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Presented at the Workshop on $p\bar{p}$ Options for the Supercollider, Chicago, IL, February 13-17, 1984

THEORETICAL PERSPECTIVES ON ELASTIC AND TOTAL CROSS SECTIONS AT THE SSC

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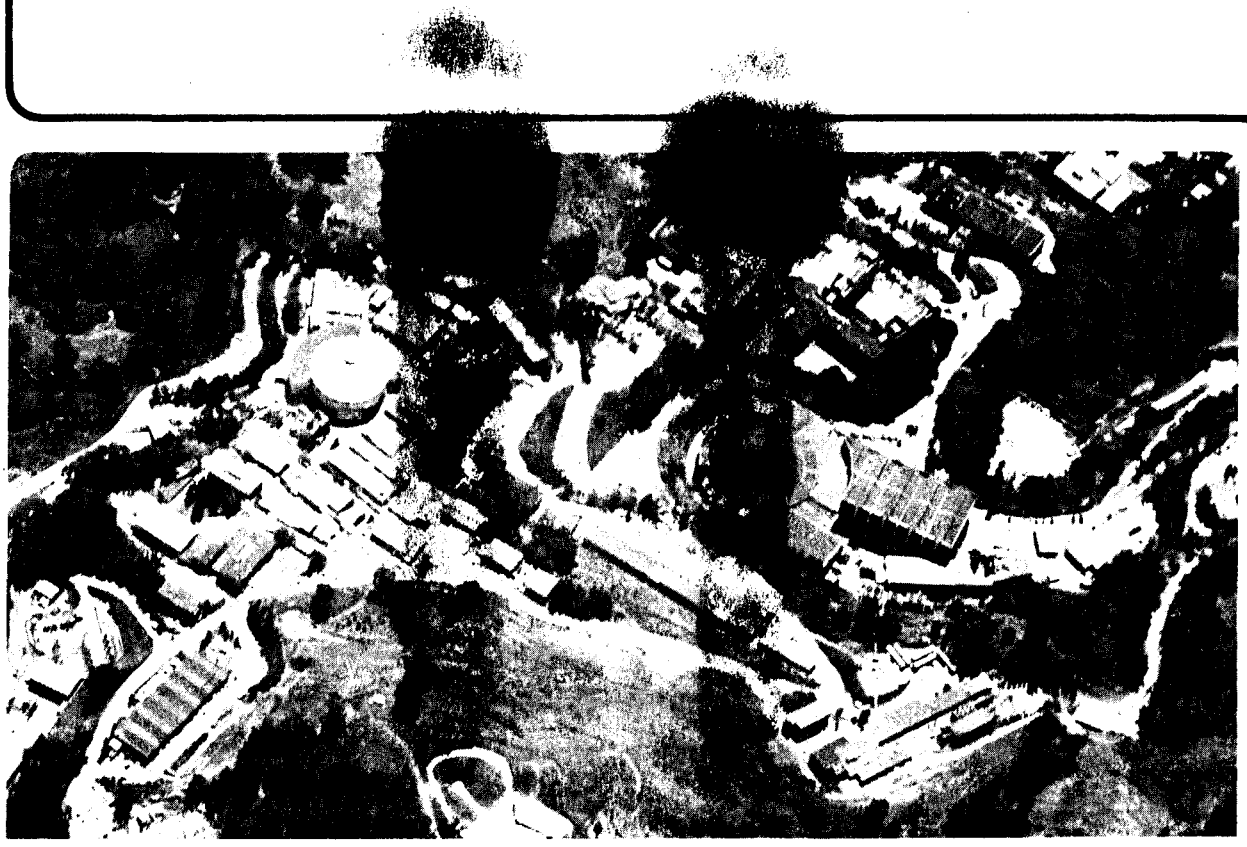
March 1984



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Theoretical Perspectives on Elastic and Total Cross Sections at the SSC*

Talk presented at the Workshop on $p\bar{p}$ Options for the Supercollider, Chicago, IL from February 13-17, 1984.

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ABSTRACT

Predictions for elastic and total cross sections at the SSC are discussed. Speculations about the role of such quantities in future theories are given.

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INTRODUCTION

Why should we care about "log s" physics, that is, scattering with low momentum transfer, when most of the high energy community — not to speak of the New York Times and the slick popular science magazines — seems interested only in heavy new particles and jets with high transverse momentum? A possible reason is that it would be somehow a neglect of our duties to ignore 99.9% of the events. This is hardly convincing since an imperative of science is to isolate those facts which are essential from the overwhelming number which are equally true but are too complex to lead to new understanding. A utilitarian response is that the soft physics must be understood because it will be a background for the more interesting hard physics. This is certainly true but does not justify a thorough program of experimental and theoretical investigation.

