Vector boson-tagged jet production in heavy ion reactions at the LHC

Hongxi Xing

NU/ANL

In collaboration with Z-B. Kang and I. Vitev
paper will be on arXiv soon

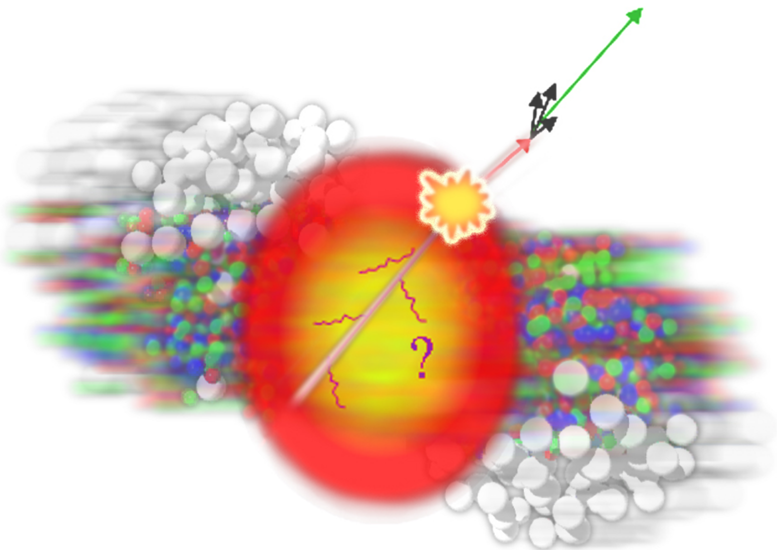
Quark Matter 2017, Chicago, Feb. 5-11, 2017

NORTHWESTERN UNIVERSITY

Argonne NATIONAL LABORATORY

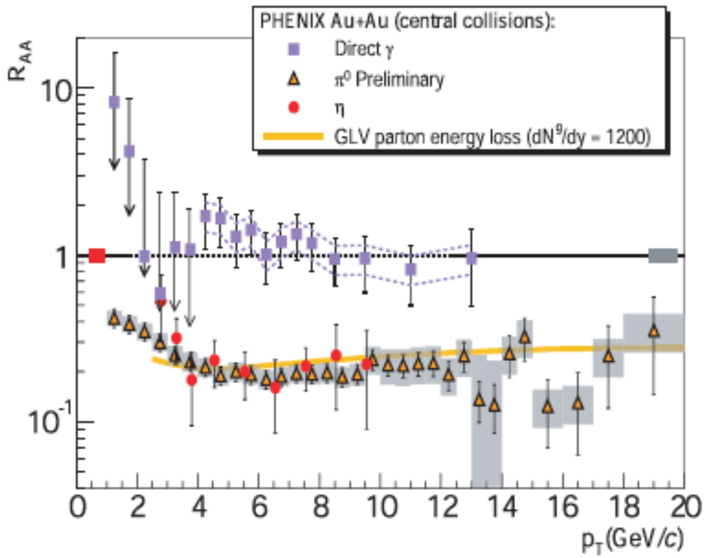
Probe of parton energy loss mechanism

Jet tomography

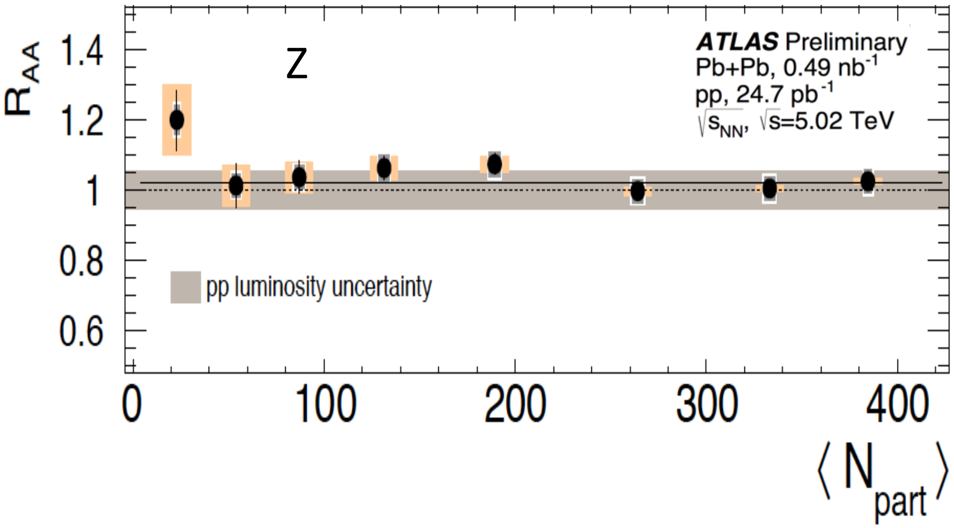


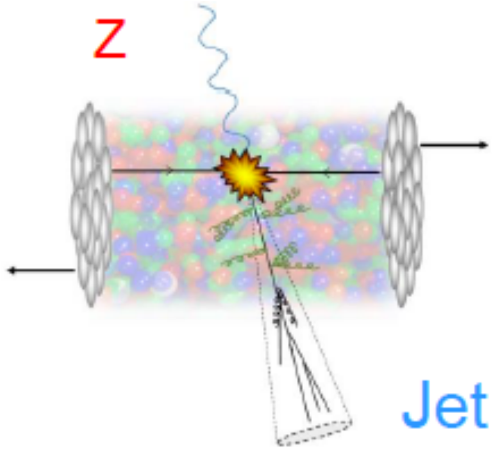
- Knowledges of initial states - pp baseline
- Jet-medium interaction
- Medium evolution

