Light and heavy flavor jet quenching

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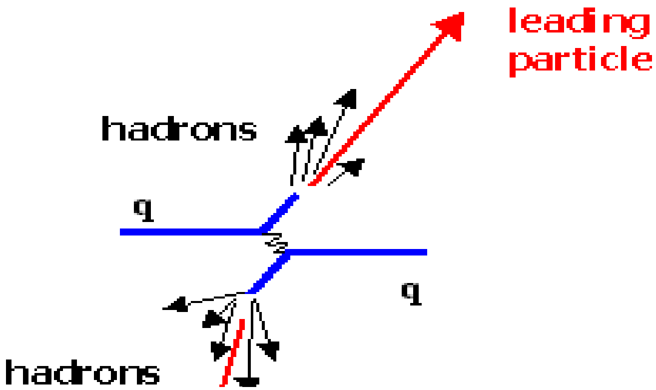
Outline

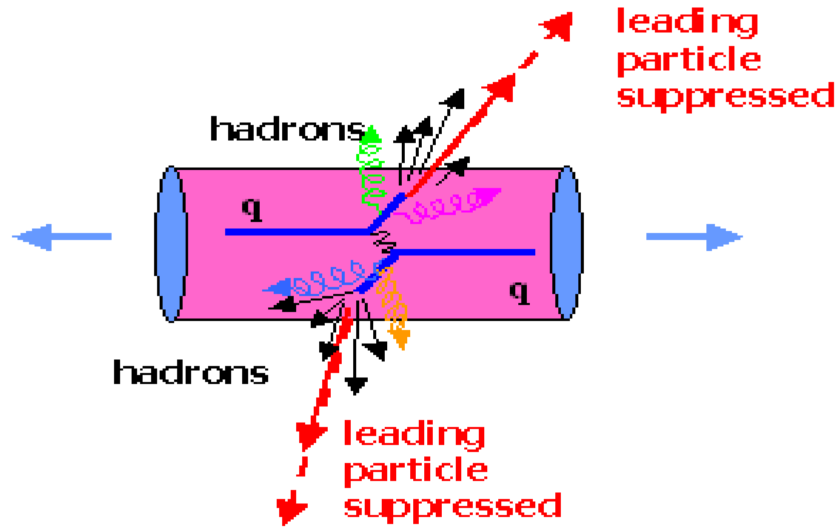
- A Linearized Boltzmann Transport (LBT) approach to *heavy & light* flavor jet quenching (with elastic & inelastic contributions)

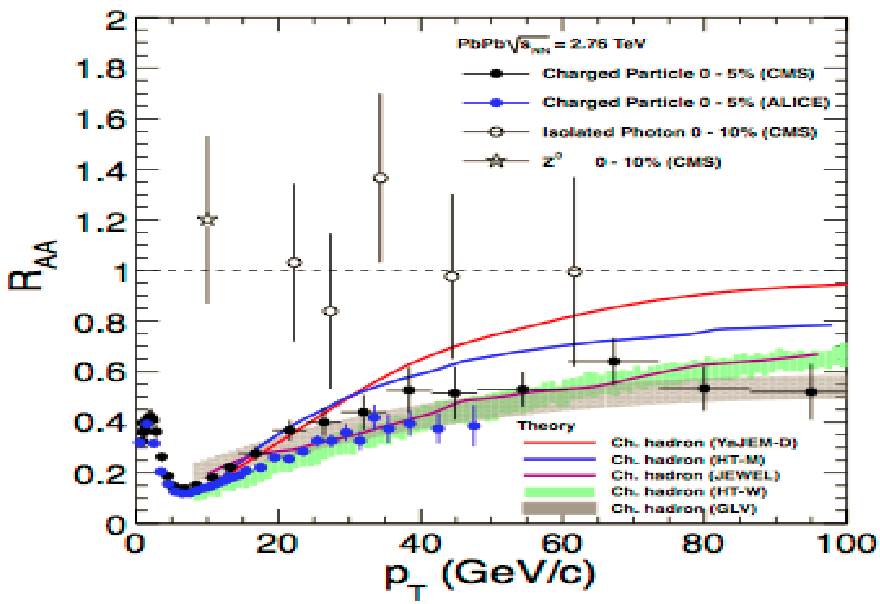
- *Full jet* energy loss and modification (collisional, radiative, broadening)

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

Jets are hard probes of QGP







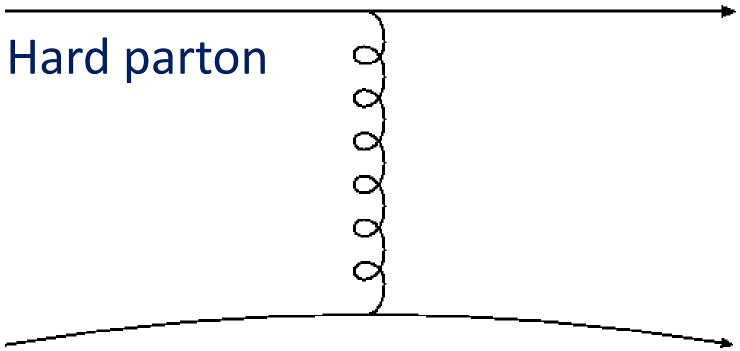
Nuclear modification factor:

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

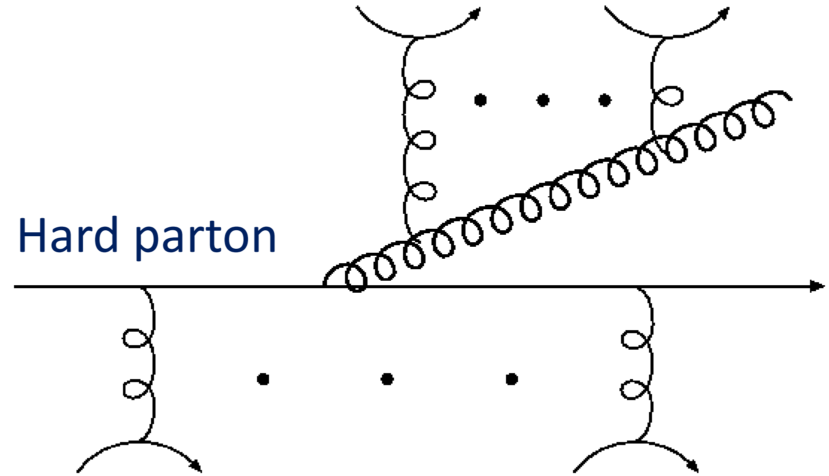
Jet quenching mainly originates from parton energy loss in hot QGP

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)**

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

GYQ, Majumder, PRC 2013

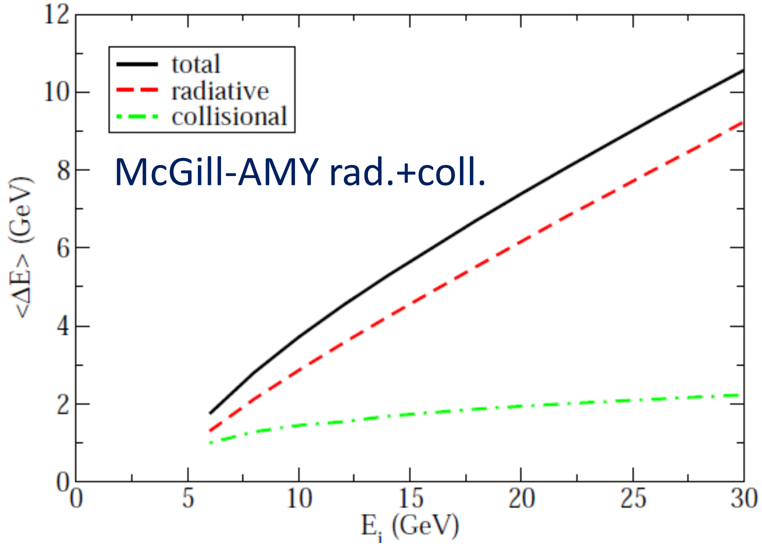
The medium-induced gluon radiation spectrum from higher-twist formalism:

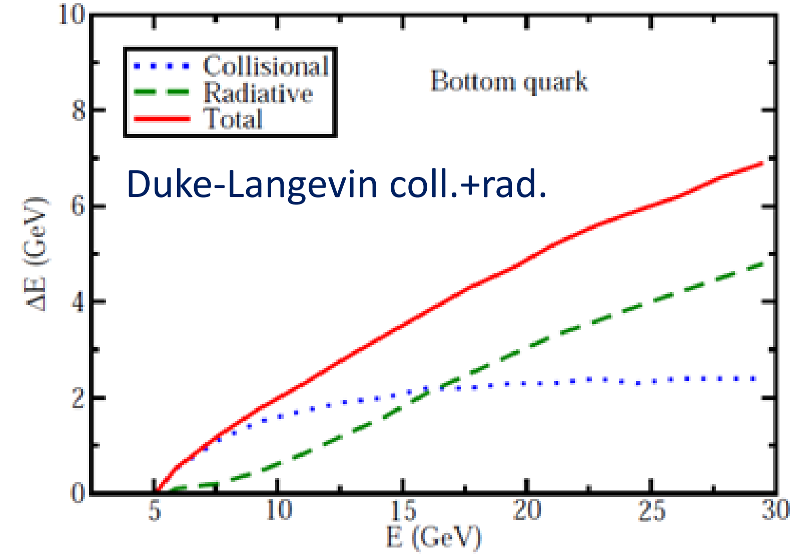
$$\frac{dN_g}{dx\, dl_\perp^2\, dz^-} \approx \frac{4\alpha_s}{\pi} P(x) \frac{D_{T,2}}{l_\perp^4} \sin^2\left(\frac{z^- - z_i^-}{2\tau_f^-} \right)$$

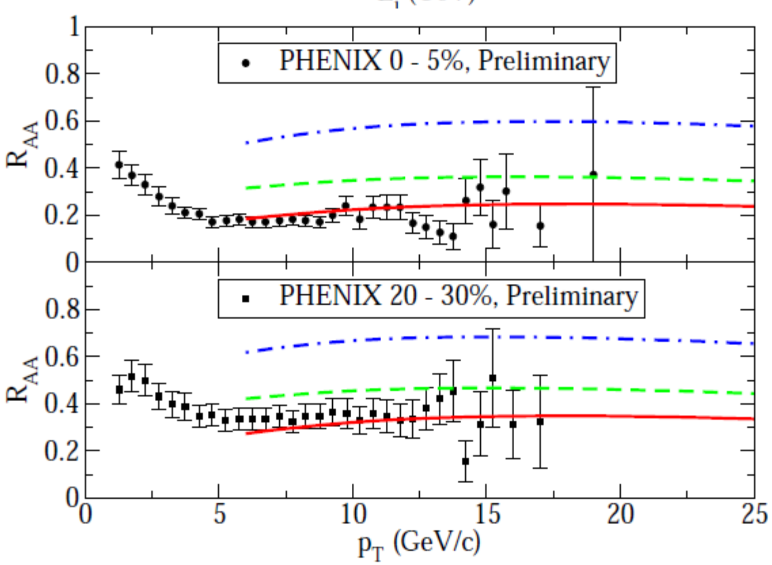
Guo, Wang, PRL, 2000
Majumder, PRD, 2012

