Probing transverse momentum broadening via dihadron and hadron-jet angular correlations

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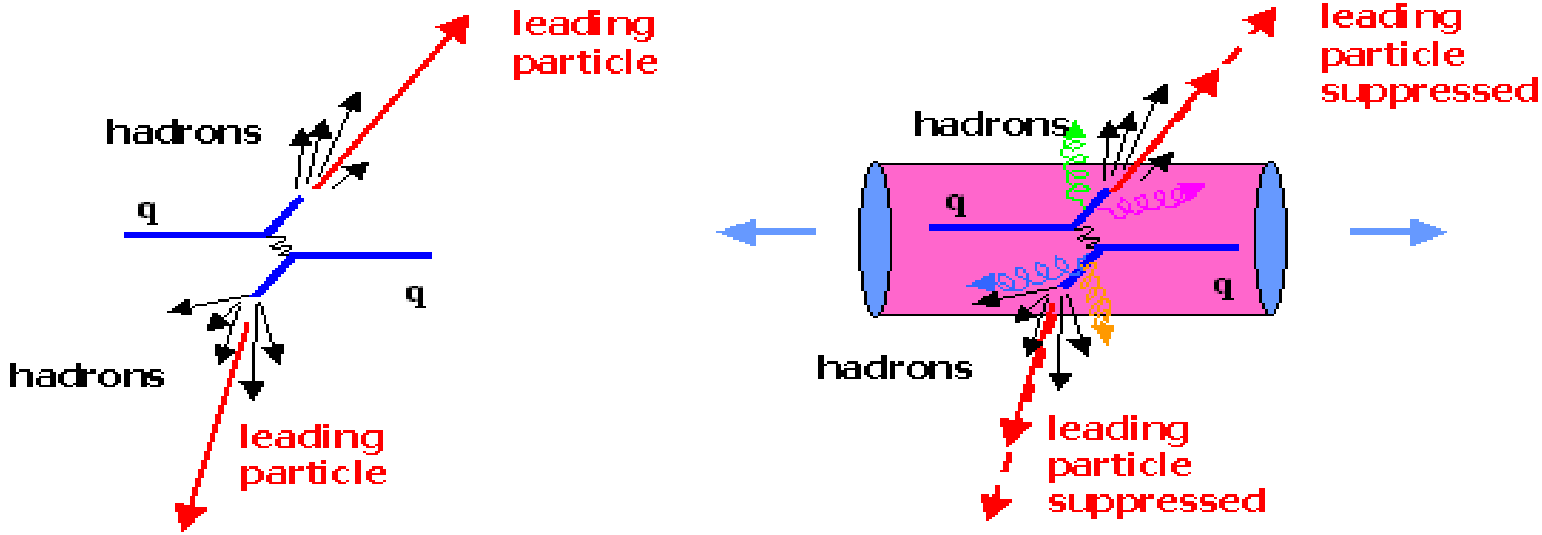
arXiv:1607.01932, arXiv:1612.04202

Outline

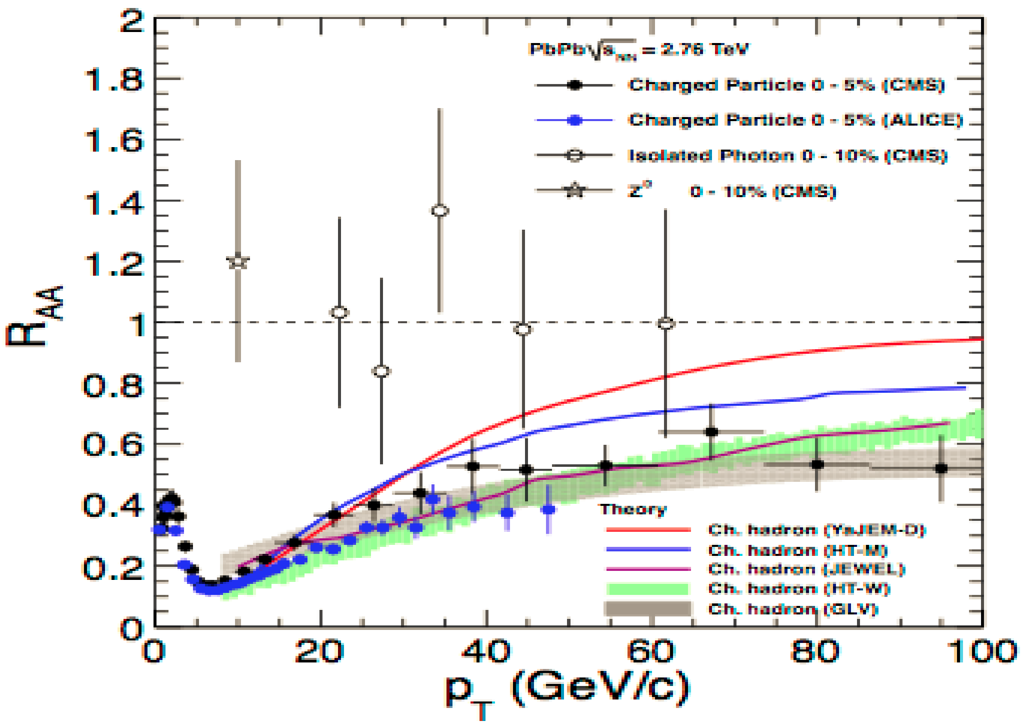
- Introduction & motivation
  - Jet quenching, parton energy loss, transverse momentum broadening, q^{hat}
- Dijet angular correlations in pp collisions (pQCD vs. resummation)
- Extract transverse momentum broadening and q^{hat} from dihadron and hadron-jet angular correlations in AA collisions
- Summary

Jets as hard probes of QGP



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

Evidences for jet quenching



Nuclear modification factor:

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

- If AA collisions are a simple combination of many NN collisions, then $R_{AA}=1$

- Hadron: $R_{AA}<1$
- Photon & Z boson: $R_{AA}=1$

- Due to final-state interaction between high energy partons and QGP, the production of high p_T hadrons (from the fragmentation of high-energy partons) is suppressed

- Jet quenching mainly originates from final-state jet-medium interaction

Jet-medium interaction & jet quenching parameter

- Two aspects of jet-medium interaction
  - Jet energy loss => modification or suppression of jet and hadron production rates
  - Transverse momentum broadening => angular deflections and decorrelations

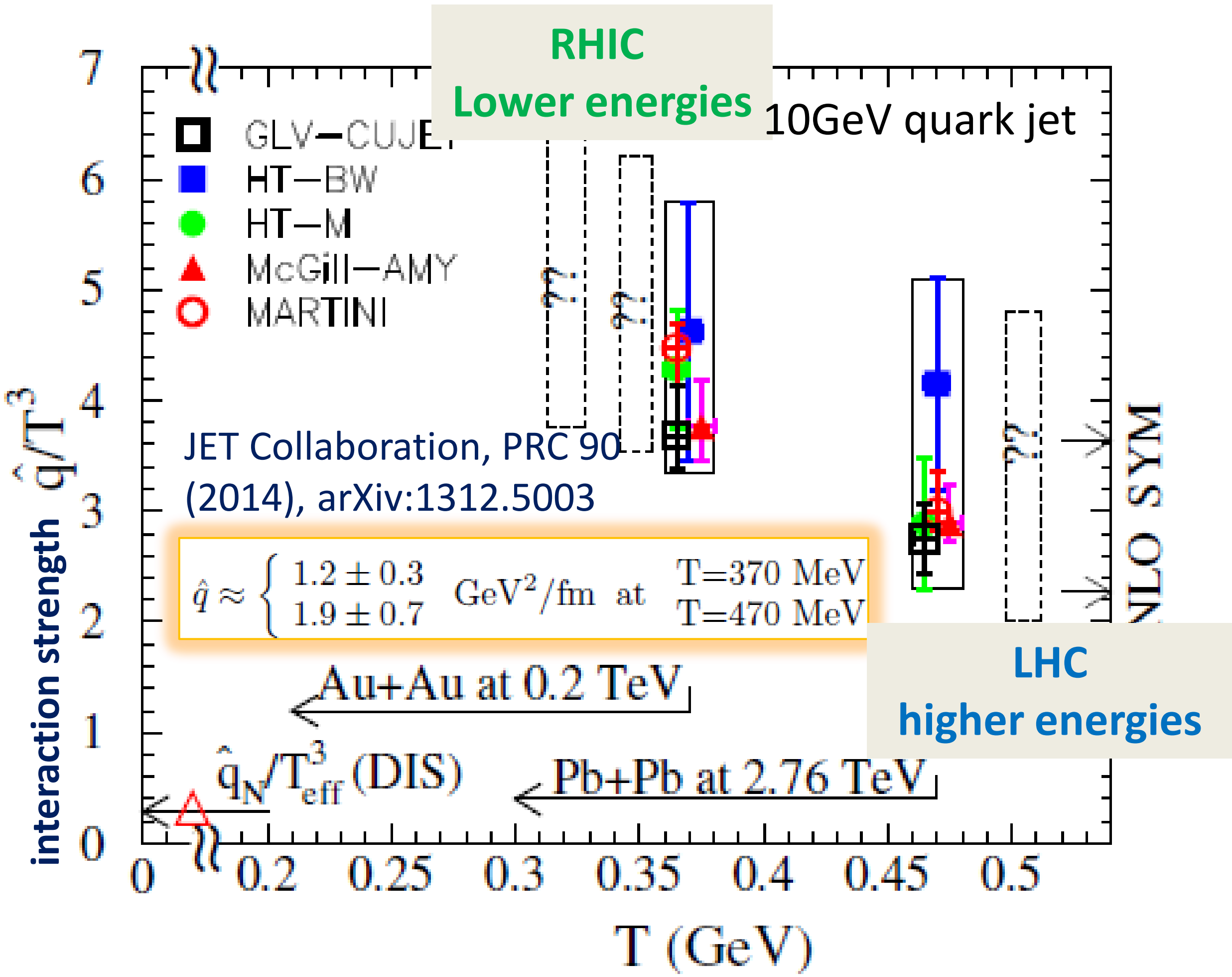
- Jet energy loss and transverse momentum broadening are closely related, e.g.,
  - BDMPS: $$\frac{dE}{dt} \approx \frac{1}{4}\alpha_s N_c \hat{q} L \qquad \hat{q} = \frac{d\langle p_\perp^2 \rangle}{dt}$$