Ideal channel for hard probes – V+Jet



Jiangyong's talk





From Yan-Jie's talk

- Electroweak bosons are not affected by the hot dense medium
- Provide good constraints on the energy and flavor origins of the away-side parton shower
- Uncertainties from background contributions are significantly reduced

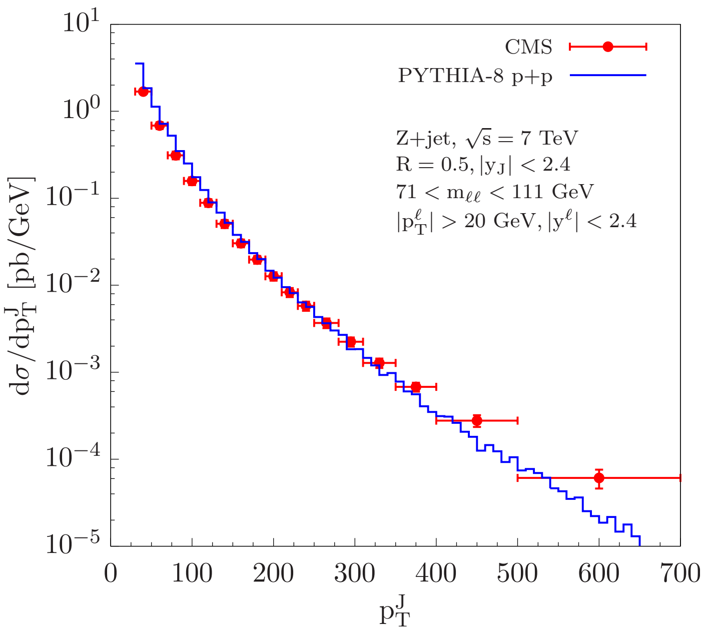
p+p baseline

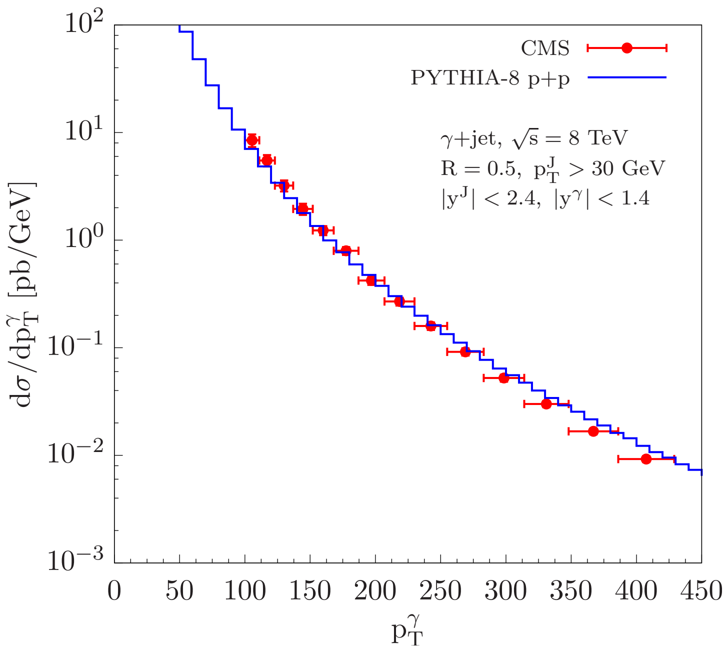
- NLO fixed order calculation

  Photon+jet: Dai, Vitev, Zhang, PRL 2012
  Z+jet: Neufeld, Vitev, PRL 2012

- Parton shower Monte Carlo simulation

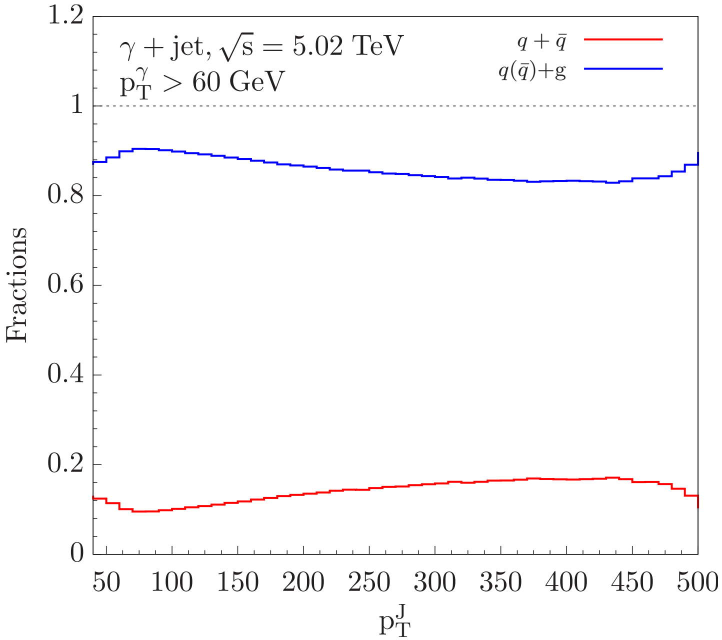
  Pythia 8: Leading order pQCD + leading logarithmic parton shower

