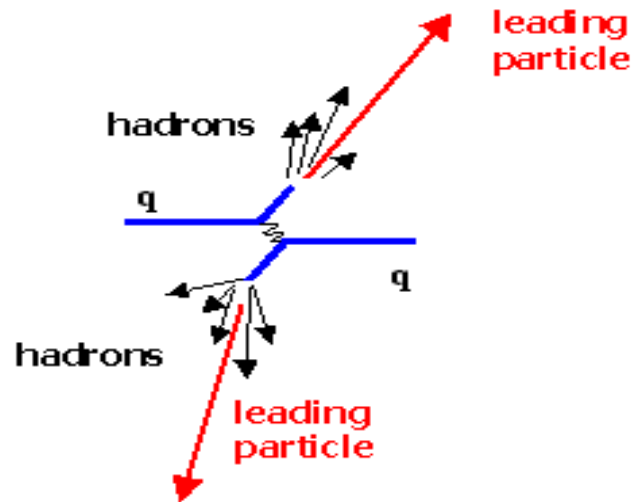# Enhancement of baryon-to-meson ratios around jets as a signature of medium response

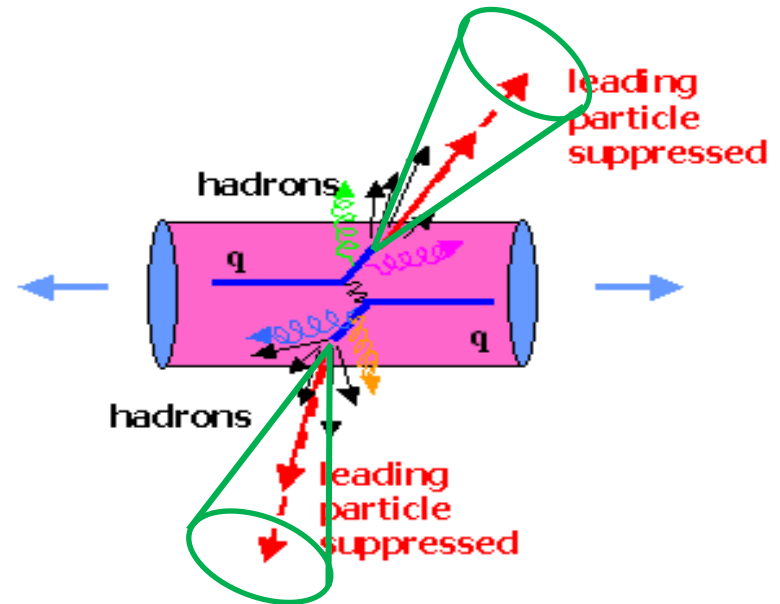**Guang-You Qin**

Central China Normal University

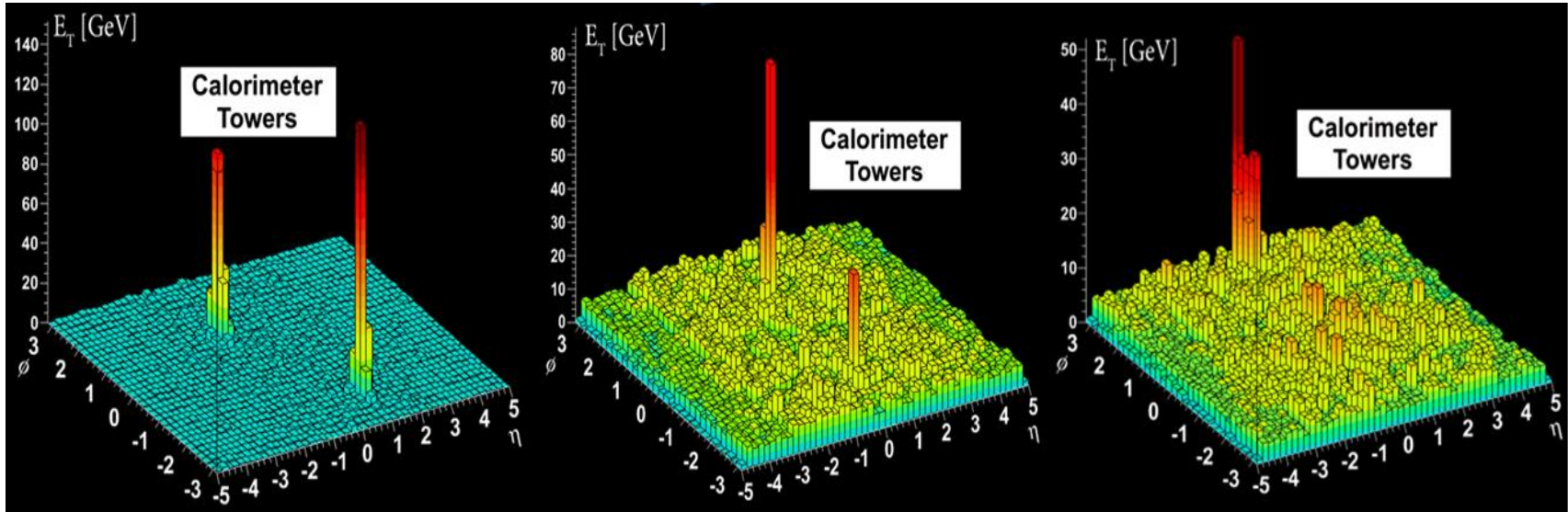**Quark Matter 2023**

Houston, Texas, USA

September 3-9, 2023

Jet quenching

N+N

A+A: jet quenching

Jet quenching: **(1) jet energy loss** **(2) jet deflection & broadening** **(3) modification of jet structure** **(4) jet-induced medium response**

Where does the lost energy go?

