EXPERIMENTAL RESULTS ON LARGE ANGLE ELASTIC pp SCATTERING

AT THE CERN ISR

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ABSTRACT

New experimental results are presented on proton-proton elastic scattering at centre-of-mass energies $\sqrt{s}$ = 23 GeV and $\sqrt{s}$ = 62 GeV. The data are obtained using the Split Field Magnet detector at the CERN Intersecting Storage Rings. The absolute differential cross-sections show an energy-dependent behaviour. The position of the diffraction minimum changes from t = (-1.44 ± 0.02) GeV^2 at 23 GeV to (-1.26 ± 0.03) GeV^2 at 62 GeV. The cross-section at the second maximum is increasing with $\sqrt{s}$. The connection of these observations with the hypothesis of "geometrical scaling" is discussed.

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Since the first observation[1] of a pronounced minimum in the differential cross-section of elastic proton-proton scattering at momentum transfers $t \approx -1.3$ GeV^2, it has been an open question whether this structure is dependent on the reaction energy. New data have been obtained over the centre-of-mass energy range $\sqrt{s} = 23$ GeV to 62 GeV using the Split Field Magnet Detector (SFM) at the CERN Intersecting Storage Rings (ISR). We report here results[2] at the two extreme energies, corresponding to integrated luminosities of 1.1×10^7/mb at 23 GeV and 2.3×10^7/mb at 62 GeV, and discuss the observed s-dependence of the differential cross-section.

The SFM Detector has been described before[3]; it contains two forward telescopes equipped with 28 multiwire proportional chambers of 2 mm wire spacing, most of them 1 m high and 2 m wide. Each chamber has a vertical and a horizontal wire plane. The average magnetic field is 1.0 T, resulting in a momentum resolution for elastically scattered protons of $\Delta p/p = \pm 0.04$ to ± 0.09. The acceptance for elastic events increases from about 0.3 at the polar scattering angle $\theta = 15$ mrad to about 0.7 at 250 mrad. The data acquisition speed is about 100 events/sec.

The trigger is defined in two steps: a fast trigger using signals from the proportional chambers and a slow trigger using their memory levels[4]. The fast trigger, requiring at least one particle in each telescope, results in a rate corresponding to nearly the total pp cross-section. The memory level trigger (decision time ≈ 2 μsec) requires rough collinearity of the two tracks and the absence of further tracks. It also determines the scattering angle θ of the event and allows a θ-dependent scaling-down; all events with large t and only a well-defined fraction of events with low t are recorded onto magnetic tape. The memory level logics reduces the trigger rate by a factor of 100 to 1000.

The recorded events are passed through three analysis programs, performing track recognition, track fitting in the magnetic field, and a kinematical fit. The results presented here are based on 380,000 (420) elastic events at 62 GeV and 63,000 (270) at 23 GeV (in brackets we give the number of events beyond the diffraction minimum).

In order to determine absolute differential cross-sections, we have to apply t-dependent acceptance corrections and an over-all normalization factor. The acceptance of the detector is calculated using Monte Carlo methods. This simulation takes into account the beam positions and their size, particle trajectories in the magnetic field, the detector geometry, absorption and scattering in the ISR beam tube and in the detector material, the trigger conditions, proportional chamber inefficiencies, and losses in the reconstruction program and in the event selection. The quality of the simulation has been extensively checked by comparing distributions in the azimuthal scattering angle of real and Monte Carlo events at

fixed t-values. Great care is taken in calculating the length ℓ of traversed material. The largest uncertainty in acceptance is in this part of the calculation, and therefore an estimated systematical uncertainty of ±0.2 of the average length ⟨ℓ⟩ is taken into account in the evaluation of the cross-section.

The absolute normalization is obtained by collecting monitor counts simultaneously with data taking. A scintillation counter monitor has been calibrated using the Van der Meer method[5]. The systematic accuracy of the monitor is estimated to be ±5% by comparing elastic scattering cross-sections determined in different subsets of the data.

We present the evaluated cross-sections in the t-region, where the beam tube absorption uncertainties do not exceed ±15%, i.e. for -t > 0.2 GeV² at 62 GeV and for -t > 0.02 GeV² at 23 GeV. The results[*] are shown in Fig. 1. The error bars represent (added quadratically) the statistical errors of the data, the statistical errors of the acceptance calculation, and the estimated systematical uncertainty of absorption in the beam tube[**]. No background has been subtracted; a study of the collinearity χ^2-distribution in several t-bins has shown that the background contamination is less than 5% for $|t| \leq 1.2$ GeV². In the region of larger t, the contamination is estimated to be less than 3×10^{-6} mb/GeV² at both energies.