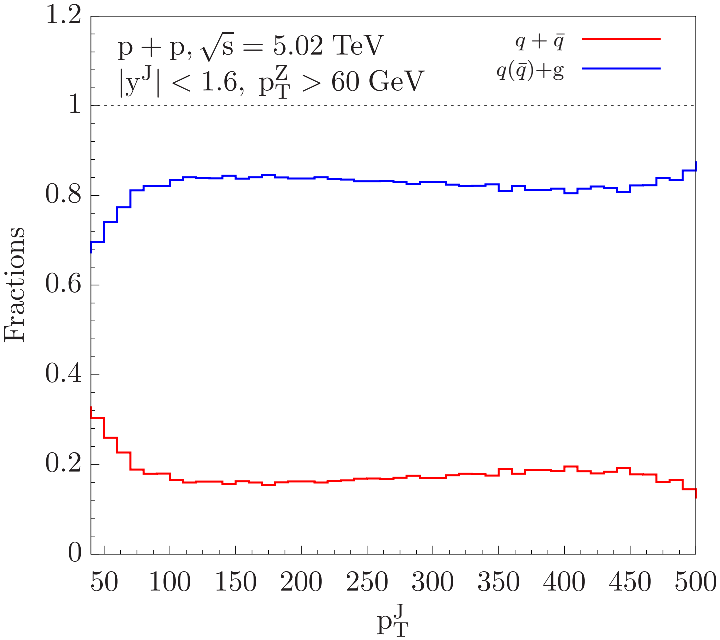


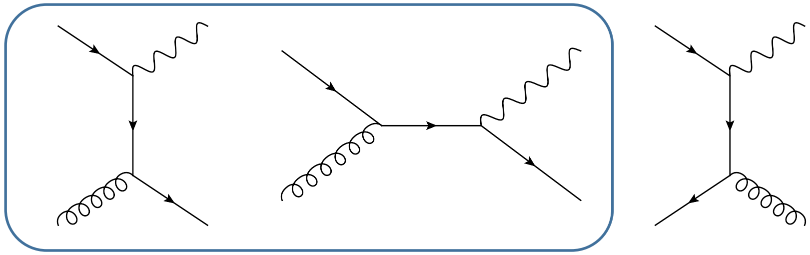


Reasonable good description of the LHC p+p data

Flavor origins of the recoiling jets





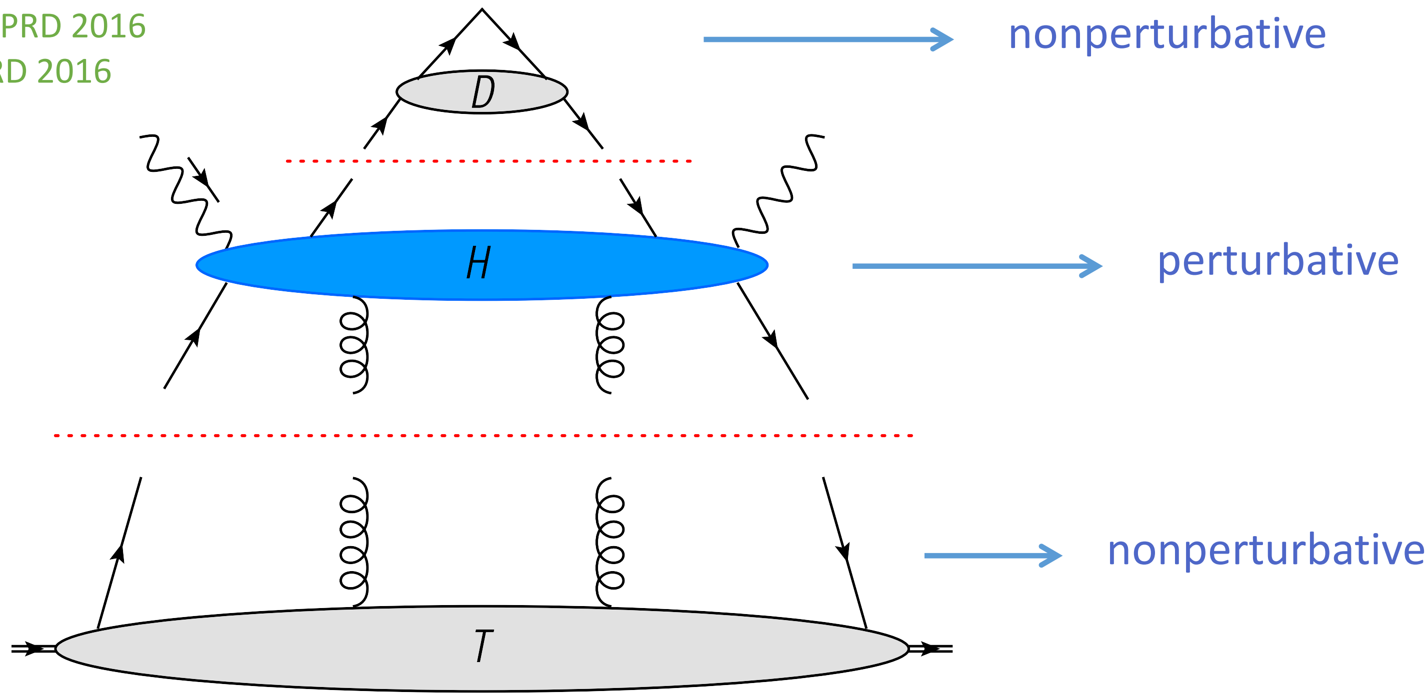


- leading logarithmic approximation
- Isolated photon: minimize contributions from jet fragmentation
- Both photon+jet, Z+jet productions are dominated by q+g channel
  -> the produced jet originates from light quark, good probe of quark energy loss effect

Theoretical foundation: multiple scattering factorization

❑ Factorization at NLO in cold nuclear matter (SIDIS)

Kang, Wang, Wang, **HX,** PRL 2014
Kang, Wang, Wang, **HX,** PRD 2016
Kang, Qiu, Wang, **HX,** PRD 2016



$$\frac{d\langle \ell_{hT}^2 \sigma\rangle}{dz_h} \propto D_{q/h}(z,\mu^2)\otimes H^{LO}(x,z)\otimes T_{qg}(x,0,0,\mu^2) + \frac{\alpha_s}{2\pi} D_{q/h}(z,\mu^2)\otimes H^{NLO}(x,z,\mu^2)\otimes T_{qg(gg)}(x,0,0,\mu^2)$$