    Baier, Dokshitzer, Mueller, Peigne, and Schiff, NPB 483 (1997), 484 (1997), 531(1998).

  - Higher twist: $$\frac{dN_g}{dx dk_\perp^2 dt} \approx \frac{2\alpha_s}{\pi} P(x) \frac{\hat{q}}{k_\perp^4} \sin^2\left(\frac{t - t_i}{2\tau_f}\right)$$

    Wang, Guo, PRL 85 (2000), NPA 696 (2001), Majumder, PRD 85 (2012)

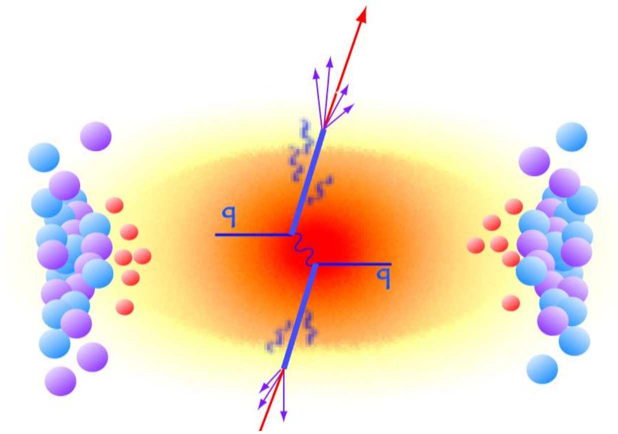
Extract q^{hat} from jet energy loss by JET

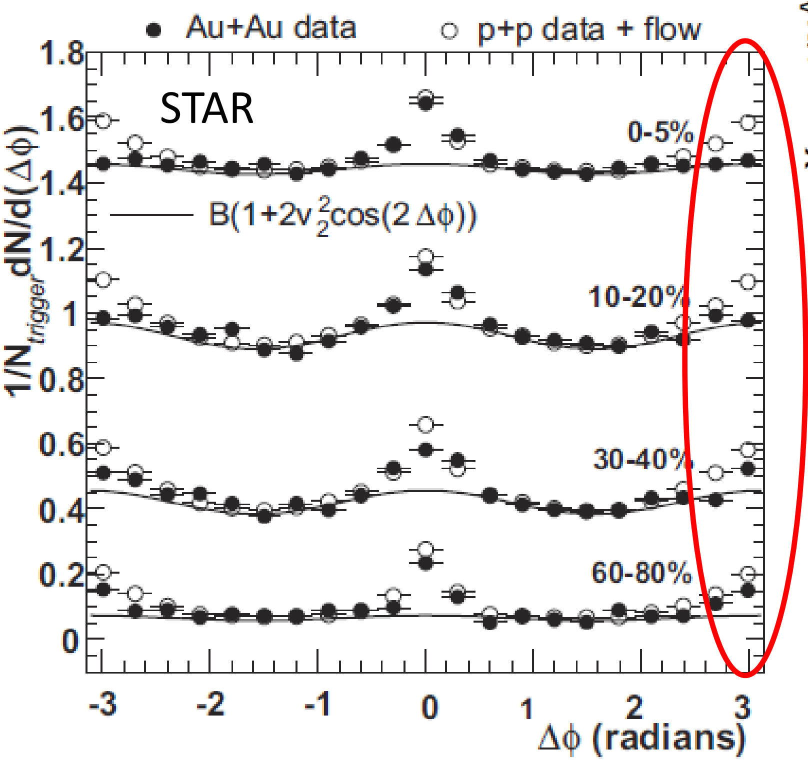


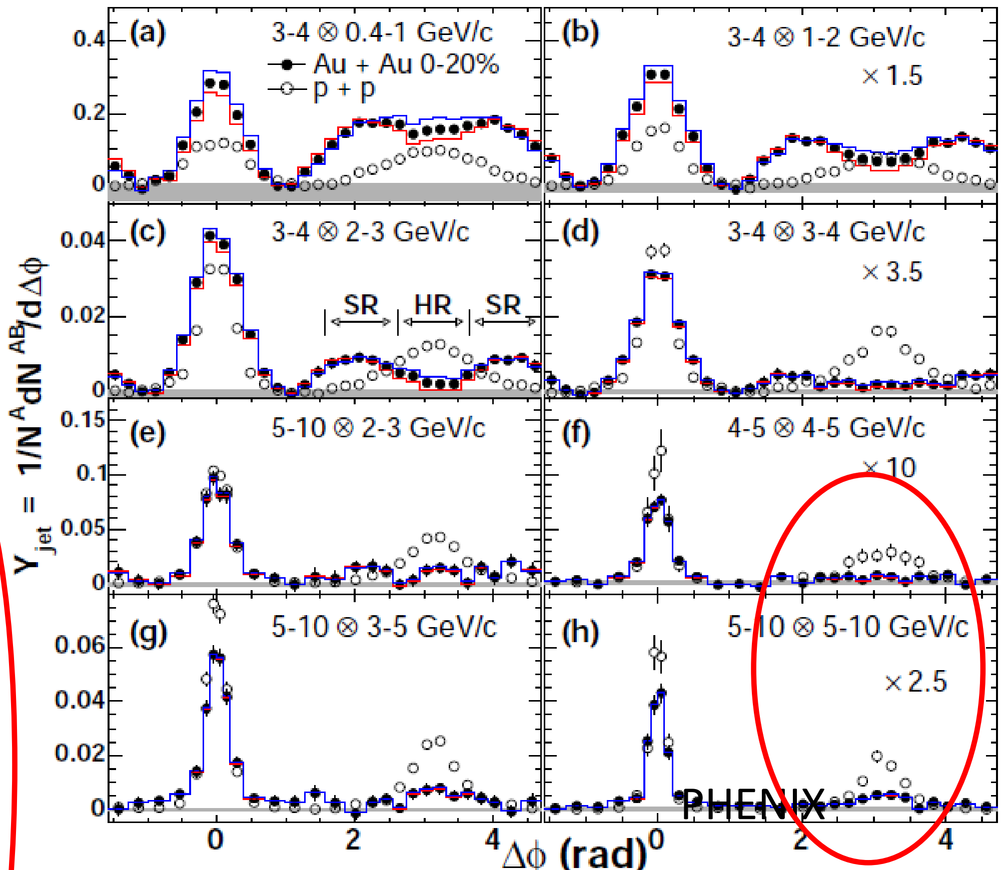
McGill-AMY:
GYQ, Ruppert, Gale, Jeon, Moore, Mustafa, PRL 2008
HT-BW:
Chen, Hirano, Wang, Wang, Zhang, PRC 2011
HT-M:
Majumder, Chun, PRL 2012
GLV-CUJET:
Xu, Buzzatti, Gyulassy, arXiv: 1402.2956
MARTINI-AMY:
Schenke, Gale, Jeon, PRC 2009
NLO SYM:
Zhang, Hou, Ren, JHEP 2013

Our approach: Jet-like angular (de)correlations provide a new & more direct method to extract medium-induced transverse momentum broadening and q^{hat}

