# Probe nuclear matter with jets at NLO

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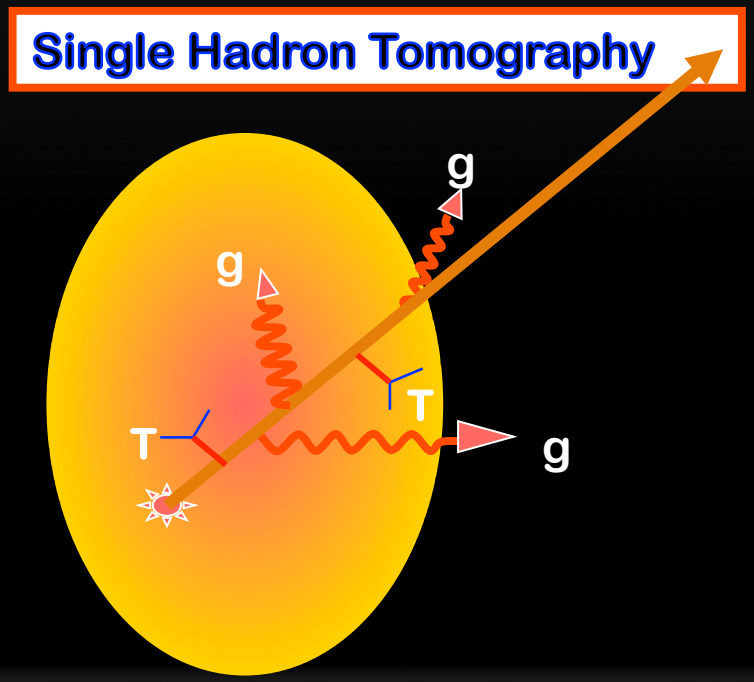
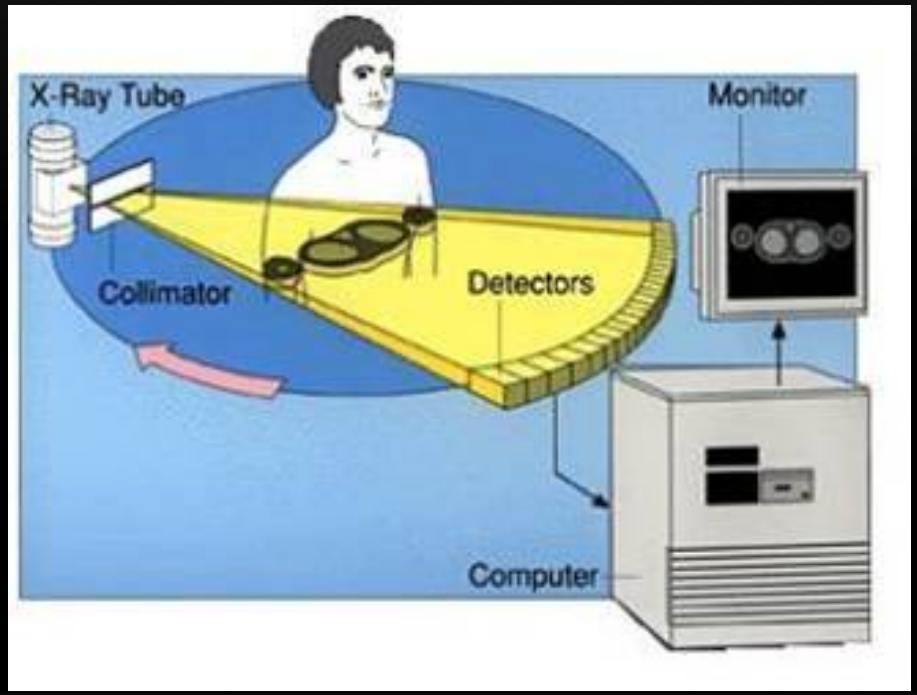
# Jet quenching: From hadrons to jets

# Jet quenching as a hard probe

Jet quenching has been proposed as an excellent probe of the hot/dense matter created at HIC.

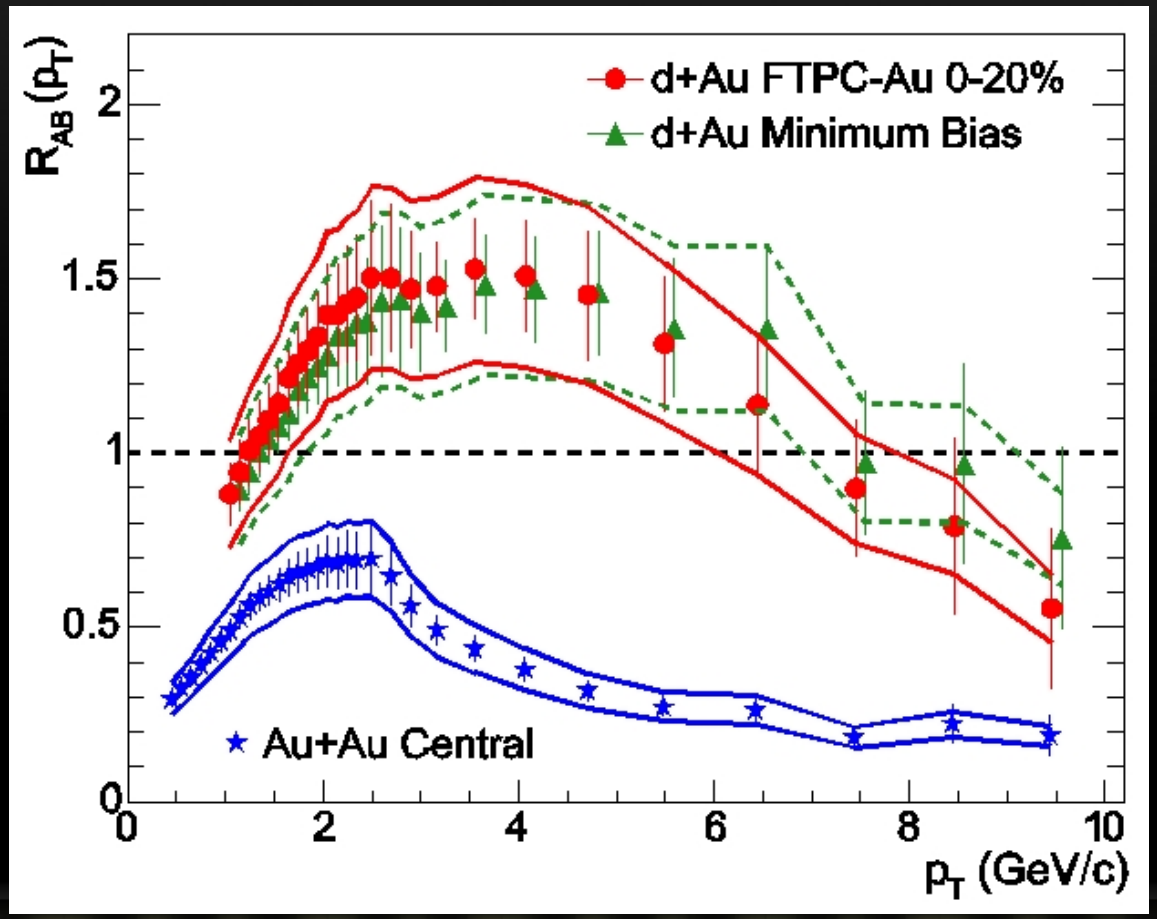



Xin-Nian Wang, M. Gyulassy, PRL68(1992)1480

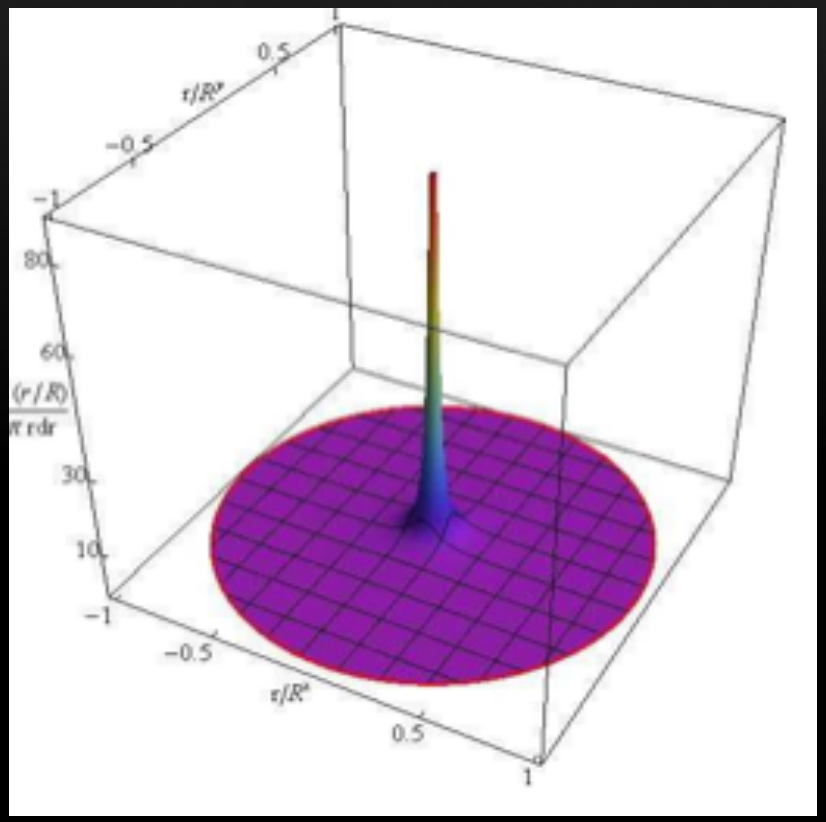
# Jet quenching at RHIC

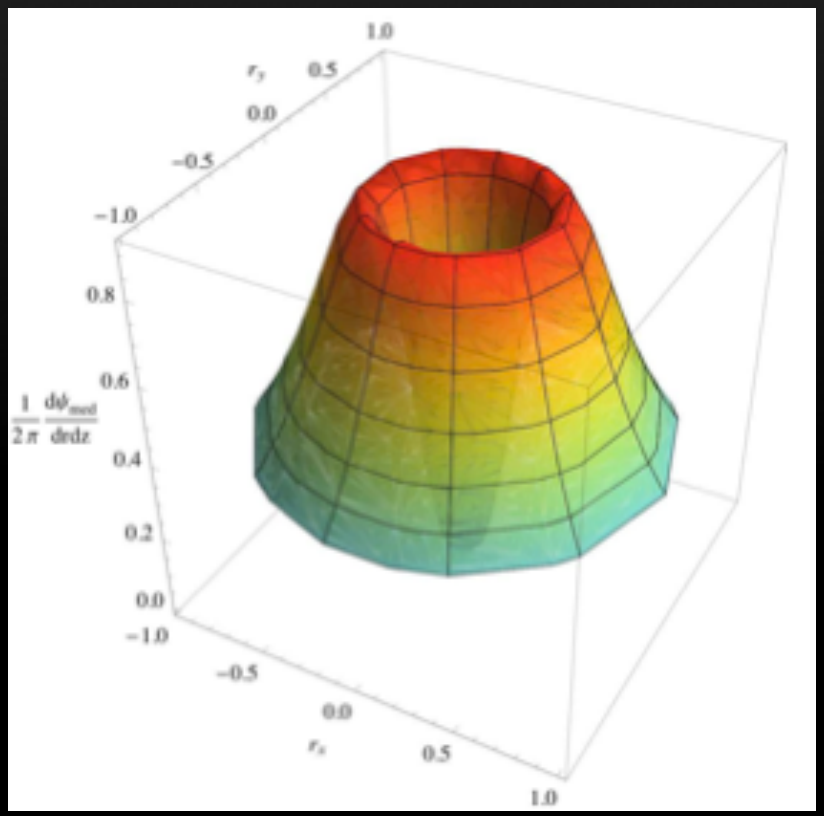
$$R_{AA} = \frac{\text{Yield}_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{\text{Yield}_{pp}}$$




Gyulassy, Vitev, X.N.Wang, BWZ, 《QGP3》 p123-191 (2004); nucl-th/0302077.

