Linear Boltzmann Transport for Jet Propagation in the Quark Gluon Plasma

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In collaboration with

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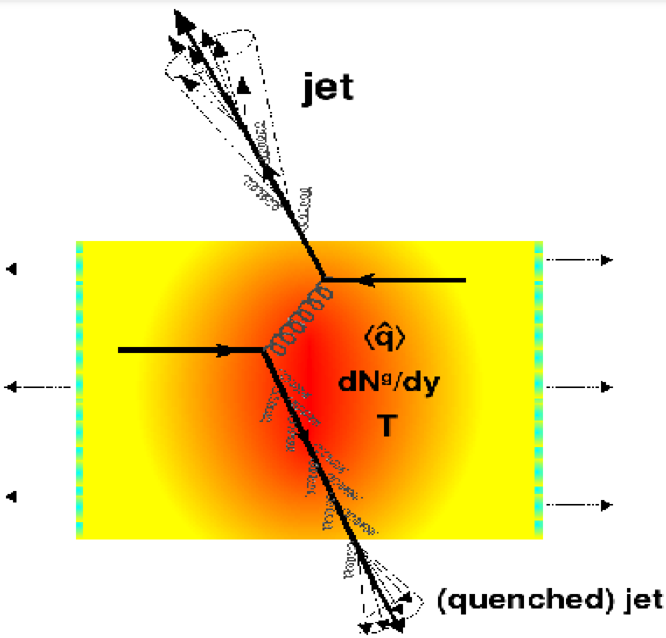
Outline

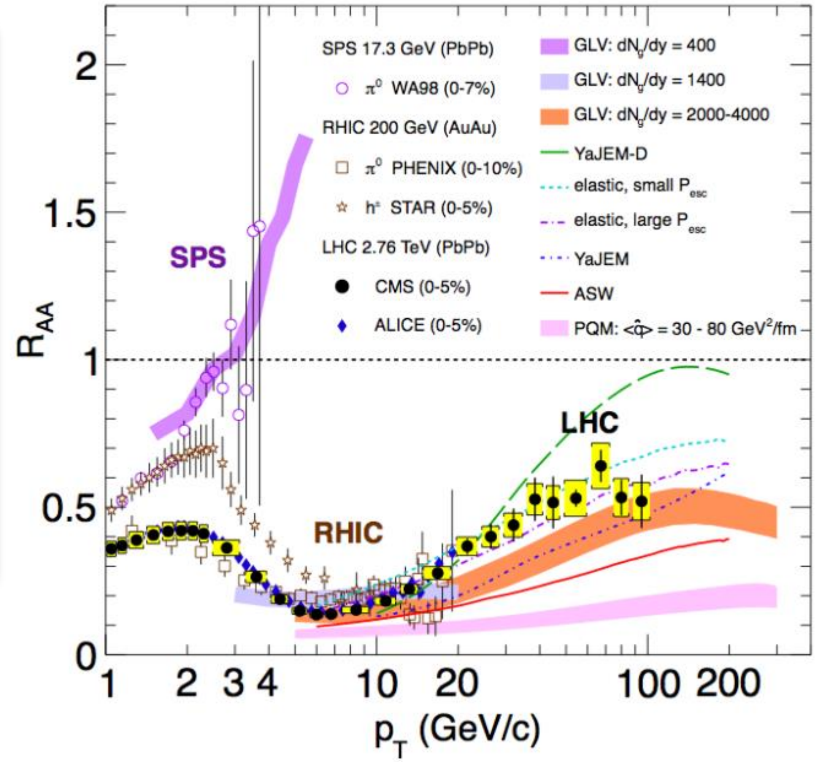
- Introduction
- Linear Boltzmann Transport (LBT) model
- Jet modification in heavy-ion collisions
- Summary and Outlook

Introduction

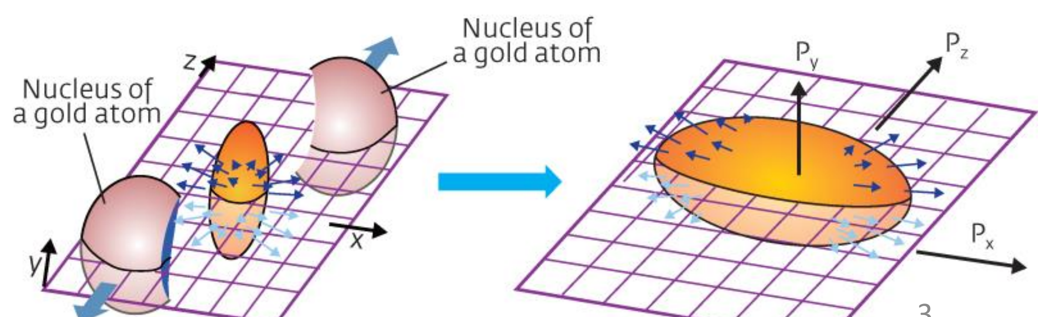
Jet-Medium interaction

- Suppression of hadrons at high pT. (R_{AA})
- Path-length dependence of jet quenching. (v_2)



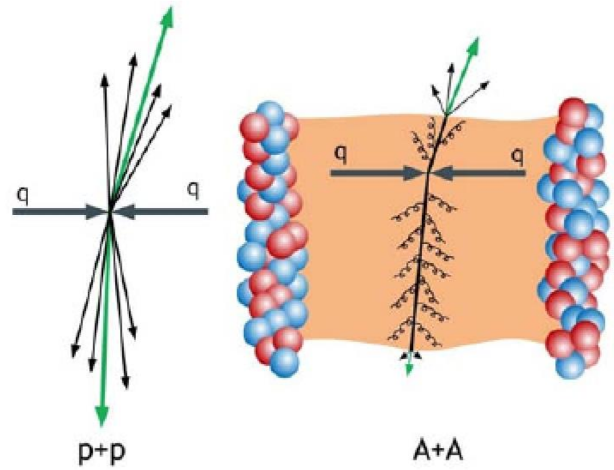


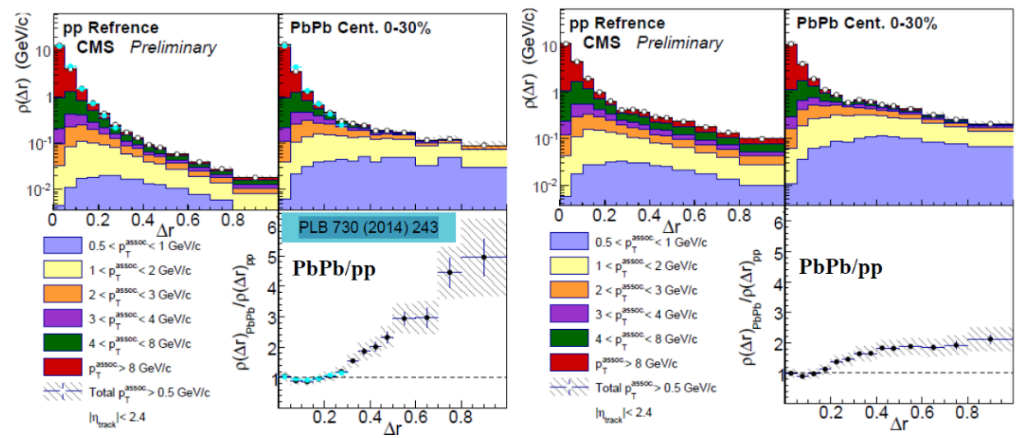
Betz, Barbara Eur.Phys.J. A48 (2012) 164
arXiv:1211.5897 [nucl-th]



Introduction

The jet shape and transverse momentum imbalance in Dijet events

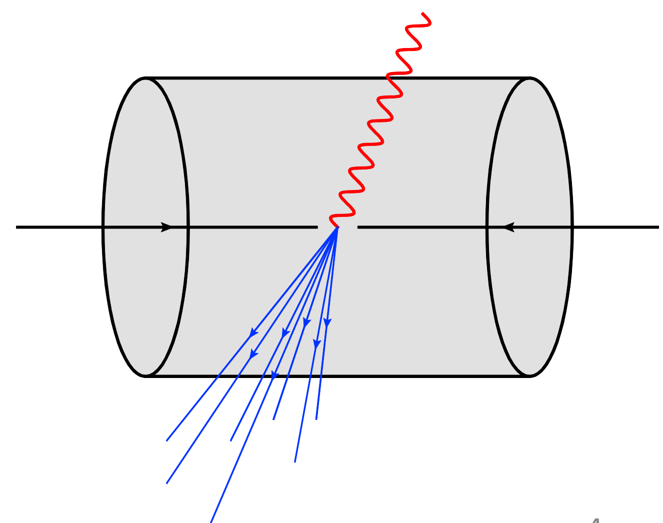




arXiv:1609.02466 CMS

Gamma-jet → *The golden channel*

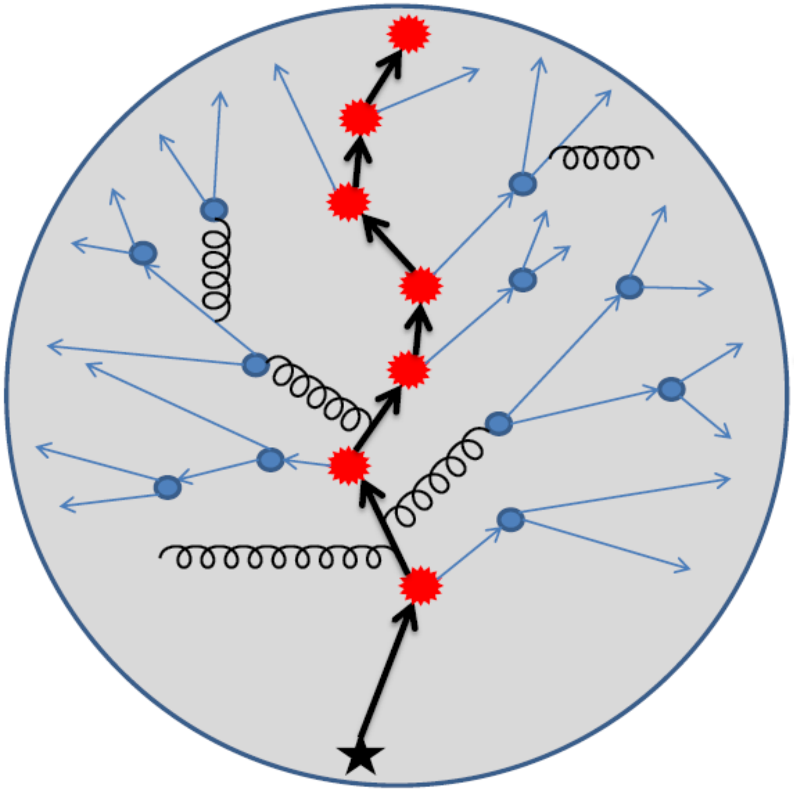
XN Wang, Z Huang Phys. Rev. Lett. 77, 231 (1996)



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

A Linear Boltzmann Transport (LBT) Model

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



Jet induced medium excitation

("Negative" parton for the back reaction)

Linear Boltzmann jet Transport

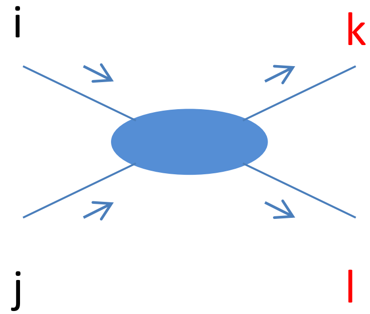
- Elastic collision + Induced gluon radiation.
- Follow the propagation of recoiled parton.
- Include recoiled parton in jet reconstruction.

Linear Approximation

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

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

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

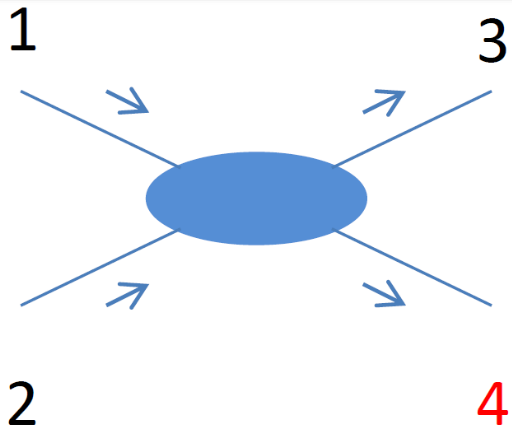
$$\times |M|^2_{ij\to kl}(s,t,u)\times S_2(s,t,u)\times(2\pi)^4\delta^4(P_1+P_2-P_3-P_4)$$

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

- 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

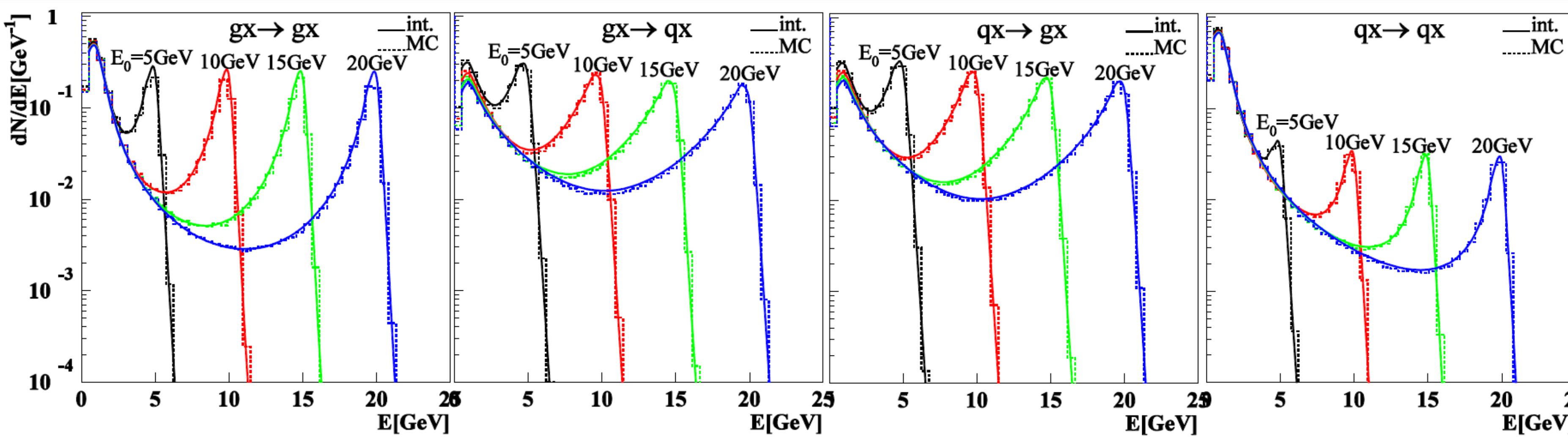
- Dominance of small angle scattering.
- Switch of flavor and species of the leading parton.

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

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

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

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



Medium-induced gluon radiations

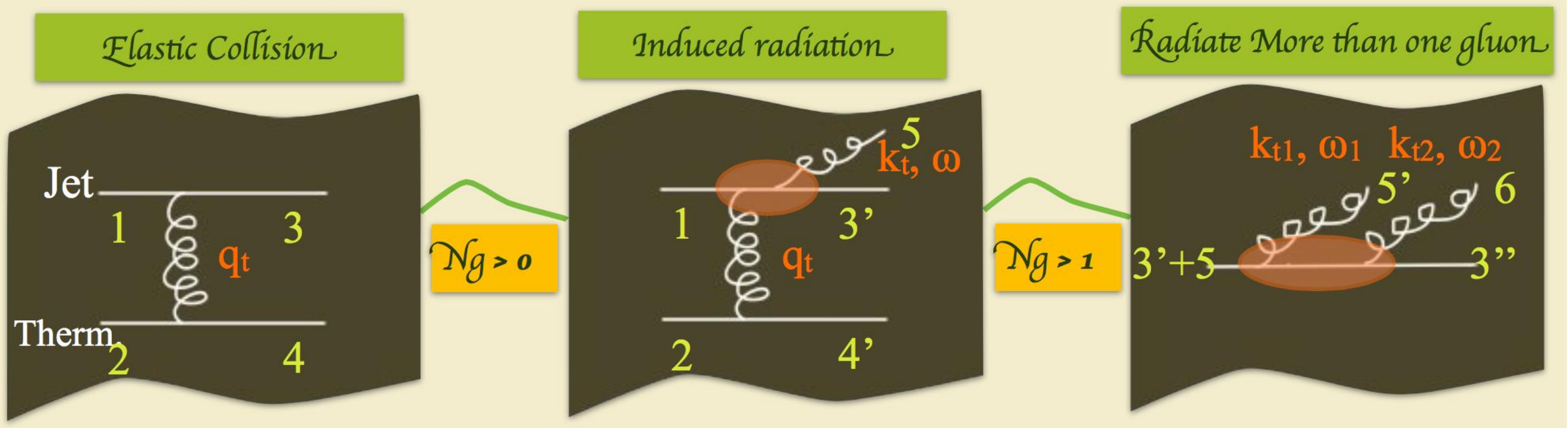
Radiated gluon distribution: X. Guo, X. Wang PRL 85 (2000) Nucl.Phys. **A696** (2001)

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

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

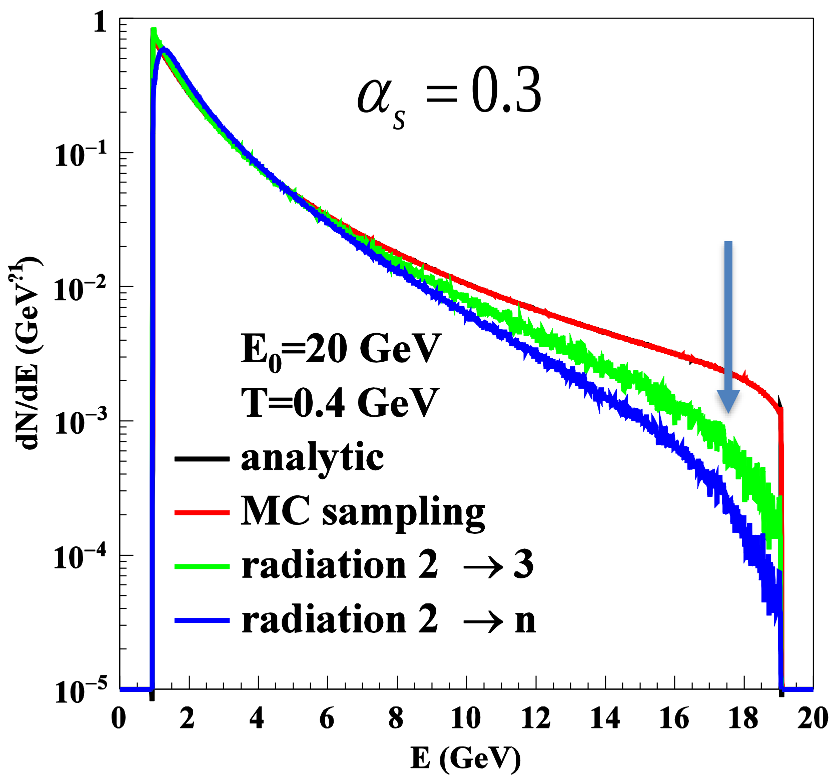
Induced radiations are accompanied by elastic collisions.

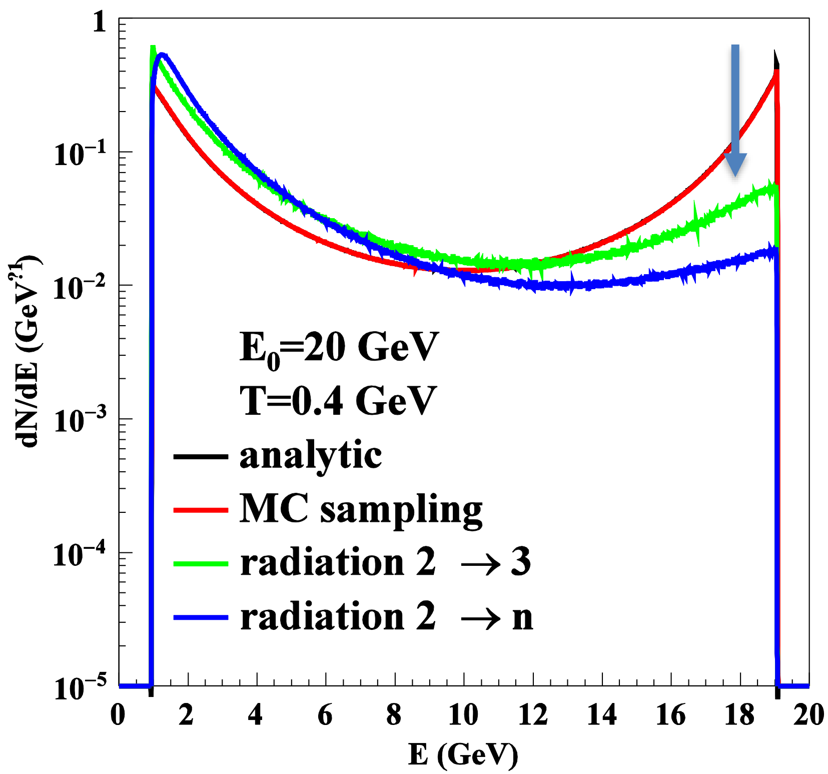
Jet medium Interaction:



Energy distribution of the radiated gluon

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



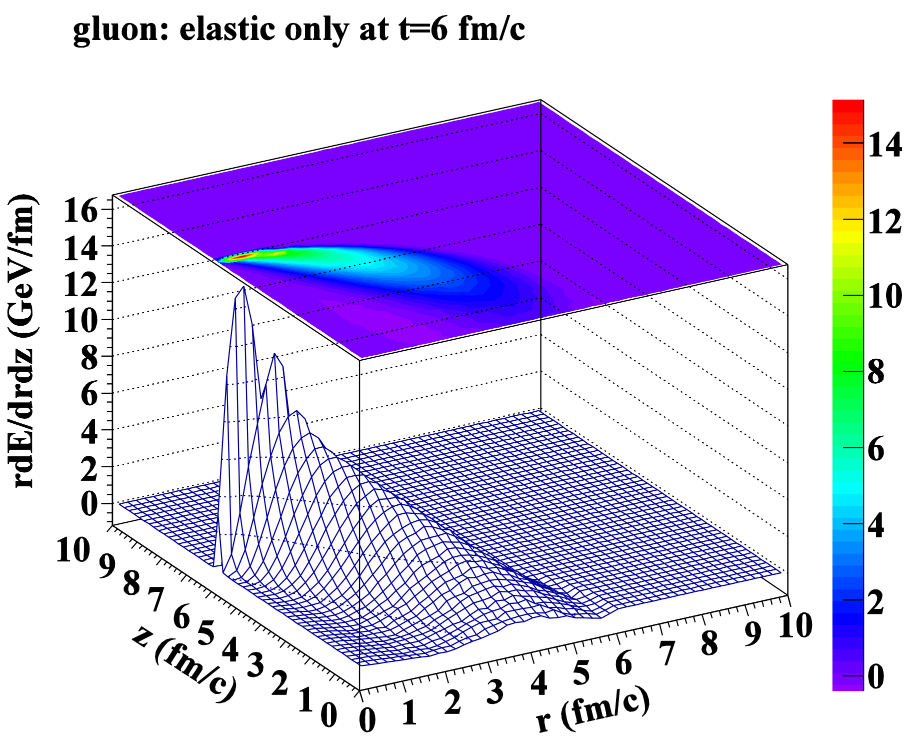


Jet induced medium excitation (Energy distribution in space)

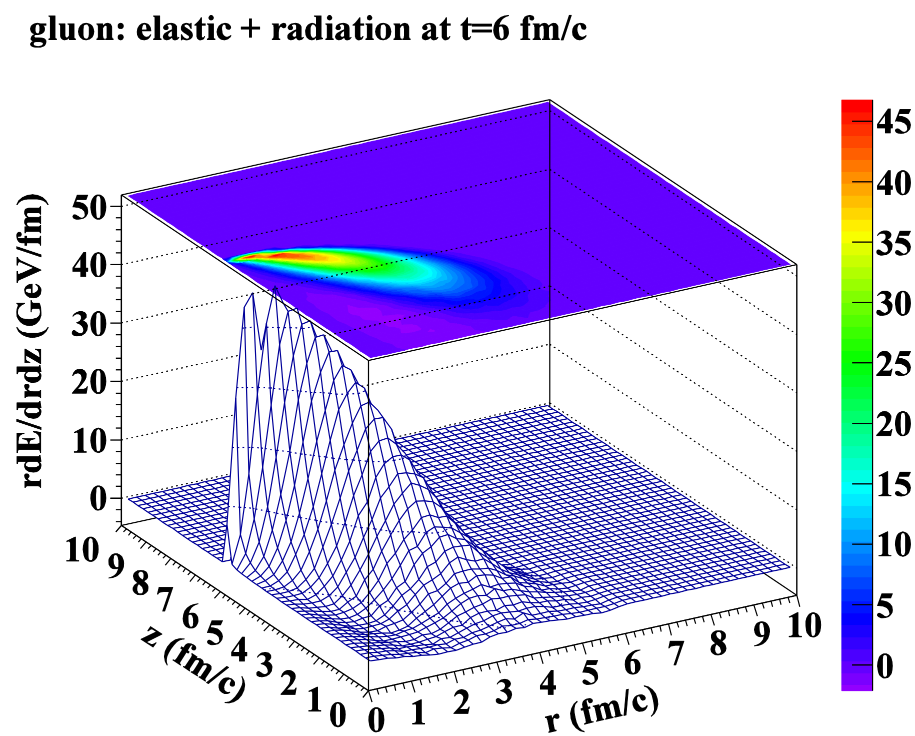
Initial jet parton: gluon
E = 100 GeV
T = 0.4 GeV $\alpha_s = 0.3$

- Mach Cone like shock wave and the diffusion wake.

