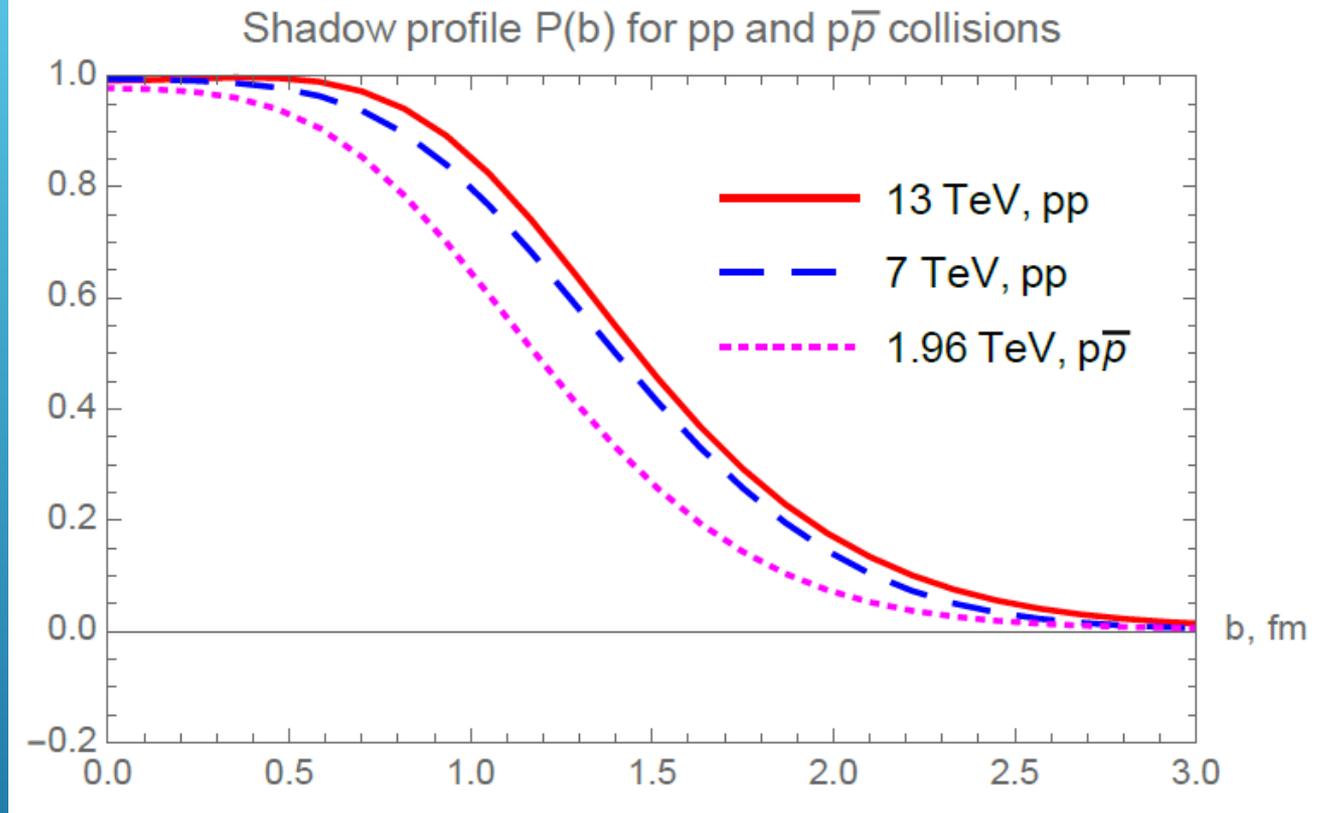
see also Lipari and Lusignoli,
[arXiv:1305.7216](https://arxiv.org/abs/1305.7216)

Imaging with shadow profile

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



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



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

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

