Jet Physics at RHIC/sPHENIX (and the LHC)

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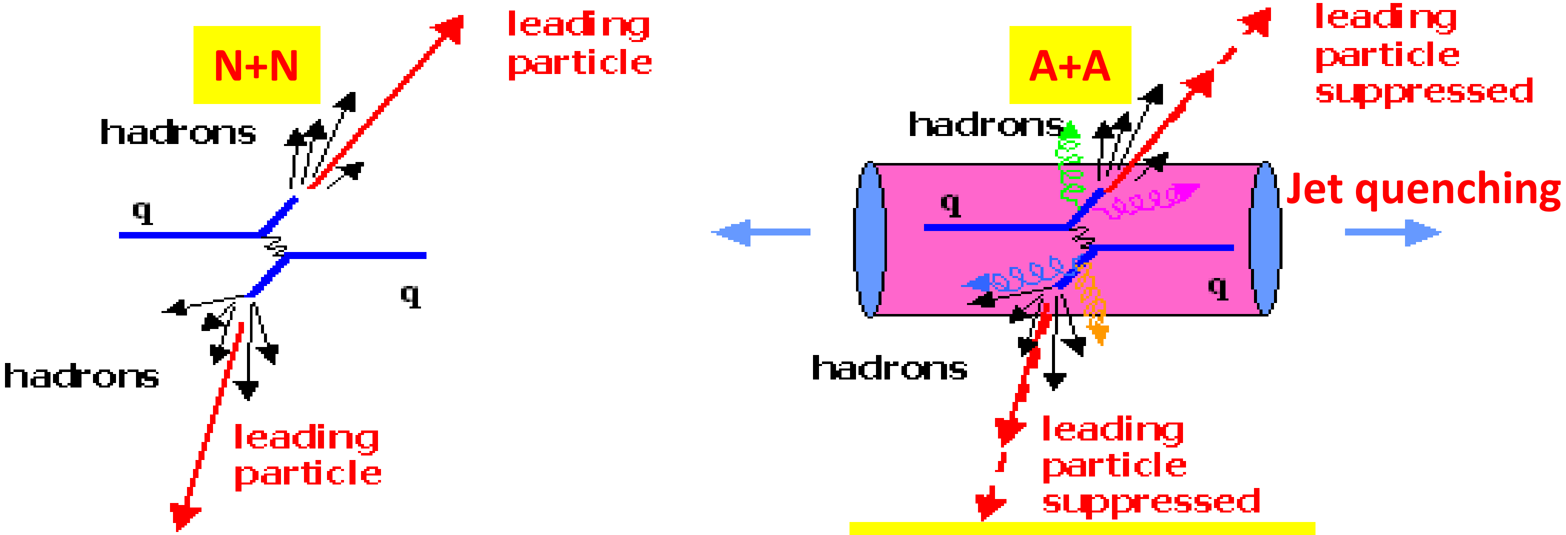
Jet-medium interaction in heavy-ion collisions

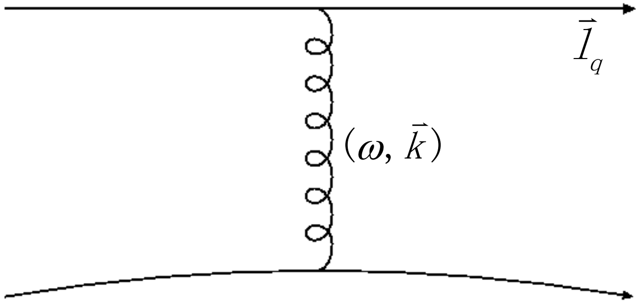


Jet quenching in QGP

Jets and **jet-medium interaction (jet quenching)** can be used to probe hot & dense QGP at *short distance scales*.

Elastic (collisional) processes

- For elastic scattering, the key quantity is the scattering rate $\frac{d\Gamma}{d\omega d^2k_\perp dt}$
- Jet transverse momentum broadening rate:



$$\hat{q} = \frac{\left\langle k_\perp^2 \right\rangle_L}{L} = \frac{1}{L}\int dt \int d\omega d^2k_\perp \frac{d\Gamma}{d\omega d^2k_\perp dt} k_\perp^2$$

$$= \frac{1}{\lambda}\int d^2k_\perp \frac{1}{\sigma}\frac{d\sigma}{d^2k_\perp} k_\perp^2 = \rho\int d^2k_\perp \frac{d\sigma}{d^2k_\perp} k_\perp^2$$

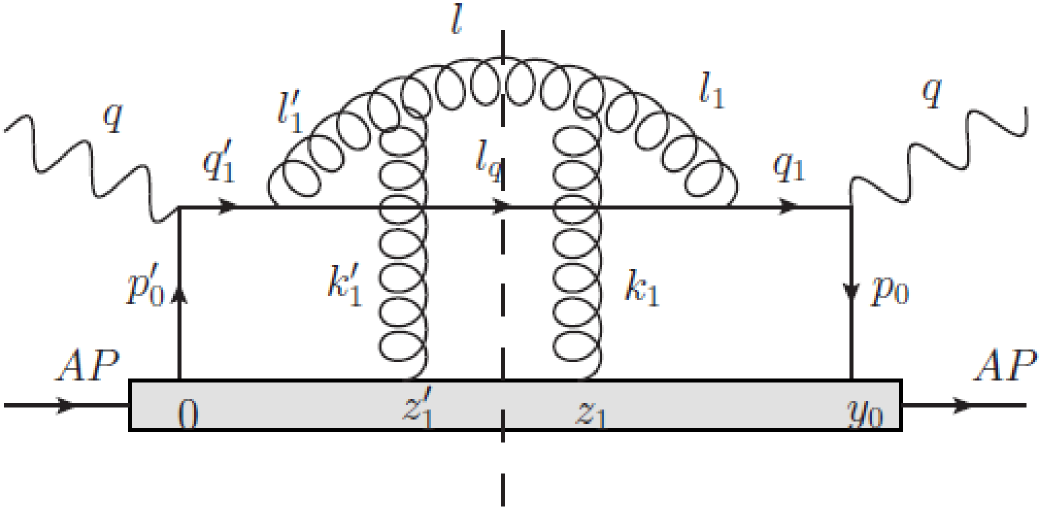
- Resum multiple scatterings & keep terms up to 2nd order in expansion,

$$\frac{\partial f(\vec{l}_{q\perp}, L)}{\partial L} = \frac{\hat{q}}{4}\nabla^2_{l_{q\perp}} f(\vec{l}_{q\perp}, L) + \ldots$$

- Including transverse broadening as well as longitudinal drag and diffusion:

$$\frac{\partial f}{\partial L^-} = \left[\frac{1}{2}D_{T2}\nabla^2_{l_{q\perp}} + D_{L1}\frac{\partial}{\partial l_q^-} + \frac{1}{2}D_{L2}\frac{\partial^2}{\partial^2 l_q^-}\right] f(\vec{l}_{q\perp}, l_q^-, L^-)$$ **GYQ, Majumder, PRC 2013**

Medium-induced inelastic (radiative) process



+ other diagrams

$$\frac{dN_g^{\rm med}}{dy\,d^2\mathbf{l}_\perp} = \frac{\alpha_s}{2\pi}\frac{P(y)}{\pi l_\perp^2}\int \frac{dZ_1^-}{\lambda_{\rm mfp}^-}\int d^2\mathbf{k}_{1\perp}\frac{1}{\sigma_{\rm el}}\frac{d\sigma_{\rm el}}{d^2\mathbf{k}_{1\perp}}$$

$$\frac{d\Gamma}{d^2k_\perp dt} = \rho\frac{d\sigma}{d^2k_\perp} = \frac{1}{\lambda}\frac{1}{\sigma}\frac{d\sigma}{d^2k_\perp}$$

$$\times\left\{C_A\left[2-2\cos\left(\frac{(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2}{l_\perp^2}\frac{Z_1^-}{\tau_{\rm form}^-}\right)\right]\left[\frac{l_\perp^2}{(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2}-\frac{1}{2}\frac{\mathbf{l}_\perp\cdot(\mathbf{l}_\perp-\mathbf{k}_{1\perp})}{(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2}-\frac{1}{2}\frac{l_\perp^2\,(\mathbf{l}_\perp-\mathbf{k}_{1\perp})\cdot(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})}{(\mathbf{l}_\perp-\mathbf{k}_{1\perp})^2\,(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})^2}\right]\right.$$

$$\left.+\left(\frac{C_A}{2}-C_F\right)\left[2-2\cos\left(\frac{Z_1^-}{\tau_{\rm form}^-}\right)\right]\left[\frac{\mathbf{l}_\perp\cdot(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})}{(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})^2}-1\right]+C_F\left[\frac{l_\perp^2}{(\mathbf{l}_\perp-y\mathbf{k}_{1\perp})^2}-1\right]\right\}$$

Not only the 2nd moment ($q^{\rm hat}$), the full distribution of the differential scattering rate (cross section) contribute to the medium-induced radiation.

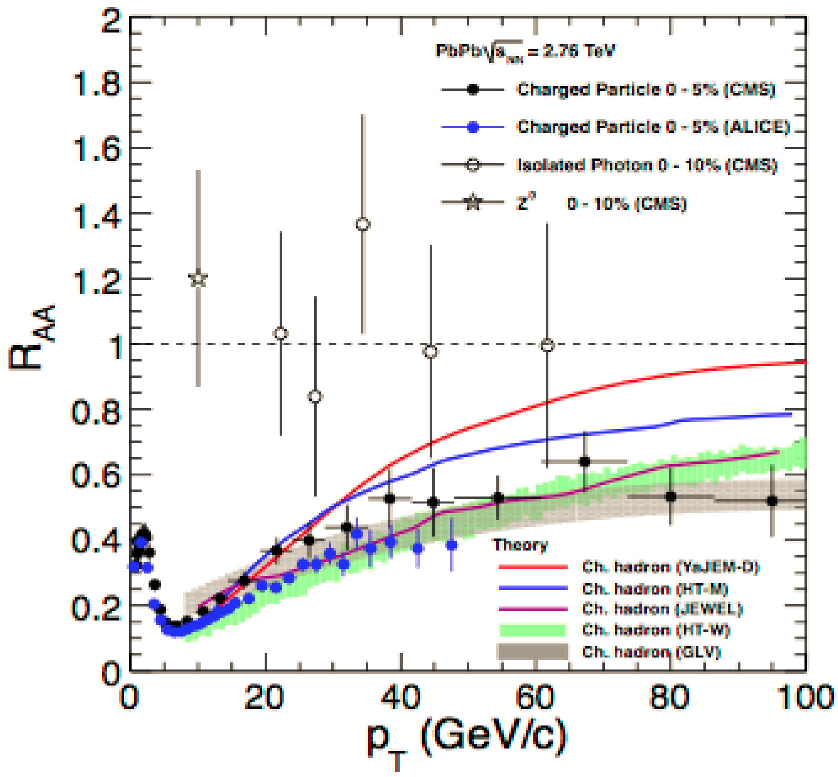
Zhang, Hou, GYQ, arXiv:1804.00470

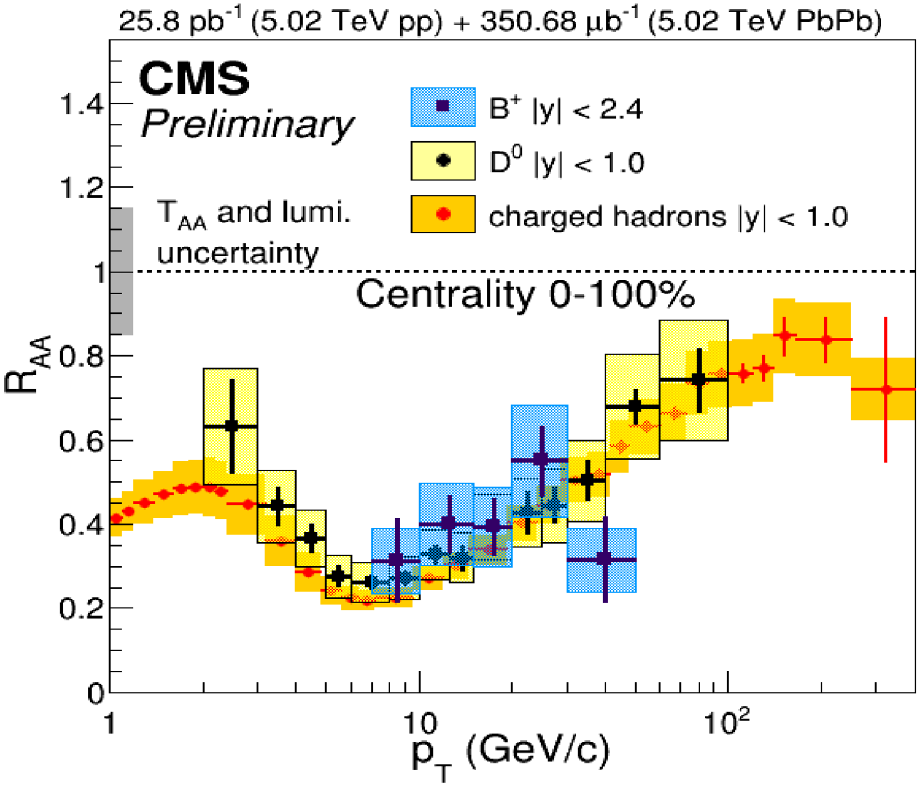
Outline

- **Leading hadrons**
- **Full jets**
- **Jet-related correlations**
- **Summary**

