Elliptic Flow of Rare High-Momentum Probes in Nuclear Collisions

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Abstract

In high energy nuclear collisions the leading parton of a jet can change flavor through interactions with the surrounding medium. This can considerably boost the relative yield of rare high momentum particles, like strange quarks and photons. We revisit these jet conversions and discuss implications for the azimuthal asymmetry $v_2$ of rare probes. We predict that the $v_2$ of kaons at RHIC falls significantly below that of pions and protons at high transverse momentum. Experimental information on the relative $v_2$ of strange hadrons could provide constraints on the mean free path of fast quarks and gluons in a quark gluon plasma.

1 Rare High-Momentum Probes

In collisions of nuclei at very high energies, the bulk of the matter is expected to form a quark gluon plasma (QGP) in which partons are deconfined and close to thermal equilibrium. Experiments at the Relativistic Heavy Ion Collider (RHIC) and, soon, at the Large Hadron Collider (LHC) are carried out to test the properties of quark gluon plasma [1]. Quantum chromodynamics (QCD) predicts that in some collisions initial hard interactions of two partons take place which generate a final state of partons with high transverse momentum $p_T$, which eventually hadronize into energetic jets of hadrons. It had been realized early on that these jets are an ideal probe for the medium formed in heavy ion collisions [2,3,5,6,7,8].
The early years of experiments at RHIC have accumulated a large sample of data which confirms the formation of a deconfined phase of quarks and gluons. Measurements of high-\(p_T\) hadrons played an important role. A large suppression of high-\(p_T\) hadrons and an almost complete extinction of away-side jet correlations has been seen, emphasizing the opacity of quark gluon plasma for fast partons \[1\].

Recently, it has been suggested that the study of energy loss and suppression of high-\(p_T\) particles should be augmented by a tracking of their flavor to obtain additional, complementary information \[9\]. Obviously, fast quarks and gluons traveling through nuclear matter can change identity through conversion processes. This was first studied in the context of conversions of light quarks into real and virtual photons \[10,11,12,13,14,15\] and the conversion of of gluons into quarks and vice versa \[16,17,18\]. Note that to simplify notations our definition of flavor here refers to the identity of any particle that can be produced at high \(p_T\), including photons and gluons. The most important consequences from these studies were worked out in detail in Ref. \[9\]: (i) the concept of a fixed flavor for the leading parton of a jet is ill-defined in a medium; (ii) rare high-\(p_T\) flavors like photons or strange quarks (the latter only at RHIC energies) can be significantly enhanced through the coupling to a chemically equilibrated medium; (iii) measurements of these rare probes could provide information about the mean free path \(\lambda\) of fast partons in the medium.

In summary, measurements of excess photons and dileptons at intermediate and high \(p_T\) and changes to the hadron abundances in the jet fragmentation region \((p_T > 6 \text{ GeV}/c \text{ at RHIC})\) could provide valuable information about the quark gluon plasma formed in these collisions. In Ref. \[19\] it was pointed out that changes in hadron chemistry at high \(p_T\) could also come about through changed multiplicities in a jet cone in nuclear collisions. This effect should be distinguished from the mechanism discussed here which is based on flavor changes of the leading parton. Possible effects for heavy quarks were studied by us in \[20\].

2 Elliptic Flow

In this Letter we want to discuss the azimuthal anisotropy \(v_2\), often referred to as elliptic flow, of rare high-\(p_T\) probes. \(v_2\) for a given hadron species is defined as the second Fourier coefficient in the decomposition of its transverse momentum spectra in terms of the azimuthal angle \(\phi\) with respect to the reaction plane.
\[
\frac{dN}{p_T dp_T d\phi} = \frac{dN}{2\pi p_T dp_T} \left[ 1 + 2v_2(p_T) \cos(2\phi) + \mathcal{O}(4\phi) \right].
\]

(1)

It has been first pointed out in [21] that real and virtual photons produced from conversions of quark and gluon jets exhibit a \(v_2\) which has a negative sign, unlike all other particle production mechanisms discussed up to that point. This contribution to the total photon or dilepton spectrum has to be folded together with other photon sources which has been the subject of an increasing number of studies very recently [15,22,23].

