TOTEM early measurements

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Abstract

The status of the TOTEM experiment is described as well as the prospects for the measurements in the early LHC runs. The primary goal of TOTEM is the measurement of the total p-p cross section, using a method independent of the luminosity. A final accuracy of 1% is expected with dedicated $\beta^* = 1540$ m runs, while at the beginning a 5% resolution is achievable with a $\beta^* = 90$ m optics. Accordingly to the running scenarios TOTEM will be able to measure the elastic scattering in a wide range of t and to study the cross-sections and the topologies of diffractive events. In a later stage, physics studies will be extended to low-x and forward physics collaborating with CMS as a whole experimental apparatus.

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1 Introduction

The TOTEM experiment at the LHC will measure [1, 2] the total cross section with ~1% uncertainty, by using the luminosity independent method, which requires simultaneous measurements of elastic p-p scattering down to the four-momentum transfer squared $-t \sim 10^{-3}\,\mathrm{GeV}^2$ and of the inelastic p-p interaction rate with an extended acceptance in the forward region. The extrapolation of the present data to the LHC energy together with the existing cosmic ray data give a typical uncertainty of $\pm 15\%$ on the total cross-section. TOTEM will also measure the elastic p-p scattering up to $-t \sim 10\,\mathrm{GeV}^2$ and study soft diffraction.

Moreover, in collaboration with CMS will study jets, W's and heavy flavour production in single diffractive (SD) and double Pomeron exchange (DPE) events, measure particle and energy flow in the forward direction and study central exclusive particle production and low-x physics.

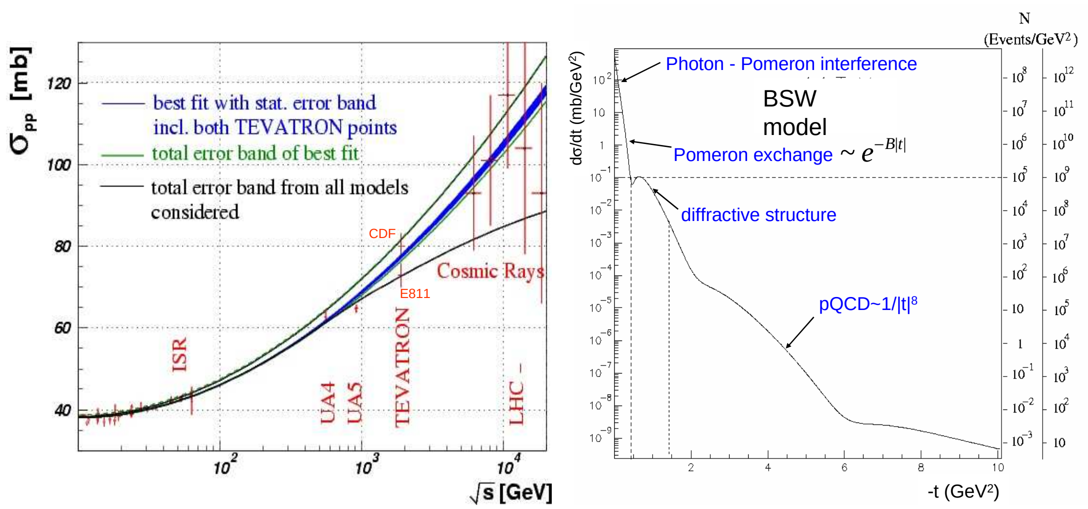

Fig. 1: Left: COMPETE predictions for total p-p cross section with PS, ISR, SPS, Tevatron and cosmic ray data. Right: elastic p-p cross section as predicted by the BSW model; the two columns on the right side show the number of events expected after 1 day running at 10^{28} and $10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ luminosity.

The TOTEM experiment is designed to measure σ_{tot} with an accuracy which is sufficient to discriminate between the current model predictions for the LHC energy ranging between 90 and 130 mb (see Fig. 1 for COMPETE [3] fits). 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.

