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CONSEQUENCES OF $Sp\bar{p}S$ COLLIDER DATA FOR EXTRAPOLATIONS OF CROSS SECTIONS AND SLOPES

M.M. Block and R.N. Cahn

October 1985

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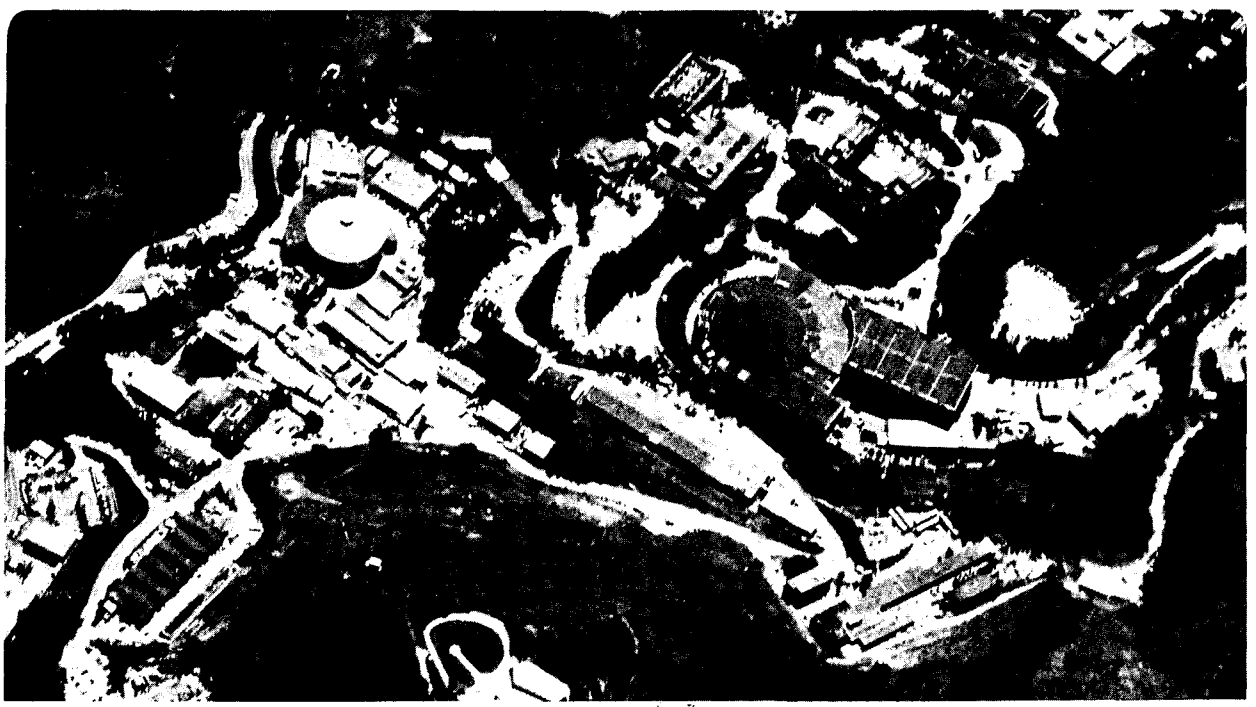

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October 1985 LBL-20501

Consequences of Sp$\bar{p}$S Collider Data for Extrapolations of Cross Sections and Slopes*

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Abstract

A variety of fits to pp and p$\bar{p}$ total cross sections and ρ (=$Re\ f/Im\ f$) values are made, including the data from the Sp$\bar{p}$S Collider. These fits are contrasted with those made without the Collider data. If the full data set ($\sqrt{s} > 5$ GeV) is used, the fits with σ growing asymptotically as $\log^2(s/s_0)$ fail. Fits with σ eventually becoming constant are successful. Fits with σ growing asymptotically as $\log^2(s/s_0)$ give an adequate fit to the data if either the Sp$\bar{p}$S data are excluded or if the data below $\sqrt{s}$ =15 GeV are excluded.

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Several years ago[1,2] we undertook a careful fitting of the pp and p$\bar{p}$ data for σ_{tot} and $\rho = Ref(t=0)/Imf(t=0)$ for energies 5 GeV $\leq \sqrt{s} \leq$ 62 GeV. About 90 pieces of data, including σ_{tot} and ρ for both pp and $p\bar{p}$ were used in the fits. No attempts were made to smooth the data. The values and experimental errors were taken directly from the publications. Among the conclusions of that study were:

1. The data were fitted quite well by simple functional forms incorporating the proper analyticity.

2.a The data were consistent with a $\log^2(s/s_0)$ growth of σ_{tot} at high energy.

2.b The data were also consistent with a form for which σ_{tot} grew as $\log^2(s/s_0)$ in the ISR energy region, but asymptotically became constant. This form introduced an extra parameter, but did not give a significantly better χ^2.

