A Linear Boltzmann Transport Model

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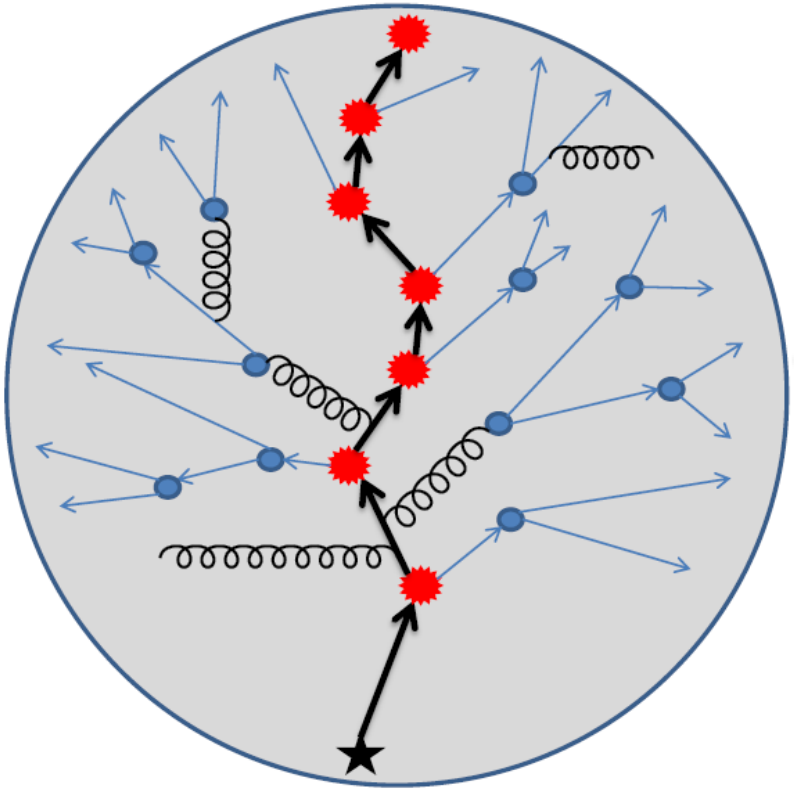
Outline

- Introduction
- A Linear Boltzmann Transport (LBT) model
- A Coupled LBT-hydro (CoLBT-hydro) model
- Summary and Outlook

A Linear Boltzmann Transport (LBT) Model

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



Jet induced medium excitation

("Negative" parton for the back reaction)

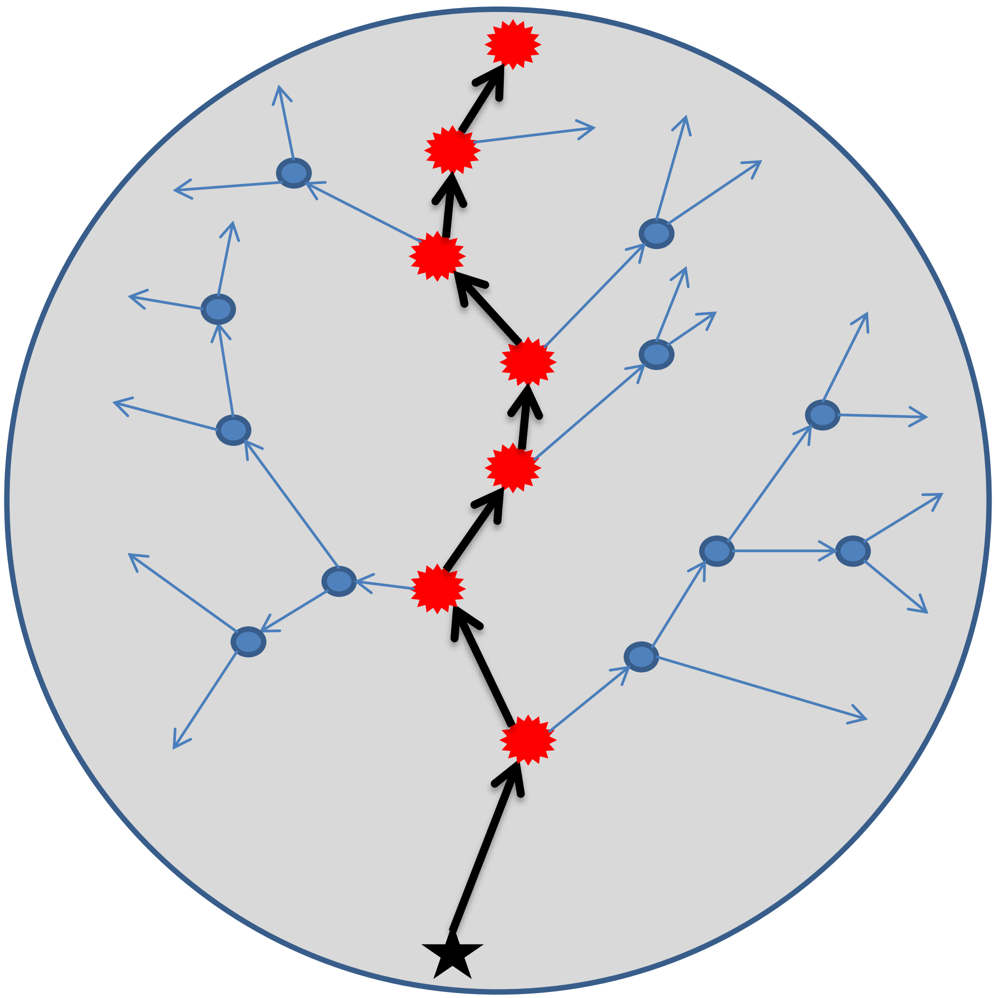
Linear Boltzmann jet Transport

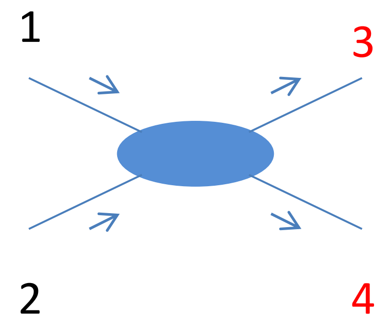
- Elastic collision + Induced gluon radiation.
- Follow the propagation of recoiled parton.
- Include recoiled parton in jet reconstruction.

Linear Approximation

It works when the jet induced medium excitation $\delta f \ll f$.

Jet induced medium excitation: recoiled parton





Leading parton-----thermal parton scattering

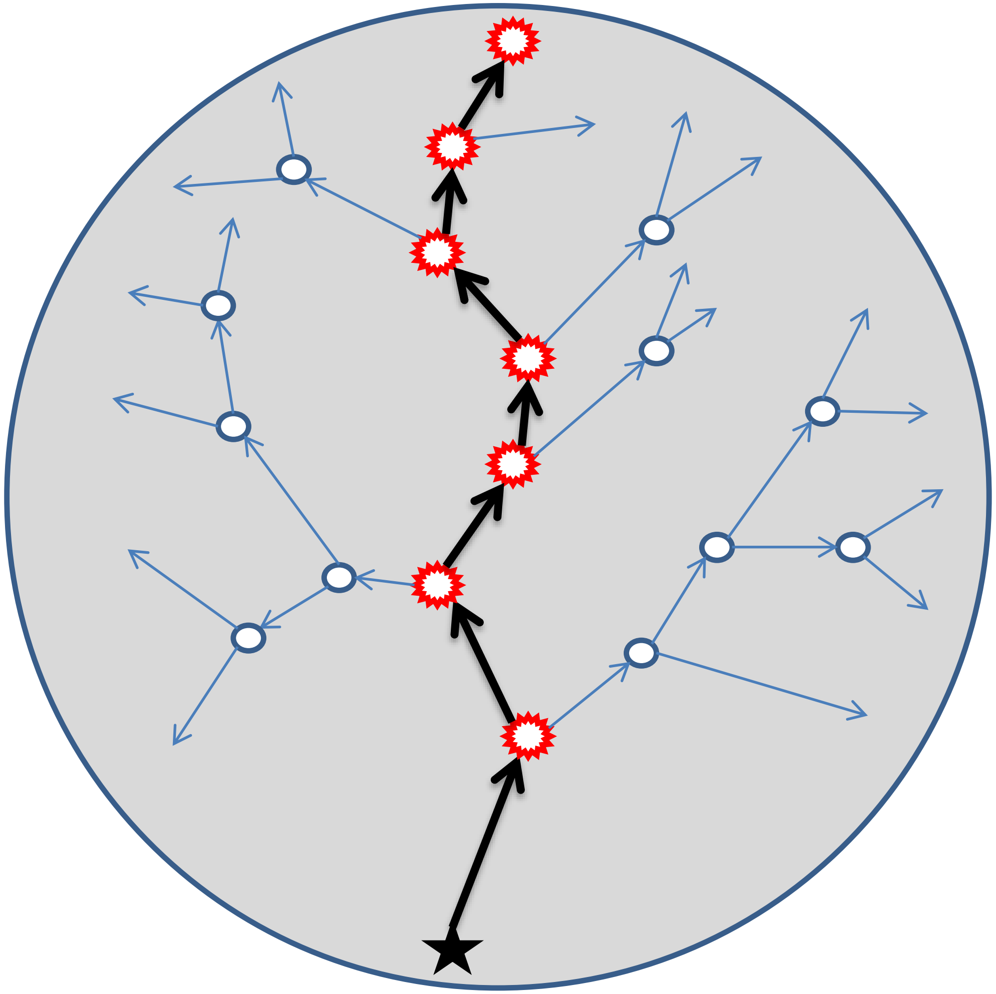
recoiled parton-----thermal parton scattering

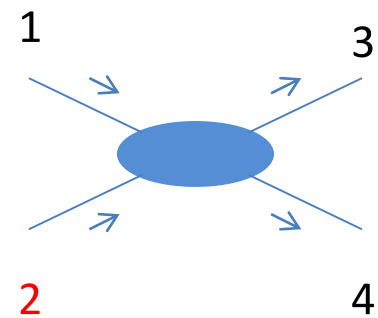
Linearized Boltzmann jet transport

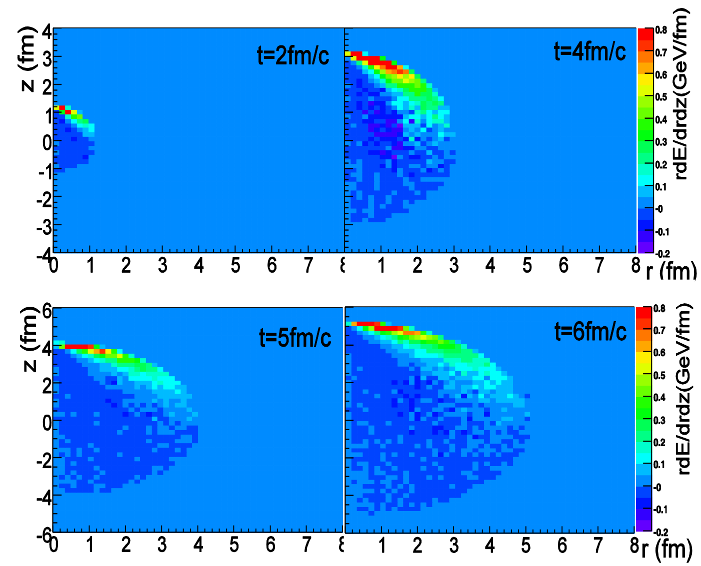
neglect scatterings between recoiled medium partons.

It's a good approximation when the jet induced medium excitation $\delta f \ll f$.

Jet induced medium excitation: particle hole

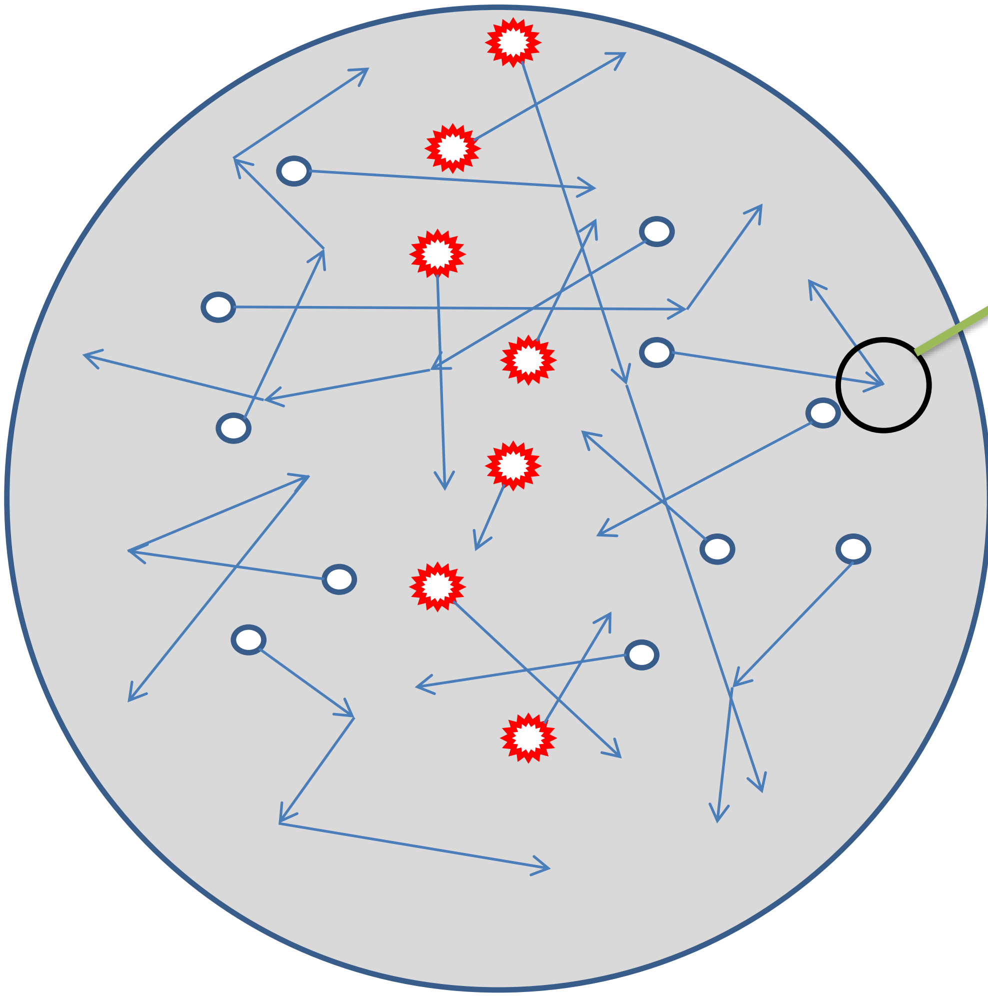


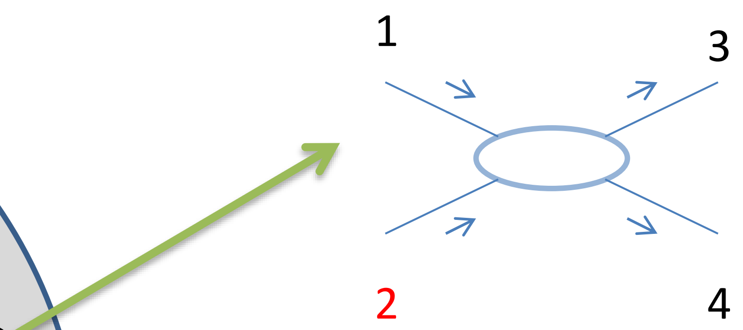




One has to subtract the 4-momentum of negative particle when combine it to jet

Jet induced medium excitation: back reaction





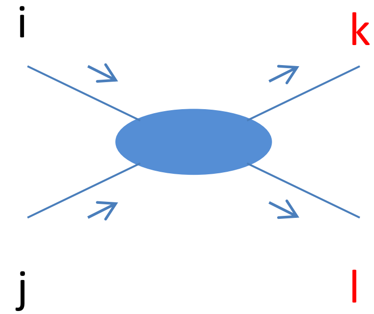
thermal parton-----thermal parton scattering

the negative particle is also traveling in the medium

One has to subtract the 4-momentum of negative particle when combine it to jet

Complete set of elastic processes

Single scattering



$$i, j = g, u, d, s, \bar{u}, \bar{d}, \bar{s}$$

Jussi Auvinen, Kari J. Eskola, Thorsten Renk

Phys.Rev. C82 024906

- Scattering rate for a process $ij \to kl$ in the local rest frame of the fluid

$$\Gamma_{ij\to kl} = \frac{1}{2E_1}\int\frac{d^3p_2}{(2\pi)^3 2E_2}\int\frac{d^3p_3}{(2\pi)^3 2E_3}\int\frac{d^3p_4}{(2\pi)^3 2E_4}\times f_j(p_2\cdot u, T)$$

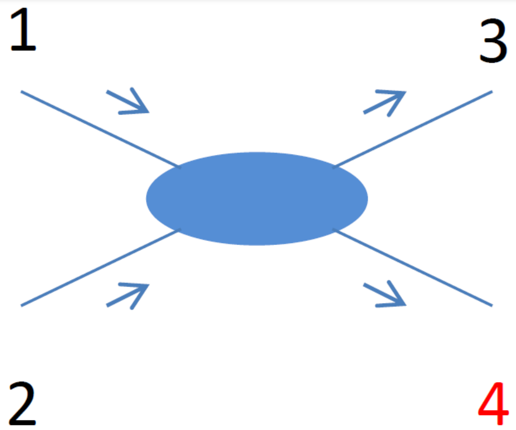
$$\times|M|^2_{ij\to kl}(s,t,u)\times S_2(s,t,u)\times(2\pi)^4\delta^4(P_1+P_2-P_3-P_4)$$

$$S_2(s,t,u) = \theta(s\geq 2\mu_D^2)\theta(-s+\mu_D^2\leq t\leq -\mu_D^2) \qquad \mu_D^2 = (\frac{3}{2})4\pi\alpha_s T^2$$

