TOTAL CROSS SECTION AND DIFFRACTIVE PROCESSES AT THE LARGE HADRON COLLIDER (LHC)

M. Haguenauer(*) and G. Matthiae(**)
CERN, Geneva, Switzerland

In this report we summarize part of the activity of the study group on "Forward Physics" and the results of many discussions that we had at the Lausanne Workshop with our colleagues, B. Andersson, E. Berger, C. Bourrely, T. Ekelöf, A. Martin, D.R.O. Morrison and P. Schlein.

We will first review the theoretical expectations on the total cross section, elastic scattering and diffraction dissociation in the multi-TeV energy range and then discuss the feasibility of the experiments at the Large Hadron Collider (LHC).

The measurement of these rather fundamental quantities at $\sqrt{s} = 20$ TeV will be of great importance for the understanding of the dynamics of strong interactions at high energy. The discovery of the rising cross section at the CERN ISR about ten years ago, modified the theoretical picture of the asymptotic domain quite drastically. The recent results at the SPS Collider, confirming the extrapolation from the ISR data, show that in the energy range which is accessible at present accelerators the elastic amplitude increases nearly as fast as permitted by general principles. It is quite clear that the new energy domain open by the LHC, with a centre of mass energy three orders of magnitude larger than at the ISR will provide a much better understanding of the high-energy regime.

1. THEORETICAL EXPECTATIONS

Data on pp and $\bar{p}p$ total cross sections are presented in fig. 1. The UA4 result at the SPS Collider agrees with the dispersion relation prediction from the ISR [1], which follows a $(\lg s)^2$ dependence. However, extrapolations at higher energy are, at present, model dependent. This is

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(*) From Ecole Polytechnique, Paris, France
(**) From University of Napoli, Italy

illustrated by the result of two fits by Martin [2] to the total cross section and the real part of the forward elastic amplitude which are also shown in fig. 1. Assuming either an asymptotically constant total cross section or a $(\lg s)^2$ behaviour, one obtains prediction in the range from ~ 90 mb up to ~ 130 mb at $\sqrt{s} = 20$ TeV while both fits represent well the present data. A strong constraint on the behaviour of σ_t in the multi-TeV energy range would be imposed, however, by a measurement of the real part of the elastic amplitude at the SPS Collider. The result of this measurement would discriminate between the two extrapolations of fig. 1.

A rather complete analysis of present data on total cross section, real part and low-t elastic scattering was performed by Gauron and Nicolescu [3] using the classical Regge picture implemented by a $(\lg s)^2$ term in the amplitude. Their result for σ_t is very similar to that shown by the dashed curve of fig. 1. The prediction for the slope parameter b near the forward direction is presented in fig. 2. At the LHC one expects $b \simeq 22$ GeV^{-2}.

The shape of the differential cross section of elastic scattering was calculated by Bourrely et al. [4] using the impact picture with numerical values of the parameters determined by the present data. The predictions of this model in the energy range $2 < \sqrt{s} < 40$ TeV are shown in fig. 3. The dip-shoulder structure observed at the ISR around $-t \simeq 1.4$ GeV^2, which evolves at the Collider in a break at $-t \simeq 0.8$ GeV^2, is predicted to move further to lower t-values as the energy increases while a new structure around $-t \sim 2$ GeV^2 will gradually emerge.

Single diffractive excitation is studied in a missing mass experiment by measuring the mass M of the produced system. The diffractive region, $M^2/s \lesssim 0.05$, corresponds to M ~ 100 GeV at the SPS Collider and M ~ 15 GeV at the ISR. We have no reason to expect that at $\sqrt{s} = 20$ TeV masses of a few TeV should not be produced diffractively.

The cross section of diffractive excitation at the LHC can be guessed, assuming a lg s extrapolation from lower energies, to be around 15-20 mb. If the production spectrum follows the same $1/M^2$ law which is observed at present energies [5], diffractive excitation of states with mass of the order of one TeV will be a rather common process, with cross section around one millibarn.

2. EXPERIMENTAL STUDY OF DIFFRACTIVE PROCESSES

The study of elastic and inelastic scattering at centre of mass energy of 20 TeV can be considered as the extrapolation of the measurements made at the SPS Collider which have been themselves the continuation of experiments previously performed at the ISR. The experimental method will be basically the same. Detectors of small size and good spatial resolution, placed inside movable sections of the vacuum chamber, which are colloquially called "Roman pots" will be used. As the machine energy increases, the typical value of the scattering angles to be measured will become smaller and therefore the "Roman pots" will have to be placed farther away from the crossing point. At the ISR they were at ~ 10 m from the crossing, at the SPS Collider at a distance of 40-60 m while at the LHC they should be placed at a distance of 200-400 m. At the SPS Collider the optics of the machine in the intersection region is crucial in determining the range of the accessible scattering angles. The same being true at the LHC, it is clear that experiments of this kind are very much linked to the structure and operation of the machine. In the next sections we discuss how to perform measurements on elastic scattering and diffractive excitation at $\sqrt{s}$ = 20 TeV.

2.1 Elastic scattering

We first study on general grounds the extrapolation to higher energy from present experience at the ISR and at the SPS Collider, starting from the beam parameters in the intersection region.

