Momentum and angular correlations in Z/γ-hadron production in relativistic heavy-ion collisions

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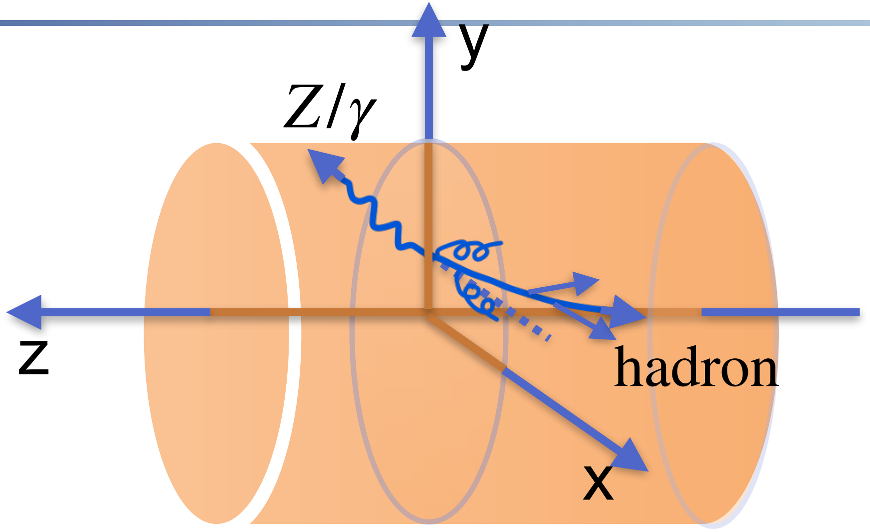
Outline

- Motivation
- Sudakov resummation improved pQCD parton model,

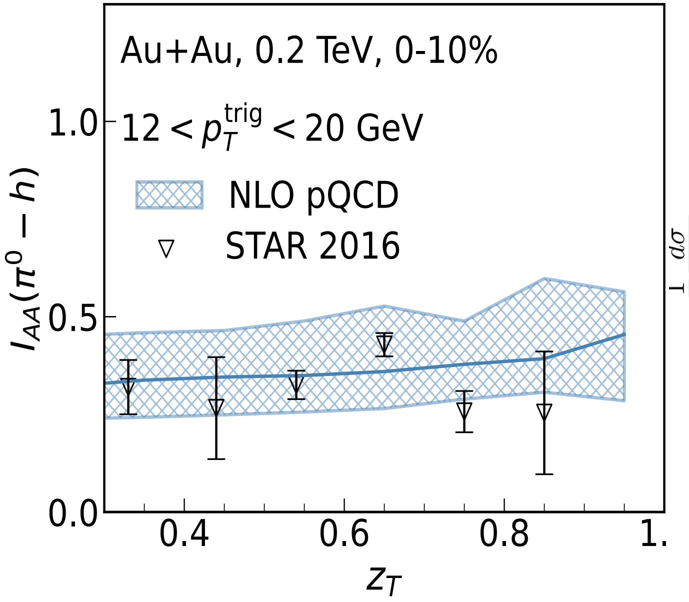
  HT ΔE & $\langle p_\perp^2 \rangle$-broadening
- Numerical results
  - Transverse momentum distribution for Z/γ-hadron
  - Azimuthal angular correlations for Z/γ-hadron
  - RMS width of $\Delta\phi$ distribution
- Summary

Motivation

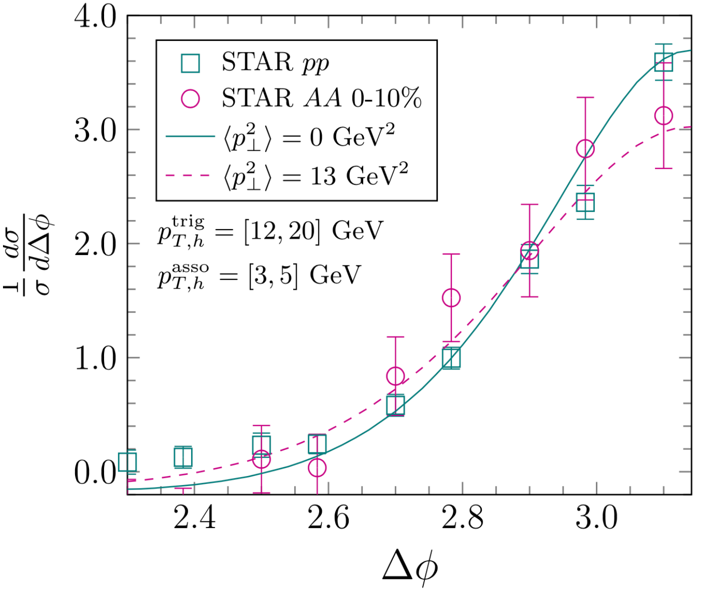


- Quark-gluon plasma (QGP) has been created in high-energy heavy-ion collisions.
- Jet quenching is an extremely useful tool to explore the transport properties of QGP.
  [X.-N. Wang and M. Gyulassy, PRL 68, 1480 (1992)]
- In jet trajectory, jets lose energy ΔE and gain transverse momentum $\langle p_\perp^2 \rangle$, due to interaction with the medium by multiple scattering.

suppression…



$\Delta\phi$ de-correlation…



[***M Xie***, WY Ke, HZ Zhang, XN Wang, PRC 108 (2023) 1, L011901]
[L Chen, GY Qin, SY Wei, BW Xiao, HZ Zhang, PLB 773, 672 (2017)]

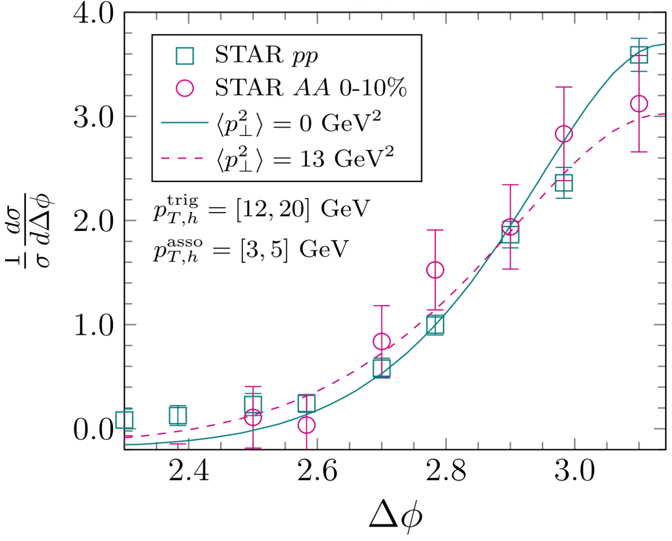
- Both of them are related to jet transport parameter

$$\hat{q} = \sum_{b,cd} \int dq_\perp^2 \frac{d\sigma_{ab\to cd}}{dq_\perp^2} \rho_b q_\perp^2 .$$

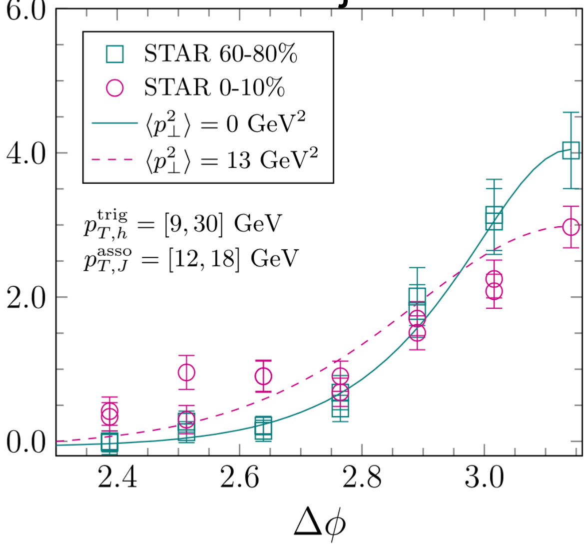
[BDMPS, NPB 483, 291 (1997) & 484 265 (1997)]

Motivation

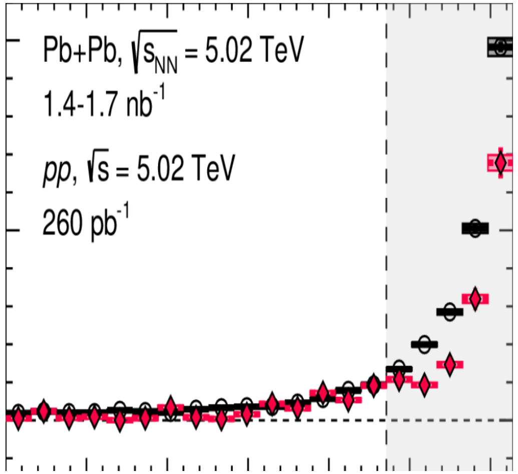
Di-hadron



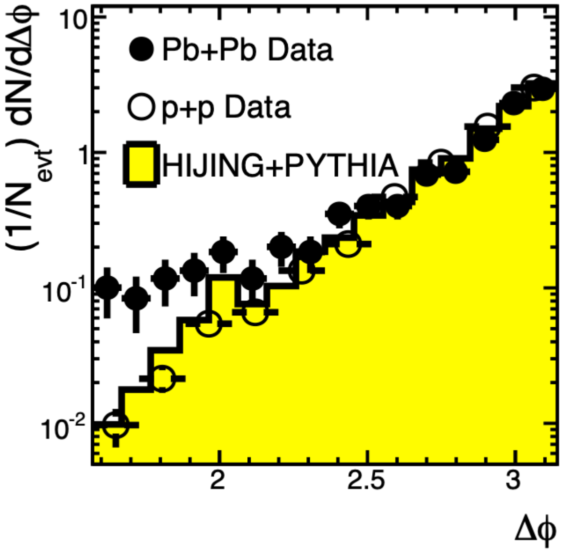
Hadron-jets



Z-hadron



Di-jets



- De-correlation caused by the $\langle p_\perp^2 \rangle$-broadening has been observed in di-hadron and hadron-jets correlations at RHIC.

