Study of QGP through jet quenching

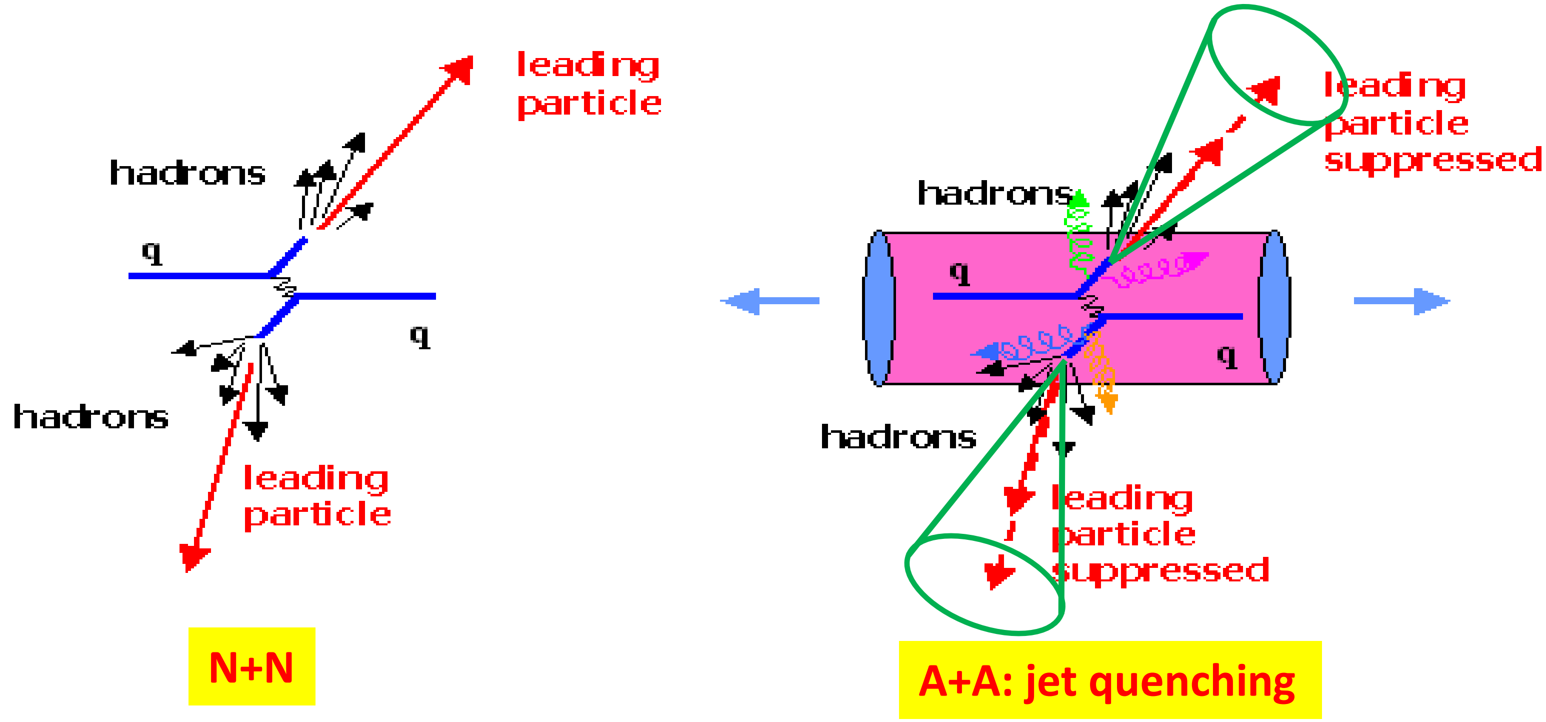
Guang-You Qin
秦广友
Central China Normal University (CCNU)
华中师范大学

Symposium on High-Energy Nuclear Physics
The 100th HENPIC e-Forum
16 April 2020

Outline

- **Introduction**
- **Heavy and light flavor jet quenching**
  - NLO pQCD framework and linearized Boltzmann transport model
  - R_{AA} for heavy and light flavor hadrons
  - Cao, Luo, GYQ, Wang, PRC 2016 & PLB 2018; Xing, Cao, GYQ, Xing, PLB 2020 (in press).
- **Full jet and medium response**
  - Full jet interacting with QGP in a coupled jet-fluid model
  - Nuclear modification of full jet yield and jet shape
  - Chang, GYQ, PRC 2016; Tachibana, Chang, GYQ, PRC 2017; Chang, Tachibana, GYQ, PLB 2020
- **Summary**

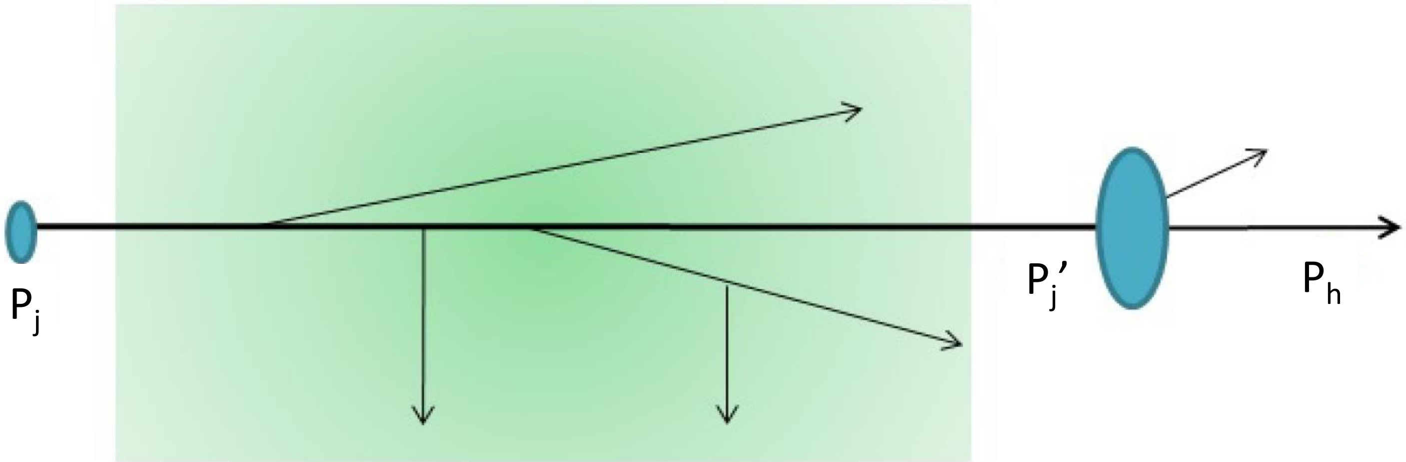
Jets are hard probes of QGP



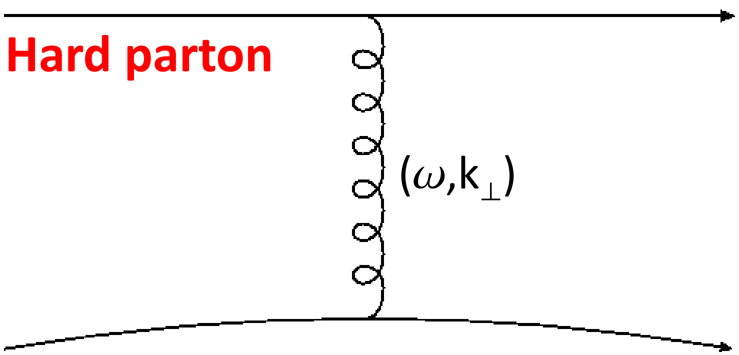
Jets (and **jet-medium interaction, jet quenching**) provide valuable tools to probe hot & dense QGP in relativistic heavy-ion collisions (at RHIC & LHC):

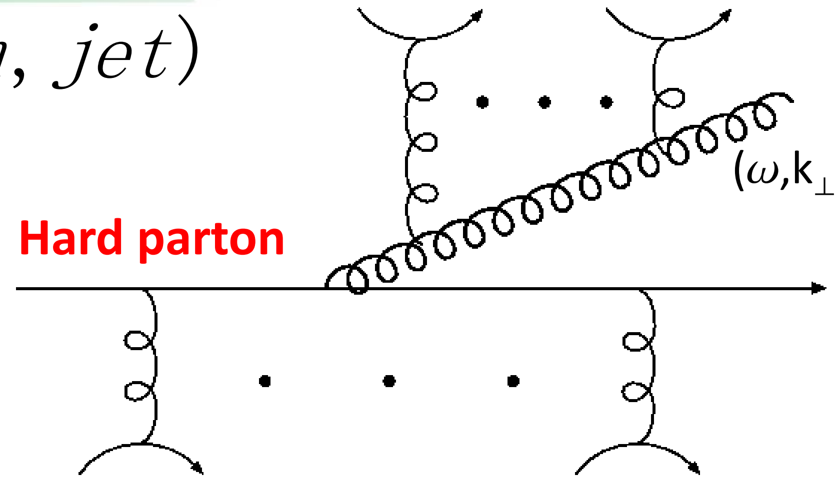
(1) parton energy loss (2) deflection and broadening (3) modification of jet (sub)structure (4) jet-induced medium excitation

Elastic and inelastic interactions



$$P_{j\to j'}(medium,\ jet)$$





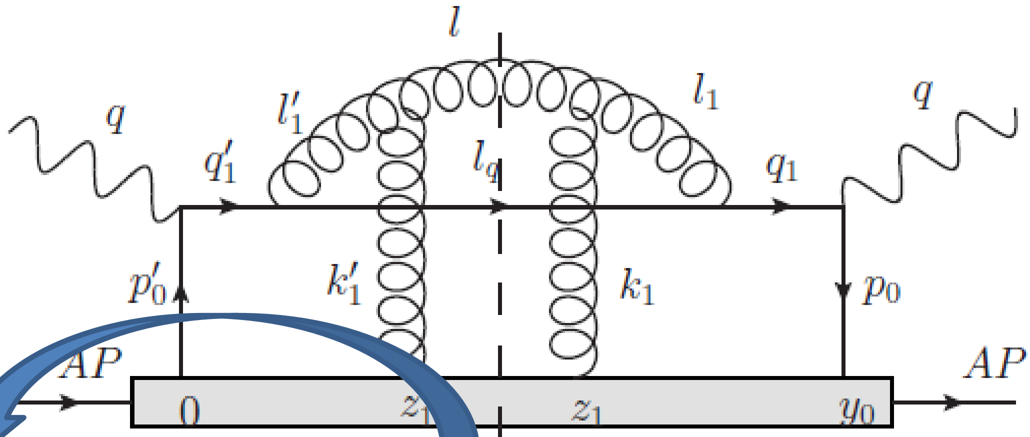
Elastic (collisional)

$$\frac{d\Gamma_{coll}}{d\omega dk_\perp^2 dt}(T, E, \ldots) = ?$$

Inelastic (radiative)

$$\frac{d\Gamma_{rad}}{d\omega dk_\perp^2 dt}(T, E, \ldots) = ?$$

Medium-induced inelastic (radiative) process



Zhang, Hou, GYQ, PRC 2018 & PRC 2019;
Zhang, GYQ, Wang, PRD 2019

+ other 20 diagrams

$$\frac{dN_g^{med}}{dy\,d^2\mathbf{l}_\perp} = \frac{\alpha_s}{2\pi^2} P(y) \int dZ_1^- \int \frac{dk^- d^2\mathbf{k}_{1\perp}}{(2\pi)^3} \mathcal{D}(k_1^-, \mathbf{k}_{1\perp})$$

$$\times \left\{ \left[2 - 2\cos\left(\frac{y(1-y)}{(y-\lambda_1^-)\,(1+\lambda_1^- - y)} \frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + (y-\lambda_1^-)^2 M^2}{l_\perp^2 + y^2 M^2} \frac{Z_1^-}{\tilde{\tau}^-_{\rm form}} \right) \right] \right.$$

$$C_A \left[\frac{1+(1+\lambda_1^- - y)^2}{1+(1-y)^2} \left(\frac{y - \frac{\lambda_1^-}{2}}{y-\lambda_1^-} \right)^2 \frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + \frac{(y-\lambda_1^-)^4 M^2}{1+(1+\lambda_1^- - y)^2}}{[(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + (y-\lambda_1^-)^2 M^2]^2} \right.$$

$$- \frac{1+(1+\lambda_1^- - y)(1-y)}{2[1+(1-y)^2]} \left(\frac{y - \frac{\lambda_1^-}{2}}{y-\lambda_1^-} \right) \frac{\mathbf{l}_\perp \cdot (\mathbf{l}_\perp - \mathbf{k}_{1\perp}) + \frac{y^2 (y-\lambda_1^-)^2}{1+(1+\lambda_1^- - y)(1-y)} M^2}{[l_\perp^2 + y^2 M^2]\,[(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + (y-\lambda_1^-)^2 M^2]}$$

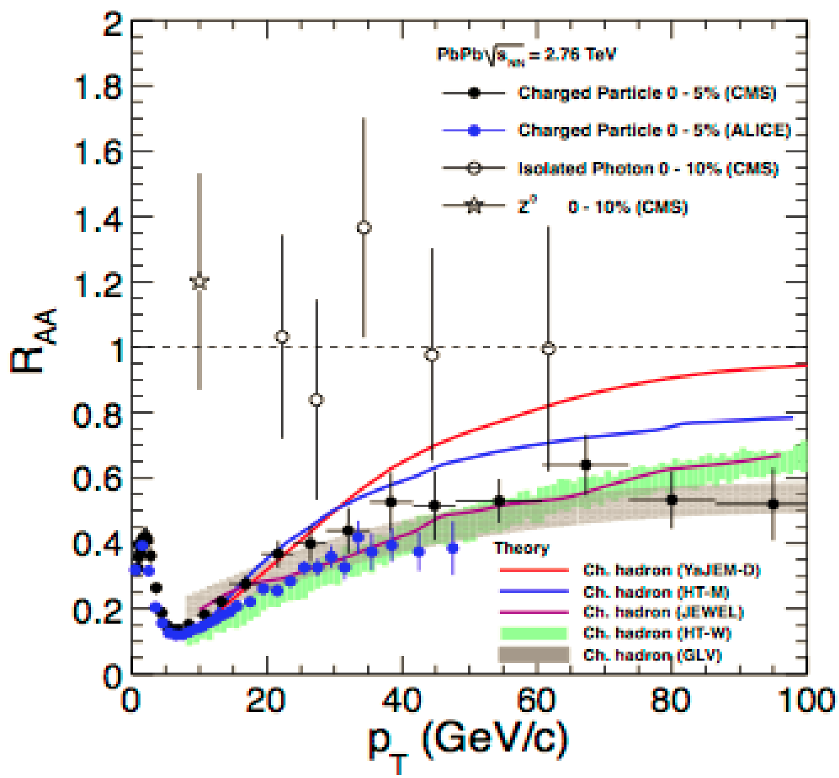
$$\left. \left. - \frac{1+(1+\lambda_1^- - y)(1-\frac{y}{1+\lambda_1^-})}{2[1+(1-y)^2]} \left(\frac{y - \frac{\lambda_1^-}{2}}{y-\lambda_1^-} \right) \frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp}) \cdot \left(\mathbf{l}_\perp - \frac{y}{1+\lambda_1^-} \mathbf{k}_{1\perp} \right) + \frac{\left(\frac{y}{1+\lambda_1^-}\right)^2 (y-\lambda_1^-)^2}{1+(1+\lambda_1^- - y)(1-\frac{y}{1+\lambda_1^-})} M^2}{\left[\left(\mathbf{l}_\perp - \frac{y}{1+\lambda_1^-} \mathbf{k}_{1\perp} \right)^2 + (\frac{y}{1+\lambda_1^-})^2 M^2 \right] [(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + (y-\lambda_1^-)^2 M^2]} \right] + \ldots\ldots \right\}$$