Elastic only



Elastic + Radiation

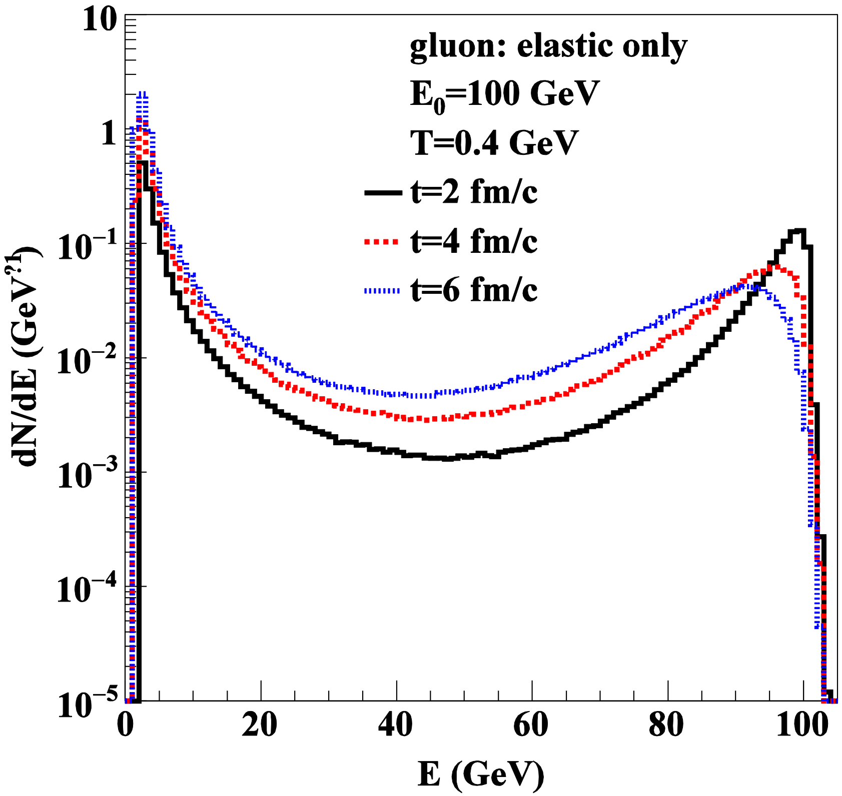


Jet induced medium excitation (Energy distribution at different time)

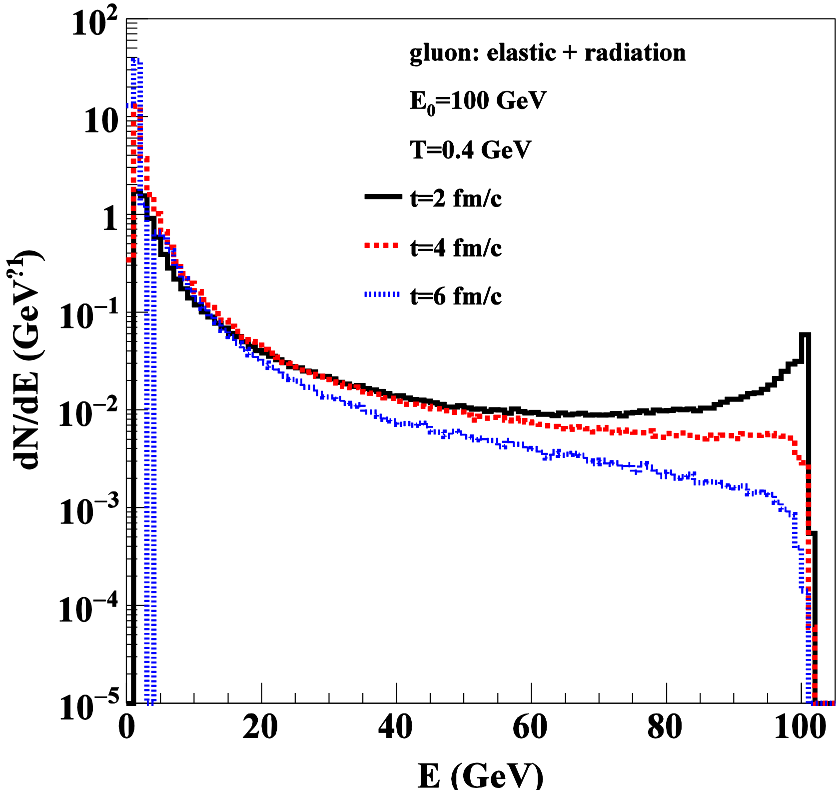
Initial jet parton: gluon
E = 100 GeV
T = 0.4 GeV $\alpha_s = 0.3$

- Depletion of the energy of the leading parton.

Elastic only

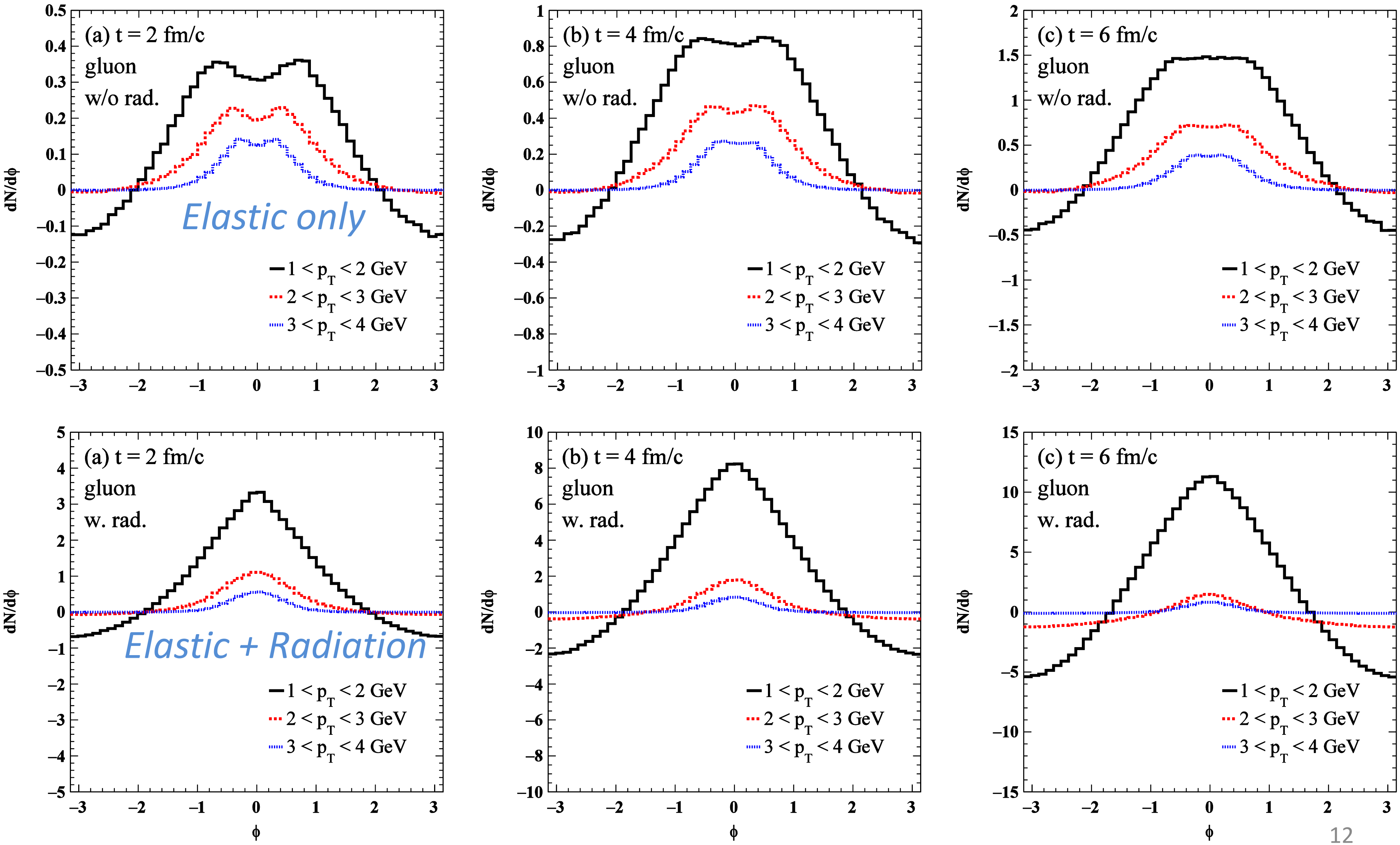


Elastic + Radiation



Jet induced medium excitation (Angular distribution)

t = 2 fm | *t = 4 fm* | *t = 6 fm*

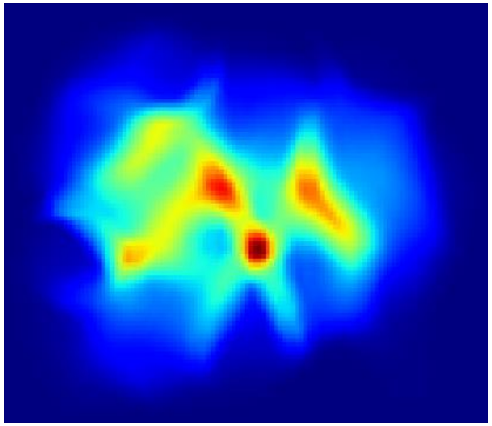


Jets in a 3+1D hydro

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

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

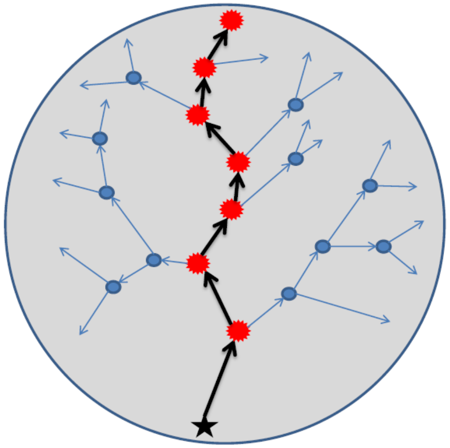
- 3+1D Ideal hydro



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

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

LBT Model



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

Jet reconstruction (Fastjet)

Inclusive jet in pp collisions

pT distribution in pp collison within Pythia8

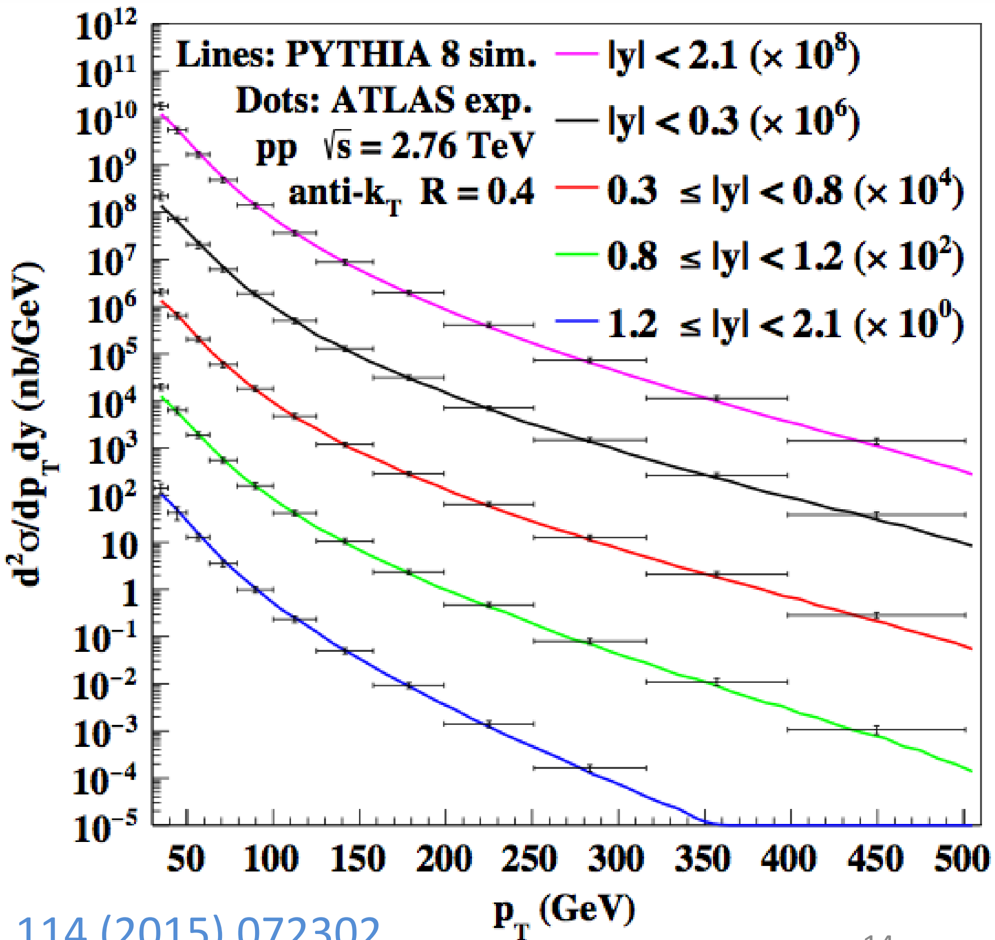
Weighted sampling in triggered p_T bins to increase the efficiency of MC simulations

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

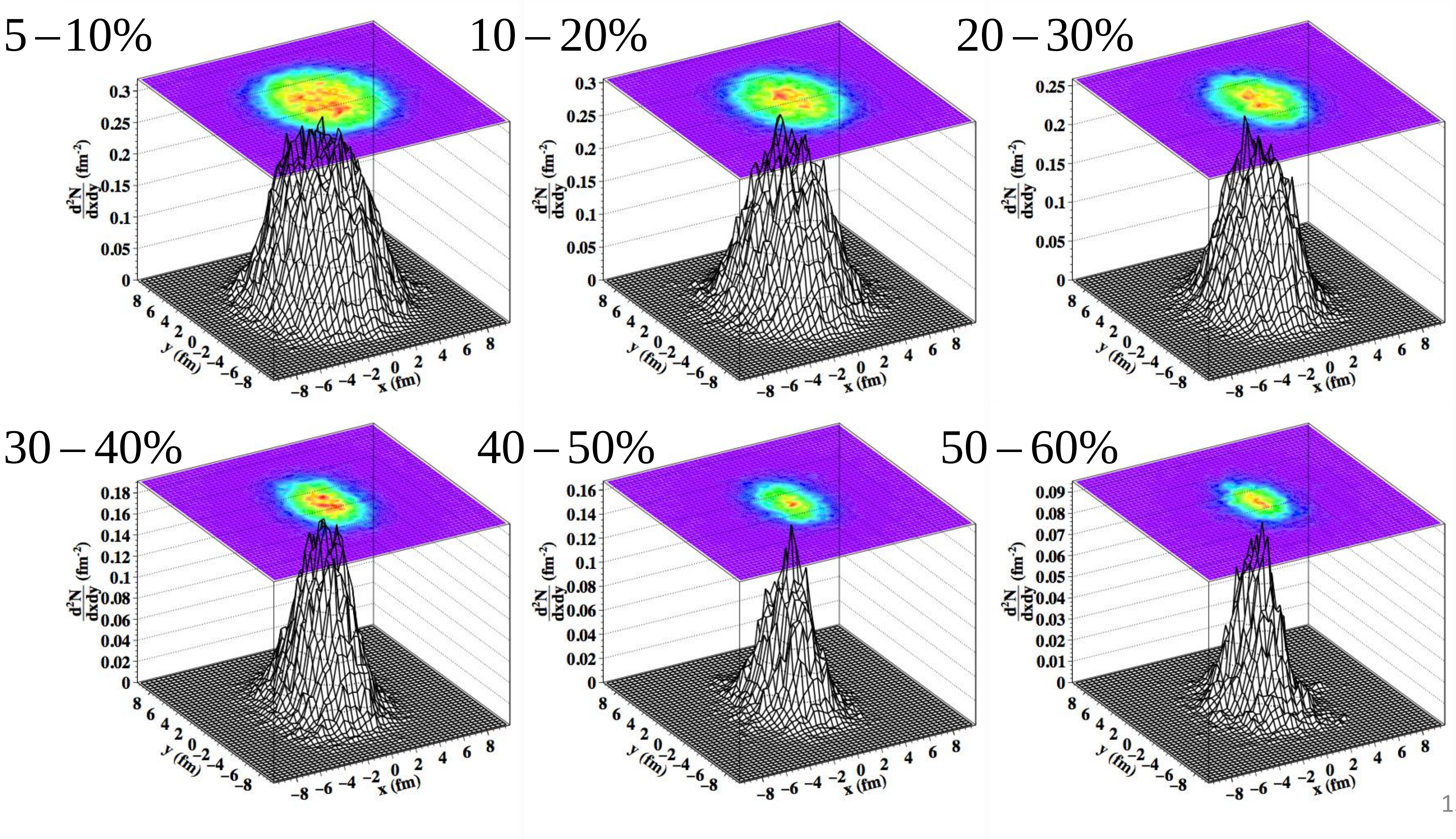
$$\omega_i = \sigma_i / \sum_i \sigma_i$$



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

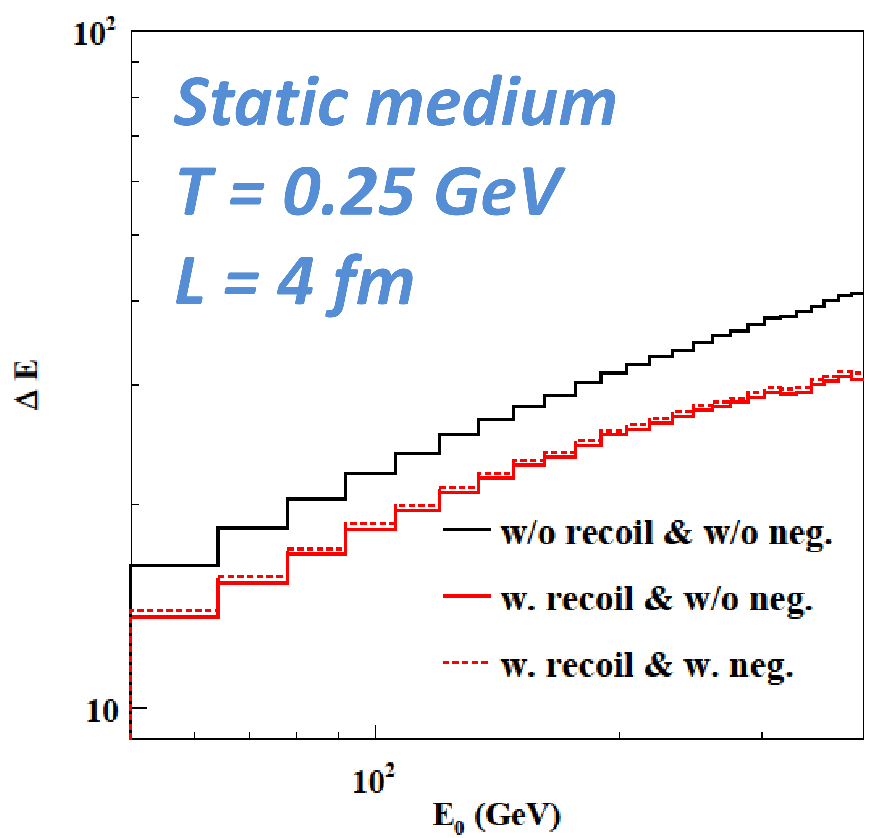
Initial geometry

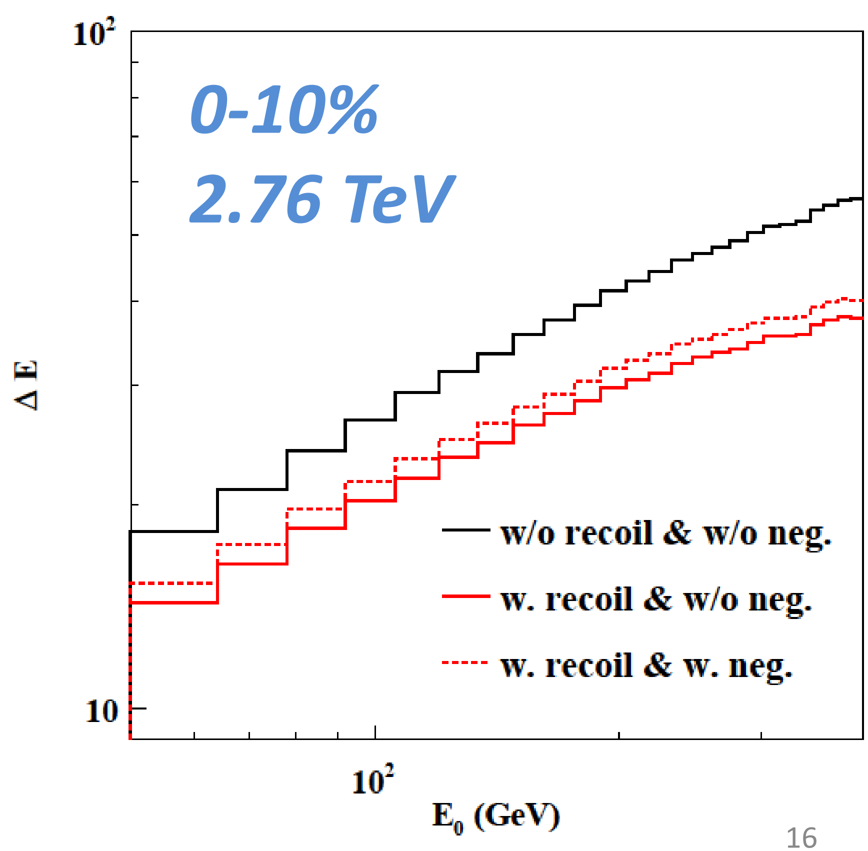
Averaged over 200 event-by-event hydro profiles



Recoiled effect in the reconstructed jets

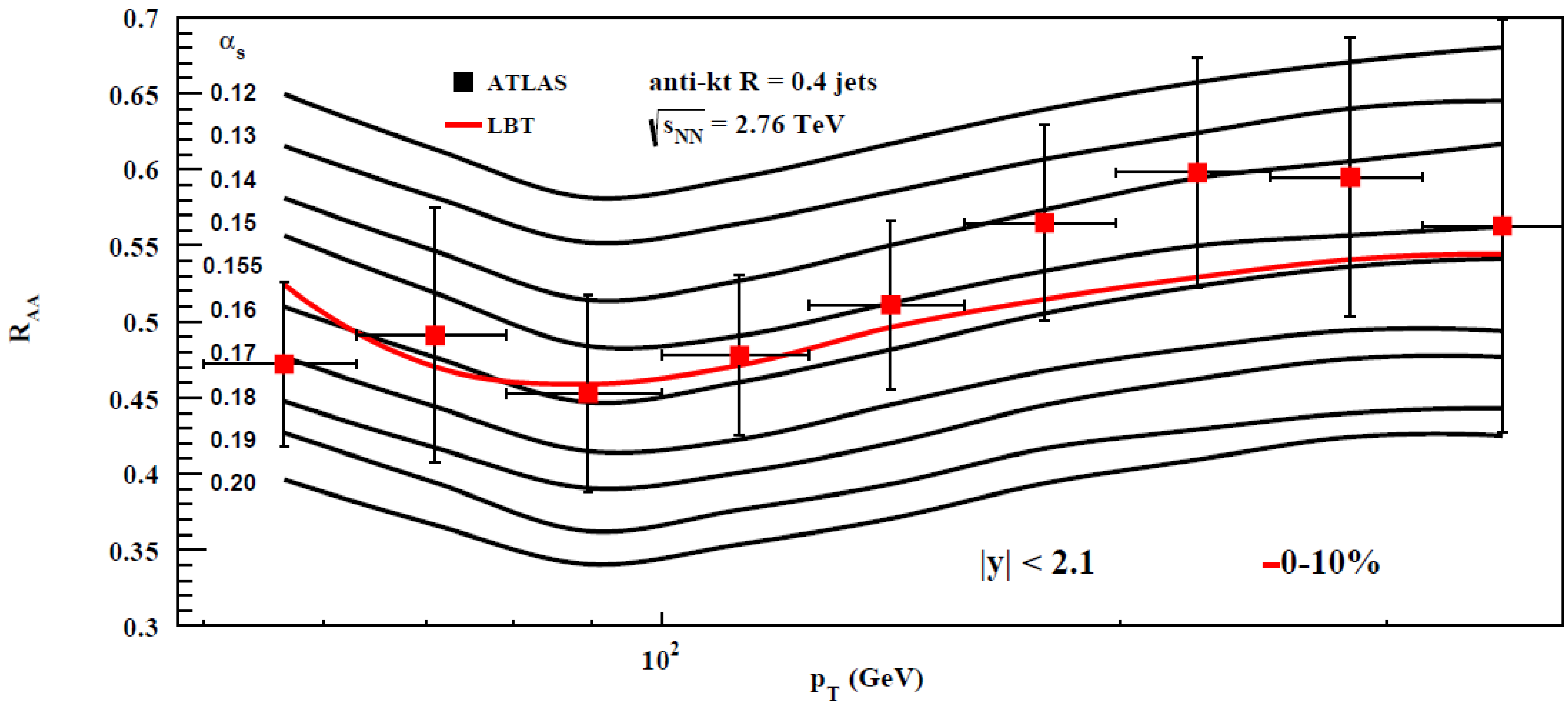
- The inclusion of the recoiled parton in the reconstructed jets will reduce the jet energy loss.
- The recoiled effect is more significant in the evolving medium.





