INT, UW, 2017

Probing $\hat{q}$ via back-to-back angular correlations & dijet asymmetry

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Contents

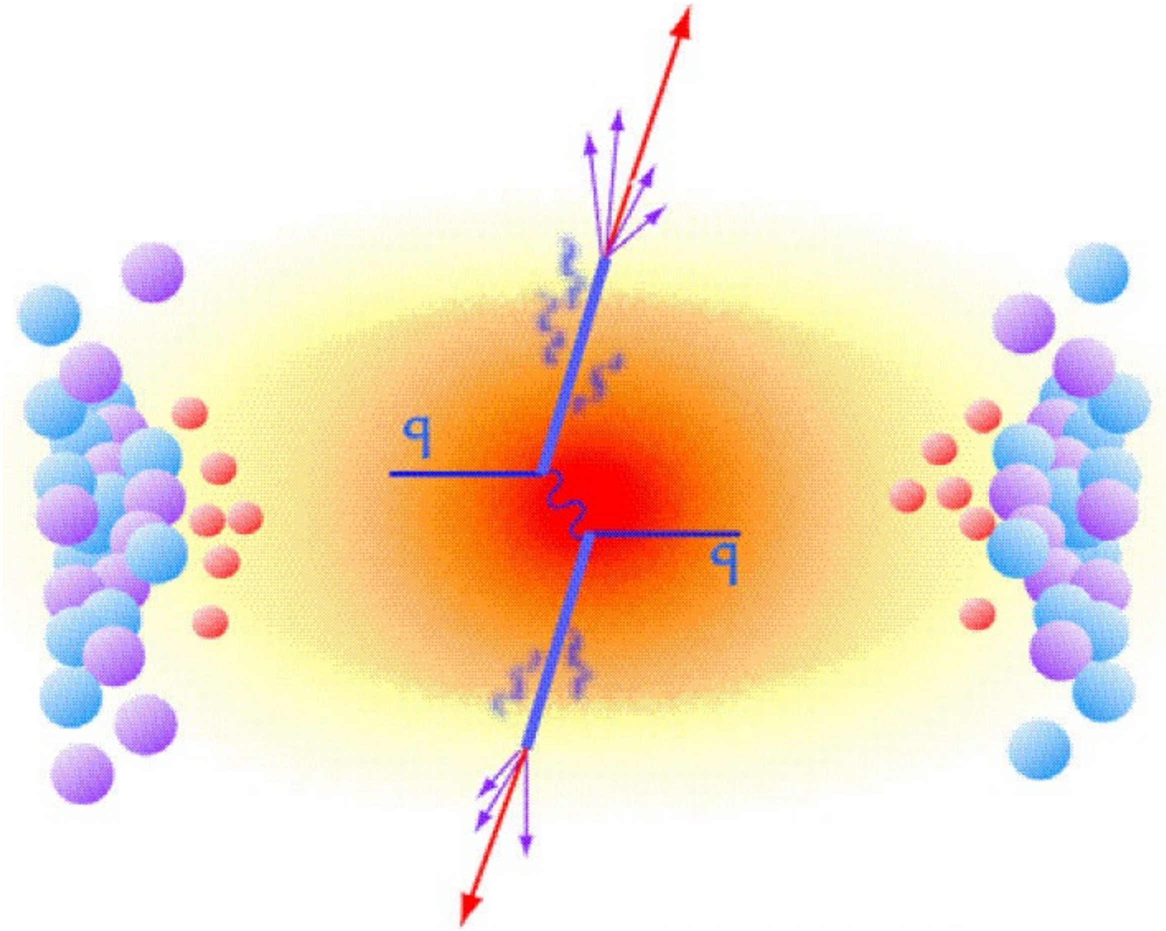
- Introduction & Sudakov Resummation
- Back-to-back angular correlations
- Dijet Asymmetry
- Summary

Introduction: Jet Quenching

Jet-medium interaction

- ☑ $k_\perp$ broadening
- ☑ Energy loss

Two sides of the same coin.



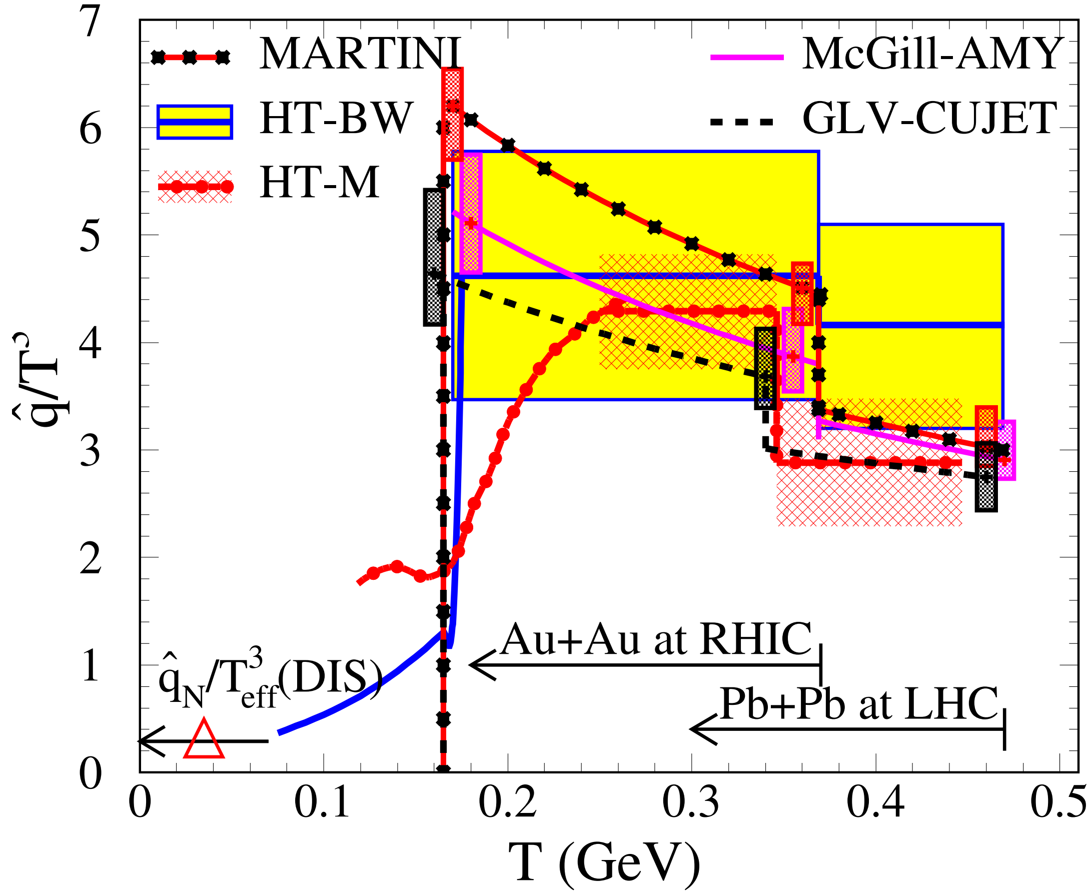
BDMPS approach

Jet transport parameter $$\hat{q} = \frac{\Delta k_\perp^2}{L} \qquad -\frac{dE}{dx} = \frac{\alpha_s N_c}{4}\hat{q}L$$

- ☑ $\hat{q}$ reflects the density of QGP

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

Energy loss - Single hadron R_{AA}



$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \mathrm{GeV}^2/\mathrm{fm} \;\; \text{at} \;\; \begin{matrix} \text{T=370 MeV,} \\ \text{T=470 MeV,} \end{matrix}$$

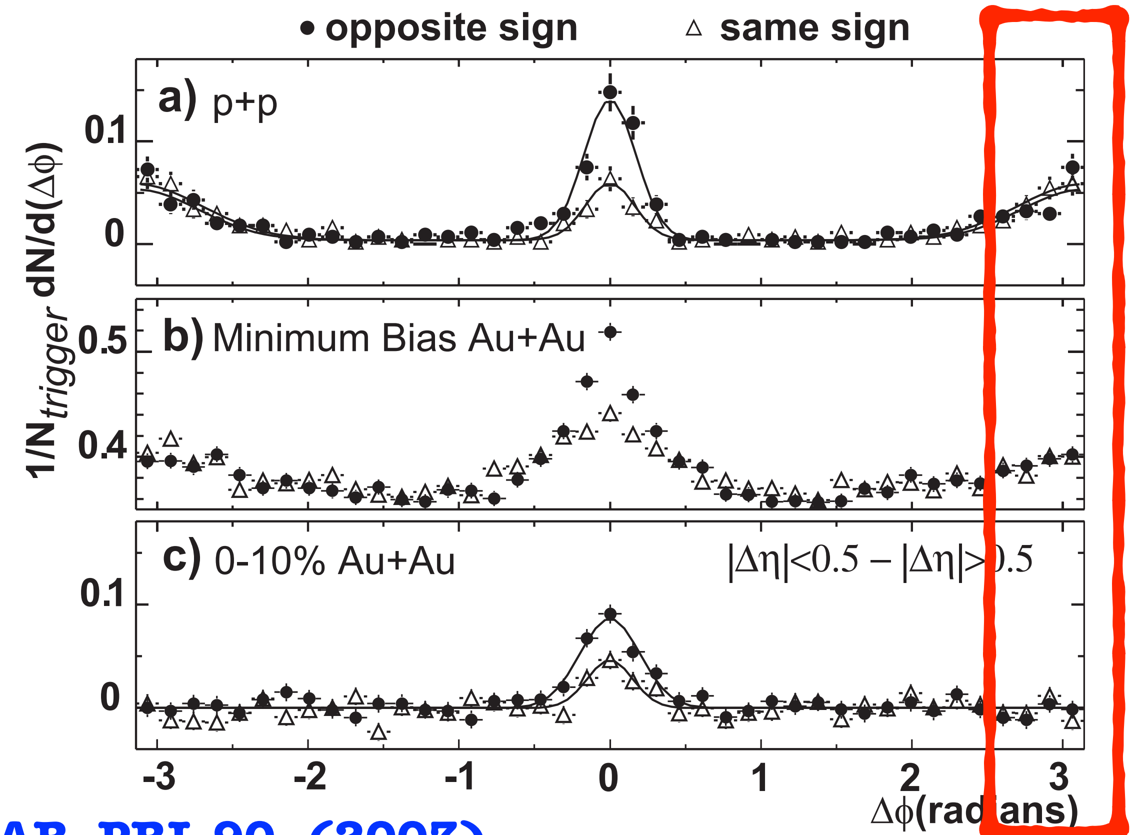
for a 10 GeV quark JET

Jet Collaboration. PRC 90, 014909, (2014)

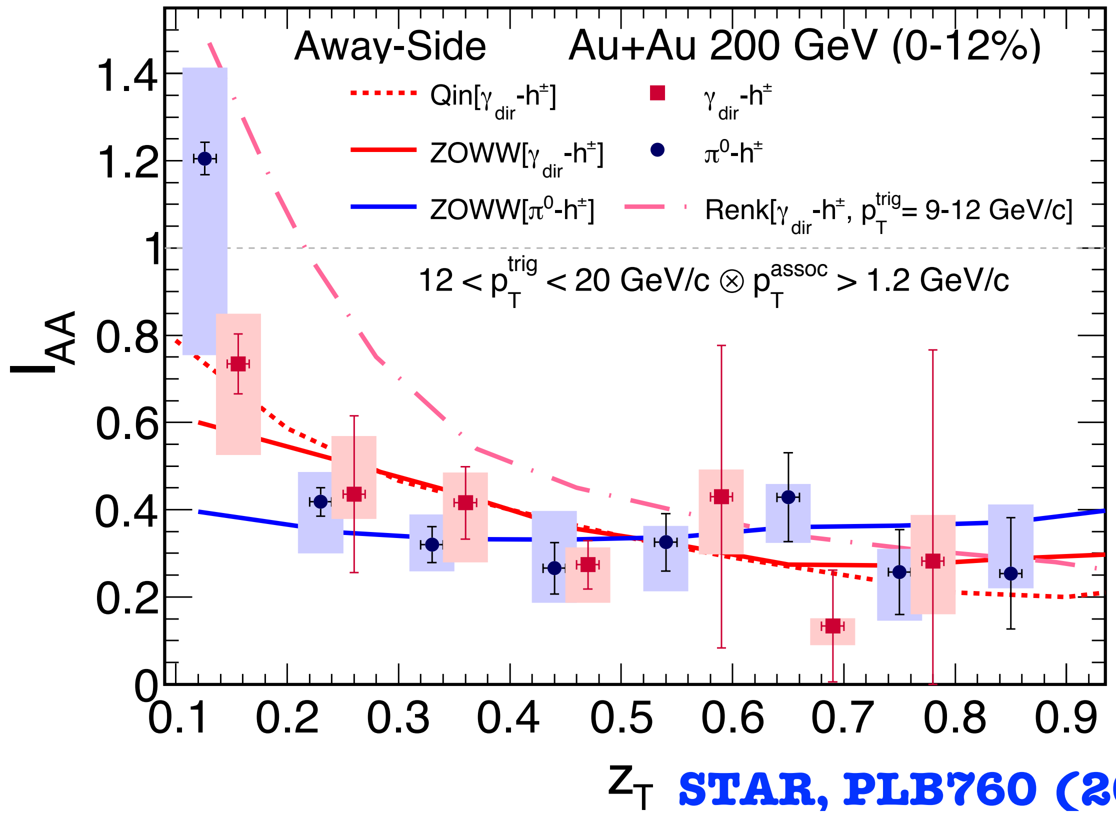
Angular decorrelation - New and complimentary method

- ☑ Extract $\hat{q}$ via angular decorrelation in the back-to-back region.

