A MEASUREMENT OF $\bar{p}p$ AND pp ELASTIC SCATTERING AT ISR ENERGIES

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ABSTRACT

We have measured the differential cross section for pp and $\bar{p}p$ elastic scattering at $\sqrt{s} = 31, 53$ and 62 GeV in the interval $0.05 < |t| < 0.85$ GeV² at the CERN ISR using the Split Field Magnet detector. At 53 and 62 GeV, for $0.17 < |t| < 0.85$ GeV² both pp and $\bar{p}p$ data show simple exponential behaviour in t ; at $\sqrt{s} = 31$ GeV the data for $0.05 < |t| < 0.85$ GeV² are consistent with a change in slope near $|t| = 0.15$ GeV².

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The differential cross sections for $\bar{p}p$ and pp elastic scattering and their energy dependence are fundamental quantities related to the dynamics of hadronic interactions. Elastic scattering for $\bar{p}p$ and pp has been well measured at lower energies, but until now only the pp reaction has been accessible at ISR energies [1-6]. The recent injection of antiprotons into one ring of the CERN ISR and into the CERN SPS collider has provided new energy regions in which to explore $\bar{p}p$ elastic scattering [7-10].

This letter reports results of a measurement of $\bar{p}p$ and pp elastic scattering at centre-of-mass energies of $\sqrt{s} = 31, 53$ and 62 GeV in the four-momentum transfer squared region, $0.05 < |t| < 0.85$ GeV². The experiment was performed at the CERN ISR using the Split Field Magnet (SFM) detector.

In the $\bar{p}p$ runs, the stored antiproton current was 2-6 mA and the proton current was about 10 A, resulting in luminosities of approximately 10^{27} cm⁻²s⁻¹. The pp runs were performed with luminosities at least 10^3 times larger.

The SFM detector [11] was used with a two stage trigger: (a) a fast trigger which required at least one hit in each of two scintillator banks surrounding the outgoing beams and no signal from proportional wire chambers in the central region, and (b) a slow trigger which required two track candidates, one on each side of the detector, co-linear in their projection parallel to the magnetic field (vertical). Data were also taken with only the fast trigger in order to evaluate the slow trigger efficiency.

The raw data were processed through the standard SFM off-line program for track finding and a special off-line program for track and vertex fitting. This program varied the track and vertex parameters to minimize a chi-square reflecting the closeness of approach of the particle trajectories to the measured points in the chambers. The colinearity of the tracks in the centre-of-mass system was used as a constraint on the fit. We rejected all events with a reduced chi-square greater than 2.5, corresponding to a confidence level greater than about one per cent. For $\bar{p}p$ most of the rejected events were beam-gas interactions.

The acceptance of the apparatus as a function of the square of the four-momentum transfer, t , and of the azimuthal angle, ϕ , was determined by processing simulated events. In order to minimize problems arising from the trigger and from the SFM geometry, only those events, for a given bin in t , were allowed that were within a limited ϕ range chosen to have a high acceptance. After all cuts we had between 50000 and 180000 events at each energy.

Using simulated events, we calculated corrections to the data for the following effects: (a) nuclear absorption (about 15%), (b) Coulomb multiple scattering (negligible in our t range), and (c) slow trigger efficiency (1-4%).

The normalization for the pp cross section at each energy was obtained by comparison to previous measurements [1-6]. The normalization for the $\bar{p}p$ data at each energy was then obtained by assuming equality with the pp cross section at the same energy in the region near $|t| = 0.3 \text{ GeV}^2$. Because of the very small slope difference between the pp and $\bar{p}p$ cross sections, the normalization is not very sensitive to the t -value chosen for this procedure. This method gives results that are consistent with other ISR $\bar{p}p$ measurements [8] and with our own luminosity measurements, which are accurate to 10% for pp measurements and 15% for $\bar{p}p$ measurements.

Fig. 1 and Table 1 give the differential cross sections for $\bar{p}p$ and pp elastic scattering at $\sqrt{s} = 31, 53$, and 62 GeV . The errors shown reflect only the t -dependent uncertainties, which include uncertainties due to acceptance and other corrections as well as statistical uncertainties. The gap in the $\sqrt{s} = 31 \text{ GeV}$ data near $|t| = 0.3 \text{ GeV}^2$ is due to low acceptance in this region.

For $0.17 < |t| < 0.85 \text{ GeV}^2$ both pp and $\bar{p}p$ data may be represented by simple exponential dependences on t :

$$d\sigma/dt = a \exp(bt). \quad (1)$$

The $\sqrt{s} = 31 \text{ GeV}$ cross sections, which have been measured over a larger t -range, $0.05 < |t| < 0.85 \text{ GeV}^2$, give better fits with either two slopes or a quadratic exponential of the form

$$d\sigma/dt = A \exp(Bt + Ct^2). \quad (2)$$

The fits to the data at $\sqrt{s} = 53$ and 62 GeV show no significant improvement when the quadratic term is added.

