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

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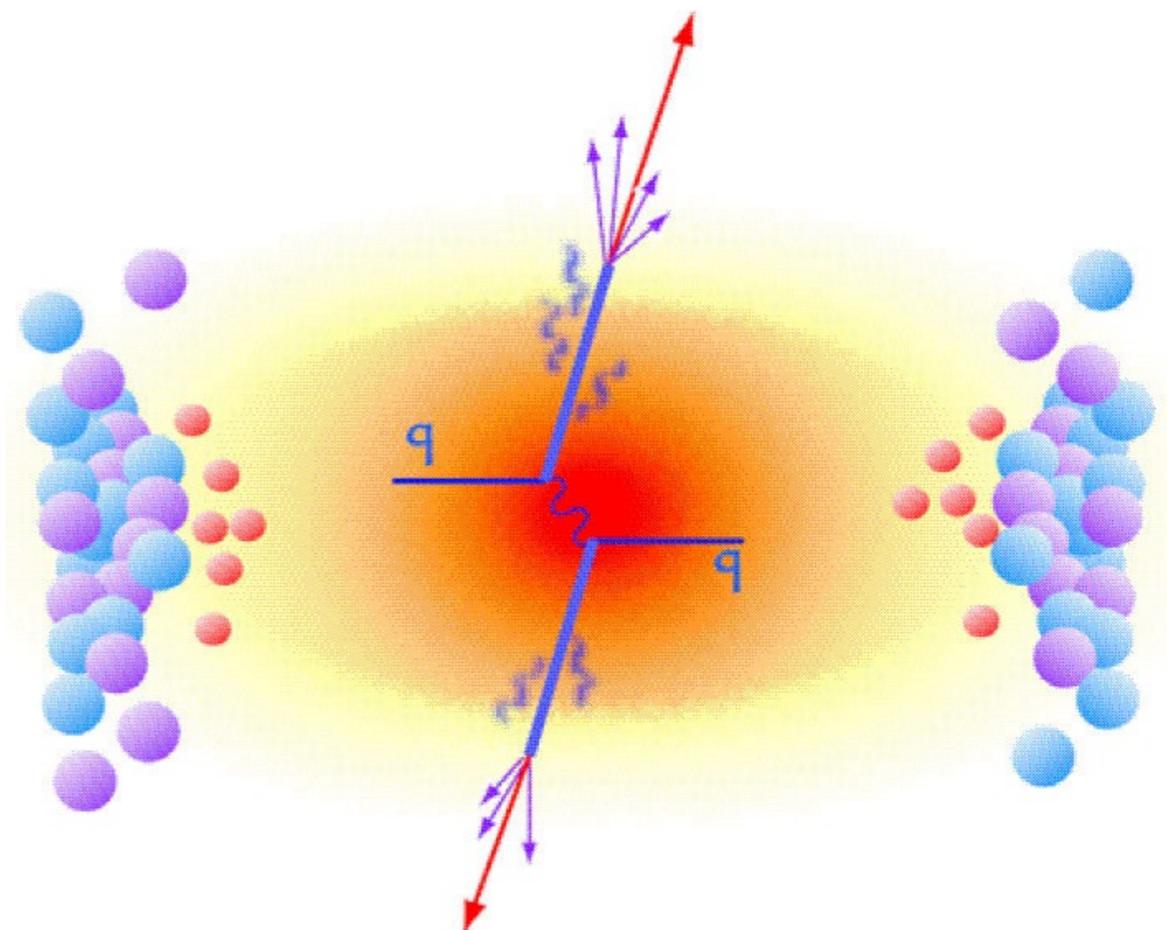
- Introduction & Sudakov resummation
- Back-to-back angular decorrelations
- Dijet asymmetry
- Summary

Introduction: Jet Quenching

Jet-medium interaction

- k_\perp broadening
- Energy loss

Two sides of the same coin.



BDMPS approach

Jet transport parameter

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

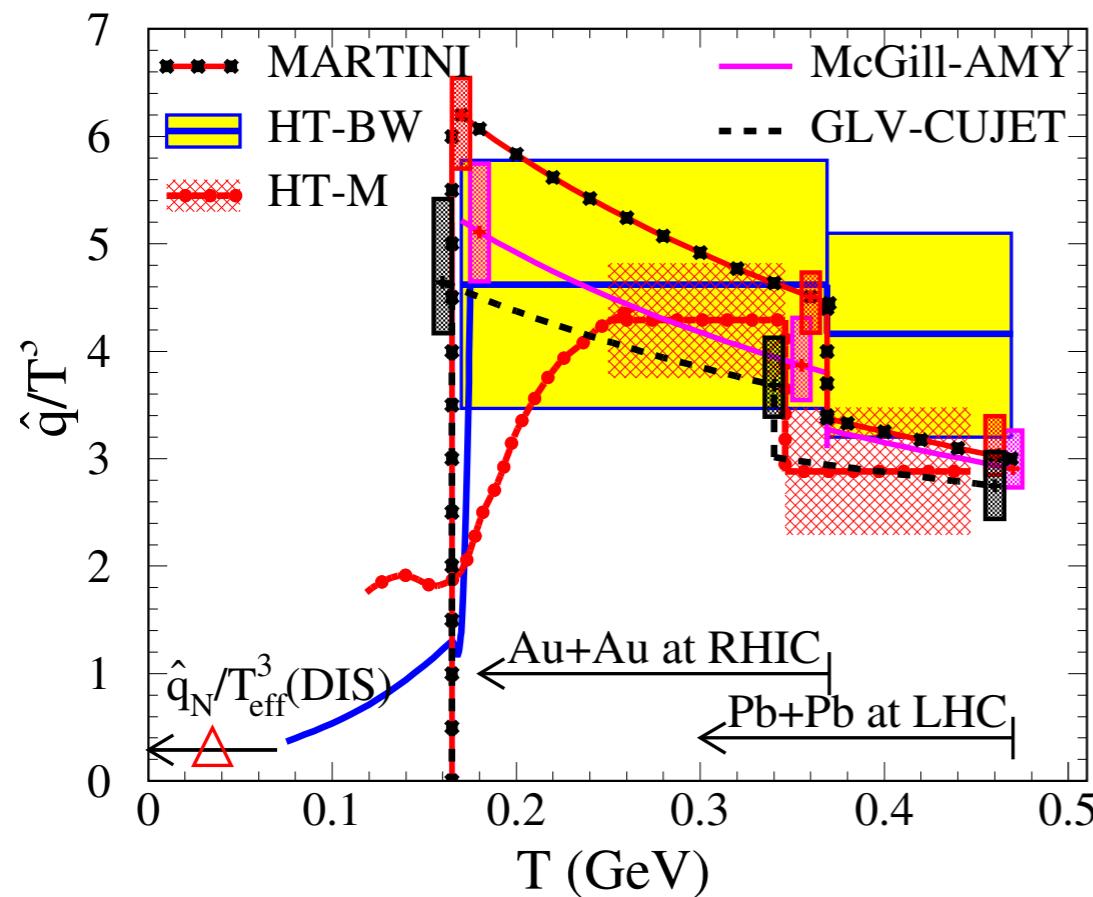
- \hat{q} reflects the density of QGP

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

Introduction

Energy loss - Single hadron R_{AA}

$R_{AA} \equiv \text{Cross Section}_{AA}/\text{Cross Section}_{pp}$



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

for a 10 GeV quark jet

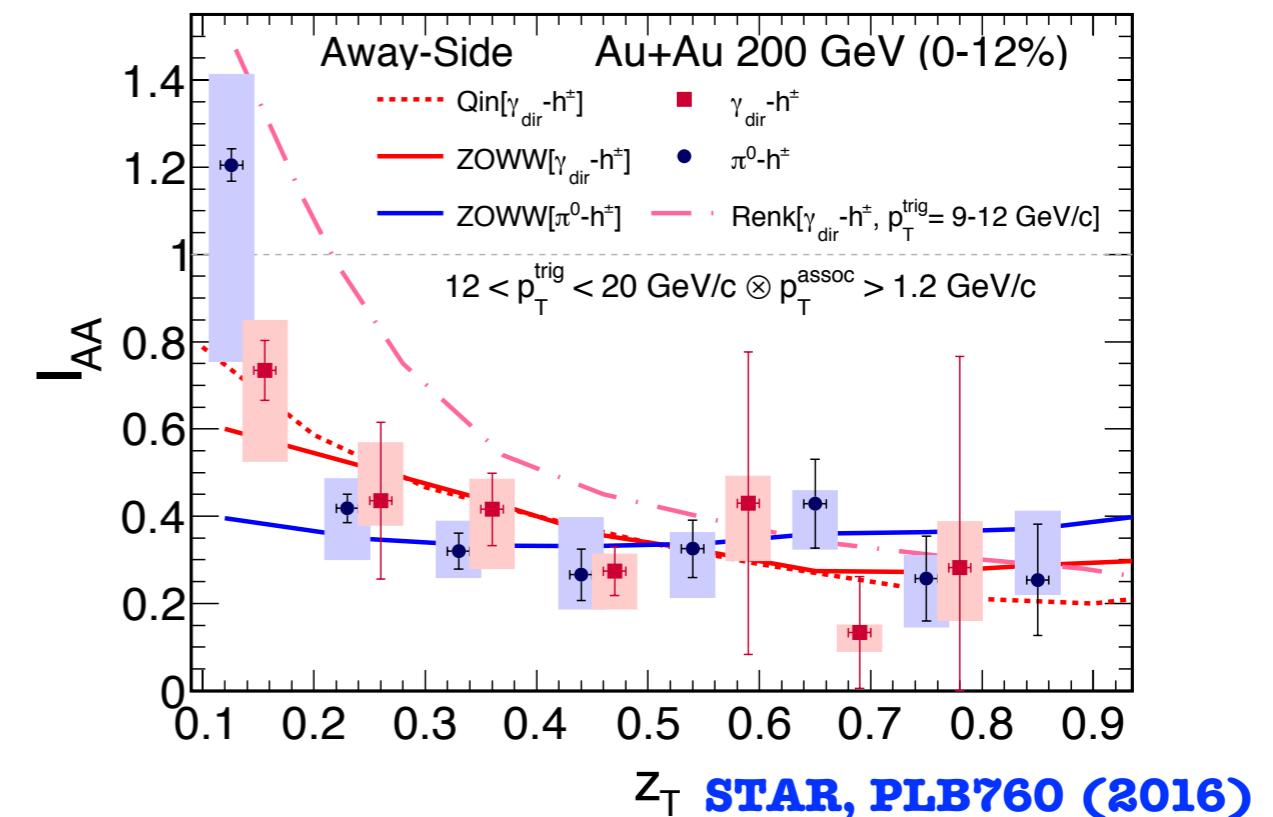
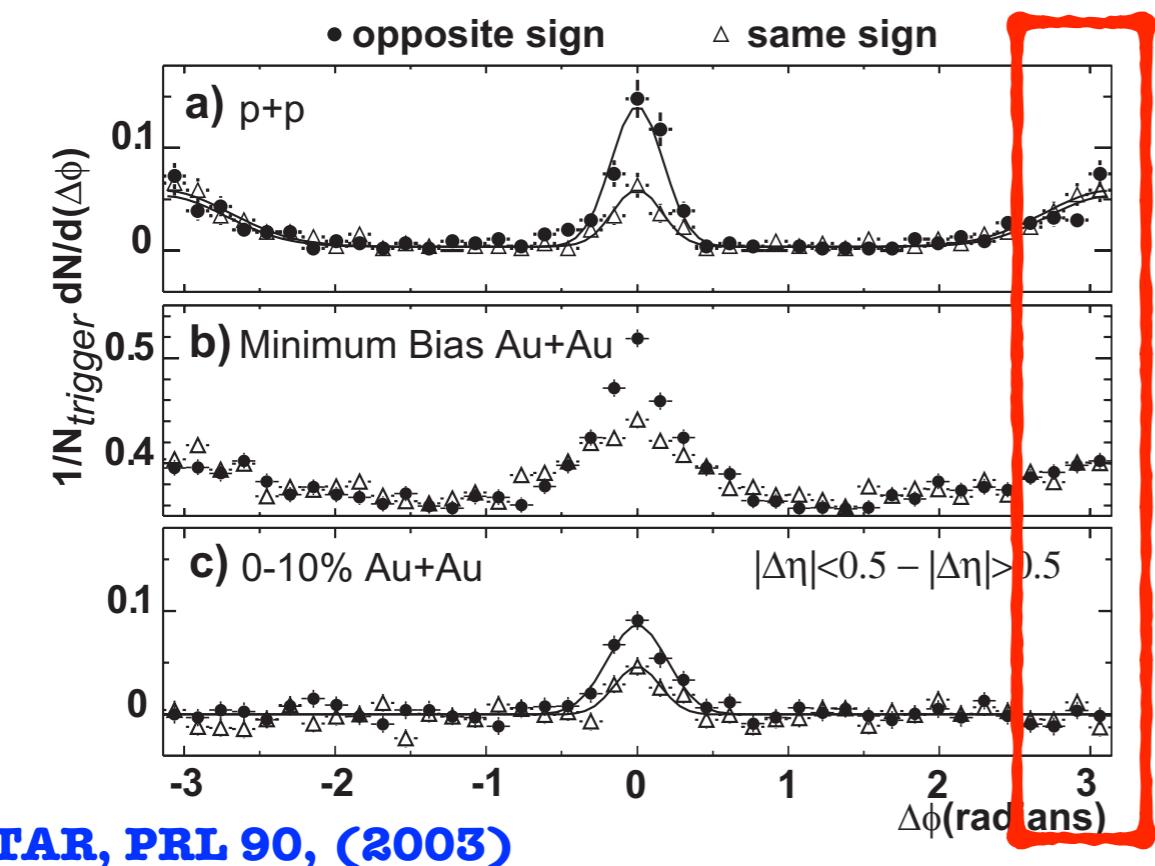
Jet Collaboration. PRC 90, 014909, (2014)

