Jet quenching and medium response

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Outline

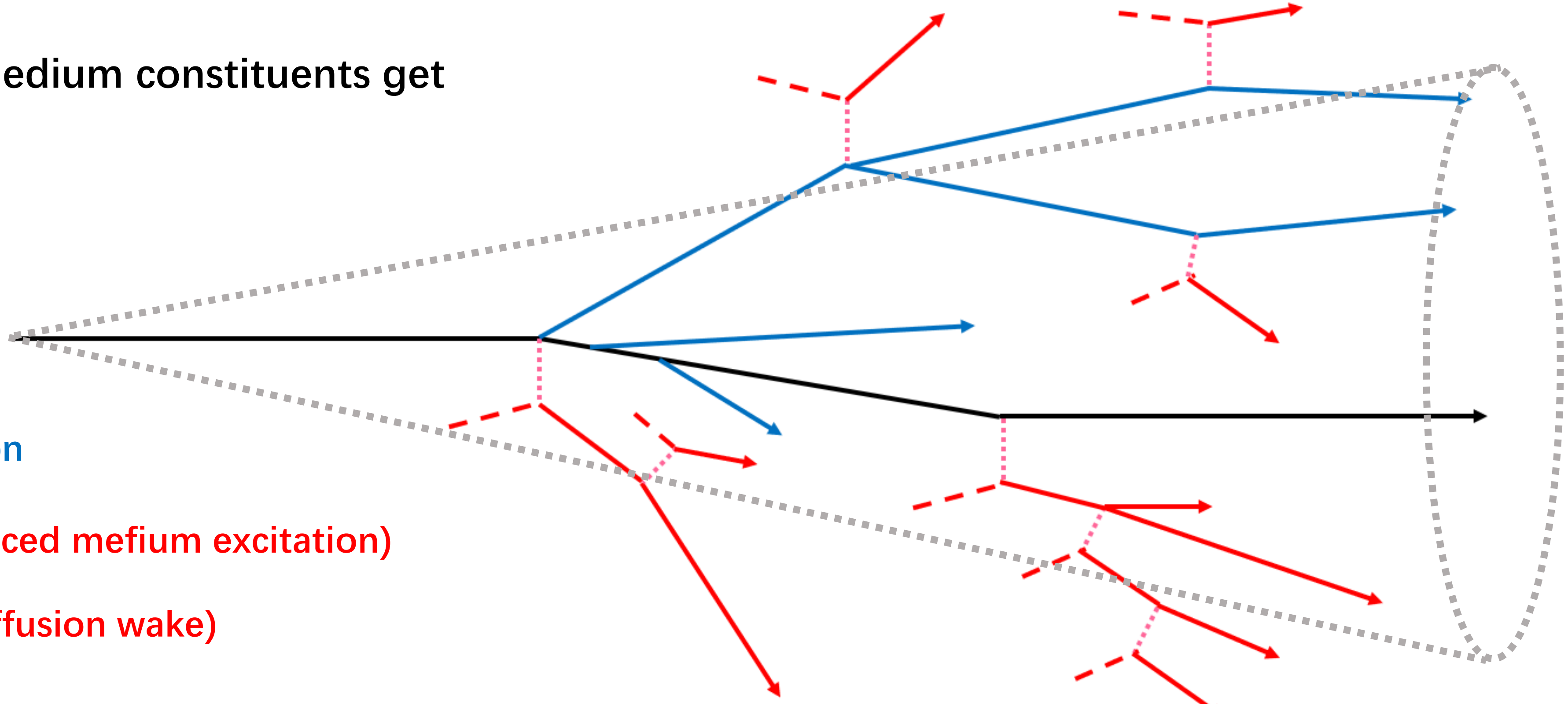
- Introduction
- Models
- Observables
- Summary

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.



Leading paton

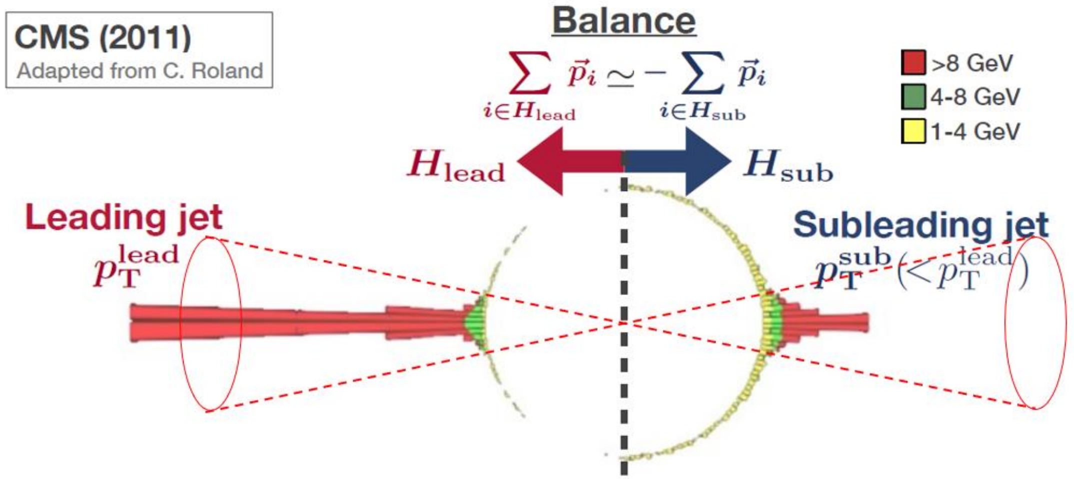
Medium induced radiation

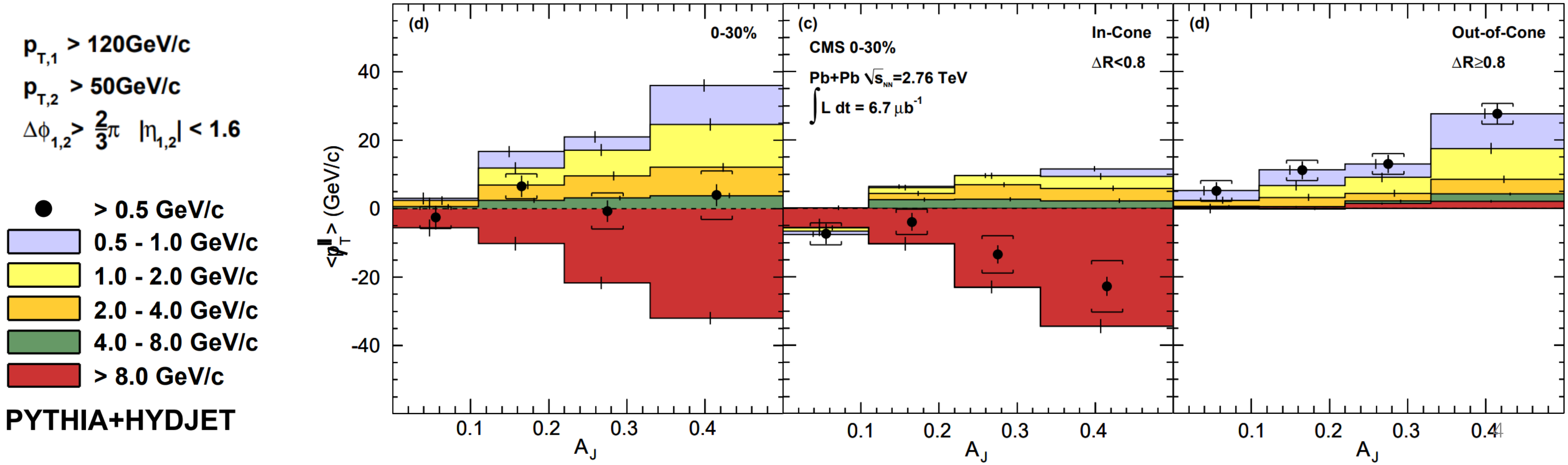
Recoiled parton (Jet induced mefium excitation)

Initial thermal parton (diffusion wake)

Where does the lost energy go ?

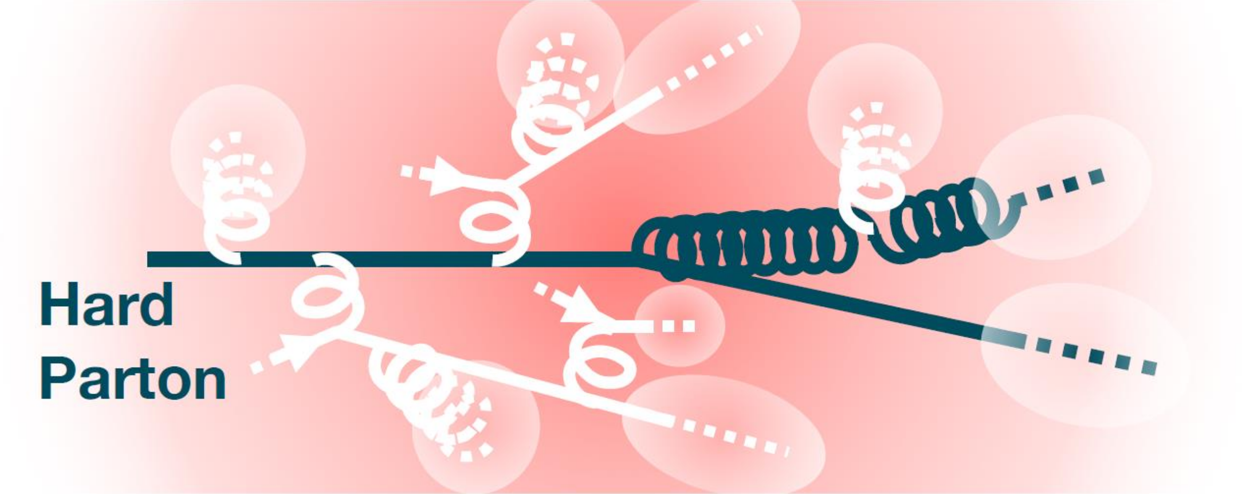
- The energy and momentum deposited by the jet shower into the medium appear at large angles away from the jet axis.



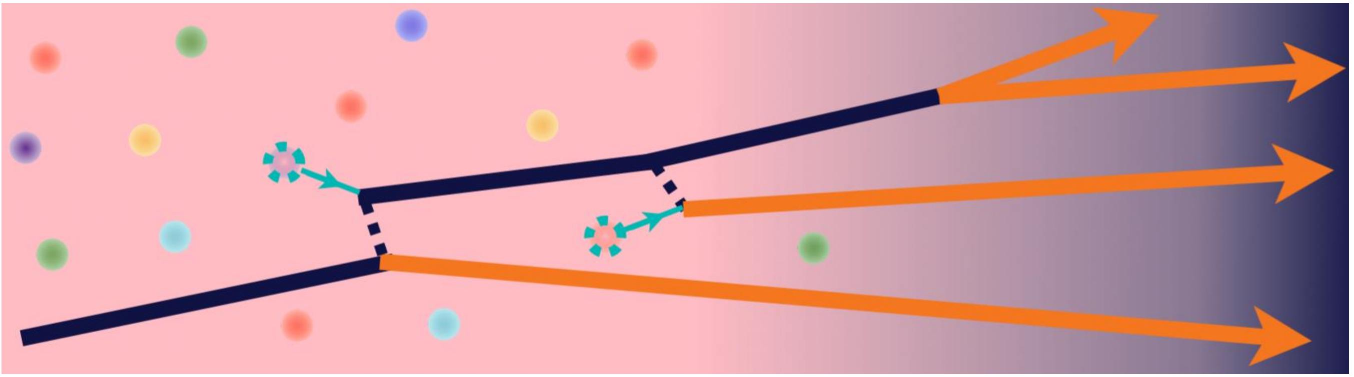


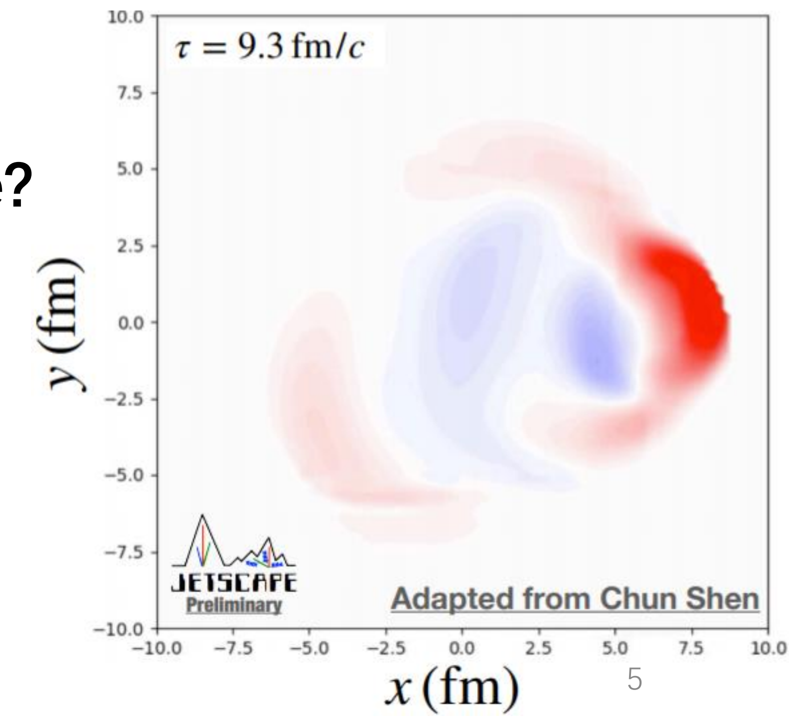
Thermalization & Propagation

- Thermalization : How does the deposited energy thermalize?



- Propagation: How does the deposited energy propagate?

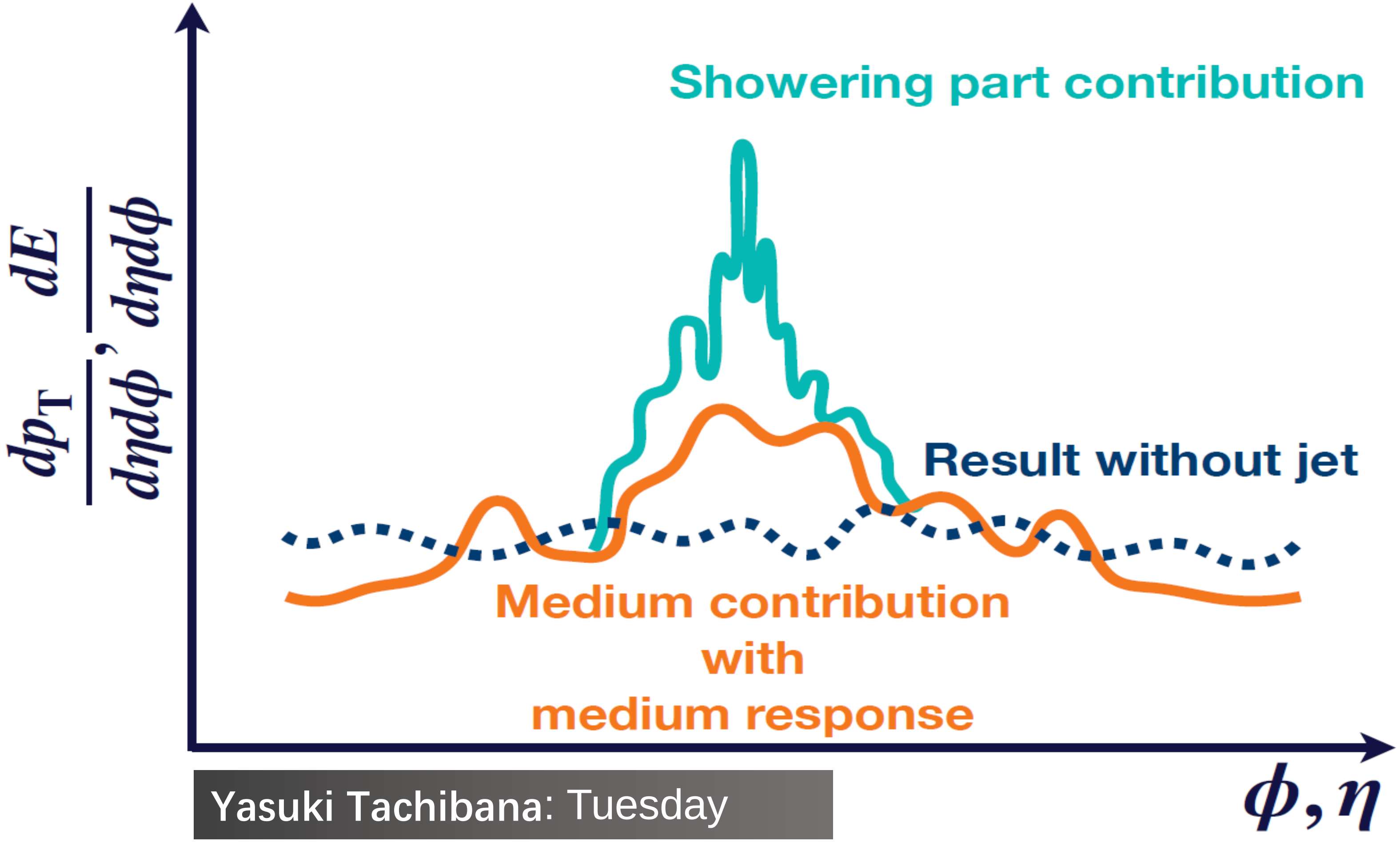




Yasuki Tachibana: Tuesday

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).

