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

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**Quark Matter 2017**

**Chicago, USA**

**Feb. 6-11, 2017**

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*arXiv:1607.01932, arXiv:1612.04202*

# Outline

- Introduction & motivation
- *Extract transverse momentum broadening and $q^{hat}$ from dihadron and hadron-jet angular correlations (arXiv:1607.01932)*
- Dijet asymmetry in the resummation improved pQCD approach compared to the fully corrected data (arXiv:1612.04202)
- Summary

# 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

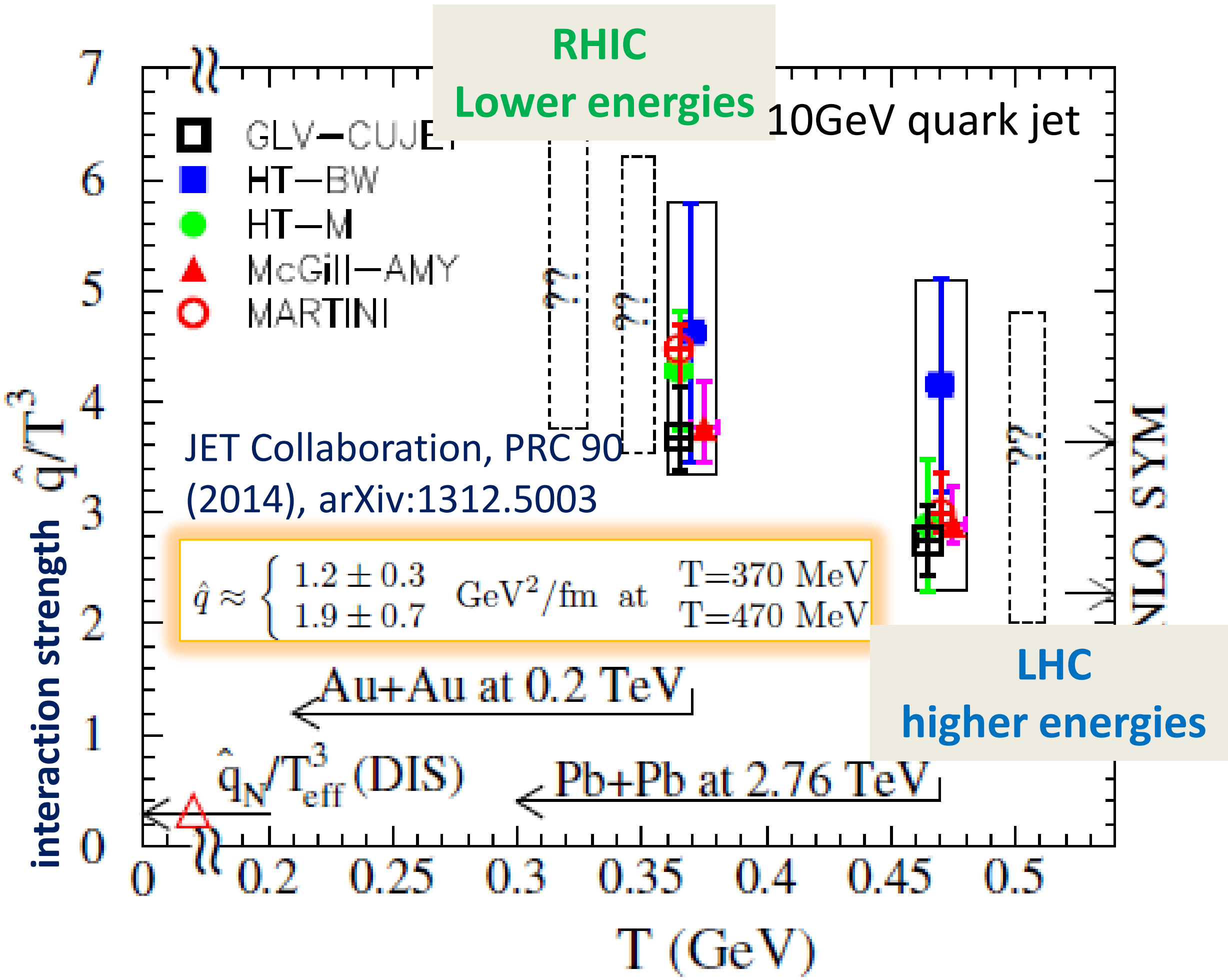
- Jet energy loss and transverse momentum broadening are closely related, e.g.,
  - BDMPS: $$\frac{dE}{dt} \approx \frac{1}{4}\alpha_s N_c \hat{q} L \qquad \hat{q} = \frac{d\langle p_\perp^2 \rangle}{dt}$$

    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)

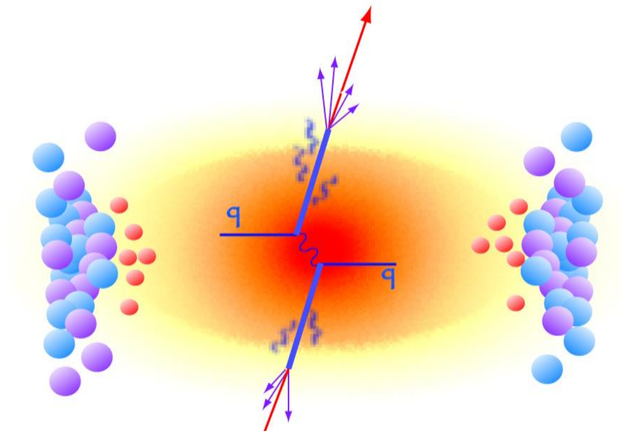
# Extract $q^{hat}$ from jet energy loss by JET

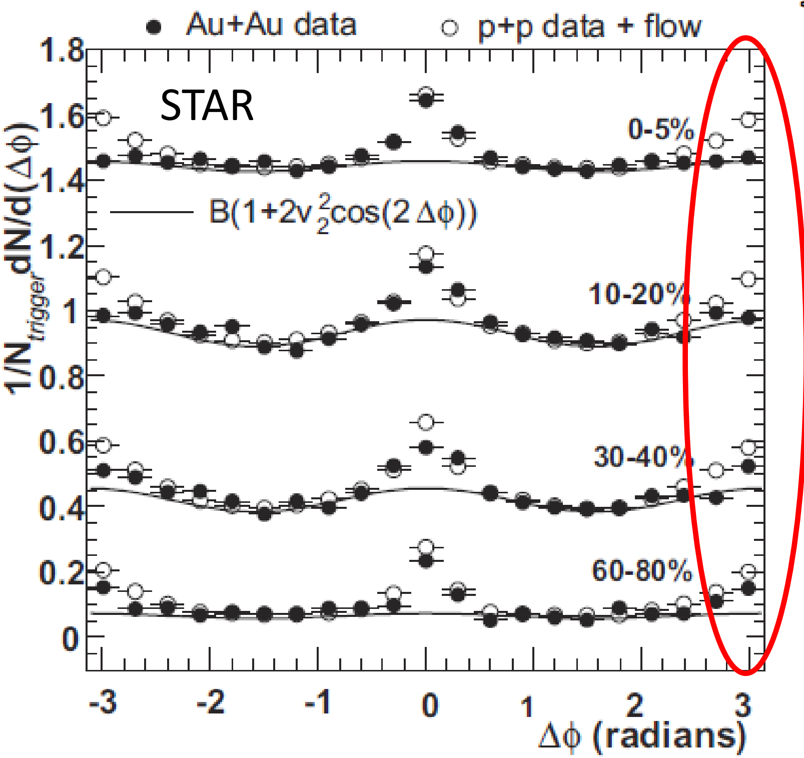


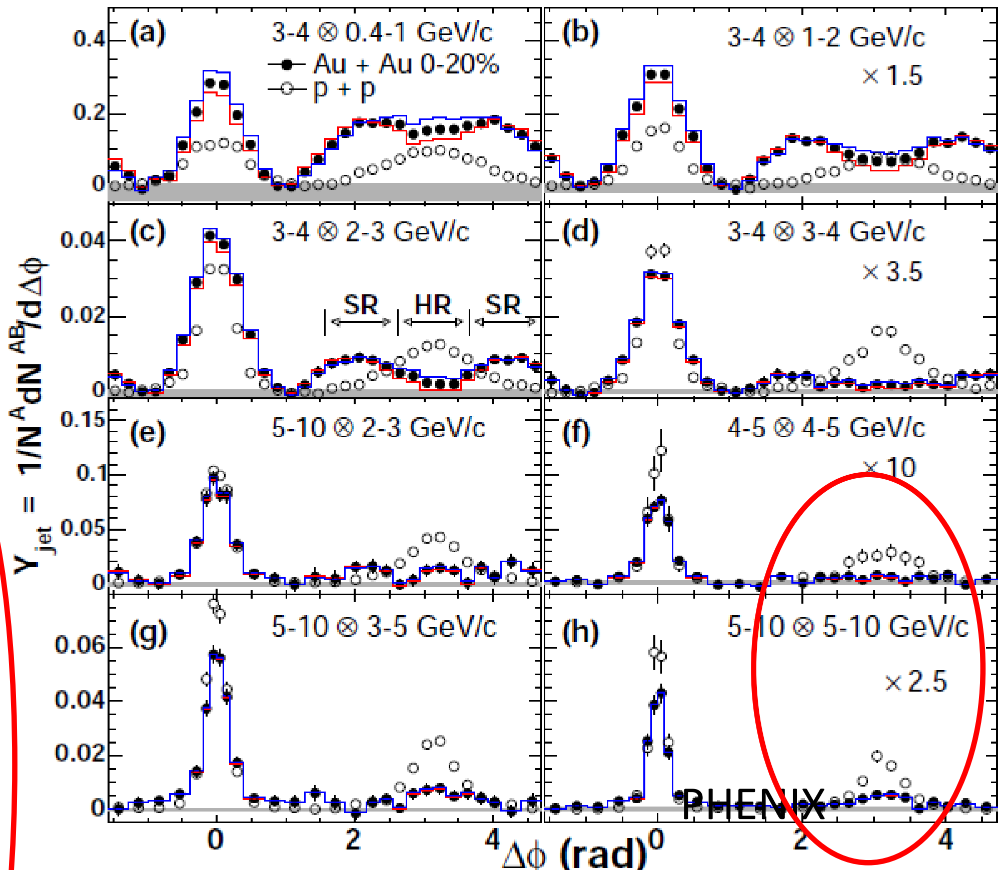

**McGill-AMY:**
GYQ, Ruppert, Gale, Jeon, Moore, Mustafa, PRL 2008
**HT-BW:**
Chen, Hirano, Wang, Wang, Zhang, PRC 2011
**HT-M:**
Majumder, Chun, PRL 2012
**GLV-CUJET:**
Xu, Buzzatti, Gyulassy, arXiv: 1402.2956
**MARTINI-AMY:**
Schenke, Gale, Jeon, PRC 2009
**NLO SYM:**
Zhang, Hou, Ren, JHEP 2013

