EPJdirect C, **4**(S1), 13 (2002)
DOI 10.1007/s1010502cs113

EPJdirect
electronic only

Total cross section and luminosity

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Received: 25 Jan 2002 / Accepted: 25 Jan 2002 / Published online: 25 Sep 2002

Abstract. The measurement of the total cross section and of the machine luminosity is the first objective of the experiment TOTEM [1, 2]. The total cross section will be measured with the luminosity independent method based on the simultaneous measurement of low momentum transfer elastic scattering and of the rate of inelastic interactions with fully inclusive trigger. Elastic scattering events will be detected with the Roman pot technique using a suitable machine optics obtained by properly tuning the quadrupoles in the intersection region. The measurement of the total cross section will be followed in due course by the study of elastic scattering at large momentum transfer and of diffractive processes.

PACS: not given

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1 Introduction

The total cross sections for proton-proton and proton-antiproton collisions at high energy are shown in Fig. 1. Data on both pp and $\bar{p}p$ exist only up to the maximum energies of the ISR ($\sqrt{s} = 62$ GeV). At these energies the pp and $\bar{p}p$ cross sections tend to approach each other. At higher energies we have data only for $\bar{p}p$ (from the SPS and Fermilab Colliders) but results on pp collisions at $\sqrt{s} = 500$ GeV are soon expected from RHIC.

A question which has been debated for a long time is whether σ_{tot} increases as $\log s$ or $(\log s)^2$. The solid line in Fig. 1 represents the result of a dispersion relation fit [3] which is based on measurements of σ_{tot} and of the parameter ρ (ratio of the real to the imaginary part of the forward amplitude) in the c.m.s. energy interval $5 \leq \sqrt{s} \leq 546$ GeV. The high-energy dependence of the total cross section was described by the term $(\log s/s_0)^\gamma$ with $s_0 = 1$ GeV^2. The best fit gives $\gamma = 2.2 \pm 0.3$.

At $\sqrt{s} = 1.8$ TeV, the fit predicts a value of the total cross section which lies in between the two measurements reported from Fermilab. The results of the experimental group E710/E811 seem to favour a $\log s$ increase while the CDF data favours the $(\log s)^2$ dependence.

Some information in the very high energy region can be derived from the study of the interaction of primary cosmic rays in the atmosphere. However, the procedure used to extract the proton-nucleon cross section from the measured proton-air absorption probability is affected by large uncertainties.

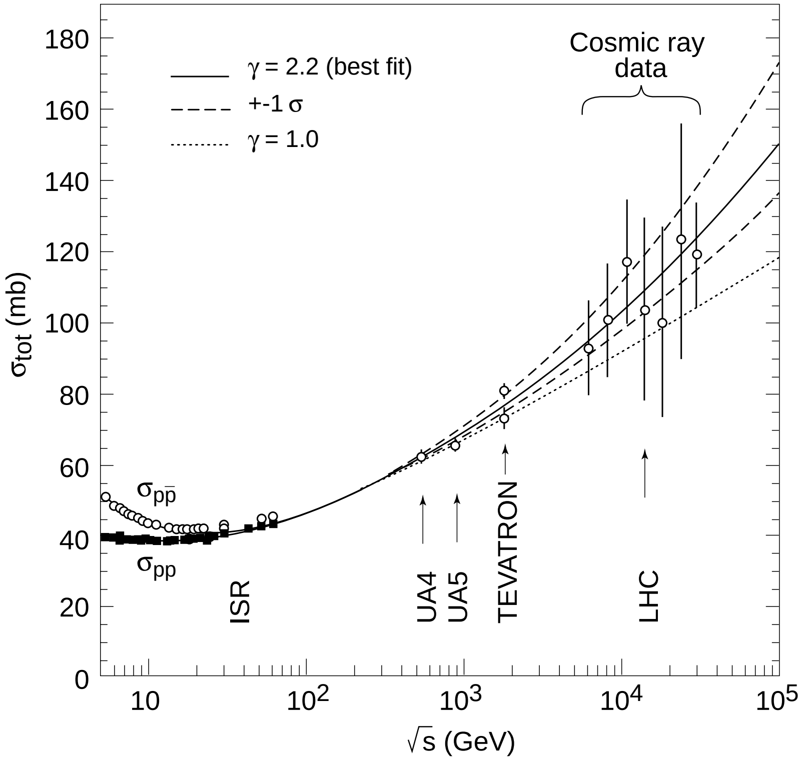

Fig. 1. The total cross section for $\bar{p}p$ and pp scattering is shown together with the prediction of the dispersion relations fit of ref.[3]. The high-energy behaviour is described by the term $(\log s)^{\gamma}$. The best fit (solid line) corresponds to γ =2.2. The region of uncertainty is delimited by the dashed lines. The result obtained with $\gamma = 1$ is shown as a dotted line

In spite of the large error on the parameter γ as derived from the best fit, the dispersion relations analysis clearly favours the $(\log s)^2$ dependence with respect to the linear rise as $\log s$. This behaviour has been often referred to as a "qualitative" saturation of the Froissart-Martin [4] bound in the sense that it corresponds to the maximum rate of rise with energy which is allowed by analyticity and unitarity, while numerically actual data lie much below the bound itself.

