Heavy and light flavor jet quenching

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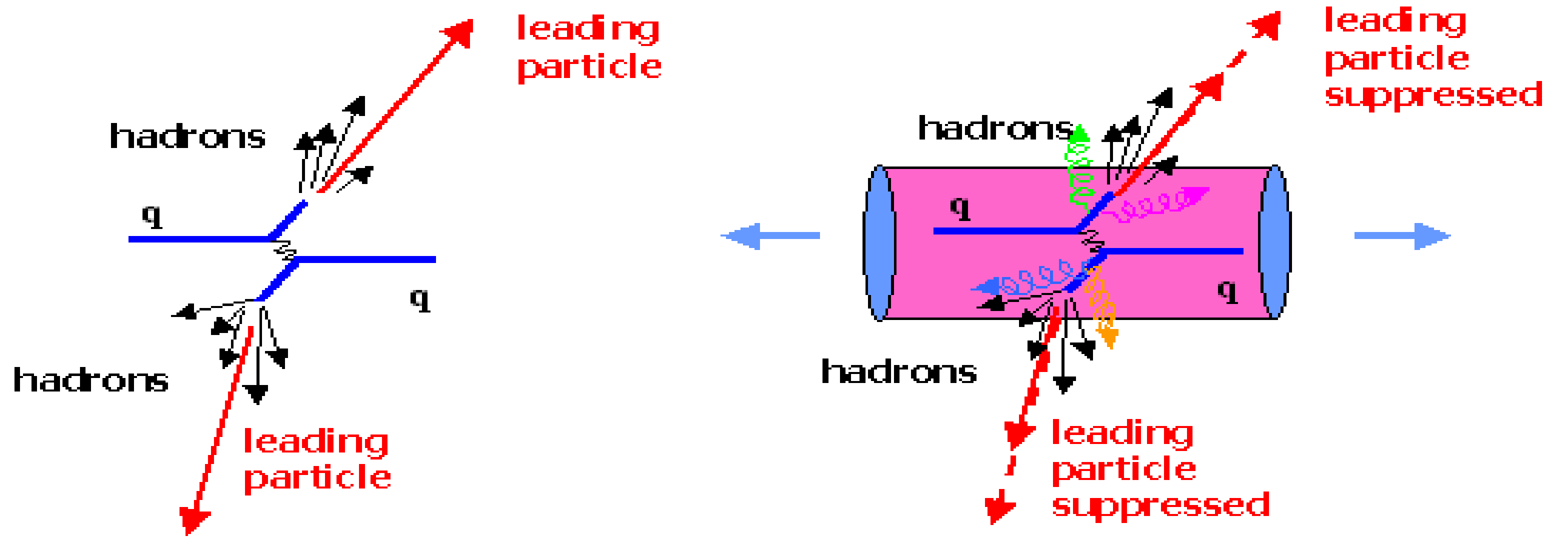
Outline

- A Linearized Boltzmann Transport (LBT) approach to heavy/light flavor jet quenching (with elastic & inelastic contributions)

- Full jet energy loss and modification (collisional, radiative, broadening)

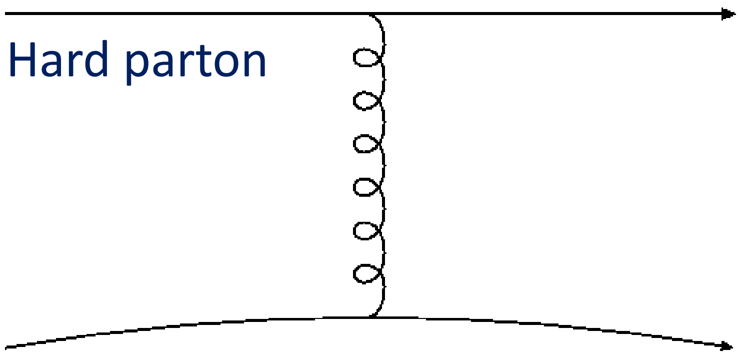
- Use jet-like angular de-correlation to probe medium-induced broadening (q^{hat})

Jet quenching

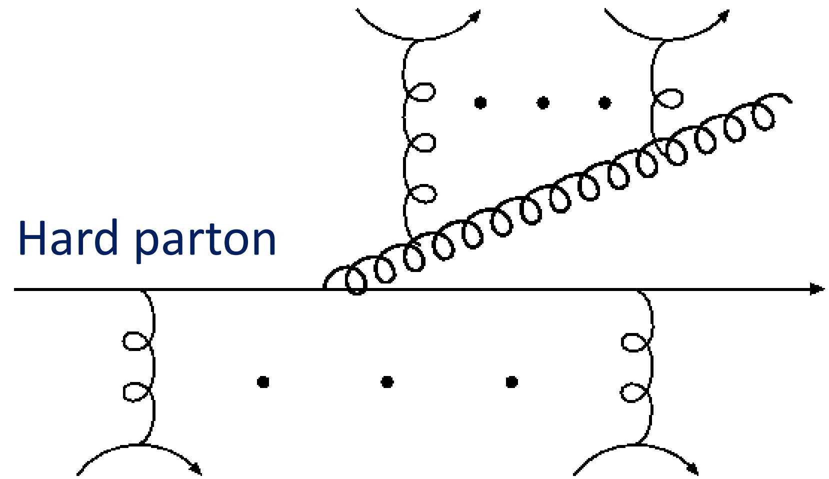


- The study of jet quenching/modification can provide valuable information about hot and dense QGP produced in heavy-ion collisions

Radiative & collisional processes



Elastic (collisional)



Inelastic (radiative)

In the limit of soft scatterings, the effect of elastic collisions can be described by FP equation **(longitudinal drag, longitudinal diffusion & transverse diffusion)**

$$\frac{\partial f}{\partial z^-} = \left[D_{L1} \frac{\partial}{\partial l_q^-} + \frac{1}{2} D_{L2} \frac{\partial^2}{\partial^2 l_q^-} + \frac{1}{2} D_{T2} \nabla^2_{\vec{l}_{q\perp}} \right] f(z^-, l_q^-, \vec{l}_{q\perp})$$

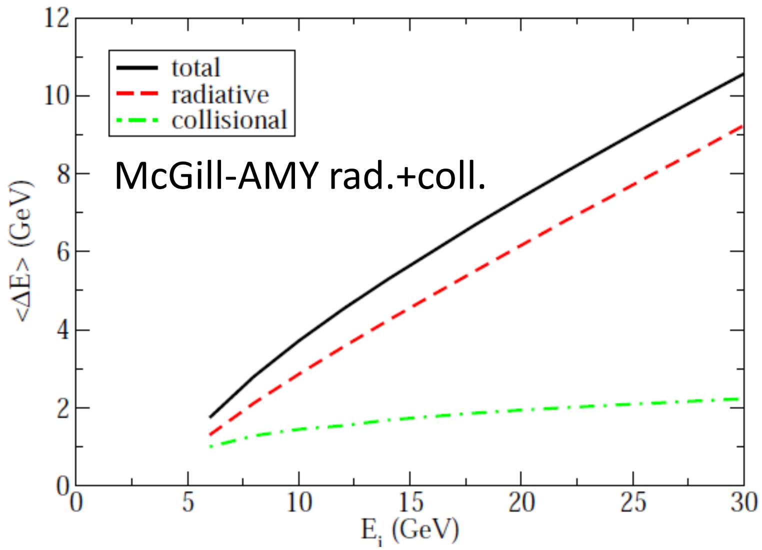
The medium-induced gluon radiation spectrum from higher-twist formalism:

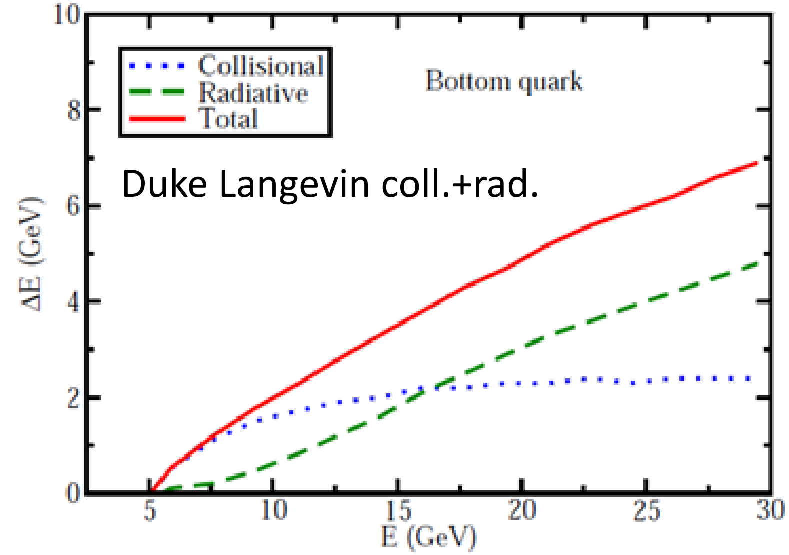
$$\frac{dN_g}{dx\,dl_\perp^2\,dz^-} \approx \frac{4\alpha_s}{\pi} P(x) \frac{D_{T,2}}{l_\perp^4} \sin^2\left(\frac{z^- - z_i^-}{2\tau_f^-} \right)$$

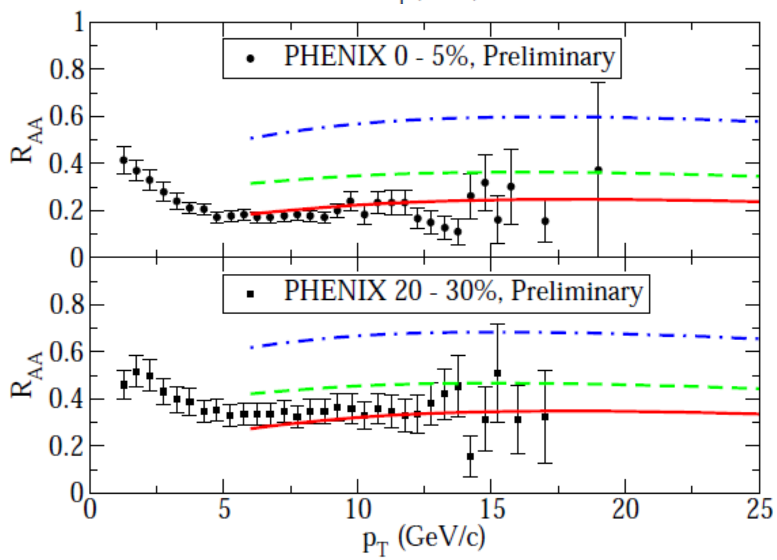
GYQ, Majumder, PRC 2013
Guo, Wang, PRL, 2000
Majumder, PRD, 2012