Jet-like dihadron correlations



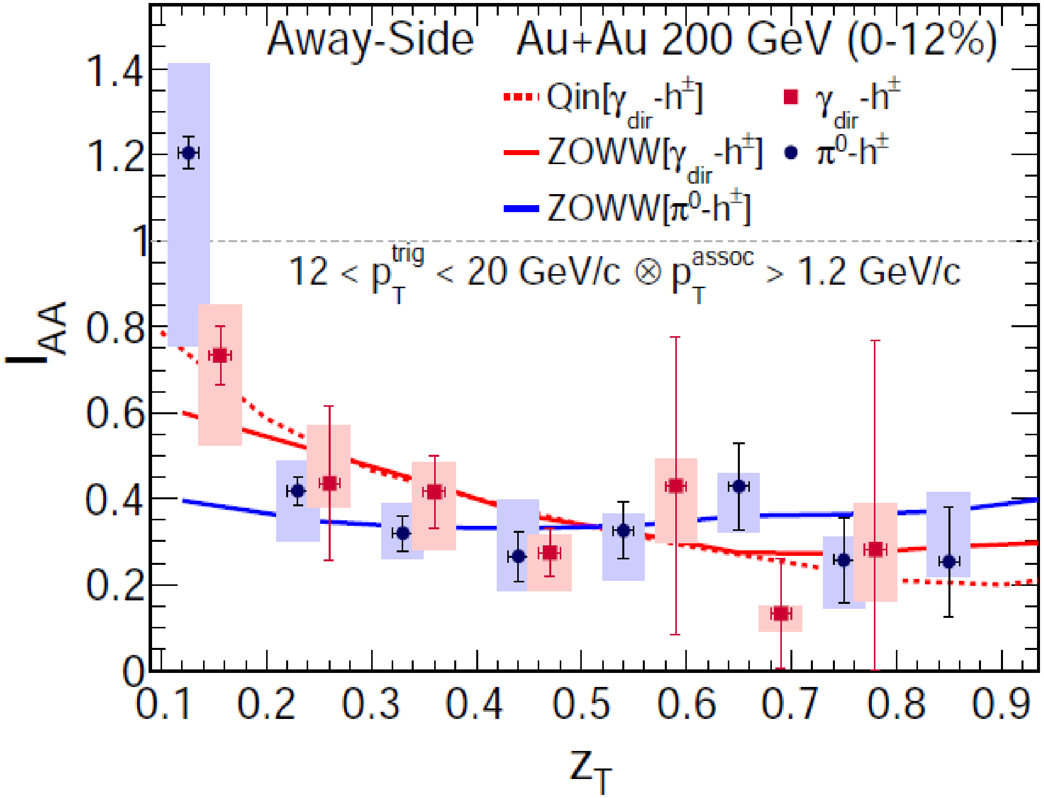




Low p_T: flow effects dominate

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

Nuclear modification of the per-trigger yield



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

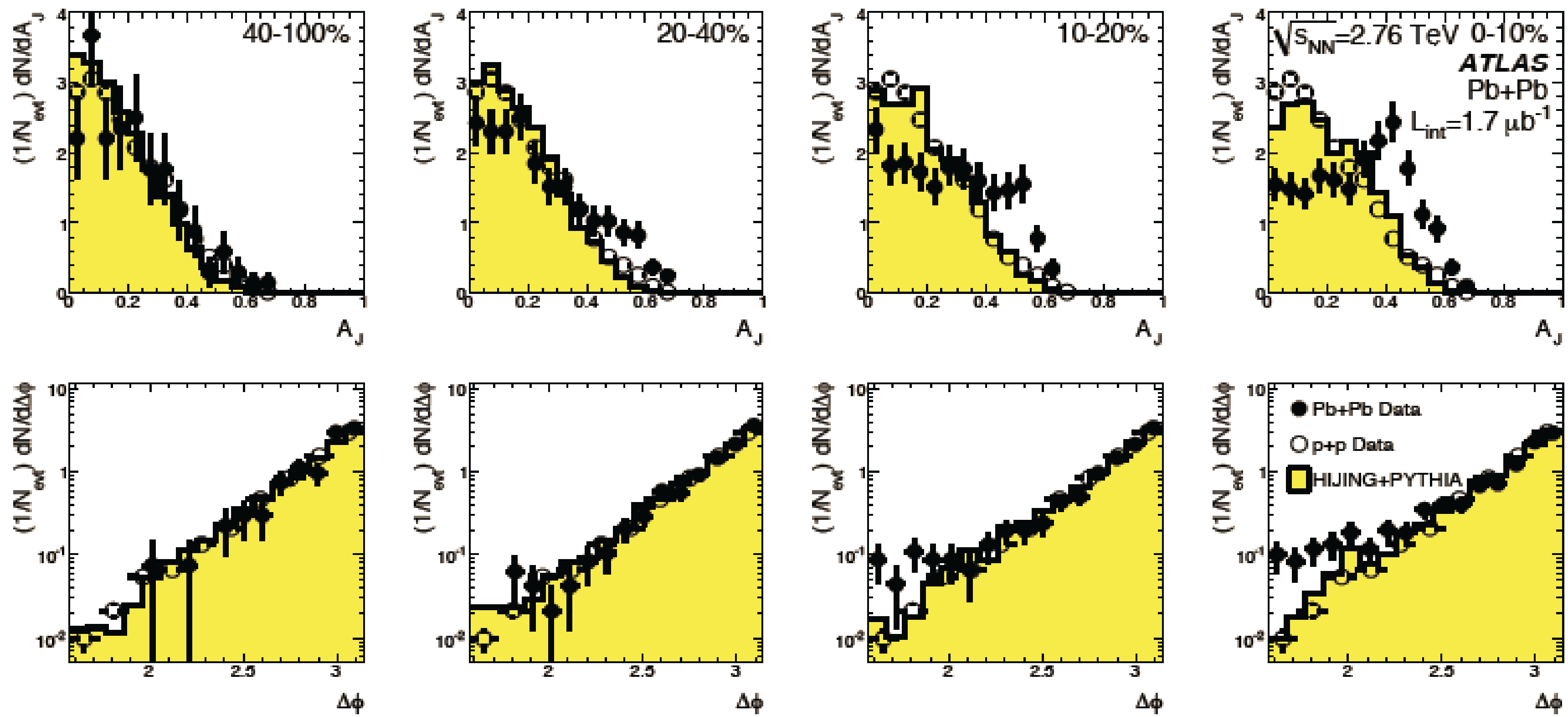
The angular correlations directly reflects the transverse momentum broadening

But quantitative studies of back-to-back angular correlations are lacking

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

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

Dijet correlations

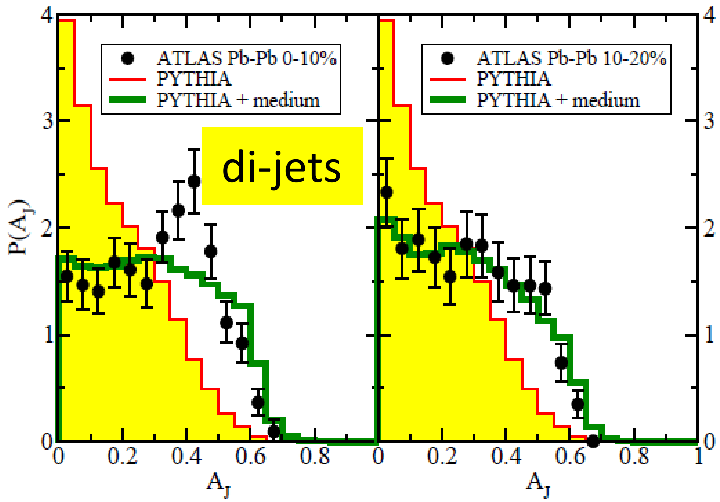


$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

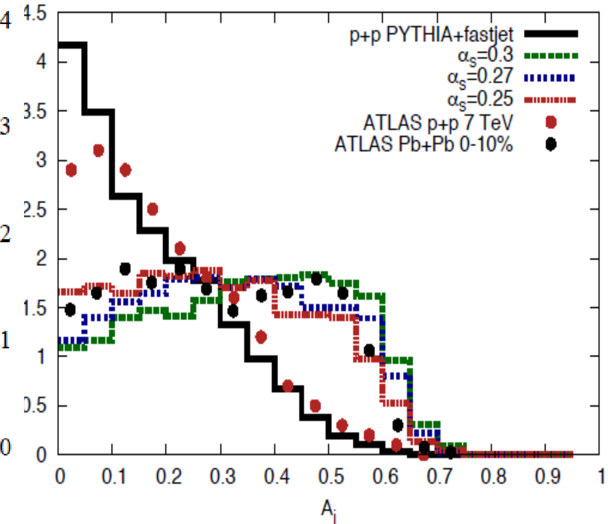
$$\Delta\phi = |\phi_1 - \phi_2|$$

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

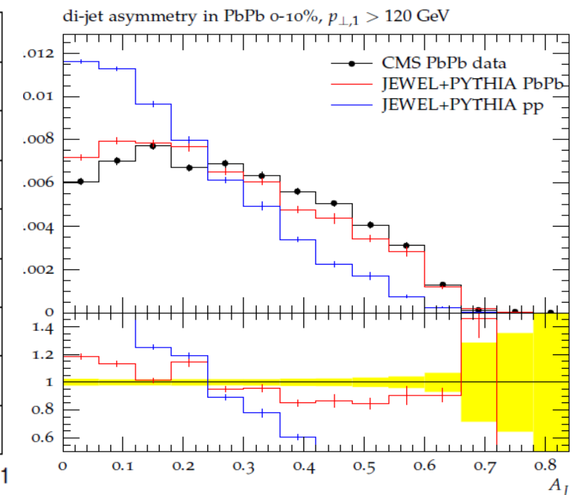
Dijet asymmetry (& γ-jet asymmetry)