3. The data were consistent with the hypothesis that $\sigma_{p\bar{p}} - \sigma_{pp} \propto s^{-\frac{1}{2}}$. Impressive limits could be placed on "odderons", odd amplitudes corresponding to Regge trajectories with intercept $\alpha_{odderon} = 1$.

4. The above conclusions were independent of the choice of $\sqrt{s_{min}}$ from 5 to 15 GeV.

In the study of 2.a and 2.b above, we used the even and odd amplitudes for $E_{lab} \gg m_P$ (with $f_{pp} = \frac{1}{2}(f_+ - f_-), f_{p\bar{p}} = \frac{1}{2}(f_+ + f_-)$)

$$\frac{4\pi}{p} f_+ = i\left[A + \frac{\beta[\ln s/s_0 - i\pi/2]^2}{1 + a[\ln s/s_0 - i\pi/2]^2} + cs^{\mu-1}e^{i\pi(1-\mu)/2}\right], \tag{1a}$$

and

$$\frac{4\pi}{p} f_- = -Ds^{\alpha-1}e^{i\pi(1-\alpha)/2}. \tag{1b}$$

Here p is the lab momentum and the total cross section is given by the optical theorem, $\sigma = (4\pi/p)Imf(t=0)$. The real parameters A, β, a, c, μ, D, and α are determined by fitting to the experimental data. The simple fits set $a = 0$, so $\sigma \sim \log^2(s/s_0)$. In conformity with the standard picture of the ρ, ω, f, and A_2 trajectories, μ, the intercept of the even trajectories, was set equal to 0.5 when this term was included. The value of α was fitted, with the result $\alpha \approx 0.50$, as expected for the odd trajectories in the standard picture.

Our original fits[1] were done before the earliest measurements of σ_{tot} at the SPS collider. Those data were not included in the later fits[2] because they had large uncertainties and would not have had any statistical significance in our fits.

The purpose of this note is to discuss the results of fits that include the recently published UA-1[3] and UA-4[4] data, as well as the data considered previously. The new inputs for our fits were not the derived cross sections, but rather the experimentally measured quantities: for UA-4, $\sigma_{tot}(1+\rho^2) = 63.3 \pm 1.5$ mb [4], for UA-1, $\sigma_{tot}(1+\rho^2)^{1/2} = 67.6 \pm 6.5$ mb.[3] Although the two measurements are consistent, the much smaller error reported by UA-4 makes it dominate the fitting procedure at high energies. The slope measurements are 15.2 ± 0.2 GeV^{-2} for UA-4 [4] and 17.1 ± 1.0GeV^{-2} for UA-1 [3].

In Table I are listed the features of fifteen fits for the total cross section and ρ values. Since our previous studies showed that the odderon amplitudes were very small, we have not included them here. Fits were made with and without Sp$\bar{p}$S collider data. The even Regge trajectory with intercept 0.5 was included ($c \neq 0$) in some fits, and excluded in others. Fits with asymptotic behavior $\sigma \sim \log^2(s/s_0)$ were tried ($a = 0$) as well as ones with asymptotically constant behavior ($a \neq 0$). The behavior $\sigma \sim \log^\gamma(s/s_0)$ with $\gamma \neq 2$ was investigated. We further investigated the sensitivity of our conclusions to our choice of $\sqrt{s_{min}}$.

Table II shows the results of fits without the Sp$\bar{p}$S data, with γ set equal to 2 and $a = 0$ so that $\sigma \sim \log^2(s/s_0)$ asymptotically. The fits are of good quality and insensitive to the inclusion of the lower energy data (5GeV $< \sqrt{s} <$ 15GeV). The inclusion of the even Regge trajectory at $\mu = 0.5$ (fit #3) has only a minor effect on the other parameters and on χ^2.

Table I

Characteristics of the fits to the cross section and ρ data. When the even Regge trajectory is included ($c \neq 0$) μ is set equal to 0.5, except in fit#15.

Fit	Characteristics		
	Parameters	$\sqrt{s_{min}}$ (GeV)	Features
# 1	5	5	No Sp$\bar{p}$S
# 2	5	15	No Sp$\bar{p}$S
# 3	6	5	No Sp$\bar{p}$S, $c \neq 0$
# 4	5	5	Sp$\bar{p}$S
# 5	5	15	Sp$\bar{p}$S
# 6	6	5	Sp$\bar{p}$S, $a \neq 0$
# 7	6	5	Sp$\bar{p}$S, $c \neq 0$
# 8	7	5	Sp$\bar{p}$S, $c \neq 0, a \neq 0$
# 9	6	5	No Sp$\bar{p}$S, $\gamma \neq 2$
# 10	6	15	No Sp$\bar{p}$S, $\gamma \neq 2$
# 11	6	5	Sp$\bar{p}$S, $\gamma \neq 2$
# 12	7	5	Sp$\bar{p}$S, $\gamma \neq 2, c \neq 0$
# 13	7	5	No Sp$\bar{p}$S, $\gamma \neq 2, c \neq 0$
# 14	6	5	Sp$\bar{p}$S, $\gamma \neq 2, s_0 = 1\text{GeV}^2, c \neq 0$
# 15	7	5	Sp$\bar{p}$S, $\gamma \neq 2, \mu \neq 0.5, s_0 = 1\text{GeV}^2, c \neq 0$

