The TOTEM Experiment at the LHC

Valentina Avati (on behalf of the TOTEM Collaboration)

CERN, Geneva, Switzerland

The TOTEM experiment at the LHC will measure the total pp cross-section, elastic scattering and diffraction. This contribution summarises the physics goals, the status of the experimental apparatus and the first results from the 2010 data taking.

§1. Introduction

The primary goal of TOTEM\(^1\),\(^2\) is to measure the total cross-section in a luminosity independent way. This requires a precise measurement of elastic scattering at small momentum transfers (|t| \( \sim \) 10\(^{-3}\) to 10\(^{-1}\) \(\text{GeV}^2\)) to enable an extrapolation to \(t = 0\), the “Optical Point”, and a careful study of diffraction (single and double diffraction and double Pomeron exchange). The elastic scattering measurement at these low t-values will need a special beam optics with \(\beta^* > 90\) m to keep the angular spread of the beam much smaller than the scattering angle.*

The elastic or quasi-elastic scattered protons are measured by silicon detectors placed in Roman Pots stations (RP), installed on both sides of the interaction point. The inelastic processes are measured by two forward telescopes (T1, T2) covering the pseudo-rapidity region \(3 < \eta < 6.5\) with full azimuthal angle acceptance.

Presently, TOTEM runs in parallel with the other experiments at \(\beta^* = 3.5\) m but only the very forward T2 telescope and the RP detectors at 220 m were installed in 2010. Nevertheless, this allows measurements of the elastic scattering at large |t|-values and first studies of diffraction using the protons in the RP detectors and the signature in T2. The T2 telescope is also used actively in the trigger to obtain first multiplicity distributions in the forward regions.

§2. Physics programme

The physics goals of the TOTEM experiment are the measurement of the total pp cross-section \(\sigma_{tot}\), the study of the pp elastic scattering over a wide range of transverse momentum \(t\) (10\(^{-3}\) < |t| < 10 \(\text{GeV}^2\)), the study of the inelastic interactions and the forward charged particle flow.

The predictions for \(\sigma_{tot}\) at the LHC energy, based on fits according to different models,\(^3\) have a big error (90–130 mb) due to large uncertainties on available high energy data. TOTEM aims to measure \(\sigma_{tot}\) with an ultimate precision of \(\sim\)1%, 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 \(\sigma_{tot}\) as a function of mea-

---

* \(\beta^*\) is the betatron amplitude (\(\beta\)) at the interaction point; the beam angular spread and hence the minimum detectable scattering angle are proportional to \(\sqrt{1/\beta^*}\).
surable rates:

\[ \sigma_{\text{tot}} = \frac{16\pi}{1 + \rho^2} \cdot \frac{dN_{\text{el}}/dt|_{t=0}}{N_{\text{el}} + N_{\text{inel}}}, \]  

where \( N_{\text{el}} \) and \( N_{\text{inel}} \) are, respectively, the elastic and inelastic rates and \( \rho \) is the ratio of the real to imaginary part of the forward nuclear elastic scattering amplitude. The quantities involved are:

- The total inelastic rate \( N_{\text{inel}} \), which includes non-diffractive minimum bias and diffractive events, will be measured by the T1 and T2 telescopes.
- The nuclear elastic rate \( N_{\text{el}} \) measured by the RP system.
- \( dN_{\text{el}}/dt|_{t=0} \): the nuclear part of the elastic cross-section extrapolated to \( t = 0 \).

To fulfil these conditions, TOTEM needs to have the full telescope system (T1+T2) installed and special beam optics. The pseudo-rapidity acceptance of T2 alone is not sufficient to minimise the systematic uncertainty of the measurement of the inelastic rate. Having the full T1 detector installed will enable the selection of pure single diffractive (SD) and double diffractive (DD) event samples using the event topologies as reconstructed in the telescopes. The measurement of the individual rates of all diffractive processes at a 5\(^{-}-10\%\) level can then be used as a consistency check for the overall inelastic rate and makes an extrapolation of the individual cross-sections possible.\(^4\)

The uncertainty on the extrapolation of \( dN_{\text{el}}/dt \) to \( t = 0 \) (optical point) depends on the acceptance for protons scattered at small \( t \)-values and hence on the beam optics. Figure 1 shows the proton acceptance for the RPs at 220 m as a function of \(|t|\) for three different running scenarios, if the minimum distance of detectors approach to the beam is \( 10\sigma_{\text{beam}} \).\(^\ast\)

