

Diffraction at TOTEM

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Abstract

The TOTEM experiment at the LHC measures the total proton-proton cross section with the luminosity-independent method and the elastic proton-proton cross-section over a wide $|t|$ -range. It also performs a comprehensive study of diffraction, spanning from cross-section measurements of individual diffractive processes to the analysis of their event topologies. Hard diffraction will be studied in collaboration with CMS taking advantage of the large common rapidity coverage for charged and neutral particle detection and the large variety of trigger possibilities even at large luminosities. TOTEM will take data under all LHC beam conditions including standard high luminosity runs to maximize its physics reach. This contribution describes the main features of the TOTEM physics programme including measurements to be made in the early LHC runs. In addition, a novel scheme to extend the diffractive proton acceptance for high luminosity runs by installing proton detectors at IP3 is described.

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1 Introduction

The TOTEM experiment [1] is dedicated to the total proton-proton (pp) cross-section measurement using the luminosity-independent method, which requires a detailed measurement of the elastic scattering rate down to a squared four-momentum transfer of $-t \sim p^2\Theta^2 \sim 10^{-3} \text{ GeV}^2$ together with the measurements of the total inelastic and elastic rates. Furthermore, by studying elastic scattering with momentum transfers up to 10 GeV^2 , and via a comprehensive study of diffractive processes – partly in cooperation with CMS [2], located at the same interaction point, TOTEM’s physics programme aims at a deeper understanding of the proton structure. To perform these measurements, TOTEM requires a good acceptance for particles produced at small and even tiny angles with respect to the beams. TOTEM’s coverage in the pseudo-rapidity range of $3.1 \leq |\eta| \leq 6.5$ ($\eta = -\ln \tan \frac{\theta}{2}$) on both sides of the interaction point (IP) is accomplished by two telescopes, T1 and T2 (Figure 1, top), for the detection of charged particles with emission angles between a few and about hundred milliradians. This is complemented by detectors in special movable beam-pipe insertions – so called Roman Pots (RP) – placed at about 147 m and 220 m from the IP, designed to detect elastically or diffractively scattered protons at merely a few millimeter from the beam center corresponding to emission angles down to a few microradians (Figure 1, bottom).

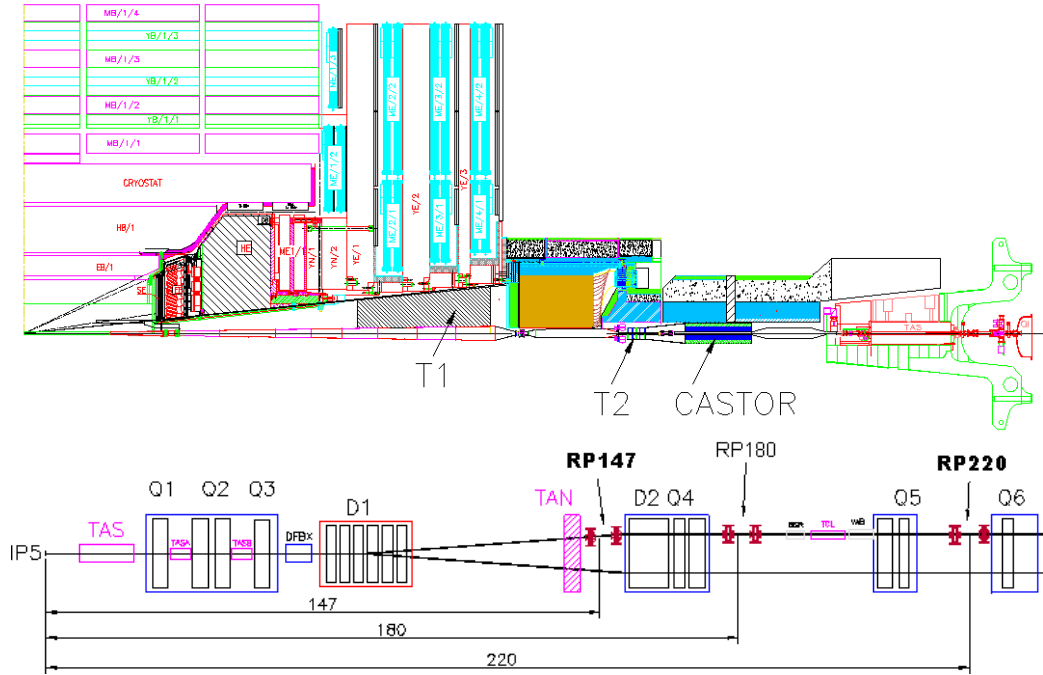


Fig. 1: Top: TOTEM forward telescopes T1 and T2 embedded in the CMS experiment together with the CMS forward calorimeter CASTOR. Bottom: LHC beam line on one side of interaction point IP5 and TOTEM Roman Pot stations at distances of about 147 m (RP147) and 220 m (RP220). RP180 at 180 m is another possible location but presently not equipped.

