EPJ Web of Conferences will be set by the publisher
DOI: will be set by the publisher

Evidence for Non-Exponential Differential Cross-Section of pp Elastic Scattering at Low $|t|$ and $\sqrt{s} = 8$ TeV by TOTEM

T. Csörgő[1,2,a] for the TOTEM Collaboration

[1] *Wigner Research Centre for Physics, Budapest, Hungary*
[2] *KRF, Gyöngyös, Hungary*

Abstract.
Recently published and preliminary results of the TOTEM experiment are presented, emphasizing a recent discovery of a non-exponential behaviour of the differential cross-section of elastic proton-proton scattering, that TOTEM measured with an unprecedented precision at the centre-of-mass energy $\sqrt{s} = 8$ TeV based on a high-statistics data sample obtained with the $\beta_* = 90$ m optics of CERN LHC. Both the statistical and systematic uncertainties remained below 1% , except for the t-independent contribution from the overall normalisation. This measurement allowed TOTEM to exclude a purely exponential differential cross-section in the range of four-momentum transfer squared $0.027 < |t| < 0.2$ GeV^2 with a significance greater than 7 σ. In this context we also highlight the innovative TOTEM recalibration of LHC optics, that used elastic scattering data measured by the world's largest and most complex Roman Pot detector system, and discuss recent preliminary TOTEM data on the Coulomb-Nuclear interference region with its physics implications.

1 Introduction

The TOTEM experiment at CERN LHC specializes in forward physics measurements, that deal with colorless exchange, including elastic proton-proton (pp) scattering, single and double diffractive pp scattering [1, 2], and has a program to measure central exclusive production in collaboration with the CMS experiment, the CMS-TOTEM Precision Proton Spectrometer (CT-PPS) project [3].

The main focus of this conference contribution is recent TOTEM the discovery of a non-exponential behaviour of the differential cross-section of elastic pp scattering [4] at low $|t|$ and at $\sqrt{s} = 8$ TeV energy of CERN LHC, which is put into context of other recent TOTEM results, in particular the recalibration of LHC optics from TOTEM data [5] and preliminary results on the observation of Coulomb-nuclear interference at very low four-momentum transfer at LHC [6].

2 Earlier results on the low-$|t|$ behaviour of $d\sigma/dt$ of elastic pp scattering

Let us first summarize what has been known before 2015 about this low-|t| region of elastic scattering in pp and $p\overline{p}$ scattering. Traditionally, the differential cross-section of elastic scattering is characterized in the low-|t| region, before the diffractive minimum, by an approximately exponential behaviour,

[a] e-mail: tcsorgo@cern.ch

$\exp(-B|t|)$, where $B \equiv B(s,t)$ is called the slope parameter, where $s = (p_1 + p_2)^2$ and $t = (p_1 - p_3)^2$ are Mandelstam variables called squared center of mass energy and the squared four-momentum transfer.

Experimental data reported before 2015 on pp and $p\overline{p}$ elastic scattering were consistent with a simple exponential behaviour, $B(s,t) = B(s)$ independent of t in the low $|t|$ region, before the vicinity of t_{dip}, the region of the diffractive minimum. The slope parameter $B = B(s)$ was measured to increase with increasing $\sqrt{s}$, corresponding to the shrinking of the diffractive cone and the increase of the total elastic cross-section of proton-proton scattering with increasing center of mass energies. Nevertheless, some of the earlier experiments reported hints of deviations from such a simple exponential behaviour. For example, small angle pp elastic scattering at $460 < \sqrt{s} < 2900$ GeV energies indicated a marked change of the slope parameter as a function of t in the $|t| = 0.1$ GeV^2 region as early as in 1972 [7]. A decade later, an indication of a break in the slope parameter B was observed in $p\overline{p}$ reactions, as a function of t, at the ISR energy of 52.8 GeV in ref. [8]. Other measurements at ISR found a simple exponential behaviour, $B \neq B(t)$ at 53 and 62 GeV ISR energies, however, found an indication of a change of the slope parameter at $|t = 0.15$ GeV^2 at the lower $\sqrt{s} = 31$ GeV colliding energies [9], and found that the data are better described by a Gaussian $\exp(-B|t| - Ct^2)$ than a simple exponential $\exp(-B|t|)$ shape. However, these early results were limited by statistics and systematic effects and the significance of these indications of non-exponential behaviour did not reach the discovery, 5σ level. In measurements of elastic $p\overline{p}$ scattering at Tevatron energies, no indications of a possible non-exponential behaviour were found. The first results on the differential cross-section of elastic pp scattering at LHC energies were reported by TOTEM in the dip region [10], but the TOTEM measurement was soon extended to the low-$|t|$ region using a special LHC run [11]. Both measurements were consistent with an exponential behaviour in the diffraction cone, and the measured slope parameter in the low-$|t|$ region was consistent with the B value determined from the data closer to the dip region. However, a high statistics low-$|t|$ data-set from a special LHC run allowed TOTEM to establish the non-exponential behaviour of the differential cross-section of elastic pp scattering with a greater than 7 σ significance at $\sqrt{s} = 8$ TeV LHC colliding energies [4].