How does the medium respond to the lost energy?
How does the lost energy redistribute and manifest in final state?
Where to search for the signal of medium response?
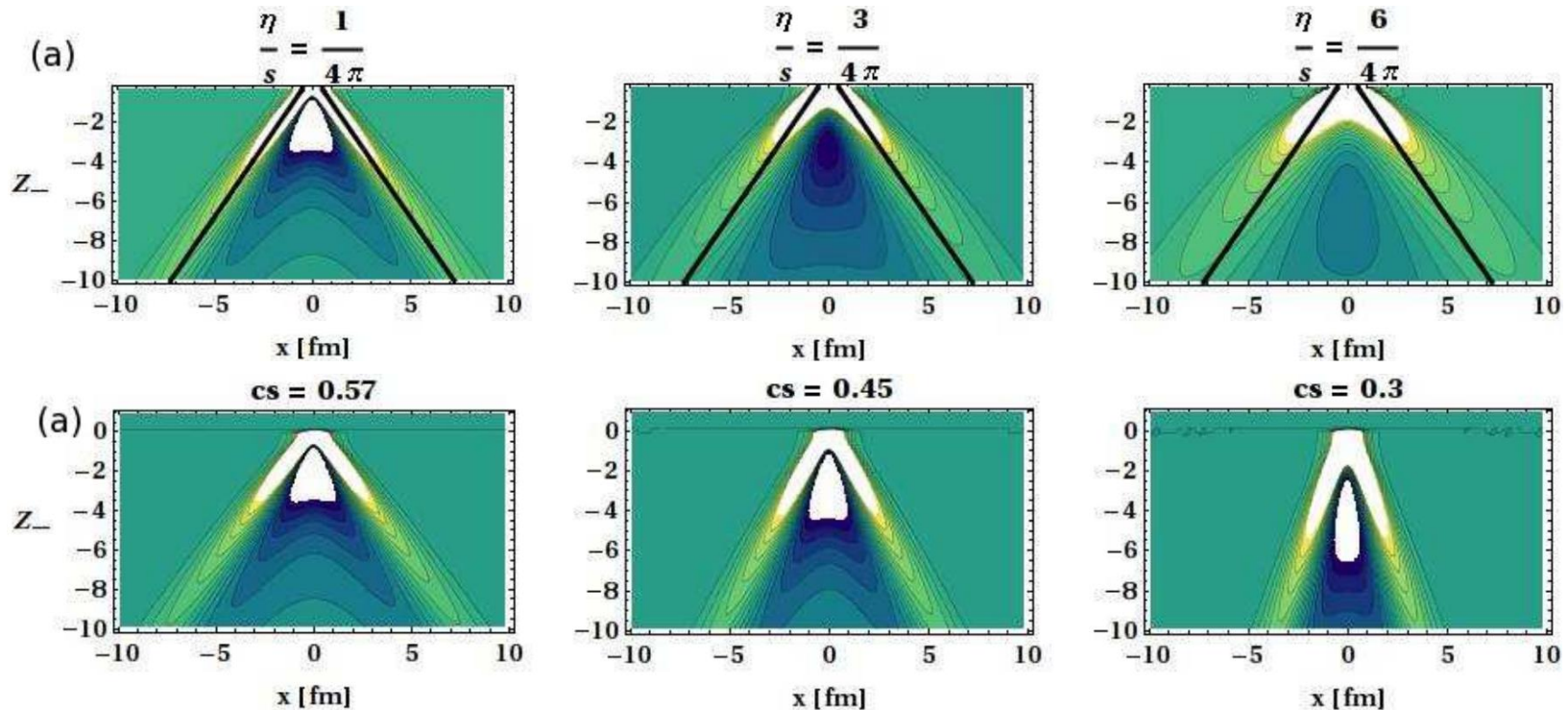How to use medium response to probe the medium properties?

Earlier works on medium response

$$T^{\mu\nu} \simeq T_0^{\mu\nu} + \delta T^{\mu\nu}; \quad \partial_\mu T_0^{\mu\nu} = 0, \quad \partial_\mu \delta T^{\mu\nu} = J^\nu.$$

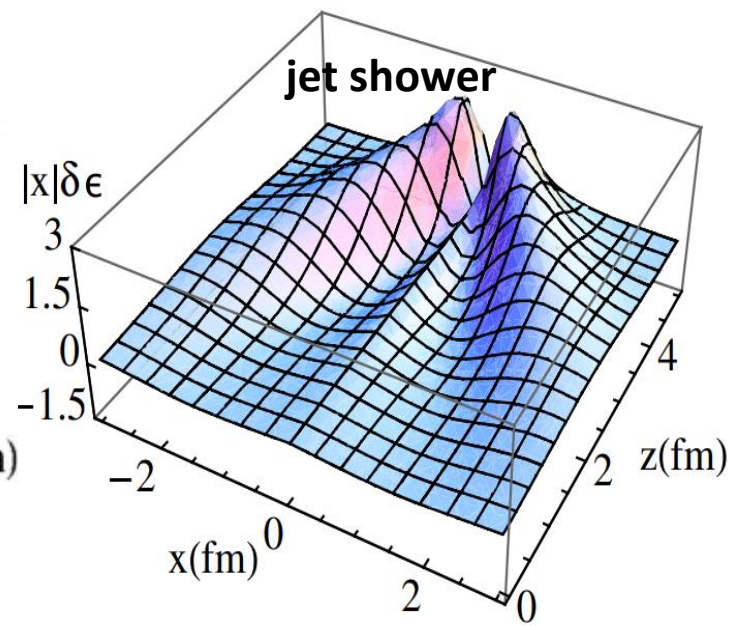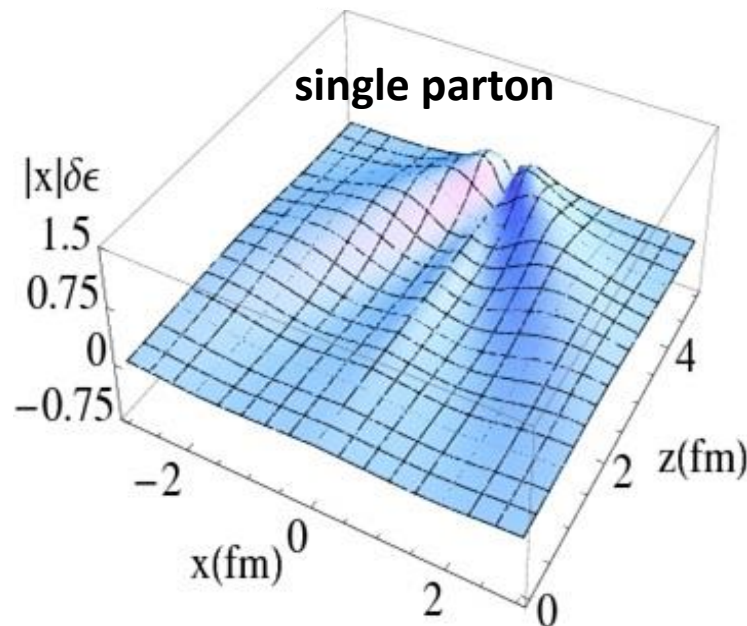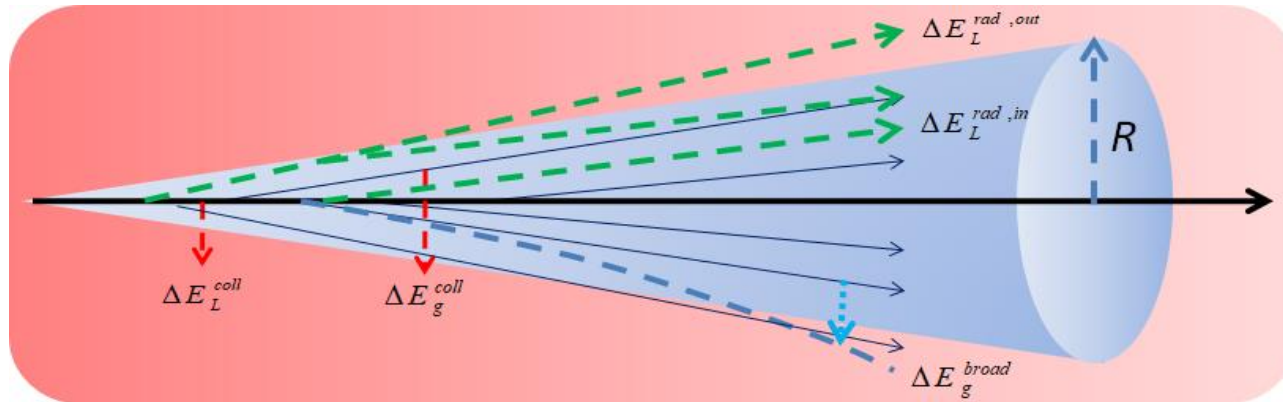$$\delta T^{00} \equiv \delta\epsilon, \qquad \delta T^{0i} \equiv g^i,$$

$$\delta T^{ij} = \delta_{ij} c_s^2 \delta\epsilon - \Gamma_s(\partial^i g^j + \partial^j g^i - \tfrac{2}{3}\delta_{ij}\nabla \cdot \vec{g}).$$

Casalderrey-Solana, Shuryak, Teaney, hep-ph/0411315; Stoecker, nucl-th/0406018; Ruppert, Muller, PLB 2005; ...