The beam emittance ε and the value of the betatron function at the crossing β^*, determine the size and angular spread of the beam at the crossing point. Their r.m.s. values are given by $\Delta y^* = 1/2\ \sqrt{\varepsilon\beta^*}$ and $\Delta\theta^* = 1/2\ \sqrt{\varepsilon/\beta^*}$, in either the horizontal or vertical plane. The actual emittance ε is related to the normalized emittance E by $\varepsilon = E/\gamma$, where γ is the Lorentz factor. The luminosity, for a given number of circulating particles, depends on the β functions in the horizontal and vertical planes as

$$L \sim \frac{1}{\sqrt{\beta^*_H}\ \sqrt{\beta^*_H}} .$$

For a particle which is scattered at the centre of the crossing region, the displacement y at the detector plane can be written, in either the horizontal or vertical plane as $y = L_{eff} \times \theta$, where θ is the relevant component of the scattering angle, while the effective distance L_{eff} is determined by the focusing elements of the machine which exist between the crossing and the detectors. The effective distance can be written as $L_{eff} = \sqrt{\beta^*}\ \beta \sin\Delta\psi$, where β is the local value of the β-function at the detector and $\Delta\psi$ the phase advance of the betatron oscillations from the crossing to the detector position, $\Delta\psi = \int ds/\beta(s)$.

At the SPS Collider data on elastic scattering with various optics were taken by the UA4 Collaboration using a system of "Roman pots". It was empirically found that the minimum distance of approach of the detectors to the beam y_m is proportional to the beam size, as expected, and can be expressed as $y_m = K\ 1/2\ \sqrt{\epsilon\beta}$ with $K \simeq 14$. It should be noted that $K \simeq 14$ corresponds to a zero value of the acceptance which becomes useful for $K \simeq 20$. This value of the parameter K corresponds to the usual SPS operation with standard scraping of the beam halo and is of course machine dependent. At the ISR with a careful and dedicated scraping, the value $K \simeq 10$ was obtained.

Therefore, the minimum scattering angle which is accessible $\theta_m = y_m/L_{eff}$ can be written as

$$\theta_m = \frac{K\ \sqrt{\epsilon}}{2\ \sqrt{\beta^*}\ \sin\Delta\psi} \quad .$$

For a given optics the smallest value of θ_m is obtained by having the detectors in the position where the phase advance $\Delta\psi$ is equal to $\pi/2$. In that configuration $\theta_m = K\ \Delta\theta^*$, i.e. the minimum accessible scattering angle is K times the r.m.s. value of the beam angular spread. Once the condition $\Delta\psi = \pi/2$ is fulfilled, in order to reduce θ_m one has to increase β^* by changing the machine optics. The minimum value of the momentum transfer t_m which corresponds to θ_m is therefore proportional to $p_o^2\epsilon/\beta^*$ where p_o is the beam momentum. The actual emittance being proportional to $1/p_o$, the value of t_m will remain constant if β^* is increased proportionally to p_o. At the same time the effective distance L_{eff} will increase approximately as $\sqrt{p_o}$.

If the spatial resolution of the detectors is sufficiently good, the momentum transfer resolution will depend only on the angular spread of the beam. This intrinsic t-resolution is given by

$$\Delta t = 2\ p_o^2\ \theta\ \Delta\theta \simeq \frac{1}{\sqrt{2}}\ p_o\ \sqrt{\epsilon/\beta^*}\ \sqrt{-t} \quad .$$

Therefore, for a given normalized emittance, the t-resolution will stay constant if β^* is increased proportionally to p_o. We then conclude that the requirement $\beta^* \sim p_o$ fixes a scaling law for elastic scattering experiments. In that case the minimum value of t which is accessible and the t-resolution remain constant as the machine energy increases. This scaling law also implies that the size of the beam at the crossing does not change with energy, while the angular spread decreases as $1/p_o$. On the other hand, if the effective distance of the detectors increases as $\sqrt{p_o}$, the detector resolution Δy has to improve with energy as $1/\sqrt{p_o}$.

The system of "Roman pots" used at the SPS Collider by the UA4 Collaboration allowed to take advantage of the various machine optics. In fig. 4 a summary is given of the range of t which could be explored in the different modes. The very high-β mode $\beta_H^* = 550$ m, $\beta_V^* = 20$ m was designed but has not been operated yet. The beam emittance at the Collider was $\epsilon \simeq 8.10^{-8}$ m.

In order to work out a possible scheme for measuring elastic scattering at the LHC we have made use of the general arguments for scaling with energy which were previously discussed. The range of scattering angles at $\sqrt{s}$ = 20 TeV can be seen from fig. 5.

Among the various machine options which have been discussed [6] we consider the mode with 3564 bunches and a luminosity of 3.10^{32} cm^{-2} s^{-1} in the low-β insertion ($\beta_H^* = \beta_V^* = 1$ m). This option corresponds to about one interaction/crossing. The normalized emittance is expected to be $E = 5.10^{-6}$ m, (~ 4 times smaller than the one of present SPS Collider operation) which gives at $\sqrt{s}$ = 20 TeV, $\varepsilon = 4.7.10^{-10}$ m. The low-β mode ($\beta_H^* = \beta_V^* = 1$ m) implies a t-resolution which is quite poor, $\Delta t = 0.15\ \sqrt{-t}$ (t in GeV^2) not adequate in the dip region and perhaps only acceptable at large-t, where no structure and no strong t-dependence is expected.

A possible scheme to measure elastic scattering at the LHC from the Coulomb region up to a momentum transfer of several GeV^2 is shown in fig. 6. We have assumed β = 50 m at the "Roman pot" position, where $\Delta\psi \simeq \pi/2$. The medium-β mode would provide ~ 1500 events/day at $-t = 3\ GeV^2$ in a t bin of 0.1 GeV^2 for an azimuthal acceptance $\frac{4\Phi}{2\pi} = 0.1$. The high-β mode allows measuring elastic scattering in the diffraction peak region. The minimum accessible value of t (~ 0.01 GeV^2) is low enough to allow an accurate extrapolation to the optical point for the determination of the total cross section. The total cross section can be obtained in the luminosity independent method by combining the measurement of elastic scattering at low t and of the total inelastic rate [7]. Alternatively, the total cross section could be obtained from elastic scattering and a measurement of the machine luminosity [8]. At the LHC this method should be as accurate as at the ISR because the luminosity could be obtained, for the pp machine, by the Van der Meer method. The very high-β mode with $\beta_H^* = \beta_V^* = 5000$ m, by making the Coulomb region accessible to detection, will provide a measurement of the phase of the forward amplitude. It might, however, represent a too large perturbation of the machine.

