Enhancement of baryon-to-meson ratios around jets as a signature of medium response

Ao Luo

Central China Normal University

June 14, 2022

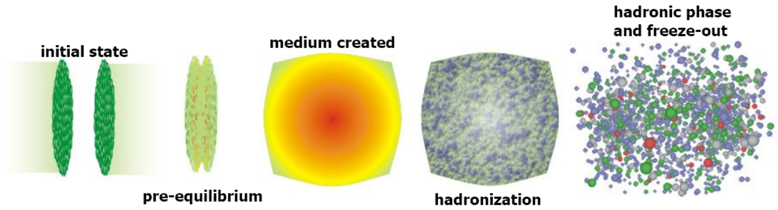
arXiv:2109.14314

In collaboration with Ya-Xian Mao, Guang-You Qin, En-Ke Wang, Han-Zhong Zhang.

Content

The Signatures of QGP

The evolution of a nucleus-nucleus collision

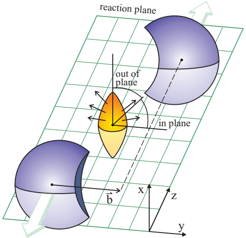


One of the main challenges of heavy-ion collision experiments is the identification of the QGP phase.

Probes of the quark-gluon plasma

- Soft probes: collective flow, baryon-to-meson enhancement.
- Hard probes: jet quenching and medium response.

Collective flow and Ncq scaling of v_2



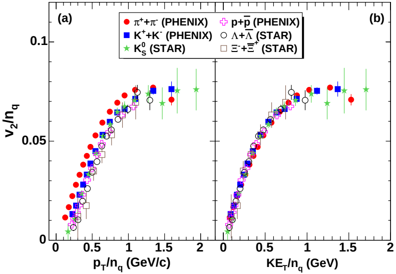
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}(1+2\sum_{n=1}^{\infty} v_n \cos(n(\phi-\Psi_{RP}))), \quad (1)$$

elliptic flow: One way to examine this anisotropy

$$v_2 = \langle \cos 2(\phi - \Psi_{RP}) \rangle , \quad (2)$$

which plays a crucial role in the study of the QCD matter formed during the collision.

[PHENIX, Phys. Rev. Lett. **98**, 162301 (2007)]

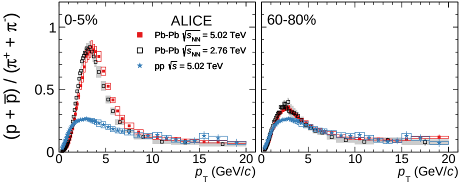


The v_2 scaled by number of constituent quarks (n_q).

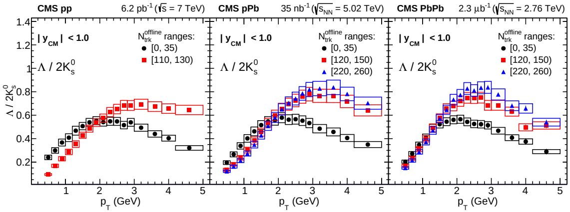
- Particle flow in quark level.
- Parton recombination is very important in forming intermediate p_T hadrons.
- Another important aspects of recombination is baryon-to-meson enhancement.

Baryon-to-meson enhancement

Baryon-to-meson enhancement as a signal of QGP.



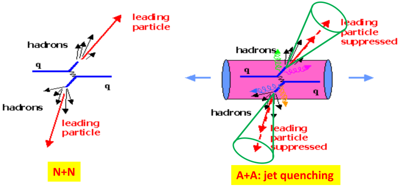
[ALICE, Phys. Rev. C **101**, no.4, 044907 (2020)]



[CMS, Phys. Lett. B **768**, 103-129 (2017)]

Jet quenching

Jet quenching provides a powerful tool to probe the novel properties of QGP.



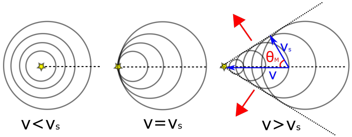
The central goal of jet quenching study is to understand in detail the interaction mechanisms between jets and medium.

Full jets in heavy-ion collisions:

- Jets are spray of particles originating from fragmentation of hard-scattered partons.
- Jet reconstruction: recombine hadron (or parton) fragments to approximate the original hard parton’s energy and momentum.
- They are expected to provide more detailed information about jet-medium interaction.

