Suppression of High-p_T Neutral Pions in Central Pb+Pb Collisions at $\sqrt{s_{NN}} = 17.3$ GeV

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Neutral pion transverse momentum spectra were measured in p+C and p+Pb collisions at $\sqrt{s_{NN}} = 17.4$ GeV at mid-rapidity ($2.3 \lesssim \eta_{lab} \lesssim 3.0$) over the range $0.7 \lesssim p_T \lesssim 3.5$ GeV/c. The spectra are compared to neutral pion spectra measured in Pb+Pb collisions at the same energy in the same experiment. For a wide range of Pb+Pb centralities ($N_{part} \lesssim 300$) the yield of π^0's with $p_T \gtrsim 2$ GeV/c is consistent with the p+C or p+Pb yields scaled with the number of inelastic nucleon-nucleon collisions (N_{coll}), while for central Pb+Pb collisions with $N_{part} \gtrsim 300$ the pion yield is suppressed.

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The study of hadron production at high transverse momentum (p_T) is a sensitive tool to characterize the matter created in ultrarelativistic heavy-ion collisions, and in particular, to detect the possible formation of a quark-gluon plasma (QGP), i.e., a thermalized phase in which quarks and gluons are the relevant degrees of freedom. Particles at high p_T result from quark and gluon scatterings with high momentum transfer ("hard scattering") which can be described by perturbative quantum-chromodynamics (pQCD). The scattered quarks and gluons will traverse the created medium as they fragment into the observable hadrons. High-p_T particle production in nucleus-nucleus (A+A) collisions was predicted to be suppressed [1, 2] as a consequence of the energy loss of the scattered partons in the dense matter ("jet quenching"). Such suppression was observed by experiments at the Relativistic Heavy Ion Collider (RHIC) in central Au+Au and Cu+Cu collisions at a center-of-mass energy of up to $\sqrt{s_{NN}} = 200$ GeV [3, 4, 5, 6, 7]. Within jet-quenching models the suppression can be related to medium properties, such as the initial gluon density [8, 9].

A crucial test for the idea of parton energy loss in the hot and dense medium created in A+A collisions is the measurement of the $\sqrt{s_{NN}}$ dependence of high-p_T hadron production [8, 9, 10, 11, 12]. In central Pb+Pb collisions at the CERN SPS energy of $\sqrt{s_{NN}} = 17.3$ GeV the initial energy density, as estimated from the measured transverse energy [13], is above the critical value $\varepsilon_c \approx 1$ GeV/fm^3 [14] for the transition to the QGP. On the other hand, the initial gluon density and the lifetime of a deconfined phase produced at $\sqrt{s_{NN}} = 17.3$ GeV will be significantly reduced as compared to RHIC energies. Results at SPS energies thereby provide a sensitive test of jet quenching model predictions.

Results on high-p_T particle production in central Pb+Pb collisions at the CERN SPS have already been published [15, 16]. However, the interpretation of these data has been complicated by the lack of reference p+p data to allow to quantify nuclear effects. Instead, parametrizations of p+p data have been employed to search for nuclear effects [15, 17], but with substantial systematic uncertainties. Moreover, hadron suppression due to parton energy loss might be compensated by an enhancement due to multiple soft scatterings of the incoming partons prior to the hard scattering process ("nuclear k_T-enhancement" or "Cronin effect"). Measurements in p+A and d+A collisions at different $\sqrt{s_{NN}}$ suggest that such enhancement is significantly stronger at $\sqrt{s_{NN}} = 17.3$ GeV than at $\sqrt{s_{NN}} = 200$ GeV [11].

In this letter neutral pion spectra are presented from p+C and p+Pb collisions at $\sqrt{s_{NN}} = 17.4$ GeV measured in the WA98 experiment. Since the nuclear k_T-enhancement in p+C is expected to be small this measurement provides a useful substitute for a p+p reference. Information on the magnitude of the nuclear k_T-enhancement may be obtained by comparison of the p+Pb and p+C spectra. The spectra are compared to neutral pion spectra measured in Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV in the same kinematic region with the same WA98 experimental setup [15].