[L Chen, GY Qin, SY Wei, BW Xiao, HZ Zhang, PLB 773, 672 (2017)]

- However, the $\langle p_\perp^2 \rangle$ effect is not yet clearly observed for di-jets, Z/γ-hadron/jets within the precision of current measurements at RHIC and the LHC.

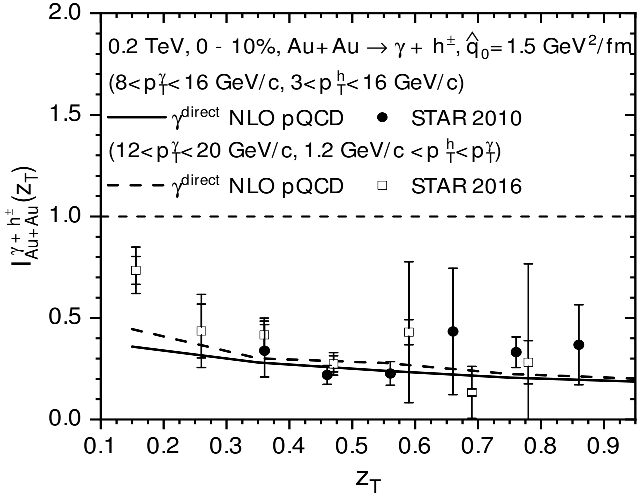
[ATLAS, PRL105 (2010) 252303] [CMS, PRL 128, 122301 (2022)]

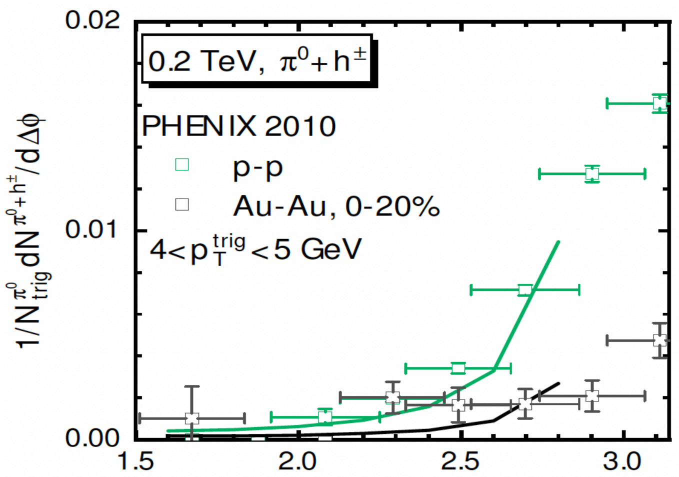
- Additional inclusion of the jet energy loss may also influence the angular correlation of two-particle.

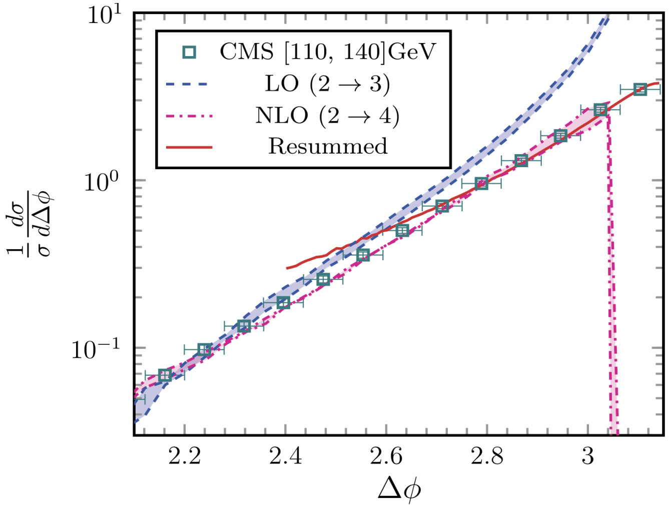
$$q_{\perp AA}^{*2} \sim q_{\perp pp}^{*2} + \langle p_\perp^2 \rangle$$

Motivation

With a pQCD parton model (ΔE) improved by the Sudakov resummation ($\langle p_\perp^2 \rangle$) technique to study the medium modification on p_{T} and $\Delta\phi$ correlations for Z/γ-hadron in HIC.







- NLO pQCD describes the p_{T} distribution well. However, its expansion fails to converge at $\Delta\phi \sim \pi$.

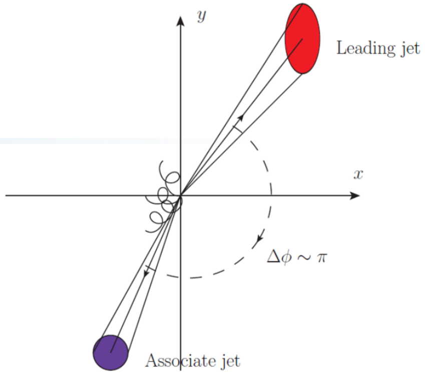
[***M Xie***, XN Wang, HZ Zhang, PRC 103, 034911 (2021)]
[J. F. Owens, PRD 65 (2002) 034011]

- The Sudakov resummation describes the data at $\Delta\phi \sim \pi$ well.

[L Chen, GY Qin, SY Wei, BW Xiao, HZ Zhang, PLB 782, 773 (2018), Mueller, Xiao, Yuan, PRL 110, 082301 (2013), & PRD 88, 114010 (2013), Sun, Yuan, Yuan, PRL 113, 232001 (2014)]

- Z/γ Preserve the momentum information of the away-side jets before they get quenched.

Sudakov resummation improved pQCD parton model



In $p+p$ collisions：

$$\frac{d\sigma_{pp\to Vh}}{d\mathscr{P}.\mathscr{S}.}=\sum_{a,b,d}\int\frac{dz_d}{z_d^2}D_{h/d}\left(z_d,\mu^2\right)\frac{|\overline{\mathscr{M}}_{ab\to Vd}|^2}{16\pi^2\hat{s}^2}x_af_{a/p}(x_a,\mu^2)x_bf_{b/p}(x_b,\mu^2)\int\frac{d^2\vec{b}_\perp}{(2\pi)^2}e^{-i\vec{q}_\perp\cdot\vec{b}_\perp}e^{-S_{\rm vac}}(Q,b_\perp)$$

$$\uparrow$$

$$\sum_{k=0}^{\infty}(-1)^k\mathcal{O}\left(\left(\alpha_s\ln^2\frac{P_\perp^2}{q_\perp^2}\right)^k\right)$$

$$S_{\rm vac}(Q,b_\perp)=S_{\rm pert}^{i}\left(Q,b_\perp\right)+S_{\rm pert}^{f}\left(Q,b_\perp\right)+S_{\rm NP}\left(Q,b_\perp\right)$$

$$S_{\rm pert}^{i}\left(Q,b_\perp\right)=\int_{\mu_b^2}^{Q^2}\frac{{\rm d}\mu^2}{\mu^2}\left[\left(A_i^{(1)}+A_i^{(2)}\right)\ln\frac{Q^2}{\mu^2}+B_i\right]$$

[Mueller, Xiao, Yuan, PRL 110 (2013) 082301, PRD 88 (2013) 114010; Sun, Yuan, Yuan, PRL 113, 232001(2014); Sun, Isaacson, Yuan, Yuan, IJMPA 33 (2018) no.11, 1841006]

In $A+A$ collisions：

$$\frac{d\sigma_{AA\to Vh}}{dP.S.}=\int d^2\vec{b}\,T_{AB}(\vec{b})\int\frac{d\phi_d}{2\pi}\sum_{abd}\int\frac{dz_d}{z_d^2}\tilde{D}_{h/d}\left(z_d,\mu^2,\Delta E_d\right)\frac{|\overline{\mathscr{M}}_{ab\to Vd}|^2}{16\pi^2\hat{s}^2}x_a\tilde{f}_{a/A}x_b\tilde{f}_{b/A}\int\frac{d^2\vec{b}_\perp}{(2\pi)^2}e^{-i\vec{q}_\perp\cdot\vec{b}_\perp}e^{-S_{\rm med}(Q,b_\perp)}$$

