γ-jet fragmentation function & jet-induced medium excitation

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"Opportunities and challenges with jets at LHC and beyond"
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Outlines

1 Introduction

2 Model description

- Linear Boltzmann transport model(LBT)
- 3+1D hydrodynamic model(CLVisc)
- CoLBT-hydro model for jet transport and jet-induced medium excitation.

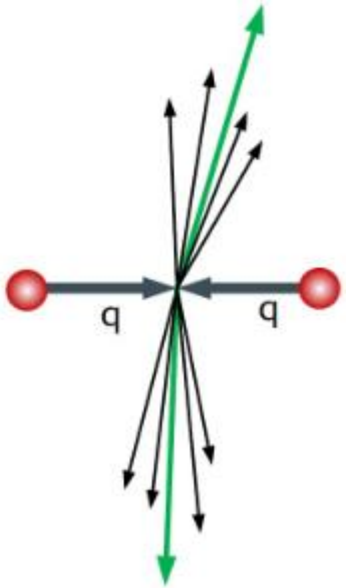
3 Results

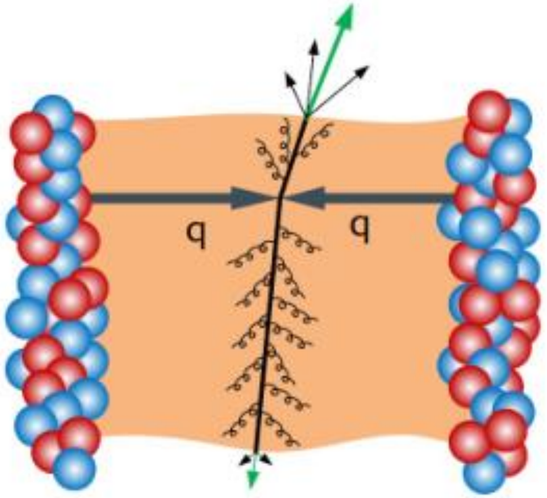
- Medium modification of γ-triggered fragmentation function at RHIC
- γ-hadron azimuthal correlation at RHIC
- Medium modification of γ-triggered fragmentation function at LHC

4 Summary and outlook

Motivation

Jet tomography for the study of QGP





QGP medium effect:

- ✓ Interaction with medium constituents
- ✓ Induced gluon radiation

Jet quenching

Leading partons energy loss

Modification of jet structure

Where does the lost energy go?

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- ✓ Thermal recoil partons excited from medium
- ✓ Energy-momentum deposition into medium

Enhancement of hadrons emission from medium along jet axis

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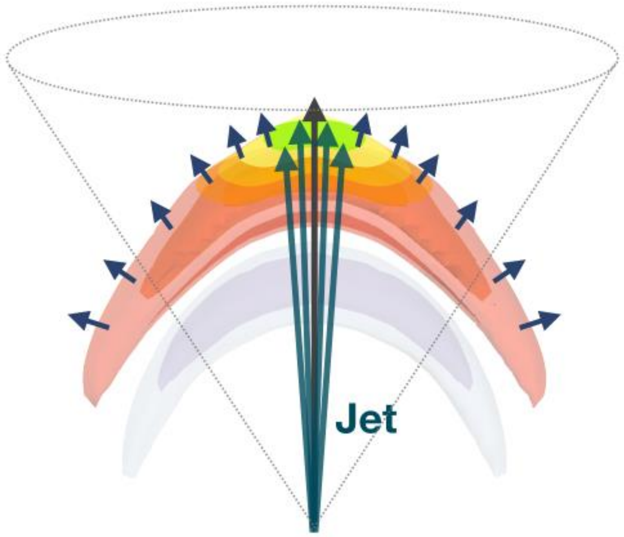
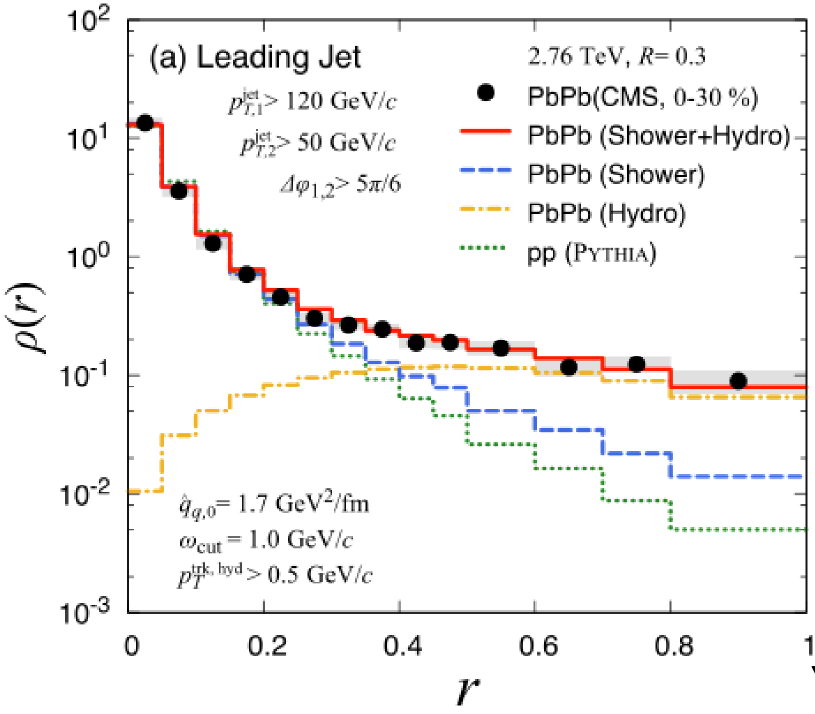
Jet-induced medium responce



The modified jet can be determined by:

- ✓ Energy loss of the leading jet shower partons.
- ✓ The redistribution of the lost energy and momentum in the medium.



Medium response contributes to many jet-observables:

- ✓ Energy redistribution in reconstructed full jet(jet shape)
- ✓ Gamma-hadron and jet-hadron fragmentation function & gamma-hadron azimuthal distribution.

and so on.

Yasuki Tachibana, N-Bo Chang ,G-Y Qin(17)

Motivation

Frameworks for the study of whole jet quenching pictures(including medium responce):

✓ Full Boltzmann transport approach

in the same Monte-Carlo transport(cross section)

✓ jet plus hydrodynamics approach

- No recoil partons contribution
- Neglect the effect of medium response on the subsequent evolution of hard jets
- No concurrent

CoLBT-hydro model

Linear Boltzmann Transport model (LBT)

+

3+1D hydrodynamic model (CLVisc)

Linear Boltzmann Jet Transport Model

Linear Boltzmann Jet Transport Model(LBT)

Monte Carlo jet transport model based on pQCD calculation:

- **Jet transport is simulated according to linear Boltzmann equation**

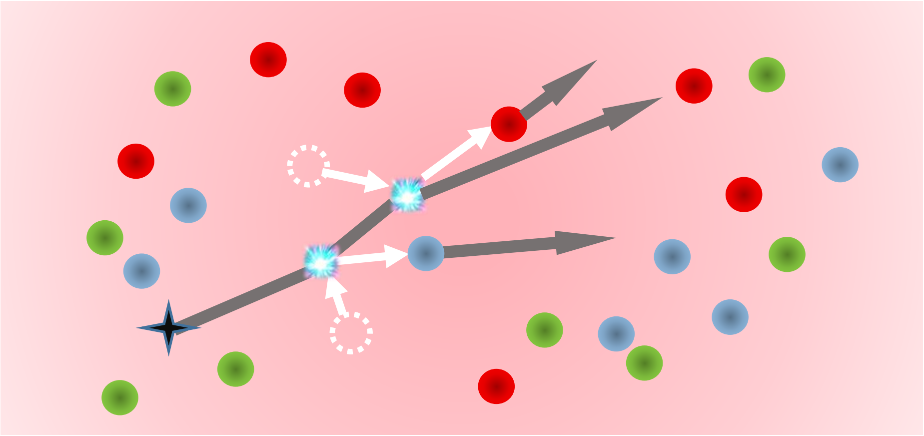
$$p_a \cdot \partial f_a = \frac{\gamma_b}{2} \int \prod_{i=b,c,d} d[p_i](f_c f_d - f_a f_b)|M_{ab\to cd}|^2$$

$$S_2(\hat{s}, \hat{t}, \hat{u})(2\pi)^4 \delta^4(p_a + p_b - p_c - p_d),$$

- **Consider both elastic and inelastic processes**

$$\frac{dN_g^a}{dz dk_\perp^2 dt} = \frac{2\alpha_s C_A P_a(z)}{\pi} \frac{k_\perp^4}{(k_\perp^2 + z^2 m^2)^4} \cdot \frac{p \cdot u}{p_0} \hat{q}_a(x) sin^2(\frac{t - t_i}{\tau_f}),$$

- **Keep track of jet shower parton and thermal recoil parton**
- **Take into account of back reaction and denote initial thermal partons in each scattering as "negative" partons**



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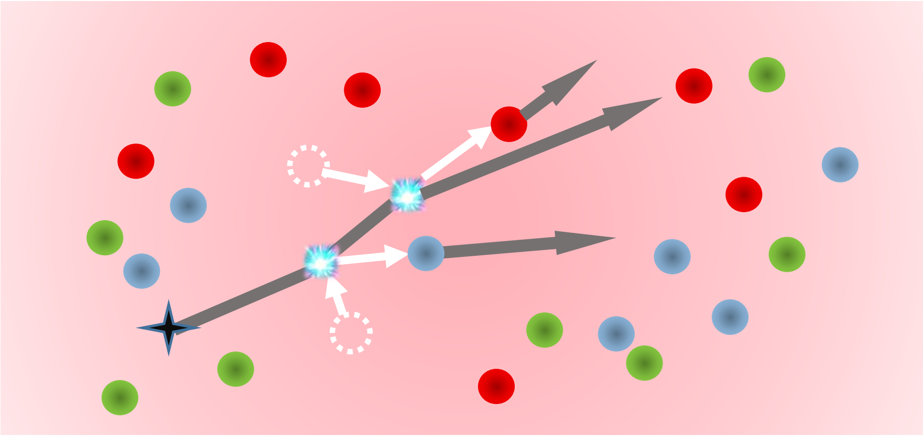
Jet-induced medium partons



Research method

3+1D hydrodynamic model(CLVisc model)

- **Hydrodynamic evolution of bulk medium**

  to solve $T^{\mu\nu}$=0 with a parameterized equation of state(Eos) s95p-pce by KT algorithm + the second Runge-Kutta method.

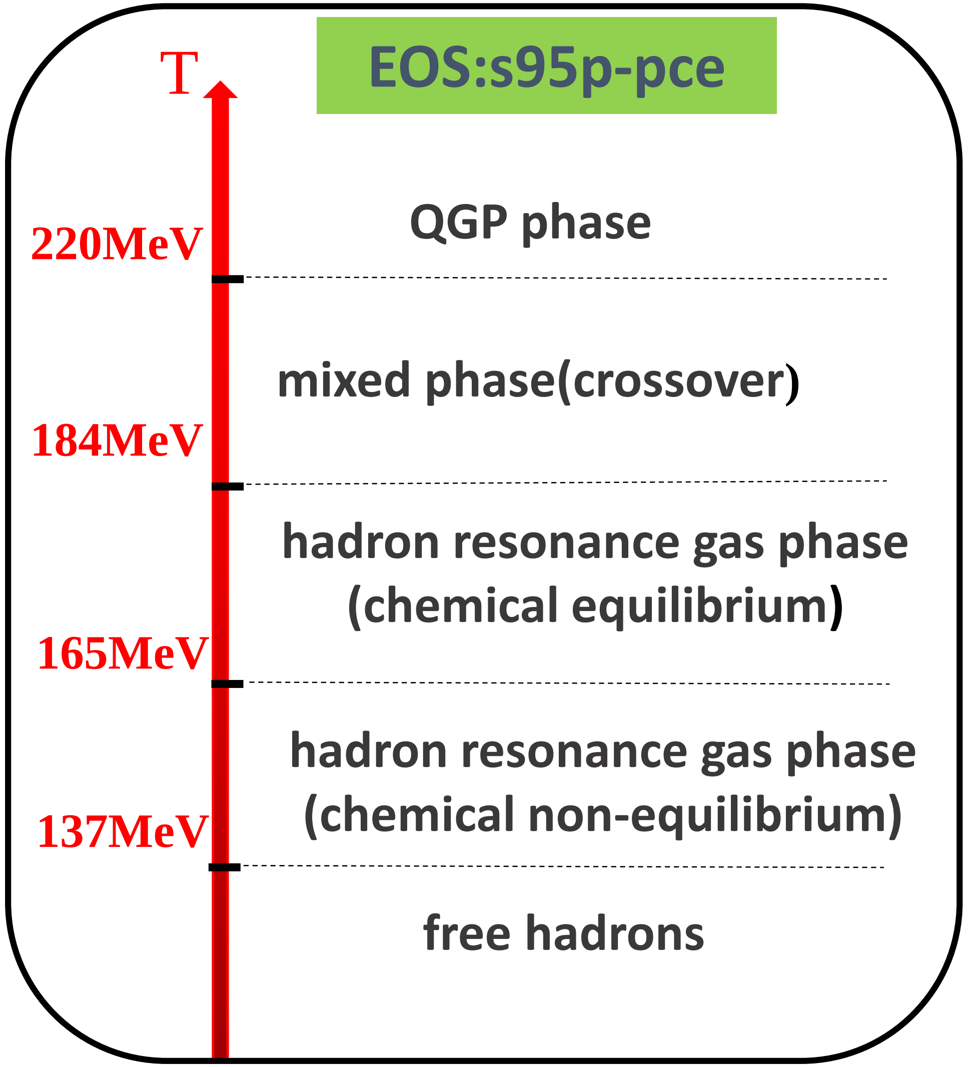
- **Calculate hadron spectrum from freeze-out hypersurface.**

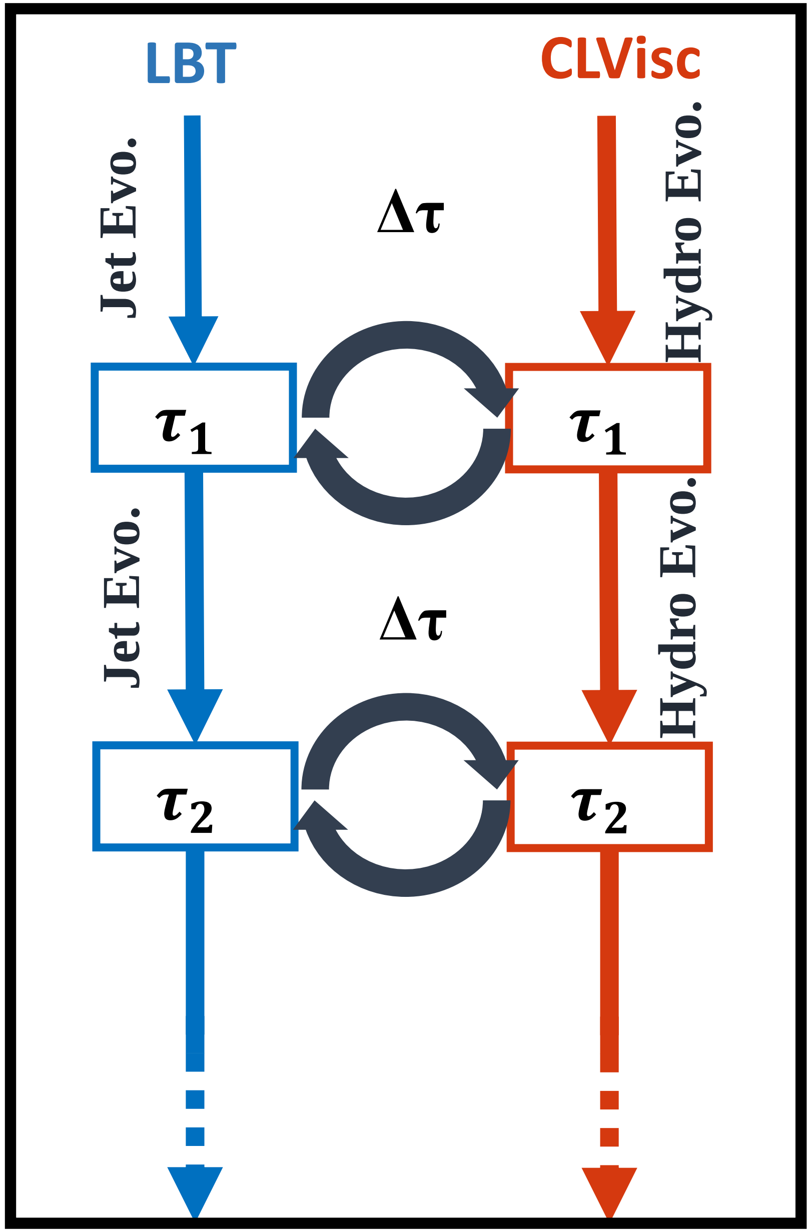
  Cooper-Frye formular:

$$\frac{dN_i}{dY p_T dp_T d\phi} = g_i \int_{\Sigma} p^{\mu} d\Sigma_{\mu} f(p \cdot u)$$

$$f(p \cdot u) = \frac{1}{(2\pi)^3} \frac{1}{exp((p \cdot u - \mu_i)/T_f) \pm 1}$$

