

Jet quenching in high-energy nuclear collisions

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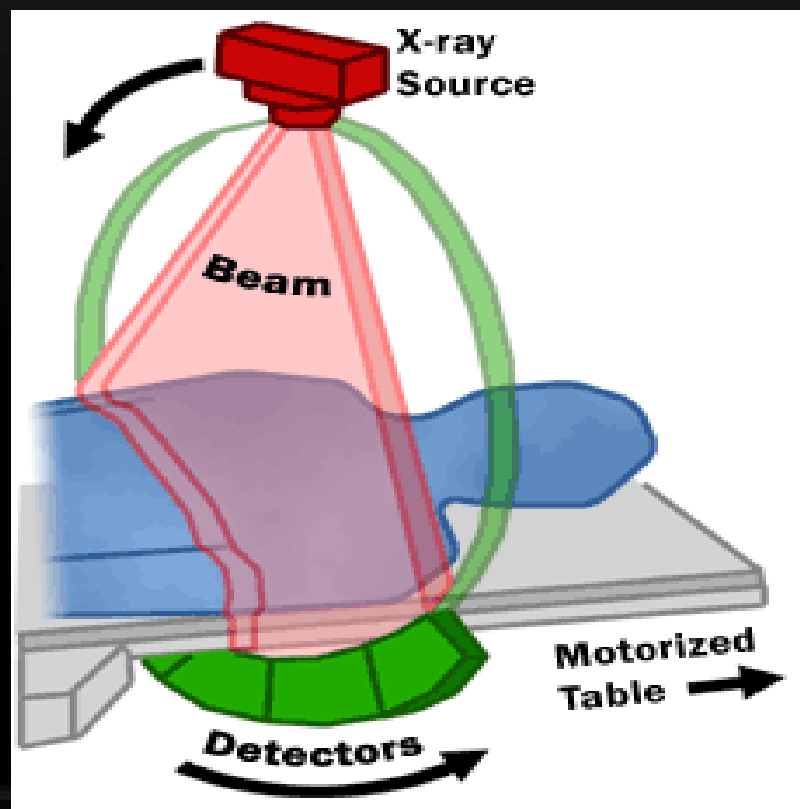
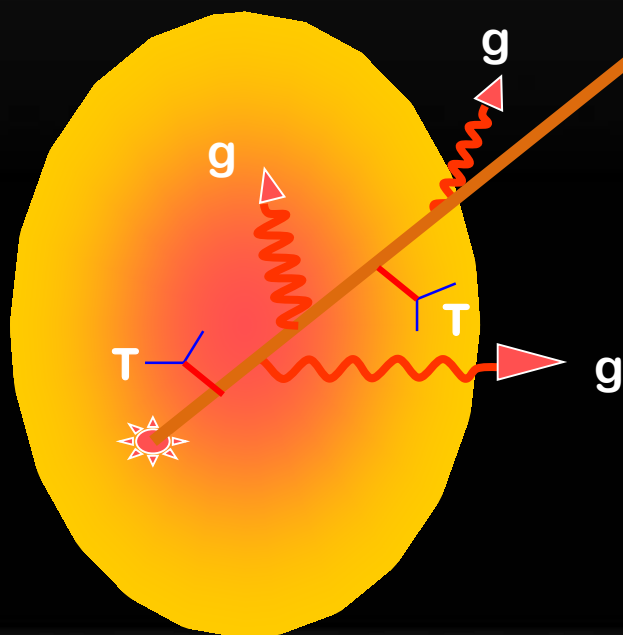
Outline

- Introduction
- Leading hadron productions
- Full jet observables
 - 1) Gauge boson tagged jets
 - 2) Double b-jet
 - 3) Z + b-jet
 - 4) Transverse sphericity
- Summary

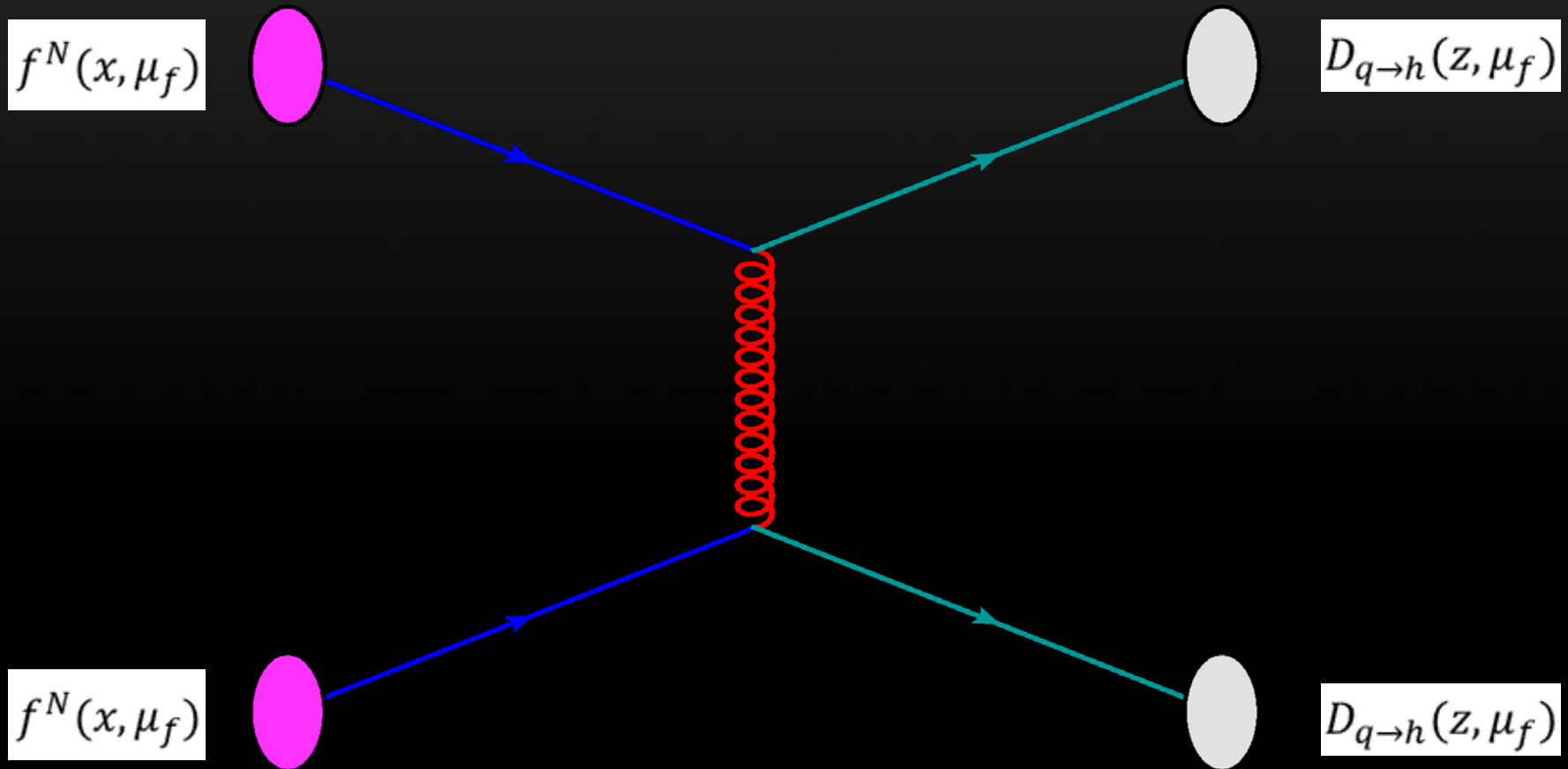
Jet quenching

Parton energy has been proposed as an excellent probe of the hot/dense matter created in HIC.

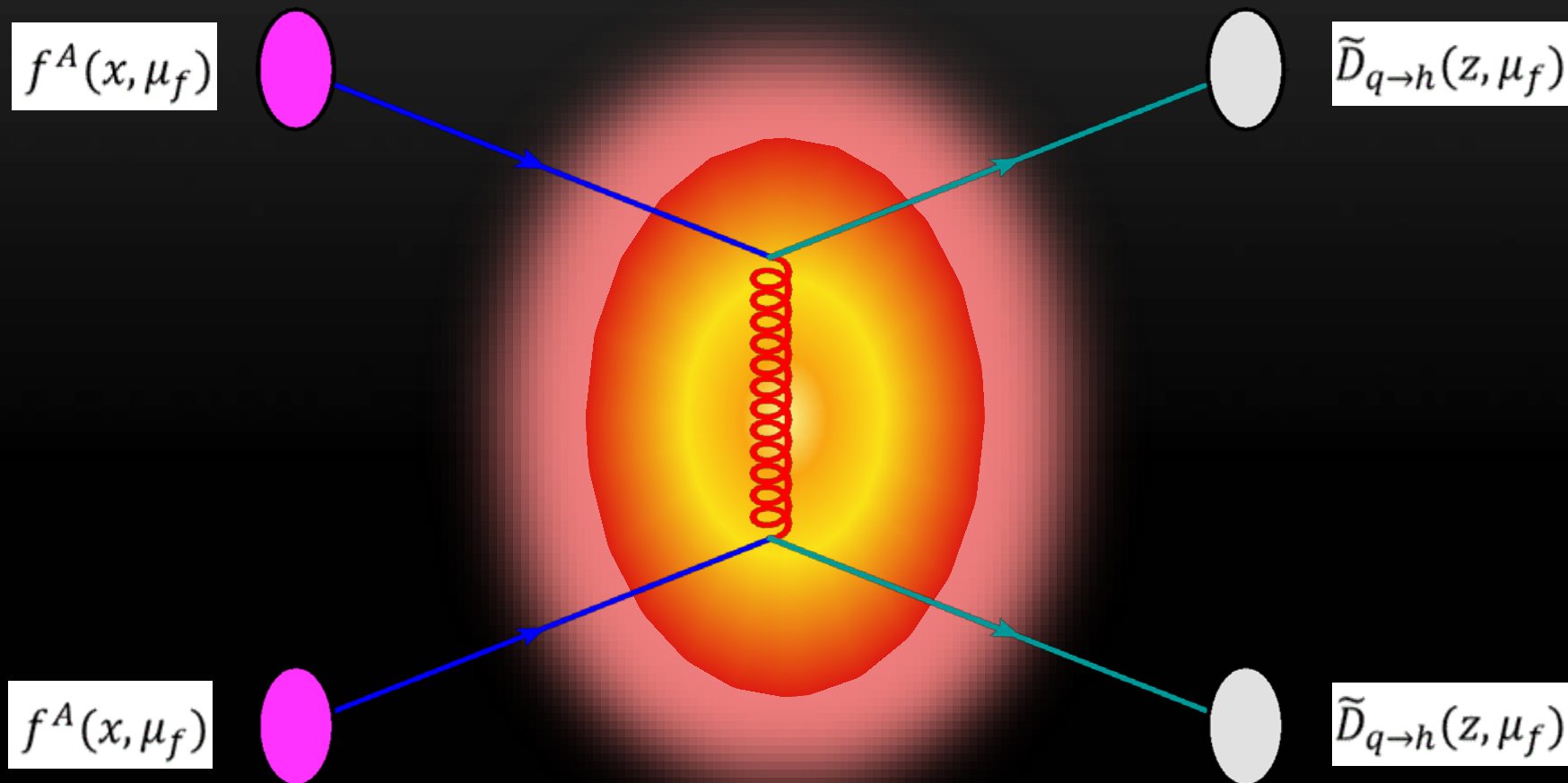
Single Hadron Tomography



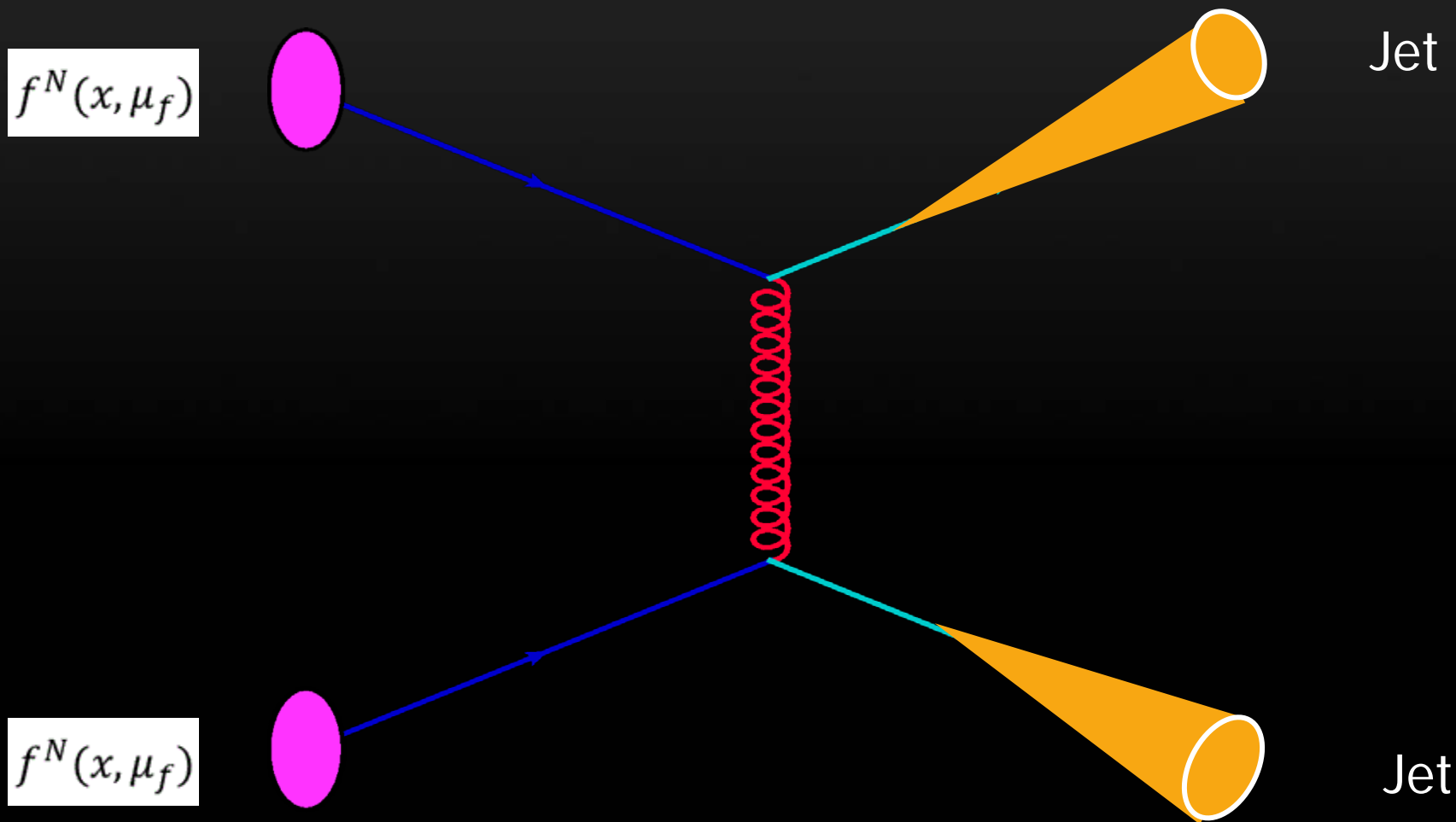
Leading hadron production



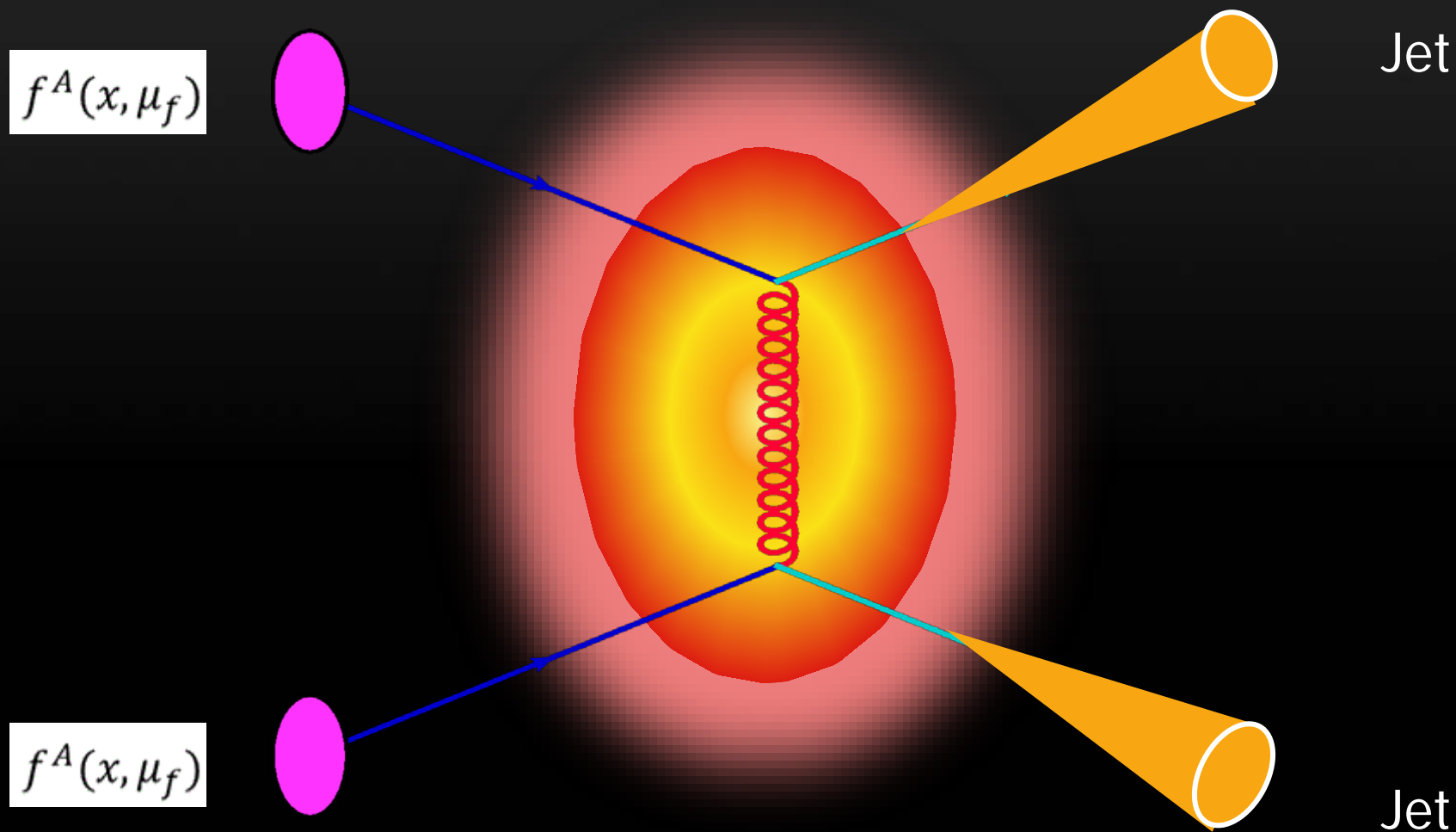
Leading hadron production



Full jets



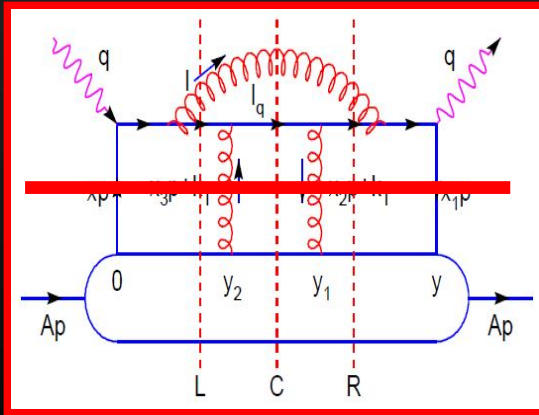
Full jets



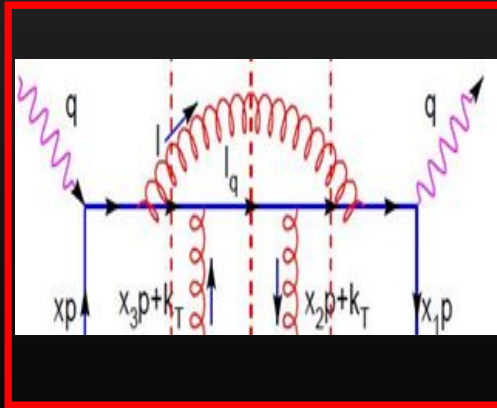
Large p_T hadrons in HIC

Jet quenching with higher twist approach

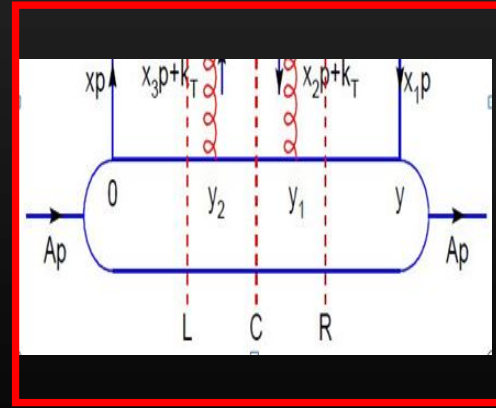
The parton energy loss due to medium-induced gluon radiation has been calculated with higher twist approach.