Forward elastic scattering is an excellent testing ground for the principles of analyticity, but this is still a rather limited objective. It can be argued that one should study "log s" physics because there may be surprises beyond our ability to anticipate. Such arguments can always be given for the physics program at an energy never before attained and indeed this is the best argument for a new accelerator in general, but it does not speak to the more specific question of "log s" physics.

I would like to suggest that by the time the SSC is operating, the soft physics may be of much greater interest than it is now. The present lack of interest is clearly the result of the absence of a useful model of soft interactions based in a convincing way on the accepted theory of hadronic interactions, QCD. Were there such a model it would presumably tell us about some of the simplest facts of pp scattering: why is the pp cross section 50% higher at the $Sp\bar{p}S$ collider than at the ISR and will the cross section continue to rise as $\log^2 s$? Such a model would presumably

make predictions about multiparticle processes as well and confront the facts and hypotheses discussed by J. Rushbrooke and A. White in these proceedings.

Of course I do not have such a model nor is one on the horizon. Lattice calculations are being used to estimate hadronic masses from QCD, but such calculations are primitive and have an objective far short of the calculation of elastic cross sections. What is needed is a less fundamental approach but one still rooted in, or better derived as an approximation to, QCD. Perhaps the Thomas-Fermi model of the atom is an example of an analogous model which gives up the description of details in order to achieve a tractable and quantitative but approximate scheme.

When much of our time is spent talking of gluinos and technipions, is it too speculative to suggest that within ten years we might have such a QCD-based model of hadronic interactions? Armed with this model we would perceive soft physics at the SSC a fantastic source of new data. It is easy to imagine that the newly opened opportunities in non-perturbative QCD would seem much more fascinating that the perturbative aspects which would have been explored so thoroughly in the preceeding fifteen years.

FORWARD ELASTIC SCATTERING AND TOTAL CROSS SECTIONS [1]

From the grandiose speculations above we turn to the concrete realities of experiment and the limited theoretical tools at our disposal. Nearly forward elastic scattering provides three experimental quantities,

$$\sigma_{\rm TOT} \sim Im\mathcal{M}, \tag{1}$$

$$\rho(0) = \frac{Re\mathcal{M}(t=0)}{Im\mathcal{M}(t=0)}, \tag{2}$$

$$B(s,t=0) = \left(\frac{d}{dt} ln \frac{d\sigma}{dt}\right)_{t=0}, \tag{3}$$

where $\mathcal{M}$ is the elastic scattering amplitude. In the very small t region ($|Bt| \ll 1$) we must add to the hadronic amplitude $\mathcal{M}$ a contribution from Coulombic scattering:

$$\mathcal{M}_{\rm TOT} \sim (i+\rho)\frac{\sigma_{TOT}}{4\pi} + \frac{2\alpha}{t}. \tag{4}$$

The first term represents the hadronic amplitude with a normalization such that (1) becomes

$$\sigma_{\rm TOT} = 4\pi Im\mathcal{M}. \tag{5}$$

The hadronic and Coulombic amplitudes are equal in magnitude at a value $-t_0$ given by (for $\rho \ll 1$)

$$\begin{aligned} -t_0 &= \frac{8\pi\alpha}{\sigma_{\rm TOT}} \\ &\approx 4\cdot 10^{-4}{\rm GeV}^2 \end{aligned} \tag{6}$$

if $\sigma_{\rm TOT} \approx 200$mb. For $p_{cm} = 20$TeV, this occurs for $\theta = \sqrt{-t_0}/p_{cm} =$ 0.001 mradians. The practicalities of this are discussed by A. Kernan in these Proceedings. Suffice to say here that the interference between the Coulombic and hadronic amplitudes will be easier to observe if the

beam energy is lowered to 5 or 10 TeV. If the true Coulomb region can be measured, where $-t$ is much less then $-t_0$, the cross section can be normalized directly and the total cross section ascertained. The differential cross section in the region around $-t_0$ can be used to determine ρ. At larger values of $-t_0$, the differential cross section falls approximately as $\exp(Bt)$. See Fig. 1 for an example of ISR data for $p\bar{p}$.

What are the expectations for σ_{TOT}, ρ and B at the SSC? M. Block and I have made extrapolations by fitting the $t = 0$ elastic scattering amplitude with functions with the proper analyticity.[2] This approach is simpler than conventional dispersion relations and allows us to fit the data for σ_{TOT} and ρ simultaneously. The simplest fit has the behavior for high s

$$\sigma_{TOT} \simeq A + \beta \log^2 s/s_0. \tag{7}$$

This fit is an excellent one, $\chi^2/d.f. = 1.146$ for 75 degrees of freedom (see Fig. 2). At $\sqrt{s} = 40$TeV we find $\sigma_{TOT} = 196 \pm 3$mb. In this fit we have assumed $\sigma_{p\bar{p}} - \sigma_{pp} \sim s^{-1/2}$ so the difference is negligible at the SSC. In Fig. 3 the corresponding fit and prediction for ρ are given. It is relatively flat with $0.15 \leq \rho \leq 0.20$ for $100\text{GeV} \leq \sqrt{s} \leq 10^5\text{GeV}$.

