

Suppression of High- p_T Neutral Pion Production in Central Pb + Pb Collisions at $\sqrt{s_{NN}} = 17.3$ GeV Relative to $p + C$ and $p + Pb$ Collisions

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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 midrapidity ($2.3 \lesssim \eta_{lab} \lesssim 3.0$) over the range $0.7 \lesssim p_T \lesssim 3.5$ GeV/ c . The spectra are compared to π^0 spectra measured in Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV 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 larger than or consistent with the $p + C$ or $p + Pb$ yields scaled with the number of nucleon-nucleon collisions (N_{coll}), while for central Pb + Pb collisions with $N_{part} \gtrsim 350$, the π^0 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 and fragment into the observable hadrons. High- p_T particle production in nucleus-nucleus ($A + A$) collisions was predicted to be suppressed [1] 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 [2–6]. Within jet-quenching models, the suppression can be related to medium properties, such as the initial gluon density or the transport coefficient [7–9].

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 [7,8,10–13]. In central Pb + Pb collisions at the CERN SPS energy of $\sqrt{s_{NN}} = 17.3$ GeV ($p_{\text{lab}} = 158A$ GeV/ c), the initial energy density, as estimated from the measured transverse energy [14], is above the critical value $\epsilon_c \approx 1$ GeV/fm³ [15] 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 [16,17]. However, the interpretation of these data has been complicated by the lack of reference $p + p$ data to allow to quantify nuclear effects. Instead, parameterizations of $p + p$ data have been employed to search for nuclear effects [16,18], 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 $\sqrt{s_{NN}} \approx 20$ GeV than at $\sqrt{s_{NN}} = 200$ GeV [11].

In this Letter, π^0 spectra are presented from $p + C$ and $p + Pb$ collisions at $\sqrt{s_{NN}} = 17.4$ GeV ($p_{\text{lab}} = 160$ GeV/ c) measured in the WA98 experiment. Since the nuclear k_T -enhancement in $p + C$ is expected to be small [19], this measurement should provide a useful sub-

stitute 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 π^0 spectra measured in Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV with the same WA98 experimental setup [16].

In the WA98 experiment, π^0 yields were measured by detection of photons from the $\pi^0 \rightarrow \gamma\gamma$ 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 $2.3 \lesssim \eta_{\text{lab}} \lesssim 3.0$. 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/cm² ¹²C (495 mg/cm² ²⁰⁸Pb) target. The WA98 minimum bias trigger condition required a minimum amount of transverse energy (E_T) in the region $3.5 \lesssim \eta_{\text{lab}} \lesssim 5.5$, 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 1.2×10^6 (1.0×10^6) 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 $\sim 100\%$ for photons with $p_T \gtrsim 0.8$ GeV/ c . An additional 1.5×10^6 (0.5×10^6) $p + C$ ($p + Pb$) HEP events were analyzed which corresponded to 3.9×10^7 (8.2×10^6) 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

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

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 [20]. The calculation was performed with the CTEQ6M [21] parton distribution functions and the ‘‘Kniehl-Kramer-Pötter’’ (KKP) set of fragmentation functions [22] 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

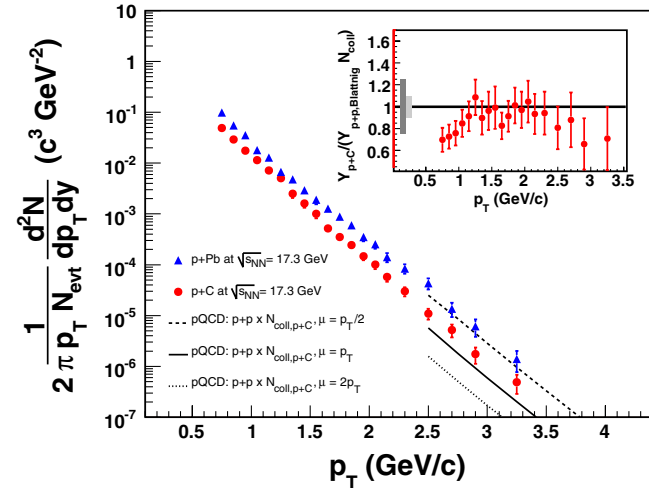


FIG. 1 (color online). Invariant π^0 yields in minimum bias $p + C$ and $p + Pb$ collisions at $\sqrt{s_{NN}} = 17.4$ GeV. The error bars represent the quadratic sum of statistical and systematic uncertainties. The lines represent next-to-leading-order pQCD calculation of the π^0 yield in $\sqrt{s} = 17.4$ GeV $p + p$ collisions for three different scales, scaled by $\langle N_{coll}^{p+C} \rangle = 1.7$. The inset shows a comparison of the $p + C$ spectrum to a parameterization of the yield in $p + p$ collisions at $\sqrt{s} = 17.3$ GeV from [23]. The dark gray box indicates the uncertainty of the parameterization estimated in [18], the light gray box the uncertainty of $\langle N_{coll}^{p+C} \rangle$.

