

The Totem experiment at the LHC

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Abstract

The TOTEM experiment at the LHC is dedicated to the measurement of the total proton-proton cross-section and to the study of the elastic scattering and diffractive dissociation processes. The main features of the TOTEM experimental apparatus and of its physics programme are here presented, together with some prospects for early measurements in the first year of the LHC.

5 Introduction

TOTEM [1] foresees specific measurements and experimental techniques which are very different from the other ‘general purpose’ experiments at LHC. A precise ‘luminosity independent’ measurement of σ_{TOT}^{pp} , based on the Optical Theorem, will be achievable in special beam optics runs by simultaneously measuring: 1) the elastic scattering rate at low transfer momentum, possibly as small as $|t| = 10^{-3} \text{ GeV}^2$, and 2) the inelastic scattering rate with the largest possible coverage to reduce losses to few percents. The first goal requires detectors located into units mounted into the vacuum chamber of the accelerator, called Roman Pots, as the scattered protons are emitted at angles of the order of $10 \mu\text{rad}$, therefore without leaving the beam-pipe. The latter requires the measurement of all the inelastically produced particles in the very forward direction with respect to the pp collision point; this can be achieved by using tracking detector telescopes with a complete azimuthal coverage around the beam-pipe. A flexible trigger provided by TOTEM detectors will allow to take data under all LHC running scenarios. The combination of the CMS and TOTEM experiments will also allow the study of a wide range of diffractive processes with an unprecedented coverage in rapidity. For this purpose the TOTEM trigger and data acquisition (DAQ) systems are designed to be compatible with the CMS ones, in order to allow common data taking periods foreseen at a later stage [2]. Finally, the aim of the TOTEM experiment to obtain accurate information on the basic properties of proton-proton collisions should also provide a significant contribution to the understanding of very high energy cosmic ray physics. In the following, after a general overview of the experimental apparatus, the main features of the TOTEM physics programme will be described.

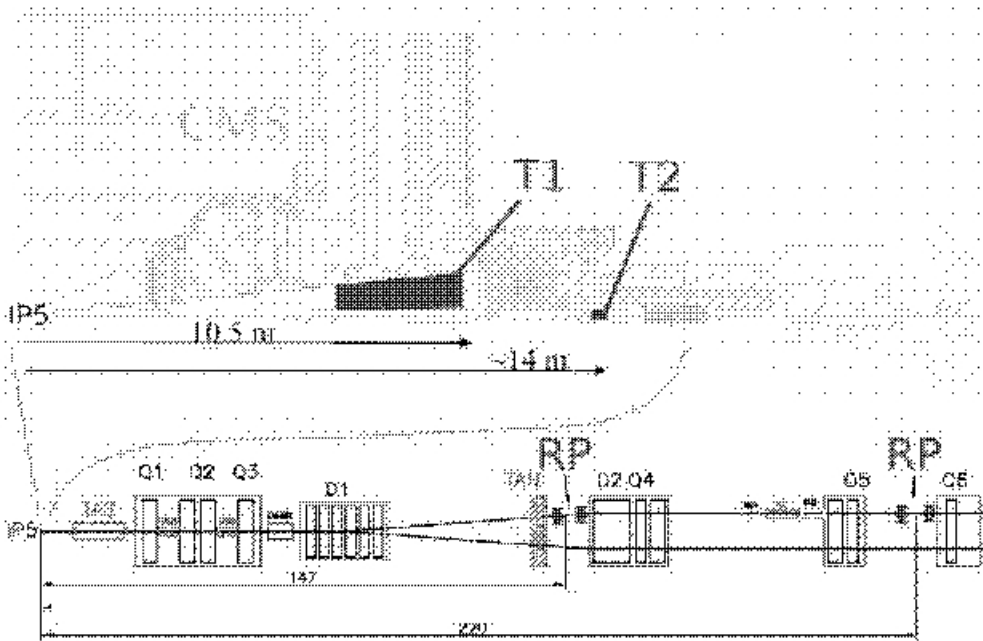


Figure 5: Top: The T1 and T2 telescopes embedded into the forward region of the CMS detector. Bottom: Roman Pots location along the LHC beam-line. All TOTEM detectors are located on both sides of IP5.

