SEARCH FOR DIRECT PHOTON PRODUCTION AT LARGE p_T IN PROTON-PROTON COLLISIONS AT $\sqrt{s}$ = 62.4 GeV*

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SUMMARY

This is a report of preliminary results from the CCOR Group, Experiment R-108, at the CERN ISR. In addition, previously published results from the Rome-Brookhaven-CERN Group at the ISR will be reviewed.

Direct photon production in proton-proton collisions is very interesting and fundamental because photons are coupled to electric charge but heavy particles do not emit much bremsstrahlung. Thus, the observation of significant direct photon emission in hadron collisions would be evidence for the existence of light pointlike electrically charged constituents inside protons.

Obviously, this is a naive and pre-QCD statement; but there was certainly interest in direct photons before QCD. In particular, the copious yield of direct single electrons and muons observed in hadron collisions[1] prompted Glennys Farrar, among others, to suggest a direct photon mechanism as the source[2]. The lepton/pion ratio of $\sim 10^{-4}$ observed for $p_T > 1.0$ GeV/c could have been explained by a γ/π^0 ratio of $\sim 10\%$. However, this turned out not to be the case[3]. Nevertheless, the emphasis "on the importance of the behavior of γ/π for illuminating the dynamics of large p_T hadron production" was well founded.

With the advent of QCD, all of these ideas have been put on a reasonably quantitative basis. One mechanism for direct photon production at large p_T is the "Inverse QCD Compton Effect"[4], i.e., quark + gluon → quark + γ. The beauty of this reaction as a hadronic probe is that the γ-ray can emerge directly from inside the hadron. No messy arguments about fragmentation are involved. In principle, the only unknown quantity is the gluon distribution inside a hadron. Thus, it would seem that the calculations of direct photon production[5,6,7,8] should be reliable. As shown in Figure 1, however, there is nearly a two order of magnitude variation in the calculations at high p_T.

In all fairness, it should be pointed out that there are at least three reasons for the wide variation of the different calculations. i) The QCD calculations predict only the inclusive direct γ cross section. The ratio of γ/π is found by dividing by the measured inclusive π^0 cross section, where available[7,8], or by extrapolating the π^0 cross section to higher p_T[5]. ii) Scaling structure functions were used originally[5,6,7], but it was pointed out by the McGill group[8] that scale-violation effects were important. iii) Finally, the shape of the gluon distribution at the reference momentum-transfer is unknown and therefore several possibilities have been tried. In Figure 1, the difference between curves (d) and (e) is the choice of the gluon distribution, $(1 - x)^4$ in (d) and $(1 - x)^5$ in (e). Figure 2 shows the effect of scaling versus scale-violating structure functions[9]. Furthermore, the shaded region represents the uncertainty in γ/π due to the different experimental determinations of the absolute π^0 cross-section[10,11].

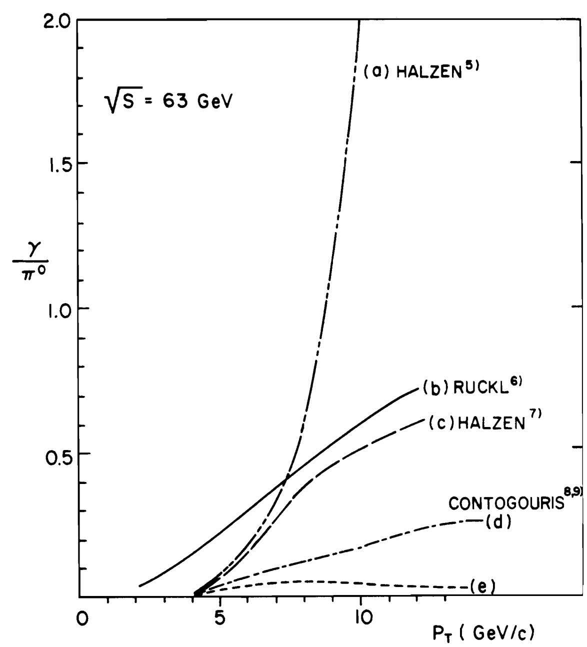

FIG. 1- QCD calculations of γ/π.

On the experimental side, one of the first searches for direct photon production was made by the Rome-Brookhaven-CERN-(Adelphi) Collaboration[12,13].