At the LHC energy, $\sqrt{s} = 14$ TeV, the fit predicts $\sigma_{tot} = 109 \pm 8$ mb while extrapolating as $\log s$, one would obtain $\sigma_{tot} \simeq 95$ mb, i.e. about 15 mb less than the $(\log s)^2$ extrapolation.

TOTEM is designed to measure the total cross section with accuracy at the level of 1 mb, which is clearly sufficient to discriminate between these two simple extrapolations and also to discriminate between the predictions of the current models which are in the interval from 100 to 130 mb.

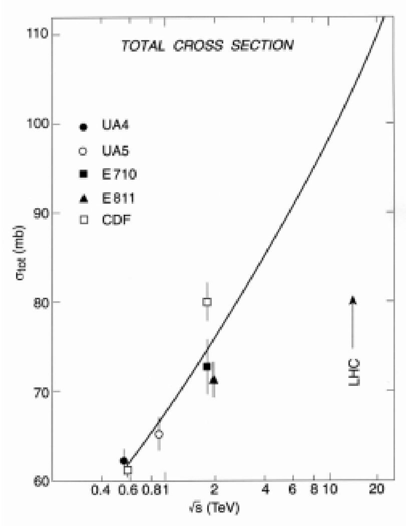

Fig. 2. Results on the $\bar{p}p$ total cross section at the highest energies. The line is the prediction of the impact picture

The total cross sections from the high energy hadron colliders are shown on an expanded scale in Fig. 2.

2 Measurement of the total cross section at the LHC

2.1 The experimental method

The best way to measure the total cross section is by means of the so called "luminosity independent" method. In fact if the machine luminosity is not known from other measurements, this is the only method of practical use. The total cross section and the integrated luminosity $\mathcal{L}$ of the machine are related by the equation

$$N_{el} + N_{inel} = \mathcal{L}\,\sigma_{tot} \tag{1}$$

where N_{el} and N_{inel} are the observed numbers of elastic and inelastic interactions, respectively.

The optical theorem which relates the total cross section to the imaginary part of the forward amplitude leads to the following equation.

$$\left(\frac{dN_{el}}{dt}\right)_{t=0} = \mathcal{L}\left(\frac{d\sigma}{dt}\right)_{t=0} = \mathcal{L}\,\frac{\sigma_{tot}^2(1+\rho^2)}{16\pi} \tag{2}$$

where$\left(\frac{dN_{el}}{dt}\right)_{t=0}$ is the elastic scattering t-distribution extrapolated to t=0.

Combining the two previous equations one may eliminate the machine luminosity and write the total cross section as a function of measurable quantities in the following way.

$$\sigma_{tot} = \frac{16\pi}{(1+\rho^2)} \frac{(dN_{el}/dt)_{t=0}}{N_{el}+N_{inel}} \quad (3)$$

This method is based on the *simultaneous measurement of elastic scattering at low t and of the inelastic interactions.*

The parameter ρ is small at high-energy, about $0.1 - 0.2$, so that it does not have to be known with high precision to get an accurate value of σ_{tot}.

The "luminosity independent method" was used at the ISR by the CERN-Pisa- Roma-Stony Brook collaboration, at the SPS Collider by UA4 and at the Fermilab Collider by E710/E811 and CDF.

2.2 Low-t elastic scattering

The elastic scattering t-distribution dN_{el}/dt is measured at small t using the Roman pot system and extrapolated to $t = 0$, i.e. to the "optical point", assuming the simple exponential dependence $e^{-B|t|}$ which is known to describe the data well in the very small t region. The measurement of elastic scattering at a high energy hadron collider requires observation of particles at very small angles (at the LHC, the typical angles are a small fraction of a *mrad*). In practice this is achieved by placing the detectors into special units mounted on the vacuum chamber of the accelerator, which have become known as "Roman pots" and were first used at the CERN ISR.

Hadron colliders are usually operated at high luminosity for the search of rare events. To obtain high luminosity, the transverse size of the beam at the crossing point is reduced by the focusing action of quadrupoles. As a consequence the angular divergence of the beams is correspondingly increased so that a large fraction of the scattered particles remain inside the acceptance of the machine itself and are not accessible to detection.