Neufeld, PRC 2009

Medium response to jet shower

$\Delta E_L^{rad,out}$

$\Delta E_L^{rad,in}$

R

ΔE_L^{coll}

ΔE_g^{coll}

ΔE_g^{broad}

single parton

jet shower

$|x|\delta\epsilon$
1.5
0.75
0
−0.75

−2

0

2

z(fm)

4

2

0

x(fm)

$|x|\delta\epsilon$
3
1.5
0
−1.5

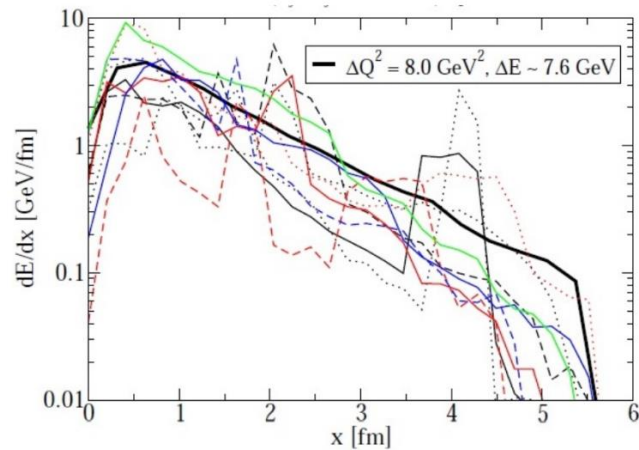−2

0

2

z(fm)

4

2

0

x(fm)

GYQ, Majumder, Song, Heinz, PRL 2009; Neufeld, Muller, PRL 2009

Complications
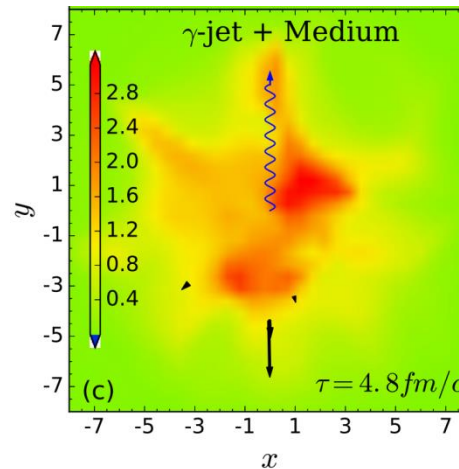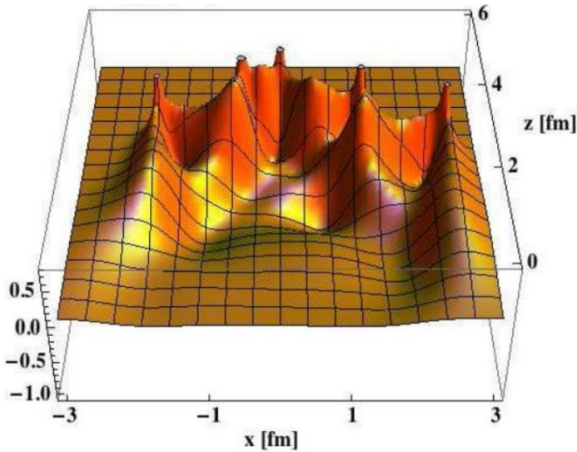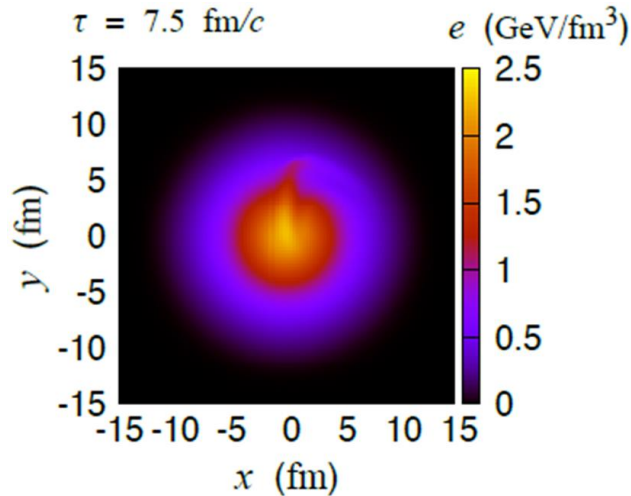
The flow of the expanding medium can distort the conic structure

Detailed distributions of the energy and momentum deposition profiles

Even-by-event fluctuations of jet shower evolution and energy loss

Large and event-by-event fluctuating background medium

Neufeld, Vitev, PRC 2012; Renk, PRC 2013; Tachibana, Chang, GYQ, PRC 2017; Chen, Cao, Luo, Pang, Wang, PLB 2018

Treatments on medium response

- **Jet + recoil**
  - **LBT (He, Luo, Cao, Zhu, Wang, et al, 1503.03313; 1803.06785)**
  - **JEWEL (Elayavalli, Zapp, Milhano, Wiedemann, 1707.01539; 1707.04142)**
  - **MARTINI (Park, Jeon, Gale, 1807.06550)**

- **Jet + hydrodynamics**
  - **Coupled Jet-Fluid Model (Tachibana, Chang, GYQ: 1701.07951; 1906.09562)**
  - **CoLBT-Hydro (Chen, Yang, Luo, He, Cao, Ke, Pang, Wang, et al, 1704.03648; 2005.09678; 2101.05422; 2203.03683)**
  - **JETSCAPE (2002.12250)**
  - **Minijet+Hydro (Pablos, Singh, Jeon and Gale, 2202.03414)**
  - **Hybrid Model (Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal, 1609.05842)**

- **Full Boltzmann**
  - **AMPT (Gao, Luo, Ma, Mao, GYQ, Wang, Zhang, 1612.02548; 2107.11751; 2109.14314)**
  - **BAMPS (Bouras, Betz, Xu, Greiner, 1201.5005; 1401.3019)**

