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Evidence for Coherent Effects in Large Angle Hadron-Hadron Scattering*

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Abstract

We suggest, by looking at pp and $\pi^{+}p$ elastic data, that the evidence for the parton prediction $d\sigma/dt \sim s^{-n}f(\theta)$ is not as convincing as is generally supposed. We also draw attention to the presence of well-defined structures in $(d\sigma/dt)_{\theta}$; these may well reveal a strong component of conventional coherent scattering effects, even at large angles.

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It is usually assumed that in hadron-hadron scattering at large angles ($\theta_{cm} \sim 90^\circ$), conventional coherent effects (such as say diffraction) are small, and that scattering at these angles is dominated by collisions between the constituent partons. Several parton theories[1] have recently been developed to describe large angle scattering, one of the most interesting predictions being that

$$d\sigma/dt \sim s^{-n} f(\theta)$$

where n depends upon the particular model and the particular particles involved in the reaction. It is generally claimed[1] that the experimental data support this prediction.

In the present paper, we examine in detail fixed angle differential cross-sections for pp and π^+p elastic scattering (where the data are most plentiful), and make the following observations: (1) The prediction $d\sigma/dt \sim s^{-n}f(\theta)$ is not well-satisfied; (2) The data in fact contains some well defined fine structure (some of which has been known for years); (3) We replot the $(d\sigma/dt)_\theta$ data in a way which strongly indicates the origin of this structure; (4) We conclude that there are substantial (conventional) coherent scattering effects present even at large angles.

<u>$(d\sigma/dt)_\theta$ v. $\ln s$ plots.</u> In Fig. 1a, we have plotted $(d\sigma/dt)_\theta$ v. $\ln s$ for pp elastic scattering[2] at fixed angles $\theta = 60^\circ$, 70°, 80°, and 90°, and in Fig. 1b the corresponding data for π^+p elastic scattering[3] at $\theta = 60^\circ$, 90° and 120°. Because of beam intensity, the pp data is considerably more accurate and more plentiful. The following features seem fairly evident <u>from the data</u>:

(a) Neither the pp nor the π^+p data follow straight lines (even if one considers only the last few points). Thus $(d\sigma/dt)_\theta$ does not go as a simple power s^{-n}.

(b) The general curvature of the data is such that rough lines through the data are convex up. Thus $(d\sigma/dt)_\theta$ goes faster than a fixed power.

(c) For different angles θ, these rough lines are not parallel. Thus the factorization of the s and θ dependence in $d\sigma/dt$ is only rather approximate.

(d) The fixed angle differential cross-sections for both pp and π^+p are in fact very rich in structure. The π^+p data has distinct dips, while the pp data (which also goes out to much higher energies) seems to possess a sequence of reasonably well-defined breaks (with convex-up sections between). We have drawn lines in Figs. 1a, b to indicate where these breaks seem to occur.[4]

Moreover, we have made an exploratory examination of some other processes ($\pi^-p \to \pi^-p$, π^-p CEX etc.), not shown here. Though the data is much less plentiful, the corresponding $(d\sigma/dt)_\theta$ also indicate structure.

These observations are quite different from those which have been made in the past. However, previous plots of the data do of course contain the curvature and the structure mentioned here (though not easily seen sometimes because of the compressed logarithmic scales used), but these features seem to have been ignored. We take the point of view that these features are presumably telling us about some reasonably strong component that is present in scattering at large angles. It seems important therefore, in view of the present interest in large angle and large $p_\perp$ scattering in elastic and inclusive processes, to try to determine the origin of this structure. In particular, what is the correlation between the succession of breaks in $(d\sigma/dt)_\theta$ for a given fixed θ, and what is the correlation between corresponding breaks for different θ's?

