Jet productions in “little bang”

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Outline

- Introduction
- Jet observables in HIC

  1) jet shape

  2) inclusive jet cross section

  3) tagged jet production

  4) di-jet momentum imbalance
- Summary

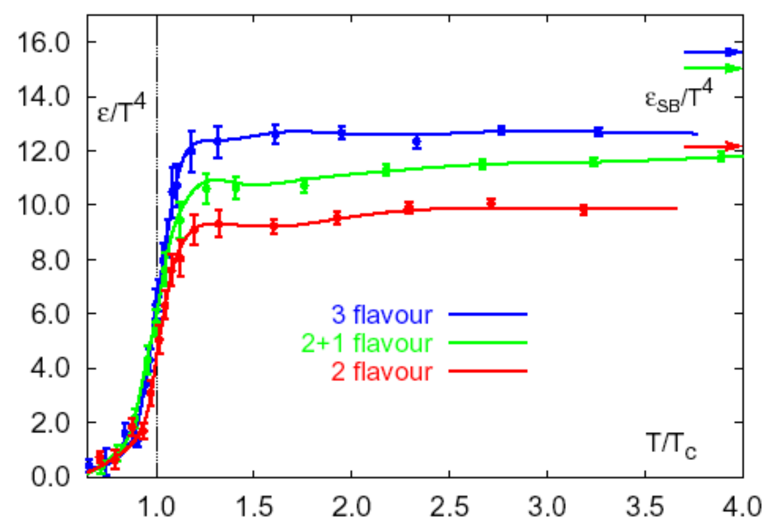
Jet quenching:
From hadrons to jets

QCD → QGP

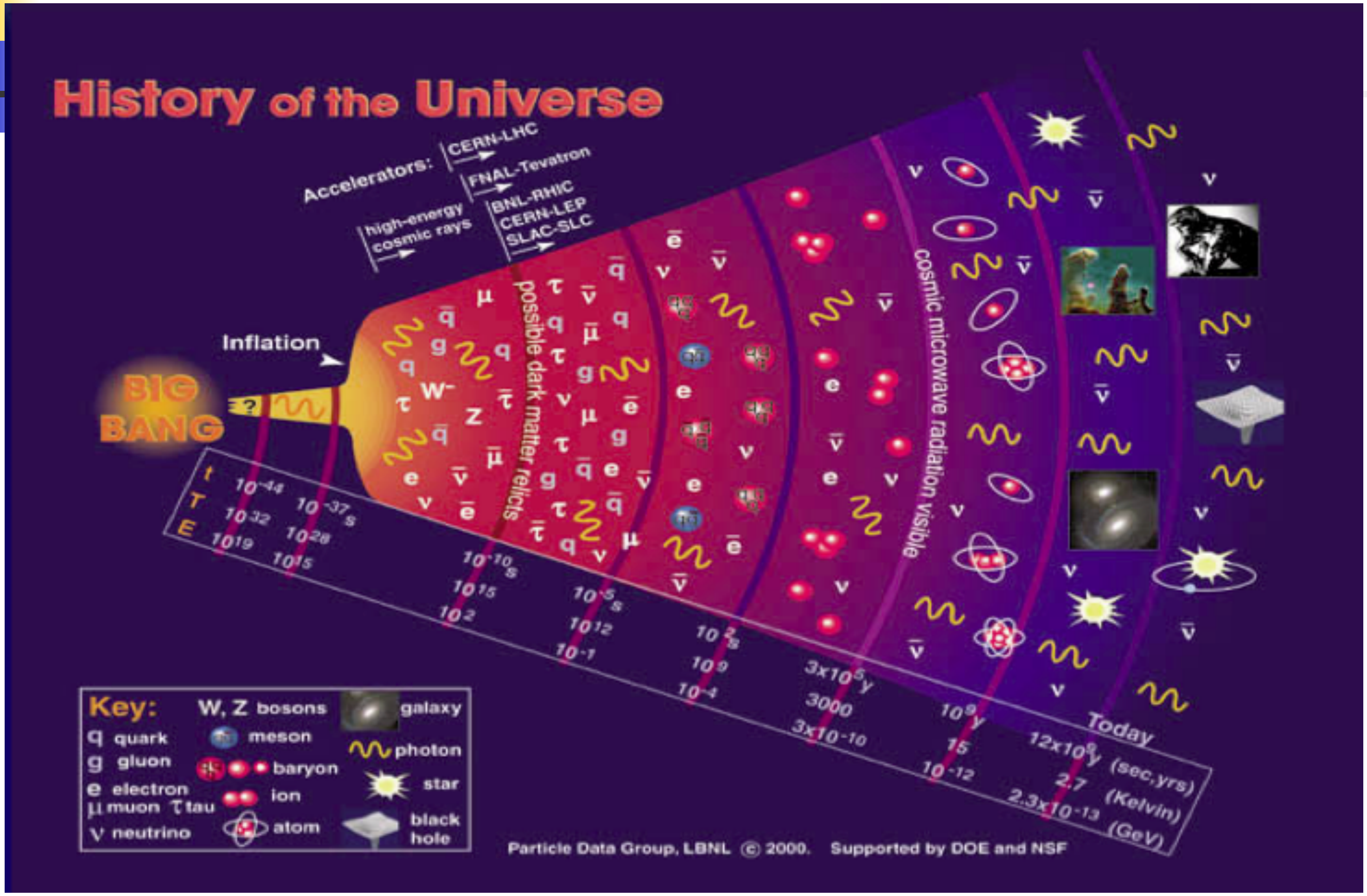
It would be interesting to explore new phenomena by distributing high energy or high nuclear density over a relatively large volume.

T. D. Lee (1978)

Lattice QCD predicts phase of thermal QCD matter with sharp rise in number of degrees of freedom near T_c=170MeV.

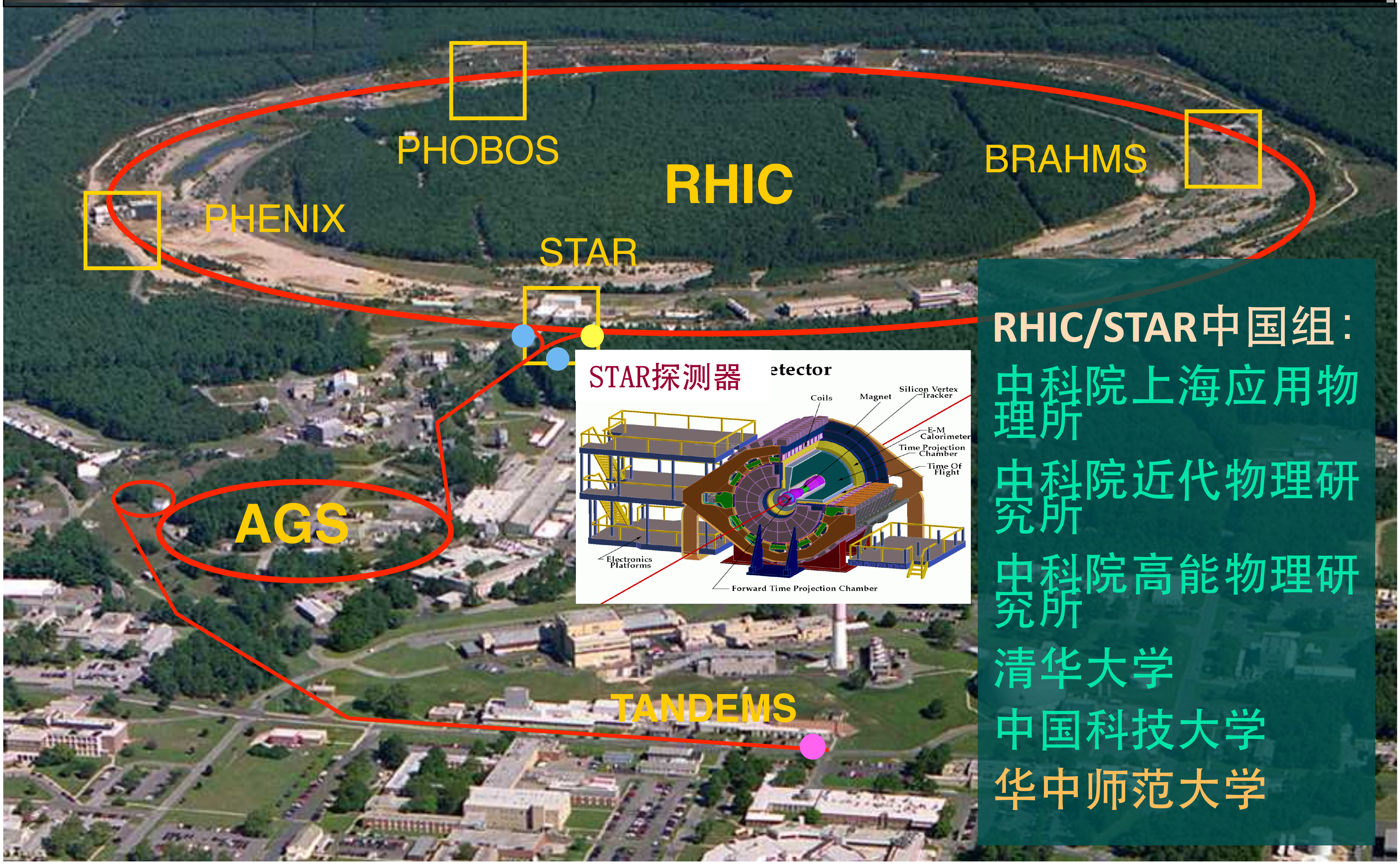


QGP & Big Bang



Investigations of the QGP help us understand the evolution of the early Universe

"Little Bang" at RHIC（2000年 – ）



RHIC/STAR中国组：

中科院上海应用物理所
中科院近代物理研究所
中科院高能物理研究所
清华大学
中国科技大学
华中师范大学

“ Little Bang” at LHC（2008年 – ）

Heavy ion实验@ CERN/LHC (27km)