**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



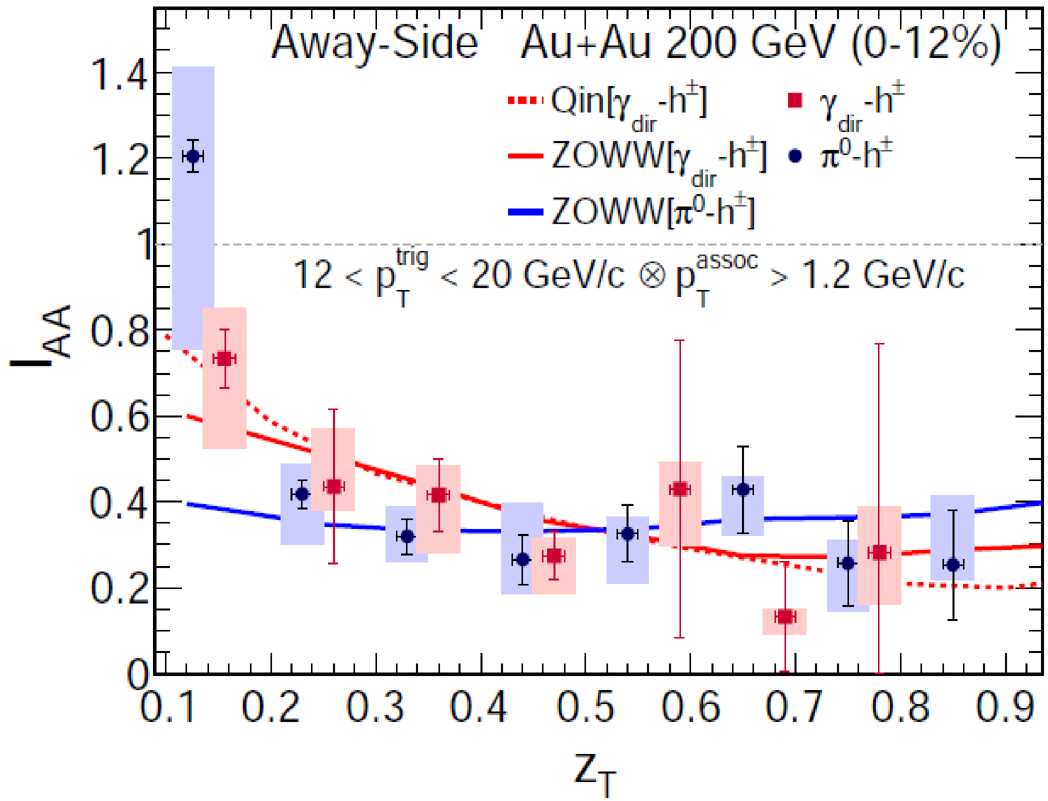




**Low $p_T$: flow effects dominate**

**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

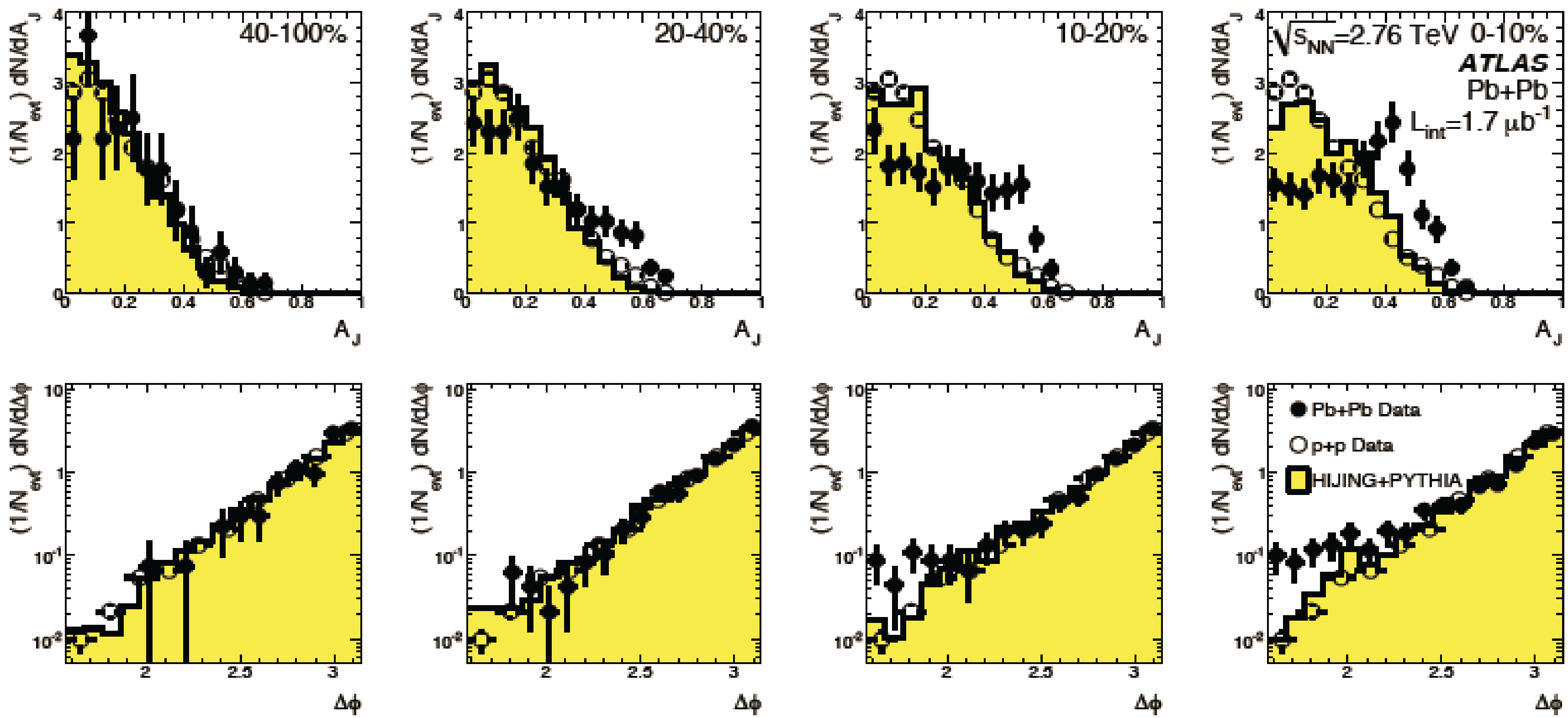
The angular correlations directly reflects the transverse momentum broadening

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

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

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

# Dijet correlations




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

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

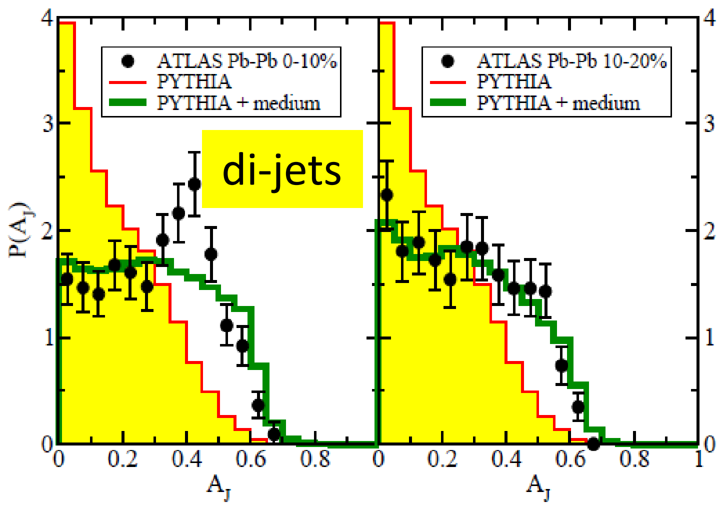
**Strong modification of momentum imbalance distribution**

=> Significant energy loss experienced by the subleading jets

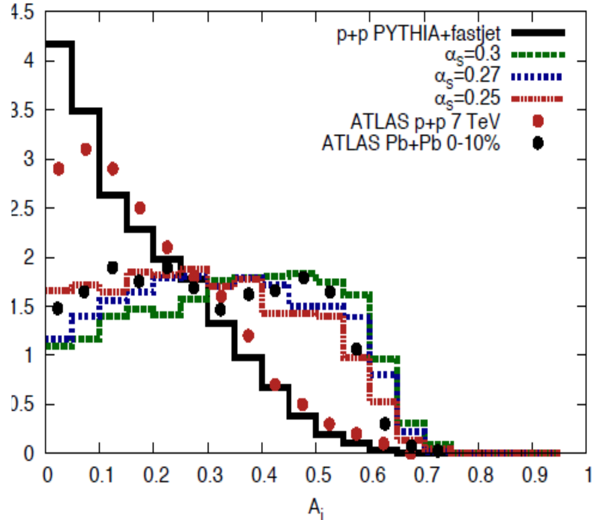
**Largely-unchanged angular distribution**

=> medium-induced broadening effect is quite modest

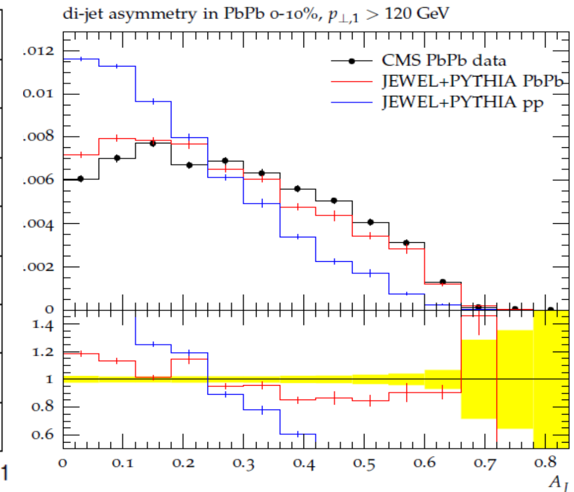
# Dijet asymmetry (& $\gamma$-jet asymmetry)



