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**Search for Direct Photon Production
in 200 A GeV S + Au Reactions: A Status Report**

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Search for direct photon production in 200 A GeV S + Au reactions: A status report

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Abstract

Direct thermal photons in the p_T range of 0 – 5 GeV/c are expected to provide a sensitive probe of the hot dense matter formed in the early stage of relativistic heavy ion collisions. The production of single photons in 200 A GeV S+Au reactions has been investigated using the 3800 element Pb-glass calorimeter of CERN experiment WA80. Neutral π^0 and η cross sections have been measured via their two-photon decay branch yields. In a first analysis of the WA80 results, a slight excess photon yield above that which may be accounted for by hadronic decays was observed for central collisions. A report on the status of the reanalysis of this data is presented.

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1. INTRODUCTION

Directly radiated thermal photons have long been considered an interesting penetrating probe with which to study the early phase of the hot and dense matter produced in relativistic nucleus-nucleus collisions. Single "direct" photons are expected at high p_T from well-known hard QCD processes, but also possibly from thermal radiation from the QGP and/or from a hadron gas in the p_T region below several GeV/c [1]. It is believed that thermal photon emission should provide information about the initial conditions of the system and thereby provide evidence for the possible formation of a Quark Gluon Plasma (QGP).

A major emphasis of the WA80 experiment has been the search for direct thermal photon production in nucleus-nucleus collisions. First results from WA80 found a slight photon excess in central collisions of $^{16}\text{O}+\text{Au}$ at 200 A GeV which, however, was within rather large experimental errors, and hence not significant [2]. For the case of $^{32}\text{S}+\text{Au}$ reactions the direct photon sensitivity of WA80 has been improved by many factors [3] including an increased data sample, an increased detector coverage, a coverage closer to mid-rapidity, and improved analysis techniques, as well as the improvement expected due to the increased projectile mass.

The first preliminary results from the WA80 $^{32}\text{S}+\text{Au}$ photon data were presented at Quark Matter '93 [3]. From this analysis, no excess photons beyond that attributable to resonance decays were observed in peripheral $^{32}\text{S}+\text{Au}$ collisions, while for central collisions, a photon excess significantly above the estimated level of uncertainty was observed. Subsequently, this preliminary result has generated a great deal of theoretical interest [4-7]. This is illustrated in Figure 1 where the preliminary WA80 result for the excess photon invariant cross section as a function of p_T for central collisions

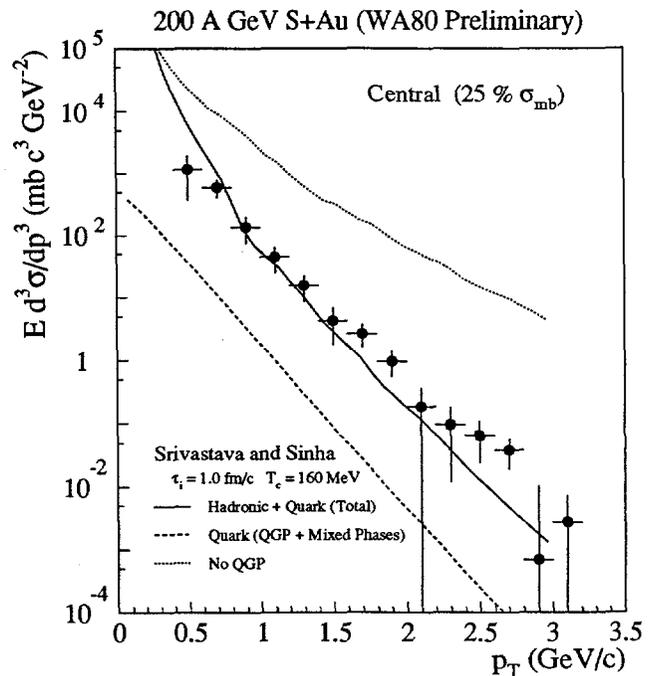


Figure 1. Single photons from central collisions of $^{32}\text{S}+\text{Au}$. Solid points are the preliminary result from experiment WA80. The calculations are from reference [5]. The theoretical predictions show the results expected for an initial formation time of $\tau_i = 1 \text{ fm/c}$ in the case in which no QGP phase transition occurs (dotted curve) and in which a QGP phase transition does occur (solid curve) with a critical temperature of $T_c = 160 \text{ MeV}$ and a freeze-out temperature of $T_f = 100 \text{ MeV}$. The dashed line shows the photon contribution from the quark matter alone.