ALICE探测器

LHC/ALICE中国组：

华中师范大学

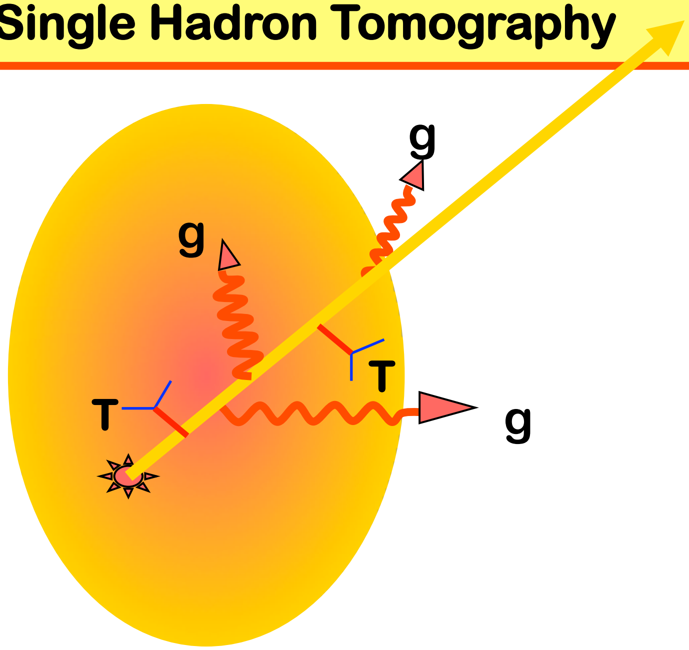
中国原子能研究院

华中科技大学

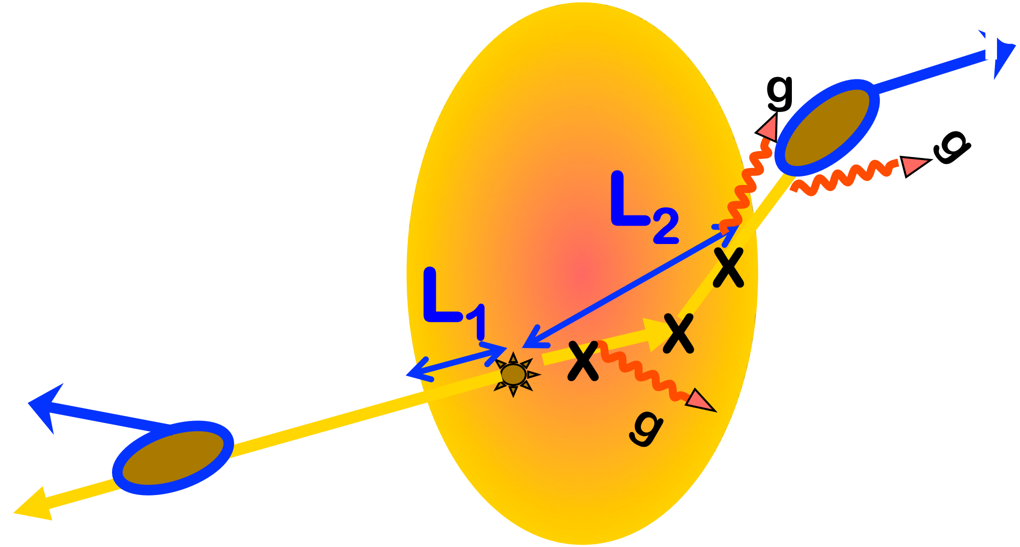
Jet quenching as a hard probe

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

Single Hadron Tomography



Di-Hadron Tomography



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

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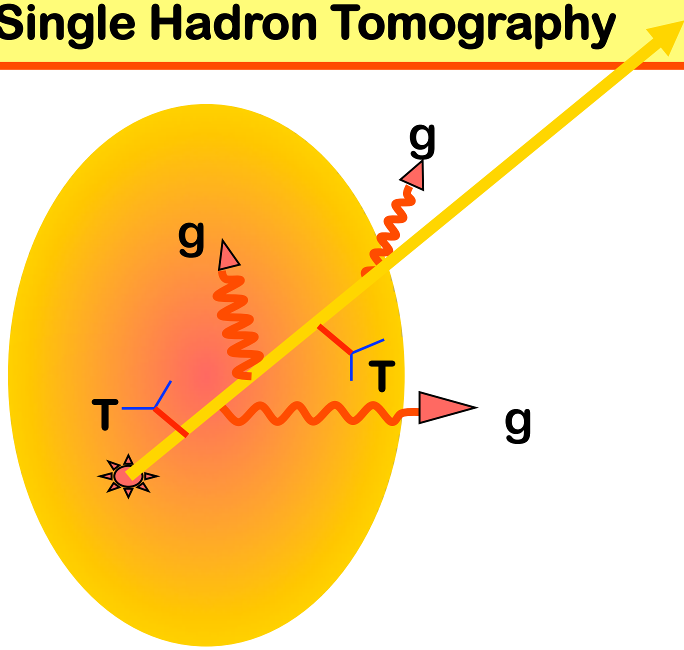
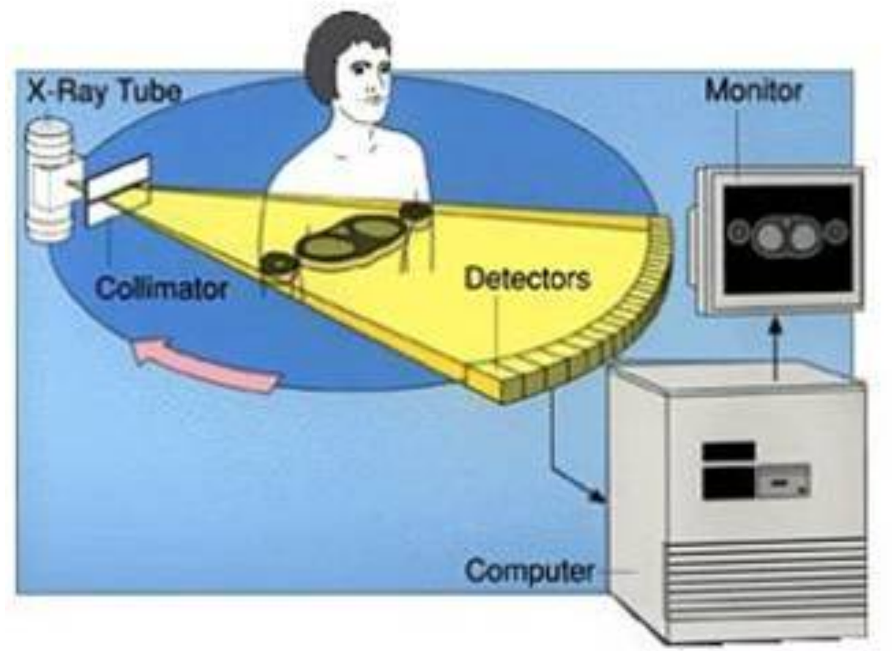
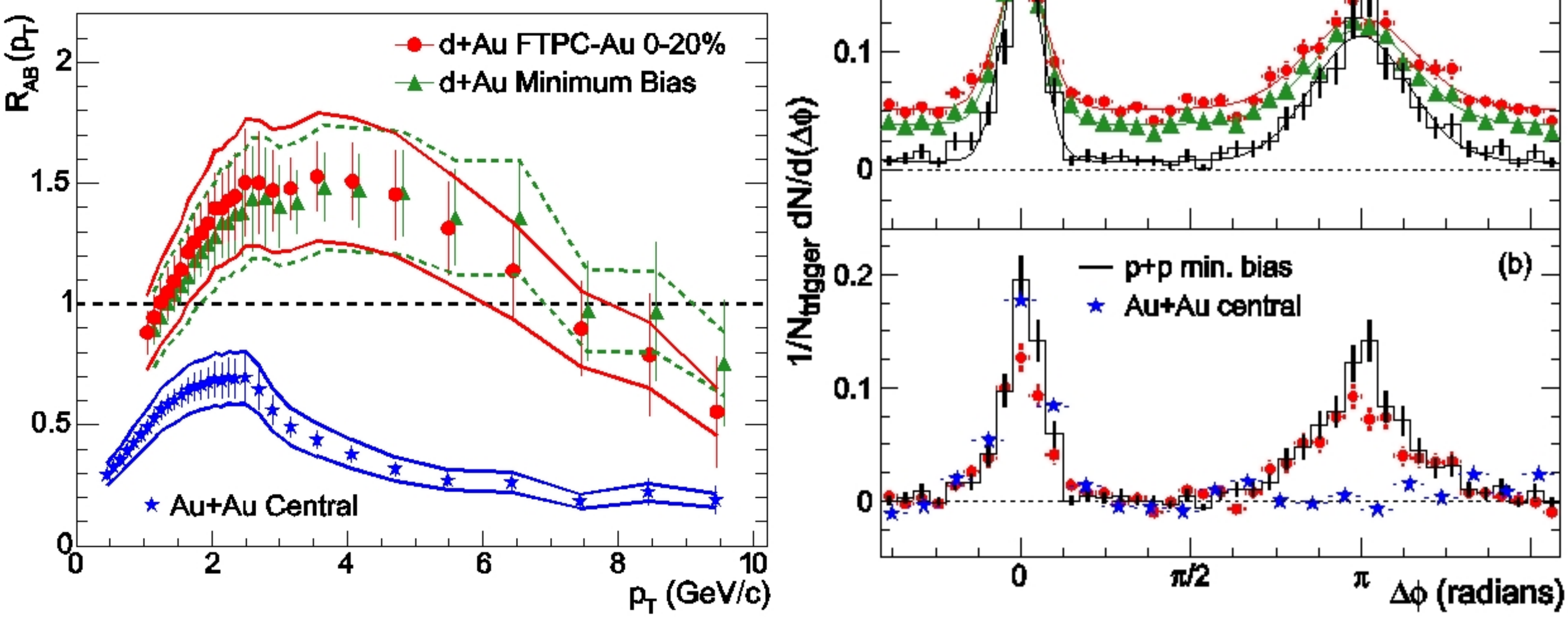




Xin-Nian Wang, M. Gyulassy, PRL68(1992)1480

Jet quenching at RHIC

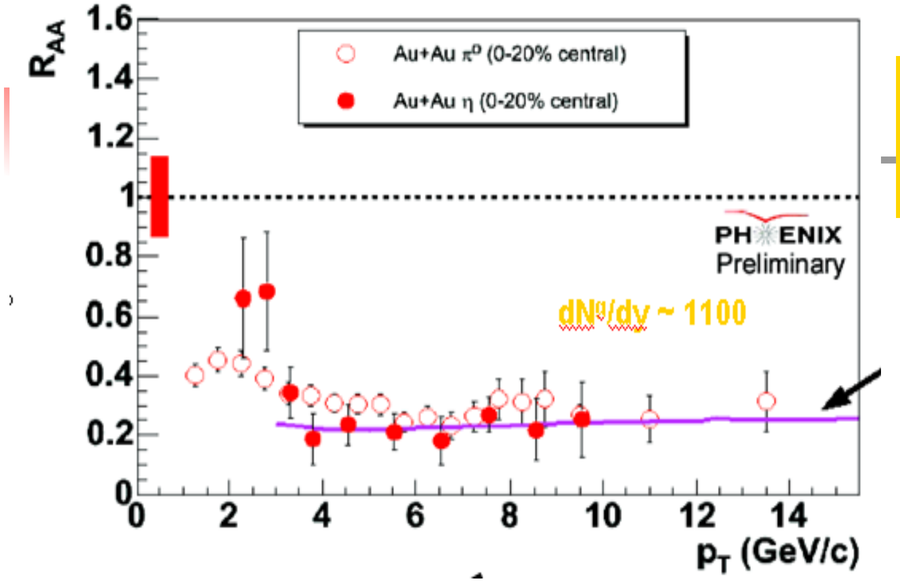
$$R_{AA} = \frac{\text{Yield}_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{\text{Yield}_{pp}}$$



Finding of the jet quenching effect in A+A collisions has been regarded as one of the most important discoveries made at RHIC.

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

Jet quenching with R_{AA}



Gyulassy-Levai-Vitev(GLV) formalism

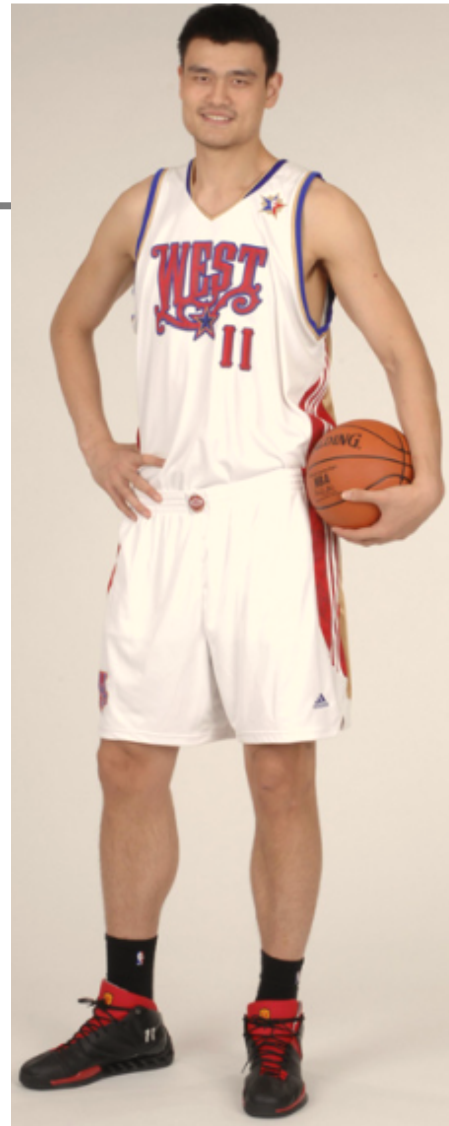
Gyulassy, Levai, Vitev, NPB 594(2001)371

$$\epsilon \approx \frac{p_0}{\tau_0 \pi R^2} \frac{dN_g}{dy} \approx 15 - 20 \frac{\text{GeV}}{\text{fm}^3}, \qquad \epsilon_A \simeq 0.16 \frac{\text{GeV}}{\text{fm}^3}.$$

- Advantage of R_{AA} : providing useful information of the hot/dense medium, with a simple physics picture.
- Disadvantage of R_{AA}: unable to resolve the order of magnitude systematic discrepancy in the extracted medium properties.