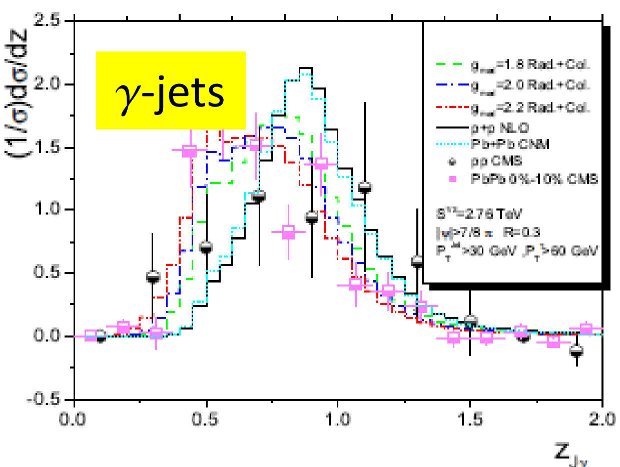

GYQ, Muller, PRL, 2011



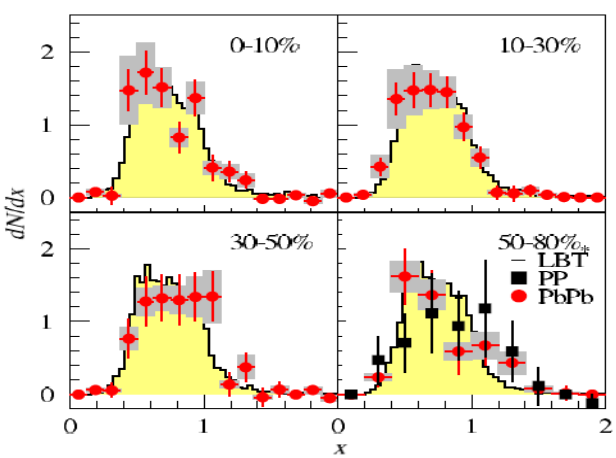

Young, Schenke, Jeon, Gale, PRC, 2011



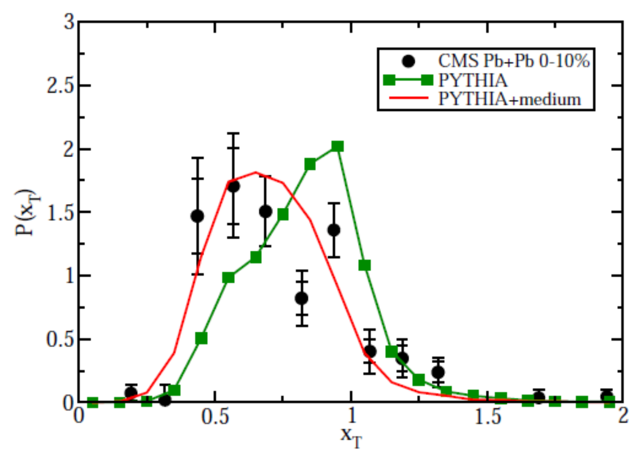

Milhano, Zapp, EPJC 2016




Dai, Vitev, Zhang, PRL 2013



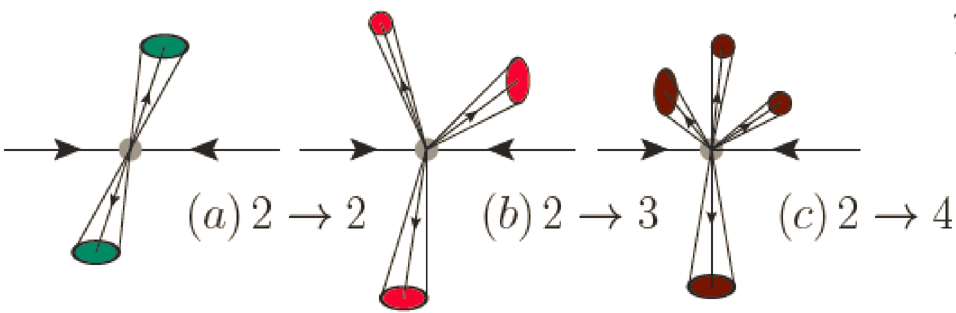

Wang, Zhu, PRL 2013




GYQ, EPJC 2014

# Dijet angular correlations in pp collisions

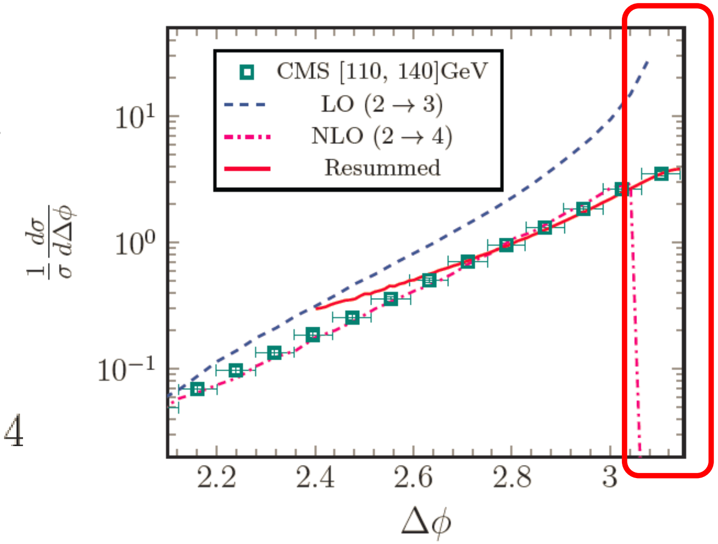
- Perturbative QCD expansion in $\alpha_s$ (2->2, 2->3, 2->4, …)




- PQCD expansion work for $\Delta\varphi$ away from $\pi$, but fails at $\Delta\varphi \sim \pi$ due to large logarithms, e.g.,

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

- Sudakov resummation: resuming arbitrary numbers of soft gluon radiation (the parton shower effect)




**pQCD expansion (schematically):**

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

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

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

**Sudakov resummation**

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

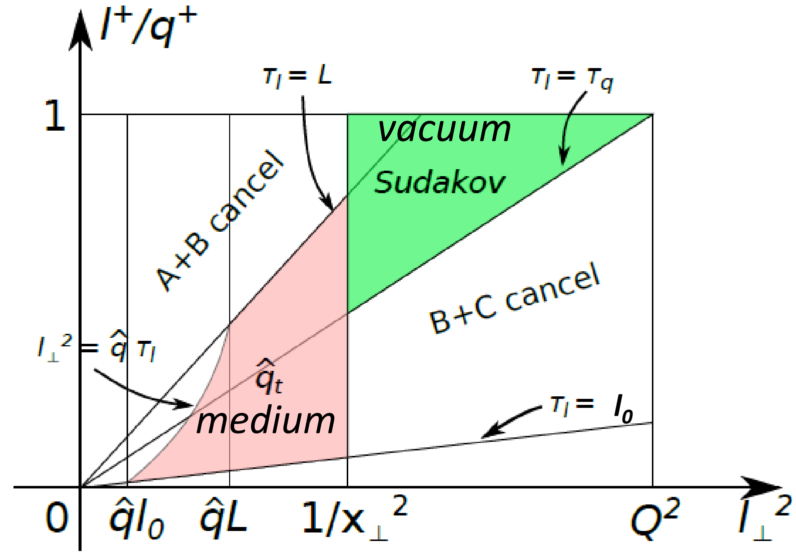
Based on: Nagy, PRL88 (2002), PRD68 (2003); **Sun, Yuan, Yuan, PRL113 (2014), PRD92 (2015)**

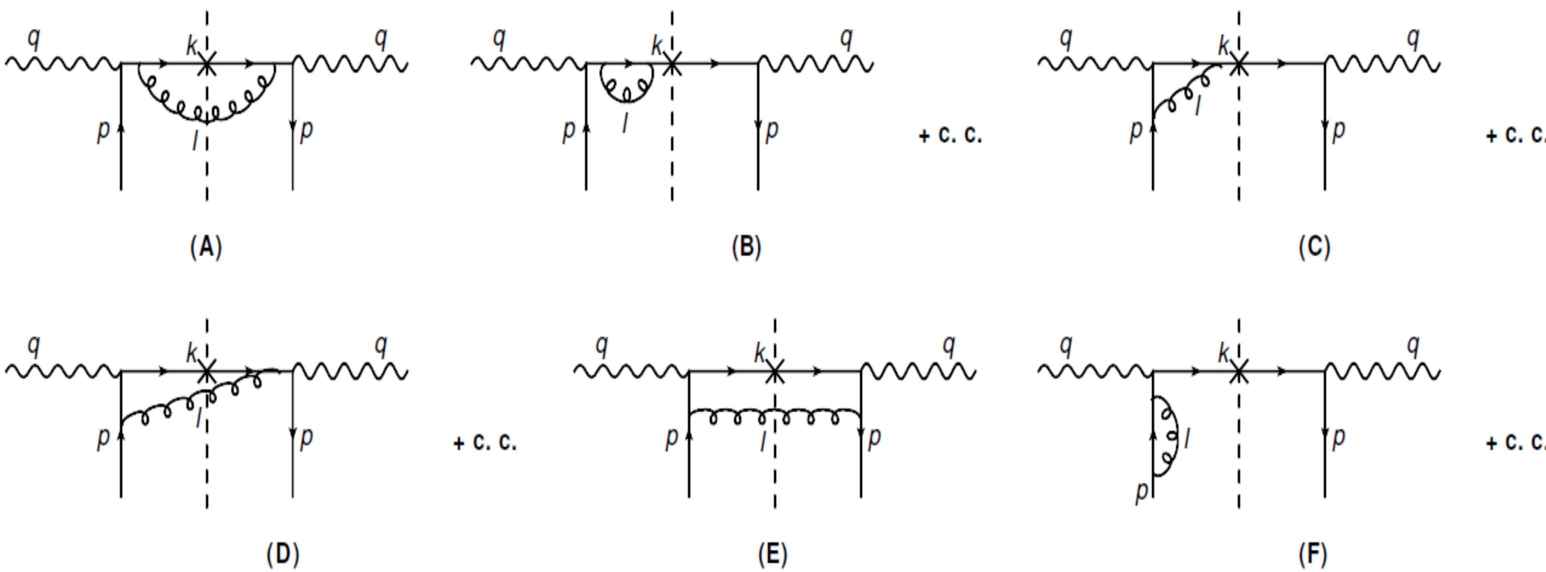
# Sudakov resummation in medium

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

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

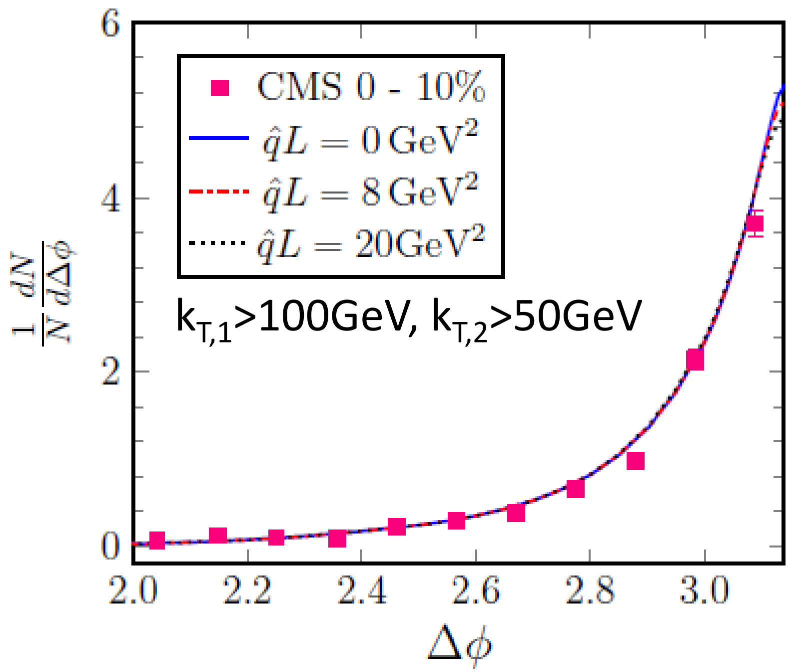
Mueller, Wu, Xiao, Yuan, arXiv:1608.07339