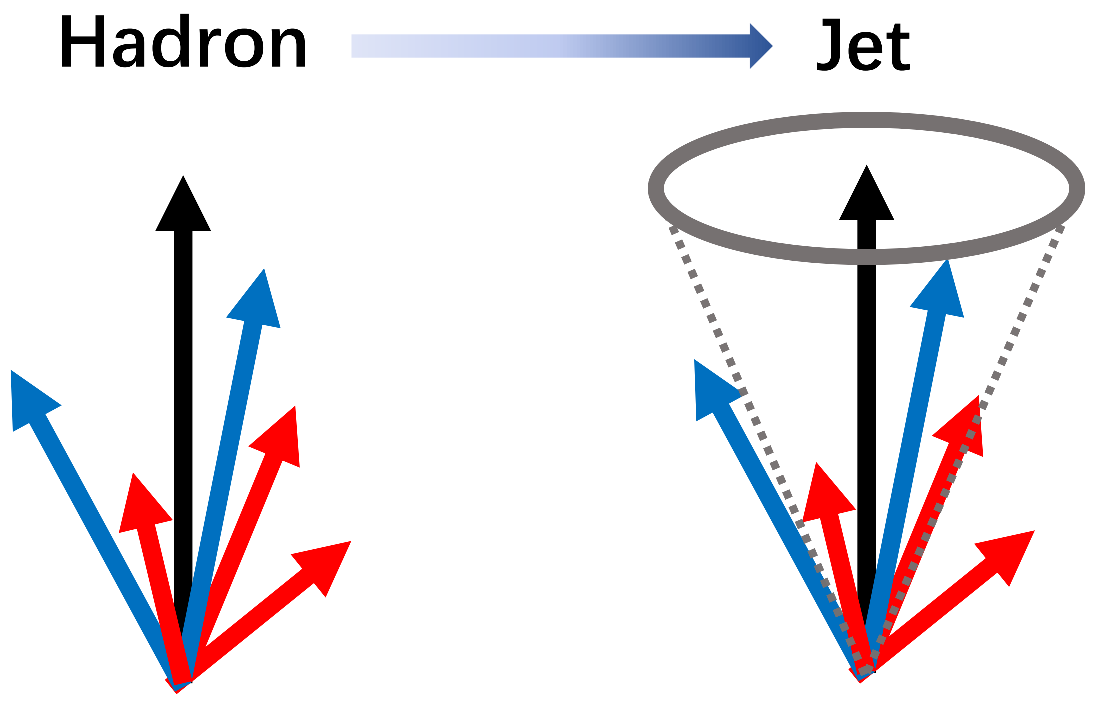


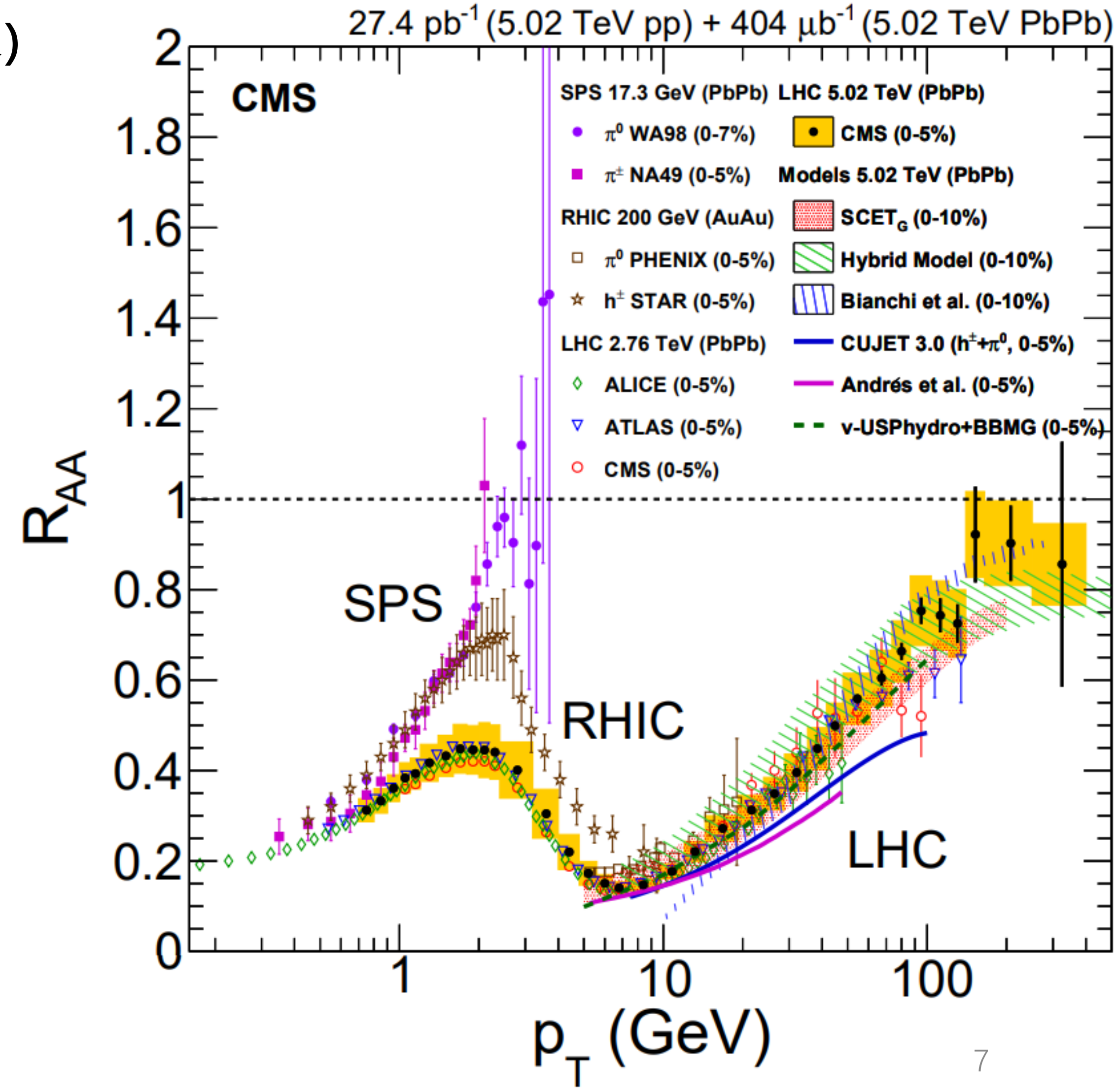
Yasuki Tachibana: Tuesday

Parton energy loss in QGP

- Jet weakly coupled to the medium
  pQCD based calculation (BDMPS-Z, GLV, AMY, HT, $\mathrm{SCET_G}$)
  (LBT, MARTINI, QPYTHIA, JEWEL, YaJEM, ...)

- Jet strongly coupled to the medium
  AdS/CFT (HYBRID)





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

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

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

Fragmentation

Recombination

LBT

Hard

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

?

No feed back

Hadronic observables

Initial profile
AMPT TRENTO

Medium evolution

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

Cooper Frye

CLvisc

Soft

A coupled LBT Hydro (CoLBT-hydro) Model

Parton shower
Pythia Sherpa

Jet propagation

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

- **Rescattering**
  Shower-thermal & recoil-thermal
  Parton above Pcut

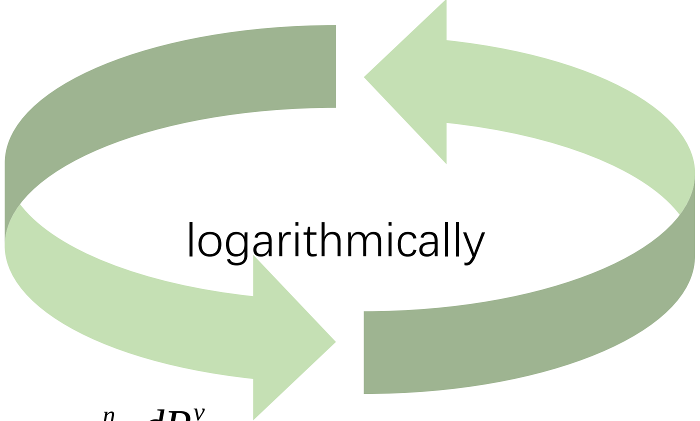
Fragmentation

Recombination

LBT
Hard

Real time feed back

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



$$j^{\nu} = \sum_{i=1}^{n} \frac{dP_i^{\nu}}{d\tau} \delta^3(\vec{X} - \vec{X}_i)\theta(P^0_{\mathrm{cut}} - P_i \cdot u)$$

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

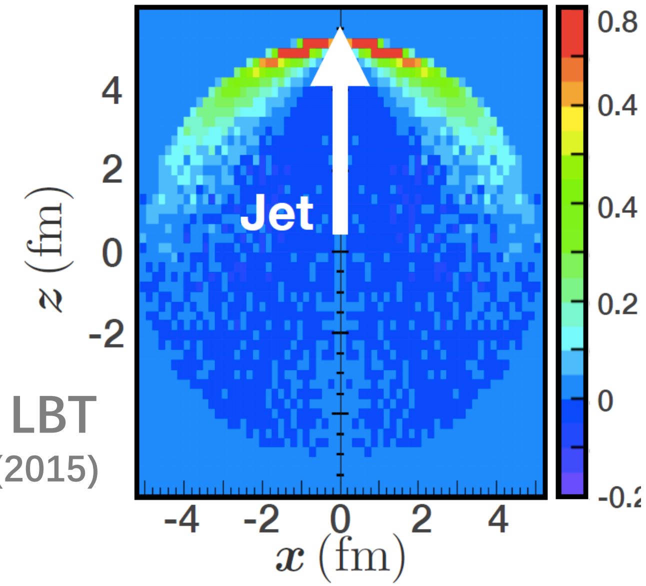
CLvisc
Soft

Jet induced medium response

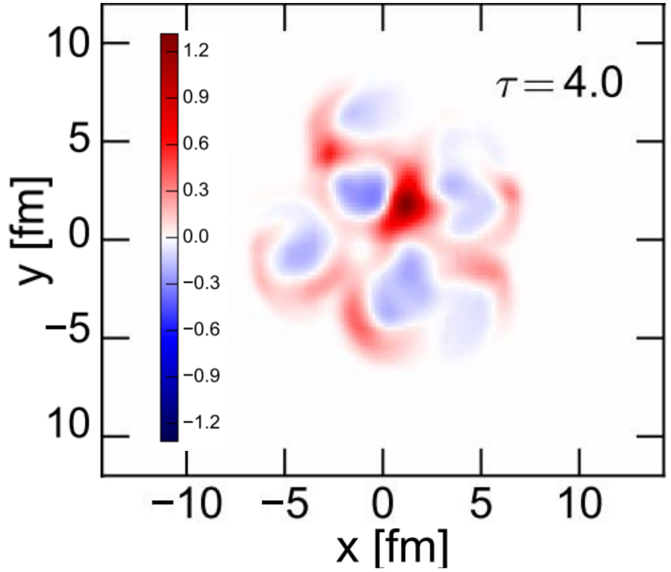
- **Structure of medium response**
  Hydro : Mach cone as hydro response.
  Transport : Mach cone like structure.

- **Diffusion wake**
  Unique structure of medium response

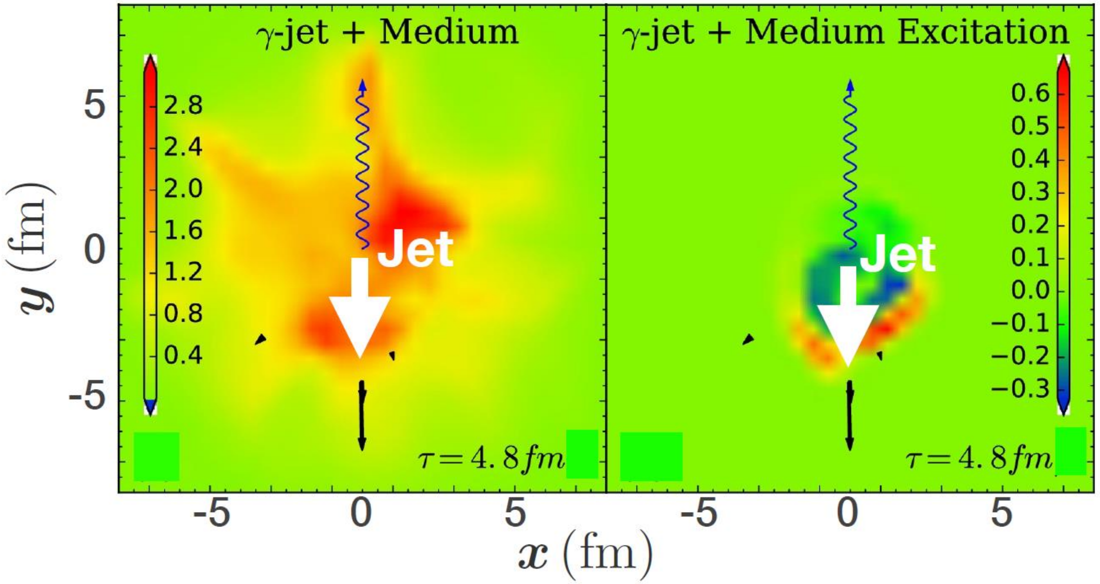
LBT
PRC 91, 054908 (2015)



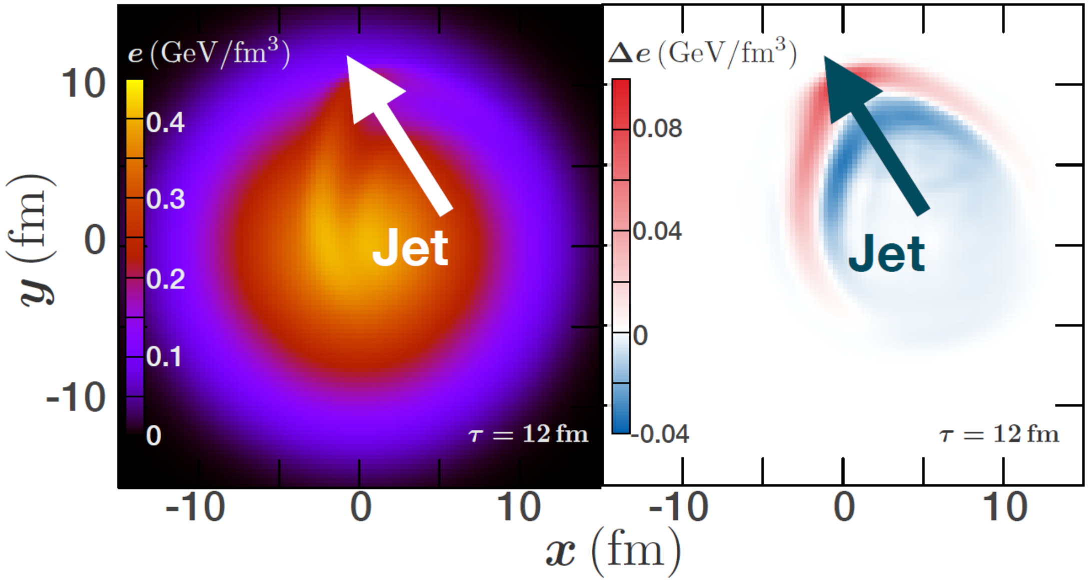
EPOS3-HQ Iurii Karpenko HP2018



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



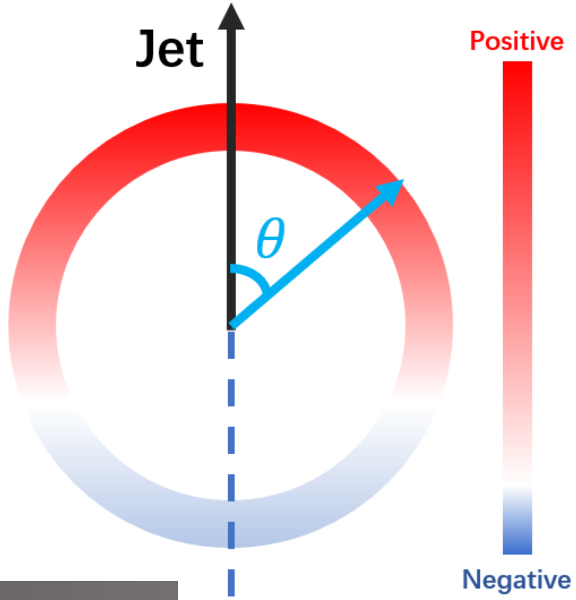
Jet-Fluid Tachibana, Chang, Qin, PRC 95, 044909

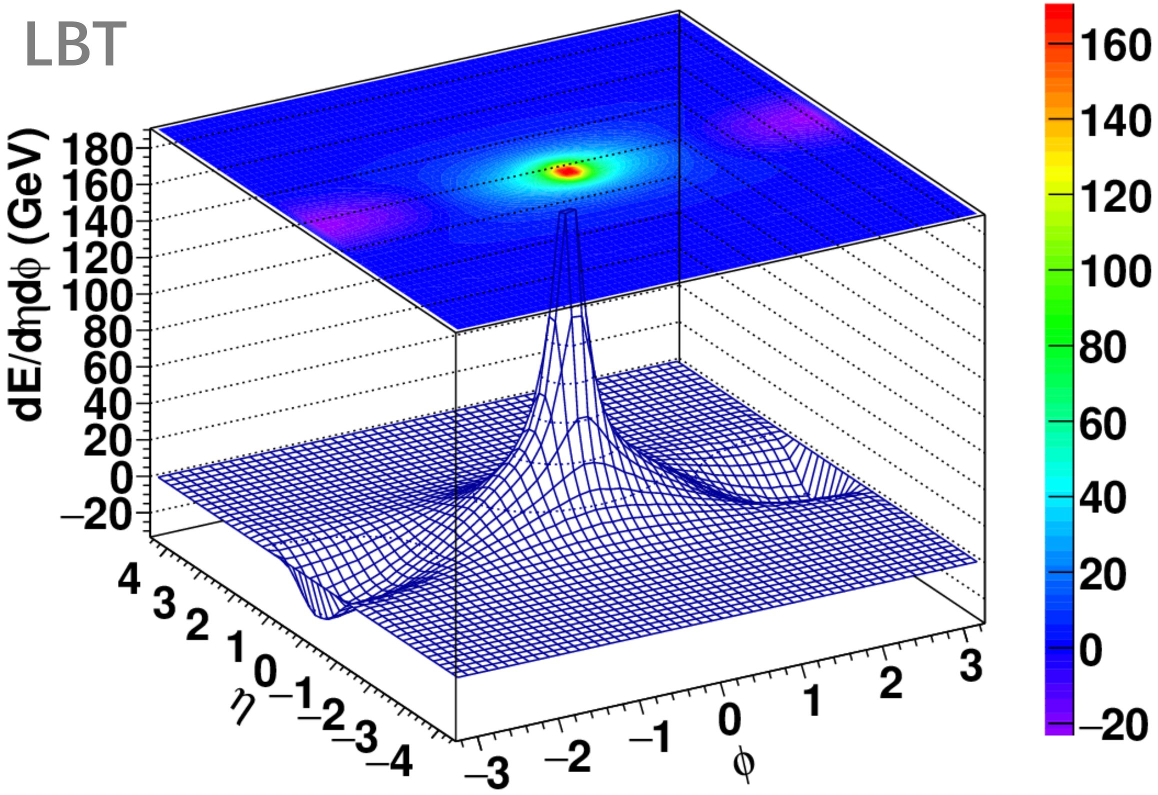


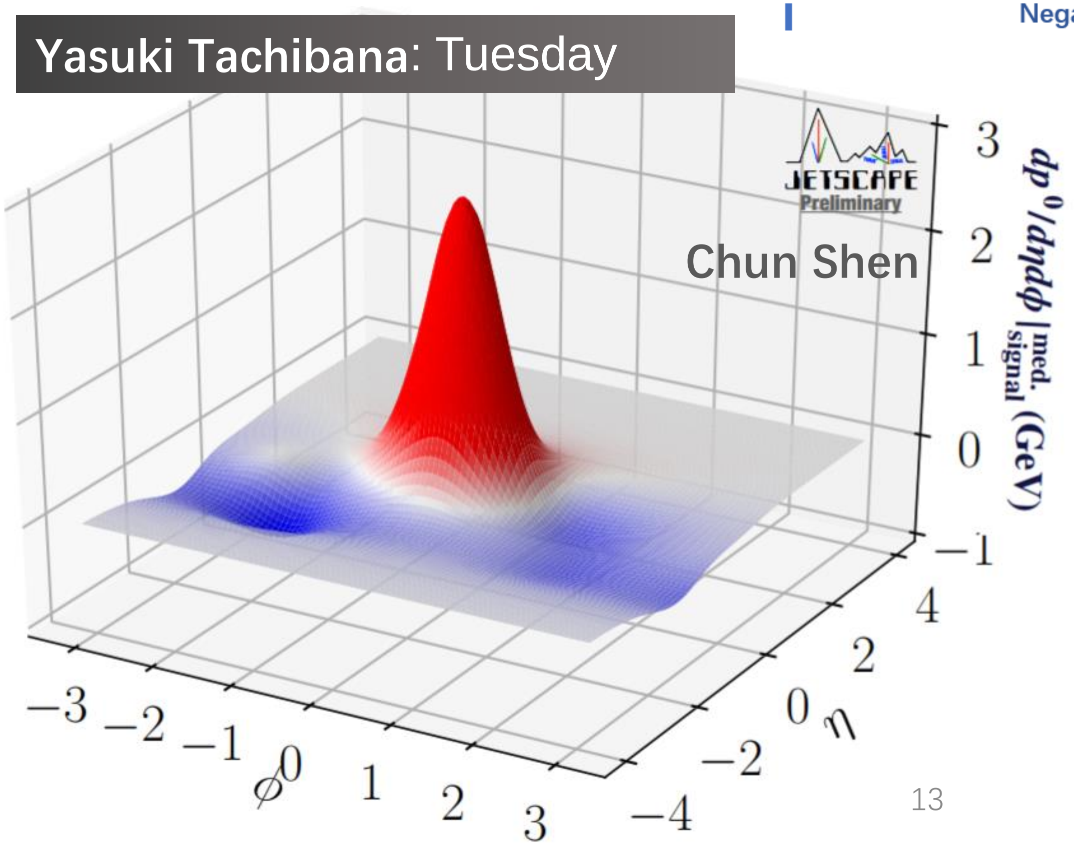
Jet induced medium response

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

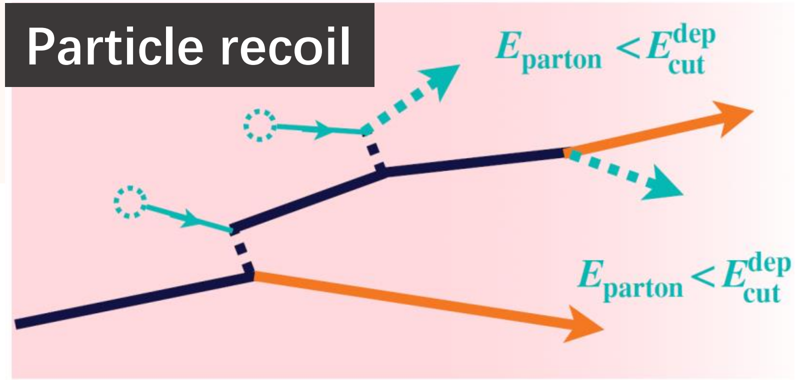
Energy propagated to large open angle and a negative wake in the back direction.