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 [20]. 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 parameterization of π^0 spectra in $p + p$ from Blattnig *et al.* [23] that has been employed to study nuclear effects in Pb + Pb collisions [18].

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

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

In the absence of nuclear effects, R'_{AA} is expected to be unity for $p_T \gtrsim 2$ GeV/c where hard scattering is expected to dominate particle production. $\langle N_{coll} \rangle$ was determined with a Glauber Monte Carlo calculation [24] using an inelastic nucleon-nucleon cross section of $\sigma_{inel}^{NN} = (31.8 \pm 2)$ mb [25]. The same Glauber calculation was used to extract $\langle N_{coll} \rangle$ values in Pb + Pb collisions. In the Glauber calculation, the transverse energy E_T was modeled by sampling a negative binomial distribution to determine the E_T contribution of each participating nucleon [24]. The bias due to the trigger selection on the measured E_T was taken into account. For minimum bias $p + C$ and $p + Pb$ collisions, values of $\langle N_{coll} \rangle_{p+C} = 1.7 \pm 0.2$ and $\langle N_{coll} \rangle_{p+Pb} = 3.8 \pm 0.4$ were obtained.

The $\langle N_{coll} \rangle$ values for Pb + Pb collisions were determined by applying cuts to the simulated E_T that corresponded to the same fraction of σ_{mb}^{Pb+Pb} as the cuts applied to the measured E_T . These $\langle N_{coll} \rangle$ values are listed in Table II and agree within systematic uncertainties with those of Ref. [16] that were determined with the VENUS 4.12 event generator in which $\sigma_{inel}^{NN} = 29.6$ mb was used. With the large acceptance of the WA98 E_T measurement, and good description of the E_T distribution, including fluctuations [14], a centrality class corresponding to the 1% most central Pb + Pb collisions could be defined to access very large $\langle N_{coll} \rangle$ values.

The $p + Pb$ π^0 spectrum appears to be flatter than the $p + C$ spectrum (see Fig. 1). The ratio of the N_{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 ($N_{part} = N_{coll} + 1$ in $p + A$) while scaling with N_{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 $p + C$.

Neutral pion spectra from Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV were published by WA98 in [16]. Figure 3 shows

TABLE II. Results of the Glauber calculation for Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV ($\sigma_{\text{inel}}^{NN} = 31.8$ mb). Centrality classes are given as a fraction (%) of $\sigma_{\text{mb}}^{\text{Pb+Pb}} \approx 6300$ mb [16]. The systematic uncertainty of $\langle N_{\text{coll}} \rangle$ was parameterized as $\sigma_{N_{\text{coll}}}^2 = 0.1^2 + [0.4 \exp(-N_{\text{coll}}/100)]^2$.

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
$\langle N_{\text{part}} \rangle$	8.2	23	54.2	123.2	218.2	289.1	347.8	382.6	322.5
$\langle N_{\text{coll}} \rangle$	6.3	22.1	67.1	202.9	433.1	627.0	803.7	912.0	727.8

the π^0 nuclear modification factor R'_{AA} as defined in Eq. (1) for three Pb + Pb collision centralities. For the 25.3–48.8% (of $\sigma_{\text{mb}}^{\text{Pb+Pb}}$) most central collisions, the data points at high- p_T ($p_T \gtrsim 2$ GeV/c) suggest a stronger nuclear k_T -enhancement than in $p + C$. On the other hand, for the 0–13% most central Pb + Pb collisions, R'_{AA} is smaller than for the 25.3–48.8% class but still consistent with unity at high- p_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. An apparent suppression of the π^0 yield in very central Pb + Pb collisions compared to peripheral collisions was noted in Ref. [16]. However, the large uncertainty of using the peripheral distribution as a 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'_{AA} for $2 < p_T < 2.5$ GeV/c and $2.5 \leq p_T < 3.0$ GeV/c is shown in Fig. 4. The π^0 yields in Pb + Pb in these p_T ranges are not suppressed for $N_{\text{part}} \lesssim 300$ ($\langle R'_{AA} \rangle \gtrsim 1$). For more central Pb + Pb collisions, $\langle R'_{AA} \rangle$ decreases with centrality indicating significant suppression of the high- p_T π^0

