Modification of jet-like correlations in Pb-Au collisions at 
158A GeV/c

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Abstract

Results of a two-particle correlation analysis of high-$p_t$ charged particles in Pb-Au collisions at 158A GeV/c are presented. The data have been recorded by the CERES experiment at the CERN-SPS. The correlations are studied as function of transverse momentum, particle charge and collision centrality. We observe a jet-like structure in the vicinity of a high-$p_t$ trigger particle and a broad back-to-back distribution. The yields of associated particles per trigger show a strong dependence on the trigger/associate charge combination. A comparison to PYTHIA confirms the jet-like pattern at the near-side but suggests a strong modification at the away-side, implying significant energy transfer of the hard-scattered parton to the medium.

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I. INTRODUCTION

The study of high-energy particle jets in ultrarelativistic heavy-ion collisions provides access to the properties of the dense medium formed in such reactions. In contrast to the situation in elementary collisions, the hard-scattered partons have to traverse the surrounding strongly interacting matter which leads to significant energy loss and to a modification of the final state particle jet \[1, 2, 3, 4\]. Particularly strong energy loss of the parton in the medium is expected if the matter is deconfined and has free color charge carriers. This may lead to a significant suppression of high transverse momentum (\(p_t\)) hadrons compared to expectations based on perturbative QCD, if a Quark-Gluon Plasma (QGP) has been formed. Furthermore, the energy which has been radiated off the parton prior to hadronization may lead to enhanced soft particle production in the angular vicinity of the parton. Possible mechanisms like Cerenkov gluon radiation \[3, 4\], shock wave formation \[4, 8\] and large angle gluon radiation \[9\] have been discussed.

A strong suppression of high-\(p_t\) hadrons in Au-Au collisions at \(\sqrt{s_{NN}} = 200\) GeV compared to p-p has been reported \[10, 11, 12, 13, 14, 15, 16, 17\]. Similarly, early studies of azimuthal correlations revealed a significant reduction of the di-jet over jet rate in such collisions which became manifest in a dramatic disappearance of the back-to-back correlation to a high-\(p_t\) trigger particle \[18\]. These observations have been interpreted as a strong indication for the formation of a dense colored medium in nuclear collisions at the Relativistic Heavy Ion Collider (RHIC).

Pioneering studies of two-pion correlations at the Super Proton Synchrotron (SPS) have indicated a significant broadening of the back-to-back correlation in Pb-Au at \(\sqrt{s_{NN}} = 17.3\) GeV but no disappearance \[19\]. A very similar broadening has also been observed at RHIC \[20, 21, 22\] when the analysis was extended to lower transverse momentum, where the back-to-back correlation exhibits a double-humped structure with a local minimum around \(\Delta \phi = \pi\). These findings have been connected to strong final state interactions of the hard-scattered parton with the matter, indicating the occurrence of significant energy transfer from the parton to the medium. Final conclusions on the relevant mechanisms at work, however, have not yet been drawn, and more conventional scenarios like jet-redirection through multiple scattering have not yet been ruled out. In this Letter, we present results of a two-particle correlation analysis in Pb-Au collisions at 158 \(A\) GeV/c. These data represent
a high-statistics measurement of jet-like particle correlations at $\sqrt{s_{NN}} = 17.3$ GeV which, in addition to existing results at higher collision energy, may help to disentangle the underlying mechanisms of jet modifications by means of a systematic energy scan.

II. EXPERIMENT AND DATA SELECTION

The data were recorded with the CERES experiment at the CERN-SPS. In 1998, the spectrometer was upgraded by a cylindrical Time Projection Chamber (TPC) with radial drift field, matching the spectrometer acceptance in pseudorapidity $2.1 < \eta < 2.6$, and with full coverage in azimuth $|\eta| < 2.6$. The TPC is hence ideally suited for studies of azimuthal correlations in the mid-rapidity region of heavy-ion collisions at $158A \text{ GeV/c} \ (y_{\text{mid}} = 2.91)$. Charged particle momenta can be reconstructed from the track curvature in the magnetic field. Measurement of the particle trajectories in up to 20 planes along the beam direction results in a momentum resolution of $\Delta p/p = ((2\%)^2 + (1\% \cdot p)^2)^{1/2}$, with $p$ in GeV/c.