Dihadron Angular decorrelation @ RHIC



STAR, PRL 90, (2003)

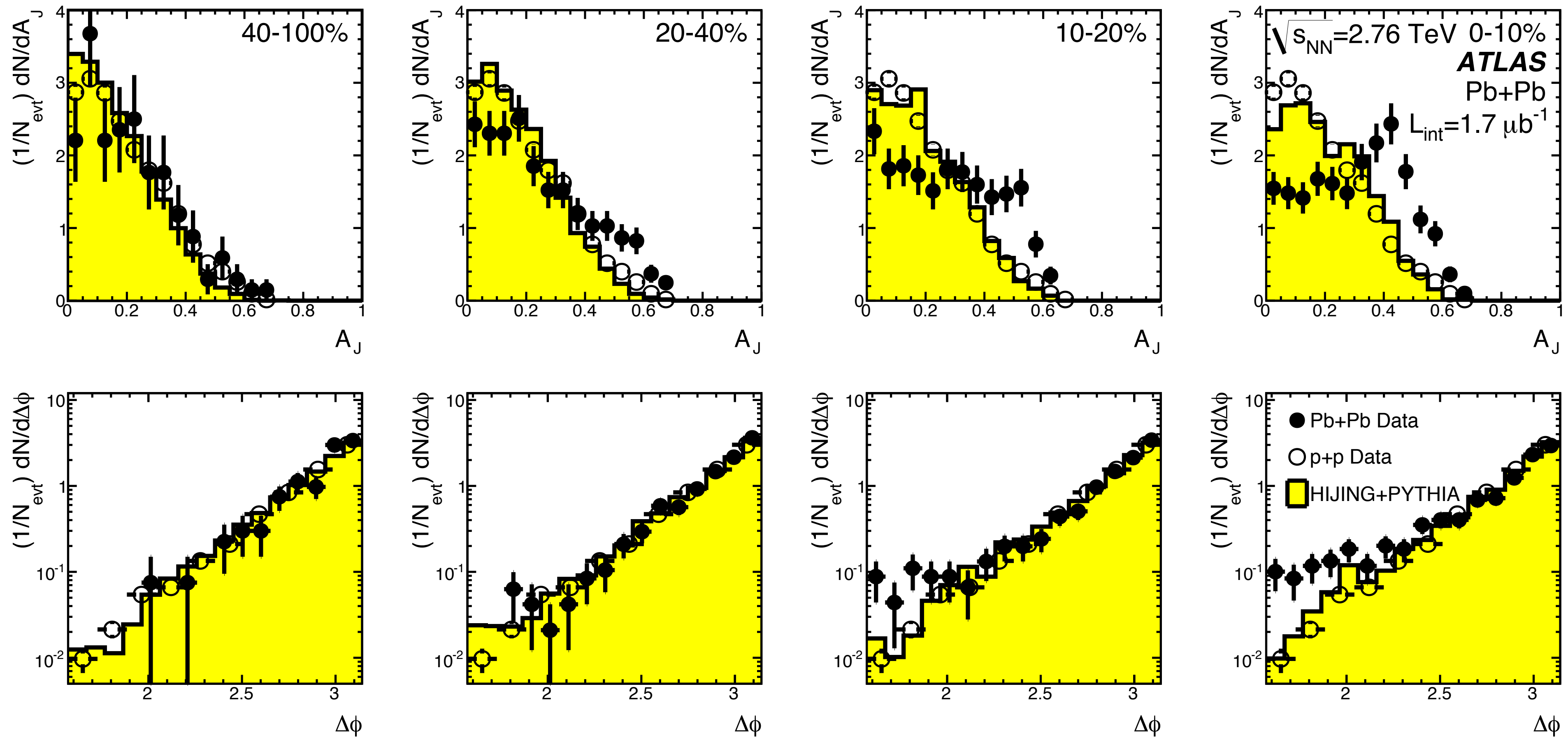


STAR, PLB760 (2016)

- ☑ Yield suppression
- ☑ Angular decorrelation: quantitative calculation is lacking

ATLAS [PRL 105, (2010)] & CMS [PRC 84, (2011)]

peripheral → central



$$A_J \equiv \frac{p_T^1 - p_T^2}{p_T^1 + p_T^2}$$

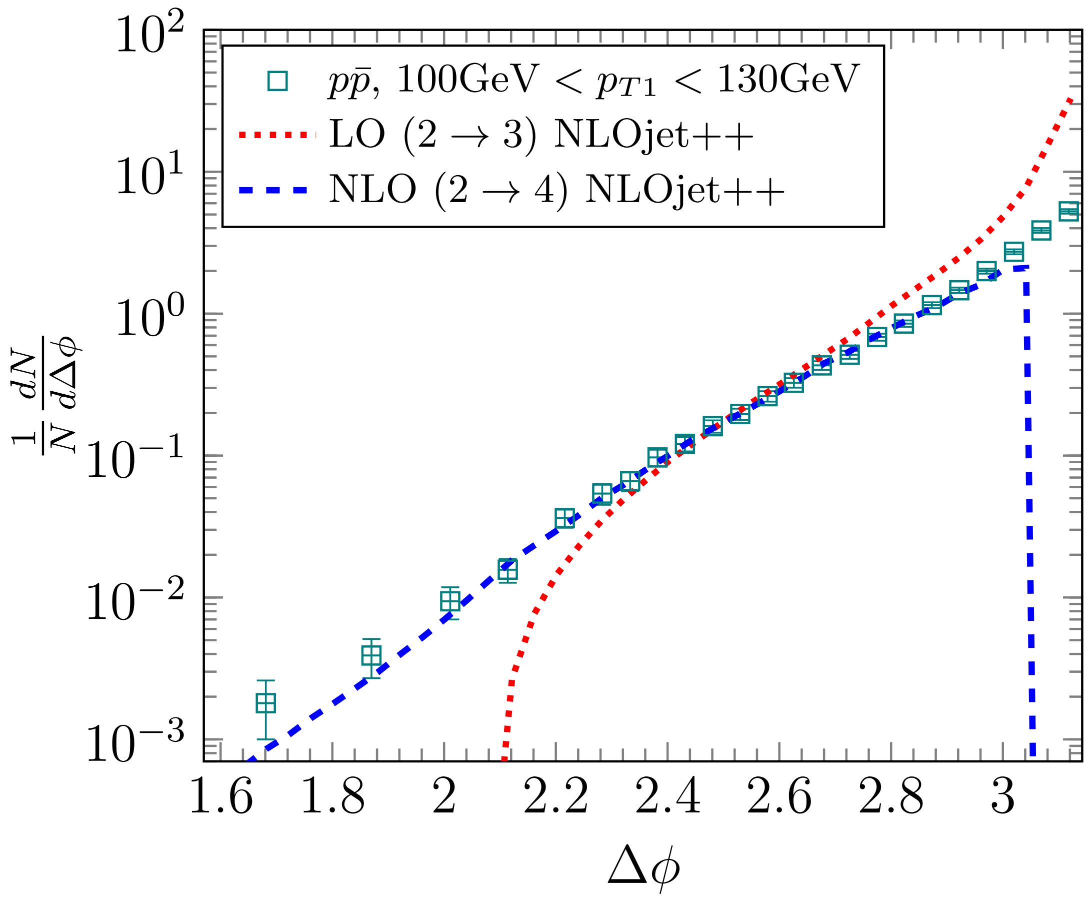
- ☑ Energy imbalance increases: Energy Loss
- ☑ No clear sign of angular decorrelation

Qin, Muller, PRL 106 (2011)

Is $\hat{q} \simeq 0$?

Puzzle: Large Energy Loss, Small p_T Broadening?

Dijet angular correlation in *pp* with perturbative expansion approach



$2 \to 3$ $\qquad$ $2 \to 3/4$

$$\frac{1}{N}\frac{dN}{d\Delta\phi} \leftrightarrow \frac{1}{\sigma_{\rm LO}}\frac{d\sigma_{\rm LO}}{d\Delta\phi} \leftrightarrow \frac{1}{\sigma_{\rm NLO}}\frac{d\sigma_{\rm NLO}}{d\Delta\phi}$$

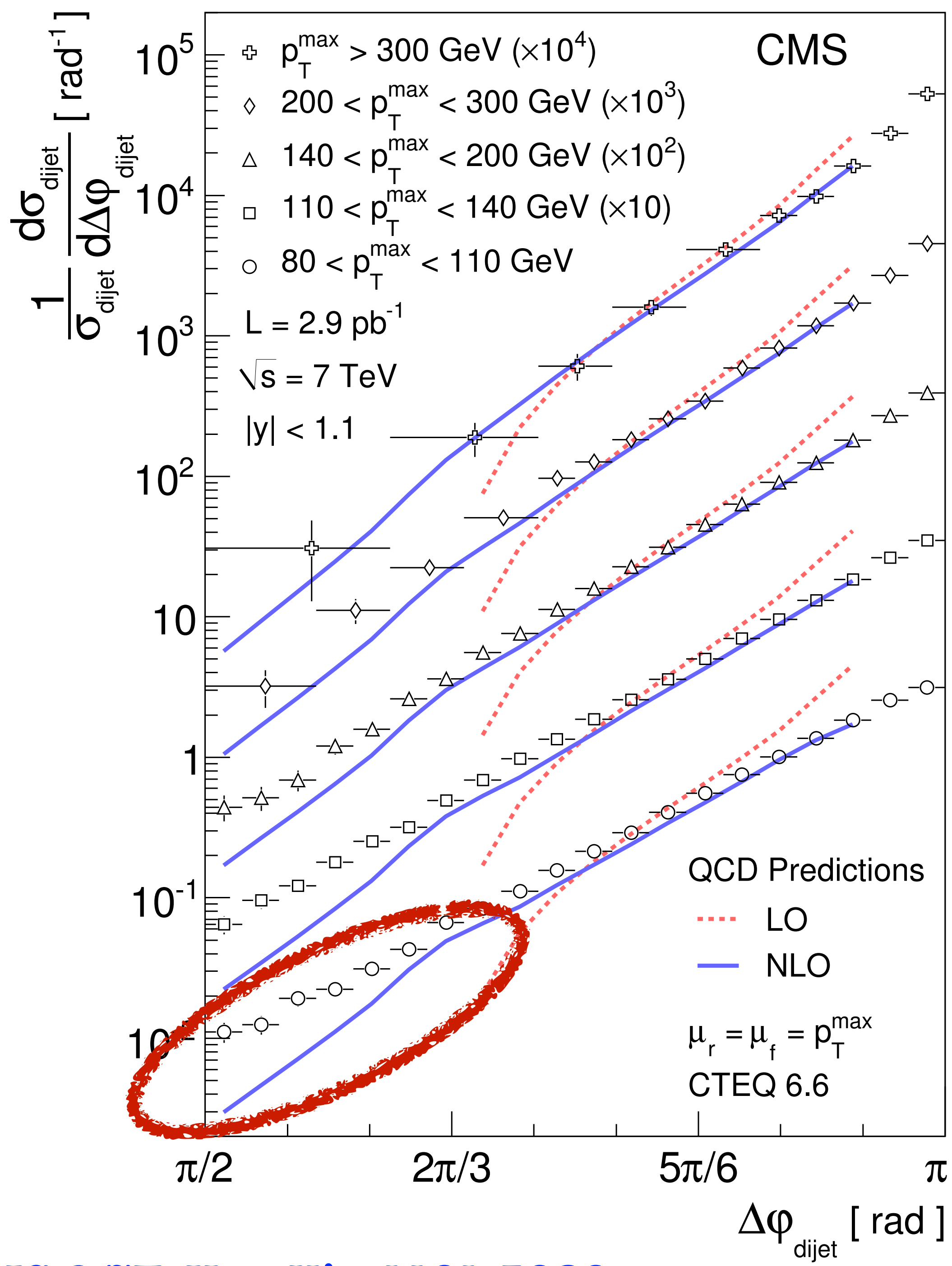
$2 \to 2$ $\qquad$ $2 \to 2/3$

D0 @ 1.96 TeV: PRL 94, 221801 (2005)

☑ NLO calculation can describe the experimental data very well.