6 Experimental Apparatus

Located on both sides of the interaction point IP5 (shared with the CMS experiment), the TOTEM experimental apparatus comprises “Roman Pot” (RP) detectors and the T1 and T2 inelastic telescopes (Fig. 5). The RPs, placed on the beam-pipe of the outgoing beam in two stations at about 147 m and 220 m from IP5, are special movable beam-pipe insertions designed to detect “leading” protons with a scattering angle down to few μrad . T1 and T2, embedded inside the forward region of CMS, provide charged track reconstruction for $3.1 < |\eta| < 6.5$ ($\eta = -\ln(\tan\frac{\theta}{2})$) with a 2π coverage and with a very good efficiency. These detectors will provide a full inclusive trigger for all inelastic and diffractive events, minimizing losses to a few percent, and will be also used for the reconstruction of the event interaction vertex, so to reject background events [3]. The read-out of all TOTEM sub-detectors is based on the digital VFAT chip [3], specifically designed for TOTEM and characterized by trigger capabilities.

The RPs host silicon detectors which are moved very close to the beam when it is in stable conditions. Each RP station is composed of two units in order to have a lever arm for local track reconstruction and trigger selections by track angle. Each unit consists of three pots, two vertical and one horizontal completing the acceptance for diffractively scattered protons. Each pot contains a stack of 10 planes of silicon strip detectors (Fig. 6, left). Each plane has 512 strips (pitch of $66 \mu\text{m}$) allowing a single hit resolution of about $20 \mu\text{m}$. As the detection of protons elastically scattered at angles down to few μrads requires a detector active area as close to the beam as $\sim 1 \text{ mm}$, a novel “edgeless planar silicon” detector technology has been developed for TOTEM RPs in order to minimize an edge dead zone to only about $50 \mu\text{m}$ [4].

Each T1 telescope arm, covering the range $3.1 < |\eta| < 4.7$, consists of five planes formed by six trapezoidal “Cathode Strip Chambers” (CSC) [1] (Fig. 6, center). These CSCs, with 10 mm



Figure 6: Left: Silicon detectors hosted in one pot. Center: One half-arm of the T1 telescope. Right: The installation of one half-arm of the T2 telescope.

thick gas gap and a gas mixture of Ar/CO₂/CF₄ (40%/50%/10%), provide three measurements of the charged particle coordinates with a spatial resolution of about 1 mm. The anode wires (pitch of 3 mm) will also provide level-1 trigger information; the cathode strips (pitch of 5 mm) are rotated by $\pm 60^\circ$ with respect to the wires.

The T2 telescope [5], based on “Gas Electron Multiplier” (GEM) technology [6], extends charged track reconstruction to the range $5.3 < |\eta| < 6.5$. Ten aligned detector planes, with a semicircular shape, are combined to form one of the half-arms located at ~ 13.5 m from IP5 (Fig. 6, right). This novel gas detector technology is ideal for the T2 telescope thanks to its good spatial resolution, excellent rate capability and good resistance to radiation. The T2 GEMs are characterized by a triple-GEM structure and a gas mixture of Ar/CO₂ (70%/30%) [5]. The read-out board has two separate layers with different patterns: 256x2 concentric circular strips (80 μm wide, pitch of 400 μm), allow the track radial coordinate reconstruction with a resolution of about 100 μm ; while a matrix of 24x65 pads (from 2x2 mm² to 7x7 mm² in size) provide level-1 trigger information and track azimuthal coordinate reconstruction.

