Jets in the Little Bang

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Outline

- Introduction
- Jet observables in HIC

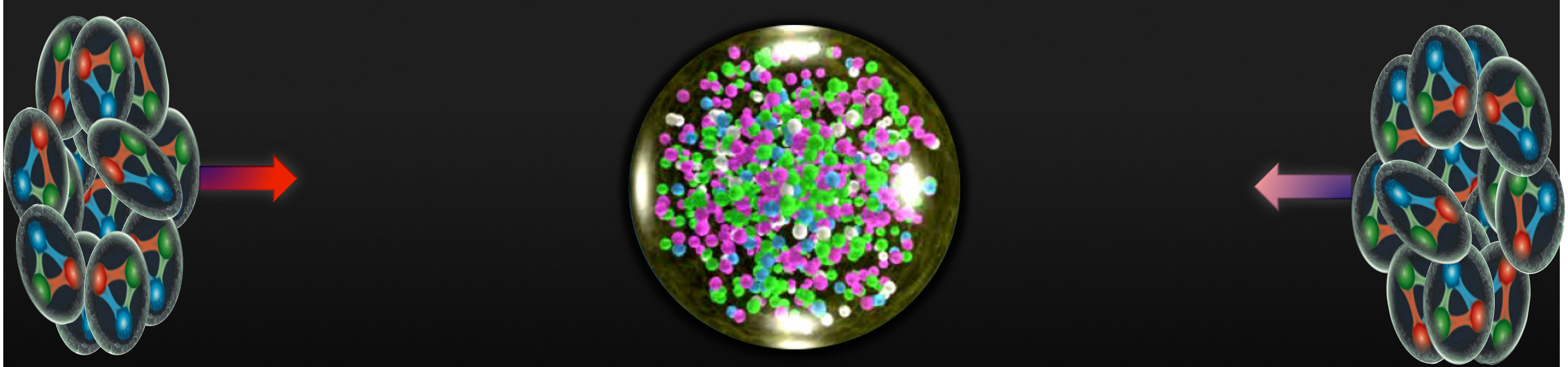
  1) inclusive jet cross section

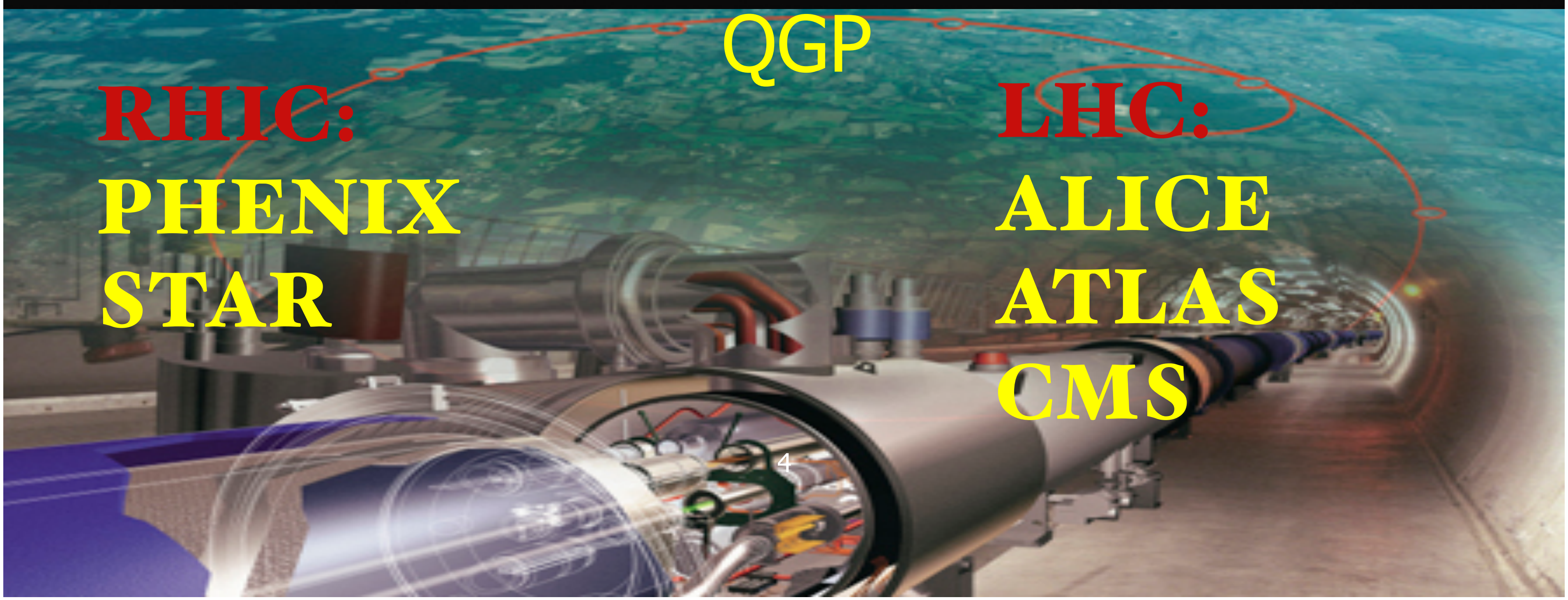
  2) di-jet production

  3) productions of tagged jets
- Summary

Jet quenching: From hadrons to jets

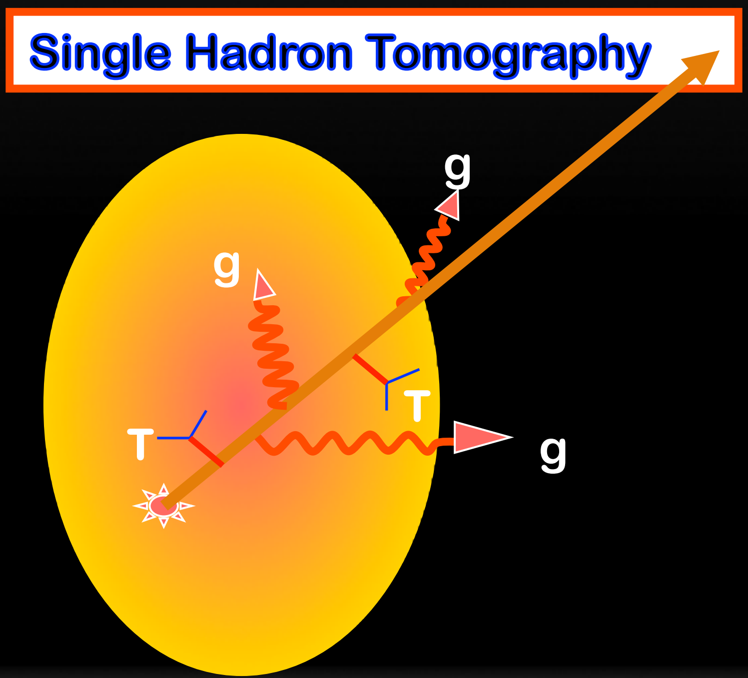
QGP and the Little Bang

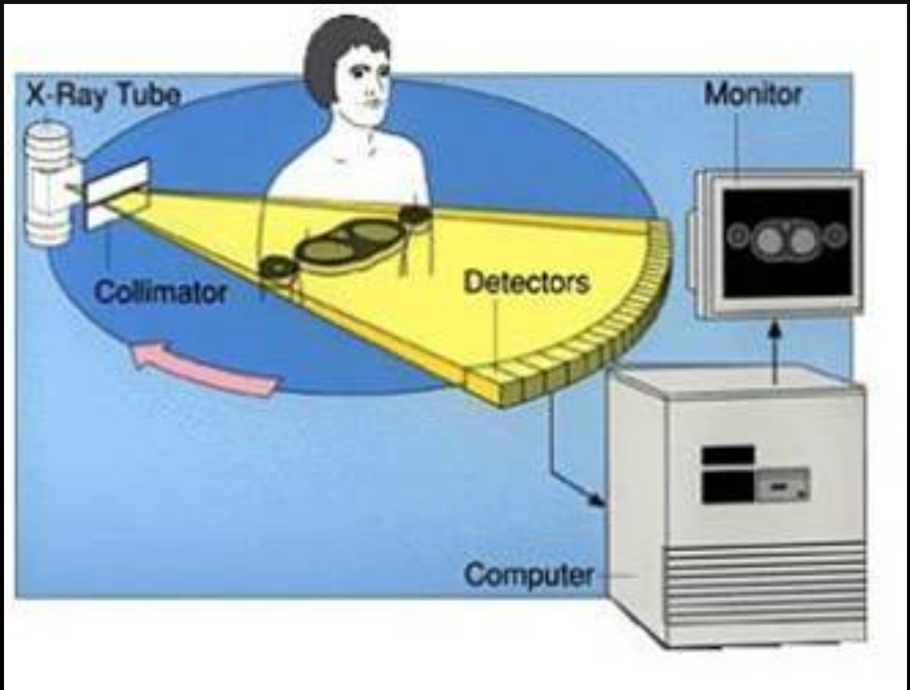




Jet quenching as a hard probe

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

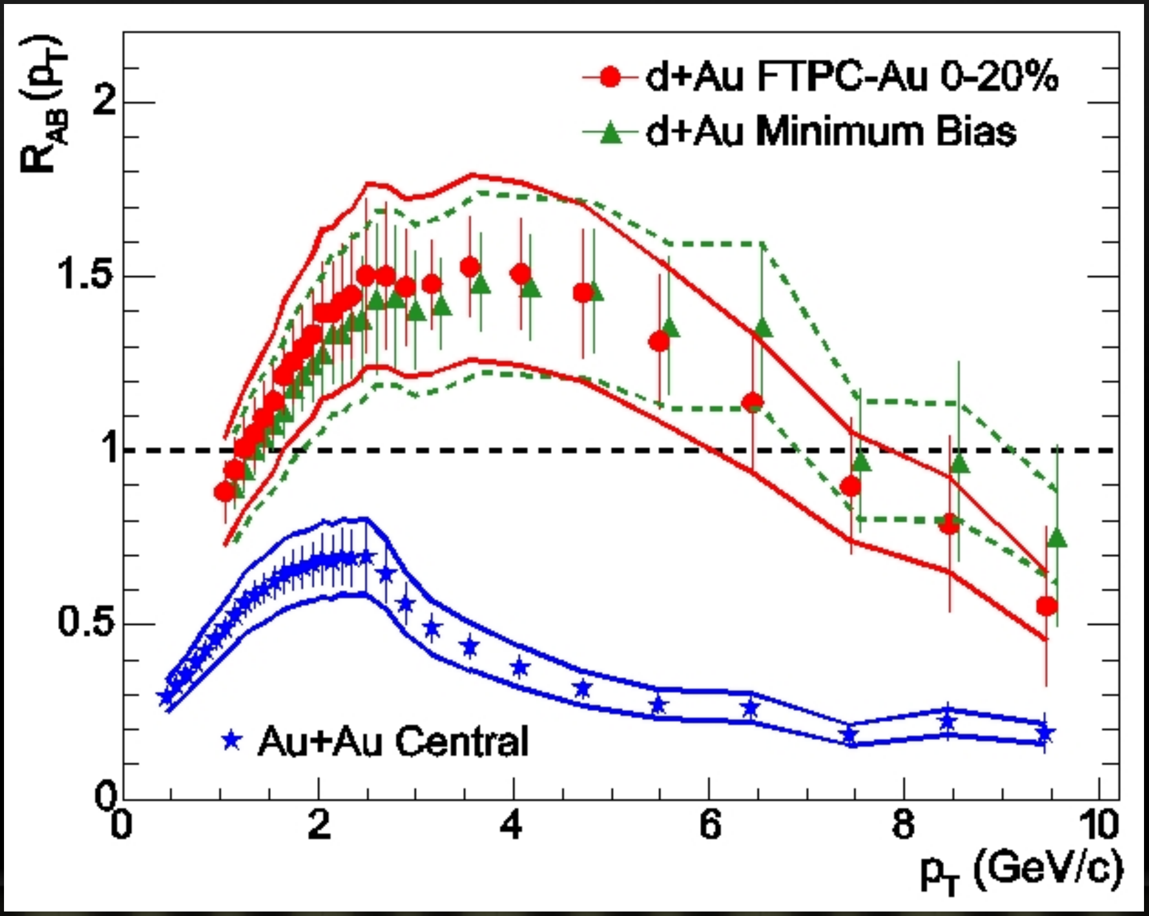




Xin-Nian Wang, M. Gyulassy, PRL68(1992)1480

Jet quenching at RHIC: leading hadrons

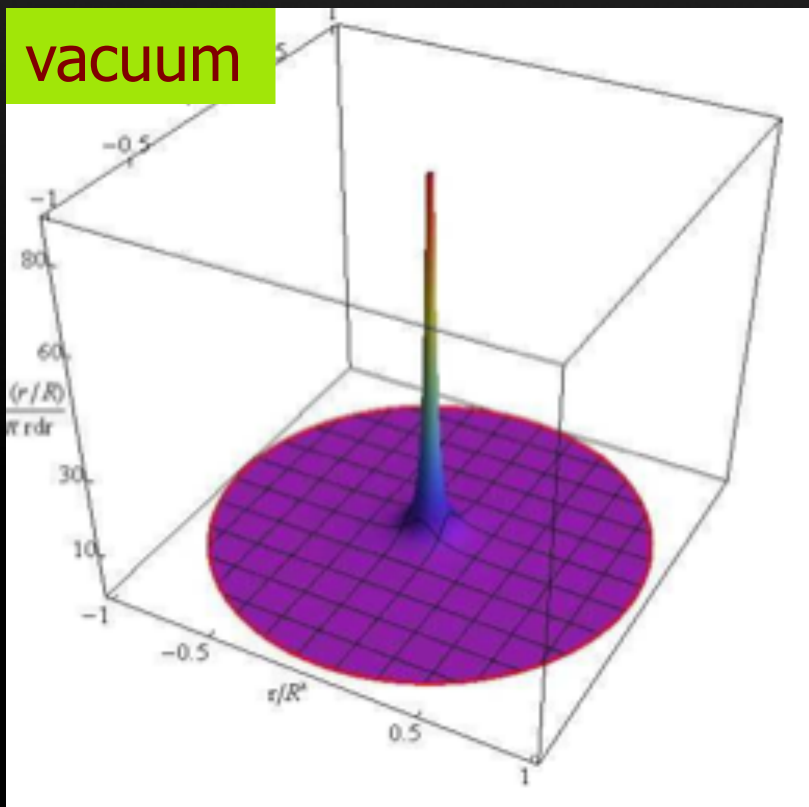
$$R_{AA} = \frac{\text{Yield}_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{\text{Yield}_{pp}}$$