We want to generalize the original argument in [21]. We point out that for any high-\(p_T\) probe \(R\) which receives an additional contribution \(\Delta R > 0\) through interactions of other probes \(J\) with the medium \(M\), the additional yield \(\Delta R\) exhibits an azimuthal asymmetry which is offset by \(\pi/2\) with respect to the reaction plane, i.e. has \(v_2^{\Delta R} < 0\). Whether this negative elliptic flow is visible in experiment depends on the probe. Typically, \(v_2\) is positive for other sources of \(R\), outshining the contribution from jet conversions. But if \(R\) is a rare probe, \(\Delta R\) might be of the same order of magnitude as the other sources, or even dominant. In that case the total \(v_2\) for \(R\) should be significantly reduced or even negative.

![Diagram Fig. 1. Three sources of particle asymmetries produced in heavy ion collisions. (i) \(v_2 > 0\) for bulk particles generated by different pressure gradients in and out of the reaction plane. (ii) \(v_2 > 0\) for quenched but abundant high-\(p_T\) partons generated by different length of propagation in and out of the reaction plane. (iii) \(v_2 < 0\) for particles produced at high and intermediate \(p_T\) from interactions of jets with the medium. The asymmetry is also generated by different path lengths of propagating jets in and out of the reaction plane. All measured high-\(p_T\) particles have contributions from both (ii) and (iii) with the relative weight depending on the initial abundance in jets and the chemical composition of the medium.

In Fig. 1 we show the three known sources of particle asymmetry and the sign
of $v_2$ that they imply. (i) $v_2$ can be generated by different pressure gradients in and out of the reaction plane, leading to more flow in the plane (i.e. in the “thinner” direction of the fireball) implying $v_2 > 0$. This is elliptic flow in the strict sense of the word. It is the dominant source of $v_2$ at low $p_T$. (ii) High-$p_T$ partons lose more energy out of the plane (i.e. the “thicker” side of the fireball), so that jet quenching is less pronounced in the plane, leading to $v_2 > 0$. This is the dominant source of $v_2$ for most high $p_T$-probes. (iii) Rare probes at high and intermediate $p_T$ are produced by interactions of jets with the medium. The longer the path length in the medium, the more of these particles are produced, leading to larger emission in the thicker direction of the fireball with $v_2 < 0$. This has been called optical $v_2$ in [21].

Most theoretical calculations for the total direct photon $v_2$ predict values which are close to zero or slightly negative at intermediate $p_T$. PHENIX has presented first measurements which are compatible with zero [24] and rule out large negative elliptic flow of all direct photons sources combined. More precise measurements in the future will hopefully be able to provide tighter constraints.

In [9] we showed that strange quarks at RHIC energies could be an ideal probe in the sense discussed in this section, since $s$ and $\bar{s}$ quarks are rare as as leading particles of jets, but almost chemically equilibrated in the bulk medium formed in the collisions. This should result in an increased yield of kaons and $\Lambda$ hyperons at high $p_T$ when compared to scaled $p+p$ collisions. We conclude immediately that this additional source of strange hadron exhibits negative $v_2$.

3 $v_2$ of Strange Quarks and Kaons

In this section we make predictions for the azimuthal asymmetry of strange quarks and kaons adding all known sources for these particles at intermediate and large $p_T$. We use the method introduced in Ref. [9] to study the propagation of jet partons ($u$, $d$, $s$, and $g$) in the QGP fireball. Energy loss and conversions are implemented through Fokker-Planck and rate equations. We use elastic perturbative cross sections between partons scaled with a $K$-factor. We refer the reader to [9] for details. After a jet parton has left the fireball we fragment into hadrons via AKK fragmentation function [25], and calculate the elliptic flow of the final state particles.

