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The TOTEM project at LHC

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The TOTEM collaboration [1]

presented by M. Buénerd
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abstract:

The TOTEM (TOTal cross section and Elastic scattering Measurement) collaboration at the LHC aims at measuring the total, elastic scattering over a large range of 4-momentum transfer, and single diffractive scattering and double Pomeron exchange cross sections in proton-proton collisions at 10 to 14 TeV center of mass energies. The physics motivations are outlined, the beam optics requirements are presented together with a first solution for a dedicated insertion. The instrumental aspects are only quoted qualitatively.

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1 Introduction

The occurence of the new high energy collider LHC will open a new era for the study of diffractive physics. It may be hoped that a much better understanding of the collision dynamics will emerge from these future investigations and that answers will be provided to some of the fundamental issues raised by the last two or three decades of investigations of these phenomena: what mechanisms govern the elastic interaction at the various regimes of 4-momentum transfer, and does the total reaction cross section grow really as fast as permitted by the general principles ?.

The purpose of this contribution is to present the TOTEM project of measuring total, elastic scattering, and diffractive dissociation cross sections at the highest energy ever reached on a hadron accelerator, which could be carried on in a foreseable future. It will be shown on the basis of present experimental and theoretical context that major steps should be accomplished on the above issues by this experimental program. The program has already been outlined previously in reports [1, 2, 3].

In the first part of the presentation, the physics motivations of the project will be outlined whereas the second part will be devoted to a discussion of the beam features required by the necessary experimental accuracy. The instrumental aspects will be quoted only very qualitatively on account of the very early stage of their design.

2 Physics motivations

The Physics interest for high energy elastic scattering studies with the new generation of colliders has already been discussed on several opportunities [4, 5]. A summary of some founding arguments will be presented here together with some aspects more specific to the present project.

Total and differential cross section - The current status of the experimental pp total cross section σ_{tot} is shown on figure 1. The superimposed solid curve results from a dispersion relation analysis to the available data in which both the experimental σ_{tot} and ρ parameter values have been used to constrain the parameters of the dispersion relation formula [6]

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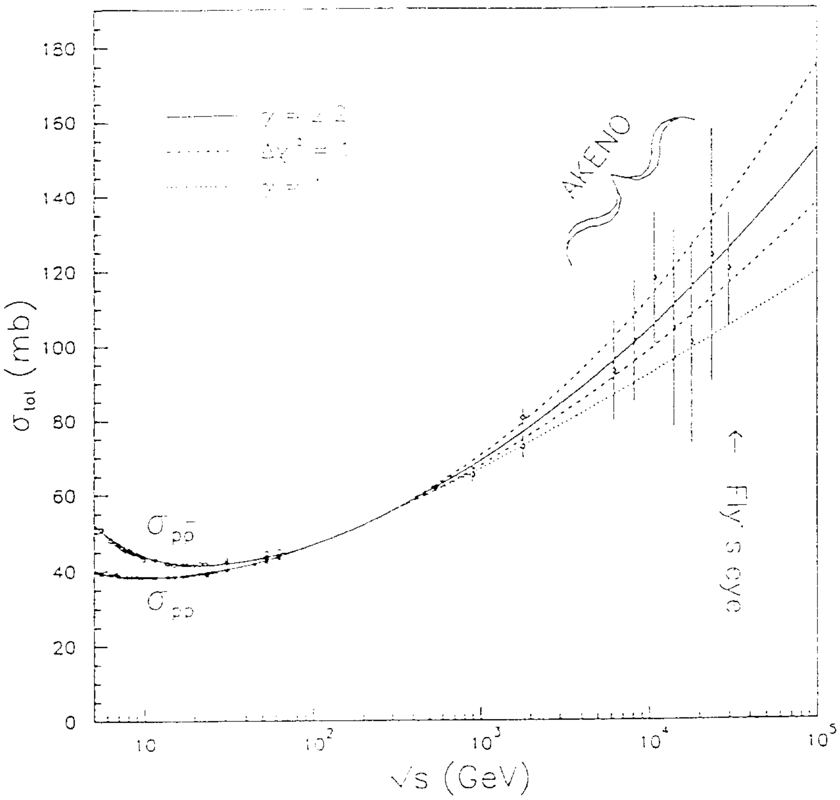

