# Elastic pp scattering at 8 TeV in the Coulomb-nuclear interference region measured by TOTEM

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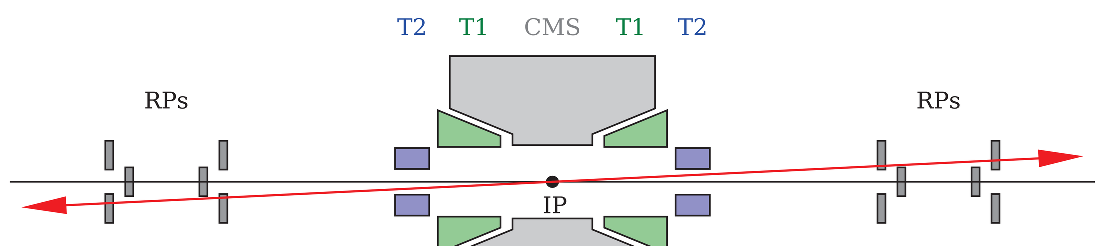
## 1. Introduction

The most frequent proton-proton collision process is elastic scattering. Its measurement has a long tradition (since the era of the CERN ISR, the first hadron collider) but the description of this exclusive process is more delicate than it may seem at first glance. The TOTEM experiment at the CERN LHC recently measured elastic scattering at $\sqrt{s} = 8$ TeV in the Coulomb-hadronic interference region; results derived from these data [1] (2015) have allowed to study some further proton characteristics that are summarized in the following.

## 2. Detection of elastically scattered protons

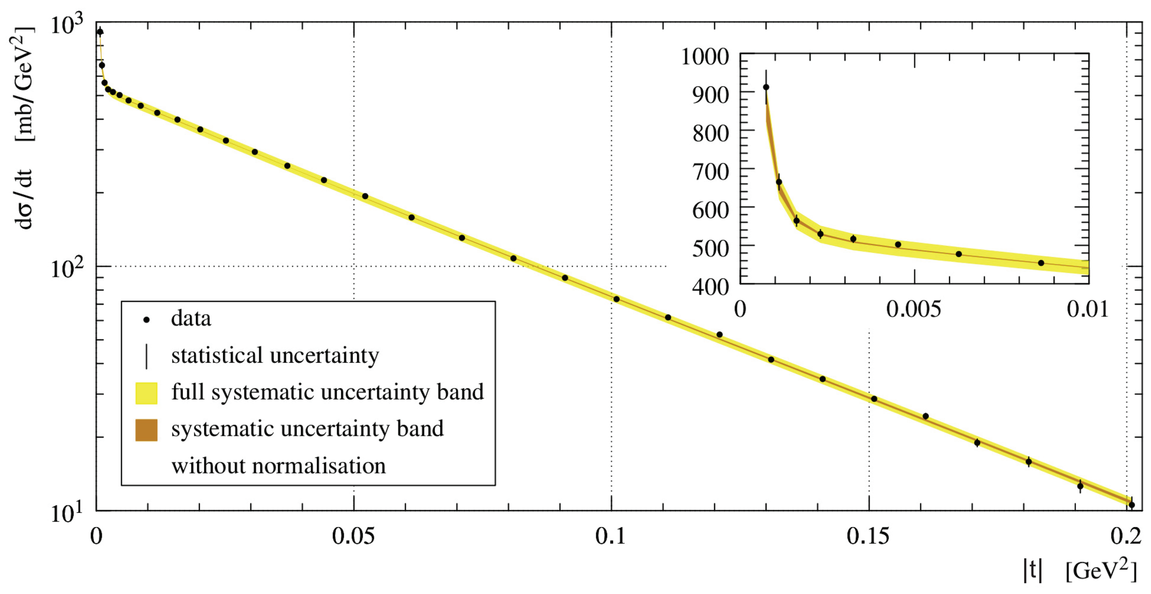



- elastic (diffractive) protons are scattered at interaction point (IP) at *very low scattering angles* $\theta$ and move along the beam
- $\Rightarrow$ two TOTEM stations of Roman Pots (RPs) at distance about 220 m far from IP on each side are used to detect the protons; the RPs (*moveable devices hosting silicon strip detectors*) may be inserted very close to the beam during dedicated stable beam conditions (staying retracted otherwise)
- motion and acceptance of the scattered protons is strongly influenced also by *magnet settings (optics) between the IP and RPs*; dedicated optics necessary to measure very low scattering angles
- knowledge of the optics and measured kinematical characteristics of protons detected by RPs enable to determine the corresponding scattering angles at IP

