TOTEM: PROSPECTS FOR TOTAL CROSS-SECTION AND LUMINOSITY MEASUREMENTS

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Abstract

With the installation of the T1 telescope and the Roman Pot stations at 147 m from IP5, the detector apparatus of the TOTEM experiment has been completed during the technical stop in winter 2010/2011. After the commissioning of the dedicated beam optics with $\beta^* = 90\,\mathrm{m}$, a first measurement of the total pp cross-section σ_{tot} and – simultaneously – the luminosity L will be possible in the upcoming running season 2011. The precision envisaged is 3% and 4% for σ_{tot} and L, respectively. An ultimate beam optics configuration with $\beta^* \sim$ 1km will later reduce the uncertainty to the 1% level.

INTRODUCTION

The motivation and concept of measuring σ_{tot} and L at LHC with the method based on the Optical Theorem have been discussed at length elsewhere [1, 2]. The central equations expressing σ_{tot} and L in terms of the measured inelastic and elastic rates, N_{inel} and N_{el}, and the extrapolation of the differential elastic rate to the optical point, $t = 0$, are

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

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

where $\rho = 0.1361 \pm 0.0015^{+0.0058}_{-0.0025}$ [3] will as a first step be taken from theory. At a later stage, a measurement at $\beta^* \sim$ 1km can be attempted (see last section of this article).

This article aims at giving an update on the expected performance, taking into account recent studies for the reduced centre-of-mass energy of 7 TeV and the running experience in 2010.

The Roman Pot (RP) stations at ±220 m from IP5 and the forward GEM telescope T2 had already been fully operational in 2010, whereas the second half of the RP spectrometer – i.e. the ±147 m stations – as well as the CSC telescope T1 were installed during the technical stop in winter 2010/2011, thus completing TOTEM's detector apparatus (Figure 1) in time for the running season 2011.

MEASUREMENT OF THE INELASTIC RATE

The inelastic trigger acceptance predicted by simulation for the TOTEM detector configuration is given in Table 1.

The trigger losses are dominated by low-mass diffractive events where the diffractive system escapes to rapidities beyond the reach of T2, i.e. $\eta > 6.5$ or masses $M \lesssim 10\,\mathrm{GeV}$. The missing part of the diffractive mass spectrum can be partially recovered by extrapolating it according to the empirical relation $\frac{dN}{dM^2} \propto \frac{1}{M^n}$ with $n \approx 2$.

Table 1: *Trigger losses at $\sqrt{s} = 7$ TeV, requiring 3 tracks pointing to the IP. The cross-sections given are the central values of rather wide ranges of predictions [4].*

Event class	σ	T1/T1 trigger and selection loss
Minimum Bias	50 mb	0.05 mb
Single Diffractive	12.5 mb	4.83 mb
Double Diffractive	7.5 mb	1.21 mb
Total	70 mb	6.1 mb

The systematic uncertainty of this procedure depends on the purity of the diffractive event sample used for the extrapolation. For example, minimum bias events misidentified as diffractive events will introduce a bias. To improve the identification of event topologies, e.g. rapidity gaps, CMS detectors at rapidities below 3.1 (central detectors) or above 6.5 (FSC [5] and ZDC) could be used.

A principal problem of the extrapolation is that the $1/M^2$ dependence of the spectrum is not theoretically justified [6]. There may be sizeable deviations at low masses; even the presence of resonances cannot be excluded. However, an independent handle on Single Diffractive (SD) events can be exploited: At $\beta^* = 90\,\mathrm{m}$ [8], the leading protons of all diffractive events with $|t| > 10^{-2}\,\mathrm{GeV}^2$ are detected in the RPs, irrespective of the diffractive mass. Thus, SD events whose diffractive system escapes detection by T2 will have the signature of *unpaired* protons in the kinematic region of elastic protons (i.e. $\xi \approx 0$).

After all corrections a total uncertainty of 1 mb (or 1.4%) in N_{inel} is expected.

MEASUREMENT OF THE ELASTIC RATE AND EXTRAPOLATION TO T = 0

Predictions [7] for the differential cross-section of elastic pp scattering at $\sqrt{s} = 7\,\mathrm{TeV}$ in the low-$|t|$ region are displayed in Figure 2(left). Deviations from the apparent exponential behaviour become visible when the exponential slope, $B(t) = \frac{\mathrm{d}}{\mathrm{d}t} \ln \frac{\mathrm{d}\sigma}{\mathrm{d}t}$ is plotted (Figure 2, right). This non-constant $B(t)$ has to be taken into account in the extrapolation fit for obtaining $\frac{\mathrm{d}\sigma}{\mathrm{d}t}(t = 0)$. The procedure is identical to the one described in [2] for $\sqrt{s} = 14\,\mathrm{TeV}$.

