Jet substructure in heavy-ion collisions

Tan Luo

Central China Normal University

Institute of Particle Physics

In collaboration with

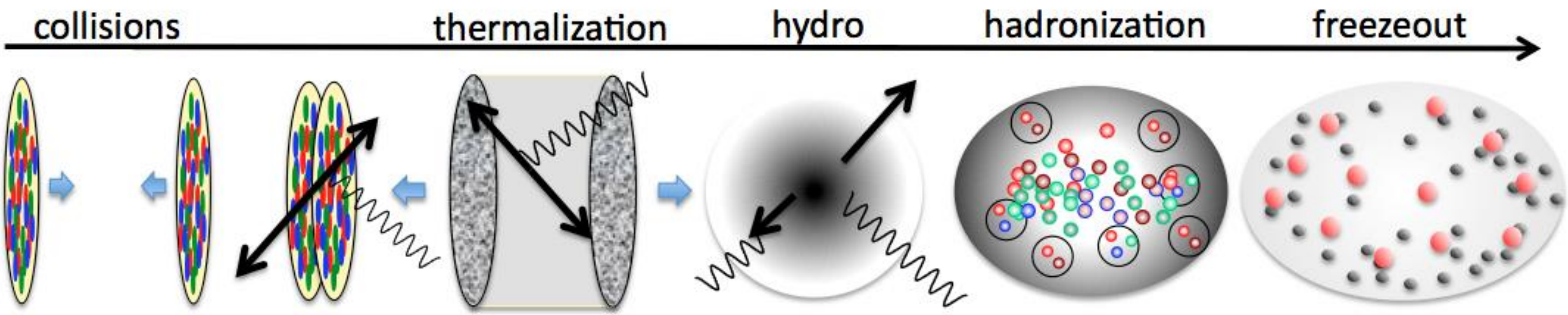
Shanshan Cao, Yayun He, Guang-You Qin and Xin-Nian Wang

Outline

- Introduction
- A Linear Boltzmann Transport (LBT) model
- Jet modification in heavy ion collisions
- Summary and Outlook

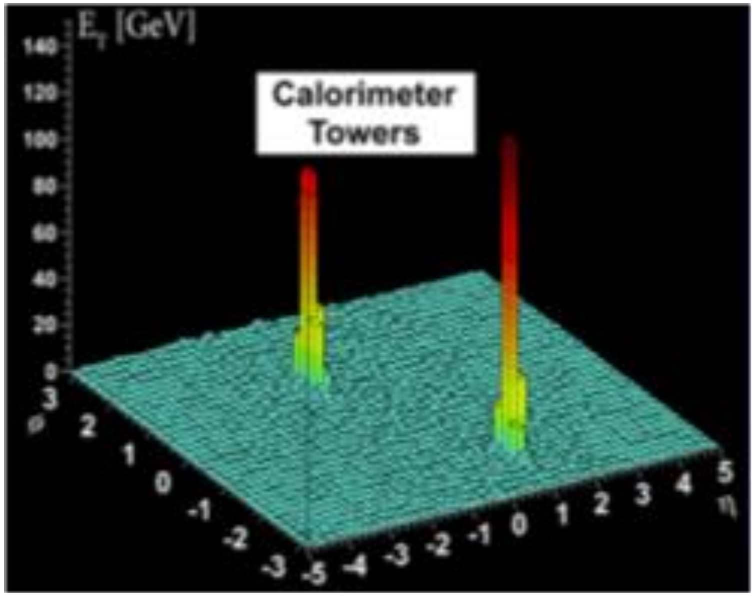
Introduction

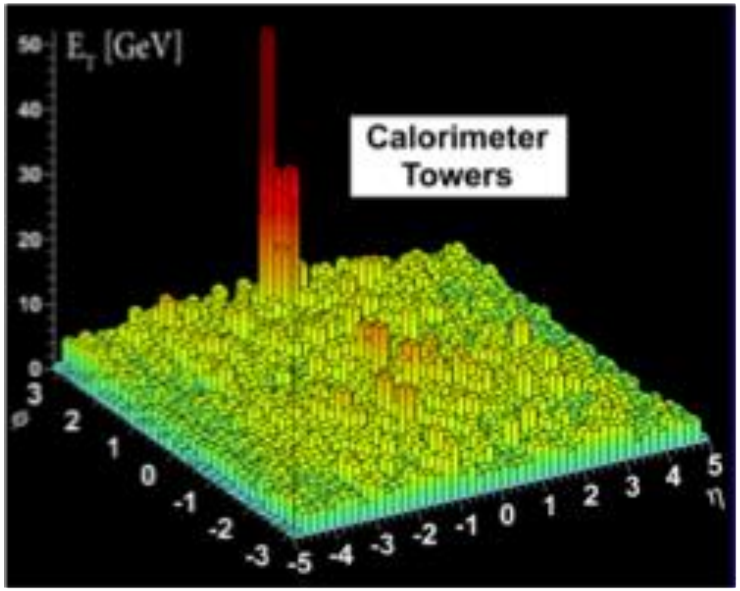
Jets in heavy ion collisions



Nonaka, Chihoet al. PTEP 2012 (2012) 01A208

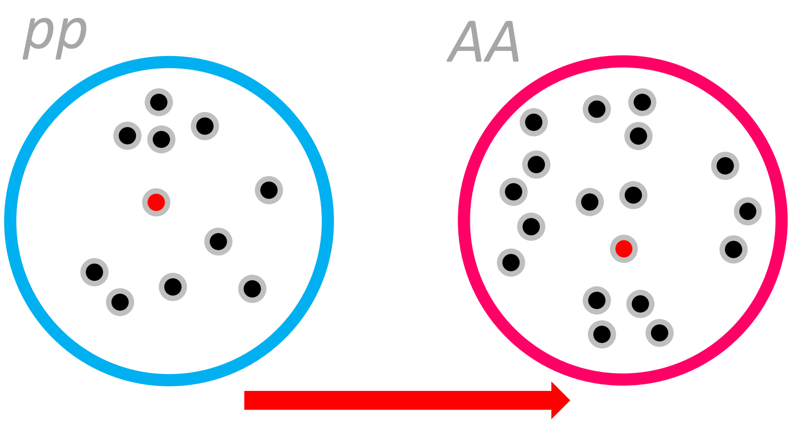
What are in the background of a reconstructed jet?



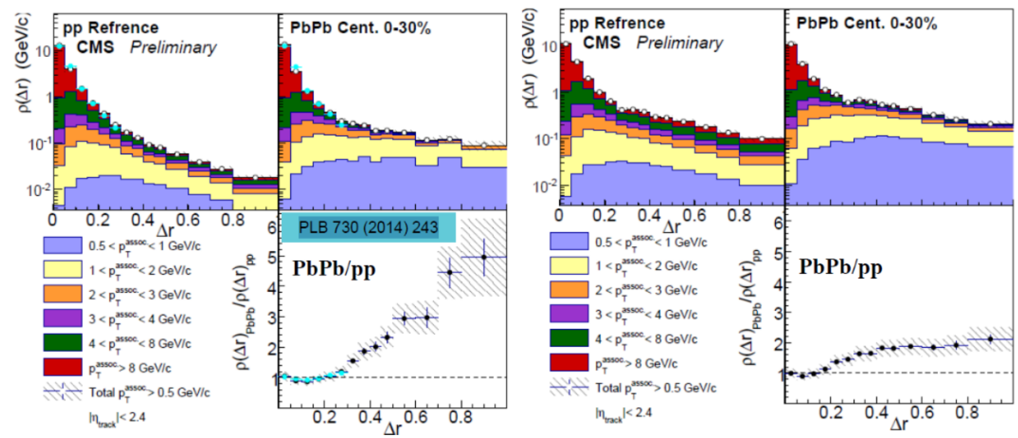


Introduction

The jet shape and transverse momentum imbalance in Dijet events



Medium modification of the jet structure

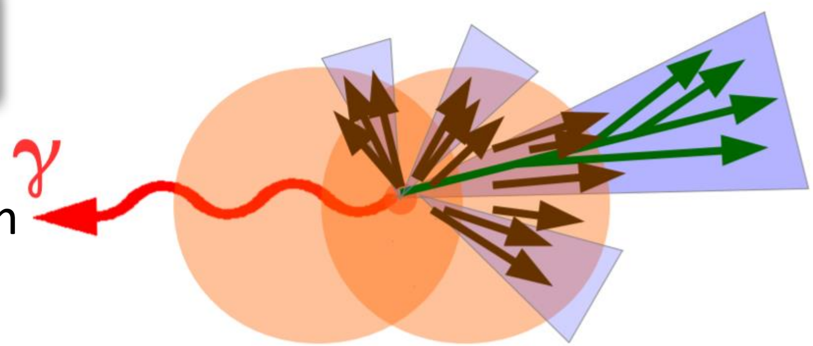


arXiv:1609.02466 CMS

Gamma-jet → *The golden channel*

XN Wang, Z Huang Phys. Rev. Lett. 77, 231 (1996)

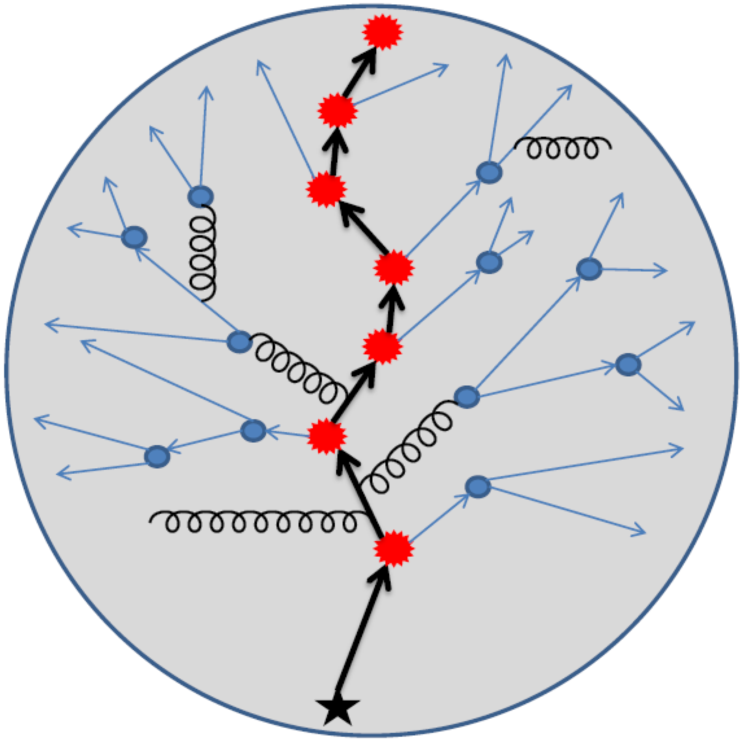
- High PT photons are unmodified by the medium
- No "surface bias" in triggered events which dijet events suffer



Kaya Tatar

A Linear Boltzmann Transport (LBT) Model

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

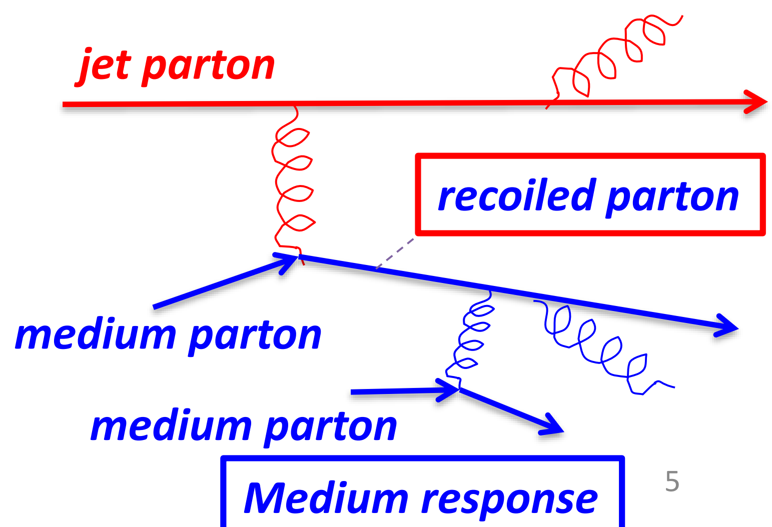


Jet induced medium excitation

Linear Boltzmann jet Transport

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

("Negative" parton for the back reaction)

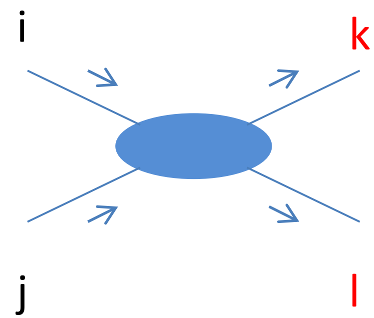


Linear Approximation

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

Complete set of elastic processes

Single scattering



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

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

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

Medium-induced gluon radiations

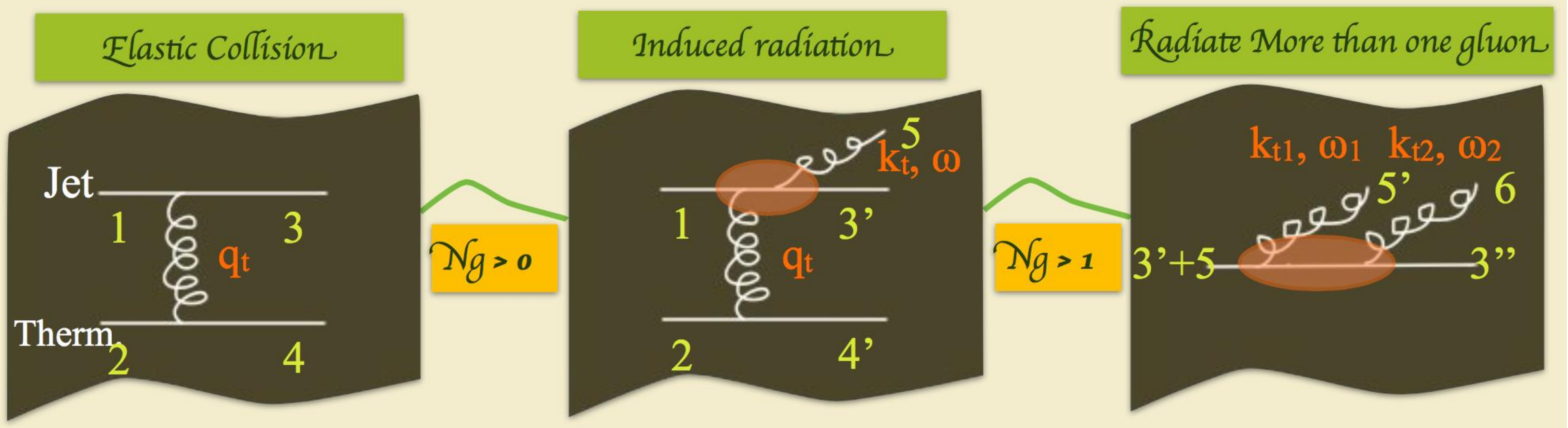
Radiated gluon distribution: Guo and Wang (2000), Majumder (2012); Zhang, Wang and Wang (2004)

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

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:



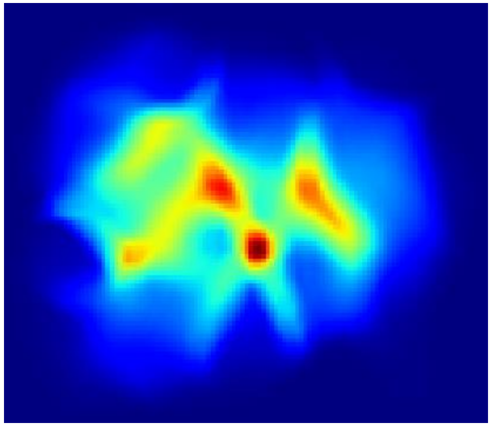
Y. He, T. Luo, X. N. Wang and Y. Zhu, PhysRevC.91.054908

Jets in a 3+1D hydro

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

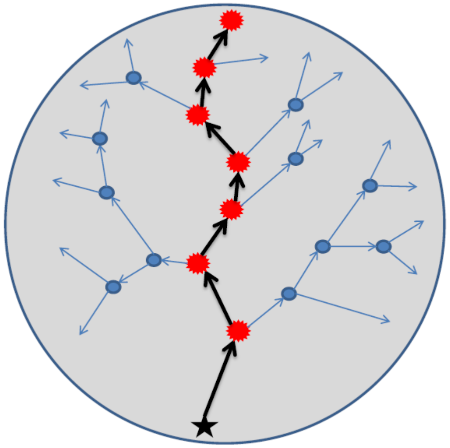
- Location of jets are decided according probability of binary collision.

- 3+1D Ideal hydro



ε T $\boldsymbol{u}$

LBT Model



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

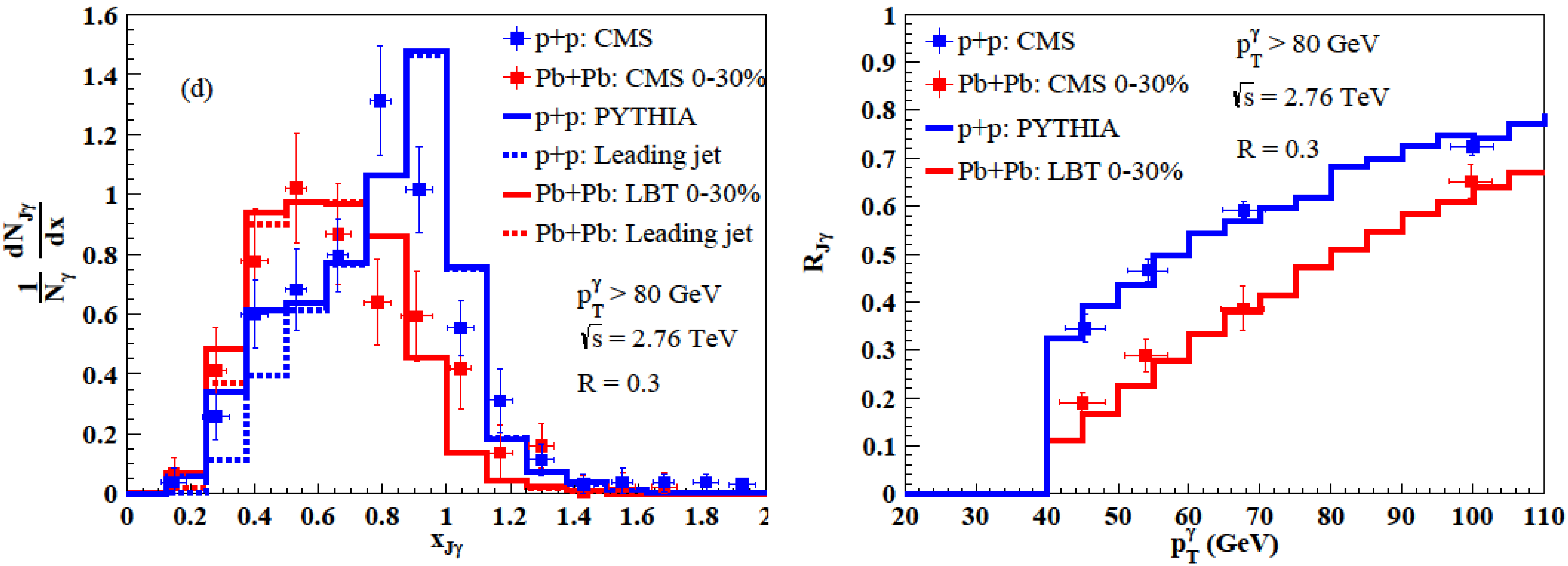
M. Cacciari, G. P. Salam and G. Soyez
Eur. Phys. J. C 72, 1896 (2012).