Particle recoil vs Hydro response

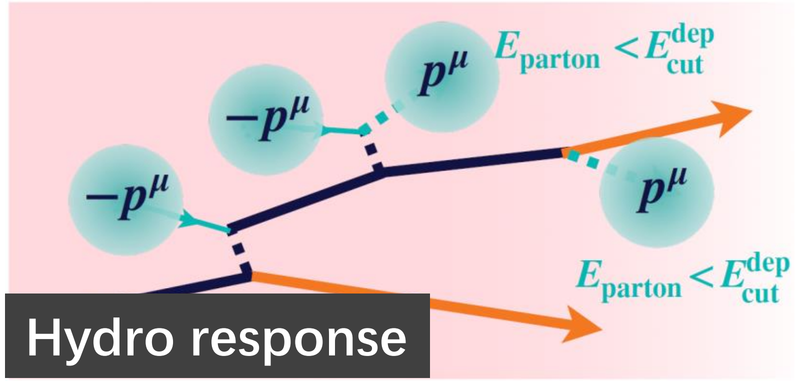


MATTER + LBT (w/ Recoil)

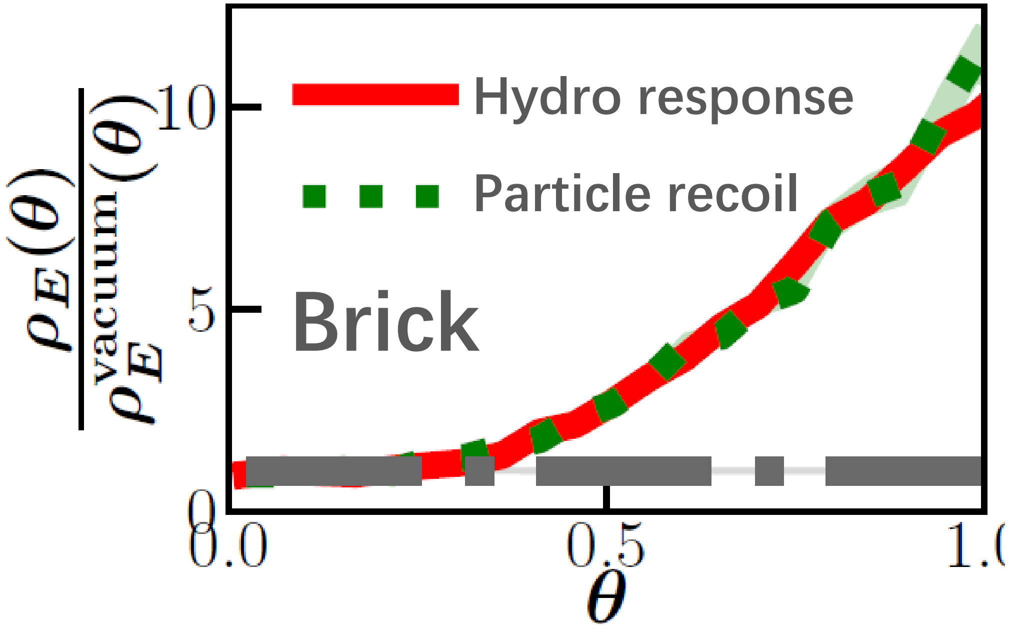
E_{dep} = 1 GeV for brick

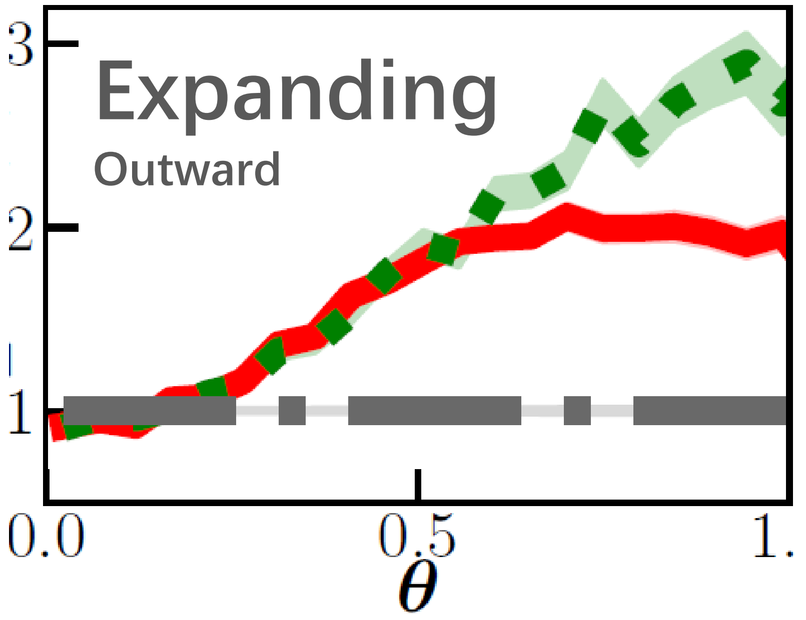
E_{dep} = 2 GeV for expanding

- Not much difference in brick.
- Difference in an expanding medium.
- Fluid plays very important roles in energy diffusion process.

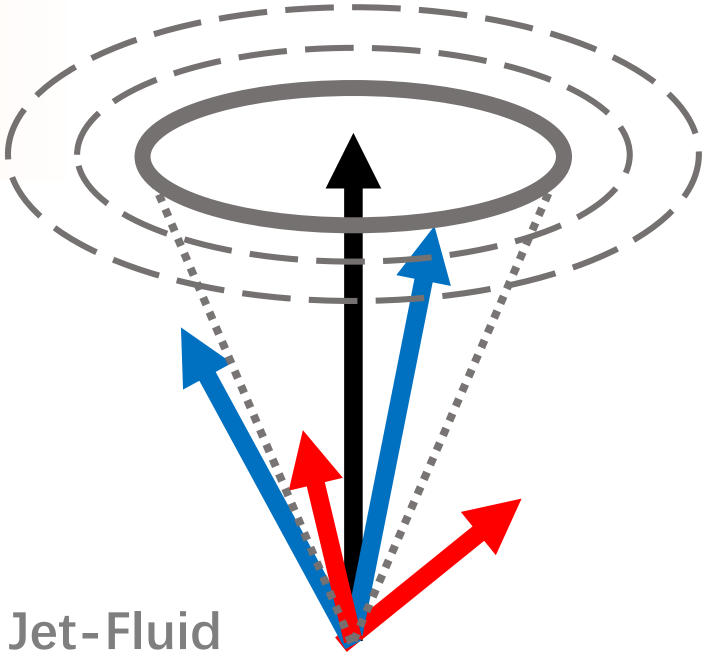


Abhijit Majumder, Yasuki Tachibana, Chun Shen





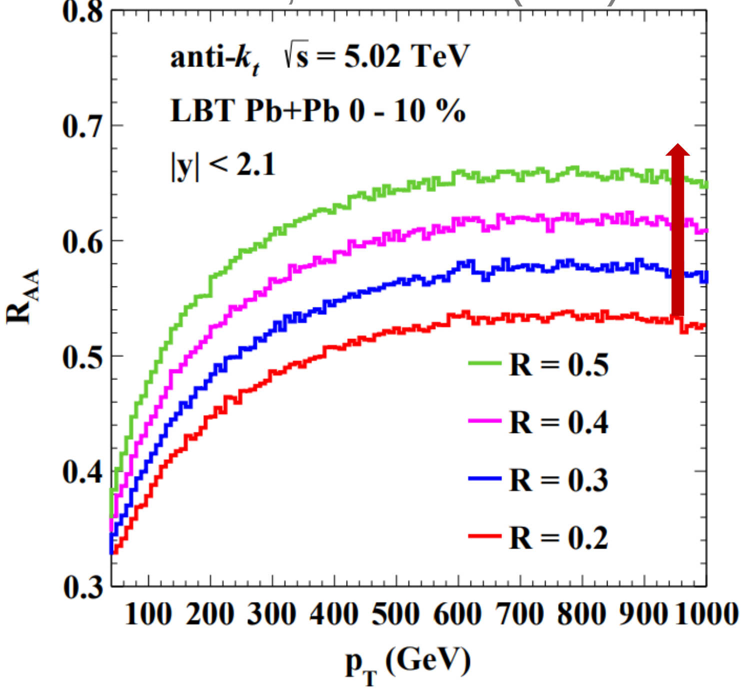
Single jet suppression



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

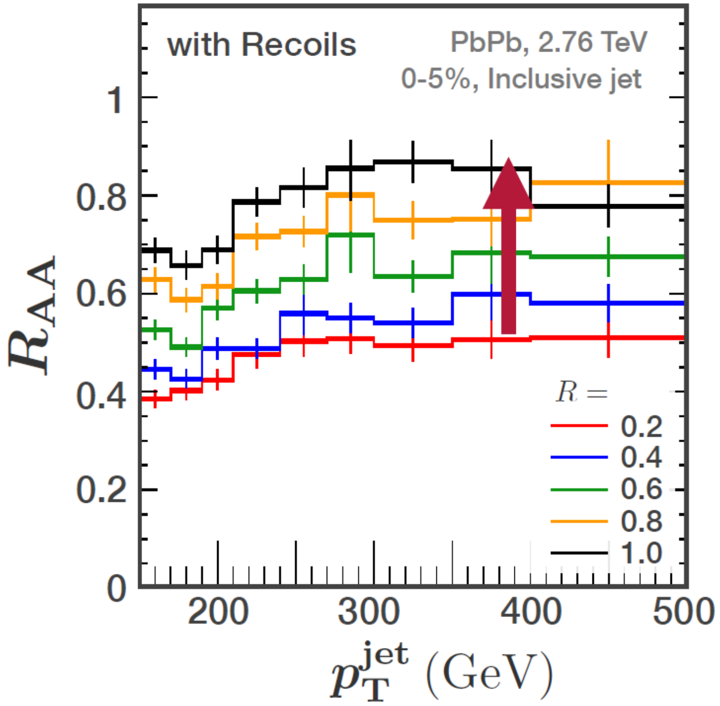
LBT

Y. He et al, 1809.02525 (2018)



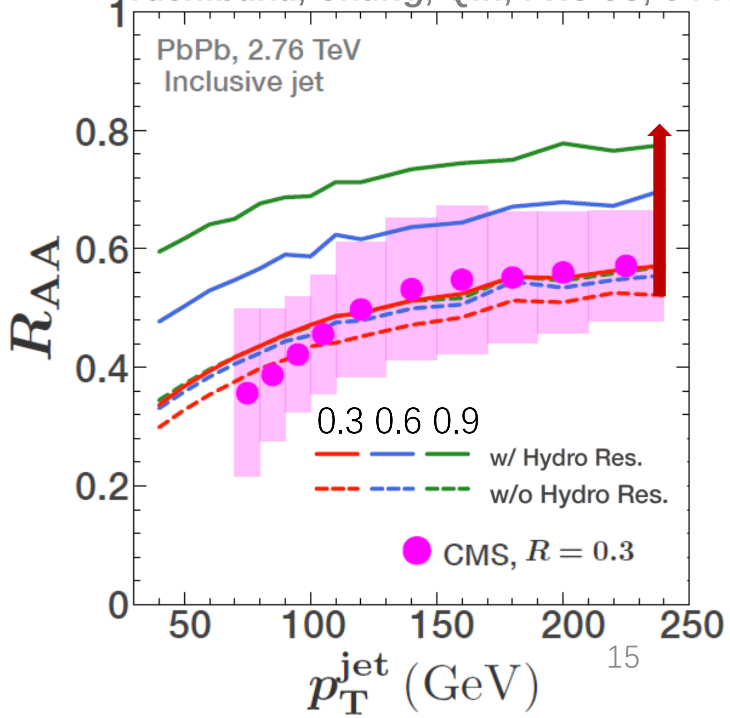
JEWEL

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

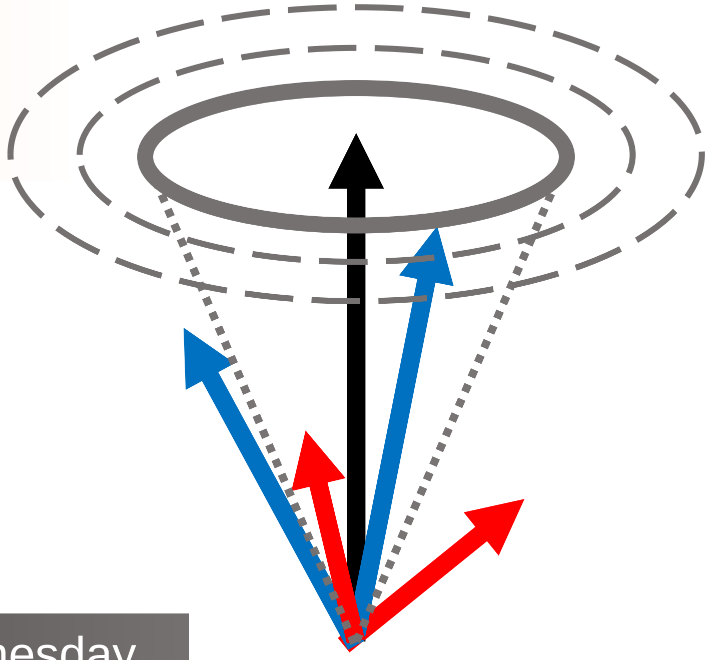


Jet-Fluid

Tachibana, Chang, Qin, PRC 95, 044909



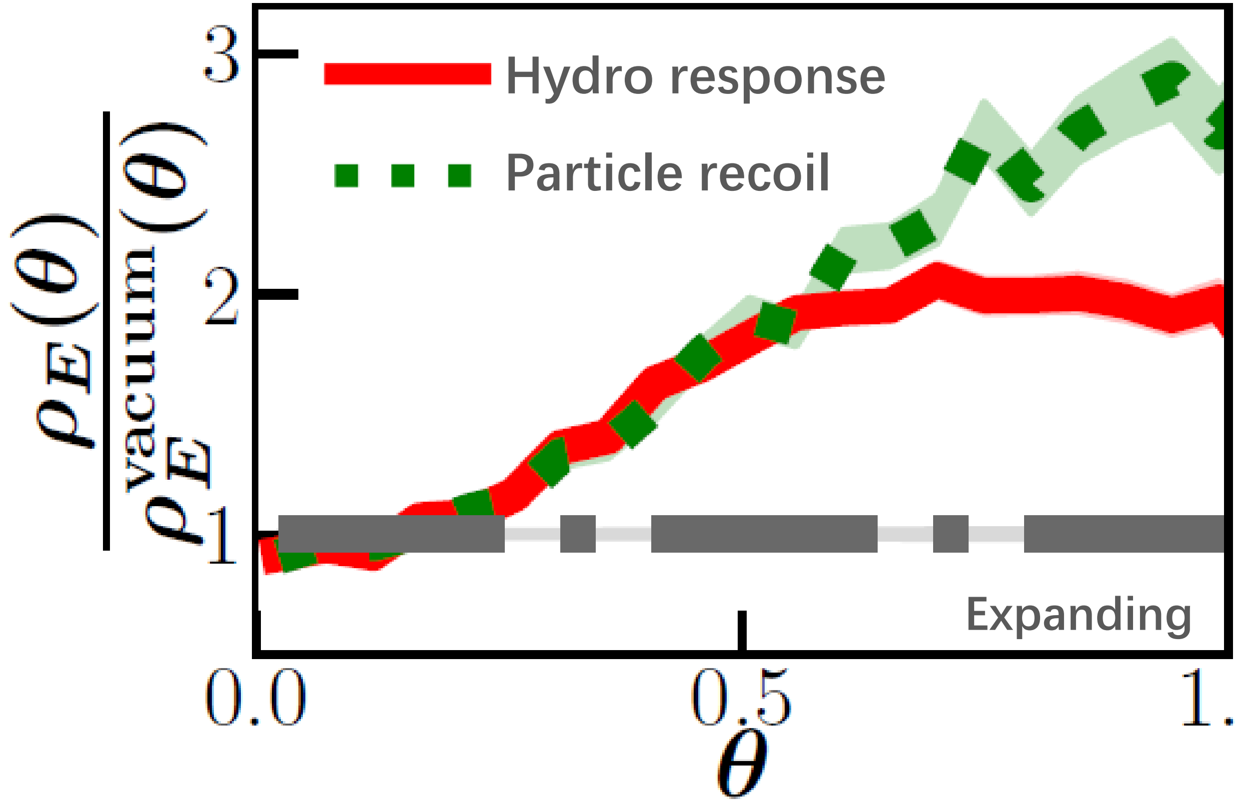
Single jet suppression



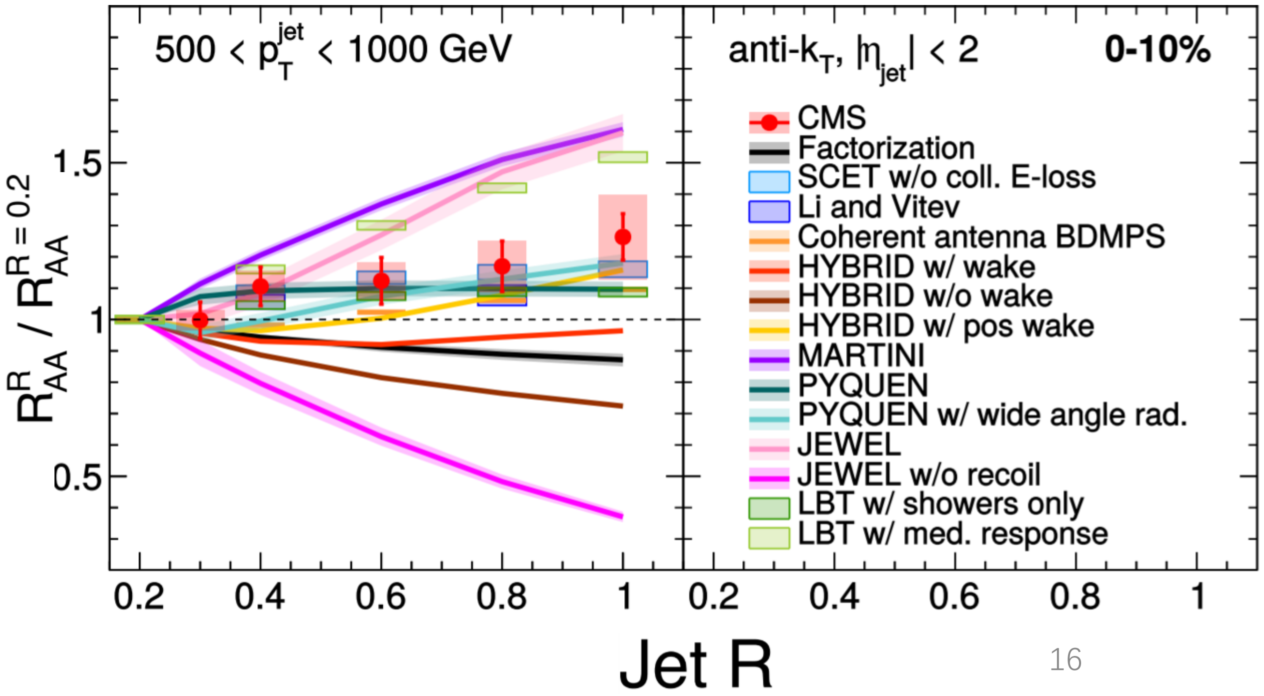
- Smaller cone size dependence → slower energy recovery.

Hydro response ?

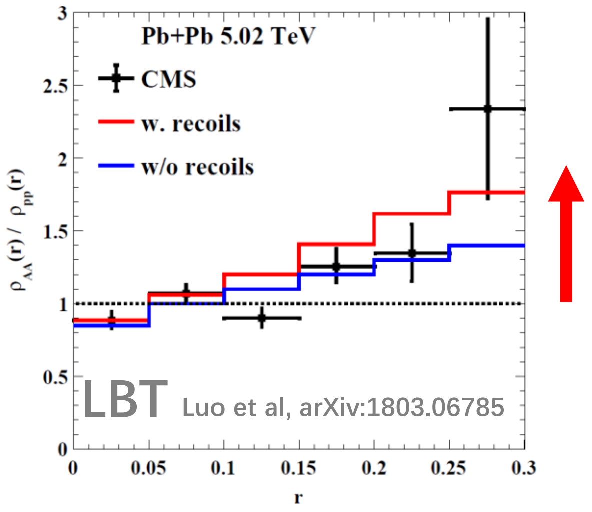
- Background subtraction.