- The mean free path

$$\Gamma_i = \sum_{j,(kl)}\Gamma_{ij\to kl} = 1/\lambda_0 \qquad P(\Delta t) = 1 - e^{-\Gamma_i\Delta t} \qquad P(ij\to kl) = \frac{\Gamma_{ij\to kl}}{\Gamma_i}$$

Energy distribution of the recoiled parton



Single scattering

- Dominance of small angle scattering.
- Switch of flavor and species of the leading parton.

$$gg \to gg$$

$$gq \to gq + g\bar{q} \to g\bar{q}$$

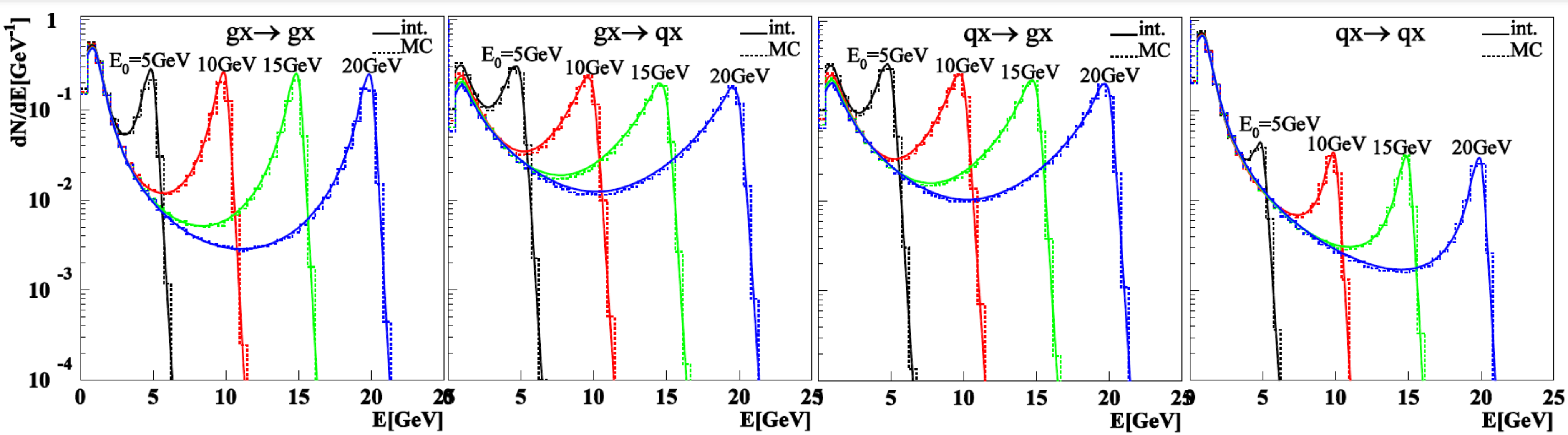
$$gg \to q\bar{q}$$

$$q_i\bar{q}_i \to gg$$

$$q_i\bar{q}_i \to q_j\bar{q}_j \qquad q_i g \to q_i g$$

$$q_i\bar{q}_i \to q_i\bar{q}_i \qquad q_i q_j \to q_i q_j$$

$$q_i q_i \to q_i q_i$$



Medium-induced gluon radiations

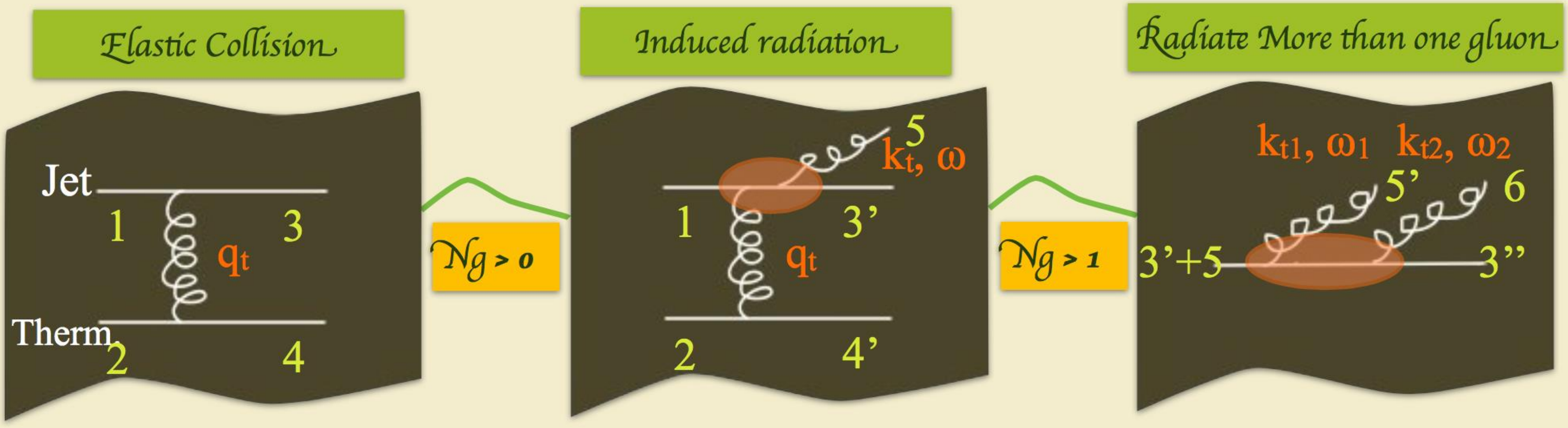
Radiated gluon distribution: Guo and Wang (2000), Majumder (2012); Zhang, Wang and Wang (2004)

$$\frac{dN_g}{dxdk_\perp^2dt} = \frac{2C_A\alpha_s P(x)}{\pi k_\perp^4}\hat{q}\left(\frac{k_\perp^2}{k_\perp^2+x^2M^2}\right)\sin^2\frac{t-t_i}{2\tau_f} \qquad \tau_f = 2Ex(1-x)/(k_\perp^2+x^2M^2)$$

Multiple gluon emissions: $P(N_g,\langle N_g\rangle) = \frac{\langle N_g\rangle^{N_g} e^{-\langle N_g\rangle}}{N_g!}$

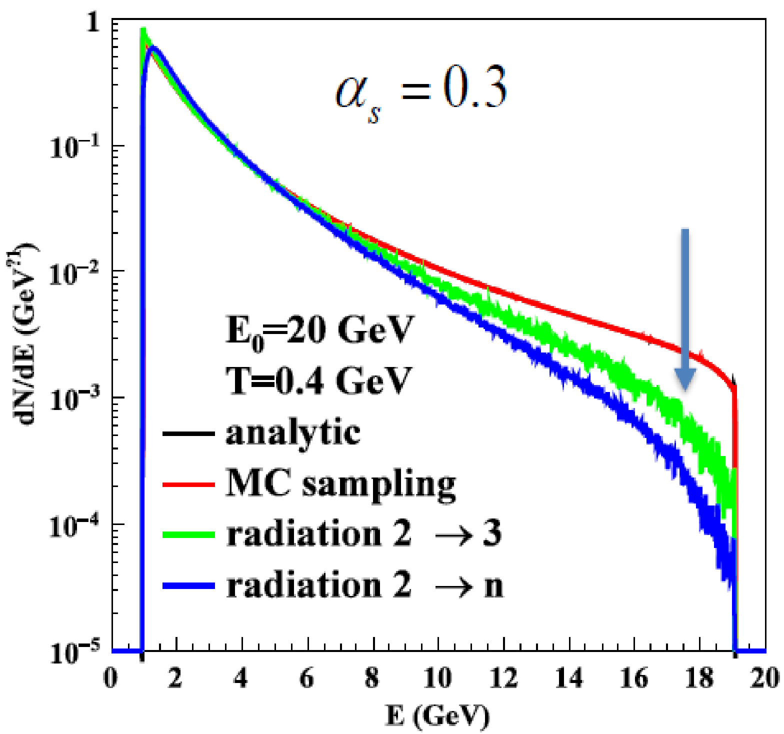
Induced radiations are accompanied by elastic collisions.

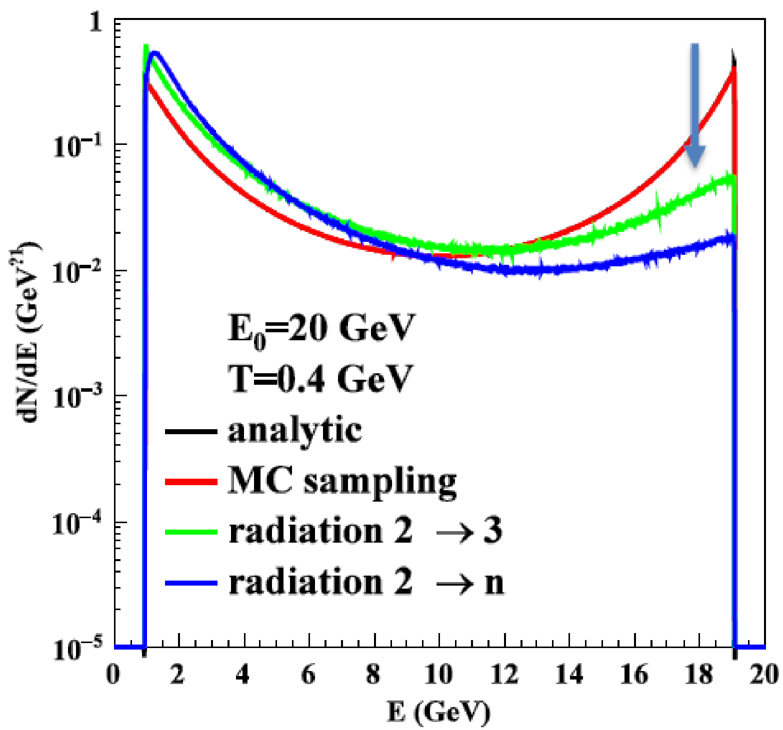
Jet medium Interaction:



Energy distribution of the radiated gluon

Global energy-momentum conservation in 2->3 and 2->n processes

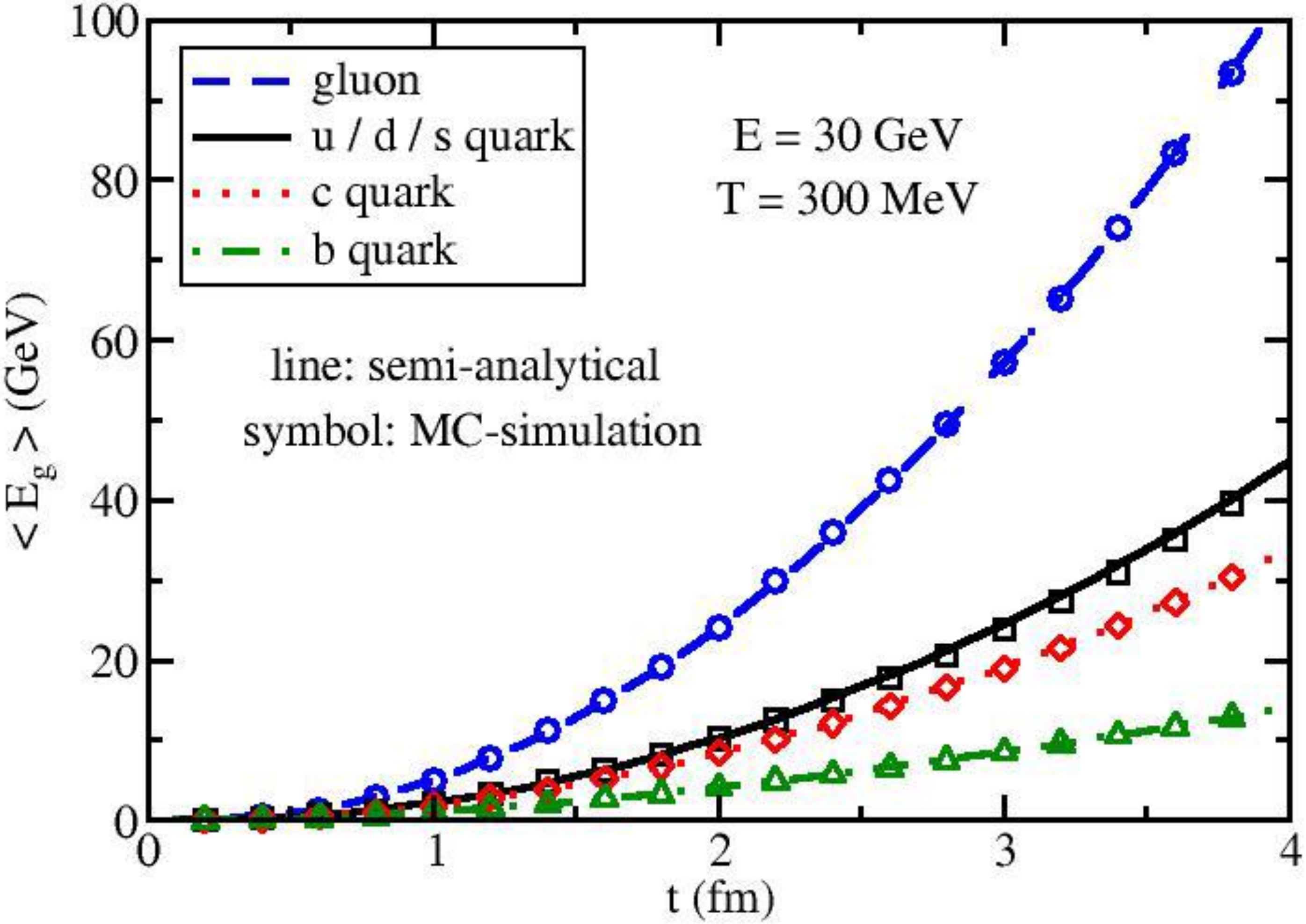




$$P_{q\to qg}(x) = \frac{(1-x)(1+(1-x)^2)}{x}$$

$$P_{g\to gg}(x) = \frac{2(1-x+x^2)^3}{x(1-x)}$$

Energy loss from radiation process in an uniform medium

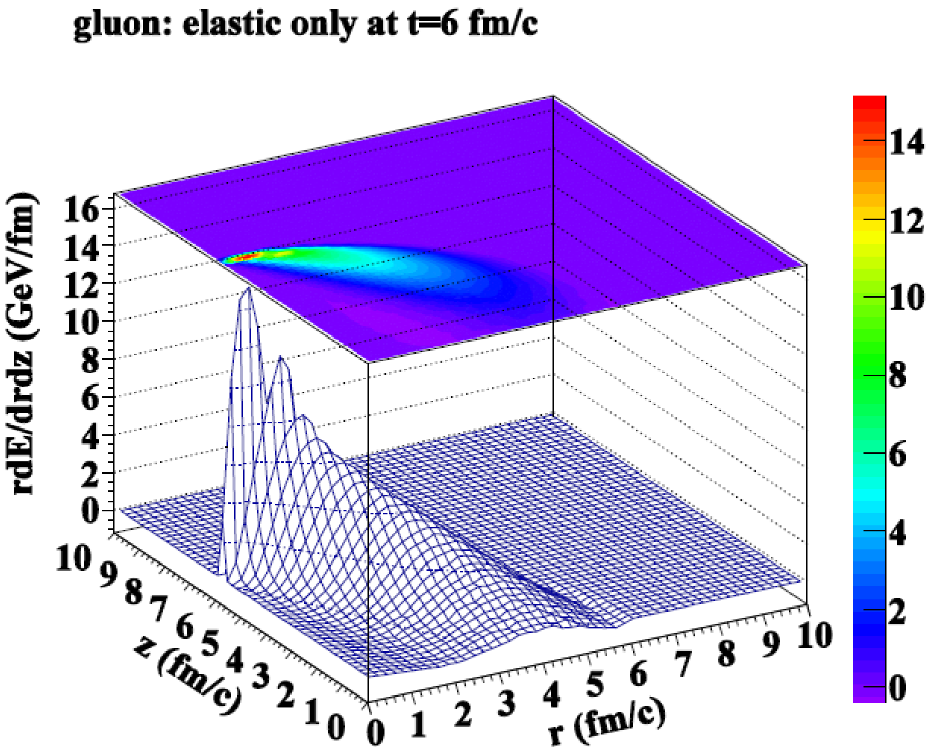


Jet induced medium excitation (Energy distribution in space)

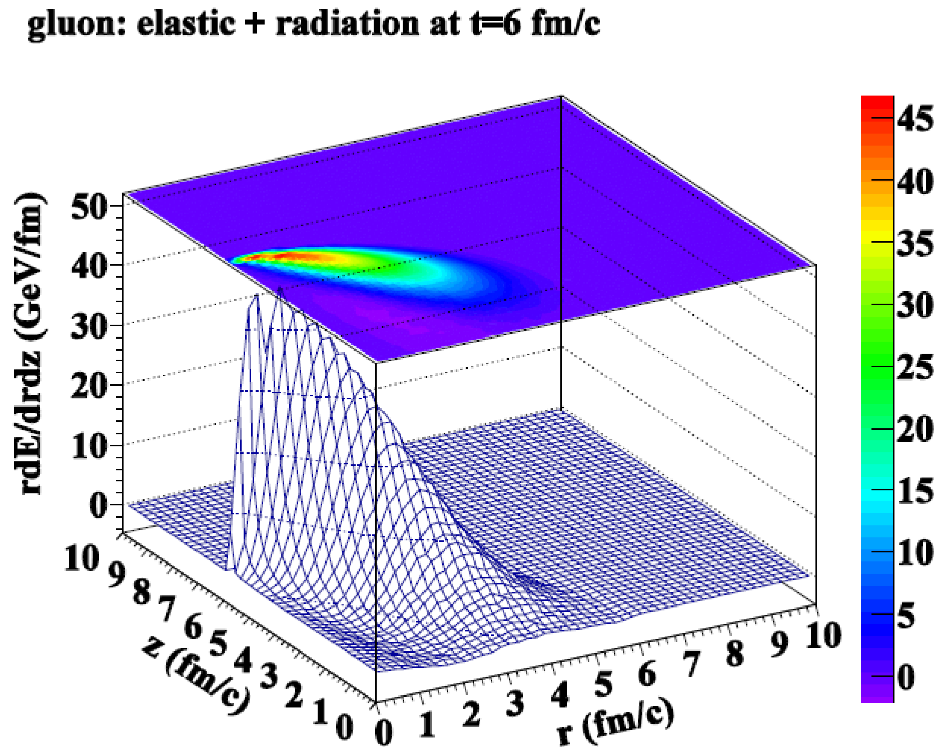
Initial jet parton: gluon
E = 100 GeV
T = 0.4 GeV $\alpha_s = 0.3$

- Mach Cone like shock wave and the diffusion wake.