In the WA98 experiment π^0 yields were measured by detection of photons from the $\pi^0 \to \gamma\gamma$ decay branch with a highly-segmented lead-glass calorimeter. This detector was located 21.5 m downstream from the target and subtended the pseudorapidity range $2.3 \lesssim \eta_{lab} \lesssim 3.0$. A 400 GeV/$c$ proton beam from the CERN SPS impinged on a beryllium production target to provide a mixed secondary beam selected to have momentum of 160 GeV/c. The secondary beam consisted primarily of protons and pions with roughly equal content. Protons were identified with use of two gas Cherenkov counters located upstream of the 1879 mg/cm^2 ^{12}C (495 mg/cm^2 ^{208}Pb) target. The WA98 minimum bias trigger condition required a minimum amount of transverse energy (E_T) in the region $3.5 \lesssim \eta_{lab} \lesssim 5.5$, measured with a sampling calorimeter with electromagnetic and hadronic sections. The measured minimum bias cross section σ_{mb} for p+C (p+Pb) of 193 mb (1422 mb) corresponds to 86 % (81 %) of the total geometric cross section. The number of analyzed minimum bias events was $1.2 \cdot 10^6$ ($1.0 \cdot 10^6$) for p+C (p+Pb). A high-energy photon (HEP) trigger based on the sum energy signal of overlapping 4×4 groups of towers in the lead-glass calorimeter was used to enhance the sample of high p_T events. The efficiency of the HEP trigger reached ~ 100 % for photons with $p_T \gtrsim 0.8$ GeV/c. An additional $1.5 \cdot 10^6$ ($0.5 \cdot 10^6$) p+C (p+Pb) HEP events were analyzed which corresponded to $3.9 \cdot 10^7$ ($8.2 \cdot 10^6$) sampled minimum bias events.

Neutral pion yields were determined statistically by counting photon pairs with invariant mass in the π^0 mass range after subtraction of the normalized background from uncorrelated pairs. The shape of this background was determined by mixing photons from different events. Only photon pairs with an energy asymmetry $\alpha = |E_1 - E_2|/(E_1 + E_2) < 0.7$ were used in the analysis. A correction for geometrical acceptance and reconstruction efficiency was applied to the raw π^0 yields. The reconstruction efficiency takes into account the loss of π^0's due to the photon identification and energy asymmetry cuts. It also modifies the π^0 yield to account for the p_T shift that results from the finite energy resolution of the lead-glass calorimeter convoluted with the steeply falling π^0 p_T spectrum. Effects of overlapping showers in the calorimeter, which were important in central Pb+Pb collisions, are negligible in p+C and p+Pb collisions. The dominant systematic uncertainties are listed in Table I. The systematic uncertainties of the peak extraction, acceptance correction, and efficiency correction are approximately independent of p_T. The energy scale of the calorimeter was confirmed by comparison of the measured p_T-dependent π^0 peak positions with GEANT simulations. The estimated uncertainty of 1.5 % on the energy scale leads to an uncertainty on the π^0 yields that increases with p_T.

The spectra of the invariant π^0 yields in p+C and p+Pb collisions at $\sqrt{s_{NN}} = 17.4$ GeV are shown in Fig. 1. The transition between the minimum bias and the HEP sample occurs at $p_T = 1.7$ GeV/c. The p+C spectrum is compared to a next-to-leading-order (NLO) pQCD calculation for p+p at the same energy [19]. The calculation

TABLE I: Systematic uncertainties (in %) on the π^0 yields in p+C and p+Pb collisions at three p_T values.

p_T (GeV/c)	1	2	3
peak extraction	6	6	6
geometric acceptance	2.5	2.5	2.5
π^0 reconstruction efficiency	11	11	11
energy scale	5	10	20
total	14	16	24