The detector to be placed inside the "Roman pots" will be a natural extrapolation of those presently used at the SPS Collider [9]. The spatial resolution of 10-20 μ which is needed, will be easily reached using small solid state detectors as the silicon "micro-strips", which can be placed inside the vacuum chamber. A sketch of a "Roman pot" for the LHC is shown in fig. 7. A small system of silicon detectors with horizontal and vertical strips is attached to a movable piece which is connected to the accelerator pipe by a bellow.

2.2 Diffraction dissociation

The process pp → pX can be studied at the LHC by measuring the momentum of the proton and detecting at the same time the decay products of the system X by a spectrometer or a calorimeter. The best way of measuring the proton momentum is to make use of the magnetic elements of the machine itself as forward spectrometer. The dipoles which fill the space (~ 80 m) between two quadrupoles of the machine lattice [6] have a total bending power of ~ 800 T.m. Therefore, a simple system of "Roman pots" measuring the particle direction in the straight section and the displacement behind the first series of dipoles, as sketched in fig. 8, will measure the proton momentum with resolution $\Delta p/p \simeq 10^{-4}$, which is comparable to the intrinsic momentum spread of the beams. The mass M of the produced system X is determined from $M^2 = s(1 - p/p_0)$ with an uncertainty $\Delta M = (s/2M)\ \Delta p/p$. For a system with mass $M = 2$ TeV, corresponding to $M^2/s = 0.01$, we have $\Delta M = 10$ GeV, i.e. a mass resolution of 1/2%. A spectrometer of this kind provides a tagging of the diffractively produced system with accurately determined mass.

3. CONCLUSIONS

The measurement of the total cross section, elastic scattering and diffractive excitation at the LHC does not present special technical problems, but for the tight connection to the machine the implications of these measurements on the intersection region are quite "special" when compared to a "90° experiment". In fact, the possibility of tuning the β-values at the crossing in order to operate the insertion with different optics without perturbing the other crossing region is very important. The best position for the "Roman pots" is very much linked to the layout of the intersection region. In addition, the distance of the insertion quadrupoles to the crossing point could be larger than for a normal low-β intersection region. In that case, the installation of calorimeters or of a forward spectrometer would be easier, thus permitting access to smaller production angles.

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FIGURES CAPTIONS

Fig. 1. Compilation of pp and $\bar{p}p$ total cross section data. The dispersion relation prediction of Amaldi et al. [1] is shown as a solid line, together with recent extrapolations by Martin [2] (dotted and dashed lines).

Fig. 2. Result of the model by Gauron and Nicolescu [3] on the forward slope parameter b.

Fig. 3 Predictions of the model by Bourrely et al. [4] on the t-distribution of elastic scattering in the multi-TeV energy range. The distributions for $\sqrt{s} > 2$ TeV are scaled up by factors of ten.

Fig. 4 Elastic scattering at the SPS Collider as studied by the UA4 Collaboration. For each machine optics the values of the β-functions at the crossing in the horizontal and vertical planes are given together with the corresponding range of momentum transfer which is explored. The t-resolution for the high and low-β modes is also given.

Fig. 5 The scattering angle θ versus t at the SPS Collider and at the LHC.

Fig. 6 Elastic scattering at $\sqrt{s} = 20$ TeV. A possible scheme with three different machine optics to measure elastic scattering from the Coulomb region to $-t \sim 10$ GeV^2 is presented.

Fig. 7 Sketch of a "Roman pot" for the Large Hadron Collider (LHC). It is assumed that the beam pipe is 4 cm in diameter.

Fig. 8 Sketch of a layout to study diffraction dissociation. The forward proton is analyzed using the magnetic elements of the machine.