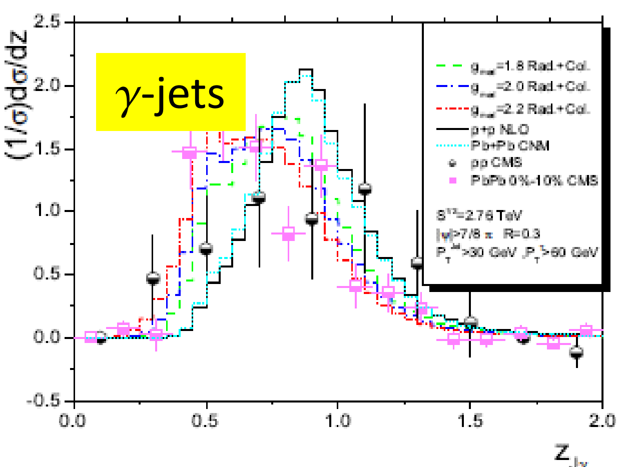
GYQ, Muller, PRL, 2011



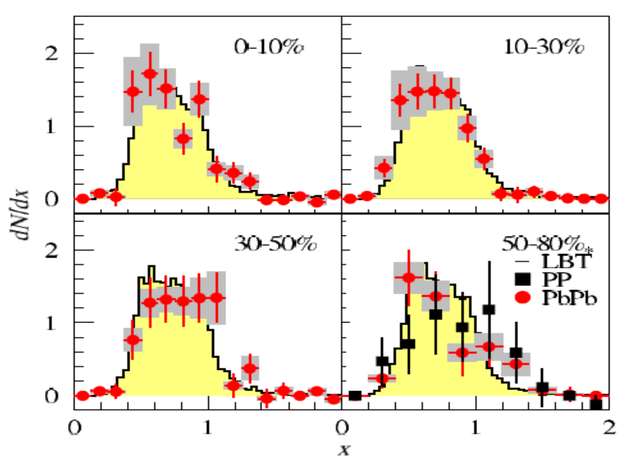
Young, Schenke, Jeon, Gale, PRC, 2011



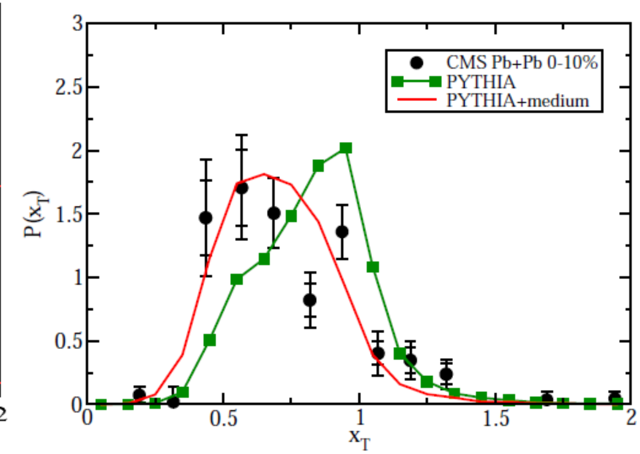
Milhano, Zapp, EPJC 2016



Dai, Vitev, Zhang, PRL 2013



Wang, Zhu, PRL 2013



GYQ, EPJC 2014

Dijet angular correlations in pp collisions

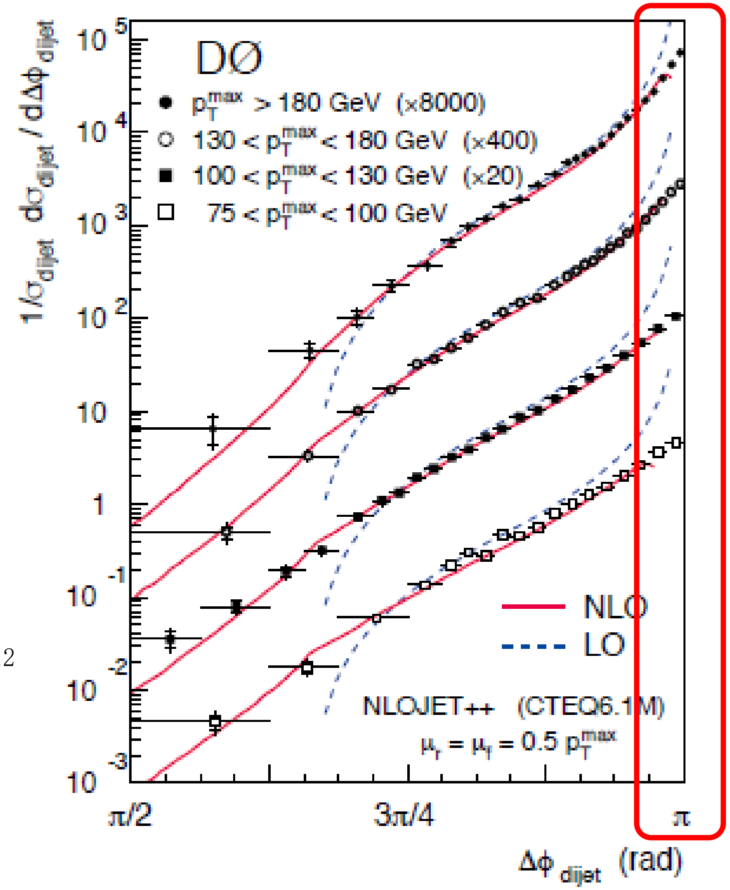
- Dijet angular correlations has been measured at Tevatron (and the LHC)

- NLO pQCD can describe dN/d$\Delta\varphi$ for $\Delta\varphi$ away from π

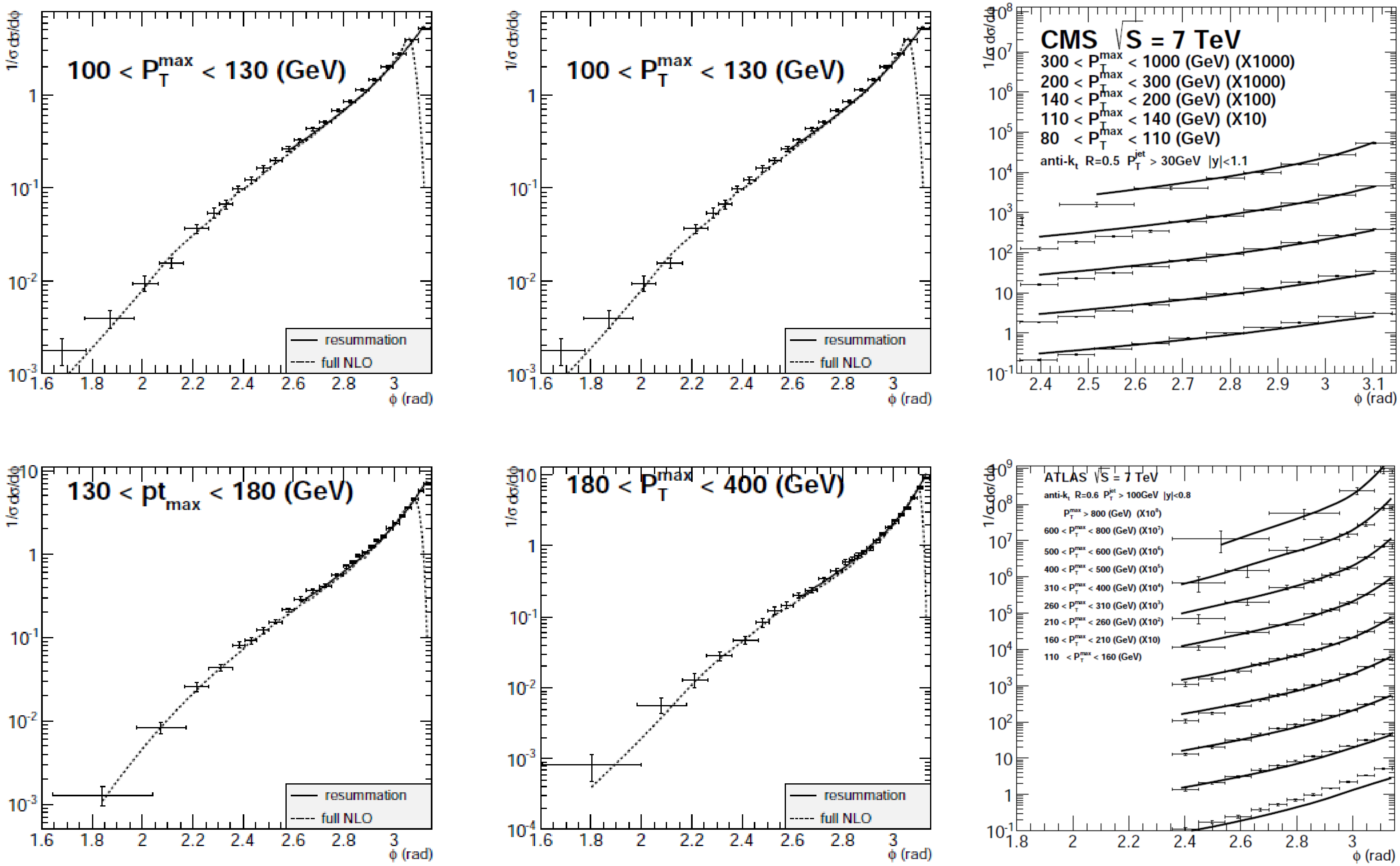
- However, pQCD fails at $\Delta\varphi \sim \pi$ due to large logarithms (originating from soft gluon radiation), e.g.,

