Reaction $p+p \rightarrow \gamma+$Anything at 205 GeV and Its Implications for π^0 Production*

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From observations of photon conversions into electron pairs in the 30-in. hydrogen bubble chamber exposed to a 205-GeV proton beam at the National Accelerator Laboratory, we have measured topological and differential cross sections for the inclusive reaction $p+p \rightarrow \gamma+$anything. Comparison with data on the same reaction at the CERN intersecting storage rings suggests that π^0 production in pp collisions has reached a scaling limit by 205 GeV. We find that for multiplicities up to about 12, the average number of π^0's per inelastic pp collision increases with the number of charged particles produced.

Recent results[1] on photon production at the CERN intersecting storage rings (ISR) at equivalent proton lab energies of 500, 1100, and 1500 GeV indicate that the invariant cross section is independent of s, the center-of-mass energy squared, i.e., the Feynman scaling limit is reached by 500 GeV. Those data were also found to be consistent with a factorized interpolation formula, valid in the ISR energy range, which estimates the average number of π^0's per inelastic pp collision as a function of s. In this Letter, we present data on photon production which test for scaling behavior at 205 GeV.

From 15000 pictures of the 30-in. hydrogen bubble chamber at the National Accelerator Laboratory exposed to a 205-GeV proton beam, we have processes the V^0 events in which a neutral particle decays (or converts) into two charged particles. These events were recorded using scan rules as described by Charlton *et al.*[2] A rescan for V^0 events yielded efficiencies of (89 ± 2)% and (94 ± 2)%, respectively, for the two scans.

Each event was examined after measurement. Kinematically ambiguous events were classified according to ionization where possible, opening angle between charged tracks, and the transverse momentum between the neutral and the negative prong.[3] After all selections,[4] 138 out of 401 associated V^0 topology events were classified as electron pairs. The neutral–strange-particle events will be discussed elsewhere.[5]

The γ events have been weighted by the inverse of their detection probability, computed from the measured potential γ path in the fiducial volume, the minimum γ path length required for efficient detection, and the pair-production cross section,[6] which is independent of photon energy above 2 GeV. The average γ conversion probability in this experiment is 0.018, and the average weighted γ distributions are consistent with the center-of-mass symmetry of the pp system. We present in Table I the number of events and the cross sections as a function of the associated charged-particle multiplicity.

We discuss the data in terms of the invariant

TABLE I. Cross sections for $p+p \to \gamma + n$ charged particles + anything.

n = Number of Charged Particles	Number of γ's Observed	Corrected and Weighted Number	$\sigma_n(pp \to \gamma$ + Anything) mb	$\langle\pi^0\rangle$/ Inelastic pp Collision
2	6	657 ± 380	11.7 ± 6.9	1.68 ± 1.0
4	17	1169 ± 320	20.8 ± 5.7	1.87 ± 0.52
6	26	2128 ± 485	37.8 ± 8.6	2.72 ± 0.63
8	31	2139 ± 418	38.1 ± 7.4	3.37 ± 0.67
10	34	2811 ± 534	49.9 ± 9.5	5.66 ± 1.12
12	21	1314 ± 320	23.3 ± 5.7	3.39 ± 0.86
14	13	1172 ± 380	20.8 ± 6.7	6.12 ± 2.05
16	4	259 ± 135	4.6 ± 2.4	2.64 ± 1.42
18	0	0	----------	----------
20	2	82 ± 59	1.6 ± 1.2	----------
22	0	0	----------	----------
Total	154	11672 ± 1090	208.6 ± 19.6	3.17 ± 0.32