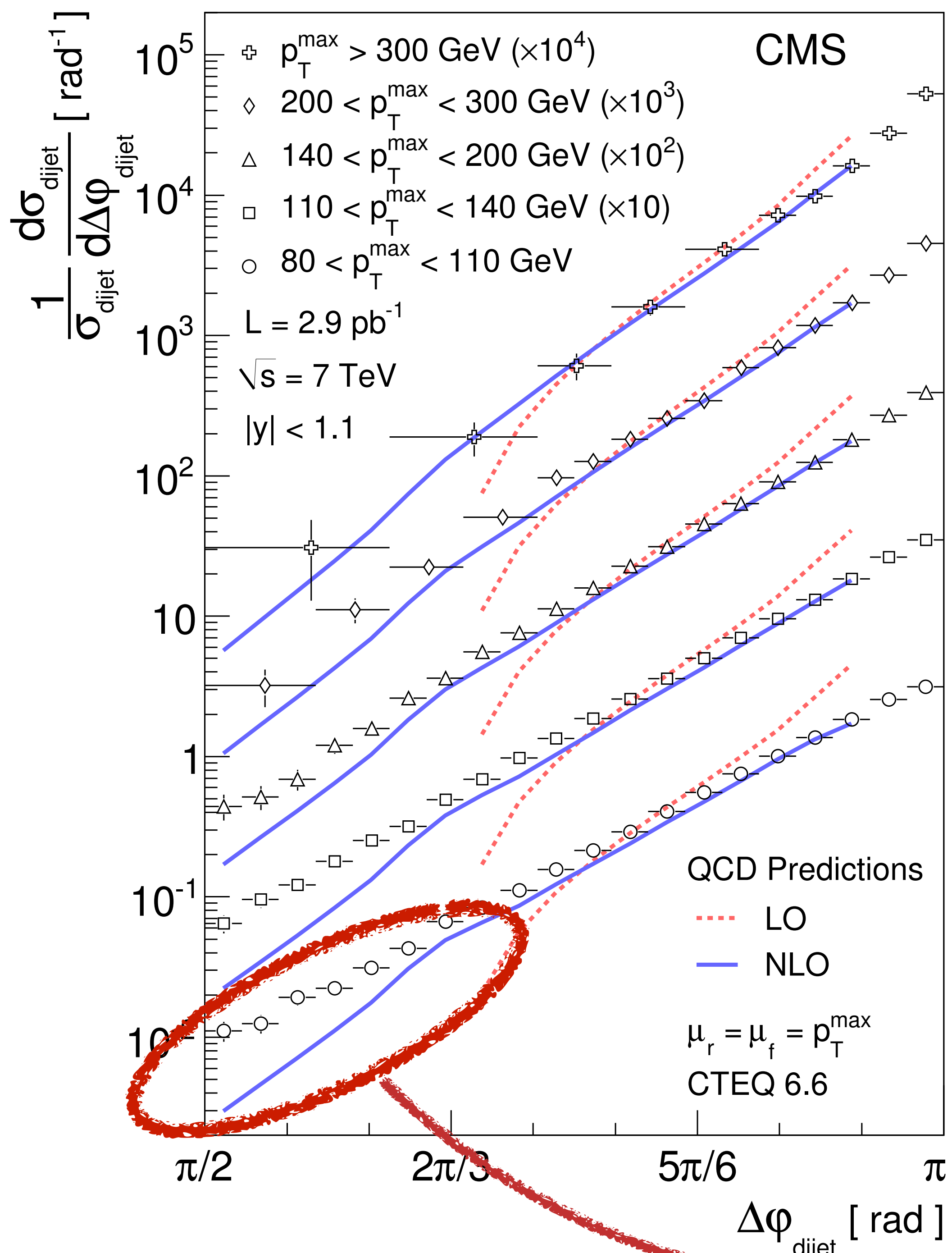
Introduction: Dijet Angular Correlation

Dijet angular correlation in *pp* with perturbative expansion approach



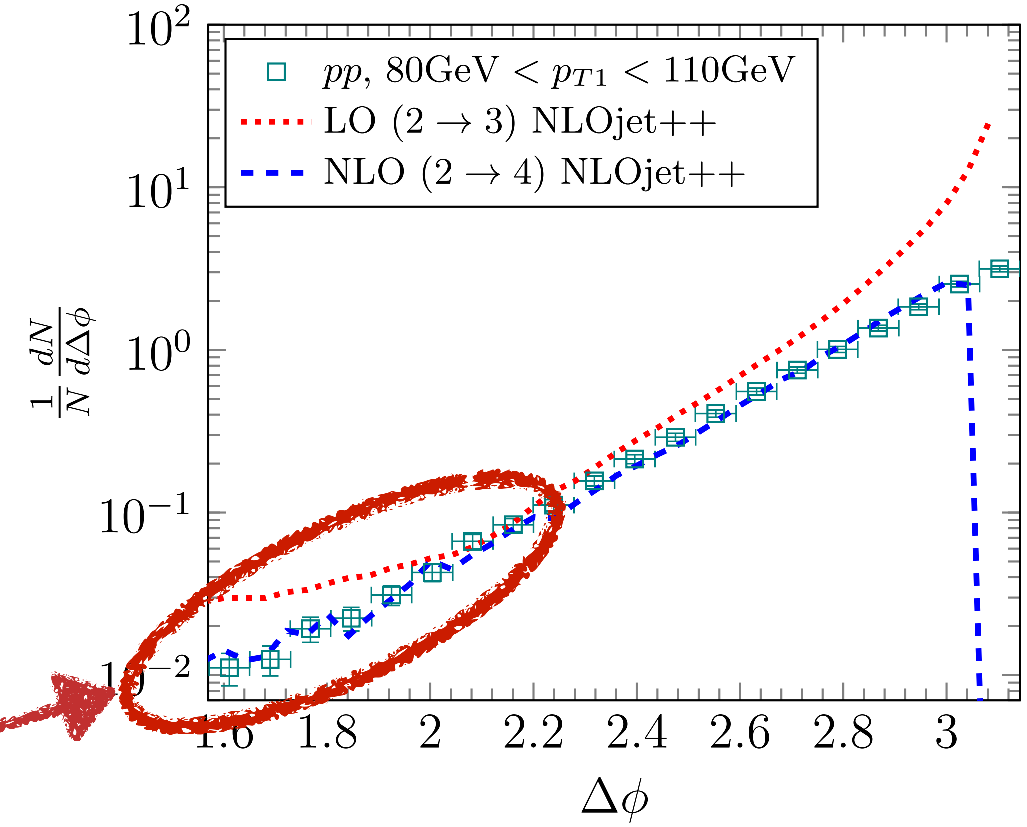
CMS @ 7TeV, arXiv:1101.5029

Dijet angular correlation in *pp* with perturbative expansion approach



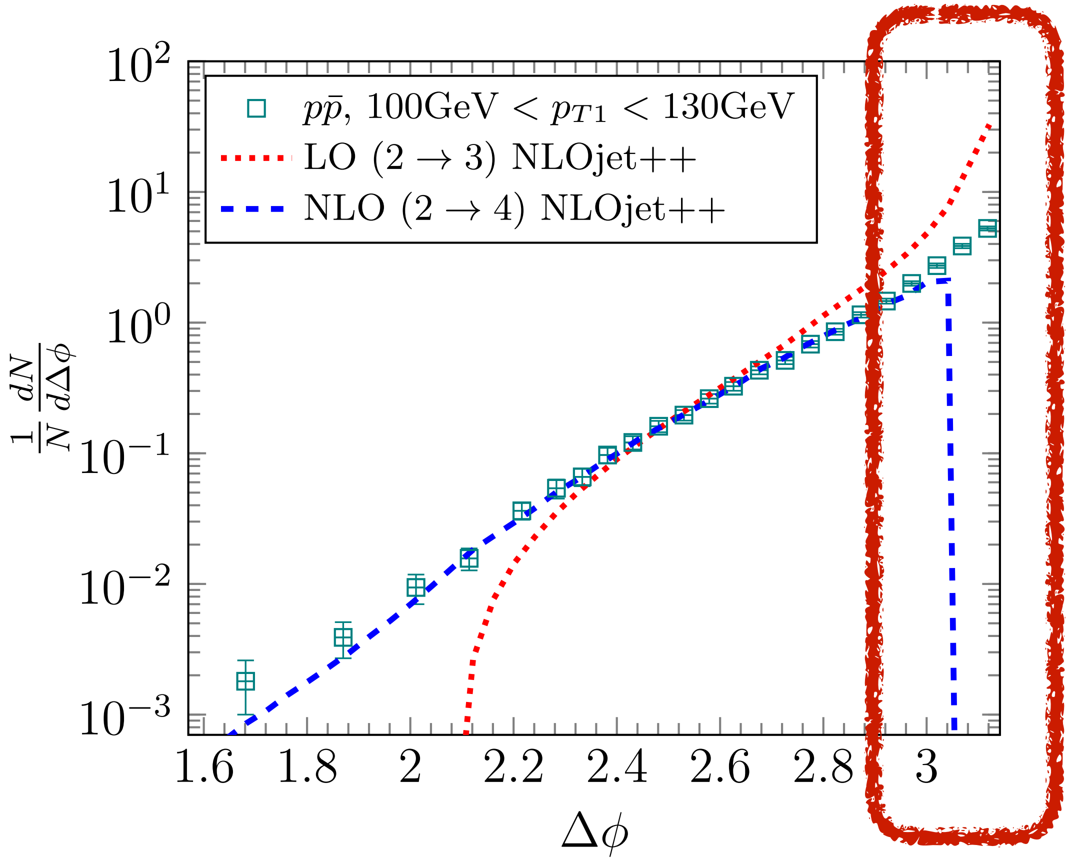
- ☑ Find leading and sub-leading jets
- ☑ Only keep the event with |y|<1.1

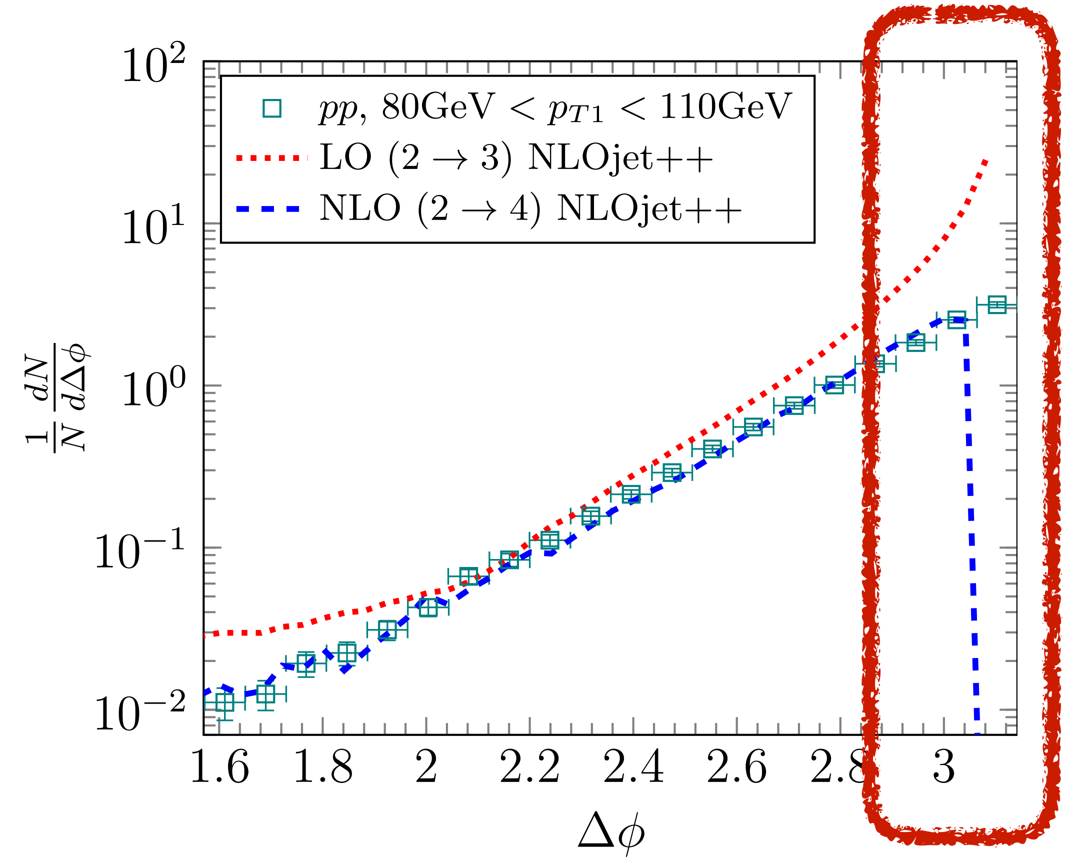
- ☑ Find (sub-)leading jets that you can observe
- ☑ Only keep the event with |y|<1.1