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

- Solution: resuming arbitrary numbers of soft gluon radiation (the parton shower effect), i.e., *Sudakov resummation*



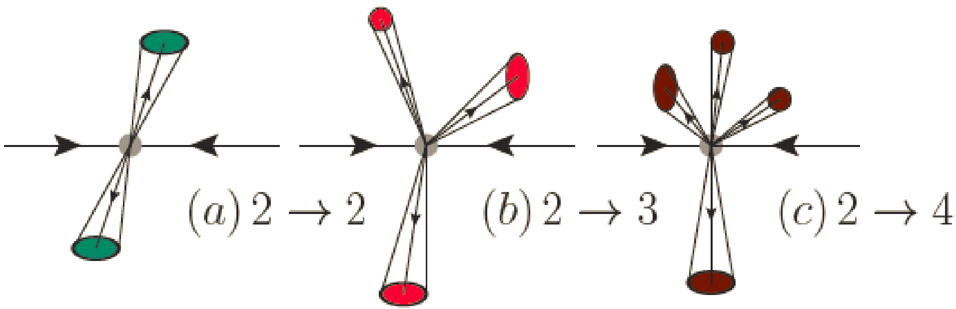
Dijet angular correlations in pp collisions



Sun, Yuan, Yuan, PRL113 (2014), PRD92 (2015)

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

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

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

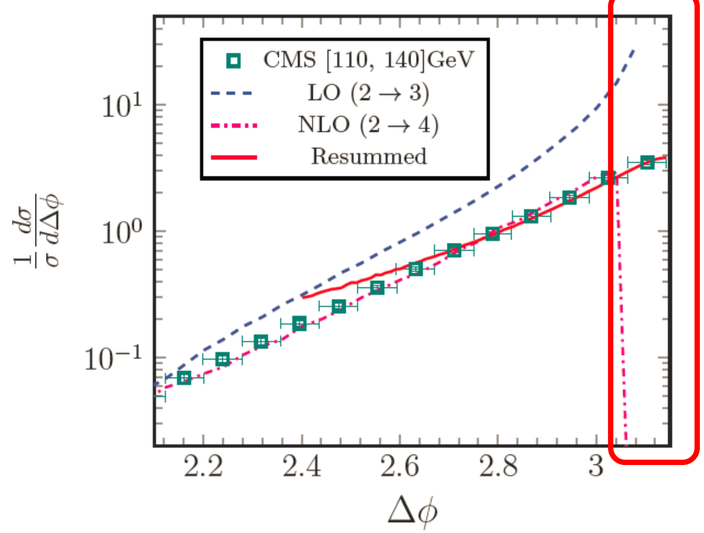
pQCD expansion (schematically):

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

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

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

Sudakov resummation



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

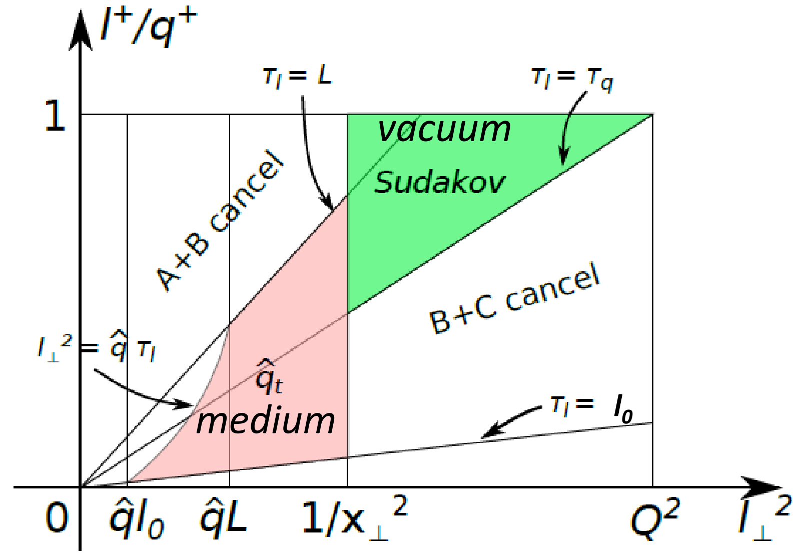
Based on: Nagy, PRL88 (2002), PRD68 (2003); Sun, Yuan, Yuan, PRL113 (2014), PRD92 (2015)

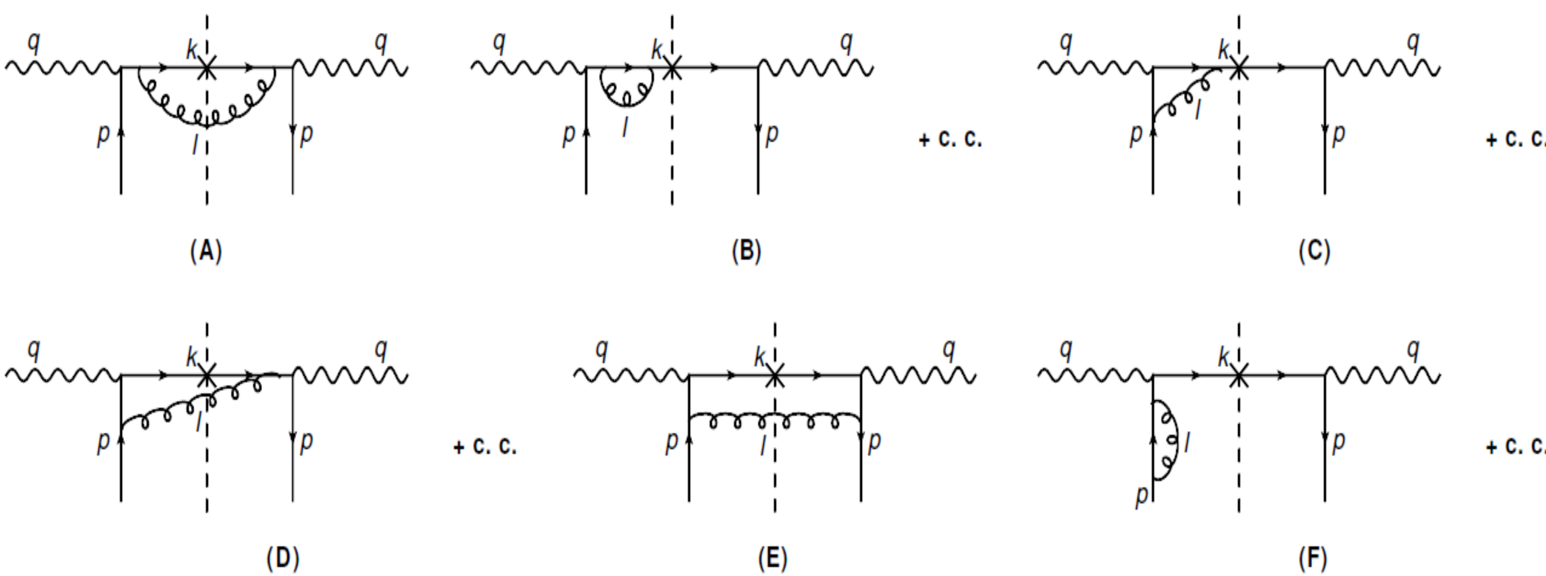
Sudakov resummation in medium

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***:

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

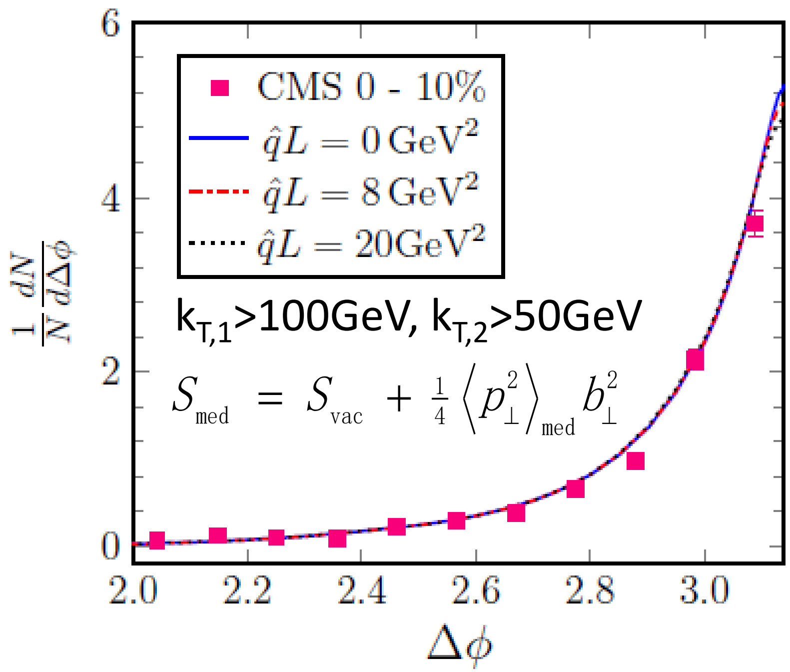
Mueller, Wu, Xiao, Yuan, arXiv:1608.07339