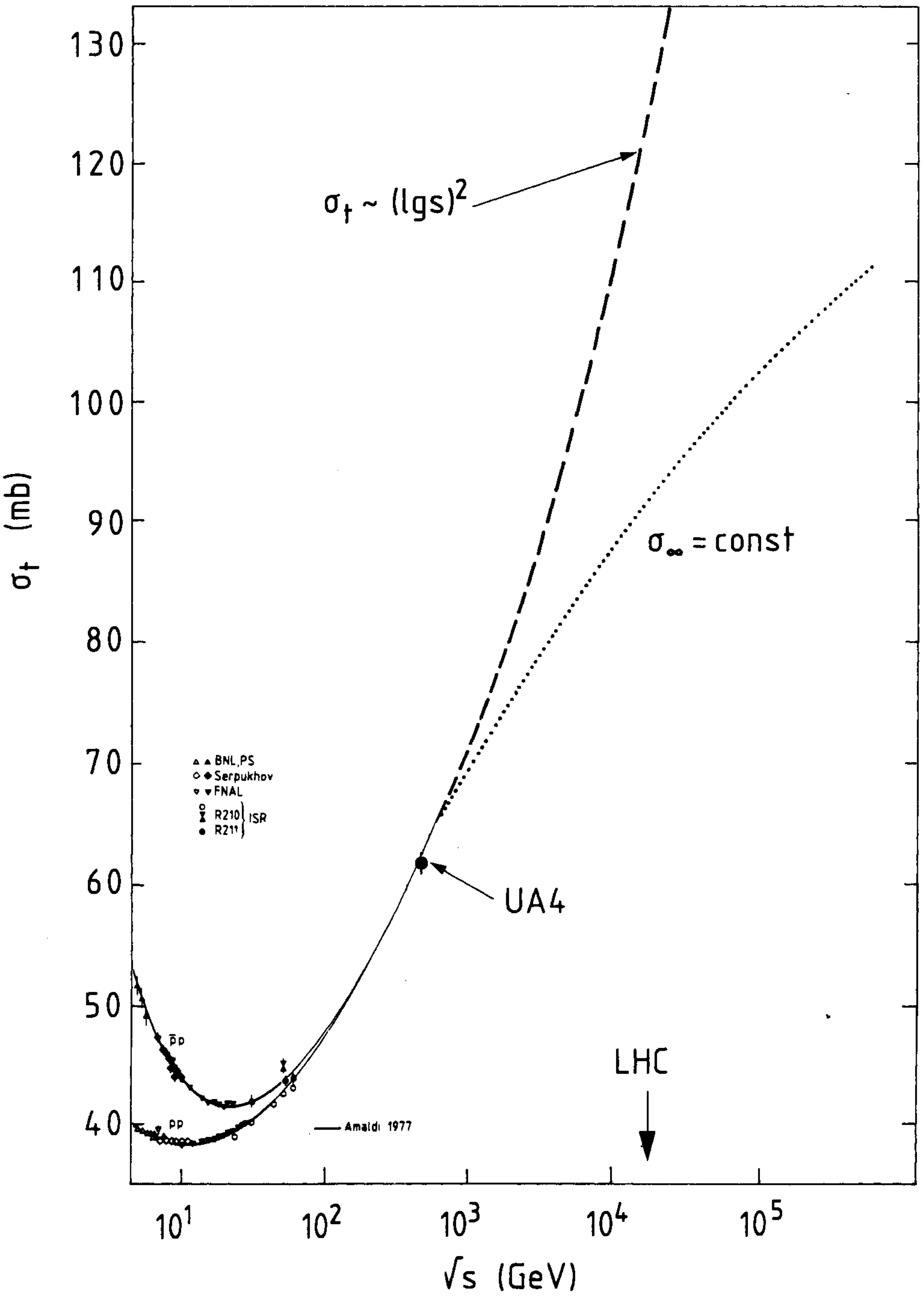
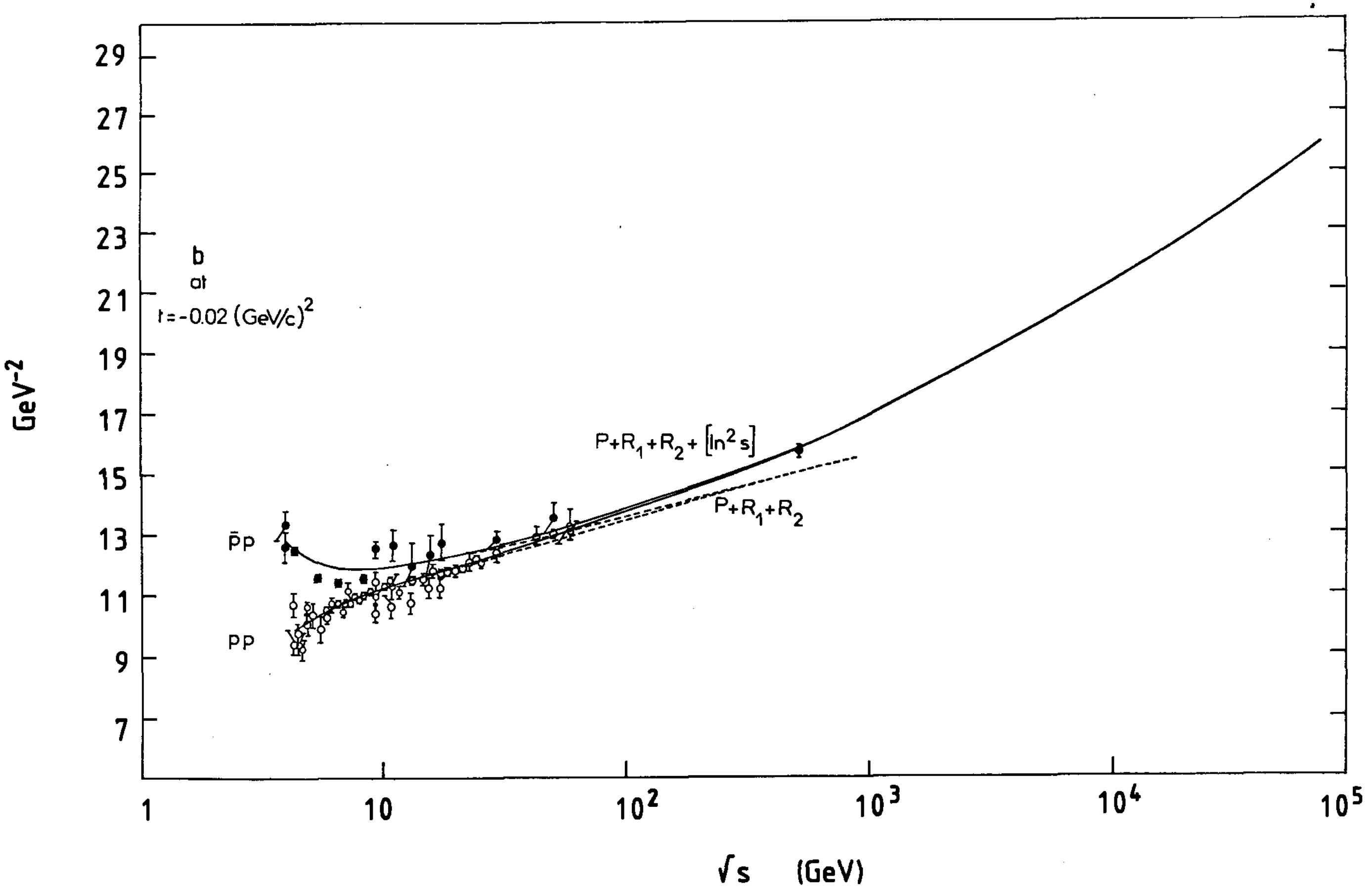