The scenarios which are for the time being considered, and have been approved, foresee optics at \( \beta^* = 1540 \text{ m and } 90 \text{ m} \). The latter one is achievable without modifying the standard LHC injection optics and is expected to be realised in 2011. The optics at 90 m will allow a preliminary measurement of \( \sigma_{\text{tot}} \) at the level of 5\%.\(^\ast\)

\(^\ast\) \( \sigma_{\text{beam}} \) is the r.m.s. transverse width of the beam at the detector: it is proportional to the \( \beta \)-function at the location and hence it depends on the optics settings.
The experimental systematic error of the measurement with $\beta^*=90\ m$ will be dominated by the evaluation of $dN_{el}/dt|_{t=0}$, while with the ultimate optics at $\beta^*=1540\ m$ the main contribution is the uncertainty on the corrections due to trigger losses in events with diffractive masses below 10 GeV. The statistical error on $\sigma_{tot}$ will be negligible after few hours of data taking even at low luminosity due to the high rates involved.

Diffractive and non-diffractive inelastic interactions represent a big fraction (around 70%) of $\sigma_{tot}$. 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 protons characterised by their $t$ and fractional momentum loss $\xi = \Delta p/p$. TOTEM will be able to measure $\xi$, $t$- and mass-distributions with acceptances depending on the beam optics.

§3. Experimental apparatus

The experimental apparatus, installed on both sides of the interaction point IP5 (shared with the CMS experiment), consists of RP detectors and the T1 and T2 inelastic telescopes.

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 forward protons. T1 and T2, embedded inside the forward region of CMS, provide charged track reconstruction for $3.1 < |\eta| < 6.5$ ($\eta = -\ln(\tan(\Theta/2))$) with a full azimuthal coverage. These detectors will provide a full inclusive trigger for all inelastic and diffractive events, minimising losses to a few percent, and will be also used for the reconstruction of the event interaction vertex, so to reject background events.

3.1. Roman Pots detectors

Each RP station consists of two units separated by 5 m which form a powerful spectrometer with an excellent position resolution (typically $40\ \mu m$ including alignment imperfections) and angular resolution (typically $10\ \mu rad$). Each unit (Fig. 2, left) consists of two vertical and one horizontal pot together with a beam position monitor (BPM). Each pot contains a stack of 10 planes of “edgeless” silicon strip detectors (Fig. 2, right) based on a novel technology developed for TOTEM in order to minimise the dead region close to the beam to about $50\ \mu m$. In 2009 the station at 220 m has been fully equipped with detectors, while the station at 147 m will be during the 2010 winter shutdown.

3.2. T2 telescope

The T2 telescope, based on triple GEM (Gas Electron Multiplier) technology covers the pseudo-rapidity range $5.3 < |\eta| < 6.5$. Ten semicircular detector planes (Fig. 3, left) per arm with a read-out board with two separate layers with circular strips allow the track radial coordinate reconstruction with a resolution of about 100 $\mu m$ and a matrix of pads provide level-1 trigger information and track azimuthal coordinate reconstruction.
3.3. T1 telescope

The T1 telescope covers the pseudo-rapidity range $3.1 < |\eta| < 4.7$ and it consists of five planes formed by six trapezoidal “Cathode Strip Chambers” (CSC). The chambers provide three measurements of the charged particle coordinates with a spatial resolution of about 1mm, and the anode wires will also provide level-1 trigger information.

The four half-arms of the T1 telescope, equipped with all CSCs, read-out electronics and services, have been installed on the SPS test beam line H8 in the North Area (Fig. 3, right). Extensive tests have been conducted in different running periods from autumn 2009 to summer 2010. Data have been taken with a pion beam interacting with a Cu target (in position roughly corresponding to the interaction point in CMS with respect to one of the two arms), and with a muon beam crossing all layers of a given sextant.

Interaction vertices have been reconstructed in multi-track events resulting from pion scattering on the target. The distributions of the vertex coordinates are shown in Fig. 4: vertices are centred around the target location, with radial and longitudinal standard deviations of about 3 cm and 85 cm, respectively (with no alignment). Muon runs have been used for a simple determination of the efficiency of chambers in
The TOTEM Experiment

Fig. 4. Distributions of the three coordinates of vertices reconstructed from pion test beam data.

Fig. 5. Hit reconstruction efficiency (using 3-coordinate coincidences) in the CSC of one sextant as a function of applied high voltage, from muon test beam data.

§4. First data at the LHC

The T2 telescope and the RP station at 220 m have been operative since the beginning of the LHC operation. Several millions of events have been recorded allowing, first of all, an accurate commissioning of the detectors and the starting of the physics programme at low $\beta^*$. 