The experimental observation of non-exponential low-$|t|$ behavior of the differential cross-section of elastic pp scattering was actually anticipated by a number of theoretical models. To explain the first experimental indications of a non-exponential behaviour at ISR energies, ref. [12] suggested that the corresponding non-linearity of the vacuum or Pomeron Regge trajectory is due to a nearby singularity, the two-pion threshold, restricted by t-channel unitarity requirements. This idea has been applied recently [13] to explain the non-exponential behaviour of preliminary TOTEM data at 8 TeV extrapolating fit parameters from ISR to LHC energies [14]. An independent line of argumentation was based on multiple diffraction theory of elastic proton-proton scattering [15] where the electromagnetic form-factor of the colliding protons and a simple phenomenological parameterizaton of the cluster-averaged parton-parton forward scattering amplitude was shown to lead naturally to a non-exponential behaviour or a t-dependent slope-parameter $B(t)$. This general quantum-optical scattering theory is also able to describe the first TOTEM data if the proton is modelled as a quark-diquark composite object, $p = (q,d)$ even if the internal structure of the quark and the diquark is a featureless Gaussian distribution as far as elastic scattering of protons is concerned. The resulting multiple diffraction theory formulas for elastic pp scattering indicate a non-exponential feature both in the “springy Pomeron" picture of Grichine [16] and the Bialas-Bzdak quark-diquark model of pp elastic scattering, [18], in particular when the non-vanishing nature of the real part of the forward scattering amplitude and the unitarity constraints are both taken into account [17].

3 Non-exponential behaviour of low-$|t|$ elastic pp scattering

In this section, the main results of ref. [4] are summarized and the method of the analysis is outlined.

Detector setup. The TOTEM experiment [1, 2] is located at the LHC interaction point (IP) 5, together with the CMS experiment. The full experimental apparatus of TOTEM consists of two inelastic telescopes, T1 and T2, based on Cathode Strip Chamber and GEM technology, respectively, and a system of Roman Pot detectors. Roman Pots are movable beam-pipe insertions that approach the LHC beam very closely in order to detect particles scattered at very small angles. Currently, 26 Roman Pot detectors belong to TOTEM and the CT-PPS project: this is the largest and most complex Roman Pot detector system that has ever been operated at a collider. In the measurement of the non-exponential shape of the differential cross-section of elastic pp scattering, only the Roman Pot (RP) system, the sub-detector relevant for elastic scattering measurement, was utilized.

The RP-s are organised in two stations placed symmetrically around the IP: one on the left side (in LHC sector 45), one on the right (sector 56). Each station is formed by two units: near (214 m from the IP) and far (220 m). Each unit includes three RPs: one approaching the beam from the top, one from the bottom and one horizontally. Each RP hosts 10 “edgeless" silicon strip sensors with a pitch of 66 μm, each having a strongly reduced insensitive edge of a few tens of micrometers facing the beam. The sensors are equipped with trigger-capable electronics. Since elastic scattering events consist of two anti-parallel protons, the detected events can have two topologies, called diagonals: 45 bottom – 56 top and 45 top – 56 bottom.

Data-set. The measurement presented here is based on data taken in July 2012, during the LHC fill number 2836 at the centre-of-mass energy $\sqrt{s} = 8$ TeV. The vertical RPs were inserted at a distance of 9.5 times the transverse beam size, $\sigma_{\rm beam}$. Initially two, later three colliding bunch-pairs were used, each with a typical population of $8 \cdot 10^{10}$ protons, corresponding to an instantaneous luminosity of about 10^{28} cm^{-2}s^{-1} per bunch. The main trigger required a coincidence between the RPs in both arms, combining the near and far units of a station in *OR* to ensure maximal efficiency. During the about 11 h long data-taking, a luminosity of 735 μb^{-1} was accumulated, giving $7.2 \cdot 10^6$ tagged elastic events.