<u>$(d\sigma/dt)_\theta$ v. t plots.</u> It will be noted from Fig. 1 that corresponding breaks in $(d\sigma/dt)_\theta$ drift in p_{lab}'ns as θ is changed from one value to another. This suggests that perhaps there is another variable where these corresponding breaks will not drift as θ is changed. Such a variable which brings this about is t, the momentum transfer squared (or possibly even more appropriate from what we will say below, the variable $\sqrt{-t}$). In Figs. 2a, b, we have plotted the same pp, π^+p $(d\sigma/dt)_\theta$ data over again, using the linear $t = -2k^2(1 - \cos\theta)$ variable along the abscissa. It is clear that all the corresponding breaks for different θ line up. To emphasize this point further, we have included in Fig. 2a the fixed angle pp $(d\sigma/dt)_\theta$ for $\theta = 40^\circ$, 30°, and even 3°! The 3° curve incorporates the recent CERN ISR data[2] at 245, 500, 1070 and 1500 GeV/c equivalent lab momenta, where pp scattering is generally believed to be dominated by optical diffraction.

<u>Where are the breaks?</u> For π^+p, the dip or break structures observed so far seem to be located rather clearly at the following positions:

$$\pi^+p: \quad t \approx -0.6,\ -2.8,\ \text{and}\ -5\ (\text{GeV/c})^2 \quad .$$

For pp, the breaks seem to us to be located at

$$\text{pp}: \quad t \approx -0.9,\ -3,\ -5.5,\ -7.5,\ \text{and}\ -10.5\ (\text{GeV/c})^2$$

as indicated by the curves drawn in Fig. 2a.

The fact that the various $(d\sigma/dt)_\theta$ curves line up with their breaks at these particular t-values, whatever the angle θ, leads to a rather simple interpretation of these breaks and to an important statement about what is happening at large (and small) angles.

Previous observations. The π^+p dips in $(d\sigma/dt)_\theta$ are of course just reflections of the well known structures in $(d\sigma/dt)_s$. (A clear demonstration of these at 4, 5 GeV/c is contained in Fig. 1a of Barger and Phillips.[5]) The breaks in $pp(d\sigma/dt)_\theta$ however indicate subtleties in $(d\sigma/dt)_s$ which are less obvious[6] to the eye. Actually some of these breaks in $pp(d\sigma/dt)_\theta$ have been known for some time. A break around $t \approx -6$ $(GeV/c)^2$, or equivalently at $\beta^2 p_\perp^2 \approx 2.6$ $(GeV/c)^2$, was first noticed by Akerlof, Krisch et al.[2,7], while more recently, Kammerud et al.[2] suggested the breaks at $t \approx -0.9$ and $-3(GeV/c)^2$. At the same time, there have been several theoretical proposals to explain these breaks; we refer the reader to Kammerud et al.[2] for a discussion of these.

Interpretation of the breaks. We wish to suggest that these fixed angle breaks are due to familiar coherent scattering phenomena. For the sake of simplicity, we shall interpret these structures in terms of the idealized gray disk model; the conclusions are essentially the same even when a more realistic optical model[8] with smooth impact parameter profiles is used.

For scattering from a gray disk, the main contribution comes from diffraction, the diffraction amplitude being of the form

$$D \sim i\, J_1(R\sqrt{-t})/R\sqrt{-t}\ .$$

If diffraction were important anywhere, that is it is present (possibly among other contributions) to a significant degree, one would expect to see its most noticeable trademark, namely the oscillations of the J_1 Bessel function. These oscillations will be fixed in t, or equivalently in $\sqrt{-t}$. We suggest that, to a large extent, this is what we see in the fixed angle $(d\sigma/dt)_\theta$.

