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Lévy imaging of elastic scattering and proton hollowness at 13 TeV

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The shape of elastic differential cross section within and beyond the diffractive cone at 13 TeV pp collision energy has been shown to be precisely described by the Lévy series expansion in whole available range of momentum transfers. This way, the crucial information about the real and imaginary parts of the elastic amplitude has been obtained resulting in precision reconstruction of the proton inelasticity profile. We have found that the profile function $P(b)$ undergoes a qualitative change at $\sqrt{s} \approx 7$ TeV collision energy. At small values of the impact parameter b a $P(b) \approx 1$ plateaux develops, which becomes depressed at larger energies, such that a shallow minimum is formed near $b = 0$. We have evaluated the corresponding error bar and found such a hotly debated proton hollowness (or "black-ring") effect with beyond 5σ significance.

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One of the most important and critical tests of Quantum Chromo Dynamics (QCD) in the infrared regime is provided by the ongoing studies of elastic differential hadron-hadron scattering cross section at various energies and momentum transfers. The characteristics of the elastic amplitude, its both real and imaginary parts, carry a plenty of information about the inner proton structure, the proton profile in the impact parameter space and its energy dependence, as well as about the properties of QCD exchange interaction at low momentum transfers. In this work, we apply the recently developed model-independent Lévy imaging technique [1, 2, 3, 4] for precision characterisation and extraction of relevant physics information about the proton structure and hence non-perturbative QCD directly from the available data on elastic cross sections at various energies. The results of our approach efficiently complement and provide an important guideline for the existing ongoing model-dependent efforts.

The first and most precise measurements of the total, elastic and differential cross sections of elastic pp collisions has recently been performed by the TOTEM Collaboration at the Large Hadron Collider (LHC) at CERN at the highest energy frontier of $\sqrt{s} = 13$ TeV (for recent TOTEM publications, see Refs. [5, 6, 7, 8, 9]). The large range in momentum transfer squared and very high precision of this set of data becomes a big challenge for a statistically acceptable description that is necessary for a reliable extraction of any physics information from such data with an appropriate statistical significance. A correct theoretical interpretation of the LHC data, together with the lower-energy Tevatron and ISR data, is a subject of intense debates and ongoing research development, see e.g. Refs. [10, 11, 12, 13, 14, 15] while a proper extraction of model-independent "data-driven" characteristics of the proton as is appears in a high-energy scattering is still lacking.

The Lévy technique for proton imaging at the femtometer scale provides not only the impact parameter dependent inelasticity profile of the proton at various energies, but also the inelasticity profile of its internal substructure. In this work, such profiles and their energy dependence are reconstructed from the top LHC collision energy down to the lowest ISR energy, together with their error bars, for the first time. At $\sqrt{s} = 13$ TeV, we find a statistically significant evidence for a hollowness (or "black-ring") effect that may fundamentally change the standard picture of pp collisions at asymptotically large energies.

The TOTEM Collaboration has established [8, 16] that at low values of the four-momentum transfer squared $t = (p_1 - p_3)^2$ the differential elastic cross-section for pp collisions differs from a conventionally assumed naive exponential form, $d\sigma/dt = A\exp(-B|t|)$, – a subtle but significant deviation. A minimal way to parametrize such a deviation is to introduce a single parameter α into the exponent as $d\sigma/dt = A\exp\left[-(R^2|t|)^{\alpha}\right]$, to the leading order. This is the so-called stretched exponential distribution. It corresponds to the Fourier-transform of a symmetric Lévy-stable source distribution [17]. This approximation with $\alpha = 0.9$ gives a statistically acceptable description of pp elastic scattering at low-t at $\sqrt{s} = 23.5$ GeV to 62.5 GeV, while at the LHC energies higher order Lévy expansion terms become relevant for description of the low-t behaviour [1]. At larger $|t|$, deviation of the data from the Lévy stable source distribution becomes even more pronounced in a vicinity of the dip-and-bump structure before turning back to a simple stretched exponential behaviour again (but with a different value of R) at large $|t|$ beyond the secondary maximum. For a detailed description of the Lévy imaging technique and the first results, see e.g. Ref. [1].

The power of the Lévy imaging technique is demonstrated in Fig. 1 where it is employed to describe the precision TOTEM data on elastic pp scattering at the highest accessible energy $\sqrt{s} =$

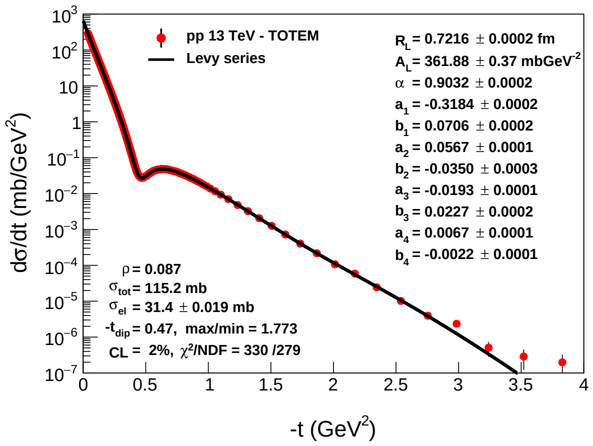

Figure 1: Lévy series expansion description of the LHC TOTEM $d\sigma/dt$ data at $\sqrt{s} = 13$ TeV.

