The 8th Asian Triangle Heavy-Ion Conference

ATHIC2021

5-9 November 2021

Inha University, Incheon, South Korea

Jet-induced medium response in heavy-ion collisions

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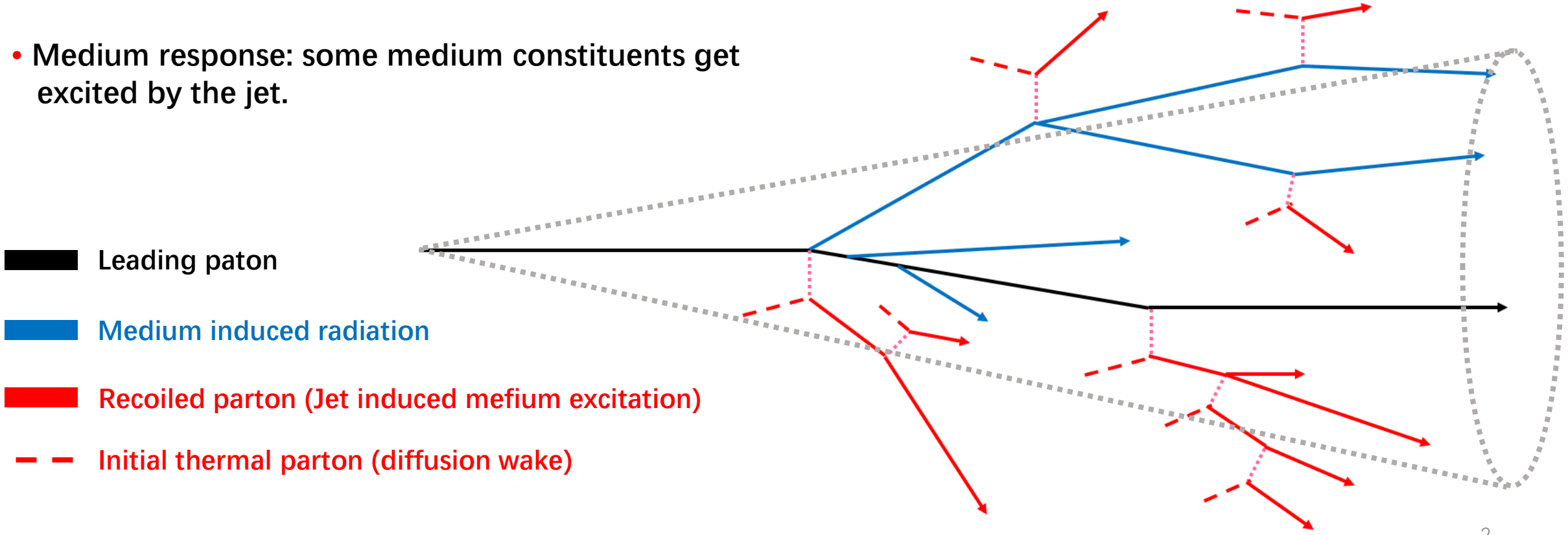
Jet propagation in the QGP medium

Jet-medium interaction

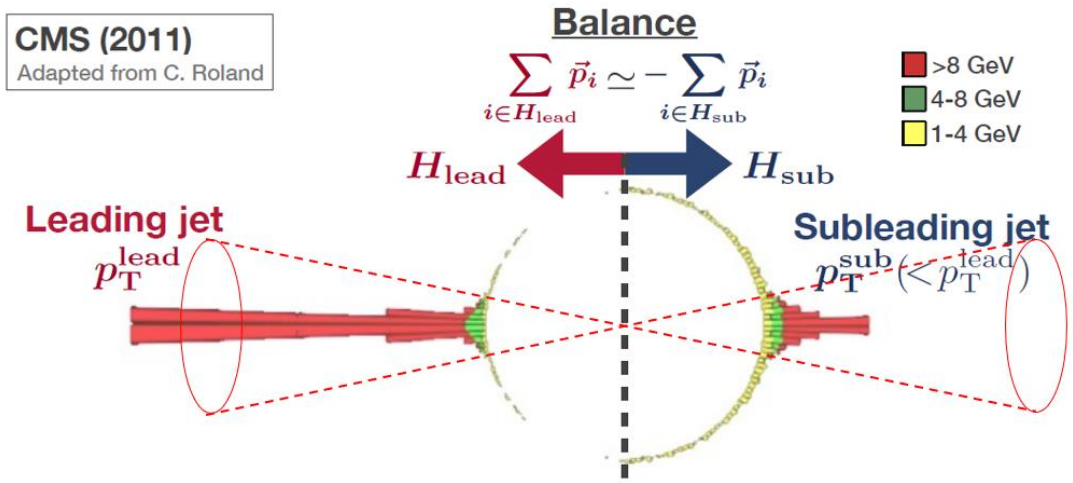
- Jet energy loss: Energy propagated outside the jet cone. (Different from parton energy loss)

- Medium response: some medium constituents get excited by the jet.



Where does the lost energy go ?

- The energy and momentum deposited by the jet shower into the medium appear at large angles away from the jet axis.



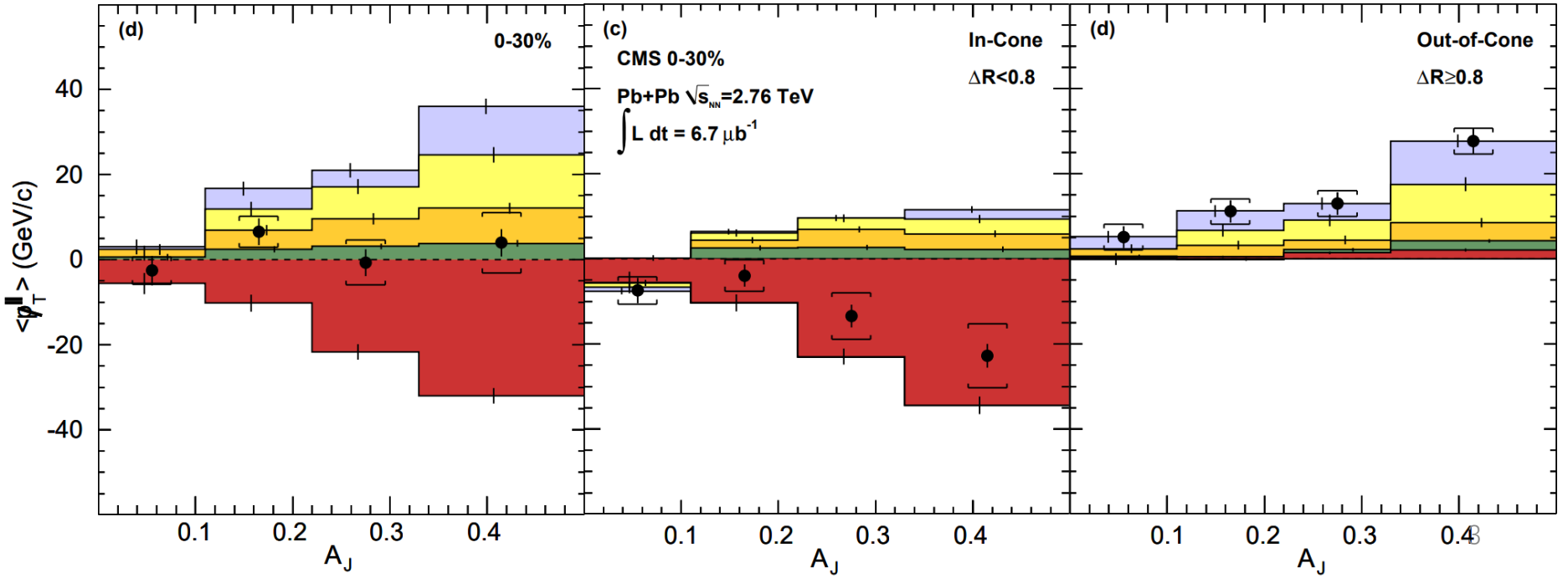
$p_{T,1}$ > 120GeV/c

$p_{T,2}$ > 50GeV/c

$\Delta\phi_{1,2} > \frac{2}{3}\pi$ $|\eta_{1,2}| < 1.6$

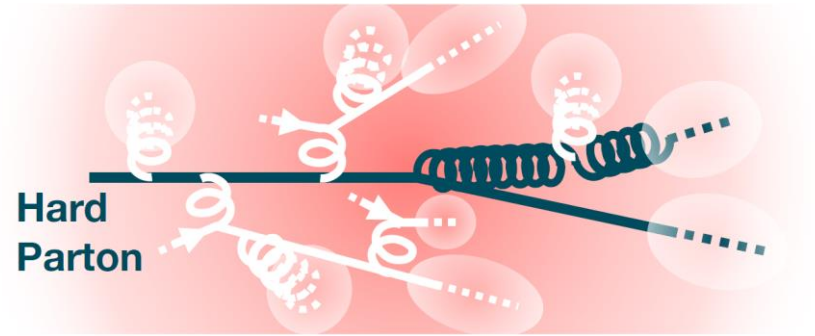
- > 0.5 GeV/c
- 0.5 - 1.0 GeV/c
- 1.0 - 2.0 GeV/c
- 2.0 - 4.0 GeV/c
- 4.0 - 8.0 GeV/c
- > 8.0 GeV/c

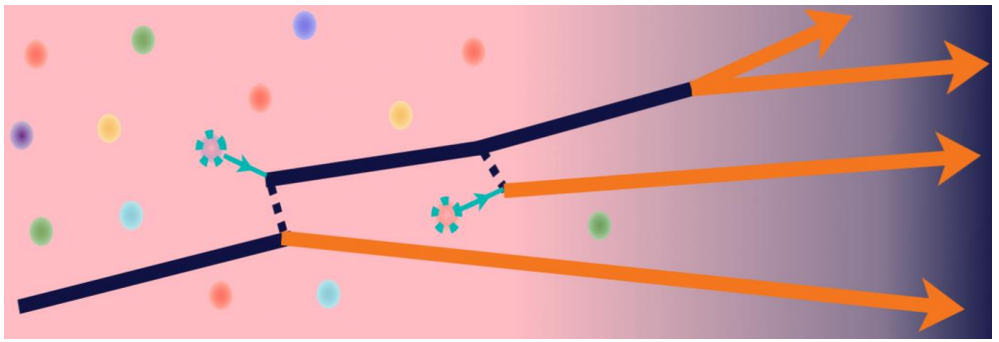
PYTHIA+HYDJET



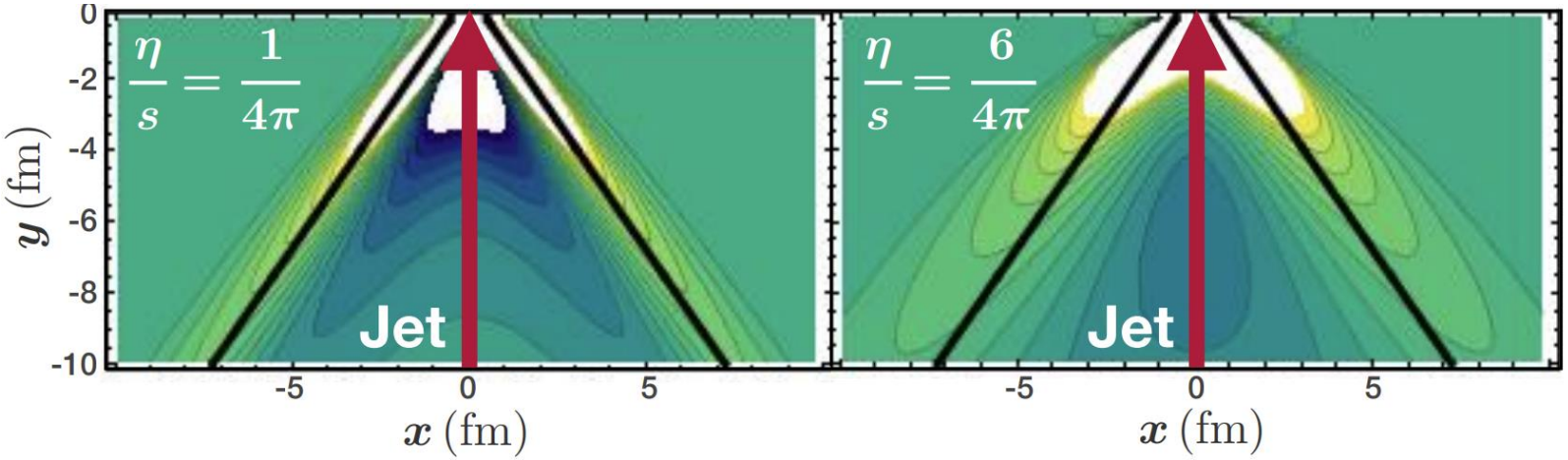
Thermalization & Propagation

- Thermalization : How does the deposited energy thermalize?
- Propagation: How does the deposited energy propagate?





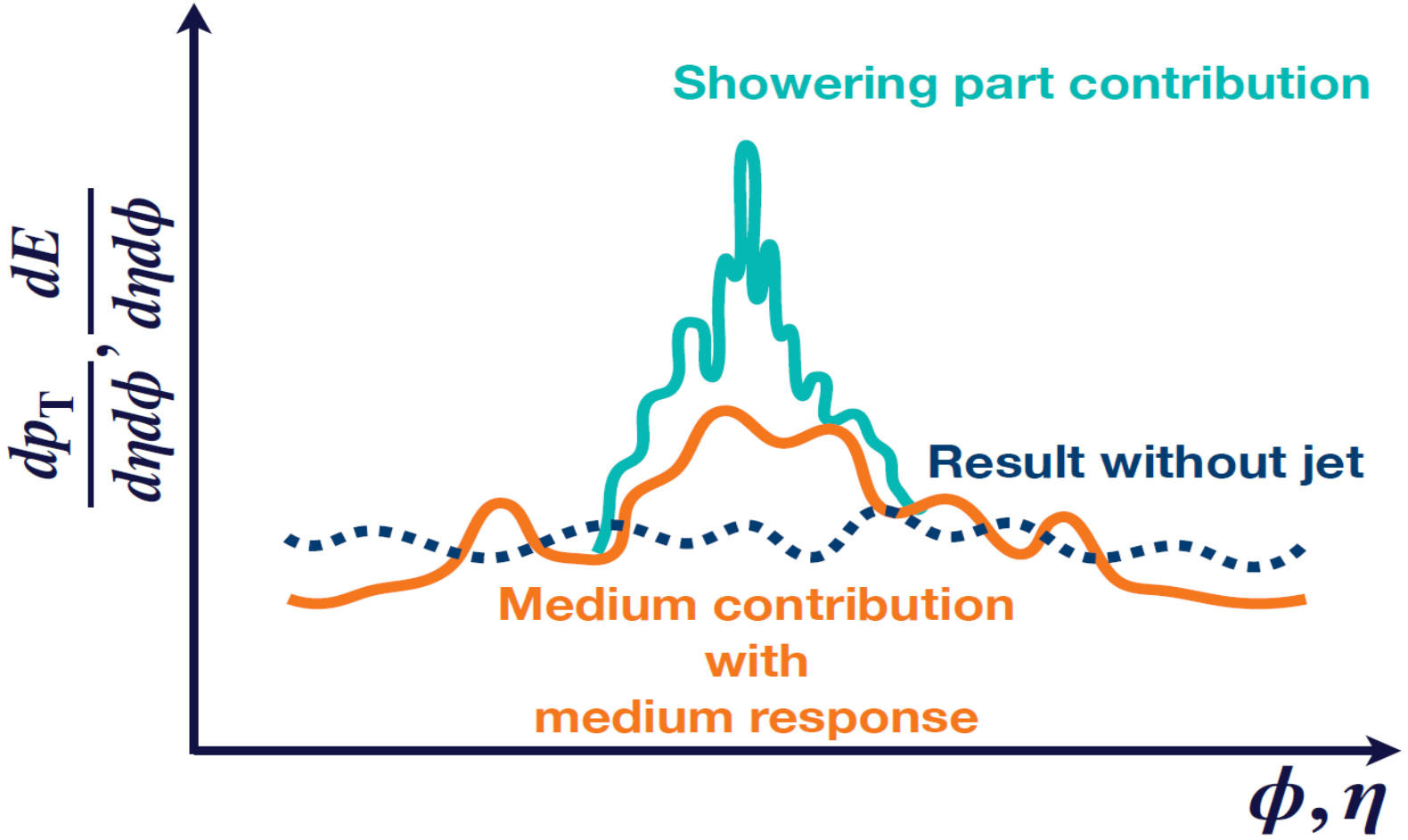
- The structure of medium response and fluid properties.



R. B. Neufeld, PRC79, 054909 (2009)

Background

- What are in the background of a reconstructed jet?
- Part of the medium background is correlated with jet (inside and outside the jet cone).



Jet quenching models with medium response

- JEWEL [BDMPS-Z] : recoiled partons transported. (modified parton shower)
- LBT [HT] : recoiled partons transported. (shower + transport)
- MARTINI [AMY] : recoiled partons transported. (shower + transport)

Recoil-medium rescattering

- CoLBT-hydro [HT] : Transport + Hydro parallel simulation. (shower + transport)
- Hybrid [AdS/CFT] : fully thermalized wake. (modified parton shower)
- Coupled Jet-Fluid [HT] : solve Boltzmann equation + Hydro simulation
- EPOS3-HQ : YaJEM + Hydro parallel simulation. (modified parton shower)

Energy momentum deposition into Hydro

Jet quenching models with medium response

modified parton shower + transport

JETSCAPE
- Matter [HT] + LBT [HT] : recoiled partons transported.
- Matter [HT] + MARTINI [AMY] : recoiled partons transported.
- Matter [HT] + ADS/CFT: Hydro simulation.