## 3. Measuring elastic $d\sigma/dt$ – main points

1. reconstruction of proton kinematics
   - optics determination
   - alignment of detectors
2. event selection
3. background subtraction
4. acceptance corrections
5. unfolding of resolutions effects
6. corrections of various inefficiencies
7. luminosity

## 4. Measured elastic $d\sigma/dt$ at 8 TeV




- TOTEM [1] measured elastic proton-proton differential cross section at the center of mass energy $\sqrt{s} = 8$ TeV and four-momentum transfers squared, $|t|$, from $6 \times 10^{-4}$ GeV$^2$ to 0.2 GeV$^2$ ($t = -4p^2 \sin^2 \frac{\theta}{2}$, momentum of one of the incident proton $p = 4$ TeV in this case)
- the measured region includes *significantly non-exponential part* (see the points corresponding to the lowest measured values of $|t|$) attributed standardly to Coulomb-hadronic interference; special beam optics ($\beta^* = 1000$ m) has been needed to reach such low values of $|t|$

## 5. Coulomb-hadronic interference

The measured $d\sigma/dt$ may be fitted using

$$\frac{d\sigma(s,t)}{dt} = \frac{\pi}{sp^2} \left| F^{C+N}(s,t) \right|^2 \qquad (1)$$

- $F^{C+N}(s,t)$ - *complete elastic scattering amplitude* of Coulomb-hadronic interaction depending on both Coulomb $F^C(s,t)$ and hadronic $F^N(s,t)$ amplitudes
- Eq. (1) has allowed *"separation" of Coulomb interaction* and to study less known hadron (nuclear) scattering; Coulomb interaction is assumed to be well known from QED

## 6. Approach of West and Yennie

*Simplified interference formula of West and Yennie* (1968) [2] with added form factors $f_1(t)$ and $f_2(t)$

$$F^{C+N}_{WY}(s,t) = \pm \frac{\alpha s}{t} f_1(t) f_2(t) e^{i\alpha\phi(s,t)} + \frac{\sigma^{tot}(s)}{4\pi} p\sqrt{s}\,(\rho(s)+i)\, e^{B(s)t/2} \qquad (2)$$

where

$$\alpha\phi(s,t) = \mp\alpha \left[ \ln\left(\frac{-B(s)t}{2}\right) + \gamma \right] \qquad (3)$$

- *used widely in the past* for determination of total hadronic cross section $\sigma^{tot}$, quantities $\rho(s,t) = \frac{\mathrm{Re}\,F^N(s,t)}{\mathrm{Im}\,F^N(s,t)}$ and diffractive slope $B(s,t) = \frac{2}{|F^N(s,t)|} \frac{d}{dt} |F^N(s,t)|$ at $t = 0$ and given energy
- *several limiting assumptions*, e.g., derived only at small $|t|$, $t$-independent phase of $F^N(s,t)$ and purely exponential $|F^N(s,t)|$ in $t$ (i.e., $t$-independent quantities $\rho(t)$ and $B(t)$); dependence of elastic hadronic collisions on impact parameter not considered

## 7. Eikonal model approach

- main motivation behind eikonal model approach has been to take into account dependence of elastic collisions of charged hadrons on *impact parameter* $b$
- main $b$-dependent characteristics of hadron collisions are represented by *profile functions* $D^X(b)$ (X = tot, el, inel; $\left(\sigma^X = \int_0^\infty db\, 2\pi b D^X(b)\right)$ introduced in analogy to description of some optics phenomena (light meeting an obstacle of a given profile which describes its absorptive properties); they determine, e.g., mean impact parameters $\sqrt{\langle b^2 \rangle^X}$ of corresponding collision type

*More general interference formula* derived by Kundrát and Lokajíček in 1994 [3] using the eikonal model

$$F^{C+N}_{KL}(s,t) = \pm \frac{\alpha s}{t} f_1(t) f_2(t) + F^N(s,t)[1 \mp i\alpha G(s,t)] \qquad (4)$$

where

$$G(s,t) = \int_{t_{min}}^{0} dt' \left\{ \ln\left(\frac{t'}{t}\right) \frac{d}{dt'}[f_1(t') f_2(t')] - \frac{1}{2\pi}\left[\frac{F^N(s,t')}{F^N(s,t)} - 1\right] I(t,t') \right\} \qquad (5)$$

and

$$I(t,t') = \int_0^{2\pi} d\Phi'' \frac{f_1(t'') f_2(t'')}{t''}. \qquad (6)$$

It enables to determine $F^N(s,t)$ from the measured data for any value of $t$.