Medium transport coefficient: $\hat{q}$

1-2.5GeV^2/fm (GLV, HT), 4-5GeV^2/fm(AMY), 10-15 GeV^2/fm(ASW)

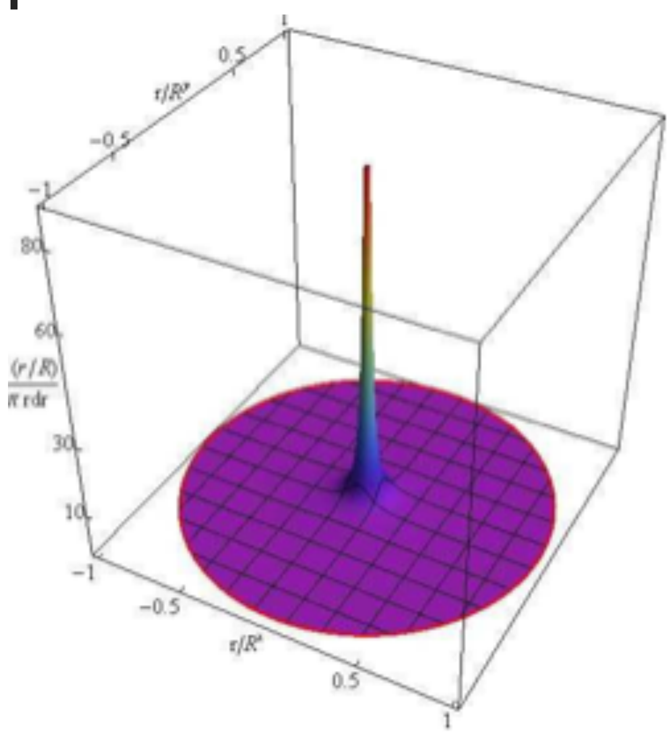


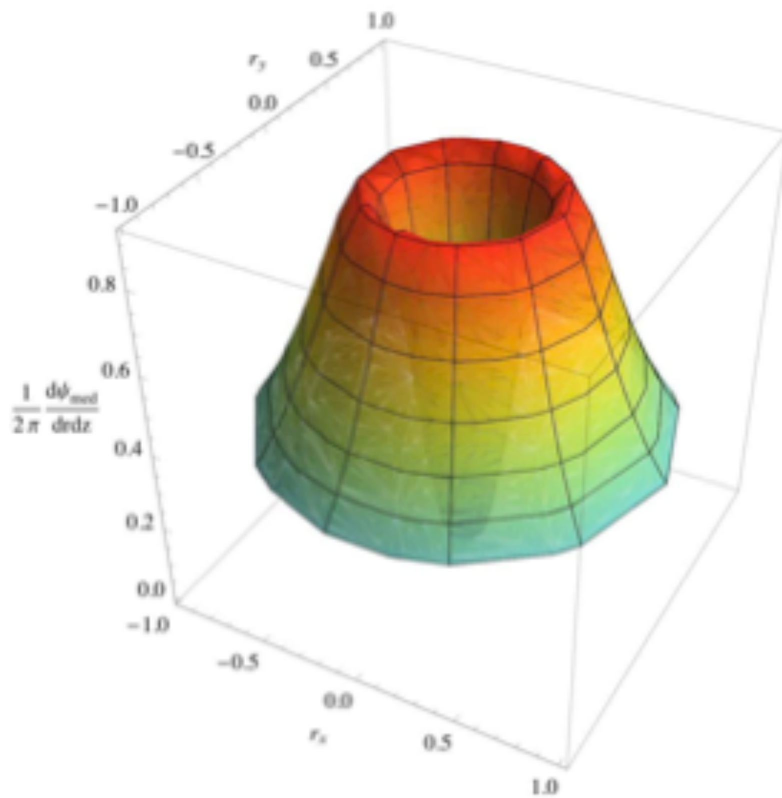
领头强子

领头强子

整体喷注

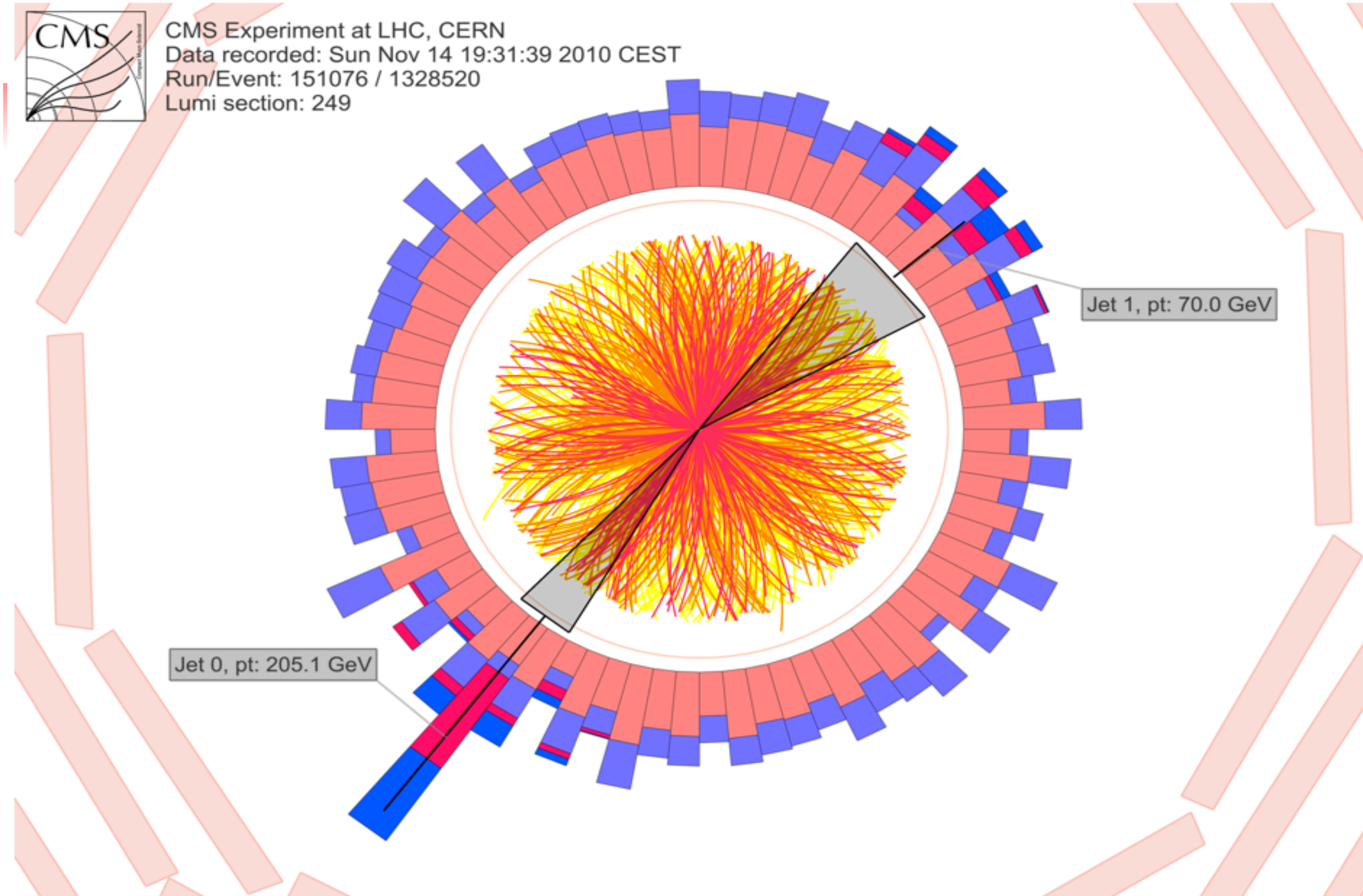
From leading hadrons to jets: Th





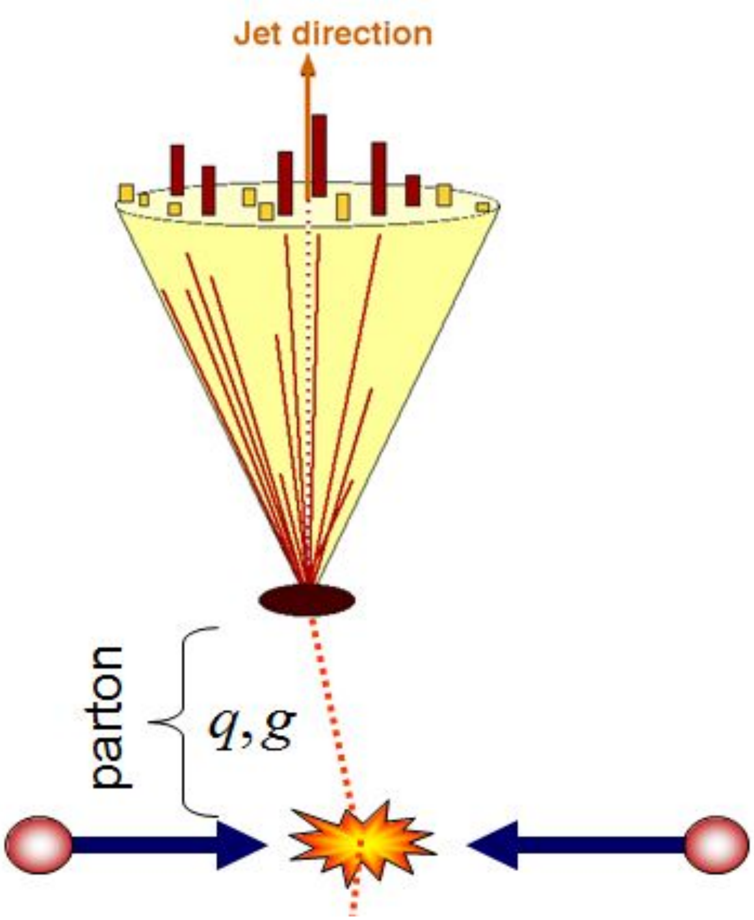
I Vitev, S Wicks, BWZ, JHEP 0811,093 (2008)

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; more precise calculations.



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

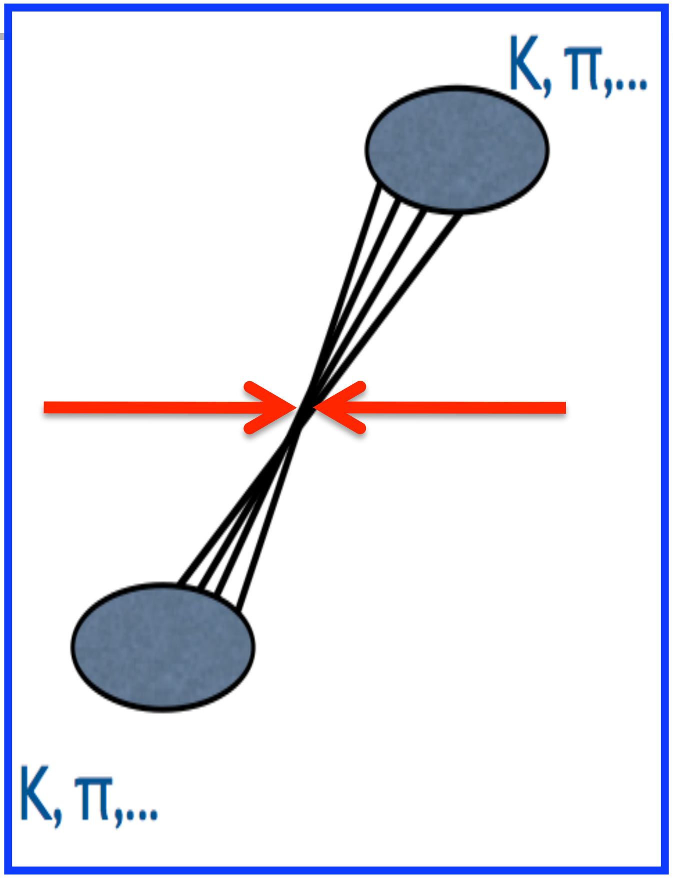
$$\phi = \sum_{i \in jet} \phi_i E_{T,i} / E_T$$

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

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

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 for gluons.
- Precise extraction of α_s is made by measuring jet event shapes.
- New physics beyond Standard Model by studying jets.