Recoil-medium rescattering

Energy momentum deposition into Hydro

- AMPT
- BAMPS

Particle scattering for both medium and jet

- Linearized viscous hydrodynamics with source

A Linear Boltzmann Transport (LBT) Model

Parton shower

Pythia Sherpa

Jet propagation

$$p_1 \cdot \partial f_1(x_1, p_1) = E_1\left(C_{elastic} + C_{inelastic}\right)$$

- **Rescattering**
  Shower-thermal & recoil-thermal
- **Back reaction**
  Track the initial thermal parton

Fragmentation Recombination

LBT
Hard

Local medium information ε T $\boldsymbol{u}$

?

No feed back

Initial profile

AMPT TRENTO

Medium evolution

$$\partial_\mu T^{\mu\nu} = 0$$

Cooper Frye

CLvisc
Soft

Hadronic observables

A coupled LBT Hydro (CoLBT-hydro) Model

Parton shower

Pythia Sherpa

Jet propagation

$$p_1 \cdot \partial f_1(x_1, p_1) = E_1\left(C_{elastic} + C_{inelastic}\right)$$

- **Rescattering**

  Shower-thermal & recoil-thermal

  Parton above Pcut

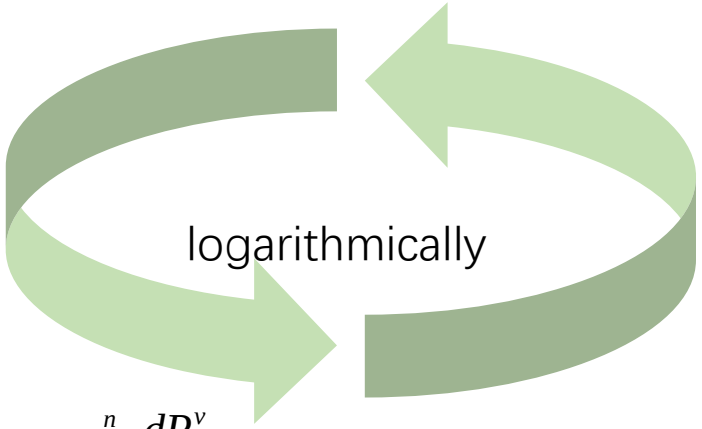
Fragmentation Recombination

LBT

Hard

Real time feed back

Local medium information ε T $\boldsymbol{u}$



$$j^{\nu} = \sum_{i=1}^{n} \frac{dP_i^{\nu}}{d\tau} \delta^3(\overrightarrow{X} - \overrightarrow{X_i}) \theta(P_{\text{cut}}^0 - P_i \cdot u)$$

Hadronic observables

Initial profile

AMPT TRENTO

Medium evolution

$$\partial_\mu T^{\mu\nu} = j^{\nu}$$

- **Source term**

  Parton below Pcut

- **Negative source**

  Initial thermal parton

Cooper Frye

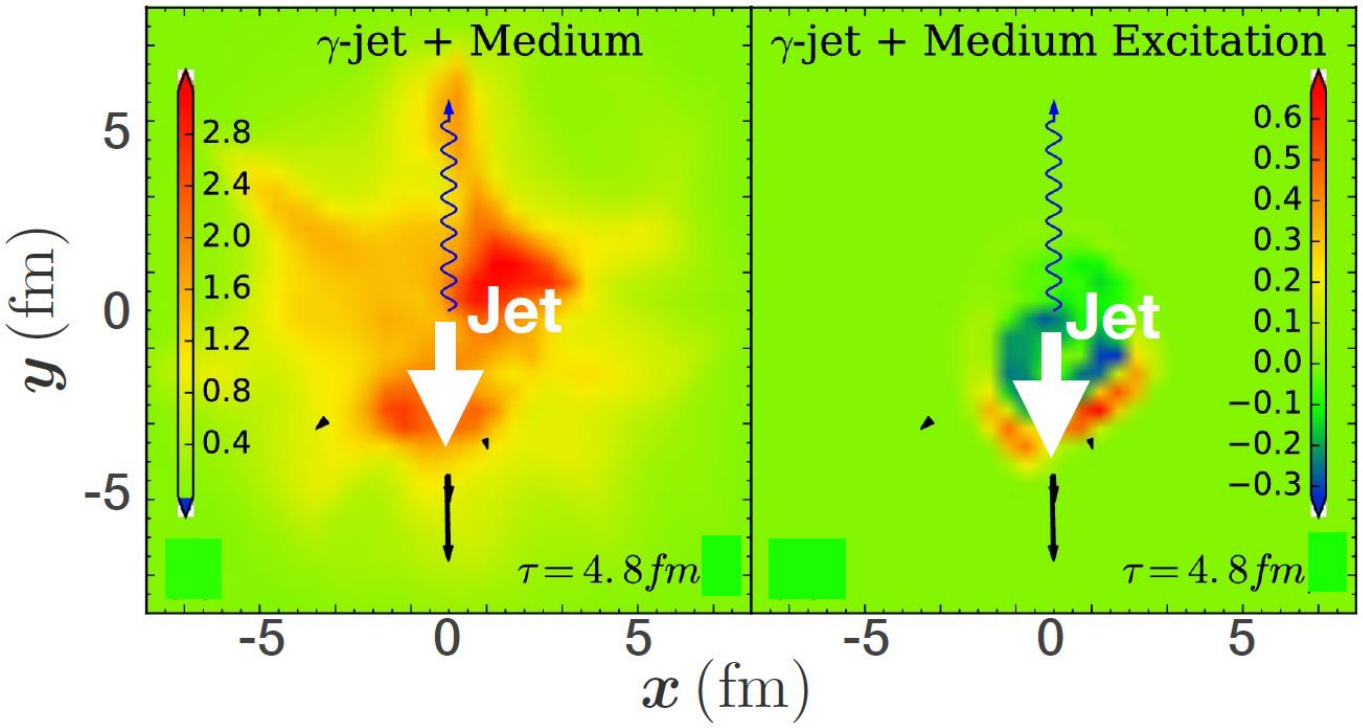
CLvisc

Soft

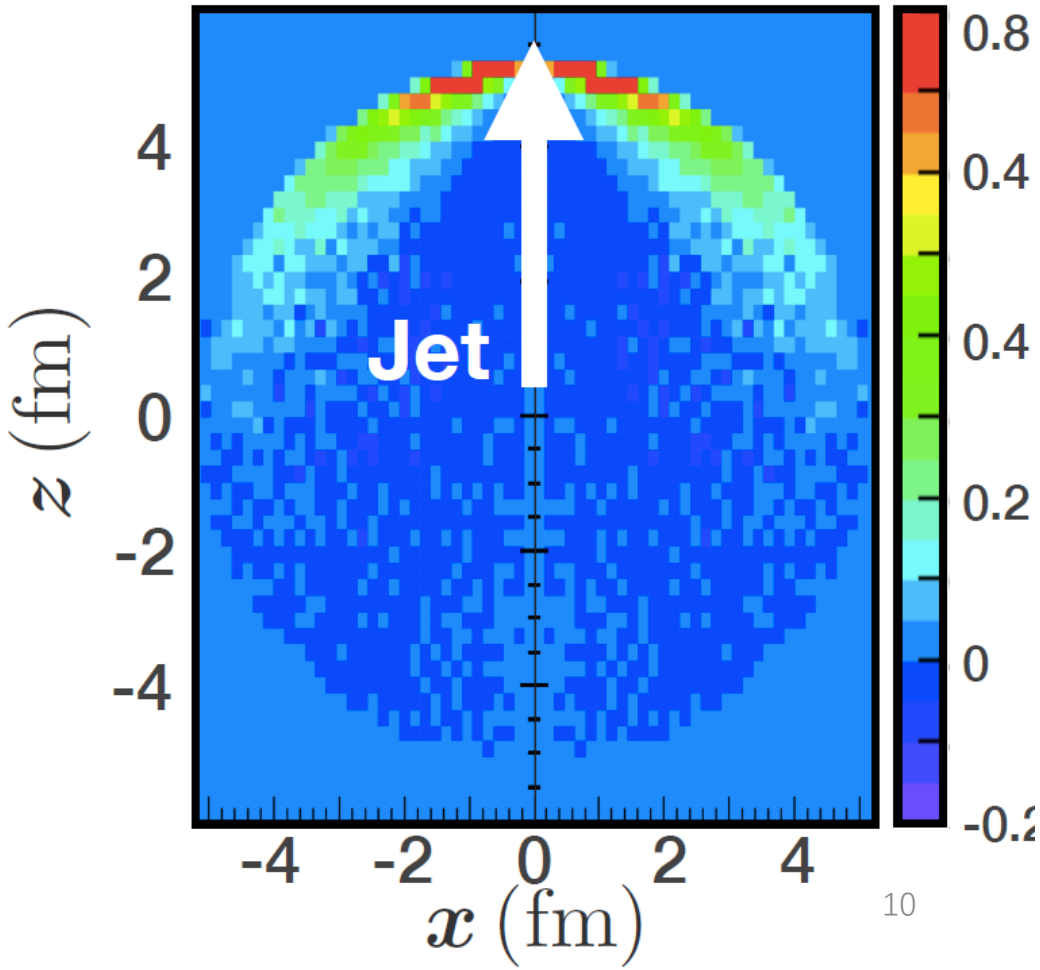
Jet induced medium response

- **Structure of medium response**
  Hydro : Mach cone as hydro response. Transport : Mach cone like structure.
- **Diffusion wake** Unique structure of medium response

CoLBT-hydro Chen et al, Phys.Lett. B777 86-90



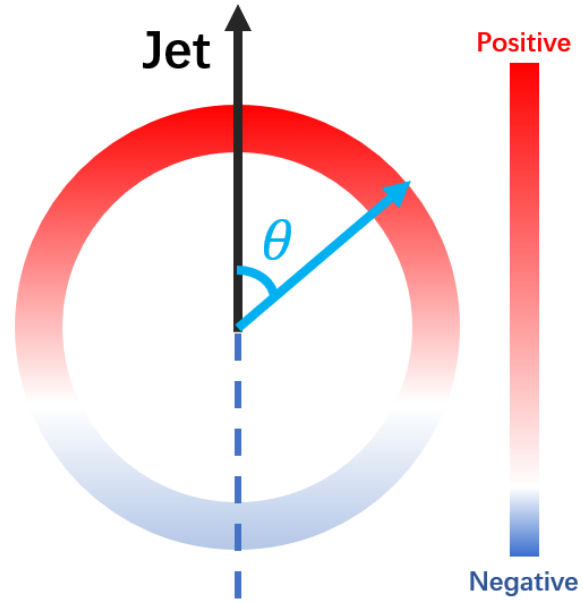
LBT PRC 91, 054908 (2015)

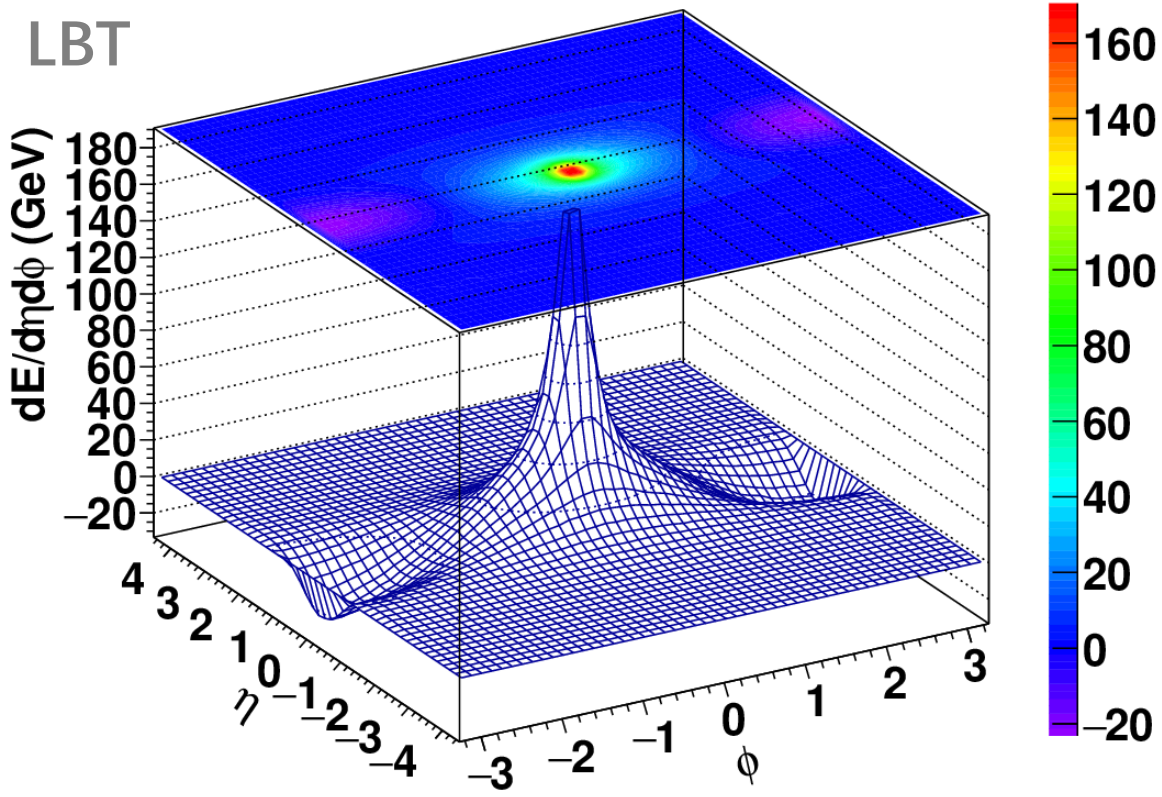


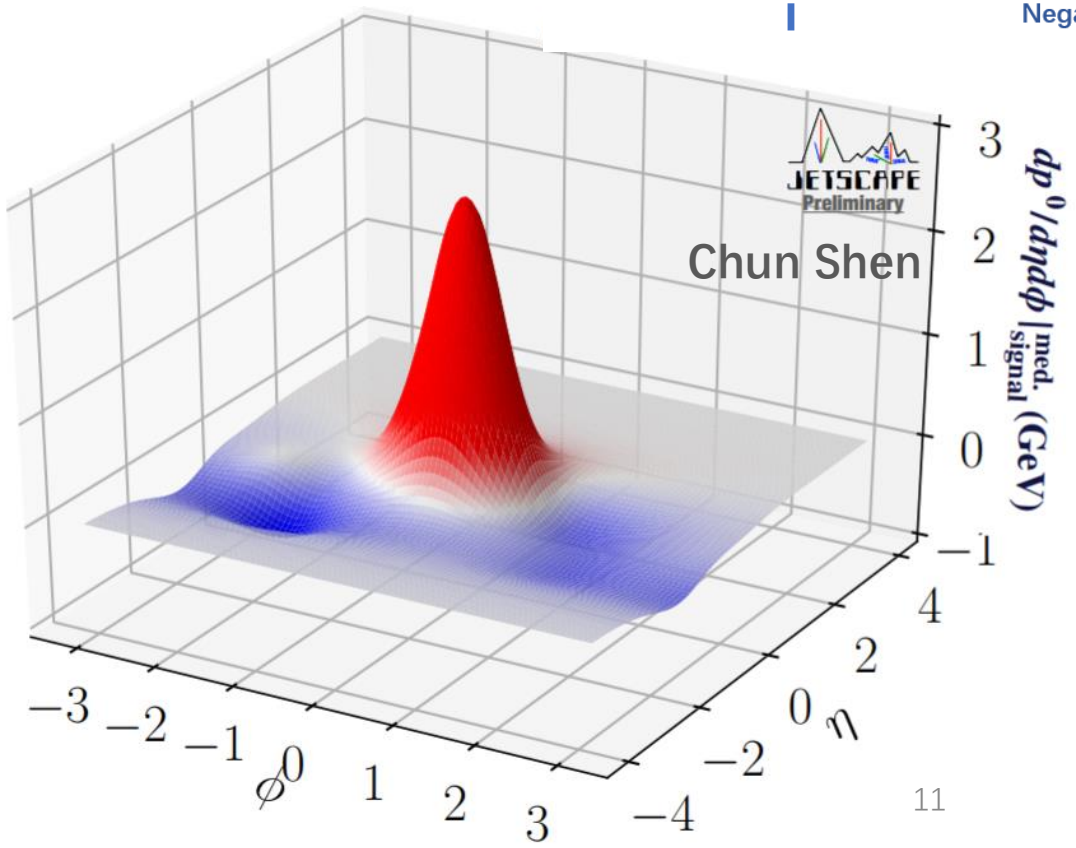
Jet induced medium response

- Structure of medium response in η-φ plane.
- A naive picture of jet induced medium response.

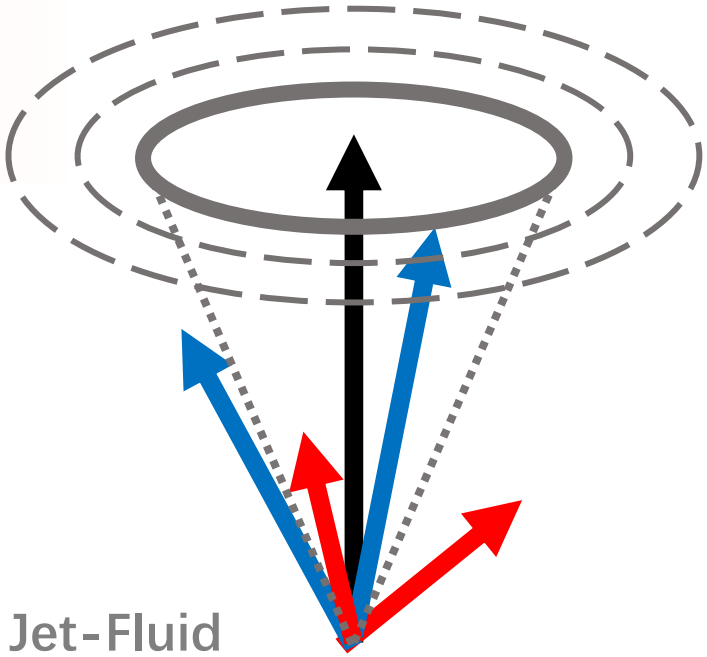
Energy propagated to large open angle and a negative wake in the back direction.