is compared to theoretical calculations taken from reference [5]. These calculations were performed assuming a standard scenario of QGP formation with subsequent evolution following boost invariant hydrodynamics with longitudinal expansion. In general, the calculations indicate that although the observed excess photon yield is far above that expected from the pure quark matter, a significant photon contribution is obtained from the hadronic matter during the later mixed and freezeout phases of the collision, such that the predicted yield in the standard scenario of QGP formation is in rather good agreement with the observed preliminary experimental result [5-7].

More importantly at this preliminary stage, is the observation that the scenario in which a QGP is not formed would imply a much greater temperature with an associated photon emission more than an order of magnitude greater than that observed experimentally (see Figure 1). The calculated photon emission does not show a strong dependence on the critical temperature assumed, nor on the detailed assumptions of boost invariance or transverse expansion [5-7], but does require an equation of state in which the temperature changes very little over a wide range of energy density, as in the case of a QGP formation [7], in order to explain the relative lack of photons observed experimentally.

For the results presented at Quark Matter '93 (see Figure 2) and here in Figure 1, a very careful analysis [8-9] had been made of many possible sources of systematic errors including the effects of non-linearity of the detector response, the shower identification criteria, the combinatorial background in the two-photon invariant mass distributions, and the sensitivity to various decay backgrounds. Since a photon excess was not observed in the case of peripheral collisions, where no excess was expected, this suggested that many of the possible systematic errors were under control. A major concern was possible centrality dependent effects, in particular the known event multiplicity dependence of the identification efficiencies. As a result of these concerns, a full reanalysis was undertaken to allow a more thorough investigation of the γ , π^0 , and η identification efficiencies. This report summarizes the present status of this reanalysis.

2. EXPERIMENTAL DETAILS

In the WA80 experiment, the direct photon excess is determined on a statistical basis. The inclusive photon yield for a particular event class is extracted, and the inclusive photon yield expected from radiative decays of long-lived resonances for the same event class is calculated via simulation. The direct photon excess is then determined from the difference of the measured and simulated distributions. The input to the simulation calculation is based on the measured WA80 cross sections for the π^0 and η mesons, and estimates (based on production rates taken from the literature and m_T -scaling) of the contributions from the decay of non-reconstructed mesons, such as ω , η' , and K^0 (the total contribution from the decay of non-reconstructed mesons is estimated to be less than 2% of the π^0 and η contributions). It is instructive to first study the γ/π^0 ratio since many factors cancel in this ratio and since the dominant source of photons are those arising from π^0 decay and therefore the π^0 yield sets the scale for the sensitivity of the direct photon search. The photon excess can then be expressed in the form

$$\frac{\gamma_{Excess}}{\pi^0} = \frac{N_\gamma}{N_{\pi^0}} \cdot \frac{\epsilon_{\pi^0}}{\epsilon_\gamma} \cdot A_{geo} - (R_{\pi^0} + R_\eta + \dots) \quad (1)$$

where N_γ and N_{π^0} represent the measured inclusive photon and π^0 yields, A_{geo} represents a straightforward geometrical acceptance factor, and ϵ_γ and ϵ_{π^0} represent the γ and π^0 identification efficiencies. These efficiencies include the effects of smearing due to energy resolution as well as corrections for the inclusion of mis-identified background. The first term in Eq. (1) corresponds to the measured inclusive γ/π^0 ratio while the second term in parenthesis represents the calculated γ/π^0 ratio based on simulation, with photon contributions, γ_x , from π^0 , η , and other radiative decays contributing as $R_x = \gamma_x/\pi^0$.

