Jet-medium interaction

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

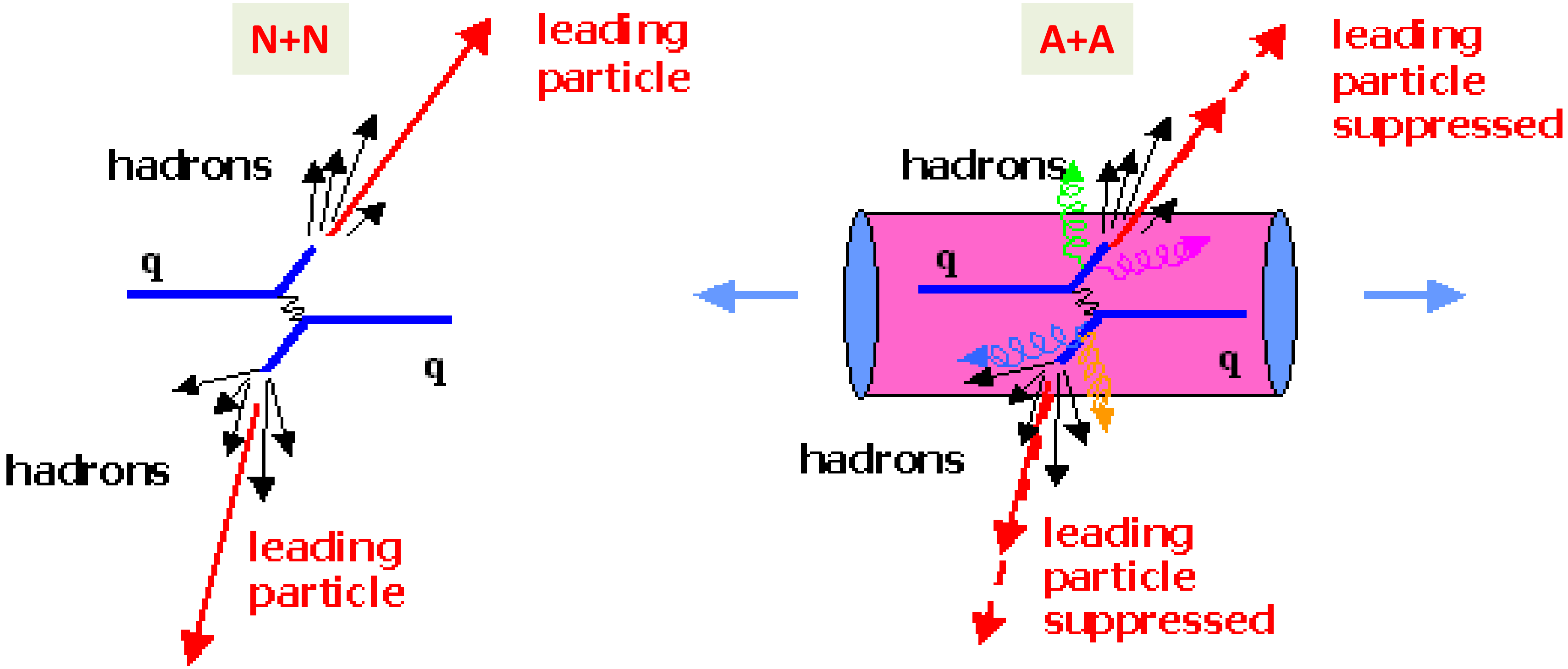
INT Program INT-17-1b
Precision Spectroscopy of QGP Properties with Jets and Heavy Quarks
May 1 - June 8, 2017

S. Cao, T. Luo, GYQ, X.N. Wang, PRC 2016; arXiv:1703.00822
N.B. Chang, GYQ, PRC 2016; Y. Tachibana, N.B. Chang, GYQ, PRC 2017
N.B. Chang, S. Cao, GYQ, to appear
L. Chen, GYQ, S.Y. Wei, B.W. Xiao, H.Z. Zhang, arXiv:1607.01932; arXiv:1612.04202

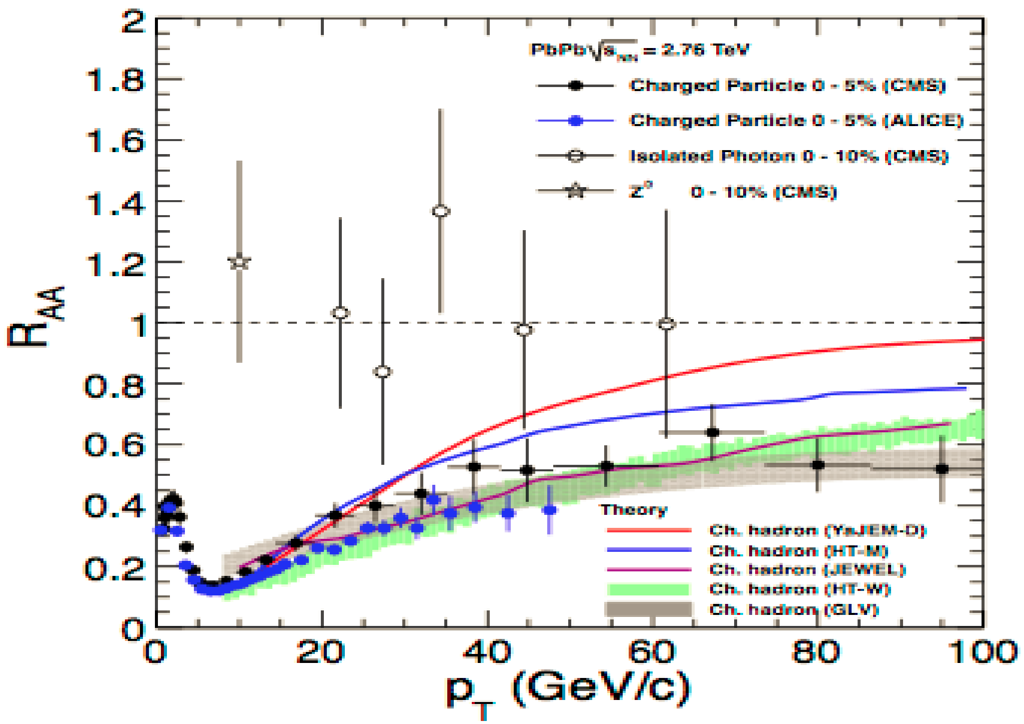
Outline

- Introduction
- Large transverse momentum hadrons
  - A Linear Boltzmann Transport (LBT) approach for light and heavy flavor jet quenching
- Full jets
  - Full jet energy loss, medium response, medium-modified jet shape and groomed jet splitting function
- Jet-related correlations
  - Dijet, dihadron and hadron-jet back-to-back angular correlations
  - Dijet asymmetry in the resummation-improved pQCD approach
- Summary

Jet quenching



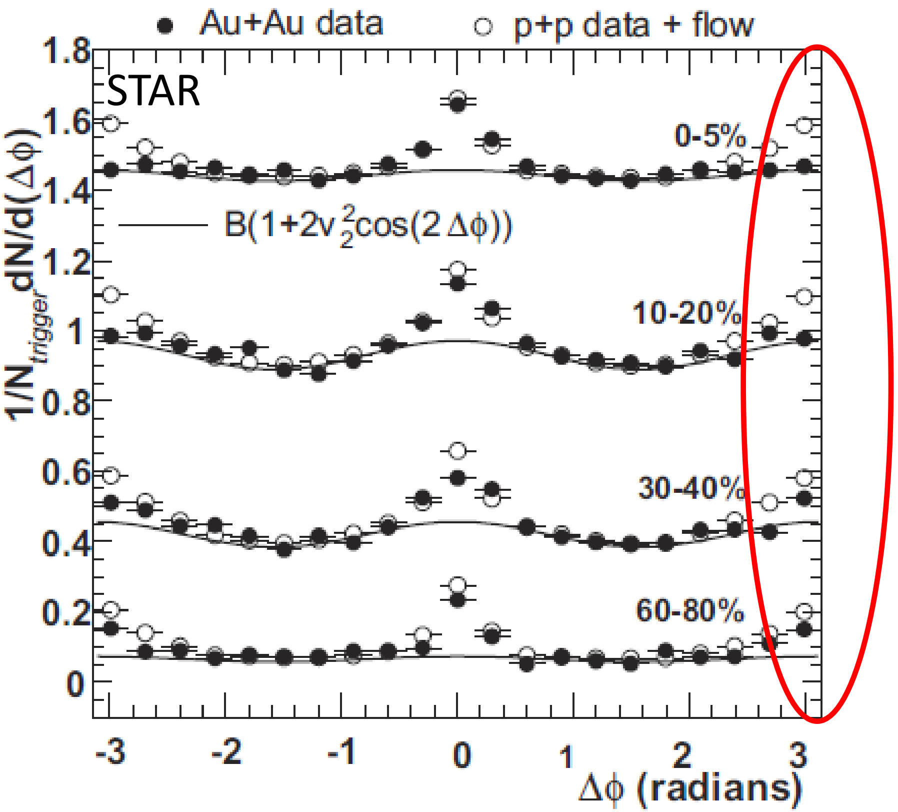
Evidence: large transverse momentum hadrons

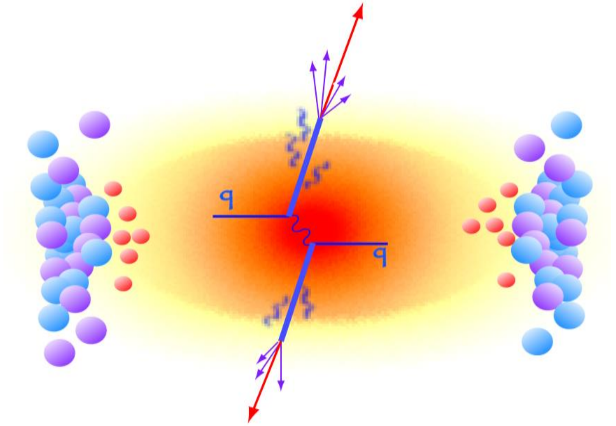


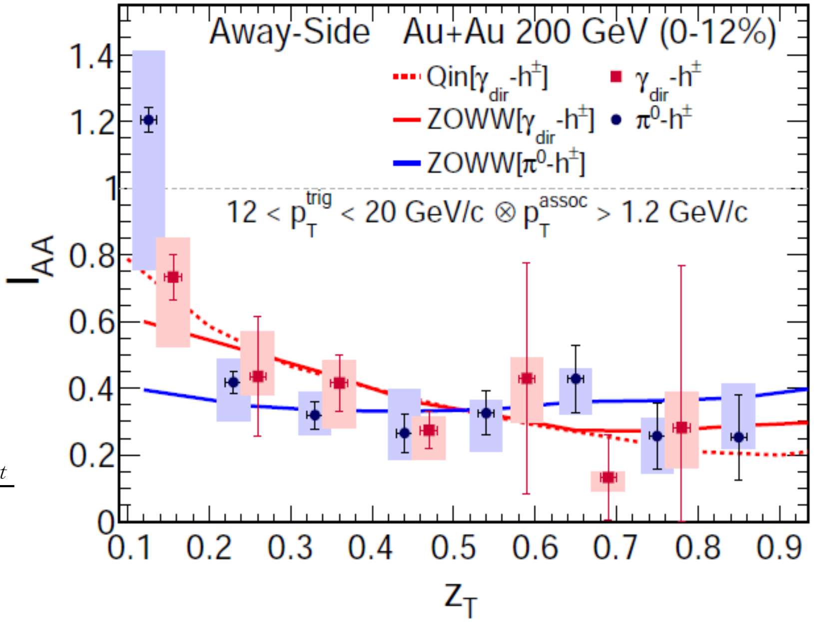
$$R_{AA} = \frac{dN^{AA} \ / \ d^2 p_T dy}{N_{\mathrm{coll}} dN^{pp} \ / \ d^2 p_T dy}$$

- If A+A collisions are just simple combination of many N+N collisions, then R_{AA}=1
- Photon & Z boson: R_{AA}=1
- Large p_T hadron: R_{AA}<1 (due to final state jet-medium interaction and parton energy loss in QGP)
- Jet quenching is mainly a final state effect

Evidence: jet-related correlations

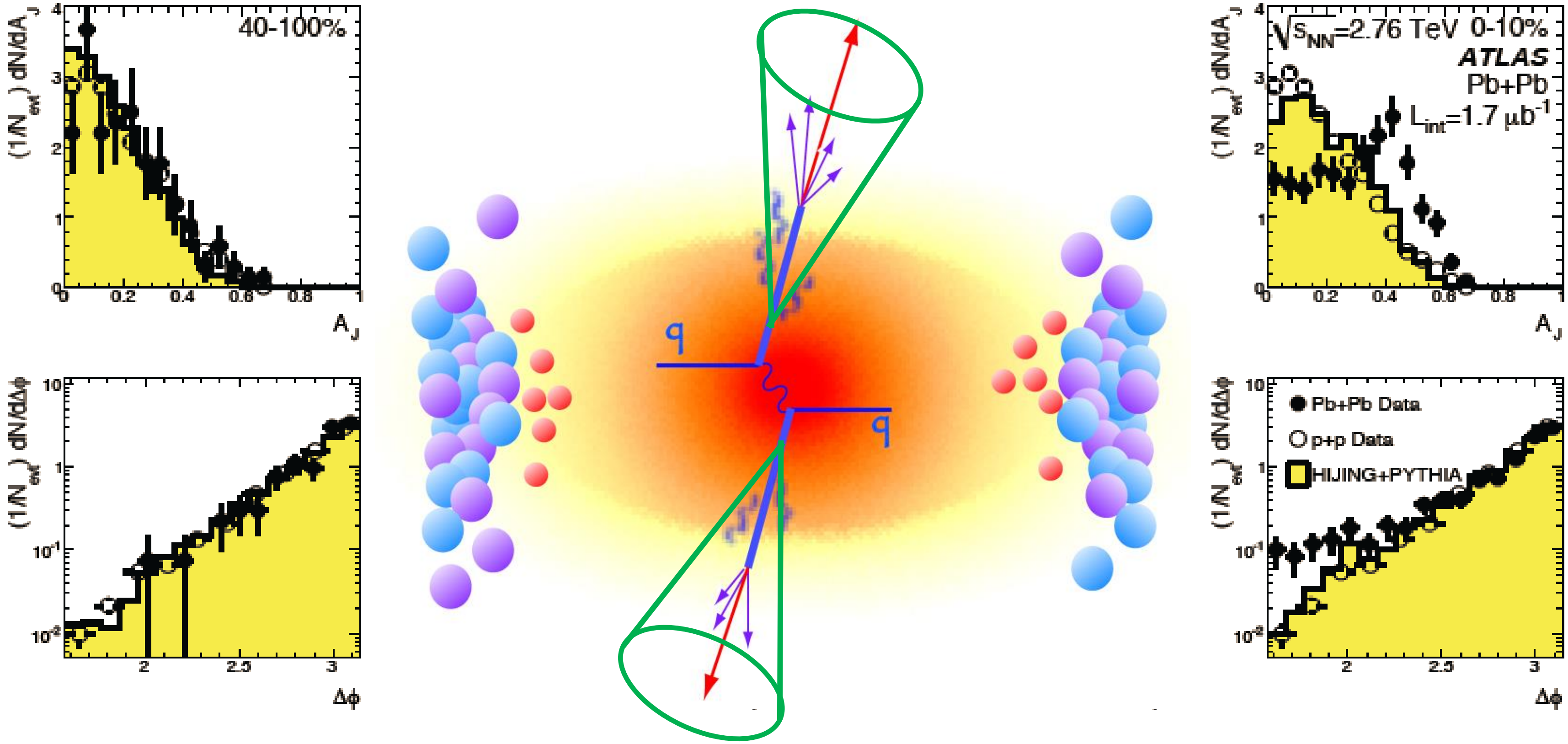






$$D\left(z_T = \frac{p_{T,a}}{p_{T,t}}\middle| p_{T,t}\right) = p_{T,t}\,\frac{dN_{t,a}(p_{T,t},p_{T,a})/dp_{T,a}dp_{T,t}}{dN_t(p_{T,t})/dp_{T,t}}$$

Evidence: full jets



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

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

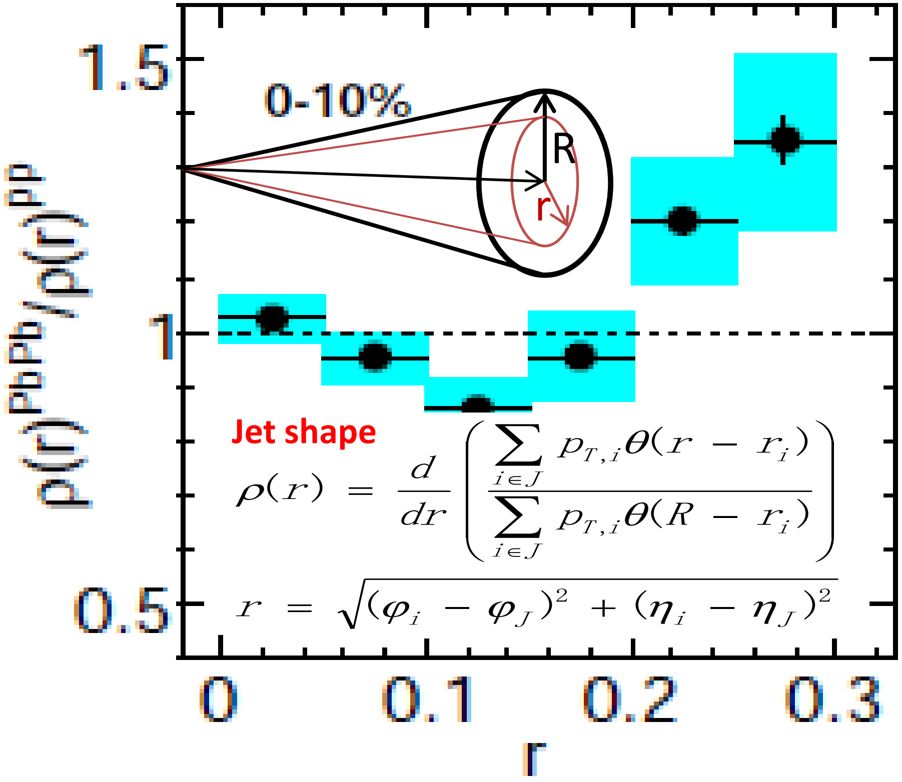
Strong modification of momentum imbalance distribution

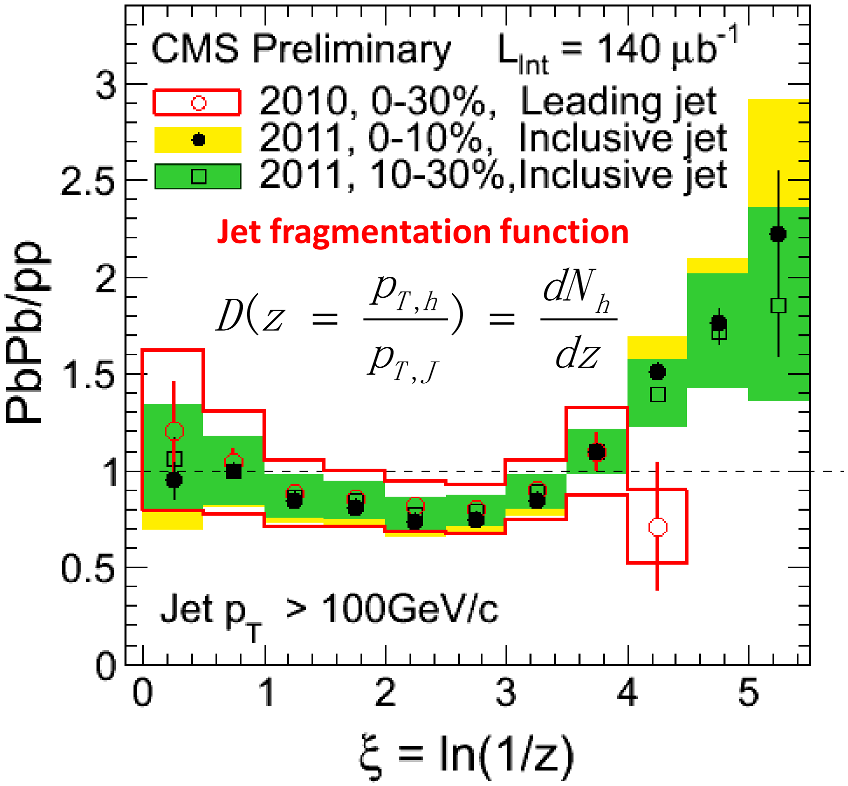
=> Significant energy loss experienced by the subleading jets

