



A LETTERS JOURNAL EXPLORING
THE FRONTIERS OF PHYSICS

OFFPRINT

**First measurement of the total proton-proton
cross-section at the LHC energy of $\sqrt{s} = 7$ TeV**

THE TOTEM COLLABORATION (G. ANTCHEV *et al.*)

EPL, **96** (2011) 21002

Please visit the new website
www.epljournal.org



A LETTERS JOURNAL EXPLORING
THE FRONTIERS OF PHYSICS

AN INVITATION TO SUBMIT YOUR WORK

www.epljournal.org

The Editorial Board invites you to submit your letters to EPL

EPL is a leading international journal publishing original, high-quality Letters in all areas of physics, ranging from condensed matter topics and interdisciplinary research to astrophysics, geophysics, plasma and fusion sciences, including those with application potential.

The high profile of the journal combined with the excellent scientific quality of the articles continue to ensure EPL is an essential resource for its worldwide audience. EPL offers authors global visibility and a great opportunity to share their work with others across the whole of the physics community.

Run by active scientists, for scientists

EPL is reviewed by scientists for scientists, to serve and support the international scientific community. The Editorial Board is a team of active research scientists with an expert understanding of the needs of both authors and researchers.



IMPACT FACTOR
2.753*
* As ranked by ISI 2010

www.epljournal.org

IMPACT FACTOR

2.753*

* As listed in the ISI® 2010 Science
Citation Index Journal Citation Reports

OVER

500 000

full text downloads in 2010

30 DAYS

average receipt to online
publication in 2010

16 961

citations in 2010
37% increase from 2007

"We've had a very positive experience with EPL, and not only on this occasion. The fact that one can identify an appropriate editor, and the editor is an active scientist in the field, makes a huge difference."

Dr. Ivar Martin

Los Alamos National Laboratory,
USA

Six good reasons to publish with EPL

We want to work with you to help gain recognition for your high-quality work through worldwide visibility and high citations.

- 1 Quality** – The 40+ Co-Editors, who are experts in their fields, oversee the entire peer-review process, from selection of the referees to making all final acceptance decisions
- 2 Impact Factor** – The 2010 Impact Factor is 2.753; your work will be in the right place to be cited by your peers
- 3 Speed of processing** – We aim to provide you with a quick and efficient service; the median time from acceptance to online publication is 30 days
- 4 High visibility** – All articles are free to read for 30 days from online publication date
- 5 International reach** – Over 2,000 institutions have access to EPL, enabling your work to be read by your peers in 100 countries
- 6 Open Access** – Articles are offered open access for a one-off author payment

Details on preparing, submitting and tracking the progress of your manuscript from submission to acceptance are available on the EPL submission website www.epletters.net.

If you would like further information about our author service or EPL in general, please visit www.epljournal.org or e-mail us at info@epljournal.org.

EPL is published in partnership with:



European Physical Society



Società Italiana
di Fisica



EDP Sciences

IOP Publishing

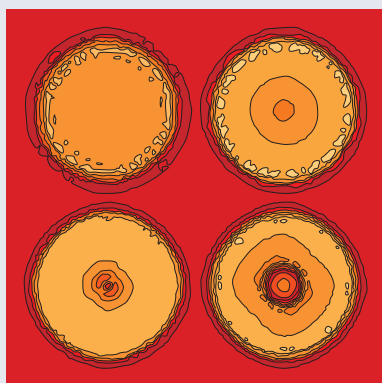
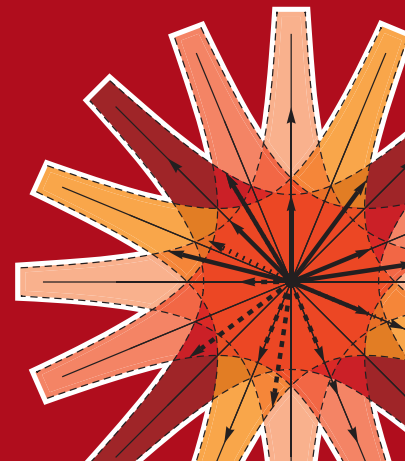
IOP Publishing



A LETTERS JOURNAL
EXPLORING THE FRONTIERS
OF PHYSICS

EPL Compilation Index

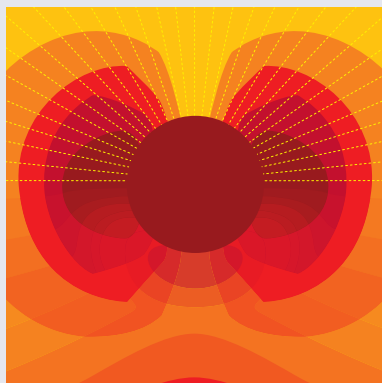
www.epljournal.org



Biaxial strain on lens-shaped quantum rings of different inner radii, adapted from **Zhang et al** 2008 *EPL* **83** 67004.



Artistic impression of electrostatic particle-particle interactions in dielectrophoresis, adapted from **N Aubry and P Singh** 2006 *EPL* **74** 623.



Artistic impression of velocity and normal stress profiles around a sphere that moves through a polymer solution, adapted from **R Tuinier, J K G Dhont and T-H Fan** 2006 *EPL* **75** 929.

Visit the EPL website to read the latest articles published in cutting-edge fields of research from across the whole of physics.

Each compilation is led by its own Co-Editor, who is a leading scientist in that field, and who is responsible for overseeing the review process, selecting referees and making publication decisions for every manuscript.