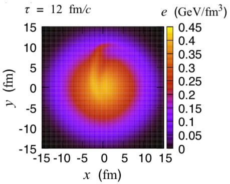
Medium response

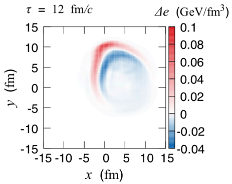
Jet induced medium excitation: Mach cone

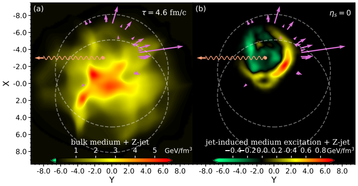


$$\theta_M = \arccos(\frac{v_s}{v_{jet}}) \tag{3}$$

Mach cone induced by the energy and momentum deposition from the jet, as well as a region of energy depletion right behind the wave front, known as the diffusion wake.







[Y. Tachibana, N.-B. Chang, and G.-Y. Qin, Phys. Rev. C 95, 044909 (2017), arXiv:1701.07951.]
[Wei Chen, Zhong Yang, Yayun He, Weiyao Ke, Long-Gang Pang, and Xin-Nian Wang, Phys. Rev. Lett. 127, 082301 (2021), arXiv:2101.05422.]

Motivation:

The lost energy from jets can diffuse to the medium.

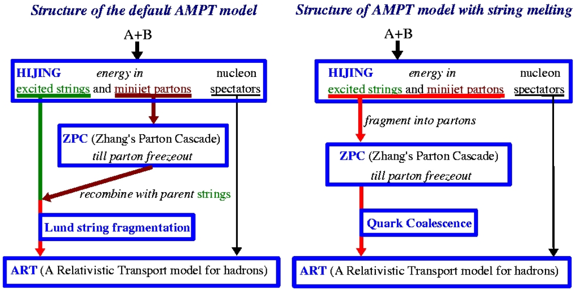
How does it affect the final state particle production around the jets?

Spectra, chemical composition: the relative yields of baryons to mesons around the quenched jets as compared to the vacuum jets.

We presents a unique signature of medium response: the enhancement of jet-induced baryon-to-meson yield ratios around the jets.

- Method: Jet induced baryon and meson yield for identified particles could be systematically studied since we get $\frac{\mathrm{d}^3 N}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\Delta\phi\mathrm{d}\Delta\eta}$ by jet-particle correlation.
- Model: AMPT.

AMPT model



Structure of the default(left) AMPT model and AMPT with string melting(right).

[Lin, Ko, Zhang, Pal, PRC72, 064901 (2005)]

We use AMPT with string melting to simulate p+p and Pb+Pb collisions. It consist of four parts:

- The initial condition: HIJING provides the spatial and momentum information with the help of the jet triggering technique.
- Parton cascade: Simulated by ZPC model which describes elastic partonic collisions among the medium partons and jet partons. The interaction strength of the elastic collisions is controlled by the partonic cross section σ.
- Hadronization: Hadronizes all partons via a simple coalescence model which combines two nearest quarks into a meson and three nearest quarks into a baryon.
- Hadronic rescatterings: ART model includes baryon-baryon, baryon-meson, meson-meson elastic and inelastic scatterings.

Reconstruct jet and correlation between jet and particles

The correlation between jet and particle

- We apply the FASTJET framework with the anti-k_{T} algorithm to reconstruct jets in Pb+Pb and p+p events. The jet cone size is taken to be $\mathrm{R} = 0.4$.
- PbPb collisions for 4 centrality:0-10%,10-30%,30-50%,50-100%.
- We use mixed-event method to correct the limited acceptance.
- After the acceptance correction, we use the side-band method to subtract the background from uncorrelated pairs and long-range correlations.
- We can construct the three-dimensional distribution $\frac{\mathrm{d}^3 N}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\Delta\eta\mathrm{d}\Delta\phi}$ of indentified particles around the jets.