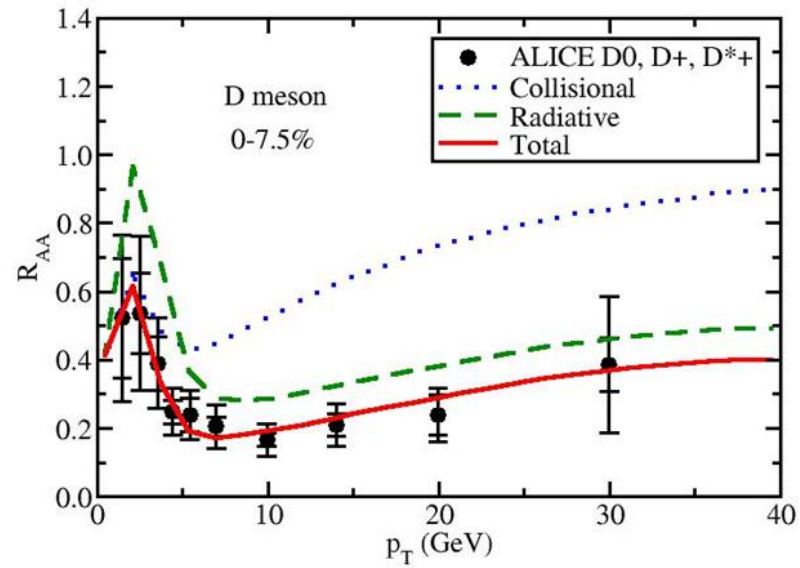
Jet transport coefficients control both collisional and radiative contributions

Radiative & collisional contributions









GYQ, Ruppert, Gale, Jeon, Moore, Mustafa, PRL 2008; Cao, GYQ, Bass, PRC 2013

A Linearized Boltzmann Transport (LBT) approach for heavy & light flavor jet quenching

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

- **Elastic collisions:**

$$\Gamma_{12\rightarrow 34} = \frac{\gamma_2}{2E_1} \int \frac{d^3p_2}{(2\pi)^3 2E_2} \int \frac{d^3p_3}{(2\pi)^3 2E_3} \int \frac{d^3p_4}{(2\pi)^3 2E_4} \times f_2(\vec{p}_2) \left[1 \pm f_3(\vec{p}_1 - \vec{k})\right] \left[1 \pm f_4(\vec{p}_2 + \vec{k})\right] S_2(s,t,u) \times (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - p_4) |\mathcal{M}_{12\rightarrow 34}|^2$$

$$P_{\rm el} = \Gamma \Delta t$$

- **Inelastic collisions:**

$$\langle N_g \rangle (E, T, t, \Delta t) = \Delta t \int dx dk_\perp^2 \frac{dN_g}{dx dk_\perp^2 dt}$$

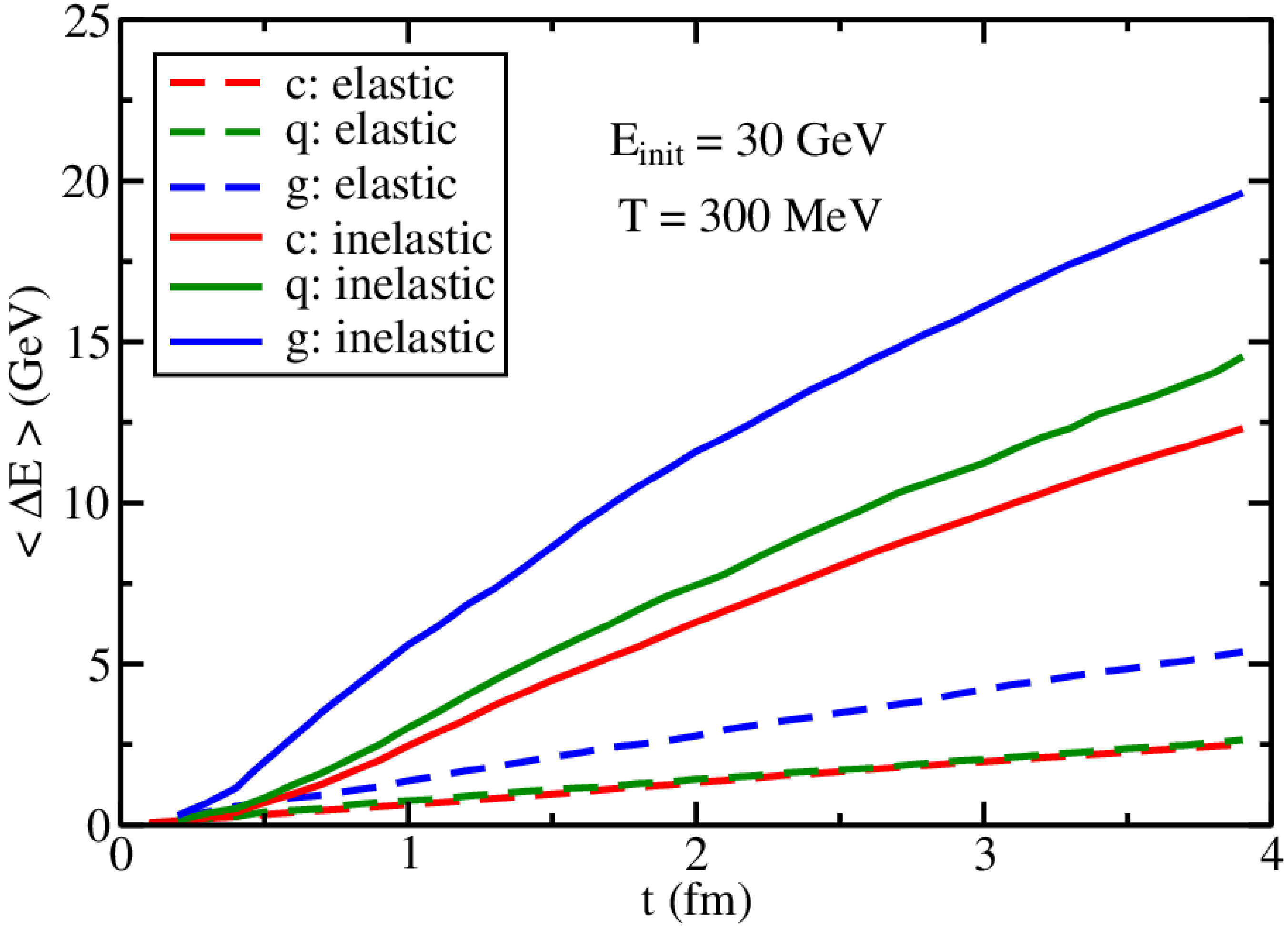
$$P(n) = \frac{\langle N_g \rangle^n}{n!} e^{-\langle N_g \rangle}$$

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

- **Elastic + Inelastic:** $P_{\rm tot} = P_{\rm el}(1 - P_{\rm inel}) + P_{\rm inel}$

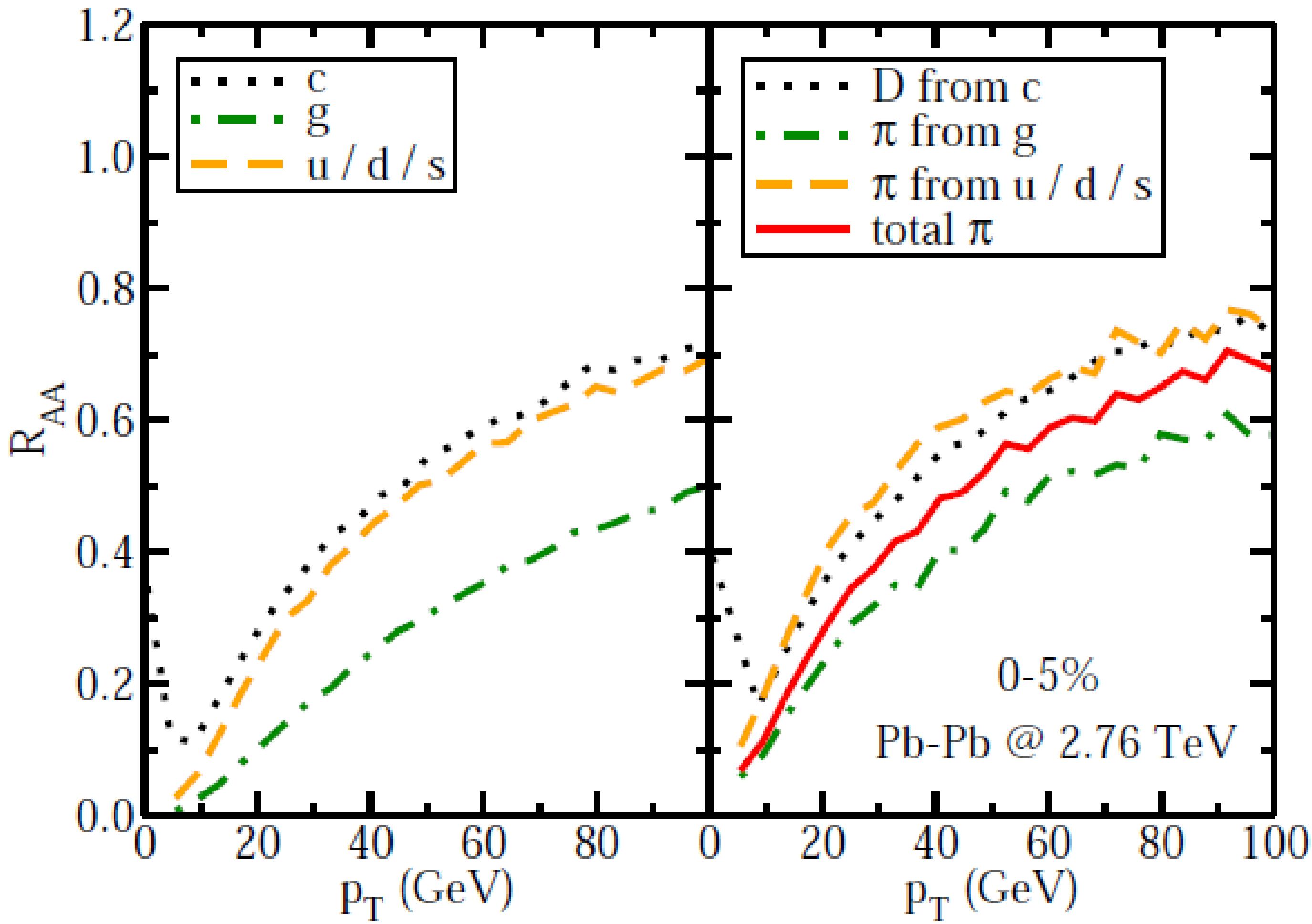
Cao, Luo, GYQ, Wang, arXiv:1605.06447 & in preparation