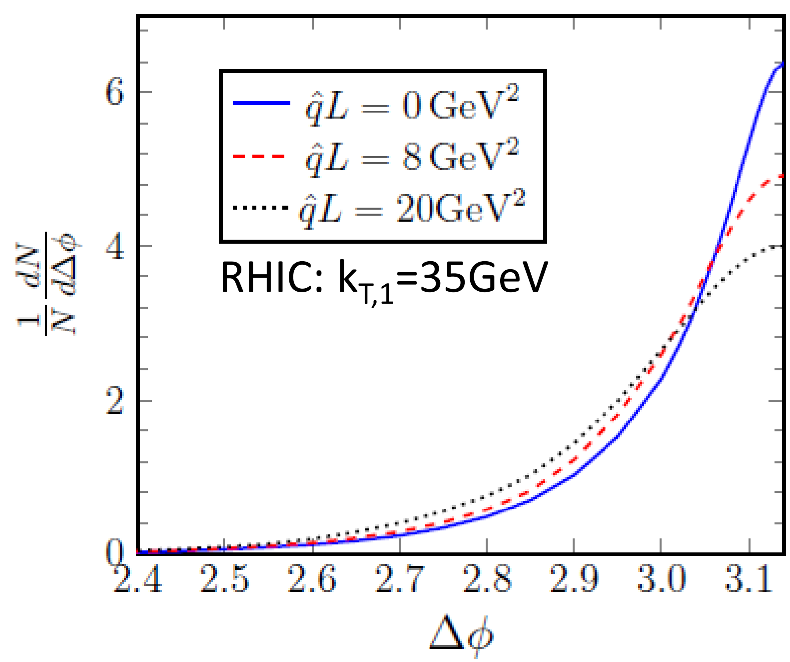


# Dijet angular correlations in AA

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




**LHC: vacuum Sudakov effect overwhelms medium-induced broadening effect**

=> essentially no angular decorrelation

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

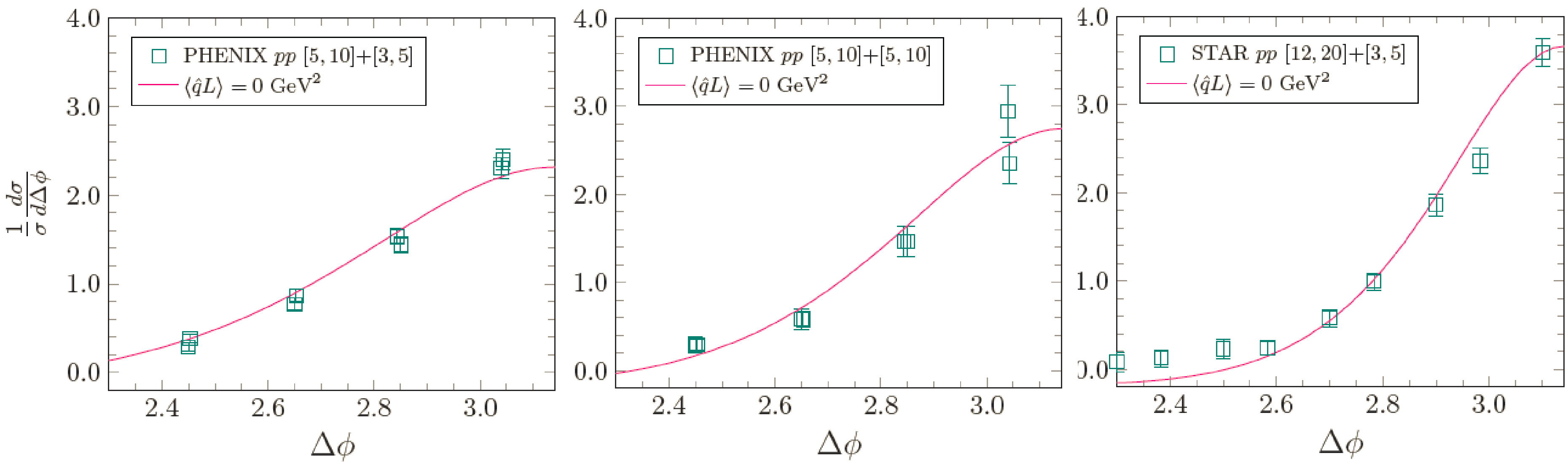
=> sizable angular decorrelation

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

# Dihadron angular correlations (pp baseline)

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

$$\int bdb \; J_0(q_\perp b) e^{-S(Q,b)} x_a f_a(x_a, \mu_b) x_b f_b(x_b, \mu_b) \frac{1}{\pi} \frac{d\sigma_{ab\to cd}}{d\hat{t}} D_c(z_c, \mu_b) D_d(z_d, \mu_b)$$

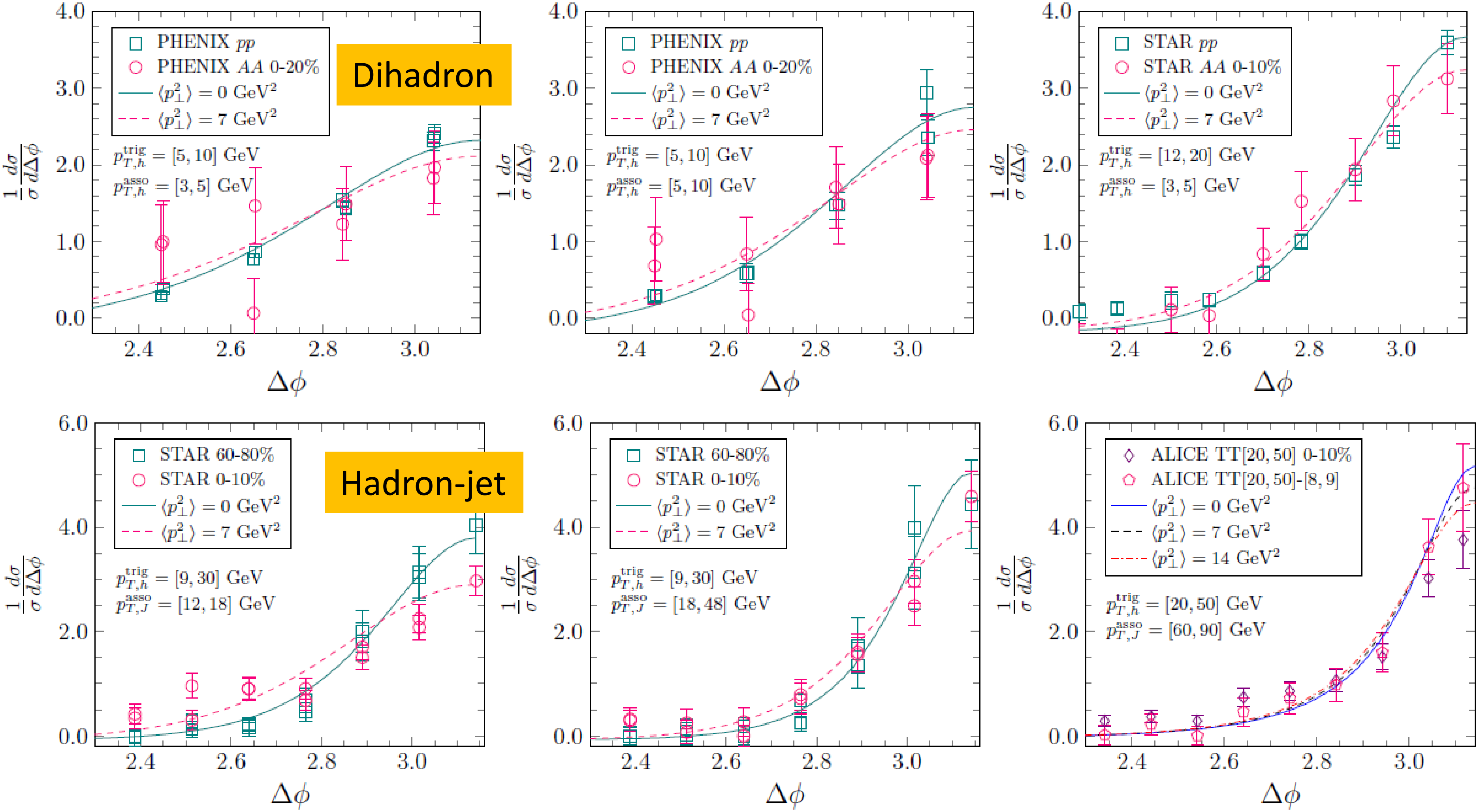



First benchmark calculation of back-to-back dihadron angular correlations in pp collisions

