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TOTEM: FORWARD PHYSICS AT THE LHC

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The TOTEM experiment with its detectors in the forward region of CMS and the Roman Pots along the beam line will determine the total pp cross-section via the optical theorem by measuring both the elastic cross-section and the total inelastic rate. TOTEM will have dedicated runs with special high-β^* beam optics and a reduced number of proton bunches resulting in a low effective luminosity between $1.6 \times 10^{28}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and $2.4 \times 10^{29}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. In these special conditions also an absolute luminosity measurement will be made, allowing the calibration of the CMS luminosity monitors needed at higher luminosities. The acceptance of more than 90 % of all leading protons in the Roman Pot system, together with CMS's central and TOTEM's forward detectors extending to a maximum rapidity of 6.5, makes the combined CMS+TOTEM experiment a unique instrument for exploring diffractive processes. Scenarios for running at higher luminosities necessary for hard diffractive phenomena with low cross-sections are under study.

1 The TOTEM Experiment: Layout and Detector Technologies

The TOTEM experiment [1] situated at IP5 of the LHC, complements the CMS detector by the forward trackers T1 and T2 inside CMS (Figure 1) and by a system of Roman Pot stations at distances of 147 m, 180 m and 220 m from the interaction point.

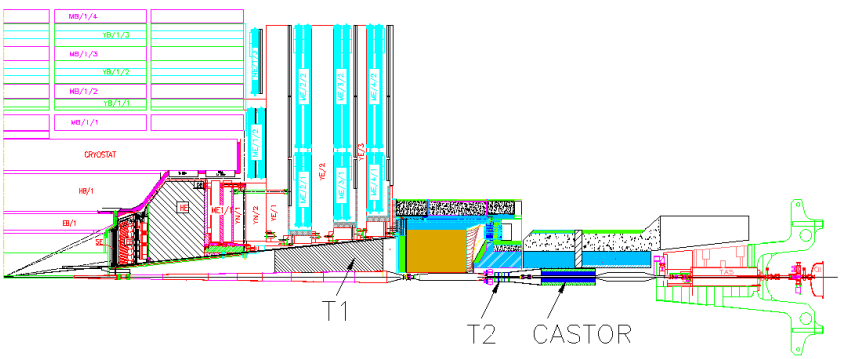

Figure 1. The CMS detector with the TOTEM forward trackers T1 and T2. Note also the planned forward calorimeter CASTOR (under CMS's responsibility).

The T1 telescopes on both sides of the interaction point will consist of five planes

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of Cathode Strip Chambers (CSC) covering the pseudorapidity range $3.1 < |\eta| < 4.7$. Each detector will measure three projections, rotated by 60^o with respect to each other: the two sets of cathode strips with a pitch of 5 mm will have an analogue read-out whereas the digital read-out of the anode wires with a pitch of 3 mm will provide trigger functionality.

For T2, extending the acceptance into the range $5.3 < |\eta| < 6.5$, the Gas Electron Multiplier (GEM) technology as used successfully in COMPASS [2] has been chosen. The read-out plane will have both pads ($\Delta\eta \times \Delta\phi = 0.06 \times 0.017\pi$) connected to digital VFAT chips for triggering, and circular strips with 400 μm pitch read out with the analogue APV25.

The Roman Pot detector system is optimised in view of measuring proton scattering angles down to a few μrad. The detector edges have to approach the beam to a distance of $10\,\sigma_{beam} + 0.5$ mm ≈ 1.3 mm. In order to minimise the dead space near the detector edge, TOTEM develops Silicon detectors with full efficiency up to less than 50 μm from their physical edge. Three approaches are under investigation: (1) the novel 3D detector technology with pillar-shaped electrodes processed through the Silicon bulk and active edges; (2) planar Silicon detectors with active n^+ doped edges; (3) planar Silicon detectors with a very narrow ($\sim 50\,\mu$m) current-terminating guard-ring structure. The electrode pitch is 66 μm resulting in a spatial resolution of about 20 μm per plane. For all three technologies first prototypes have been built and tested with X-rays or muon beams. The width of the efficiency transition from 10 % to 90 % was found to range between 15 μm (1) and 50 μm (3). Further muon beam tests, for the first time with final-sized detectors ($\sim 9\,\mathrm{cm}^2$) and close-to-final electronics will be performed in summer / autumn 2004.