- **Hadron resonance decay**



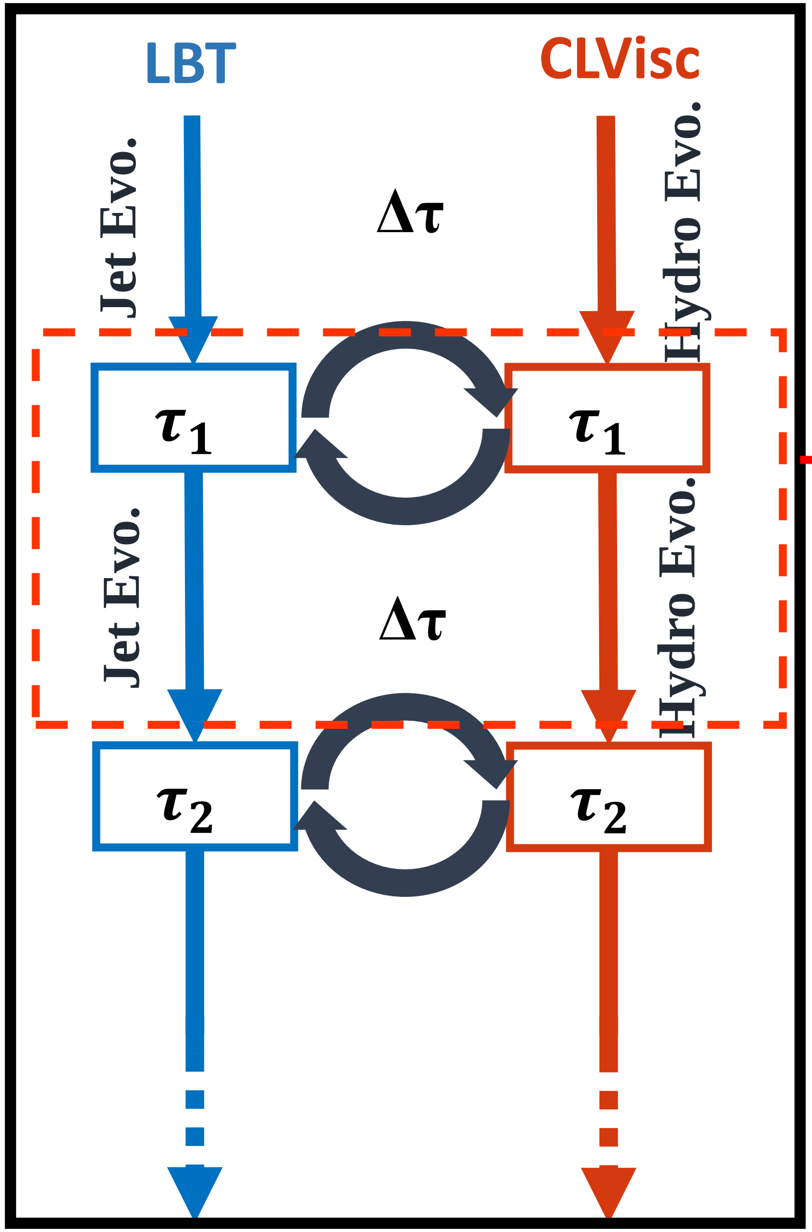


CoLBT-hydro model

Linear Boltzmann Transport model (LBT) **+** 3+1D hydrodynamic model (CLVisc)

- ✓ formulated in Milne coordinates $(\tau, x_\perp, \eta_s)$
- ✓ simulated in sync with each other

CoLBT-hydro model



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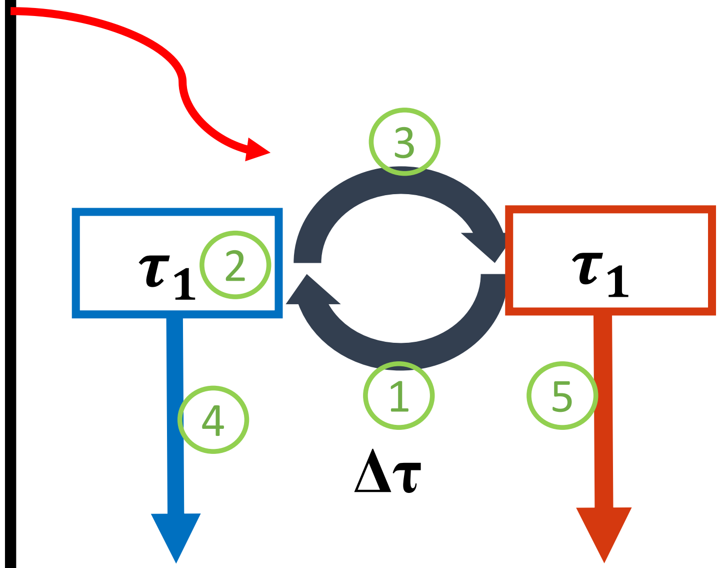

1. provide medium info (T, u) to jet partons
2. carry out jet shower partons' transport according to medium info.
3. soft($p \cdot u < p^0_{cut}$) and 'negative'($p \cdot u < 0$) partons deposited into medium as source term
4. hard($p \cdot u \geq p^0_{cut}$) partons propagate in LBT frame
5. update the medium info through solving $\partial_\mu T^{\mu\nu} = j^\nu$

Hydrodynamic equations with source term

Assumption: Instantaneous local thermalization of deposited energy and momentum

Hydrodynamic equation with source term

$$\partial_\mu T^{\mu\nu}_{QGP}(x) = j^\nu_{jet}(x)$$

Energy-momentum tensor of QGP fluid

Energy and momentum deposited from jet

source term: $$j^\nu_{jet}(x) = \sum_i \frac{\theta(p^0_{cut} - p_i \cdot u) p^\nu_i}{\Delta\tau} \delta^3(\vec{x} - \vec{x}_i)$$

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soft partons
($p \cdot u < p^0_{cut}$)

negative partons
($p \cdot u < 0$)

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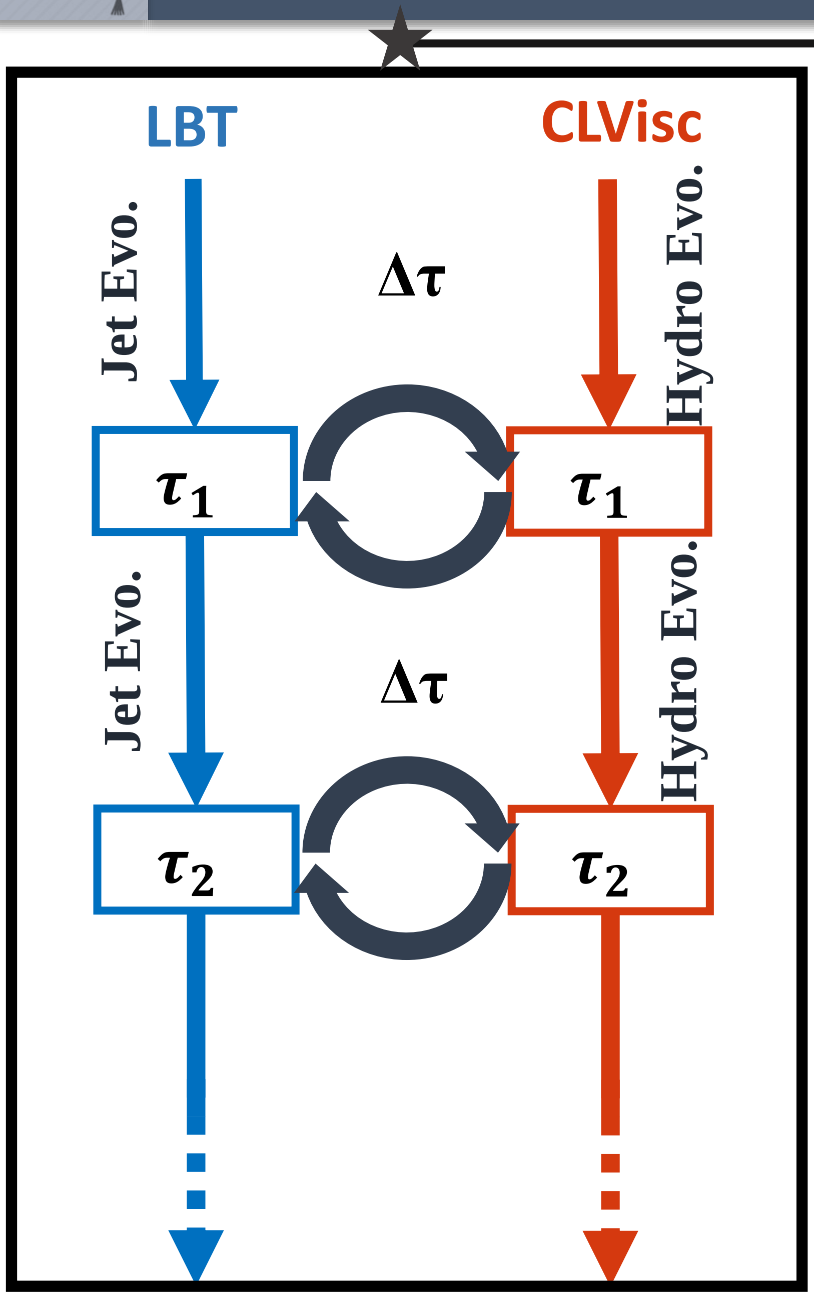
soft partons ($p \cdot u < p^0_{cut}$)

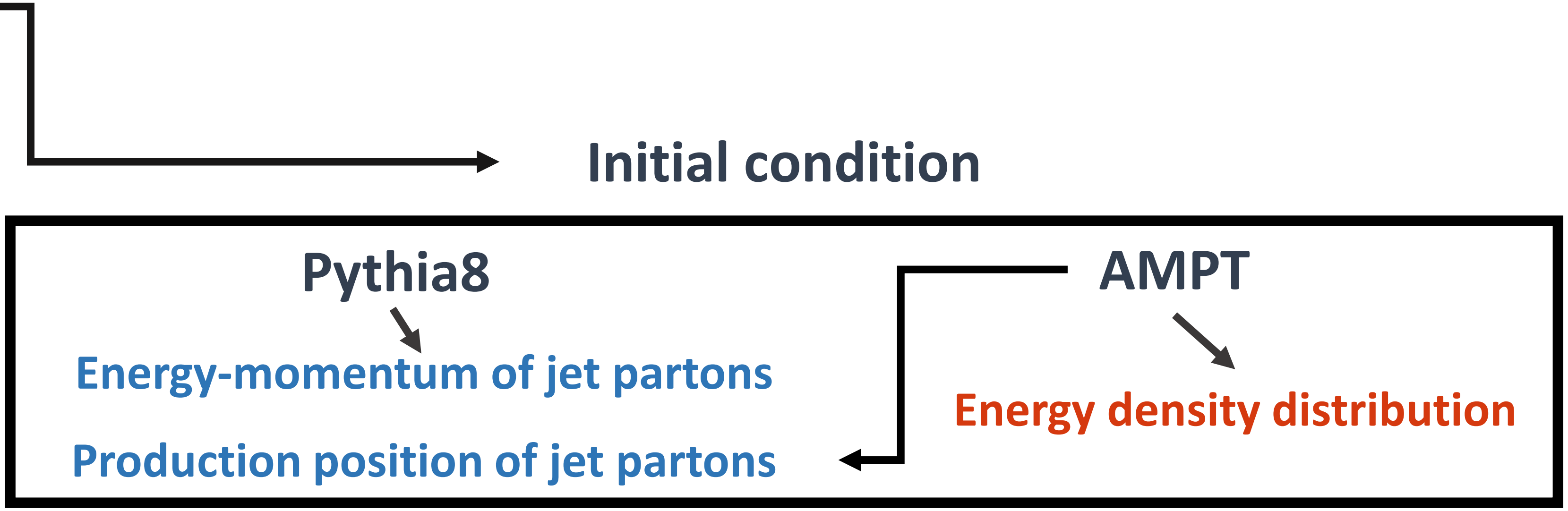
negative partons ($p \cdot u < 0$)

Gaussian approximation:

$$\frac{\delta^3(\vec{x} - \vec{x}_i)}{\Delta\tau} \rightarrow \frac{1}{\tau\Delta\tau(2\pi)^{3/2}\sigma_r^2\sigma_{\eta_s}} exp[-\frac{(\vec{x}_\perp - \vec{x}_{\perp i})^2}{2\sigma_r^2} - \frac{(\eta_s - \eta_{si})^2}{2\sigma^2_{\eta_s}}]$$

Initial condition





AMPT:

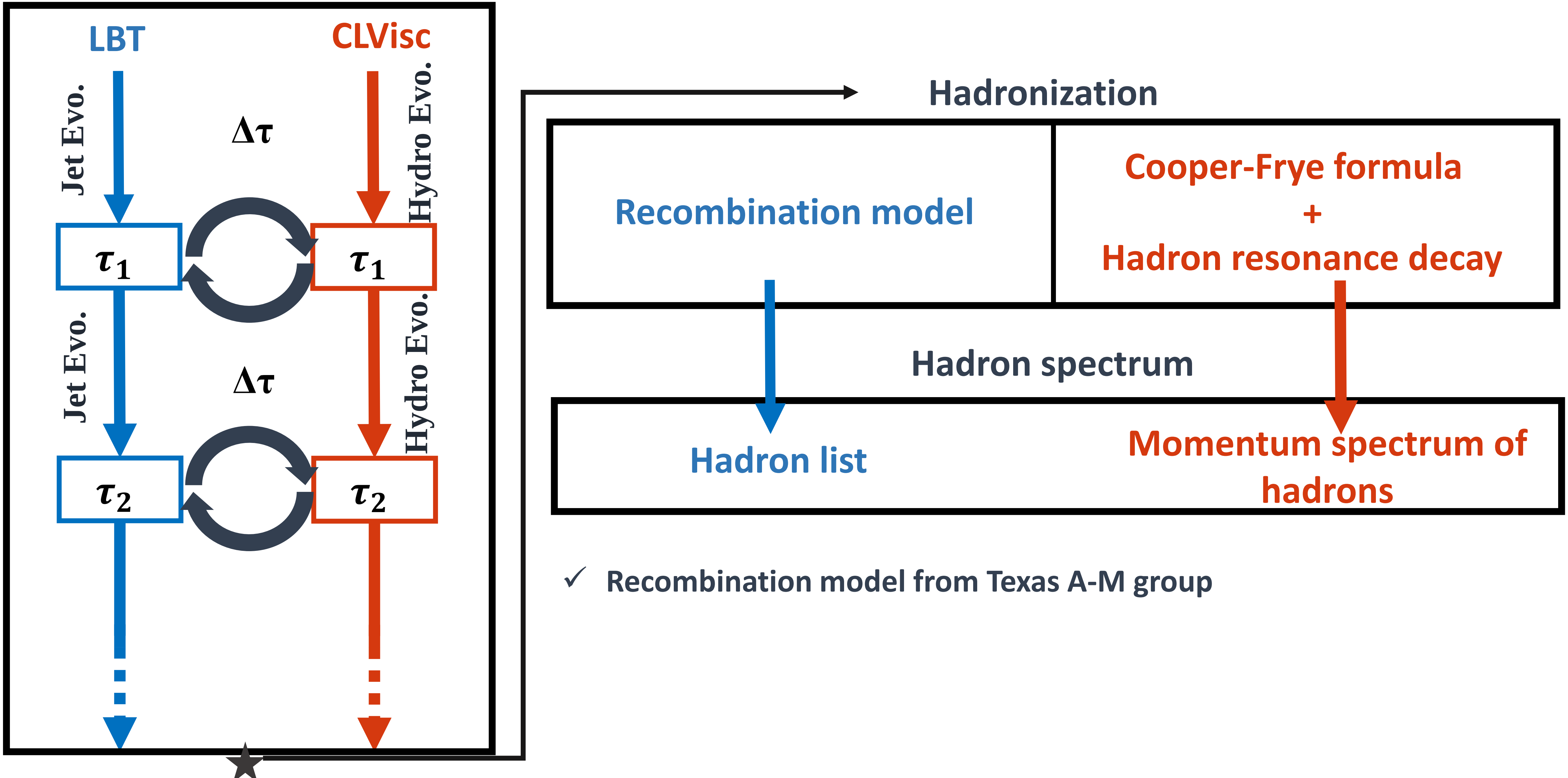
- ✓ Energy density distribution includes transverse and longitudinal fluctuation.
- ✓ Production positions of jet partons: sampled from spatial distribution of binary hard processes.

Pythia8:

- ✓ Energy-momentum of jet partons

different in each event.