[GLM, NPB 21 (1970) 135] [CT18A PRD 103(1), 014013 (2021)] [EPPS 21, EPJC 82 (2022) 5, 413] [S. Kretzer, PRD **62**, 054001 (2000)]

$$\tilde{D}_{h/d}(z_d,\mu^2,\Delta E_d)=(1-e^{-N_g})\left[\frac{z_d'}{z_d}D_{h/d}(z_d',\mu^2)+N_g\frac{z_g{}'}{z_d}D_{h/g}(z_g{}',\mu^2)\right]+e^{-N_g}D_{h/d}(z_d,\mu^2)$$

[XN Wang, PRC70 (2004) 031901], [HZ Zhang, JF Owens, EK Wang, XN Wang, PRL 98.212301 (2007);103, 032302 (2009)]

$$S_{\rm med}(Q,b_\perp)=S_{\rm vac}(Q,b_\perp)+\frac{b_\perp^2}{4}\langle p_\perp^2\rangle$$

[AH Mueller, B Wu, BW Xiao, Y Feng, PLB 763 (2016) 208-212], [J Yong J, BW Xiao, Y Feng, PRD 101, 094008 (2020)]

ΔE and $\langle p_\perp^2 \rangle$

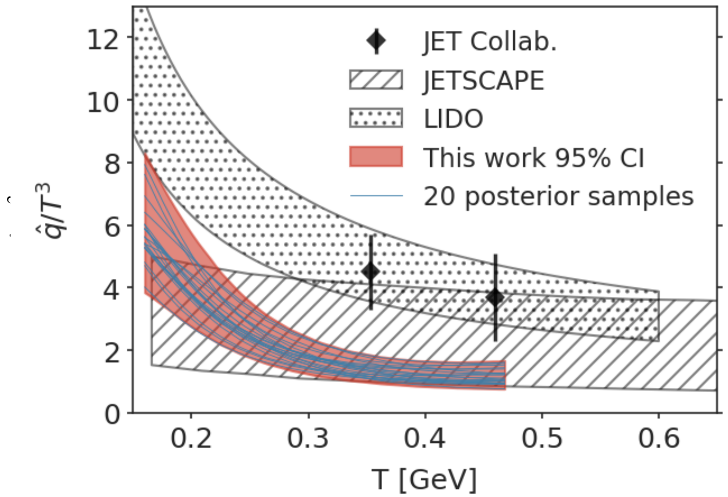
High-Twist approach [WT Deng, XN Wang, PRC 81, 024902(2010), E. Wang, XN Wang, PRL 87, 142301 (2001); 89, 162301 (2002), NB Chang, WT Deng, XN. Wang, PRC 89, 03491 (2014)]

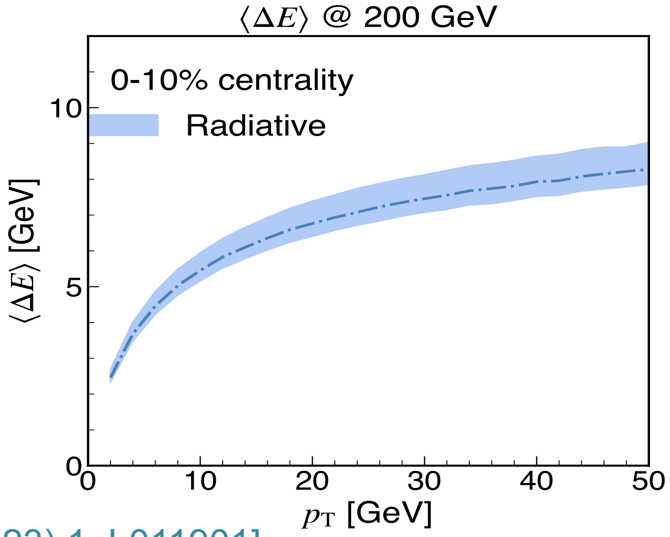
$$\frac{dN_d^{\mathrm{med}}}{dz\,dl_\mathrm{T}^2\,d\tau} = \frac{2C_A\alpha_s}{\pi l_\mathrm{T}^4}\left[\frac{1+(1-z)^2}{z}\right]\hat{q}_d\left(\tau, \vec{r}+(\tau-\tau_0)\,\vec{n}\right)\sin^2\left[\frac{l_\mathrm{T}^2(\tau-\tau_0)}{4z(1-z)E}\right]$$

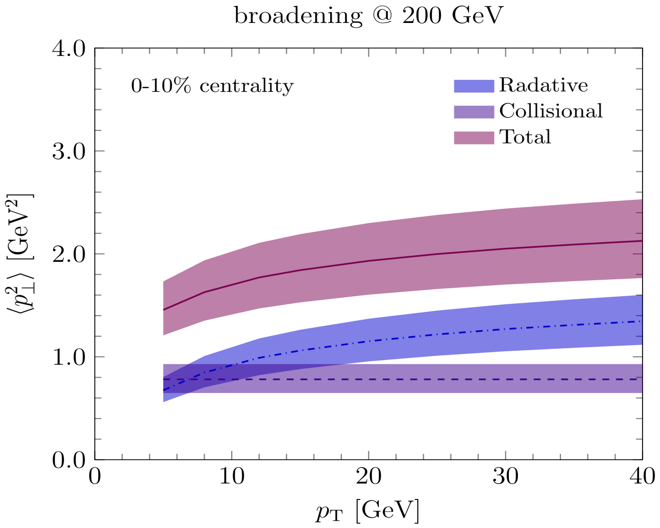
$$N_g^d = \int d\tau \int dl_\mathrm{T}^2 \int dz \frac{dN_d^{\mathrm{med}}}{dz\,dl_\mathrm{T}^2\,d\tau}, \qquad \frac{\Delta E_d}{E} = \int d\tau \int dl_\mathrm{T}^2 \int dz \left(z\frac{dN_d^{\mathrm{med}}}{dz\,dl_\mathrm{T}^2\,d\tau}\right)$$

$$\langle p_\perp^2\rangle_{\mathrm{tot}} = \langle p_\perp^2\rangle_{\mathrm{el}} + \langle p_\perp^2\rangle_{\mathrm{rad}}, \quad \langle p_\perp^2\rangle_{\mathrm{el}} = \left\langle \int d\tau\,\hat{q}_d\left(\tau, \vec{r}+(\tau-\tau_0)\,\vec{n}\right)\right\rangle, \quad \langle p_\perp^2\rangle_{\mathrm{rad}} = \left\langle \int d\tau \int dl_\mathrm{T}^2 \int dz \left(l_\mathrm{T}^2\frac{dN_d^{\mathrm{med}}}{dz\,dl_\mathrm{T}^2\,d\tau}\right)\right\rangle$$

[A Majumder and B Muller, PRC 77, 054903 (2008), GY Qin, A Majumder, PRC 87, 024909 (2013), H. Clayton, M. D. Sievert, and W. A. Horowitz, EPJC 82, 437 (2022)]





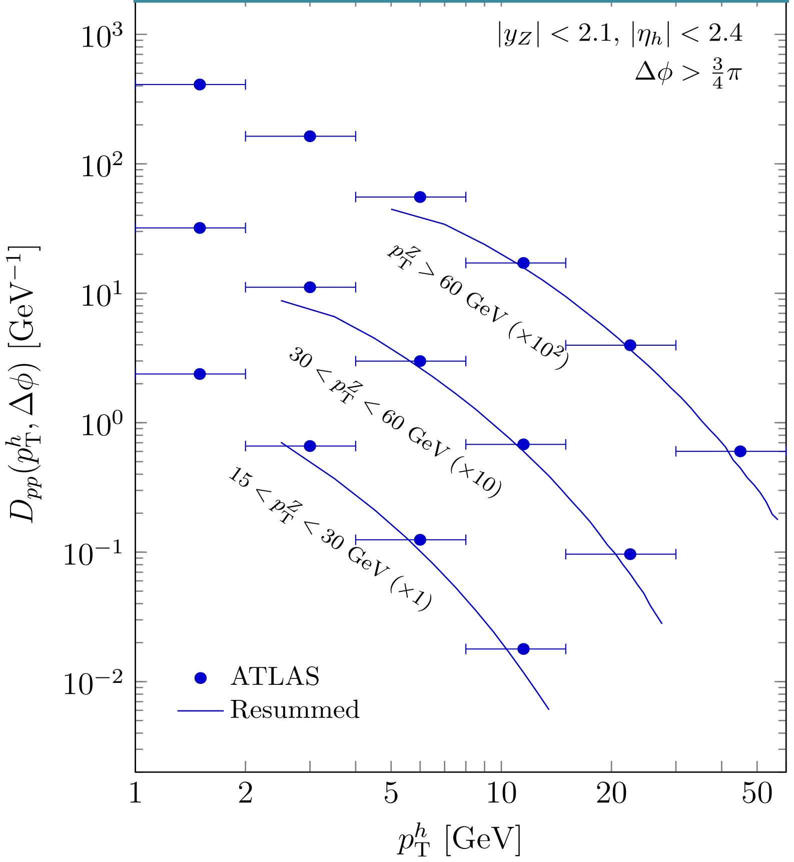


[***M. Xie***, WY Ke, HZ Zhang, XN Wang, PRC 108 (2023) 1, L011901]

