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INTERSECTING STORAGE ACCELERATOR NOTES

Physics with ISABELLE

C. Quigg

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INTERSECTING STORAGE ACCELERATOR NOTES

Physics with ISABELLE

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I. INTRODUCTION

Much has been made already of the promise ISABELLE holds for revealing new features of the weak interaction, and of the guarantee that we shall learn from ISABELLE how (or if ?) unitarity is implemented in Nature. I will concentrate here on some of the ways we may expect to learn more about the constitution and interactions of hadrons by means of strong and electromagnetic interaction experiments at ISABELLE energies. I shall discuss reactions leading to many-particle final states in both pp and ep collisions, with some emphasis on experiments well-suited to storage rings.

The body of my talk will be divided into three segments. In Section II, I will review what the ISR experiments are telling us, and some of the questions ISR may not be able to settle. [Whether ISABELLE can give all the answers is left as an exercise for the Summer Study.] In Section III, I summarize some recent work on multiplicity fluctuations in high-energy collisions which was done in collaboration with Wang and Yang. Some speculations on the reactions $e+p \to$ hadrons in the Bjorken limit, made in collaboration with Wang, take up Section IV.

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II. RECENT RESULTS FROM ISR

In a brief review it is of course impossible to do justice to the multitude of exciting physics results emerging from the intersecting storage rings program at CERN. I shall confine my attention to results on single-particle inclusive cross sections, but even with that restriction will barely scratch the surface. For a more complete survey, see J. C. Sens' talk at the Oxford Conference (April, 1972).[1] Results on the fragmentation region indicate that the concepts of limiting fragmentation and scaling and the tools of Mueller-Regge phenomenology, all so fruitful at AGS energies, remain useful in the new energy regime.[2] But the new information we are getting from the ISR concerns the "central" region of $x \equiv p_{\parallel}^{*}/p_{max}^{*} \approx 0$ (the asterisk denotes cm quantities). The data in Figs. 1 and 2 indicate that for the reactions $pp \to \pi^{\pm}$ + anything limiting behavior <u>is</u> approached near $x = 0$ at ISR energies, i.e., that

$$\frac{d\sigma(s;x,p_{\perp}^{2})}{d^{3}p/E} \to \rho_{1}(x,p_{\perp}^{2}) ,$$

independent of s. In addition these data verify a Pomeranchuk Theorem sort of expectation of equal cross sections for particle-antiparticle production, near $x = 0$, as $s \to \infty$.

Some puzzlement has been expressed over the tendency of $x \approx 0$ cross sections to <u>rise</u> to their asymptotic limits between AGS and ISR energies. Bear in mind that if the mean multiplicity of secondaries is to vary linearly with log s, the inclusive cross section $d\sigma/dx$ must approach a $1/x$ form near $x = 0$. To the extent that this singularity is not present at AGS energies, it must be built by a cross section rising with s. But how does the cross section

rise? Ferbel[5] finds that all the $x = 0$ cross sections for the reactions $a+b \to \pi$ + anything could be consistent with

$$\frac{1}{\sigma_{t,\infty}(a\ b)}\ \frac{d\sigma}{dx} = A + B(a,b)/p_{LAB}^{1/4},$$

as Mueller-Regge phenomenology would suggest.[6] His data compilation is shown in Fig. 3. Again, with strong enough prejudices, one can find the asymptotic trends present already at AGS energies. From the standpoint of dual resonance model interpretations of the Mueller theorem, the rising cross sections are a fly in the ointment, for in straightforward applications of the dual resonance model[7] $x = 0$ cross sections should descend to their asymptotic limits.

Also found at the ISR is something resembling a "central plateau" (which is concomitant with the logarithmic increase of multiplicities and $d\sigma/dx \propto 1/x$) for inclusive pion production.[8]

Fig. 4 shows that not everything is so asymptotic as the pion cross sections, as the $x = 0$ cross sections for

$$p + p \to (p,\bar{p}) + \text{anything}$$

still differ by a factor of 2 at $p_{Lab} = 1500$ GeV/c. It is not clear whether one can give a rigorous Pomeranchuk Theorem for inelastic reactions,[9] but in any model worthy of serious contemplation, the $x = 0$ proton and antiproton cross sections will have to become equal at high energies. If it is true that the difference between proton and antiproton cross sections at $x = 0$ varies as $p_{LAB}^{-1/4}$, the cross sections will still differ at ISABELLE by a factor of 3/2. Lacking as we do any real understanding of the reluctance of $p\bar{p}$ pairs to be produced it will be important to have precise measurements of $d\sigma/dx$ for $pp \to \bar{p}$ + anything not only at ISABELLE, but also at lower energies now available. It is unthinkable that this cross section should fail to approach a $1/x$ form; therefore it is important to check.

III. MULTIPLICITY FLUCTUATIONS AND MULTIPARTICLE DISTRIBUTION FUNCTIONS IN HIGH ENERGY COLLISIONS

I will briefly recount here some work done recently with Wang and Yang,[10] emphasizing the kinds of experiments appropriate for storage rings. The study of multiplicity fluctuations is especially suited to storage rings because we can gain insight into the nature of the interaction without making momentum measurements. One of the important questions to be resolved is whether the incoming particles fragment independently, or whether they first amalgamate and then break up into secondaries. The first possibility is characteristic of the so-called "fragmentation models", whereas the second represents "independent emission models" of the multiperipheral or bremsstrahlung type. In independent emission models, wide multiplicity fluctuations are quite unlikely. However according to the hypothesis of limiting fragmentation, wide fluctuations are allowed because fragmentation into very few fragments is expected to occur with finite probability, although the average multiplicity continues to increase with s.