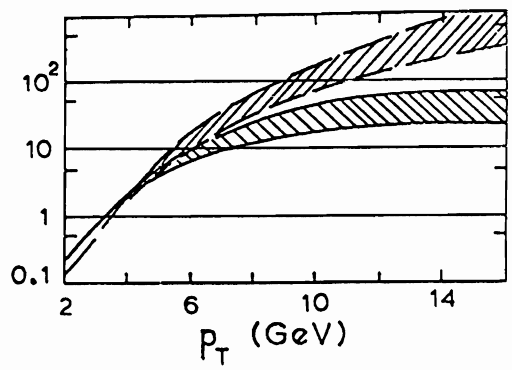

FIG. 2 - γ/π in percent at $\sqrt{s}$ = 63 GeV, from Contogouris[8,9].

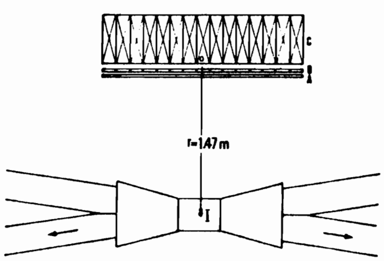

FIG. 3 - Apparatus of Rome-BNL-CERN Group[12,13] at the ISR.

Their detector, shown in Figure 3, consisted of a matrix of 9 by 15 lead glass blocks, 10 × 10 cm² in area and 35 cm long, placed behind two matrices of scintillation counters which allowed the rejection of charged particles.

A γ-ray cluster was defined as an isolated cluster of energy in any set of up to 2 by 2 lead glass counters. A reconstructed π^0 or η^0 was defined as two γ-ray clusters having the correct invariant mass corresponding to π^0 or η^0. Only events with one or two clusters observed in the lead glass matrix were considered in the analysis, and the single-γ signal was obtained only from the one cluster events. Thus, direct photons accompanied by other photons within the solid angle of the detector would be missed.

The main problem with this method is that there is a big single γ-ray signal, typically $\sim$20% of π^0. This signal has nothing to do with direct γ-rays but originates from the following backgrounds:

i) The decays $\pi^0 \to \gamma\gamma$ or $\eta^0 \to \gamma\gamma$ in which either a) one γ is outside the detector or below threshold or b) the two γ-rays are not geometrically resolved.

ii) Neutral hadrons like $\bar{n}$, n, K^0_L, etc.

In order to obtain the direct γ-ray signal from the single γ-ray signal, these backgrounds must be painstakingly understood and subtracted. A typical calculation is shown below:

	Observed Single-γ Signal	Calculated Background Due to π^0	η^0	$\bar{n}$	Direct γ-Ray Signal
$\frac{\gamma}{\pi^0}$	0.201±0.006	0.135	0.032	0.013	0.022±0.010

The difficulty is apparent, since the direct γ-ray signal remaining is only about 10% of the observed single γ-ray signal.

The results of this measurement for γ/π^0 at $\sqrt{s}$ = 53 GeV are shown in Figure 4 as a function of p_T.

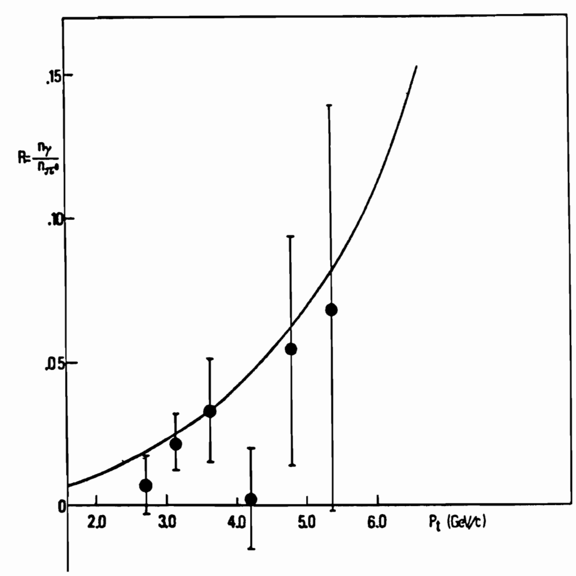

FIG. 4 - γ/π from Rome-BNL-CERN at $\sqrt{s}$ = 53 GeV.

The black line shown is a QCD prediction[14], similar to curve (c) of Figure 1. It is not clear whether the data support the QCD prediction or are consistent with a zero value for γ/π^0. For instance, taking the average over the interval $3.0 \leq p_T \leq 5.0$ GeV/c, the result is $\langle\gamma/\pi^0\rangle = 0.020 \pm 0.008$.