Angular decorrelation - New and complimentary method

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

Introduction

Dihadron Angular decorrelation @ RHIC



- Yield suppression
- Angular decorrelation: quantitative calculation is lacking

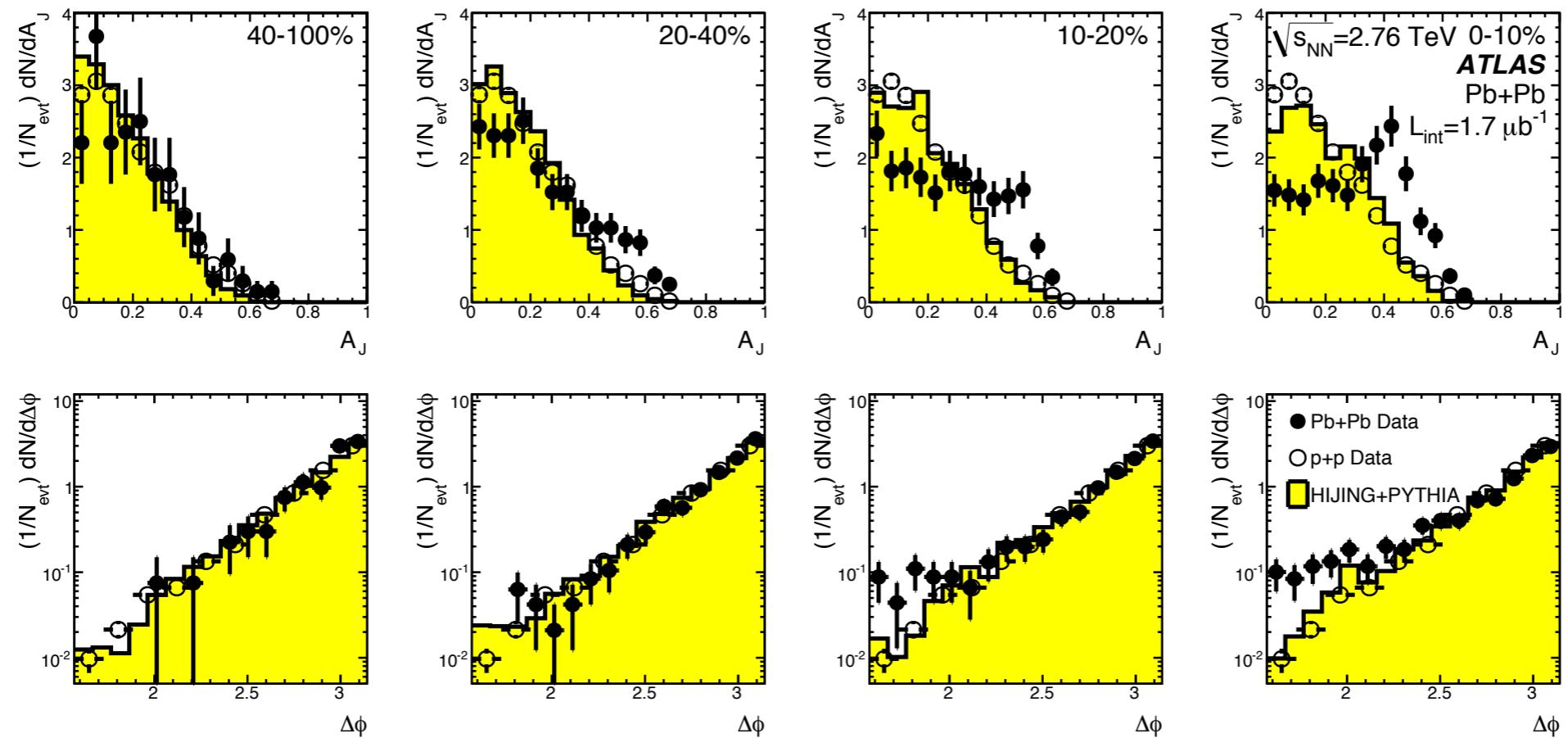
Introduction

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

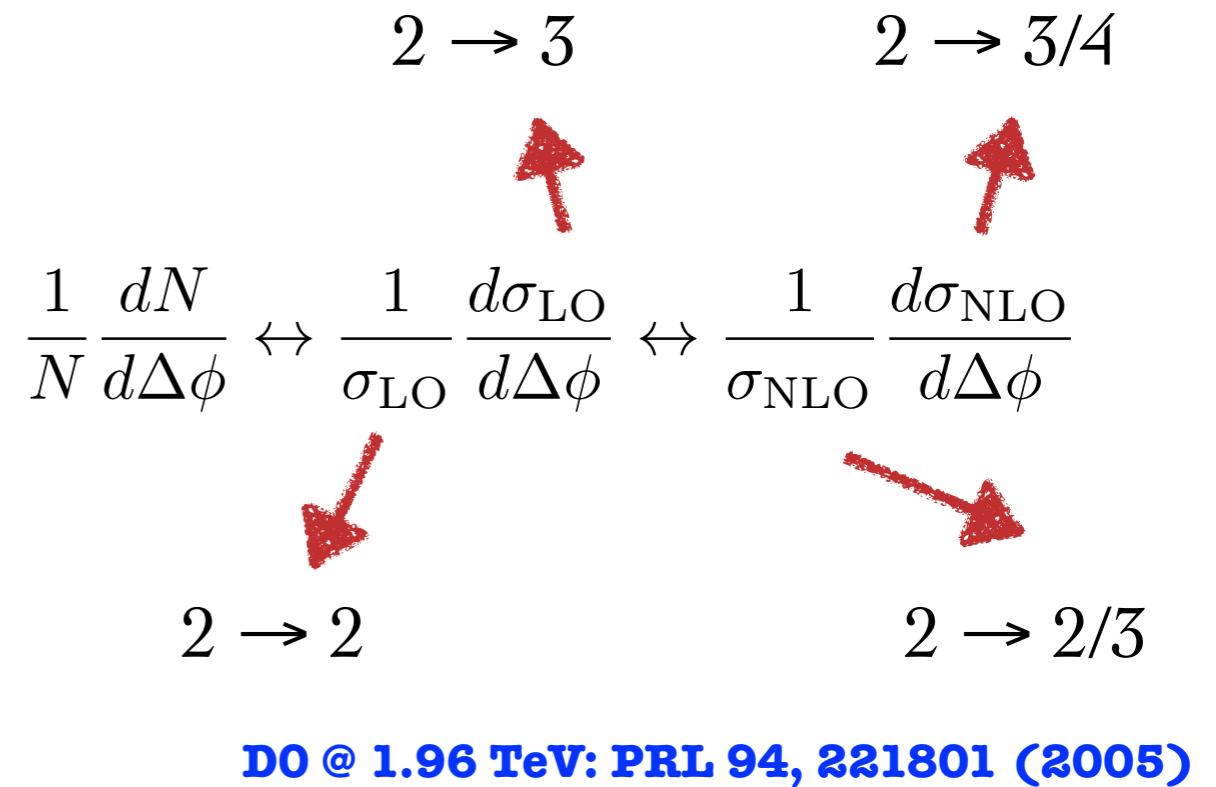
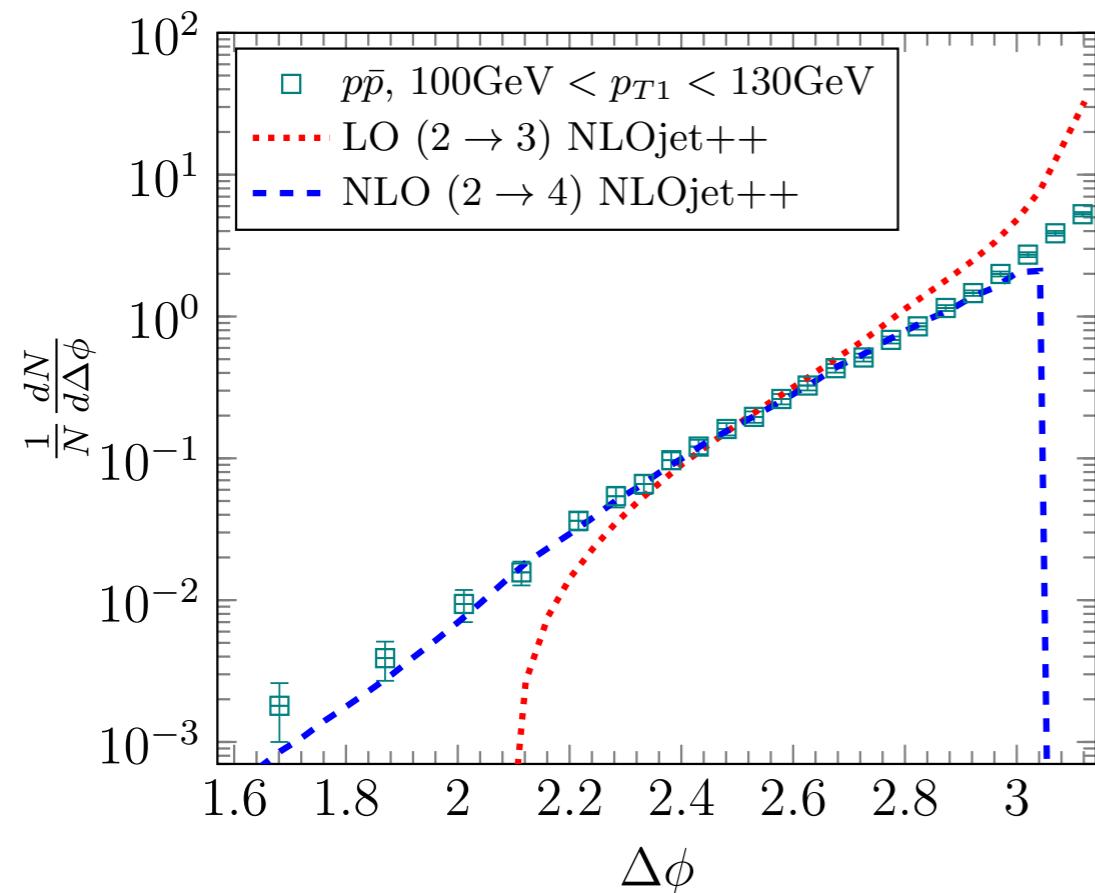
Qin, Muller, PRL 106 (2011)

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

Puzzle: Large Energy Loss, Small p_T Broadening?

Introduction: Dijet Angular Correlation

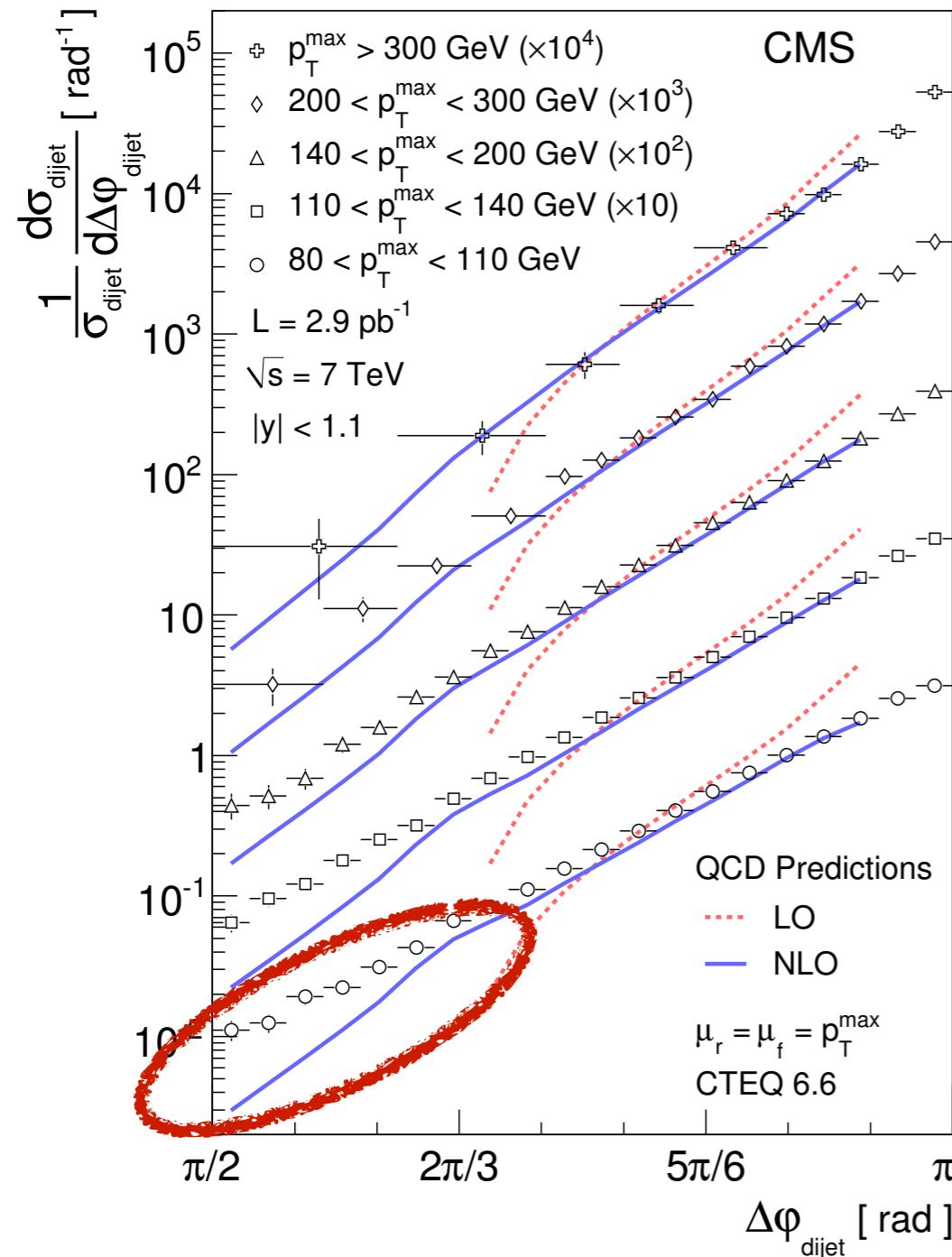
Dijet angular correlation in $p\bar{p}$ with perturbative expansion approach



- NLO calculation can describe the experimental data very well.