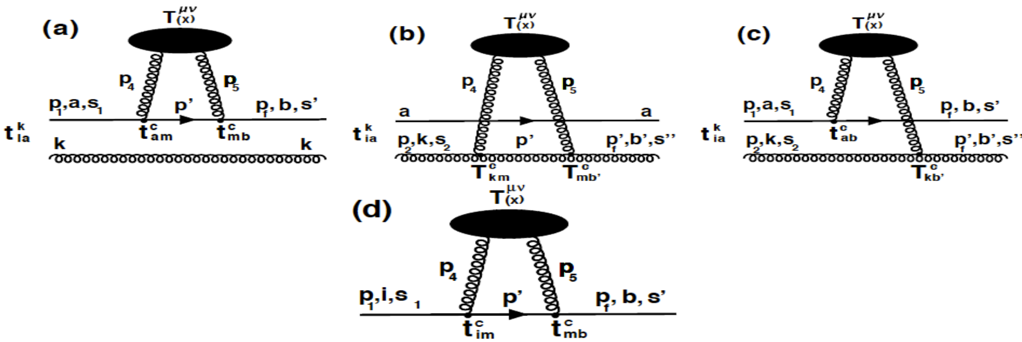
Multiple scattering hard part coefficients and twist-4 matrix element (medium properties) can be factorized!!!

Jet energy loss in nuclear medium

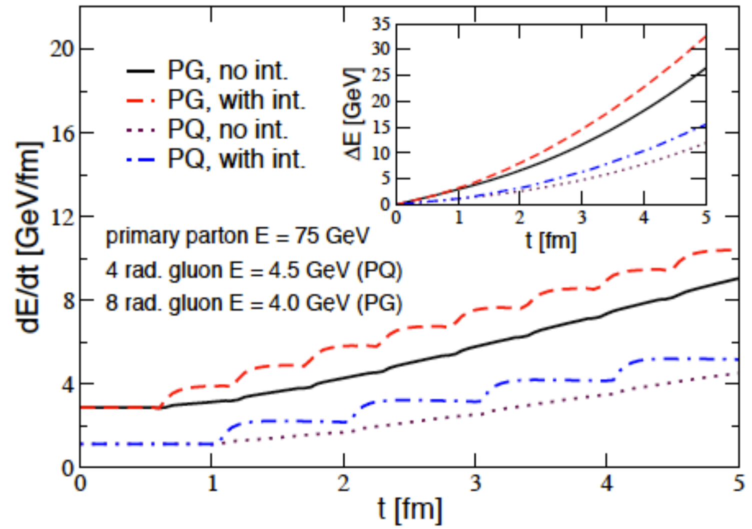
Final-state quark-gluon plasma effects include medium-induced parton splitting and the dissipation of the energy of the parton shower through collisional interactions in the strongly-interacting matter.

- Parton shower energy dissipation in the QGP

Neufeld, Vitev, PRC 2012
Neufeld, Vitev, **HX**, PRD 2014



$$\partial_\mu T^{\mu\nu} = C_p J^\nu_a(x,u_1,u_1) + C_A J^\nu(x,u_2,u_2) - \frac{C_A}{2}\left[J^\nu(x,u_1,u_2) + J^\nu(x,u_2,u_1)\right]$$



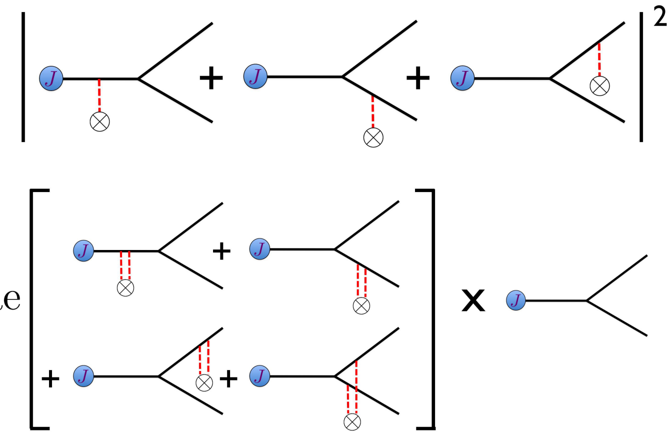
Medium induced radiative energy loss

- SCET$_G$ (Idilbi, Majumder, Ovanesyan, Vitev …)

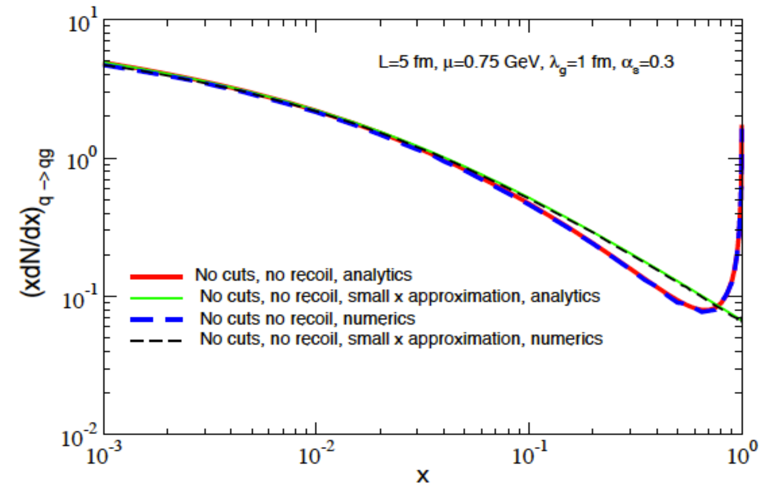
$$\mathcal{L}_{\mathrm{SCET_G}}(\xi_n, A_n, A_G) = \mathcal{L}_{\mathrm{SCET}}(\xi_n, A_n) + g \sum_{p,p'} e^{-i(p-p')x} \left(\bar{\xi}_{n,p'} T^a \frac{\bar{n}\!\!\!/}{2} \xi_{n,p} - i f^{abc} A^{\lambda c}_{n,p'} A^{\nu b}_{n,p}\, g^{\perp}_{\nu\lambda}\, \bar{n}\cdot p \right) n\cdot A^a_G(x)$$