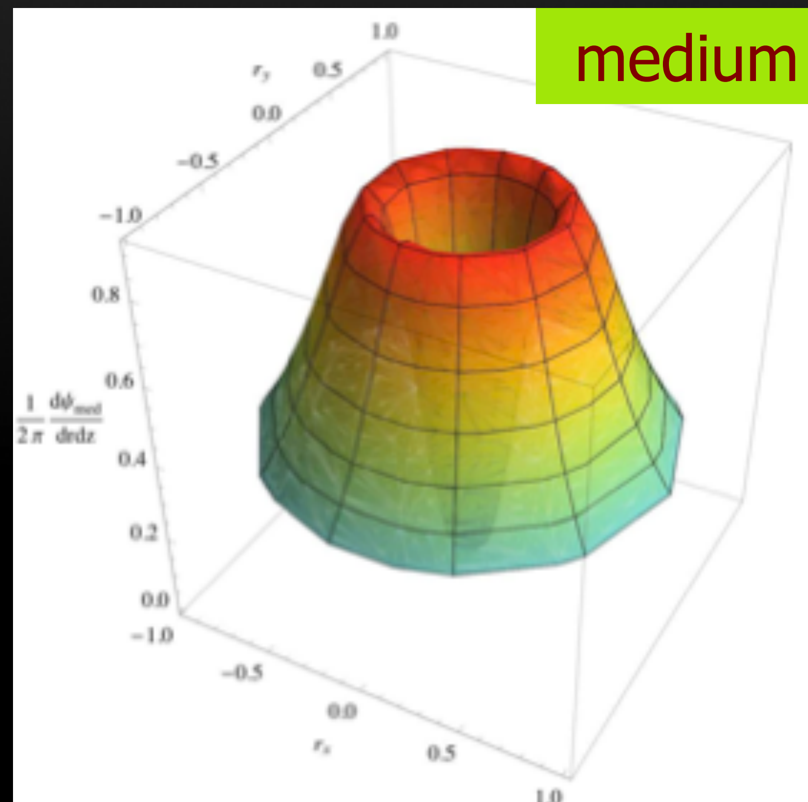


Gyulassy, Vitev, X.N.Wang, BWZ, 《QGP3》 p123-191 (2004); nucl-th/0302077.

From leading hadrons to jets: Th

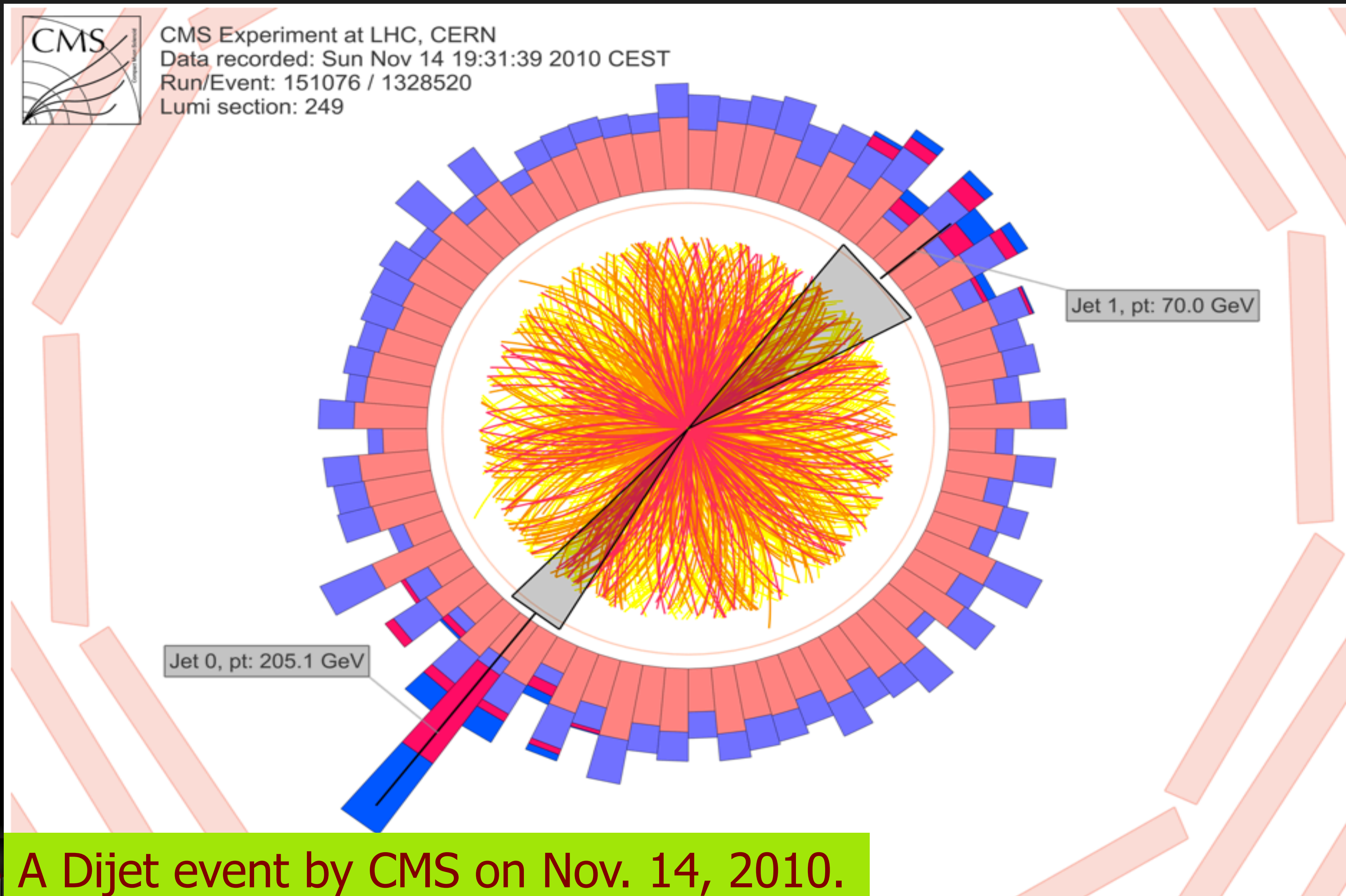
Jet shape





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

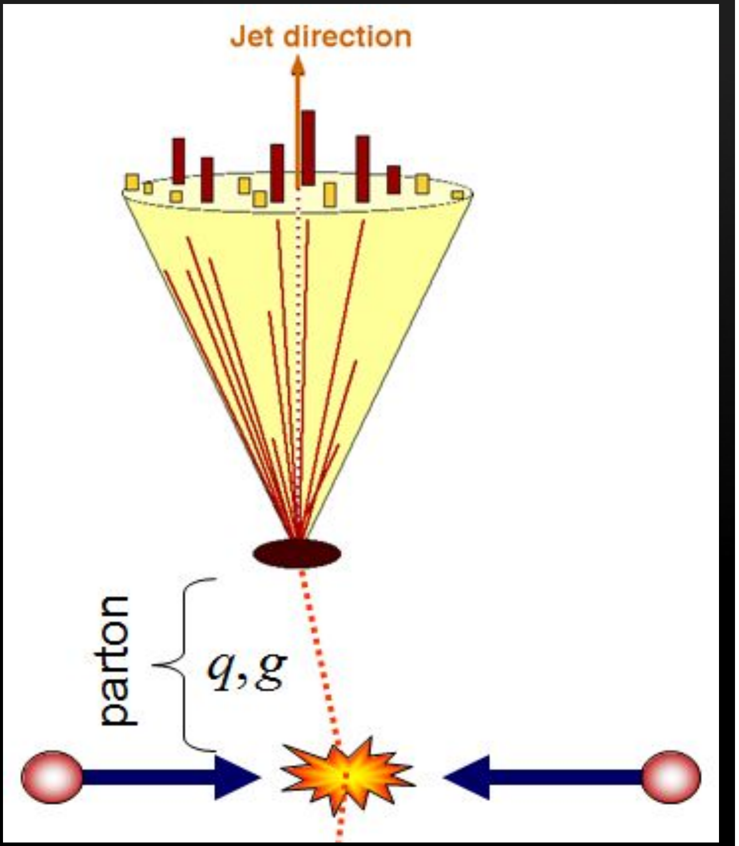
From leading hadrons to jets: Exp



A Dijet event by CMS on Nov. 14, 2010.

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.
- In pQCD local-parton-hadron duality (LPHD) is used
- Jet: more precise and powerful



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

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

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

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

Briefing: jets at HEP

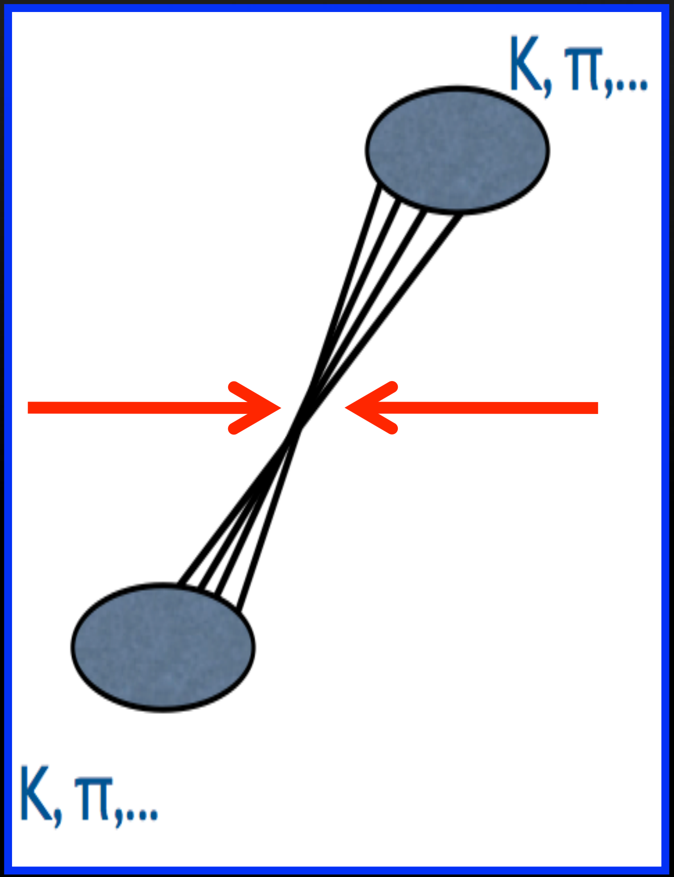
- Sterman&Weinberg('77) defined a two-jet event and made an analytic calculation.

- Feynman, Field, Fox ('77) made a numerical calculation of the inclusive jet prod.

- Discovery of three-jet events in e+e- gave a first evidence of gluons.

- Precise extraction of α_s is made by measuring jet event shapes.

- New physics beyond Standard Model by studying jets.