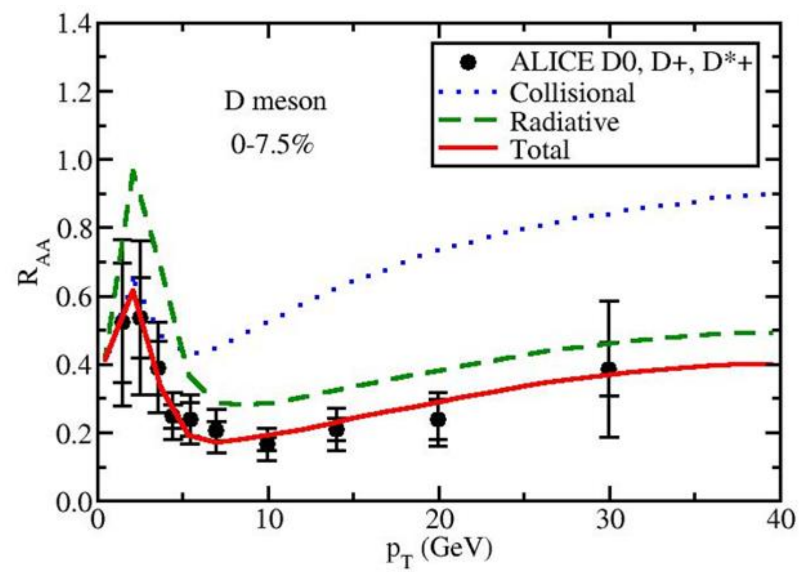
Jet transport coefficients control both collisional and radiative contributions

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:**

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

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

- **Inelastic collisions:**

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

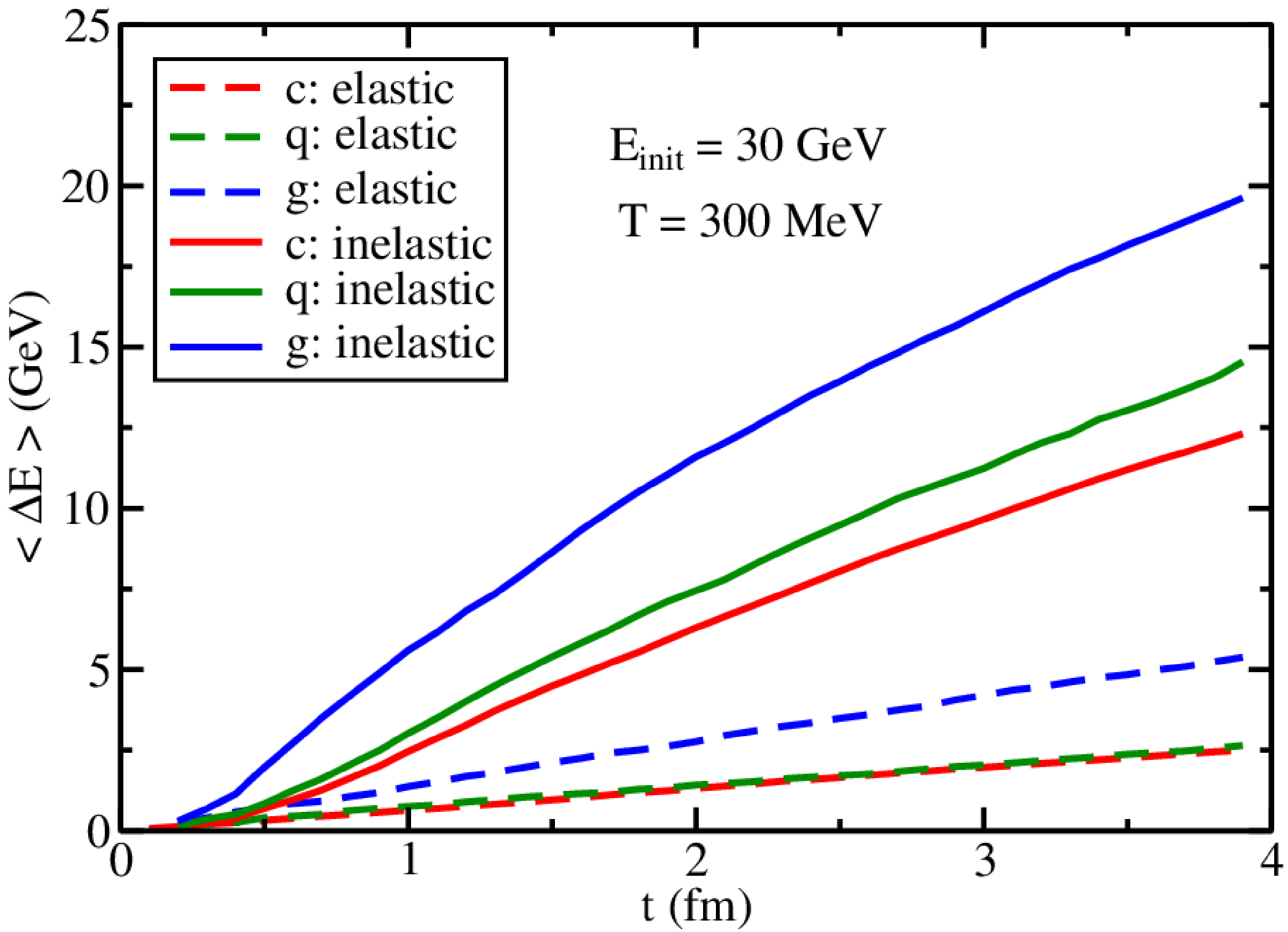
$$P(n) = \frac{\langle N_g \rangle^n}{n!} e^{-\langle N_g \rangle}$$

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

- **Elastic + Inelastic:** $P_{\mathrm{tot}} = P_{\mathrm{el}} + P_{\mathrm{inel}} - P_{\mathrm{el}} P_{\mathrm{inel}}$

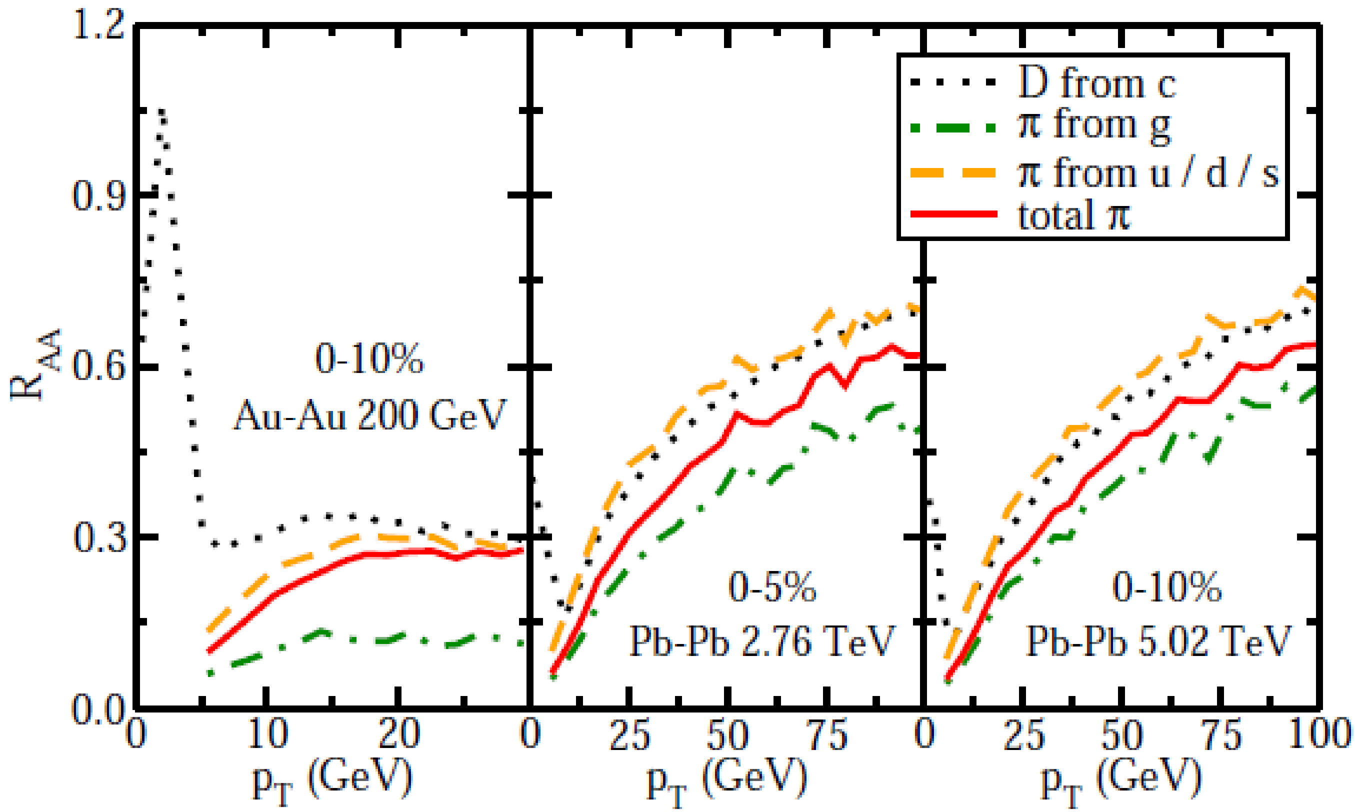
Cao, Luo, GYQ, Wang, PRC 2016 & in preparation

Elastic & inelastic energy loss from LBT



Cao, Luo, GYQ, Wang, PRC 2016 & in preparation

Light and heavy flavor jet quenching

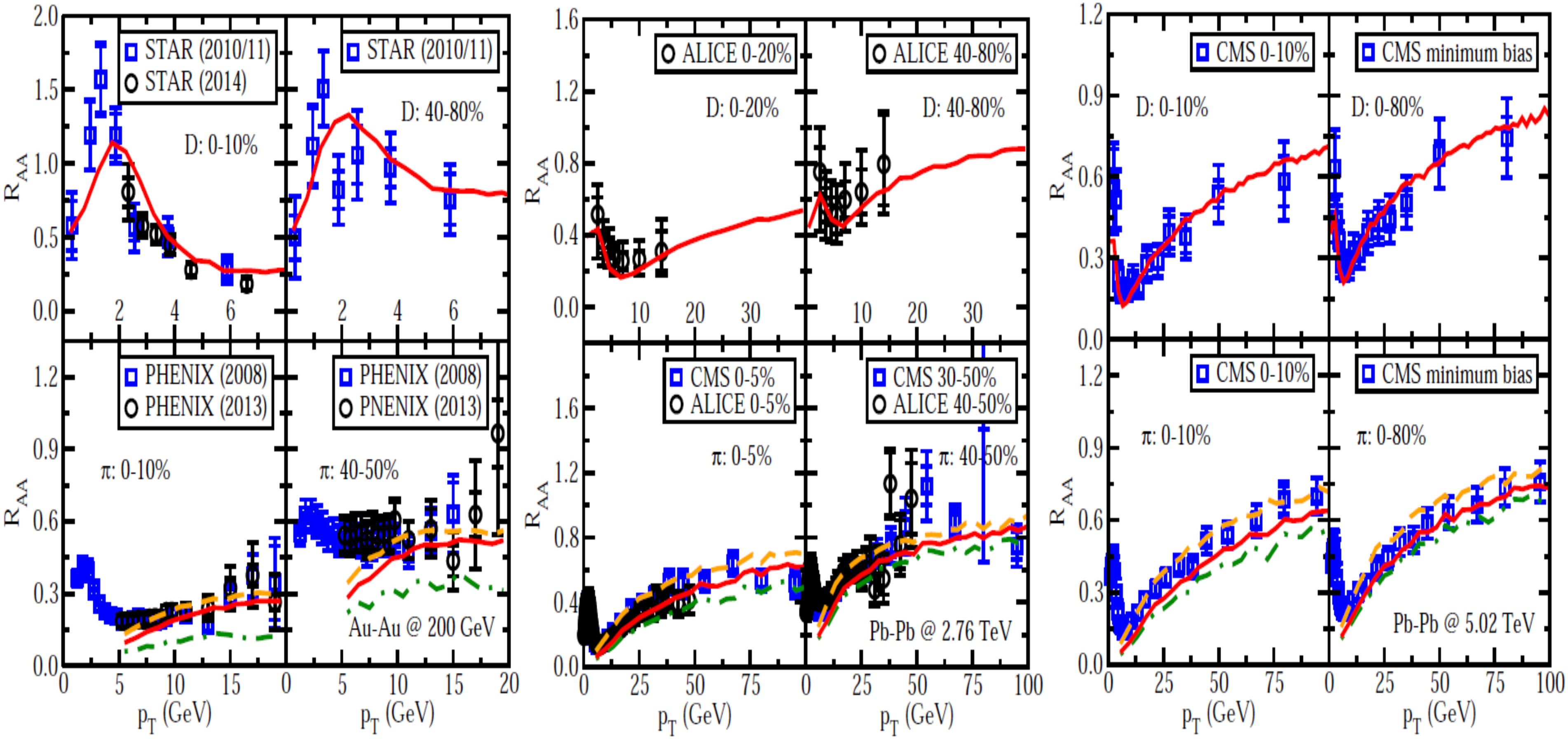


R_{AA} for D's can be smaller than that R_{AA} for π's from light quarks, mainly due to *different shapes of fragmentation functions and initial parton spectra*