cross section

$$F(x, P_\perp, s) = \frac{2E}{\pi\sqrt{s}} \frac{d^2\sigma}{dx\, dP_\perp^2},$$

where E is the energy of the photon, $P_\perp$ ($P_\parallel$) its transverse (longitudinal) momentum, and $x = 2P_\parallel/\sqrt{s}$, all variables being computed in the pp center-of-mass system. We define $F_1(x)$ and $F_2(P_\perp^2)$ to be the integrals, over $P_\perp^2$ and x, respectively, of the invariant cross section. Figure 1 shows $F_1(x)$ and $F_2(P_\perp^2)$, as well as $d\sigma/dx$ and $d\sigma/dP_\perp^2$. We also show $2P_\perp F_2$ as a function of $P_\perp$. Note that we have used the pp c.m. symmetry by folding about $x=0$ and averaging our data. The curves in Fig. 1 correspond to the interpolation formula used by Neuhofer *et al.*[1] to parametrize their data on the same reaction measured at the CERN ISR. Their interpolation formula was primarily utilized to represent the data over the region $0 \le x \le 9.15$, $0.1 \le P_\perp \le 0.6$ and is shown in Fig. 1 as a solid line over this region. Within these limits, our data are consistent with their results. Earlier data at 24 GeV[7] were shown by Neuhofer *et al.* not to agree with s independence of the invariant cross section. This implies that the reaction $p+p \to \gamma +$anything reaches scaling behavior somewhere between 24 and 205 GeV.

Our data are insufficient to test whether $F(x,P_\perp, s)$ factorizes in x and $P_\perp$. We note, however [Fig. 1(c)], that our data are not in agreement

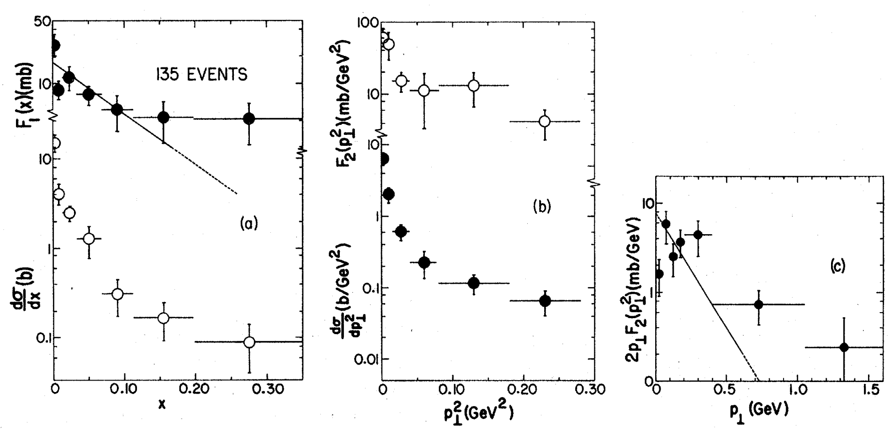

FIG. 1. (a) $F_1(x)$ and $d\sigma/dx$, (b) $F_2(P_\perp^2)$ and $d\sigma/dP_\perp^2$, and (c) $2P_\perp F_2$ versus $P_\perp$, as defined in the text. The curves are given by the ISR interpolation formula as described in the text ($c=1$).

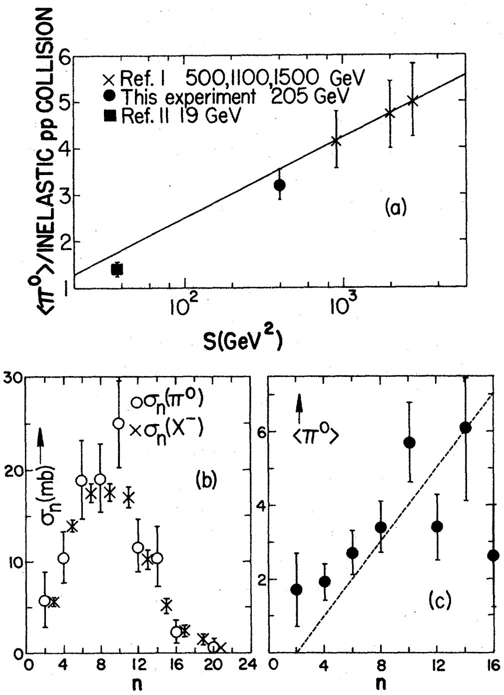

FIG. 2. (a) Average number of π^0's produced per inelastic pp collision, as a function of s. The curve corresponds to the formula $\langle\pi^0\rangle = 1.51 \ln(0.512\sqrt{s})$, given in Ref. 1. (b) $\sigma_n(\pi^0)$ and $\sigma_n(x^-)$ as a function of n. (c) The average number of π^0's produced per inelastic pp collision, $\langle\pi^0\rangle$, as a function of n. The dashed line corresponds to the number of negative tracks per topology.

with the functional form[1] $\exp(-P_\perp/0.162)$ for $P_\perp > 0.6$ GeV/c and $P_\perp < 0.1$ GeV/c.[8]