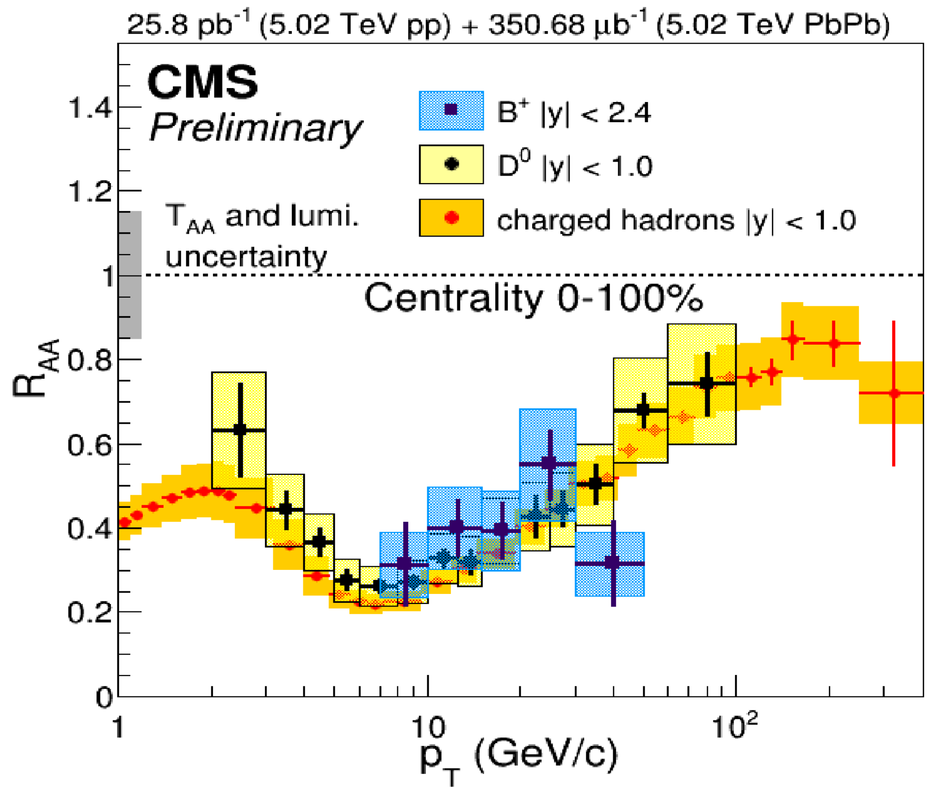
$$\mathcal{D}(k_1^-, \mathbf{k}_{1\perp}) = (2\pi)^3 \frac{dP_{\rm el}}{dk_1^- d^2\mathbf{k}_{1\perp} dZ_1^-}$$

$$\hat{q}_{lc} = \frac{d\langle k_{1\perp}^2 \rangle}{dL^-} = \int \frac{dk_1^- d^2\mathbf{k}_{1\perp}}{(2\pi)^3} \mathbf{k}_{1\perp}^2 \mathcal{D}(k_1^-, \mathbf{k}_{1\perp})$$

Medium-induced gluon emission **beyond collinear expansion & soft emission limit** with transverse & longitudinal scatterings for massive quarks

Nuclear modifications of large p_T hadrons





$$R_{AA} = \frac{1}{N_{\rm coll}} \frac{dN^{AA} / d^2 p_T dy}{dN^{pp} / d^2 p_T dy}$$

Color & flavor dependences of parton energy loss: $\boldsymbol{\Delta E_g > \Delta E_{uds} > \Delta E_c > \Delta E_b}$?

Observed similar R_{AA} for D mesons & charged hadrons at **p_T > 6-8 GeV**

Heavy & light flavor jet quenching for large p_T hadrons: overview of our framework and main result

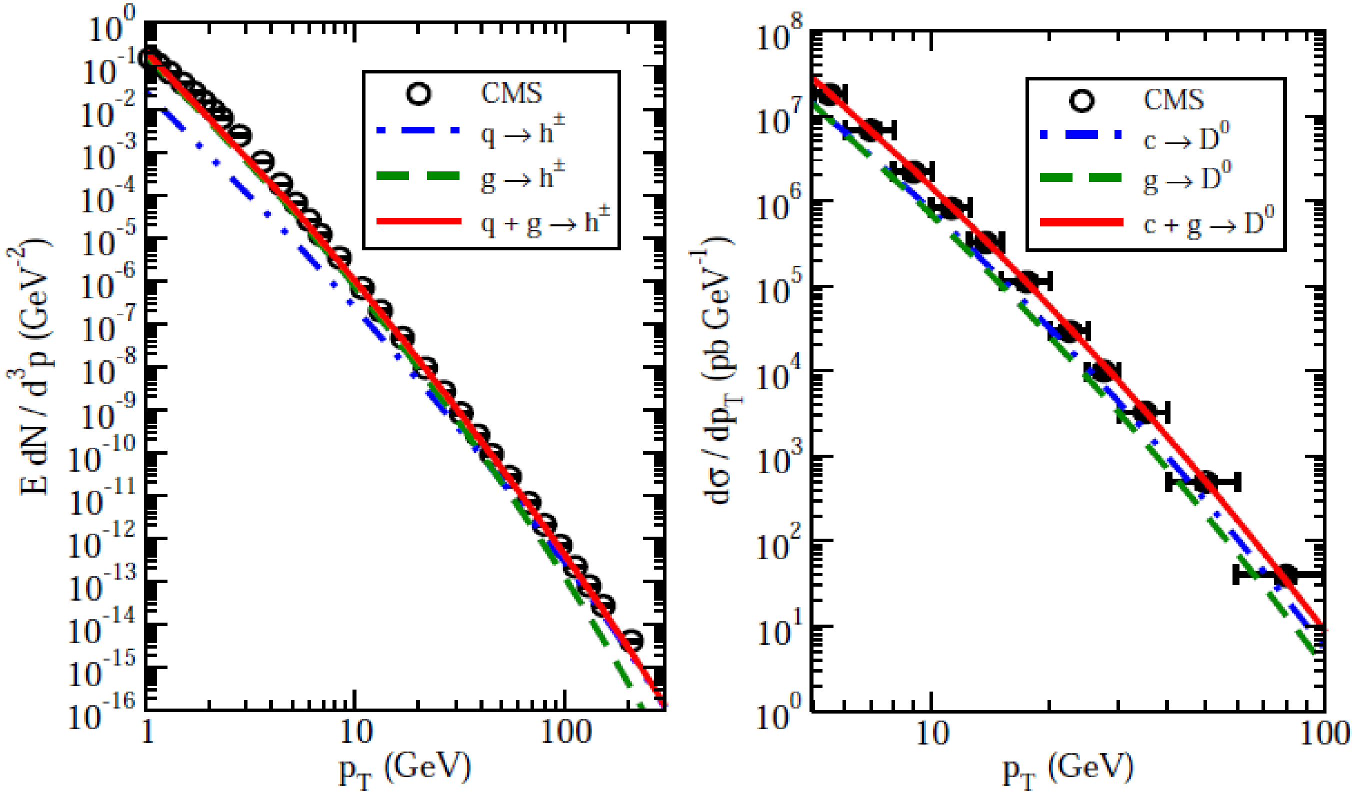
- **A NLO pQCD framework for light and heavy flavor parton and hadron productions, taking into account both quark and gluon contributions to hadron production.**

- **A linear Boltzmann transport model combined with hydrodynamics simulation for studying the energy loss and medium modification of heavy and light flavor jets in QGP, taking into account both radiative and collisional interactions.**

- **The first satisfactory description of R_{AA} for charged hadrons, D mesons, B mesons and B-decayed D mesons simultaneously over a wide range of transverse momenta (8-300 GeV).**

Xing, Cao, GYQ, Xing, arXiv:1906.00413

Hadron productions in pp collisions



Xing, Cao, GYQ, Xing, arXiv:1906.00413

$$d\sigma_{pp\to hX} = \sum_{abc} \int dx_a \int dx_b \int dz_c f_a(x_a) f_b(x_b)\, d\hat{\sigma}_{ab\to c} D_{h/c}(z_c)$$

NLO: Jager, Schafer, Stratmann, Vogelsang, Phys. Rev.D67, 054005 (2003); Aversa, Chiappetta, Greco, Guillet, Nucl. Phys.B327, 105 (1989).

FF: Kretzer, Phys. Rev.D62, 054001 (2000); Kneesch, Kniehl, Kramer, Schienbein, Nucl. Phys.B799, 34 (2008); Kniehl, Kramer, Schienbein, Spies-berger, Phys. Rev.D77, 014011 (2008).

Linearized Boltzmann Transport (LBT) Model

- **Boltzmann equation:** $p_1 \cdot \partial f_1(x_1, p_1) = E_1 C[f_1]$

- **Elastic collisions:**

$$\Gamma_{12\to34} = \frac{\gamma_2}{2E_1} \int \frac{d^3p_2}{(2\pi)^3 2E_2} \int \frac{d^3p_3}{(2\pi)^3 2E_3} \int \frac{d^3p_4}{(2\pi)^3 2E_4} \times f_2(\vec{p}_2) \left[1 \pm f_3(\vec{p}_1 - \vec{k})\right] \left[1 \pm f_4(\vec{p}_2 + \vec{k})\right] \times (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - p_4) |\mathcal{M}_{12\to34}|^2$$

$$P_{el} = 1 - e^{-\Gamma_{el}\Delta t}$$

Matrix elements taken from LO pQCD

- **Inelastic collisions:**

$$\langle N_g \rangle = \Gamma_g \Delta t = \Delta t \int dx dk_\perp^2 \frac{dN_g}{dx dk_\perp^2 dt}$$

$$P_{inel} = 1 - e^{-\langle N_g \rangle}$$

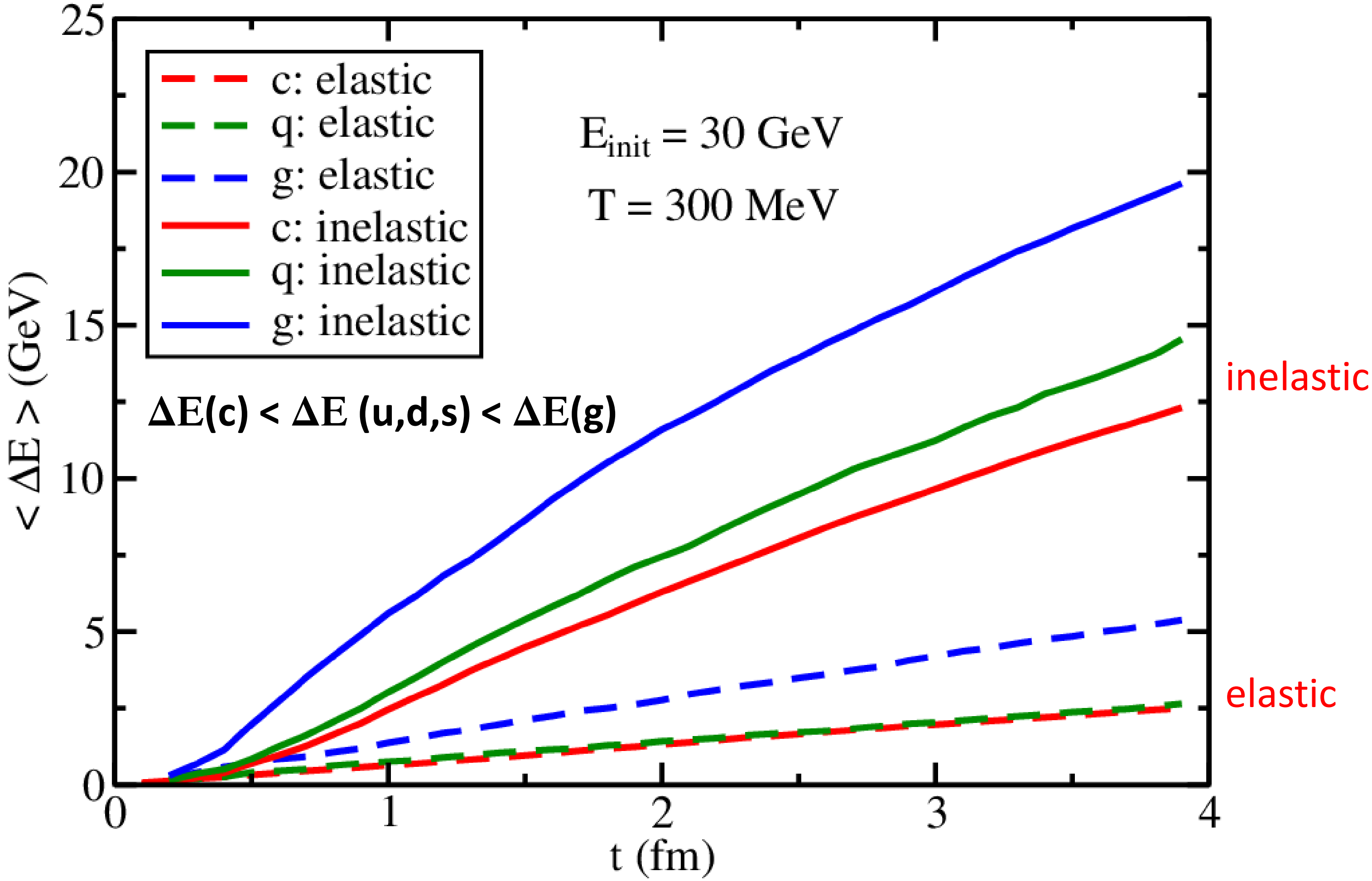
Radiation spectra taken from Guo, Wang PRL 2000; Zhang, Wang, Wang 2004

- **Elastic + Inelastic:**

$$P_{tot} = 1 - e^{-\Gamma_{tot}\Delta t} = P_{el} + P_{inel} - P_{el}P_{inel}$$

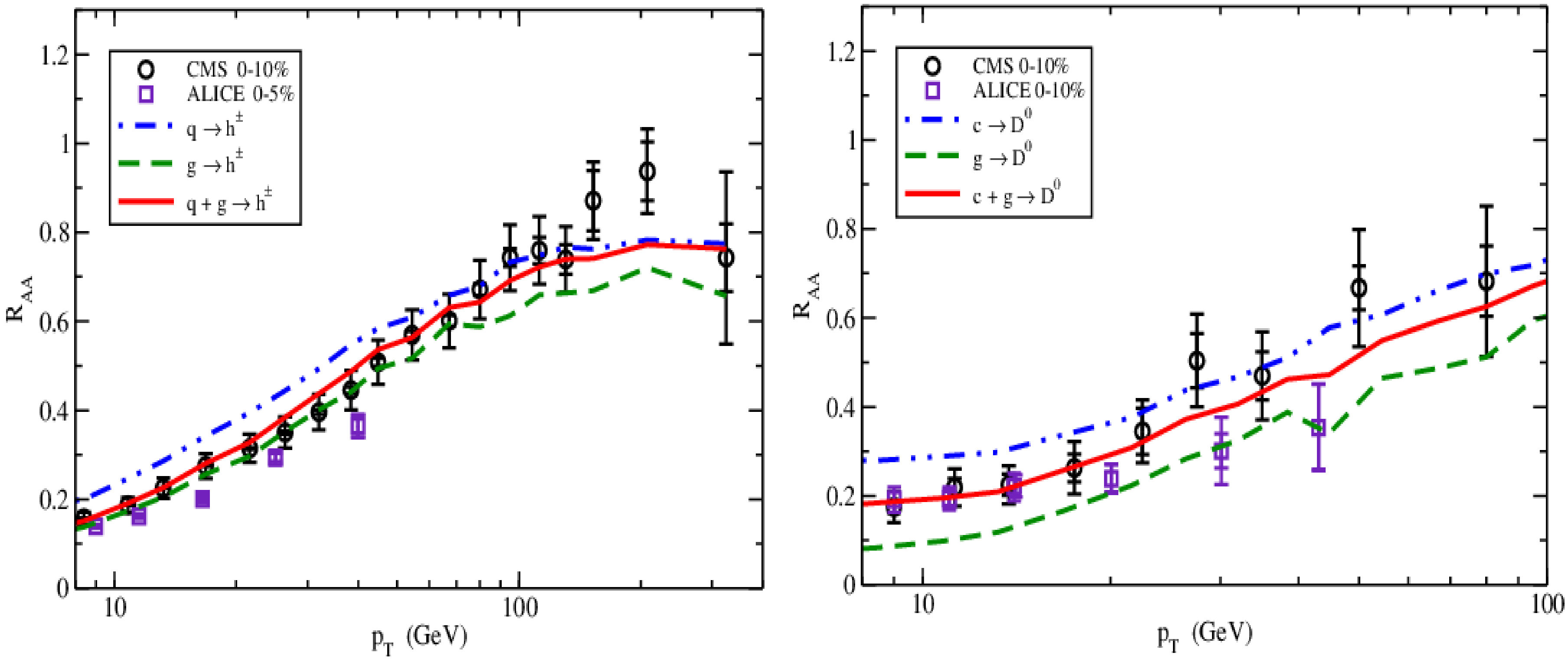
He, Luo, Wang, Zhu, PRC 2015; Cao, Luo, GYQ, Wang, PRC 2016, PLB 2018; etc.

