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Study of Antiproton-Proton Annihilations Using the Topological Cross Section Differences Between $\bar{p}p$ and pp Interactions at 48.9 GeV/c*

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Abstract

The multiplicity cross section differences between $\bar{p}p$ and pp interactions are determined. To the extent that these cross section differences measure the values of σ_n^A, the topological cross sections for annihilations, we present evidence for a decided break from the single cluster model prediction for the parameter f_2^{A--}. We find $< n^A > = 7.57 \pm 0.31$, $D^A = 2.77 \pm 0.10$, $f_2^{A--} = -1.86 \pm 0.20$, and $< n^A >/D = 2.73 \pm 0.15$.

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A large total cross section difference between antiproton-proton and proton-proton interactions: $\Delta\sigma(p^{\mp}p) \equiv \sigma(\bar{p}p) - \sigma(pp)$ which decreases rapidly with energy, is a well known experimental fact [1]. There have been two different theoretical approaches advanced to interpret this experimental observation [2,3]: (a) The magnitude and energy dependence of $\Delta\sigma(p^{\mp}p)$ is a direct measure of the annihilation cross section which we denote by $\sigma^{A}(\bar{p}p)$. (b) The magnitude and energy dependence of $\Delta\sigma(p^{\mp}p)$ can be attributed to the contribution of both inelastic non-annihilation as well as annihilation processes present in the total $\bar{p}p$ cross section. If "b" is the correct interpretation, then the physical content of $\Delta\sigma(p^{\mp}p)$ is not clear. In the following paragraphs we discuss the merits of both points of view and argue that although for low multiplicities $\sigma_n(p^{\mp}p)$ may not completely give the topological annihilation cross section $\sigma_n^{A}(\bar{p}p)$; nevertheless, for higher multiplicities ($n \gtrsim 4$) the topological cross sections differences are indeed dominated by annihilation processes. We define $\Delta\sigma_n(p^{\mp}p) \equiv \sigma_n(\bar{p}p) - \sigma_n(pp)$ where σ_n denotes the measured topological cross section with n observed <u>charged</u> particles.

<u>Empirical arguments to relate $\Delta\sigma$ and $\Delta\sigma_n$ to annihilation processes</u>

It has been noted that the total cross section difference $\Delta\sigma^{\mp}$ at high energies connects and smoothly continues the power law energy dependence of the $\bar{p}p$ annihilation cross section [4] which is measured directly below about 10 GeV/c. While this suggests that the total cross section difference (or more correctly the difference in total <u>inelastic</u> cross sections) may well represent the annihilation process, it does not necessarily follow that each of the individual topological cross section differences directly measures the corresponding annihilation topological cross section.

One clear example of a possible problem is the zero-prong (charge-annihilation) cross section $\sigma_0(\bar{p}p) = \Delta\sigma_0(p^{\mp}p)$, which has no counterpart in the

$\bar{p}p$ interaction to cancel the meson exchange processes which, in addition to annihilation, must certainly be present. Figure 2 of our preceding paper [5] shows that $\sigma_o(\bar{p}p)$ drops rather sharply as a function of the beam momentum with a dependence $s^{-1.45 \pm 0.14}$. The exclusive non-annihilation reaction $\bar{p} + p \rightarrow \bar{n} + n$ has been measured [6] below 10 GeV to have an energy dependence $s^{-1.97 \pm 0.13}$, consistent with pion exchange (s^{-2}). This cross section extrapolates to 5% of the measured $\sigma_o(\bar{p}p)$ at 50 GeV. Measurements of neutral pion production in zero prong interactions at 15 GeV/c indicate [7] that the <u>inclusive</u> zero-prong non-annihilation cross section at 50 GeV/c is about 0.02 mb or 15% of our measured value of 0.149 ± 0.057 mb. Thus the annihilation component of σ_o at 50 GeV/c could be as large at 85% of $\Delta\sigma_o$, so that even in this case the topological cross section difference may be dominated by annihilations. However, $\Delta\sigma_o$ is relatively small when compared to the $\Delta\sigma_n(p^{\mp}p)$ for $n \geq 4$, and we find its effect on the multiplicity moments to be negligible.