Let us discuss the multiplicity of charged pions produced in pp collisions, and define

$$n = n^R + n^L ,$$

where the superscripts R and L refer to the right and left hemispheres in the c.m. system for the outgoing momenta. The hemisphere R is defined as the one for which $x > 0$. According to the hypothesis of limiting fragmentation, for a fixed n^R, the cross section $\sigma(n^R)$ approaches a limit at high energies. Existing

data, collected in Fig. 5, do not test this idea adequately. Assuming constancy of the total cross section, and assuming that $\langle n^R \rangle$ increases linearly with log s, it is natural to take

$$\lim_{s\to\infty} \sigma(n^R) = \text{constant}/(n^R)^2, \quad \text{for large } n^R.$$

This choice leads to moments of the multiplicity distribution

$$\langle (n^R)^2 \rangle \propto \sqrt{s}\,,$$

$$\langle (n^R)^3 \rangle \propto s,$$

etc., in contradistinction to the expectations of independent emission models in which the moments are proportional to logarithms of s.

A number of other expectations can be checked with data at a single (high) energy. Because we picture independent fragmentation of the two incoming hadrons,

$$\langle n^R n^L \rangle \to \langle n^R \rangle \langle n^L \rangle\,, \quad \text{as } s \to \infty\,;$$

$$\langle (n^R)^2 \rangle \gg \langle n^R n^L \rangle\,, \quad \text{as } s \to \infty\,.$$

If these speculations are correct, the multiplicity fluctuation will be large <u>within each hemisphere</u>, and measurements of $\langle (n^R + n^L)^2 \rangle$ would see a watered-down effect. Independent of the shape of the multiplicity cross section distribution $\sigma(n^R)$, the basic notion of two separately fragmenting hadrons implies that the relative cross sections $\sigma(n^R)$ should be essentially independent of n^L.

Another way to display the same kind of experimental information[11] is to plot the cross sections for observing n^L charged pions in the left hemisphere

and $n-n^L$ charged pions in the right hemisphere, for a fixed total number of particles n, as a function of n^L. In pp collisions this distribution is necessarily symmetric about $n^L = n/2$, but its behavior near the symmetry point is quite sensitive to the shape of $\sigma(n^R)$. In a fragmentation picture, with the possibility of large fluctuations within each hemisphere,

$$\sigma(n^L, n-n^L) \propto (n^L)^{-2}(n-n^L)^{-2}$$

is <u>minimal</u>

for $n^L = n/2$, as shown in Fig. 6. In a simple multiperipheral model, illustrated in Fig. 7,

$$\sigma(n^L, n-n^L) \propto [n^L!]^{-1}\,[(n-n^L)!]^{-1}$$

is <u>maximal</u> for $n^L = n/2$. In fact it is not hard to show that if $\sigma(n^L)$ goes to zero faster (slower) than an exponential for large n^L, the distribution $\sigma(n^L, n-n^L)$ is maximal (minimal) at the symmetry point $n^L = n/2$.

In addition to these rather general questions, we have many specific expectations for the inclusive cross sections[10] which can be confronted if momenta are measured, but in the interest of brevity, I shall not discuss them here.

IV. INCLUSIVE SPECTRA IN DEEPLY INELASTIC ep COLLISIONS

The electron ring option for ISABELLE will allow exploration of hitherto uncharted reaches of the (Q^2, ν) plane. [I adopt the standard notation $Q^2 = -(\text{invariant mass of the virtual photon})^2$, ν = energy of γ_V in the target proton rest system, $X = Q^2/2M\nu$. The laboratory momentum of γ_V is defined as longitudinal.] Beyond the question of whether Bjorken scaling persists in new

kinematic regions, we shall be able to study how very virtual systems interact by measuring inclusive hadron spectra in the Bjorken limit X = fixed, $Q^2 \to \infty$. Wang and I have recently written down some speculations about $\gamma_V p$ collisions in the ISABELLE regime, in terms of some simple and specific models.[12] Here I shall simply describe the background to and spirit of our work, without entering into the mathematical details.

Some four years ago, when the MIT-SLAC experiments first revealed scaling of the invariant electroproduction structure functions, the theoretical models of the day were uniform in their prediction that the mean multiplicity of produced hadrons should depend on Q^2 and ν only through the scaling variable X. Such a prediction is however at odds with nearly everyone's gut feeling that when you hit a hadron harder, more pieces will come out. Chou and Yang[13] gave kinematical reasons why very virtual photons are unable to fragment in gentle collisions as real hadrons do, and it is helpful to review their argument. The reasoning is most easily followed in the brickwall frame for the ep collision, in which I will specify the two-momenta of the colliding particles as $(p_{\parallel}, E)$. Initially these are $(Q,0)$ for γ_V and $(-M\nu/Q, M\nu/Q)$ for the target proton. In the Bjorken limit the proton is fast, has timelike momentum, and can fragment as usual in a gentle collision involving an infinitesimal energy transfer, an infinitesimal longitudinal momentum transfer, and a finite transverse momentum transfer. Because of its energy deficiency γ_V <u>cannot so fragment</u>. But we suppose that γ_V joins with a fraction y of the proton to form an amalgam with timelike momentum $(Q-yM\nu/Q,\ yM\nu/Q)$ which can fragment. The condition that the momentum of the amalgam be timelike is $y \geq X$. In the spirit of the hypothesis of limiting fragmentation it is supposed

that the largest allowable fraction of the proton fragments as usual, i.e., that $y = X$.