- Graphene
- Liquid Crystals
- High Transition Temperature Superconductors
- Quantum Information Processing & Communication
- Biological & Soft Matter Physics
- Atomic, Molecular & Optical Physics
- Bose-Einstein Condensates & Ultracold Gases
- Metamaterials, Nanostructures & Magnetic Materials
- Mathematical Methods
- Physics of Gases, Plasmas & Electric Fields
- High Energy Nuclear Physics

If you are working on research in any of these areas, the Co-Editors would be delighted to receive your submission. Articles should be submitted via the automated manuscript system at www.epletters.net

If you would like further information about our author service or EPL in general, please visit www.epljournal.org or e-mail us at info@epljournal.org



IOP Publishing

Image: Ornamental multiplication of space-time figures of temperature transformation rules (adapted from T. S. Bíró and P. Ván 2010 *EPL* **89** 30001; artistic impression by Frédérique Swist).

First measurement of the total proton-proton cross-section at the LHC energy of $\sqrt{s} = 7$ TeV

THE TOTEM COLLABORATION

G. ANTICHEV^(a), P. ASPELL⁸, I. ATANASSOV^{8(a)}, V. AVATI⁸, J. BAECHLER⁸, V. BERARDI^{5b,5a}, M. BERRETTI^{7b}, E. BOSSINI^{7b}, M. BOZZO^{6b,6a}, P. BROGI^{7b}, E. BRÜCKEN^{3a,3b}, A. BUZZO^{6a}, F. S. CAFAGNA^{5a}, M. CALICCHIO^{5b,5a}, M. G. CATANESI^{5a}, C. COVAULT⁹, T. CSÖRGŐ⁴, M. DEILE⁸, K. EGGERT⁹, V. EREMIN^(b), R. FERRETTI^{6a,6b}, F. FERRO^{6a}, A. FIERGOLSKI^(c), F. GARCIA^{3a}, S. GIANI⁸, V. GRECO^{7b,8}, L. GRZANKA^{8(d)}, J. HEINO^{3a}, T. HILDEN^{3a,3b}, M. R. INTONTI^{5a}, J. KAŠPAR^{1a,7}, J. KOPAL^{1a,8}, V. KUNDRÁT^{1a}, K. KURVINEN^{3a}, S. LAMI^{7a}, G. LATINO^{7b}, R. LAUHAKANGAS^{3a}, T. LESZKO^(c), E. LIPPMAN², M. LOKAJÍČEK^{1a}, M. LO VETERE^{6b,6a}, F. LUCAS RODRÍGUEZ⁸, M. MACRÌ^{6a}, L. MAGALETTI^{5b,5a}, A. MERCADANTE^{5b,5a}, S. MINUTOLI^{6a}, F. NEMES^{4(e)}, H. NIEWIADOMSKI⁸, E. OLIVERI^{7b}, F. OLJEMARK^{3a,3b}, R. ORAVA^{3a,3b}, M. ORIUNNO^{8(f)}, K. ÖSTERBERG^{3a,3b}, P. PALAZZI^{7b}, J. PROCHÁZKA^{1a}, M. QUINTO^{5a}, E. RADERMACHER⁸, E. RADICIONI^{5a}, F. RAVOTTI⁸, E. ROBUTTI^{6a}, L. ROPELEWSKI⁸, G. RUGGIERO⁸, H. SAARIKKO^{3a,3b}, G. SANGUINETTI^{7a}, A. SANTRONI^{6b,6a}, A. SCRIBANO^{7b}, W. SNOEYS⁸, J. SZIKLAI⁴, C. TAYLOR⁹, N. TURINI^{7b}, V. VACEK^{1b}, M. VITEK^{1b}, J. WELT^{3a,3b} and J. WHITMORE¹⁰

^{1a} Institute of Physics of the Academy of Sciences of the Czech Republic - Praha, Czech Republic, EU

^{1b} Czech Technical University - Praha, Czech Republic, EU

² National Institute of Chemical Physics and Biophysics NICPB - Tallinn, Estonia, EU

^{3a} Helsinki Institute of Physics - Helsinki, Finland, EU

^{3b} Department of Physics, University of Helsinki - Helsinki, Finland, EU

⁴ MTA KFKI RMKI - Budapest, Hungary, EU

^{5a} INFN Sezione di Bari - Bari, Italy, EU

^{5b} Dipartimento Interateneo di Fisica di Bari - Bari, Italy, EU

^{6a} Sezione INFN di Genova - Genova, Italy, EU

^{6b} Università degli Studi di Genova - Genova, Italy, EU

^{7a} INFN Sezione di Pisa - Pisa, Italy, EU

^{7b} Università degli Studi di Siena and Gruppo Collegato INFN di Siena - Siena, Italy, EU

⁸ CERN - Geneva, Switzerland

⁹ Case Western Reserve University, Department of Physics - Cleveland, OH, USA

¹⁰ Penn State University, Department of Physics - University Park, PA, USA

received on 27 September 2011; accepted by M. Schreiber on 28 September 2011
published online 10 October 2011

PACS 13.60.Hb – Total and inclusive cross sections (including deep-inelastic processes)

Abstract –TOTEM has measured the differential cross-section for elastic proton-proton scattering at the LHC energy of $\sqrt{s} = 7$ TeV analysing data from a short run with dedicated large- β^* optics. A single exponential fit with a slope $B = (20.1 \pm 0.2^{\text{stat}} \pm 0.3^{\text{syst}}) \text{ GeV}^{-2}$ describes the range of the four-momentum transfer squared $|t|$ from 0.02 to 0.33 GeV^2 . After the extrapolation to $|t| = 0$, a total elastic scattering cross-section of $(24.8 \pm 0.2^{\text{stat}} \pm 1.2^{\text{syst}}) \text{ mb}$ was obtained. Applying the optical theorem and using the luminosity measurement from CMS, a total proton-proton cross-section of $(98.3 \pm 0.2^{\text{stat}} \pm 2.8^{\text{syst}}) \text{ mb}$ was deduced which is in good agreement with the expectation from the overall fit of previously measured data over a large range of center-of-mass energies. From the total and elastic pp cross-section measurements, an inelastic pp cross-section of $(73.5 \pm 0.6^{\text{stat}} \pm_{-1.3}^{+1.8} \text{syst}) \text{ mb}$ was inferred.

open access

editor's choice

Introduction. – The observation of the rise of the total cross-section with energy was one of the highlights at the ISR, the first CERN collider [1–4]. Some indirect indications for this unforeseen phenomenon had already come earlier from high-energy cosmic-ray showers [5–7]. A long series of total proton-antiproton cross-section measurements followed in the last decades both at the CERN Sp̄pS collider [8, 9] and at the TEVATRON [10–13].