CMS @ 7TeV, arXiv:1101.5029

Dijet angular correlation in *pp* with perturbative expansion approach





Perturbative Expansion	Resummation
$\sigma_0 \sum_{i=0}^{n} \Big((\alpha_s \text{Log})^i + \alpha_s^i C_i \Big)$	$\sigma_0 \sum_{i=0}^{n} \Big((\alpha_s \text{Log})^i \Big) + \sigma_0 \sum_{n+1}^{\infty} \Big((\alpha_s \text{Log})^i \Big)$

- ☑ Perturbative Expansion: α_s is small
- ☑ Resummation: large logs

Dijet angular correlation in *pp* with Resummation approach

Perturbative Expansion

paradigm shift

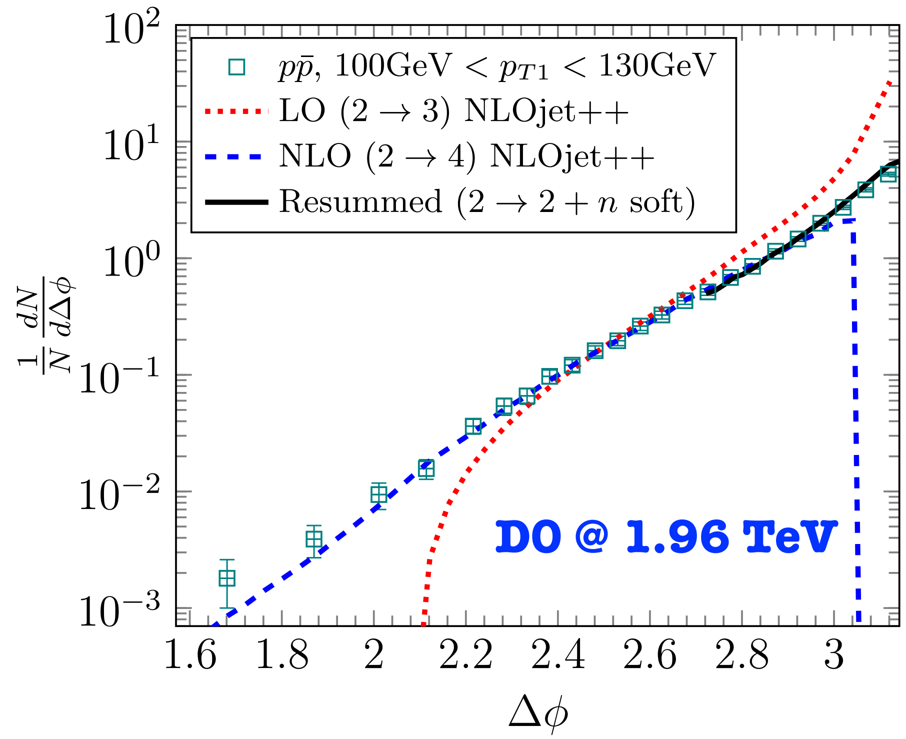
large logarithms

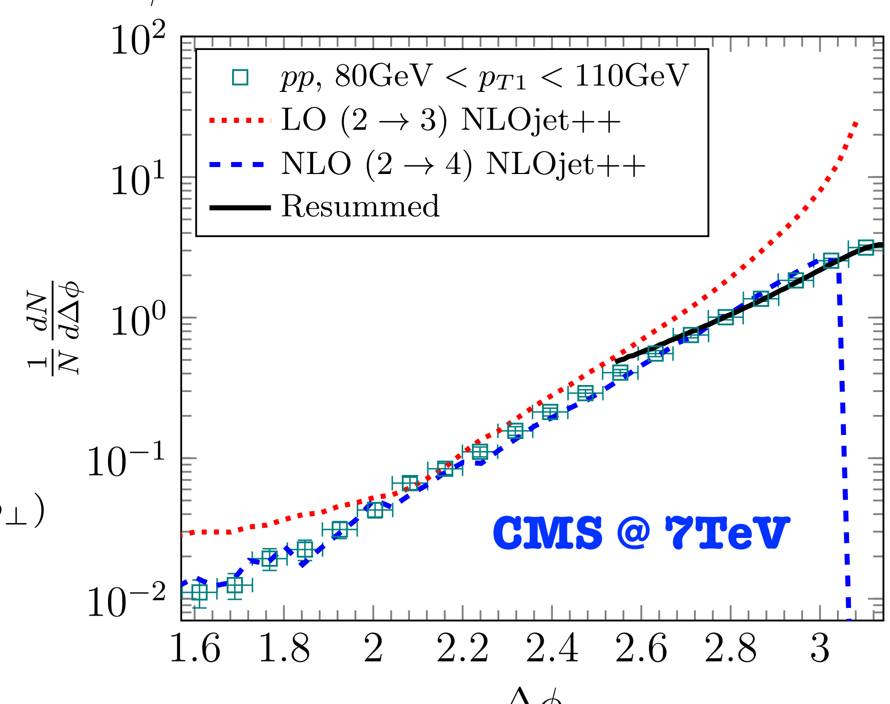
$$(\alpha_s \ln^2 \frac{p_T^2}{q_\perp^2})^n$$

Sudakov Resummation

$2 \rightarrow 2 + n$ Soft gluon radiations (parton shower)

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





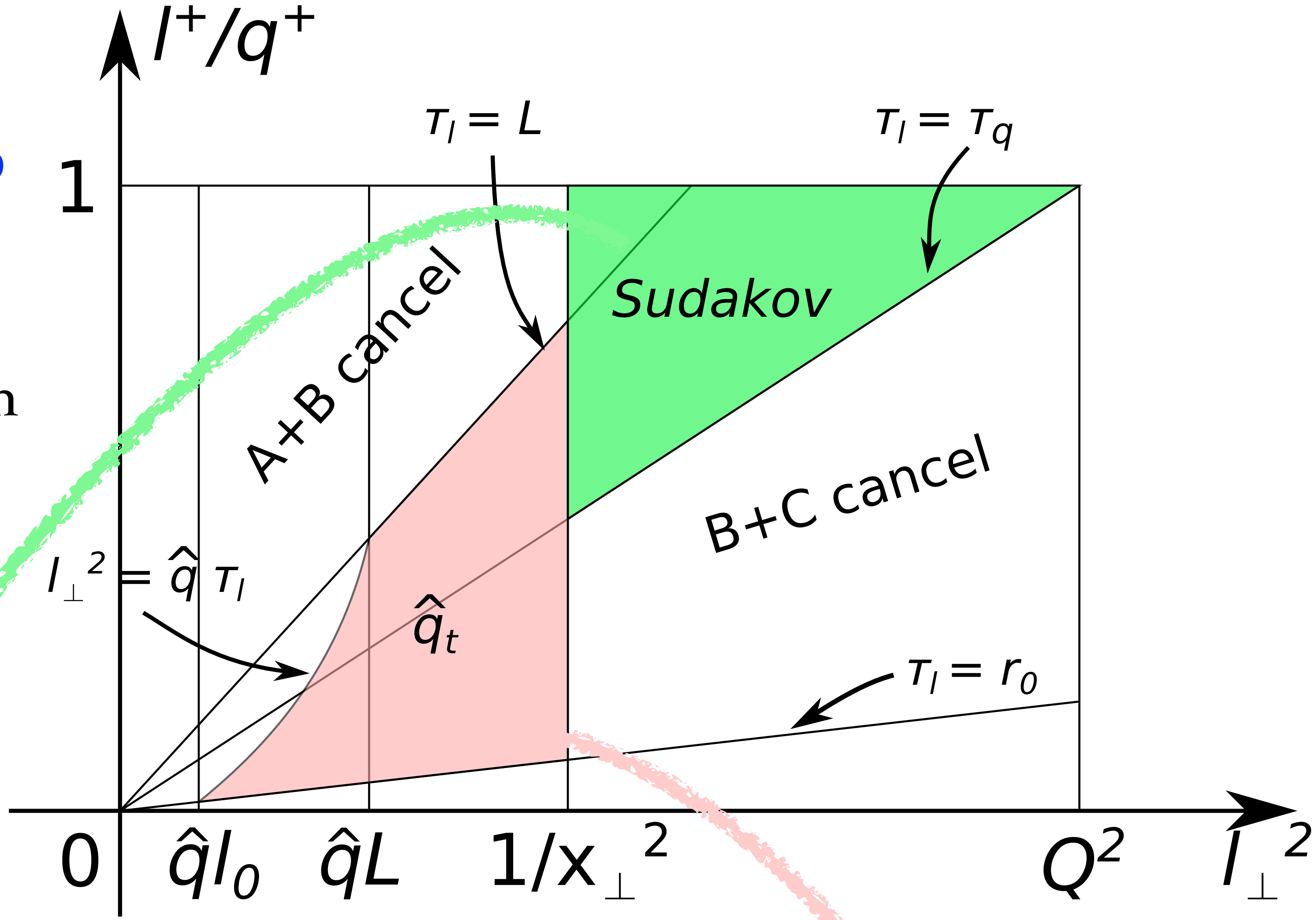
NLL resummation

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

From *pp* to *AA*

Mueller, Wu, Xiao, Yuan, arXiv:1608.07339

Considering one gluon radiation in the large medium, Medium Induced Radiation and Vacuum Parton Shower can be separated.