Parton energy loss in LBT



He, Luo, Wang, Zhu, PRC 2015; Cao, Luo, GYQ, Wang, PRC 2016 ; PLB 2018; etc.

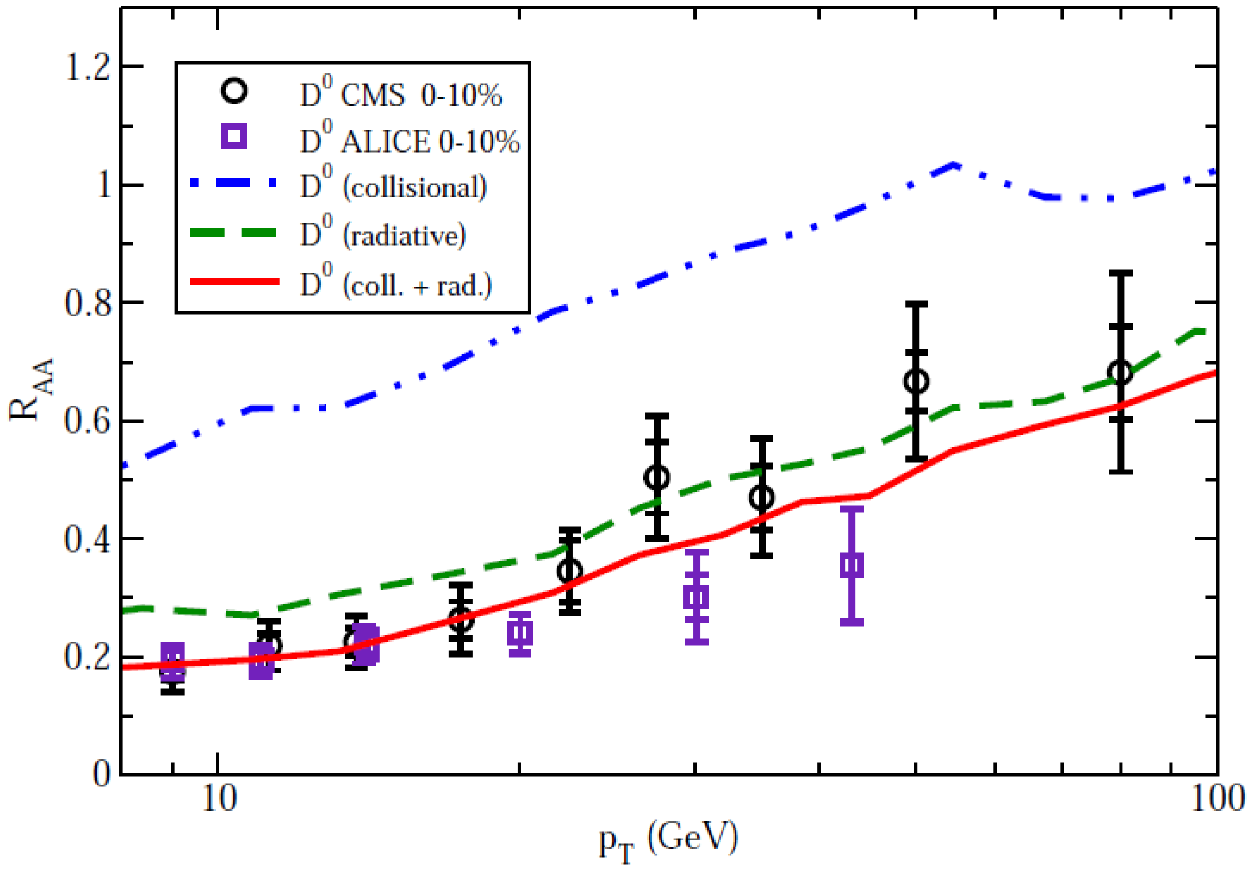
Flavor hierarchy of jet quenching



Xing, Cao, GYQ, Xing, arXiv:1906.00413

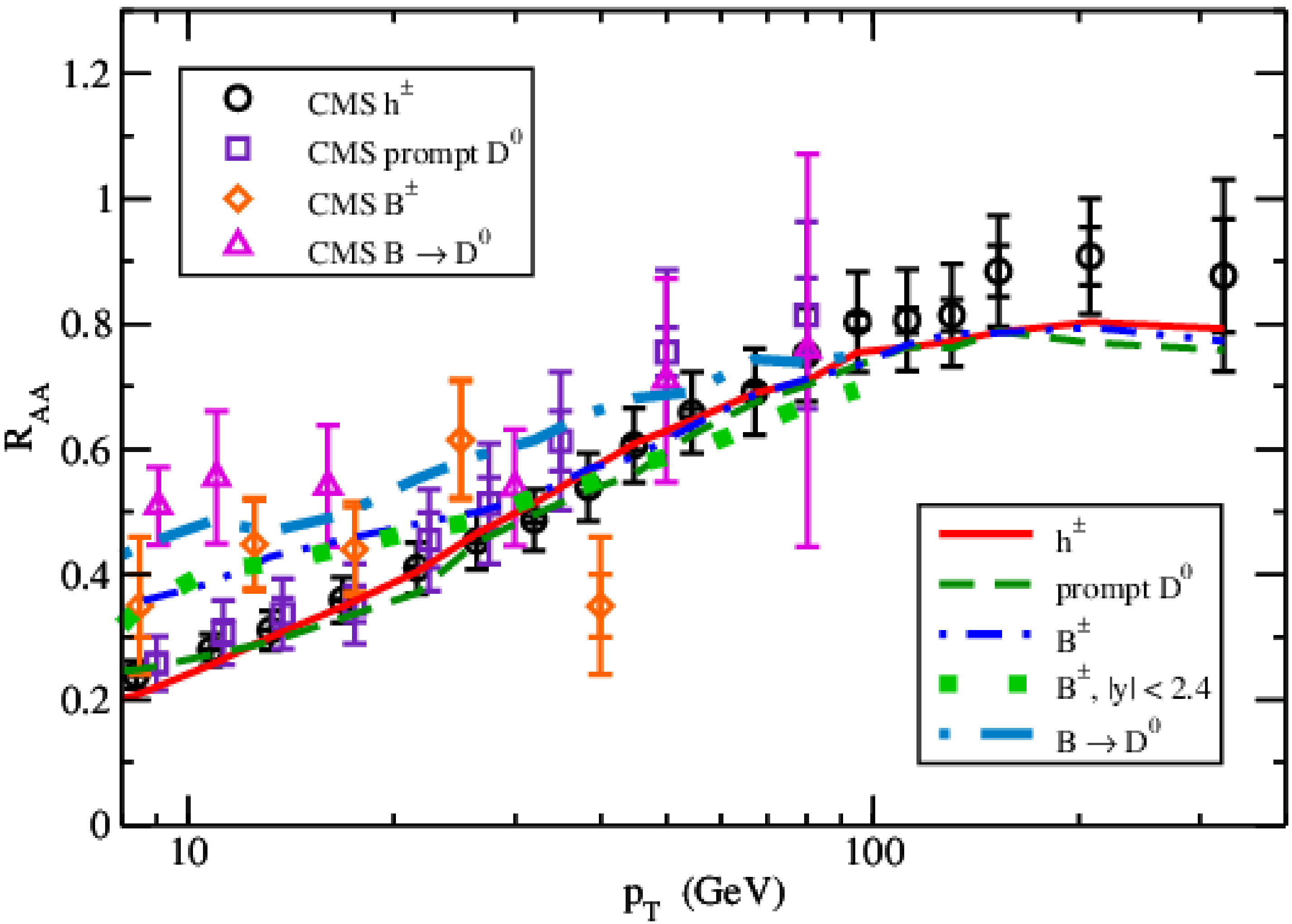
NLO: Jager, Schafer, Stratmann, Vogelsang, Phys. Rev.D67, 054005 (2003); Aversa, Chiappetta, Greco, Guillet, Nucl. Phys.B327, 105 (1989).
FF: Kretzer, Phys. Rev.D62, 054001 (2000); Kneesch, Kniehl, Kramer, Schienbein, Nucl. Phys.B799, 34 (2008); Kniehl, Kramer, Schienbein, Spies-berger, Phys. Rev.D77, 014011 (2008).

Radiative and collisional contributions



- **Radiative E loss provides more dominant contributions to R_{AA}, collisional E loss also has sizable contributions to R_{AA} at not-very-high p_T regime and decreases with increasing p_T.**

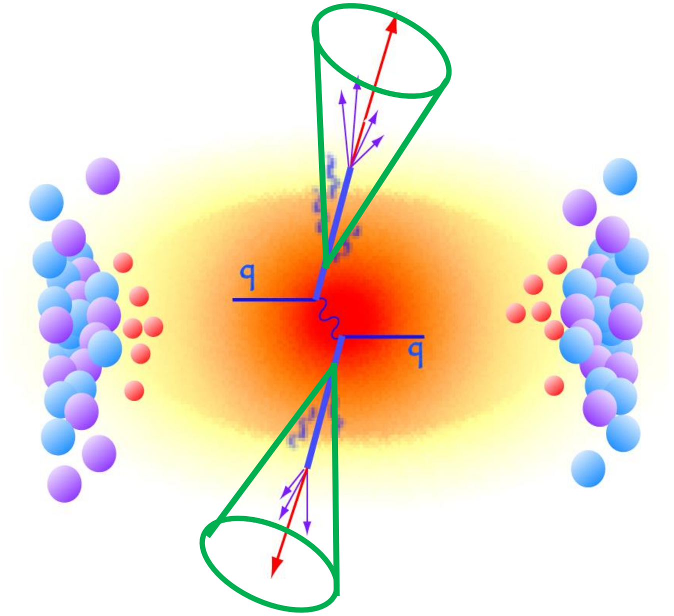
Flavor hierarchy of jet quenching



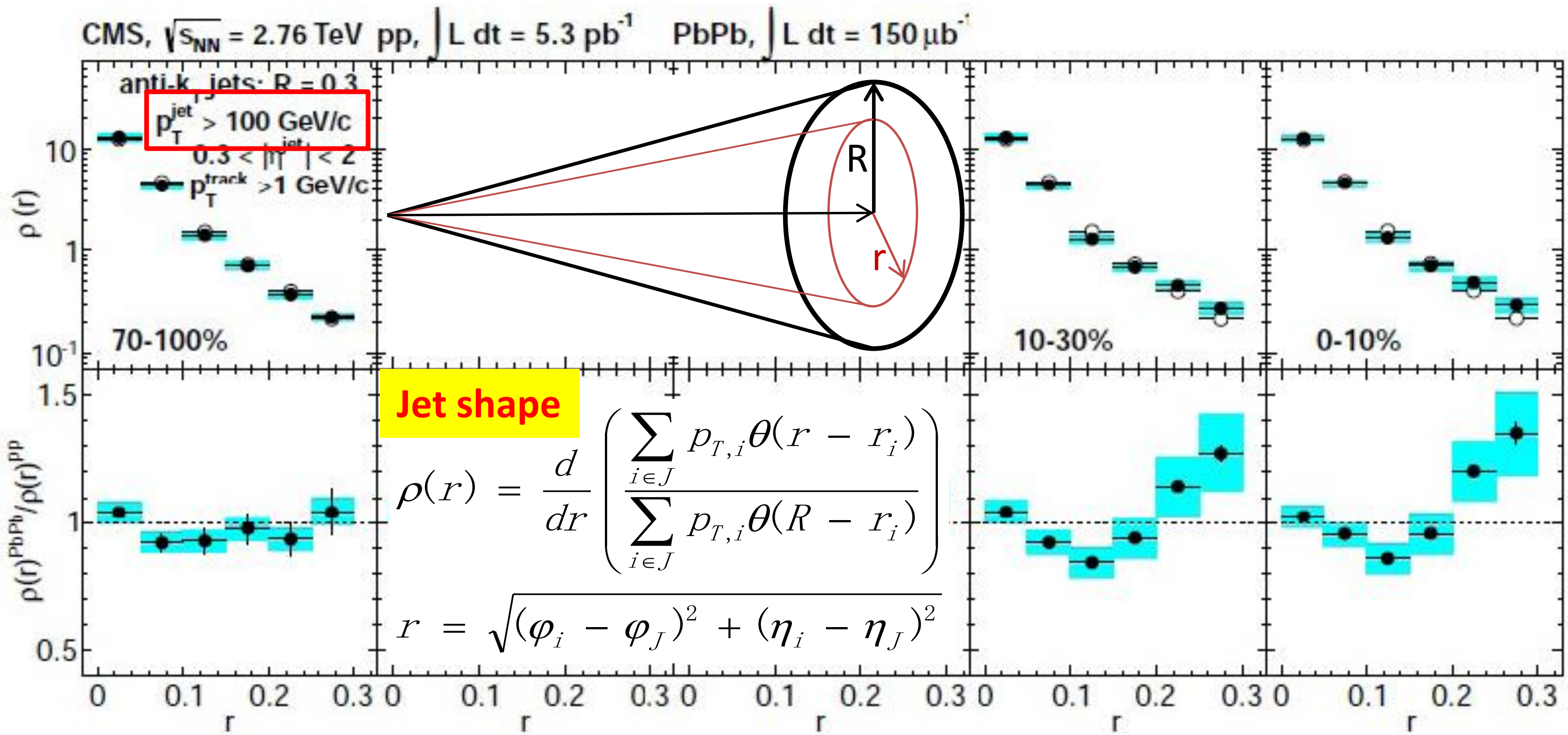
Xing, Cao, GYQ, Xing, arXiv:1906.00413

Full jets in heavy-ion collisions

- Jets are spray of particles originating from fragmentation of hard-scattered partons
- Jet reconstruction: recombine hadron (or parton) fragments to approximate the original hard parton's energy and momentum
- Parameters: e.g., jet size R
- With the inclusion of sub-leading fragments, fully reconstructed jets are expected to provide more detailed information than leading hadron observables

