

# TOTEM physics

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The TOTEM experiment (Total Cross Section Elastic Scattering and Diffraction Dissociation at the LHC) will measure the total  $pp$  cross section at the LHC by measuring separately the elastic and inelastic rate. The TOTEM experimental apparatus accounts for two inelastic telescopes and two Roman Pot stations equipped with the leading proton detectors. The detectors will be placed in the forward region of the CMS experiment. An extensive joint program for the study of the diffractive physics is under preparation by the TOTEM and CMS collaborations.

## 1. Introduction

The TOTEM experiment at the LHC will measure [1,2]:

- the total cross section with 1-2% error, by using the luminosity independent method, which requires simultaneous measurements of elastic  $pp$  scattering down to the four-momentum transfer squared  $-t \sim 10^{-3} \text{ GeV}^2$  and of the inelastic  $pp$  interaction rate with an extended acceptance in the forward region. Present extrapolations of the world data to the LHC energy together with the existing cosmic ray data have a typical uncertainty of  $\pm 15\%$
- the elastic  $pp$  scattering up to  $-t \sim \text{few } 10 \text{ GeV}^2$
- the diffractive dissociation, including single, double and central diffraction.

The TOTEM experiment is designed to measure  $\sigma_{tot}$  with an accuracy which is sufficient to discriminate between the current model predictions for the LHC energy ranging between 100 and 130 mb; recent fits performed by the COMPETE collaboration [3] using all the available data, have estimated  $\sigma_{tot} = 111.5 \pm 1.2^{+4.1}_{-2.1} \text{ mb}$  (see Fig.1).

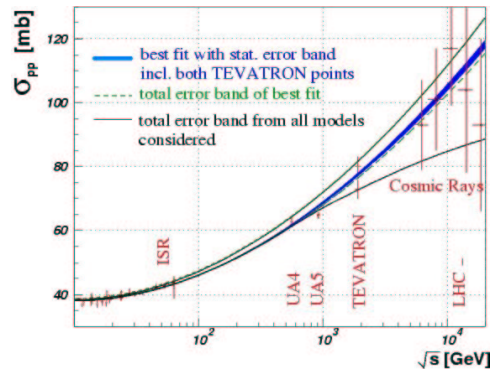


Figure 1. Predictions for total  $pp$  cross section [3], with PS, ISR, SPS, Tevatron and cosmic ray data.

Using the optical theorem the total cross section can be written as:

$$\sigma_{tot} = \frac{16\pi}{(1 + \rho^2)} \frac{(dN_{el}/dt)_{t=0}}{(N_{el} + N_{inel})},$$

where  $N_{el}$  and  $N_{inel}$  are respectively the elastic and inelastic rate.

The precise measurement of  $\sigma_{tot}$  provides also an absolute calibration of the machine luminosity:

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

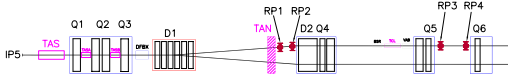


Figure 2. The LHC beam line with the Roman Pots at 147 and 220 m.

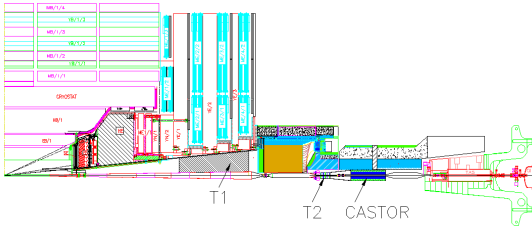


Figure 3. The TOTEM detectors T1 and T2 installed in the CMS forward region.

TOTEM needs few one-day runs, with the special running conditions of a high  $\beta^* \sim 1500$  m and a low luminosity of  $\mathcal{L} \approx 10^{28} \text{ cm}^{-2} \text{ s}^{-1}$ . The  $\beta$  value at the interaction point requires zero crossing-angle, due to the increase of the beam size (proportional to  $\beta$ ), and then a reduced number of bunches which is compatible with the LHC injection scheme. The most likely configuration is 36 proton bunches with  $2.5 \mu\text{s}$  spacing.

Almost half of the total cross-section at the LHC is predicted to be from coherent elastic scattering, single, double and central diffractive processes.