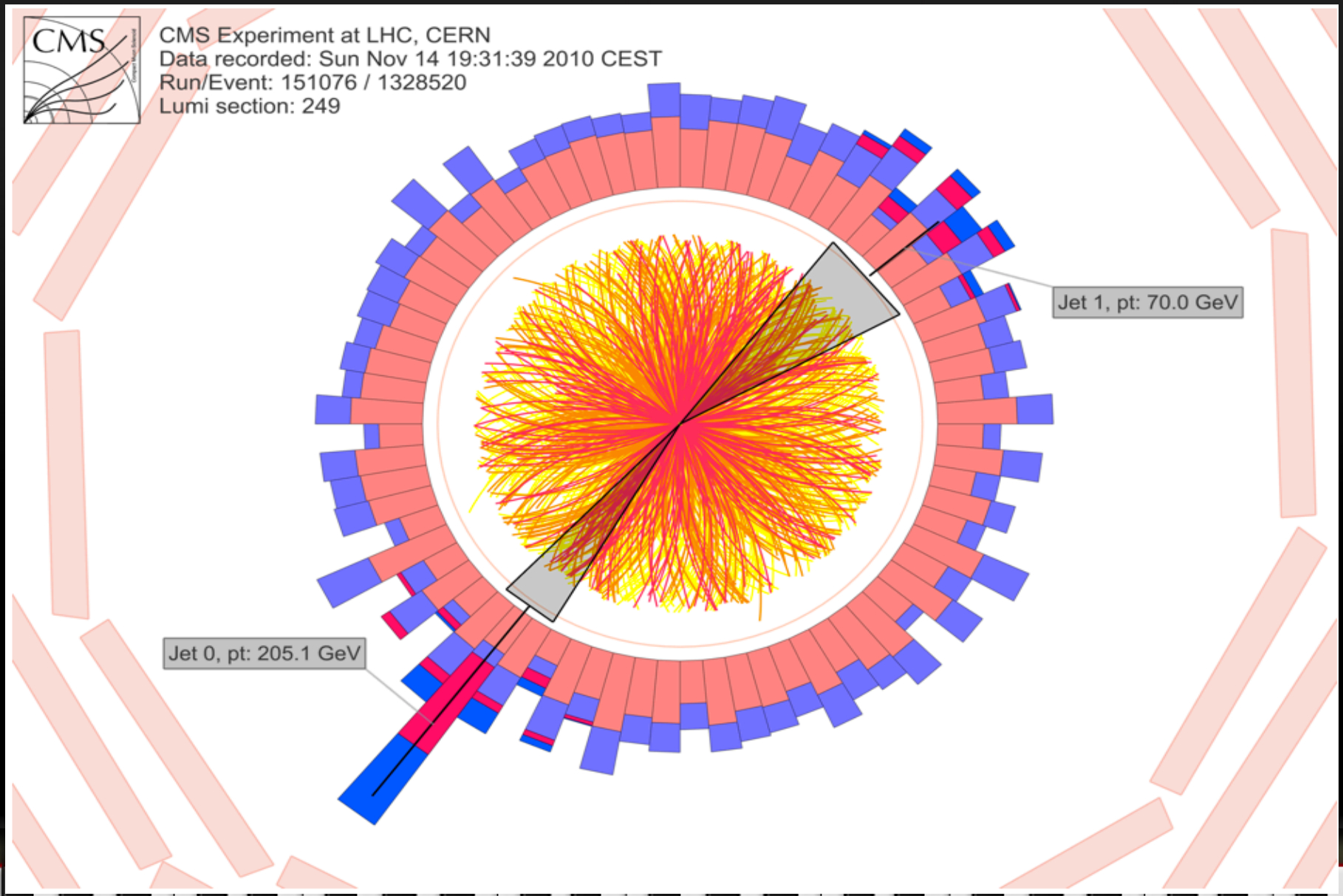
# From leading hadrons to jets: Th



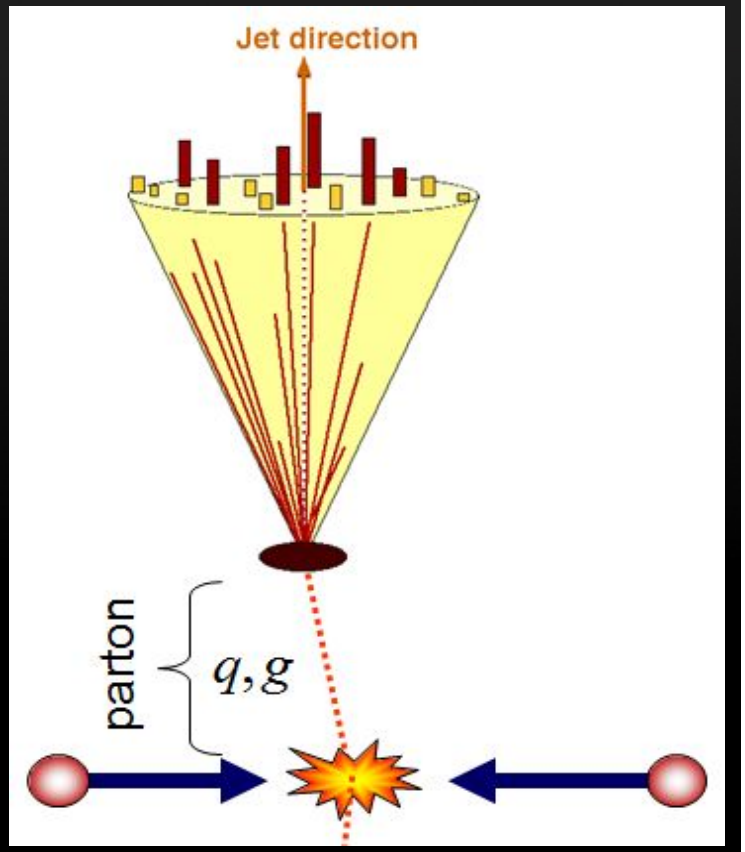

I Vitev, S Wicks, BWZ, JHEP 0811,093 (2008)

# From leading hadrons to jets: Exp



# What is a jet?

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



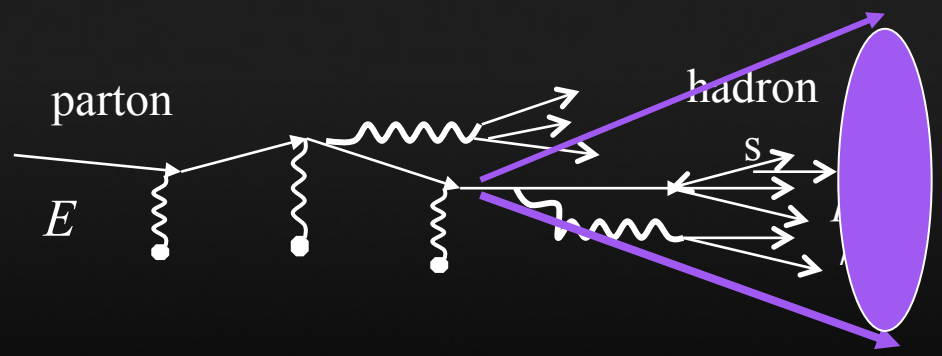

$$E_T = \sum_{i \in jet} E_{T,i}$$

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

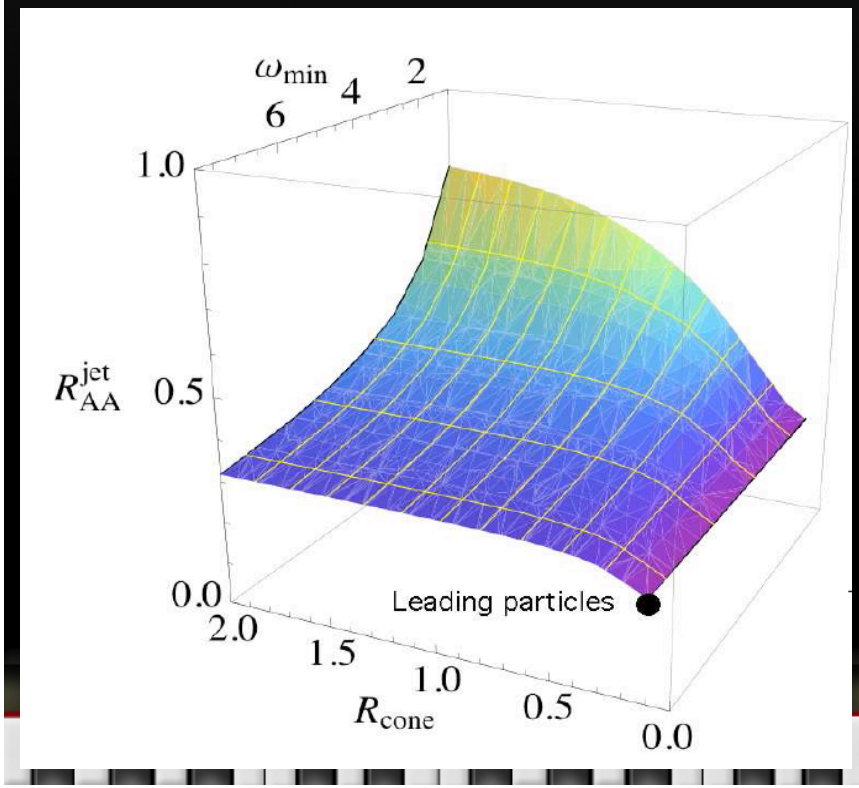
$$\phi = \sum_{i \in jet} \phi_i E_{T,i} / E_T$$

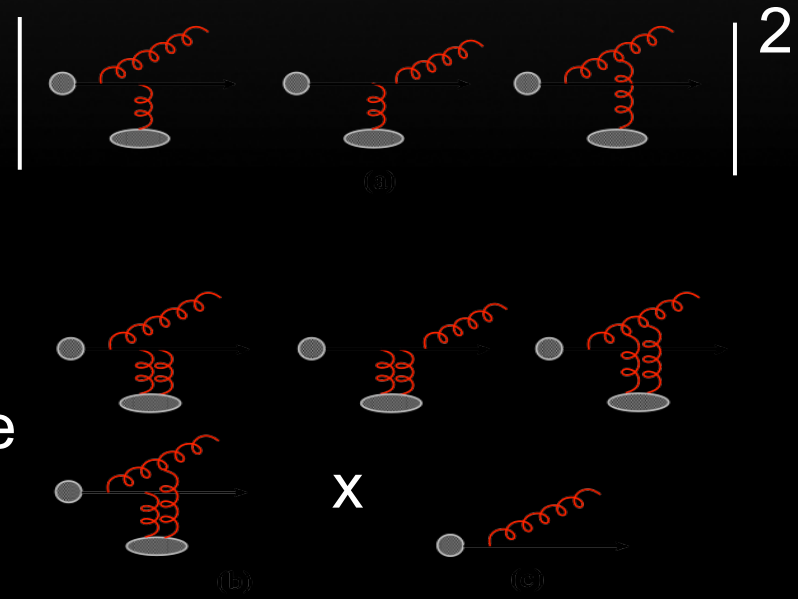
$$R_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}$$

# Jets in medium




Gyulassy-Levai-Vitev



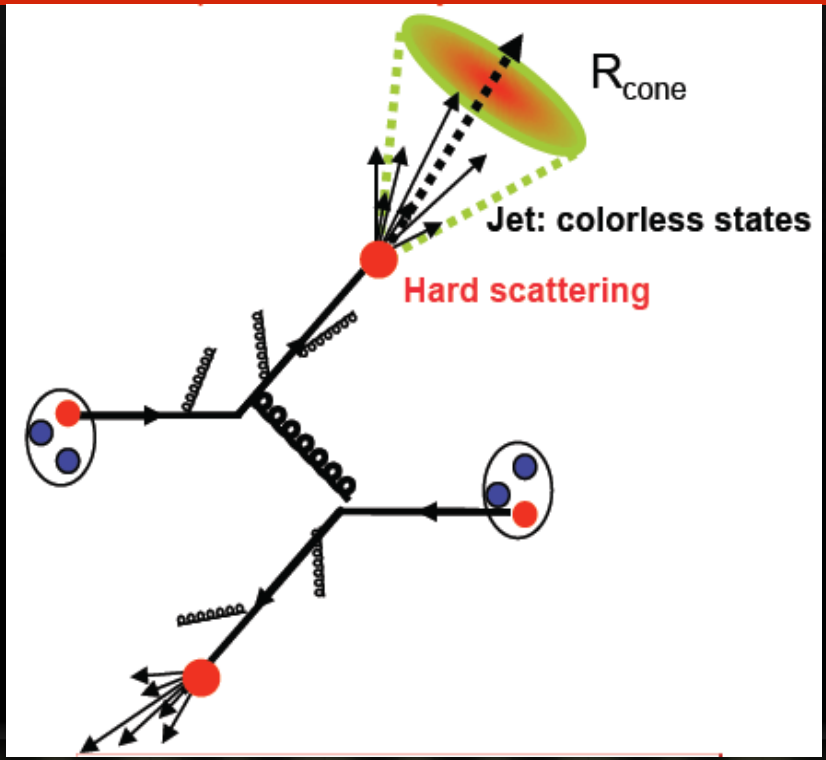
# Jets in HIC

1) inclusive jet spectrum

2) $Z^0$ tagged jet production

3) dijet correlation

# Inclusive jet cross section in HIC at NLO




I Vitev, BWZ, PRL 104,132001 (2010).

# Jet cross section at NLO in p+p

- Jet cross sections at NLO in p+p :

$$\frac{d\sigma^{\text{jet}}}{dE_T dy} = \frac{1}{2!}\int d\{E_T, y, \phi\}_2 \frac{d\sigma[2\to 2]}{d\{E_T, y, \phi\}_2} S_2(\{E_T, y, \phi\}_2) + \frac{1}{3!}\int d\{E_T, y, \phi\}_3 \frac{d\sigma[2\to 3]}{d\{E_T, y, \phi\}_3} S_3(\{E_T, y, \phi\}_3)$$

- Function $S_2$ and $S_3$ contain jet find algorithm:

2 --→ 2

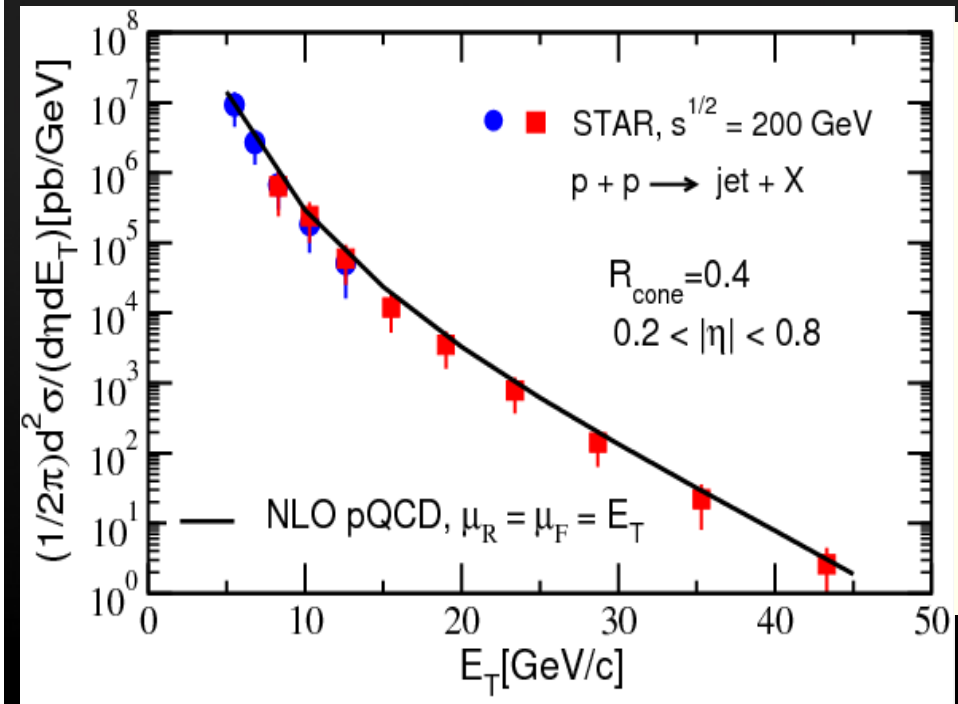
$$S_2 = \sum_{i=1}^{2} S(i) = \sum_{i=1}^{2} \delta(E_{T_i} - E_T)\delta(y_i - y)$$