hot medium

$$S_{AA}(Q,b) = S_{pp}(Q,b) + \frac{\langle \hat{q}L\rangle b^2}{4}$$

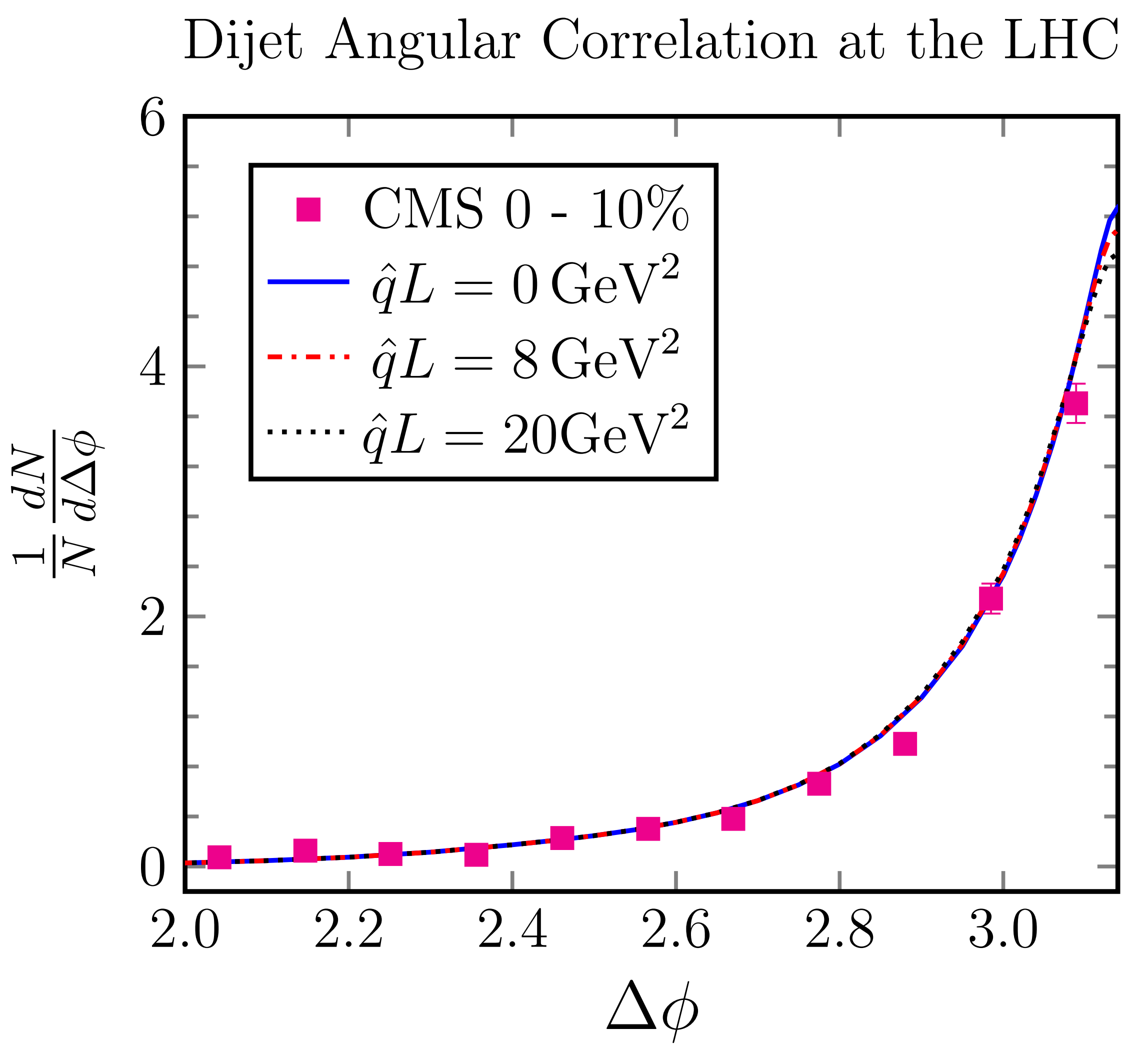
Vacuum parton shower

k_T broadening

Multiple scattering

Medium induced radiation

Dijet angular correlation in *AA*



$$S_{AA}(Q,b) = S_{pp}(Q,b) + \frac{\langle \hat{q}L\rangle b^2}{4}$$

$\sqrt{S_{NN}} = 2.76$ TeV

$p_T^1 > 150$ GeV

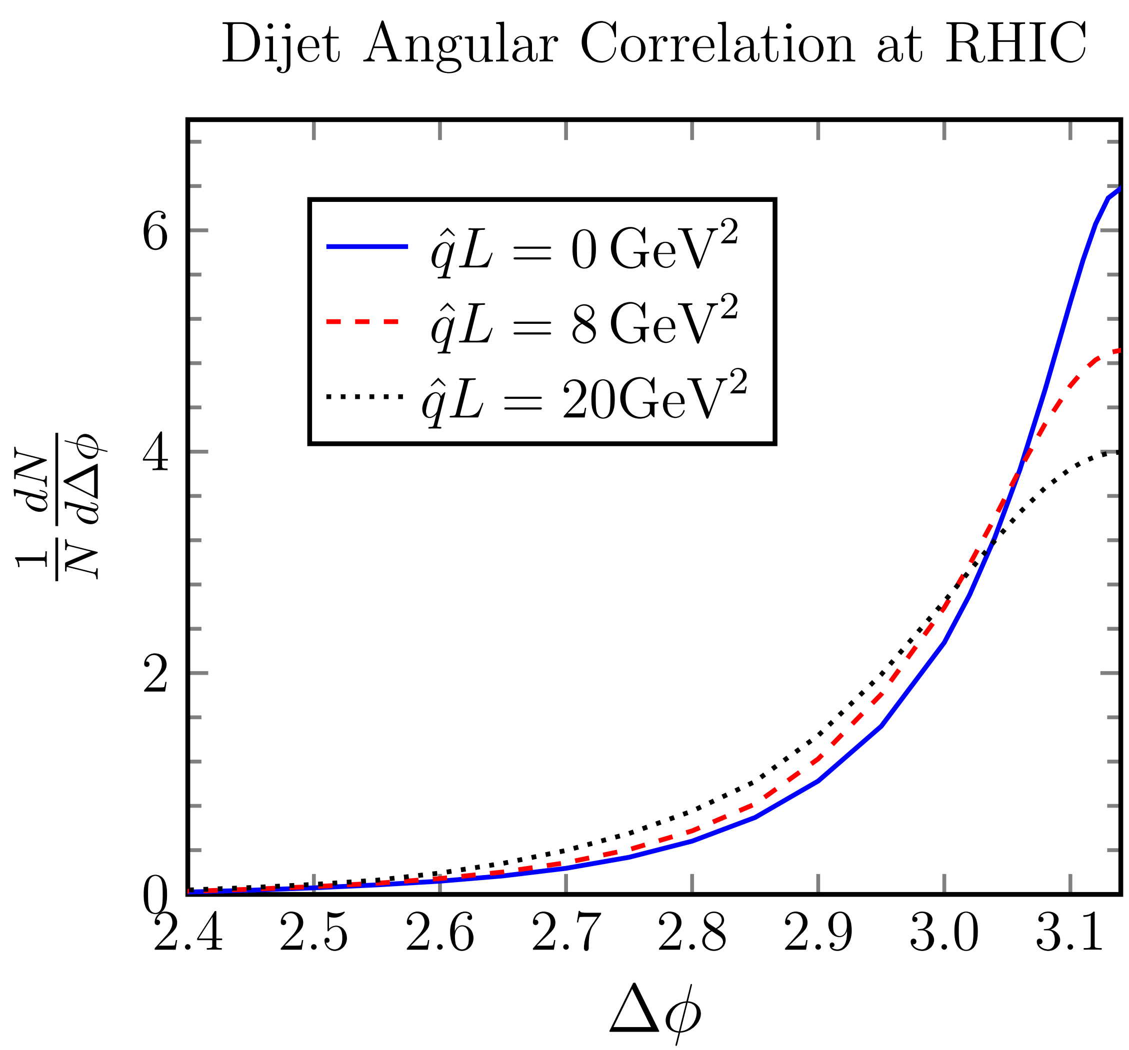
$p_T^2 > 50$ GeV

Vacuum Sudakov Effect ≫ Medium Broadening Effect

This explains why the LHC did not observe the angular decorrelation.

Mueller, Wu, Xiao, Yuan, arXiv:1604.04250

Dijet angular correlation in *AA*



$$S_{AA}(Q,b) = S_{pp}(Q,b) + \frac{\langle \hat{q}L\rangle b^2}{4}$$

$$\sqrt{S_{NN}} = 200 \text{ GeV}$$

$$p_T^1 > 35 \text{ GeV}$$

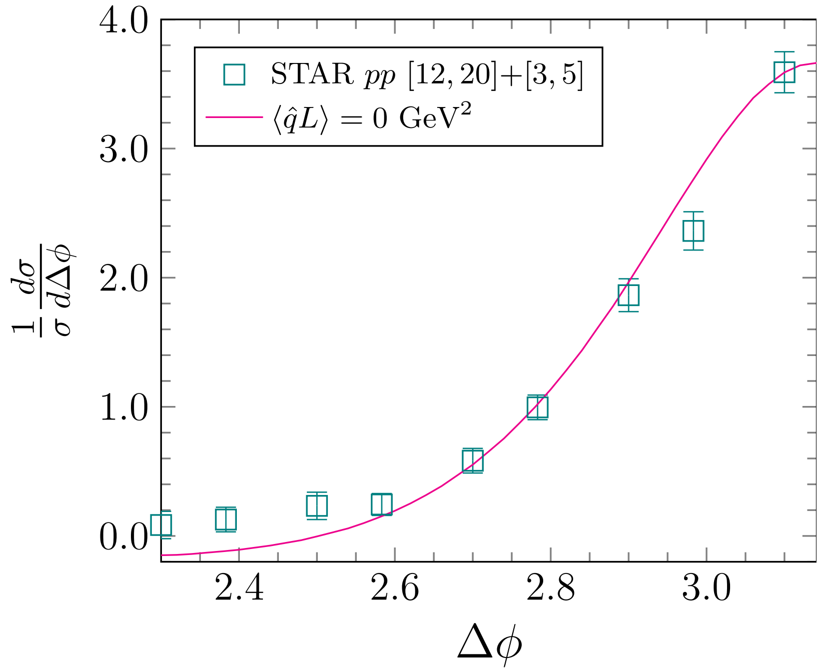
$$p_T^2 > 15 \text{ GeV}$$

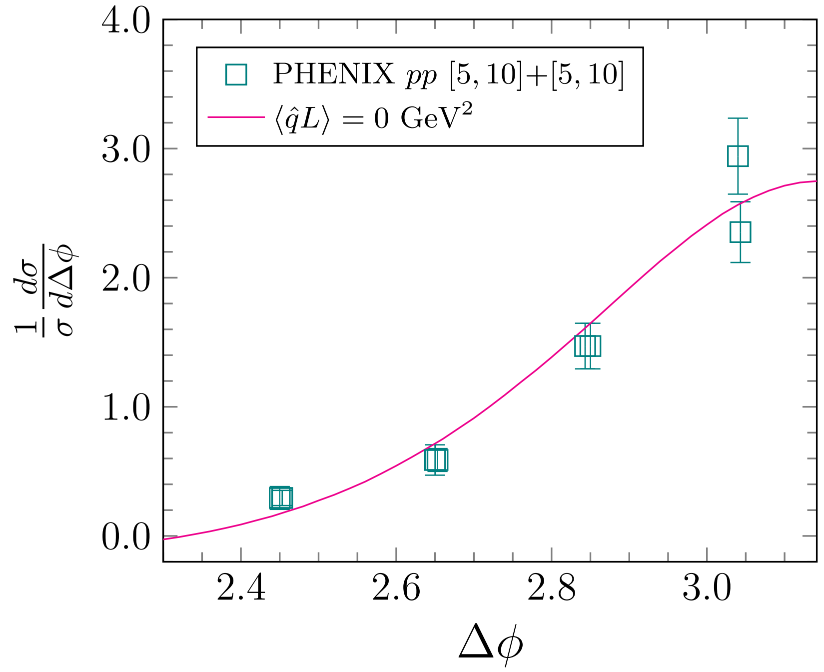
Vacuum Sudakov Effect ~ Medium Broadening Effect

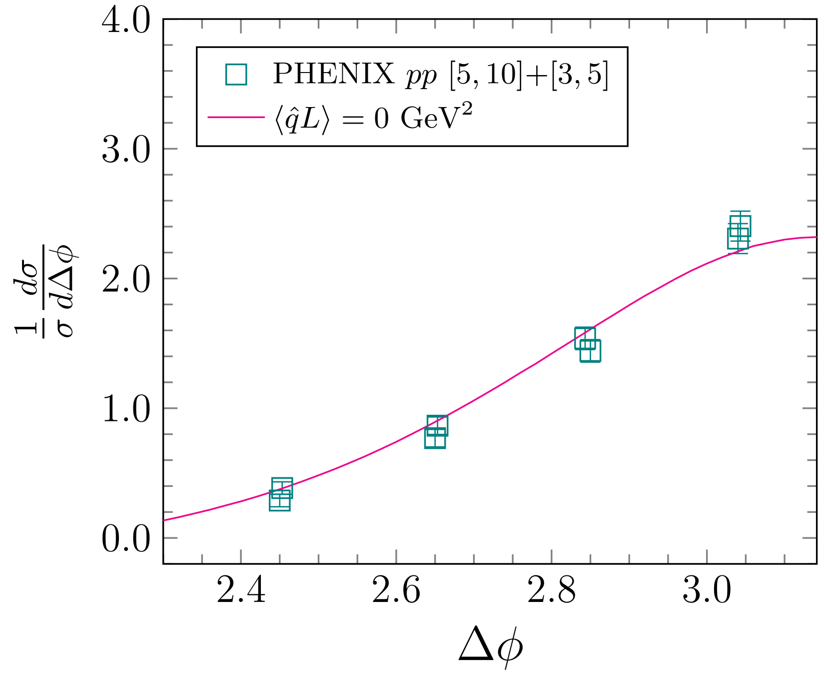
Decrease the center of mass energy or measure small p_{T} jet.