Nuclear modification factor

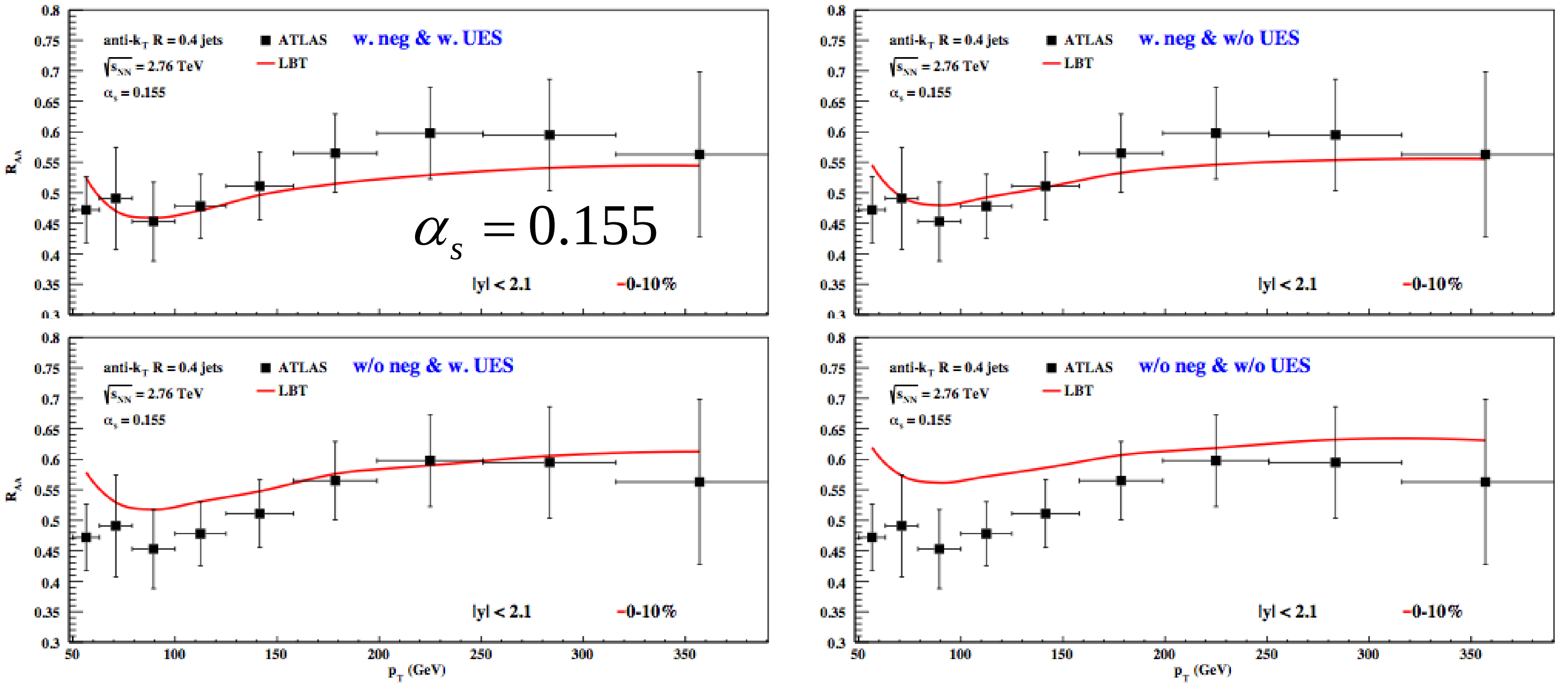
- The only parameter strong coupling constant α_s is fixed.
- We first calculate the single jet R_{AA} to extract the value of α_s . (fix the strength of jet-medium interaction)



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

Nuclear modification factor

- The inclusion of back reaction (negative parton) will lead to suppression. (on the whole pT range)
- The Underlying Event Subtraction will lead to suppression. (on the low and intermediate pT range)

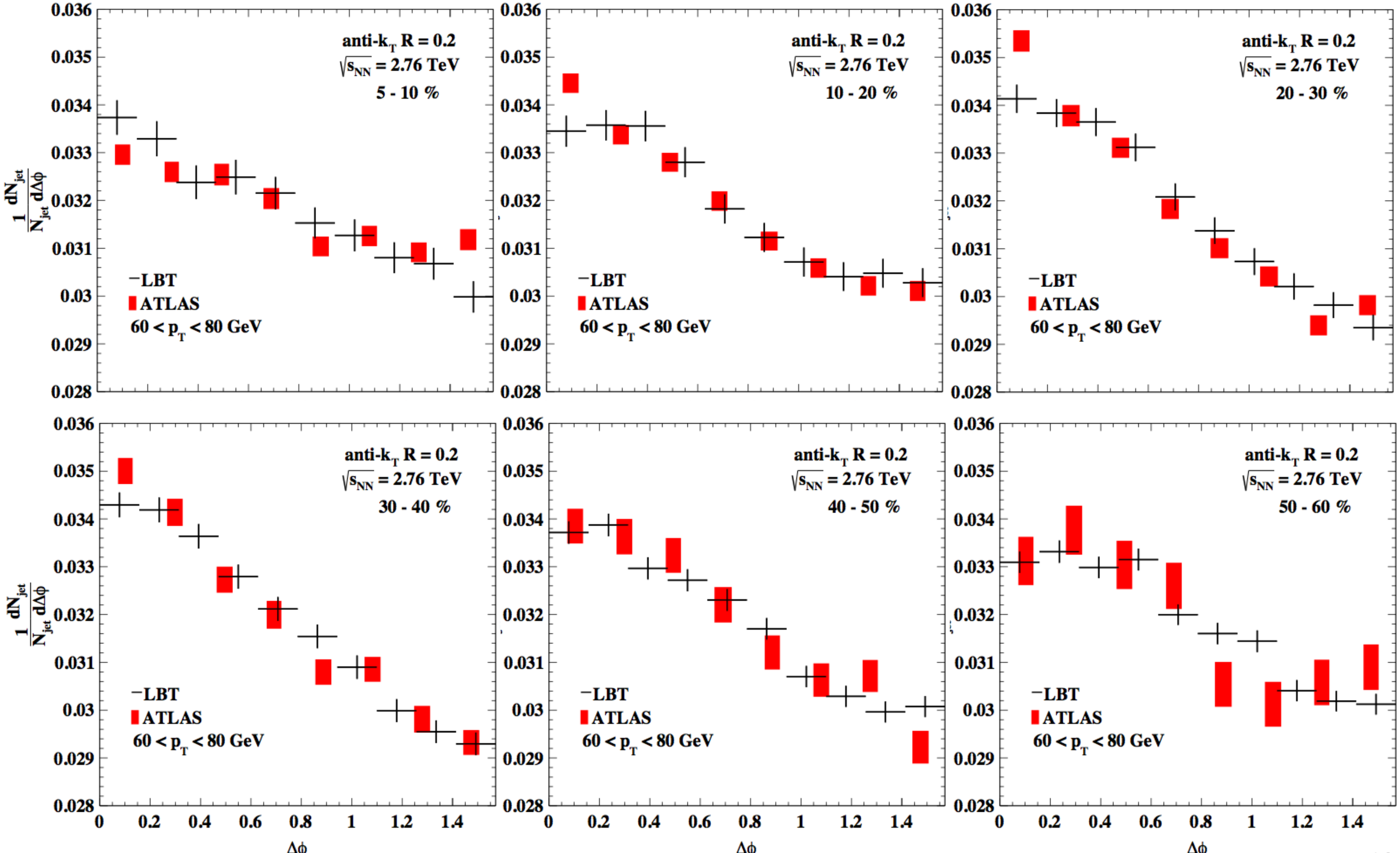


Data ref.: ATLAS Collaboration, Phys. Rev. Lett. 114 (2015) 072302

Jet azimuthal distribution with different centralities

Anisotropy shows up

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

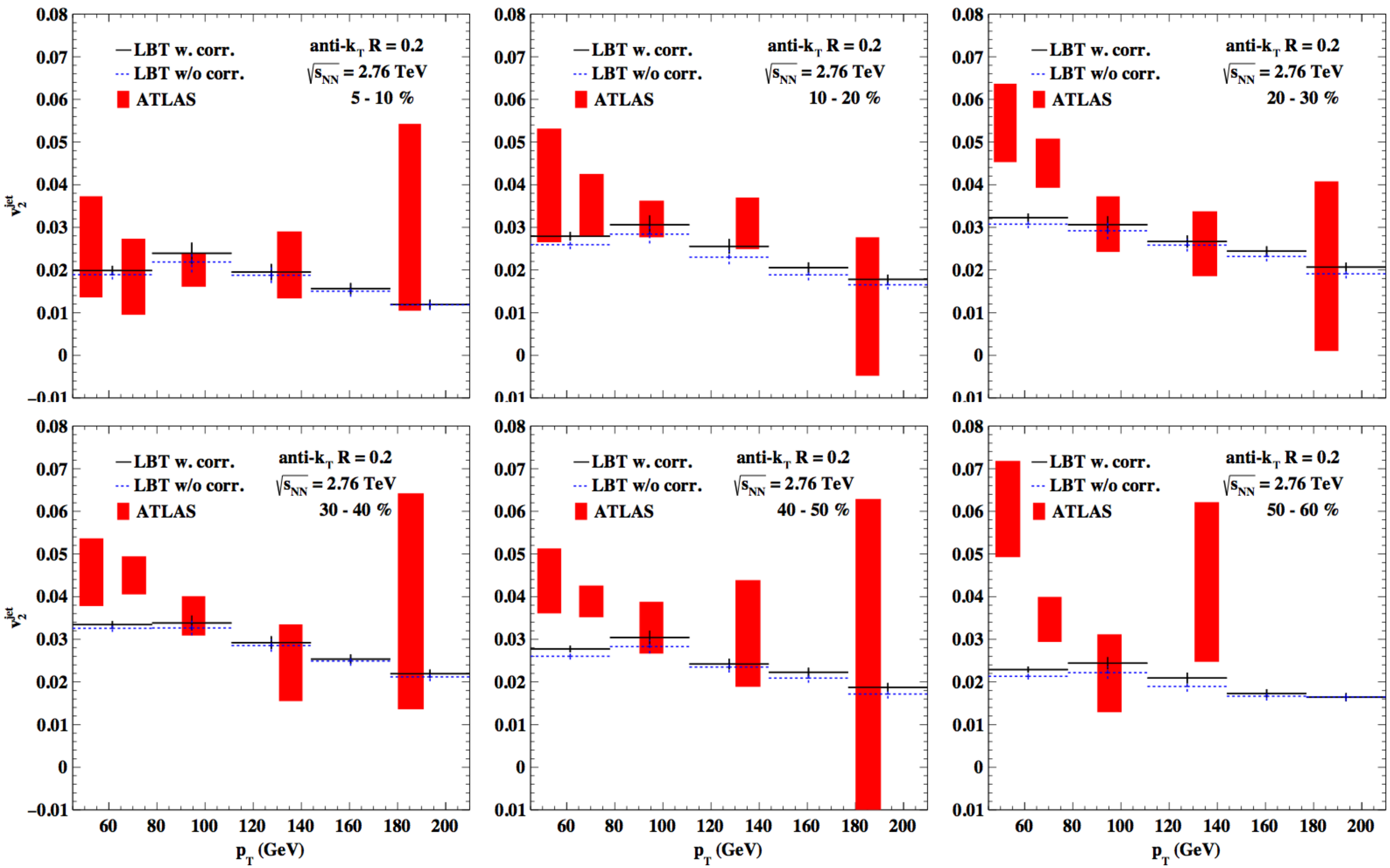


Data ref.: ATLAS Collaboration, Phys. Rev. Lett.111 152301 (2013)

Jet v2 with different centralities

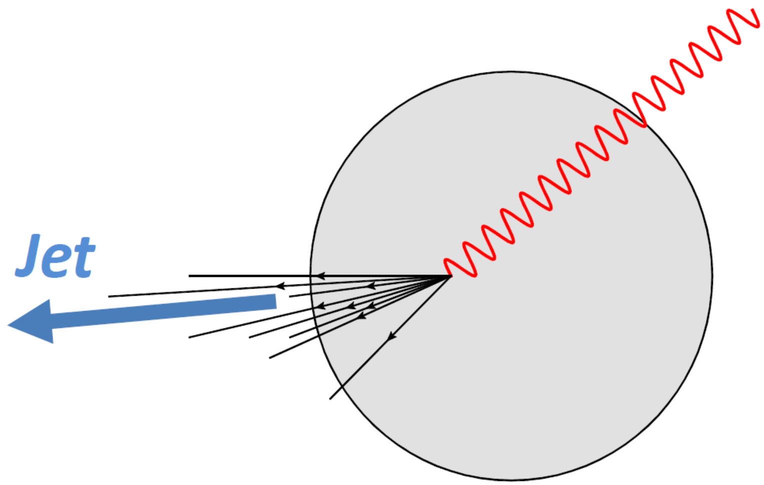
$$v_2^{jet} = < \cos(2[\phi^{jet} - \Psi_2]) >$$

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



Asymmetry distribution of gamma-jet in heavy-ion collisions

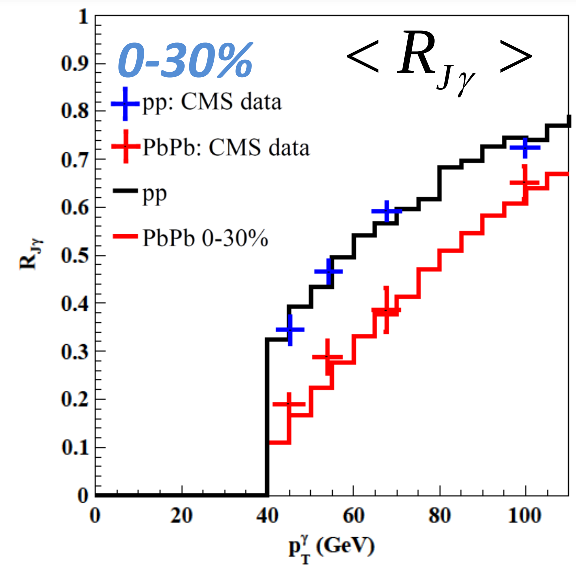
- fix the parameter α_s via the comparison with the γ-jet asymmetry



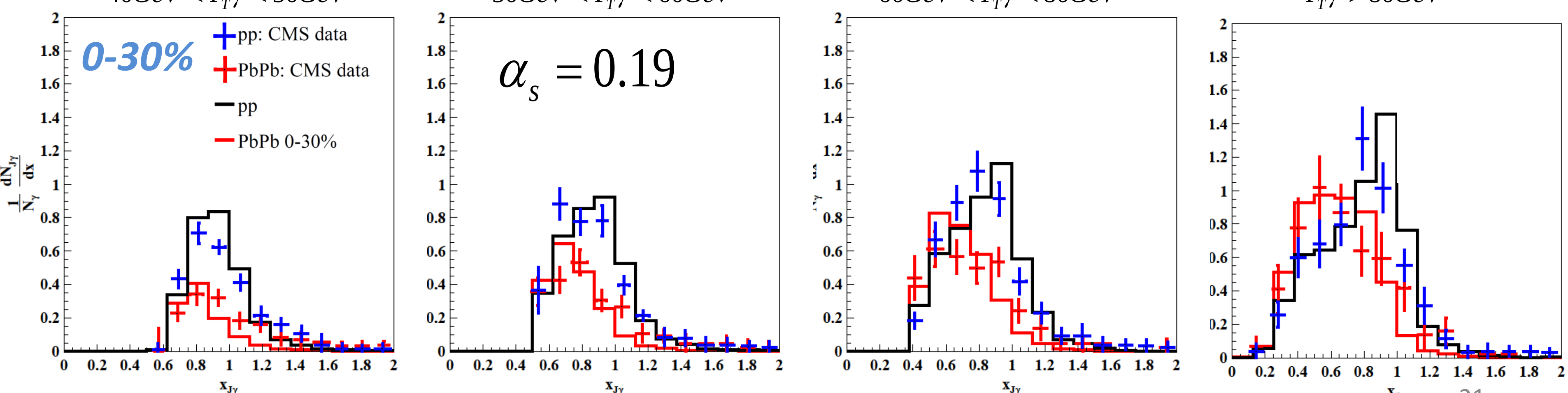
$|\eta_\gamma| < 1.44$

$P_{Tjet} > 30GeV$

$|\eta_{jet}| < 1.6$



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

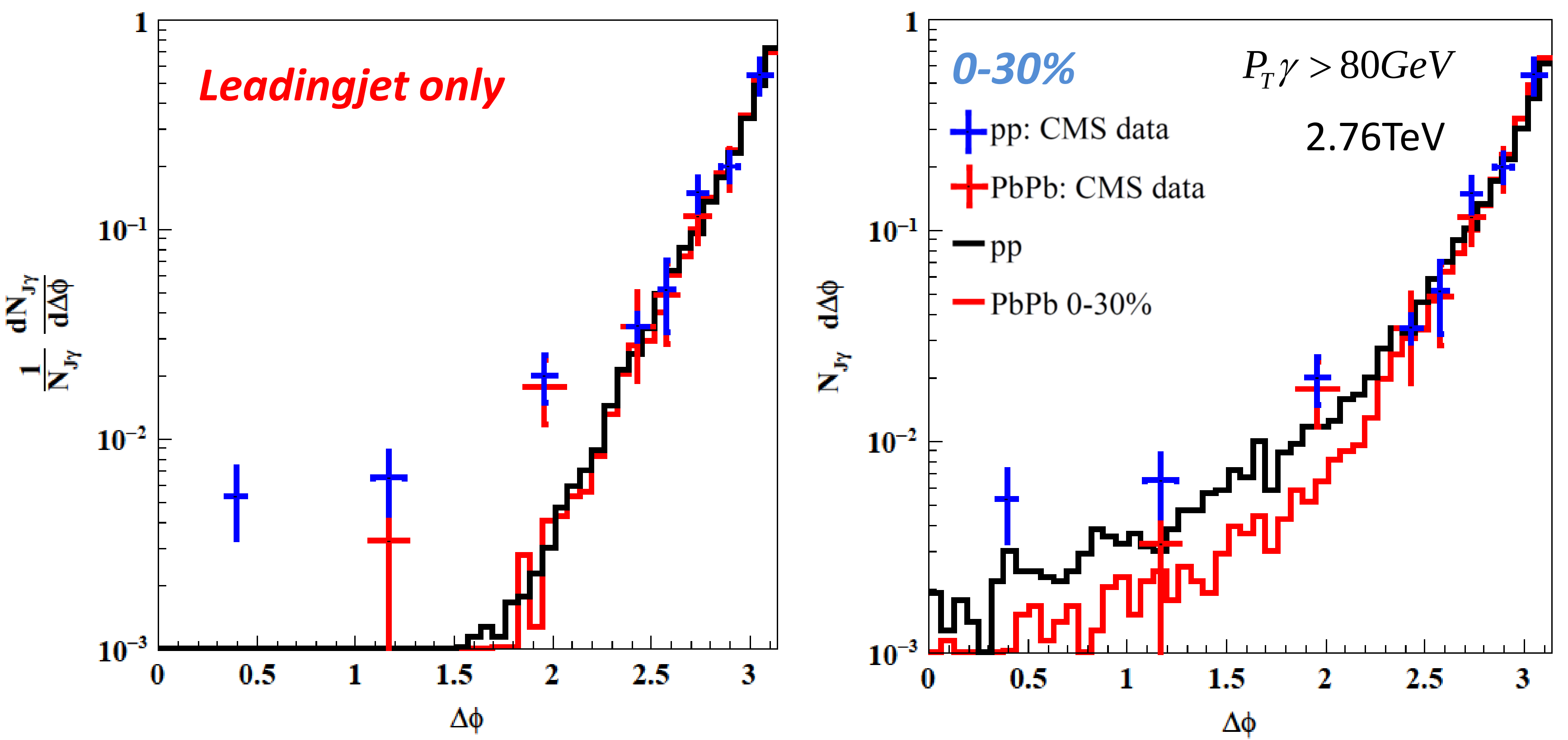


Azimuthal distribution of gamma-jet in heavy-ion collisions

- 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-jet events



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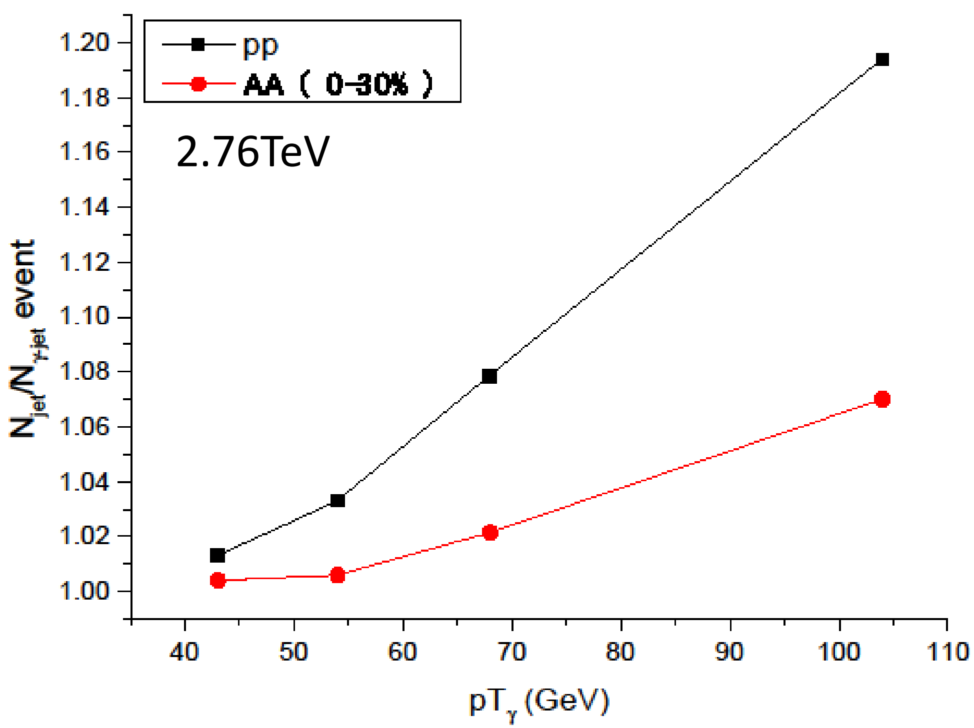
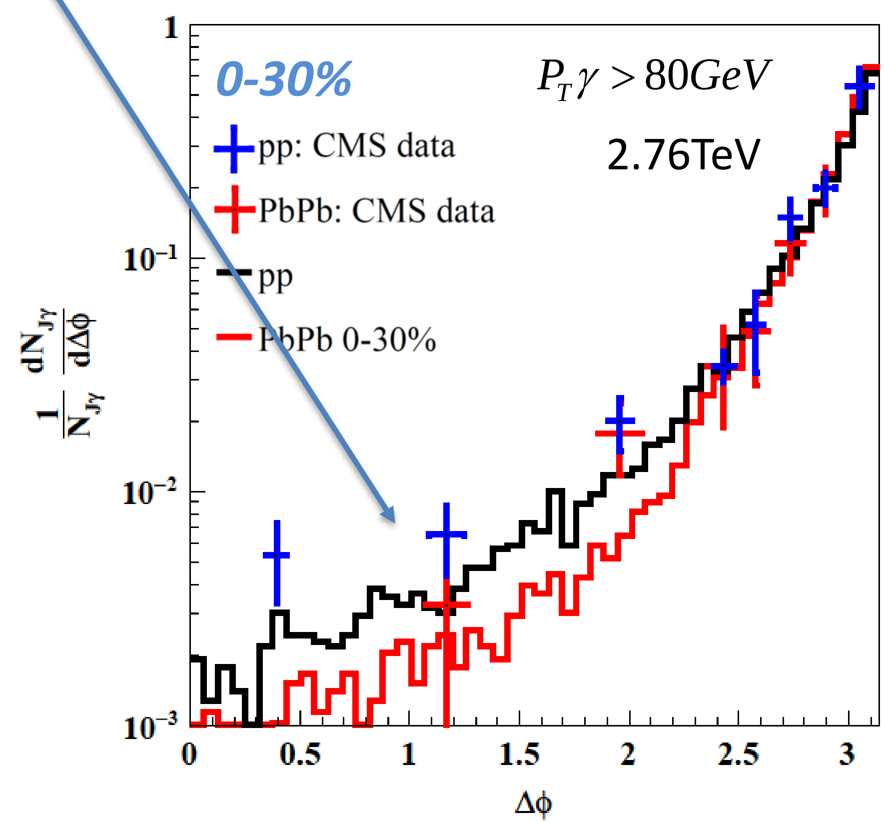
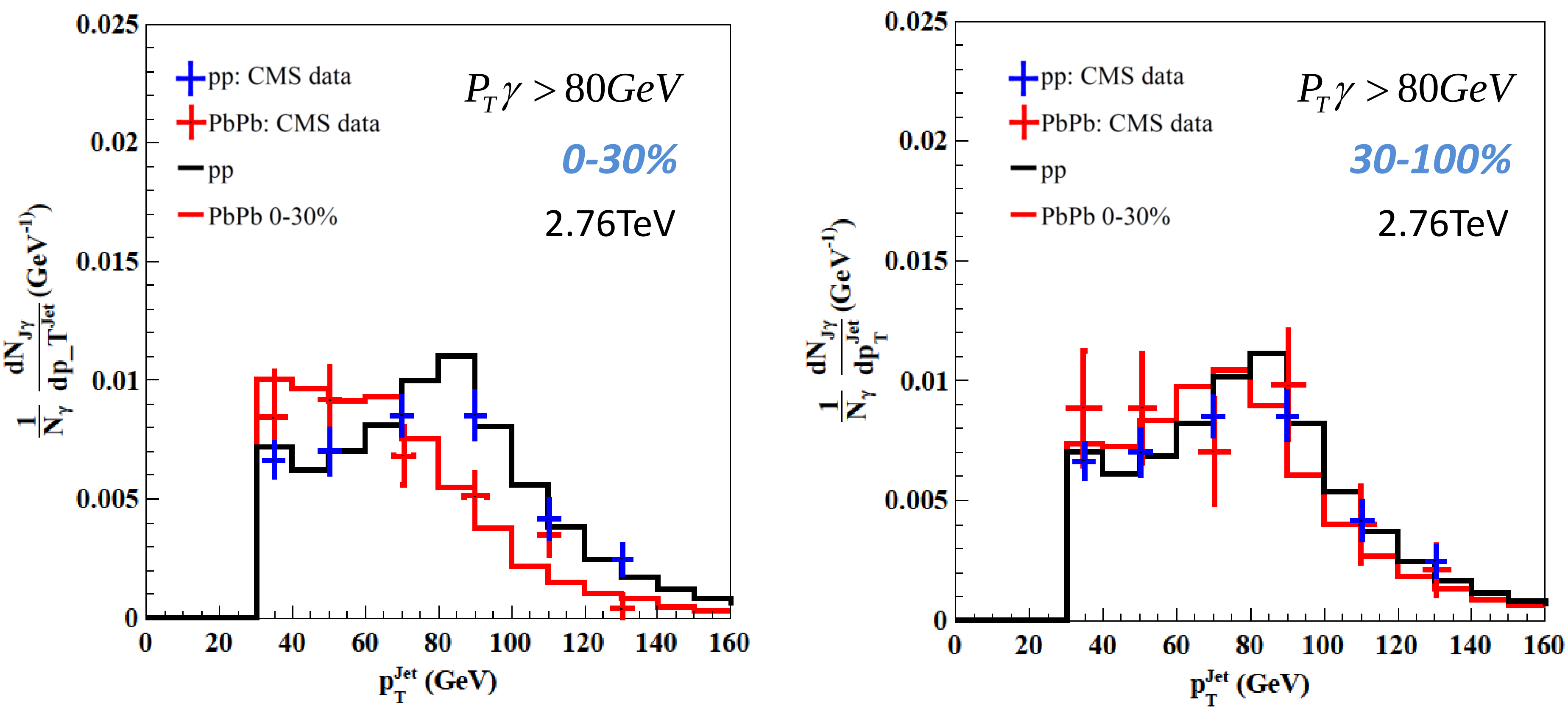