While a cross section growing as $\log^2 s$ has some aesthetic appeal in that this is the fastest growth allowed by the Froissant bound, it may be that this apparent form for the growth is transitory and does not persist indefinitely. In order to quantify this, we introduced[3] an analytic form which gives a cross section

$$\sigma_{TOT} \simeq A' + \beta' \frac{\log^2 s/s_0}{1 + a\log^2 s/s_0}. \tag{8}$$

For a small positive a this gives a cross section which is asymptotically constant but which for a large range of s near s_0 is nearly identical to (7). If we fit the form (8), the smallness of a is a measure of our confidence in the simpler form (7). Our most recent fits give $a = 0.0082 \pm 0.003$. The parameter a is analogous to the parameter Λ used to quantify the agreement between QED and experiment. There Λ is a mass scale in a hypothetical form factor for the electron. A large Λ means QED is working well. Here a small a means the Froissant bound form is working. The curves corresponding to this fit are shown also in Fig. 2 and 3. It is apparent that a total cross section of $\sim$ 100mb at the SSC can be accommodated by allowing $a \neq 0$. The fit is again excellent with $\chi^2/d.f. = 1.112$ for 74 degrees of freedom.

All data are consistent with the usual assumption:

$$\Delta\sigma = \sigma_{p\bar{p}} - \sigma_{pp} \sim s^{\alpha-1}$$

with $\alpha \approx 1/2$. There is, however, no convincing theoretical argument that $\Delta\sigma$ must decrease if σ_{pp} and $\sigma_{p\bar{p}}$ increase. Indeed, if $\sigma_{TOT} \sim (\log s)^\gamma$ then $\Delta\sigma \sim (\log s)^{\gamma/2}$ is permissible. Accordingly, Block and I have tried fits to σ_{pp}, $\sigma_{p\bar{p}}$, ρ_{pp}, and $\rho_{p\bar{p}}$ with the high energy cross sections behaving as $\sigma_{TOT} \sim \log^2 s$, $\Delta\sigma \sim (\log s)$. In Figs. (4) and (5) we show the results. At the SSC our best fit has $\sigma_{pp} - \sigma_{p\bar{p}} \sim 5\text{mb} \pm 2.5\text{mb}$. We interpret this as saying the present data do not require the term with $\Delta\sigma \sim \log s$, but they are consistent with such behavior of the indicated magnitude. The effect on ρ is much more dramatic: at the SSC $\rho_{p\bar{p}} - \rho_{pp} \approx 0.10$.

The moral is clear: pp and $p\bar{p}$ elastic scattering may well be nearly identical at the SSC, but the data available until now are not

inconsistent with there being substantial differences. To find out which is the case, we need both pp and $p\bar{p}$.

NON-FORWARD ELASTIC SCATTERING

Away from the forward direction, we do not have as effective contraints from analyticity and models assume a more prominent role. Although M. Islam presented a model at this meeting in which $d\sigma/dt$ is not the same for pp and $p\bar{p}$, and Alan White conjectured that there would be a difference at high energies if the color group had turned out to be SU(n) for n > 3, it is commonly assumed that the two differential cross sections will be nearly identical at the SSC.

The models of the 60's and 70's have not been completely successful in detail in predicting results for the ISR and the SPS Collider. Still, they have certain features which remain attractive. We mention a few briefly.

i. Chou-Yang Model [4]

A simple and attractively physical model in which elastic scattering is the shadow of the absorption. This absorption is postulated to be due to a hadronic matter distribution which is the same as the charge distribution measured by the electromagnetic form factors. Thus the only unknown is the strength of the absorption and this is fixed by requiring that the total cross section be reproduced. The simplest version of the Chou-Yang model cannot fit the ISR data completely, but some modifications have been suggested which improve the agreement. The original model had a purely imaginary elastic amplitude and very sharp diffraction minima. An estimate can be made of the real part of the amplitude and its inclusion fills in the dips somewhat.

ii. Cheng-Walker-Wu Model [5]

Field theoretic studies by Cheng and Wu suggested that at high energies the elastic scattering amplitude should be viewed as due to a series of exchanges, each of which gave a behavior $s^{1+\epsilon}$. In the CWW model the Froissart bound is regained by eikonalizing. An up-to-date version of this model was presented at this meeting by C. Chiu. His prediction for the SSC has a prominent dip at $-t = 0.45\text{GeV}^2$.

iii. Geometrical Scaling Model [6]