The splitting of π and D meson R_{AA} at high p_T becomes larger from RHIC to the LHC energies due to increasing *gluon contribution to light hadron production (at same p_T)*

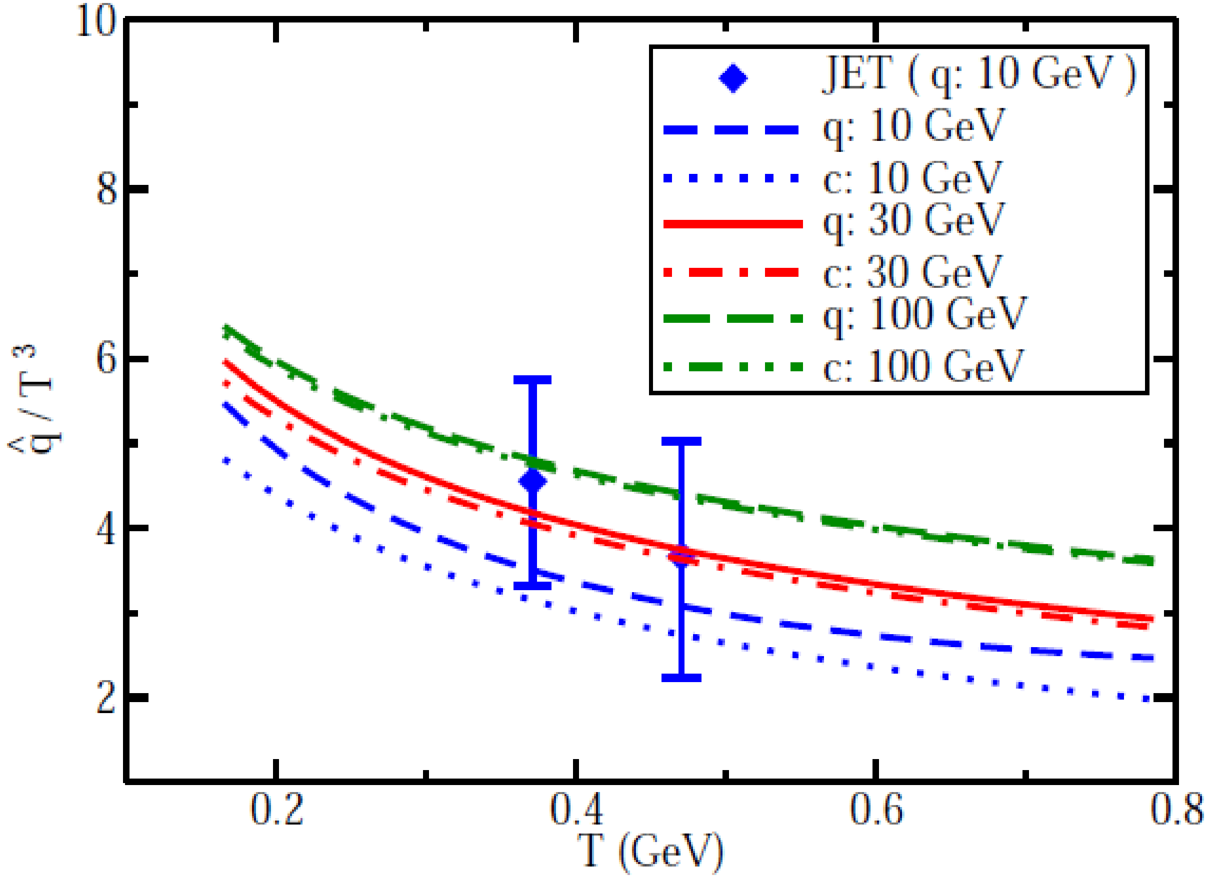
Cao, Luo, GYQ, Wang, PRC 2016 & in preparation

Light and heavy flavor jet quenching



Cao, Luo, GYQ, Wang, PRC 2016 & in preparation

Jet quenching parameter



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

Cao, Luo, GYQ, Wang, PRC 2016 & in preparation

Medium-induced radiation with *transverse* and *longitudinal* scattering

- Medium-induced radiative gluon spectrum with both **transverse and longitudinal** momentum exchange:

$$\frac{dN_g}{dy\,dl_\perp^2} = \frac{\alpha_s}{2\pi}\frac{P_{q\to g}(y)}{l_\perp^2}\int_0^{L^-} dZ_1^- \left\{ \left(-\frac{4-3y^2+y^3}{2[1+(1-y)^2]}G_0 - \frac{2(1-2y)}{1-y}G_1 - \frac{C_F}{C_A}\frac{y^2(1-y)}{1+(1-y)^2}(2-G_0) \right) \frac{D_{L1}}{yq^-} \right.$$

$$+ \left(\frac{18-2y-y^2+2y^3-4y^4}{8[1+(1-y)^2]}G_0 + \frac{8-28y+31y^2-8y^3-3y^4+2y^5}{(1-y)^2[1+(1-y)^2]}G_1 + \frac{(1-2y)^2}{(1-y)^2}G_2 + \frac{C_F}{C_A}\frac{y^3(y-(1-y)(2-G_0))}{1+(1-y)^2} \right) \frac{D_{L2}}{y^2 q^{-2}}$$

$$\left. + \left[(2-y)G_0 - 2(2-y)G_1 + 4G_2 + \frac{C_F}{C_A}2y^2 \right] \frac{D_{T2}}{l_\perp^2} \right\}$$

Gluon: Zhang, Cao, Hou, GYQ, in preparation
Photon: Zhang, Hou, GYQ, PRC, in press

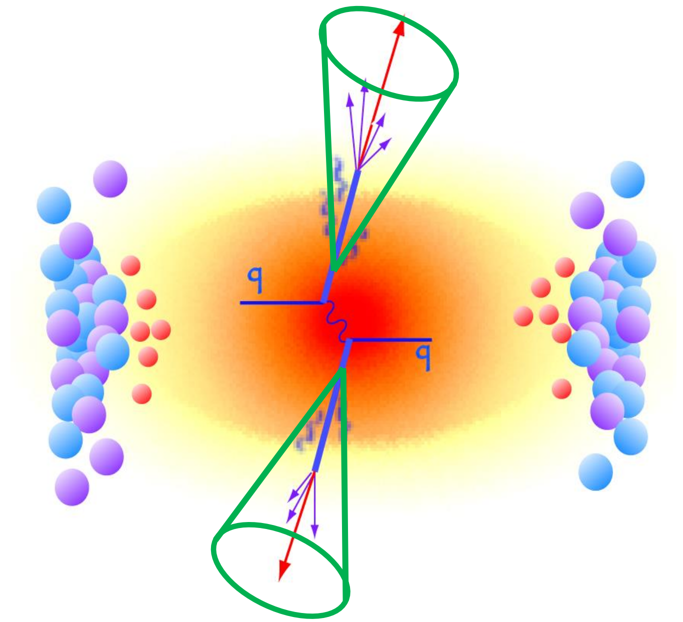
Guo, Wang, PRL 2000; NPA 2001

Contrary to transverse momentum broadening which induces additional radiation, **the longitudinal drag tends to reduce the medium-induced radiation**

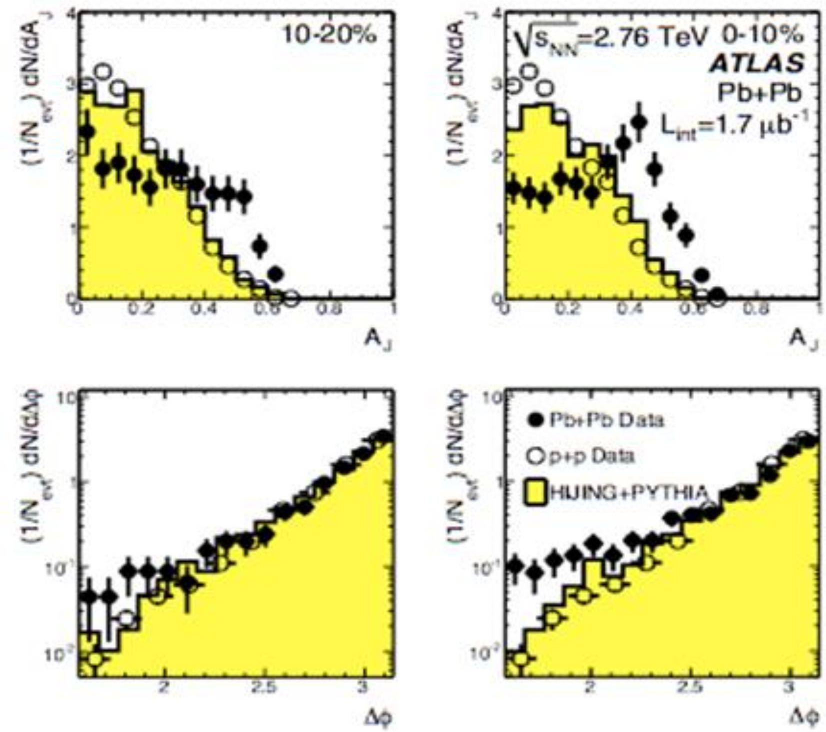
Radiative and collisional contributions are coupled to each other; they are both controlled by the same jet transport coefficients

Full jets in heavy-ion collisions

Fully-reconstructed jets are expected to provide more detailed information than single hadron observables