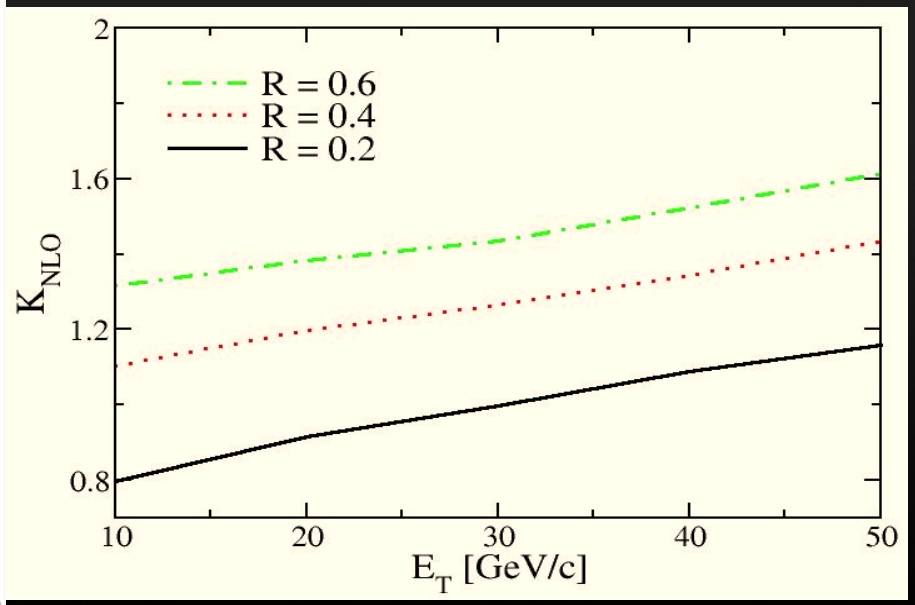
2 --→ 3

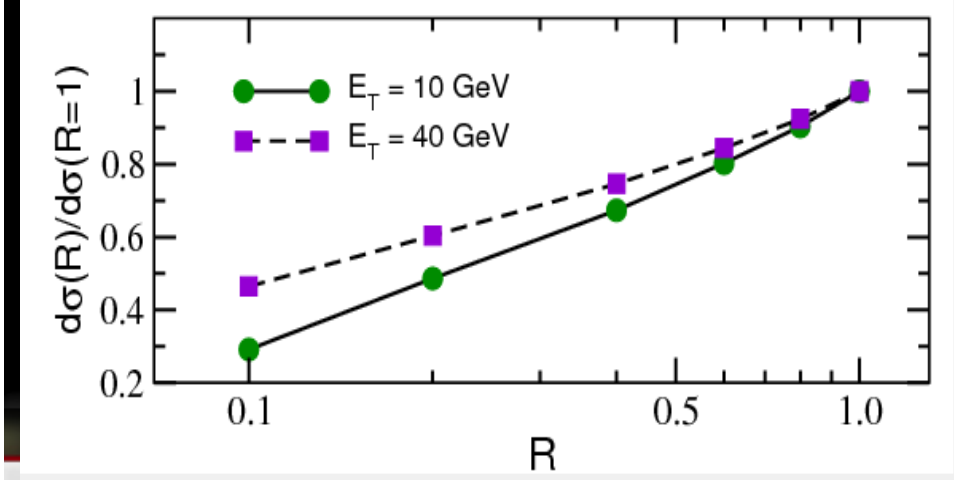
$$S_3 = \sum_i \delta(p_i - p_J)\delta(y_i - y_J) \prod_{j(j\neq i)} \theta\left(R_{ij} > \frac{p_i + p_j}{\max(p_i, p_j)} R\right) + \sum_{i,j(i<j)} \delta(p_i + p_j - p_J)\delta\left(\frac{p_i y_i + p_j y_j}{p_i + p_j} - y_J\right)\theta\left(R_{ij} < R_{\text{rc}}\right)$$

Ellis, Kunszt, Soper, PRL 64:2121(1990); PRL 69:1496(1992)

# Jets in p+p at RHIC



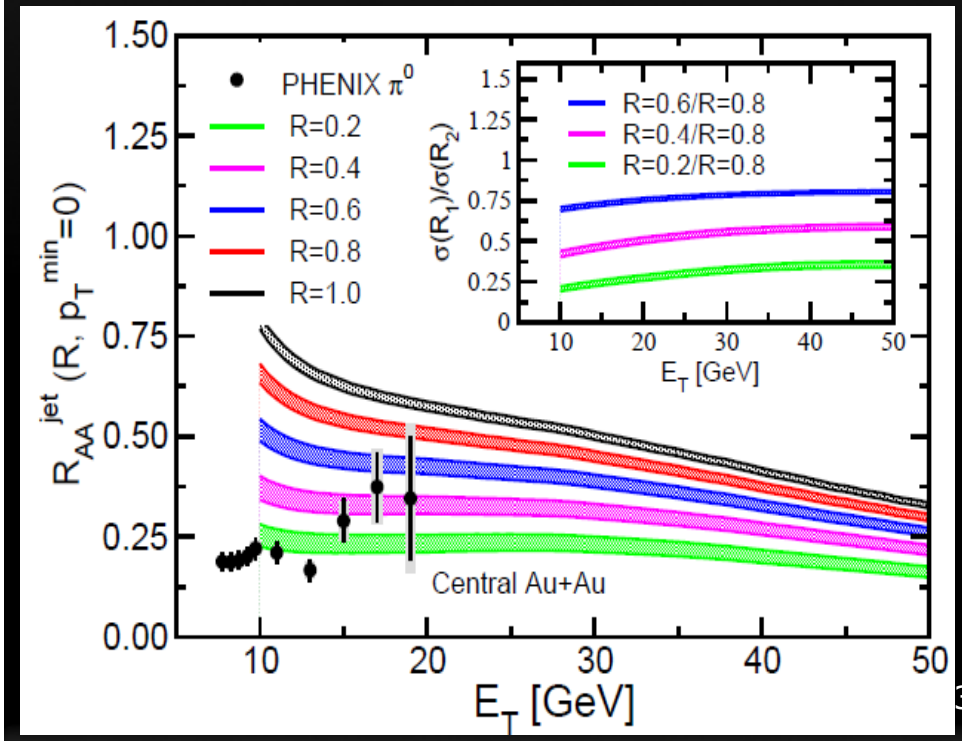



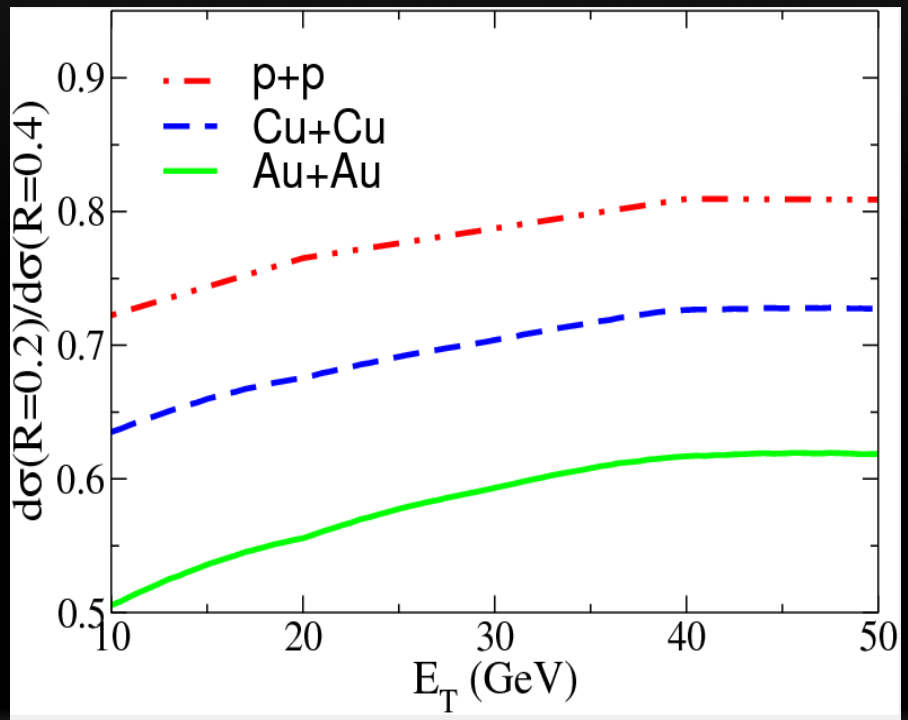




- Very good agreement between data and theory is achieved;
- $K_{NLO}$=NLO/LO can be smaller than 1 at small cone radius.

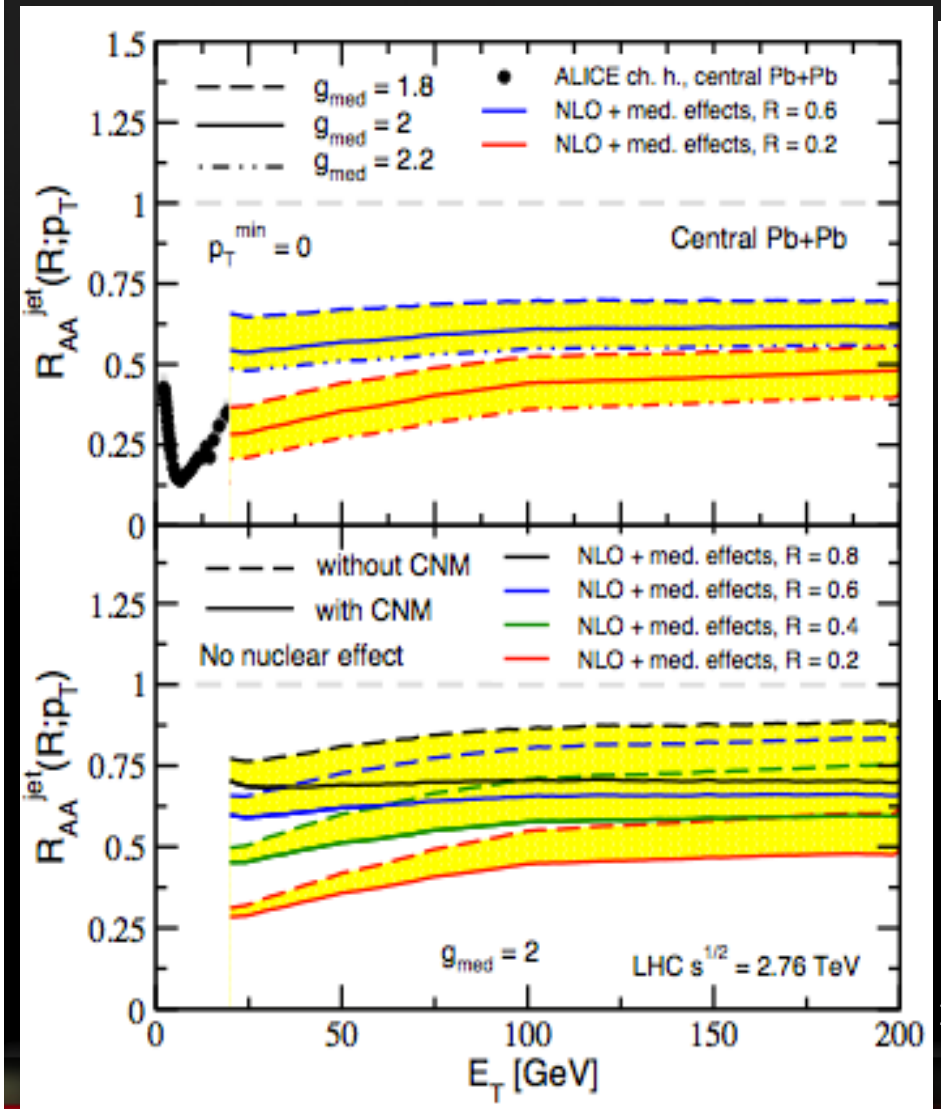
# Inclusive jets in A+A at RHIC

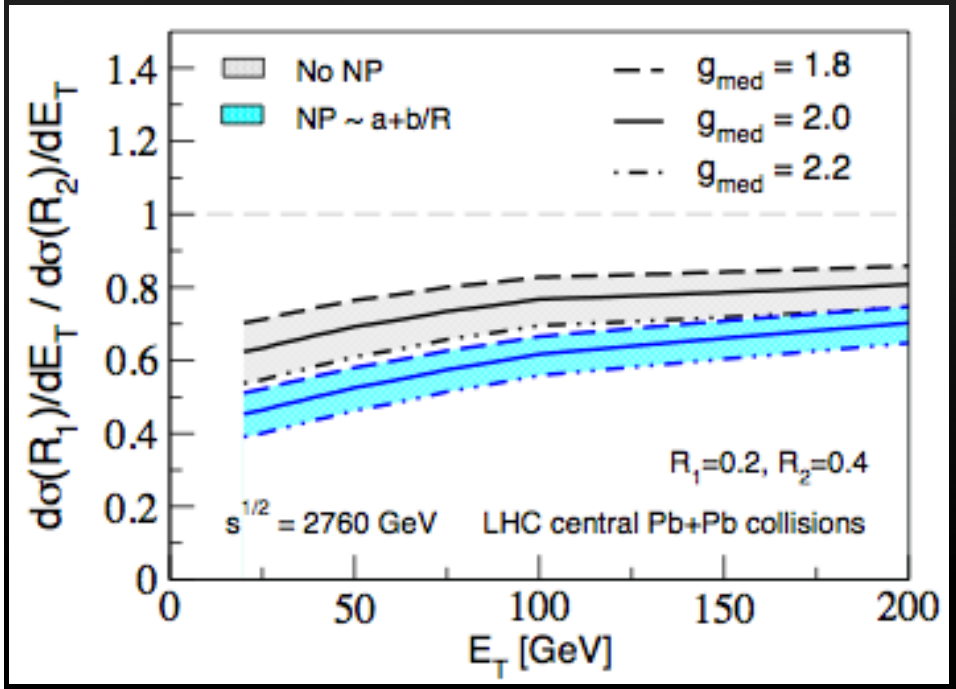
- $R_{AA}$ for inclusive jets evolves continuously with cone size R,
- Ratios of jet cross sections at different R in p+p, Cu+Cu and Au+Au have a similar trend with different magnitudes.