Introduction: Dijet Angular Correlation

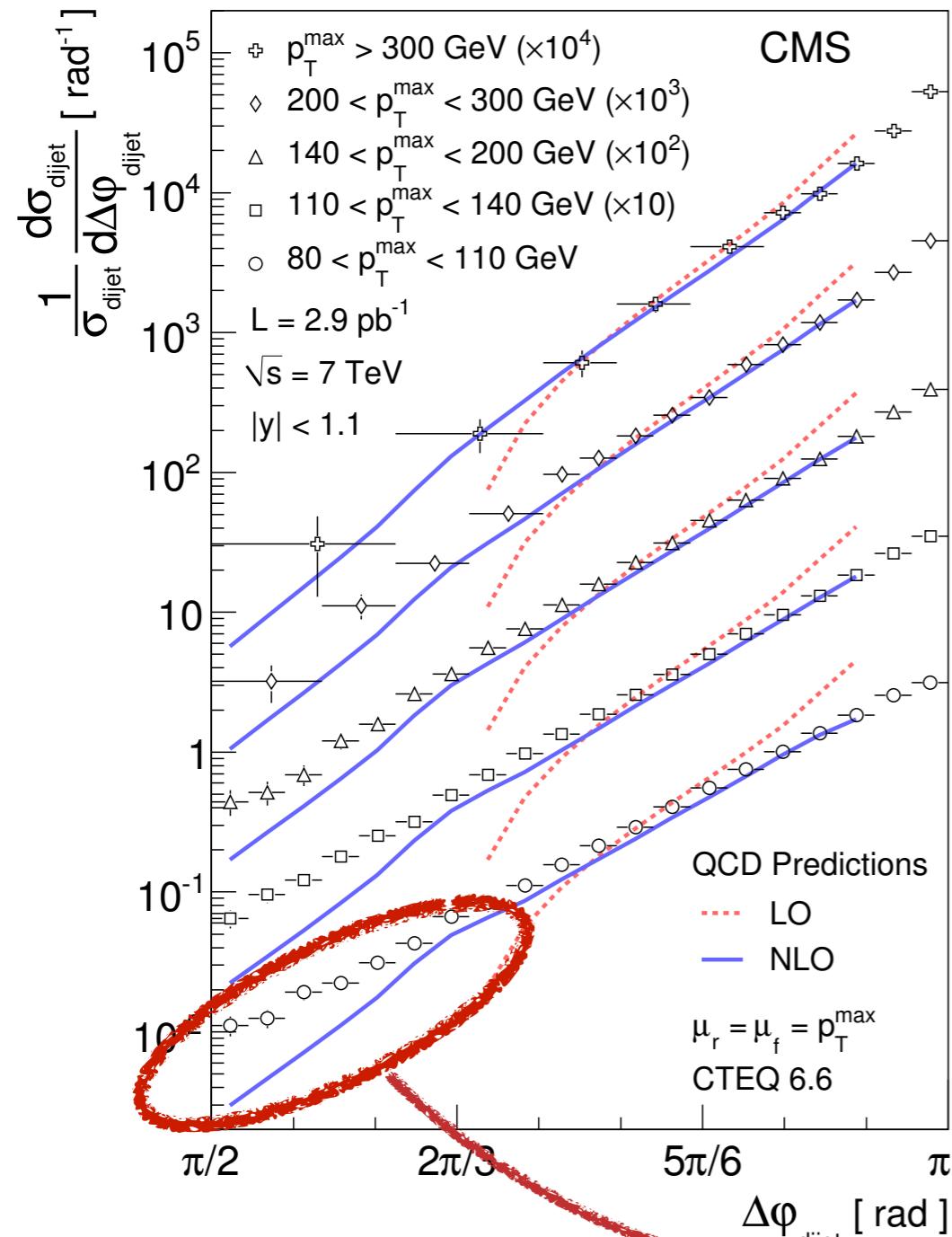
Dijet angular correlation in pp with perturbative expansion approach



CMS @ 7TeV, arXiv:1101.5029

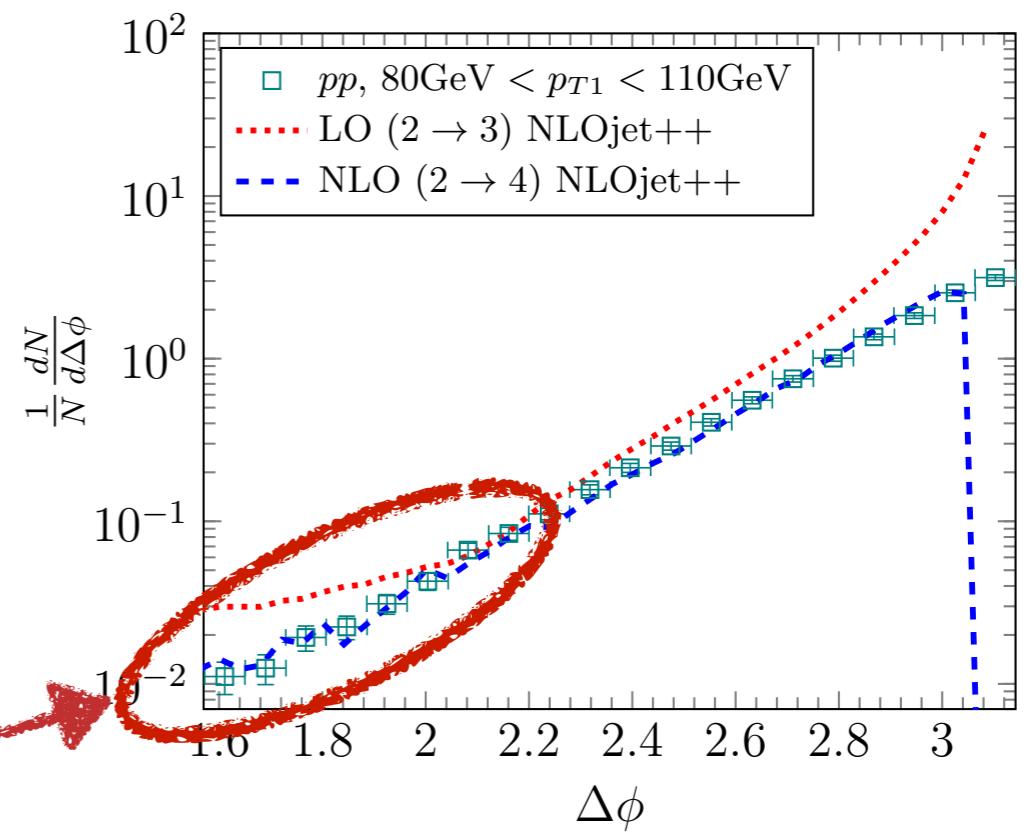
Introduction: Dijet Angular Correlation

Dijet angular correlation in pp with perturbative expansion approach



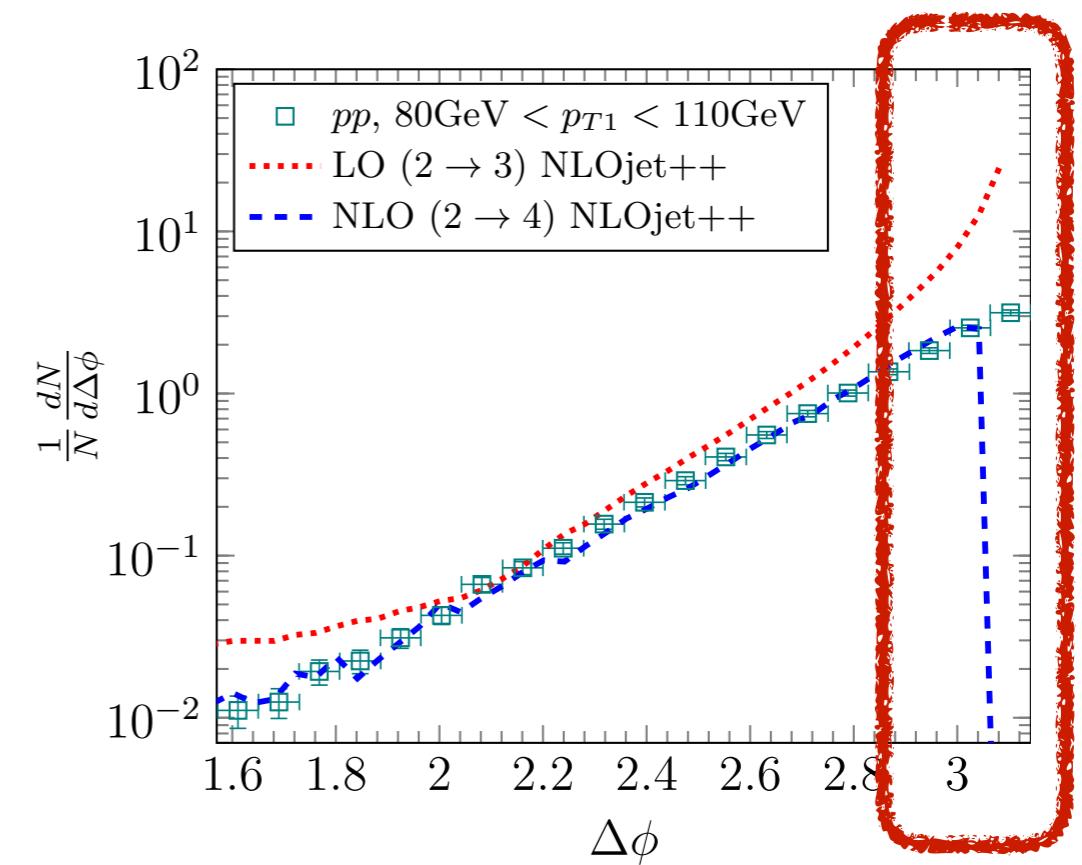
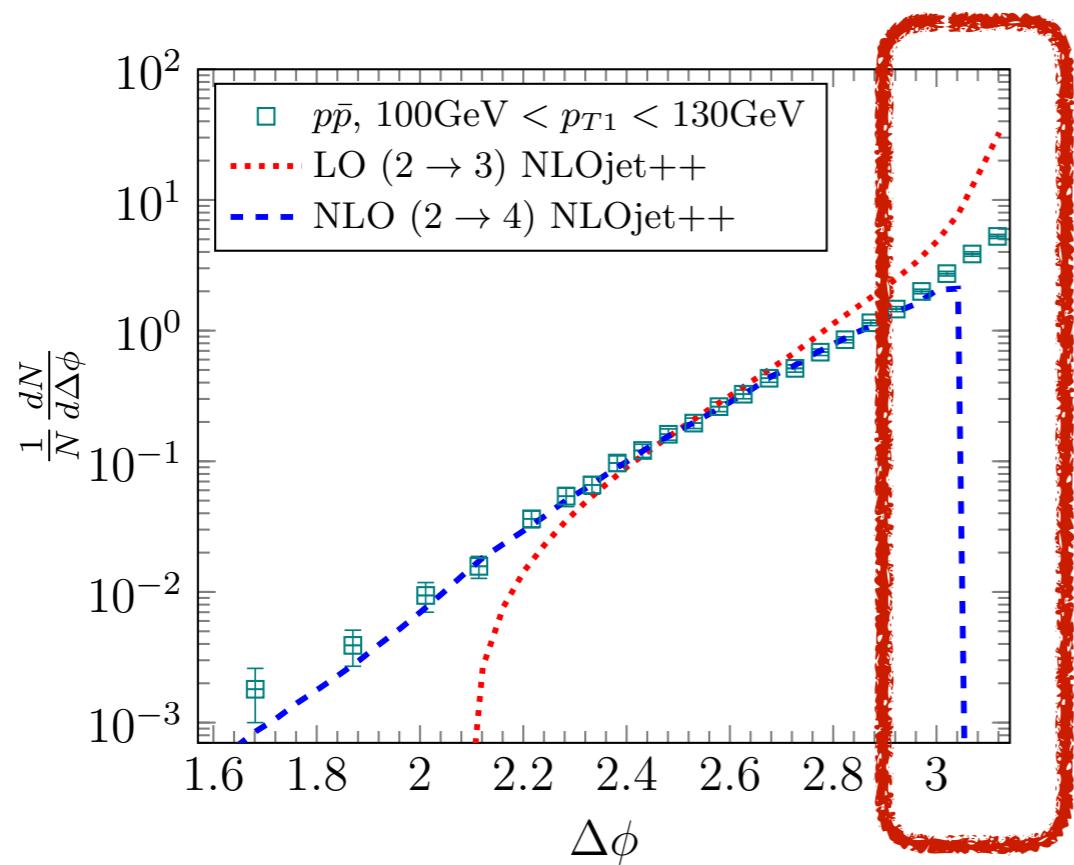
CMS @ 7TeV, arXiv:1101.5029