The average values of the photon momentum components are $\langle|P_\parallel|\rangle = 0.53 \pm 0.05$ GeV/c and $\langle P_\perp\rangle = 0.20 \pm 0.02$ GeV/c. Assuming that the dominant source of photons at high energy is π^0 decay,[9] we obtain $\langle P_\perp(\pi^0)\rangle = 0.40 \pm 0.04$ GeV/c, consistent with typical values for charged pions at all energies.[10] With the same assumption, the total inclusive cross section $\sigma(p + p \to \pi^0 + \text{anything})$ is 104 ± 10 mb at 205 GeV. Using our inelastic cross section measurement,[2] we find the average number of π^0's per inelastic pp collision, $\langle\pi^0\rangle$, to be 3.17 ± 0.32. For comparison, the data of Ref. 2 yield $\langle\pi^-\rangle = 2.82 \pm 0.08$ (if kaon emission is neglected). Figure 2(a) shows the available data[1,11] on $\langle\pi^0\rangle$ as a function of s. The solid line corresponds to the relation $\langle\pi^0\rangle = 1.51 \ln(0.512\sqrt{s})$ fitted by Neuhofer *et al.* to their ISR data.[1] To the extent that our data are consistent with theirs in the differential distributions $F_1(x)$ and $F_2(P_\perp^2)$, our value for $\langle\pi^0\rangle$ must be consistent with this curve, as is indeed the case.

Since the rates for $p + p \to \pi^+, \pi^0, \pi^- + \text{anything}$ are all independent,[12] data on π^0 production provide additional constraints on models which predict multiplicity distributions. In Fig. 2(b), we plot the cross section for $p + p \to \pi^0 + n$ charged particles + anything, $\sigma_n(\pi^0)$, as a function of the charge multiplicity together with the corresponding inclusive cross sections[2] for producing negative particles, $\sigma_n(x^-)$. The similarity between the two distributions shows that the rates for π^0 and for π^- production are very similar for the individual topologies. Our 205-GeV data suggest a rise in $\langle\pi^0\rangle$ with n up to about 12. This is shown in Fig. 2(c).

This same positive correlation between numbers of photons and charged particles has been recently observed in an ISR experiment[13] and is in contrast to the conslusion[11] reached at 19 GeV that $\langle\pi^0\rangle$ is almost independent of n. Earlier multiperipheral models[14] which predict that $\langle\pi^0\rangle$ decreases with increasing n are inconsistent with both results.

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[1]G. Neuhofer *et al.*, Phys. Lett. 38B, 51 (1972), and 37B, 438 (1971).

[2]G. Charlton *et al.*, Phys. Rev. Lett. 29, 515 (1972).

[3]About 10% of the events were classified by use of the transverse momentum distribution of the negative tracks relative to the V^0, which peaks near 0, 0.1, or 0.2 GeV/c for the γ, $\Lambda/\bar{\Lambda}$, or K^0 hypotheses, respectively.

[4]We used a fiducial volume about 85% of that used in Ref. 2 for the primary pp interaction. The minimum accepted length before conversion was 4 cm. Events with a χ^2 probability less than 1% were excluded from distributions. For cross-section purposes, we used the latter events and included electron pairs which were clearly recognized on the scan table but had one unmeasurable track. We also counted 5 out of 9 un-

measurable V^0's as γ's, in the ratio of γ's over total V^0's. This yielded the total of 154 events quoted in Table I.

[5]G. Charlton *et al.*, ANL Report No. AN/HEP 7245, 1972 (to be published).

[6]T. M. Knasel, DESY Reports No. 70/2 and No. 70/3, 1970 (unpublished). The pair-production cross section drops from its asymptotic value by a factor ≥ 2 for photon momenta below 100 MeV/c. We have, therefore, eliminated three events having less than 100 MeV/c lab momentum. We have corrected for this by doubling the weight factors of those events which, on the Peyrou plot, fall under the reflection (about zero c.m. longitudinal momentum) of the curve corresponding to $P_{1ab} = 100$ MeV/c. This minimum lab-momentum cut excludes a negligibly small area near the origin of the Peyrou plot, bounded by $P_\perp \leq 10$ MeV/c and $0 \leq P_L \leq 5$ MeV/c.