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⊗



$$\begin{aligned} \tilde{D}_{q \rightarrow h}(z_h, \mu^2) &\equiv D_{q \rightarrow h}(z_h, \mu^2) + \int_0^{\mu^2} \frac{d\ell_T^2}{\ell_T^2} \frac{\alpha_s}{2\pi} \int_{z_h}^1 \frac{dz}{z} [\Delta\gamma_{q \rightarrow qg}(z, x, x_L, \ell_T^2) D_{q \rightarrow h}(z_h/z) \\ &+ \Delta\gamma_{q \rightarrow gq}(z, x, x_L, \ell_T^2) D_{g \rightarrow h}(z_h/z)] , \end{aligned}$$

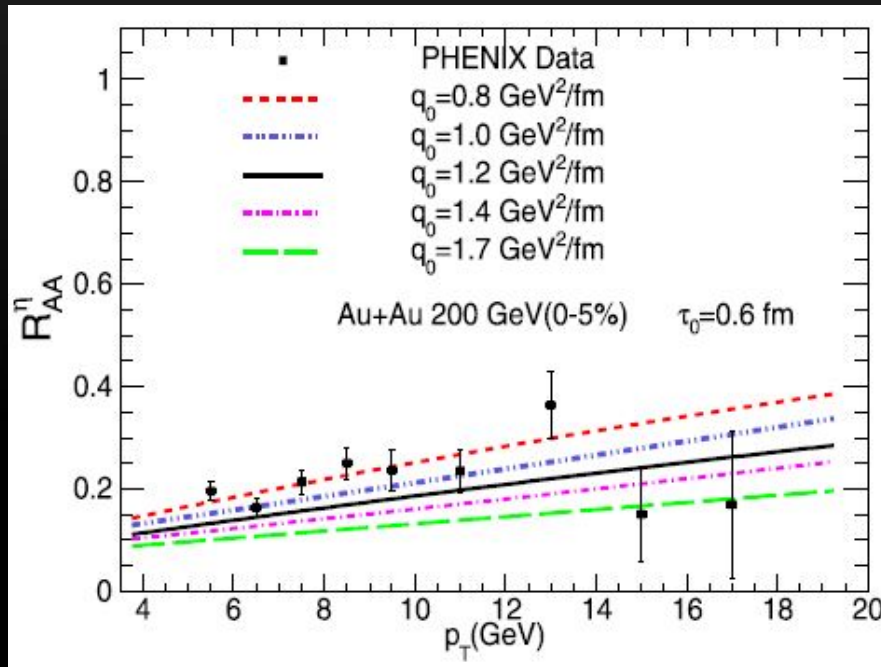
$$\begin{aligned} \frac{1}{N_{\text{bin}}^{AB}(b)} \frac{d\sigma_{AB}^h}{dy d^2p_T} &= \sum_{abcd} \int dx_a dx_b f_{a/A}(x_a, \mu^2) f_{b/B}(x_b, \mu^2) \\ &\times \frac{d\sigma}{d\hat{t}}(ab \rightarrow cd) \frac{\langle \tilde{D}_c^h(z_h, Q^2, E, b) \rangle}{\pi z_c} + \mathcal{O}(\alpha_s^3). \end{aligned}$$

X Guo, X N Wang, PRL(2001); X Guo, X N Wang, NPA (2001);
BWZ, X N Wang, NPA(2003) ; BWZ, E Wang, X N Wang, PRL (2004)

η in heavy-ion collisions at NLO

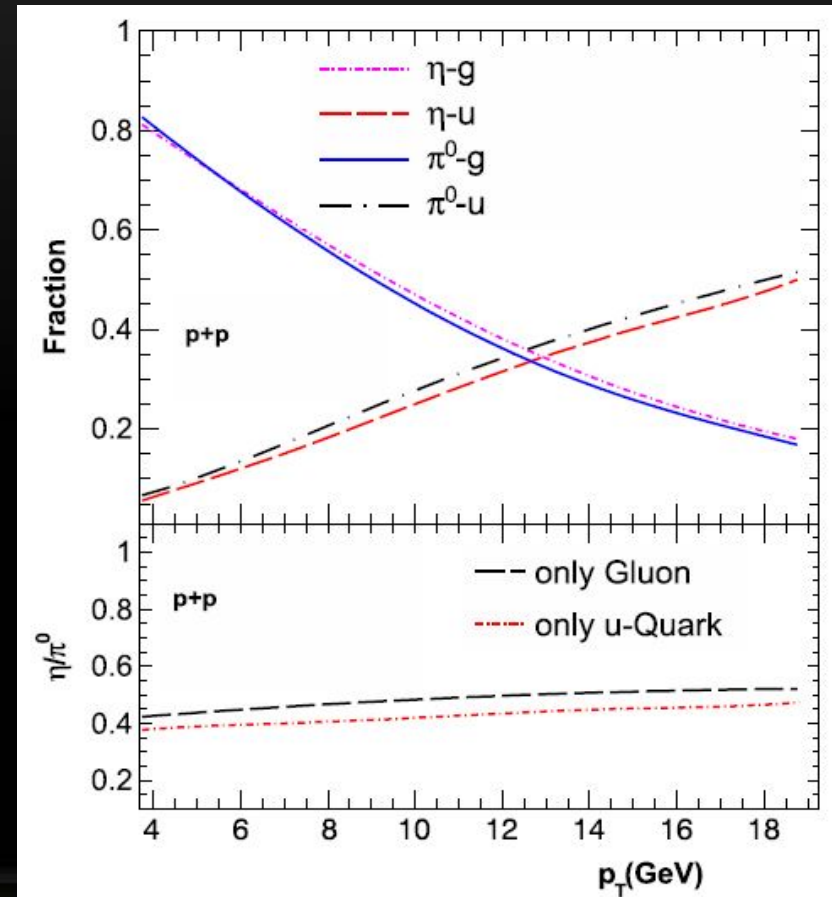
- Production of eta meson in HIC has been calculated;
- Flavor composition has very small effect on the ratio η/π^0 .

$$(dE/dx)_{\text{rad}} = -C_2 \hat{q} L$$



$$G^{\eta, \pi^0}(p_T) = \frac{\int f_g(\frac{p_T}{z_h}) \cdot D_{g \rightarrow \eta, \pi^0}(z_h, p_T) \frac{dz_h}{z_h^2}}{\frac{1}{p_T} \frac{d\sigma_{\pi^0, \eta}}{dp_T}}$$

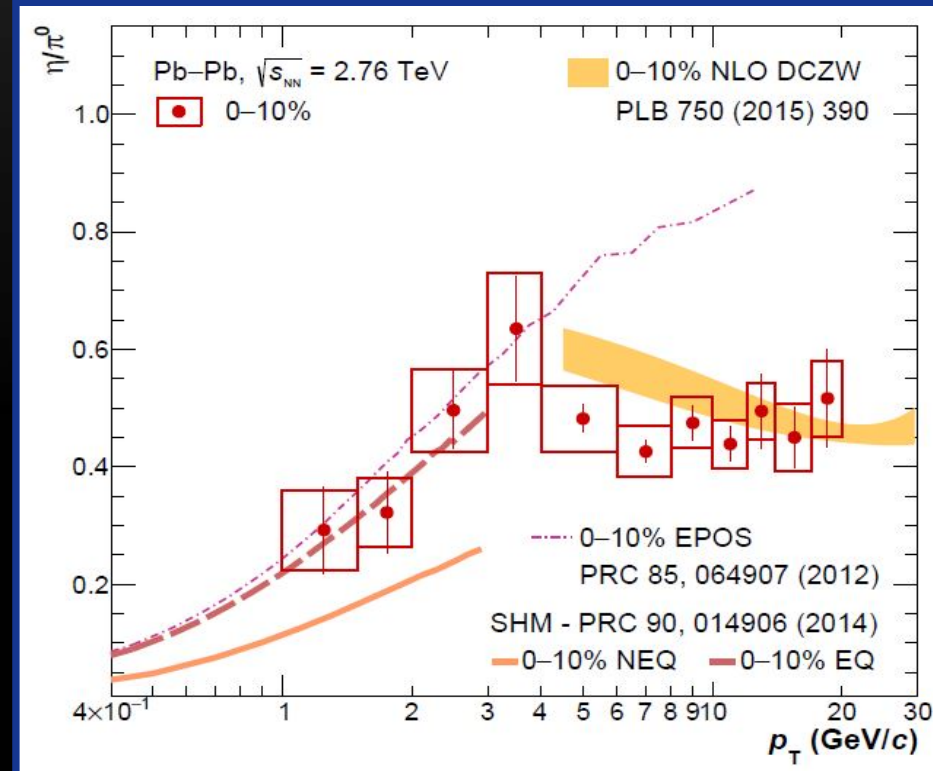
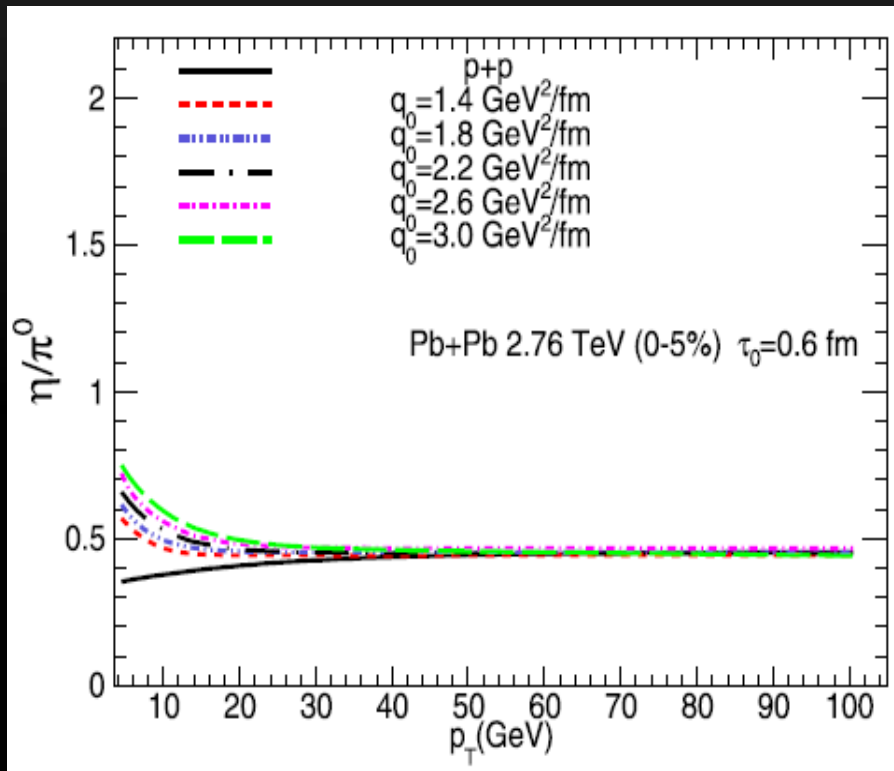
$$G^{\pi^0}(p_T) \approx G^{\eta}(p_T)$$



η/π^0 in HIC at NLO

11

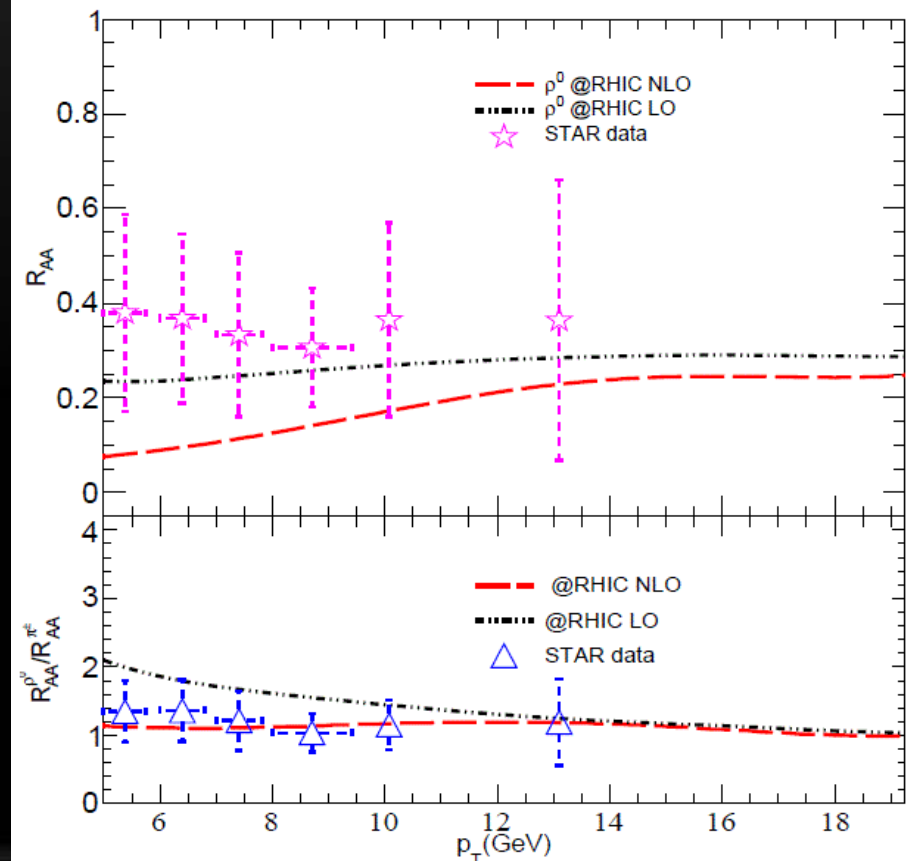
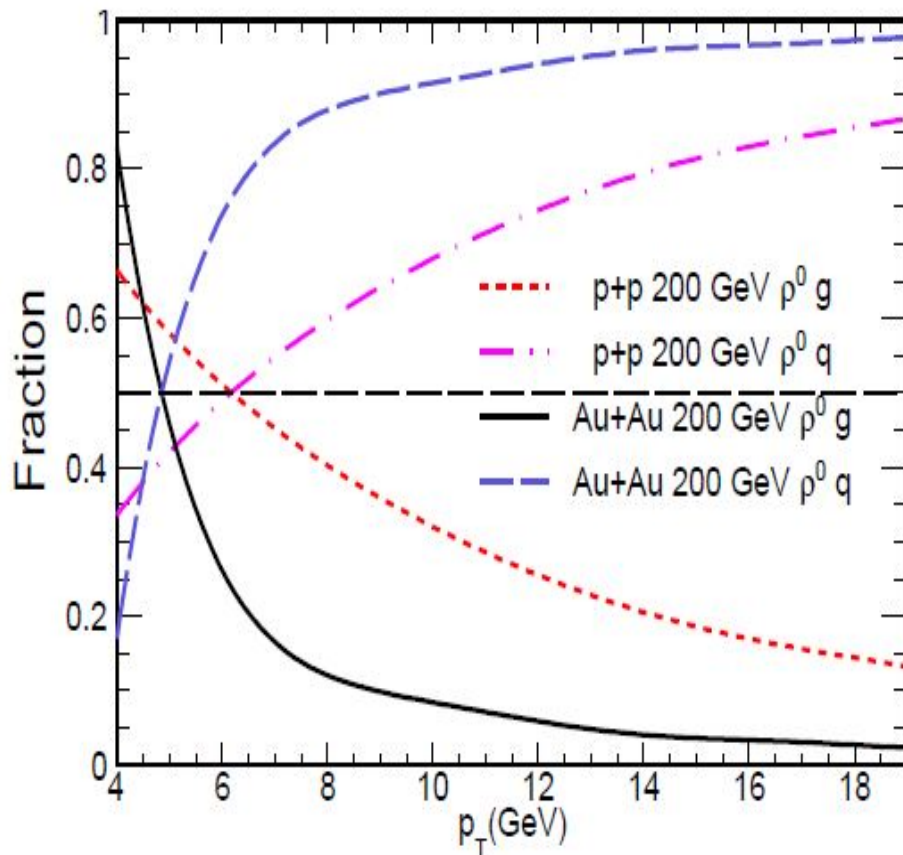
- η/π^0 ratio is almost same (~ 0.5) for p+p, Au+Au and Pb+Pb collision.
- Prediction on η/π^0 ratio has been confirmed by ALICE.