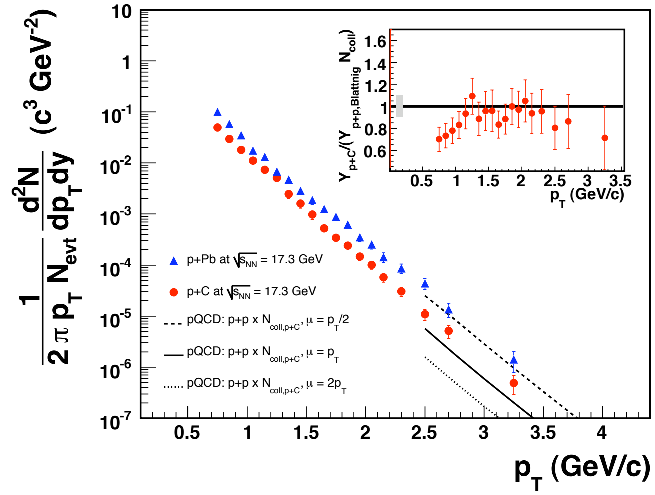

FIG. 1: Invariant π^0 yields in minimum bias p+C and p+Pb collisions at $\sqrt{s_{\rm NN}} = 17.4$ GeV. The error bars represent the quadratic sum of statistical and systematic uncertainties. The lines represent next-to-leading-order pQCD calculation of the π^0 yield in $\sqrt{s} = 17.4$ GeV p+p collisions for three different scales, scaled by the average number of nucleon-nucleon collisions in p+C ($\langle N_{\rm coll}^{\rm p+C}\rangle = 1.7$). The inset shows a comparison of the p+C spectrum to a parametrization of the yield in p+p collisions at $\sqrt{s} = 17.3$ GeV from [18]. The box indicates the systematic uncertainty of $N_{\rm coll}^{\rm p+C}$.

was performed with the CTEQ6M [20] parton distribution functions and the "Kniehl-Kramer-Pötter" (KKP) set of fragmentation functions [21] with renormalization and factorization scales set to be the same at $\mu = p_T/2$, p_T, or $2p_T$. For comparison with the p+C data the pQCD calculations have been scaled by the average number of nucleon-nucleon collisions in p+C. The pQCD calculation shows a large uncertainty related to the arbitrary choice of scale. It has been suggested that the NLO perturbative expansion is not sufficient at low energies and that threshold resummation corrections must be taken into account [19]. The large theoretical uncertainties demonstrate that pQCD calculations cannot be used as a reliable reference at CERN SPS energies. The inset of Fig. 1 shows that the π^0 yields per nucleon-nucleon collision measured in p+C are in good agreement with a parametrization of π^0 spectra in p+p from Blattnig et al. [18] that has been employed to study nuclear effects in Pb+Pb collisions [17].

Nuclear effects in π^0 production can be quantified with the nuclear modification factor defined as

$$R'_{\rm AA} = \frac{\langle N_{\rm coll}^{\rm p+B}\rangle}{\langle N_{\rm coll}^{\rm A+A}\rangle} \frac{{\rm d}N_{\pi^0}/{\rm d}p_T|_{\rm A+A}}{{\rm d}N_{\pi^0}/{\rm d}p_T|_{\rm p+B}}\,. \quad (1)$$

In the absence of nuclear effects $R'_{\rm AA}$ is expected to be unity for $p_T \gtrsim 2\,{\rm GeV}/c$ where hard scattering is expected to dominate particle production. The average number of nucleon-nucleon collisions was determined with a Glauber Monte Carlo calculation [22] using an inelastic nucleon-nucleon cross section of $\sigma_{\rm inel}^{\rm NN} = (31.8 \pm 2)\,{\rm mb}$ [23]. The same Glauber calculation was used to extract $\langle N_{\rm coll}\rangle$ values in Pb+Pb collisions. In the Glauber calculation the transverse energy was modelled by sampling a negative binomial distribution to determine the E_T contribution of each participating nucleon [22]. The bias due to the trigger selection on the measured transverse energy was taken into account. For minimum bias p+C and p+Pb collisions values of $\langle N_{\rm coll}\rangle_{\rm p+C} = 1.7 \pm 0.2$ and $\langle N_{\rm coll}\rangle_{\rm p+Pb} = 3.8 \pm 0.4$ were obtained.

The $\langle N_{\rm coll}\rangle$ values for Pb+Pb collisions were determined by applying cuts to the simulated E_T that corresponded to the same fraction of $\sigma_{\rm mb}^{\rm Pb+Pb}$ as the cuts applied to the measured E_T. These $\langle N_{\rm coll}\rangle$ values are listed in Table II and agree within systematic uncertainties with those of Ref. [15] that were determined with the VENUS 4.12 event generator in which $\sigma_{\rm inel}^{\rm NN} = 29.6\,{\rm mb}$ was used. With the large acceptance of the WA98 E_T measurement, and good description of the E_T distribution, including fluctuations [13], a centrality class corresponding to the 1 % most central Pb+Pb collisions could be defined to access very large $\langle N_{\rm coll}\rangle$ values.