The comparison of the RP acceptances in t for the two

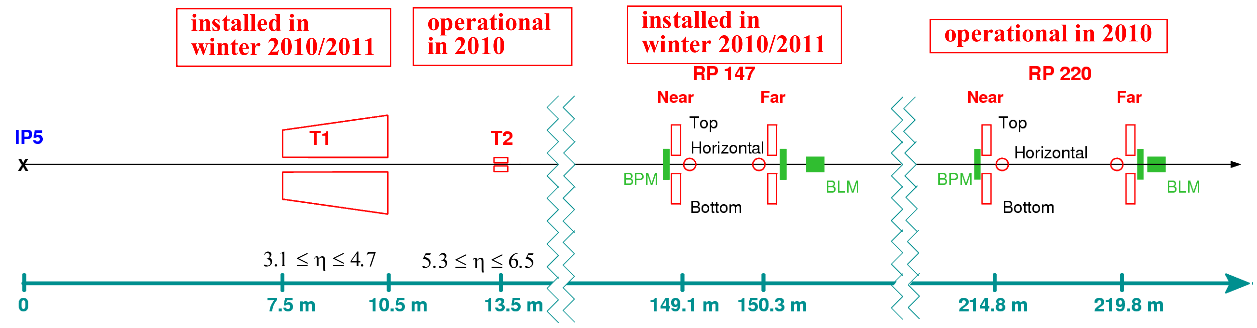

Figure 1: *Schematic overview of the TOTEM detector configuration. The apparatus is symmetric w.r.t. IP5, but only the arm in Sector 5-6 is drawn.*

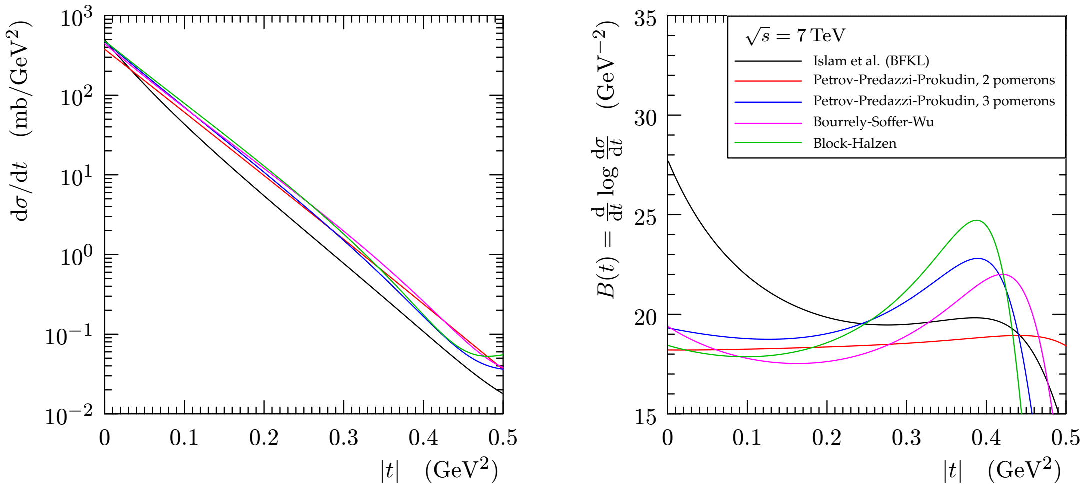

Figure 2: *Left: elastic differential cross-section at low $|t|$ as predicted by different models [7]. Right: exponential slope of (left).*

high-β^* optics foreseen (Figure 3) shows the significantly better reach of the $\beta^* = 1540$ m to low $|t|$ as compared to 90 m. In both cases, the lower centre-of-mass energy is advantageous: reducing $\sqrt{s}$ from 14 TeV to 7 TeV results in a factor 0.5 in the lowest reachable $|t|$-value (see Figure 4 and [4]).