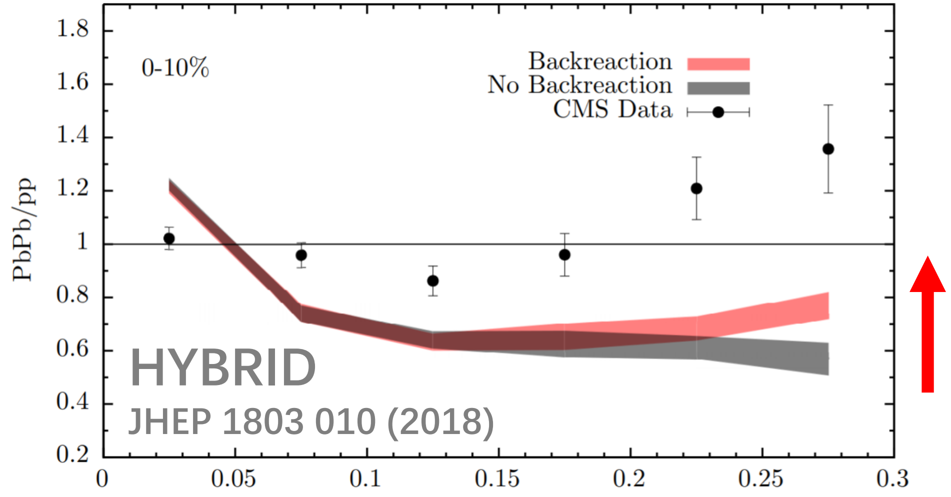


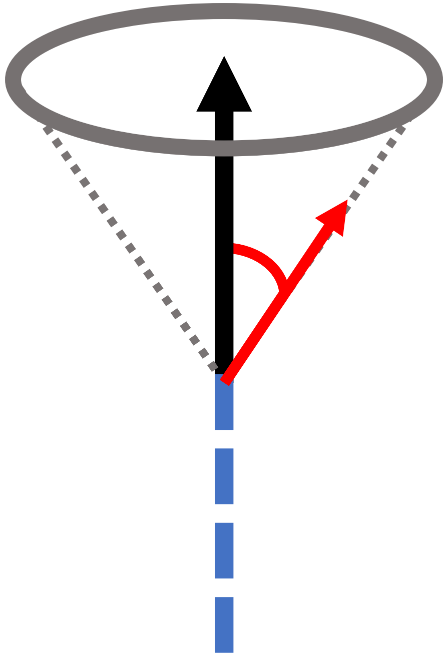
Molly Taylor : Wednesday



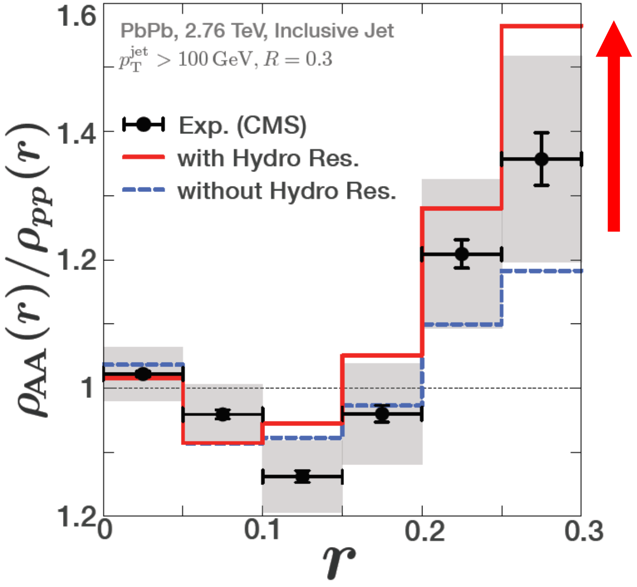
Jet shape (inside jet cone)



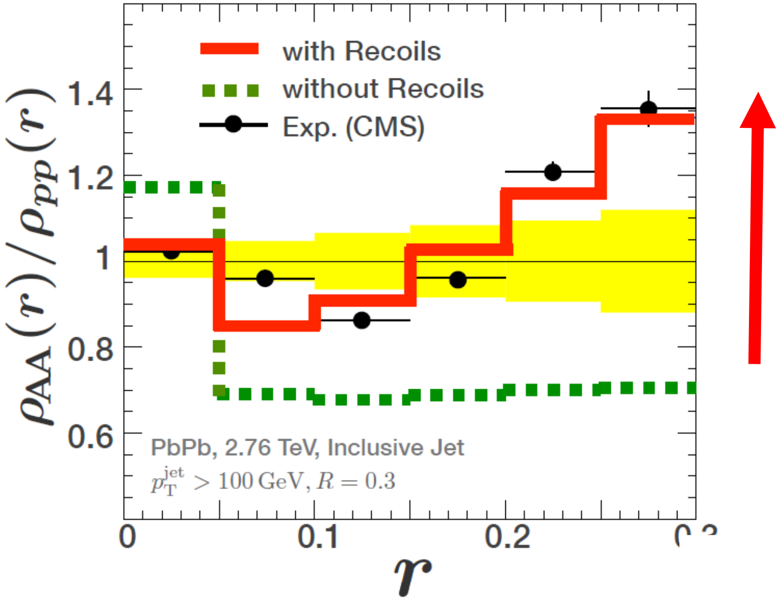




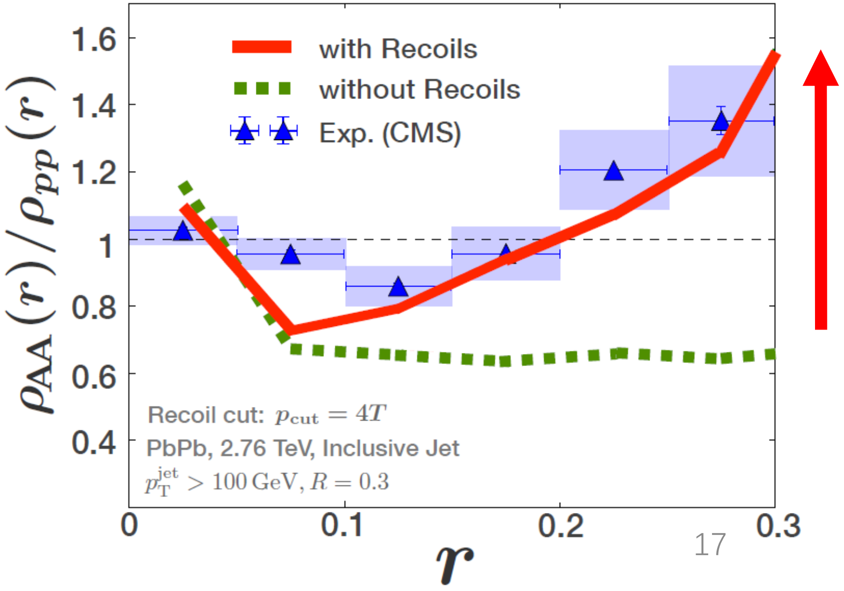
Jet-Fluid Tachibana, Chang, Qin, PRC 95, 044909



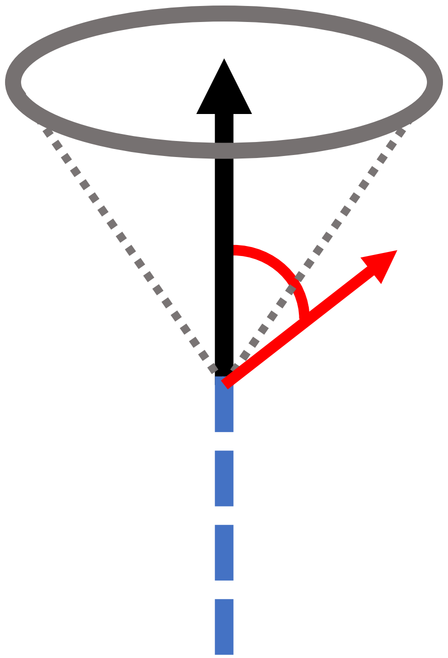
JEWEL R. K. Elayavalli, K. C. Zapp, JHEP 1707, 141



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



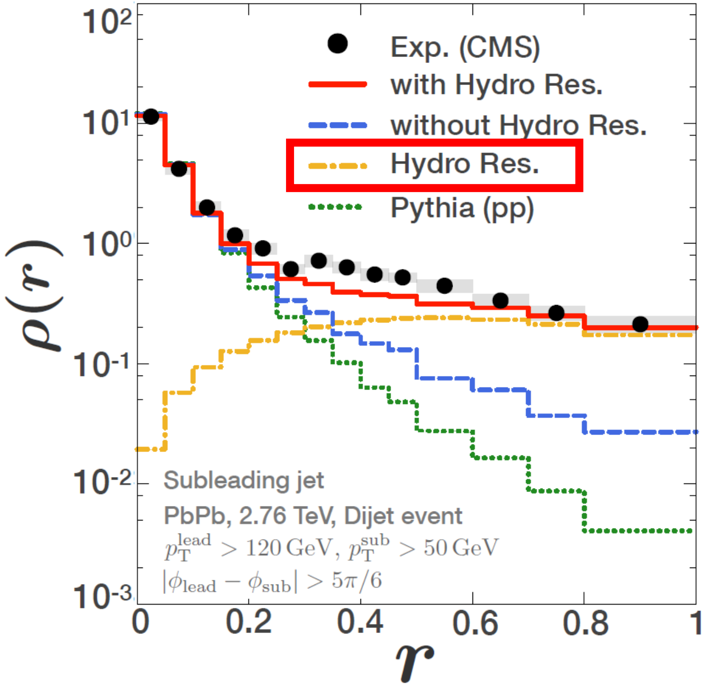
Jet shape (outside jet cone)



- 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.

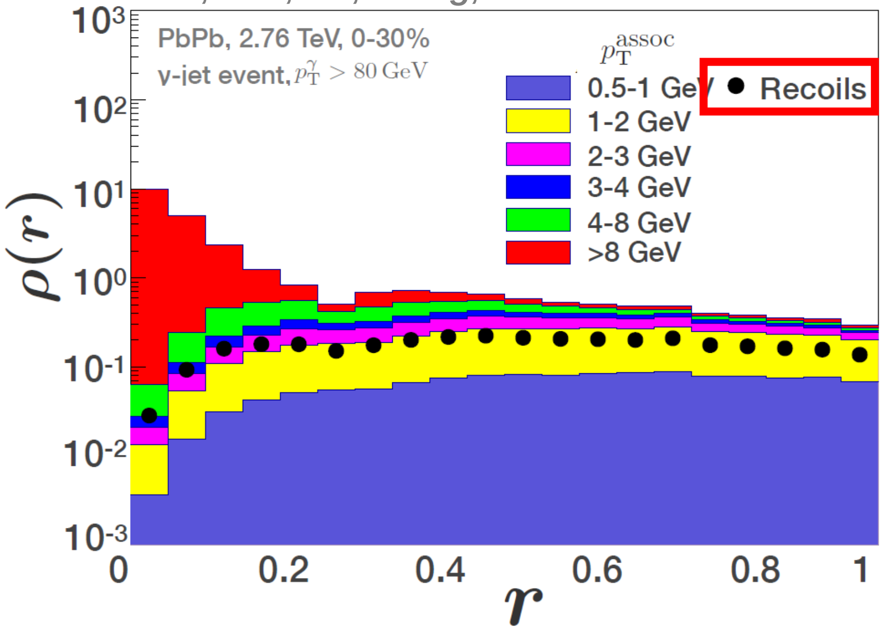
Jet-Fluid

Tachibana, Chang, Qin, PRC 95, 044909

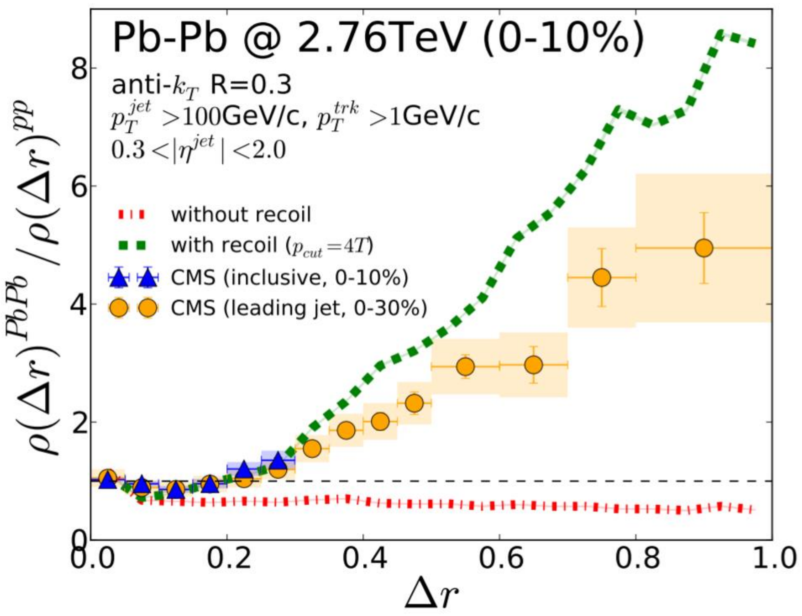


LBT

Luo, Cao, He, Wang, arXiv:1803.06785



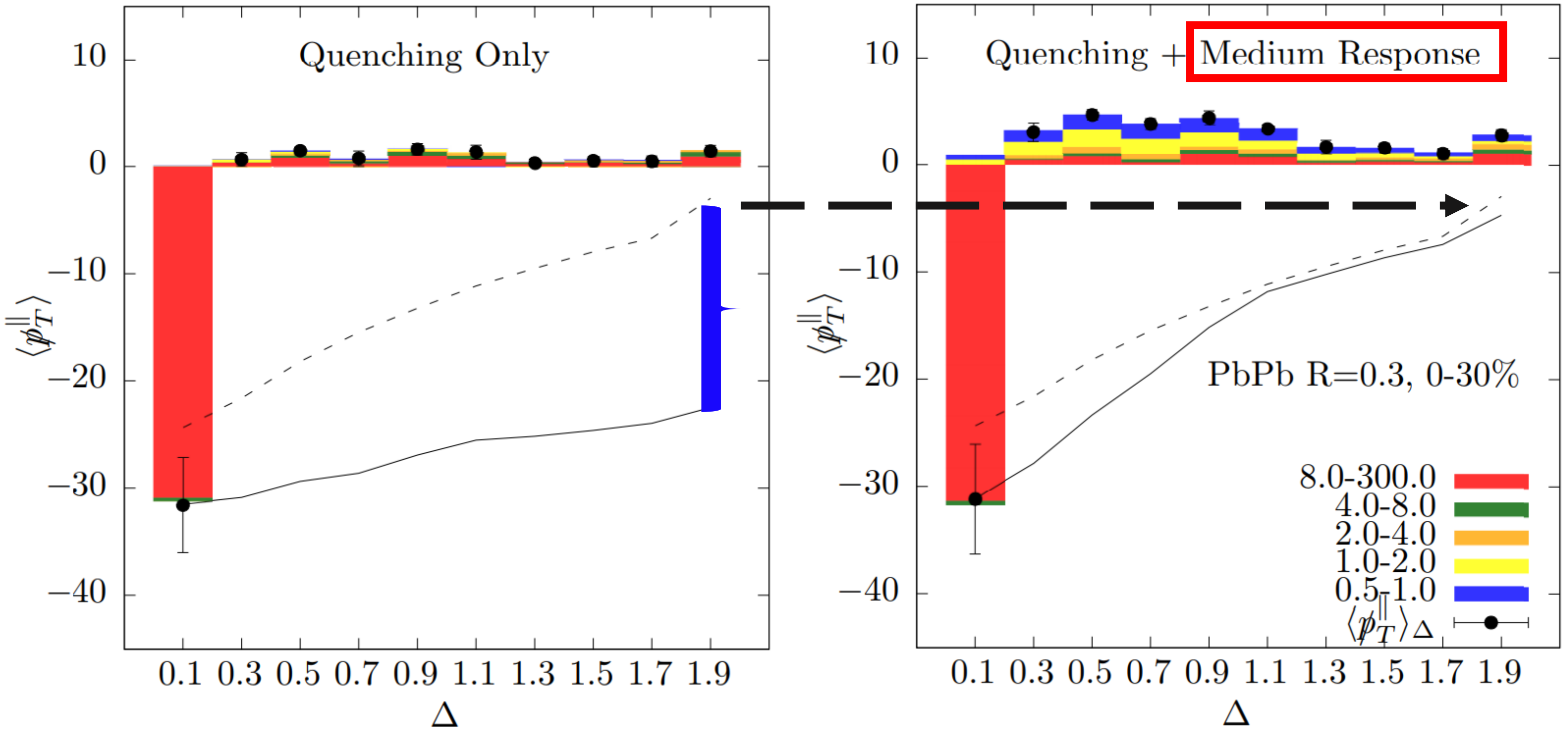
MARTINI C. Park, S. Jeon, C. Gale ('18)

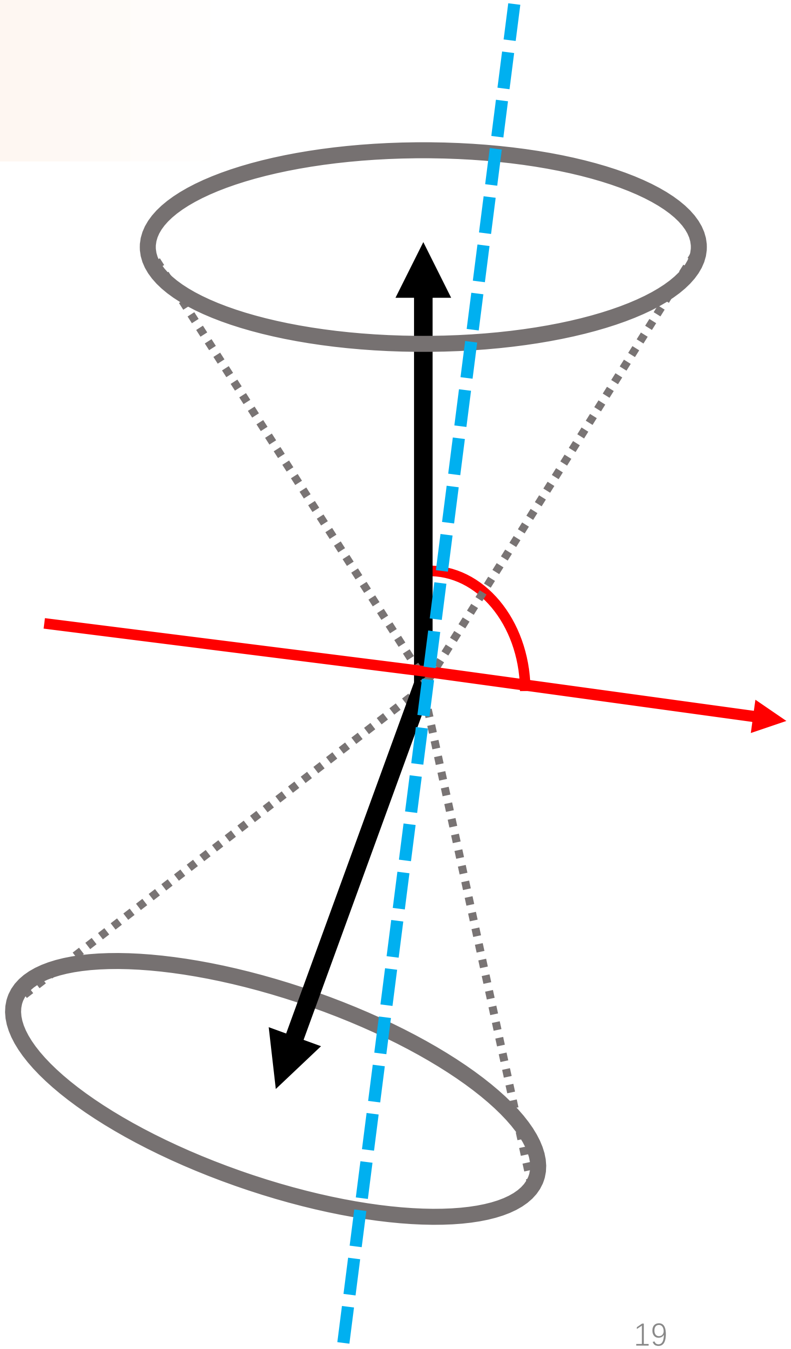


Missing pT (full picture)