Largely-unchanged angular distribution

=> medium-induced broadening is quite modest

Evidence: jet structure



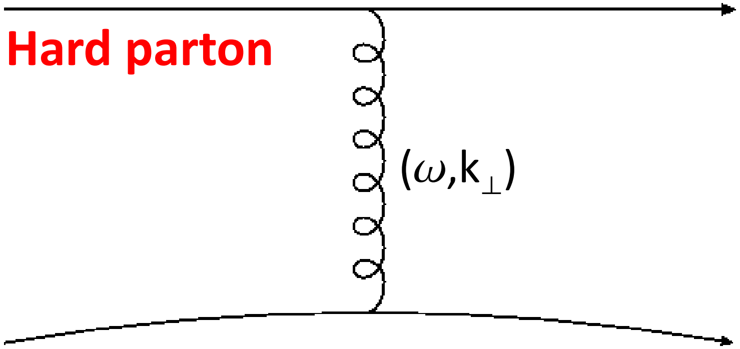


Medium modification of jet fragment (shape) profiles

- The enhancement at large r is consistent with the jet broadening
- The enhancement at low z is expected from medium-induced radiation
- The soft outer part of jets is easier to be modified, while the modification of the inner hard cone is more difficult

Large Transverse Momentum Hadrons

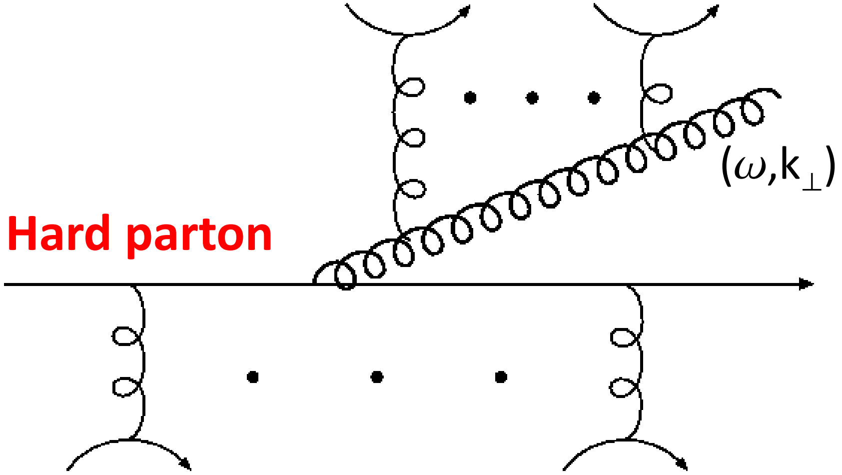
Jet-medium interaction



Elastic (collisional)

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

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; GYQ, Majumder, 2013…



Inelastic (radiative)

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

BDMPS-Z: Baier-Dokshitzer-Mueller-Peigne-Schiff-Zakharov
ASW: Amesto-Salgado-Wiedemann
AMY: Arnold-Moore-Yaffe
DGLV: Djordjevic-Gyulassy-Levai-Vitev
HT: Wang-Guo-Majumder
Caron-Huot, Gale 2010; Djordjevic, Heinz, 2008; Djordjevic, Djordjevic, 2012; Majumder 2012…

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

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

- **Elastic collisions:**

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

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

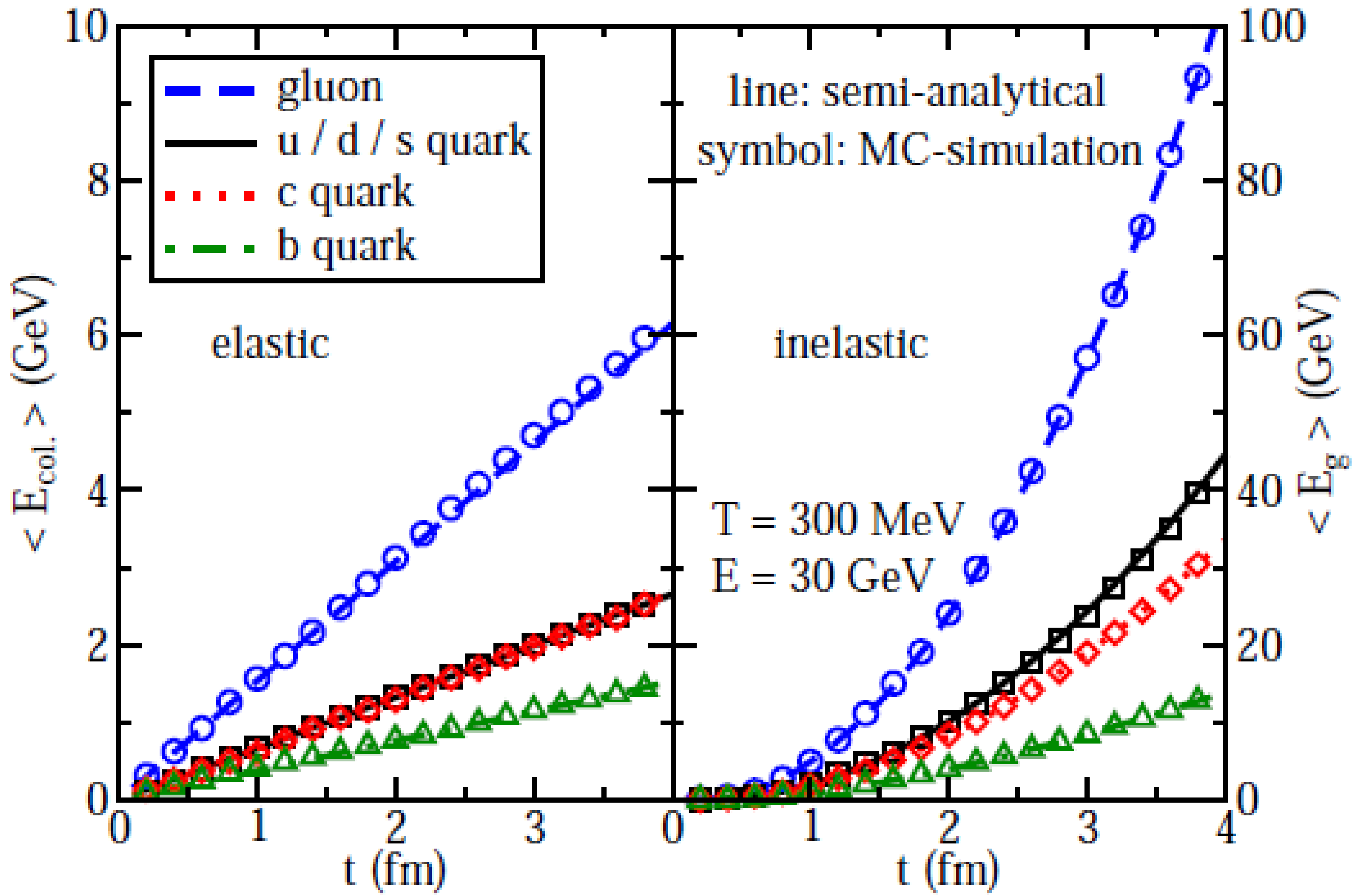
- **Inelastic collisions:**

$$\langle N_g\rangle(E,T,t,\Delta t) = \Delta t\int dx dk_\perp^2 \frac{dN_g}{dx dk_\perp^2 dt}$$
$$P(n) = \frac{\langle N_g\rangle^n}{n!}e^{-\langle N_g\rangle}$$
$$P_{inel} = 1 - e^{-\langle N_g\rangle}$$

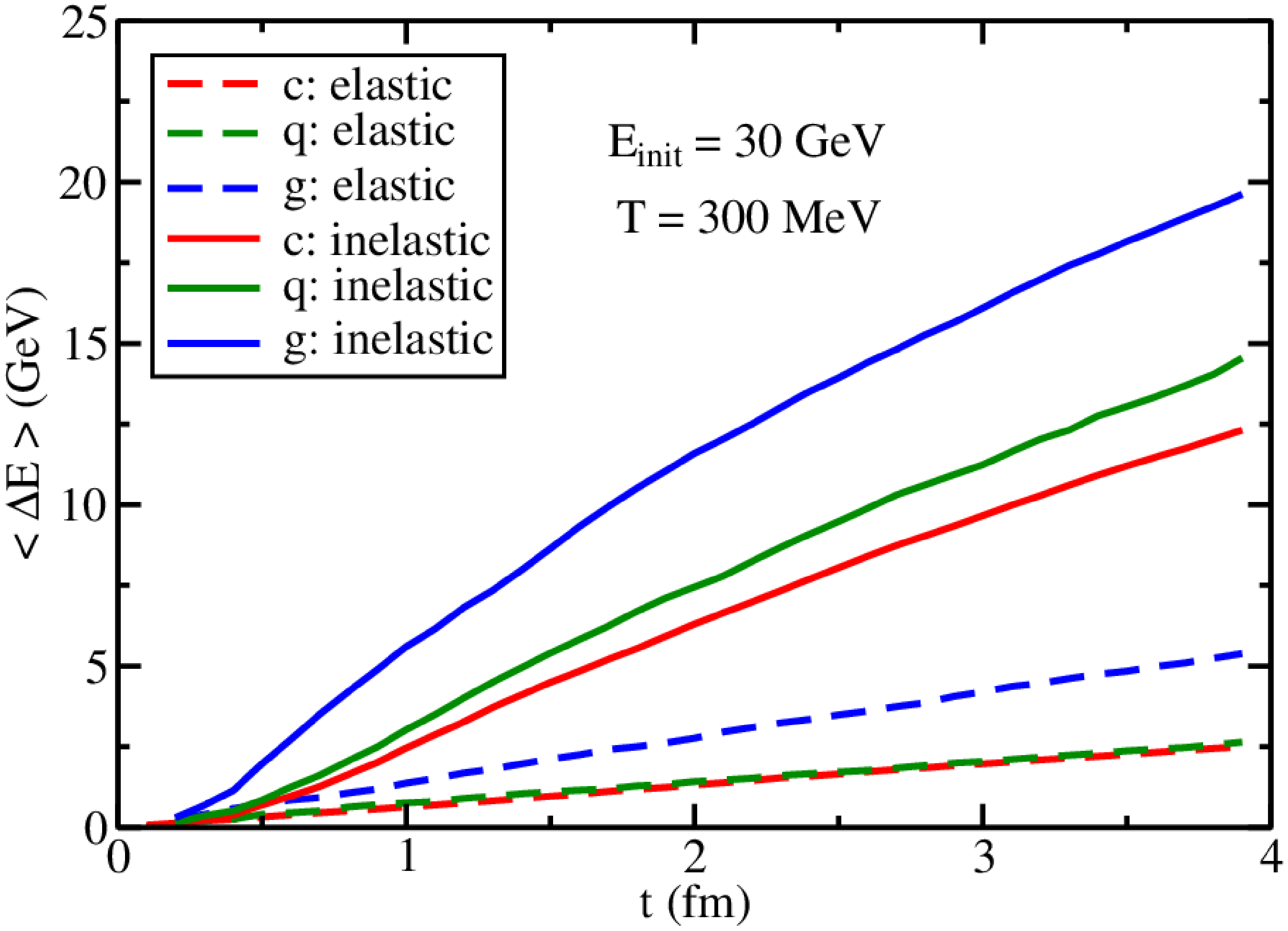
- **Elastic + Inelastic:** $P_{tot} = P_{el} + P_{inel} - P_{el}P_{inel}$

Cao, Luo, GYQ, Wang, PRC 2016 ; arXiv:1703.00822; etc.

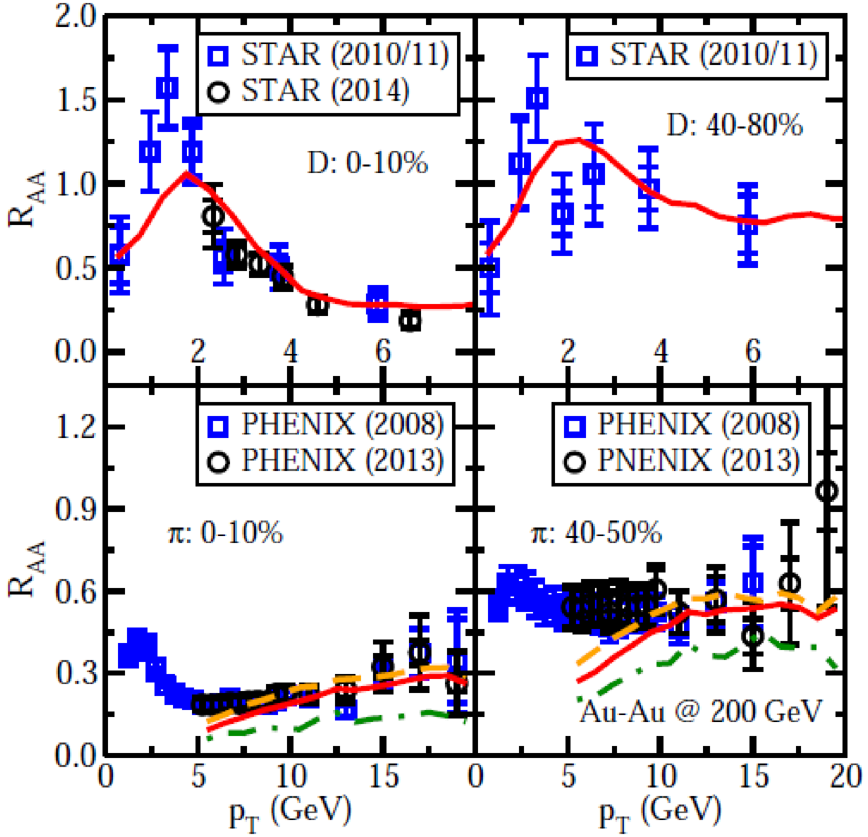
Model validation

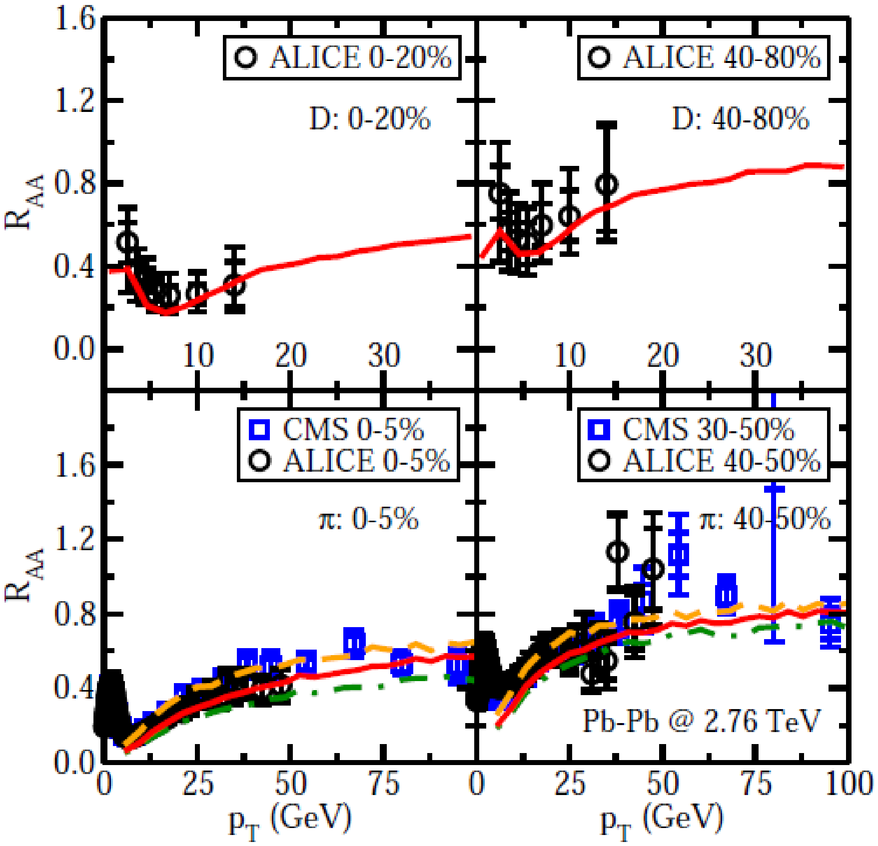


Realistic simulation: parton energy loss

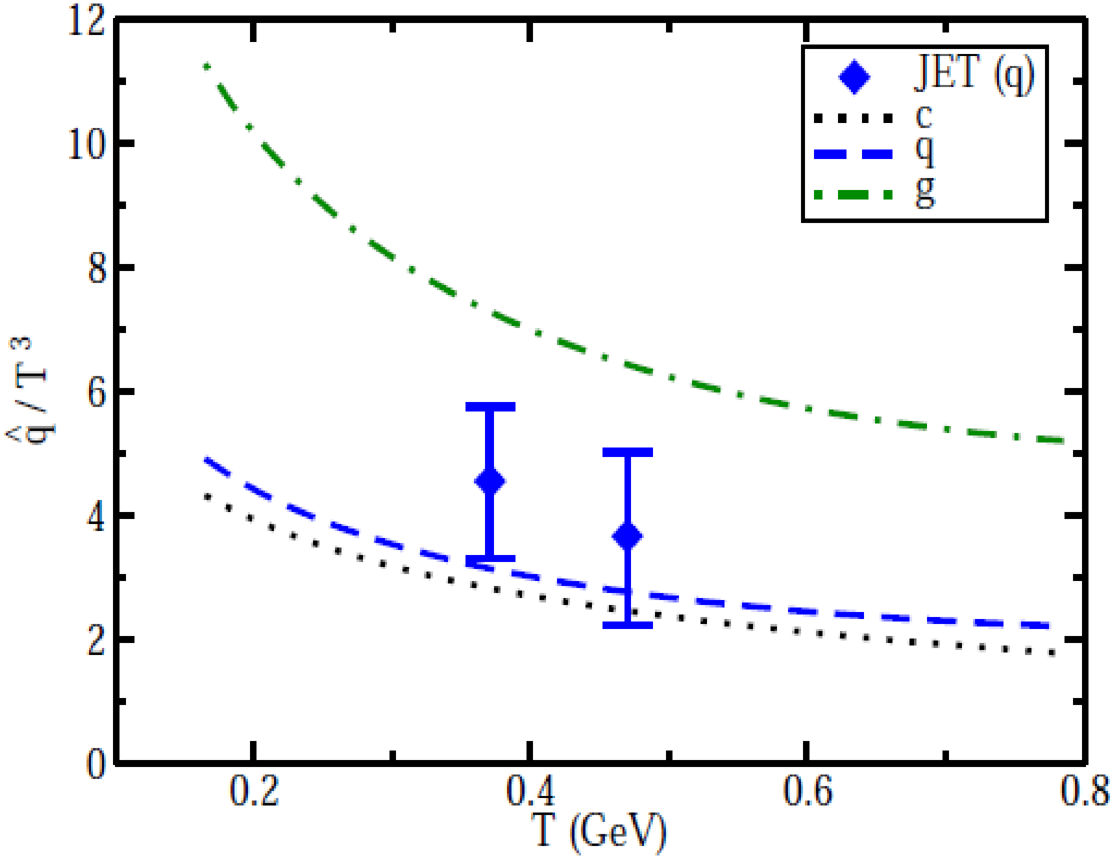


Heavy and light flavor jet quenching





Extract $\hat{q}$ from parton energy loss (by LBT)



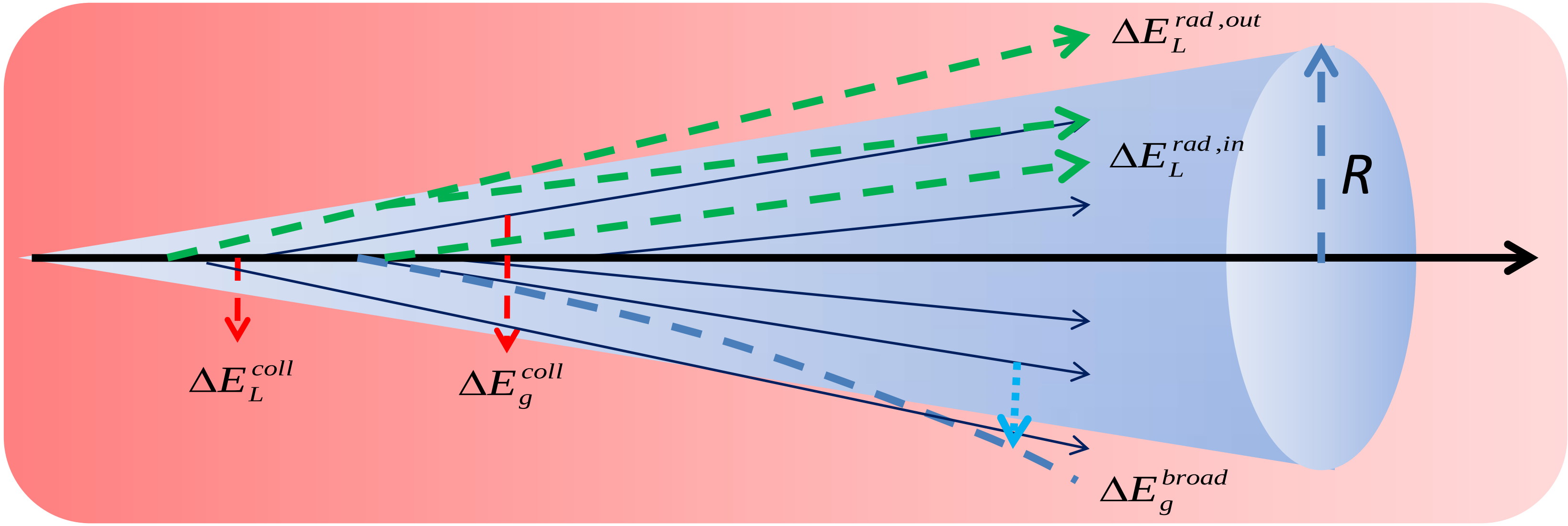
Cao, Luo, GYQ, Wang, PRC 2016; arXiv:1703.00822

Linear-Boltzmann Transport approach: $p^{\mu}\partial_{\mu}f(\vec{x},\,\vec{p},\,t) = E\big(C_{col}[f] + C_{rad}[f]\big)$

See talks from Shanshan Cao, Tan Luo and Wei Chen for more results from LBT

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.

