Jet-medium interactions in QCD matter

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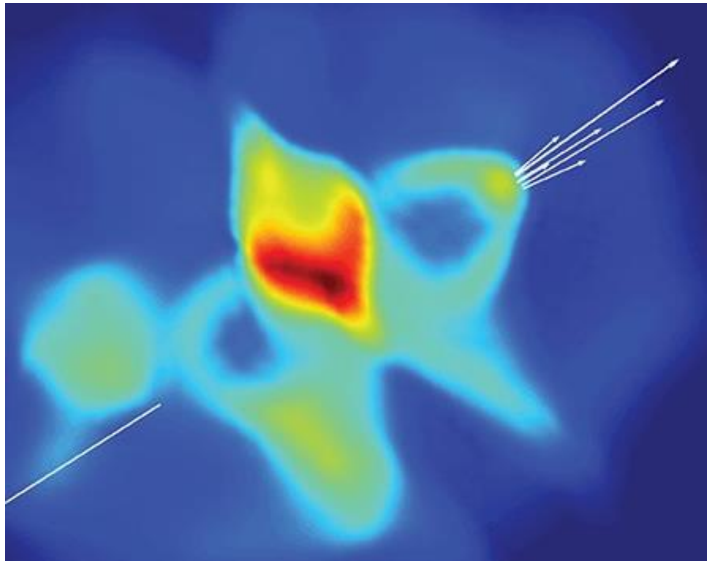
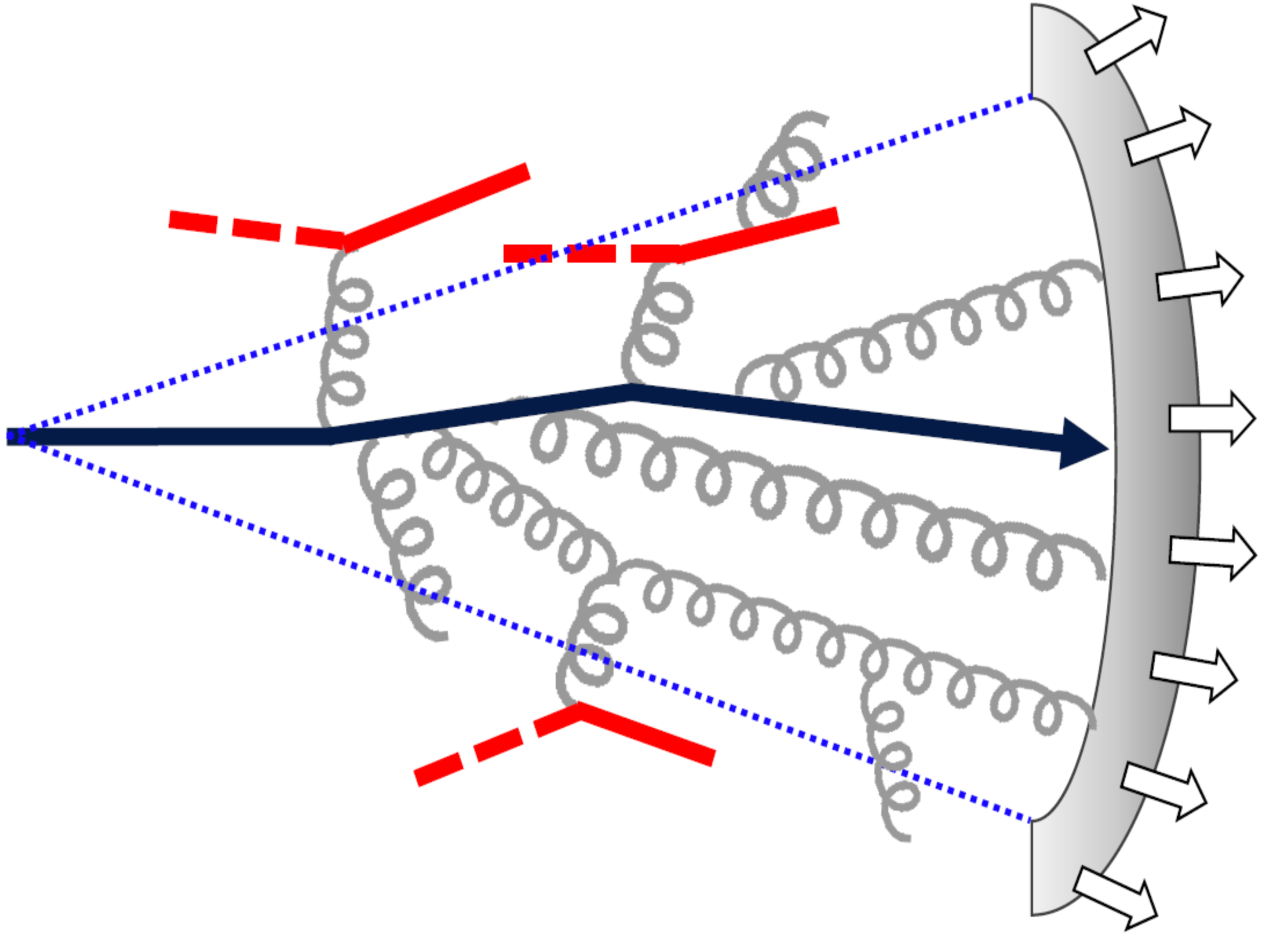


Outline

- Introduction
- Models
- Observables
- Summary

Jet induced medium response

Jet propagation in the QGP medium



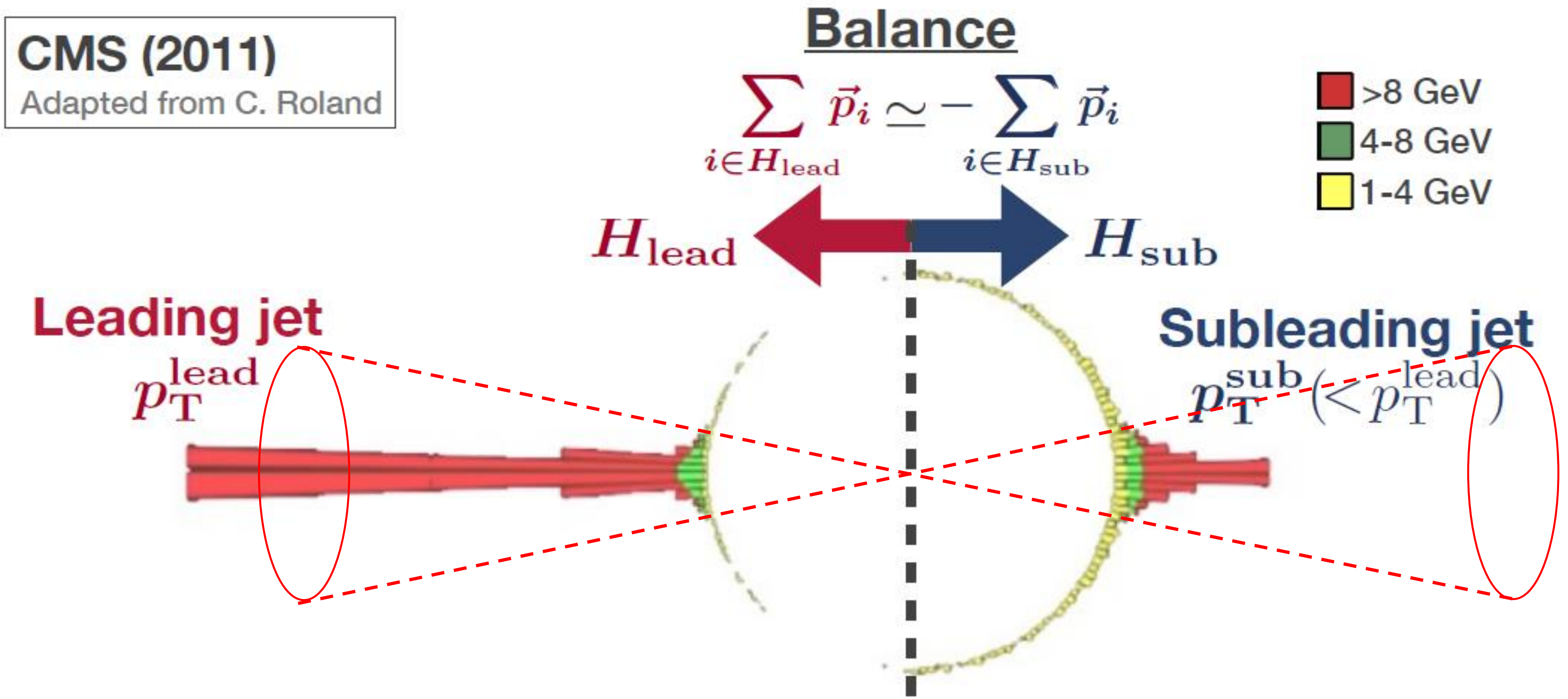
- Jet: a spray of particles correlated to an initial hard parton. (defined by the jet algorithm)
- Jets are multiscale probes to explore the properties of the quark-gluon plasma.

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 ?

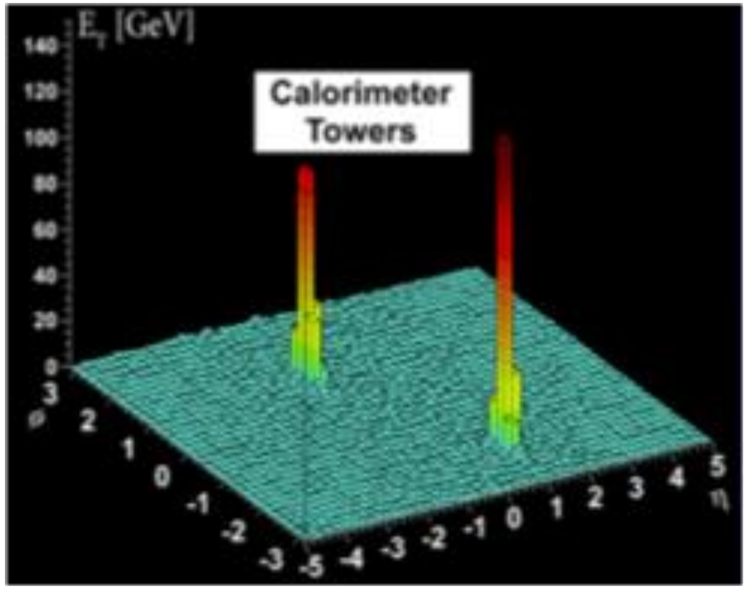
- The energy and momentum deposited by the jet shower into the medium appear at large angles away from the jet axis.

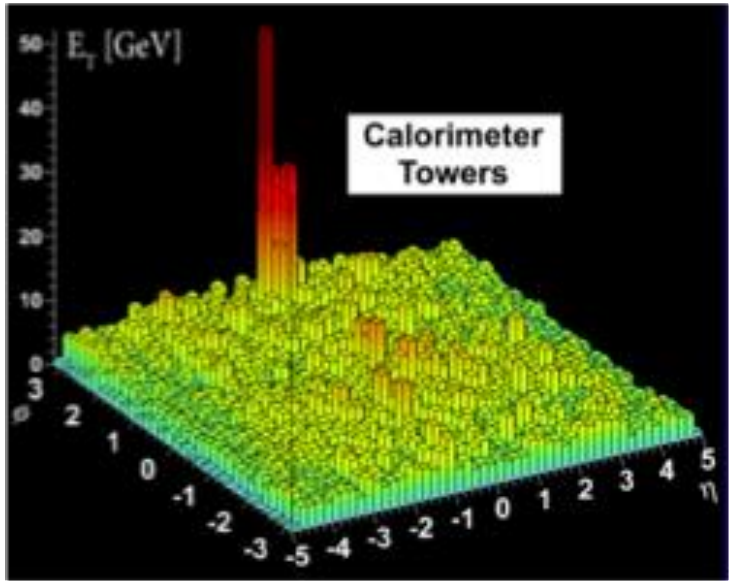


Jet induced medium response

- Thermalization : How does the deposited energy thermalize?
- Propagation: How does the deposited energy propagate?
- What are in the background of a reconstructed jet?

Part of the medium background is correlated with jet (inside and outside the jet cone).