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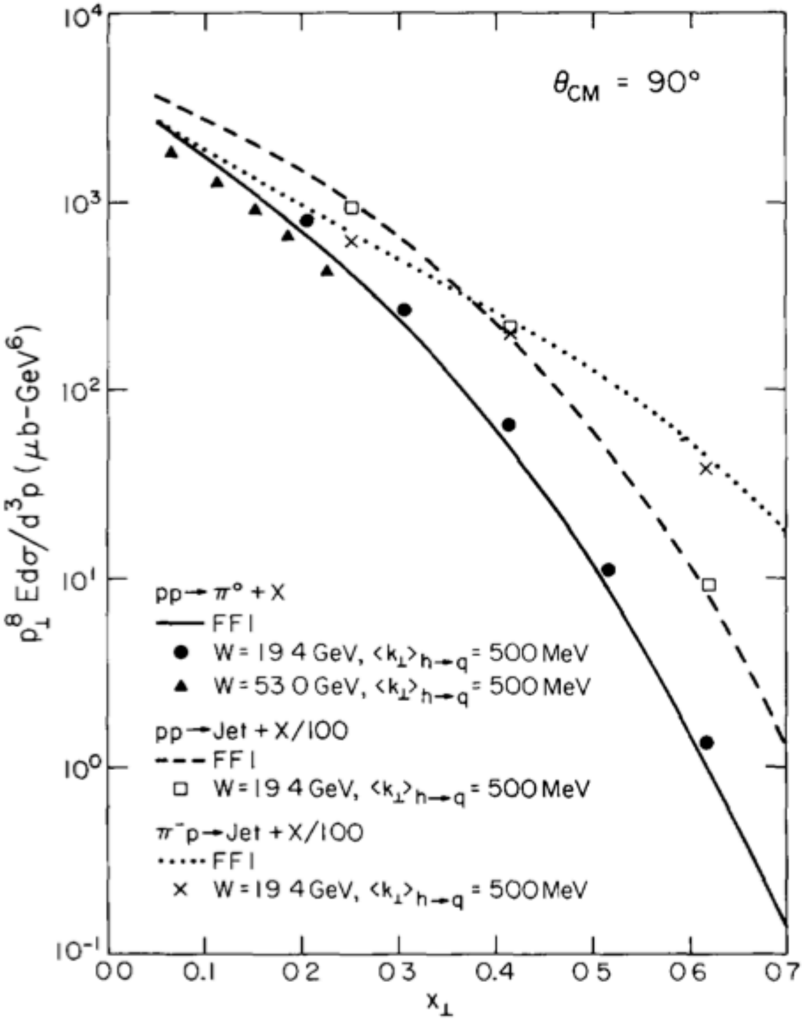

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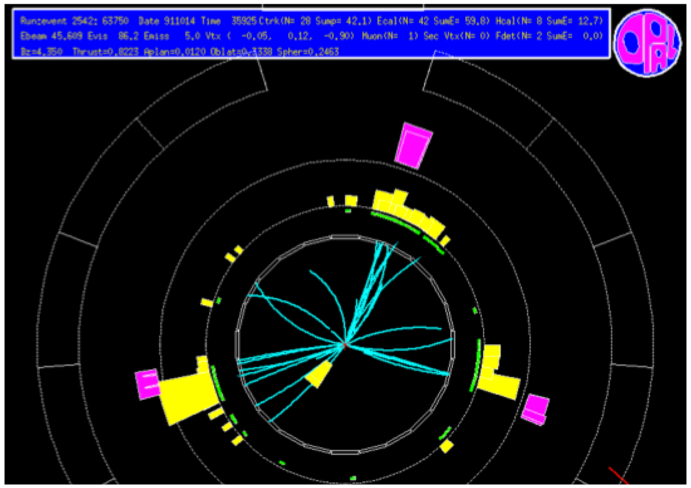
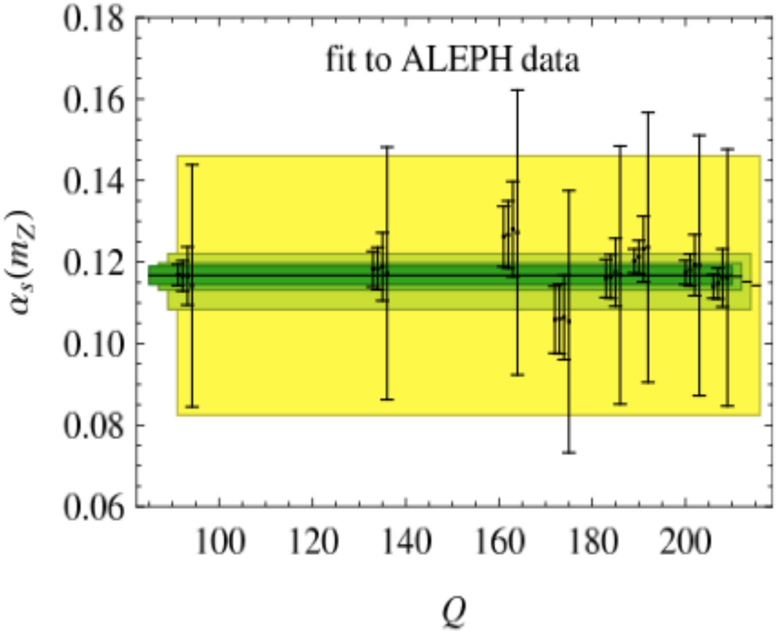
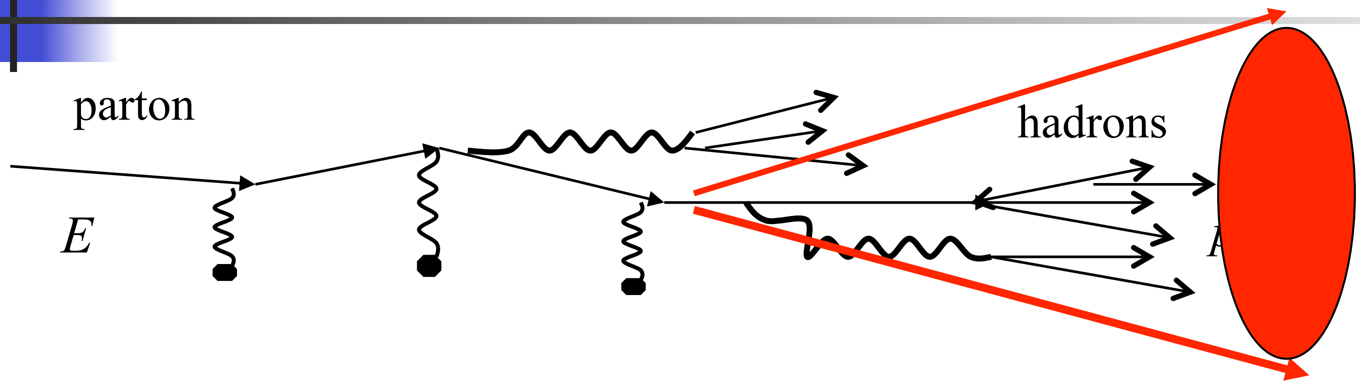
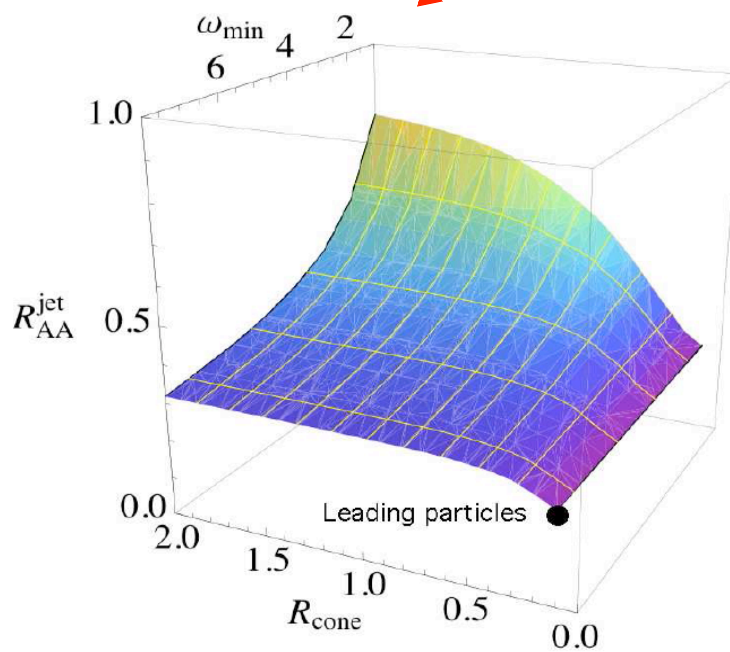




How a "jet" quenches in HIC?



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



Full jets in HIC

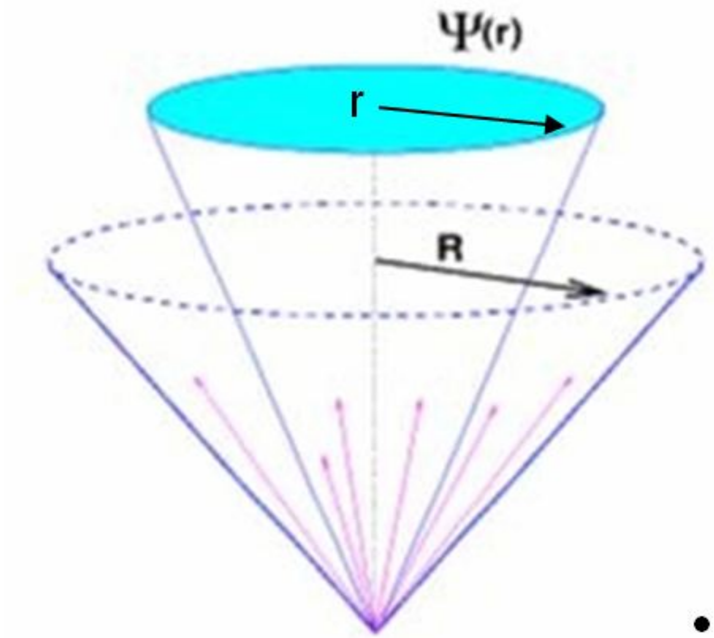
1) jet shape
2) inclusive jet spectrum
3) tagged jet production
4) dijet correlation

Jet shape in HIC

$$\Psi_{\text{int}}(r;R) = \frac{\sum_i (E_T)_i \Theta(r-(R_{\text{jet}})_i)}{\sum_i (E_T)_i \Theta(R-(R_{\text{jet}})_i)},$$

$$\psi(r;R) = \frac{d\Psi_{\text{int}}(r;R)}{dr}.$$

$$\Psi_{\text{int}}(r=R,R)=1$$



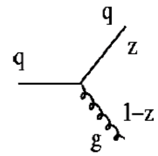
I Vitev, S Wicks, BWZ,

JHEP 0811,093 (2008); EPJC 62, 139 (2009).