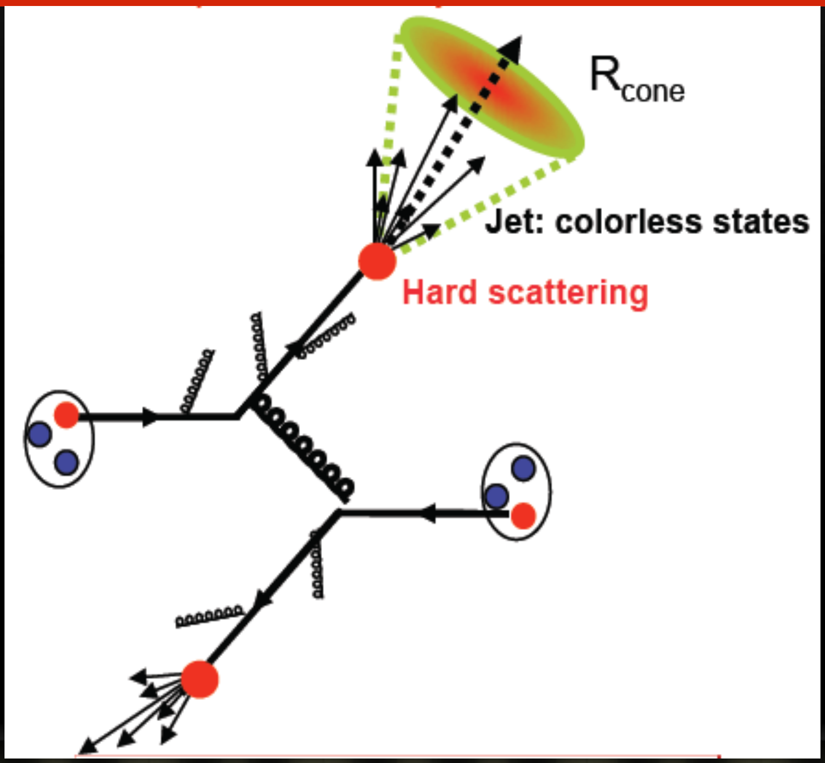
Jets in HIC

1) inclusive jet spectrum

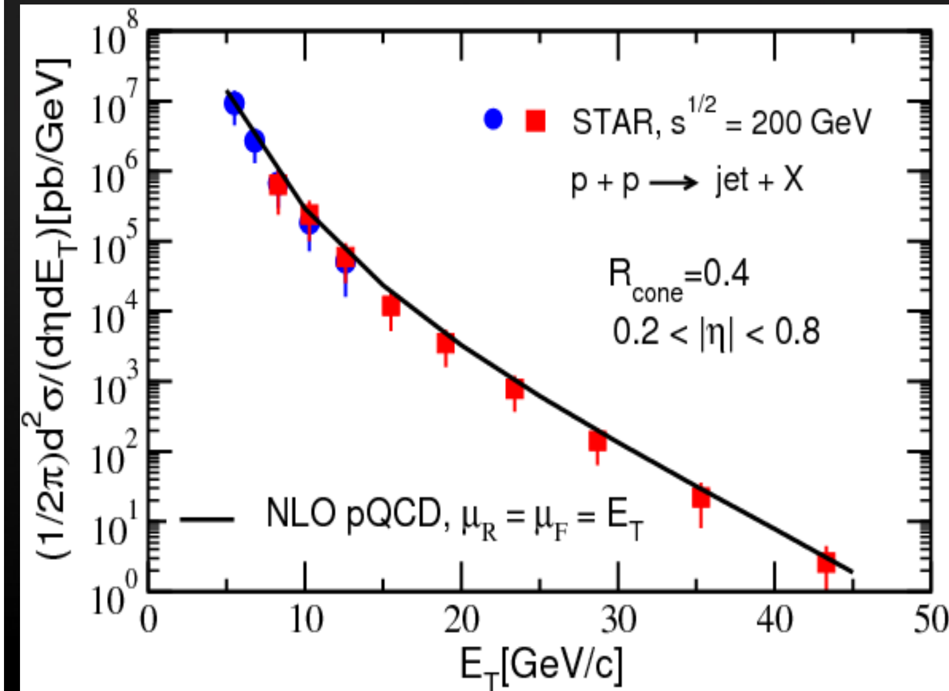
2) dijet asymmetry

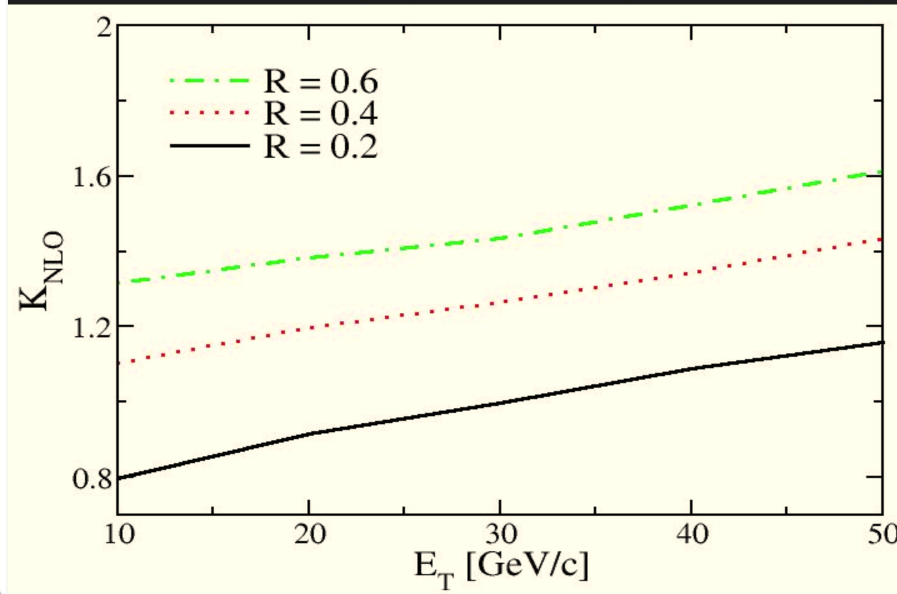
3) Z^0 and photon tagged jets productions

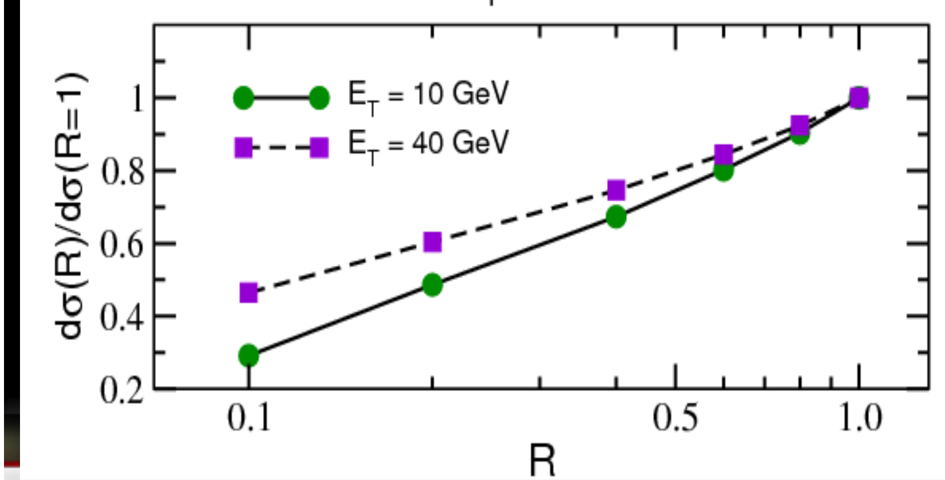
Inclusive jet cross section in HIC at NLO



Inclusive jet in p+p at NLO

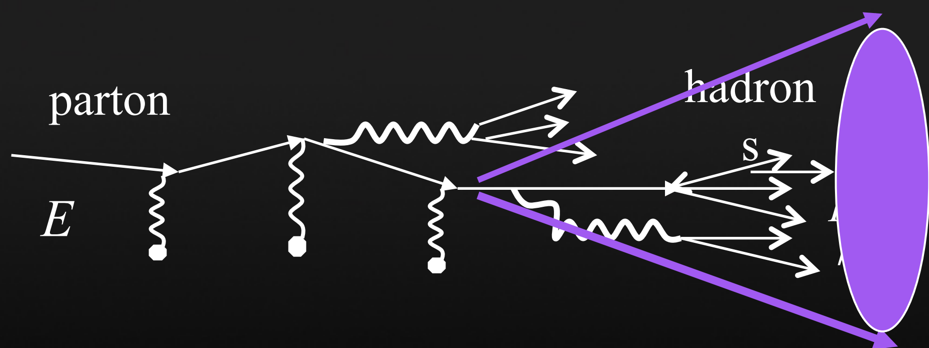




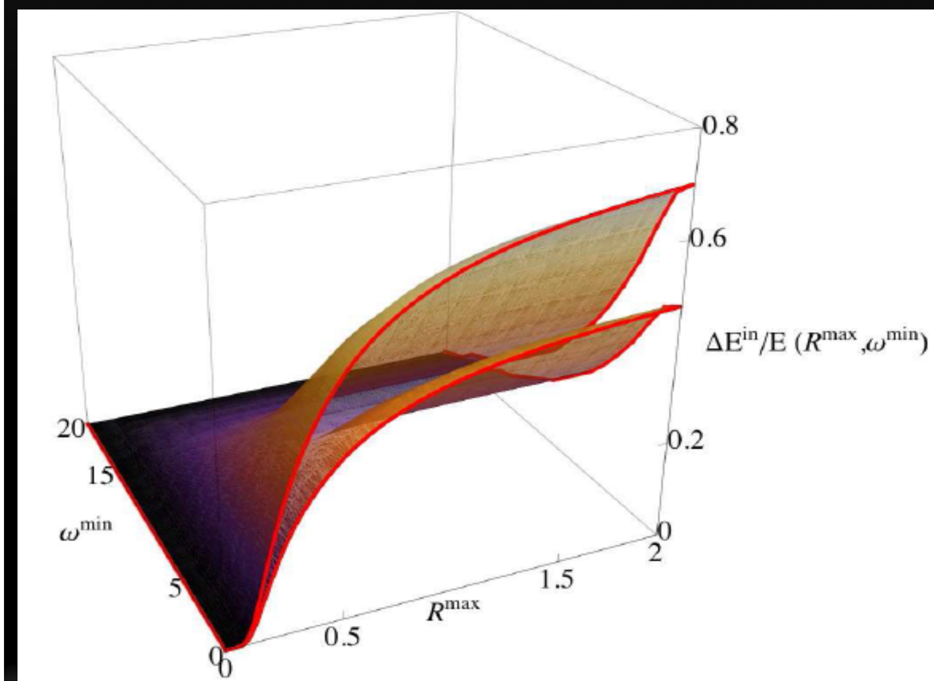


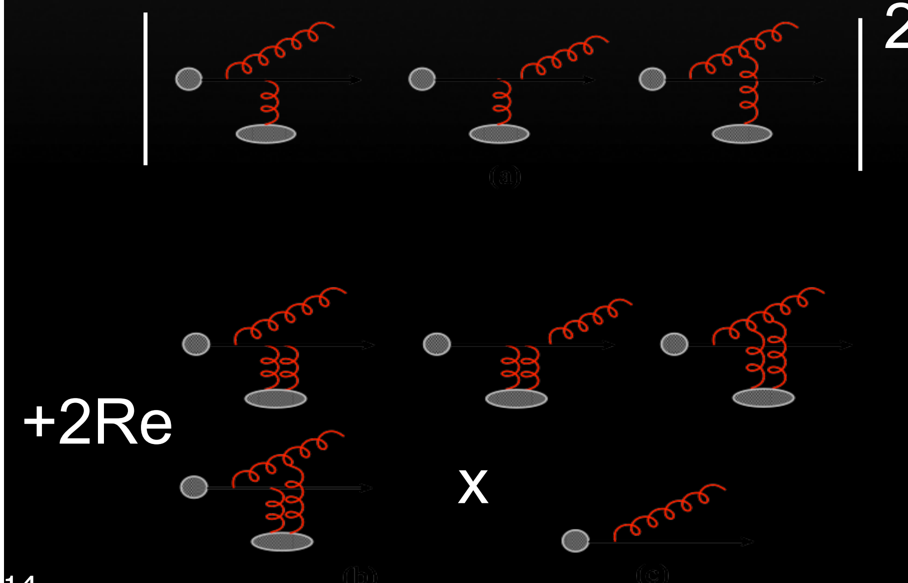
- Very good agreement between data and theory is achieved;
- K_{NLO}=NLO/LO can be smaller than 1 at small cone radius.

Jets in medium



Gyulassy-Levai-Vitev

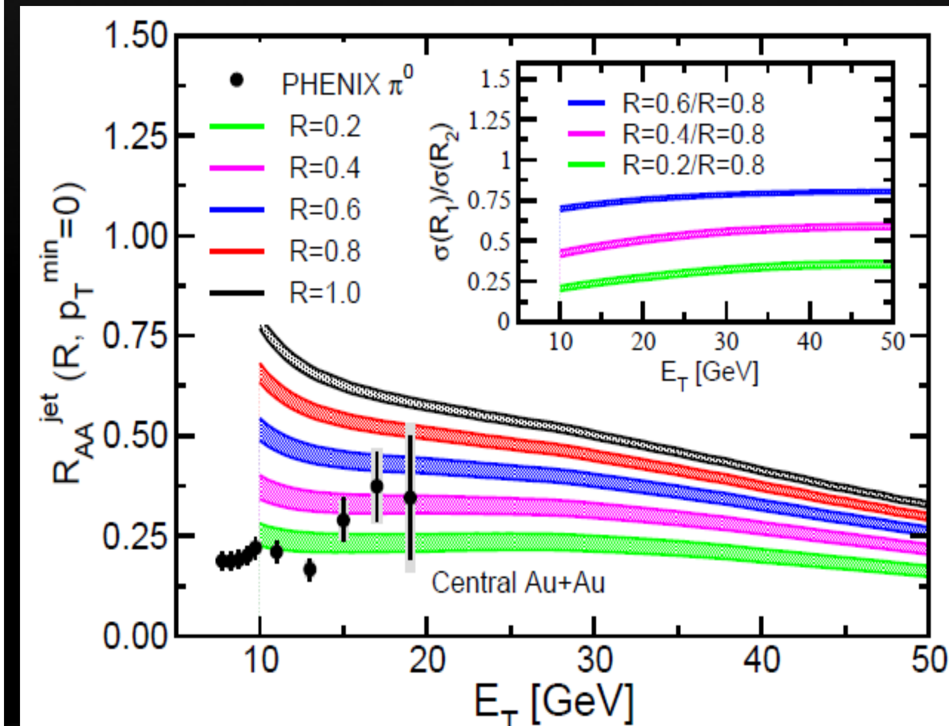


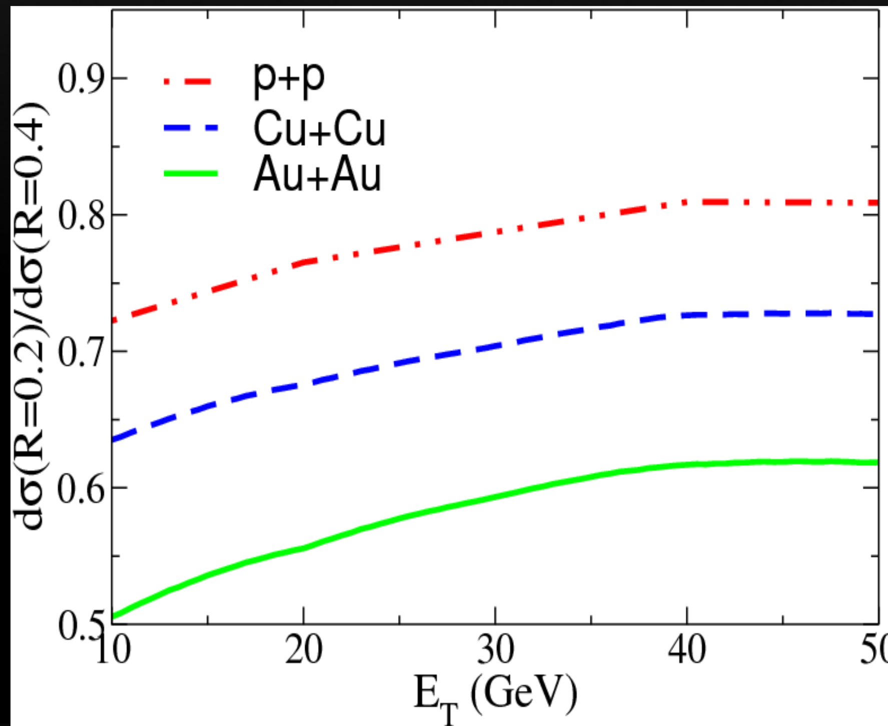


I Vitev, S Wicks, BWZ, JHEP 0811,093 (2008)