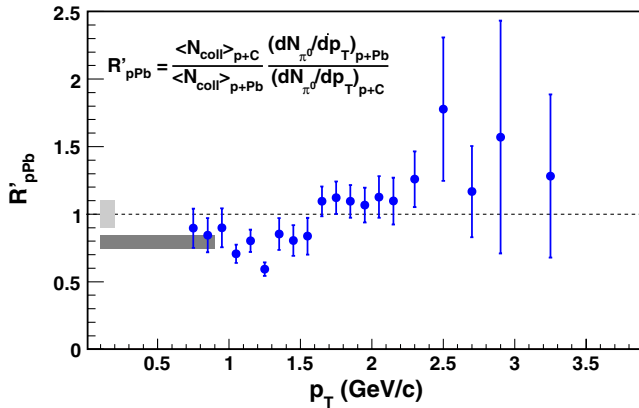


FIG. 2 (color online). The N_{coll} -normalized ratio of π^0 yields in $p + Pb$ and $p + C$ collisions. The box at $R'_{pPb} \approx 0.8$ represents the expectation for the case of scaling with N_{part} rather than N_{coll} . The box at unity indicates the N_{coll} systematic uncertainty. The error bars represent the quadratic sum of the statistical and remaining systematic uncertainties. The energy scale uncertainty was assumed to cancel.

yield. The apparent lack of suppression, or enhancement even, for $N_{\text{part}} \lesssim 300$ may be due to competing effects of suppression due to parton energy loss and nuclear k_T -enhancement.

In summary, π^0 spectra were measured in minimum bias $p + C$ and $p + Pb$ collisions at $\sqrt{s_{NN}} = 17.4$ GeV in the range $0.7 \leq p_T \leq 3.5$ GeV/c. Based on these spectra, the nuclear modification factors R'_{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 $\sigma_{\text{mb}}^{\text{Pb+Pb}}$), a significant suppression of high- p_T neutral pions was observed ($R'_{AA} \approx 0.5 \pm 0.14$) that is reminiscent of the high- p_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, constrain jet-quenching models and may help clarify the behavior of the energy loss of partons in strongly interacting matter.

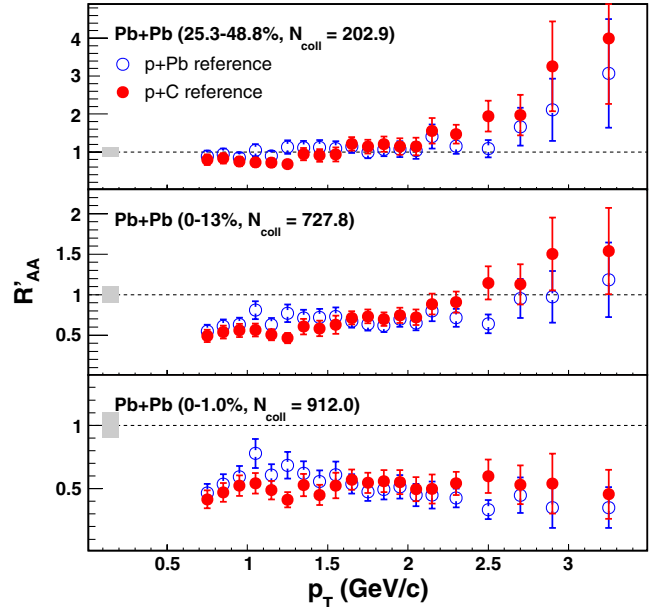


FIG. 3 (color online). π^0 R'_{AA} in Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV for three centrality classes using $p + C$ or $p + Pb$ spectra as a reference. The boxes around unity reflect the systematic uncertainties related to $\langle N_{\text{coll}} \rangle$.

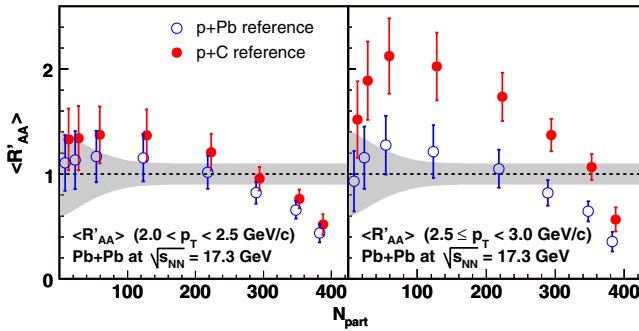


FIG. 4 (color online). Centrality dependence of the average $\langle R'_{AA} \rangle$ for $2 < p_T < 2.5$ GeV/c and $2.5 \leq p_T < 3.0$ GeV/c. The bands around unity indicate the systematic uncertainty of $\langle N_{coll} \rangle$. The error bars represent the quadratic sum of the statistical and systematic uncertainties. The N_{part} values for the full points were shifted by +5 for better visibility.

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