Hadronization



✓ Recombination model from Texas A-M group

GPU parallel computation

We need to increase calculation efficiency of the CoLBT-hydro model:

- ✓ the final observables needs abundant event statistics
- ✓ one event calculation in single core of CPU takes long time (6-7 hours/event)

	single core(CPU)
Hydrodynamics evolution of medium	30-40 min
Hadron spectrum calculation in FO hypersurface	Almost 2 h
Hadron resonance decay	3-4 h

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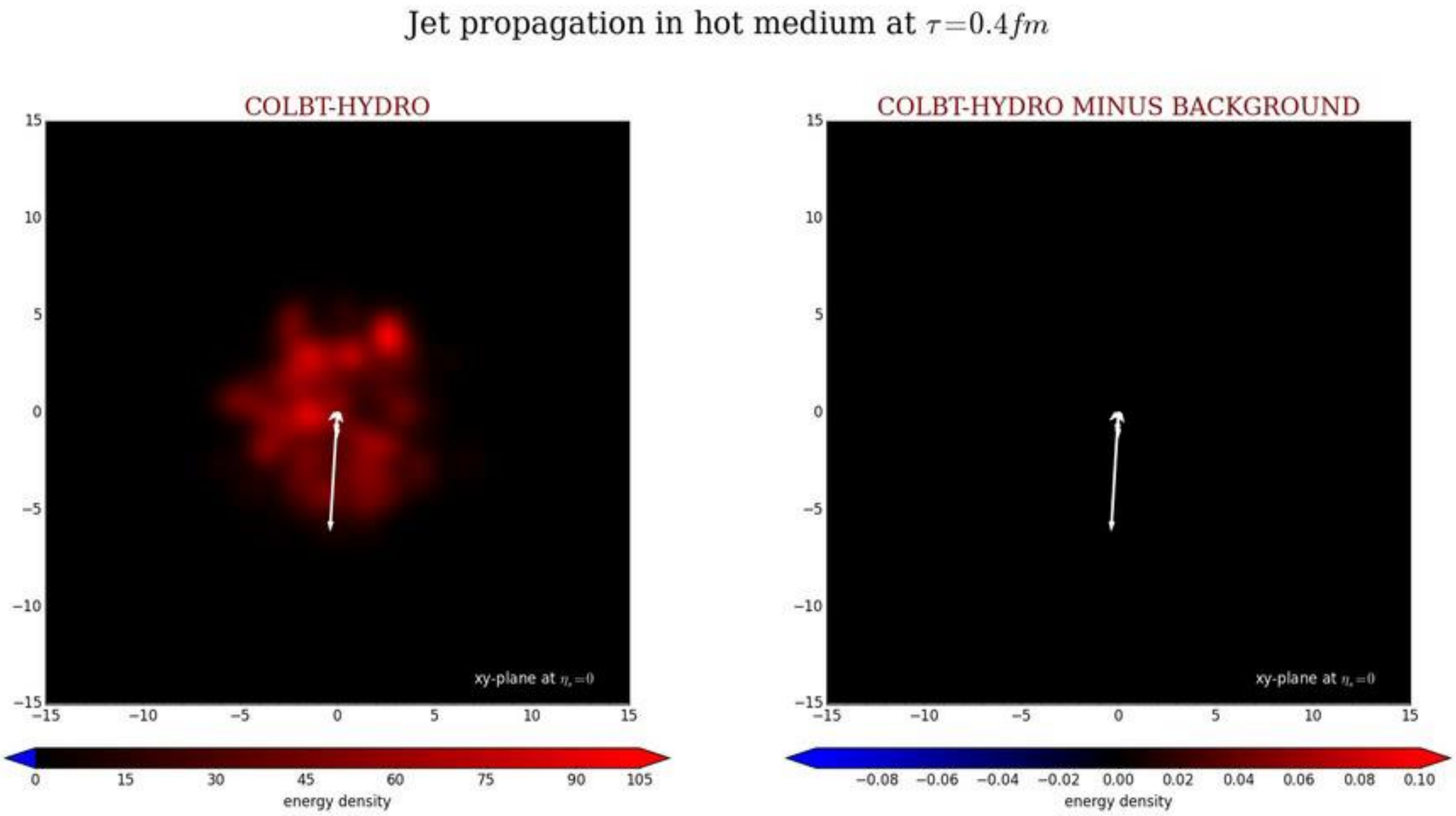
GPU parallel computation + GPU cluster

CoLBT-hydro for event-by-event simulations

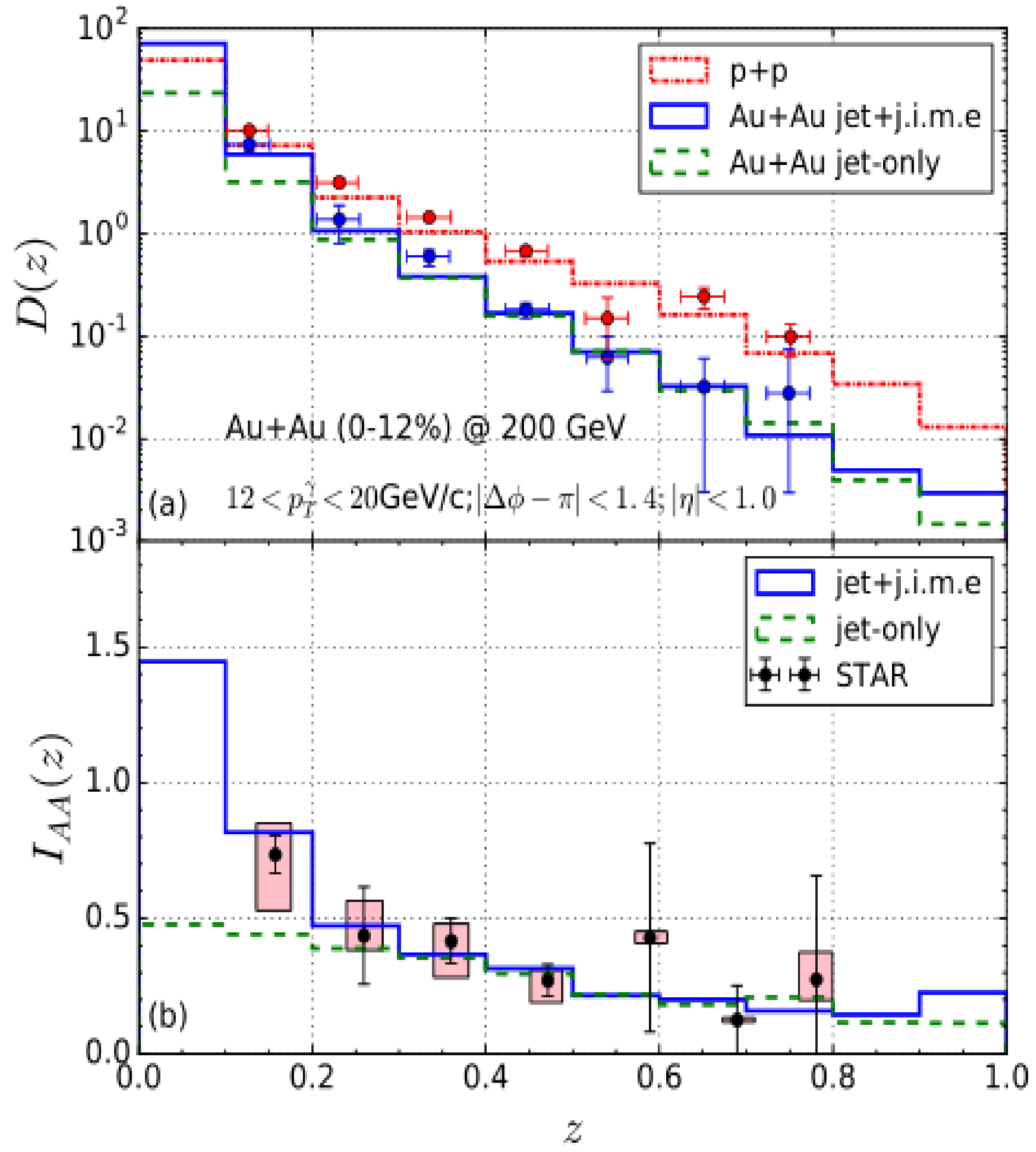
	single core(CPU)	GPU
Hydrodynamics evolution of medium	30-40 min	20-30 sec
Hadron spectrum calculation in FO hypersurface	Almost 2 h	1-2 min
Hadron resonance decay	3-4 h	2-3 min

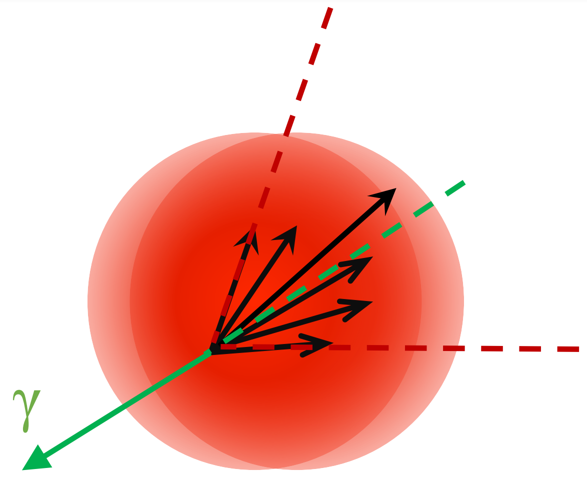
More than 100 times faster

Jet transport and jet-induce medium excitation



Medium modification of γ-triggered fragmentation function





$$z = \frac{p_T^h}{p_T^\gamma} \qquad D(z) = \frac{1}{N_{event}} \frac{dN}{dz}$$

$$I_{AA}(z) = \frac{D_{AA}(z)}{D_{pp}(z)}$$

In our calculation:

✓ **p+p results :**

jet partons from Pythia8 + recombination model

✓ **Au+Au results ：**

$$D(z) = \left.\frac{dN_h}{dydz}\right|_{LBT} + \left.\frac{dN_h}{dydz}\right|_{hydro}^{w/jet} - \left.\frac{dN_h}{dydz}\right|_{hydro}^{no/jet}$$

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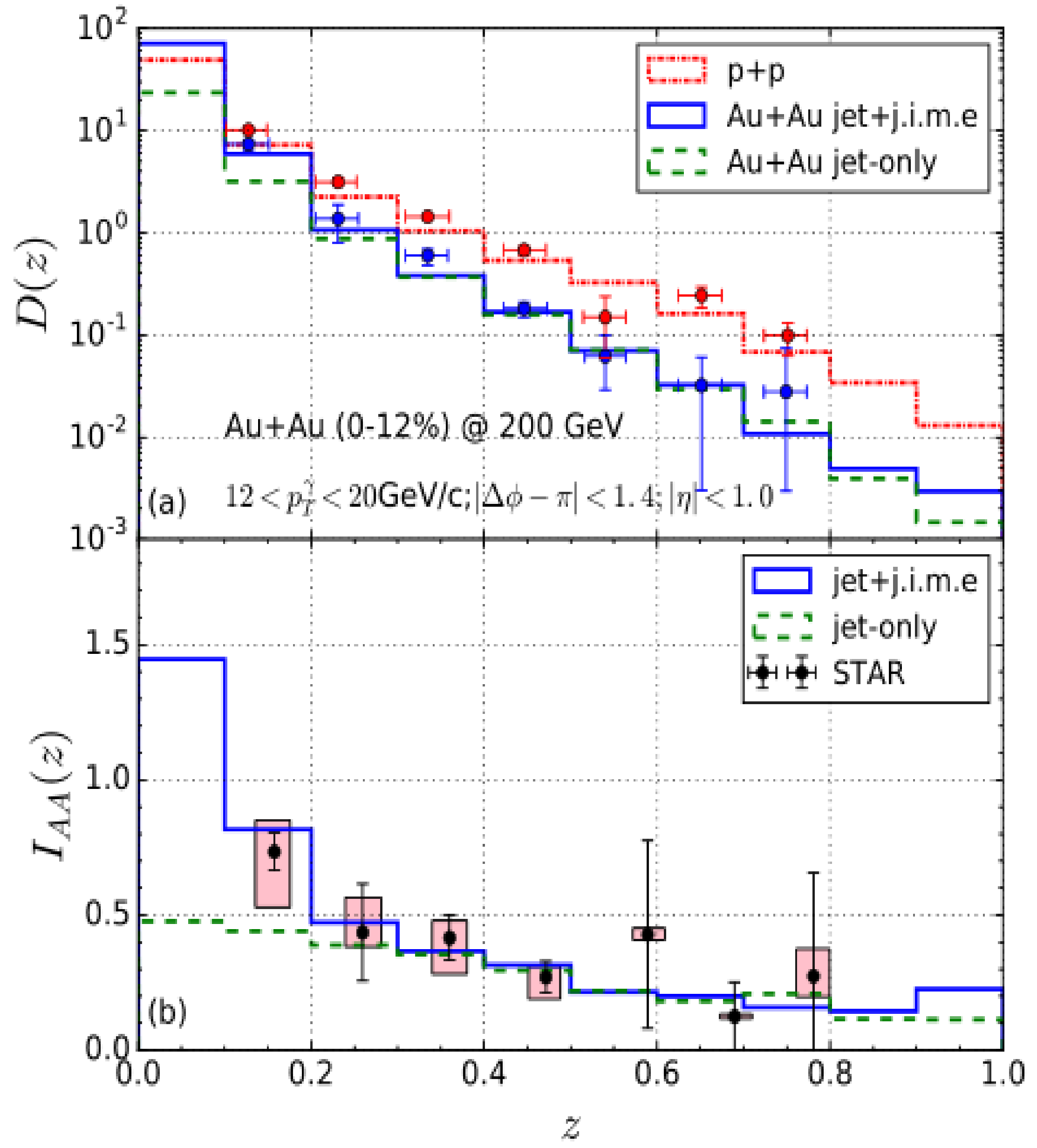

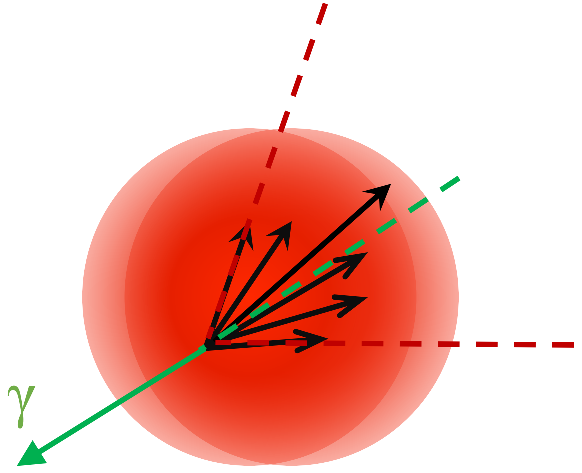

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background

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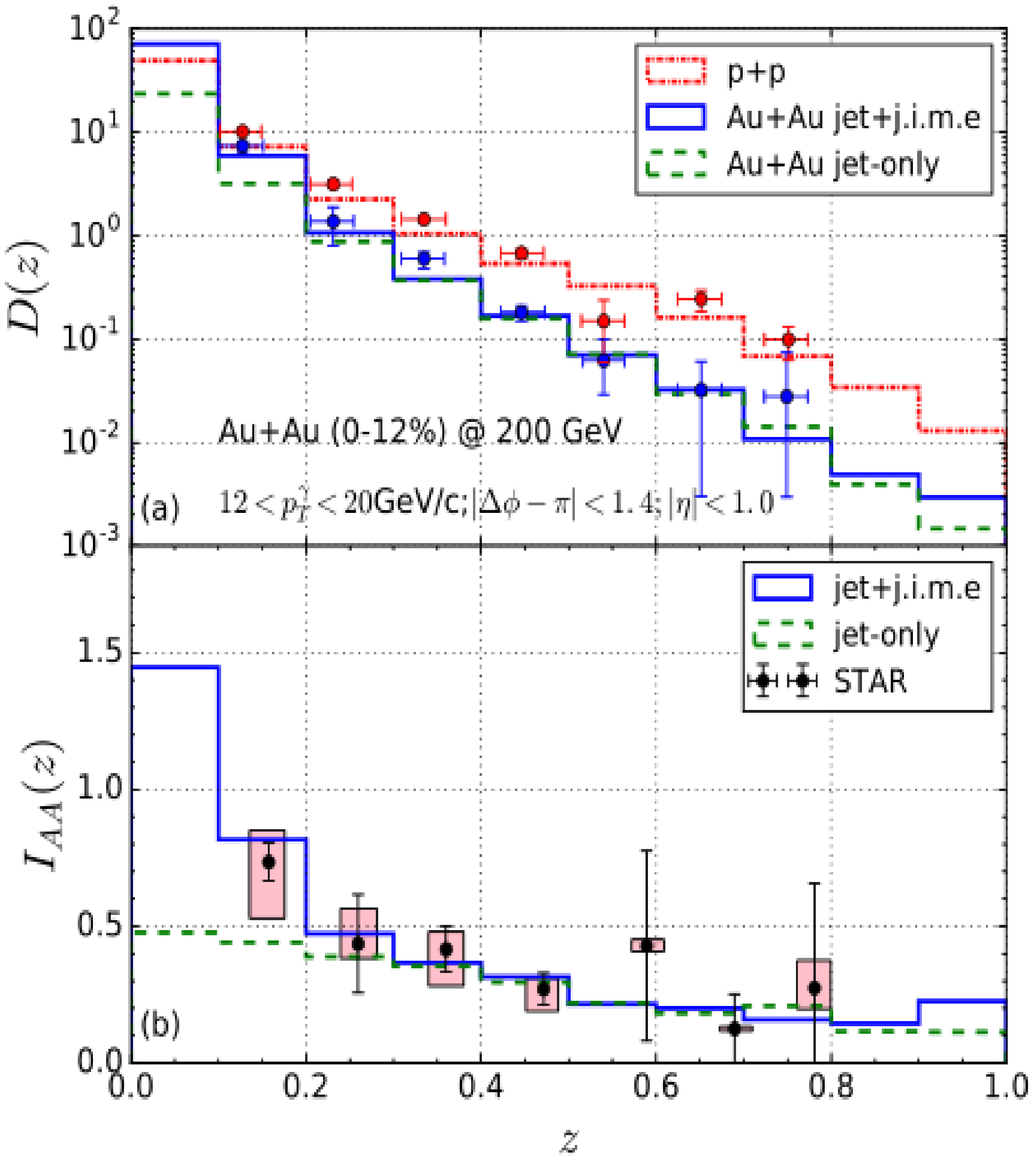