Elastic only



Elastic + Radiation

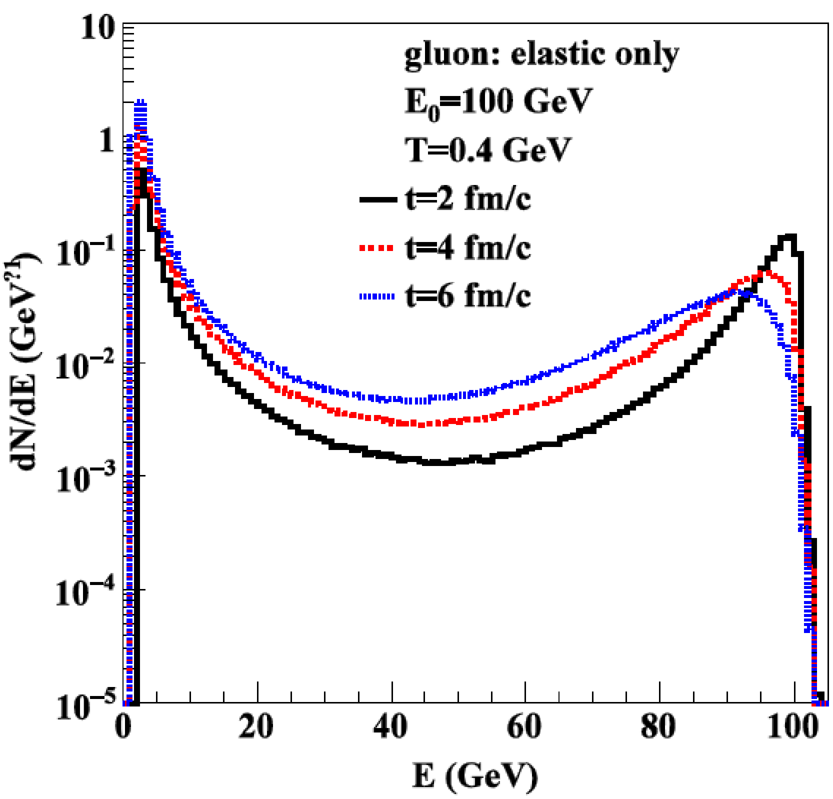


Jet induced medium excitation (Energy distribution at different time)

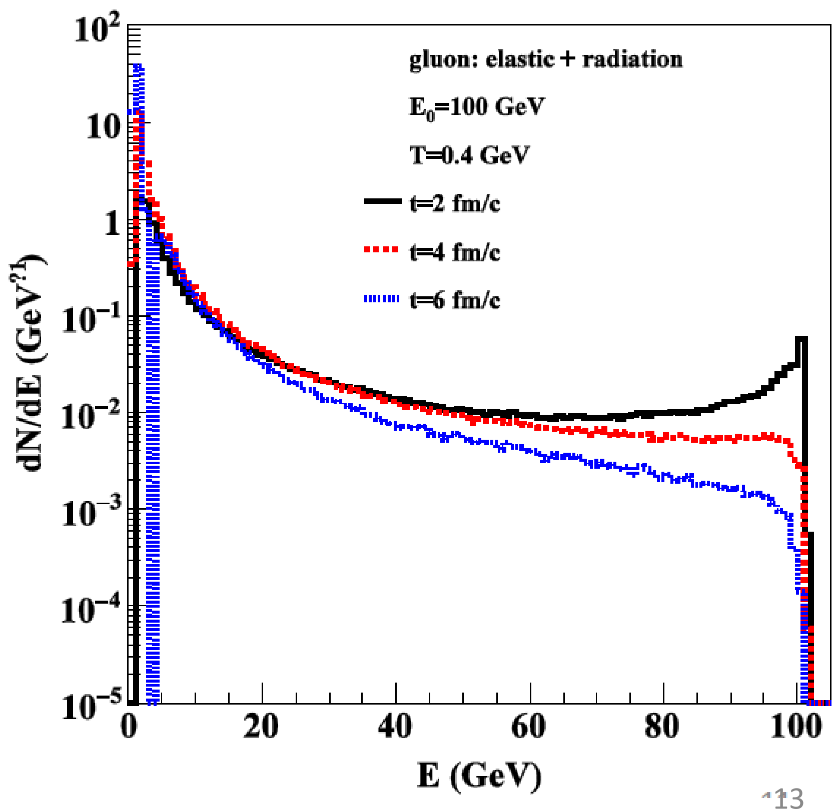
Initial jet parton: gluon
E = 100 GeV
T = 0.4 GeV $\alpha_s = 0.3$

- Depletion of the energy of the leading parton.

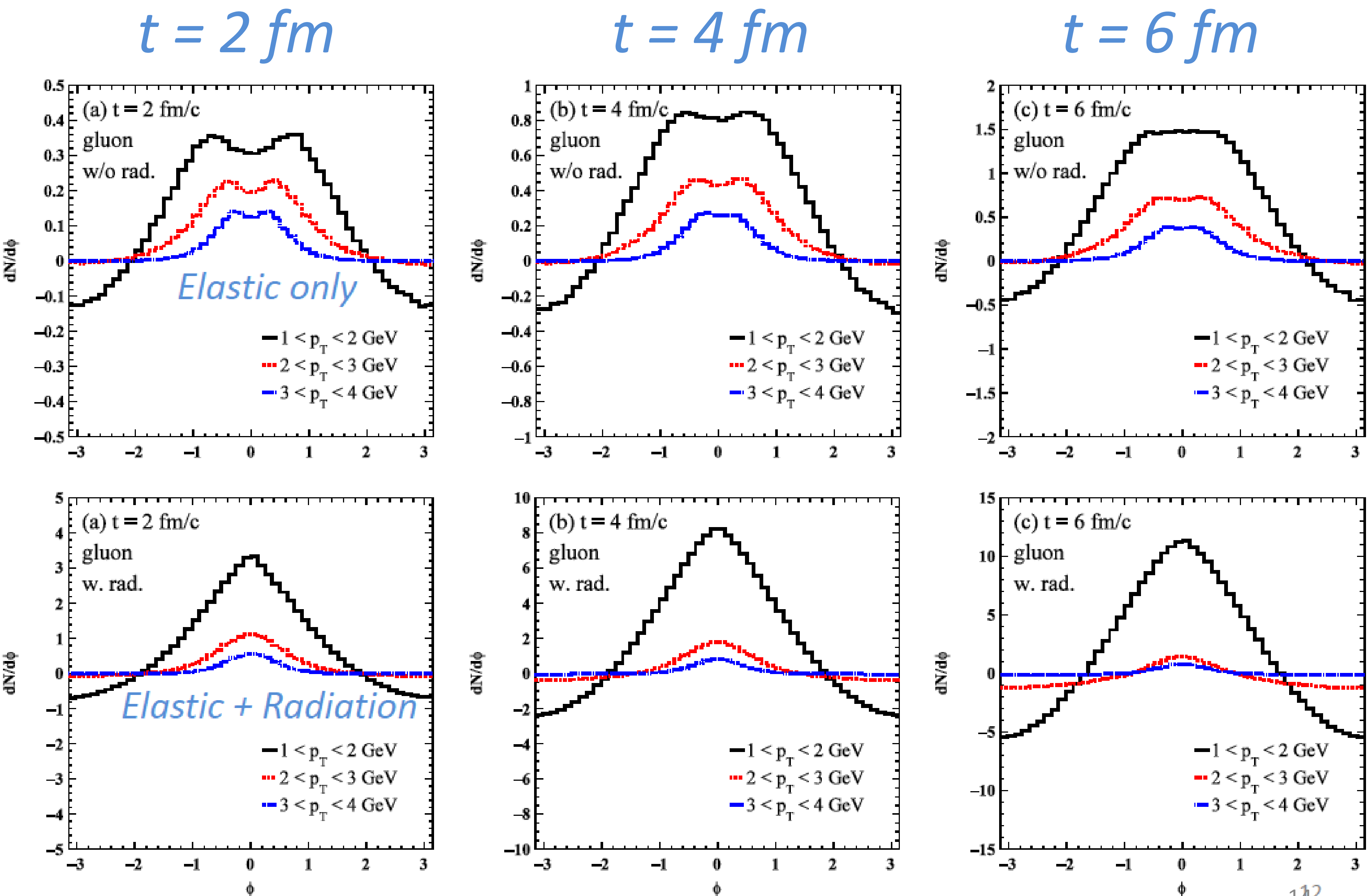
Elastic only



Elastic + Radiation



Jet induced medium excitation (Angular distribution)

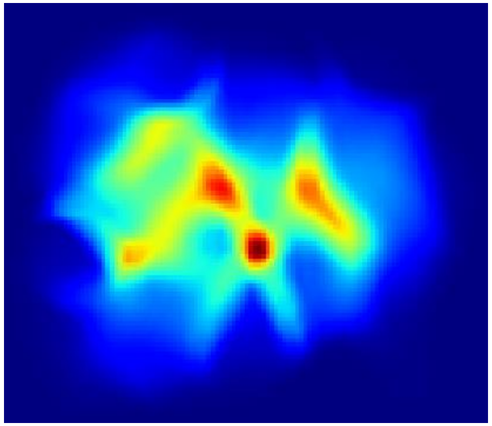


Jets in a 3+1D hydro

Initial jet shower partons from a p+p collision (Pythia or Hijing)

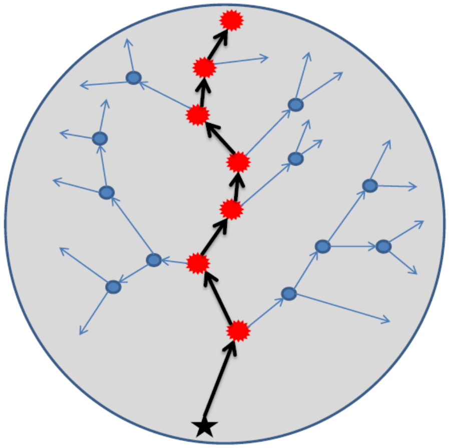
- Location of jets are decided according probability of binary collision.

- 3+1D Ideal hydro



ε T $\boldsymbol{u}$

LBT Model



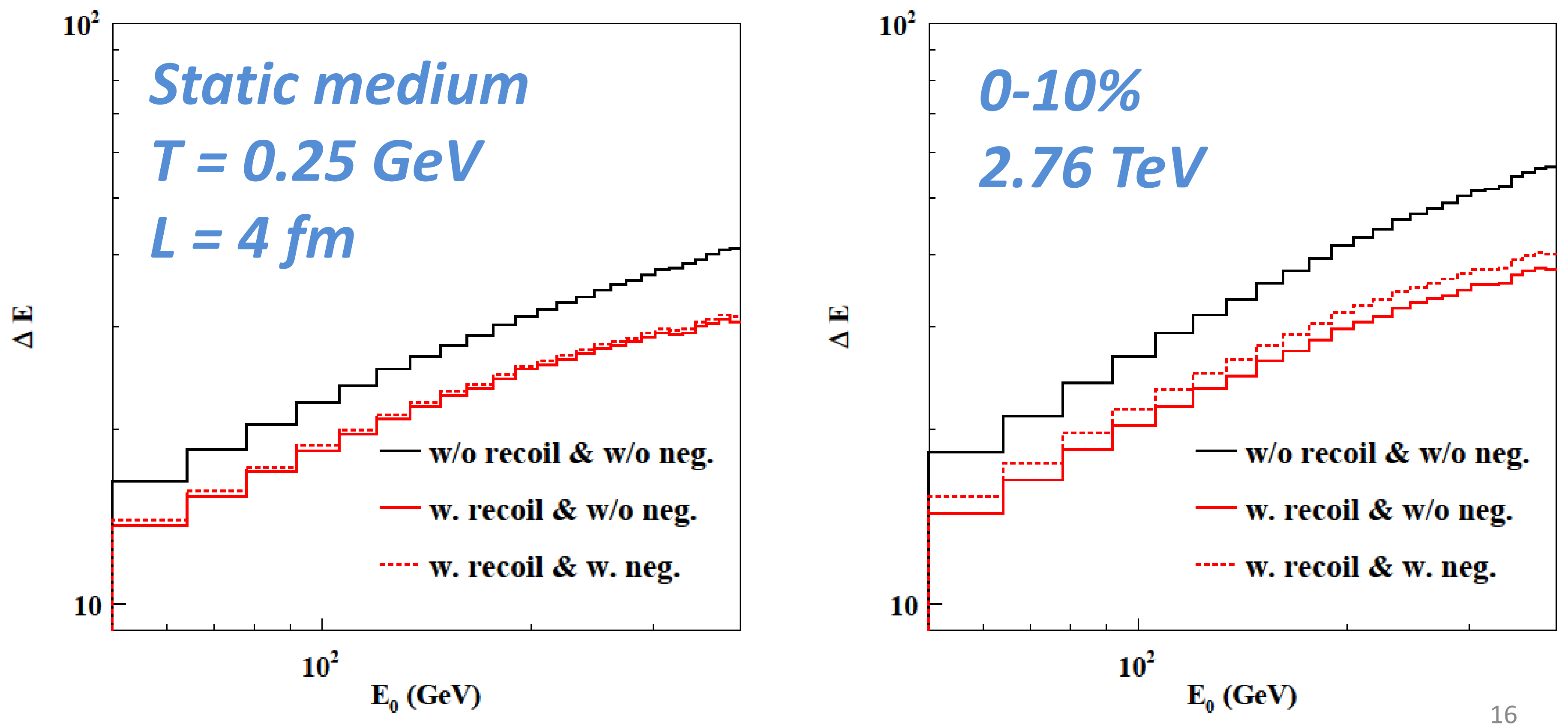
L-G. Pang, Q. Wang, X-N. Wang
Phys.Rev. C86 (2012) 024911

M. Cacciari, G. P. Salam and G. Soyez
Eur. Phys. J. C 72, 1896 (2012).

Jet reconstruction (Fastjet)

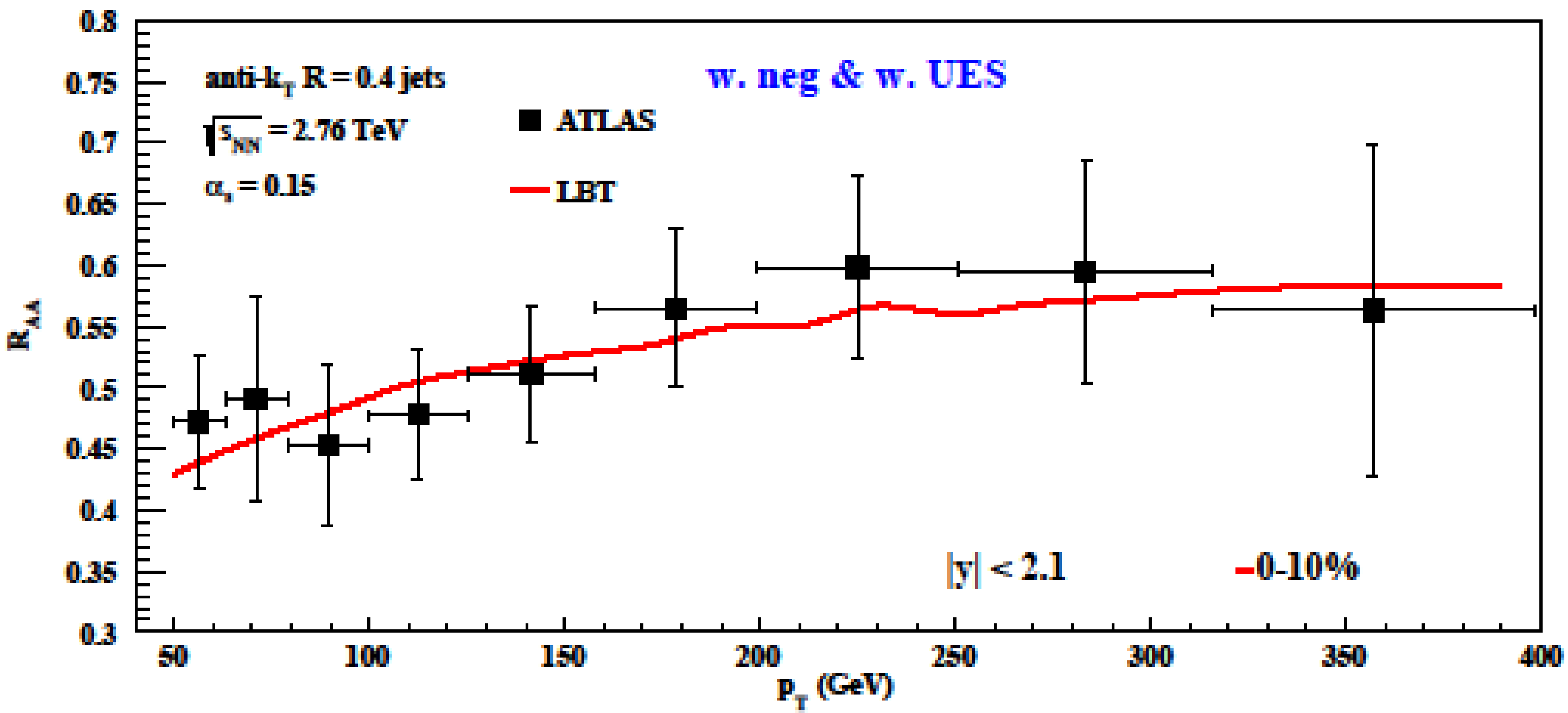
Recoiled effect in the reconstructed jets

- The inclusion of the recoiled parton in the reconstructed jets will reduce the jet energy loss.
- The recoiled effect is more significant in the evolving medium.