For the sulphur beam run period of experiment WA80, photons have been measured in a 3800 element Pb-glass array which covers 60% of the azimuth in the rapidity range from 2.1 to 2.9. The total data sample of $8 \cdot 10^6$ S+Au events has been analyzed [8]. The WA80 S+Au minimum bias cross section is 3600 mb. The preliminary WA80 γ/π^0 ratios, as presented at Quark Matter '93 [3] are shown in Figure 2 as a function of p_T for central and peripheral events. The circles indicate the inclusive photon yield, and the histograms show the yield which can be accounted for by hadronic decays based on simulation. Thus the direct photon excess, as presented in Figure 1, can be extracted from the difference between the data points and the simulation, together with the measured π^0 cross section. The errors shown on the experimental points and simulation results are the quadratic sum of the statistical errors and all estimated sources of systematic errors. The systematic errors on the data include preliminary error estimates for the γ and π^0 reconstruction efficiencies (including uncertainties of the combinatorial background subtraction), geometrical acceptance, and detector non-linearities. The systematic errors on the simulation results include the estimated uncertainties on the η/π^0 ratio and the form of the m_T -scaling distribution, on the production rates of the unmeasured hadrons which contribute additional radiative decay photons, and extrapolation of the hadron distributions to phase-space regions outside of the region of measurement.

A small excess of photons (over those which can be attributed to hadronic decays) is observed in central collisions with a significance at about the $2 - 3\sigma$ level. However,

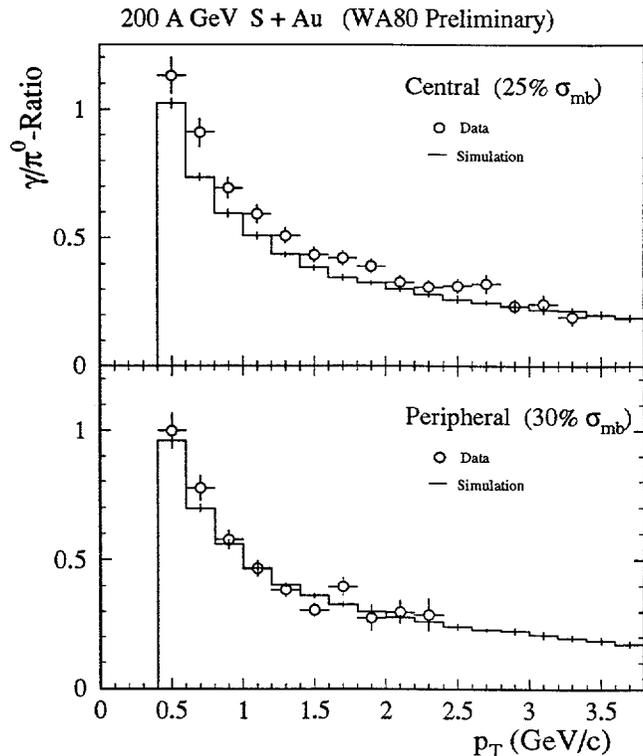


Figure 2. The inclusive γ/π^0 ratio for central and peripheral interactions of 200 A GeV S+Au. The open points indicate the experimental results while the histograms indicate the ratio expected from long-lived radiative decays. The errors on the experimental and simulation results include separate statistical and estimated systematic errors.

within errors, no excess is observed in peripheral collisions. As noted above, the fact that the central and peripheral data have been measured and analyzed under identical circumstances and that no excess is observed in peripheral collisions, for which photon emission is not expected to be important, suggests that the sources of systematic error are basically under control. However, it is important to note that other centrality-dependent effects might yet be responsible for the observed excess in central events. In particular, due to the detector occupancy in central collisions, the γ and π^0 reconstruction efficiencies are dependent on the event centrality, and therefore centrality-dependent efficiencies must be used in the analysis.