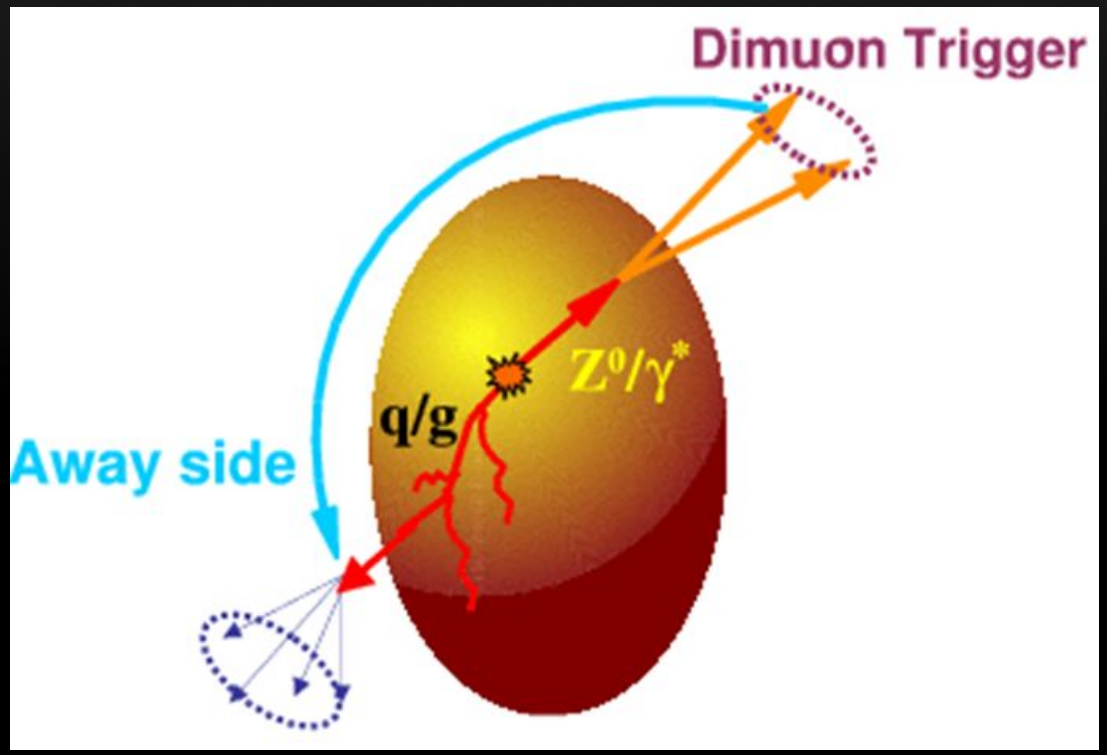
# Inclusive jets in Pb+Pb at LHC

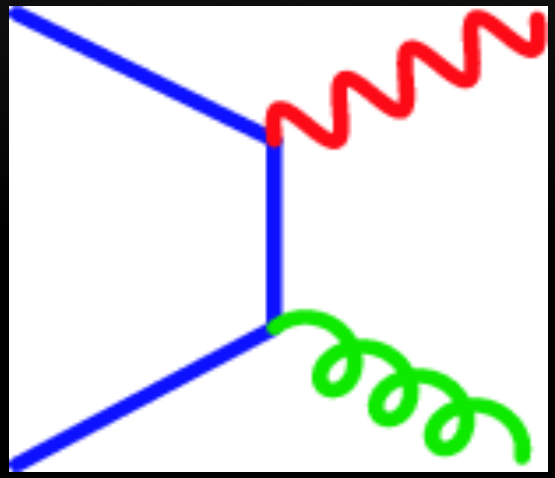



Y He, Vitev, BWZ, PLB (2012)

# Tagged jet production in HIC at NLO



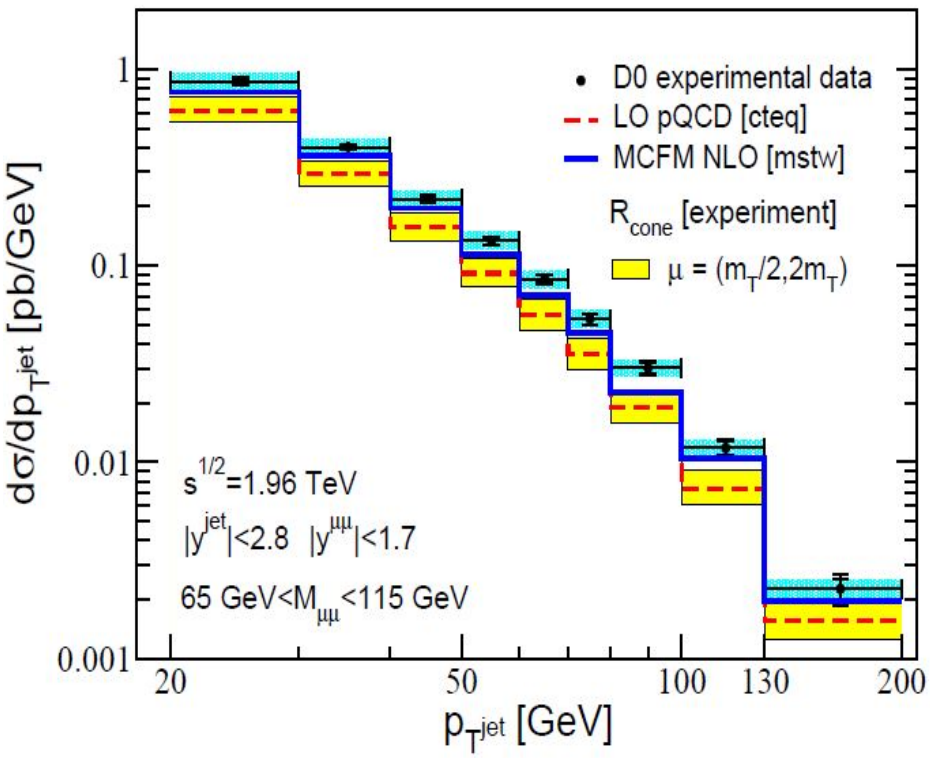



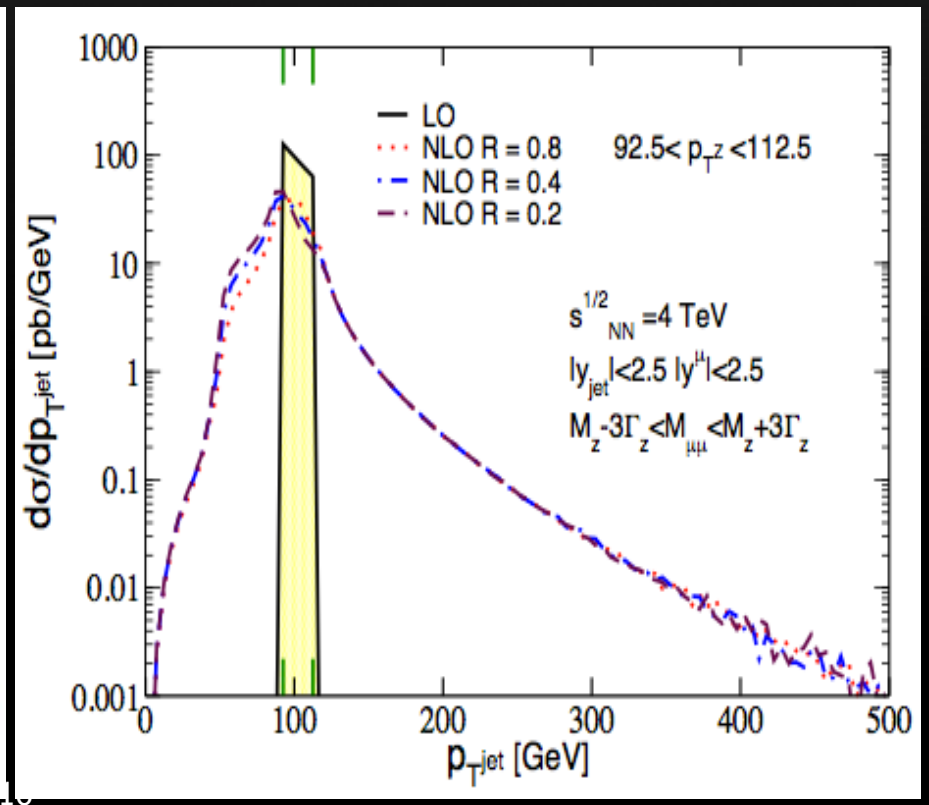


Neufeld, Vitev, BWZ, PRC 83, 034902 (2011).

# $Z^o$ + jet in h+h

- NLO pQCD gives a good description of the data at D0
- The momentum balance is broken due to NLO contribution



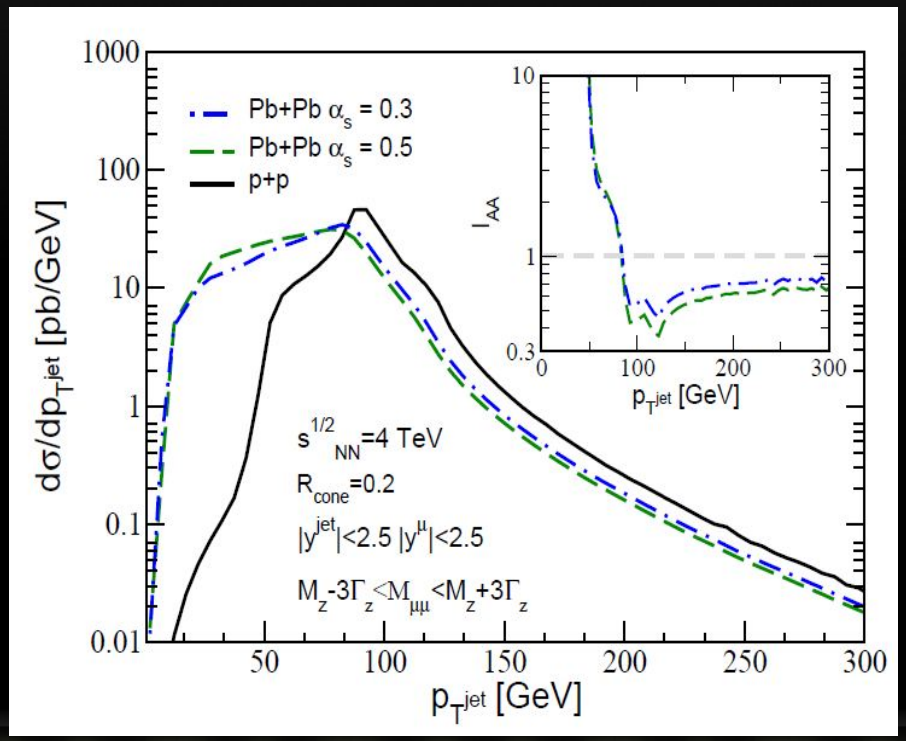



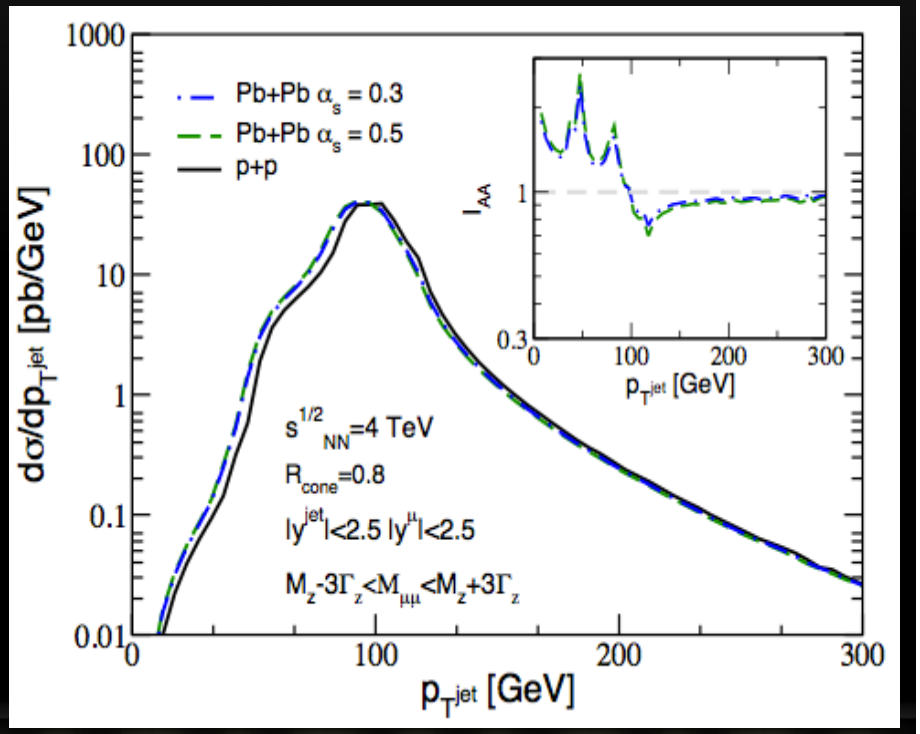

$p_T \in (92.5\text{GeV}, 112.5\text{GeV})$

# Z° + jet in A+A: Iaa

- A sharp transition from tagged jet suppression above ~pT of Z to tagged jet enhancement below ~pT of Z

$$I_{AA}^{\rm jet}(R,\omega_{\rm min}) = \frac{1}{\langle N_{\rm bin}\rangle}\frac{d\sigma_{AA}}{dp_{T\,(Z)}dp_{T\,(Q)}}\Bigg/\frac{d\sigma_{pp}}{dp_{T\,(Z)}dp_{T\,(\rm jet)}}$$



