Jet Quenching and Medium Excitation in High-Energy Heavy-Ion Collisions

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Outline

- Jet Quenching in Heavy Ion Collisions
- Linearized Boltzmann Transport Model
- Results (in a uniform and hydrodynamic medium)
  - Jet Energy Loss
  - Jet Structure Evolution
  - γ-jet Correlation
- Summary and Outlook

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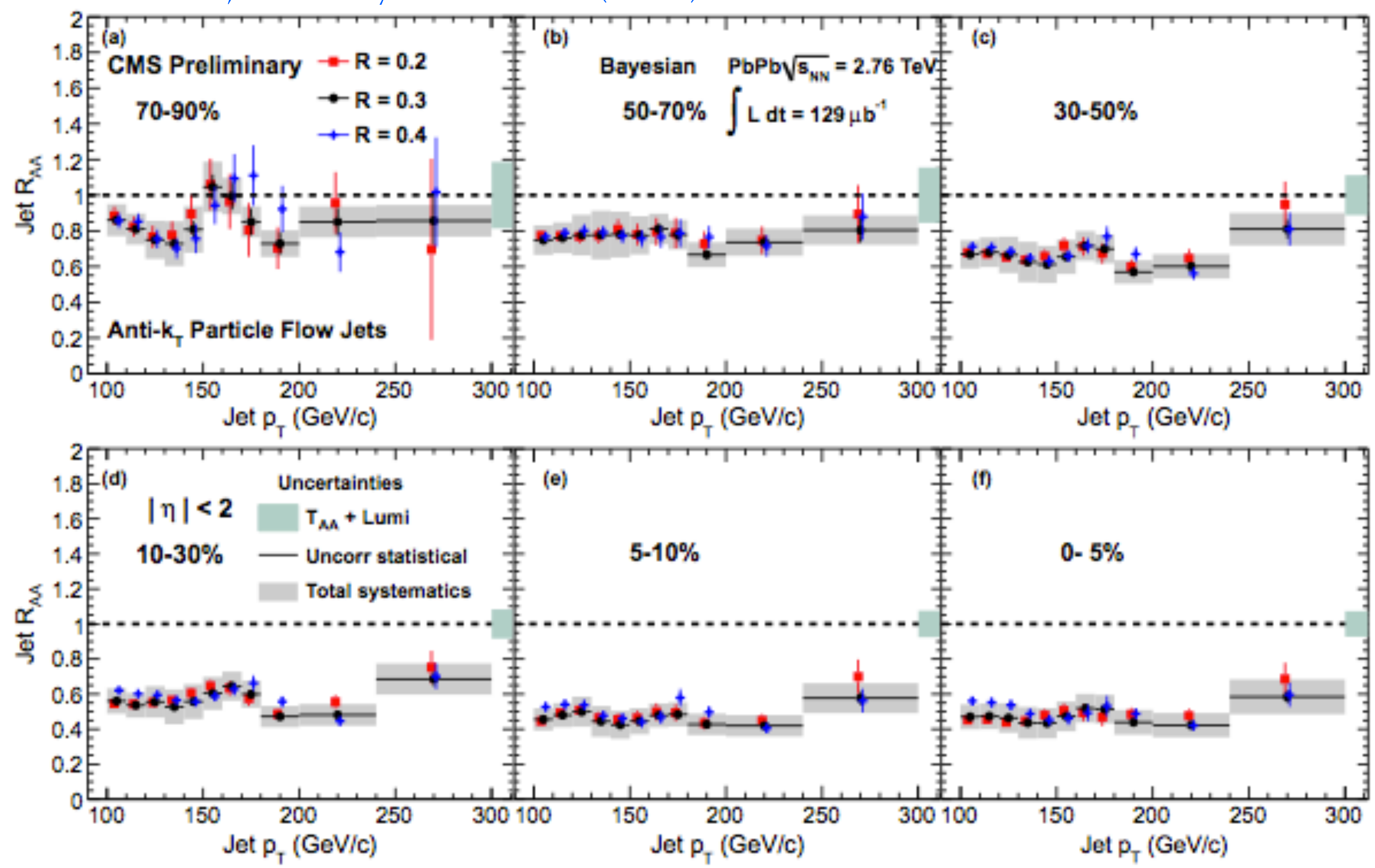
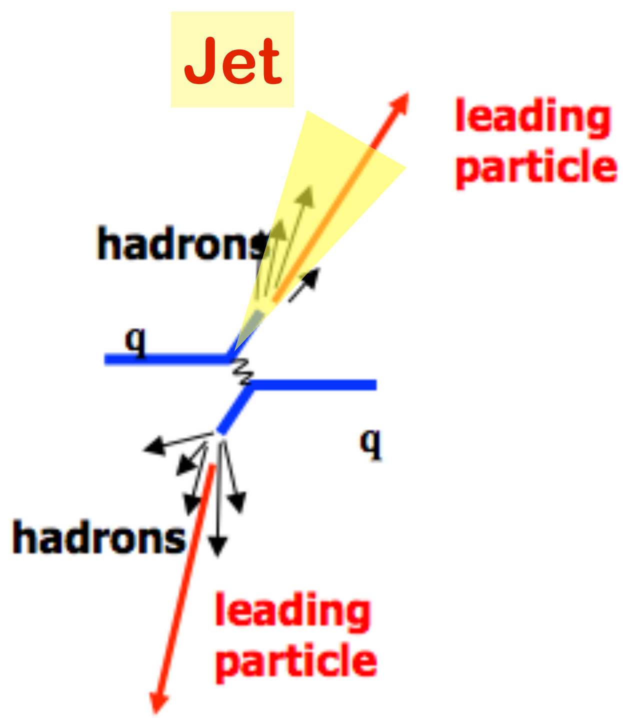
Jet Quenching

CMS, Nucl.Phys. **A904-905** (2013) 713c-716c

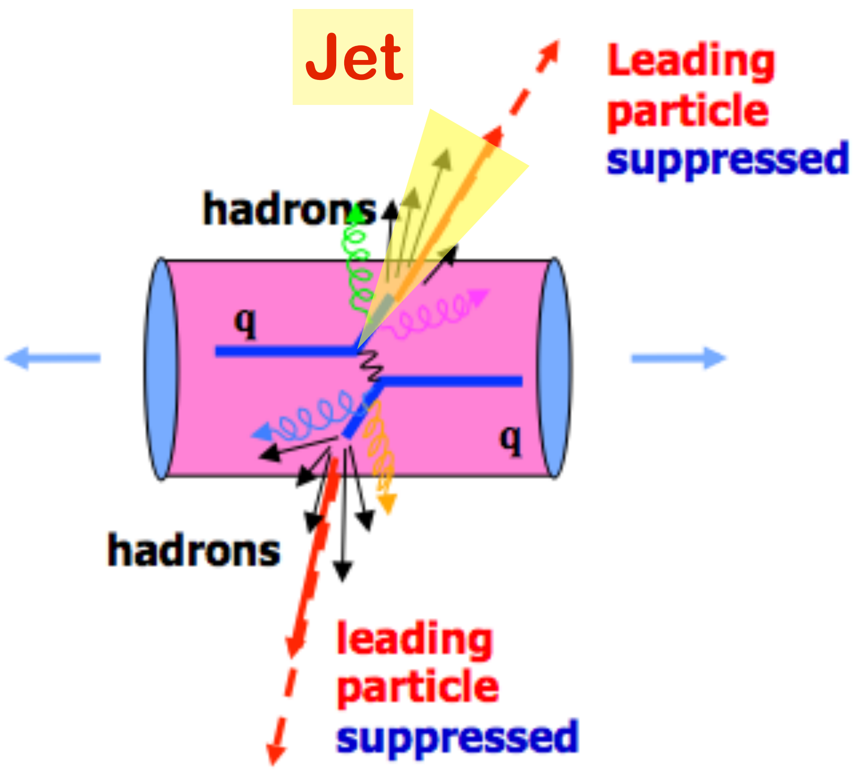


✦High P_T leading particles (hadrons)/ jets suppressed in AA collisions w.r.t. PP collisions!