Figure 1: *Center of mass energy dependence of the total pp cross section (see ref [6] for the origin of the data).*

over the c.m. energy range $5 \leq \sqrt{s} \leq 546$ GeV. The resulting asymptotic dependence found for the total cross section is $\sigma_{tot} \approx [log(s/s_0)]^{2.2\pm0.3}$, i.e., close to the Froissart bound. The dashed lines correspond to one standard deviation on the χ^2 value (varying the asymptotic exponent) and the dotted line corresponds to the $(log\, s)$ dependence of the cross section. The extrapolated values of σ_{tot} at the phase 1 ($\sqrt{s}$ = 10 GeV) and phase 2 ($\sqrt{s}$ = 14 GeV) LHC energies are 103±7 mb and 112±10 mb respectively. If one assumes an experimental accuracy of say, 1 to 2 % based on the recent results from UA4 [8], and CDF [9] (see below), then it appears that the already favored $(log\, s)^2$ dependence of σ_{tot} should be unambiguously established or definitively contradicted by the new measurements since a $(log\, s)$ dependence would imply $\sigma_{tot} \approx 95$ mb at 14 TeV.

The ratio of the real to the imaginary part of the forward scattering amplitude $F(t)$, $\rho = \mathcal{R}e\{F(0)\}/\mathcal{I}m\{F(0)\}$, is also a quantity of major interest, mainly because of its close relationship with the energy integrated inelasticty of the collision via the dispersion relation [6] (see also [7]). It is in principle accessible to measurement at the LHC energies. The kinematical range to be covered corresponds to the Coulomb-nuclear interference (CNI) region centered at $|t_0| \approx 8\pi\alpha/\sigma_{tot}$, or $0.071/\sigma_{tot}$(mb), where the cross section is most sensitive to the interference term [10]. The expected $|t_0|$ value at the LHC can then be estimated to about $7 \cdot 10^{-4}$ (GeV/c)^2 which sets the scattering angles to be measured around 4-5 μrad for 10-14 TeV protons. The feasibility of cross section measurements at such extremely small angles critically depends on the beam optics and on the detection technique. It will be further discussed below. Note however that it had been considered at the SSC [11].

The motivations for measuring the elastic scattering cross section, would they need to be justified, can be leaned on arguments all dealing with the energy dependence of the cross section, over the full t range.

At very small angles ($-t \leq 0.5$ (GeV/c)^2), the investigation of cross section is most important because of the σ_{tot} determination that can be obtained from the extrapolation of $\frac{d\sigma(t)}{dt}$ to the optical point ($t=0$). Practically, the smallest possible t (above the CNI region) value has to be reached in order to minimize the extrapolation error. The shape of the forward cross section has an approximately exponential slope $\frac{d\sigma(t)}{dt} \approx e^{Bt}$ which parameter increases with energy (shrinking phenomenon). At LHC energies the value of B is expected to be around 20 GeV^{-2}. Assuming $|t_{min}| \approx 10^{-2}$ (GeV/c)^2 would imply an extrapolation of the cross section by about 20% and should allow an estimated uncertainty of 2% on σ_{tot}.

The shape of the cross section is in fact slightly concave at the ISR and SPS energies [12]. This curvature has disappeared at the Tevatron energy [13, 14]. This feature occurs naturally in the impact parameter approach of the scattering amplitude [15] which predicts the shape to become convexe at the LHC energies.