To measure elastic scattering, the opposite scheme is actually required. The beam size at the crossing point is made relatively large while the beam divergence becomes very small. Nearly parallel beams are normally used. This implies that the β-function at the crossing point has to be large. In fact it can be shown [1],[2] that the minimum detectable value of the momentum transfer is proportional to $1/\beta^*$. The corresponding loss of luminosity is not a problem because the differential cross section of elastic scattering is large at small t.

For a given value of β^*, the best arrangement is obtained when the machine optics corresponds to parallel-to-point focusing from the crossing point to the detectors. This has the very convenient property that measuring the particle position at the detectors allows the scattering angle to be reconstructed in a straightforward way.

2.3 The machine optics

The behaviour of the β functions for the actual high-β insertion designed for TOTEM with β^*= 1100 m is shown in Fig. 3. This optics is realized without adding new quadrupoles or displacing those already foreseen for the low-β mode. Existing quadrupoles are used with properly tuned values of the currents. The

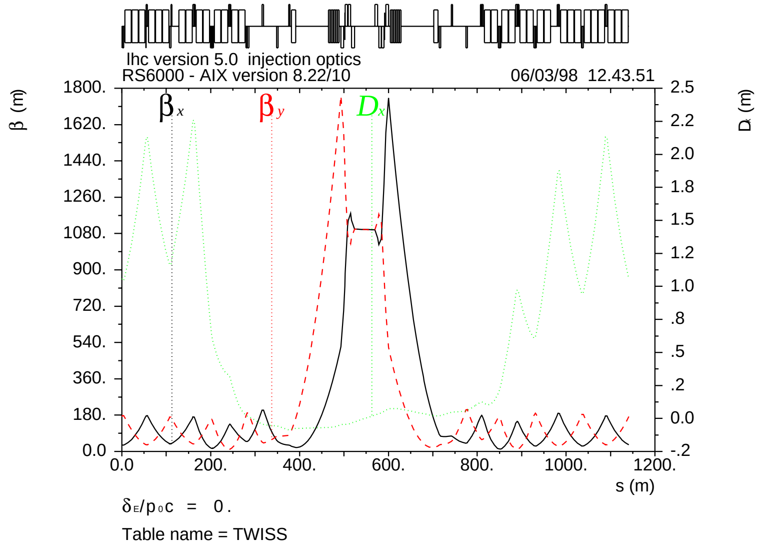

Fig. 3. The high-β insertion of TOTEM for the measurement of low-t elastic scattering. At the crossing $\beta^* = 1100$ m in both the horizontal and the vertical plane

quadrupole triplet Q1, Q2 and Q3, with focussing properties DFD in the vertical plane is adjusted to provide a parallel-to-point focus at a distance of 150 m from the crossing point. At this location the Roman pot station RP2 is placed.

The effective distances of these Roman pots from the crossing are

- $L^H_{eff} = 100$ m
- $L^V_{eff} = 148$ m

The layout is shown in Fig. 4. The detectors are placed in the long straight section of the accelerator symmetrically on both sides of the crossing point. Each station is a telescope of two Roman pot units. The telescope will not measure the direction of scattered protons with an accuracy sufficient for the determination of the scattering angle which is instead obtained from the position of the trajectory at the Roman pot telescopes and from the known values of the effective distances L_{eff}. Telescopes, however, are needed to reconstruct the position of the collision points on the transverse plane at the crossing. We know from our previous experience at the SPS collider that this is important to remove background due to beam-gas and beam-wall interactions.

The properties of the high-β optics with parallel-to-point focussing in the vertical plane are illustrated in Fig. 5. The trajectories of protons scattered in the vertical plane at an angle of 20 μrad (corresponding to $-t = 2{\times}10^{-2}$ GeV^2) are shown for two different vertical positions of the collision point, y*= 0 and

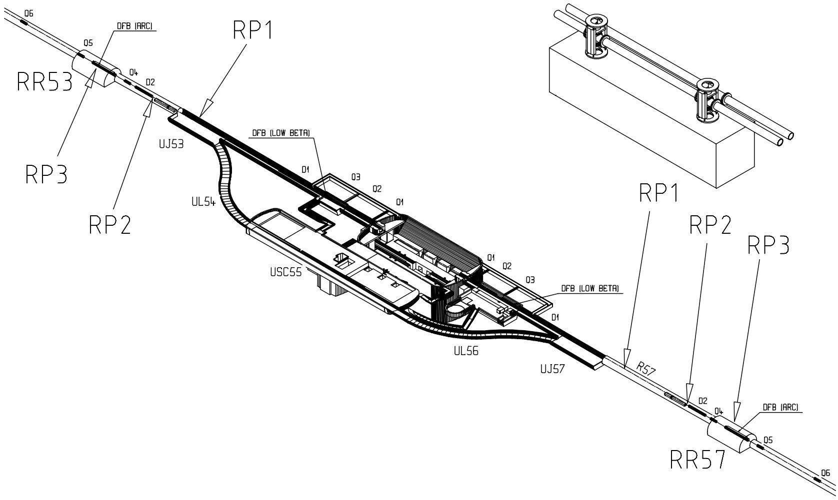

Fig. 4. Sketch of the installation of the Roman pot stations of TOTEM in the straight section 5 of the LHC. As shown on the upper right corner a station is a telescope of two Roman pot units. For low-t elastic scattering the station RP2 is used. The other stations are used for study of diffractive processes