The results of the fits to exponential and quadratic exponential expressions are given in Table 2.

From the quadratic exponential fits one may compute the local slope at a certain t value via the relation $b = B + 2C|t|$. The local slopes at $|t| = 0.2$ and 0.4 GeV^2 are given in Table 3. The slopes determined by the exponential fits correspond to the local slopes at a mean value of 0.4 GeV^2 . The comparison of the b values from Tables 2 and 3 indicates a good agreement between the determinations from simple exponential and quadratic exponential fits.

Our local b values for pp scattering agree within errors with the values of previous measurements. The b values for pp scattering agree with and join smoothly to measurements at lower and higher energies [7,9]. One is now able to make a more complete picture of the energy dependence of the local slope at $|t| = 0.2 \text{ GeV}^2$ and $|t| = 0.4 \text{ GeV}^2$ in $p\bar{p}$ and pp elastic scattering, as shown in Figure 2.

From figs 1 and 2 and Tables 1 and 2 it is seen that there may be a slight difference in the slopes of the $p\bar{p}$ and pp differential cross sections. We have fitted the ratios of the differential cross sections for $|t| > 0.17 \text{ GeV}^2$ to an exponential dependence

$$[d\sigma/dt]_{p\bar{p}} / [d\sigma/dt]_{pp} = A' \exp(\Delta b t) \quad (3)$$

The results of the fits to eq. (3) are given in Table 4. There may be a difference in slope, but because of the size of the errors it is not possible to determine if there is an energy dependence. Note that because of our normalization procedure, the fit results for A' are not significant.

The total elastic cross sections may be obtained by integration of the differential cross sections to the optical point, assuming a change of slope at about $|t| = 0.15 \text{ GeV}^2$, as measured by other experiments [6].

The values obtained are given in Table 5, which also summarizes a number of parameters commonly used in the analysis of high energy elastic scattering data. For this purpose σ_{el}/σ_{tot} (≈ 0.175) and b/σ_{tot} ($\approx 0.30 \text{ mb}^{-1} \text{ GeV}^{-2}$) are nearly independent of energy and nearly equal for pp and $\bar{p}p$ collisions.

In conclusion, we report the results of a measurement of the differential cross sections for $\bar{p}p$ and pp elastic scattering at $\sqrt{s} = 31, 53, \text{ and } 62 \text{ GeV}$ in the region $0.05 < |t| < 0.85 \text{ GeV}^2$. These data, together with the results of the measurements of the $\bar{p}p$ and pp total cross sections, determine most of the forward elastic scattering parameters in the ISR energy range.

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TABLE CAPTIONS

- Table 1 Values of $d\sigma/dt$ in mb/GeV^2 . Quoted errors include statistical and point-to-point uncertainties arising from the corrections. The systematic scale error is estimated to be 10% for pp data and 15% for $\bar{p}p$ data.
- Table 2 Results of the fits of linear and quadratic exponential functions to the data.
- Table 3 Local slopes computed from quadratic exponential fits.
- Table 4 Fits to cross section ratios.
- Table 5 A compilation of some common parameters of elastic scattering. The total cross sections are averages of the available data: the $t = 0$ optical values have been computed from the average σ_{tot} . The forward slopes are either from this experiment or from the literature. The integrated elastic cross sections have been computed as explained in the text.