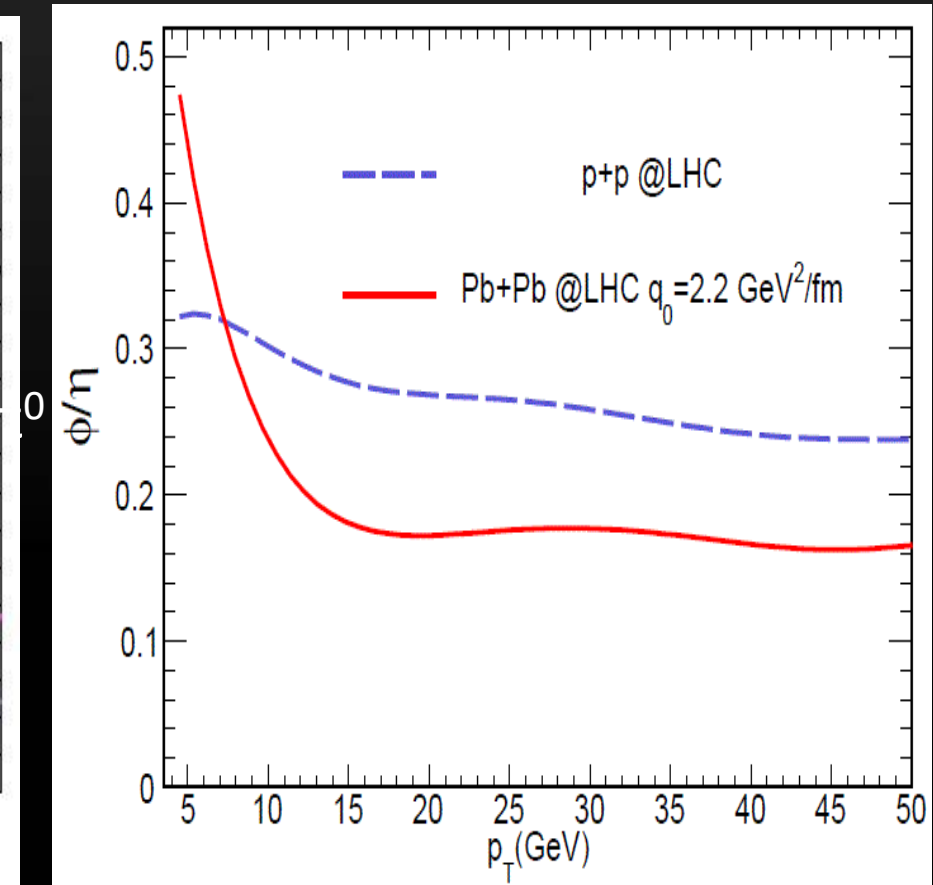
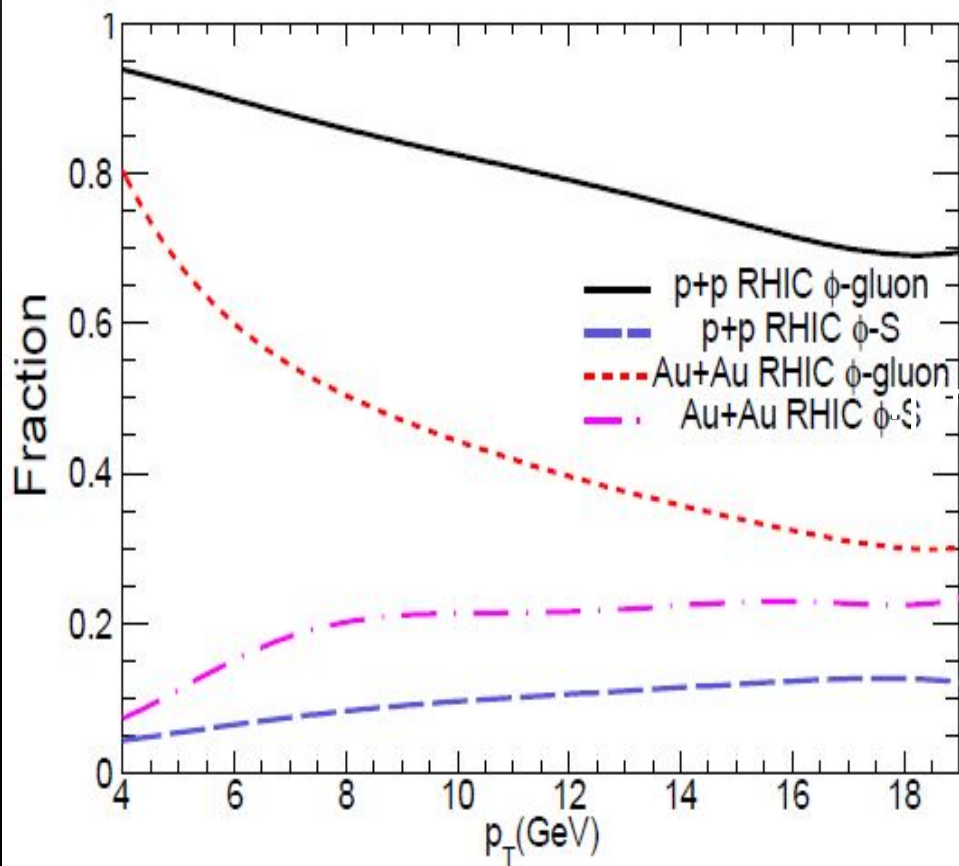
ALICE, arXiv: 1803.05490

ρ production in A+A at NLO

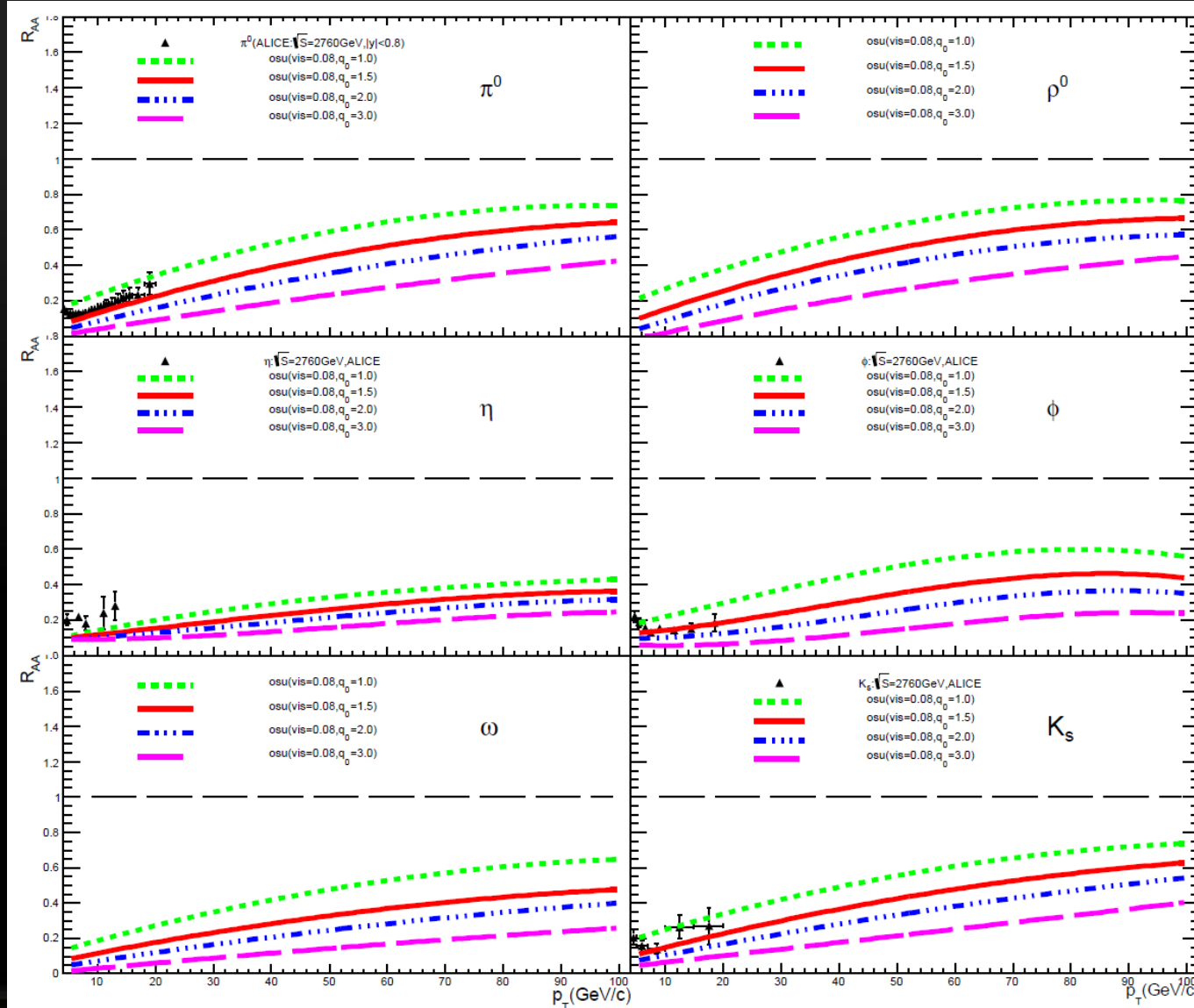
- A broken SU(3) model has been utilized to get ρ FFs in p+p.
- Dominant contributions of quark fragmentations both in p+p and in A+A.