7 Physics Programme

The physics goals of the TOTEM experiment are the measurement of the total pp cross section (σ_{tot}) with an ultimate precision of $1\div 2\%$, the study of the nuclear elastic pp differential cross section ($d\sigma_{el}/dt$) over a wide range of $|t|$ ($\sim 10^{-3} < |t| < 10 \text{ GeV}^2$) and the study of the inelastic interactions by measuring the cross section of soft diffractive processes and the forward charged particle flow. TOTEM can perform this programme operating in stand-alone mode, while the cooperation with CMS will make possible the study of hard diffraction, low-x physics, central exclusive diffractive production and the combination of particle multiplicity and energy flow in the forward region [2]. TOTEM measurements will allow to distinguish among different models of soft proton interactions, giving a deeper understanding of the proton structure.

Fig. 7 (left), summarizing the existing measurements on pp and $p\bar{p}$ scattering, shows predictions for σ_{tot} from the COMPETE Collaboration based on fits according to different models [7]. The best fit predicts $\sigma_{tot} = 111.5 \pm 1.2^{+4.1}_{-2.1}$ mb for the LHC energy ($\sqrt{s} = 14 \text{ TeV}$). The large uncertainties on available high energy data give a big error ($90\div 130$ mb), depending on the model used for the extrapolation. TOTEM aims to measure σ_{tot} with a precision down to

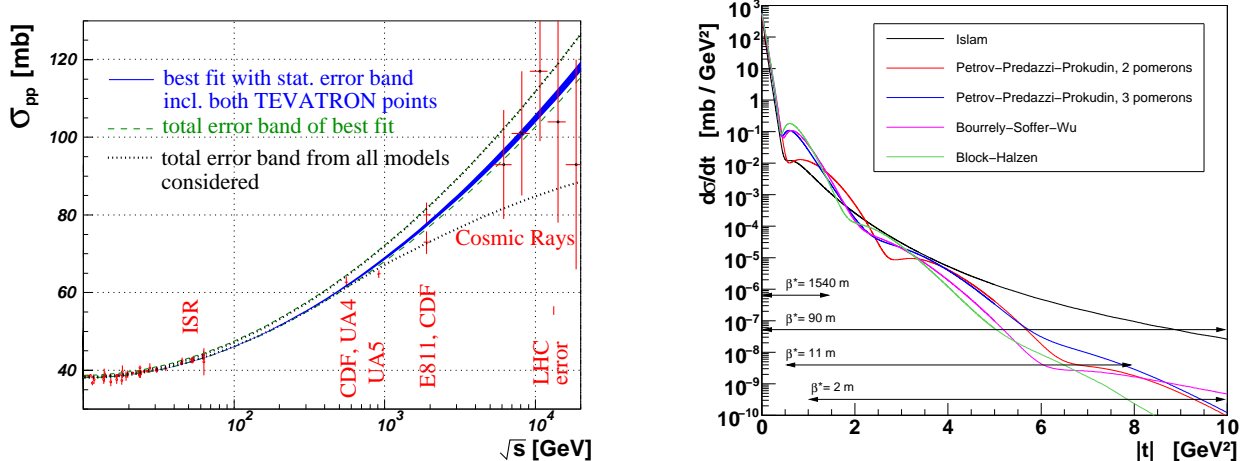


Figure 7: Left: Fits from the COMPETE Collaboration to available pp and $p\bar{p}$ scattering and cosmic ray data. Right: $d\sigma_{el}/dt$ at the LHC as predicted by different models; t -acceptance ranges for different machine optics are also shown.