Mixed-event method for jet-particle correlation

The signal pair distribution $S(\Delta\eta, \Delta\phi)$ represents the yield of jet-particles pairs from the same jet-triggered event, normalized by N_{jet},

$$S(\Delta\eta, \Delta\phi) = \frac{1}{N_{\mathrm{jet}}} \frac{\mathrm{d}^2 N^{\mathrm{same}}}{\mathrm{d}\Delta\eta \mathrm{d}\Delta\phi}. \tag{4}$$

The mixed-event pair distribution $ME(\Delta\eta, \Delta\phi)$ is

$$ME(\Delta\eta, \Delta\phi) = \frac{1}{N_{\mathrm{jet}}} \frac{\mathrm{d}^2 N^{\mathrm{mix}}}{\mathrm{d}\Delta\eta \mathrm{d}\Delta\phi}. \tag{5}$$

The ratio $ME(0,0)/ME(\Delta\eta, \Delta\phi)$ is the normalized correction factor.
the two-dimensional particle yield (distribution) per trigger jet is obtained as follows:

$$\frac{1}{N_{\mathrm{jet}}} \frac{\mathrm{d}^2 N}{\mathrm{d}\Delta\eta \mathrm{d}\Delta\phi} = \frac{ME(0,0)}{ME(\Delta\eta, \Delta\phi)} S(\Delta\eta, \Delta\phi), \tag{6}$$

Mixed-event method for jet-induced identified particles

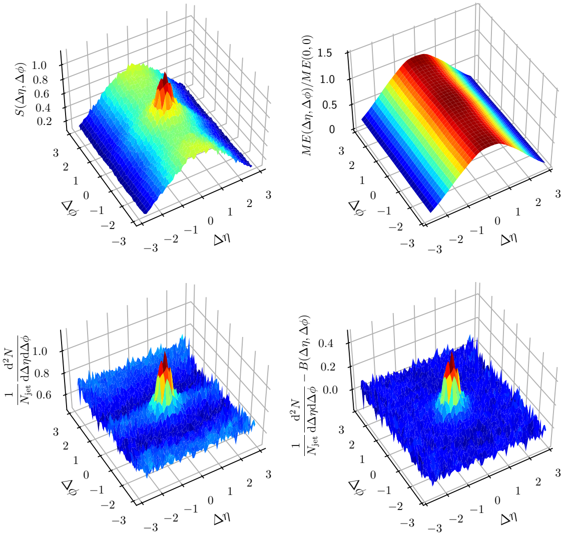
$\frac{d^3N}{dp_T d\Delta\phi d\Delta\eta}$ for identified particles.

We apply the mixed-event method for jet-induced identified particles. Here is illustrated using $0-10\%$ Pb+Pb collisions with proton in $2 < p_T < 3$ GeV.

- The upper left is the signal pair distribution $S(\Delta\eta, \Delta\phi)$,
- the upper right is the normalized mixed-event pair distribution $ME(\Delta\eta, \Delta\phi)$,
- the lower left is the acceptance-corrected distribution,
- the lower right is the final background-subtracted jet-triggered proton yield.

Similar procedure apply to 4 centrality ($0-10\%$, $10-30\%$, $30-50\%$, $50-100\%$) and 7 different p_T bin ($1-2$, $2-3$, $3-4$, $4-6$, $6-8$, $8-10$, $10-12$ GeV) for p, π, Λ and K.

- $\pi = \frac{1}{3}(\pi^+ + \pi^- + \pi^0)$, $p = \frac{1}{2}(p + \bar{p})$,
- $K = \frac{1}{3}(K^+ + K^- + K^0_S)$, $\Lambda = \frac{1}{2}(\Lambda + \bar{\Lambda})$.



p_{T} and Δr distribution of the jet-correlated particles

Using the three-dimensional particle distribution $\frac{\mathrm{d}^3 N}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\Delta\phi\mathrm{d}\Delta\eta}$ around the jets, we may integrate out the pseudorapidity and angular parts ($\Delta\eta$ and $\Delta\phi$) to obtain the p_{T} distributions of identified particles around reconstructed jets:

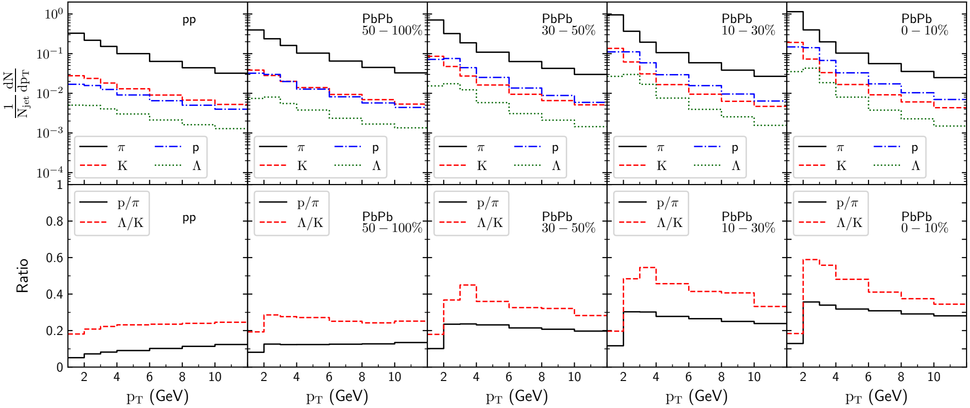
$$\frac{\mathrm{d}N}{\mathrm{d}p_{\mathrm{T}}} = \int \mathrm{d}\Delta\phi \int \mathrm{d}\Delta\eta \frac{\mathrm{d}^3 N}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\Delta\phi\mathrm{d}\Delta\eta}\bigg|_{\Delta r<1}. \tag{7}$$