Production of ϕ in HIC at NLO

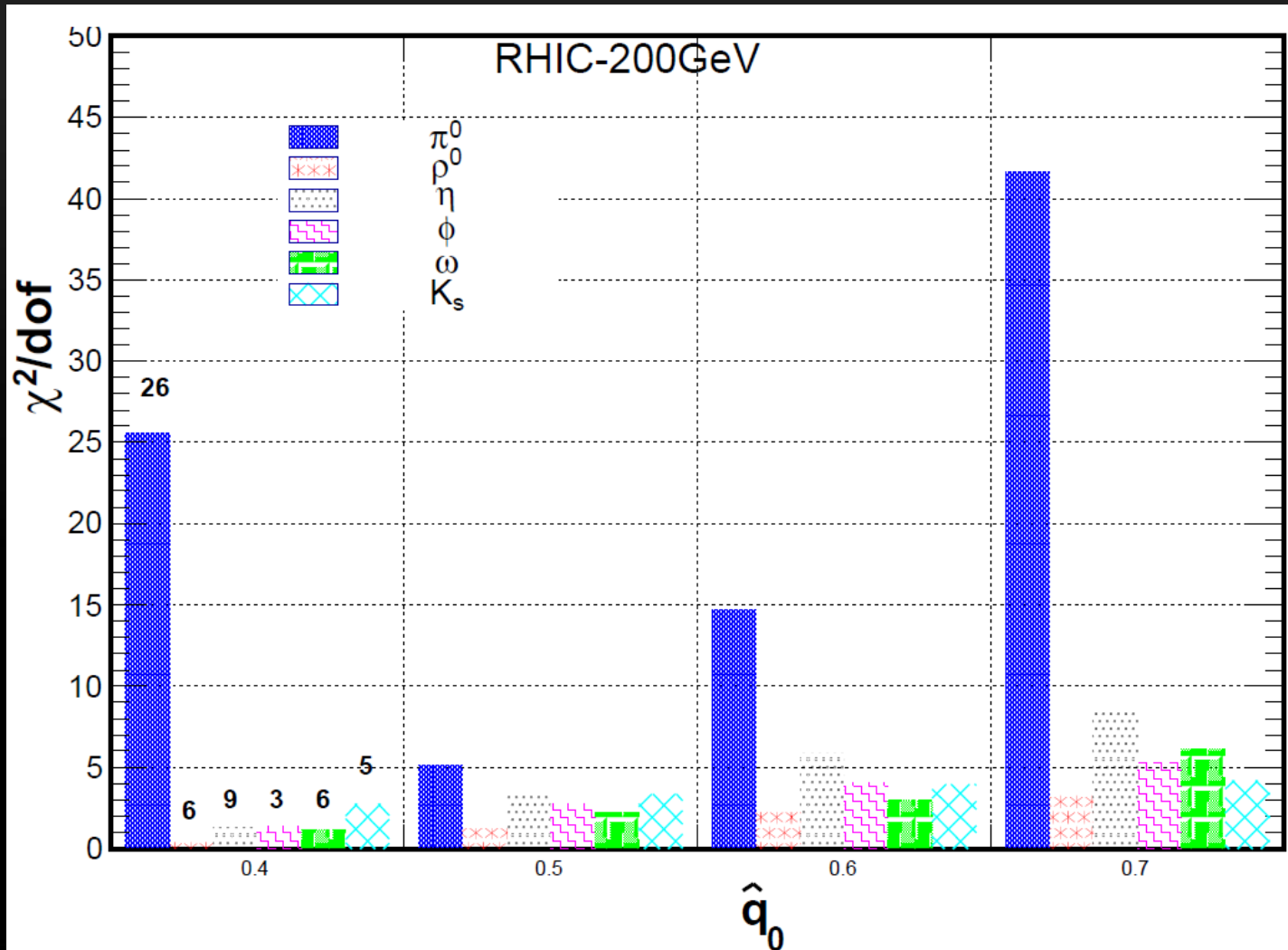


Identified mesons in HIC at NLO

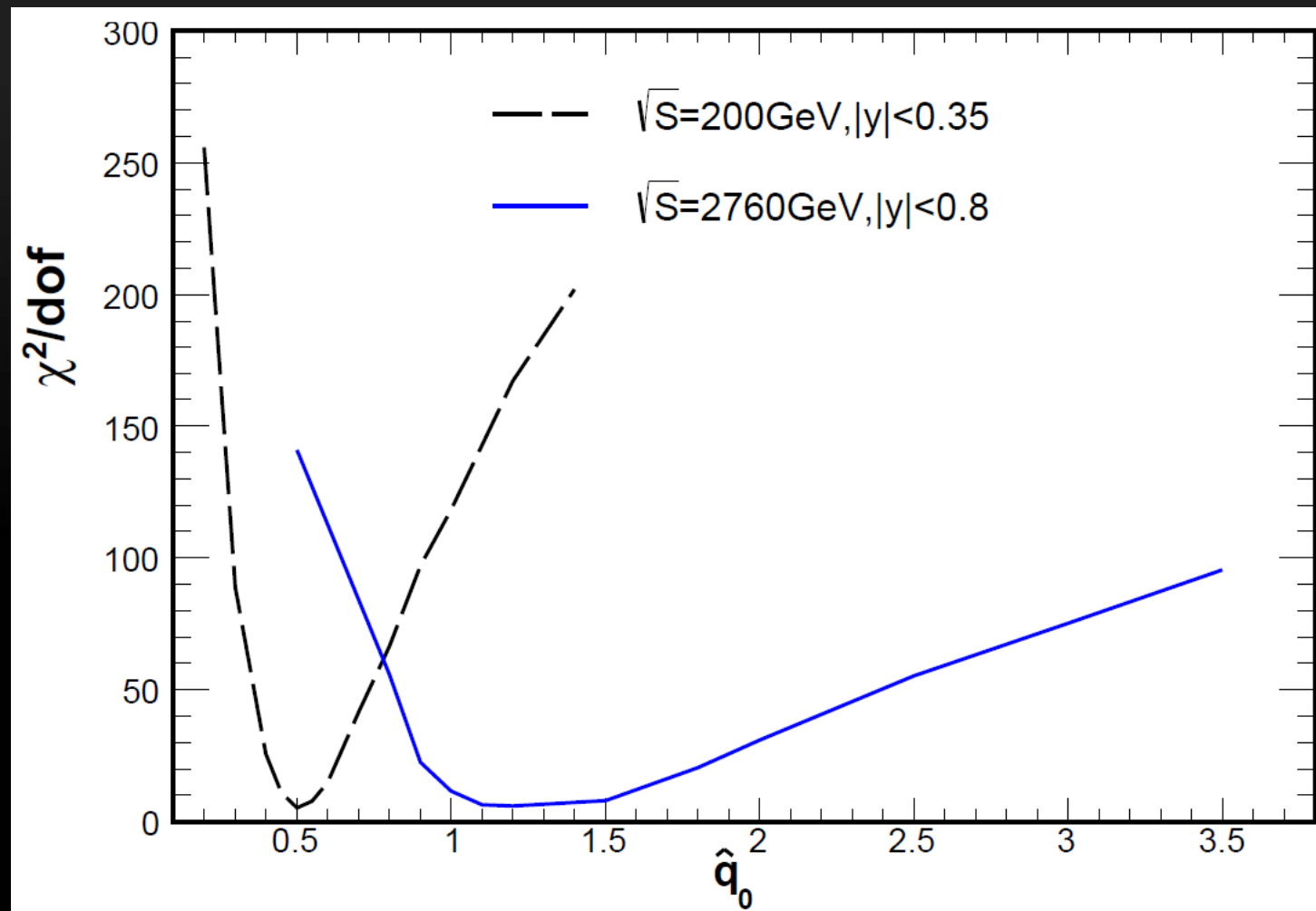


iEBE-VISHNU
hydro

Global extraction of \hat{q}

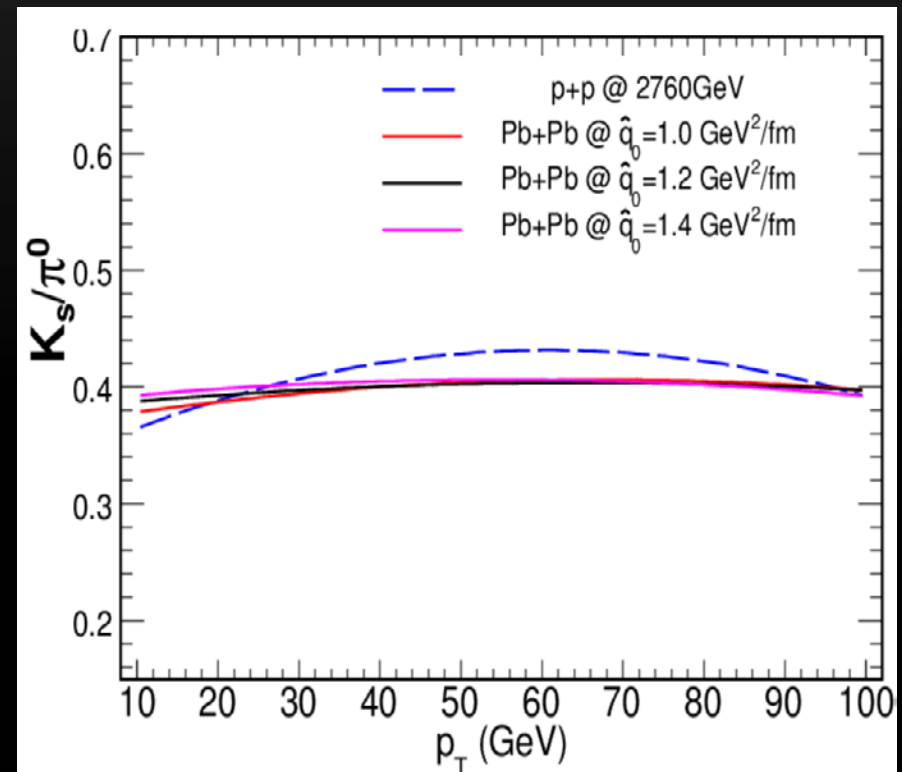
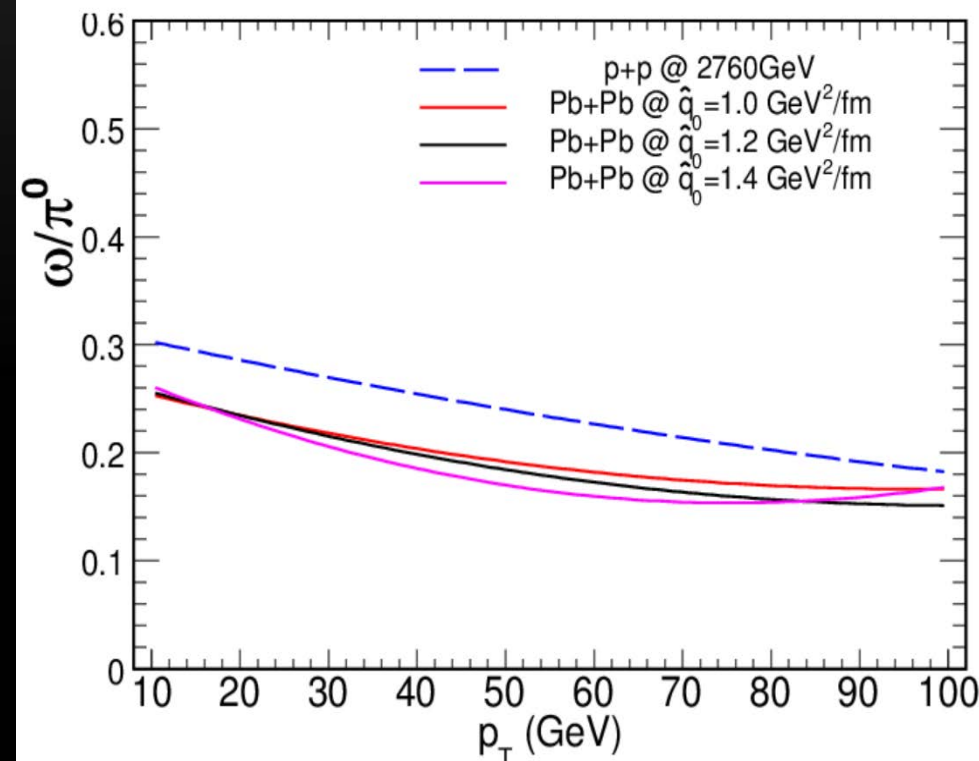


Global extraction of q_{hat}



Yield ratios of identified hadrons

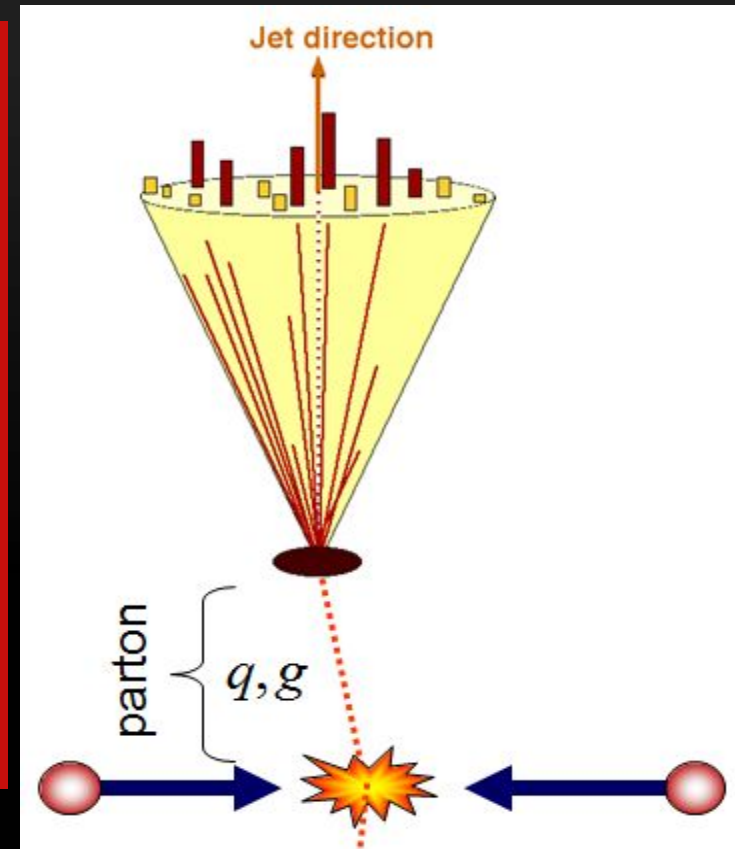
- Theoretical results and related predictions for a few yield ratios of identified hadrons at the RHIC and the LHC are available for the first time.



Jets in HIC

What is a jet?

- A jet is a spray of final-state particles roughly moving in the same direction and defined by jet finding algorithms.
- At LO pQCD, jet \approx parton.
- In pQCD local-parton-hadron duality (LPHD) is used
- Jet: more precise and powerful



$$E_T = \sum_{i \in \text{jet}} E_{T,i}$$

$$y = \sum_{i \in \text{jet}} y_i E_{T,i} / E_T$$

$$\phi = \sum_{i \in \text{jet}} \phi_i E_{T,i} / E_T$$

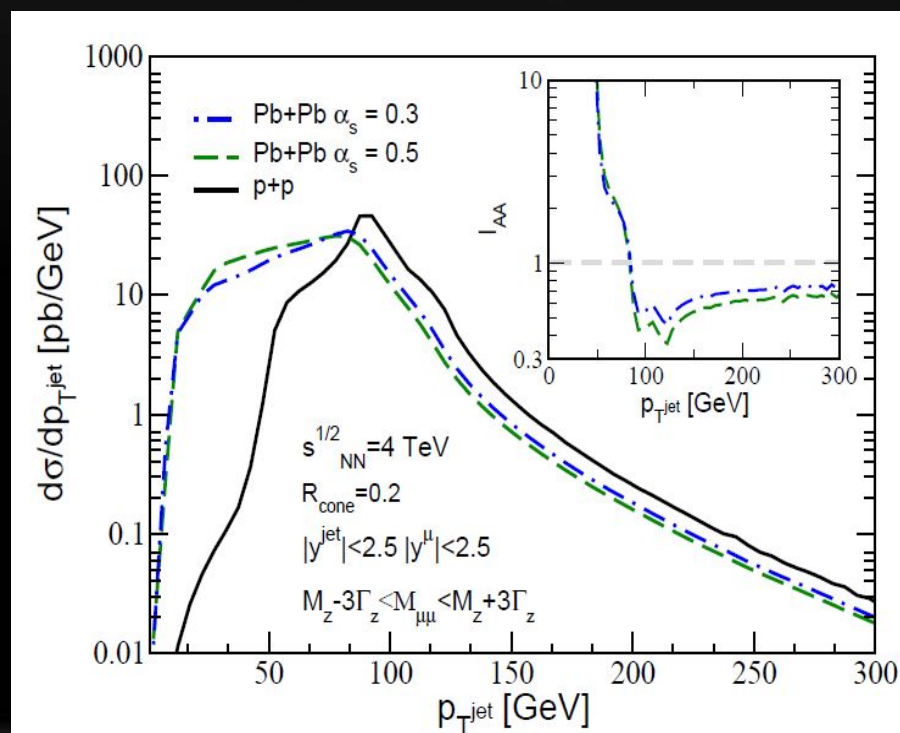
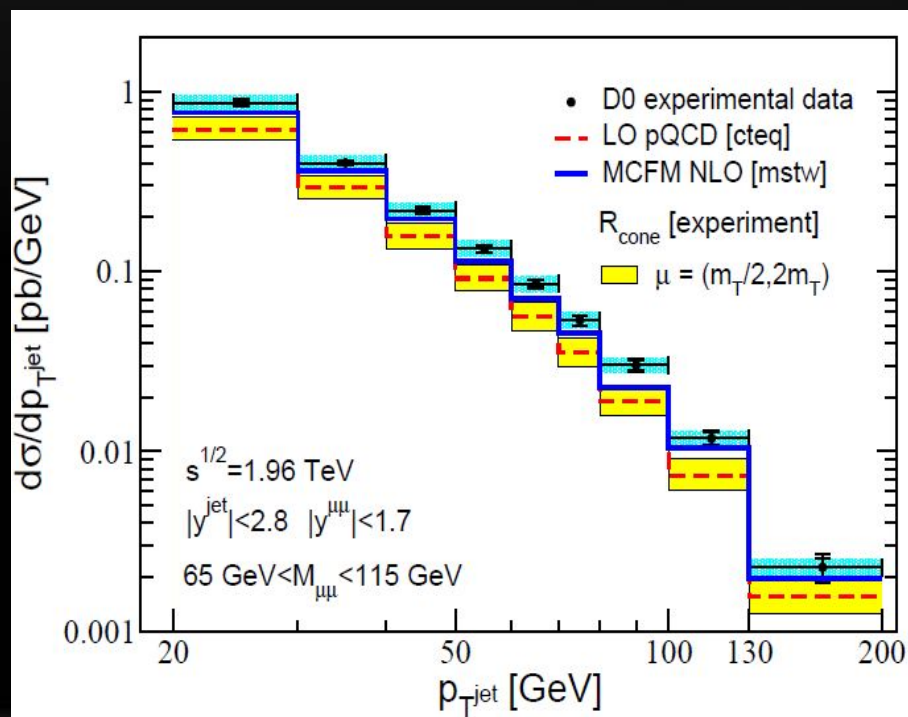
$$R_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}$$

Z⁰ + jet in A+A: Iaa

- A sharp transition from tagged jet suppression above $\sim p_T$ of Z to tagged jet enhancement below $\sim p_T$ of Z

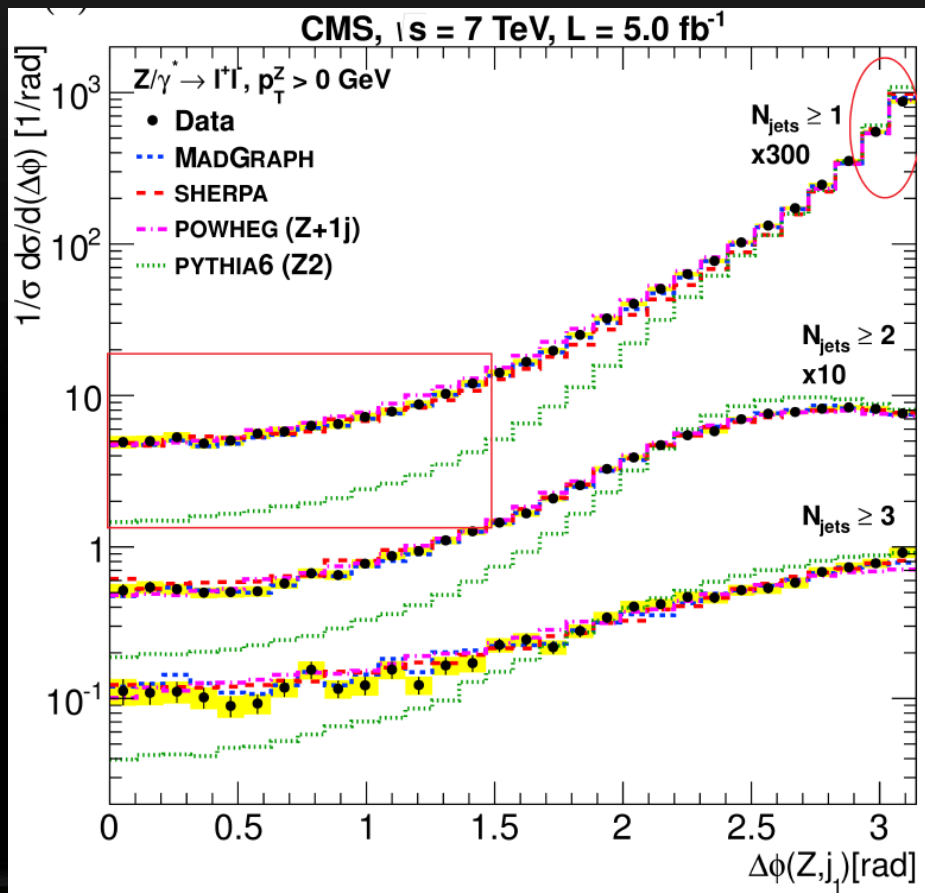
$$I_{AA}^{\text{jet}}(R, \omega_{\text{min}}) = \frac{1}{\langle N_{\text{bin}} \rangle} \frac{d\sigma_{AA}}{dp_T(Z) dp_T(Q)} \bigg/ \frac{d\sigma_{pp}}{dp_T(Z) dp_T(\text{jet})}$$

NLO



Angular correlation in Z+jet

- NLO calculations fail at angular difference $\sim \pi$;
- LO+PS calculations fail at small angular difference.
- Z+jet in A+A: NLO+PS+Eloss



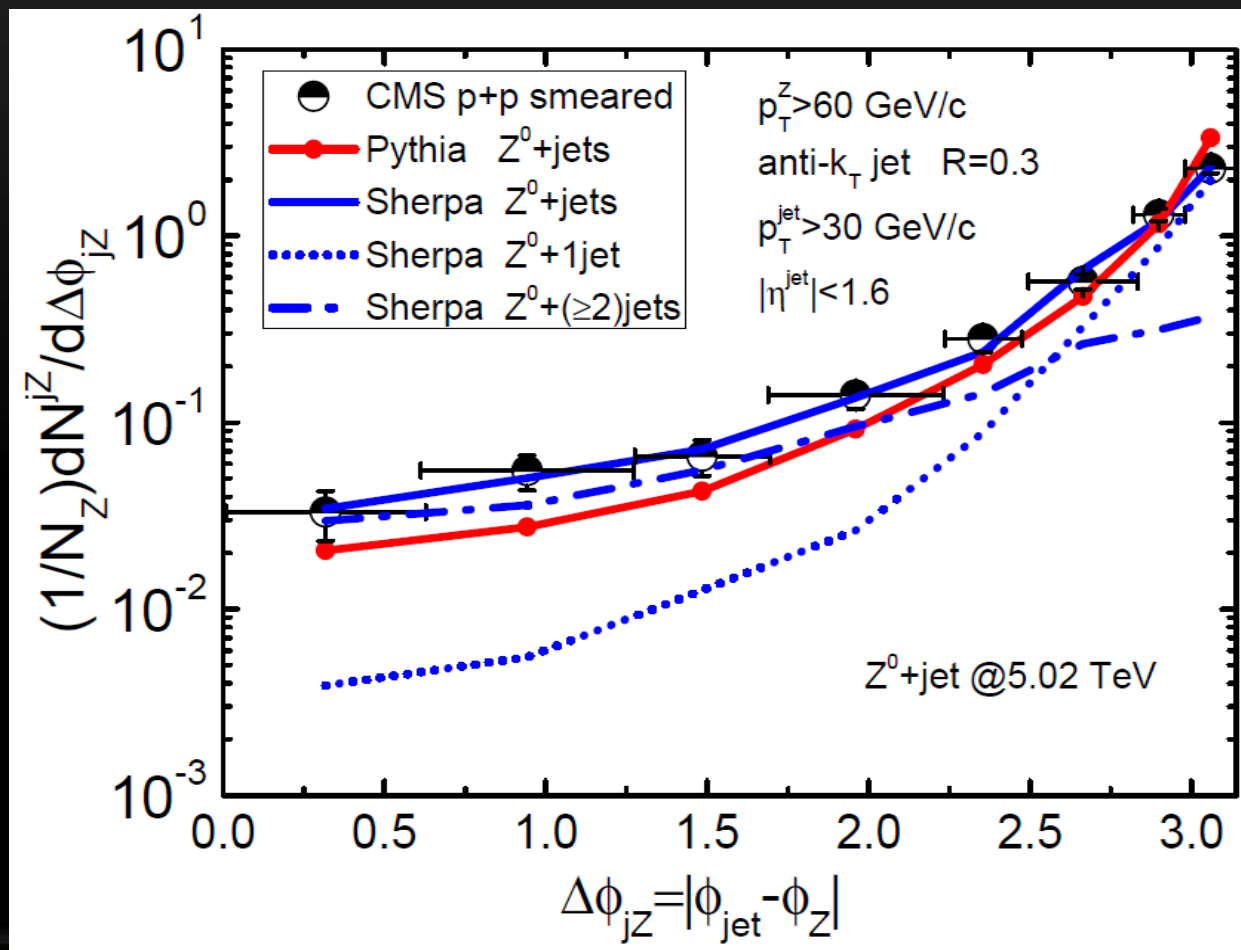
CMS, PLB

722 (2013) 238

NLO +PS
+ELOSS

Z+jet in p+p: NLO+PS

- Results with NLO+PS by Sherpa give good descriptions on angular correlation and momentum imbalance of in p+p



Linear Boltzmann Transport Model

- Elastic scattering:

$$\begin{aligned}
 p_1 \cdot \partial f_1(p_1) &= - \int dp_2 dp_3 dp_4 (f_1 f_2 - f_3 f_4) |M_{12 \rightarrow 34}|^2 \\
 &\quad \times (2\pi)^4 \delta^4(P_1 + P_2 - P_3 - P_4) \\
 dp_i &\equiv \frac{d^3 p_i}{2E_i (2\pi)^3}, \quad |M_{12 \rightarrow 34}|^2 = C g^2 (s^2 + u^2) / (t + \underline{\mu}^2)^2 \\
 f_i &= 1 / (e_i^{p \cdot u / T} \pm 1) \quad (i = 2, 4), \quad f_i = (2\pi)^3 \delta^3(\vec{p} - \vec{p}_i) \delta^3(\vec{x} - \vec{x}_i) \quad (i = 1, 3)
 \end{aligned}$$

Yayun He's talk
W J Xing's talk
parallel III-1,
Nov. 3

X N Wang, Y Zhu, PRL(2013); He, Luo, Wang, Zhu, PRC (2015)

