Probing medium response via hadron chemistry around quenched jets

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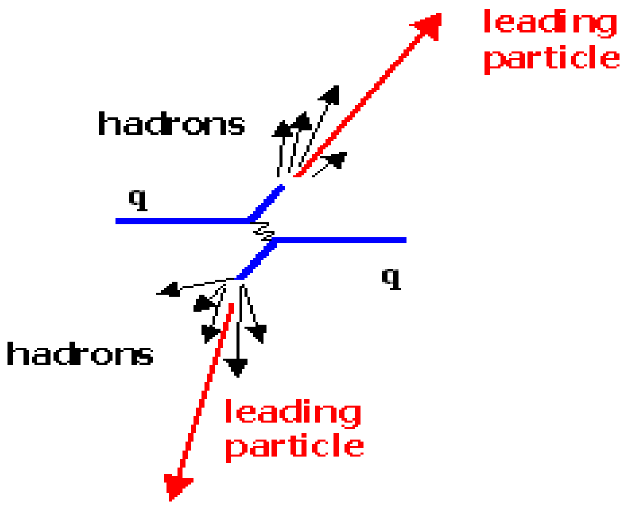
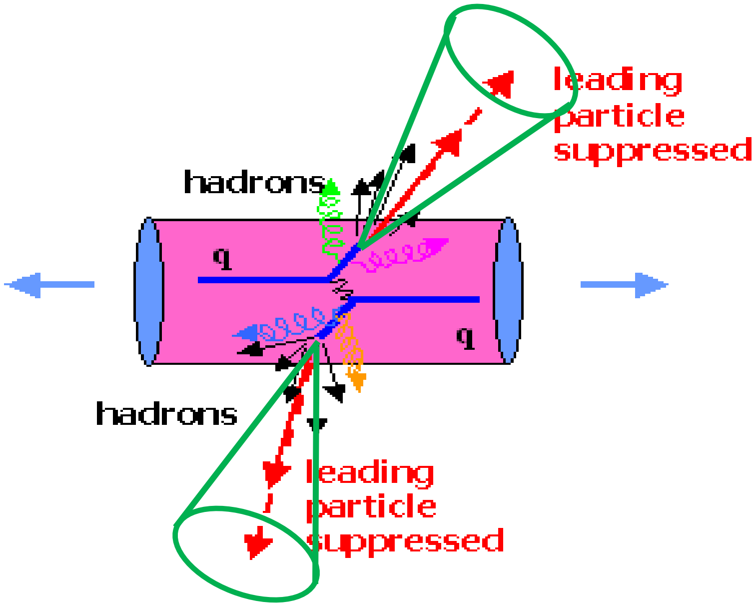
Jet quenching



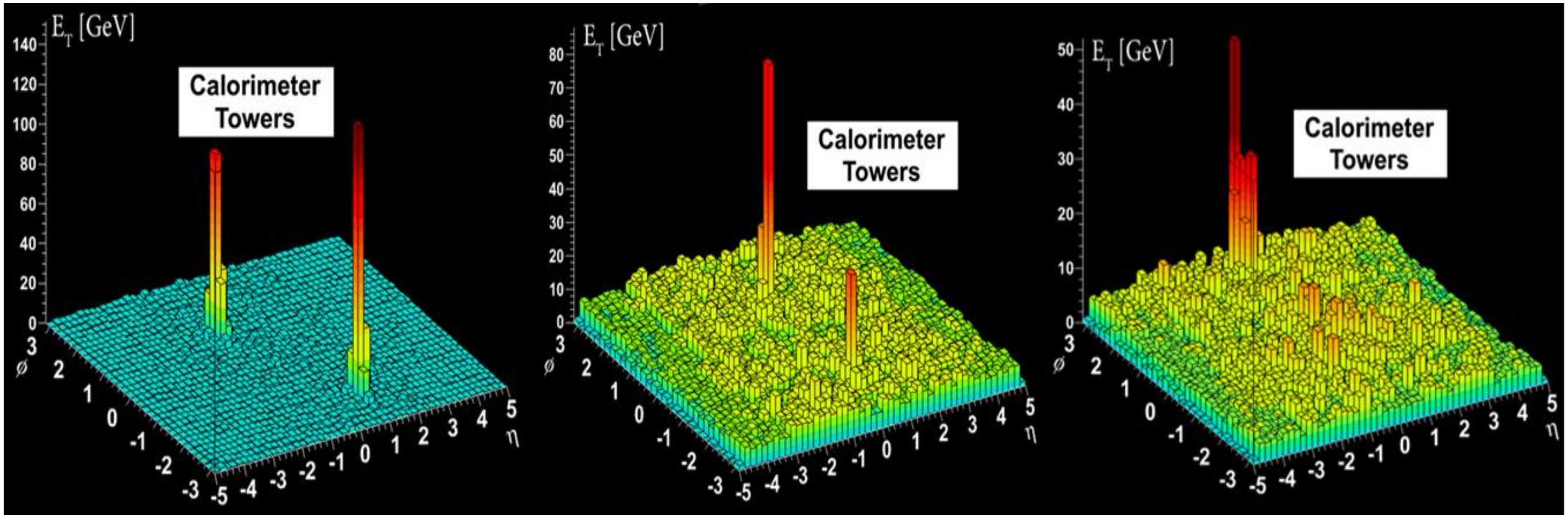
N+N



A+A: jet quenching

Jet quenching: (1) jet energy loss (2) jet deflection & broadening (3) modification of jet substructure (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?