One may further study the Δr distribution of identified particles in the region with $\Delta r < 1$ around jets, which can be obtained as follows:

$$\frac{\mathrm{d}N}{\mathrm{d}\Delta r} = \int \mathrm{d}\Delta\phi \int \mathrm{d}\Delta\eta \int dp_{\mathrm{T}} \frac{\mathrm{d}^3 N}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\Delta\phi\mathrm{d}\Delta\eta} \times \delta(\Delta r - \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}). \tag{8}$$

In practice, we construct the above identified particle distribution in annular rings of width $\delta r = 0.05$ around jet axis.

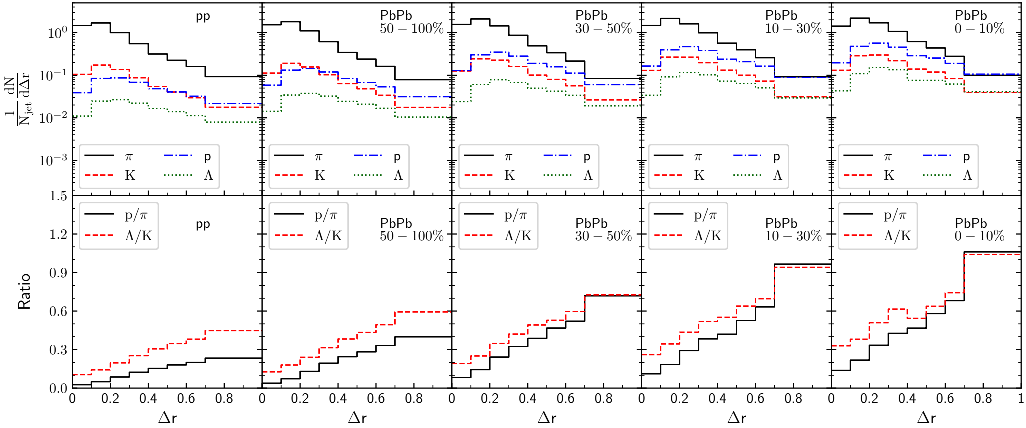
The enhancement of p/π and Λ/K ratios around jets: p_T dependence



Jet-induced identified particle yields in the region $\Delta r < 1$ around the jets with $p_T^{jet} > 120$ GeV, $R = 0.4$ and $|\eta_{jet}| < 1.6$.

- Strong enhancement of jet-induced p/π and Λ/K ratios around the jets in Pb+Pb collisions compared to p+p collisions.
- The enhancement of jet-induced baryon-to-meson ratios is most prominent at intermediate p_T region (around $2 - 6$ GeV). This is a unique signature of parton coalescence.
- More pronounced in more central collisions in which jet quenching effect is larger.

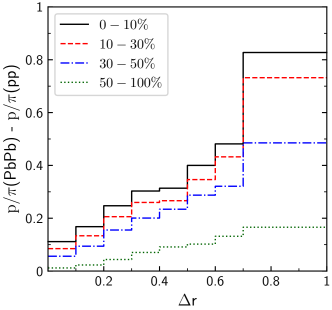
The enhancement of p/π and Λ/K ratios around jets: Δr dependence

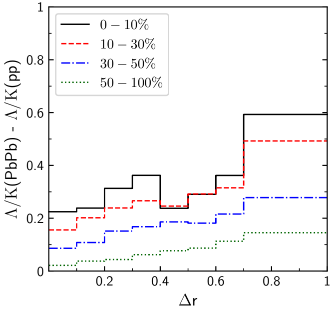


Jet-induced identified particle yields around the jets with particle $p_T = 2 - 6$ GeV as a function of Δr.