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

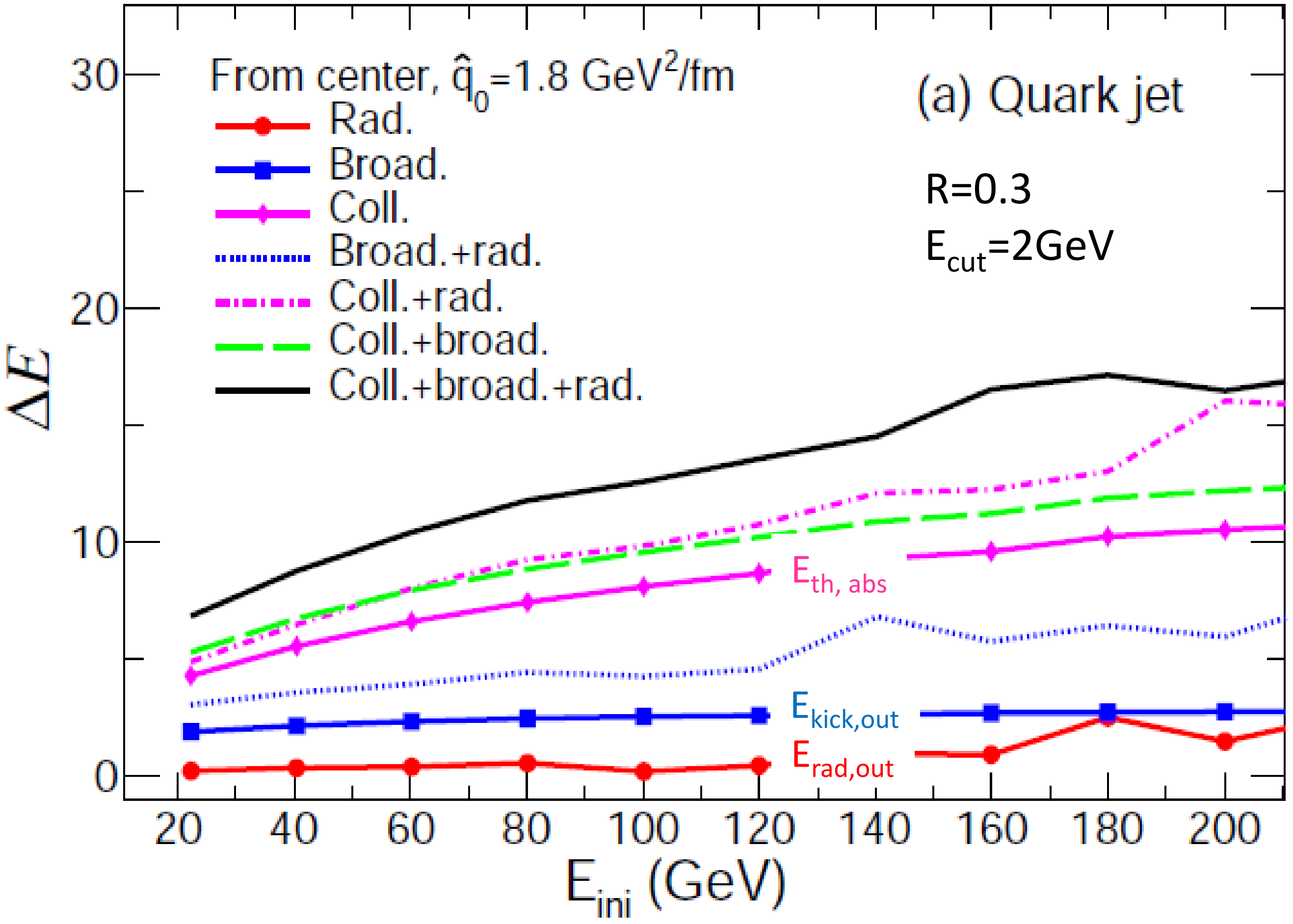
$$-\sum_i \int d\omega_i dk_{i\perp}^2 \frac{d\tilde{\Gamma}_{j\to i}(\omega_i, k_{i\perp}^2 | \omega_j, k_{j\perp}^2)}{d\omega_i d^2k_{i\perp} dt} f_j(\omega_j, k_{j\perp}^2, t)$$

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

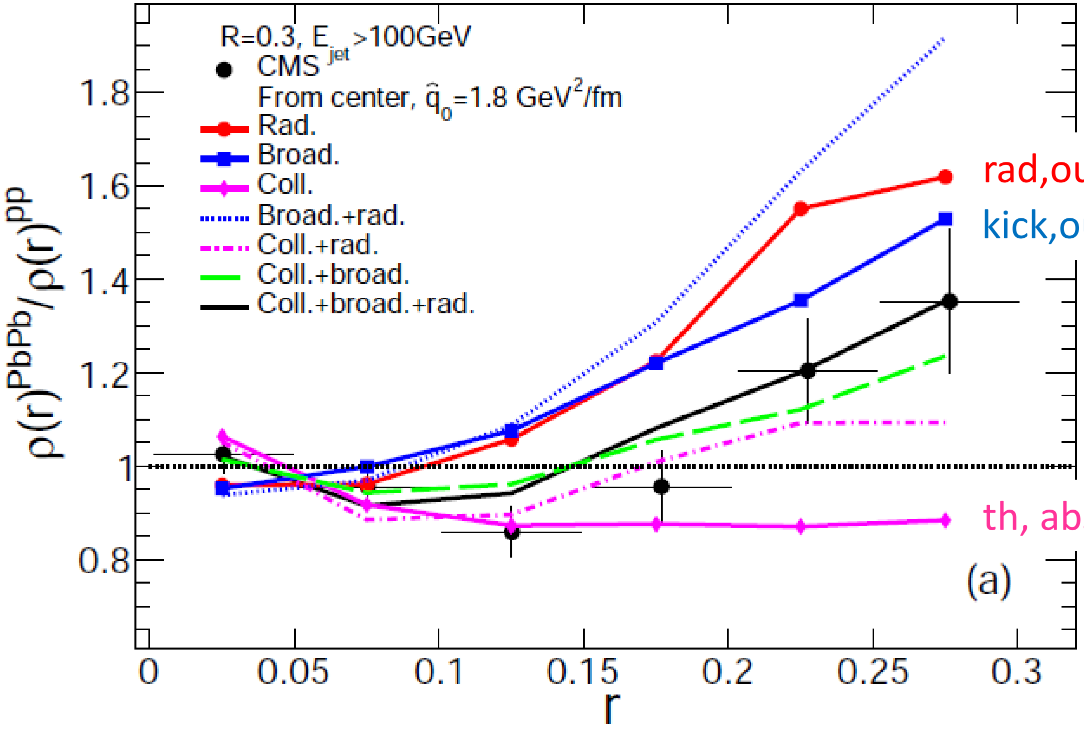
Full jet energy loss (radiative, collisional, broadening)



N. B. Chang, GYQ, PRC 2016

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

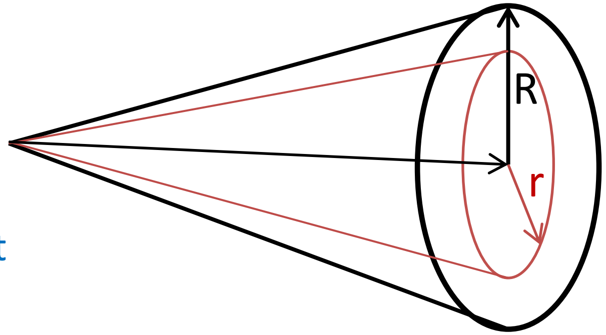
Jet shape function: interplay of different mechanisms



rad,out

kick,out

th, abs



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

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

The soft outer part is easier to be modified, while the inner hard core is more difficult

The enhancement at large r is consistent with medium-induced radiation, transverse momentum broadening

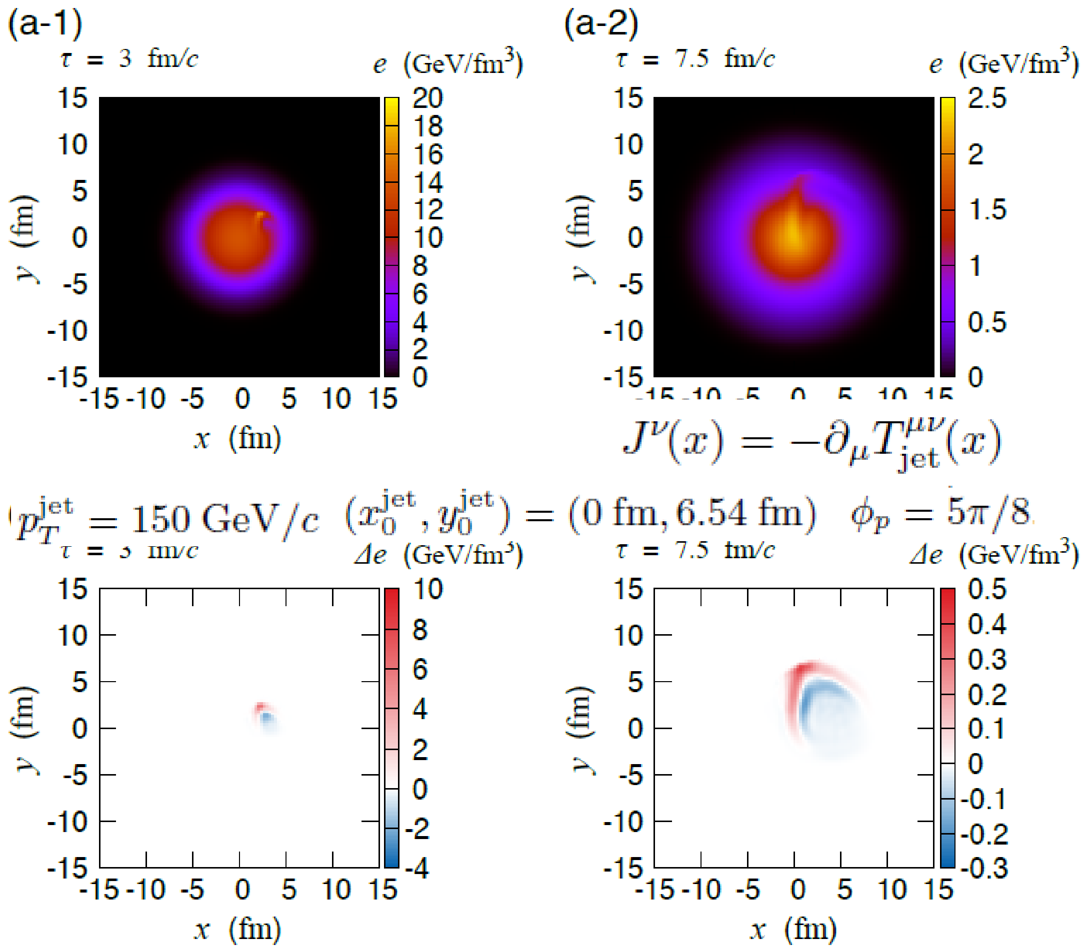
The final jet shape is the interplay of different jet-medium interaction mechanisms

N. B. Chang, GYQ, PRC 2016

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

Medium response to jet-deposited energy/momentum

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



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

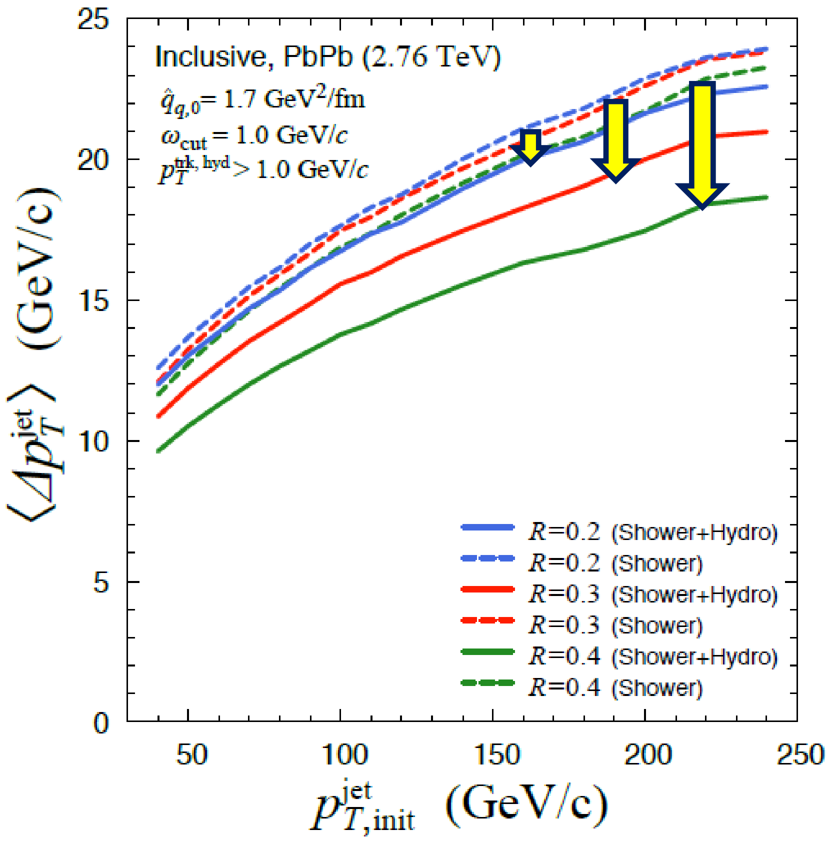
$$p_T^{\mathrm{jet}} = 150\ \mathrm{GeV}/c \quad (x_0^{\mathrm{jet}}, y_0^{\mathrm{jet}}) = (0\ \mathrm{fm}, 6.54\ \mathrm{fm}) \quad \phi_p = 5\pi/8$$

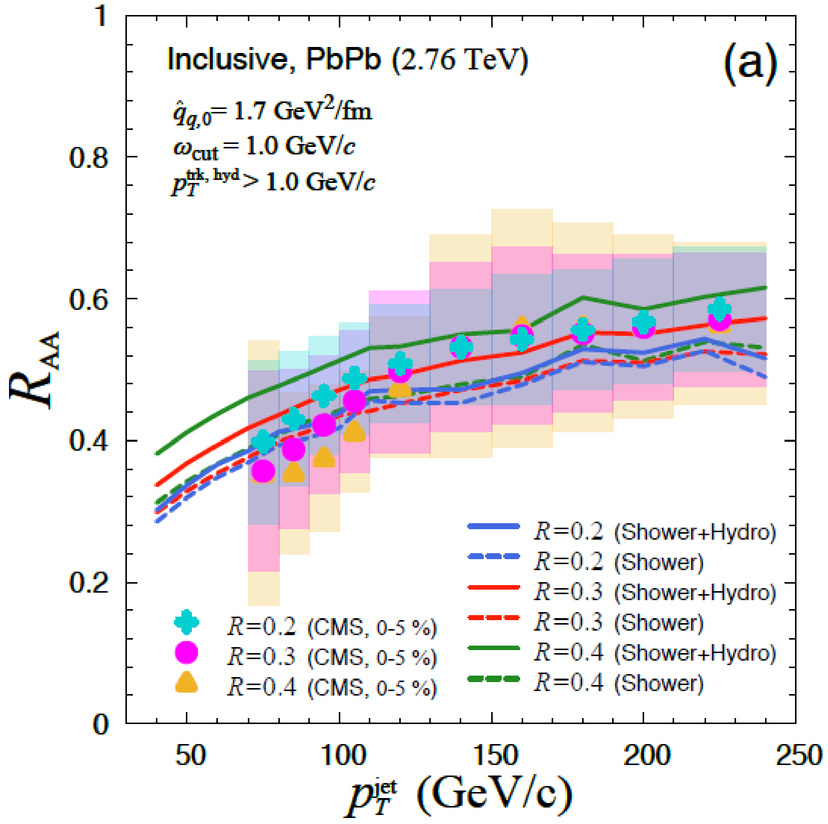
V-shaped wave fronts are induced by the propagating jet, and develop with time

The wave fronts carry the energy and momentum, propagates outward and 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

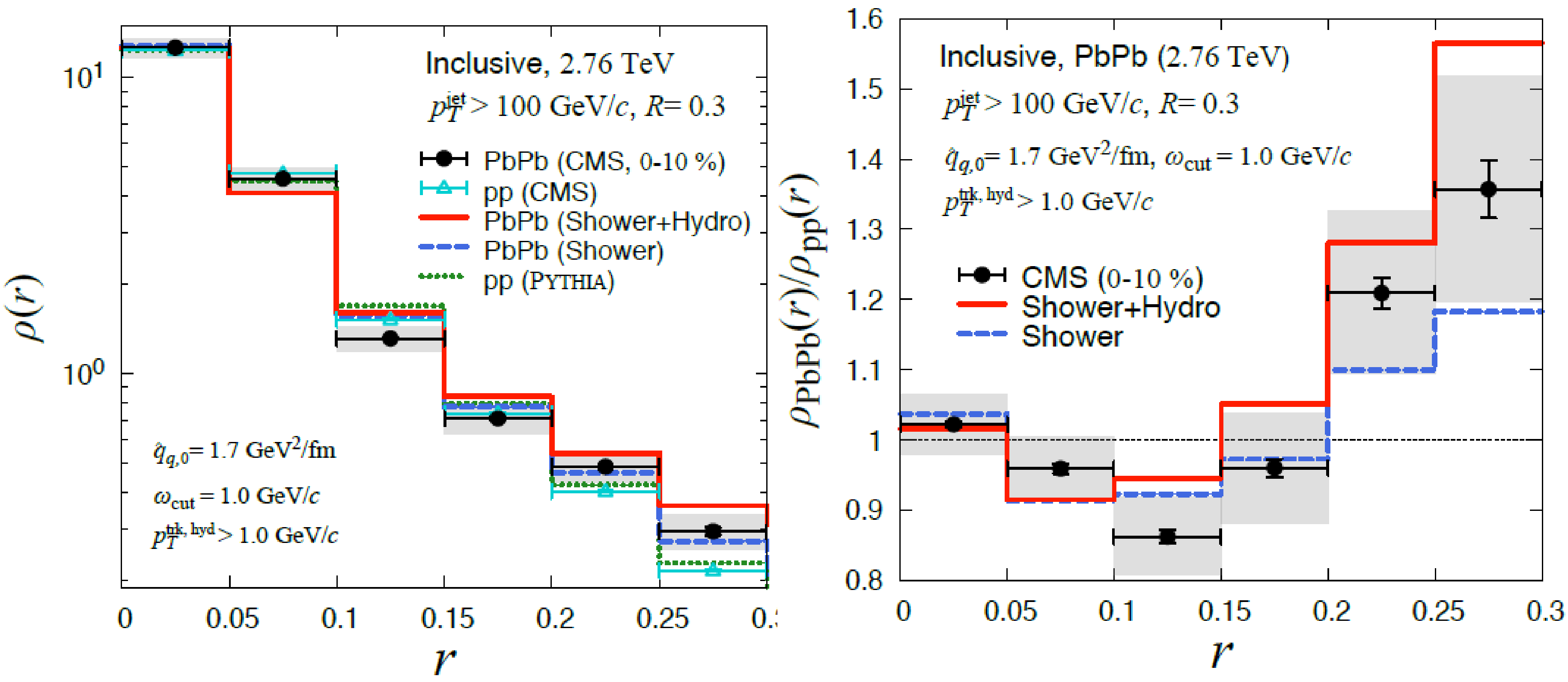




Hydro part (the lost energy from the shower part still inside the jet cone) partially compensates the energy loss experienced by jet shower part.