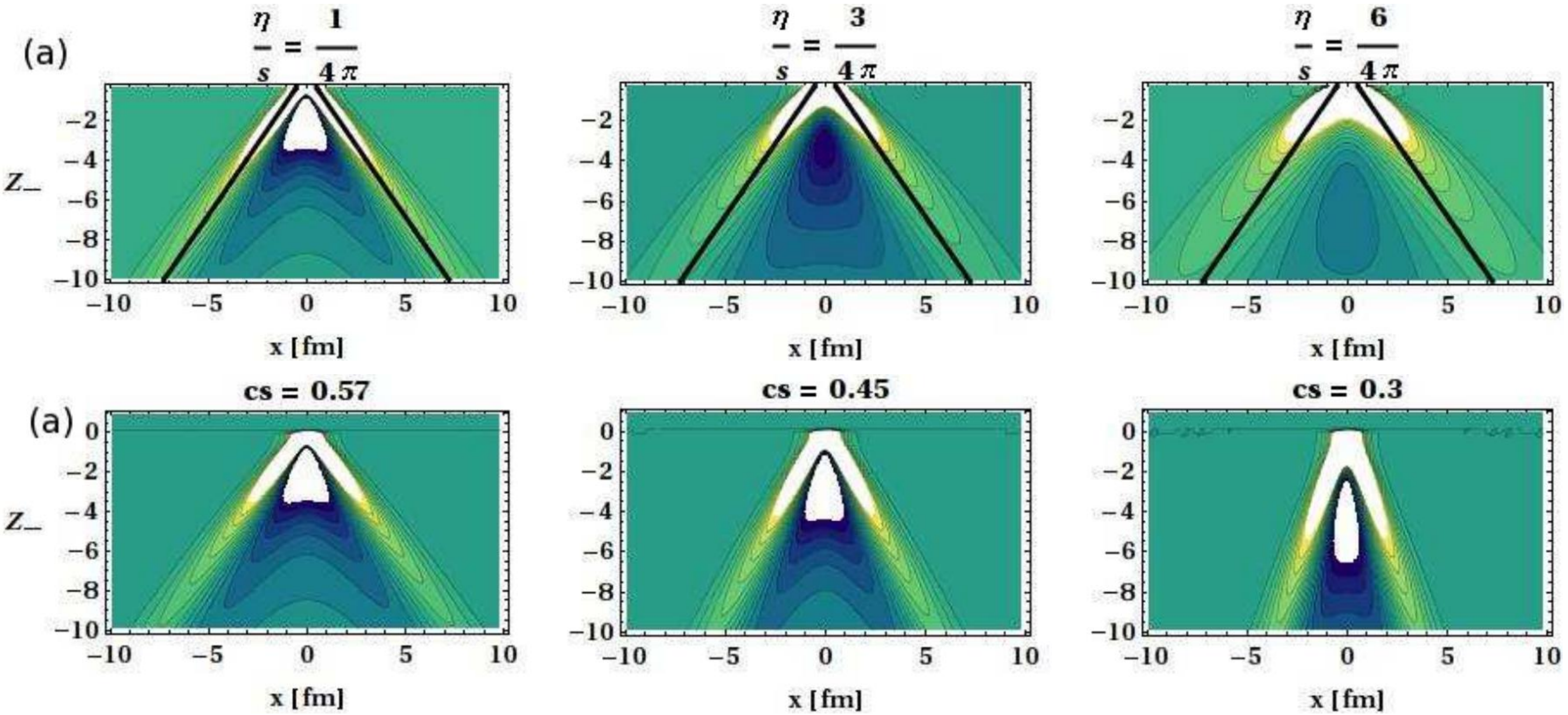
Earlier works on medium response

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

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

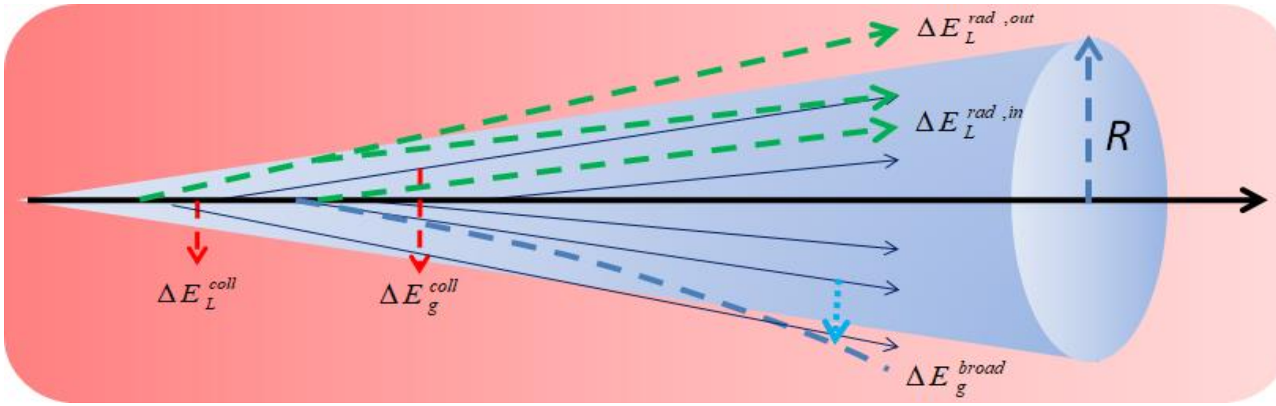
$$\delta T^{ij} = \delta_{ij} c_s^2 \delta\epsilon - \Gamma_s (\partial^i g^j + \partial^j g^i - \tfrac{2}{3}\delta_{ij} \nabla \cdot \vec{g}).$$

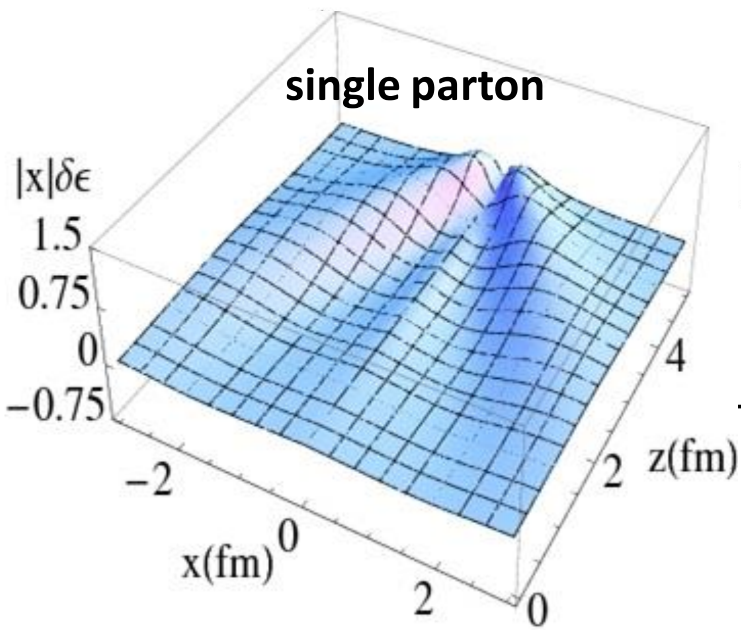
Casalderrey-Solana, Shuryak, Teaney, hep-ph/0411315; Stoecker, nucl-th/0406018; Ruppert, Muller, PLB 2005; ...

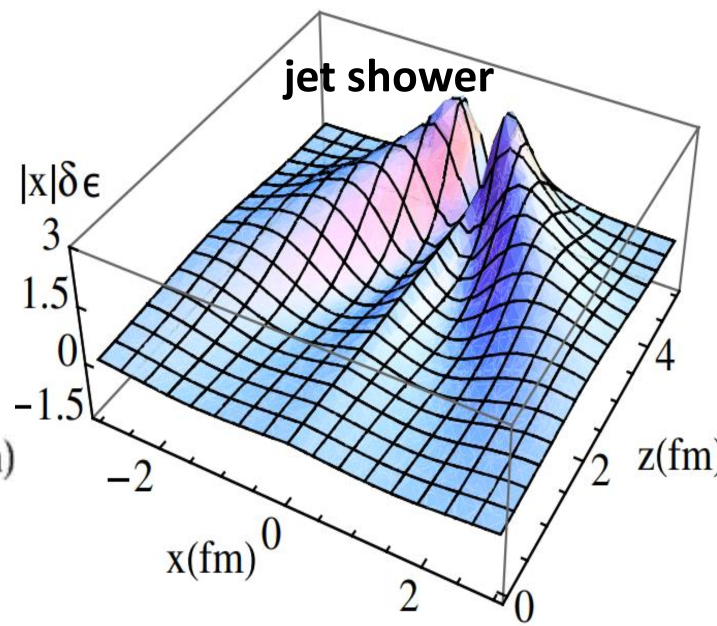


Neufeld, PRC 2009

Medium response to jet shower

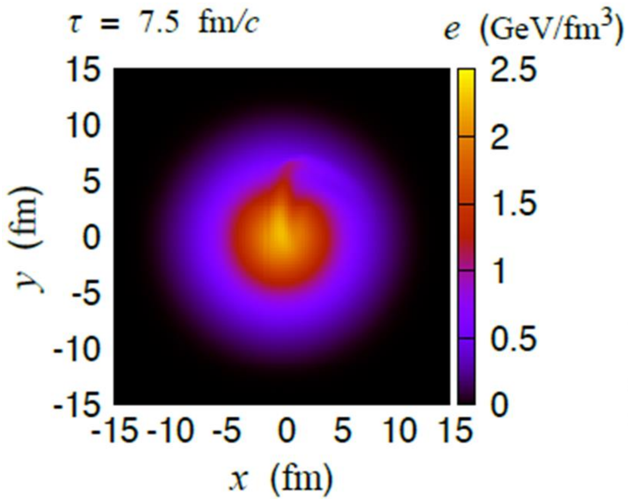


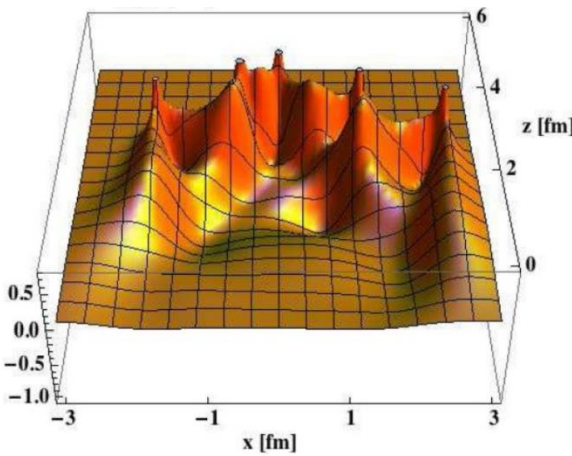


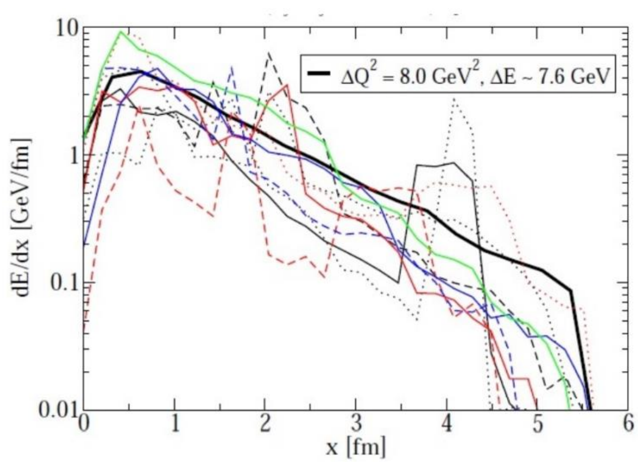


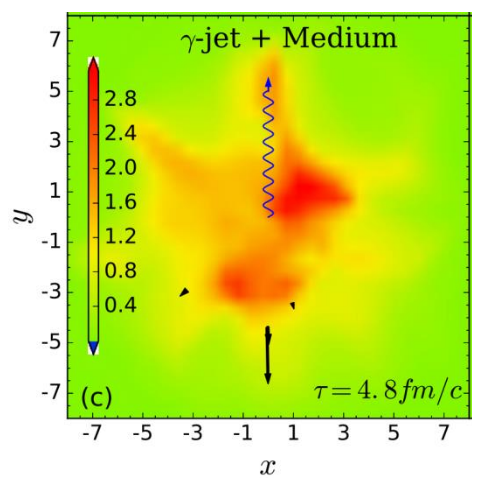
GYQ, Majumder, Song, Heinz, PRL 2009; Neufeld, Muller, PRL 2009