A sensitive testground for theories is provided by the difference observed between pp and $p\overline{p}$ cross sections in the region of the minimum where the current ideas on the interaction dynamics have been tested. On this long standing problem, the approach of refs [17, 18] incorporating $\mathcal{P} + \mathcal{P} \oplus \mathcal{P}$ and 3 gluon exchange contributions (see also [22]) provides an explanation to the observed differences. It competes with a similar success of the impact picture [15, 19], originating from the high energy QED based approach of [20] (see also [21]).

Measurements at the LHC energies, in the region of the minimum and second maximum of the angular distribution which, together with the large momentum cross section, is the most sensitive to the exchange mechanism, should bring some new elements in the long standing discussion about the nature of the minimum: does it arise from the interference between the Regge-type one Pomeron and two Pomeron exchange amplitudes [17, 22, 23], or is it a purely diffractive minimum occuring from the absorptive properties of the scattering system [24] ?.

Beyond the second maximum of the angular distribution, i.e., for t transfers larger than about 3-4 (GeV/c)^2, the interaction dynamics approaches and enters progressively into the domain of Perturbative Quantum Chromo Dynamics (PQCD), where the 3 gluon exchange (ggg) multiple scattering interaction amplitude has been shown to account for the empirical t^{-8} dependence of the differential cross section [25]. The experimental pp and $p\overline{p}$ cross sections at the ISR energies and above, decrease continuously [33] accross this t-range. At the LHC energies, a similar behaviour of the large t cross section is expected if the interaction is to be governed by the ggg exchange amplitude.

This is to be contrasted with the results of both the impact picture approach of [15] and the recent Regge type analysis of [26] which predict an oscillating cross section with secondary minima and maxima at LHC energies (fig 2). Note that the predictions of these two calculations are different however. The cross section at large t values for 10-14 TeV is therefore likely to contain a unique information on the semi-hard scattering dynamics.

The count rate at large t values can be estimated, assuming a conservative luminosity of 10^{31} cm^{-2}s^{-1}, about 10 times below the expected value, and using the values of cross section given in the figure [26], to around 50 counts per day in a 1 (GeV/c)^2 bin at $t=5$ (GeV/c)^2 at 14 TeV. Clearly the nominal luminosity of the LHC should allow to achieve significant measurements up to about 8-10 (GeV/c)^2.

Inelastic Processes - The third part of the physics program of TOTEM beside the σ_{tot} and $\frac{d\sigma(t)}{dt}$ elastic scattering measurement, deals with the inelastic diffractive cross section, namely the single diffractive dissociation cross section (SDD) in which one of the two colliding protons dissociates $pp \rightarrow pX$. These measurements will be performed with a dedicated instrumentation as described further below. It is also hoped to do measurements