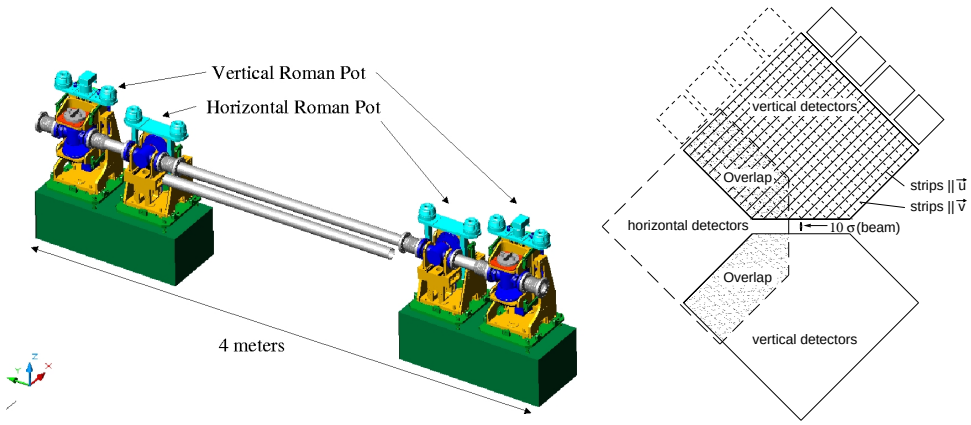

Figure 2. Left: Roman Pot station. Right: arrangement of the detectors in the two vertical and the one horizontal Roman Pots of a station.

Each Roman Pot station (Figure 2a) consists of two units with a distance of 4 m. Each unit has two vertical pots approaching the beam from the top and the bot-

tom, and one lateral pot sensitive to diffractive protons. Furthermore, the overlap between the horizontal and the vertical pots (Fig. 2b) will serve for measuring the relative distance of the vertical detectors. Each pot will contain 10 planes of Silicon detectors, 6 equipped with analogue APV25 read-out chips for precise tracking, and 4 equipped with digital VFAT chips providing trigger and tracking information.

2 Beam Optics and Running Scenarios

For the precise measurement of proton scattering angles on the few μrad level a special beam optics scheme with $\beta^* = 1540\,\mathrm{m}$ was developed. It is characterised by a small beam divergence in the interaction point ($0.29\,\mu$rad) and a focal point in the Roman Pot station at 220 m for both the horizontal (x) and the vertical (y) track projections. In order to avoid parasitical bunch crossings downstream of the nominal interaction point due to the parallelism and large width ($\sim 0.4\,\mathrm{mm}$) of the two beams, the number of bunches will be reduced from 2808 to initially 43 and later 156. Scenario 1 in Table 1 will serve for measuring the elastic cross-section at low $|t|$, the total cross-section, the absolute luminosity and soft diffraction. To minimize the emittance, these runs will be done with a smaller bunch population. Higher luminosities for (semi-) hard diffraction (scenarios 2 and 3) can be reached by increasing the number of bunches and the bunch population. The details of the optics for Scenario 3 are still under development. Scenario 4 was introduced for measuring elastic scattering at large $|t|$.

Running scenario	1	2		3	4
β^* [m]	1540	1540		200–400	18
Number of bunches	43	156		936	2808
Protons per bunch	$0.3 \cdot 10^{11}$	$0.6 \cdot 10^{11}$	$1.15 \cdot 10^{11}$	$1.15 \cdot 10^{11}$	$1.15 \cdot 10^{11}$
Transverse norm. emittance [μm rad]	1	1	3.75	3.75	3.75
beam size at IP [μm]	454	454	880	317–448	95
beam divergence at IP [μrad]	0.29	0.29	0.57	1.6–1.1	5.28
$\frac{1}{2}$ crossing angle [μrad]	0	0		100–200	160
$\mathcal{L}$ [$\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	$1.6 \cdot 10^{28}$	$2.4 \cdot 10^{29}$		$\sim 10^{31}$	$3.6 \cdot 10^{32}$

Table 1. TOTEM running scenarios.

While elastic scattering, the total cross-section and soft diffractive processes can be measured by TOTEM alone, hard diffraction will be studied together with CMS, i.e. TOTEM will technically act as a subdetector with level-1 trigger capability. The trigger signal from the Roman Pots at 220 m arrive at the CMS global trigger still within its latency time. With Roman Pots further away, level-1 triggering would not be possible.