Leading hadrons

Large transverse momentum hadrons





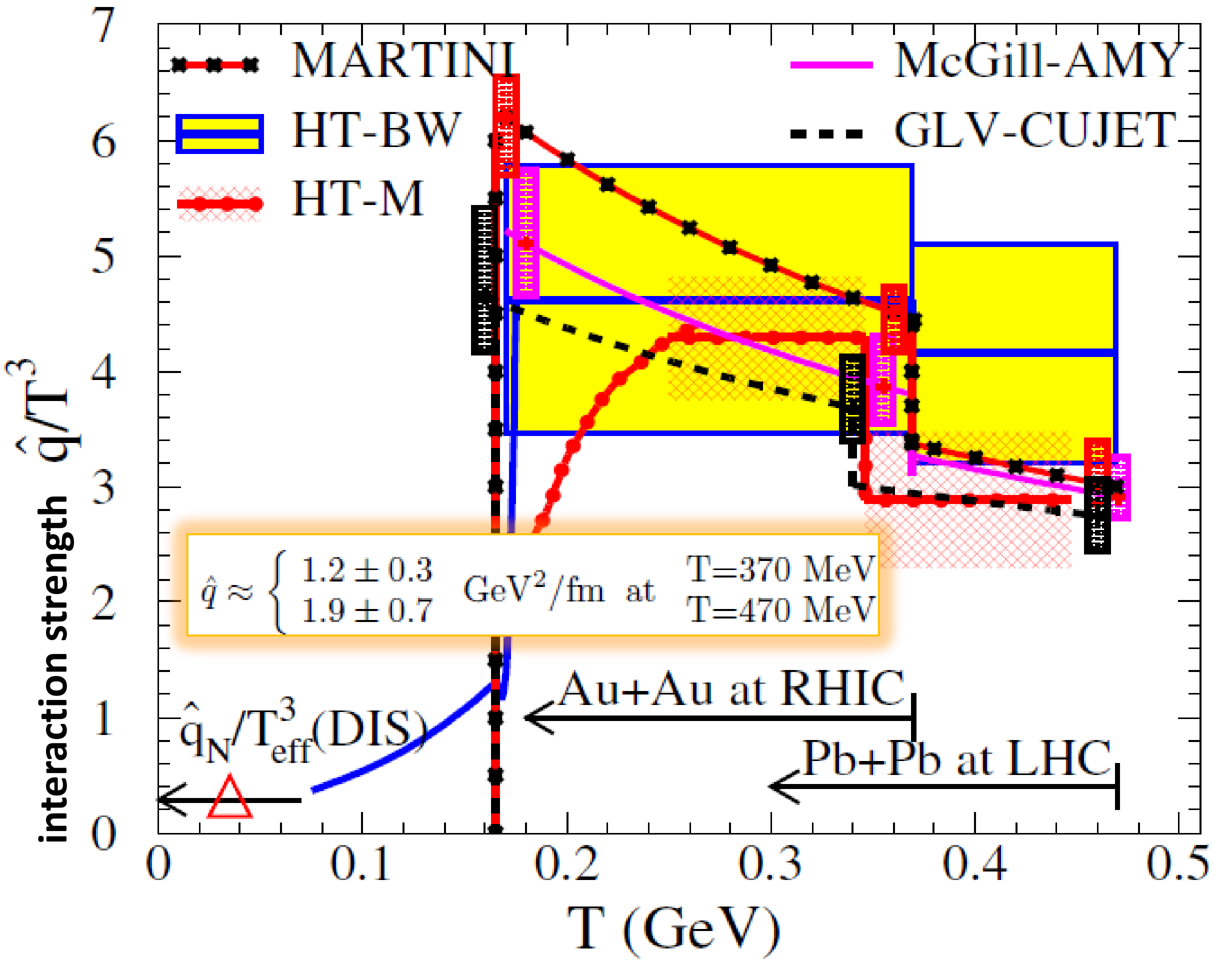
$$R_{AA} = \frac{dN^{AA} / d^2 p_T dy}{N_{\mathrm{coll}} dN^{pp} / d^2 p_T dy}$$

1) Energy loss mechanisms

2) Color and flavor dependences of E loss

$\boldsymbol{\Delta E_g > \Delta E_{uds} > \Delta E_c > \Delta E_b}$**?**

Jet transport parameter

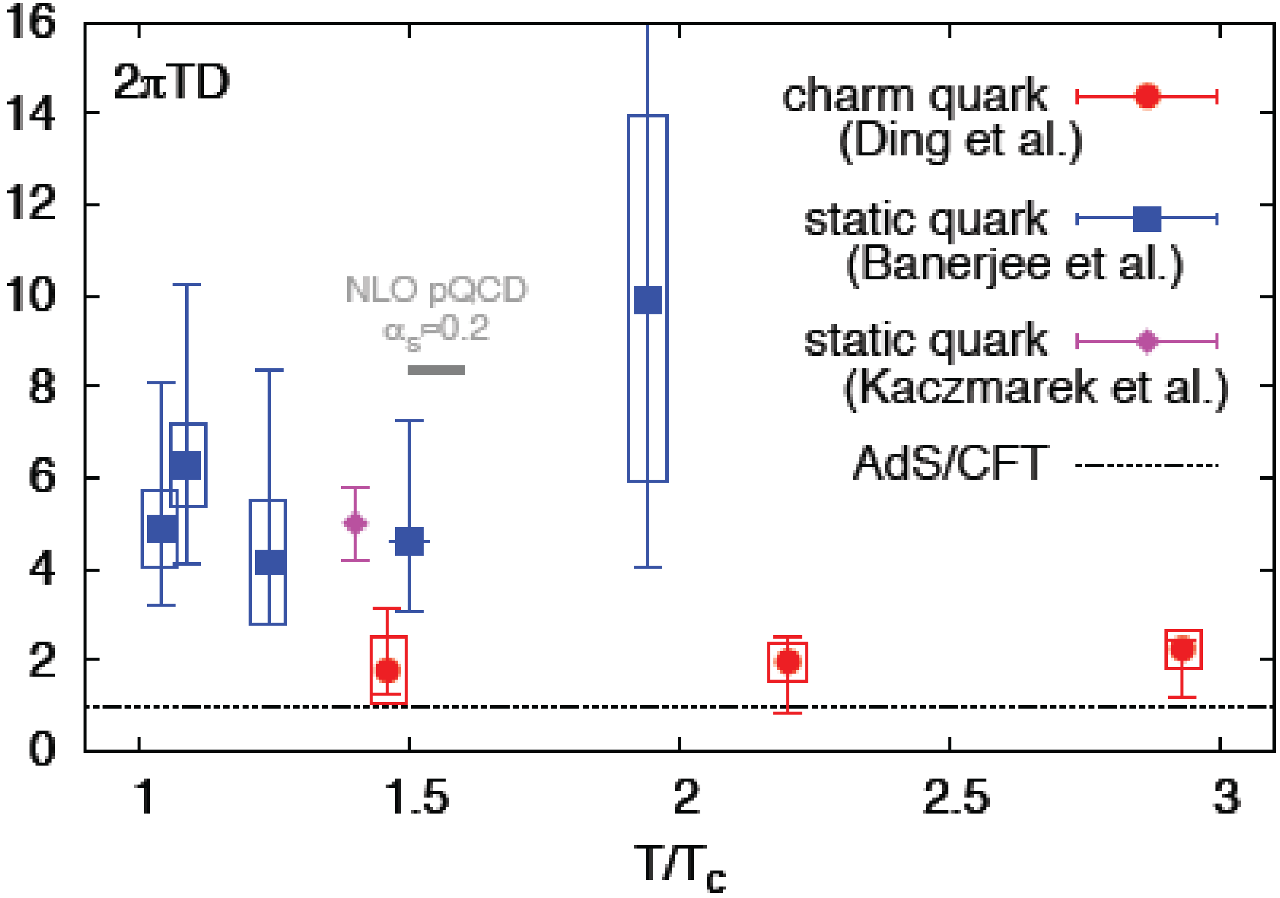


McGill-AMY:
GYQ, Ruppert, Gale, Jeon, Moore, Mustafa, PRL 2008
HT-BW:
Chen, Hirano, Wang, Wang, Zhang, PRC 2011
HT-M:
Majumder, Chun, PRL 2012
GLV-CUJET:
Xu, Buzzatti, Gyulassy, arXiv: 1402.2956
MARTINI-AMY:
Schenke, Gale, Jeon, PRC 2009

JET Collaboration, PRC 2014, arXiv:1312.5003

Future: precise determination of T (& E) dependence of jet transport parameters

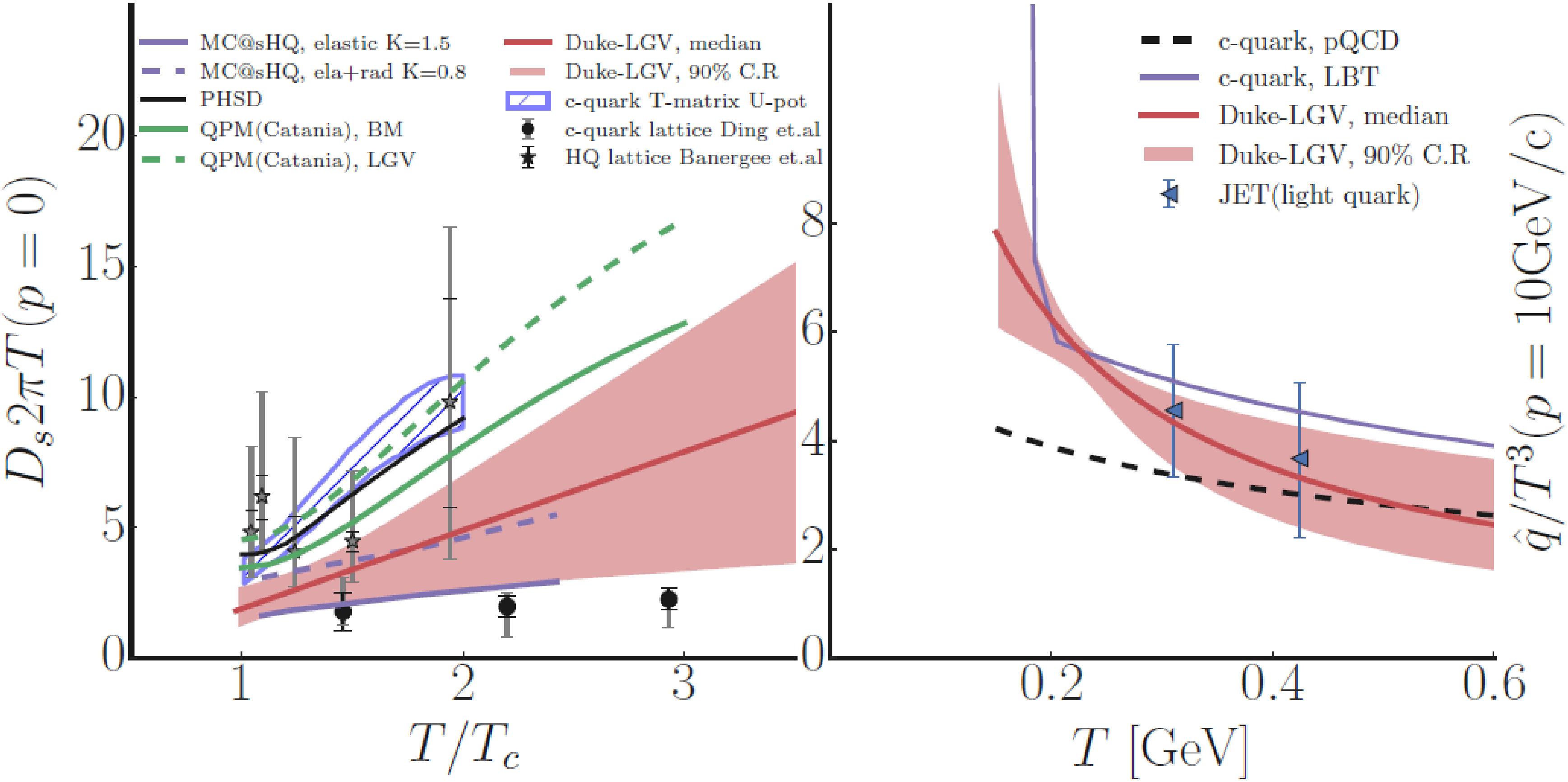
Heavy quark diffusion coefficients



Still large uncertainties from Lattice QCD calculation.