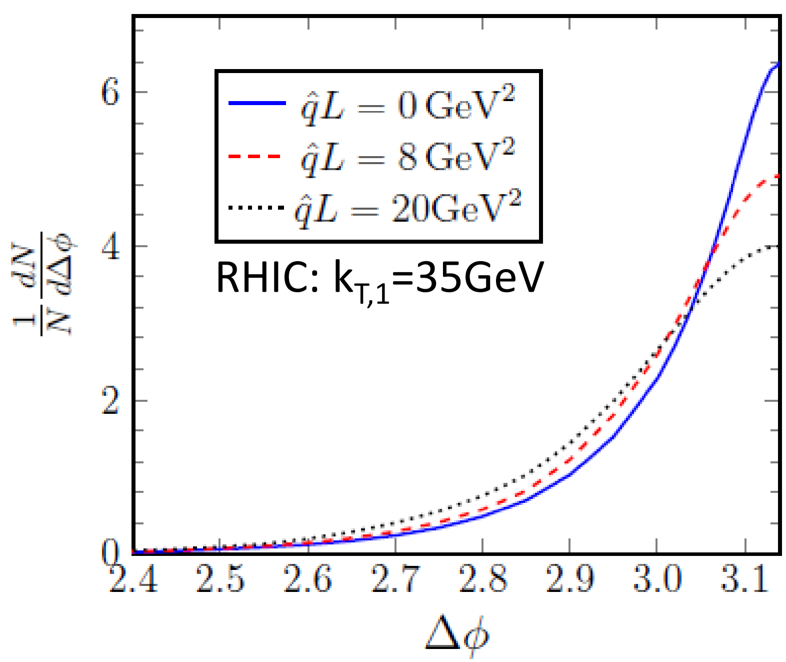




Dijet angular correlations in AA

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





LHC: vacuum Sudakov effect overwhelms medium-induced broadening effect

=> essentially no angular decorrelation

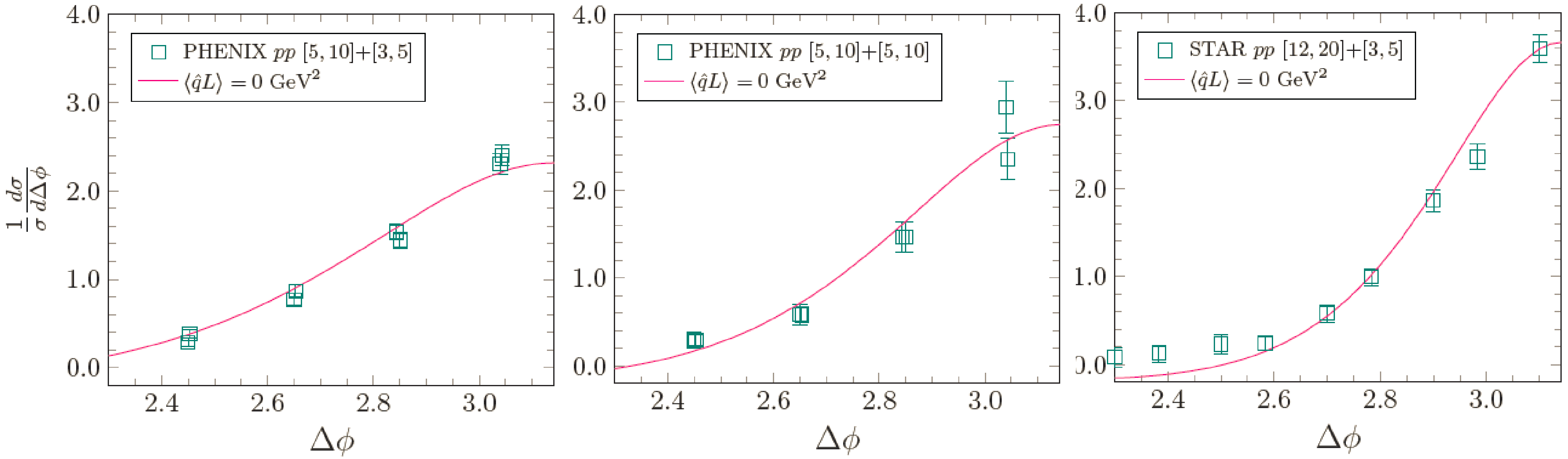
RHIC: medium-induced broadening effect comparable to vacuum Sudakov effect

=> sizable angular decorrelation

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

Dihadron angular correlations (pp baseline)

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

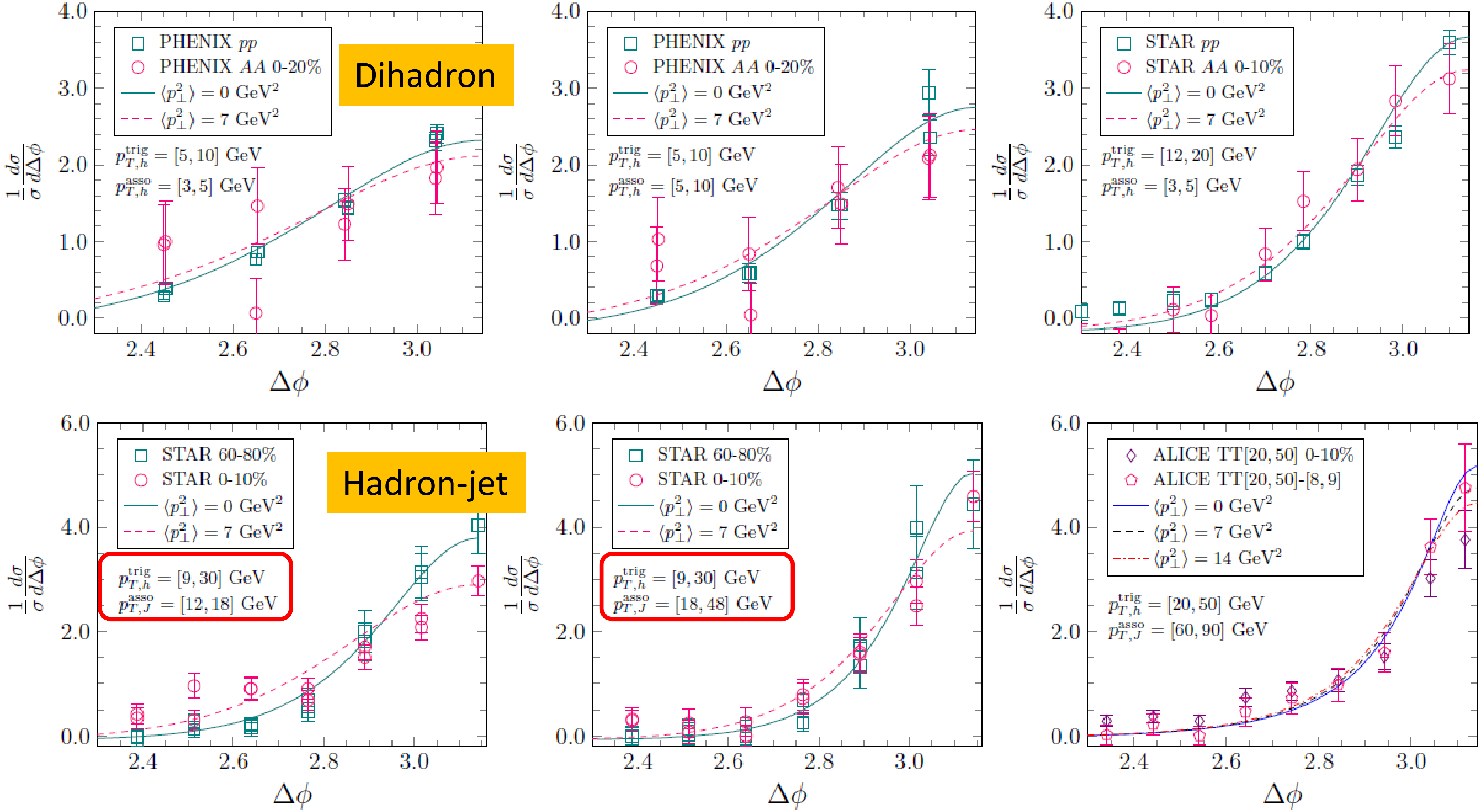


First benchmark calculation of back-to-back dihadron angular correlations in pp collisions