- 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 $|y| < 1.1$



Introduction: Dijet Angular Correlation

Dijet angular correlation in $p\bar{p}$ with perturbative expansion approach



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

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

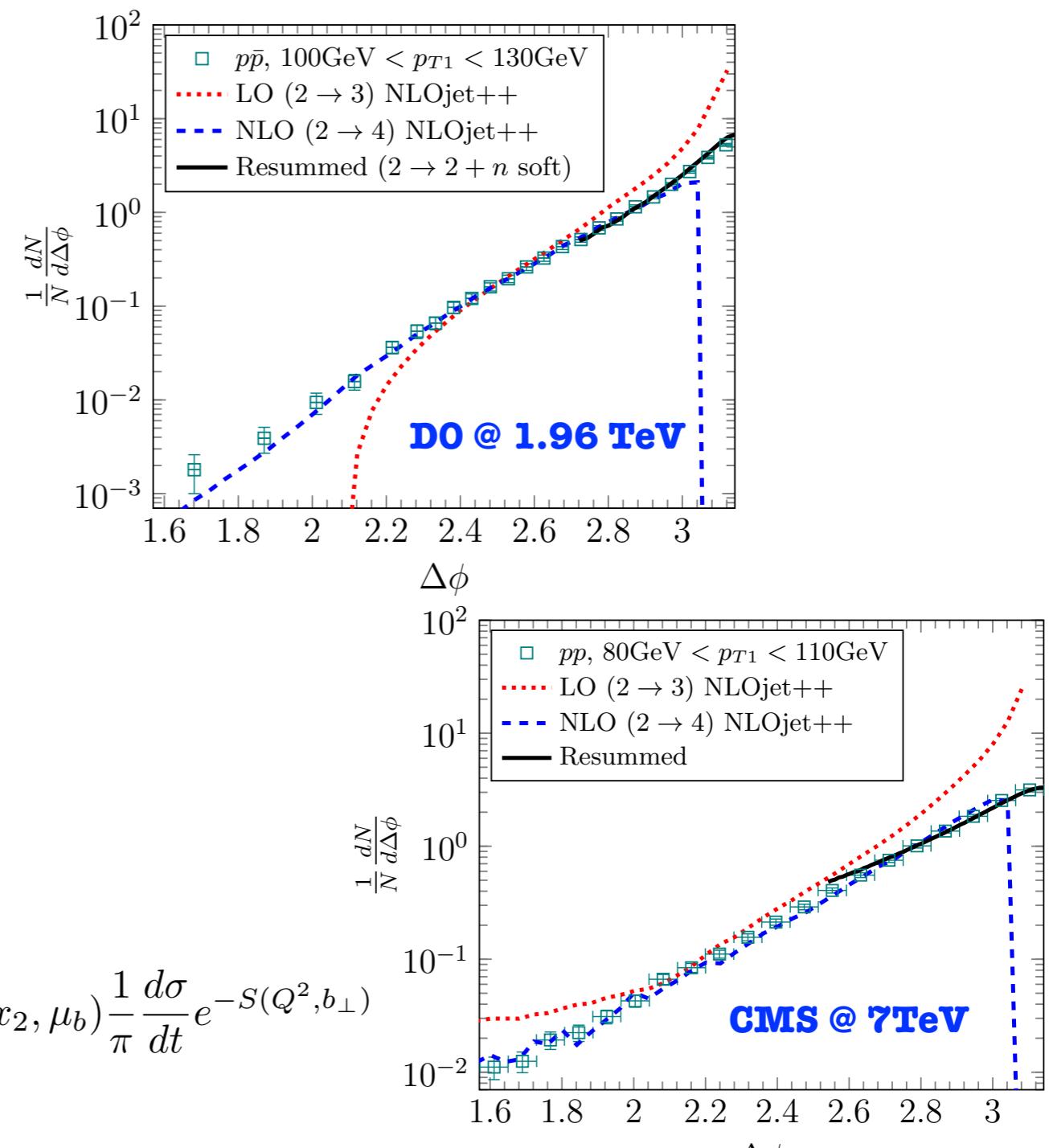
Sudakov Resummation

Dijet angular correlation in $p\bar{p}$ with Resummation approach

Perturbative Expansion

paradigm shift

large logarithms

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


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

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

NLL resummation

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

Sudakov Resummation

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

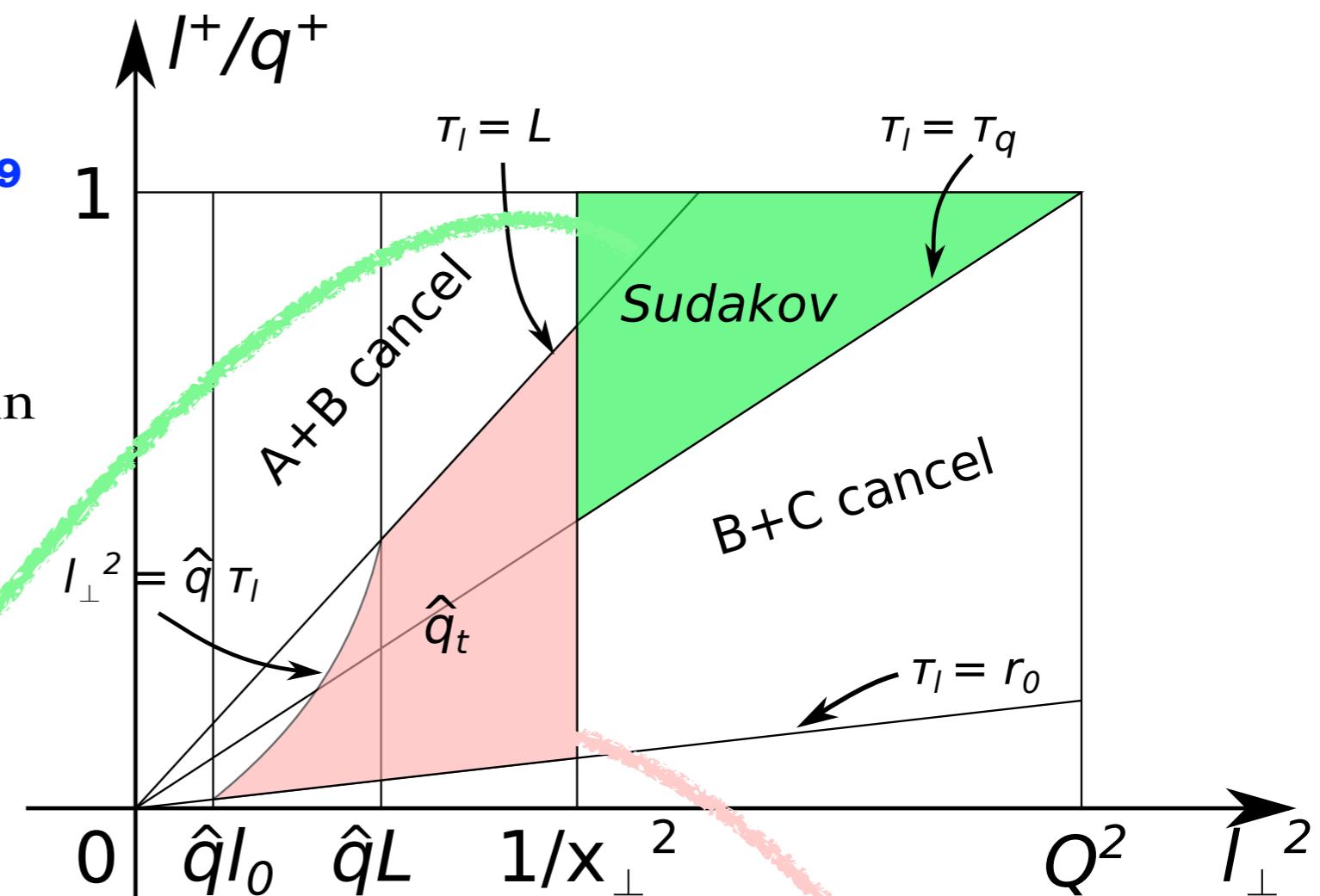
can be separated.

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

Vacuum parton shower

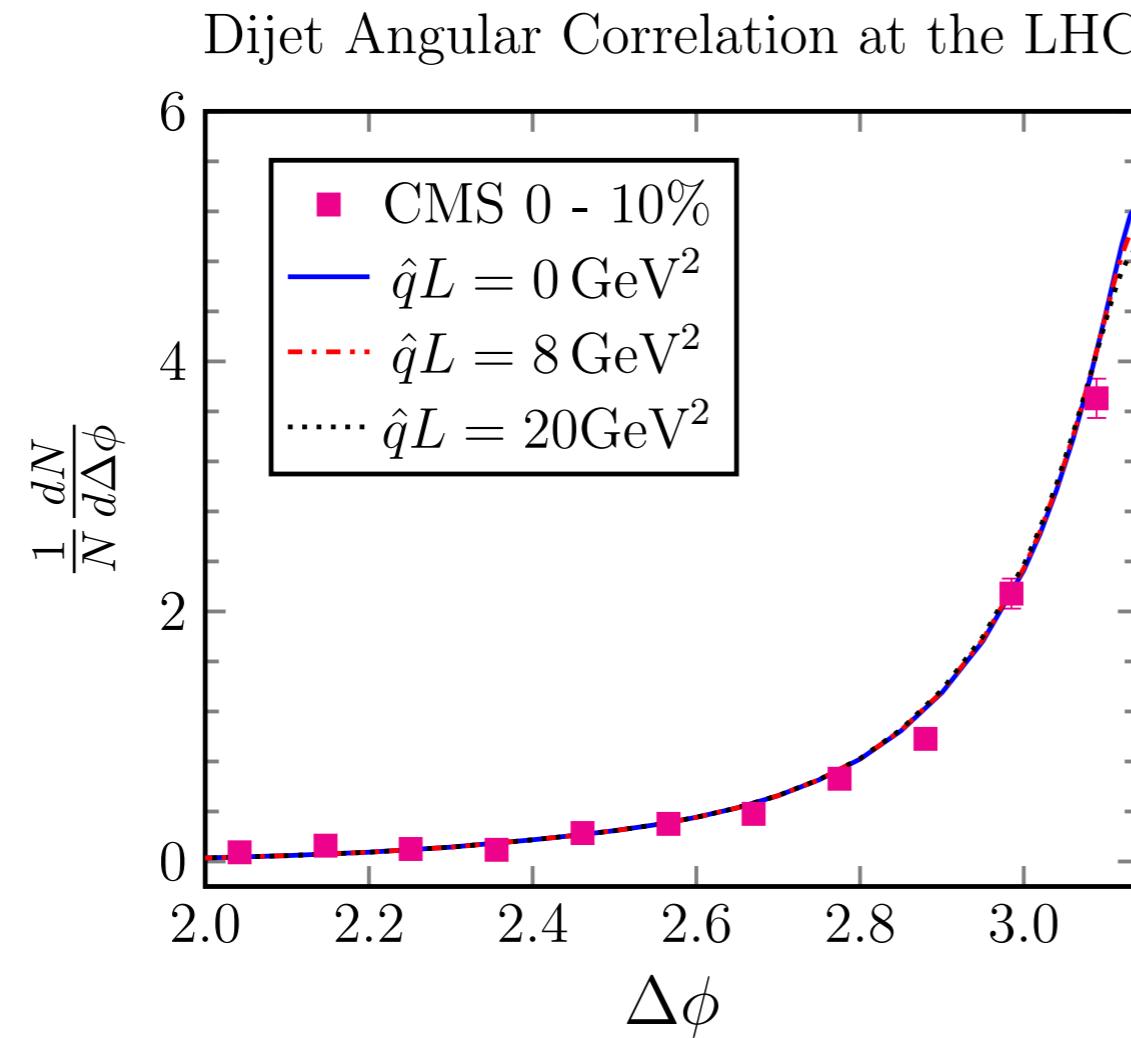
k_T broadening

Multiple scattering
Medium induced radiation



Sudakov Resummation

Dijet angular correlation in AA



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

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

$$p_T^1 > 150 \text{ GeV}$$

$$p_T^2 > 50 \text{ GeV}$$

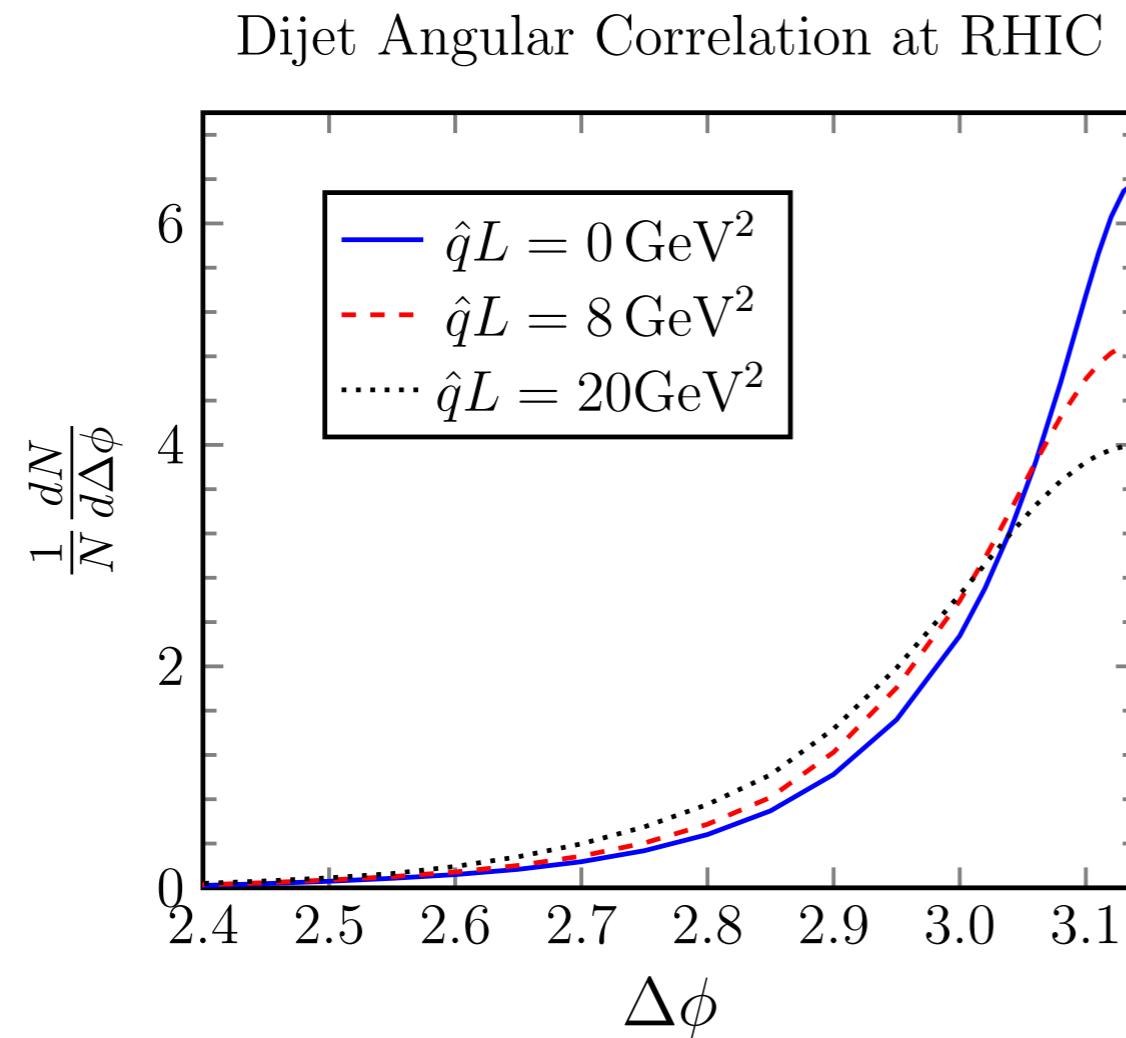
Vacuum Sudakov Effect \gg Medium Broadening Effect

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

Mueller, Wu, Xiao, Yuan, arXiv:1604.04250

Sudakov Resummation

Dijet angular correlation in AA



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

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

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

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

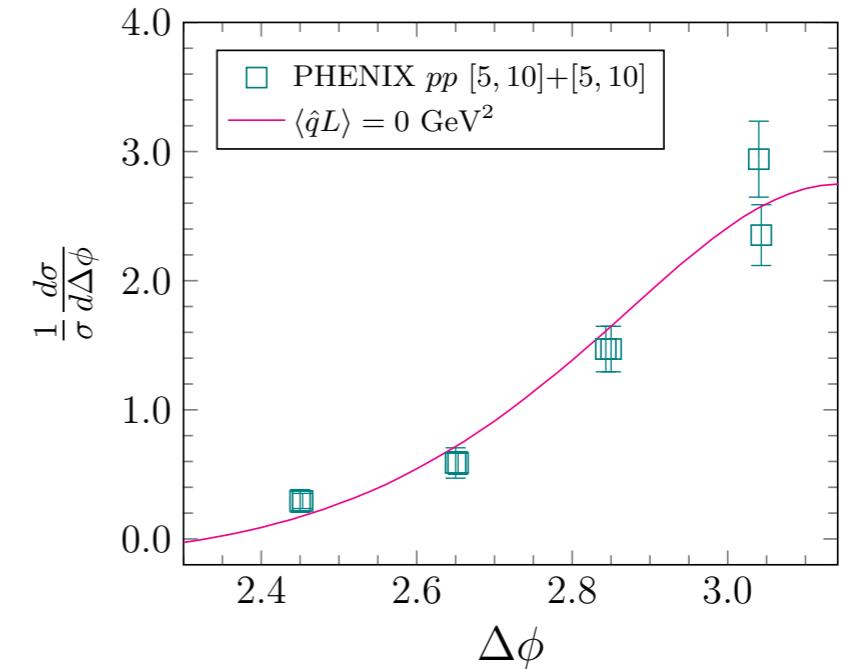
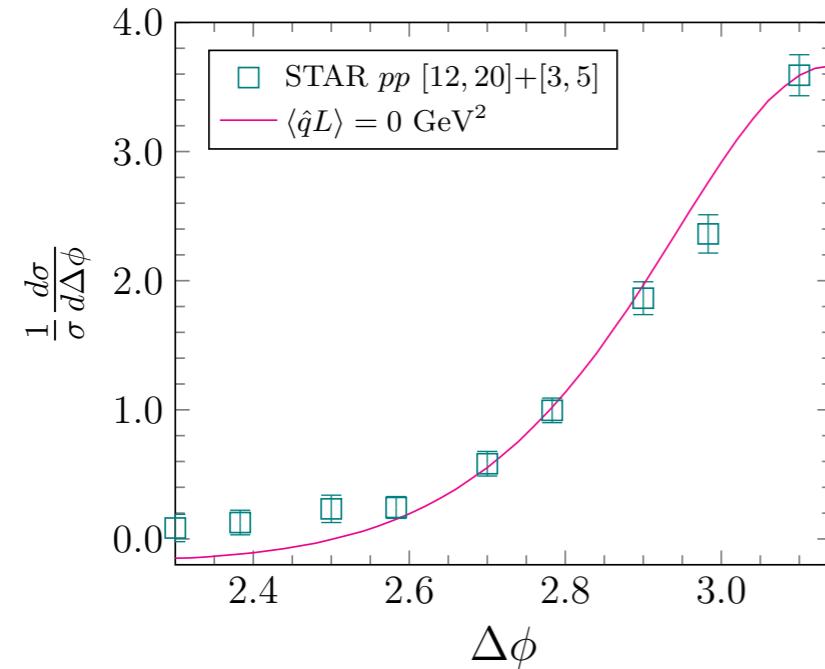
Vacuum Sudakov Effect \sim Medium Broadening Effect

Decrease the center of mass energy or measure small p_T jet.