Elastic & inelastic energy loss from LBT



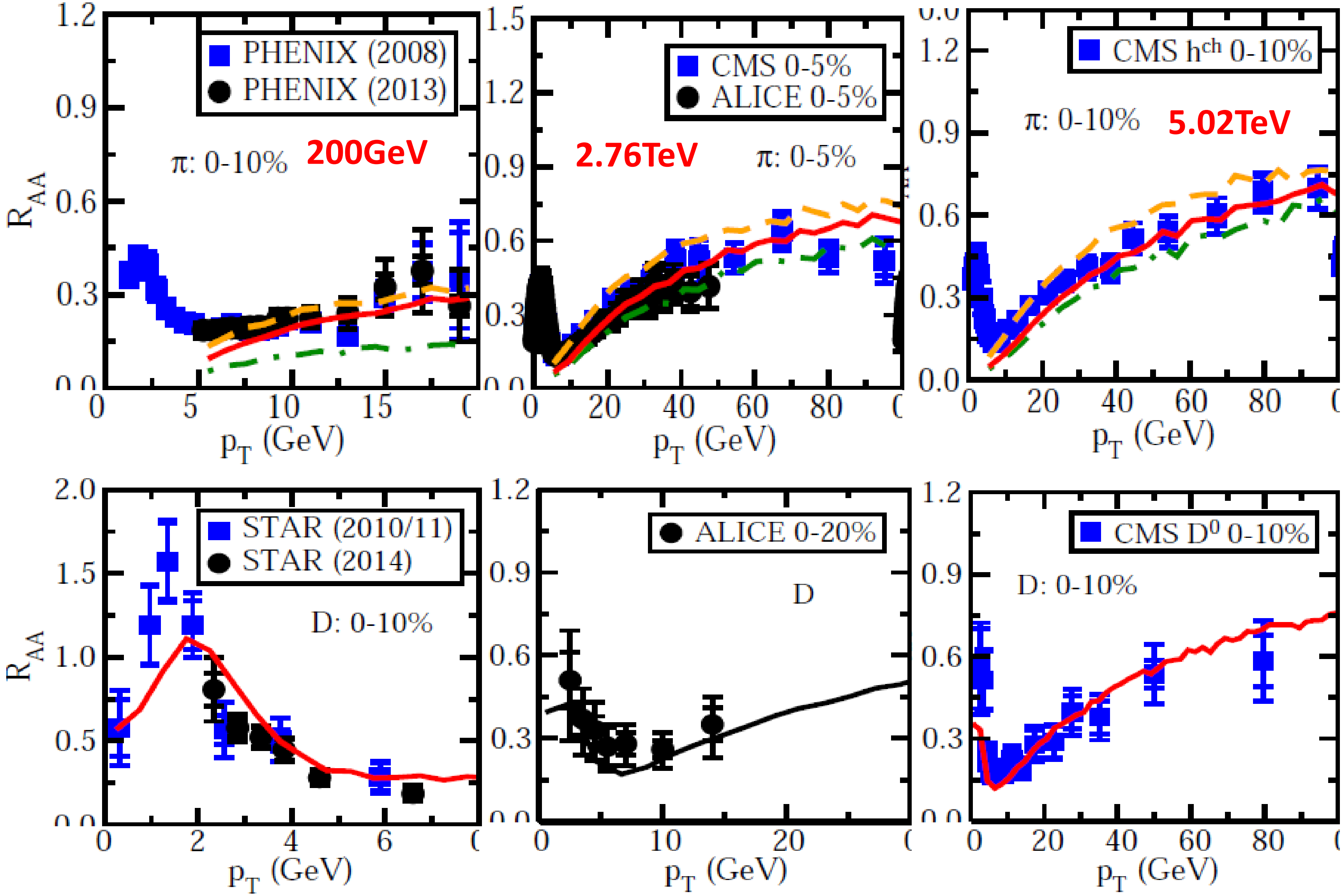
Cao, Luo, GYQ, Wang, arXiv:1605.06447 & in preparation

Quenching hierarchy

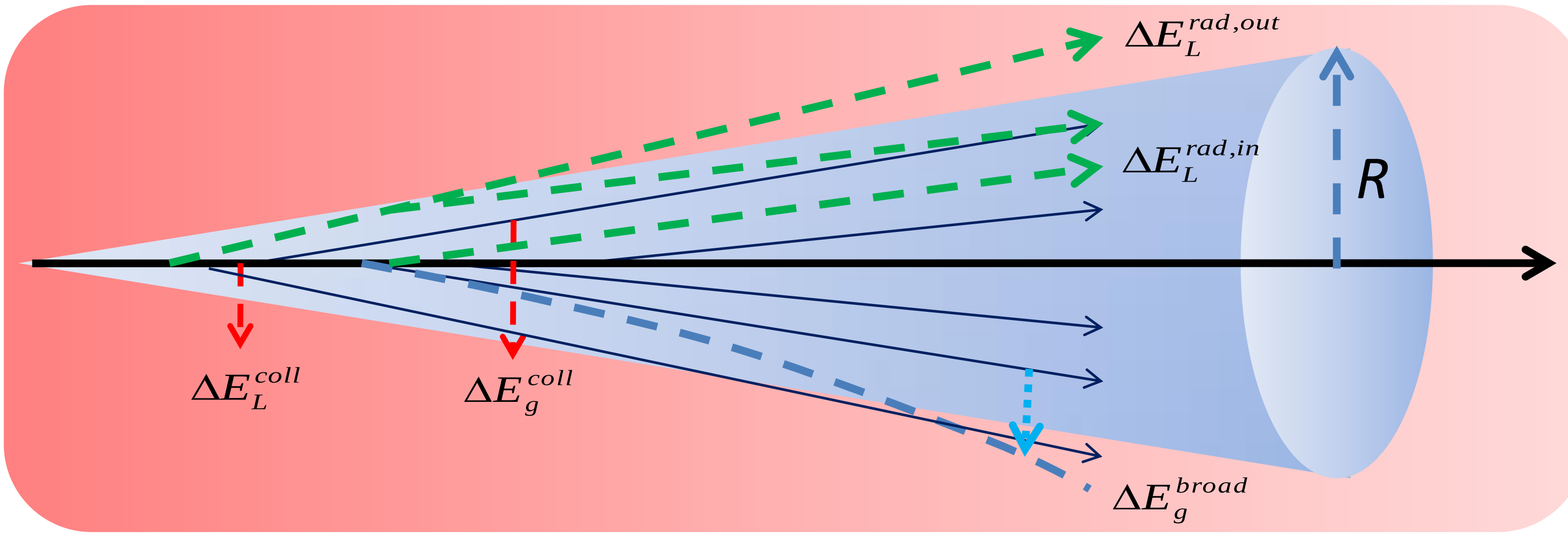


Cao, Luo, GYQ, Wang, arXiv:1605.06447 & in preparation

R_{AA} from LBT (heavy & light flavor hadrons)



Full jet evolution in medium



Not only the interaction of the leading hard parton with the medium constituents, but also the fate of radiated shower partons

$E_{jet} = E_{in} + E_{lost}$

$= E_{in} + E_{out}(\text{radiation}) + E_{out}(\text{broadening}) + E_{th}(\text{collision})$

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; 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