130
120
110
100
90
80
70
60
50
40
σ_t (mb)
$\sigma_t \sim (\lg s)^2$
$\sigma_\infty = \text{const}$
UA4
LHC
BNL,PS
Serpukhov
FNAL
R210
R211
ISR
p̄p
pp
Amaldi 1977
10^1
10^2
10^3
10^4
10^5
√s (GeV)

Fig. 1

Fig. 2


29
27
25
23
21
19
17
15
13
11
9
7
GeV^{-2}
b
at
t = -0.02 (GeV/c)^2
$\bar{p}$p
pp
P+R$_1$+R$_2$+[ln^2 s]
P+R$_1$+R$_2$
1
10
10^2
10^3
10^4
10^5
$\sqrt{s}$ (GeV)

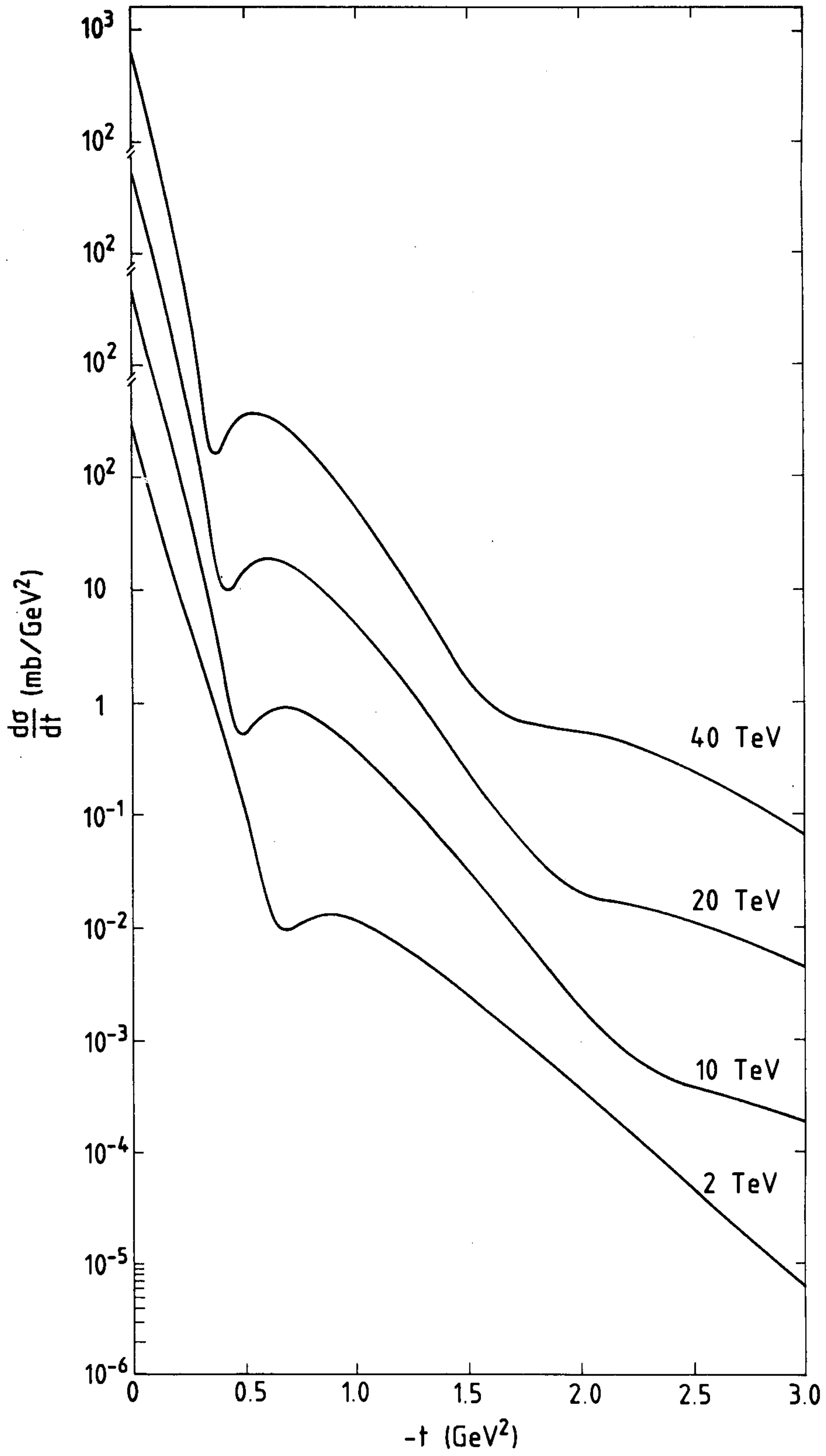

10^3
10^2
10^2
10^2
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$\frac{d\sigma}{dt}$ (mb/GeV^2)
0
0.5
1.0
1.5
2.0
2.5
3.0
$-t$ (GeV^2)
40 TeV
20 TeV
10 TeV
2 TeV