4.1. T2 telescope

The T2 settings in hardware and electronics have been investigated and optimised: Figure 6 shows the hit efficiency of the detectors calculated by using data from physics runs. While the efficiency of pads is reaching the expected level, the efficiency of strips is affected, in some detectors, by some cross-talk induced noise.

Extensive analyses are going on to tune and optimise the alignment algorithm: based on tracks reconstructed in the detector the planes are align with respect to each other and the four quarters are then align with respect to the global TOTEM/CMS reference system. The satisfactory results of the application of the alignment algorithm in terms of vertex reconstruction are clearly visible in Fig. 7.
In order to allow steady operations of the Si detectors in the movable devices a delicate work of calibration of the movement of the RPs has been carried out in collaboration with the LHC operation and collimation groups.

The insertion of the RPs and the approach to the beam is a delicate procedure and hence was done by intermediate steps, taking data at 30, 25, 20 and 18 σbeam in standard runs (β∗ = 3.5 m) with a few hundred bunches. The approach of the RPs at closer distance (7σbeam) was possible during special dedicated runs with low number of bunches and reduced intensity.
The precise alignment of the RP detectors with respect to each other and to the beam is vital. The misalignment within the detector assembly is resolved with local tracks while tracks passing through the overlap of the vertical and horizontal detectors allow the relative alignment of the three units (Fig. 8, left). The alignment of the RPs w.r.t. the beam takes advantage of the sharp edge of the proton beam created by the LHC collimator system during the special collimator/RP setup runs. In addition, the distribution of the diffractive protons in the horizontal detectors is used for the vertical alignment of the pots (Fig. 8, right) and the well-defined and constrained elastic scattering events is used for the horizontal alignment and the left-right alignment of the spectrometers.

During 2010 the RPs have recorded, with a left-right coincidence trigger, an integrated luminosity of $\sim 4\text{ pb}^{-1}$ at a distance of $18\sigma_{\text{beam}}$ and $\sim 10\text{ nb}^{-1}$ at a distance of $7\sigma_{\text{beam}}$. After a preliminary selection, these data include $\sim 10\text{ k}$ elastic events at $2 < |t| < 3.5\text{ GeV}^2$ and $\sim 80\text{ k}$ elastic events at $0.4 < |t| < 2.8\text{ GeV}^2$.

Figure 9 shows the track distribution (in space coordinates) of a sample taken with a coincidence trigger between the vertical RP detectors in the two arms. The distribution of these tracks over the top and the bottom detectors, shows three distinct regions: the $x < 0$ side is mainly populated by the background like e.g. beam halo, whereas the diffractive protons are shifted to the $x > 0$ side due to their momentum loss. The elastic scattering events are distributed in a very narrow band around $x = 0$.

An estimation of the systematic errors that can affect the measurements is still in progress and accounts for contributions coming from uncertainties of the machine parameters (optical functions, crossing angle, etc.), from the background induced by the machine (beam halo, beam gas interaction) and from uncertainties on the detector performances (trigger efficiency, track reconstruction efficiency, etc.).

The data analysis at low $\beta^*$ is still in progress, providing for the time being a preliminary $t$-distribution of the elastic scattering at $|t| > 0.4\text{ GeV}^2$. 

---

Fig. 8. Principles of the Roman Pot alignment. Left: tracks passing through the overlap to align the units. Right: diffractive proton distribution in the horizontal pot to align the vertical pots w.r.t. to the beam.
Fig. 9. Track distribution (in space coordinates) in the vertical pots (sector 45) for coincidences between the two arms.

§5. Conclusions

The complete TOTEM physics programme can be pursued only after the full installation of all the detectors and with dedicated low luminosity/high-$\beta^*$ runs. In 2011 all the detectors will be installed. TOTEM plans to run constantly during the standard LHC runs to improve statistics of the large-$t$ elastic scattering sample. Moreover TOTEM will require special runs where the RPs can approach closer the beam to extend the elastic scattering acceptance at low-$t$ values. The commissioning and carrying out of the high-$\beta^*$ optics will allow the first measurement of the total cross section.

Acknowledgements

The author would like to thank the organisers of the HESI2010 workshop for the support given by the Yukawa International Program for Quark-Hadron Sciences at Yukawa Institute for Theoretical Physics, Kyoto University.

References

1) TOTEM Collaboration, “Technical Design Report”, CERN-LHCC-2004-002; addendum, CERN-LHCC-2004-020.
2) G. Anelli et al. (TOTEM Collaboration), JINST 3 (2008), S08007.
3) J. R. Cudell et al., Phys. Rev. Lett. 89 (2002), 201801.
4) TOTEM Collaboration, “TOTEM Results and Perspectives for 2010/2011”, CERN-LHCC-2010-014 / LHCC-G-154 September 2010.