Jet Quenching



P+P

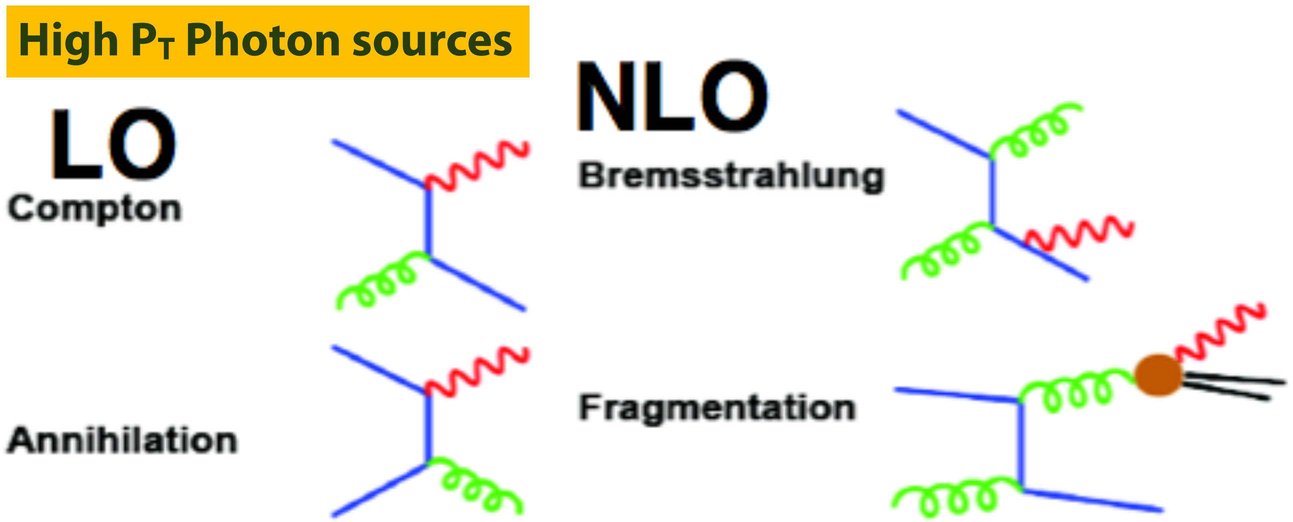


A+A

- High P_T leading particles (hadrons)/ jets suppressed in AA collisions w.r.t. PP collisions!

γ-jet Correlation

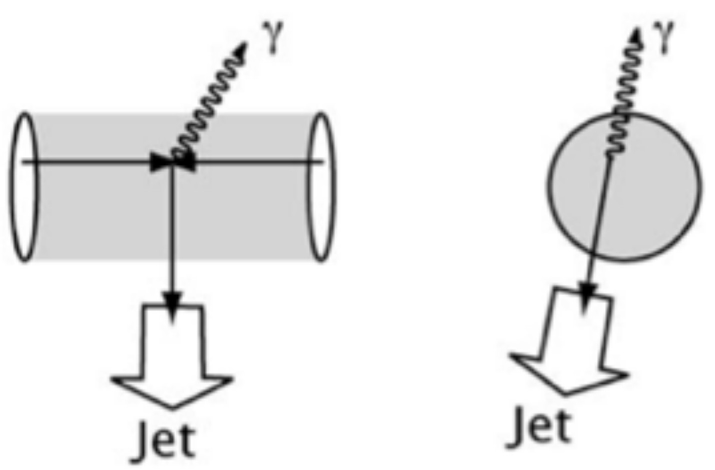
Z. Huang, I. Sarcevic, X. Wang, Phys.Rev.Lett. **77** (1996) 231-234



- High P_T photons are unmodified by the medium

- No "surface bias" in triggered events which involved in dijet events

P. Stankus, Ann. Rev. Nucl. Part. Sci. 55, 517 (2005)



LBT: Linearized Boltz. Transport

Boltzmann Equation:

$$p_1 \cdot \partial f_1(p_1) = -\int dp_2 dp_3 dp_4 (f_1 f_2 - f_3 f_4)|M_{12\to34}|^2$$
$$\times \quad (2\pi)^4 \delta^4(P_1 + P_2 - P_3 - P_4)$$

$$dp_i \equiv \frac{d^3 p_i}{2E_i (2\pi)^3}, \; |M_{12\to34}|^2 = Cg^2(s^2 + u^2)/(t + \mu^2)^2$$

$$f_i = 1/(e_i^{p.u/T} \pm 1)(i = 2, 4), f_i = (2\pi)^3 \delta^3(\vec{p} - \vec{p}_i)\delta^3(\vec{x} - \vec{x}_i)(i = 1, 3)$$

- Recoiled medium partons are included in Linearized Boltzmann Jet Transport.
- Recoiled medium partons (depletion of medium) play an important role in the reconstructed jet cone.

LBT: Linearized Boltz. Transport

Boltzmann Equation:

$$p_1 \cdot \partial f_1(p_1) = -\int dp_2 dp_3 dp_4 (f_1 f_2 - f_3 f_4)|M_{12\to 34}|^2 \times (2\pi)^4 \delta^4(P_1 + P_2 - P_3 - P_4)$$

$$dp_i \equiv \frac{d^3 p_i}{2E_i(2\pi)^3}, \ |M_{12\to 34}|^2 = Cg^2(s^2+u^2)/(t+\mu^2)^2$$

$$f_i = 1/(e_i^{p.u/T} \pm 1)(i=2,4), f_i = (2\pi)^3 \delta^3(\vec{p} - \vec{p}_i)\delta^3(\vec{x} - \vec{x}_i)(i=1,3)$$

- Both elastic and inelastic processes can be included.
- Linearized Boltzmann jet transport - neglect scatterings between shower and recoiled medium partons.
- It’s a good approximation when the jet induced medium excitation $\delta f \ll f$.

Medium Induced Radiation

- **Radiated gluon distribution:** X. Guo, X. Wang, Nucl.Phys. **A696** (2001) 788-832

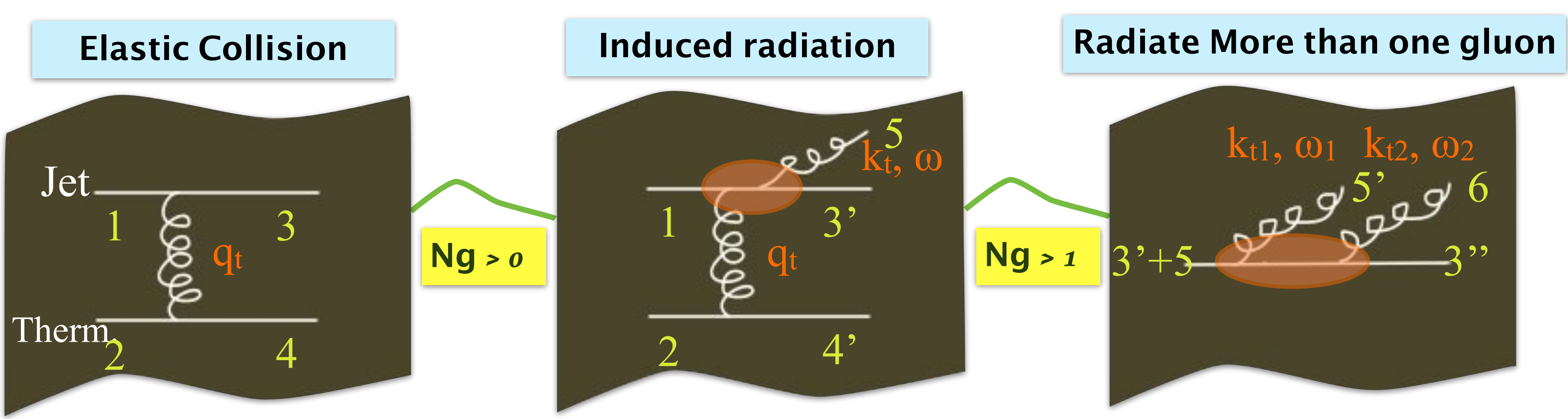
$$\frac{dN_g}{dx dk_\perp^2 dt} = \frac{2C_A \alpha_s P(x) \hat{q}}{\pi k_\perp^4} \sin^2 \frac{t - t_i}{2\tau_f},$$