TOTEM operation with normal LHC beam optics ($\beta^* = 0.5\,\mathrm{m}$) and $\mathcal{L} \geq 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ is under study but not yet part of the official TOTEM programme.

3 Physics Programme and Performance

3.1 Elastic Scattering

TOTEM will measure the elastic pp cross-section in a $|t|$-range from $2 \times 10^{-3}\,\mathrm{GeV}^2$ to $8\,\mathrm{GeV}^2$ (Figure 3, left). Since the acceptance for the $\beta^* = 1540\,\mathrm{m}$ optics ends at $2\,\mathrm{GeV}^2$ (Figure 3, right) and since at higher $|t|$ more luminosity is needed, the $\beta^* = 18\,\mathrm{m}$ optics was created to extend the range. Accessing the Coulomb and interference region at $|t| < 2 \times 10^{-3}\,\mathrm{GeV}^2$ will be attempted either by approaching the Roman Pot detectors closer than $10\,\sigma + 0.5\,\mathrm{mm}$ to the beam or by running the LHC with a reduced centre-of-mass energy $\leq 6\,\mathrm{TeV}$.

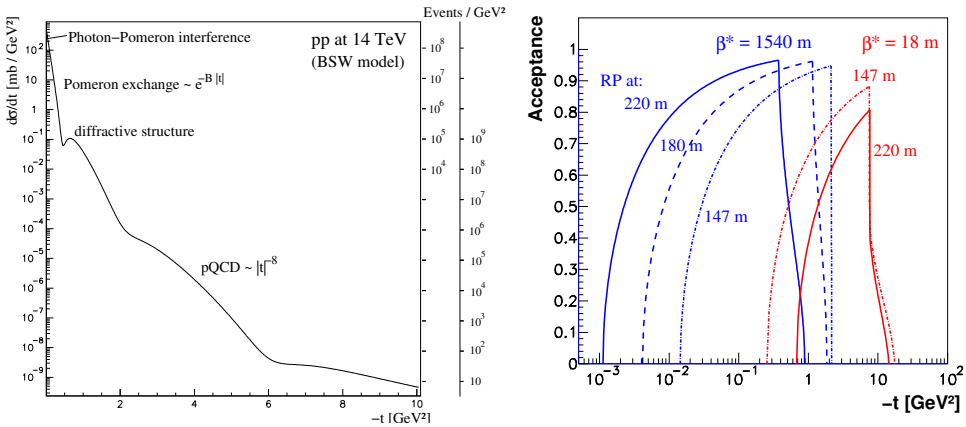

Figure 3. Left: elastic cross-section predicted by the BSW model [3]; the number of events on the right-hand scales correspond to integrated luminosities of 10^{33} and $10^{37}\,\mathrm{cm}^{-2}$ (about 1 day with Scenarios 1 and 4). Right: t-Acceptance for elastic scattering with the 1540 m and the 18 m optics and for the different Roman Pot stations.

The t-resolution achieved with the conditions of Scenario 1 and a detector resolution of $20\,\mu\mathrm{m}$ is $\sigma(t)/t \approx 7\,\%/\sqrt{t/0.002\,\mathrm{GeV}^2}$. Due to the parallel-to-point focussing at 220 m in both track projections, a good azimuthal resolution of $\sigma(\phi) \approx 50\,\mathrm{mrad}/\sqrt{t/0.002\,\mathrm{GeV}^2}$ is achieved, which helps reducing beam halo background by testing the collinearity of protons detected in the two opposite arms of the experiment. Furthermore, the measurement of ϕ can help determining the parity of exclusively produced particles.

3.2 Total pp Cross-Section and Luminosity

The total pp cross-section and the luminosity will be measured via the Optical Theorem and are given by

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

The extrapolation of the elastic cross-section to $t = 0$ suffers mainly from insufficient knowledge of the functional form and from uncertainties in beam energy, detector alignment and crossing angle. The expected systematic error is about 0.5 % whereas the statistical error is less than 0.1 % for only 10 hours of running. The uncertainty of the total rate ($N_{el} + N_{inel}$) is given by trigger losses and beam-gas background; it amounts to 0.8 %. Taking also into account the uncertainty in $\rho = 0.12 \pm 0.02$, σ_{tot} and the luminosity can be measured with about 1 % precision.