In Fig. [2] we show the elliptic flow of light quarks ($u$, $d$), strange quarks $s$ and gluons $g$ with conversions ($K = 4$ for jet conversion cross sections, left panel) and without conversions ($K = 0$ for conversion cross sections, right panel) in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV for the $20 - 30\%$ centrality.
bin. The elliptic flow of all partons decreases with increasing transverse momentum $p_T$ consistent with the behavior of the drag coefficients discussed in [9]. If the flavor of quark and gluon jets is kept fixed ($K = 0$), gluons exhibit larger elliptic flow than quarks. Jet conversions drive the $v_2$ of light quarks and gluons toward each other as expected for particles that can easily convert into each other. In complete detailed balance the curves should be the same. On the other hand, $s$ quarks have the same $v_2$ as light quarks with conversions switched off. When conversions are switched on, strange quark $v_2$ drops significantly due to the large number of extra strange quarks produced throughout the thicker part of the fireball.

In the left panel of Fig. 3 we show the resulting $v_2$ for neutral kaons and pions. We have added hadrons from recombination of quarks in order to take into account hadrons from sources other than jets which are increasingly important for lower transverse momenta $p_T < 6 \text{ GeV}/c$ [28,29,30,31]. We see that the $v_2$ for kaons is systematically below the $v_2$ for pions due to jet conversions. At $p_T = 15 \text{ GeV}/c$ the difference can be as large as a factor of two. We also show experimental data which has very large error bars above 6 GeV/c and does not extend beyond 10 GeV/c. For comparison, in the right panel of Fig. 3 we plot the resulting $v_2$ for protons and $\Lambda$ hyperons at high transverse momentum. We notice that the difference of elliptic flow between strange and non-strange baryons is much smaller than that between strange and non-strange mesons. This can be traced back to the dominance of gluon fragmentation for baryon production in the fragmentation functions. Thus, hadronization dilutes the rather clear signal for strange quarks, but it appears that kaons are nevertheless a good probe.
One point of caution here is the fact that jet quenching calculations (even without resolving particle chemistry) have great difficulties to explain the relatively large values of $v_2$ at large $p_T$ with realistic fireball models, see e.g. [32,33]. A sign of this can also be seen in our calculation which underestimates the data between 4 and 7 GeV/$c$. No final conclusion has been emerged on this phenomenon. However, we are confident that whatever the absolute value for the elliptic flow of pions, the $v_2$ of kaons should be suppressed relative to it.

We conclude with another thought. No calculation has been presented on the $v_2$ of identified hadrons coming from changed multiplicities in jet cones as advocated in [19]. Naively, we would expect that this mechanism has less impact on the $v_2$ of strange hadrons. This might lead the way to a possible distinction between both mechanisms.

4 Summary

We have discussed the fact that the azimuthal asymmetry of high-$p_T$ particles created in interactions of jets with the surrounding medium in nuclear collisions is negative. This should lead to a significant reduction in the total $v_2$ observed for any rare high-$p_T$ probe, as already demonstrated for the example of photons. Here, we showed for the first time a prediction for the suppression of the $v_2$ of strange hadrons with respect to non-strange hadrons at large $p_T$. The $v_2$ of kaons could be as much as a factor of two smaller than that of
pions, and could potentially be an unambiguous signal for jet conversions in
the quark gluon plasma.

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References

[1] I. Arsene et al. (PHOBOS Collaboration), Nucl. Phys. A 757, 1 (2005); B. B.
Back et al. (BRAHMS Collaboration), Nucl. Phys. A 757, 28 (2005); J. Adams
et al. (STAR Collaboration), Nucl. Phys. A 757, 102 (2005); K. Adcox et al.
(PHENIX Collaboration), Nucl. Phys. A 757, 184 (2005).

[2] X. N. Wang and M. Gyulassy, Phys. Rev. Lett. 68, 1480 (1992); M. H. Thoma
and M. Gyulassy, Nucl. Phys. A 544, 573C (1992).

[3] R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigne and D. Schiff, Nucl. Phys.
B 483, 291 (1997); Nucl. Phys. B 484, 265 (1997).

[4] B. G. Zakharov, JETP Lett. 63, 952 (1996).