Jet reconstruction (Fastjet)

Gamma-jet energy loss

Gamma-jet Luo, Cao, He & XNW, arXiv:1803.06785

- The only parameter effective strong coupling constant α_s is fixed. (fix the strength of jet-medium interaction)

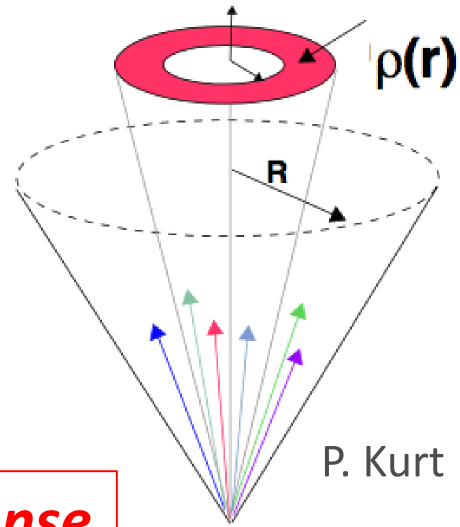


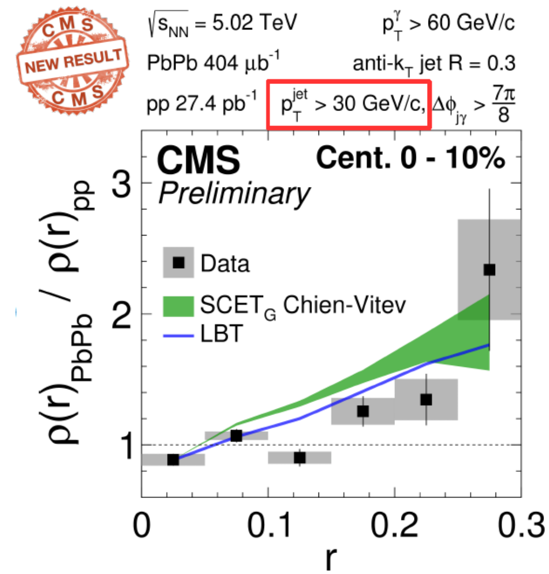
gamma-jet asymmetry gamma-jet ratio

Jet shape of gamma-jet in heavy-ion collisions

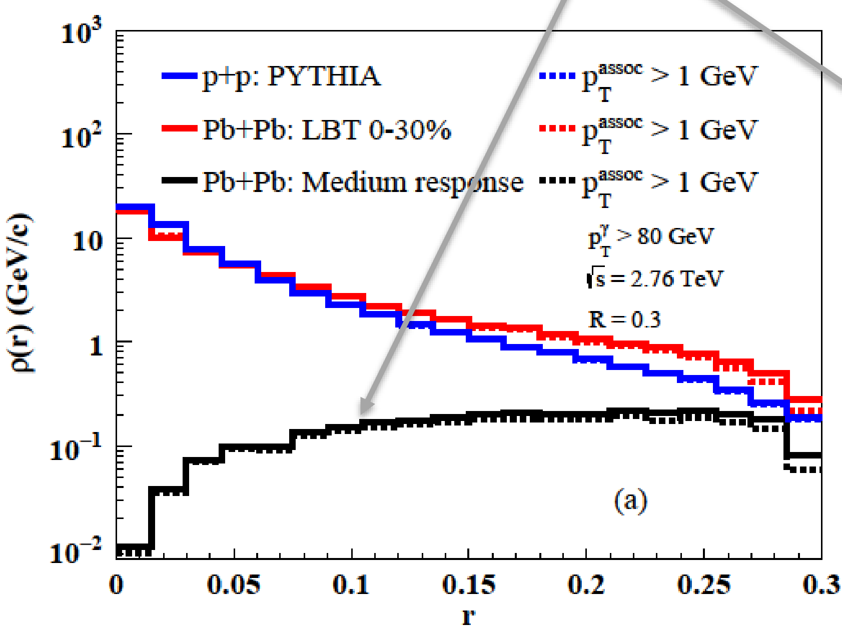
Jet shape

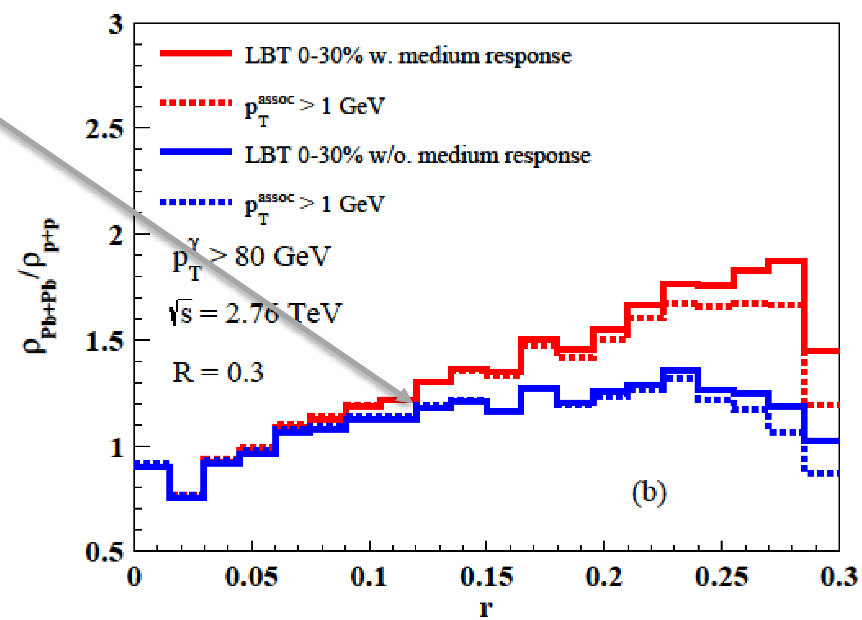
$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N_{jet}}\sum_{jets}\frac{p_t(r-\frac{\Delta r}{2}, r+\frac{\Delta r}{2})}{p_t(0,R)}$$





Medium response

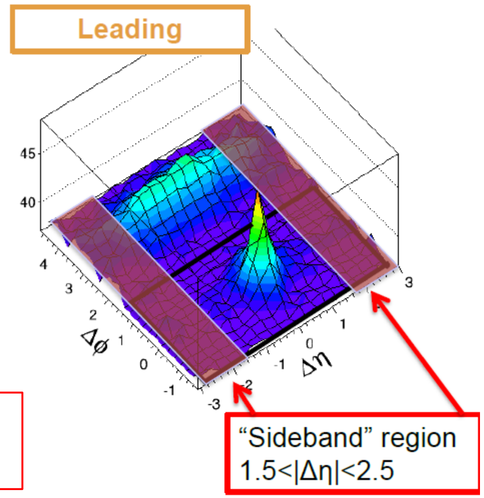


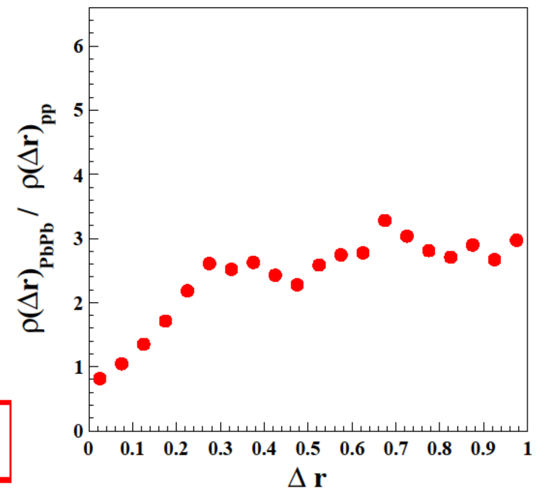


Luo, Cao, He & XNW, arXiv:1803.06785

Jet shape of gamma-jet in heavy-ion collisions

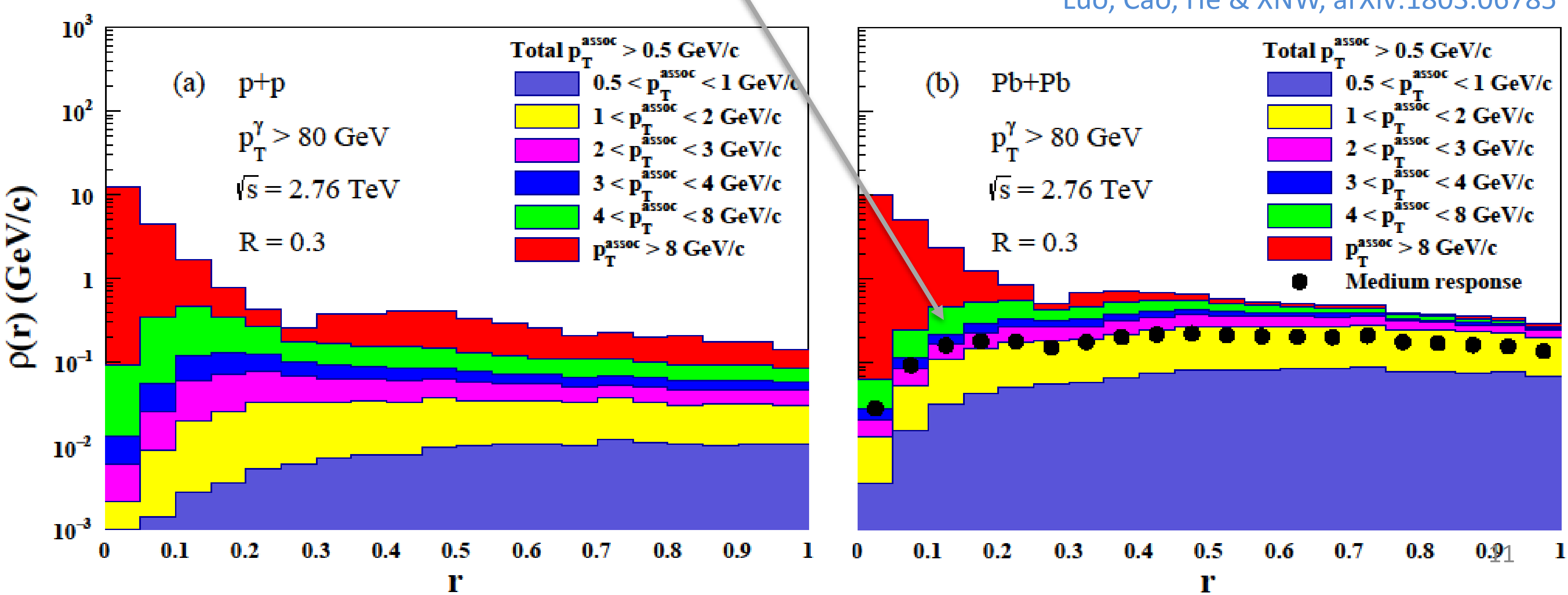
- Energy lost by the hard parton is transport out of the jet cone by the soft parton.



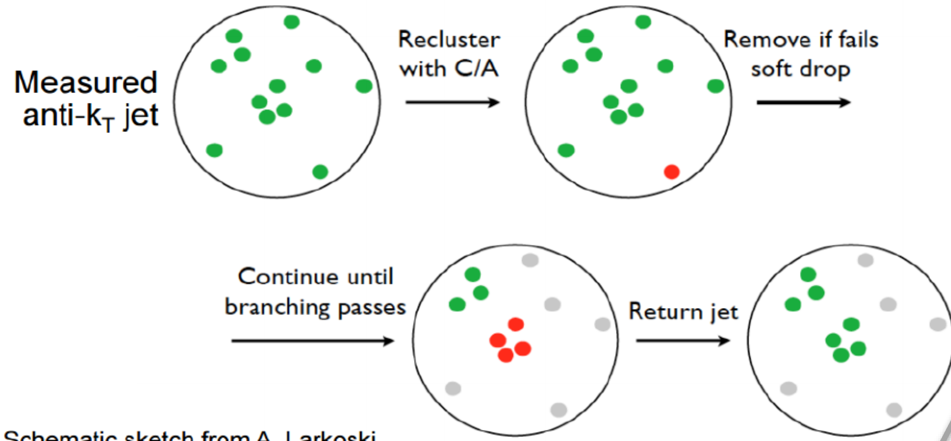


Medium response

Luo, Cao, He & XNW, arXiv:1803.06785



Jet substructure (jet grooming)

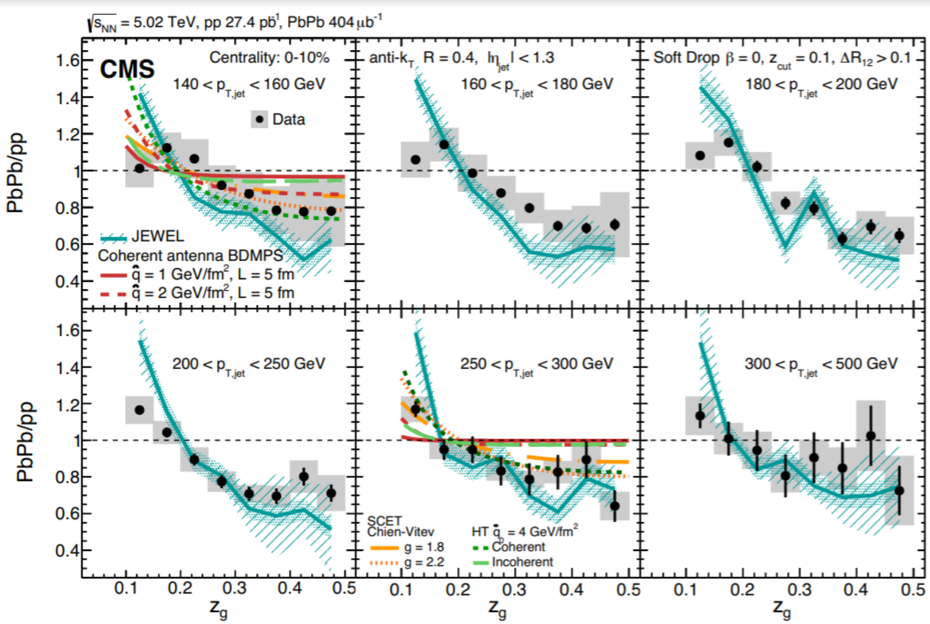


Schematic sketch from A. Larkoski
LPC Workshop JetMET Jan. 2014

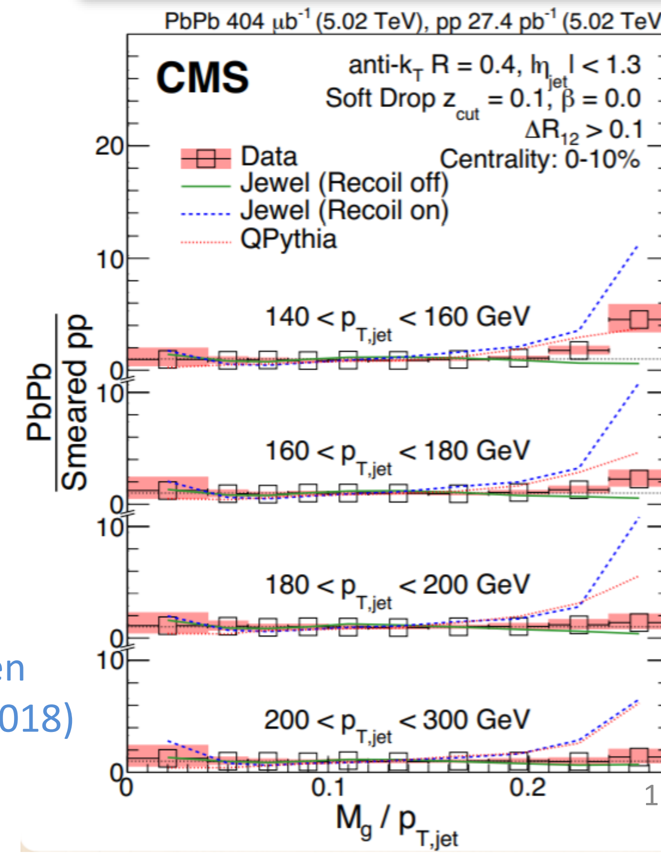
$$z_g \equiv \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut} \left(\frac{\Delta R}{R_0}\right)^{\beta}$$