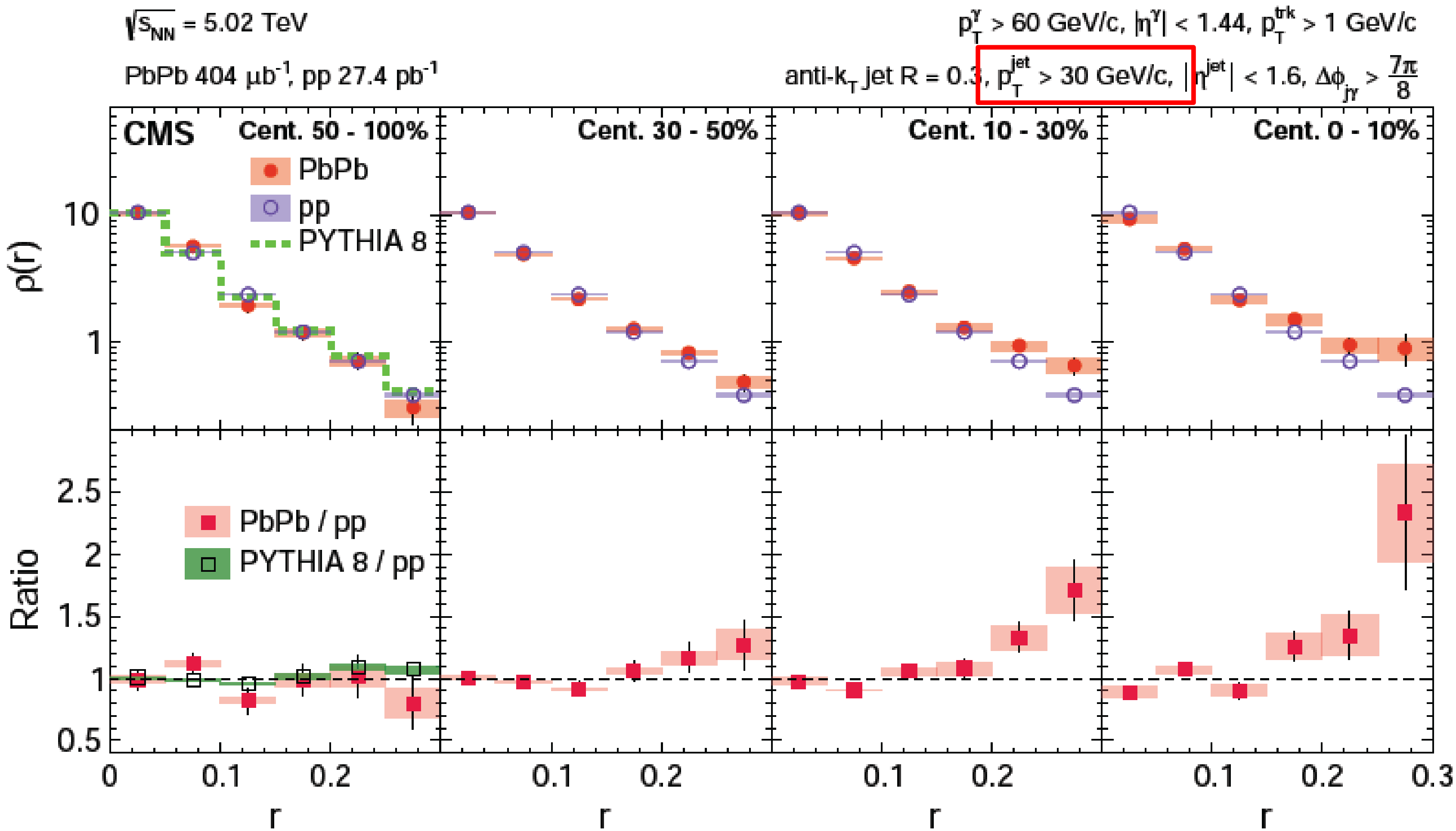


Jet shape for inclusive jets



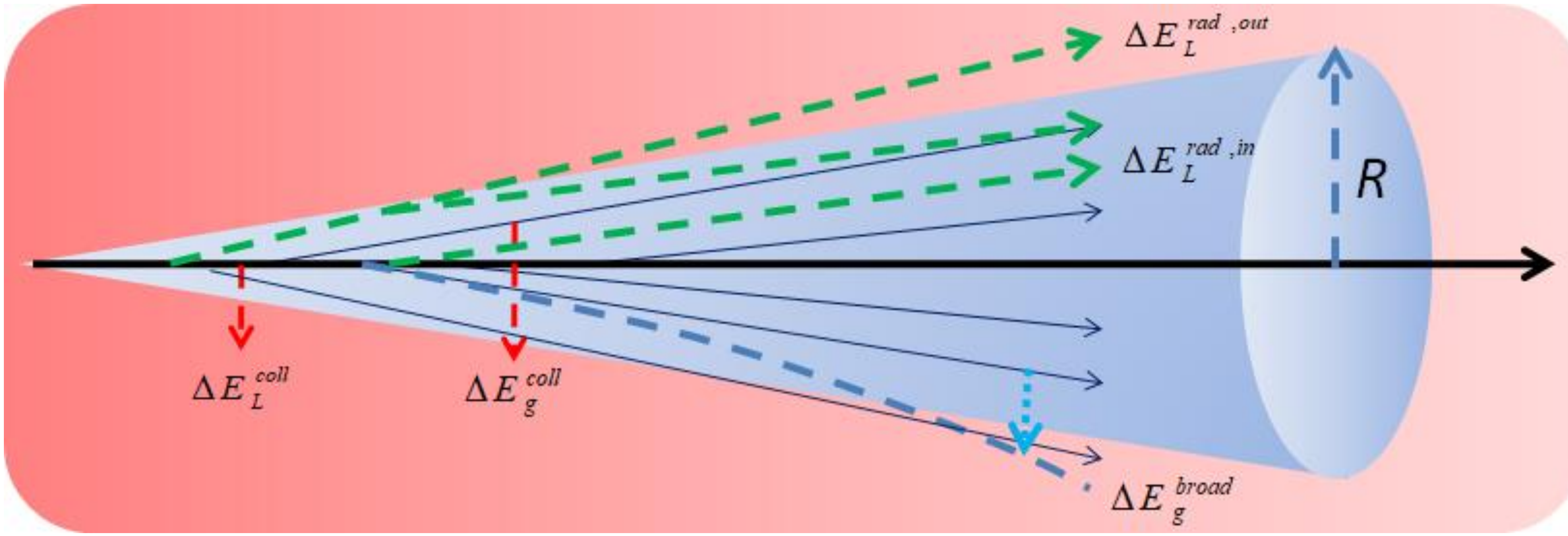
- **The observed enhancement at large r** is consistent with jet broadening (& medium-induced radiation)
- The soft outer part of the jet is easier to modify, while there is little modification to the inner hard cone

Jet shape in photon-jets



While a significant fraction of single inclusive jets are from gluons, photon-jets are mostly quark-initiated jets. **Does this explain the observed difference?**

Full jet evolution & energy loss in medium



$$E_{jet} = E_{in} + E_{lost} = E_{in} + E_{rad,out} + E_{kick,out} + (E_{th} - E_{th,in})$$

GYQ, Muller, PRL, 2011; Casalderrey-Solana, Milhano, Wiedemann, JPG 2011; Young, Schenke, Jeon, Gale, PRC, 2011; Dai, Vitev, Zhang, PRL 2013; Wang, Zhu, PRL 2013; Blaizot, Iancu, Mehtar-Tani, PRL 2013; Chang, Qin, PRC 2016; Tachibana, Chang, Qin, PRC 2016; etc.

Full jet evolution in medium

- Solve the 3D (energy & transverse momentum) evolution for shower partons inside the full jet
- Include both collisional (the longitudinal drag and transverse diffusion) and all radiative/splitting processes

$$\frac{d}{dt} f_j(\omega_j, k_{j\perp}^2, t) = \left(\hat{e}_j \frac{\partial}{\partial \omega_j} + \frac{1}{4} \hat{q}_j \nabla_{k_\perp}^2 \right) f_j(\omega_j, k_{j\perp}^2, t)$$

Drag & transverse broadening

$$+ \sum_i \int d\omega_i dk_{i\perp}^2 \frac{d\tilde{\Gamma}_{i\to j}(\omega_j, k_{j\perp}^2 | \omega_i, k_{i\perp}^2)}{d\omega_j d^2 k_{j\perp} dt} f_i(\omega_i, k_{i\perp}^2, t)$$

Gain terms

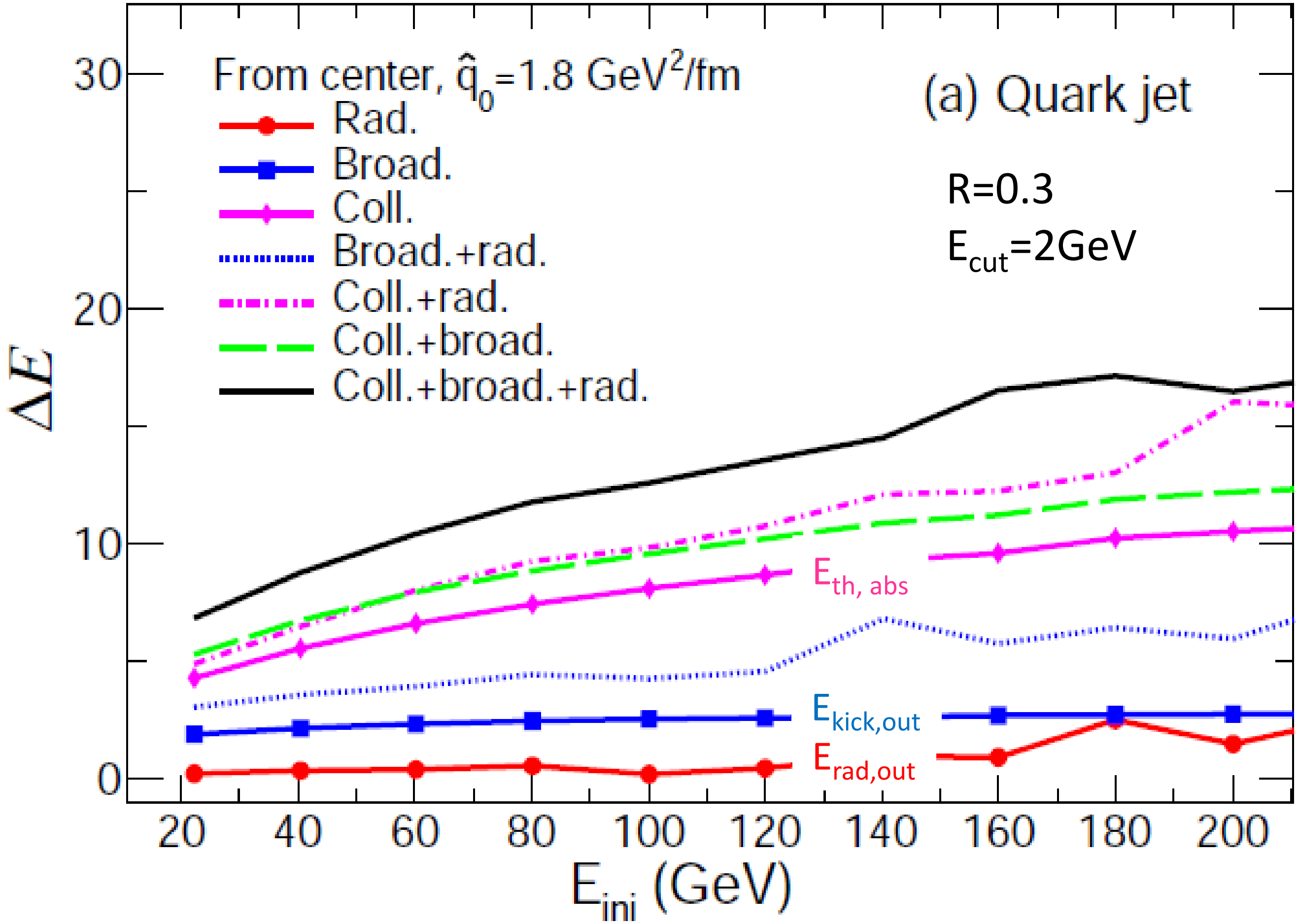
$$- \sum_i \int d\omega_i dk_{i\perp}^2 \frac{d\tilde{\Gamma}_{j\to i}(\omega_i, k_{i\perp}^2 | \omega_j, k_{j\perp}^2)}{d\omega_i d^2 k_{i\perp} dt} f_j(\omega_j, k_{j\perp}^2, t)$$

Loss terms

$$E_{jet}(R) = \sum_i \int_R \omega_i f_i(\omega_i, k_{i\perp}^2) d\omega_i dk_{i\perp}^2$$

Chang, GYQ, PRC 2016

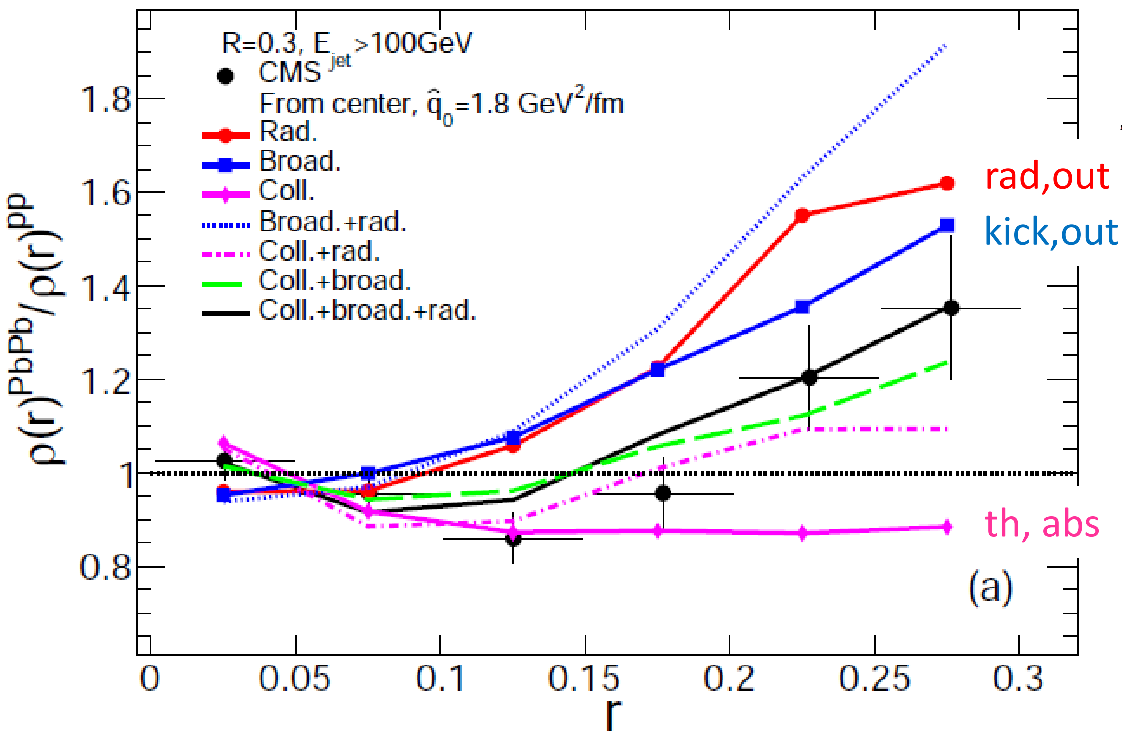
Full jet energy loss (radiative, collisional, broadening)

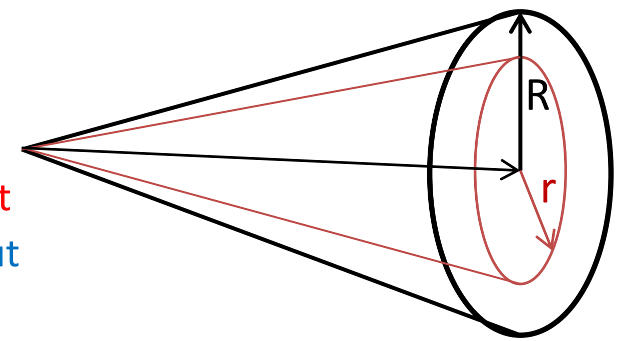


Chang, GYQ, PRC 2016

$$\frac{df(\vec{p},t)}{dt} = C_{coll.E.loss}\left[f\right] + C_{coll.broad}\left[f\right] + C_{rad}\left[f\right]$$

Nuclear modification of jet shape function





$$\rho(r) = \frac{d}{dr}\left(\frac{\sum_{i\in J} p_{T,i}\theta(r - r_i)}{\sum_{i\in J} p_{T,i}\theta(R - r_i)}\right)$$