The method used to determine the identification efficiencies, ϵ_γ and ϵ_{π^0} (and ϵ_η), is to insert test showers into real events in the same data analysis pass used to extract the γ , π^0 , and η yields. The test showers are taken from a database of simulated showers which have been calculated with GEANT 3.15 with the WA80 detector geometry and with parameters adjusted to match test beam measurements. The shower database includes single γ 's as well as γ pairs from π^0 , and η decays and also showers from various background particles such as n , p , \bar{n} , \bar{p} , π^\pm , and K^\pm all of which have been distributed uniformly in p_T and pseudo-rapidity. For each event, the raw data is first analyzed to extract and record on a data summary tape (DST) the number of showers in the event together with their identifying characteristics, such as position, energy, size, and whether accompanied by a hit in the charged-particle veto detector. Next, a GEANT particle is selected and its properly digitized shower information is added on top of the original raw event data. This superimposed event is then fully analyzed again with the same analysis chain, and the results of this analysis are compared to the results obtained for the actual event. All new showers found, as well as any showers of the original event which are missing in the reanalysis are recorded on the DST, together with information about the original simulation particle. This is repeated for several GEANT particles per raw data event and is done for the full WA80 data sample.

The data on the DST can then be analyzed applying different identification criteria for the photons, such as requirements on the shower size, or lack of a charged-particle veto. The same criteria are simultaneously applied to the GEANT test showers which can then be used to determine the identification efficiencies when properly weighted according to the measured distributions. When the efficiencies have been properly calculated the efficiency-corrected yields N/ϵ in Eq. (1) should be independent of the identification criteria applied. This has been the main topic of investigation in the present reanalysis in order to test more thoroughly for multiplicity-dependent systematic errors in the efficiency-corrected yield extraction.

3. PRESENT STATUS

In the extraction of the excess photon yield as indicated in Eq. (1), the most important contributions are from the determination of the efficiency-corrected inclusive photon yield which enters as N_γ/ϵ_γ ; the efficiency-corrected π^0 yield which enters as $N_{\pi^0}/\epsilon_{\pi^0}$ and as input to the simulation to determine R_{π^0} ; and the efficiency-corrected η yield which also enters as input to the simulation to determine R_η . We now discuss the present status of the reanalysis for each of these contributions.

3.1. Inclusive Photons

In the preliminary analysis, the photon identification was performed without the aid of the charged-particle veto information. The identification was made solely on the basis of the shower shape. Although this may seem surprising at first, it is not unreasonable for the WA80 fixed target experiment where the laboratory energies corresponding to the p_T region of interest are quite high and therefore one benefits greatly from the fact that the Pb-glass presents only about one interaction length to the background hadrons which thereby deposit only a small fraction of their energy in the Pb-glass and hence have apparent p_T much lower than their actual p_T . As a result, over the p_T region of interest, the hadron contamination at a given p_T corresponds to only about 5% of the photon yield. In the preliminary analysis, this contribution was determined based on estimates of the hadron distributions, most importantly those of the charged pions which in turn were based on the measured π^0 distributions. It also relied on the calculated response in the Pb-glass, with the corresponding probability for the hadrons to falsely satisfy the photon shower shape identification criterion [8]. It was verified that within the estimated systematic errors, the results obtained did not depend on the shower shape identification criterion applied.

In the present reanalysis, the photon identification has been performed with and without using the charged-particle veto information. Using the charged-particle veto has the disadvantages that its efficiency must be determined, and that its use gives rise to a much decreased photon efficiency for central collisions due to the higher particle multiplicities and the greater chance overlap of charged-hadron and photon showers. As an example, applying the charged-particle veto in the identification criteria reduces the π^0 efficiency by about a factor of 2 for central collisions. Its use therefore provides a stringent test that the identification efficiency is well understood.

In the reanalysis, the numerical method used for extraction of the efficiency was also checked. In the preliminary analysis, the efficiency was determined by an iterative method in which, for each iteration, the GEANT showers used for determination of the efficiency are weighted according to the efficiency-corrected distributions obtained from the previous iteration. This was compared to an unfolding method in which an efficiency response matrix is reconstructed which can then be applied directly to the observed distribution to obtain the efficiency-corrected result.