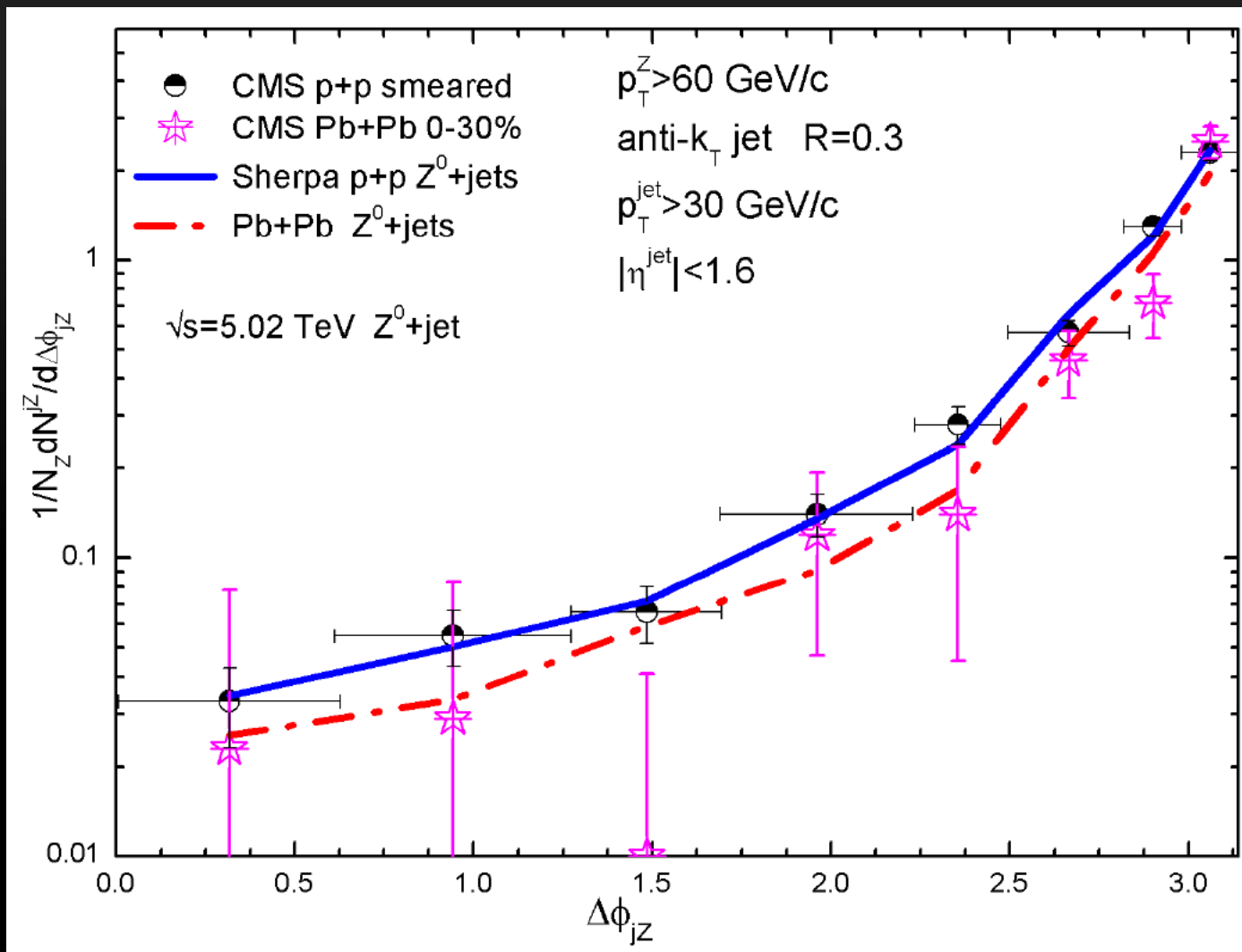
- Inelastic scattering by the higher twist approach:

$$\frac{dN_g}{dx dk_{\perp}^2 dt} = \frac{6\alpha_s C_A P(x) \hat{q}}{\pi k_{\perp}^4} \left(\frac{k_{\perp}^2}{k_{\perp}^2 + x^2 M^2} \right)^2 \sin^2 \left(\frac{t - t_i}{2\tau_f} \right)$$

Guo, X N Wang, PRL(2002); BWZ, X Wang, NPA(2003);

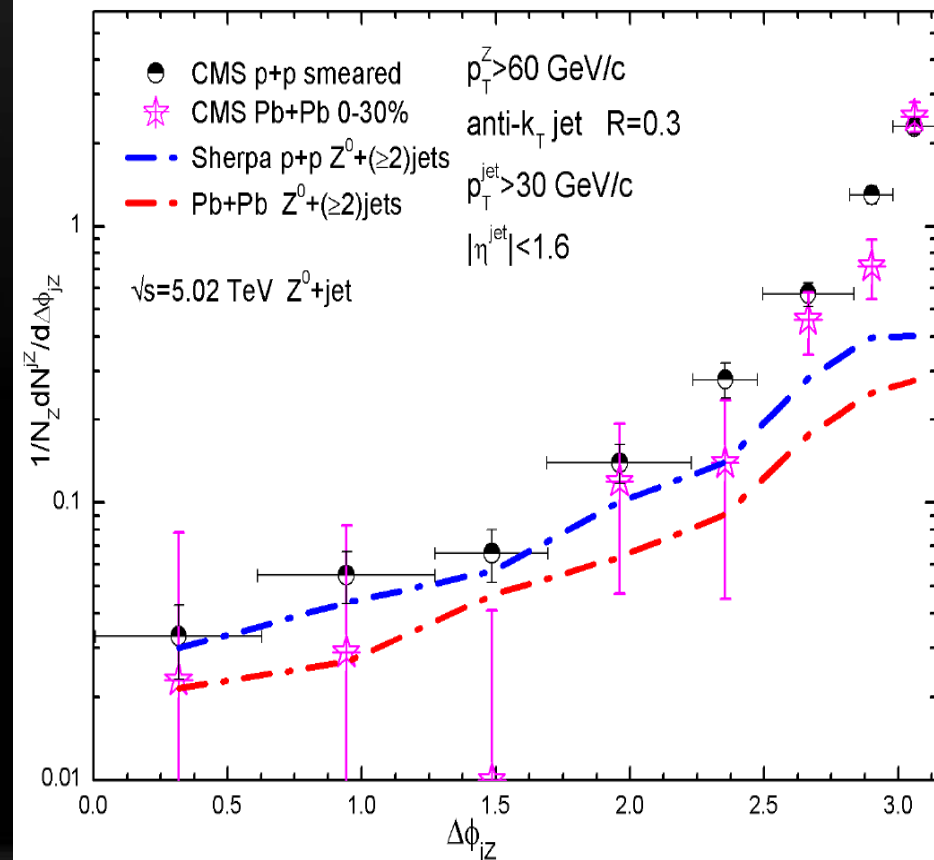
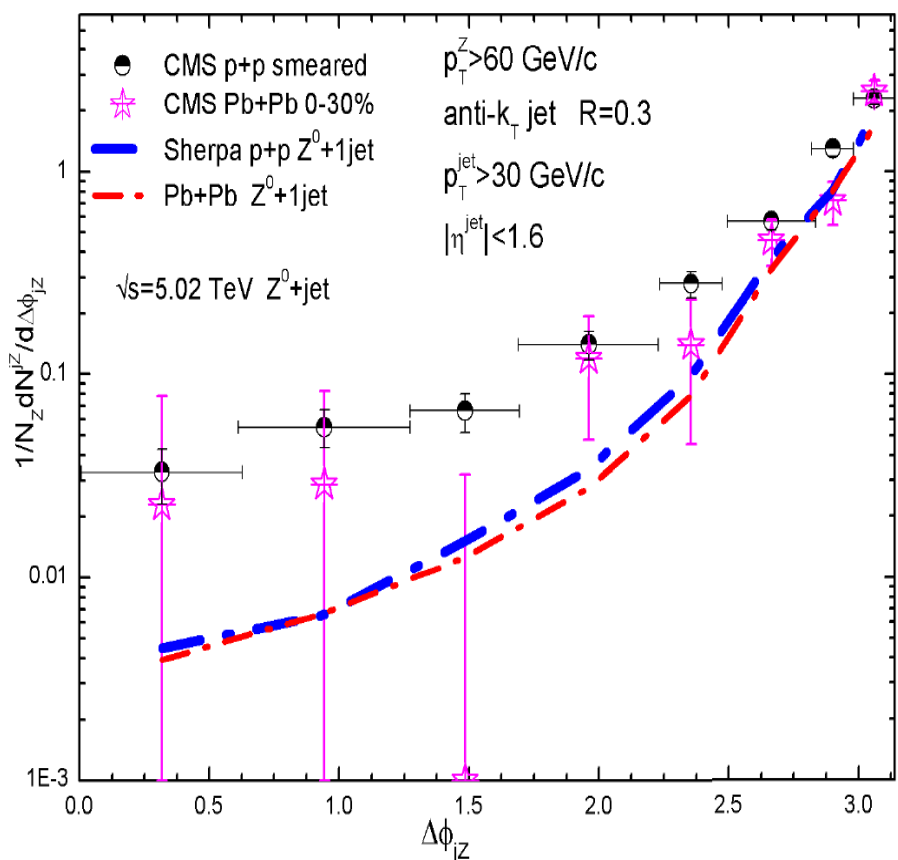
BWZ, E Wang, X N Wang, PRL (2004); Majumder, PRD(2012)

Angular Correlation of Z+jet (I)

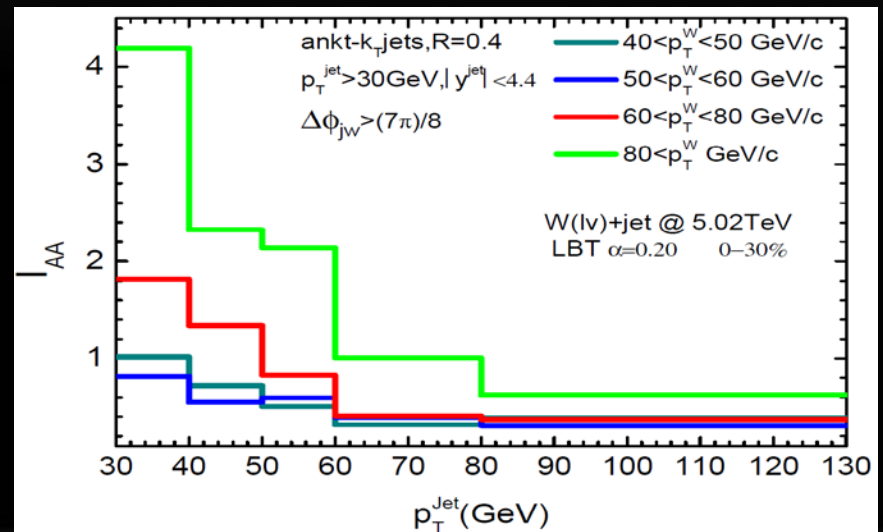
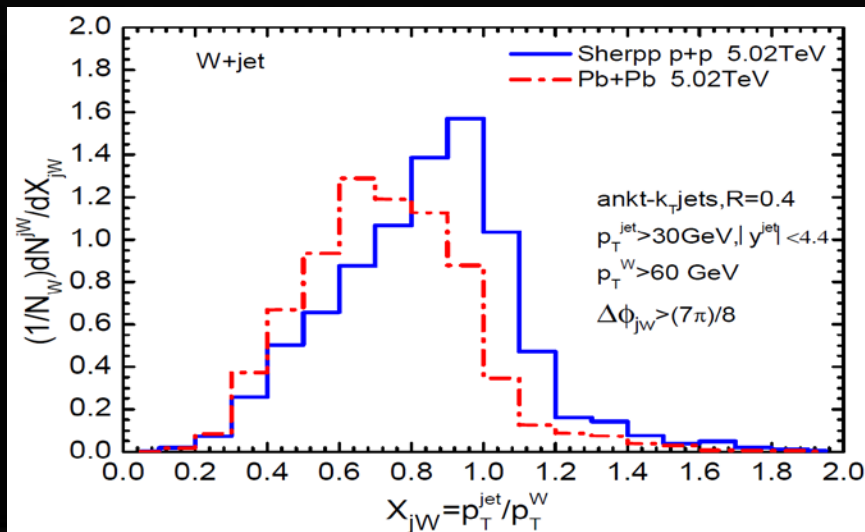
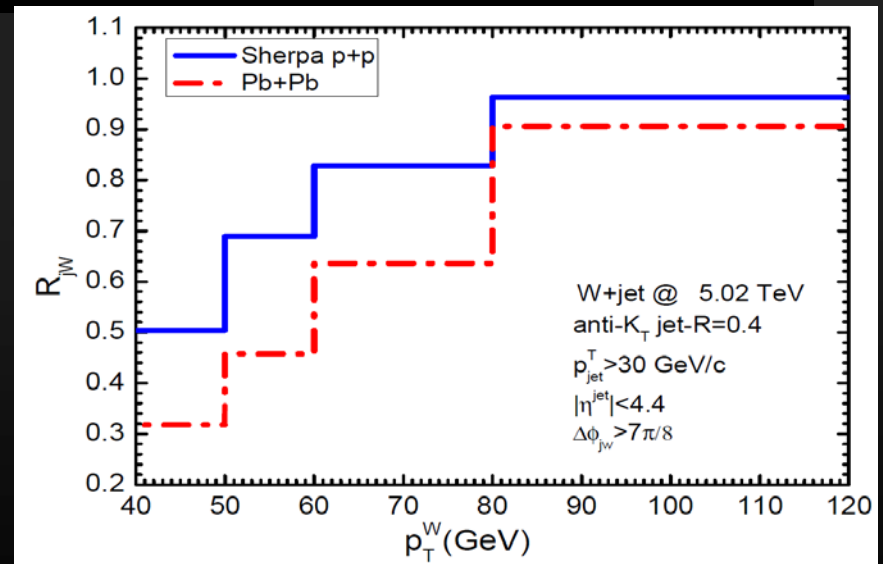
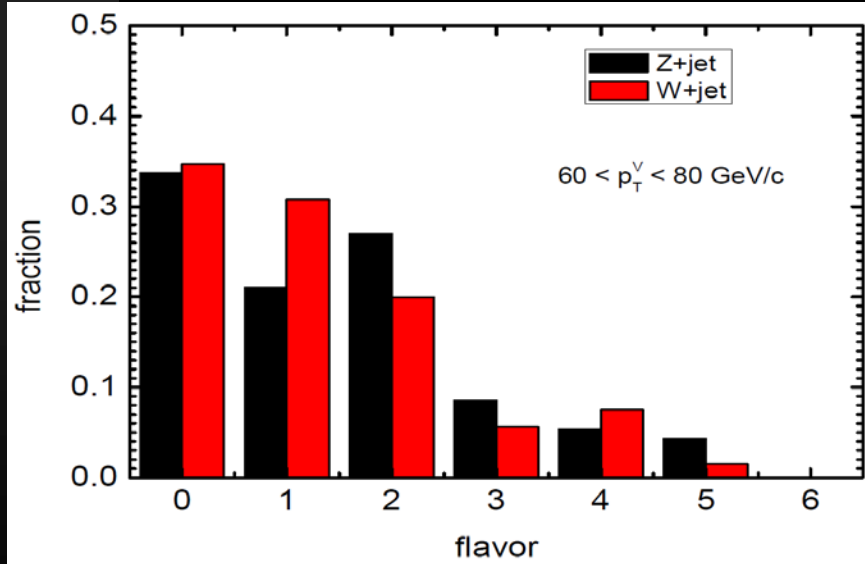


Angular Correlation of Z+jet (II)

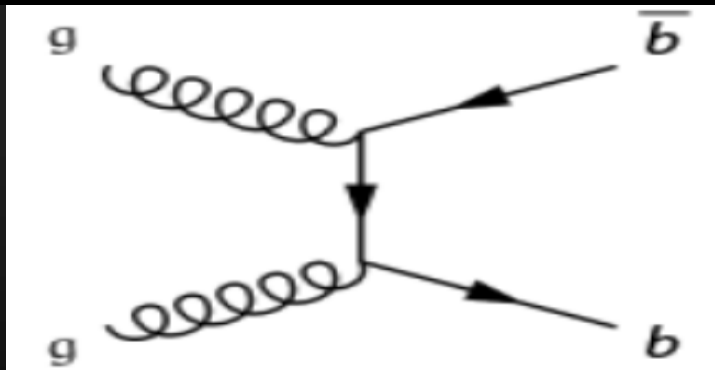
- Suppression to Z+1jet processes is rather small;
- Considerable suppression to Z+ (>2)jets is observed due to jet quenching effect; kinematical cut: $p_T > 30$ GeV



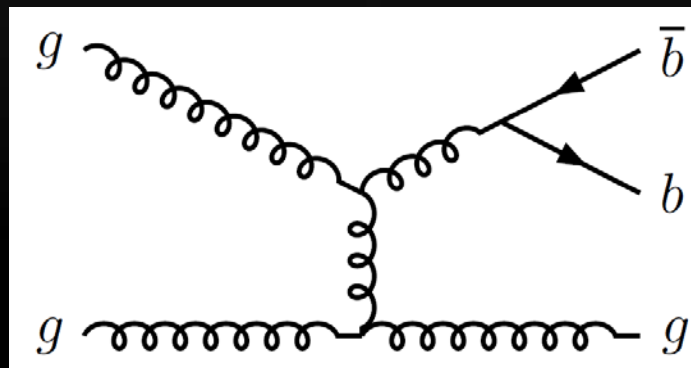
W+jet in HIC



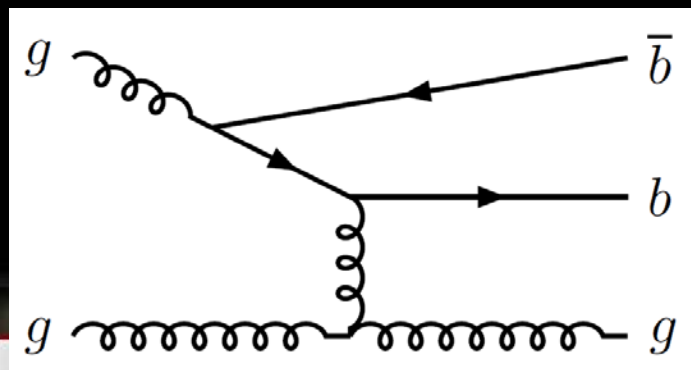
double b-jet production



flavor creation (FCR)