An *ad hoc* but rather successful model has been developed by Dias de Deus and co-workers. It proceeds from the assumption that the elastic scattering amplitude is a function of $t\sigma_{\text{TOT}}$ only. Since the only dimensionful parameter in the model is σ_{TOT}, it follows that $\sigma_{\text{el}}/\sigma_{\text{TOT}}$ and σ_{TOT}/B must be constant. This holds at the ISR, but not at lower energy and perhaps not at the SPS Collider. Again, a real part may added to the elastic amplitude by a plausible prescription.

iv. Ball-Zachariasen Model [7]

In 1972, Ball and Zachariasen developed a model by solving self-consistently the multiperipheral model for diffractive scattering. The result was a model in which $\sigma_{\text{TOT}} \sim \log s$, $\sigma_{\text{el}} \sim$ constant, and the diffraction peak shrank as $\log^2 s$. The differential cross section corresponded to that produced by a disk whose radius grew as $\log s$ but whose blackness decreased as $(\log s)^{-1}$.

v. Donnachie-Landshoff Model [8]

A very recent model has been proposed in which elastic scattering must be view as resulting from numerous exchanges. At low t, single Pomeron exchange dominates. At large t, it is triple gluon exchange which is most important. In between, double Pomeron exchange is especially

important. Several terms are included as well. The result is an excellent fit to ISR data.

CONCLUSIONS

The great advances in our theoretical understanding which have been achieved in the past few years - the orthodoxy of QCD and the electroweak unification - have not shed much light on elastic scattering. We may still hope that a connection will be achieved between QCD and soft physics. If that occurs, the data from the SSC will be invaluable because the enormous step in energy will clarify the trends we are beginning to see at the SPS Collider. If there are no theoretical breakthroughs, the elastic scattering data will continue to play its traditional role : a test of analyticity and of detailed phenomenological models.

There is no convincing evidence that there should be a difference between pp and $p\bar{p}$ scattering at the SSC, but a careful analysis of existing data shows that such a difference cannot be excluded. There could be differences in the total cross sections of a few millibarns and the ρ values could differ by 0.1. Such a discovery would be of enormous significance but is unattainable unless we have both pp and $p\bar{p}$ data at these high energies. While such a comparison would be quite interesting, in the absence of more compelling motivation for expecting a difference, our advocacy of having both pp and $p\bar{p}$ must be appropriately modest.

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[1] This material comes from a review currently being written in collaboration with M. Block.

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[6] See *e.g.* A.J. Buras and J. Dias de Deus, Nucl. Phys. **B71**, 481 (1974); J. Dias de Deus and P. Kroll, J. Phys. G9: L81 (1983).

[7] J.S. Ball and F. Zachariasen, Phys. Lett. **40B**, 411 (1972).

[8] A. Donnachie and P.V. Landshoff, Phys. Lett. **123B**, 345 (1983) and Cambridge Univ. preprint M/C TH-83/13.

FIGURE CAPTIONS

Fig. 1 Data for $p\bar{p}$ elastic scattering in the Coulomb interference region. The sharp rise at very low $-t$ is from the pure Coulombic interaction. Data obtained by the Northwestern-Louvain Collaboration. Figure courtesy of M.M. Block.

Fig. 2 The pp (dots) and $p\bar{p}$ (crosses) total cross sections as a function of $\sqrt{s}$. At low energies the solid curve is a fit for pp, the broken curve is a fit for $p\bar{p}$. At very high energies in this fit $\sigma_{pp} \simeq \sigma_{p\bar{p}}$. The upper curve corresponds to Eq. (7) and the lower to Eq. (8). (Refs. 1,2).

Fig. 3 The ρ values for pp and $p\bar{p}$ as a function of $\sqrt{s}$. As in Fig. 2, at very high energies the two curves correspond to two different fits. The upper curve goes with the fit which gives Eq. (7) and the lower goes with Eq. (8). (Ref. 1,2).

Fig. 4 The pp and $p\bar{p}$ total cross sections as a function of $\sqrt{s}$. Both cross sections rise asymptotically as $\log^2 s$, but their difference here is allowed to vary as $\log s$. At very high energies $\sigma_{pp} > \sigma_{p\bar{p}}$. (Ref. 1,2)

Fig. 5 The ρ values for pp and $p\bar{p}$ as a function of $\sqrt{s}$ when $\Delta\sigma$ is allowed to grow as $\log s$ for $\sigma \approx \log^2 s$ The upper curve is $p\bar{p}$, the lower pp. (Ref. 1,2).