Nuclear modification factor

- The only parameter strong coupling constant α_s is fixed.
- We first calculate the single jet R_{AA} to extract the value of α_s .
  (fix the strength of jet-medium interaction)

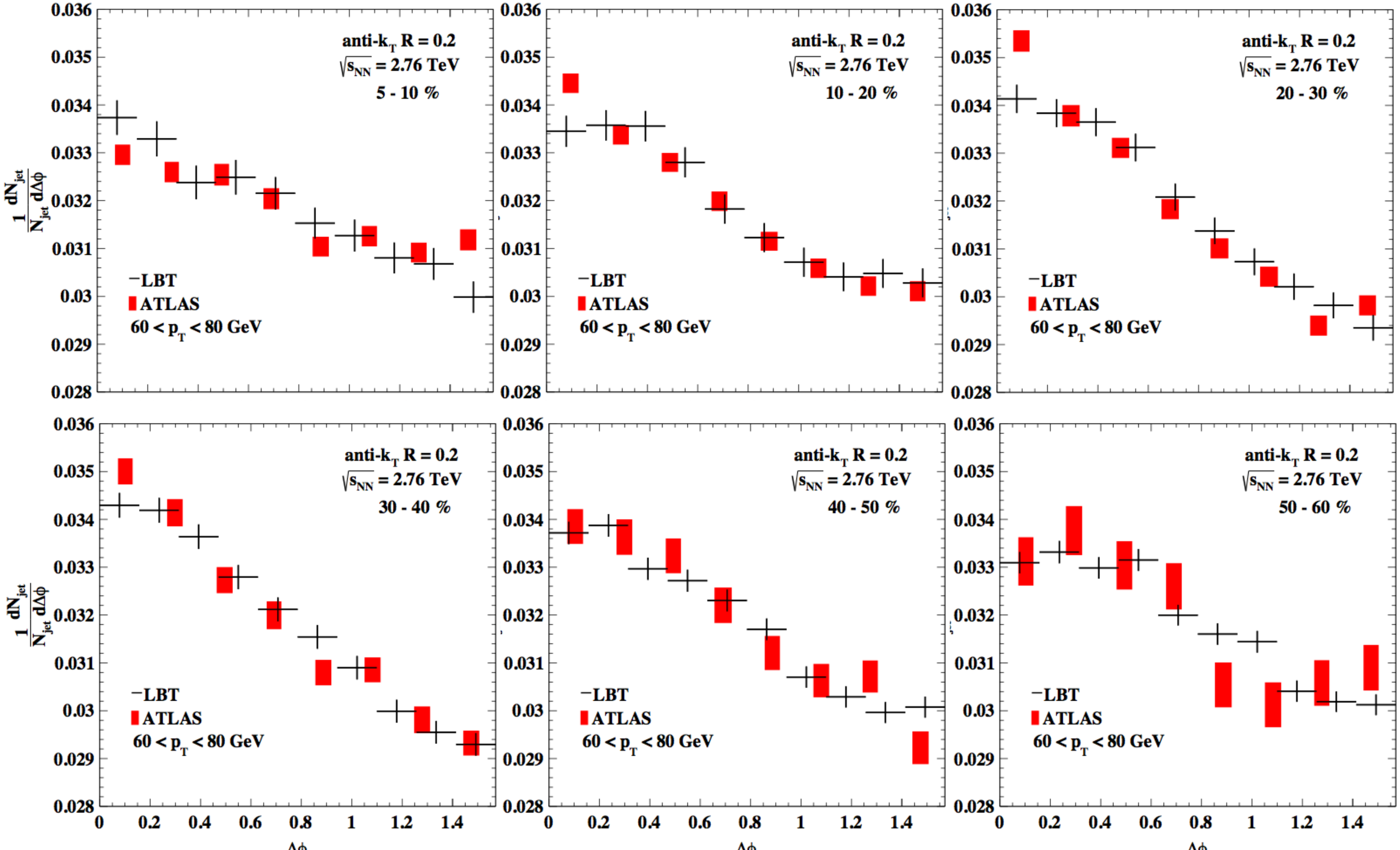


Data ref.: ATLAS Collaboration, Phys. Rev. Lett. 114 (2015) 072302

Jet azimuthal distribution with different centralities

Anisotropy shows up

$$\Delta\phi = \phi^{jet} - \Psi_2$$

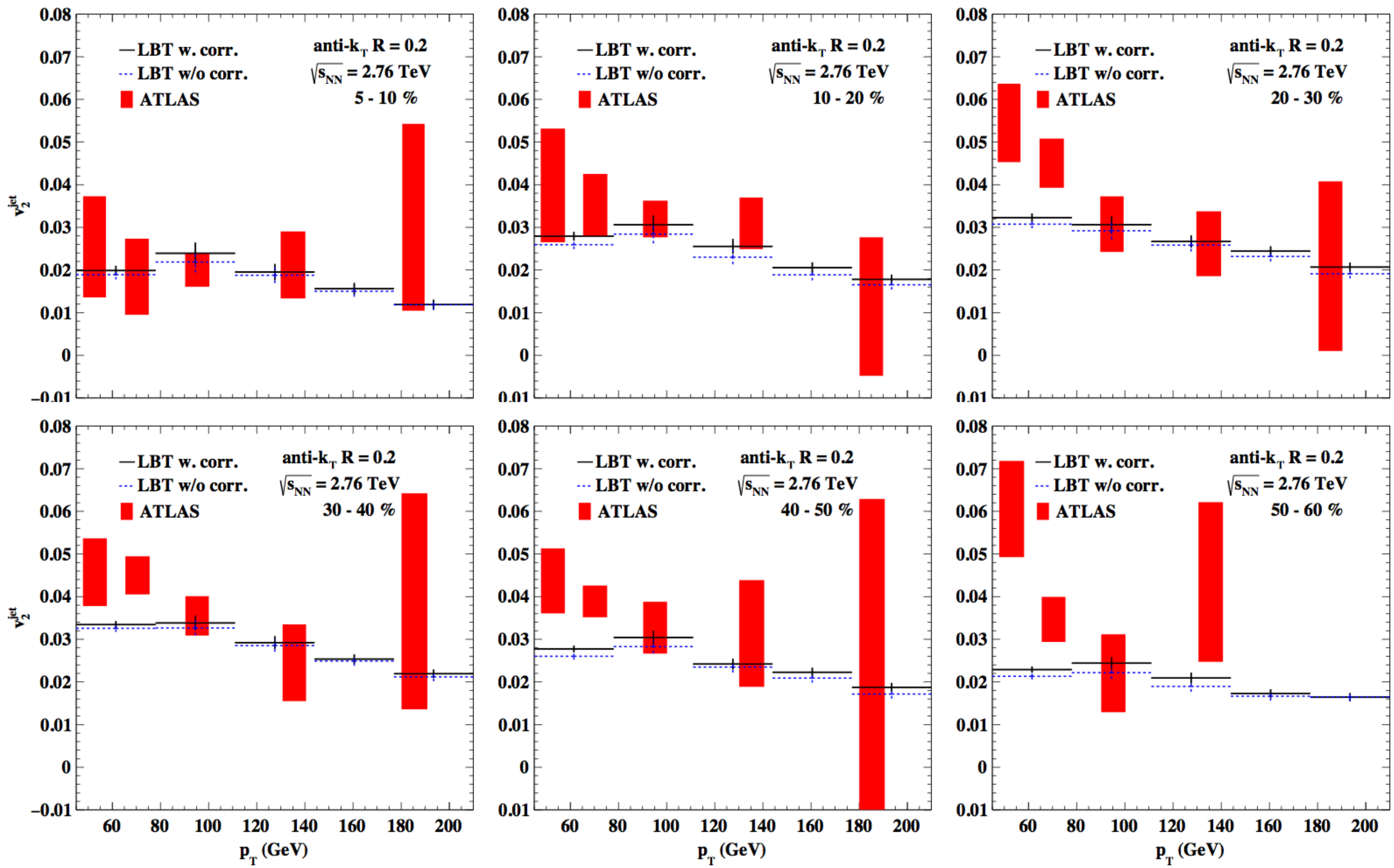


Data ref.: ATLAS Collaboration, Phys. Rev. Lett.111 152301 (2013)

Jet v2 with different centralities

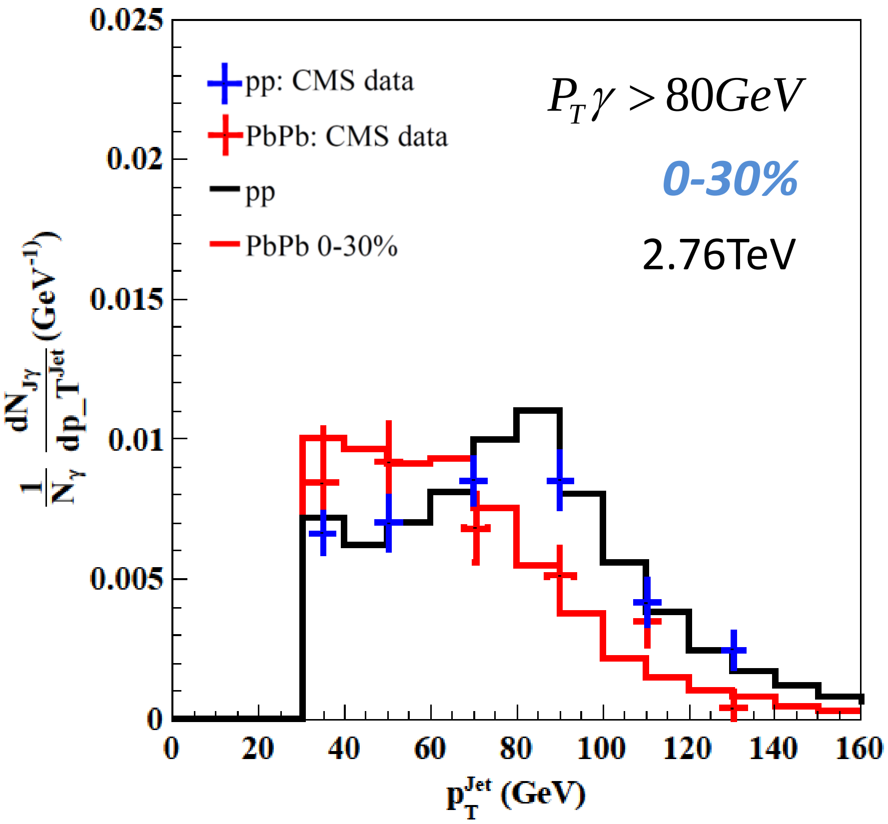
$$v_2^{jet} = < \cos(2[\phi^{jet} - \Psi_2]) >$$

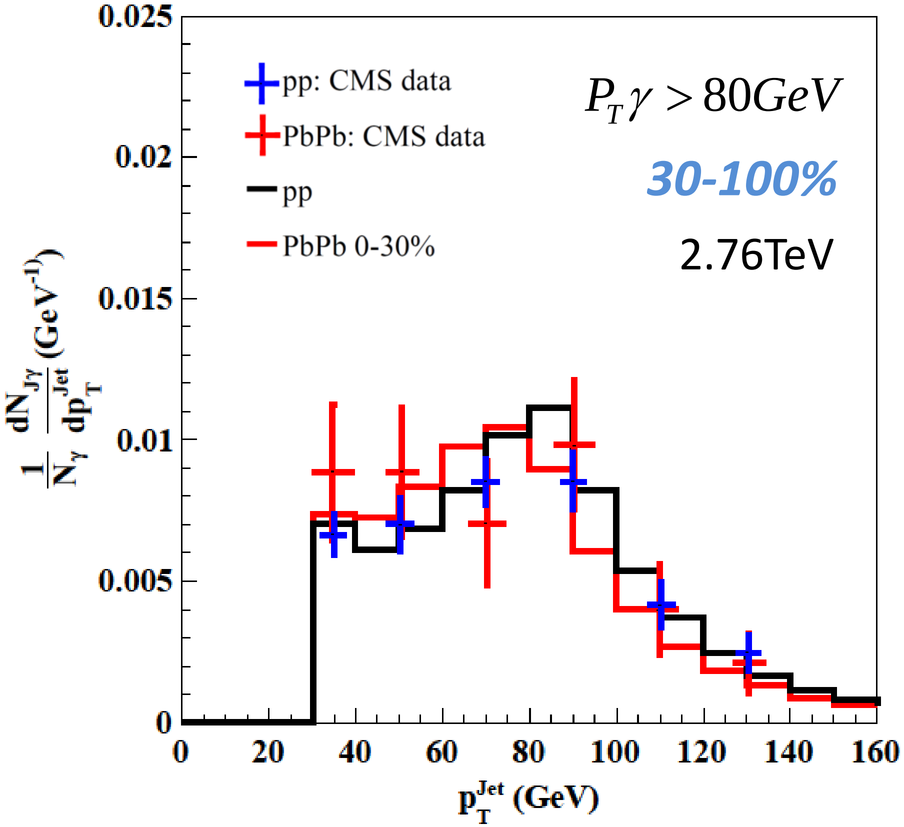
$$v_2^{jet} = \frac{< v_2^{soft} \cos(2[\phi^{jet} - \Psi_2]) >}{\sqrt{< (v_2^{soft})^2 >}}$$



pT distribution of gamma-jet in heavy-ion collisions

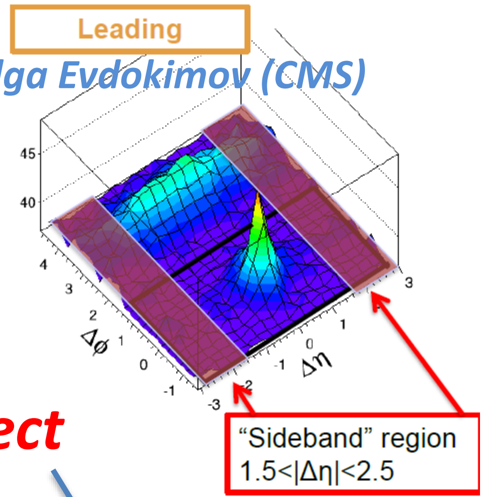
- Shift of the peak of the pt distribution
- Path length dependence of the energy loss

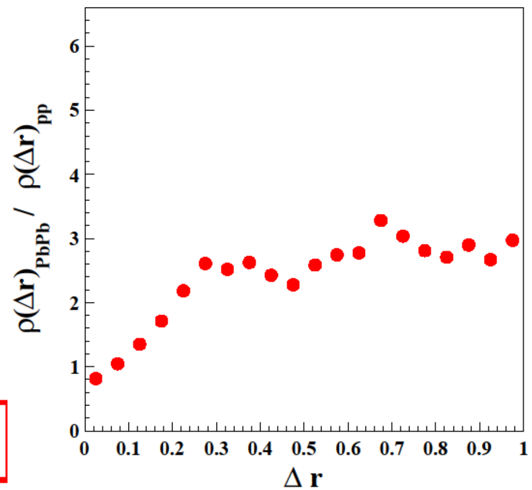




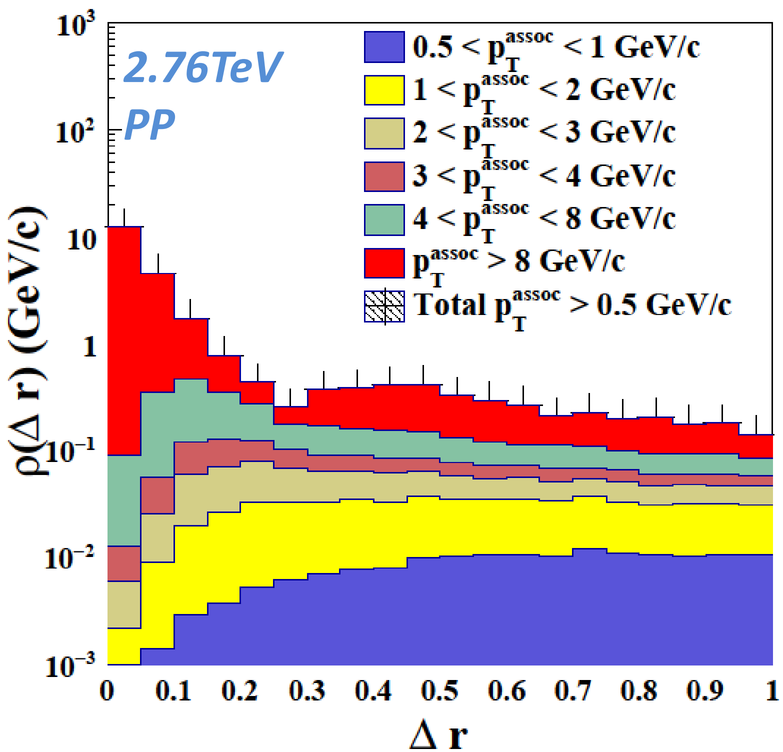
Jet shape of gamma-jets in heavy-ion collisions

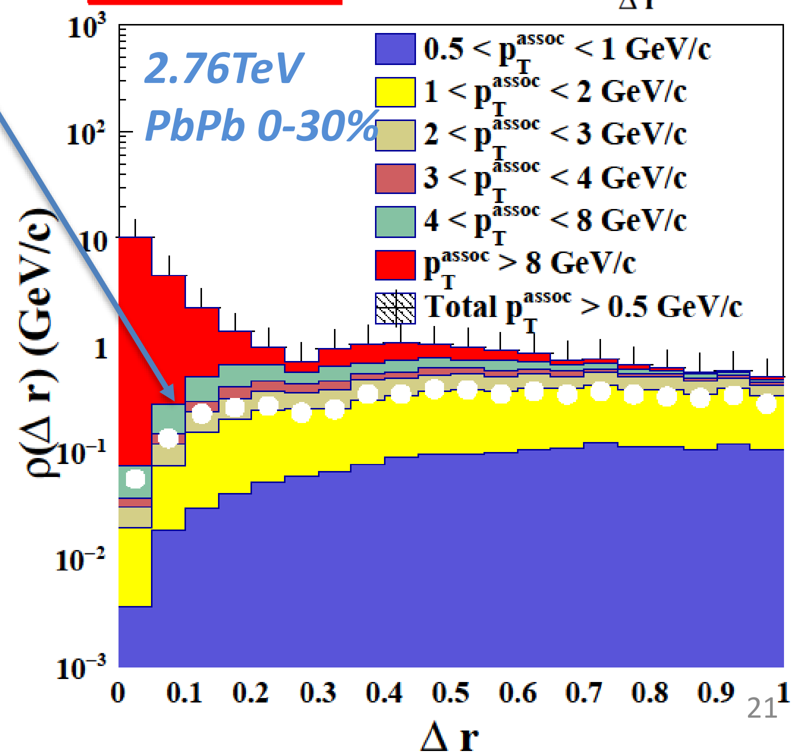
- Energy lost by the hard parton is transport out of the jet cone by the soft parton.