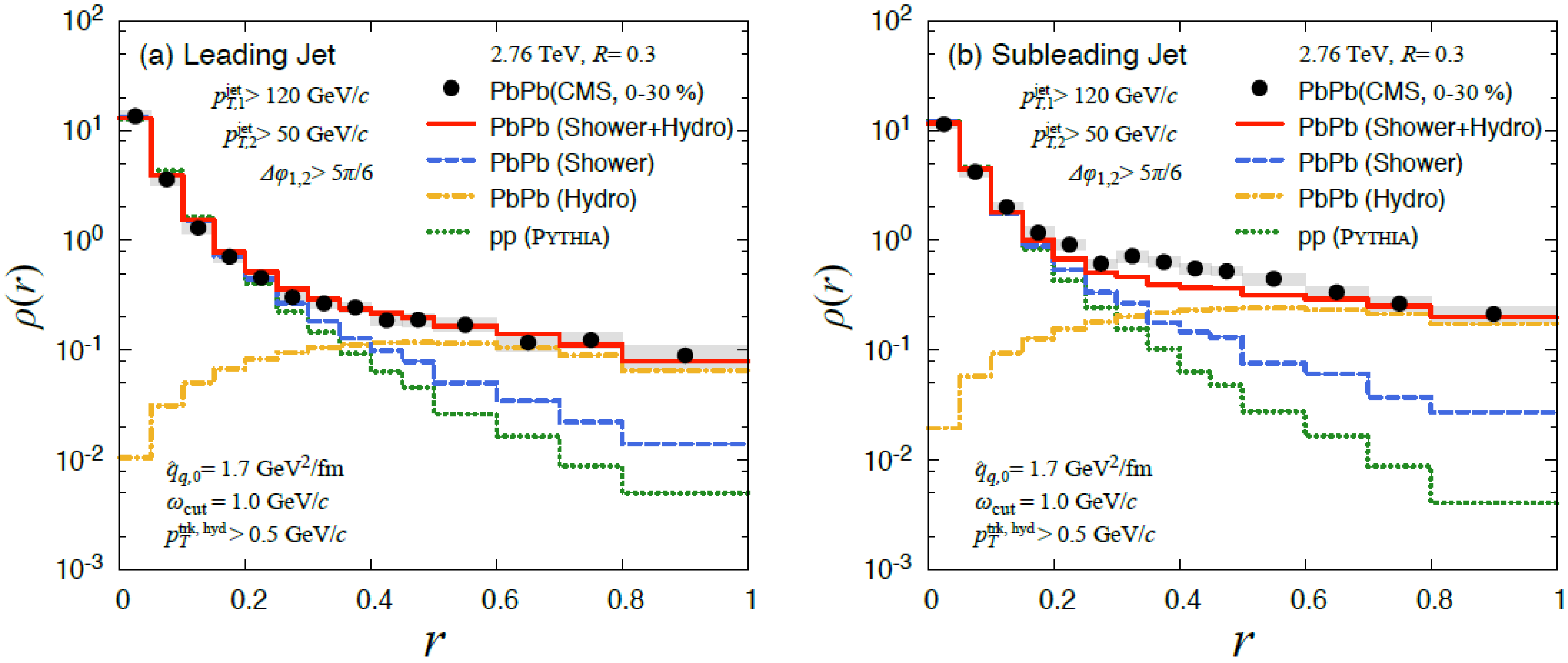
Jet-induced flow evolves with medium, diffuses, and spreads widely around jet axis, leading to stronger jet cone size dependence.

Effect of jet-induced flow on jet shape



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)

Evidence of jet-induced medium flow (excitation) in full jet shape measurements



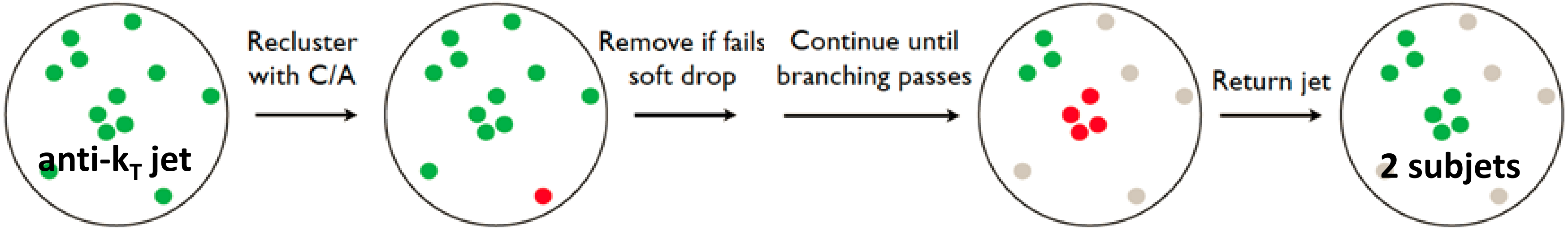
The contribution from the hydro part is quite flat and finally dominates over the shower part in the region with r > 0.5.

Jet shape function for subleading jets is broader than leading jets due to more jet-medium interaction

Y. Tachibana, N. B. Chang, GYQ, PRC 2017

Medium-Modified Jet Splitting

Jet grooming via soft drop declustering



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

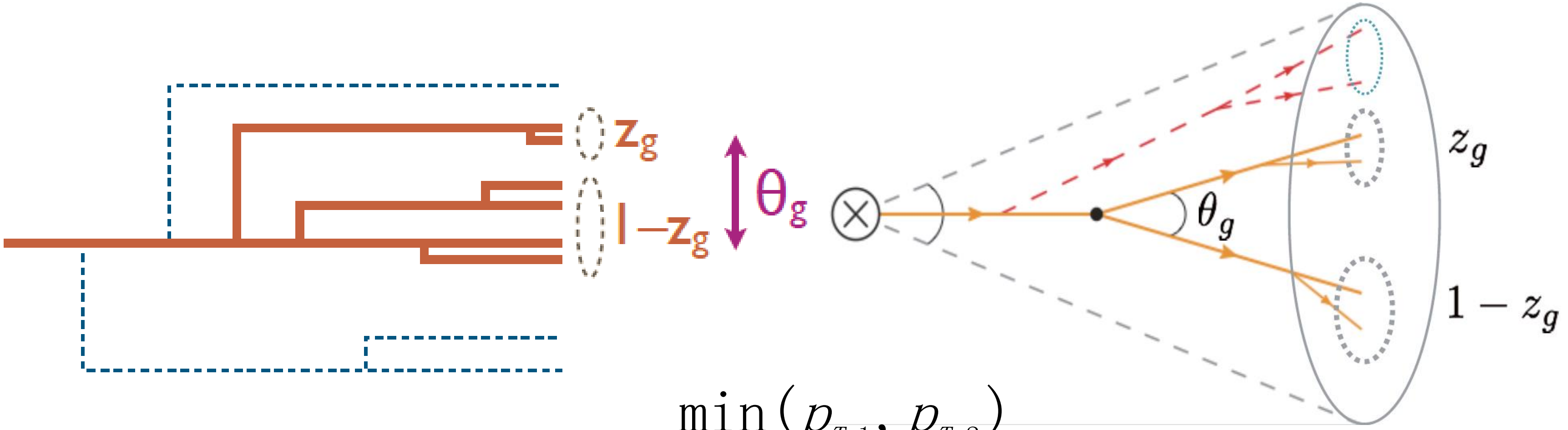
Idea: recursively removes soft wide-angle radiation from a jet
Experimental implementation: re-cluster anti-k_T jet with Cambridge/Aachen (C/A) algorithm, then de-cluster the angular-ordered C/A tree by dropping soft branches

Two parameters for soft drop procedure: a soft energy threshold z_{cut} and an angular exponent β:

$$z > z_{cut}\theta^{\beta} = z_{cut}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

Additional soft drop condition: CMS also requires two subjets $\Delta R_{12} > 0.1$, with ΔR_{12} the η-ϕ separation between the two subjets

Observable after jet grooming: Momentum sharing fraction z_g distribution



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

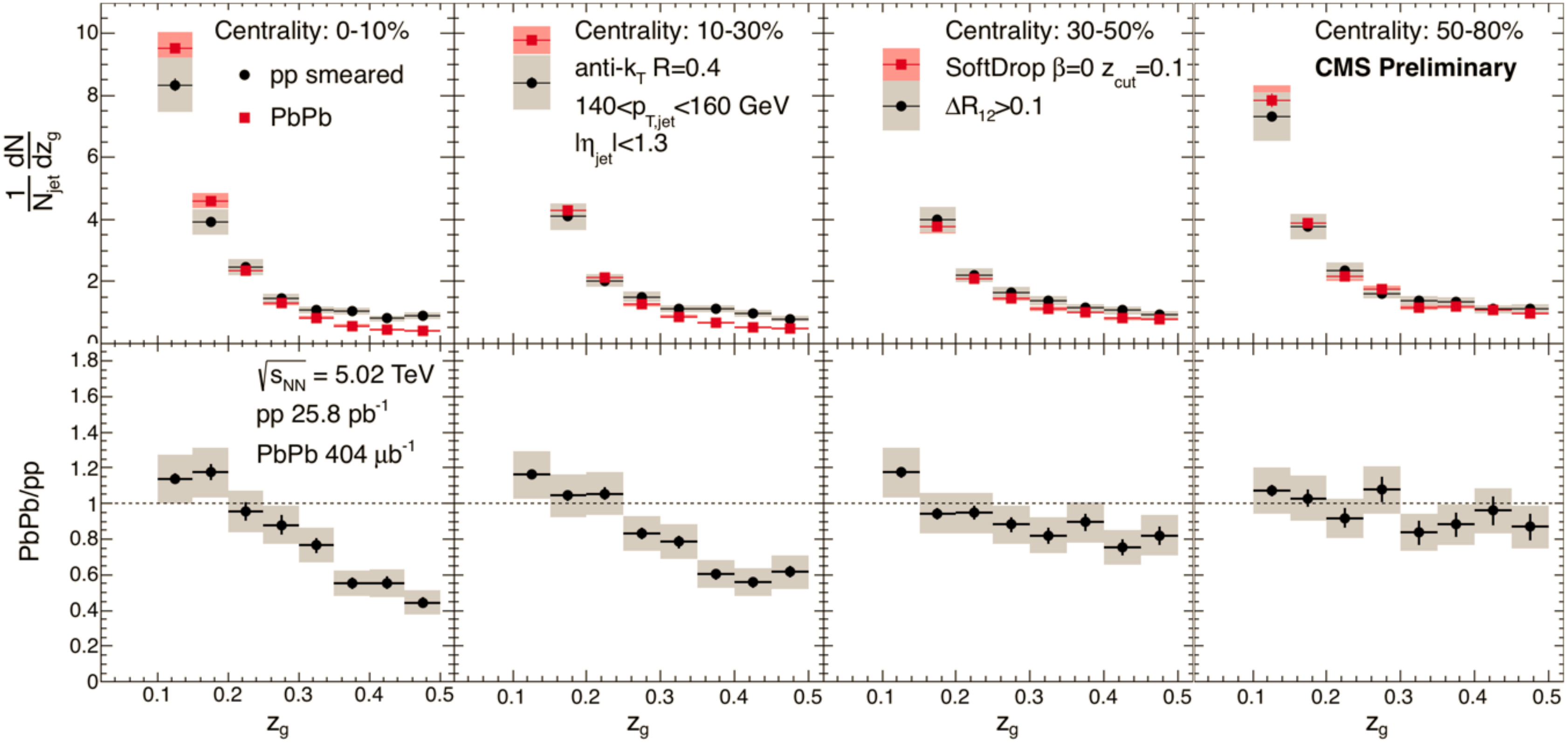
z_g **is the momentum fraction carried by the subleading subjet in the groomed jet**

One observable:

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

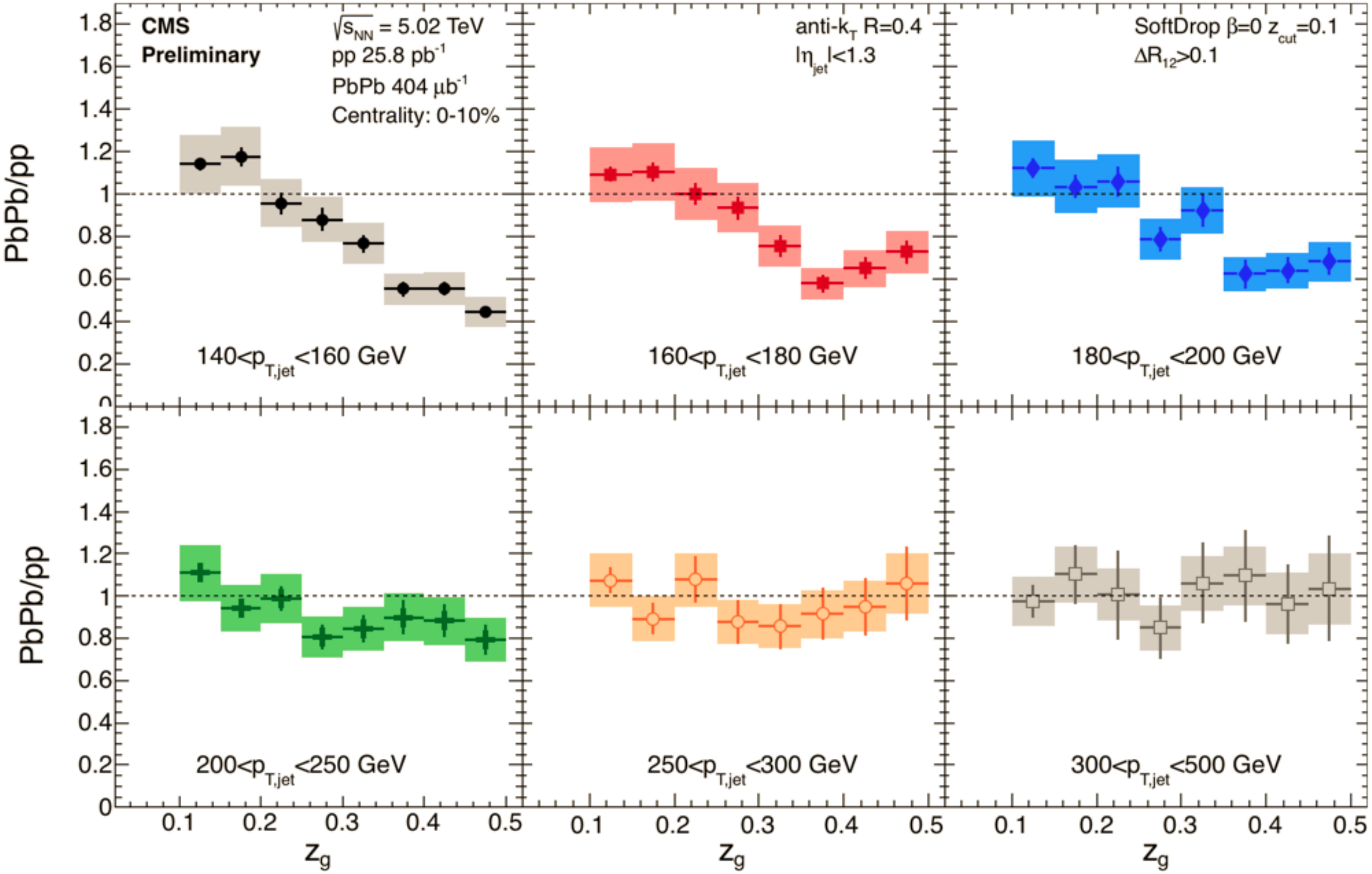
The splitting function $p(z_g)$ for soft dropped jets encodes the momentum sharing fraction for the hardest splitting/branching

CMS results (centrality dependence)



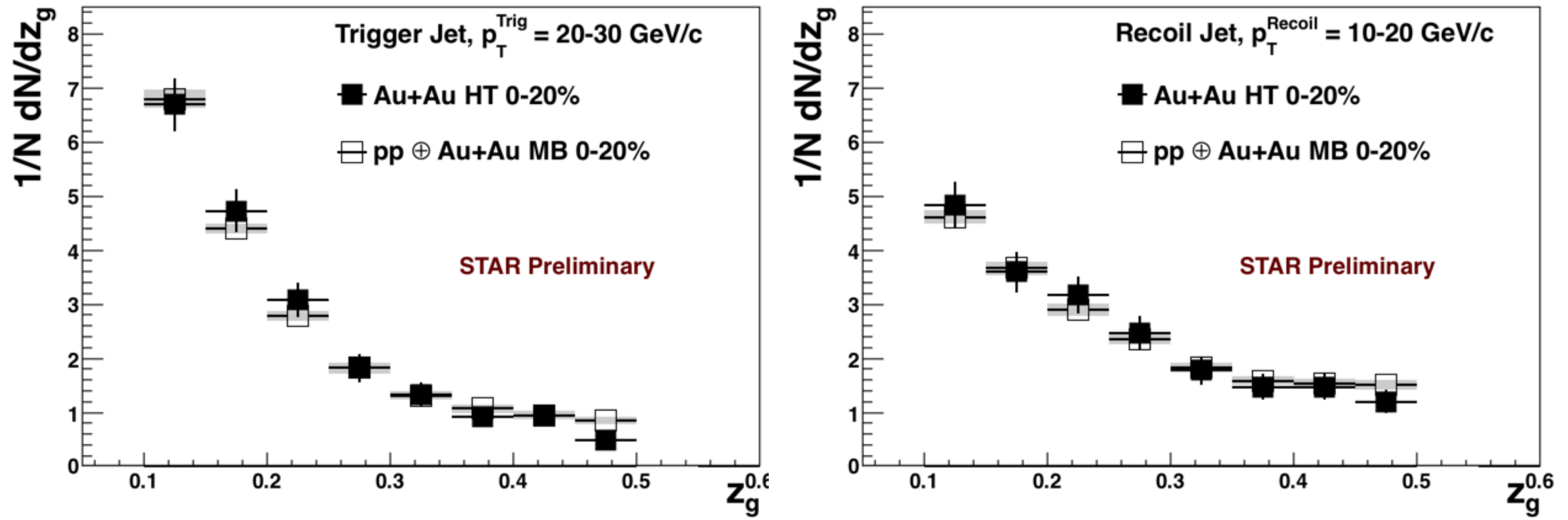
CMS: more imbalanced splitting (branching) in more central PbPb collisions.

CMS results (jet energy dependence)



CMS: stronger modification for decreasing jet energy

STAR result (jet energy dependence)



STAR: no significant modification of groomed jet splitting function (z_g distribution for soft dropped jet) in Au+Au collisions as compared to pp collisions

Not expected from the CMS result: strong modification for z_g distribution at the LHC (and **stronger modification for lower jet energy**)

Soft dropped jet splitting function in vacuum

Normalized p(z$_g$) distribution: $p(z_g) = \frac{1}{N_{jet}} \frac{dN}{dz_g}$

Theoretical framework:

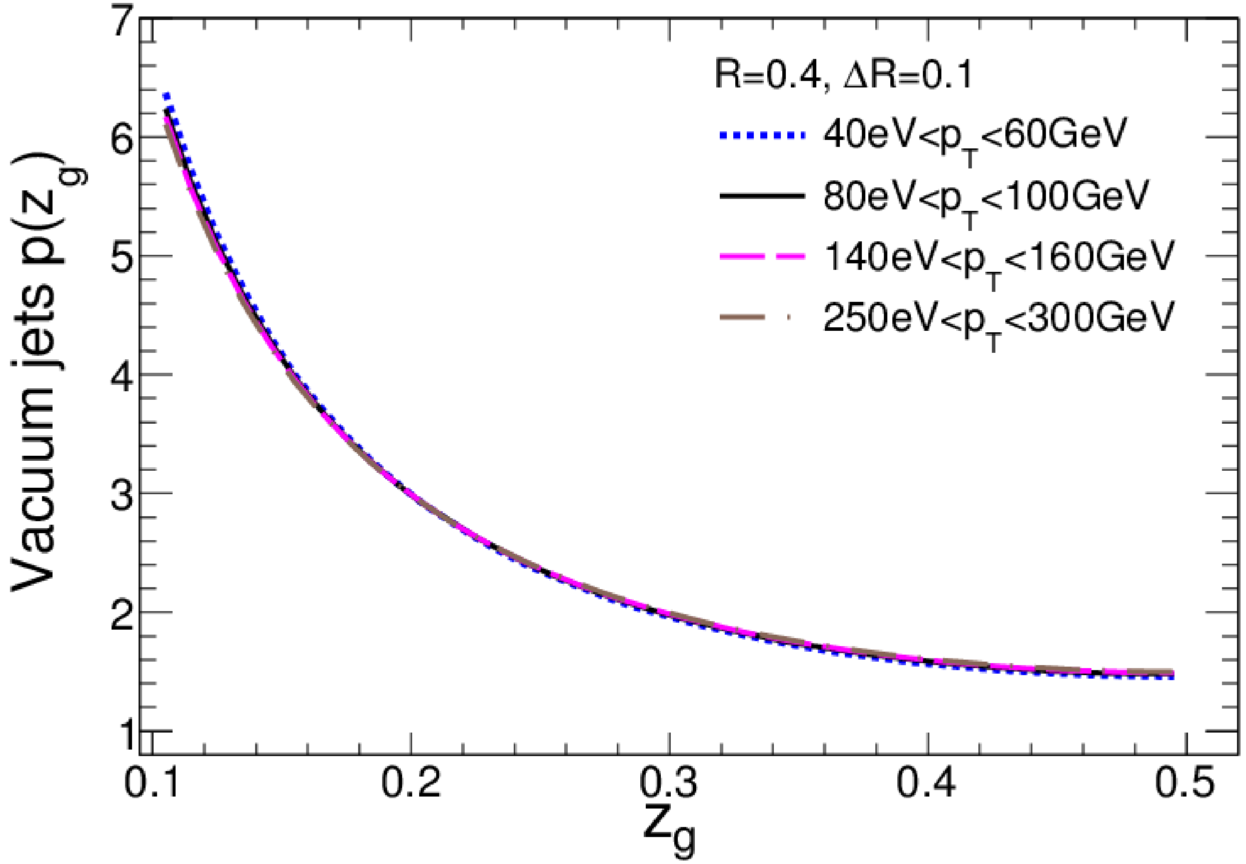
$$p(z_g) = \frac{1}{\sigma_{\rm total}} \sum_{i=q,g} \int_{PS} d\eta dp_T \frac{d\sigma^i}{d\eta dp_T} p_i(p_T, z_g)$$

$$p_i(z_g) = \frac{\int_{k_\Delta^2}^{k_R^2} dk_\perp^2 \, \overline{\mathcal{P}}_i(z_g, k_\perp^2)}{\int_{z_{\rm cut}}^{1/2} dx \int_{k_\Delta^2}^{k_R^2} dk_\perp^2 \, \overline{\mathcal{P}}_i(x, k_\perp^2)}$$

$$\begin{aligned} k_\Delta &= 2p_T x(1-x) \tan\tfrac{\Delta}{2} \\ k_R &= 2p_T x(1-x) \tan\tfrac{R}{2} \end{aligned}$$

$$\overline{\mathcal{P}}_i(x, k_\perp^2) = \sum_{j,l} \left[\mathcal{P}_{i\to j,l}(x, k_\perp^2) + \mathcal{P}_{i\to j,l}(1-x, k_\perp^2) \right]$$