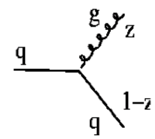
LO & Resummation: p+p

An analytic approach to the energy distribution of jet

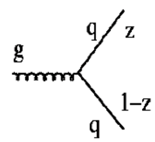
Seymour, M. (1998)



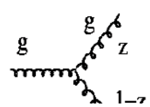
$$P^{(1)}_{qq}(x) = C_2(F)\left[(1+x^2)\left(\frac{1}{1-x}\right)_+ + \frac{3}{2}\delta(1-x)\right]$$



$$P^{(1)}_{gq}(x) = C_2(F)\,\frac{(1-x)^2+1}{x}$$



$$P^{(1)}_{qg}(x) = T(F)\left[(1-x)^2 + x^2\right]$$



$$P^{(1)}_{gg}(x) = 2C_2(A)\left[\frac{x}{(1-x)_+} + \frac{1-x}{x} + x(1-x)\right] + \left(\frac{11}{6}C_2(A) - \frac{2}{3}T(F)n_f\right)\delta(1-x),$$

Jet shape at LO with the acceptance cut

$$\psi_a(r;R) = \sum_b \frac{\alpha_s}{2\pi}\frac{2}{r}\int_{z_{min}}^{1-Z} dz\, zP_{a\to bc}(z).$$

$$z_{min} = \omega^{min}/E_T$$

Collinear divergence requires Sudakov resummation:

$$\begin{aligned} P(<r) &= \exp(-P_1(>r)) \\ &= \exp\left(-\int_r^R dr'\,\psi_{\rm coll}(r')\right) \end{aligned}$$

$$\psi_{RS}(r) = \frac{dP(r)}{dr}$$

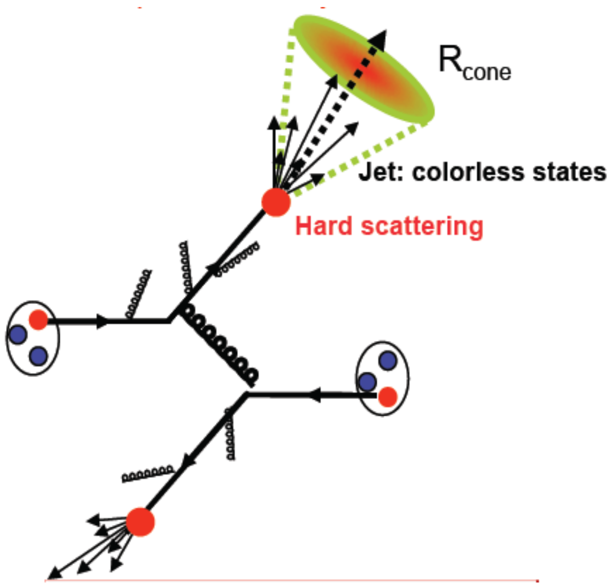
Power corr. & IS radia.

- Power correction: include running coupling inside the z integration and integrate over the Landau pole.

$$\bar{\alpha_0}'(Q_0, k_{min}) = \frac{1}{Q_0}\int_{k_{min}}^{Q_0} dk\, \alpha_s(k)$$

non-perturbative scale Q_0.

$$\bar{\alpha_0}'(2\,\mathrm{GeV}, 0) = 0.52\ ,\quad \bar{\alpha_0}'(3\,\mathrm{GeV}, 0) = 0.42$$



- Initial-state radiation should be included, which gives:

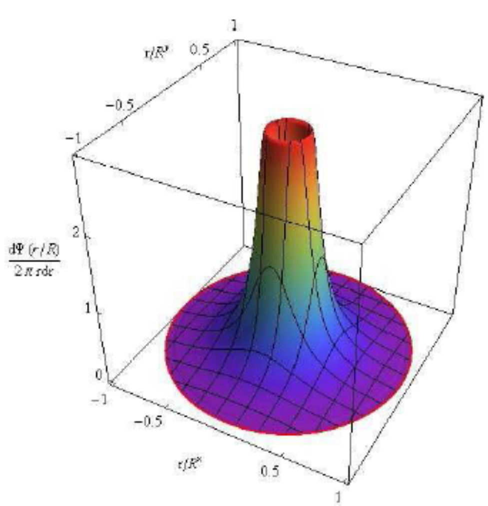
$$\psi_i(r) = \frac{C\alpha_s}{2\pi} 2r \left(\frac{1}{Z^2} - \frac{1}{(1-z_{min})^2}\right)$$

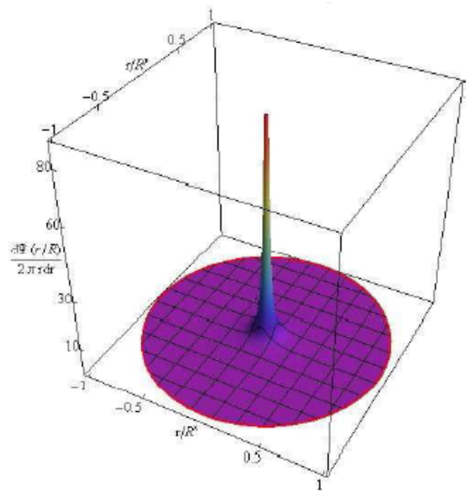
Jet shape p+p: baseline

$$\psi(r) = \psi_{\rm coll}(r)\,(P(r)-1) + \psi_{\rm LO}(r) + \psi_{i,\rm LO}(r) + \psi_{\rm PC}(r) + \psi_{i,\rm PC}(r)\,,$$

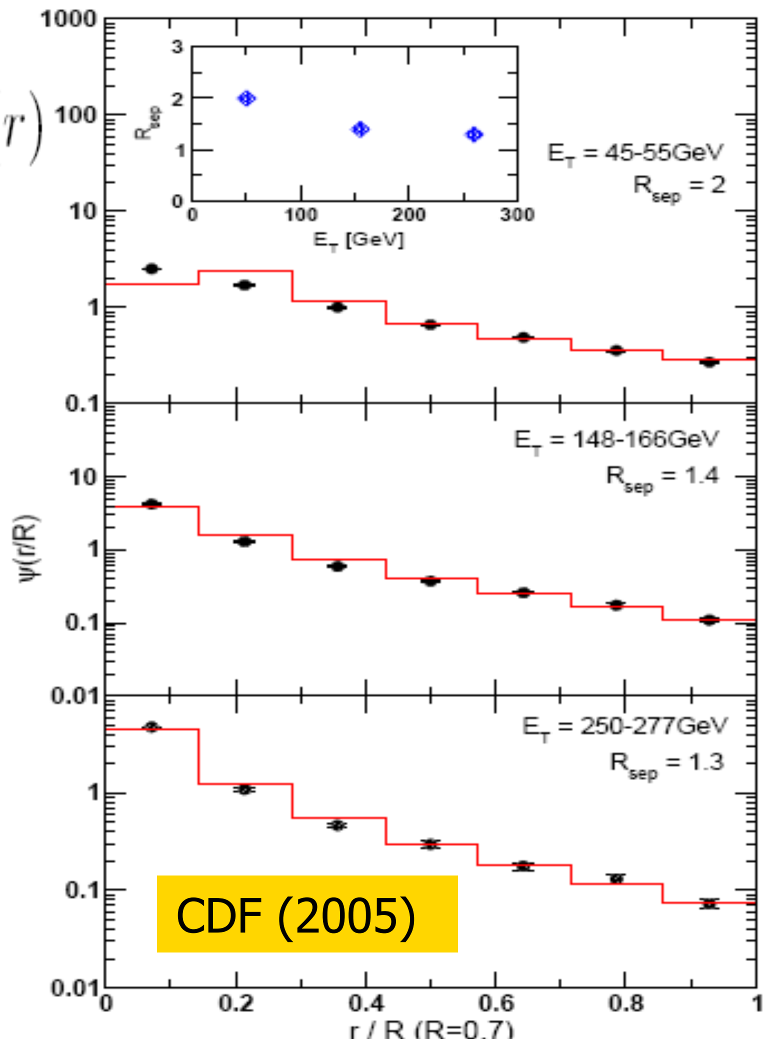
20 GeV

500 GeV





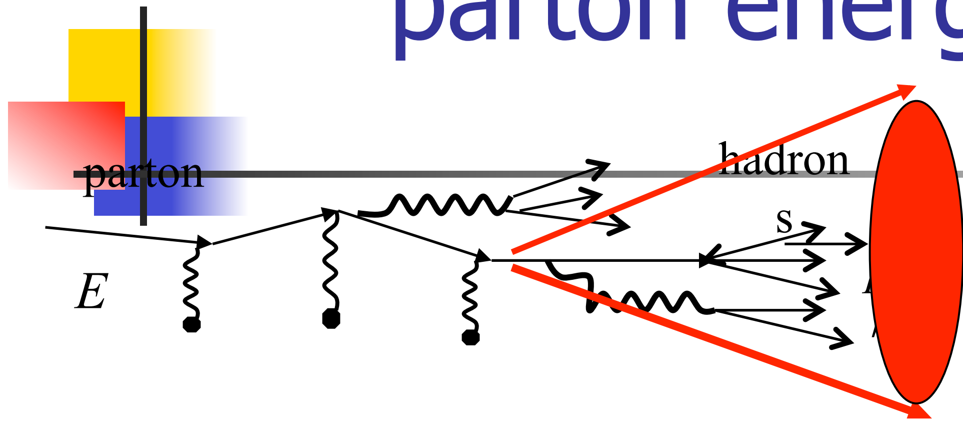
LHC



CDF (2005)

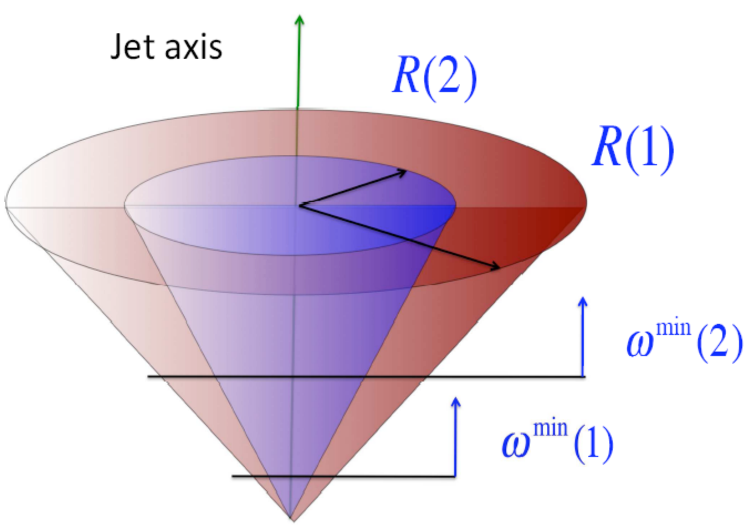
$\sqrt{s} = 1960$ GeV

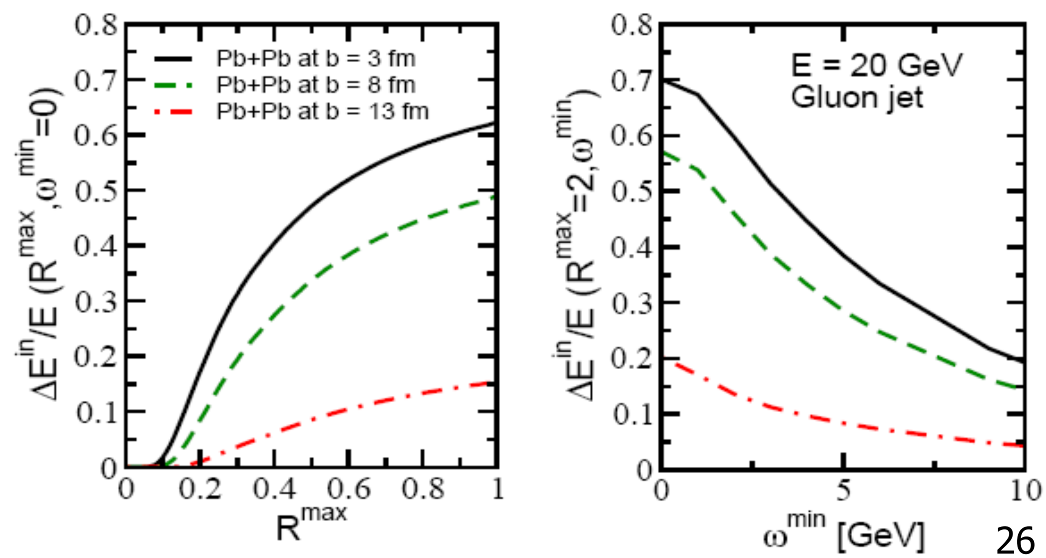
parton energy loss in QGP



Gyulassy-Levai-Vitev

$$\frac{\Delta E^{in}}{E}(R^{\max},\omega^{\min}) = \frac{1}{E}\int_{\omega^{\min}}^{E} d\omega \int_0^{R^{\max}} dr \frac{dI^g}{d\omega dr}(\omega,r)$$