π^+p breaks. For an interaction radius R = 0.9 Fermi, the zeros of the J_1 Bessel function occur at $t \approx -0.7$, -2.4 and -5.1 $(GeV/c)^2$, which indeed are very close to the positions of the breaks observed.

pp breaks. The break structure for pp seems to be slightly more complicated than in the π^+p case (probably because the data are much better), and it would seem that a simple diffractive piece $i\, J_1(R\sqrt{-t})/R\sqrt{-t}$ alone with $R \approx 0.8$ Fermi which has zeros at $t \approx -0.9$, -3, -6.5, -11 $(GeV/c)^2$ is not sufficient; one needs in addition a peripheral piece, which is typically of the form $i\, J_0(R\sqrt{-t})$. (A peripheral piece of this type is of course highly desirable anyway to help explain the crossover in pp, $\bar{p}p$ $(d\sigma/dt)_s$ at $t \approx -0.2$ $(GeV/c)^2$.) The peripheral piece is almost swamped by the diffractive piece in the forward directions, but for large $|t|$ the two pieces can become comparable and cause a slightly more complicated pattern of oscillations. Our numerical calculations[8,9] bear this out.

Corroborative evidence. In a recent experiment at Argonne, Abshire et al.[10] measured the polarization parameter P for pp elastic scattering at 12.33 GeV/c out to very large values of the momentum transfer $|t| \leq 6.5\ (\text{GeV/c})^2$. This experiment revealed the extremely interesting result that at this energy the pp polarization has a sequence of double zeros, at $t \approx -0.8$, -2.4, and $-5.5\ (\text{GeV/c})^2$. This surprising result is very difficult to explain in terms of say Regge theories but is easily interpretable[9] (in fact it was predicted[8]) in terms of a gray disk type of optical model: taking the diffraction amplitude with a (peripheral) flip amplitude, one anticipates polarization of the form $[J_1(R\sqrt{-t})]^2/R\sqrt{-t}$. With R = 0.8 Fermi, one gets double zeros close to the positions observed, indicating again that the diffractive piece plays a very important role at least out to $|t| \approx 6\ (\text{GeV/c})^2$.

Conclusions.

(1) We have examined fixed angle $(d\sigma/dt)_\theta$ for both π^+p and pp elastic scattering. The evidence for a simple law of the form $d\sigma/dt \sim s^{-n}f(\theta)$ does not seem to be as convincing as has been claimed.

(2) On the other hand, we draw attention to the presence of structure in these fixed angle differential cross-sections, which can all be lined up (whatever the value of θ) when $(d\sigma/dt)_\theta$ is plotted against t.

(3) In the case of pp scattering, these breaks tie in nicely with the double zeros of the elastic polarization.[11]

(4) The above points (1)-(3) follow from an examination of the data alone, and do not depend on any model. We note, however, that all the observed structures occur at or near the zeros of Bessel functions, suggesting a substantial diffractive component (and possibly also some peripheral component) even out at large angles ($\theta \sim 90^{\circ}$). It seems reasonable to conclude therefore that conventional coherent effects, though small at large angles, are certainly not negligible there (as is usually presumed to be the case[1]), and in fact, are present to a rather noticeable degree.

This observation may have important implications for other processes, such as high energy inclusive processes. For example, a well known property of inclusive differential cross-sections $E\, d^3\sigma/dp^3$ is that for larger $p_\perp$, the data gets flatter, rather reminiscent of the elastic pp differential cross-sections. It will be interesting to see if it is possible also to interpret some of this inclusive data in terms of more standard volume and surface phenomena, which are characterized by a geometric interaction radius rather than by a specific dynamical model.

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References

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2. O. Benary et al., NN Compilation UCRL - 20000 (1970), 1 - 21 GeV/c; R. Kammerud et al., Phys. Rev. D4, 1309 (1971), 1.5 - 5.5 GeV/c; A. Böhm et al., CERN report (1973) 250 - 1500 GeV/c. The data were graphed separately for each energy. Smooth curves were drawn by hand through the data in order to obtain interpolations between points, when necessary.