13 TeV [8] with confidence level CL = 2 %. Given such an unprecedented precision of these data spanning ten orders of magnitude, the Lévy expansion thus represents them in a statistically acceptable manner which still remains a big challenge for alternative model dependent approaches.

As usual, we notice a nearly exponential diffractive cone at low $|t|$ that is followed by a dip, then by a subsequent maximum and a secondary diffractive cone at large t. The maximal t value accessed by the measurement $-t_{\max} \approx 4$ GeV^2 provides an estimate for a minimal spatial resolution of $\hbar/\sqrt{-t_{\max}} \approx 0.1$ fm. Remarkably, such a high resolution achieved at LHC energies enables to resolve smaller structures inside the colliding protons. Likewise, the Lévy imaging technique is also useful to characterise the results of the earlier measurements of elastic pp and $p\bar{p}$ scattering including those at ISR and Tevatron energies and hence to probe the proton structure in the full range of $\sqrt{s}$ from 23.5 GeV up to 13 TeV. Full $|t|$ range fits are used to obtain the shadow profiles $P(b)$ while fits in the large $|t|$ regions are used to get the shadow profiles for the substructures inside the protons. These fits are detailed in Appendix A as well as Appendix C of Ref. [1].

The inelasticity (or shadow) profile function $P(b)$ of the protons undergoes a qualitative change at around $\sqrt{s} \approx 7$ TeV collision energy. At small values of the impact parameter b a $P(b) \approx 1$ plateaux develops, which becomes depressed at larger energies, and a shallow minimum is formed near $b = 0$. Such a dip or hollowness may correspond to $\sigma_{\rm el} \geq \sigma_{\rm tot}/4/\left(1+\rho_0^2\right)$ [18]. The existence of such a hollow in high energy pp scattering is a hotly debated, current topic in the literature. We recommend Refs. [19, 20, 21, 22, 23] for early papers as well as Refs. [24, 25, 26, 27, 28, 29, 30] and Ref. [18] for more recent theoretical discussions as well as an experimental outlook on this fundamental nature of pp scattering at LHC and asymptotic energies. The maximal value of $P(s, b=0) \approx 1/(1+\rho_0^2) = 1-H$ at $\sigma_{\rm el}(s) \approx \sigma_{\rm tot}(s)/4/(1+\rho^2)$ seems to be rather independent of the detailed b-dependent shape of the inelastic collisions, see for example Refs. [29, 18].

At high enough energies, hollowness may thus become a generic property of the shadow profile functions, that characterizes the impact parameter distribution of inelastic scatterings. This effect contradicts the asymptotic black disc behaviour generally expected by the community [31] and thus it deals with a fundamental property of protons at asymptotically high energies.

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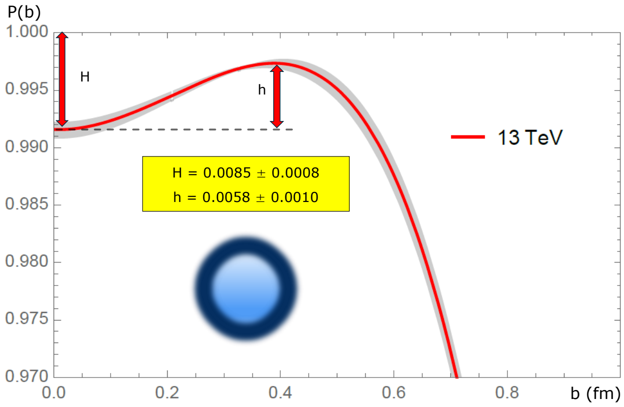

Figure 2: The inelasticity (or shadow) profile function extracted from the TOTEM 13 TeV data using the Lévy expansion method, together with the associated error bar, zoomed in around the peak value.

We have carefully studied the small-b region of profile functions for all existing data sets and found that such a hollow indeed appears in the proton, but only at currently highest LHC energy of 13 TeV. Fig. 2 zooms in the $P(b)$ inelastic scattering profile at 13 TeV in a vicinity of its peak value indicating the presence of such a hollow, in agreement with several estimates in the literature. This hollowness effect is a small but significant, much more than a 5σ effect, characterized by a hollowness strength parameter of $h = 0.0058 \pm 0.0010$. The value of the depression at $b = 0$ is even more significant, it is characterized by $H = 1 - P(b = 0) = 0.0085 \pm 0.0008$ as illustrated on Fig. 2. Our findings presented above are driven by the most recent and precise data from the LHC and by the power of the Lévy imaging technique. These results may have a profound impact on our theoretical understanding of the proton structure. Apparently, we found the first, statistically significant result, that suggests that at energies of $\sqrt{s} = 13$ TeV, the protons start to interact like black rings rather than conventionally assumed black discs.

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