Fig. 3

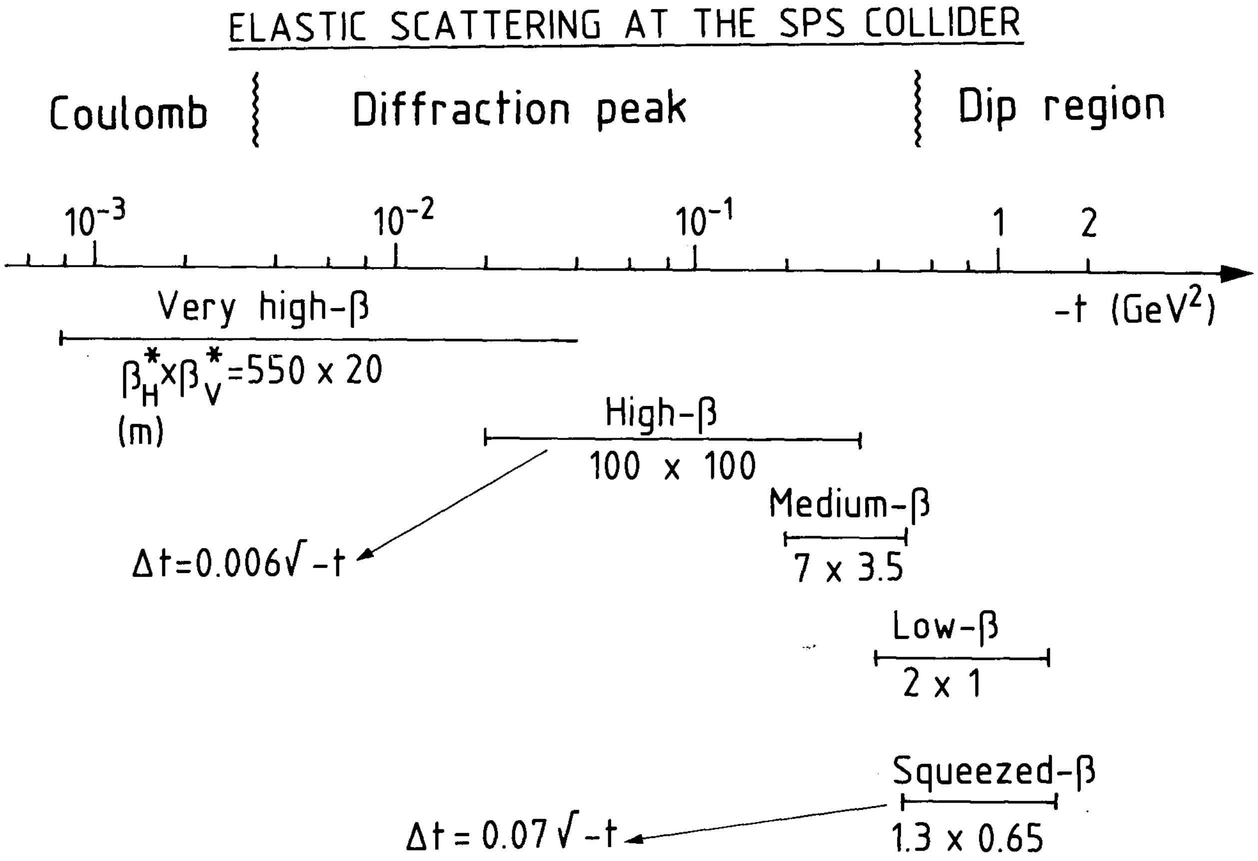

ELASTIC SCATTERING AT THE SPS COLLIDER
Coulomb
Diffraction peak
Dip region
10^{-3}
10^{-2}
10^{-1}
1
2
-t (GeV^2)
Very high-β
$\beta_H^* \times \beta_V^* = 550 \times 20$
(m)
High-β
100 x 100
$\Delta t = 0.006\sqrt{-t}$
Medium-β
7 x 3.5
Low-β
2 x 1
Squeezed-β
1.3 x 0.65
$\Delta t = 0.07\sqrt{-t}$