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

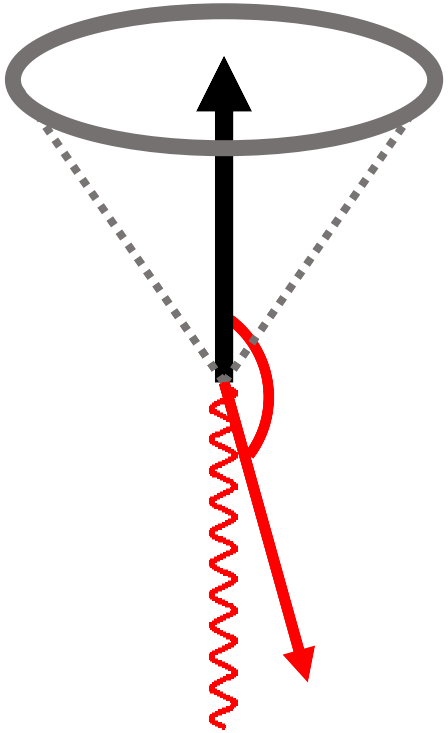
HYBRID Z. Hulcher, D. Pablos, K. Rajagopal, JHEP 1803 010 (2018)

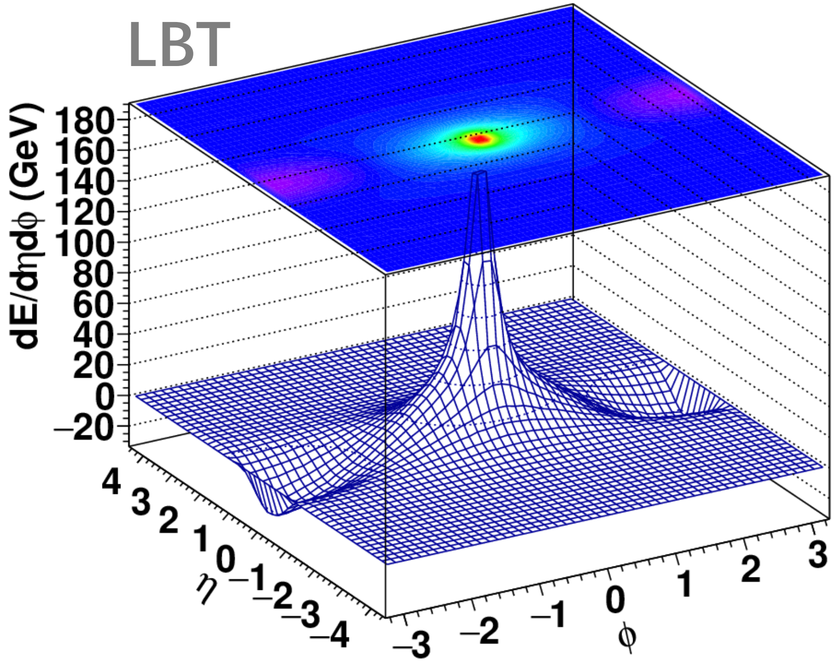


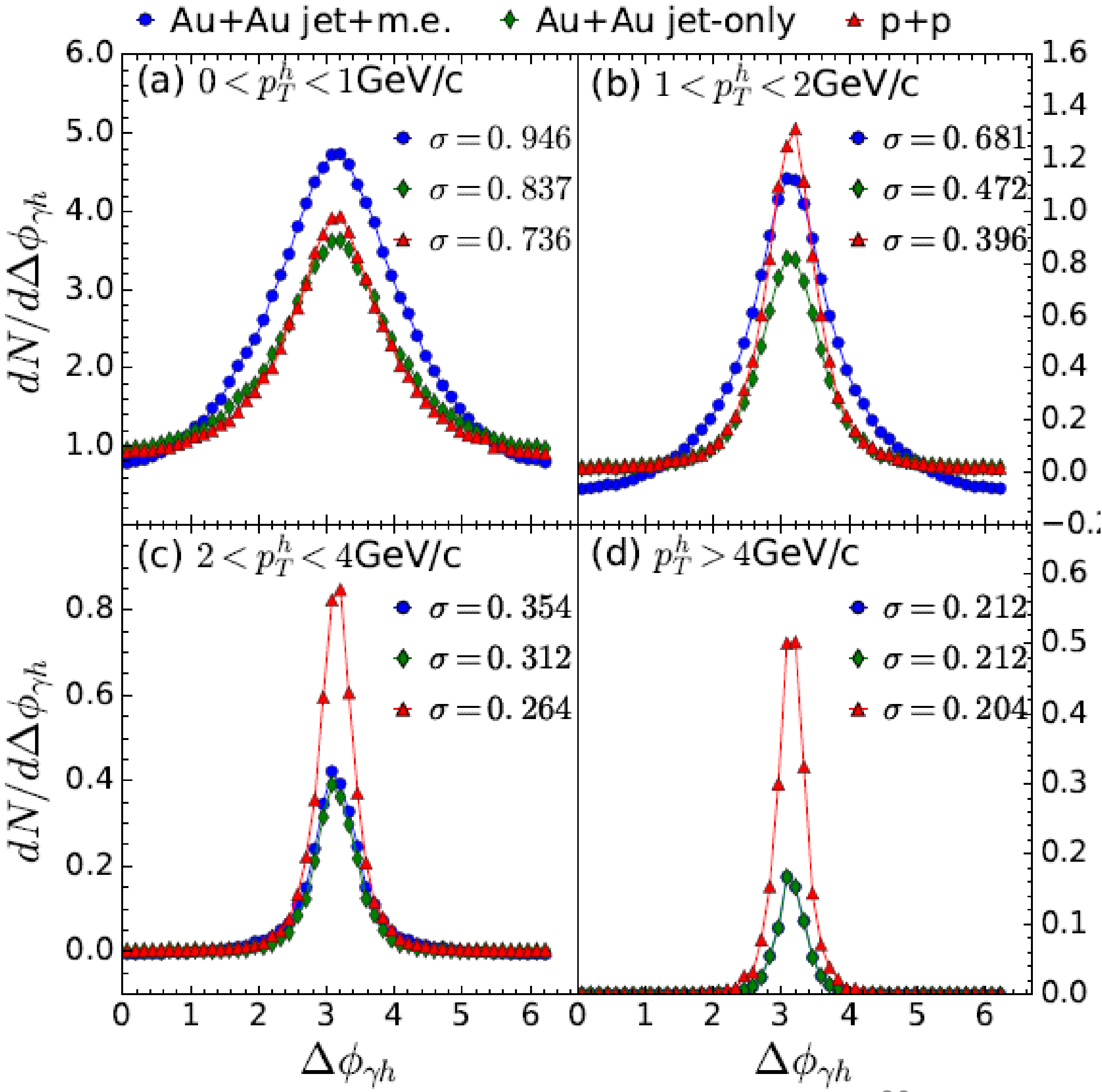


γ-hadron correlations (back direction)

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





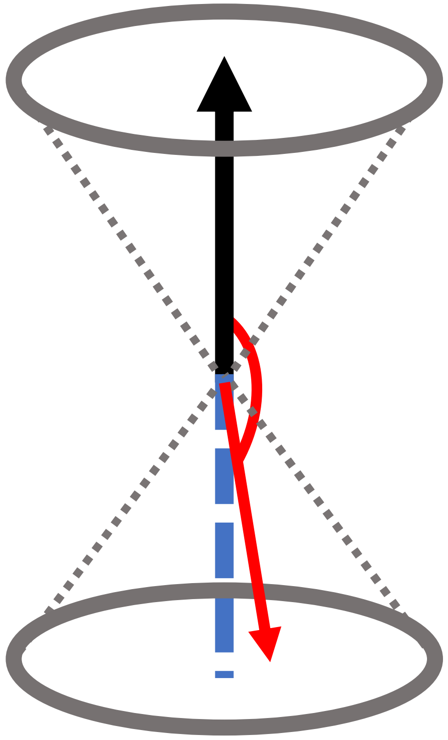


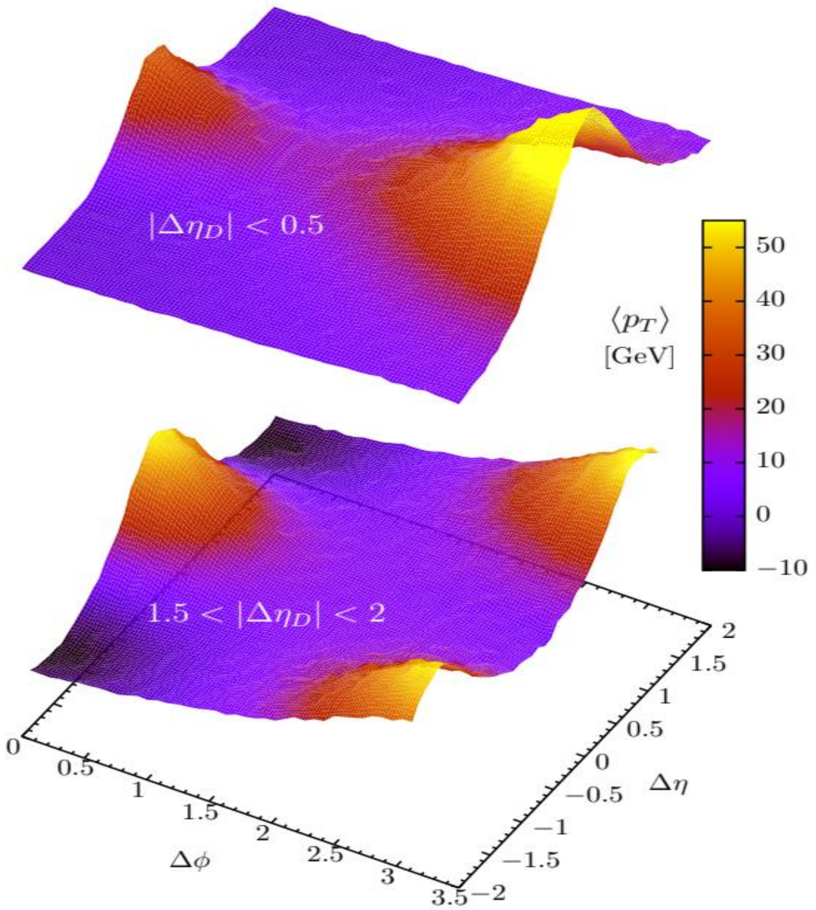
CoLBT-hydro Chen, Cao, Luo, Pang, Wang Phys.Lett. B777 (2018) 86-90

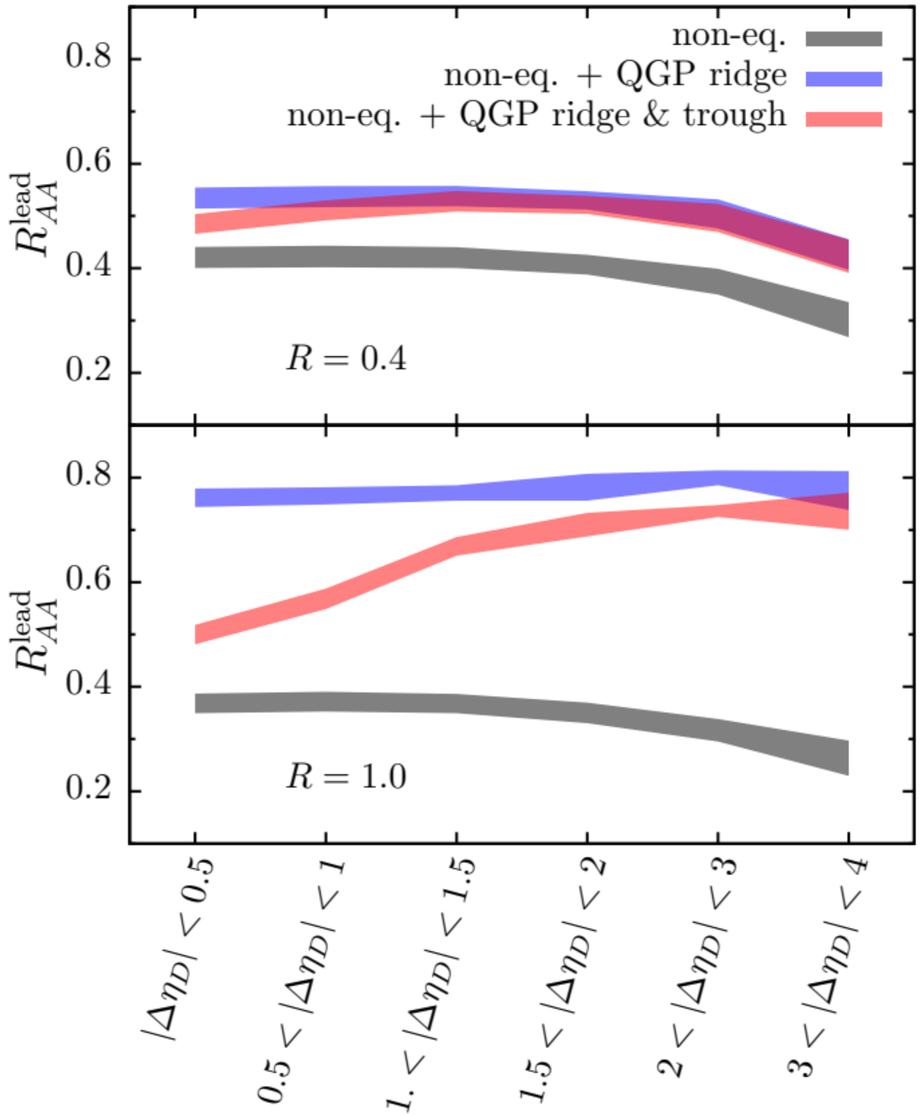
Leading jet suppression in dijet event (diffusion wake)