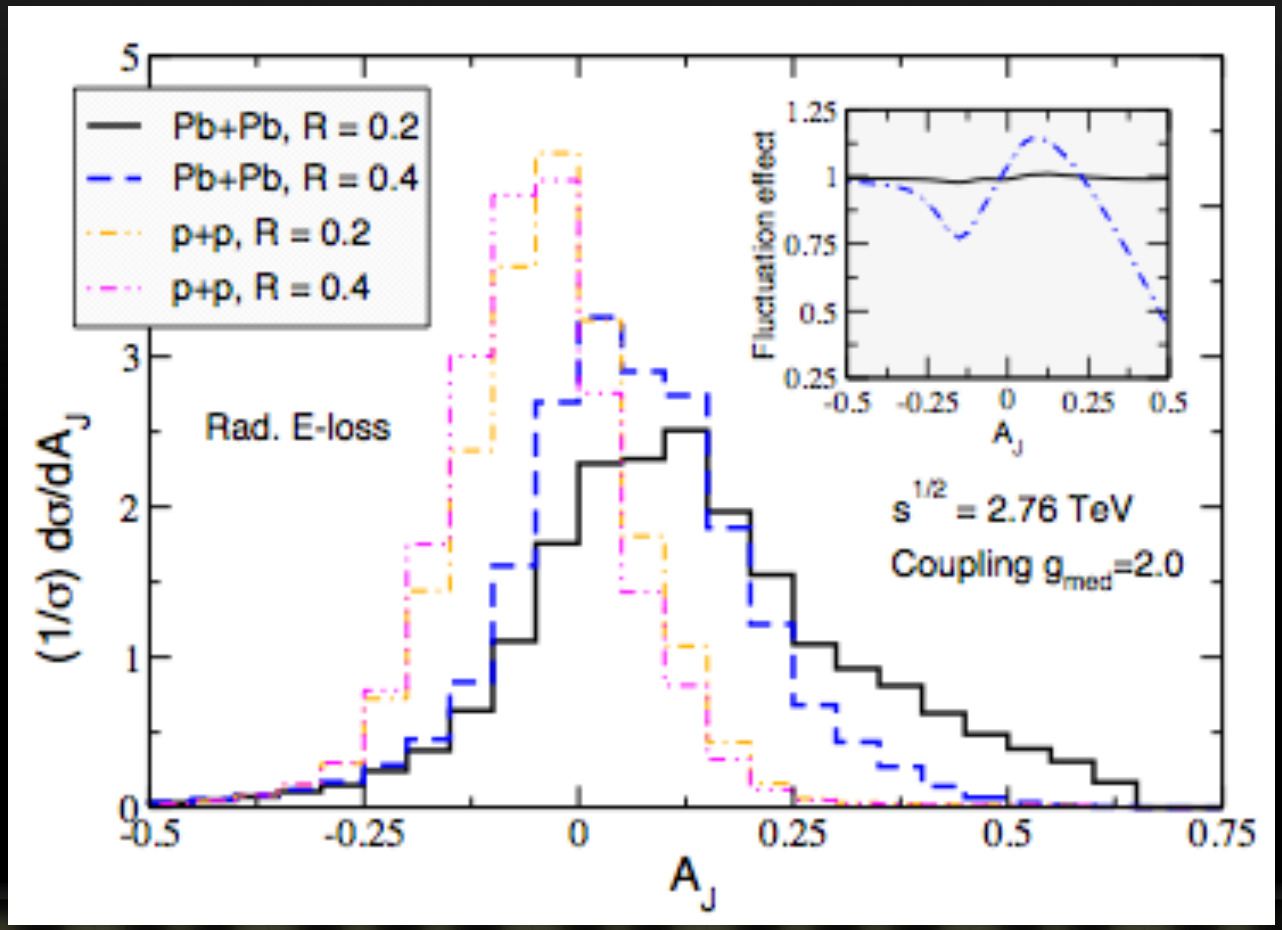




Neufeld, Vitev, BWZ, PRC 83, 034902 (2011).

$p_T \in (92.5\text{GeV}, 112.5\text{GeV})$

# $Z^o$ + jet in A+A: asymmetry

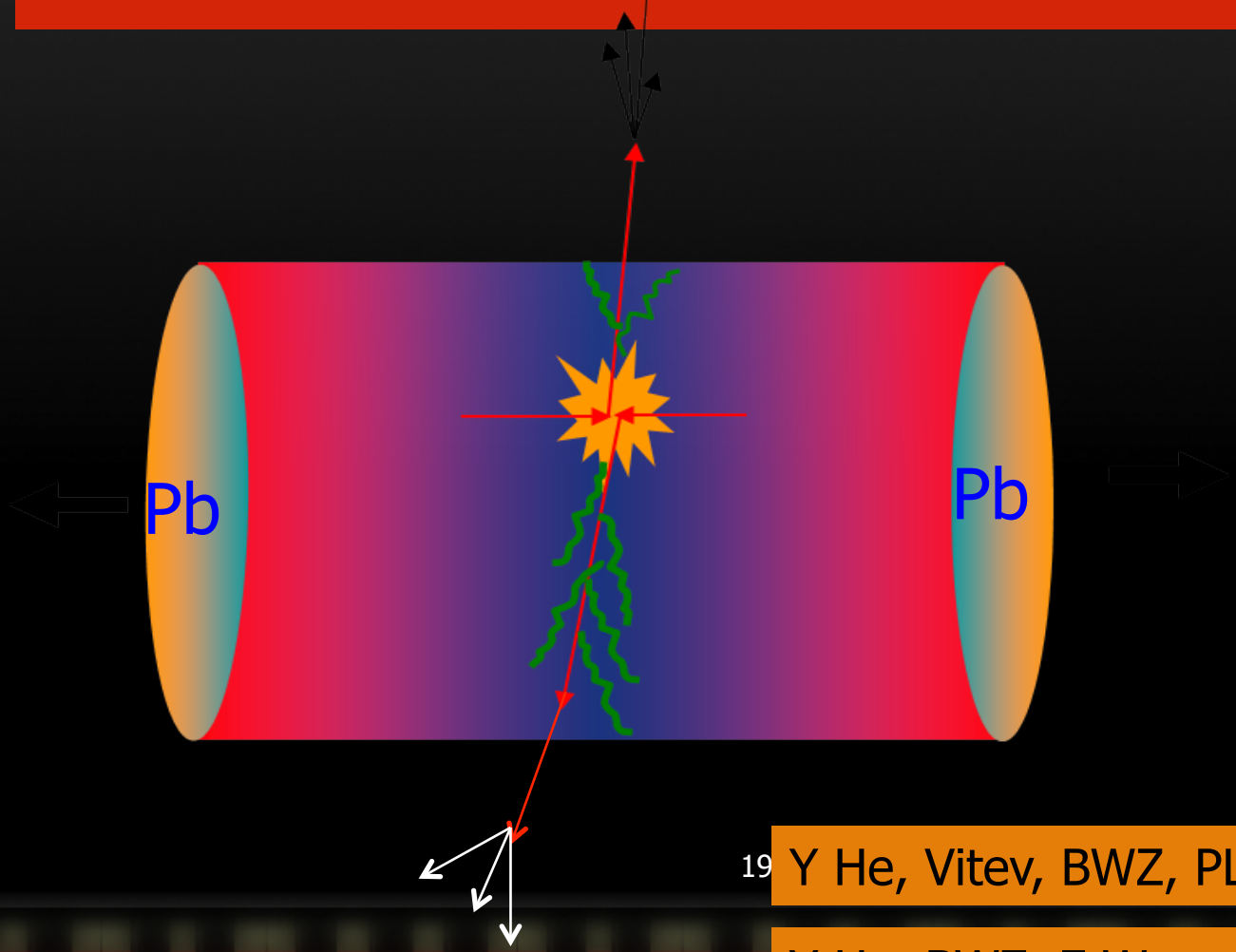
- AJ distributions in Pb+Pb are strongly shifted to large AJ region and broader with a positive average AJ.




$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

Neufeld, Vitev, arxiv: 1202.5556

# Dijet production in HIC at NLO

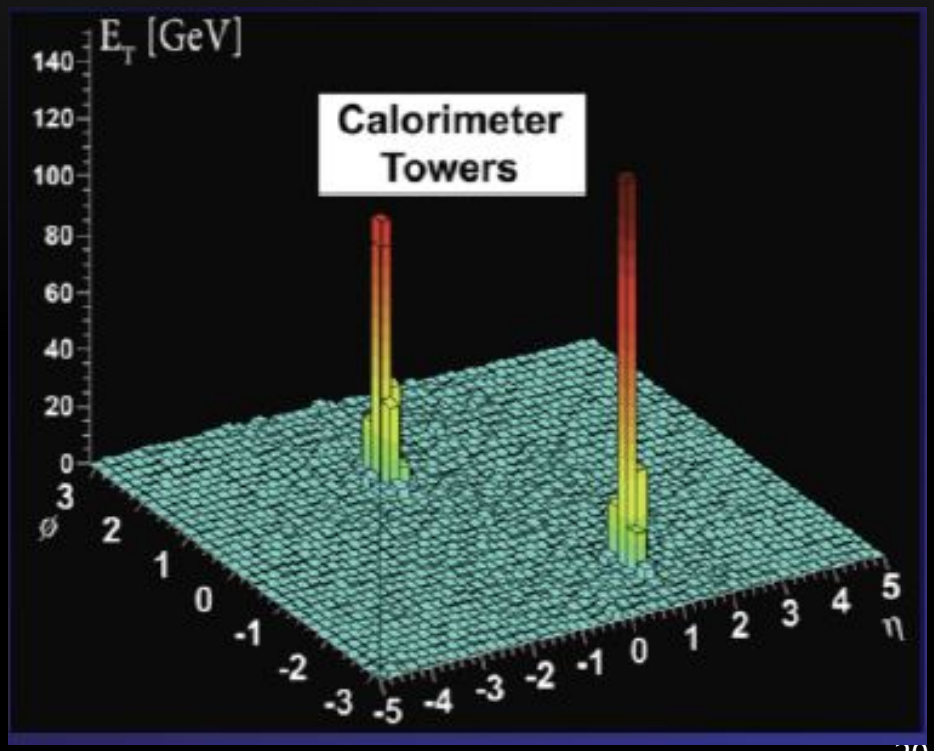


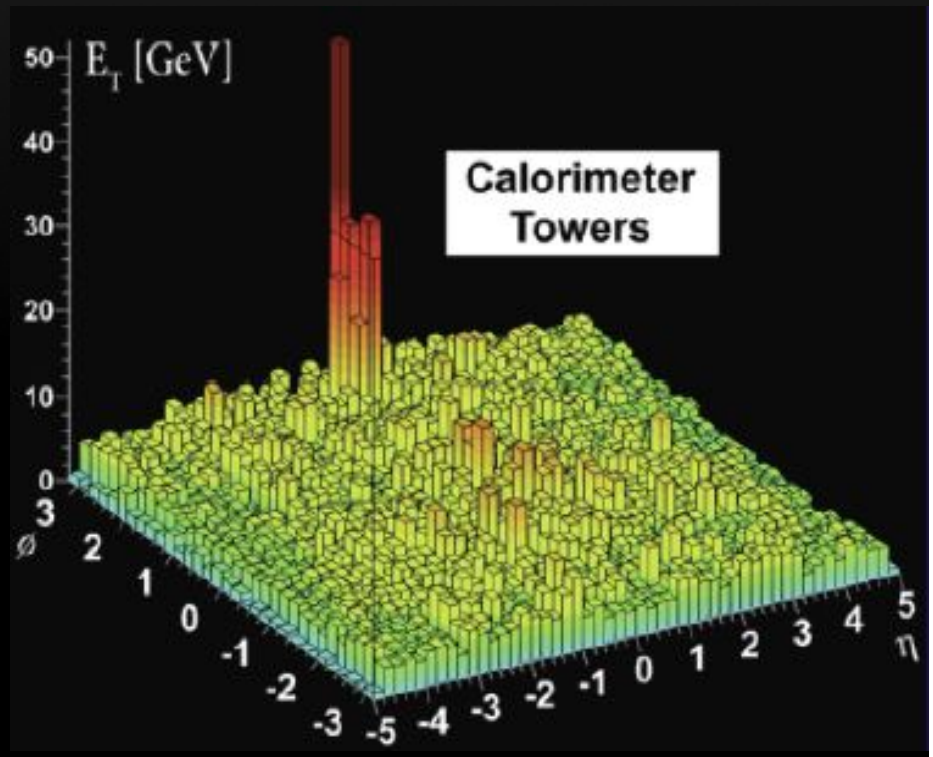

Y He, Vitev, BWZ, PLB (2012)

Y He, BWZ, E Wang, EJPC (2012)

# Measuring Dijets in Pb+Pb

- Jet quenching at LHC has been observed for the first time in dijet productions at Pb+Pb by ATLAS and CMS。



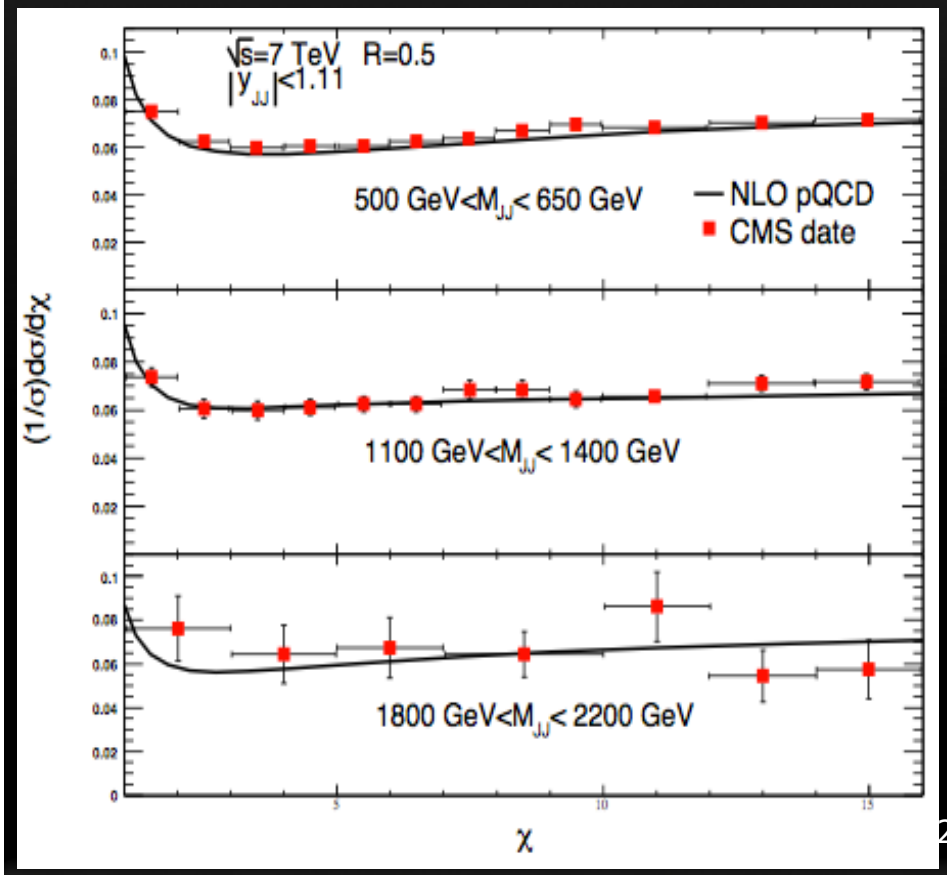



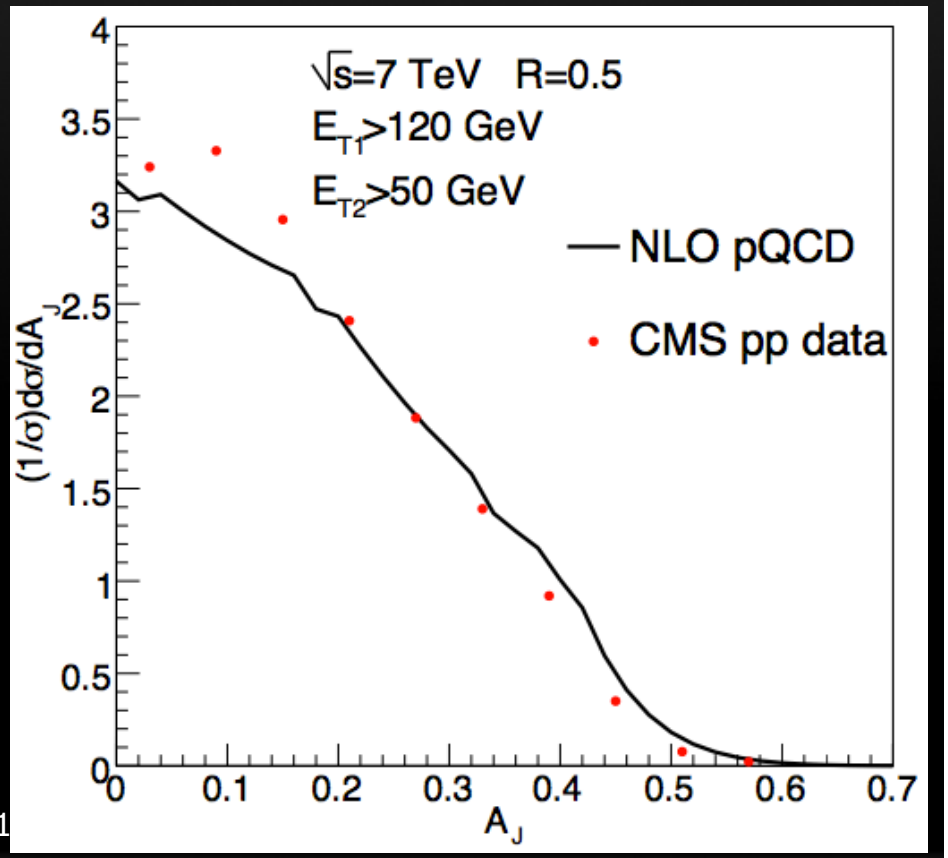

ATLAS, arXiv:1011.6182, PRL (2011); CMS, arXiv: 1102.1957, PRC(2011)