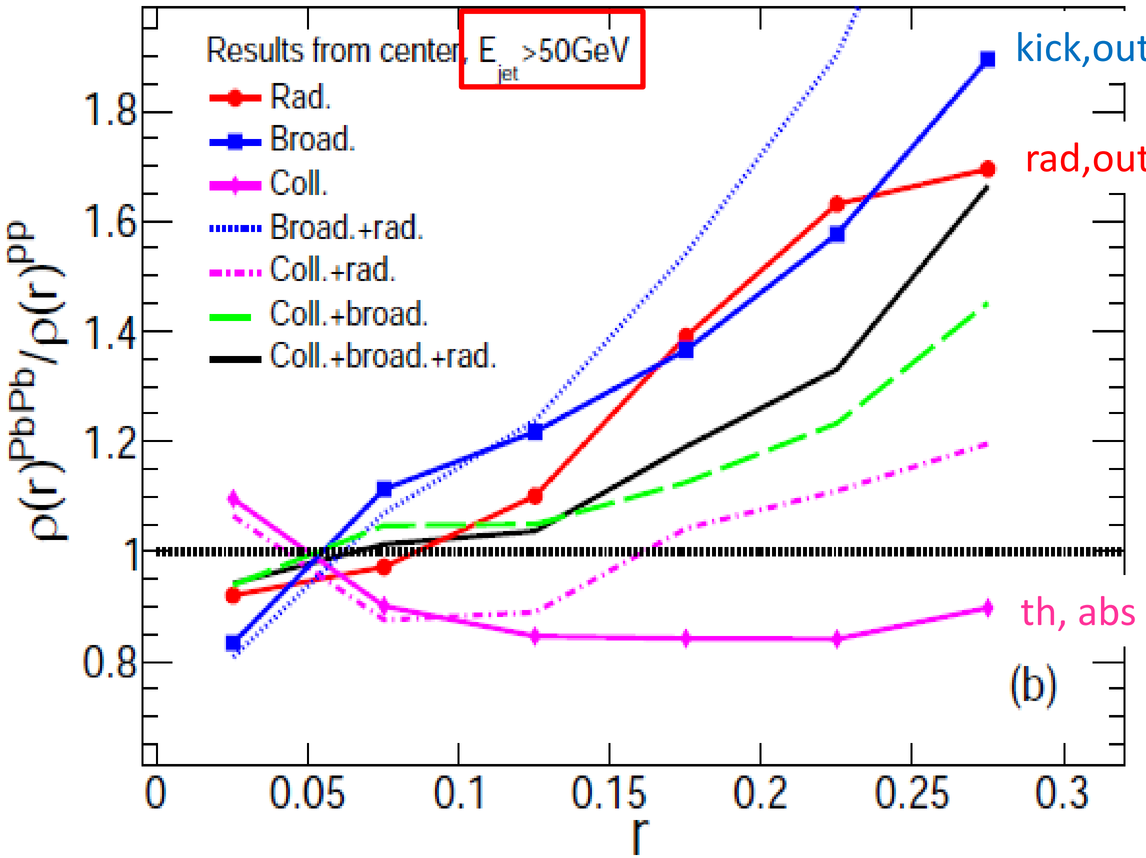
$$r_i = \sqrt{(\varphi_i - \varphi_J)^2 + (\eta_i - \eta_J)^2}$$

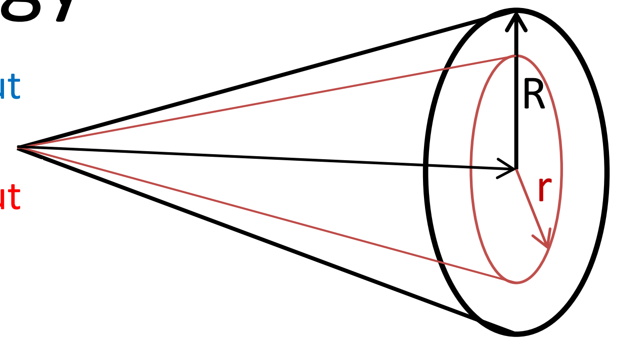
The enhancement at large r is consistent with jet broadening (& medium-induced radiation)
The soft outer part is easier to modify, while changing the inner hard cone is more difficult
The final jet shape is the interplay of different jet-medium interaction mechanisms

Chang, GYQ, PRC 2016

$$\frac{df(\vec{p},t)}{dt} = C_{coll.E.loss}\left[f\right] + C_{coll.broad}\left[f\right] + C_{rad}\left[f\right]$$

Nuclear modification of jet shape function: lower jet energy





There is a chance to see the modification of jet core for lower energy jets (at RHIC) since the jet core is not too hard to be modified.

Nuclear modification of jet shape has strong dependence on jet energies.

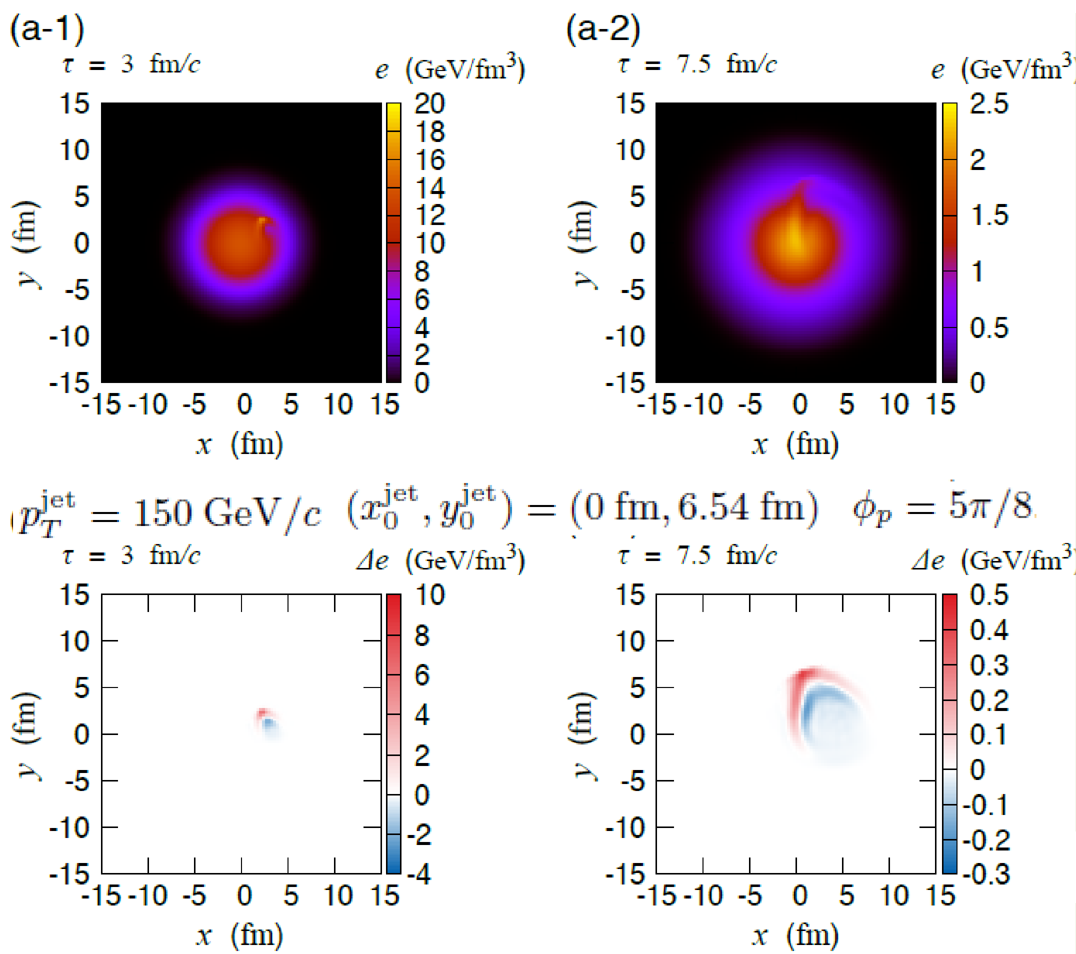
Chang, GYQ, PRC 2016

$$\frac{df(\vec{p},t)}{dt} = C_{coll.E.loss}[f] + C_{coll.broad}[f] + C_{rad}[f]$$

A coupled jet-fluid model: jet evolution & medium response

$$\frac{df(\vec{p},t)}{dt} = C_{coll.E.loss}[f] + C_{coll.broad}[f] + C_{rad}[f]$$

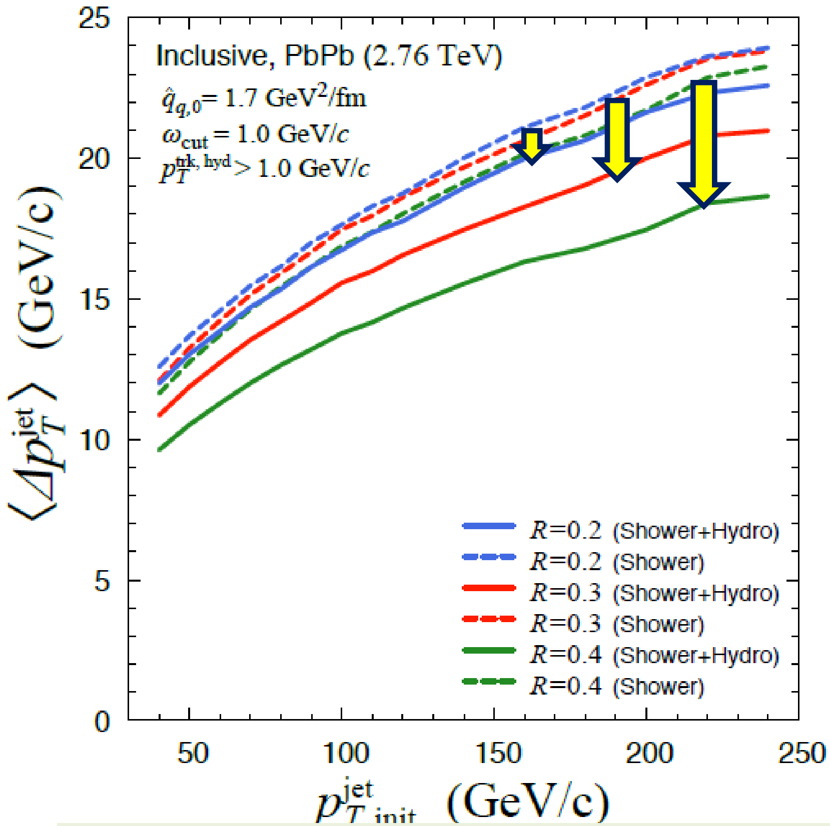
$$\partial_\mu T^{\mu\nu}_{\mathrm{QGP}}(x) = J^\nu(x) = -\partial_\mu T^{\mu\nu}_{\mathrm{jet}}(x) = -\frac{dP^\nu_{\mathrm{jet}}}{dtd^3x} = -\sum_j \int \frac{d^3k_j}{\omega_j} k_j^\nu k_j^\mu \partial_\mu f_j(\boldsymbol{k}_j, \boldsymbol{x}, t)$$

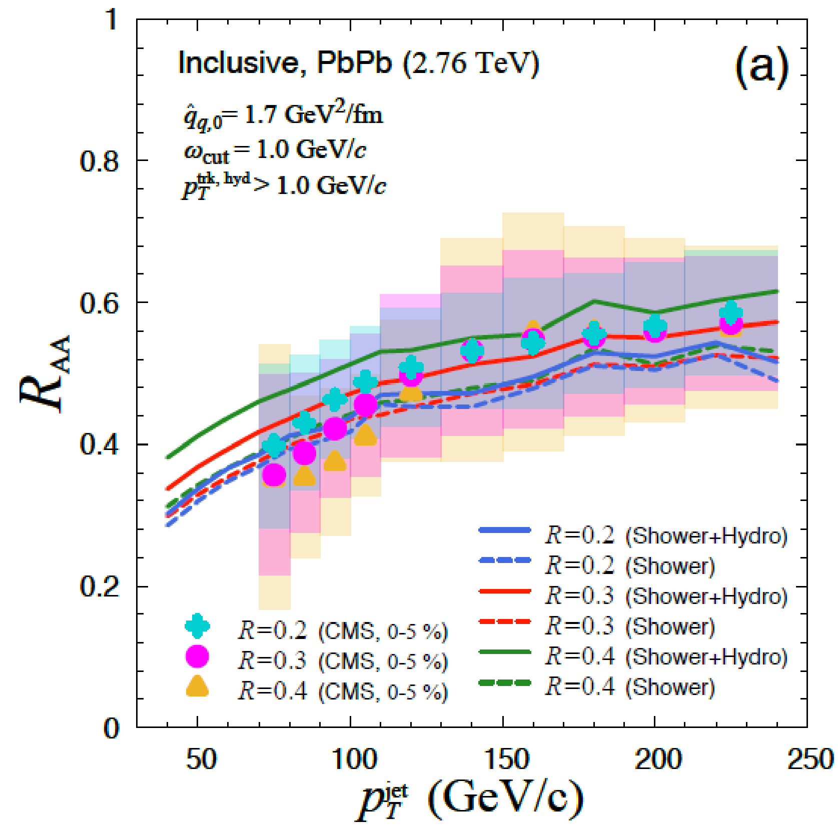


- V-shaped wave fronts are induced by the jet, and develop with time
- The wave fronts carry the energy & momentum, propagates outward & lowers energy density behind the jet
- Jet-induced flow and the radial flow of the medium are pushed and distorted by each other

Tachibana, Chang, GYQ, PRC 2017

Effect of jet-induced flow on jet energy loss & suppression

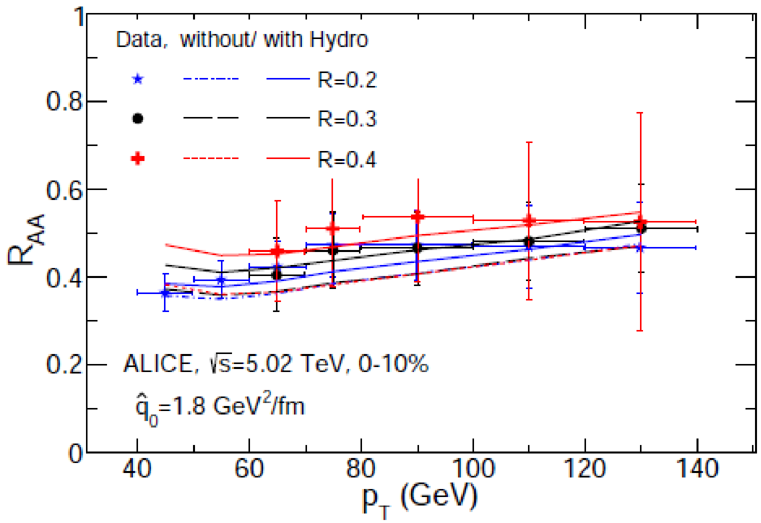


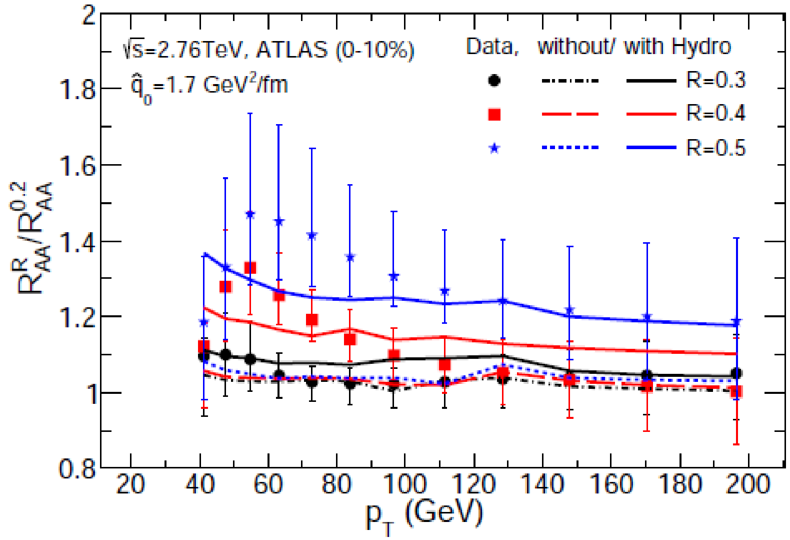


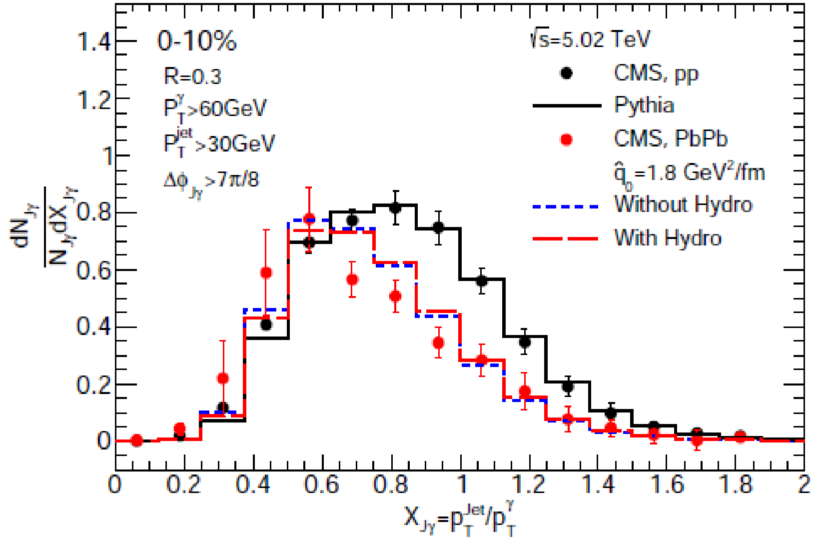
- Hydro part (the lost energy from shower part to medium still inside the jet cone) partially compensates the energy loss experienced by jet shower part.
- Jet-induced flow evolves with medium, diffuses, and spreads widely around jet axis, leading to stronger jet cone size dependence.