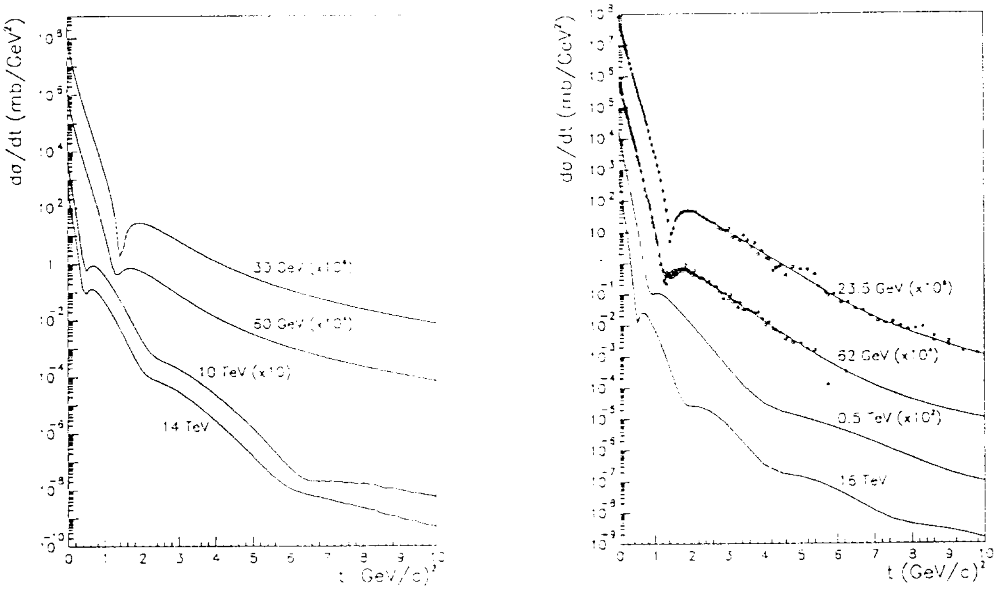

Figure 2: *Theoretical pp cross sections from the ISR to the LHC energies, from refs [15,16] (left) and [26,27] (right).*

of the double Pomeron exchange cross section ($pp \to ppX$) with the same set up as for the elastic scattering measurements.

The Single Diffractive Dissociation cross section at colliders energies represents a quite significant part of the total pp and $p\bar{p}$ total cross sections which amounts to approximately 10-20% of σ_{tot} at collider energies [12]. The SDD cross section measured by UA4 [28] and recently by CDF [29] is clearly growing with the cm energy. It is however increasing slower than σ_{tot}, so that the ratio σ_{SD}/σ_{tot} decreases by about 30-40% over the range extending from the ISR energies up to the Tevatron. This is shown on figure 3.

The dynamics of the SDD process has been discussed at this meeting by K. Goulianos (see also [30]. A measurement of the SDD cross section at the LHC is highly desirable since it should clearly bring a most significant information on the energy dependence of the process.

The other important feature about the SDD process to be investigated is the mass dependence of the double differential cross section $\frac{d\sigma(t)}{dt dM^2}$. At energies up to the SPS a $1/M_x^2$ dependence is observed [28] (see ref [29] however). It is interpreted in terms of triple $\mathcal{P}$ exchange [30]. An upper limit to the mass range accessible is set on the basis of elementary quantum mechanical arguments [30, 31] (see also [32]) leading to the coherence condition:

$$\frac{M_x^2 - M_p^2}{s} \leq \frac{m_\pi}{M_p} \approx 0.15 \tag{1}$$

The mass range is thus proportional to the cm energy. At the LHC, the mass range set by the coherence condition is about 4 TeV and it should thus be possible to investigate the difractive peak over about 7 orders of magnitude ! (fig 4). Extrapolating the experimental cross section from [28] to the upper mass limit and assuming a $1/M_x^2$ dependence leads to an estimate of the count rate to be expected at the upper limit of the mass range (lower range of cross section). A luminosity of 10^{32}cm^{-2}s^{-1} will be required for a rate around 5

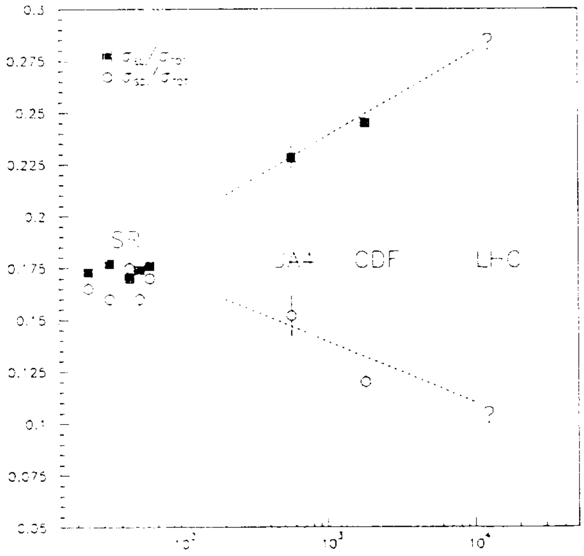

Figure 3: *Energy dependence of* σ_{el}/σ_{tot} *and* σ_{SD}/σ_{tot} *from refs [12,13].*

events per day in $\delta M \approx 1$ TeV and $\delta t \approx 0.05$ (GeV/c)^2 mass and t bins respectively, and for an azimuthal coverage $\Delta\phi/2\pi \approx 0.5$ (figure 4).