$1 \div 2\%$, therefore allowing to discriminate among the different models. The measurement will be based on the “luminosity independent method” which, combining the optical theorem with the total rate, gives σ_{tot} and the machine luminosity (\mathcal{L}) as a function of measurable rates:

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

where N_{el} and N_{inel} are respectively the elastic and inelastic rate and ρ is the ratio of real to imaginary part of the forward nuclear elastic scattering amplitude (given by theoretical predictions). Therefore, TOTEM will also provide an absolute measurement of \mathcal{L} to be used for calibration purposes. The uncertainty on the extrapolation of dN_{el}/dt to $t = 0$ (optical point) depends on the acceptance for protons scattered at small $|t|$ values, hence at small angles. This requires a small beam angular divergence at the IP, which can be achieved in special runs with high β^* machine optics and typically low \mathcal{L} . An approved optics with $\beta^* = 1540$ m (and $\mathcal{L} \sim 10^{28} \text{ cm}^{-2}\text{s}^{-1}$) will give a σ_{tot} (\mathcal{L}) measurement at the level of $1 \div 2\%$ (2%). Another approved optics with $\beta^* = 90$ m (and $\mathcal{L} \sim 10^{30} \text{ cm}^{-2}\text{s}^{-1}$), achievable without modifying the standard LHC injection optics, is expected to allow a preliminary σ_{tot} (\mathcal{L}) measurement at the level of $\sim 5\%$ (7%) in the first period of the LHC running. The experimental systematic error for the measurement with $\beta^* = 90$ m will be dominated by the evaluation of $dN_{el}/dt|_{t=0}$, while with $\beta^* = 1540$ m it will be dominated by the uncertainty on the corrections to trigger losses in Single Diffraction events for masses below $\sim 10 \text{ GeV}/c^2$ [3]. Given the high rates involved, the statistical error on σ_{tot} will be negligible after few hours of data taking even at low \mathcal{L} . The theoretical uncertainty related to the estimate of the ρ parameter is expected to give a contribution on the relative uncertainty of less than 1.2% (considering for instance the full error band on ρ extrapolation as derived in ref [7]).

Fig. 7 (right) shows the distributions of $d\sigma_{el}/dt$ at $\sqrt{s} = 14$ TeV as predicted by different models in the whole $|t|$ -range accessible by TOTEM according to the different LHC optics settings [3]. Several regions are found at increasing $|t|$: for $|t| < 6.5 \times 10^{-4} \text{ GeV}^2$ (the Coulomb

region) $d\sigma_{el}/dt \sim 1/|t|^2$ is dominated by photon exchange; for $|t|$ up to $\sim 10^{-3}$ GeV², the hadronic and Coulomb scattering interfere; for $10^{-3} < |t| < 0.5$ GeV² there is the hadronic region, e.g. described by “single-Pomeron exchange”, characterized by an approximately exponential fall ($d\sigma_{el}/dt \sim e^{-B|t|}$); the diffractive structure of the proton is then expected for $0.5 < |t| < 1$ GeV²; for $|t| > 1$ GeV² elastic collisions are described by pQCD, e.g. in terms of triple-gluon exchange with $d\sigma_{el}/dt \sim |t|^{-8}$. TOTEM will allow to discriminate among different models with a precise measurement of $d\sigma_{el}/dt$ over all the accessible t -region, where $d\sigma_{el}/dt$ spans over 11 orders of magnitude. In the hadronic region, important for the extrapolation of $d\sigma_{el}/dt$ to $t = 0$, a fit on $B(|t|)$ is typically performed in the $|t|_{min} < |t| < 0.25$ GeV² range, $|t|_{min}$ depending on the acceptance for protons scattered at small angles, hence on the beam optics. Fig. 8 (left) shows the proton acceptance for the RPs at 220 m as a function of t for three different running scenarios, where the 50% acceptance is marked for each β^* value. For safety reasons, the minimum distance between RP detectors and the LHC beam is $10\sigma_{beam}$; by adding an extra 0.5 mm to take in account the distance from the edge of the sensitive detector area to the bottom of the RP window, this distance is about 1.3 mm for RP220 with $\beta^* = 1540$ m, corresponding to a minimum angle of about 5 μ rad or equivalently 10^{-3} GeV² of squared 4-momentum transfer.