The region away from $\pi$ is dominated by rare hard processes

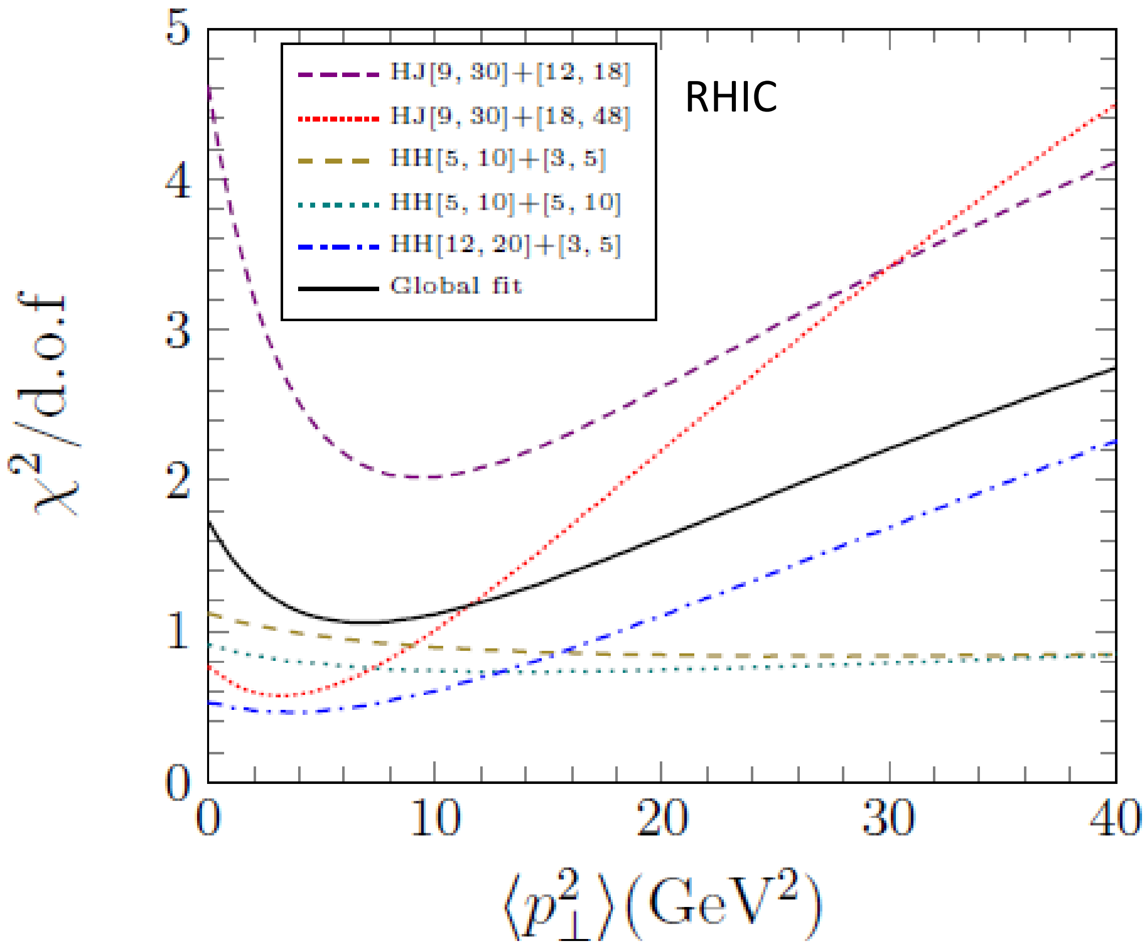
Baseline for studying angular decorrelation from medium-induced effects in *AA* collisions

# Dihadron & hadron-jet angular decorrelations in AA




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

# Extraction of medium-induced broadening @ RHIC




High statistics data would be extremely helpful to reduce the uncertainty

$$\langle p_\perp^2 \rangle_{\mathrm{tot}} = 2\langle p_\perp^2 \rangle_{\Delta\phi} = 14^{+42}_{-14}\,\mathrm{GeV}^2$$

# 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:

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

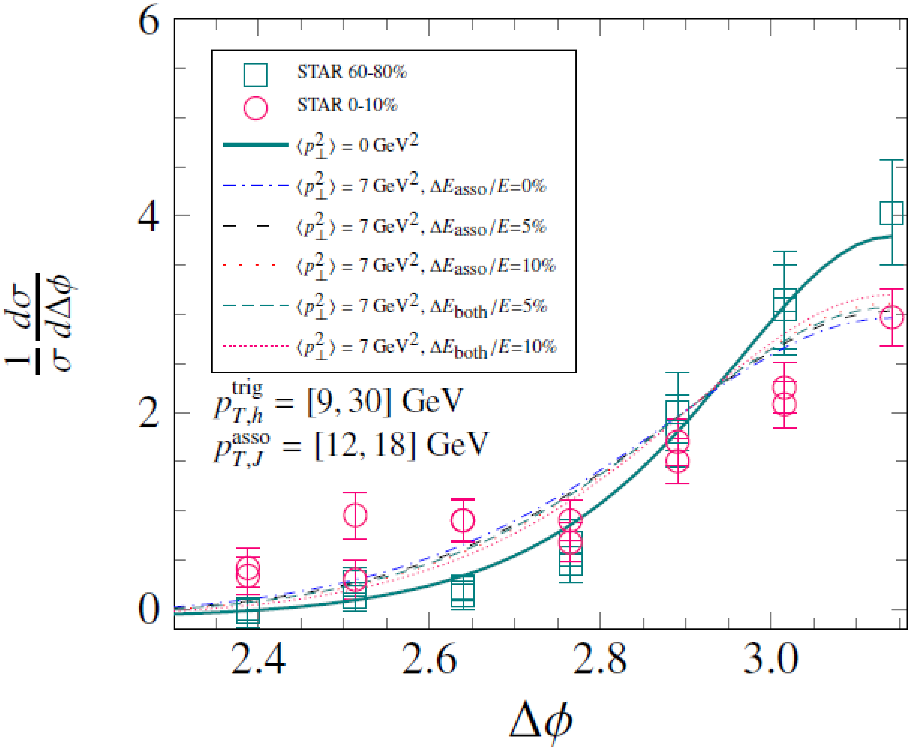
Liou, Mueller, Wu, NPA 916 (2013)

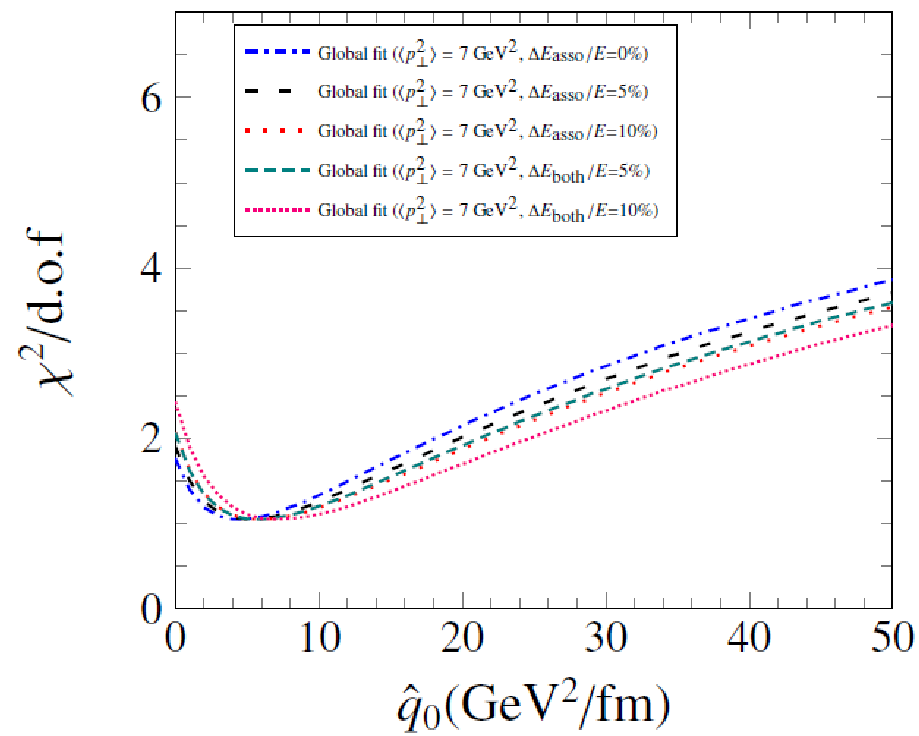
  - Relate the leading-order $q^{hat}$ to T as: $\hat{q} \propto T^3$

- Global $\chi^2$ analysis at RHIC gives: $\hat{q}_0 = 4^{+16}_{-4}\,\mathrm{GeV}^2/\mathrm{fm}$

- 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

Due to the flatness (originating from experimental uncertainties) around minimum $\chi^2$ value, a 5-10% energy loss leads to the increase of the central $q^{hat}$ value by 20-50%