- 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





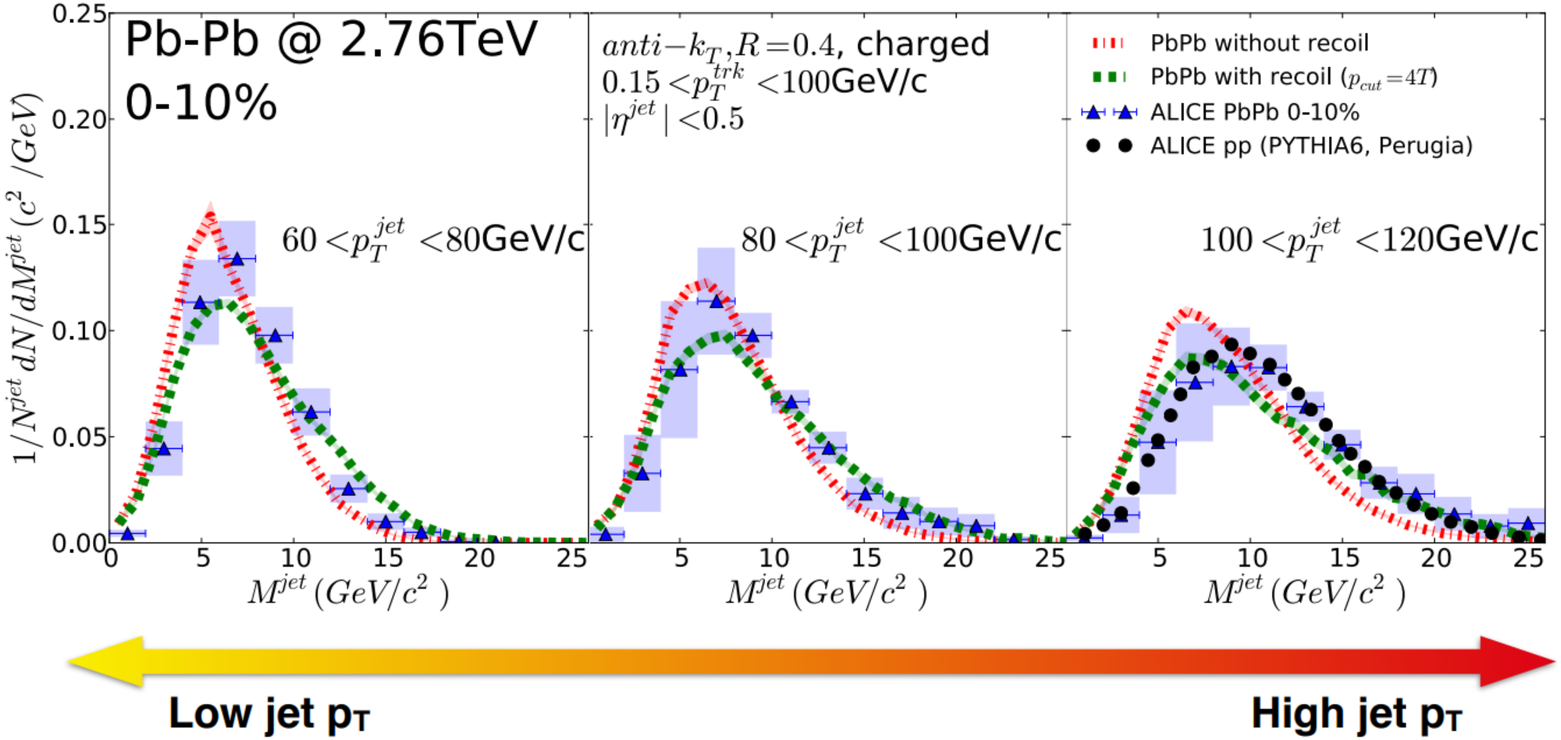


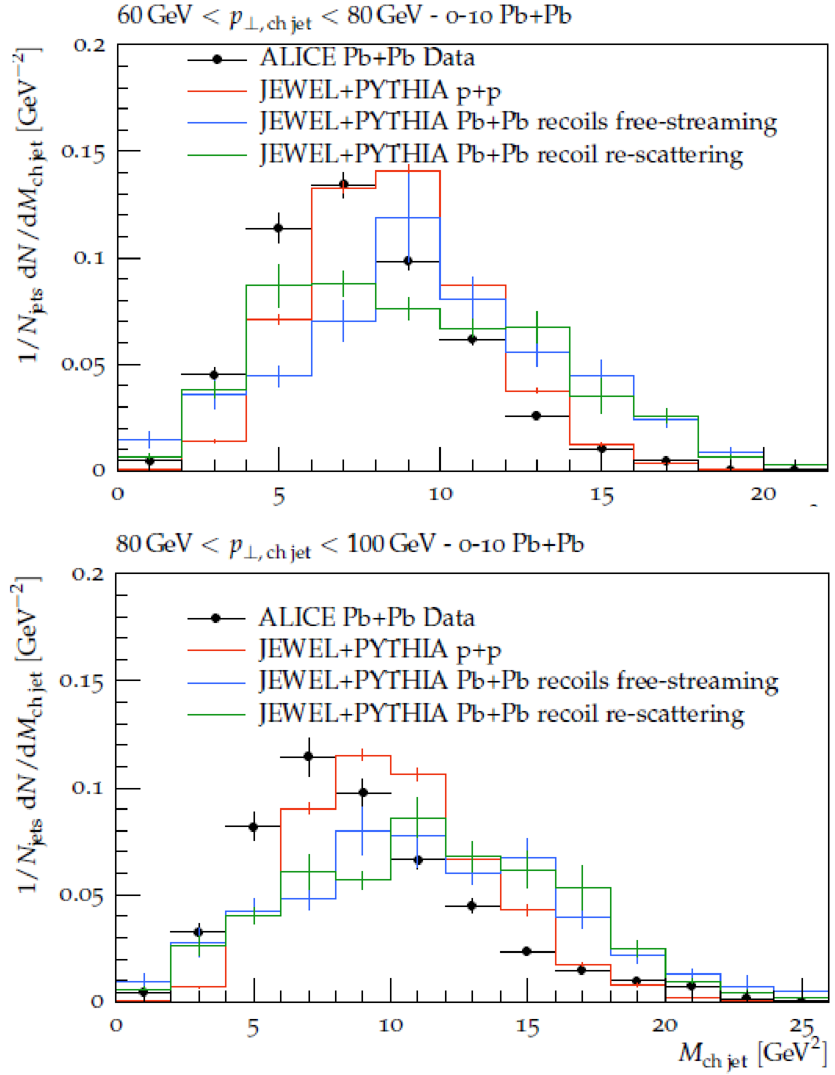
Jet mass

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

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

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





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

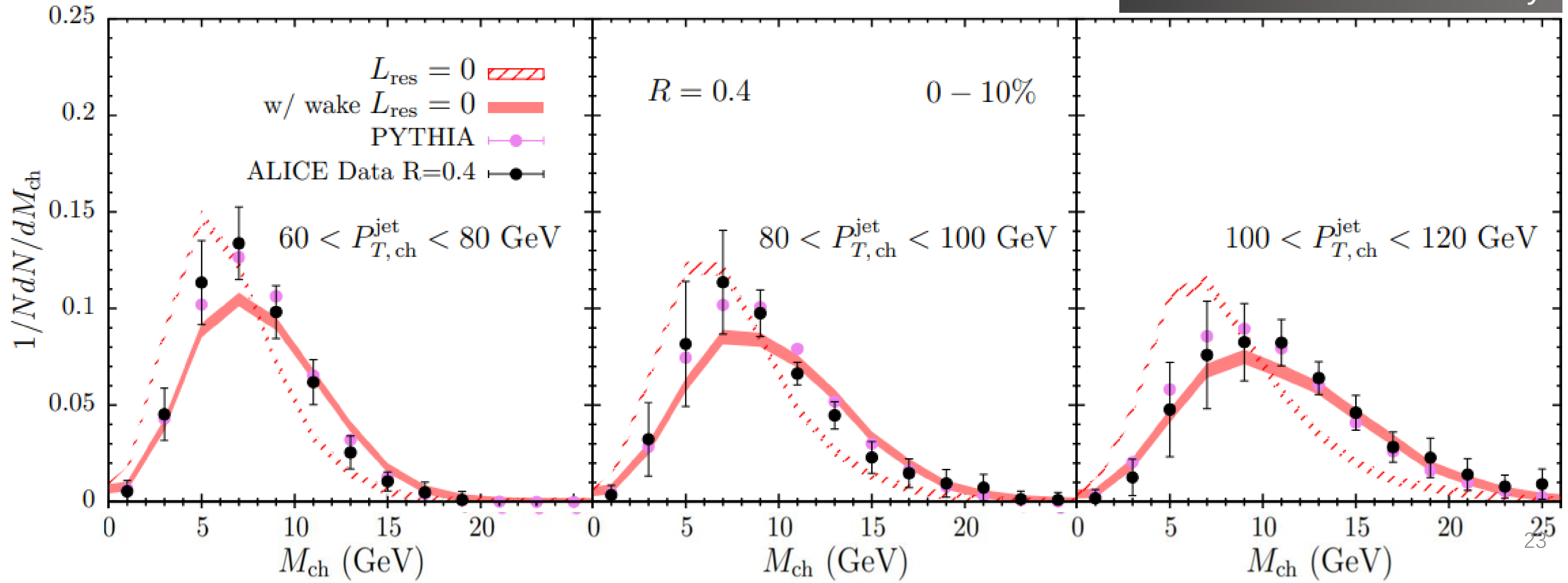
Jet mass

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

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

HYBRID Casalderrey, Milhano, Pablos, Rajagopal arXiv:1907.11248

Daniel Pablos: Wednesday

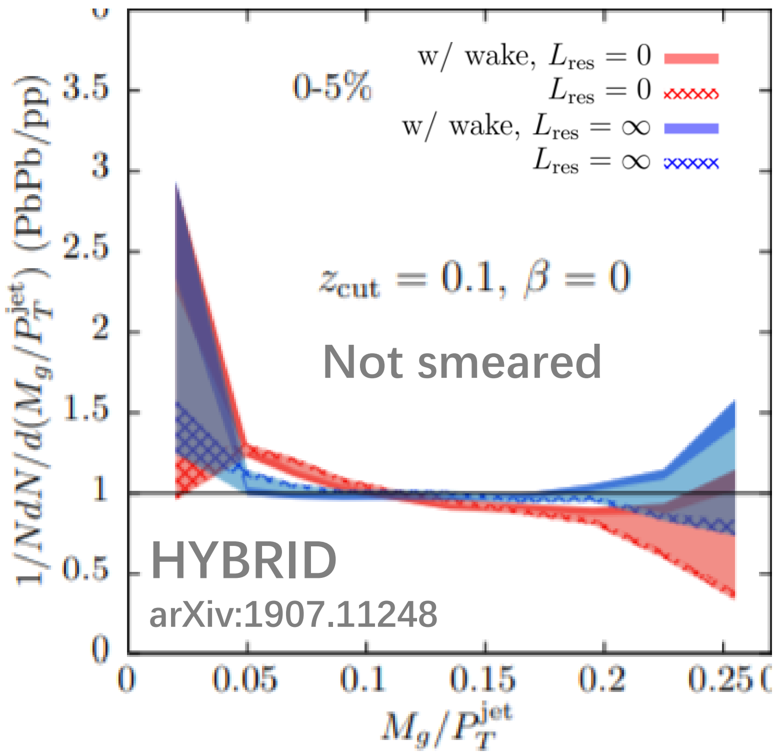


Groomed jet mass

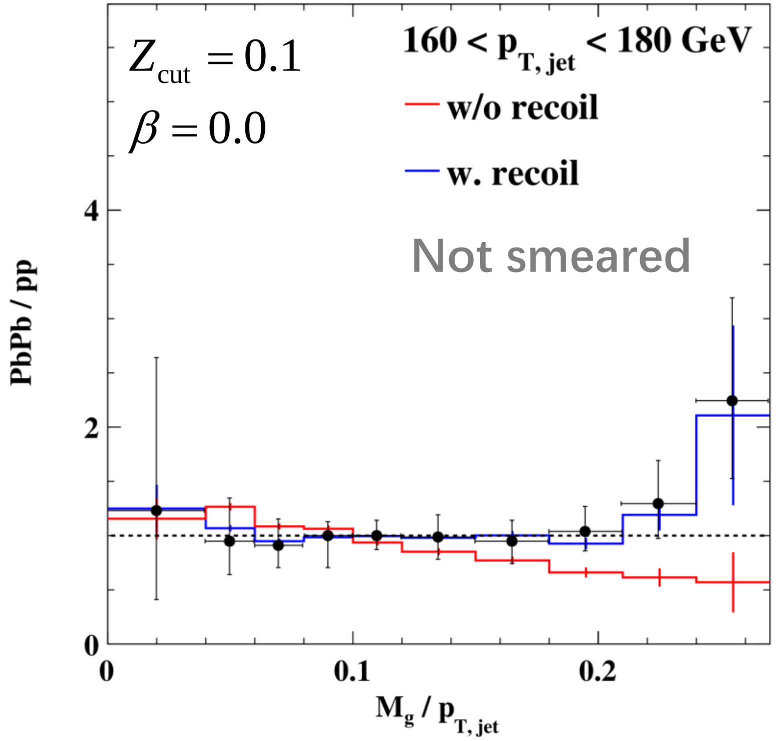
$$\frac{M_g}{p_T^{jet}} = \frac{\sqrt{(E_1+E_2)^2 - (\vec{p}_1+\vec{p}_2)^2}}{p_T^{jet}}$$

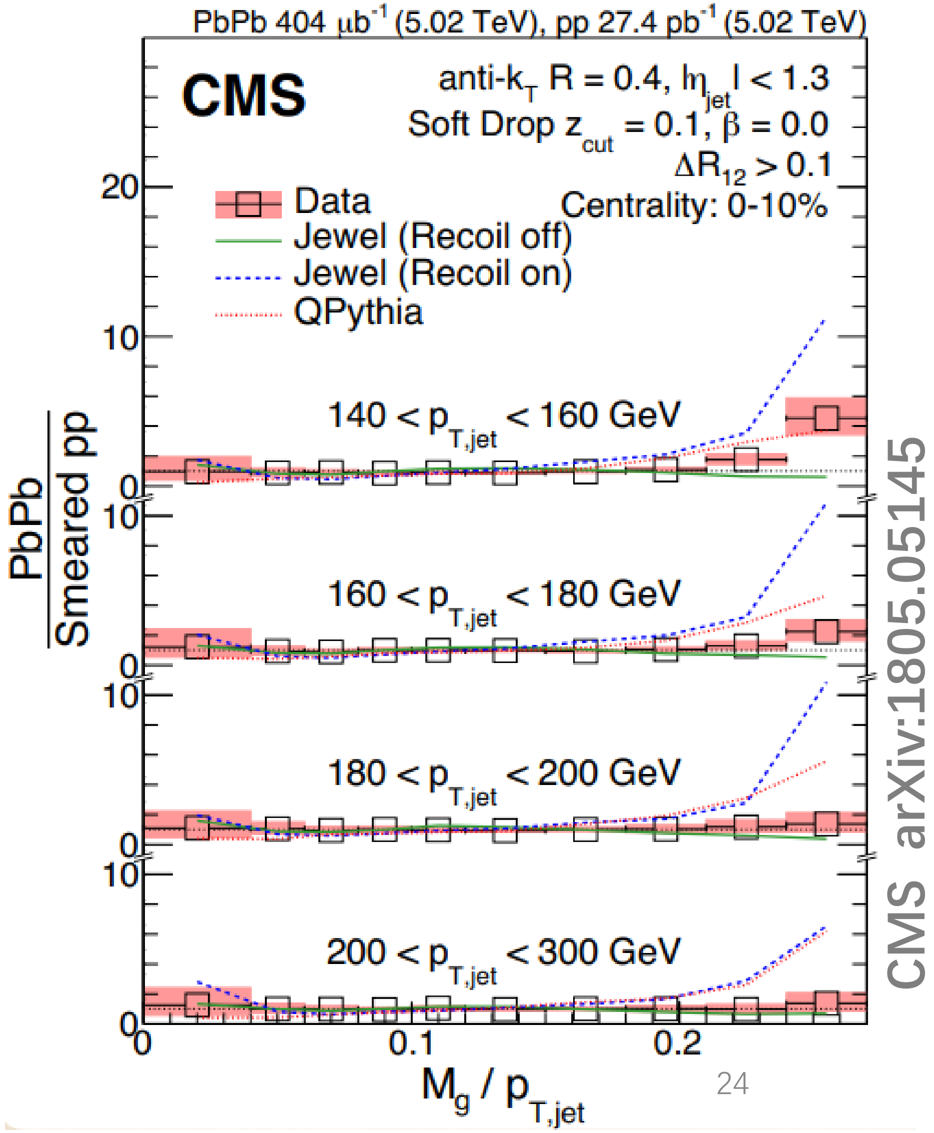
- Enhancement of the large mass range.
- The rise in large mass tail is caused by medium response in JEWEL, LBT and Hybrid.

Daniel Pablos: Wednesday



LBT Luo, Cao, He, Qin, Wang





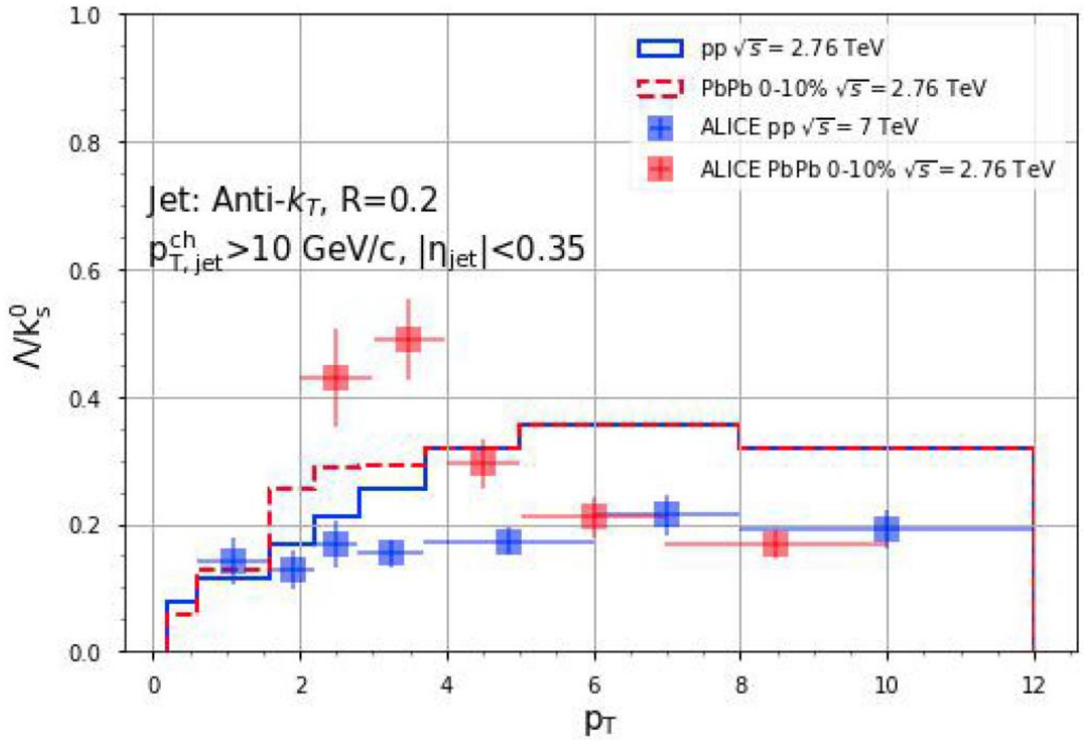
Particle ratio inside jet

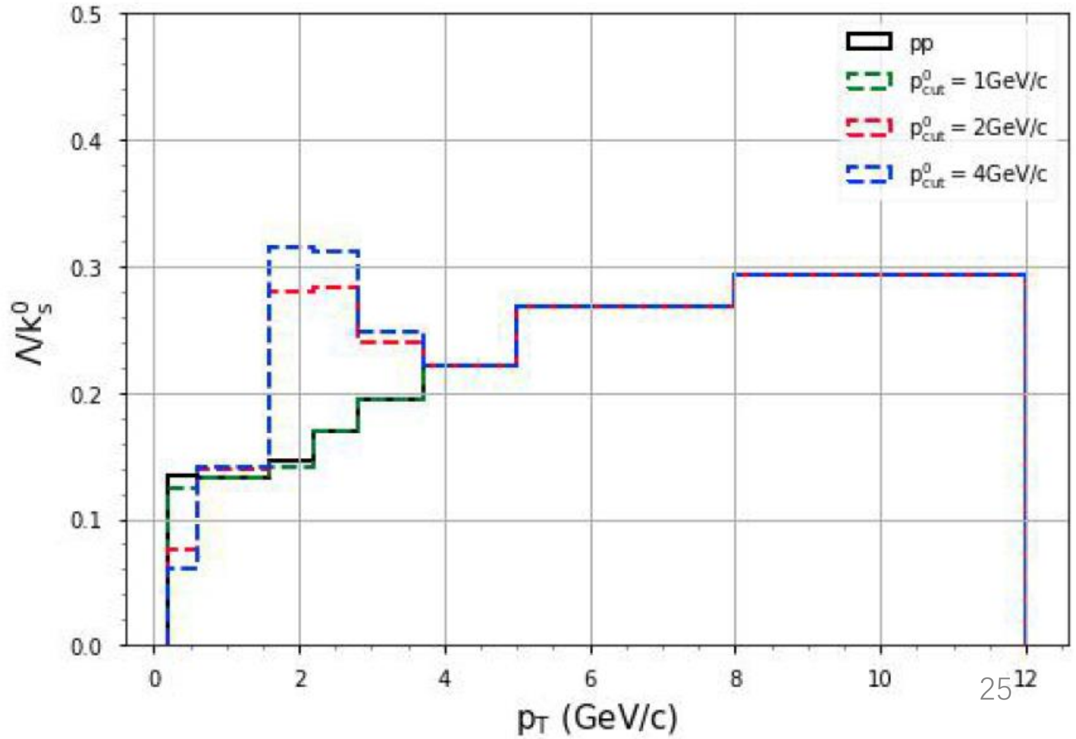
- Strange baryon-to-meson ratio in jet increases at intermediate pT range in Pb-Pb collisions.

- Sensitive to the deposition energy cut p_{cut}^{0} between hard and soft.

CoLBT-hydro

Wei Chen: Tuesday





Summary

- To achieve a consistent description of jet-medium interactions with total energy momentum conservation we need to include the jet induced medium response.

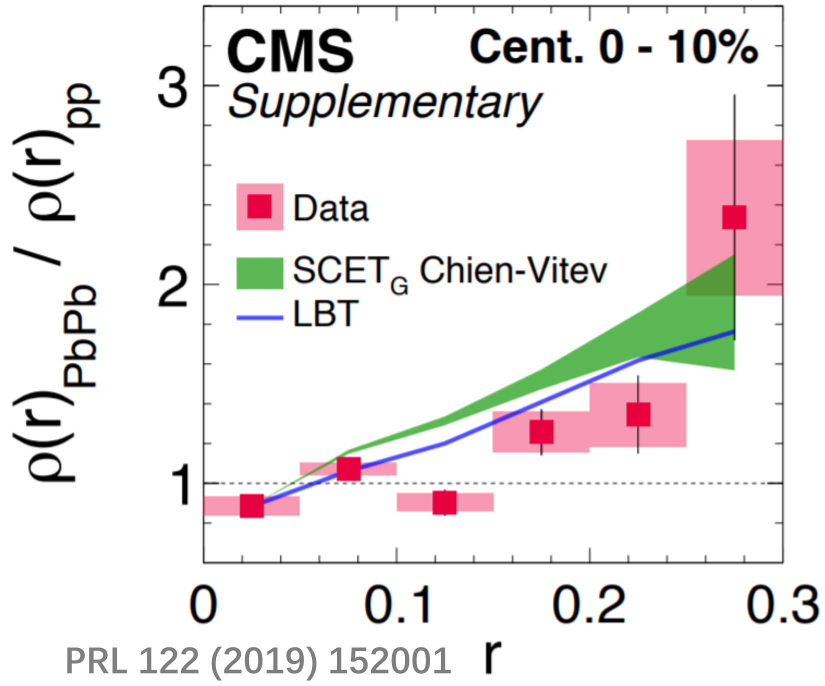
- Two ways for the implementation of medium response.
(Particle recoil vs Hydro response)

- Medium response effect in various jet observables especially on the enhancement of the soft particles at the large angle around jets.

Summary

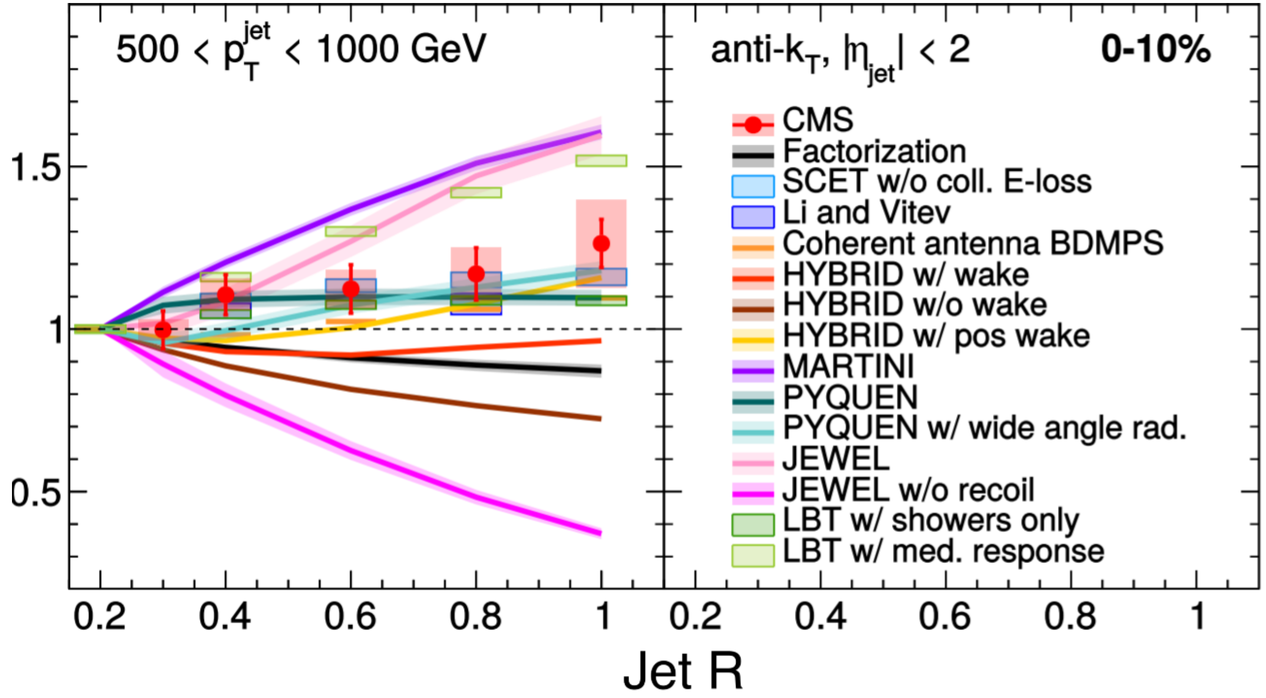
- What do we learn ?