pT distribution of gamma-jet in heavy-ion collisions

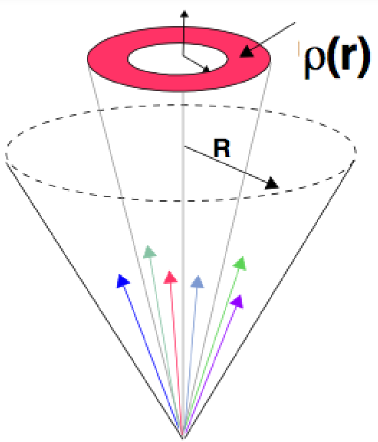
- Shift of the peak of the pt distribution
- Path length dependence of the energy loss



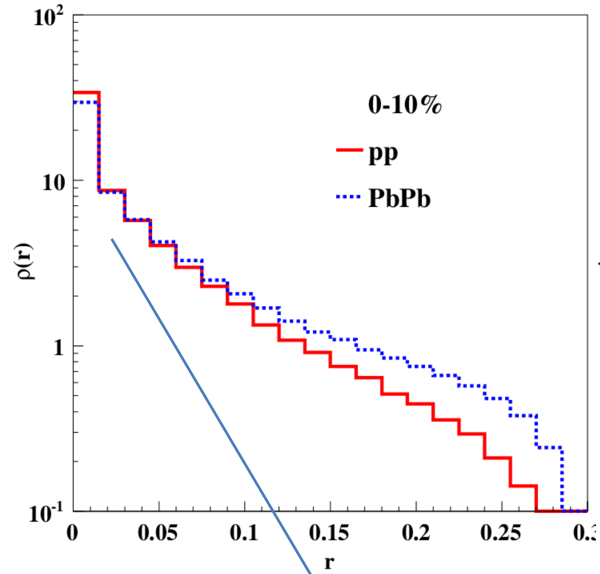
Modification of gamma-jet structure

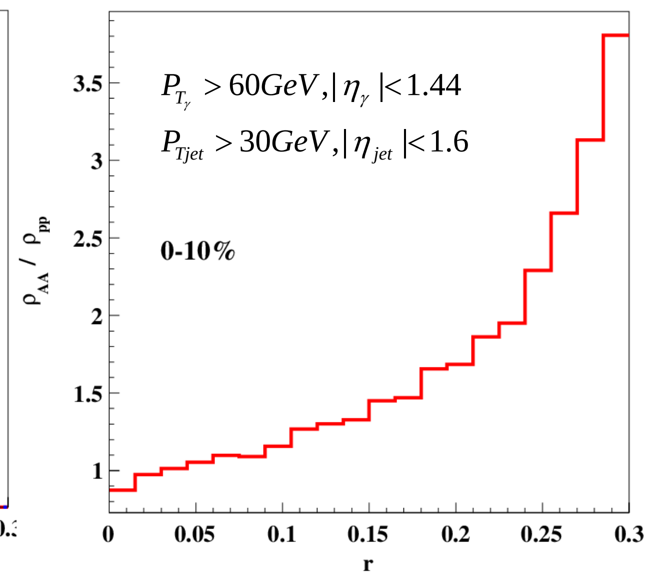
Jet shape

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

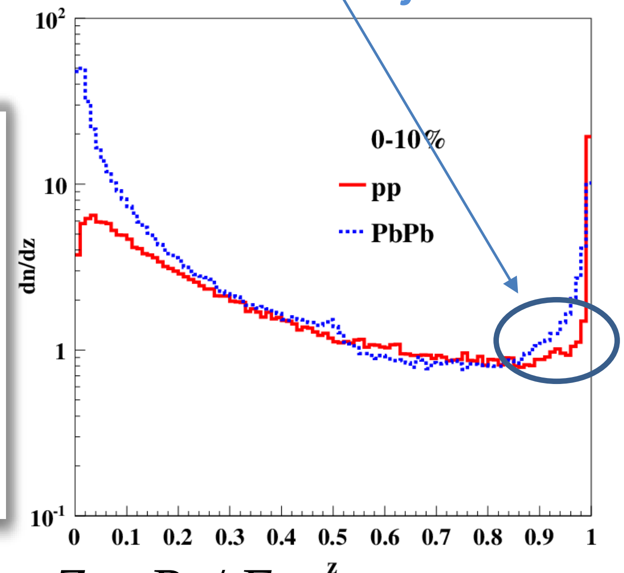


P. Kurt



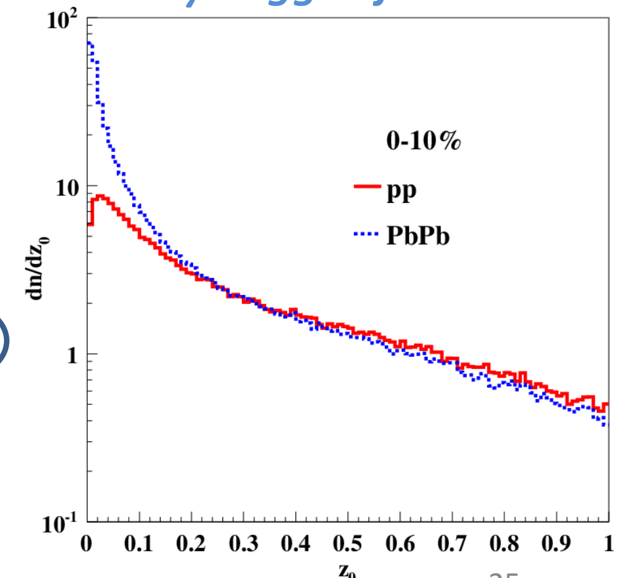


Reconstructed jet FF



$$Z = P_L / E_{jet}$$

γ-tagged jet FF

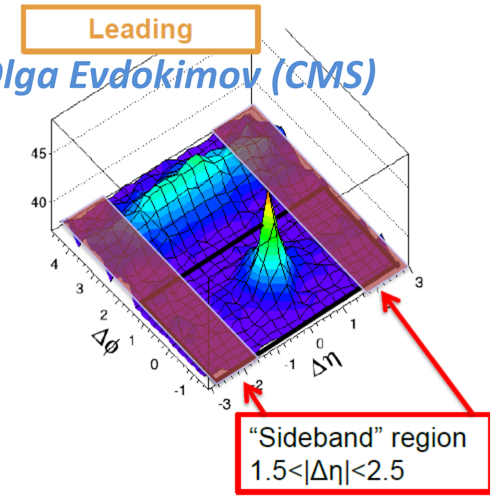


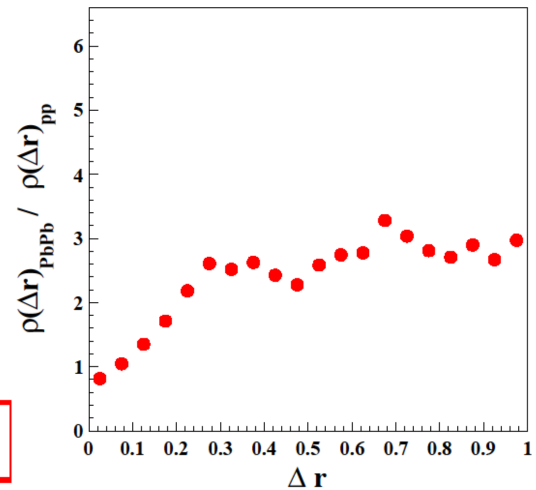
$$Z_0 = P_L / E_\gamma$$

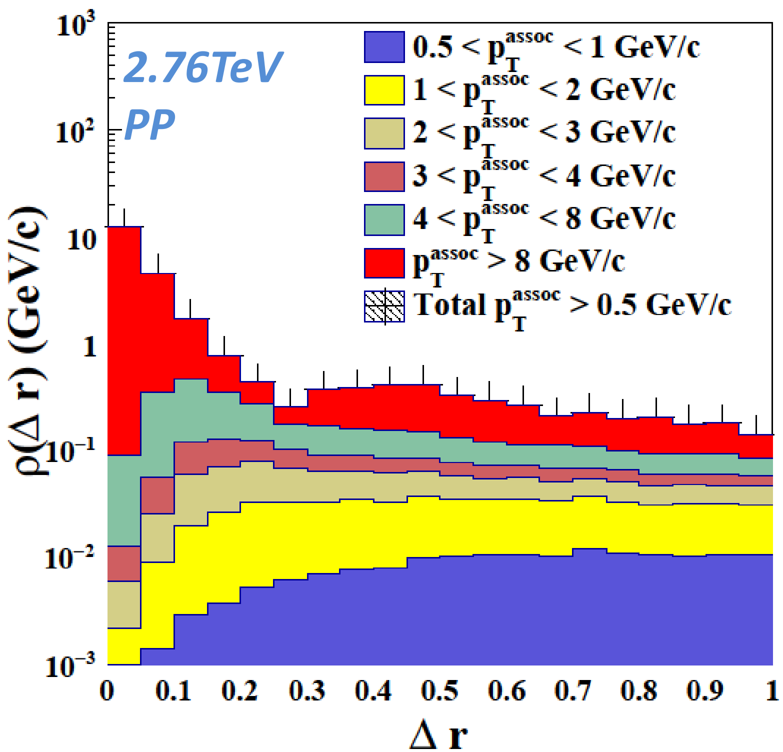
- The large energy fraction of leading particles in a reconstructed jet.
- γ-tagged jet FF, a better probe for the γ-jet study.

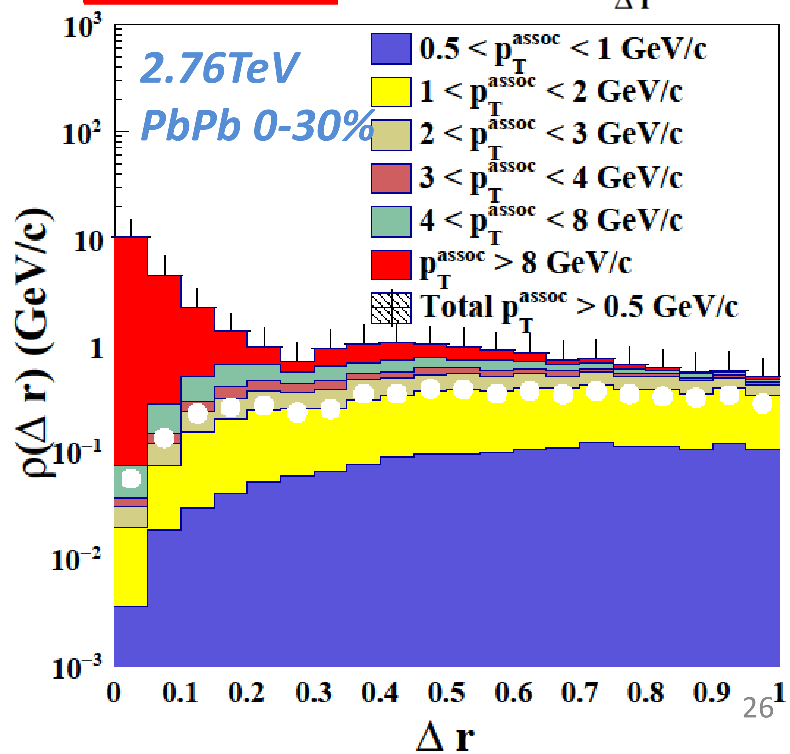
Jet shape of gamma-jets in heavy-ion collisions

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





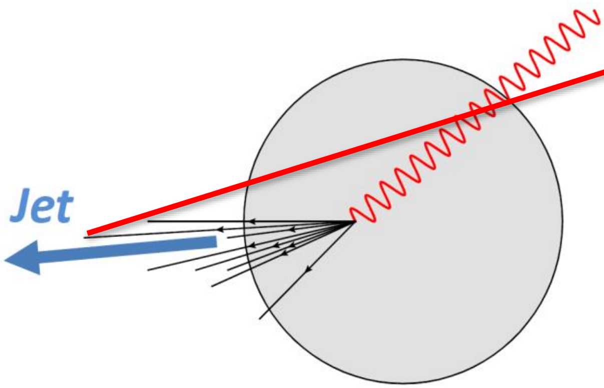


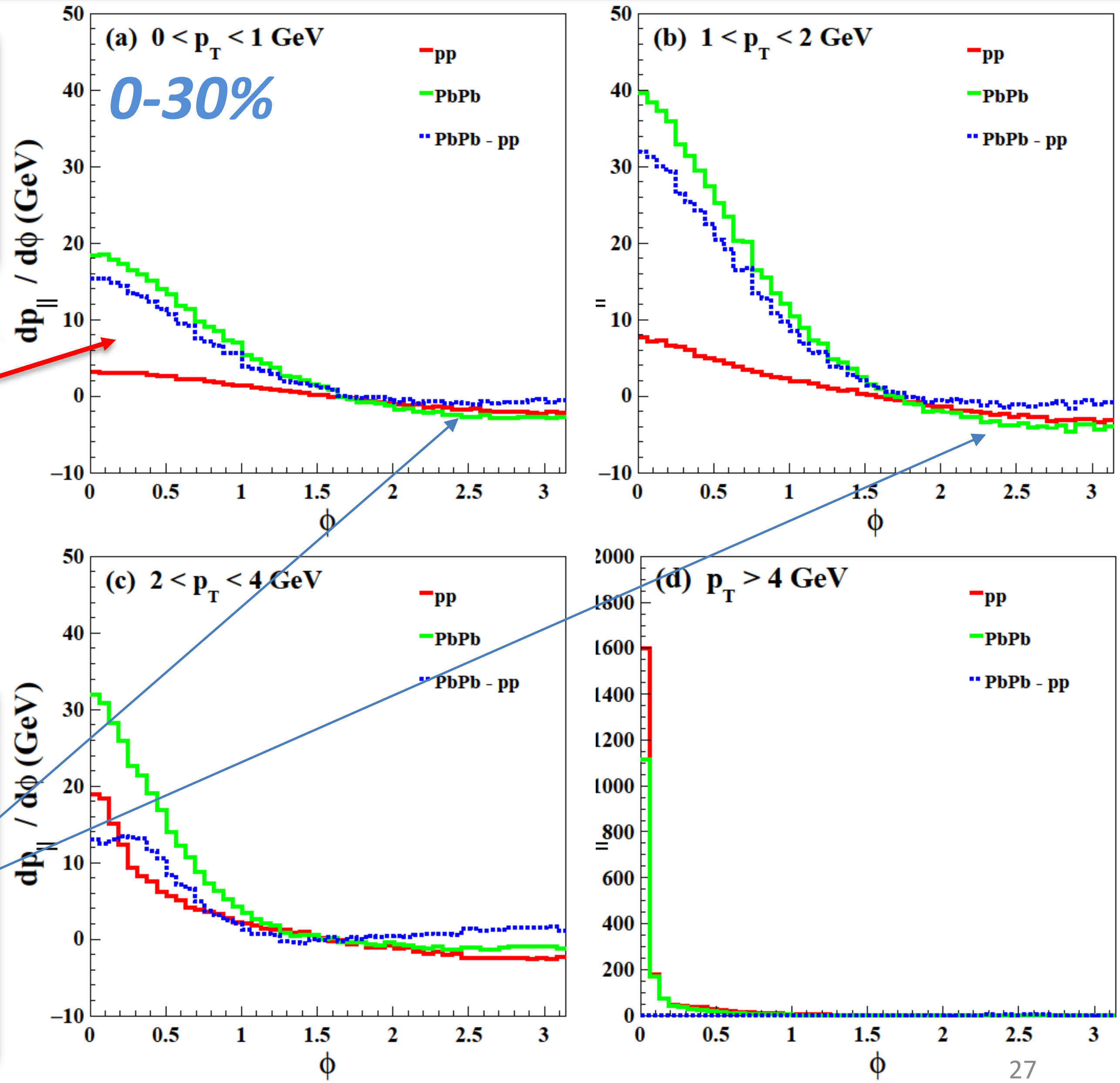


Energy flow in gamma-jets events

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

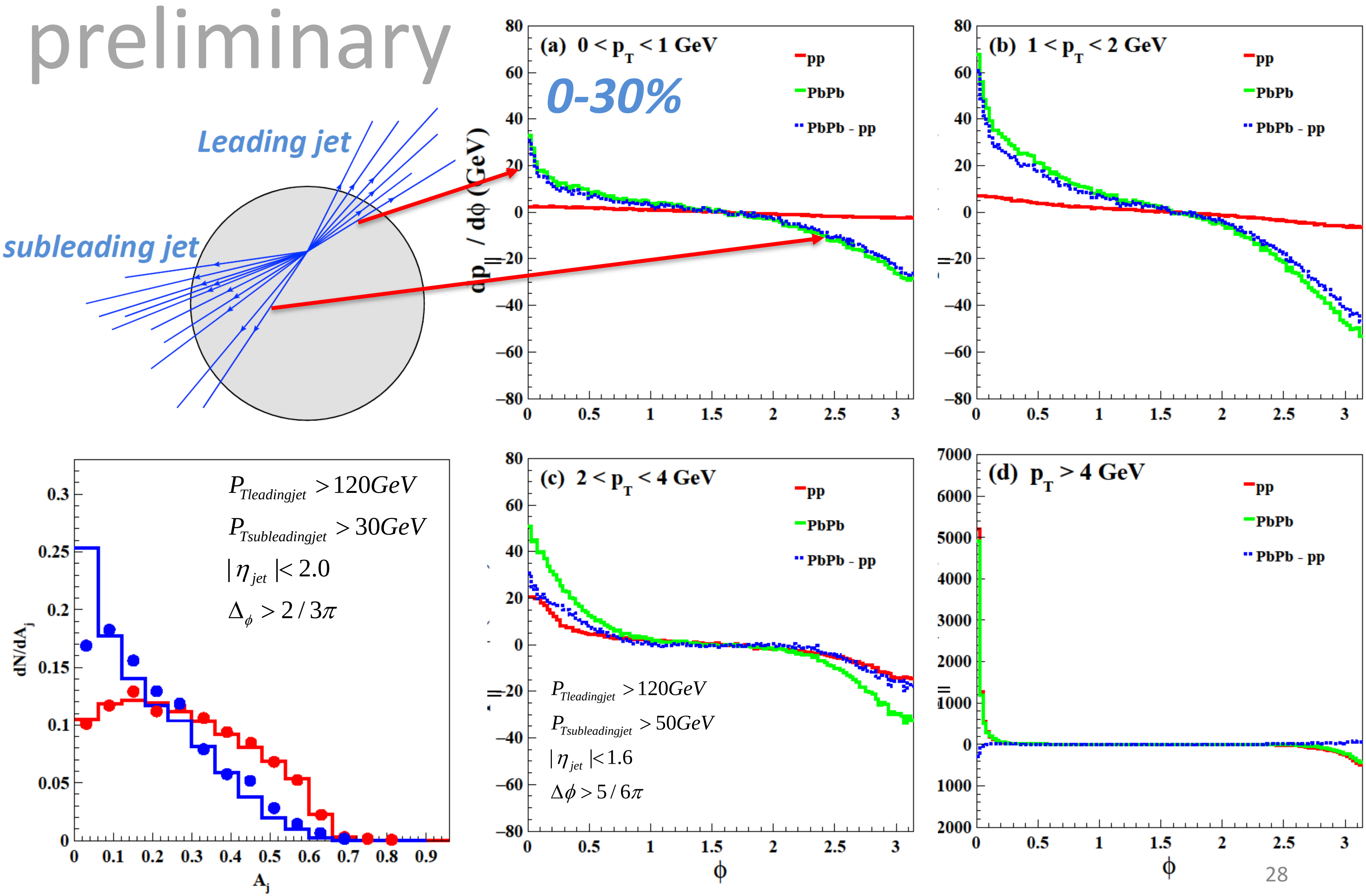
$$\phi = |\phi_{parton} - \phi_{leadingjet}|$$