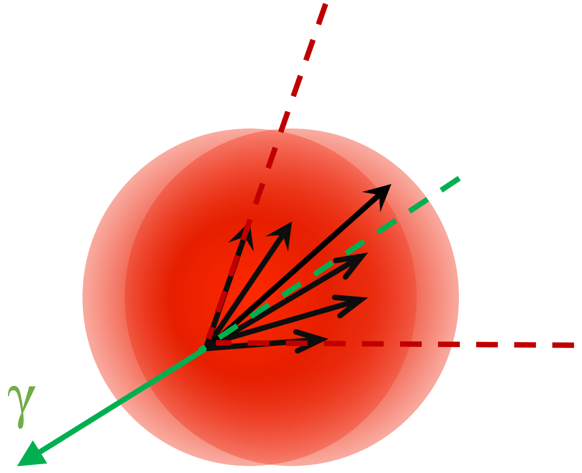

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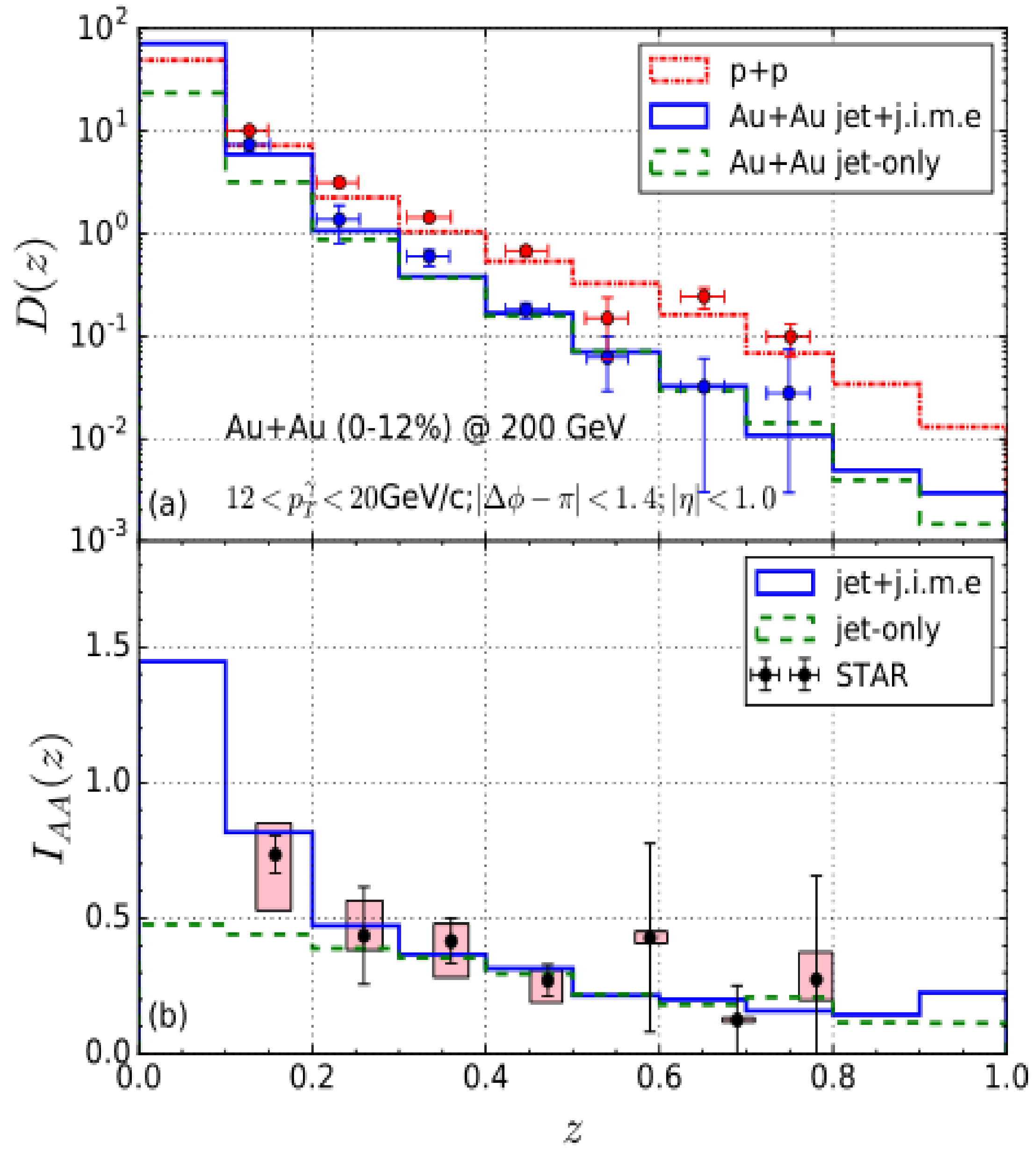
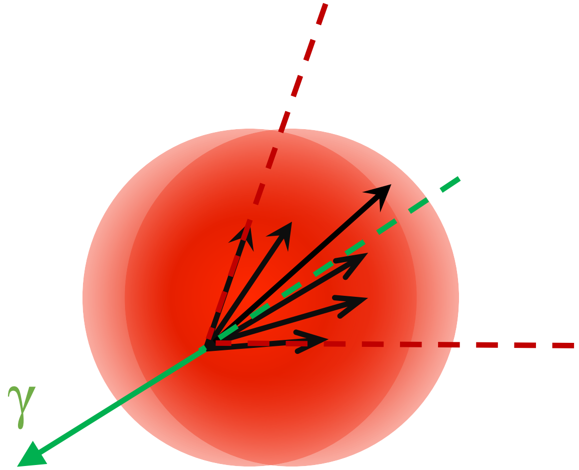
Medium response by energy-momentum deposition

Medium modification of γ-triggered fragmentation function





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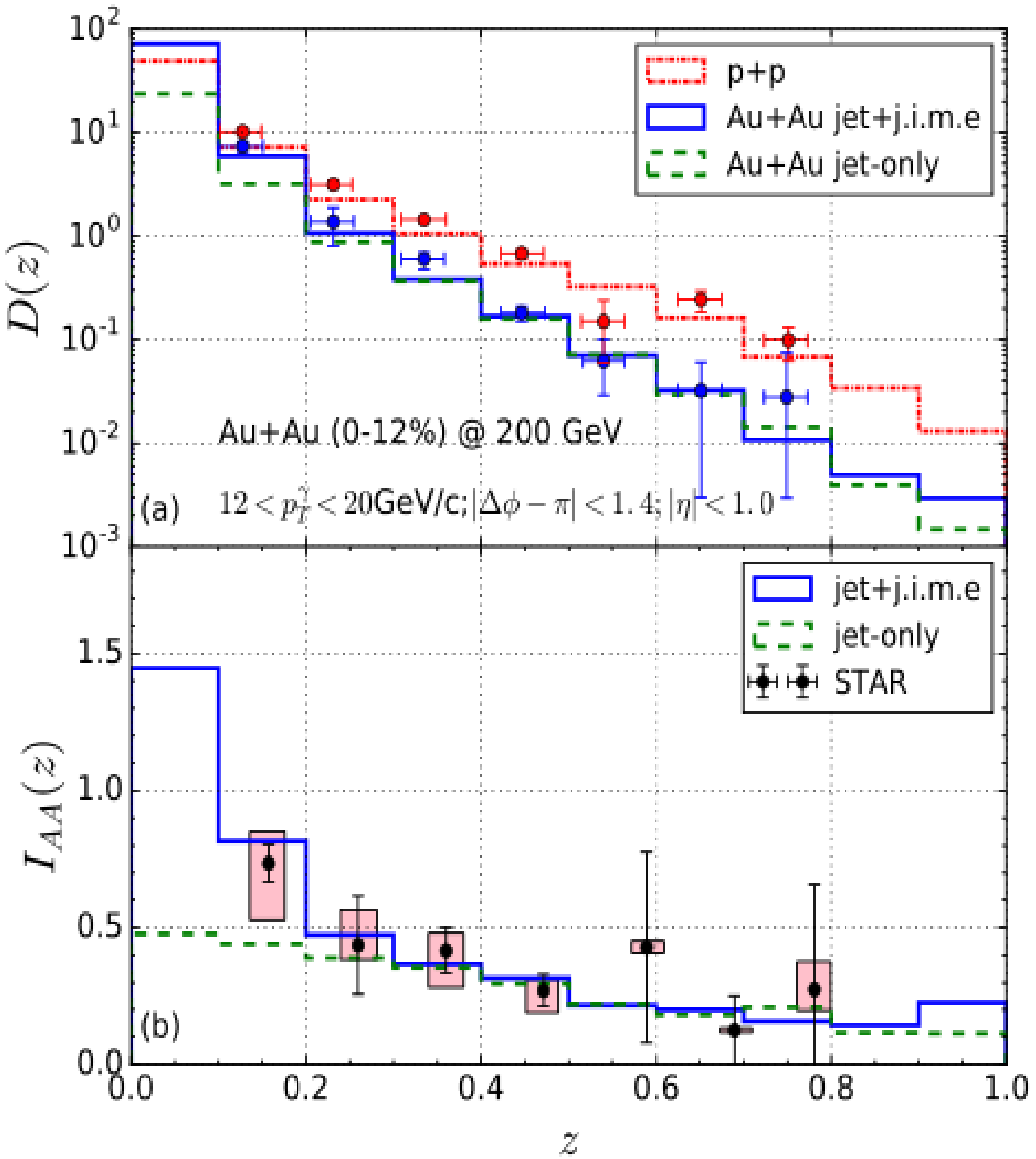
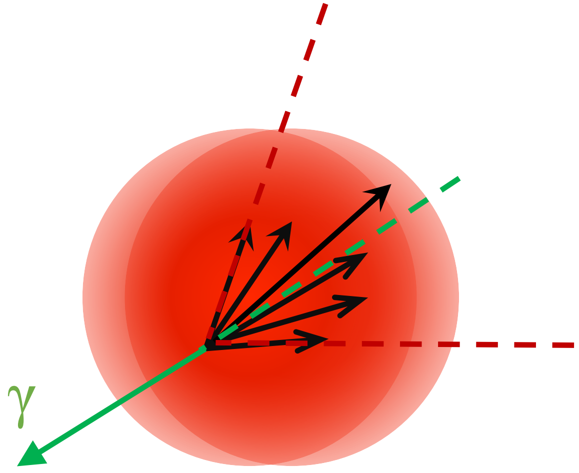
Remnant recoil parton contribution

Medium response by energy-momentum deposition

Medium modification of γ-triggered fragmentation function





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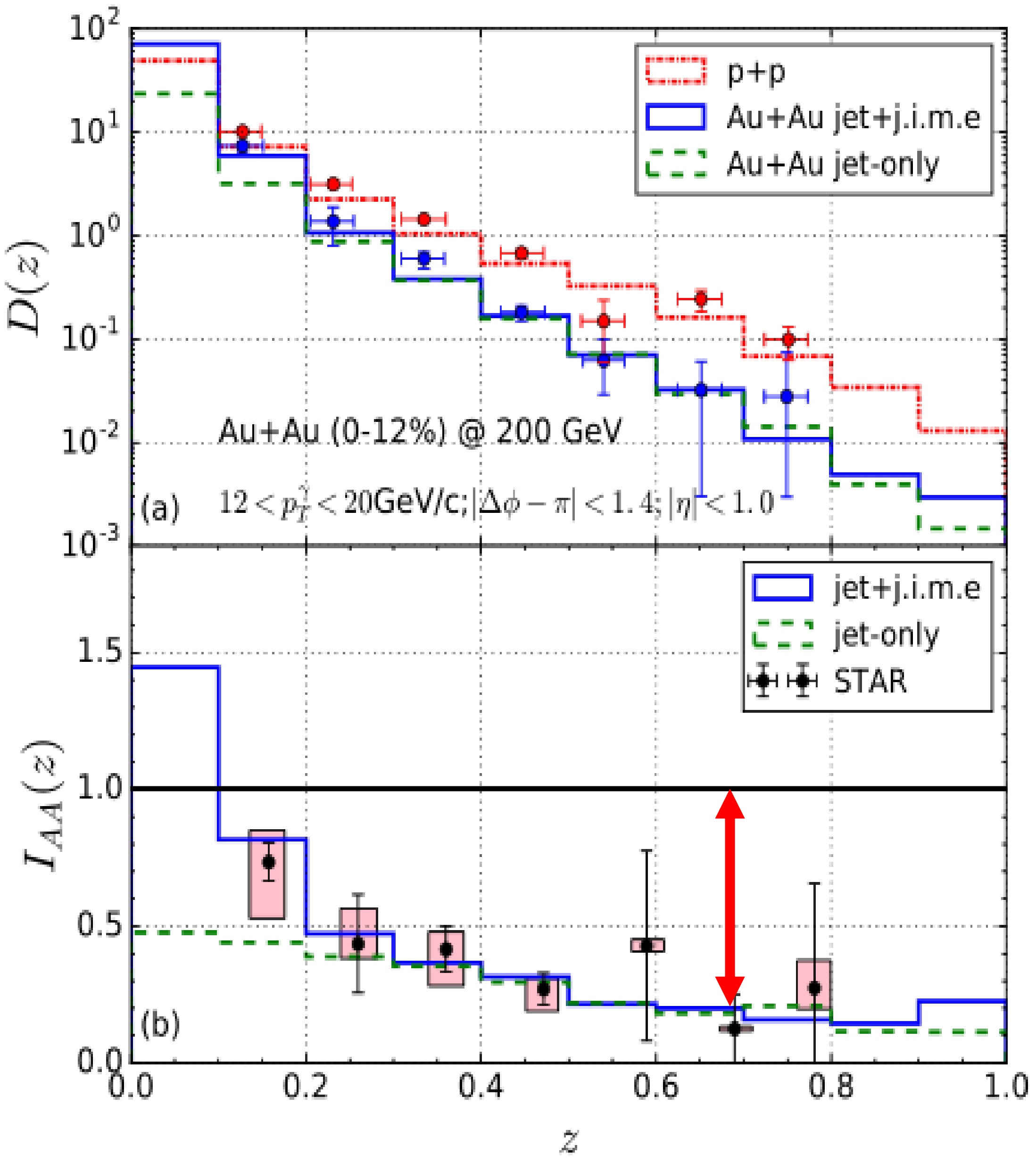
background

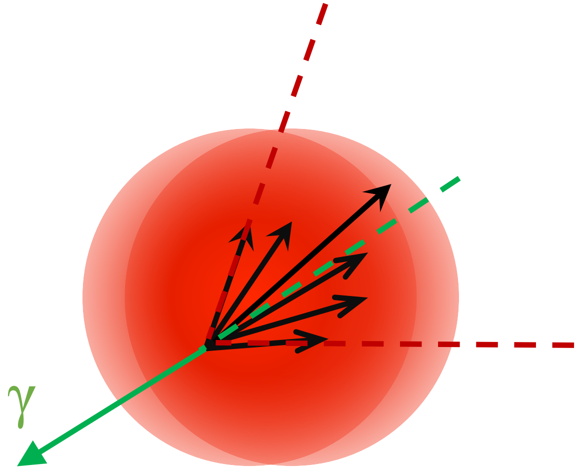
Remnant recoil parton contribution

Medium response by energy-momentum deposition

jet-induced medium excitation(j.i.m.e)