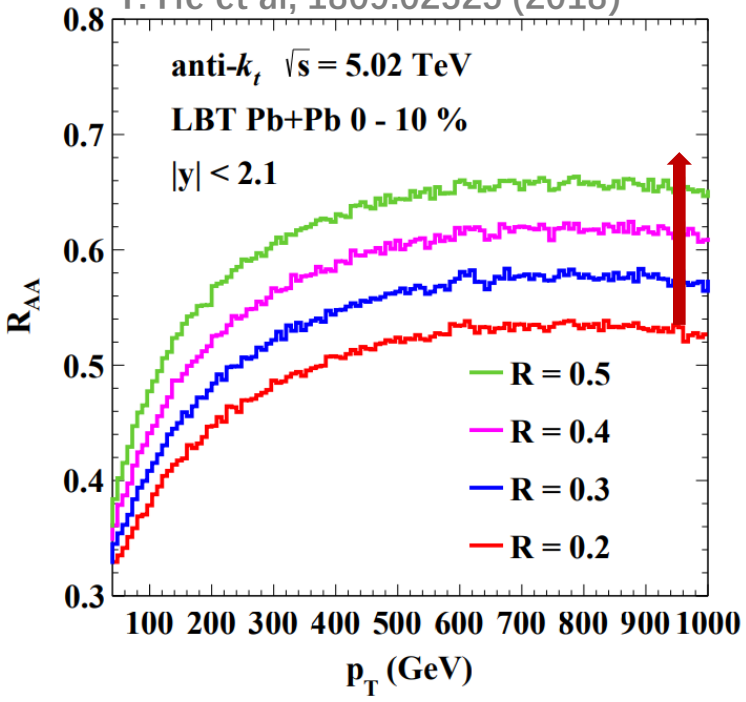
Angular structure (Single jet suppression)



- The cone size dependence is quantitatively depended on jet energy loss.
- Energy recovered at large angle via the inclusion of medium response.

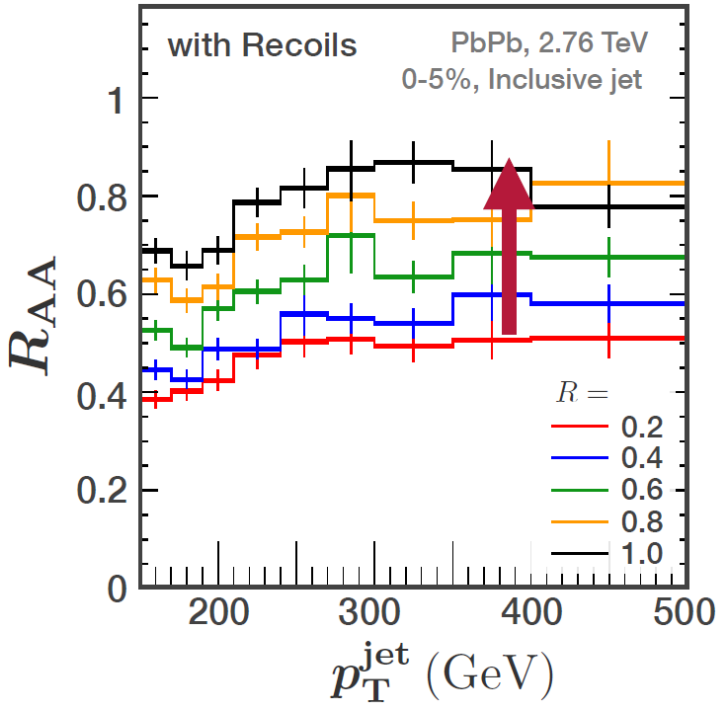
LBT

Y. He et al, 1809.02525 (2018)



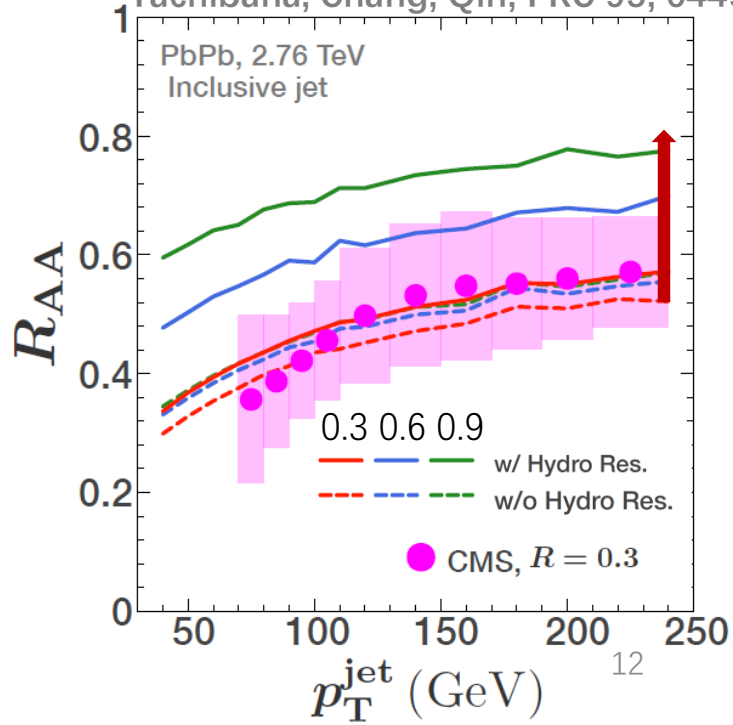
JEWEL

R. K. Elayavalli, K. C. Zapp, JHEP 1707, 141

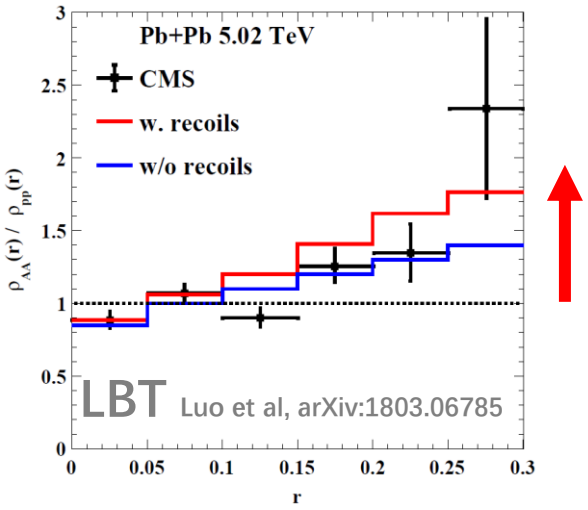


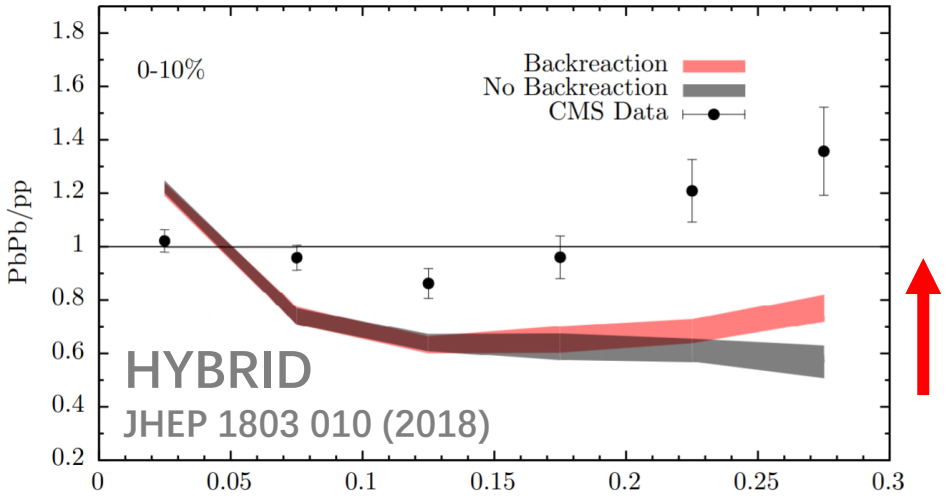
Jet-Fluid

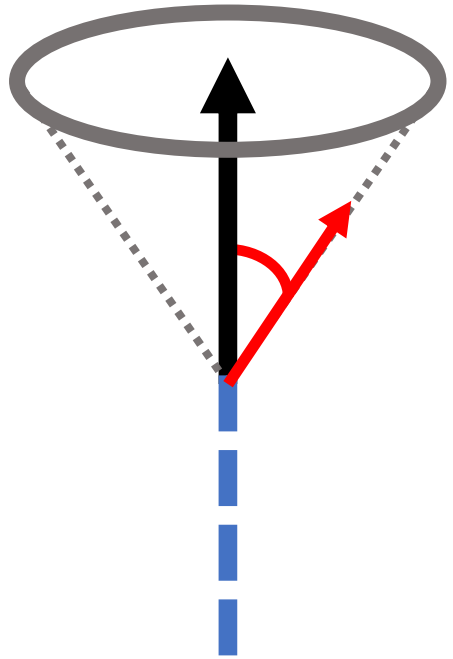
Tachibana, Chang, Qin, PRC 95, 044909



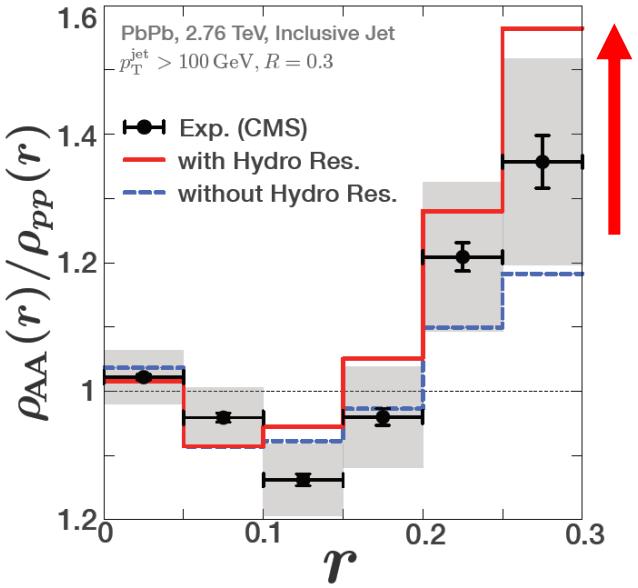
Angular structure (Jet shape)



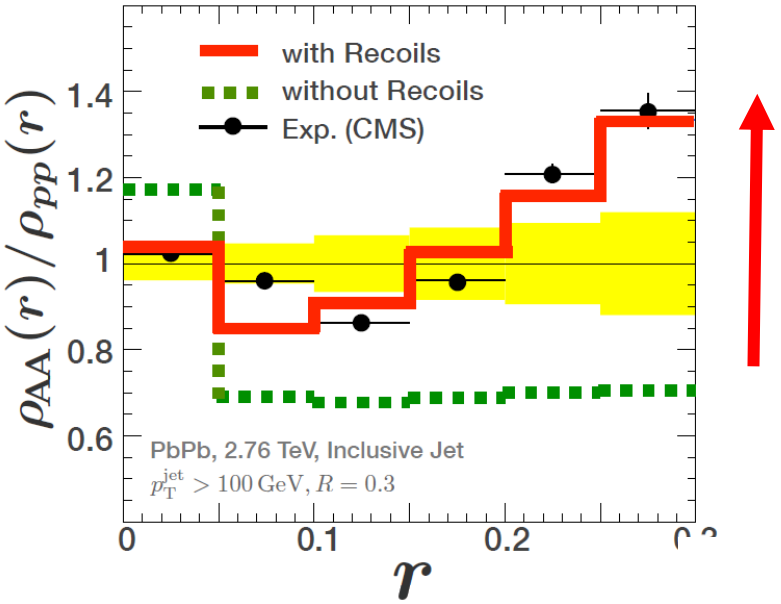




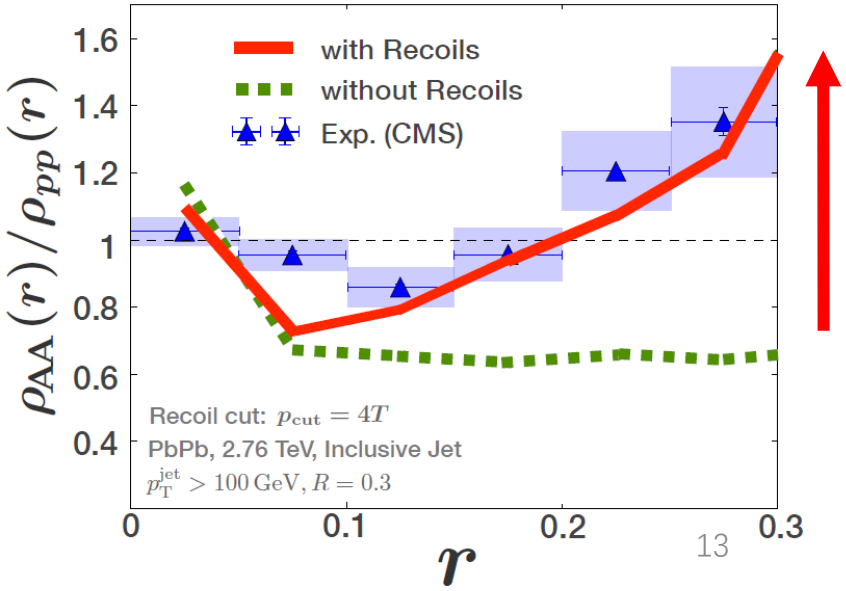
Jet-Fluid Tachibana, Chang, Qin, PRC 95, 044909



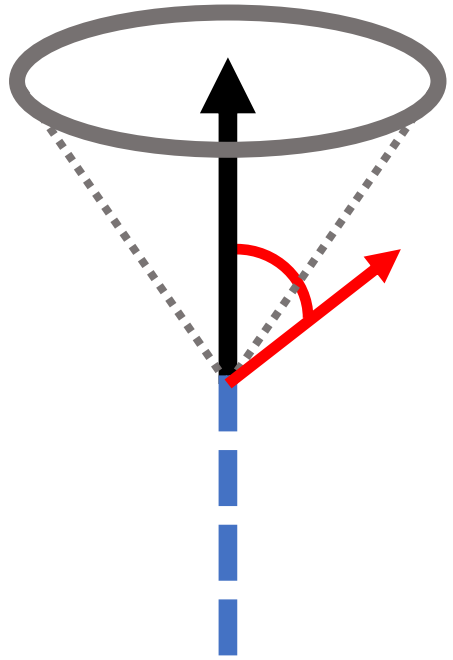
JEWEL R. K. Elayavalli, K. C. Zapp, JHEP 1707, 141



MARTINI C. Park, S. Jeon, C. Gale ('18)



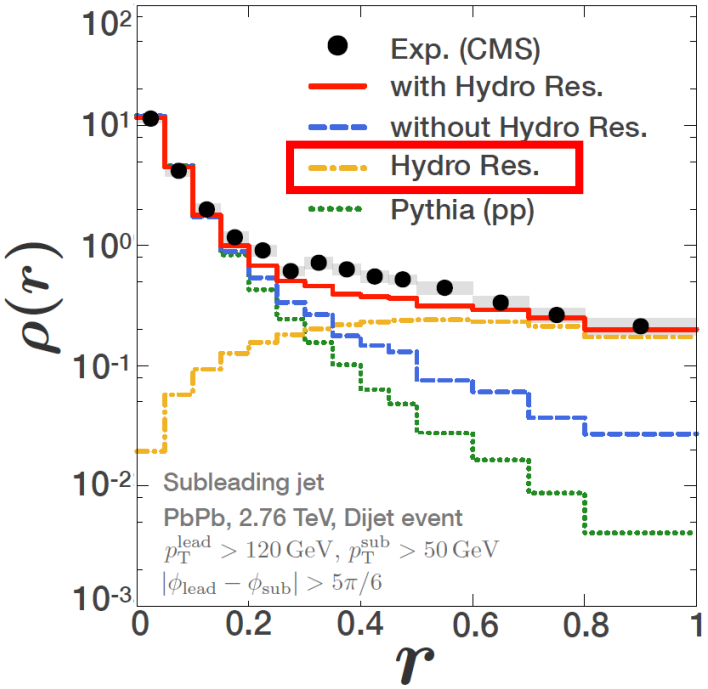
Angular structure (Jet shape)



- Energy lost by the hard parton is transported out of the jet cone by soft particles.
- Medium response to jet generally lead to enhancement at large angle.