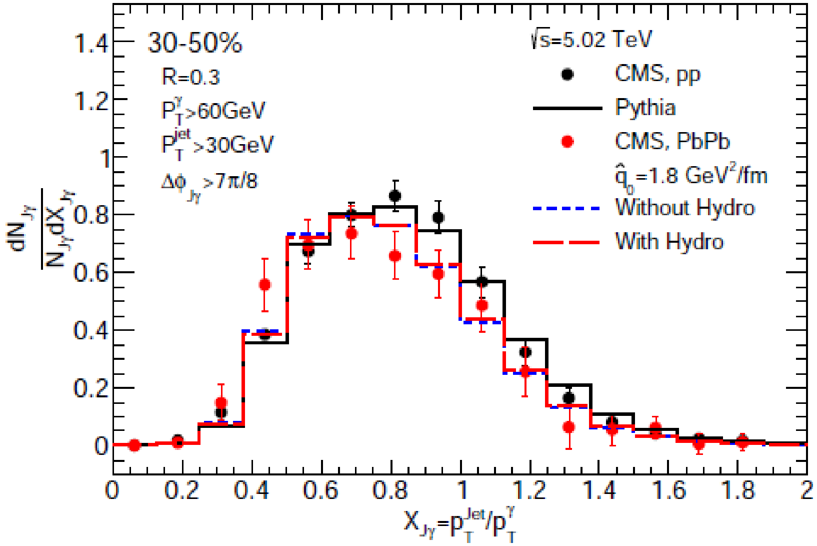
Tachibana, Chang, GYQ, PRC 2017

R_{AA} and photon-jet asymmetry



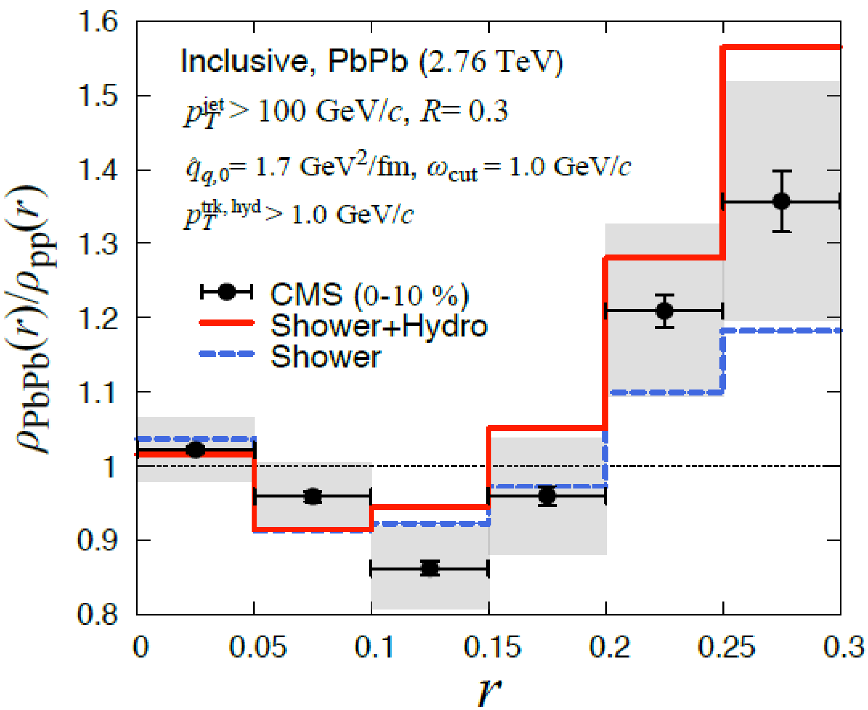


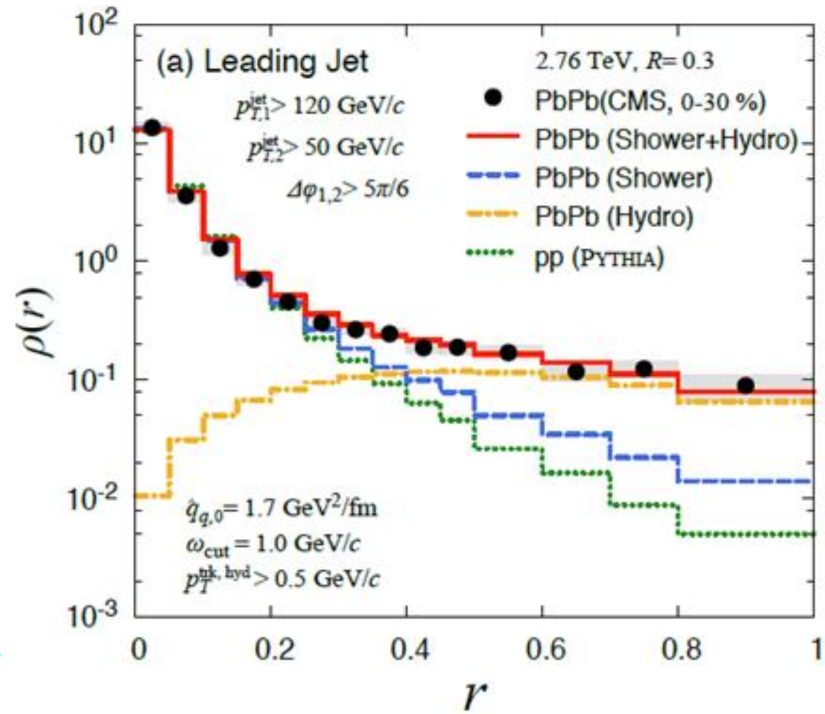




Chang, Tachibana, GYQ, PLB 2020

Effect of jet-induced flow on jet shape





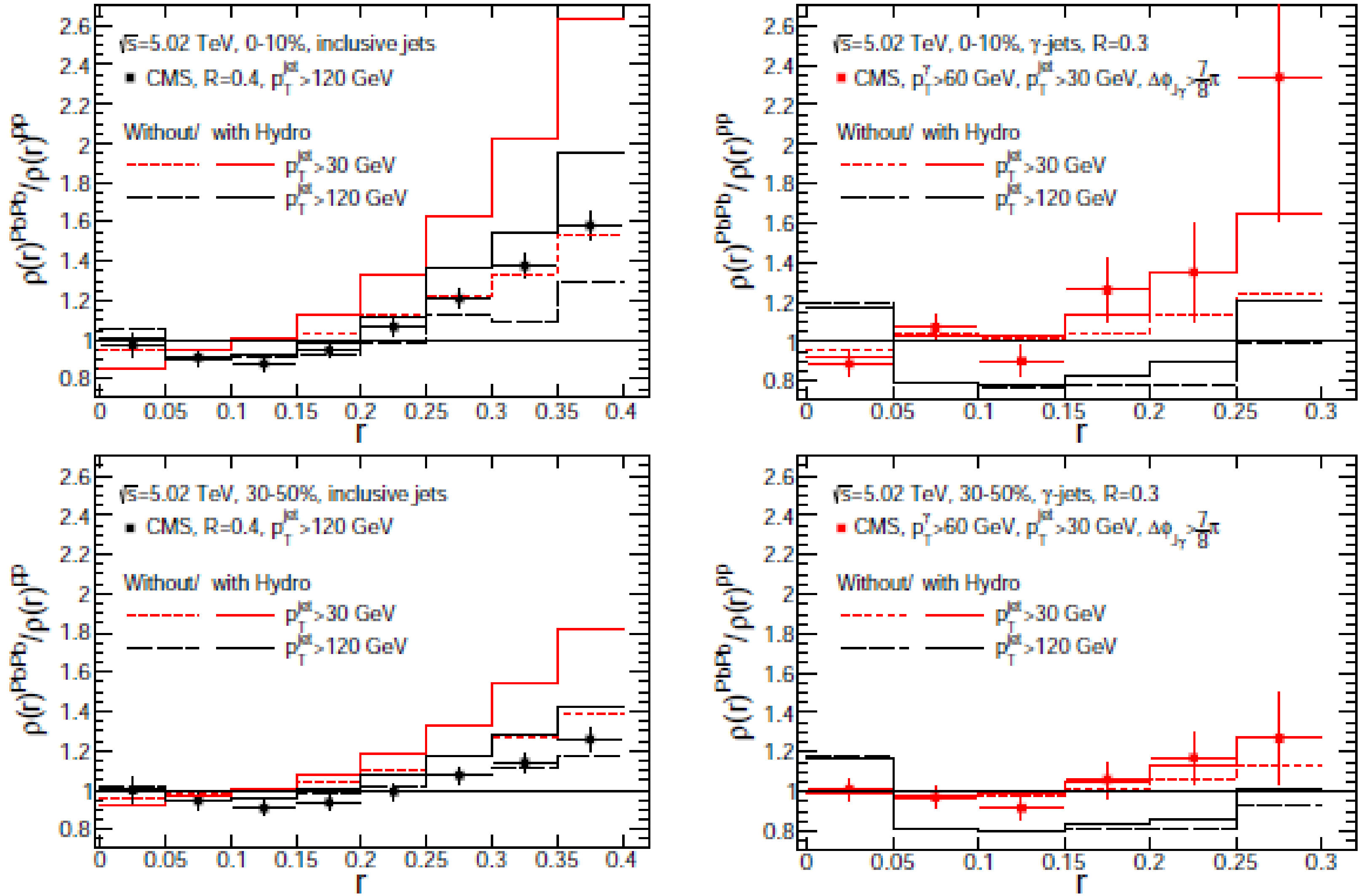
Tachibana, Chang, GYQ, PRC 2017

The inclusion of jet-induced medium flow does not modify jet shape at small r, but significantly enhance jet broadening effect at large r (r > 0.2-0.25).

The energy distribution from the hydrodynamic response part is quite flat and finally dominates over the shower part in the region from r = 0.4-0.5.

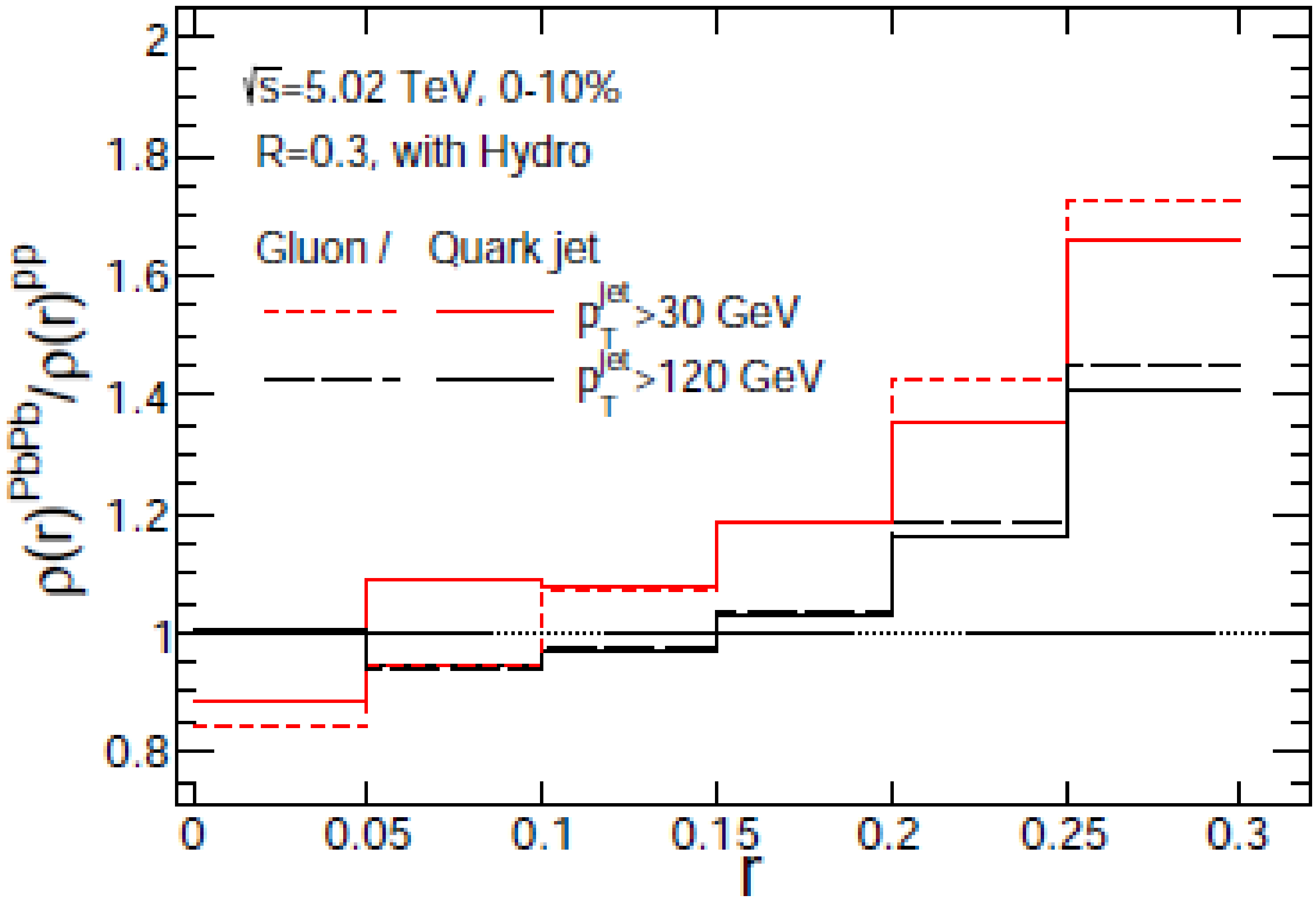
Signal of jet-induced medium excitation in full jet shape at large r.