In this letter, we report the first measurement of the total and elastic proton-proton cross-sections at the CERN Large Hadron Collider (LHC) using the optical theorem together with the luminosity provided by the CMS experiment [14, 15]. With a dedicated beam optics configuration ($\beta^* = 90$ m) TOTEM has measured the differential cross-section of elastic scattering for four-momentum transfer squared values $|t|$ to $2 \times 10^{-2} \text{ GeV}^2$, making the extrapolation to the optical point at $|t| = 0$ possible. This allows the determination of the elastic scattering cross-section as well as the total cross-section.

The Roman Pot detectors. – To detect leading protons scattered at very small angles, silicon sensors are placed in movable beam-pipe insertions —so-called “Roman Pots” (RP)— located symmetrically on either side of the LHC interaction point IP5 at distances of 215–220 m from the IP [16].

Each RP station is composed of two units separated by a distance of about 5 m. A unit consists of 3 RPs, two approaching the outgoing beam vertically and one horizontally. Each RP is equipped with a stack of 10 silicon strip detectors designed with the specific objective of reducing the insensitive area at the edge facing the beam to only a few tens of micrometers. The 512 strips with $66 \mu\text{m}$ pitch of each detector are oriented at an angle of $+45^\circ$ (five “ u ”-planes) and -45° (five “ v ”-planes) with respect to the detector edge facing the beam. During the measurement the detectors in the horizontal RPs overlap with the ones in the vertical RPs, enabling a precise ($10 \mu\text{m}$) relative alignment of all three RPs in a unit by correlating their positions via common particle tracks. The precision and the reproducibility of the alignment of all RP detector planes with respect to each other and to the position of the beam centre is one of the most delicate and difficult tasks of the experiment [17].

In a station, the long lever arm between the near and the far RP units has two important advantages. First, the local track angles in the x - and y -projections

perpendicular to the beam direction are reconstructed with a precision of 5 to $10 \mu\text{rad}$. Second, the proton trigger selection by track angle can use all RPs independently: the stations on the opposite sides of the IP, the near and far units of each station, and the u and v planes in each unit. This redundancy can be used to obtain high trigger efficiency or purity.

The special LHC optics. – After an elastic scattering interaction in IP5 with the transverse vertex position (x^*, y^*) and with scattering angle projections (Θ_x^*, Θ_y^*) , the displacement (x, y) of the proton trajectory from the beam centre at the RP position s_{RP} is given by

$$x = L_x \Theta_x^* + v_x x^*, \quad y = L_y \Theta_y^* + v_y y^*, \quad (1)$$

where the optical functions $L_{x,y}$ and $v_{x,y}$ at the RP position s_{RP} are determined by the beta function: $L_{x,y} = \sqrt{\beta_{x,y} \beta^*} \sin \Delta\mu_{x,y}$ and $v_{x,y} = \sqrt{\frac{\beta_{x,y}}{\beta^*}} \cos \Delta\mu_{x,y}$ with the phase advance $\Delta\mu_{x,y} = \int_{IP}^{s_{RP}} \frac{1}{\beta_{x,y}(s)} ds$ relative to the IP. To maximise the sensitivity of the position measurement to the scattering angle while minimising its dependence on the vertex position, special optics are designed to have minimum beam divergence σ_Θ^* at the IP (imposing large values of β^* via $\sigma_\Theta^* = \sqrt{\varepsilon_n / \beta^*}$), large values of L and $v = 0$, and thus $\Delta\mu = \pi/2$ in at least one projection. In the ultimate TOTEM optics with $\beta^* = 1540$ m [18] this so-called “parallel-to-point focussing” condition will be fulfilled in both x and y . As a first step towards this goal, the intermediate optics with $\beta^* = 90$ m was developed [19–21]. Since this intermediate optics is reachable by gradually increasing β^* from 11 m (the value at injection) to 90 m (“un-squeezing”), the commissioning is easier than for the ultimate optics. The $\beta^* = 90$ m exhibits parallel-to-point focussing only in the vertical plane ($\Delta\mu_y \approx \pi/2$, $L_y \approx 260$ m, $v_y \approx 0$), whereas in the horizontal plane $\Delta\mu_x \approx \pi$ and hence $L_x \approx 0$ which helps separating elastic and diffractive events. The beam divergence is $\sigma_\Theta^* \approx 2.5 \mu\text{rad}$. The vertical scattering angle Θ_y^* can then be directly reconstructed from the track position y , whereas due to $L_x \approx 0$ the horizontal component Θ_x^* is optimally reconstructed from the track angle $\Theta_x = \frac{dx}{ds}$ at the RP:

$$\Theta_y^* = \frac{y}{L_y}, \quad \Theta_x^* = \frac{1}{\frac{dL_x}{ds}} \left(\Theta_x - \frac{dv_x}{ds} x^* \right), \quad (2)$$

where the unmeasured vertex produces a smearing term $\propto x^*$. However, this smearing is eliminated later in the analysis since the vertex term cancels due to the correlation between the collinear tracks of the two outgoing protons.

Data collection and event selection. – The data presented here were collected in the first LHC run with the $\beta^* = 90$ m optics. Each beam had two bunches with populations of 1×10^{10} and 2×10^{10} protons. Given the normalised transverse emittances of $(1.8\text{--}2.6) \mu\text{mrad}$ depending on the bunch, this filling scheme led to an instantaneous luminosity of about $8 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$. Thanks

^(a) INRNE-BAS, Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences - Sofia, Bulgaria, EU.