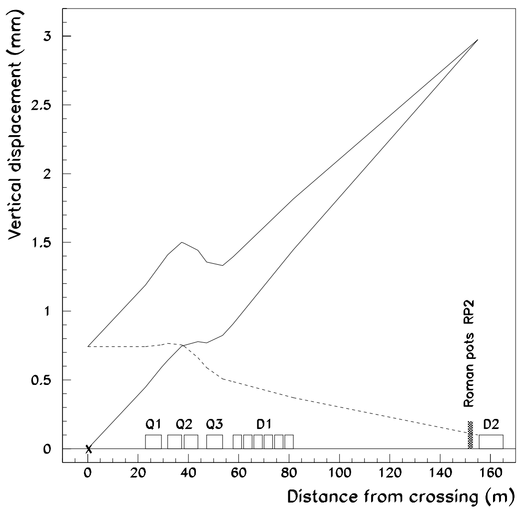

Fig. 5. Trajectories of protons scattered in the vertical plane at the same angle of 20 μrad, corresponding to $-t$=2x10^{-2} GeV^2 with two different vertical position of the collision point, y* equal to zero and to the r.m.s. value of 0.74 mm (full lines). The r.m.s. value σ_{beam} of the beam size is shown as a dashed line

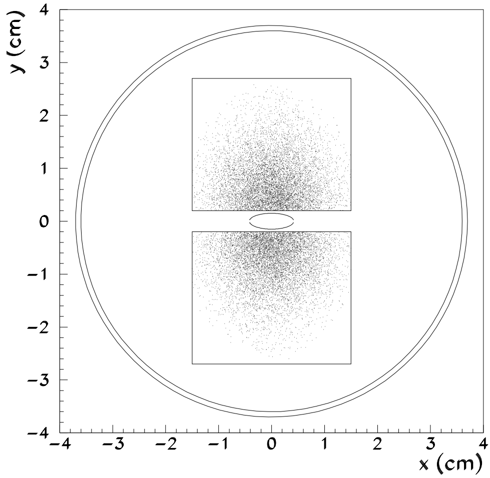

Fig. 6. Sketch of the geometry at the Roman pot detector. The ellipse represents the contour of $15\times\sigma_{beam}$. In the vertical plane $15\times\sigma_{beam} = 1.5$ mm. The edge of the detector is 0.5 mm farther away. The detector size is 3 cm horizontal $\times$ 2.5 cm vertical. The circle indicates the vacuum chamber

$y^*=\sigma_{beam}$. The two trajectories join at the Roman pot position, in front of the dipole D2, where the vertical size of the beam σ_{beam} (r.m.s. value) is equal to 0.1 mm. For the value of t considered, the displacement of the trajectories at the detectors is about 30 times larger than σ_{beam}.

Detailed calculations on the system of collimation foreseen for the LHC [5] have shown that the collimators will remove the halo of the beam at distances above $10\times\sigma_{beam}$. Therefore the value of $10\times\sigma_{beam}$= 1 mm is presumably a lower limit for the edge of the pot while $15\times\sigma_{beam}$= 1.5 mm should be a safe estimate. The window of the pot will be only 0.1 mm thick. The detectors located inside the Roman pot may not have full efficiency down to their physical edge. An inefficiency region of a few tenths of *millimeter* has to be foreseen.

We assume the detector to be efficient at 2.0 mm from the beam (corresponding to $15\times\sigma_{beam}$ + 0.5 mm). A sketch indicating the relevant geometrical parameters as the size of the beam, of the detectors (3.0 cm $\times$ 2.5 cm, horizontal $\times$ vertical) and of the vacuum chamber is given in Fig. 6 while the distribution of the hits on the detector for three values of the momentum transfer is shown in Fig. 7.

In Fig. 8 Monte Carlo calculation of the geometrical acceptance at the lower extreme of the t-range is shown. The minimum value of t where acceptance can still be used with confidence should be $-t \simeq 2\times10^{-2}$ GeV^2 or slightly smaller. The overall geometrical acceptance in the full t-range is shown in Fig. 9.