Soft dropped jet splitting function in vacuum



Soft dropped jet splitting function $p(z_g)$ in vacuum is the same for quark & gluon jets, and is a little steeper for lower energy jets

Soft dropped jet splitting function in medium

$$\mathcal{P}_i(x,k_\perp^2)=\mathcal{P}_i^{\rm vac}(x,k_\perp^2)+\mathcal{P}_i^{\rm med}(x,k_\perp^2)$$

$$p_i(z_g)=\frac{\int_{k_\Delta^2}^{k_R^2}dk_\perp^2\left[\overline{\mathcal{P}}_i^{\rm vac}(z_g,k_\perp^2)+\overline{\mathcal{P}}_i^{\rm med}(z_g,k_\perp^2)\right]}{\int_{z_{cut}}^{1/2}dx\int_{k_\Delta^2}^{k_R^2}dk_\perp^2\left[\overline{\mathcal{P}}_i^{\rm vac}(x,k_\perp^2)+\overline{\mathcal{P}}_i^{\rm med}(x,k_\perp^2)\right]}$$

Here we take higher-twist jet energy loss formalism:

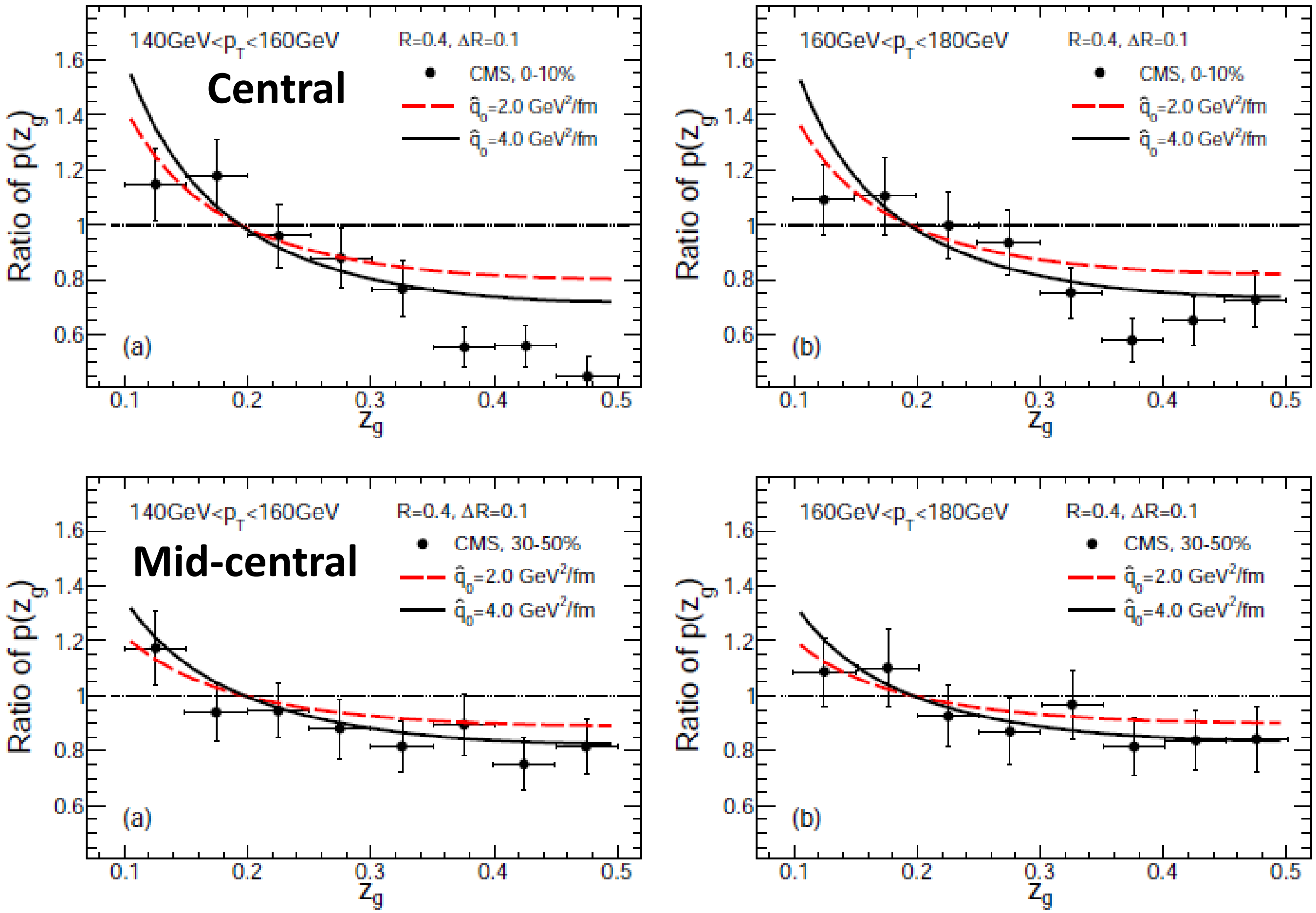
$$\mathcal{P}_i^{\rm med}(x,k_\perp^2)=\frac{2C_A\alpha_s}{\pi k_\perp^4}\mathcal{P}_i^{\rm vac}(x)\int dt\hat{q}_i(t)\sin^2\left(\frac{t}{2\tau_f}\right)$$

Soft dropped jet splitting $p(z_g)$ in medium is expected to be steeper than in vacuum

Incorporate the out-of-cone energy loss of the jet as follows:

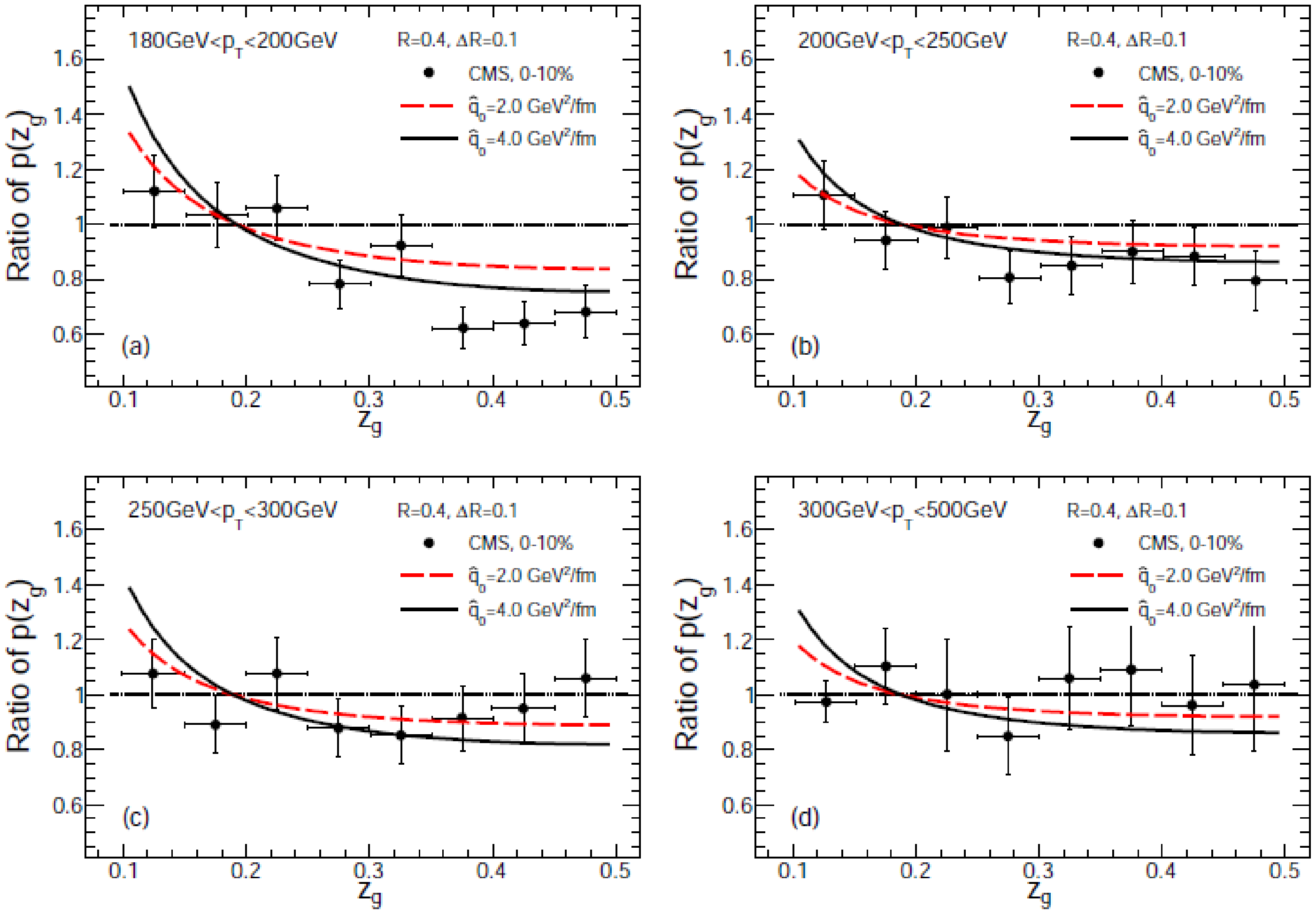
$$p^{\rm obs}(z_g,p_{\rm T})=\frac{1}{\sigma_{\rm total}}\sum_{i=q,g}\int_{\rm PS}d^2Xd^2p_{\rm T}\frac{d\sigma_i(\vec{X},p_{\rm T}+\Delta E_i)}{d^2Xd^2p_{\rm T}}p_i(p_{\rm T}+\Delta E_i,z_g)$$

Soft dropped jet splitting function @LHC



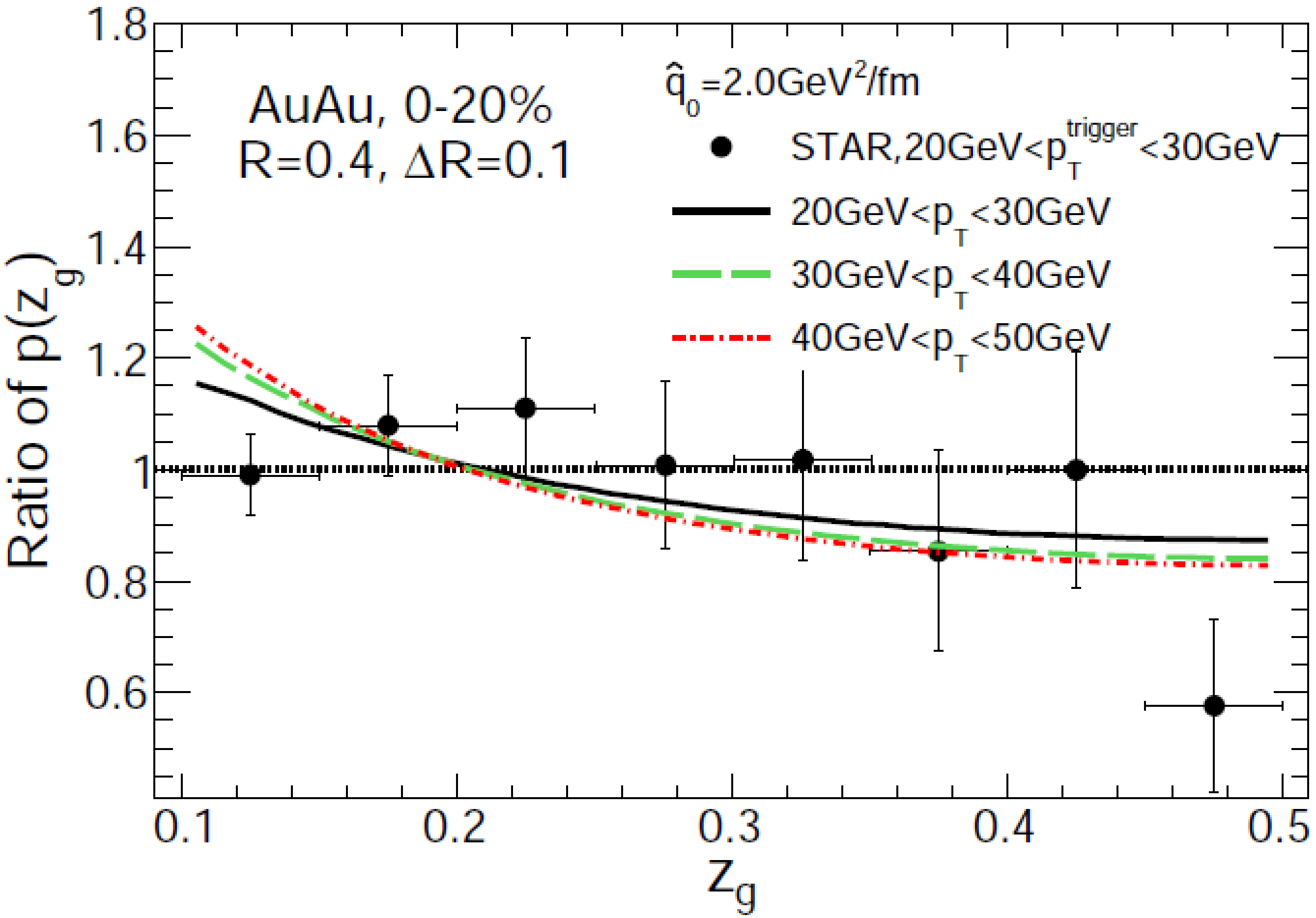
More jet-medium interaction, steeper splitting function for soft dropped jet

Jet energy dependence of jet splitting function @LHC



CMS: smaller jet energy, large nuclear modification on soft dropped jet splitting function

Jet energy dependence of jet splitting function @RHIC

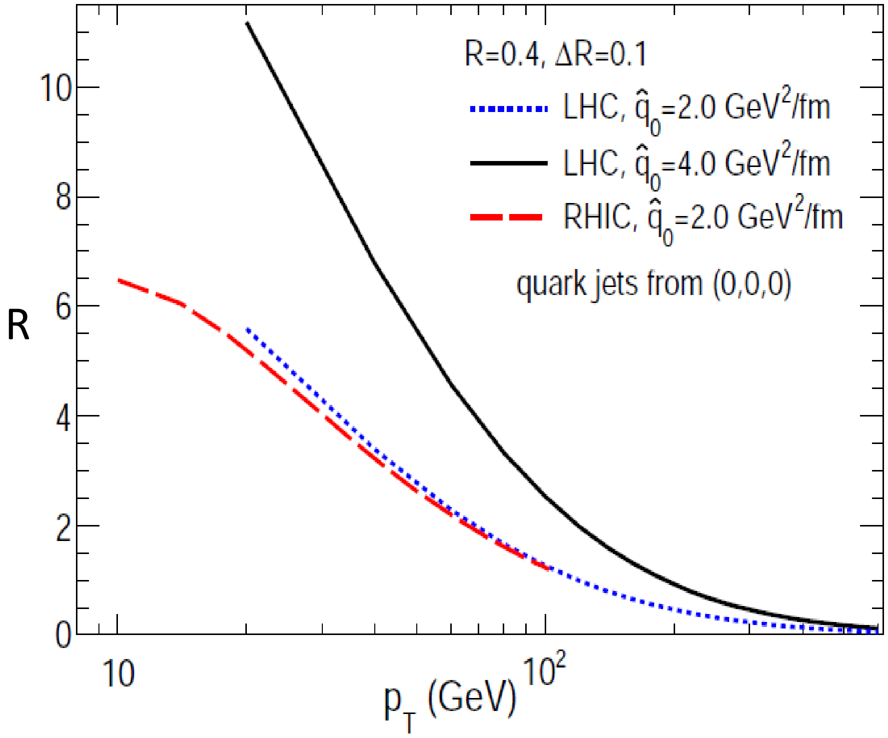


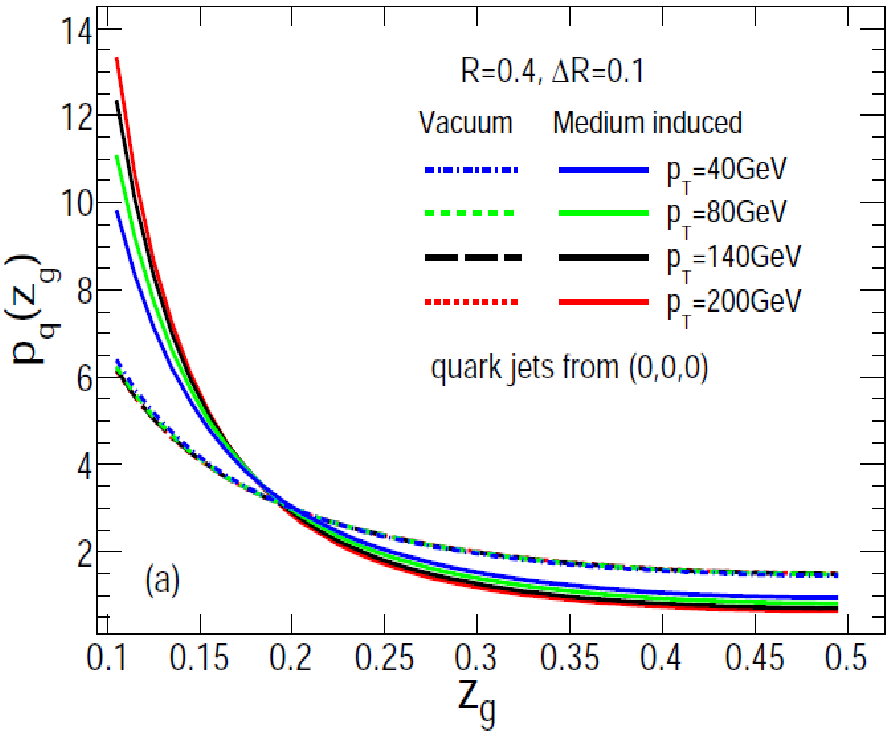
RHIC: smaller jet energies, less nuclear modification

CMS: smaller jet energies, more nuclear modification

Non-monotonic jet energy dependence is observed for p(z_g)

Non-monotonic jet energy dependence for $p(z_g)$



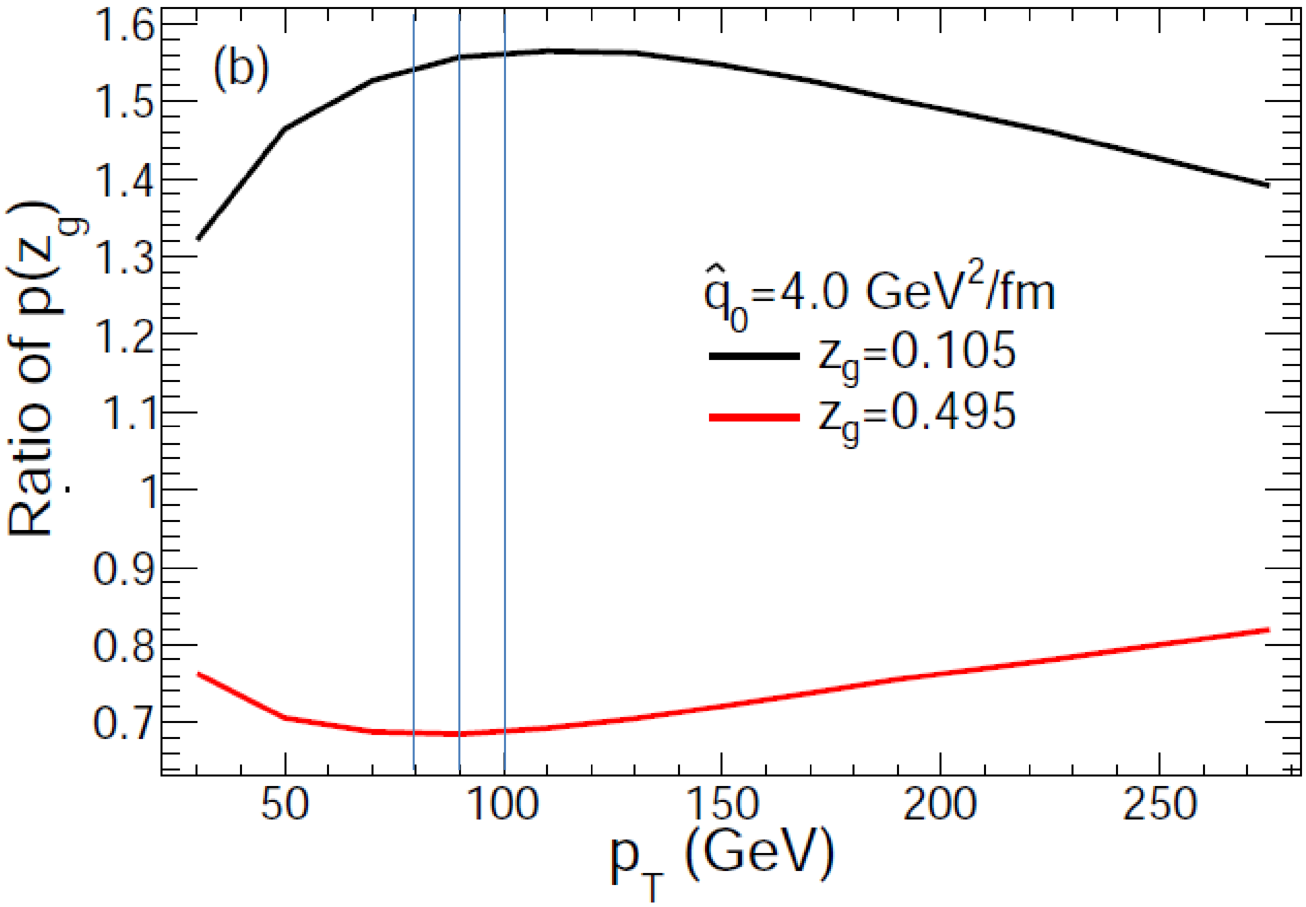


$$p_i(z_g) = \frac{\int_{k_\Delta^2}^{k_R^2} dk_\perp^2 \left[\overline{\mathcal{P}}_i^{\rm vac}(z_g, k_\perp^2) + \overline{\mathcal{P}}_i^{\rm med}(z_g, k_\perp^2)\right]}{\int_{z_{cut}}^{1/2} dx \int_{k_\Delta^2}^{k_R^2} dk_\perp^2 \left[\overline{\mathcal{P}}_i^{\rm vac}(x, k_\perp^2) + \overline{\mathcal{P}}_i^{\rm med}(x, k_\perp^2)\right]}$$

$$\int_{k_\Delta^2}^{k_R^2} dk_\perp^2 \overline{\mathcal{P}}_i^{\rm med}(x, k_\perp^2) \to \begin{cases} 1/x\,, & \text{small } E \\ 1/x^3\,, & \text{large } E \end{cases}$$

