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The TOTEM experiment: Total cross-section measurement and soft diffraction at LHC

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Abstract. The TOTEM experiment intends to measure the total proton proton cross-section at 14 TeV and the LHC luminosity with a precision of $\leq 5\,\%$ in short runs with a special $\beta^* = 90$ m optics at an early stage of LHC operation. Furthermore, this will allow a measurement of the elastic proton proton scattering cross-section in a $|t|$-range from 0.04 to $1\,\mathrm{GeV}^2$, a study of soft proton proton diffraction with a large diffractive proton acceptance as well as provide precise information on the horizontal distribution of the proton proton interaction vertices.

1. Introduction

The precise measurement of the total proton proton (pp) cross-section, σ_{tot}, with the luminosity-independent method is one of the main physics aims of the TOTEM experiment [1]. σ_{tot} and the luminosity $\mathcal{L}$ are related to the forward elastic scattering amplitude via the optical theorem:

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

This method requires the simultaneous measurement of the total elastic (N_{el}) and inelastic (N_{inel}) rates and the extrapolation of the differential elastic scattering rate ($dN_{el}/d|t|$) to the optical point, $|t| = 0$, where $|t|$ is the squared four-momentum transfer. The parameter $\rho = \mathcal{R}[f_{el}(0)]/\mathcal{I}[f_{el}(0)]$, where $f_{el}(0)$ is the forward elastic scattering amplitude, is taken from theoretical predictions, e.g. [2]. Since $\rho \sim 0.14$ enters only as a $1+\rho^2$ term, its impact is small.

The TOTEM apparatus is placed symmetrically with respect to the CMS experiment at interaction point five (IP5) of LHC. Inelastic events are recorded with two tracking telescopes T1 and T2 at distances 7.5 and 14 m from IP5 covering a rapidity interval of $3.1 \leq |\eta| \leq 6.5$. Roman Pot stations at a distance of 147 m and 220 m (RP220) from IP5 measure forward protons.

Precise total cross-section measurement require special high-β^* LHC optics to reach lowest possible values of $|t|$ in elastic pp scattering. For this purpose a special LHC optics with $\beta^* = 1540$ m has been designed [3]. Since this optics will need a non-standard injection scheme, its commissioning is complex and only foreseen at a later stage. TOTEM, therefore, proposes to have short runs at LHC startup with an optics having a β^* of 90 m [4] that uses the standard injection and has favorable beam conditions for early LHC running: no crossing angle and at most 156 bunches with low proton densities resulting in a $\mathcal{L}$ between 10^{28} and $6\times10^{29}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

The transverse displacement $(x(s), y(s))$ of a scattered proton originating from the transverse vertex (x^*, y^*) with a fractional momentum loss $\xi = \Delta p/p$ and a scattering angle Θ^* can be

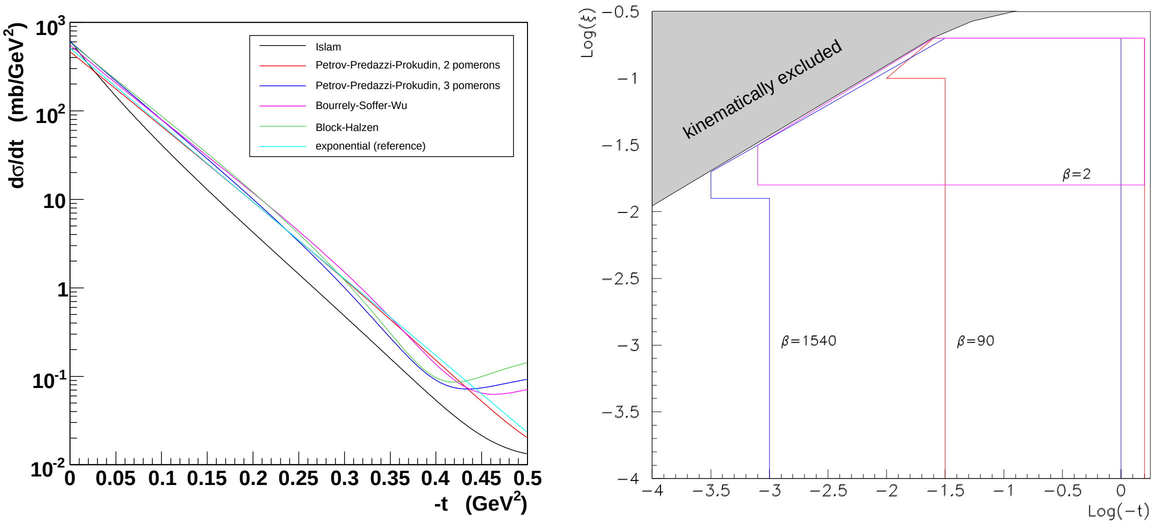

Figure 1. Left: Predictions of the differential elastic proton proton scattering cross-section at 14 TeV. Right: Forward proton acceptance in squared four momentum transfer $\log_{10}(|t|)$ and fractional proton momentum loss $\log_{10}(\xi)$ for different LHC optics. Contours at 10 % acceptance.

expressed using the optical functions: effective length L, magnification v and dispersion $D(s)$ [1]:

$$x(s) = v_x(s) \cdot x^* + L_x(s) \cdot \Theta_x^* + \xi \cdot D(s) \quad \text{and} \quad y(s) = v_y(s) \cdot y^* + L_y(s) \cdot \Theta_y^*$$

The $\beta^* = 90$ m optics has been optimized to have the following features at $s = 220$ m: vertical offset independent of the vertical interaction point ($v_y = 0$), large vertical acceptance for RP220 in Θ^* (L_y large) and horizontal offset independent of the horizontal scattering angle ($L_x = 0$). This implies for elastically scattered protons that the measured vertical offset at RP220 is directly proportional to Θ_y^* and the measured horizontal offset directly proportional to x^*. Thus, the horizontal distribution of elastically scattered protons at RP220 gives a measure of the size of the horizontal interaction region. Given the large statistics for elastically scattered protons within the acceptance, this size can be monitored at μm level in a time window of a few minutes.