Ran Bi: Wednesday



PRL 122 (2019) 152001

Molly Taylor : Wednesday

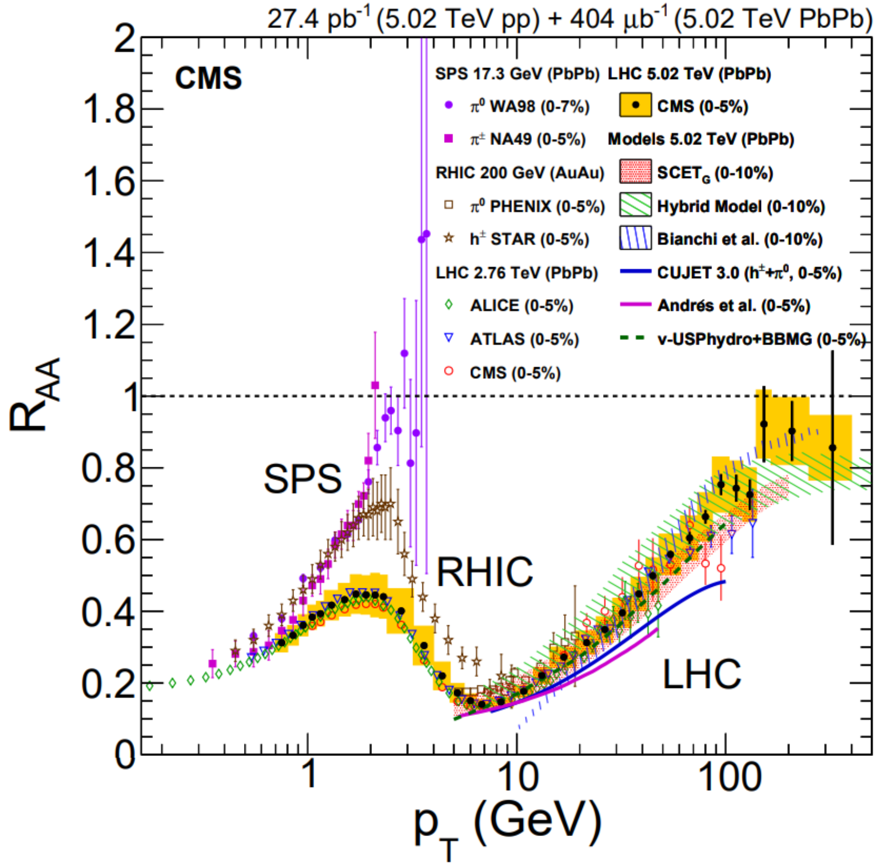


- **Unique identification of medium response effect in jet**

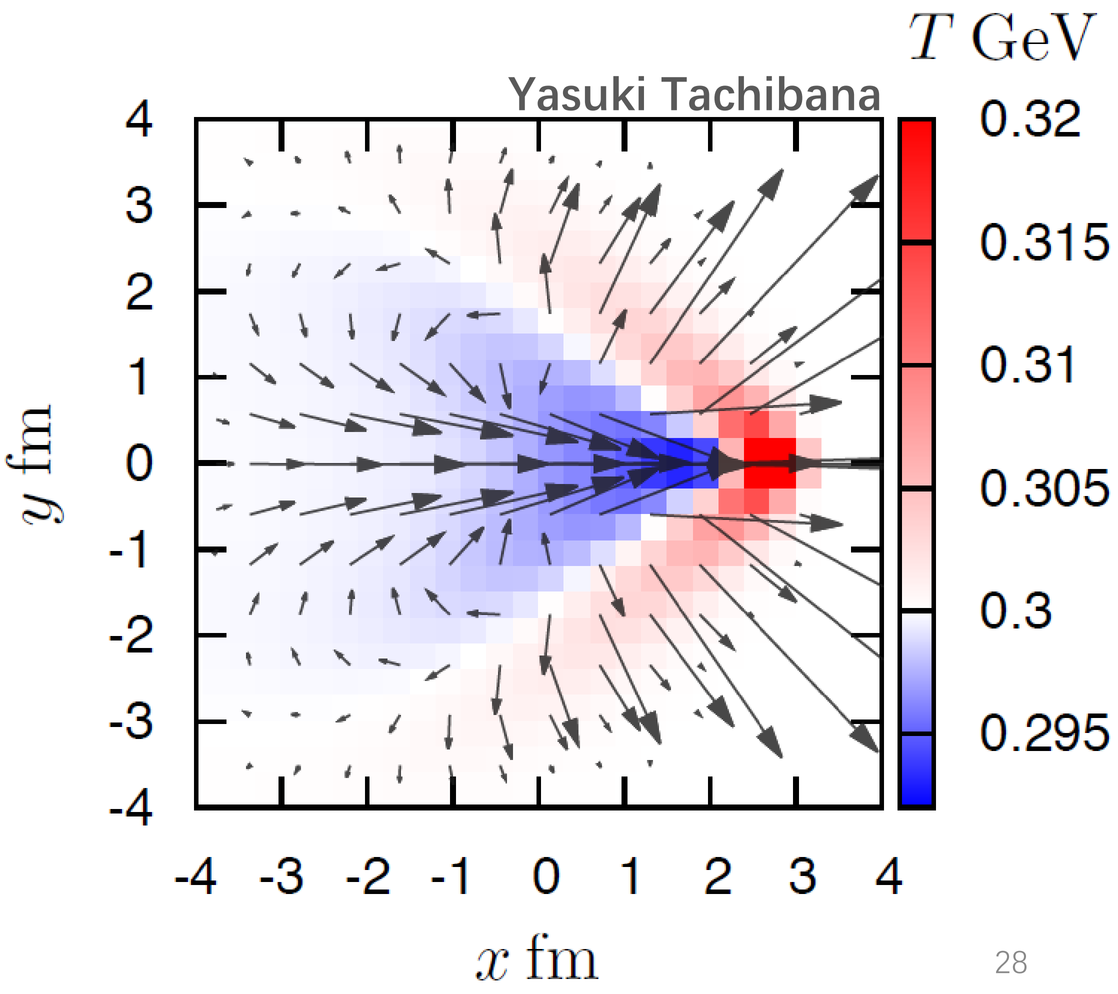
  Diffusion wake, Particle ratio inside the jet

Outlook

- **Intermediate pT range**



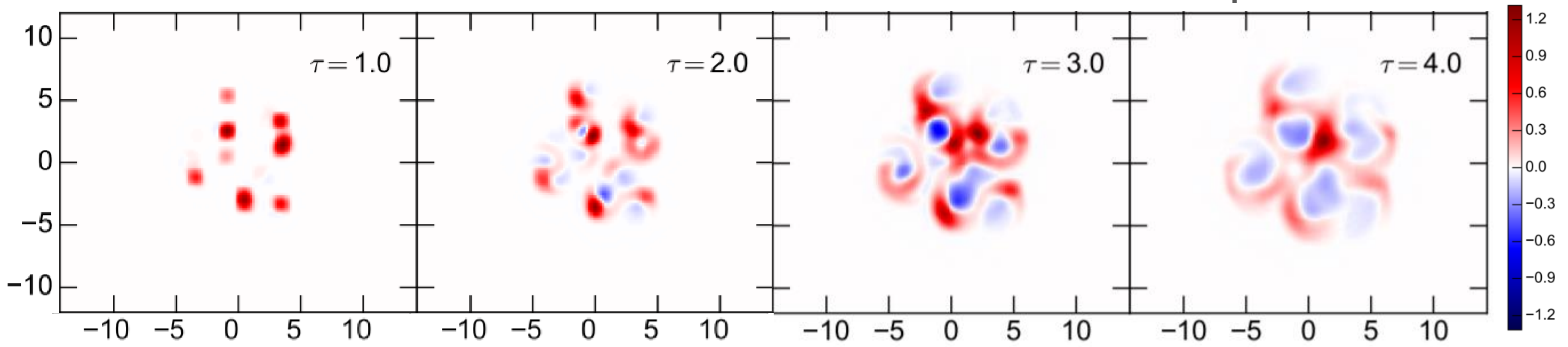
- **Searching for Mach Cone**



Outlook

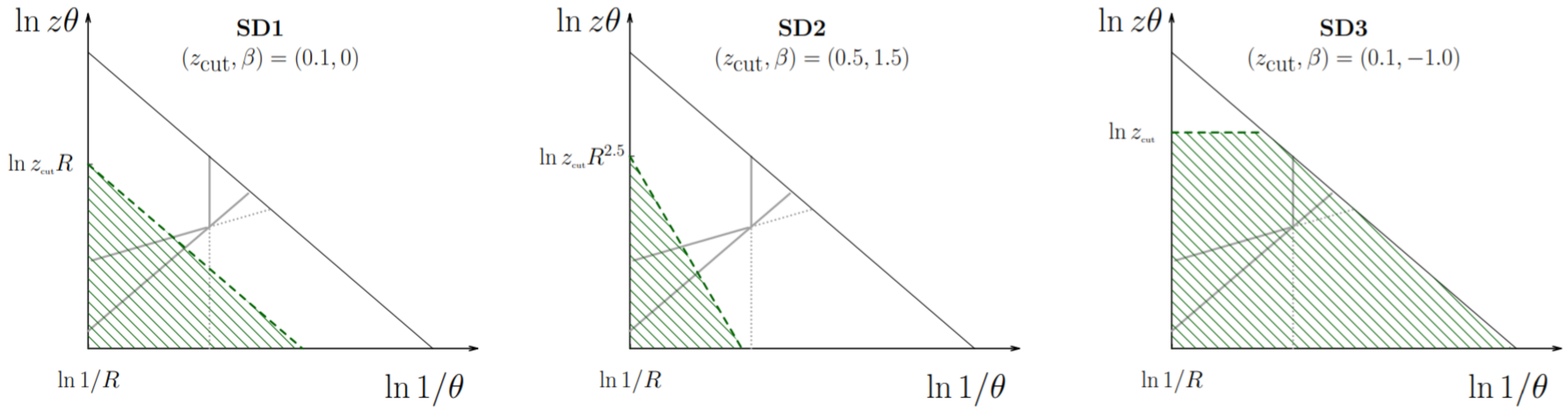
- **Jet interference**

Iurii Karpenko HP2018



- **Searching in phase space with jet grooming**

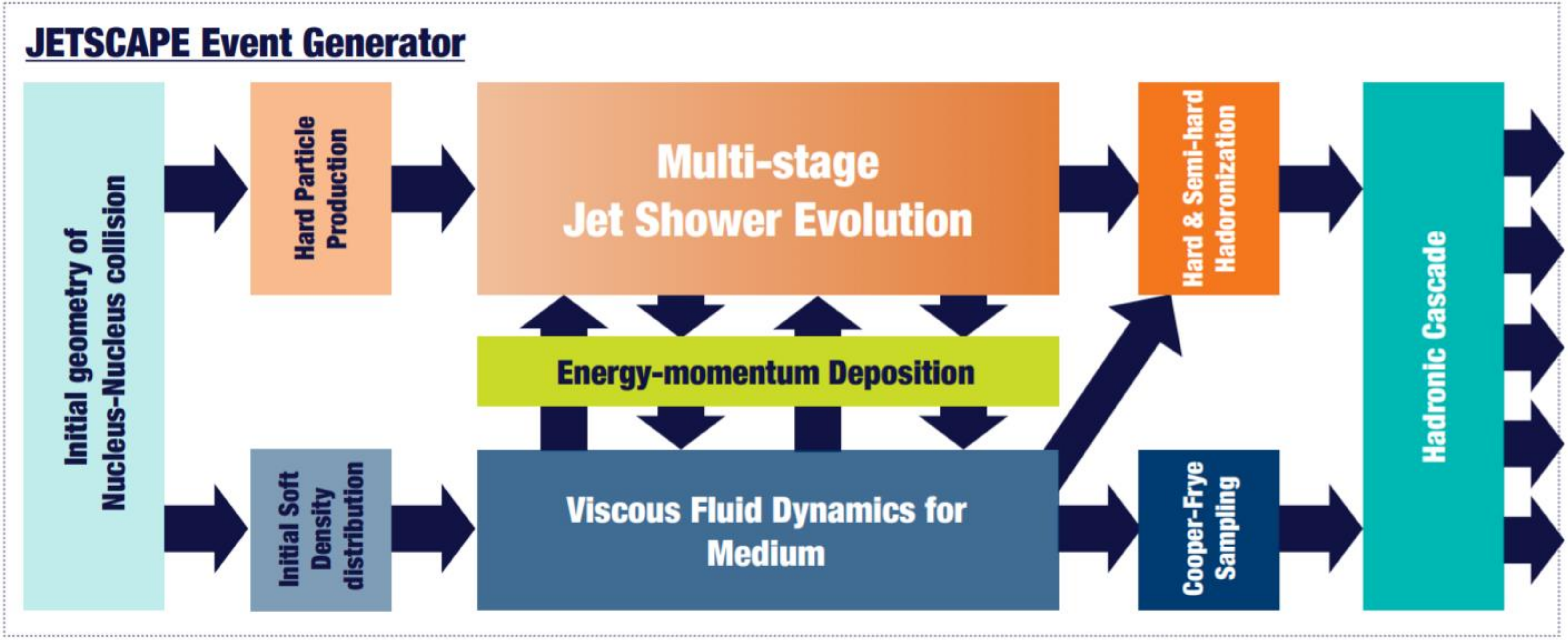
Andrews et al, arXiv:1808.03689



Jet tools 2017, Jet tools 2019, EMMI RRTF

Outlook

- **JETSCAPE:** "Framework" of Event Generator for heavy ion collisions



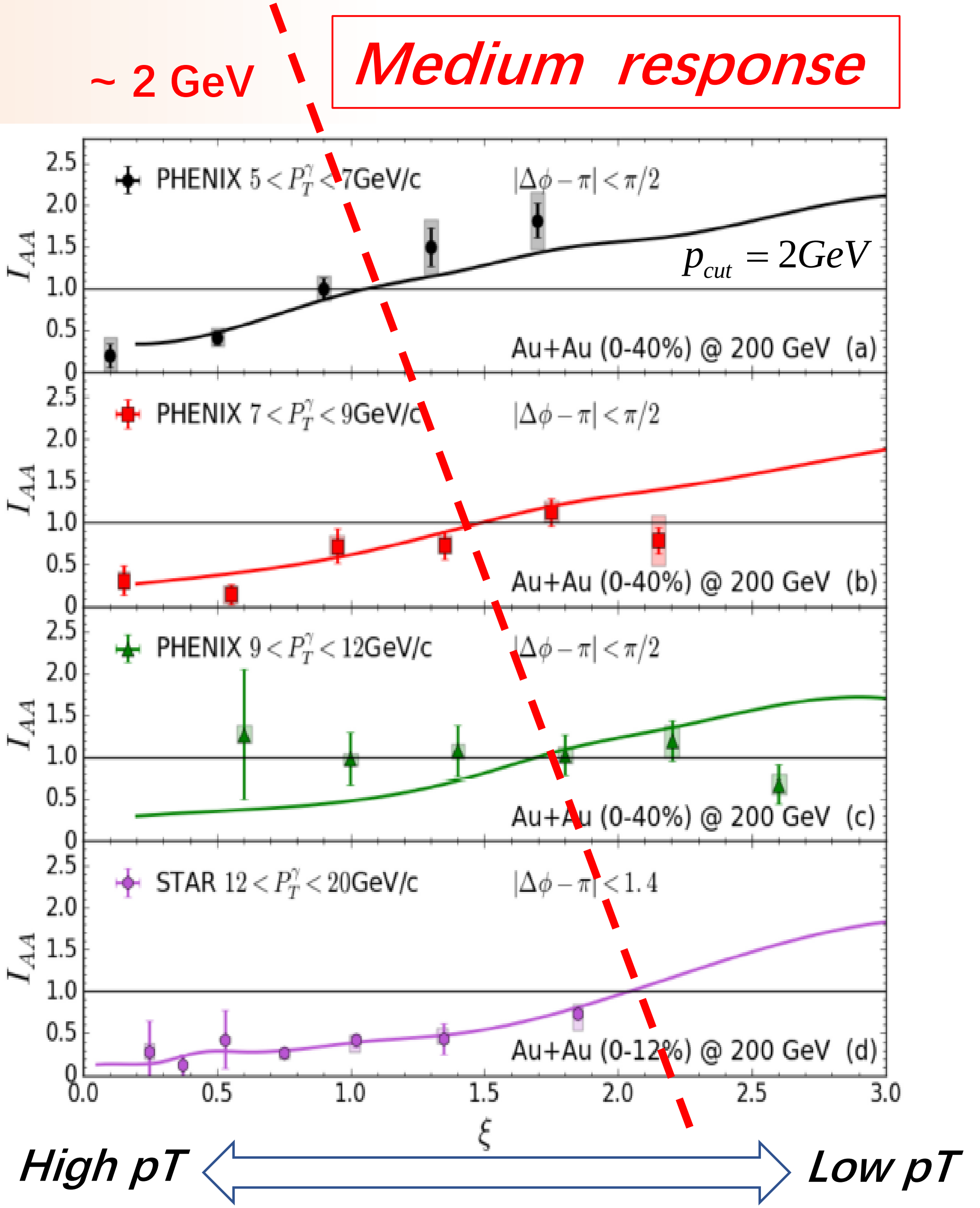
Thanks

γ-hadron correlations

- The suppression of high pT hadrons
  LBT: hard parton energy loss
- The enhancement of soft hadrons at small pT
  Hydro: medium excitation
- With increasing pT-gamma transition point from suppression to relative enhancement shifts to larger ξ .
- This transition point corresponds to a fixed pT range.