Practically, single diffractive events will be tagged with both the recoil proton from the interaction in one arm, and the fragmentation products in the opposite arm. The diffractive mass will be measured measured from the recoil proton momentum measurement by exploiting the dispersive properties of the beam line of the LHC (in the horizontal plane).

The investigation of the double $\mathcal{P}$ exchange process is also part of the measurements planned by TOTEM with the purpose of investigating the structure of the $\mathcal{P}$ in a way complementary to that of lepton scattering (this Conference proceedings).

3 The experimental method

The general experimental method has been already used in most collider experiments [13, 33, 34] and the same basic techniques will be applied in TOTEM. However, the design of the experiment is confronted to some new challenges mainly because of some required features, demanding detector performances at the limit or even beyond those currently available. The measurements need only a very narrow angular range to be covered, typically less than 1 mrad. The scattered particles will have then to be detected very close to beam particles and their angle measured with respect to the projectile direction. This can be achieved only by resorting to special beam optics requiring a dedicated insertion, and to the "Roman Pots" technique [12].

The parallel-to-point focussing method used to this purpose consists of building highly parallel beams in the crossing region (CR) and focus at a tranverse distance y from the beam axis all particles scattered at an angle θ according to $y = L_{eff}\theta$, where L_{eff} is called the effective length defined by the insertion optics in the focal plane of the system (it is the M_{12} element of the transfer matrix of the transport line [35] between CR and detectors). The mean radial and angular spreads are given by [35, 1] $\sigma_y = \sqrt{\epsilon\beta}$ and $\sigma_\theta = \sqrt{\epsilon/\beta}$, ϵ

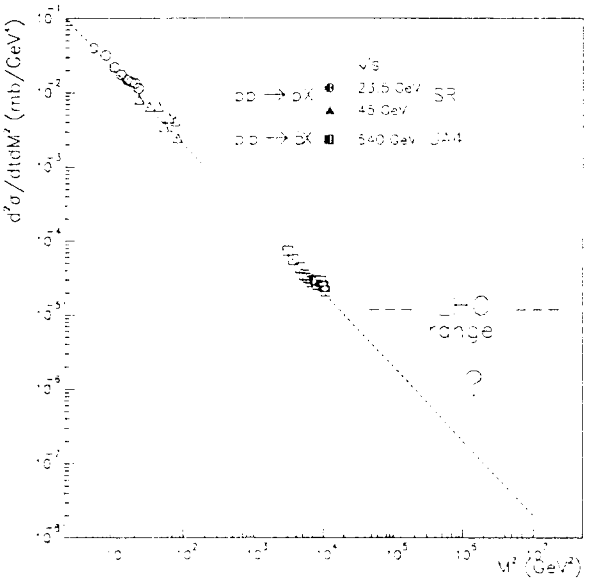

Figure 4: *Experimental double differential cross section for diffractive dissociation measured at 0.05 (GeV/c)^2, as a function of of the square excited mass M_x showing the $1/M_x^2$ dependence (see ref [28]).*

being the beam emittance and β the betatron function at the considered location along the beam line. The decrease of the nominal collider luminosity occuring from the transversly extended colliding beams at crossing is compensated by the very large cross-section at the very small t values to be measured.

For some given optics, the accessible t range is limited on the large-t side by the maximum measurable angle set by the beam pipe diameter. On the low-t side the minimum angle is set by the minimum distance of approach to the beam. The latter of course, critically depends on the beam halo and is then difficult to predict on sound grounds. However, it is known to be empirically proportionnal to the beam size at the detector, i.e., $y_{min} = K \cdot \sigma_y$ [1]. A value of K=20 is considered as safe, although lower values have been considered in some projects [11].