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

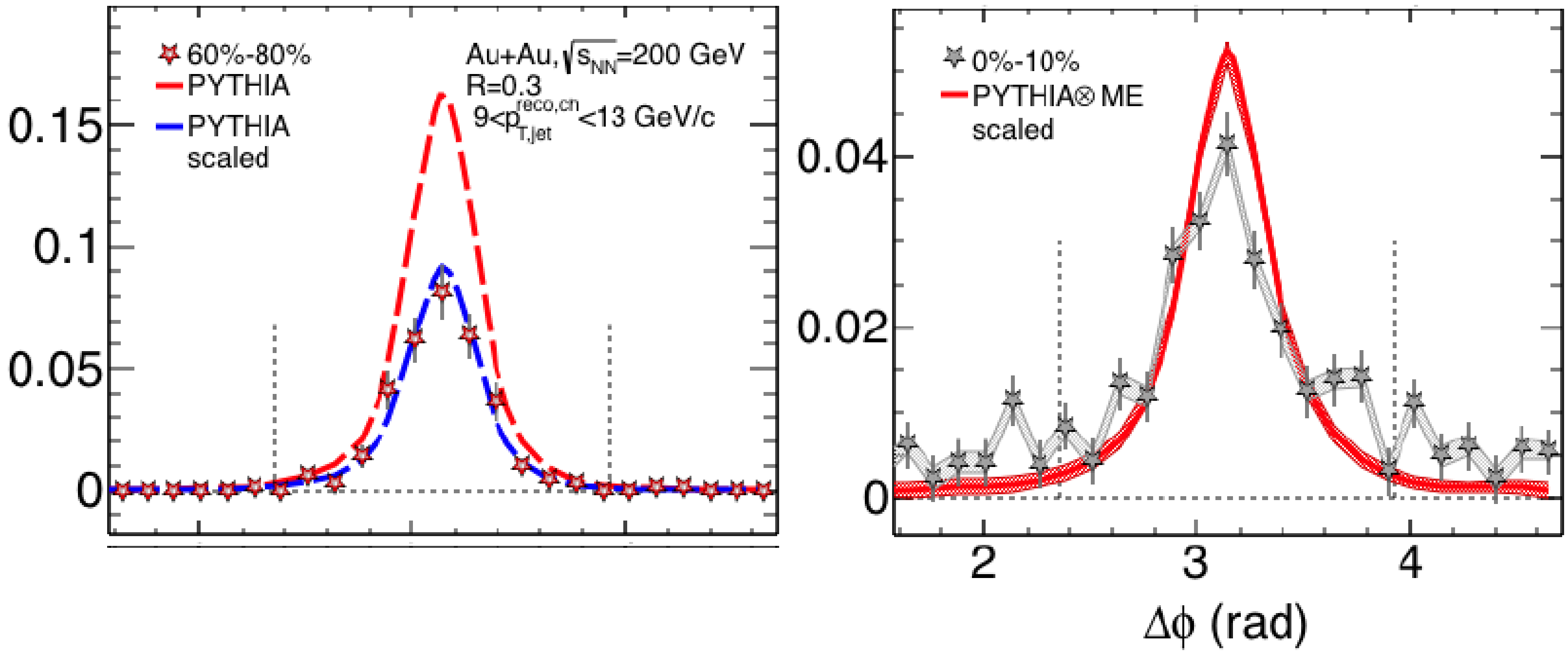
M. J. Tannenbaum

**arXiv:1702.00840**

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

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

**STAR: arXiv:1702.01108**



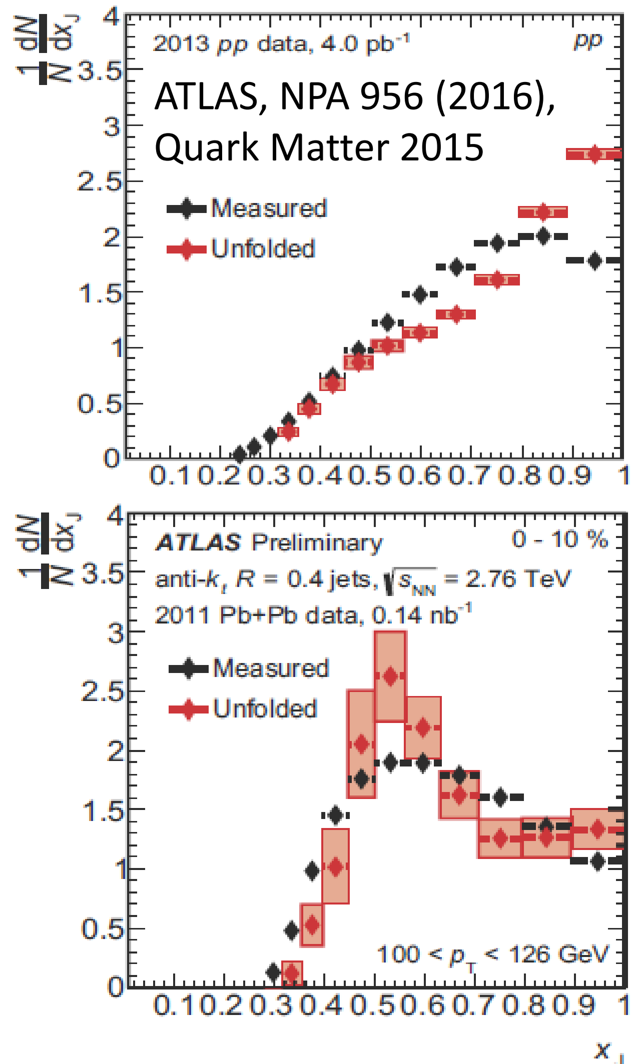
# Dijet asymmetry $A_J$ ($x_J$)

- 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
- *Reduce large ambiguities in theory-to-experiment comparison in studying jet energy loss effect*

- **Our goal:** to establish a benchmark calculation that can describe the fully corrected data in pp collisions and to study medium effect and extract $q^{hat}$ in AA collisions
- **Our approach:** the resummation-improved pQCD approach



# Dijet asymmetry in pQCD expansion

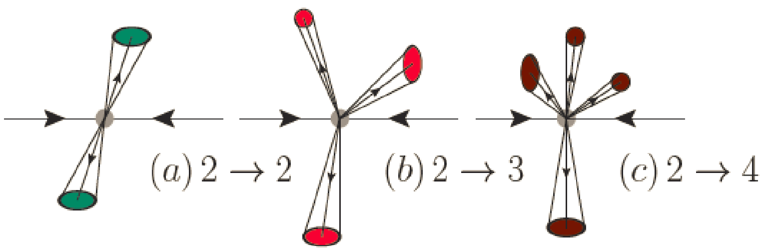
- Perturbative QCD expansion in $\alpha_s$ (2->2, 2->3, 2->4, …)
- PQCD expansion has an interesting upper (lower) bound for $A_J$ ($x_J$) distribution
  - Assuming energy/momentum conservation & perfect detector with $4\pi$ coverage
  - For n-jet final state (2->n),

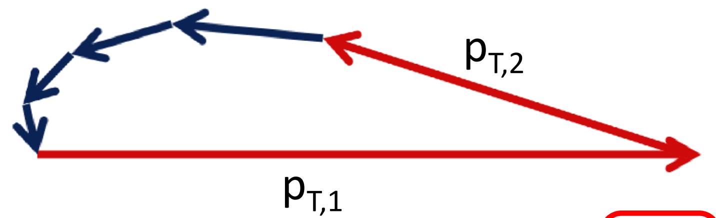
$$p_{T,1} = \left|\vec{p}_{T,2} + \ldots + \vec{p}_{T,n}\right| \le p_{T,2} + \ldots + p_{T,n} \le (n-1)p_{T,2}$$

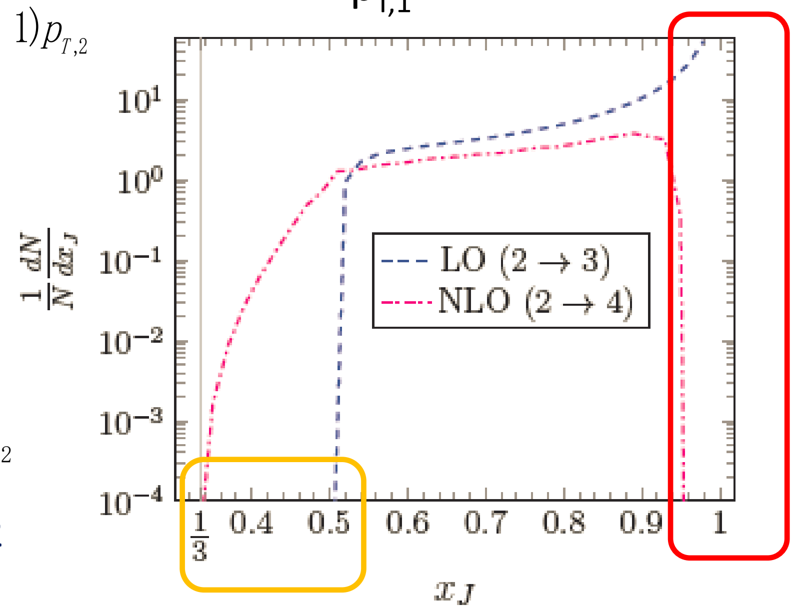
$$X_J^{2\to n} = \frac{p_{T,2}}{p_{T,1}} \ge \frac{1}{n-1} \qquad A_J^{2\to n} \ge \frac{n-2}{n}$$

- PQCD expansion in $\alpha_s$ 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)