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

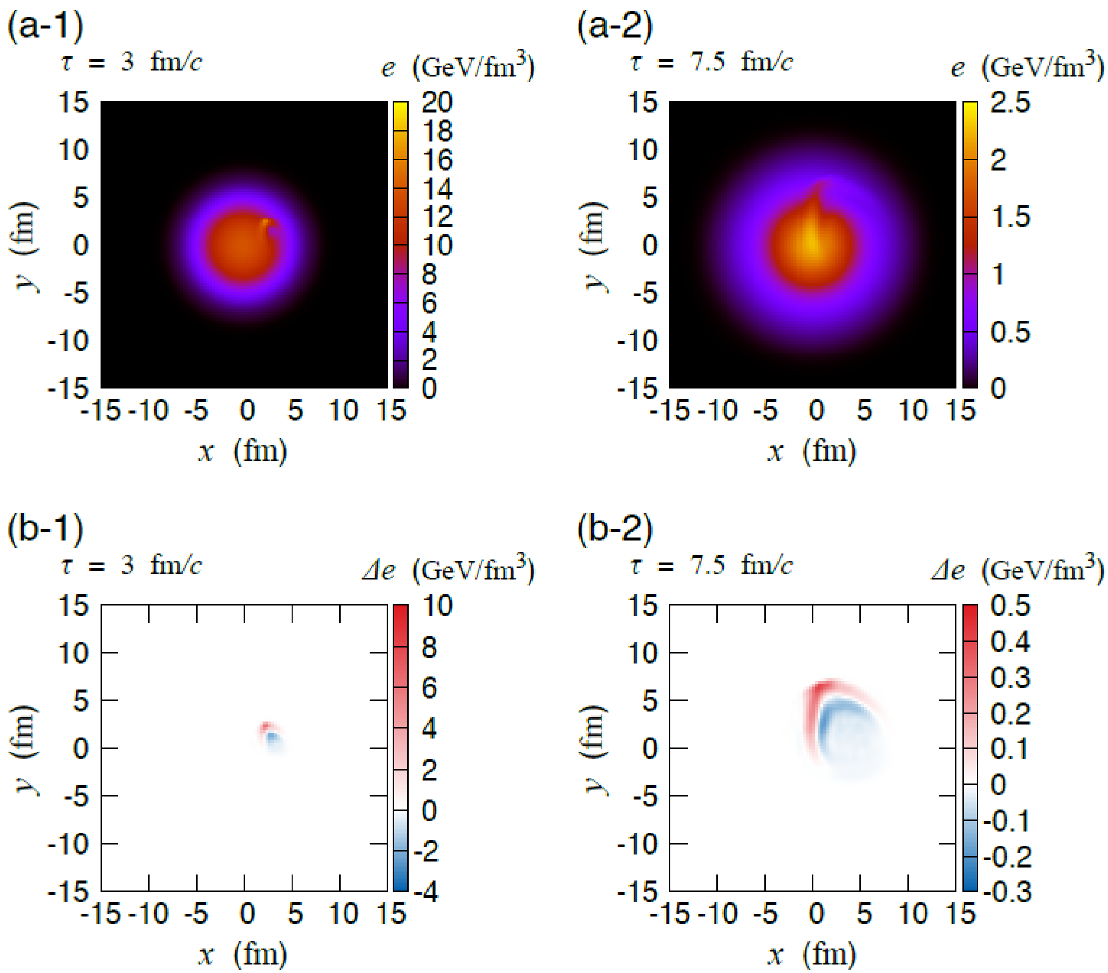
- **Jet + recoil**
  - **LBT (He, Luo, Cao, Zhu, Wang, et al, 1503.03313; 1803.06785)**
  - **JEWEL (Elayavalli, Zapp, Milhano, Wiedemann, 1707.01539; 1707.04142)**
  - **MARTINI (Park, Jeon, Gale, 1807.06550)**

- **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



$$\frac{df}{dt} = C[f], \partial_\mu T^{\mu\nu} = J^\nu$$

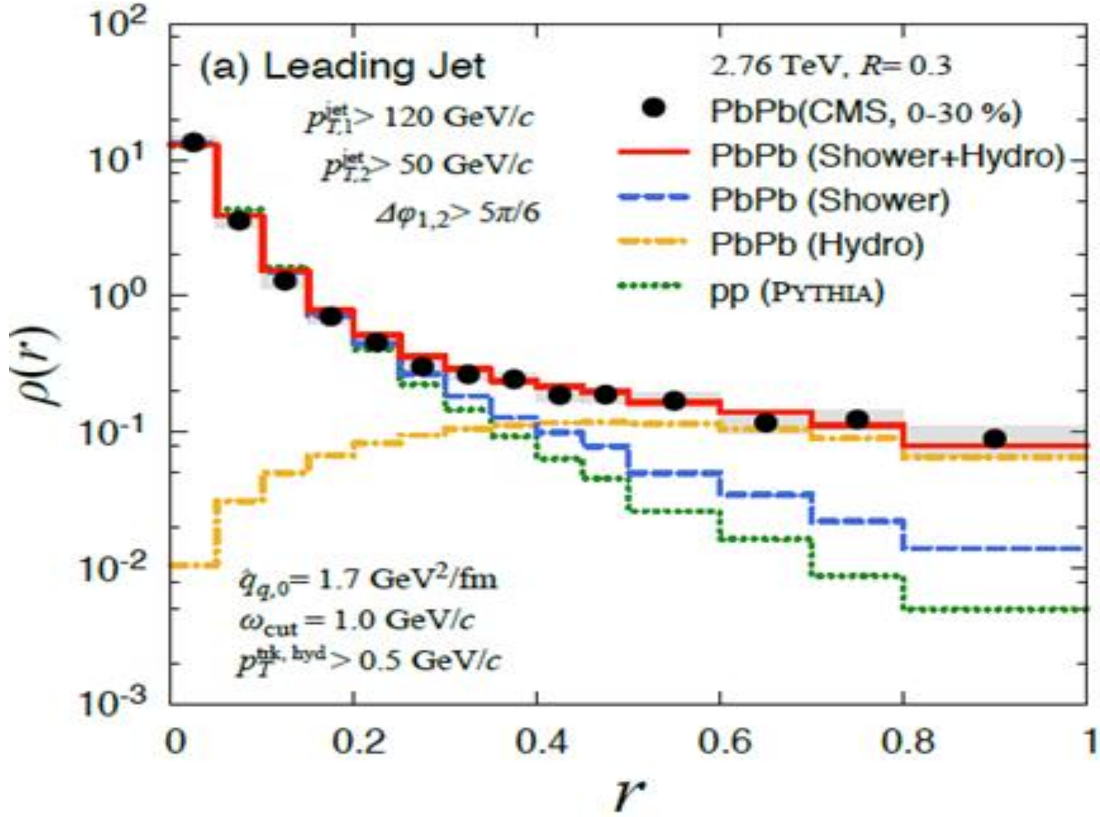
Jet deposits energy and momentum into medium, and induces medium excitations (wave fronts)

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

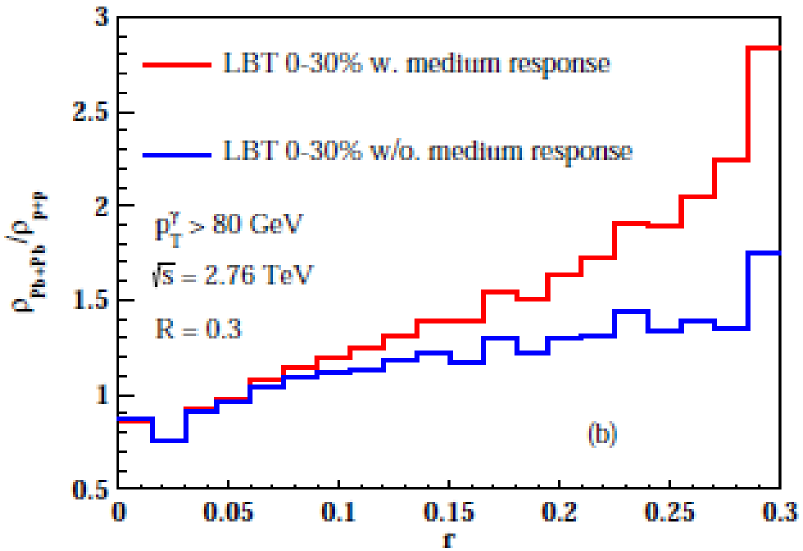


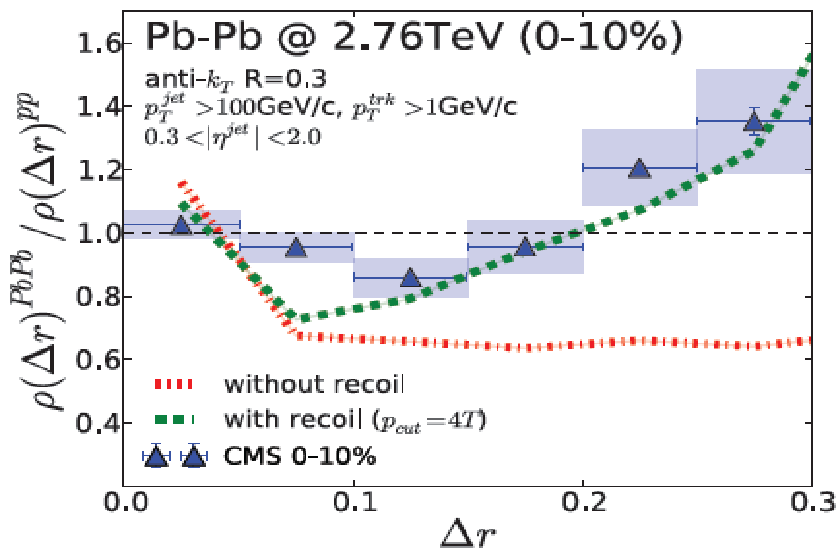
The contribution from the hydro part is quite flat and finally dominates over the shower part in the region from r = 0.4-0.5.