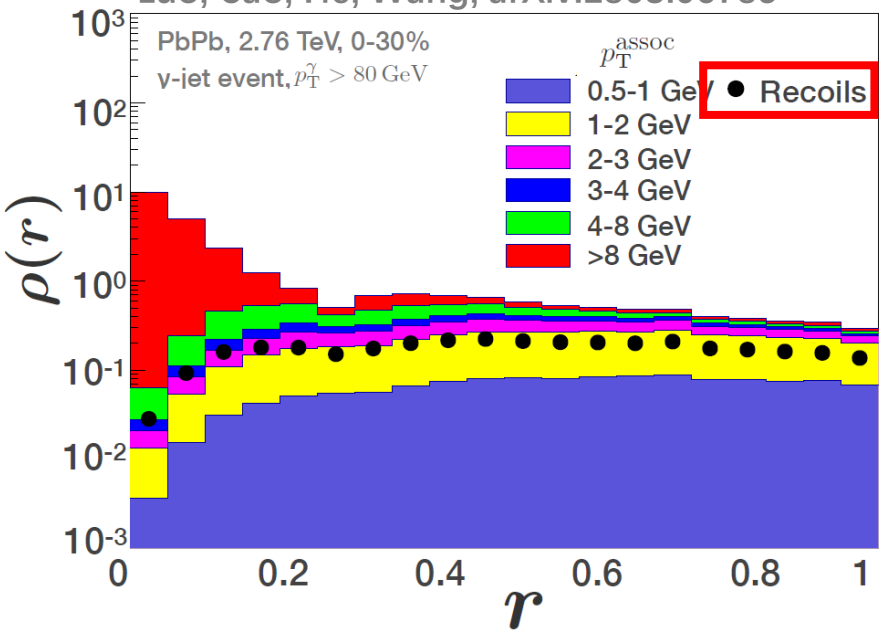
Jet-Fluid

Tachibana, Chang, Qin, PRC 95, 044909



LBT

Luo, Cao, He, Wang, arXiv:1803.06785



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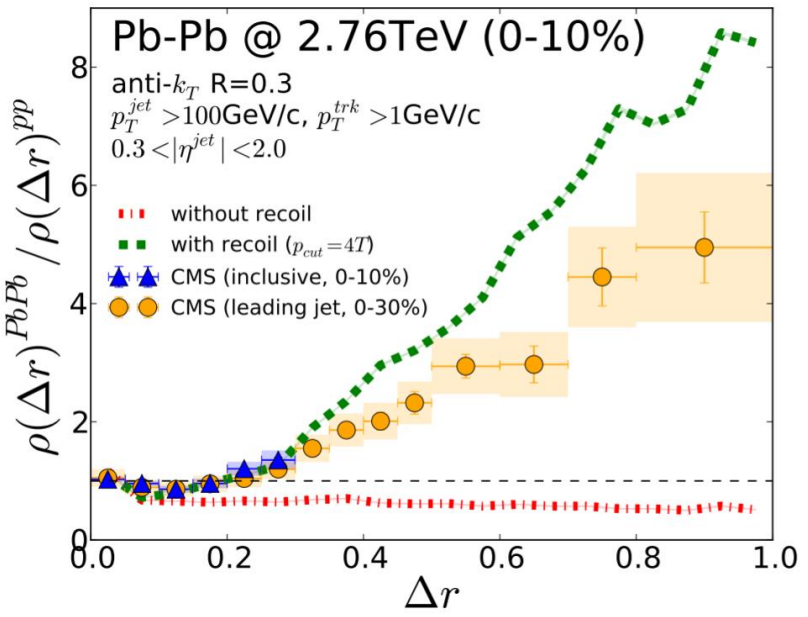
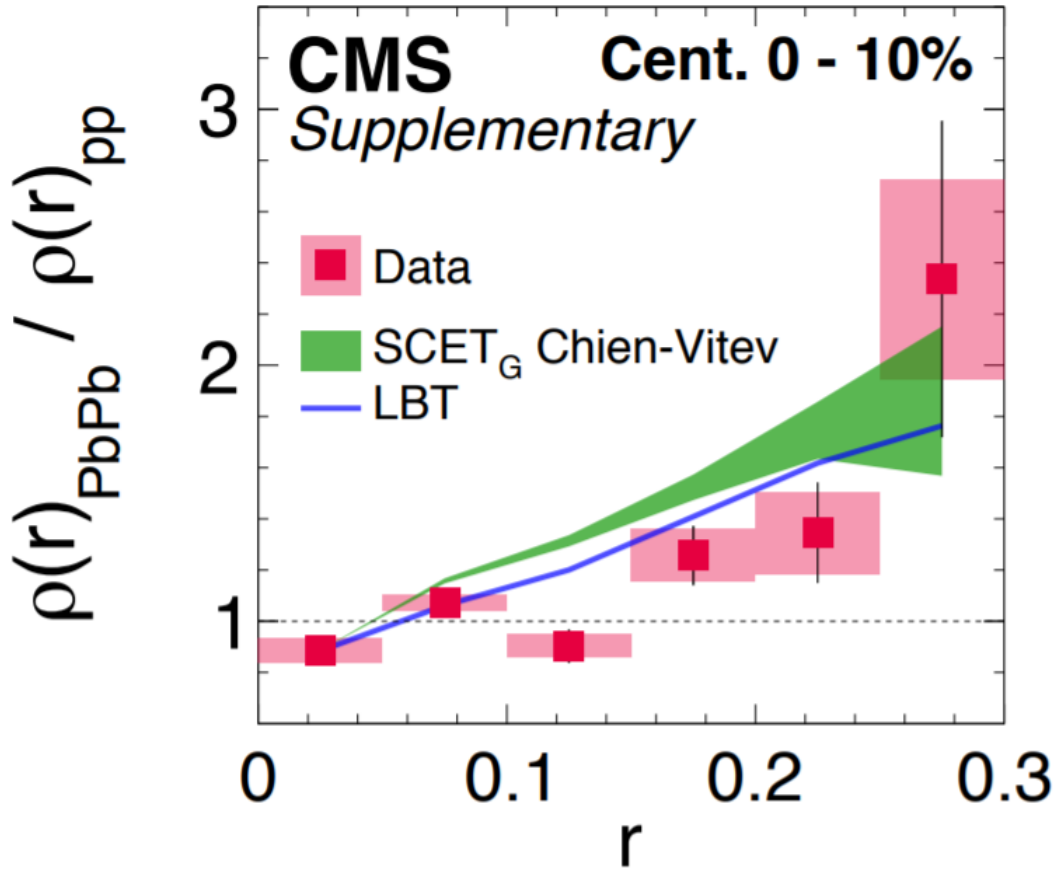


Angular structure (Jet shape)

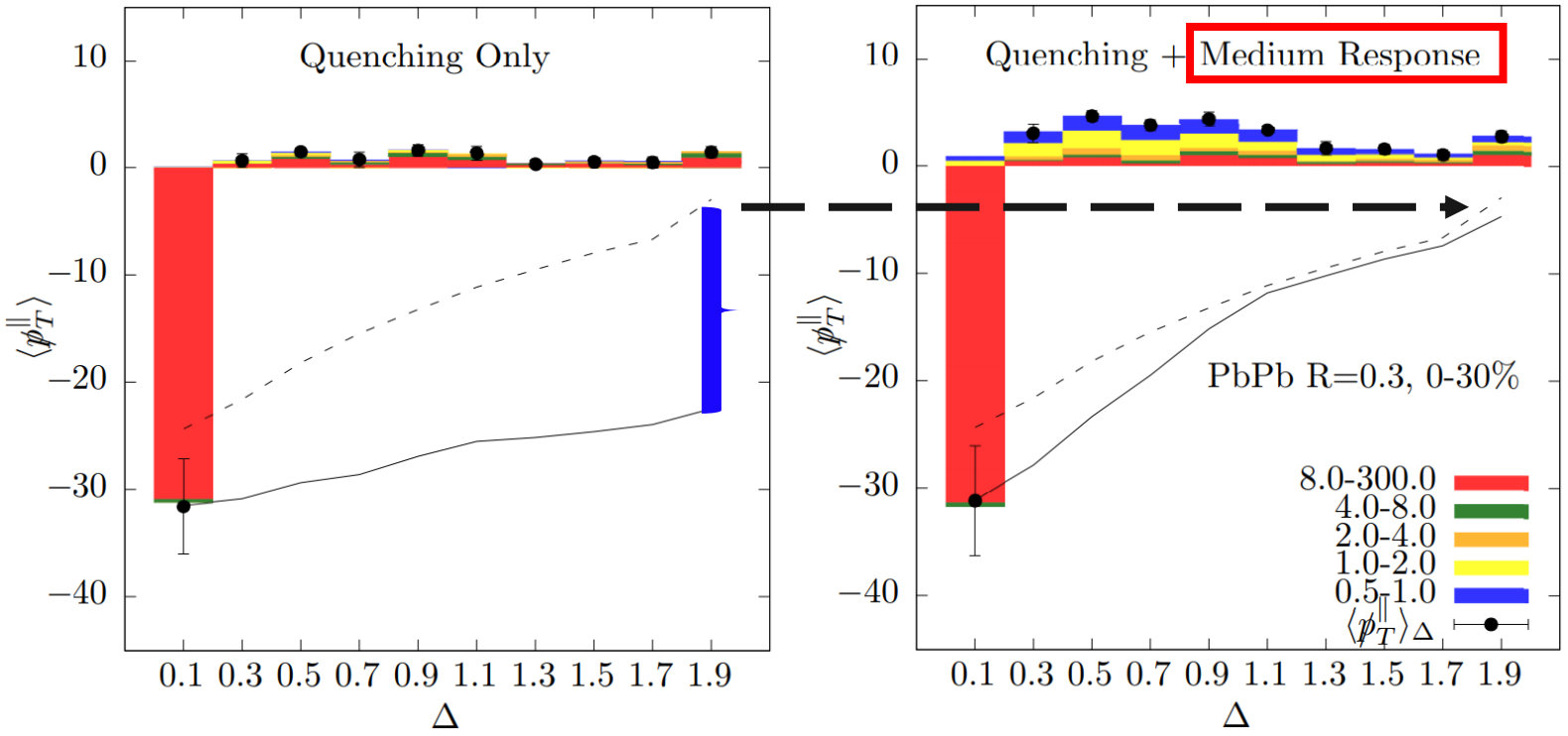
- Some theoretical calculations without the implementation of medium response can also describe the data.
- Jet induced medium response and large angle radiation usually lead to similar effect.
- Some unique feature of medium response.

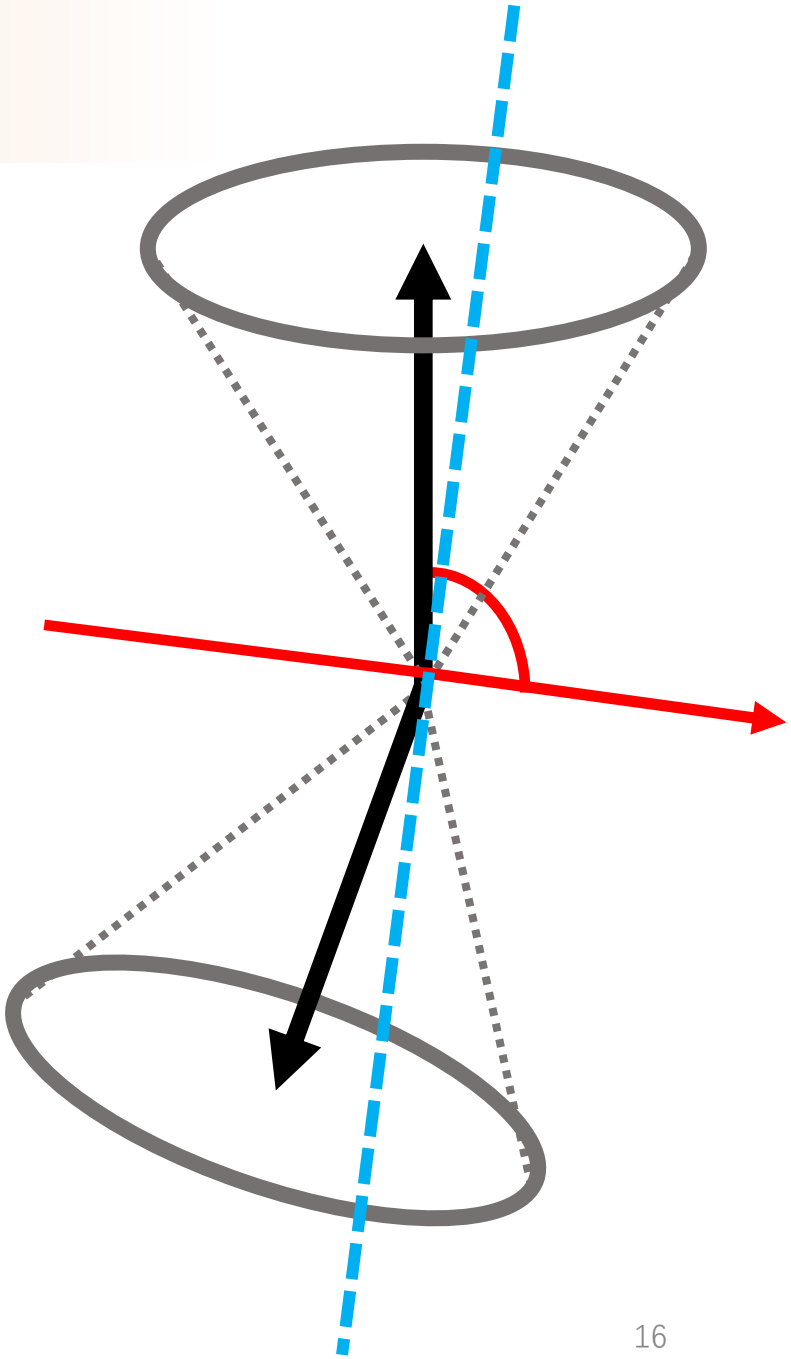


Angular structure (Dijet missing pT)

- Energy is recovered at large angles in the form of soft particles.
- Adding medium response is essential for a full understanding of jet quenching.

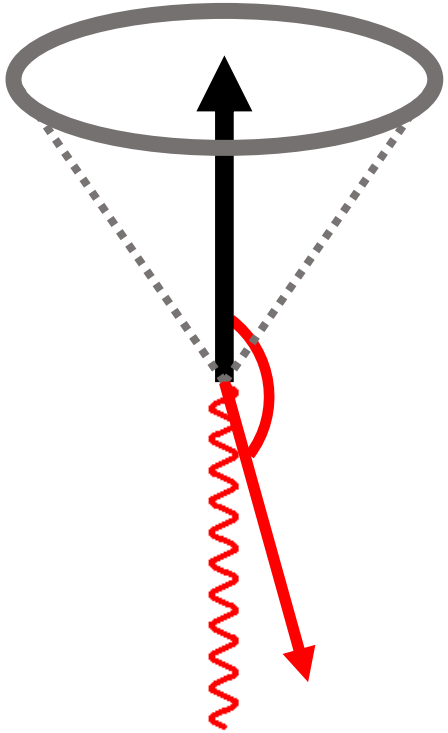
HYBRID Z. Hulcher, D. Pablos, K. Rajagopal, JHEP 1803 010 (2018)



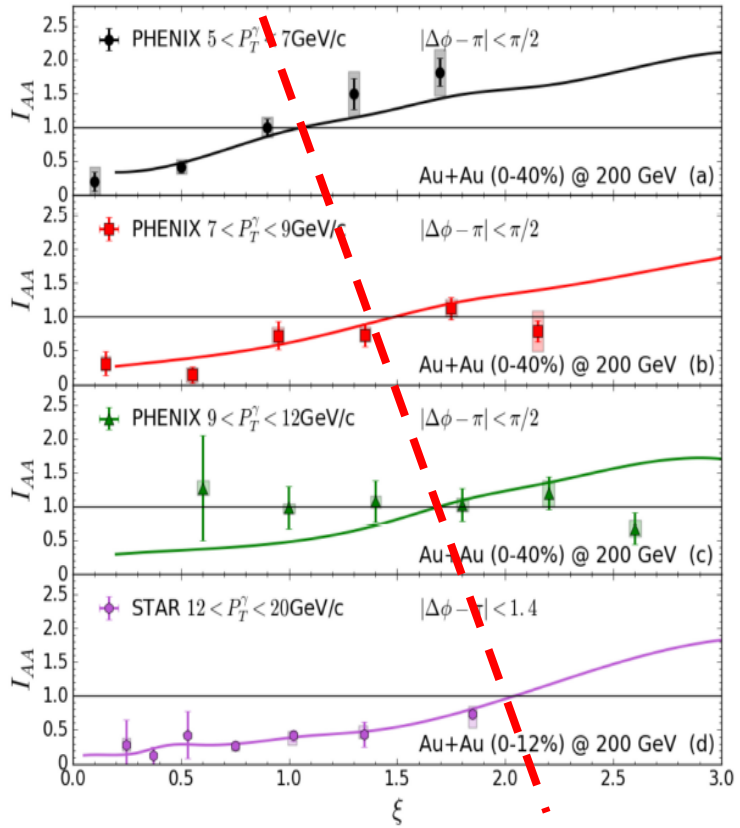


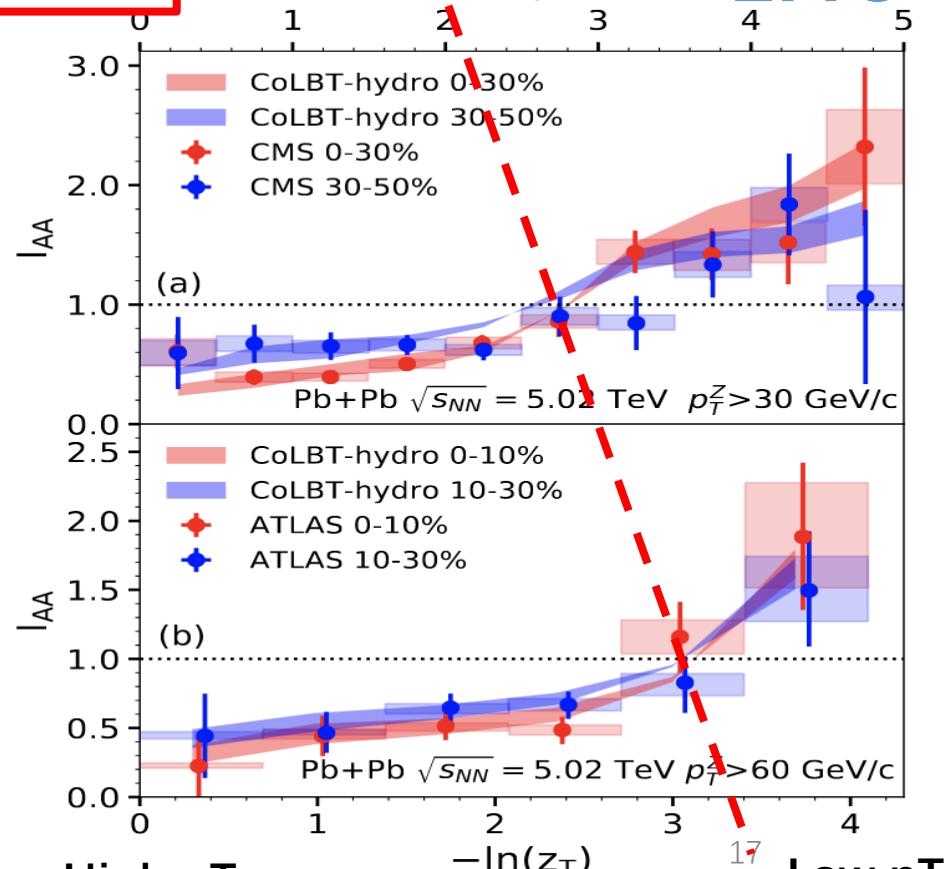
Energy distribution (γ/Z-hadron correlations)

- With increasing pT-gamma transition point from suppression to relative enhancement shifts to larger ξ. This transition point corresponds to a fixed pT range.