$$P(x) = \frac{1 + (1-x)^2}{x}, \quad \tau_f = 2Ex(1-x)/k_\perp^2,$$

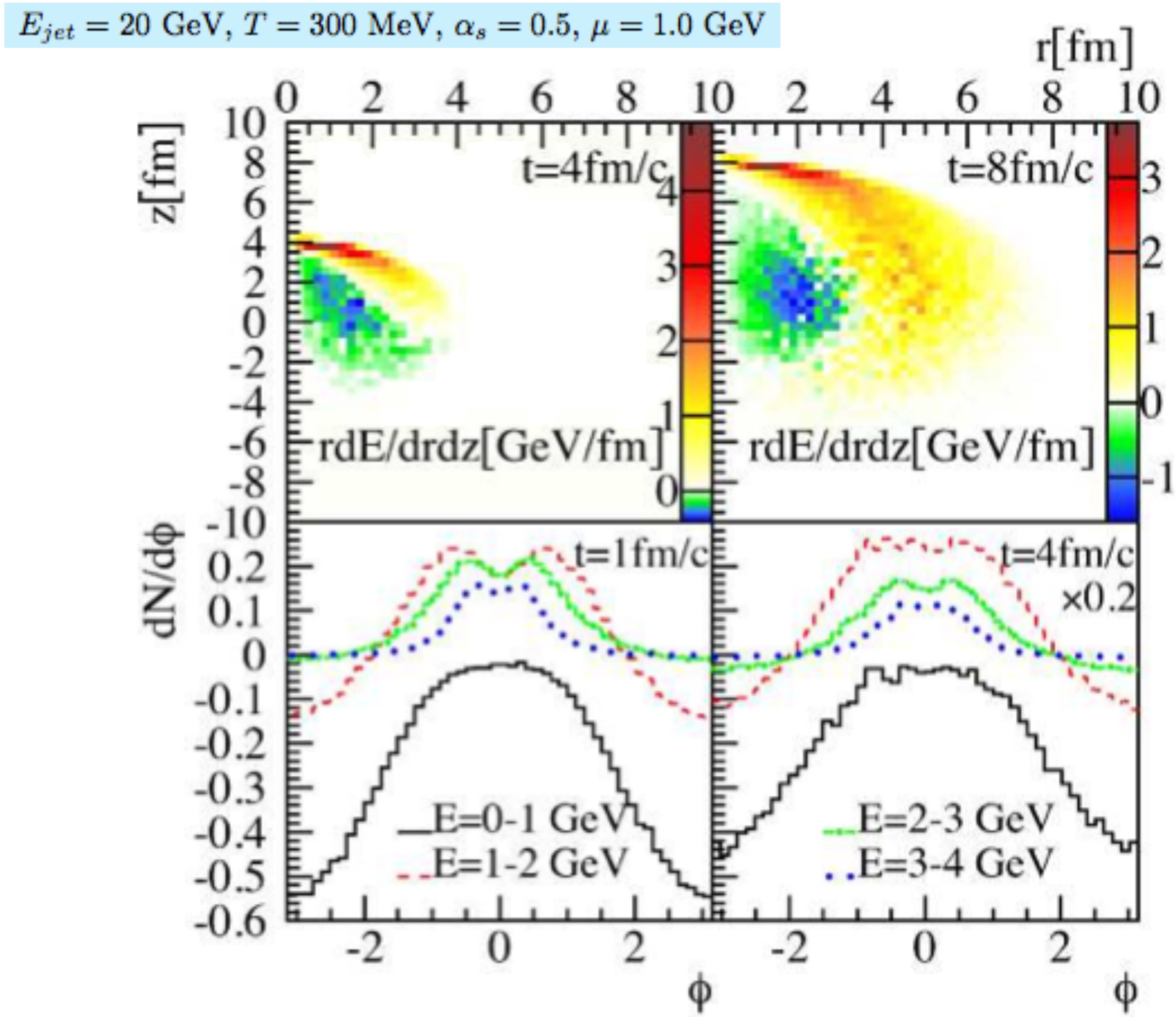
$$P(N_g, \langle N_g \rangle) = \frac{\langle N_g \rangle^{N_g} e^{-\langle N_g \rangle}}{N_g!}$$

- **Induced radiations are accompanied by elastic collisions.**

- **Jet medium Interaction:**



Medium Excitation



Li, Liu, Ma, Wang and Zhu, PRL106(2010) 012301

Not only the ordinary particles, but also the "particle hole"--- recoiled medium partons from one phase space to another one!

Jet Energy Loss and p_T Broadening

- According to the high twist approach, the radiative energy loss for a single parton is

$$\Delta E_a \approx \frac{3\alpha_s}{2} \int d\tau (\tau - \tau_0)(\hat{p} \cdot u)\hat{q}_a \ln \frac{2E}{(\tau - \tau_0)\mu_D^2}$$

- In the meantime, the corresponding p_T broadening is

$$\langle \Delta p_T^2 \rangle = \int d\tau (\hat{p} \cdot u)\hat{q}_a$$

- For a constant jet transport parameter $\hat{q}_a = \hat{q}_a^0$ in a uniform and static medium,

$$\Delta E_a \sim L^2$$

$$\langle \Delta p_T^2 \rangle \sim L$$

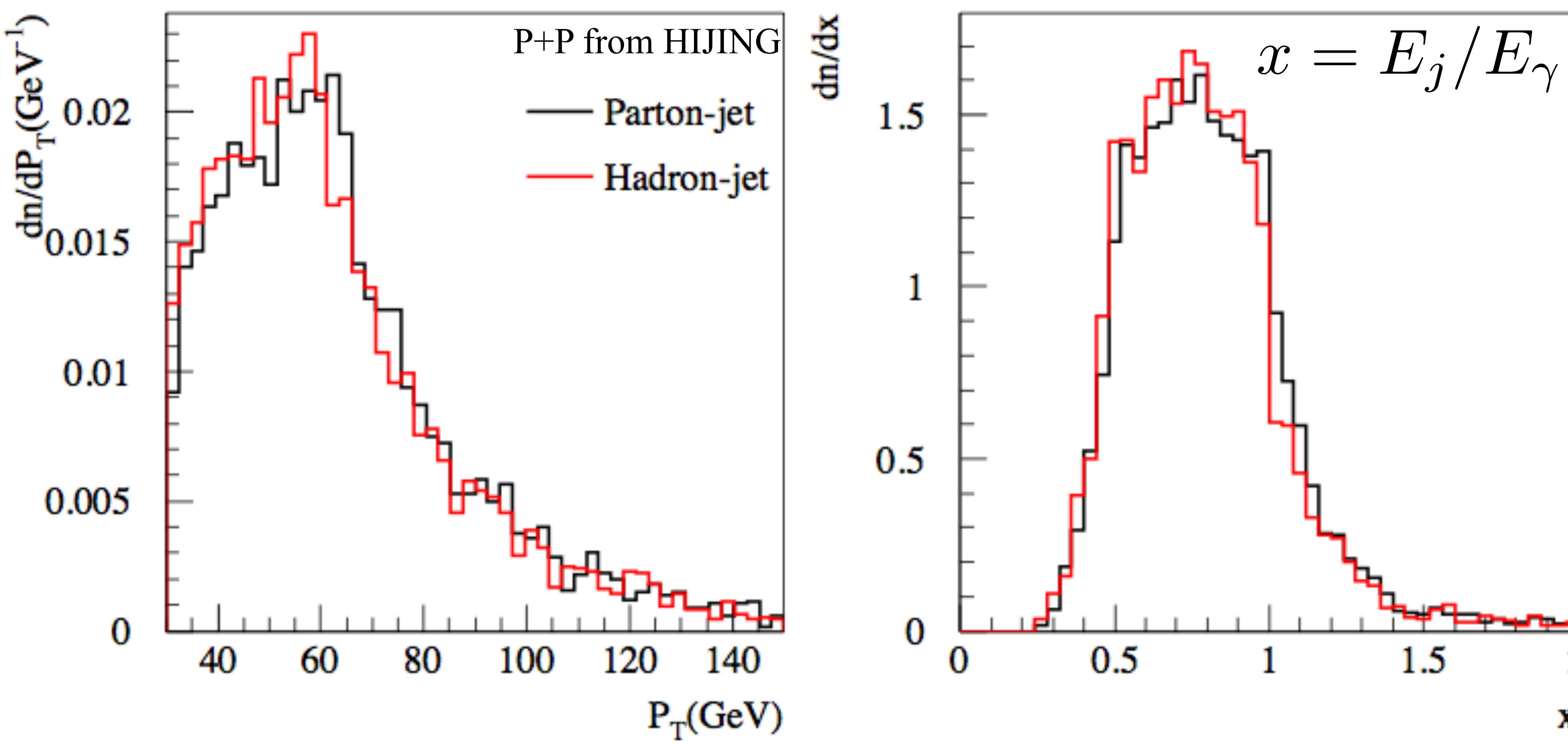
- In a 3D expansion medium, $\hat{q}_a = \hat{q}_a^0 (\tau_0/\tau)^{1+\alpha}$