Fragments of the proton behave as in normal collisions of real hadrons, except that their total momentum in the $\gamma_V p$ c.m. is $\frac{1}{2}(1-X)W$, not $\frac{1}{2}W$ (where $W = (2M\nu - Q^2 + M^2)^{\frac{1}{2}}$ is the invariant mass of the $\gamma_V p$ system). What of the pieces of the amalgam? The process of amalgamation and subsequent breakup, which Chou and Yang call "pulverization", is a violent one, so it is appealing to assume that the pulverization multiplicity is large, of order $\nu^{\alpha(X)}$, where $\alpha(o) = 0$. As an example they take $\alpha(X) = aX$, $a < \frac{1}{2}$, which gives $\langle n \rangle \propto \nu^{aX}$. In the absence of experimental results, how violent an occurrence the breakup of the amalgam might be is a matter for conjecture. Chou and Yang envisage a pulverization process so violent that <u>only</u> large multiplicity events can take place, in the Bjorken limit. This leads them to expect that in terms of the coordinate x, the pulverization products give rise to a $\delta(x)$-distribution. The possibility raised by them seems to us not to be unique, but only the most extreme possibility which can be entertained. We agree that the more violent a collision, the less likely should be the production of low multiplicities. However, uncertainty principle arguments suggest to us that the coherence of γ_V and the violence of the $\gamma_V p$ collision are determined by X, rather than Q^2 as believed by Chou and Yang.

Abstracting from these arguments, Wang and I formulated a simple mathematical model which exhibits the following properties:

(i) Inclusive hadron cross sections satisfy the hypothesis of limiting fragmentation;

(ii) In the limit of real photons ($Q^2 \to 0$) the model of Ref. 10 is recovered;

(iii) Wide multiplicity fluctuations and corresponding strong correlations in multiparticle distribution functions occur;

(iv) Invariant structure functions scale in the Bjorken limit;

(v) The mean multiplicity of produced hadrons does not scale, but increases like a power of Q^2: $\langle n \rangle \propto (Q^2)^{aX}$;

(vi) For $x = 0+$ (slow cm secondaries in the direction of γ_V), $d\sigma/dx \propto x^{-(1+2aX)}$; i.e., the inclusive cross section becomes more sharply peaked near $x = 0$, the more virtual (as measured by X) is γ_V.

All of these predictions, which are discussed in greater detail in Ref. 12, can be tested at ISABELLE, in single-arm and double-arm spectrometers.

V. SUMMARY

Although I have used specific physical pictures, I have tried to concentrate on gross properties of high-energy collisions which can be illuminated through relatively simple strong and electromagnetic interaction experiments at ISABELLE. While the CERN ISR is showing us how exciting storage-ring physics can be, especially for the study of inclusive reactions, it will not be capable of all the interesting experiments we can contemplate even at this early moment. Deeply inelastic ep collisions at ISABELLE will allow us to uncover the connections between Bjorken scaling and the hypothesis of limiting fragmentation, provided both persist. How very virtual photons behave is of key importance for refining our ideas about the constitution of hadrons.

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[10]C. Quigg, J. M. Wang and C. N. Yang, Phys. Rev. Letters 28, 1290 (1972).

[11]This mode of presentation was suggested to me by S. Nussinov. For elaboration, see S. Nussinov, C. Quigg and J. M. Wang (to be published).

[12] C. Quigg and J. M. Wang, "Inclusive Spectra in Deeply Inelastic ep Collisions", Stony Brook preprint, May, 1972.