Medium modification of γ-triggered fragmentation function





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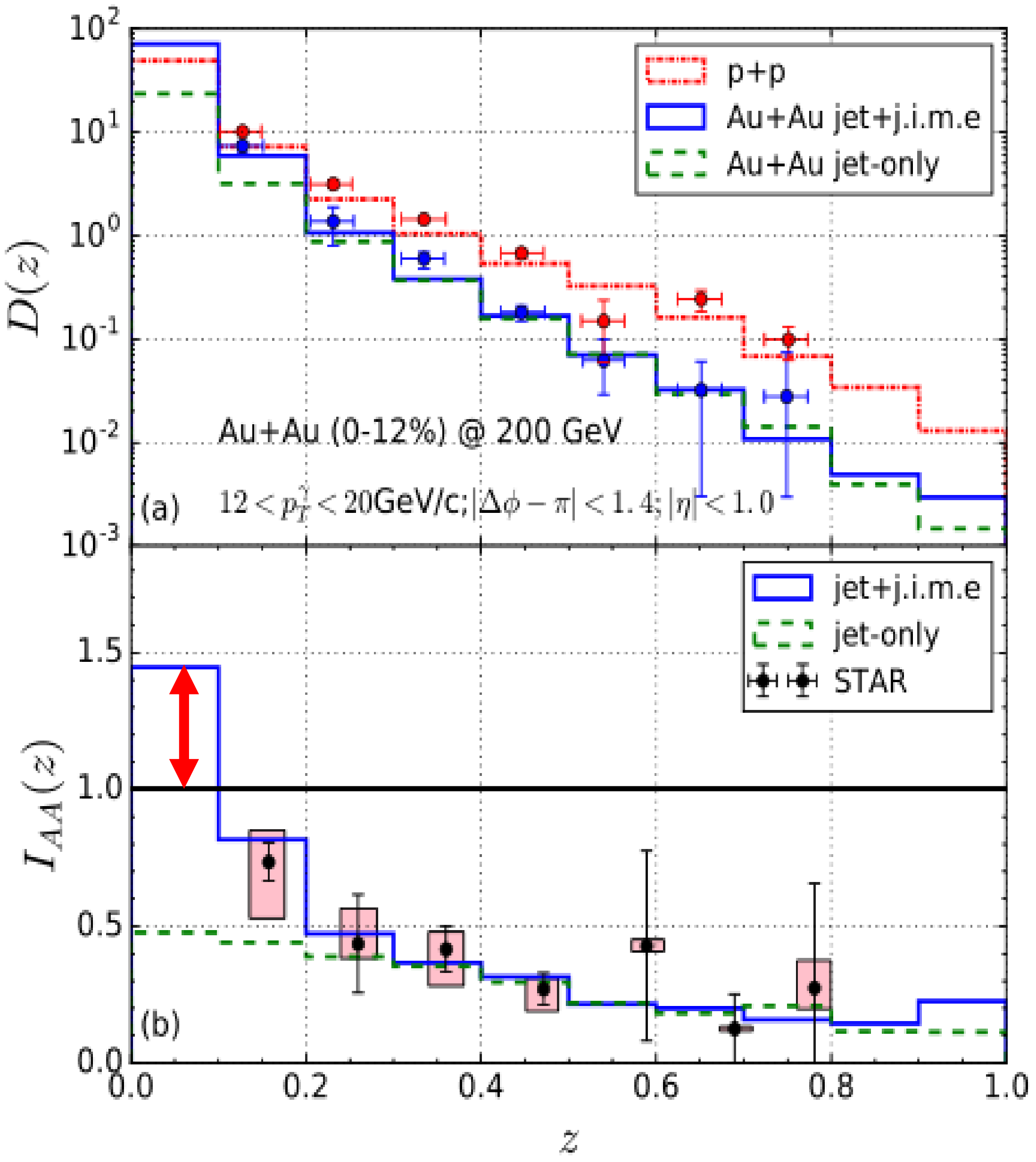
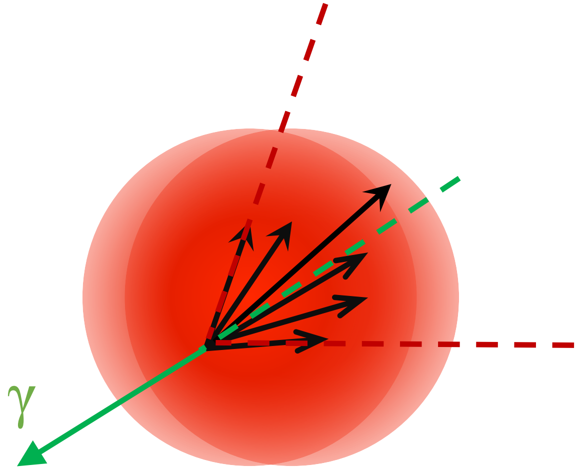
✓ **The suppression of leading hadron yield at the intermediate and high z**

⟵ **energy loss of jet partons due to interaction with hot medium**

Medium modification of γ-triggered fragmentation function





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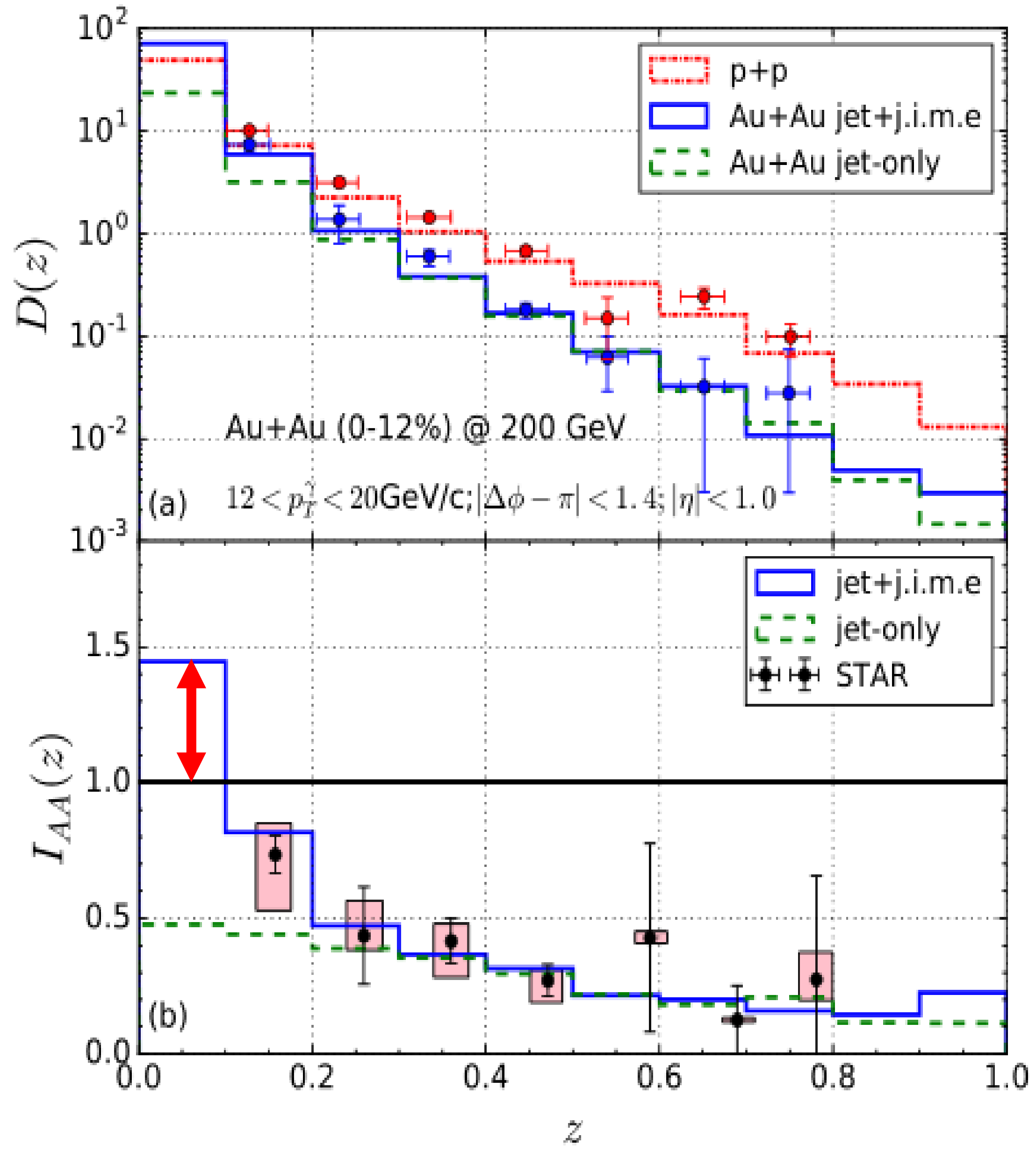
✓ **The suppression of leading hadron yield at the intermediate and high z**

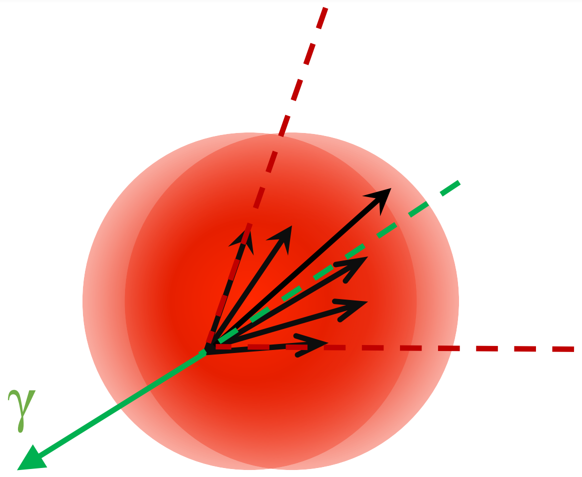
← energy loss of jet partons due to interaction with hot medium.

✓ **The enhancement of soft hadrons yield at small z**

← jet-induced medium excitation.

Medium modification of γ-triggered fragmentation function





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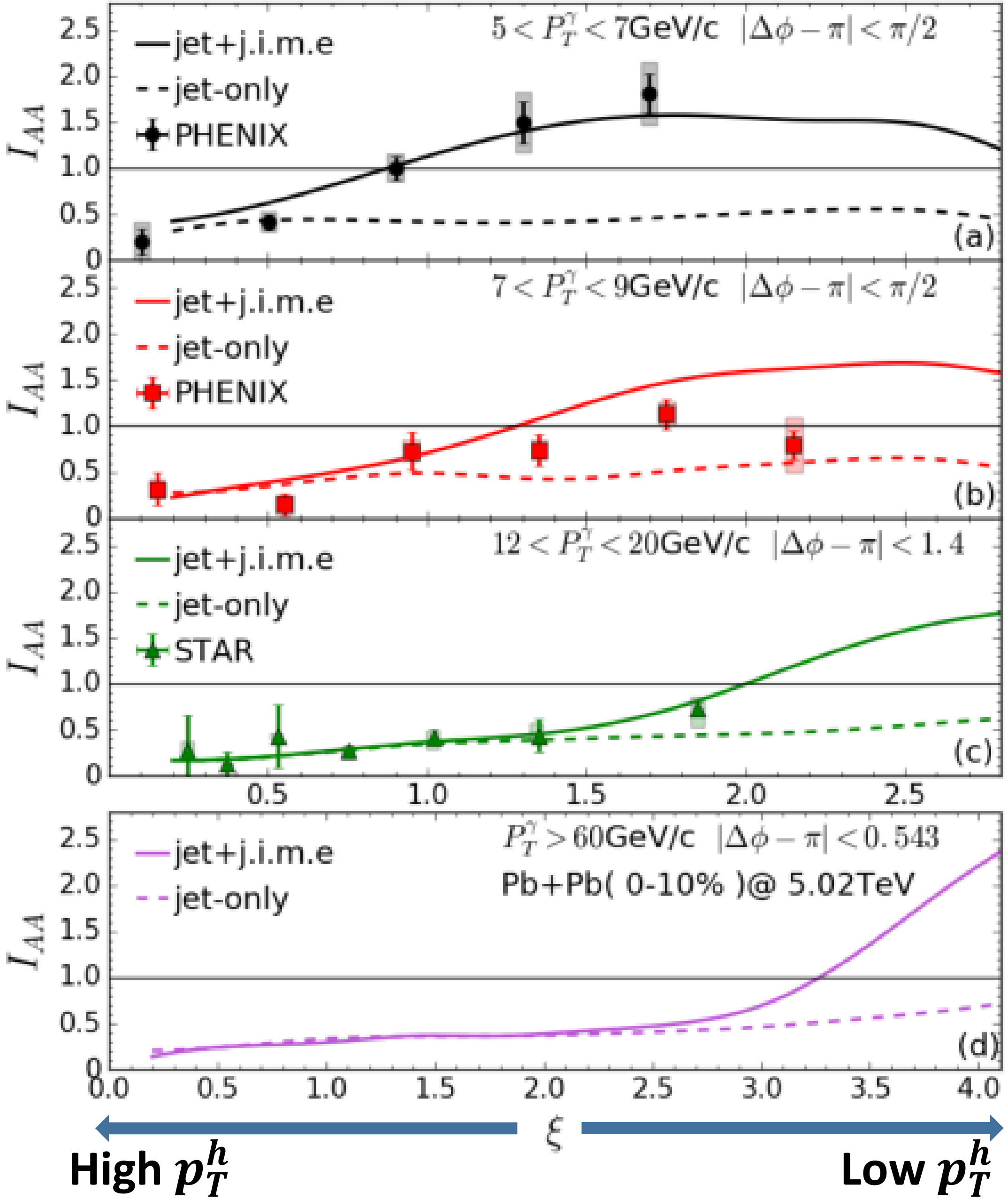
energy loss of jet partons due to interaction with hot medium.

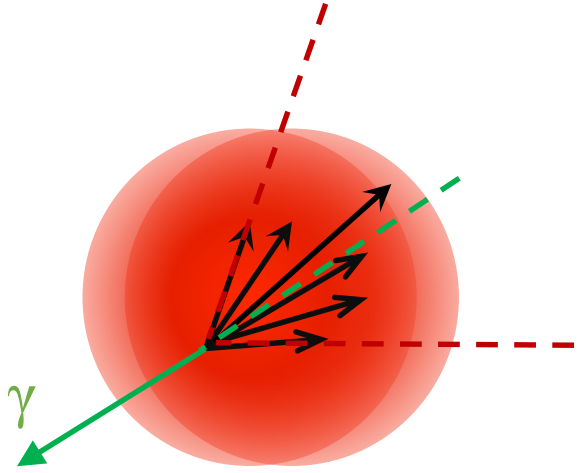
✓ **The enhancement of soft hadrons yield at small z**

jet-induced medium excitation.

$\alpha_s = 0.3 \quad and \quad p_{cut}^0$=2 GeV/c

Medium modification of γ-triggered fragmentation function



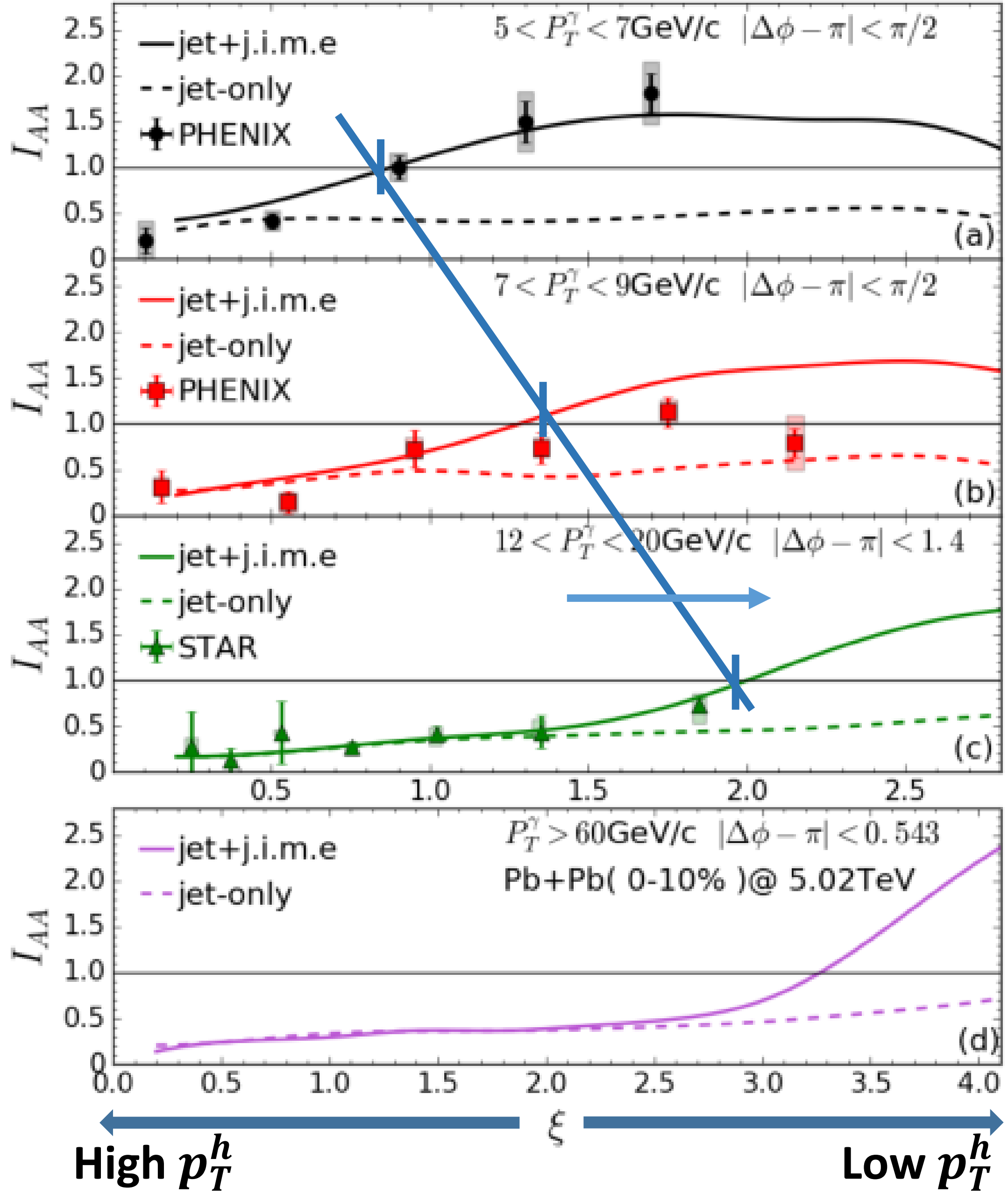


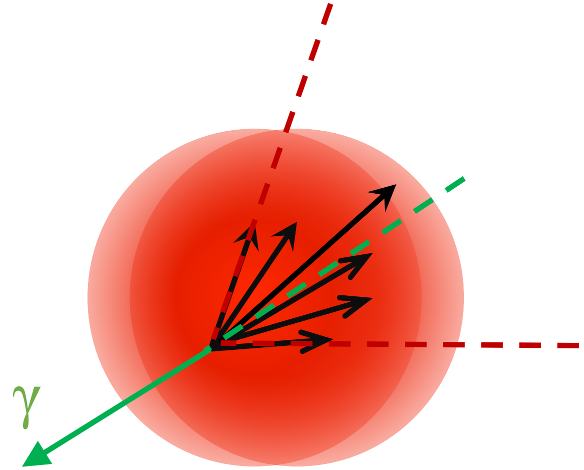
$$z = \frac{p_T^h}{p_T^\gamma} \qquad \varepsilon = \log\frac{1}{z}$$

$$I_{AA}(\varepsilon) = \frac{D_{AA}(\varepsilon)}{D_{pp}(\varepsilon)}$$

- ✓ **The suppression of leading hadron at small ε**
- ✓ **The enhancement of soft hadrons at large ε**