A dominant property of the differential cross-section is the narrow minimum near $t = -1.3$ GeV². This has already been observed at the three other ISR energies, 31, 45 and 53 GeV, by Böhm et al.[1] without conclusions on its energy dependence. Our data show clearly that the position of the minimum changes to lower values of $|t|$ for increasing energy as expected from diffraction on an object of increasing radius. To determine the precise position of the minimum, we attempt to describe the data by a function[6] of the form

$$\frac{d\sigma}{dt} = \left| \sqrt{A} \ e^{Bt/2} + \sqrt{C} \ e^{Dt/2+i\phi} \right|^2 , \tag{1}$$

folding it with the experimental resolution in t. The Monte Carlo simulation gives one-standard-deviation resolutions of $\Delta t = \pm0.013$ GeV² at 23 GeV and ±0.028 GeV² at 62 GeV in the vicinity of the minimum. Equation (1) gives an excellent description of the data in the t-range between -0.6 and -3.6 GeV², the best fit values for the position of the minimum being:

$$t_{min} = -(1.44 \pm 0.02) \text{ GeV}^2 \text{ at } \sqrt{s} = 23 \text{ GeV}$$

$$t_{min} = -(1.26 \pm 0.03) \text{ GeV}^2 \text{ at } \sqrt{s} = 62 \text{ GeV} .$$

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*) Tables are available from the authors on request.

**) The systematical errors are not independent in different t-bins.

The errors include the one-standard-deviation of the fit and an estimated systematical uncertainty in the t-scale of $\Delta t = 0.008$ (0.015) GeV^2 at 23 (62) GeV.

We note the following further features of the data:

i) Between $t = -0.25$ GeV^2 and $t = -0.6$ GeV^2, $d\sigma/dt$ has an exponential shape compatible with energy-independence.

ii) The slope between -0.6 GeV^2 and -1.1 GeV^2 increases with energy.

iii) The differential cross-section at the second maximum, as determined by averaging the experimental cross-section in a t-range of ± 0.2 GeV^2 around the fitted maximum position, rises with energy.

iv) $d\sigma/dt$ for $-t > 2.0$ GeV^2 is again compatible with energy independence.

Observations (i) to (iii) and the position of the minimum are summarized in Table 1, where we also show values of the proton-proton total cross-section[7]. The ratios of the observed quantities at $\sqrt{s} = 62$ GeV and $\sqrt{s} = 23$ GeV can be compared to the predictions derived from the hypothesis of geometrical scaling[8]. If the opacity of the colliding protons is a function of only one variable $\rho = r/R(s)$, where r is the impact parameter, the observed quantities should depend on the scaling parameter R(s) as given in line 4.

Property (iv) of the data has been predicted in a two-amplitude model of Phillips and Barger[6]; elastic scattering in the large t-region is described by coherent superposition of two exponential amplitudes, where the second one is energy independent and the first one is shrinking with increasing energy. We have tested this hypothesis by fitting the two data sets in the range -0.6 to -3.6 GeV^2 with Eq. (1) and imposing equal values of the parameters C and D for both energies[*]. The quality of the fit is good as can be seen in Fig. 2.

Acknowledgements

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[*] The parameters of the best fit are: $A_{23} = (14.7 \pm 1.3)$ mb/GeV^2; $A_{62} = (31.8 \pm 6.3)$ mb/GeV^2; $B_{23} = (7.8 \pm 0.1)$ GeV^{-2}; $B_{62} = (9.4 \pm 0.3)$ GeV^{-2}; $C = (0.0032 \pm 0.0008)$ mb/GeV^2; $D = (2.01 \pm 0.11)$ GeV^{-2}; $\cos \phi_{23} = -0.987 \pm 0.007$; $\cos \phi_{62} = -0.973 \pm 0.014$; $\chi^2 = 72.2$ (80 D.F.).