Diffractive (due to colour singlet exchange) and non-diffractive (due to colour exchange) inelastic interactions represent a big fraction (around $70 \div 75$ %) of σ_{tot} . Nevertheless many details of these processes, with close ties to proton structure and low-energy QCD, are still poorly understood. The majority of diffractive events exhibits intact (“leading”) protons characterized by their t and fractional momentum loss $\xi \equiv \Delta p/p$. TOTEM will be able to measure ξ -, t - and mass-distributions with acceptances depending on the beam optics. The diffractive proton acceptance for the RPs at 220 m has been computed for different optics as a function of ξ and t (Fig. 8, right). For $\beta^* = 1540$ m or 90 m most of the protons are seen independently of their momentum loss. For low β^* values, elastic scattering is detectable only for $|t| > 2$ GeV², while diffracted protons are seen for $\xi > 2\%$ for all $|t|$ values.

When leading protons are detected on both sides of IP5, as in the case of Double Pomeron Exchange (DPE), the central mass M acceptance is shown in Fig. 9, left. By combining data from low, intermediate and high β^* runs, the differential cross-section as a function of M can be measured with good precision over the full mass range.

8 Early Physics Programme

LHC will soon restart with a beginning center of mass energy of 7 TeV and a low β^* optics. We are studying the TOTEM performance under these conditions, however we are also asking for $\beta^* = 90$ m for short runs in 2010. The acceptance for protons at the 220 m RP stations is shown in Fig. 9 (right); they are mainly seen for a momentum loss $\xi > 2\%$, with a resolution on ξ slightly less than 10^{-2} . These results are for a low β^* optics, they depend very strongly on the beam optics and little on the energy, so that they are similar to those obtained for 14 TeV. For DPE, the predicted central diffractive mass distribution would start at around 250 GeV, a significant difference from the very low mass of few GeV reachable with a high β^* optics (see

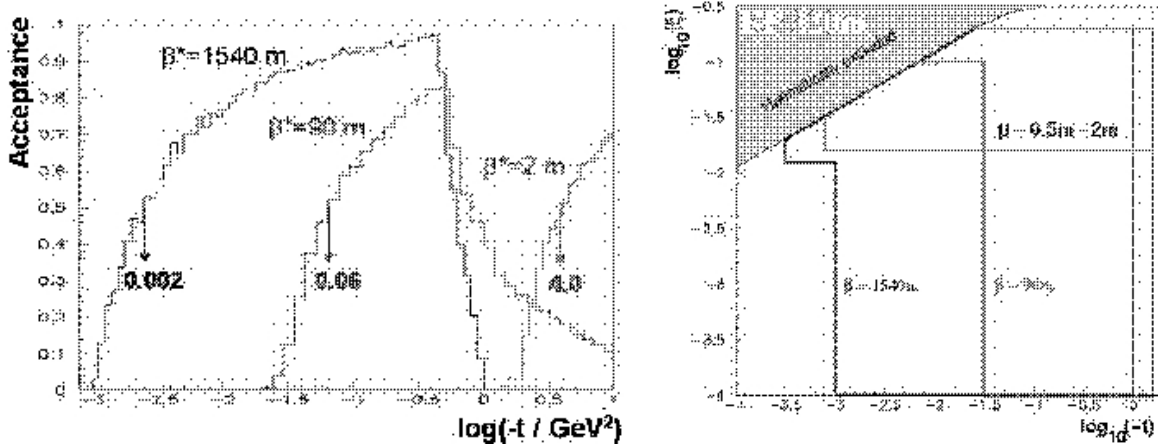


Figure 8: Left: Proton acceptance for the RPs at 220 m as a function of t for three different running scenarios, where the 50% acceptance is marked for each β^* value. Right: Diffractive proton acceptance for the RPs at 220 m for different optics as a function of ξ and t .