For the luminosity-independent total cross-section measurement, TOTEM has to reach the lowest possible $|t|$ values in elastic pp scattering. Elastically scattered protons close to the beam can be detected downstream on either side of the IP if the displacement at the detector location is large enough and if the beam divergence at the IP is small compared to the scattering angle. To achieve these conditions special LHC optics with high beta value at the IP (β^*) are required: the larger the β^* , the smaller the beam divergence ($\sim 1/\sqrt{\beta^*}$) will be. Two optics are proposed: an ultimate one with $\beta^* = 1540$ m and another one, possibly foreseen for 2009, with $\beta^* = 90$ m. The latter uses the standard injection optics ($\beta^* = 11$ m) and beam conditions typical for early LHC running: zero degree crossing-angle and consequently at most 156 bunches together with a low number of protons per bunch.

The versatile physics programme of TOTEM requires different running scenarios that have to be adapted to the LHC commissioning and operation in the first years. A flexible trigger can be provided by the two telescopes and the Roman Pot detectors. TOTEM will take data under all optics conditions, adjusting the trigger schemes to the luminosity. The DAQ will allow trigger rates up to a few kHz without involving a higher level trigger. The high- β^* runs (Table 1) with 156 bunches, zero degree crossing-angle and maximum luminosity between 10^{29} and 10^{30} $\text{cm}^{-2}\text{s}^{-1}$, will concentrate on low- $|t|$ elastic scattering, total cross-section, minimum bias physics and soft diffraction. A large fraction of forward protons will be detected even at the lowest ξ values. Low- β^* runs (Table 1) with more bunches and higher luminosity ($10^{32} - 10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$) will be used for large- $|t|$ elastic scattering and diffractive studies with $\xi > 0.02$. Hard diffractive events come within reach. In addition, early low β^* runs will provide first opportunities for measurements of soft diffraction at LHC energies and for studies of forward charged multiplicity.

β^* [m]	k	$N/10^{11}$	\mathcal{L} [$\text{cm}^{-2}\text{s}^{-1}$]	$ t $ -range [GeV^2] @ $\xi = 0$	ξ -range
1540	43 ÷ 156	0.6 ÷ 1.15	$10^{28} \div 2 \cdot 10^{29}$	0.002 ÷ 1.5	< 0.2
90	156	0.1 ÷ 1.15	$2 \cdot 10^{28} \div 3 \cdot 10^{30}$	0.03 ÷ 10	< 0.2
11	43 ÷ 2808	0.1 ÷ 1.15	$\sim 10^{30} \div 5 \cdot 10^{32}$	0.6 ÷ 8	0.02 ÷ 0.2
0.5 ÷ 3	43 ÷ 2808	0.1 ÷ 1.15	$\sim 10^{30} \div 10^{34}$	2 ÷ 10	0.02 ÷ 0.2

Table 1: Running scenarios at different LHC optics (k : number of bunches, N : number of particles per bunch, \mathcal{L} : estimated luminosity). The $|t|$ ranges for elastically scattered protons correspond to the $\geq 50\%$ combined RP147 and RP220 acceptance.

In the following, after a brief description of the TOTEM detectors and the principles of proton detection, the main features of the TOTEM physics programme will be given. This will be followed by a description of the early physics programme. Finally the novel idea of proton detection at IP3 will be presented. A detailed technical description of the TOTEM experiment can be found in Ref. [3].

2 TOTEM detectors and performance

2.1 Inelastic detectors

The measurement of the inelastic rate requires identification of all beam-beam events with detectors capable to trigger and reconstruct the interaction vertex. The main requirements of these

detectors are:

- to provide a fully inclusive trigger for minimum bias and diffractive events, with minimal losses at a level of a few percent of the inelastic rate;
- to enable the reconstruction of the primary vertex of an event, in order to disentangle beam-beam events from the background via a partial event reconstruction.

These requirements are fulfilled by the T1 telescope (centered at $z = 9$ m), consisting of Cathode Strip Chambers (CSC) and T2 telescope (centered at $z = 13.5$ m) exploiting Gas Electron Multipliers (GEM). The η coverage of T1 and T2 is $3.1 \leq |\eta| \leq 4.7$ and $5.3 \leq |\eta| \leq 6.5$, respectively. Each T1 telescope arm consists of five planes made up of six trapezoidal formed CSC's with a spatial resolution of ~ 1 mm. Each T2 telescope arm consists of 20 semicircular shaped triple-GEM detectors with a spatial resolution of $\sim 100 \mu\text{m}$ in the radial direction and a inner radius that matches the beam-pipe. Ten aligned detectors mounted back-to-back are combined to form one T2 half arm on each side of the beam-pipe. For charged particles with momenta typical of particles produced within the detector acceptances in inelastic events, the particle η can be determined with a precision that increases with $|\eta|$ and is between 0.02 and 0.06 in T1 and between 0.04 and 0.1 in T2. The corresponding azimuthal angle resolution for both detectors is $\sim 1^\circ$. The magnetic field at the detector locations is too weak to allow for a momentum determination for the charged particles. The primary vertex can be reconstructed with a precision of ~ 1.5 cm in the radial direction and ~ 20 cm in the beam direction in presence of the CMS magnetic field. Vertex resolutions one order of magnitude better can be achieved running with the CMS magnetic field switched off.