- Medium induced gluon radiation

$\frac{dN}{dx} \sim$ (diagrams) $+\ 2\mathrm{Re}$ (diagrams)



Ovanesyan, Vitev, 2012



$$\frac{dN^g_{q,g}(\omega,r)}{d\omega dr} \propto C_R \alpha_s \int_0^\infty d\Delta z \frac{1}{\lambda_g(\Delta z)} \left[\int d^2\mathbf{q} \left(\frac{1}{\sigma_{el}(\Delta z)} \frac{d\sigma_{el}(\Delta z)}{d^2\mathbf{q}} - \delta^2(\mathbf{q}) \right) \right] \times \frac{2\mathbf{k}\cdot\mathbf{q}}{\mathbf{k}^2(\mathbf{k}-\mathbf{q})^2} \left\{ 1 - \cos\left[\frac{(\mathbf{k}-\mathbf{q})^2}{2\omega} \Delta z \right] \right\}$$

V+jet production in heavy ion collisions

- Suppression of jets (soft gluon approximation)

$$\frac{1}{\langle N_{\rm bin}\rangle}\frac{d\sigma^{AA}}{dp_T^V dp_T^J} = \sum_{q,g}\int_0^1 d\epsilon P_{q,g}(\epsilon) J_{(q,g)}(\epsilon) \frac{d\sigma_{q,g}^{\rm LO+PS}\left(p_T^V, J_{(q,g)}(\epsilon) p_T^J\right)}{dp_T^V dp_T^J}$$

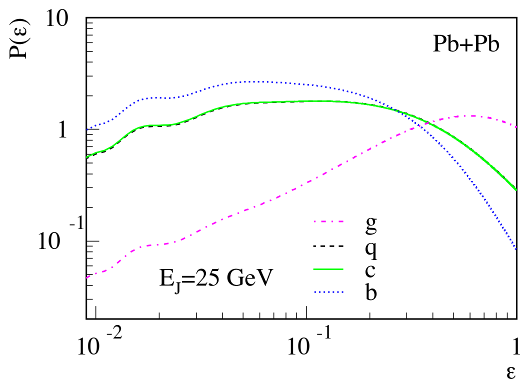
- Superposition of proto-jets of initially higher transverse momentum

$$P_T = J_{q,g}(\epsilon) p_T^J = \frac{p_T^J}{1 - f_{q,g}\cdot\epsilon}$$

- Fraction of the energy redistributed outside the jet

$$f_{q,g}(R,\omega^{\rm coll}) = 1 - \frac{\int_0^R dr \int_{\omega^{\rm coll}}^E d\omega \frac{\omega d^2 N_{q,g}^g}{d\omega dr}}{\int_0^{R_{max}} dr \int_0^E d\omega \frac{\omega d^2 N_{q,g}^g}{d\omega dr}}$$

- probability to lose energy due to multiple gluon emission

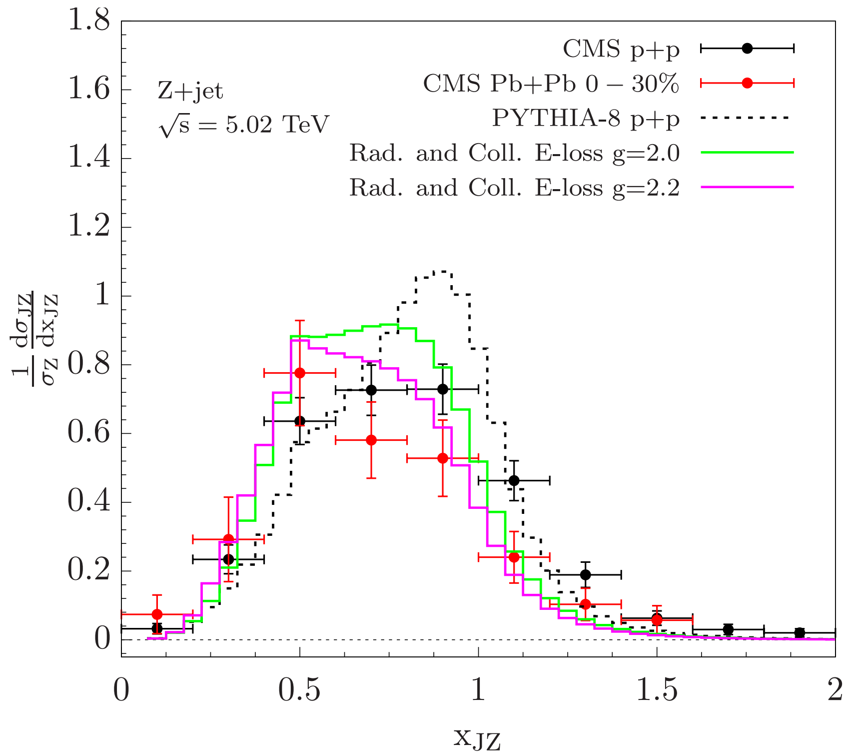


$$\int d\epsilon P(\epsilon) = 1 \qquad \int d\epsilon P(\epsilon)\epsilon = \frac{\langle \Delta E\rangle}{E}$$