- **See Cao, GYQ, 2211.16821 [nucl-th] (https://doi.org/10.1146/annurev-nucl-112822-031317) for a recent review.**
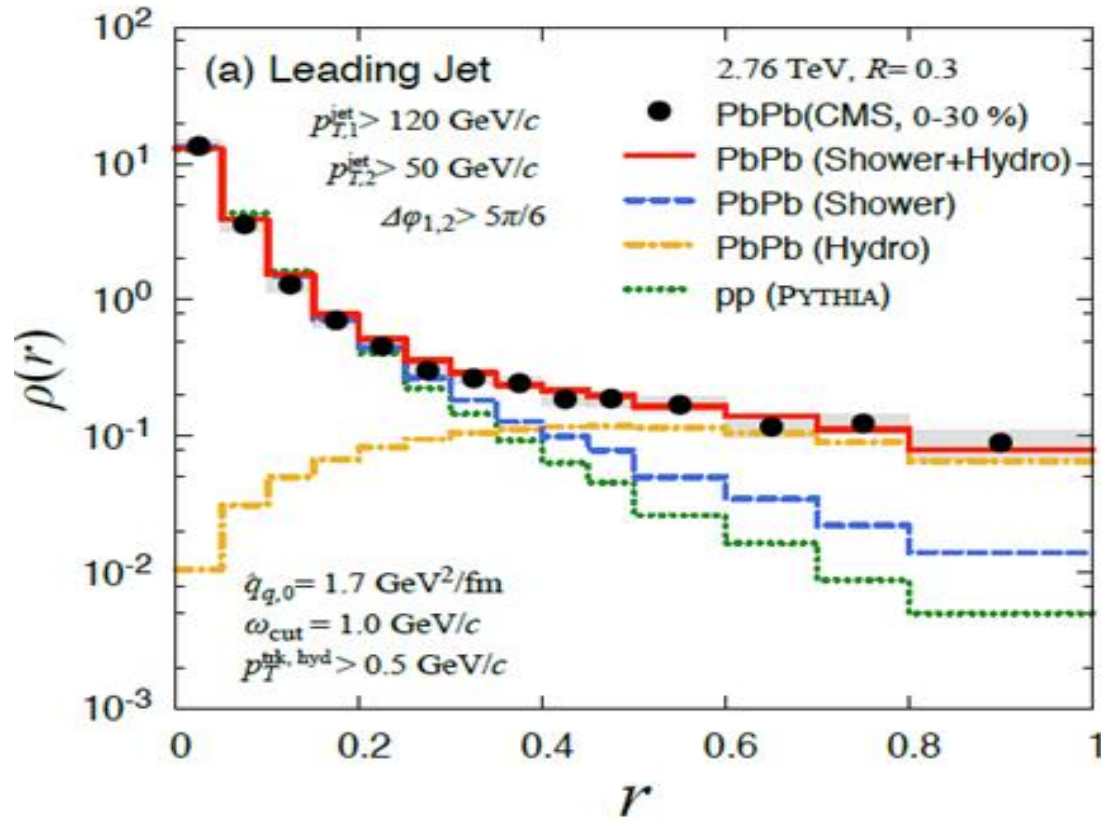
Jet evolution & medium response
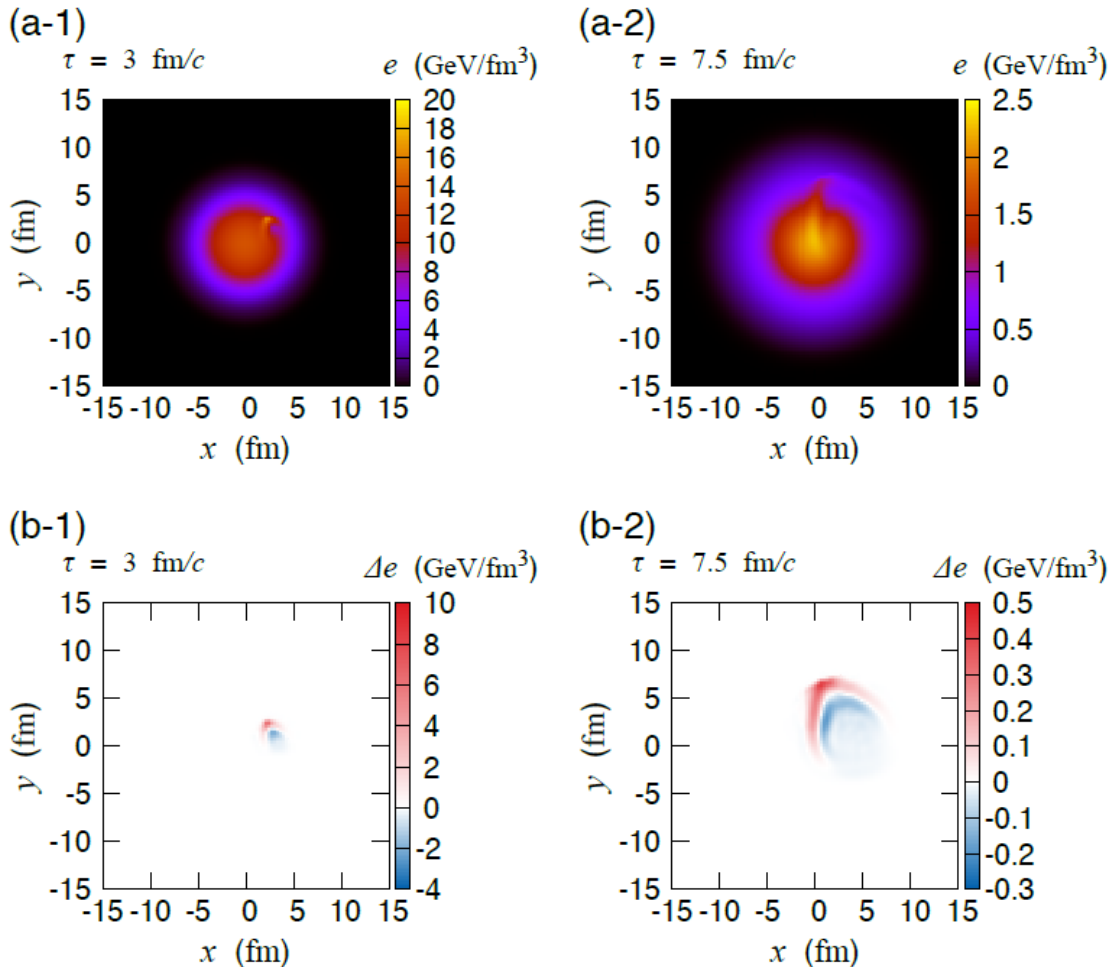
$$\frac{df}{dt} = C[f], \partial_\mu T^{\mu\nu} = J^\nu$$

Jet deposits energy and momentum into medium, and induces V-shaped wave fronts

The wave fronts carry energy and momentum, propagates forward and outward, and depletes the energy behind the jet (diffusion wake)

Jet-induced flow and the radial flow of medium are pushed and distorted by each other