2.2 Proton detectors

To measure elastically and diffractively scattered protons with high acceptance requires the reconstruction of the protons tracks by “trigger capable” detectors moved as close as ~ 1 mm from the center of the outgoing beam. This is obtained with two RP stations installed, symmetrically on both sides of IP5, at a distance of ~ 147 m and ~ 220 m from IP5. These positions are given by an interplay between the development of the special TOTEM optics and the constraints given by the LHC accelerator elements. Each RP station is composed of two units at a distance of several meters. This large lever arm allows local track reconstruction and a fast trigger selection based on the track angle. Each unit consists of three pots, two approaching the beam vertically from the top and the bottom and one horizontally to complete the acceptance for diffractively scattered protons, in particular for the low β^* optics. Furthermore, the overlap of the detector acceptance in the horizontal and vertical pots is vital for the relative alignment of the three pots via common particle tracks. The position of the pots with respect to the beam is given by Beam Position Monitors mechanically fixed to all three pots in one unit. Each pot contains a stack of 10 planes of silicon strip “edgeless” detectors with half with their strips oriented at an angle of $+45^\circ$ and half at an angle of -45° with respect to the edge facing the beam. These detectors, designed by TOTEM with the objective of reducing the insensitive area at the edge facing the beam to only a few tens of microns, have a spatial resolution of $\sim 20 \mu\text{m}$. High efficiency up to the physical detector border is essential in view of maximizing the elastic and diffractive proton acceptances. For the same reason, the pots’ stainless steel bottom foil that faces the beam has been reduced to a thickness of $150 \mu\text{m}$.

2.3 Proton detection

The transverse displacement $(x(s), y(s))$ of an elastically or diffractively scattered proton at a distance s from the IP is related to its origin $(x^*, y^*, 0)$, scattering angles $\Theta_{x,y}^*$ and fractional momentum loss ξ ($= \Delta p/p$) value at the IP via the optical functions L and v , and the dispersion D :

$$x(s) = v_x(s) \cdot x^* + L_x(s) \cdot \Theta_x^* + \xi \cdot D(s) \quad \text{and} \quad y(s) = v_y(s) \cdot y^* + L_y(s) \cdot \Theta_y^* \quad (1)$$

L , v and D determining the explicit path of the proton through the LHC elements, depend mainly on the position along the beam line i.e. on all the elements traversed before reaching that position and their settings, which is an optics dependent repetition, and hence the RP acceptance for leading protons will depend on the optics. The allowed minimum distance of a RP to the beam center on one hand being proportional to the beam size $((10 - 15) \cdot \sigma_{x(y)}(s))$ as well as constraints imposed by the beam-pipe or beam screen size on the other hand will determine the proton acceptance of a RP station.

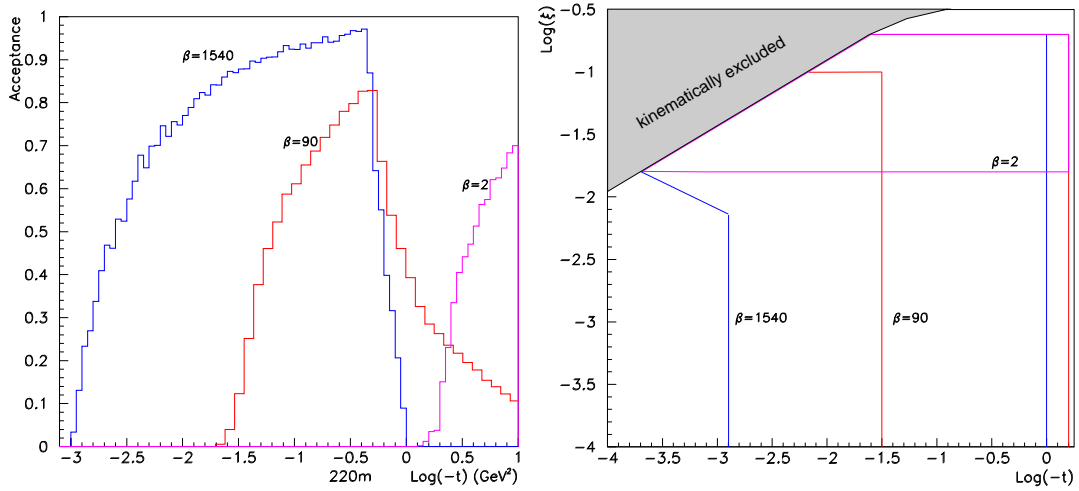


Fig. 2: Left: RP220 $\log_{10} |t|$ acceptance for elastically scattered protons at different optics configurations. Right: contour lines of 10 % acceptance for RP220 in $\log_{10} |t|$ and $\log_{10} \xi$ for diffractively scattered protons at different optics configurations.