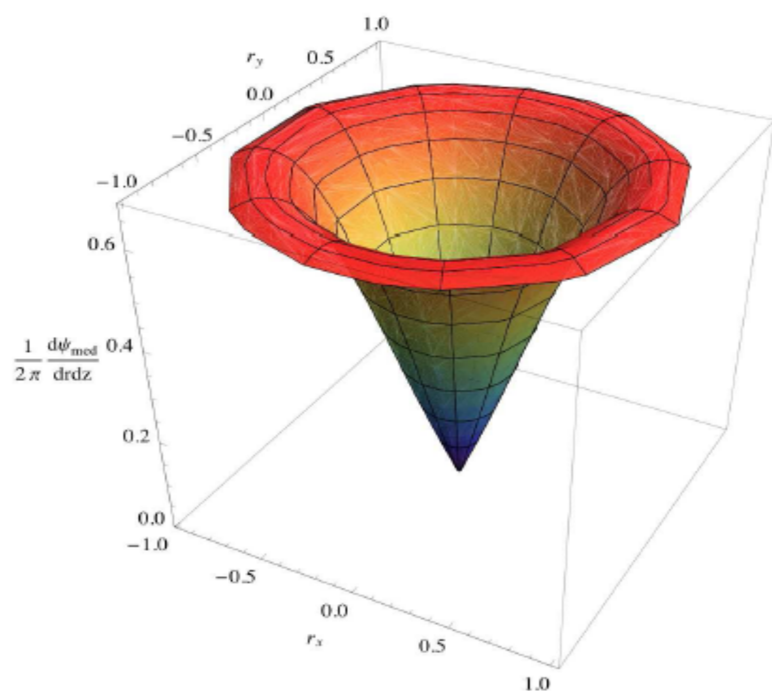


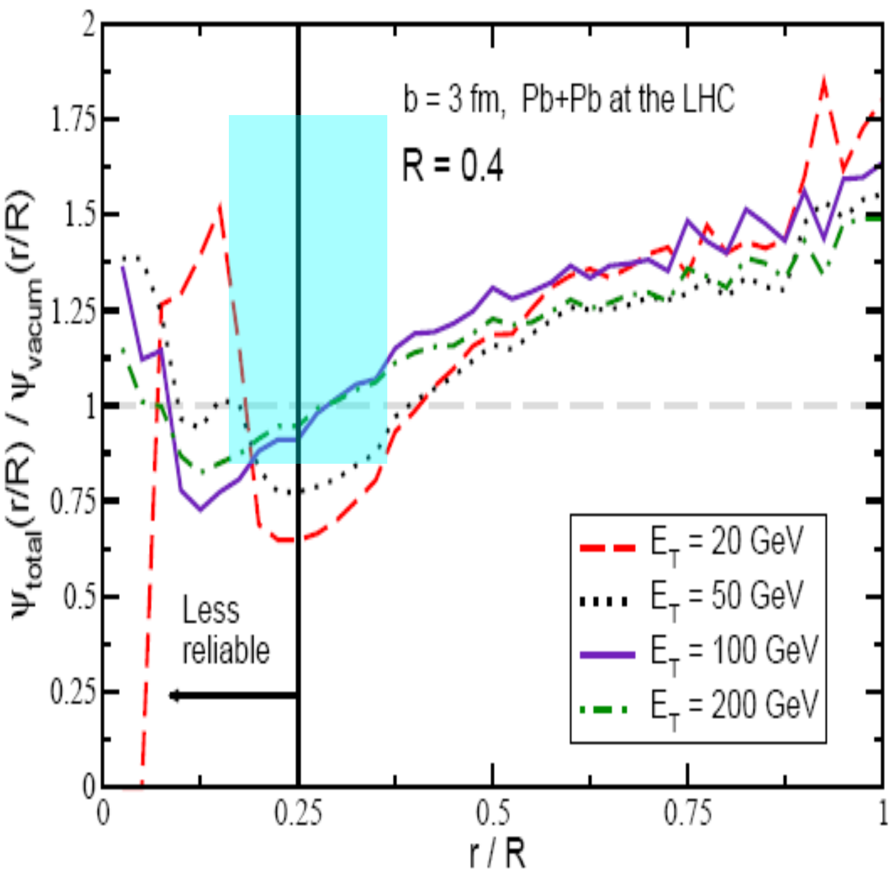


Total jet shape in HIC

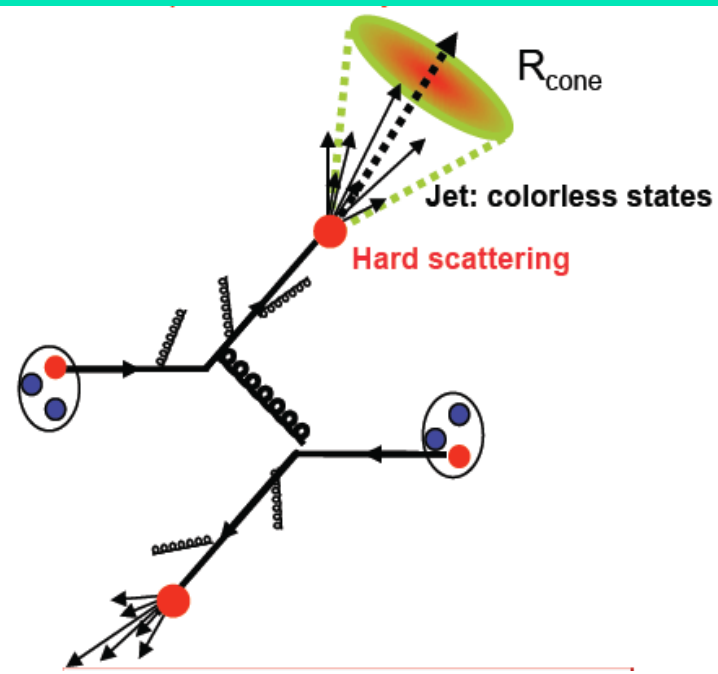
- Medium-induced jet shape is much broader than the jet shape in p+p

$$\psi_{\mathrm{tot.}}(r/R) = \frac{1}{\mathrm{Norm}} \int_{\epsilon=0}^{1} d\epsilon \sum_{q,g} P_{q,g}(\epsilon) \frac{1}{(1-(1-f_{q,g})\cdot\epsilon)^3} \times \frac{\sigma_{q,g}^{NN}(R,\omega^{\min})}{d^2E'_T dy} \left[(1-\epsilon)\ \psi_{\mathrm{vac.}}^{q,g}(r/R) + f_{q,g}\cdot\epsilon\ \psi_{\mathrm{med.}}^{q,g}(r/R) \right]$$





Inclusive jet cross section in HIC at NLO



I Vitev, BWZ, PRL 104,132001 (2010), arXiv: 0910.1090.

Jet cross section at NLO in p+p

- Jet cross sections at NLO in p+p :

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

- Function S_2 and S_3 contain jet find algorithm:

2 --→ 2

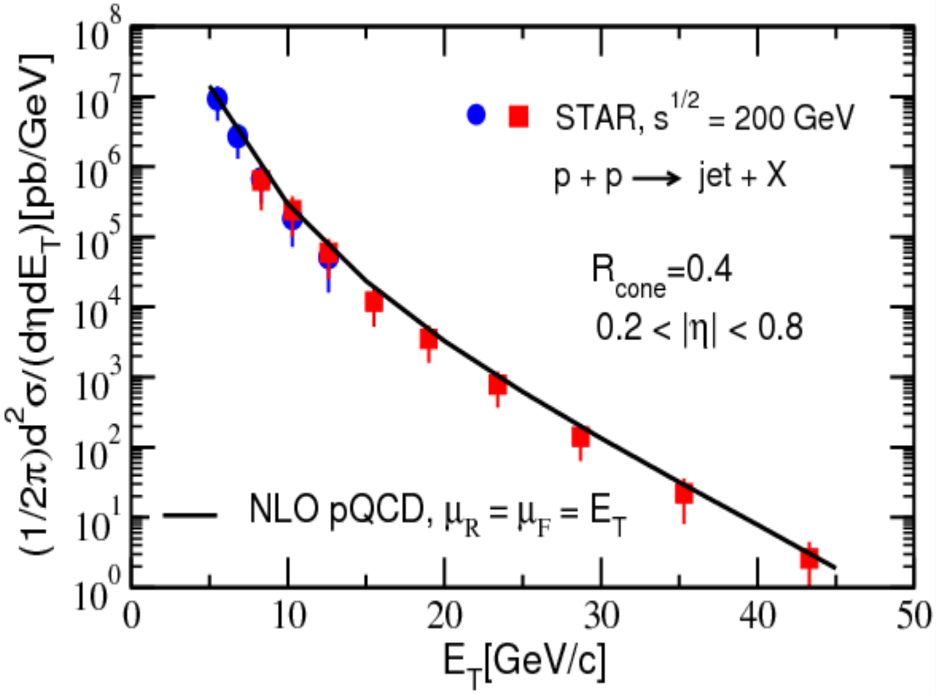
$$S_2 = \sum_{i=1}^{2} S(i) = \sum_{i=1}^{2} \delta(E_{T_i} - E_T)\delta(y_i - y)$$

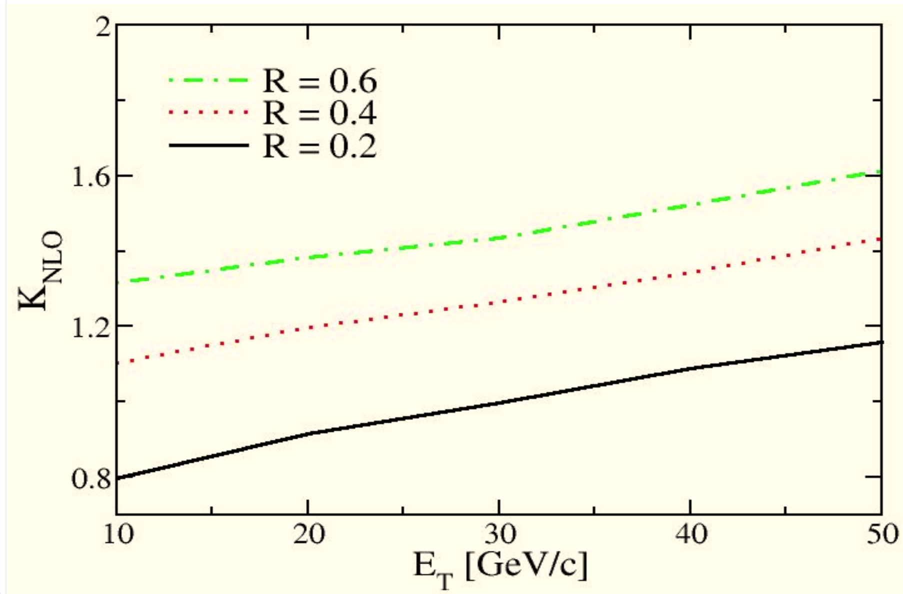
2 --→ 3

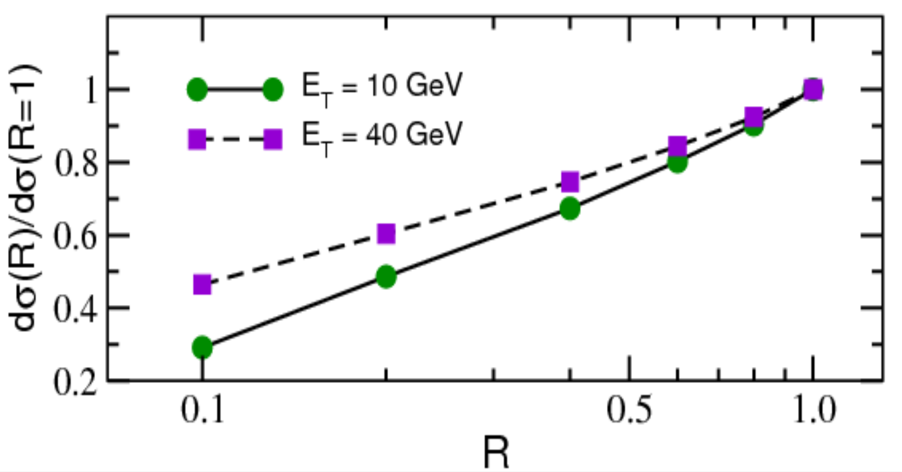
$$S_3 = \sum_i \delta(p_i - p_J)\delta(y_i - y_J) \prod_{j(j\neq i)} \theta\left(R_{ij} > \frac{p_i + p_j}{\max(p_i,p_j)} R\right) + \sum_{i,j(i<j)} \delta(p_i + p_j - p_J)\delta(\frac{p_i y_i + p_j y_j}{p_i + p_j} - y_J)\theta(R_{ij} < R_{\rm rc})$$