Table II

Fits to the data excluding Sp$\bar{p}$S points.

Fit	#1	#2	#3
A	41.74± 0.37	41.66± 0.12	41.36± 0.25
β	0.66 ± 0.01	0.60 ± 0.04	0.63 ± 0.03
s_0	337 ± 8	306 ± 27	299 ± 25
D	-39.3 ± 1.6	-34.6 ± 6.8	-40.4 ± 1.8
α	0.48 ± 0.01	0.51 ± 0.04	0.47 ± 0.01
c	0	0	7.3 ± 4.6
$\chi^2/d.f.$	$91.6/76 = 1.20$	$32.5/29 = 1.12$	$89.0/75 = 1.19$

Table III shows fits including the Sp$\bar{p}$S data with γ still set equal to 2. Good fits are obtained only when $a \neq 0$, *i.e.* only when the cross section does not grow asymptotically as $\log^2(s/s_0)$. We conclude that the $\log^2(s/s_0)$ form is incapable of fitting both the Sp$\bar{p}$S data and the lower energy data simultaneously. Again, this conclusion is unchanged either by restricting the data to $\sqrt{s} > 15$GeV (fit # 5) or including the even Regge term ($c \neq 0$, fit #7). The consequences of both restricting our considerations to higher energy data *and* including the even Regge terms ($c \neq 0$) are discussed below. The values of a obtained in the fits # 6 and # 8 are consistent with our pre-Sp$\bar{p}$S value, $a = 0.0056 \pm 0.0030$ [1,2] , but have much greater statistical significance, being about five standard deviations away from zero. The functional forms that give asymptotically constant cross sections yield acceptable χ^2's. The value of a and its uncertainty are determined nearly entirely by the UA-4 point.

Fits #7 and #8 are shown in Figs. 1a and 1b. In both cases, at lower energies the pp and p$\bar{p}$ are clearly separated with the pp data lower. In this region the fits #7 and #8 are indistinguishable. At higher energies, the data coalesce, but #7 and #8 diverge. As the figures show, at high energies fit #7 ($a = 0$) gives larger values of σ and ρ than does fit #8. Fits #4, #5, and #7, where σ grows asymptotically as $\log^2(s/s_0)$, give *unsatisfactory* χ^2. In particular, the UA-4 point is consistently significantly lower than the fit and contributes inordinately to χ^2. The statistically less significant UA-1 point is not in disagreement with the fits, as is seen in Fig. 1.

Table III

Fits including the Sp$\bar{p}$S data. Fits # 4,# 5, and # 7 rise indefinitely as $\log^2(s/s_0)$.

Fit	#4	#5	#6	#7	#8
A	41.69± 0.36	41.44± 0.12	41.70± 0.36	40.82 ± 0.24	41.14 ± 0.20
β	0.63 ± 0.01	0.52 ± 0.03	0.64 ± 0.01	0.56 ± 0.23	0.59 ± 0.02
s_0	345 ± 8	262 ± 26	330 ± 8	252 ± 42	278 ± 19
D	−38.1 ± 1.5	−34.3 ± 6.6	−38.8 ± 1.5	−40.7 ± 1.9	−41.2 ± 1.9
α	0.49 ± 0.01	0.52 ± 0.04	0.49 ± 0.01	0.46 ± 0.02	0.47 ± 0.01
c	0	0	0	16.2 ± 4.2	10.4 ± 3.6
a	0	0	0.0075 ± 0.0015	0	0.0072 ± 0.0015
$\chi^2/d.f.$	128.7/78 =1.65	47.7/31 =1.54	91.3/77 =1.19	113.7/77 =1.48	82.7/76 =1.09

The failure of the $\log^2(s/s_0)$ fits with $a = 0$ prompted an investigation of a more general class in which the exponent of $\log(s/s_0)$ was varied from the Froissart bound value of two. The forms used were those of Eq. (1a) with $a = 0$ and the exponent 2 changed to a parameter, γ. The results are displayed in Table IV.

Table IV

Fits with variable γ in $\log^\gamma(s/s_0)$. Only fits # 11 and # 12 include the Sp$\bar{p}$S data.