Figure 1

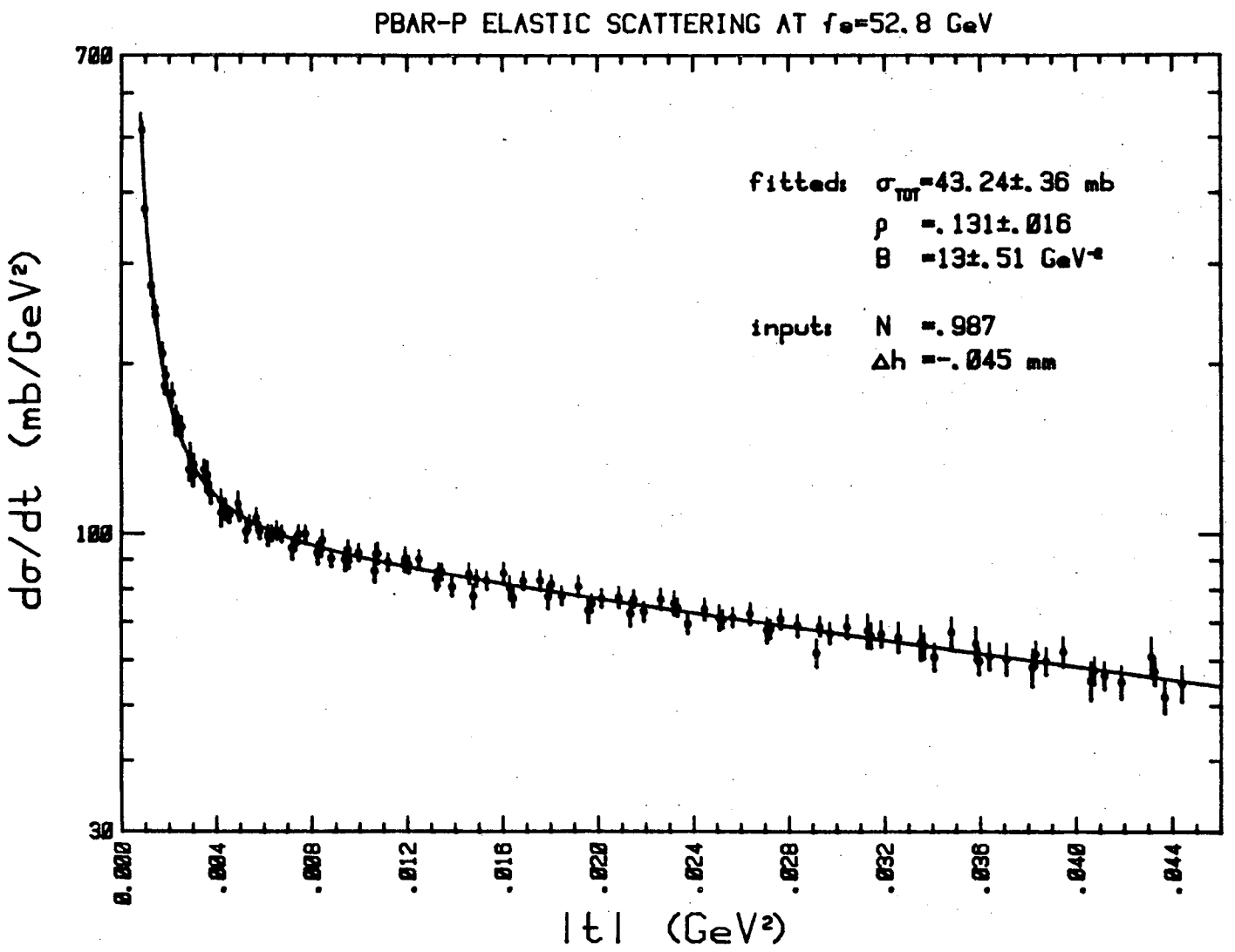
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Figure 2