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

Groomed Jet splitting function



Groomed jet mass



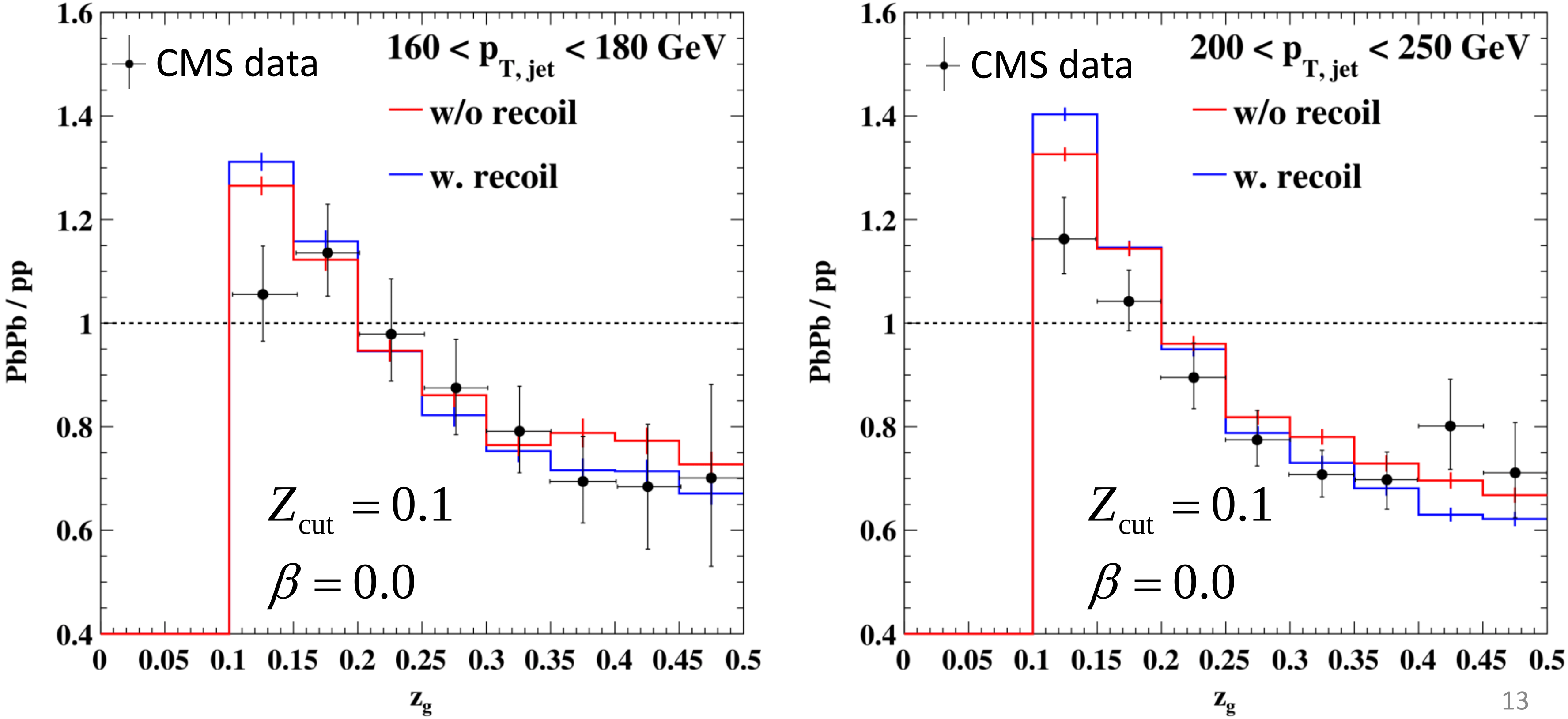
Yi Chen (QM2018)

Groomed jet splitting function

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

preliminary

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$

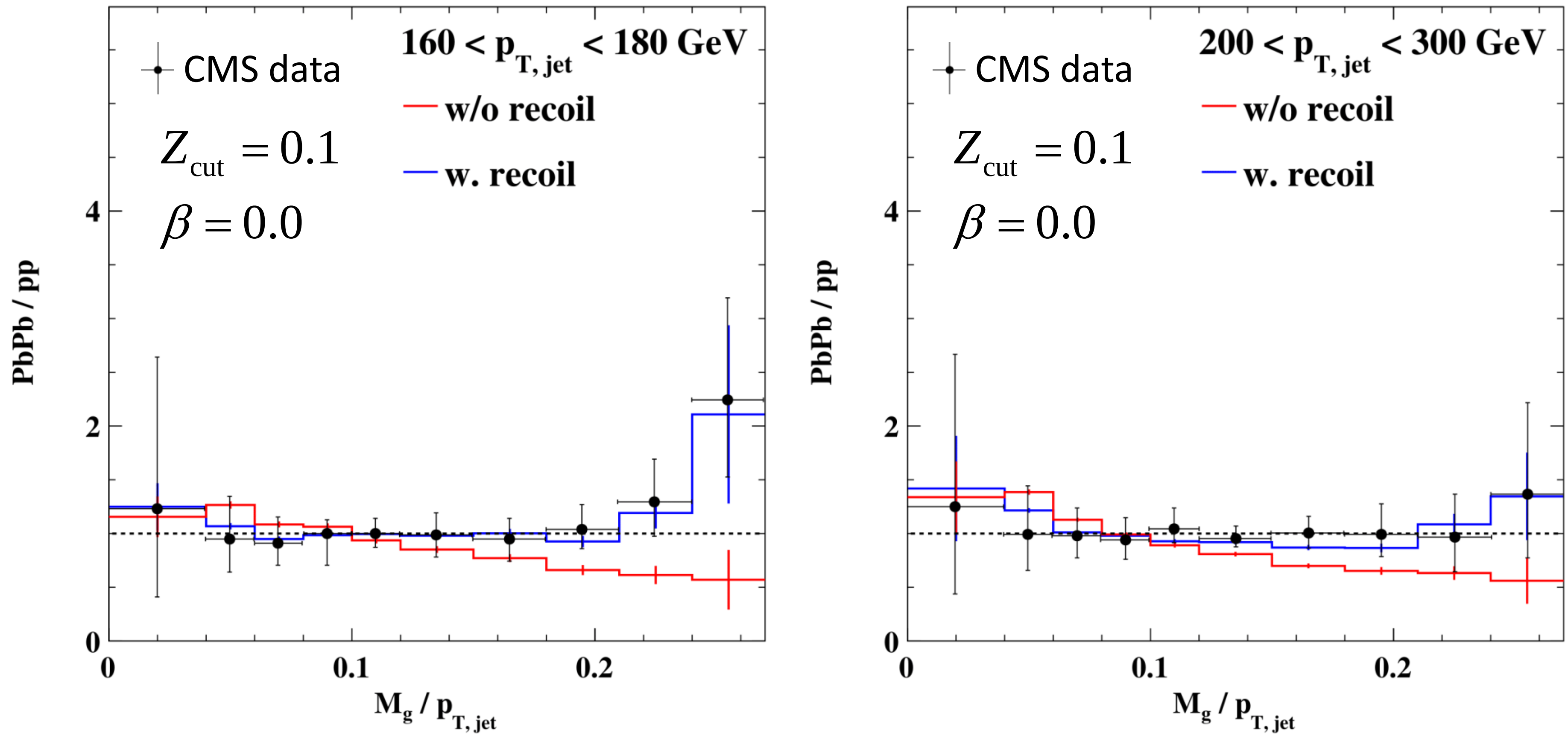


Groomed jet mass

- The inclusion of recoiled partons will lead to the enhancement of the large groomed mass tail.

preliminary

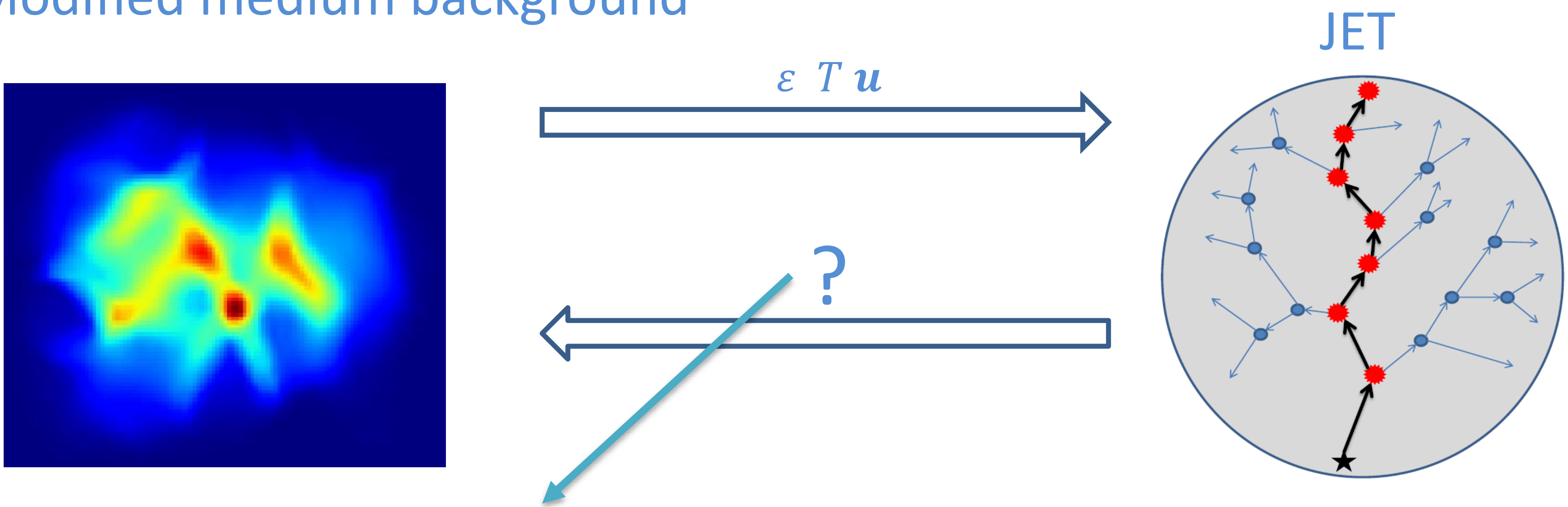
$$\frac{M_g}{p_T^{jet}} = \frac{\sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}}{p_T^{jet}}$$



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



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

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

CoLBT-hydro

(A coupled LBT Hydro (3+1D) Model)

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 find it is crucial to include medium response to describe the modification of jet structure in heavy ion collisions.

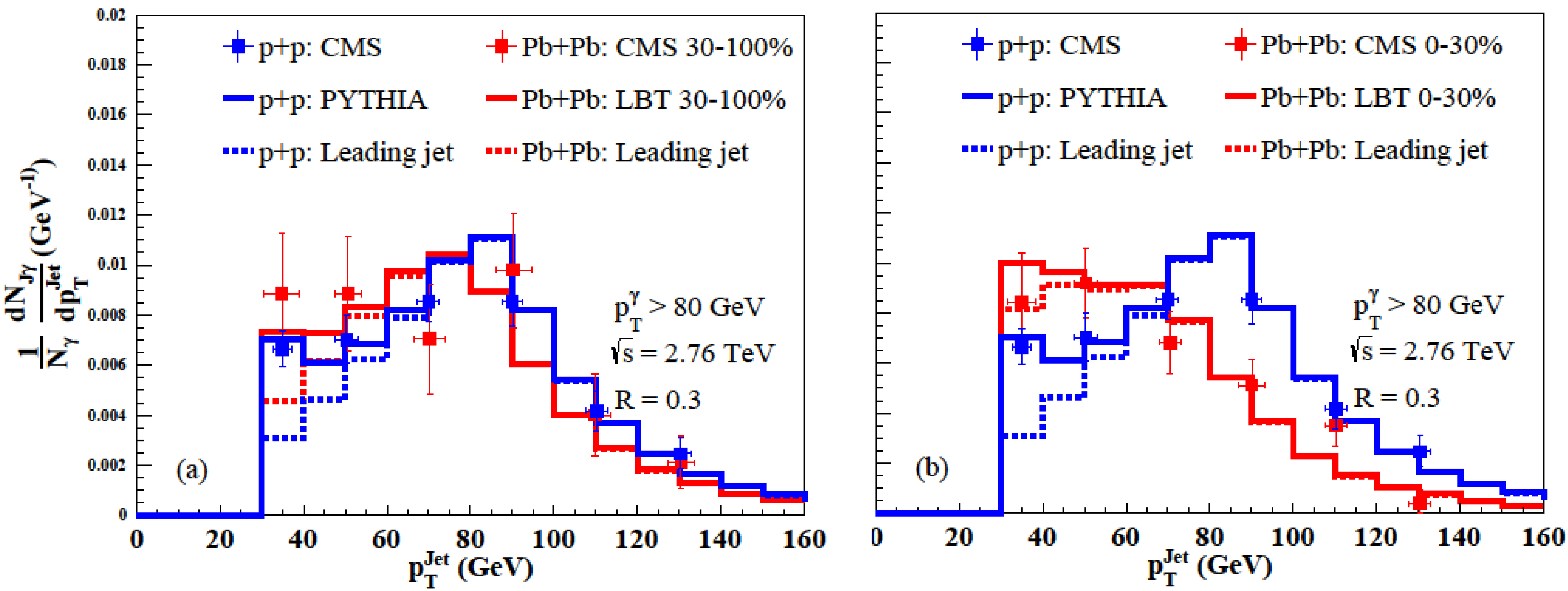
Outlook

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

Thanks

pT distribution of gamma-jet in heavy-ion collisions

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

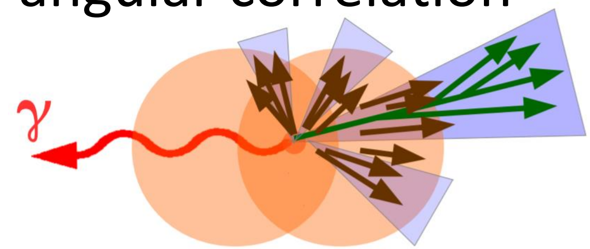


Luo, Cao, He & XNW, arXiv:1803.06785

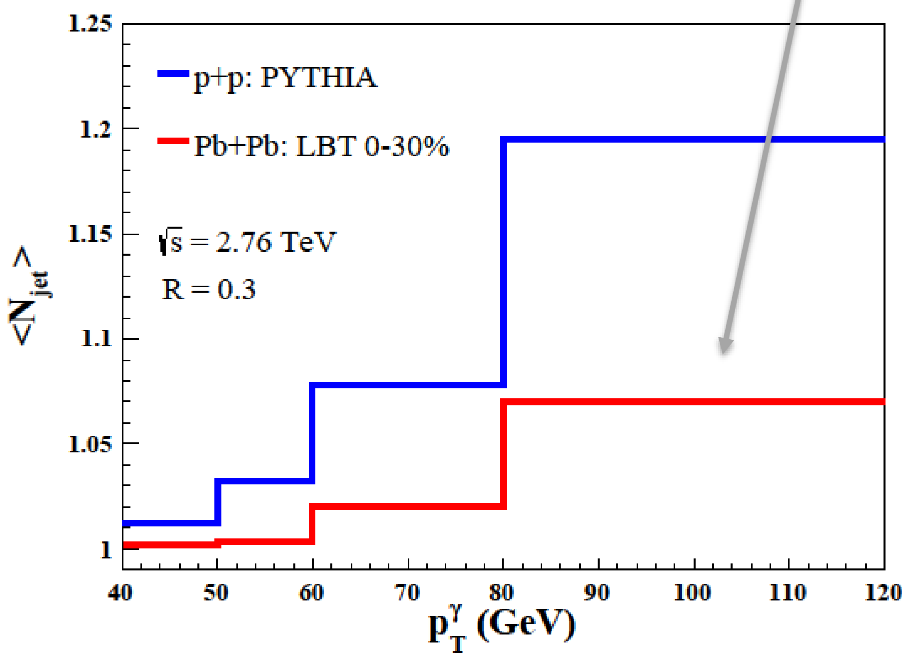
Azimuthal distribution of gamma-jet in heavy-ion collisions

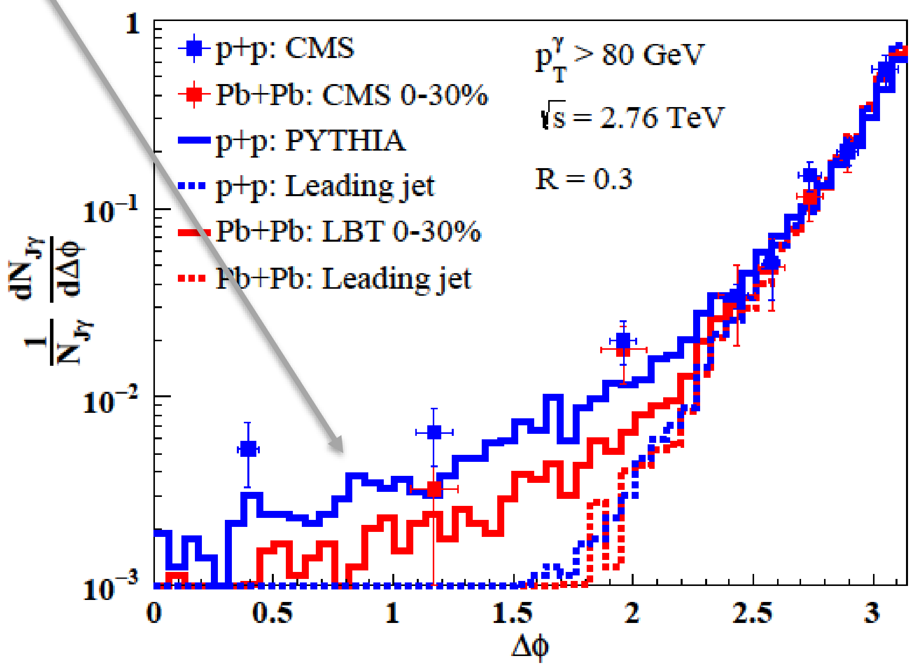
- Dominance of the initial state radiation in angular correlation

L Chen, GY Qin, SY Wei, BW Xiao, HZ Zhang **arXiv:1607.01932**
A. H. Mueller, B Wu, BW Xiao, F Yuan **arXiv:1604.04250**



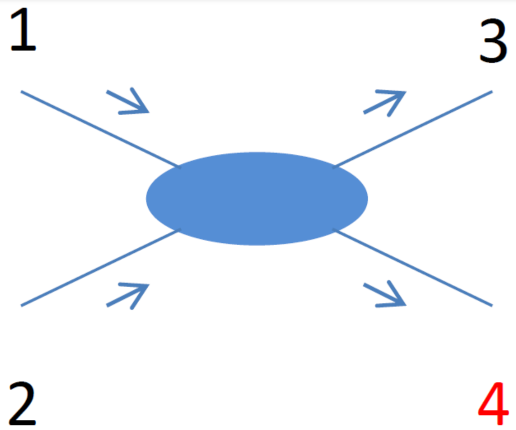
- Multiple jets in gamma-jets events





Luo, Cao, He & XNW, arXiv:1803.06785

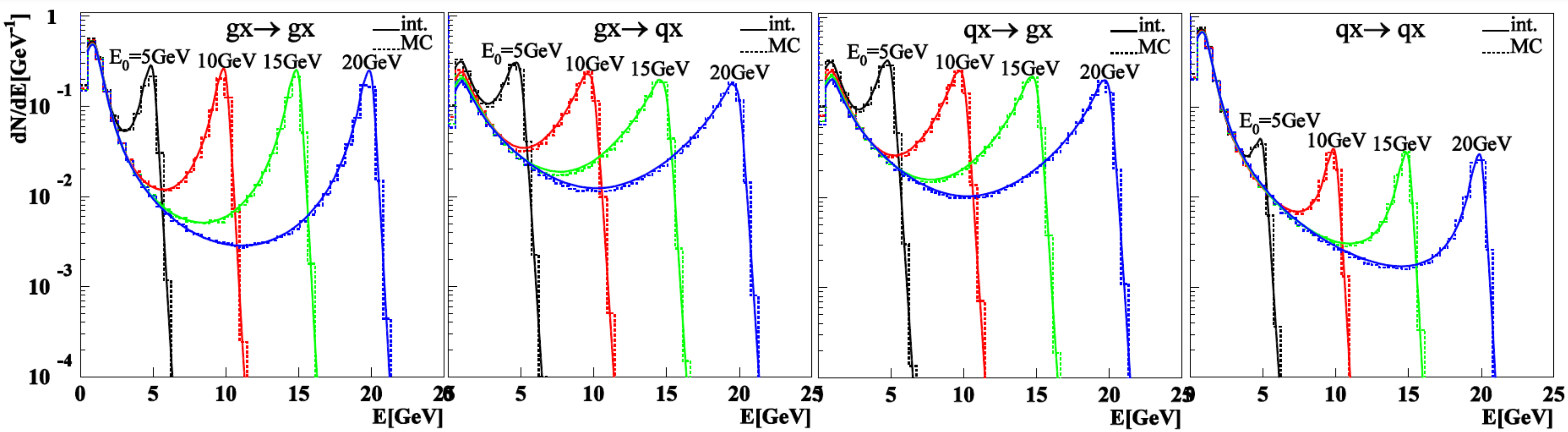
Energy distribution of the recoiled parton