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

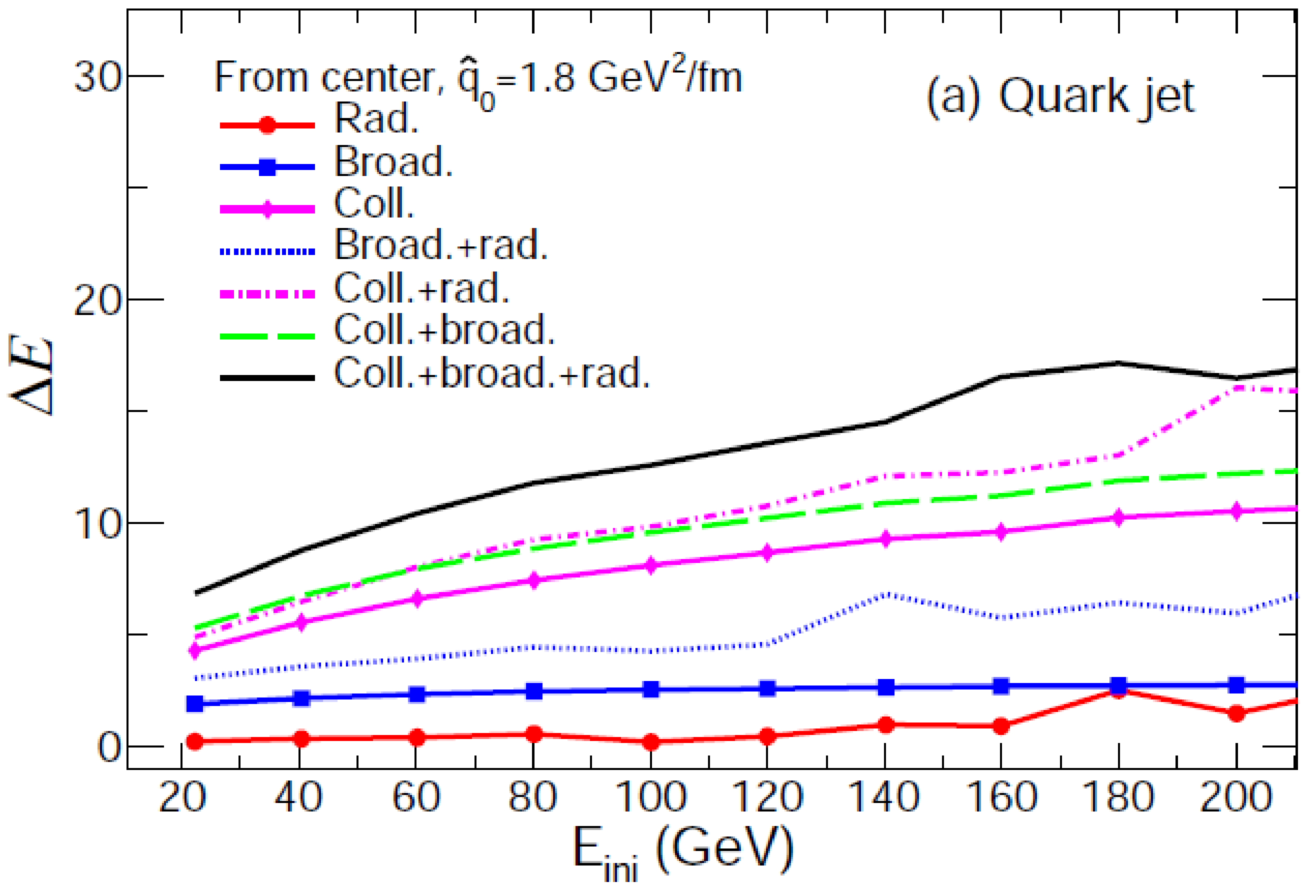
$$+\sum_i \int d\omega_i dk_{i\perp}^2 \frac{d\tilde{\Gamma}_{i\to j}(\omega_j, k_{j\perp}^2|\omega_i, k_{i\perp}^2)}{d\omega_j d^2k_{j\perp}dt} f_i(\omega_i, k_{i\perp}^2, t) \quad \textit{Gain terms}$$

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

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

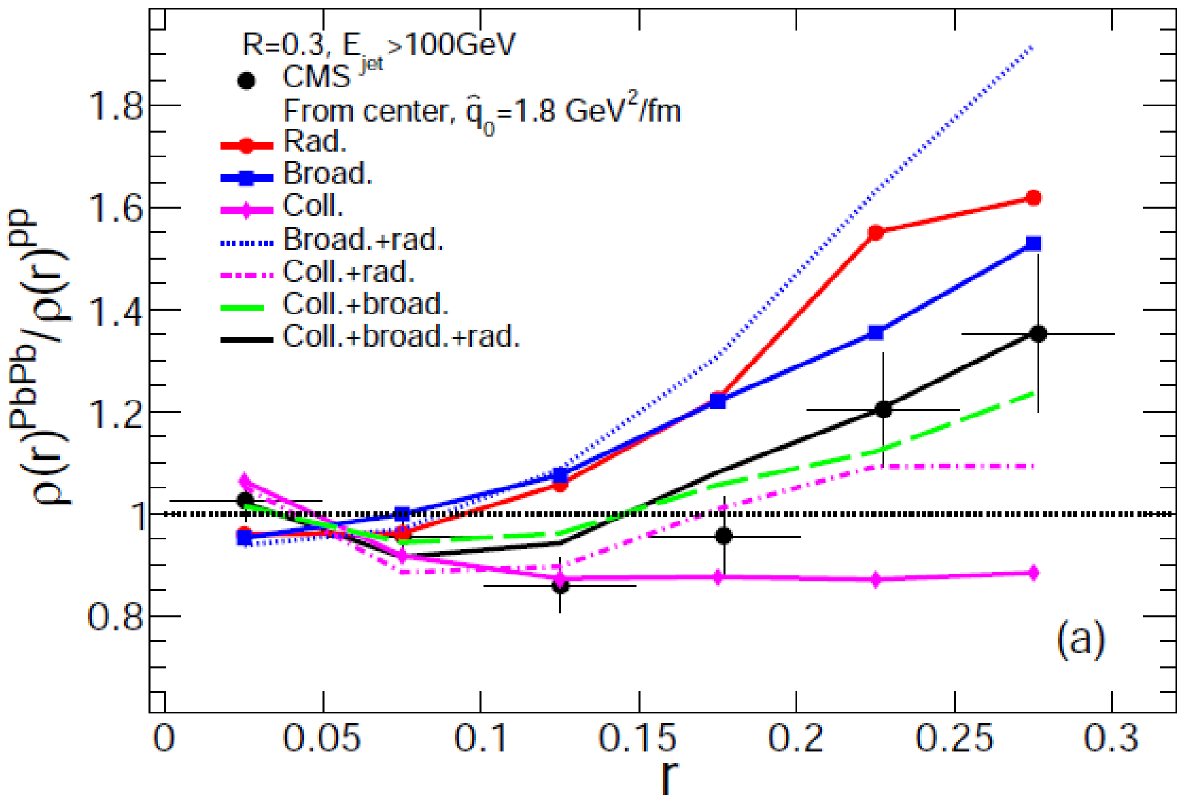
Ningbo Chang, GYQ, arXiv:1603.01920

Full jet energy loss (radiative, collisional, broadening)



Ningbo Chang, GYQ, arXiv:1603.01920

Nuclear modification of jet shape



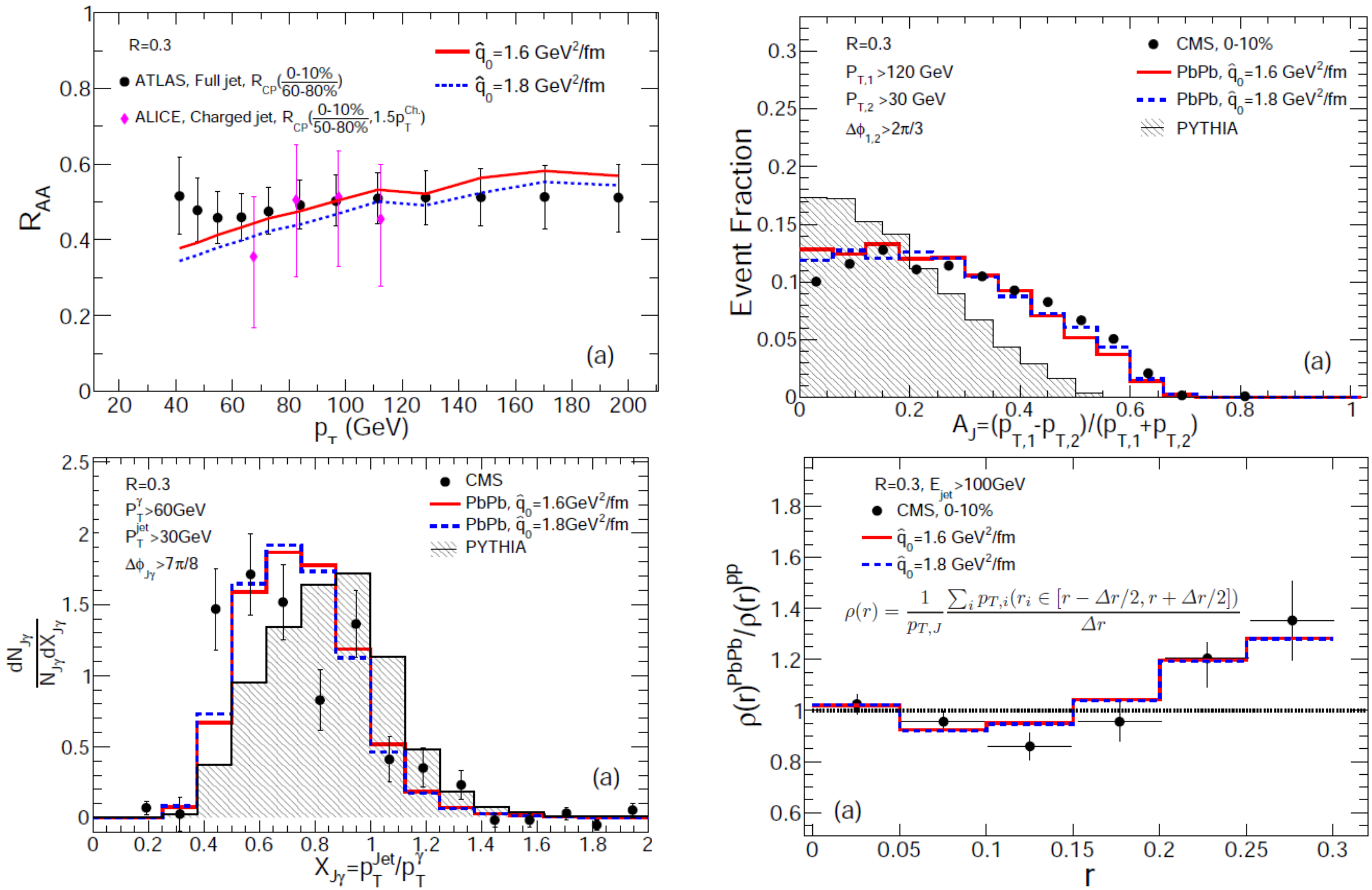
The soft outer part of jets is easier to be modified (some absorbed by medium), while the modification of the inner hard cone is more difficult

The enhancement at large r is consistent with the broadening

The final modification of jet shape comes from the interplay of different contributions