The present analysis is based on $3 \cdot 10^7$ Pb-Au collisions recorded with the TPC in the year 2000. The event sample is analyzed in three bins of centrality (0-5%, 5-10%, and 10-20% of the most central of the total geometric cross section $\sigma_{\text{geom}}$, respectively). The centrality is determined via the multiplicity of charged particles measured in the TPC and a telescope of Silicon Drift Detectors (SDD) close to the target [24].

The charged particle tracks used for this analysis are selected from the polar angle range $0.14 < \theta < 0.24$. To provide sufficient momentum resolution, the tracks are required to have at least 12 out of 20 possible points used in the momentum fit. The accepted tracks are subdivided into a trigger and an associate sample, based on the transverse momentum $p_t$ of the tracks. In a given event, the trigger is the particle of highest transverse momentum within the trigger $p_t$ range. Except for the study of the transverse momentum dependence, we choose trigger ($T$) and associate ($A$) particles in the ranges $2.5 < p_t(T) < 4.0 \text{ GeV/c}$ and $1.0 < p_t(A) < 2.5 \text{ GeV/c}$, respectively. Using this selection, the overall number of events, trigger particles and associated particles per trigger in the different centrality classes are given in Table I.

The single track efficiency for this set of cuts has been determined by a Monte Carlo pro-

\footnote{For the trigger-induced distribution of the events within the centrality bins see [24].}
TABLE I: Number of events $N_{ev}$, triggers $N_T$ and associated particles per trigger $N_A/N_T$ in the different centrality bins.

| $\sigma/\sigma_{\text{geom}}(\%)$ | $N_{ev}$   | $N_T$     | $N_A/N_T$ |
|----------------------------------|------------|-----------|-----------|
| 0.0 - 5.0                        | $1.5 \cdot 10^7$ | $2.5 \cdot 10^6$ | 14.5      |
| 5.0 - 10.0                       | $9.7 \cdot 10^6$  | $1.4 \cdot 10^6$ | 12.2      |
| 10.0 - 20.0                      | $3.7 \cdot 10^6$  | $4.2 \cdot 10^5$ | 9.9       |

procedure where simulated tracks were embedded into real data events. This method provides a detailed simulation of the TPC response to charged particles in a realistic track density environment. The efficiency was found to be $\epsilon = 0.78$ for particles with $p_t > 1.0 \text{ GeV/c}$, with no significant dependence on rapidity, transverse momentum and charge of the particle.

Within the same Monte Carlo study, the momentum resolution was determined as function of the polar angle $\theta$, the number of fitted points in the TPC, the transverse momentum, and the charge of the particle. For typical trigger and associate ranges ($2.5 < p_t(T) < 4.0 \text{ GeV/c}$ and $1.0 < p_t(A) < 2.5 \text{ GeV/c}$) as used in this analysis, the mean transverse momentum of trigger and associated particles is $\langle p_t(T) \rangle = 2.88 \text{ GeV/c}$ and $\langle p_t(A) \rangle = 1.3 \text{ GeV/c}$, respectively. The typical transverse momentum resolution is $\Delta p_t/p_t = 7.5\%$ for the trigger particles and $\Delta p_t/p_t = 4.0\%$ for associated particles.

The resolution of the azimuthal and polar angles is better than 3 mrad and 1 mrad, respectively, for particles with $p_t > 1 \text{ GeV/c}$ and hence negligible for the shape and magnitude of the angular correlations presented in this study.

The limited efficiency to reconstruct two tracks with small angular separation was studied by dividing the distribution of opening angles of pairs from the same event by a reference distribution obtained by combining particles from different events. For opening angles greater than 15 mrad the two-track inefficiency is less than 1%. A corresponding cut is applied to all signal- and mixed-event distributions accumulated in this analysis.
Jet-like correlations are studied by measuring, for a trigger particle and all associated particles in an event, the distribution \( S(\Delta \phi) \) where \( \Delta \phi = \phi_1 - \phi_2 \) is the difference in the azimuthal angle between trigger and associated particle. Correlations arising due to slight non-uniformities of the single-track acceptance are accounted for by division by a mixed-event distribution \( B(\Delta \phi) \), where trigger and associated particles are taken from different events of the same centrality class. To reduce the statistical uncertainty in the background distribution, ten events were mixed for each signal event.