Chang, GYQ, PRC 2016; Tachibana, Chang, GYQ, PRC 2017; Chang, Tachibana, GYQ, PLB 2020
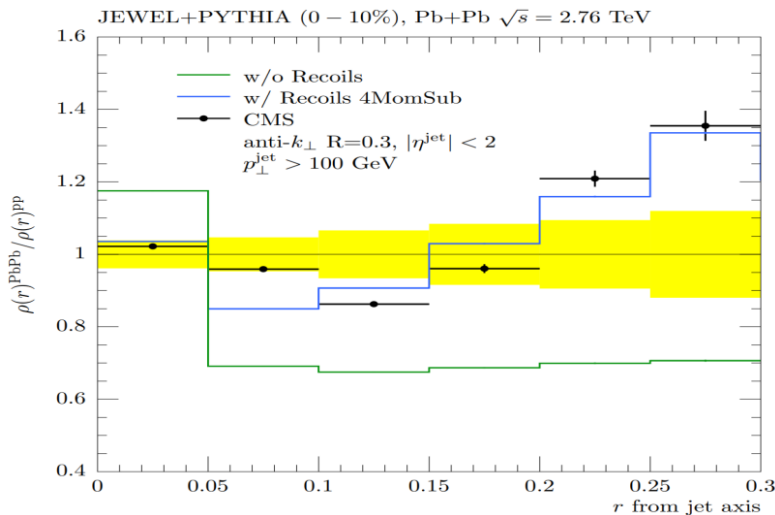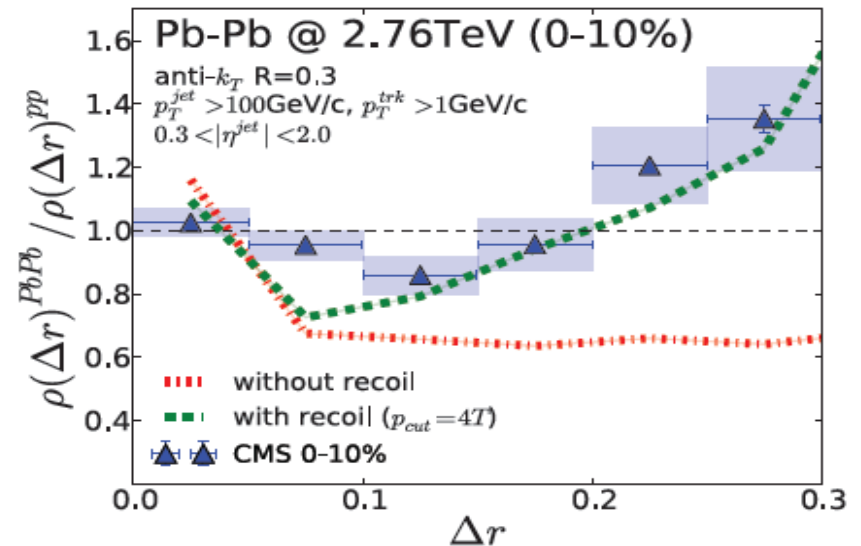
Redistribution of lost energy from quenched jets

The contribution from the hydro part is quite flat and finally dominates over the shower part in the region from r = 0.4-0.5.
Signal of jet-induced medium excitation in full jet shape at large r.

Chang, GYQ, PRC 2016; Tachibana, Chang, GYQ, PRC 2017; Chang, Tachibana, GYQ, PLB 2020

Other similar results on medium response
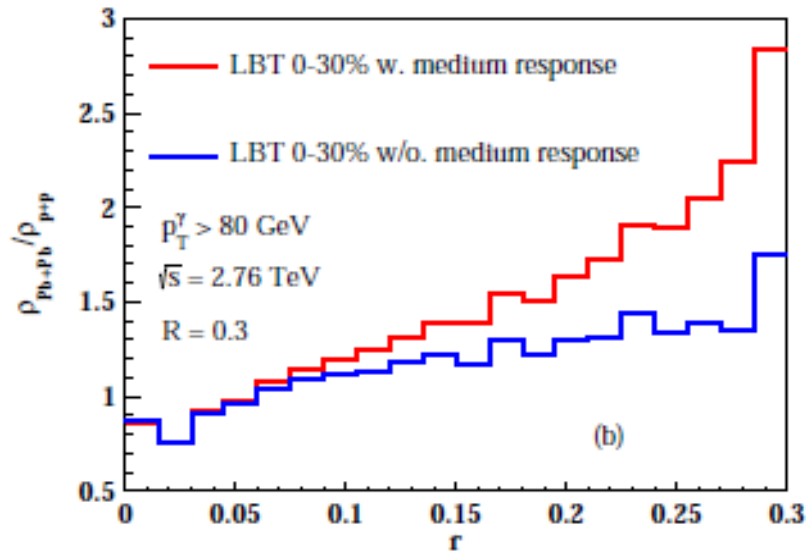
Luo, Cao, He, Wang, PLB 2018;
C. Park, S. Jeon, C. Gale, 2018;
Elayavalli, Zapp, JHEP 2017;

The inclusion of medium response can naturally explains the enhancement of jet shape at larger radius.

How about particle compositions around jets?

- **Due to the interaction with the medium, the lost/deposited energy will be (partially) thermalized.**

- **The particles (and their chemical compositions) produced from jet-excited energy should be different from those from vacuum-like energy.**

- **As a result of the coalescence of jet-excited partons, jet-medium interaction can lead to the enhancement of baryon-to-meson ratio at intermediate p_T around the quenched jets.**