A second example of a possible problem occurs in the two-prong events, where the value of $\Delta\sigma_2$ (see Table 1) is zero within errors (0.10 ± 0.28 mb). For this partial cross section, we extrapolate the energy dependence $\sigma_2^A = 1540\ s^{-2.46}$ based [8] on measurements at energies up to 9 GeV to obtain $\sigma_2^A = 0.022$ mb which is consistent with the measured Δ_2^σ at 50 GeV/c. Again, the moments of the annihilation multiplicity distribution are not very sensitive to this topological cross section, since the bulk of the measured annihilation cross section lies at higher charged multiplicities, even at the lower energies where it is measured directly.

For multiplicities $n \geq 4$, there are four observations which suggest that the identification $\Delta\sigma_n = \sigma_n^A$ is a good approximation. Firstly, the high energy $\Delta\sigma_n$ values smoothly continue those of σ_n^A measured at lower energies [4], and similar behavior is seen in the moments of these distributions as discussed below. Secondly, the distribution of $\Delta\sigma_n$ is found to peak at relatively large charged multiplicities, in agreement with the pattern found in directly measured annihilations. Thirdly, the $\pi^{\mp}p$ topological cross section differences [4] $\Delta\sigma_n(\pi^{\mp}p) = \sigma_n(\pi^- p) - \sigma_n(\pi^+ p)$ are close to zero for $n \gtrsim 4$. Although the meson exchange contributions to $\Delta\sigma_n(\pi^{\mp}p)$ are dominated by ρ-exchange because of G-parity constraints, both ρ and ω-exchange can contribute to $\Delta\sigma_n(p^{\mp}p)$. However, by ω-ρ universality [4], it seems plausible that all meson exchange contributions to $\Delta\sigma_n(p^{\mp}p)$ must be very small for $n \gtrsim 4$. Thus the observed large values of $\Delta\sigma_n(p^{\mp}p)$ in the higher multiplicities are presumably dominated by annihilation.

Finally, we note that if annihilation dominates the difference then the quantities $R_n^* = \Delta\sigma_n/\sigma_{n+2}(pp)$ can be written as

$$R_n^* = \frac{\sigma_n^A(\bar{p}\,p)}{\sigma_{n+2}(pp)} \qquad (1)$$

Upon evaluating all possible quark exchange diagrams for $\sigma_{n+2}(pp)$ and annihilation diagrams for $\sigma_n^A(\bar{p}\,p)$ in the leading order [3] one obtains the general form for R_n^*

$$R_n^* = \beta^n s^{-\alpha} \qquad (2)$$

where β and α are independent of n and s. Since β is expected theoretically to be 3/2, R_n^* would increase as a function of n at fixed s. As is discussed later Equation 2 gives an adequate representation of our data. We emphasize that the result expressed in equation 2 depends on simple counting rules used in quark duality diagram models [9] and not on details of the Eylon-Harari model [3]. Henceforth, we identify $\Delta\sigma_n(p^{\mp}p)$ with the n prong annihilation topological cross section; $\sigma_n^A(\bar{p}p)$, for $n \geq 4$.

In this letter we report on a study of the $\Delta\sigma_n(p^{\mp}p)$ distribution at 48.9 GeV/c based on the present experiment and on a parameterization of existing pp data at several energies. The 48.9 GeV/c $\bar{p}p$ data consisting of 10,000 events are presented in the preceding paper [5]. The existing 50 GeV/c pp topological cross sections, based on some 2,000 events [10], would contribute excessively to the statistical errors on the computed cross section differences. We have therefore parameterized the relatively abundant pp topological cross section data at a series of energies to obtain improved values at 48.9 GeV/c.

Proton-proton topological cross section parameterization

Many authors have parameterized topological cross sections and their moments as a function of energy [11-17]. Fits of both logarithmic ($\sim \ln s$) and power-law ($\sim s^{\alpha}$) forms of energy dependence to existing data on $< n >$, the average charged multiplicity, indicate that the energy dependence gradually changes from $\sim s^{\alpha}$ at low energy ($\lesssim 10$ GeV) to $\sim \ln s$ at high energies ($\gtrsim 100$ GeV/c) [18]. This transition is necessarily reflected in the topological cross sections, although how it affects each one separately is not clear.