From the present analysis it is found that the efficiency-corrected photon yields N_γ/ϵ_γ all agree to within statistics for all efficiency determination methods, and whether or not the charged-particle veto information is used in the photon identification. It is therefore unlikely that an unforeseen systematic error in the inclusive photon determination can explain the observed excess photon yield in central collisions.

3.2. η Production

In order to search for single direct photon radiation, it is first necessary to accurately determine the much more abundant photon yield from radiative decays, predominantly those of the π^0 and η mesons. For this reason, it is necessary to measure the π^0 and η cross sections in the same p_T and rapidity region over which one wishes to search for direct photons. In WA80 this is done by extracting the π^0 and η yield via their two-photon decay branch from their mass peaks in the two-photon invariant mass distributions, $m_{\gamma\gamma}$. In the search for thermal photon radiation in relativistic heavy-ion collisions, it is the p_T

region below 5 GeV/c which is of primary interest. Unfortunately, due to the large photon multiplicity in high-energy heavy-ion reactions, a large number of false combinatorial photon pairs occur in the $m_{\gamma\gamma}$ -distribution, with the result of very low peak-to-background ratios in the π^0 , and especially the η , mass regions. However, through the application of an event-mixing technique [10-11], similar to that used in Hanbury-Brown-Twiss type analyses, it is possible to reconstruct the combinatorial background and accurately extract the π^0 and η yield above the combinatorial background. The results are mainly limited by the statistical significance of the peak above the combinatorial background. This is illustrated in Figure 3 where the mixed-event combinatorial background has been subtracted from the real-event $m_{\gamma\gamma}$ -distribution.