Kang and Vitev, PRD 84,014034 (2011)

Transverse momentum asymmetry (Z+jet)

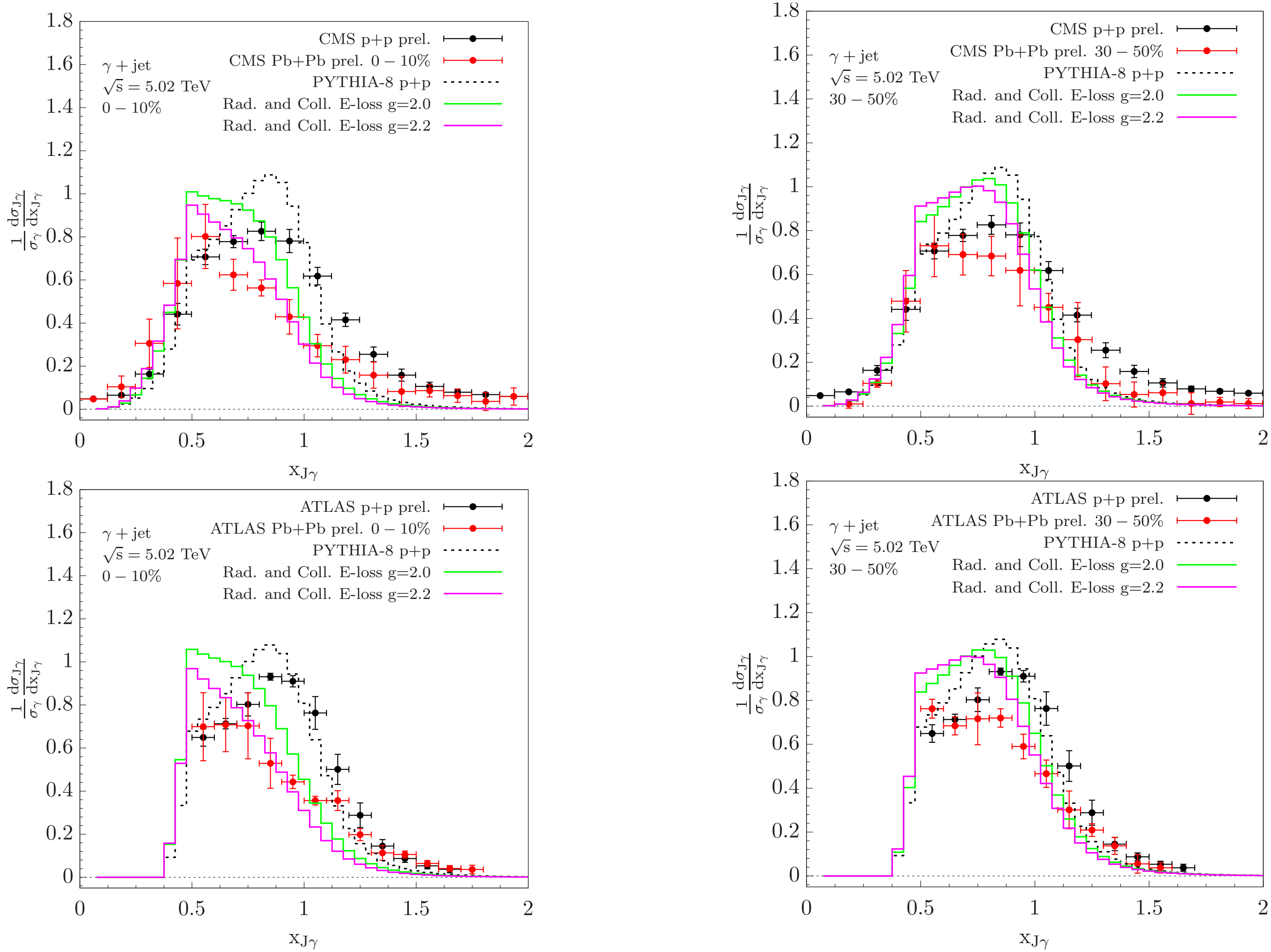
$$\frac{d\sigma}{dX_{JV}} = \int_{p_T^{J\,min}}^{p_T^{J\,max}} dp_T^J \frac{p_T^J}{X_{JV}^2} \frac{d\sigma(X_{JV}, p_T^V(X_{JV}, p_T^J))}{dp_T^V dp_T^J} \, . \qquad X_{JV} = \frac{p_T^J}{p_T^V}$$



Part of the parton shower energy is redistributed outside of the jet cone radius, the jets pT are pushed to lower values, with boson pT unchanged. This redistribution results in the downshift of X_{JV} distribution.