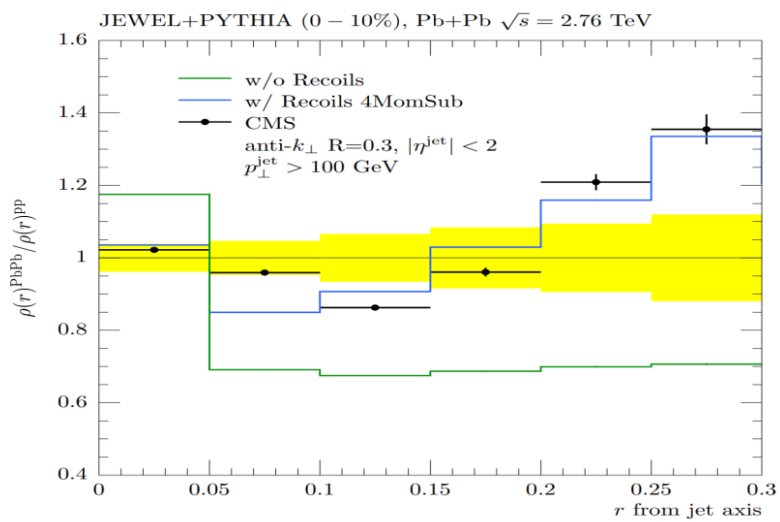
Signal of jet-induced medium excitation in full jet shape at large r.

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

Other similar results on medium response



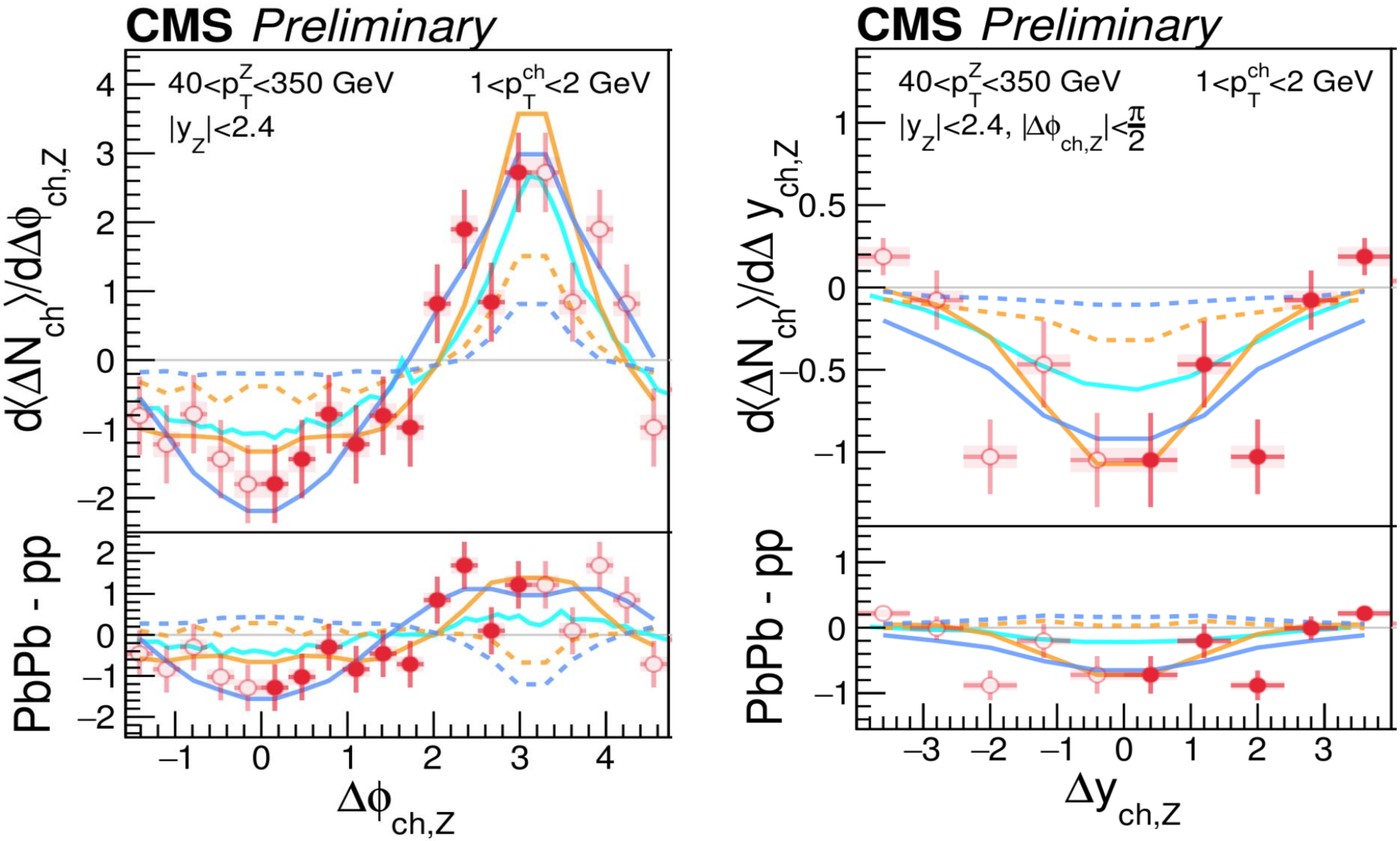




Luo, Cao, He, Wang, PLB 2018;
C. Park, S. Jeon, C. Gale, 2018;
Elayavalli, Zapp, JHEP 2017;