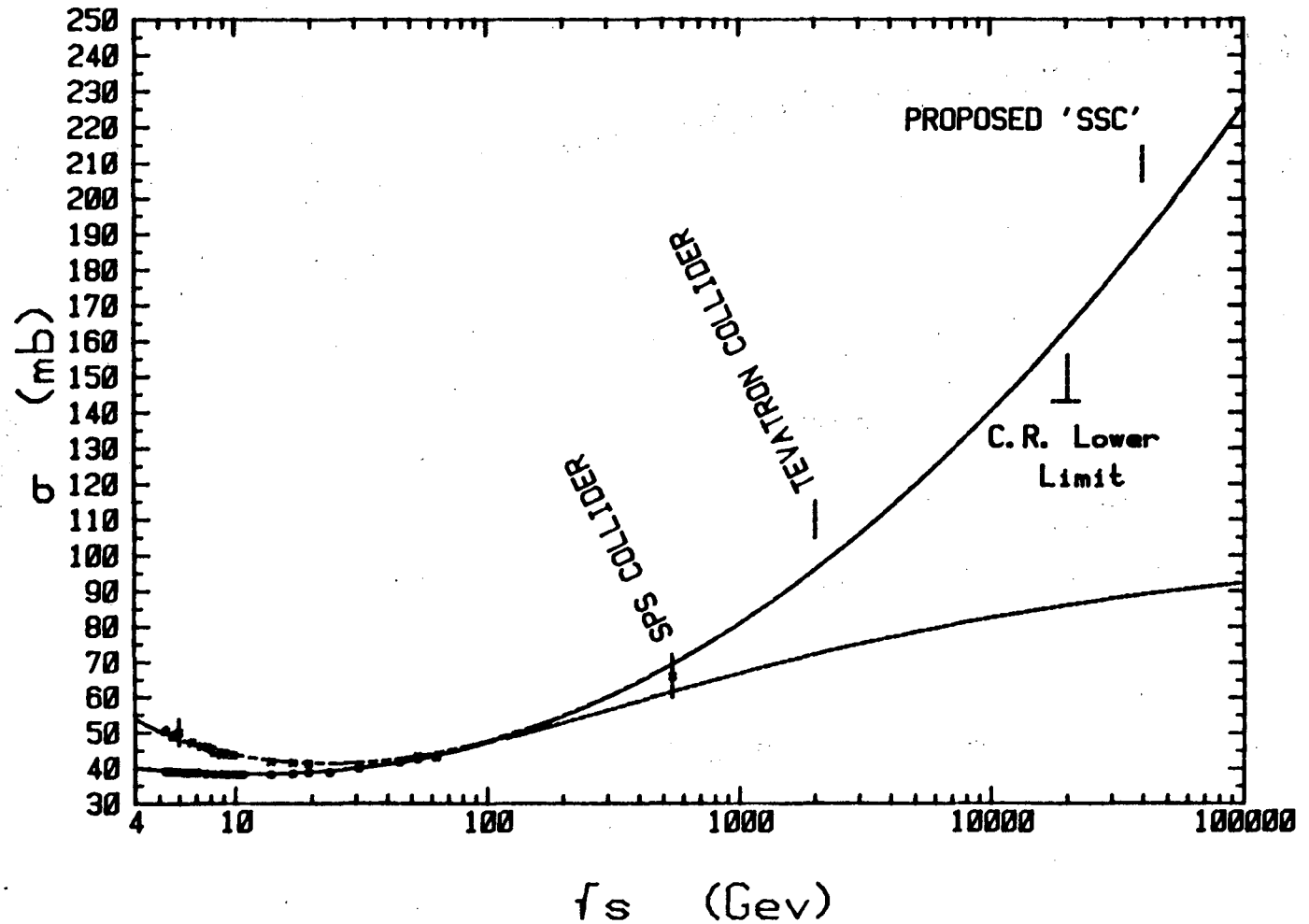
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Figure 3

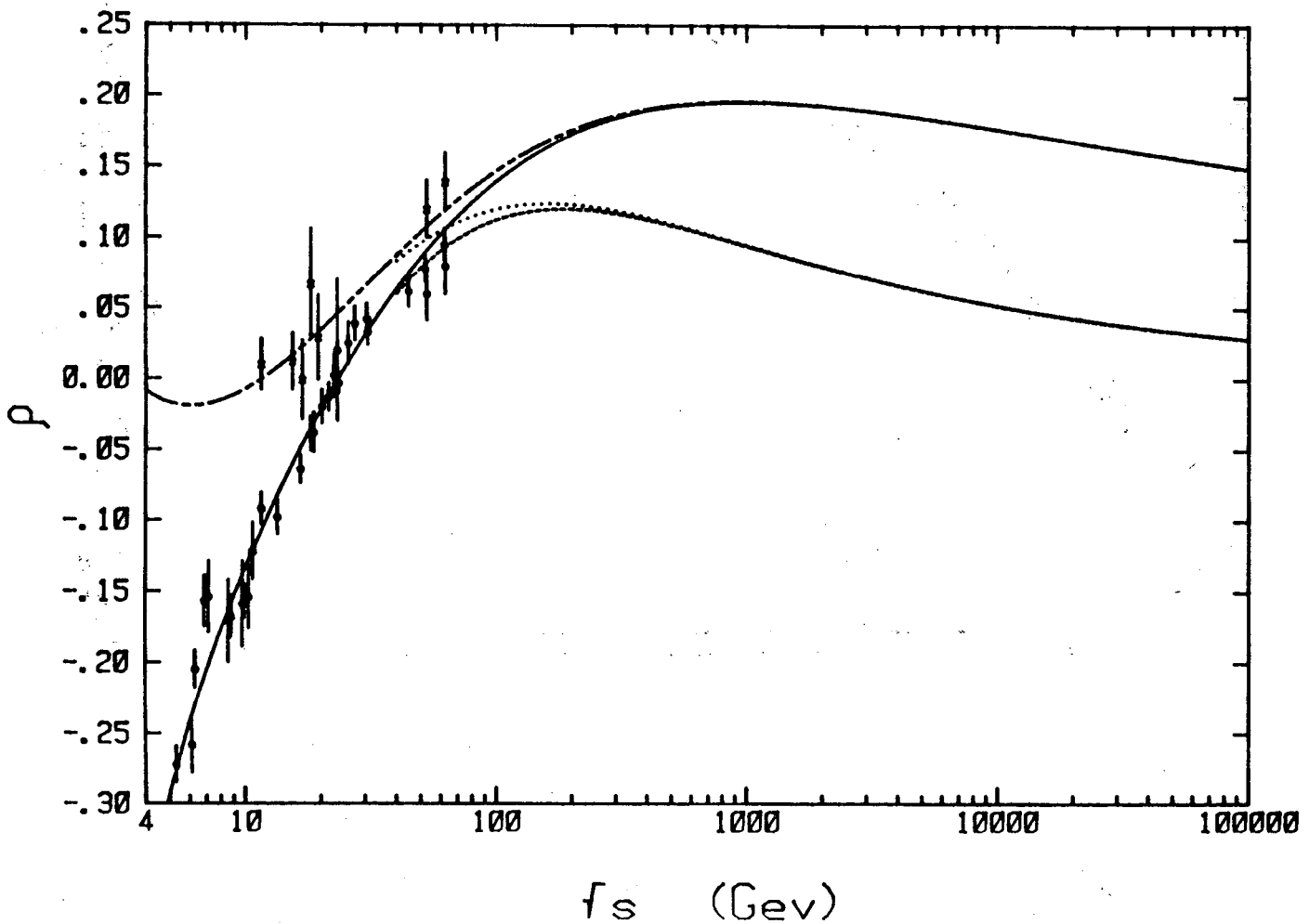
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Figure 4