Fit	#9	#10	#11	#12	#13
A	41.72± 0.04	41.70± 0.12	41.67± 0.38	40.81 ± 0.28	41.72 ± 0.40
β	0.66 ± 0.01	0.62 ± 0.04	0.63 ± 0.01	0.56 ± 0.03	0.66 ± 0.04
s_0	376 ± 20	334 ± 49	385 ± 21	250 ± 39	375 ± 72
D	−41.0 ± 1.9	−37.0 ± 8.4	−39.8 ± 1.8	−40.7 ± 1.9	−41.1 ± 1.9
α	0.46 ± 0.02	0.50 ± 0.05	0.47 ± 0.02	0.47 ± 0.02	0.46 ± 0.02
c	0	0	0	16.4 ± 4.9	0.1 ± 7.9
γ	2.015 ± 0.007	2.007 ± 0.011	2.016 ± 0.007	2.000 ± 0.008	2.015 ± 0.011
$\chi^2/d.f.$	86.4/75 =1.15	32.0/28 =1.14	123.6/77 =1.61	113.7/76 =1.50	86.4/74 =1.17

The fits # 11 and # 12 which include the Sp$\bar{p}$S points are unsatisfactory. All the fits prefer values of γ very near the canonical $\gamma = 2$. It is not possible to accommodate the Sp$\bar{p}$S data simply by changing γ. Once again, the UA-4 point lies significantly below the fit and is responsible for the very large χ^2.

It has long been popular to use an early fit to the ISR data presented by Amaldi *et al.*[5] The form used in that fit is

$$\sigma = B_1 + B_2(\log s)^\gamma + C_1 E^{-\nu_1} \mp C_1 E^{-\nu_2} \tag{2}$$

where the upper sign is for pp and the lower for $p\bar{p}$. In the second term s is measured in GeV^2, *i.e.* the scale is *arbitrarily* set as $s_0 = 1$ GeV^2. Since the fit was made in 1976, the ISR data included no $p\bar{p}$ experiments. Moreover no values of $\rho(p\bar{p})$

were used in the fit at any energy. No χ^2 is quoted for the fit. The ρ values for pp were calculated from the form of Eq. (2) for pp and $p\bar{p}$ cross sections using singly subtracted dispersion relations.

We have investigated fits of the type $\log^\gamma$, à la Amaldi, using our analytic technique, setting $a = 0$, $s_0 = 1\text{GeV}^2$ and replacing the exponent 2 by the parameter γ in Eq. (1a), and allowing $c \neq 0$. The results are shown in Table V.

Table V

Amaldi-type fits: $s_0 = 1\text{GeV}^2$. Fit #14 fixes $\mu = 0.5$ corresponding to $\nu_1 = 0.5$ in Eq. (2), whereas fit #15 allows μ to vary.

Fit	#14	#15
A	33.08 ± 0.22	11.95 ± 4.77
β	0.155 ± 0.003	0.310 ± 0.023
s_0	1.0	1.0
D	-37.82 ± 1.82	-41.84 ± 2.07
α	0.48 ± 0.02	0.46 ± 0.02
c	76.5 ± 1.9	59.2 ± 3.2
γ	1.977 ± 0.003	1.999 ± 0.014
μ	0.5	0.81 ± 0.03
$\chi^2/d.f.$	348/77 =4.5	96.0/76 =1.26

We have used all our usual data in the fit including the UA1 and UA4 points. The even Regge interecept, μ, is expected to be near 0.5. If we fix it to be 0.5, the resulting fit has χ^2/d.f. = 4.5 which is completely unsatisfactory. If we allow μ to vary, the best fit occurs for $\mu = 0.81$ and $\gamma = 1.999$. The χ^2/d.f. is then 1.26. Although the χ^2/d.f. is not unreasonable, the fit is suspect, since the value of μ is far from the 0.5 expected from Regge analysis. We conclude that the Amaldi-type fit cannot be reconciled with the full set of data, even when varying γ.

The result of the fifteen fits described above is simple. The fits that exclude the $Sp\bar{p}S$ data are all satisfactory. The fits that include the $Sp\bar{p}S$ points are unsatisfactory unless $a \neq 0$, *i.e.* unless the asymptotic growth of σ_{tot} is much slower than $\log^2(s/s_0)$. Since this result is contrary to the expectations of many, we have sought to find under what circumstances a $\log^2(s/s_0)$ fit including the $Sp\bar{p}S$ data would be adequate.

