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The Reaction $pp \rightarrow \gamma + \text{Anything}$ 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-inch 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 $pp \rightarrow \gamma + \text{anything}$. Comparison with data

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on the same reaction at the CERN ISR 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 particle produced.

Recent results⁽¹⁾ on photon production at the CERN 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 15,000 pictures of the 30-inch hydrogen bubble chamber at the National Accelerator Laboratory exposed to a 205 GeV proton beam, we have processed 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 in Ref. 2. A rescan for V^0 events yielded efficiencies of $(89 \pm 2)\%$ and $(94 \pm 2)\%$, 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

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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 gamma 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 weight factor per event is 75. The 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 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. Fig. 1 shows $F_1(x)$ and $F_2(P_{\perp}^2)$, as well as $\frac{d\sigma}{dx}$ and $\frac{d\sigma}{dP_{\perp}^2}$. We also show $2P_{\perp} F_2$ as a function of $P_{\perp}$. Note that we have used the pp CM 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 parameterize their data on the same reaction measured at the CERN ISR. Their interpolation formula was

primarily utilized to represent the data over the region $0 \leq x \leq 0.15$, $0.1 \leq P_{\perp} \leq 0.6$ 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 a independence of the invariant cross section. This implies that the reaction $pp \rightarrow \gamma + \text{anything}$ 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 with the functional form⁽¹⁾ $e^{-P_{\perp}/0.162}$ 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 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 $\sigma(pp \rightarrow \pi^0 + \text{anything})$ 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). Fig. 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 $pp \rightarrow \pi^+, \pi^0, \pi^- + \text{anything}$ 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 $pp \rightarrow \pi^0 + n$ 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 conclusion⁽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.

We thank the staff of the National Accelerator Laboratory and the 30-inch bubble chamber group for a remarkably smooth first run, and the scanning and measuring personnel at Argonne National Laboratory for their dedicated work. We appreciate many enlightening discussions with E. L. Berger and G. H. Thomas and thank D. Colley for his help in the final analysis.

References

1. G. Neuhofer et al., Phys. Letters 38B, 51 (1972) and Phys. Letters 37B, 438 (1971).
2. G. Charlton et al., Phys. Rev. Letters 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 chi-squared 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 unmeasurable 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., "Neutral Strange Particle Production in 205 GeV pp Interactions," ANL/HEP 7245 (1972), to be published.
6. T. M. Knasel, "The Total Pair Production Cross Section in Hydrogen and Helium," DESY Reports No. 70/2 and 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 3 events having less than 100 MeV/c laboratory

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 cm longitudinal momentum) of the curve corresponding to $P_{\text{lab}} = 100 \text{ MeV/c}$. This minimum laboratory momentum cut excludes a negligibly small area near the origin of the Peyrou plot, bounded by $P_{\perp} \leq 10 \text{ MeV/c}$ and $0 \leq P_L \leq 5 \text{ MeV/c}$.

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

8. The turnover of $2P_{\perp} F_2$ at small $P_{\perp} (< 0.05 \text{ GeV/c})$ is expected for finite F_2 . Results at 12.4 GeV/c show a sharp decrease for $P_{\perp} < 0.1 \text{ GeV/c}$; see J. H. Campbell et al., "The Reaction $pp \rightarrow \gamma + \text{Anything at } 12.4 \text{ GeV/c}$," submitted to the XVI International Conference on High Energy Physics (1972) (unpublished).

9. Evidence in support of this assumption is discussed by G. R. Charlton and G. H. Thomas, *Phys. Letters* 40B, 378 (1972); and by S. N. Ganguli and P. K. Malhotra, *Phys. Letters* 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 $2 \cdot \langle P_{\perp}(\gamma) \rangle$. An exact relation $\langle P_{\perp}(\pi^0)^2 \rangle = 3 \cdot \langle P_{\perp}(\gamma)^2 \rangle - \frac{1}{2} m_{\pi^0}^2$ (G. I. Kopylov, *Phys. Letters* 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. Letters* 28, 862 (1972).

13. G. Flügge et al., "Observation of Correlations Between Single γ -Rays and Charged Particles Produced in pp Collisions at the ISR," submitted to the XVI International Conference on High Energy Physics (1972) (unpublished).
14. J. W. Elbert et al., Nucl. Phys. B19, 85 (1970) discuss $\langle \pi^0 \rangle$ in π^-p interactions. See also Report "P," No. 1411/VI/PH by the Bucharest-Budapest-Cracow-Dubna-Hanoi-Serpukhov-Sofia-Tashkent-Tbilisi-Ulan-Bator-Warsaw Collaboration (1972), (to be submitted to Phys. Letters); $\langle \pi^0 \rangle$ 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, "Correlations Between Neutral and Charged Pions in Multiparticle Production," ANL/HEP 7240 (1972) (unpublished).

Table I
Cross Sections for $pp \rightarrow \gamma + n$ Charged + Anything

n = Number of Charged Particles	Number of γ 's Observed	Corrected and Weighted Number	$\sigma_n(pp \rightarrow \gamma$ + 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

Figure Captions

Fig. 1 (a) $F_1(x)$ and $\frac{d\sigma}{dx}$, (b) $F_2(P_\perp^2)$ and $\frac{d\sigma}{dP_\perp^2}$, (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) The 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.

Fig. 1

Fig. 2