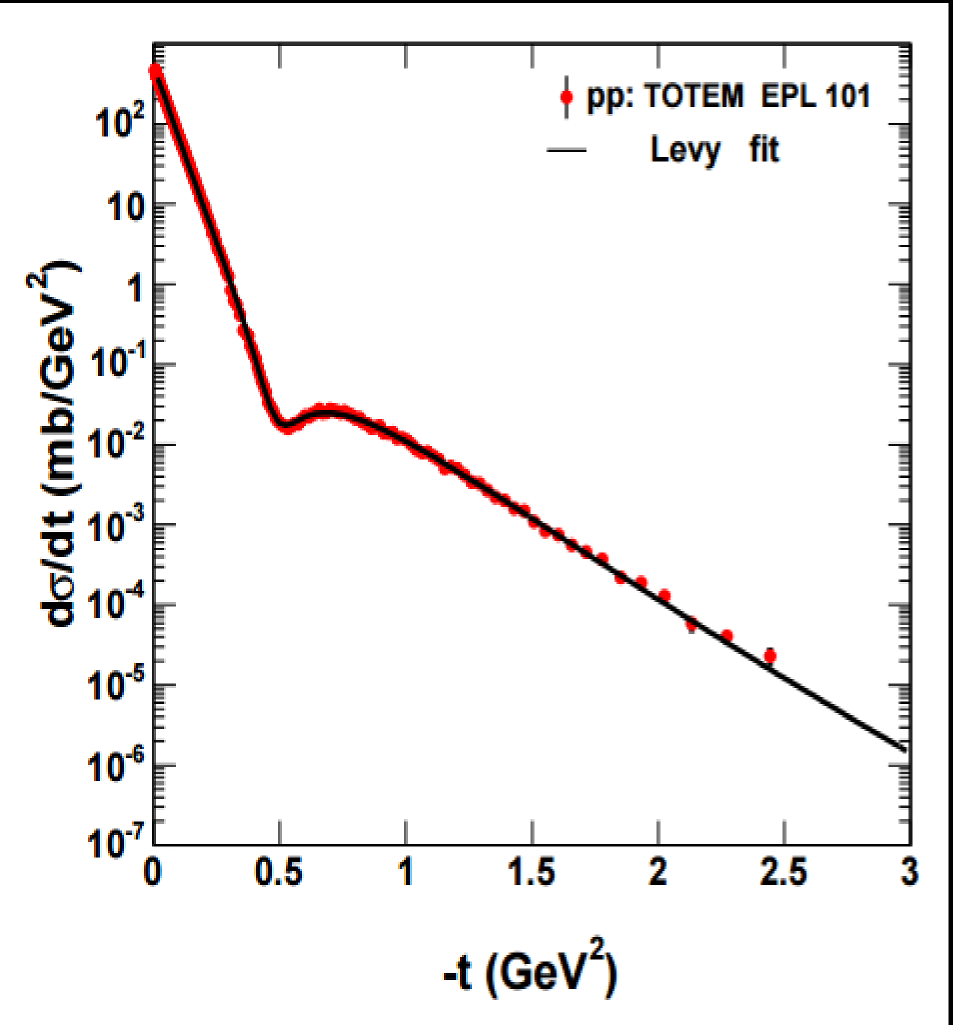
Model independent analysis method for the differential cross-section of elastic pp scattering



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OUTLINE

Model-independent shape analysis:

- General introduction
- Edgeworth, Laguerre
- Levy expansions
- Application in elastic pp scattering

Summary

MODEL - INDEPENDENT SHAPE ANALYIS I.

experimental properties:

i) The correlation function tends to a constant for large values of the relative momentum Q.

ii) The correlation function has a non-trivial structure at a certain value of its argument.

The location of the non-trivial structure in the correlation function is assumed for simplicity to be close to $Q = 0$.

Model-independent but experimentally testable:

- $w(t)$ measure in an abstract H-space
- approximate form of the correlations
- **t: dimensionless scale variable**

$$\int dt w(t) h_n(t) h_m(t) = \delta_{n,m},$$

$$f(t) = \sum_{n=0}^{\infty} f_n h_n(t),$$

$$f_n = \int dt w(t) f(t) h_n(t).$$

e.g. $t = Q_I R_I$

MODEL - INDEPENDENT SHAPE ANALYIS II.

$$C_2(\mathbf{k}_1, \mathbf{k}_2) = \frac{N_2(\mathbf{k}_1, \mathbf{k}_2)}{N_1(\mathbf{k}_1)\, N_1(\mathbf{k}_2)},$$

$$R_2(\mathbf{k}_1, \mathbf{k}_2) = C_2(\mathbf{k}_1, \mathbf{k}_2) - 1.$$

Let us assume, that the function $g(t) = R_2(t)/w(t)$ is also an element of the Hilbert space H. This is possible, if

$$\int dt\, w(t) g^2(t) = \int dt\, \left[R_2^2(t)/w(t)\right] < \infty, \qquad (6)$$

Then the function *g* can be expanded as

$$g(t) = \sum_{n=0}^{\infty} g_n h_n(t),$$

$$g_n = \int dt\, R_2(t) h_n(t).$$

From the completeness of the Hilbert space and from the assumption that *g*(*t*) is in the Hilbert space:

$$R_2(t) = w(t) \sum_{n=0}^{\infty} g_n h_n(t).$$

MODEL - INDEPENDENT SHAPE ANALYIS III.