- The p/π and Λ/K ratios clearly dependence on collision centrality.
- A clear enhancement of particle yields in Pb+Pb collisions relative to p+p collisions could be observed at larger Δr. This means that a significant fraction of the lost energy from jets is carried by soft particles at large angles with respect to the jet direction.

The enhancement of p/π and Λ/K ratios around jets: different centrality



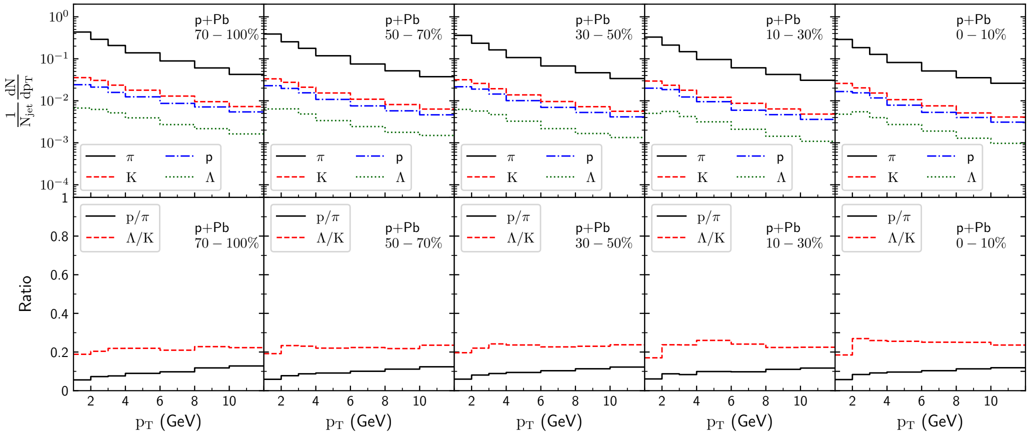


- The enhancement is more pronounced in more central collisions due to jet quenching effect.
- The enhancement of jet-induced baryon-to-meson ratios is stronger for larger distance Δr. Because the lost energy from the quenched jets can diffuse to large angles.

Summary

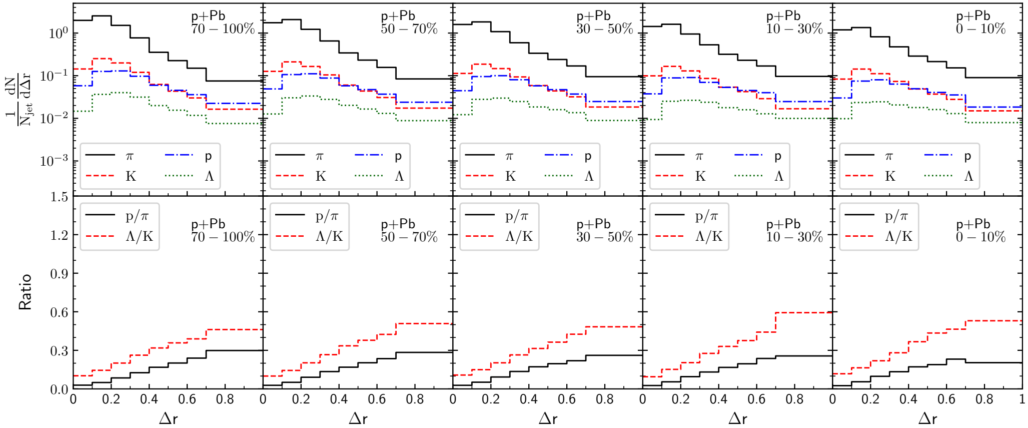
- We present a unique signature of medium response to jet quenching: a strong enhancement of the baryon-to-meson ratios around the quenched jets. Since the baryon-to-meson enhancement is a general feature of parton coalescence, irrespective of the details of the coalescence models, our prediction of this unique signal of medium response should be very robust.
- Our prediction can be systematically tested by experiments using the same jet-particle correlation method. Once confirmed by experiment, it will provide an unambiguous evidence for the medium response to jet quenching in heavy-ion collision.
- A very interesting future direction is to apply our method to various small system, which may provide a sensitive tool to detect the signal of jet quenching in small systems.

Thank you!



- We apply our current method to p+Pb collisions, the enhancement of p/π and Λ/K ratios around jets is relative small compare to Pb+Pb collisions.

No baryon-to-meson enhancement observed in p+Pb collisions



- It may indicate that the lifetime and volume of QGP produced in p+Pb collisions are relatively small.