^(b) Ioffe Physical-Technical Institute of Russian Academy of Sciences - St Petersburg, Russian Federation.

^(c) Warsaw University of Technology - Warsaw, Poland, EU.

^(d) Institute of Nuclear Physics, Polish Academy of Sciences - Cracow, Poland, EU.

^(e) Department of Atomic Physics, ELTE University - Budapest, Hungary, EU.

^(f) SLAC National Accelerator Laboratory - Stanford, CA, USA.

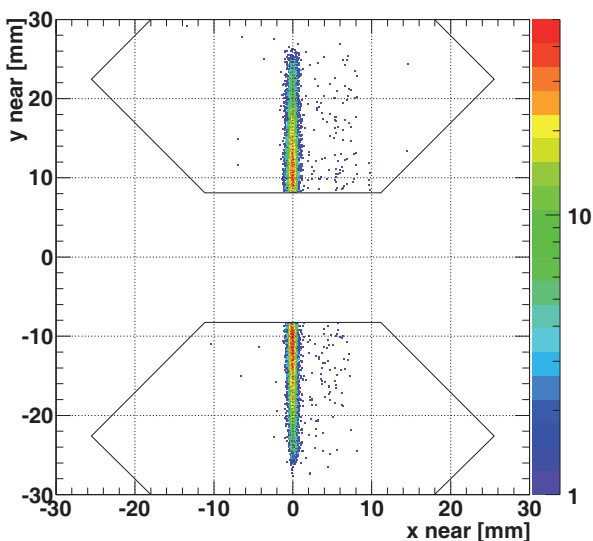


Fig. 1: (Colour on-line) The intersection points of all reconstructed tracks in this data set with the RP silicon detectors (black lines indicate the detector sensitive area) at the RP 220 m station. In order to represent the pp scattering configuration, the tracks visualized in the bottom silicon detector refer to one side and in the top detector to the other side of the interaction point.

to the low beam intensity, the RP detectors could safely approach the beam centre to a distance of 10 times the transverse beam size. After verifying that the beam orbit did not significantly differ from the one with nominal beam optics ($\beta^* = 1.5$ m), the RP positions were defined relative to the reference beam centre determined one month earlier in a beam-based alignment exercise for $\beta^* = 1.5$ m. Within the running time of 33 minutes, an integrated luminosity of $1.7 \mu\text{b}^{-1}$ was delivered, and 66950 events were recorded with a very loose trigger requiring a track segment in any of the vertical RPs in at least one of the two transverse projections (u, v). The data sample relevant for this analysis consisted of 15973 events characterised by the elastic double-arm signature in the vertical RPs (*top left of IP-bottom right of IP* or *bottom left of IP-top right of IP*). Figure 1 shows the intersection points of the selected tracks with the RP detectors at the RP 220 m stations on both sides of the IP.

Analysis. –

Elastic tagging. Due to the purity of the data obtained in the conditions of this special run, the final refinement of the elastic event selection — requiring collinearity of the two outgoing protons reconstructed with full detector efficiency within 3 standard deviations in their scattering angle correlation (fig. 2) — reduces the sample to 14685 elastic events. No further cuts, *e.g.*, for excluding diffractive events, are necessary. The reconstructed and selected elastic events from the two allowed diagonal topologies (7315 events on *top left of IP-bottom right of IP* and 7370 events on *bottom left of IP-top right of IP*) showed that

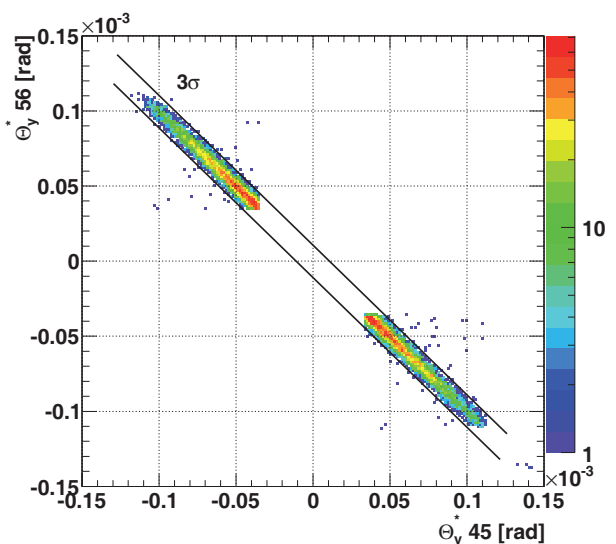
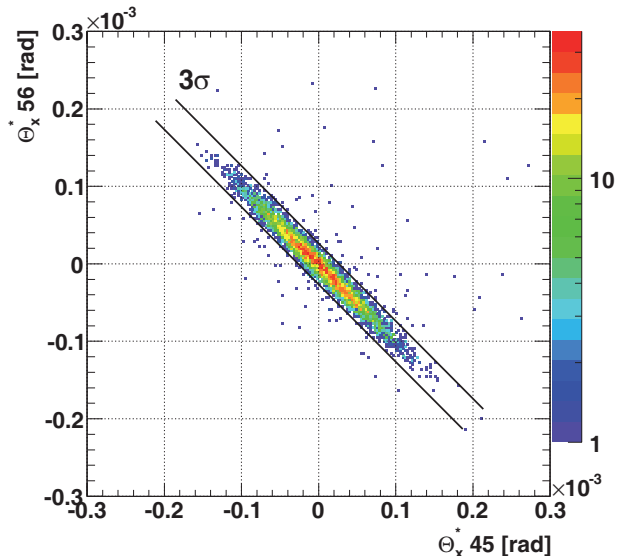


Fig. 2: (Colour on-line) The correlation between the reconstructed proton scattering angles Θ_x^* (top) and Θ_y^* (bottom) on both sides of the IP (“45” = left of IP5, “56” = right of IP5).

their acceptance was the same and that the RP system was well aligned. The Θ_y^* resolution was $1.7 \mu\text{rad}$, originating directly from the beam divergence since detector effects are suppressed given the large value of L_y . In the Θ_x^* resolution the beam divergence contribution is convoluted with the detector resolution and the vertex distribution, but the vertex effect is factorised out once the pairs of elastic protons are reconstructed together.