At  $\beta^* \sim 1500$  m, the TOTEM experiment efficiently detects protons with  $-t > 0.004 \text{ GeV}^2$ , i.e. 97% of all the diffractively scattered protons, independent of their longitudinal momentum loss in the range of  $10^{-8} < \Delta p/p < 0.2$ . With the TOTEM acceptance extending up to the pseudorapidities of 6.6, and with the efficient proton detection capabilities close to the LHC beams, the diffractively excited states with masses higher

than  $4 \text{ GeV}/c^2$  are seen by the experiment.

The precise luminosity independent measurement of the total cross section requires the measurement of  $d\sigma_{el}/dt$  down to  $-t \sim 10^{-3} \text{ GeV}^2$ , which corresponds to a proton scattering angle of  $5 \mu\text{rad}$ , and the extrapolation to the optical point ( $t = 0$ ).

The leading proton, which will be used as an event trigger, will be detected by silicon detectors placed inside movable sections of the vacuum pipe (Roman Pots), located symmetrically with respect to the interaction point (IP) (Fig. 2). In order to measure the inelastic rate, two separate forward telescopes will be installed on both sides of the CMS detector with a rapidity coverage of  $3.1 < |\eta| < 6.6$  (Fig. 3). With these additional detectors, a fully inclusive trigger, also for single diffraction, can be provided with an expected uncertainty on the inelastic rate of the order of 1%, after corrections.

## 2. LHC optics

The detection of forward protons from elastic or diffractive scattering at LHC energies requires the measurement of very small scattering angles ( $5\text{--}10 \mu\text{rad}$ ).

These particles remain close to the beam and can be detected on either side of the IP if the displacement at the detector location is large enough. The beam divergence at the IP must be small compared to the scattering angle.

To obtain these conditions, a special high- $\beta^*$  insertion is required. A large value ( $\text{O}(\text{km})$ ) of the  $\beta$ -function at the IP ( $\beta^*$ ) and a smaller beam emittance reduce the beam divergence. A large effective length  $L^{eff}$  at the detector location ensures a sizeable displacement. In fact the displacement of a scattered proton at distances from the IP ( $x(s), y(s)$ ) is given by the proton coordinates ( $x^*, y^*$ ) and scattering angle  $\theta_{x,y}^*$  at the interaction point, together with  $L^{eff}$ , the magnification  $v$  and the dispersion of the machine  $D$ :

$$y(s) = v_y(s) \cdot y^* + L_y^{eff} \cdot \theta_y^*$$

$$x(s) = v_x(s) \cdot x^* + L_x^{eff} \cdot \theta_x^* + \frac{\Delta p}{p} \cdot D(s)$$

$$L_{x,y}^{eff} = \sqrt{\beta_{x,y}\beta^*} \sin \Delta\mu(s) \quad \text{and}$$

$$v_{x,y} = \sqrt{\frac{\beta_{x,y}}{\beta^*}} \cos \Delta\mu(s).$$

For an ideal optics,  $L^{eff}$  should be as large as possible and  $v \simeq 0$ , in order to reduce the dependence on the proton coordinates at the vertex. This condition of parallel-to-point focusing is achieved by requiring the betatron phase advance  $\Delta\mu(s) = \pi/2$  at the detector location, which also maximizes  $L^{eff}$ . The LHC optics with  $\beta^* = 1540$  m, limited by the strength of the insertion quadrupoles, provides large  $L_{eff}$  values and parallel-to-point focusing conditions in both projections at 220 m from the IP.

### 3. The experimental apparatus

The TOTEM experiment uses precision detectors inserted in Roman Pots (movable sections of vacuum chamber) installed in the machine tunnel, at 147 and 220 m from the IP, to measure the elastically and diffractively scattered protons close to the beam direction.

In order to measure the elastic scattering to the smallest  $|t|$  values, the detectors should be active as close to their physical edge as possible. In particular the detectors will have to be efficient up to  $20\mu\text{m}$  to their edge. In order to build the edgeless elastic detectors two modern technologies are being considered: “cold planar” and “3D” silicon detectors.

The first solution (Fig. 4) exploits the fact that these devices can be operated without guard rings if operated when cooled down to 130 K [4], thus obtaining a drastic reduction of the inefficient material at the border of the detector.

The second one follows a novel idea [5] which foresees that the  $p^+$  and  $n^+$  electrodes are processed inside the bulk of the silicon wafer, rather than being implanted on its surface as in planar devices (Fig. 4). Test-beam’s performed at the CERN SPS have shown that the transition region at the edge of the 2003 prototype detectors has a width of  $\sim 6\mu\text{m}$  for the 3D and  $\sim 60\mu\text{m}$  for the cold planar.