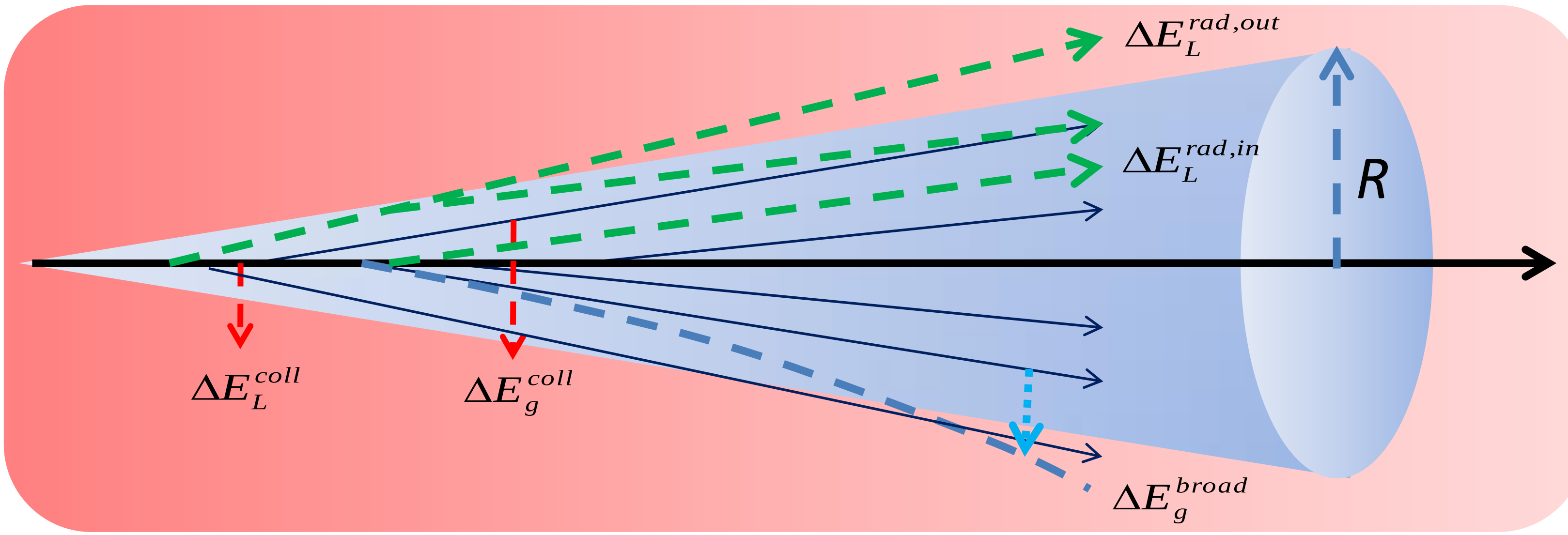


$$A_J = \frac{E_{J,1} - E_{J,2}}{E_{J,1} + E_{J,2}}, \Delta\phi = \left|\phi_1 - \phi_2\right|$$



Strong modification of momentum imbalance & largely-unchanged angular distribution
=> significant energy loss experienced by the away-side subleading jets

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**

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

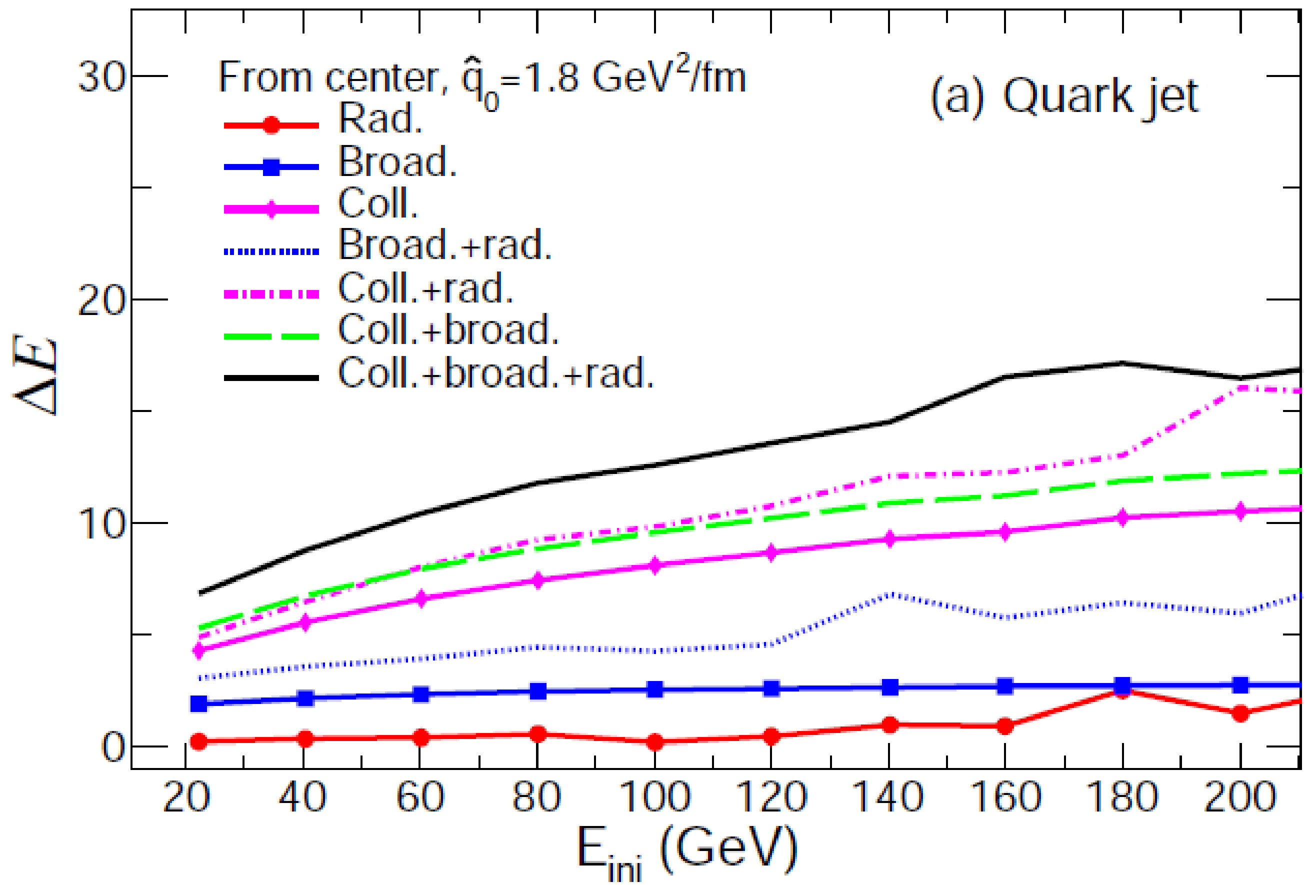
$$+\sum_i\int d\omega_i dk_{i\perp}^2\frac{d\tilde{\Gamma}_{i\to j}(\omega_j,k_{j\perp}^2|\omega_i,k_{i\perp}^2)}{d\omega_j d^2k_{j\perp}dt}f_i(\omega_i,k_{i\perp}^2,t)$$ *Gain terms*

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

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

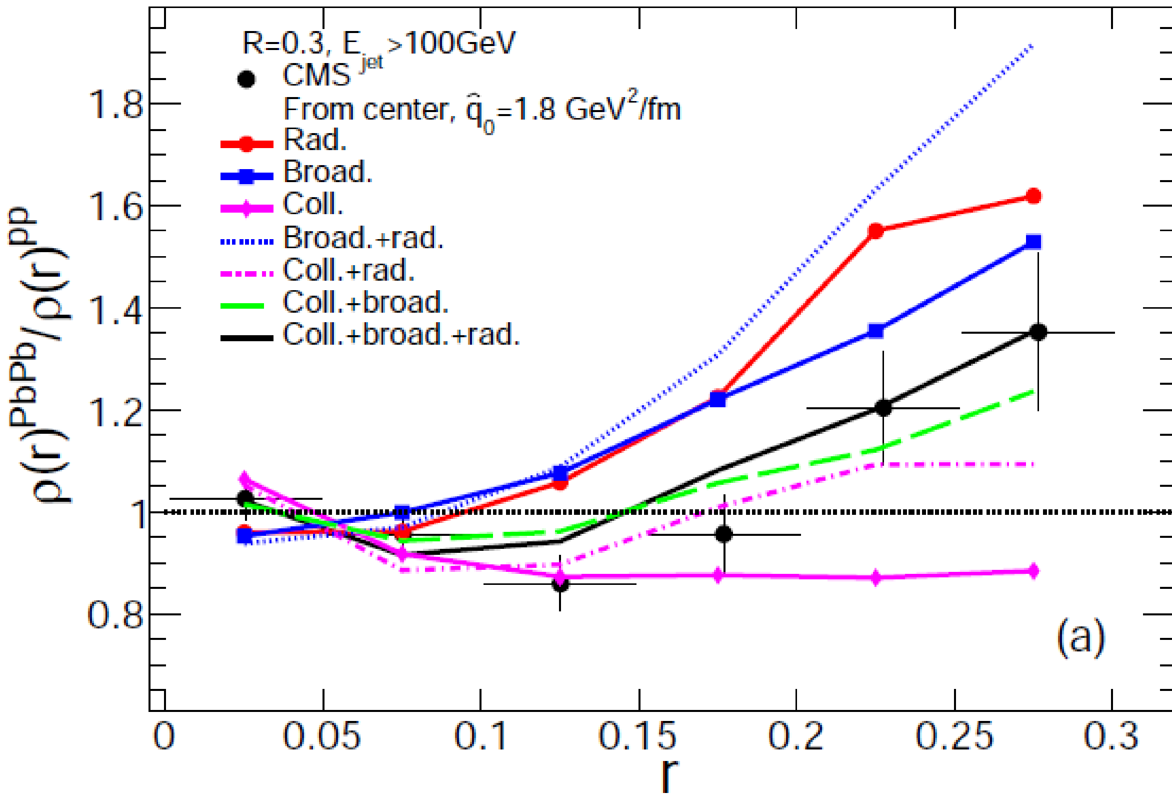
Ningbo Chang, GYQ, PRC 2016

Full jet energy loss (radiative, collisional, broadening)



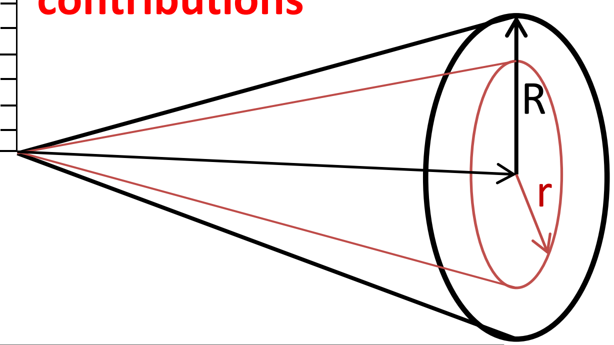
Ningbo Chang, GYQ, PRC 2016

Nuclear modification of jet shape function



The soft outer part of full jets is easier to be modified (some absorbed by medium). The inner hard cone is more difficult to be modified