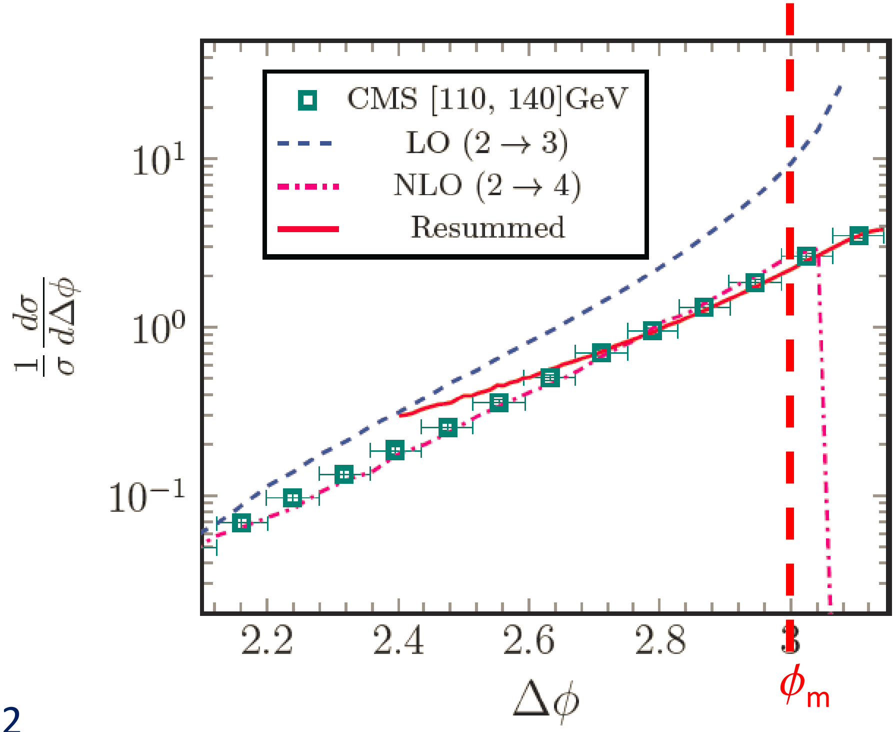
# Resummation-improved pQCD approach

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

NLO pQCD provides very good result at small $x_J$ region

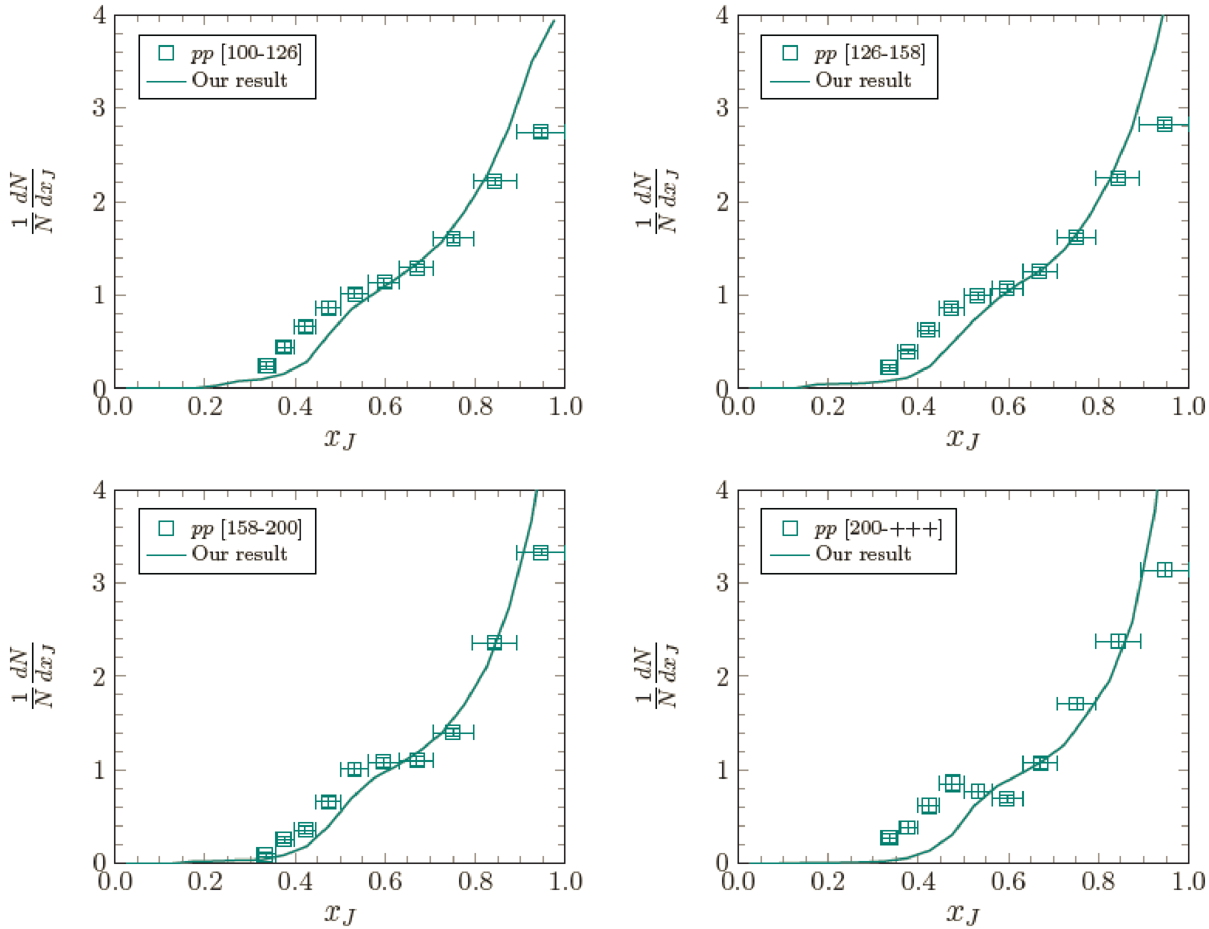
Sudakov resummation resums the alternating-sign series of large logarithms at $x_J$->1 region

Essentially no free parameter in our improved approach




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 in resummation-improved pQCD approach




At very small $x_J$ region, higher order contributions might become relevant

The small difference at small $x_J$ affects very little on the extraction of $q^{hat}$

# Dijet asymmetry in PbPb collisions @ LHC

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

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

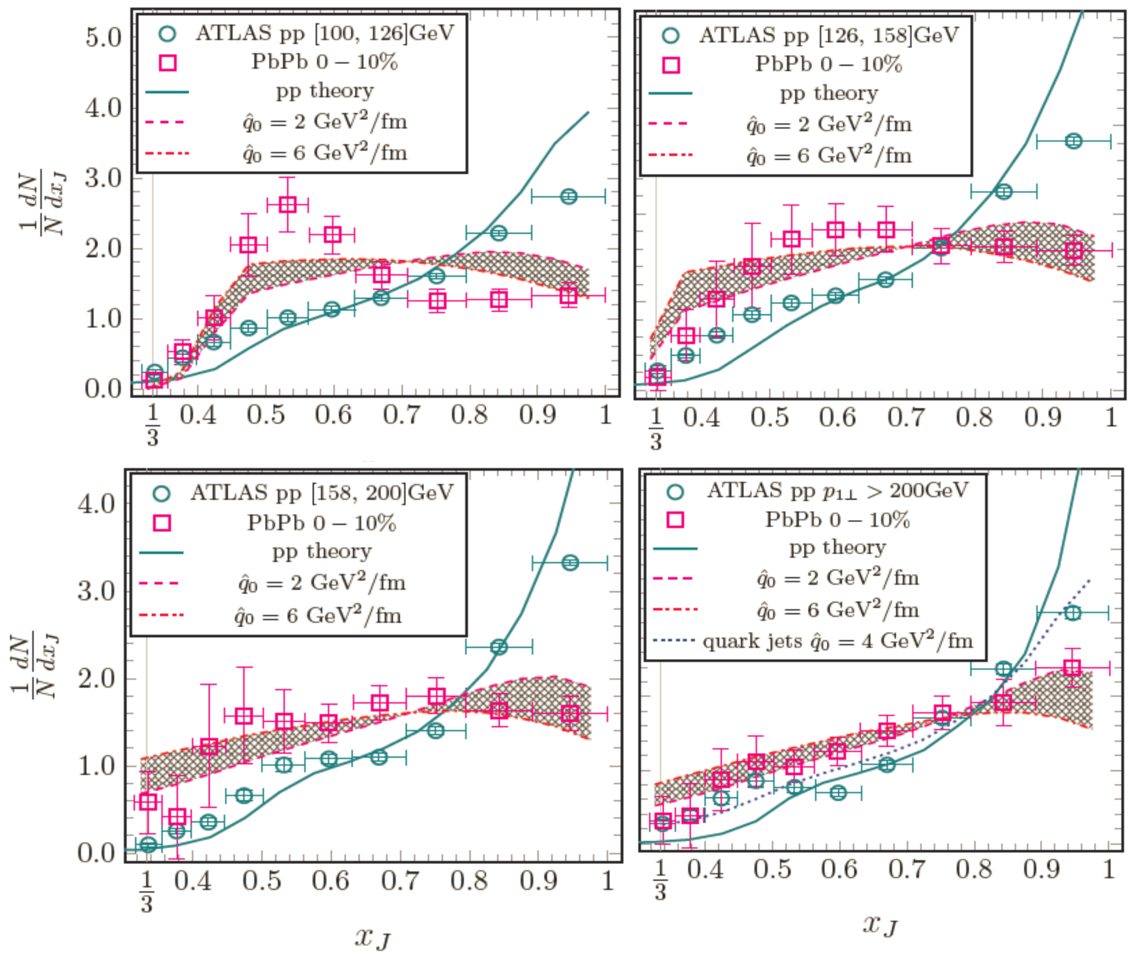
$$\omega_c \equiv \int dL\ \hat{q}L \quad \alpha \equiv \frac{2\alpha_s C_R}{\pi}$$

- 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

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

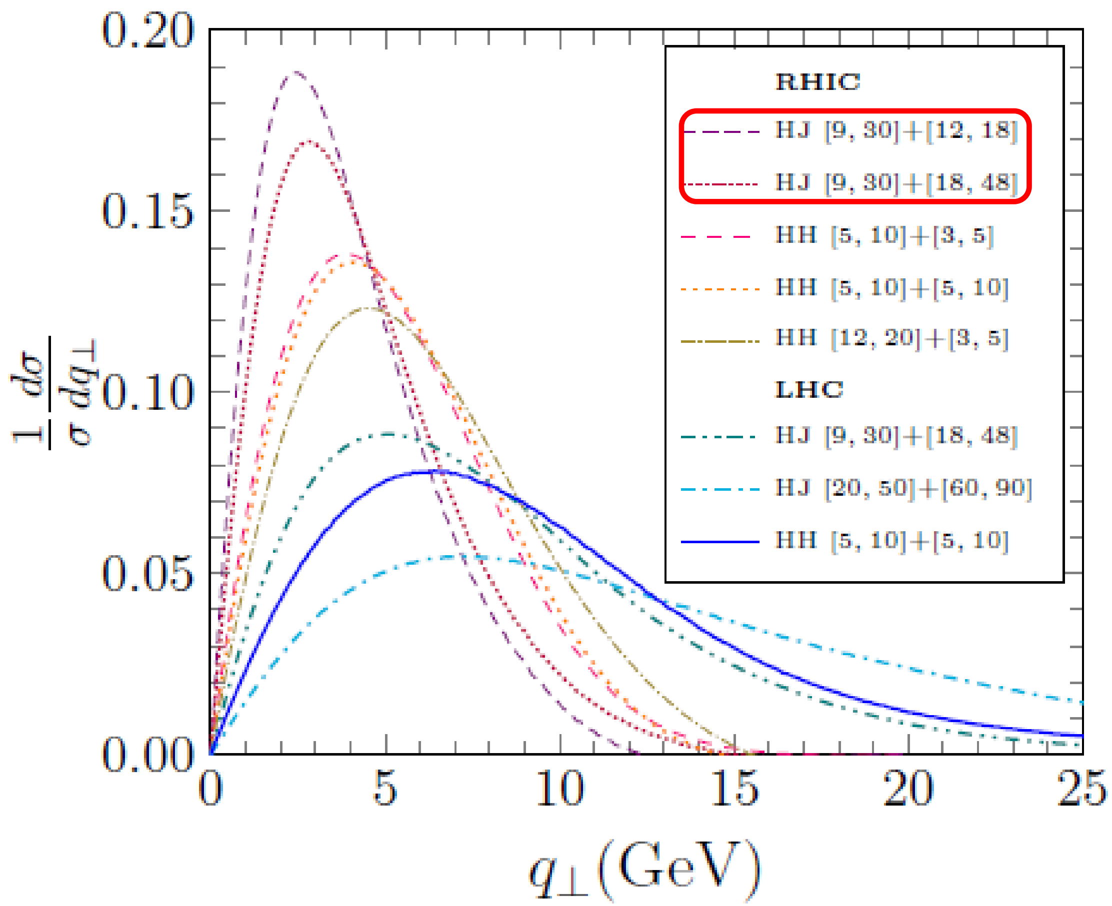


# Summary

- **Dihadron and hadron-jet angular correlations**
  - *Provide a new and more direct method to extract $p_T$ broadening & $q^{hat}$*
  - Perform the first benchmark calculation of back-to-back dihadron and hadron-jet angular correlations at RHIC and the LHC
  - Use realistic hydrodynamics to extract the transverse momentum broadening (14GeV$^2$) and $q^{hat}$ (4GeV$^2$/fm) at RHIC