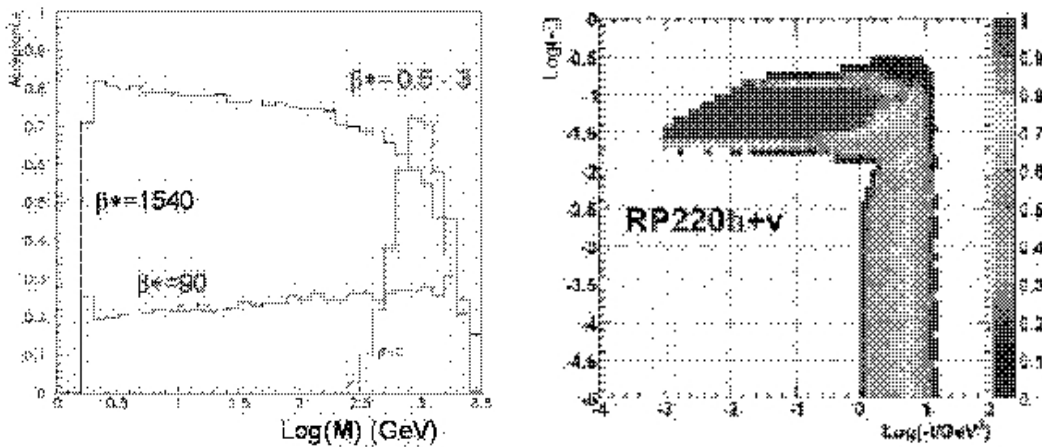


Figure 9: Left: The DPE central mass M distribution for three β^* values. Right: Proton acceptance for early runs at the 220 m RP stations.

Fig. 9, left). Therefore the very first measurements with a low β^* will consist in: 1) by using the horizontal RPs, in Single Diffractive and DPE for high masses of the diffractive system; 2) by using the vertical RPs for the measurement of the elastic scattering over a range of $1 < |t| < 10 \text{ GeV}^2$, which would not allow a measurement of σ_{tot} but, however, it will already allow to discriminate among different models for the prediction of $d\sigma_{el}/dt$.

The T1 and T2 telescopes will provide a measurement of charged particle multiplicity for different processes as well as the identification and measurement of rapidity gaps. Primary cosmic rays in the PeV (10^{15} eV) energy range and above are a challenging issue in astrophysics. The LHC center of mass energy corresponds to a 100 PeV energy for a fixed target collision in the air, at the same time providing a high event rate relative to the very low rate of cosmic particles in this energy domain. A primary cosmic ray entering the upper atmosphere experiences a nuclear interaction, with the production of nuclear fragments and π mesons, starting an

air shower with hadronic, electromagnetic and muon components. The real challenge is to determine the nature of the primary interaction and the energy and composition of the incident particle from the measurement of the shower. Several high energy hadronic interaction models are nowadays available, which predict energy flow, multiplicity and other quantities of such showers. There are large differences between the predictions of currently available models, with significant inconsistencies in the forward region. Among the several quantities that can be measured by TOTEM and compared with model predictions, the charged particle multiplicity in the T1 and T2 acceptance region shows significant differences in the predictions obtained by different available hadronic interaction models for cosmic ray showers, once the events are passed through the simulation of T1 and T2. Therefore this measurement can already be used in early runs to validate/tune the generators [2].

9 Summary and Conclusions

The TOTEM experiment will be ready for data taking at the LHC restart. Running under all beam conditions, it will perform an important and exciting physics programme involving the measurement of σ_{tot} and $d\sigma_{el}/dt$ in pp interactions as well as studies on diffractive processes and on forward charged particle production. Special high β^* runs will be required in order to measure σ_{tot} at the level of $\sim 5\%$ (early measurement with $\beta^* = 90$ m) and $\sim 1 \div 2\%$ ($\beta^* = 1540$ m). $d\sigma_{el}/dt$ will be studied in the range $\sim 10^{-3} < |t| < 10 \text{ GeV}^2$ allowing to distinguish among several theoretical predictions. A common physics programme with CMS on soft and hard diffraction as well as on forward particle flow studies is also foreseen in a later stage.

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