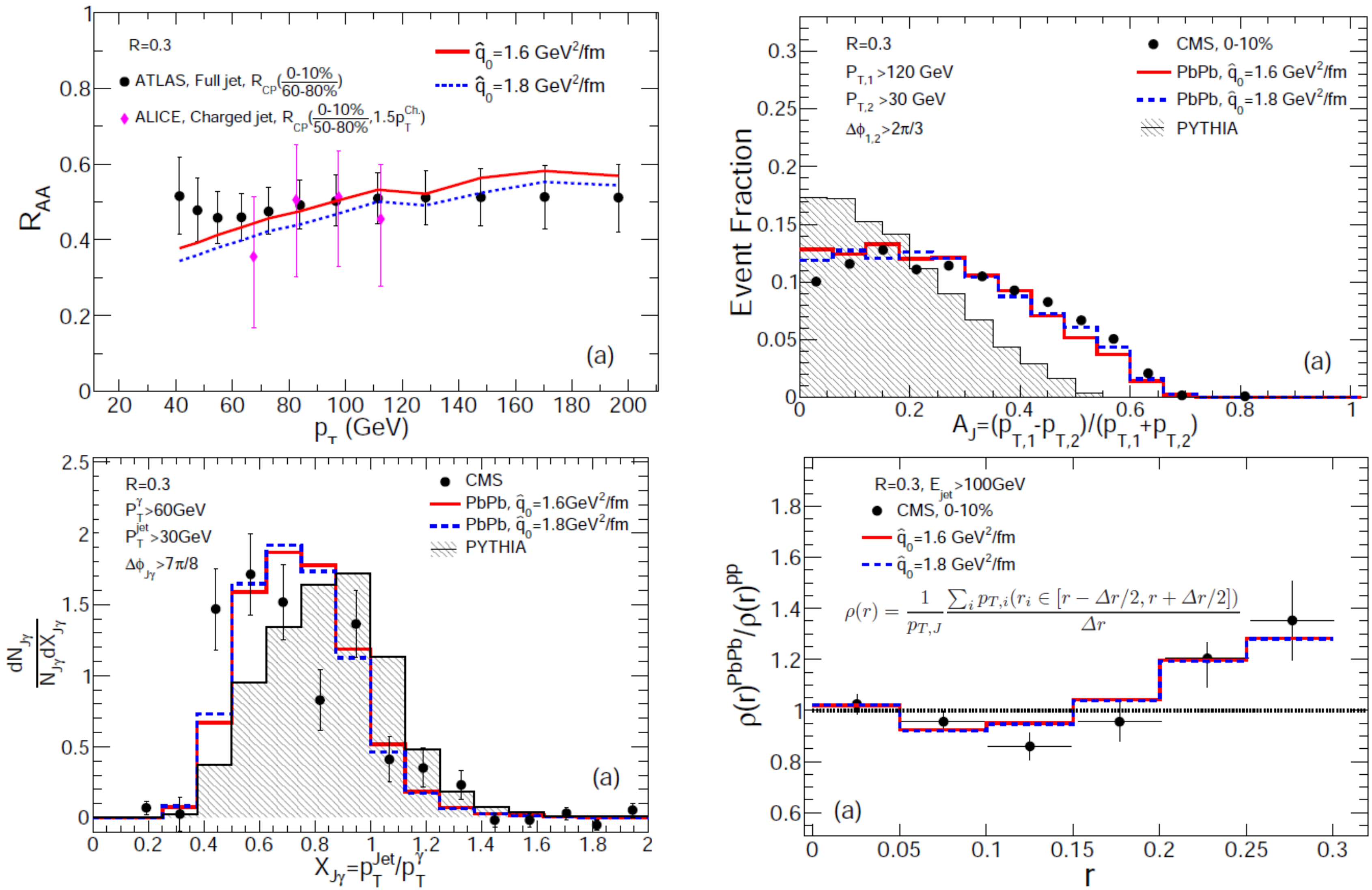
The final modification of jet shape results from the interplay of different contributions



$$\rho(r) = \frac{d}{dr}\left(\frac{\sum_{i\in J} p_{T,i}\theta(r - r_i)}{\sum_{i\in J} p_{T,i}\theta(R - r_i)}\right), r = \sqrt{(\varphi_i - \varphi_J)^2 + (\eta_i - \eta_J)^2}$$

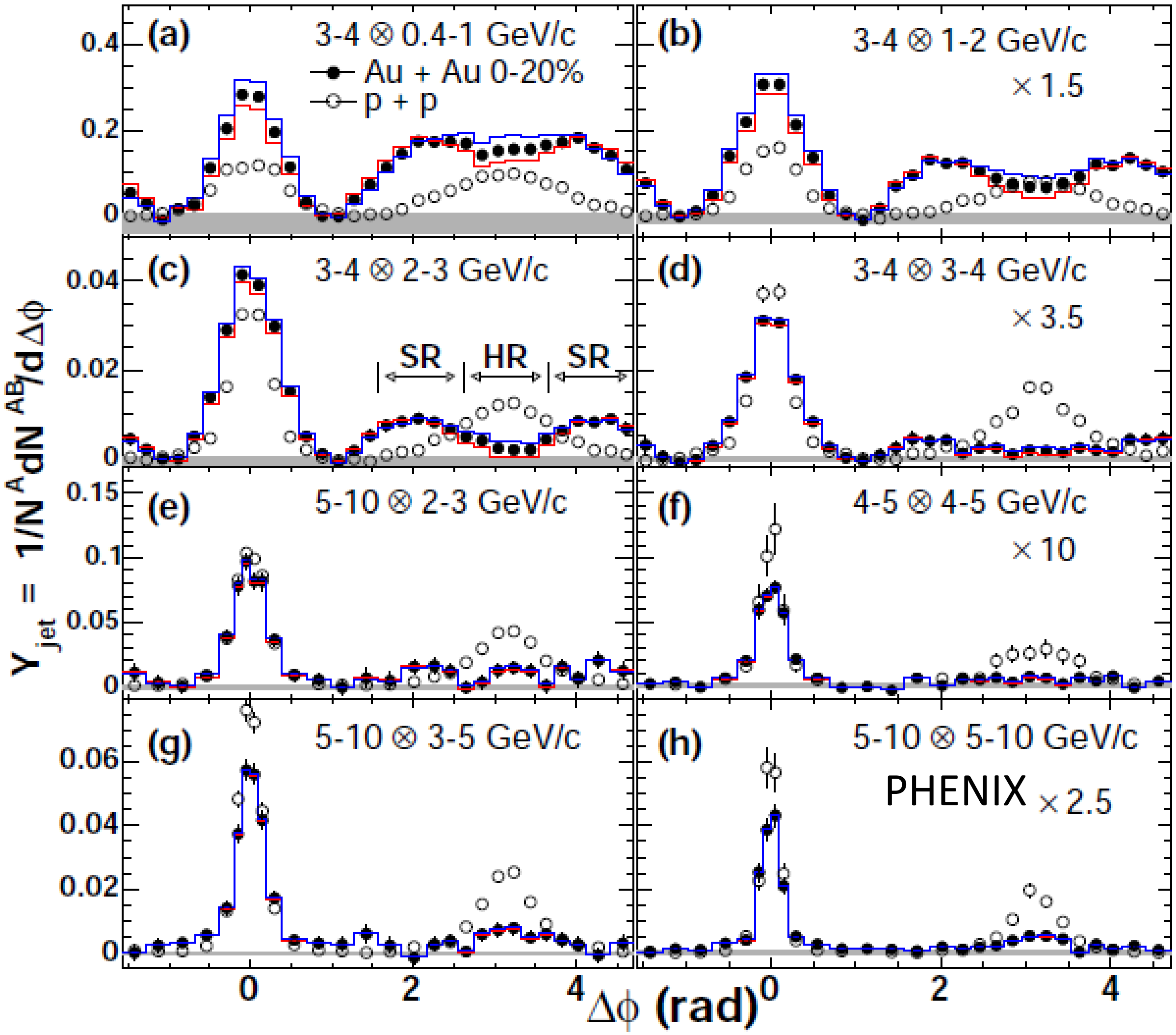
Ningbo Chang, GYQ, PRC 2016

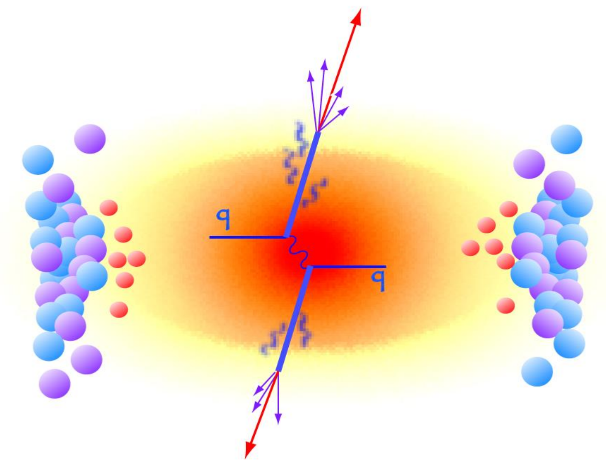
Various full jet observables



Ningbo Chang, GYQ, PRC 2016

Dihadron correlations



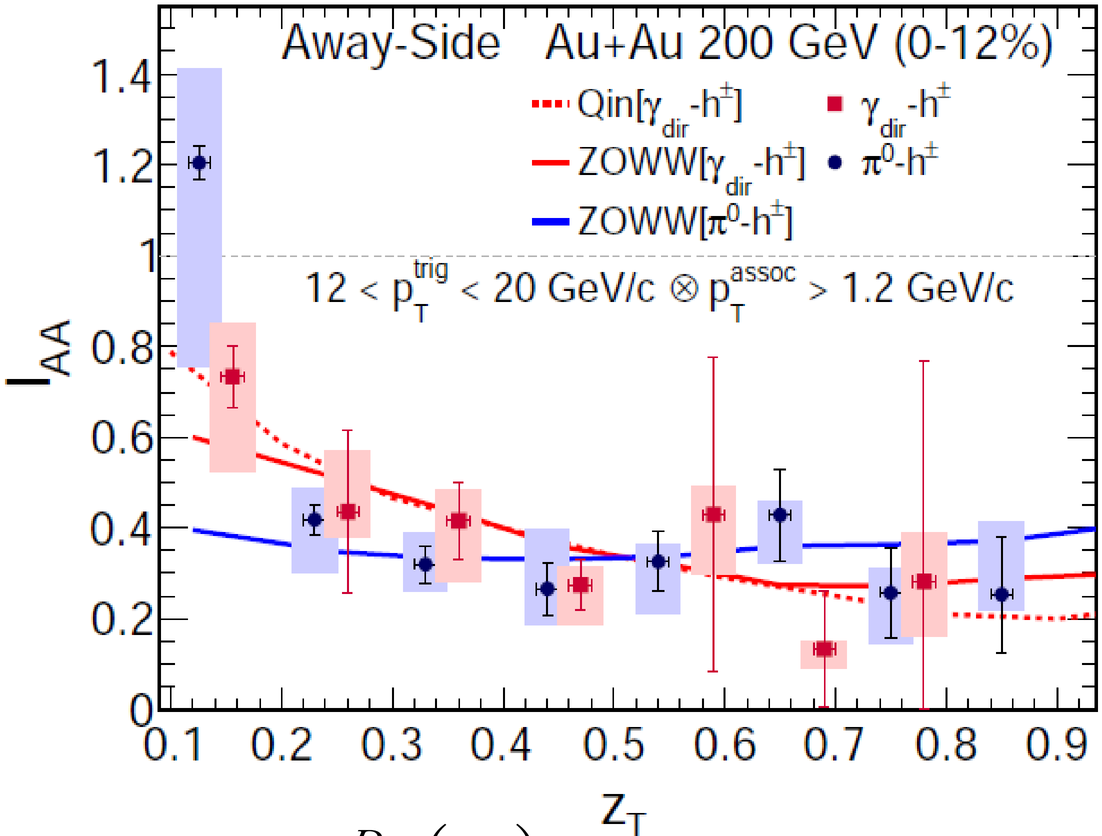


Low p_T: flow effects dominate

High p_T: ***jet-like correlations***

Both per-triggered yield and the shape of the angular distribution are modified by the QGP medium

Nuclear modification of per-trigger yield



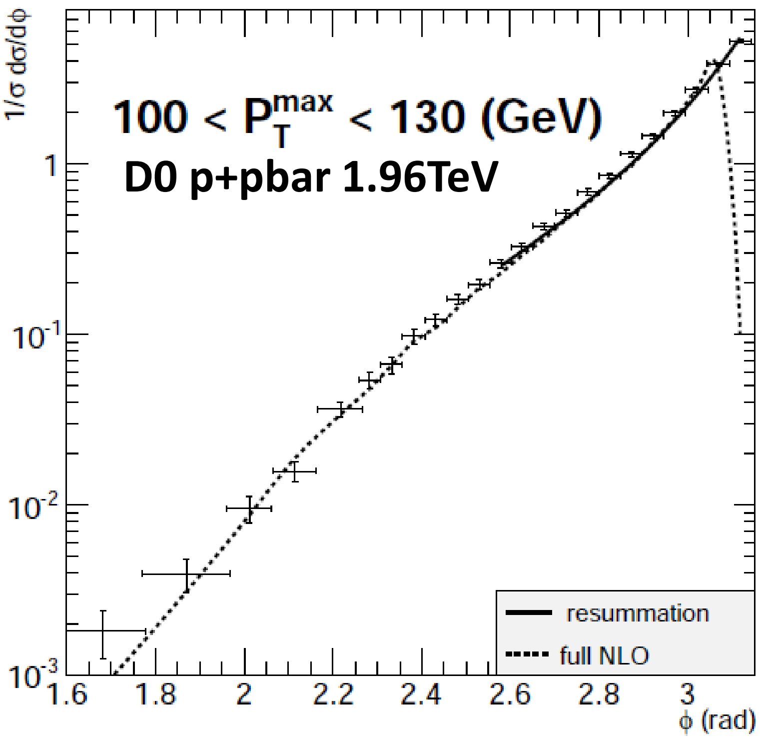
Most of (theoretical) studies on jet-like correlations in AA collisions mainly focused on parton energy loss and its effect on the nuclear modification of the (per-trigger) yield