p_{T} distribution for Z-hadron

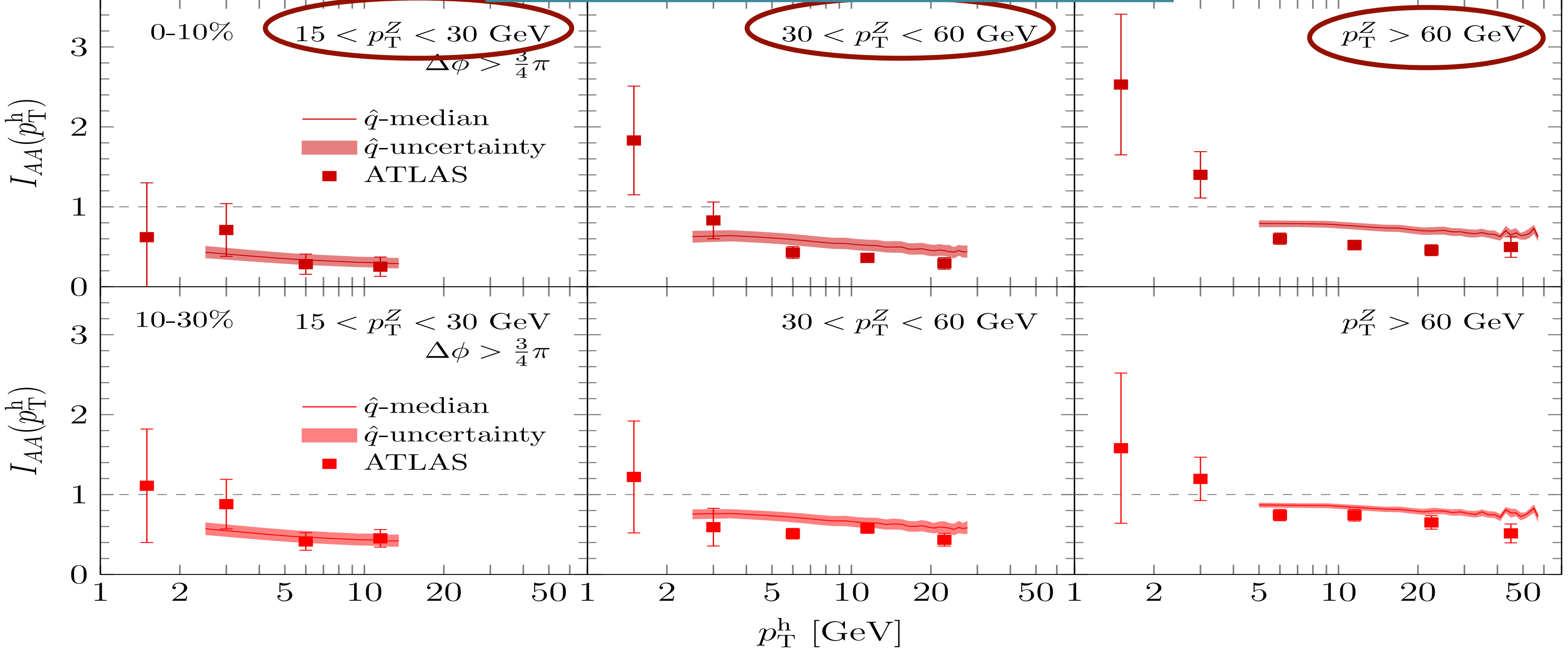
$$D_{pp}(p_{\mathrm{T}}^{h}) = \frac{1}{N_V^{pp}}\frac{dN_{Vh}^{pp}}{dp_{\mathrm{T}}^{h}} = \frac{\int d\Delta\phi\, dp_{\mathrm{T}}^{V}(d^3\sigma_{Vh}^{pp}/dp_{\mathrm{T}}^{V}dp_{\mathrm{T}}^{h}d\Delta\phi)}{\int dp_{\mathrm{T}}^{V}(d\sigma_{V}^{pp}/dp_{\mathrm{T}}^{V})} \qquad I_{AA}(p_{\mathrm{T}}^{h}) = D_{AA}(p_{\mathrm{T}}^{h})/D_{pp}(p_{\mathrm{T}}^{h})$$

$p+p->Z+h$ @ 5.02 TeV



Data from [ATLAS, PRL 126, 072301 (2021)]

$Pb+Pb->Z+h$ @ 5.02 TeV



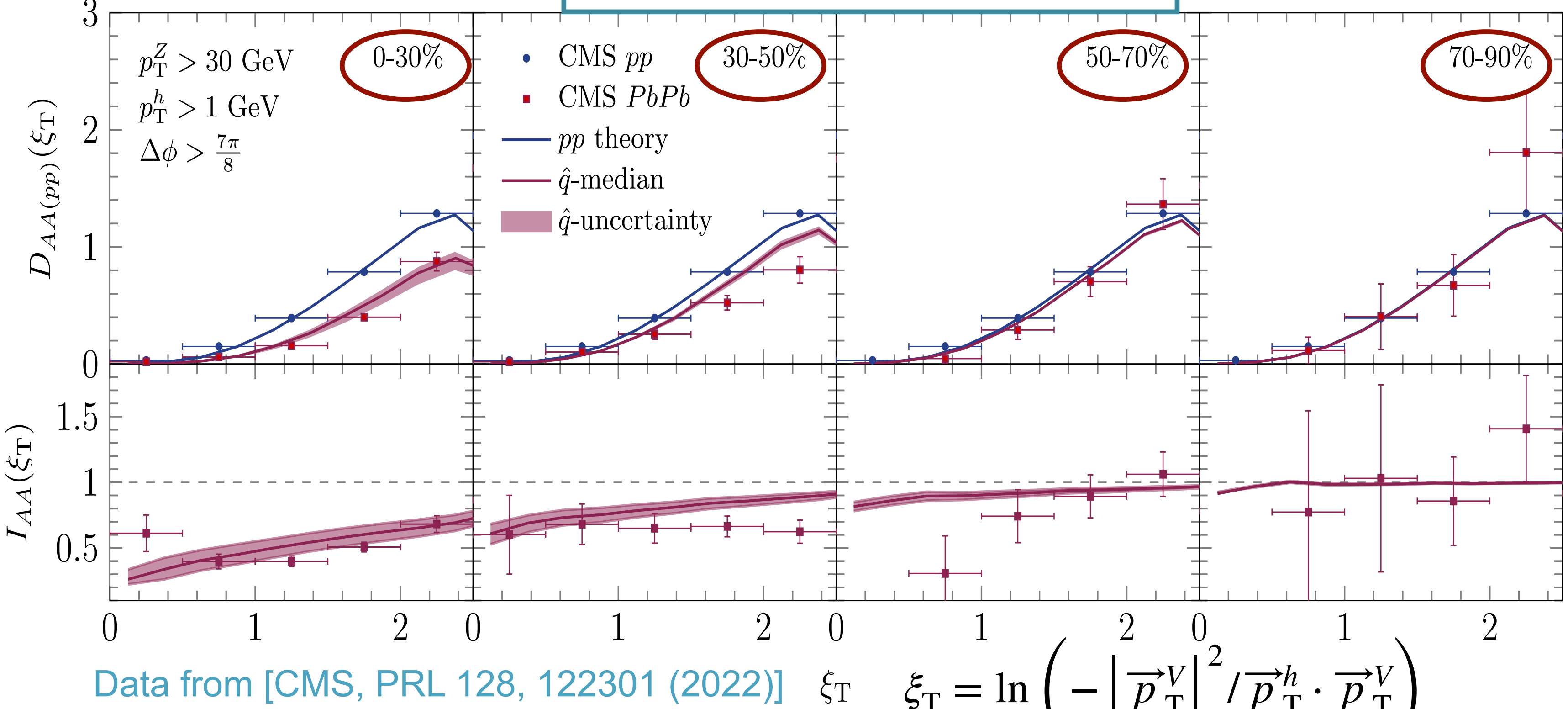
- Sudakov resummation improved pQCD parton model with ΔE & $\langle p_{\perp}^{2}\rangle$ describes the p_{T} distribution of Z-hadron correlation well.
- As the p_{T}^{Z} increases, the suppression decreases.

p_{T} distribution for Z/γ-hadron

Data from [STAR, PRC 82, 034909 (2010)