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

Jets in p+p at RHIC



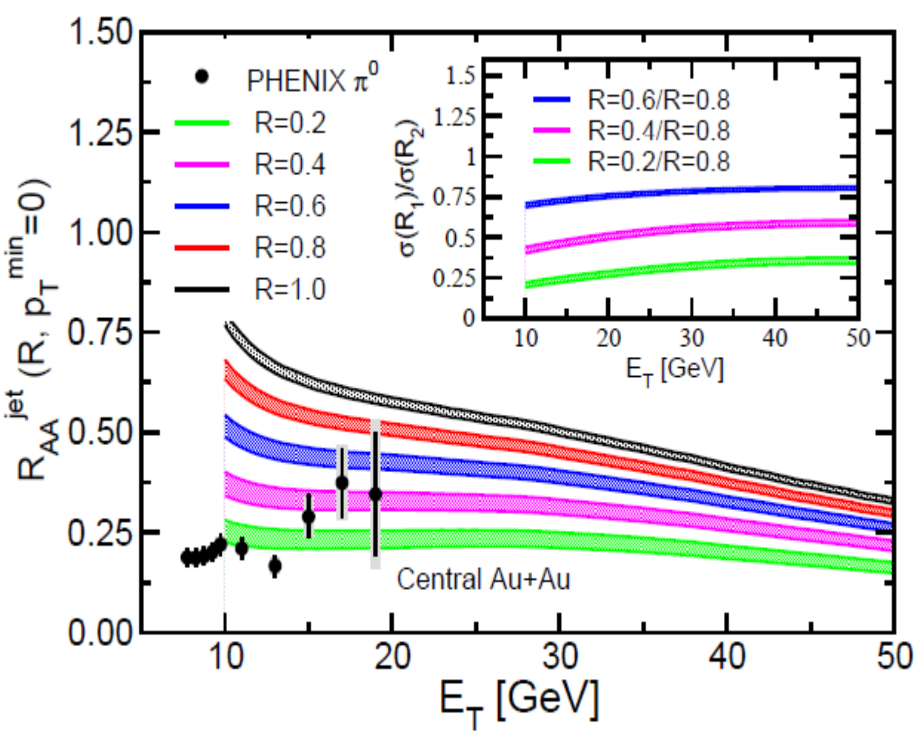


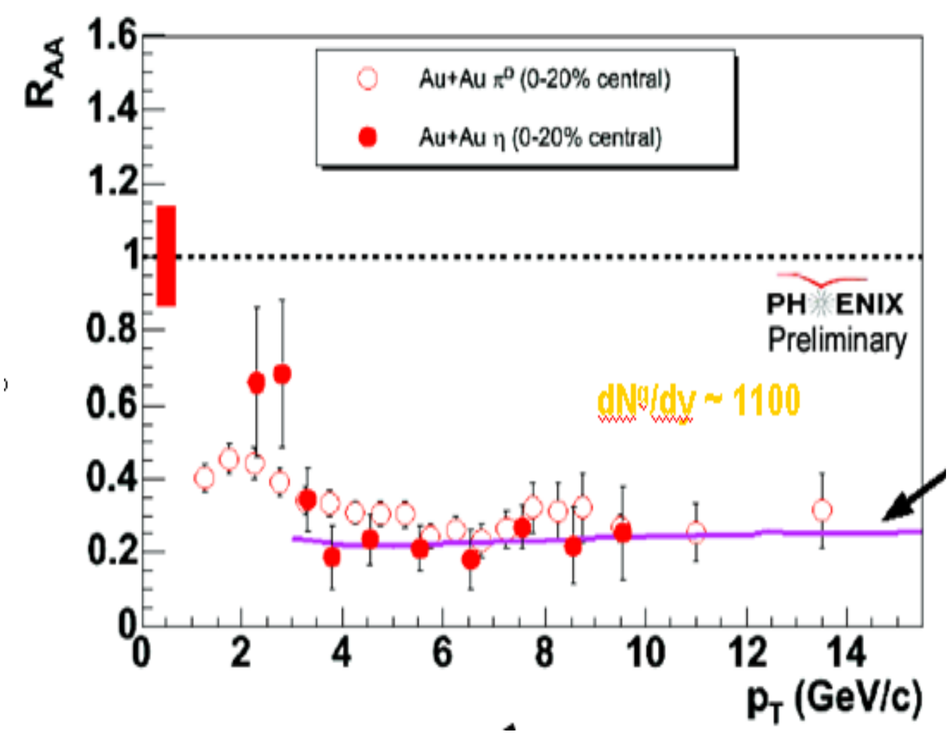


- Very good agreement between data and theory is achieved;
- K_{NLO}=NLO/LO can be smaller than 1 at small cone radius.

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.





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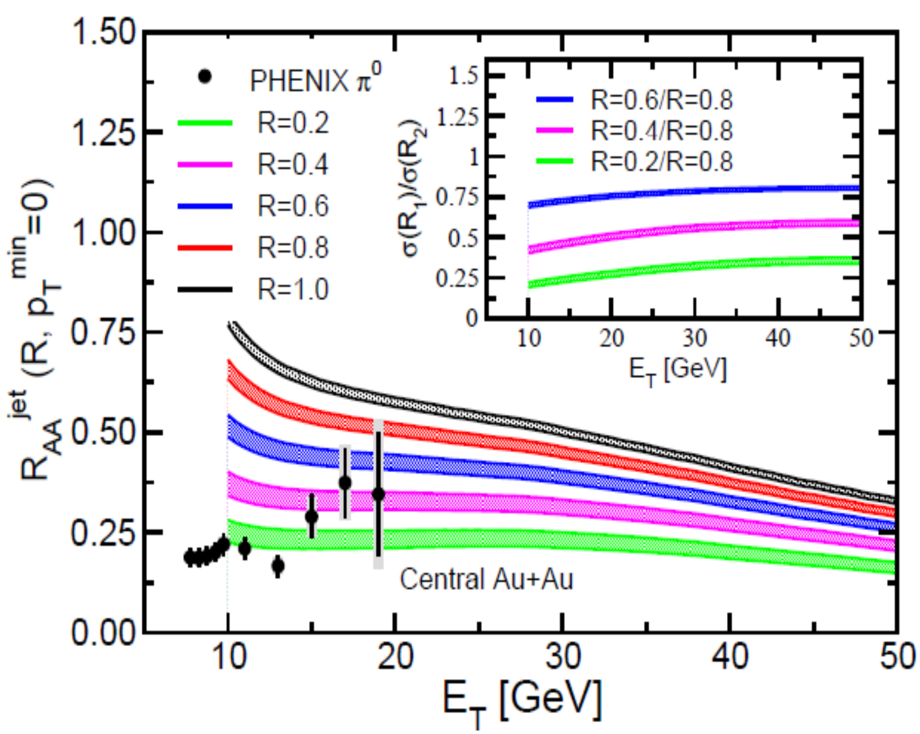
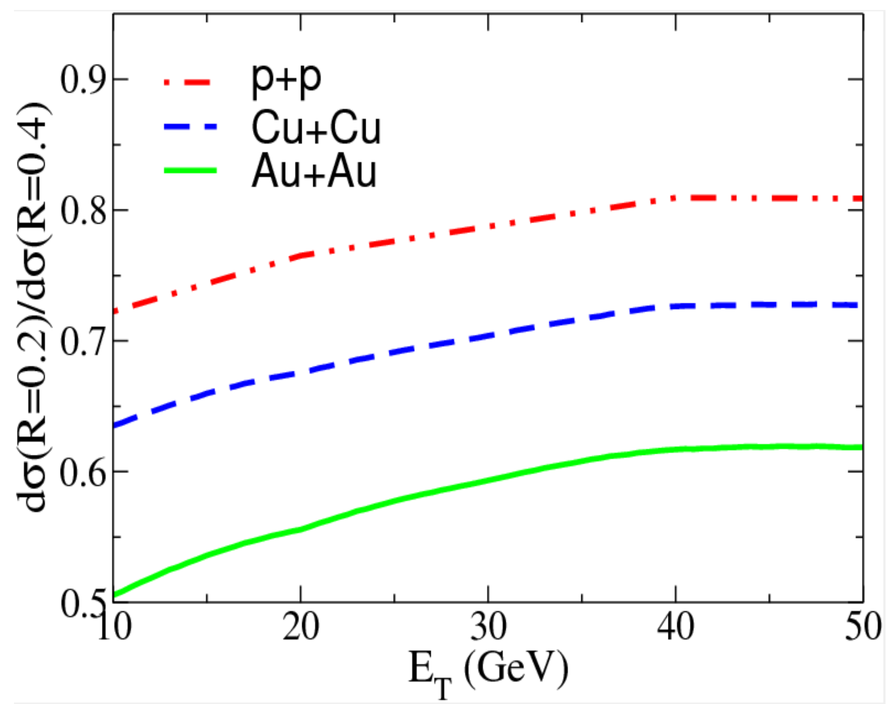
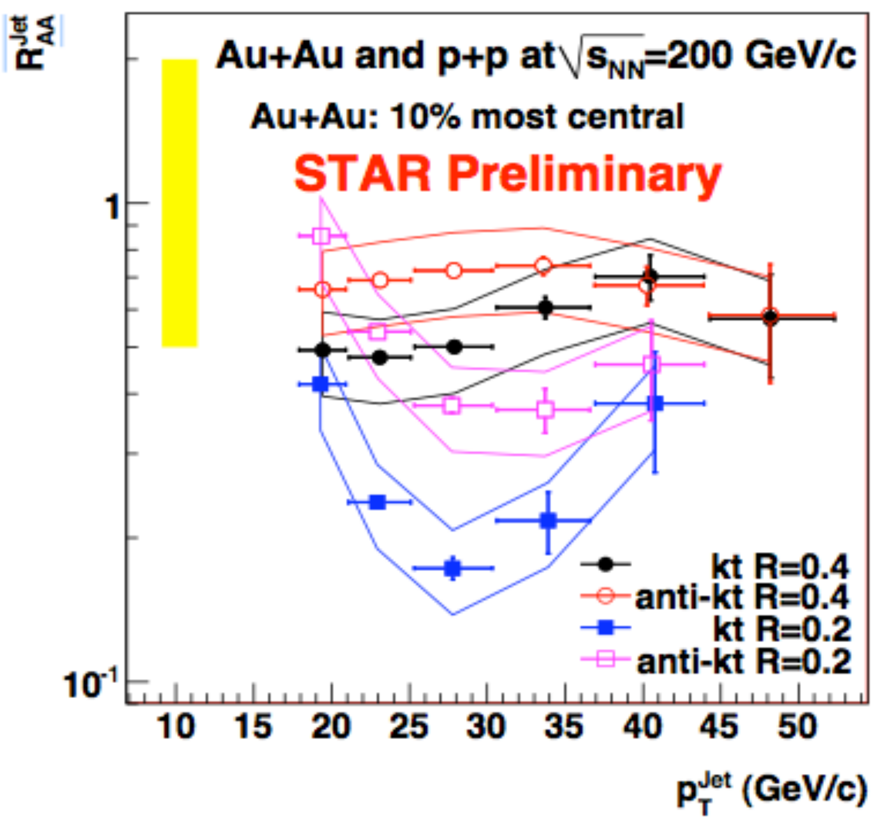
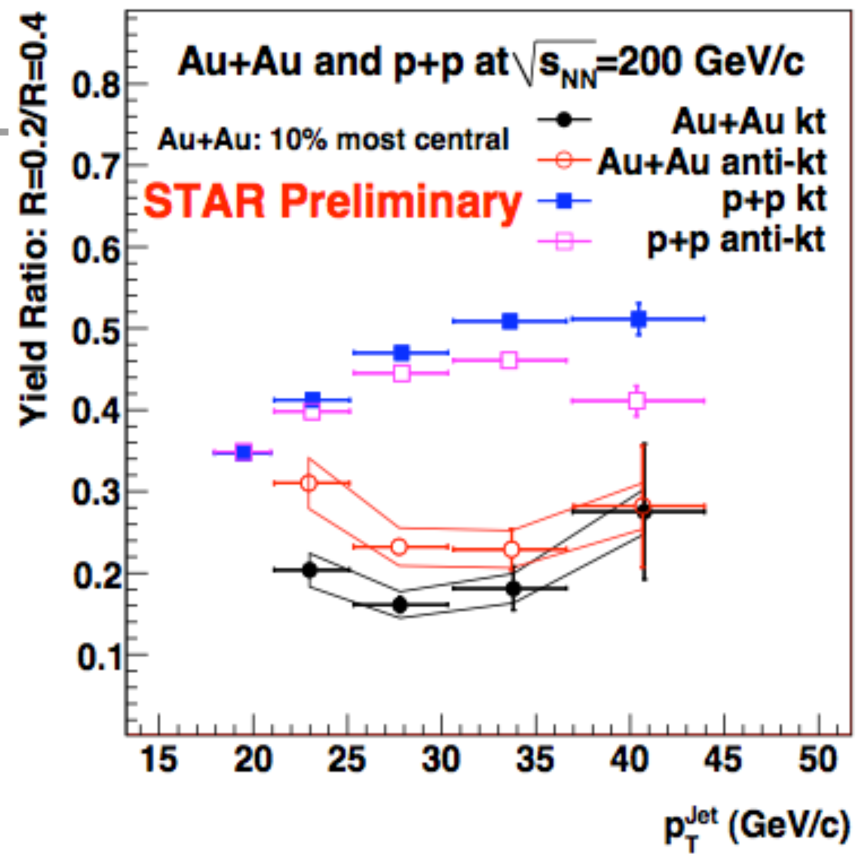