3.3 Diffraction

The acceptance for diffractive protons with the $\beta^* = 1540\,\mathrm{m}$ optics as a function of t and $\xi \equiv \Delta p/p$ is shown in Figure 4. For $|t| > 0.002$ all protons are detected independent of ξ. In addition, there is acceptance for protons with $0.02 \lesssim \xi \lesssim 0.2$ independent of t.

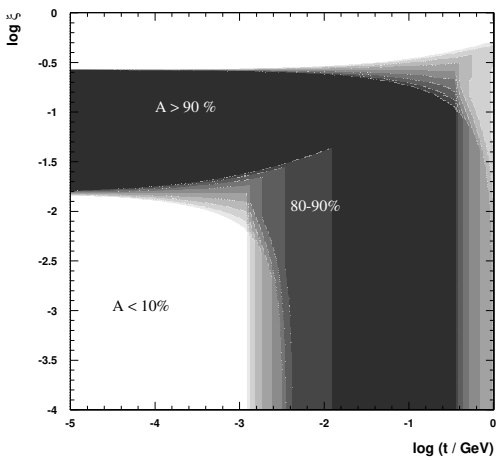

Figure 4. Acceptance for diffractive protons with the 1540 m optics in the RP station at 220 m.

Folding the acceptance with an assumed cross-section $\frac{d\sigma}{dt\,d\xi} \propto \frac{1}{\xi} \mathrm{e}^{-7|t|}$ yields a total acceptance of more than 90 %. The ξ resolution using the RP stations at 147 m and 220 m with the dipole D2 in between is 0.5 %. For the optics of Scenario 3, an improvement of a factor 5 will be attempted.

Table 2 shows the event rates of diffractive processes for the running scenarios 1 and 2.

Some examples for exclusive production by DPE are listed in Table 3 with their expected rates at three different luminosities.

Evidently, detecting a 120 GeV Higgs is hopeless at luminosities below $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, but other interesting processes are within reach even at low luminosity where the leading proton acceptance is very good.

At standard LHC running conditions ($\beta^* = 0.5\,\mathrm{m}$) and with Roman Pots at 220 m, the lower edge of the ξ acceptance of the Roman Pot trigger would be at

Process	Estimated cross-section	Rate at $\mathcal{L}\,[\mathrm{cm}^{-2}\mathrm{s}^{-1}] =$	
		1.6×10^{28}	2.4×10^{29}
Elastic scattering	30 mb	480 Hz	7.2 kHz
Single diffraction	14 mb	240 Hz	3.6 kHz
Double diffraction	7 mb	120 Hz	1.8 kHz
Double Pomeron Exchange	0.5 mb	8 Hz	120 Hz

Table 2. Diffractive Event rates.

X	σ	Decay channel	BR	Rate at $\mathcal{L}\,[\mathrm{cm}^{-2}\mathrm{s}^{-1}] =$		
				2.4×10^{29}	10^{31}	10^{33}
excl. Dijets ($E_T > 10$ GeV)	7 nb	jj	1	720 / h	10 / s	1000 / s
χ_{c0} (3.4 GeV)	3 μb	$\gamma J/\psi \to \gamma\mu^+\mu^-$	6×10^{-4}	1.5 / h	62 / h	6200 / h
		$\pi^+\pi^-K^+K^-$	0.018	46 / h	1900 / h	53 / s
χ_{b0} (9.9 GeV)	4 nb	$\gamma\Upsilon \to \gamma\mu^+\mu^-$	$\leq 10^{-3}$	≤ 0.07 / d	≤ 3 / d	≤ 300 / d
H (SM) (120 GeV)	3 fb	$b\bar{b}$	0.68	0.02 / y	1 / y	100 / y

Table 3. Examples of exclusive DPE processes (p + p $\to$ p + X + p). The rates do not account for any acceptance or analysis cuts. For cross-sections see e.g. [4].

0.025 corresponding to a diffractive mass of 350 GeV for exclusive production in the limit $\xi_1 = \xi_2$. Furthermore, the ξ resolution is only 0.001, corresponding to 14 GeV in the diffractive mass. Additional RP stations in the cryogenic LHC region (at 308 m, 338 m and 420 m) would bring the acceptance limit down to $\xi > 0.002$ and the resolution to $\sigma_\xi \gtrsim 0.0002$. Due to technical difficulties such stations are not forseen in the current LHC design but may be considered at a later stage after ruling out other possibilities (e.g. local optics modifications for an enhanced dispersion at 220 m).

References

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