Beam requirements - As quoted previously, the angular range corresponding to the CNI region extends around $\theta_{CNI} \approx 4$ μrad. For the expected beam emittance of $4 \cdot 10^{-10}$m·rad at 7 TeV, the beam divergence should be such that at the minimum scattering angle the resolution on t would be acceptable, of the order of say, 10% (see below). This requires a very high value of the betatron function, of the order of 30000 m, which constitutes a challenge very difficult to meet for the beam optics.

Considering the t range above these frontier values, two optics have been studied which meet to an acceptable extent the experimental requirements. One is a high β insertion for measurements in the diffractive region, the other aims at covering the large t range with a medium β (tunable) settings. Although these optics have to be worked on yet, they provide some first grounds to elaborate the project.

The upper Figure 5 shows a sketch of the optical configuration found in a preliminary study of the high β insertion for measurements at very small t values [36]. The locations of the detector elements are also shown on the figure. The Roman pots would be placed at about 230 m each side of the crossing. The forward vertex detectors for total cross

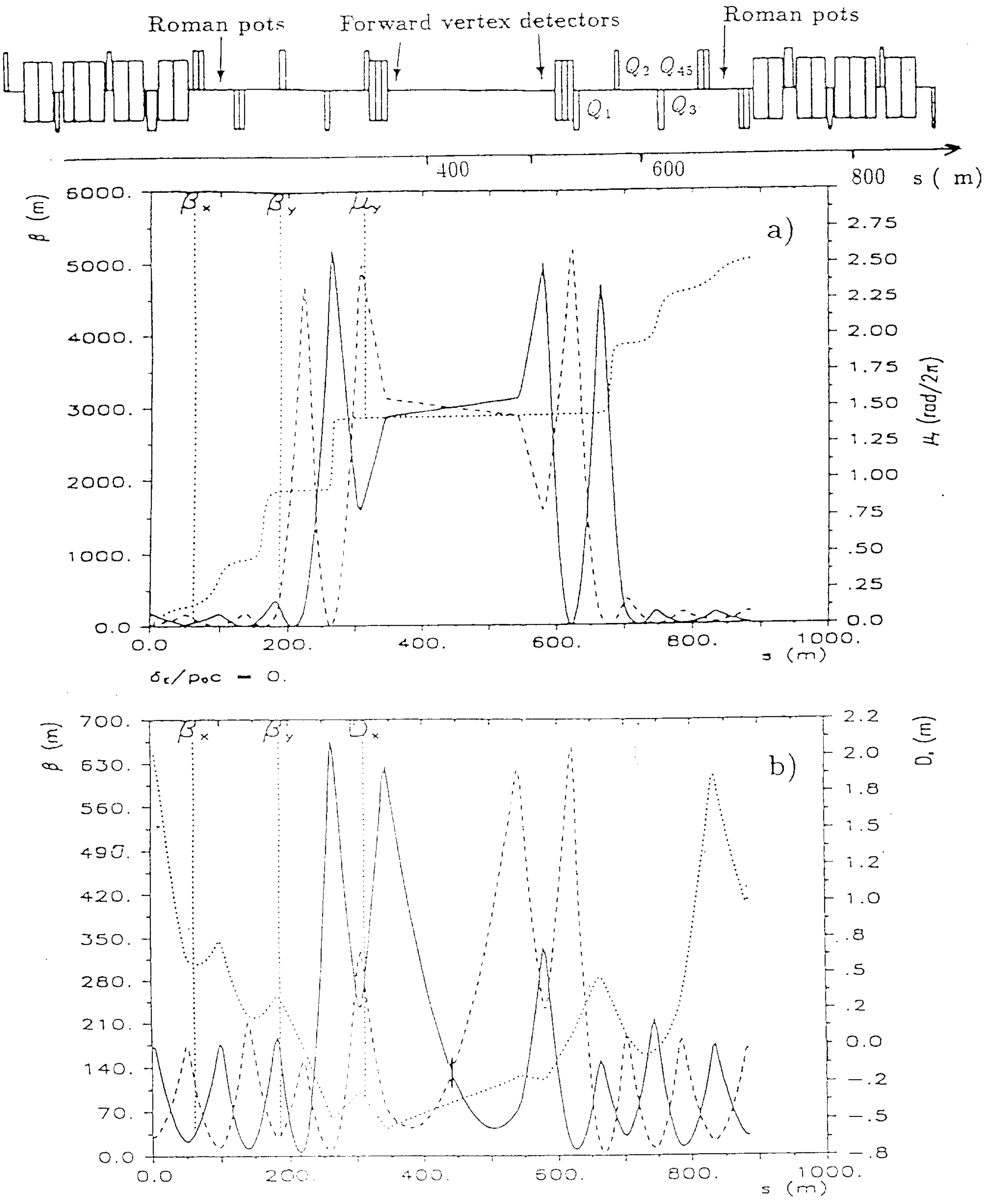

Figure 5: Top: Schematic representation of the high β insertion with indication of detector locations. a) Betatron functions in H (solid line) and V (dashed line) planes (the dotted curve is the relative phase $\Delta\Psi$) for the High β solution. b) Betatron functions for intermediate β solution with the same insertion. from ref [36]. The dotted line is the dispersion function.

section and single diffractive dissociation measurements would be installed at each end of the straight section, in front of the sets of separating dipoles.

figure 5a shows the corresponding betatron functions along the insertion. The value of $\beta^* \approx 3000$ m at crossing matches the experimental requirements for small t measurements. The corresponding beam divergence and transverse size are $\sigma_\theta{}^* \approx 0.4$ μrad and $\sigma_y{}^* \approx 1$ mm respectively whereas at the Roman pot location in the focal plane, $\beta \approx 1.5$ m, $\sigma_\theta \approx 16$ μrad and $\sigma_y \approx 25$ μm.