Inclusive jets in A+A at RHIC

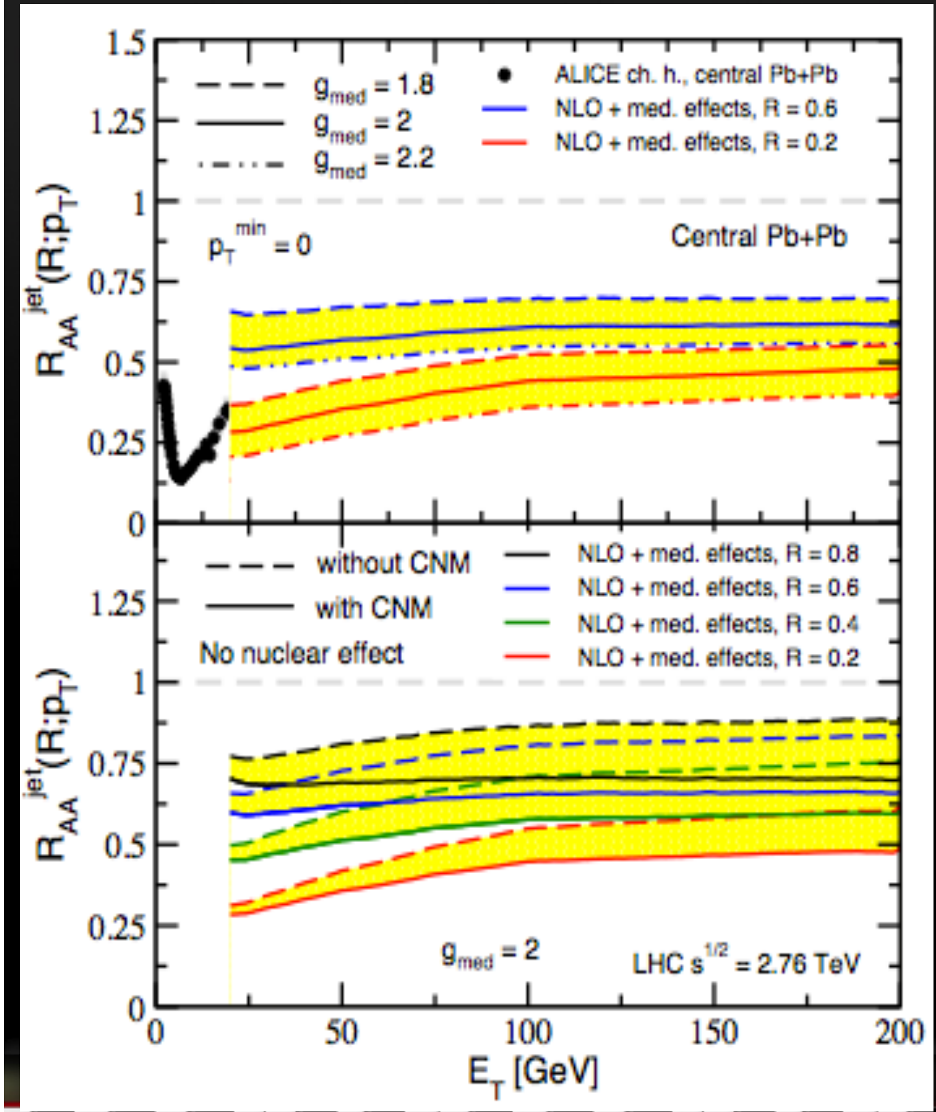
$$\frac{1}{\langle N_{\rm bin}\rangle}\frac{d\sigma^{AA}(R)}{d^2E_Tdy} = \int_{\epsilon=0}^{1} d\epsilon \sum_{q,g} P_{q,g}(\epsilon,E)\frac{1}{(1-(1-f_{q,g})\cdot\epsilon)^2}\frac{d\sigma_{q,g}^{\rm CNM,NLO}(R)}{d^2E_T'dy}$$

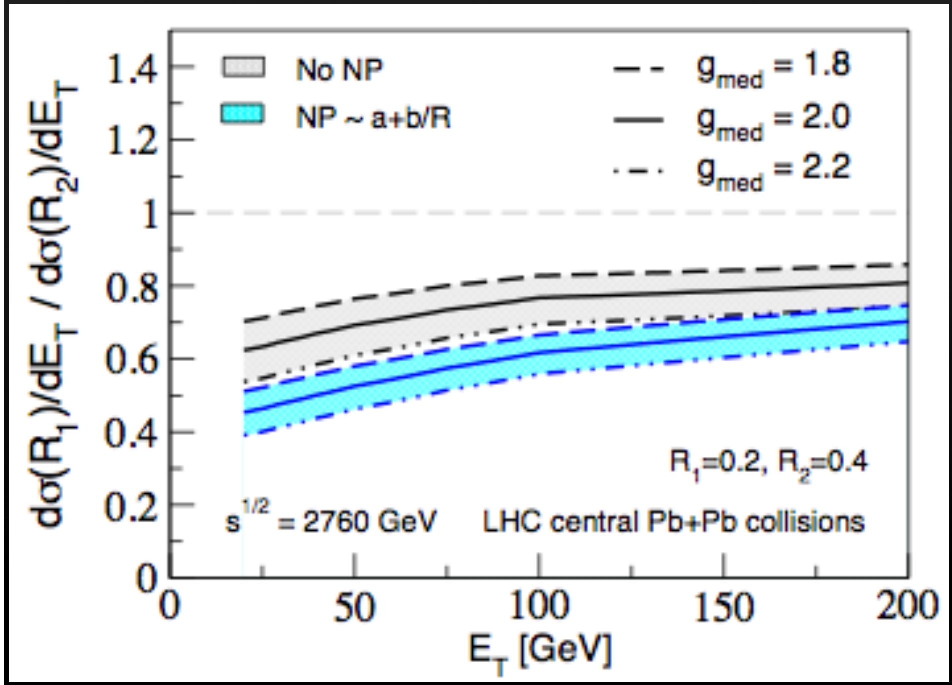




I Vitev, BWZ， PRL 104,132001 (2010).

Inclusive jets in Pb+Pb at LHC

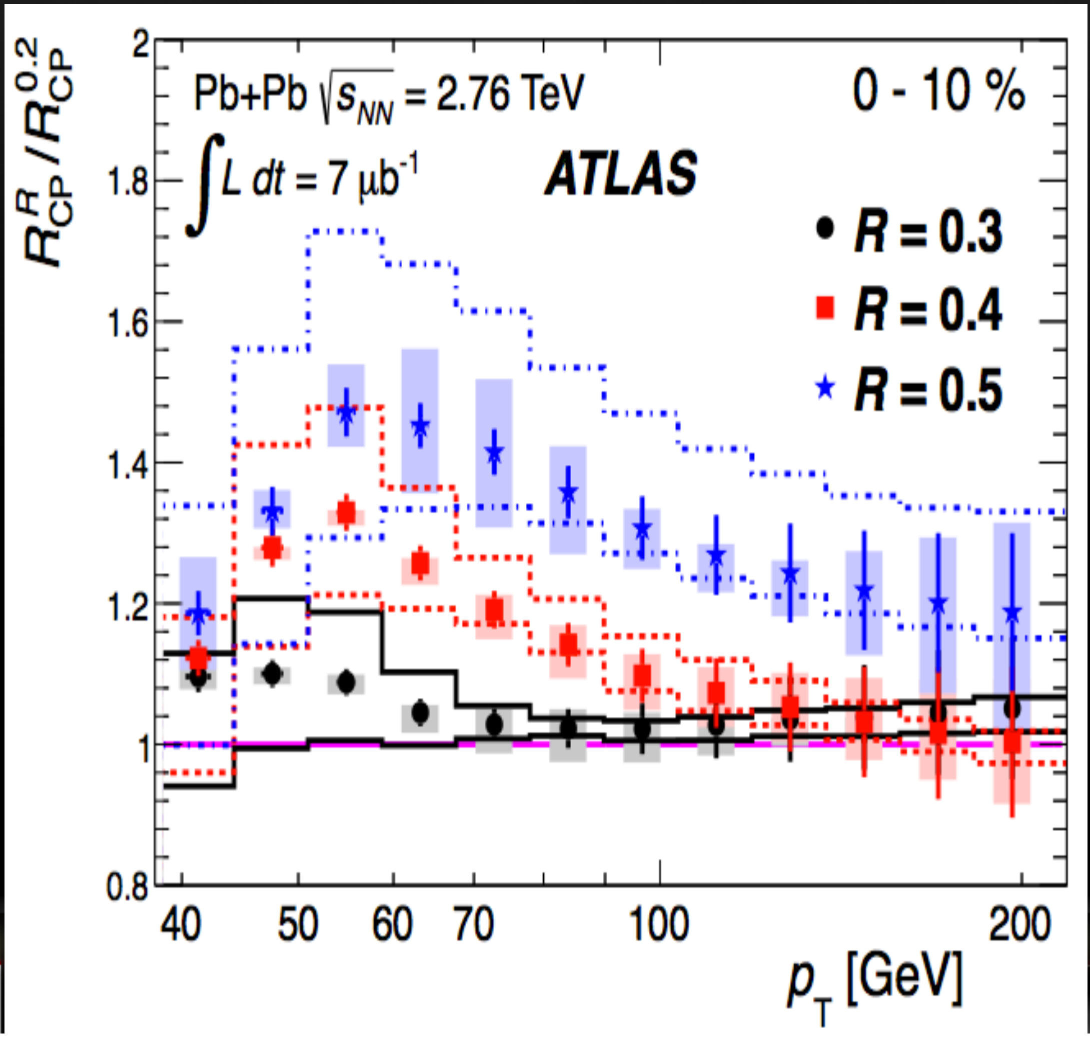




Y He, Vitev, BWZ, PLB (2012)
arXiv: 1105.2566

Inclusive jet in Pb+Pb: Exp.

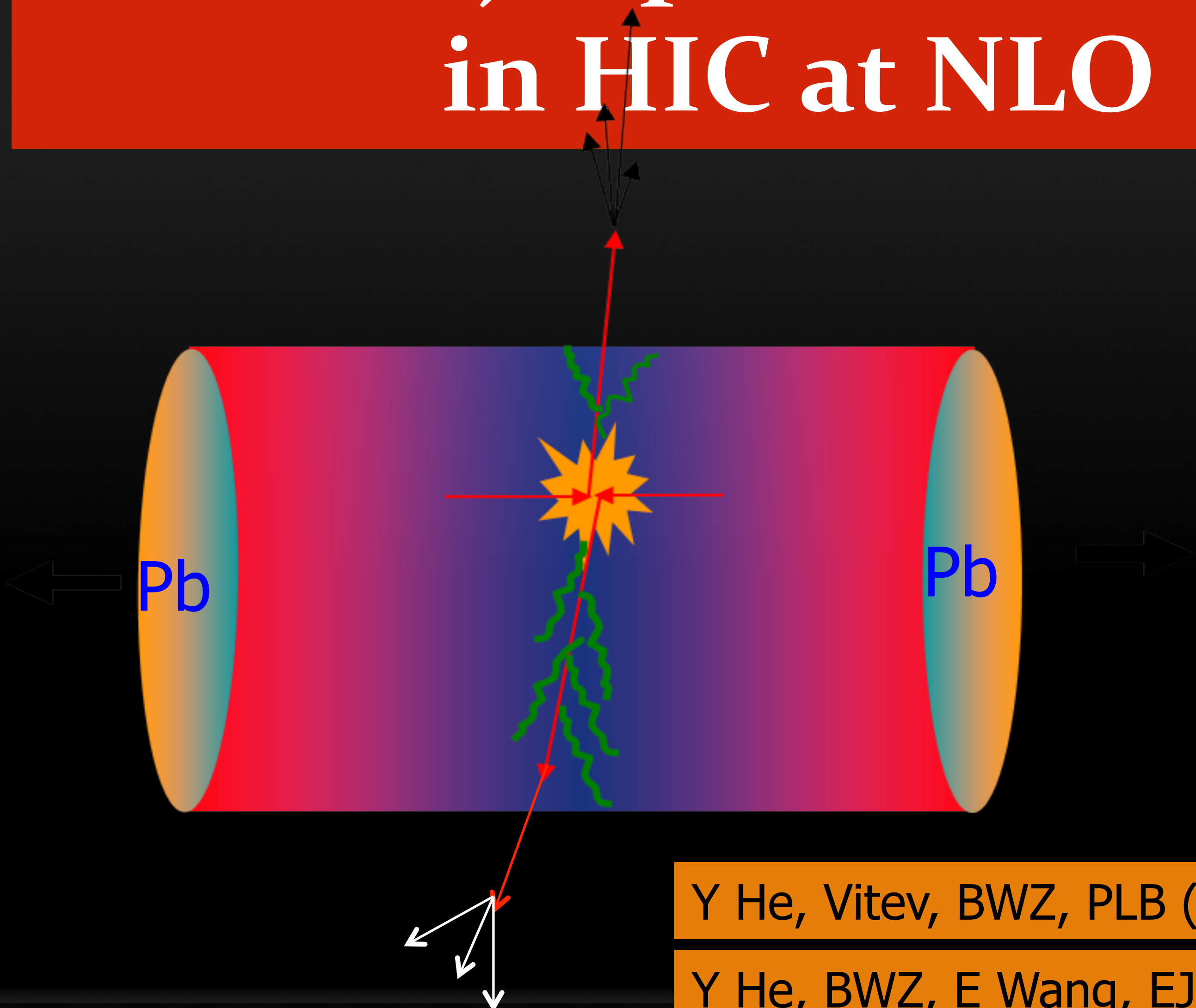
- The jet radius dependence of Raa on inclusive jets has been confirmed by ATLAS measurements most recently.