Mueller, Wu, Xiao, Yuan, arXiv:1604.04250

Dihadron correlations in *pp* - Establish Baseline



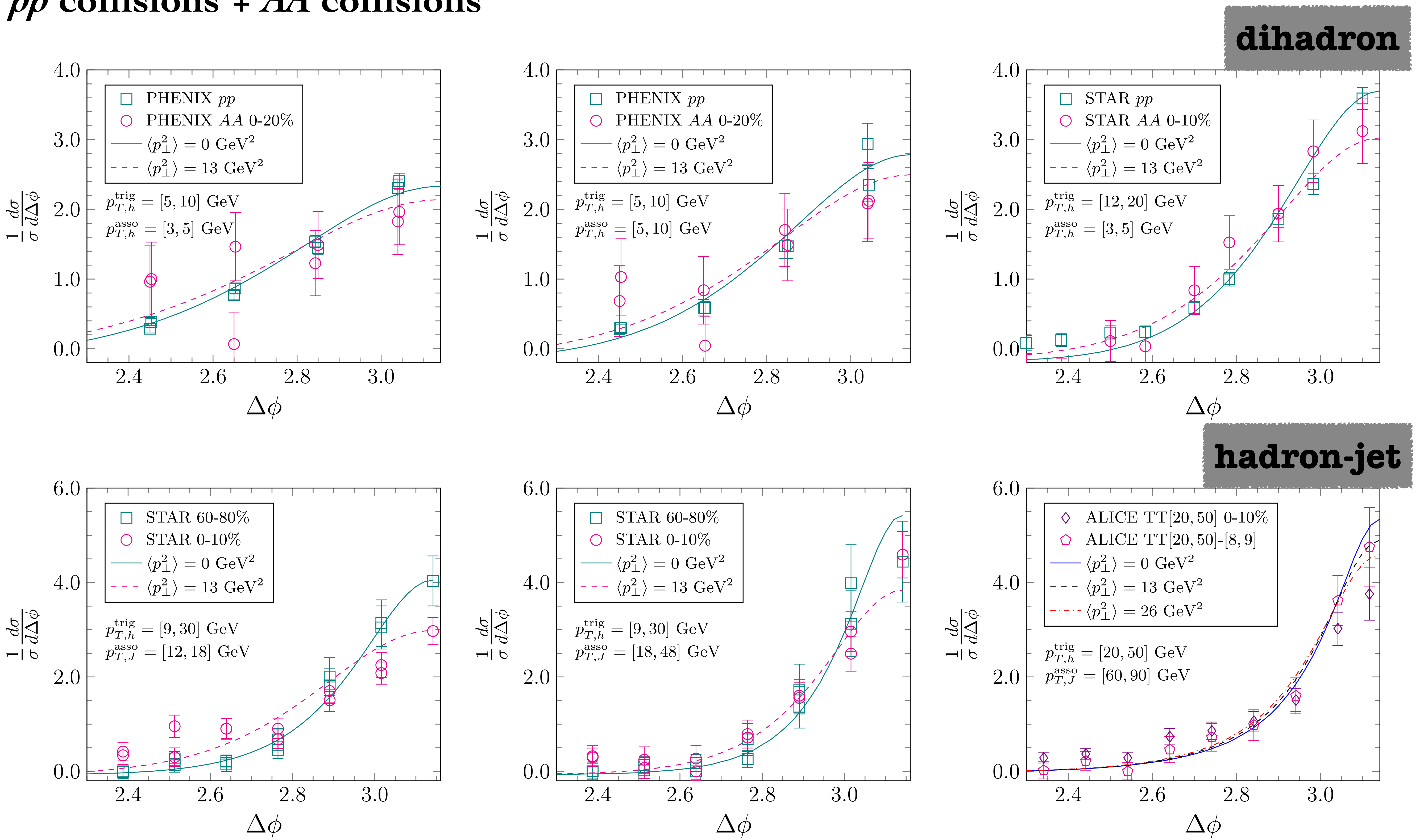




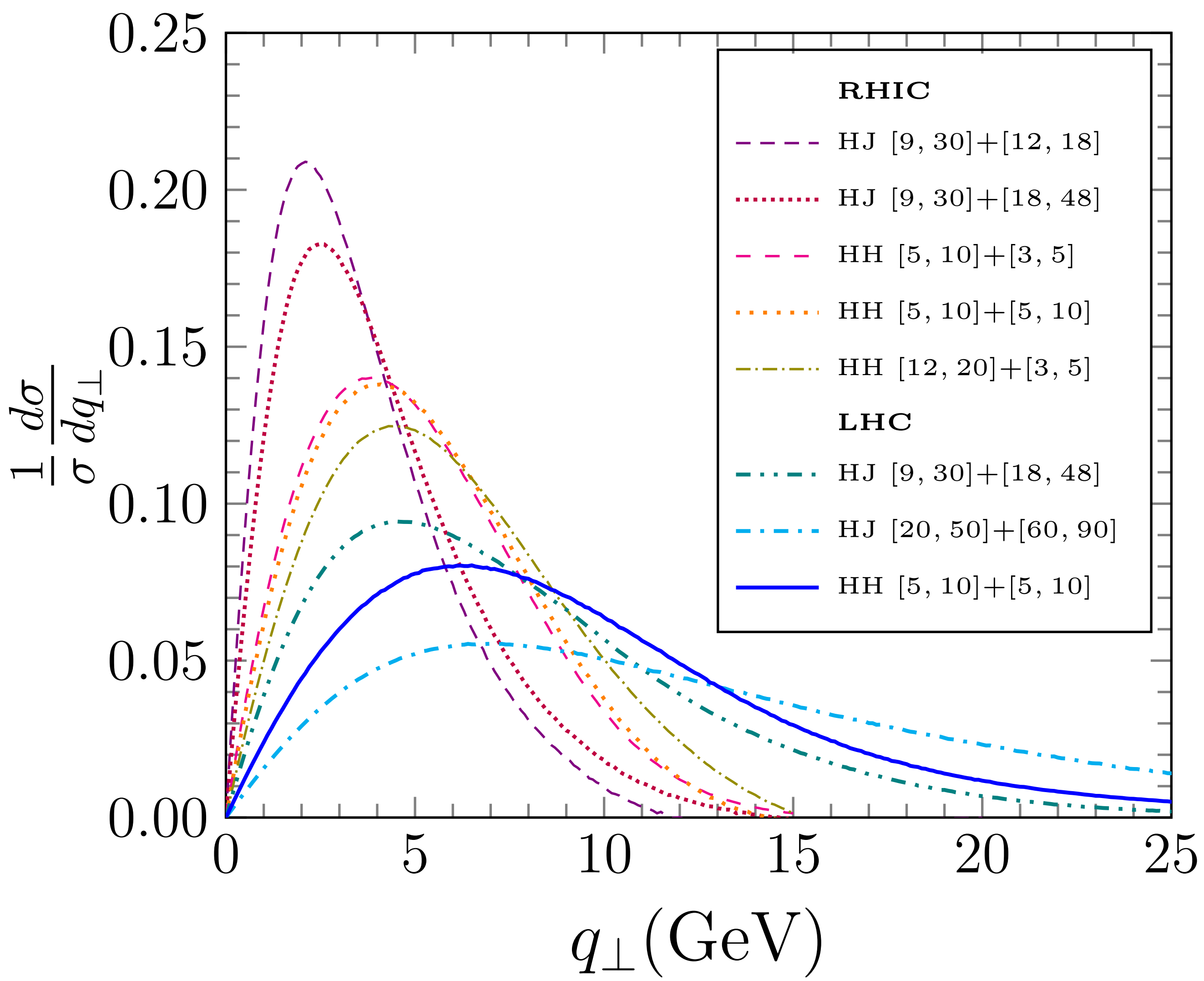
- ☑ For the first time we can describe the back-to-back angular correlation.
- ☑ Established a baseline to study the angular decorrelation in *AA* collisions.

Back-to-back angular correlations

pp collisions + *AA* collisions



Normalized $q_\perp$ distributions



$$q^{*2}_{\perp \mathrm{AA}} \simeq q^{*2}_{\perp \mathrm{pp}} + \langle \hat{q} L \rangle$$

Large p_T events are not sensitive to the medium induced k_T broadening, since the vacuum Sudakov effect is too large.

Back-to-back angular correlations

Extracting $\hat{q}_0$

- Collision geometry and the dynamical evolution of QGP.
- LL resummed $\hat{q}$ **Liou, Mueller, and Wu, NPA916 (2013)**

$$\langle p_\perp^2 \rangle = \langle \hat{q} L \rangle = \hat{q}_0 \frac{T^3}{T_0^3} L I_1 [2\sqrt{\bar{\alpha}_s} \ln(L^2/l_0^2)] \frac{1}{\sqrt{\bar{\alpha}_s} \ln(L^2/l_0^2)}$$

Global χ^2 analysis with STAR data

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

T_0 = 378 MeV;1 σ; quark jet

$$\hat{q}_0 = 1.2 \pm 0.3 \mathrm{GeV}^2/\mathrm{fm}$$

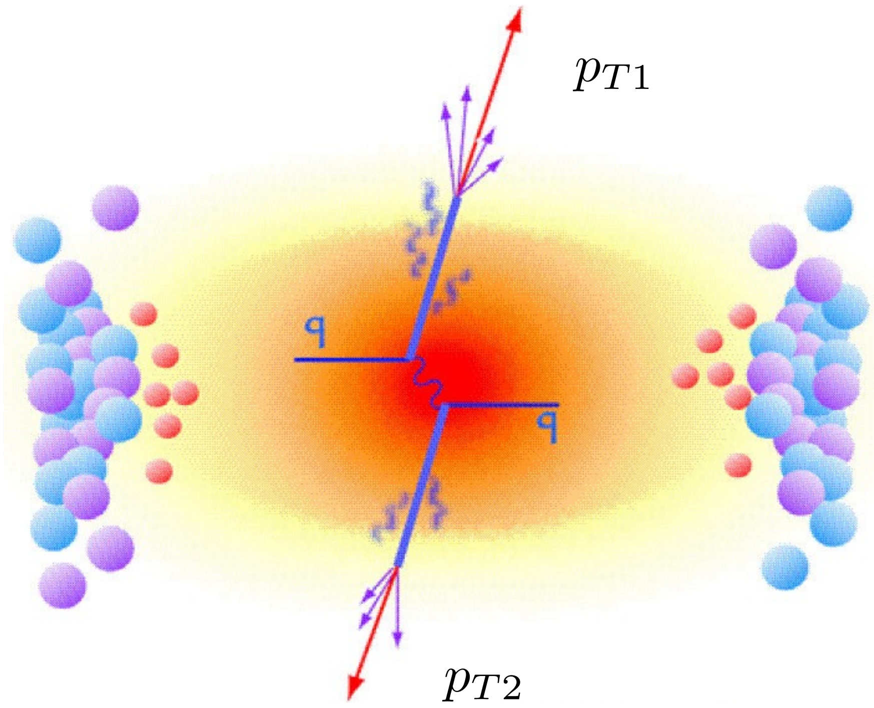
JET Collaboration; 10 GeV quark jet

a few times larger than (not inconsistent with) that from JET collaboration.

What is dijet asymmetry?

Two jets with largest transverse energy

- ☑ Leading Jet: P_{T1}
- ☑ Sub-leading Jet: P_{T2}



Dijet asymmetry

$$A_J \equiv \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}} \qquad x_J \equiv \frac{p_{T2}}{p_{T1}}$$

$$A_J = \frac{1 - x_J}{1 + x_J}$$

$$x_J = \frac{1 - A_J}{1 + A_J}$$

- ☑ Intuitive picture on the jet energy loss.
- ☑ Sensitive to geometry, $\hat{q}$, evolution of medium, energy loss formalism…

First Thing: baseline in *pp* collisions

- Most of the previous theoretical studies are using Event Generators.

Pythia …

You always have parameters to tune…

- All the previous theoretical studies are comparing with the uncorrected data.

Smearing: Another parameter to make the curve look pretty.

ELSEVIER

Nuclear Physics A 956 (2016) 653–656

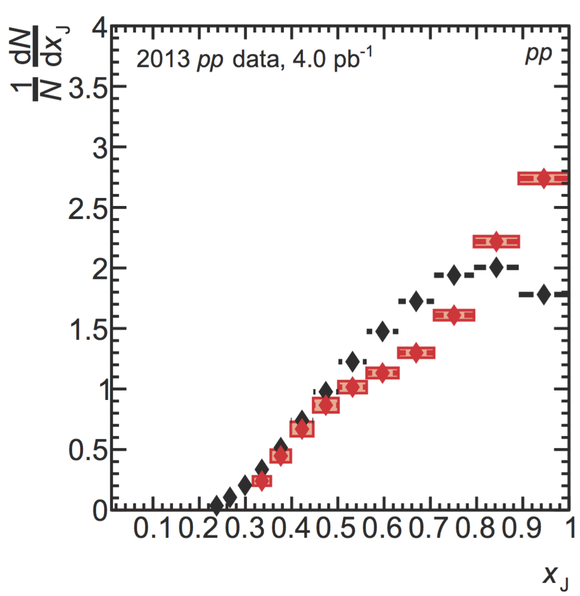
www.elsevier.com/locate/nuclphysa

Quark Matter 2015

New results on fully corrected dijet asymmetry in Pb+Pb collisions with ATLAS

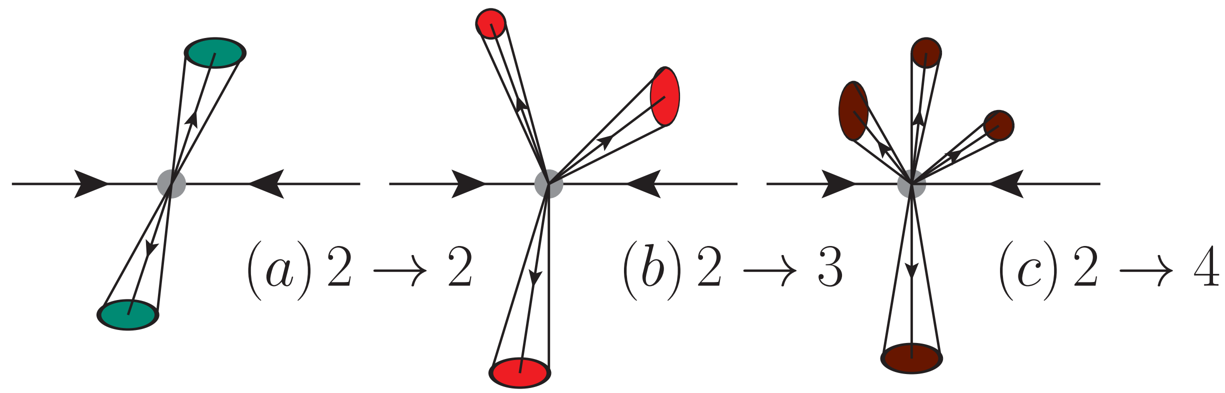
Dennis V. Perepelitsa (on behalf of the ATLAS Collaboration)[1]

Physics Department, Brookhaven National Laboratory, Upton NY, 11973 USA



Establish a baseline that can describe the **fully corrected** data without any **free parameters**.