[5] U. A. Wiedemann, Nucl. Phys. A 690, 731 (2001).

[6] M. Gyulassy, P. Lévai, and I. Vitev, Phys. Rev. Lett. 85, 5535 (2001); Nucl.
Phys. B 594, 371 (2001).

[7] P. Arnold, G. D. Moore and L. G. Yaffe, JHEP 0206, 030 (2002); S. Jeon and
G. D. Moore, Phys. Rev. C 71, 034901 (2005).

[8] X. N. Wang, Phys. Lett. B 579, 299 (2004).

[9] W. Liu and R. J. Fries, Phys. Rev. C, to appear, Preprint 0801.0453 [nucl-th].

[10] R. J. Fries, B. Muller, and D. K. Srivastava, Phys. Rev. Lett. 90, 132301 (2003).

[11] R. J. Fries, B. Muller and D. K. Srivastava, Phys. Rev. C 72, 041902 (2005).

[12] D. K. Srivastava, C. Gale and R. J. Fries, Phys. Rev. C 67, 034903 (2003); S.
Turbide, C. Gale, D. K. Srivastava and R. J. Fries, Phys. Rev. C 74, 014903
(2006).

[13] C. Gale, T. C. Awes, R. J. Fries and D. K. Srivastava, J. Phys. G 30, S1013
(2004).

[14] S. Turbide, C. Gale, S. Jeon, and G. Moore, Phys. Rev. C 72, 014906 (2005).
[15] S. Turbide, C. Gale, E. Frodermann and U. Heinz, Preprint arXiv:0712.0732 [hep-ph].

[16] W. Liu, C. M. Ko, and B. W. Zhang, Phys. Rev. C 75, 051901(R) (2007); J. Mod. Phys. E 16, 1930 (2007).

[17] C. M. Ko, W. Liu, and B. W. Zhang, Few Body Syst. 41, 63 (2007).

[18] A. Schäfer, X. N. Wang and B. W. Zhang, Nucl. Phys. A 793, 128 (2007).

[19] S. Sapeta and U. A. Wiedemann, Preprint arXiv:0707.3494 [hep-ph].

[20] W. Liu and R. J. Fries, Preprint arXiv:0805.1093 [nucl-th].

[21] S. Turbide, C. Gale and R. J. Fries, Phys. Rev. Lett. 96, 032303 (2006).

[22] R. Chatterjee, E. S. Frodermann, U. W. Heinz and D. K. Srivastava, Phys. Rev. Lett. 96, 202302 (2006); R. Chatterjee, D. K. Srivastava, U. W. Heinz and C. Gale, Phys. Rev. C 75, 054909 (2007).

[23] B. Z. Kopeliovich, A. H. Rezaeian and I. Schmidt, Preprint arXiv:0712.2829 [hep-ph].

[24] S. S. Adler et al. (PHENIX Collaboration), Phys. Rev. Lett. 96, 032302 (2006); V. S. Pantuev [PHENIX Collaboration], J. Phys. G 34, S805 (2007).

[25] S. Albino, B. A. Kniehl and G. Kramer, Nucl. Phys. B 725, 181 (2005).

[26] D. Winter, Nucl. Phys. A 774, 545 (2006).

[27] B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C 77, 054901 (2008).

[28] V. Greco, C. M. Ko, and P. Lévai, Phys. Rev. Lett. 90, 022302; Phys. Rev. C 68, 034904 (2003).

[29] R. J. Fries, B. Muller, C. Nonaka, and S. A. Bass, Phys. Rev. Lett. 90, 202303 (2003); Phys. Rev. C 68, 044902 (2003).

[30] R. J. Fries, J. Phys. G 30, 853 (2004).

[31] R. C. Hwa and C. B. Yang, Phys. Rev. C 67, 034902 (2003); 67, 064902 (2003).

[32] E. V. Shuryak, Phys. Rev. C 66, 027902 (2002).

[33] J. Adams et al. (STAR Collaboration), Phys. Rev. Lett. 93, 252301 (2004).