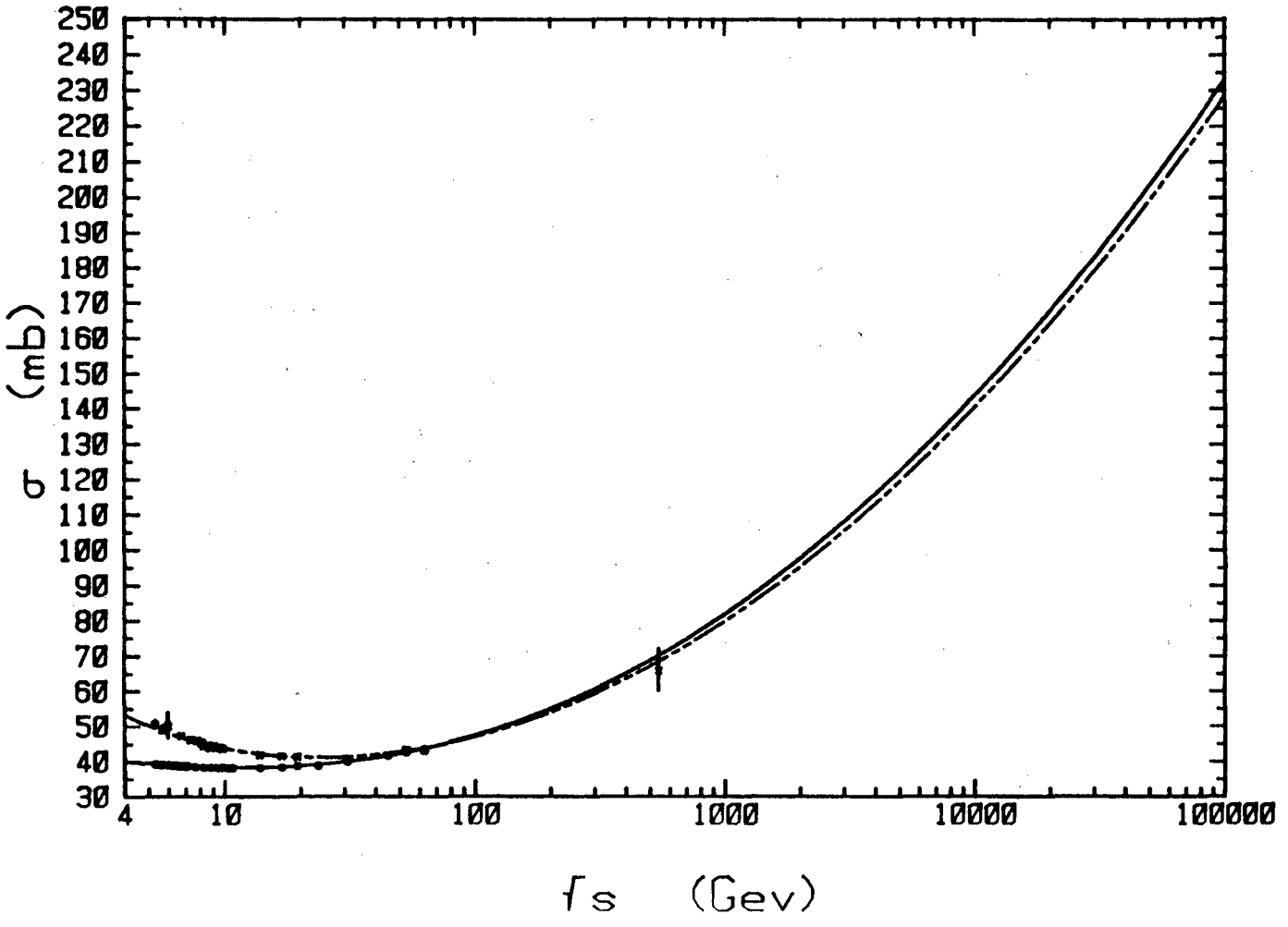
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