With these parameters the t range limits at 10 TeV would be $t_{min} \approx 1.6\ 10^{-3}(\mathrm{GeV/c})^2$ for K=20. However, the corresponding value of $y_{min} \approx 0.5$ mm ($y_{min} = L_{eff} \cdot \theta_{min}$, $t_{min} \approx (p\theta_{min})^2$) is probably too small for measurements at such a small distance from the beam to be considered as realistic. It would raise severe technical problems for the detector design. Taking a more conservative value $y_{min} \approx 2$ mm would set $t_{min} \approx 2\ 10^{-2}(\mathrm{GeV/c})^2$, which should be considered as a more likely limit, not close enough however to the critical value for an accurate extrapolation to the optical point. These figures for y_{min} show that the small value of β at the detectors implies a too small effective length ($L_{eff} = \sqrt{\beta\beta^*}$ at $sin\Delta\Psi=1$ [1, 35]) of about 65 m. A convenient value of L_{eff} would sit around 200 m. The upper limit would be $t_{max} \approx 0.35$ $(\mathrm{GeV/c})^2$. These figures are just doubled at 14 TeV. The upper limit t_{max} of the t range is found to be fine for both energies since it would allow to cover a sound part of the forward peak of the cross section. This limit is due to the beam size reaching the beam pipe diameter in the quadrupole Q3 on the figure.

The beam size at the detectors fixes the spatial resolution required for the latter to $\delta y \approx 25$ μm. Such a performance is currently achievable with microstrip type detectors although some specific technical problems will have to be solved for a dedicated counter.

The 4-momentum transfer resolution is fixed by the beam divergence at crossing. It is given the angular accuracy according to, $\frac{\delta t}{t} = 2p_0 \frac{\delta\theta}{\sqrt{-t}}$ which gives, with the numbers quoted previously, $[\frac{\delta t}{t}]_{t_{min}} \approx 0.1$, an acceptable value, improving with increasing t.