# Dijet in p+p at NLO

$$\chi = \frac{1+\cos\theta^*}{1-\cos\theta^*}$$

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$



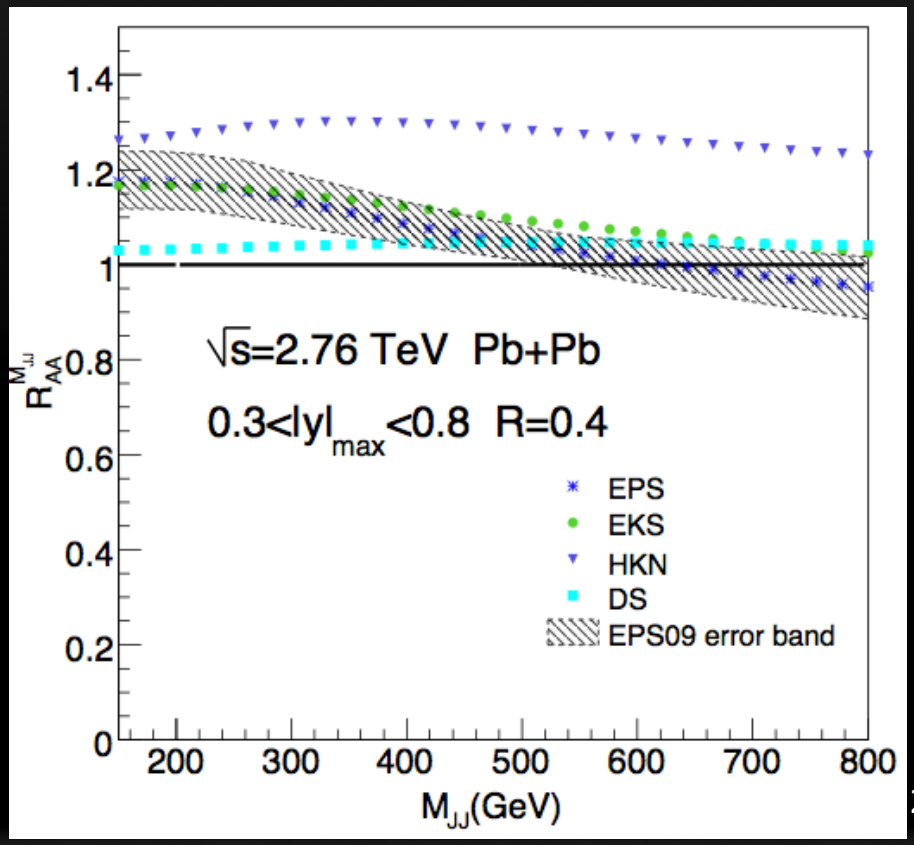



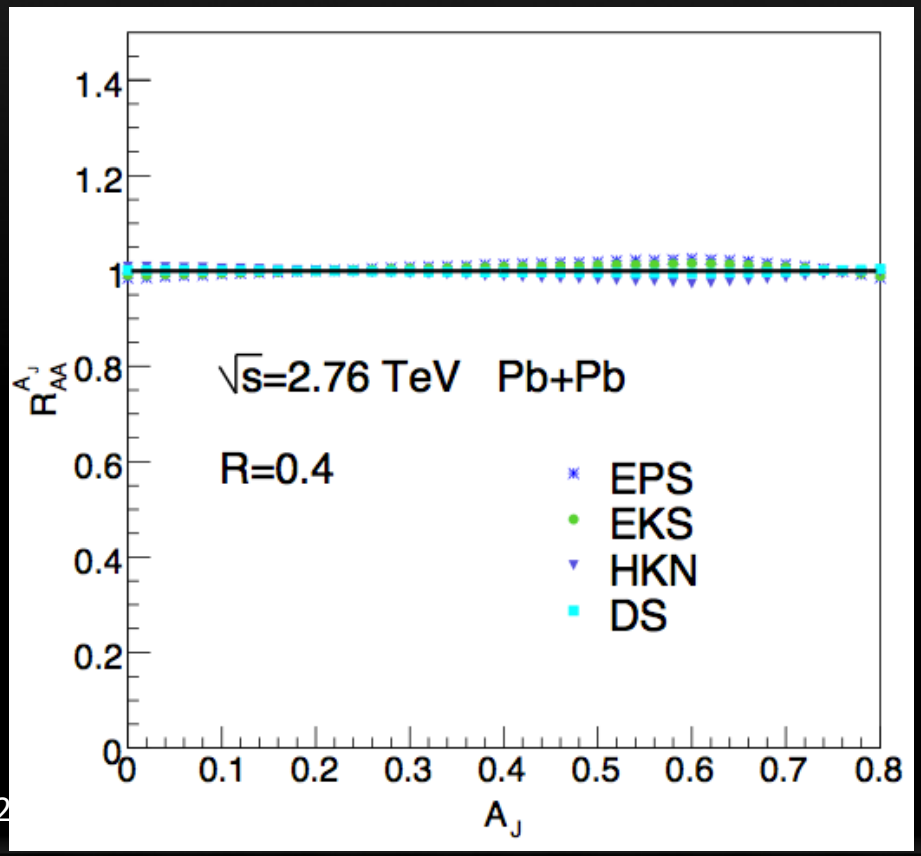

Y He, BWZ, E Wang, EPJC (2012)

# Dijet in HIC: CNM

$$M_{jj}^2 = 2p_T^2[1 + cosh(y_1 - y_2)]$$

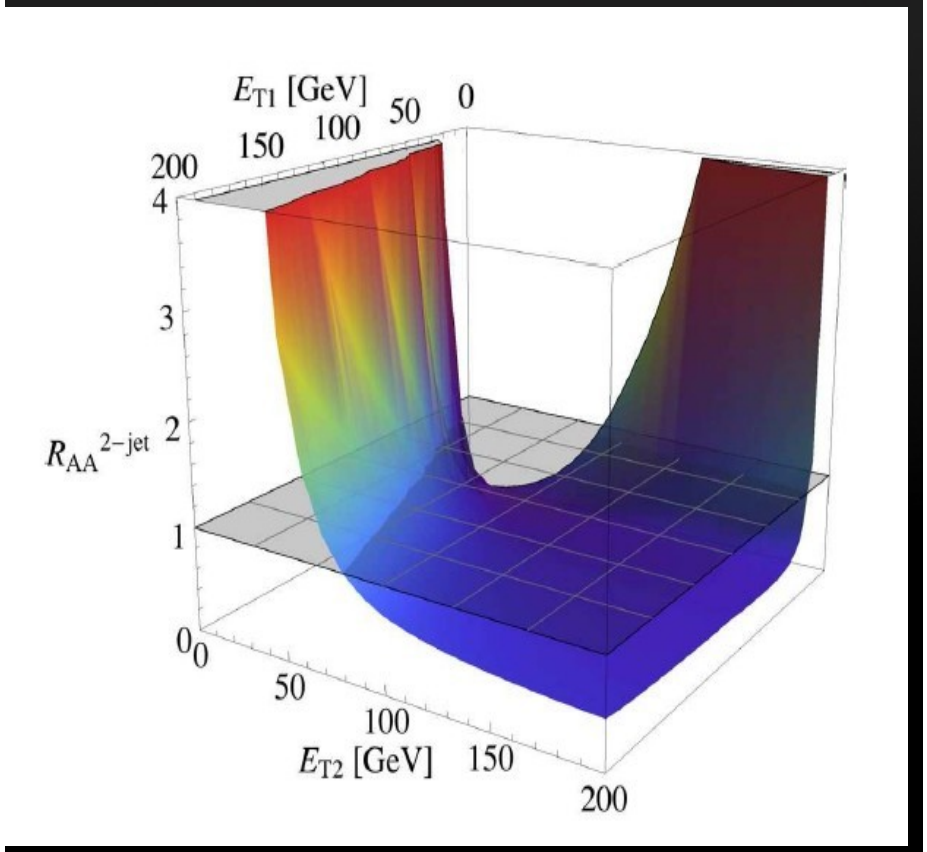
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

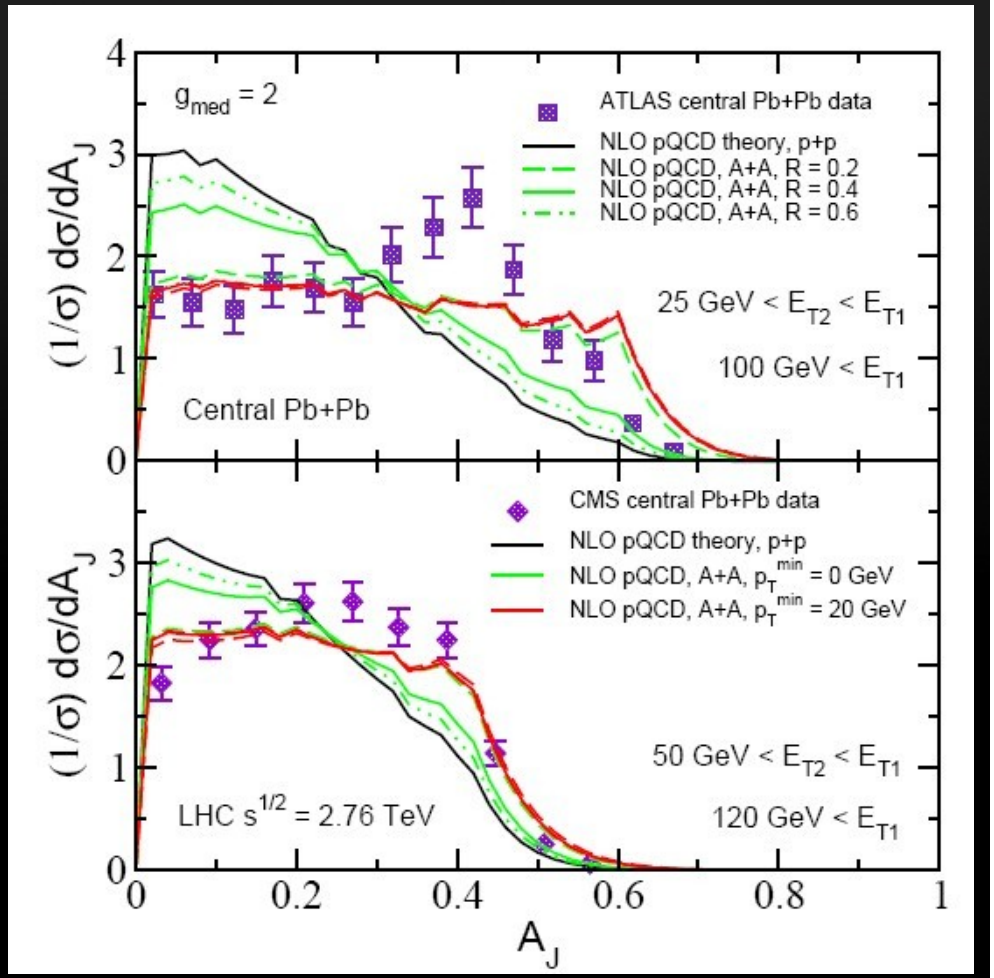



Y He, BWZ, E Wang, EPJC (2012)