The normalized correlation function

\[
C_2(\Delta \phi) = \frac{\int B(\Delta \phi')d(\Delta \phi') \cdot S(\Delta \phi)}{\int S(\Delta \phi')d(\Delta \phi') \cdot B(\Delta \phi)} \cdot \int S(\Delta \phi')d(\Delta \phi') \frac{B(\Delta \phi')}{B(\Delta \phi)} \quad (1)
\]

contains physical correlations from jets as well as azimuthal anisotropies due to the finite impact parameter of the collision. To separate the jet-like correlations from the bulk anisotropies known as elliptic flow, we assume that each particle pair can be attributed to either of the two contributions. In this two-source approach the correlation function is decomposed into the jet-like contribution \( C_{2,\text{jet}} \) and a contribution arising due to elliptic flow,

\[
C_2(\Delta \phi) = C_{2,\text{jet}}(\Delta \phi) + b \cdot (1 + 2\langle v_T^2 \rangle \langle v_A^4 \rangle \cos(2\Delta \phi)), \quad (2)
\]

where \( \langle v_T^2 \rangle \) and \( \langle v_A^4 \rangle \) are the average elliptic flow coefficients determined in the trigger and associate \( p_t \) range, respectively. Assuming that the jet yield vanishes at its minimum (the ZYAM assumption [22, 25]), the elliptic flow contribution is adjusted by variation of \( b \) to a polynomial fit of \( C_2(\Delta \phi) \) and subtracted. The polynomial fit of \( C_2(\Delta \phi) \) is used in order to be less sensitive to point-by-point fluctuations of the correlation function. We obtain the conditional yield \( \hat{J}_2(\Delta \phi) \) as the number of jet-associated particles per trigger:

\[
\hat{J}_2(\Delta \phi) \equiv \frac{1}{N_T} \frac{dN_{TA}}{d\Delta \phi} = \frac{1}{\epsilon} \frac{C_{2,\text{jet}}(\Delta \phi)}{\int C_2(\Delta \phi')d(\Delta \phi')} \frac{N_A}{N_T}, \quad (3)
\]

where \( N_T \) and \( N_A \) are the total numbers of triggers and associates, and \( N_{TA} \) is the number of jet-associated particles with the trigger after subtraction of the flow-modulated background. The yield is corrected for the single track efficiency \( \epsilon = 0.78 \).

The \( p_t \)-dependent elliptic flow coefficients in the trigger and associated ranges have been determined by a centrality dependent analysis of azimuthal correlations [26]. For these studies, the usual reaction plane method has been employed. The analysis has been performed
for all charged particles, as well as for positively or negatively charged particles only. Auto-correlations have been removed by exclusion of particle $i$ from the reaction plane calculation. In events with jets, however, particles are clustered and the reaction plane could be biased to the jet axis even after removal of particle $i$ from the reaction plane calculation. To study the impact of this potential bias, separate analyses have been performed for events with and without a trigger particle. In addition, the results of the triggered events have been compared to an analysis where only particles with $p_t < 1$ GeV/$c$ have been used for the calculation of the reaction plane. In all cases, the extracted flow coefficients after correction for the resolution of the reaction plane agree within their statistical uncertainties.

IV. RESULTS AND DISCUSSION

The upper row of Fig. 1 shows the correlation function $C_2(\Delta \phi)$ and the estimated contribution from elliptic flow in three different bins of collision centrality. The blue and red lines indicate the uncertainty arising from the systematic error of the $v_2$ coefficients which are about 10% and 25% in the associate and trigger $p_t$ range, respectively. These errors have been added linearly because a strong correlation is assumed, hence leading to a conservative estimate of the resulting uncertainty bands. The lower row in Fig. 1 shows the extracted conditional yields, corrected for the single track efficiency. At all centralities, we observe a narrow peak at the near side ($\Delta \phi \approx 0$) and a broad distribution at the away-side ($\Delta \phi \approx \pi$). No significant change of yield and shape on the near- and away-side is observed within the centrality range under study. The narrow peak on the near-side is indicative of jet-like correlations to a high-$p_t$ trigger particle. The away-side is broad, reminiscent of similar observations in Au-Au collisions at higher collision energies, where the shape is in contrast to observations in p-p collisions at the same energies. These findings have been discussed in the context of strong final state interactions of the hard-scattered parton in a dense medium.