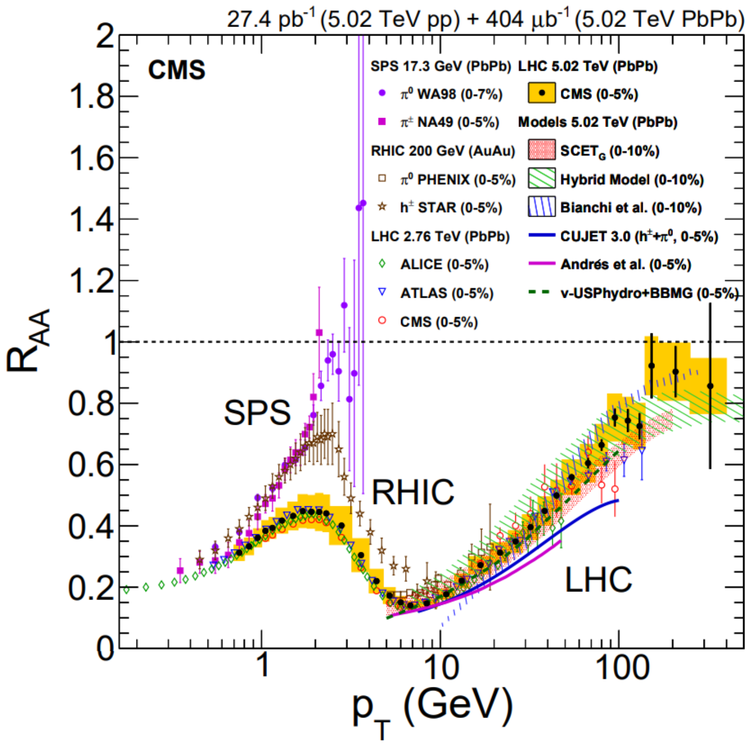


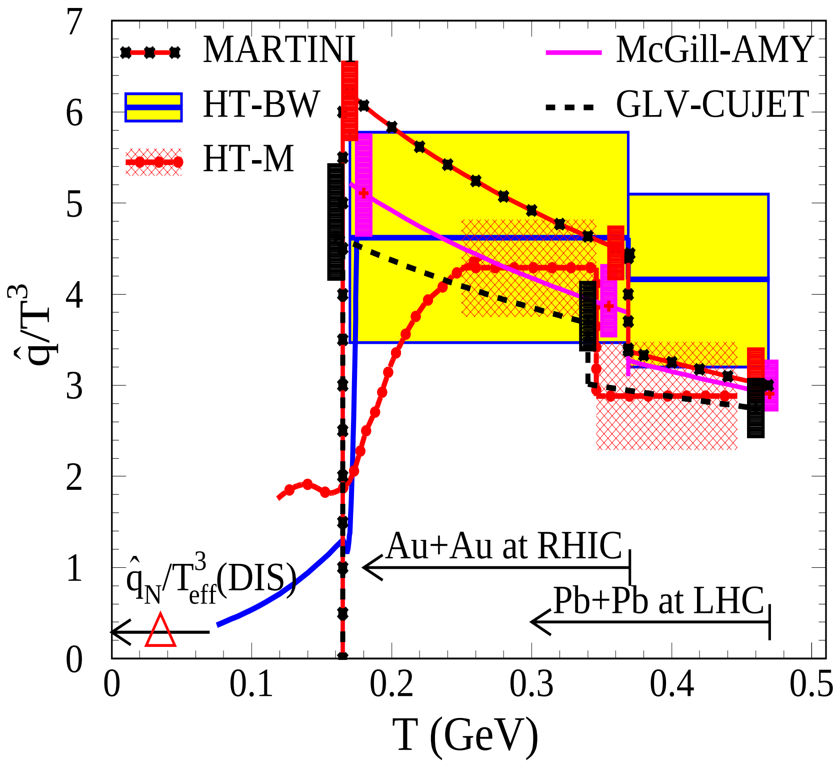


Parton energy loss in QGP

- 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

- LBT [HT] : recoiled partons transported. (shower + transport)
  Recoil-medium interaction
- CoLBT-hydro [HT] : Transport + Hydro parallel simulation. (shower + transport)
  Recoil-medium interaction
- MARTINI [AMY] : recoiled partons transported. (shower + transport)
  Recoil-medium interaction
- JEWEL [BDMPS-Z] : recoiled partons free-stream. (modified parton shower)
  No recoil-medium interaction
- Hybrid [AdS/CFT]: fully thermalized wake. (modified parton shower)
  Recoil-medium interaction (simplified)
- Coupled Jet-Fluid [HT] : solve Boltzmann equation semi analytically + Hydro simulation
  Recoil-medium interaction
- AMPT, BAMPS, etc

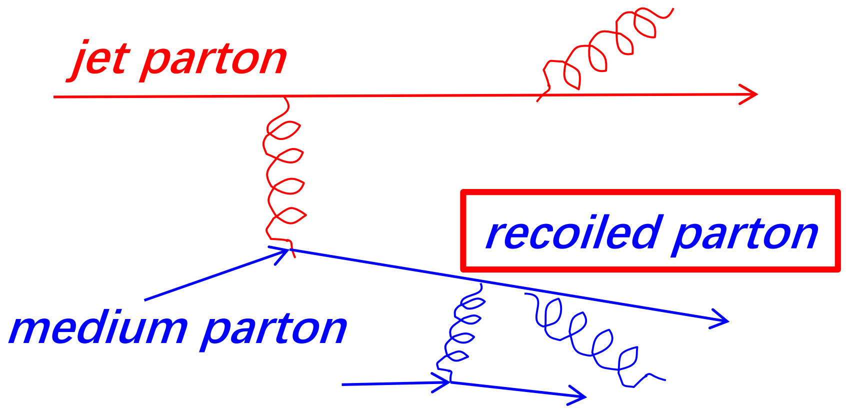
}

Monte Carlo
Jet evolution

A Linear Boltzmann Transport (LBT) Model

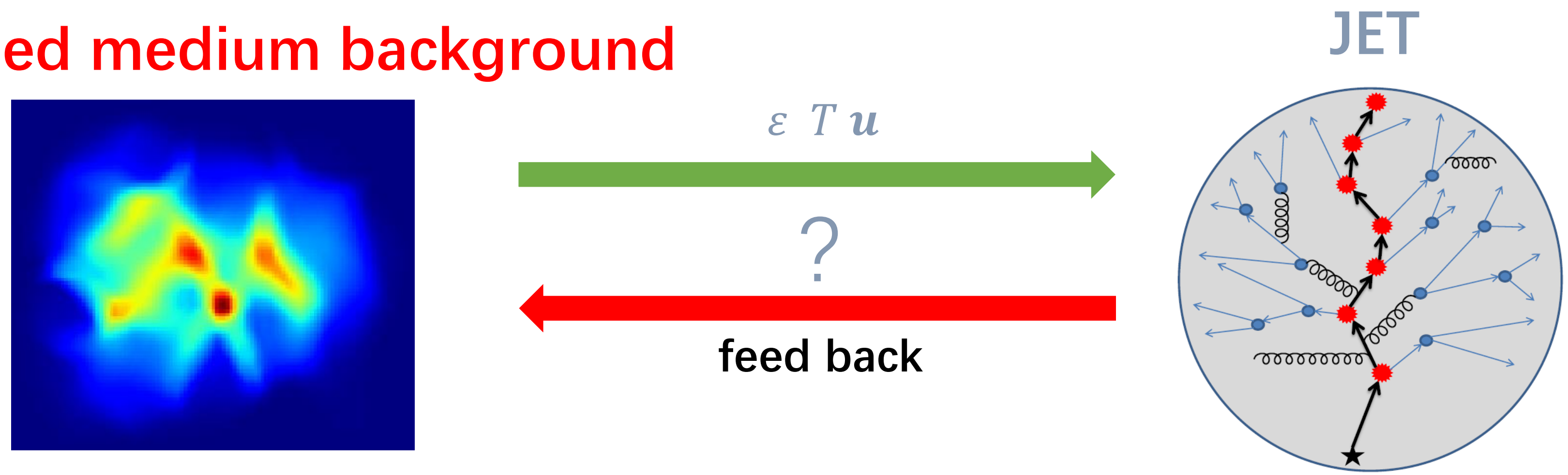
$$p_1 \cdot \partial f_1(x_1, p_1) = E_1 \left(C_{elastic} + C_{inelastic} \right)$$

- Elastic collision + Induced gluon radiation.
- Follow the propagation of recoiled parton.
- Back reaction of the Boltzmann transport.



- Rescattering of the soft partons beyond pQCD .
- Jet-Medium interaction : Where is the feed back to the thermal background ?

Unmodified medium background



A coupled LBT Hydro (CoLBT-hydro) Model

- CoLBT-hydro : LBT + CLVisc

Hydro ⟷ ***Pcut*** ⟷ **LBT**

Soft — Hard

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

$$\partial_\mu T^{\mu\nu} = j^\nu \qquad \frac{1}{p.u} p^\mu \partial_\mu f = C$$

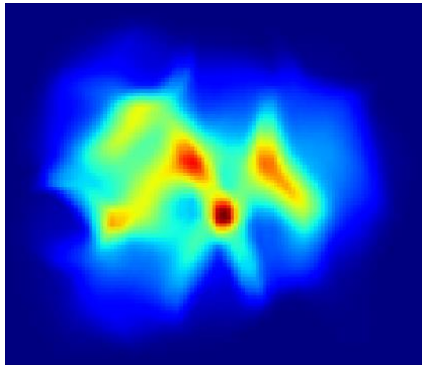
Source term (soft partons in LBT)