RHIC 2~2.5 GeV **Medium response** 2~3.0 GeV LHC





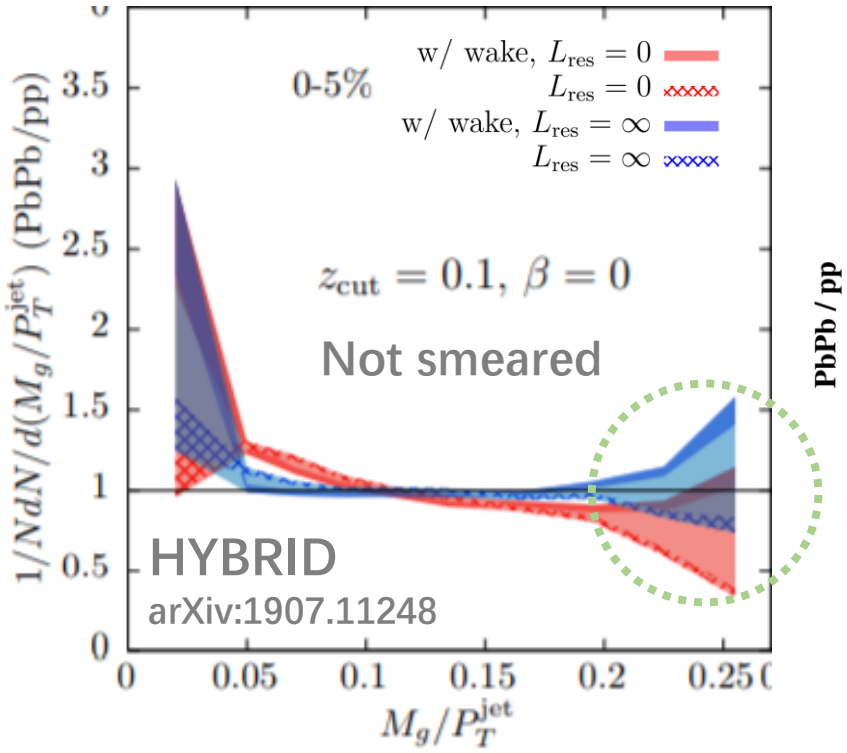
High pT ⟷ Low pT

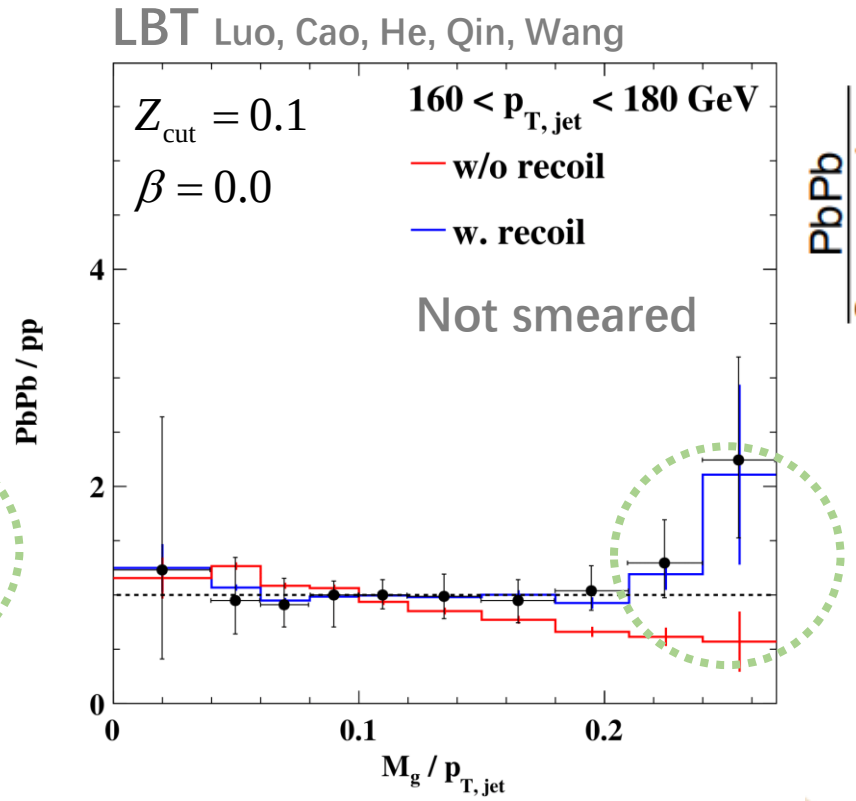
CoLBT-hydro Phys.Lett. B777 (2018) 86-90, Phys.Rev.Lett. 127 (2021) 8, 082301

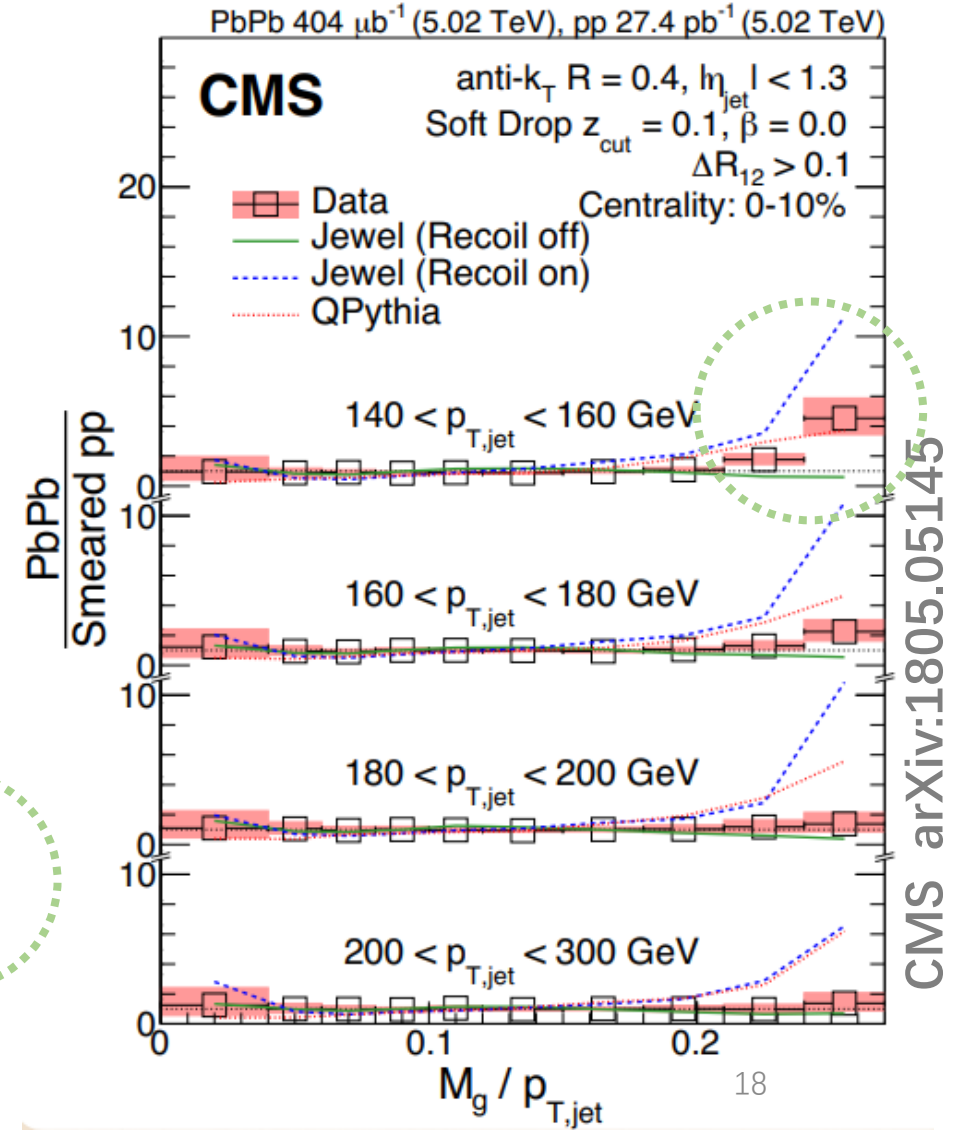
Groomed jet mass

$$\frac{M_g}{p_T^{jet}} = \frac{\sqrt{(E_1+E_2)^2-(\vec{p}_1+\vec{p}_2)^2}}{p_T^{jet}}$$

- Enhancement of the large mass range.
- The rise in large mass tail is caused by medium response in JEWEL, LBT and Hybrid.

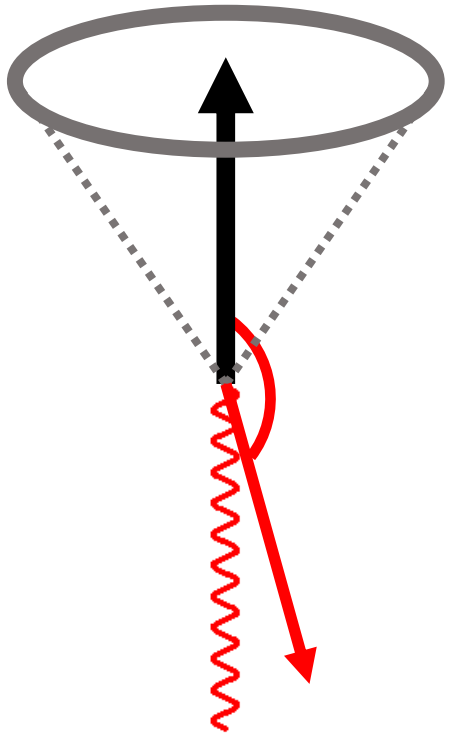


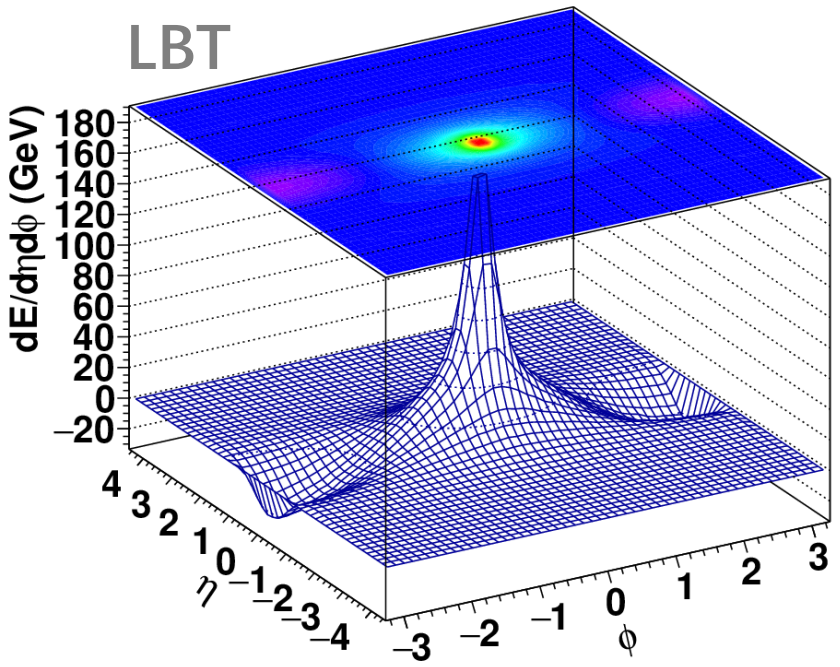


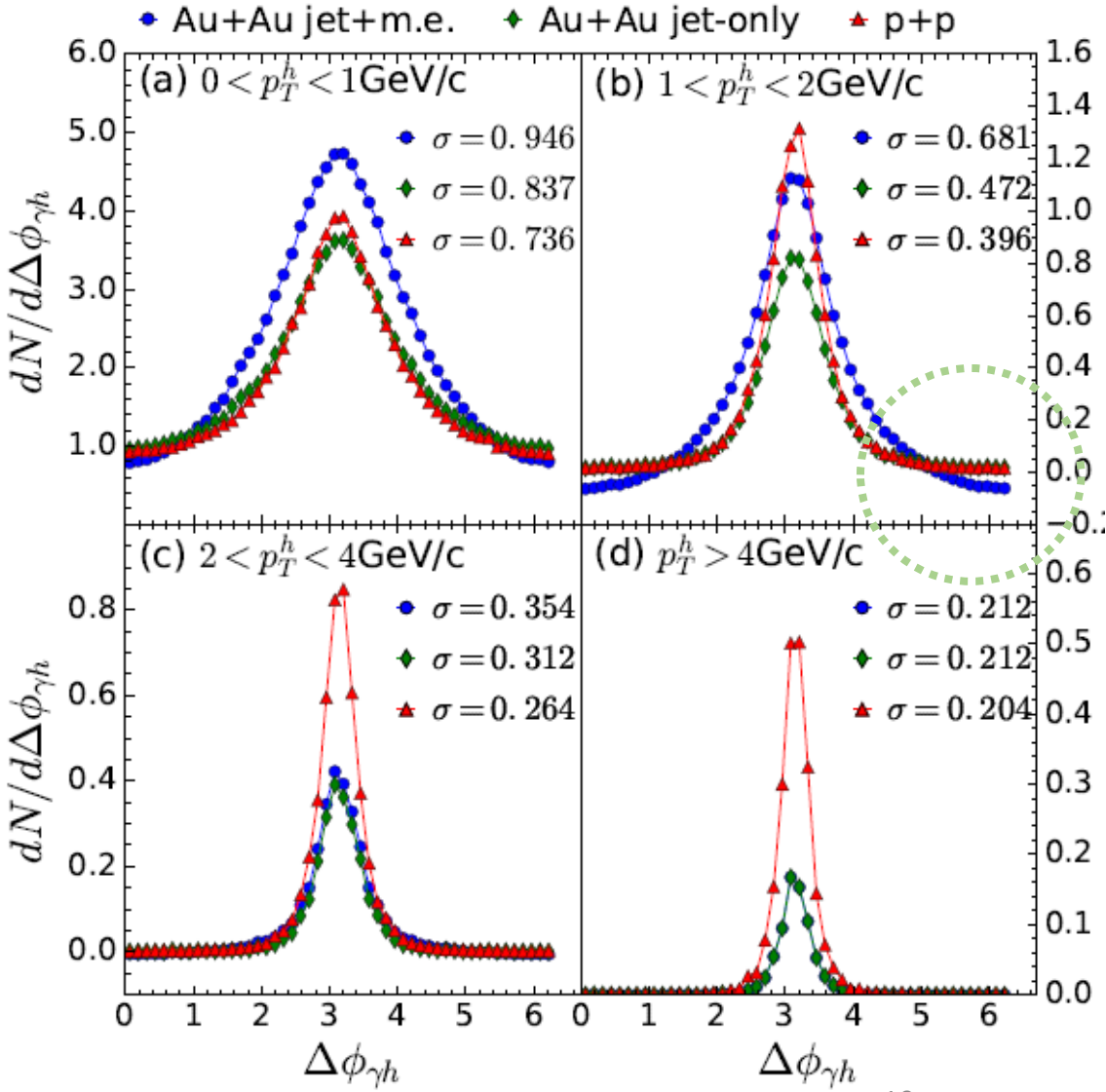


The diffusion wake (γ-hadron correlations)

- A broaden peak at small pT range.
- Suppression of hadron yield at small pT range in the near side due to diffusion wake.