$$C_2(\mathbf{k}_1, \mathbf{k}_2) = \frac{N_2(\mathbf{k}_1, \mathbf{k}_2)}{N_1(\mathbf{k}_1)\, N_1(\mathbf{k}_2)},$$

$$C_2(t) = \mathcal{N}\left\{1 + \lambda_w\, w(t) \sum_{n=0}^{\infty} g_n h_n(t)\right\}$$

Model-independent AND experimentally testable:

- method for any approximate shape *w*(*t*)
- the core-halo intercept parameter of the CF is $$\lambda_* = \lambda_w \sum_{n=0}^{\infty} g_n h_n(0)$$
- coefficients by numerical integration (fits to data) $$g_n = \int dt\, R_2(t) h_n(t)$$
- condition for applicability: experimentally testabe $$\int dt\, \left[R_2^2(t)/w(t)\right] < \infty$$

EDGEWORTH EXPANSION: ~ GAUSSIAN

$$t = \sqrt{2} Q R_E,$$

$$w(t) = \exp(-t^2/2),$$

$$\int_{-\infty}^{\infty} dt \, \exp(-t^2/2) H_n(t) H_m(t) \propto \delta_{n,m},$$

$$H_n(t) = \exp(t^2/2) \left(-\frac{d}{dt}\right)^n \exp(-t^2/2).$$

$$H_1(t) = t,$$
$$H_2(t) = t^2 - 1,$$
$$H_3(t) = t^3 - 3t,$$
$$H_4(t) = t^4 - 6t^2 + 3, \; \ldots$$

$$C_2(Q) = \mathcal{N} \left\{ 1 + \lambda_E \exp(-Q^2 R_E^2) \times \left[1 + \frac{\kappa_3}{3!} H_3(\sqrt{2} Q R_E) + \frac{\kappa_4}{4!} H_4(\sqrt{2} Q R_E) + \ldots \right] \right\}.$$

3d generalization straightforward

- Applied by NA22, L3, STAR, PHENIX, ALICE, CMS (LHCb?)

LAGUERRE EXPANSIONS: ~ EXPONENTIAL

Model-independent but experimentally tested:

- $w(t)$ exponential
- t: dimensionless
- Laguerre polynomials

$$t = QR_L,$$
$$w(t) = \exp(-t)$$
$$\int_0^\infty dt \, \exp(-t) L_n(t) L_m(t) \propto \delta_{n,m},$$

$$L_n(t) = \exp(t) \frac{d^n}{dt^n} (-t)^n \exp(-t).$$

$$L_0(t) = 1,$$
$$L_1(t) = t - 1,$$

$$C_2(Q) = \mathcal{N} \left\{ 1 + \lambda_L \exp(-QR_L) \left[1 + c_1 L_1(QR_L) + \frac{c_2}{2!} L_2(QR_L) + ... \right] \right\}$$