Ningbo Chang, GYQ, arXiv:1603.01920

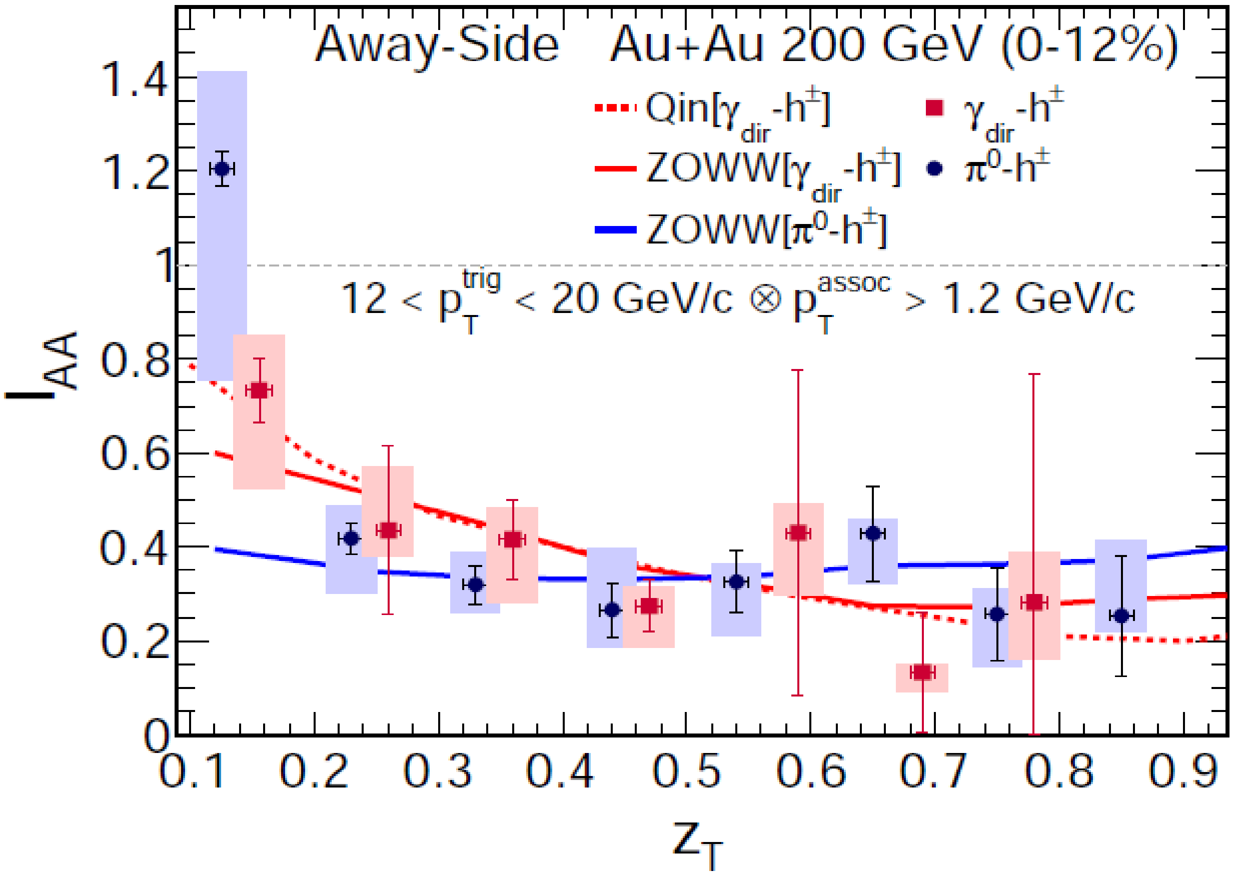
Various full jet observables



Ningbo Chang, GYQ, arXiv:1603.01920

Jet-like correlations

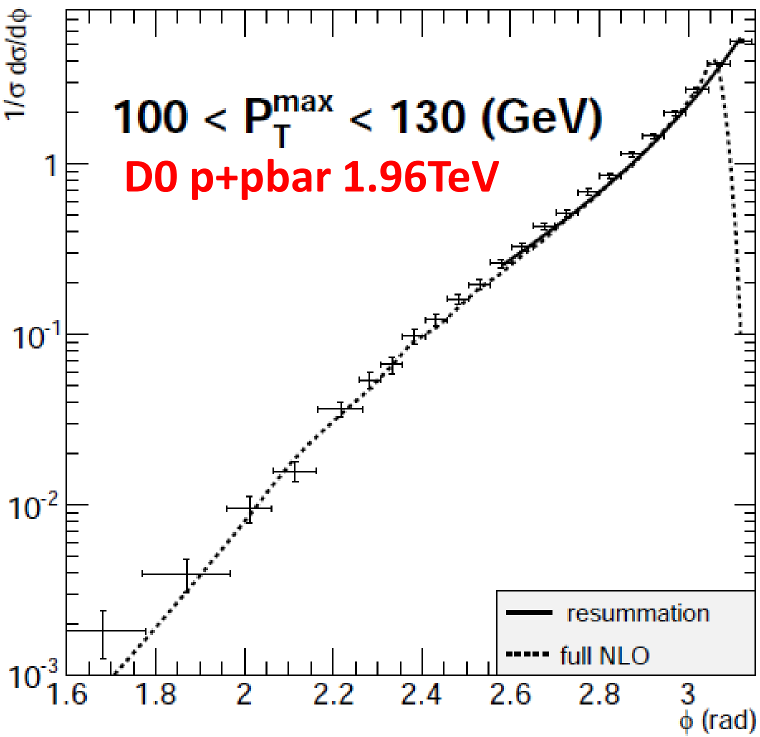
Jet-like correlations

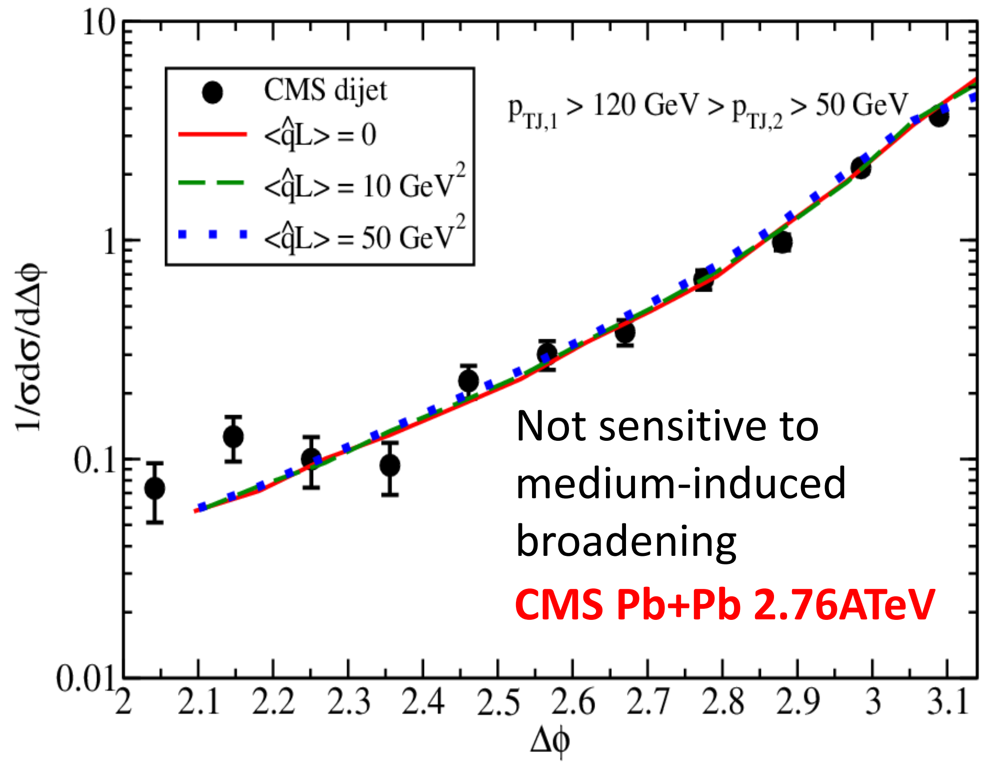


Most of (theoretical) studies on jet-like correlations in AA collisions mainly focus on the nuclear modification of the (per-trigger) yield