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

CLVisc: (3+1)D viscous hydrodynamics parallelized on GPU using OpenCL

MC Jet propagation + MC Hydro evolution

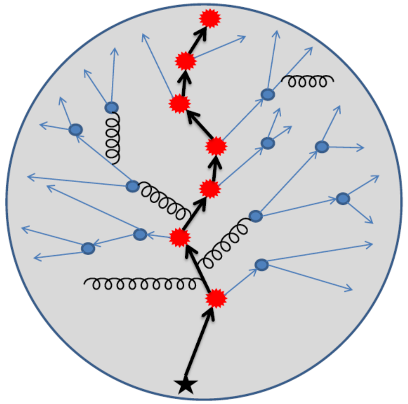
Modified medium background



$\varepsilon\ T\ \boldsymbol{u}$

feed back

JET



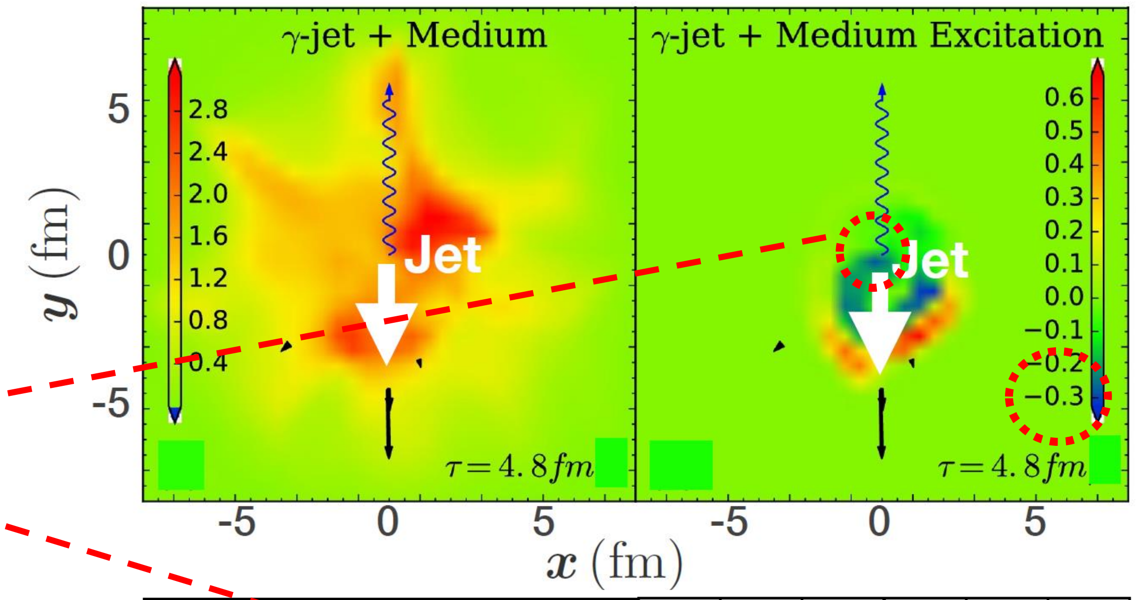
Jet induced medium response

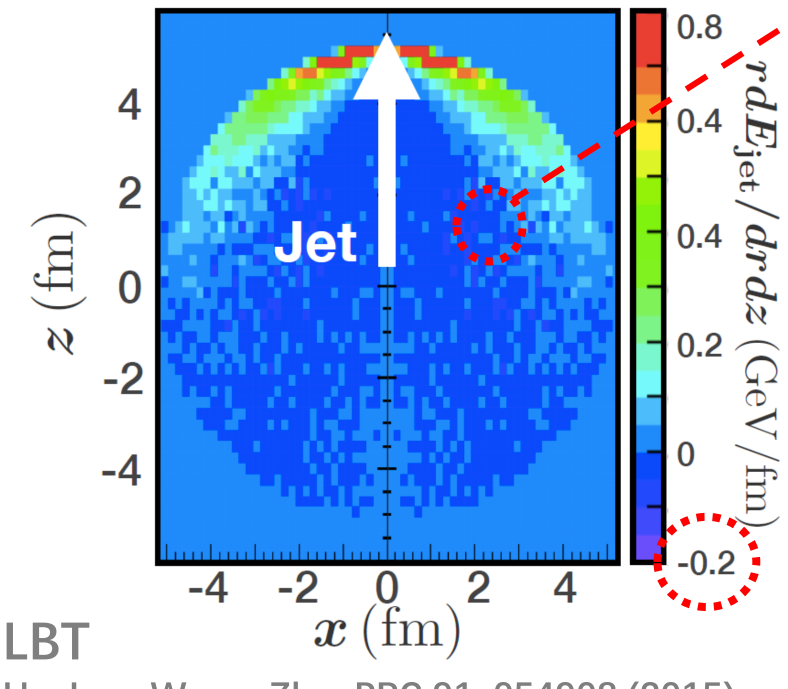
CoLBT-hydro
Chen, Cao, Luo, Pang, Wang, Phys.Lett. B777 86-90

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

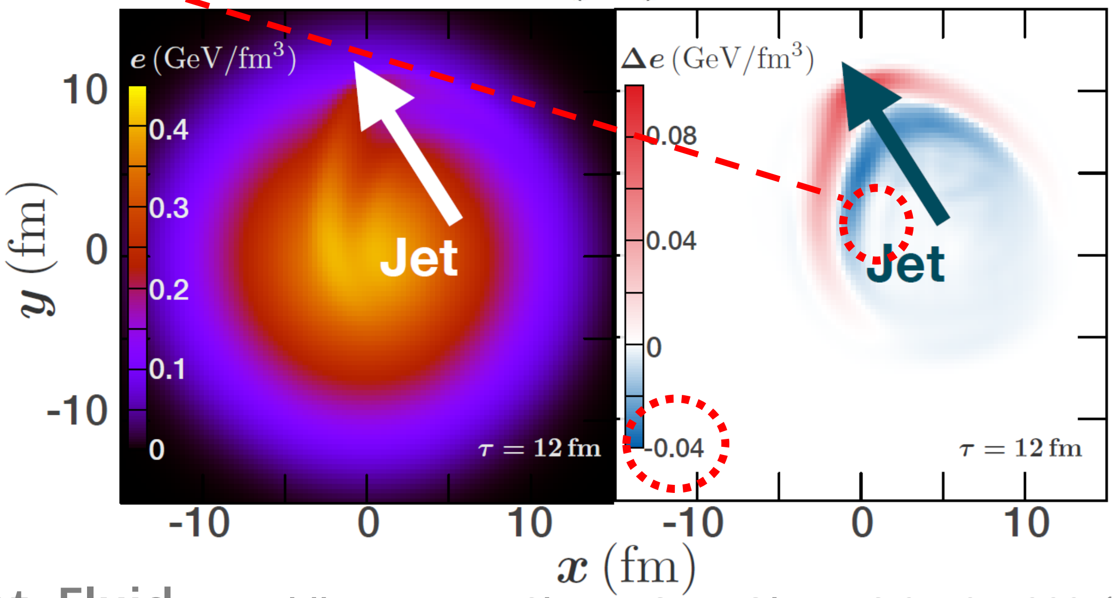
- **Diffusion wake**
  Unique structure of medium response

Diffusion wake





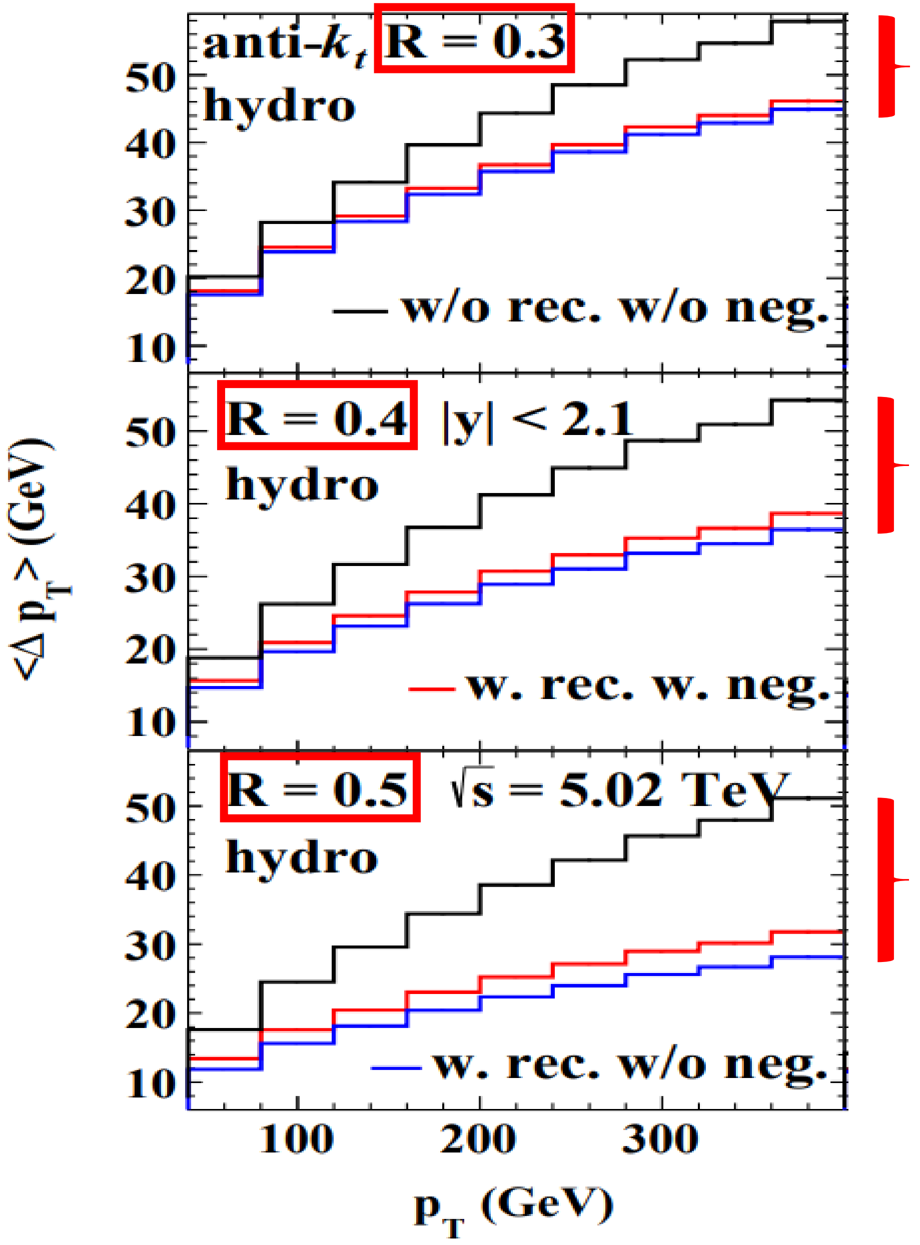
LBT
He, Luo, Wang, Zhu, PRC 91, 054908 (2015)



Jet-Fluid Y. Tachibana, N.-B. Chang, G.-Y. Qin, PRC 95, 044909

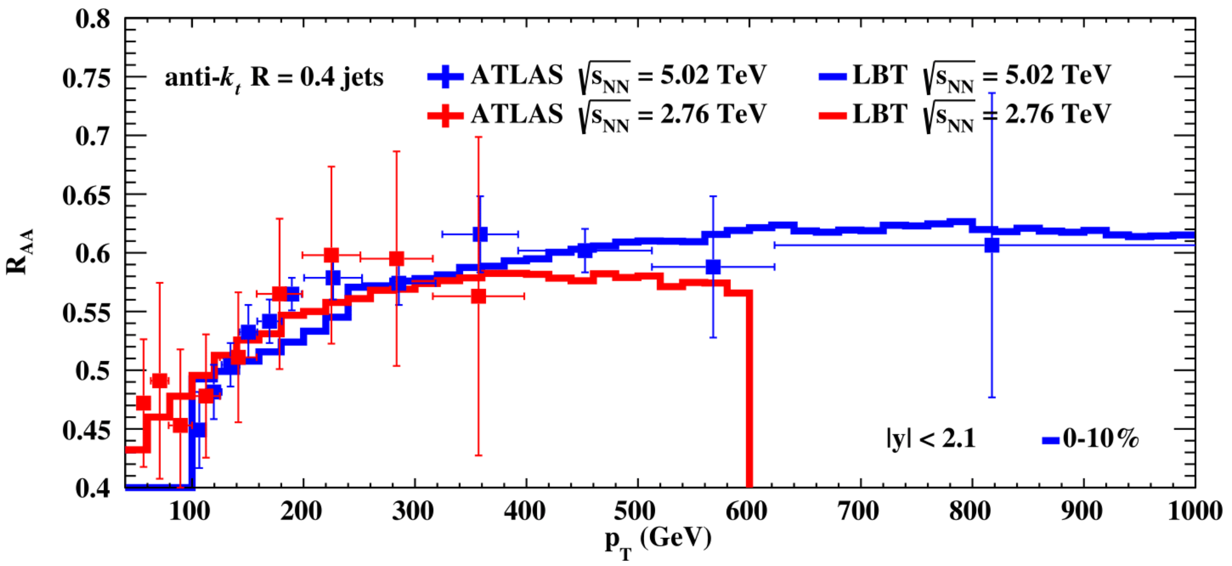
Single jet suppression

Yayun He : Thursday



- 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)

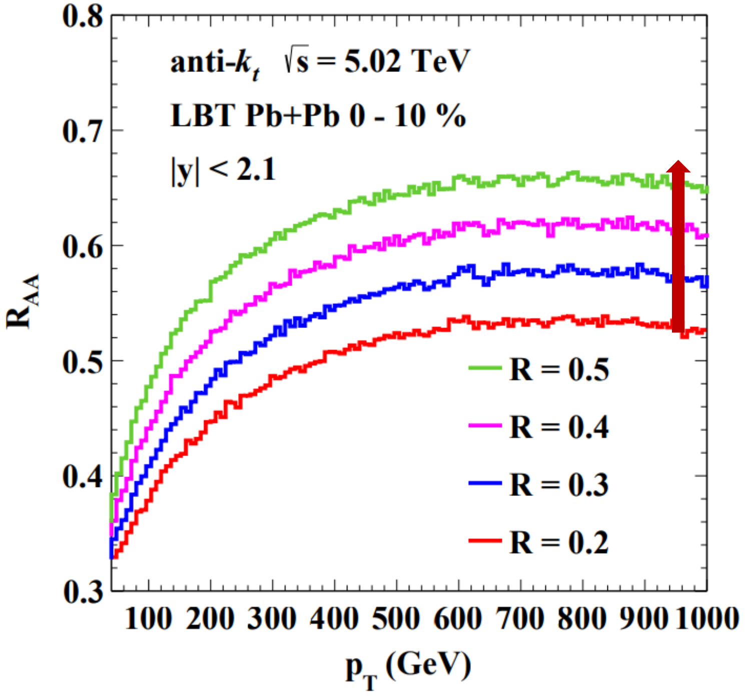
Single jet suppression (Cone size dependence)