Fig. 4

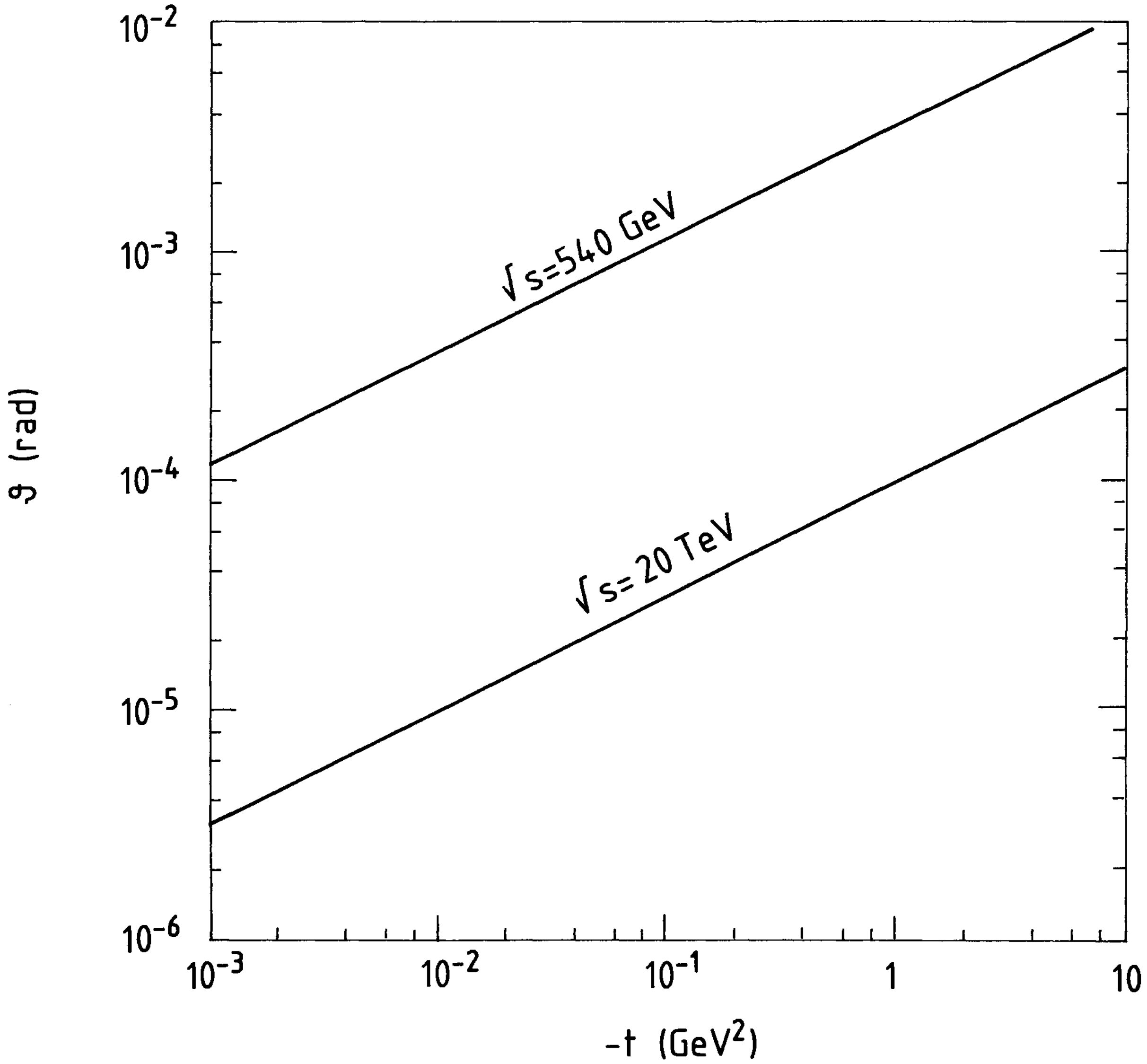

ϑ (rad)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$\sqrt{s}$=540 GeV
$\sqrt{s}$= 20 TeV
10^{-3}
10^{-2}
10^{-1}
1
10
-t (GeV^2)

Fig. 5

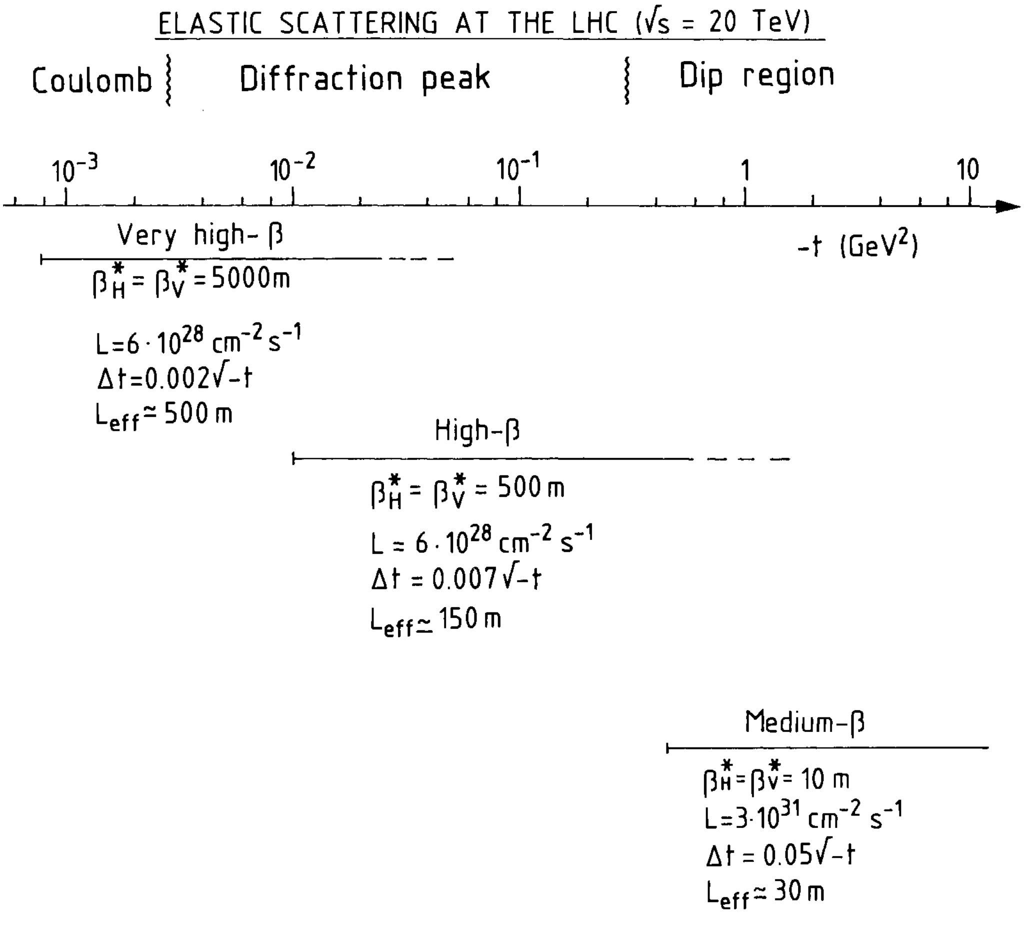

ELASTIC SCATTERING AT THE LHC (√s = 20 TeV)
Coulomb
Diffraction peak
Dip region
10^-3
10^-2
10^-1
1
10
-t (GeV^2)
Very high-β
β*_H = β*_V = 5000m
L=6·10^28 cm^-2 s^-1
Δt=0.002√-t
L_eff ≃ 500 m
High-β
β*_H = β*_V = 500 m
L = 6·10^28 cm^-2 s^-1
Δt = 0.007√-t
L_eff ≃ 150 m
Medium-β
β*_H = β*_V = 10 m
L=3·10^31 cm^-2 s^-1
Δt = 0.05√-t
L_eff ≃ 30 m