LHC Optics Determination at $\beta_* = 90$ m. For the determination of the total cross-section and the differential cross-section of elastic pp collisions with unprecedented precision by TOTEM, a precise experimental control of the LHC optics was necessary, which was achieved from the recalibration of the LHC optics at IP5 using measurement of elastic pp scattering with RP-s. For the measurement of the non-exponential shape of $d\sigma/dt$, a special LHC optics with $\beta^* = 90$ m was used, with essentially the same characteristics as at $\sqrt{s} = 7$ TeV. In the vertical plane, this optics features parallel-to-point focusing ($v_y \approx 0$) and large effective length L_y. In the horizontal plane, the almost vanishing effective length L_x simplifies the separation of elastic and diffractive events: any sizeable horizontal displacement must be due to a momentum loss ξ. Figures 1 indicate, that TOTEM achieved a precise control of LHC imperfections with perturbed LHC optics and recalibration from data at IP5: Monte-Carlo simulations indicate that the nominal uncertainties of LHC optics have been reduced by factors of 2 - 10, see Refs. [5], [4] for details of this innovative TOTEM method.

Analysis steps. The precise control of LHC optics, together with kinematic cuts that are based on the physics of elastic scattering were needed to measure precisely the differential cross-section. The applied analysis steps included detector alignment, optics recalibration, elastic event selection based on kinematic cuts, resolution unfolding, acceptance correction, background subtraction, detection and efficiency correction, corrections for angular resolution, normalization and binning.

Compatible results have been obtained from the data originating from different bunches, different diagonals and different time periods. In addition, the complete analysis chain has been applied in two independent analysis implementations, yielding compatible results. The details of these steps of the analysis are described in ref. [4].

Results on the non-exponential behaviour. The differential cross-section of elastic pp scattering at 8 TeV is indicated on the top panel of Figure 2, tabulated in Table 3 of ref. [4]. The binning

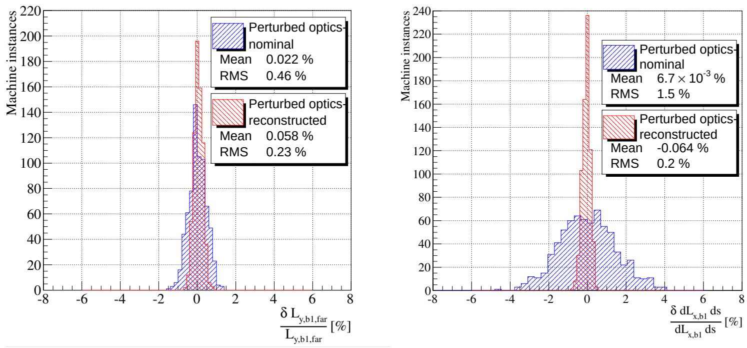

Figure 1. Monte-Carlo error distribution of $\beta_* = 90$ m LHC Optical Functions L_y and dL_x/ds for E = 4 TeV before and after the estimation of the LHC Optics from TOTEM *pp* elastic scattering data [5].

of this plot is optimized so that the bin size corresponds to 1σ of the resolution in t. In order to visualise small deviations from the leading pure-exponential behaviour, the bottom panel of Figure 2 shows also the relative difference of the cross-section from a reference exponential (pure exponential fit using statistical uncertainties only). This plot indicates the non-exponentiality of the data: pure exponentials would look like (nearly) linear functions in this kind of representation.

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

$$\frac{d\sigma}{dt}(t) = \frac{d\sigma}{dt}(t = 0) \times \exp\left(\sum_{i=1}^{N_b} b_i\, t^i\right) , \tag{1}$$

which includes the exponential fit as a special case for ($N_b = 1$) and its straight-forward extensions ($N_b = 2, 3$). The fits have been performed by the standard least-squares method, using the covariance matrix including both the statistical and systematic components. For a detailed description of the determination of the systematic errors, as well as for a discussion on the significance of these observations, see ref. [4]. Two independent lines of analysis indicate that the significance of the non-exponential behaviour in these TOTEM measurements is greater than 7σ. Using the refined, non-exponential parameterizations to extrapolate to the optical point, $t = 0$, yields total cross-section valued compatible with earlier TOTEM determinations, in all cases neglecting the effects due to the Coulomb interactions.