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

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

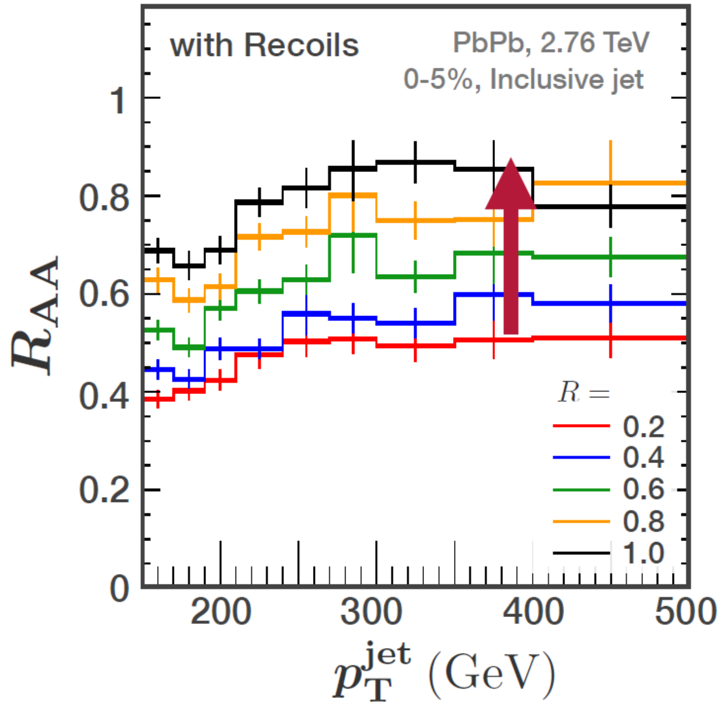
LBT

Y. He et al, 1809.02525 (2018)



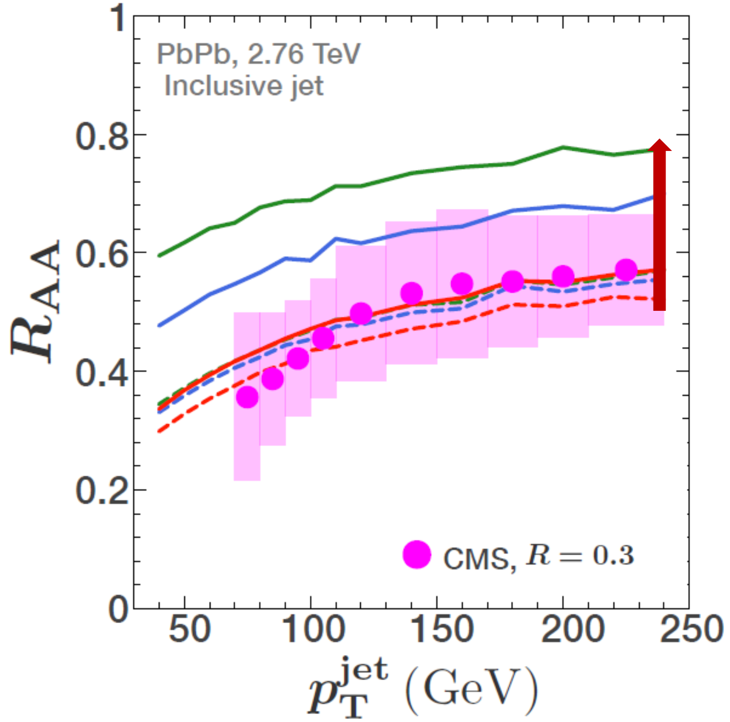
JEWEL

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

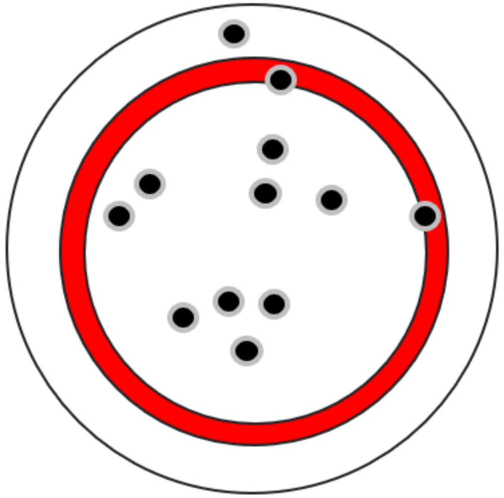


Jet-Fluid

Tachibana, Chang, Qin, PRC 95, 044909

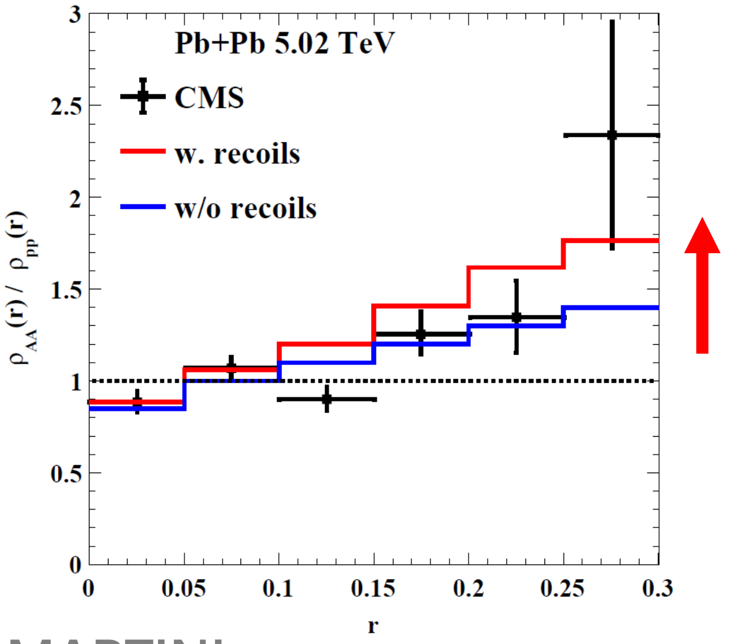


Jet shape (inside jet cone)



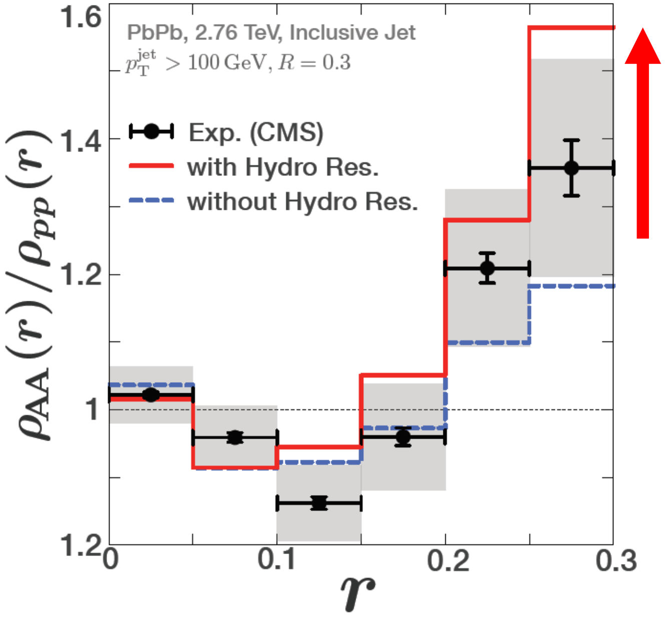
$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N_{jet}}\sum_{jets}\frac{p_t(r-\frac{\Delta r}{2}, r+\frac{\Delta r}{2})}{p_t(0,R)}$$

LBT Luo, Cao, He, Wang, arXiv:1803.06785



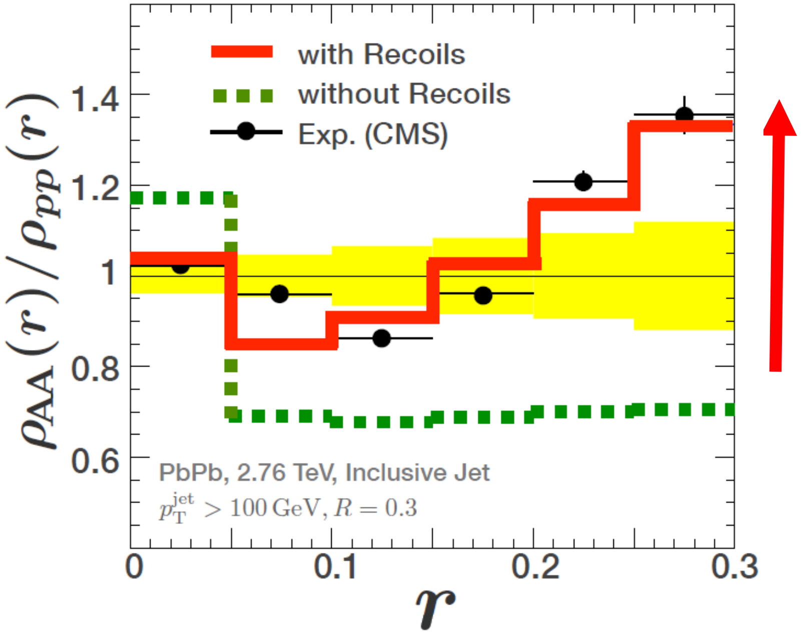
Jet-Fluid

Tachibana, Chang, Qin, PRC 95, 044909

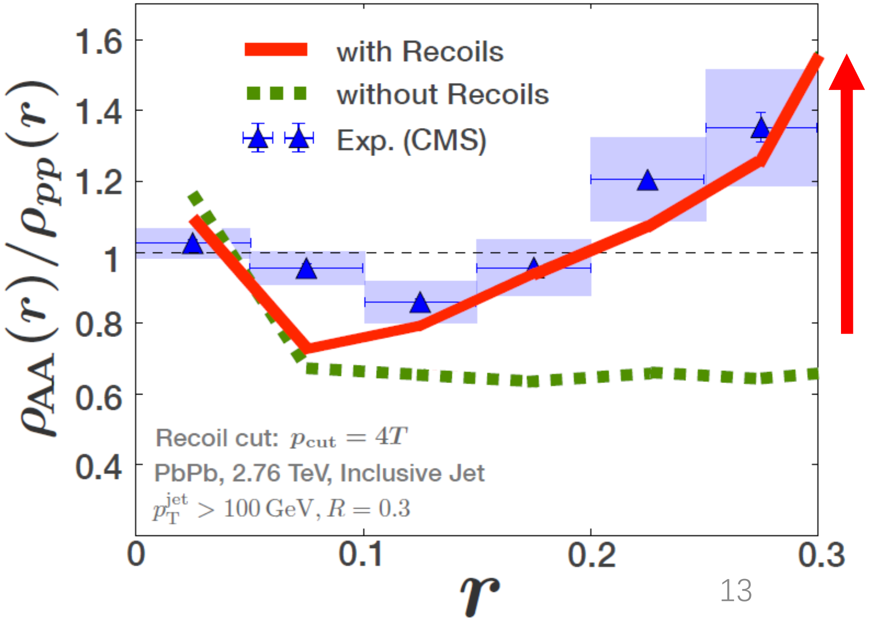


JEWEL

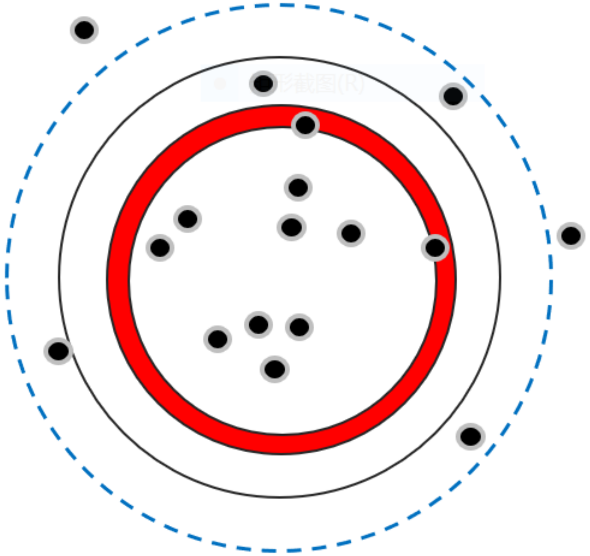
R. K. Elayavalli, K. C. Zapp, JHEP 1707, 141