Fig. 6

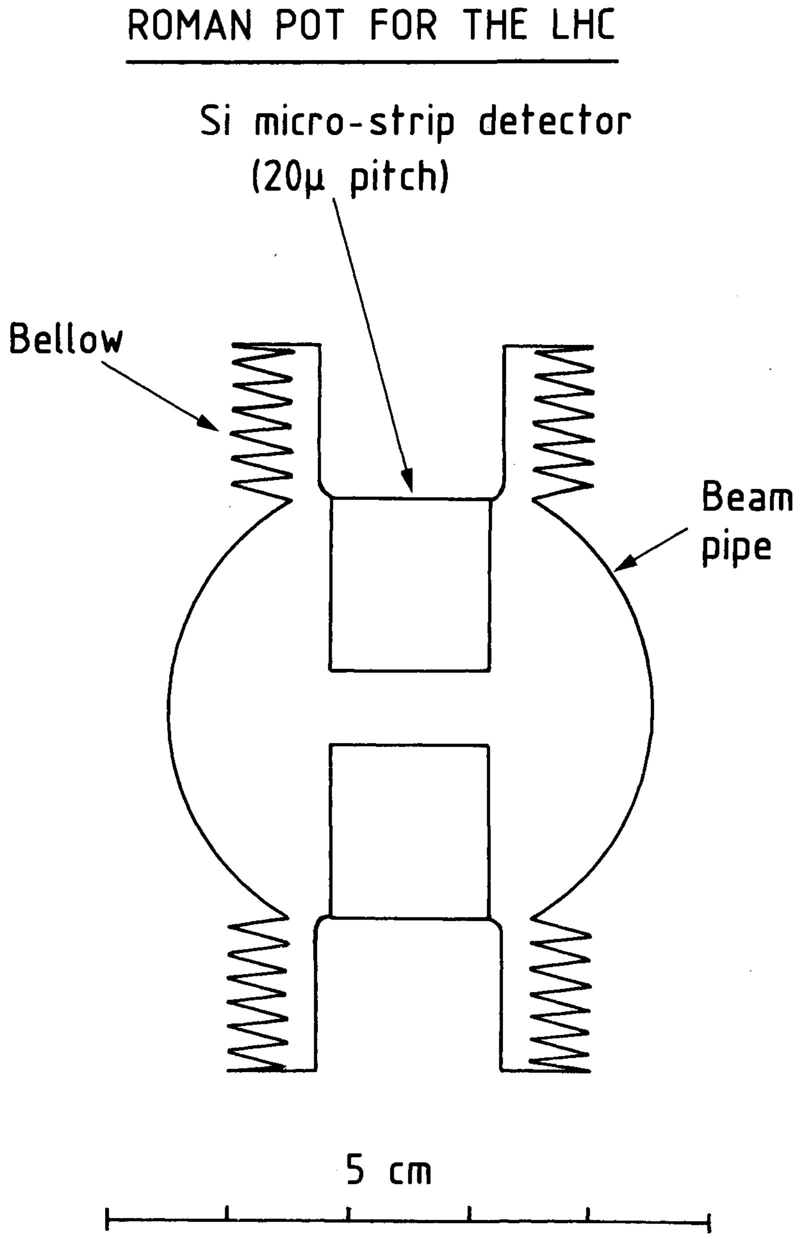
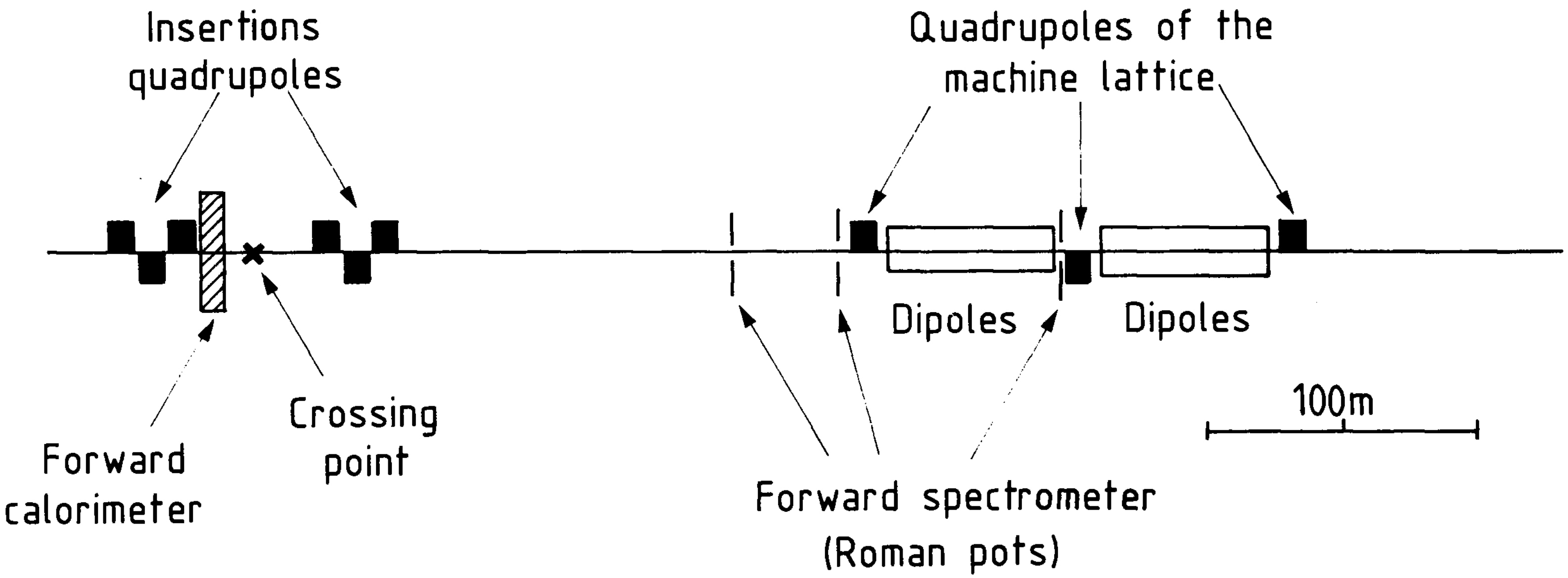

ROMAN POT FOR THE LHC
Si micro-strip detector
(20μ pitch)
Bellow
Beam
pipe
5 cm

Fig. 7

Fig. 8


SKETCH OF A DIFFRACTION DISSOCIATION EXPERIMENT