Several studies of charged multiplicity data [14], [15], [19-24] confirm that there are certain features of the data which are essentially energy-independent at sufficiently high energy thus affording an energy independent parametrization of the data. They are:

(1) KNO scaling [25] sets in precociously [13], [16], ($P_{LAB} < 25$ GeV/c) that is at energies below those where Feynman-scaling of single particle inclusive reactions is observed. This result is primarily responsible for the success of normal and quasi-normal multiplicity distribution parameterizations [14, 15].

(2) Global and local charge conservation models strongly favor charged pair production over independent single-particle emission, so the greatest success in parameterizing the multiplicity data is found where the variable used is $n_- = n/2 - 1$ for pp interactions [15, 21].

(3) Modal multiplicity (m) is less dependent upon the poorly-determined tails of the distribution than is the mean $< n >$, so it is desirable to parameterize multiplicity in terms of m rather than $< n >$ [23] [15].

We have used a parameterization model, due to Tomozawa [15], which possesses all three features. The model predicts a KNO-like quasinormal multiplicity-scaling function, expanded about the modal multiplicity m_- of the negative charged particles. We chose the form given below since it appears to work best at high multiplicity (form B in Ref. [15]).

$$m_- \frac{\sigma_{n_-}}{\sigma_{inel}} = \frac{1}{\sqrt{2\pi}\, b} \exp \left[- \frac{1}{2d^2} \left(\frac{n_-}{m_-} - 1\right)^2 + \frac{a_3}{d^3} \left(\frac{n_-}{m_-} - 1\right)^3 + \ldots \right] \qquad (3)$$

We have attempted to improve the fit reported in [15] by including recent 60 GeV/c pp topological cross sections [26] and by updating the other cross sections [10, 27, 32, 33]. Using 50, 60, 69, 102, 205, and 300 GeV/c data, we obtain the following best-fit parameters (almost identical to those found in Ref. [15]):

$b = 0.94 \pm 0.01$, $d = 1.02 \pm 0.02$, $a_3 = 0.040 \pm 0.003$, and $m_-(50) = 1.34 \pm 0.03$

The parameters b, d and a_3 were found to be independent of energy and the best fit modal multiplicities found for the other input energies are $m_-(60) = 1.38 \pm 0.03$, $m_-(69) = 1.52 \pm 0.02$, $m_-(102) = 1.67 \pm 0.03$, $m_-(205) = 2.11 \pm 0.03$, and $m_-(300) = 2.38 \pm 0.04$. The χ^2 per degree of freedom for this fit is 114./51. We did not include data at 28.5 GeV/c [16] because the resulting prediction at 50 GeV/c changes only slightly and the χ^2 per degree of freedom for that fit is 180./57. The results for 50 GeV/c pp are shown along with our 48.9 GeV/c $\bar{p}p$ data and the cross section differences in Table 1. Moments of the $\Delta\sigma_n(p^{\mp}p)$ multiplicity distribution are given in Table 2.

Figure 1 shows the moments $< n_- >$ and f_2^{--} plotted as functions of energy and of $<n_->$, respectively. Our data points smoothly interpolate between the neighboring points at 32 and 100 GeV/c [28] [8]. The value of $f_2^{--} = -1.86 \pm 0.20$ for 50 GeV/c ($\bar{p}p$ - pp) clearly agrees with the upward trend away [8] from the single cluster model line [29] [30]. Our result is 2 standard deviations away from the single cluster model prediction (other parameterizations of pp topological cross sections yield even larger deviations from this linear prediction). Our result therefore adds credence to the notion that there is multiple cluster formation in the $\bar{p}p$ annihilation reaction for $p_{LAB} \gtrsim 30$ GeV/c.

Figure 2 shows the energy dependence of the variable $<n>/D$. As in Fig. 1, we have plotted both $\bar{p}p$ annihilation data and high energy $\bar{p}p$ - pp difference data together. The nearly constant value of $<n>/D \sim 2.73$ requires the upturn of f_2^{--} as a function of $<n_->$, as shown by the lower dashed curve in Fig. 1b. This follows from the definition†:

$$f_2^{--} \equiv (<n>/D)^{-2} <n_->^2 - <n_->. \qquad (4)$$

The well-known constancy of $<n>/D \simeq 2$ for high energy non-annihilation reactions (eg. pp) [5] yields an upturn in f_2^{--} at $<n_-> \simeq 1$ whereas $<n>/D \simeq 2.73$ for $\bar{p}p$ - pp yields the upturn at about $<n_-> \simeq 3$ (see Fig. 1). Whether the energy behavior of $<n>/D$ or f_2^{--} is more fundamental is a matter of speculation at this time. We note, however, that the independent fireball (cluster) model due to D. Levy [17] may provide a physical interpretation for $<n>/D$. In this model, multiparticle production proceeds by independent (Poisson) emission of identical clusters. Each cluster then decays into a fixed number of pions at a given energy. The assumption of independent emission combined with the definition of $<n>/D$ implies that $<c>$, the average number of clusters emitted is:

$$<c> = (<n>/D)^2 \qquad (5)$$

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†Note that this formula is only valid for Q = 0 reactions, for Q =2 such as pp, the formula reads $f_2^{--} = (<n>/D)^{-2} <n_- + 1>^2 - <n_->$

It is known that this model works very well in predicting topological cross sections of proton-proton interactions [17]. In this case $\langle c \rangle$ approaches the constant value of $\langle c \rangle = 4$. If, however, we apply the formula to antiproton-proton annihilation reactions, then $\langle c \rangle \simeq 7.5$. Upon accepting the approach in Ref. [17] the $\langle c \rangle \simeq 7.5$ result is in clear contradiction with the single cluster model from which the straight line prediction was obtained in Fig. 1b.

Finally we have considered the duality diagram model of Eylon and Harari (EH) [3] and have fitted the form $R_n^* = s^{-\alpha}\beta^n$ to our 50 GeV/c data where R_n^* is defined in Eq. 1. Here, one expects that $\beta = 3/2$, based on quark duality diagram counting, and $\alpha = 2\alpha_M(0)$ where $\alpha_M(0)$ is the intercept of the leading Regge meson exchange trajectory at $t = 0$. Our results, shown in Fig. 3, are well fitted by this expression, and we obtain fitting parameters $\beta = 1.49 \pm 0.04$ and $\alpha = 0.80 \pm 0.05$, with a χ^2 per degree of freedom = 10.9/4, in remarkable agreement with theoretical expectations† and with the well-known value of the intercept of the ρ meson trajectory. We emphasize that our R_n^* is distinct from the $R_n = \Delta\sigma_n/\sigma_n(pp)$ given by EH, equation 21, and used by the authors of Ref. [8] in fitting their 100 GeV data and data at lower energies.† Fitting our data for R_n, as opposed to R_n^*, we obtain $\beta = 1.30 \pm 0.04$ and $\alpha = 0.75 \pm 0.06$, very close to the values found at 100 GeV. The χ^2 per degree of freedom is 8.0/4. An R_n^* analysis of the 100 GeV data gives $\beta = 1.35 \pm 0.04$ and $\alpha = .71 \pm .06$ with a $\chi^2/NDF = 3.49/5$. We have also investigated the effect of including a $\bar{p}p$ non-annihilation term in the theoretical expression for

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†As EH themselves state, the counting rules deal with produced mesons, which for annihilations means all final state particles, while for both pp and $\bar{p}p$ nonannihilation reactions it means all final state particles excluding the two original baryons. Due to the lack of information on π^0 production in pp interactions and on n, $\bar{n}$ production in $\bar{p}p$ and pp interactions we have assumed that n original produced particles corresponds to n or (n + 2) observed charged particles for annihilations (non-annihilations), respectively.

R_n^*, and find in fitting that it contributes to the 4, 6, and ≥ 8 prong topologies a fraction equal to 30%, 8%, and less than 2% respectively. This strengthens our conviction that annihilation dominates the cross section difference $\Delta\sigma_n(p^{\mp}p)$ in the higher multiplicities.