We will use the angular correlations to probe the transverse momentum broadening

Dijet angular correlations in pp & AA

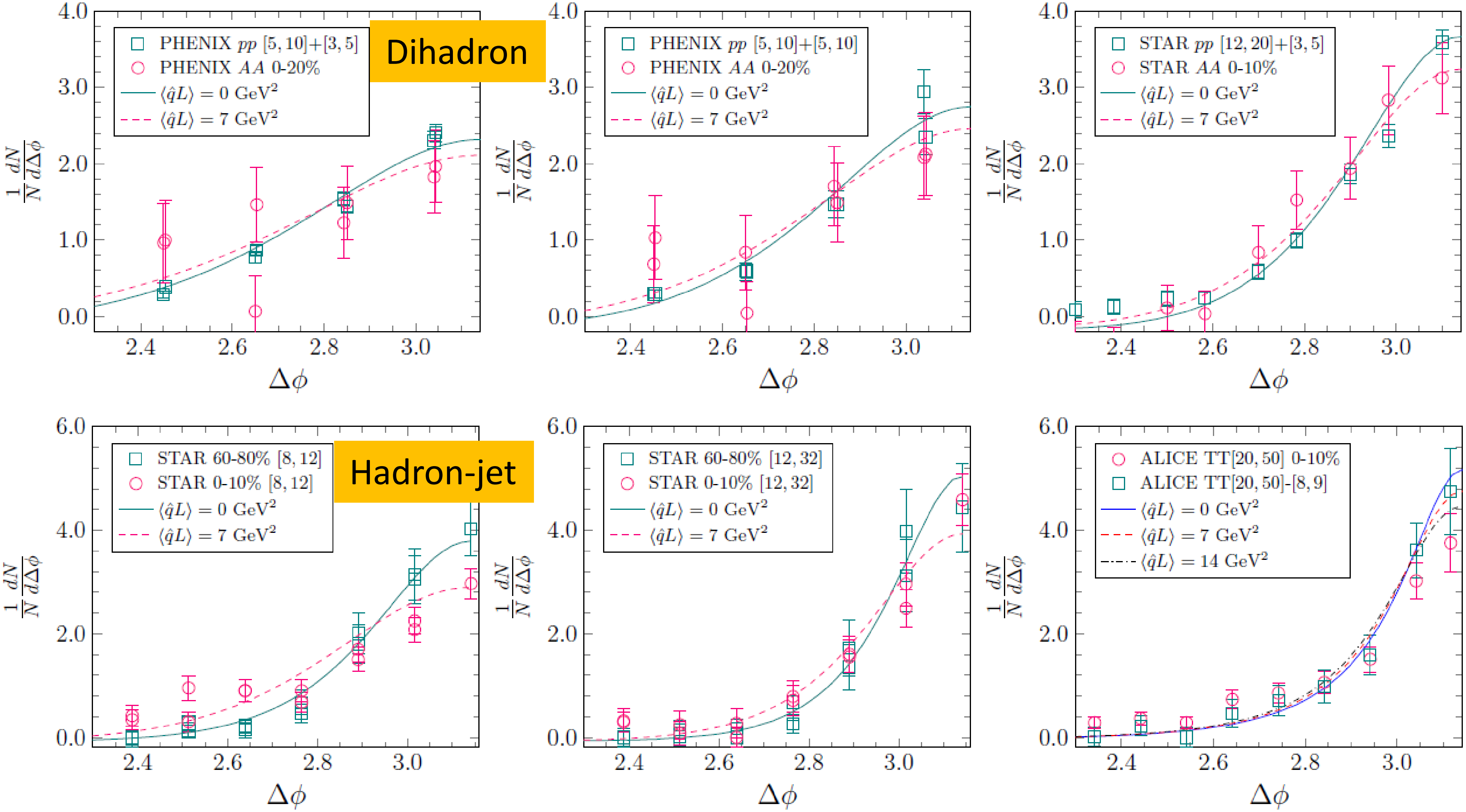




Resum all order soft gluon radiation **in vacuum** at NLL for dijet anglar correlation by *Sun, Yuan, Yuan, PRL 2014; PRD 2015*

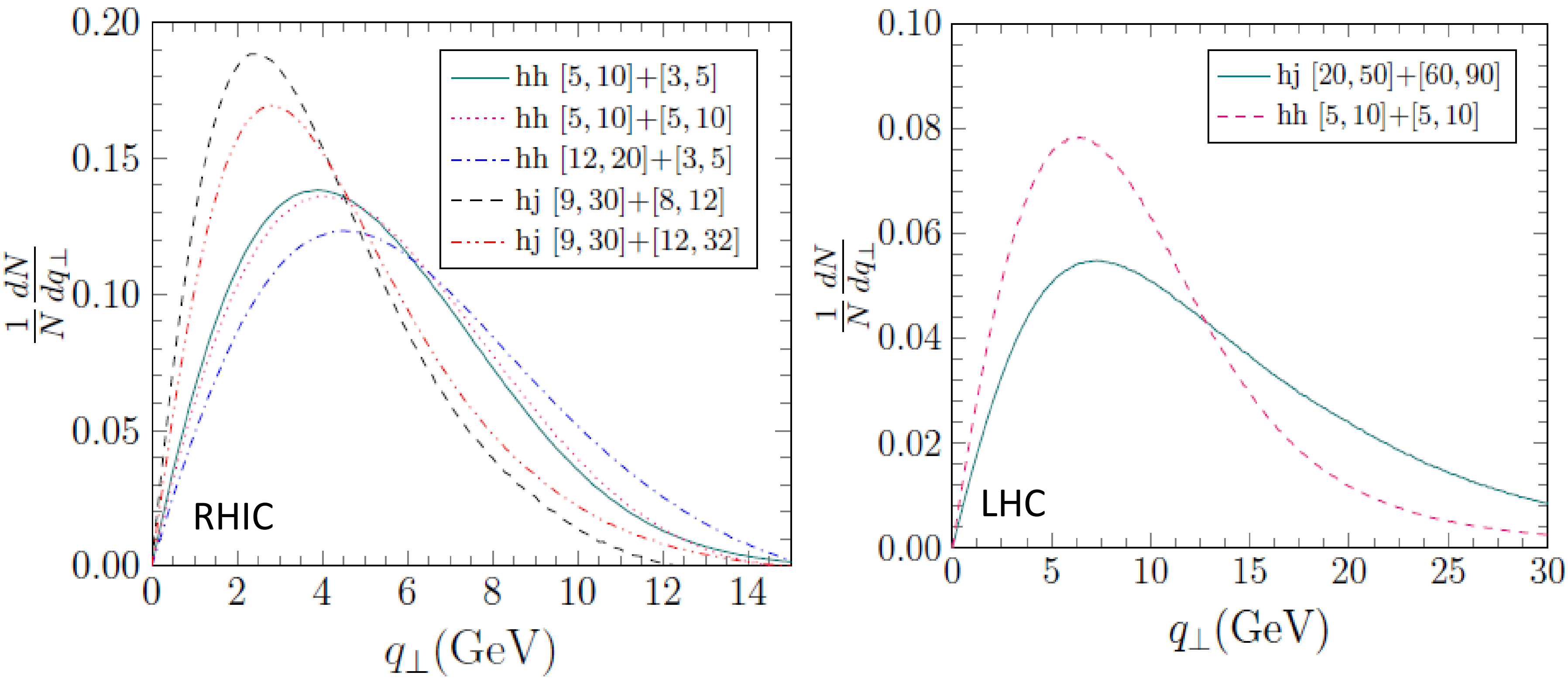
Extend the formalism to include the broadening effect induced by **the QCD medium** for dijet anglar correlation by *Mueller, Wu, Xiao, Yuan, arXiv:1604.04250*

Probing q^{hat} via dihadron & hadron-jet angular correlations



Lin Chen, GYQ, Shu-Yi Wei, Bo-Wen Xiao, Han-Zhong Zhang, in preparation

Momentum imbalance q_T distribution (in pp)



$$\vec{q}_\perp = \vec{p}_{T,1} + \vec{p}_{T,2}$$

$$\left\langle q_\perp^2 \right\rangle_{AA} \approx \left\langle q_\perp^2 \right\rangle_{pp} + \left\langle \hat{q} L \right\rangle_{AA}$$

Lin Chen, GYQ, Shu-Yi Wei, Bo-Wen Xiao, Han-Zhong Zhang, in preparation

Summary

- ***Radiative* & *collisional* processes play different roles in different probes and observables**
  - Light & heavy flavor jet quenching, full jet energy loss, nuclear modification of jet shape

- **Jet transport coefficients control both *collisional* and *radiative* contributions**

- **Probe medium-induced *broadening* (q^{hat}) via jet-like angular correlations**