Ding, Karsch, Mukherjee, arXiv:1504.05274

Heavy quark diffusion coefficients



Data-driven analysis: **Xu, Bernhard, Bass, Nahrgang, Cao, arXiv: 1710.00807**

Heavy & light flavor jet quenching in LBT

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

$$\Gamma_{12\to34} = \frac{\gamma_2}{2E_1}\int\frac{d^3p_2}{(2\pi)^3 2E_2}\int\frac{d^3p_3}{(2\pi)^3 2E_3}\int\frac{d^3p_4}{(2\pi)^3 2E_4} \times f_2(\vec{p}_2)\left[1 \pm f_3(\vec{p}_1 - \vec{k})\right]\left[1 \pm f_4(\vec{p}_2 + \vec{k})\right] S_2(s,t,u) \times (2\pi)^4\delta^{(4)}(p_1 + p_2 - p_3 - p_4)|\mathcal{M}_{12\to34}|^2$$

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

Matrix elements taken from LO pQCD

- **Inelastic collisions:**

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

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

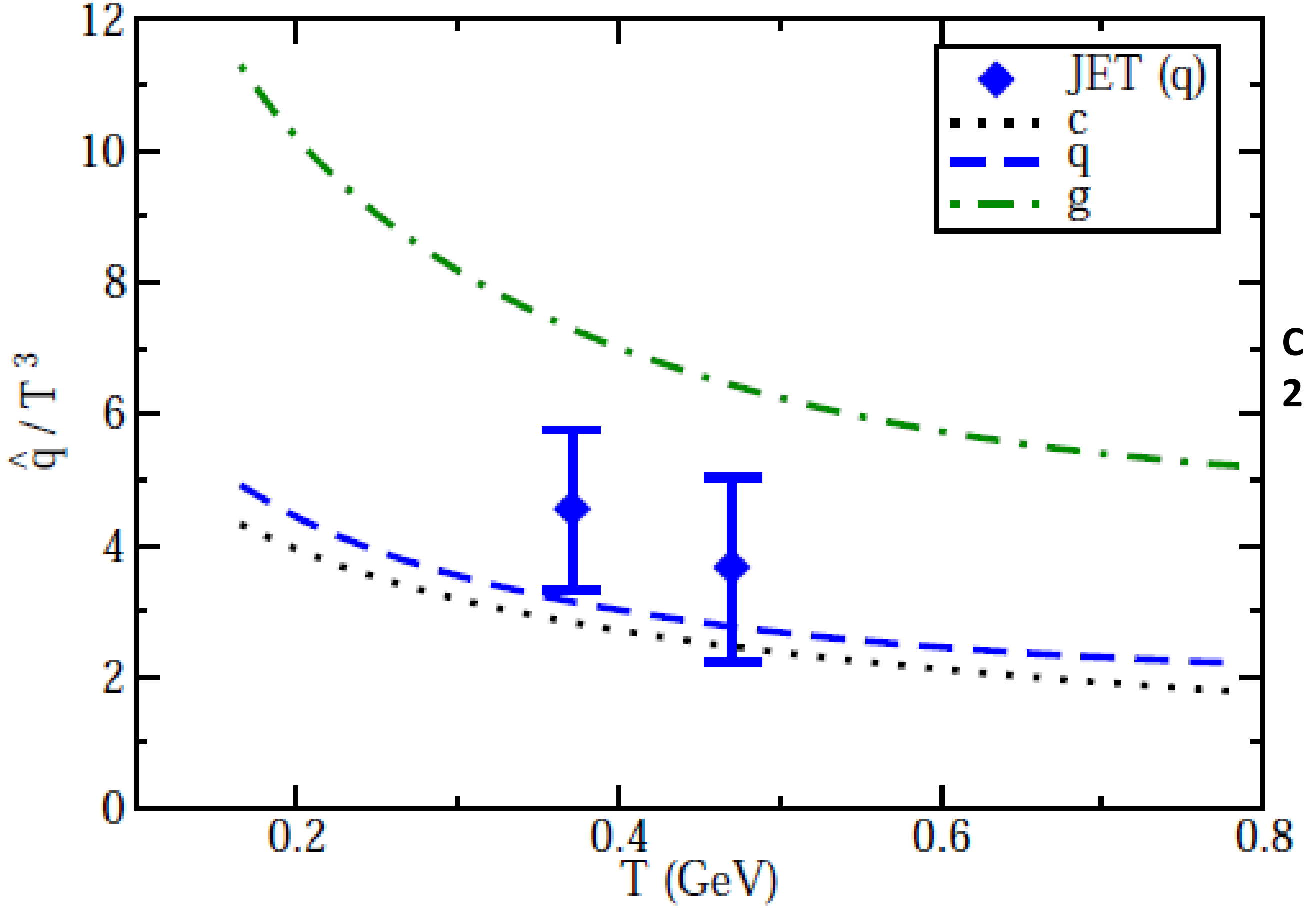
Radiation spectra taken from Guo, Wang PRL 2000; Zhang, Wang, Wang 2004

- **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.

Heavy and light flavor jet transport coefficients in LBT



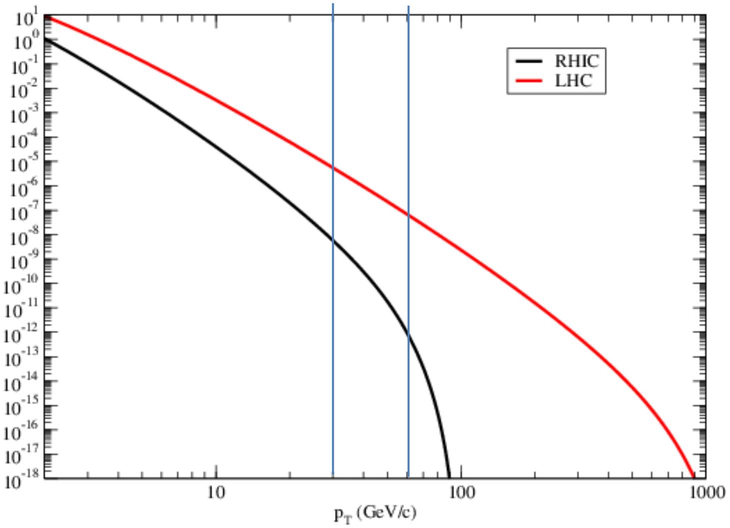
Cao, Luo, GYQ, Wang, PLB 2018, arXiv:1703.00822

1) Extraction of jet transport parameter needs a wide range of jet E and medium T.
2) RHIC (and BES) is better for studying near T_c behavior.

Initial jet parton spectra

- For the same energy loss (fraction), R_{AA} is different at RHIC and the LHC
- For a power law distribution, $\frac{dN}{dp_{T,i}} = \frac{A}{p_{T,i}^n}$

  where n is larger at RHIC than LHC



The same energy loss fraction (for the same jet) leads to larger suppression at RHIC

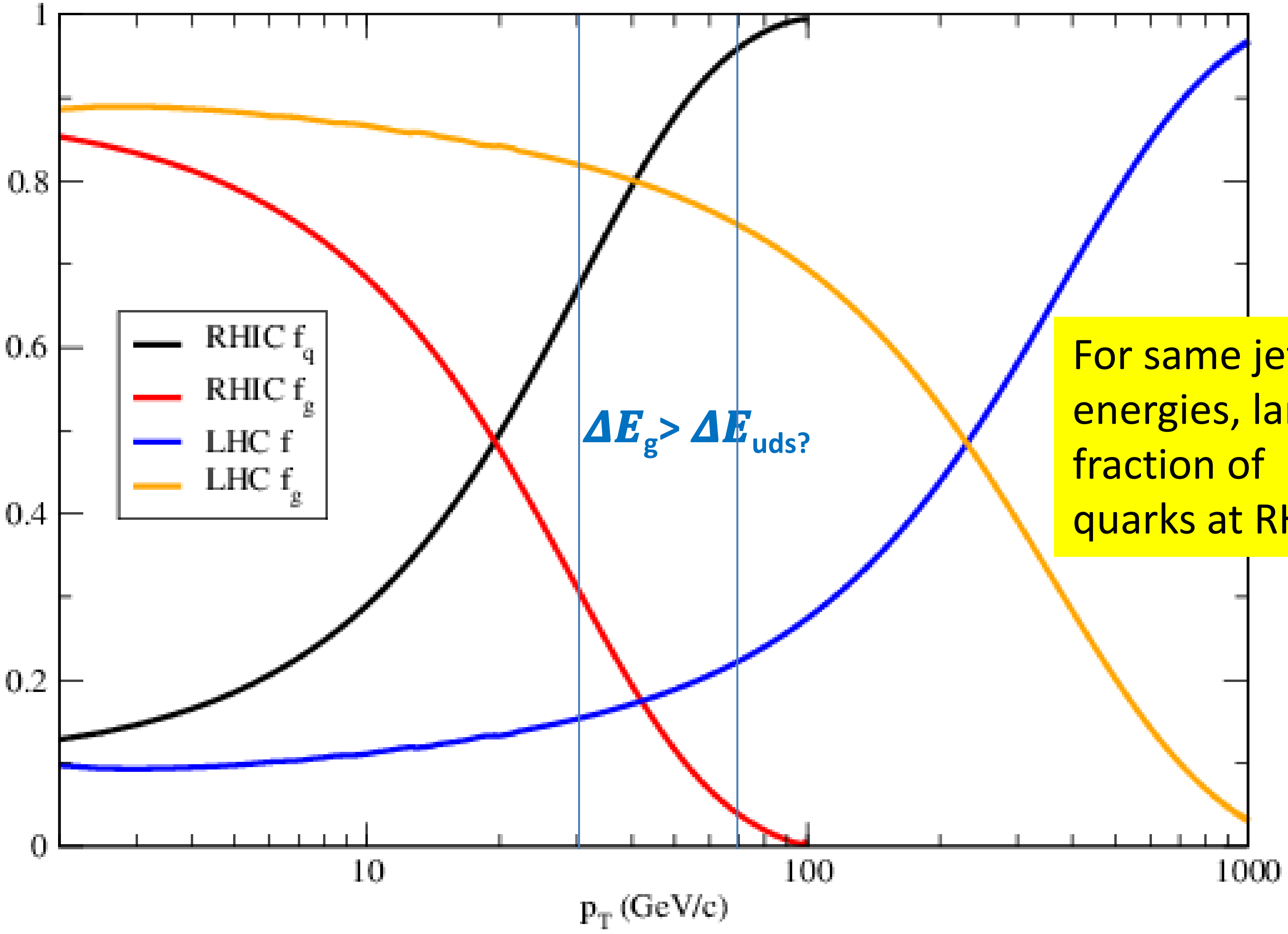
- After constant energy loss fraction ϵ,

$$\frac{dN}{dp_{T,f}} = \frac{\partial p_{T,i}}{\partial p_{T,f}} \left. \frac{dN}{dp_{T,i}} \right|_{p_{T,i}=\frac{p_{T,f}}{1-\varepsilon}} = \frac{A(1-\varepsilon)^{n-1}}{p_{T,f}^n}$$

$$R_{AA} = (1-\varepsilon)^{n-1}$$

- The same energy loss fraction with larger n gives larger suppression

Quark and gluon fractions



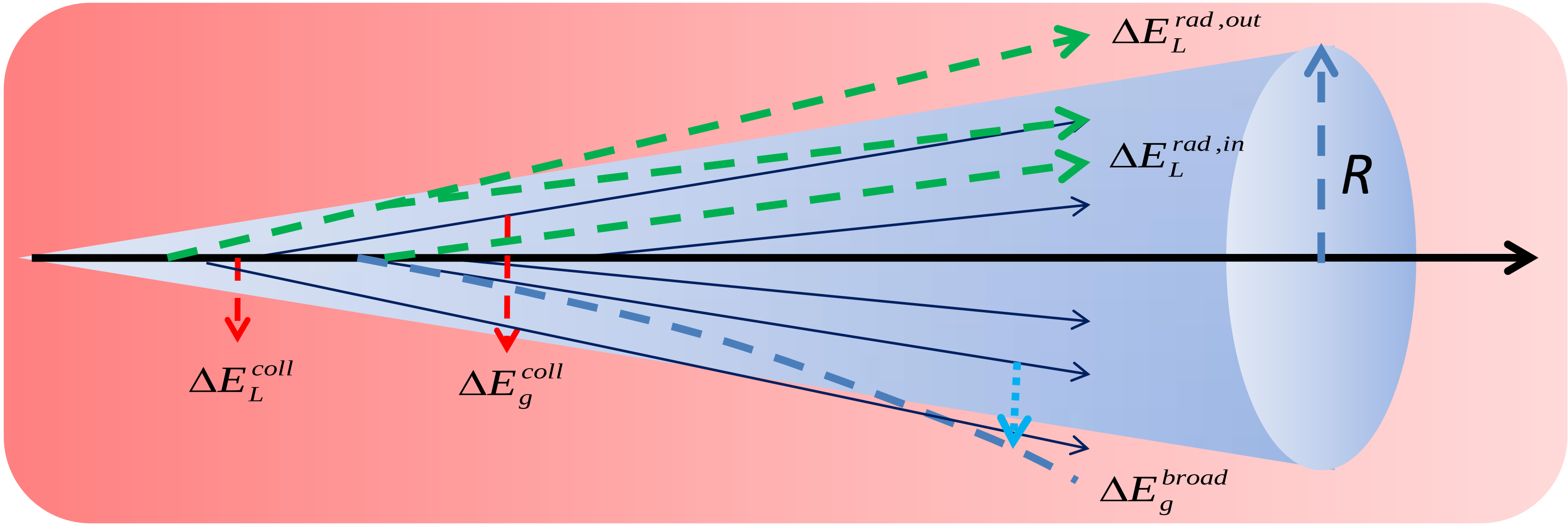
$\Delta E_g > \Delta E_{uds}$?