ATLAS,

arXiv: 1208.1967

Dijet production in HIC at NLO



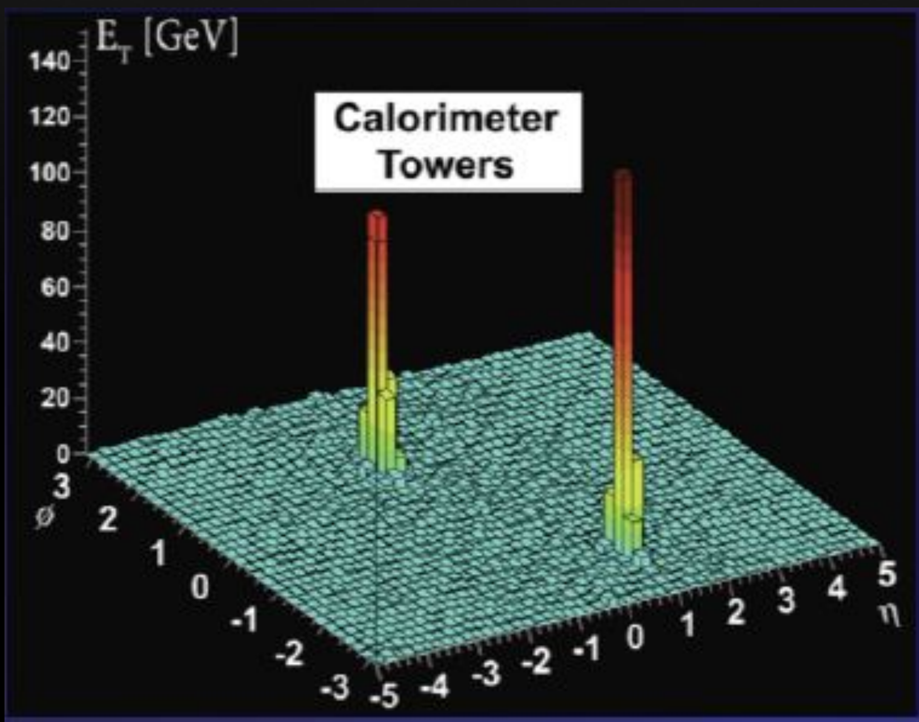
Y He, Vitev, BWZ, PLB (2012)

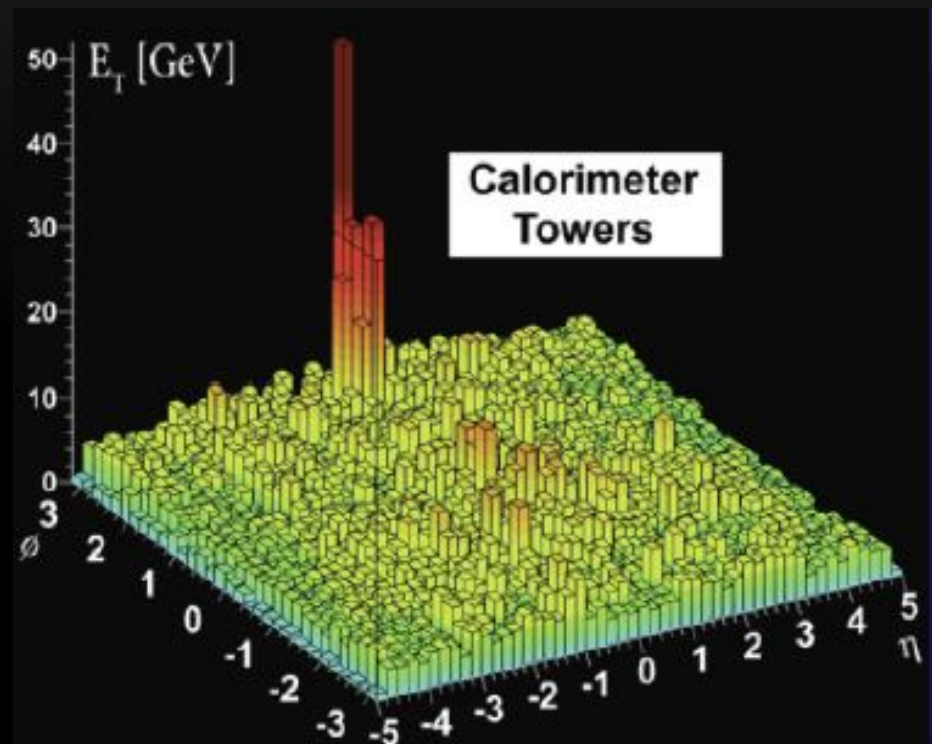
Y He, BWZ, E Wang, EJPC (2012)

Y He, Neufeld, Vitev, BWZ, in preparation

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。



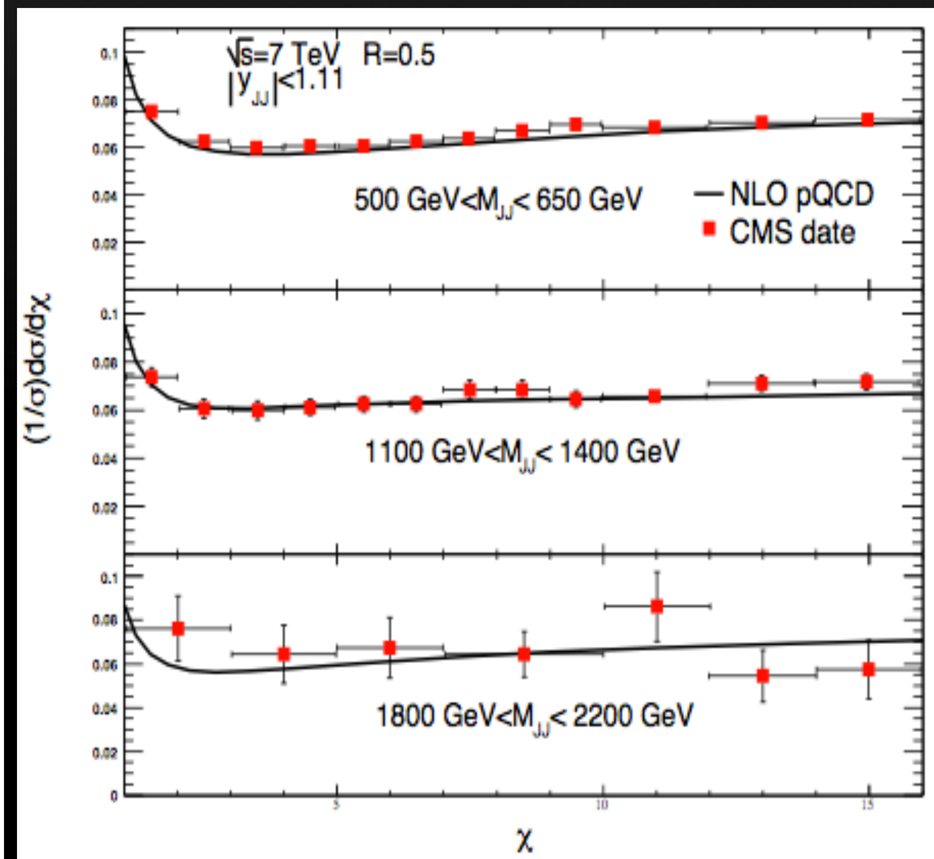


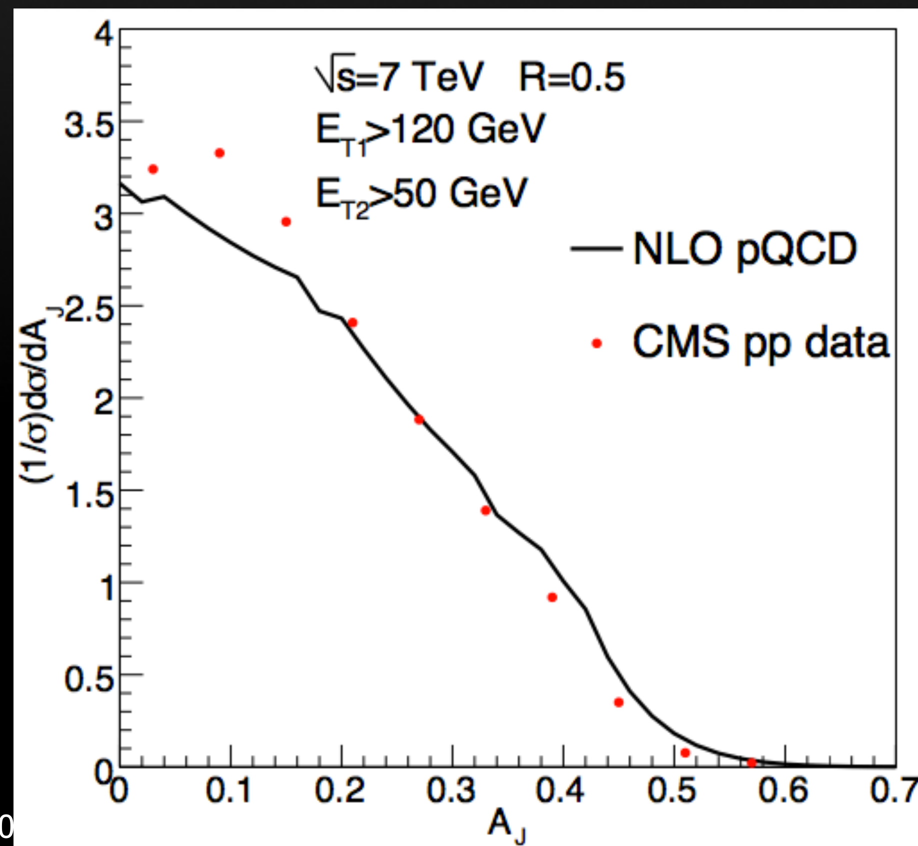
ATLAS, arXiv:1011.6182, PRL (2011); CMS, arXiv: 1102.1957, PRC(2012)