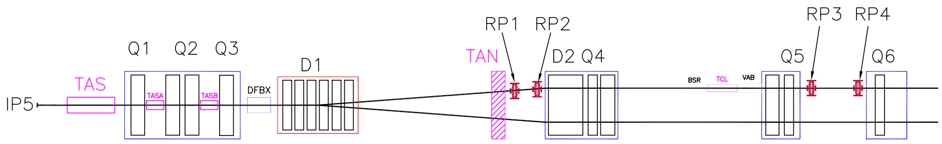

Fig. 2: The LHC beam line with the Roman Pots at 147 and 220 m.

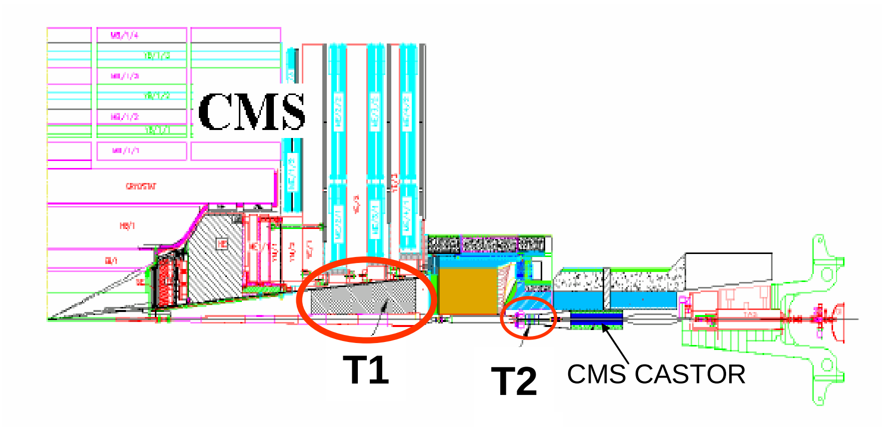

Fig. 3: The TOTEM detectors T1 and T2 installed in the CMS forward region.

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

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

TOTEM needs to run with special running conditions ($\beta^* = 1540$ m and luminosity $\mathcal{L} \approx 10^{28}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$). The β value at the interaction point requires zero crossing-angle, due to the increased beam size (proportional to β), and then a reduced number of bunches which is compatible with the LHC injection scheme. Almost half of the total cross–section at the LHC is predicted to come from elastic scattering, single, double and central diffractive processes. With the TOTEM acceptance extending up to the pseudorapidities of 6.5, and with the efficient proton detection capabilities close to the LHC beams, the diffractively excited states with masses higher than $10\,\mathrm{GeV}/c^2$ 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 $-t \sim 10^{-3}\,\mathrm{GeV}^2$, which corresponds to a proton scattering angle of $5\,\mu\mathrm{rad}$, and the extrapolation of $d\sigma_{el}/dt$ to the optical point ($t = 0$). The leading proton 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, with a rapidity coverage of $3.1 < |\eta| < 6.5$ (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 (5–10 μrad). 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-β^* insertion optics is required. A large value (O(km)) of the β-function at the IP (β^*) 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 $(x(s), y(s))$ of a scattered proton at distance s from the IP can be described by the following formula, where $\theta^*_{x,y}$ is the scattering angle at the interaction point, L^{eff} the effective length, v the magnification and D the dispertion of the machine:

$$x(s) = v_x(s) \cdot x^* + L_x^{eff} \cdot \theta_x^* + \frac{\Delta p}{p} \cdot D(s) \quad \text{and} \quad y(s) = v_y(s) \cdot y^* + L_y^{eff} \cdot \theta_y^*$$

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. This is the ideal scenario for TOTEM to measure the total cross section and to study minimum bias events and soft diffraction.

This large-β^* optics requires an injection optics different from the one which will be used at the starting runs of LHC. For this reason, an intermediate-β^* optics (β^*=90 m), which can use the standard LHC injection optics and can thus be operated in the first period of physics runs, has been proposed [4]. This optics provides parallel-to-point focusing only in the vertical plane and a measurement of t down to $-t \sim 3 \cdot 10^{-2}$ GeV^2, about one order of magnitude higher than with the nominal TOTEM optics, but nevertheless very useful.