For same jet energies, larger fraction of quarks at RHIC

A convolution of initial jet spectrum, quark and gluon factions, jet energy loss and jet fragmentation function

Full Jets

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; etc.

A model for 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

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

Gain terms

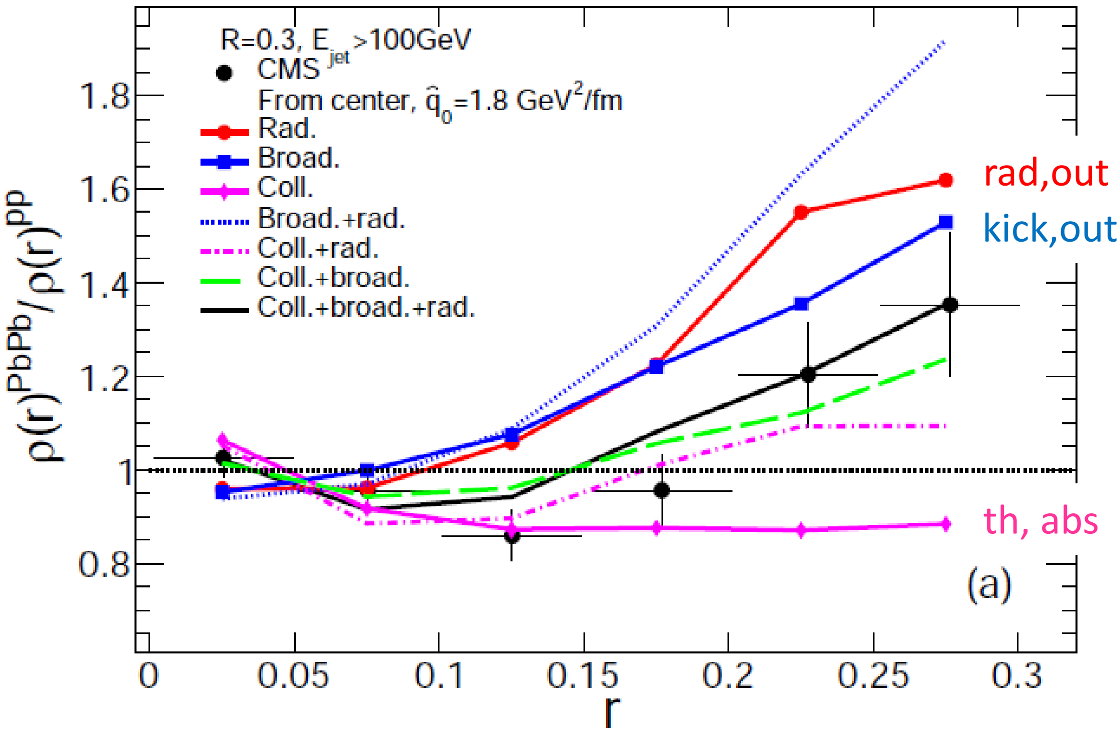
$$-\sum_i\int d\omega_i dk_{i\perp}^2\frac{d\tilde{\Gamma}_{j\to i}(\omega_i,k_{i\perp}^2|\omega_j,k_{j\perp}^2)}{d\omega_i d^2k_{i\perp}dt}f_j(\omega_j,k_{j\perp}^2,t)$$

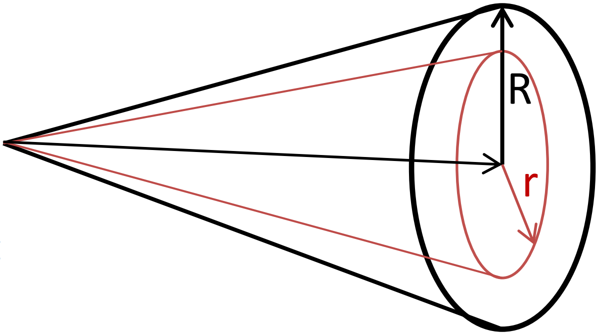
Loss terms

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

Ningbo Chang, GYQ, PRC 2016

Nuclear modification of jet shape function





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

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

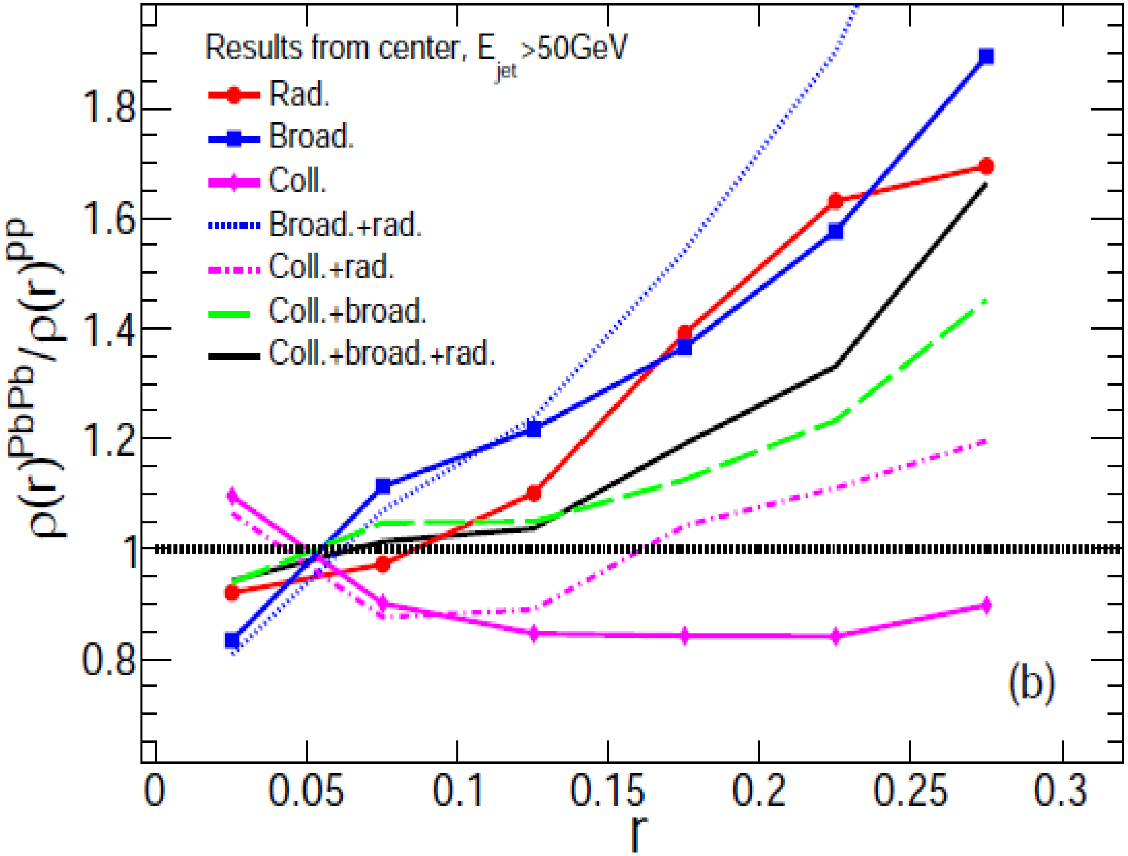
The enhancement at large r is consistent with jet broadening (& medium-induced radiation)

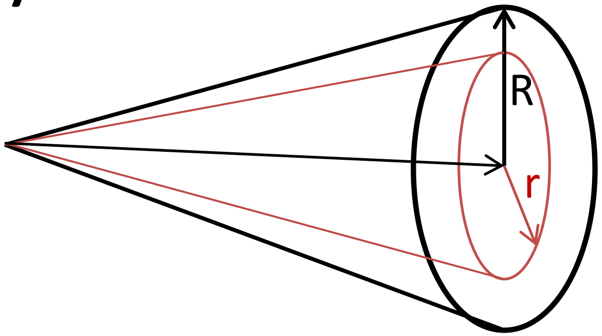
The soft outer part is easier modify, while changing the inner hard cone is more difficult

The final jet shape is the interplay of different jet-medium interaction mechanisms

N. B. 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





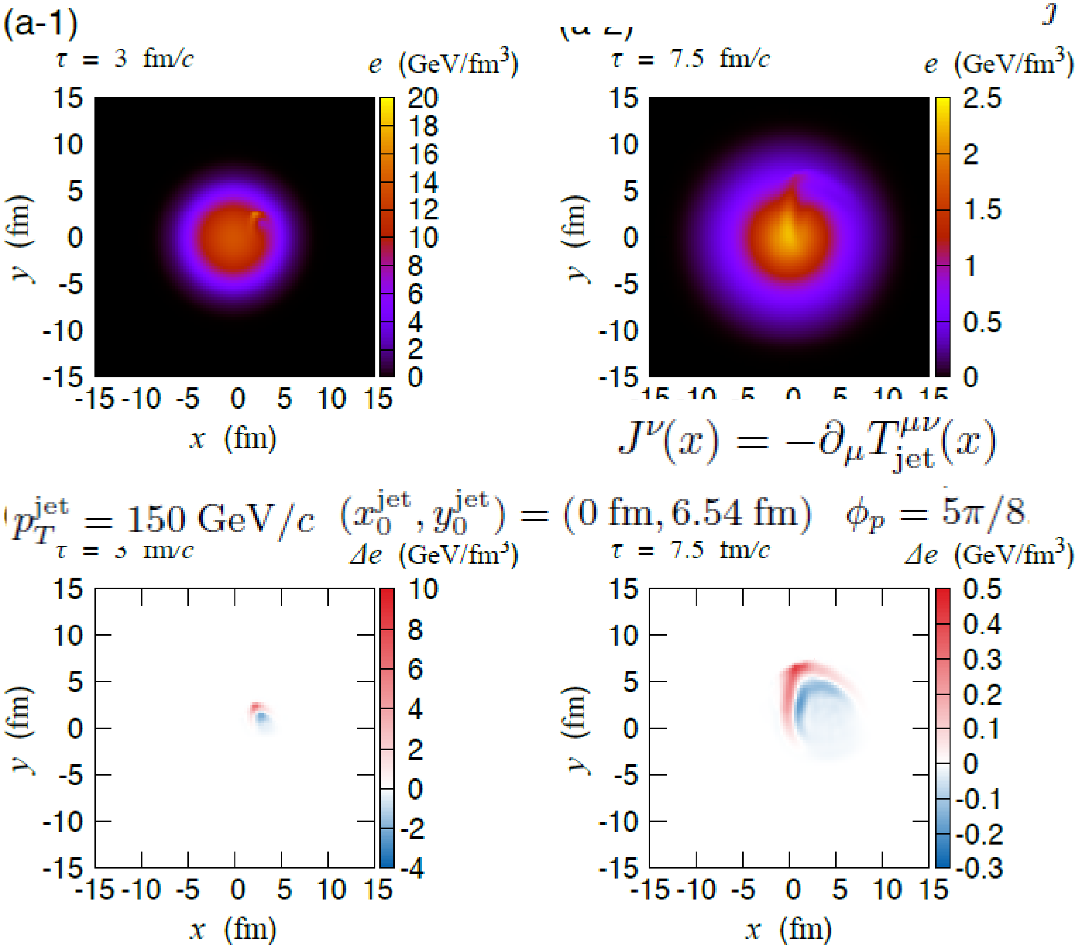
There is a chance to see the modification of jet core for lower energy jets (at RHIC) since the jet core is not too hard to be modified

Ningbo Chang, GYQ, PRC 2016

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

A combined jet-fluid model: medium response to jet-deposited energy/momentum

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



$$J^\nu(x) = -\partial_\mu T^{\mu\nu}_{\mathrm{jet}}(x)$$

$$p_T^{\mathrm{jet}} = 150\ \mathrm{GeV}/c \quad (x_0^{\mathrm{jet}}, y_0^{\mathrm{jet}}) = (0\ \mathrm{fm}, 6.54\ \mathrm{fm}) \quad \phi_p = 5\pi/8$$