Mueller, Wu, Xiao, Yuan, arXiv:1604.04250

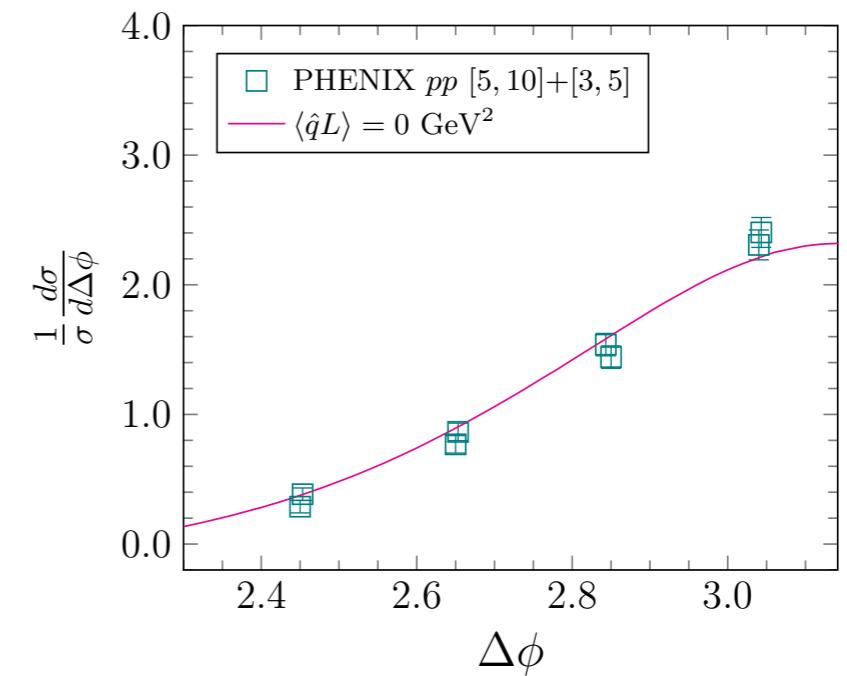
Back-to-back angular correlations

Dihadron correlations in pp - Establish Baseline



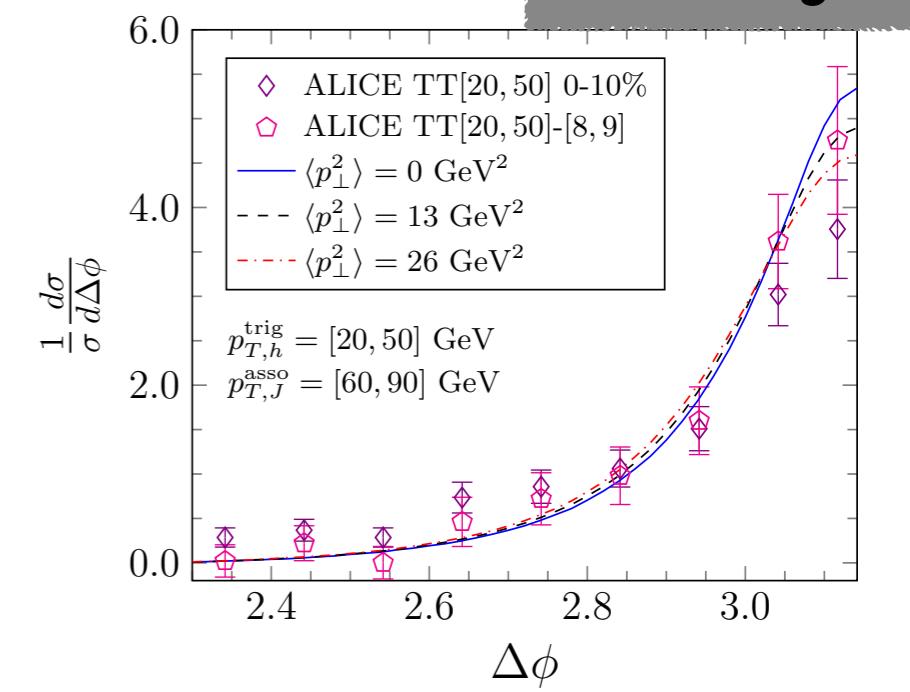
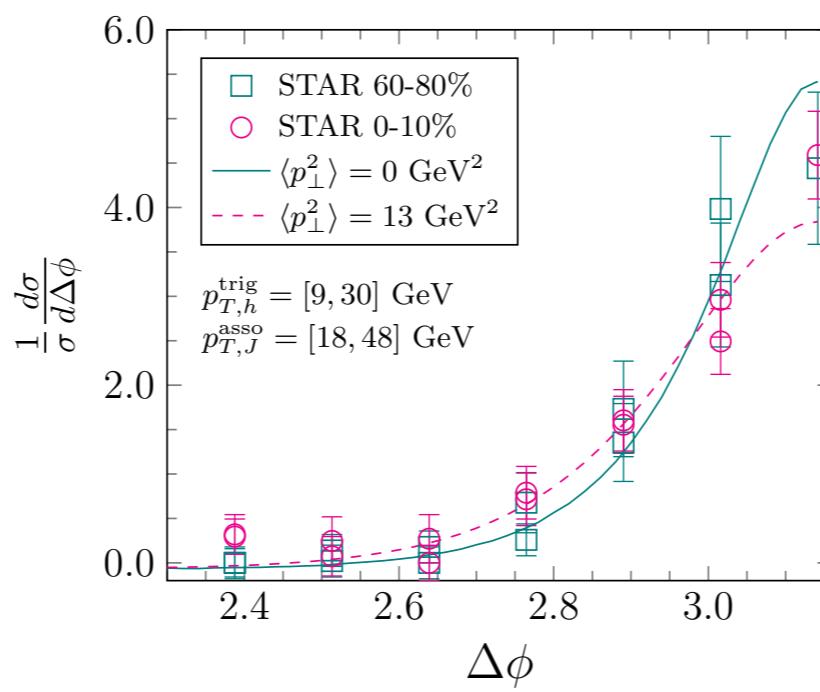
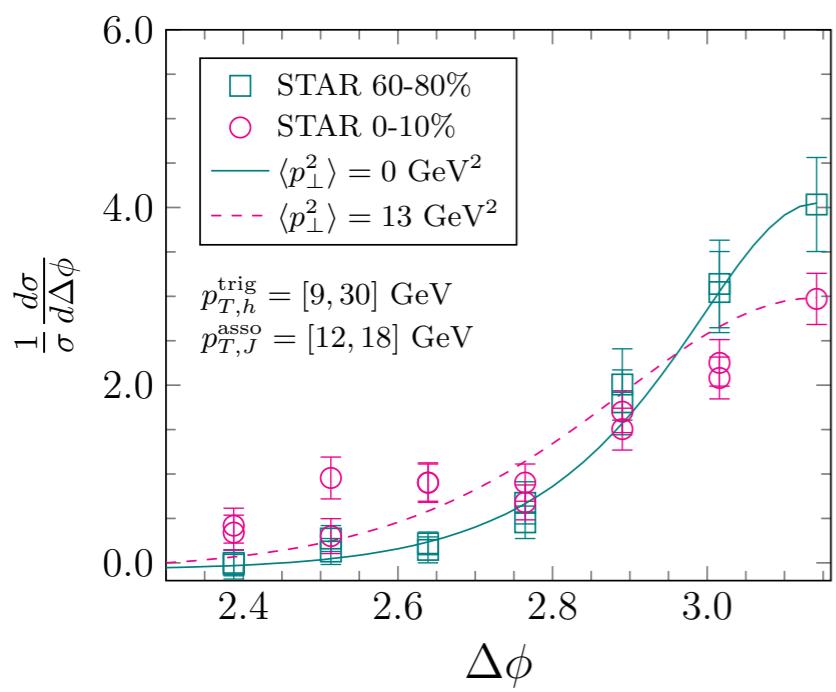
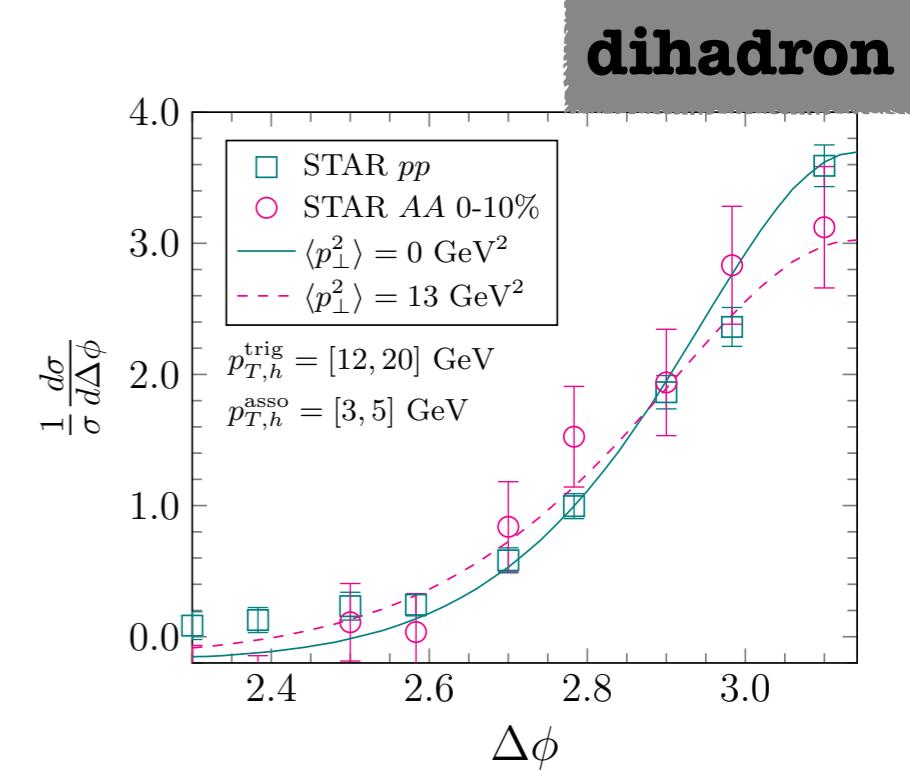
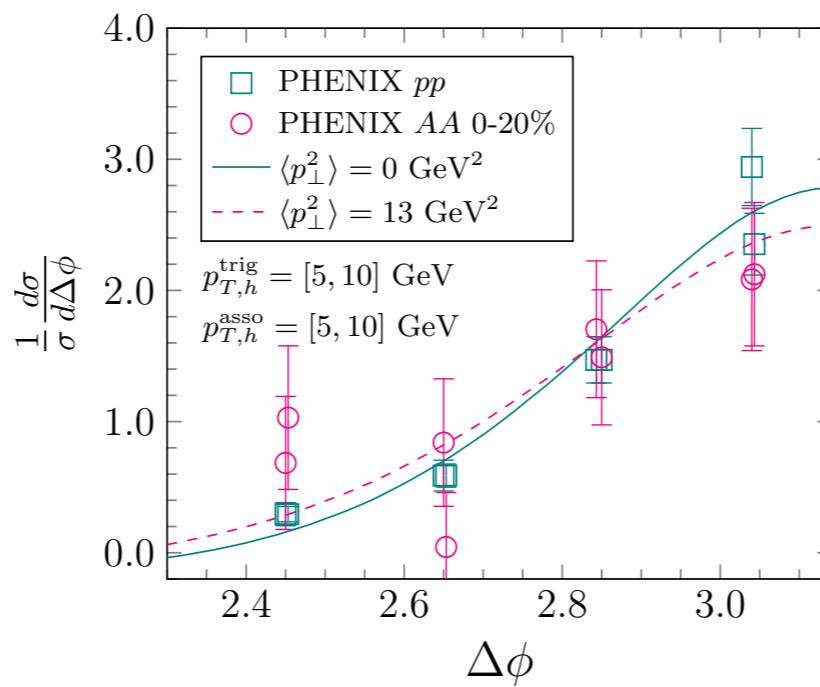
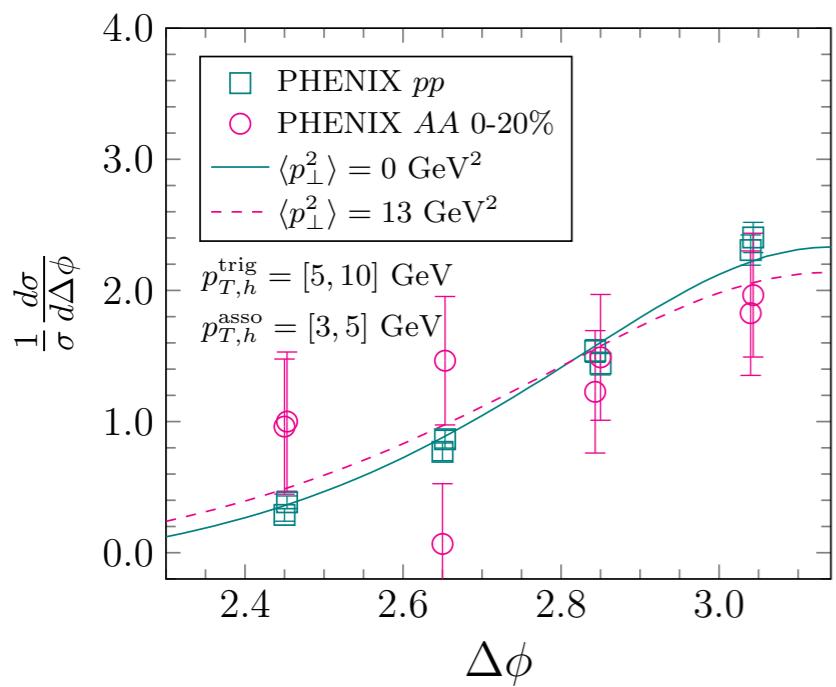
For the first time we can describe the back-to-back angular correlation.