Single scattering

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

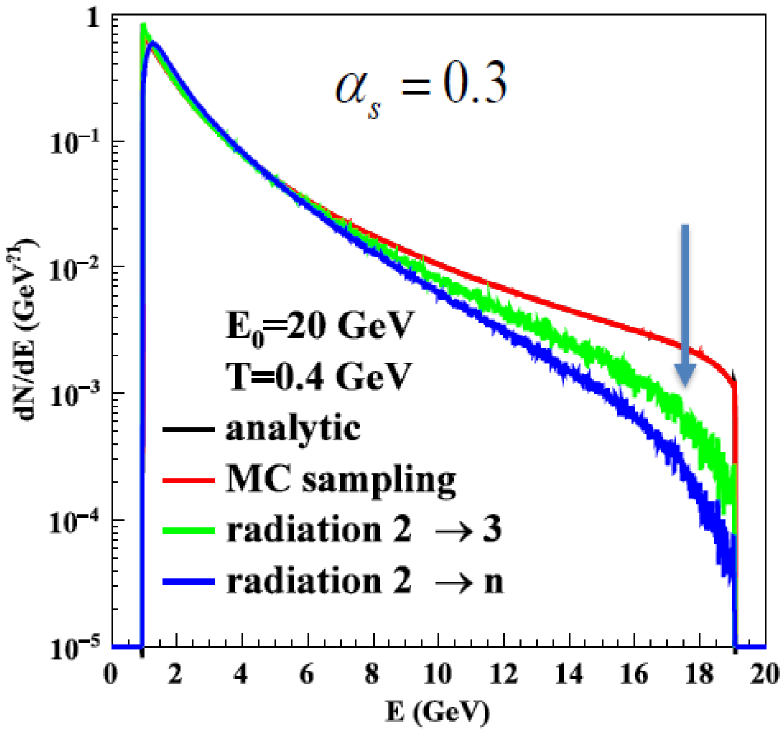
$$gg \to gg$$
$$gq \to gq + g\bar{q} \to g\bar{q}$$
$$gg \to q\bar{q}$$
$$q_i\bar{q}_i \to gg$$
$$q_i g \to q_i g$$
$$q_i\bar{q}_i \to q_j\bar{q}_j \qquad q_i q_j \to q_i q_j$$
$$q_i\bar{q}_i \to q_i\bar{q}_i \qquad q_i q_i \to q_i q_i$$

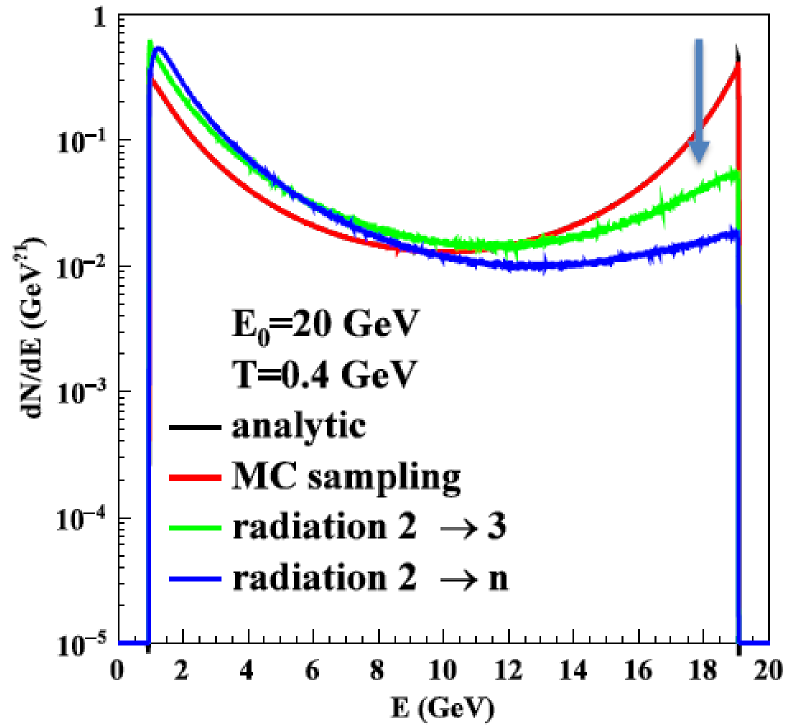


Y. He, T. Luo, X. N. Wang and Y. Zhu, PhysRevC.91.054908

Energy distribution of the radiated gluon

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





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

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

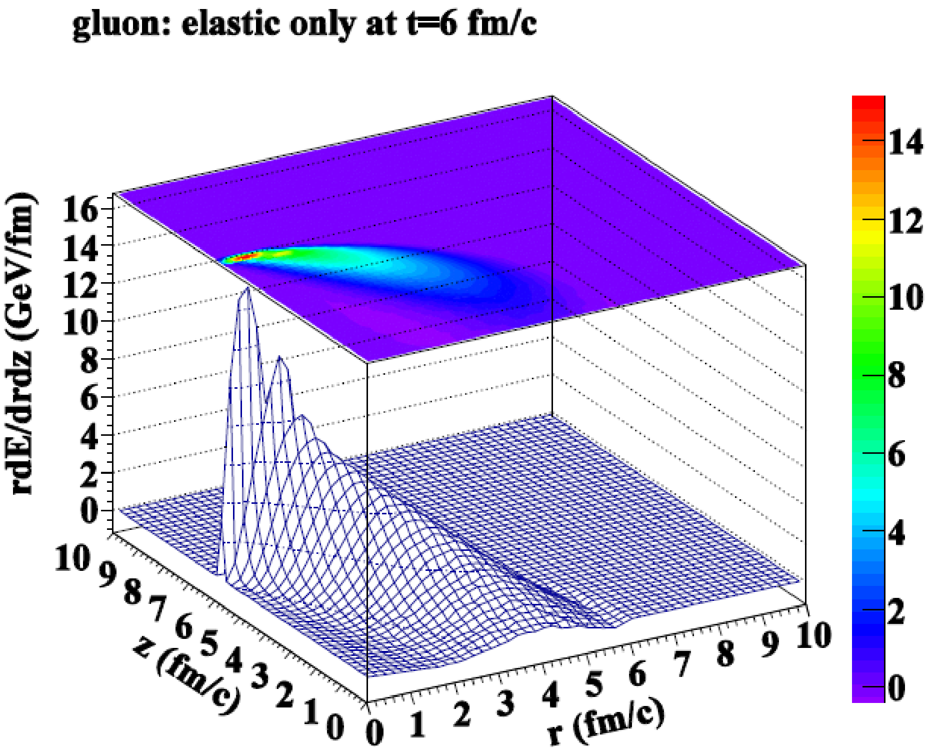
Luo, Cao, He & XNW in preparation

Jet induced medium excitation (Energy distribution in space)

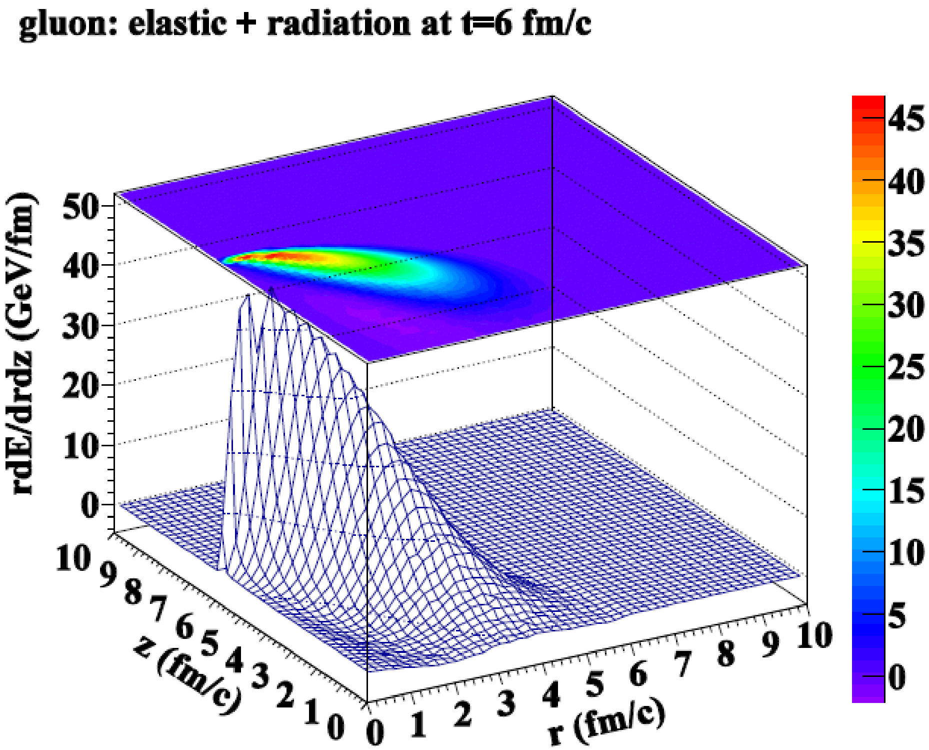
Initial jet parton: gluon
E = 100 GeV
T = 0.4 GeV $\alpha_s = 0.3$

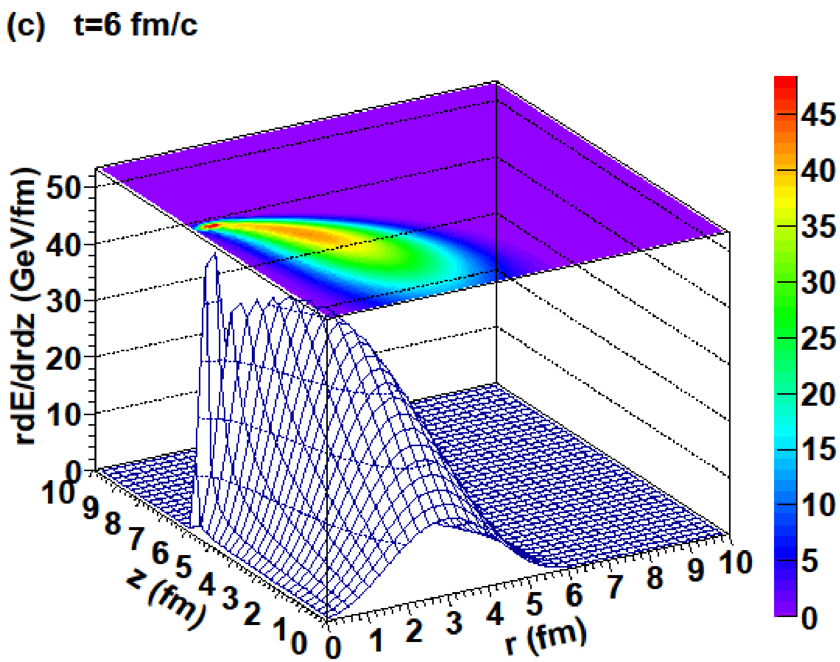
- Mach Cone like wave and the diffusion wake.

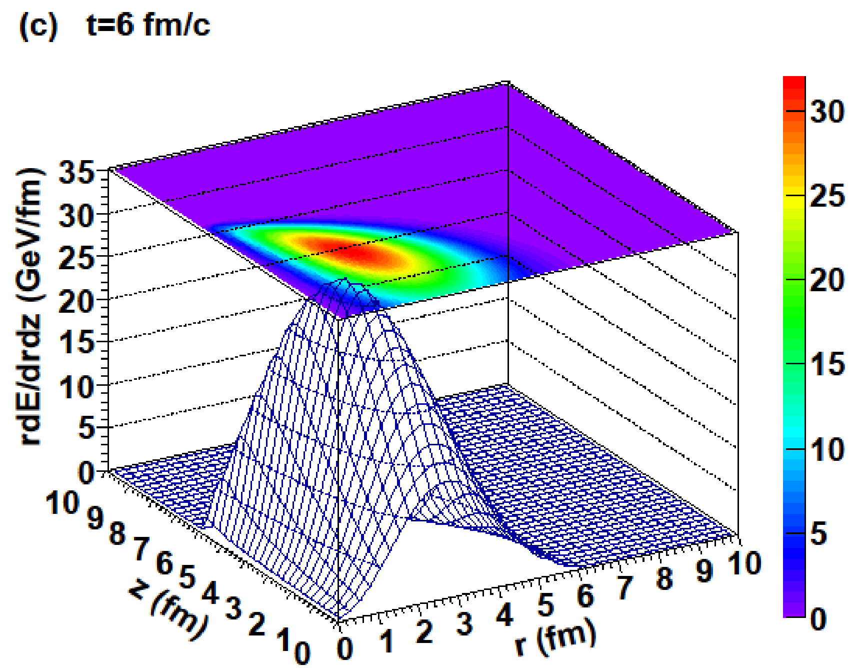
Elastic only



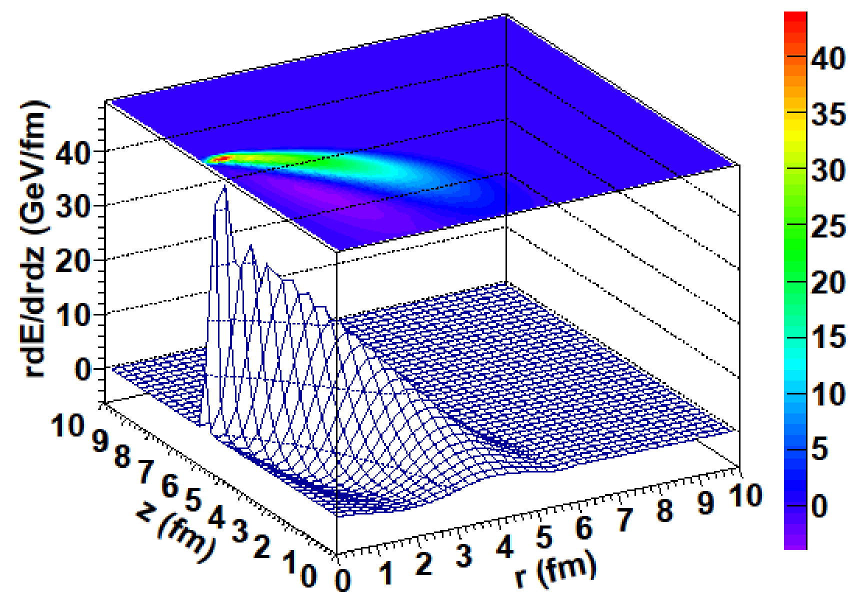
Elastic + Radiation





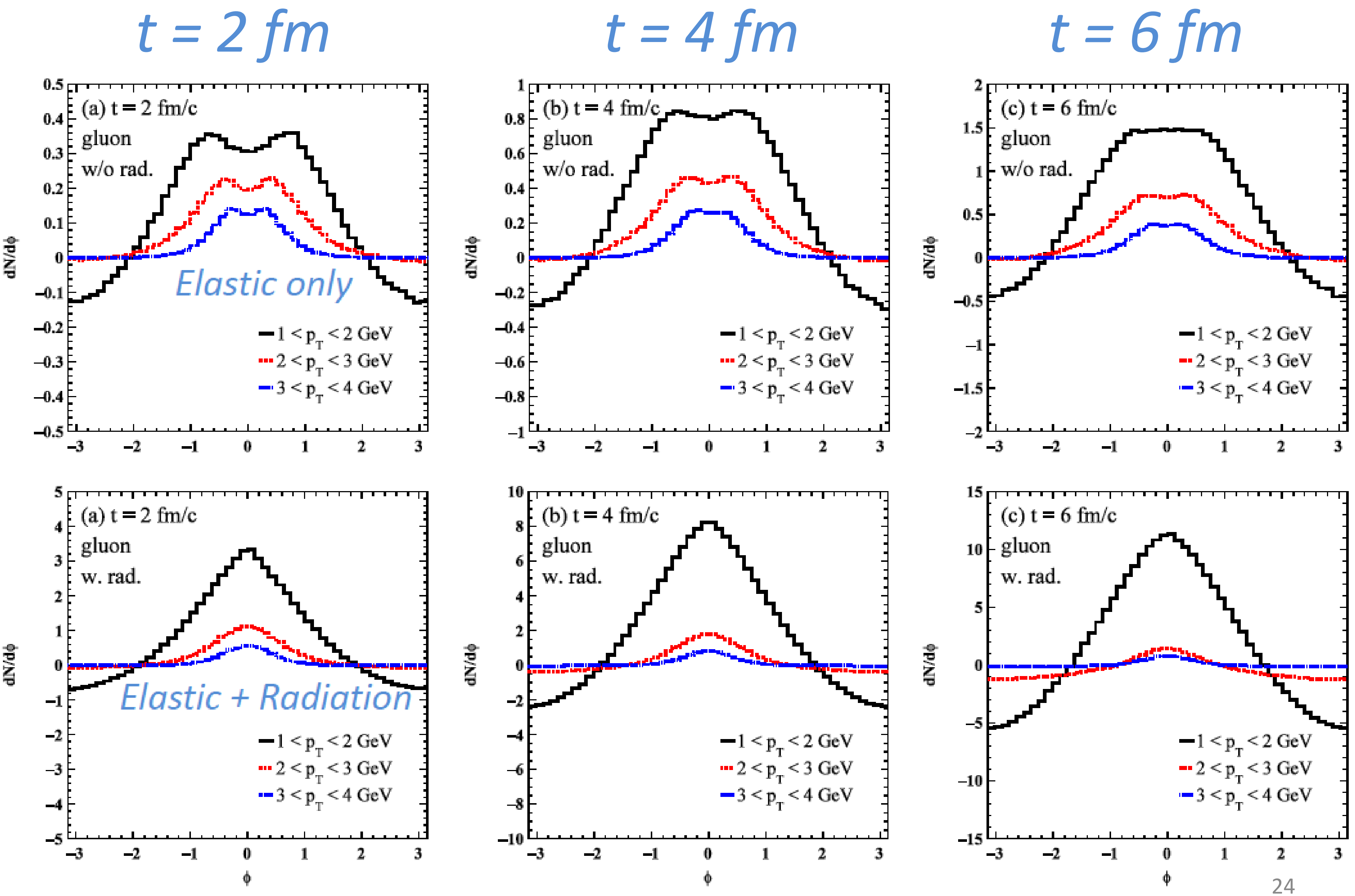


Positive
(recoiled parton
+ emitted gluon)