In fit #5, only data above $\sqrt{s} = 15$ GeV were considered and c was set equal to zero. The fit was a failure. In fit #7, the full data set ($\sqrt{s} > 5$ GeV) was used, but the even Regge trajectory with intercept 0.5 was included ($c \neq 0$). This, too, was inadequate, giving $\chi^2/d.f. = 113.7/77$. By combining the options in fits #5 and #7 - restricting the data set to $\sqrt{s} > 15$ GeV *and* introducing the parameter $c \neq 0$, we increase the likelihood of finding an acceptable fit. Such a fit is, however, open to serious objection. The even Regge trajectory with contribution proportional to c describes a piece of the total cross section that vanishes as s increases. The restricted data set, however, covers almost exclusively the region of *rising* total cross section, even for $p\bar{p}$. Without the many high precision data at lower energy, the parameter c could take on a new role: it could decouple the fit in the region $15 < \sqrt{s} < 62$ GeV from the fit to the $Sp\bar{p}S$ points.

Not surprisingly, the fit with $\sqrt{s} > 15$ GeV and $c \neq 0$ is successful. See Table VI.

Table VI

A fit to the data for $\sqrt{s} > 15$ GeV using the even Regge term ($c \neq 0$).

Fit	#16
A	37.25 ± 1.66
β	0.36 ± 0.05
s_0	47.2 ± 35.5
D	-40.5 ± 9.9
α	0.47 ± 0.05
c	62 ± 18
$\chi^2/d.f.$	33.4/30 =1.11

Of course this fit cannot be dismissed completely because of the inherent problems

in fitting $c \neq 0$ with high energy data. However, there are some features of the fit that set it apart from the others. All fifteen other fits have coefficient, β, of the $\log^2(s/s_0)$ term near 0.6, while here $\beta = 0.36$. Furthermore, all other fits have $s_0 \approx 300$ GeV^2, while for fit #16, $s_0 = 47$ GeV^2. In addition, those previous fits for which c was not zero gave $c < 20$, while here $c = 62$.

The new fit differs dramatically from the other fifteen. If it is accepted, then the others must be rejected. In its sharpest form, the choice is between, say, fit #1, which fits 81 data points from $\sqrt{s} = 5$ GeV to $\sqrt{s} = 62$ GeV and fit #16, which fits 36 data points from $\sqrt{s} = 15$ GeV to $\sqrt{s} = 540$ GeV. A good fit may be obtained either by dropping the UA-4 datum point at 540 GeV or the 47 data below $\sqrt{s}$ of 5 GeV. The choice is a subjective one since we cannot know *a priori* that the functional forms we have chosen are necessarily adequate for describing the full range $\sqrt{s} > 5$ GeV. Nevertheless, there are clear reasons for extreme caution in embracing fit # 16.

We have repeated our analysis of the slope parameter

$$B(s) = \frac{d}{dt} \log \frac{d\sigma}{dt} \qquad \text{at } t = 0 \tag{3}$$

including data from the Sp$\bar{\text{p}}$S Collider. Because the lower energy data lack the consistency and precision of the σ_{tot} and ρ data, in our earlier analyses[2,6] of the slope data,[7] we found it necessary to select a subset of the available data that was reasonably consistent. Even after this expedient, the χ^2's were not impressive.

In the present analysis we follow our earlier procedure[2,6] of parameterizing separately the slopes associated with the even and odd parts of the amplitude, writing

$$B^+(s) = C^+ + D^+ \log s + E^+ \log^2 s \tag{4a}$$

and

$$B^-(s) = C^- + D^- \log s. \tag{4b}$$

It is essential that $B^+(s)$ grow as $\log^2 s$ if σ_{tot} does[2,6,7] since one has the approximate relation

$$\frac{\sigma_{el}}{\sigma_{tot}} \approx \frac{\sigma_{tot}}{16\pi B}. \tag{5}$$

The slope parameters for pp and p$\bar{\text{p}}$ are determined from Eqs. (4a) and (4b) together with the $t = 0$ elastic scattering amplitudes as explained in Ref. 2,6, and 7. For the $t = 0$ amplitudes, we have used fits #3 and #7. The results of our fits are given in Table VI and Fig.3.

Table VI

Fits for the slope parameter. See Eqs. (4a), (4b).

Fit	No Sp$\bar{\text{p}}$S	With Sp$\bar{\text{p}}$S
C^+	10.79 ± 0.59	9.86 ± 0.30
D^+	-0.049 ± 0.202	0.287 ± 0.088
E^+	0.040 ± 0.017	0.012 ± 0.006
C^-	21.5 ± 5.1	18.3 ± 5.0
D^-	1.23 ± 1.08	2.0 ± 1.0
$\chi^2/d.f.$	78.8/52 =1.52	85.6/54 =1.59

The most significant difference between the fits is that the fit including the Sp$\bar{\text{p}}$S points predicts lower values for the slope at very high energies. In particular, the UA-4 slope measurement is significantly below the value predicted using lower energy data.