[7]M. Fidecaro *et al.*, Nuovo Cimento 24, 73 (1962).

[8]The turnover of $2P_\perp F_2$ at small $P_\perp$ (< 0.05 GeV/c) is expected for finite F_2. Results at 12.4 GeV/c show a sharp decrease for $P_\perp < 0.1$ GeV/c; see J. H. Campbell *et al.*, in Proceedings of the Sixteenth International Conference on High Energy Physics, National Accelerator Laboratory, Batavia, Illinois, 1972 (to be published).

[9]Evidence in support of this assumption is discussed by G. R. Charlton and G. H. Thomas, Phys. Lett. 40B, 378 (1972); and by S. N. Ganguli and P. K. Malhotra, Phys. Lett. 39B, 632 (1972).

[10]If the distributions in $P_\perp^2$ for π^- and π^0 are similar, one overestimates $\langle P_\perp(\pi^0)\rangle$ by a few percent using $2 \times \langle P_\perp(\gamma)\rangle$. An exact relation, $\langle P_\perp(\pi^0)^2\rangle = 3\langle P_\perp(\gamma)^2\rangle - \frac{1}{2}m_{\pi 0}^2$ [G. I. Kopylov, Phys. Lett. 41B, 371 (1972)], gives $\langle P_\perp(\pi^0)^2\rangle = 0.22 \pm 0.04$.

[11]H. Bøggild *et al.*, Nucl. Phys. B27, 285 (1971).

[12]See, for example, H. J. Lipkin and M. Peshkin, Phys. Rev. Lett. 28, 862 (1972).

[13]G. Flügge *et al.*, in Proceedings of the Sixteenth International Conference on High Energy Physics, National Accelerator Laboratory, Batavia, Illinois (to be published).

[14]J. W. Elbert *et al.*, Nucl. Phys. B19, 85 (1970), discuss $\langle\pi^0\rangle$ in $\pi^- p$ interactions. See also Bucharest-Budapest-Cracow-Dubna-Hanoi-Serpukhov-Sofia-Tashkent-Tbilisi-Ulan Bator-Warsaw Collaboration Report "P," No. 1411/VI/Ph, 1972 (to be published); $\langle\pi^0\rangle$ in pp collisions has been discussed by H. Bøggild *et al.*, Ref. 11. For a comparison between data and a number of current models of high-energy multiplicities, see E. L. Berger, D. Horn, and G. H. Thomas, ANL Report No. ANL/HEP 7240, 1972 (unpublished).

Role of π in High-Energy n-p Charge Exchange

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The forward peak in n-p charge-exchange reactions is accounted for by a simple Born model. The value of the peak is shown to be due to u-channel π^0 exchange, whereas its shape is found to be determined by the interference between the above mentioned π^0 contribution and a π^+ exchange in the t channel. The agreement with the data is fairly good for all incident momenta above 3 GeV/c and for a range of momentum transfer $0 < |t| < 0.005$ (GeV/c)^2.

Forward-direction n-p charge-exchange scattering exhibits a narrow peak[1] characteristic of t-channel pion exchange, i.e., a peak whose width is about m_π^2. One-pion exchange (OPE) calculations in the Born model yield, however, a vanishing contribution in the forward direction. Possible elimination of this disagreement is offered by an absorptive modification of the OPE Born amplitude.[2] Phillips[3] has accounted for the forward peak by a different, though not completely unrelated, method, namely, by the addition of a slowly varying background which interferes destructively with the OPE amplitude. The absorptive corrections as well as Phillips's background term are treated phenomenologically and fitted to the data. Muzinich[4] attempted to explain the data by a single Reggeized ρ exchange whose parameters were *fitted* to the data. Phillips in a further publication[5] showed that such a model cannot fit all the data and must, moreover, possess a rapidly varying residue function.

Islam and Preist[6] suggested a Born model in which the ρ *and* π are exchanged *both* in the t *and* the u channel. Their ρ is coupled only electrically to the nucleon, and the fitted coupling constant is smaller than the commonly accepted value. This is probably due to the non-Reggeized treatment of the ρ. The sharp forward peak is obtained by assigning a steep form factor to the ρ-nucleon vertex. Another strange feature of Ref. 6 is curve b in Fig. 2 which shows a very low pion contribution in the forward direction in