With smaller jet energies, the medium-induced contribution is increasing, but the medium-induced part of the splitting function is flatter

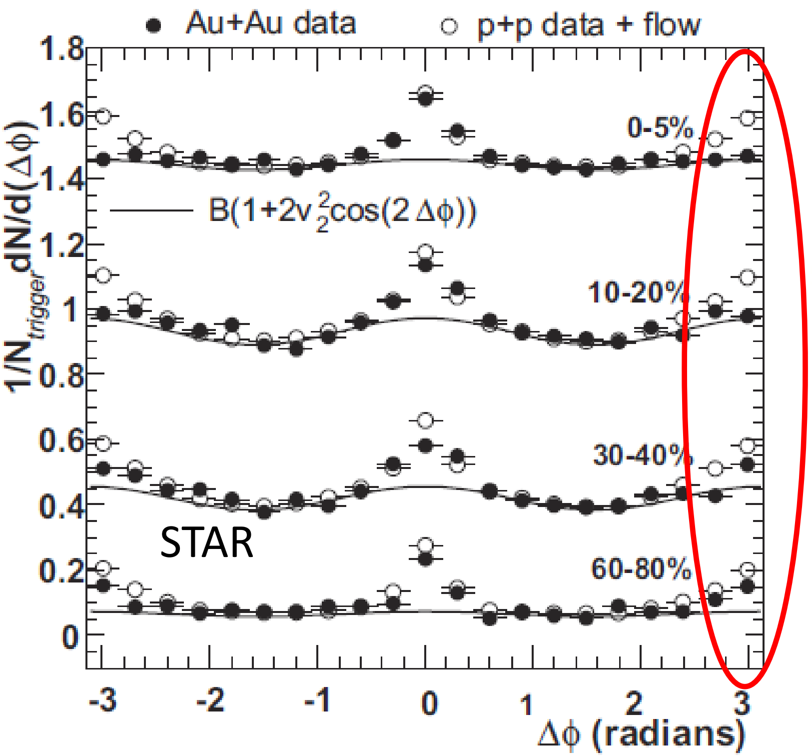
Jet energy dependence for $p(z_g)$ @ LHC

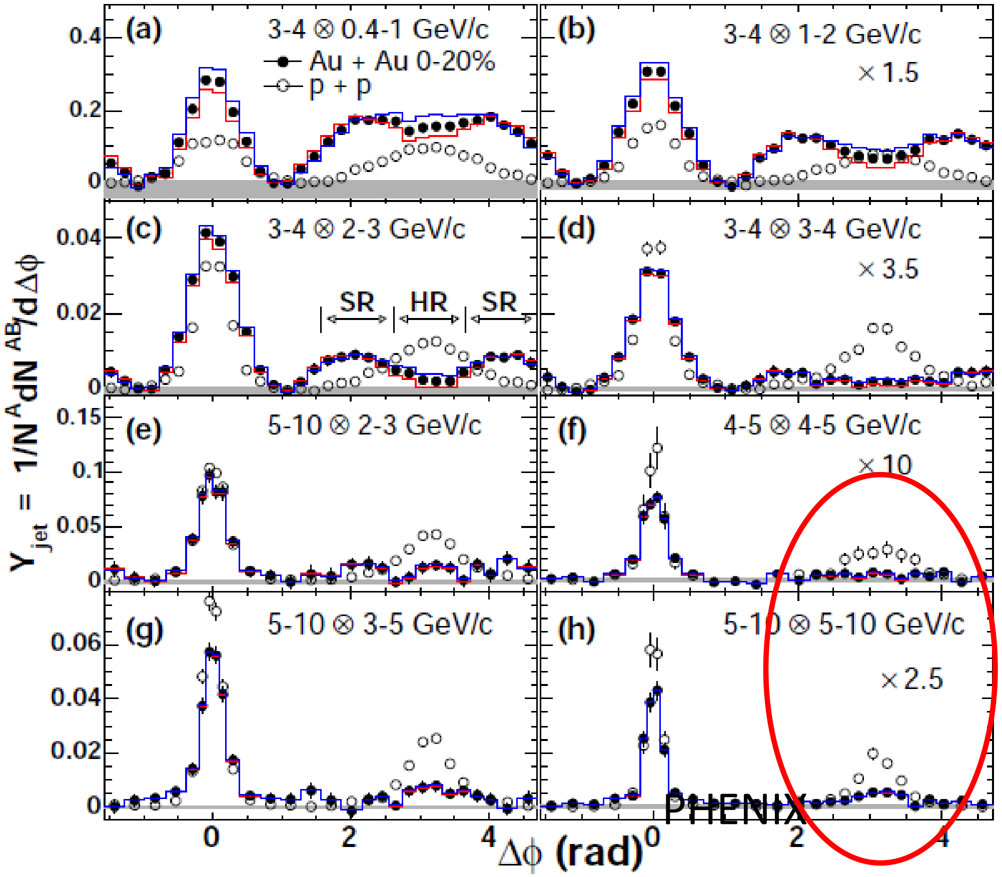


Non-monotonic jet energy dependence for $p(z_g)$

Jet-related correlations

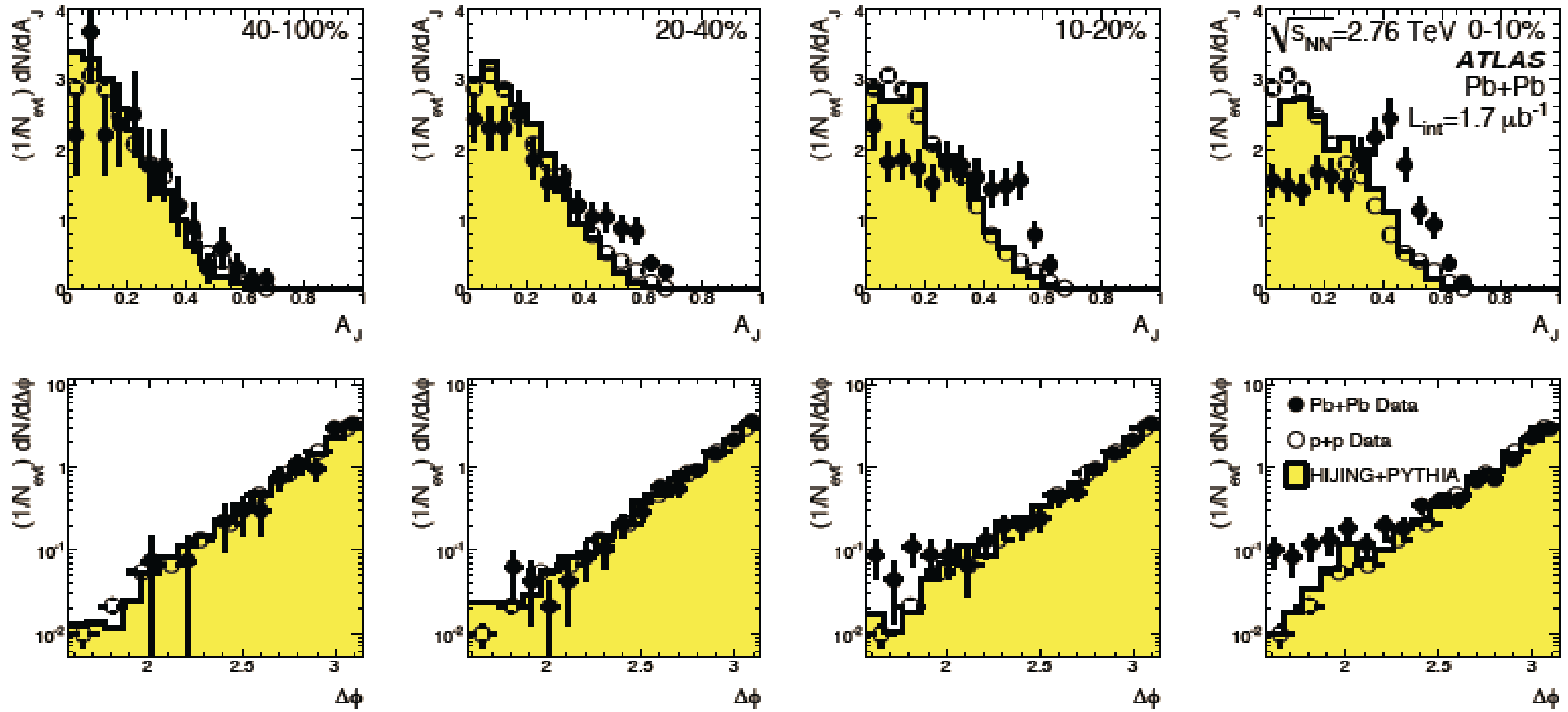
Jet-related correlations





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

Dijet correlations



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

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

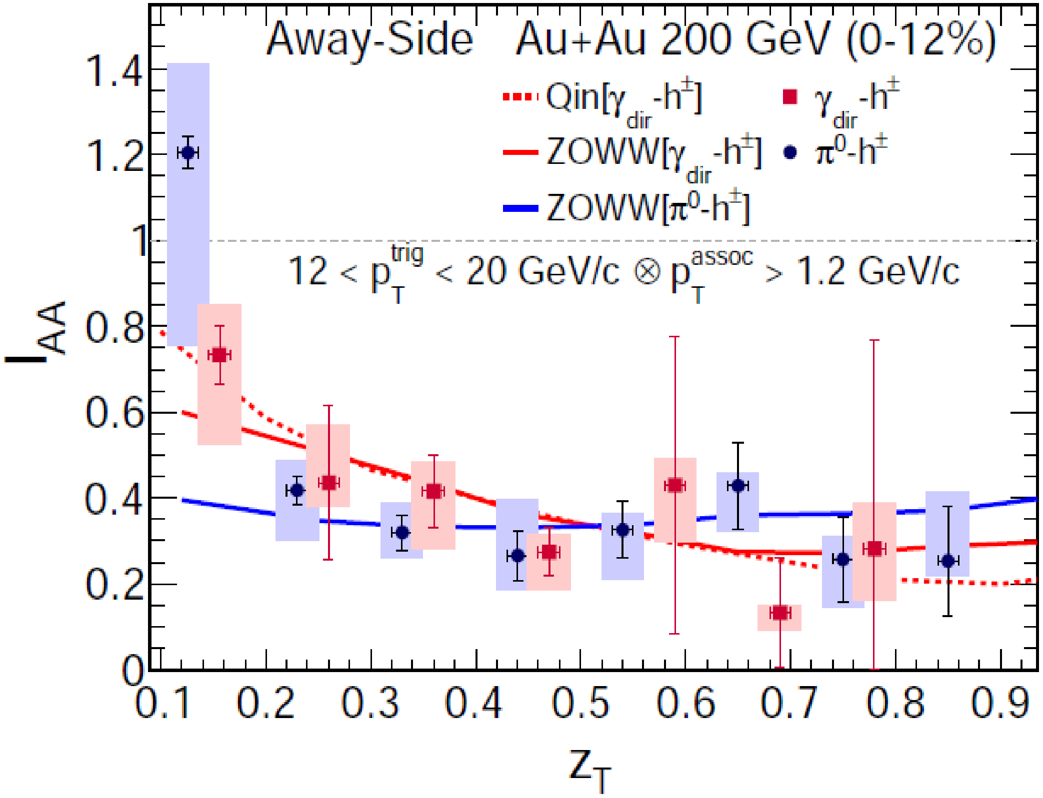
Strong modification of momentum imbalance distribution

=> Significant energy loss experienced by the subleading jets

Largely-unchanged angular distribution

=> medium-induced broadening is quite modest

Nuclear modification of per-trigger yield



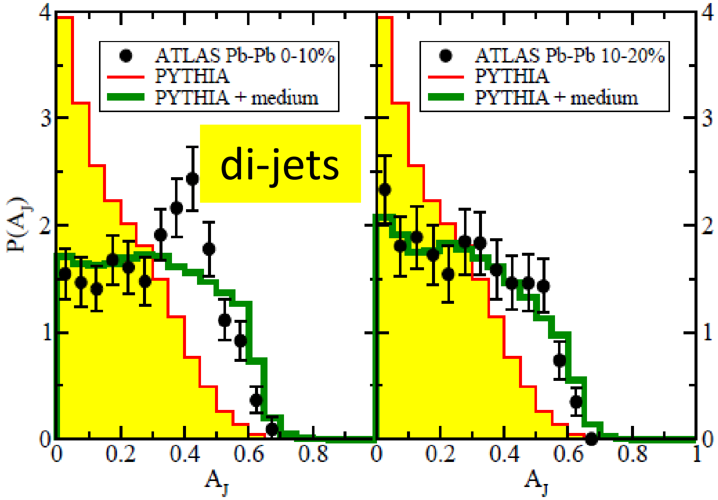
Most theoretical studies on related correlations in AA have mainly focused on parton energy loss and its effect on the nuclear modification of the per-trigger yield

The back-to-back angular correlations directly reflects the transverse momentum broadening, but quantitative studies are lacking

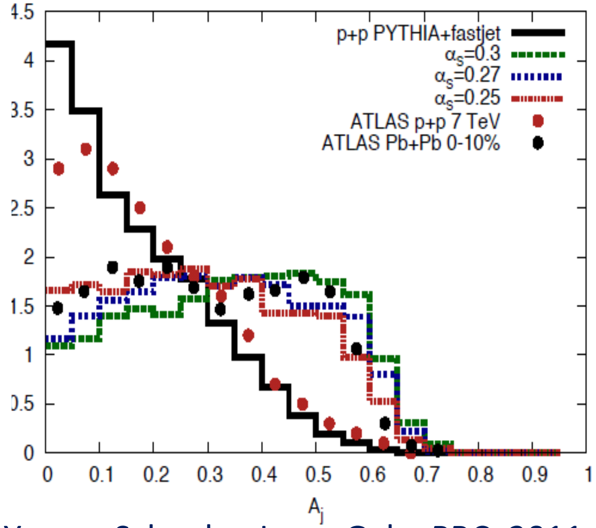
$$I_{AA}(z_T) = \frac{D_{AA}(z_T)}{D_{pp}(z_T)}, \; z_T = \frac{p_{T,a}}{p_{T,t}}$$

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

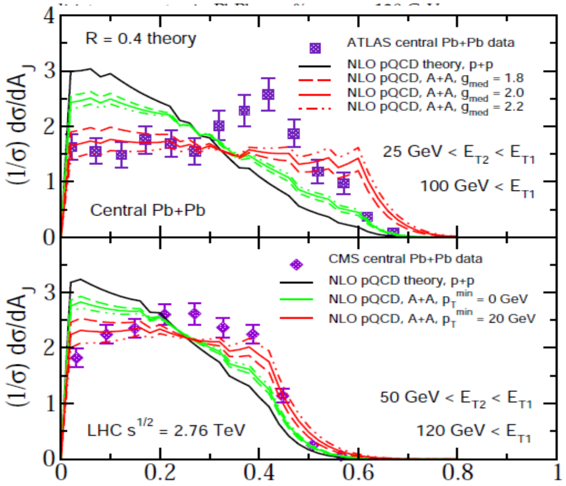
Nuclear modification of dijet (& γ-jet) asymmetry



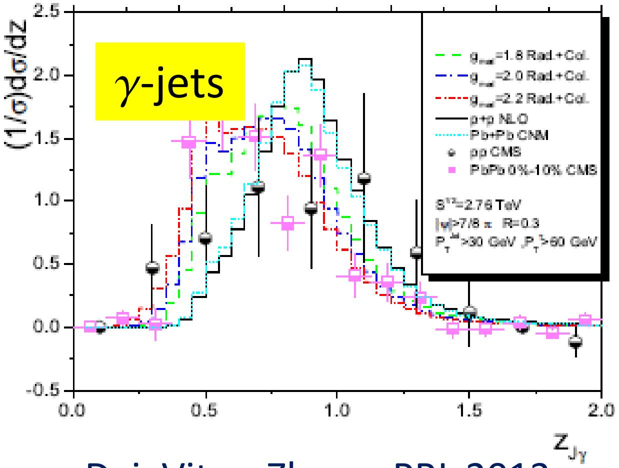
GYQ, Muller, PRL, 2011



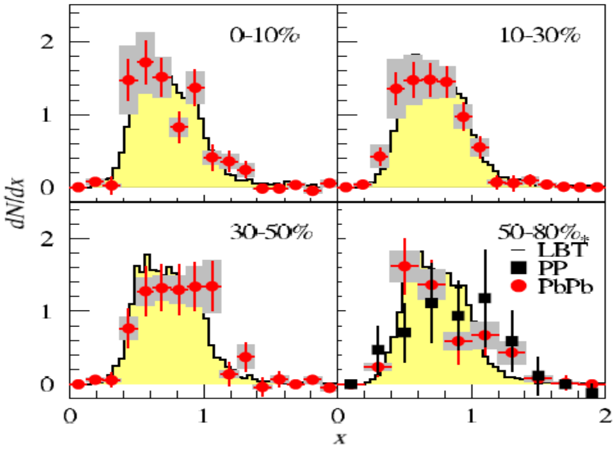
Young, Schenke, Jeon, Gale, PRC, 2011



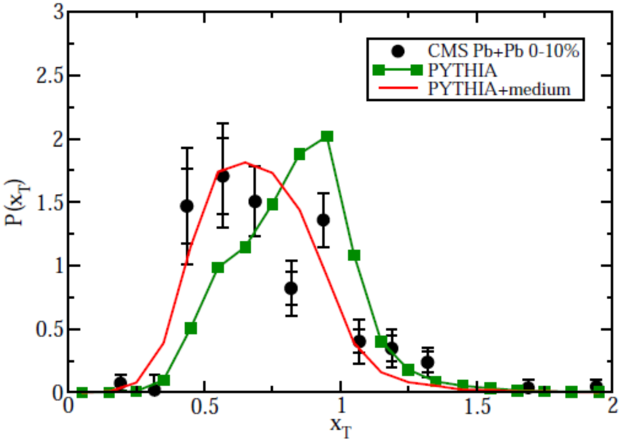
He, Vitev, Zhang, PLB 2012



Dai, Vitev, Zhang, PRL 2013



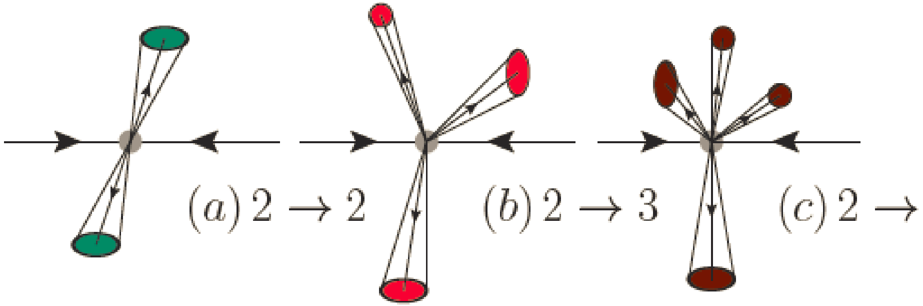
Wang, Zhu, PRL 2013

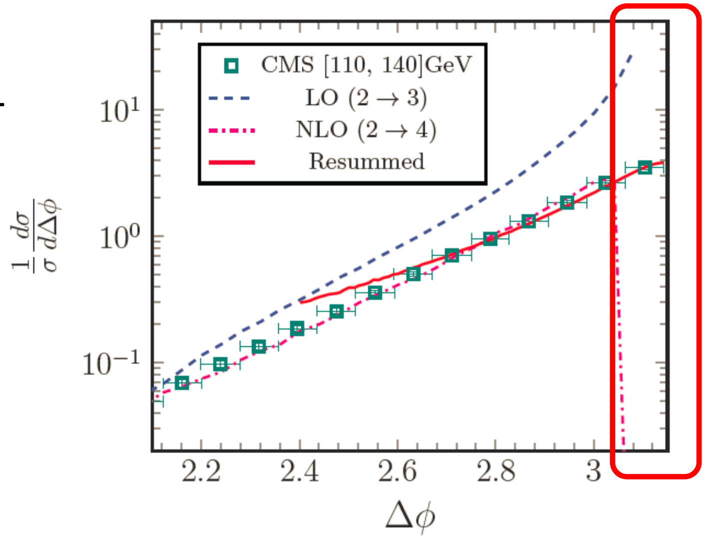


GYQ, EPJC 2014

Dijet angular correlations in pp collisions

- Perturbative QCD expansion in α_s (2->2, 2->3, 2->4, …)