Preliminary TOTEM Results on the Coulomb-Nuclear Interference. In a preliminary analysis, TOTEM investigated if the origin of the non-exponentiality at low-$|t|$, still dominated by the hadronic interactions, can be due to Coulomb interference effects or not. This was achieved with a measurement of the elastic scattering in the Coulomb-Nuclear Interference (CNI) region. The preliminary TOTEM data, shown in Fig. 3, extend the four momentum transfer range of the TOTEM measurements down to $|t| \approx 6x10^{-4}$ GeV^2. These results indicate that the non-exponential behaviour of $d\sigma/dt$ around 0.1 GeV^2 is not due to Coulomb interference effects, but is a property of the hadronic amplitude [6], which allows TOTEM to exclude the simplified West-Yennie interference formula [22]. The constraining power of this TOTEM preliminary analysis on the hadronic phase allows us to study the impact parameter dependence of elastic *pp* scattering and to measure the parameter ρ. The results of this TOTEM preliminary analysis confirm earlier total *pp* scattering cross-sections measurements of TOTEM, that neglected the Coulomb-Nuclear Interference effects.

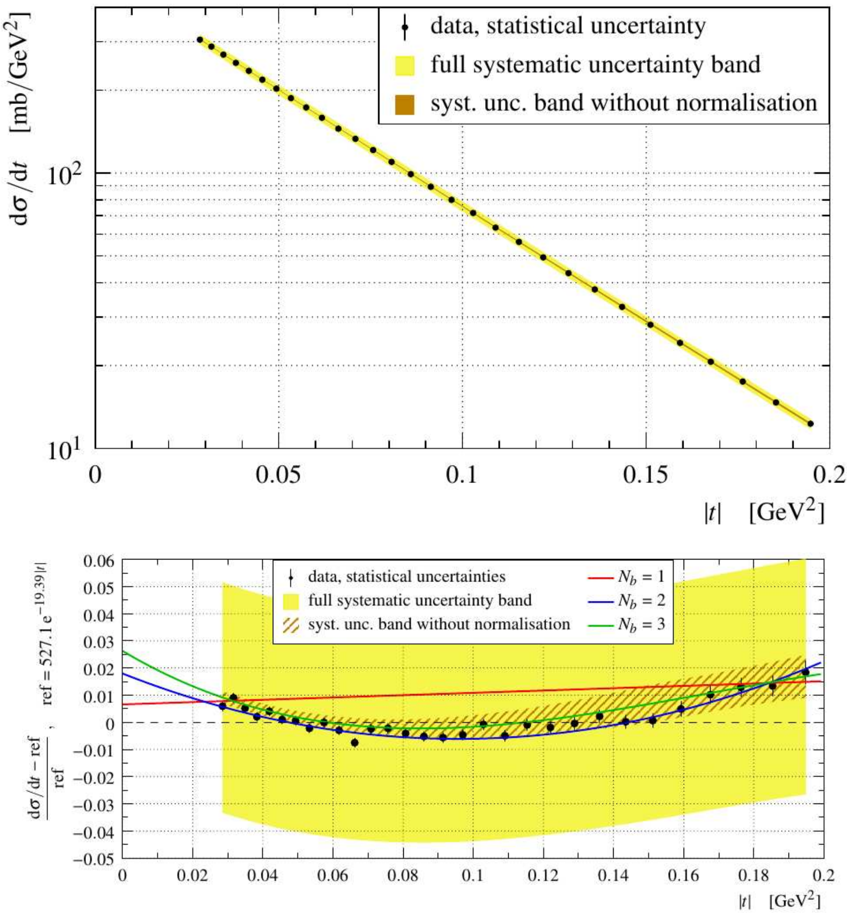

Figure 2. The *top panel* shows the differential cross-section of elastic *pp* scattering at 8 TeV as measured by TOTEM at CERN LHC. The black dots represent TOTEM data with statistical uncertainty bars. The widest error band (yellow) corresponds to full systematic uncertainty, including the normalization error. The narrow band around the data points indicate all systematic errors except the overall normalization uncertainty. Both bands are centered around the fit curve with $N_b = 3$. The *bottom panel* shows the same data points, however, now the relative deviation from an exponential reference distribution is shown (see the vertical axis). From ref. [4].