Optics, t -scale. The LHC optics with $\beta^* = 90$ m is very insensitive to machine parameter variations. This led to systematic uncertainties on Θ_x^* and Θ_y^* of just 1.3% and 0.4%, respectively. Non-linearities were observed and corrected in the observable Θ_x^* as a function of the reconstructed y position. The correction was benchmarked on

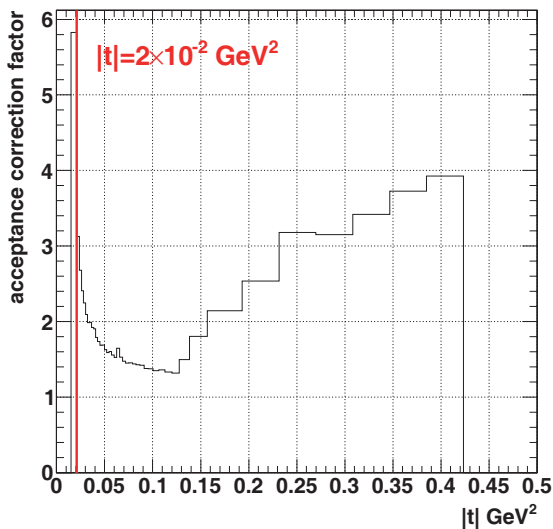


Fig. 3: (Colour on-line) The acceptance correction factor and the t -limit of this analysis.

the isotropy of the ϕ distribution of the elastic candidate events, and it was cross-checked by repeating the analysis using L_x to reconstruct the relevant physics variables. The overall propagated systematic uncertainty on the t scale for one arm is 0.8% at low $|t|$ and 2.6% at large $|t|$.

Acceptance. The acceptance limitations at low $|t|$ have been corrected for the geometry and beam divergence related factors (fig. 3).

The TOTEM experiment has thus measured $|t|$ down to the limit of $2 \times 10^{-2} \text{ GeV}^2$ (constraining the total acceptance correction at low $|t|$ to be ≤ 3 in order to minimise the systematics). The acceptance loss (due to aperture limitations) at the high end of the $|t|$ spectrum measurable with this optics has also been treated, thus allowing measurements of $|t|$ up to 0.42 GeV^2 . Therefore, a comparative analysis with the previously published TOTEM results [22] is possible.

Efficiency. The detector and reconstruction efficiency per pot has been evaluated directly from the data, by repeating the analysis of the elastic events using three pots out of four and permutating on the missing pot. The inefficiency of the near pots was about 1.5%, while the inefficiency of the far pots was about 3%: such a difference is expected due to the probability of a proton having a hadronic interaction in a near pot, inducing a shower onto its corresponding far pot. The overall inefficiency for both diagonals has been computed to be 8.9% and 8.7%, counting also the uncorrelated probabilities to have more than one pot inefficient at the same time. The special trigger combination with all detector components in OR, used for this data taking, has allowed checking and excluding all combinations of correlated inefficiencies.

Background. The data did not show any measurable background ($< 0.1\%$) affecting the selection of elastic

events. Single Gaussian fits precisely describe (without any non-Gaussian tails) the distributions resulting from the selection cuts, guaranteeing efficiency and purity of these cuts. In fact, the special optics run and the two colliding low-intensity bunches ensured the absence of pile-up from single diffraction; moreover, the data have shown that double pomeron exchange events could not satisfy the collinearity requirements in both dimensions at the same time even at very low $|t|$, as verified by selecting events with momentum loss $\Delta p/p > 1\%$.

Resolution. After deconvolution of the vertex, the effective resolution in Θ_x^* has contributions of $1.7 \mu\text{rad}$ from the beam divergence and $4.0 \mu\text{rad}$ from the RP detector resolution. The resolution in Θ_y^* is $1.7 \mu\text{rad}$ from the beam divergence. Hence the bin migration correction as a function of t was contained between +1% and -3%. This resolution-unfolding correction has been computed with high precision (systematic uncertainty of 0.7%) taking into account the acceptance effects, given the different resolutions in the two angular components.

Extrapolation to $t = 0$. The elastic differential cross-section has been measured down to $|t| = 2 \times 10^{-2} \text{ GeV}^2$. The data were then extrapolated to $t = 0$ assuming the functional form

$$\frac{d\sigma_{\text{el}}}{dt} = \left. \frac{d\sigma_{\text{el}}}{dt} \right|_{t=0} e^{-B|t|}. \quad (3)$$

The statistical and the propagated systematic uncertainties of the extrapolation are given separately in table 1.

Luminosity, trigger, normalisation. This data analysis was based on a large fraction of the data taken during run 5657, excluding the period of initial beam adjustment, in fill 1902 on 29 June 2011. The luminosity was recorded by CMS with an uncertainty of 4% [14, 15]; the additional uncertainty contribution due to pile-up, found by CMS in 2011 [23] does not apply to the very low luminosity discussed here. The trigger efficiency for elastic events was greater than 99.9%. Thus, the effective integrated luminosity was equal to $1.65 \mu\text{b}^{-1}$.

Results. – After including all the analysis corrections described above, the final differential cross-section for the elastic proton-proton scattering with its statistical errors is shown in fig. 4.