The complementarity of the acceptances for different optics configurations is shown in Figure 2. The TOTEM-specific optics with $\beta^* = 1540$ m (blue graphs in Figure 2) is particularly optimized for accepting protons down to very low $|t|$ -values. For the diffractive case all kinematically allowed values of ξ are accepted. With the $\beta^* = 90$ m optics (red graphs in Figure 2), diffractively scattered protons are still accepted independently of their ξ -value, but the t -acceptance is reduced compared to $\beta^* = 1540$ m optics. With the standard high luminosity optics ($\beta^* = 0.5 \div 3$ m, magenta graphs in Figure 2) elastically scattered protons can only be detected at very large $|t|$ and diffractively scattered protons are accepted independently of their t value in the horizontal pots for ξ values above 2 %.

	$\beta^* = 0.5 - 3$ m	$\beta^* = 90$ m	$\beta^* = 1540$ m
$\sigma(\xi)$	0.001 \div 0.006	~ 0.0015 (w CMS vtx) ~ 0.006 (w/o CMS vtx)	0.002 \div 0.006 [‡]
$\sigma(t)$ [GeV ²]	(0.3 \div 0.45) $\sqrt{ t }$	$\sigma(t_y) \sim 0.04 \sqrt{ t_y }$	$\sim 0.005 \sqrt{ t }$
$\sigma(M)$ [GeV] in central diffraction	(0.02 \div 0.05) M	< 18 for $R > 0.6$ (w CMS vtx) < 80 for $R > 0.6$ (w/o CMS vtx)	$\sim 20 M^b$ [‡] $b = 0.17$ for $R = 0.5 \div 1$

Table 2: Summary of resolutions for the RP220 proton reconstruction at different optics configurations. “w CMS vtx” and “w/o CMS vtx” refers to whether vertex position information from CMS is available or not (relevant for $\beta^* = 90$ m), $R = \xi_{lower}/\xi_{higher}$ to the momentum loss symmetry between the two outgoing protons and “‡” to reconstruction using also RP147.

The reconstruction of the proton kinematics is optics dependent. The main resolutions are given in Table 2. More details can be found in Ref. [4]. A feature of the $\beta^* = 90$ m optics is that $L_y \gg L_x$ and hence t_y is determined with almost an order of magnitude better precision than t_x . For central diffraction, the diffractive mass can be reconstructed from the ξ measurements of the two protons according to

$$M^2 = \xi_1 \xi_2 s. \quad (2)$$

The mass resolution for central diffractive events at different optics is also quoted in Table 2. If the scattering vertex is determined with high precision ($\sim 30 \mu\text{m}$) with the CMS tracking detectors during common data taking, a substantial improvement in the ξ and M measurement is achieved at $\beta^* = 90$ m.

3 TOTEM physics programme

Given its unique coverage for charged particles at high rapidities, TOTEM is ideal for studies of forward phenomena, including elastic and diffractive scattering. Its main physics goals, precise measurements of the total cross-section and of elastic scattering over a large range in $|t|$, are of primary importance for distinguishing between different models of soft pp interactions. Furthermore, as energy flow and particle multiplicity of inelastic events peak in the forward region, the large rapidity coverage and proton detection on both sides allow the study of a wide range of processes in inelastic and diffractive interactions.

3.1 Elastic scattering and diffraction

Much of the interest in large-impact-parameter collisions centers on elastic scattering and soft inelastic diffraction. The differential cross-section of elastic pp interactions at 14 TeV, as predicted by different models [5–8], is given in Figure 3 (left). Increasing $|t|$ means looking deeper into the proton at smaller distances. Several $|t|$ -regions with different behavior (at $\sqrt{s} = 14$ TeV) can be distinguished:

- $|t| < 6.5 \cdot 10^{-4} \text{ GeV}^2$: The Coulomb region dominated by photon exchange: $d\sigma/dt \sim 1/t^2$.
- $10^{-3} \text{ GeV}^2 < |t| < 0.5 \text{ GeV}^2$: The nuclear region, described in a simplified way by “single-Pomeron exchange”: $d\sigma/dt \sim e^{-Bt}$, is crucial for the extrapolation of the differ-

ential counting-rate dN_{el}/dt to $t = 0$, needed for the luminosity-independent total cross-section measurement.

- $0.5 \text{ GeV}^2 < |t| < 1 \text{ GeV}^2$: A region exhibiting the diffractive structure of the proton.
- $|t| > 1 \text{ GeV}^2$: Domain of central elastic collisions, described by perturbative QCD, e.g. via triple-gluon exchange with a predicted cross-section $\propto |t|^{-8}$. The model dependence of the predictions being very pronounced in this region, measurements will test the validity of different models.

TOTEM will cover the full elastic $|t|$ -range from 0.002 up to 10 GeV^2 by combining data from runs at several optics configurations as indicated in Figure 3 (left). With typical expected LHC machine cycle times of $10^4 - 10^5$ s, enough statistics at low $|t|$ values can be accumulated in one run. This statistics is also sufficient for track-based alignment of the RP detectors. The overlap between the acceptances of the different optics configurations will allow for cross-checks of the measurements.