Established a baseline to study the angular decorrelation in AA collisions.



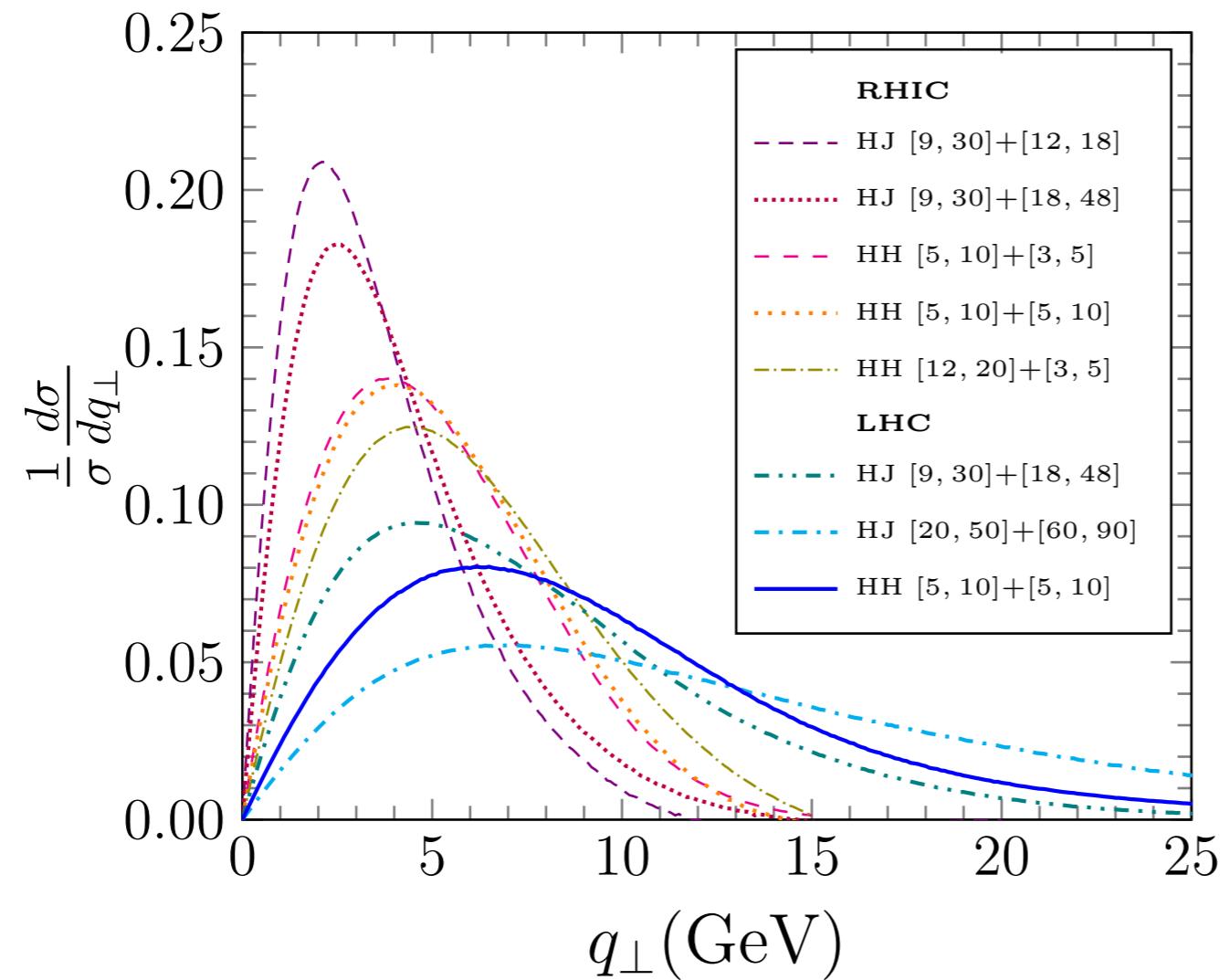
Back-to-back angular correlations

pp collisions + AA collisions



Back-to-back angular correlations

Normalized q_\perp distributions



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

Large ρ_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

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

[T₀ = 378 MeV; 1 σ; quark jet](#)

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

[JET Collaboration; 10 GeV quark jet](#)

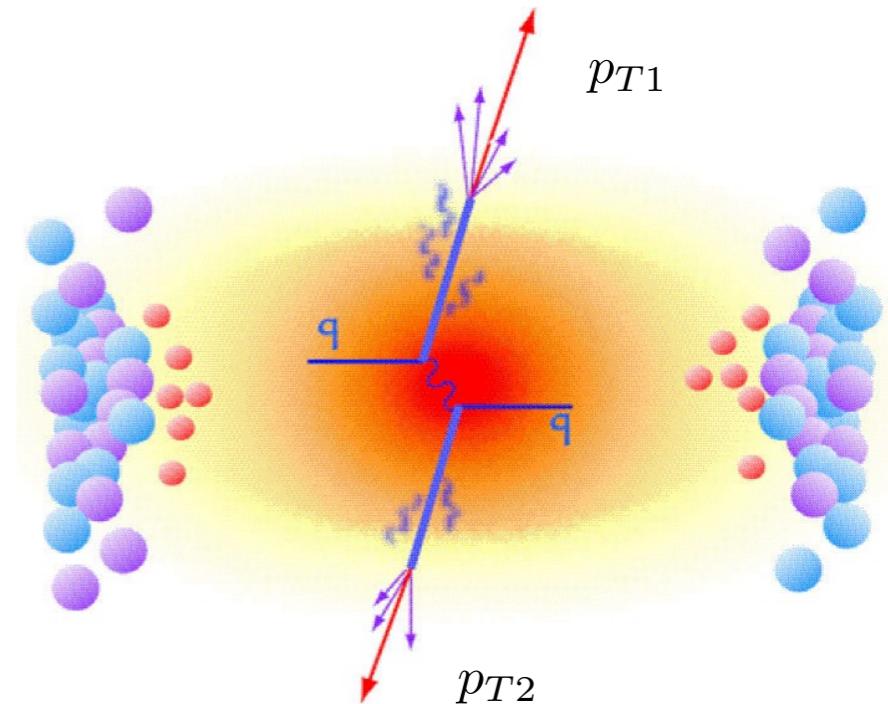
a few times larger than (not inconsistent with) that from JET collaboration.

Dijet Asymmetry

What is dijet asymmetry?

Two jets with largest transverse energy

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



Dijet asymmetry

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

$$x_J \equiv \frac{p_{T2}}{p_{T1}}$$

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

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

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

Dijet Asymmetry

First Thing: baseline in pp collisions

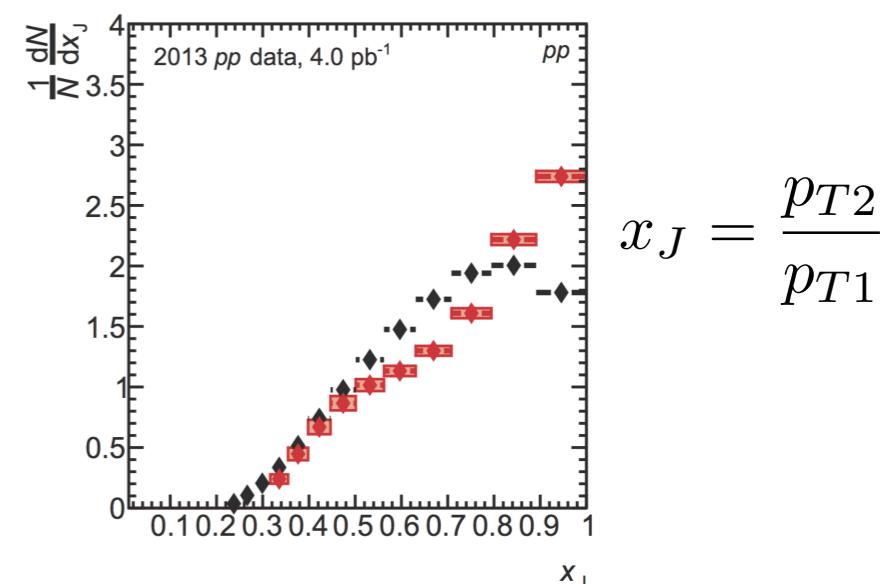
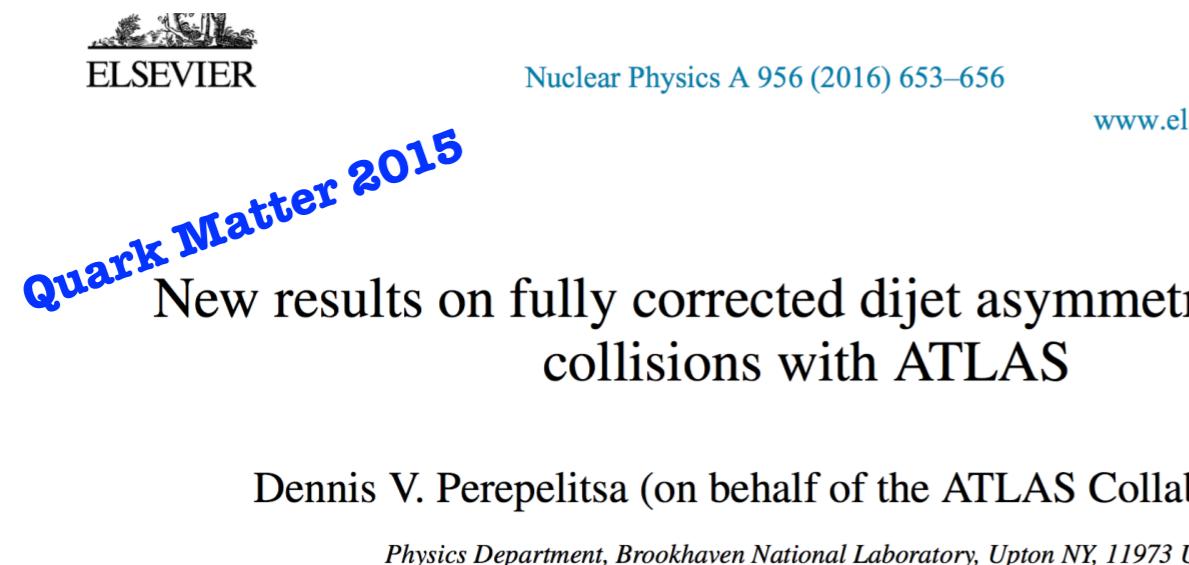
- ✓ Most of the previous theoretical studies are using Event Generators.

Pythia ...

You always have parameters to tune...

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

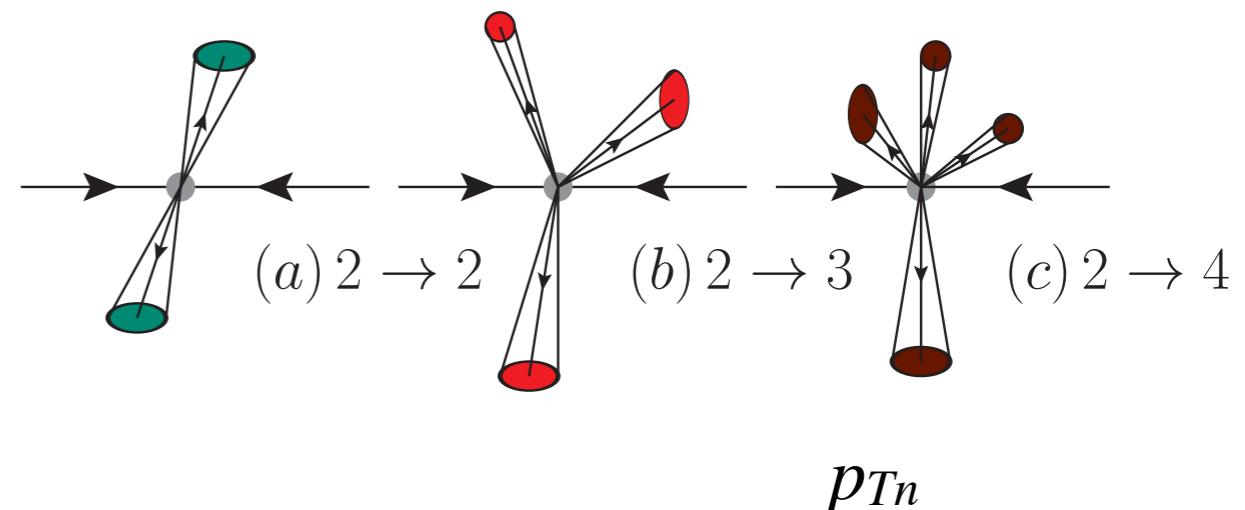
Smearing: Another parameter to make the curve look pretty.