Negative
(initial thermal parton)

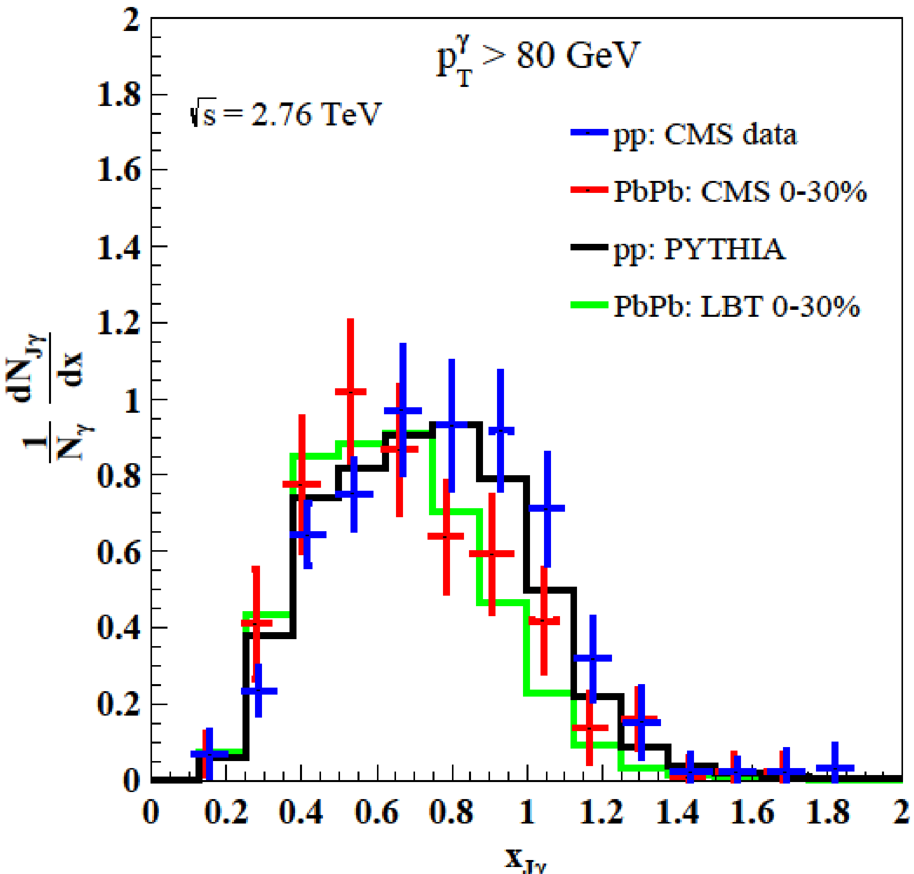
Jet induced medium excitation (Angular distribution)



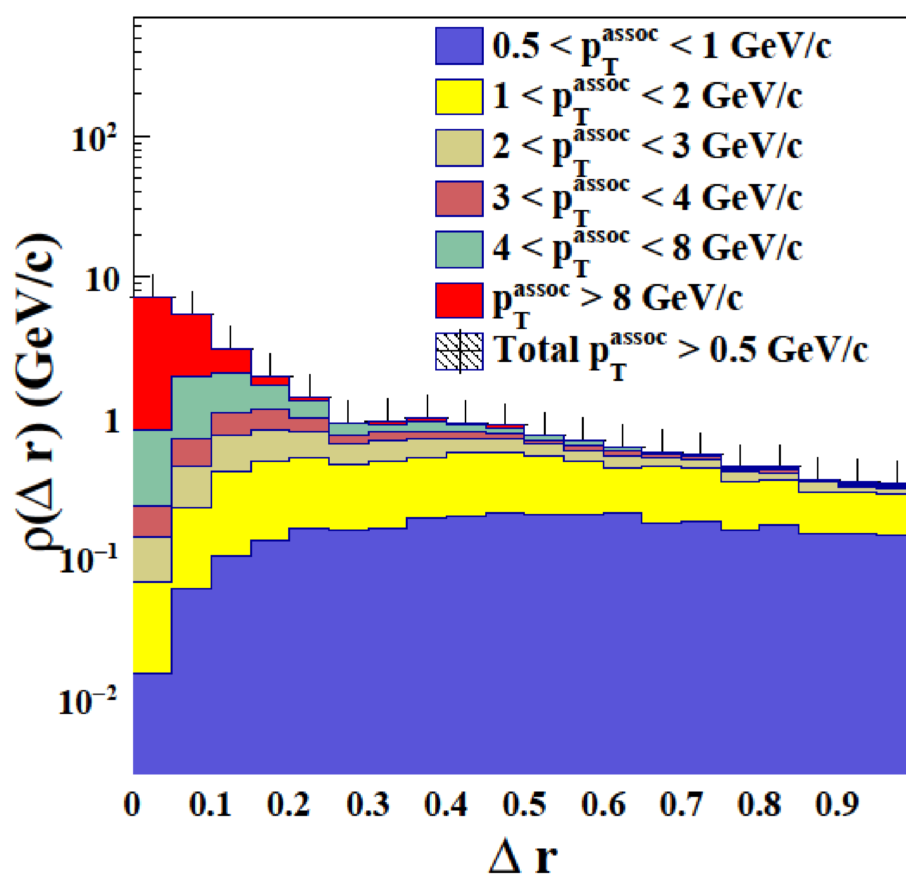
Jet reconstruction on hadron level with recombination model

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

Gamma-jet asymmetry

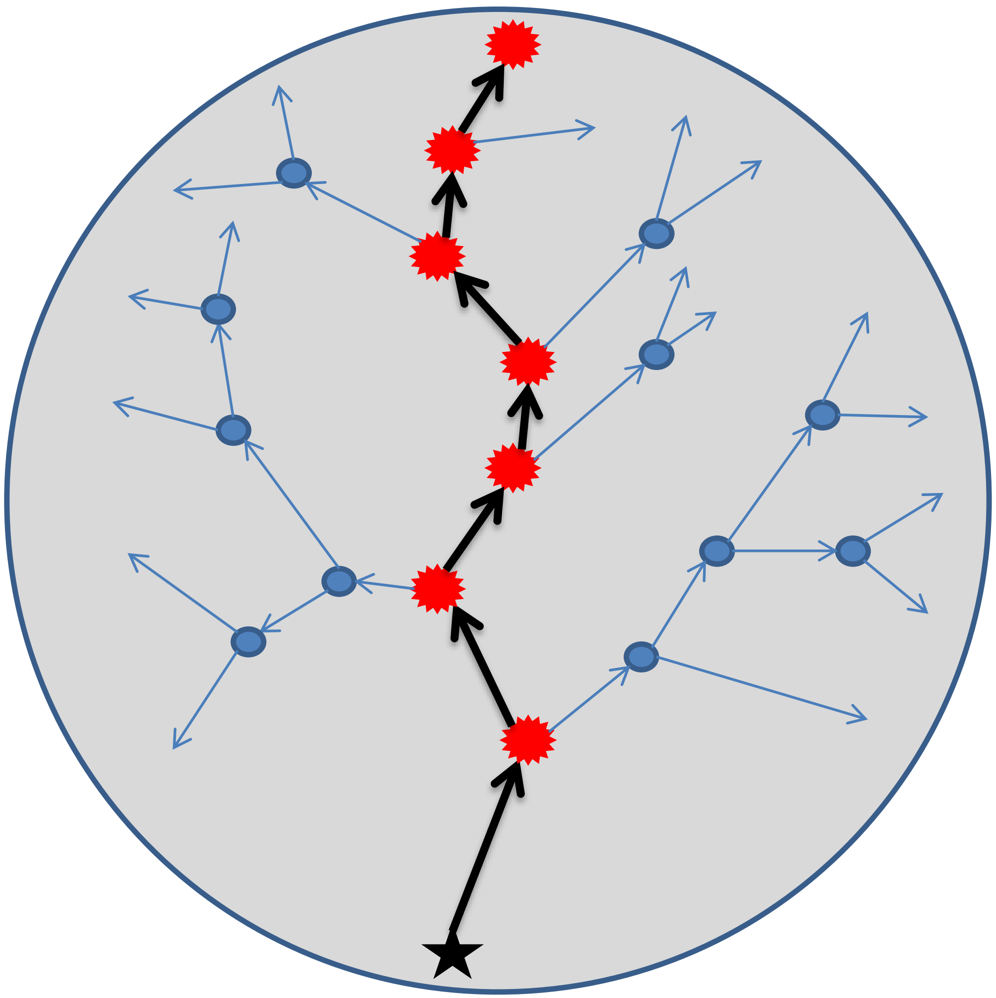


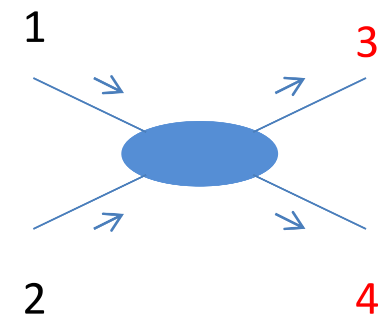
Jet shape



preliminary

Jet induced medium excitation: recoiled parton





Leading parton-----thermal parton scattering

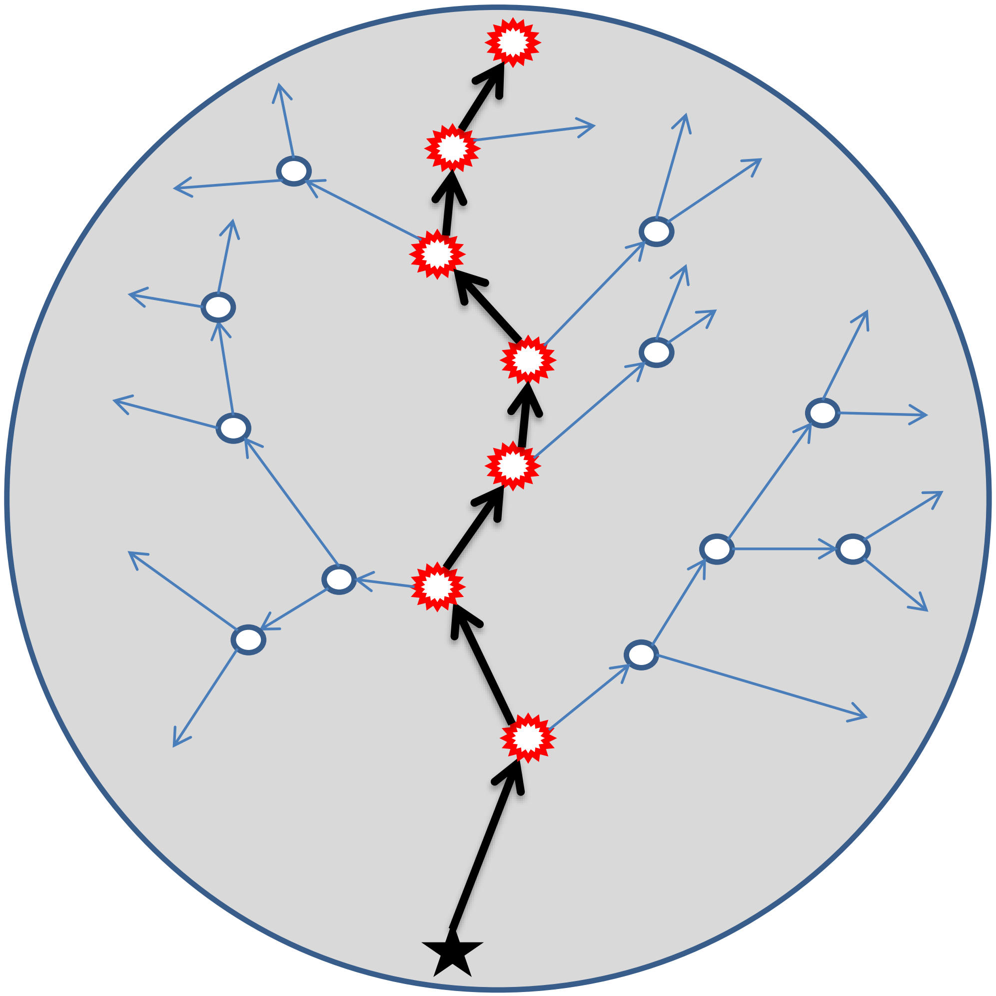
recoiled parton-----thermal parton scattering

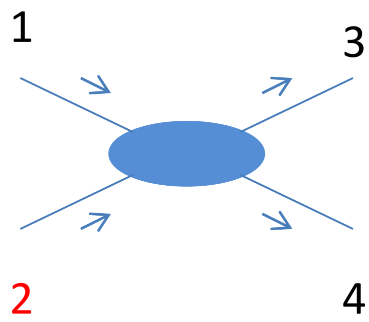
Linearized Boltzmann jet transport

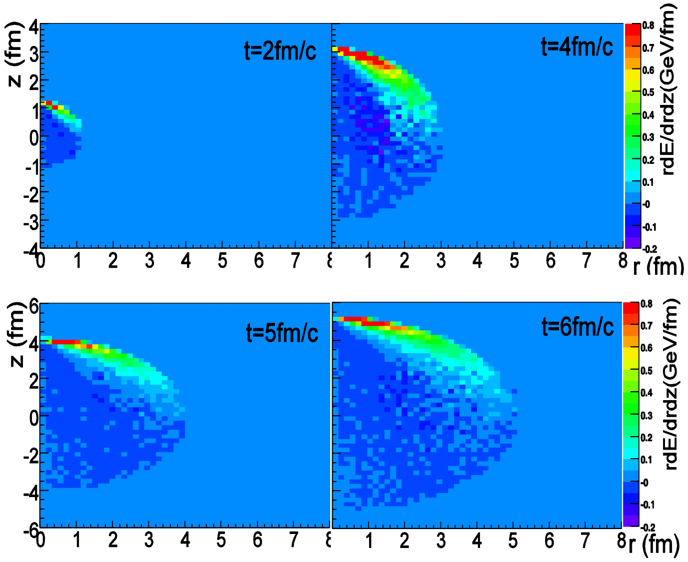
neglect scatterings between recoiled medium partons.

It's a good approximation when the jet induced medium excitation δf<<f.

Jet induced medium excitation: particle hole

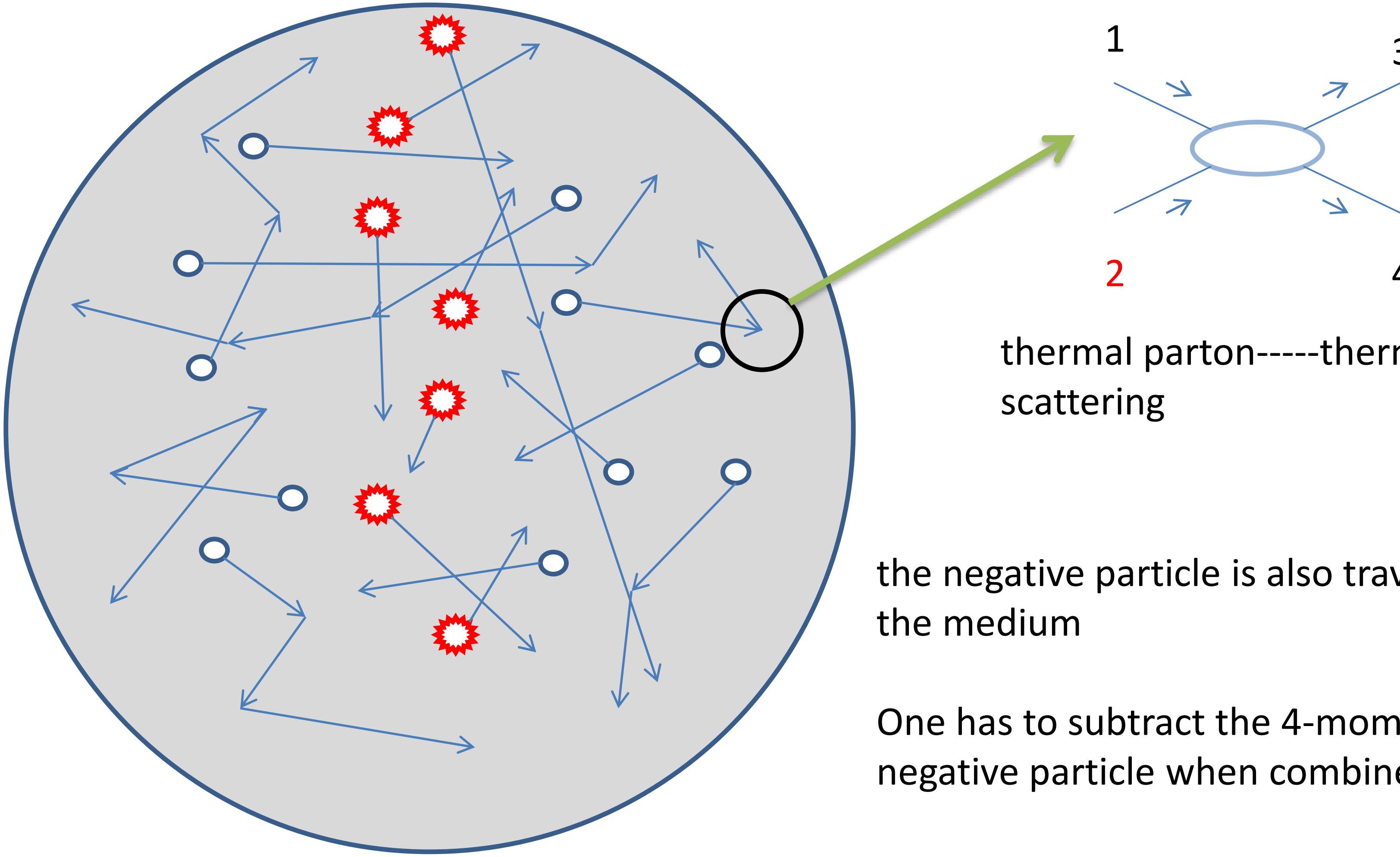






One has to subtract the 4-momentum of negative particle when combine it to jet

Jet induced medium excitation: back reaction



thermal parton-----thermal parton scattering

the negative particle is also traveling in the medium

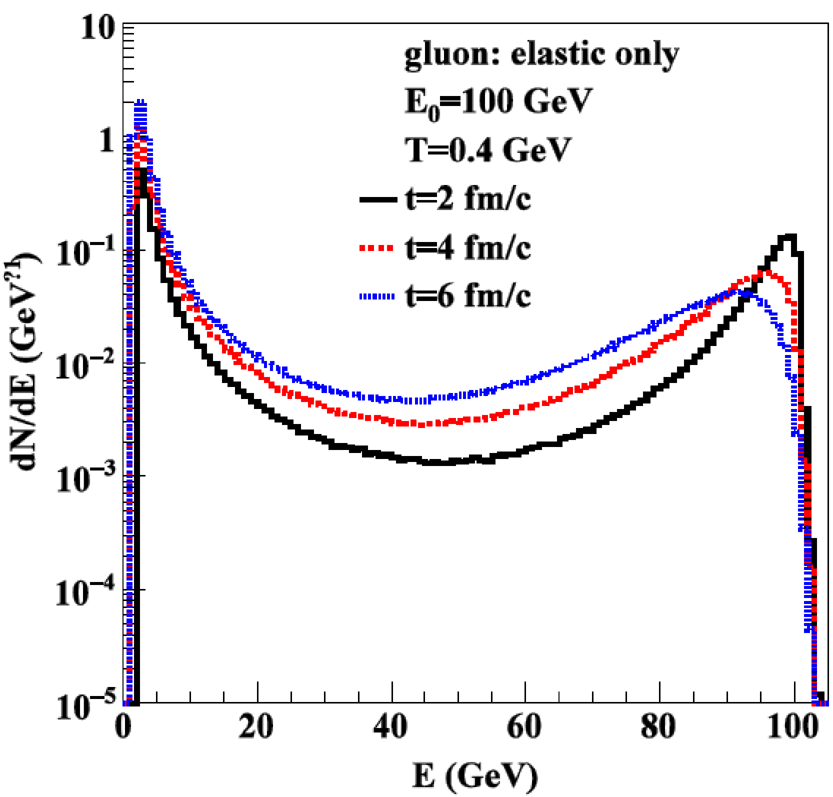
One has to subtract the 4-momentum of negative particle when combine it to jet