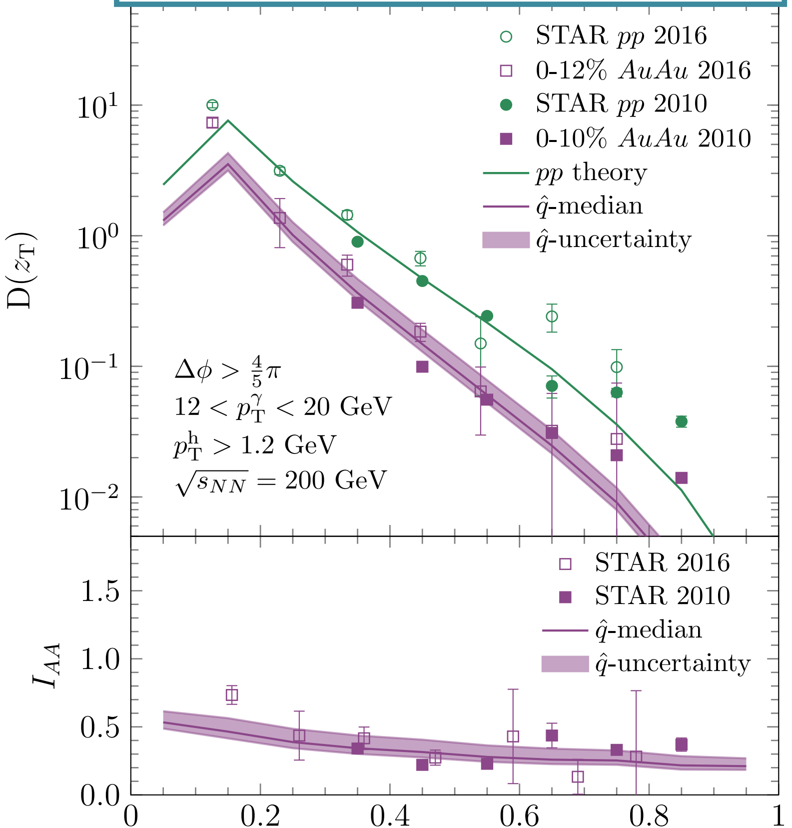
$Pb + Pb -> Z + h$ @ 5.02 TeV

$Au + Au -> \gamma + h$ @ 200 GeV



Data from [CMS, PRL 128, 122301 (2022)]

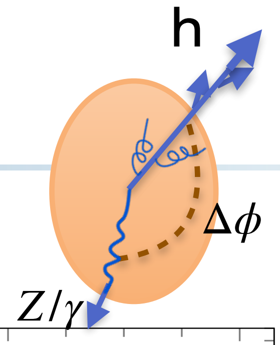
$$\xi_{\mathrm{T}} = \ln\left(-\left|\overrightarrow{p}_{\mathrm{T}}^{V}\right|^{2} / \overrightarrow{p}_{\mathrm{T}}^{h} \cdot \overrightarrow{p}_{\mathrm{T}}^{V}\right)$$



$$z_{\mathrm{T}} = p_{\mathrm{T}}^{h} / p_{\mathrm{T}}^{V}$$

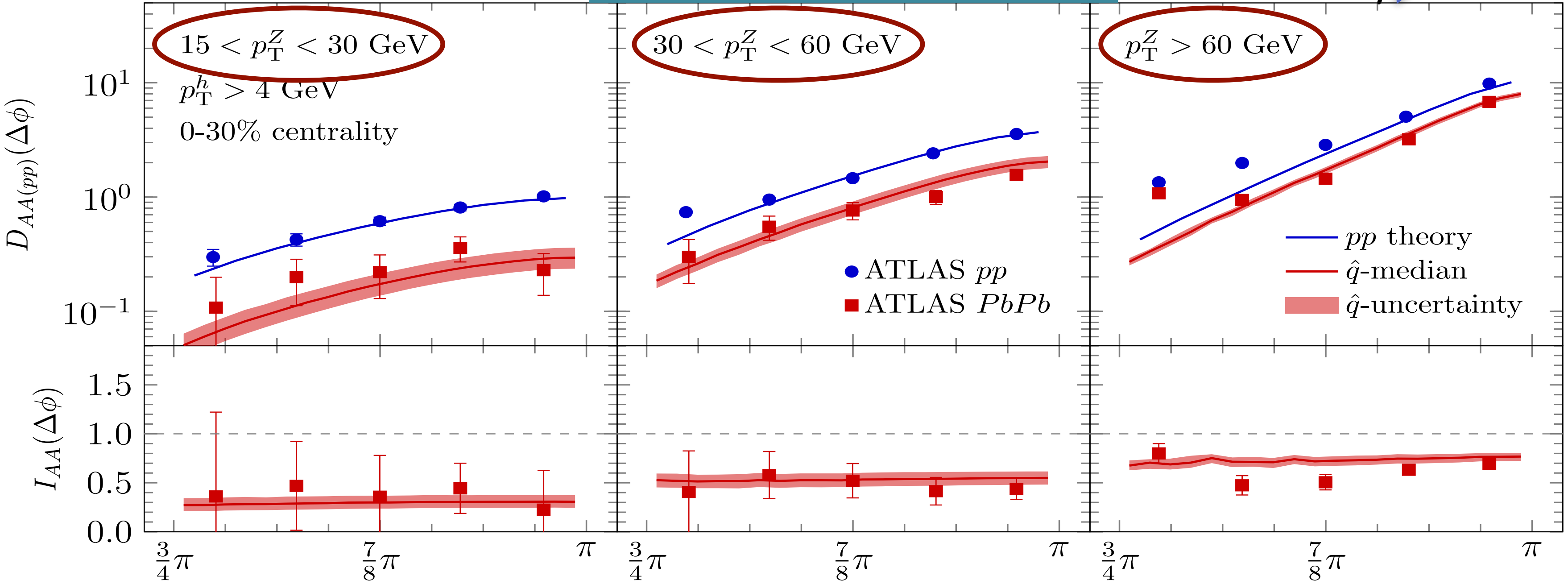
- The uncertainty is mainly from ΔE.
- $\langle p_{\perp}^{2} \rangle$ mainly affects the azimuthal angular and hardly affects the yield.
- Sudakov resummation improved pQCD describes the medium modification on p_{T} distribution for Z/γ-hadron correlations well, including the p_{T}^{V} and centrality dependence at both RHIC and LHC.

$\Delta\phi$ distribution for Z/γ-hadron



Data from [STAR, PLB 760, 689 (2016)]

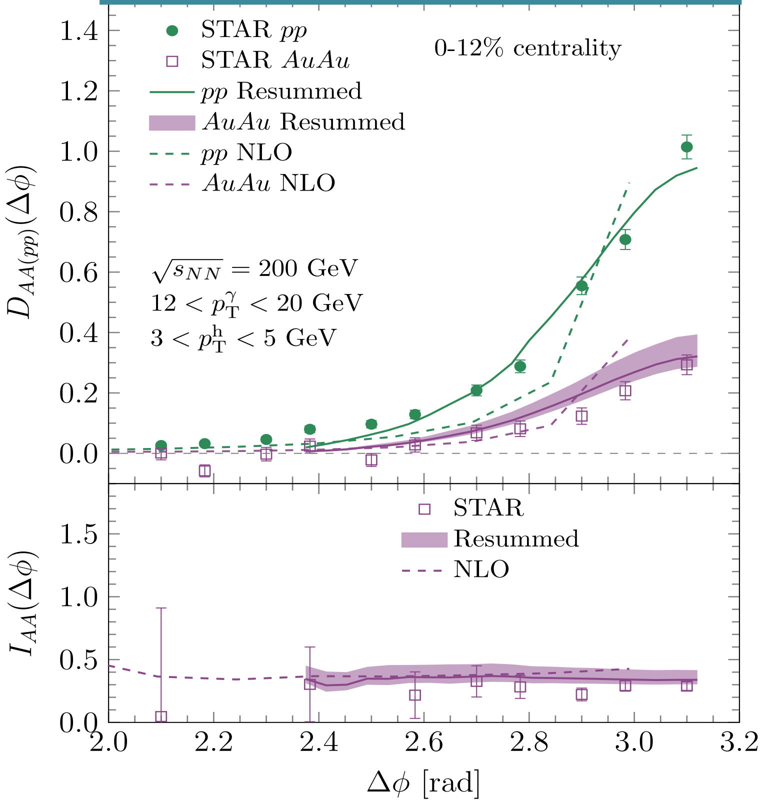
$Pb + Pb -> Z + h$ @ 5.02 TeV



$\Delta\phi$ [rad] $\Delta\phi = |\phi_V - \phi_h|$

Data from [ATLAS, PRL 126, 072301 (2021)]