The new data can be described by a single exponential fit ($\chi^2/\text{d.o.f.} = 0.8$) over the complete $|t|$ range of $(0.02\text{--}0.33) \text{ GeV}^2$ with the slope $B = (20.1 \pm 0.2^{\text{stat}} \pm 0.3^{\text{syst}}) \text{ GeV}^{-2}$. The TOTEM result for B at low $|t|$ confirms the trend of an increase with \sqrt{s} [10, 24–29]. As a comparison, the exponential fit at the lower end of the $|t|$ range of our previous measurement [22] which covered $(0.36\text{--}2.5) \text{ GeV}^2$ is also shown in fig. 4. The agreement between the two measurements that were done with different optics is excellent. It is worth noting that the slope in the $|t|$ interval of $(0.36\text{--}0.47) \text{ GeV}^2$ is significantly larger: $(23.6 \pm 0.5^{\text{stat}} \pm 0.4^{\text{syst}}) \text{ GeV}^{-2}$.

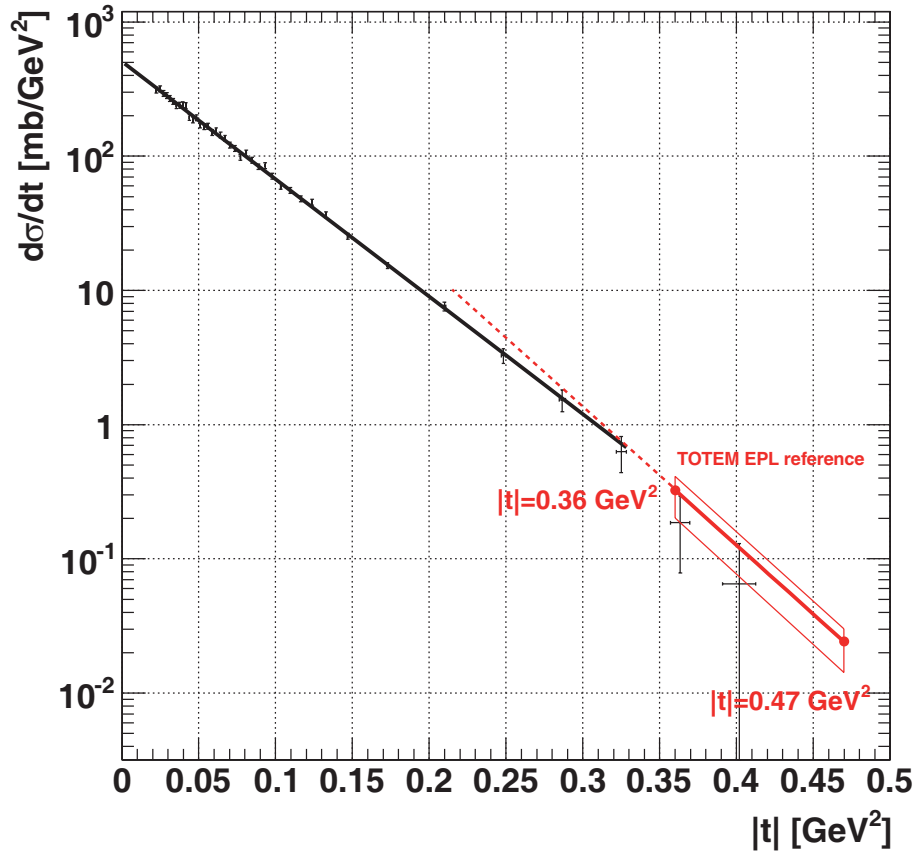


Fig. 4: (Colour on-line) The measured pp elastic scattering differential cross-section $d\sigma/dt$. The superimposed fits and their parameter values are discussed in the text.

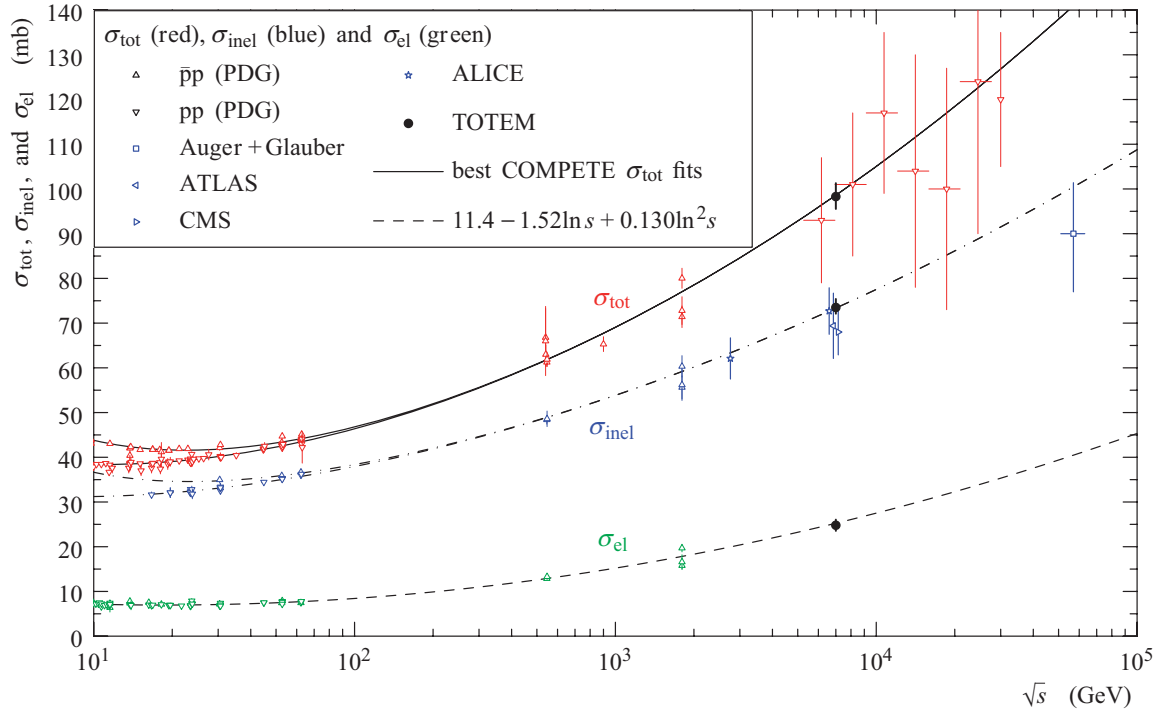


Fig. 5: (Colour on-line) Compilation of measurements of total (σ_{tot}), inelastic (σ_{inel}) and elastic (σ_{el}) cross-section measurements [30–35].