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

Energy flow in dijet events



Jet shape of leading jet in heavy-ion collisions

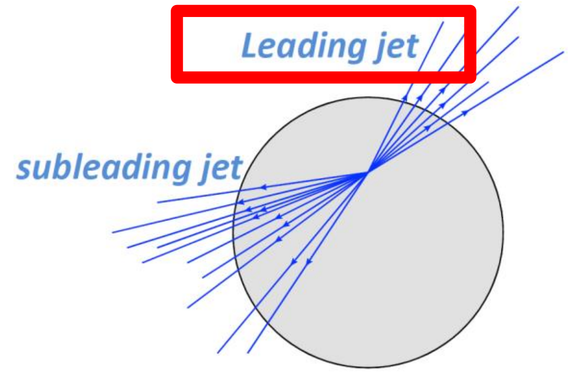
preliminary

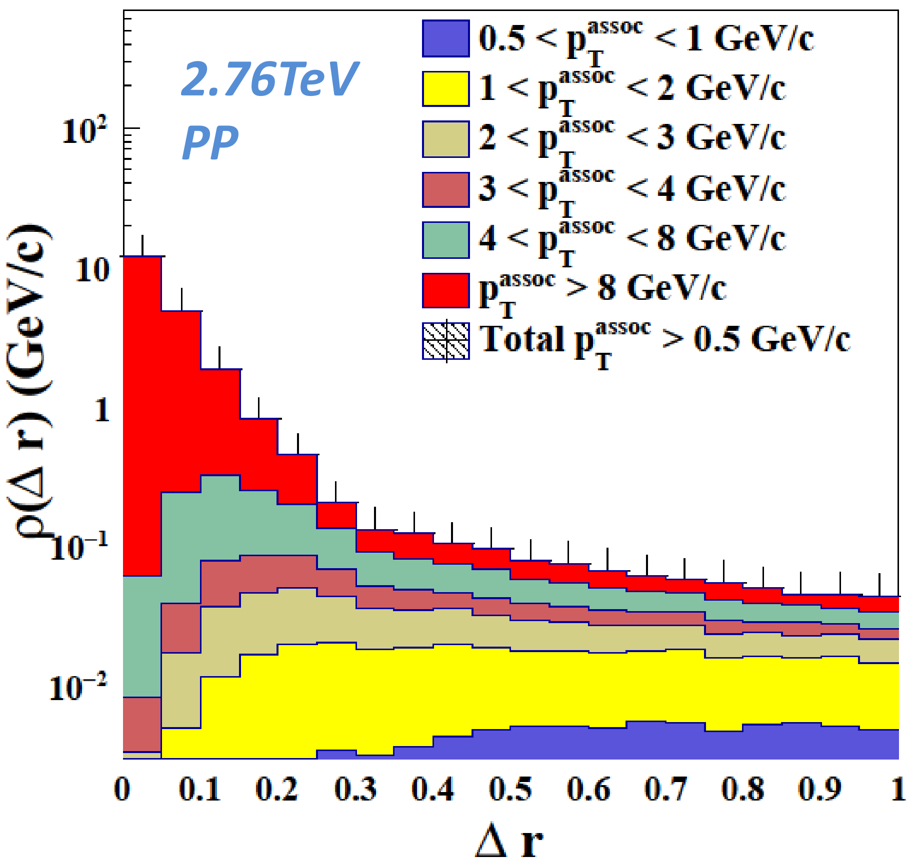
$P_{T leadingjet} > 120 GeV$

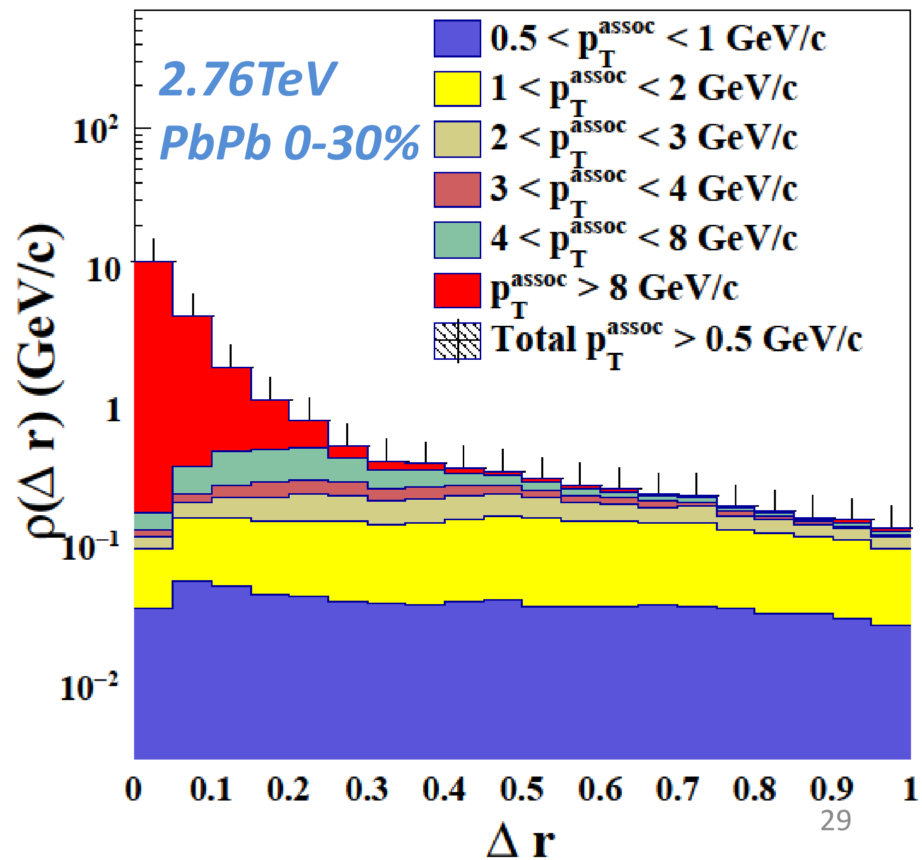
$P_{T subleadingjet} > 50 GeV$

$|\eta_{jet}| < 1.6$

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







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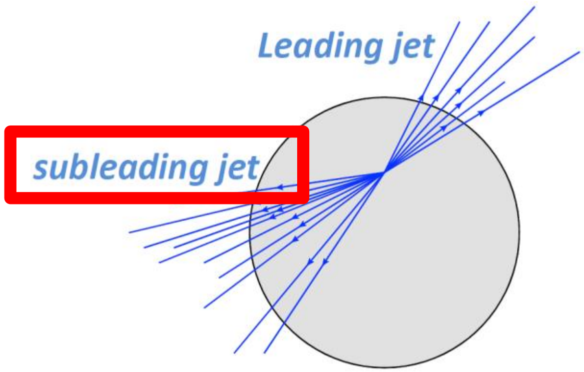
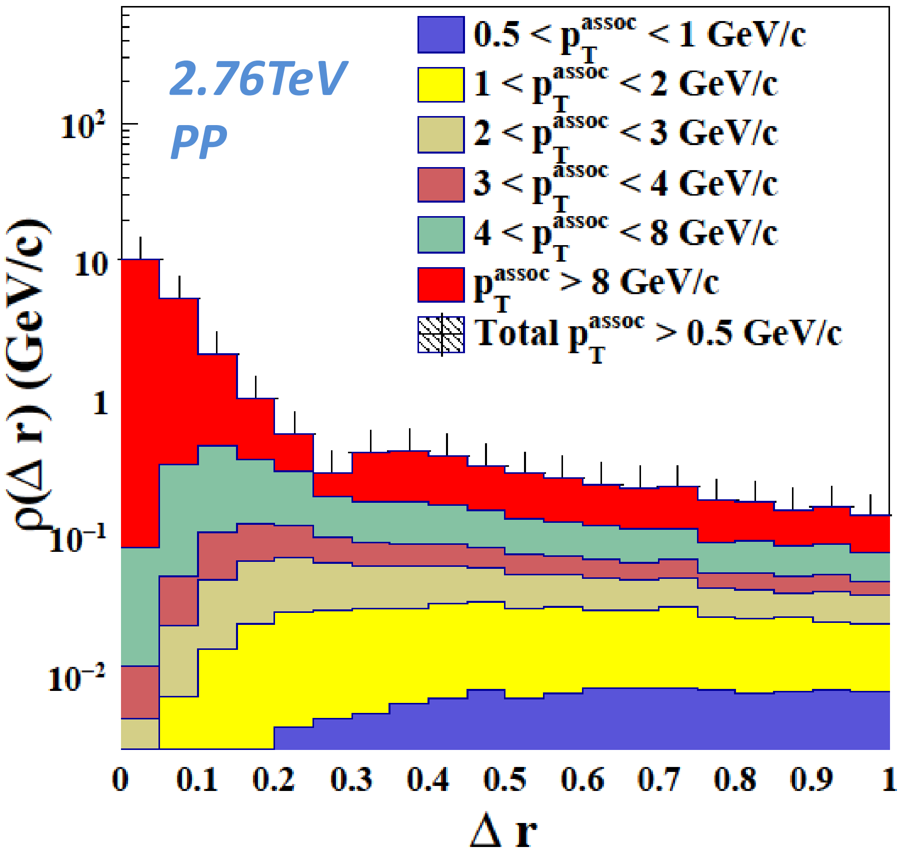
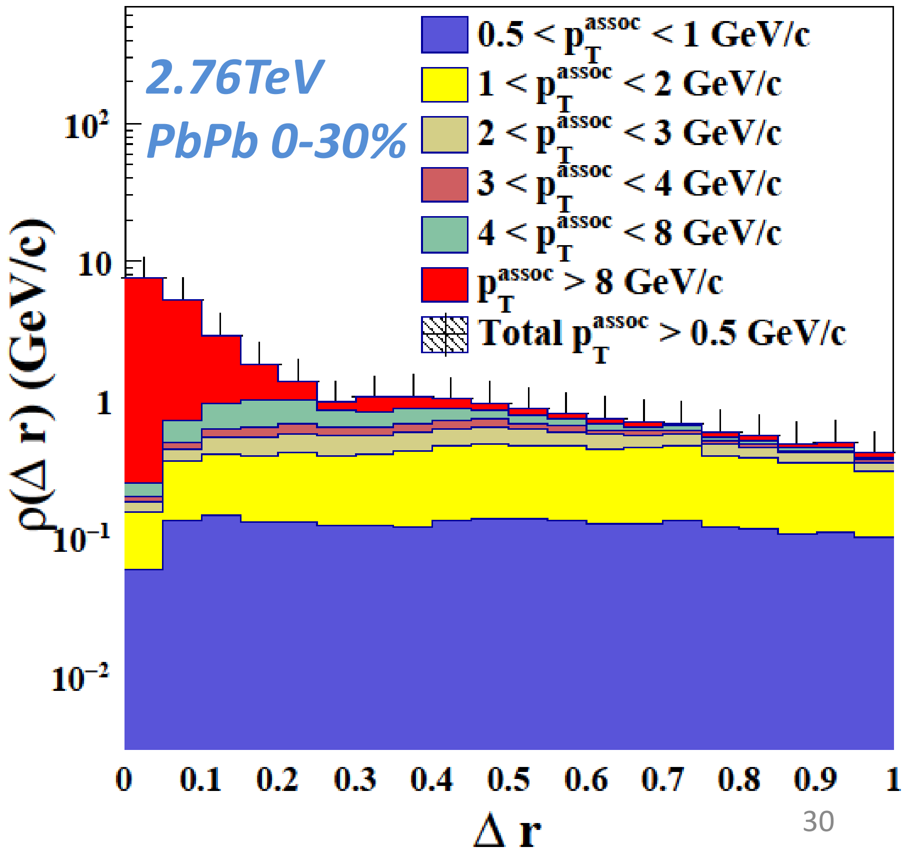
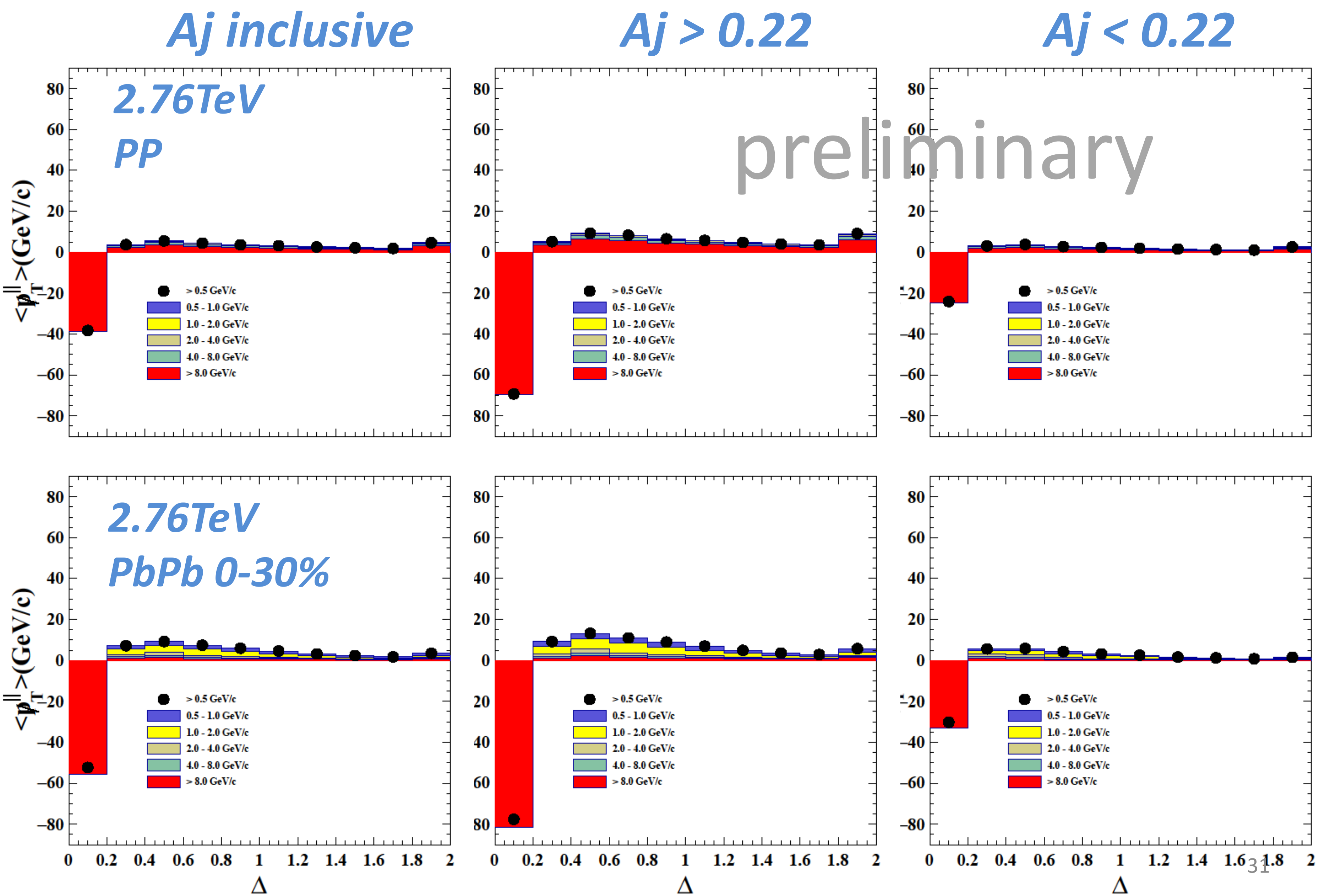
$\Delta_{\phi} > 5/6\pi$







pT imbalance of dijet in heavy-ion collisions



Summary

- We present a computation of jets modification in QGP within the Linear Boltzmann Transport model in which both the elastic and inelastic processes are included.

Outlook

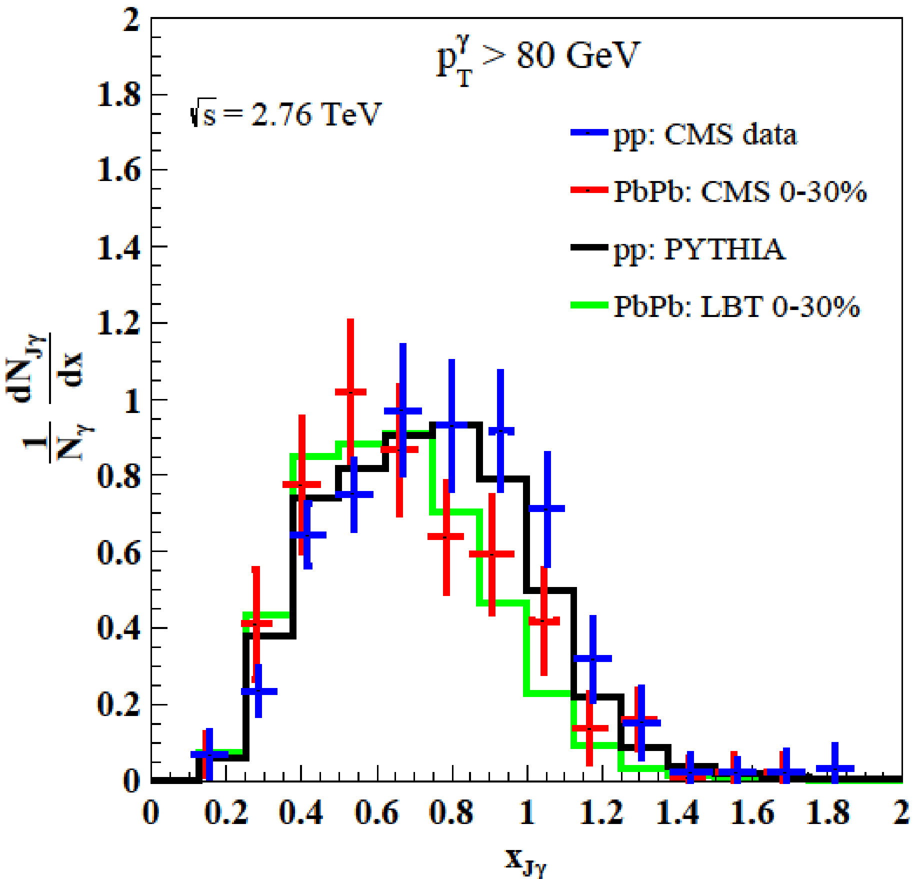
- *Hadron jet and Heavy quark jet*

(with the recombination model developed by Texas A&M group)

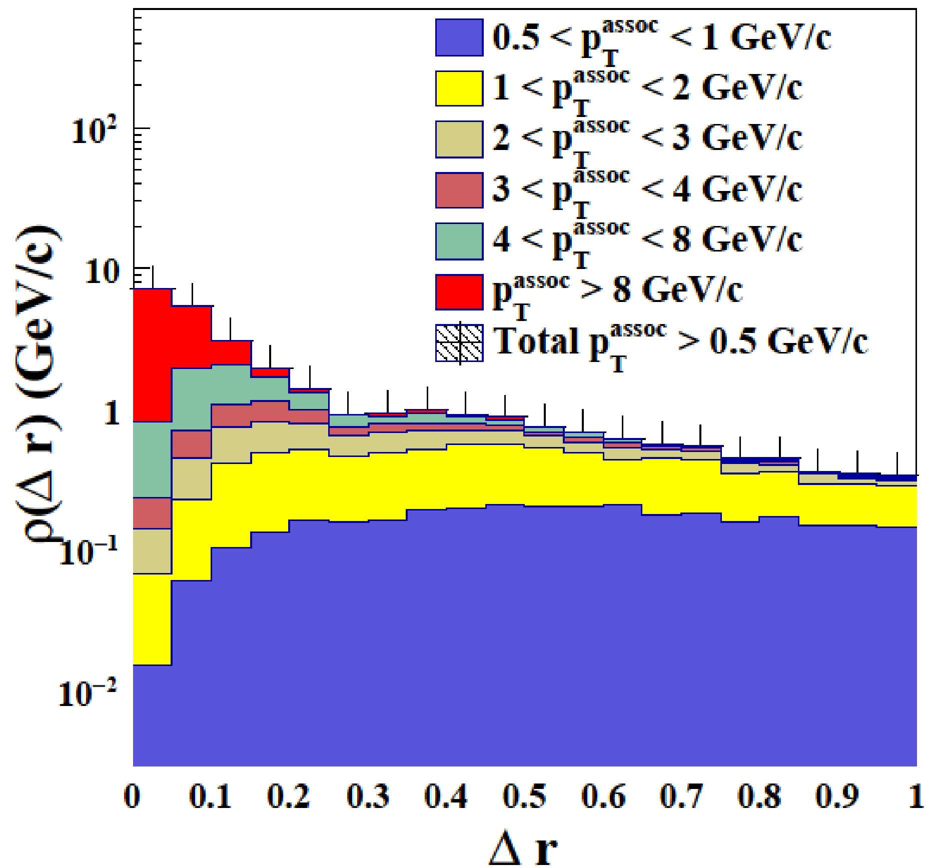
Rainer's talk

Jet reconstruction with recombination model

Gamma-jet asymmetry



Jet shape



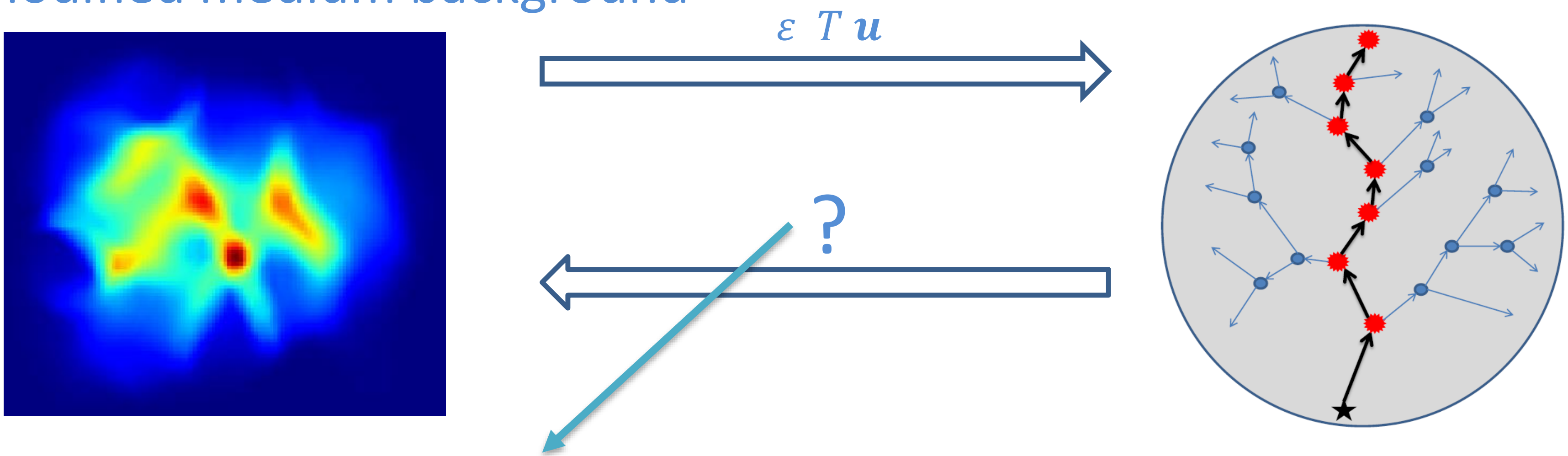
preliminary

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



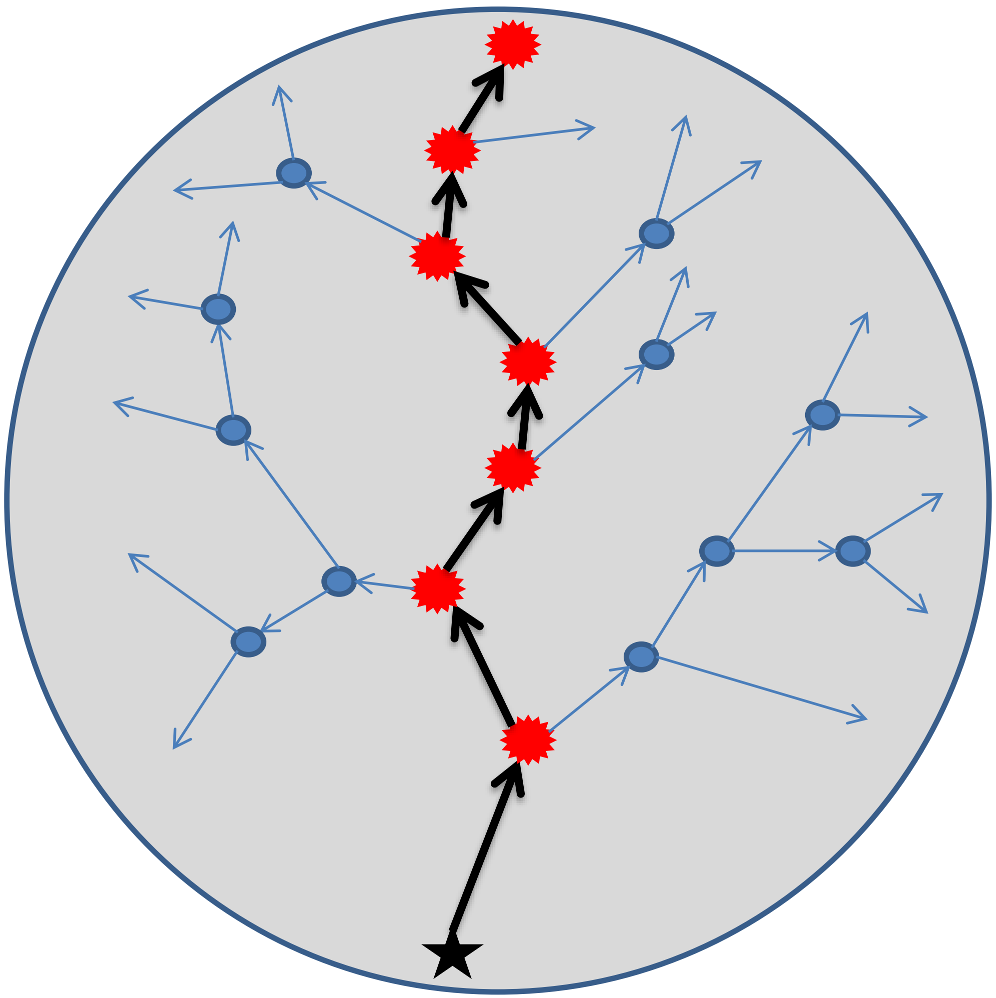
Energy and momentum deposited from the jets as source terms into hydro

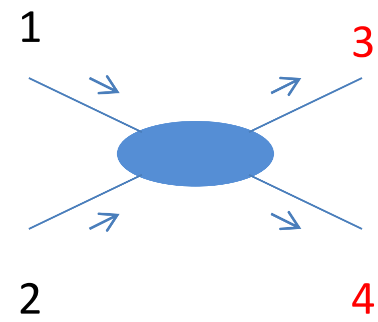
CoLBT-Hydro model
(A coupled LBT Hydro (3+1D) Model)