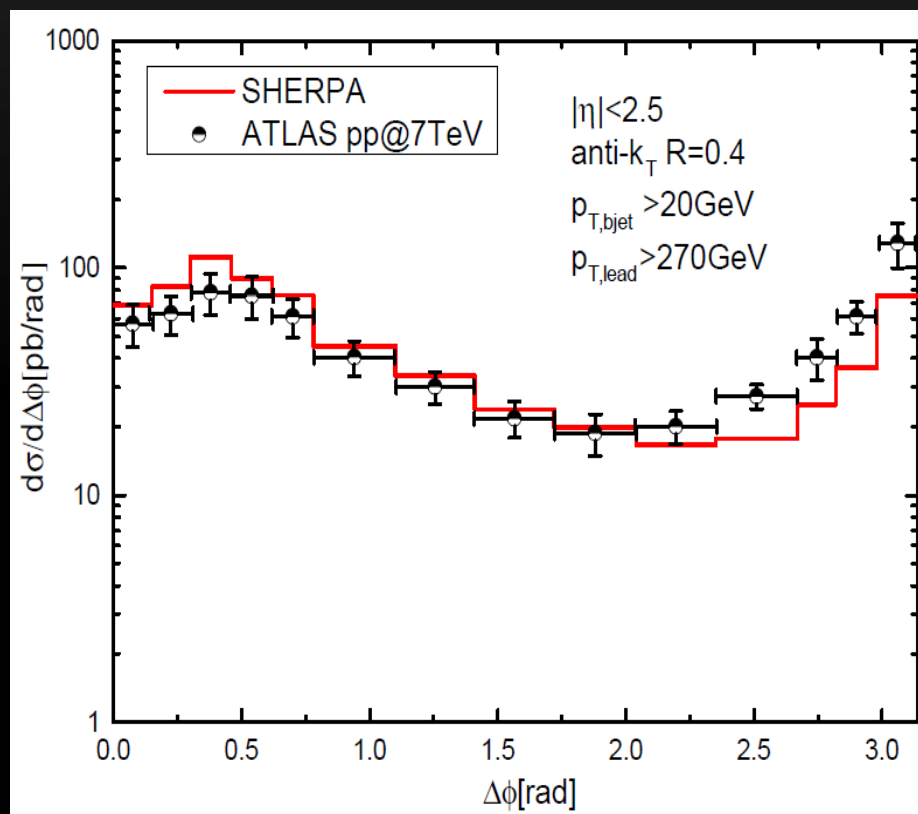
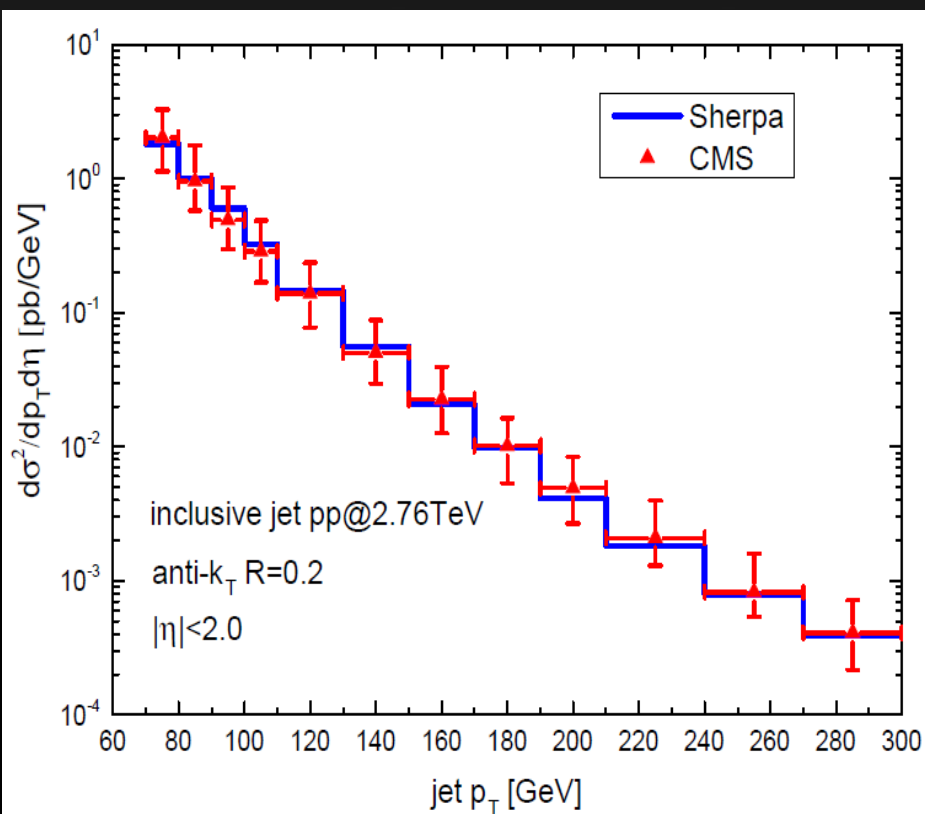
gluon splitting (GSP)



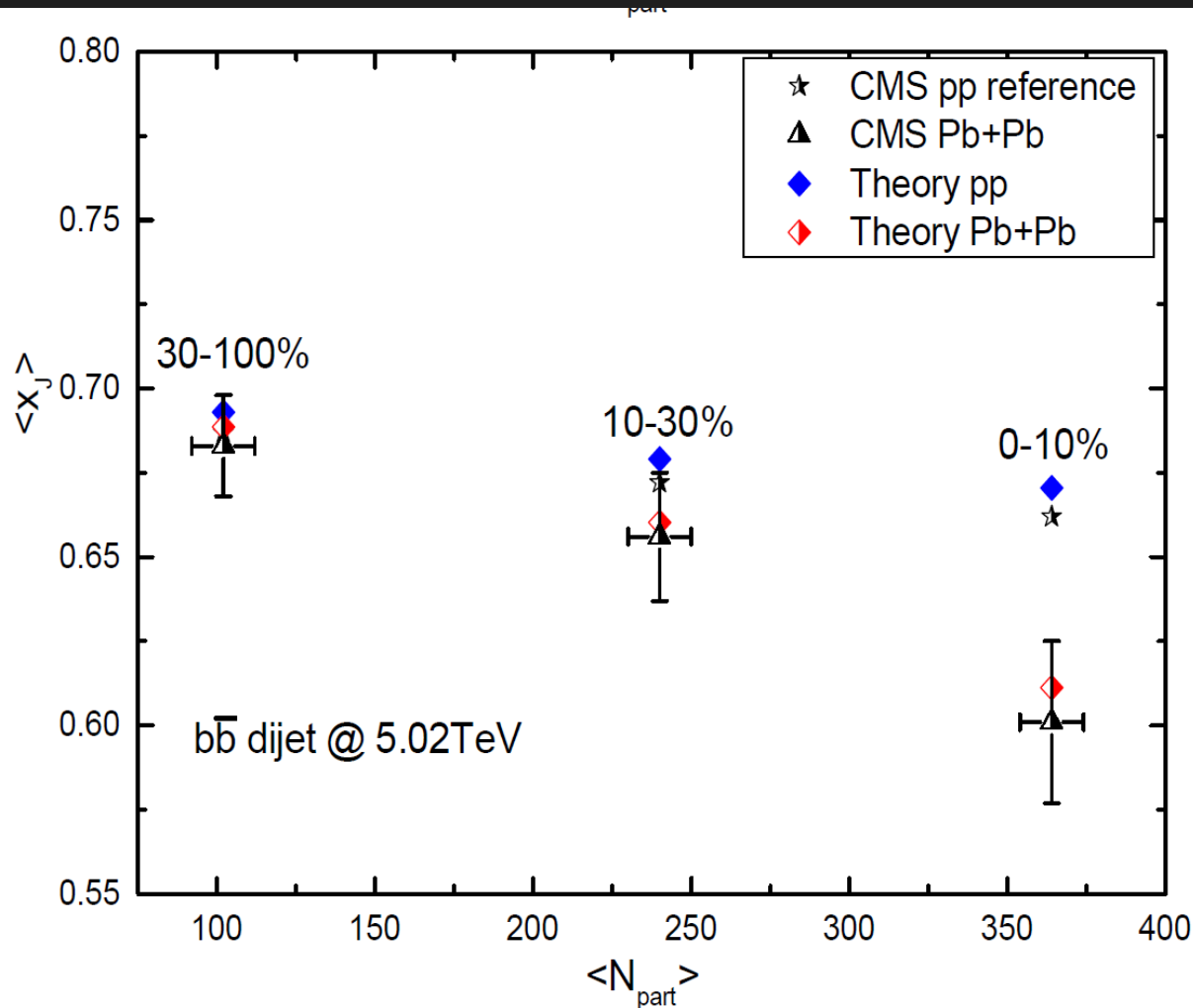
flavor excitation (FEX)

p+p baseline for double b-jet

- Simulations with NLP+PS by Sherpa should give very nice descriptions on inclusive jets, dijets as well as double b-jet.



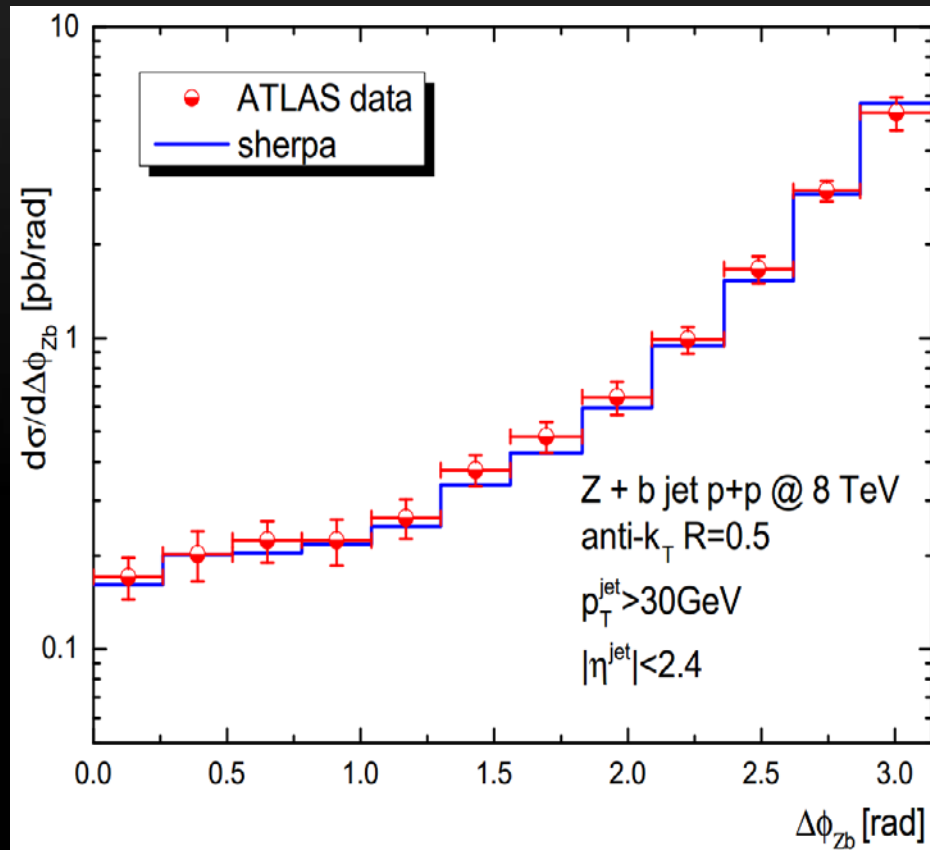
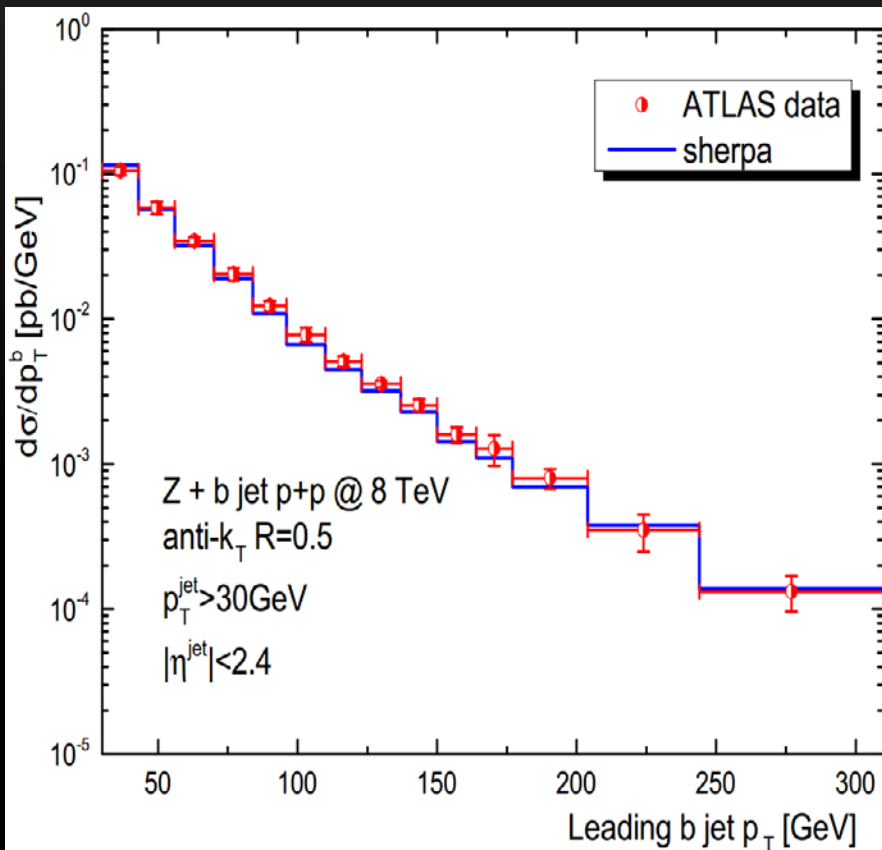
Mean values of momentum imbalance



Wei Dai's talk
parallel III-1, 11-3

Z + b-jet in HIC(I)

- B-jet production in association with Z boson in HIC could be calculated in the same formalism (NLO+PS+Eloss)



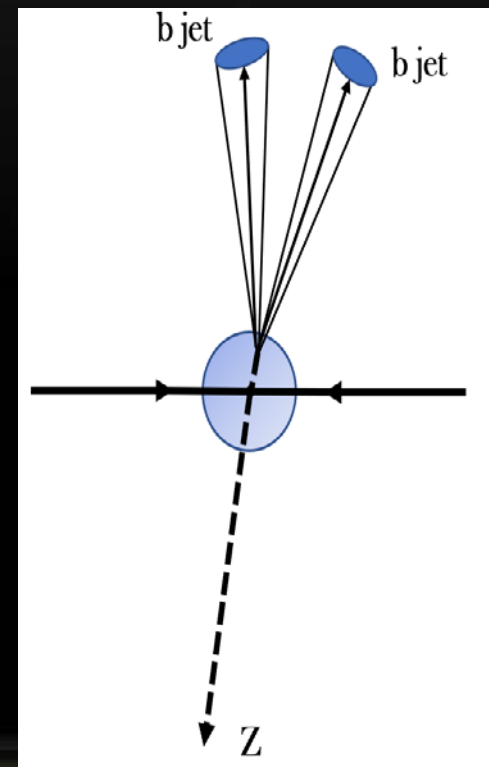
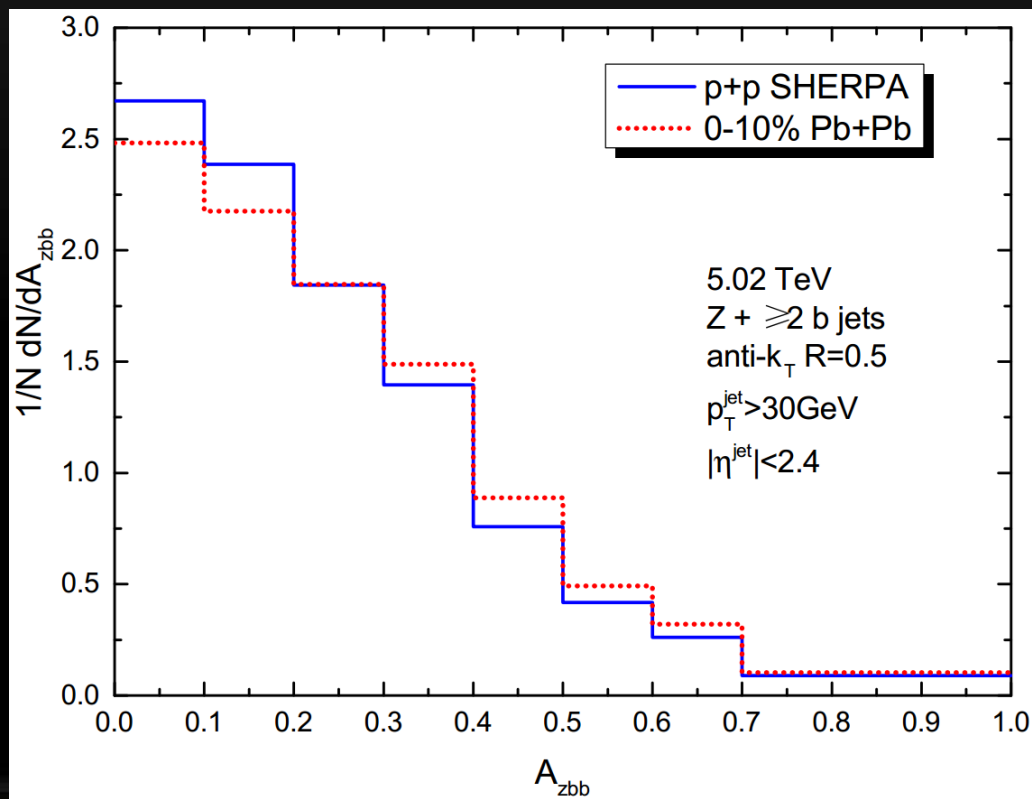
$$\Delta\phi_{zb} = |\phi_Z - \phi_{bjet}|$$

Z + b-jet in HIC(II)

- B-jet production in association with Z boson in HIC could be calculated in the same formalism (NLO+PS+Eloss)

$$\Delta R_{zb} = \sqrt{(\Delta\phi_{zb})^2 + (\Delta\eta_{zb})^2}$$

$$A_{Zbb} = \frac{\Delta R_{Zb}^{max} - \Delta R_{Zb}^{min}}{\Delta R_{Zb}^{max} + \Delta R_{Zb}^{min}}$$



Transverse sphericity

- Event shape observables measure geometrical properties of the energy flow in QCD final states: transverse sphericity

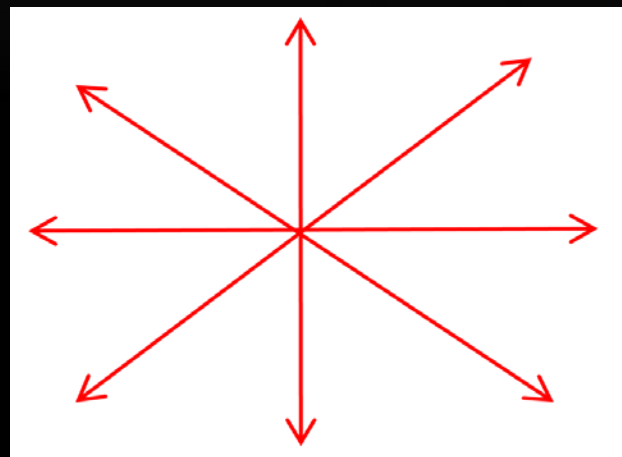
$$M_{xyz} = \sum_i \begin{pmatrix} p_{xi}^2 & p_{xi}p_{yi} & p_{xi}p_{zi} \\ p_{yi}p_{xi} & p_{yi}^2 & p_{yi}p_{zi} \\ p_{zi}p_{xi} & p_{zi}p_{yi} & p_{zi}^2 \end{pmatrix}$$