$Au + Au -> \gamma + h$ @ 200 GeV



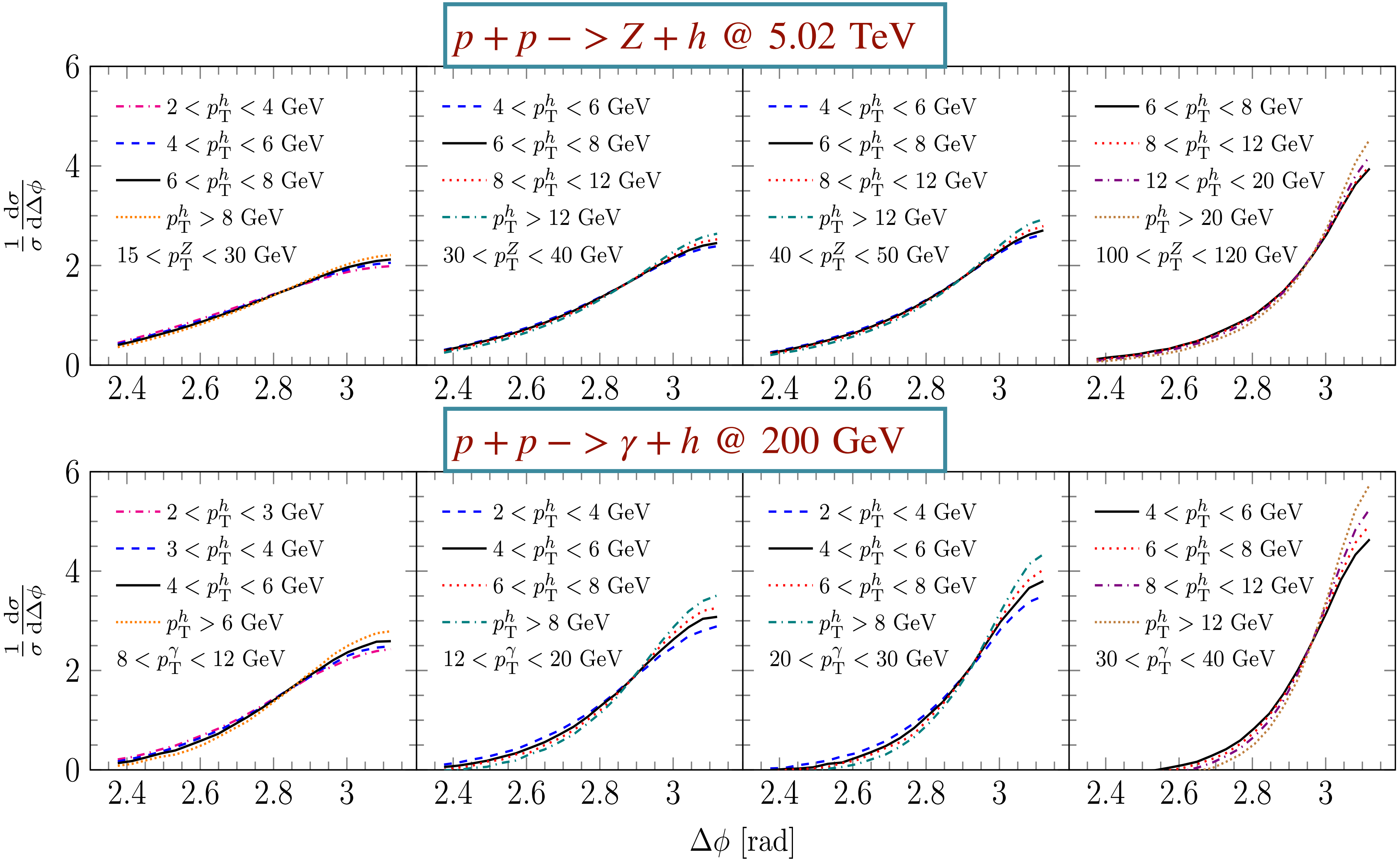
- NLO pQCD can fit the data away from π; Sudakov resummation can fit the data near π.

[P Sun, CP Yuan, F Yuan PRL 113, 232001 (2014)] [C Lin, HZ Zhang, et al., PLB 782 (2018) 773–778]

- Sudakov resummation improved pQCD describes the medium modification on p_T & $\Delta\phi$ distribution for Z/γ-hadron well, including the p_T^V and centrality dependence at both RHIC and LHC.

Normalized $\Delta\phi$ distribution for pp collisions

- Normalized the $\Delta\phi$ distribution to unity to manifest the difference of $\Delta\phi$ correlation between AA and pp.



$p+p->Z+h$ @ 5.02 TeV

$p+p->\gamma+h$ @ 200 GeV

$$\frac{1}{\sigma}\frac{d\sigma}{d\phi}$$

- With different p_T^V ranges
- With different p_T^h ranges

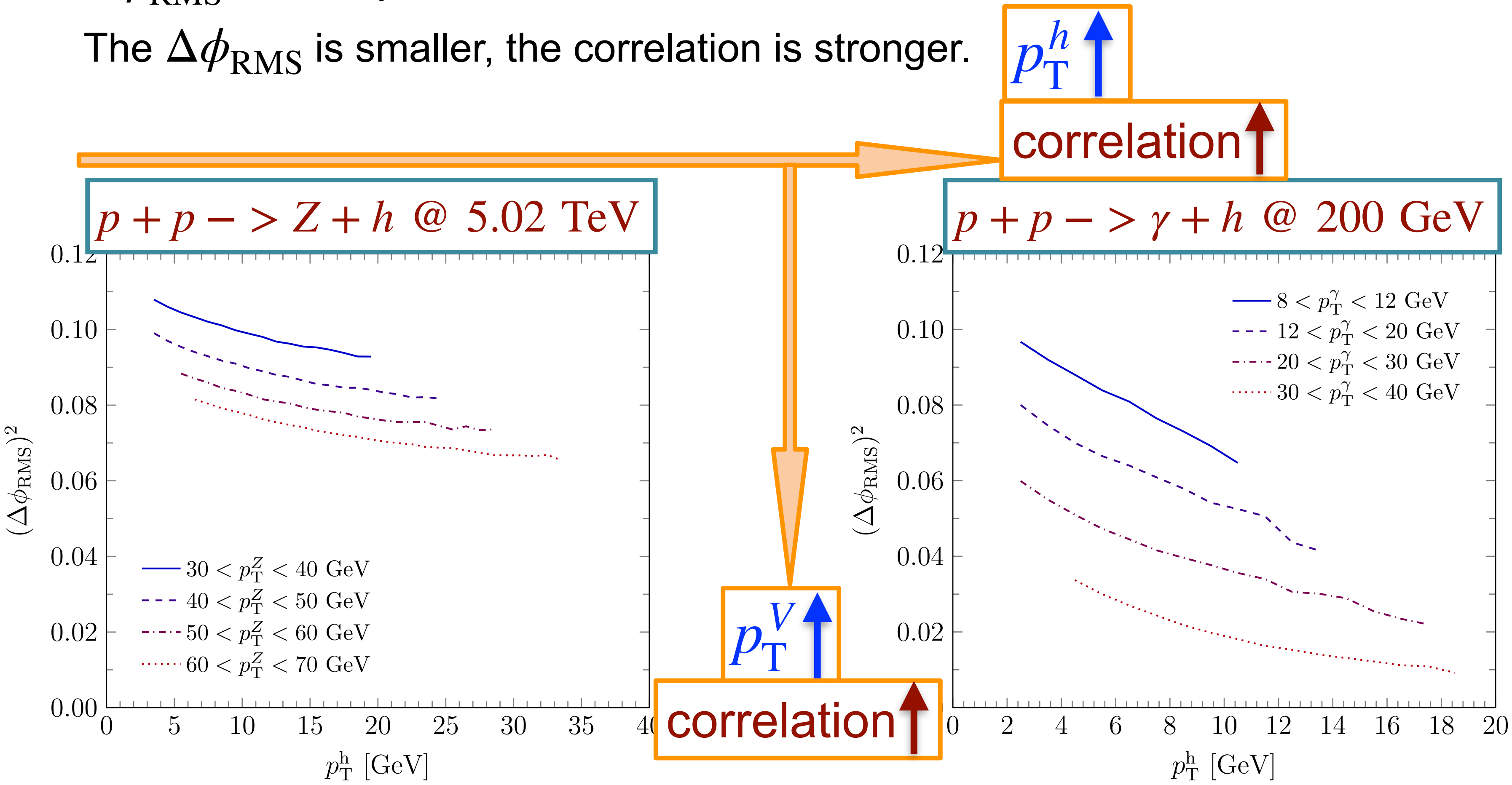
RMS analysis to the width of $\Delta\phi$ distribution

- To quantify the angular correlation strength by the RMS width: $\Delta\phi_{\mathrm{RMS}} = \sqrt{\frac{\int \mathrm{d}\Delta\phi (\Delta\phi - \pi)^2 \frac{\mathrm{d}\sigma}{\mathrm{d}\Delta\phi}}{\int \mathrm{d}\Delta\phi \frac{\mathrm{d}\sigma}{\mathrm{d}\Delta\phi}}}$.

  [JY Jia, SY Wei, BW Xiao, F Yuan, PRD 101, 094008 (2020)]

$\Delta\phi_{\mathrm{RMS}}$=0, totally back-to-back.

The $\Delta\phi_{\mathrm{RMS}}$ is smaller, the correlation is stronger.



- Correlation is stronger both with the p_T^h & p_T^V increasing;
- Correlation is weaker at LHC than at RHIC;
- At LHC, as the Q^2 increases, the Sudakov effect enhances.