Wei Chen's talk

Thanks

Positive particles : Medium Excitation





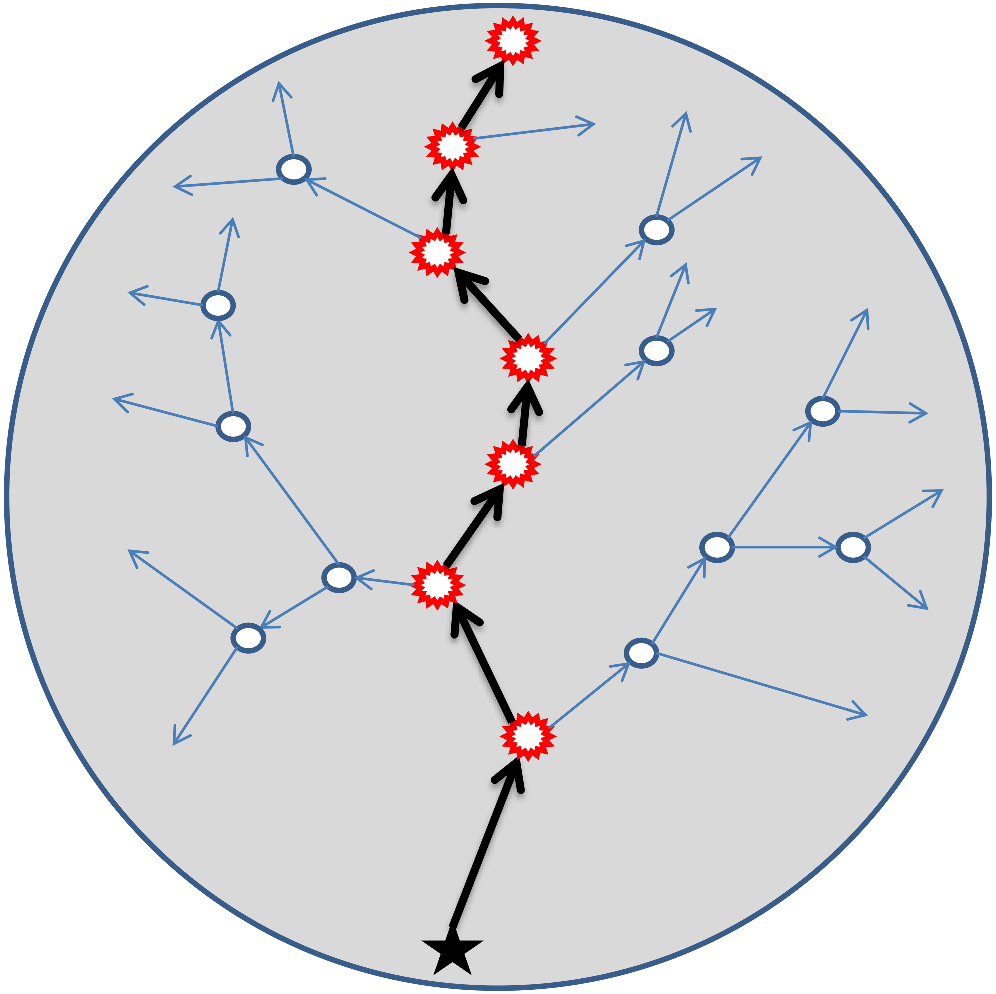
Leading parton-----thermal parton scattering

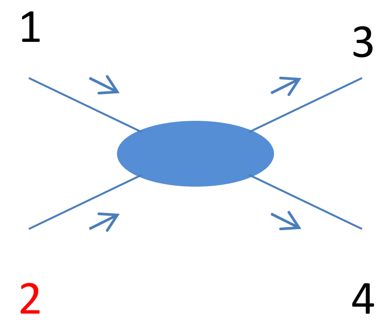
recoiled parton-----thermal parton scattering

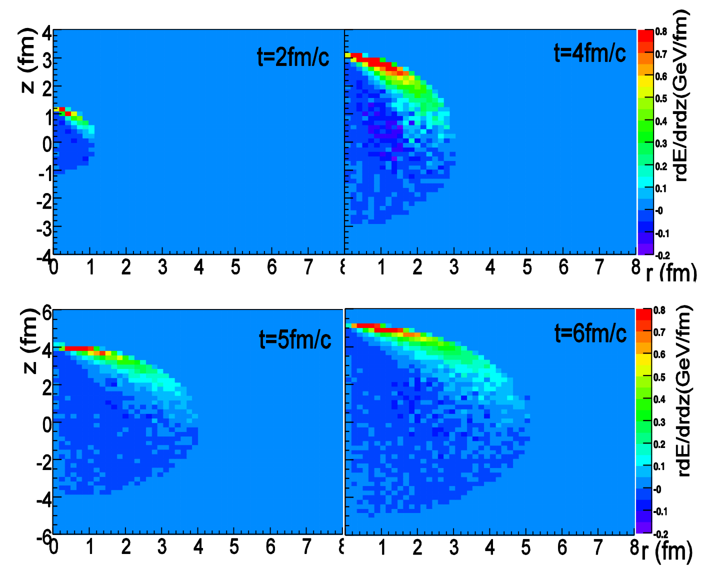
Linearized Boltzmann jet transport
neglect scatterings between recoiled medium partons.

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

Negative particles : the particle hole

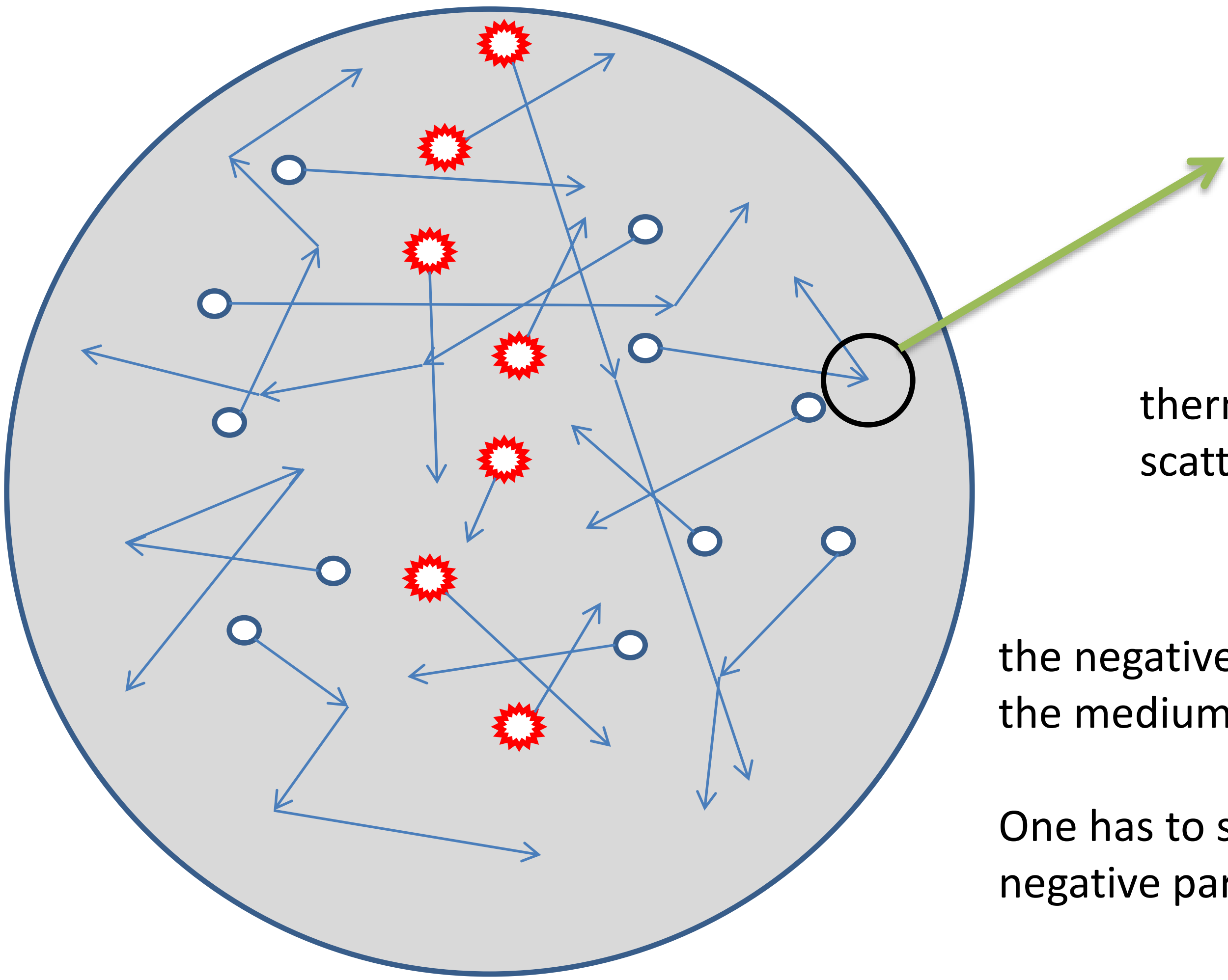


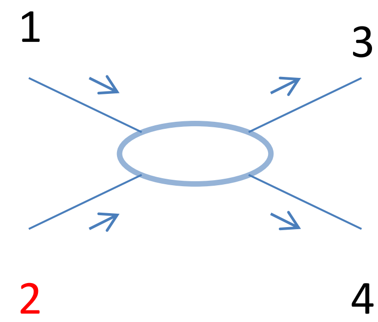




One has to subtract the 4-momentum of negative particle when combine it to jet

Negative particles : how do we deal with them?





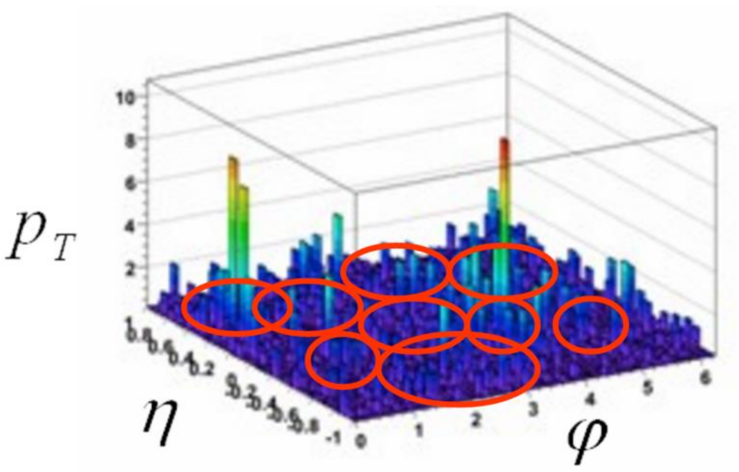
thermal parton-----thermal parton scattering

the negative particle is also traveling in the medium

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

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

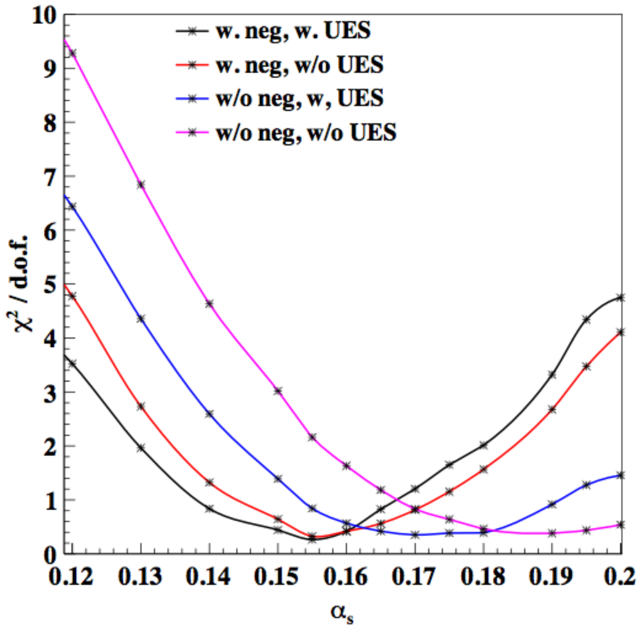
$$E_T^{max}/E_T^{ave} > 4$$

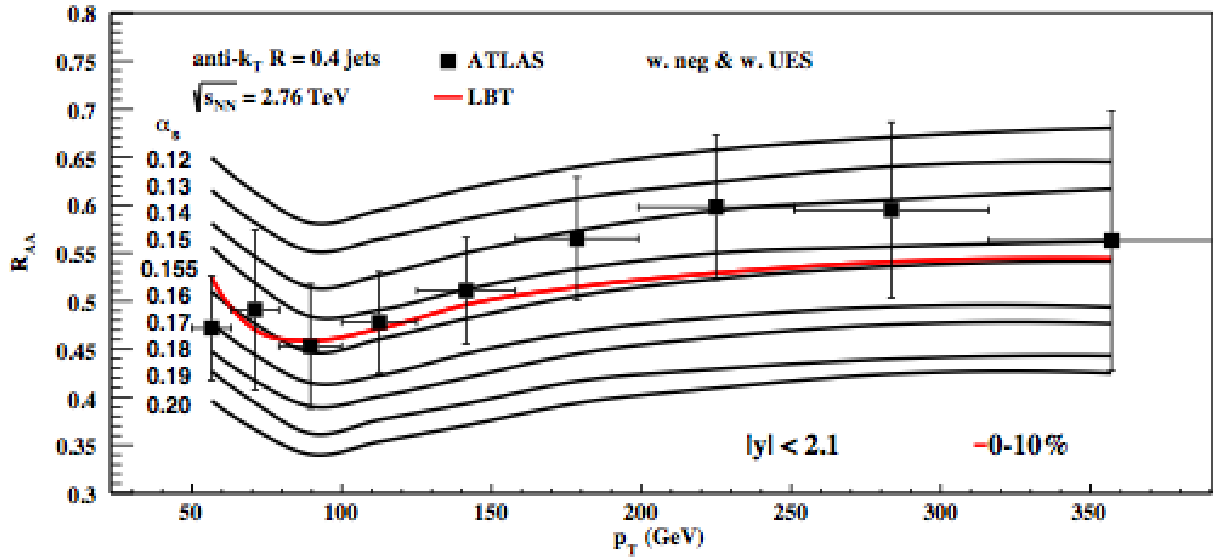
ATLAS Collaboration, Phys. Lett. B 719, 220 (2013).

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

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

Nuclear modification factor





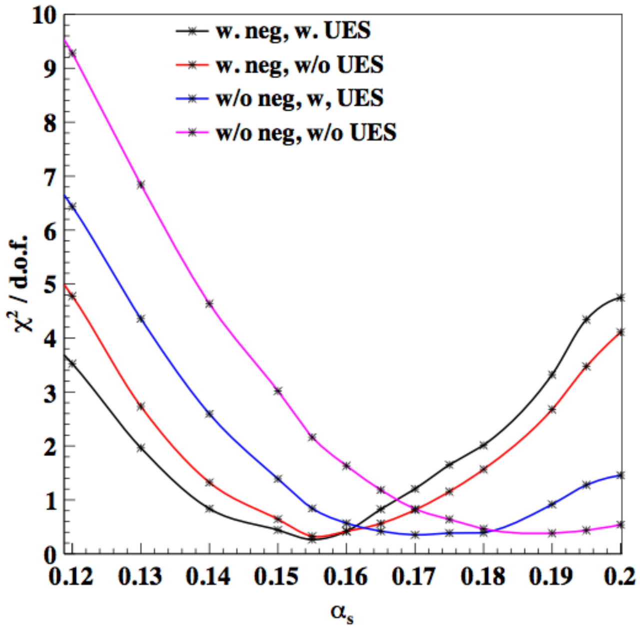
$$\chi^2 = \frac{(Theo. - Exp.)^2}{(\delta Exp.)^2}$$

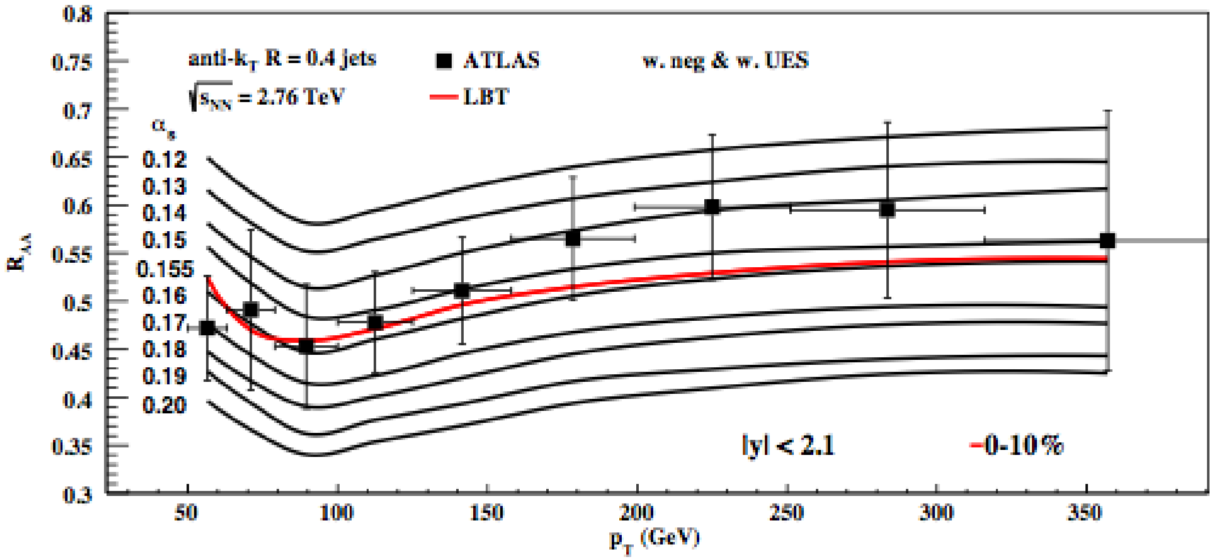
$$R_{AA} = \frac{\frac{1}{N_{evt}} \frac{d^2 N_{jet}^{AA}}{dp_T dy}}{\frac{1}{N_{evt}} \frac{d^2 N_{jet}^{pp}}{dp_T dy}}$$

We use the best χ^2 fit to extract the fixed value α_s in the LBT model

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

Nuclear modification factor





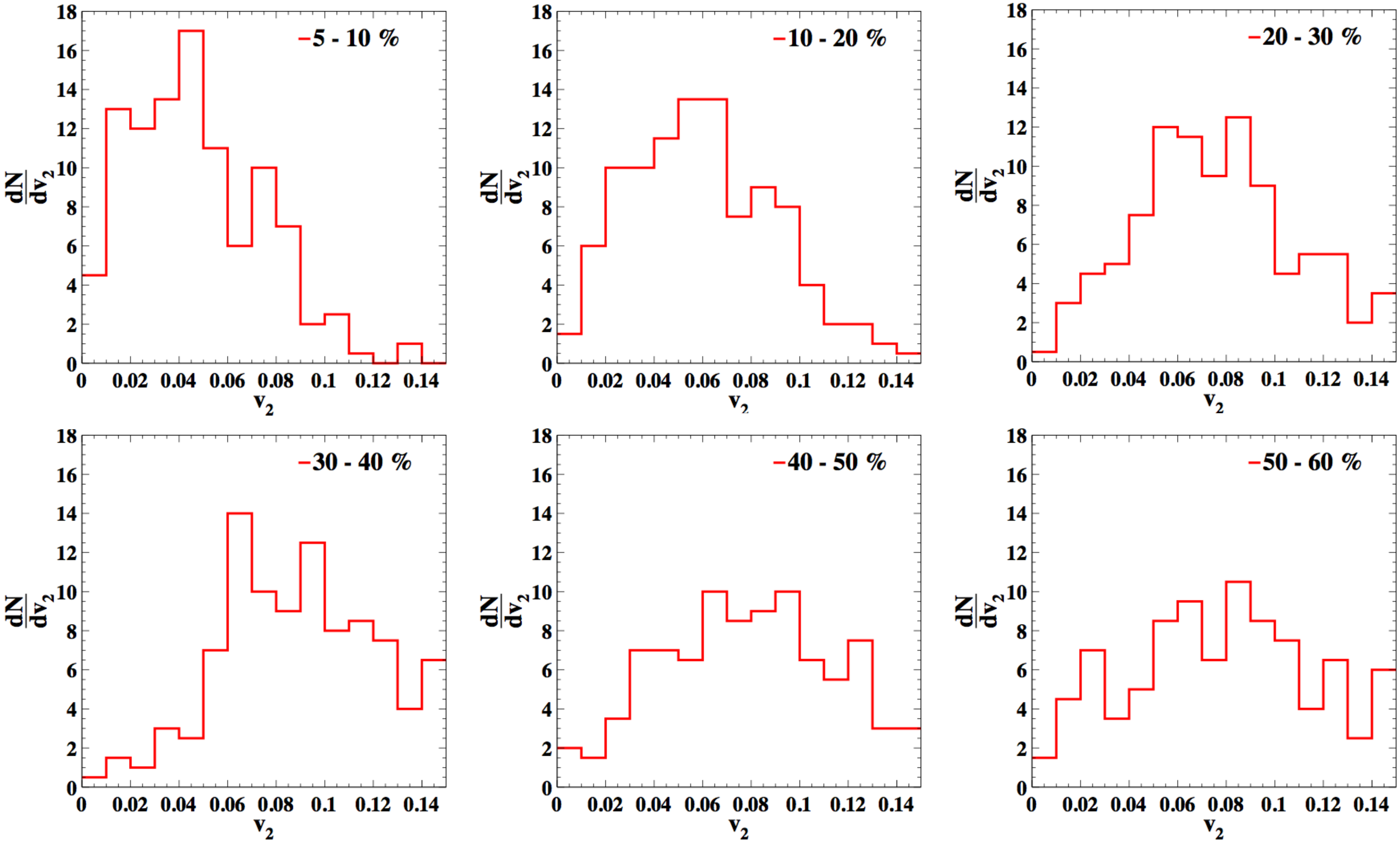
$$\chi^2 = \frac{(Theo. - Exp.)^2}{(\delta Exp.)^2}$$

$$R_{AA} = \frac{\Sigma_i w_i \frac{1}{N_{events}} \frac{dN_i^{jets}}{dp_T} |AA}{\Sigma_i w_i \frac{1}{N_{events}} \frac{dN_i^{jets}}{dp_T} |pp|}$$

We use the best χ^2 fit to extract the fixed value α_s in the LBT model

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

v_2 of soft particles from hydro profiles

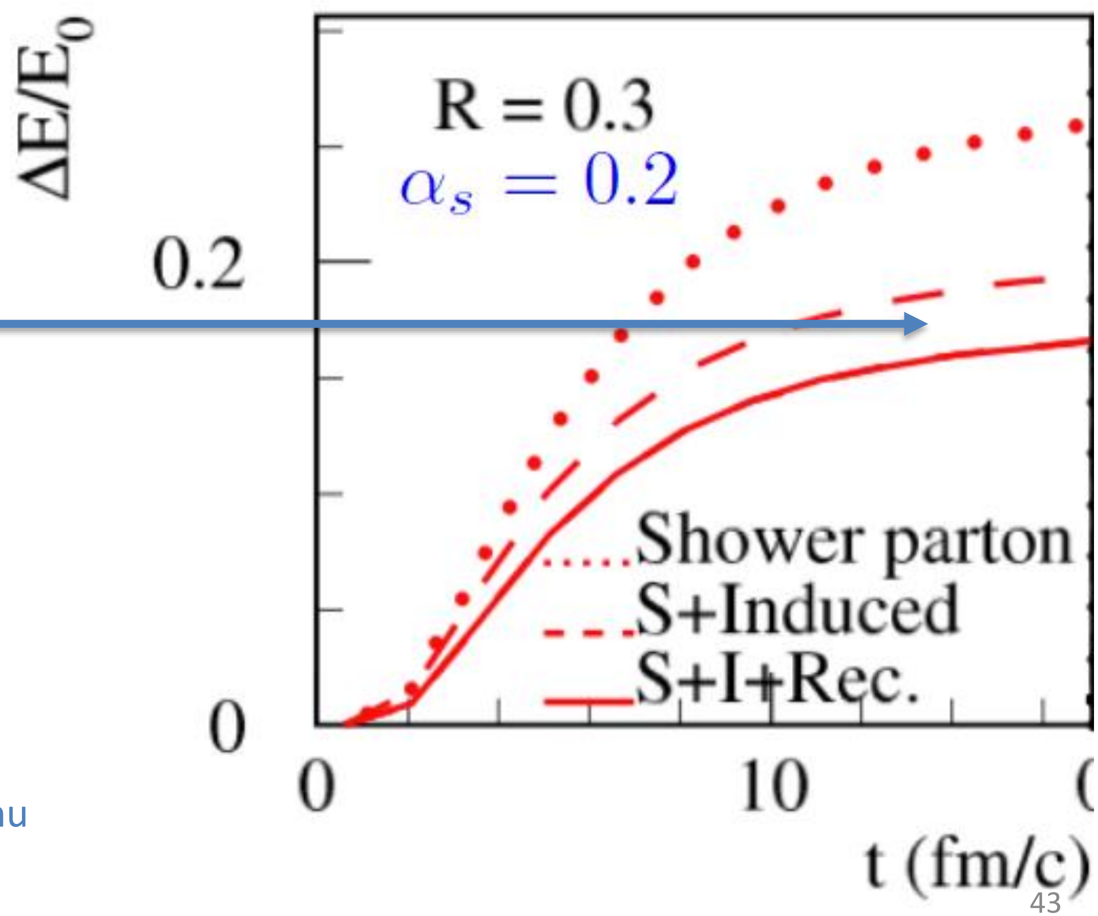


Jets in a 3+1D hydro

- 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.