3. C. Lovelace et al., πN Compilation LBL-63 (1973), 0.5 - 1.5 GeV/c; K. Abe et al., Maryland Report 73-104 (1973), 1.2 - 2.3 GeV/c; C. T. Coffin et al., Phys. Rev. 159, 1169 (1967), 2.3 - 4 GeV/c; B. B. Brabson et al., Phys. Rev. Letts. 25, 553 (1970), 3 - 5 GeV/c; D. Rust et al., (unpublished), 3 and 4 GeV/c (agrees with Brabson et al.); D. Rust et al., Phys. Rev. Lett. 24, 1361 (1970), 5 GeV/c; V. Chabaud et al., Phys. Lett. 38B, 441 (1972) and to be published, 5 and 10 GeV/c.

   C. W. Akerlof et al., Phys. Rev. Lett. 27, 219 (1971), 5 GeV/c. The data of Chabaud et al., at 5 GeV/c lie below the data of Rust et al. and Akerlof et al. (which agree) by a factor of roughly 2. The Rust et al. data also agrees with other low-t measurements.

4. In the case of π^+p between 5 and 10 GeV/c where there is no large angle data available, we have indicated (Fig. 1b) where we expect the breaks to occur - this has been inferred from Fig. 2b, where the breaks occur at fixed t.

5. V. Barger and R. J. N. Phillips, Nucl. Phys. B33, 22 (1971).

6. The change of slope in $pp(d\sigma/dt)_s$ at $t \approx -1.4\ (GeV/c)^2$ is well known. Other features however, such as a point of inflection at $t \approx -3\ (GeV/c)^2$ for $10 \leqslant p_{lab} \leqslant 20$ GeV/c, are less discernible.

7. A. Krisch, Phys. Rev. Letters 19, 1149 (1967).

8. S.-Y. Chu and A. W. Hendry, Phys. Rev. D6, 190 (1972), ibid D7, 86 (1973).

9. A. W. Hendry and G. Abshire, submitted to Phys. Rev. Letts.

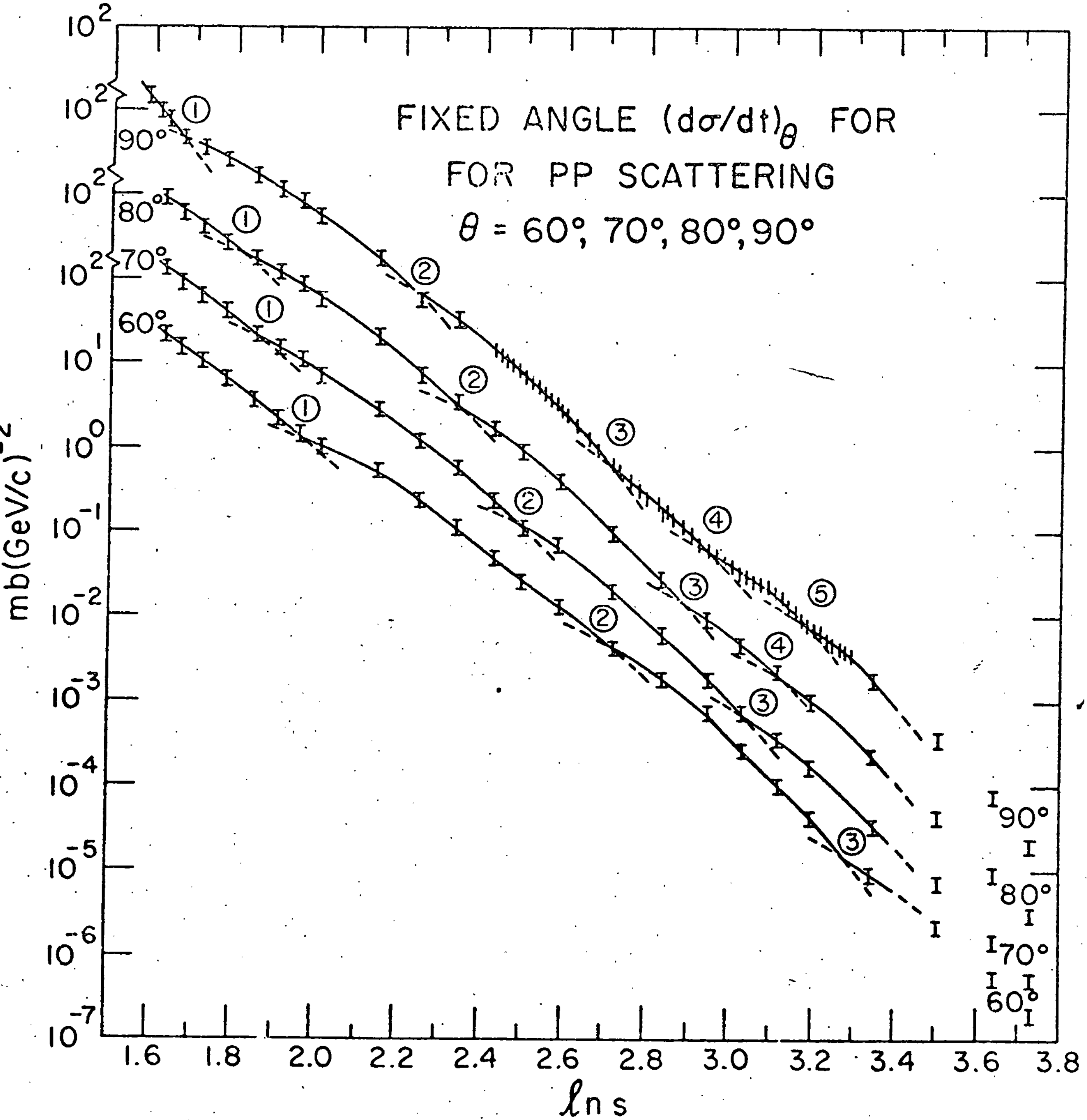
10. G. Abshire et al., submitted to Phys. Rev. Letts.