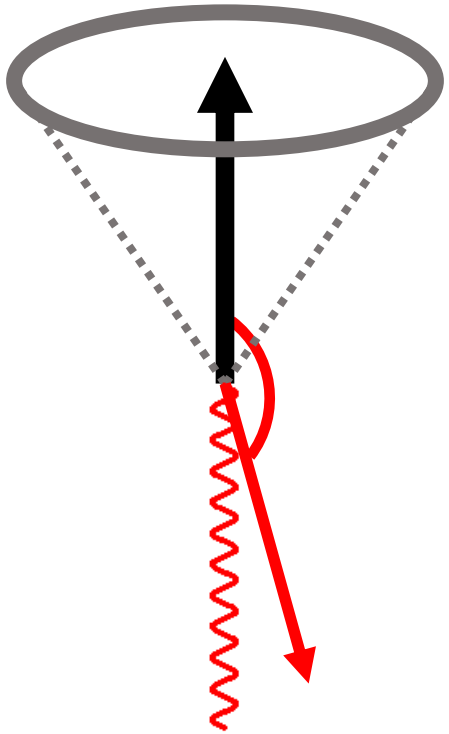


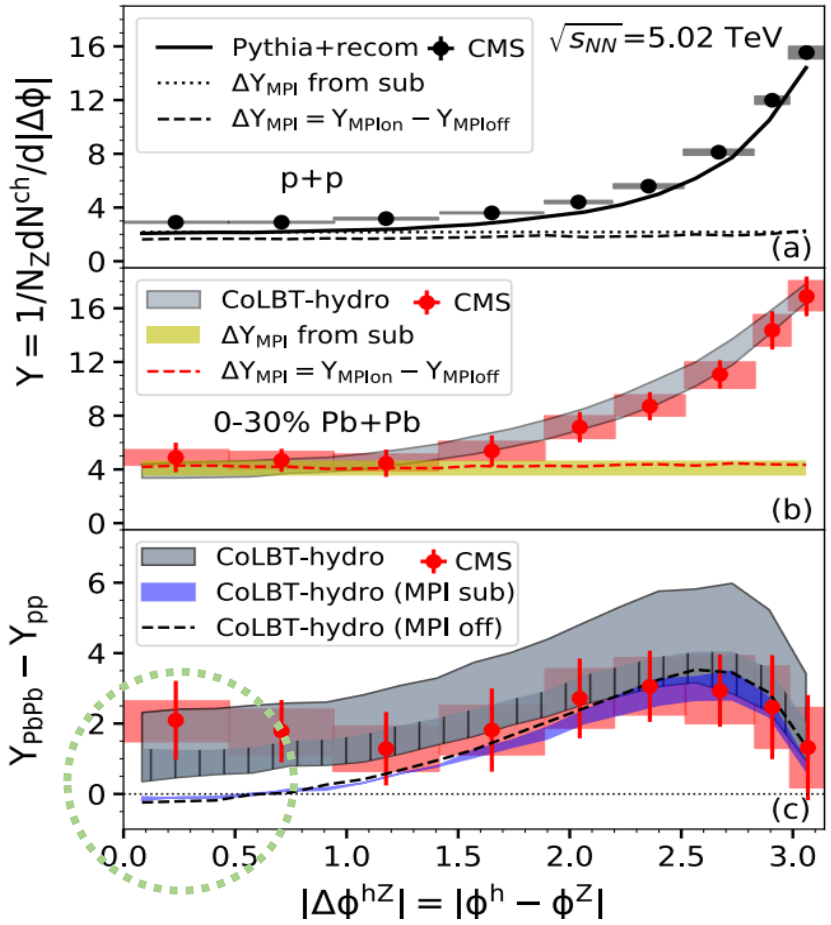


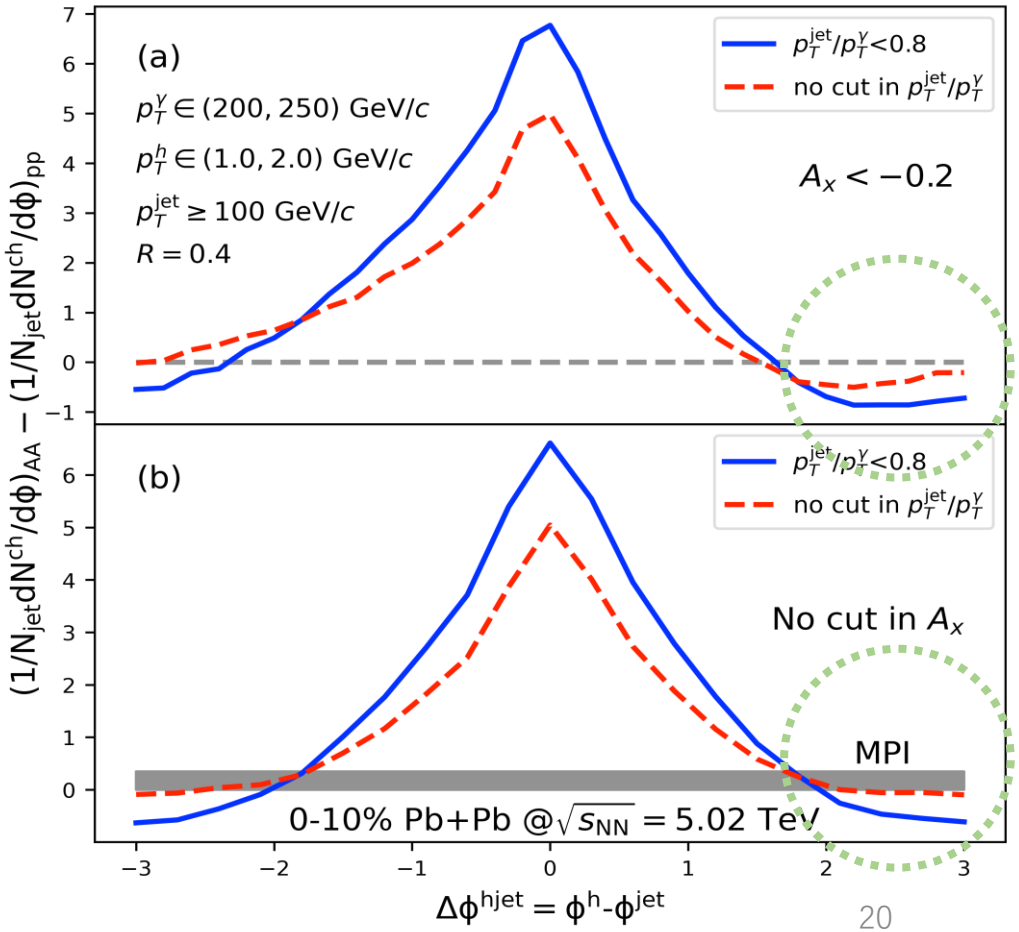
CoLBT-hydro Chen, Cao, Luo, Pang, Wang Phys.Lett. B777 (2018) 86-90

The diffusion wake (γ-hadron correlations)

- Enhancement at both trigger and jet side due to MPI.
- Enhance the signal of the wake with 2D jet tomography.



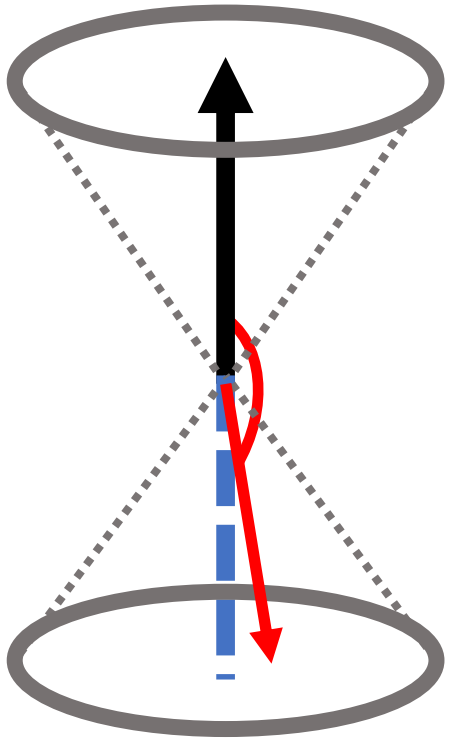


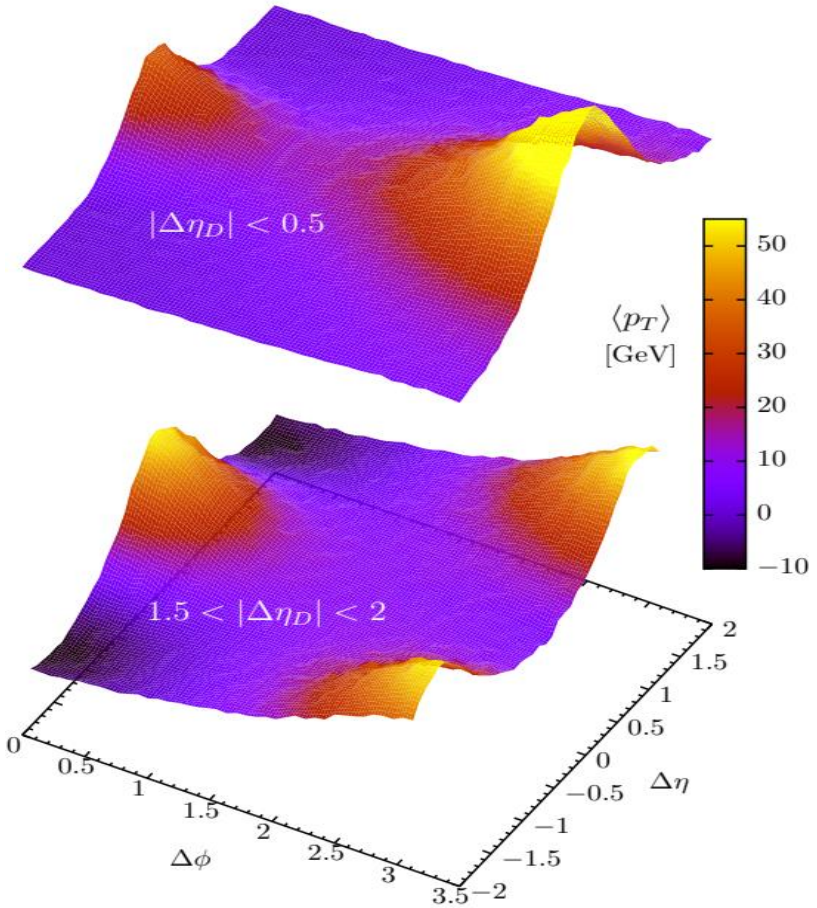


CoLBT-hydro Chen, Yang, He, Ke, Pang, Wang Phys.Rev.Lett. 127 (2021) 8, 082301

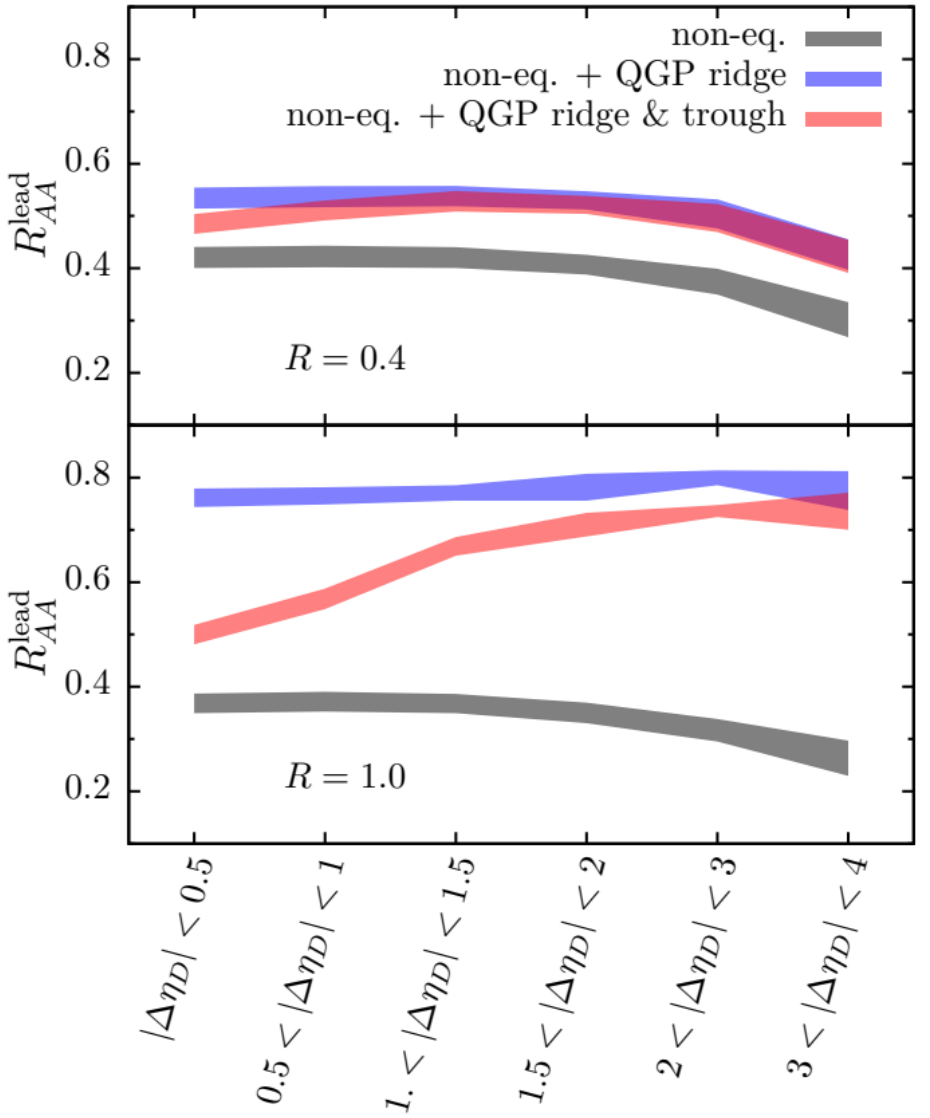
The diffusion wake (Leading jet suppression)

- The effect of the diffusion wake could be observed by looking at leading jet suppression in dijet events with different rapidity configuration.



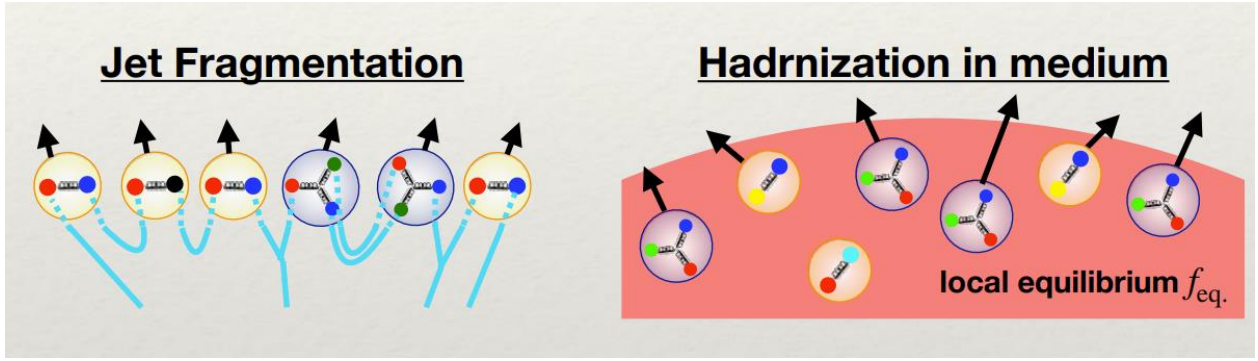


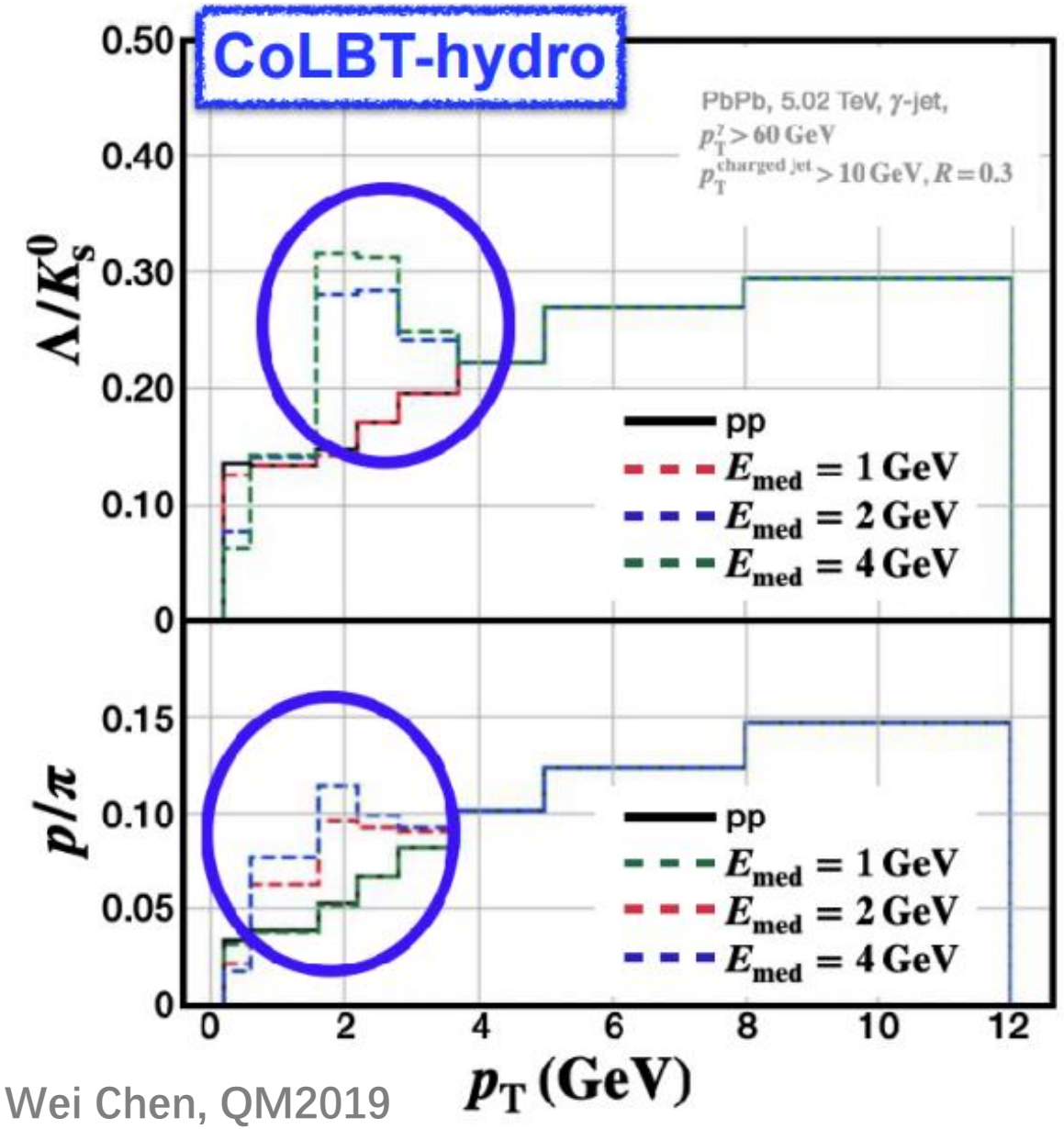
HYBRID Daniel Pablos arXiv:1907.12301



Particle ratio inside jet

- Baryon-to-meson ratio in jet increases at intermediate pT range in Pb-Pb collisions.
- Sensitive to the deposition energy cut between hard and soft.