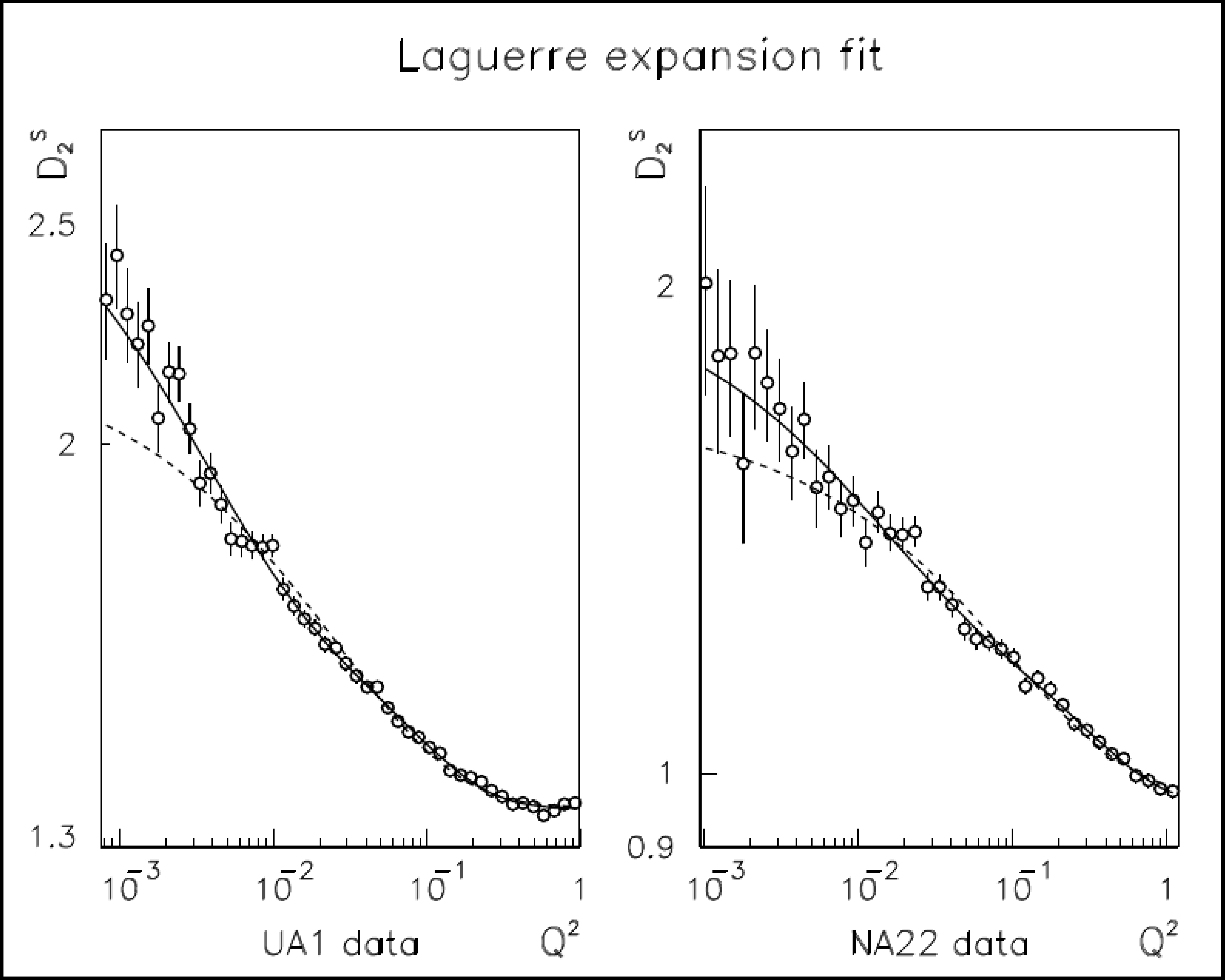
First successful tests

- NA22, UA1 data
- convergence criteria satisfied
- intercept parameter ~ 1

$$\int_0^\infty dt \, R_2^2(t) \exp(+t) < \infty,$$

$$\lambda_* = \lambda_L [1 - c_1 + c_2 - ...],$$
$$\delta^2 \lambda_* = \delta^2 \lambda_L \left[1 + c_1^2 + c_2^2 + ... \right] + \lambda_L^2 \left[\delta^2 c_1 + \delta^2 c_2 + ... \right]$$

LAGUERRE EXPANSIONS: ~ superEXPONENTIAL



T. Csörgő and S: Hegyi, hep-ph/9912220, T. Csörgő, hep-ph/001233

MINIMAL MODEL ASSUMPTION: LEVY

experimental conditions:
(i) The correlation function tends to a constant for large values of the relative momentum Q.
(ii) The correlation function deviates from its asymptotic, large Q value in a certain domain of its argument.

(iii) The two-particle correlation function is related to a Fourier transformed space-time distribution of the source.

Model-independent but:

- Assumes that Coulomb can be corrected
- No assumptions about analyticity yet
- For simplicity, consider 1d case first
- For simplicity, consider factorizable *x k*
- Normalizations :
  - density
  - multiplicity
  - single-particle spectra

$$C_2(\mathbf{k}_1, \mathbf{k}_2) = \frac{N_2(\mathbf{k}_1, \mathbf{k}_2)}{N_1(\mathbf{k}_1)\, N_1(\mathbf{k}_2)}$$

$$S(x,k) = f(x)\, g(k)$$

$$\int \mathrm{d}x\, f(x) = 1, \qquad \int \mathrm{d}k\, g(k) = \langle n \rangle,$$

$$N_1(k) = \int \mathrm{d}x\, S(x,k) = g(k).$$

T. Cs, S. Hegyi, W.A. Zajc, EPJ C36, 67 (2004)

MINIMAL MODEL ASSUMPTION: LEVY

Model-independent but:

- not assumes analyticity
- C_2 measures a modulus squared Fourier-transform vs relative momentum
- Correlations non-Gaussian
- Radius not a variance
- $0 < \alpha \le 2$

$$C_2(k_1, k_2) = 1 + |\tilde{f}(q_{12})|^2,$$

$$\tilde{f}(q_{12}) = \int \mathrm{d}x \, \exp(\mathrm{i} q_{12} x) \, f(x),$$

$$C(q;\alpha) = 1 + \lambda \exp\left(-|qR|^{\alpha}\right).$$

T. Cs, S. Hegyi, W.A. Zajc, EPJ C36, 67 (2004)

UNIVARIATE LEVY EXAMPLES

Include some well known cases:

- $\alpha = 2$
  - Gaussian source, Gaussian C_2

$$f(x) = \frac{1}{(2\pi R^2)^{1/2}} \exp\left[-\frac{(x-x_0)^2}{2R^2}\right]$$

$$C(q) = 1 + \exp\left(-q^2 R^2\right)$$

- $\alpha = 1$
  - Lorentzian source, exponential C_2

$$f(x) = \frac{1}{\pi} \frac{R}{R^2 + (x-x_0)^2},$$

$$C(q) = 1 + \exp\left(-|q\, R|\right).$$

- asymmetric Levy:
  - asymmetric support
  - Streched exponential

$$f(x) = \sqrt{\frac{R}{8\pi}} \frac{1}{(x-x_0)^{3/2}} \exp\left(-\frac{R}{8(x-x_0)}\right)$$