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

Direct evidence of diffusion wake

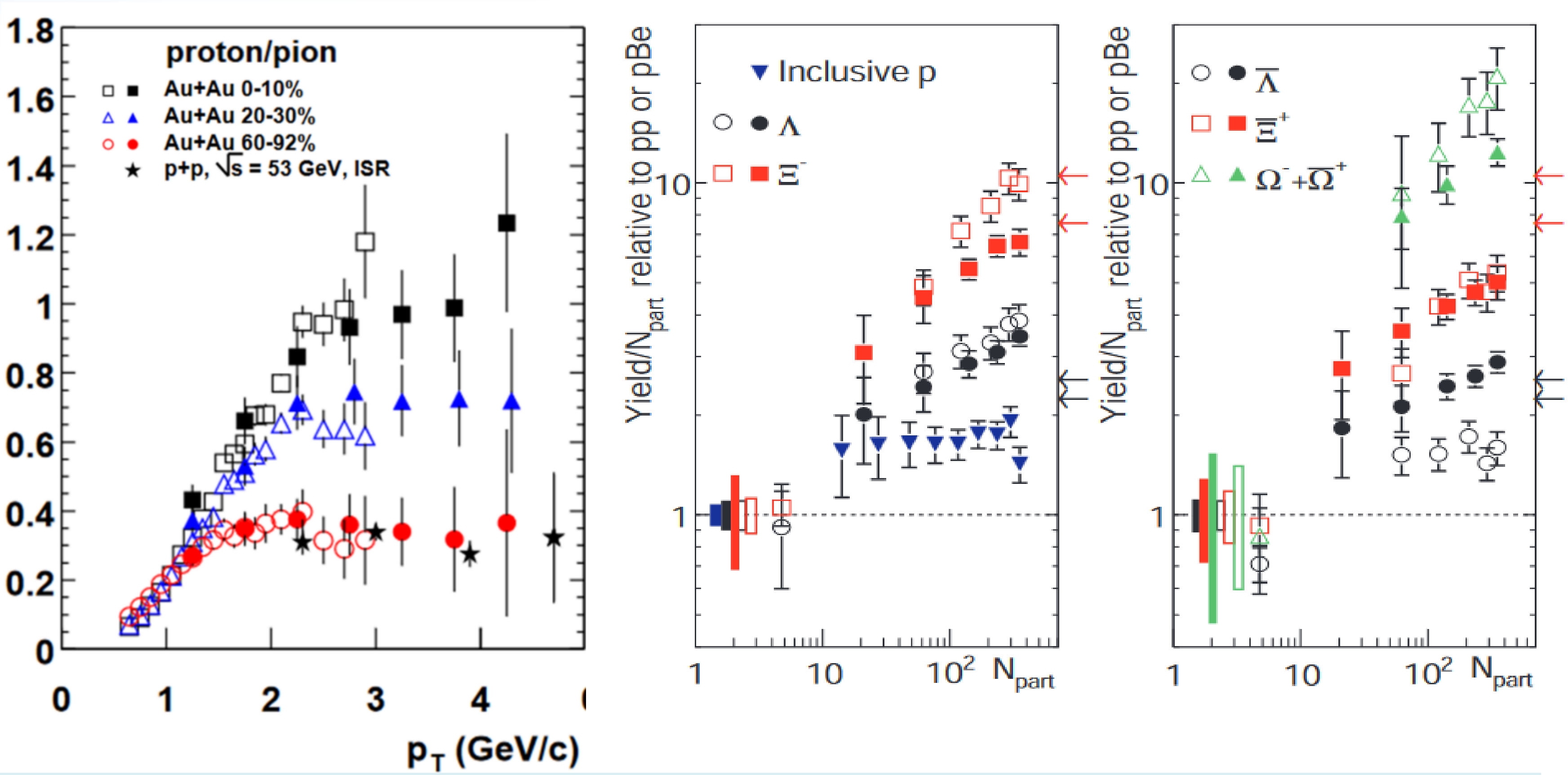


Y.-J. Lee, talk at Hard Probes 2024

How about particle compositions around jets?

- Due to the interaction with the medium, the lost/deposited energy will be (partially) thermalized.
- Hadrons produced from jet-excited energy (& their chemical compositions) should be different from those from vacuum-like energy.
- Jet-induced medium excitation can lead to baryon-to-meson and strangeness enhancement **around** the quenched jets.
- Since the lost energy can flow to **large angles**, we expect that the baryon-to-meson and strangeness enhancement should depend on the distance with respect to the jet axis.

B/M and strangeness enhancement of bulk matter

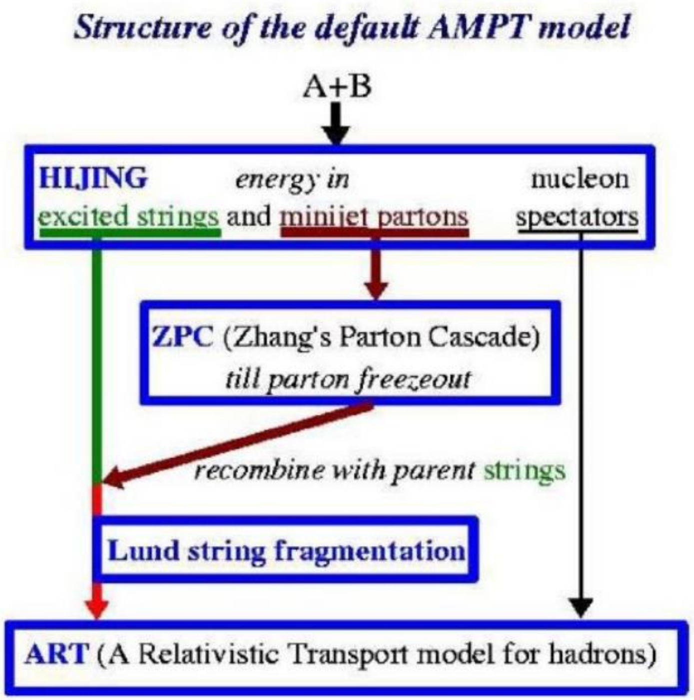


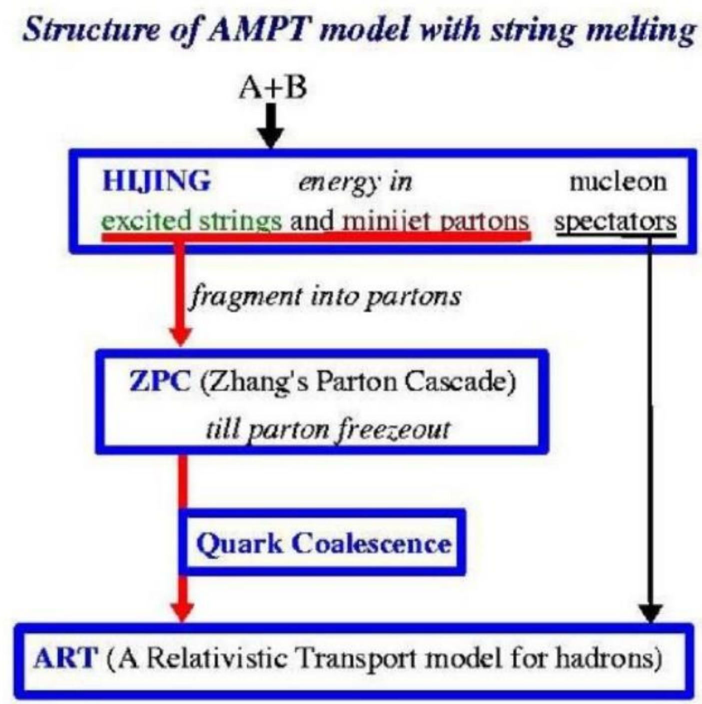
Enhancement of B/M and strangeness production has been regarded as important signatures for the QGP formation.

This work is interested in the pure jet-induced particle production, which requires to subtract the large & fluctuating bulk contribution.

The jet-particle correlation method is utilized.

A Mult-Phase Transport (AMPT) Model

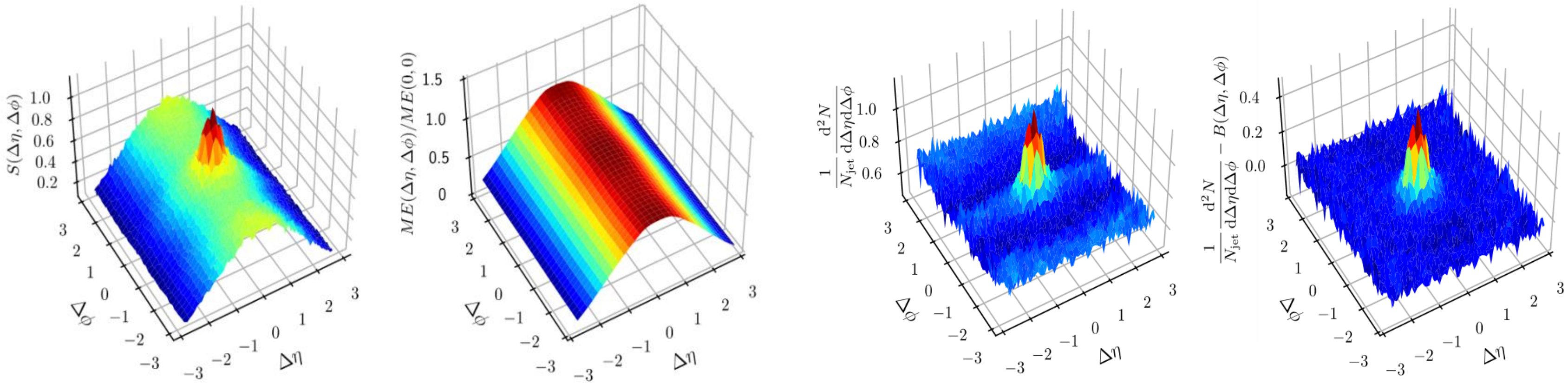




AMPT contains 4 main stages: initial condition, parton cascade, hadronization and hadron cascade.