- **Since the lost energy can flow to large angles, we expect that the B/M enhancement should depend on the distance with respect to the jet axis.**
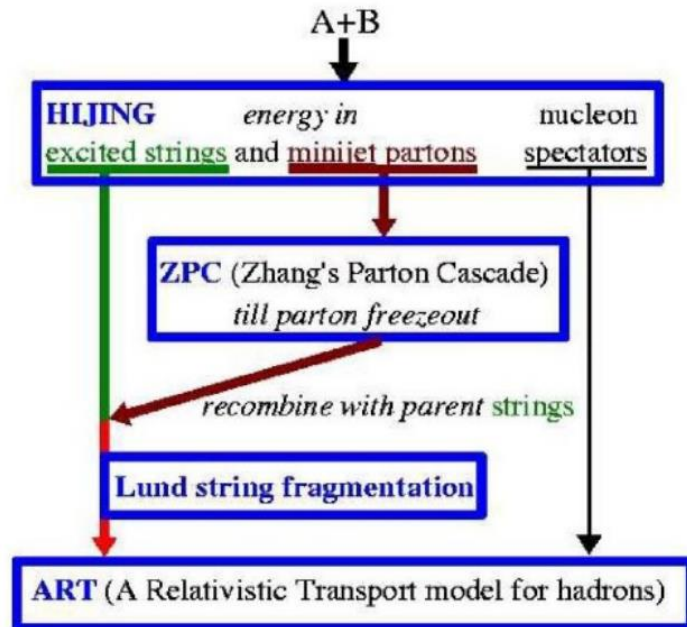
B/M enhancement & v_2 NCQ scaling of bulk matter
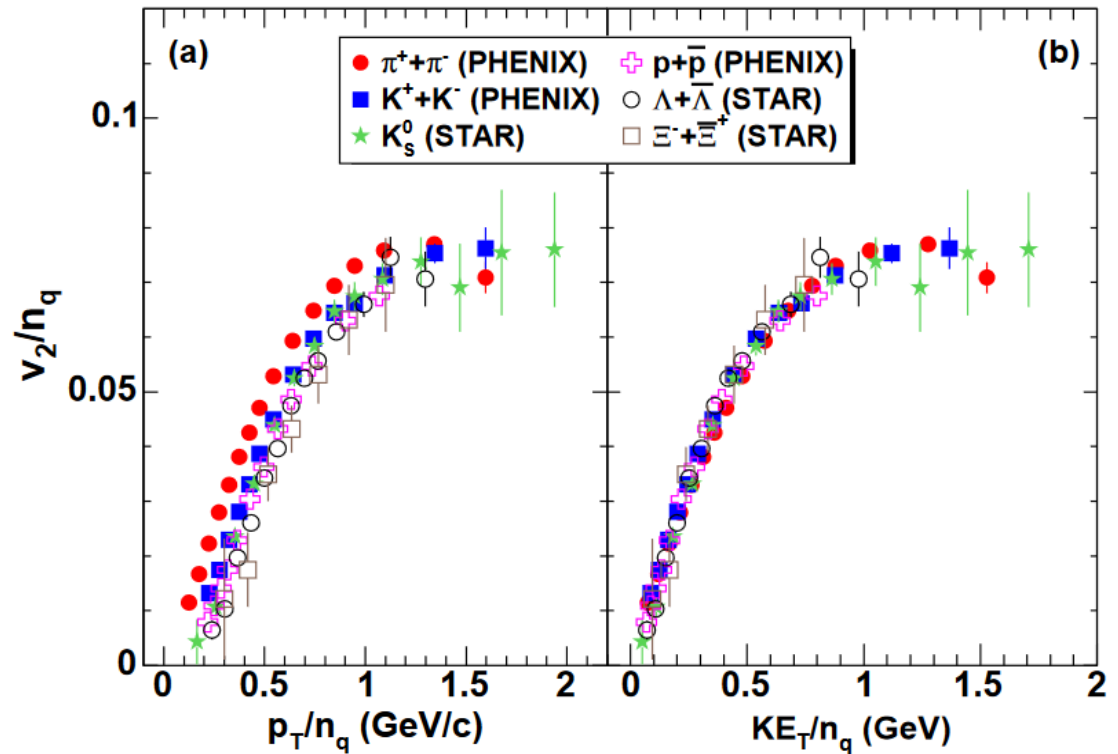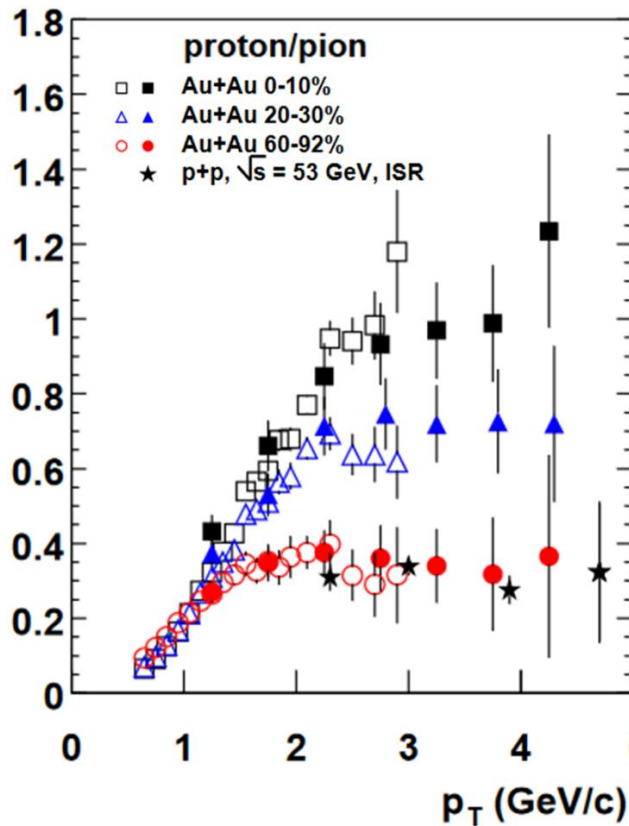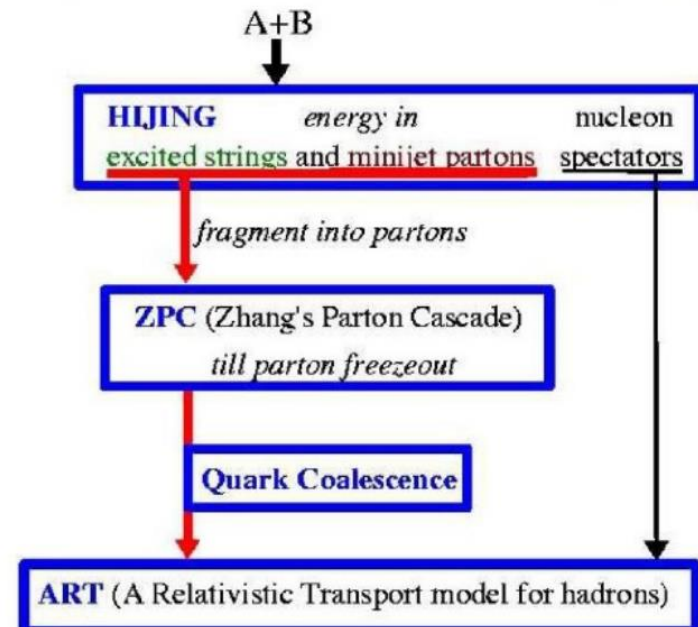

Coalescence of thermal partons from QGP can naturally explain the NSQ scaling of v_2 and the enhancement of baryon-to-meson ratio at intermediate p_T.

A Mult-Phase Transport (AMPT) Model

Structure of the default AMPT model

A+B

HIJING — *energy in* — nucleon
excited strings and minijet partons — spectators

ZPC (Zhang's Parton Cascade)
till parton freezeout

recombine with parent strings

Lund string fragmentation

ART (A Relativistic Transport model for hadrons)

Structure of AMPT model with string melting

A+B

HIJING — *energy in* — nucleon
excited strings and minijet partons — spectators

fragment into partons

ZPC (Zhang's Parton Cascade)
till parton freezeout

Quark Coalescence

ART (A Relativistic Transport model for hadrons)