The region away from π is dominated by rare hard processes

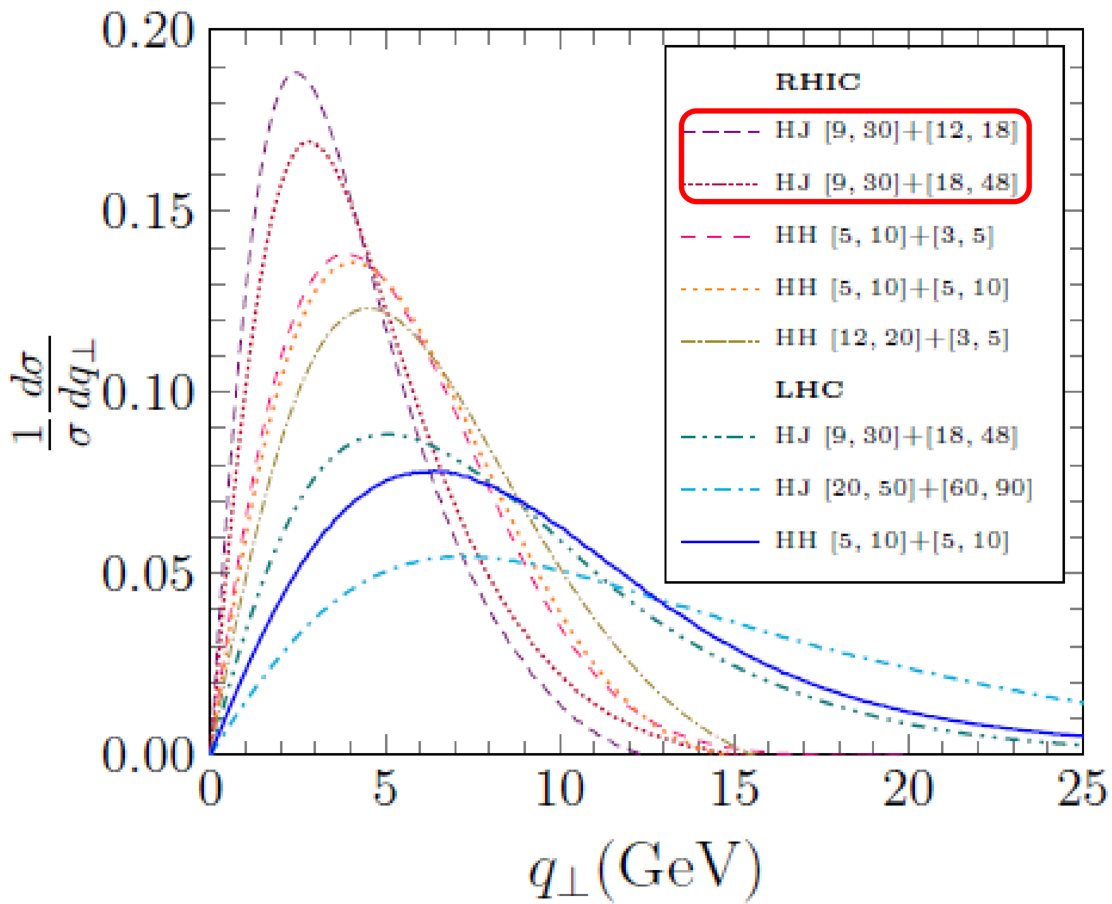
Baseline for studying angular decorrelation from medium-induced effects in *AA* collisions

Dihadron & hadron-jet angular decorrelations in AA



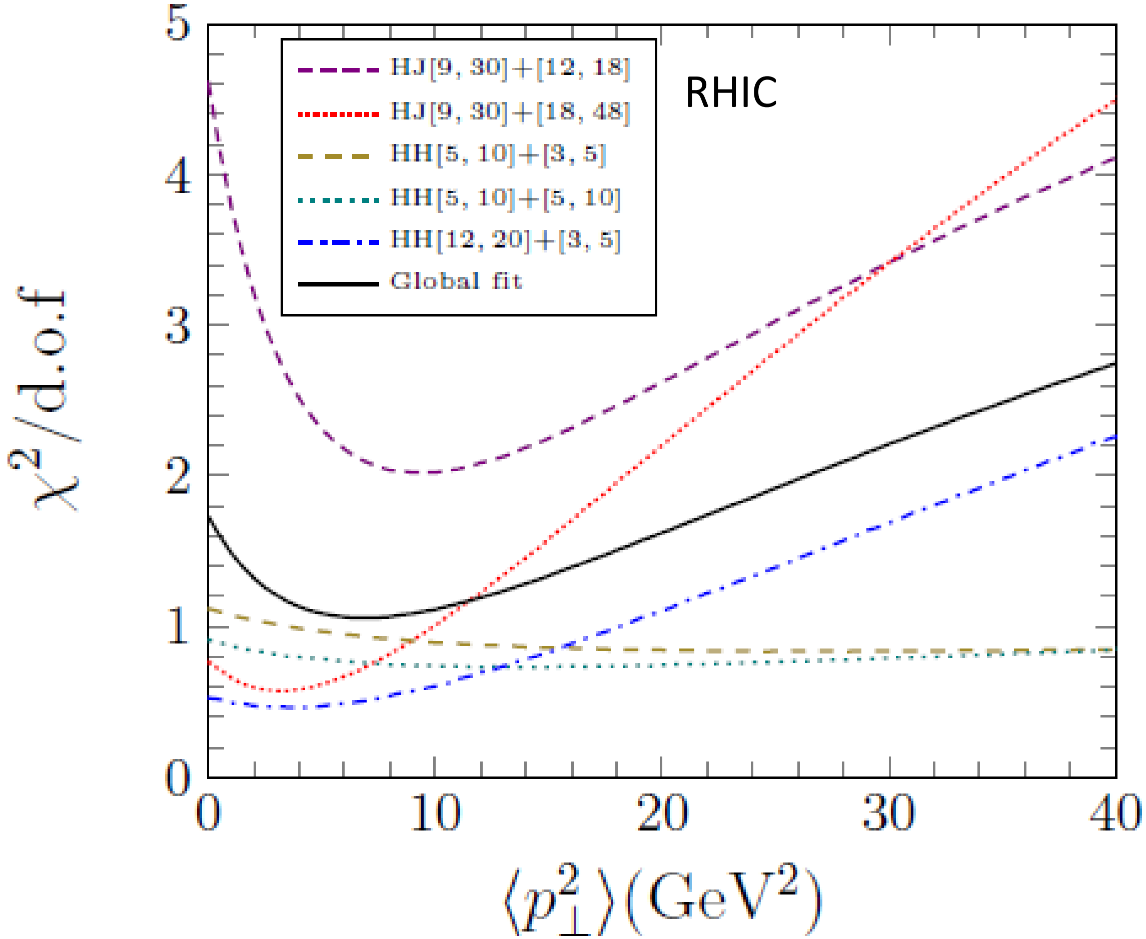
Angular decorrelations: a new & more direct method to probe medium broadening (q^hat)

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



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

Extraction of medium-induced broadening @ RHIC



$$\left\langle p_\perp^2 \right\rangle_{\mathrm{tot}} = 2\left\langle p_\perp^2 \right\rangle_{\Delta\phi} \approx 14\mathrm{GeV}^2$$

Realistic simulation: extraction of q^{hat}@ RHIC

- 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:

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

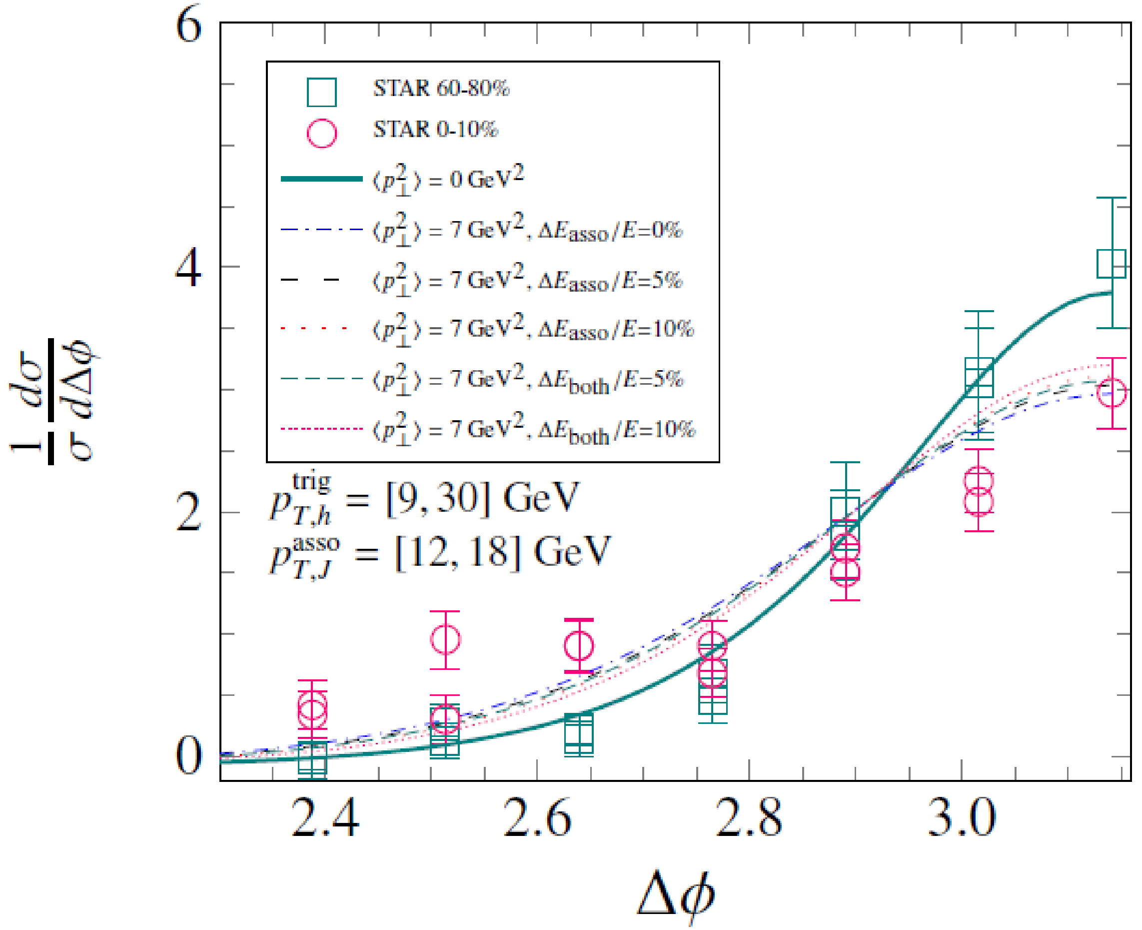
Liou, Mueller, Wu, NPA 916 (2013)