The telescopes for the detection of the inelastic events have a good trigger capability, provide tracking with a good angular resolution and al-

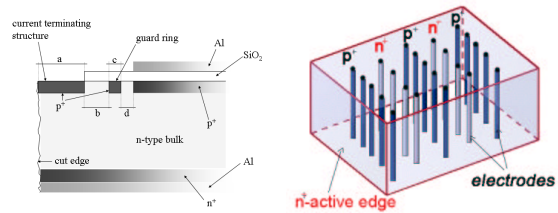


Figure 4. A cold planar detector (left). 3D detector (right): the electrodes and the active edges are fabricated inside the detector bulk.

low the measurement of the trigger efficiency. To discriminate beam-beam from beam-gas events, the telescope will identify the primary interaction vertex with an accuracy at the level of a cm by reconstructing a few tracks from each side of the interaction point; the knowledge of the full event is not needed.

The T1 telescope (Fig. 5) is made of 5 planes of 6 trapezoidal Cathode Strip Chambers (CSC) [6] and will be placed in the CMS end-caps in the rapidity range  $3 < |\eta| < 5$  with a  $2\pi$  azimuthal coverage. T2 is made of 16 half circular sectors of GEM [7] (Gas Electron Multiplier) detectors, similar to those used for the COMPASS experiment [8]; it will be placed in the shielding behind the CMS Hadronic Forward (HF) calorimeter as a complement of the T1 telescope at larger  $\eta$ . With the present dimension of the vacuum pipe, the T2 telescope will cover with good efficiency the range  $5.3 < |\eta| < 6.6$ . In order to discriminate beam-beam events with respect to beam-gas ones, it is necessary to achieve a good resolution in the primary vertex reconstruction. Preliminary results from the simulation of minimum bias events show that the primary vertex position in the  $(R,z)$  plane can be reconstructed with the following resolutions:  $\sigma_R = 2.9$  mm and  $\sigma_z = 4.5$  cm.

### 4. Elastic scattering

The  $x,y$  coordinates of the scattered proton are measured in the Roman Pot stations by the sil-

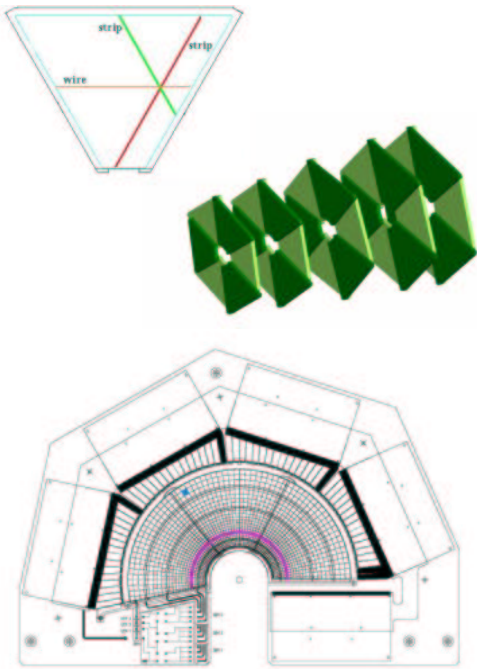


Figure 5. The TOTEM telescopes: a CSC and a arm of T1(top), a T2 triple-GEM detector(bottom).

icon detectors. Assuming that the edgeless silicon detectors are 100% efficient at a distance  $10 \cdot \sigma_{beam} + 0.5$  mm from the beam center, one can calculate the geometrical acceptance with different beam optics in the different Roman Pot stations. In order to measure the elastic scattering at very low  $t$ , it is necessary to use a very high  $\beta^*$  optics ( $\beta^* = 1540$  m) and the Roman Pot station at 220 m from the IP.

As mentioned in the introduction, the measurement of the total cross section with the luminosity independent method needs to extrapolate the rate  $dN/dt$  to  $t = 0$ . The curve of the acceptance (see Fig. 6) shows that the lowest  $t$  value at which the acceptance is still 50% is  $|t| = 2.3 \cdot 10^{-3}$  GeV<sup>2</sup>. Simulating a huge number of elastic events, it has been possible to estimate that the statisti-

cal uncertainty on the extrapolation can be as low as  $\sim 0.1\%$  (if one uses  $10^7$  reconstructed elastic events, which corresponds to roughly 10 hours data taking at a LHC high- $\beta^*$  fill with a luminosity of  $10^{28}$  cm<sup>-2</sup>s<sup>-1</sup>).