AMPT contains 4 main stages: initial condition, parton cascade, hadronization and hadron cascade.
AMPT has been able to describe many bulk and jet observables: flow, dijet and gamma-jet asymmetries, jet shape, jet fragmentation function, etc.
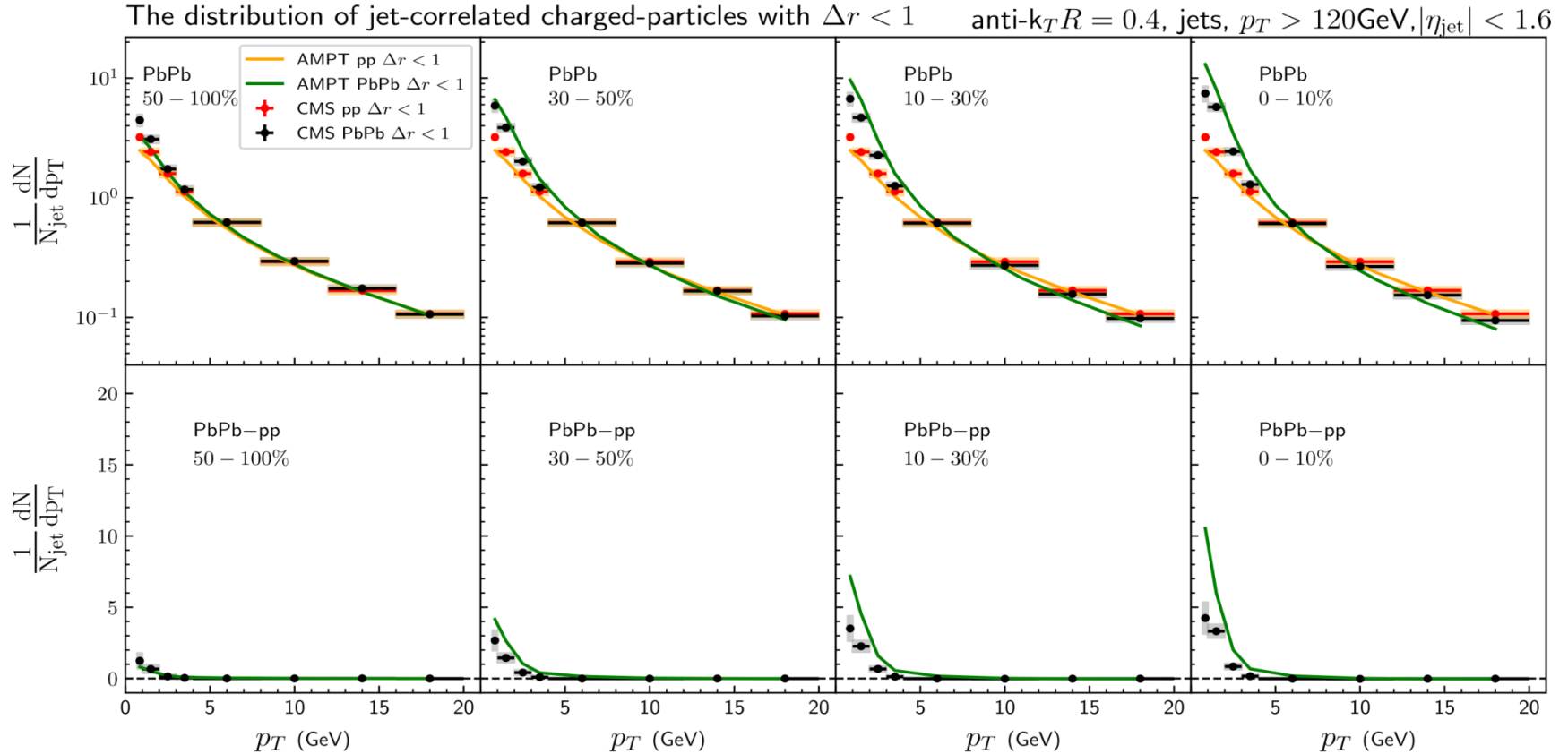
Jet-particle correlations
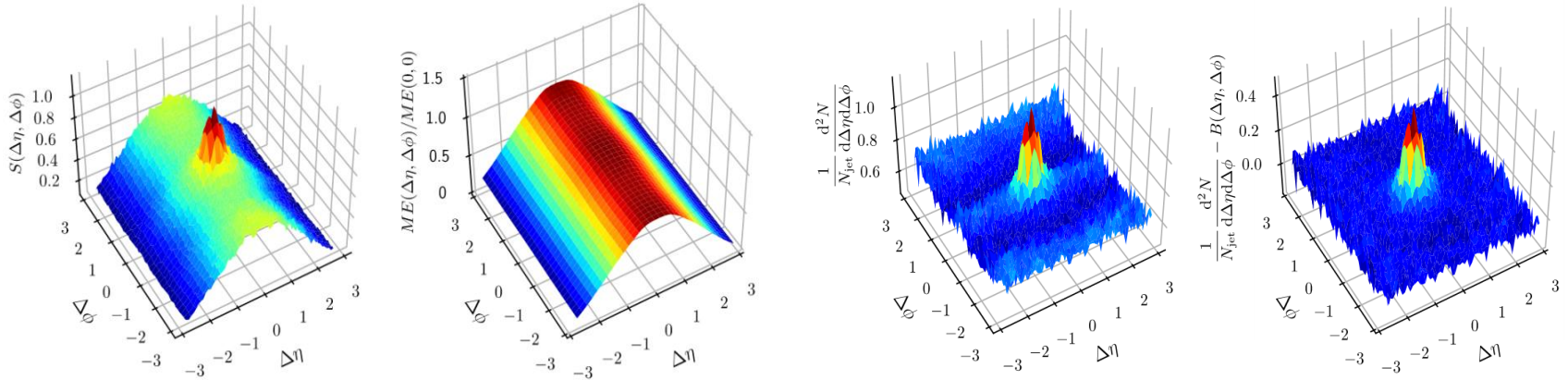
$$\frac{1}{N_{\text{jet}}} \frac{d^2N}{d\Delta\eta d\Delta\phi} = \frac{ME(0,0)}{ME(\Delta\eta, \Delta\phi)} S(\Delta\eta, \Delta\phi) \quad \Longrightarrow \quad \frac{d^3N}{dp_T d\Delta\phi d\Delta\eta}$$

$$\frac{dN}{dp_T} = \int d\Delta\phi \int d\Delta\eta \frac{d^3N}{dp_T d\Delta\phi d\Delta\eta}\bigg|_{\Delta r < 1}$$

$$\frac{dN}{d\Delta r} = \int d\Delta\phi \int d\Delta\eta \int dp_T \frac{d^3N}{dp_T d\Delta\phi d\Delta\eta} \delta(\Delta r - \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2})$$

Luo, Mao, GYQ, Wang, Zhang, PLB 2023

Jet-induced particle yield around jets

The distribution of jet-correlated charged-particles with $\Delta r < 1$. anti-k_T $R = 0.4$, jets, $p_T > 120\,\text{GeV}, |\eta_{\text{jet}}| < 1.6$

Jet quenching leads to the enhancement of soft particles and the suppression of hard particles around the jets. Such effect is more pronounced for more central collisions.