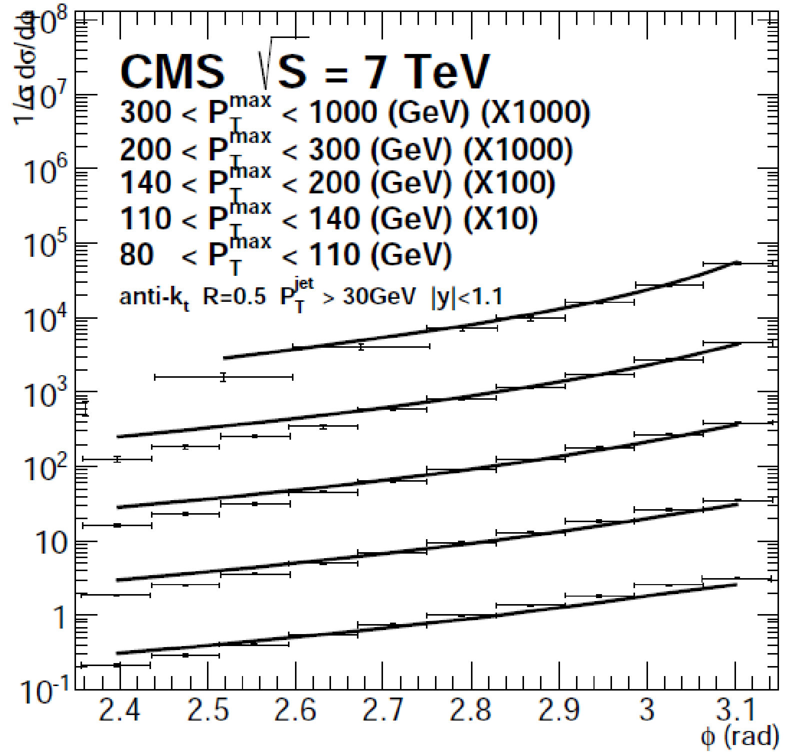
The angular correlations can directly probe the transverse momentum broadening

$$I_{AA}(z_T) = \frac{D_{AA}(z_T)}{D_{pp}(z_T)}, \; z_T = \frac{p_{T,a}}{p_{T,t}}$$

$$D(z_T | p_{T,t}) = p_{T,t} f(p_{T,a} | p_{T,t}) = p_{T,t} \frac{dN_{t,a}(p_{T,t}, p_{T,a})/dp_{T,a}dp_{T,t}}{dN_t(p_{T,t})/dp_{T,t}}$$

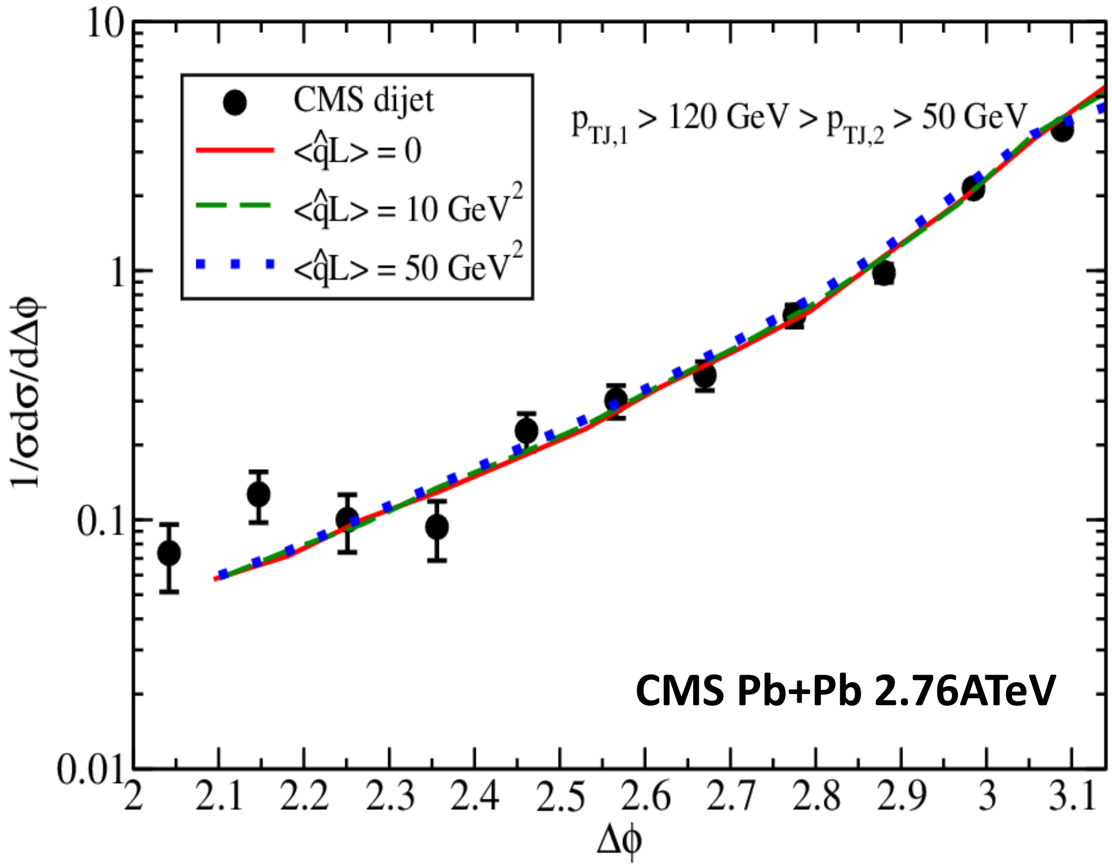
Dijet angular correlations in pp collisions





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

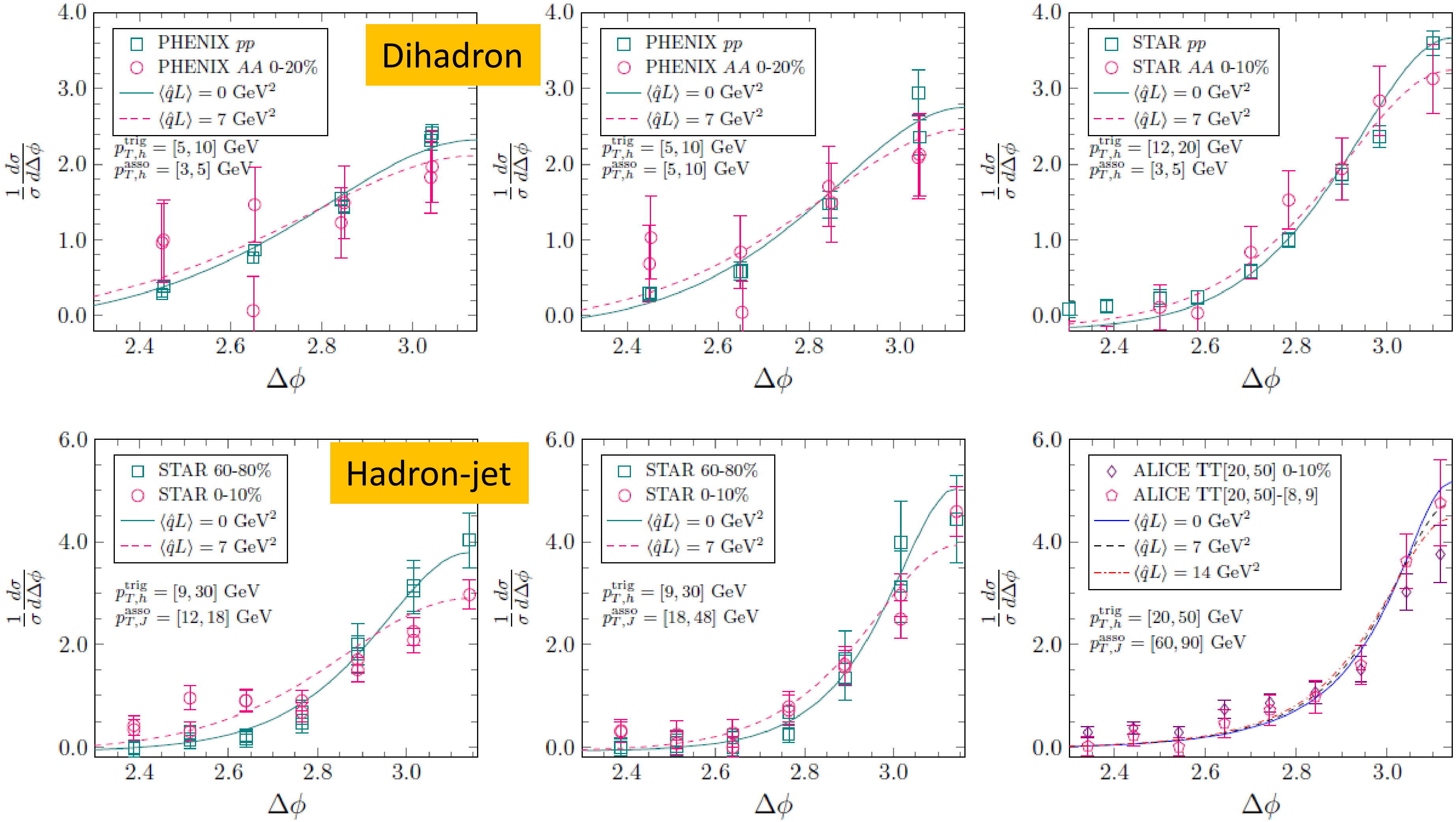
Dijet angular correlations in AA (at the LHC)



The angular de-correlations of dijets at the LHC are dominated by vacuum radiation, and not sensitive to the medium-induced broadening effect