Extrapolation at $\beta^* = 90\,m$

The contributions to the extrapolation uncertainty at $\sqrt{s} = 7$ TeV are expected to be very similar to those at $\sqrt{s} = 14$ TeV discussed in [2]. The key advantage of the lower energy, however, is the about 50% shorter extrapolation interval, which will reduce the fit-induced statistical error and the systematic uncertainty contribution from the model dependence of the extrapolation function. The beam divergence at 7 TeV is higher than at 14 TeV by a factor $\sqrt{14/7} = \sqrt{2}$ (i.e. 3.3 μrad instead of 2.4 μrad), but as explained in [2] (Section 6.3.2), this effect leads to a shift in the extrapolation result which can be corrected for. The optical functions are expected to be known to within ~1%, which would translate into an extrapolation uncertainty contribution of 1.5%. The statistical uncertainty after an 8 hour long run – with conditions explained in the next section and Table 2 – would be on the 1% level.

In summary, a total error estimate of ~ 2% for the extrapolation at $\beta^* = 90$ m and 7 TeV can be considered as conservative.

Running Scenario for the $\beta^* = 90\,m$ Optics in 2011

After the commissioning of the unsqueeze from the injection optics to $\beta^* = 90$ m [9], TOTEM is aiming at four well separated runs of typically 8 hours length, enabling systematic comparisons between the individual results and successive improvement of the beam conditions. As outlined above, the key element in reducing the extrapolation uncertainty is the minimisation of the $|t|$-interval to be bridged, by extending the acceptance to the lowest possible $|t|$ and hence by moving the RPs as close as possible to the beam. As shown in Table 2, this is accomplished by a twofold strategy:

- Reduce d_{RP}/σ_{beam}. In special runs in 2010, success-

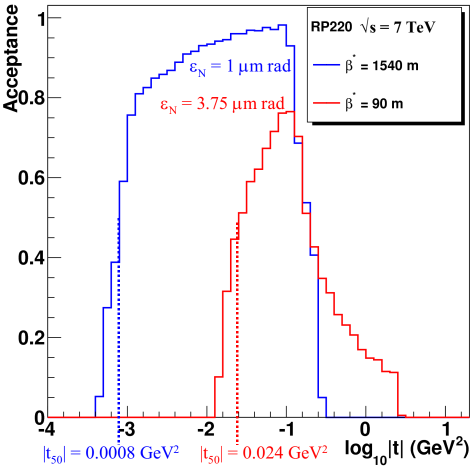

Figure 3: *Acceptance of the RP220 station for elastically scattered protons in terms of t for the two high-β^* optics and for a detector-beam distance of $10\,\sigma$. The point where the acceptance reaches 50% on the lower-$|t|$ side is called t_{50}; it characterises the typical minimum $|t|$ useable for extrapolation purposes.*

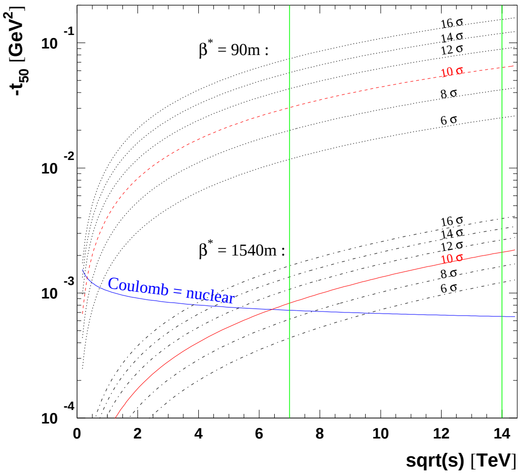

Figure 4: *$|t|$-value at which the RP220 acceptance reaches 50%, as a function of the centre-of-mass energy, for different distances between the RP window and the beam. The sensitive detector volume begins $\delta = 0.5\,\mathrm{mm}$ further away (due to window thickness and window-detector gap). The $|t_{50}|$-values take δ into account. The upper and lower blocks of curves represent the $\beta^* = 90\,m$ (with $\varepsilon_{\mathrm{n}} = 3.75\,\mu\mathrm{m\,rad}$) and $\beta^* = 1540\,m$ (with $\varepsilon_{\mathrm{n}} = 1\,\mu\mathrm{m\,rad}$), respectively. At the blue line, the Coulomb and the nuclear scattering amplitudes have equal moduli.*

ful data taking took place as close as $7\,\sigma$ from the beam, i.e. in the shadow of only the primary collimators. For machine protection reasons, this approach imposes a limit on the total beam current[1].

- Reduce the transverse beam emittance and hence the width σ_{beam}. Thus for a given d_{RP}/σ_{beam}, the pots are moved to a smaller absolute distance d_{RP}.