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



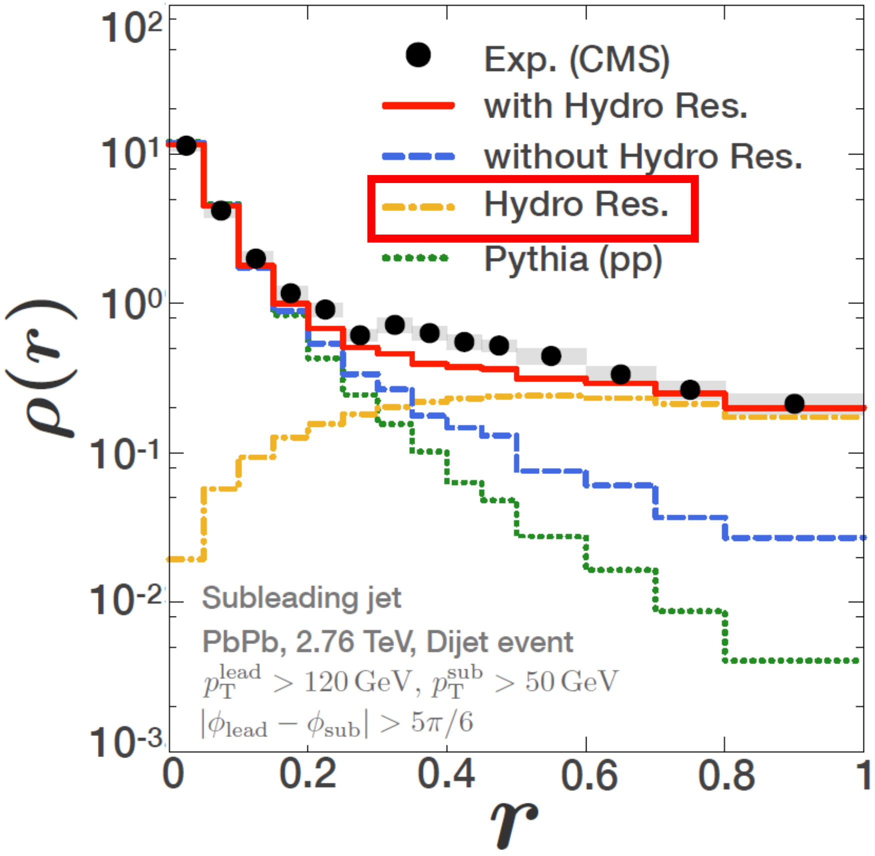
Jet shape (outside jet cone)



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

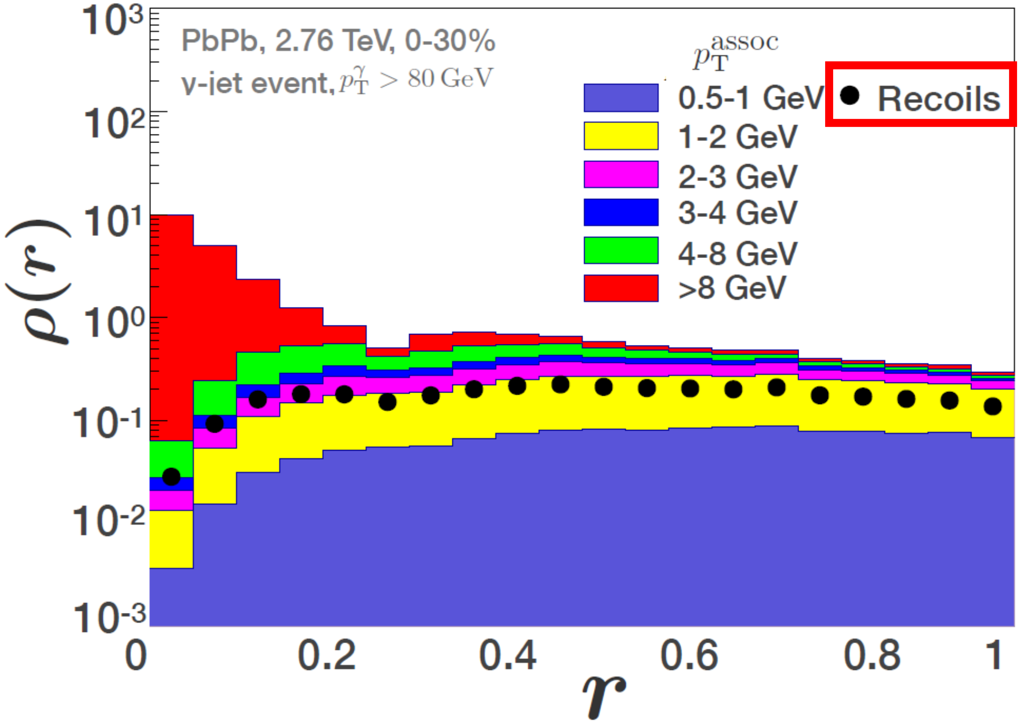
Jet-Fluid

Tachibana, Chang, Qin, PRC 95, 044909



LBT

Luo, Cao, He, Wang, arXiv:1803.06785



Missing pT (full picture)

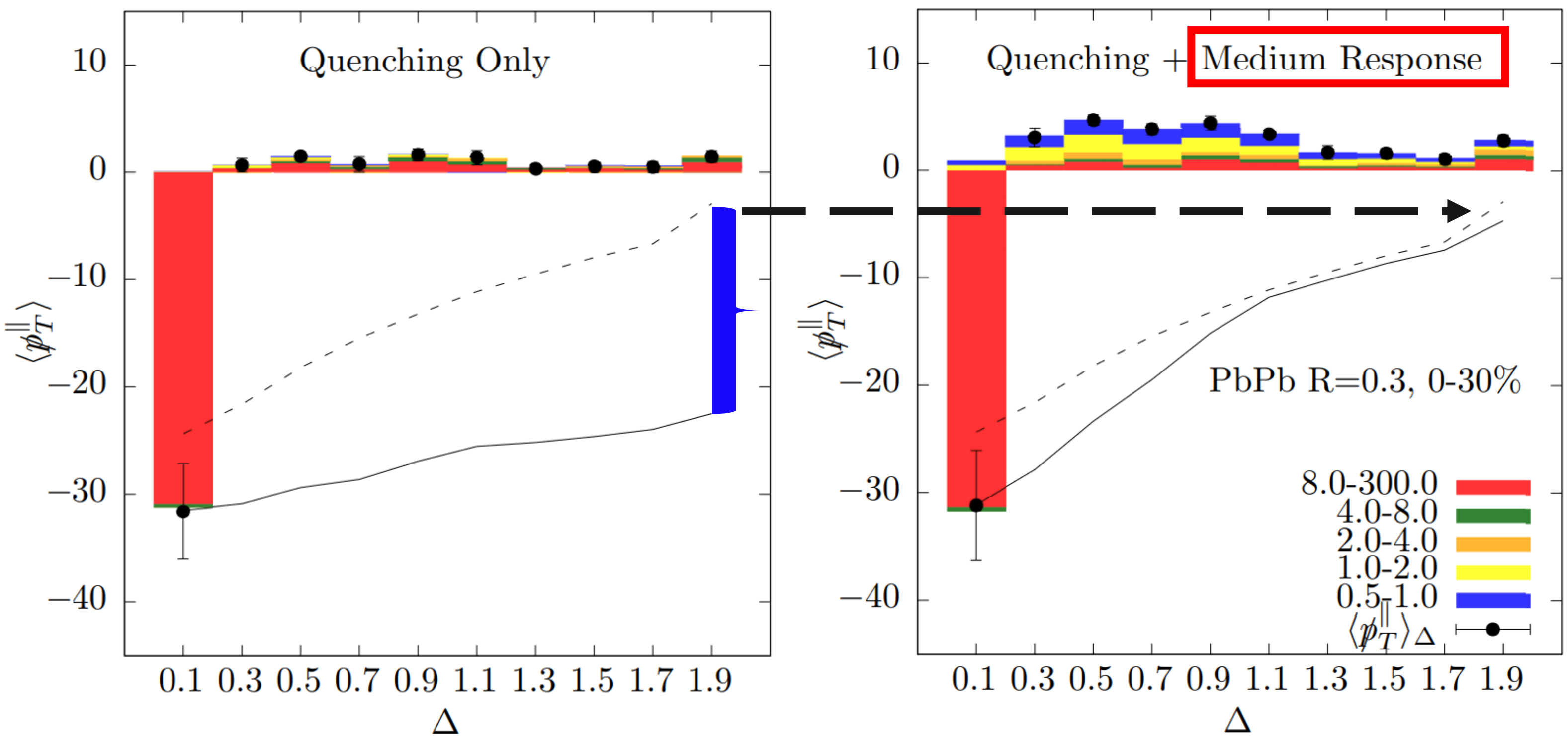
- **Energy is recovered at large angles in the form of soft particles.**
- **Adding medium response is essential for a full understanding of jet quenching.**

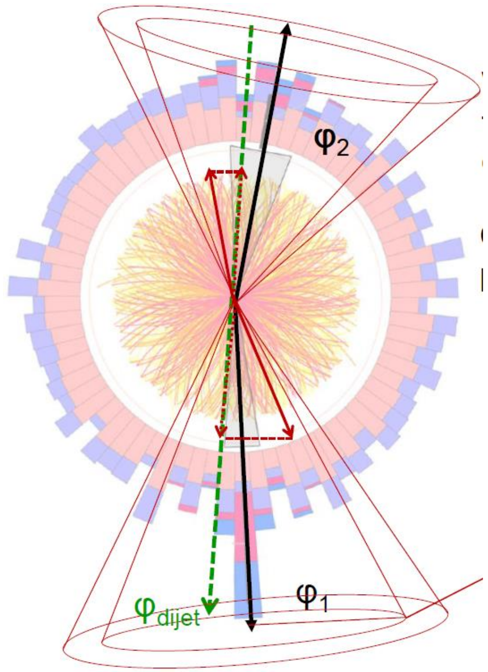
$$\Delta = \sqrt{\Delta\phi^2_{Trk,jet} + \Delta\eta^2_{Trk,jet}}$$

$$p_T^{\parallel} = \left(\sum_i -p_T^i \cos(\phi_i - \phi_{dijet}) \right) \Big| R_{down} < \Delta < R_{up}$$