11. We expect this to be the case also when πp polarizations are measured out to large $|t|$.

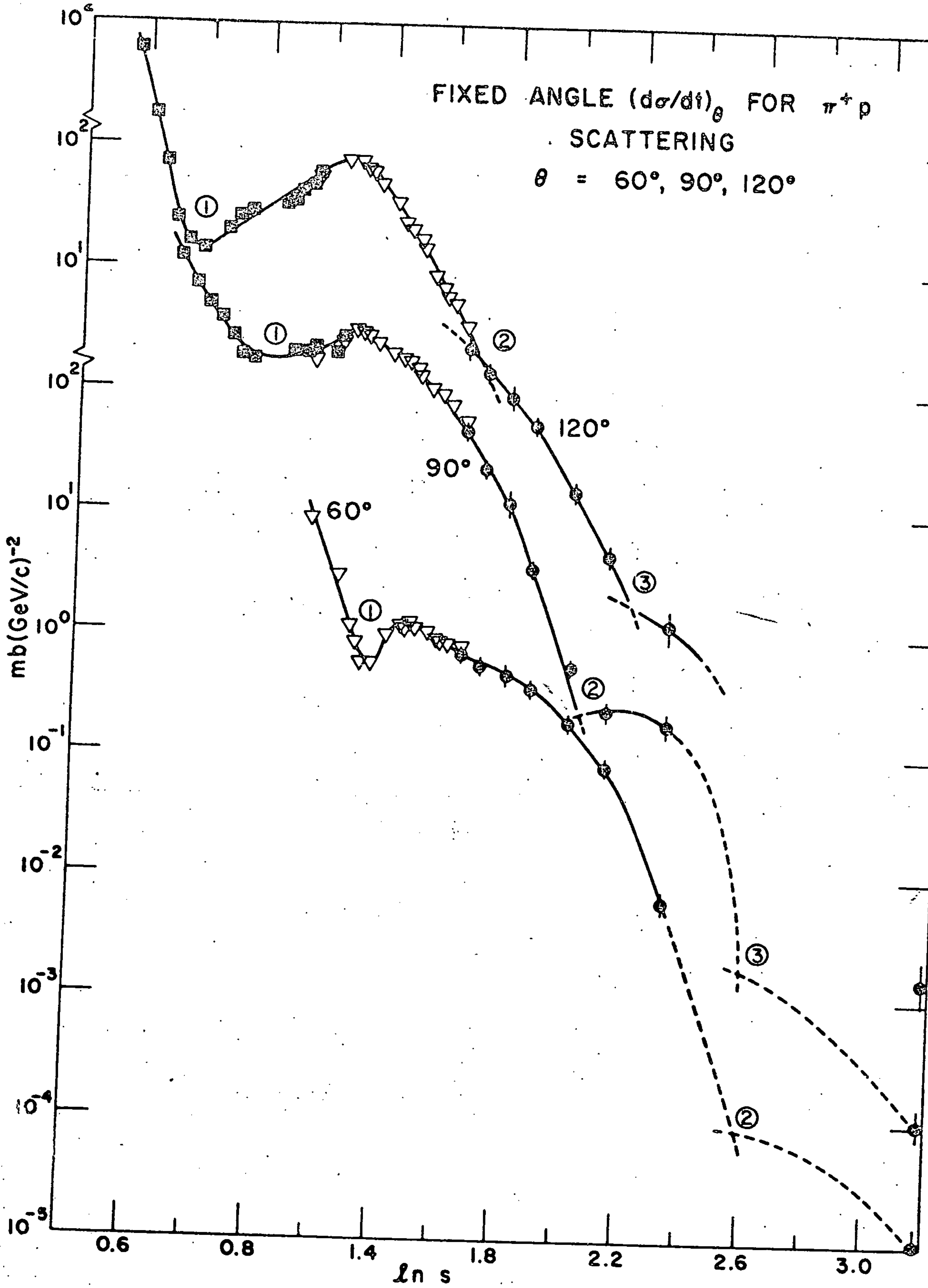
Figure Captions

Fig. 1 Fixed angle differential cross-sections for (a) pp, (b) π^+p elastic scattering plotted against $\ln s$. Data from Refs. 2, 3.