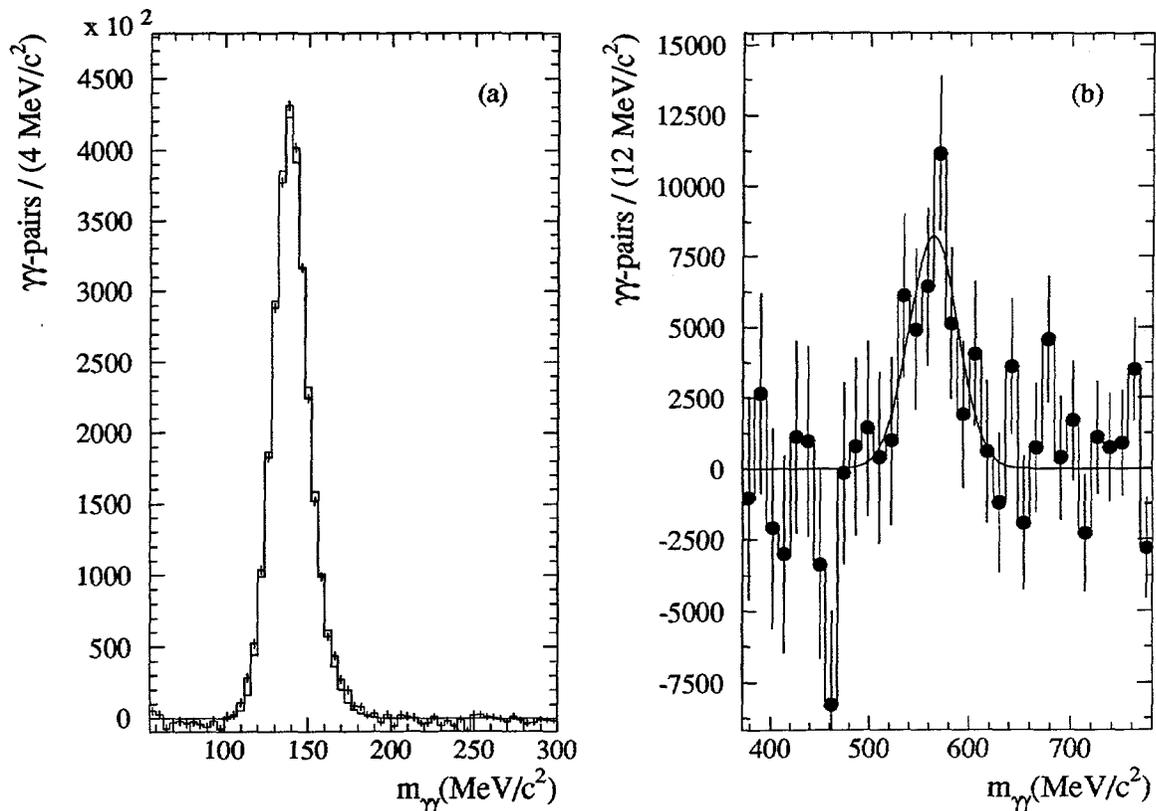


Figure 3. Background subtracted invariant mass distributions in the (a) π^0 and (b) η mass regions for transverse momenta of $0.5 \leq p_T \leq 1.0$ GeV/c.

The higher-statistics data and improved combinatorial background evaluation make it possible for the first time to extract η meson p_T -distributions in nucleus-nucleus collisions [11]. Nevertheless, despite a large η yield in the detector acceptance (see Figure 3) the statistical significance of the η peak over the combinatorial background is the limiting factor in the η yield determination. In the reanalysis, in order to minimize possible systematic errors in the determination of the yield in the η peak, a two-dimensional fit in p_T and invariant mass has been made to the background subtracted invariant mass spectra, with the η mass and width taken as p_T -independent parameters.

In Figure 4 the measured η cross section is compared to the π^0 cross section, plotted as a function of the transverse mass, $m_T = \sqrt{m^2 + p_T^2}$, for minimum bias reactions of S+Au and of S+S. The solid lines are the results of power-law fits to the π^0 m_T -distributions with the form

$$E \frac{d^3\sigma}{dp^3} = A \cdot \left(\frac{\beta}{\beta + m_T} \right)^n. \quad (2)$$

The dotted curves show the same power-law form renormalized to fit the η m_T -distributions. The present results are consistent with the conclusion that the η production cross section has the same functional form as the π^0 cross section when plotted as a function of m_T . The ratio of the normalizations of the m_T -distribution fits shown in Figure 4 are $R_{\eta/\pi^0} = 0.53 \pm 0.07$ and 0.43 ± 0.15 for S interactions on Au and S, respectively.

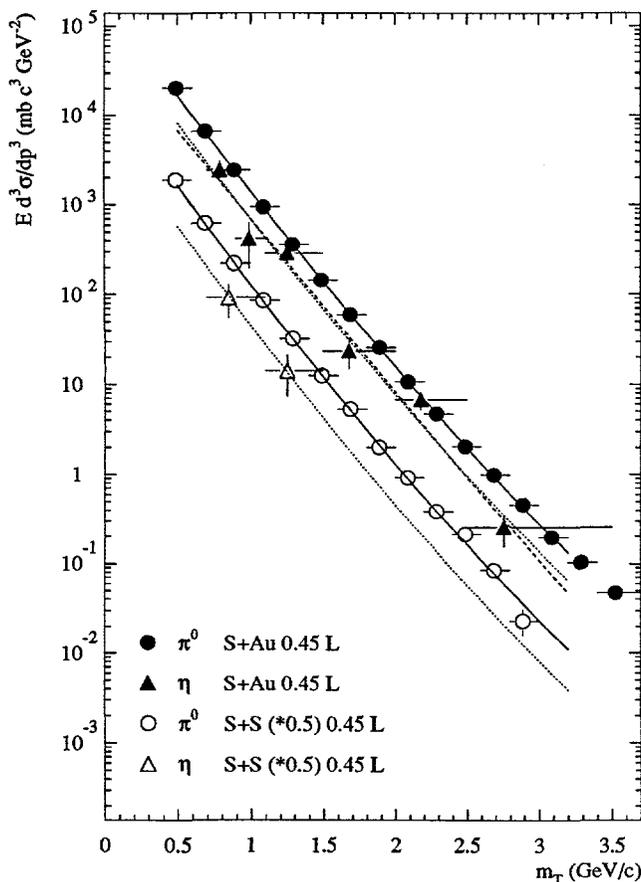


Figure 4. Neutral π^0 and η transverse mass distributions for minimum bias reactions. The solid curves represent fits to the π^0 m_T -distributions (see text) with $\beta = 6.8(7.7)$ and $n = 37.5(41.7)$ for interactions on Au (or S).