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

Perturbative Expansion

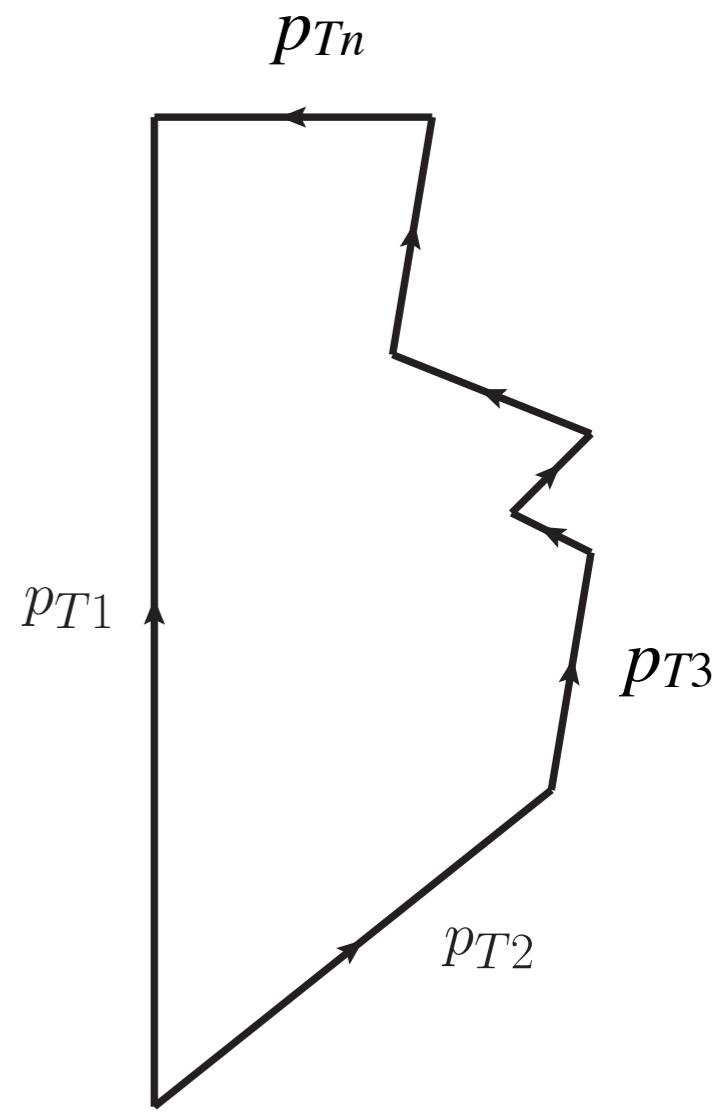
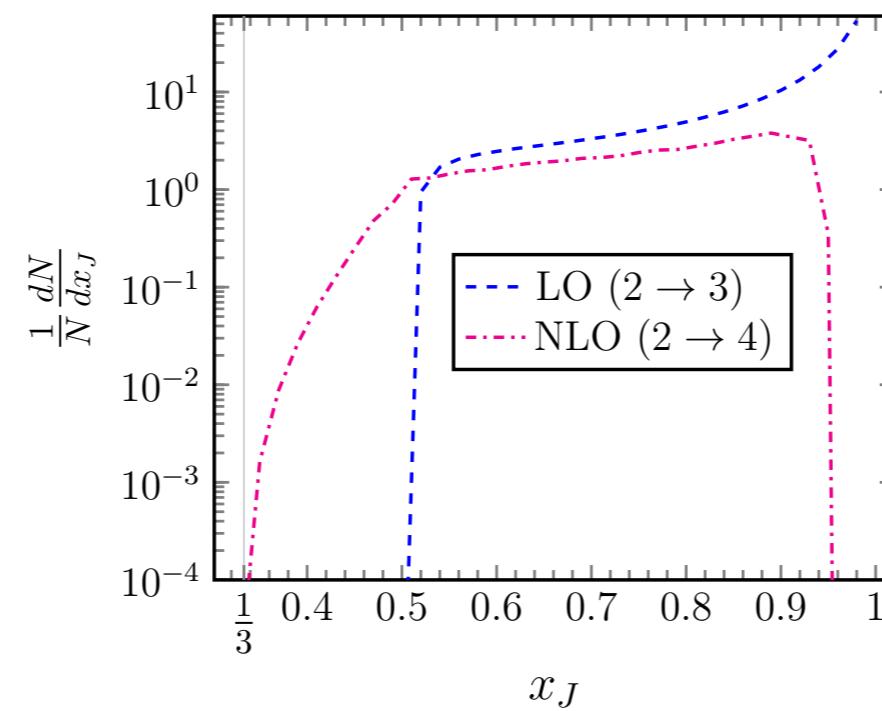
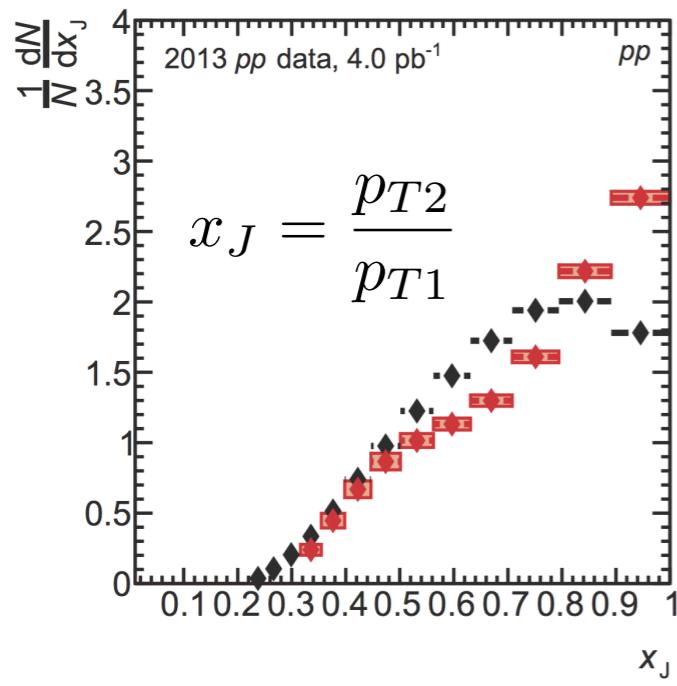
- energy conservation
- 4π coverage (no missing jet)
- leading and sub-leading jets



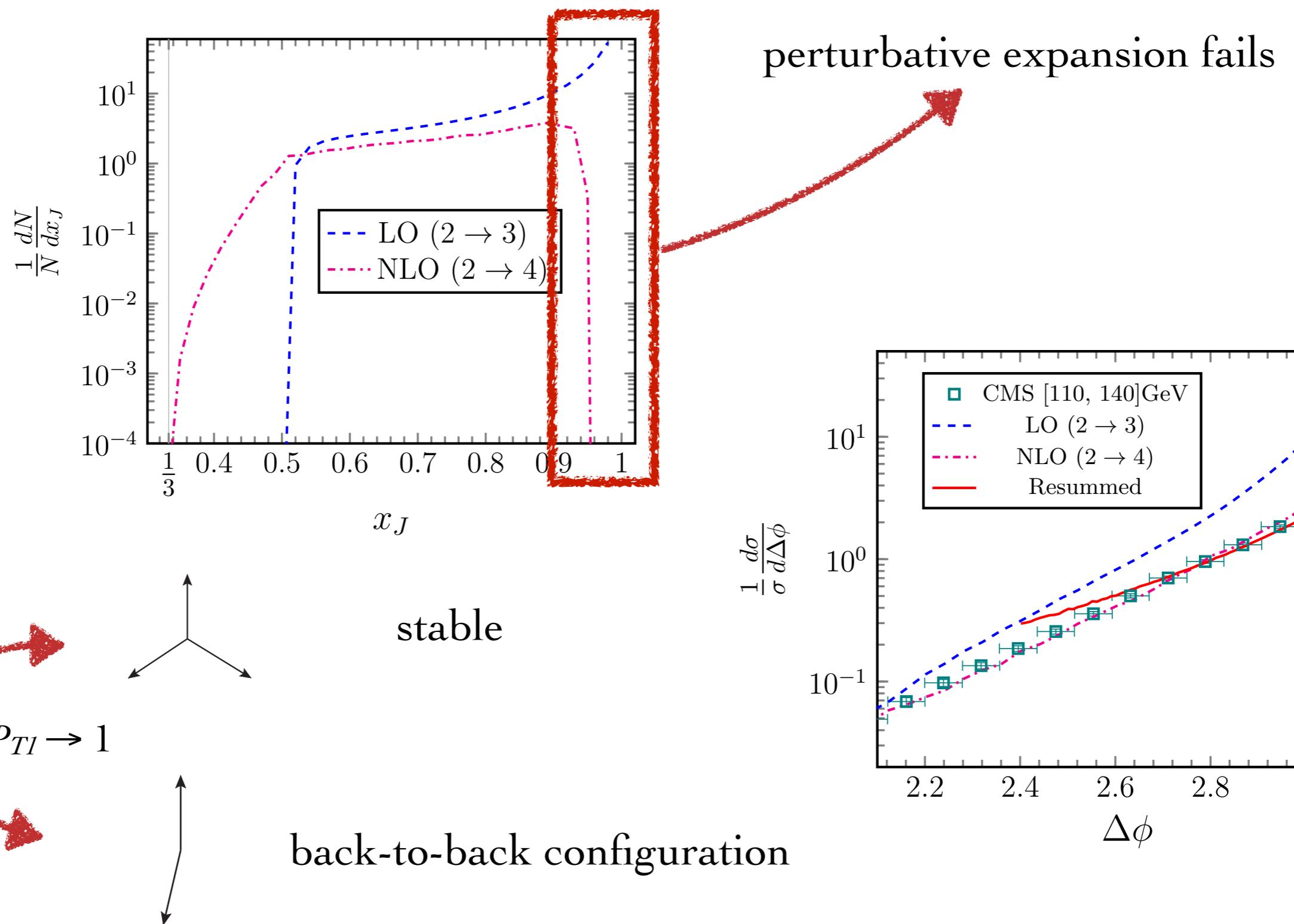
For n -jet final state

$$(n - 1)p_{T2} \geq p_{T1}$$

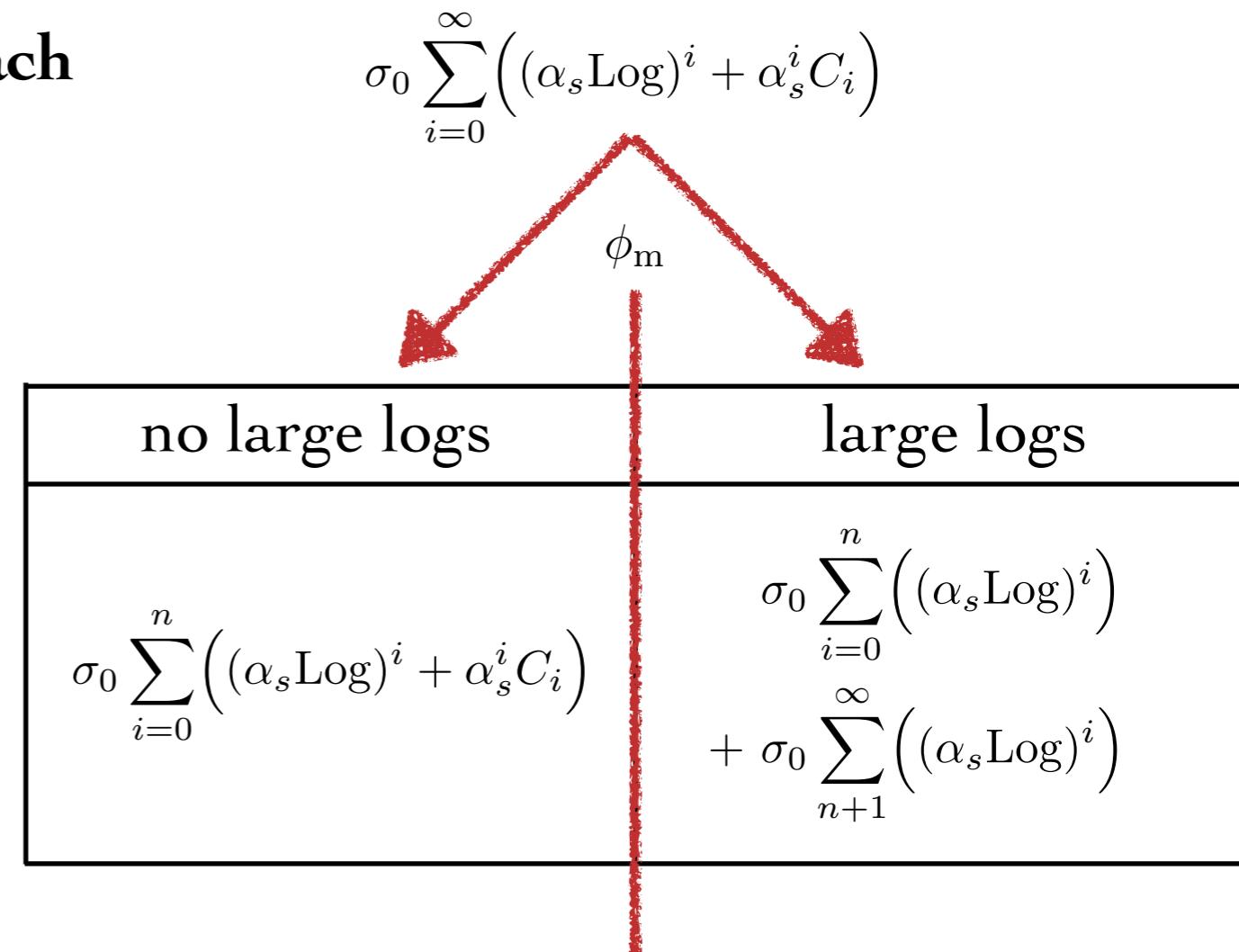
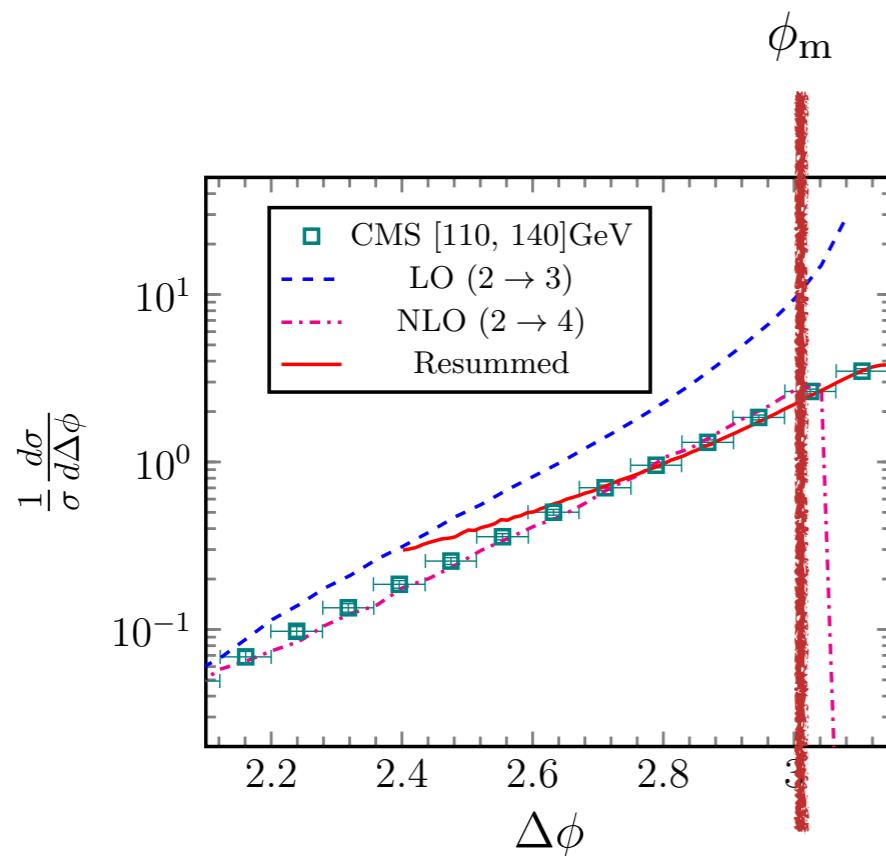
$$x_J^{2 \rightarrow n} \geq \frac{1}{n - 1}$$