Very recently this group has reported[13] measurements at $\sqrt{s}$ = 30.6 GeV. Again, there is very little signal, if any. However, if it is assumed that the γ/π^0 ratio is a universal function of $x_T = 2p_T/\sqrt{s}$, then the measurements at both $\sqrt{s}$ values can be averaged to give

$\langle\gamma/\pi^0\rangle = 0.016 \pm 0.050$ for $0.10 \leq x_T \leq 0.20$.

The data for both $\sqrt{s}$ values are plotted as a function of x_T in Figure 5.

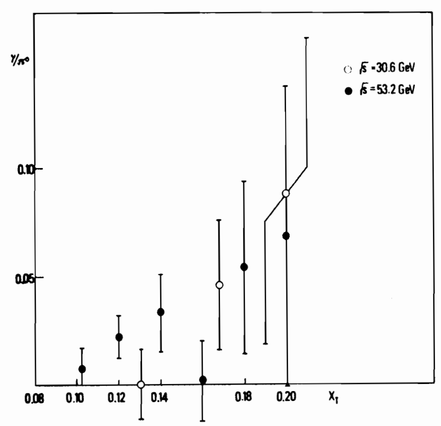

FIG. 5 - Rome-BNL-CERN values for γ/π as a function of x_T for the $\sqrt{s}$ values 30.6 and 53.2 GeV.

A completely different approach has been taken by the CCOR Group, also working at the CERN ISR. In this experiment, the two photons from a π^0 can not be resolved geometrically. The average number of photons in an energy cluster is determined statistically by measuring the probability for the photon or group of photons in the cluster to pass through material without any conversion taking place. The converter is 1.0 radiation length of aluminum.

The non-conversion probability per photon after a thickness of material t is given by Tsai[15]

$$N = \exp\left(\frac{-7}{9}\frac{t}{X_0}[1-\zeta]\right).$$

For a single photon, the non-conversion probability in $1.0X_0$ of aluminum varies between

$$N_1 = 0.474 \quad \text{to} \quad 0.466$$

for photon energies between 2 and 10 GeV. For $\pi^0 \rightarrow \gamma\gamma$, the non-conversion probability is

$$N_2 \simeq N_1^2 = 0.220.$$

The non-conversion probability is relatively independent of the π^0 energy, since the two photons average over all lower energies. This is confirmed by the E.G.S. Monte Carlo[16].

A list of the physicists who have performed the experiment is given in Figure 6. The detector (Figure 7) consisted of two arrays of lead glass Cerenkov counters, denoted "inside" and "outside," which each covered a solid angle of $\Delta\phi = \pm 30^0$ and $\Delta\theta = \pm 33^0$ around $\theta = 90^0$. The arrays were located on either side of a superconducting solenoid magnet containing cylindrical drift chambers which were used to measure charged particles. Two hodoscopes of scintillation counters (B) located just outside the solenoid were also used. The coil and cryostat of the solenoid served as the converter.

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FIG. 6 - Members of the CCOR Collaboration.

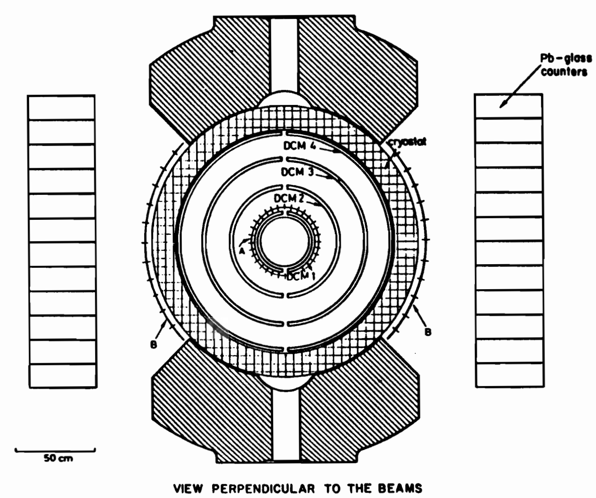

FIG. 7 - The CCOR Detector at the CERN ISR.