Further studies of the high β insertion are being conducted at CERN and Grenoble, and promising progress have been made recently, while this report was written, on the high β optics to meet the requirements discussed above [37]. The measurement at large t values will require medium-low tunable β optics ($\beta \approx 10$ m). A possible solution is shown on fig 5b with the same insertion which would then have to be only retuned for the large t range measurements.

Total cross section and Single Diffractive scattering - The measurement of the total cross section by the luminosity independent method will require a) the simultaneous measurement of the elastic and inelastic rates which will provide the determination of the elastic and total reaction cross section, and b) the extrapolation of the elastic cross section to the optical point (see for example [3]). It is given by the relation:

$$\sigma_{tot} = \frac{16\pi}{1+\rho^2} \frac{[dR_{el}/dt]_{t=0}}{R_{el}+R_{in}} \tag{2}$$

in $(\hbar c)^2$ units, where R_{el} and R_{in} are the elastic and inelastic rates respectively.

The measurement of the total inelastic rate will require a maximum angular coverage for the detection of inelastic events and a discrimination against sources of background arising from beam-gas and beam-wall interactions. To this purpose a detector similar to those used in previous similar measurements ref [9, 28, 38] with tracking capability good enough to reject events from outside the interaction region will be used. The diffractive clusters produced are spread kinematically over a range of rapidity $\pm ln(M_x/m)$ (m proton mass), centered around $\overline{\eta} \approx ln\sqrt{s}/M_x)$. A coverage of 3 units of pseudo-rapidity in kinematical range below $\eta_{max} \approx y_{beam} - 1$ i.e., between $\eta \approx$5.8 and $\eta \approx$8.8 at 14 TeV, should allow to extrapolate to the full inelastic cross section to within about a few percents [2, 29]. This corresponds to an angular coverage of 0.3 to 6 mrad of the proton dissociation products.

The diffractive mass range of interest extends from $M_x \approx 2\ GeV$, above the nucleon resonances, up to the limit set by the coherence condition, i.e., about 4 TeV. Practically, the size and natural momentum spread of the beam ($[\Delta P/P_0)]_{beam} \approx 10^{-4}$) will limit the lower mass accessible to the recoil proton spectrometer to about 0.3 TeV and the beam pipe diameter will set the upper limit to $M_x \approx$1.2 TeV. A way is being searched to push up this latter limit. The mass resolution would decrease from 10% in the low mass range down to 0.6% for the highest mass.

The limits of the rapidity coverage corresponding to the mass limits set by the recoil proton spectrometer mentioned above are $\eta_{min} \approx$2. and $\eta_{max} \approx$3.5.

Position measurements of the recoil proton will be performed by (at least) two detector stations. The proton momentum and angle will be calculated from the measured impact coordinates at the stations located along the beam line at positions allowing the best accuracy on momentum measurement [2, 11, 29, 39], and from the transfer matrix of the line. They will be used to calculate the Feynman scaling variable $x = p/p_0$, the diffractive mass $M_x^2 = (1-x)s$, and the 4-momentum transfer $t = -m^2(1-x)^2/x - 2p_0^2 x(1 - cos\theta)$, m being the proton mass.

For Double $\mathcal{P}$exchange measurements, two recoil protons, each having the properties of the recoil proton in SDD measurements, have to be detected and their momentum and scattering angles measured. This will be performed with the same spectrometer as for elastic scattering measurements.

4 Status of the project

The project has been formally presented to the CERN LHCC in an "Expression of Interest" in 1992 [?]. The committee reacted positively to this first document and raised some questions which were discussed in two more documents about the beam optics requirements of the experiment [40]. A Letter of Intent is currently being prepared.

5 Conclusion

The TOTEM project at the LHC intends to cover rather exhaustively the various aspects of diffractive physics with a dedicated instrumentation. The years available before the first beams run into the collider make possible the undertaking of research and development programs for a fulle use of the accelerator capabilities.

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