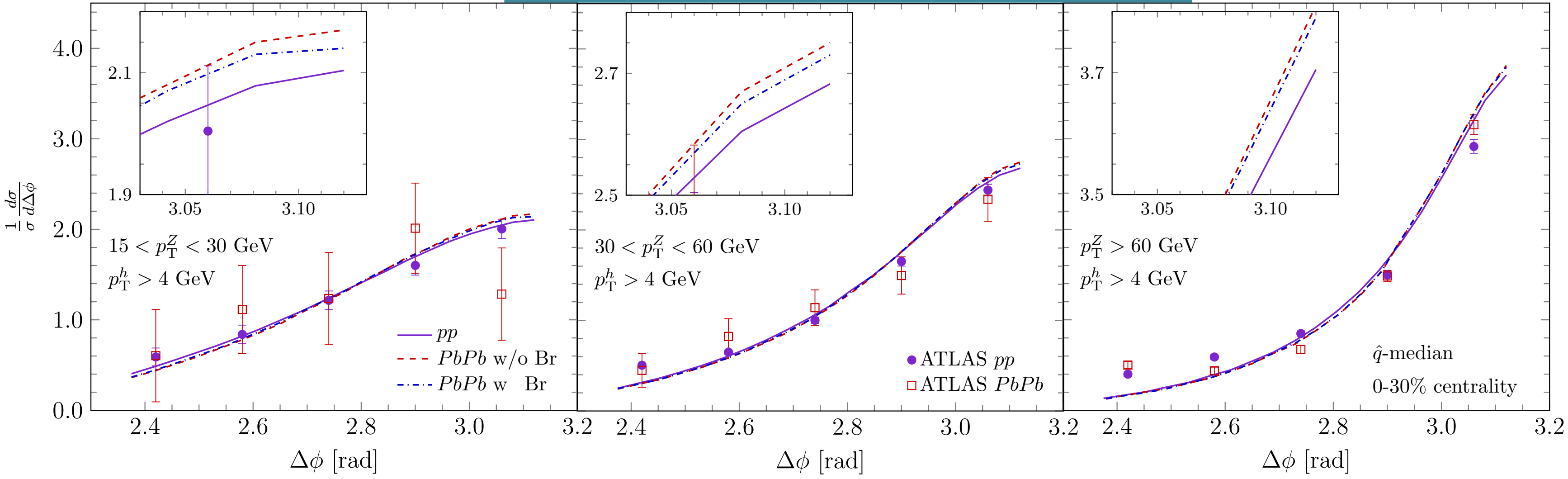
$$S^i_{\mathrm{pert}}(Q, b_\perp) = \int_{\mu_b^2}^{Q^2} \frac{\mathrm{d}\mu^2}{\mu^2} \left[\left(A_i^{(1)} + A_i^{(2)} \right) \ln \frac{Q^2}{\mu^2} + B_i \right]$$

Normalized $\Delta\phi$ distribution for AA collisions

$$\tilde{D}_{h/d}\left(z_d, \mu^2, \Delta E_d\right)$$

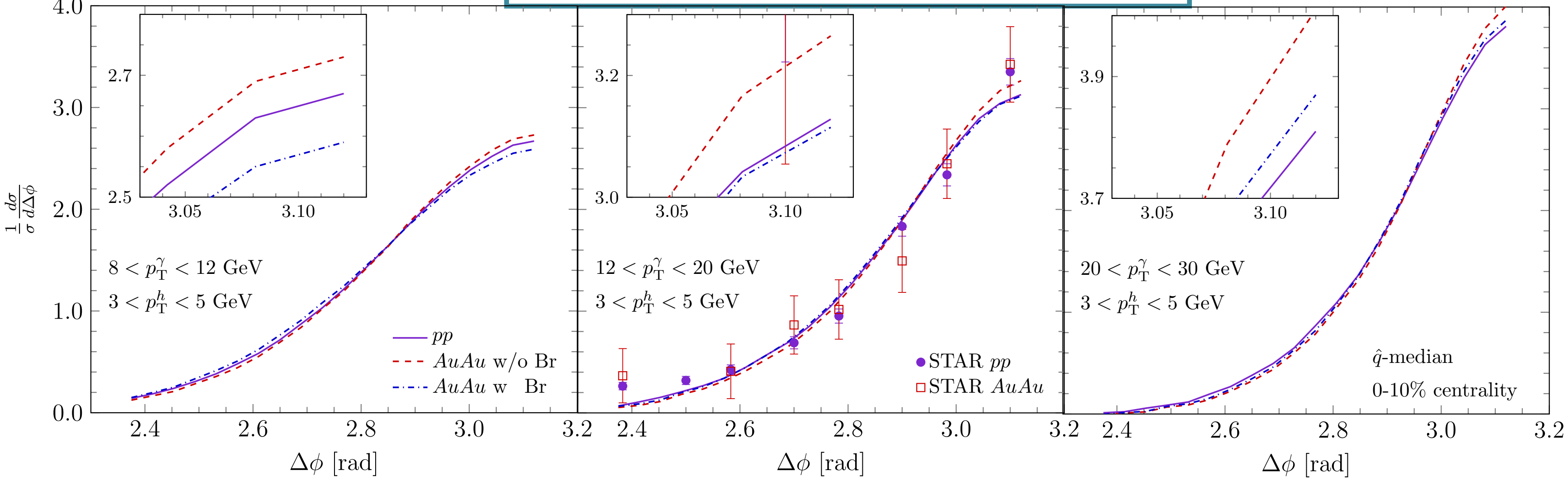
$$S_{\rm med}(Q, b_\perp) = S_{\rm vac}(Q, b_\perp) + \frac{b_\perp^2}{4}\langle p_\perp^2\rangle$$

$Pb + Pb -> Z + h$ @ 5.02 TeV



- ΔE makes the correlation stronger.
- $\langle p_\perp^2\rangle$ makes the de-correlation stronger.

$Au + Au -> \gamma + h$ @ 200 GeV

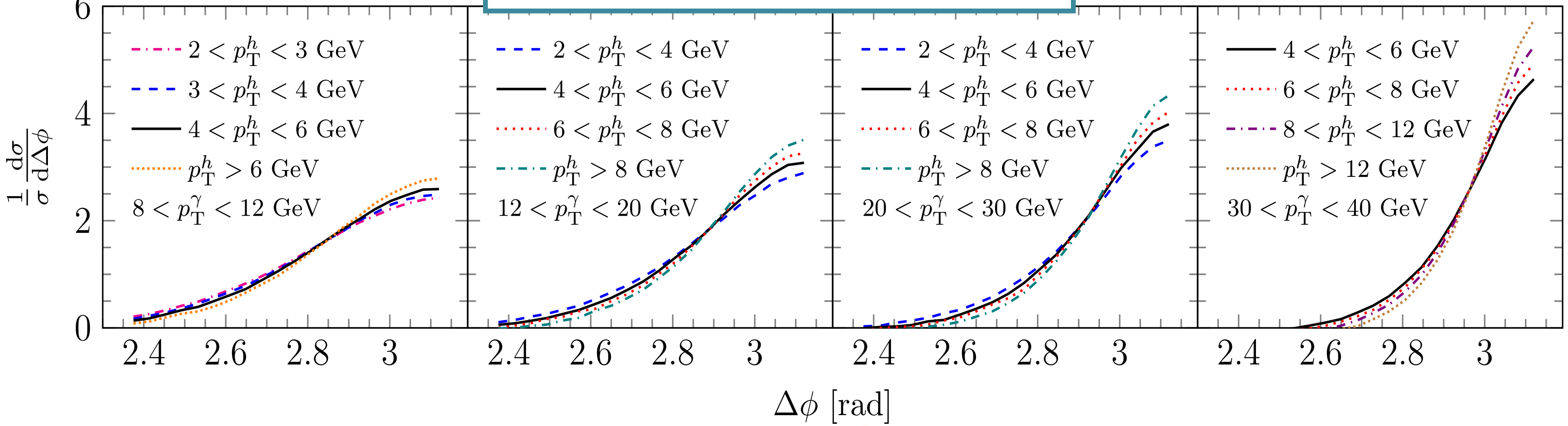


At the LHC:

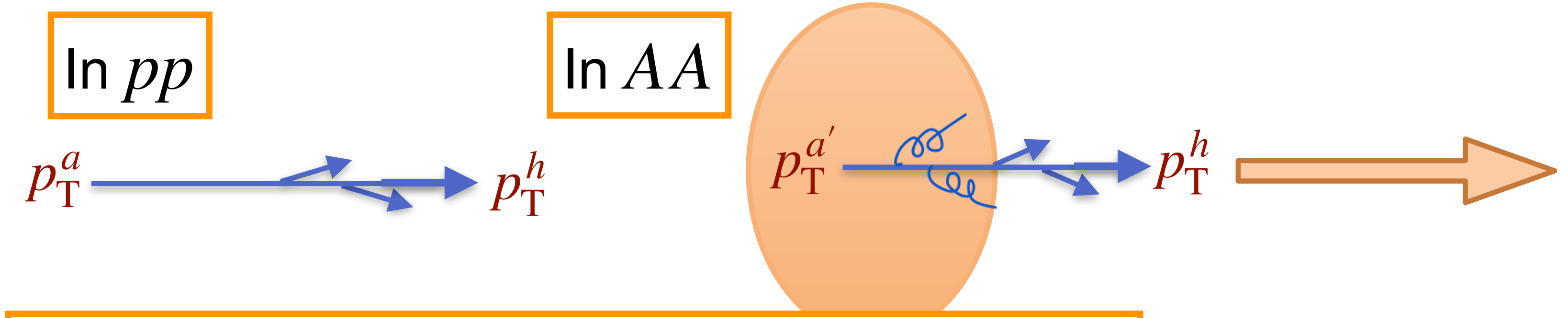
- $\langle p_\perp^2\rangle$ effect is barely visible.
- $S_{\rm vac}$ dominates.