Medium modification of γ-triggered fragmentation function





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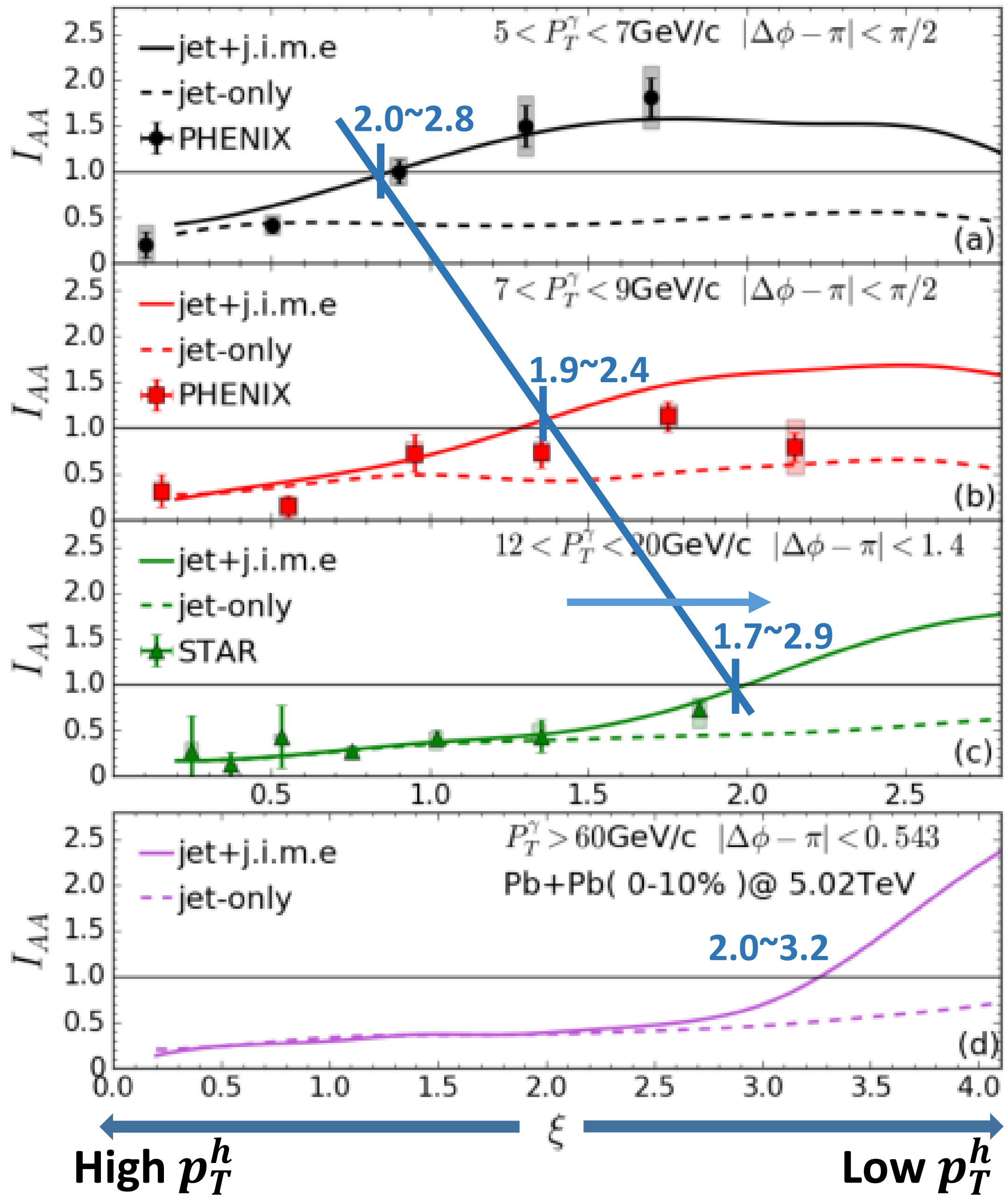
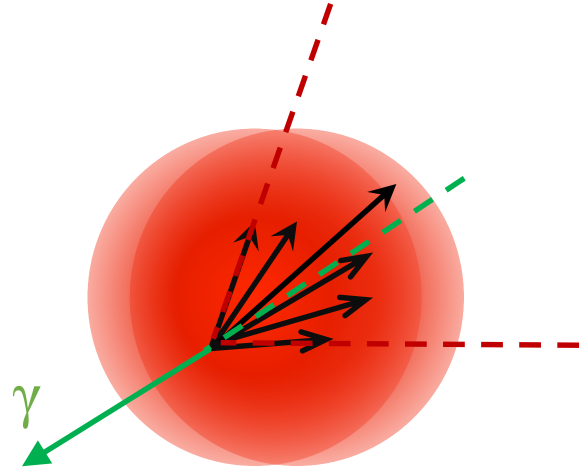
- ✓ **The suppression of leading hadron at small ε**
- ✓ **The enhancement of soft hadrons at large ε**

When p_T^γ range increases:

- ✓ **Transition point($I_{AA} = 1$) from relative enhancement to suppression shift to large ε.**

Medium modification of γ-triggered fragmentation function





$$z = \frac{p_T^h}{p_T^\gamma} \qquad \varepsilon = \log\frac{1}{z}$$

$$I_{AA}(\varepsilon) = \frac{D_{AA}(\varepsilon)}{D_{pp}(\varepsilon)}$$

- ✓ **The suppression of leading hadron at small ε**
- ✓ **The enhancement of soft hadrons at large ε**

When p_T^γ range increases:

- ✓ **Transition point($I_{AA} = 1$) from relative enhancement to suppression shift to large ε.**
- ✓ **Transition point corresponds to the fixed p_T^h range (p_T^h~2 GeV/c at RHIC, p_T^h~3 GeV/c at LHC)**

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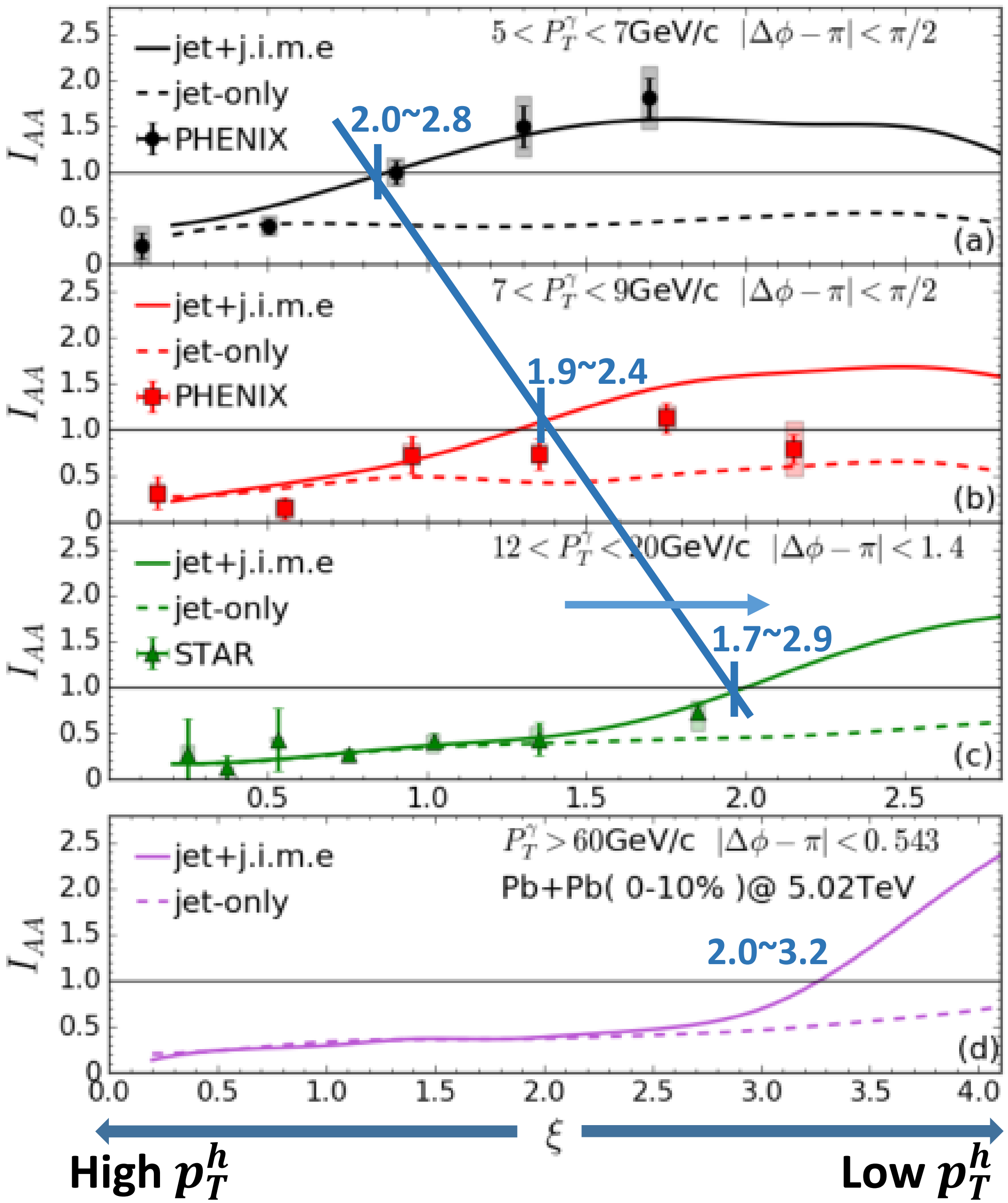

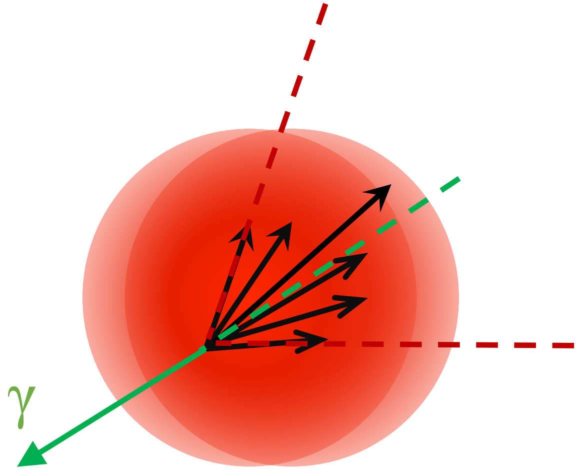

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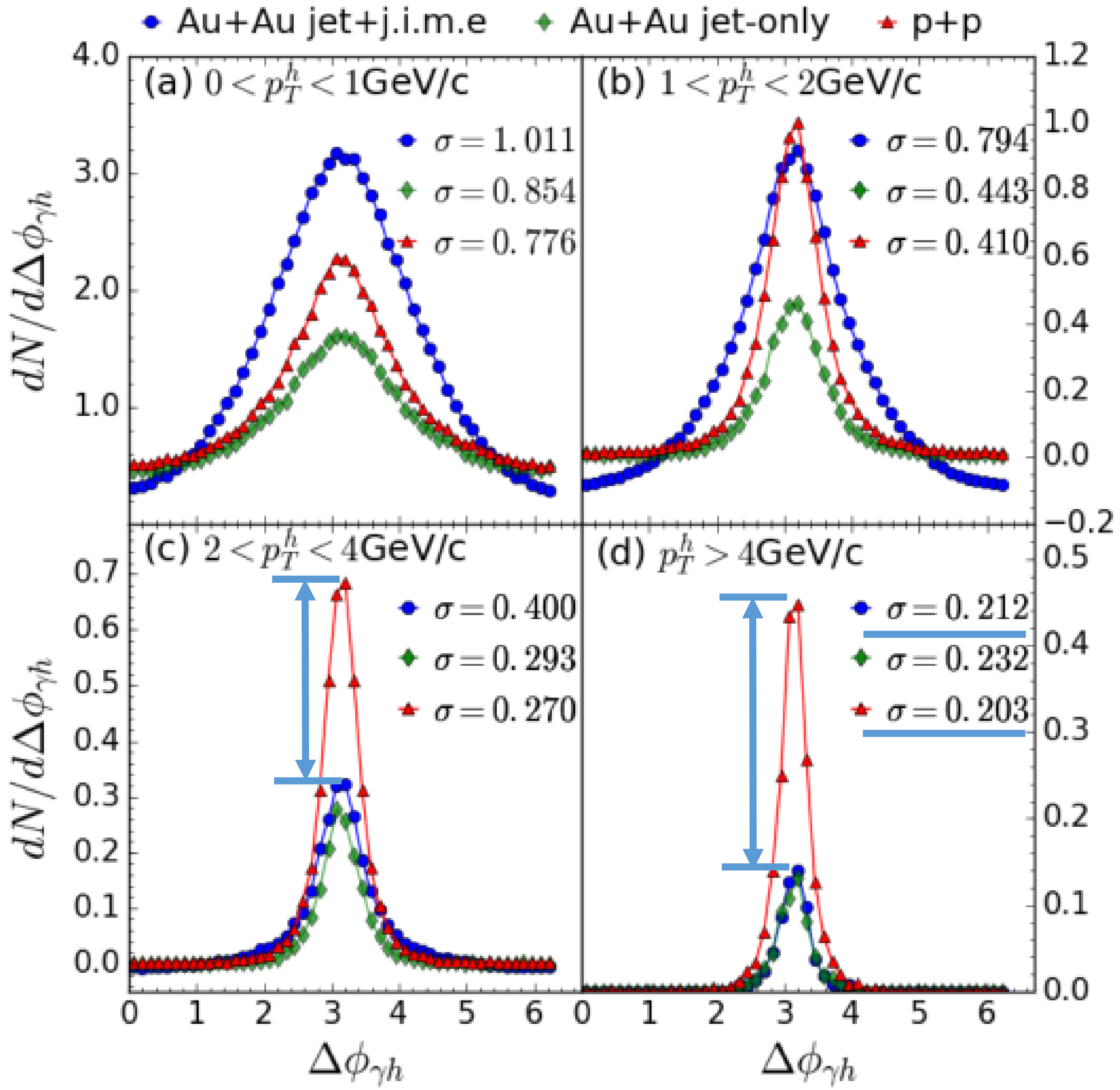
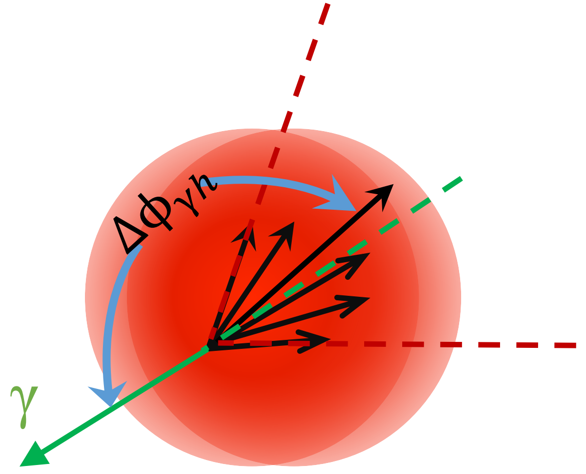
soft hadrons from j.i.m.e. carry an average thermal energy that is independent of the jet energy