Recoiled effect

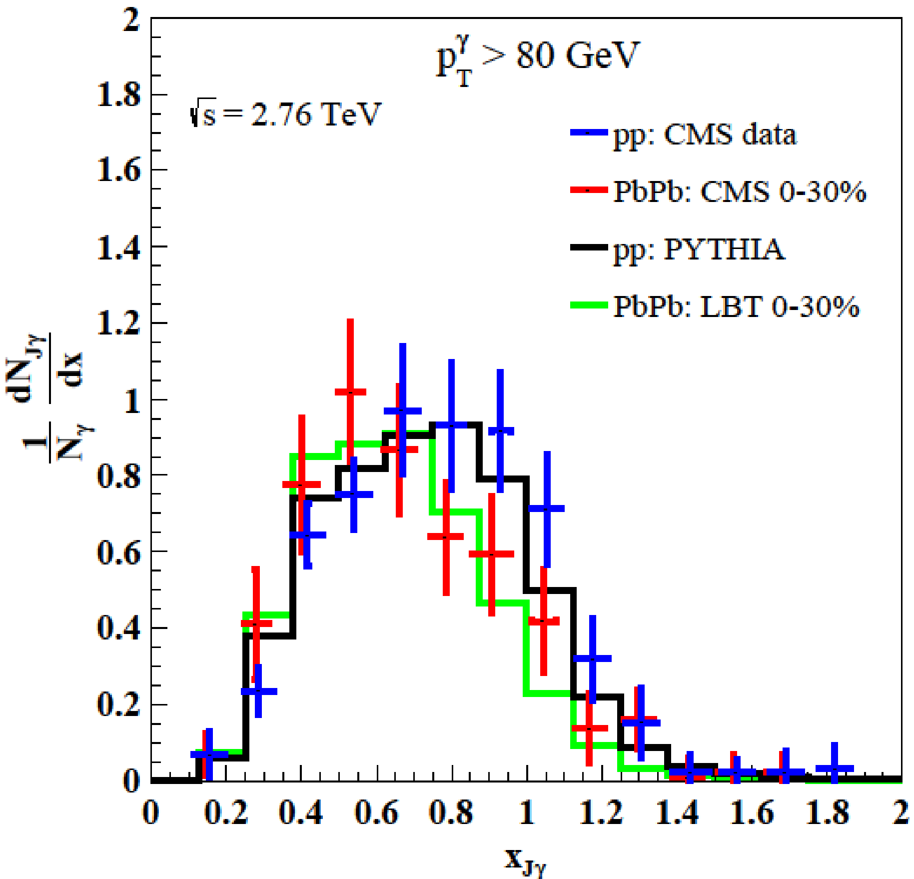




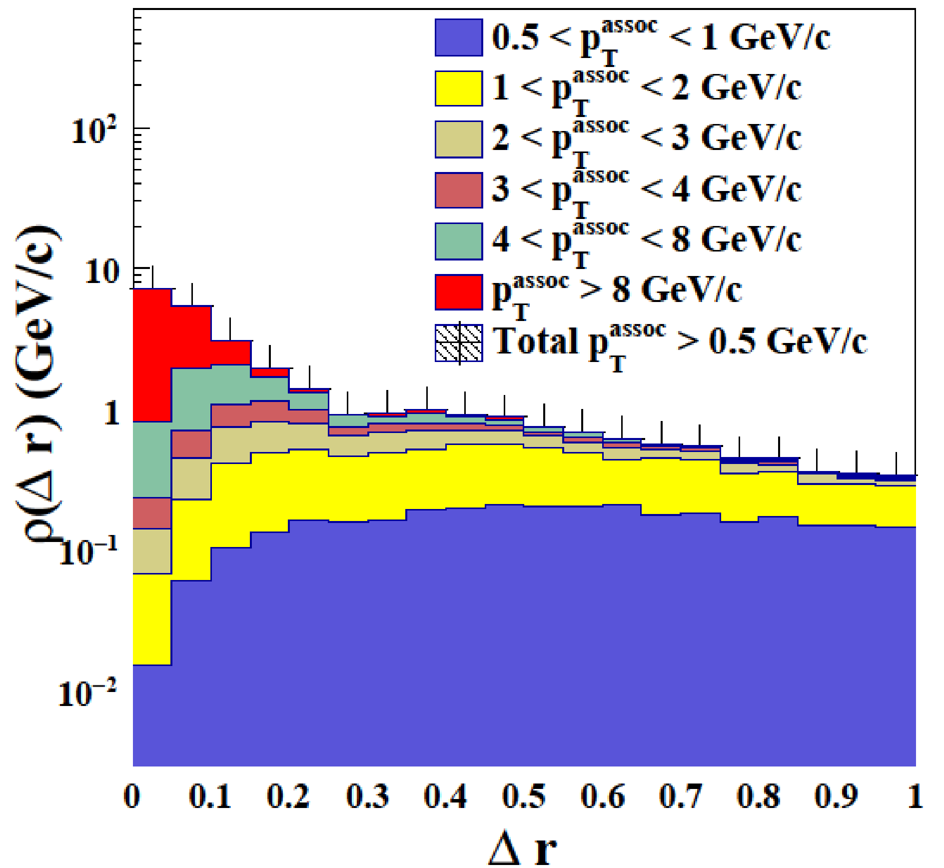
Jet reconstruction with recombination model

Han, Fries and Ko, Phys. Rev. C93 (2016) 045207

Gamma-jet asymmetry



Jet shape

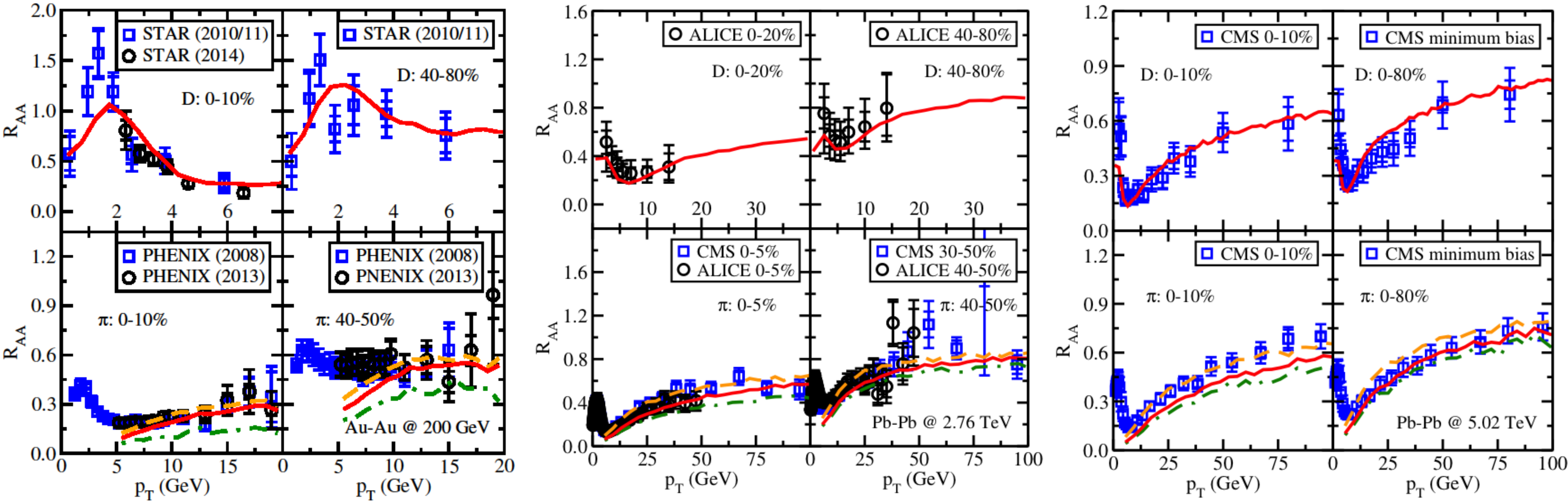


preliminary

Hadron R_{AA} in heavy ion collision

- Simultaneous description of single hadron R_{AA} from RHIC to LHC (AuAu@200GeV, PbPb@2760GeV and PbPb@5020GeV, 2 centrality bins for each system, 6 data sets in total)

AuAu@200GeV PbPb@2760GeV PbPb@5020GeV

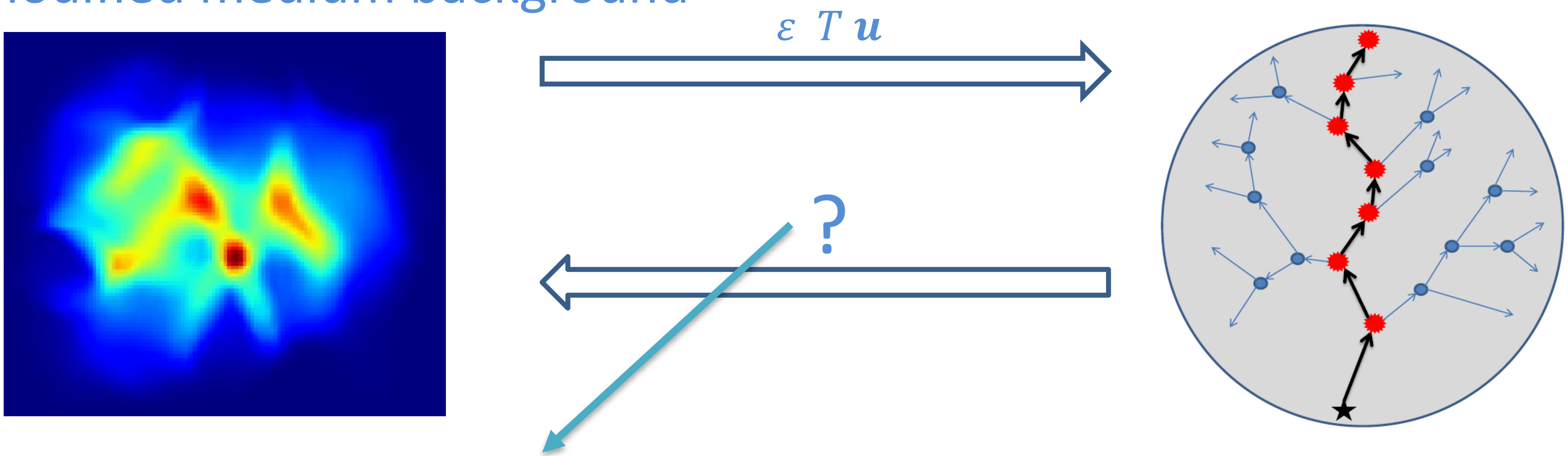


Beyond LBT model (modified medium background)

- Linear approximation : jet induced medium excitation δf<<f .
- Jet-Medium interaction : Where is the modification of the thermal background ?

Modified medium background

JET



Energy and momentum deposited from the jets as source terms into hydro

CoLBT-Hydro model
(A coupled LBT Hydro (3+1D) Model)

A coupled LBT hydro (3+1D) model

P < Pcut

Hydro ⟷ LBT

Soft — Hard

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

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

$$\frac{1}{p.u} p^\mu \partial_\mu f = C$$

Proper time coordinate

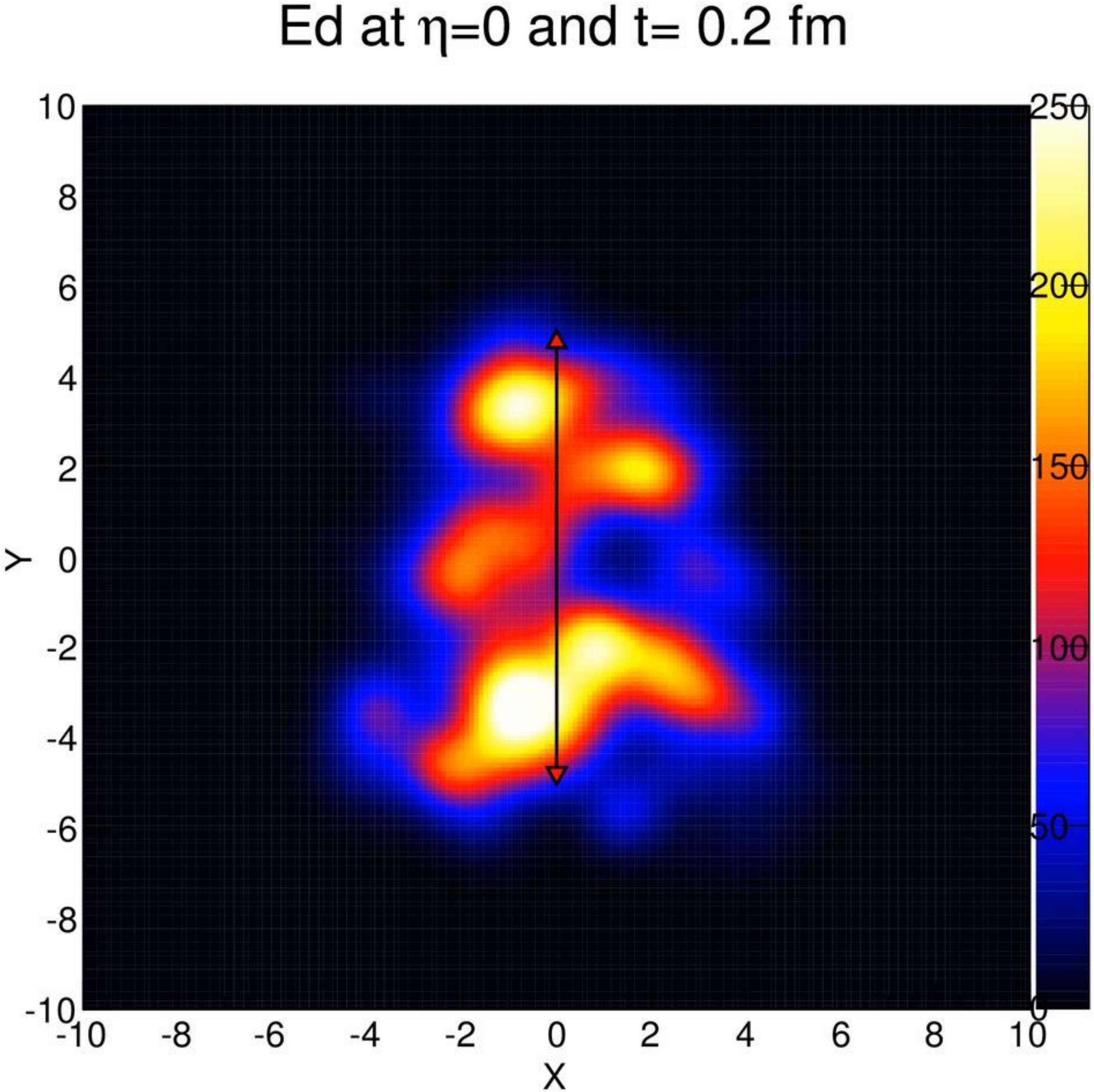
Source term
(soft partons in LBT)