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



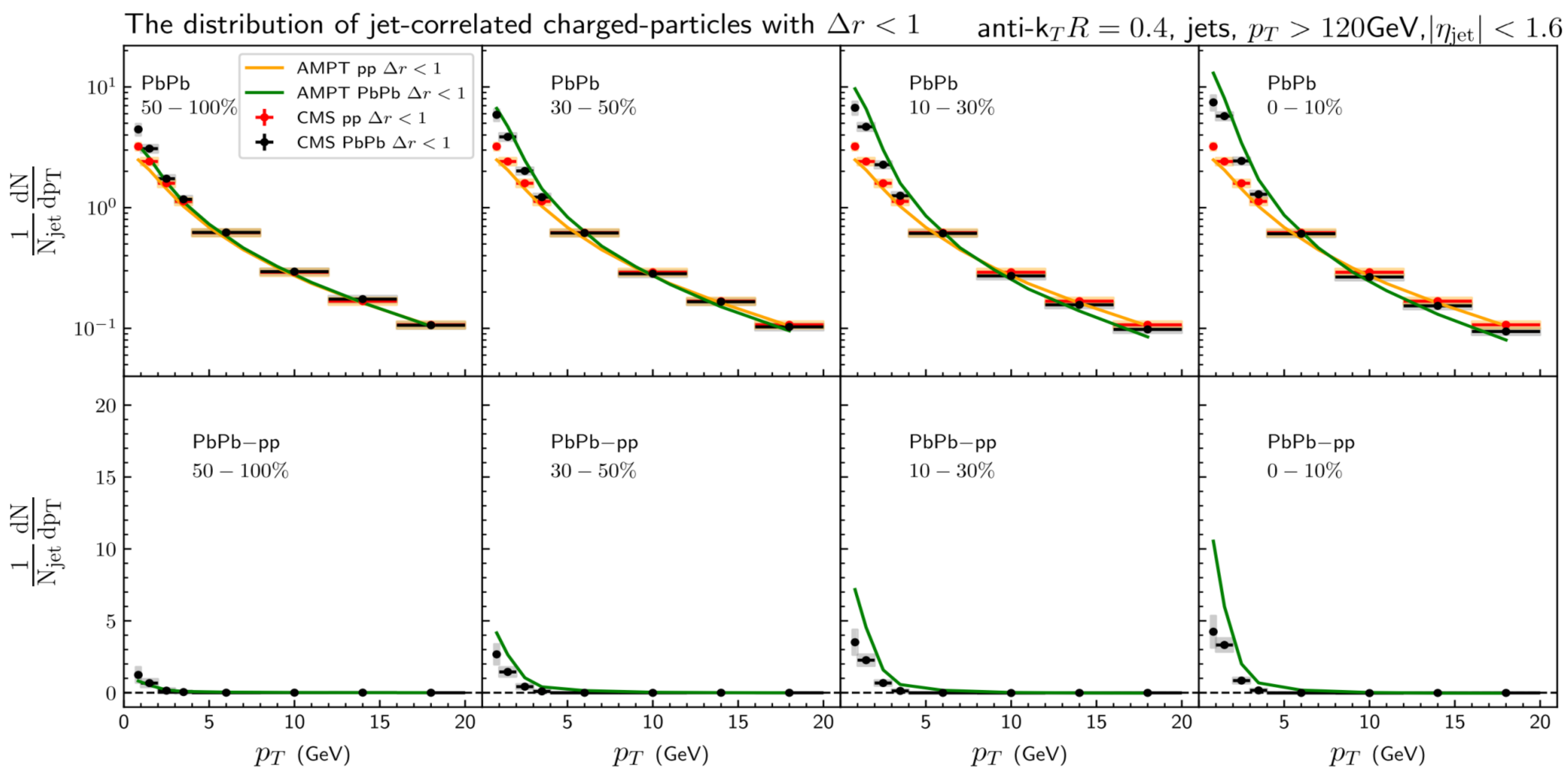
$$\frac{1}{N_{\rm jet}}\frac{d^2N}{d\Delta\eta d\Delta\phi} = \frac{ME(0,0)}{ME(\Delta\eta, \Delta\phi)} S(\Delta\eta, \Delta\phi) \Rightarrow \frac{d^3N}{dp_T d\Delta\phi d\Delta\eta}$$

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

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

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

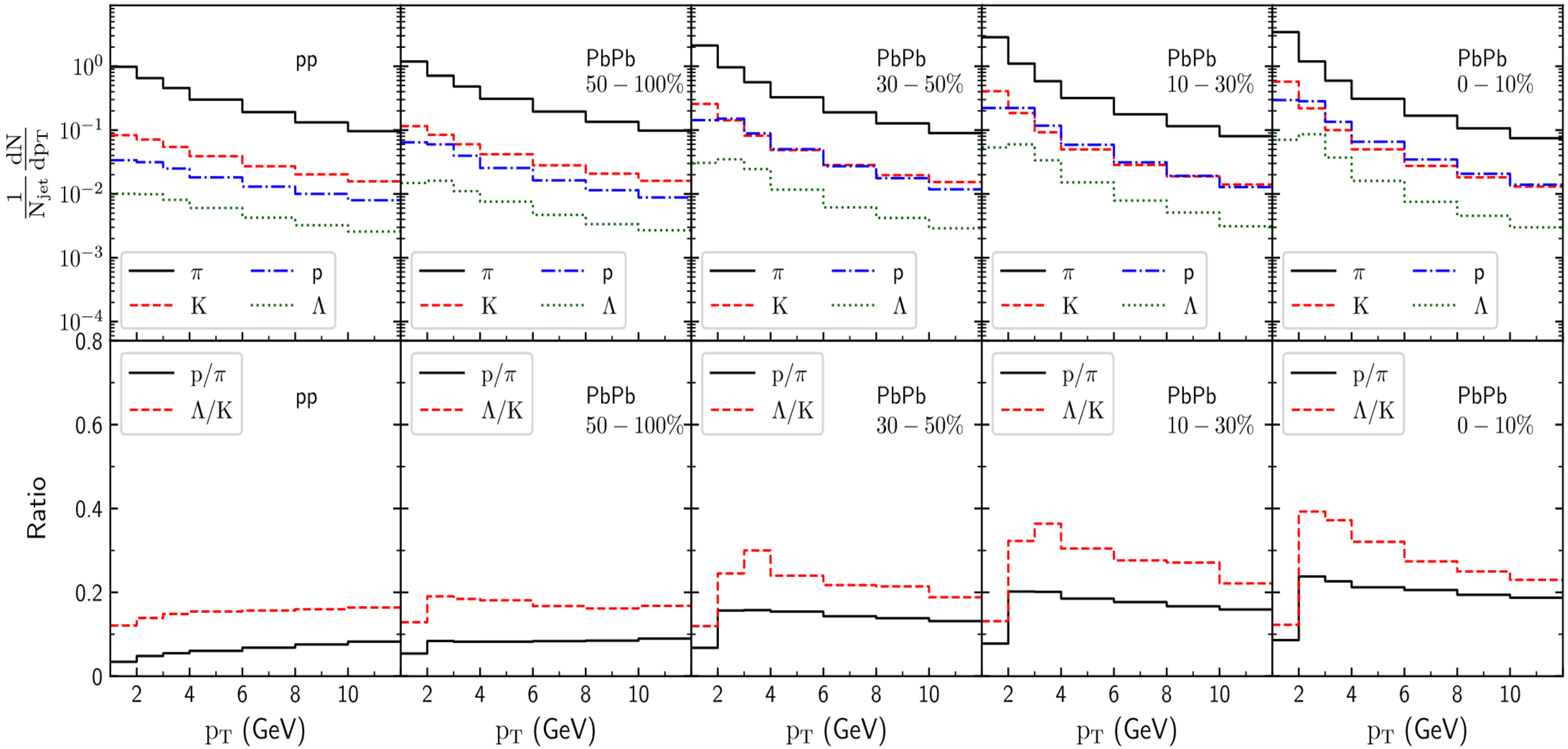
Jet-induced particle yield around jets



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

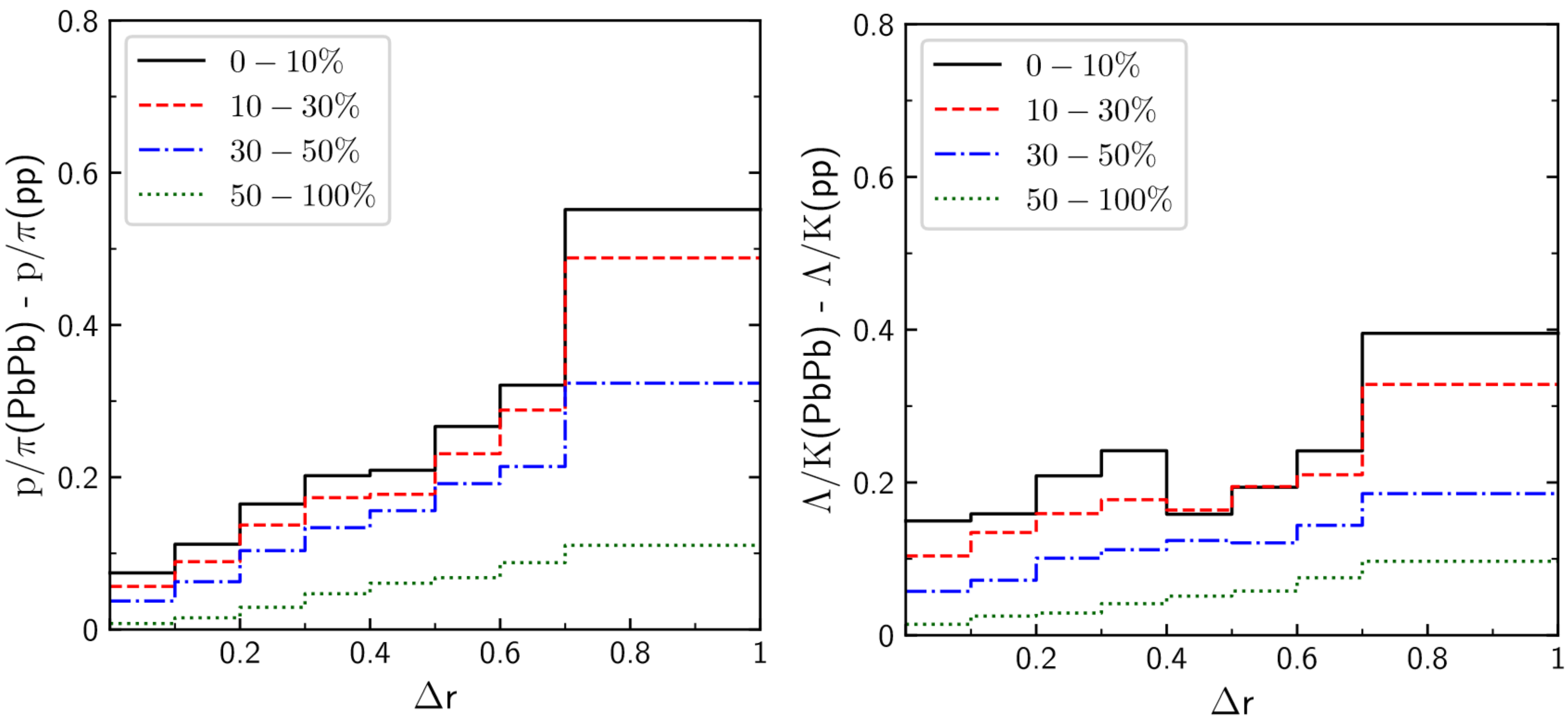
B/M enhancement around jets: p_T dependence