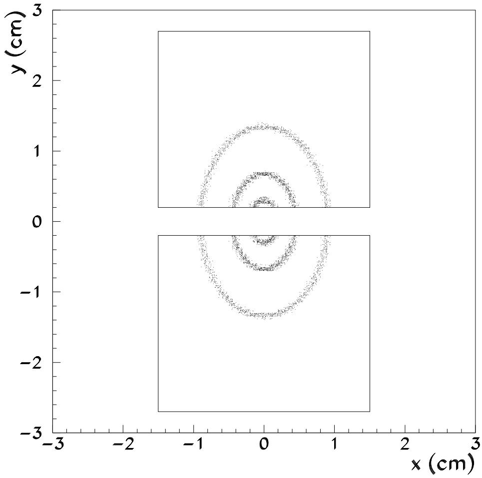

Fig. 7. Distribution of the impact points on the Roman pots for three different values of the momentum transfer, 0.02, 0.1 and 0.4 GeV^2 for the high-β optics

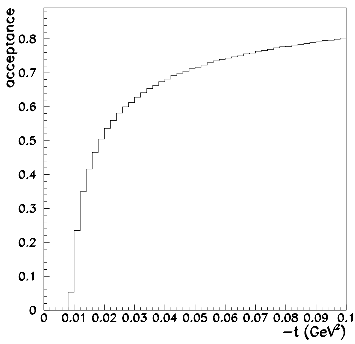

Fig. 8. The geometrical acceptance of the Roman pots station RP2 in the low-t region

For the high-β runs the expected luminosity [2] is around $\mathrm{L} = 10^{28}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. This corresponds to about 10^3 interactions/s out of which about 30% should be elastic events.

In our Technical Proposal beam size and angular divergence are calculated using the standard value of the normalized emittance, $\epsilon^* = 3.75\ \mu\mathrm{m}$. Most likely operation with transverse emittance reduced by a factor of 2 or 3 is possible for not too large beam densities. The consequence will be a reduction of the minimum value of t.

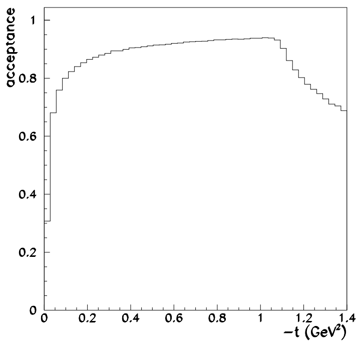

Fig. 9. The full geometrical acceptance of RP2 for the high-β optics

2.4 The Roman pot detectors

At present we are designing a mechanical system of conventional design on the basis of our previous experience at the ISR and at the SPS Collider and of recent work at the Tevatron and HERA. The basic requirement is to avoid interference with the machine vacuum. The sketch of the Roman pot unit shown in Fig. 10 is compatible with the presence of the other LHC beam and with space availability in the machine tunnel.

As a baseline for the present design of the actual Roman pot we consider the unit made at CERN which is shown in Fig. 11. The thin window is about 3 cm x 3 cm in size.

Silicon microstrip detectors are considered for use in the Roman pots. In this respect an important development is now going on at CERN for TOTEM on

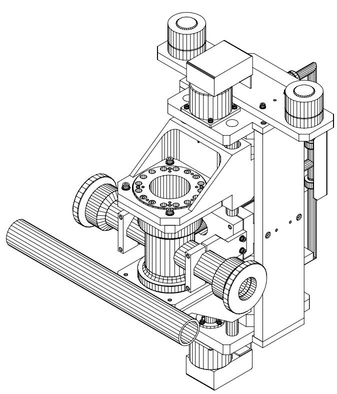

Fig. 10. Sketch of the mechanical support structure of the Roman pots of TOTEM. A short section of the two beam pipes 20 cm far apart is also visible

Fig. 11. Picture of a Roman pot made at CERN. This conventional design is taken as a baseline for the new Roman pots at the LHC

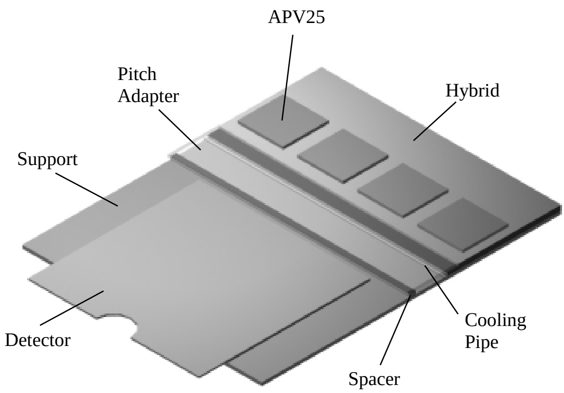

Fig. 12. The cryogenic silicon detector for the Roman pots of TOTEM. The detector (3 cm$\times$2.5 cm) has a semicircular indentation to favour a close approach to the beam

the design of cryogenic silicon detectors [6]. Operation of the detectors at low temperature, about 130 K, gives a strong reduction of the leakage current.