Acknowledgments: T. Cs. would like to thank the Organizers of this Symposium for their support and for an inspiring and useful meeting. This work was supported by the Magnus Ehrnrooth foundation (Finland), the Waldemar von Frenckell foundation (Finland), the Academy of Finland, the Finnish Academy of Science and Letters (the Vilho, Yrjö and Kalle Väisälä Fund), and the OTKA grant NK 101438 (Hungary).

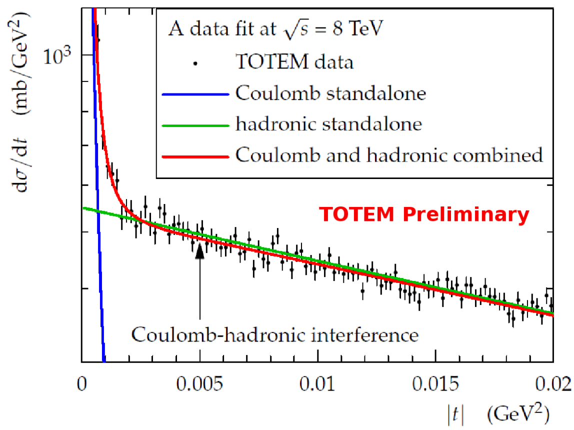

Figure 3. TOTEM preliminary results with a special β_* = 1000 m run, Roman Pots approaching the beam as close as 3.5 σ probe the Coulomb-Nuclear Interference (CNI) region. From [6].

References

[1] G. Anelli *et al.* [TOTEM Collaboration], JINST **3**, S08007 (2008).

[2] G. Antchev *et al.* [TOTEM Collaboration], Int. J. Mod. Phys. A **28**, 1330046 (2013).

[3] M. Albrow, *et al.* [CMS and TOTEM Collaborations] preprint CERN-LHCC-2014-021, TOTEM-TDR-003, CMS-TDR-13, Sept. 2014, `http://cds.cern.ch/record/1753795` .

[4] G. Antchev *et al.* [TOTEM Collaboration], Nucl. Phys. B **899**, 527 (2015).

[5] G. Antchev *et al.* [TOTEM Collaboration], New J. Phys. **16**, 103041 (2014).

[6] M. Deile for the TOTEM Collaboration and the CT-PPS Project, *Status Report of TOTEM and the CT-PPS Roman Pot Operations* talk at the LHCC Open Session, September 23, 2015.

[7] G. Barbiellini *et al.*, Phys. Lett. B **39**, 663 (1972).

[8] M. Ambrosio *et al.* Phys. Lett. B **115**, 495 (1982).

[9] A. Breakstone *et al.* Nucl. Phys. B **248**, 253 (1984).

[10] G. Antchev *et al.* [TOTEM Collaboration], Europhys. Lett. **95**, 41001 (2011).

[11] G. Antchev *et al.* [TOTEM Collaboration], Europhys. Lett. **101**, 21002 (2013).

[12] G. Cohen-Tannoudji, V. V. Ilyin and L. L. Jenkovszky, Lett. Nuovo Cim. **5S2**, 957 (1972).

[13] L. Jenkovszky and A. Lengyel, Acta Phys. Polon. B **46**, no. 4, 863 (2015).

[14] D. A. Fagundes, L. Jenkovszky, E. Q. Miranda, G. Pancheri and P. V. R. G. Silva, arXiv:1509.02197 [hep-ph].

[15] R. J. Glauber and J. Velasco, Phys. Lett. B **147**, 380 (1984).

[16] V. M. Grichine, Eur. Phys. J. Plus **129**, 112 (2014).

[17] F. Nemes, T. Csörgő and M. Csanád, Int. J. Mod. Phys. A **30**, no. 14, 1550076 (2015).

[18] A. Bialas and A. Bzdak, Acta Phys. Polon. B **38**, 159 (2007).

[19] J. R. Cudell *et al.* [COMPETE Collaboration], Phys. Rev. Lett. **89**, 201801 (2002).

[20] S. Chatrchyan *et al.* [CMS and TOTEM Collaborations], Eur. Phys. J. C **74**, no. 10, 3053 (2014).

[21] G. Antchev *et al.* [TOTEM Collaboration], Eur. Phys. J. C **75**, no. 3, 126 (2015).

[22] G. B. West and D. R. Yennie, Phys. Rev. **172**, 1413 (1968).