Dijet in p+p at NLO

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

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

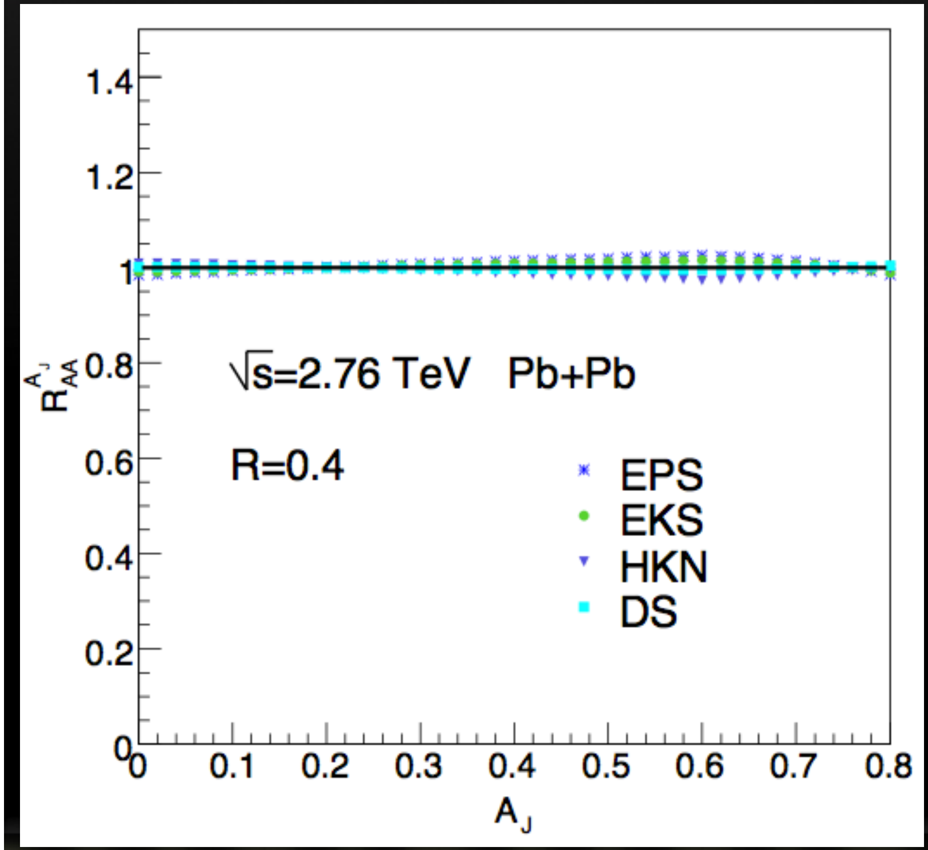


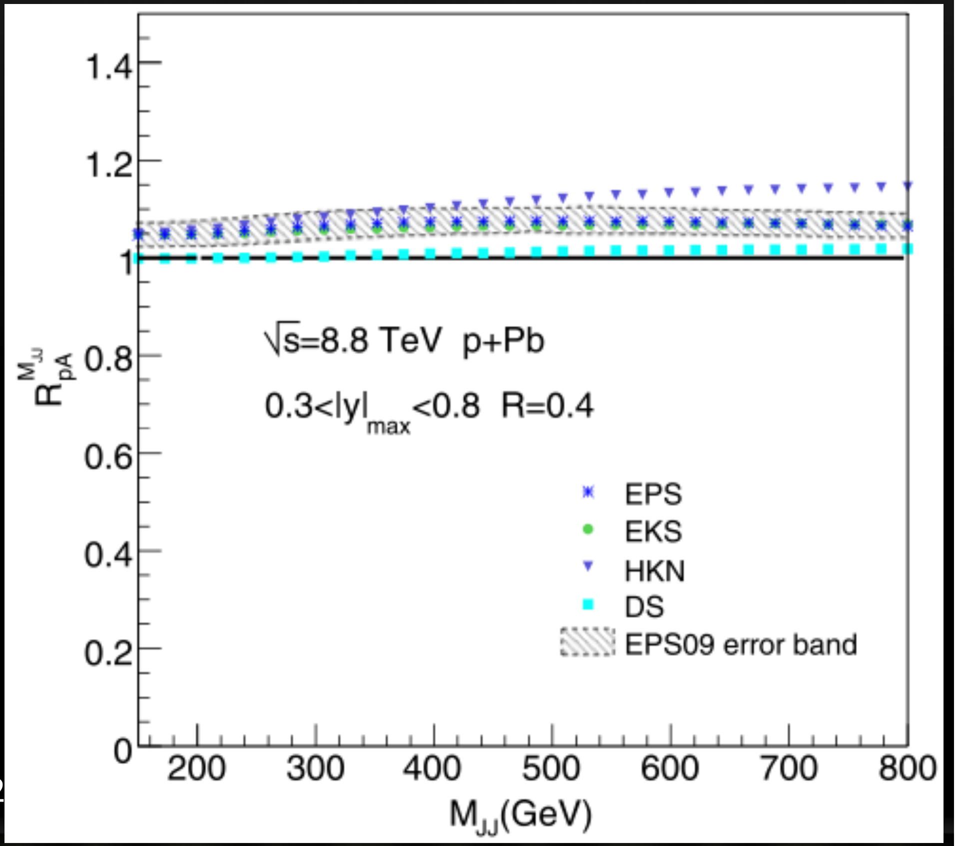


Dijet in HIC: CNM

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

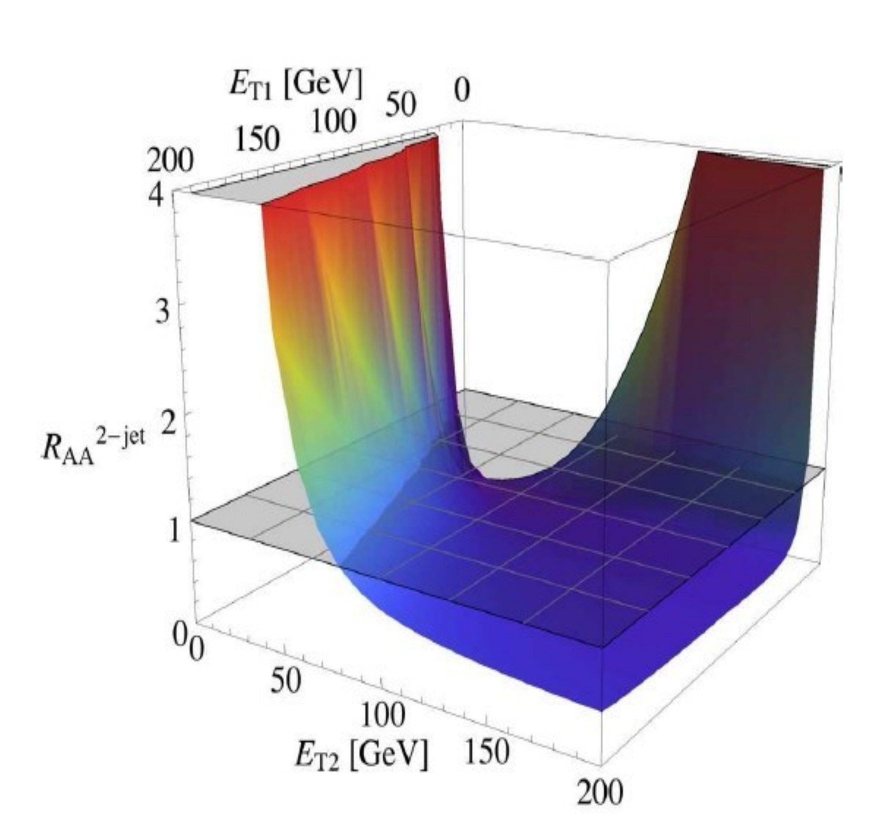
$$M_{jj}^2 = 2p_T^2[1 + cosh(y_1 - y_2)]$$

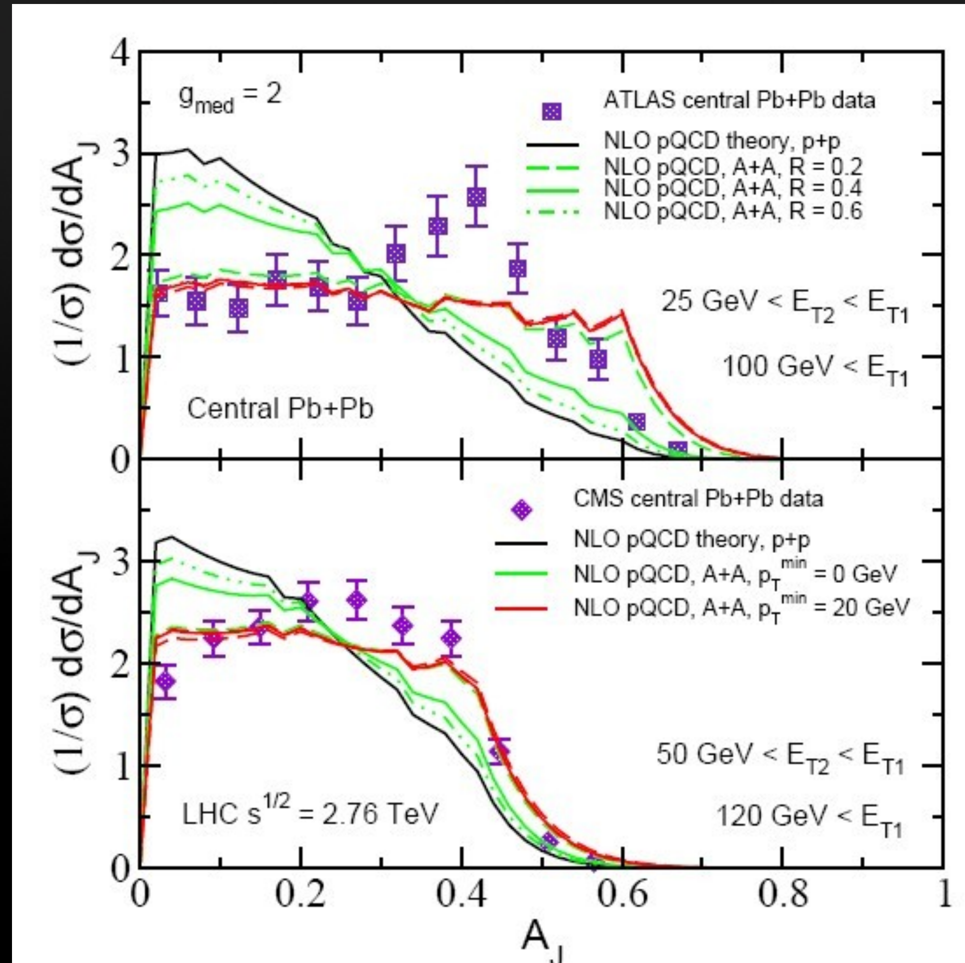




Y He, BWZ, E Wang, EPJC (2012)

Dijet in Pb+Pb at LHC



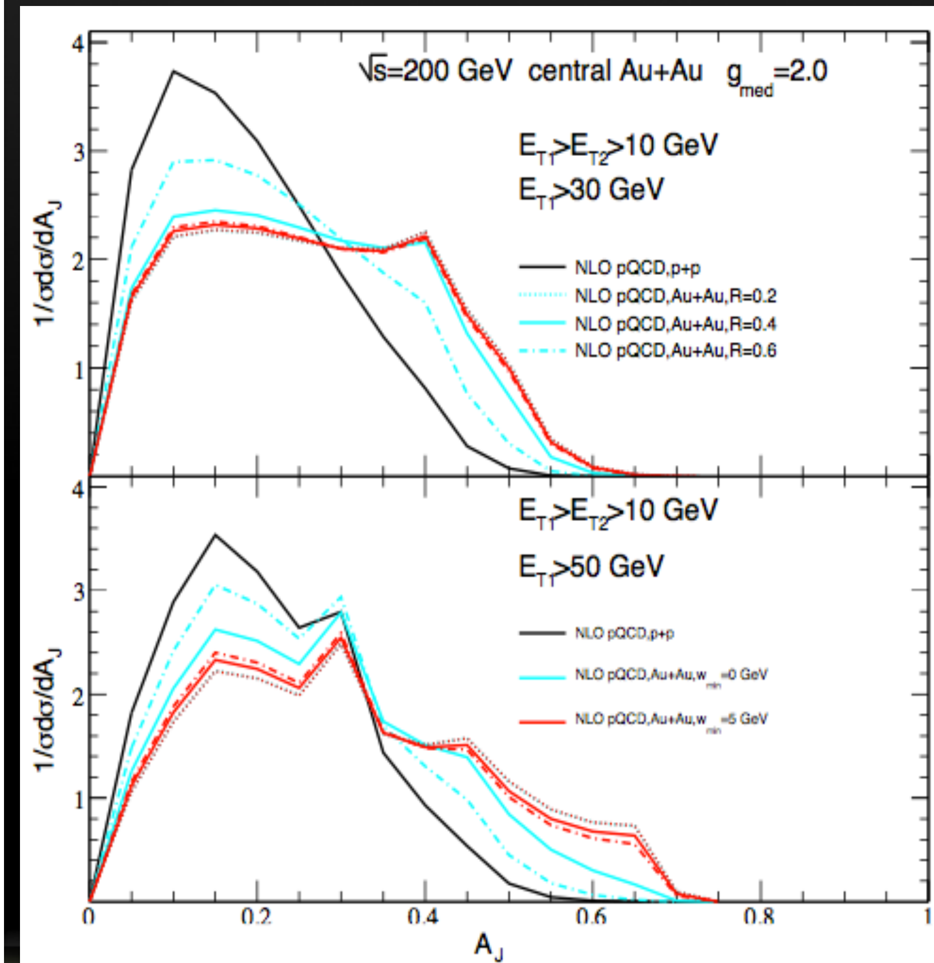


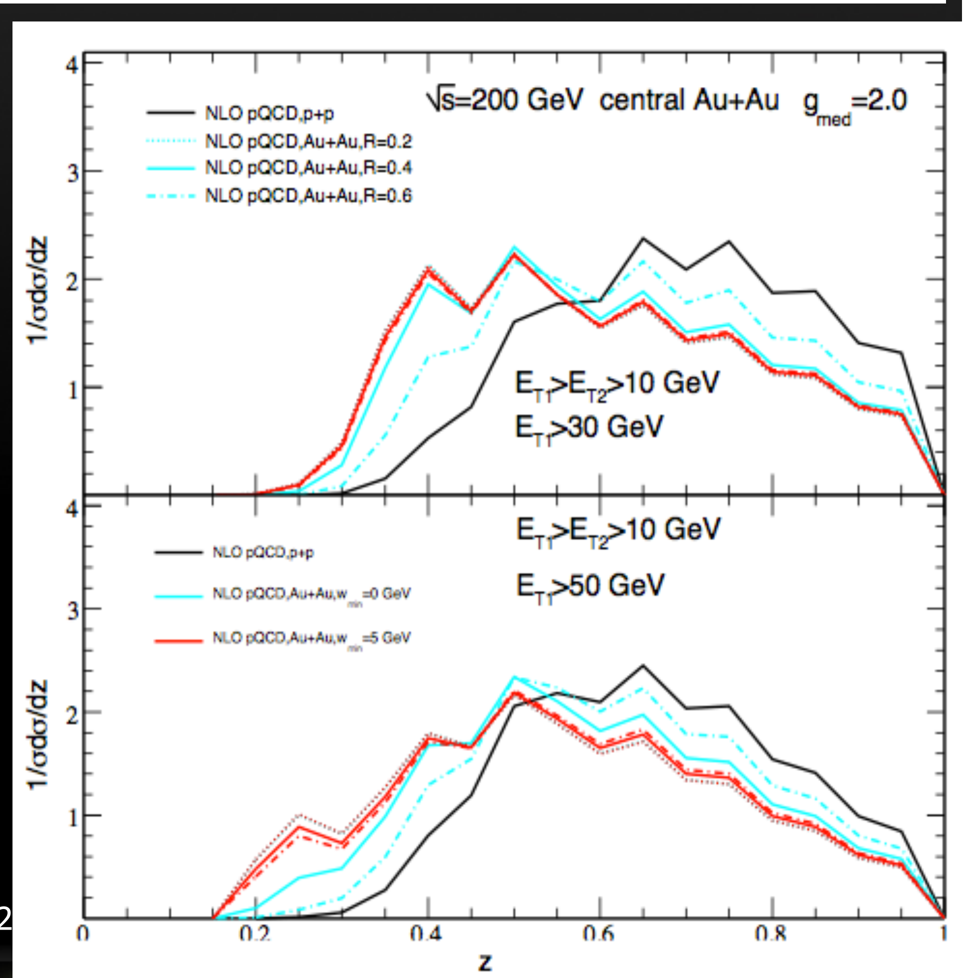
Y He, Vitev, BWZ, PLB (2012)