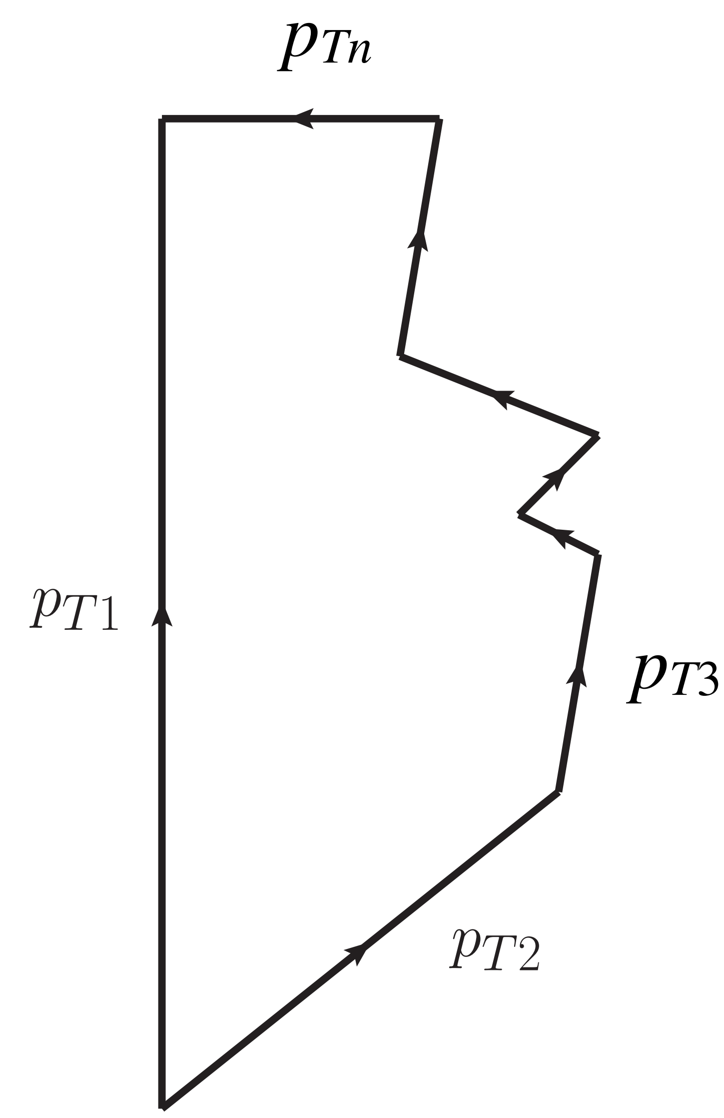
Dijet Asymmetry Establish baselines without free parameters



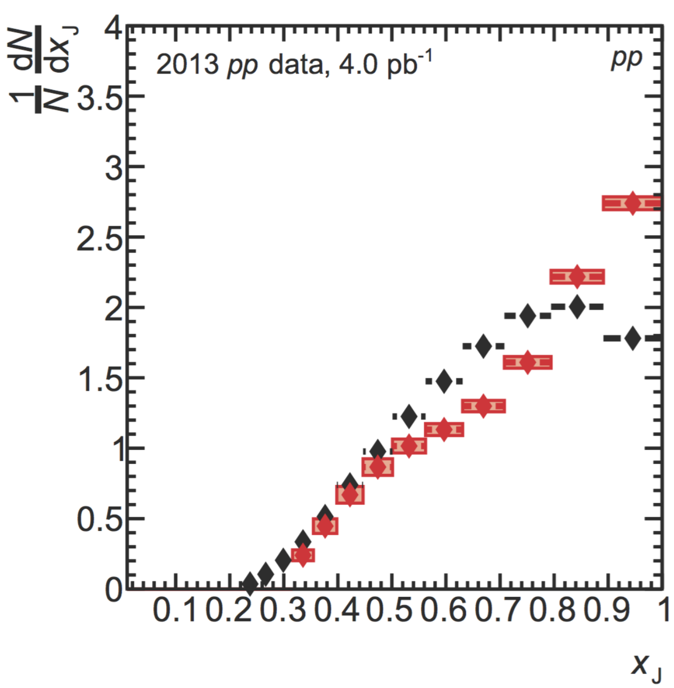
Perturbative Expansion

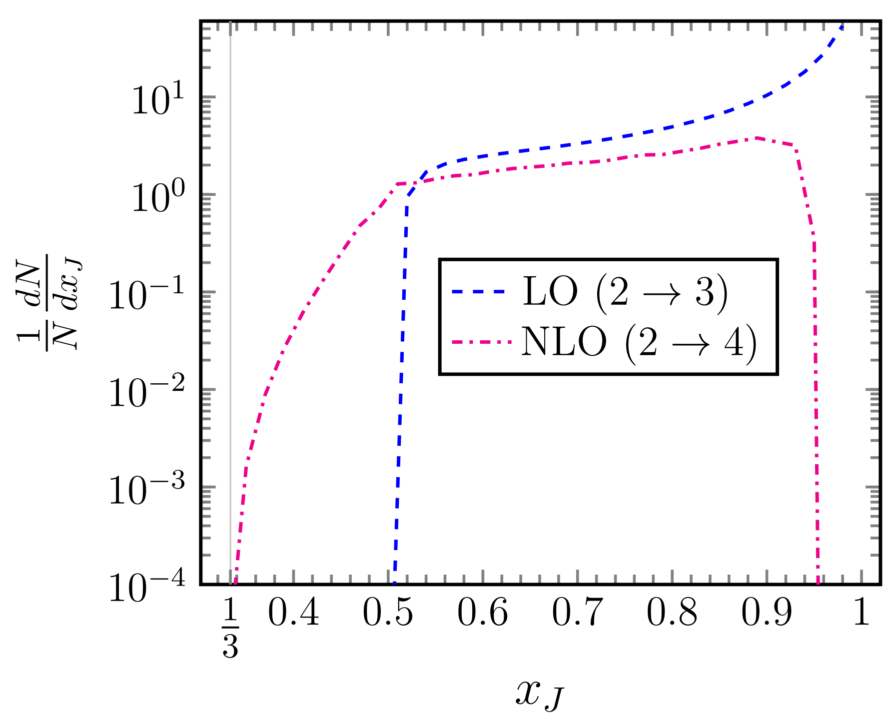
- ☑ energy conservation
- ☑ 4π coverage (no missing jet)
- ☑ leading and sub-leading jets