Ordering the eigenvalues

$$S_{\perp} = \frac{2\lambda_2}{\lambda_1 + \lambda_2} \quad 0 \leq S_{\perp} < 1$$

$p_{T,2}$  $p_{T,1}$

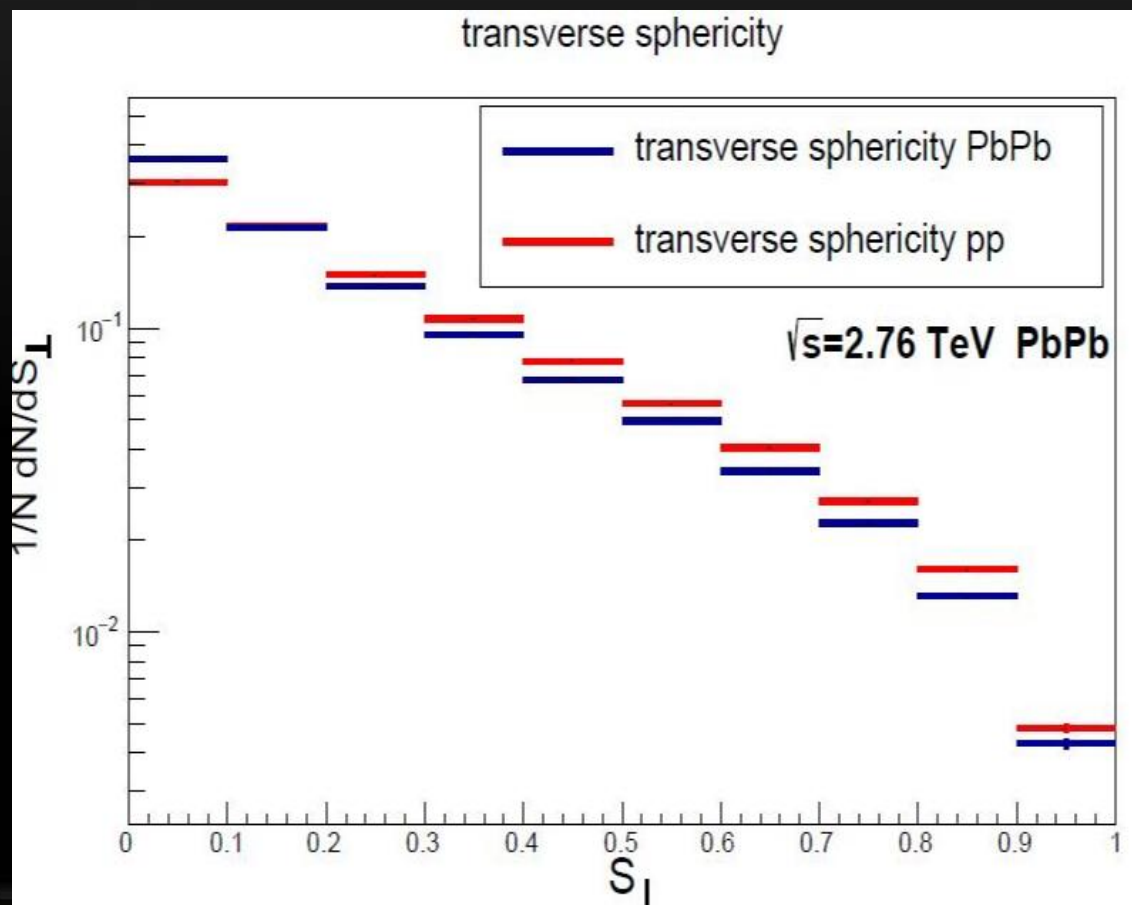
$S_{\perp} = 0$ (pencil-like)



$S_{\perp} = 1$ (sphere-like)

Transverse sphericity in HIC(I)

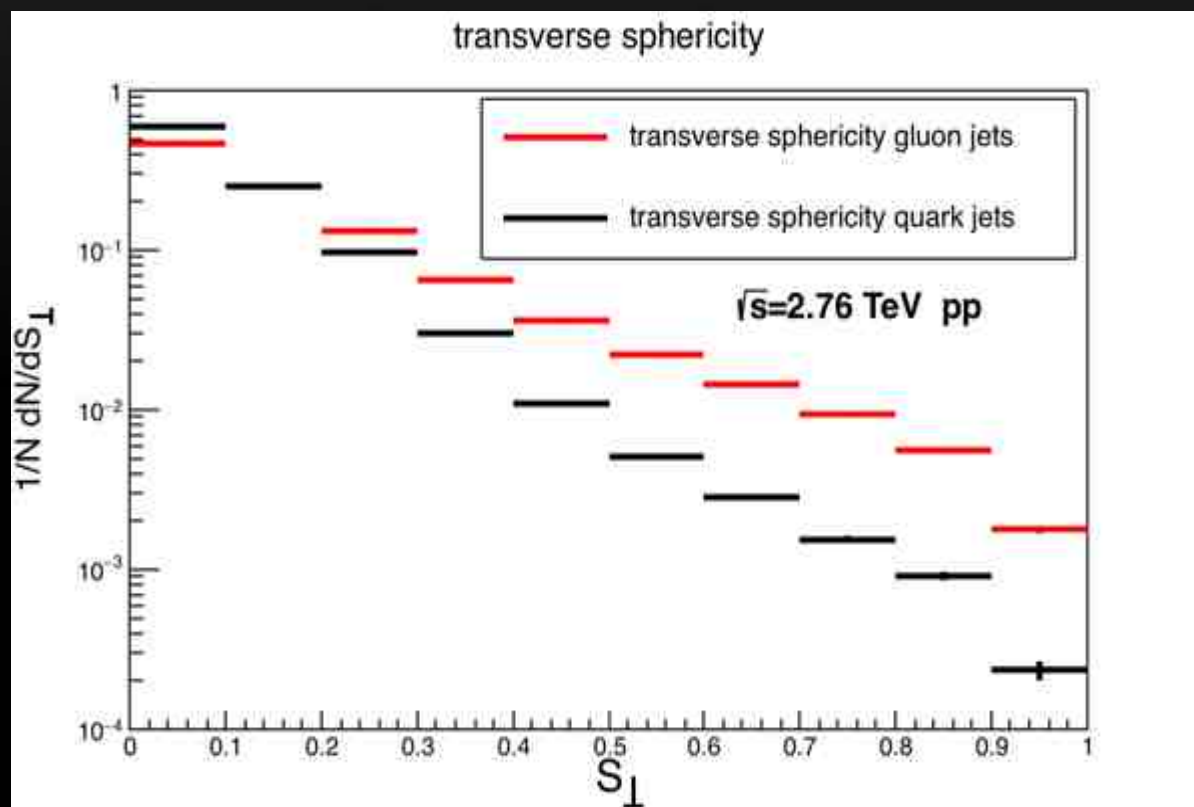
- Transverse sphericity in HIC is computed with NLO+PS+Eloss.
- A suppression is observed in large S_{\perp} , and enhancement in small S_{\perp} .



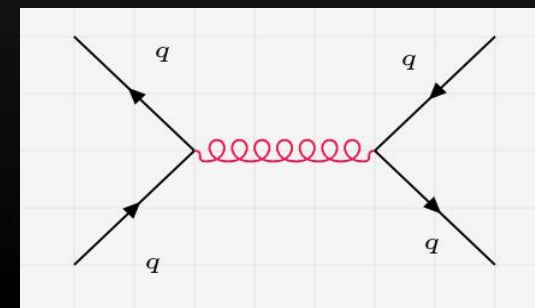
$110 < p_{T,1} < 170 \text{ GeV}$
 $p_{T,2} > 30 \text{ GeV} \quad p_{T,n} > 20 \text{ GeV}$
 $|\eta_n| < 2.4 \quad \text{anti-K}_T : R = 0.4$

S_{\perp} : gluon VS quark

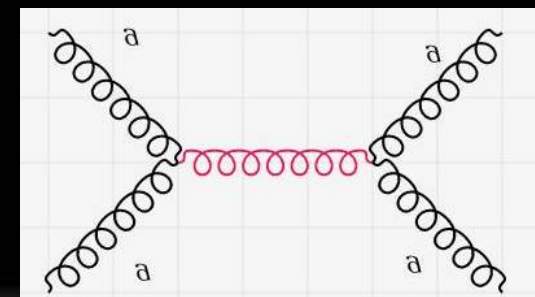
- Events with gluon-initiated jets are more isotropic than that with quark-initiated jets.
- At large S_{\perp} the distribution of gluon jets are larger.



quark jets

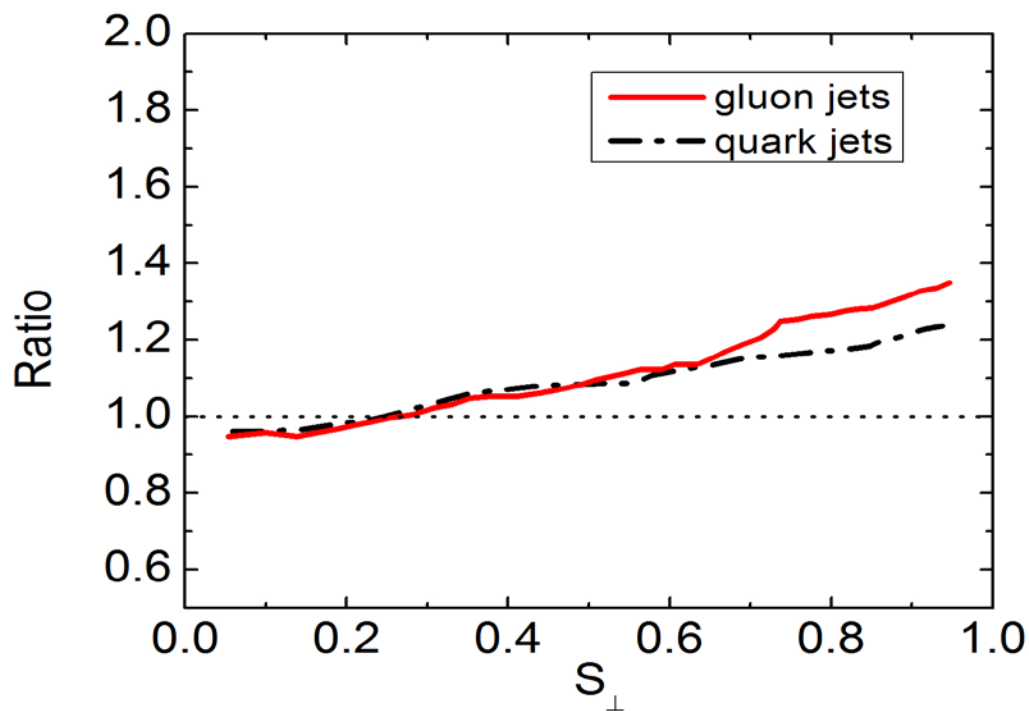


gluon jets



Energy loss effect

- Energy loss effect will make the event more isotropic, i.e. enhancement.
- The fact that gluon will lose more energy than quark leads to a suppression of the distribution at large S_{\perp} relative to p+p.



Shi-Yong Chen's talk
parallel III-2, Nov. 3

Summary

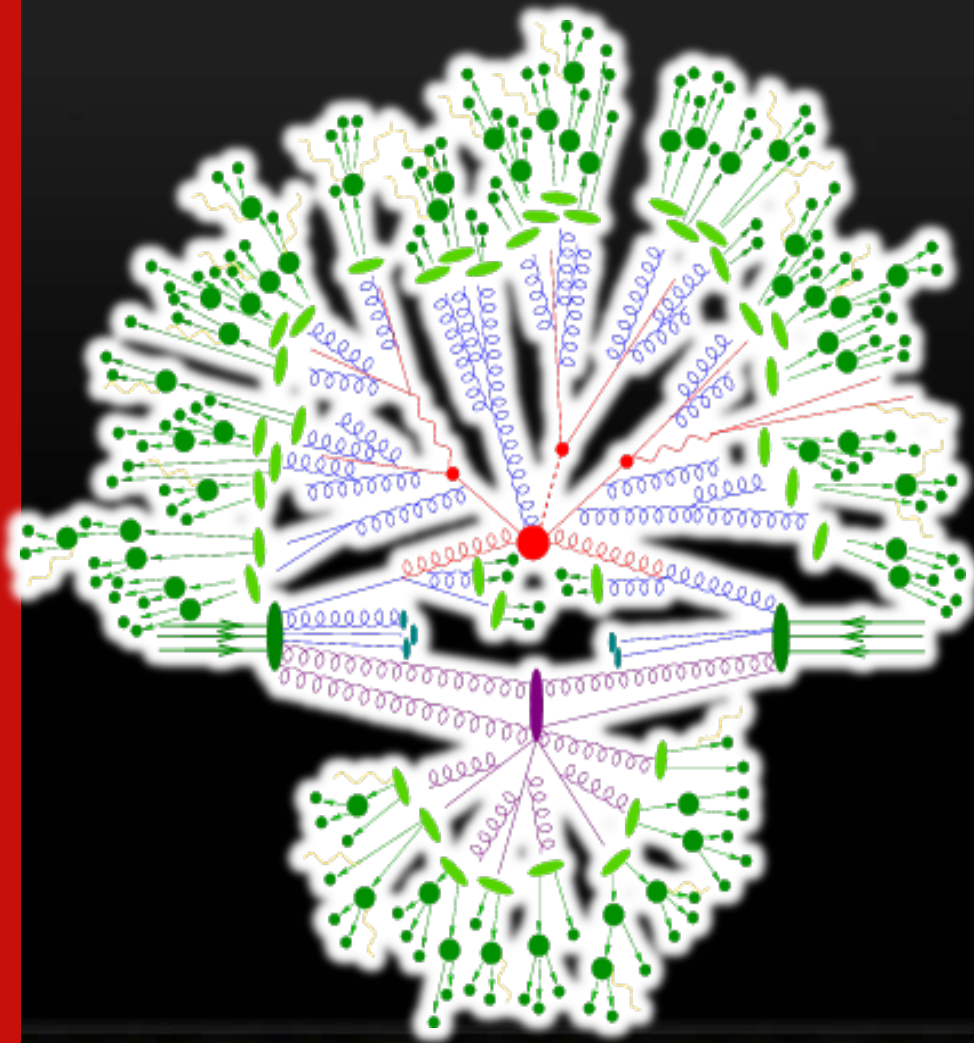
- A systematic study of identified mesons at NLO in HIC has been made.
- A framework of combining NLO+PS for initial hard production with parton energy loss in the QGP has been developed.
- Our calculations provide nice descriptions of experimental data on Z+jet and double b-jet.
- Theory predictions on several novel jet observables are provided to be tested by future experiments.

Backup

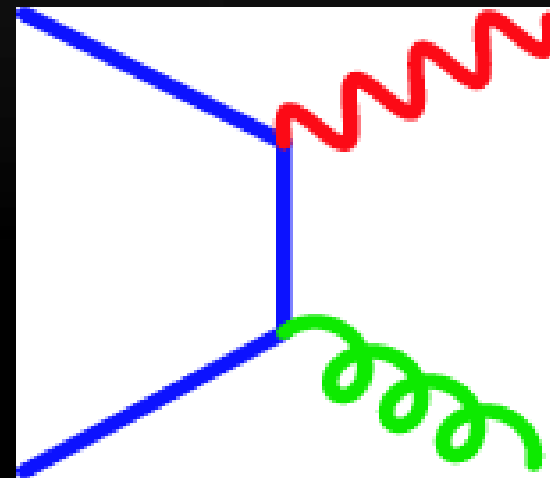
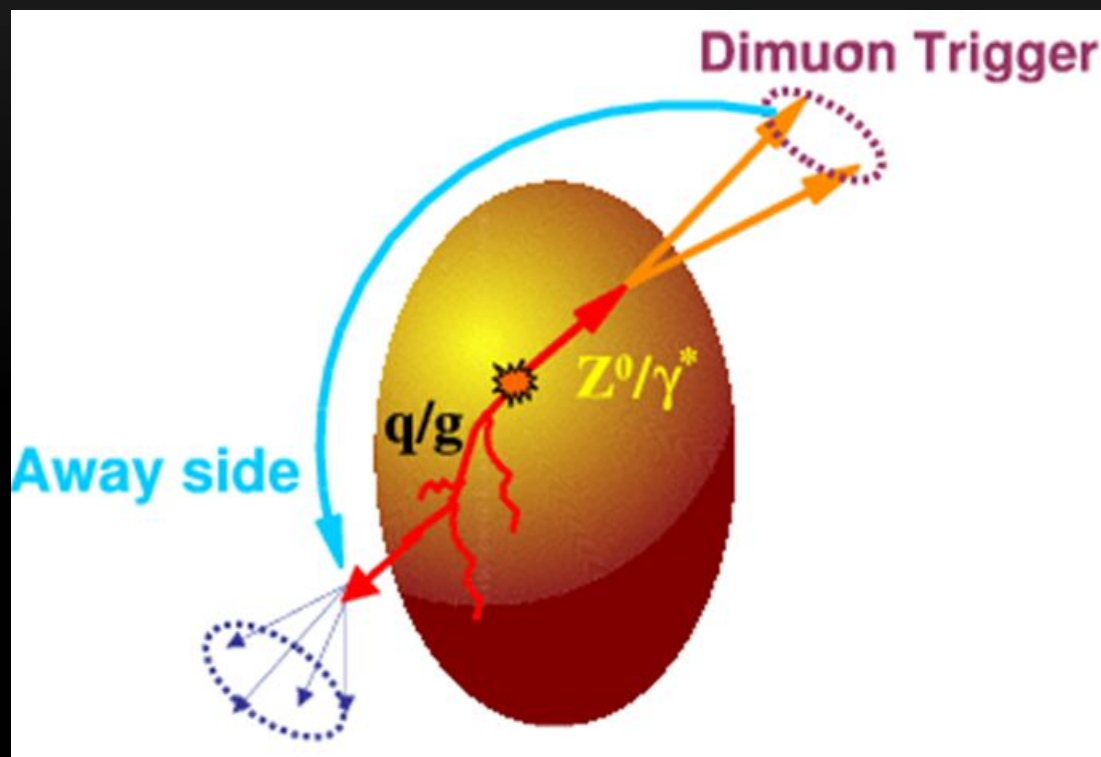