The study has been done simulating elastic events generated accordingly to a distribution  $e^{-Bt}$  (with  $B = 20$  GeV<sup>-2</sup>) with the  $\beta^* = 1540$  m optics.

The extrapolation accuracy due to experimental effects is much more important than that due to the statistics. The main sources of systematic uncertainties are the beam divergence, the beam energy and the beam position offset.

The effects of a non-exponential behaviour of  $d\sigma/dt$  have to be taken into account when extrapolating to the optical point: even at low  $|t|$  there may be important deviations of the hadronic cross section from the exponential behaviour. The influence of the Coulomb scattering becomes significant for  $|t| < 0.01$  GeV<sup>2</sup>. To study the impact of these effects on the precision of the extrapolation, an exponential function  $f_{th}(t) = f_{th}(0)e^{-Bt}$  has been fitted to the expected cross section. The upper limit of the fit interval has been fixed to 0.1 GeV<sup>2</sup>, while the lower one was varied from  $|t_{min}| = 0.0012$  to 0.1 GeV<sup>2</sup>; the study resulted in an expected systematic uncertainty of 0.25% [1].

The final overall uncertainty on the extrapolated elastic rate has been estimated to be  $\sim 0.5\%$ .

## 5. Inelastic scattering and total cross section

The measurement of the inelastic rate requires a trigger as inclusive as possible and a clear discrimination of beam-beam events from background interactions. With a double arm trigger more than 99% of non-diffractive events can be detected, while with a single arm one can detect the events escaping the double arm trigger and most of the diffractive interactions with all visible tracks in one arm only. The main background is due to beam-gas events, which can be rejected with an accurate primary vertex reconstruction. Simulation studies show that only  $\sim 3\%$  of the beam-gas events are misidentified as beam-beam,

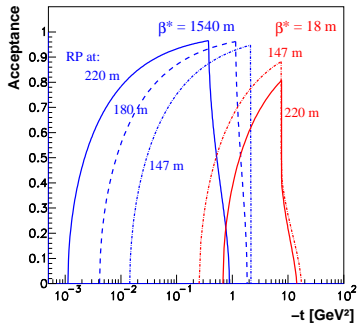


Figure 6. Geometrical acceptance of the detectors at 147 and 220 m with two different beam optics.

corresponding to a rate well below 1 Hz. Moreover, the detection of the surviving proton, with more than 90% efficiency, can be a powerful tool in the discrimination between beam-gas and single diffractive events.

The studies show that single and double diffractive events are responsible for the major loss in the inelastic rate. With a single arm trigger, a fraction of these events, corresponding to  $\sim 2.8$  mb, escapes detection. The lost events are mainly those with a very low mass (below  $\sim 10$  GeV/c), since all the particles are generated at pseudo-rapidities above 7 and escape therefore the detection.

To obtain the total inelastic rate, the fraction of events lost because of the incomplete angular coverage can be estimated by extrapolation. In the case of single diffraction, the reconstructed  $1/M^2$  distribution has been linearly fitted for  $M > 10$  GeV/c and the extrapolation to low masses has then be compared with the Monte Carlo. For single diffraction, the extrapolated number of events differs from the Monte Carlo by 4%, corresponding to a 0.6 mb uncertainty on the total cross section. The same estimation for the double diffraction and double Pomeron exchange gives 0.1 mb and 0.2 mb of uncertainty respectively.

The combination of the elastic and inelastic scattering uncertainties, after the extrapolations,

gives a final error on the total cross section of  $\sim 1\%$ .

## 6. Conclusion

The TOTEM collaboration has recently published its TDR [1,2], where a full description of the experiment is described.

The main aspects of the TOTEM scientific program are the measurement of the total  $pp$  cross section and of the elastic scattering up to  $-t = 8$  GeV<sup>2</sup>. TOTEM will use dedicated short runs of the LHC with high  $\beta^*$  optics and low luminosity.

The study of the physics performance has shown that an accuracy of  $\sim 1\%$  on the value of the total cross section is achievable with the foreseen experimental apparatus.

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