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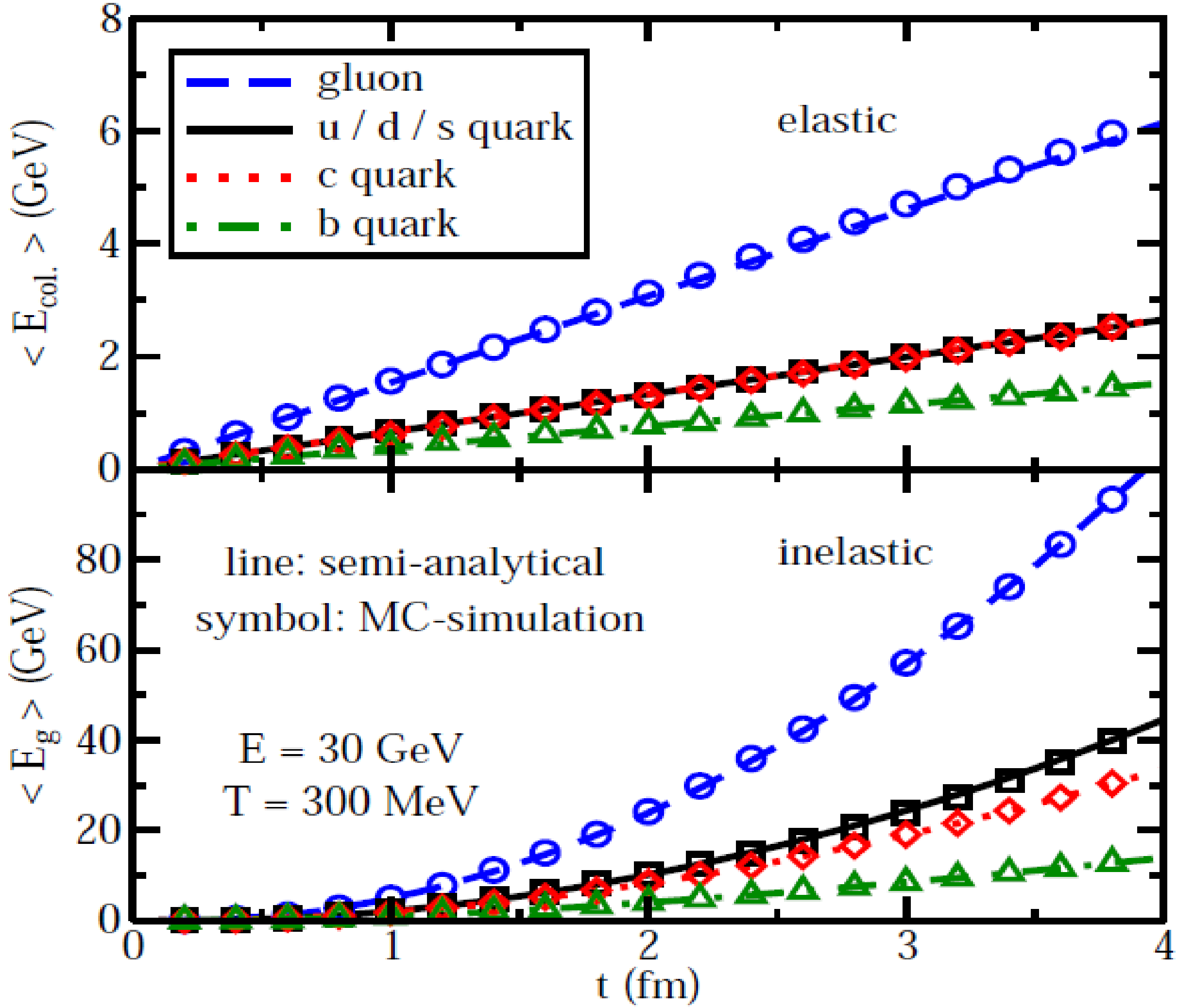
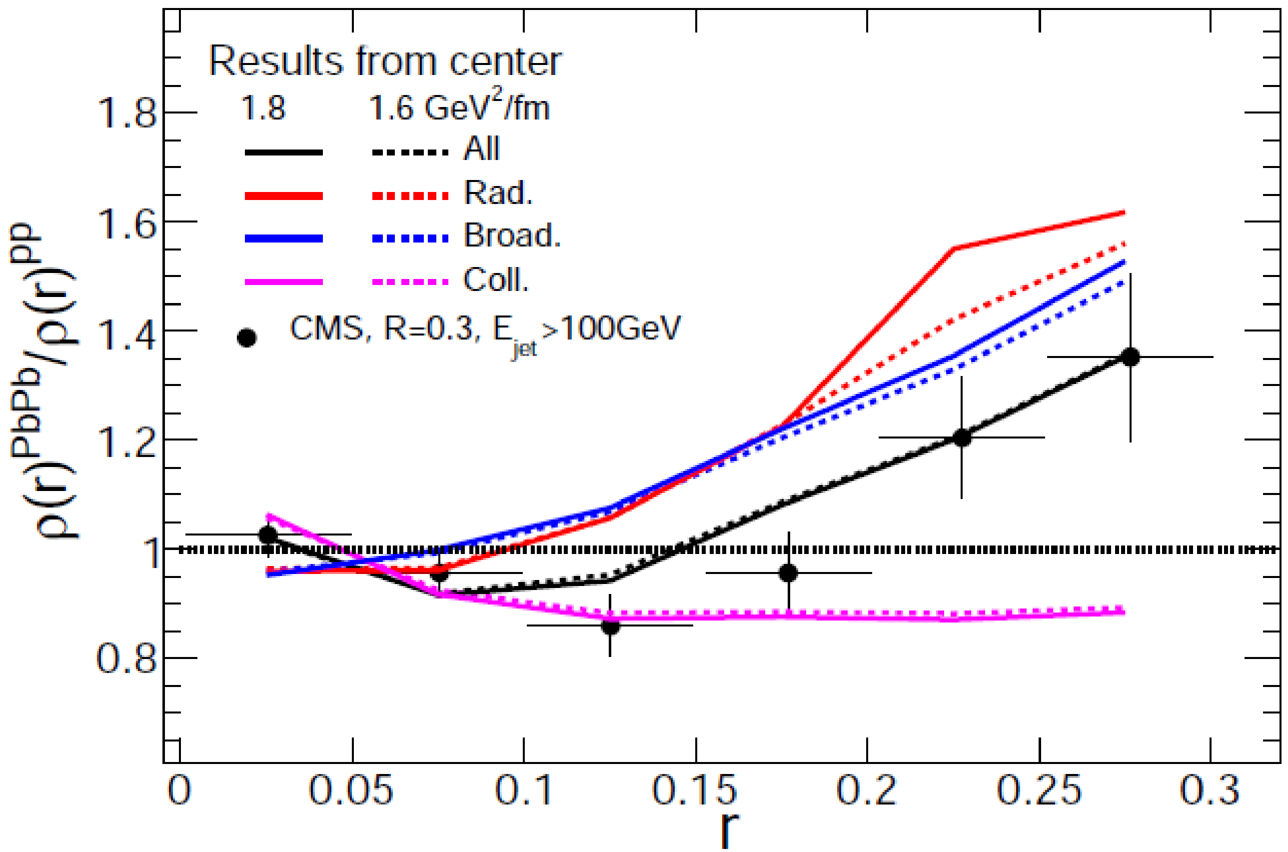
Test for collisional & radiative energy loss from LBT



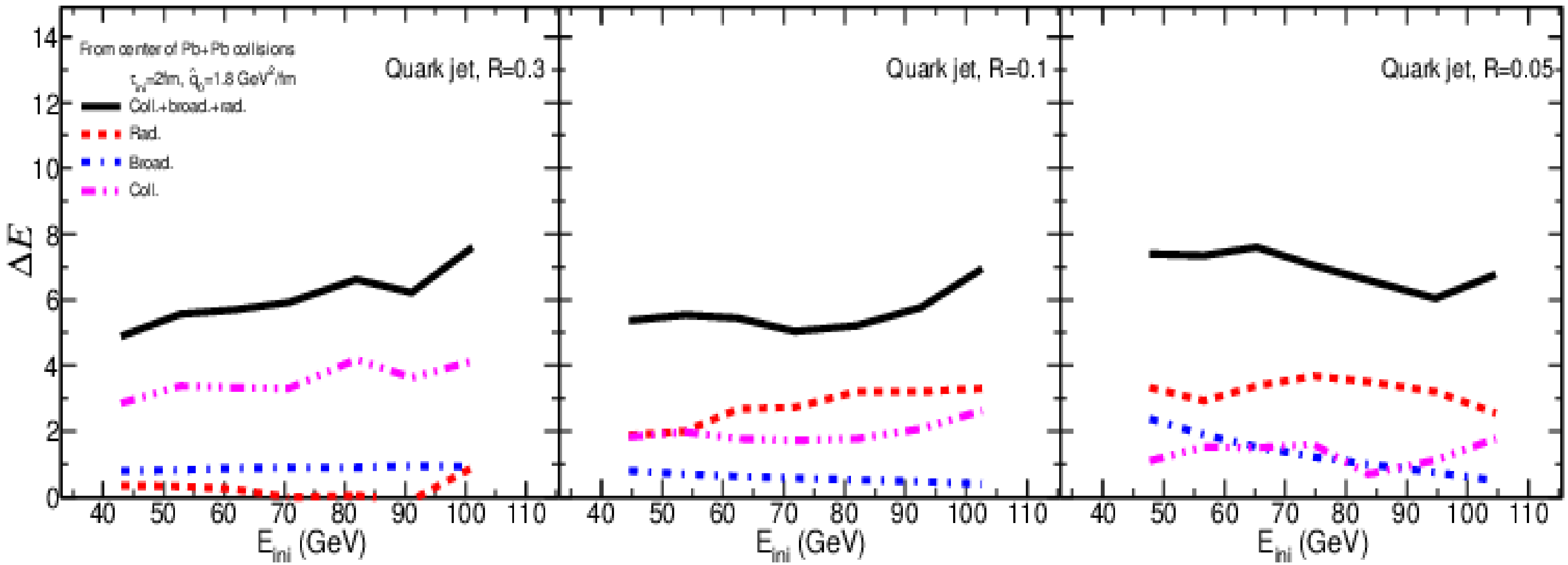
Cao, Luo, GYQ, Wang, arXiv:1605.06447 & in preparation

Sensitivity to jet transport parameter

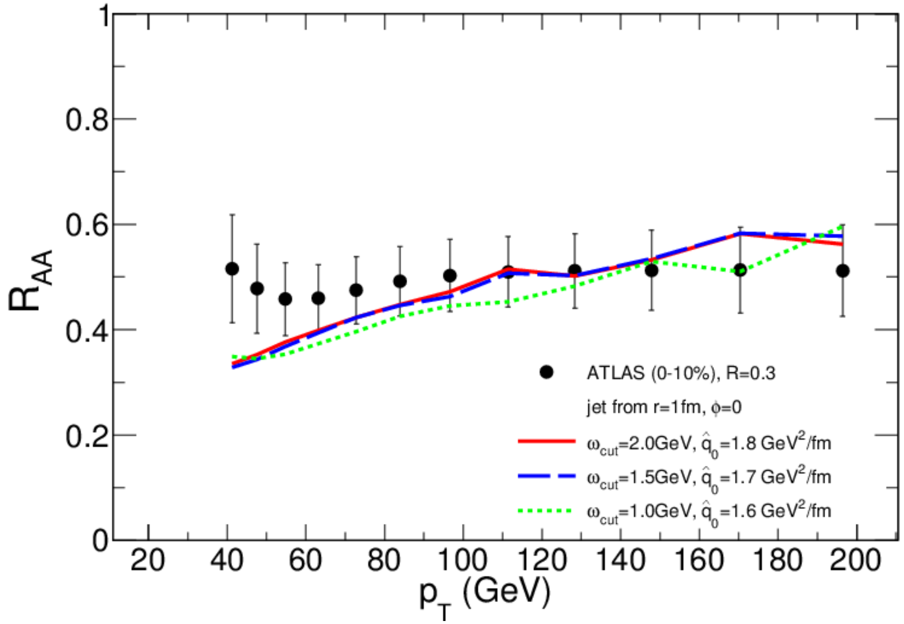


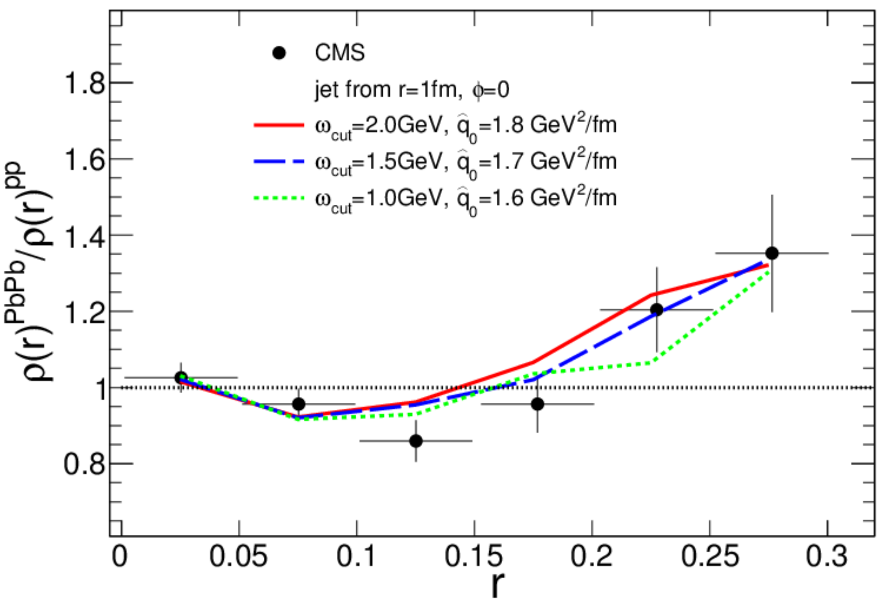
Ningbo Chang, GYQ, arXiv:1603.01920

Full jet energy loss
(jet size dependence of different contributions)