A cluster was defined as an isolated distribution of energy in a matrix of up to 3 by 3 lead glass blocks. For transverse momenta $p_T > 3$ GeV/c, the two γ-rays from π^0 decay were unresolved and appeared as a single cluster. A conversion was defined by the presence of more than 1.5 single ionization in the B counters facing the cluster, after subtraction of the contribution of any charged particle tracks observed. The non-conversion fraction for all clusters as a function of

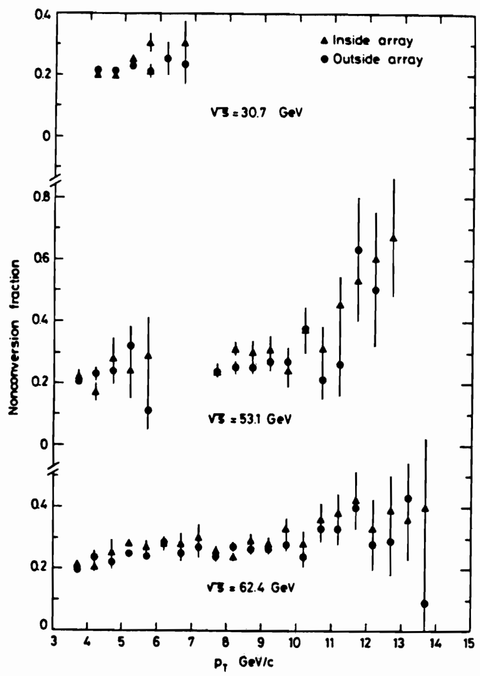

FIG. 8 - Non-conversion fraction versus p_T for three different $\sqrt{s}$ values.

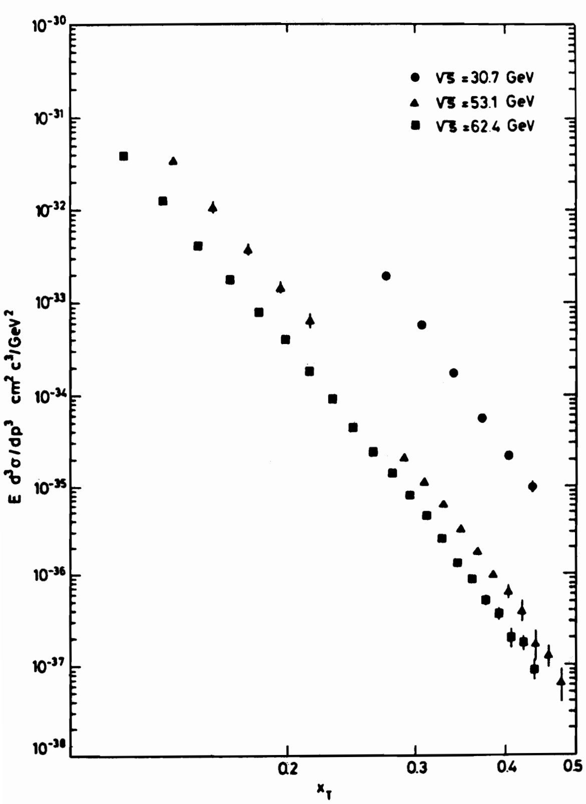

FIG. 9 - CCOR inclusive π^0 cross section versus x_T for three different $\sqrt{s}$ values.

p_T has been given in a previous publication[10] and is shown in Figure 8. It was concluded from this figure that the clusters were consistent with all being due to two photons; and a single photon contribution of more than 30% could be excluded for the region $4.0 \leq p_T \leq 10.5$ GeV/c. The clusters were all taken to be π^0, and the inclusive π^0 cross section was obtained as a function of x_T for three different values of $\sqrt{s}$. (Figure 9). Since this conference has produced such a hullabaloo about gluons[17], I feel compelled to point out that the data of Figure 9, published nearly a year ago[10], represent a confirmation that high p_T particle production is caused by the scattering of pointlike constituents via asymptotically free vector gluon exchange[18].

In any constituent-hard-scattering model, the cross section can be written[19] as a scaling law, p_T^{-n}, times "a dimensionless function of dimensionless kinematic variables"[18]. The parameter n is related to the type of constituents and the force law that governs their scattering. In particular, near 90^0 in the c.m. system

$$E\,\frac{d^3\sigma}{dp^3} = \frac{1}{p_T^{\,n}}\,F(2p_T/\sqrt{s}) = \frac{1}{\sqrt{s}^{\,n}}\,G(x_T).$$

The data at the $\sqrt{s}$ values 53.1 and 62.4 GeV in Figure 9 are a factor of ~ 4 apart at lower x_T and a factor of ~ 2 apart at higher x_T. This clearly shows that n changes from the value of $n \simeq 8$ in the range $2.5 \leq p_T \leq 7.0$ GeV/c to a value $n = 5.1 \pm 0.4$ in the range $7.5 \leq p_T \leq 14$ GeV/c. The value $n = 4$ would be characteristic of QED or asymptotic QCD. I should also like to point out that this new high p_T range, $p_T > 7.5$ GeV/c, has not yet been achieved at Fermilab and thus is only available at present at the CERN ISR[10,11,20].