## 8. Optical theorem

Determination of total hadronic cross section based on the validity of optical theorem (in both WY and the eikonal model approach):

$$\sigma^{tot}(s) = \frac{4\pi}{p\sqrt{s}} \mathrm{Im}\, F^N(s, t=0) \qquad (7)$$

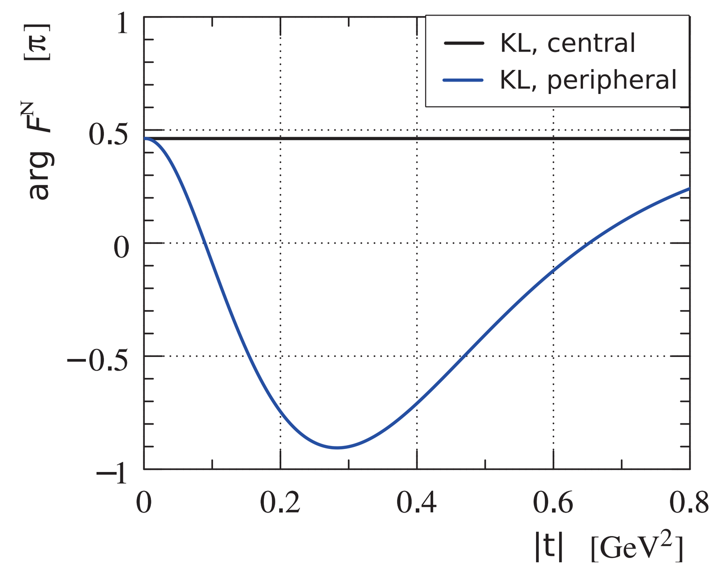
## 9. Results fitted at 8 TeV

Some characteristics of hadron scattering may be calculated from fitted $F^N(s,t)$. Several fits of the measured elastic $d\sigma/dt$ at 8 TeV have been performed in [1] using Eq. (1), and the *eikonal interference formula* (4); assuming (non-)exponential modulus of $F^N(s,t)$ in fitted $t$-region and

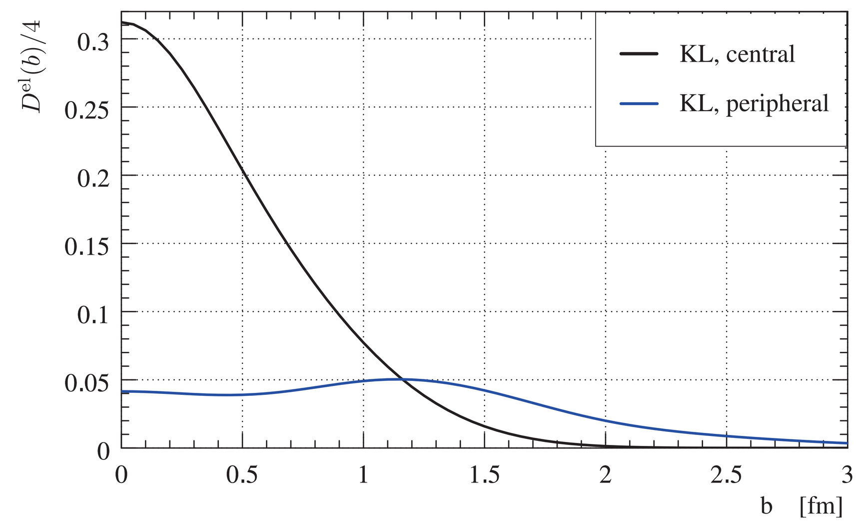
- *t-independent (constant) phase* of $F^N(s,t)$ (as assumed in the approach of WY) which leads to *central* character of elastic scattering $\left(\sqrt{\langle b^2 \rangle^{el}} < \sqrt{\langle b^2 \rangle^{inel}}\right)$, or
- *strongly t-dependent phase* of $F^N(s,t)$ to obtain a *peripheral* $\left(\sqrt{\langle b^2 \rangle^{el}} > \sqrt{\langle b^2 \rangle^{inel}}\right)$ behaviour of elastic collisions