In summary, both the total cross section and slope parameter measured by UA-4 lie below the predictions made from lower energy data (if it is assumed that σ grows asymptotically as $\log^2(s/s_0)$). We note, in passing, that since the total cross section was determined in the UA-4 experiment by extrapolating the measured differential elastic cross section to $t = 0$ using the slope parameter, B, the values of B and σ are directly correlated. The correlation is such that a low value for B also leads to a low value for σ.

We conclude with a comparison of the predictions of several of the fits for collider energies. In Table VII are displayed the predictions of two fits, one with $\sigma \sim \log^2(s/s_0)$ ($a = 0$, fit # 7) and the other with σ asymptotically constant ($a = 0.0072$, fit # 8). The predictions diverge quite dramatically at very high energies. Forthcoming measurements at the Sp$\bar{\text{p}}$S and the Tevatron Collider should be able to clarify which fit is better and make predictions for the Superconduction Super Collider (SSC) more reliable.

Table VII

Predictions of fits # 7 ($a = 0$) and # 8 ($a \neq 0$)

$\sqrt{s}$ (GeV)	540	540	2000	2000	40 000	40 0
	σ_{tot} (mb)	ρ	σ_{tot} (mb)	ρ	σ_{tot} (mb)	ρ
$a = 0$	67.2 ± 0.7	0.184 ± .004	91.5 ± 1.5	0.185 ± .003	176±4	0.156±
$a = 0.0072$	62.5 ± 1.1	0.116 ± .011	74.2 ± 2.8	0.088 ± .012	94±7	0.041±

We see that the $pp/p\bar{p}$ total cross sections and ρ values remain interesting topics for investigation and may still hold some surprises.

Acknowledgments

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Figure Captions

1.a The total pp and $p\bar{p}$ cross section data and fits #7 and #8 . At low energies the pp data is lower than the $p\bar{p}$ data and the two fits coincide. At higher energies, the data coalesce but the predictions diverge. Fit #7 ($a = 0$) lies higher than fit #8.

1.b The pp and $p\bar{p}$ ρ data and fits #7 and #8 . At low energies the pp data is lower than the $p\bar{p}$ data and the two fits coincide. At higher energies, the data coalesce but the predictions diverge. Fit #7 ($a = 0$) lies higher than fit #8.

2 The slope data and fit. At lower energies, the $p\bar{p}$ slope is greater than the pp slope.

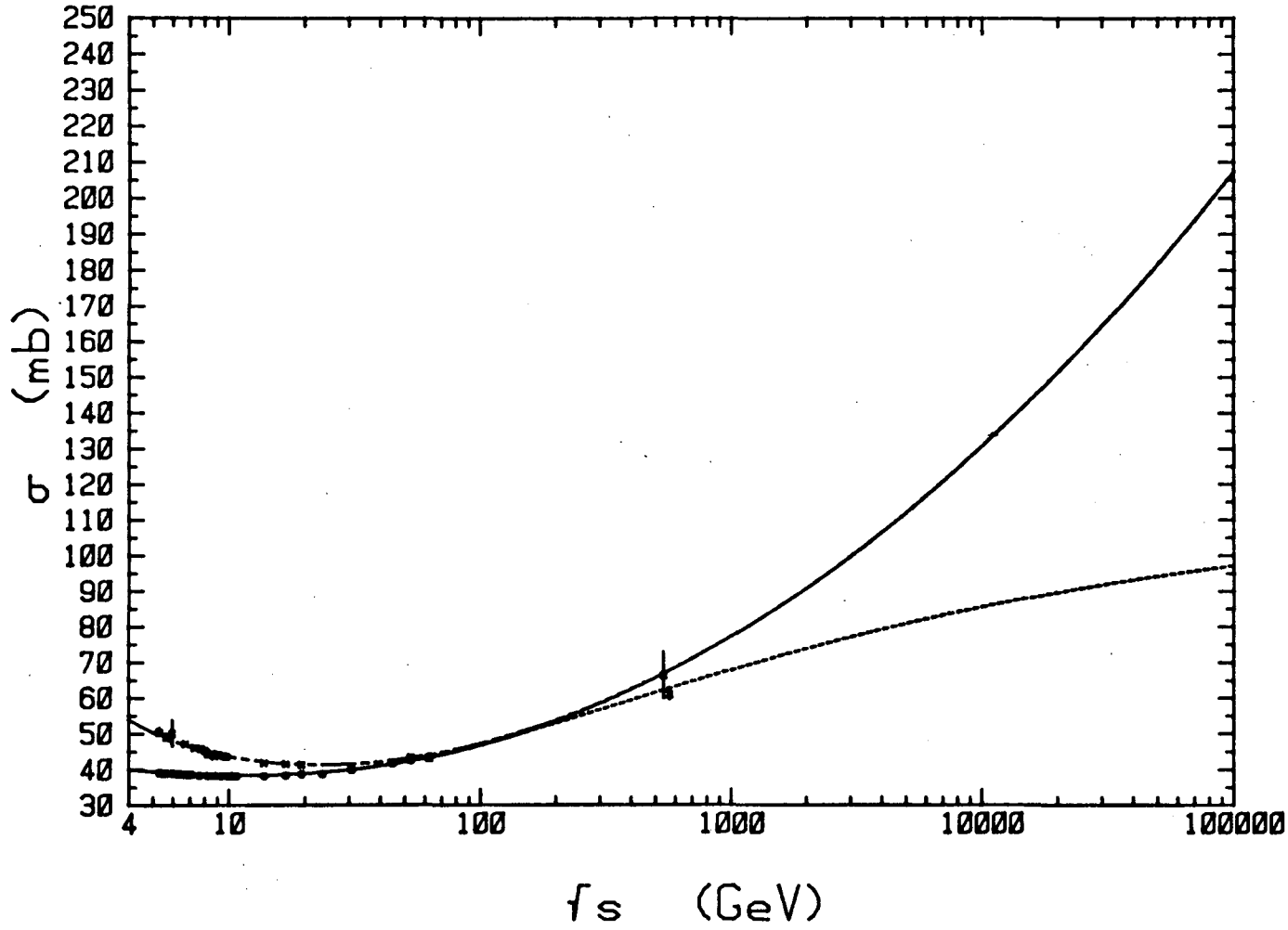
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Fig. 1.a