Daniel Pablos : Thursday

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





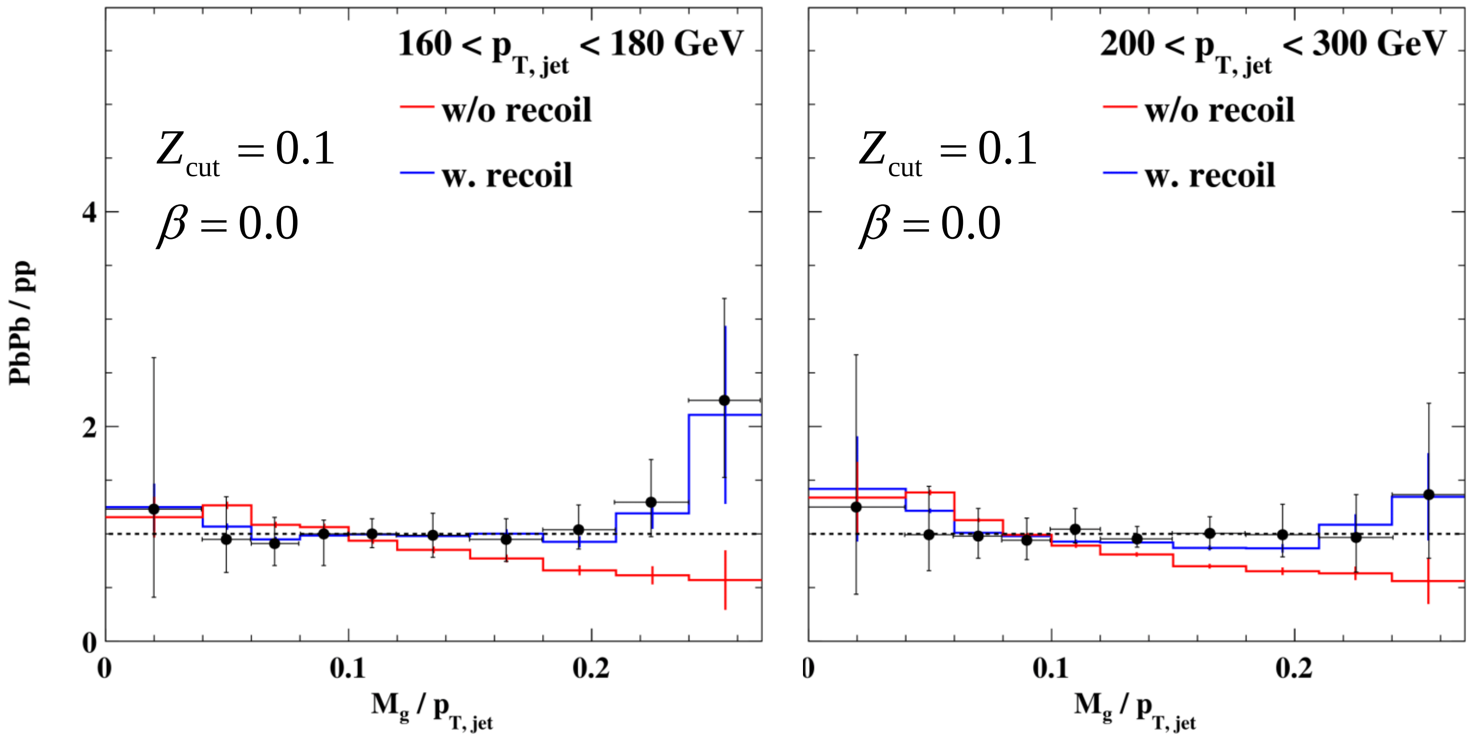
CMS

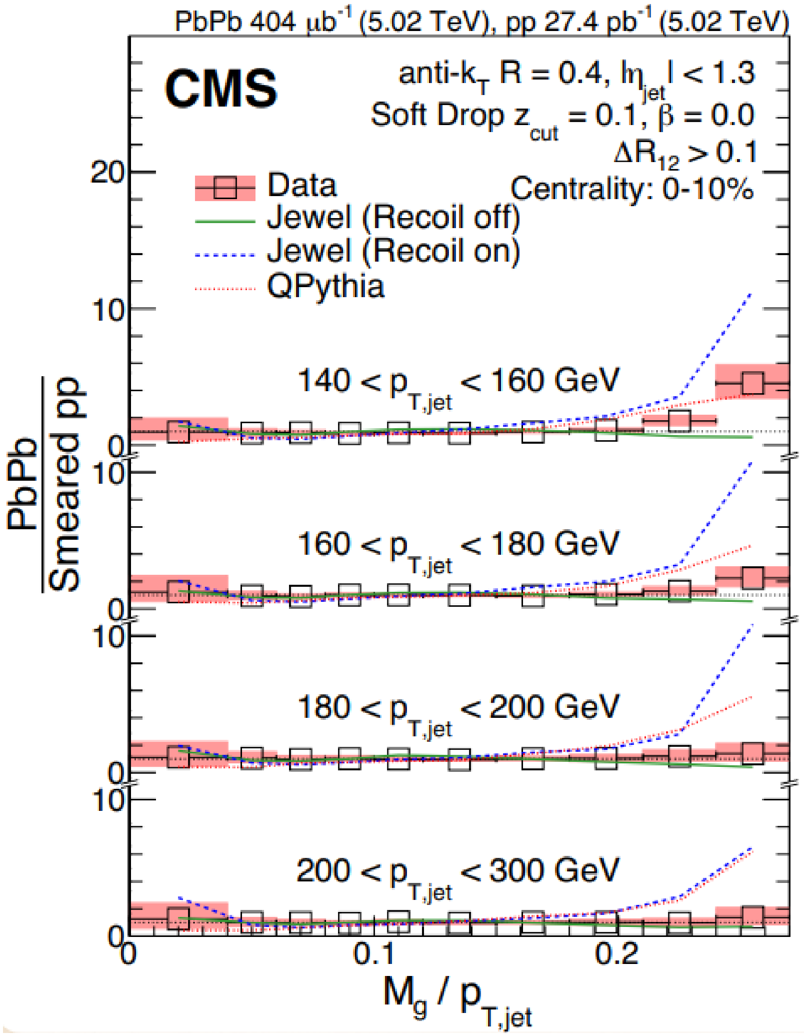
Groomed jet mass

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

- Enhancement of the large mass range.
- The rise in large mass tail is possibly due to the recoil particles scattered at larger angles.

LBT T Luo, SS Cao, Y He, GY Qin, XN Wang in preparartion





Xin-Nian Wang : Wednesday

Yang-Ting Chien : Wednesday

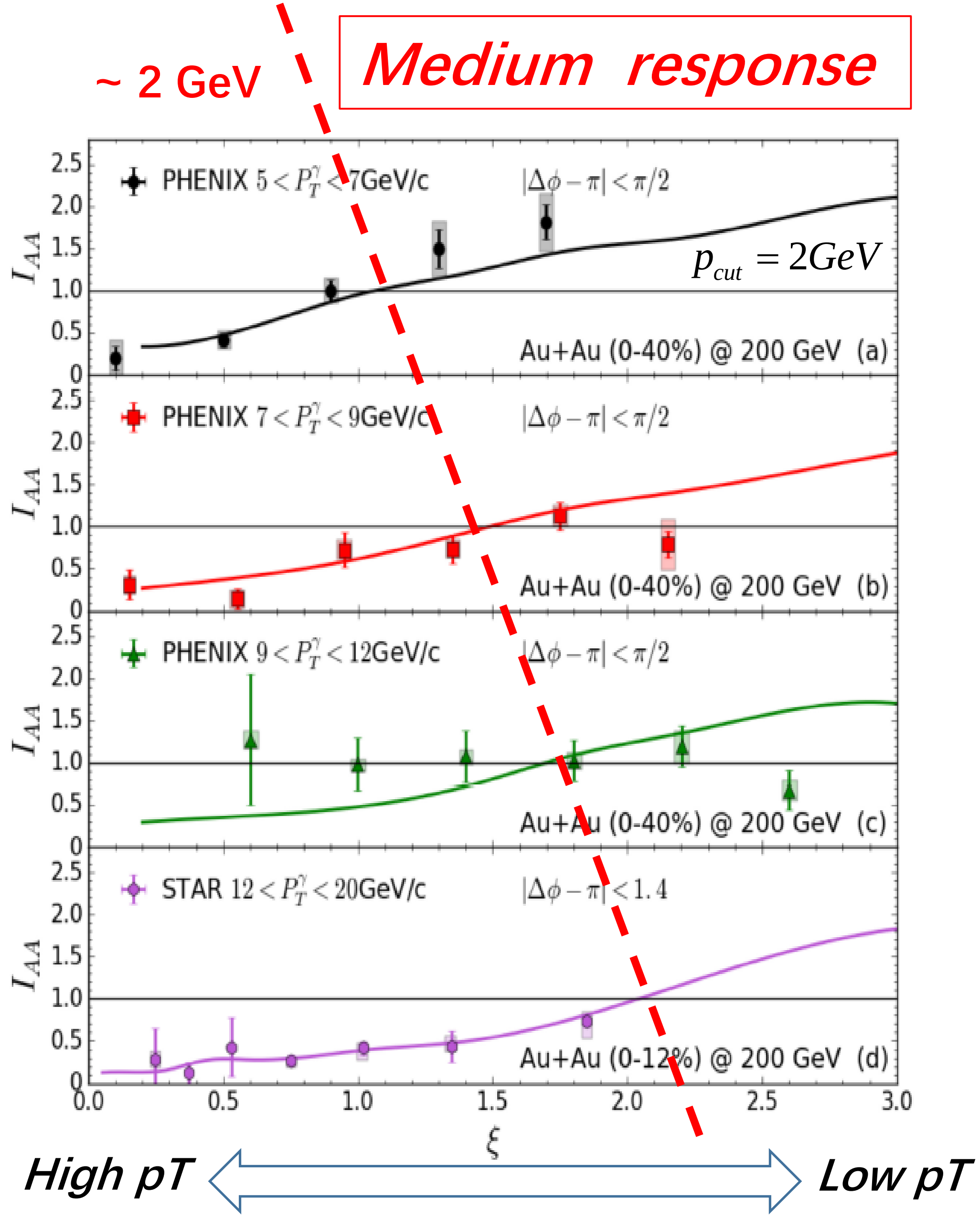
CMS arXiv:1805.05145

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

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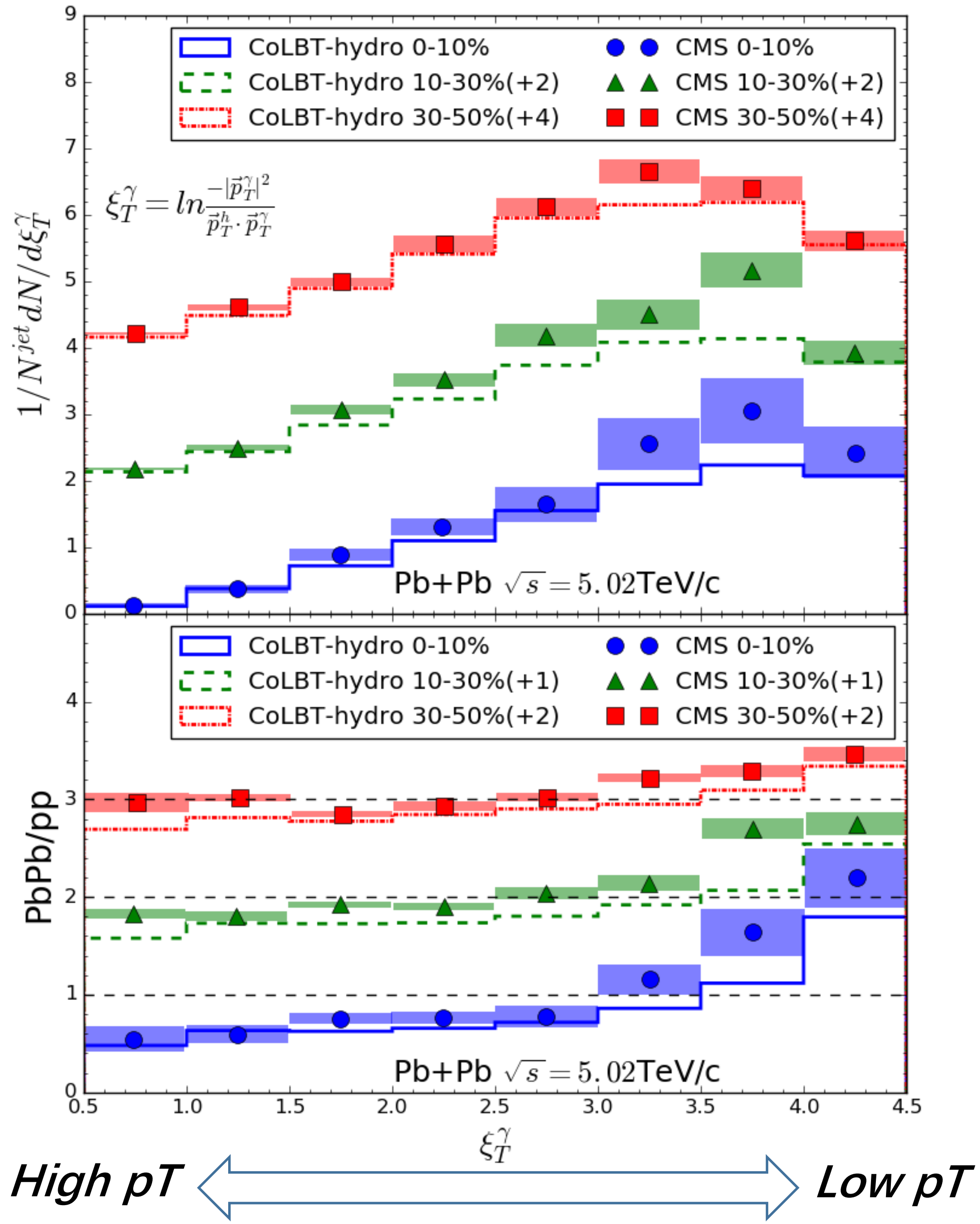
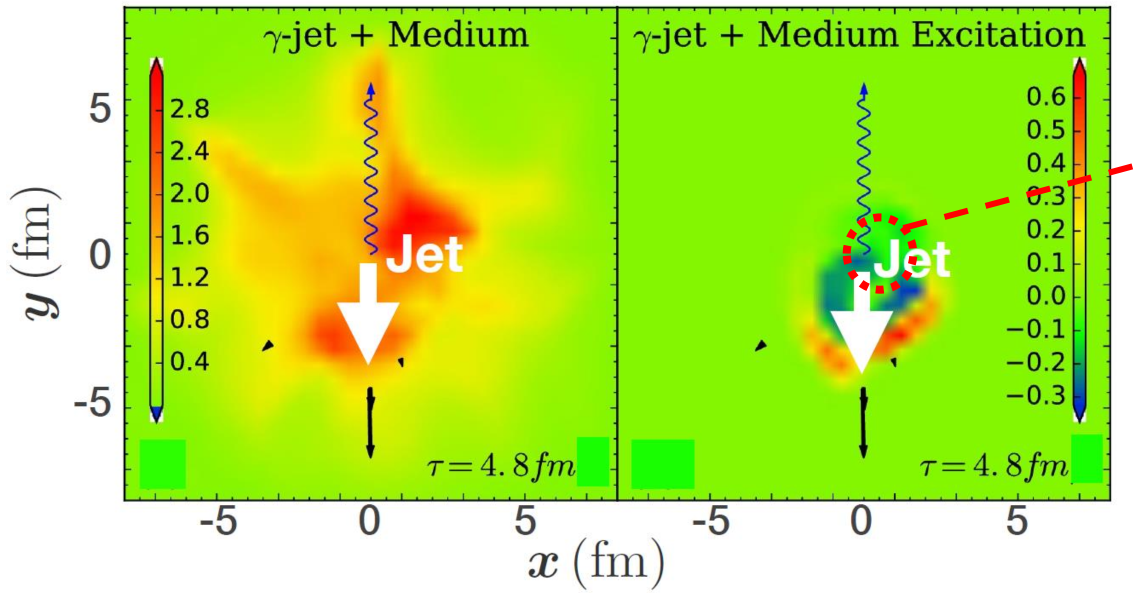
Wei Chen : Tuesday