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Fig. 1

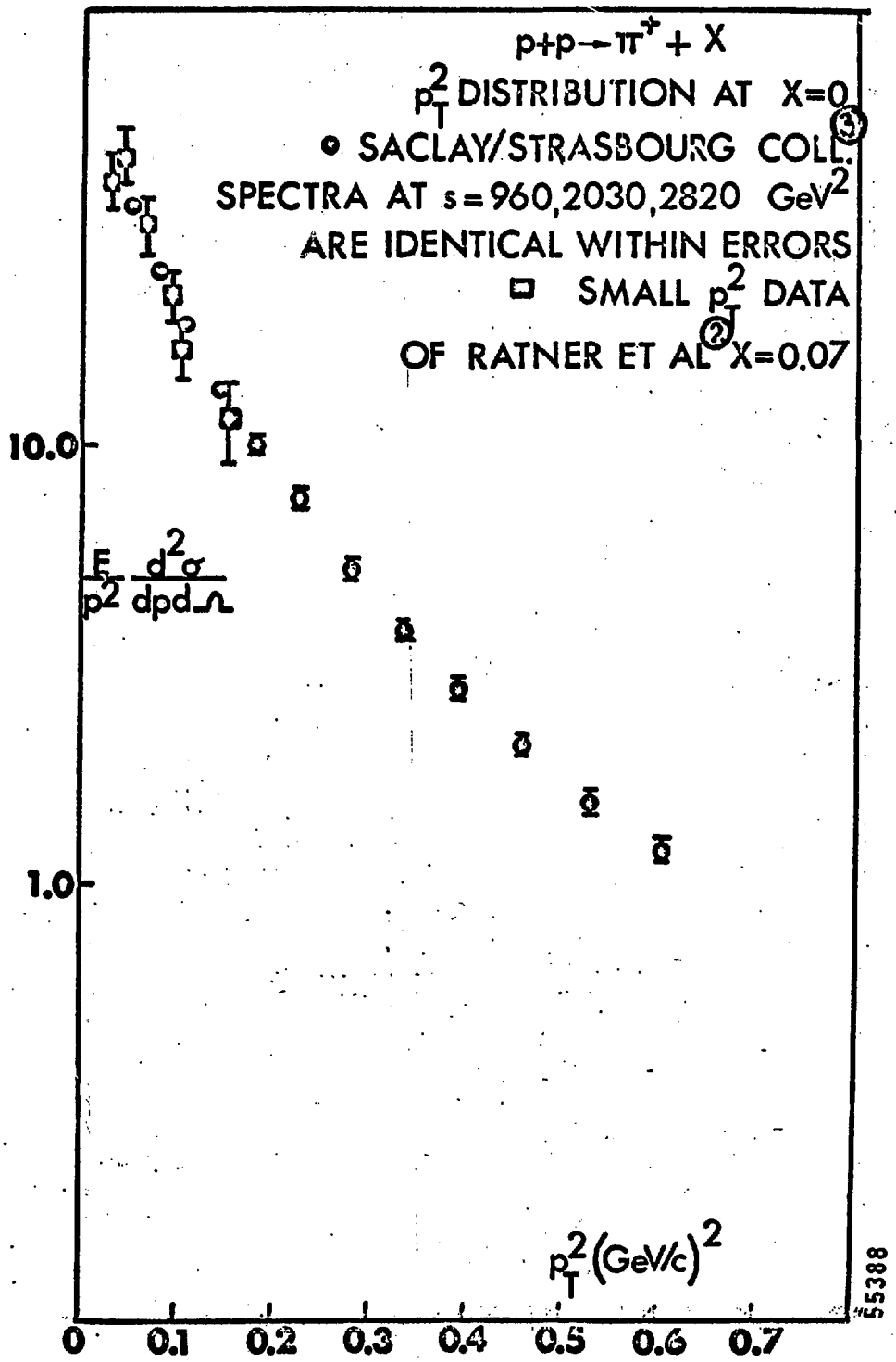
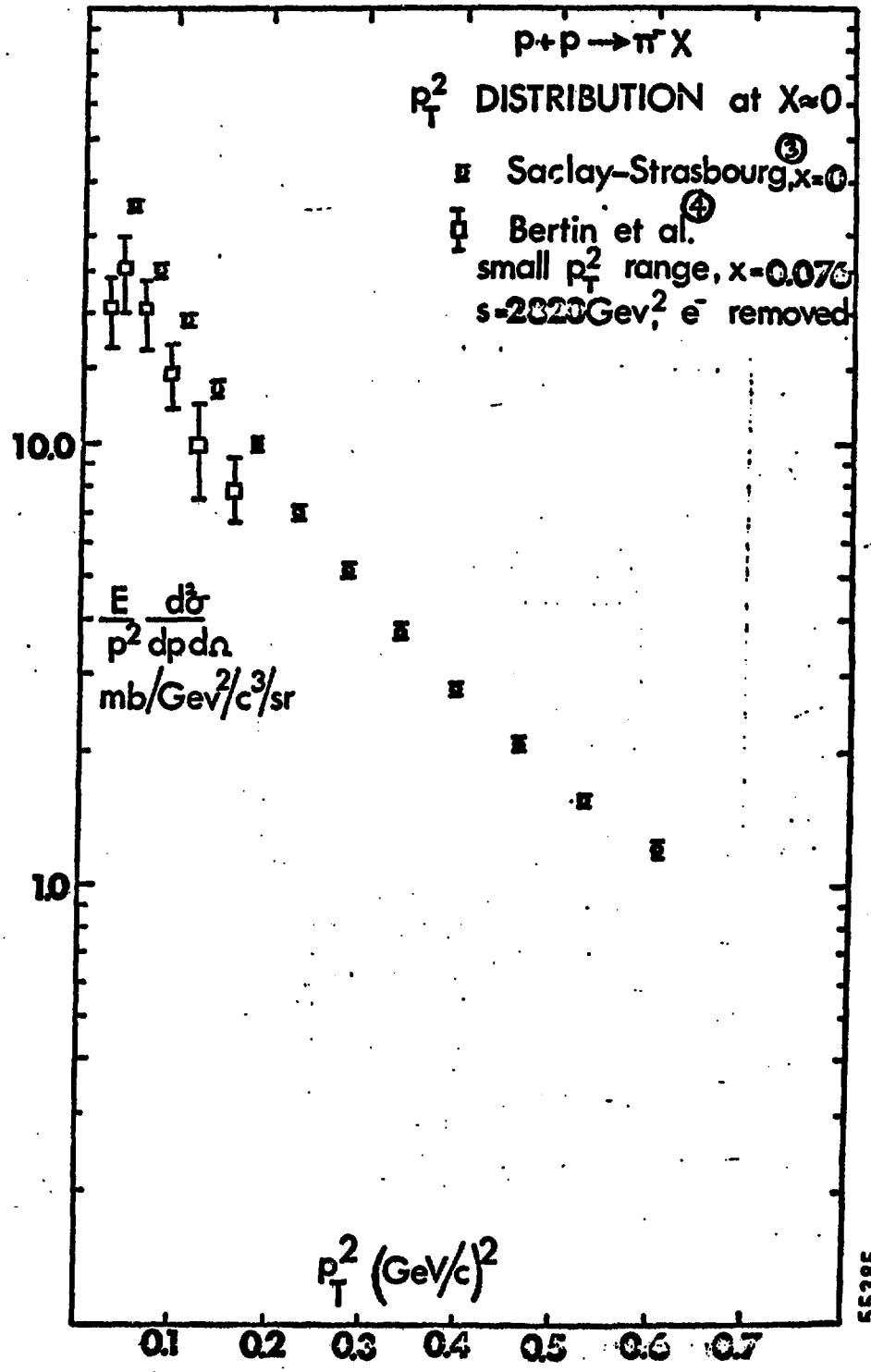