- For $\Delta\varphi$ away from π, L~C, pQCD expansion in α_s works well

$$\alpha_s \log^2\left(\frac{p_T^2}{q_T^2}\right) \qquad q_T = \left|\vec{p}_{T,1} + \vec{p}_{T,2}\right|$$

- For $\Delta\varphi$ around π, $q_T \ll p_T$, L>>C, pQCD expansion fails. Need to resum large logarithms to all order (arbitrary numbers of soft gluon radiation)

pQCD expansion (schematic):

$$\sigma_0 \sum_{i=0}^{\infty} \alpha_s^i \left(L^i + C^{(i)}\right)$$

$$\sigma_0 \sum_{i=0}^{n-1} \alpha_s^i L^i \;\Big|\; \sigma_0 \sum_{i=0}^{n-1} C^{(i)}$$

$$\sigma_0 \sum_{i=n}^{\infty} \alpha_s^i L^i \;\Big|\; \sigma_0 \sum_{i=n}^{\infty} C^{(i)}$$

Sudakov resummation

Chen, GYQ, Wei, Xiao, Zhang, arXiv:1612.04202

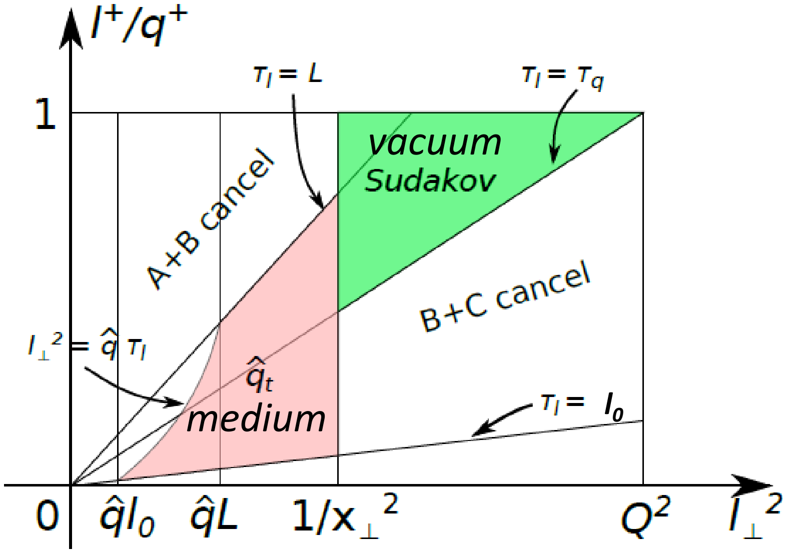
Based on: Nagy, PRL88 (2002), PRD68 (2003); Sun, Yuan, Yuan, PRL113 (2014), PRD92 (2015)

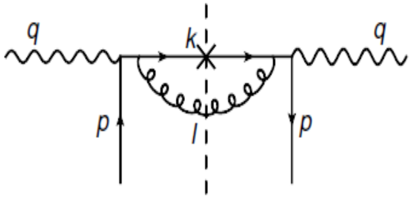
Sudakov resummation in medium

In large medium, the double logarithms due to ***vacuum*** *Sudakov effects* and ***medium-induced*** *broadening effects* come from ***different*** regions of the phase space for the radiated gluon. The Sudakov factors ***factorize***:

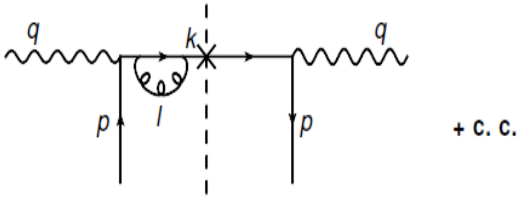
$$S_{\rm med} = S_{\rm vac} + \frac{1}{4}\left\langle p_\perp^2\right\rangle_{\rm med} b_\perp^2$$

Mueller, Wu, Xiao, Yuan, arXiv:1608.07339

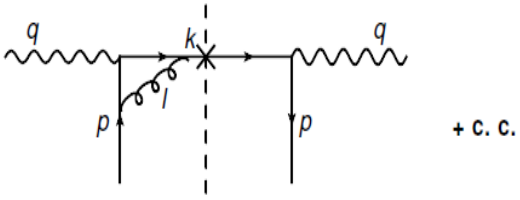




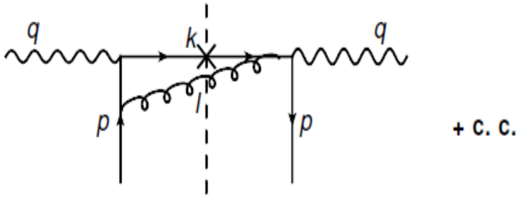
(A)



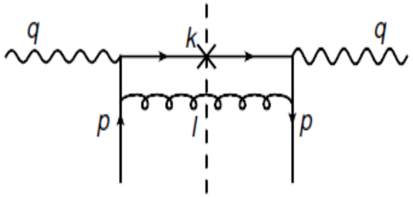
(B)



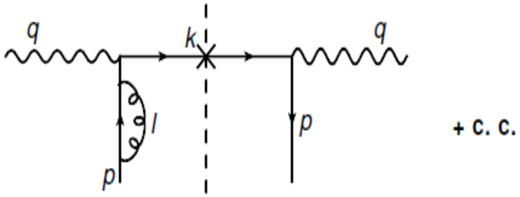
(C)



(D)



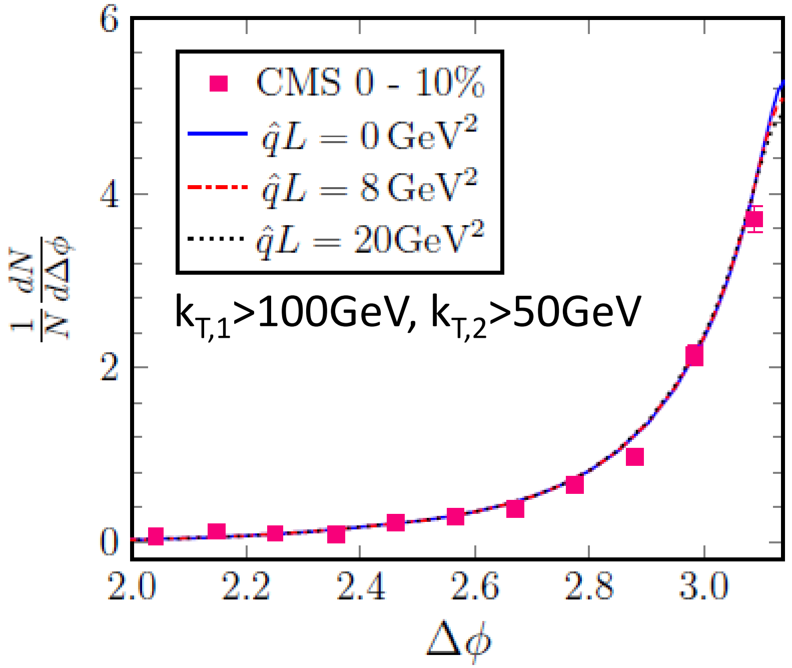
(E)



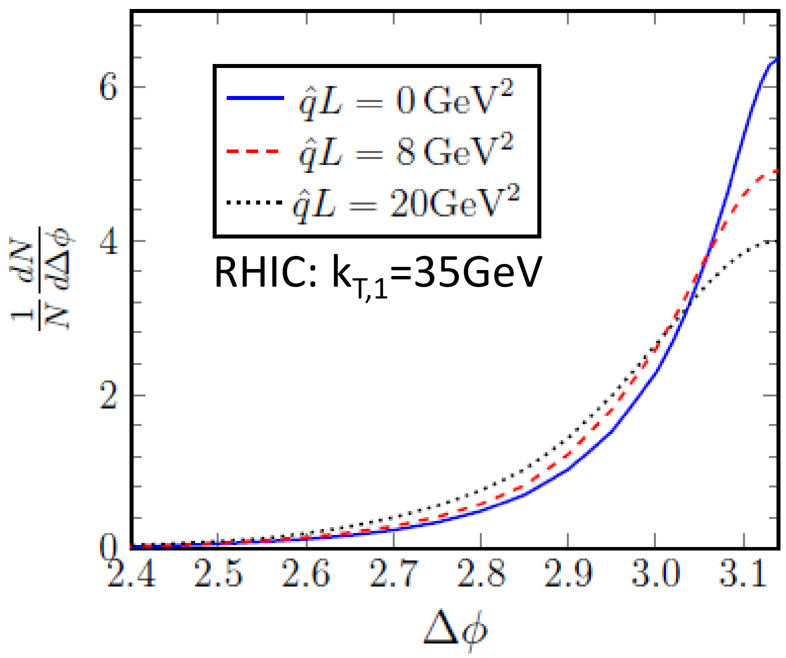
(F)

Dijet angular correlations in AA

$$\frac{d^4\sigma}{dy_1 dy_2 dk_{1\perp}^2 d^2k_{2\perp}} = \sum_{ab} \sigma_0 \int \frac{d^2\vec{b}_\perp}{(2\pi)^2} e^{-i\vec{q}_\perp\cdot\vec{b}_\perp}\, x_1\, f_a(x_1,\mu_b) x_2\, f_b(x_2,\mu_b) e^{-S(Q^2,b_\perp)}$$



$k_{T,1}$>100GeV, $k_{T,2}$>50GeV



RHIC: $k_{T,1}$=35GeV

LHC: vacuum Sudakov effect overwhelms medium-induced broadening effect

=> Very small angular decorrelation

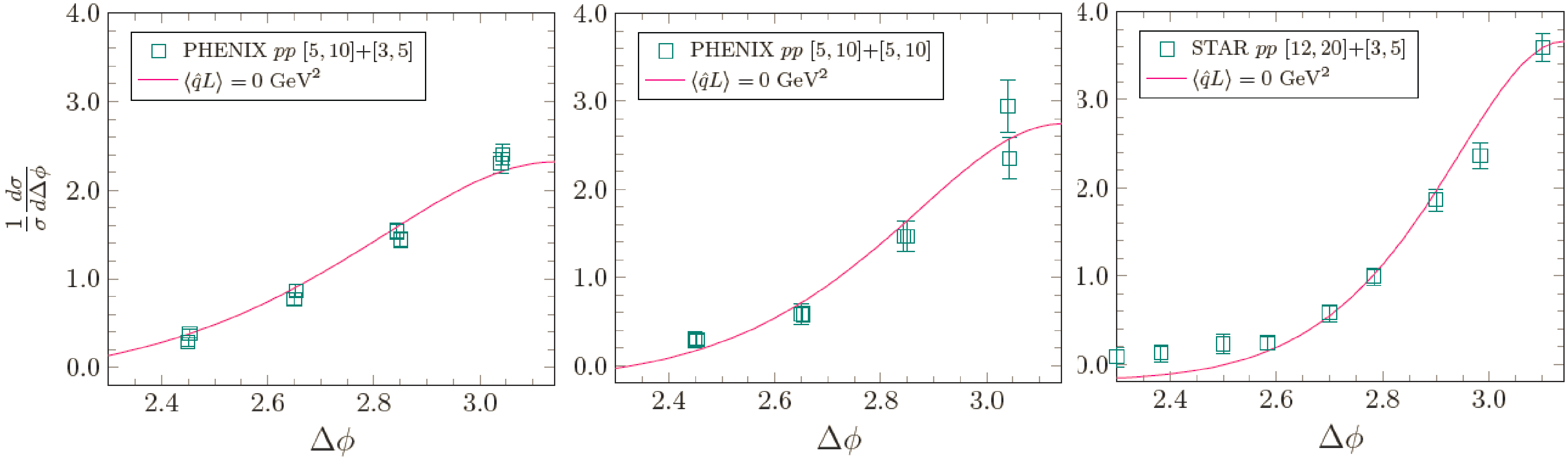
RHIC: medium-induced broadening effect comparable to vacuum Sudakov effect

=> Sizable angular decorrelation

Mueller, Wu, Xiao, Yuan, PLB763 (2016)

Dihadron angular correlations (pp baseline)

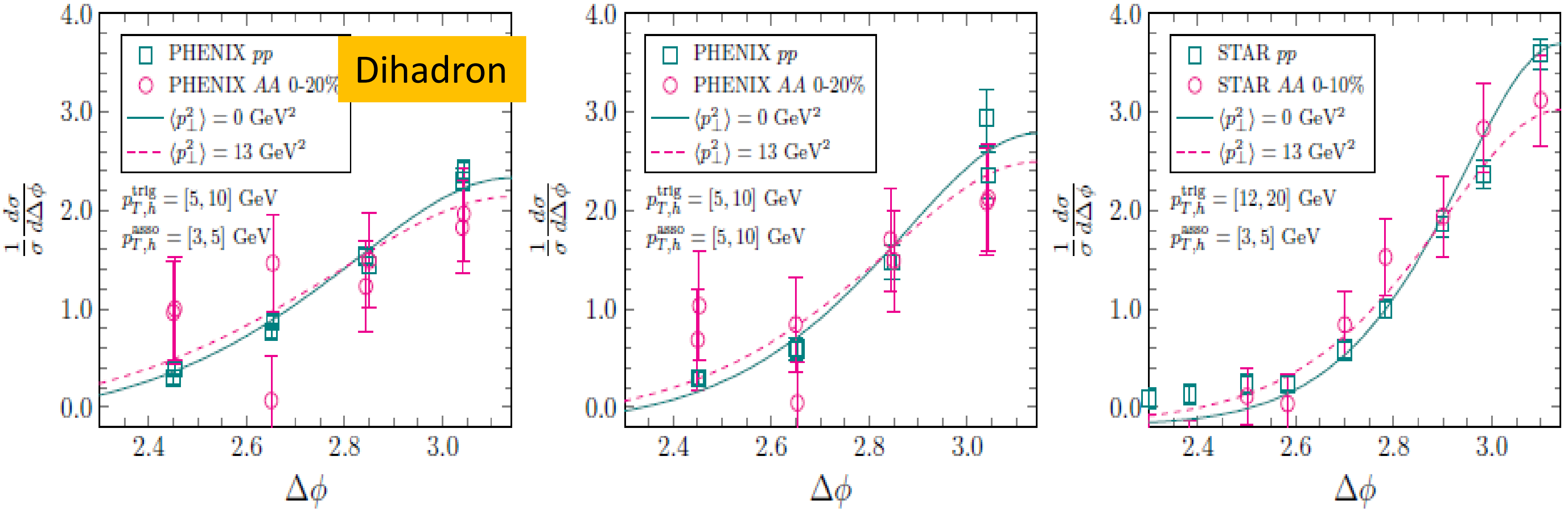
$$\frac{d\sigma}{d\Delta\phi} = \sum_{a,b,c,d} \int p_T^{h_1} dp_T^{h_1} \int p_T^{h_2} dp_T^{h_2} \int \frac{dz_c}{z_c^2} \int \frac{dz_d}{z_d^2}$$
$$\int bdb\ J_0(q_\perp b) e^{-S(Q,b)} x_a f_a(x_a,\mu_b) x_b f_b(x_b,\mu_b) \frac{1}{\pi} \frac{d\sigma_{ab\to cd}}{d\hat{t}} D_c(z_c,\mu_b) D_d(z_d,\mu_b)$$



First benchmark calculation of back-to-back dihadron angular correlations in pp collisions

Baseline for studying angular decorrelation from medium-induced effects in *AA* collisions

Dihadron back-to-back angular decorrelations

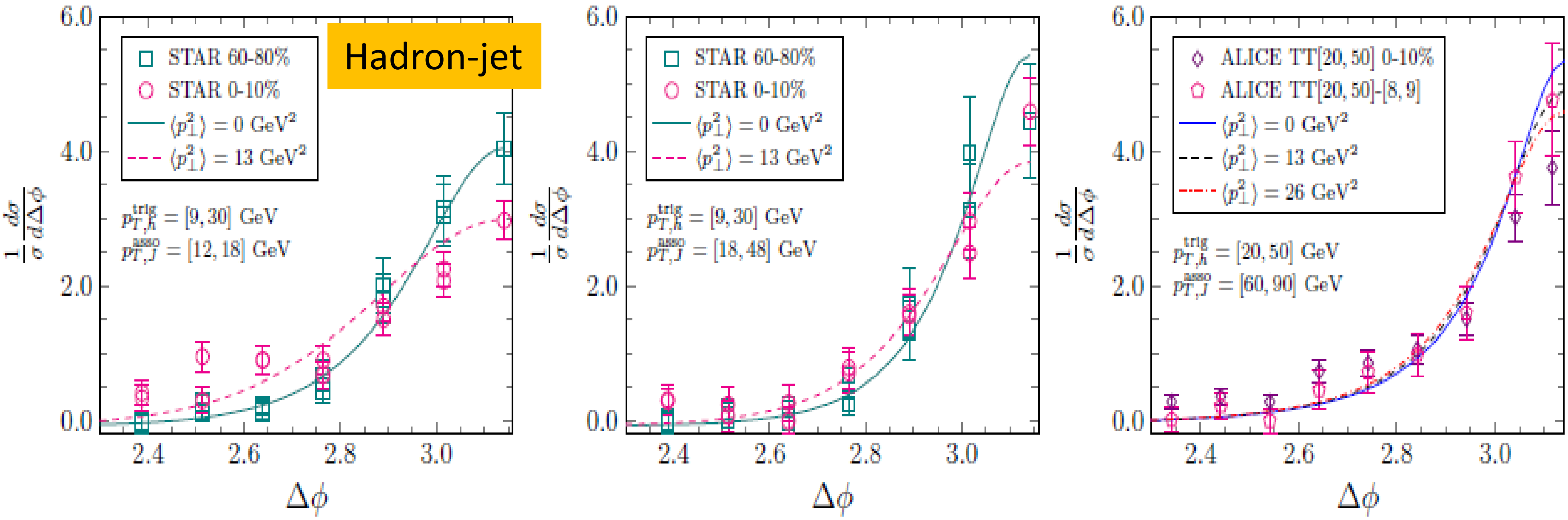


Dihadron

Angular decorrelations: a new & more direct method to probe medium broadening (q^{hat})

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

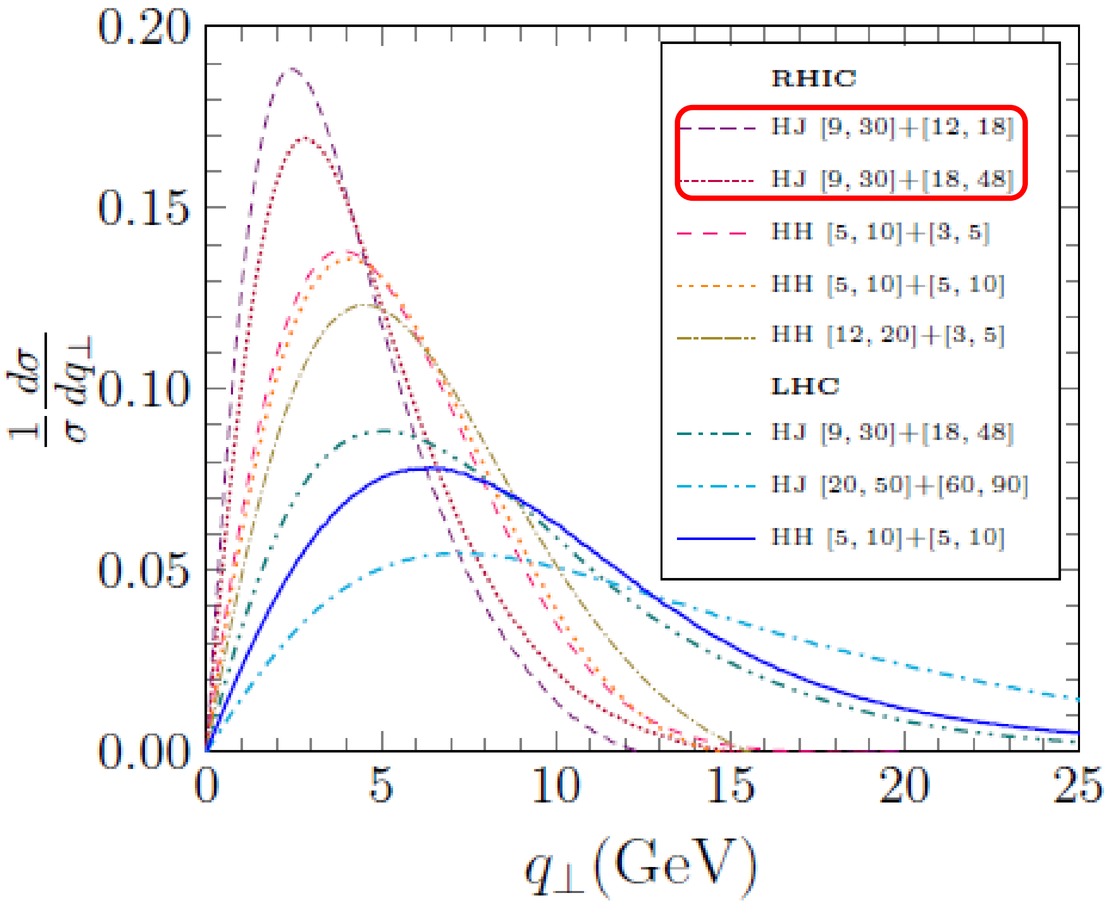
Hadron-jet back-to-back angular decorrelations