Normalized $\Delta\phi$ distribution for AA collisions

$p+p->\gamma+h$ @ 200 GeV

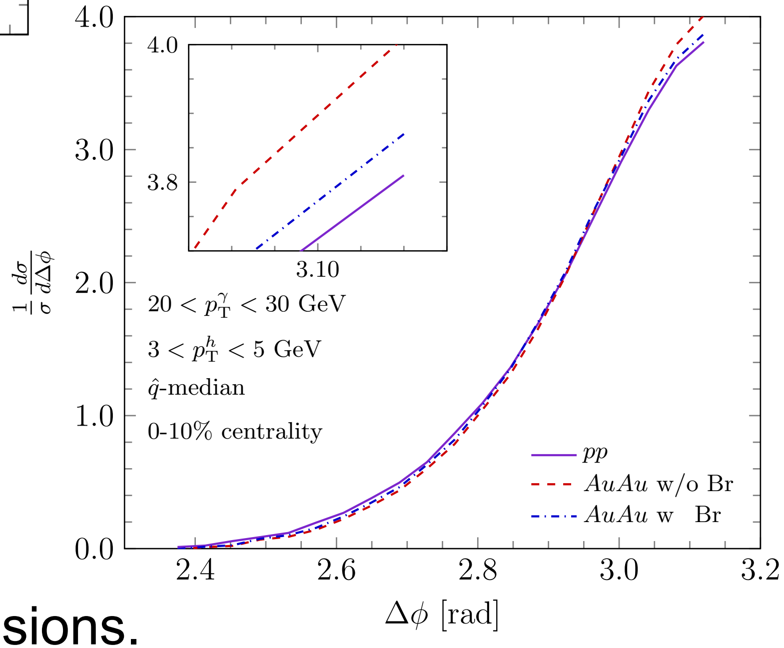


- The more larger the p_T is, the more stronger the angular correlation is from the Sudakov effects.



In pp

In AA



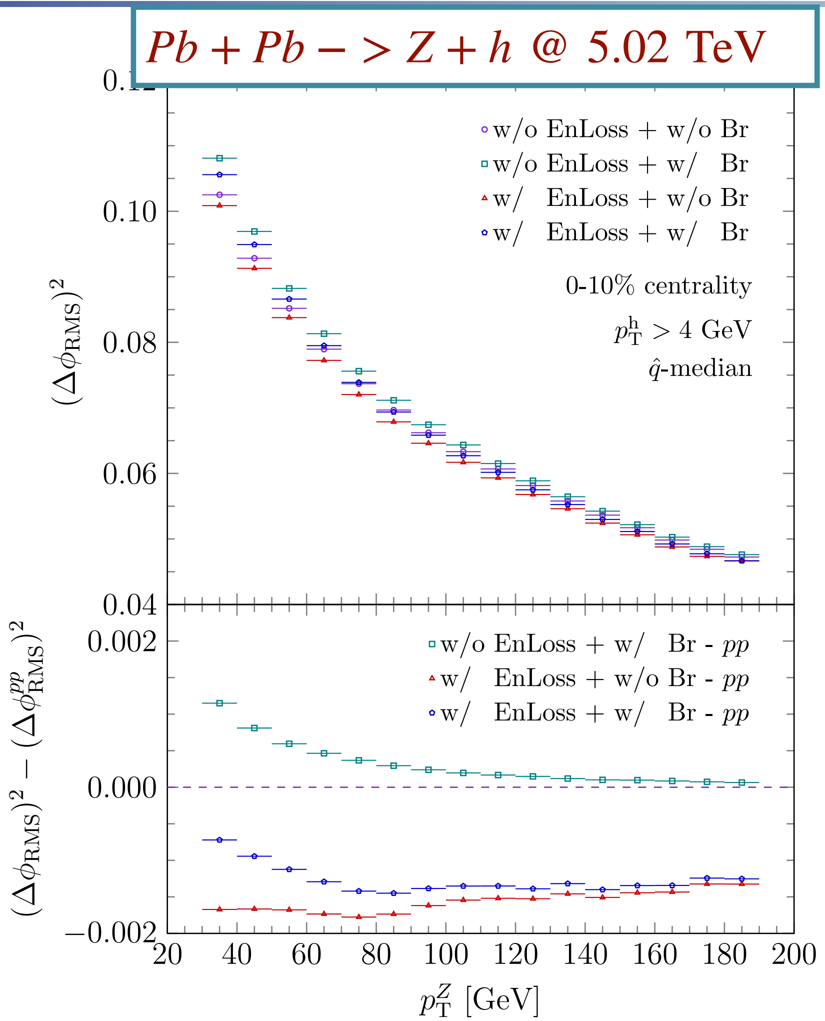
p_T^a(weaker correlation) < $p_T^{a'}$(stronger correlation)

Due to the bias of the same kinematics cuts between AA and pp collisions.

- ΔE makes the correlation stronger: Anti-broadening effect.
- $\langle p_\perp^2 \rangle$ makes a de-correlation stronger: Broadening effect.

RMS width of $\Delta\phi$ distribution

- With or without ΔE
- With or without $\langle p_\perp^2 \rangle$



- $\langle p_\perp^2 \rangle$: broadening +
- ΔE: anti-broadening -

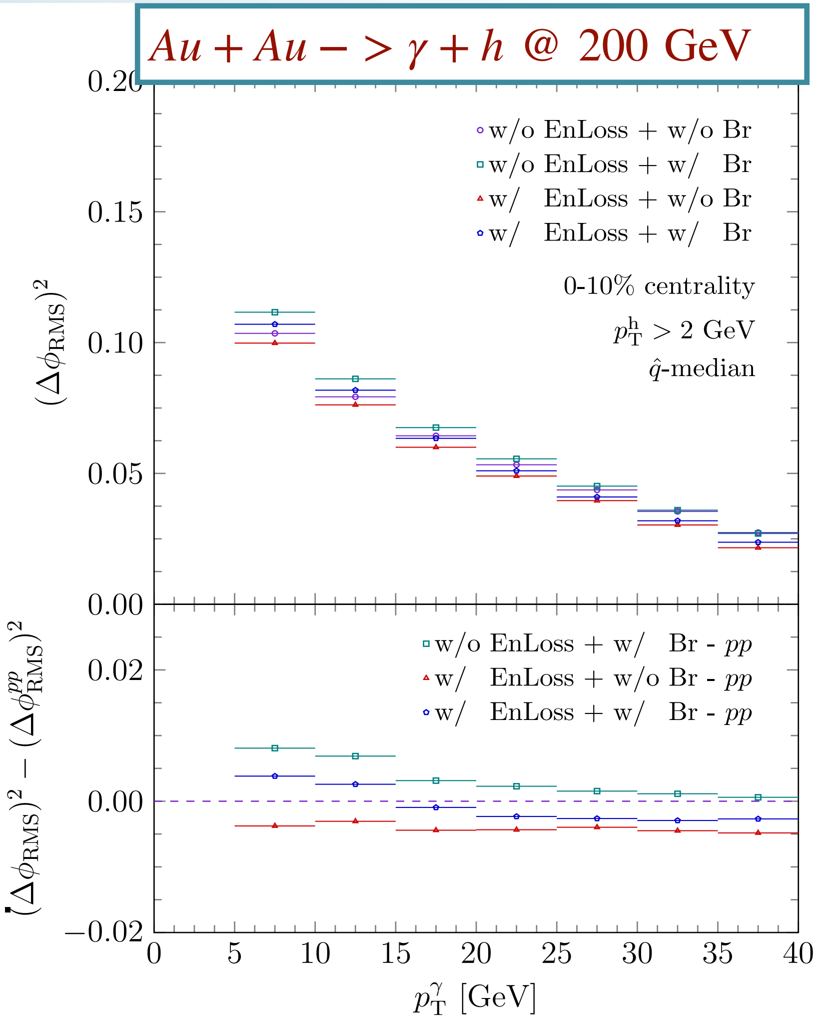
Competition results:

At the LHC

- “-”: correlation stronger;
- almost invisible.

At RHIC

- “+”: de-correlation for small p_T^γ;
- “-”: correlation stronger for large p_T^γ.



At LHC, the negative effect of jet energy loss overwhelms the positive effect of the medium-induced broadening effect; therefore, the decorrelation of two-particle was not be observed;

At RHIC, their competition result precisely manifests the decorrelation of dihadron and hadron-jets.

Summary

- We study the Z/γ-hadron production on p_{T} & $\Delta\phi$ correlation using the Sudakov resummation improved pQCD parton model, including the HT ΔE and medium-induced $\langle p_\perp^2 \rangle$-broadening effect.
- Our model can reproduce the Z/γ-hadron data on p_{T} & $\Delta\phi$ distribution to a good degree.
- ΔE has an opposing anti-broadening effect compared to the $\langle p_\perp^2 \rangle$-broadening effect in the $\Delta\phi$ distribution.
- At LHC, the negative effect of jet energy loss overwhelms the positive effect of the medium-induced broadening effect; therefore, the decorrelation of the two-particle was not observed. At RHIC, their competition result precisely manifests the decorrelation of dihadron and hadron-jets.

Thanks for your attention!