The bunch population N is not only limited by the low-current requirement but most importantly in view of keeping the inelastic pile-up fraction $\mu_{inelastic}$ below 10% which is essential for an accurate measurement of the inelastic rate. With one bunch of $(6 \div 7) \times 10^{10}$ p/b, each of the four runs requested can provide an elastic extrapolation with the required precision $\sim 1\%$.

Table 2: *Tentative scenario for the beam conditions in four physics runs with the $\beta^* = 90\,m$ optics at 3.5 TeV beam energy*[2]*. d_{RP} denotes the distance between the outer window surface of the pots and the centre of the beam. The additional distance of 0.5 mm to the sensitive detector volume has been taken into account in the calculation of $|t_{50}|$, i.e. the $|t|$-value where the acceptance reaches 50%. $\mu_{inelastic}$ is the inelastic pile-up fraction. $\delta\sigma_{el}(t=0)$ is the precision of the elastic cross-section extrapolation to $t = 0$.*

Run	1	2	3	4
ε_n [μm rad]	3	3	1	1
d_{RP}/σ_{beam}	8	6	8	6
$N/10^{10}$	7	7	6	6
L [$10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	6.1	6.1	13	13
$\mu_{inelastic}$	0.04	0.04	0.08	0.08
$\lvert t_{50}\rvert$ [GeV^2]	0.016	0.0096	0.0060	0.0037
$\int_0^{8h} L\,\mathrm{d}t$ [nb^{-1}]	0.2	0.2	0.3	0.3
$\delta\sigma_{el}/\sigma_{el}(t=0)$	$\sim 1.5\%$	$\sim 1\%$	$< 1\%$	$< 1\%$

COMBINED UNCERTAINTY AT $\beta^* = 90$ m

The error contributions from all measured quantities and from the theoretical knowledge of ρ are listed in Table 3. The combined uncertainties in σ_{tot} and L result from an error propagation calculation taking into account the correlations. Note that the precision in L is slightly worse due to its squared dependence on $(N_{el} + N_{inel})$, as compared to the linear dependence of σ_{tot} (see Eqns. (1) and (2)).

Table 3: *Error contributions from all ingredients to Eqns. (1) and (2) for $\beta^* = 90\,m$.*

Extrapolation of $\frac{\mathrm{d}\sigma_{elastic}}{\mathrm{d}t}$ to $t = 0$	$\pm 2\%$
Total elastic rate (strongly correlated with extrapolation)	$\pm 1\%$
Total inelastic rate	$\pm 1.4\%$
Error contribution from $(1+\rho^2)$ using full COMPETE error band $\delta\rho/\rho = 33\%$	$\pm 1.2\%$
Total uncertainty in σ_{tot} incl. correlations	$\pm 3\%$
Total uncertainty in L incl. correlations	$\pm 4\%$

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[1] The quantitative current limit for $\beta^* = 90\,\mathrm{m}$ runs remains to be decided by the Machine Protection Panel and the collimation group.

[2] This table has been modified w.r.t. the 4.0 TeV version presented in the workshop slides.

OUTLOOK: PERFORMANCE AT $\beta^* = 1540\,\mathrm{m}$

The $\beta^* = 1540\,\mathrm{m}$ optics, studied in detail for $\sqrt{s} = 14\,\mathrm{TeV}$ [2], extends the measurable $|t|$-range to values of the order $10^{-3}\,\mathrm{GeV}^2$ and thus enables an elastic extrapolation with an uncertainty at the 0.2% level. Consequently, the precision in σ_{tot} improves to ~ 1%.

Scaling the optics properties to $\sqrt{s} = 7\,\mathrm{TeV}$ shows an even further enhancement of the acceptance reach to low $|t|$ (Figure 4, bottom block of curves). Inserting the RPs to 8 or 6 σ_{beam} would give access to the elastic scattering zone dominated by the Coulomb interaction and thus permit a measurement of ρ, avoiding any need for theoretical input to the σ_{tot} determination via the Optical Theorem. At $\sqrt{s} = 14\,\mathrm{TeV}$ this opportunity will not be offered.

However, the current version of the $\beta^* = 1540\,\mathrm{m}$ optics for TOTEM is only compatible with operation at $\sqrt{s} = 10\,\mathrm{TeV}$ to $14\,\mathrm{TeV}$ [9]. At lower energy the two main limiting parameters are the minimum strength allowed in the insertion quadrupoles and the aperture. One way to avoid these limitations would be to loosen the constraints on the phase advance by abandoning the condition to have "parallel-to-point focussing" in both transverse projections. Alternative optics at very high β^*, compatible with operations at $\sqrt{s} = 7\,\mathrm{TeV}$ are under study.

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