p+p→π⁺+X
p_T² DISTRIBUTION AT X=0
SACLAY/STRASBOURG COLL. (3)
SPECTRA AT s=960,2030,2820 GeV²
ARE IDENTICAL WITHIN ERRORS
SMALL p_T² DATA
OF RATNER ET AL (2) X=0.07
10.0
1.0
E/p² d²σ/dpdΩ
p_T² (GeV/c)²
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
55388

Fig. 2


p+p → π⁻ X
p_T^2 DISTRIBUTION at X≈0
Saclay–Strasbourg, x=0 ③
Bertin et al. ④
small p_T^2 range, x=0.076
s=2820 Gev², e⁻ removed
10.0
1.0
$\frac{E}{p^2}\frac{d\sigma}{dp\,d\Omega}$
mb/Gev²/c³/sr
p_T^2 (GeV/c)²
0.1
0.2
0.3
0.4
0.5
0.6
0.7
55385

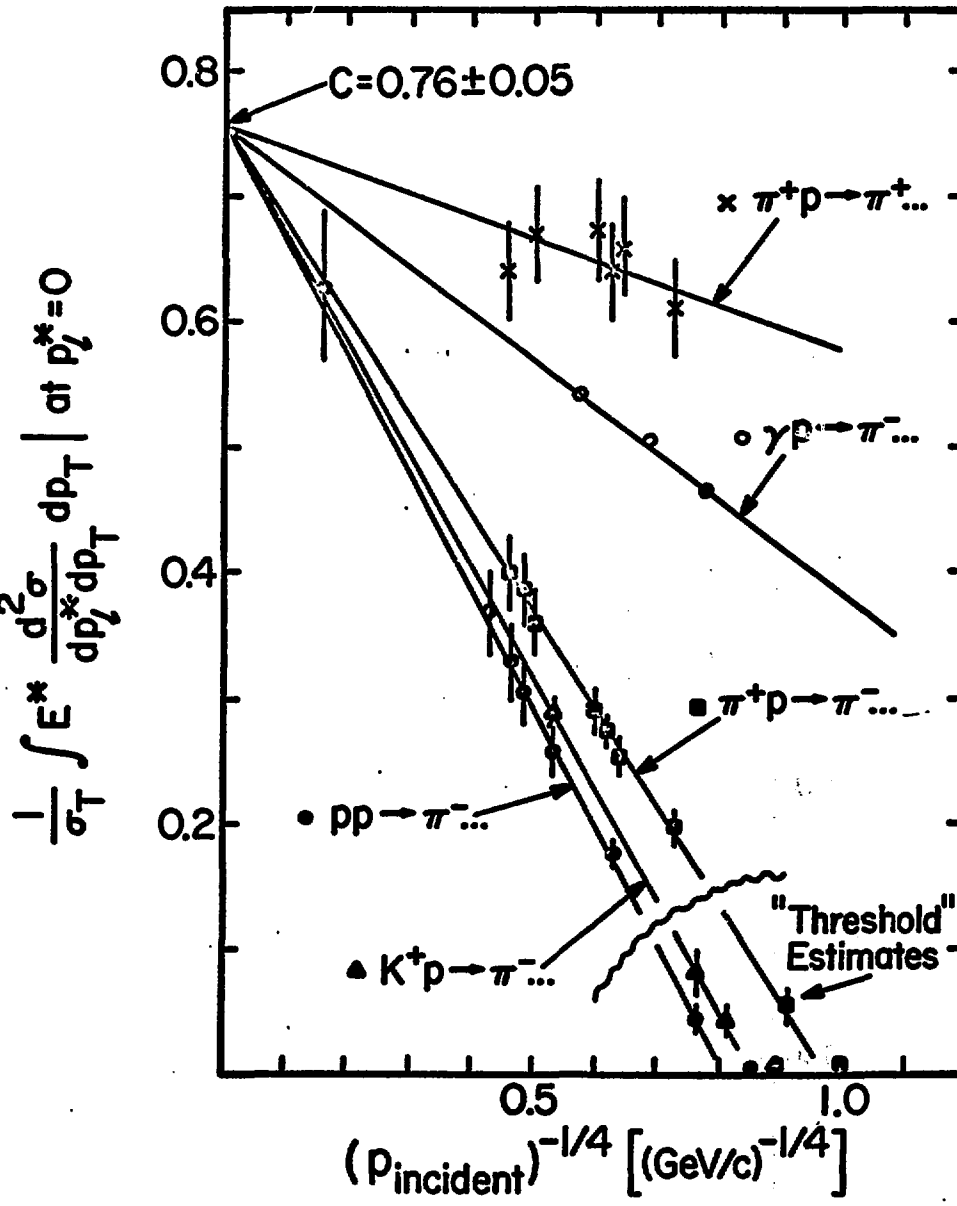
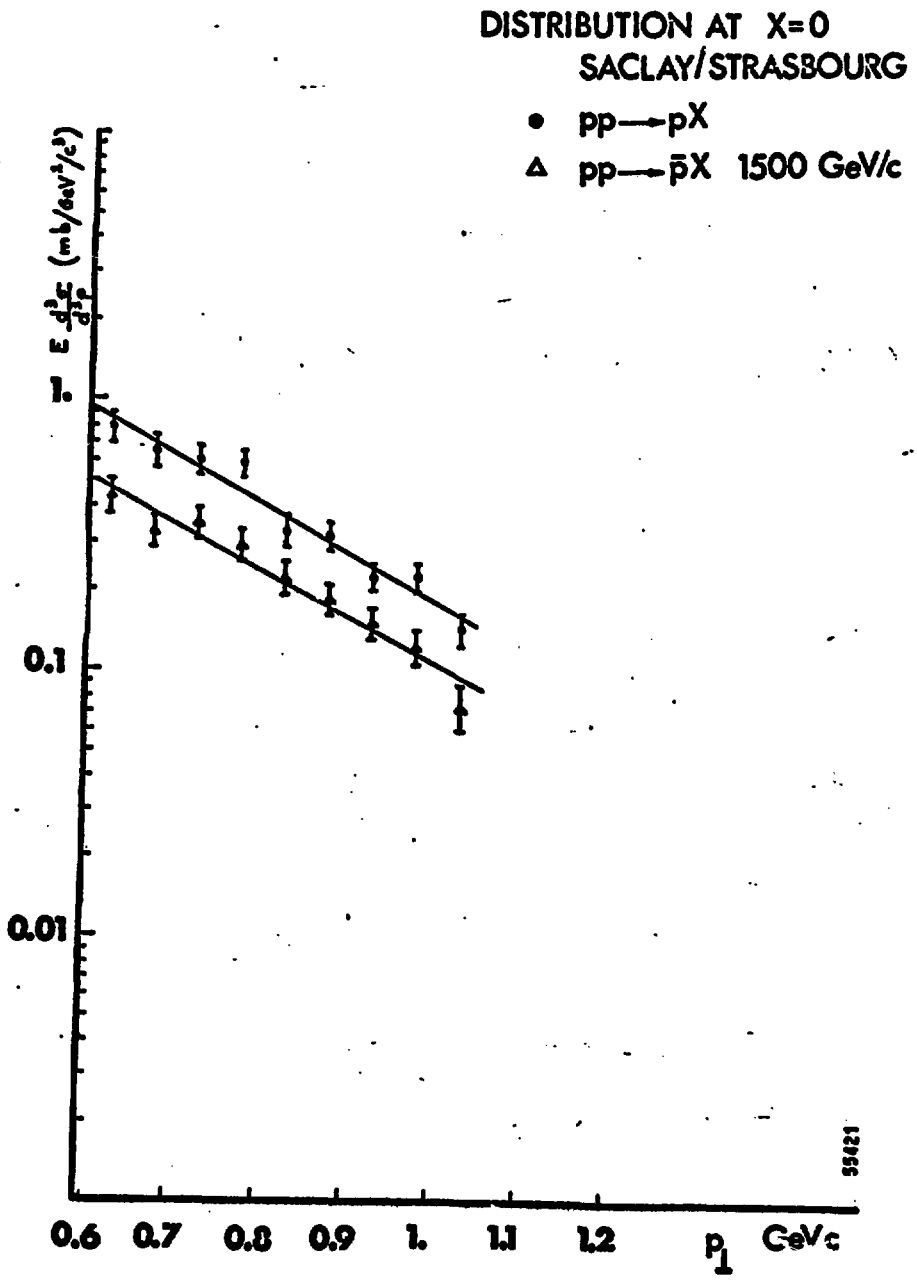

C=0.76±0.05
× π⁺p→π⁺...
○ γp→π⁻...
■ π⁺p→π⁻...
● pp→π⁻...
▲ K⁺p→π⁻...
"Threshold" Estimates
0.8
0.6
0.4
0.2
0.5
1.0
$\frac{1}{\sigma_T}\int E^* \frac{d^2\sigma}{dp_\ell^* dp_T} dp_T \Big|$ at $p_\ell^*=0$
$(p_{incident})^{-1/4}$ $[(GeV/c)^{-1/4}]$

Fig. 3

Fig. 4


DISTRIBUTION AT X=0
SACLAY/STRASBOURG
pp→pX
pp→p̄X 1500 GeV/c
E d³σ/d³p (mb/GeV²/c³)
1.
0.1
0.01
0.6
0.7
0.8
0.9
1.
1.1
1.2
p⊥ GeV/c
55421