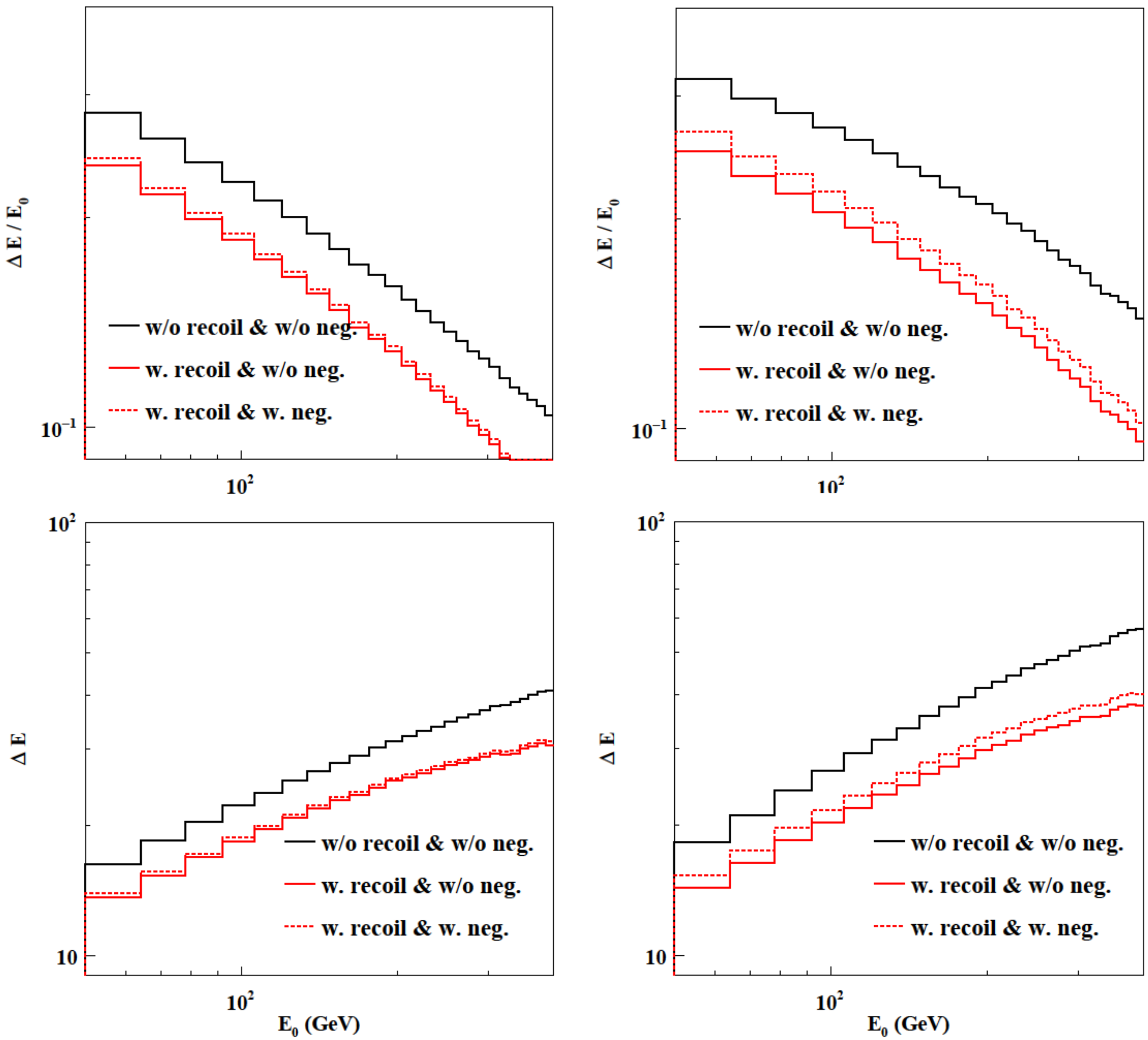
Recoiled effect in the reconstructed jets

The contribution of the recoiled parton in the reconstructed jets



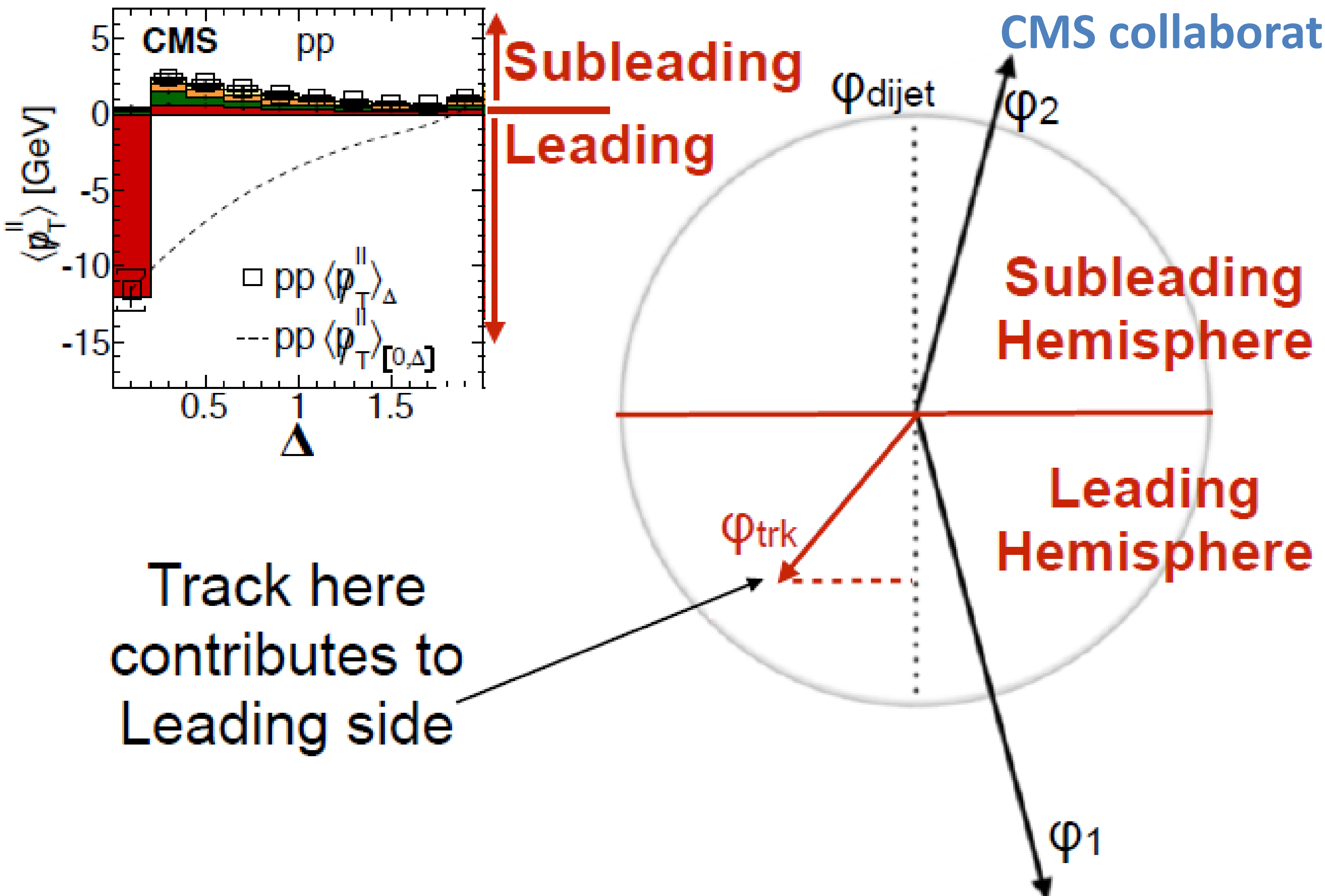
HL Li, FM Liu, GL Ma, XN Wang, Y Zhu
Phys.Rev.Lett. 106, 012301
Xin-Nian Wang, Yan Zhu
Phys.Rev.Lett. 111, 062301
Yayun He, Tan Luo, Xin-Nian Wang, Yan Zhu
Phys.Rev. C91 (2015) 054908

Recoiled effect in the reconstructed jets



pT imbalance of dijet in heavy-ion collisions

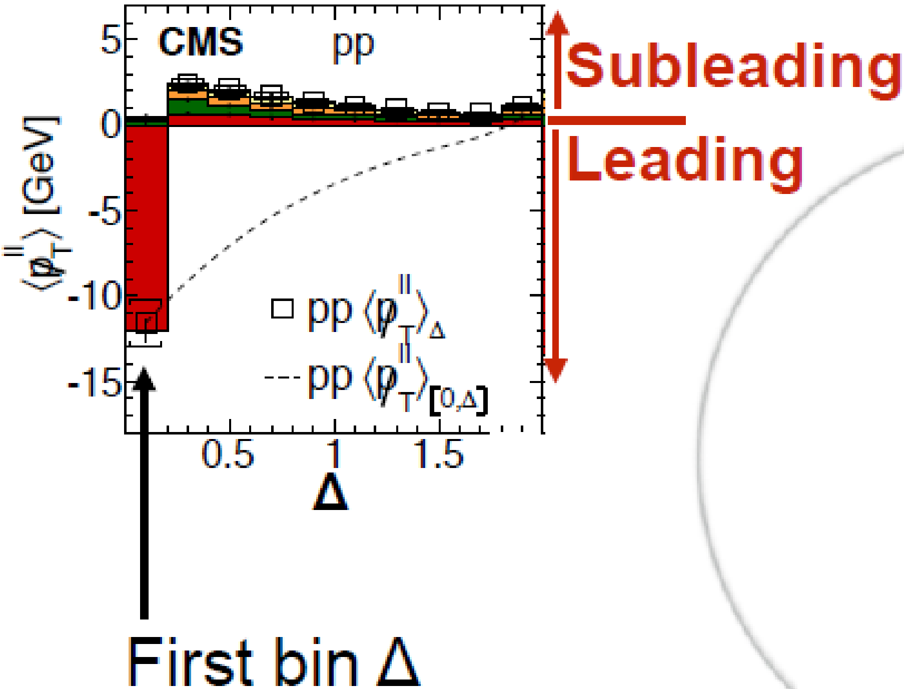
Christopher McGinn
CMS collaboration

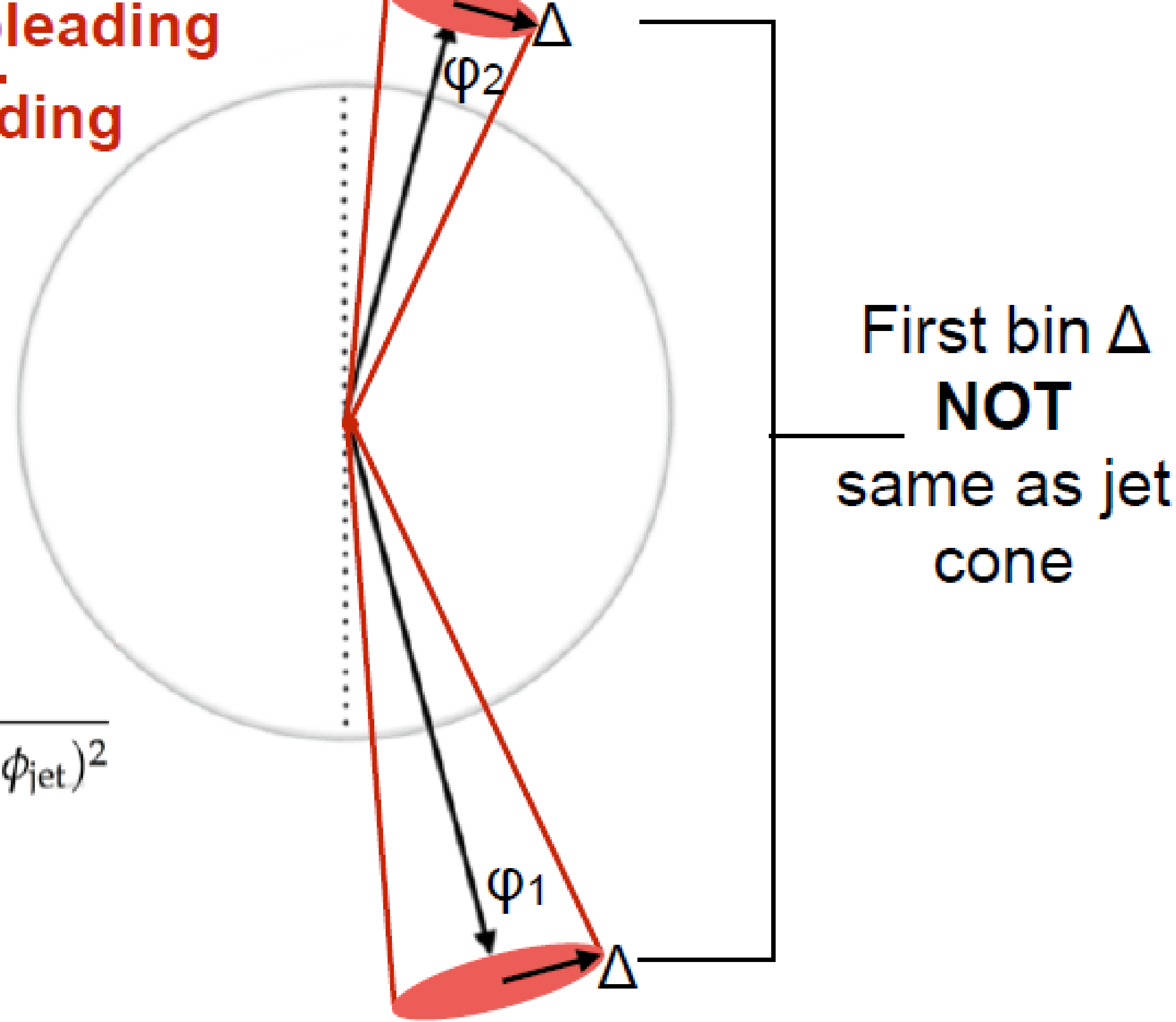


$$p_T^{||} = -c^{trk} \times p_T^{trk} \times \cos\left(\phi_{trk} - \phi_{dijet}\right)$$

pT imbalance of dijet in heavy-ion collisions

Christopher McGinn
CMS collaboration

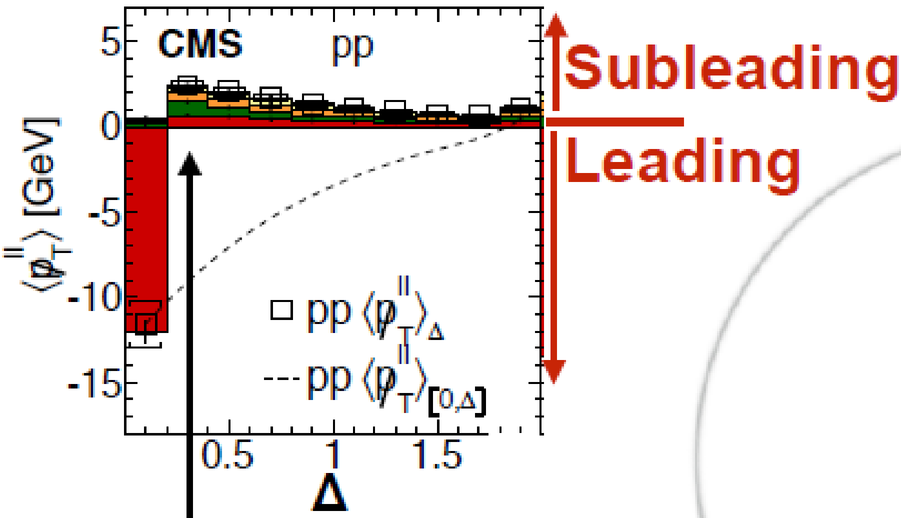




$$\Delta = \sqrt{(\eta_{trk} - \eta_{jet})^2 + (\phi_{trk} - \phi_{jet})^2}$$

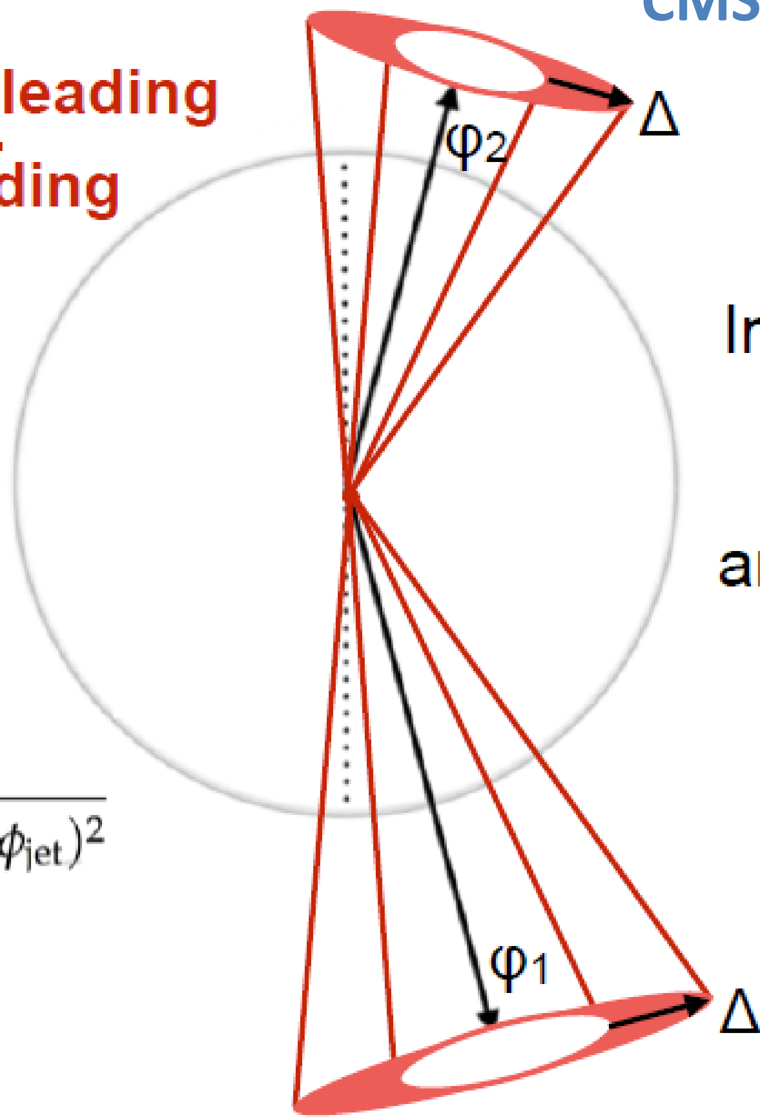
pT imbalance of dijet in heavy-ion collisions

Christopher McGinn
CMS collaboration



Second bin Δ

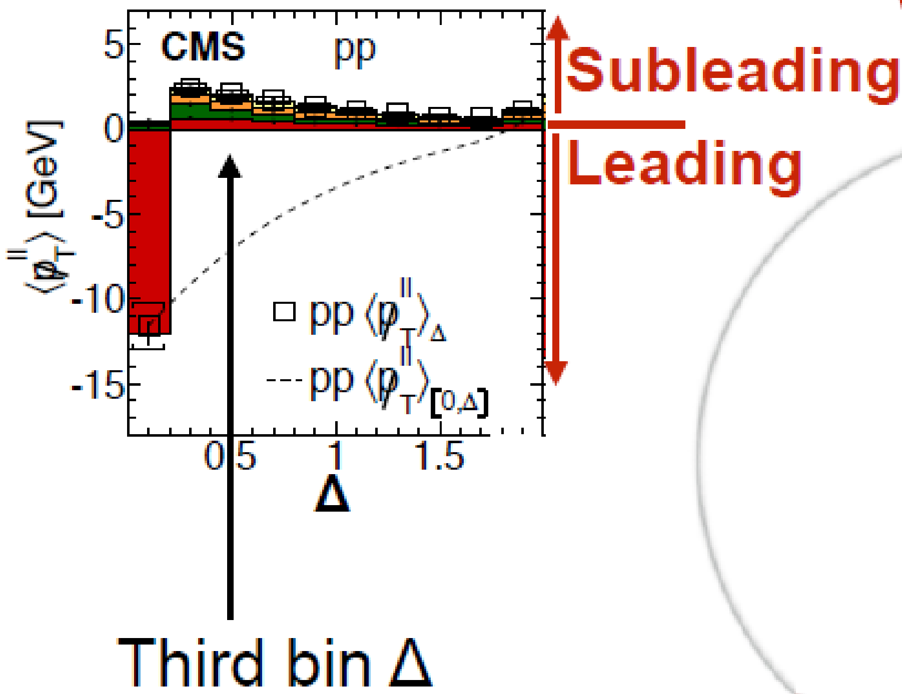
$$\Delta = \sqrt{(\eta_{trk} - \eta_{jet})^2 + (\phi_{trk} - \phi_{jet})^2}$$



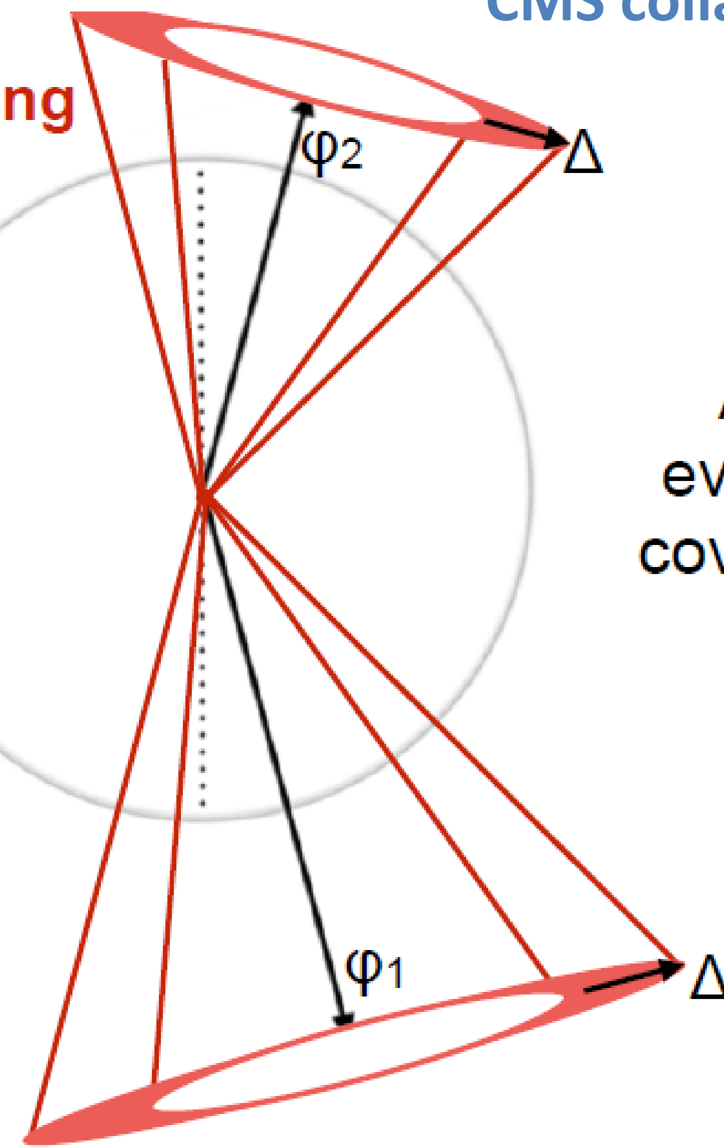
Increasing Δ -> Move away from leading and subleading jets