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Table 1

Summary of observed energy dependence

	b [GeV^{-2}] $0.25 < -t < 0.6$	b [GeV^{-2}] $0.6 < -t < 1.1$	$-t_{min}$ [GeV^2]	$\frac{d\sigma}{dt}(2^{nd}_{max})$ [mb/GeV^2]	σ_{tot} [mb] a)
$\sqrt{s}$ = 62 GeV	10.3 ± 0.3	11.8 ± 0.3	1.26 ± 0.03	$(7.2 \pm 1.0) \times 10^{-5}$	44.1 ± 0.9
$\sqrt{s}$ = 23 GeV	10.3 ± 0.2	9.1 ± 0.1	1.44 ± 0.02	$(4.5 \pm 0.5) \times 10^{-5}$	38.7 ± 0.7
Ratio	1.00 ± 0.04	1.29 ± 0.04	$(1.14 \pm 0.02)^{-1}$	$(1.27 \pm 0.11)^2$	1.14 ± 0.03
Scaling b) prediction	$\propto R^2$	$\propto R^2$	$\propto R^{-2}$	$\propto R^4$	$\propto R^2$

a) Ref. 7

b) Ref. 8

Figure captions

Fig. 1 : Differential cross-sections of elastic proton-proton scattering at the two extreme ISR energies. The error bars represent statistical and estimated systematical errors for each t-bin. An additional over-all scale uncertainty of ±5% is to be added separately for each energy.