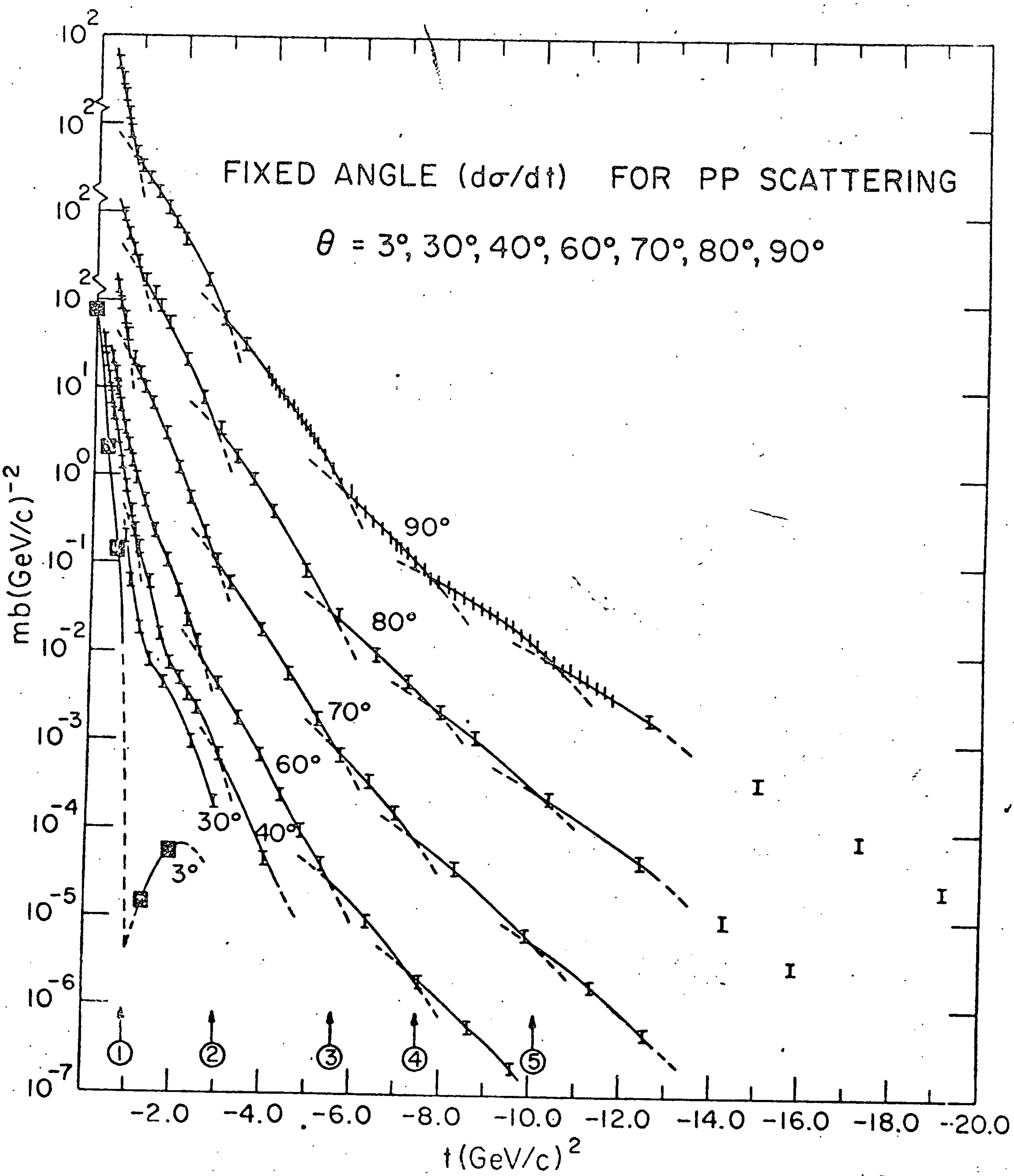
Fig. 2 Fixed angle differential cross-sections for (a) pp, (b) π^+p elastic scattering plotted against t. Data from Refs. 2, 3.