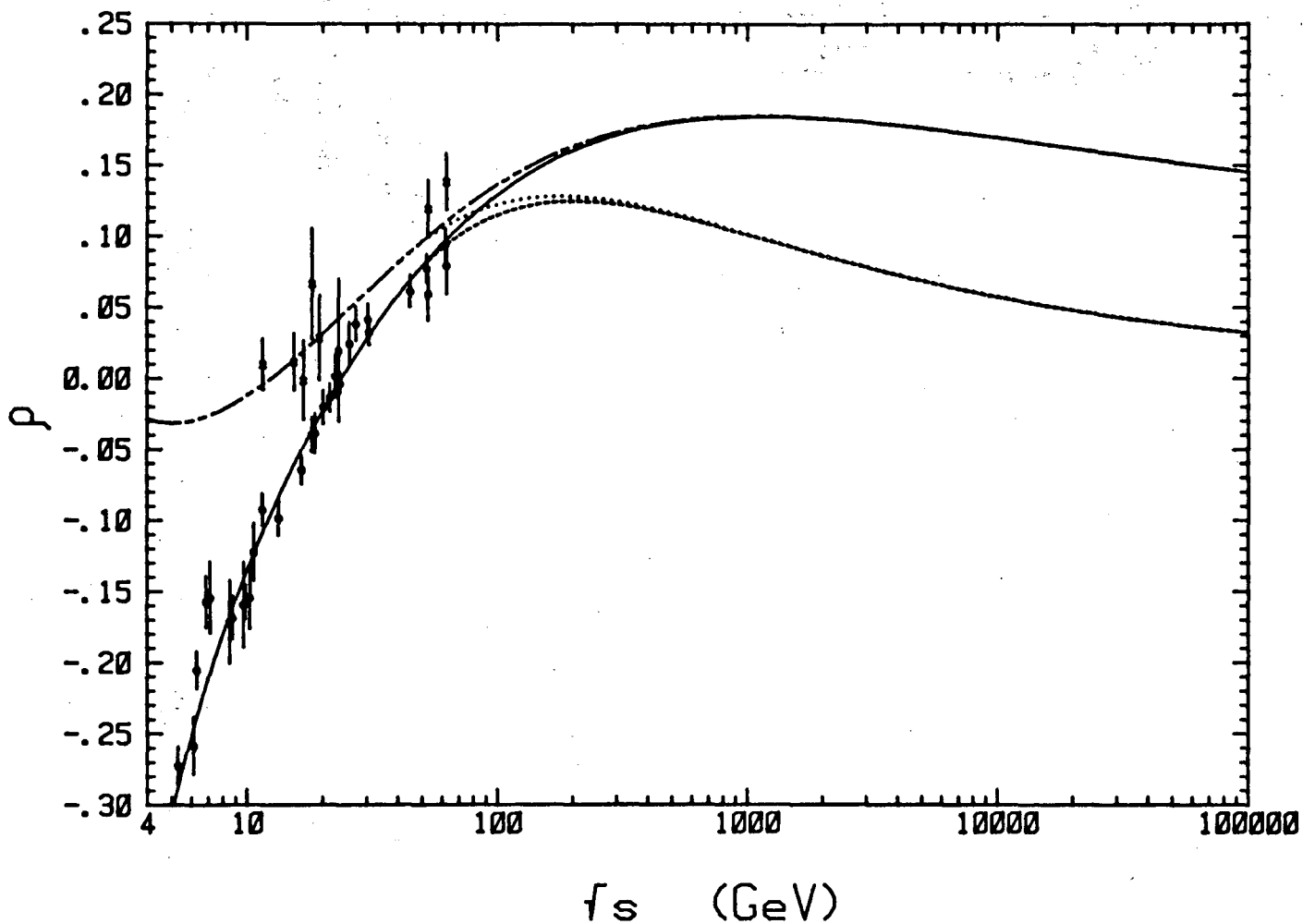
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Fig. 1.b