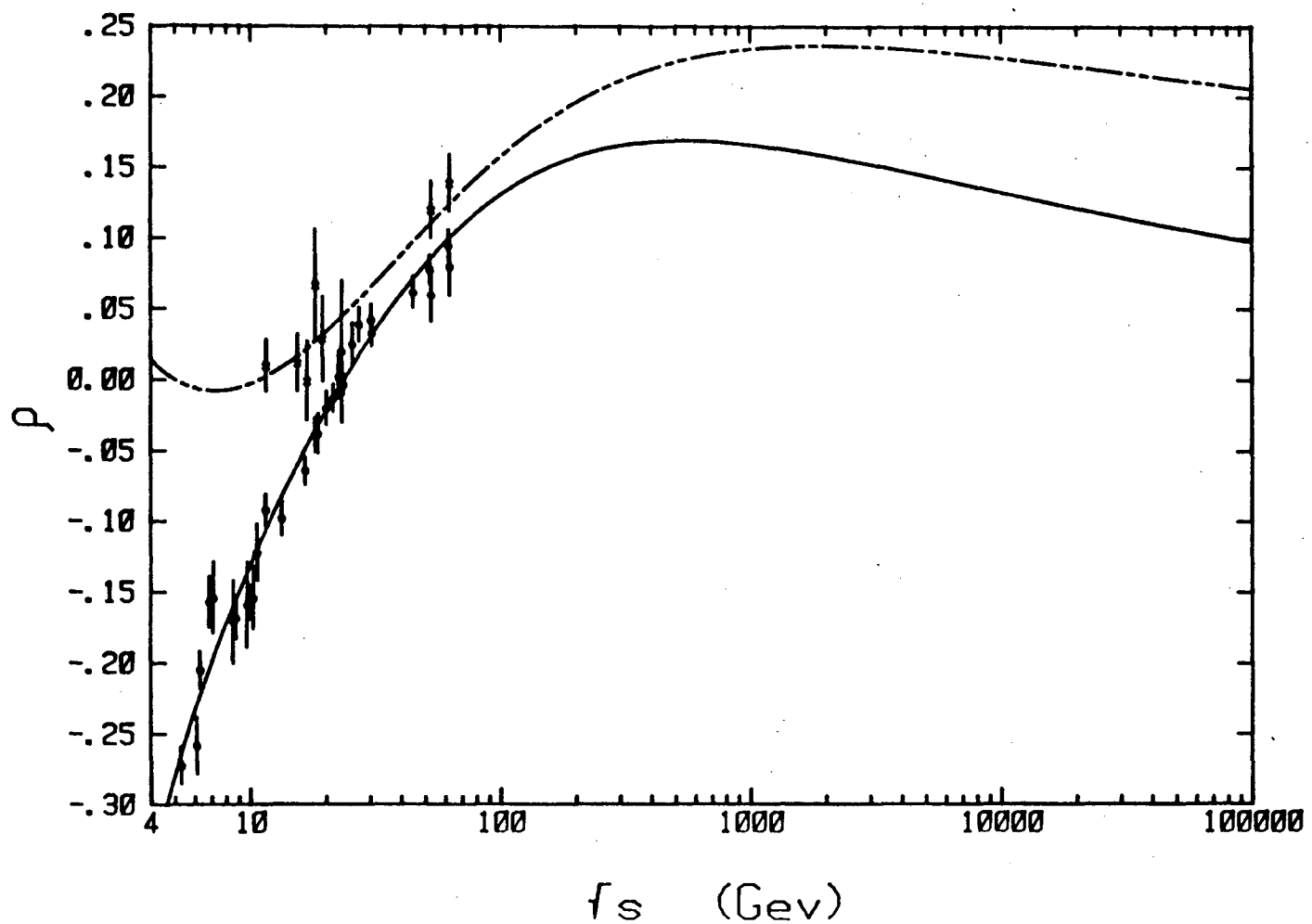
Figure 5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