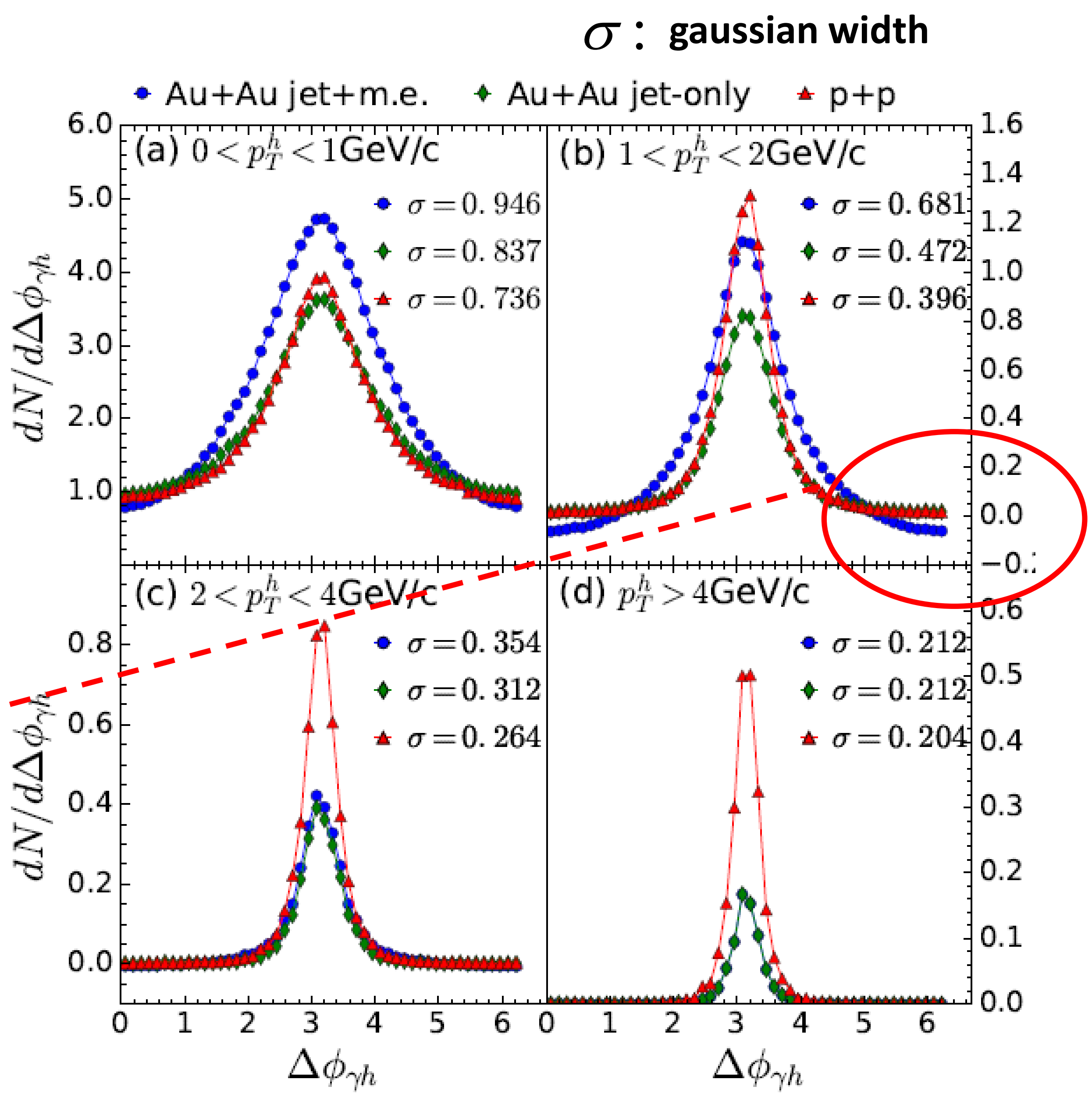


CoLBT-hydro W Chen, SS Cao, T Luo, LG Pang, XN Wang Phys.Lett. B777 (2018) 86-90

γ-hadron correlations

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



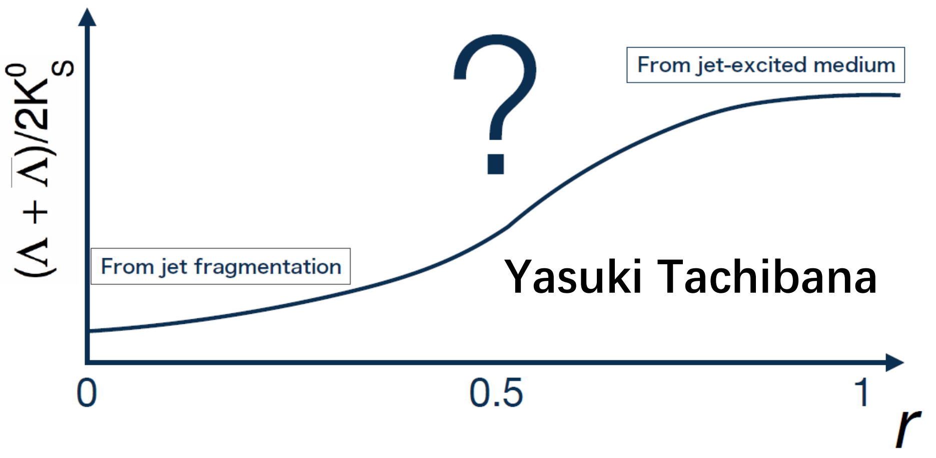


CoLBT-hydro W Chen, SS Cao, T Luo, LG Pang, XN Wang Phys.Lett. B777 (2018) 86-90

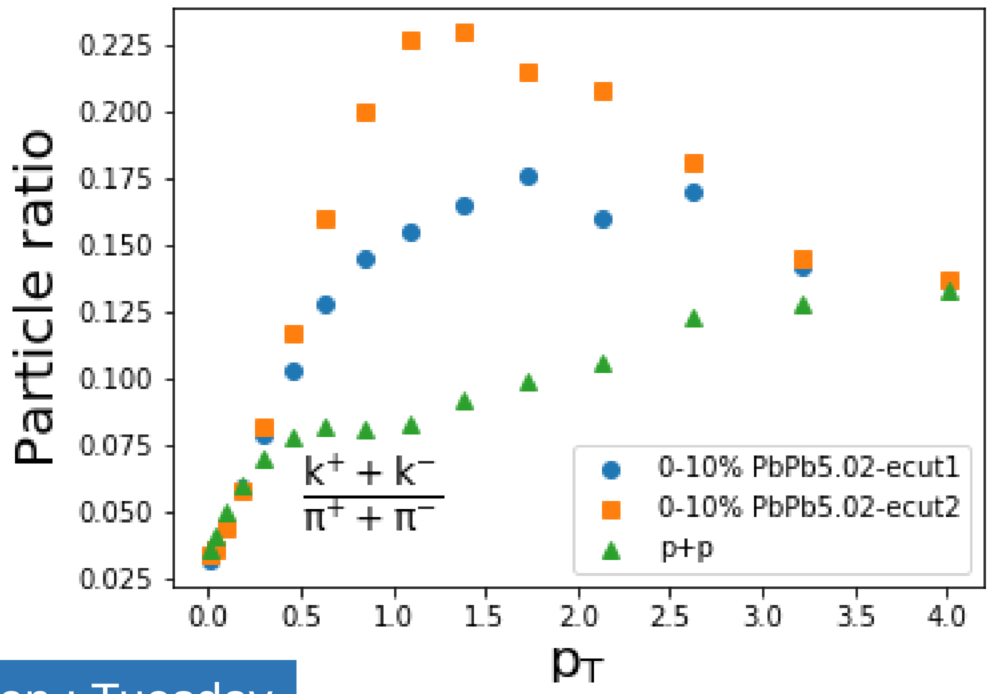
Jet chemistry

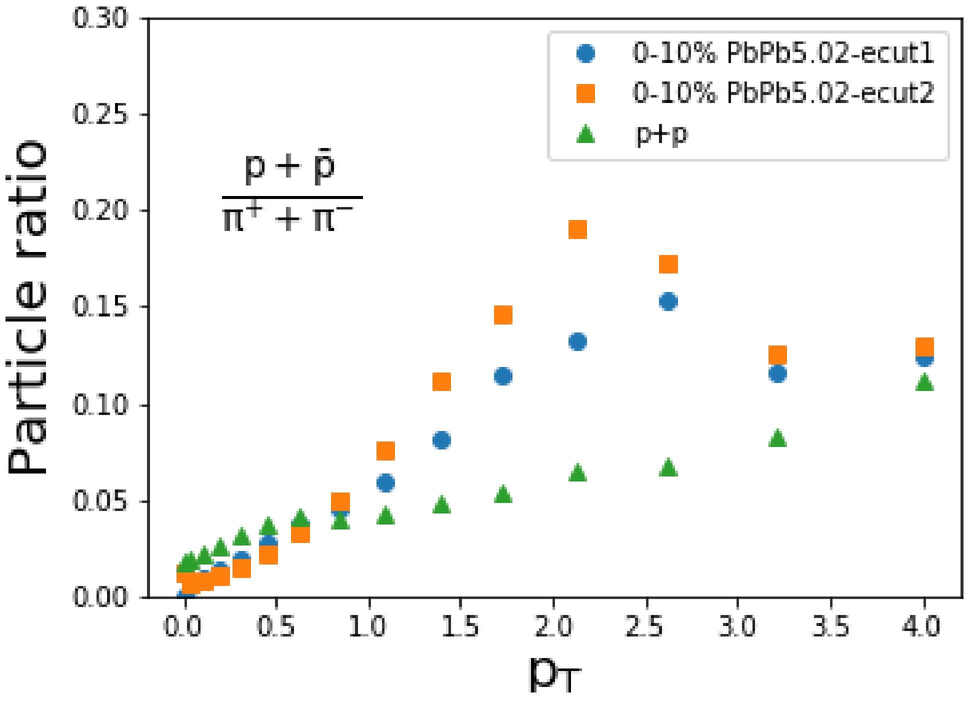
- Challenge for jet hadronization
- Focusing on ratio between different hadrons

- baryon/meson ratio in jet as a function of *r*



CoLBT-hydro preliminary





Wei Chen : Tuesday

Things I have not covered

- **Jet anisotropy and substructure**

Ning-Bo Chang : Tuesday

Haitao Li : Tuesday

Konrad Tywoniuk : Wednesday

Guang-You Qin : Wednesday

- **Jets in non-equilibrium medium**

Intrigue Hauksson : Tuesday

- **Machine learning**

Yue Shi Lai : Tuesday

Yang-Ting Chien : Wednesday

Xin-Nian Wang : Wednesday

Tianyu Dai : Tuesday

- **A lot more ……**

11 Parallel sessions, 2 focus on Jet-medium interaction on Tuesday 16:30

Summary

- **Medium response is important to achieve a complete description of jet-medium interactions**