Hadron-jet

Angular decorrelations: a new & more direct method to probe medium broadening ($q^{\rm hat}$)

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

Sensitivity to medium-induced effect: dijet relative q_T distribution (in pp)



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

Extraction of p_T broadening & $\hat{q}$ @ RHIC

- Using CERN MINUIT package, our χ^2 analysis at RHIC gives:

$$\left\langle p_{\perp}^{2} \right\rangle \approx 13_{-4}^{+6}\,\mathrm{GeV}^{2}$$

- To directly compare to JET result:
  - Use OSU (2+1)D viscous hydrodynamics code to simulate the medium evolution
  - Use the double-log resummed expression for transverse broadening:

$$\langle p_{\perp}^{2} \rangle = \hat{q} L \frac{I_1\left[2\sqrt{\bar{\alpha}_s}\ln\left(\frac{L^2}{l_0^2}\right)\right]}{\left[\sqrt{\bar{\alpha}_s}\ln\left(\frac{L^2}{l_0^2}\right)\right]} \qquad \bar{\alpha}_s = \frac{\alpha_s N_c}{4\pi}$$

Liou, Mueller, Wu, NPA 916 (2013)

  - Relate the leading-order q^{hat} to T as: $\hat{q} \propto T^3$

- Realistic simulation at RHIC gives: $\hat{q}_0 \approx 3.9_{-1.2}^{+2.5}\,\mathrm{GeV}^2/\mathrm{fm}$

- JET result at RHIC: $\hat{q}_0 = 1.2 \pm 0.3\,\mathrm{GeV}^2/\mathrm{fm}$

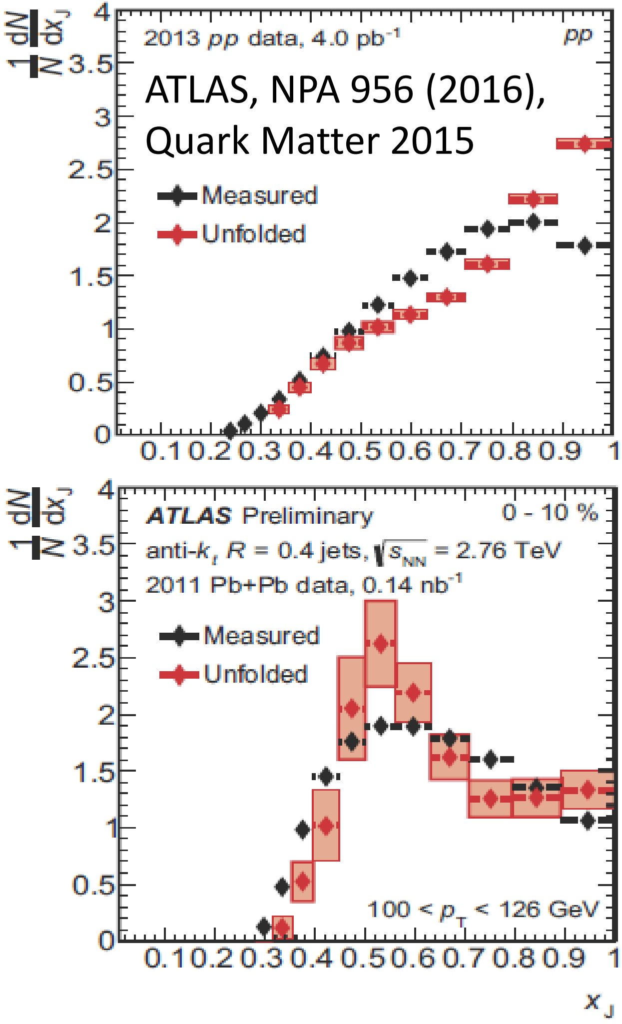
Dijet asymmetry A_J (x_J)

- Previous theoretical studies have compared to the uncorrected data which contain detector artifacts

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

- *Fully corrected dijet asymmetry data* have become available, and *reduce large ambiguities in theory-to-experiment comparison in studying jet energy loss effect*

- We use *the* ***resummation-improved pQCD approach*** to describe ***the fully corrected data*** in pp collisions and to study the medium effect in AA collisions


ATLAS, NPA 956 (2016), Quark Matter 2015

Dijet asymmetry in pQCD expansion

- Perturbative QCD expansion in α_s (2->2, 2->3, 2->4, …)
- PQCD expansion has an interesting upper (lower) bound for A_J (x_J) distribution
    - Assuming energy/momentum conservation & perfect detector with 4π coverage
    - For n-jet final state (2->n),

$$p_{T,1} = \left|\vec{p}_{T,2} + \ldots + \vec{p}_{T,n}\right| \le p_{T,2} + \ldots + p_{T,n} \le (n-1)p_{T,2}$$

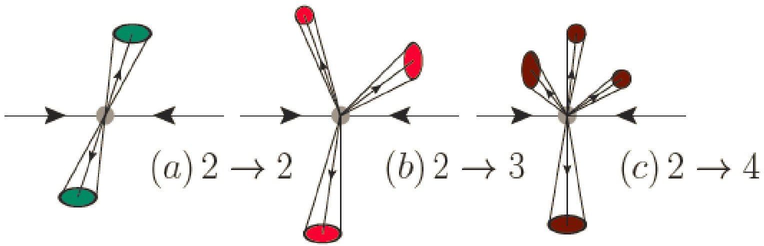
$$X_J^{2\to n} = \frac{p_{T,2}}{p_{T,1}} \ge \frac{1}{n-1} \qquad A_J^{2\to n} \ge \frac{n-2}{n}$$

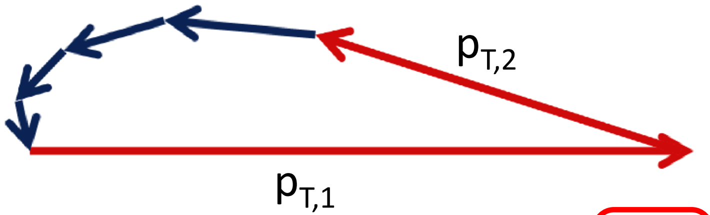
- PQCD expansion in α_s fails at x_J->1, which is similar to dijet, dihadron, hadron-jet angular correlations at $\Delta\varphi\sim\pi$ due to the appearance of large logarithms

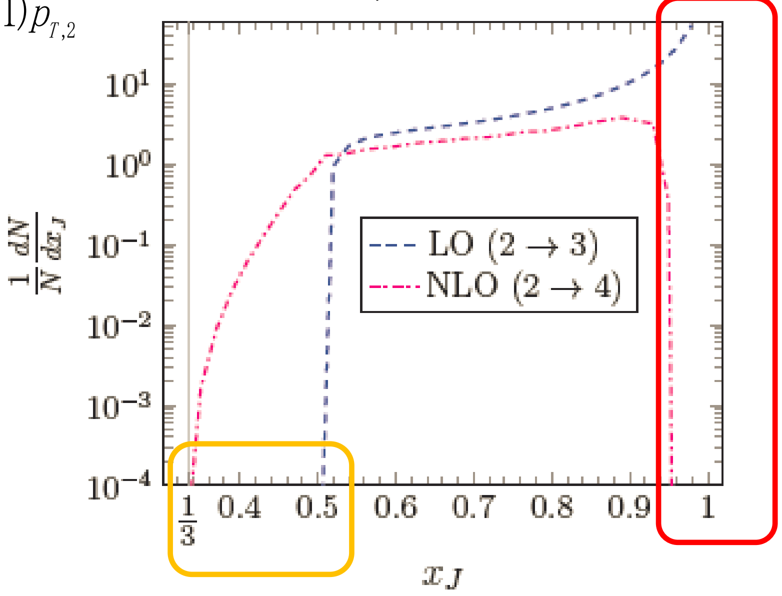
$$\alpha_s \log^2\left(\frac{p_T^2}{q_T^2}\right) \qquad q_T = \left|\vec{p}_{T,1} + \vec{p}_{T,2}\right| << p_{T,1}, p_{T,2}$$

Chen, GYQ, Wei, Xiao, Zhang, arXiv:1612.04202

Based on: Nagy, PRL88 (2002), PRD68 (2003)







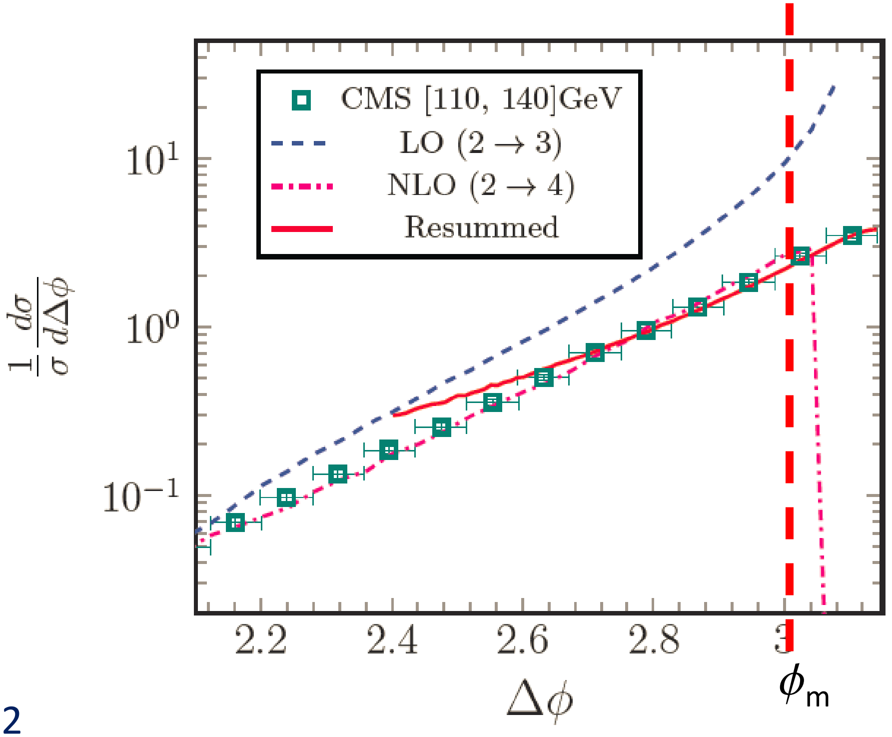
Sudakov-improved pQCD approach

$$\frac{1}{\sigma}\frac{d\sigma}{dx_J}\bigg|_{\text{Improved}} = \frac{1}{\sigma_{\text{NLO}}}\frac{d\sigma_{\text{NLO}}}{dx_J}\bigg|_{\Delta\phi<\phi_m} + \frac{1}{\sigma_{\text{Sudakov}}}\frac{d\sigma_{\text{Sudakov}}}{dx_J}\bigg|_{\pi>\Delta\phi>\phi_m}$$

NLO pQCD provides very good result at small X_J region

Sudakov resummation resums the alternating-sign series of large logarithms at x_J->1 region

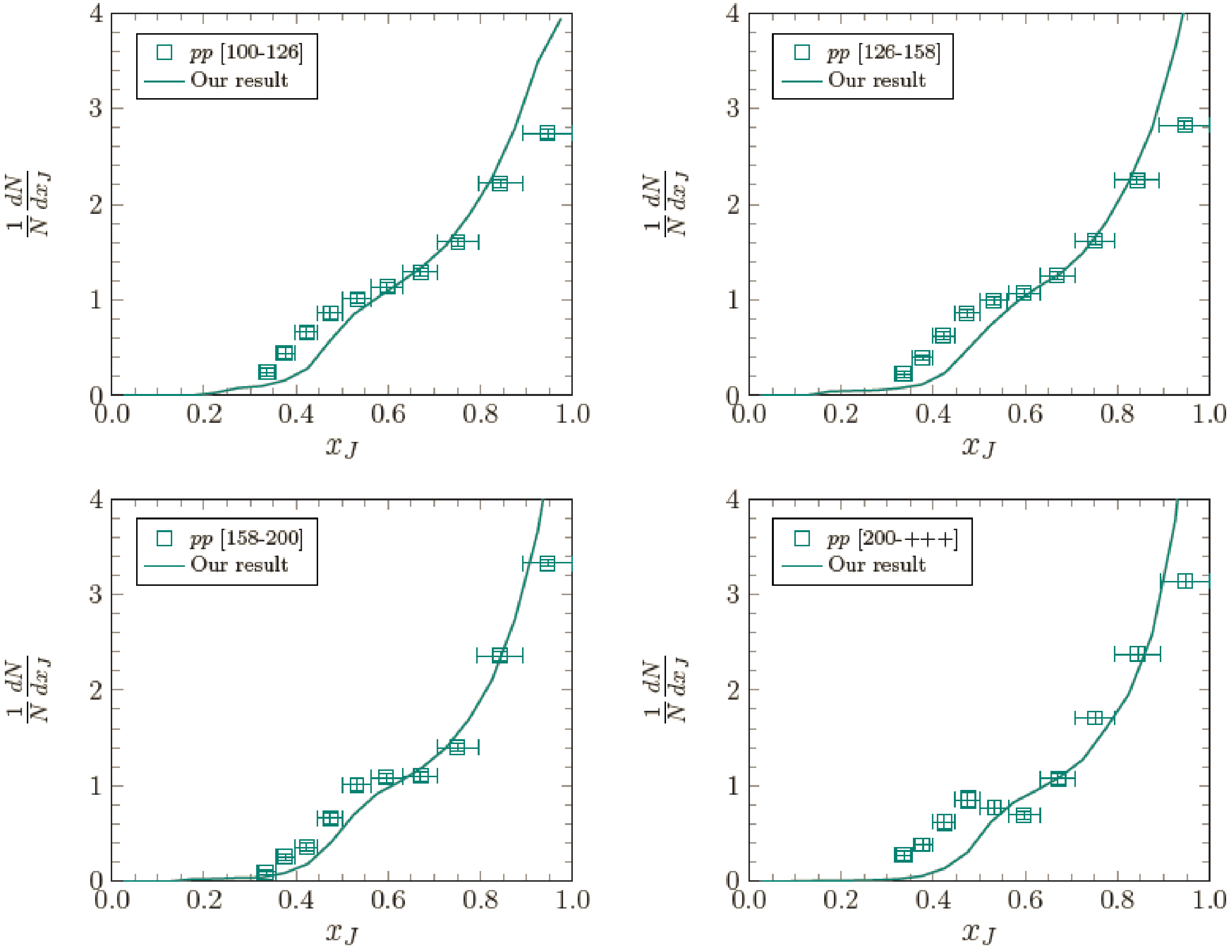
Essentially no free parameter in this approach (weak dependence on ϕ_m)



Chen, GYQ, Wei, Xiao, Zhang, arXiv:1612.04202

Based on: Nagy, PRL88 (2002), PRD68 (2003); Sun, Yuan, Yuan, PRL113 (2014), PRD92 (2015)

Dijet asymmetry in pp collisions



Dijet asymmetry in PbPb collisions @ LHC

- Using BDMPS jet energy loss probability distribution (hep-ph/9608322)

$$D(\epsilon) = \alpha\sqrt{\frac{\omega_c}{2\epsilon}}\exp\Big(-\frac{\pi\alpha^2\omega_c}{2\epsilon}\Big)$$

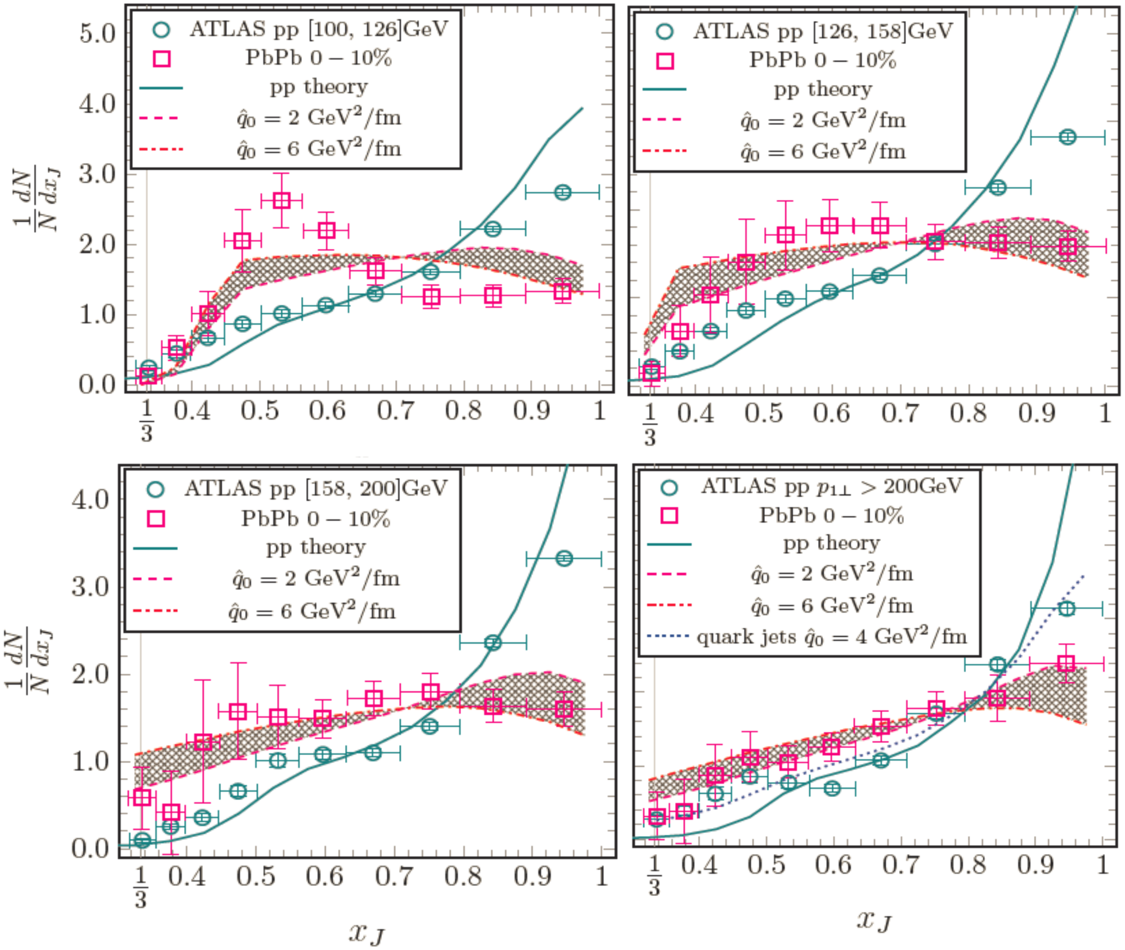
$$\omega_c \equiv \int dL\ \hat{q}L \qquad \alpha \equiv \frac{2\alpha_s C_R}{\pi}$$

- Combining with hydrodynamic simulation for medium and assuming gluon jets

$$\hat{q} = 2 - 6\mathrm{GeV}^2/\mathrm{fm}$$
$$@\ \mathrm{T} = 481\mathrm{MeV}$$

- Consistent with the original BDMPS estimate

$$\hat{q} = 0.3 - 0.8\mathrm{GeV}^2/\mathrm{fm}$$
$$@\ T = 250\mathrm{MeV}$$



Summary

- **Large transverse momentum hadrons**
  - Light and heavy flavor jet quenching on the same footing in LBT

- **Full jets**
  - Full jet in-medium evolution and energy loss: interplay of different mechanisms
  - Jet shape: evidence of jet-induced medium excitation at large r
  - Medium-modified groomed jet splitting function: non-monotonic dependence on jet energy for the nuclear modification of $p(z_g)$ distribution

- **Jet-related correlations**
  - Back-to-back angular correlations provide a new and more direct method to extract medium induced broadening and q^{hat}
  - Developed the resummation improved pQCD approach to describe the fully corrected dijet asymmetry data