$$x_0 < x < \infty,$$

$$C(q) = 1 + \exp\left(-\sqrt{|q\, R|}\right).$$

T. Cs, hep-ph/0001233, T. Cs, S. Hegyi, W.A. Zajc, EPJ C36, 67 (2004)

LEVY EXPANSIONS: ~ 1d LEVY

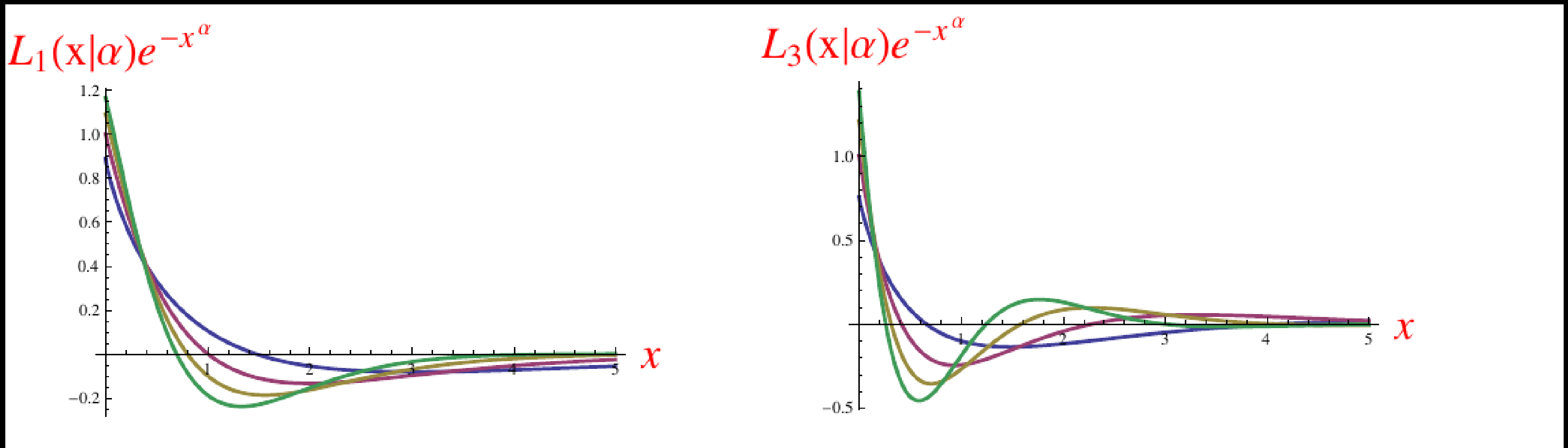
Model-independent but:

- Levy generalizes exponentials and Gaussians
- ubiquoutous in nature
- How far from a Levy?
- Need new set of polynomials orthonormal to a Levy weight

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

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

$$\mu_{r,\alpha} = \int_0^\infty dx\ x^r f(x\,|\,\alpha) = \frac{1}{\alpha}\Gamma\left(\frac{r+1}{\alpha}\right)$$



Lévy polynomials of first and third order times the weight function e^{-x^α} for $\alpha = 0.8, 1.0, 1.2, 1.4$.

1st-order Lévy polynomial	$\gamma\left[1+\lambda e^{-R^\alpha Q^\alpha}\left[1+c_1 L_1(Q\vert\alpha,R)\right]\right]$
3rd-order Lévy polynomial	$\gamma\left[1+\lambda e^{-R^\alpha Q^\alpha}\left[1+c_1 L_1(Q\vert\alpha,R)+c_3 L_3(Q\vert\alpha,R)\right]\right]$

M. de Kock, H. C. Eggers, T. Cs: arXiv:1206.1680v1 [nucl-th]

LEVY EXPANSIONS: ~ 1d LEVY

In case of $\alpha = 1$ Laguerre is ok

$$
\begin{aligned}
L_0(t\,|\,\alpha = 1) &= 1, \\
L_1(t\,|\,\alpha = 1) &= t - 1, \\
L_2(t\,|\,\alpha = 1) &= t^2 - 4t + 2.
\end{aligned}
$$

These reduce to the Laguerre expansions and Laguerre polynomials.

LEVY EXPANSIONS: ~ 1d LEVY

In case of α = 2 instead of Edgeworth new formulae for one-sided Gaussian:

$$
\begin{aligned}
L_0(t\,|\,\alpha=2) &= \frac{\sqrt{\pi}}{2}, \\
L_1(t\,|\,\alpha=2) &= \frac{1}{2}\left\{\sqrt{\pi}t-1\right\}, \\
L_2(t\,|\,\alpha=2) &= \frac{1}{32}\left\{(\pi-2)t^2-\sqrt{\pi}t+2-\frac{\pi}{2}\right\}.
\end{aligned}
$$

Provides a new expansion around a Gaussian shape that is defined for the non-negative values of *t* only.