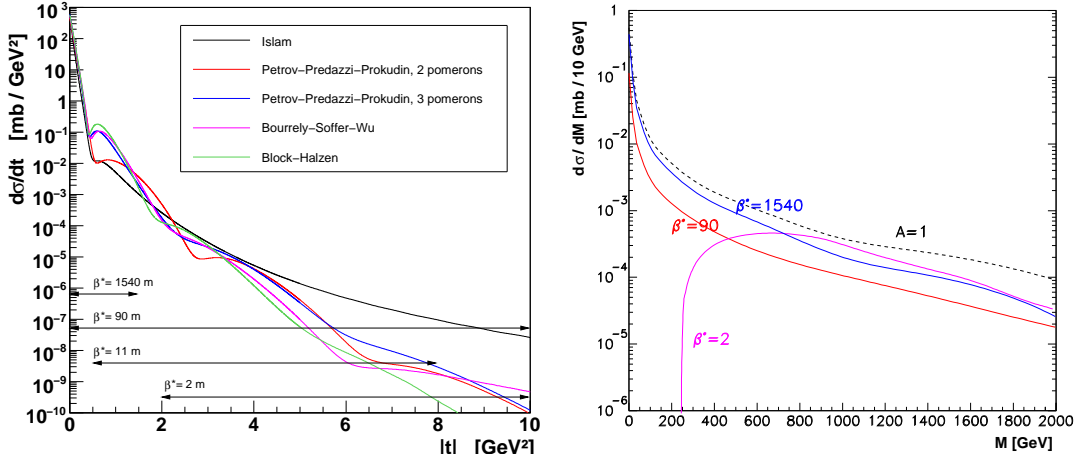


Fig. 3: Left: differential cross-section of elastic scattering at $\sqrt{s} = 14 \text{ TeV}$ as predicted by various models together with the t -acceptance ranges of different optics configurations. Right: predicted differential cross-section of central diffraction at $\sqrt{s} = 14 \text{ TeV}$ with (solid) and without (dashed) taking the proton acceptance into account for different optics configurations.

Diffractive scattering comprises single diffraction, double diffraction, central diffraction (a.k.a. “double Pomeron exchange”), and higher order (“multi Pomeron”) processes, shown in Figure 4 with their cross-sections as measured at Tevatron [9–12] and as predicted for LHC [5–8, 13–15]. Together with elastic scattering these processes represent about 50 % of the total cross-section. Many details of these processes with close ties to proton structure and low-energy QCD are still poorly understood. Majority of diffractive events (Figure 4) exhibits intact (“leading”) protons in the final state, characterized by their t and ξ . For large β^* (see Figure 2, right) most of these protons can be detected in the RP detectors. Already at an early stage, TOTEM will be able to measure ξ -, t - and mass-distributions in soft central and single diffractive events. The full structure of diffractive events with one or more sizeable rapidity gap in the particle distribution

(Figure 4) will be optimally accessible when the detectors of CMS and TOTEM will be combined for common data taking with an unprecedented rapidity coverage, as discussed in [2].

Figure 3 (right) shows the predicted central diffractive mass distribution [15] together with the acceptance corrected distributions for three different optics. With high and intermediate β^* optics, all diffractive mass values are observable. For low β^* optics on the other hand, the acceptance starts at ~ 250 GeV but higher statistics for high masses will be collected due to the larger luminosity. By combining data from runs at low β^* with data from high or intermediate β^* runs, the differential cross-section as function of the central diffractive mass can be measured with good precision over the full mass range.