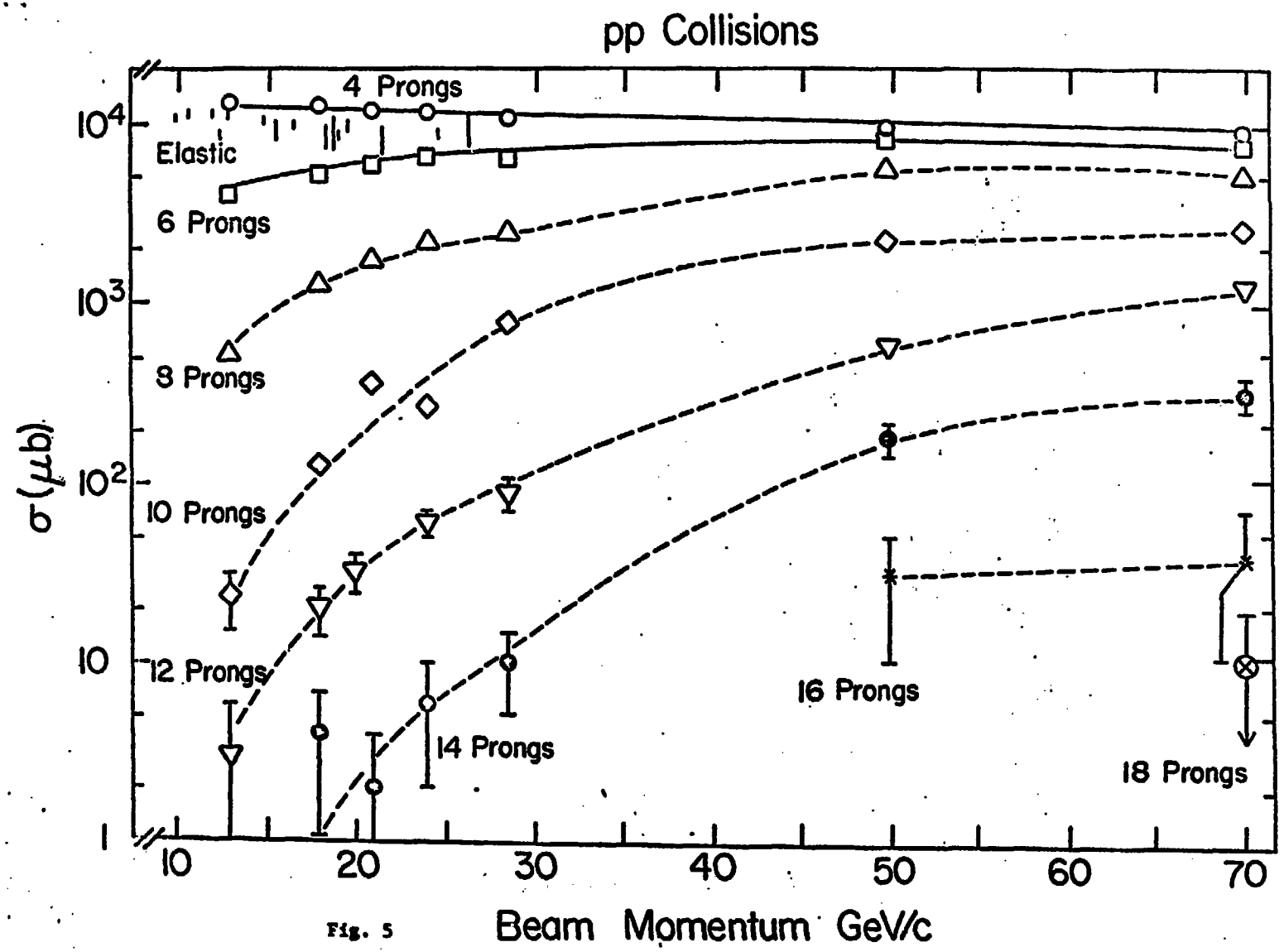

pp Collisions
4 Prongs
Elastic
6 Prongs
8 Prongs
10 Prongs
12 Prongs
14 Prongs
16 Prongs
18 Prongs
10^4
10^3
10^2
10
1
$\sigma(\mu b)$
10
20
30
40
50
60
70
Beam Momentum GeV/c