Table 1: Results of the TOTEM measurements at the LHC energy of $\sqrt{s} = 7$ TeV.

	Statistical uncertainties	Systematic uncertainties	Result
t	$\pm[3.4-11.9]\%$ single measurement ^(*)	$\pm[0.6-1.8]\%$ optics $\pm < 1\%$ alignment	
$\frac{d\sigma}{dt}$	5% / bin	$\pm 4\%$ luminosity $\pm 1\%$ analysis $\pm 0.7\%$ unfolding	
B	$\pm 1\%$	$\pm 1\%$ t -scale $\pm 0.7\%$ unfolding	(20.1 \pm 0.2^{stat} \pm 0.3^{syst}) GeV⁻²
$\frac{d\sigma}{dt} _{t=0}$	$\pm 0.3\%$	$\pm 0.3\%$ optics $\pm 4\%$ luminosity $\pm 1\%$ analysis	(503.7 \pm 1.5^{stat} \pm 26.7^{syst}) mb/GeV²
$\int \frac{d\sigma}{dt} dt$	$\pm 0.8\%$ extrapolation	$\pm 4\%$ luminosity $\pm 1\%$ analysis	
σ_{tot}	$\pm 0.2\%$	$\left(\begin{smallmatrix} +0.8\% \\ -0.2\% \end{smallmatrix}\right)^{(\rho)} \pm 2.7\%$	(98.3 \pm 0.2^{stat} \pm 2.8^{syst}) mb
$\sigma_{\text{el}} = \int \frac{d\sigma}{dt} dt$	$\pm 0.8\%$	$\pm 5\%$	(24.8 \pm 0.2^{stat} \pm 1.2^{syst}) mb
σ_{inel}	$\pm 0.8\%$	$\left(\begin{smallmatrix} +2.4\% \\ -1.8\% \end{smallmatrix}\right)$	(73.5 \pm 0.6^{stat} \pm 1.8^{syst}) mb
σ_{inel} (CMS)			(68.0 \pm 2.0 ^{syst} \pm 2.4 ^{lumi} \pm 4 ^{extrap}) mb
σ_{inel} (ATLAS)			(69.4 \pm 2.4 ^{exp} \pm 6.9 ^{extrap}) mb
σ_{inel} (ALICE)			(72.7 \pm 1.1 ^{model} \pm 5.1 ^{lumi}) mb

(*) Corrected after unfolding.

analysis (includes tagging, acceptance, efficiency, background).

Assuming a constant slope B for the nuclear scattering, the differential cross-section at the optical point $t = 0$ was determined to be $\frac{d\sigma}{dt}|_{t=0} = (503.7 \pm 1.5^{\text{stat}} \pm 26.7^{\text{syst}}) \text{mb/GeV}^2$. Integrating the differential cross-section yields a total elastic scattering cross-section of $(24.8 \pm 0.2^{\text{stat}} \pm 1.2^{\text{syst}}) \text{mb}$, out of which 16.5 mb were directly observed.

The total proton-proton cross-section is related to the elastic cross-section via the optical theorem

$$\sigma_{\text{tot}}^2 = \frac{16\pi(\hbar c)^2}{1 + \rho^2} \left. \frac{d\sigma_{\text{el}}}{dt} \right|_{t=0}. \quad (4)$$

Taking the COMPETE prediction [30] of $0.14_{-0.08}^{+0.01}$ for the parameter $\rho = \frac{\mathcal{R}[f_{\text{el}}(0)]}{\mathcal{I}[f_{\text{el}}(0)]}$, where $f_{\text{el}}(0)$ is the forward nuclear elastic amplitude, σ_{tot} was thus determined to be

$$\sigma_{\text{tot}} = \left(98.3 \pm 0.2^{\text{stat}} \begin{smallmatrix} +2.8 \\ -2.7 \end{smallmatrix}^{\text{syst}} \right) \text{mb}. \quad (5)$$

The errors are dominated by the extrapolation to $t = 0$ and the luminosity uncertainty.

Subtracting the elastic scattering cross-section, we obtain a value for the inelastic cross-section which can then be compared with the measurements of the CMS [31], ATLAS [32], and ALICE [33] experiments.

The results (table 1) are consistent within the quoted errors of CMS, ATLAS, and ALICE, which took into account the uncertainties of the model predictions for the unobserved very-forward diffractive processes.

In fig. 5, the values of the TOTEM total and elastic cross-sections are compared with results at lower energies and from cosmic rays together with an overall fit of the COMPETE Collaboration [30]. The TOTEM total cross-section is in excellent agreement with the extrapolation from lower energies. To guide the eye, a parabolic fit was

used for the energy dependence of the elastic cross-section. The ratio of the elastic to total cross-section $\sigma_{\text{el}}/\sigma_{\text{tot}} = 0.25 \pm 0.01^{\text{stat} \oplus \text{syst}}$.

Table 1 lists the values of the measured observables and the final results for the physics quantities along with their statistical and systematic uncertainties.

Outlook. – TOTEM foresees taking data in dedicated runs with $\beta^* = 90$ m still in 2011. It is expected that the RP detectors can approach the beam centre as close as 5 times the transverse beam width. The lowest accessible $|t|$ -values will then be around 0.005GeV^2 , improving the measurement of the slope B and the extrapolation of the differential cross-section to $|t| = 0$. Furthermore, with a running time of at least 5 hours the statistics can be considerably improved. Inclusion of the TOTEM inelastic telescopes, T1 and T2, will allow a luminosity-independent measurement of the total cross-section as well as a detailed study of low-mass diffraction. If larger values of β^* (around 1 km) can be reached during the year 2012, the acceptance for low- t elastic scattering can be extended into the Coulomb-Nuclear-Interference region below 10^{-3}GeV^2 . A measurement of the ρ -parameter might then come into reach.