In the most central collisions, we observe that the shape of the distribution is significantly non-Gaussian and exhibits a local minimum around $\Delta \phi = \pi$. The PHENIX experiment at RHIC reported similar measurements in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV and $\sqrt{s_{NN}} = 62.4$ GeV [27]. PHENIX covers approximately the same pseudorapidity acceptance and uses the same trigger and associate $p_t$ ranges as in the present analysis. We observe qualitative
agreement with these RHIC results, in particular with respect to the shapes of the near- and away-side distributions. Quantitatively, a weaker near-side correlation is observed at SPS, which can be explained by a lower average jet energy at a given trigger threshold. For the same reason, the away-to-near-side yield ratio at SPS is larger than at RHIC. The latter observation is also in agreement with the expectation of a larger di-jet to mono-jet rate at SPS in the acceptance, since a given trigger threshold biases the measurement towards larger $x_t = 2 \cdot p_t / \sqrt{s_{NN}}$ at lower beam energy, and hence to more symmetric parton-parton collisions around mid-rapidity.

The yields of particles associated with a high-$p_t$ trigger in central events have been studied in different windows of the trigger and associated $p_t$. For this study, associated particles at
$|\Delta \phi| < 1$ have been assigned to the near-side, and $1 < |\Delta \phi| < 2\pi - 1$ to the away-side, respectively. The jet-associated yield $\frac{1}{N_T} \frac{dN_{\text{jet}}}{dp_t}$ at the near- and away-side, integrated over the respective $\Delta \phi$ ranges and for sliding windows of the trigger $p_t$ is shown in Fig. 2 (left and middle panel). We observe that the spectrum at the near-side is significantly steeper than at the away-side for $p_t(A) < 1 \text{ GeV}/c$, independent of the trigger $p_t$. Such behaviour can be explained by the requirement of a hard trigger, which, biasing the fragmentation, softens the observed spectrum of associated particles at the near-side, whereas the away-side spectrum remains unbiased. Similar softening is observed in calculations using the PYTHIA event generator [28], corroborating the fragmentation picture at the near-side. In detail, the measured $p_t$ dependence of this effect reveals distinct differences to PYTHIA. This is demonstrated in Fig. 2 (right panel), where the ratio of the away- to near-side yield is compared to the same quantity from PYTHIA. For $p_t < 2 \text{ GeV}/c$, the data indicate an enhanced yield at the away-side as compared to the expectation from vacuum fragmentation implied by PYTHIA.

FIG. 2: (Color online) Jet-associated yield per trigger as function of the associated $p_t$ for the near-side (left panel) and the away-side (middle panel) in central Pb-Au collisions at 158A GeV/c. The right panel shows the ratio of the integrated jet-associated yield distributions away/near in comparison to PYTHIA predictions. The data shown elsewhere in this paper are all obtained using $1 < p_t(A) < 2.5 \text{ GeV}/c$ for the associated particles.

A more detailed view of the possible mechanisms of jet modifications can be provided by investigating the charge dependence of two-particle correlations. The conditional jet-
associated yields for different charge combinations of trigger and associated particles in central events are shown in Fig. 3. All charge combinations show a narrow, jet-like peak at the near-side and a broad structure at the away-side, with a pronounced dip around $\Delta \phi = \pi$ for the unlike-sign charge combinations. Moreover, we observe dramatic differences of the relative yields. At the near-side, unlike-sign combinations are more abundant than like-sign combinations with the same trigger charge. This is in agreement with local charge conservation in the jet fragmentation process. At the away-side, positive associates are more abundant than negative ones, for both trigger charges. This asymmetry is also observed in PYTHIA and characterizes hard scattering at SPS energies as being dominated by large-$x$ partons, hence reflecting the positive net charge of valence quarks. We have verified with PYTHIA that this asymmetry vanishes at RHIC energies and beyond, consistent with observation [18, 29].

![Graph showing jet-associated yield per trigger for different charge combinations](image)

**FIG. 3:** (Color online) Jet-associated yield per trigger for different trigger/associated charge combinations in central Pb-Au collisions at 158$A$ GeV/c. The open symbols are reflected about $\Delta \phi = \pi$. The blue and red lines and histograms, and the grey band indicate the systematic uncertainty in the flow subtraction and determination of the $b$-parameter, respectively.