The advantages of this technique are quite important for TOTEM. Especially relevant are the much better resistance to radiation, the reduction of the edge surface current and therefore the possibility of having nearly edgeless detectors.

A sketch of the module is shown in Fig. 12.

2.5 The inelastic rate

The total number of inelastic events N_{inel} will be measured by the *inelastic detector* which fulfills two basic requirements.

- Provide a "fully inclusive" trigger, also called "minimum bias trigger".
- Reconstruct the collision vertex in order to disentangle beam-beam events from background.

The fraction of inelastic events escaping detection should be mantained at the 1% level.

Events of non single diffractive type (NSD) are observed by a double arm, left-right trigger which is normally rather clean, at least for stable machine operation. This trigger will also detect events of double diffraction dissociation.

On the other hand, detection of the events of single diffraction dissociation (SD) demands a single arm trigger which is generally affected by sizeable background.

The TOTEM detector is integrated with CMS in IP5 as shown in Fig. 13. The system is left-right symmetric with respect to the interaction point (IP). Each arm is splitted in two telescopes, T1 and T2 covering the pseudorapidity interval from 3 to 7. Information on the geometry of the two telescopes of the inelastic detector together with the expected charged particle multiplicity is reported in Table 1.

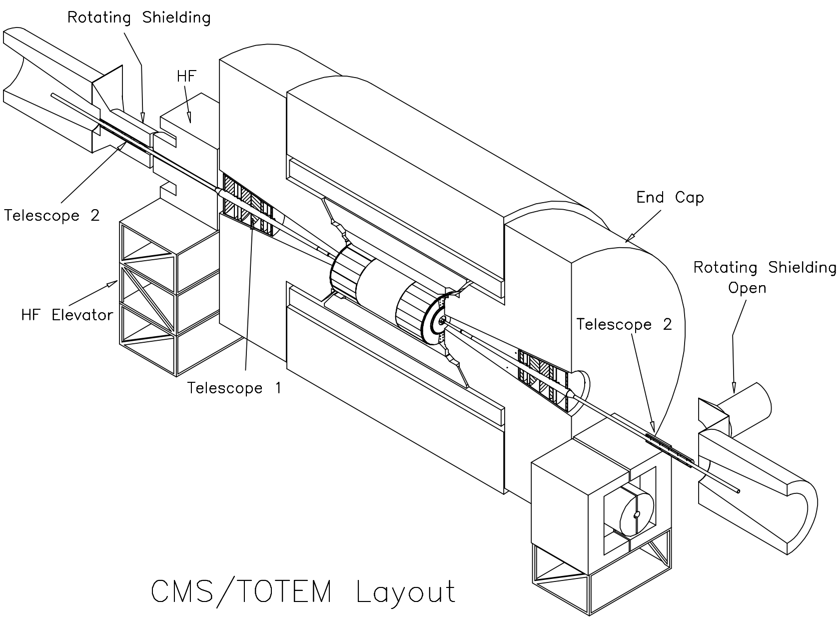

Fig. 13. The inelastic detectors T1 and T2 of TOTEM integrated with CMS

Table 1. Parameters of the inelastic detector of TOTEM

	T1	T2
Distance from IP	7.5 – 10.5 m	15 – 18 m
Pseudorapidity coverage	3 – 4.9	5 – 7
Polar angle coverage	15 – 100 mrad	1.8 – 13.5 mrad
$< n_{ch} >$	15	10

2.6 Trigger efficiency

In order to study the efficiency of the minimum bias trigger, a simulation of the inelastic events was done [7] using the standard program PYTHIA [8] with an appropriate tuning of the parameters which control the low-p_t particle production.

The procedure to measure the number of inelastic interactions, N_{inel}, is the following.

- Detection of practically all the NSD events using the **double arm trigger**. This is the main trigger of the experiment. It is expected to be rather clean and without any special complication on the reconstruction of the collision vertex because charged tracks at relatively large angles are observed on both hemispheres.

  A simple extrapolation of present data to the LHC energy indicates that the NSD events should correspond to a large fraction of the overall number of inelastic interactions, at least 85%.

- Use of the **single arm trigger** to detect a large fraction of the SD events. Obviously the single arm trigger will include the NSD events already seen by double arm trigger which have to be properly accounted for to avoid double counting. The single arm trigger is affected by background. Reconstruction of the collision vertex is also more difficult because, on the average, the tracks have smaller polar angles. However, this measurement is needed only for a relatively small fraction of the overall inelastic rate (about 15% or probably less).

The efficiency of the double arm trigger for NSD events is shown in Fig. 14 for the minimum requirement of one track on the left and one on the right hemisphere.

For the TOTEM acceptance, $\eta_{min} = 3$ and $\eta_{max} = 7$, the expected loss of the double arm trigger on NSD events is plotted in Fig. 15 as a function of the total number of charged tracks. The loss is less than 1% for two tracks and remains below 2% up to a total number of tracks equal to 6 which should be a confortablerequirement.