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

- χ^2 analysis at RHIC gives: $\hat{q}_0 \approx 4^{+14}_{-4}\,\mathrm{GeV}^2/\mathrm{fm}$

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

Check the energy loss effect



The influence of jet energy loss on the angular distribution is weak

Summary

- **Dihadron and hadron-jet angular correlations provide a new and more direct method to extract p_T broadening & q^{hat}**

- **We perform the first calculation of back-to-back dihadron and hadron-jet angular correlations at RHIC and the LHC**

- **Combining with realistic hydrodynamics, we extract the transverse momentum broadening (14GeV^2) and q^{hat} (4GeV^2/fm) at RHIC**

- **Future higher statistics data will allow us to obtain more precise values for transverse momentum broadening and q^{hat}**

- **To combine transverse momentum broadening with parton energy loss together to study both yield and shape for dijet, dihadron, hadron-jet correlations**

Dijet production in pp in Sudakov approach

- In collinear factorization

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

$$\mu_b = c_0/b_* \qquad c_0 \equiv 2e^{-\gamma_E} \qquad b_* \equiv b/\sqrt{1+b^2/b_{\max}^2}$$

Sun, Yuan, Yuan, PRL113 (2014), PRD92 (2015);
Sun, Isaacson, Yuan, Yuan, 1406.3073; Prokudin, Sun, Yuan, PLB 2015)

- Using b* description, the vacuum contribution to the Sudakov factor may be separated into perturbative & non-perturbative parts:

$$S(Q,b) = S_{\mathrm{p}}^i(Q,b) + S_{\mathrm{p}}^f(Q,b) + S_{\mathrm{np}}(Q,b)$$

- At one-loop order, the contribution from the initial state to the perturbative part of Sudakov factor reads:

$$S_{\mathrm{p}}^i(Q,b) = \sum_{i=a,b} \int_{\mu_b^2}^{Q^2} \frac{d\mu^2}{\mu^2} \left[A_i \ln\left(\frac{Q^2}{\mu^2}\right) + B_i \right] \qquad S_p^f = \sum_f \int_{\mu_b^2}^{Q^2} \frac{d\mu^2}{\mu^2} \left[D_f \ln\left(\frac{1}{R_f^2} \right) \right]$$

- For final state jets, the cone size R is to regulate collinear gluon radiation associated with final state jets.
- The contribution from initial and final states to non-perturbative Sudakov factor is, e.g., for quarks,

$$S_{\mathrm{np}}^q(Q,b) = \frac{g_1}{2} b^2 + \frac{g_2}{2} \ln\frac{Q}{Q_0} \ln\frac{b}{b_*} \qquad S_{\mathrm{np}}^g(Q,b) = \frac{C_A}{C_F} S_{\mathrm{np}}^q(Q,b)$$

- The resummation was performed in the auxilary b-space,

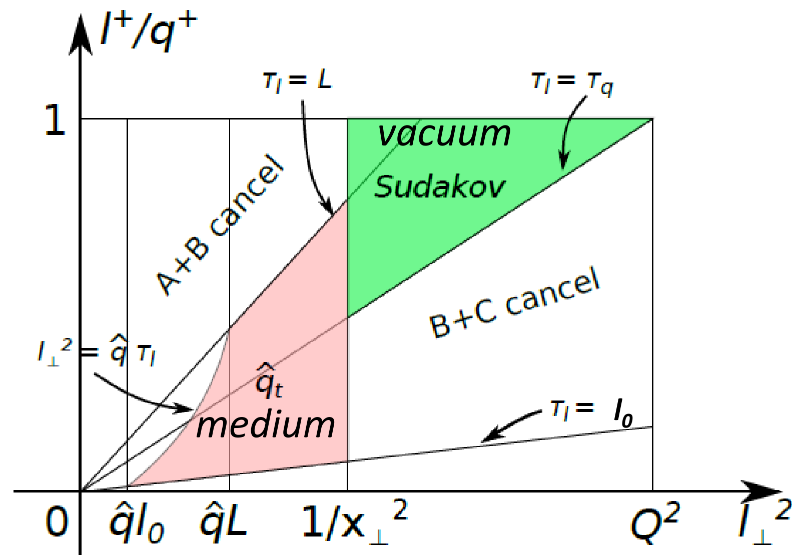
$$\frac{d\sigma}{d^2q_\perp} = \sigma_0 \sum_n \frac{(-1)^n}{n!} \int d^2k_{1\perp} \cdots d^2k_{n\perp} S(k_{1\perp}) \cdots S(k_{n\perp}) \delta^{(2)}(k_{1\perp} + \cdots k_{n\perp} - q_\perp) = \sigma_0 \int \frac{d^2b_\perp}{(2\pi)^2} e^{-iq_\perp \cdot b_\perp} e^{-S(b_\perp)}$$

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 of the radiated gluon, thus 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



Vacuum Sudakov double log:

(1) $l_T^2 > k_T^2 = 1/x_T^2$: softer l_T values cancel
(2) $l_T^2 < Q^2$
(3) $\tau_l = 2l_+/l_T^2 > \tau_q = 2q_+/Q^2$
(4) $l_+ < q_+$

$$\mathcal{E}_{\rm Sud} = 2\frac{\alpha_s C_F}{2\pi}\int_{q_+/[Q^2x_\perp^2]}^{q_+}\frac{dl_+}{l_+}\int_{1/x_\perp^2}^{\frac{l_+}{q_+}Q^2}\frac{dl_\perp^2}{l_\perp^2} = \frac{\alpha_s C_F}{2\pi}\ln^2\left(Q^2x_\perp^2\right)$$

$$\int_{\hat{q}r_0}^{\hat{q}L}\frac{dl_\perp^2}{l_\perp^2}\int_{l_\perp^2 r_0}^{(l_\perp^2)^2/\hat{q}}\frac{dl_+}{l_+} + \int_{\hat{q}L}^{1/x_\perp^2}\frac{dl_\perp^2}{l_\perp^2}\int_{l_\perp^2 r_0}^{l_\perp^2 L}\frac{dl_+}{l_+}$$

Medium-induced double log:

(1) $\tau_l < L$: gluon produced in medium
(2) $\tau_l > l_0$: fluctuations live longer than the size of medium constituents
(3) $l_T < 1/x_T$: gluon transverse distance larger than dipole size
(4) $l_+ < q_+$
(5) $l_T^2 > q^{hat}\tau_l$: to get double log

Dijet, dihadron, hadron-jet angular correlations

- Dijet angular correlations

$$\frac{d\sigma}{d\Delta\phi} = \sum_{a,b,c,d} \int p_T^{j_1} dp_T^{j_1} \int p_T^{j_2} dp_T^{j_2}$$
$$\int bdb\ J_0(q_\perp b) e^{-S(Q,b)} x_a f_a(x_a, \mu_b) x_b f_b(x_b, \mu_b)\ \frac{1}{\pi} \frac{d\sigma_{ab\to cd}}{d\hat{t}}$$

- Dihadron angular correlations

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

- Hadron-jet angular correlations

$$\frac{d\sigma}{d\Delta\phi} = \sum_{a,b,c,d} \int p_T^{h_1} dp_T^{h_1} \int p_T^{j_2} dp_T^{j_2} \int \frac{dz_c}{z_c^2}$$
$$\int bdb\ J_0(q_\perp b) e^{-S(Q,b)} x_a f_a(x_a, \mu_b) x_b f_b(x_b, \mu_b)\ \frac{1}{\pi} \frac{d\sigma_{ab\to cd}}{d\hat{t}} D_c(z_c, \mu_b)$$

Measurement of $\hat{q}$ in Relativistic Heavy Ion Collisions using di-hadron correlations

M. J. Tannenbaum

arXiv:1702.00840

$$\langle \hat{q}L\rangle/2 = \left[\frac{\hat{x}_h}{\langle z_t\rangle}\right]^2 \left[\frac{\langle p^2_{\rm out}\rangle_{AA} - \langle p^2_{\rm out}\rangle_{pp}}{x_h^2}\right] \qquad \langle \hat{q}L\rangle = 3.5 \pm 1.4\ {\rm GeV}^2$$

Measurements of jet quenching with semi-inclusive hadron+jet distributions in Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV

STAR: arXiv:1702.01108