Alternatively, the η/π^0 -ratio is plotted as a function of p_T in Figure 5. The O- and S-induced results of WA80 are shown by the solid symbols for comparison with a compilation of p- and π -induced results at similar CM-energies ($\sqrt{s} = 19.4 - 62.0$ GeV) shown by the open symbols [8]. The fit to the $^{32}\text{S}+\text{Au}$ π^0 m_T -distribution of Figure 4 is shown again by the solid curve in Figure 5 with the η/π^0 relative normalization taken as a fitted parameter with a value of $R_{\eta/\pi^0} = 0.55 \pm 0.07$ obtained. For comparison, the p-induced η/π^0 results were similarly fitted, as shown by the dashed curve in Figure 5, with a value of $R_{\eta/\pi^0} = 0.55 \pm 0.02$ obtained.

We conclude that m_T -scaling of η production in nucleus-nucleus collisions is consistent with the phenomenological m_T -scaling previously established in hadron-hadron and hadron-nucleus reactions[12]. This conclusion is used to extrapolate the η p_T -distribution into unmeasured regions and also to estimate the p_T -distributions for other unmeasured hadrons which give small additional photon decay contributions. Furthermore, within

the experimental uncertainties, no evidence is found for an enhancement of η production in central collisions, which might otherwise give rise to an apparent photon excess through additional η decay photons.

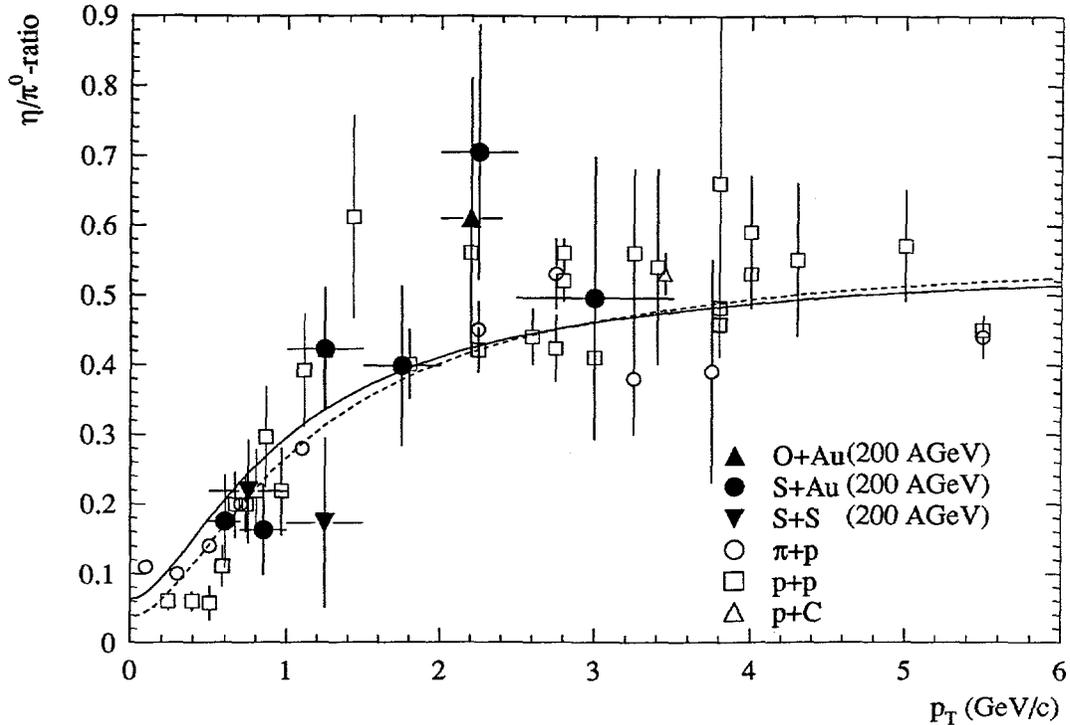


Figure 5. The η/π^0 -ratio as a function of transverse momentum for various reactions. The solid curve shows a fit to the WA80 $^{32}\text{S}+\text{Au}$ data while the dashed curve shows a fit to the p-induced results.