Luo, Mao, GYQ, Wang, Zhang, EPJC 2022

B/M enhancement around jets: p_T dependence
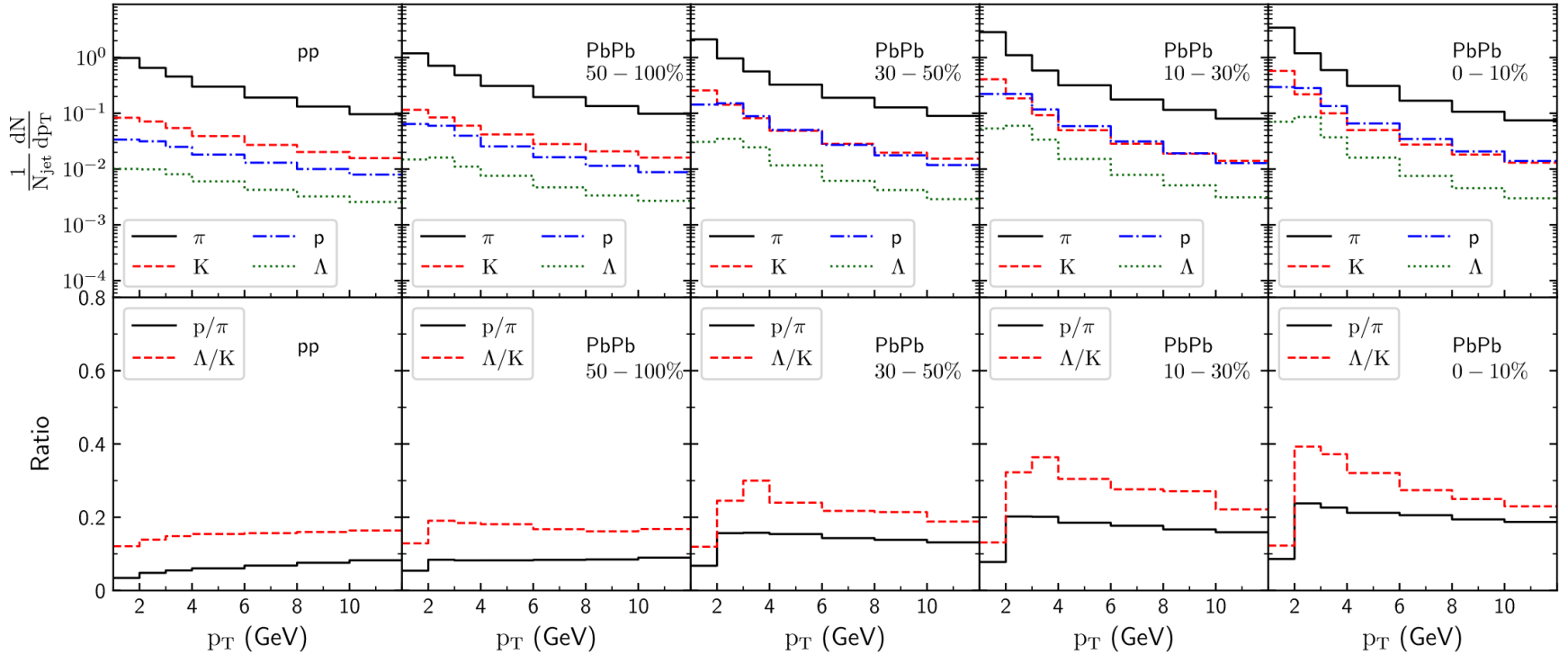
We find a strong enhancement of B/M ratios for associated particles at intermediate p_T around the quenched jets, due to the coalescence of jet-excited medium partons.

Luo, Mao, GYQ, Wang, Zhang, PLB 2023

B/M enhancement around jets: radial dependence
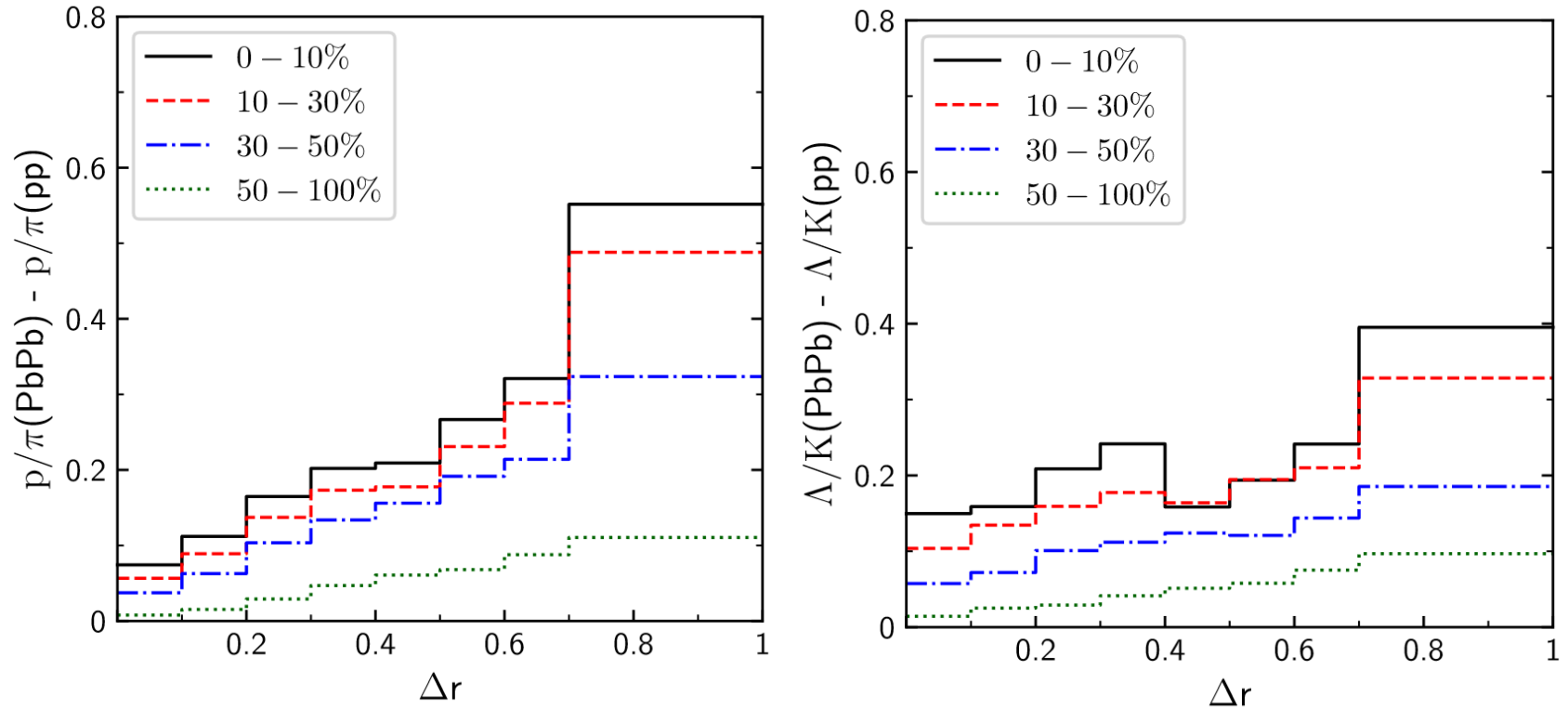
For intermediate p_T (2-6GeV) regime, the enhancement of jet-induced B/M ratios is stronger for larger distance because the lost energy from quenched jets can diffuse to large angle.

Luo, Mao, GYQ, Wang, Zhang, PLB 2023

Summary

- **Medium response is an important aspect of jet quenching.**

- **The energy deposited by the quenched jet is carried by soft particles at large angles.**

- **The enhancement of the baryon-to-meson ratio at intermediate p_T around the quenched jets**
  - **A unique signature of medium response.**
  - **Does not depend on the model details of jet quenching and parton coalescence.**

- **Include more ingredients such as inelastic scattering processes (or use more sophisticated model, e.g., CoLBT-Hydro) for more precise description/prediction.**

- **Use medium response to probe EOS and transport properties of QGP.**