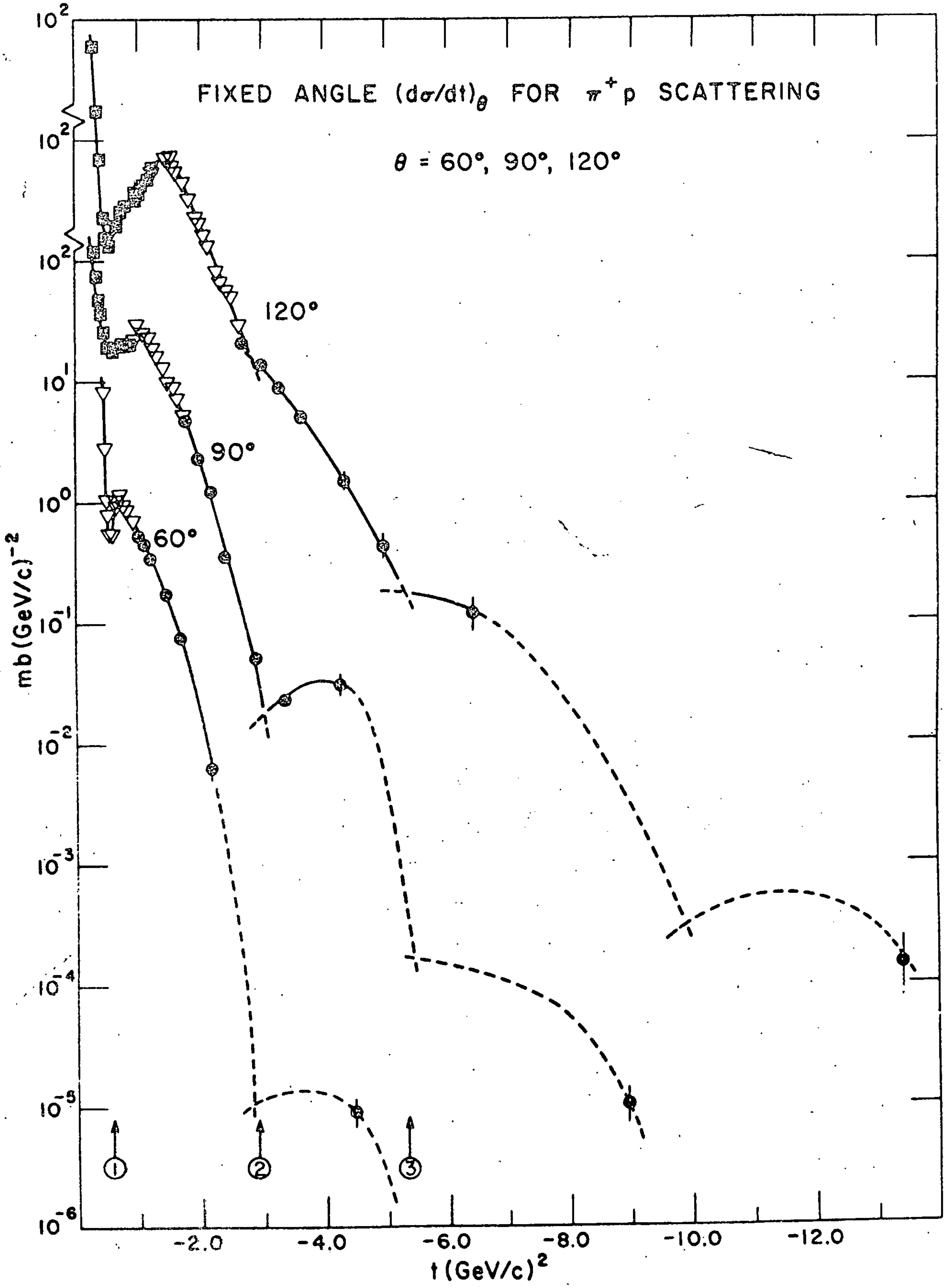


FIXED ANGLE (dσ/dt)θ FOR
FOR PP SCATTERING
θ = 60°, 70°, 80°, 90°
mb(GeV/c)⁻²
ln s
90°
80°
70°
60°



FIXED ANGLE $(d\sigma/dt)_\theta$ FOR $\pi^+ p$ SCATTERING
θ = 60°, 90°, 120°
120°
90°
60°
mb(GeV/c)$^{-2}$
ln s
0.6
0.8
1.4
1.8
2.2
2.6
3.0


FIXED ANGLE (dσ/dt) FOR PP SCATTERING
θ = 3°, 30°, 40°, 60°, 70°, 80°, 90°
mb(GeV/c)^-2
t(GeV/c)^2
90°
80°
70°
60°
30°
40°
3°
-2.0 -4.0 -6.0 -8.0 -10.0 -12.0 -14.0 -16.0 -18.0 -20.0
10^2 10^2 10^2 10^2 10^1 10^0 10^-1 10^-2 10^-3 10^-4 10^-5 10^-6 10^-7
1 2 3 4 5



FIXED ANGLE (dσ/dt)θ FOR π⁺p SCATTERING
θ = 60°, 90°, 120°
120°
90°
60°
mb(GeV/c)⁻²
t (GeV/c)²
10²
10²
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
-2.0
-4.0
-6.0
-8.0
-10.0
-12.0
1
2
3