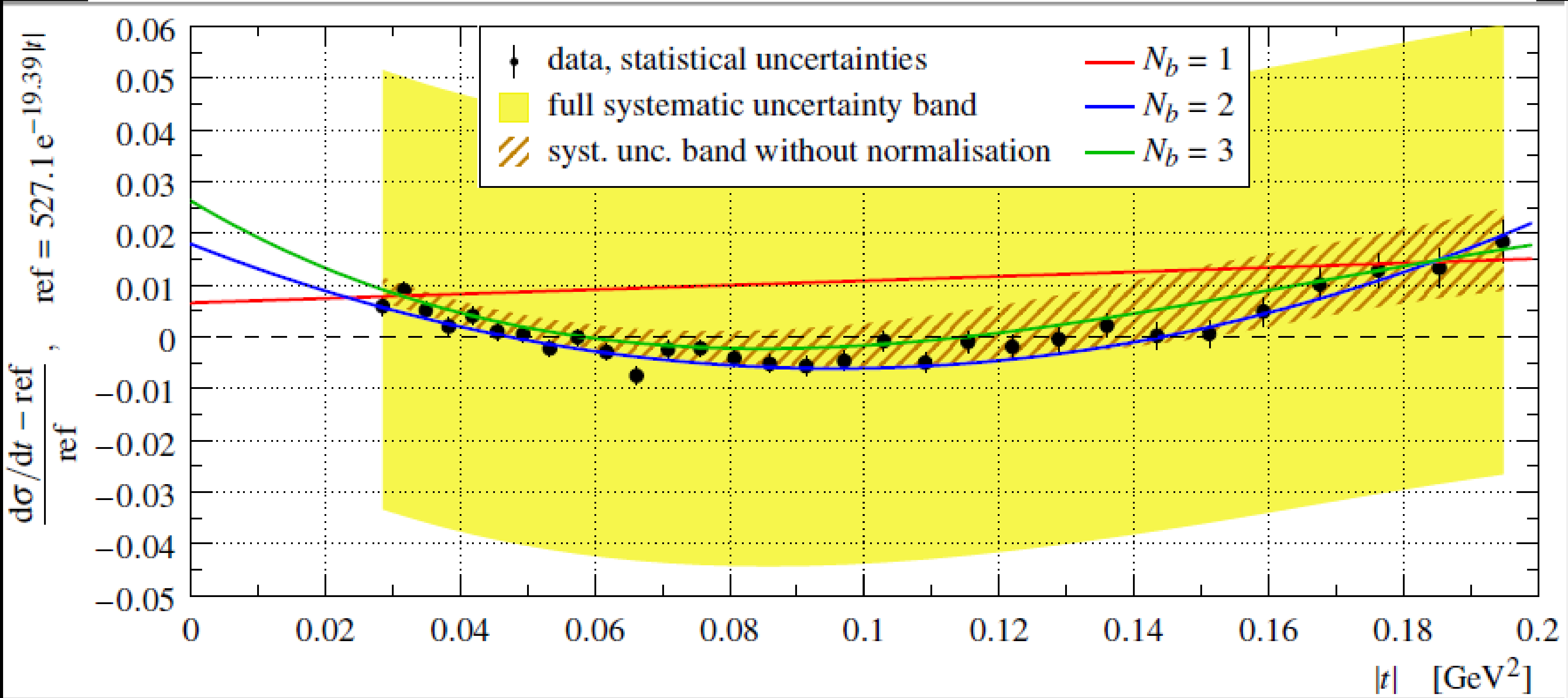
arXiv:1604.05513 [physics.data-an]

Non-Exponential Differential cross-section

To study the detailed behaviour of the differential cross-section, a series of fits has been made using the parametrisation:

$$\frac{d\sigma}{dt}(t) = \left.\frac{d\sigma}{dt}\right|_{t=0} \exp\left(\sum_{i=1}^{N_b} b_i t^i\right) , \qquad (15)$$

which includes the pure exponential ($N_b = 1$) and its straight-forward extensions ($N_b = 2, 3$).