- **Implementation of jet induced medium response**
  Recoil vs Hydro

- **Medium response effect on the observables**
  Modifications of both jet energy and jet substructures
  Enhancement of soft particles at large angle around jets

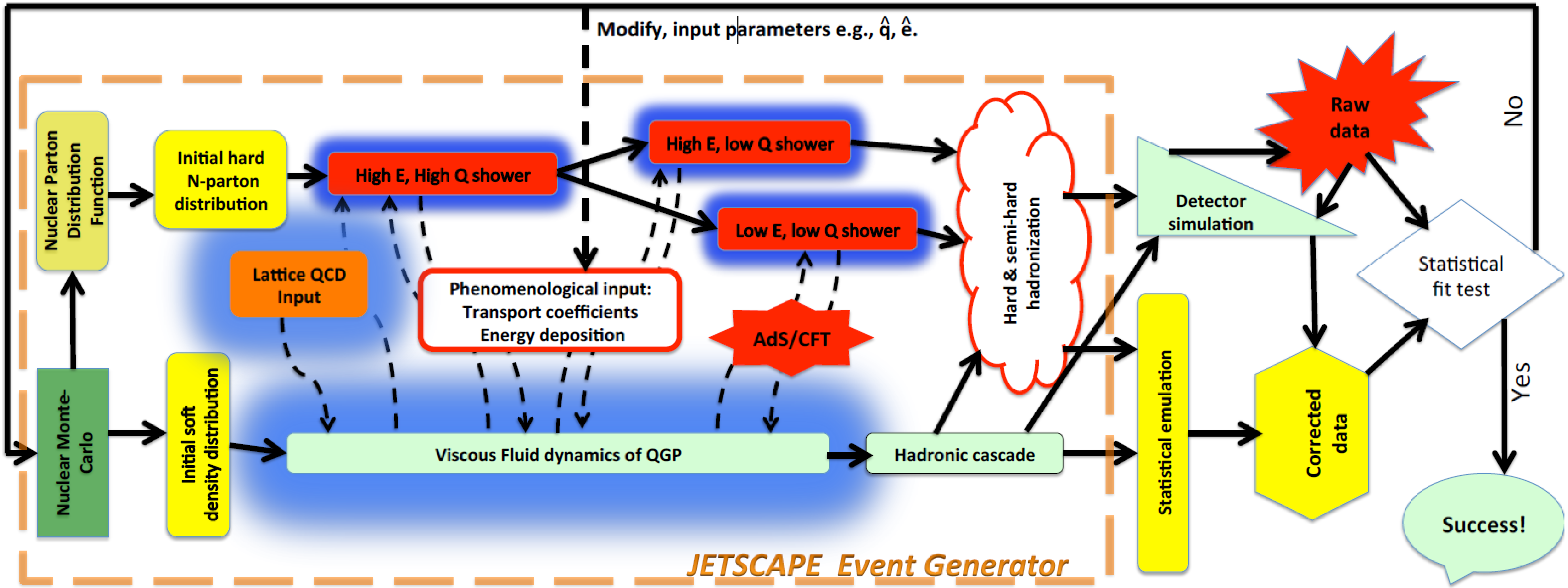
- **Unique identification of medium response effect in jet**
  Diffusion wake
  Jet chemistry

Outlook

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

Poster by Joern Putschke

Poster by Rainer Fries



Ron Soltz : Tuesday

Yasuki Tachibana : Wednesday

Chanwook Park : Thursday

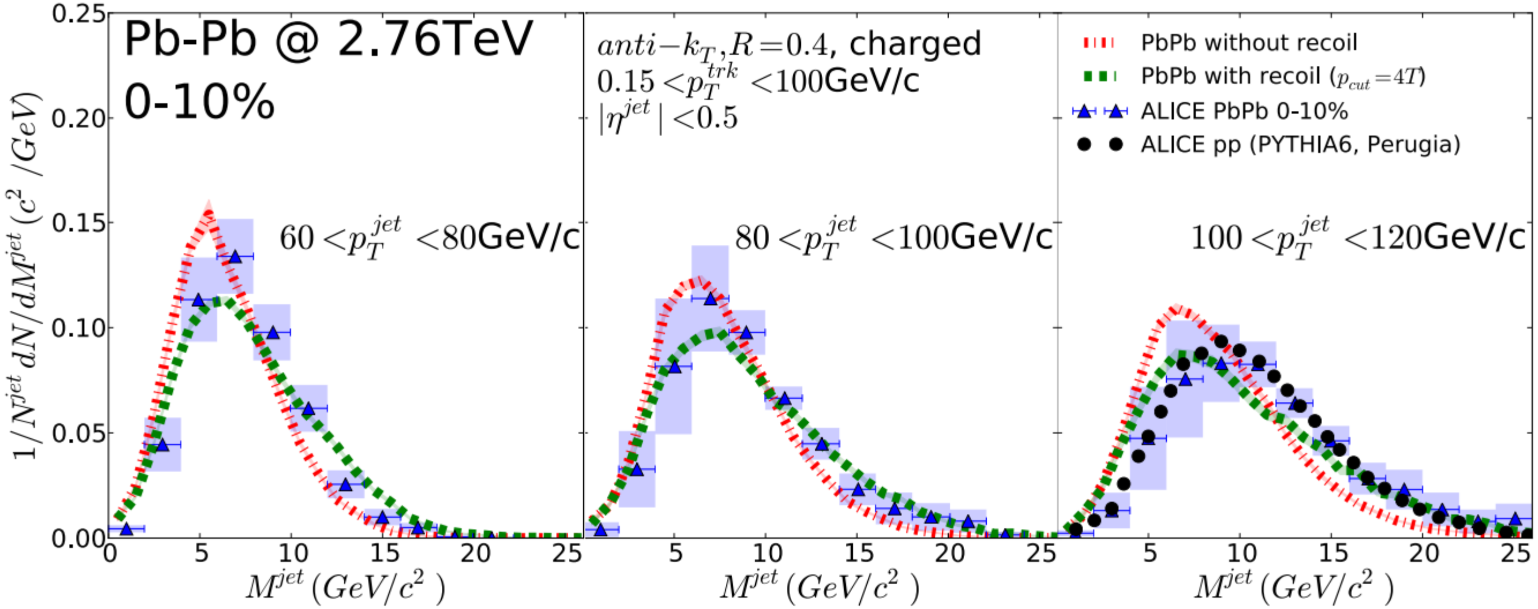
Thanks

Jet mass

- Two competing effects : Decrease by jet quenching + Increase by including medium recoil
- Recoil affects on the jet mass

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

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

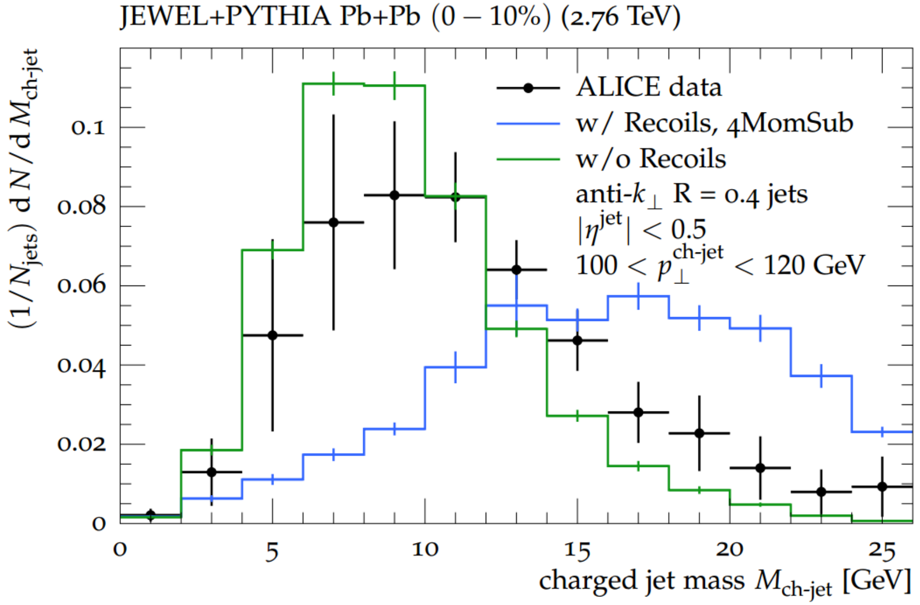


Low jet p_T

High jet p_T

JEWEL

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



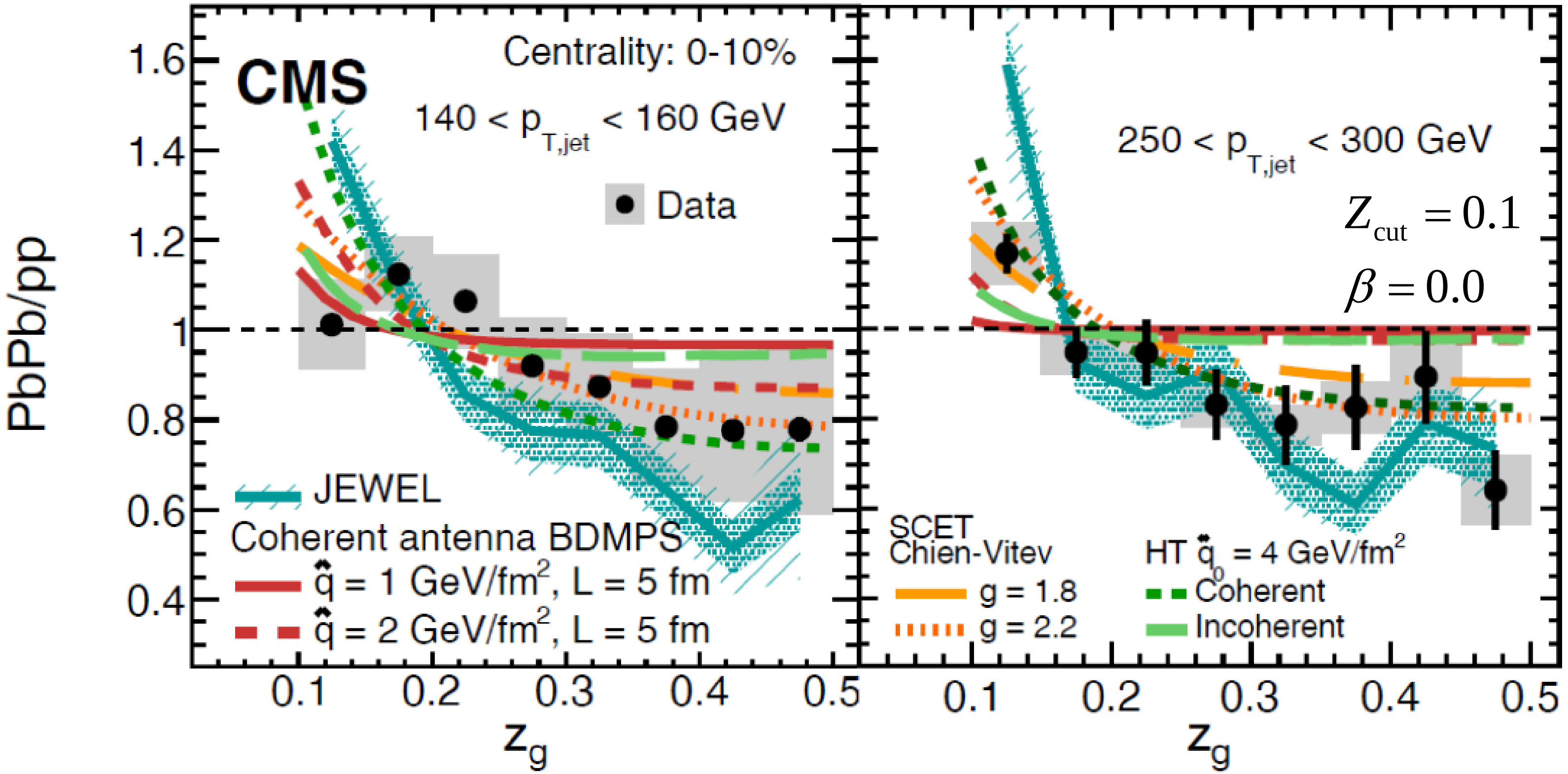
Jet splitting function

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

- 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.

arXiv:1708.09429



LBT model Recoil