Conclusions

Using a smooth pp topological cross section parameterization model evaluated at 50 GeV/c and using our 48.9 GeV/c $\bar{p}p$ data, the resulting differences $\Delta\sigma_n(p^{\mp}p) = \sigma_n(\bar{p}p) - \sigma_n(pp)$ yield multiplicity moments in good agreement with the energy dependences indicated by other experiments. In particular, $<n_->$ (Fig. 1a) rises steadily as a functions of ln(s), at a constant difference of ~2 units above the pp values; and f_2^{--} (Fig. 1b) is definitely turning upward away from a linear dependence on $<n_->$. The constancy of the variable $<n>/D \cong 2.7$ between 1 and 100 GeV/c determines the shape of f_2^{--} versus $<n_->$ and it follows from KNO scaling (i.e. c_2 in Table 2 is approximately constant). The magnitude of $<n>/D$ is determined by the shape of the KNO scaling curve [31],[16]. Since the parabolic shape of f_2^{--} versus $<n_->$ follows from KNO scaling it is not clear that the upturn of f_2^{--} is caused by the onset of multiple cluster formation.

Finally we observe a remarkable agreement with theoretical predictions for R_n^*, an experimental ratio based on a strict application of the counting rules for quark duality diagrams [3], [9], and we find evidence that in the topological cross section difference $\Delta\sigma_n(p^{\mp}p)$ the non-annihilation contribution becomes progressively more negligible as n increases.

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TABLE 1. Topological cross sections for 48.9 GeV/c $\bar{p}p$, parameterized pp, and the topological cross section difference ($\Delta\sigma_n$) between $\bar{p}p$ and pp as a function of the charged particle multiplicity.

n	σ_n ($\bar{p}p$) (mb)	σ_n (pp)‡ (mb)	$\Delta\sigma_n$ ($\bar{p}p$ - pp) (mb)
0	0.149 ± 0.039		0.149 ± 0.039*
2(inel)	5.69 ± 0.22	5.585 ± 0.178	0.10 ± 0.28*
4	10.34 ± 0.20	9.094 ± 0.196	1.25 ± 0.28
6	9.27 ± 0.19	8.410 ± 0.115	0.86 ± 0.22
8	6.42 ± 0.16	4.848 ± 0.112	1.57 ± 0.20
10	2.85 ± 0.11	1.912 ± 0.099	0.94 ± 0.15
12	0.994 ± 0.067	0.566 ± 0.048	0.43 ± 0.08
14	0.288 ± 0.036	0.138 ± 0.018	0.15 ± 0.04
16	0.042 ± 0.017	0.031 ± 0.006	0.012 ± 0.018
18	0.009 ± 0.007	0.007 ± 0.002	0.002 ± 0.007

‡ The overall normalization error has been minimized by setting $\sigma_{inel} = \sigma_{tot} - \sigma_{el}$ with σ_{tot} from Ref. [32] and σ_{el} from Ref. [33].

*0-prong and inelastic 2-prongs are replaced by 0 and 0.022 mb, resp., see Ref. [8].

TABLE 2. Moments of the difference multiplicity distribution $\Delta\sigma_n(\bar{p}p - pp)$