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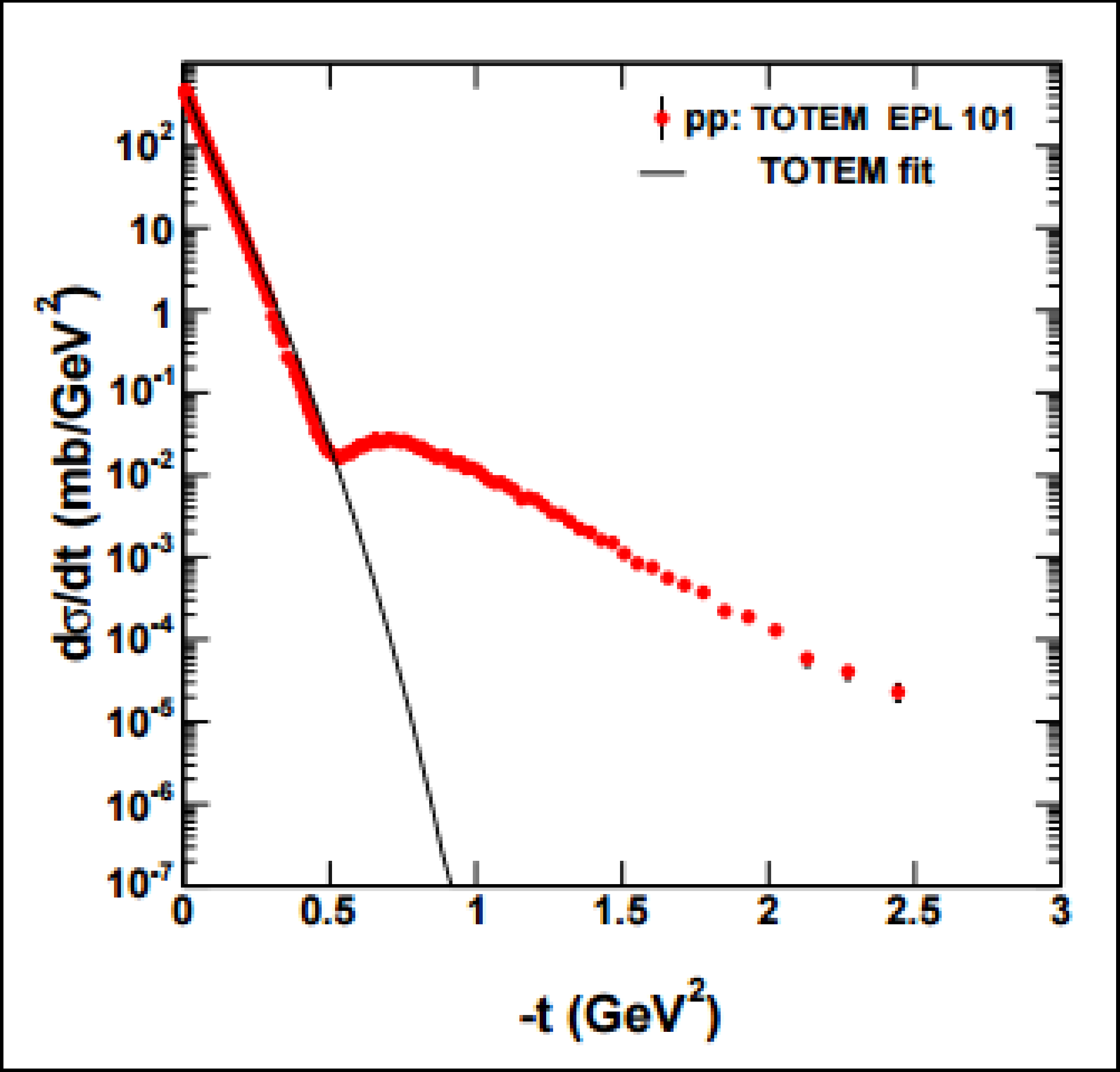
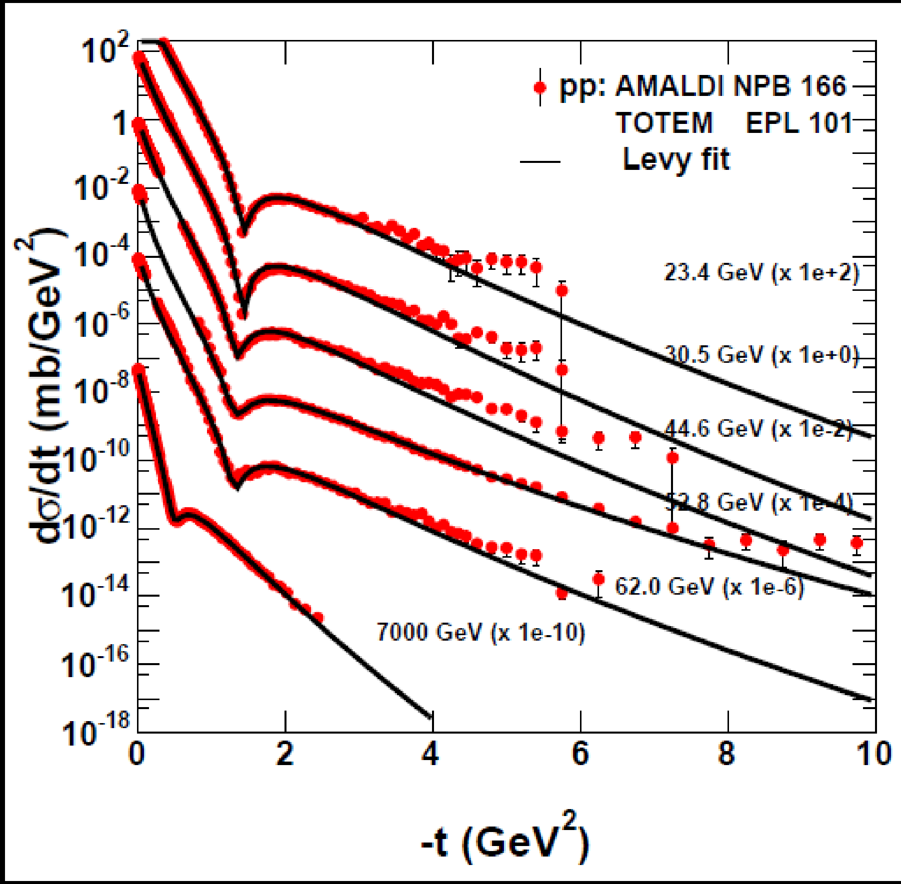
However, this method does not extrapolate well