$$\Delta E_a \sim (\leq L)$$

$$\langle \Delta p_T^2 \rangle \sim (\leq \ln L)$$

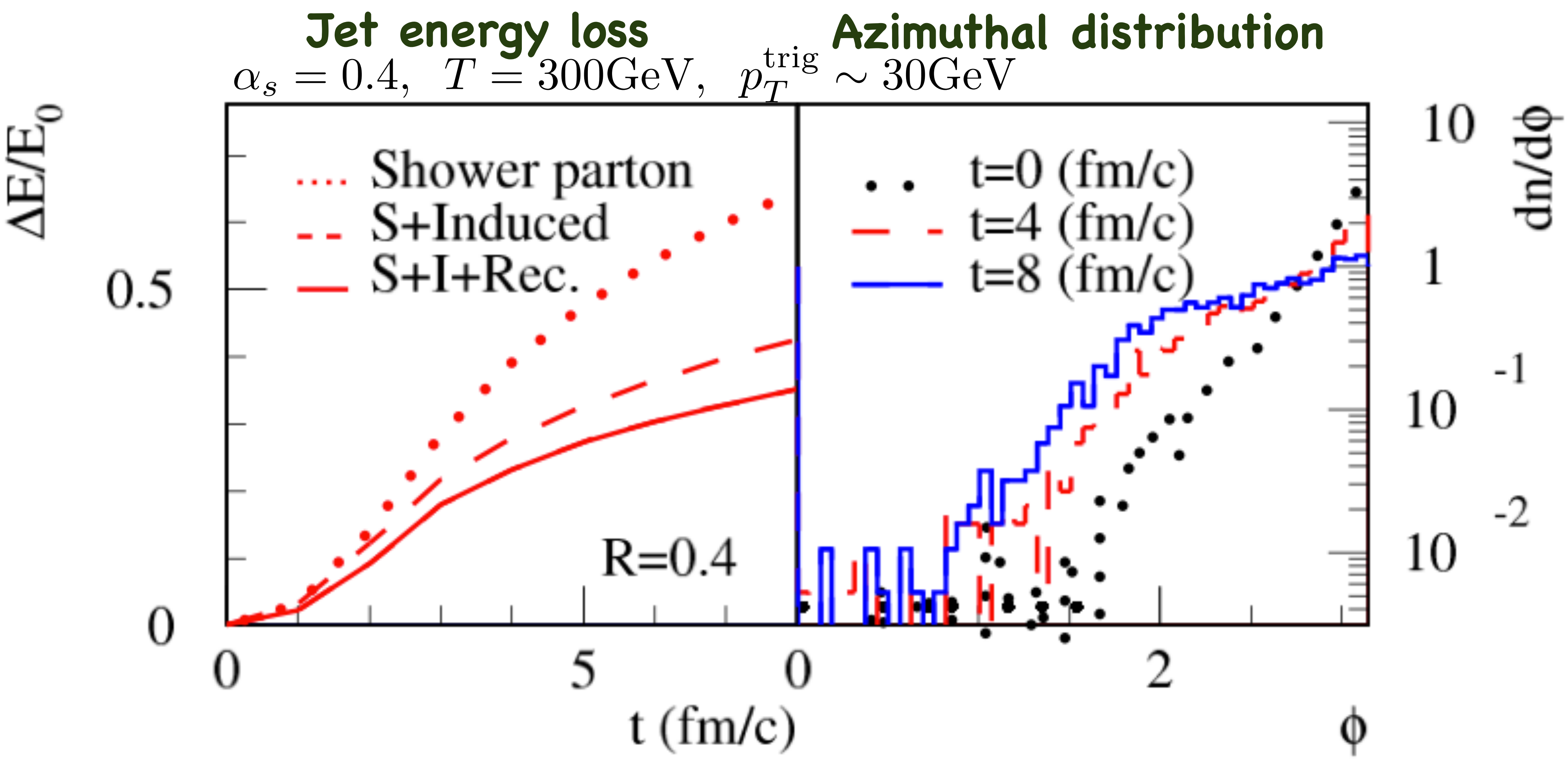
Jet Reconstruction

- Anti-K_t algorithm in FASTJET is used to reconstruct jets.
- For the "particle hole", we subtract their 4-momentum when doing the jet reconstruction.



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

Jet Modification

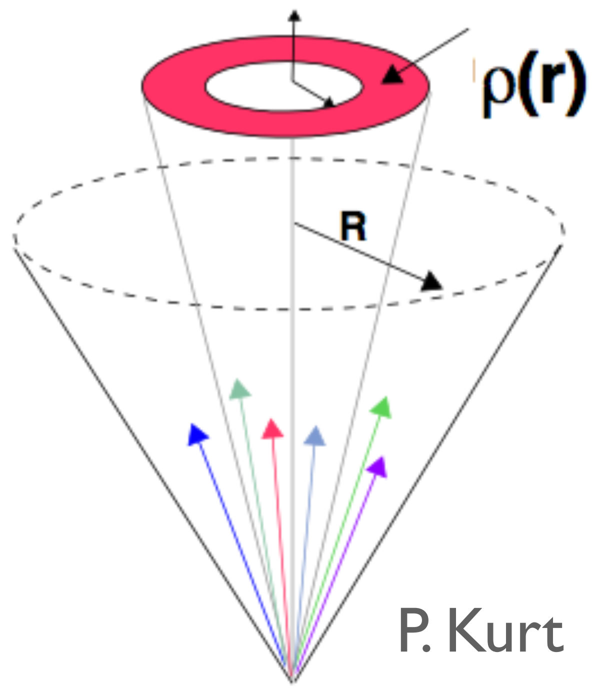


- The energy loss is distributed outside the reconstructed cone.
- Azimuthal angle broadening of jets is observed.