P < Pcut
(comoving frame)

$$j^\nu = \sum_{i=1}^{n} \frac{dP_i^\nu}{d\tau} \delta^3(\vec{X} - \vec{X}_i)$$

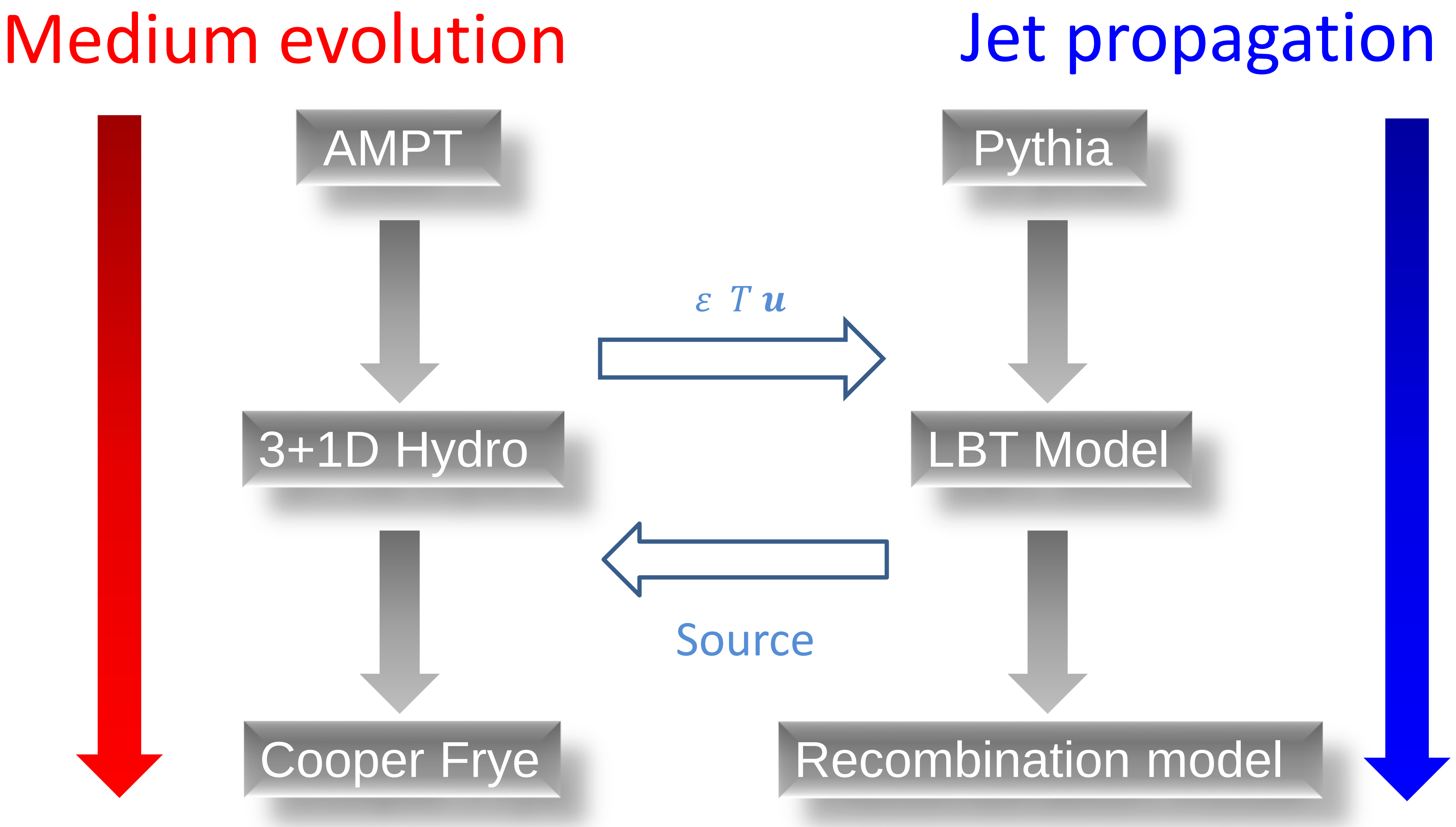
event-by-event (3+1)D hydrodynamics

Longgang Pang, Qun Wang, Xin-Nian Wang **Phys.Rev. C86 (2012) 024911**



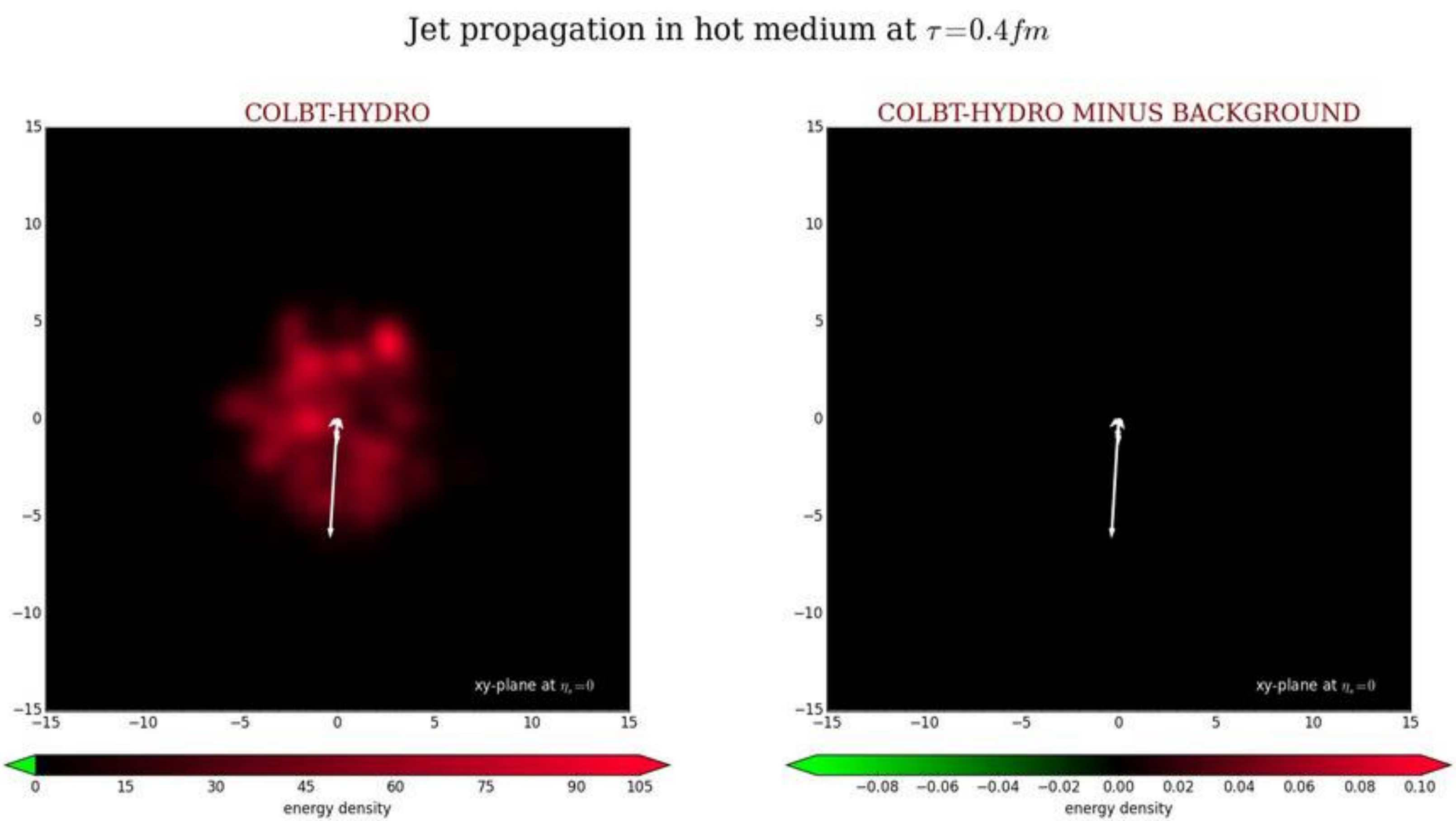
Ed at η=0 and t= 0.2 fm
Y
X
10
8
6
4
2
0
-2
-4
-6
-8
-10
250
200
150
100
50
0

A coupled LBT hydro (3+1D) model



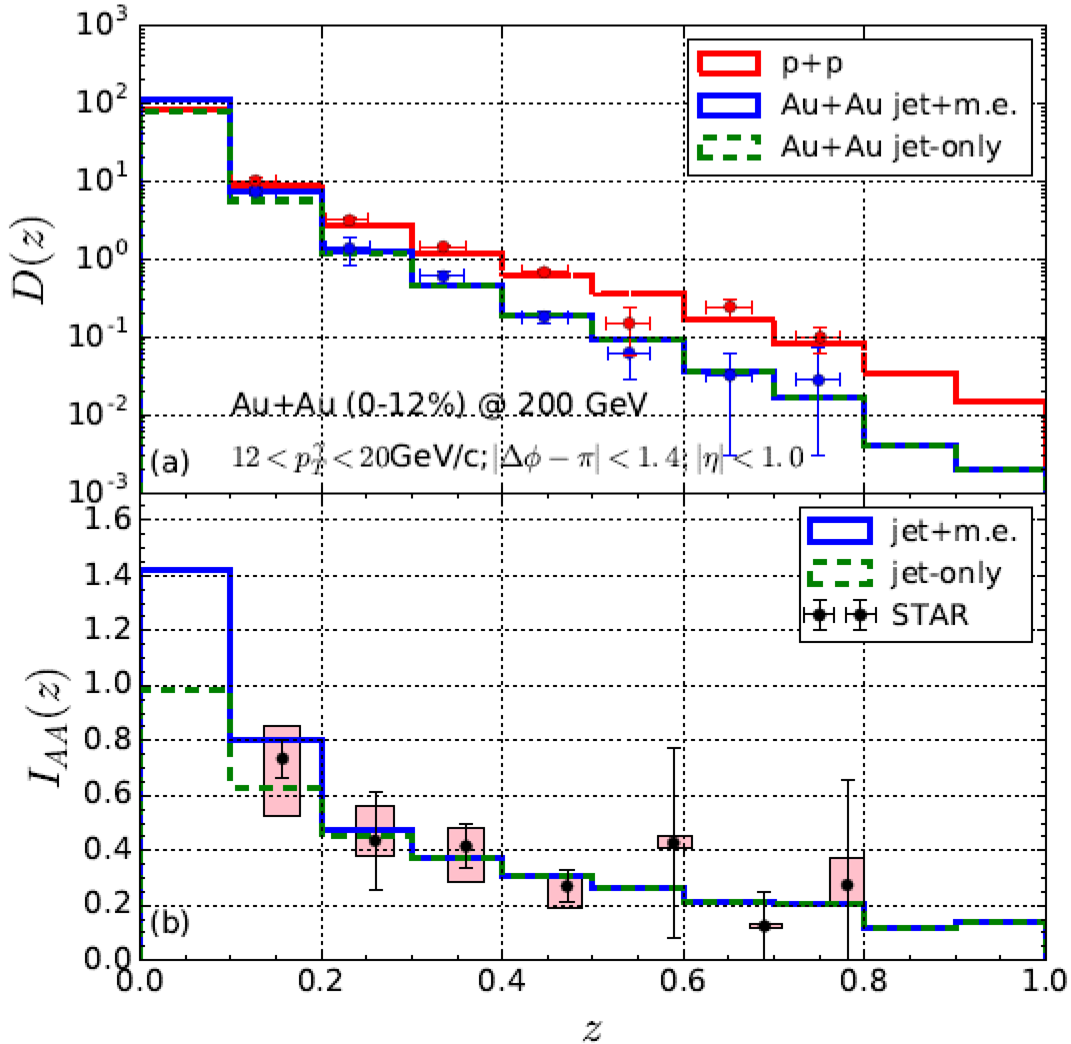
(Jet+medium) - (medium without jet) in the end

Gamma-jet evolution within CoLBT-hydro model



Medium modification of gamma-triggered hadron yields in RHIC energy

CoLBT-hydro: $$D(z) = \frac{dN_h}{dydz}\Big|_{LBT} + \frac{dN_h}{dydz}\Big|^{w/\,jet}_{hydro} - \frac{dN_h}{dydz}\Big|^{w.o/\,jet}_{hydro} \qquad z = p_T^h / p_T^\gamma$$



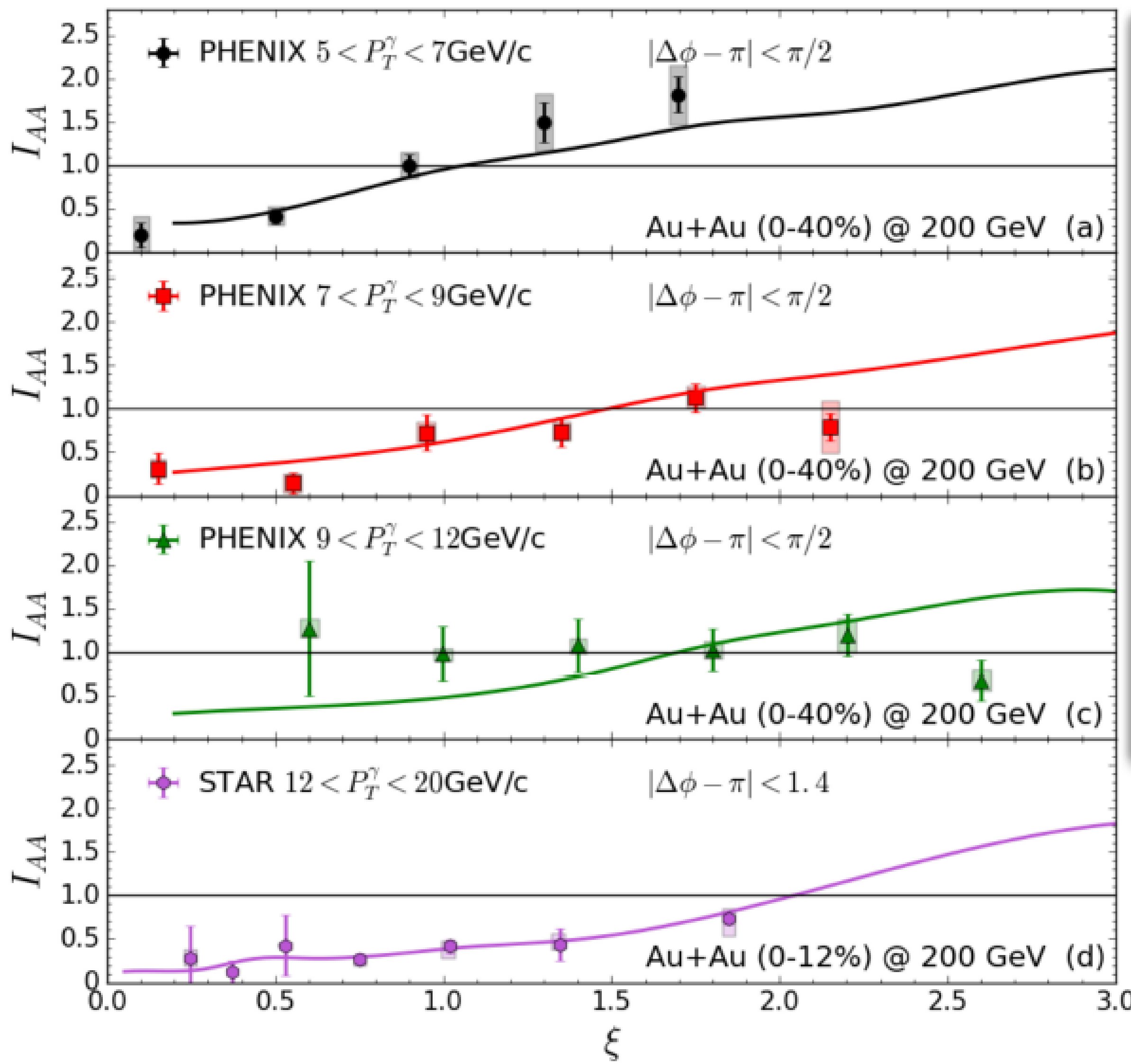
- The suppression of leading hadrons at intermediate and large z
  LBT:
  hard parton energy loss