Since detailed measurements of direct photon production are possibly a quantitative check of QCD, particularly in the gluon sector, the CCOR Group has attempted to improve on the results shown in Figure 8. Using new data taken at $\sqrt{s} = 62.4$ GeV with an integrated luminosity of 3.5×10^{37} cm^{-2} (about twice that of Figure 8), the non-conversion fraction has again been obtained for all clusters. (Figure 10). There are two systematic problems with this data: i) The inside and outside arrays systematically disagree. ii) The non-conversion fraction rises at lower p_T. The latter effect is particularly puzzling since all previous measurements[3,12] for $\sqrt{s} > 50$ GeV indicate that $\gamma/\pi < 0.02$ for $p_T < 5$ GeV/c.

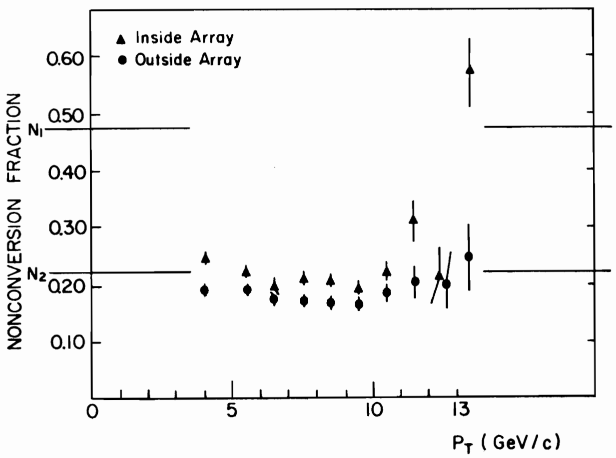

FIG. 10 - New CCOR non-conversion fraction at $\sqrt{s}$ = 62.4 GeV.

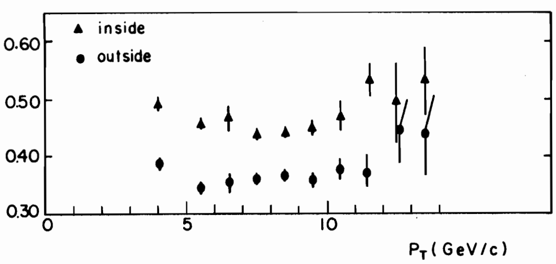

FIG. 11 - Fraction of events with no overlaps on B counters. Note offset zero.

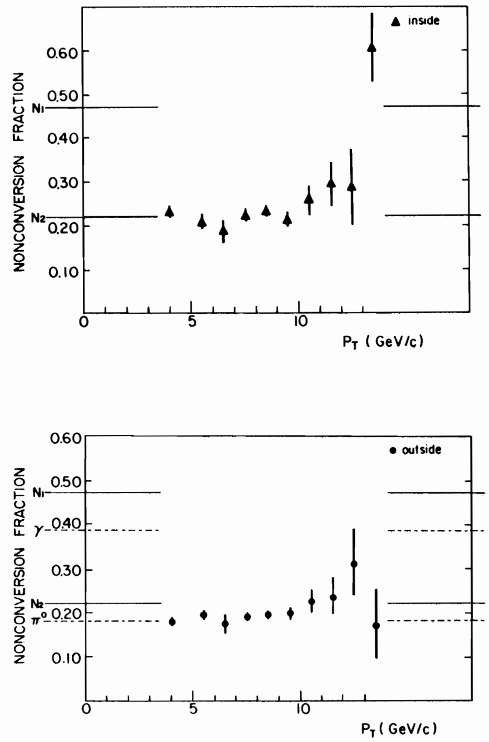

FIG. 12 - Non-conversion fraction for events with no overlaps on B counters.