TABLE 1

-t GeV ²	31 GeV		53 GeV		62 GeV	
	pp	$\bar{p}p$	pp	$\bar{p}p$	pp	$\bar{p}p$
0.05	49.4 ± 2.2	50.5 ± 2.1	21.49 ± 0.90	19.63 ± 0.68	17.31 ± 0.71	19.27 ± 1.00
0.07	42.0 ± 2.0	43.1 ± 1.6	16.39 ± 0.38	17.20 ± 0.51	13.09 ± 0.39	13.03 ± 0.51
0.09	35.6 ± 2.0	30.5 ± 1.3	12.44 ± 0.31	12.94 ± 0.37	10.96 ± 0.29	10.82 ± 0.37
0.11	29.1 ± 2.2	25.5 ± 1.4	10.82 ± 0.28	11.06 ± 0.34	8.77 ± 0.22	9.07 ± 0.32
0.13	18.3 ± 1.2	21.4 ± 1.2	8.77 ± 0.25	8.80 ± 0.30	6.86 ± 0.19	7.04 ± 0.27
0.15	16.0 ± 1.0	16.5 ± 1.0	7.19 ± 0.22	6.86 ± 0.28	5.55 ± 0.15	5.71 ± 0.22
0.17	12.8 ± 0.6	12.2 ± 0.6	5.82 ± 0.24	5.92 ± 0.27	4.52 ± 0.13	4.30 ± 0.18
0.19	9.06 ± 0.41	9.91 ± 0.56	5.20 ± 0.37	4.76 ± 0.24	3.61 ± 0.13	3.50 ± 0.16
0.21	7.44 ± 0.37	7.05 ± 0.41	3.59 ± 0.29	3.48 ± 0.20	3.04 ± 0.11	2.82 ± 0.13
0.23	5.68 ± 0.35	5.03 ± 0.45	3.22 ± 0.32	2.57 ± 0.15	2.35 ± 0.09	2.28 ± 0.12
0.25	4.82 ± 0.42	4.01 ± 0.38	2.61 ± 0.14	2.00 ± 0.14	2.00 ± 0.85	1.96 ± 0.12
0.27	4.02 ± 0.42	3.51 ± 0.62	2.10 ± 0.26	1.67 ± 0.15	1.61 ± 0.07	1.56 ± 0.10
0.29			1.53 ± 0.21	1.43 ± 0.14	1.284 ± 0.064	1.18 ± 0.08
0.31			1.13 ± 0.14	1.14 ± 0.09	0.984 ± 0.053	0.850 ± 0.073
0.33			0.941 ± 0.072	0.831 ± 0.070	0.759 ± 0.044	0.697 ± 0.052
0.35	1.59 ± 0.23	0.95 ± 0.12	0.706 ± 0.040	0.645 ± 0.052	0.504 ± 0.035	0.433 ± 0.051
0.37	1.25 ± 0.11	0.695 ± 0.066	0.465 ± 0.029	0.420 ± 0.040	0.275 ± 0.023	0.252 ± 0.037
0.39	0.992 ± 0.092	0.418 ± 0.044	0.271 ± 0.021	0.256 ± 0.029	0.213 ± 0.017	0.174 ± 0.032
0.42	0.720 ± 0.049	0.309 ± 0.040	0.170 ± 0.022	0.152 ± 0.021	0.141 ± 0.013	0.100 ± 0.028
0.46	0.490 ± 0.040	0.183 ± 0.027	0.119 ± 0.018	0.102 ± 0.017	0.095 ± 0.009	0.086 ± 0.021
0.50	0.375 ± 0.037	0.117 ± 0.023	0.063 ± 0.013	0.056 ± 0.013	0.046 ± 0.005	0.048 ± 0.010
0.54	0.197 ± 0.027	0.088 ± 0.021	0.035 ± 0.008	0.033 ± 0.008	0.014 ± 0.004	0.019 ± 0.006
0.58	0.143 ± 0.023	0.040 ± 0.010	0.018 ± 0.007	0.018 ± 0.005	0.007 ± 0.002	0.007 ± 0.003
0.62	0.115 ± 0.029	0.029 ± 0.009	0.009 ± 0.003	0.007 ± 0.003		
0.68	0.048 ± 0.009	0.012 ± 0.005				
0.76	0.033 ± 0.009					
0.85	0.013 ± 0.006					

TABLE 2

Linear Exponential Fits

$\sqrt{s}$ GeV	$-t$ GeV ²	pp			$\bar{p}p$		
		a mb/GeV ²	b GeV ⁻²	χ^2/DF	a mb/GeV ²	b GeV ⁻²	χ^2/DF
31	.05-.15	93.0 $\pm$ 5.5	11.70 $\pm$ 0.62	9.3/4	90.4 $\pm$ 5.1	11.37 $\pm$ 0.60	4.8/4
	.17-.85	74.0 $\pm$ 3.6	10.92 $\pm$ 0.15	12.0/16	75.6 $\pm$ 4.6	11.16 $\pm$ 0.20	14.3/14
53	.17-.85	72.5 $\pm$ 2.2	11.06 $\pm$ 0.11	11.9/19	78.0 $\pm$ 3.2	11.50 $\pm$ 0.15	12.0/19
	.17-.85	66.4 $\pm$ 1.7	10.71 $\pm$ 0.08	11.2/9	72.3 $\pm$ 3.0	11.12 $\pm$ 0.15	9.2/19