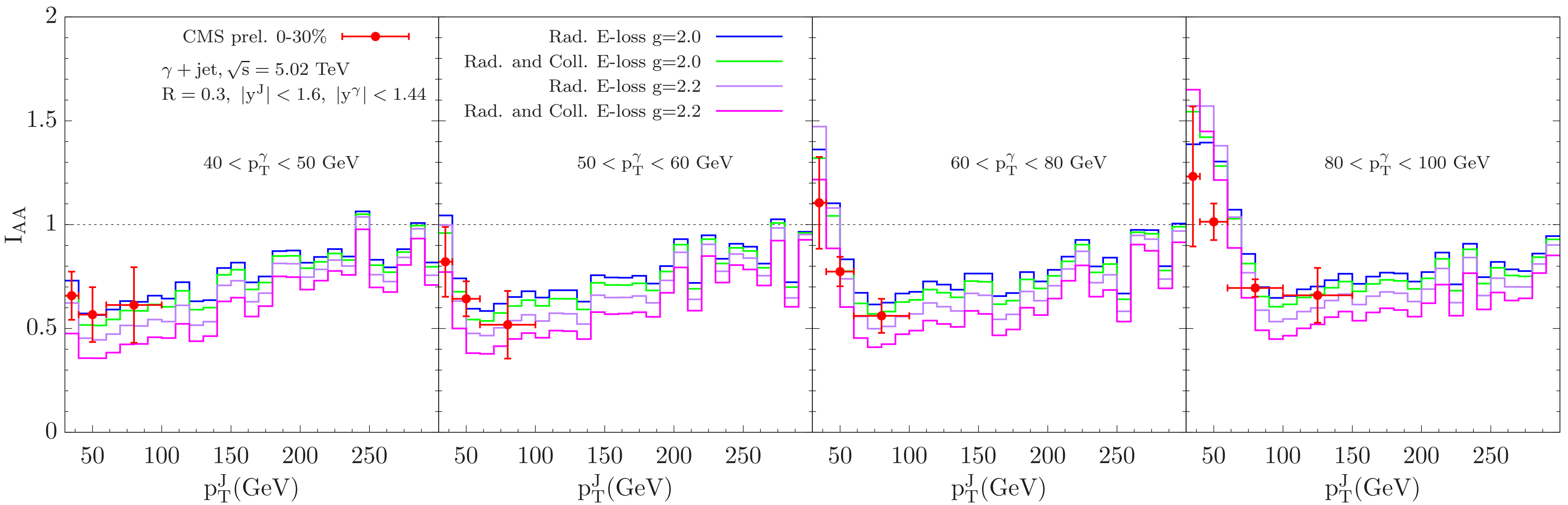
Pythia pp baseline is narrower than CMS measured X_{JZ}, mainly due to the smearing in CMS measurements.

Transverse momentum asymmetry (photon+jet)



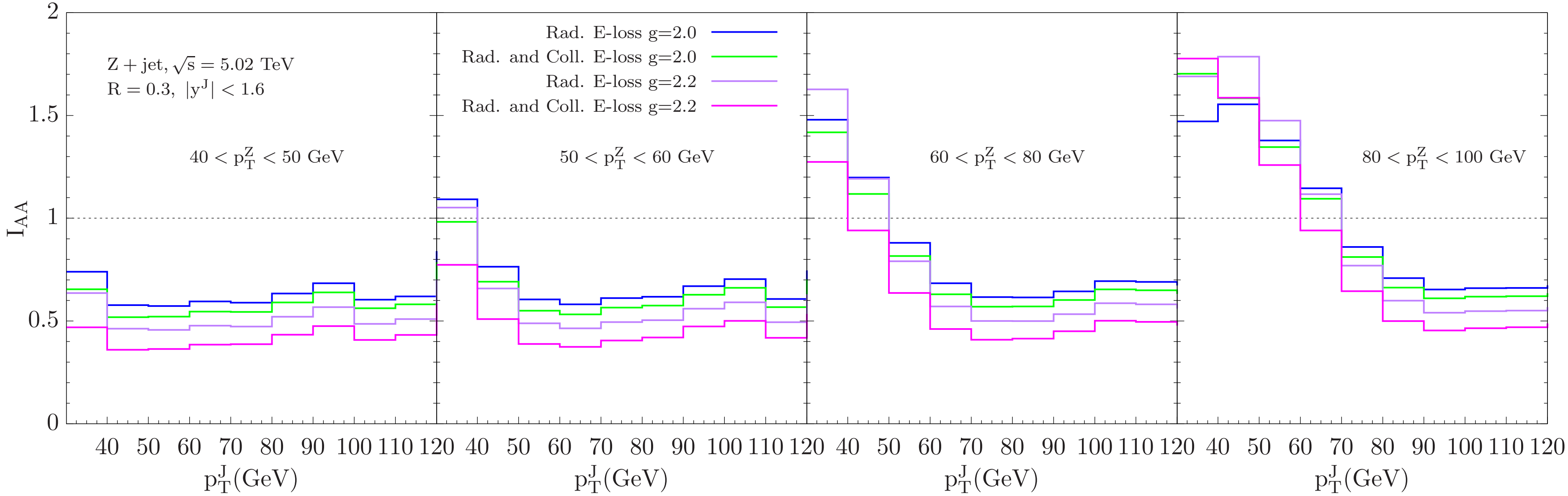
Nuclear modification factor I_{AA} (photon+jet)

$$I_{AA} = \frac{\frac{d\sigma^{AA}}{dp_T^V dp_T^J}}{\langle N_{bin} \rangle \frac{d\sigma^{pp}}{dp_T^V dp_T^J}}$$



- Kinematic cuts play a role
  - larger suppression at the LHC along the main diagonal
  - enhancement in the region of $p_{TJ} < p_{TV}$ and suppression in the region of $p_{TJ} > p_{TV}$, which is characteristic of in-medium tagged-jet dynamics.