Jet Transverse Profile

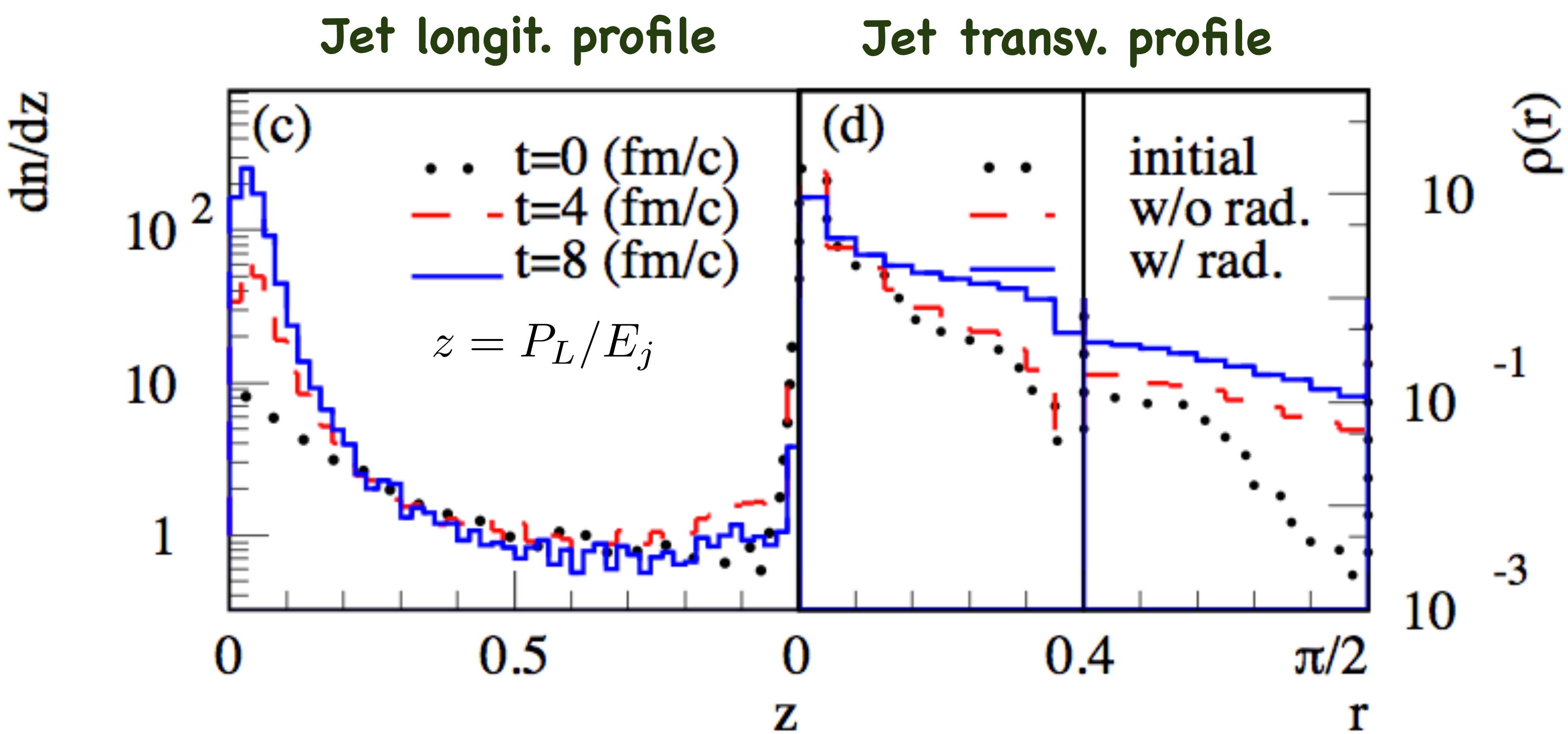
Jet transverse profile (jet shape) is the average fraction of the jet transverse momentum inside an annulus in the η-Φ plane of inner (outer) radius r-Δr/2 (r+Δr/2) concentric to the jet axis.

$$\rho(r) = \frac{1}{\Delta r} \frac{1}{N^{\rm jet}} \sum_{\rm jets} \frac{p_T(r-\Delta r/2, r+\Delta r/2)}{p_T(0,R)},$$



- Jet transverse profile is expected to be distorted by the interaction with thermal medium.
- It is also interesting to look into the transverse momentum distribution outside the jet cone.
- Jet transverse profile is studied with 0<r<R (inside the cone) and R<r<π/2 (outside the cone).

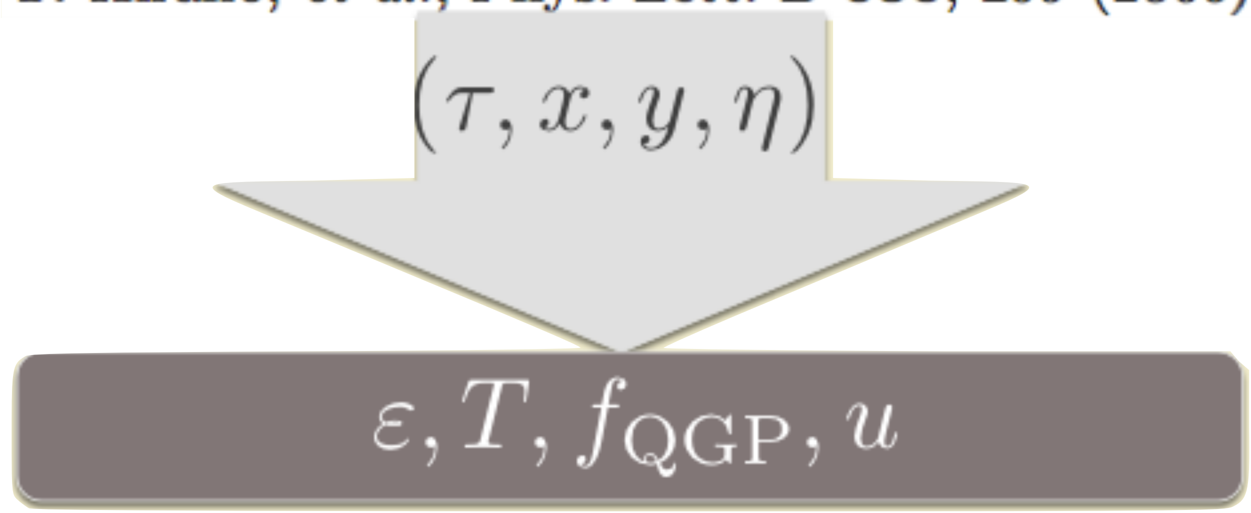
Jet Profile



- Jet longitudinal profile is enhanced in the low momentum and suppressed in high momentum.
- Jet transverse profile is broadened inside jet cone and redistribute to the outside of jet cone.