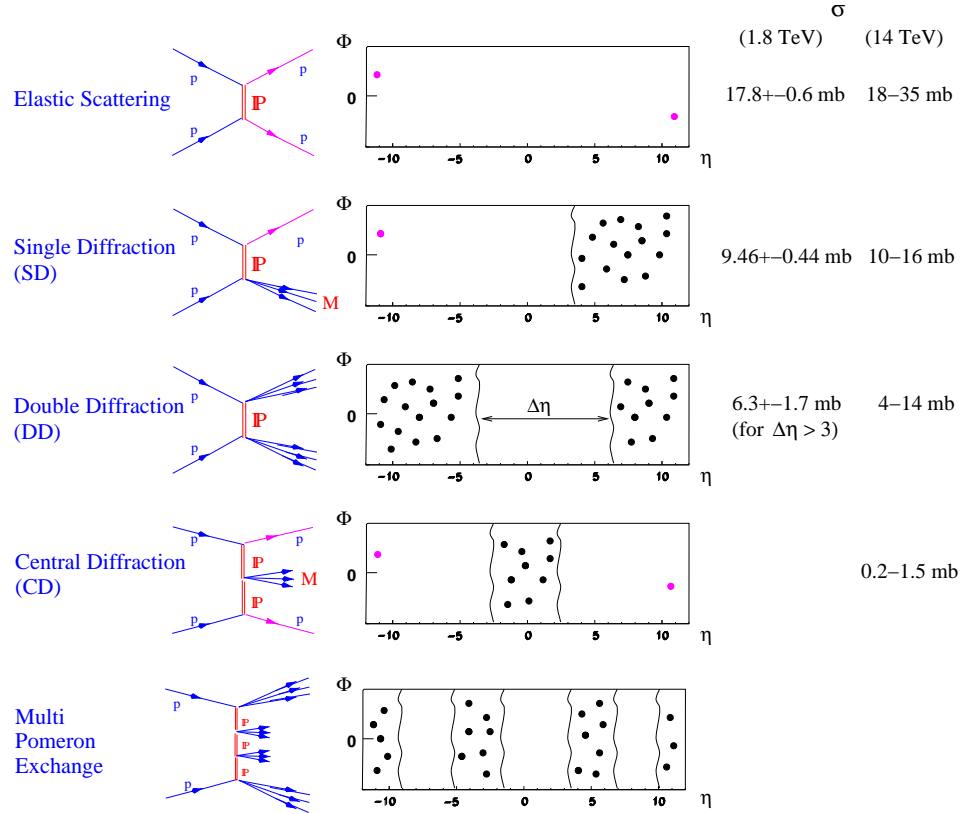


Fig. 4: Different classes of diffractive processes and their cross-sections as measured at Tevatron and as estimated for the LHC.

3.2 Total pp cross-section

The optical theorem relates the total pp cross-section σ_{tot} and the luminosity \mathcal{L} to the differential elastic counting-rate dN_{el}/dt at $t = 0$ and the total elastic N_{el} and inelastic N_{inel} rates as:

$$\sigma_{tot} = \frac{16\pi}{1 + \rho^2} \cdot \frac{dN_{el}/dt|_{t=0}}{N_{el} + N_{inel}} \quad \text{and} \quad \mathcal{L} = \frac{1 + \rho^2}{16\pi} \cdot \frac{(N_{el} + N_{inel})^2}{dN_{el}/dt|_{t=0}}. \quad (3)$$

The parameter $\rho = \mathcal{R}[f_{el}(0)]/\mathcal{I}[f_{el}(0)]$, where $f_{el}(0)$ is the forward nuclear elastic amplitude, has to be taken from theoretical predictions. Since $\rho \sim 0.14$ enters only as a $1 + \rho^2$ term, its impact is small. The extrapolation of existing σ_{tot} measurements to LHC energies leaves a wide range for the expected value of σ_{tot} at LHC, typically between 85 and 120 mb, depending on the model used for the extrapolation. TOTEM aims at a 1 % σ_{tot} measurement. Hence the quantities to be measured are the following:

- the inelastic rate N_{inel} consisting of both non-diffractive minimum bias events and diffractive events, which can almost completely be measured by T1, T2 and the RP detectors;
- the total nuclear elastic rate N_{el} measured exclusively by the RP system;
- $dN_{el}/dt|_{t=0}$: the nuclear part of the elastic cross-section extrapolated to $t = 0$.

A summary of the uncertainties on σ_{tot} at different high β^* optics configurations is given in Table 3. Here only the main uncertainties are described. The extrapolation procedure and uncertainty estimates are described in more detailed in Ref. [3]. At $\beta^* = 90$ m, protons with $|t| > 0.03$ GeV² are observed, whereas $|t|_{min} = 10^{-3}$ GeV² at $\beta^* = 1540$ m, leading to a significantly smaller uncertainty contribution due to N_{el} , 0.1 % compared to 2 %, and to the extrapolation of dN_{el}/dt to $t = 0$, 0.2% compared to 4%.

Uncertainty	$\beta^* = 90$ m	$\beta^* = 1540$ m
Extrapolation of dN_{el}/dt to $t = 0$	± 4 %	± 0.2 %
Elastic rate N_{el}	± 2 %	± 0.1 %
Inelastic rate N_{inel}	± 1 %	± 0.8 %
ρ parameter	± 1.2 %	± 1.2 %
Total σ_{tot}	$\pm 4-5$ %	$\pm 1-2$ %

Table 3: Relative uncertainty on the total pp cross-section σ_{tot} measurement estimated at different high β^* optics configurations. Note that the total uncertainty takes into account the correlations between the uncertainties, notably the strong correlation between the extrapolation of the differential elastic counting-rate dN_{el}/dt to $t = 0$ and the elastic rate N_{el} .

The largest contribution to the uncertainty on σ_{tot} at $\beta^* = 90$ m comes from the extrapolation of dN_{el}/dt to $t = 0$; mainly due to systematics in the t -measurement from uncertainties in L and v (see Eq.1). This contribution will be reduced to 0.1 % at $\beta^* = 1540$ m requiring, however, an improved knowledge of L and v and a RP alignment precision of better than 50 μ m. The dominating uncertainty, 0.2 %, will then be due to the model-dependent extrapolation procedure. For $\beta^* = 1540$ m, the largest contribution to the σ_{tot} uncertainty will most likely come from N_{inel} , mainly from trigger losses in single and double diffractive events. The lost events, corresponding to ~ 3 mb, have very low diffractive mass M (below ~ 10 GeV/ c^2). As a consequence, all particles have pseudo-rapidities beyond the T2 acceptance and hence escape detection of the single arm trigger. To obtain the total inelastic rate, the fraction of events lost due to the incomplete angular coverage is estimated by extrapolating the reconstructed $1/M^2$ distribution. The uncertainty on N_{inel} after corrections is estimated to be 0.8 and 1 % for $\beta^* = 1540$ and 90 m optics, respectively. The uncertainty on the ρ parameter as estimated from lower energy measurement [16] gives a σ_{tot} uncertainty of 1.3 %. A reduction is expected when ρ

is measured at the LHC via the interference between Coulomb and nuclear contributions to the elastic scattering cross-section [17].