$$I_{AA}(z) = D_{AA}(z) / D_{pp}(z) \qquad z = p_T^h / p_T^\gamma$$

$$\xi = \log \frac{1}{z}$$

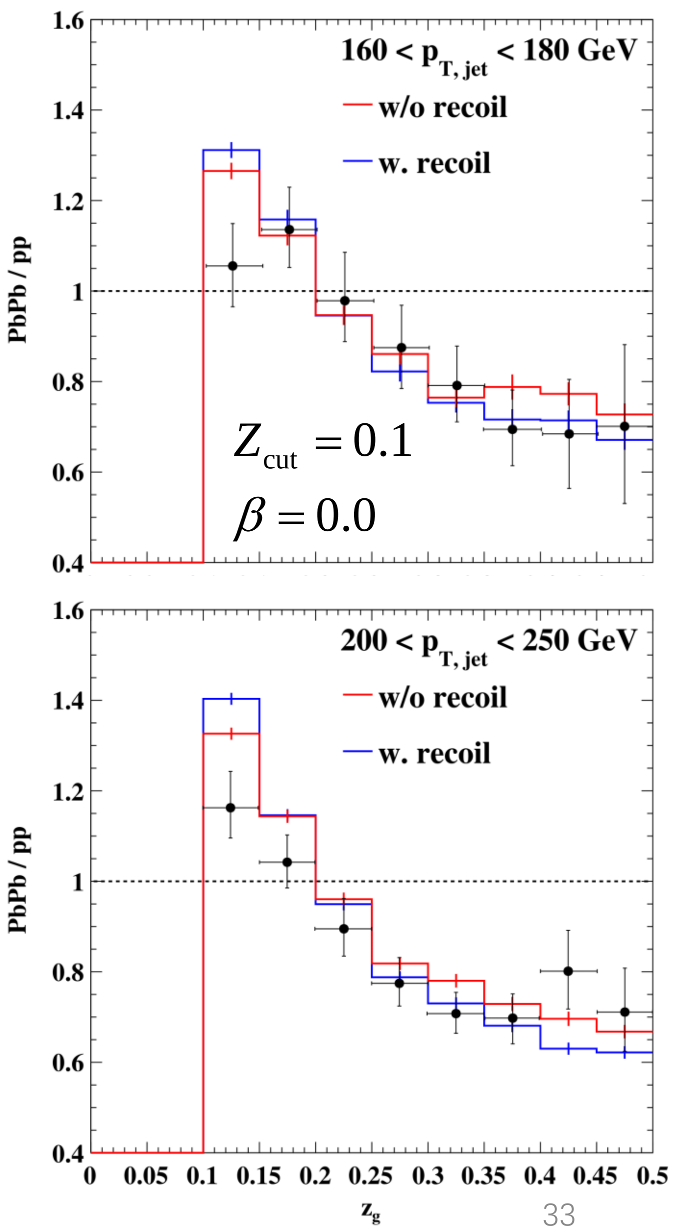


CoLBT-hydro W Chen, SS Cao, T Luo, LG Pang, XN Wang Phys.Lett. B777 (2018) 86-90

Jet splitting function

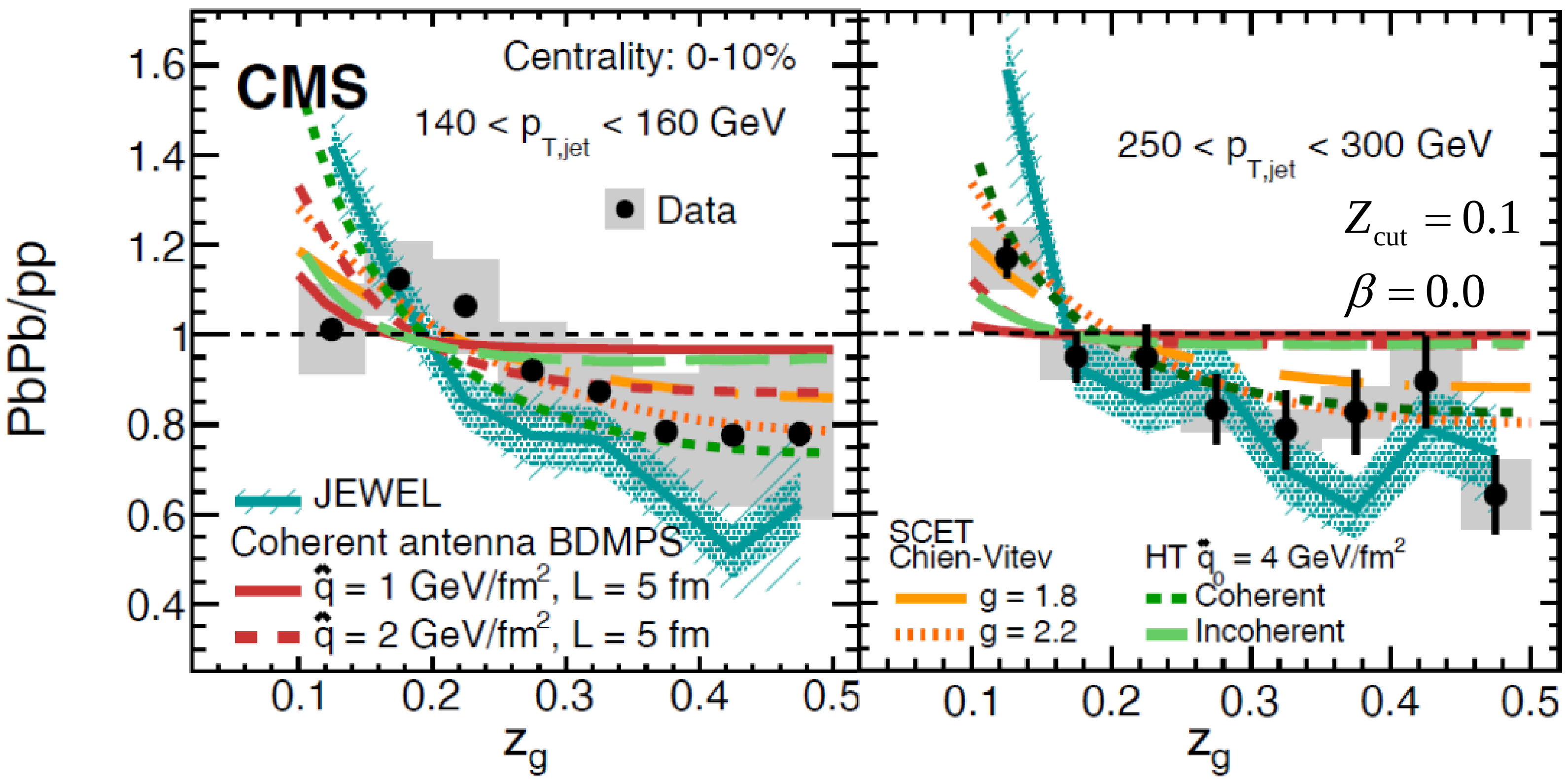
$$z_g \equiv \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut} (\frac{\Delta R}{R_0})^{\beta}$$

LBT



- 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.

arXiv:1708.09429



Backup

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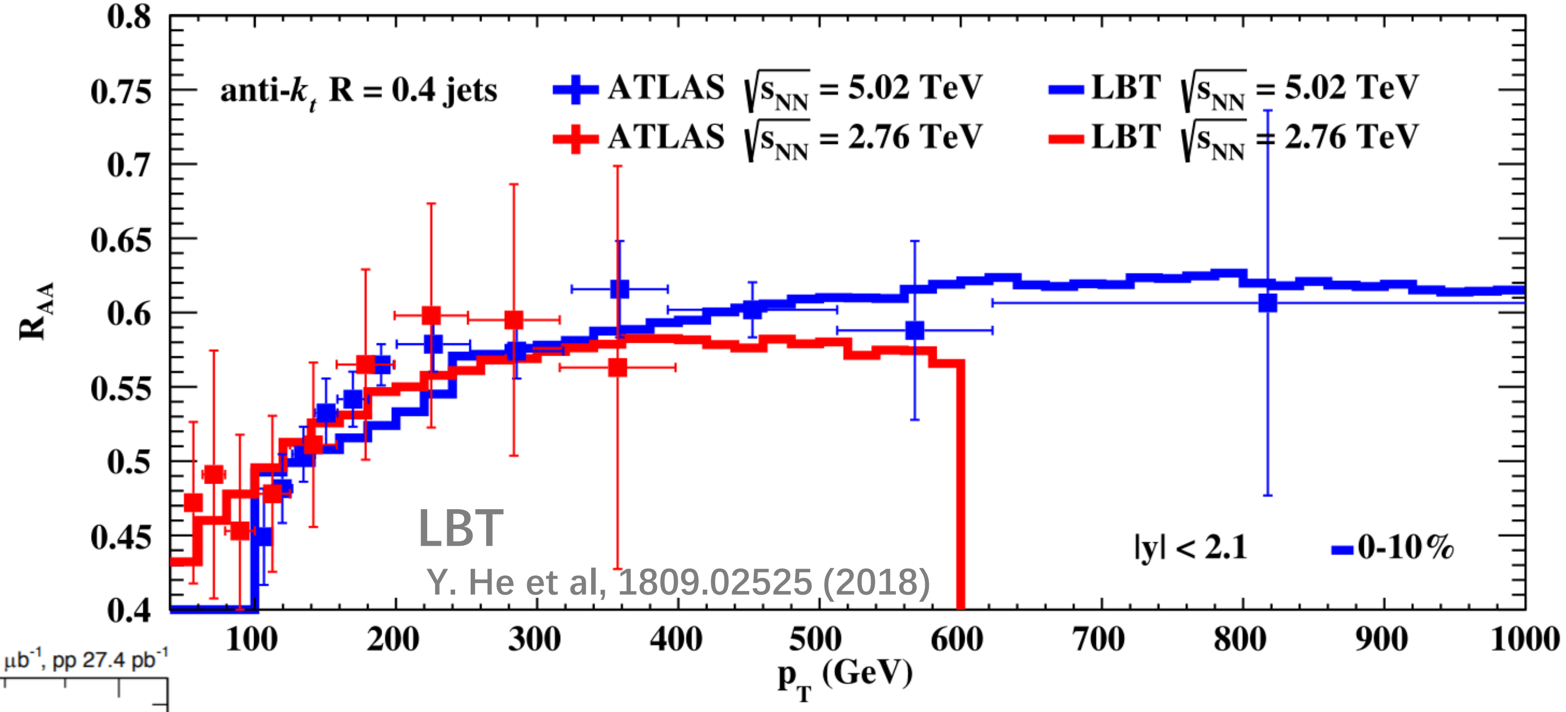
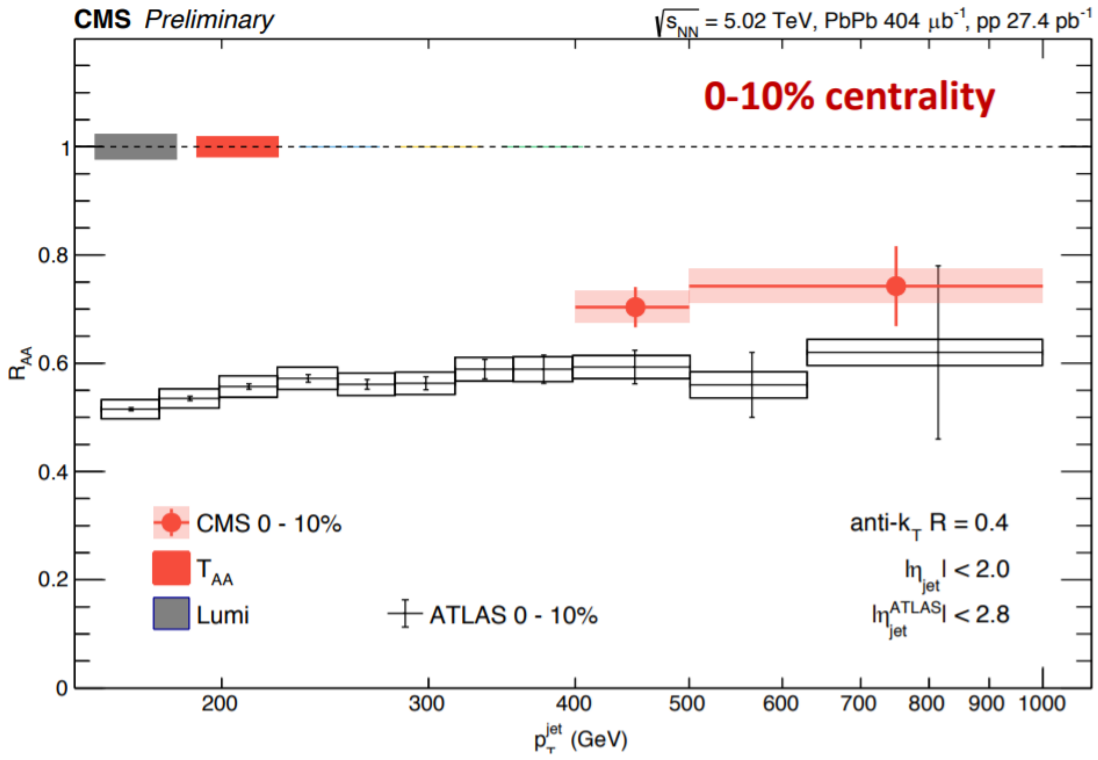
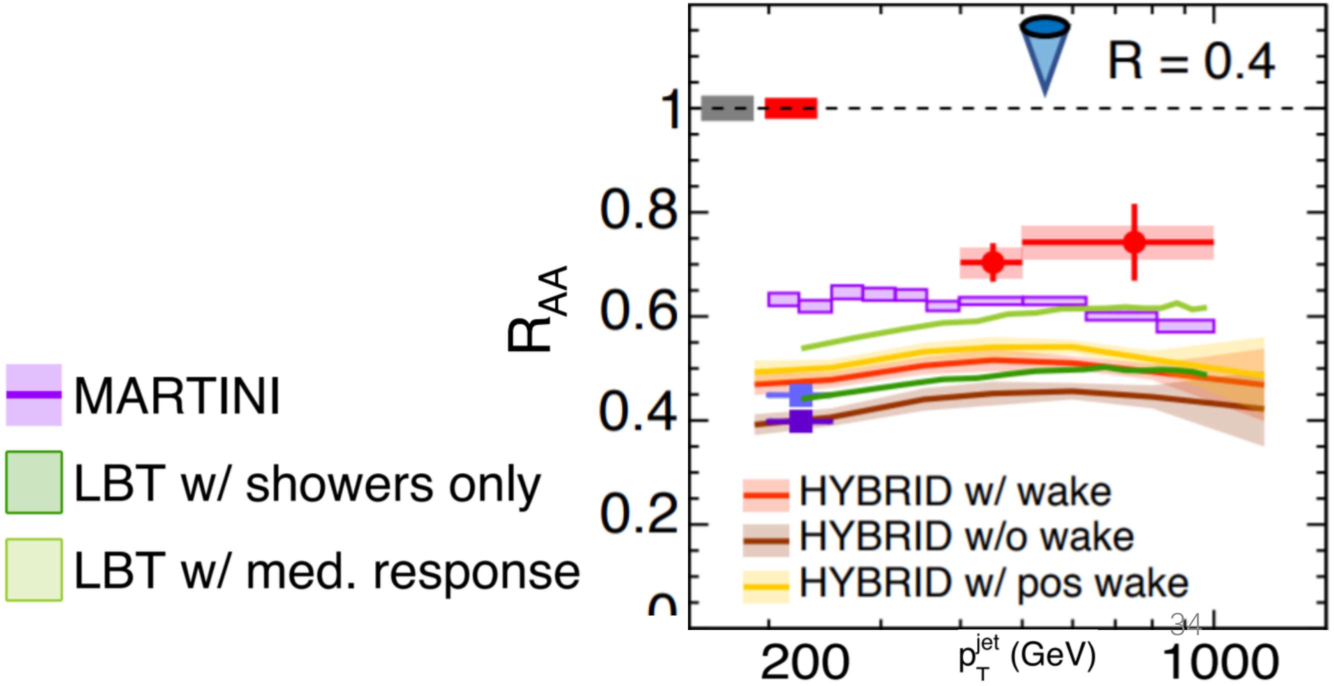
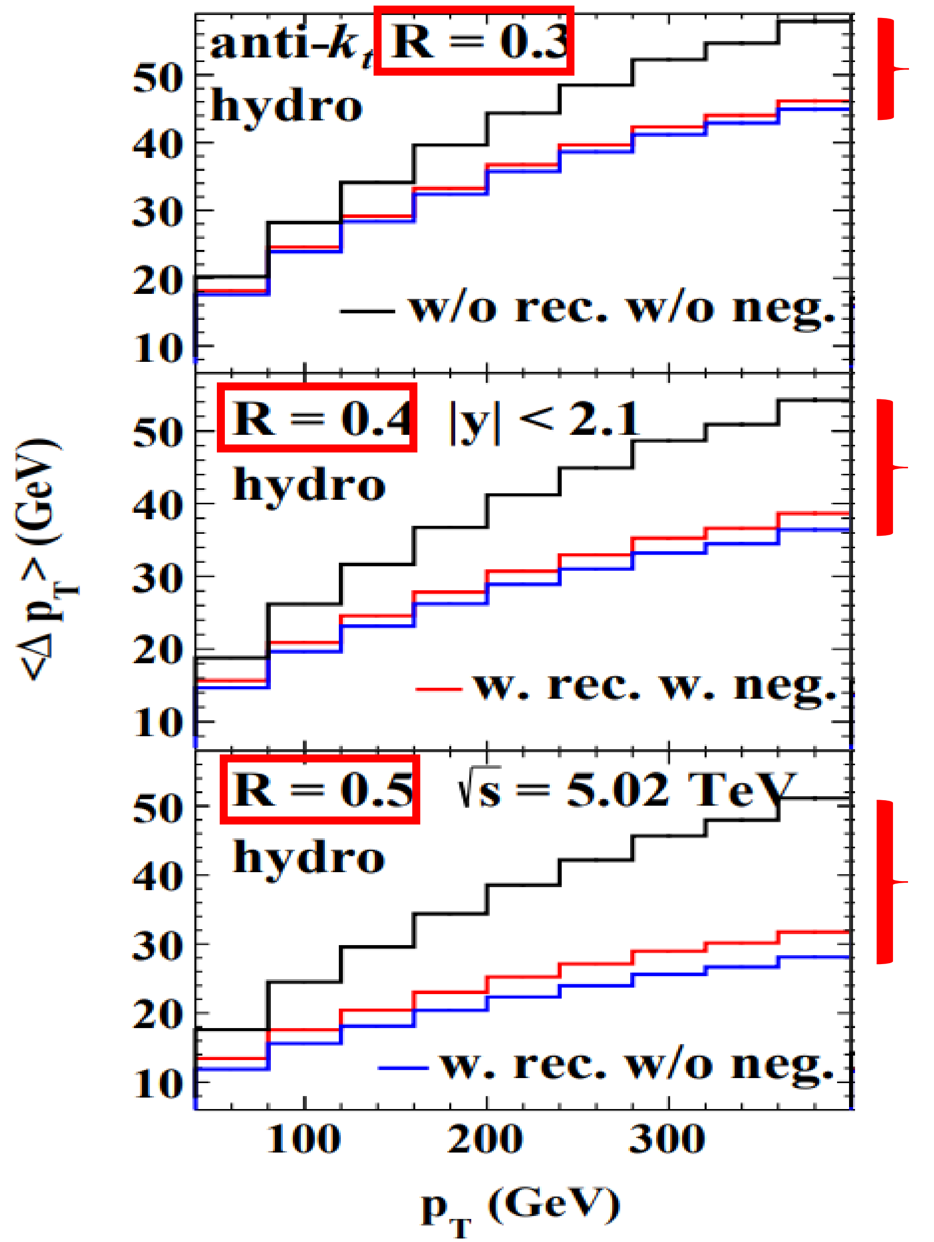




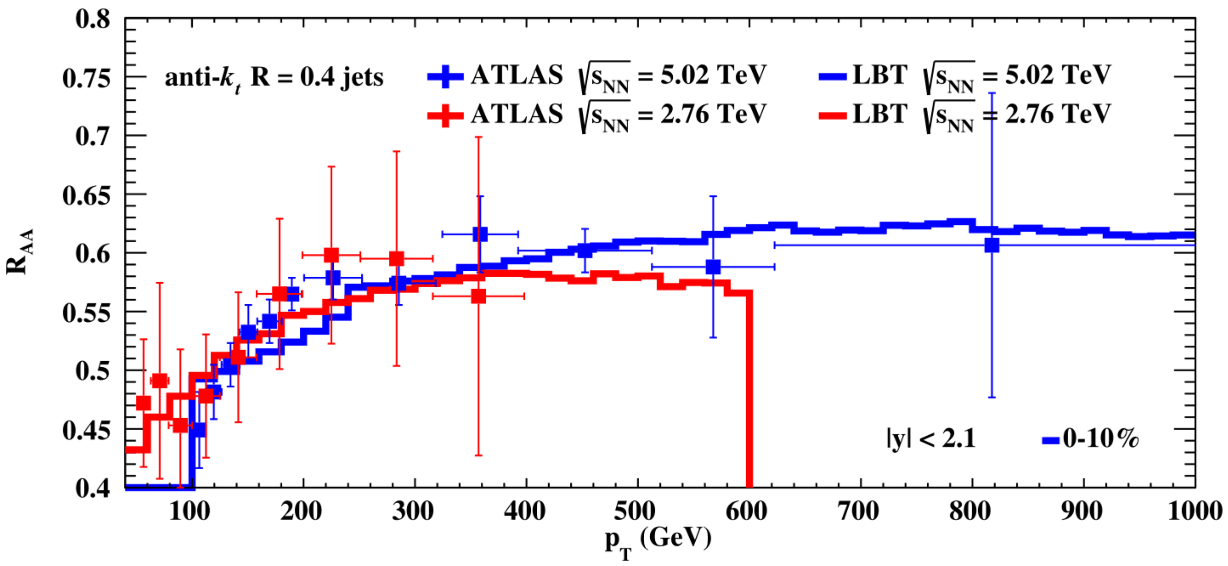


Single jet suppression



- Effect of medium response (black vs red)
- Effect of diffusion wake (red vs blue)

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{d^2 N_{jet}^{AA} / d\eta_p dp_T^{jet}}{d^2 N_{jet}^{pp} / d\eta_p dp_T^{jet}}$$



LBT Y He, SS Cao, W Chen, T Luo, LG Pang, XN Wang 1809.02525 (2018)