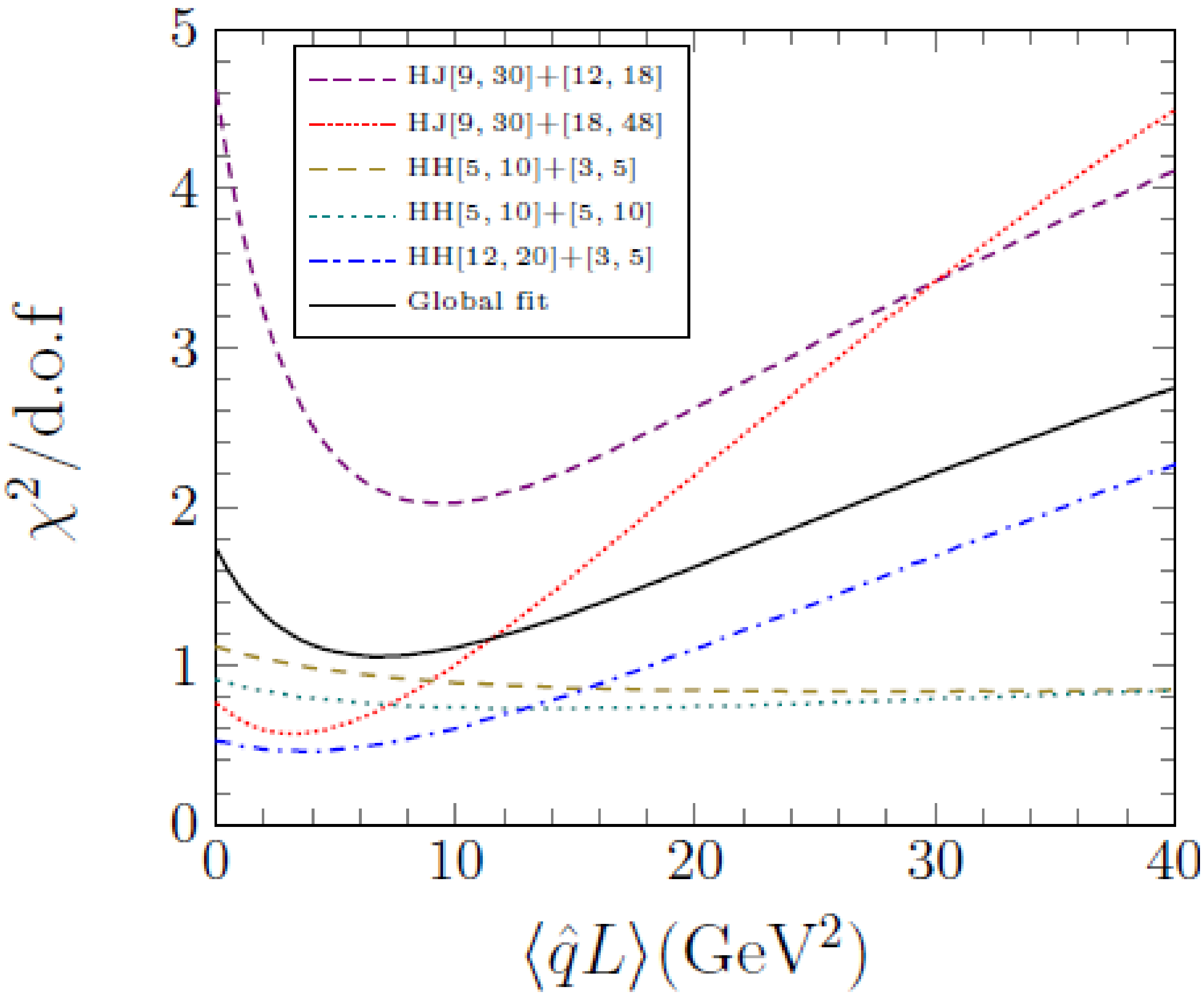
Extend the formalism to include the broadening effect induced by **the QCD medium** for dijet anglar correlation by *Mueller, Wu, Xiao, Yuan, arXiv:1604.04250*

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



Lin Chen, GYQ, Shu-Yi Wei, Bo-Wen Xiao, Han-Zhong Zhang, arXiv:1607.01932

Medium-induced broadening at RHIC



$$\langle \hat{q} L \rangle_{\mathrm{tot}} = 14^{+42}_{-14}\ \mathrm{GeV}^2$$

Compare to JET result:

$$\hat{q} = 1.2 \pm 0.3\ \mathrm{GeV}^2/\mathrm{fm}$$

Note:

radiative correction

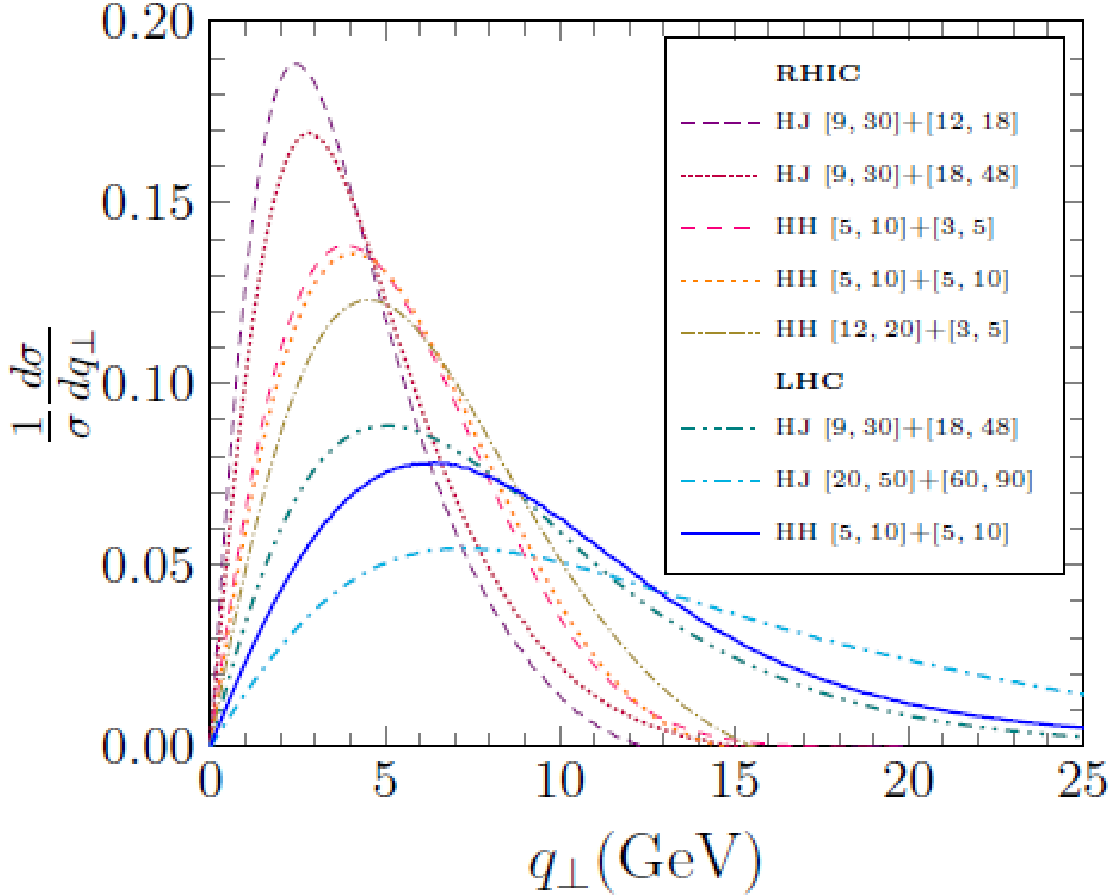
realistic effective path length

cold nuclear matter effect

Intrinsic broadening of FF

Jet energy loss

Momentum imbalance q_T distribution (in pp)



$$\vec{q}_\perp = \vec{p}_{T,c} + \vec{p}_{T,d} \qquad \left\langle q_\perp^2 \right\rangle_{AA} \approx \left\langle q_\perp^2 \right\rangle_{pp} + \left\langle \hat{q} L \right\rangle_{AA}$$

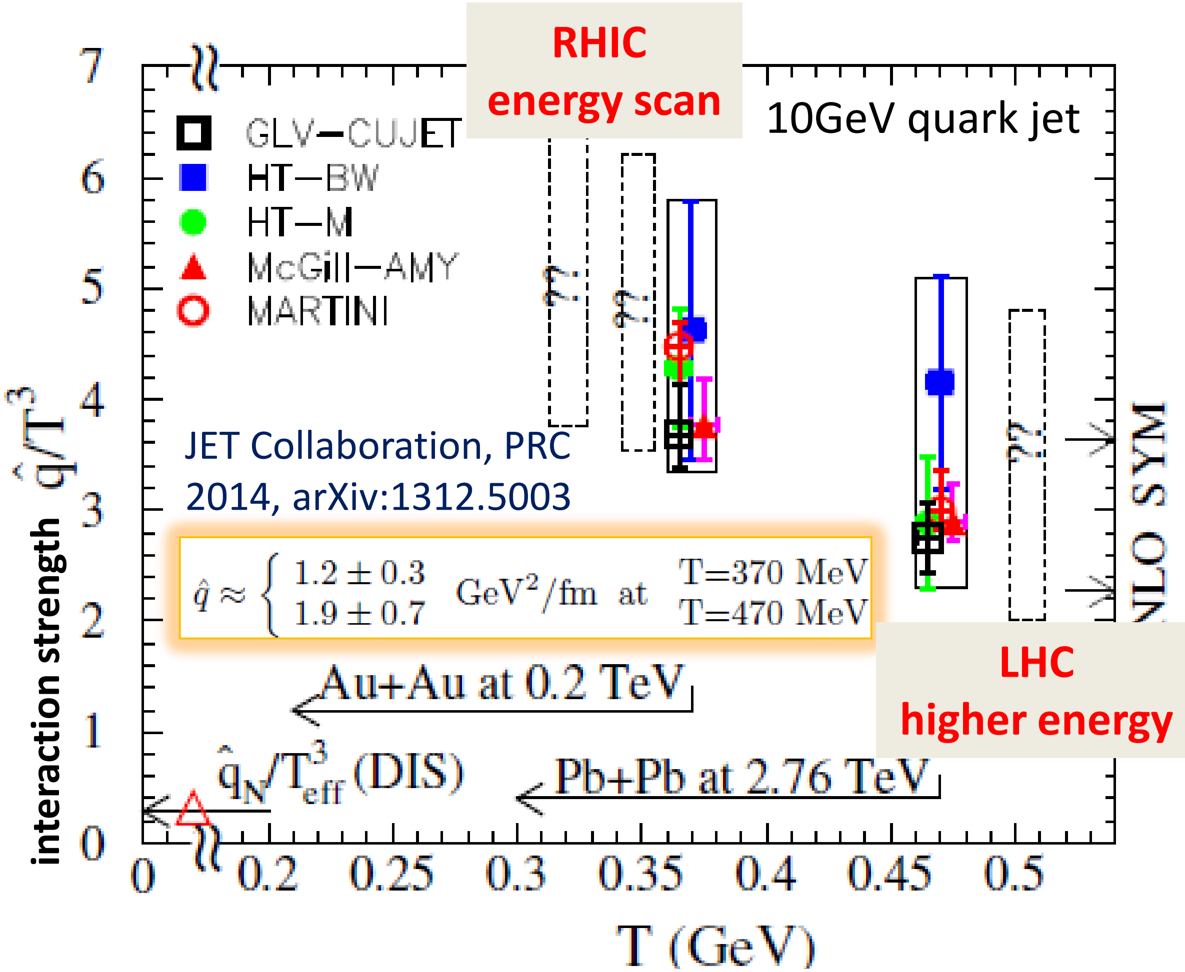
Lin Chen, GYQ, Shu-Yi Wei, Bo-Wen Xiao, Han-Zhong Zhang, arXiv:1607.01932

Summary

- **A Linearized Boltzmann Transport (LBT) approach to *light* & *heavy* flavor jet quenching**
- ***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**

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

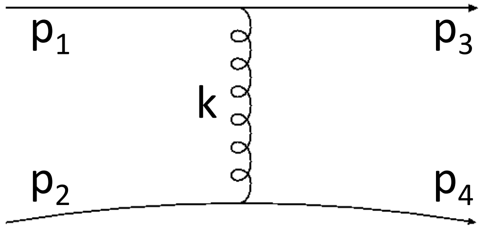
GLV-CUJET:
Xu, Buzzatti, Gyulassy, arXiv: 1402.2956

MARTINI-AMY:
Schenke, Gale, Jeon, PRC 2009

NLO SYM:
Zhang, Hou, Ren, JHEP 2013

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

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



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

- **The collision term is the sum of gain and loss contributions**

$$C[f_1] \equiv \int d^3k \left[w(\vec{p}_1 + \vec{k}, \vec{k}) f_1(\vec{p}_1 + \vec{k}) - w(\vec{p}_1, \vec{k}) f_1(\vec{p}_1) \right]$$