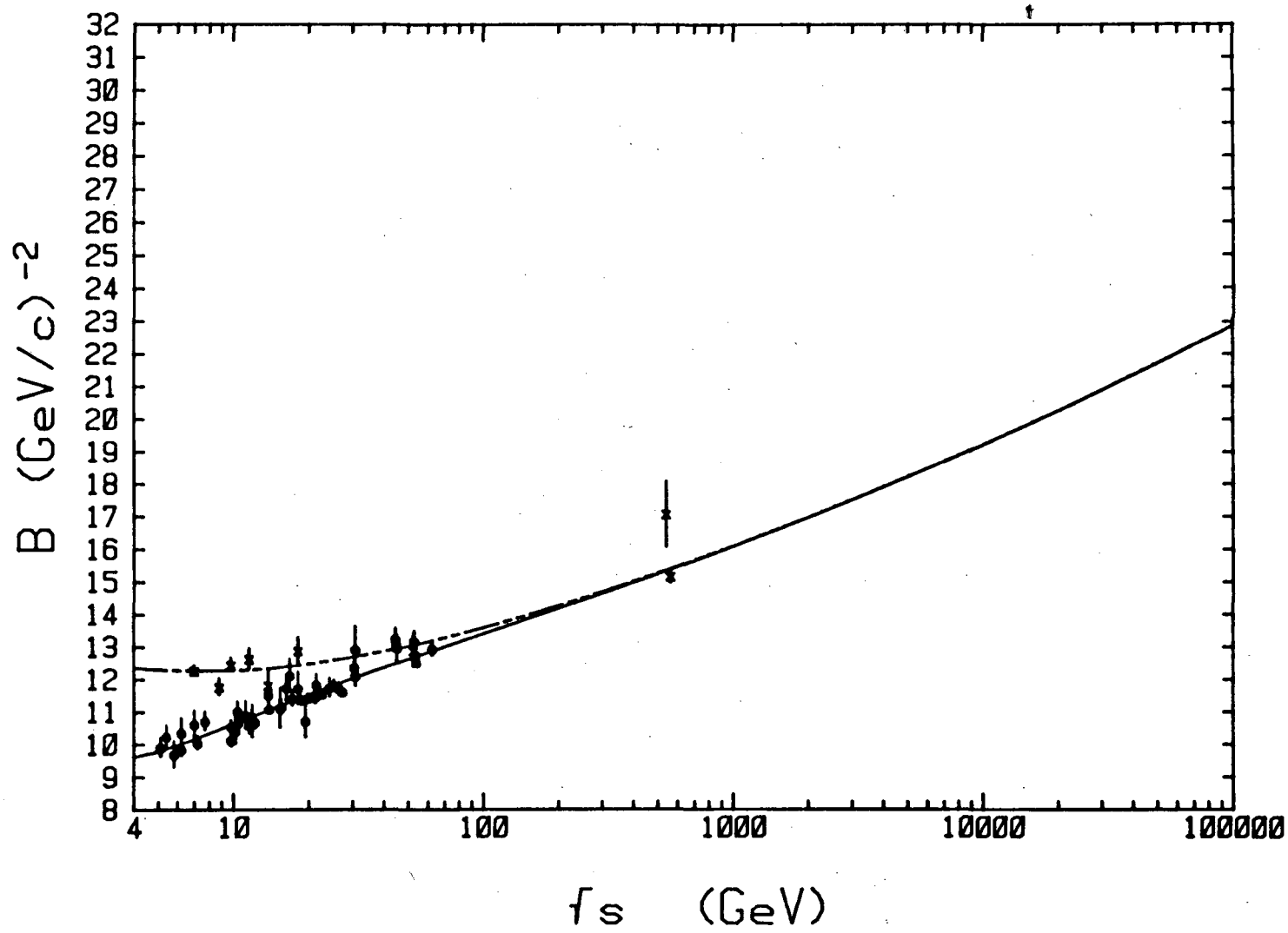
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Fig. 2

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