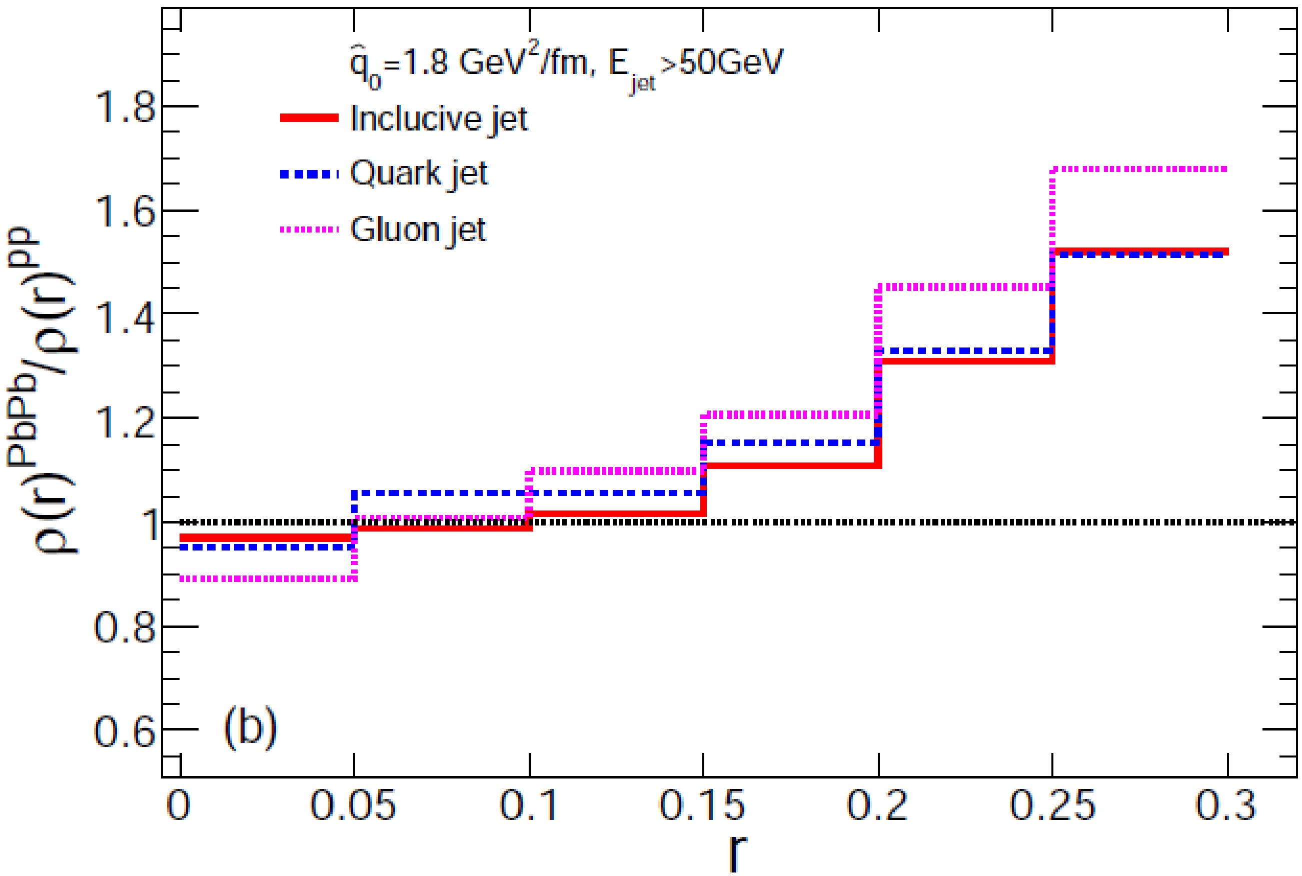


Uncertainty from ω_{cut}





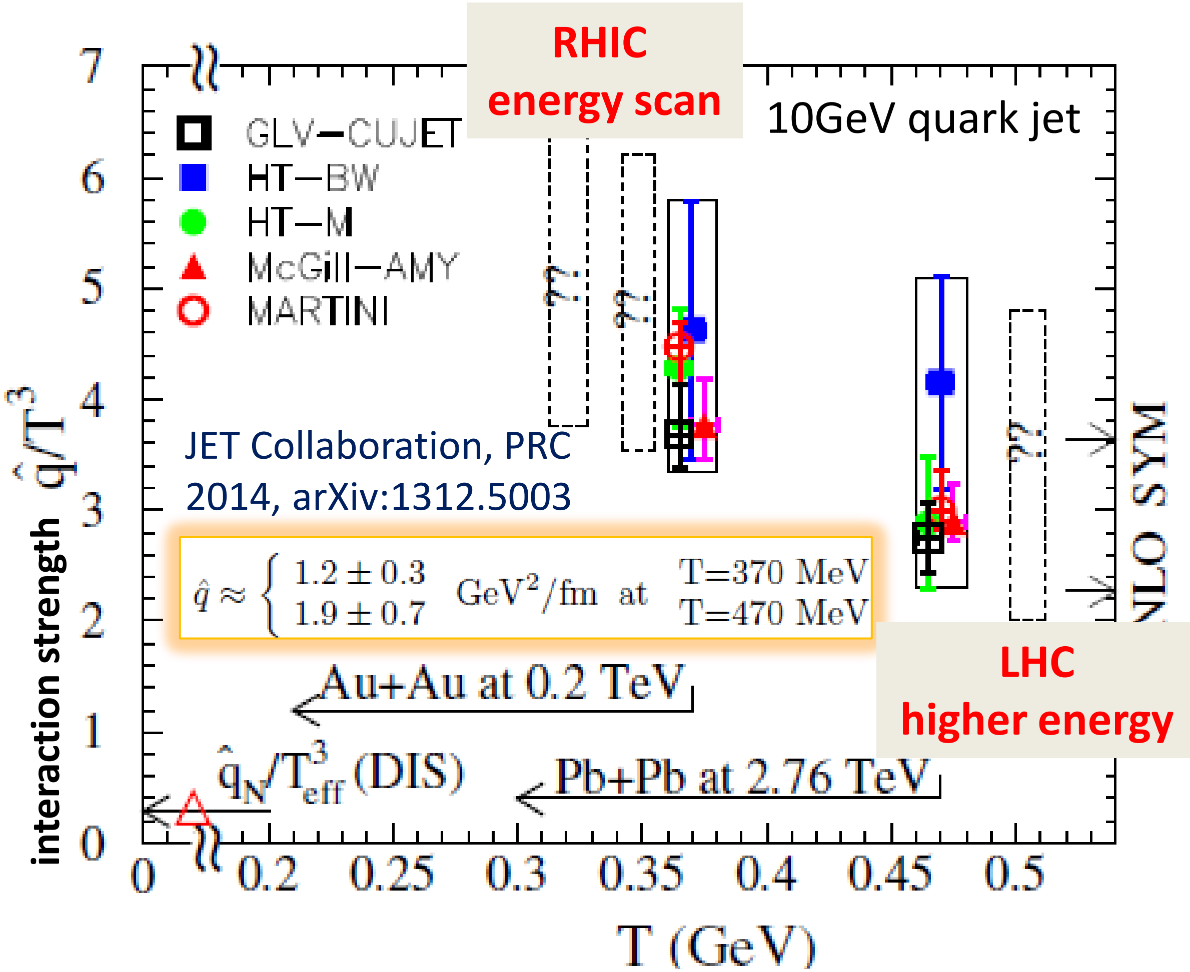
Nuclear modification of jet shape



Ningbo Chang, GYQ, arXiv:1603.01920

Extraction of jet transport parameter

Jet transport coefficients control both collisional and radiative contributions



McGill-AMY:
GYQ, Ruppert, Gale, Jeon, Moore, Mustafa, PRL 2008
HT-BW:
Chen, Hirano, Wang, Wang, Zhang, PRC 2011
HT-M:
Majumder, Chun, PRL 2012
GLV-CUJET:
Xu, Buzzatti, Gyulassy, arXiv: 1402.2956
MARTINI-AMY:
Schenke, Gale, Jeon, PRC 2009
NLO SYM:
Zhang, Hou, Ren, JHEP 2013

$$\hat{q} = \frac{d\langle \Delta p_\perp^2 \rangle}{dt} = \int d^2k_\perp k_\perp^2 \frac{d\Gamma(k_\perp)}{d^2k_\perp dt} \approx \frac{8\pi^2\alpha_s C_R}{N_c^2 - 1} \int dy^- \langle F^{\mu+}(0) F_\mu^+(y^-) \rangle$$

Dihadron correlation

$$\frac{d\sigma}{d\Delta\phi} = \sum_{a,b,c,d} \int p_T^{h_1} dp_T^{h_1} \int p_T^{h_2} dp_T^{h_2} \int \frac{dz_c}{z_c^2} \int \frac{dz_d}{z_d^2}$$

$$\times \int b\, db\, J_0(q_\perp b) e^{-S(Q,b)} x_a f_a(x_a, \mu_b) x_b f_b(x_b, \mu_b)$$

$$\times \frac{1}{\pi} \frac{d\sigma_{ab\to cd}}{d\hat{t}} D_c(z_c, \mu_b) D_d(z_d, \mu_b)$$

$$S(Q,b) = S_{\rm p}^i(Q,b) + S_{\rm p}^f(Q,b) + S_{\rm np}(Q,b)$$
$$+ \frac{b^2}{4} \left(\langle \hat{q}_c L\rangle + \langle \hat{q}_d L\rangle\right),$$