Quadratic Exponential Fits

s GeV	-t GeV ²	pp			$\bar{p}p$			X ² /DF
		A mb/GeV ²	B GeV ⁻²	C GeV ⁻⁴	A mb/GeV ²	B GeV ⁻²	C GeV ⁻⁴	
31	.05-.85	99.4 ± 4.1	12.83 ± 0.34	2.64 ± 0.56	101.6 ± 4.0	13.06 ± 0.39	2.58 ± 0.65	17.0/19
53	.11-.85	62.0 ± 3.7	10.09 ± 0.47	-1.31 ± 0.74	70.0 ± 3.8	10.96 ± 0.44	-0.56 ± 0.74	20.5/21
62	.11-.85	59.9 ± 2.7	10.12 ± 2.9	-0.74 ± 0.40	73.4 ± 4.8	11.30 ± 0.45	0.38 ± 0.69	18.0/21

TABLE 3

		$-t = 0.2 \text{ GeV}^2$	$-t = 0.4 \text{ GeV}^2$	GeV^{-2}
31 GeV	pp	11.77 ± 0.28	10.72 ± 0.32	
	$\bar{p}p$	12.03 ± 0.34	11.00 ± 0.38	
53 GeV	pp	-	11.14 ± 0.32	
	$\bar{p}p$	-	11.41 ± 0.36	
62 GeV	pp	-	10.71 ± 0.24	
	$\bar{p}p$	-	11.00 ± 0.34	

TABLE 4

$\sqrt{s}$ GeV	$-t$ GeV^2	Δb GeV^{-2}
31	0.17-0.85	0.28 ± 0.23
53	0.17-0.85	0.37 ± 0.18
62	0.17-0.85	0.29 ± 0.17

TABLE 5

	$\sqrt{s} = 31 \text{ GeV}$		$\sqrt{s} = 53 \text{ GeV}$		$\sqrt{s} = 62 \text{ GeV}$	
	pp	$\bar{p}p$	pp	$\bar{p}p$	pp	$\bar{p}p$
$\sigma_{\text{tot}}, \text{ mb}$	40.2 ± 0.2 (a,b)	42.0 ± 0.5 (b)	42.9 ± 0.2 (a,b)	43.9 ± 0.5 (b)	43.9 ± 0.3 (a,b)	43.9 ± 0.6 (b)
$\langle d\sigma/dt \rangle_{t=0}$ (optical) mb/GeV^2	82.5 ± 1.0	90.0 ± 2.0	94.0 ± 1.0	98.4 ± 2.5	98.7 ± 2.0	101.8 ± 3.0
$b_{(-t < 0.15)}$ GeV^{-2}	11.70 ± 0.62 (a)	11.37 ± 0.60	13.00 ± 0.20 (c)	13.64 ± 0.50 (c)	13.30 ± 0.30 (a,b)	13.1 ± 0.6 (d)
$b_{(-t > 0.15)}$ GeV^{-2}	10.92 ± 0.15	11.16 ± 0.20	11.06 ± 0.11	11.50 ± 0.15	10.71 ± 0.08	11.12 ± 0.15
$\sigma_{\text{el}}, \text{ mb}$	7.12 ± 0.34	7.94 ± 0.39	7.37 ± 0.13	7.35 ± 0.30	7.61 ± 0.22	7.12 ± 0.40
$\sigma_{\text{el}}/\sigma_{\text{tot}}$	0.177 ± 0.008	0.189 ± 0.010	0.172 ± 0.003	0.167 ± 0.007	0.173 ± 0.005	0.180 ± 0.009
$b_1/\sigma_{\text{tot}}^{-2}$ $\text{mb}^{-1} \text{GeV}^{-2}$	0.291 ± 0.015	0.271 ± 0.015	0.303 ± 0.005	0.311 ± 0.011 (a,b,c)	0.303 ± 0.007 (b,c)	0.298 ± 0.014 (a,b,c)
$b_2/\sigma_{\text{tot}}^{-2}$ $\text{mb}^{-1} \text{GeV}^{-2}$	0.272 ± 0.004	0.266 ± 0.006	0.258 ± 0.003	0.261 ± 0.005	0.244 ± 0.003	0.253 ± 0.005

(a) Average value from the compilation of ref. [6].

(b) Estimated from an interpolation of the data of refs [7], [8] and [13].

(c) Estimated average values from the data of refs [7] and [8].

(d) Value from the data of ref. [8].

FIGURE CAPTIONS

Fig. 1 Elastic differential cross sections at $\sqrt{s} = 31, 53,$ and 62 GeV. Only t -dependent errors are shown. The systematic scale error is estimated at 10% for pp data and 15% for $\bar{p}p$ data. The 31 (53) GeV data have been scaled by a factor of 100 (10) for clarity.

Fig. 2 Compilation of local slopes at $-t = 0.2$ and 0.4 GeV^2 as functions of equivalent laboratory beam momentum. The solid lines in fig. 2(a) are the fits of ref. [14], the dashed lines in fig. 2(b) are included only to show the trend of the data.

Fig. 1

Fig. 2