We are indebted to the beam optics development team (A. VERDIER in the initial phase, H. BURKHARDT, G. MÜLLER, S. REDAELLI, J. WENNINGER, S. WHITE) for the design, the thorough preparations and the successful commissioning of the $\beta^* = 90$ m optics. We congratulate the CERN accelerator groups for the very smooth operation during the optics test run in June 2011. We thank M. FERRO-LUZZI and the LHC machine coordinators for scheduling the dedicated fills.

We are grateful to CMS for the fruitful and effective collaboration and for providing their luminosity measurements.

We thank M. BORRATYNSKI, E. CROCIANI, T. JÄÄSKELÄINEN, H. JUNTUNEN, P. KACZMARCZYK, S. PODGORSKI, M. POLNIK, J. SMAJEK, J. SZYMANEK, T. TAJAKKA, P. WYSZKOWSKI for their help in software development.

This work was supported by the institutions listed on the front page and partially also by NSF (US), the Magnus Ehrnrooth foundation (Finland), the Waldemar von Frenckell foundation (Finland), the Academy of Finland, the OTKA grant NK 73143 (Hungary) and by the NKTH-OTKA grant 74458 (Hungary).

REFERENCES

- [1] AMALDI U. *et al.*, *Phys. Lett. B*, **44** (1973) 112.
 [2] AMENDOLIA S. *et al.*, *Phys. Lett. B*, **44** (1973) 119.
 [3] BAKSAY L. *et al.*, *Nucl. Phys. B*, **141** (1978) 1.
 [4] AMALDI U. *et al.*, *Nucl. Phys. B*, **145** (1978) 367.
 [5] AKIMOV V. *et al.*, *Measurements of the inelastic proton-proton and proton-carbon cross-sections at energies 10^{10} to 10^{12} eV on board the satellites proton 1, 2 and 3*, in *Proceedings of the 11th International Cosmic Ray Conference (ICRC 1969), 25 August–4 September, 1969, Budapest, Hungary*, 1969, pp. 211–214.
 [6] YODH G., PAL Y. and TREFIL J., *Phys. Rev. Lett.*, **28** (1972) 1005.
 [7] DAWSON B., *Measurement of the total proton proton cross-section using the Fly’s Eye*, in *Proceedings of Elastic and diffractive scattering, New York*, 1987, pp. 337–346.
 [8] BATTISTON R. *et al.*, *Phys. Lett. B*, **117** (1982) 126.
 [9] ARNISON G. *et al.*, *Phys. Lett. B*, **128** (1983) 336.
 [10] AMOS N. *et al.*, *Phys. Rev. Lett.*, **63** (1989) 2784.
 [11] ABE F. *et al.*, *Phys. Rev. D*, **50** (1994) 5550.
 [12] SADR S. *et al.*, *Anti-p p collisions at $s^{1/2} = 1.8$ TeV: rho, sigma(t), and B*, in *Proceedings of the International Conference On Elastic and Diffractive Scattering (5th Blois Workshop), Providence, Rhode Island, 1993*, pp. 59–63.
 [13] AVILA C. *et al.*, *Phys. Lett. B*, **445** (1999) 419.
 [14] CMS-COLLABORATION, Performance Analysis Note CMS-PAS-EWK-10-004 (2010).
 [15] CMS-COLLABORATION, Detector Performance Note CMS-DP-2011-002 C (2011).
 [16] ANELLI G. *et al.*, *JINST*, **3** (2008) S08007.
 [17] DEILE M. *et al.*, *The First 1 1/2 Years of TOTEM Roman Pot Operation at LHC*, in *Proceedings of IPAC’11, San Sebastian, Spain*, 2011, p. MOPO011.
 [18] VERDIER A., CERN-LHC-Project-Note-369-2005 (2005).
 [19] EGGERT K., *TOTEM Physics*, presented at the *XI International Conference on Elastic and Diffractive Scattering Towards the High Energy Frontiers (XVII Rencontre de Blois), Blois, France, May 15–20, 2005*.
 [20] TOTEM-COLLABORATION, CERN-LHCC-2007-013/G-130 (2007).
 [21] BURKHARDT H. and WHITE S., CERN-LHC-Project-Note-431-2010 (2010).
 [22] ANTCHEV G. *et al.*, *EPL*, **95** (2011) 41001.
 [23] CMS-COLLABORATION, Performance Analysis Note CMS-PAS-EWK-11-001 (2011).
 [24] BÜLTMANN S. *et al.*, *Phys. Lett. B*, **579** (2004) 245.
 [25] ABE F. *et al.*, *Phys. Rev. D*, **50** (1994) 5518.
 [26] AMOS N. A. *et al.*, *Phys. Rev. Lett.*, **61** (1988) 525.
 [27] AMOS N. A. *et al.*, *Phys. Lett. B*, **247** (1990) 127.
 [28] AMOS N. A. *et al.*, *Nuovo Cimento A*, **106** (1993) 123.
 [29] BRANDT A., *PoSD*, **IS2010** (2010) 059 FERMILAB-CONF-10-547.
 [30] CUDELL J. *et al.*, *Phys. Rev. Lett.*, **89** (2002) 201801.
 [31] CMS-COLLABORATION, Performance Analysis Note CMS-PAS-FWD-11-001 (2011).
 [32] AAD G. *et al.*, arXiv:1104.0326 [hep-ex] (2011).
 [33] POGHOSYAN M. G. *et al.*, arXiv:1109.4510 [hep-ex] (2011).
 [34] PARTICLE DATA GROUP (NAKAMURA K. *et al.*), *J. Phys. G*, **37** (2010) 075021.
 [35] BLOCK M. M., arXiv:1109.2940 [hep-ph] (2011).