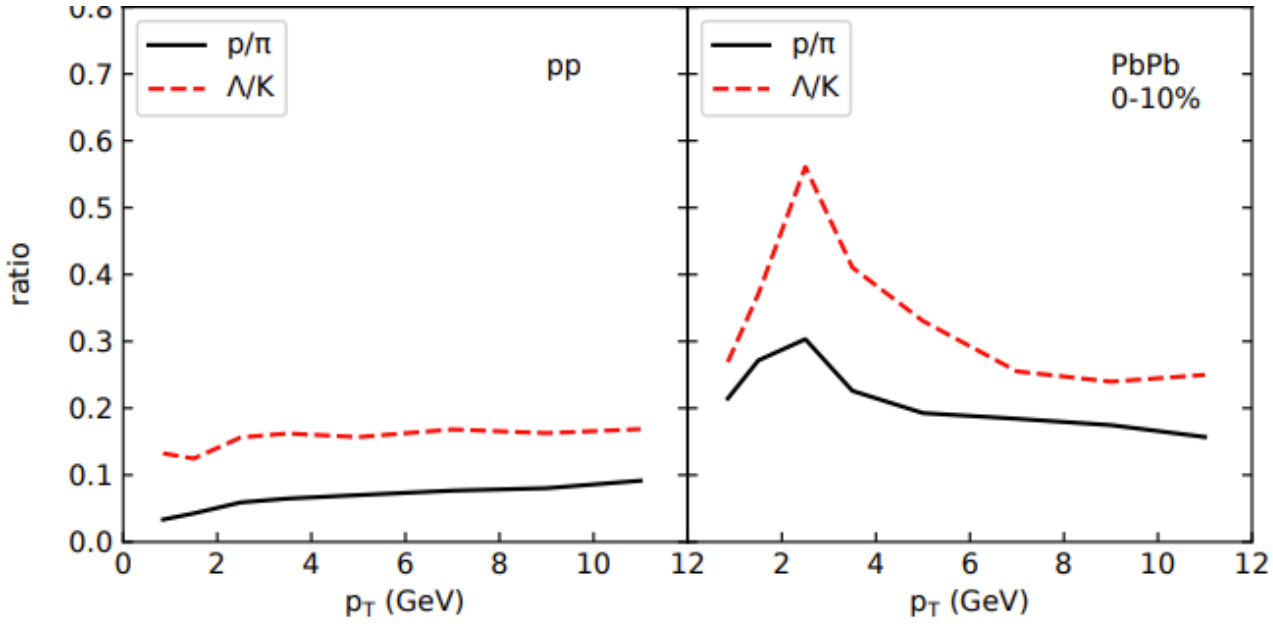


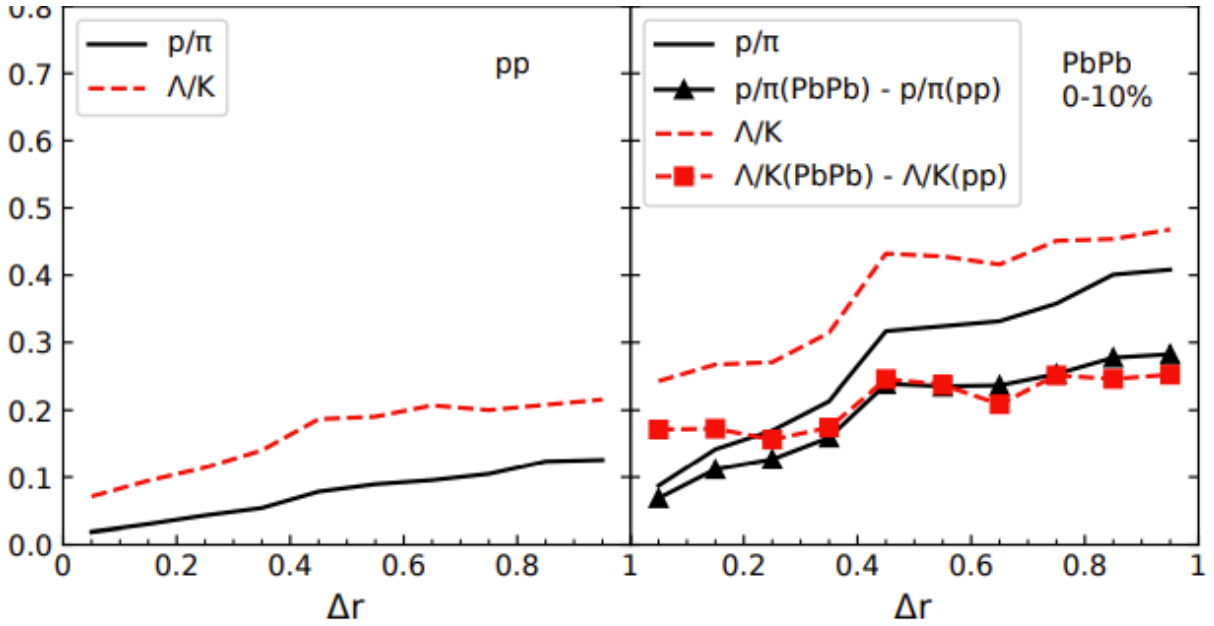
CoLBT-hydro Wei Chen, QM2019

Jet chemistry

- The enhancement is strongest at intermediate pT region as a result of the coalescence of medium partons which are excited by jet partons.

- The enhancement increase with Δr since the lost energy from jets can flow to large angles.





AMPT Ao Luo, Ya-Xian Mao, Guang-You Qin, En-Ke Wang Han-Zhong Zhang arXiv:2109.14314

Summary

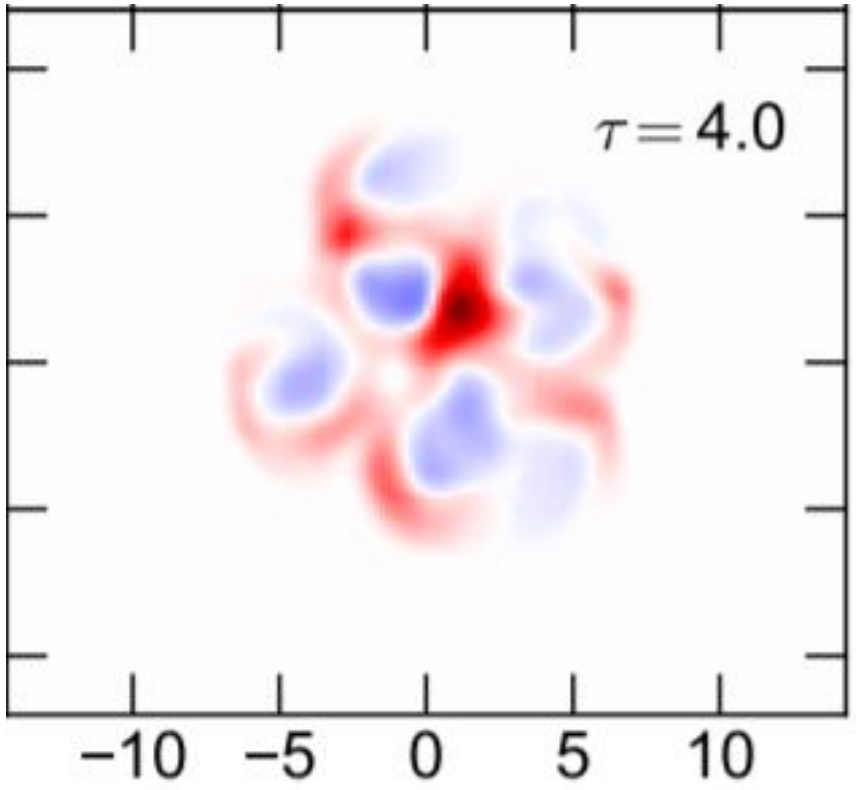
- Different implementations of medium response.
  (Particle recoil vs Hydro response)

- Medium response effect in various jet observables.
  (The enhancement of the soft particles at the large angle around jets.)

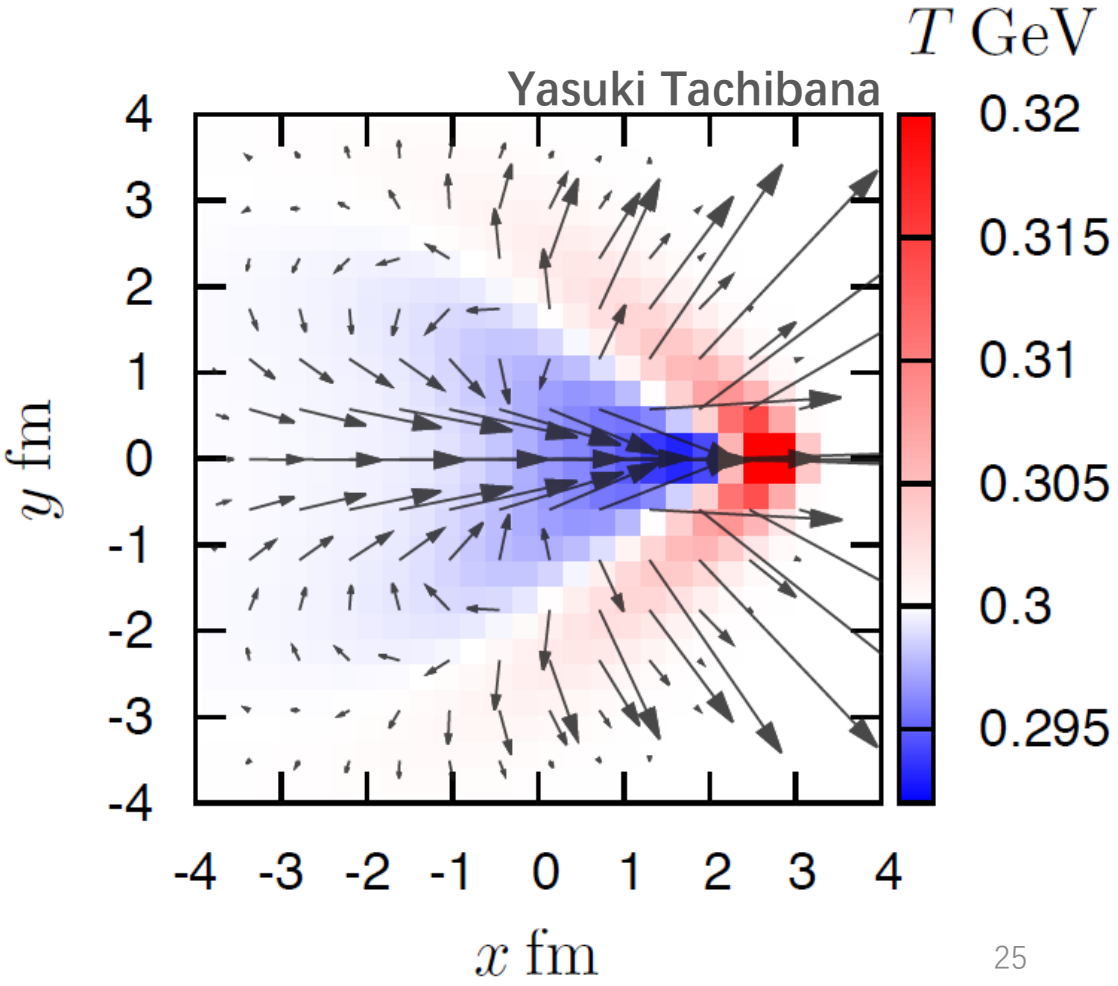
- Searching for unique signatures of jet induced medium response.
  (Hadron ratio, diffusion wake)

Outlook

- Jet interference



- Search for Mach Cone



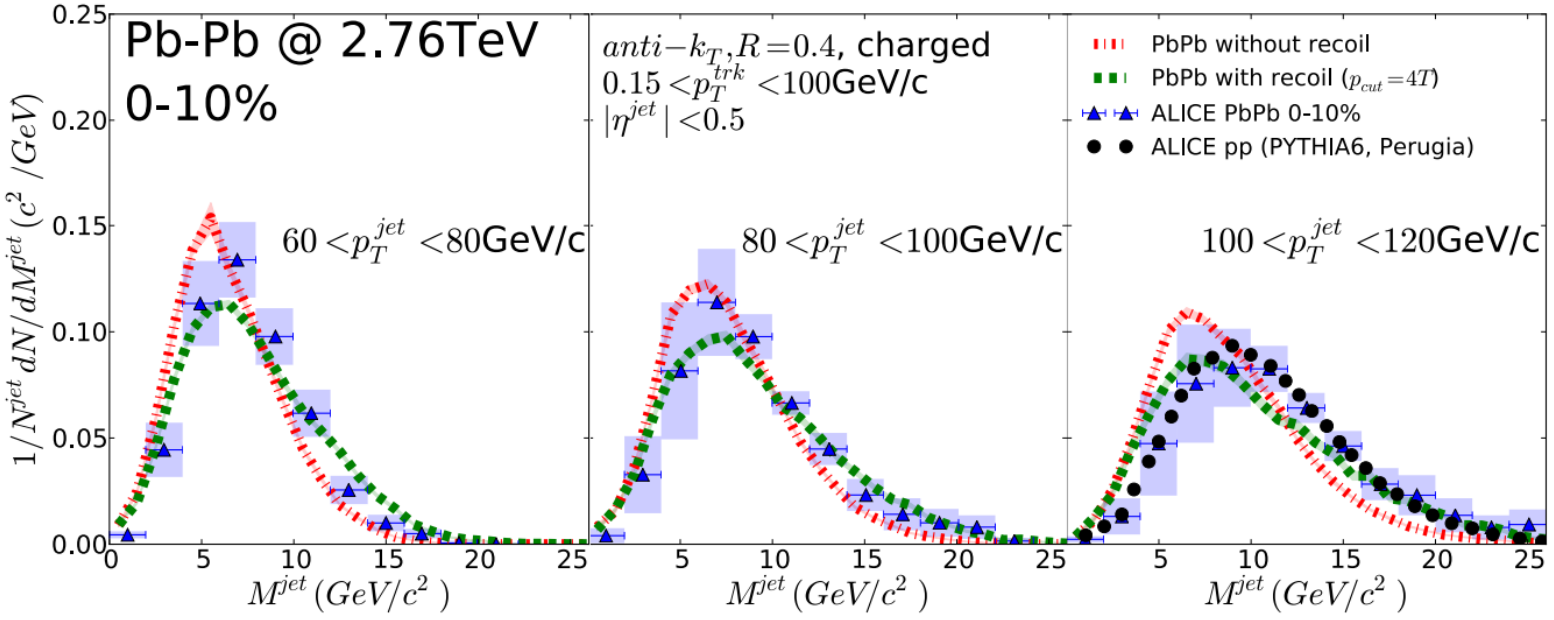
Thanks

Jet mass

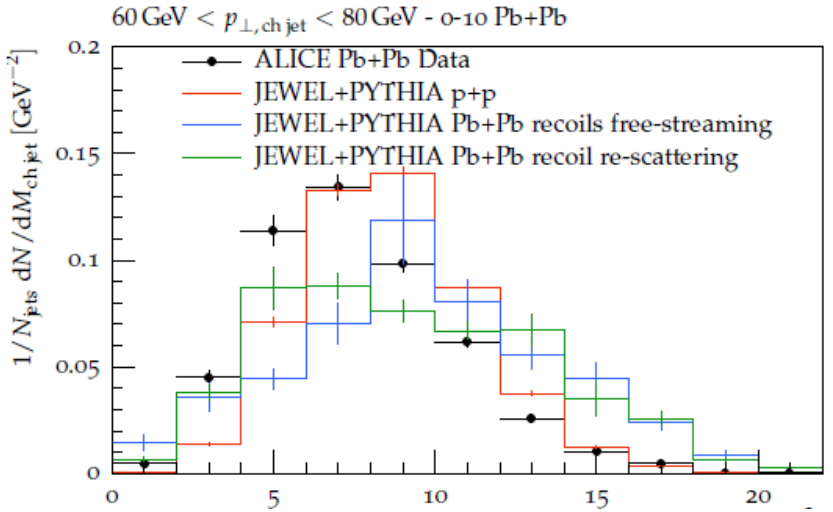
$$m^2 = \left(\sum_{i \in jet} p_i^{\mu} \right)^2$$

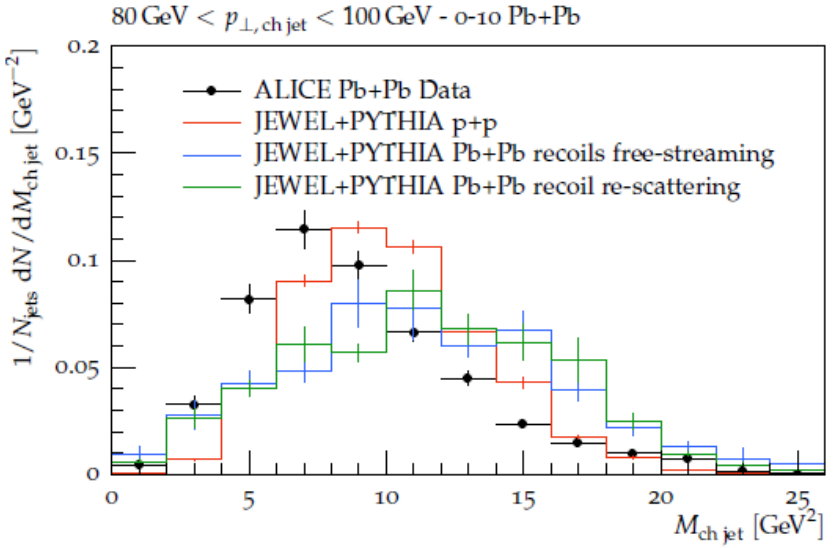
- Decrease by jet quenching.
- Increase by including medium response.