Perturbative Expansion



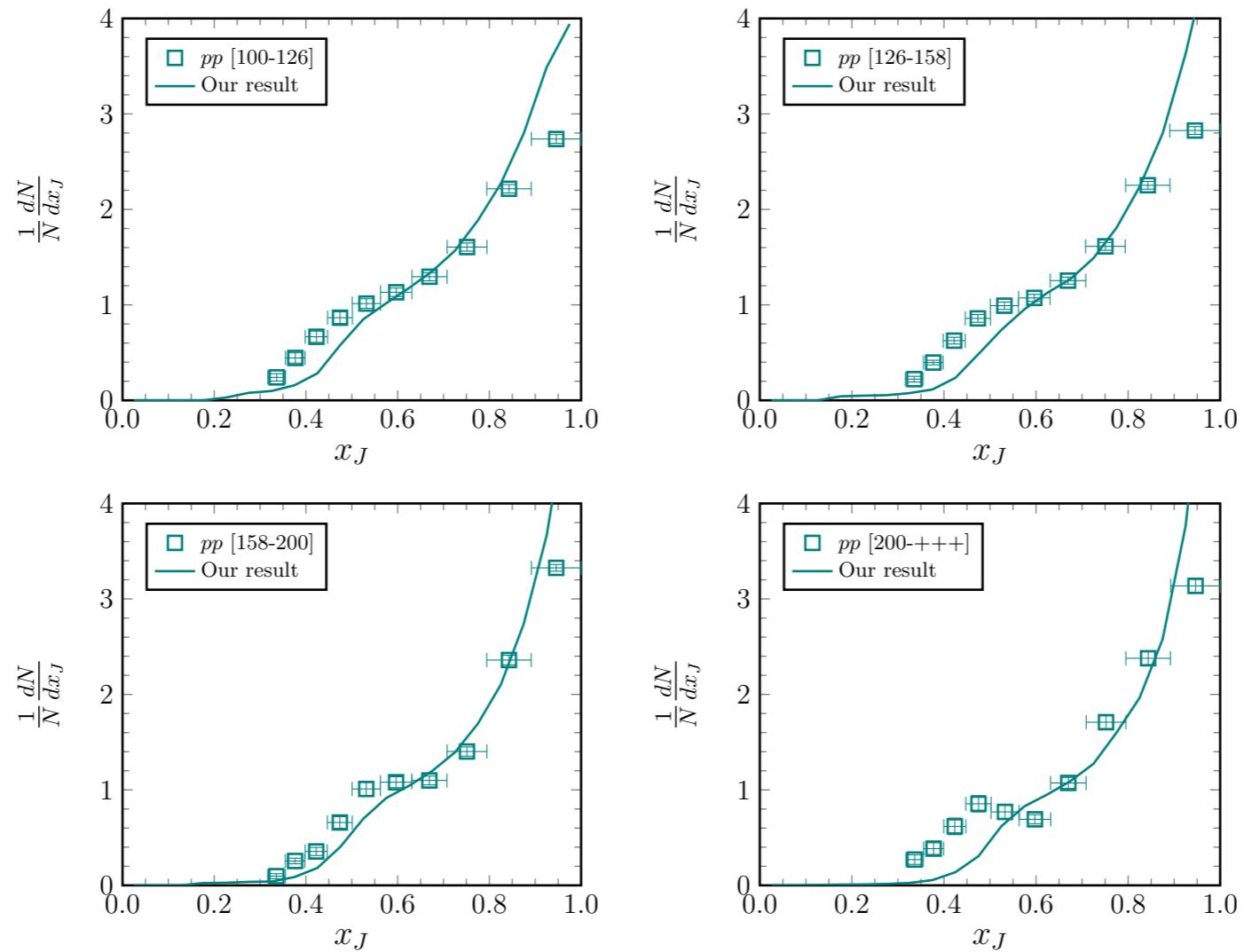
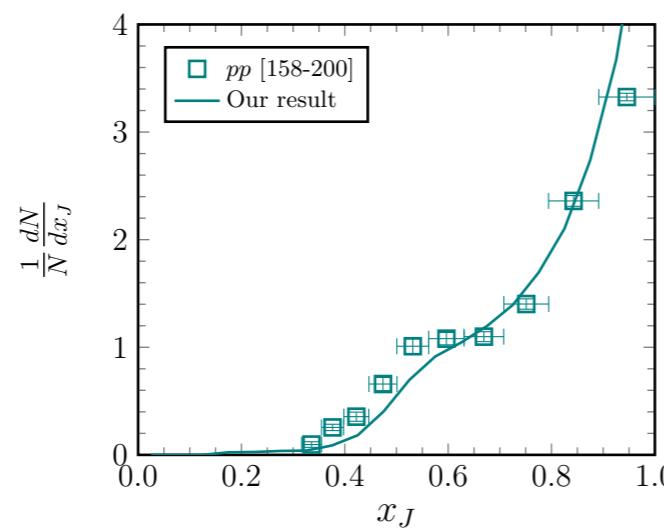
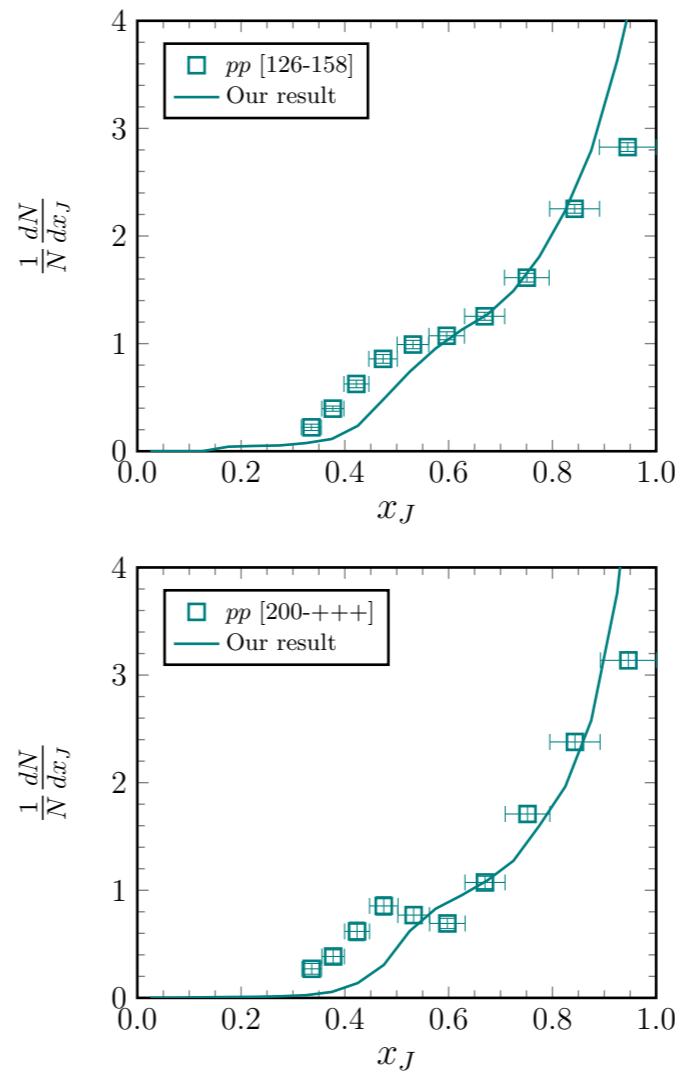
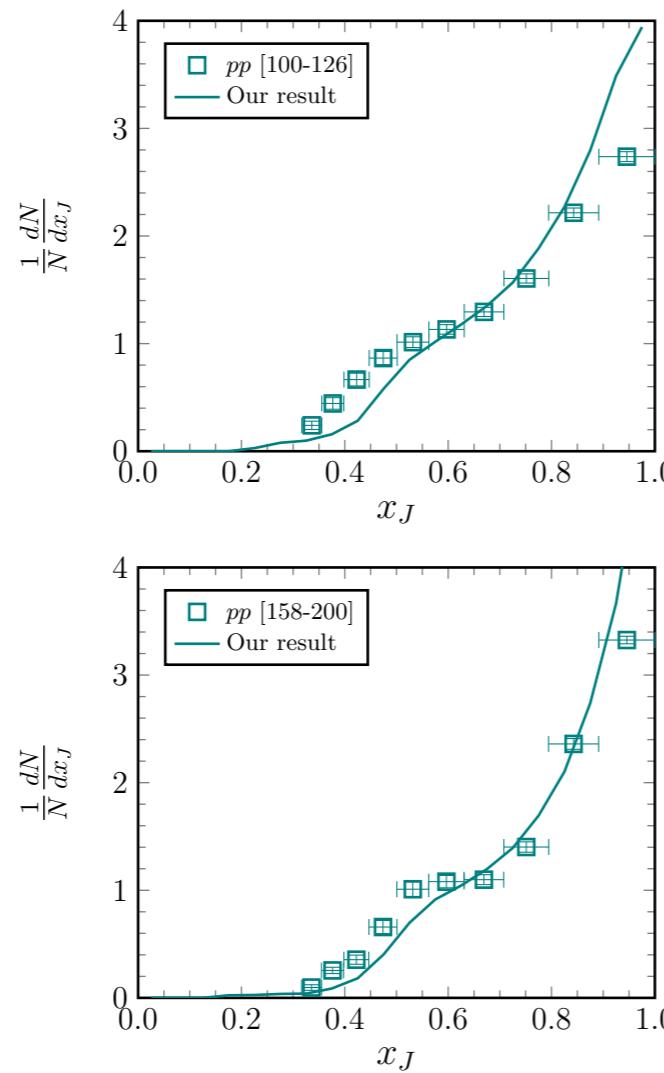
Resummation Improved pQCD approach



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

- 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



$$x_J = \frac{p_{T2}}{p_{T1}}$$

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

Dijet Asymmetry in PbPb Collisions

BDMPS formalism

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

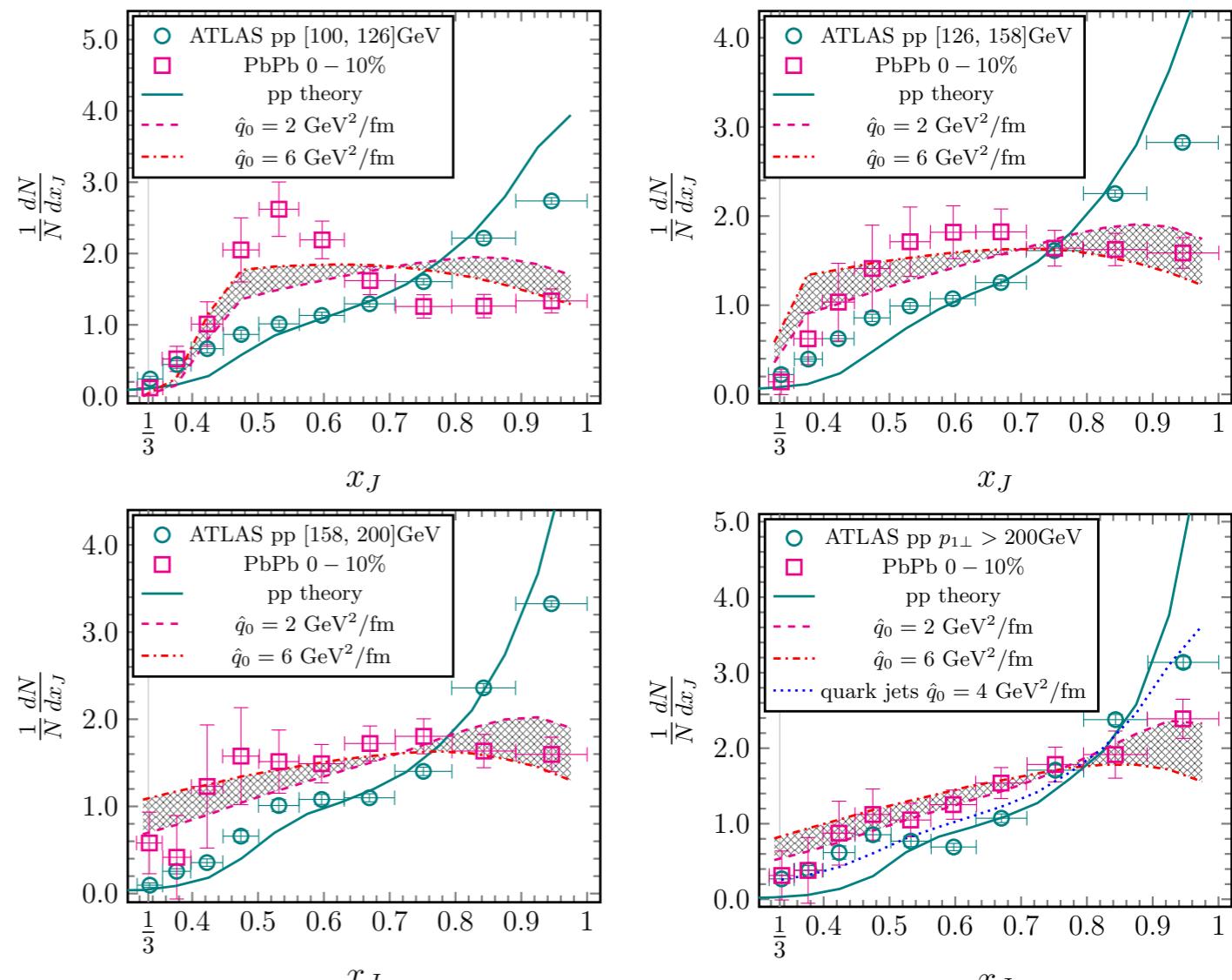
$$\omega_c \equiv \int dL \hat{q}L \quad \alpha \equiv \frac{2\alpha_s C_R}{\pi}$$

Probability for a jet to lose energy ϵ

Results:

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

$$x_J = \frac{p_{T2}}{p_{T1}}$$



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

[hep-ph/9608322](https://arxiv.org/abs/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 $\hat{q}_0 = 3.9^{+1.5}_{-1.2} \text{ GeV}^2/\text{fm}$ for a quark jet at $T_0 = 378 \text{ MeV}$.

Dijet Asymmetry

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

Thank you very much for your attention!

The End