- The enhancement of soft hadrons at small z
  Hydro:
  medium excitation

$$p_{cut} = 2GeV$$

$$I_{AA}(z) = D_{AA}(z) / D_{pp}(z)$$

Medium modification of gamma-triggered hadron yields in RHIC energy



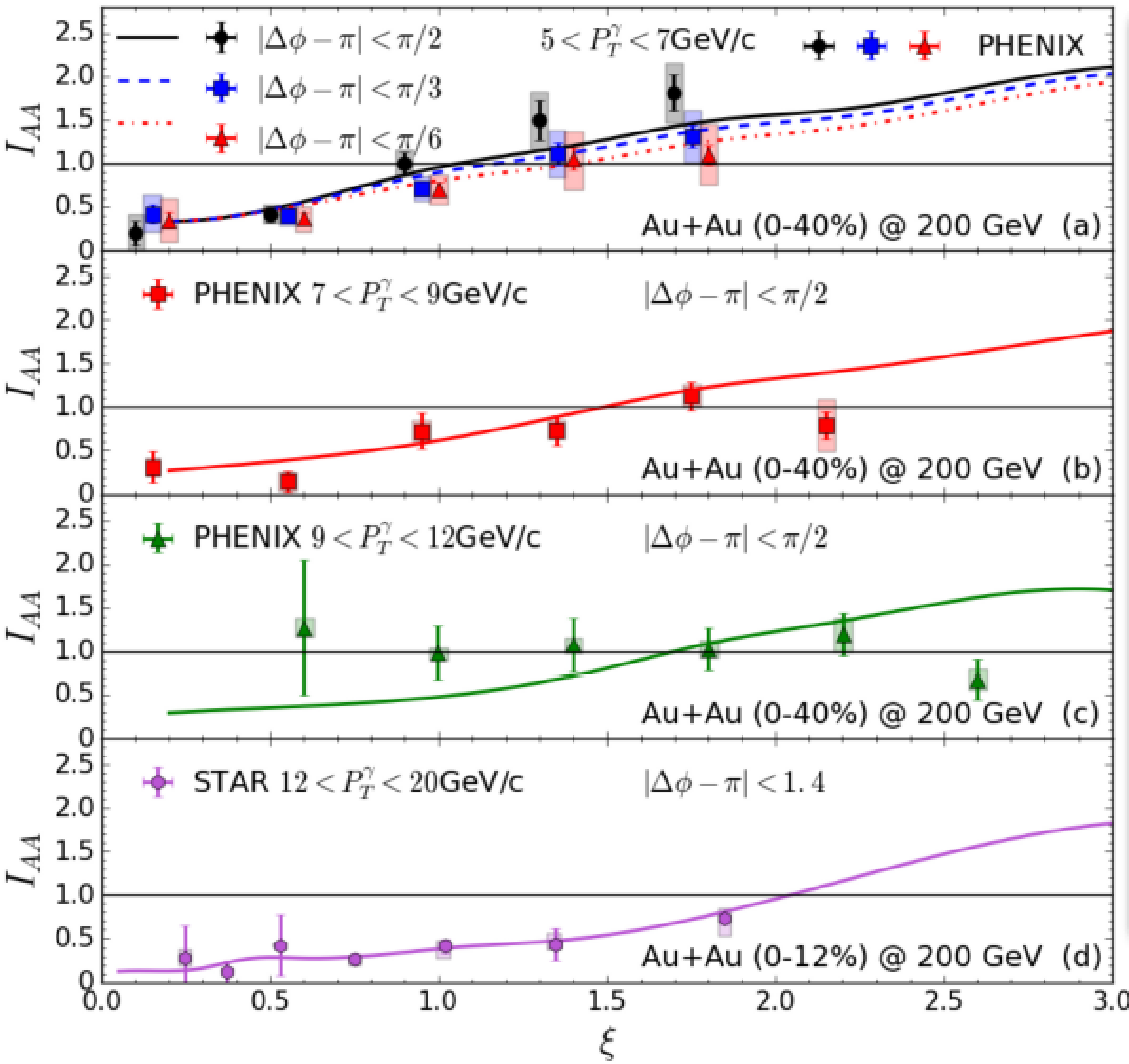
With increasing pT-gamma

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

$$z = p_T^h / p_T^\gamma$$

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

Medium modification of gamma-triggered hadron yields in RHIC energy

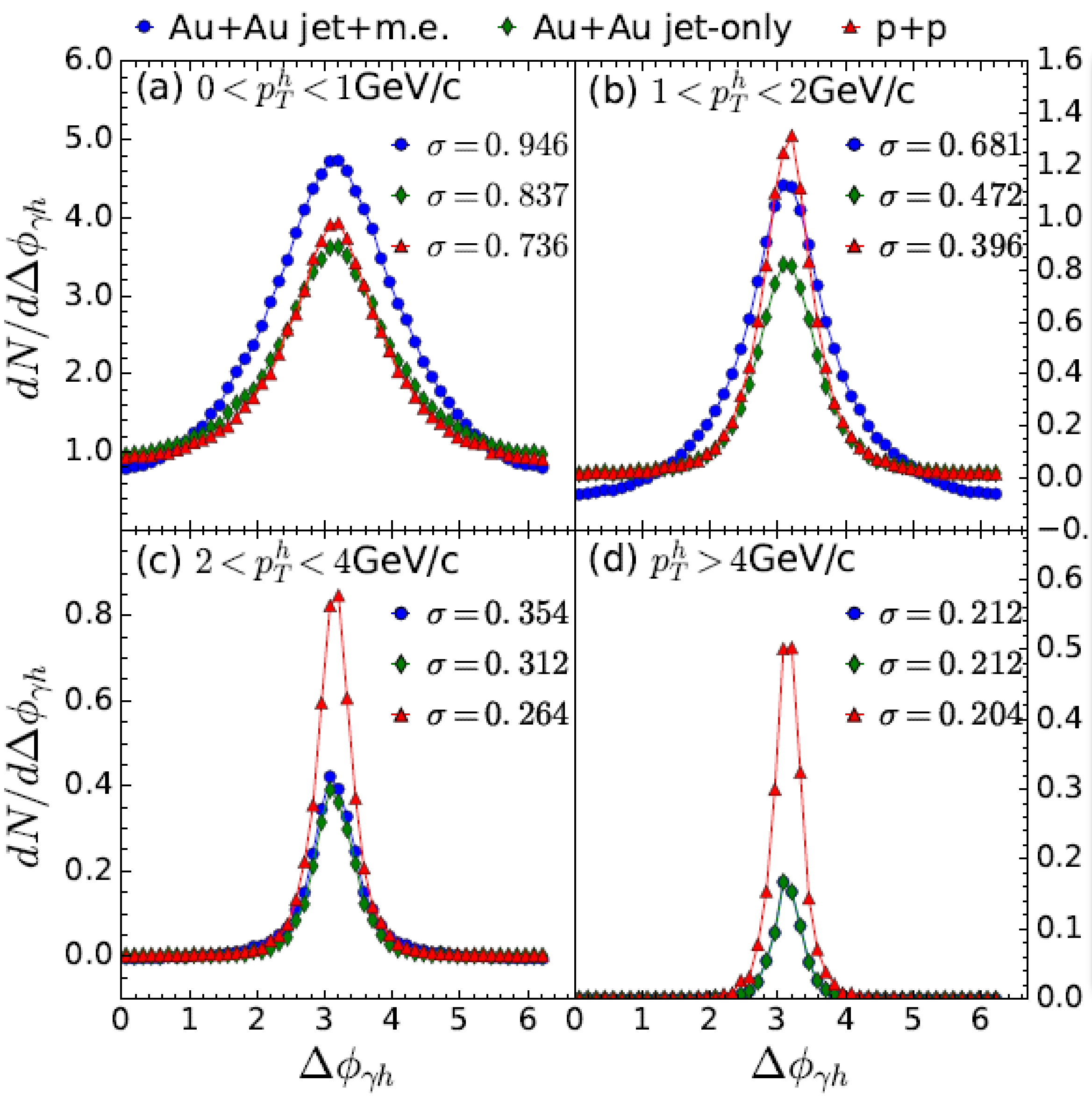


With decreasing azimuthal angle range

- The enhancement at large ξ becomes smaller.
- The transition point shifts to the large ξ.

The soft hadron enhancement has significant contributions from both small and large angle azimuthal angle relative to the jet direction.

Gamma-hadron azimuthal correlation in RHIC energy



σ : gaussian width

- 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.

Summary

- We present a computation of jets modification in QGP within the Linear Boltzmann Transport (**LBT**) model in which both the elastic and inelastic processes are included.
- We develop a coupled LBT hydro (**CoLBT-hydro**) model for the further study of jet-medium interaction.

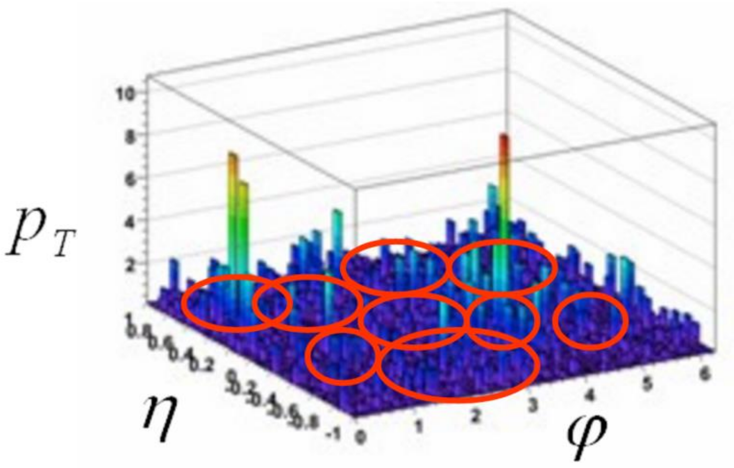
Outlook

- *Jet in hadron level. (Hardon jet, Heavy flavor jet)*
  (with the recombination model developed by Texas A&M group)
- *Ideal hydro to viscous hydro.*
- *Heavy quarkonium.*

Thanks

Underlying Event Subtraction (UES)

UE: collisions of beam remnant, fluctuation of the background, non-perturbative effects. Subtraction is needed to exclude the soft particles.



Seed jet: $E_T > 3\,\mathrm{GeV}$ for at least one parton,and

$$E_T^{max}/E_T^{ave} > 4$$

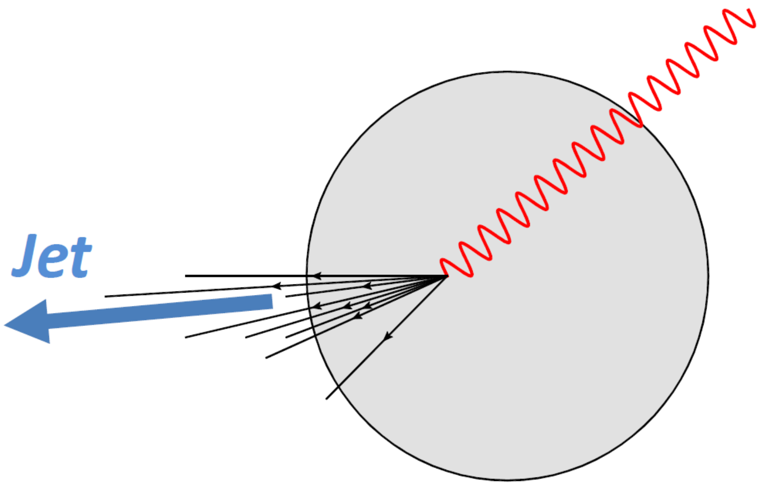
ATLAS Collaboration, Phys. Lett. B 719, 220 (2013).

$$E_T^{UES} = E_T^{seedjet} - A^{seedjet}\rho(1 + 2v_2\cos[2(\phi_{jet} - \Psi_2)])$$

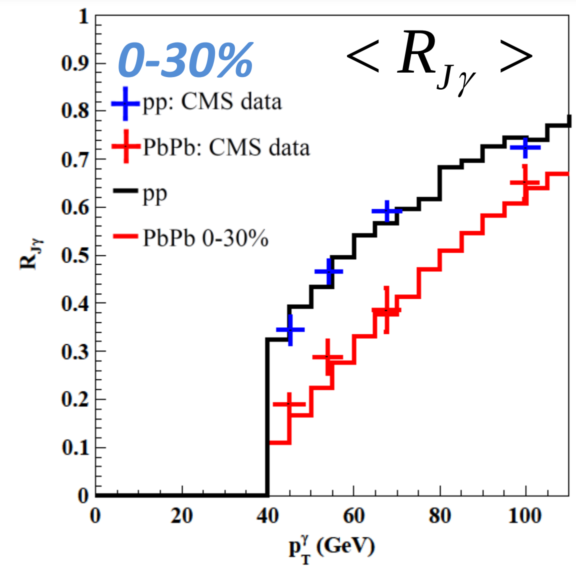
We only subtract the energy of seed jets,
and count all the final jets!

Asymmetry distribution of gamma-jet in heavy-ion collisions

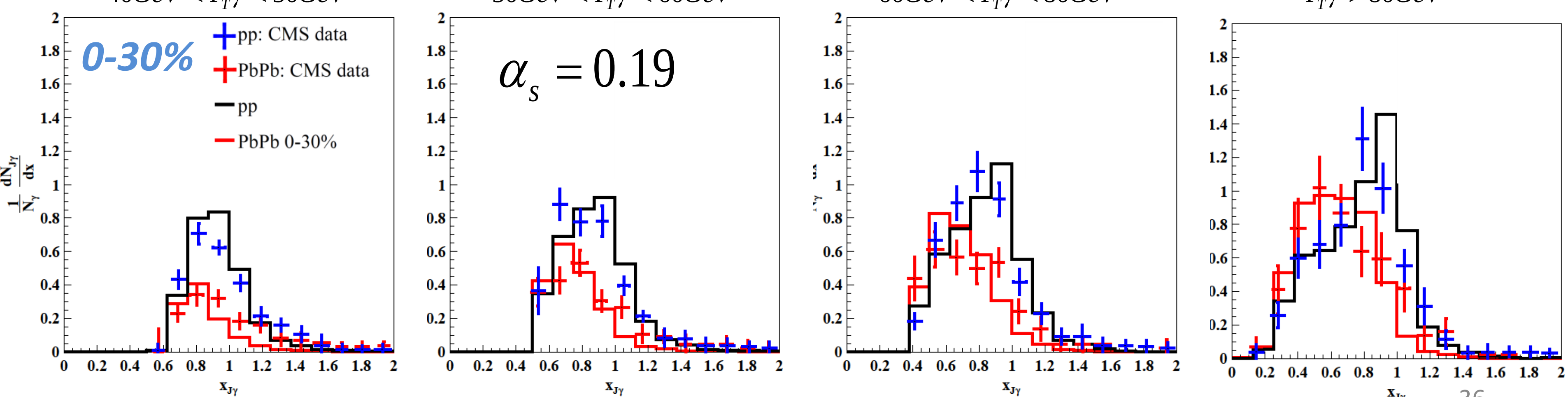
- fix the parameter α_s via the comparison with the γ-jet asymmetry



$$|\eta_\gamma| < 1.44$$
$$P_{Tjet} > 30GeV$$
$$|\eta_{jet}| < 1.6$$



$40GeV < P_T\gamma < 50GeV$ | $50GeV < P_T\gamma < 60GeV$ | $60GeV < P_T\gamma < 80GeV$ | $P_T\gamma > 80GeV$

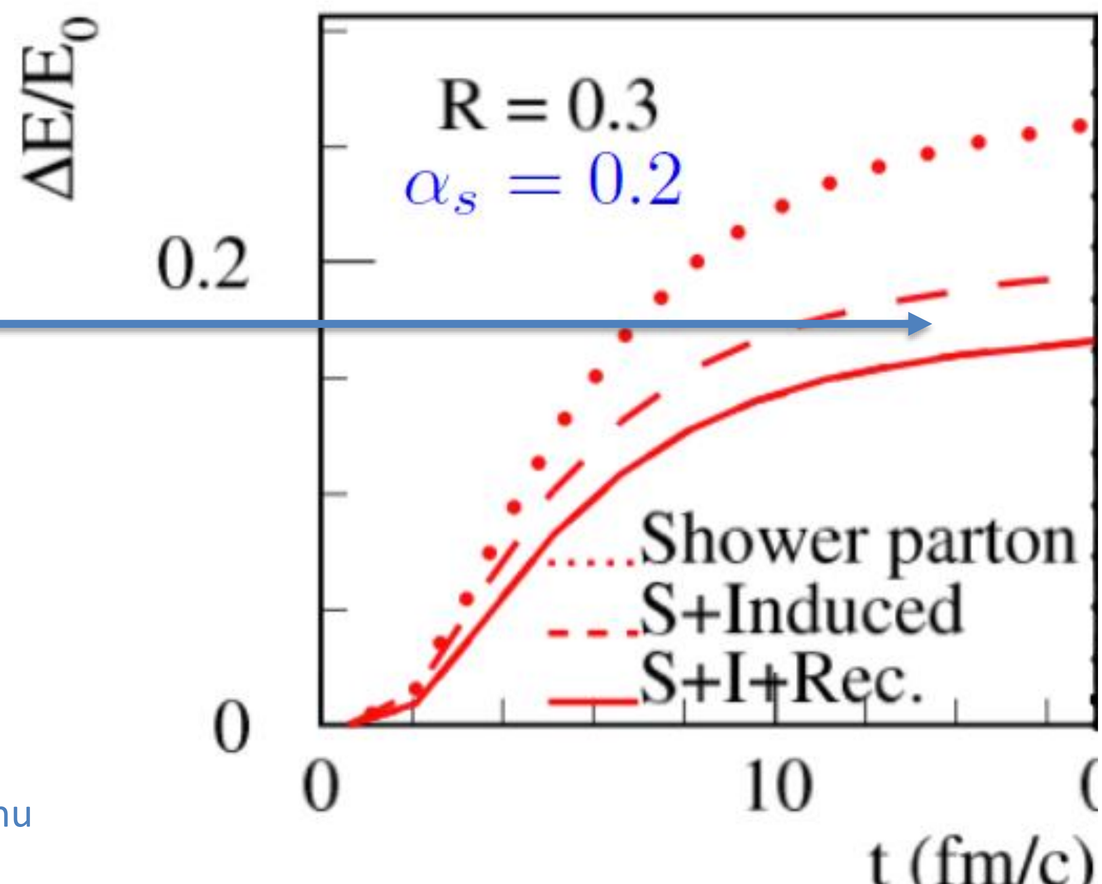


Jets in a 3+1D hydro

- 3+1D Ideal hydro **Longgang Pang, Qun Wang, Xin-Nian Wang Phys.Rev. C86 (2012) 024911**
- Location of gamma-jet is decided according probability of binary collision.