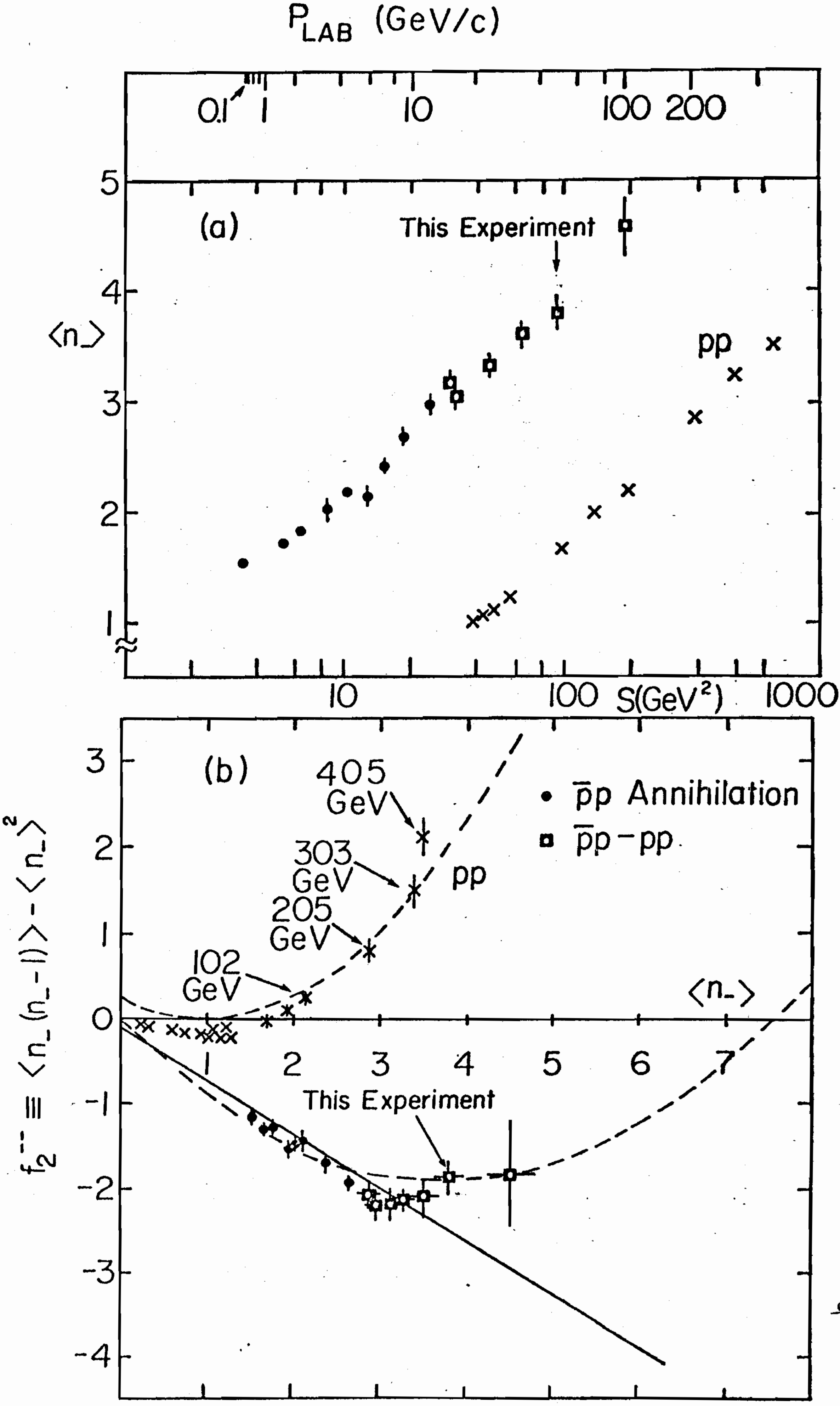
$\langle n\rangle = 7.57 \pm 0.31$	$D = \sqrt{\langle n^2\rangle - \langle n\rangle^2} = 2.77 \pm 0.10$	$f_2^{--} = -1.86 \pm 0.20$
$\langle n\rangle / D = 2.73 \pm 0.15$	$\text{skewness} = \dfrac{\langle (n - \langle n\rangle)^3\rangle}{D^3}$	$f_2^{cc} = \langle n(n-1)\rangle - \langle n\rangle^2$
$c_2 = \dfrac{\langle n^2\rangle}{\langle n\rangle^2} = 1.134 \pm .015$	$= 0.32 \pm 0.14$	$= 0.12 \pm 0.62$.

Figure Captions

Figure 1. (a) The average negative particle multiplcity, $\langle n_- \rangle$, as a function of s, for $\bar{p}p$ annihilations (closed circles) and for the $\bar{p}p$ - pp topological cross section differences (open squares). The X represents the pp data.
(b) The second multiplicity moment, $f_2^{--} \equiv \langle n_-(n_- -1) \rangle - \langle n_- \rangle^2$ as a function of s. Symbols are the same as in (a). The straight line corresponds to the single cluster model with $f_2^{--} = -0.61 \langle n_- \rangle -0.20$. The dashed lines are given by equation (4) with $\langle n \rangle /D = 1.99$ for pp and $\langle n \rangle /D = 2.73$ for annihilations and for the $\bar{p}p$ - pp differences.

Figure 2. The ratio $\langle n \rangle /D$ as a function of $\langle n_- \rangle$, for $\bar{p}p$ annihilations (closed circles) and for the $\bar{p}p$ - pp differences (open squares). The dashed horizontal line at a value of 2.0 represents the average value of $\langle n \rangle /D$ for pp interactions with $50 \leq p_{LAB} \leq 400$ GeV/c.