As a next step, we study the ratio $R_{-+}$ of the observed yields of negative over positive
particles at the near- and the away-side in the jet-like component. We obtain for a given trigger charge

\[ R_{-+} = \frac{\int_{\Delta \phi_1}^{\Delta \phi_2} \hat{J}_2^{-}(\Delta \phi) d\Delta \phi}{\int_{\Delta \phi_1}^{\Delta \phi_2} \hat{J}_2^{+}(\Delta \phi) d\Delta \phi}, \]  

(4)

where \( \hat{J}_2^{-} \) and \( \hat{J}_2^{+} \) are the jet-associated yields of negatively and positively charged associated particles, respectively. Integration limits are as above \( \Delta \phi_1 = -1, \Delta \phi_2 = 1 \) for the near-side and \( \Delta \phi_1 = 1, \Delta \phi_2 = 2\pi - 1 \) for the away-side. The results for \( 2.5 < p_t(T) < 4.0 \text{ GeV/c} \) and \( 1.0 < p_t(A) < 2.5 \text{ GeV/c} \) in central Pb-Au collisions are shown as function of the trigger charge \( q_T \) in Fig. 4. As a reference for vacuum fragmentation, we calculate these ratios with PYTHIA. To this end, calculations of p-p, n-n, p-n, and n-p collisions have been properly weighted according to their occurence in Pb-Au collisions, assuming binary collision scaling.

On the near-side, the PYTHIA calculations match very well the observed ratios \( R_{-+} \) for negative and positive triggers, as seen in the upper panel in Fig. 4. This supports the view that the near-side correlations are characterized by vacuum fragmentation of jets. At the away-side, we compare our results also to the inclusive charge ratio of bulk hadrons \((h^-/h^+)\) in the associate \( p_t \) range, indicated by the shaded band in Fig. 4. For positive triggers, the observed ratio \( R_{-+} \) is a factor three smaller than the PYTHIA calculation. Remarkably, the measurement is much closer to the medium charge ratio, suggesting that the jet energy has been transferred to the medium prior to hadronization. Incidentally, the PYTHIA prediction coincides with the medium charge ratio for negative trigger particles, thus allowing no discrimination between vacuum fragmentation and energy deposition to the medium. The measurement for negative trigger particles is in agreement with both scenarios.

To summarize, we have presented results of a high-\( p_t \) two-particle correlation analysis in Pb-Au collisions at SPS. The data exhibit a narrow peak at the near-side, indicative of jet correlations, and a broad structure at the away-side. In central collisions, we observe a significant dip of the two-particle yield at \( \Delta \phi = \pi \), which is most pronounced for unlike-sign charge combinations. The \( p_t \) spectrum of associated particles at the near-side is softer than at the away-side, in accordance with the expectation of a trigger bias and in qualitative agreement with PYTHIA. However, a more detailed comparison to PYTHIA discloses an excess of soft particles \((p_t < 2 \text{ GeV/c})\) on the away-side and suggests it is created in response to the energy deposition of the hard-scattered parton. The study of the charge dependence
FIG. 4: (Color online) Ratio of negative to positive associated particles $R_{-+}$ at the near- and away-side in central Pb-Au collisions at 158 A GeV/c. Results as function of the trigger charge $q_T$ are shown in comparison to PYTHIA calculations. The statistical uncertainties of the PYTHIA calculations are reflected in the thickness of the lines. Indicated as a shaded band is the inclusive $h^-/h^+$ ratio in the associated $p_t$ range.

of the two-particle yield and a comparison to PYTHIA reveals that the near-side correlation, in particular its charge composition, is clearly jet-like. In contrast, the away-side charge composition is inconsistent with vacuum fragmentation represented by PYTHIA. It is, however, in agreement with the bulk charge composition in this $p_t$ range, suggesting that the correlated particles do not stem from fragmentation directly but emerge due to a local energy deposition of the parton, implying a medium-modified fragmentation function. In essence, the present data demonstrate that jet properties in nucleus-nucleus collisions are modified at SPS energies, indicating that also at these energies matter of considerable opaqueness is created. The charge composition and transverse momentum dependence of the away-side yield are consistent with a scenario including significant energy transfer of the parton to the medium.
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