Jet shape function for inclusive jets and γ-jets



Chang, Tachibana, GYQ, PLB 2020

Jet energy and flavor dependences



Chang, Tachibana, GYQ, PLB 2020

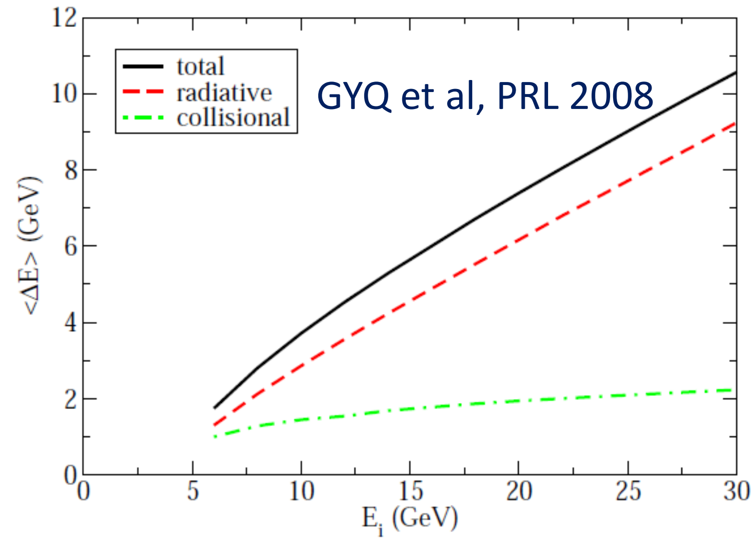
Summary

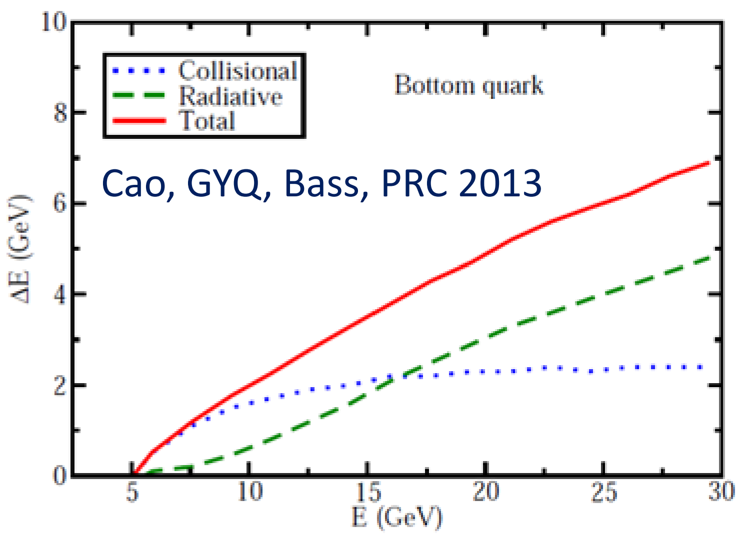
- **Heavy and light flavor jet quenching**
  - NLO pQCD including both quark and gluon contributions to hadron productions
  - A linearized Boltzmann transport model for light and heavy flavor jet evolution in QGP
  - First satisfactory description of R_{AA} for charged hadrons, D, B & B-decayed D over a wide range of p_T

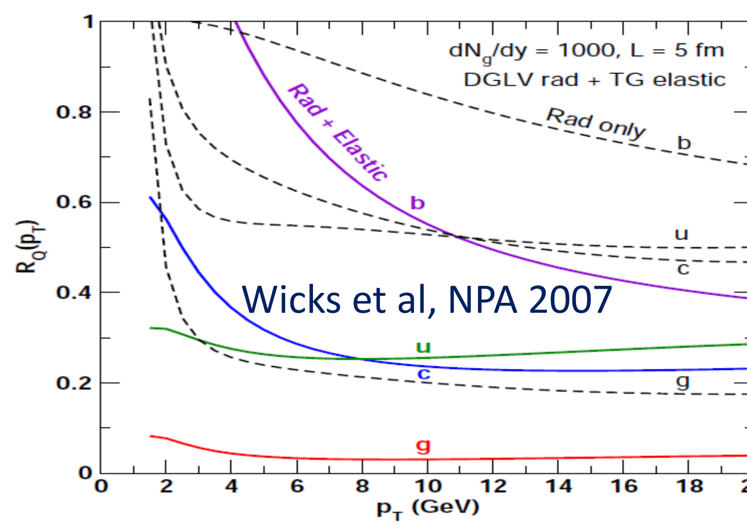
- **Full jet and medium response**
  - Full jet evolution and nuclear modifications of full jet yield and jet shape
  - Interplay of different mechanisms in full jet evolution, energy loss and jet shape modification
  - Signal of jet-induced medium excitation in jet shape at large r
  - Jet shape modification has strong jet energy dependence & weaker jet flavor dependence

Elastic (collisional) energy loss

- **First studied by Bjorken:**
  - Bjorken 1982; Bratten, Thoma 1991; Thoma, Gyulassy, 1991; Mustafa, Thoma 2005; Peigne, Peshier, 2006; Djordjevic (GLV), 2006; Wicks et al (DGLV), 2007; GYQ et al (AMY), 2008...
- **Main findings:**
  - **dE/E small compared to rad. for large E**
  - **But non-negligible in R_{AA} calculation (especially for heavy flavors)**
  - **Important when studying full jet energy loss and medium response**



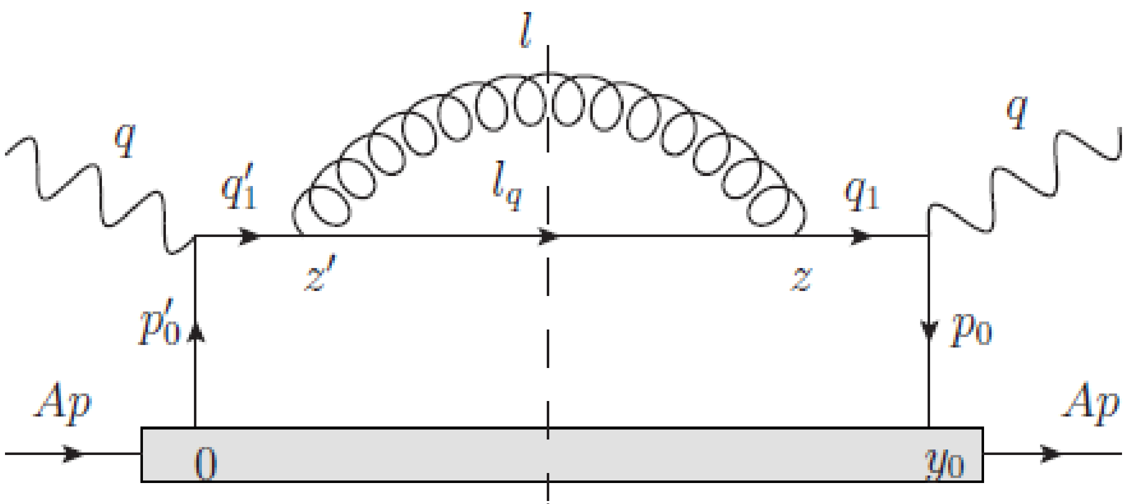




Medium-induced inelastic (radiative) process

- **pQCD-based formalisms**
  - **BDMPS-Z**: Baier-Dokshitzer-Mueller-Peigne-Schiff-Zakharov
  - **ASW**: Amesto-Salgado-Wiedemann
  - **AMY**: Arnold-Moore-Yaffe (& Caron-Huot, Gale)
  - **GLV**: Gyulassy-Levai-Vitev (& Djordjevic, Heinz)
  - **HT**: Wang-Guo (& Zhang, Wang, Majumder)
- **Various approximations:**
  - High energy & eikonal approximations
  - Soft gluon emission approximation (ASW, GLV)
  - Collinear expansion (BDMPS-Z, HT)
  - Gluon emission induced by transverse scatterings
- **Recent improvements:**
  - Include non-eikonal corrections within the path integral formalism (Apolinrio, Armesto, Milhano, Salgado, arXiv:1407.0599)
  - Reinvestigate the GLV formalism by relaxing the soft gluon emission approximation (Blagojevic, Djordjevic, Djordjevic, arXiv:1804.07593; Sievert, Vitev, arXiv:1807.03799)
  - Generalize the HT formalism by going beyond the collinear expansion and soft gluon emission approximation, including both transverse and longitudinal scatterings, for massless and massive quarks (Zhang, Hou, GYQ, PRC (2018) arXiv:1804.00470; arXiv:1812.11048; Zhang, GYQ, Wang, arXiv:1905.12699)

Gluon emission in vacuum



$$\frac{dN_g^{\mathrm{vac}}}{dy\, d^2 l_\perp} = C_F \frac{\alpha_s}{2\pi^2} P(y) \frac{l_\perp^2 + \frac{y^4}{1+(1-y)^2} M^2}{(l_\perp^2 + y^2 M^2)^2}.$$

Only transverse scatterings

- Modeling the traversed nuclear medium by heavy static scattering centers (only transverse scatterings)

$$
\begin{aligned}
\frac{dN_g^{\rm med}}{dy d^2\mathbf{l}_\perp} &= \frac{\alpha_s}{2\pi^2} P(y) \int dZ_1^- \int d^2\mathbf{k}_{1\perp} \frac{dP_{\rm el}}{d^2\mathbf{k}_{1\perp} dZ_1^-} \\
&\times \Bigg\{ C_A \left[2 - 2\cos\left(\frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + y^2 M^2}{l_\perp^2 + y^2 M^2} \frac{Z_1^-}{\tilde{\tau}^-_{\rm form}} \right) \right] \times \left[\frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + \frac{y^4}{1+(1-y)^2} M^2}{\left[(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + y^2 M^2 \right]^2} \right. \\
&- \frac{1}{2} \frac{\mathbf{l}_\perp \cdot (\mathbf{l}_\perp - \mathbf{k}_{1\perp}) + \frac{y^4}{1+(1-y)^2} M^2}{[l_\perp^2 + y^2 M^2] \left[(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + y^2 M^2 \right]} - \frac{1}{2} \left. \frac{(\mathbf{l}_\perp - \mathbf{k}_{1\perp}) \cdot (\mathbf{l}_\perp - y\mathbf{k}_{1\perp}) + \frac{y^4}{1+(1-y)^2} M^2}{\left[(\mathbf{l}_\perp - y\mathbf{k}_{1\perp})^2 + y^2 M^2 \right] \left[(\mathbf{l}_\perp - \mathbf{k}_{1\perp})^2 + y^2 M^2 \right]} \right] \\
&+ \left(\frac{C_A}{2} - C_F \right) \left[2 - 2\cos\left(\frac{Z_1^-}{\tilde{\tau}^-_{\rm form}} \right) \right] \left[\frac{\mathbf{l}_\perp \cdot (\mathbf{l}_\perp - y\mathbf{k}_{1\perp}) + \frac{y^4}{1+(1-y)^2} M^2}{[l_\perp^2 + y^2 M^2] \left[(\mathbf{l}_\perp - y\mathbf{k}_{1\perp})^2 + y^2 M^2 \right]} - \frac{l_\perp^2 + \frac{y^4}{1+(1-y)^2} M^2}{[l_\perp^2 + y^2 M^2]^2} \right] \\
&+ C_F \left[\frac{(\mathbf{l}_\perp - y\mathbf{k}_{1\perp})^2 + \frac{y^4}{1+(1-y)^2} M^2}{\left[(\mathbf{l}_\perp - y\mathbf{k}_{1\perp})^2 + y^2 M^2 \right]^2} - \frac{l_\perp^2 + \frac{y^4}{1+(1-y)^2} M^2}{[l_\perp^2 + y^2 M^2]^2} \right] \Bigg\} .
\end{aligned}
$$

Soft gluon emission approximation

- Further taking soft gluon emission approximation $y^2 M \ll yM \sim l_\perp \sim k_{1\perp}$:

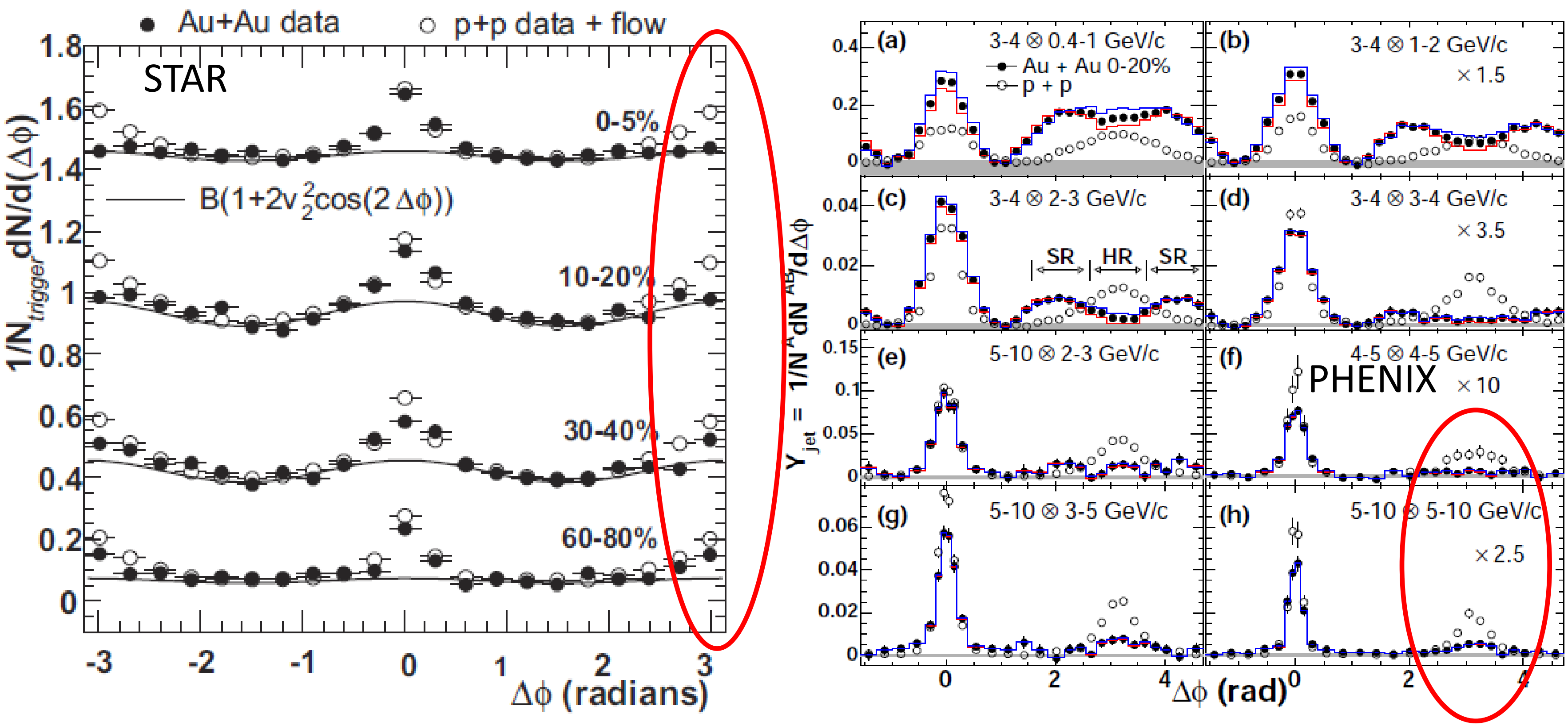
$$\frac{dN_g^{\rm med}}{dyd^2\mathbf{l}_\perp} = \frac{\alpha_s}{2\pi^2}P(y)\int dZ_1^- \int d^2\mathbf{k}_{1\perp}\frac{dP_{\rm el}}{d^2\mathbf{k}_{1\perp}dZ_1^-} \times C_A\left[2-2\cos\left(\frac{(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+y^2M^2}{l_\perp^2+y^2M^2}\frac{Z_1^-}{\tilde{\tau}_{\rm form}^-}\right)\right] \times \left[\frac{(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2}{\left[(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+y^2M^2\right]^2} - \frac{\mathbf{l}_\perp\cdot(\mathbf{l}_\perp-\mathbf{k}_{1\perp})}{[l_\perp^2+y^2M^2]\left[(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2+y^2M^2\right]}\right].$$

- This agrees with the DGLV first-order-in-opacity formula.