Figure 3. The ratio $R_n^* \equiv \Delta\sigma_n(p^{\mp}p)/\sigma_{n+2}(pp)$ as a function of n, the total number of charged particles. The straight line is a best fit to the form $R_n^* = s^{-\alpha} \beta^n$ with $\beta = 1.49 \pm 0.04$ and $\alpha = 0.80 \pm 0.05$.



P_LAB (GeV/c)
0.1
1
10
100 200
5
4
3
2
1
(a)
This Experiment
⟨n₋⟩
pp
10
100
S(GeV²)
1000
(b)
405 GeV
303 GeV
205 GeV
102 GeV
pp
• p̄p Annihilation
▫ p̄p − pp
⟨n₋⟩
This Experiment
f₂⁻⁻ ≡ ⟨n₋(n₋−1)⟩ − ⟨n₋⟩²
0
1
2
3
4
5
6
7
-1
-2
-3
-4

fig. 1

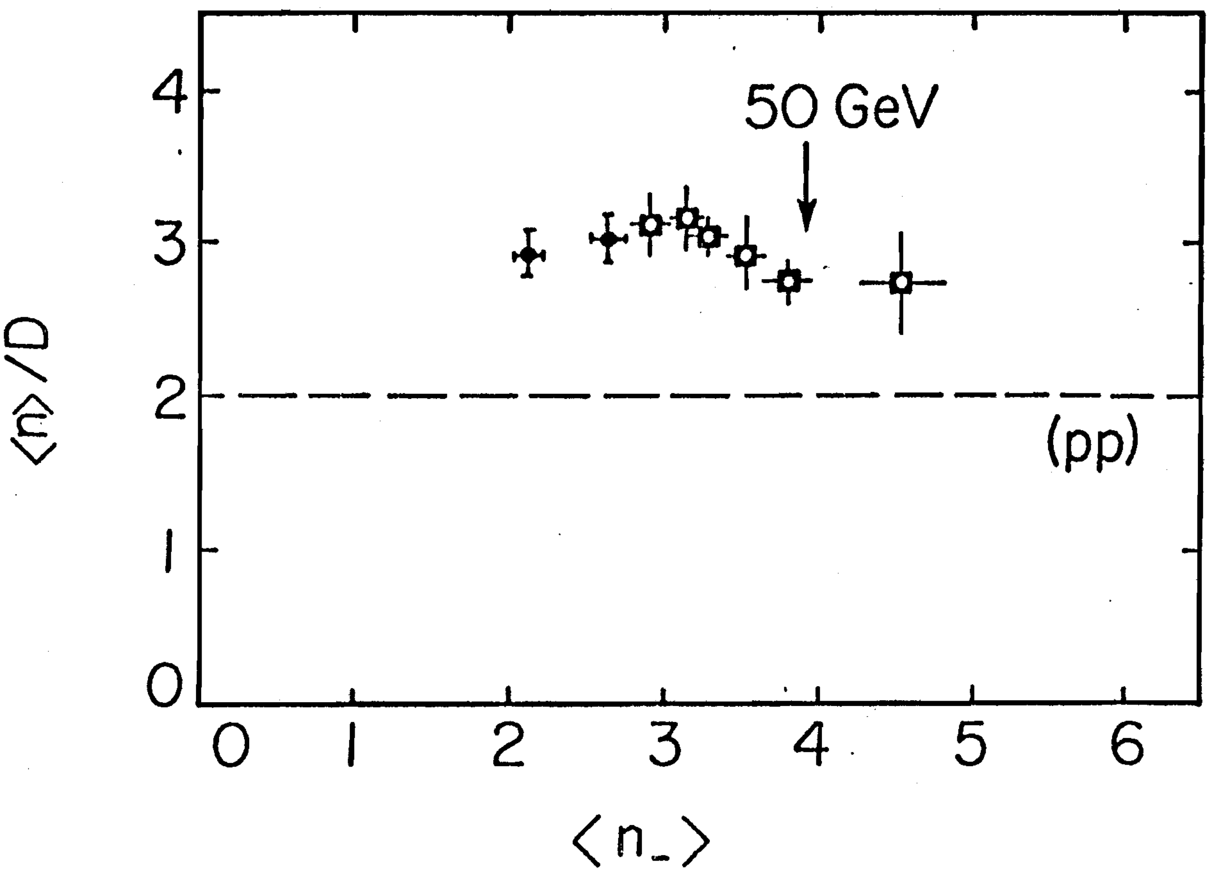
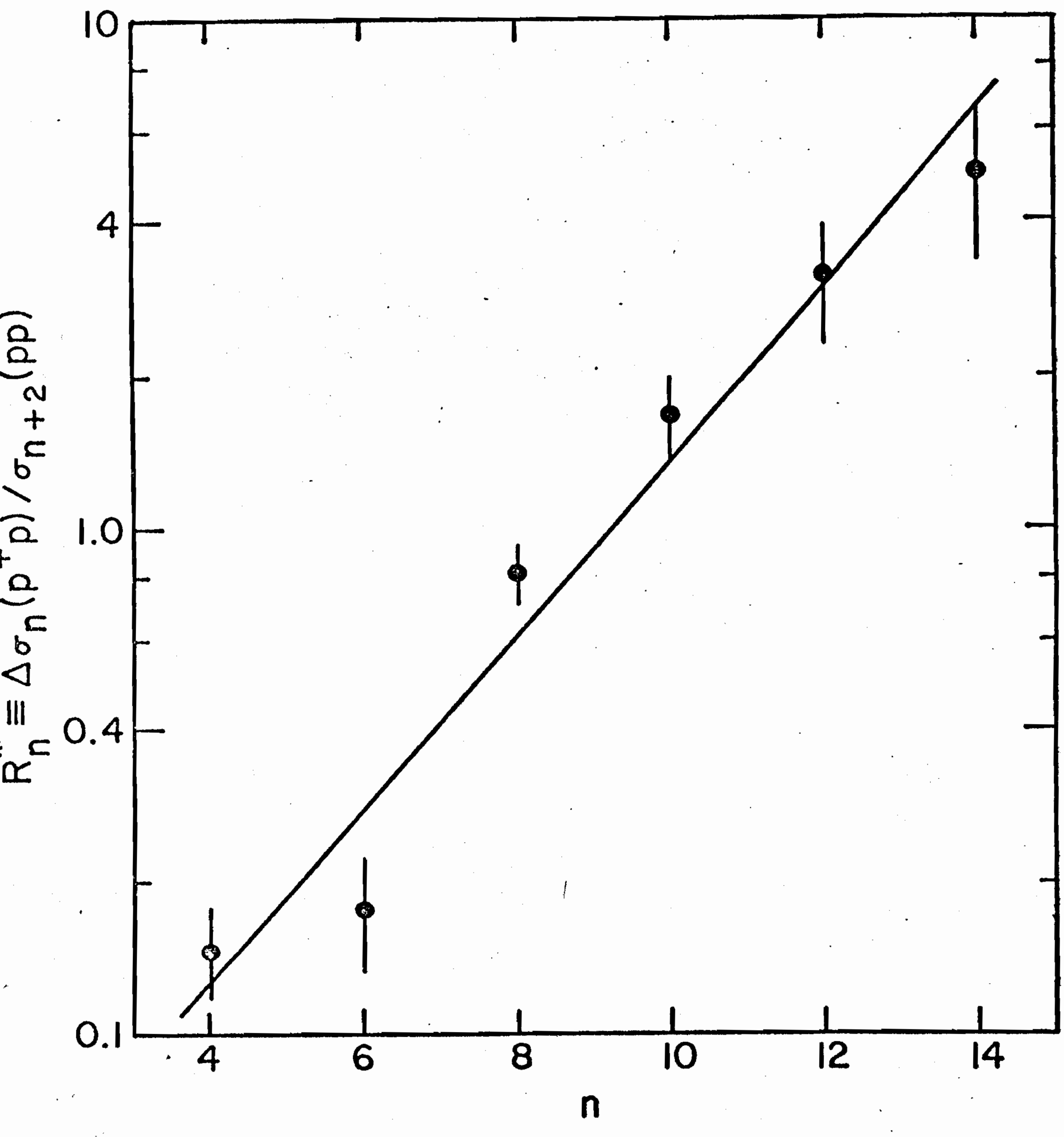


fig 3.



10
4
1.0
0.4
0.1
$R_n^* \equiv \Delta\sigma_n(p^{\mp}p)/\sigma_{n+2}(pp)$
4
6
8
10
12
14
n

Fig 3