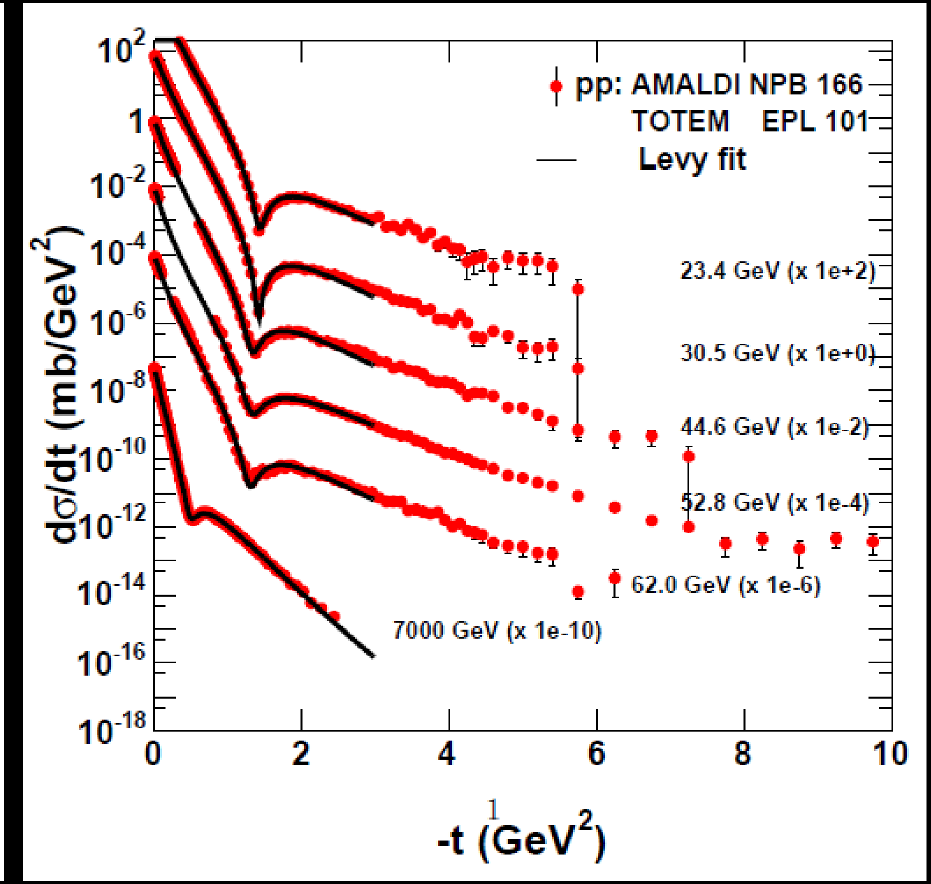


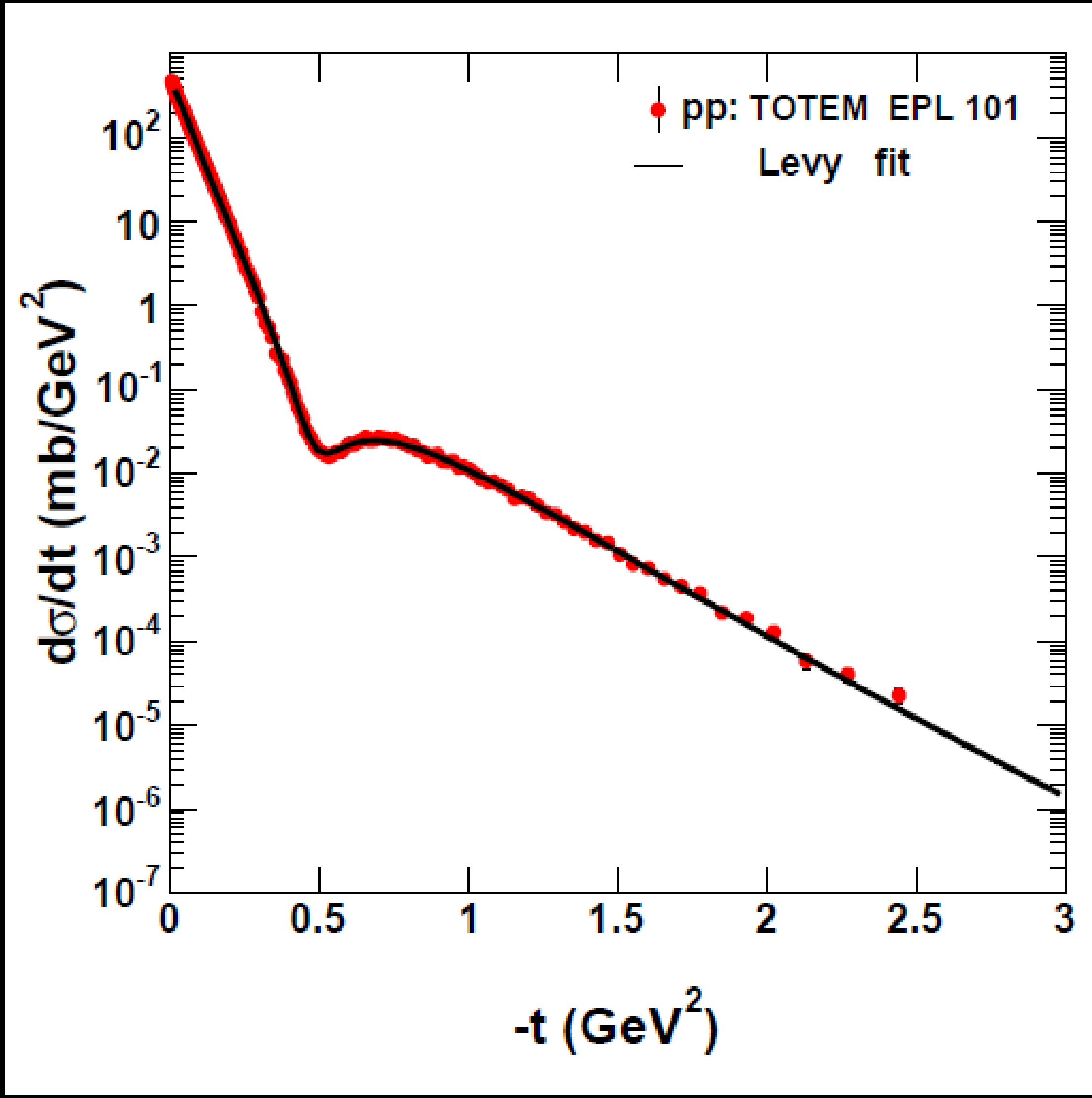
LEVY EXPANSION FIT

$$z = \sqrt{|t|}\, R$$

$$\frac{d\sigma}{dt} = \left.\frac{d\sigma}{dt}\right|_{t=0} \exp(-z^{\alpha})\ |1 + c_1 L_1(z|\alpha) + c_2 L_2(z|\alpha) + \ldots|^2$$







pp: TOTEM EPL 101
Levy fit
dσ/dt (mb/GeV²)
-t (GeV²)
10²
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
0
0.5
1
1.5
2
2.5
3

FIT RESULTS

Fit range:

Up to $-t$=10 GeV^2

Energy (GeV)	α	χ^2/NDF	CL
23.5	1.036 ±0.011	159.9/127 = 1.3	0.026
30.5	1.077 ±0.009	307.9/166 = 1.9	0.000
44.6	1.017 ±0.007	744.6/198 = 3.8	0.000
52.8	0.856 ±0.008	112.1/111 = 1.0	0.453
62.1	0.976 ±0.011	230.3/117 = 2.0	0.000
7000.0	1.152 ±0.006	145.8/159 = 0.9	0.766

Up to $-t$=3 GeV^2

Energy (GeV)	α	χ^2/NDF	CL
23.5	1.066 ±0.014	94.2/106 = 0.9	0.786
30.5	1.131 ±0.012	181.1/145 = 1.2	0.023
44.6	1.072 ±0.009	525.9/174 = 3.0	0.000
52.8	0.918 ±0.018	64.9/ 82 = 0.8	0.918
62.1	1.040 ±0.017	155.9/ 95 = 1.6	0.000
7000.0	1.152 ±0.006	145.8/159 = 0.9	0.766

α significantly different from 1 only at LHC

FIT RESULTS - PARAMETERS

R	σ_0	$c1_{re}$	$c1_{im}$	$c2_{re}$	$c2_{im}$
11.0 ± 0.4	24 ± 1	1.508 ± 0.024	0.677 ± 0.024	-0.180 ± 0.003	-0.071 ± 0.003
9.7 ± 0.3	75 ± 3	0.628 ± 0.027	-0.458 ± 0.032	-0.108 ± 0.005	0.070 ± 0.003