Jet induced medium excitation (Energy distribution at different time)

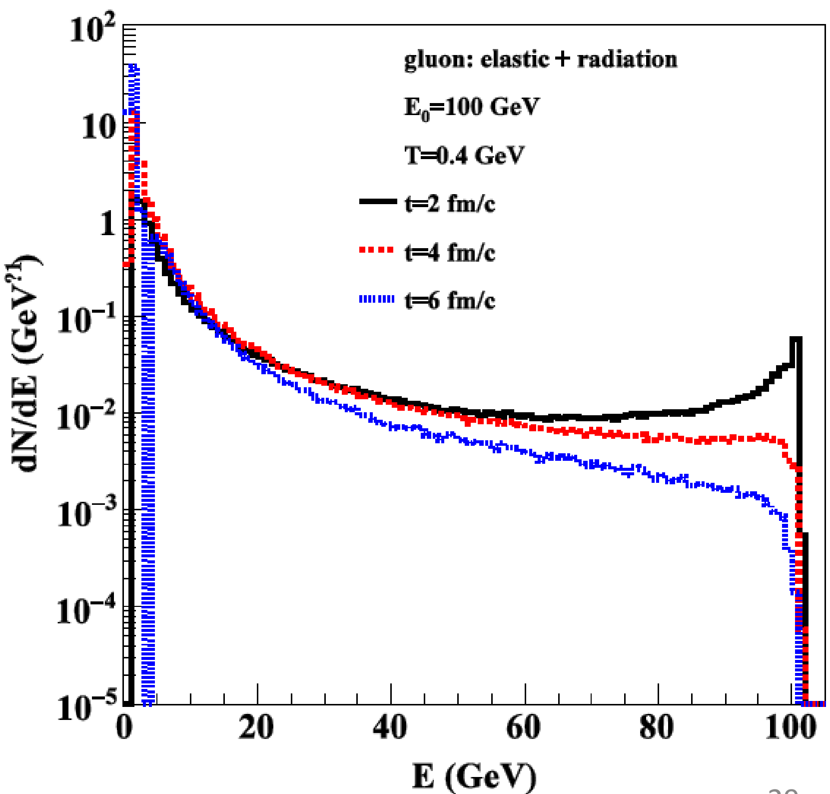
Initial jet parton: gluon
E = 100 GeV
T = 0.4 GeV $\alpha_s = 0.3$

- Depletion of the energy of the leading parton.

Elastic only



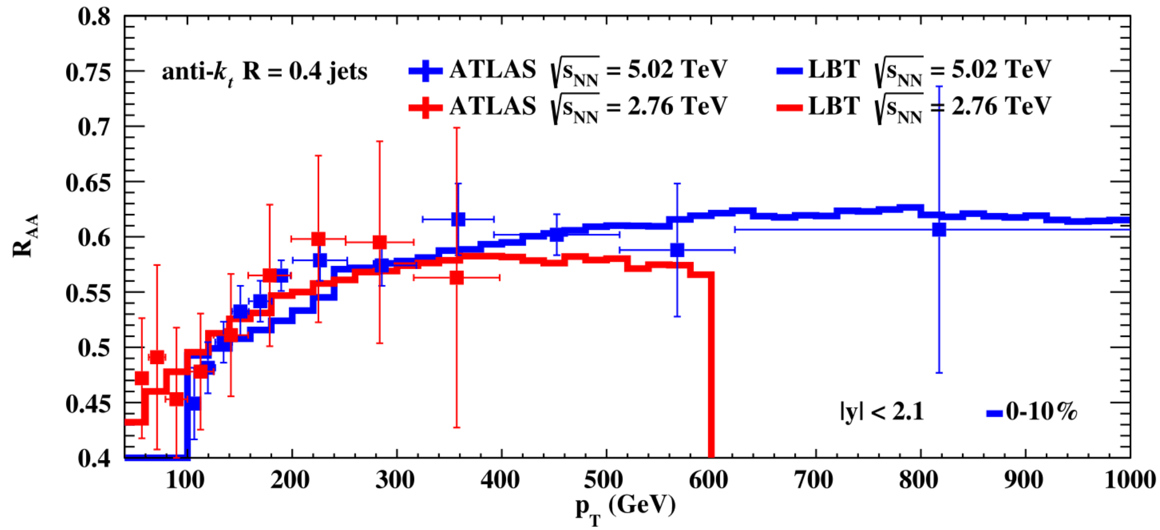
Elastic + Radiation



Jet energy loss

- Single jet R_{AA}

The only parameter effective strong coupling constant α_s is fixed. (fix the strength of jet-medium interaction)



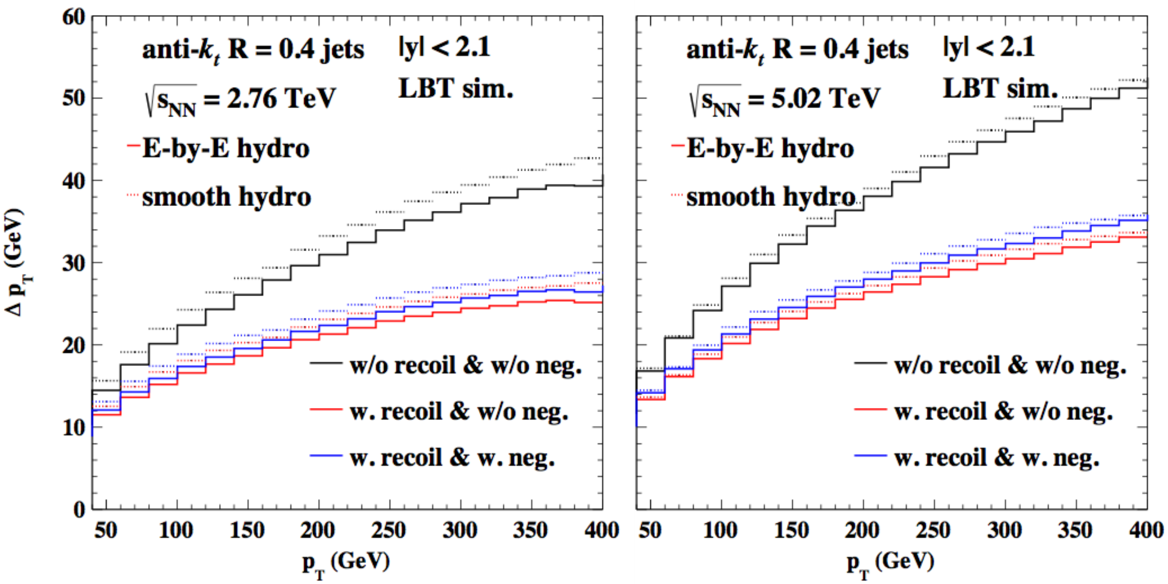
He, Cao, Luo & XNW to be published

- Fluctuation effect

  (solid vs dotted)
- Recoiled effect

  (black vs blue)
- Back reaction effect

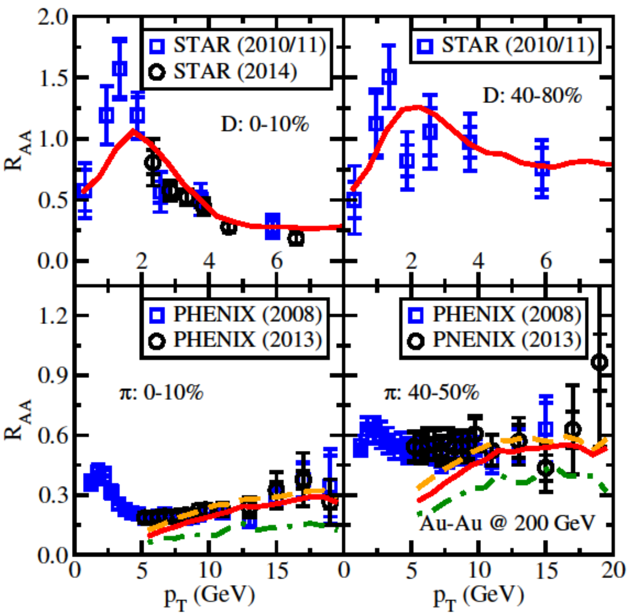
  (red vs blue)



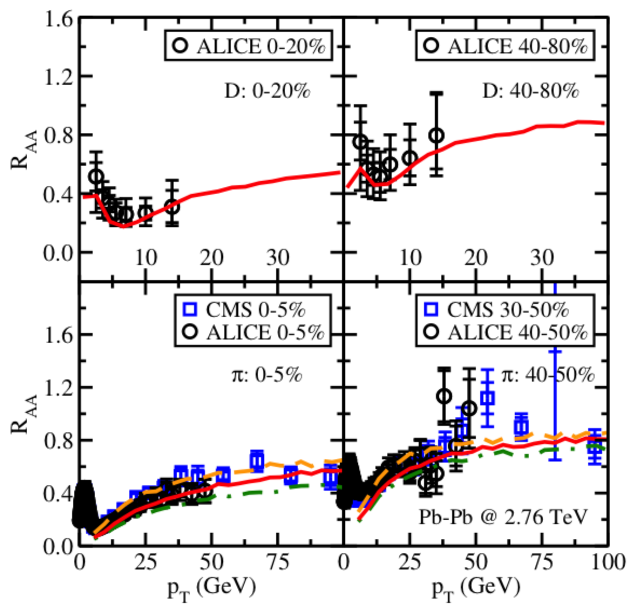
Hadron R_{AA} in heavy ion collision

- 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)

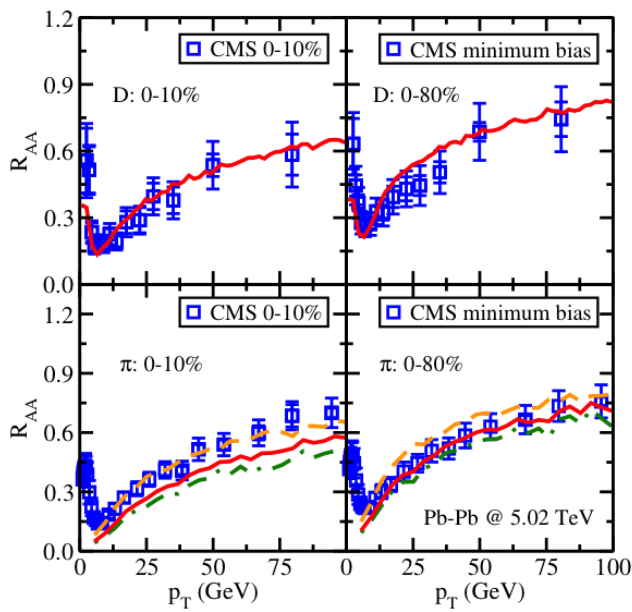
AuAu@200GeV



PbPb@2760GeV



PbPb@5020GeV

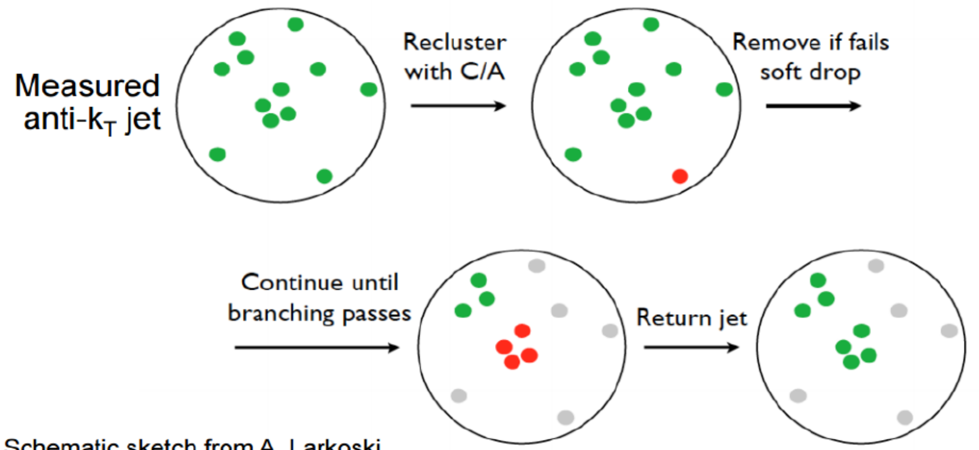


Jet substructure

Jet grooming

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

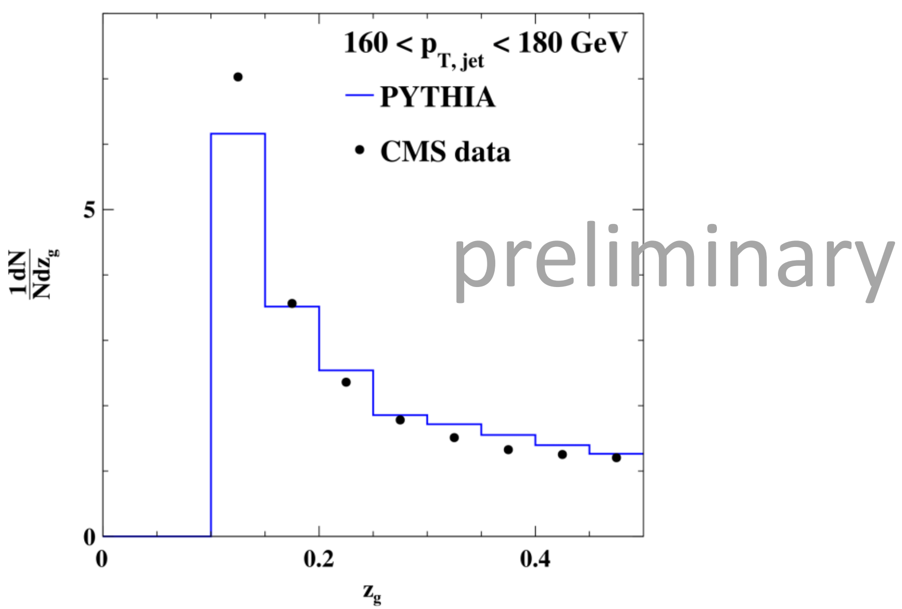
$$\frac{M_g}{p_T^{jet}} = \frac{\sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}}{p_T^{jet}}$$

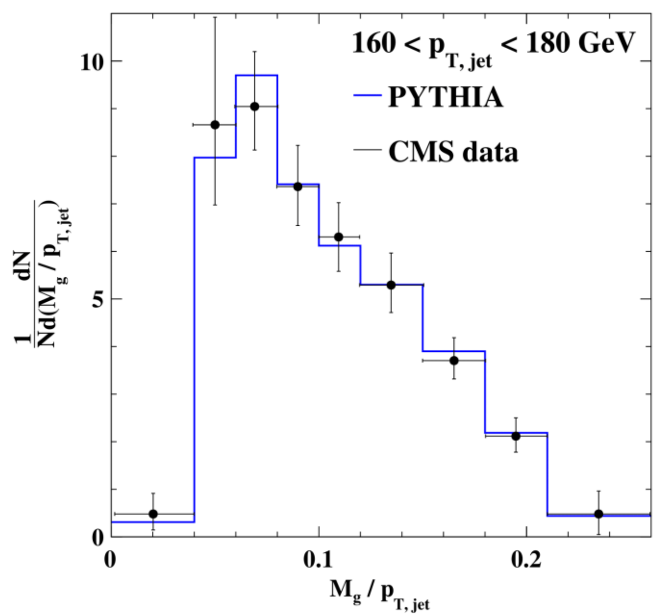


Schematic sketch from A. Larkoski
LPC Workshop JetMET Jan. 2014

Groomed Jet splitting function (pp)