Fig. 5

Fig. 6

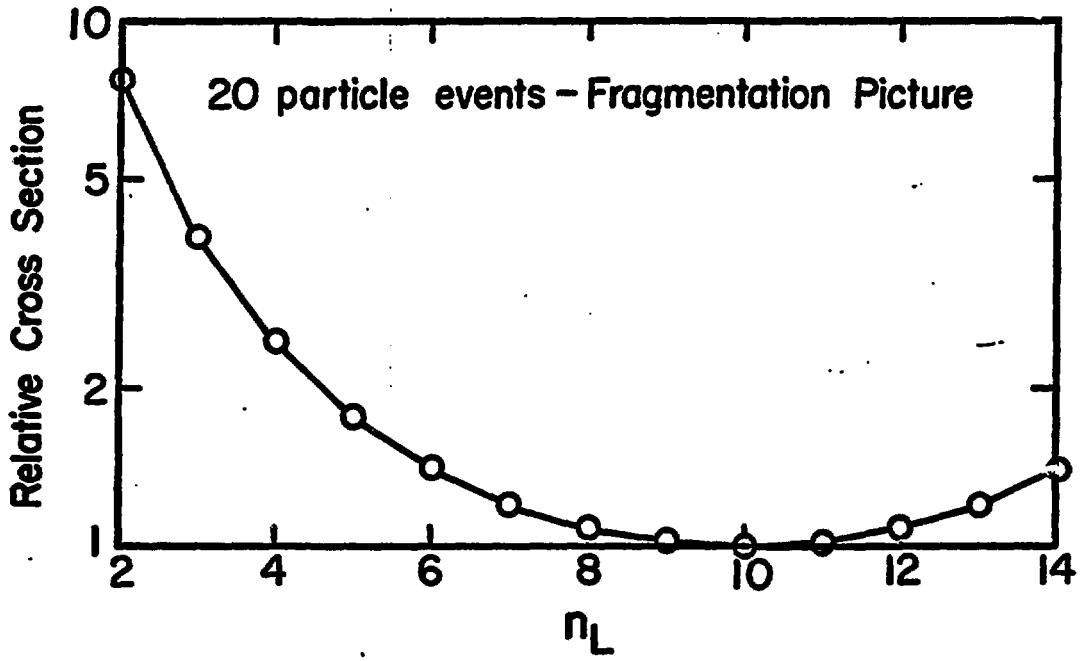
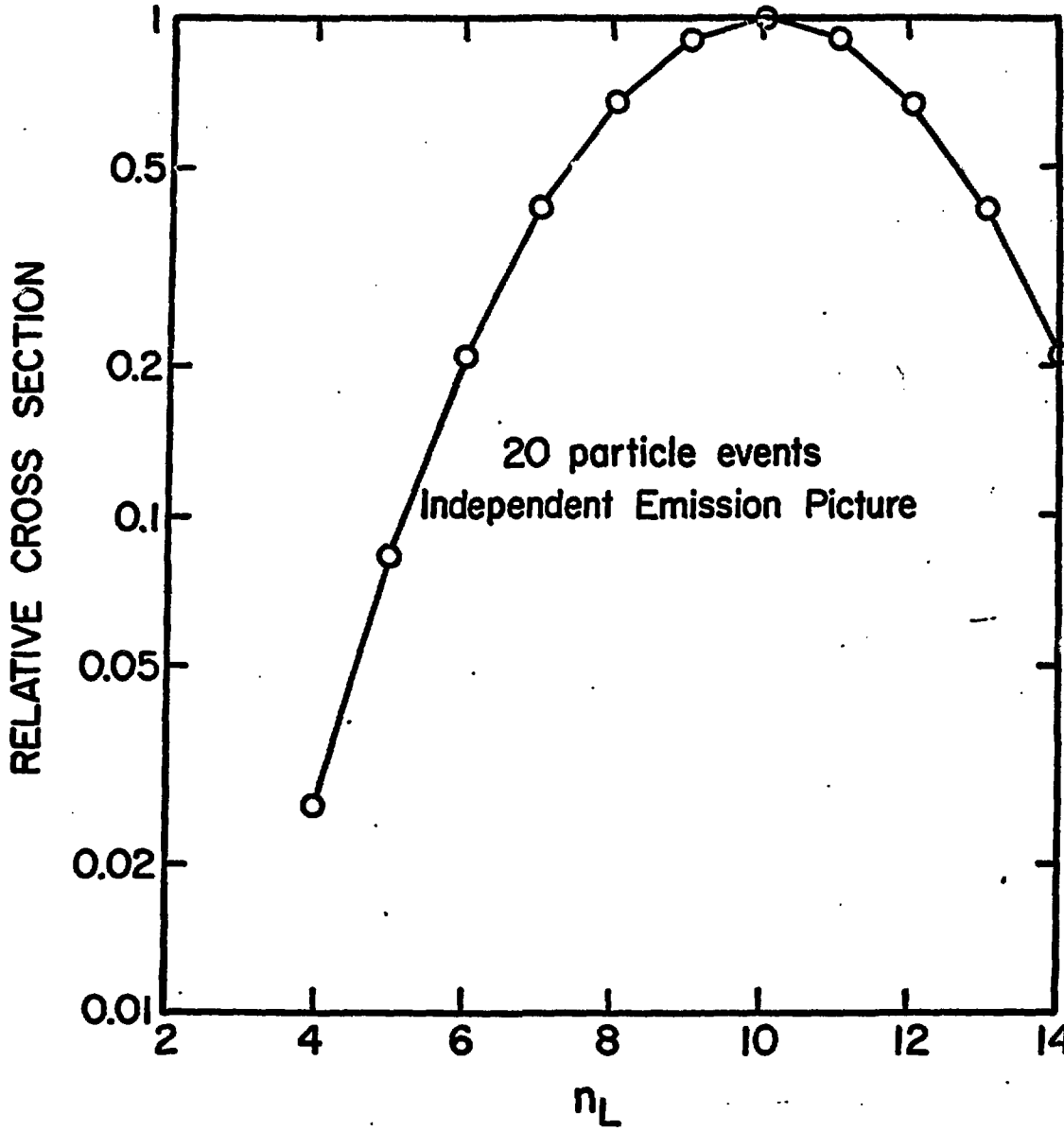

20 particle events – Fragmentation Picture
Relative Cross Section
10
5
2
1
2
4
6
8
10
12
14
n_L

Fig. 7


RELATIVE CROSS SECTION
1
0.5
0.2
0.1
0.05
0.02
0.01
2
4
6
8
10
12
14
n_L
20 particle events
Independent Emission Picture