3 The experimental apparatus

The TOTEM experiment uses precision silicon microstrip detectors inserted in Roman Pots, movable sections of vacuum chamber (Fig. 4), 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. Each Roman Pot station consists of 2 units with a distance of 4 (for 220 m station) and 1.5 m (for 147 m station). Each unit consists of 3 roman pots, 1 horizontal and 2 vertical (top and bottom). The lever arm among different units allows local track reconstruction and a fast trigger selection based on track angle. 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 a few tens of microns to their edge. These are planar silicon detectors with a current terminating structure, which consists in replacing the commonly used voltage terminating guard rings (usually 0.5-1 mm wide) with a 50μm wide structure of rings which strongly reduces the influence of the current generated at the detector edge on the active detector volume [5]. The detectors inside the 220 m stations will be installed during year 2009.

The telescopes for the detection of the inelastic events have a good trigger capability, provide tracking with a good angular resolution and allow the measurement of the trigger efficiency.

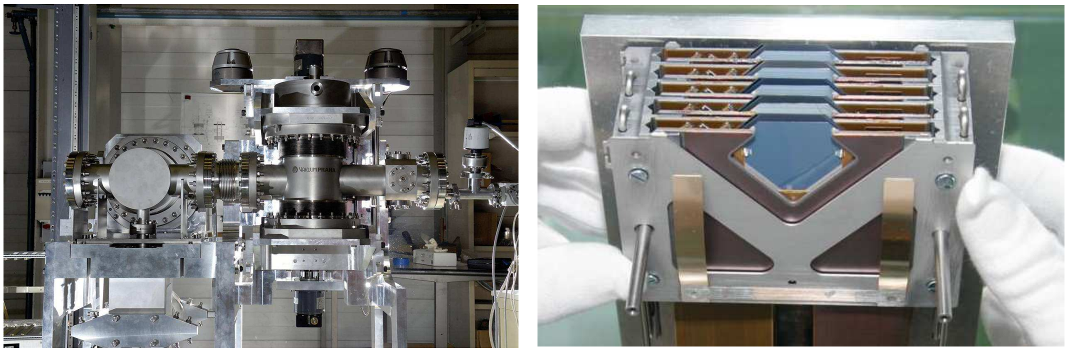

Fig. 4: Left: horizontal and vertical roman pots. Right: mounted silicon detectors.

To discriminate beam-beam from beam-gas events, the telescopes will identify the primary interaction vertex with an accuracy at the level of a cm in the transverse plane 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 $3.1 < |\eta| < 4.7$ with a 2π azimuthal coverage. It will provide a spatial resolution of $\sim$1 mm. T2 (Fig. 5) is made of 20 half circular sectors of triple-GEM [7] (Gas Electron Multiplier) detectors mounted back-to-back and which will provide a spatial resolution of $\sim$ 100 μm in the radial direction; it will be placed in the shielding behind the CMS Hadronic Forward (HF) calorimeter to extend the coverage at larger η. With the present dimension of the vacuum pipe, the T2 telescope will cover with good efficiency the range $5.3 < |\eta| < 6.5$.
Both telescopes will be ready for the installation during year 2009.

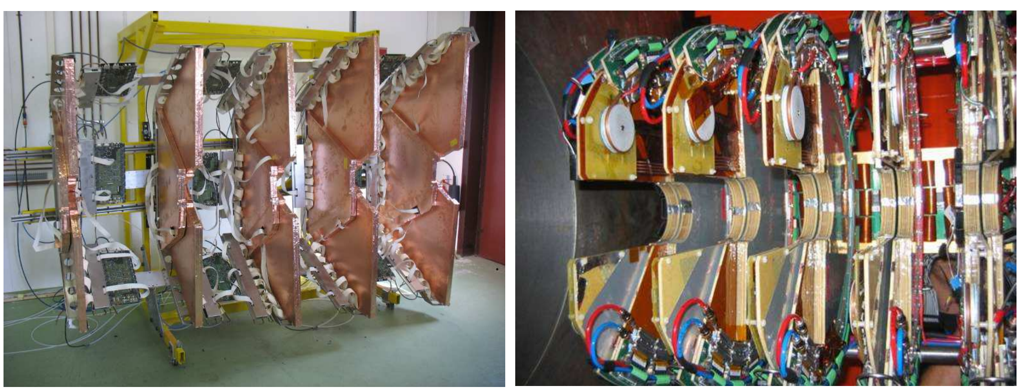

Fig. 5: Left: T1 quarter ready for the installation. Right: T2 quarter ready for the installation.