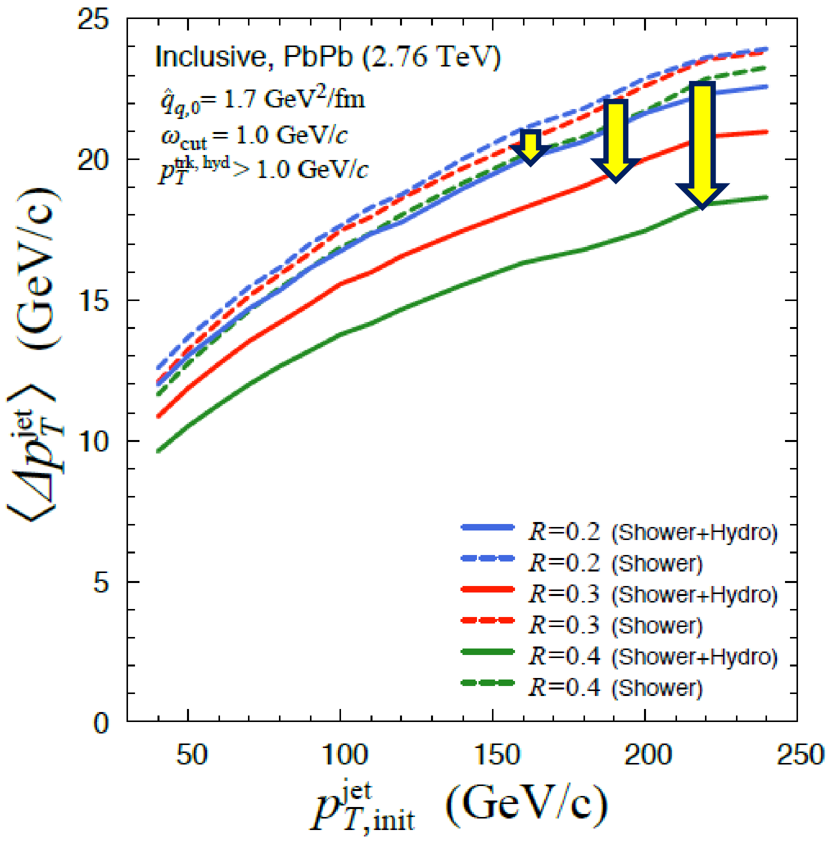
Tachibana, Chang, GYQ, PRC 2017

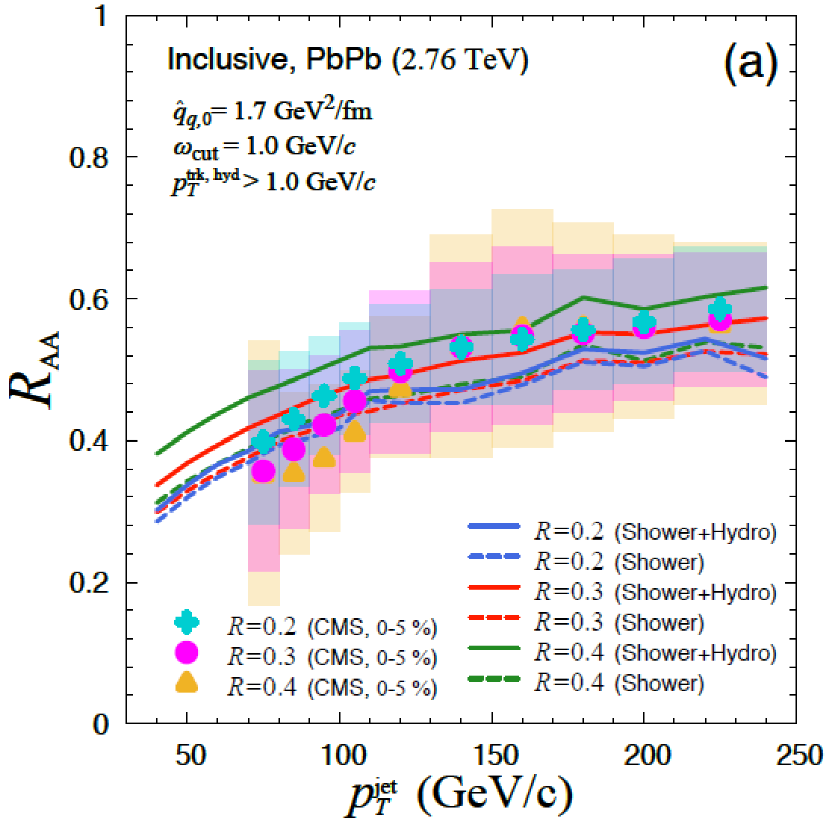
V-shaped wave fronts are induced by the propagating jet, and develop with time

The wave fronts carry energy and momentum, propagates outward, which lowers energy density behind the propagating jet

Jet-induced flow and the radial flow of the medium are pushed and distorted by each other

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

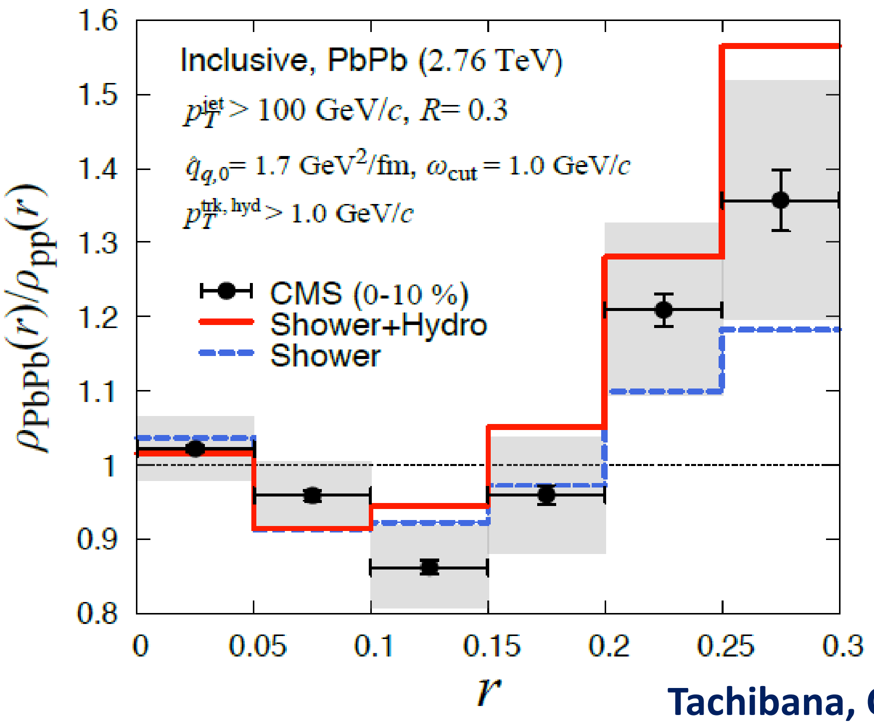


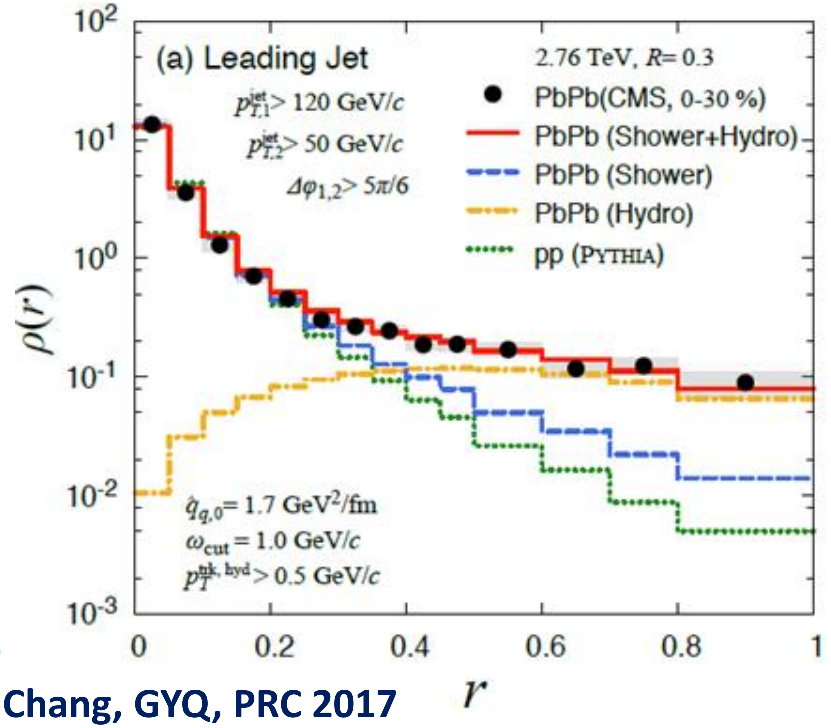


Hydro part (the lost energy from the shower part still inside the jet cone) partially compensates the energy loss experienced by jet shower part.

Jet-induced flow evolves with medium, diffuses, and spreads widely around jet axis, leading to stronger jet cone size dependence.

Effect of jet-induced flow on jet shape





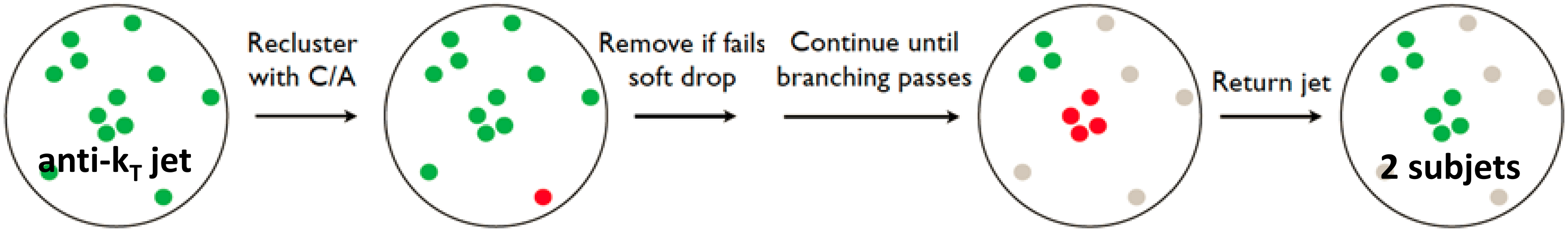
Tachibana, Chang, GYQ, PRC 2017

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 contribution from the hydro part is quite flat and finally dominates over the shower part in the region from r = 0.4-0.5.

The dynamical evolution and the final-state manifestation of jet-induced medium excitations depend on **jet energies, jet energy deposition profiles, and QGP medium**

Jet grooming via soft drop declustering

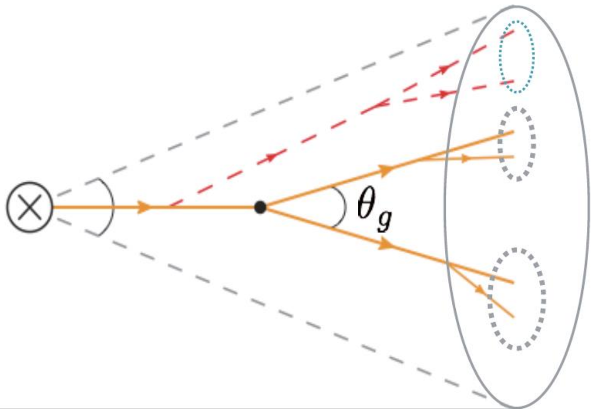


Larkoski, Marzani, Soyez, Thaler, JHEP (2014), arXiv:1402.2657;
Larkoski, Marzani, Thaler, PRD (2015), arXiv:1502.01719

Idea: recursively removes soft wide-angle radiation from a jet

Experimental implementation: re-cluster anti-k_T jet with Cambridge/Aachen (C/A) algorithm, then de-cluster the angular-ordered C/A tree by dropping soft branches

2 parameters (energy threshold z_{cut} & angular exponent β): $z > z_{cut}\theta^{\beta} = z_{cut}\left(\Delta R_{12} / R\right)^{\beta}$