# Dijet in Pb+Pb at LHC



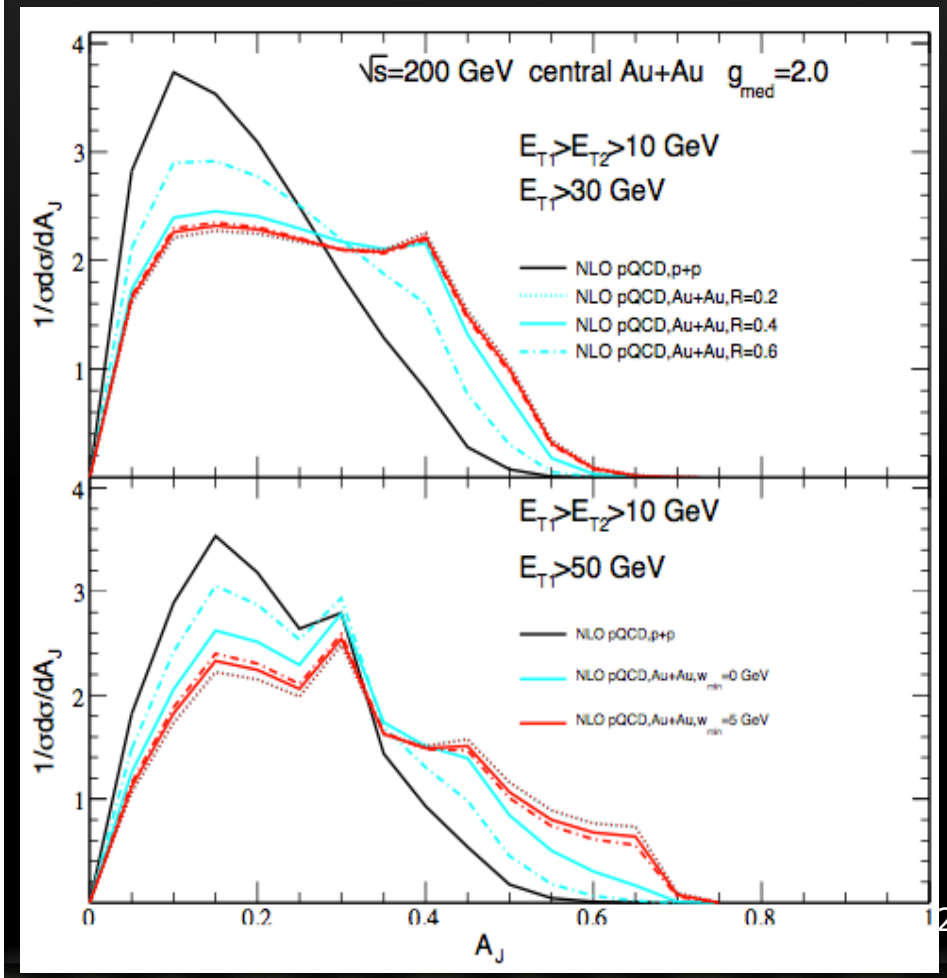

Y He, Vitev, BWZ, PLB (2012)

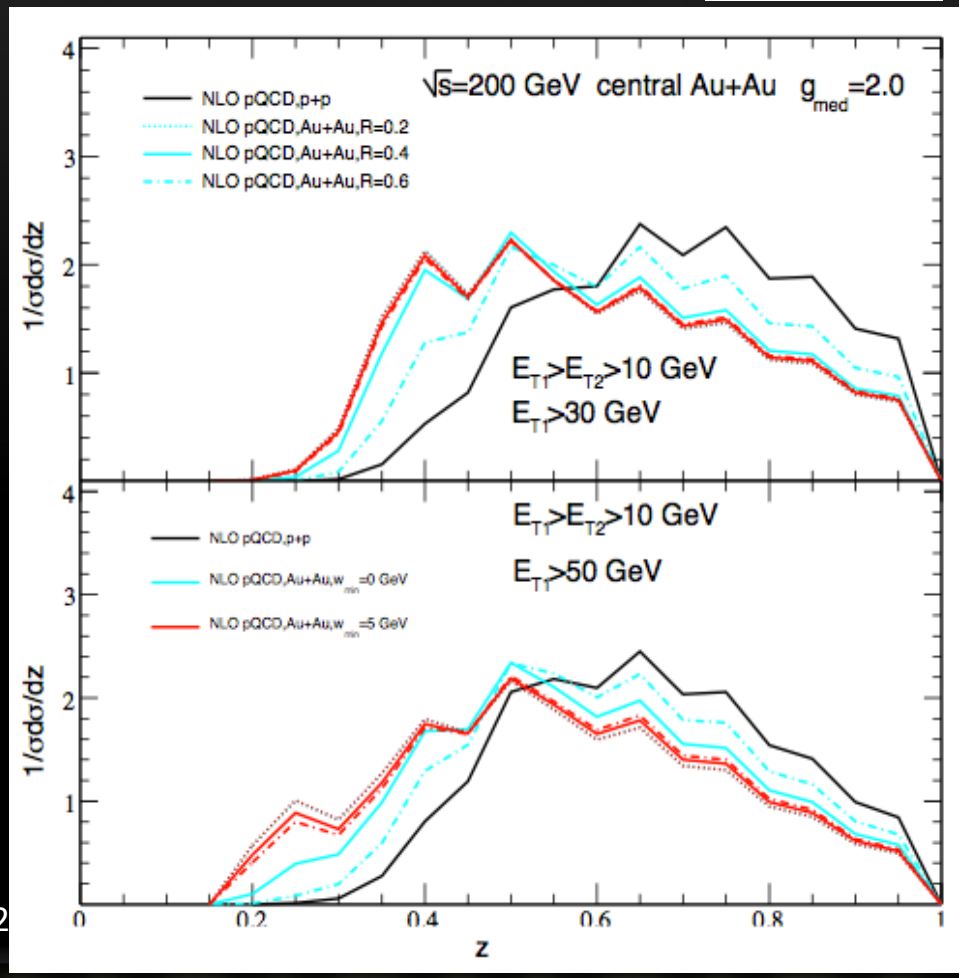
ATLAS, PRL (2011);

CMS, PRC(2012).

# Dijet in Au+Au at RHIC

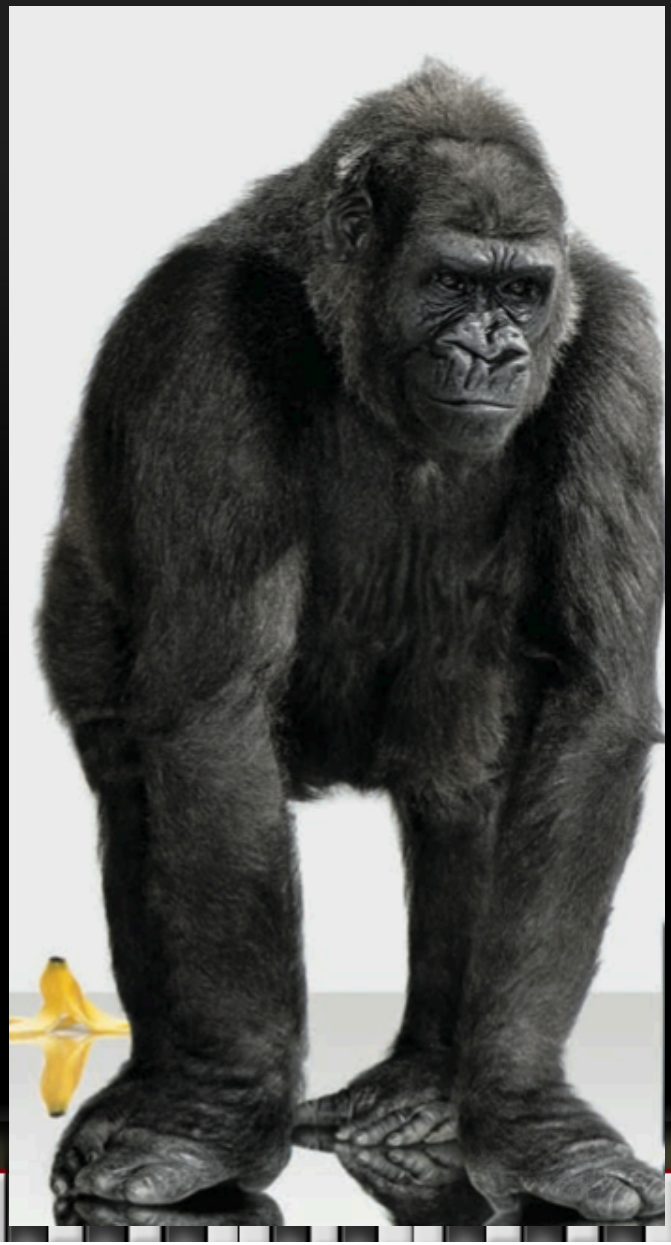
$$z = \frac{E_{T2}}{E_{T1}}$$




Y He, Neufeld, Vitev, BWZ, in preparation

# Recap



leading hadrons

# Recap

leading hadrons

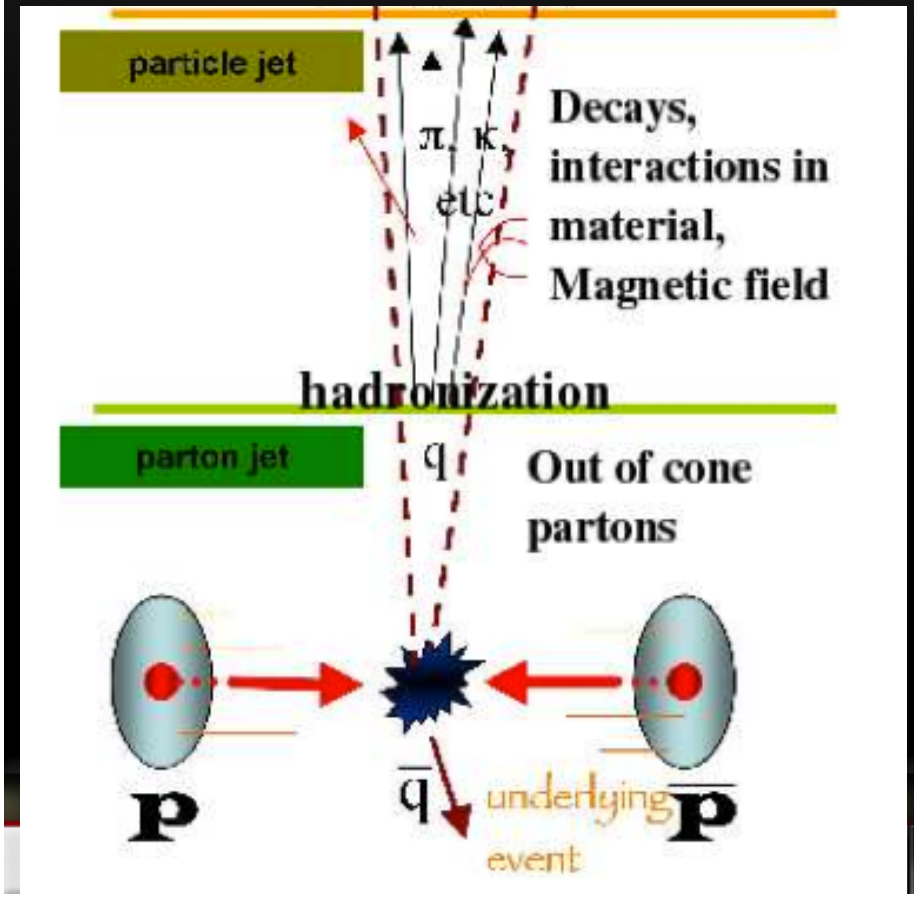
jets

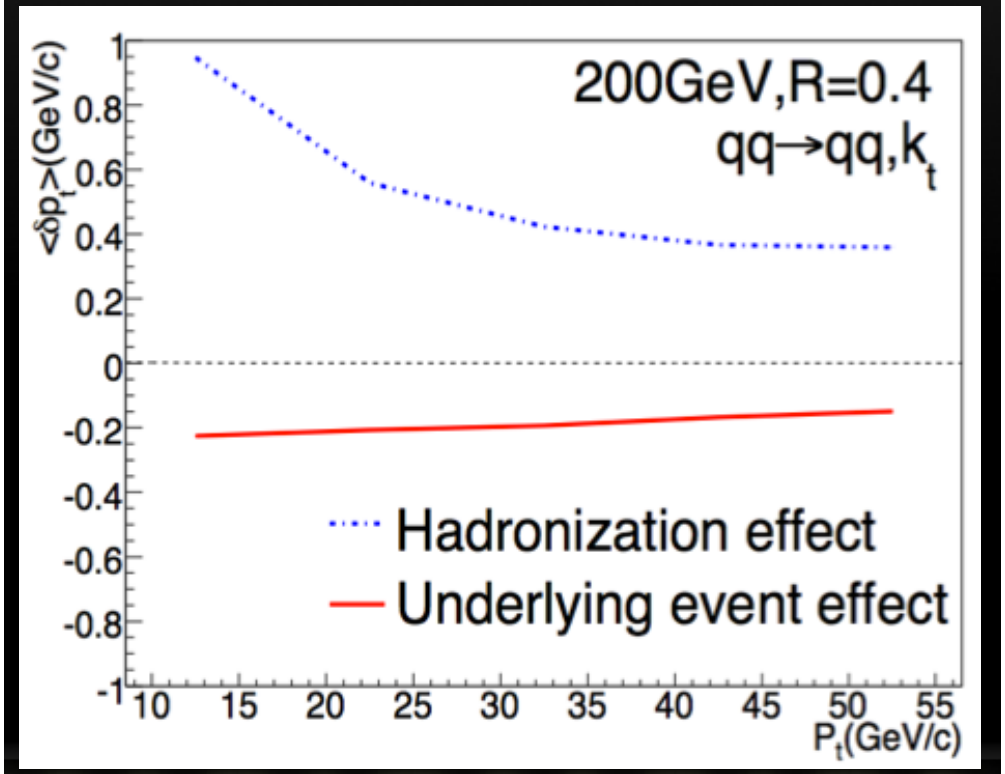
非常感谢！

Thank you!

# Non-perturbative effects

- Non-perturbative effects: hadronization & underlying event.
- Two effects will go in opposite direction: partial cancellation between "splash-out" effect and "splash-in" effect.