Prediction of I_{AA} for Z+jet

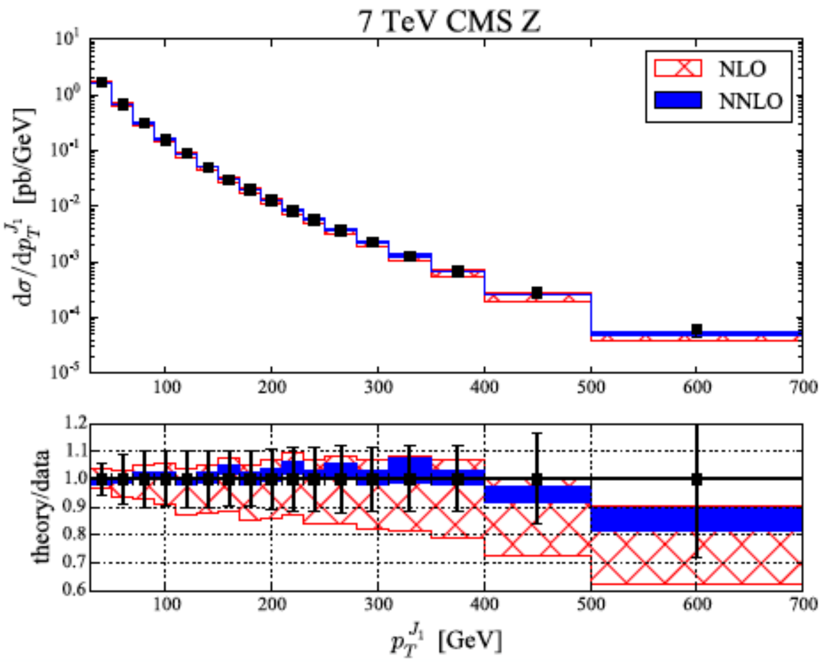


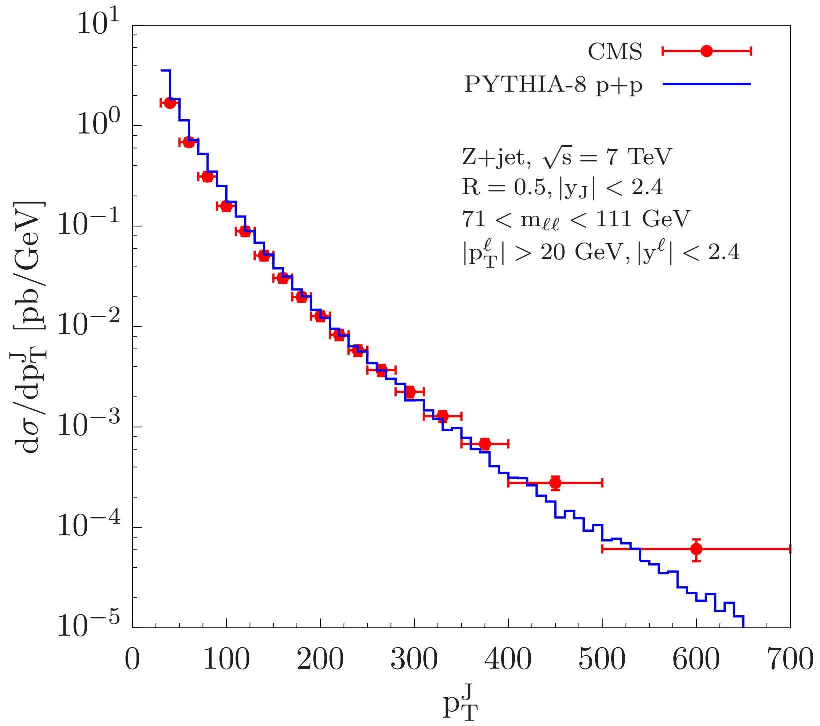
What is our precision goal?

- Knowledge of initial states - pp baseline
- Jet-medium interaction $SCET_G$
- Medium evolution

Outlook – precision calculation of p+p baseline

- NNLO Z+jet — Boughezal, Liu, Petriello, PRL, PLB 2016





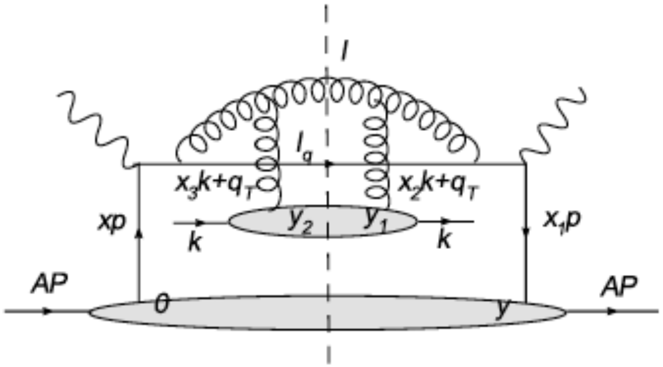
Excellent agreement of NNLO results with CMS data over the entire P_{Tj1} range, not only the overall normalization, but the shape which is significant for the implementation of parton energy loss effect

Outlook - evolution of jet transport parameter

- Related to jet transport parameter

J. Casalderrey-Solana and X.-N. Wang (2008)

Kang, Wang, **HX,** PRL 2014
Kang, Qiu, Wang, **HX,** PRD 2016



$$\mu^2 \frac{\partial}{\partial \mu^2} T_{qg}(x_B, 0, 0, \mu_f^2) = \frac{\alpha_s}{2\pi} \int_{x_B}^{1} \frac{dx}{x} \left[P_{qq}(\hat{x}) T_{qg}(x, 0, 0, \mu^2) + \Delta P_{qg\to qg}(\hat{x}) \otimes T_{qg} + P_{qg}(\hat{x}) T_{gg}(x, 0, 0, \mu^2) \right]$$

$$T_{qg}(x_B, 0, 0, \mu_f^2) \approx \frac{N_c}{4\pi^2 \alpha_s} f_{q/A}(x_B, \mu_f^2) \int dy^- \hat{q}(\mu_f^2, y^-)$$

qhat evolution (scale dependence)

Summary

- We have evaluated Z+jet and photon+jet productions in Pb+Pb collisions at 5 TeV.

- Strong medium modification effects as observed in X_{JV} and I_{AA} distributions can be explained by energy loss effects, which include medium-induced parton splitting and the dissipation of the energy of the parton shower through collisional interactions in the strongly-interacting matter.

- Stay tuned for more precise calculation (NNLO pp baseline and qhat evolution).