It was thought that both these effects were due to charged and neutral particles overlapping the B counters used for the non-conversion measurement, since the main cluster intercepts only 1/5 the length of the B counters. Thus a cut was made to insist that no charged track or neutral energy (apart from the main cluster)overlap the B counters of interest. There is very little p_T dependence in the fraction of events that satisfy this cut. (Figure 11). The effect on the non-conversion fraction is due to the collimation caused by the jet structure of the events[21]. The non-conversion fractions for the events satisfying this "no overlap" cut are shown separately for the inside and outside arrays in Figures 12a and 12b.

The data from the inside array look reasonable and are consistent with the value expected for $\pi^0 \to \gamma\gamma$ clusters. The exact value for γ/π^0 is computed by assuming that the total signal contains only two components, namely γ and π^0.

$$\gamma/\pi^0 = (N_{OBS} - N_2)/(N_1 - N_{OBS}).$$

The data from the outside array look reasonable in shape but are still systematically below the value expected for π^0 clusters. It is believed that this effect is due to overlapping tracks that give ionization in the B counters but are not reconstructed. This effect is much worse in the outside array because of the ISR center-of-mass motion. In order to overcome this problem, we have made use of previous measurements[3,12] (see Figure 4) that indicate

$$\langle\gamma/\pi^0\rangle = 0.020 \pm 0.008 \text{ for } 3.0 \leq p_T \leq 5.0 \text{ GeV/c}.$$

Thus we take this p_T region as a calibration of N_{π^0} for a pure π^0 signal. The effect of single γ-ray production is observed by the change in the non-conversion fraction from the value measured in the calibration zone, $3 \leq p_T \leq 5$ GeV/c. The only other number required to complete the measurement is the non-conversion fraction to be expected for a pure single γ-ray signal. For the preliminary results presented here, we have taken the value corresponding to the assumption of identical overlaps in the case of both π^0 and single γ-rays, namely

$$N_\gamma \equiv N_1 \times N_{\pi^0}/N_2$$

Note that this assumption will lead to an overestimate of QCD-Compton γ-rays since these are supposed to be produced cleanly without any accompanying fragments. Nevertheless, the values of γ/π^0 obtained for both the inside and outside arrays are in agreement, so that they are averaged in the preliminary results presented in Figure 13.

The errors shown in Figure 13 include both statistics and the systematic error associated with the calibration procedure. A major additional systematic uncertainty not included in the figure is the effect of the production of particles having three to six photon decays which might obscure a single γ-ray signal. The following decays have been investigated:

Particle	Assumed Production/π^0	Decay	$c\tau$ (cm)	Branching Ratio
η^0	0.55	$\gamma\gamma$	--	0.38
η^0	0.55	$\pi^0\pi^0\pi^0$	--	0.30
K^0_S	0.40	$\pi^0\pi^0$	2.68	0.31
ω^0	0.50	$\pi^0\gamma$	--	0.09

The net result is an overall systematic correction to the values of γ/π^0 shown in Figure 13 of $+0.047 \pm 0.027$, independently of p_T; where π^0 is still taken to include all clusters not ascribed to single γ-ray production. This definition of π^0 corresponds to the definition used in our published cross section measurements[10] and in the McGill prediction[8,9] of γ/π^0 so that Figure 13 shifted up by +0.047 can be compared directly to Figure 1 as shown in Figure 14. It is clear that only curves (d) and (e) remain in the game; but to distinguish them requires an experiment with an order of magnitude better statistics for $p_T > 10$ GeV/c, and/or an order of magnitude improvement in systematic uncertainties.

As a parting note, I should like to point out some difficulties in comparing the data of Figure 13 with the data of other experiments which measure γ/π^0, where π^0 is taken from reconstructed $\gamma\gamma$ events with the correct mass[22]. For this comparison, the data of Figure 14 should be corrected upward by a factor of ~ 1.3; but the exact correction is uncertain because it depends on detailed knowledge of η^0/π^0, K^0_S/π^0 and

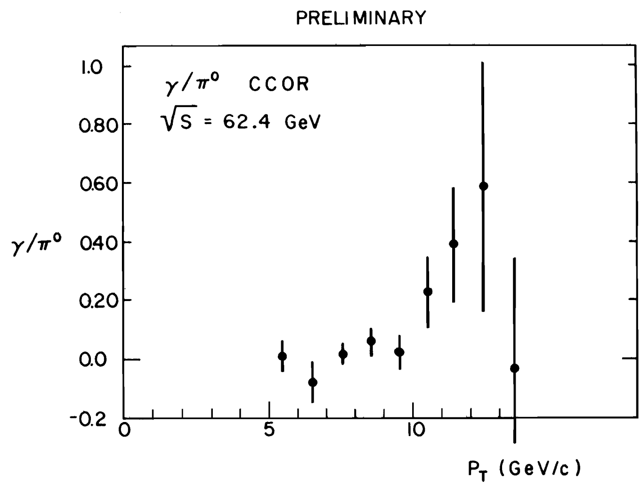

FIG. 13 - Preliminary CCOR result for γ/π^0.