4 TOTEM programme and early physics

4.1 Elastic scattering

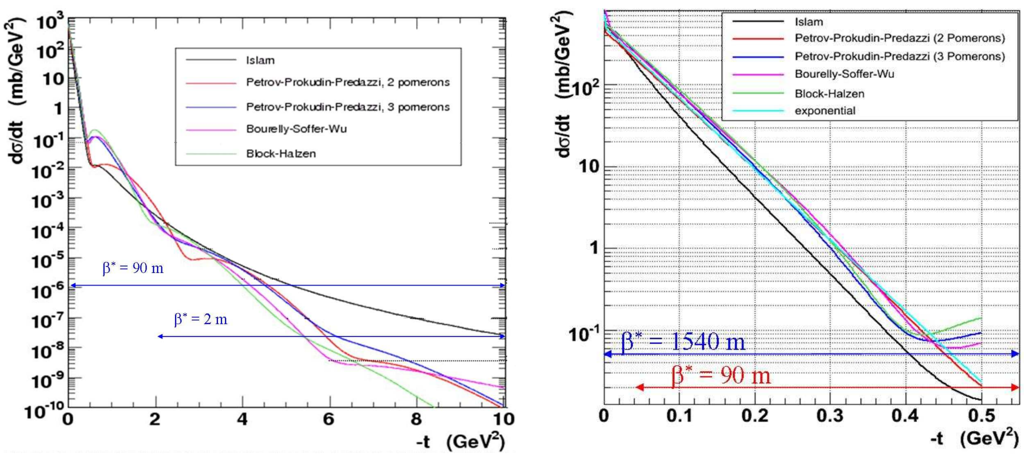

Fig. 6: Left: elastic cross section for different theoretical models and t acceptance for $\beta^* = 90$ and 2 m optics. Right: elastic cross section zoomed in the exponential region (the pure exponential behavior is plotted as reference) and t acceptance for $\beta^* = 1540$ m and 90 m optics.

The measurement of the elastic cross-section is one of the main goals of TOTEM. Different theoretical models [8–11] predict different behaviors of the differential cross-section $d\sigma/dt$, as shown in Fig. 6. All these t ranges can be accessed by TOTEM using different running scenarios. In particular, for what concerns the nuclear region ($10^{-3} < t < 0.5\ \mathrm{GeV}^2$), it can be accessed with high and intermediate β^* optics (Fig. 6). Due to the high cross-sections involved even at very low luminosities ($10^{28} < \mathcal{L} < 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$) enough statistics can be accumulated in a few runs (at least for low-t values). The measurement in the nuclear region, which is theoretically described by the exchange of a single Pomeron, is crucial for the extrapolation of $d\sigma_{el}/dt$ to the optical point ($t = 0$), needed for the measurement of the total p-p cross-section. This can be done fitting and extrapolating the measured rate with a generalized exponential function $e^{B(t)}$. The early LHC runs will be characterized by low β^* optics with a reduced number of bunches and a lower number of protons per bunch, with respect to the nominal ones. Under these conditions only elastic events with $|t|$ values between 2 GeV^2 and 10 GeV^2 will be at reach, allowing TOTEM to study high-t elastic scattering. The exponential region will be accessible only if a high/intermediate β^* optics will be included in the early physics LHC programme.

4.2 Inelastic rate and total cross-section

The measurement of the inelastic rate will be done using all TOTEM detectors and using various trigger and offline analysis strategies, depending on the actual running scenario. At low luminosities a single arm trigger which requires activity in one side of T1 or T2 can be utilized to have very high efficiency; it misses only low mass single diffractive events but it would suffer from beam-gas interactions, which strongly depend on the beam current. With a double arm

T1/T2 trigger the beam-gas background can be suppressed but, on the other hand, the efficiency in detecting single diffractive events is quite reduced. Offline, the sample purity can be enhanced reconstructing the primary interaction vertex. Moreover, the rate of low mass diffractive events which escape detection can be partly recovered extrapolating the measured cross-section with theoretical assumptions on $d\sigma/dM^2$.