- **For *elastic* (1+2->3+4) process, the transition rate is related to the cross section as:**

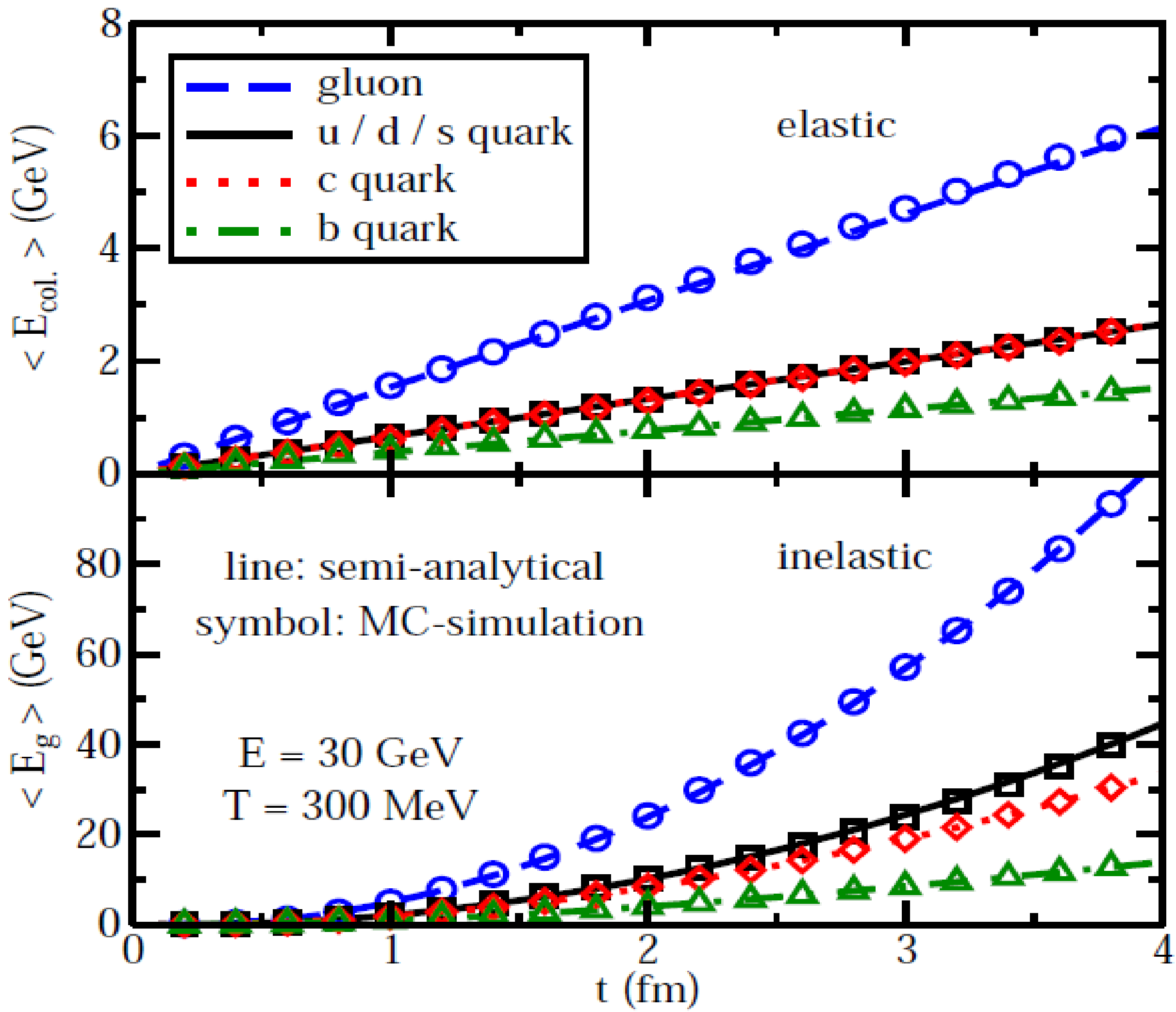
$$w(\vec{p}_1, \vec{k}) = \gamma_2 \int \frac{d^3p_2}{(2\pi)^3} f_2(\vec{p}_2) \left[1 \pm f_3(\vec{p}_1 - \vec{k})\right] \times \left[1 \pm f_4(\vec{p}_2 + \vec{k})\right] v_{\mathrm{rel}} d\sigma(\vec{p}_1, \vec{p}_2 \to \vec{p}_1 - \vec{k}, \vec{p}_2 + \vec{k})$$

- **The *elastic* scattering rate for (1+2->3+4) process:**

$$\Gamma_{12\to 34}(\vec{p}_1) = \int d^3k\, w(\vec{p}_1, \vec{k})$$

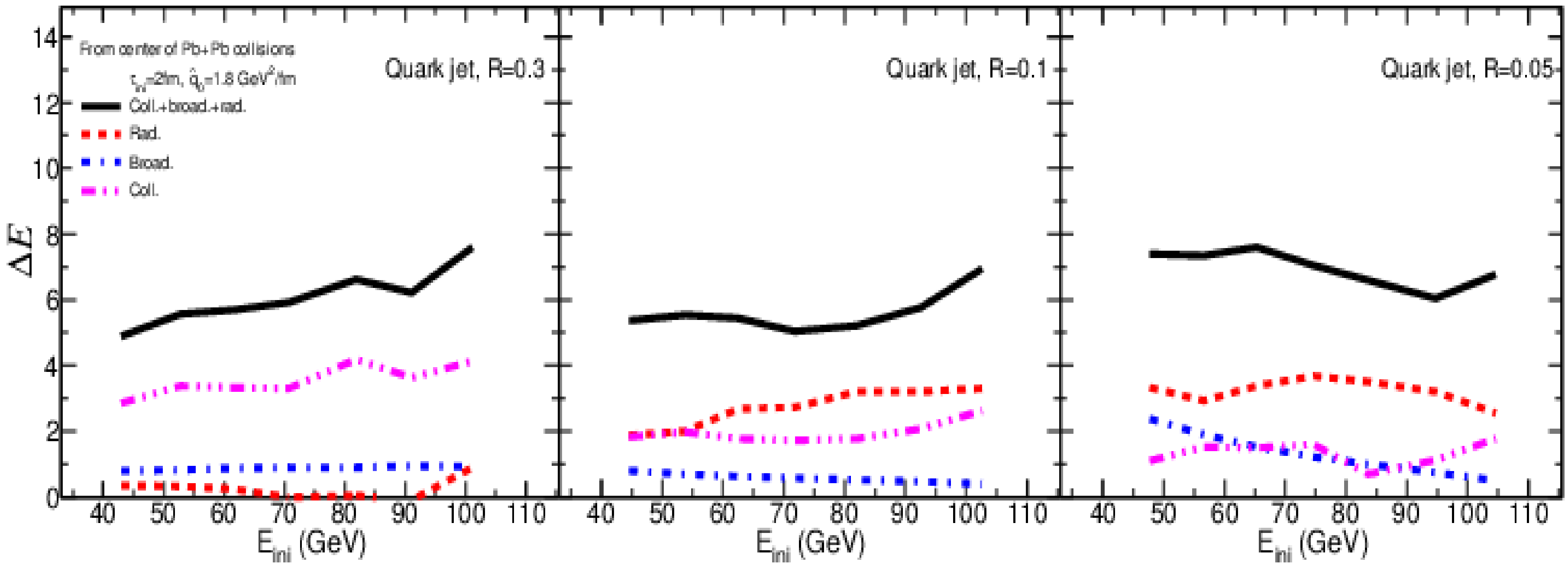
Cao, Luo, GYQ, Wang, arXiv:1605.06447 & in preparation

LBT test

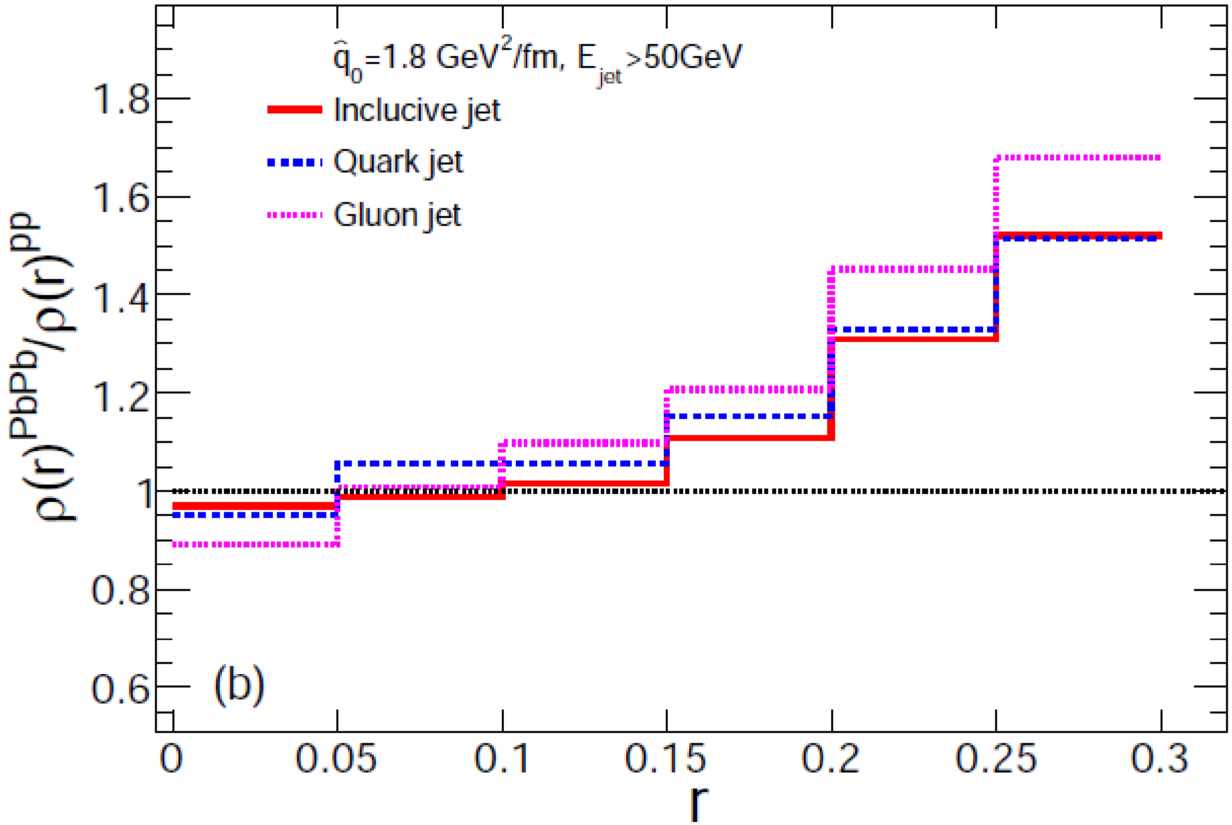


Cao, Luo, GYQ, Wang, PRC 2016 & in preparation

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



Nuclear modification of jet shape function



The final modification of jet shape function does not lie between those for quark & gluon jets, due to the sensitive to the ratios of quark & gluon jet shape functions as well as the fractions of quark and gluon jets (more quark jets in Pb+Pb than p+p collisions due to jet-medium interaction)

A little more modification for gluon than quark jets, but the difference is moderate.

While jet-medium interaction does not affect much the inner core of very high energy jets, it can produce a sizable effect on the inner core of lower energy jets.

Ningbo Chang, GYQ, PRC 2016

Dihadron correlation

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

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

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

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