Dijet in Au+Au at RHIC

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

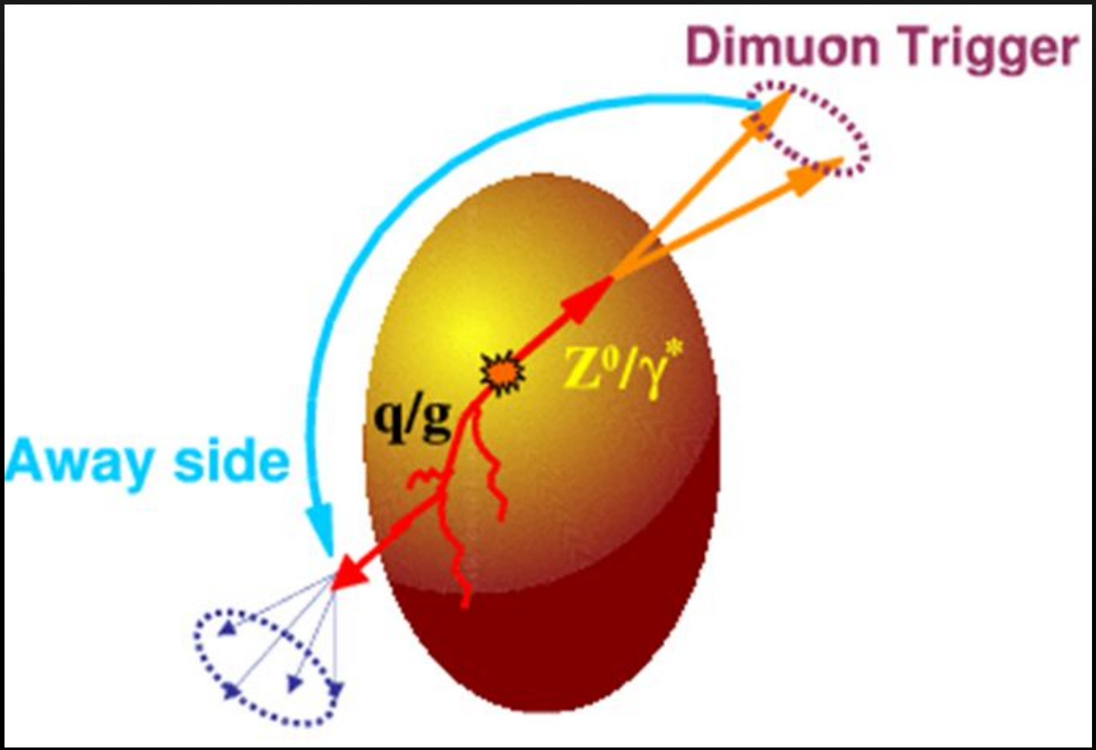
$$\frac{d\sigma}{dz} = \int_{E_{T\,2\ \mathrm{min}}}^{E_{T\,1}} dE_{T\,2}\, \frac{E_{T\,2}}{z^2} \times \frac{d\sigma[E_{T\,1}(A_J, E_{T\,2})]}{dE_{T\,1} dE_{T\,2}}$$

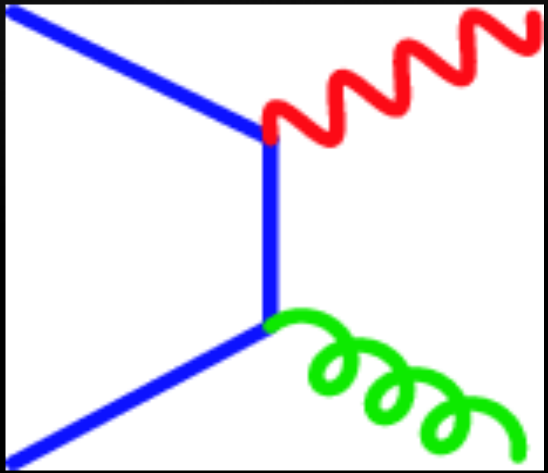




Y He, Neufeld, Vitev, BWZ, in preparation

Tagged jet production in HIC





Neufeld, Vitev, BWZ, PRC (2011).

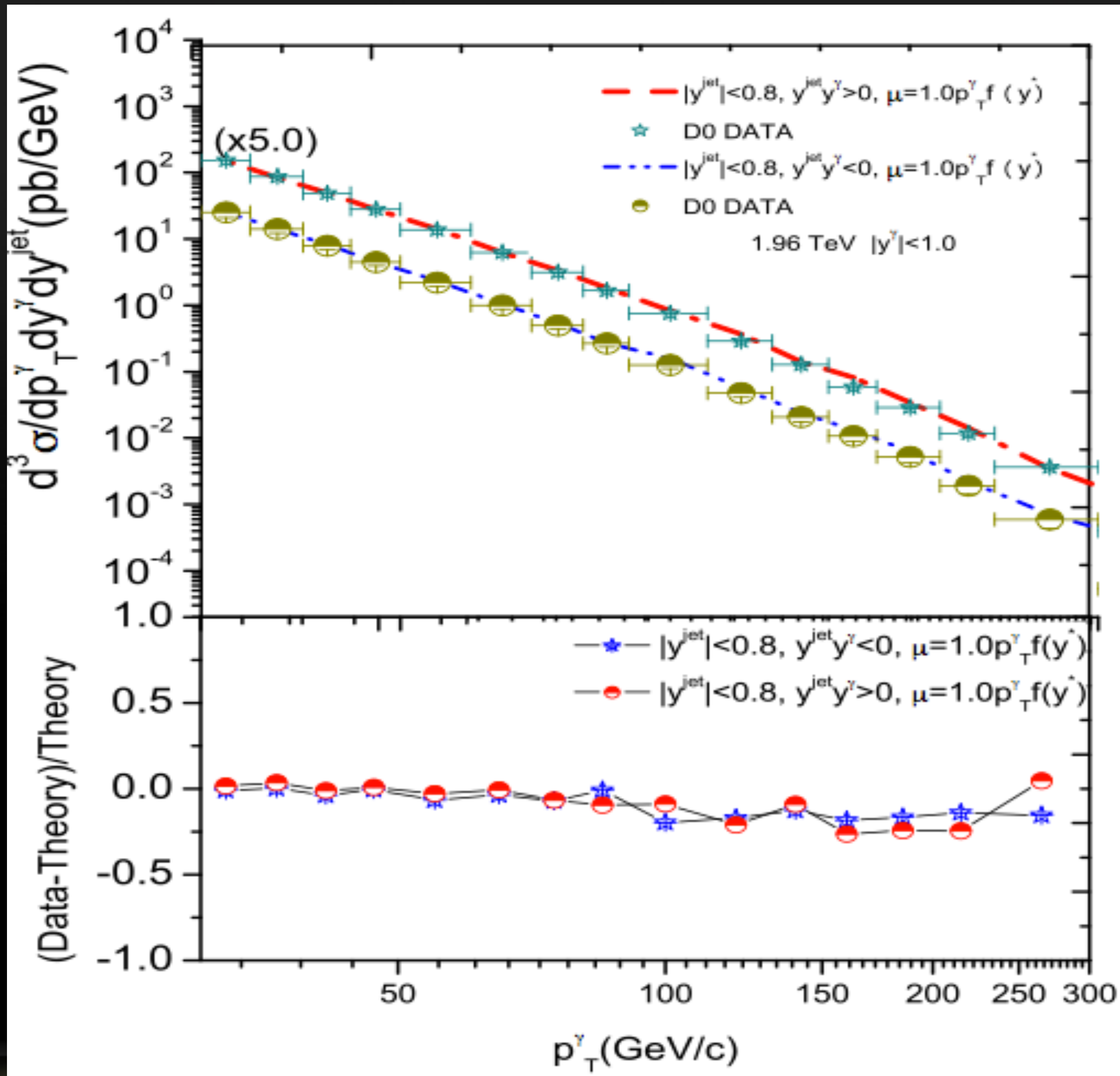
W Dai, Vitev, BWZ, PRL (2013); arXiv:1207.5177.

Tagged jet production in HIC

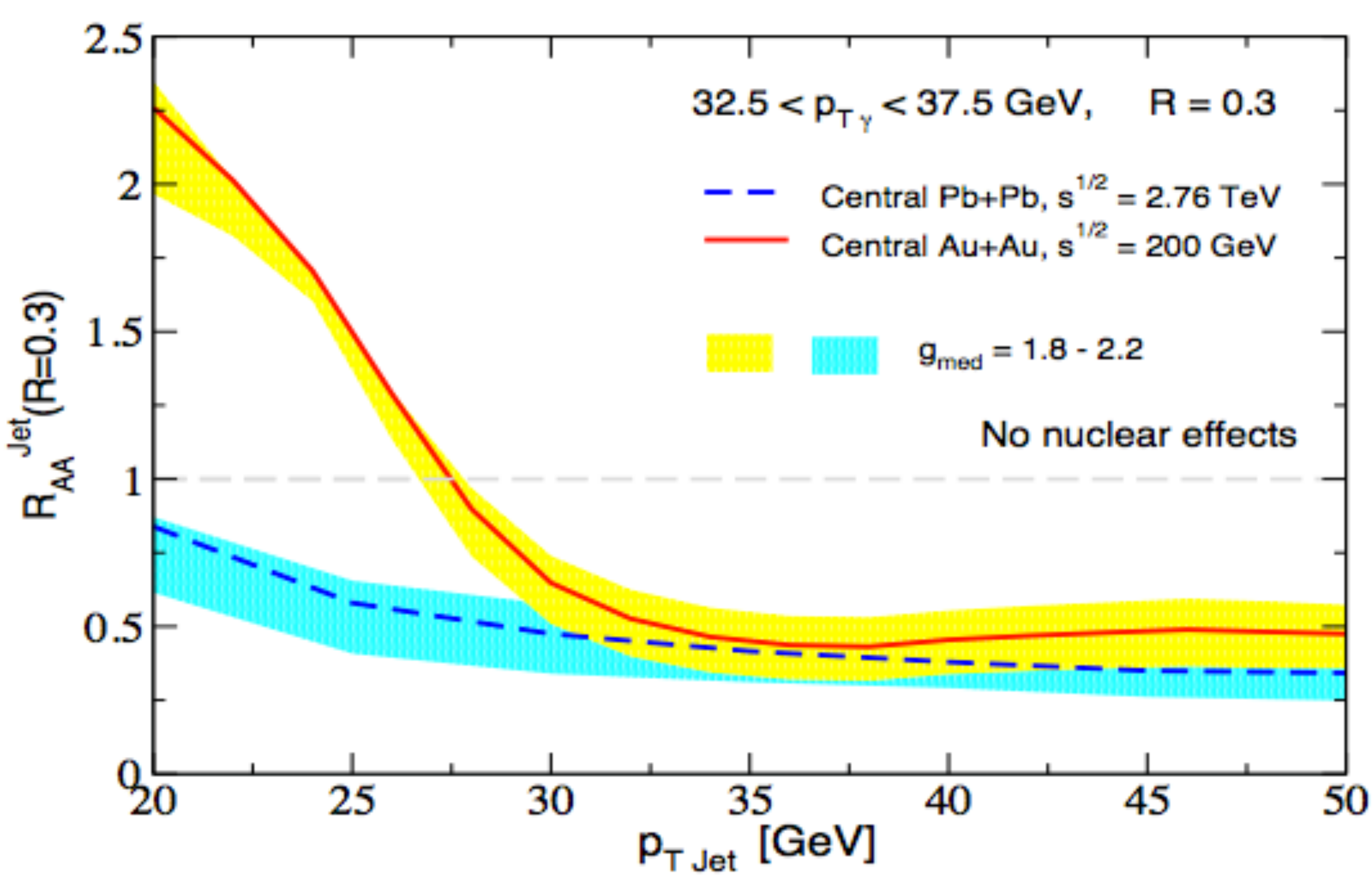
photon + jet	Z^0 + jet
Advantage: large yield Disadvantage: final-state effects	Disadvantage: small cross section Advantage: no final-state effects
Dai, Vitev, BWZ, PRL (2013)	Neufeld, Vitev, BWZ, PRC (2011)

You are so light, I am too heavy.