At an early stage in 2009 with non-optimal beams and $\beta^* = 90$ m, TOTEM will measure $\sigma_{tot}(\mathcal{L})$ with a 4–5 % (7 %) relative precision. After having understood the initial measurements and with improved beams at $\beta^* = 1540$ m, a final relative precision on $\sigma_{tot}(\mathcal{L})$ of 1 % (2%) should be achievable.

4 Early physics with TOTEM

The early runs at the LHC start will be characterized by low β^* beams with a reduced number of bunches and a lower number of protons per bunch. Under these conditions diffractive protons in the ξ range of 0.02 - 0.2 will be within the acceptance of RP220 giving TOTEM ample opportunities to make first soft diffractive studies. The early physics programme of TOTEM in stand-alone runs will concentrate on measurements of individual cross-sections and event topologies for the following processes:

- central diffractive events with diffractive masses between ~ 250 GeV and ~ 2.8 TeV;
- single diffractive events with diffractive masses between ~ 2 TeV and ~ 6 TeV;
- elastic scattering events with $|t|$ values between ~ 2 GeV² and ~ 10 GeV²;
- forward charged particle multiplicity of inelastic pp events in the $3.1 \leq |\eta| \leq 6.5$ region.

The cross-sections for the above processes are large ($\gtrsim 5 \mu\text{b}$) even if the TOTEM acceptance is included, with the exception of high- $|t|$ elastic scattering. As an example, the BSW model [6] predicts an integrated elastic cross-section of ~ 60 nb for $|t| > 2$ GeV². This prediction, together with the predictions of Ref. [13–15], imply that for an integrated luminosity of ~ 10 pb⁻¹, TOTEM would collect more than 10^7 central and 10^8 single diffractive events, together with $\sim 10^5$ high- $|t|$ elastic events allowing a first test of the validity of different models as discussed in section 3.1. The main background to diffractive events at low β^* is either due to two overlapping pp collisions, like e.g. two overlapping single diffractive events for central diffraction, or one pp collision overlapping with beam induced proton background. Hence the event purity will depend strongly on the average number of pp collisions per bunch crossing, which should be significantly smaller than one. The beam induced proton background not due to pp collisions in IP5 will be studied in bunch crossings where normal bunches meet "empty" bunches. The interest in the forward charged particle multiplicity is two-fold: first as a basic measurement of pp interaction at LHC energies and secondly as valuable input to the modeling of very high energy cosmic rays [2].

The installation schedule of the TOTEM detectors depends crucially on the CMS installation schedule as well as on the LHC commissioning schedule. The full experiment is planned to be installed for the 2009 LHC running. The focus in the early LHC runs will be to understand the performance of the detectors and other vital parts like trigger and data acquisition, especially the approach of the RP detectors to the beam. The feasibility and time scale of the early physics programme will critically depend on the LHC performance in terms of luminosity and beam induced background in the TOTEM detectors.

5 Diffractive proton detection at IP3

It has been suggested that the central exclusive diffractive process

$$pp \rightarrow p + X + p, \quad (4)$$

where a "+" denotes a rapidity gap, could complement the standard methods of searching and studying new particles ("X") at LHC, see e.g. Ref. [18]. The main advantage is that the mass of the centrally produced particle X can be reconstructed from the measured ξ values of the outgoing protons as shown in Eq. 2. Provided that the two ξ values can be determined with sufficient precision, peaks corresponding to particle resonances may appear in the reconstructed diffractive mass distribution independent of the particles' decay modes. These measurements should be performed with high luminosity optics since the cross-sections are expected to be small. The work presented here aims to find the best detector locations at LHC in terms of ξ acceptance and resolution for the proton measurement in central diffractive events.

The diffractive proton acceptance of near beam detectors is determined by the ratio D_x/σ_x between horizontal dispersion and beam width. With larger D_x the protons are deflected further away from the beam center, while the closest safe approach of a detector to the beam is given by a multiple – typically 10 to 15 – of σ_x . By construction, the LHC region where D_x and D_x/σ_x are maximized and hence the sensitivity to particle X , is the momentum cleaning insertion in IP3, where off-momentum beam protons are intercepted. The idea is to install proton detectors pairs with a lever arm of several tens of meters close to IP3 to detect diffractive protons in both beams just before they are absorbed by the momentum cleaning collimators. In addition to promising perspectives in diffraction, the placement of detectors in front of the collimators has advantages for accelerator diagnostics and protection. The technical aspects of placing proton detectors at IP3 is being worked out together with the LHC collimation group.