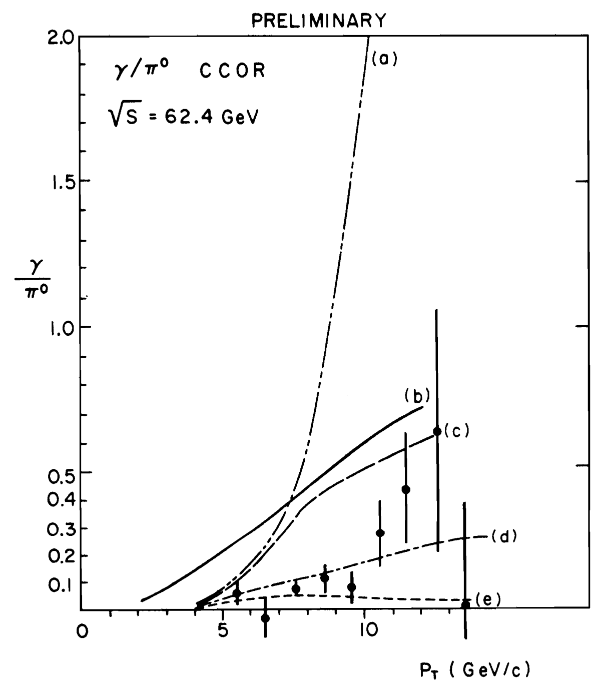

FIG. 14 - Corrected preliminary CCOR data for γ/π^0 at $\sqrt{s} = 62.4$ GeV compared to QCD calculations.

ω^0/π^0 as a function of p_T at $\sqrt{s}$ = 62.4 GeV. Furthermore, official QCD direct photons are supposed to have no associated fragments, while π^0 certainly have associated particles. Thus any cleaning-up cut might enhance the γ/π^0 measurement from the inclusive value. For instance, if direct γ-rays originate only from the QCD Compton effect, the data shown in Figure 11 imply that the results of Figure 14 should be corrected down by a factor of 2. Hopefully, much of this confusion can be eliminated if both the experimenters and the theorists would quote the inclusive direct γ-ray cross section.

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DISCUSSION

J. Feller, Columbia University: What are the parameters of your fit to the π^0 spectrum?

Tannenbaum: $n = 5.1 \pm 0.4$.

Feller: Why do you claim to have discovered the gluon? Shouldn't the exponent be 4?

Tannenbaum: Yes, at the asymptotic limit. However, in the non-asymptotic case, the weakening of the QCD coupling constant, and scale-violation effects will give a slightly larger value (see Ref. 18).

J. Rosen, Northwestern University: Did you not think to add another radiation length of Aℓ in front of at least a portion of the detector for check purposes?

Tannenbaum: Yes, we did, but the 1 X_0 thick converter was already spoiling our energy resolution. We would have preferred to have made the measurement with several independent converters adding up to 1 X_0, but the coil of the magnet didn't permit this.

Feller: You gave no explanation of why the non-conversion fraction at low p_T is lower than expected. You simply took the data from Amaldi et al., which showed no direct γ production at low p_T. Can you explain why your non-conversion fraction is low?

Tannenbaum: We believe the effect is due to track reconstruction inefficiency which is a much larger effect in the outside array due to the center-of-mass motion.

T. DeGrand, USCB: A comment: Comparing γ/π, to QCD predictions of γ/π^0, where the "γ" part is calculated and "π^0" is taken from data, is dangerous since QCD calculations of π^0 are still uncertain to an order of magnitude or so. A calculation could predict a good γ (theory)/π^0 (data) ratio but poor γ or π^0 separately. Better for experimentalists to plot $Ed\sigma/d^3p$ ($pp \rightarrow \gamma x$) vs. p_T, not γ/π, and keep theorists honest.

Tannenbaum: We're going to do just that!