MARTINI C. Park, S. Jeon, C. Gale ('18)



Low jet p_T → High jet p_T





JEWEL K. C. Zapp's talk at EMMI RRTF
R. K. Elayavalli, K. C. Zapp, JHEP 1707, 141

Jet mass

$$m^2 = \left(\sum_{i \in jet} p_i^{\mu} \right)^2$$

- Decrease by jet quenching.
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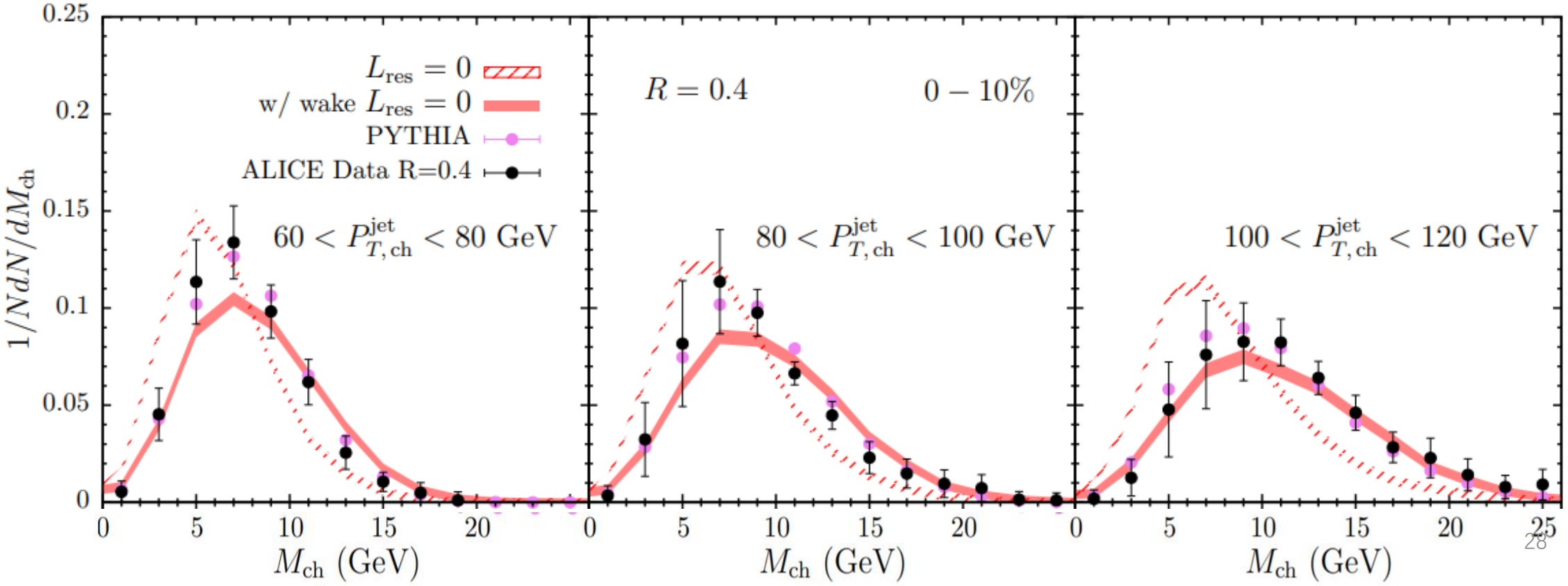
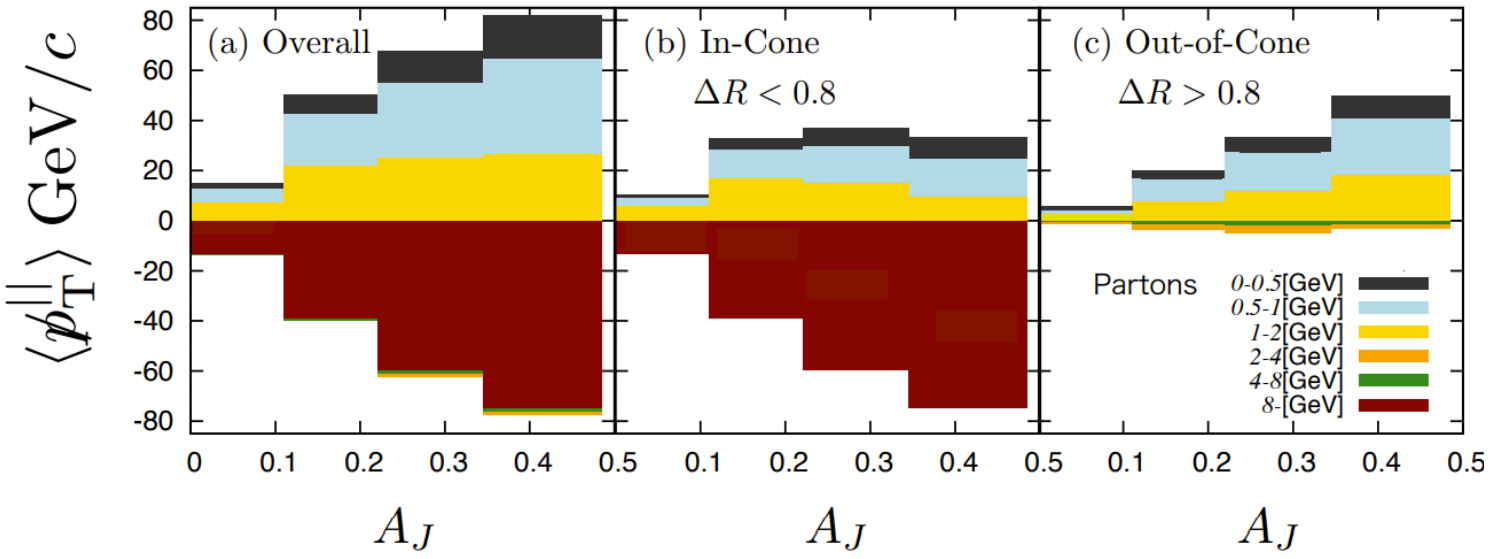
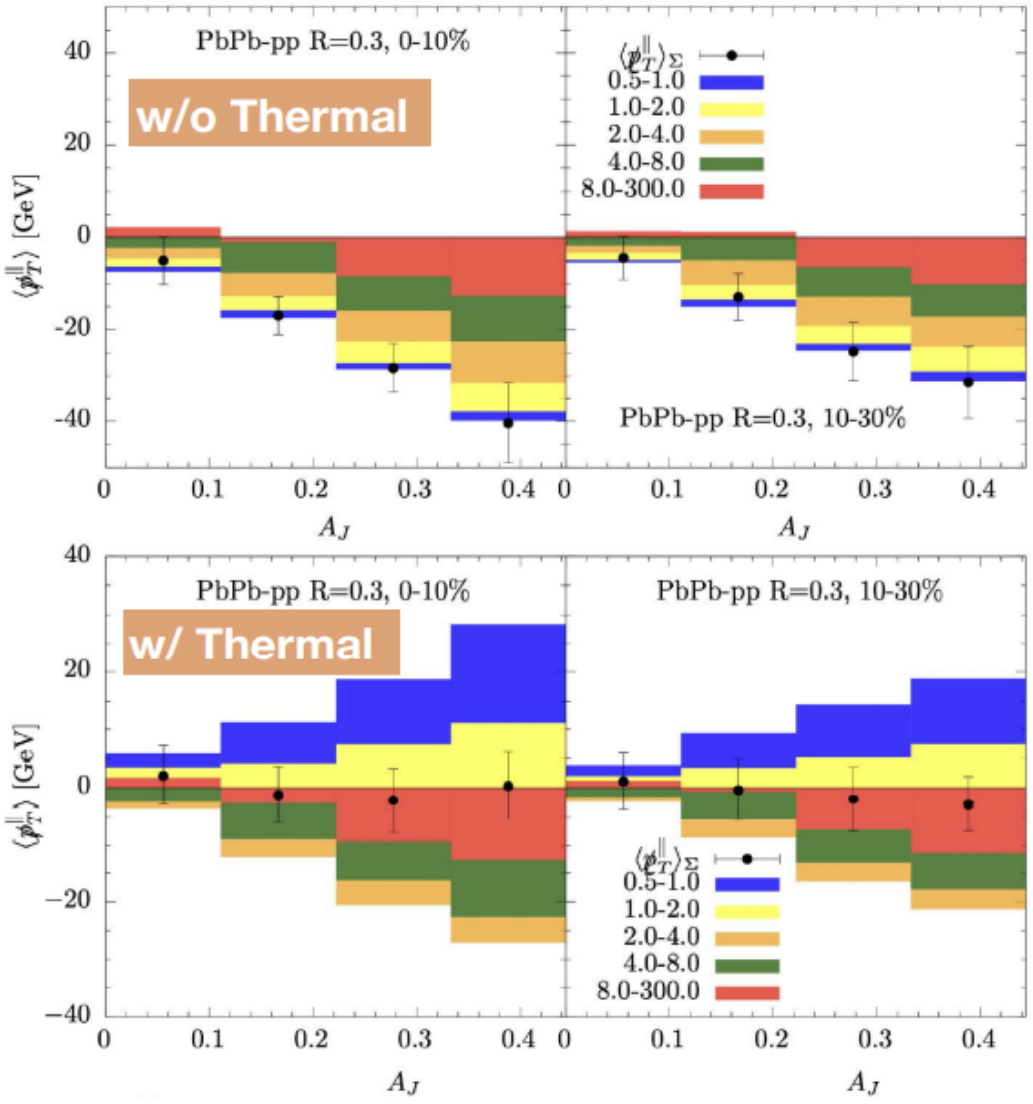
HYBRID Casalderrey, Milhano, Pablos, Rajagopal arXiv:1907.11248



Angular structure (Dijet momentum imbalance)

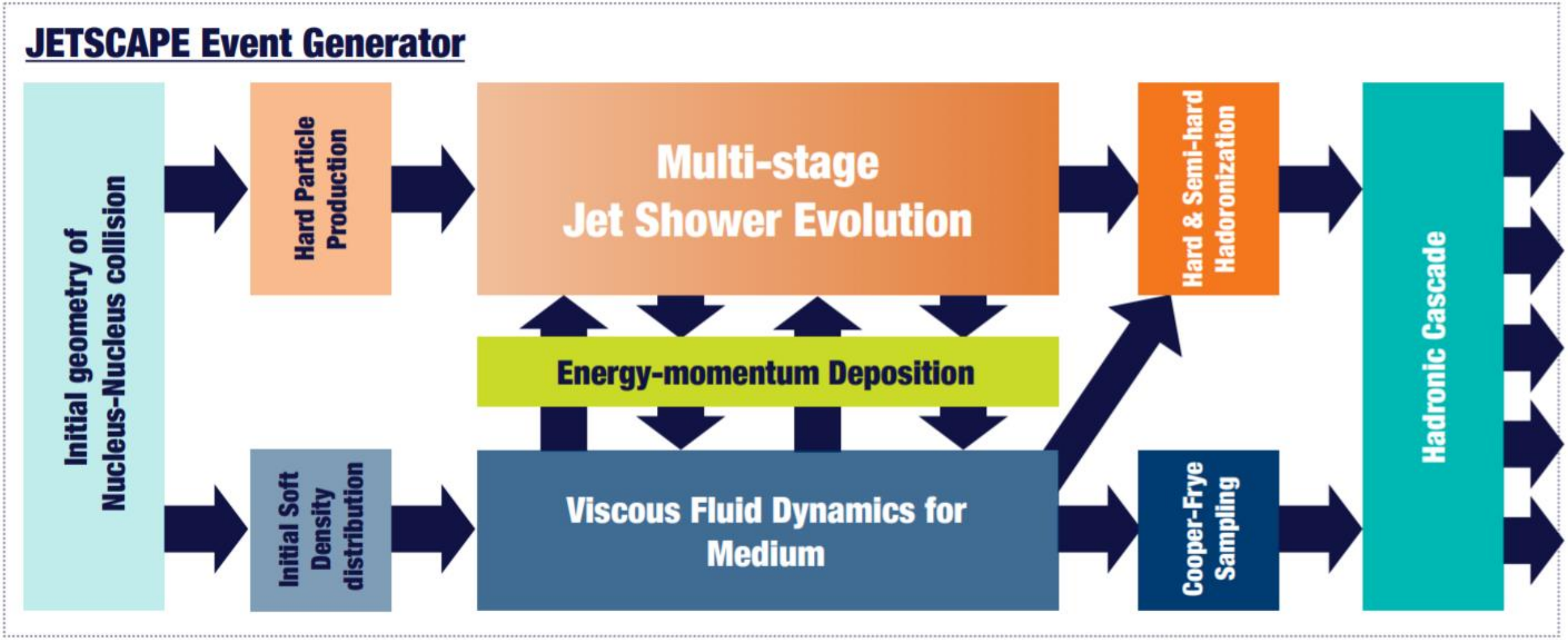
- Energy is recovered at large angles in the form of soft particles.
- Adding medium response is essential for a full understanding of jet quenching.





Outlook

- JETSCAPE: “Framework” of Event Generator for heavy ion collisions

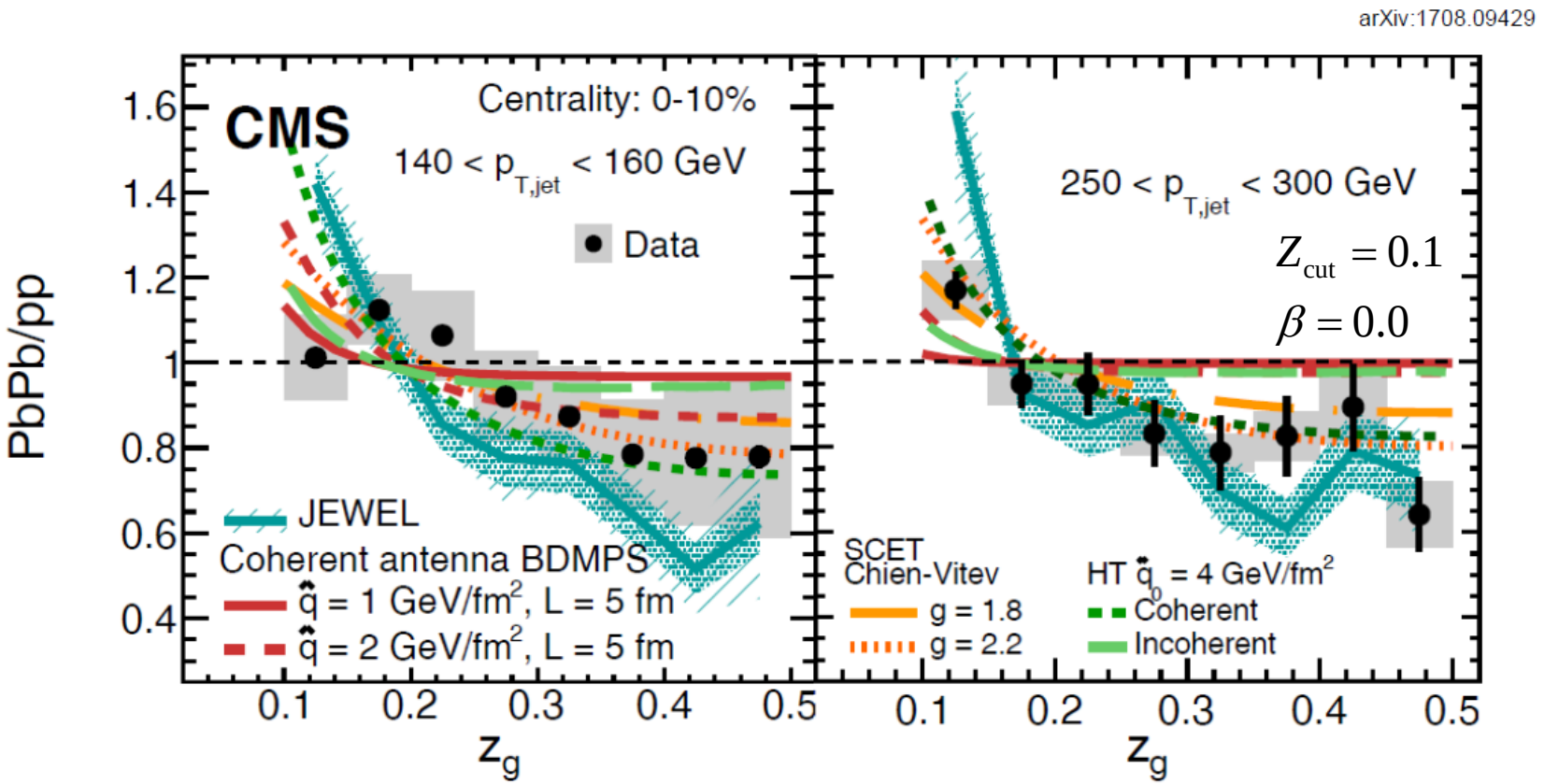


Jet splitting function

$$z_g \equiv \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut}\left(\frac{\Delta R}{R_0}\right)^{\beta}$$

- Some theoretical calculation suggest that the data prefer coherent energy loss.

- The MC calculation show that the inclusion of the recoil (medium response) will lead to stronger modification of the groomed jet splitting function.



LBT