The fractional loss of the single arm trigger for SD events is shown in Fig. 16. For the TOTEM acceptance the loss is expected at the 10–15% level.

This simulation study indicates that TOTEM will be able to detect inelastic events with a loss at the level of 2–3%. Working on real data it should not be difficult to evaluate the actual loss by a Monte Carlo, properly tuned on the

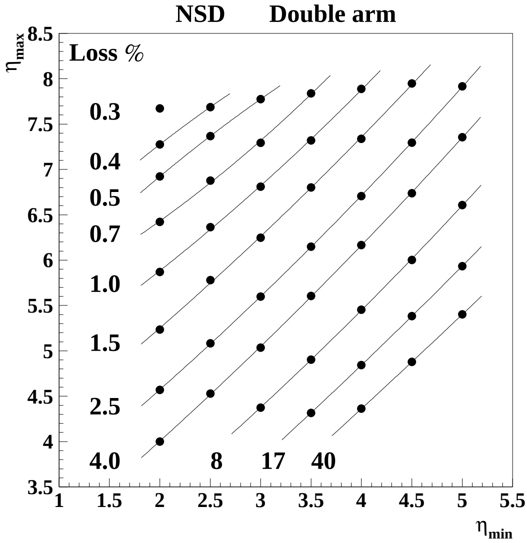

Fig. 14. Efficiency of the double arm trigger for NSD events. Lines of constant fractional loss are plotted in the η_{max} vs. η_{min} plane. At least one track is required in each hemisphere

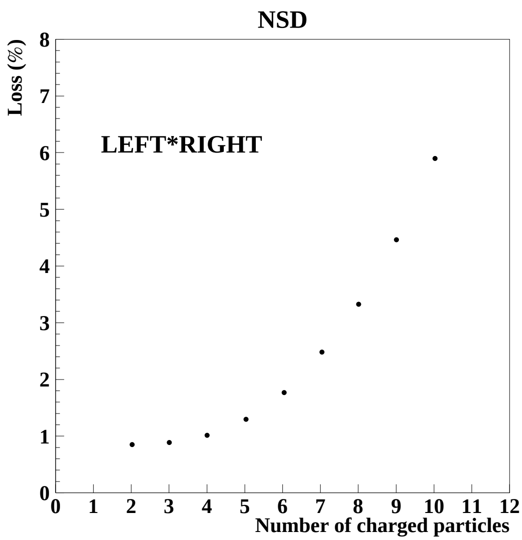

Fig. 15. The fractional loss of the TOTEM left-right trigger for NSD events is plotted as a function of the total number of observed tracks. The pseudorapidity interval is from $\eta_{min} = 3$ to $\eta_{max} = 7$

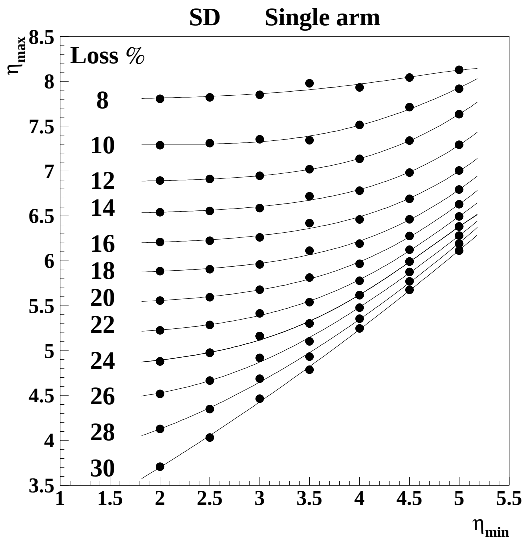

Fig. 16. The efficiency of the single-arm trigger for SD events. Lines of constant fractional loss are plotted in the η_{max} vs. η_{min} plane

data itself, in order to make a correction and remain with an error on N_{inel} at the 1% level.

2.7 The detectors

A telescope consists of 5 equally spaced planes of wire chambers with cathode strip read-out (CSC). Each chamber plane provides a point measurement of the particle track with accuracy of a fraction of mm. Extrapolation of the trajectories to the crossing allows reconstruction of the collision point with accuracy at the level of a cm.

Each CSC plane consists of 6 adjacent sectors with cathode strips inclined at 30^0. The geometry of the wires and cathode strips is shown in Fig. 17.

The CSC chambers telescope will be triggered by the coincidence of two Resistive Plate Chambers (RPC) which have a fast response, are insensitive to the stray magnetic field and are simple and inexpensive to build. Each chamber will be realized by two RPC monogaps with pad readout. The pads will have projective geometry to select the central region of the straight section.