Isolated photon + jet in h+h

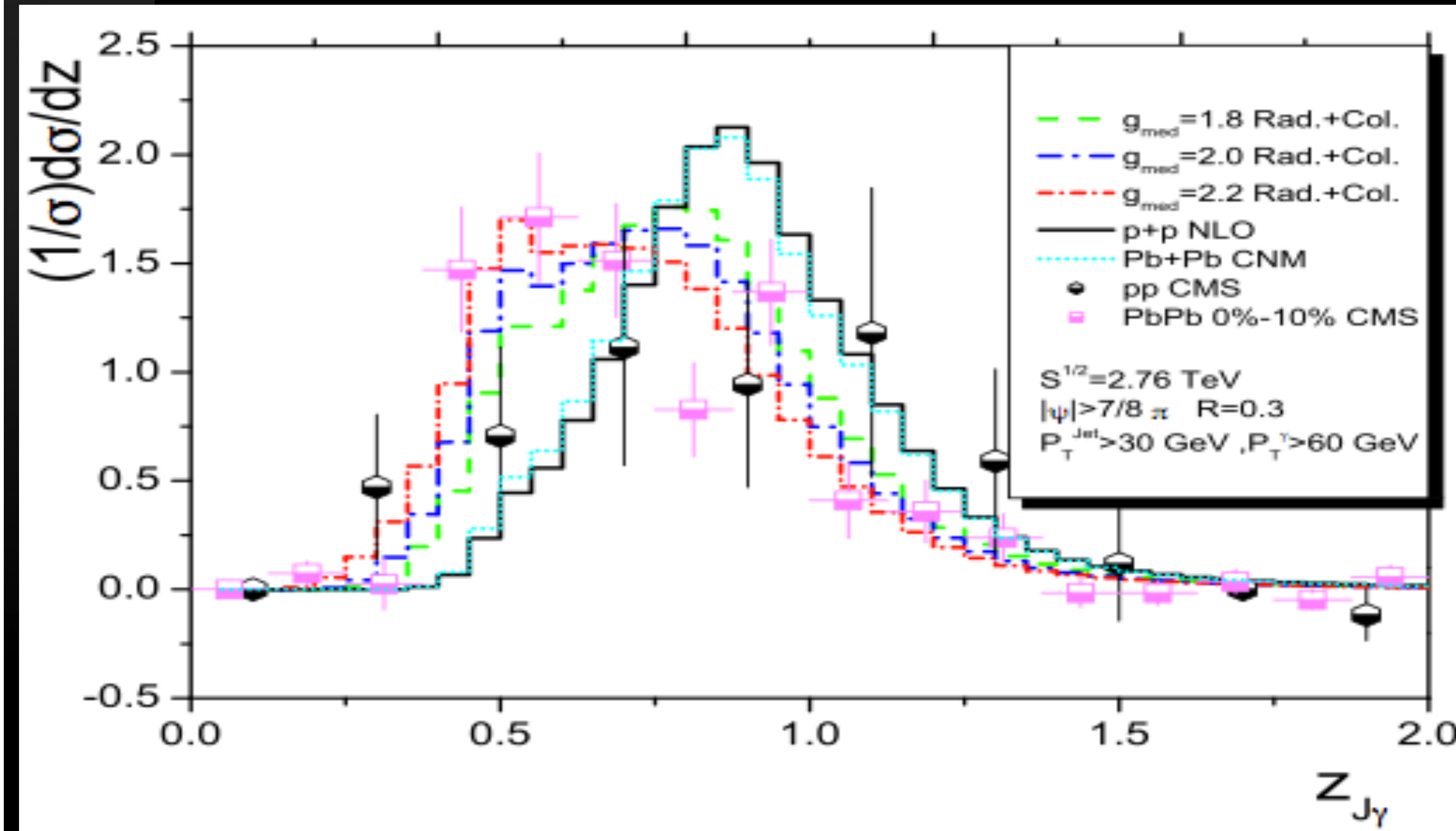


photon + jet in A+A (I)



W Dai, Vitev, BWZ, Phys. Rev. Lett. (2013); arXiv:1207.5177

photon + jet in A+A (II)



$$z_{J\gamma} = \frac{p_{T_{\rm jet}}}{p_{T_\gamma}}$$

System	$\langle z_{J\gamma}\rangle_{\rm LHC}$	$\langle z_{J\gamma}\rangle_{\rm RHIC}$
p+p	0.94	0.90
A+A, CNM	0.94	0.89
A+A, $g_{med} = 1.8$,Rad.+Col.	0.84	0.78
A+A, $g_{med} = 2.0$,Rad.+Col.	0.80	0.74
A+A, $g_{med} = 2.2$,Rad.+Col.	0.71	0.70

CMS, PLB(2013)

$$\langle z_{J\gamma}\rangle = 0.73 \pm 0.02$$

Dai, Vitev, BWZ, PRL(2013)

Summary

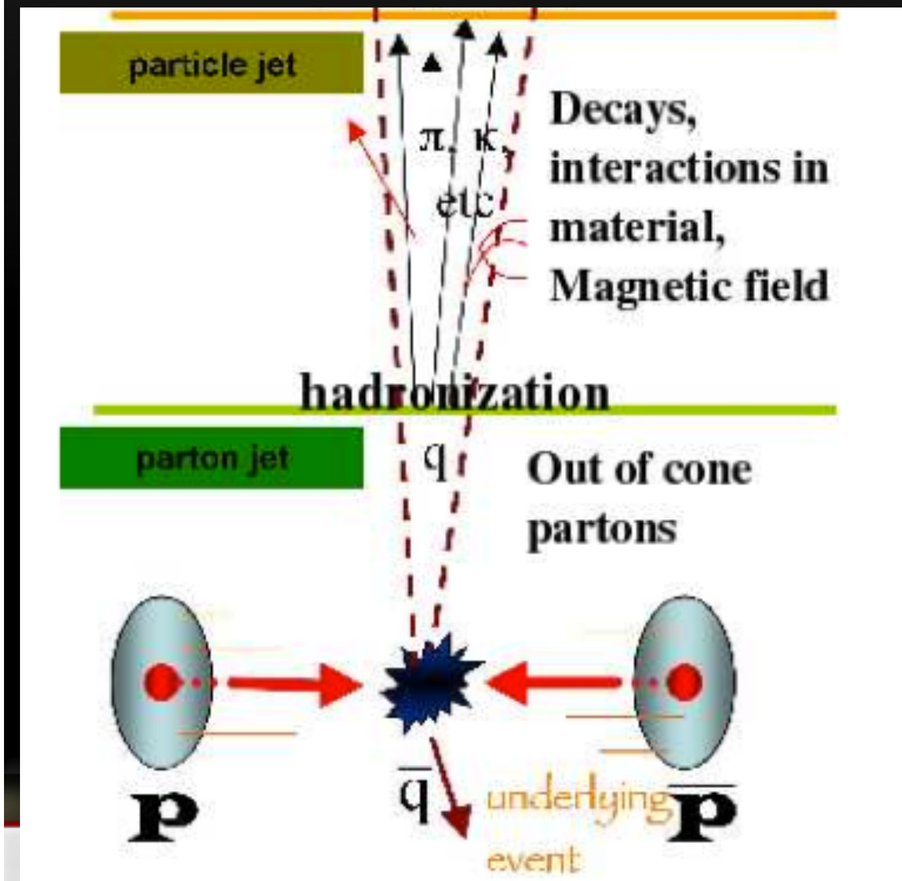
- A variable quenching of R_{AA} for jet cross section in A +A collisions is demonstrated, which is contrary to single result of R_{AA} for leading particle and has been observaed by ATLAS Collaboration.
- Dijet momentum imbalance AJ distribution becomes flatter with the peak shifted to middle AJ regime, whereas distribution of z=Et2/Et1 shifted to the left with smaller z.
- Similary approach has consistently applied to Z and photon tagged jet production. The mean value of <z> in A+A is reduced due to jet quenching effect in photon tagged jet production.

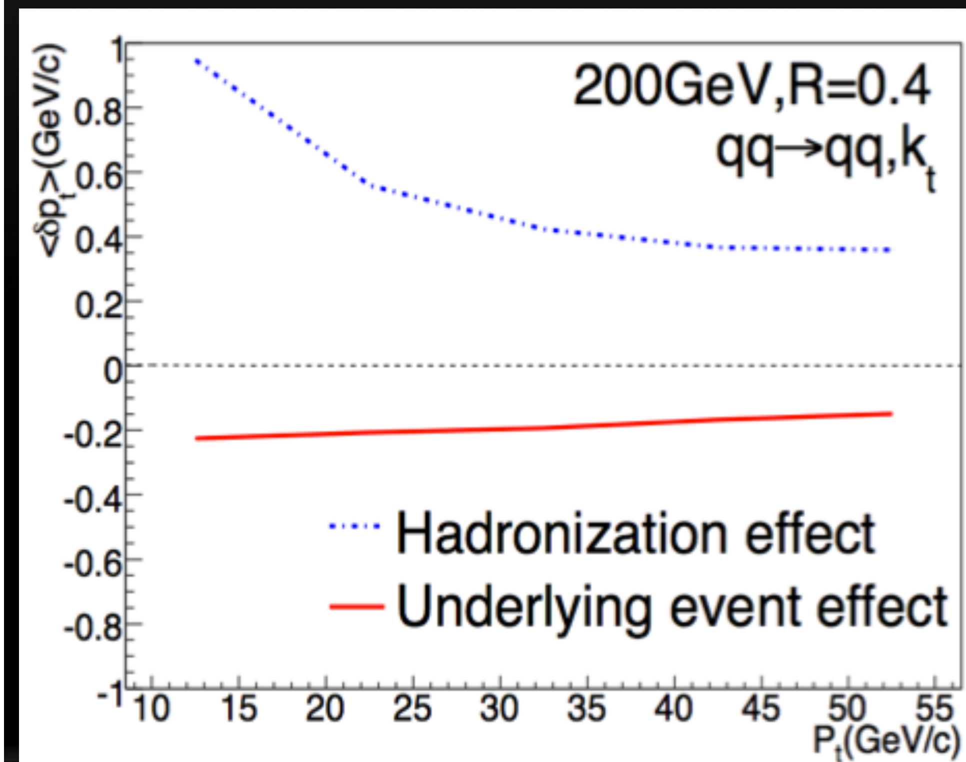
非常感谢！

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.



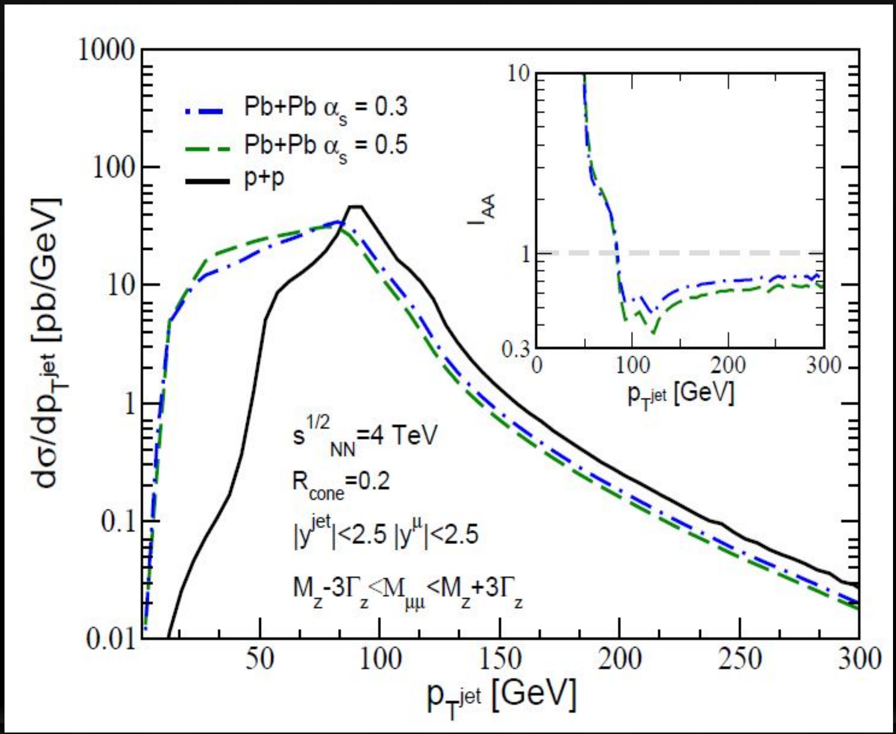


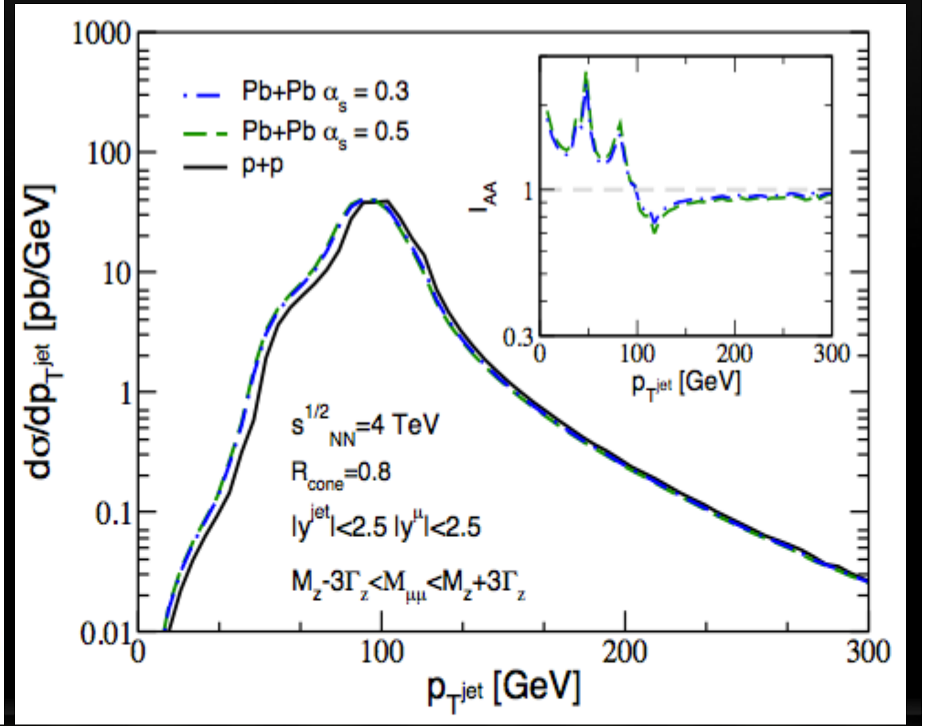
H Li, BWZ, E Wang (2013)

Z^o + jet in A+A: Iaa

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

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





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

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

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

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

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

Jet finding algorithms

- Cone algorithm
- Midpoint cone algorithm
- k_T algorithm

$$k^2_{T,i} = p^2_{T,i}$$

$$k^2_{T,(i,j)} = \min(p^2_{T,i}, p^2_{T,j}) \frac{R^2_{i,j}}{D^2}$$

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

- Anti-k_T algorithm
- Seedless algorithm

Parton merge parameter

NLO

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

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