Combining the uncertainties that come from the measurement of the inelastic and elastic rate and from the extrapolation of the diffractive cross-section to the optical point, it results that a 1% error on the total cross-section is achievable with the dedicated $\beta^* = 1540$ m optics and a 5% can be reachable in an earlier stage with the intermediate 90 m optics (see Table 1).

With T1 and T2 detectors minimum bias events can be studied, mainly focusing on the charged multiplicity in the covered η range.

Uncertainty	$\beta^* = 90$ m	$\beta^* = 1540$ m
$dN_{el}/dt \to 0$	4%	0.2%
N_{el}	2%	0.1%
N_{inel}	1%	0.8%
ρ	1.2%	1.2%
σ_{tot}	5%	1-2%

Table 1: Contributions to the total cross-section for two different LHC optics.

4.3 Diffraction

During the early runs with low β^* beams, diffractive protons with $\xi = \frac{\Delta p}{p}$ in the range 0.02-0.2 will be detectable by the Roman Pots at 220 m (Fig. 7). This will allow TOTEM to measure the differential cross-section for single diffractive events ($d\sigma^{SD}/dM$) for masses from 2 to 6 TeV/c^2 ($M = \sqrt{\xi s}$) with a mass resolution of 10% or better. Also double Pomeron exchange events (DPE) can be detected with sufficient statistics and the differential cross section can be measured in the range $0.25 < M < 2.8$ TeV/c^2 with a mass resolution of 10% or better. Using a higher β^* optics a much larger fraction of diffractive protons can be observed ($\sim 65\%$ for $\beta^* = 90$ m and $\sim 95\%$ for $\beta^* = 1540$ m). Since with these optics protons with ξ values down to 10^{-8} can be detected, all the mass spectrum for SD and DPE events can be investigated.

5 Conclusion

The TOTEM detectors will be operational for the first physics runs of the LHC. The accessible physics is strongly dependent on the running condition of the accelerator. At the beginning, with a low-β^* optics, diffraction at large masses and elastic scattering at large t can be studied. The use of an intermediate $\beta^* = 90$ m optics will allow even at an early stage to measure, even if with a ~5% precision the total $p-p$ cross-section, which the main goal of the experiment. A better precision will be achieved only when the TOTEM nominal optics ($\beta^* = 1540$ m) is available. Moreover, at a later stage, a common physics progamme about low-x and forward physics will be brought on with CMS [12].

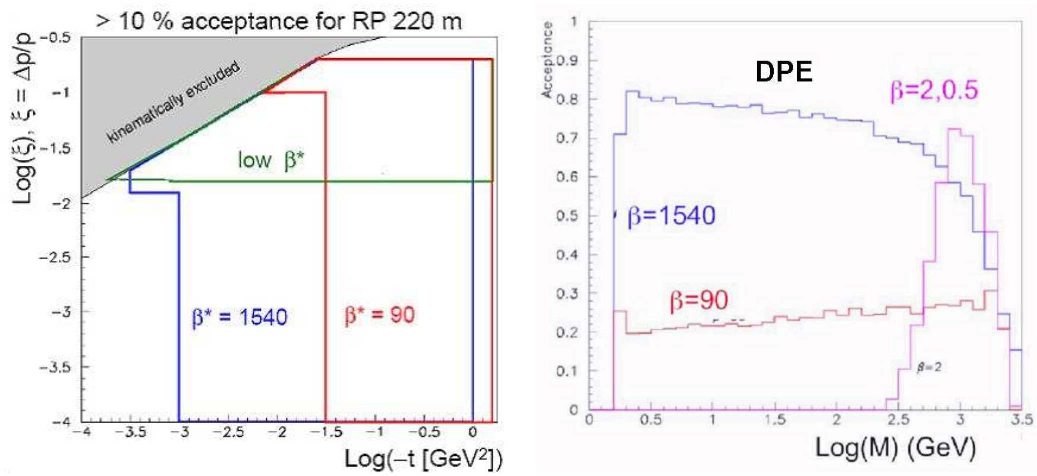

Fig. 7: Left: acceptance in $log_{10}t$ and $log_{10}\xi$ for diffractive protons at RP220 for different optics. Right: acceptance for DPE protons for different optics (both protons detected).

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