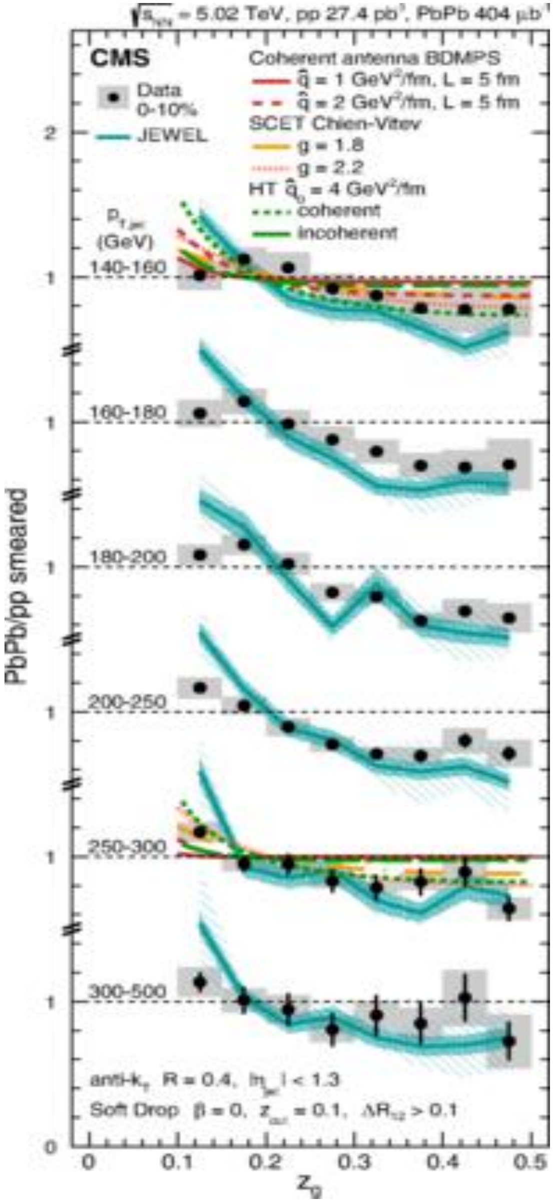
$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

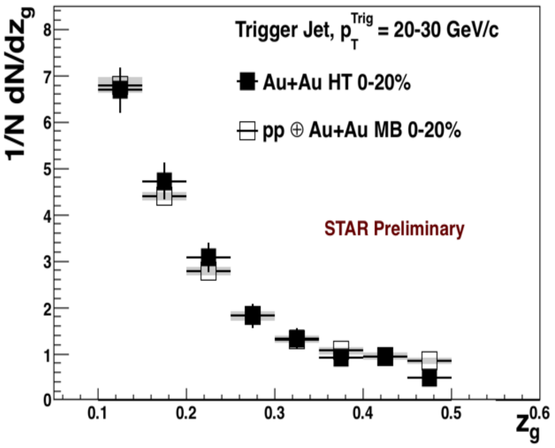
Momentum sharing distribution:

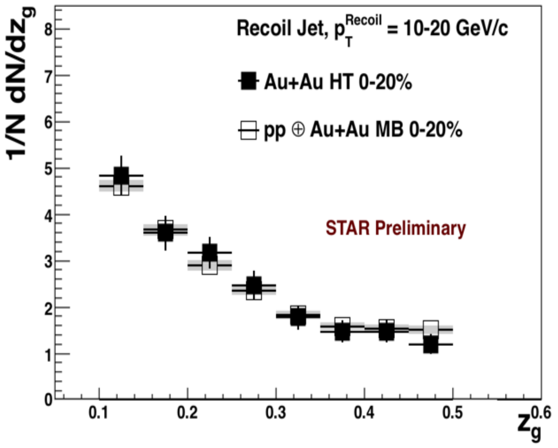
$$p(z_g) = \frac{1}{N_{jet}} \frac{dN}{dz_g}$$

$p(z_g)$ for soft dropped jets encodes the momentum sharing for the hardest splitting/branching

CMS & STAR groomed jets (jet energy dependence)





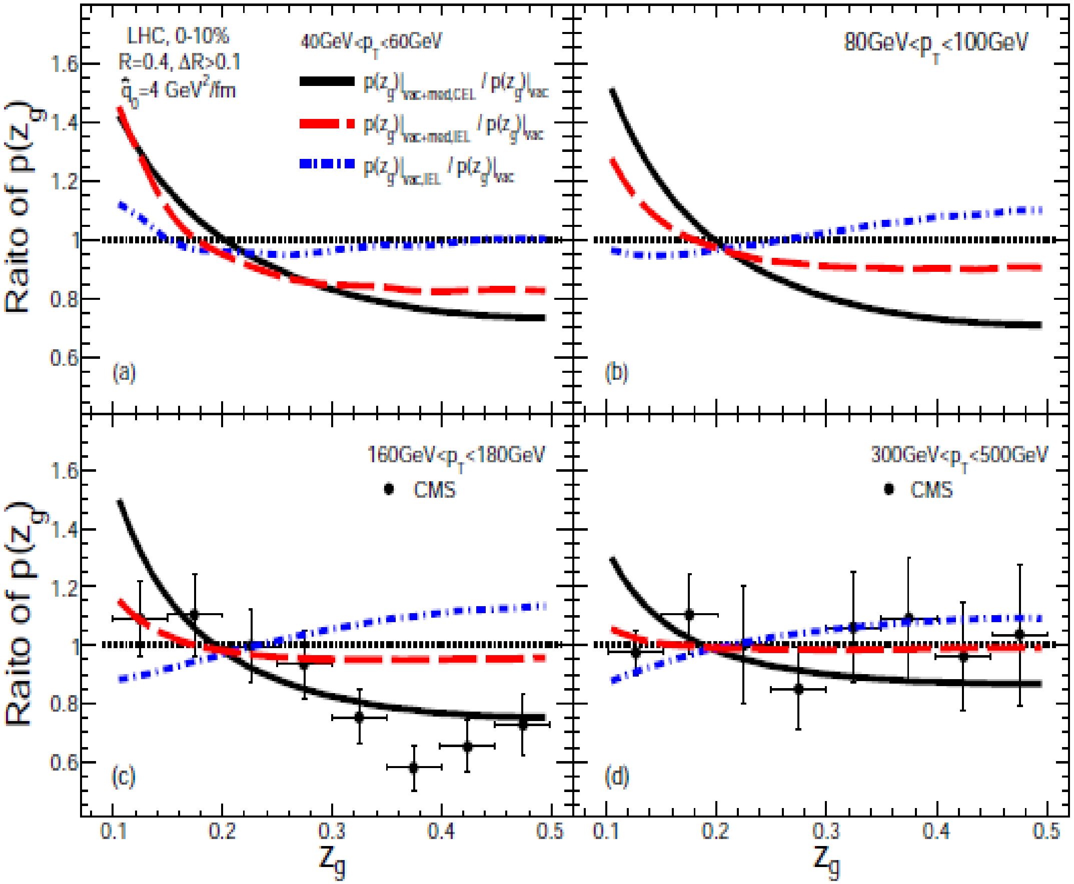


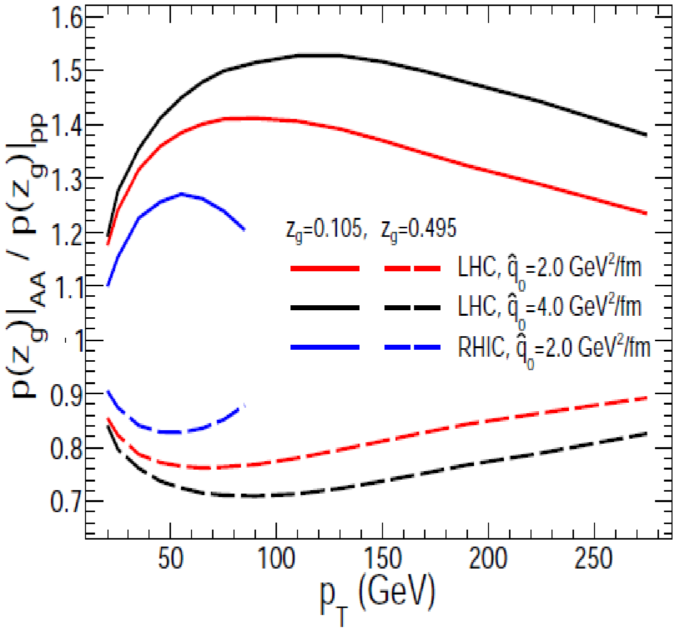
CMS: **strong** nuclear modification groomed jet z_g distribution, **stronger** modification for **lower** jet energy

STAR: **no** significant modification in Au+Au collisions as compared to pp collisions

Chien, Vitev, PRL 2017; Mehtar-Tani, Tywoniuk, JHEP 2017; Chang, Cao, GYQ, PLB 2018; Milhano, Wiedemann, Zapp, PLB 2017

Non-monotonic jet energy dependence





Nuclear modification for jet substructure is different for different jet energies

Solid black for medium-modified splitting with coherent energy loss (CEL) of subjets

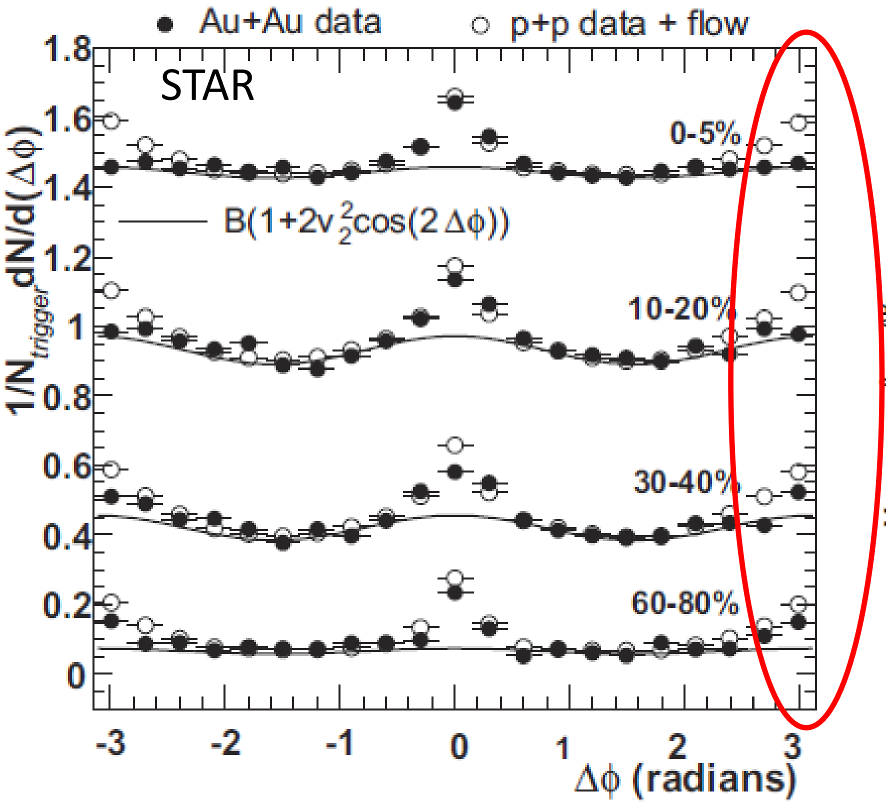
Dashed red for medium-modified splitting with independent energy loss (IEL) of subjets

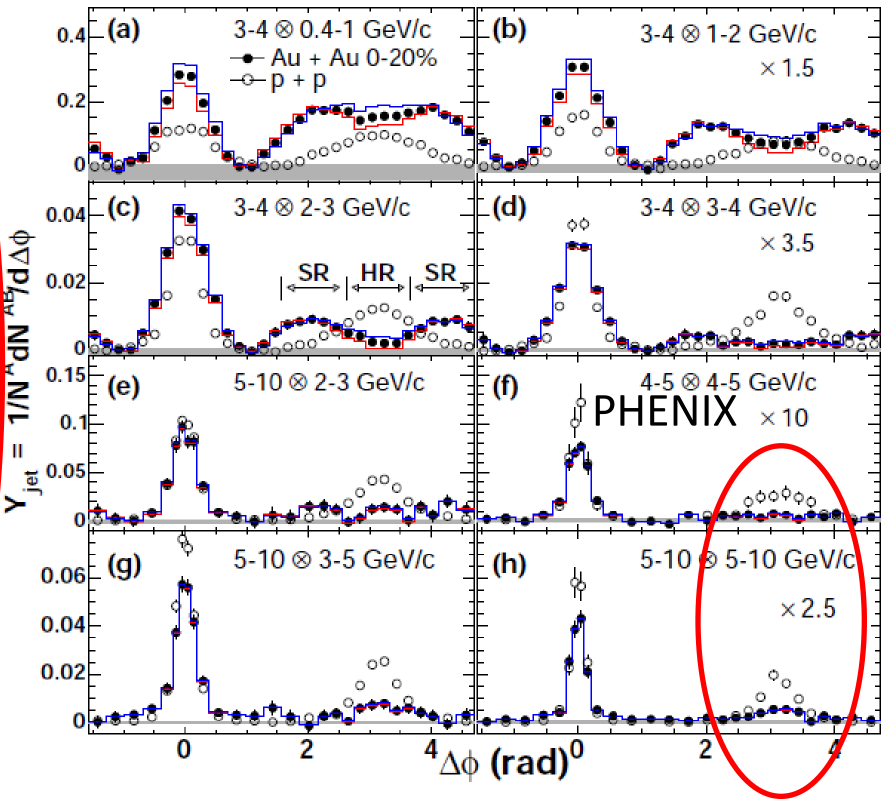
Dash-dotted blue for vacuum splitting with IEL of subjets