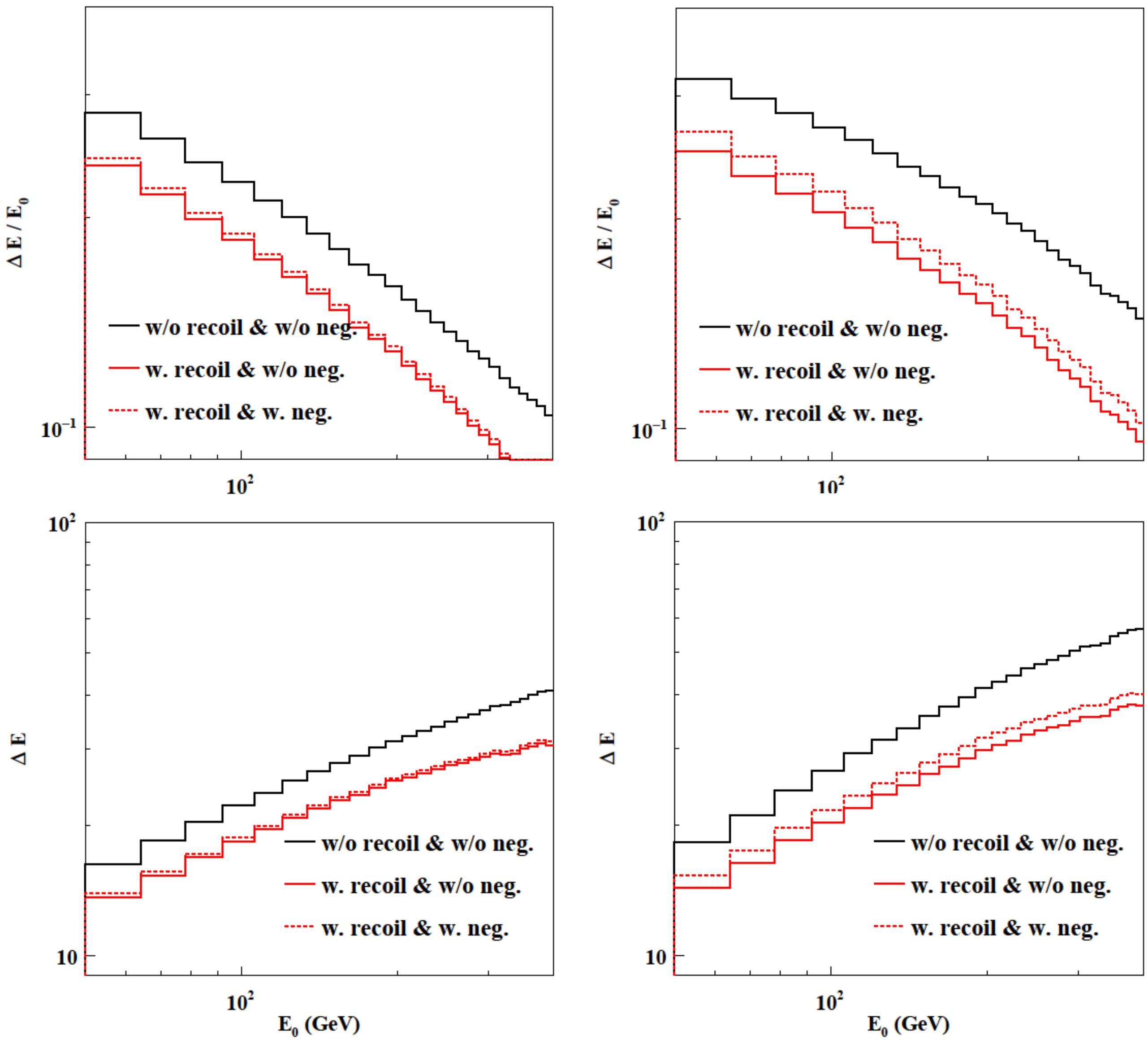
Recoiled effect in the reconstructed jets

The contribution of the recoiled parton in the reconstructed jets



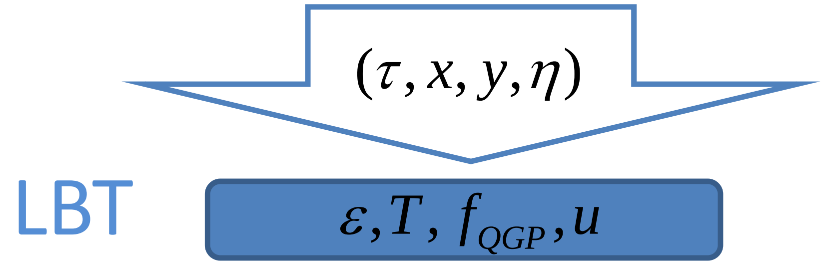
HL Li, FM Liu, GL Ma, XN Wang, Y Zhu
Phys.Rev.Lett. 106, 012301
Xin-Nian Wang, Yan Zhu
Phys.Rev.Lett. 111, 062301
Yayun He, Tan Luo, Xin-Nian Wang, Yan Zhu
Phys.Rev. C91 (2015) 054908

Recoiled effect in the reconstructed jets



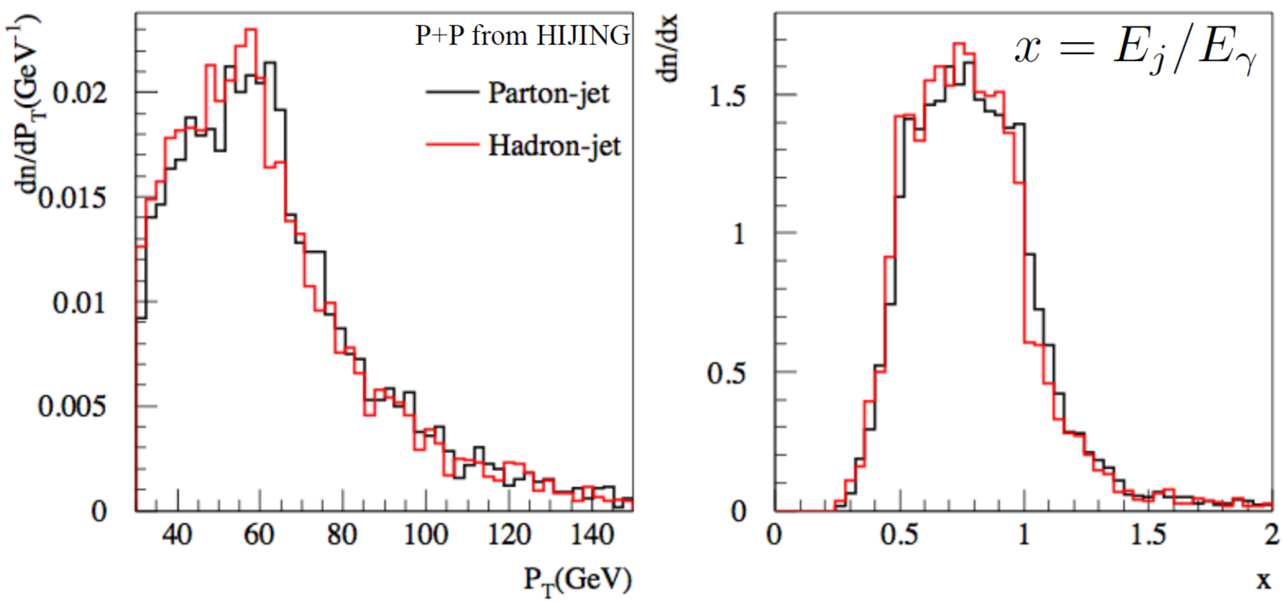
Gamma-jets in a 3+1D hydro

- 3+1D Ideal hydro Longgang Pang, Qun Wang, Xin-Nian Wang Phys.Rev. C86 (2012) 024911



- Location of gamma-jet is decided according probability of binary collision.

- Small difference between parton-jet and hadron-jet.



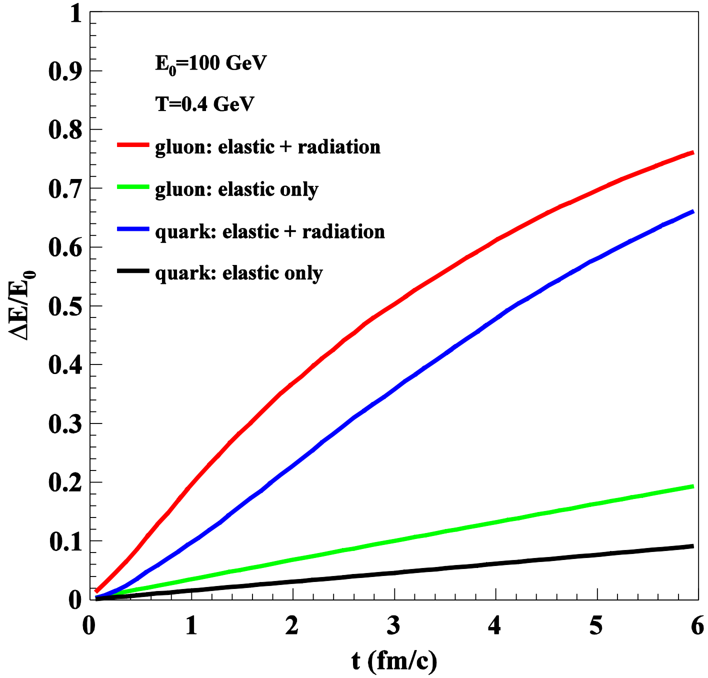
Nontrivial path length dependence on parton energy loss

Leading parton energy loss

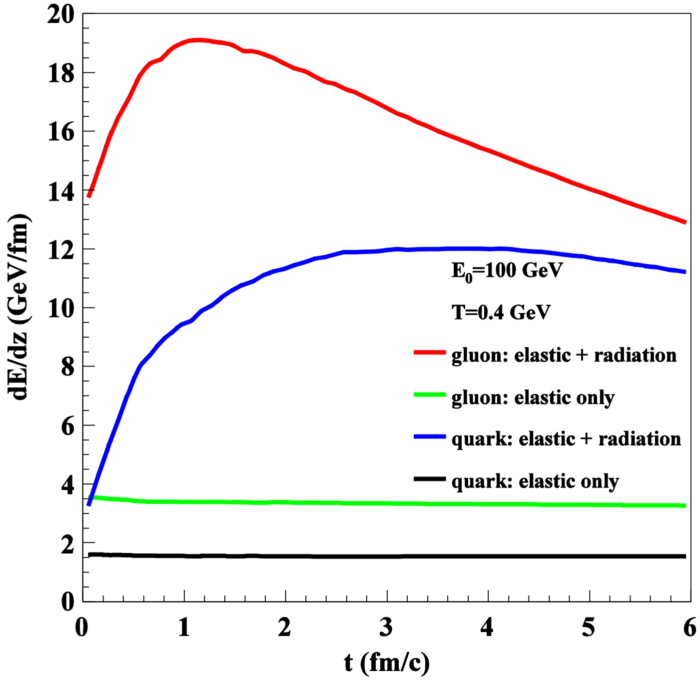
Propagation of a single initial jet parton in a uniform medium

$\alpha_s = 0.3$ E = 100 GeV T = 0.4 GeV

Fractional energy loss



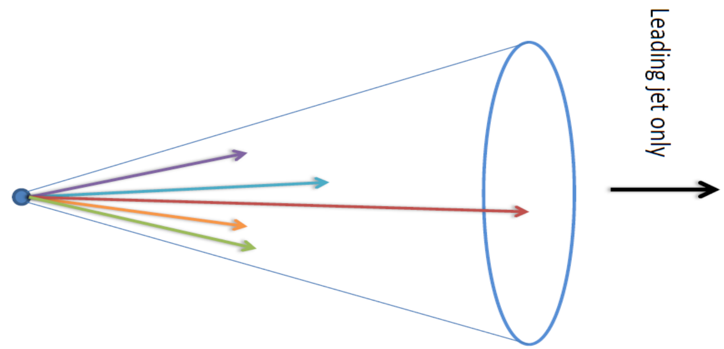
Energy loss per unit length



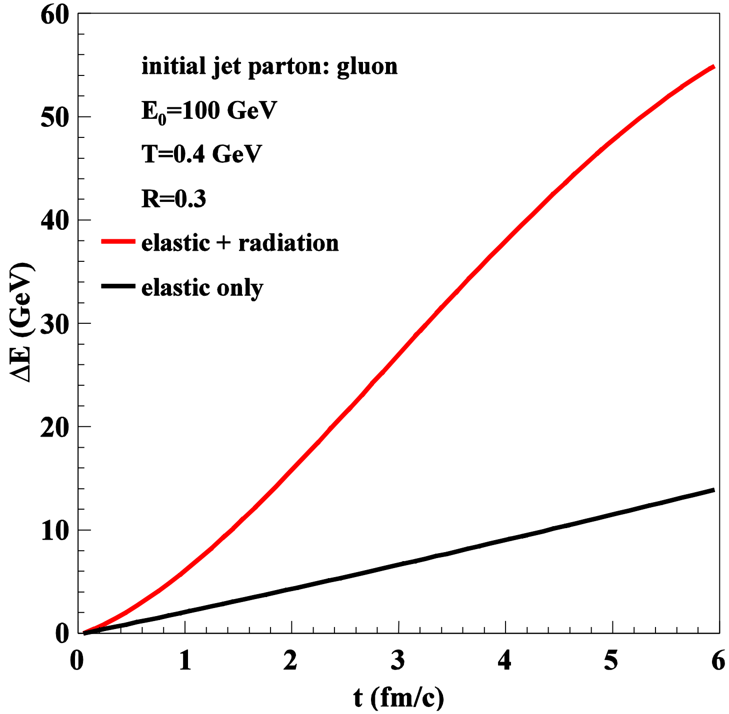
Path length dependence on parton energy loss

Leading jet energy loss

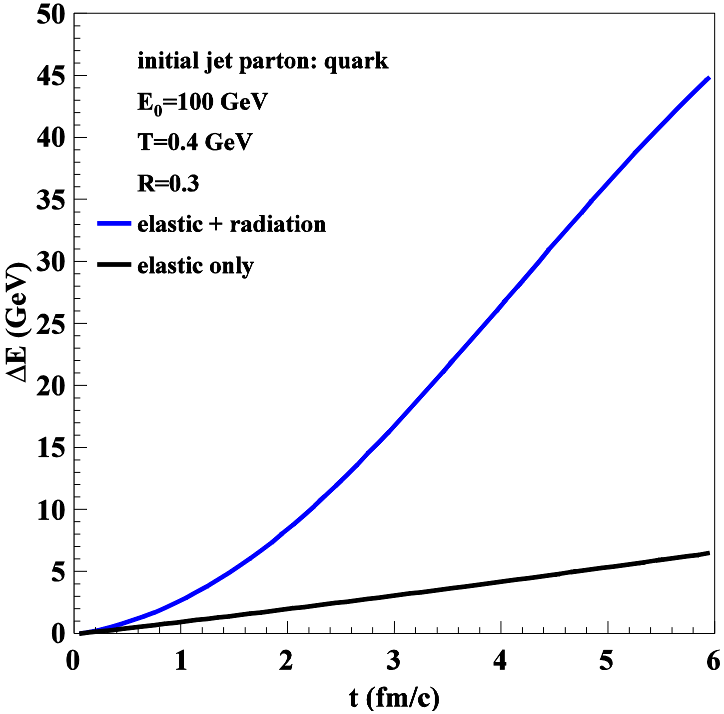
- Leading jet recover some of the energy lost by the leading parton.



Initial jet parton: gluon



Initial jet parton: quark



Inclusive jet in pp collisions

pT distribution in pp collison within Pythia8

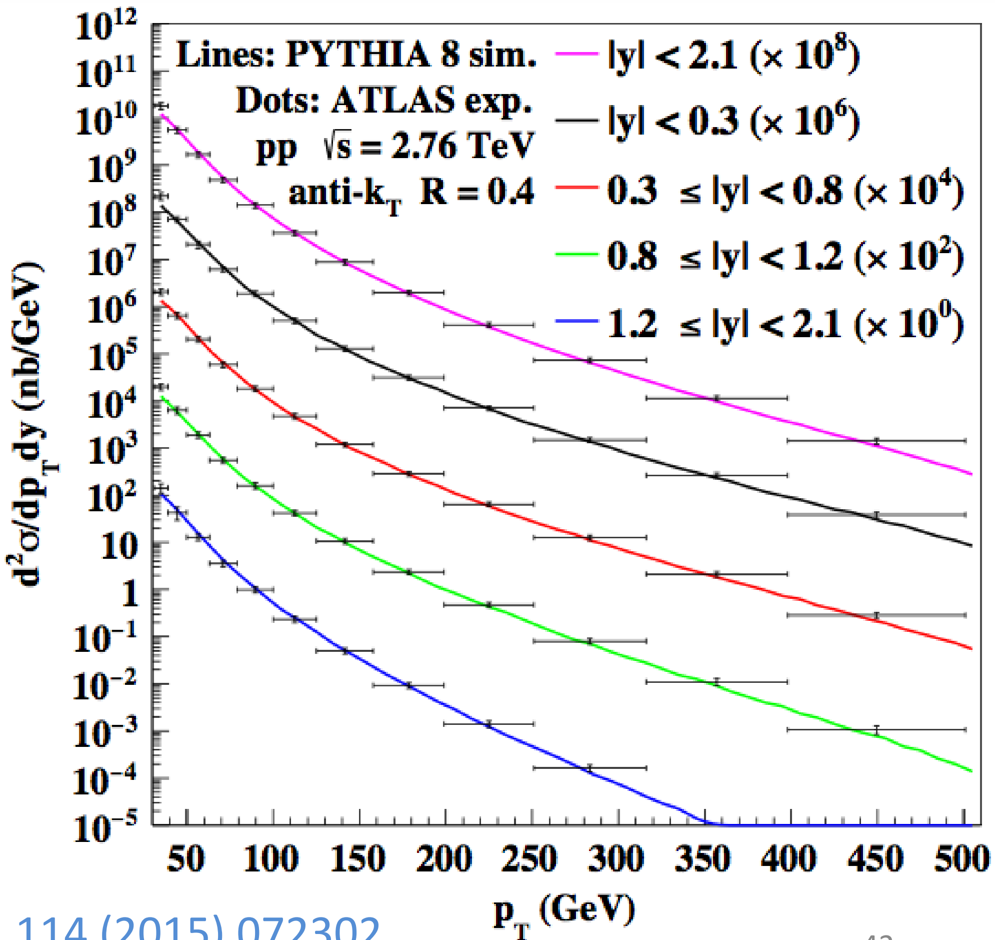
Weighted sampling in triggered p_T bins to increase the efficiency of MC simulations

In PYTHIA 8 one can obtain the cross section for each triggered pT bin

$$\frac{d^2\sigma}{dp_T dy} = \sum_i \sigma_i \frac{1}{N_{events}} \frac{dN_i^{jets}}{dp_T \Delta y}$$

For each bin, the weight is

$$\omega_i = \sigma_i / \sum_i \sigma_i$$



Data ref.: ATLAS Collaboration, Phys. Rev. Lett. 114 (2015) 072302

Initial geometry

Averaged over 200 event-by-event hydro profiles