The proton acceptance and resolution of an experiment with detectors at the TOTEM RP220 location and at IP3 have been studied [19] by fully tracking the protons along the LHC ring with the MAD-X [20] program using standard LHC high luminosity $\beta^* = 0.55$ optics. The detector acceptance at IP3 for protons originating from diffractive scattering in IP5 is $0.0016 \leq \xi \leq 0.004$ and $0.0016 \leq \xi \leq 0.01$ for protons turning clockwise ("B1") and anticlockwise ("B2") in the LHC, respectively. This complements well the $0.02 \leq \xi \leq 0.20$ acceptance of RP220 for both beams. The IP3 acceptance for B1 protons is reduced since these protons have to pass through the aperture limiting betatron cleaning insertion at IP7. In case of central diffraction [15], this gives access to diffractive masses from 25 GeV to 2.8 TeV as shown in Fig. 5 (left). A ξ resolution $\leq 10^{-4}$ for protons detected at IP3 is obtained in the study implying that the resolution will be limited by the beam energy spread of $1.1 \cdot 10^{-4}$. Combined with protons detected at RP220, this leads to a relative mass resolution ranging between 1 and 5 % for central diffractive events over the whole mass range as shown in Fig. 5 (right). The mass resolution depends on the ratio ξ_1/ξ_2 , where ξ_1 and ξ_2 are the ξ value of the clockwise and anticlockwise turning proton, respectively.

The protons detectors at IP3 would in fact see diffractive protons with similar acceptance from all LHC interaction points (IP) and could by measuring the difference of the proton arrival times determine at which IP the event occurred. This way the low mass central diffractive spectrum could be determined independently for each IP and be used as means of an inter-experimental luminosity calibration.

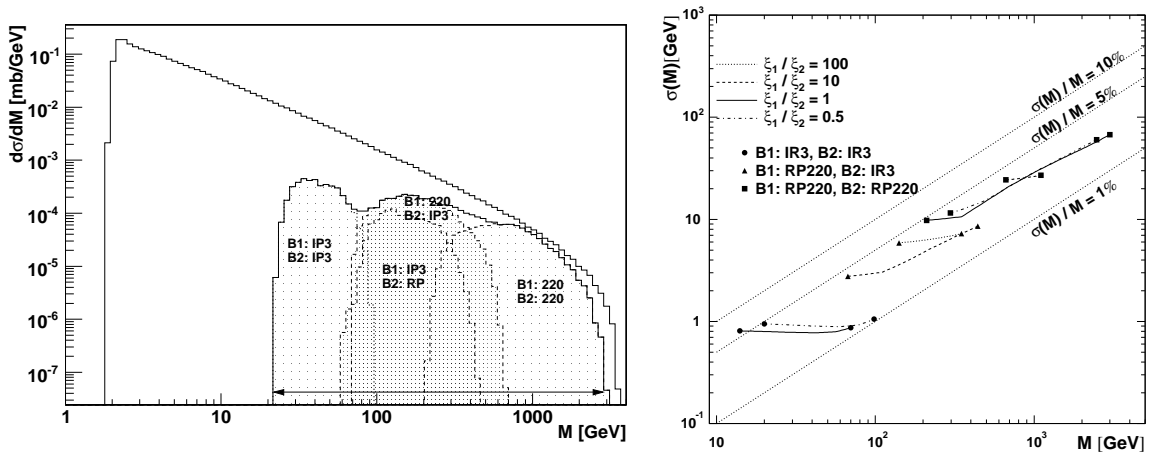


Fig. 5: Left: predicted diffractive mass distribution for central diffractive events with events indicated that have both protons within the acceptance of different combinations of the IP3 and RP220 detectors. Right: mass resolution for central diffractive events for some ξ_1/ξ_2 ratios. B1 and B2 refers to protons turning clockwise and anticlockwise, respectively, in the LHC.

6 Summary

The TOTEM physics program aims at a deeper understanding of the proton structure by measuring the total and elastic pp cross sections and by studying a comprehensive menu of diffractive processes. TOTEM will run under all LHC beam conditions to maximize the coverage of the studied processes. Special high β^* runs are needed for the total pp cross section measurement with the luminosity-independent method and for soft diffraction with large forward proton acceptances. At an early stage with non-optimal beams and an intermediate β^* , TOTEM will measure σ_{tot} with a 4–5 % precision. With improved understanding of the beams and $\beta^* = 1540$ m, a precision on σ_{tot} of 1% should be achievable. The measurement of elastic scattering in the range $10^{-3} < |t| < 10 \text{ GeV}^2$ will allow to distinguish among a wide range of predictions according to current theoretical models. Early low β^* runs will provide first opportunities for measurements of soft diffraction for masses above ~ 250 GeV and ~ 2 TeV in central and single diffractive events, respectively, as well as studies of the forward charged multiplicity in inelastic pp events. Having proton detectors at IP3 would highly extend the diffractive mass acceptance of TOTEM for high luminosity runs giving e.g. a continuous mass acceptance from 25 GeV to 2.8 TeV for central diffractive events. Finally, hard diffraction as well as many forward physics subject will be studied in collaboration with CMS taking advantage of the unprecedented rapidity coverage for charged and neutral particles.

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