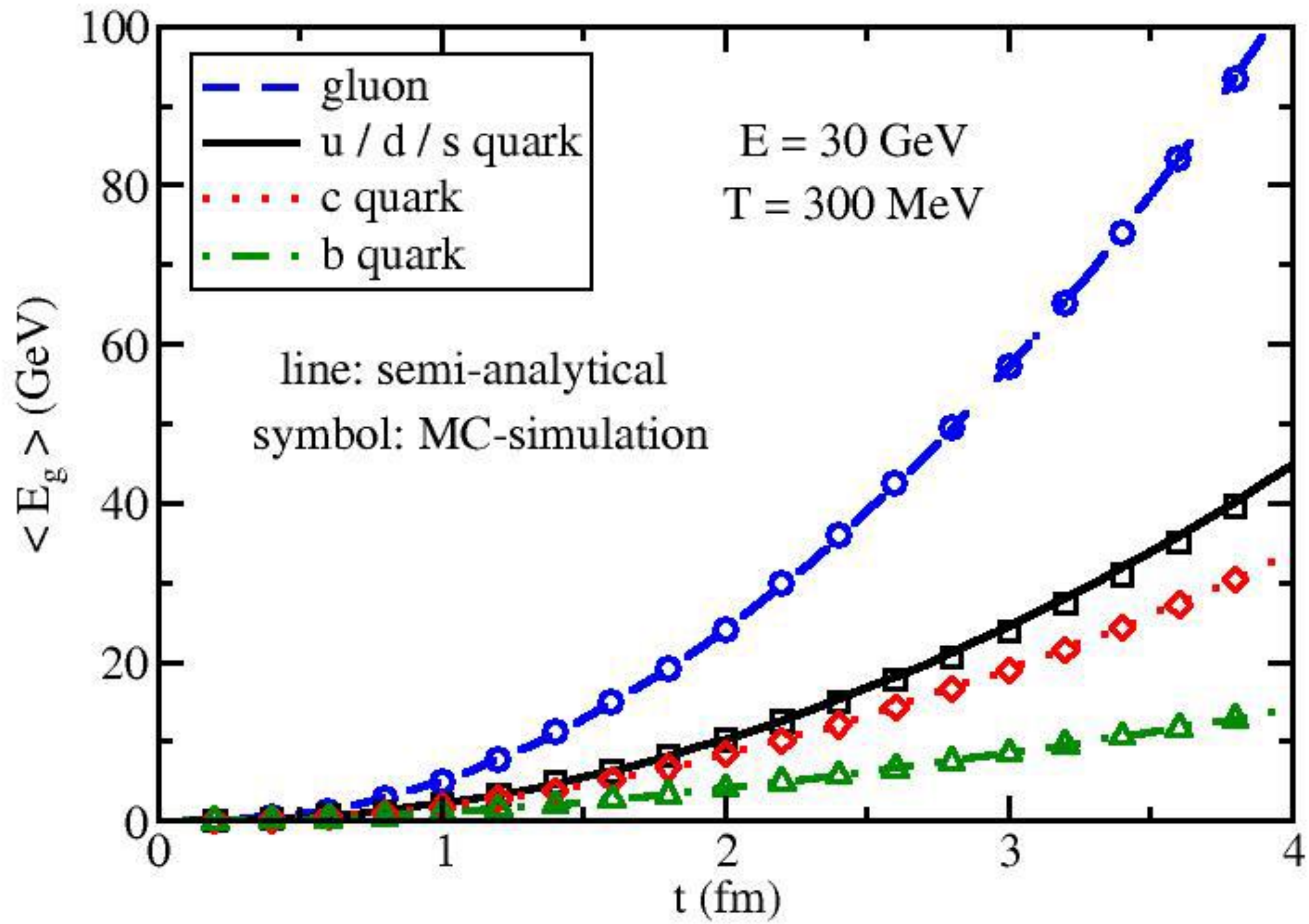
Groomed jet mass (pp)





Energy loss from radiation process in an uniform medium

- Energy of the leading parton is recovered at each time step in MC to compare with the semi-analytical calculation. (a crosscheck of the MC implementation in LBT)



S. Cao, T. Luo, G. Y. Qin and X. N. Wang, Phys. Rev. C 94, no. 1, 014909 (2016).

Gamma-jets in a 3+1D hydro

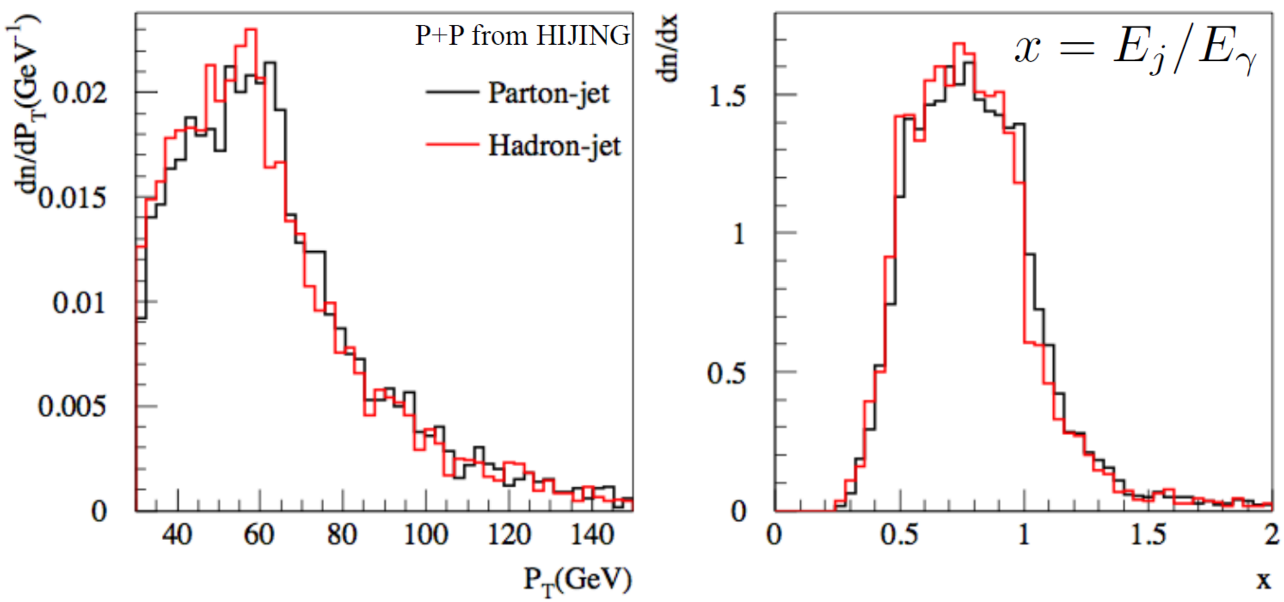
- 3+1D Ideal hydro Longgang Pang, Qun Wang, Xin-Nian Wang Phys.Rev. C86 (2012) 024911

$$(\tau, x, y, \eta)$$

LBT $\varepsilon, T, f_{QGP}, u$

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

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



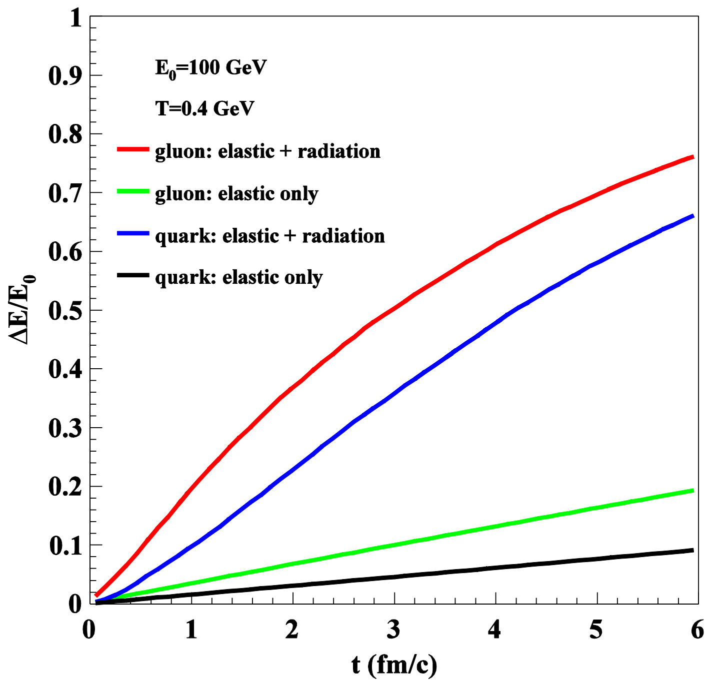
Nontrivial path length dependence on parton energy loss

Leading parton energy loss

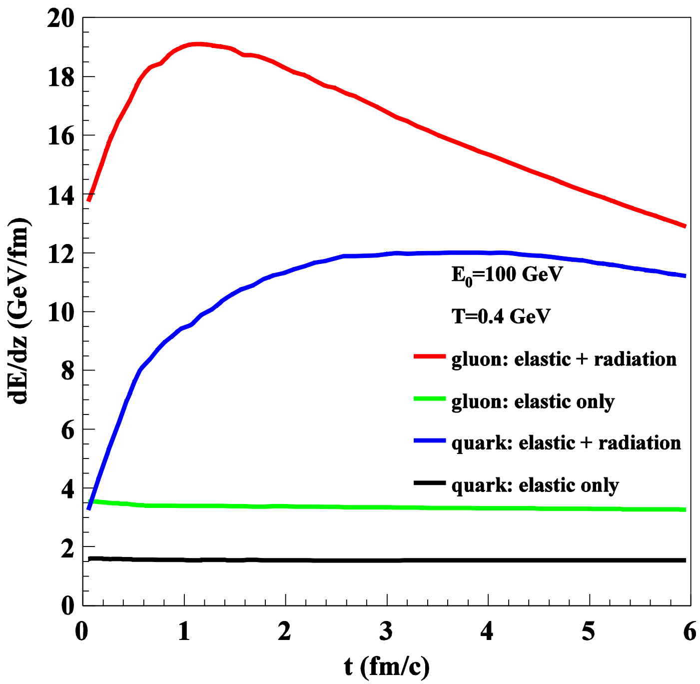
Propagation of a single initial jet parton in a uniform medium

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

Fractional energy loss



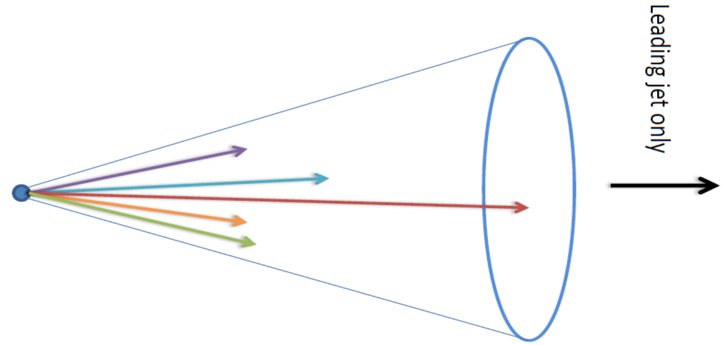
Energy loss per unit length



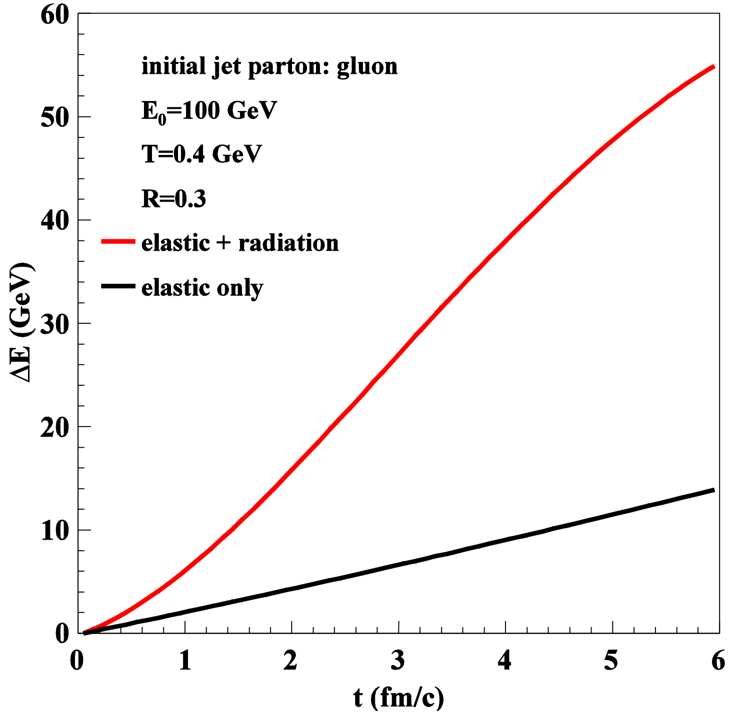
Path length dependence on parton energy loss

Leading jet energy loss

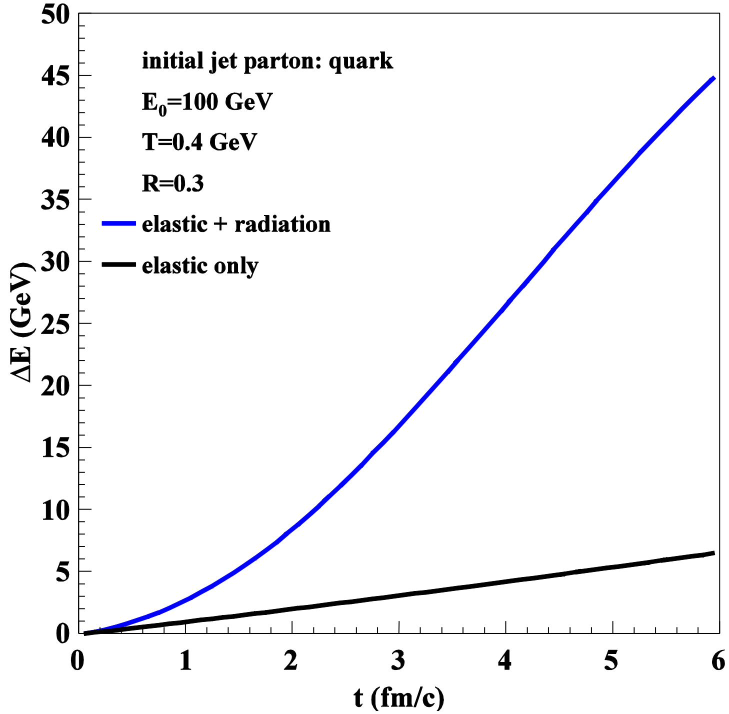
- Leading jet recover some of the energy lost by the leading parton.