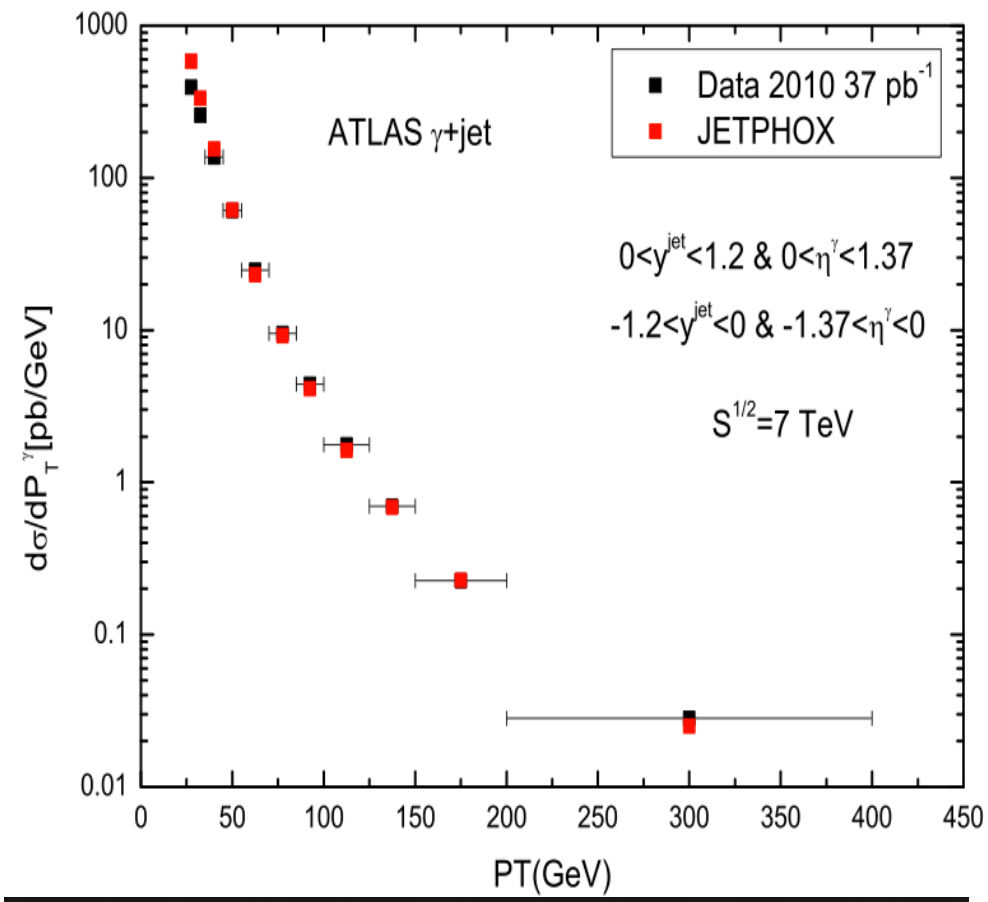


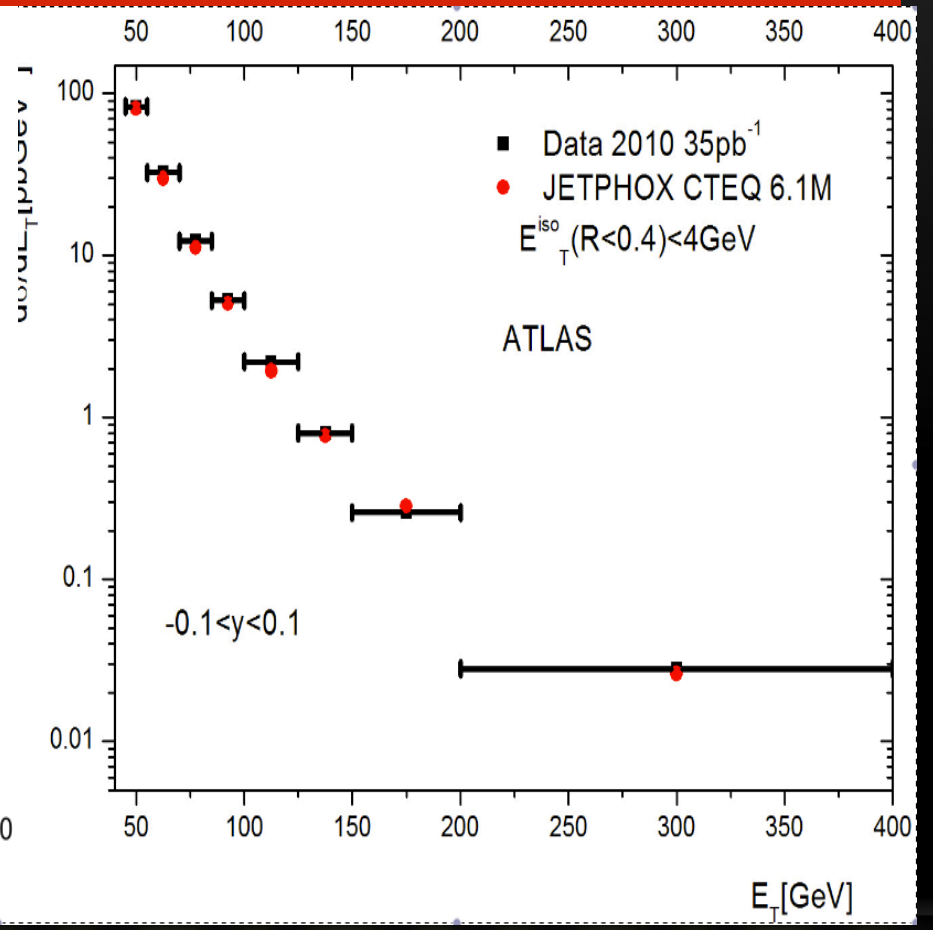




H Li, BWZ, E Wang (2012)

# Photon + jet: stay tuned

- A good baseline for photon+jet in hadron-hadron production has been given by the NLO pQCD.

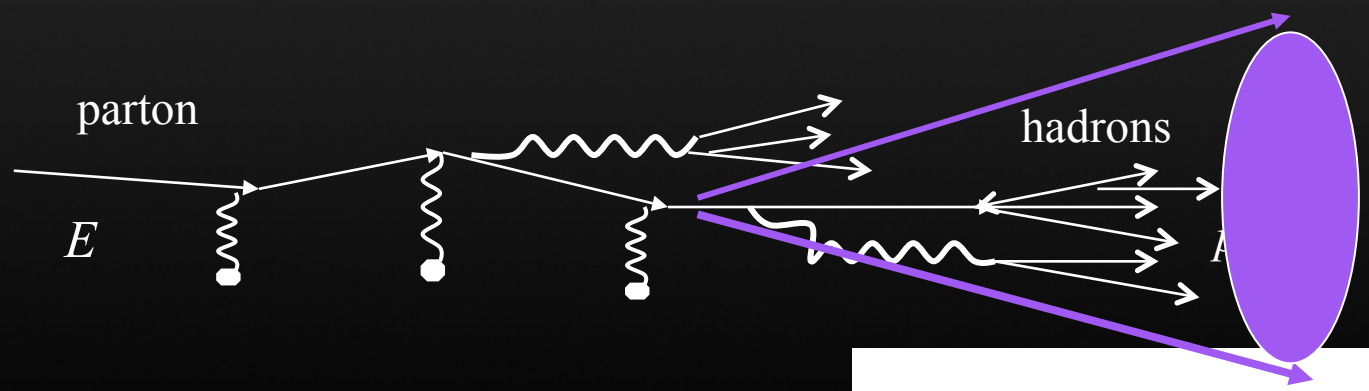


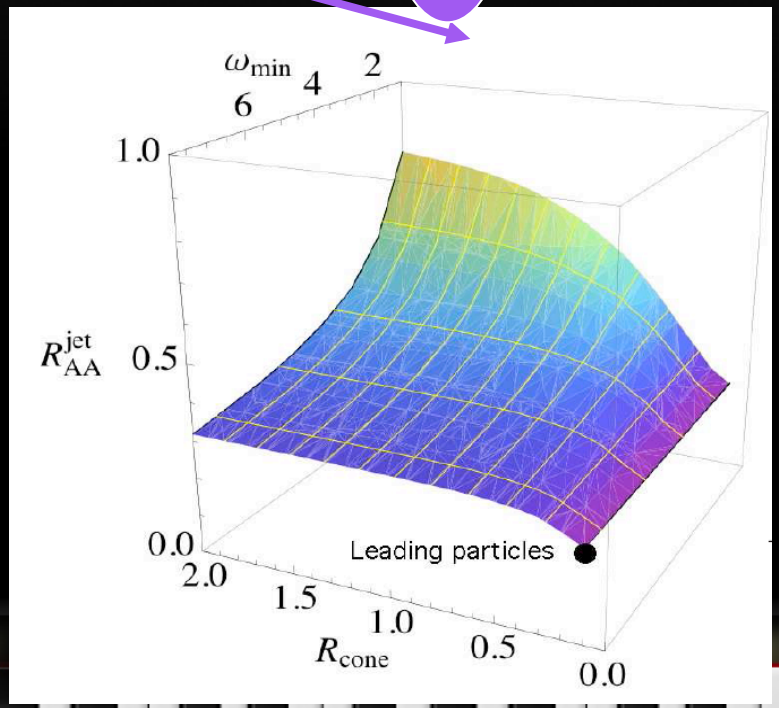

ATLAS, 1203.3161

ATLAS, 1012.4389

# How a "jet" quenches in HIC?




- Radiated gluon can fall inside the jet area.
- Two leverage variables: jet size R & minimum momentum cut $pT_{min}$ .



# Jet finding algorithms

- Cone algorithm
- Midpoint cone algorithm
- $k_T$ algorithm

$$k_{T,i}^2 = p_{T,i}^2$$

$$k_{T,(i,j)}^2 = \min(p_{T,i}^2, p_{T,j}^2)\frac{R_{i,j}^2}{D^2}$$

$$\text{if } k_{T,(i,j)}^2 < k_{T,i}^2, \text{ merge}$$

- Anti-$k_T$ algorithm
- Seedless algorithm

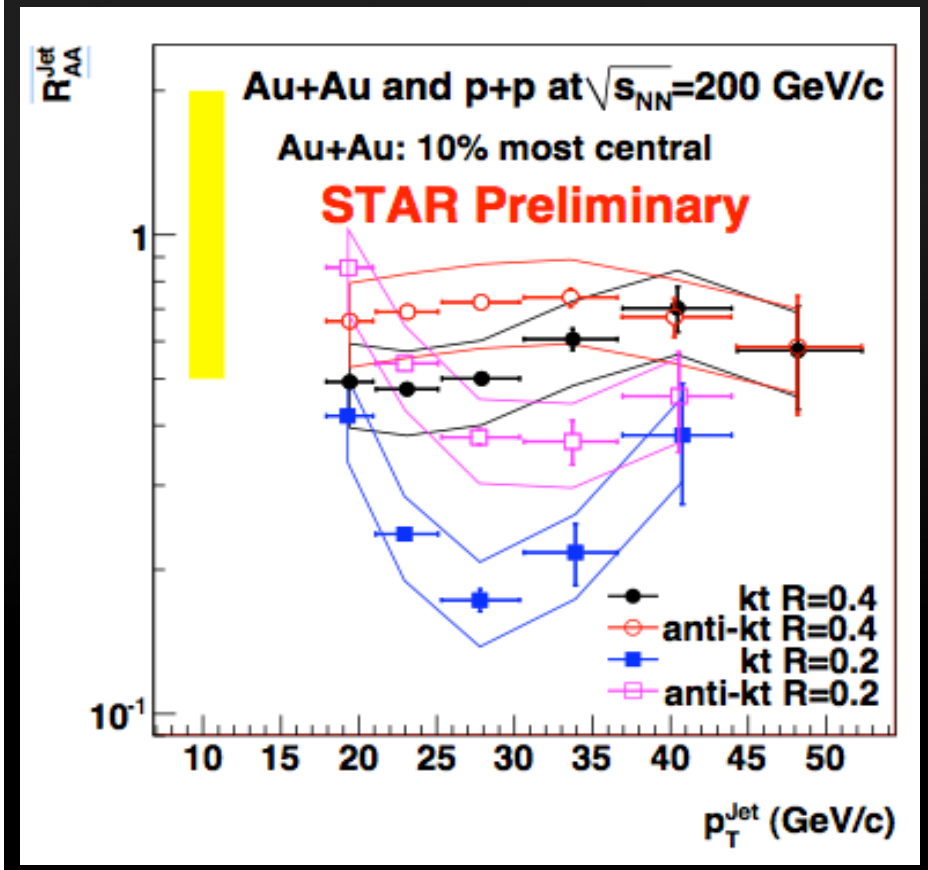
Parton merge parameter

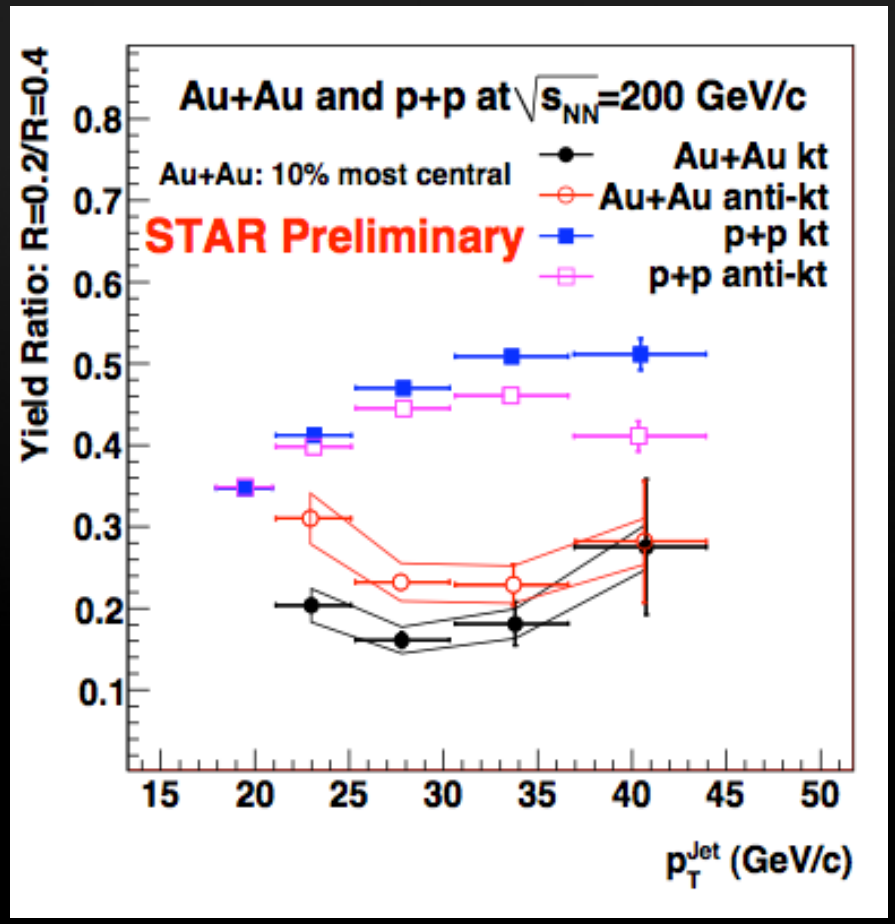
NLO

$$R_{\rm rc} = \min\left(R_{sep}R, \frac{E_{T_i} + E_{T_j}}{\max(E_{T_i}, E_{T_j})}R\right)$$

- Midpoint cone $R_{sep} = 2$
- Cone $1 < R_{sep} < 2$
- $K_T$ $D = R,\ R_{sep} = 1$

# Jet measuring at RHIC




- Jets in Au+Au by STAR

M. Poloszkon et al, (2010)

S. Salur et al, (2010)