Fig. 2 : Differential cross-sections for momentum transfer $-t > 0.6$ GeV^2. The t-resolution in the vicinity of the minimum is ±0.013 GeV^2 at 23 GeV and ±0.028 GeV^2 at 63 GeV. The solid lines represent the best fit results of a two-amplitude model[6].
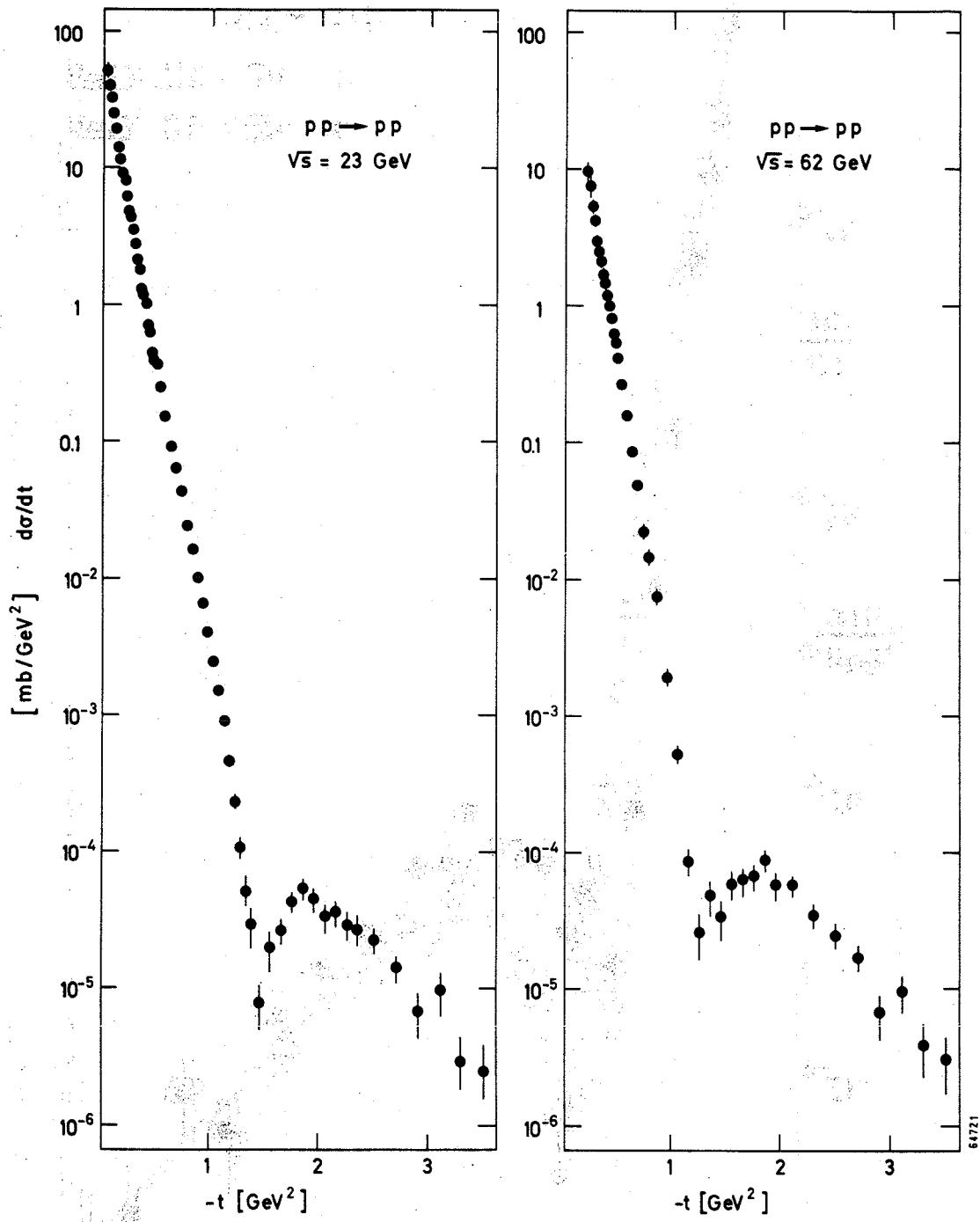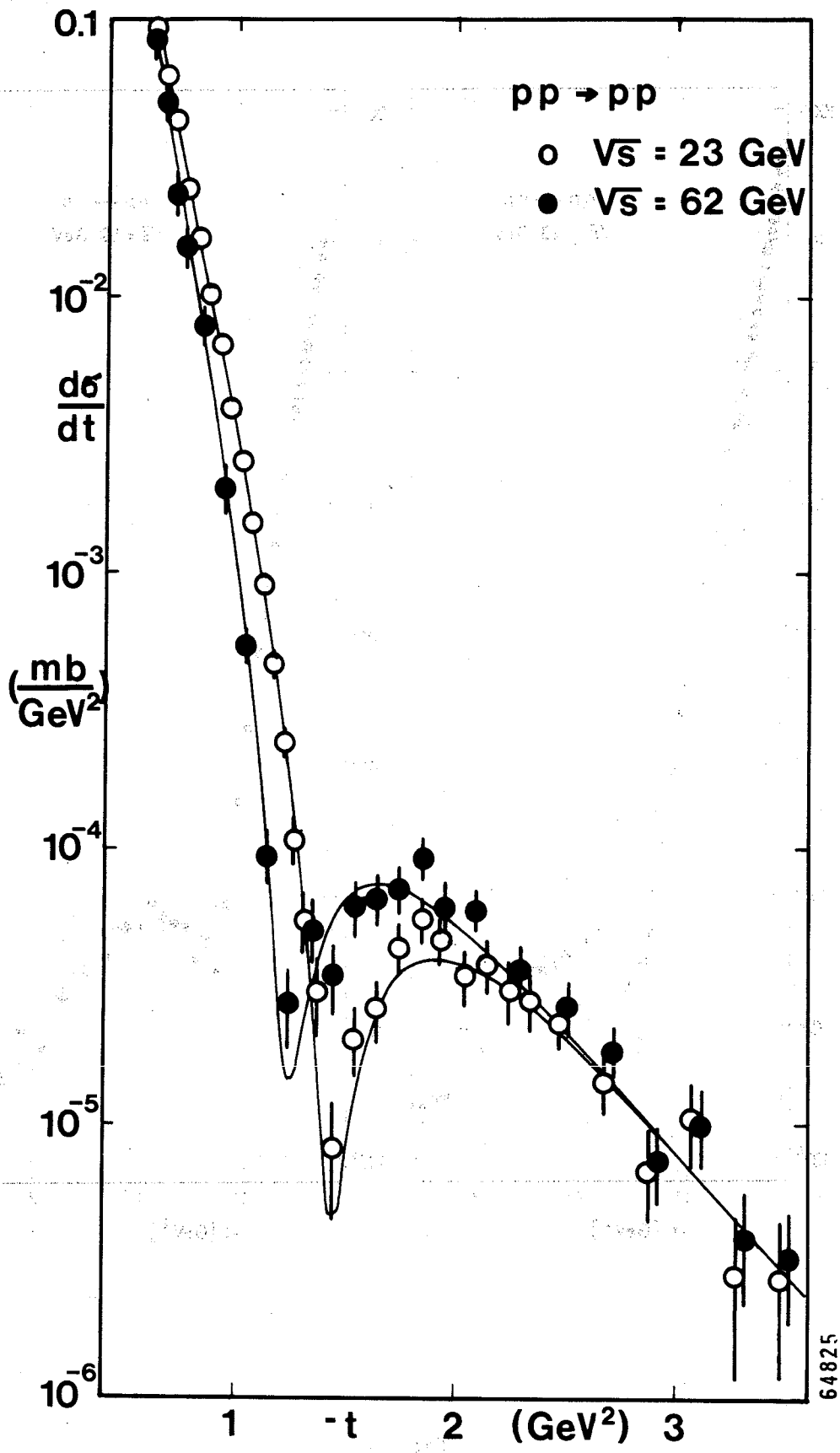
Fig. 1

Fig. 2