11.8 ± 0.3	92 ± 2	0.614 ± 0.017	-0.409 ± 0.018	-0.071 ± 0.003	0.038 ± 0.002
22.0 ± 0.9	86 ± 15	0.740 ± 0.112	-0.321 ± 0.037	-0.017 ± 0.002	0.008 ± 0.001
13.6 ± 0.5	109 ± 4	0.586 ± 0.023	0.351 ± 0.025	-0.049 ± 0.004	-0.024 ± 0.002
10.0 ± 0.1	452 ± 8	0.559 ± 0.008	0.030 ± 0.067	-0.264 ± 0.009	0.025 ± 0.024

$-t<10\mathrm{GeV}^2$

R	σ_0	$c1_{re}$	$c1_{im}$	$c2_{re}$	$c2_{im}$
10.0 ± 0.4	43 ± 11	0.898 ± 0.221	0.724 ± 0.084	-0.140 ± 0.016	-0.097 ± 0.007
8.4 ± 0.3	78 ± 2	0.554 ± 0.022	0.373 ± 0.041	-0.142 ± 0.008	-0.077 ± 0.005
10.1 ± 0.3	94 ± 2	0.563 ± 0.014	0.344 ± 0.024	-0.095 ± 0.005	-0.055 ± 0.003
16.7 ± 1.2	115 ± 9	0.562 ± 0.042	-0.305 ± 0.036	-0.026 ± 0.004	0.015 ± 0.002
11.1 ± 0.6	109 ± 3	0.538 ± 0.020	-0.291 ± 0.038	-0.076 ± 0.008	0.032 ± 0.003
10.0 ± 0.1	452 ± 8	0.559 ± 0.008	0.030 ± 0.067	-0.264 ± 0.009	0.025 ± 0.024

$-t<3\mathrm{GeV}^2$

SUMMARY AND CONCLUSIONS

Several model-independent methods:

- Based on matching an abstract measure in H to the approximate shape of data
- Gaussian: Edgeworth expansions
- Exponential: Laguerre expansions
- Levy ($0 < \alpha \leq 2$): Levy expansions
- TOTEM paper: exclude a purely exponential diff. cross-section at low $|t|$
- Levy expansion: exclude a purely exponential diff. cross-section up to $-t$=3.0 GeV^2
- Deviation from exponential measured by 1 parameter: α