pT imbalance of dijet in heavy-ion collisions

Christopher McGinn
CMS collaboration



$$\Delta = \sqrt{(\eta_{trk} - \eta_{jet})^2 + (\phi_{trk} - \phi_{jet})^2}$$

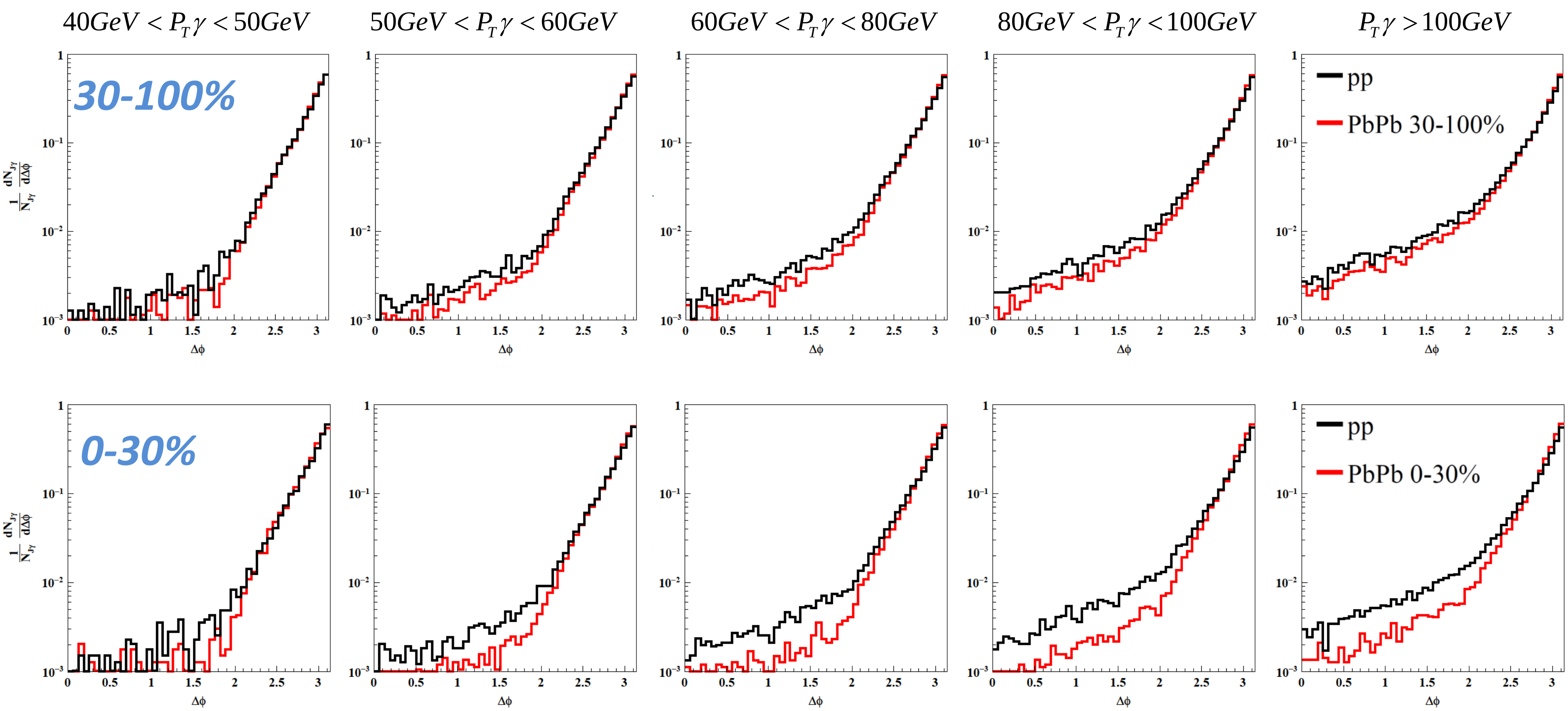


Annuli eventually cover entire event

Azimuthal distribution of gamma-jets in heavy-ion collisions

5.02TeV

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

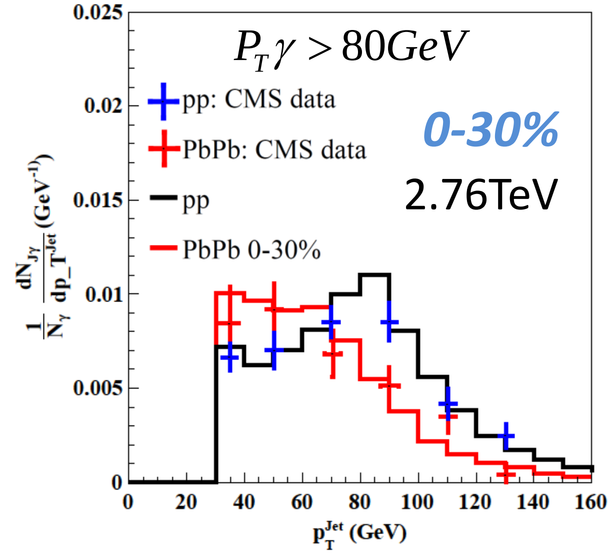


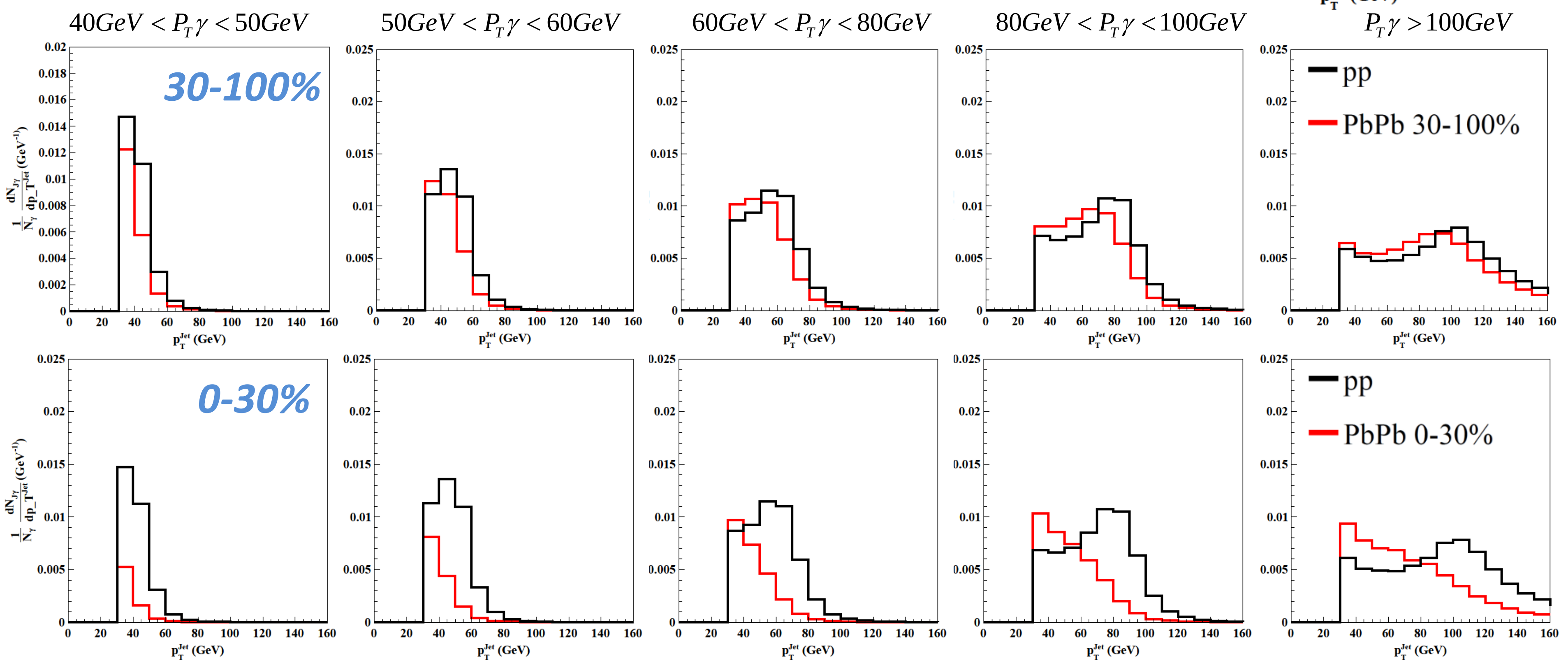
pT distribution of gamma-jets in heavy-ion collisions

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

5.02TeV

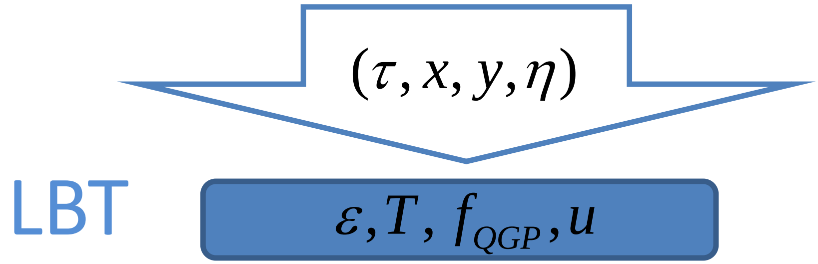
$$\Delta\phi_{J\gamma} > 7/8\pi$$





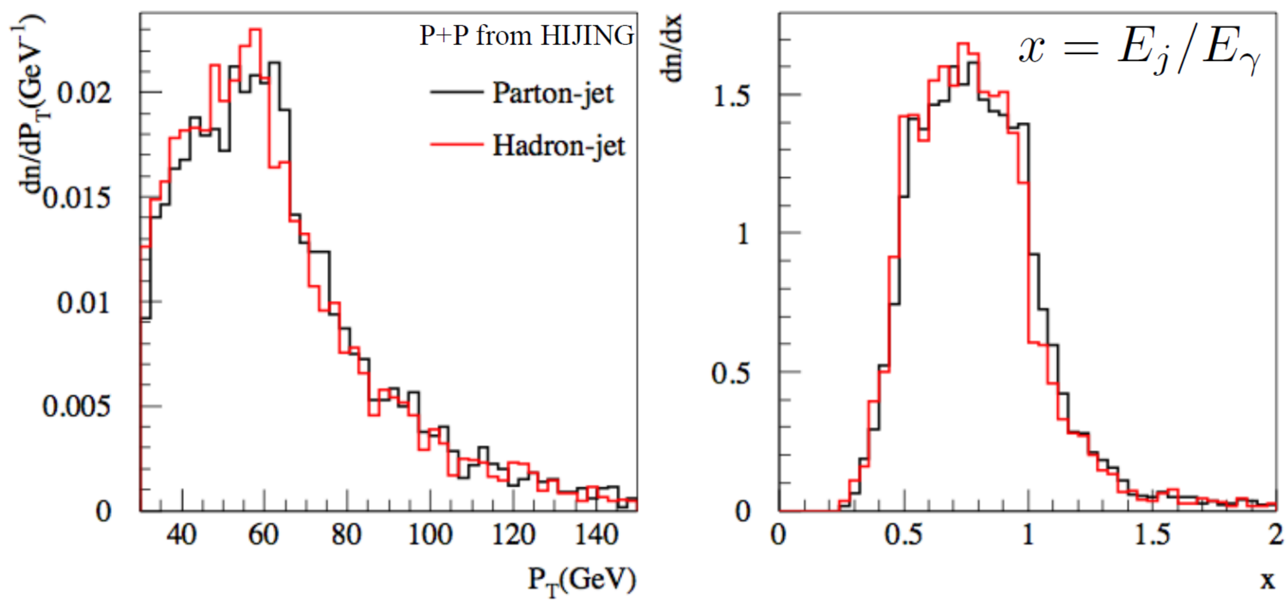
Gamma-jets in a 3+1D hydro

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



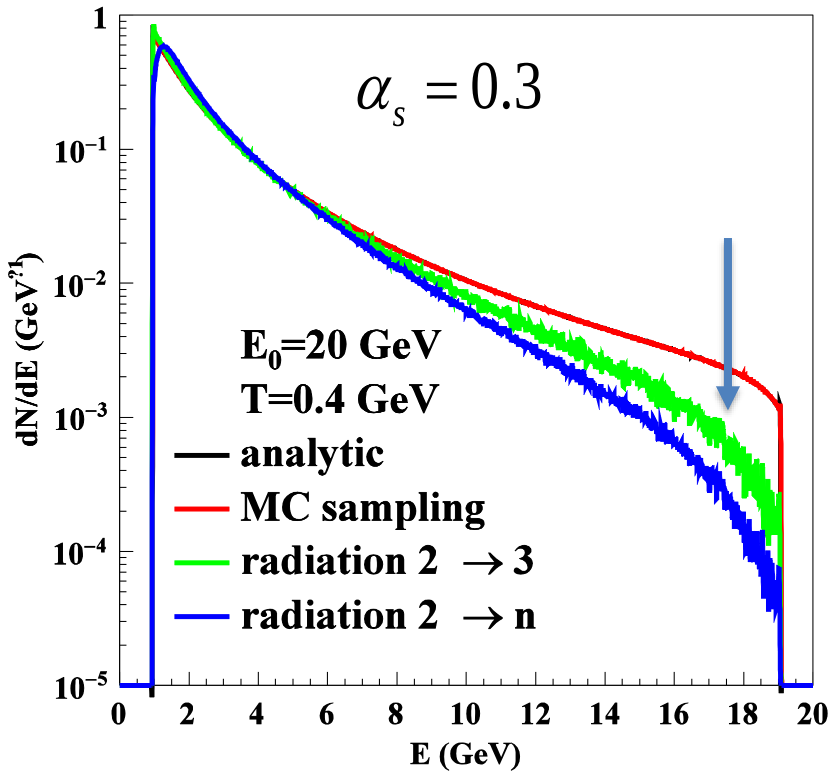
- Location of gamma-jet is decided according probability of binary collision.

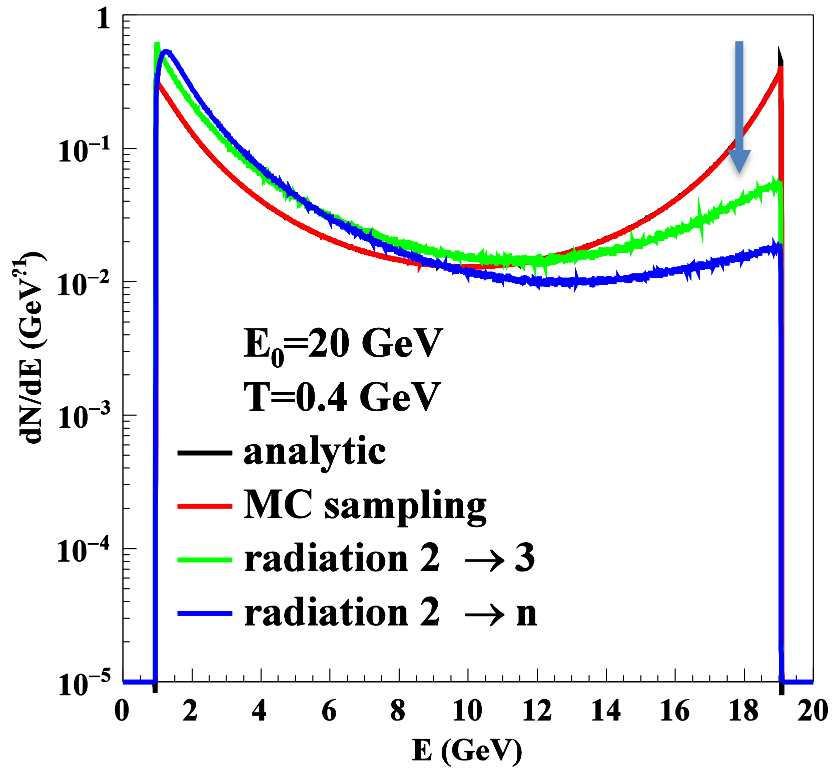
- Small difference between parton-jet and hadron-jet.



Energy distribution of the radiated gluon

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



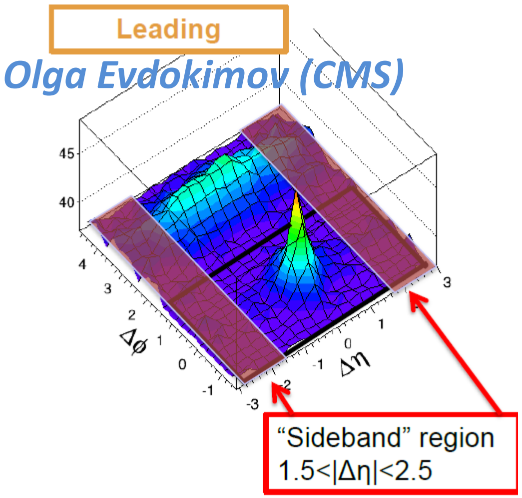


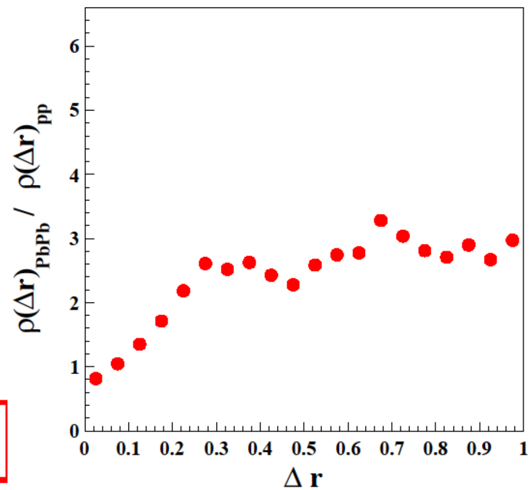
$$P_{q\to qg}(x) = C_A \frac{(1-x)(1+(1-x)^2)}{x}$$

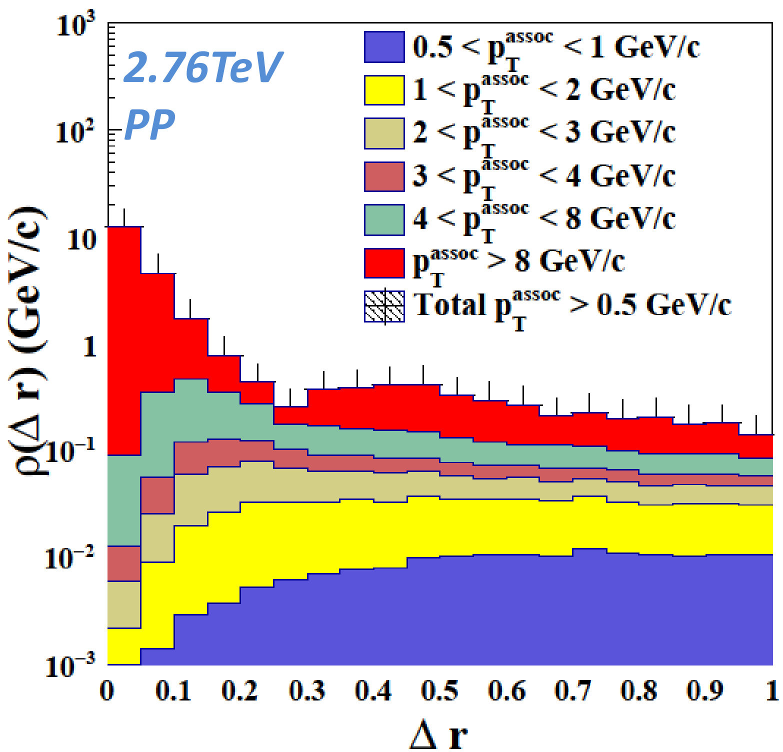
$$P_{g\to gg}(x) = 2N_C \frac{(1-x+x^2)^3}{x(1-x)}$$

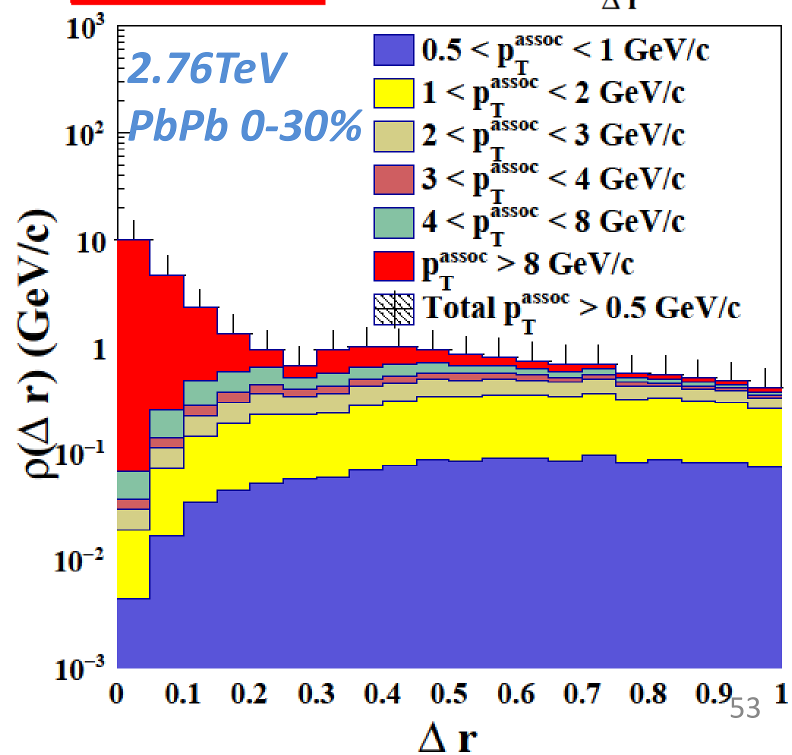
Jet shape of gamma-jets in heavy-ion collisions

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









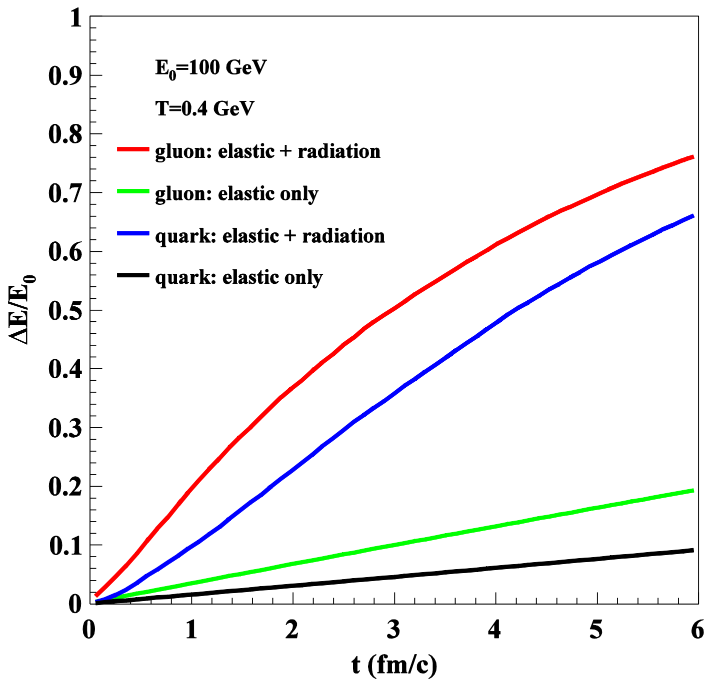
Nontrivial path length dependence on parton energy loss

Leading parton energy loss

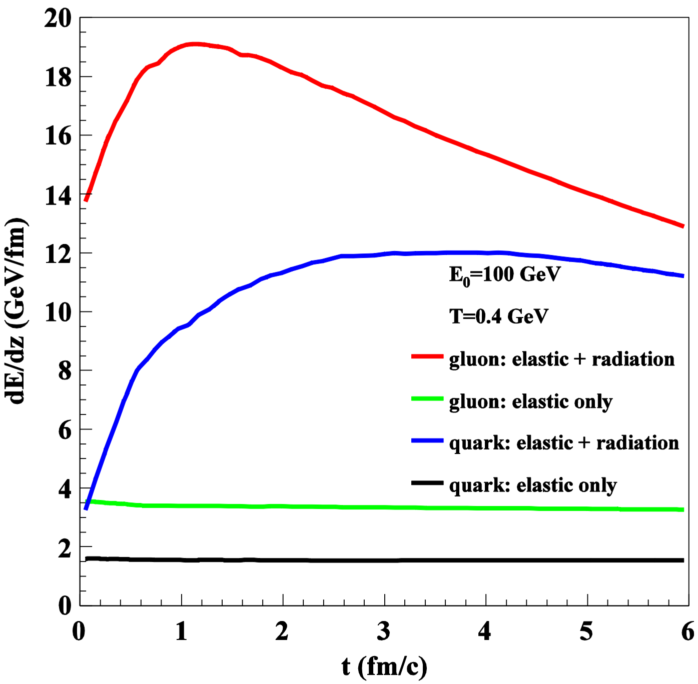
Propagation of a single initial jet parton in a uniform medium

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

Fractional energy loss



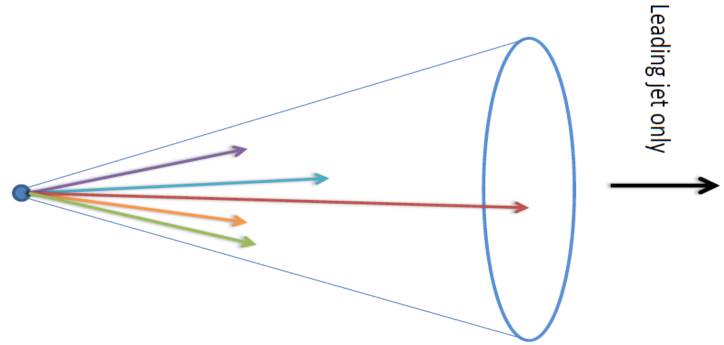
Energy loss per unit length



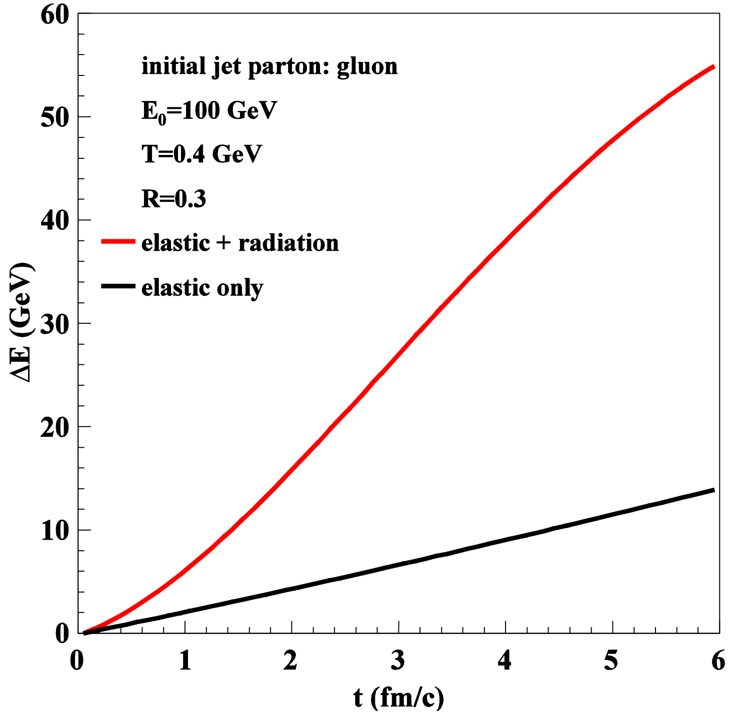
Path length dependence on parton energy loss

Leading jet energy loss

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



Initial jet parton: gluon



Initial jet parton: quark