TABLE II: Results of the Glauber calculation for Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 17.3$ GeV ($\sigma_{\rm inel}^{\rm NN} = 31.8\,{\rm mb}$). Centrality classes are given as a fraction (%) of $\sigma_{\rm mb}^{\rm Pb+Pb} \approx 6300$ mb [15].

class	1	2	3	4	5	6	7	8	$6-8$
from	82.8	67.0	48.8	25.3	13.0	6.8	1.0	0	0
to	100	82.8	67.0	48.8	25.3	13.0	6.8	1.0	13.0
$\langle N_{\rm part}\rangle$	8.2	23	54.2	123.2	218.2	289.1	347.8	382.6	322.5
$\langle N_{\rm coll}\rangle$	6.3	22.1	67.1	202.9	433.1	627.0	803.7	912.0	727.8

The p+Pb π^0 spectrum appears to be flatter than the p+C spectrum (see Fig. 1). The ratio of the $N_{\rm coll}$-normalized p+Pb and p+C spectra is shown in Fig. 2. At low p_T (~ 1 GeV/c) the ratio is consistent with scaling with the number of participating nucleons ($N_{\rm part} = N_{\rm coll} + 1$ in p+A) while scaling with $N_{\rm coll}$ is observed at higher p_T (~ 2 GeV/c). In fact, for $p_T \gtrsim 2$ GeV/c the ratio tends to be above unity, consistent with an expected stronger nuclear k_T-enhancement in p+Pb than in p+C.

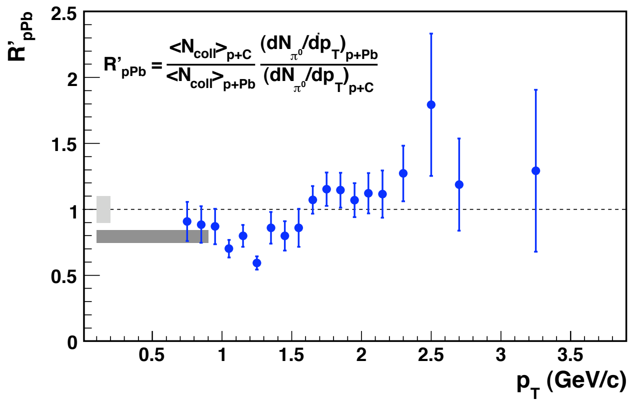

FIG. 2: The $N_{\rm coll}$-normalized ratio of π^0 yields in p+Pb and p+C collisions. The box at $R'_{\rm pPb} \approx 0.8$ represents the expectation for the case of scaling with $N_{\rm part}$ rather than $N_{\rm coll}$. The box at unity indicates the $N_{\rm coll}$ systematic uncertainty.

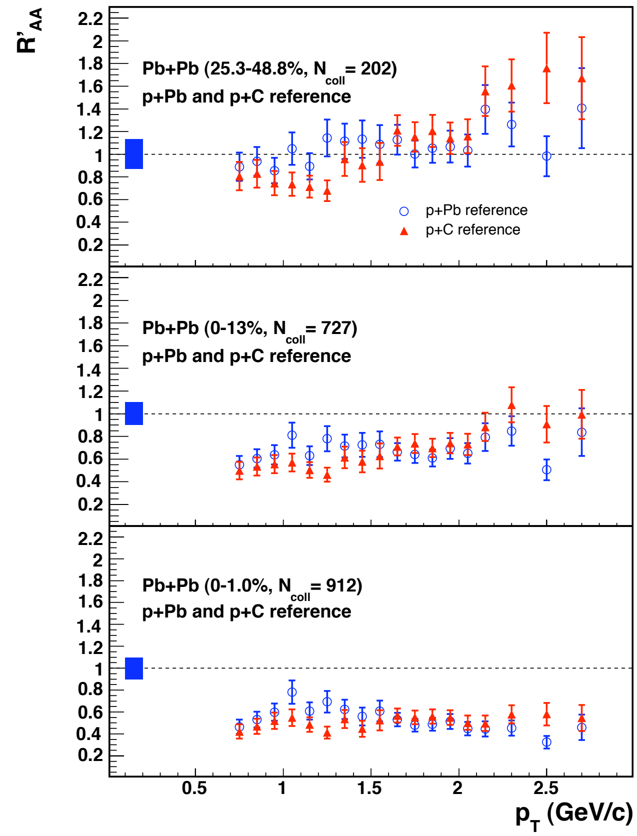

FIG. 3: π^0 $R'_{\rm AA}$ in Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 17.3$ GeV for three centrality classes using p+C or p+Pb spectra as reference. The boxes around unity reflect the systematic uncertainties related to $\langle N_{\rm coll}\rangle$.