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

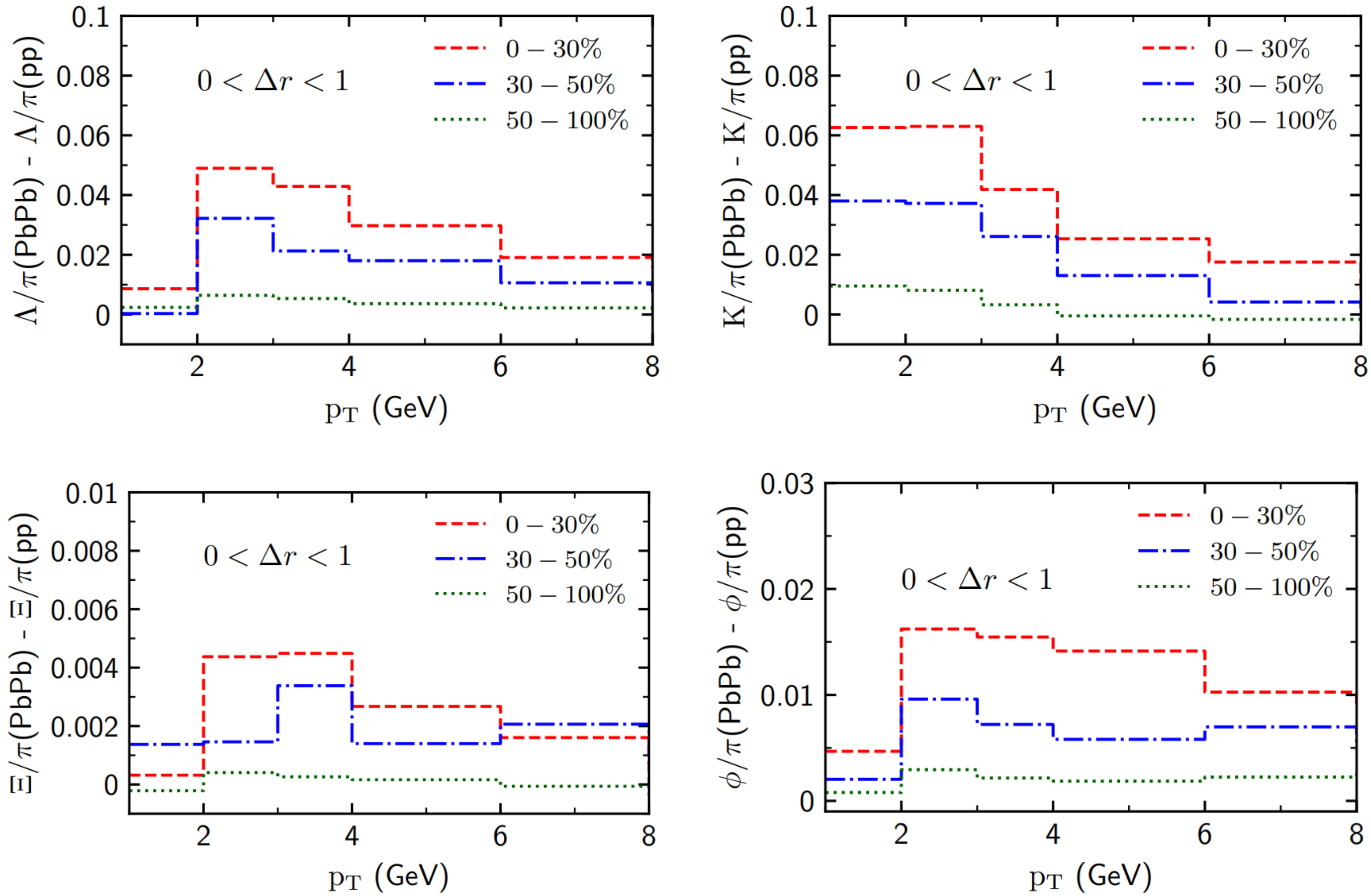
B/M enhancement around jets: radial dependence



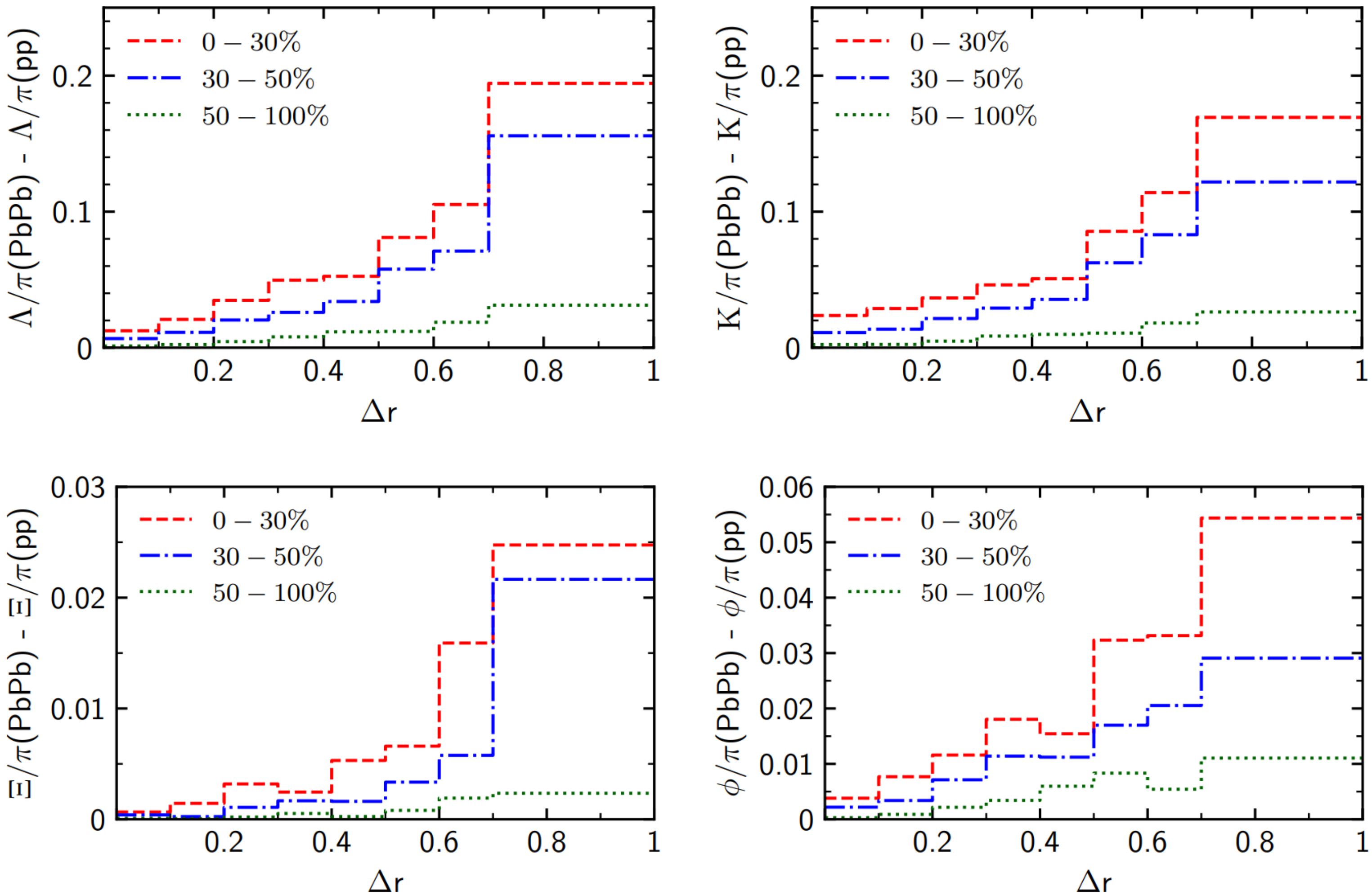
For intermediate p_T (2-6GeV) regime, the enhancement of jet-induced B/M ratios is stronger for larger distance because the lost energy from quenched jets can diffuse to large angle.