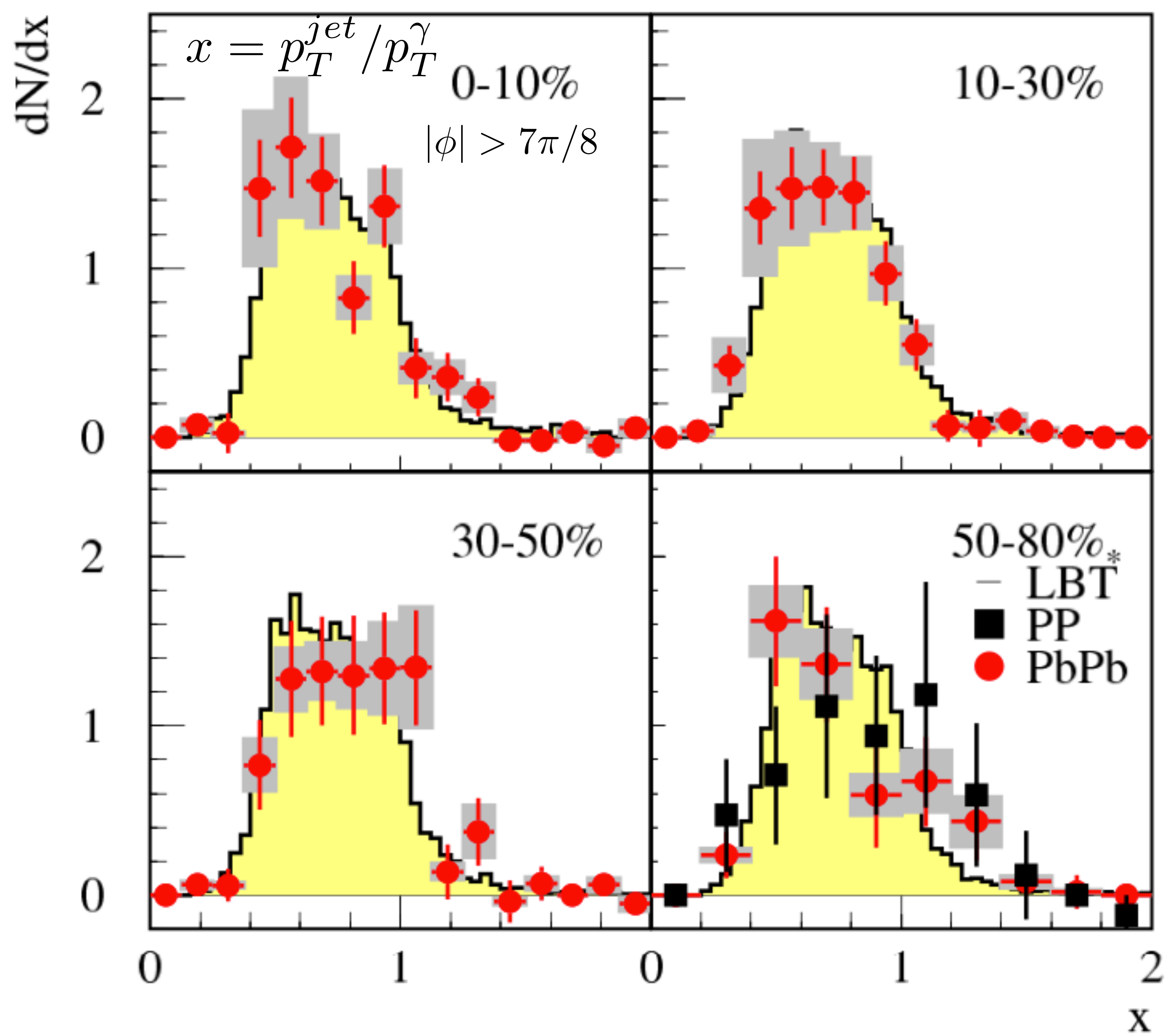
Jets in a 3+1D hydro

- Trigger a gamma-jet with $P_T \sim 60$GeV in P+P @ 2.76TeV from HIJING:
  - CMS $P_{T\gamma} > 60\text{GeV}, |\eta_\gamma| < 1.44,$
  - ATLAS $60\text{GeV} < P_{T\gamma} < 90\text{GeV}, |\eta_\gamma| < 1.3.$
- 3+1D hydro T. Hirano, *et al.*, Phys. Lett. B **636**, 299 (2006).



- Location of gamma-jet is decided according to the Wood-Saxon distribution.

γ-jet correlation in CMS



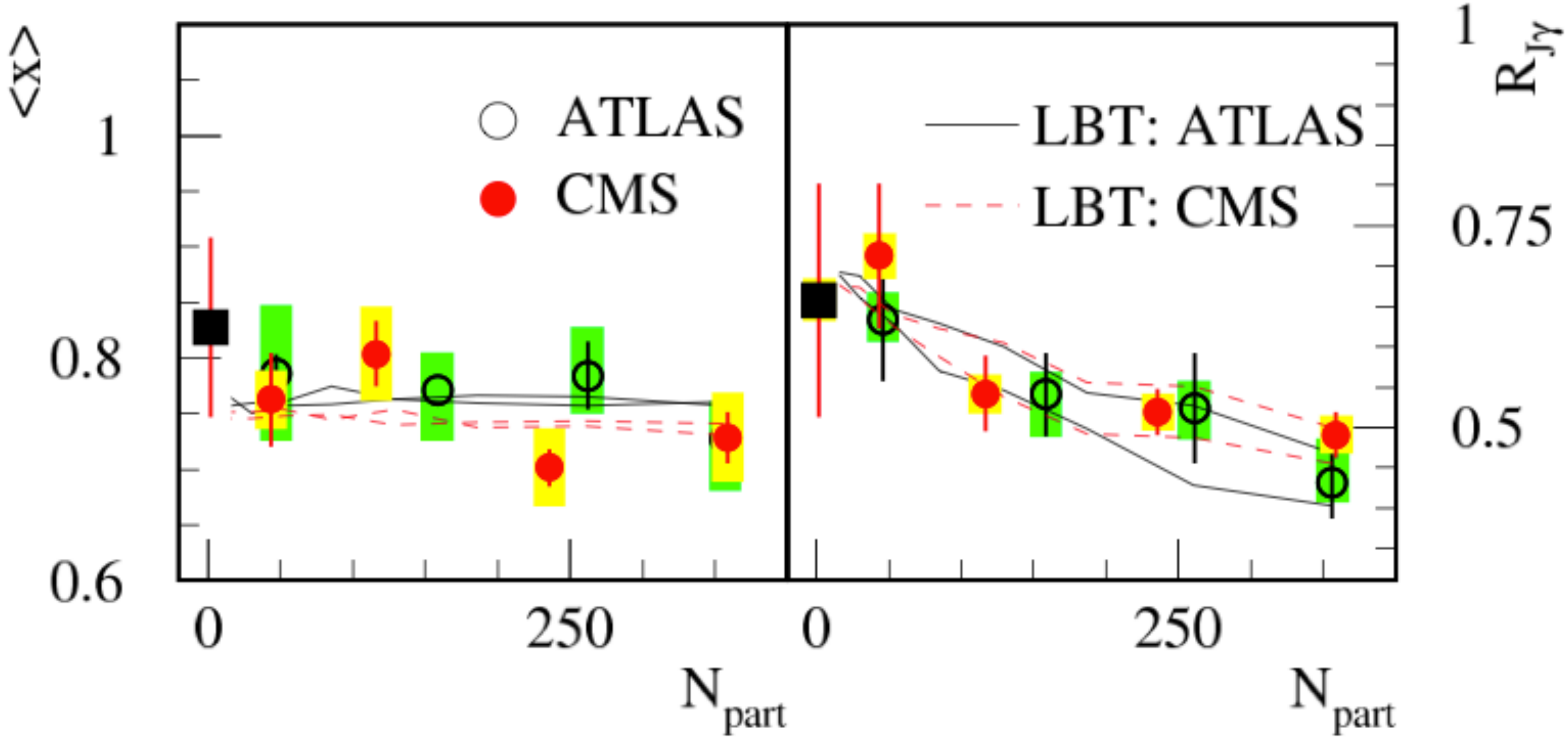
Data from [arXiv:1205.0206]

✦With $\alpha_s = 0.2$, the linearized Boltzmann transport simulation can describe γ-jet asymmetry distribution successfully.

γ-jet correlation

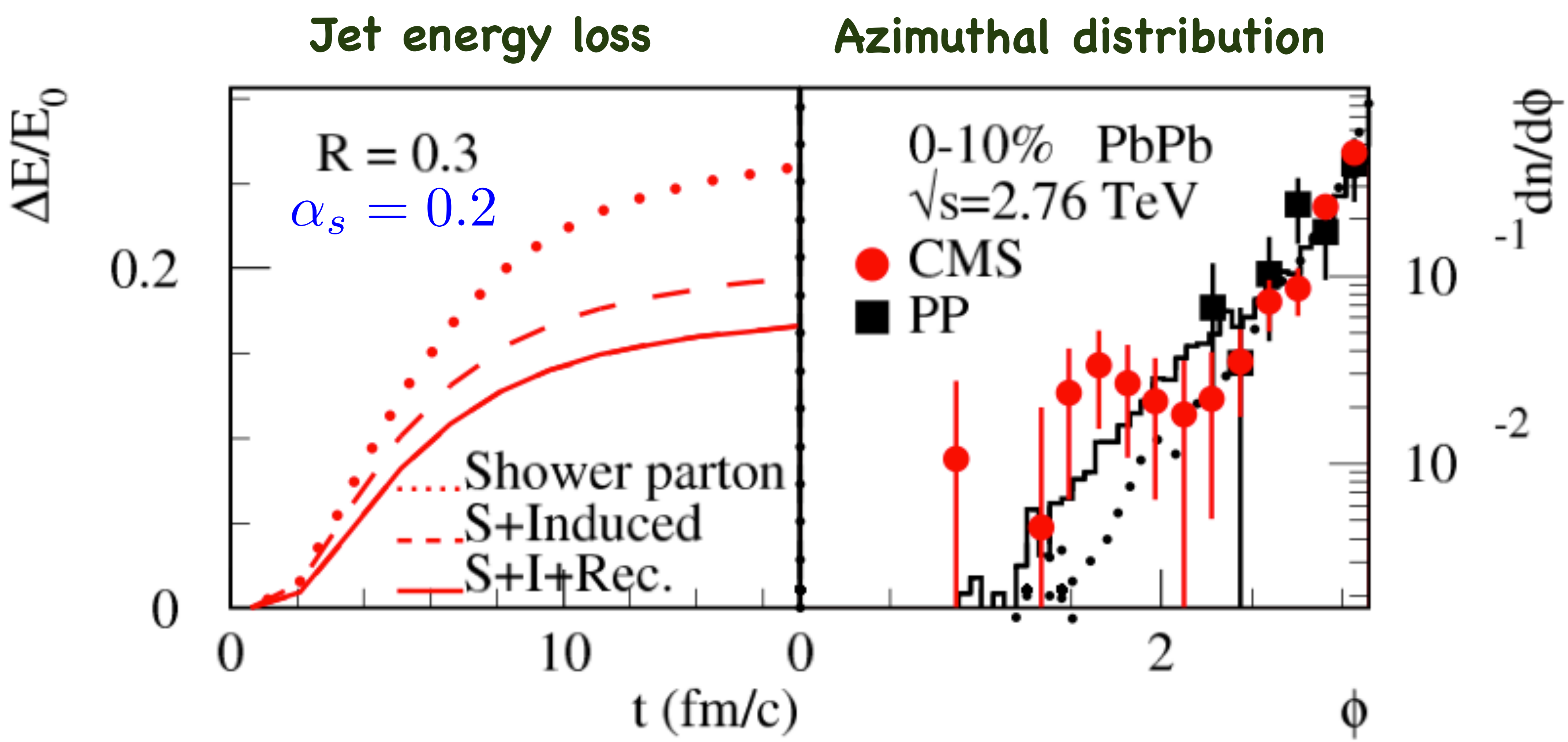
CMS: $p_T^{\gamma} > 60\text{GeV}, \quad |\eta^{\gamma}| < 1.44, \quad p_T^{Jet} > 30\text{GeV}, \quad |\eta^{Jet}| < 1.6.$