Sherpa: NLO+PS

- Initial state parton shower(PS)
- Final state PS
- NLO matrix elements (ME)
- Signal process
- Fragmentation
- Hadron decays
- Underlying event
- QED radiation



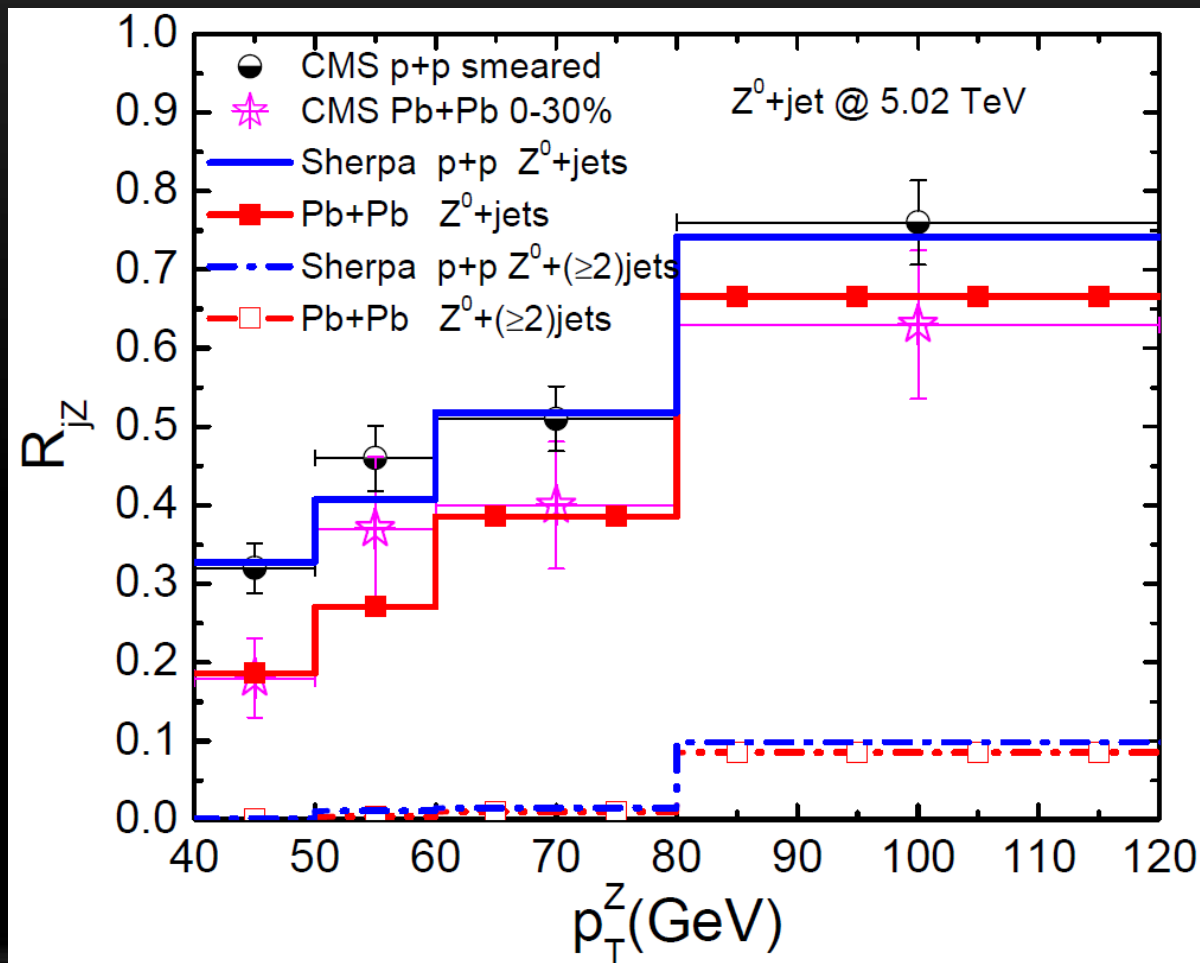
Tagged jet production in HIC



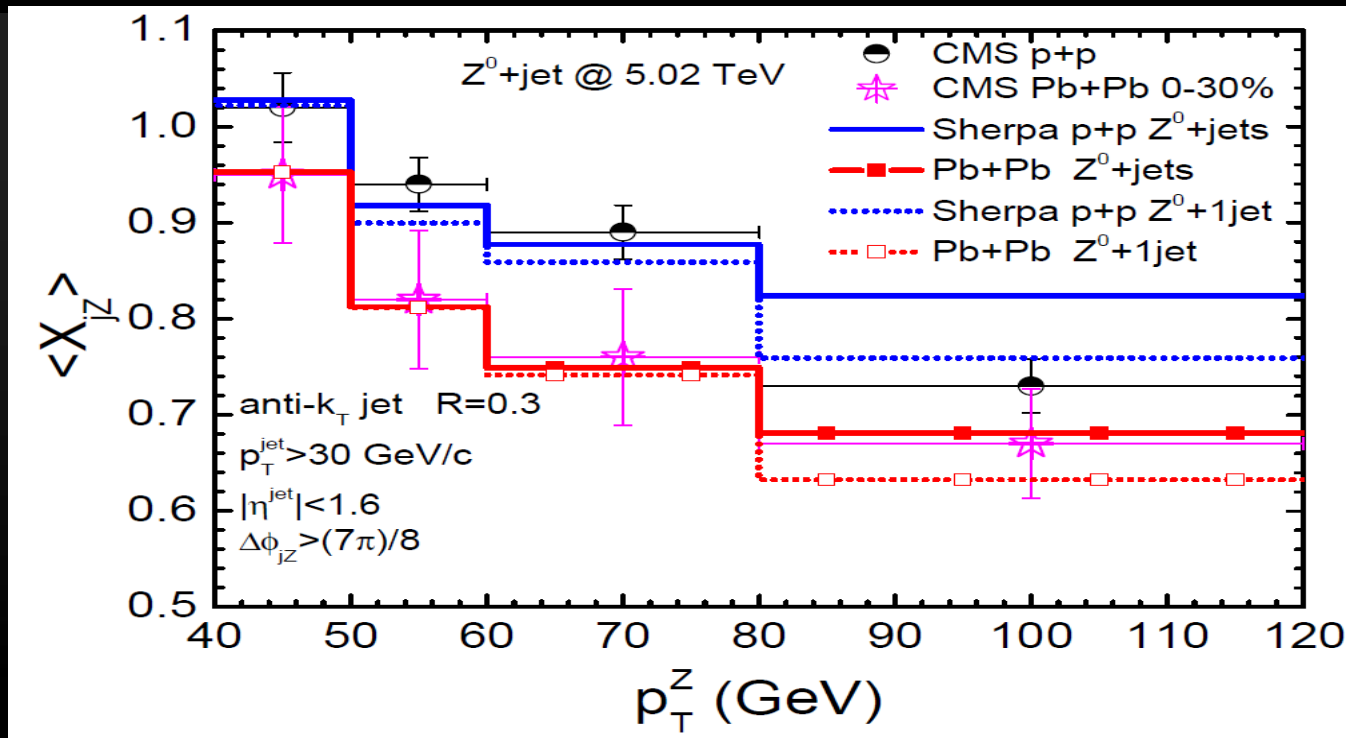
"golden channel"

Averaged number of tagged jets

$$R_{jZ} = N_{jZ}/N_Z$$



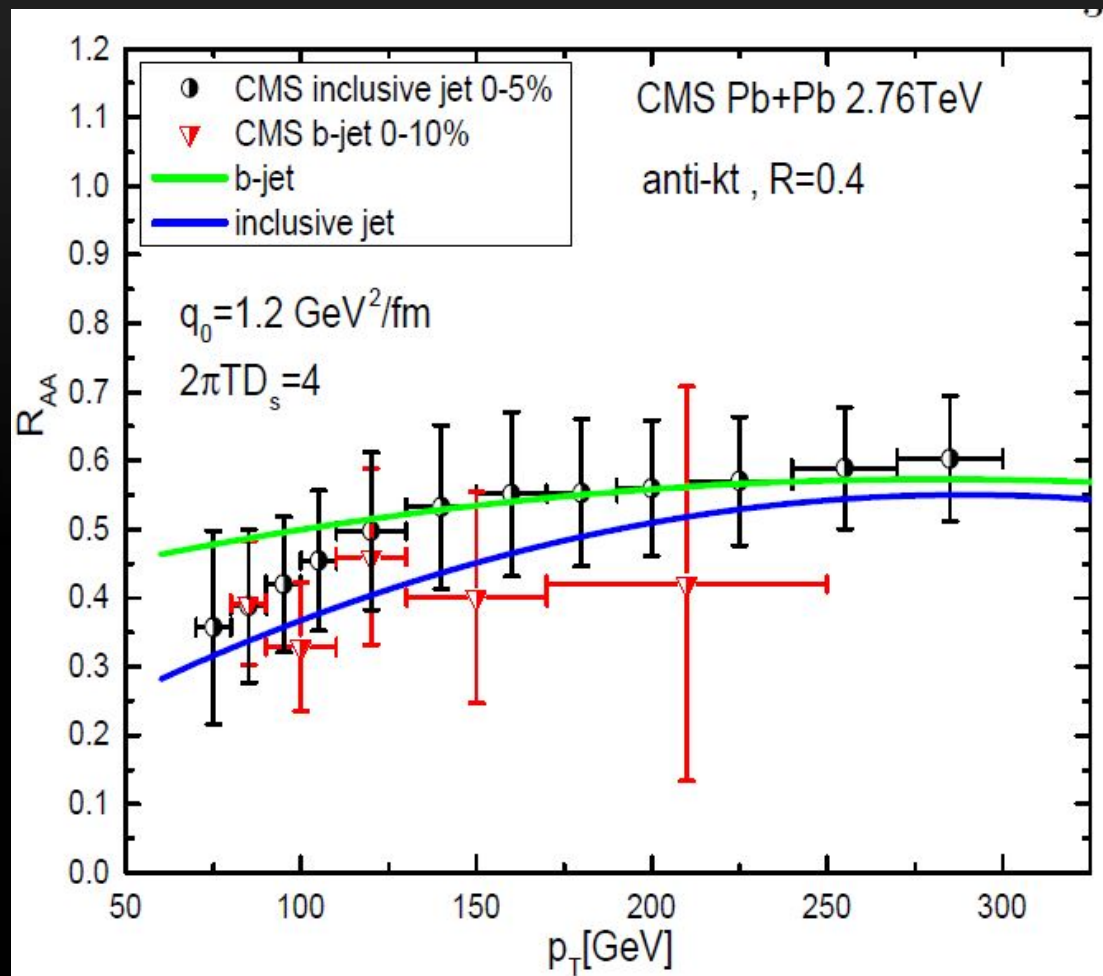
Momentum imbalance



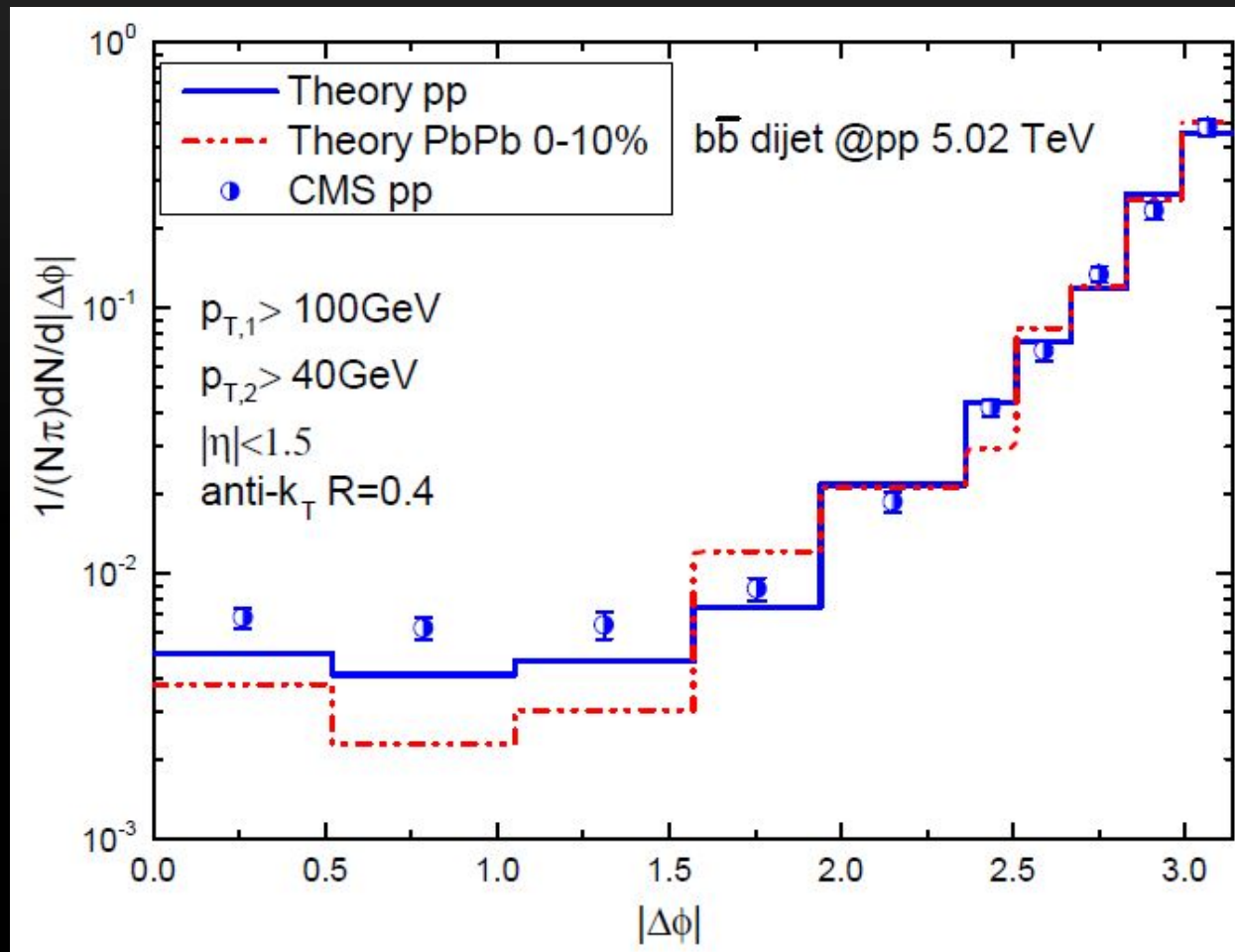
$$\Delta\langle x_{jZ} \rangle = \langle x_{jZ} \rangle_{p+p} - \langle x_{jZ} \rangle_{Pb+Pb}$$

p_T^Z (GeV)	40-50	50-60	60-80	> 80
CMS data	0.07 ± 0.106	0.12 ± 0.148	0.13 ± 0.158	0.06 ± 0.088
$\Delta\langle x_{jZ} \rangle$	0.075	0.106	0.128	0.143

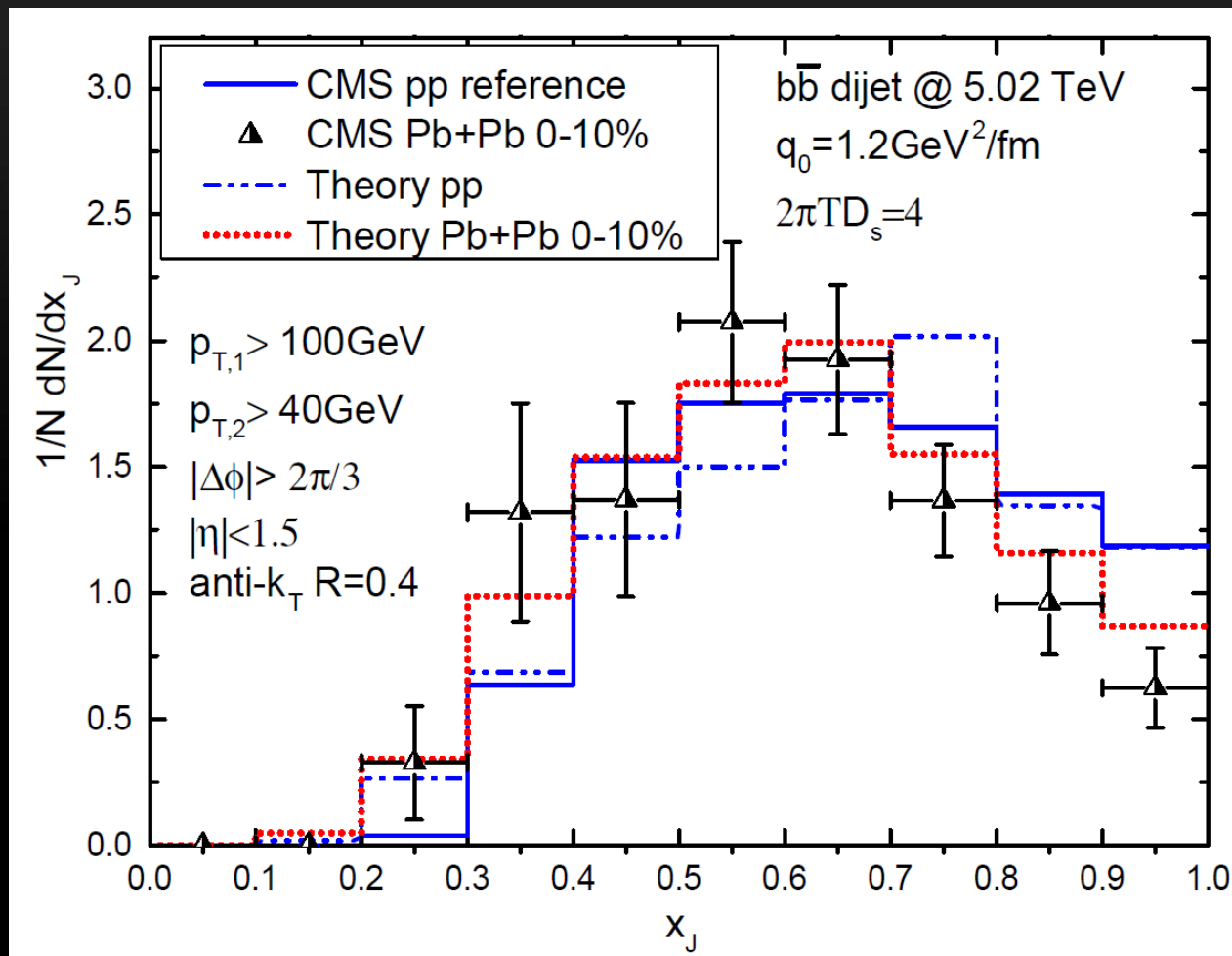
Inclusive jet and b-jet in HIC



Angle correlation of double b-jet



double b-jet in HIC: momentum imbalance



Event Shape