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

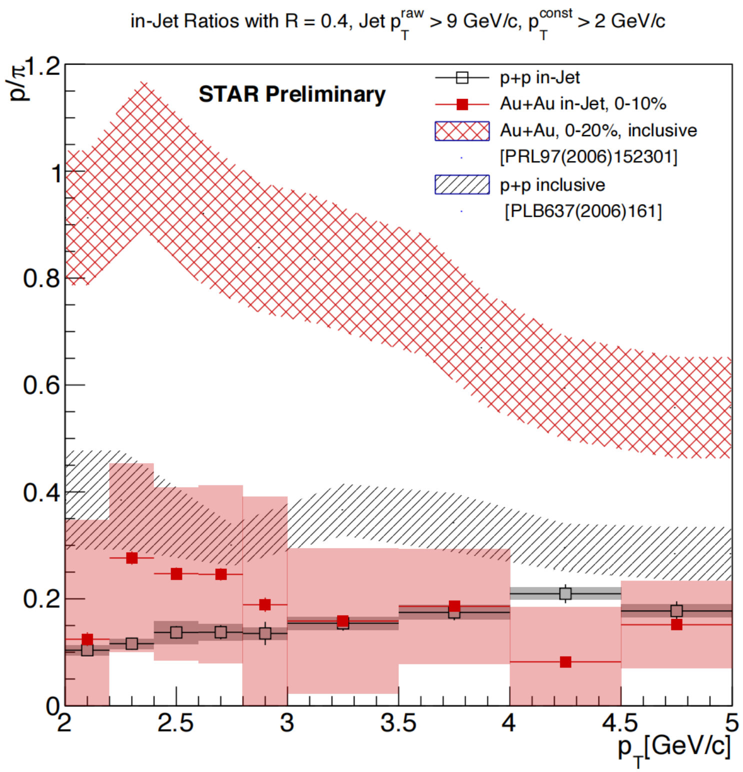
Strangeness enhancement around jet: p_T dependence

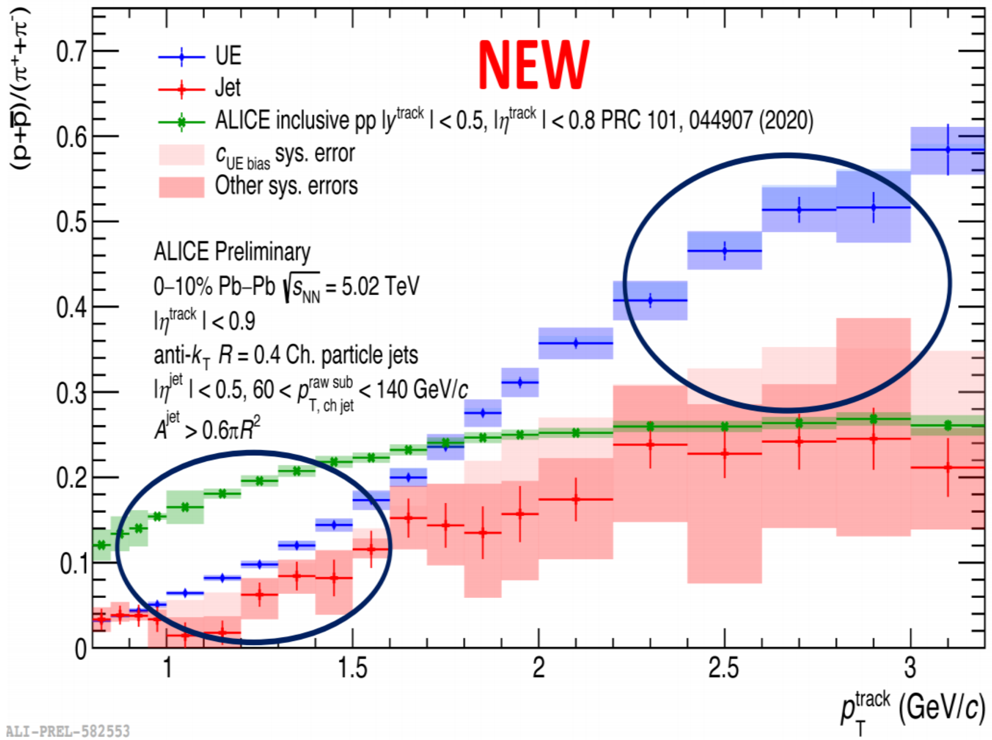


Strangeness enhancement around jet: radial dependence



Experimental result on in-jet B/M

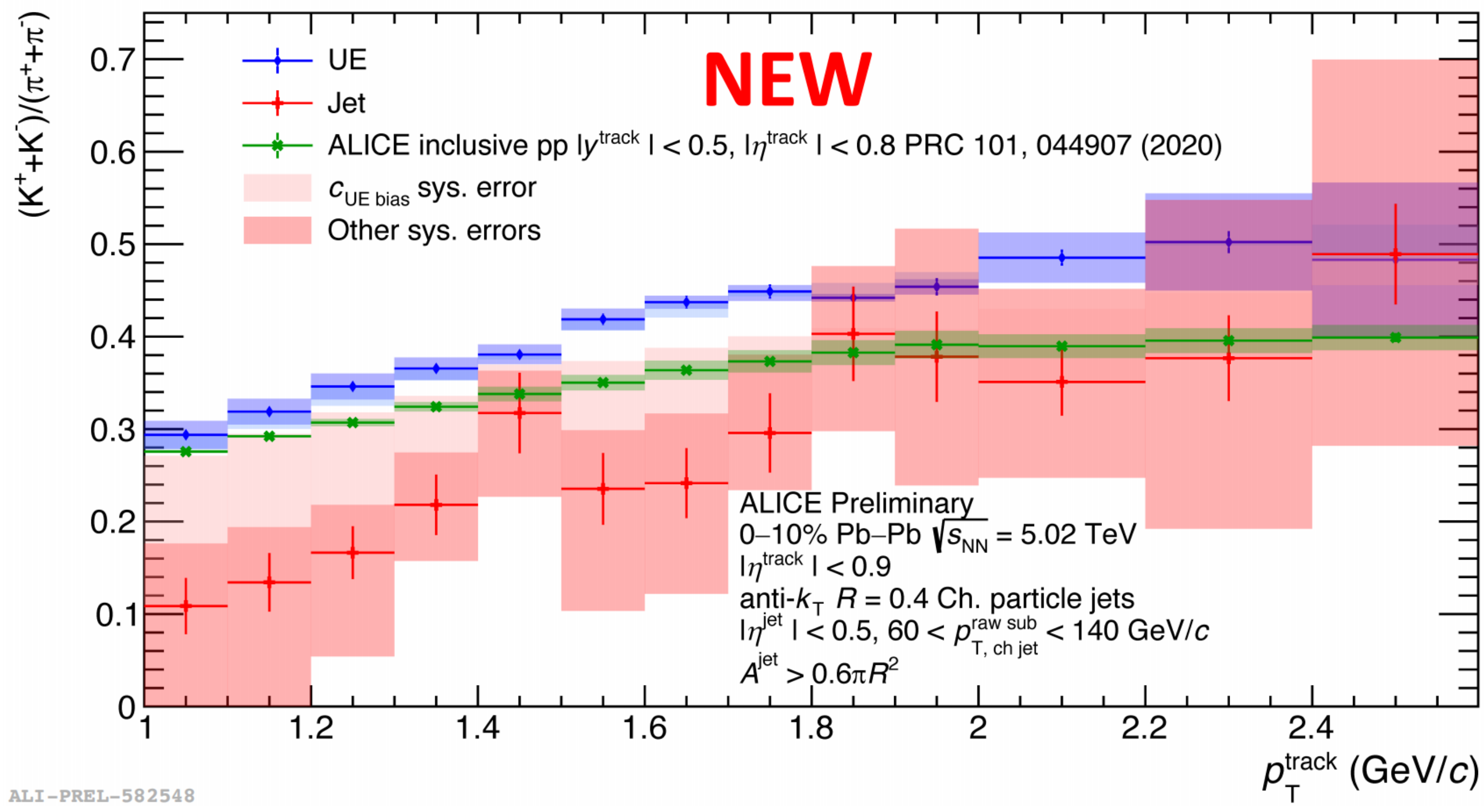




Can we measure hadron chemistry around (outside) the quenched jets?

Gabriel Dale-Gau (for STAR) & Sierra Cantway (for ALICE), talks at Hard Probes 2024

Experimental result on in-jet K/π



Can we measure hadron chemistry around (outside) the quenched jets?

Sierra Cantway (for ALICE), talks at Hard Probes 2024

Summary

- **Medium response is an important aspect of jet quenching.**
- **Energy deposited by quenched jet is carried by soft particles at large angles.**
- **Enhancement of B/M and strangeness production around quenched jets are unique signatures of medium response.**
- **Include more ingredients such as inelastic processes and fragmentation for more precise description/prediction.**
- **Perform calculations using experimental kinematics**
- **Use medium response to probe EOS and transport properties of QGP.**