ATLAS: $60GeV < p_T^{\gamma} < 90GeV, \quad |\eta^{\gamma}| < 1.3, \quad p_T^{Jet} > 25GeV, \quad |\eta^{Jet}| < 2.1.$



✦There is a very good agreement between data and LBT with $\alpha_s = 0.15 - 0.23\ (0.2 - 0.27)$ for CMS (ATLAS).

Jet Energy Loss

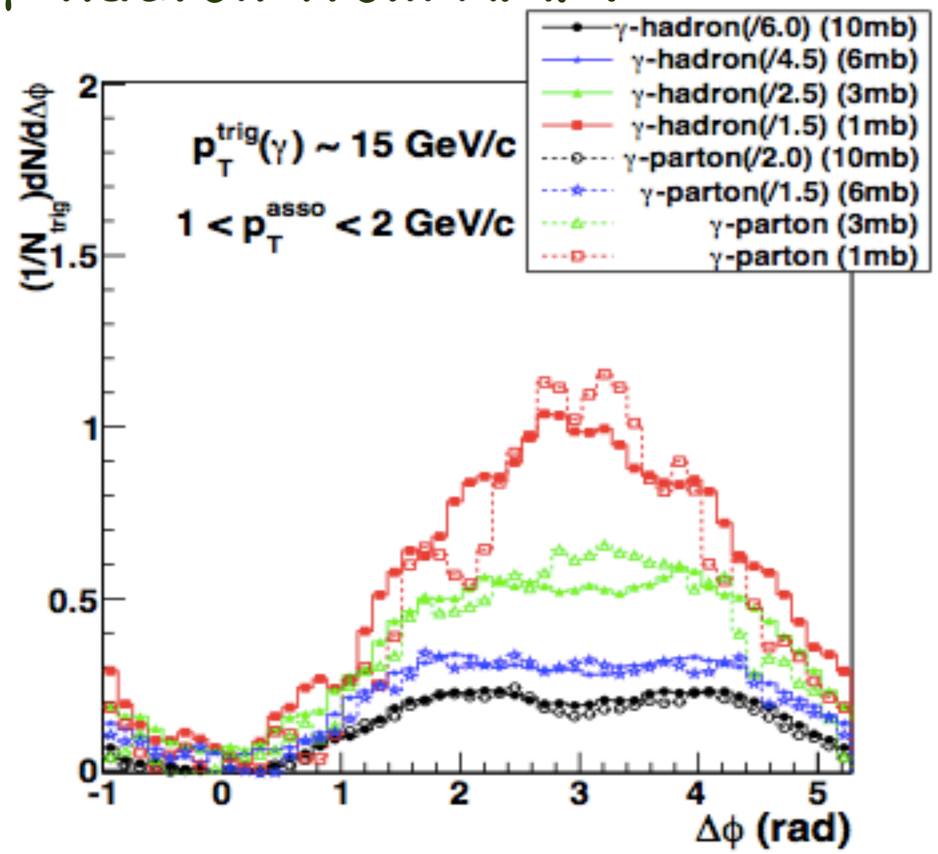


✦15% energy is distributed outside the reconstructed cone.

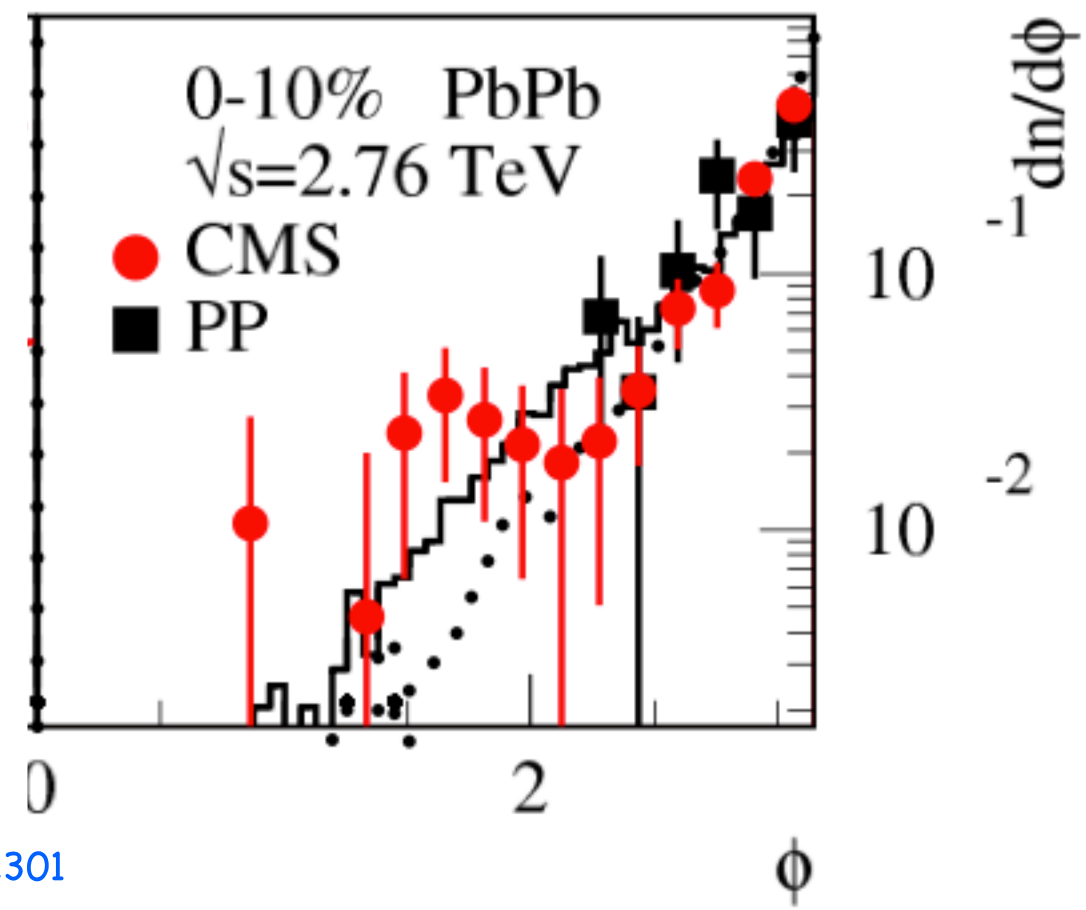
✦Small but non-negligible azimuthal angle broadening in central PbPb collisions.