Chang, Cao, GYQ, PLB 2018, 1707.03767

Jet-related correlations

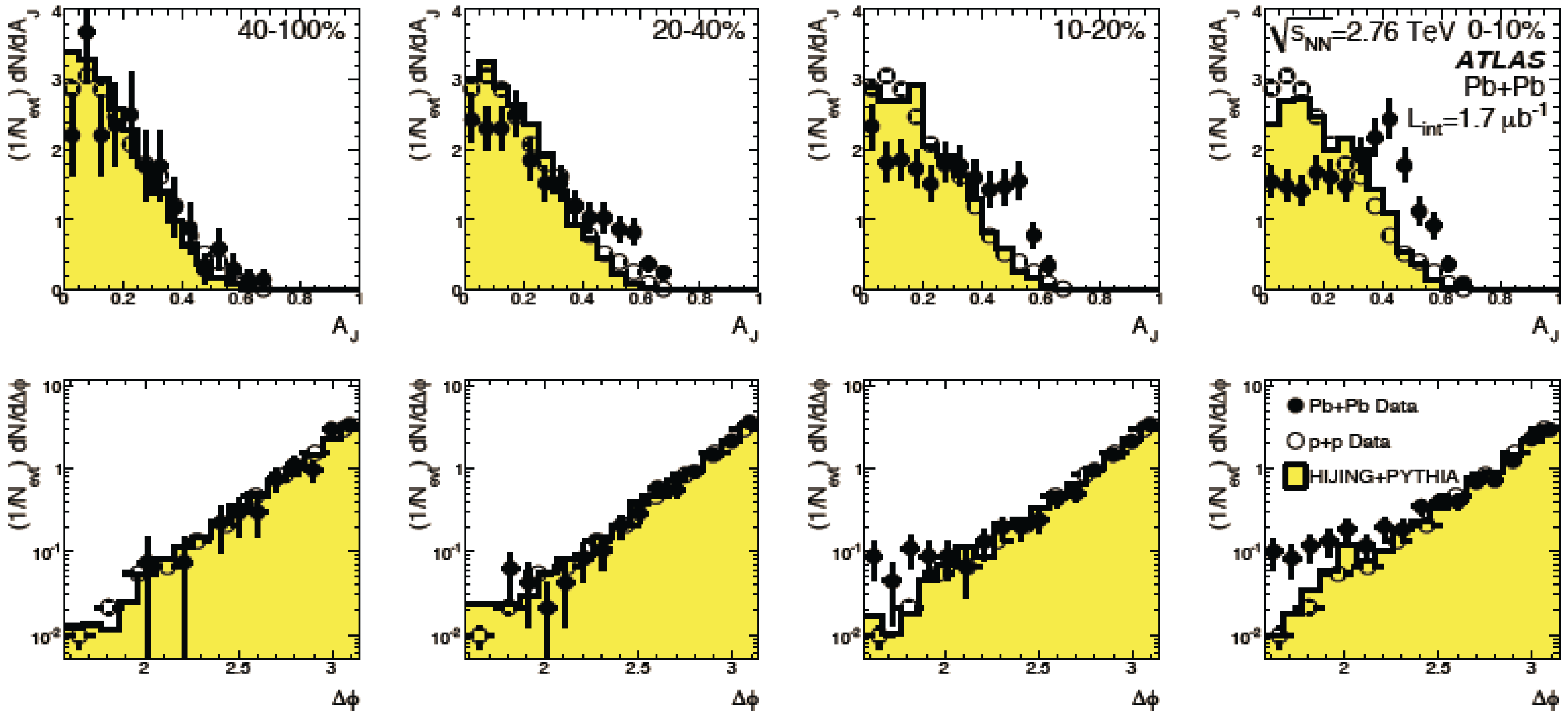
Jet-related correlations





High p_T jet-related correlations: both per-trigger yield and the shape of the angular distribution are modified by QGP medium

Dijet correlations



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

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

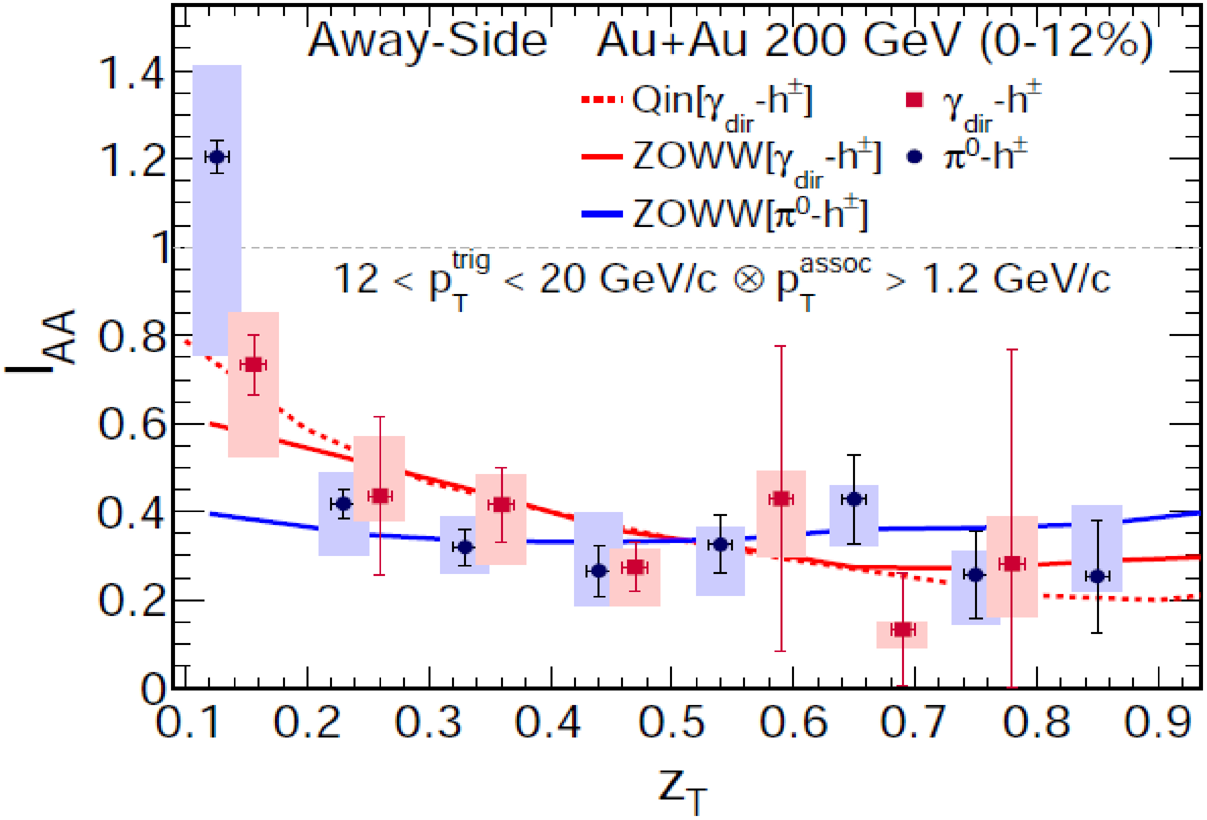
Strong modification of momentum imbalance distribution