Neutral pion spectra from Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 17.3$ GeV were published by WA98 in [15]. Fig. 3 shows the π^0 nuclear modification factor $R'_{\rm AA}$ as defined in Eq. 1 for three Pb+Pb collision centralities. For the $25.3-48.8\,\%$ (of $\sigma_{\rm mb}^{\rm Pb+Pb}$) centrality selection the data points at high $p_{\rm T}$ ($p_{\rm T} \gtrsim 2$ GeV/c) suggest a stronger nuclear $k_{\rm T}$-enhancement than in p+C. On the other hand, for the $0-13\,\%$ most central Pb+Pb collisions $R'_{\rm AA}$ is smaller than for the $25.3-48.8\,\%$ class but still consistent with unity at high $p_{\rm T}$. For the $0-1\,\%$ most central collisions the π^0 yield is significantly suppressed compared to either p+Pb or p+C as reference, with $R'_{\rm AA} \approx 0.5$. An apparent suppression of the π^0 yield in very central Pb+Pb collisions compared to peripheral collisions was noted in Ref. [15]. However the large uncertainty of using the peripheral distribution as reference did not allow to draw a firm conclusion. The observed suppression is qualitatively consistent with expectations from jet-quenching.

The centrality dependence of the average $R'_{\rm AA}$ in the range $2 < p_{\rm T} < 2.5$ GeV/c is shown in Fig. 4. $\langle R'_{\rm AA}\rangle$ in this $p_{\rm T}$ range is consistent with unity for $N_{\rm part} \lesssim 300$. For more central Pb+Pb collisions $\langle R'_{\rm AA}\rangle$ decreases with centrality indicating significant suppression of the high $p_{\rm T}$ π^0 yield. The apparent lack of suppression, or enhancement even, for $N_{\rm part} \lesssim 300$ may be due to offsetting effects of suppression due to parton energy loss and nuclear $k_{\rm T}$-enhancement.

In summary, neutral pion spectra were measured in minimum bias p+C and p+Pb collisions at $\sqrt{s_{\rm NN}} = 17.4$ GeV in the range $0.7 \lesssim p_{\rm T} \lesssim 3.5$ GeV/c. Based on these spectra the nuclear modification factors $R'_{\rm AA}$ for Pb+Pb collisions at CERN SPS energies could be determined using a measured p+A reference. In very central Pb+Pb collisions ($0-1\,\%$ of $\sigma_{\rm mb}^{\rm Pb+Pb}$) a significant suppression of high-$p_{\rm T}$ neutral pions was observed ($R'_{\rm AA} \approx 0.5$) that is reminiscent of the high-$p_{\rm T}$ hadron suppression observed in Cu+Cu and Au+Au collisions at RHIC. The pion suppression reported here, together with the results at higher energies from RHIC, will allow to constrain the energy dependence of hadron suppression as predicted by jet-quenching models.

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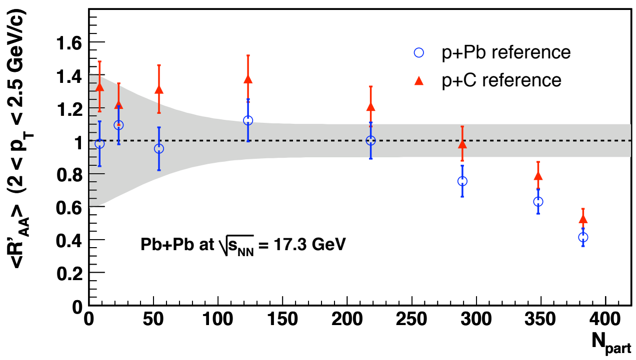

FIG. 4: Centrality dependence of the average $\langle R'_{\mathrm{AA}} \rangle$ in the range $2 < p_{\mathrm{T}} < 2.5$ GeV/c. The band around unity indicates the systematic uncertainty of the average number of binary nucleon-nucleon collisions.

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