γ-hadron azimuthal correlation in RHIC

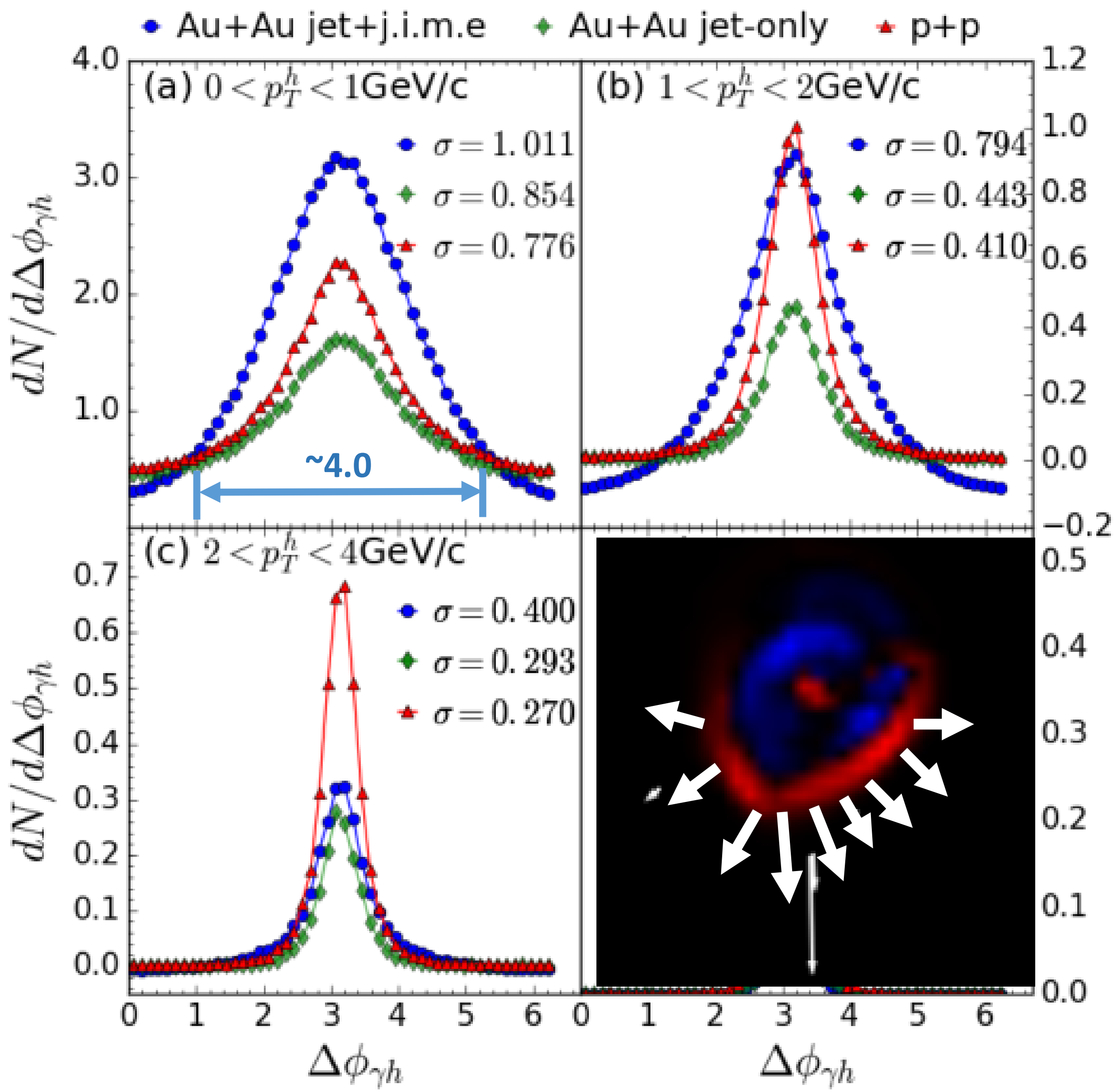


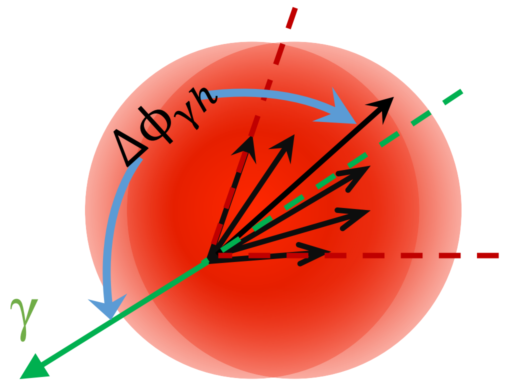


σ: half gaussian width

✓ **Large p_T hadron yield are suppressed in Au+Au and the width of their angular distribution remain approximately unchanged from p+p**

γ-hadron azimuthal correlation in RHIC





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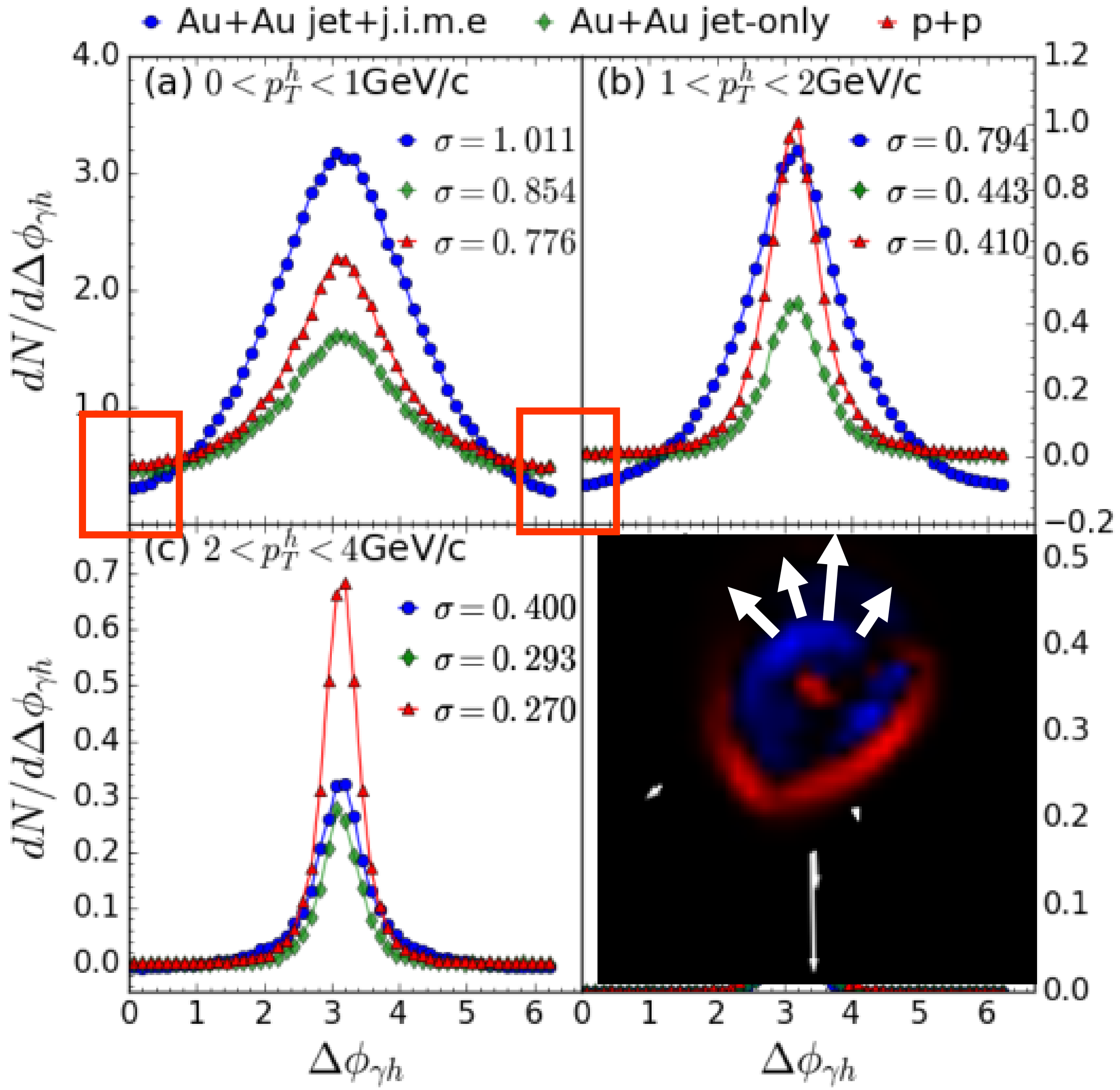
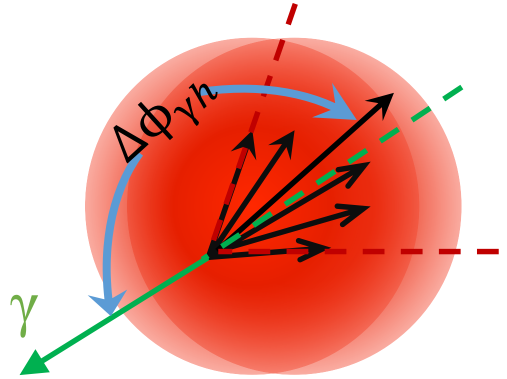
- ✓ **Large p_T hadron yield are suppressed in Au+Au and the width of their angular distribution remain approximately unchanged from p+p**
- ✓ **The angular distributions for the enhanced soft hadrons in Au+Au are significantly broadened.**

  → soft hadrons from j.i.m.e propagate at large angle relative to the jet direction

γ-hadron azimuthal correlation in RHIC

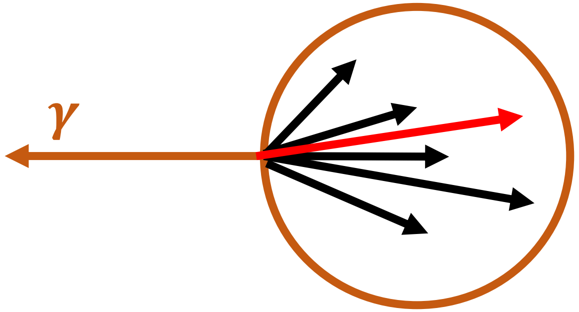




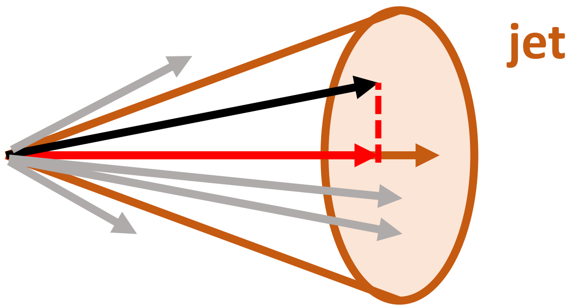
σ: half gaussian width

- ✓ Large p_T hadron yield are suppressed in Au+Au and the width of their angular distribution remain approximately unchanged from p+p
- ✓ The angular distributions for the enhanced soft hadrons in Au+Au are significantly broadened.
  ⇒ soft hadrons from j.i.m.e propagate at large angle relative to the jet direction
- ✓ soft hadrons yield in Au+Au collision along gamma direction become smaller than one in pp collision.
  ⇒ the effect of diffusion wake caused by the deposition of energy-momentum into the medium

Fragmentation function at RHIC and LHC



$$z = \frac{p_T^h}{P_T^\gamma}$$



$$z = \frac{p_{||}^h}{p^{jet}}$$

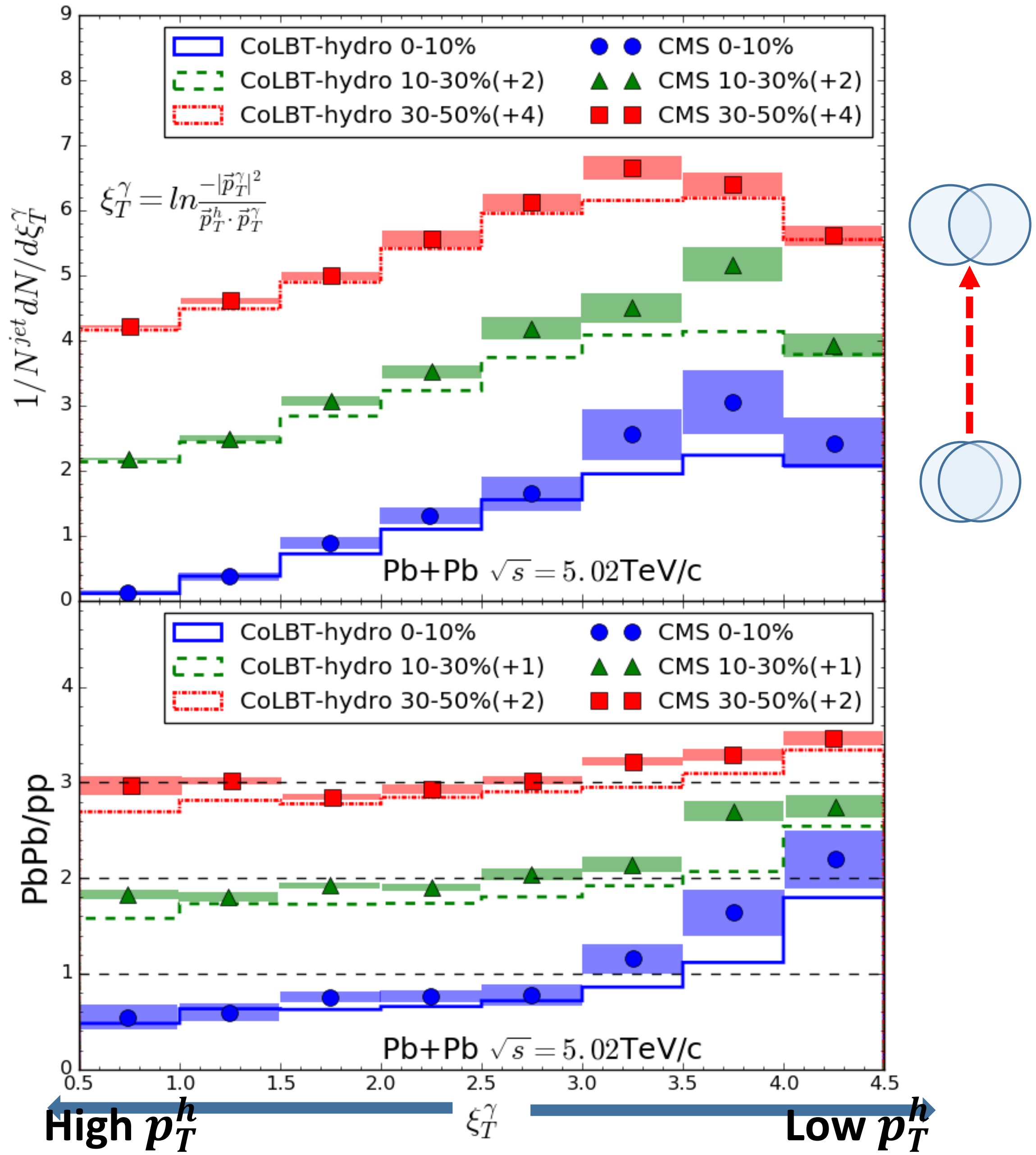
STAR(PHENIX)

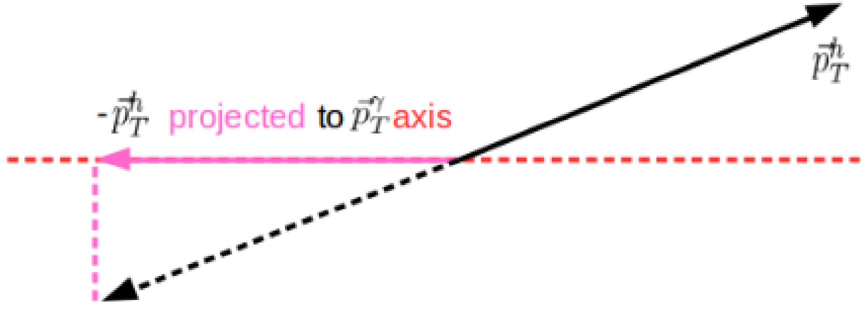
- ✓ Photon-hadrons FF, no reconstructed jets
- ✓ Take hadrons away from the triggering object(photon)
- ✓ Look at the fraction of hadron p_T in photon p_T

CMS

- ✓ jet+hadrons FF, reconstructed jets
- ✓ Take hadrons in side the jet cone
- ✓ Project $p_T^h(p^h)$ onto jet axis and look at the fraction in $p_T^{jet}(p^{jet})$