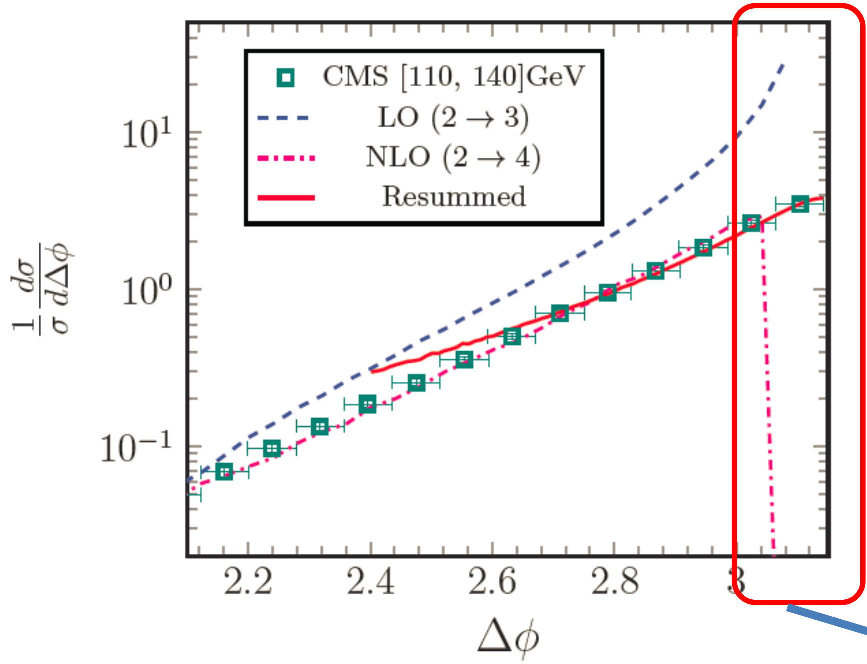
- **Dijet asymmetry**
  - Develop the Resummation Improved pQCD formalism and establish the baseline calculation to describe the fully corrected dijet asymmetry data
  - *Reduce large ambiguities in theory-to-experimental comparison when studying jet energy loss via dijet asymmetries*
  - Combine BDMPS energy loss model and realistic hydrodynamics to extract $q^{hat}$ (2-6 GeV$^2$/fm) at the LHC

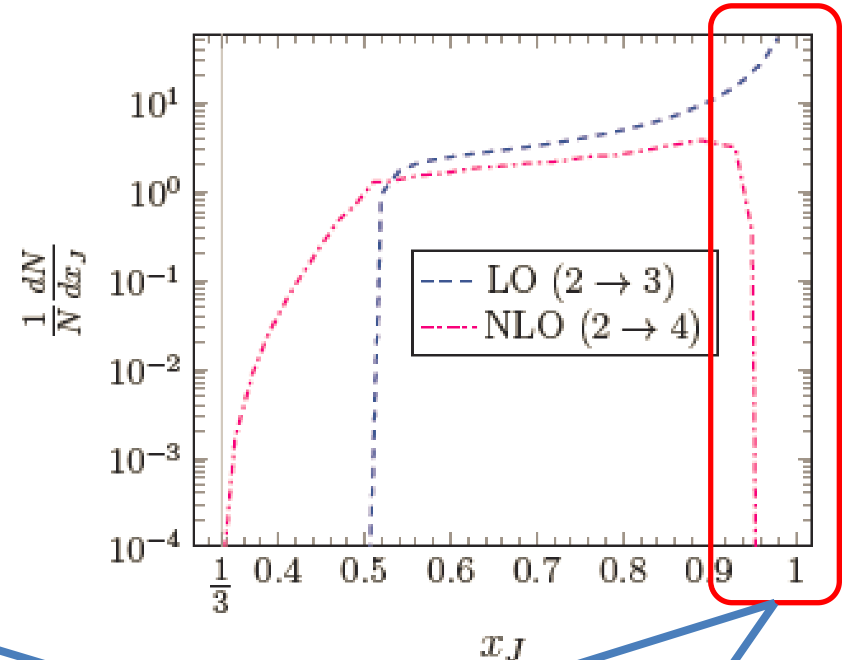
# Sensitivity to medium-induced effect: dijet relative transverse momentum $q_T$ distribution (in pp)

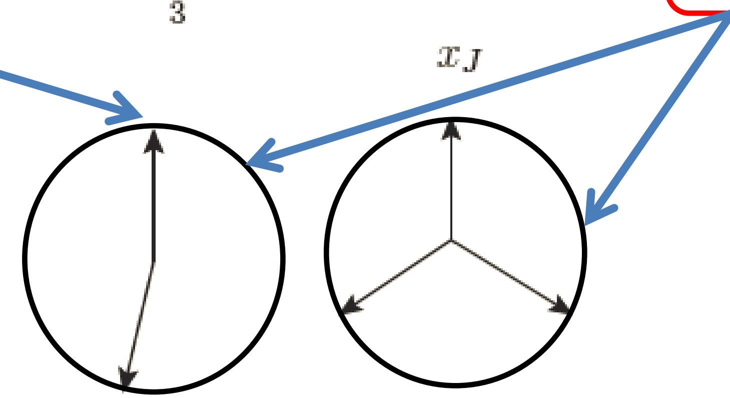



$$\vec{q}_\perp = \vec{p}_{T,1} + \vec{p}_{T,2} \qquad \left\langle q_\perp^2 \right\rangle_{AA} \approx \left\langle q_\perp^2 \right\rangle_{pp} + \left\langle p_\perp^2 \right\rangle_{AA}$$

# Angular & asymmetry distributions



**For back-to-back configuration:**

$$q_T = \left|\vec{p}_{T,1} + \vec{p}_{T,2}\right| << p_{T,1}, p_{T,2}$$

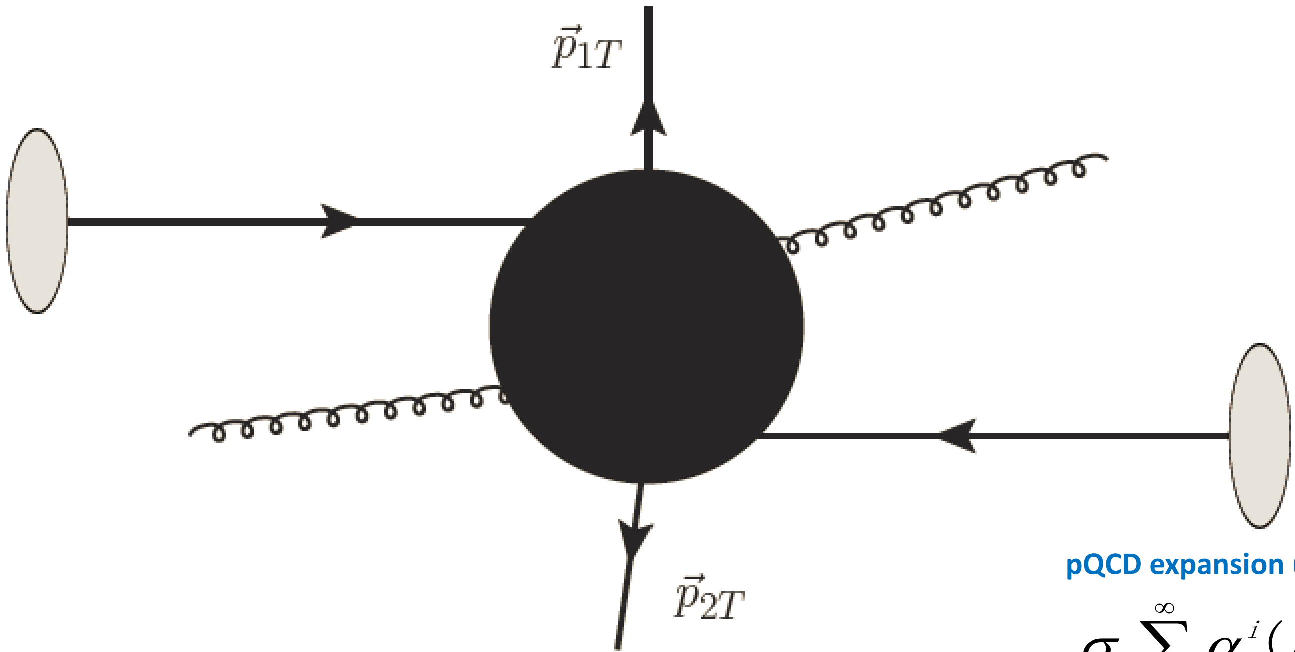
**Need to resum the large logarithms, e.g.,**

$$\alpha_s \log^2\left(\frac{p_T^2}{q_T^2}\right)$$

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

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

# Sudakov resummation for dijet production




At kinematic region (back-to-back configuration):

$$q_T = \left|\vec{p}_{T,1} + \vec{p}_{T,2}\right| << p_{T,1} \approx p_{T,2}$$

one needs to resum the large logarithms:

$$\alpha_s \log^2\left(\frac{p_T^2}{q_T^2}\right)$$

**pQCD expansion (schematically):**

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

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

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

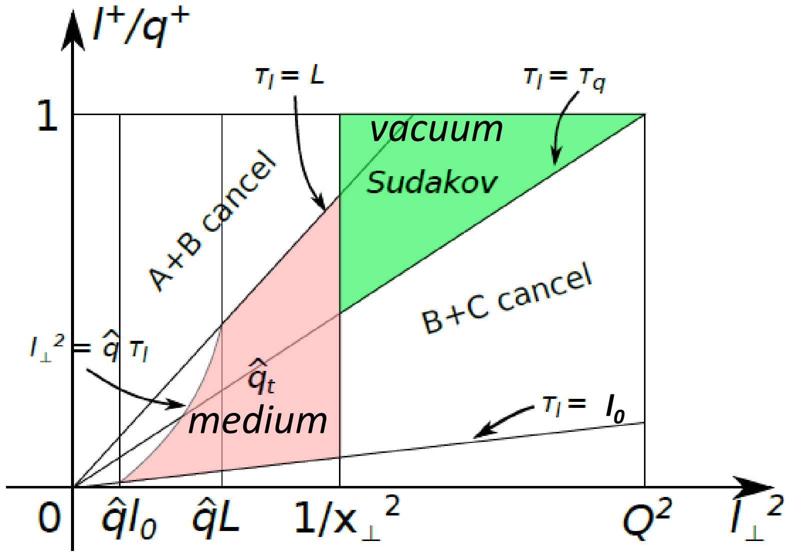
**Sudakov resummation**

# 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 and ***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) $l_+ < q_+$

***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

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

# Sudakov factors

- The resummation is done in auxilary b-space,

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

- 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:

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

- The final state contribution to Sudakov factor is similar to initial states for hadron production, and takes a cone dependent factor $D\ln(1/R^2)$ for jet production. At mid-rapidity, only ½ of final state Sudakov factor contributes to the azimuthal angle correlations.
- The contribution from initial and final states to non-perturbative Sudakov factor is, e.g., for quark,

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

Sun, Yuan, Yuan, PRL113 (2014), PRD92 (2015)
Mueller, Wu, Xiao, Yuan, arXiv:1608.07339

- The contribution from medium-induced broadening to Sudakov factor is included as:

$$S(Q,b) = S_{\mathrm{p}}^i(Q,b) + S_{\mathrm{p}}^f(Q,b) + S_{\mathrm{np}}(Q,b) + \frac{b^2}{4}\left(\langle p_\perp^2 \rangle_c + \langle p_\perp^2 \rangle_d\right)$$