3.3. π^0 Production

After the determination of the inclusive photon yield itself, the determination of the π^0 yield is the most important factor in the search for excess photons, since about 85% of the observed photons result from π^0 decay. In the reanalysis effort, the π^0 yield has been extracted with and without use of the charged-particle veto detector. As mentioned above, the use of the veto counter results in about a factor of 2 loss in efficiency due to the veto of photon showers by overlapping charged hits. It therefore provides a stringent check of the efficiency determination. In the preliminary analysis, the π^0 efficiency was determined by testing whether the GEANT π^0 's inserted into real events, satisfied the π^0 mass window used in the data analysis after the superimposed event was analyzed. For example, due to the effects of energy resolution, or shower overlap, the GEANT π^0 could shift in mass or p_T and be lost. In the present analysis effort, this method has been used along with another method in which no attempt is made to identify the showers associated with the original π^0 photons. Instead, the invariant mass distributions of all photon shower pairs are accumulated for both the original data events and the events with superimposed GEANT showers. Both distributions are later analyzed in the same

way to extract the π^0 yields. The number of identified GEANT π^0 's is then given by the difference in these results, and the π^0 efficiency is obtained by comparing this to the known number of GEANT test π^0 's used. This efficiency method should be superior to the method used in the preliminary analysis since the efficiency is determined in a way which more closely follows the way in which the data is analyzed.

Although this analysis is still in progress, in the spirit of a status report we can state that the present indications are that for the case of the peripheral $^{32}\text{S}+\text{Au}$ data, both efficiency methods for analyses with and without the charged-particle veto all appear to give consistent results. For the case of the central data, the indications are that consistency is observed between the results obtained either with or without the charged-particle veto when the new efficiency determination method is used, as well as with the old efficiency method when using the charged-particle veto. On the other hand, the results obtained with the old efficiency method when not using the charged-particle veto, that is with an analysis similar to that used in the preliminary analysis, appears to give inconsistent results by an amount greater than the estimated level of systematic error. The discrepancy is in the direction which would decrease the observed photon excess (see Figure 2). Obviously, this is being studied more carefully with the intention to have the final result soon. On the basis of the current reanalysis we expect to have much greater confidence in our estimates of the systematic errors of the direct photon analysis. In the meantime, the above should serve as a word of caution against over-interpreting the preliminary WA80 results of Figures 1 and 2.

On the other hand, it should be remarked that the current reanalysis has for the most part confirmed the results of the preliminary analysis, with the noted exception of the discrepancies in the π^0 yield which are small, but significant for the excess photon search. In terms of the results presented in Figure 2, in the worse case this could imply that there is no observed photon excess within the level of experimental uncertainty. This would further imply that the results of Figure 1 (slightly modified) would instead become an upper limit to the observed photon excess. One may foresee that the experimental result will remain approximately an order of magnitude below the current predictions for the scenario in which a phase transition does not occur [5,7].

4. CONCLUSION

The preliminary result from the WA80 experiment on direct photon production in $^{32}\text{S}+\text{Au}$ reactions has been presented and the status of the current analysis towards the final result has been discussed. A large analysis effort has been undertaken to confirm the preliminary result and better estimate possible sources of systematic error, particularly those of the γ , π^0 , and η identification efficiencies. The present status of the inclusive photon and π^0 analysis has been reviewed. The final WA80 result for the p_T distribution of the η meson has been presented and shown to be consistent with m_T -scaling. The current reanalysis indicates that the experimentally observed direct photon excess will likely remain approximately an order of magnitude below current predictions for the case in which a phase transition does not occur [5,7]. The preliminary results appear to be consistent with the formation of a Quark Gluon Plasma. It will be interesting to learn whether improved theoretical calculations will be able to reproduce the relatively small amount of photon emission observed experimentally, without invoking QGP formation.

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