1. purely exponential $|F^N(s,t)|$ and constant (central) hadronic phase - excluded
   - corresponds to assumptions included in the WY interference formula (2)
   - bad quality of fit in fitted $t$-region (using both the WY and eikonal interference formula)
   - purely exponential $|F^N(s,t)|$ in disagreement with observation of a diffractive minimum at higher $|t|$ values
2. purely exponential $|F^N(s,t)|$ and peripheral hadronic phase
   - acceptable fit quality in fitted $t$-region but seems disfavoured from other perspectives [1]
3. non-exponential $|F^N(s,t)|$ and both central and peripheral hadronic phases - good fit quality

the two fitted phases of hadronic amplitude




corresponding elastic profile functions




values of some physically interesting quantities

| fit/case | | central | peripheral |
|---|---|---|---|
| $\sigma^{tot}$ | [mb] | $102.9 \pm 2.3$ | $103.0 \pm 2.3$ |
| $\rho(t=0)$ | | $0.12 \pm 0.03$ | $0.12 \pm 0.03$ |
| $B(t=0)$ | [GeV$^{-2}$] | $20.47 \pm 0.14$ | $19.56 \pm 0.13$ |
| $\sqrt{\langle b^2 \rangle^{tot}}$ | [fm] | 1.26 | 1.23 |
| $\sqrt{\langle b^2 \rangle^{el}}$ | [fm] | 0.88 | 1.99 |
| $\sqrt{\langle b^2 \rangle^{inel}}$ | [fm] | 1.38 | 0.79 |

- *these two fits of the same data* correspond to completely different behaviour of the collisions in dependence on impact parameter $\Rightarrow$ correspond necessarily to two very different structures of proton (see also [4] from 1981)
- these results at LHC energy of 8 TeV may be compared to similar analysis of experimental data at ISR energy of 53 GeV, see [5] (and also [6])

## 10. Two main open problems and questions

1. value of $t = 0$ in the case of long-ranged Coulomb interaction corresponds to infinite value of $b$ which does not correspond to experimental conditions
2. real dependence of elastic (hadronic) collisions on impact parameter?

The results following from different assumptions concerning the influence of impact parameter values should be derived and experimentally tested in future research, see [5].

## 11. Conclusion

TOTEM has measured elastic pp differential cross section at 8 TeV in Coulomb-hadronic region. It allowed to apply two interference formulae at much higher energy than whenever before. The traditionally used simplified formula of West and Yennie might be hardly denoted as acceptable for analysis of experimental data. Using the eikonal model approach two very different interpretations of elastic collisions in dependence on impact parameter (central and peripheral), leading to similar total cross section and $\rho$ values, have been shown. Further detailed analysis of (elastic) particle collisions in dependence on impact parameter may provide deeper understanding of the structure and interactions of fundamental particles.

## 12. References

[1] TOTEM Collaboration, "Measurement of elastic pp scattering at $\sqrt{s} = 8$ TeV in the Coulomb-nuclear interference region – determination of the $\rho$-parameter and the total cross-section", CERN-PH-EP-2015-325 (2015).

[2] G. B. West and D. R. Yennie, "Coulomb interference in high-energy scattering", Phys. Rev. **172**, 1413–1422 (1968).

[3] V. Kundrát and M. V. Lokajíček, "High-energy scattering amplitude of unpolarized and charged hadrons", Z. Phys. **C63**, 619–630 (1994).

[4] V. Kundrát, M. Lokajíček, and M. V. Lokajíček, "Are elastic collisions central or peripheral?", Czech. J. Phys. **B31**, 1334 (1981).

[5] J. Procházka, M. V. Lokajíček, and V. Kundrát, "Dependence of elastic hadron collisions on impact parameter", arXiv: 1509.05343 (2015).

[6] J. Kašpar, V. Kundrát, M. Lokajíček, and J. Procházka, "Phenomenological models of elastic nucleon scattering and predictions for LHC", Nucl.Phys. **B843**, 84–106 (2011).