The $\beta^* = 90$ m optics is much easier to commission than the $\beta^* = 1540$ m, according to studies by LHC experts. In addition, larger vertical beam size at RP220 (625 μm vs. 80 μm) eases the commissioning and movements of the RP detectors in the beginning of LHC operation.

2. Total cross section measurement

The measurement of the inelastic rate is largely based on inclusive triggers with the telescopes T1 and T2 and hence almost independent of the LHC optics, exceptions being Single Diffraction (SD) and Double Pomeron Exchange (DPE), where forward protons are part of the trigger signature. To reduce beam-gas background, a double-arm trigger strategy is preferred. The estimate of the uncertainty – mainly systematics from trigger losses – proceeds along the line explained in [1]. The result is 0.8 mb or 1 % of the predicted inelastic cross-section of 80 mb.

Elastic pp scattering events will be measured with the two RP220's placed symmetrically on each side of IP5. The determination of total cross-section requires two aspects of elastic scattering to be measured: the total elastic rate and the extrapolation of the differential cross-section $d\sigma/d|t|$ to the optical point $|t| = 0$. Obviously the measured elastic rate has to be complemented by the extrapolated part, so that this extrapolation enters twice in the procedure.

In view of minimizing the systematic error of the extrapolation, the elastic cross-section has to be measured down to the lowest reachable $|t|$-values. Under the assumption that the sensitive edge of the detector is at a distance of $10\,\sigma_{beam} + 0.5\,\mathrm{mm} \sim 6.75\,\mathrm{mm}$, from the beam center, protons with $|t_y| > 0.03\,\mathrm{GeV}^2$ are observed in RP220 (see Fig. 1 (right)).

Most models [5] predict an exponential behaviour of the cross-secion up to $|t| \sim 0.25$ GeV^2, as shown in Figure 1 (left). In this $|t|$ range, all deviations from a purely exponential shape can be parameterized by a second order polynomial in the variable $B(t) = d\ln(d\sigma d|t|)\,/d|t|$ for all the models and hence used as a model-independent fitting function for the extrapolation to $|t| = 0$. The statistical precision of the extrapolation for elastic scattering events corresponding to a 5 hour run at a luminosity of 10^{29} cm^{-2} s^{-1} is smaller than 1 %.

Systematical uncertainties dominates the uncertainty on the extrapolation to $|t| = 0$. Key systematical effects are: smearing effects of the t-measurement, especially due to the beam angular divergence, $-2\,\%$, systematic uncertainty of the t-measurement, especially the uncertainty on $L_y(220\text{ m})$, $3\,\%$ and model-dependent biases in the extrapolation procedure $1\,\%$.

The relative uncertainty on σ_{tot} has the following main contributions: the uncertainty due to the inelastic rate $1\,\%$, the extrapolation of the elastic cross-section $\leq 4\,\%$, the elastic rate $\leq 2\,\%$ and the ρ-value $2\,\%$. Combining all the uncertainties taking into account their correlations yields an error of $4\,\%$. Therefore, the total uncertainty of a σ_{tot} measurement using the $\beta^* = 90$ m optics is estimated to be 5 % or better. Similar uncertainty is expected for the luminosity.

At $\beta^* = 1540$ m optics, elastically scattered protons can be measured down to $|t| = 3 \times 10^{-2}$ and hence the uncertainties on the elastic rate and the extrapolation of the elastic cross-section are significantly reduced leading to an expected uncertainty on the σ_{tot} measurement of 1 % [1].

3. Soft diffraction and elastic scattering

Most diffractive processes (SD and DPE) have intact protons in the final state, characterized by their fractional momentum loss $\xi = \Delta p/p$ and their $|t|$. The RP220 acceptance for these forward protons depends considerably on the LHC optics. Fig. 1 (right) shows the $(|t|, \xi)$ acceptances for low-β^* optics (0.5 m and 2 m similar), 90 m and 1540 m. In low-β^* optics, only protons with $\xi > 2\,\%$ are observed, corresponding to rather high diffractive masses ($M > 300\,\mathrm{GeV}$ in the case of DPE). For the two other optics, all ξ-values are accepted for $|t| > 3 \times 10^{-2}$ $(2 \times 10^{-3})\,\mathrm{GeV}^2$ for $\beta^* = 90\,\mathrm{m}$ (1540 m). Consequently, a large fraction of the diffractive protons is observed: $65\,\%$ for $\beta^* = 90\,\mathrm{m}$ and $95\,\%$ for 1540 m, allowing first measurements of SD and DPE at LHC.

The RP220 will cover the full $|t|$ scale for elastic scattering by combining data from runs at different LHC optics. The high-β^* optics will allow to explore the low-$|t|$ exponential region, important for the extrapolation to $|t| = 0$, and the region where diffractive structure appears ($0.5 < |t| < 1$ GeV^2). The large-$|t|$ region, where the predicted cross-section is proportional to $|t|^{-8}$, described in terms of triple-gluon exchange, will be investigated with low-β^* optics.

Conclusions

Short runs with $\beta^* = 90$ m optics will allow a total cross-section measurement with a precision of $\leq 5\,\%$. Also soft diffraction with a good proton acceptance as well as elastic scattering in a wide $|t|$-range can be studied. The precise determination of the horizontal vertex distribution at IP5 can be used for a second independent luminosity measurement assuming the optical functions.

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