- Jet transport parameter is related to the differential elastic scattering rate as follows:

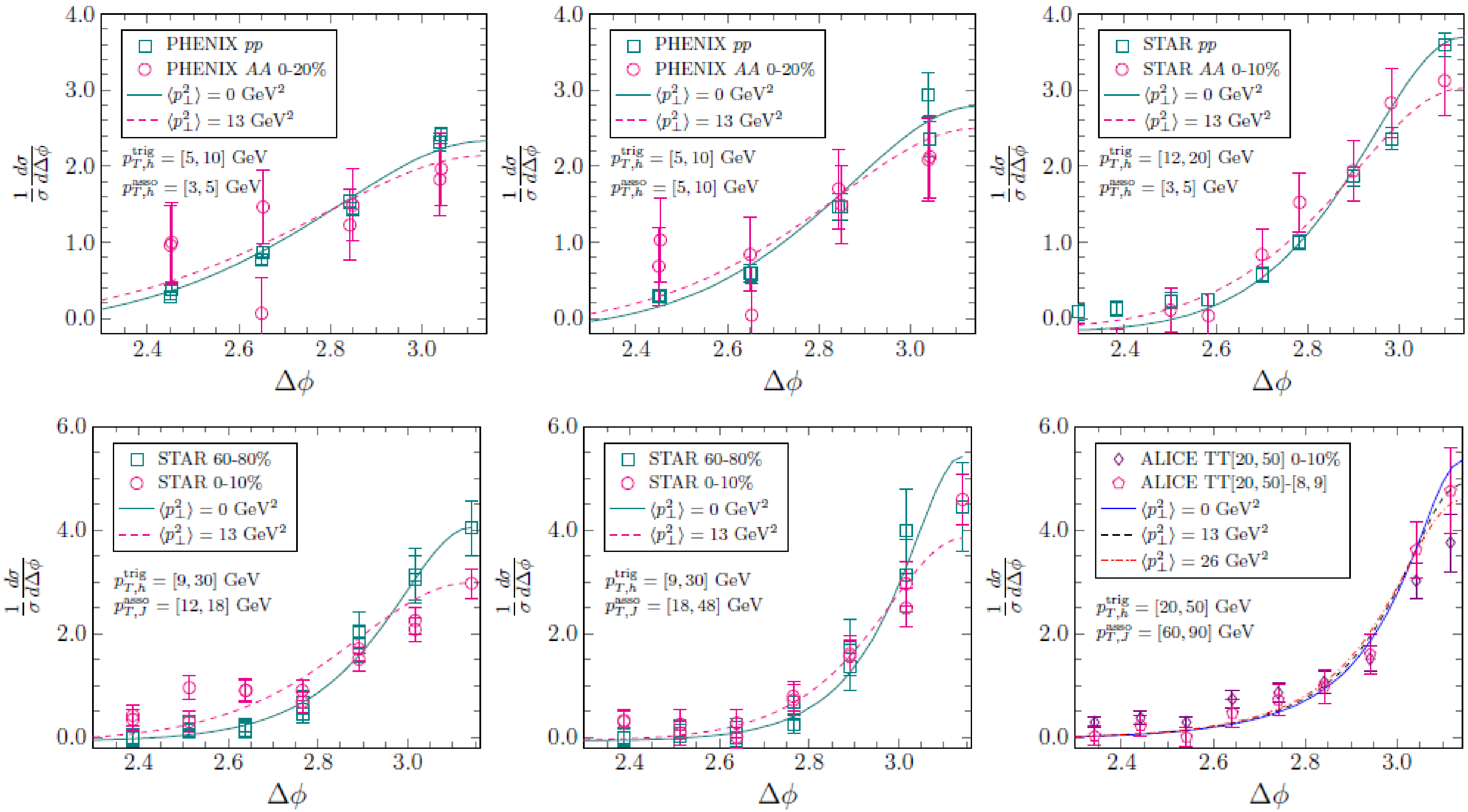
$$\hat{q}_{lc} = \frac{d\langle k_{1\perp}^2\rangle}{dL^-} = \int\frac{dk_1^- d^2\mathbf{k}_{1\perp}}{(2\pi)^3}\mathbf{k}_{1\perp}^2\mathcal{D}(k_1^-,\mathbf{k}_{1\perp}) = \int\frac{d^2\mathbf{k}_{1\perp}}{(2\pi)^2}\mathbf{k}_{1\perp}^2\mathcal{D}_\perp(\mathbf{k}_{1\perp}) = \int d^2\mathbf{k}_{1\perp}\mathbf{k}_{1\perp}^2\rho^-\frac{d\sigma_{\rm el}}{d^2\mathbf{k}_{1\perp}}.$$

Jet-related correlations



Both per-trigger yield and the shape of the angular distribution are modified by QGP. Can probe parton energy loss and angular deflection (broadening) effects.

Dihadron and hadro-jet angular correlations



Chen, GYQ, Wei, Xiao, Zhang, PLB 2017

Generalized k_T family of jet reconstruction algorithms

- (1) Consider all particles in the list, and compute all distances d_{iB} and d_{ij}
- (2) For particle i, find $\min(d_{ij}, d_{iB})$
- (3) If $\min(d_{iB}, d_{ij}) = d_{iB}$, declare particle i to be a jet, and remove it from the list of particles. Then return to (1)
- (4) If $\min(d_{iB}, d_{ij})=d_{ij}$, recombine i & j into a single new particle. Then return to (1)
- (5) Stop when no particles are left

$$d_{iB} = p_{T,i}^{2p}$$

$$d_{ij} = \min(p_{T,i}^{2p}, p_{T,j}^{2p}) \frac{\Delta R_{ij}^2}{R^2}$$

$$\Delta R_{ij}^2 = (\phi_i - \phi_j)^2 + (\eta_i - \eta_j)^2$$

p=1: k_T algorithm
p=0: Cambridge/Aachen algorithm
p=-1: anti-k_T algorithm

Jet substructure observables

- **Jet shape** $$\rho(r) = \left\langle \frac{1}{p_{T,J}} \sum_{i \in J} p_{T,i} \delta(r - r_i) \right\rangle_{jets}$$ **Transverse profile**

- **Jet fragmentation function** $$D(z) = \left\langle \sum_{i \in J} \delta(z - \frac{p_{T,i}}{p_{T,J}}) \right\rangle_{jets}$$ **Longitudinal profile**

- **Girth** $$g = \frac{1}{p_{T,J}} \sum_{i \in J} p_{T,i} r_i$$ **Transverse size**

- **Jet mass** $$m_J^2 = \left(\sum_{i \in J} p_i^{\mu} \right)^2$$ **Energy & size**

- **Groomed jet** $$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut}\theta^{\beta} = z_{cut}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$ **momentum sharing (splitting function)**

Medium response to jet-deposited energy/momentum

$$\partial_\mu T^{\mu\nu}_{\rm QGP}(x) = J^\nu(x) = -\partial_\mu T^{\mu\nu}_{\rm jet}(x) = -\frac{dP^\nu_{\rm jet}}{dtd^3x} = -\sum_j \int \frac{d^3k_j}{\omega_j} k_j^\nu k_j^\mu \partial_\mu f_j(\boldsymbol{k}_j, \boldsymbol{x}, t)$$

$$= -\sum_j \int \frac{d^3k_j}{\omega_j} k_j^\nu k_j^\mu \left[\partial_\mu f_j(\boldsymbol{k}_j, \boldsymbol{x}, t)|_{\hat{e},\hat{q}}\right] + \sum_j \int \frac{d^3k_j}{\omega_j} k_j^\nu k_j^\mu \left[\partial_\mu f_j(\boldsymbol{k}_j, \boldsymbol{x}, t)|_{\rm rad.}\right]$$

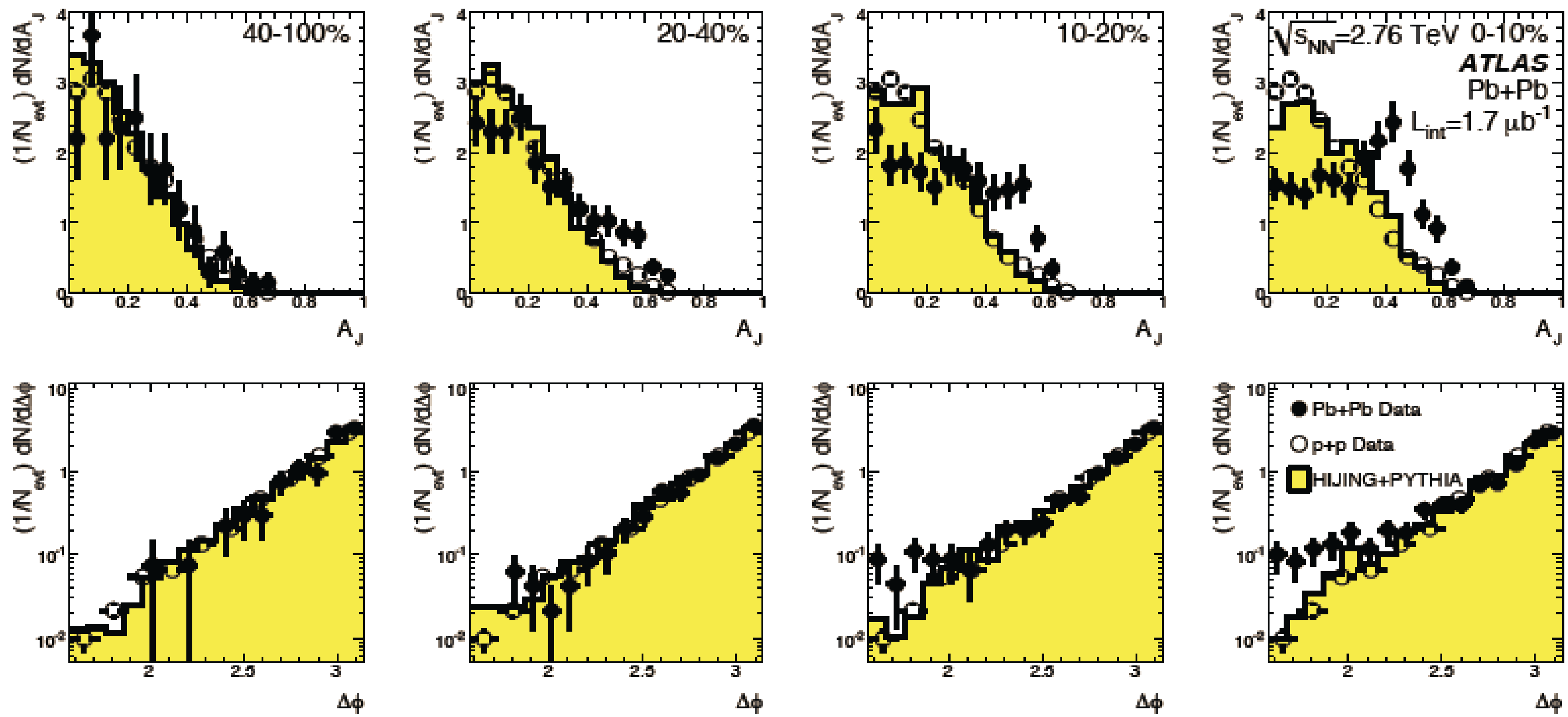
$$= -\sum_j \int d^3k_j k_j^\nu \left.\frac{df_j(\boldsymbol{k}_j, t)}{dt}\right|_{\rm col.} \delta^{(3)}\left(\boldsymbol{x} - \boldsymbol{x}_0^{\rm jet} - \frac{\boldsymbol{k}_j}{\omega_j} t\right)$$

$$J^\nu(x) \approx -\frac{1}{2\pi r t^3}(x^\nu - x^\nu_{{\rm jet},0}) \left.\frac{dE^{\rm jet}}{dtdr}\right|_{\rm col.} \delta\left(|\boldsymbol{x} - \boldsymbol{x}_0^{\rm jet}| - t\right)$$

$$\left.\frac{dE^{\rm jet}}{dtdr}\right|_{\rm col.} = \sum_j \int d\omega dk^2_{j\perp} \omega_j \left.\frac{df_j\left(\omega_j, k^2_{j\perp}, t\right)}{dt}\right|_{\rm col.} \delta\left(r - \frac{k_{j\perp}}{\omega_j}\right)$$

$$J^{\bar{\nu}}(\tau, x, y, \eta_s) = -\frac{dP^{\bar{\nu}}_{\rm jet}}{\tau d\tau dx dy d\eta_s} = \Lambda^{\bar{\nu}}_\mu J^\mu(x) = -\Lambda^{\bar{\nu}}_\mu \frac{dP^\mu_{\rm jet}}{dtd^3x}$$

Dijet (γ-jet) correlations

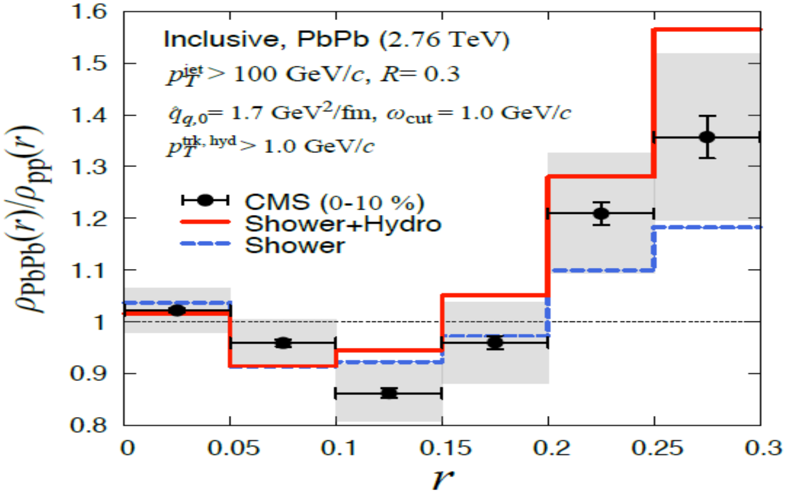


$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

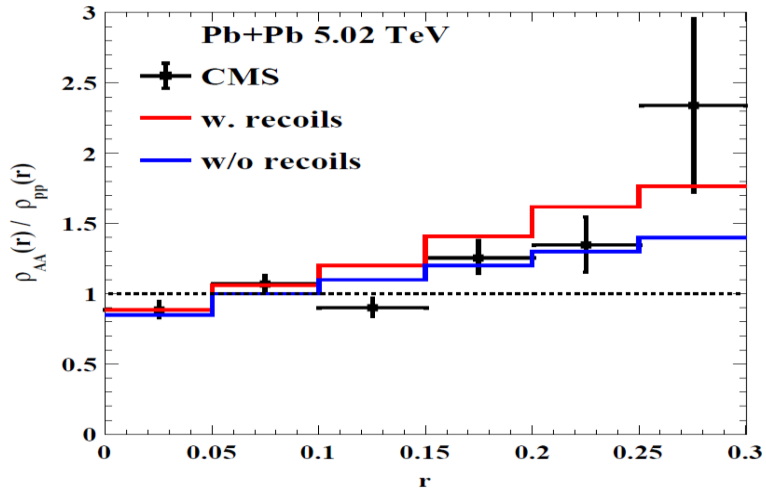
$$\Delta\phi = |\phi_1 - \phi_2|$$

Strong modification of momentum imbalance distribution
=> Significant energy loss experienced by the subleading jets
Largely-unchanged angular distribution
=> medium-induced broadening effect is quite modest (here)

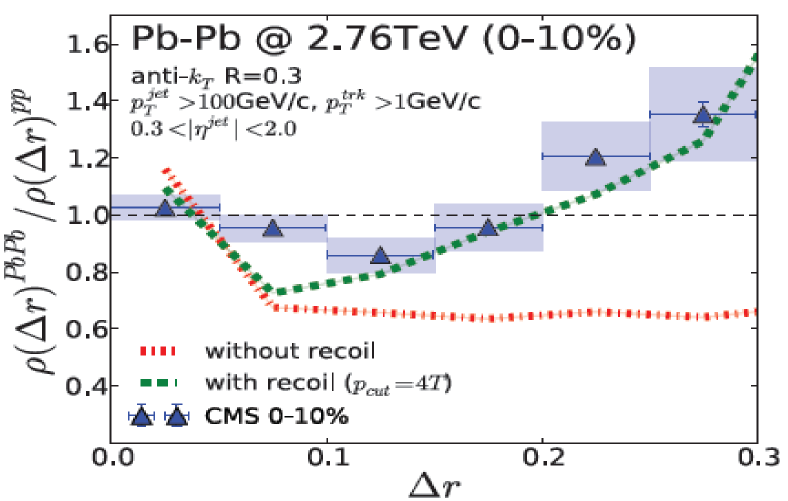
Effect of jet-induced flow on jet shape



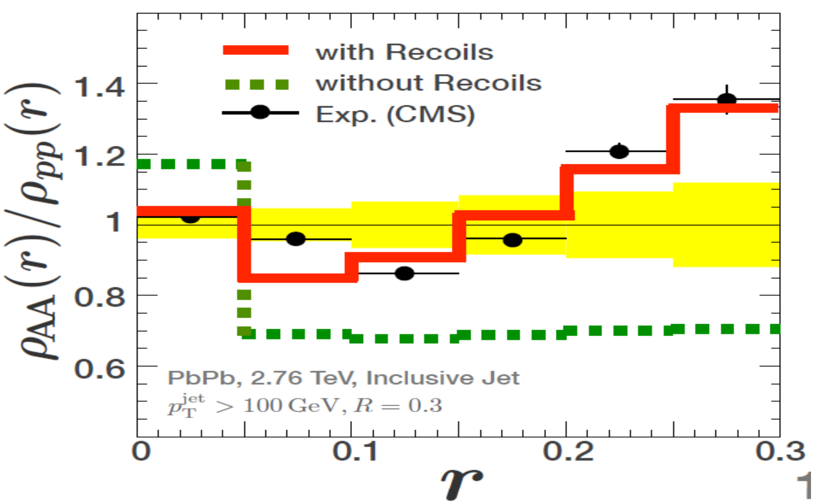
Tachibana, Chang, GYQ, PRC 2017



Luo, Cao, He, Wang, arXiv:1803.06785



C. Park, S. Jeon, C. Gale, 2018



Elayavalli, Zapp, JHEP 2017