=> Significant energy loss experienced by the subleading jets

Largely-unchanged angular distribution

=> medium-induced broadening is quite modest

Dihadron (γ-hadron) suppression



$$I_{AA}(z_T) = \frac{D_{AA}(z_T)}{D_{pp}(z_T)}$$

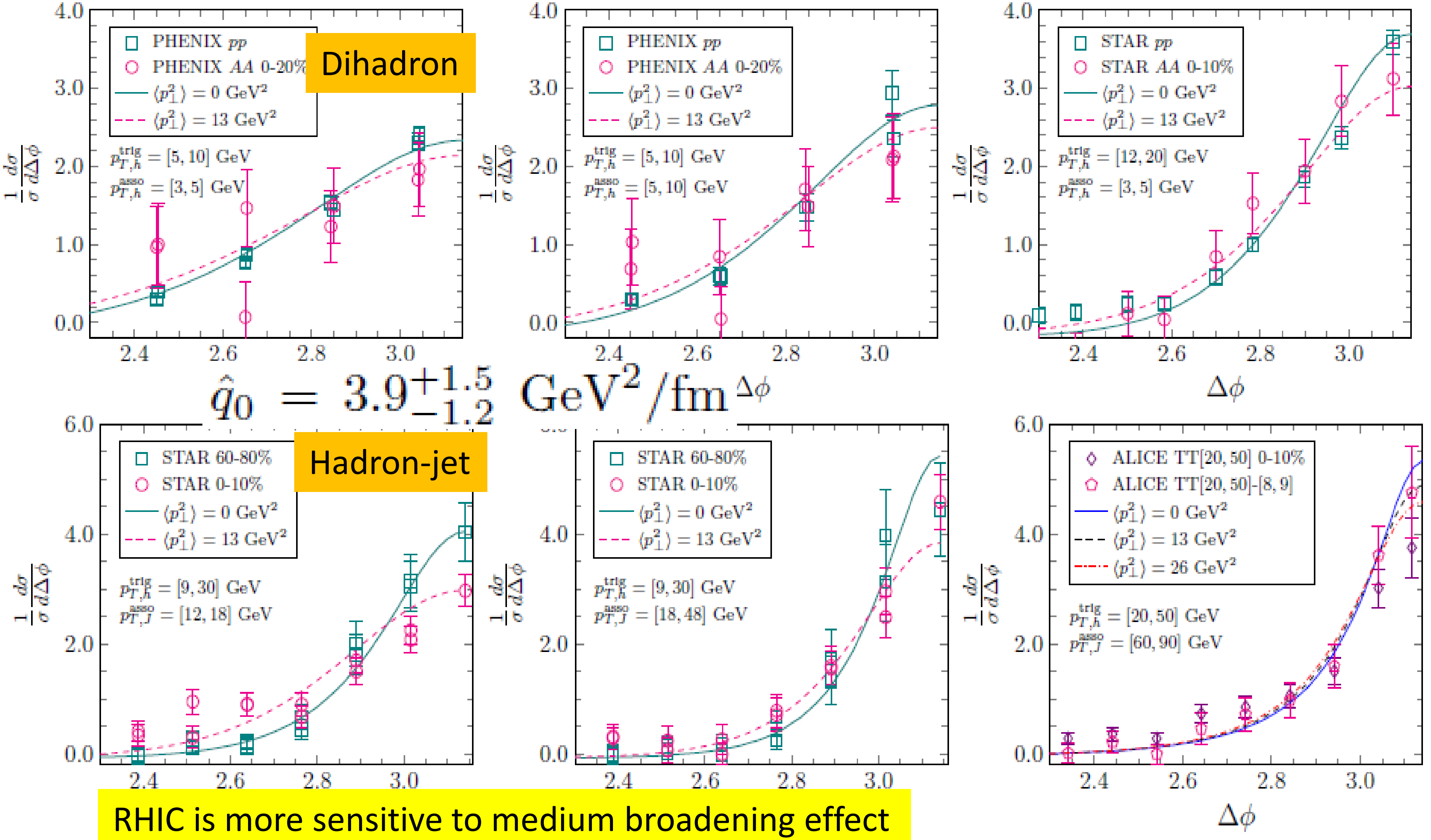
$$z_T = \frac{p_{T,a}}{p_{T,t}}$$

Strong modification of away-side per-triggered yield for dihadrons & γ-hadrons

=> Significant energy loss experienced by away-side jet

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

Dihadron (hadron-jet) angular decorrelations



Dihadron

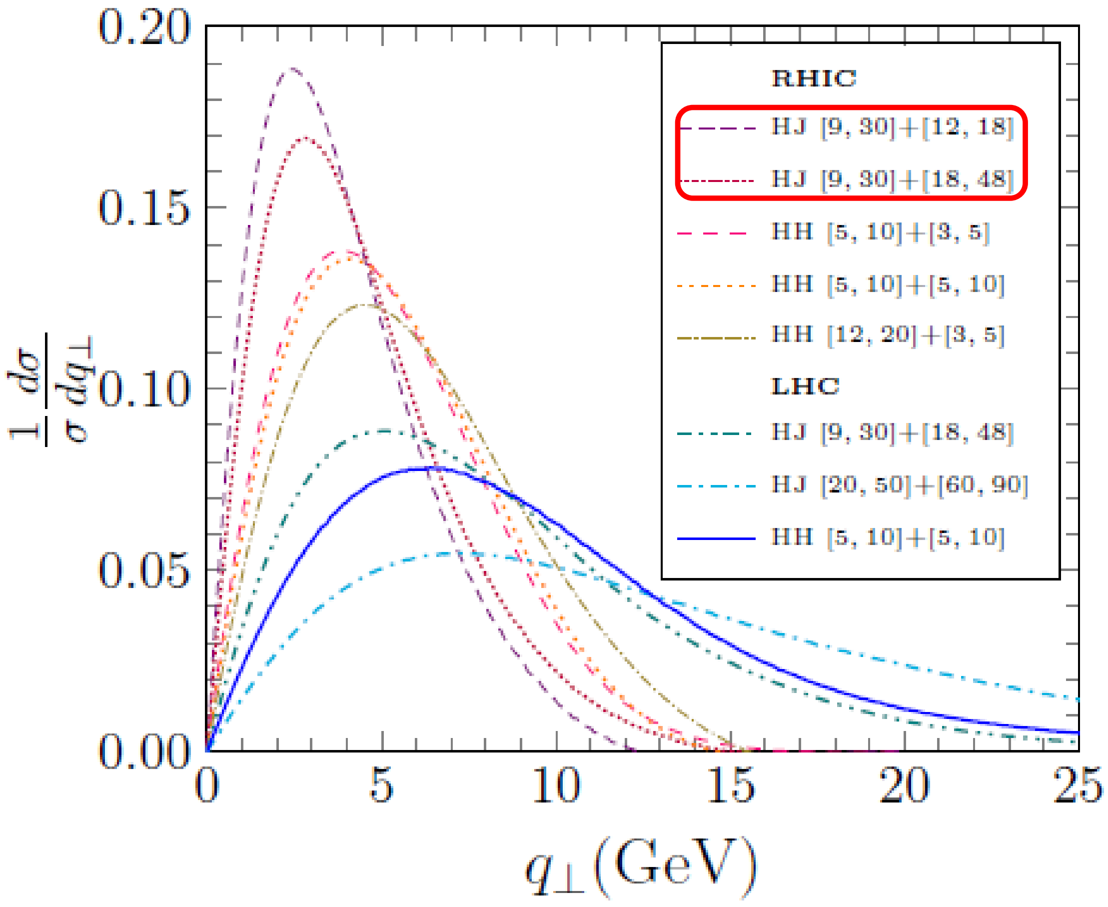
Hadron-jet

$$\hat{q}_0 = 3.9^{+1.5}_{-1.2}\ \mathrm{GeV}^2/\mathrm{fm}$$

RHIC is more sensitive to medium broadening effect

L. Chen, GYQ, S.Y. Wei, B.W. Xiao, H.Z. Zhang, PLB 2017, arXiv:1607.01932

Dijet relative q_T distribution (in pp)

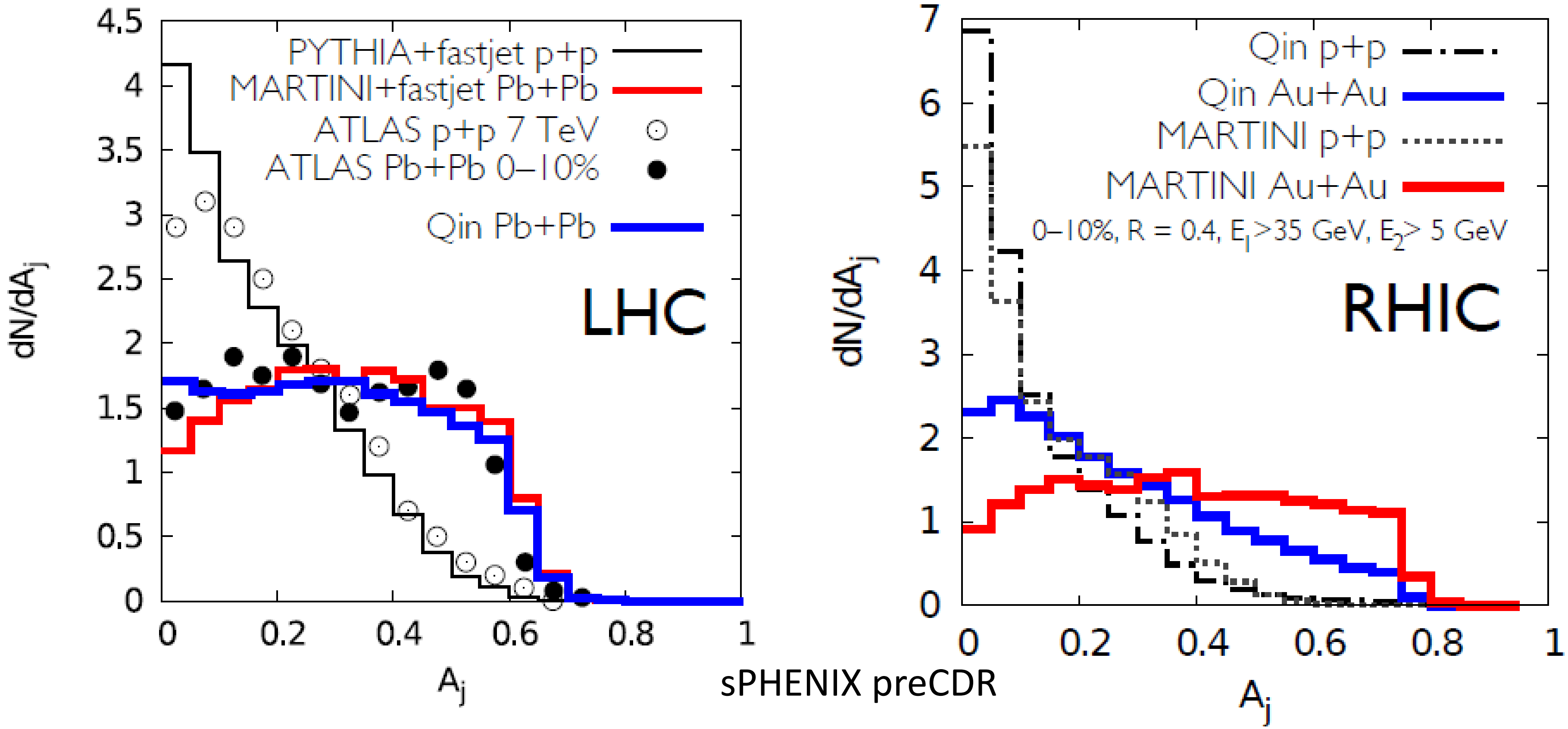


RHIC is more sensitive to medium broadening effect due to smaller vacuum shower effect and smaller jet energies

$$\vec{q}_\perp = \vec{p}_{T,1} + \vec{p}_{T,2} \qquad \left\langle q_\perp^2 \right\rangle_{AA} \approx \left\langle q_\perp^2 \right\rangle_{pp} + \left\langle \hat{q}L \right\rangle_{AA}$$

L. Chen, GYQ, S.Y. Wei, B.W. Xiao, H.Z. Zhang, PLB 2017, arXiv:1607.01932

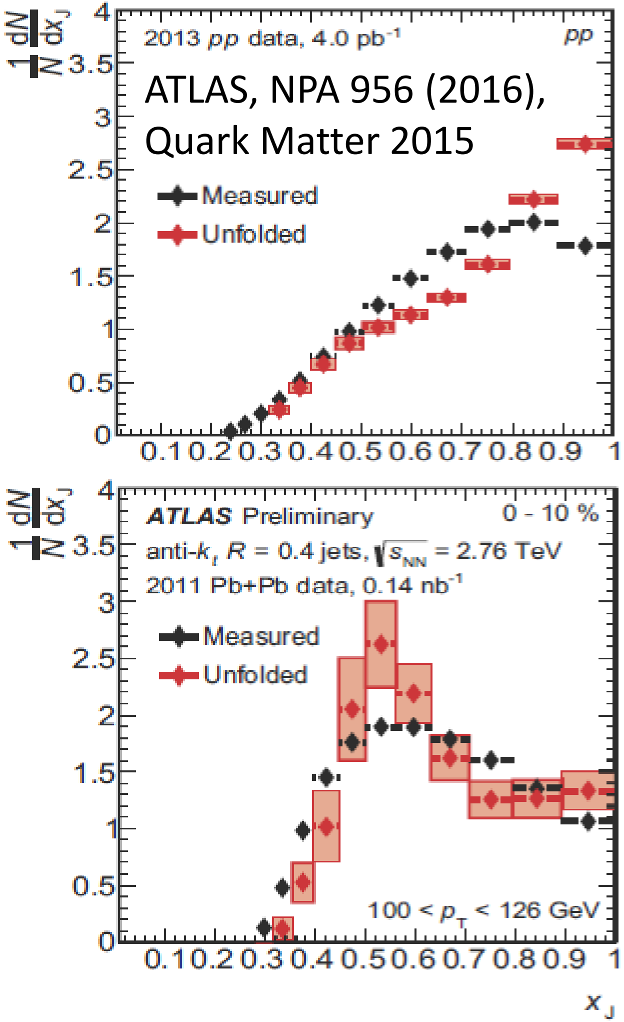
Dijet asymmetry



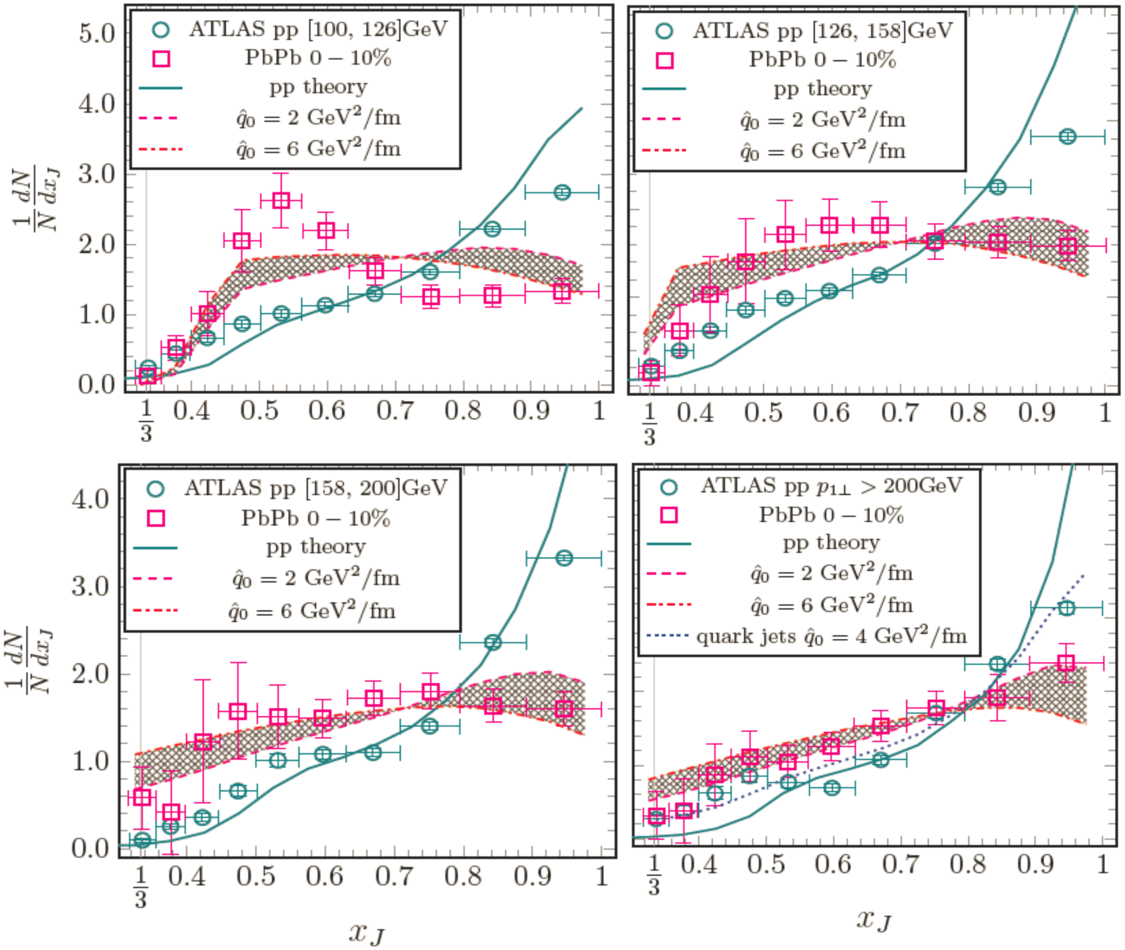
sPHENIX preCDR

Dijet (gamma-jet) asymmetry for the reference pp collisions is more peaked at A_J=0 and x_J=1, thus should be more sensitive to energy loss

Dijet asymmetry



ATLAS, NPA 956 (2016), Quark Matter 2015



L. Chen, GYQ, S.Y. Wei, B.W. Xiao, H.Z. Zhang, arXiv:1612.04202

Summary

- **Extraction of jet transport parameters as a function E and T needs a wide range of jet and collision energies**
- **RHIC medium is smaller, but more sensitivity to near T_c behavior**
- **Initial jet spectrum at RHIC is deeper, more sensitivity to (the same) energy loss fraction than the LHC**
- **Quark and gluon fractions are different**
- **Strong jet (collision) energy dependence for medium modifications of jet shape, and groomed jet splitting function**
- **Medium modification of jet-related angular decorrelation is more sensitive to lower collision energy and smaller jet energy**
- **Dijet (γ-jet) asymmetry for pp reference at RHIC is more peaked at A_J=0 (x_J=1), thus is more sensitive to energy loss (unfolding is also important)**