Initial jet parton: gluon



Initial jet parton: quark



Jet shape of leading jet in heavy-ion collisions

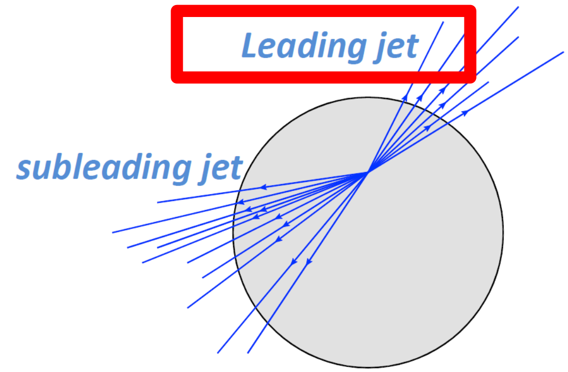
preliminary

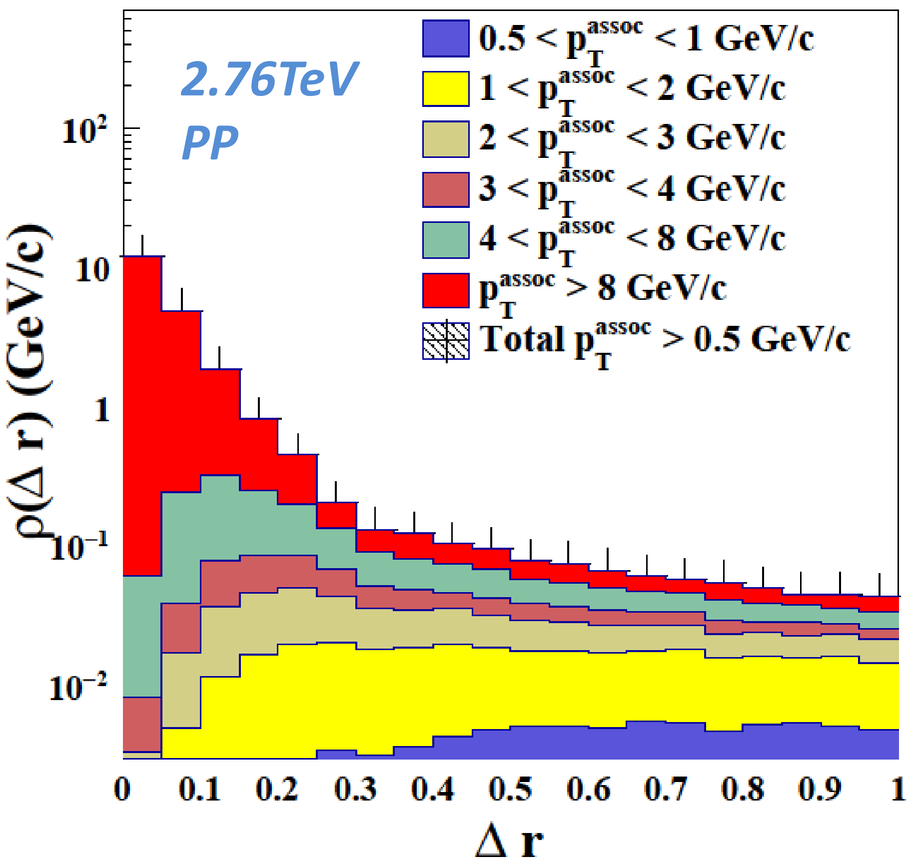
$P_{T leadingjet} > 120 GeV$

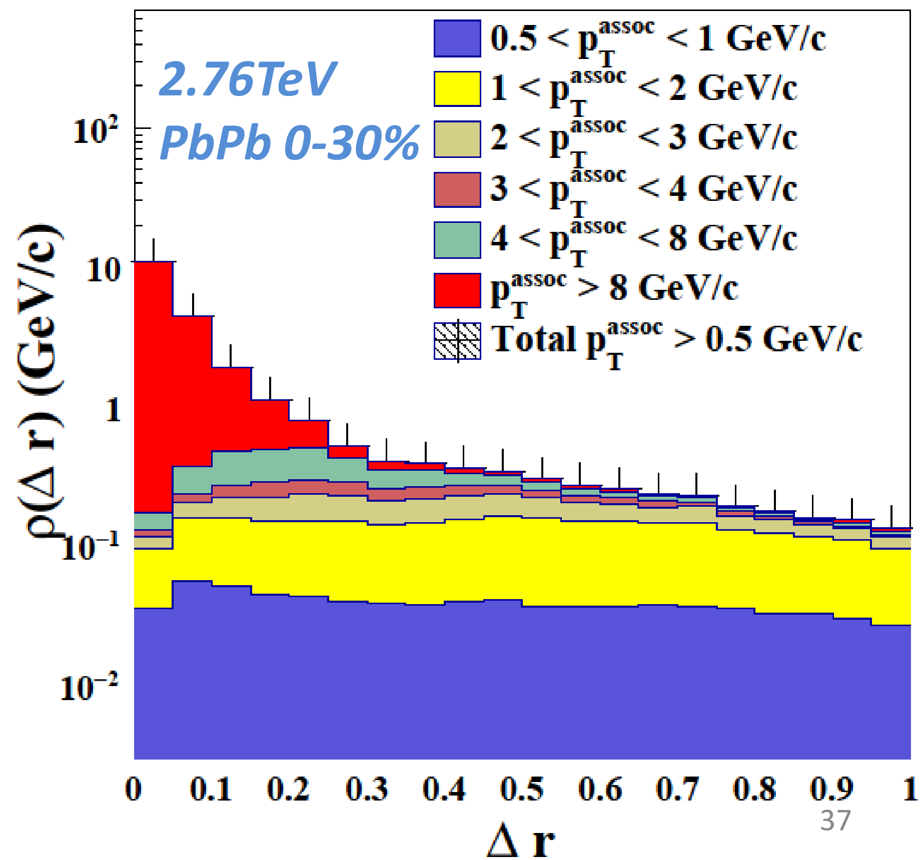
$P_{T subleadingjet} > 50 GeV$

$|\eta_{jet}| < 1.6$

$\Delta_{\phi} > 5/6\pi$







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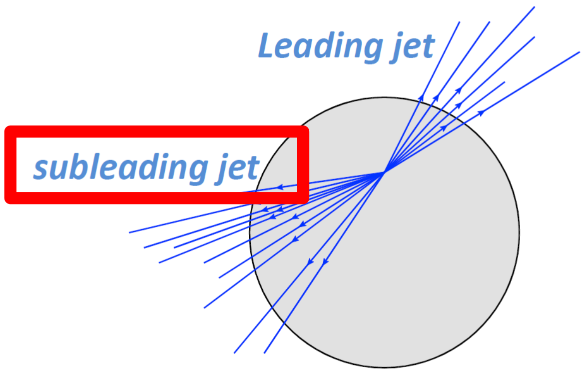
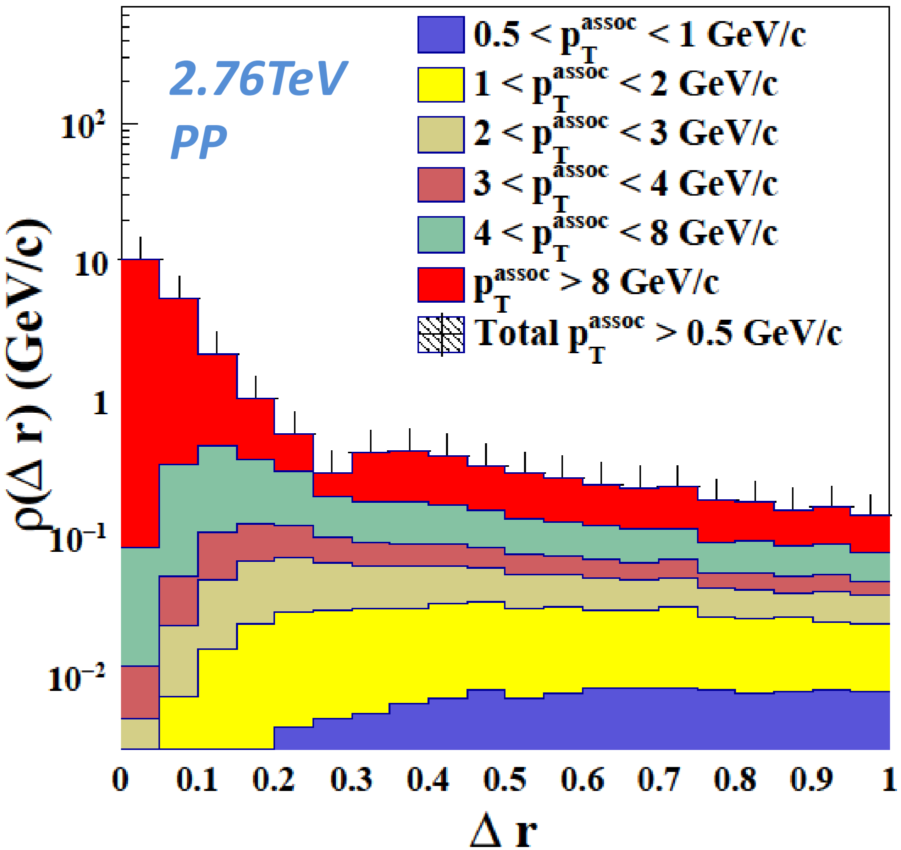
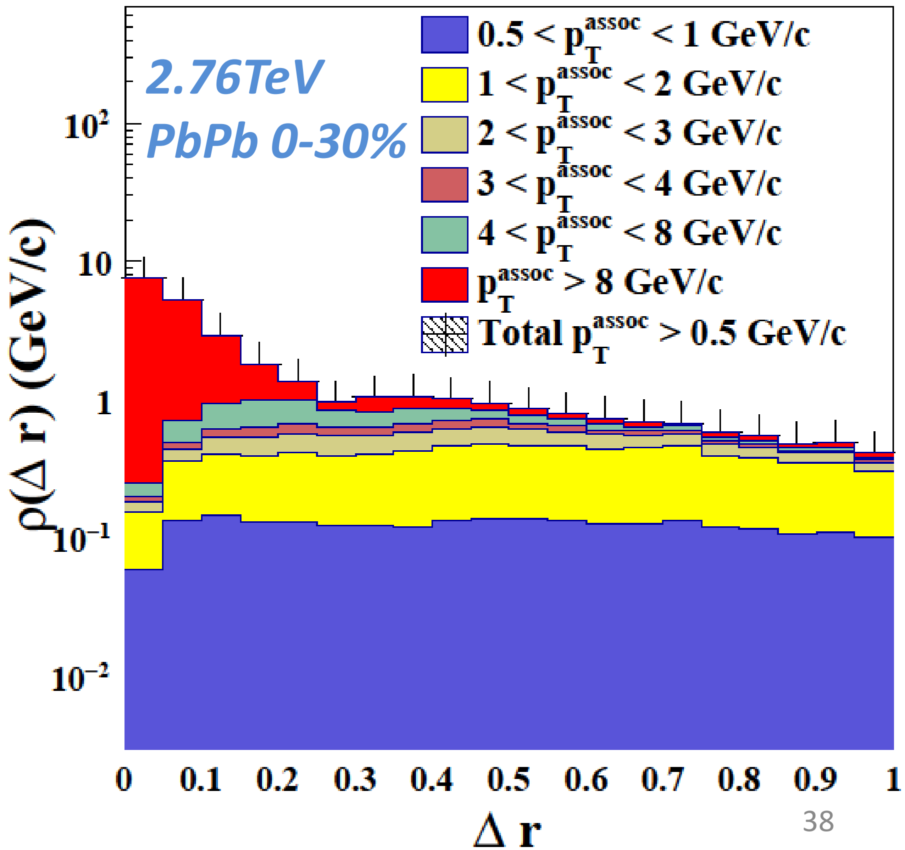


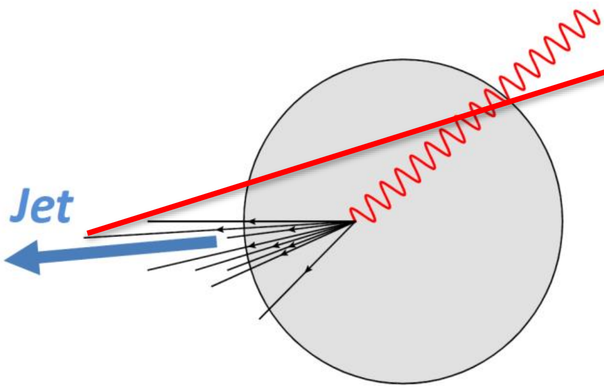


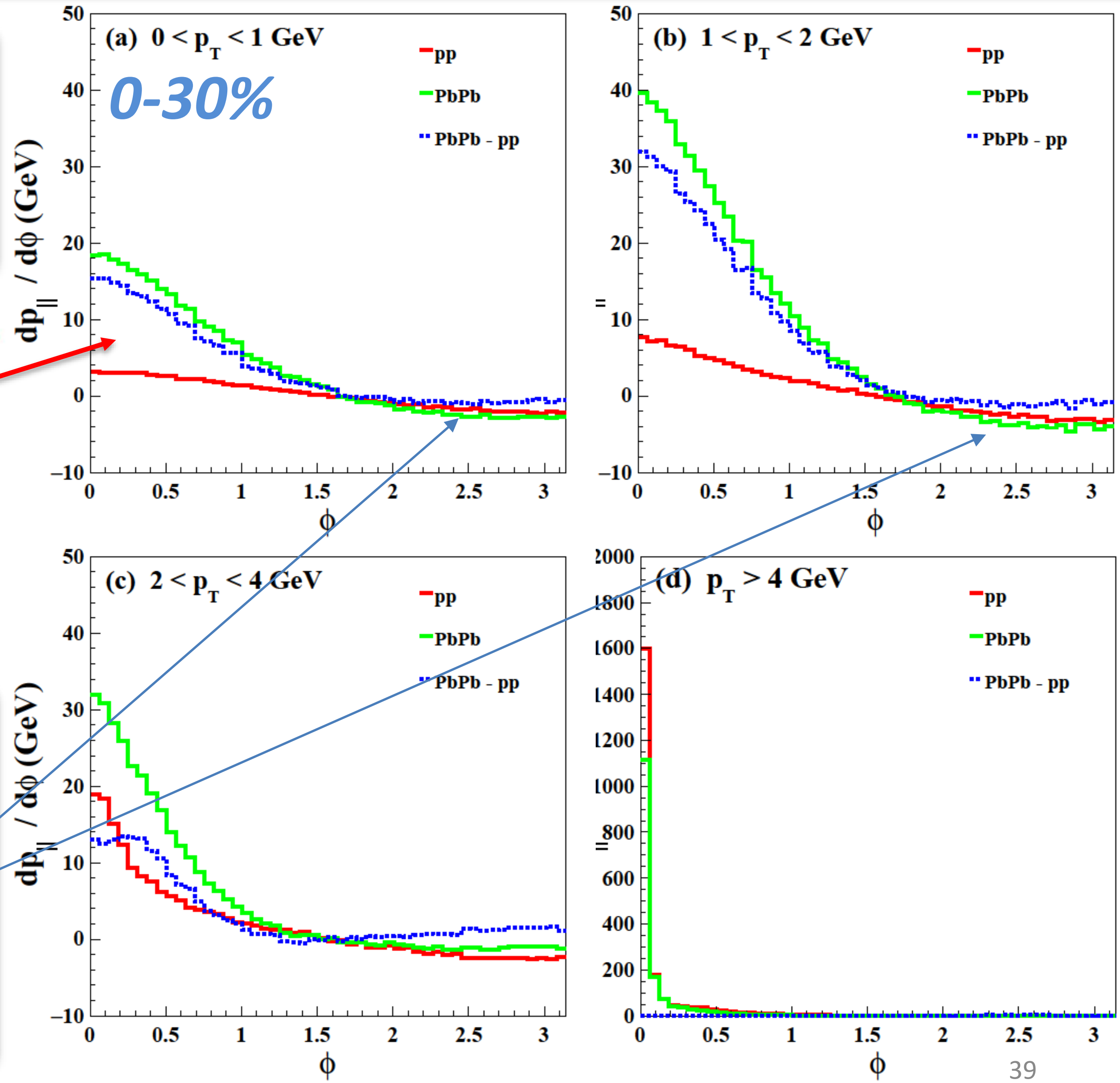


Energy flow in gamma-jets events

$$P_{\parallel} = \sum_i P_{i(parton)} * \cos\theta_{i(parton-leadingjet)}$$

$$\phi = |\phi_{parton} - \phi_{leadingjet}|$$

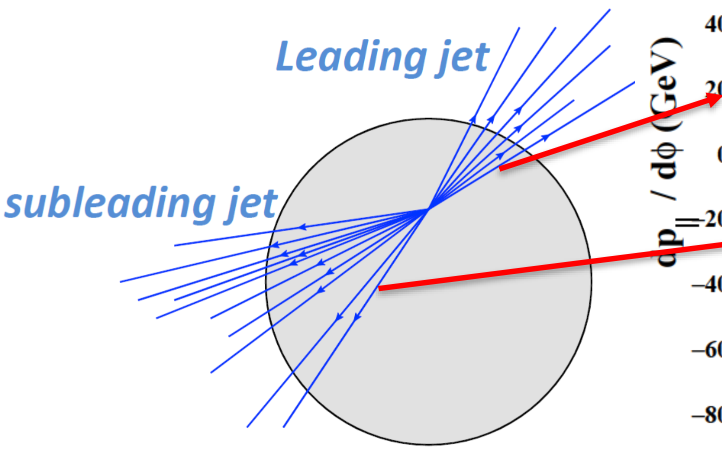


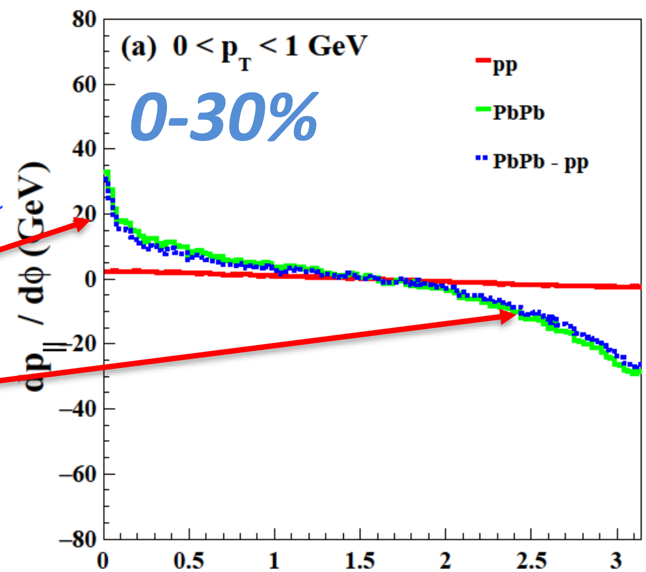


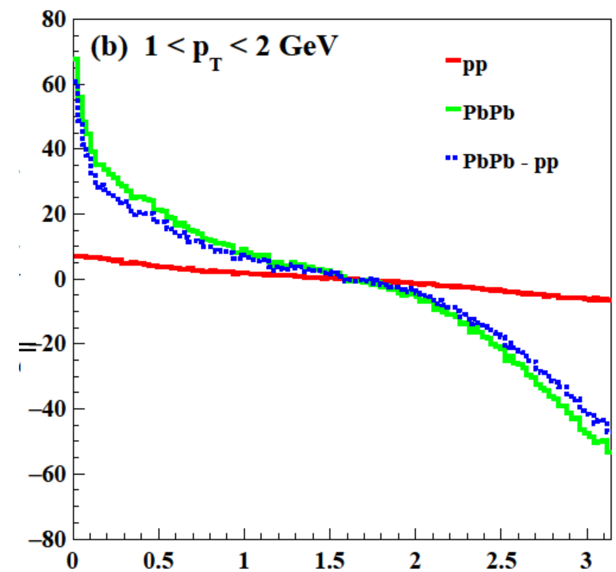
- Suppression of the hard parton, enhancement of the soft parton.
- Energy flow to the opposite direction of the jet

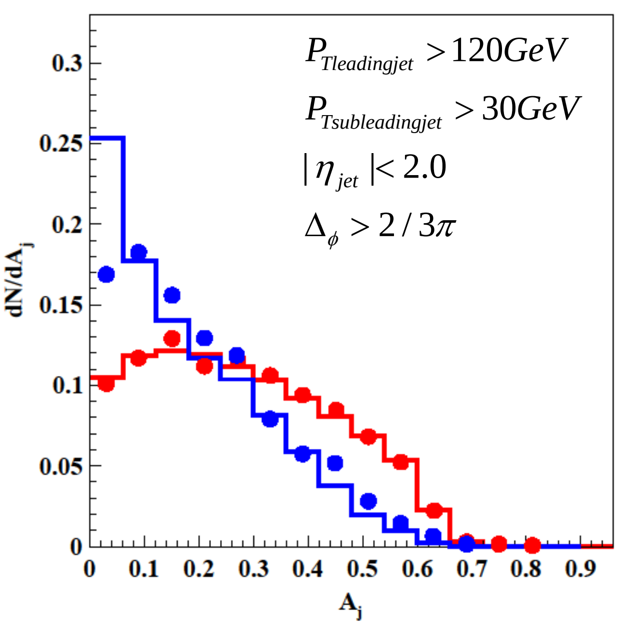
Energy flow in dijet events

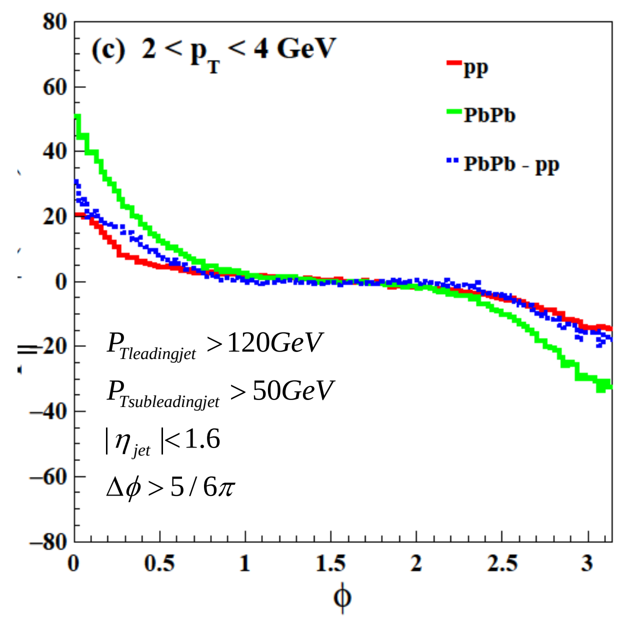
preliminary

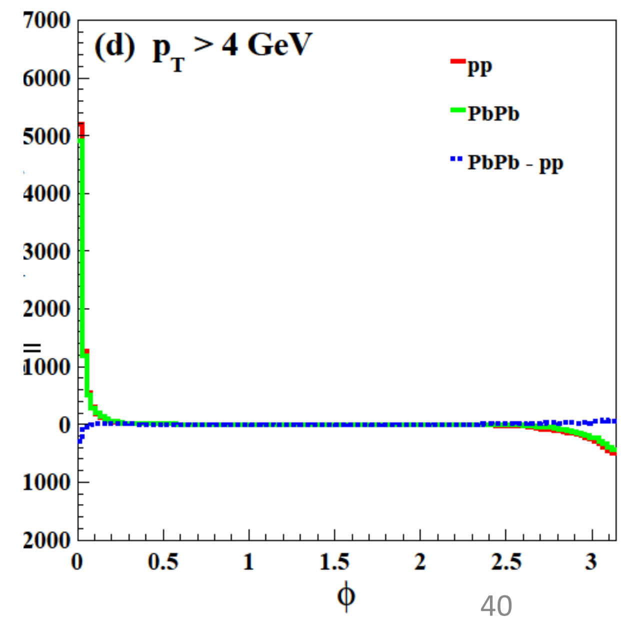












pT imbalance of dijet in heavy-ion collisions