Fragmentation function at LHC

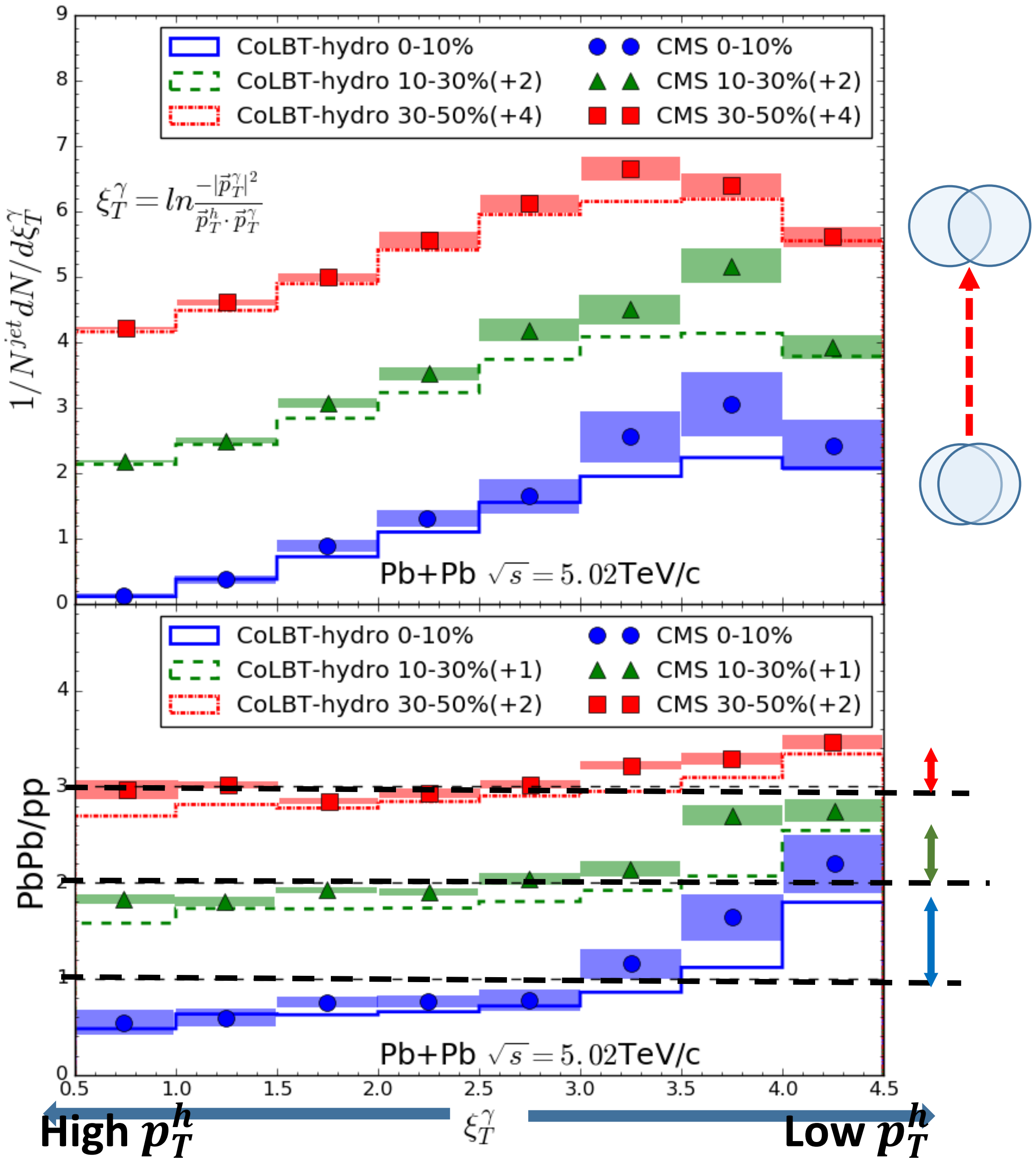


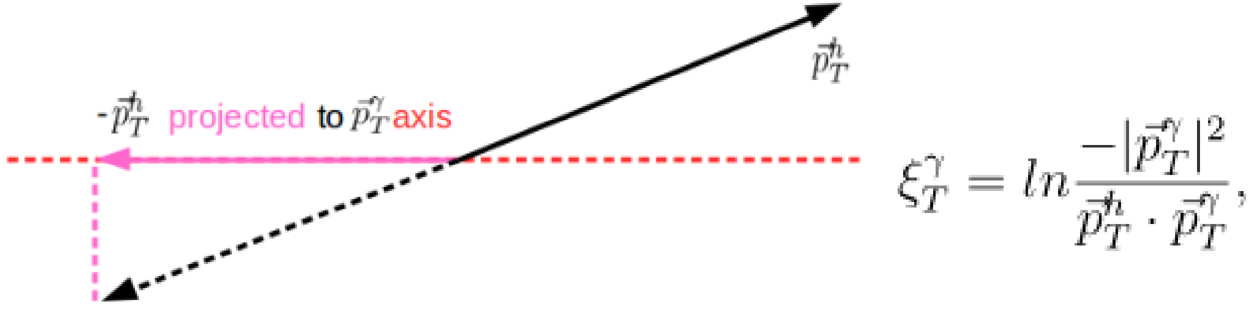


$$\xi_T^\gamma = ln\frac{-|\vec{p}_T^\gamma|^2}{\vec{p}_T^h \cdot \vec{p}_T^\gamma},$$

- ✓ **Based on photon energy, proxy for the parton energy before jet quenching.**

Fragmentation function at LHC





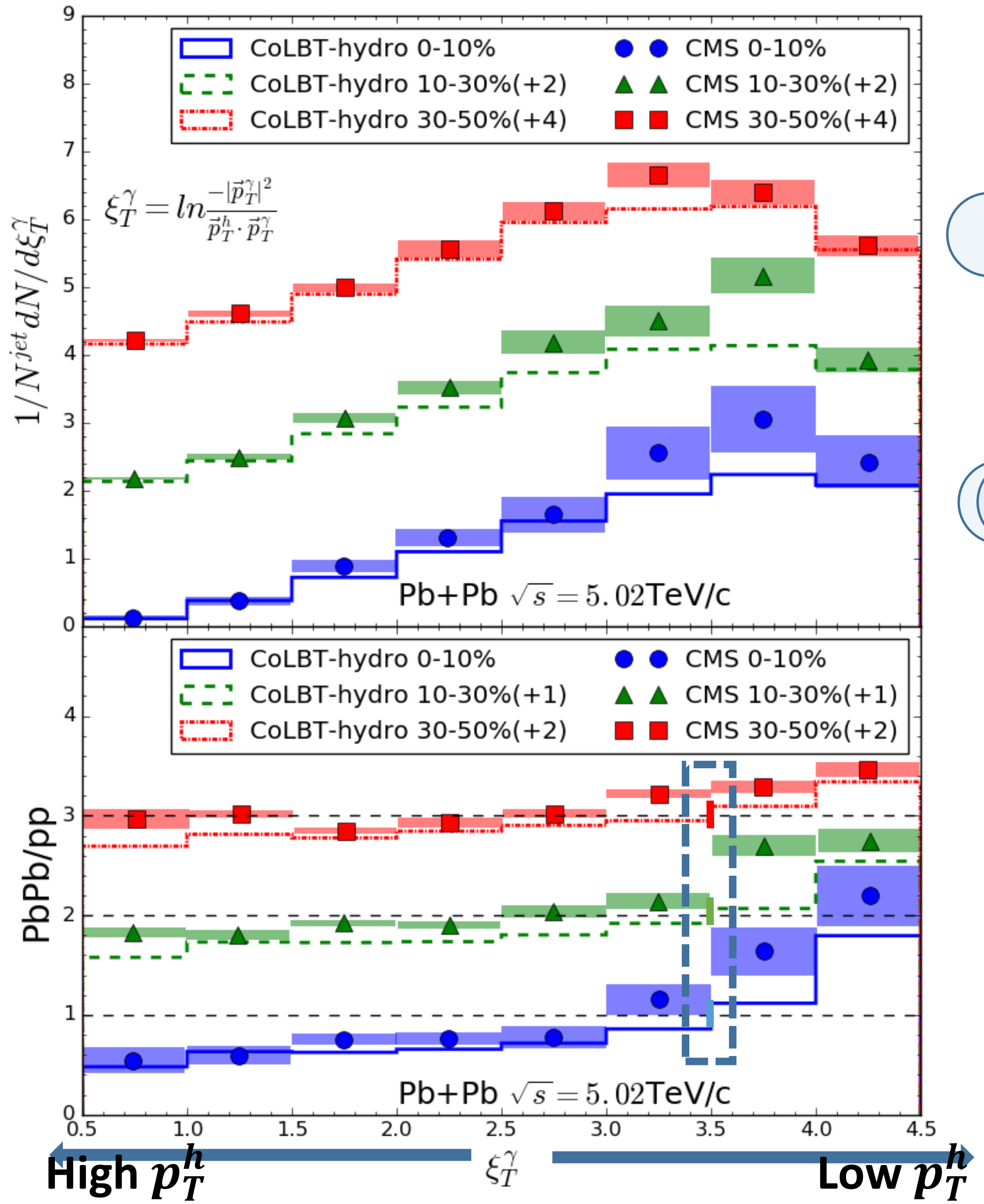
- ✓ **Based on photon energy, proxy for the parton energy before jet quenching.**

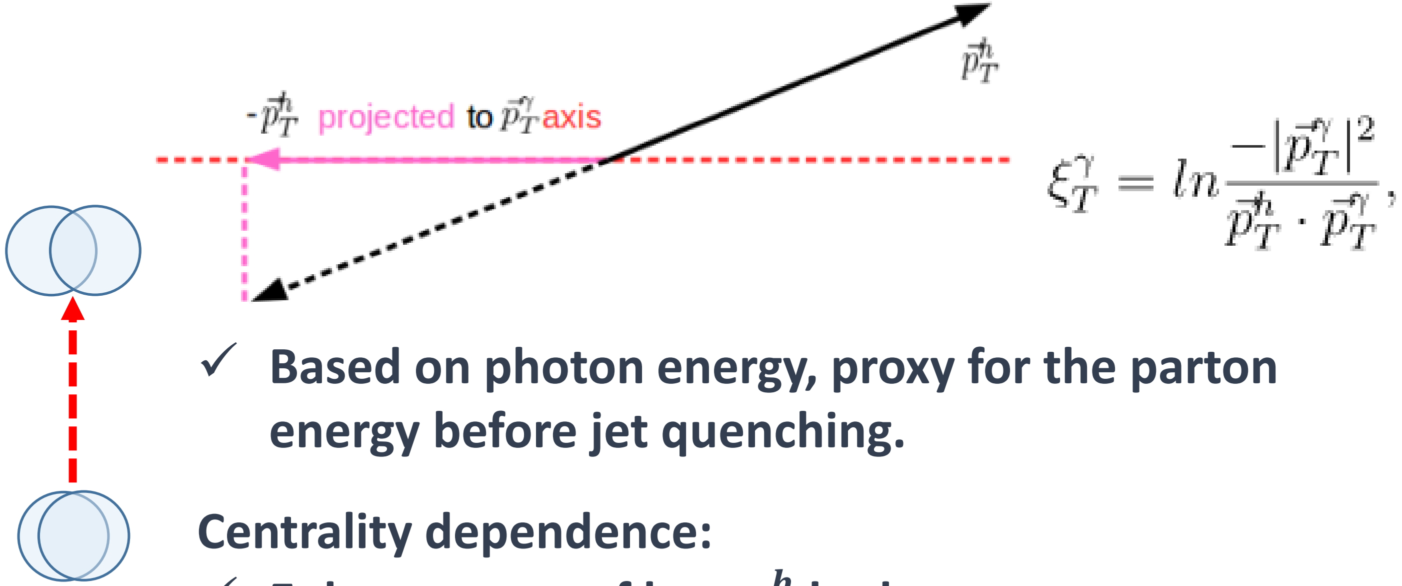
Centrality dependence:

- ✓ **Enhancement of low p_T^h hadrons**
- ✓ **Suppression of high p_T^h hadrons**

→ path length and temperature different

Fragmentation function at LHC





- ✓ Based on photon energy, proxy for the parton energy before jet quenching.

Centrality dependence:

- ✓ Enhancement of low p_T^h hadrons
- ✓ Suppression of high p_T^h hadrons

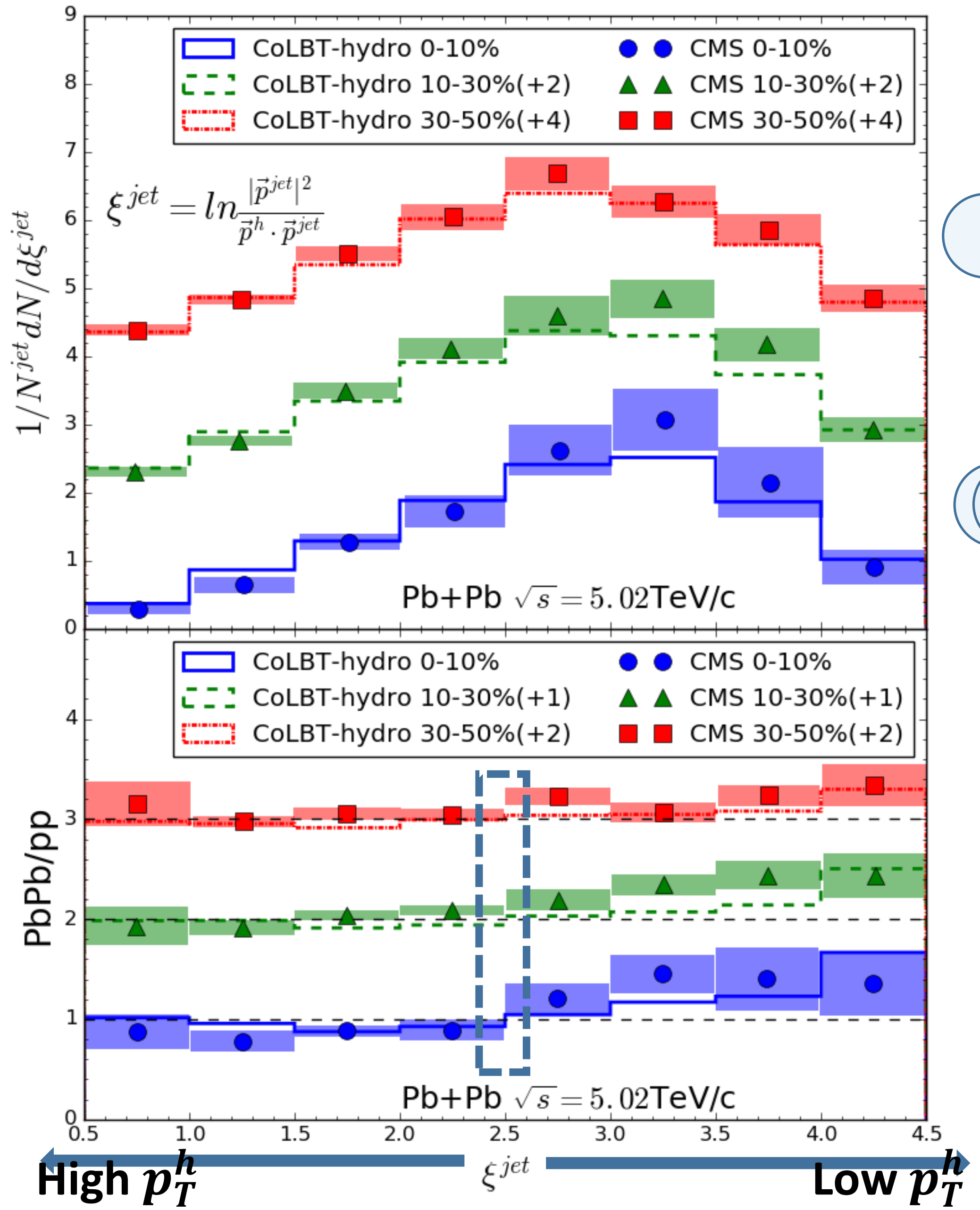
→ path length and temperature different

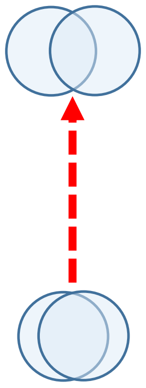
No(slightly) centrality dependence:

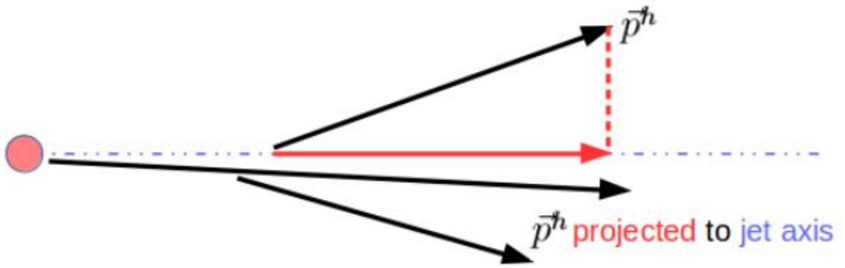
- ✓ Transition point ($I_{AA}=1$) from relative enhancement to suppression.

$$\varepsilon_T^\gamma \approx 3.5 \rightarrow p_T^h \approx 2\sim3 \text{ GeV}$$

Fragmentation function at LHC







$$\xi^{jet} = ln\frac{|\vec{p}^{jet}|^2}{\vec{p}^h \cdot \vec{p}^{jet}}$$

✓ **Based on reconstructed jet energy**

Centrality dependence:

✓ **Enhancement of low p_T^h hadrons**

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path length and temperature different

No(slightly) centrality dependence:

✓ **Transition point ($I_{AA} = 1$) from relative enhancement to suppression.**

$$\varepsilon^{jet} \approx 2.5 \rightarrow p_T^h \approx 2\text{~}3 \text{ GeV}$$

Summary

Summary

- ✓ We develop CoLBT-Hydro model for simultaneous event-by-event simulations of jet propagation and hydrodynamic evolution of the bulk medium including jet-induced medium excitation.
- ✓ CoLBT-hydro describes well both the suppression of leading hadrons due to parton energy loss and enhancement of soft hadrons due to jet-induced medium excitation
- ✓ The onset of soft hadron enhancement at a constant p_T^h with broadened angular distribution and depletion of soft hadrons in the γ direction

Outlook

The model needs to be improved in

- ✓ Ideal hydrodynamic
- ✓ Neglect hadronization between jet shower partons and thermal partons
- ✓ Neglect the interaction between hadrons
- ✓ Only use AMPT as initial condition for medium hydrodynamic evolution
- ✓ Light quark on shell

……………

The model can be used to calculate

- ✓ Nuclear modification factor R_{AA}
- ✓ dihadron correlation
- ✓ jet shape
- ✓ dijet correlation

and many other observables