Jet Energy Loss

γ-hadron from AMPT



Azimuthal distribution



Li, Liu, Ma, Wang and Zhu, PRL106(2010) 012301
Ma and Wang, PRL106(2011) 162301

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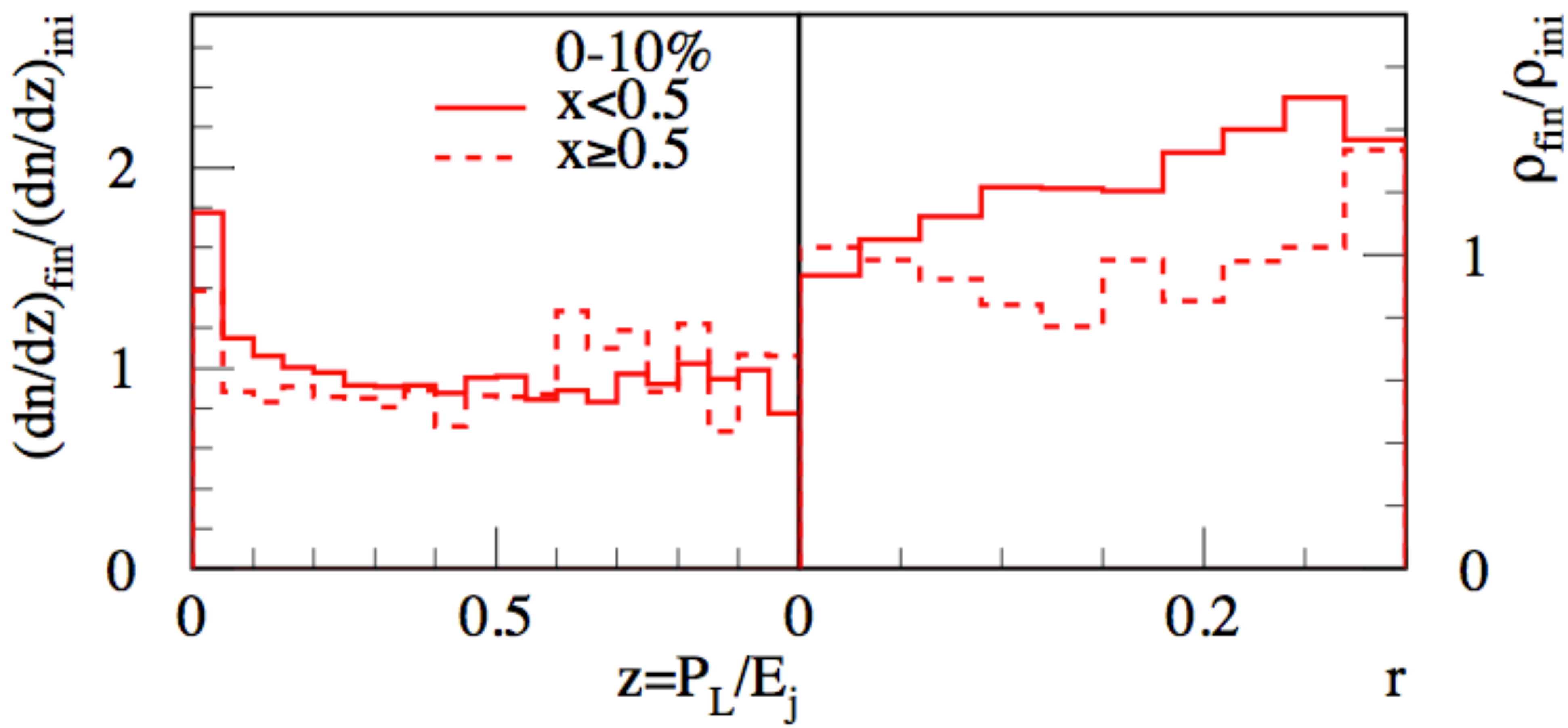
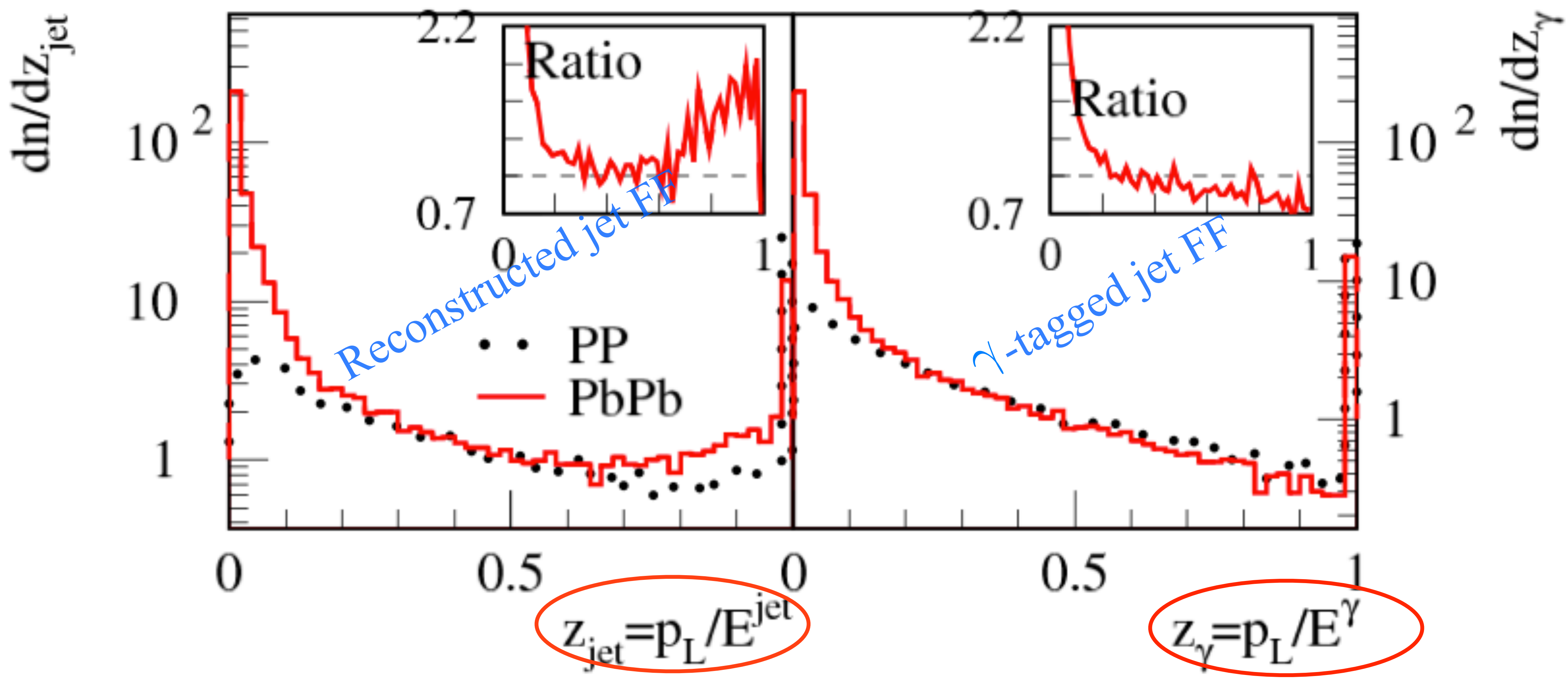
Jet fragmentation



✦Jet with lager energy loss has more low P_L partons within the jet cone.

✦Jet is more broadened for jet with larger energy loss.

"Jet Frag. Function"



✦Reconstructed jet FF: The reconstructed jet energy is dominated by leading partons.

✦γ-tagged jet FF: Fragmentation function is strongly suppressed w.r.t. the initial jet energy.

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Summary and Outlook

- A medium induced radiation included multiple scattering linearized Boltzmann transport is used to study the jet medium interaction.
    - The lost jet energy is taken away by recoiled and radiation partons outside the jet cone.
    - Jet structure is distorted by the interaction with thermal partons.
- Simulation results for γ-jet correlation describe the experiment data successfully.
- A γ-tagged jet FF was suggested as a more sensitive probe to jet medium interaction.
- Embedding elastic scatterings for different channels is ongoing.
- Di-jet correlation in linearized Boltzmann jet transport simulation is straight forward.