For *n*-jet final state

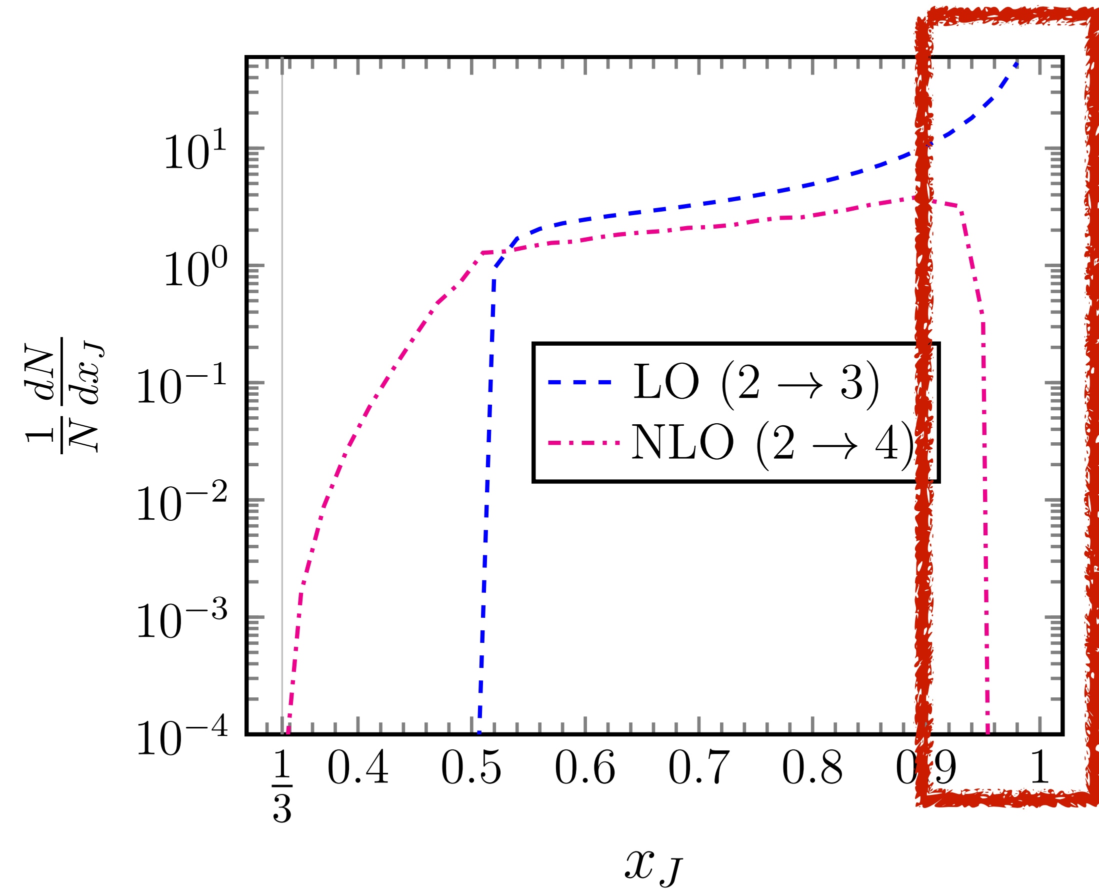


$$(n-1)p_{T2} \geq p_{T1} \qquad x_J^{2\to n} \geq \frac{1}{n-1}$$

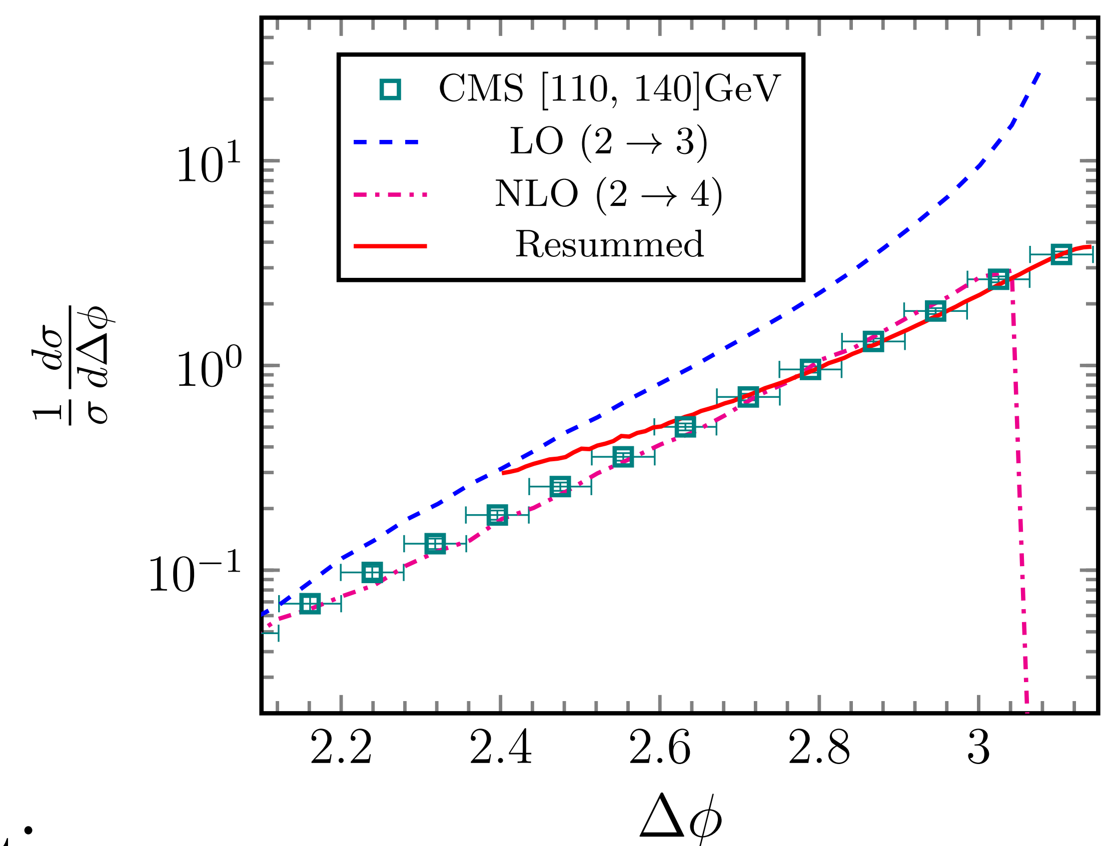




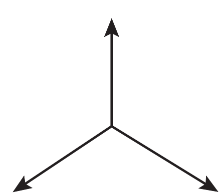
Perturbative Expansion



perturbative expansion fails



$X_J \to 1$

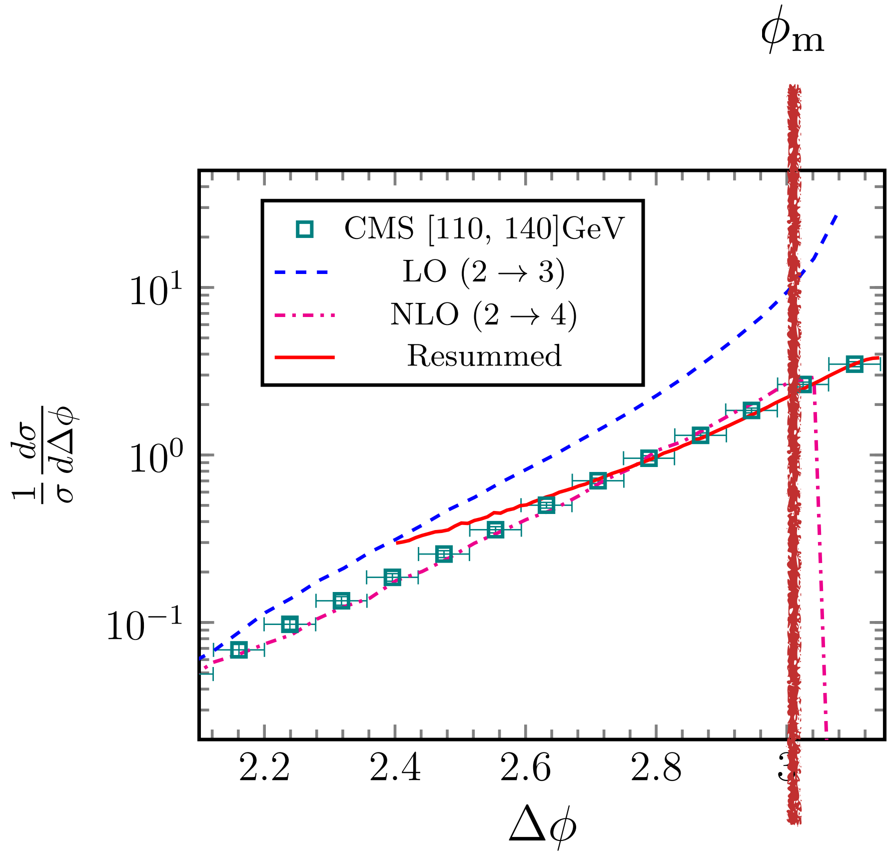


stable

back-to-back configuration

Resummation Improved pQCD approach

$$\sigma_0 \sum_{i=0}^{\infty}\Big((\alpha_s \mathrm{Log})^i + \alpha_s^i C_i\Big)$$



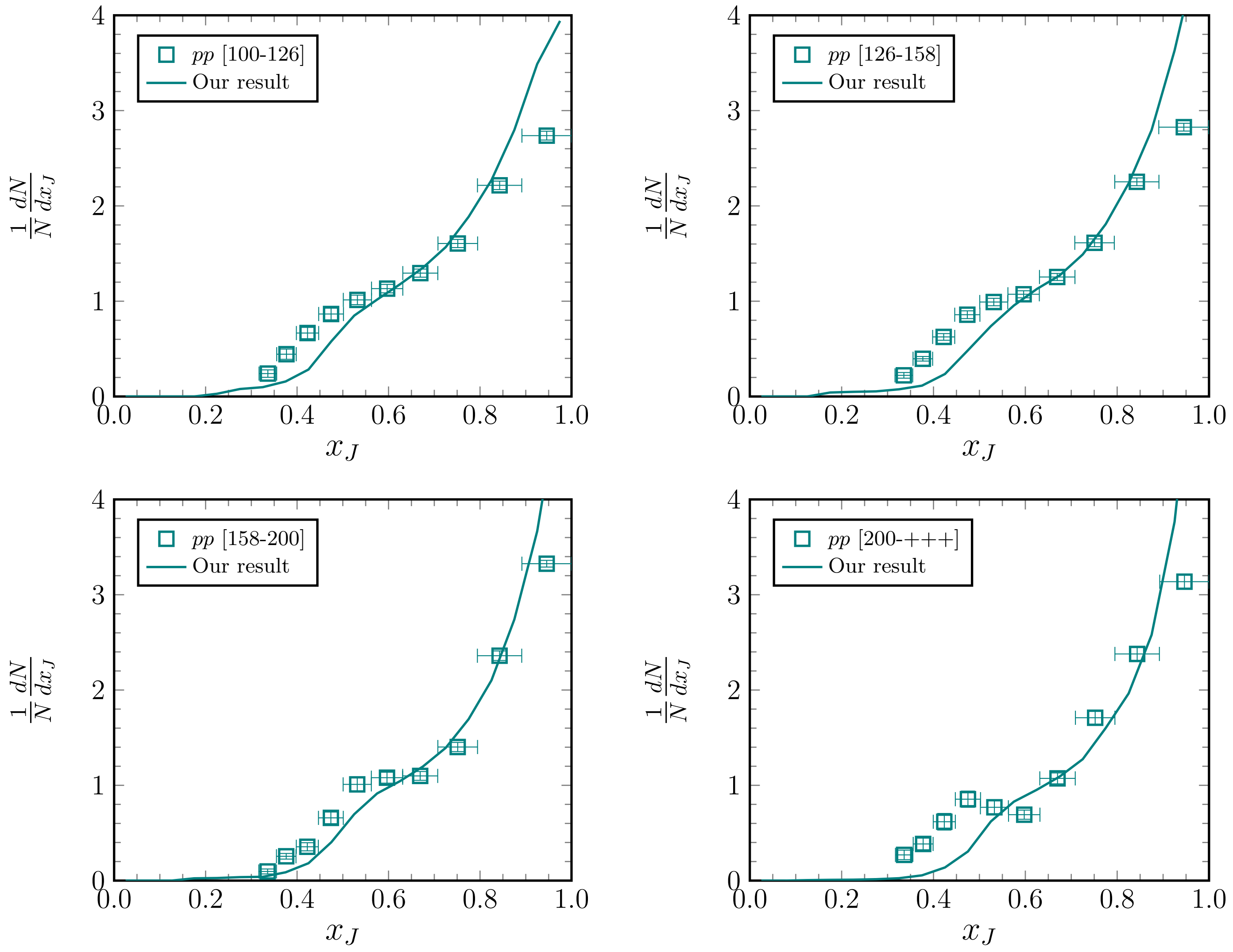
ϕ_{m}

no large logs	large logs
$\sigma_0 \sum_{i=0}^{n}\Big((\alpha_s \mathrm{Log})^i + \alpha_s^i C_i\Big)$	$\sigma_0 \sum_{i=0}^{n}\Big((\alpha_s \mathrm{Log})^i\Big) + \sigma_0 \sum_{n+1}^{\infty}\Big((\alpha_s \mathrm{Log})^i\Big)$

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

- ☑ NLO pQCD provides very precious result at small X_{J} region.
- ☑ Sudakov resummation resums the alternating sign series of large logarithms.
- ☑ There is no free parameter in this calculation.

Resummation Improved pQCD approach



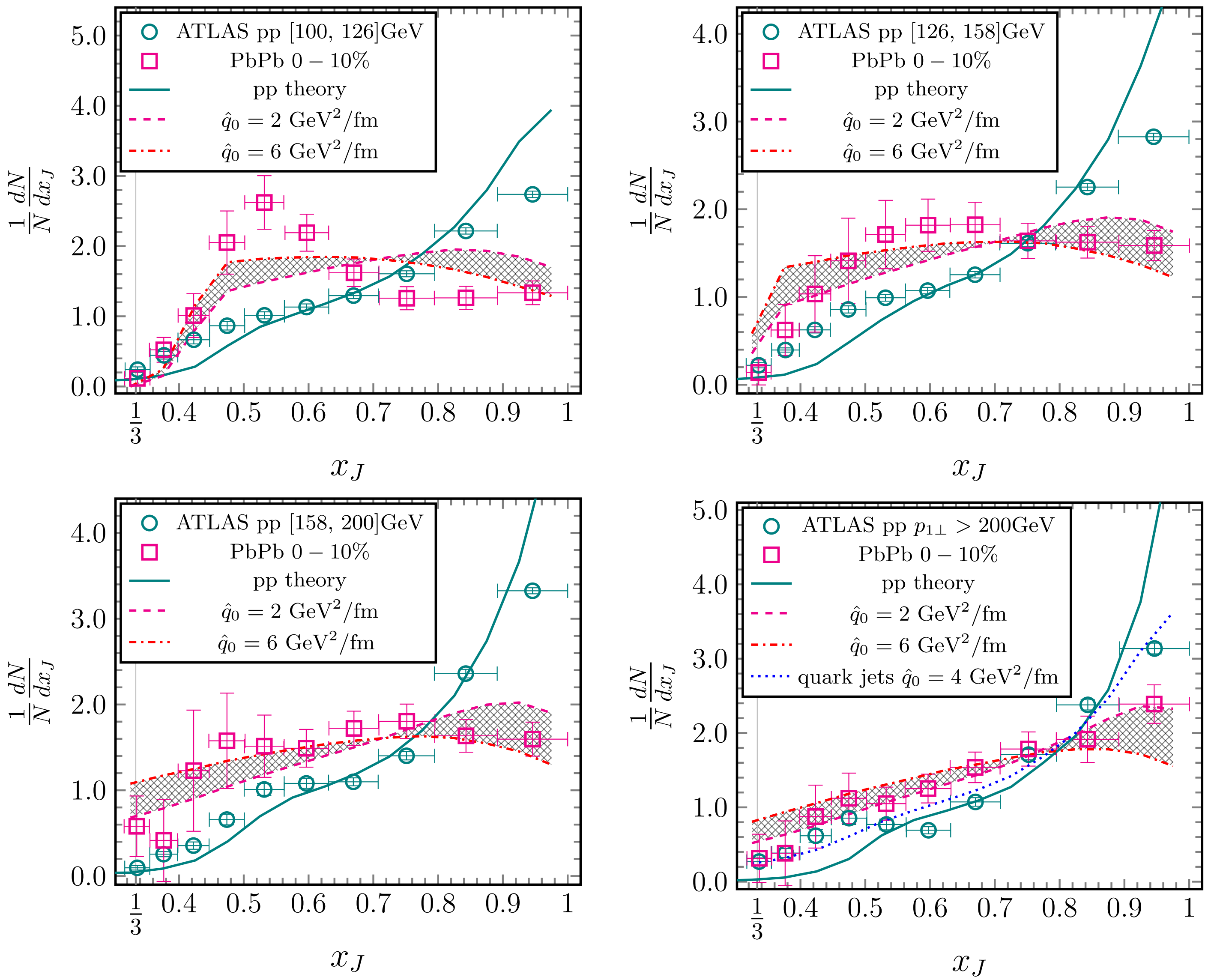
$$\frac{1}{\sigma}\frac{d\sigma}{dx_J}\bigg|_{\text{Improved}} = \frac{1}{\sigma_{\text{NLO}}}\frac{d\sigma_{\text{NLO}}}{dx_J}\bigg|_{\Delta\phi<\phi_m} + \frac{1}{\sigma_{\text{Sudakov}}}\frac{d\sigma_{\text{Sudakov}}}{dx_J}\bigg|_{\pi>\Delta\phi>\phi_m}$$

BDMPS formalism

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

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

- ☑ Probability for a jet to lose energy ε



Results:

- ☑ Assuming all the jets are gluon jets.
- ☑ Typical energy loss is 20 ~ 30 GeV.
- ☑ $\hat{q}_0$ is 2 ~ 6 GeV ^{2} / fm at T_0 = 481MeV.
- ☑ Agrees with the original BDMPS estimate $\hat{q}$ ~ 0.3-0.8 GeV^2 / fm at T = 250 MeV.

$$\frac{d\sigma}{dp'_{T1}dp'_{T2}} = \int d\epsilon_1 d\epsilon_2 D(\epsilon_1)D(\epsilon_2)\frac{d\sigma}{dp_{T1}dp_{T2}}\Big|_{p_{T1}=p'_{T1}+\epsilon_1;\ p_{T2}=p'_{T2}+\epsilon_2}$$

hep-ph/9608322

Summary

Back-to-back angular correlation

- For the first time we can describe the back-to-back dihadron/hadron-jet angular correlation measured at RHIC & LHC.
- The dijet, dihadron and hadron-jet angular correlations can provide a new gateway to quantify the medium induced k_T broadening.
- We extracted that $\hat{q}_0 = 3.9^{+1.5}_{-1.2}\mathrm{GeV}^2/\mathrm{fm}$ for a quark jet at T_0 = 378 MeV.

Dijet Asymmetry

- We developed the Resummation Improved pQCD formalism
- Based on BDMPS approach, $\hat{q}_0 = 2 \sim 6\mathrm{GeV}^2/\mathrm{fm}$ at T_0 = 481 MeV

Thank you very much for your attention!

The End