The RPC chambers of the telescope T1 will be divided into 4 quadrants. A prototype of a quadrant is shown in Fig. 18. For this prototype the pad size is 4 cm $\times$ 4 cm.

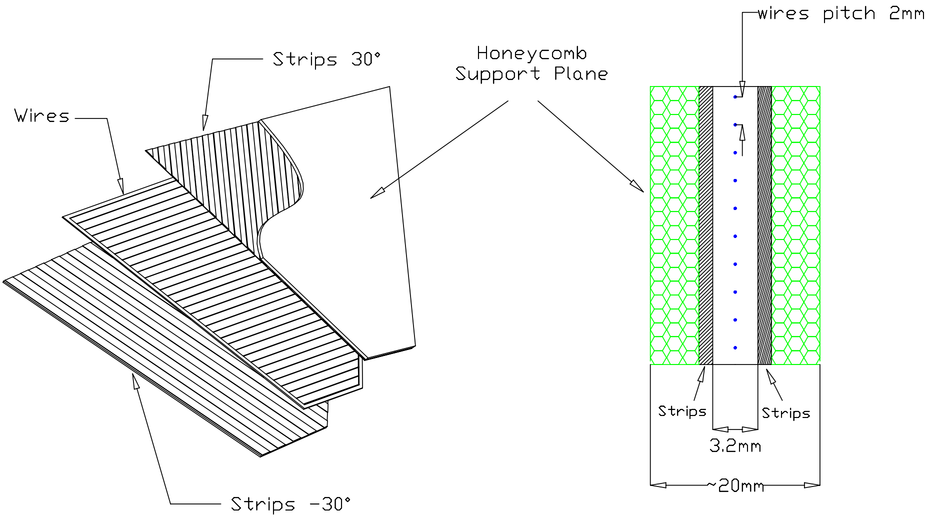

Fig. 17. Sketch of the Cathode Strip Chambers (CSC). Each plane is divided into 6 sectors with inclined cathode strips

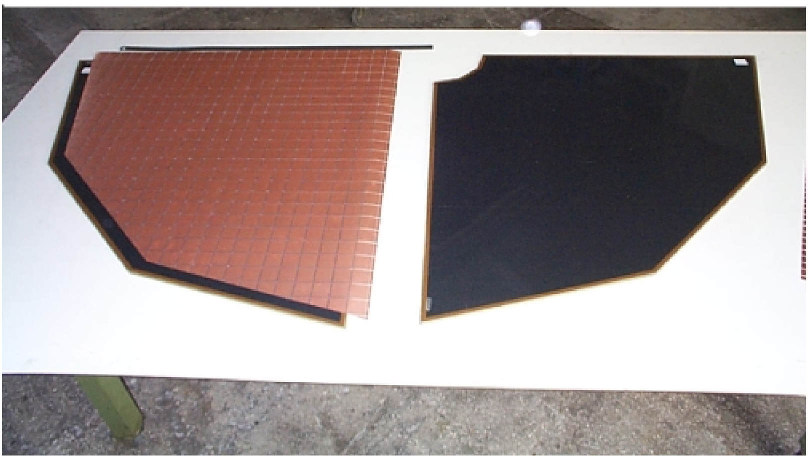

Fig. 18. Prototype of the RPC chamber for the telescope T1. A quadrant is shown together with the pad layout of the readout printed board plane

3 The machine luminosity

The absolute calibration of the machine luminosity is obtained in the high-β runs at the same time as the total cross section. In fact from Eqs. (1) and (2) one gets the integrated luminosity in terms of measurable quantities, the elastic t-distribution extrapolated to t=0 and the number of inelastic interactions.

$$\mathcal{L} = \frac{(1+\rho^2)}{16\pi} \frac{(N_{el}+N_{inel})^2}{(dN_{el}/dt)_{t=0}} \tag{4}$$

Once the basic requirement of negligible contamination from background events is satisfied, any appropriate combination of detectors of TOTEM and/or CMS can be used as Luminosity Monitor.

A simple and promising Monitor is given by the double arm (left-right coincidence) $\mathbf{T1}_L$ **x** $\mathbf{T1}_R$ which has high efficiency for NSD events (about 75% of N_{inel}) and should be scarcely affected by background.

Measuring the total number N_{Mon} of Monitor events (real beam-beam) in the high-β run allows deriving the *"effective"* Monitor cross section as follows,

$$\sigma_{Mon} = \sigma_{tot} \left[\frac{N_{Mon}}{N_{el}+N_{inel}} \right]$$

In fact this procedure corresponds to establish the *absolute calibration* of the Monitor.

Afterwards, in the normal LHC runs, the integrated machine luminosity will be obtained from the measured Monitor counts N_{Mon} according to the relation.

$$\mathcal{L} = \frac{N_{Mon}}{\sigma_{Mon}}$$

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