Jet measuring at RHIC



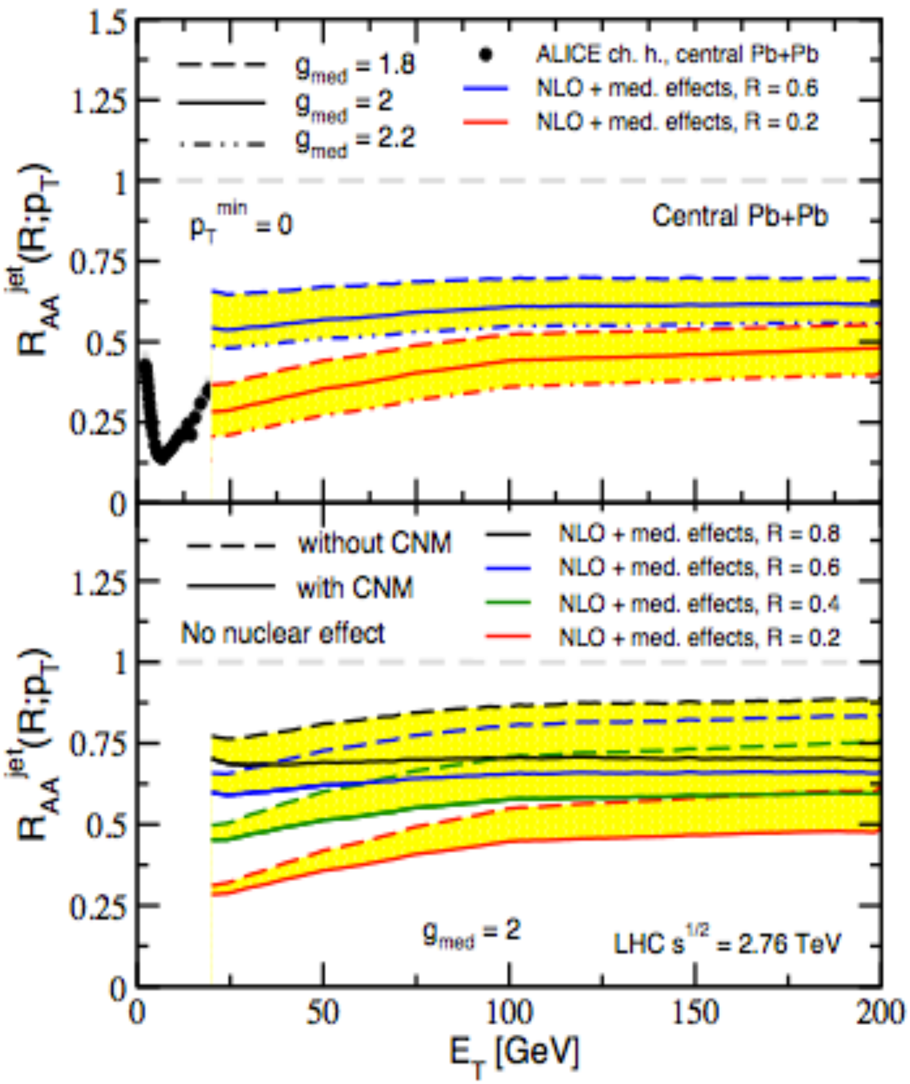


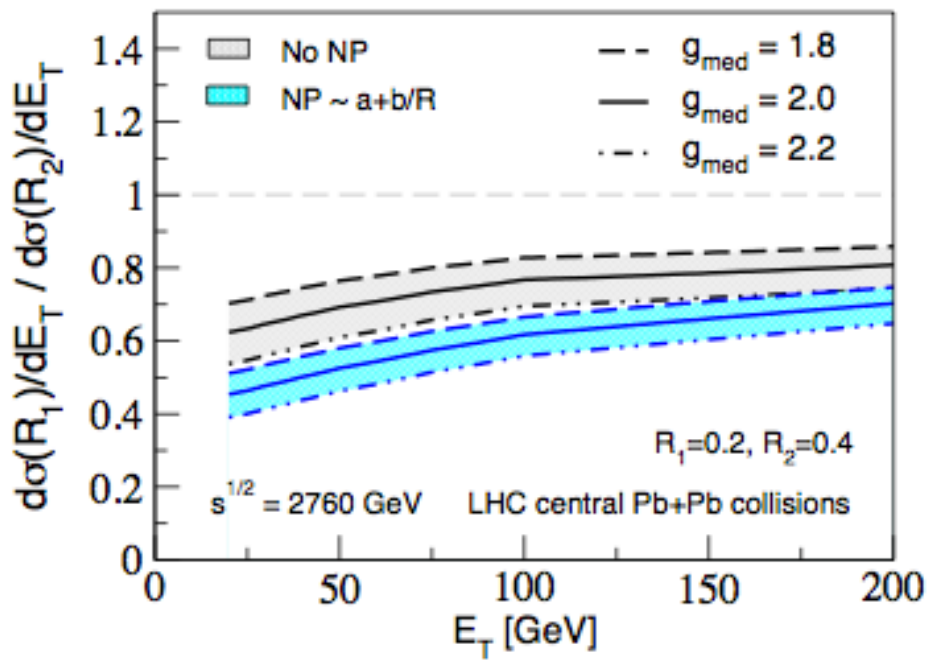
- Jets in Au+Au by STAR

M. Poloszkon et al, (2010)

S. Salur et al, (2010)

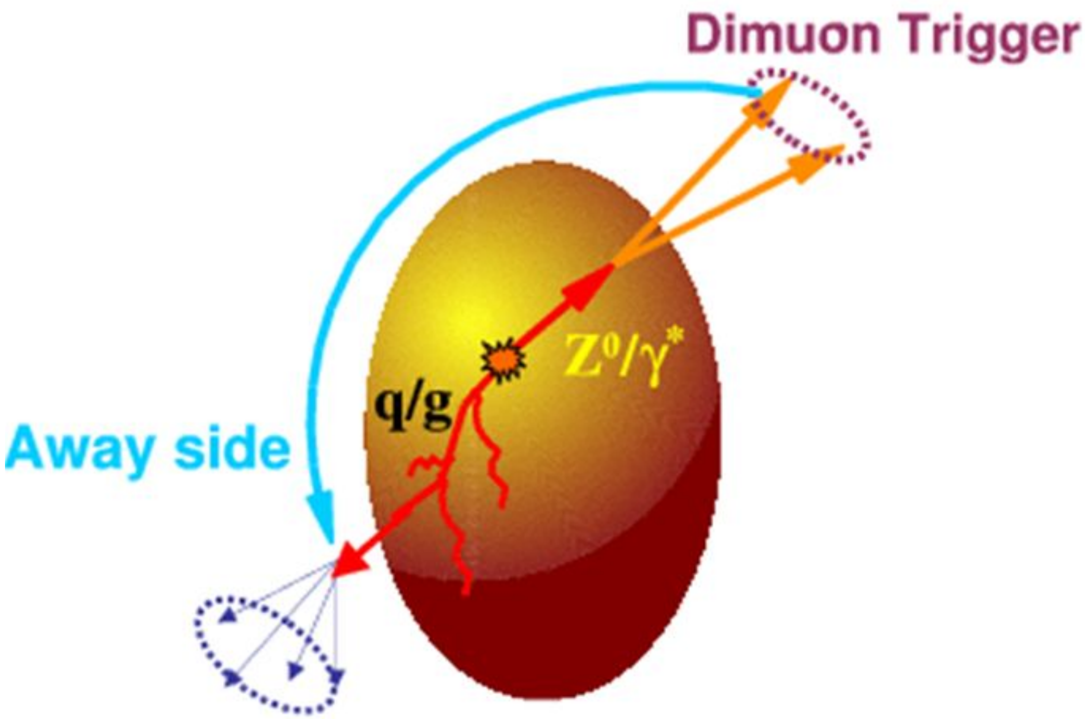
Inclusive jets in Pb+Pb at LHC

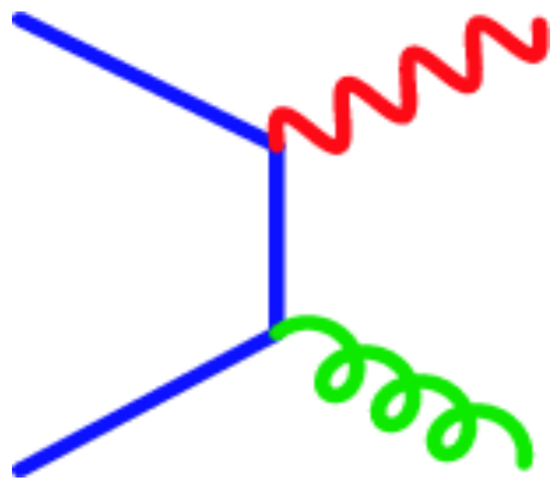




Y He, Vitev, BWZ, arXiv:1105.2566

Tagged jet production in HIC at NLO





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

Tagged jet production in HIC

photon + jet

- Advantage: large yield
- Disadvantage: final-state effects

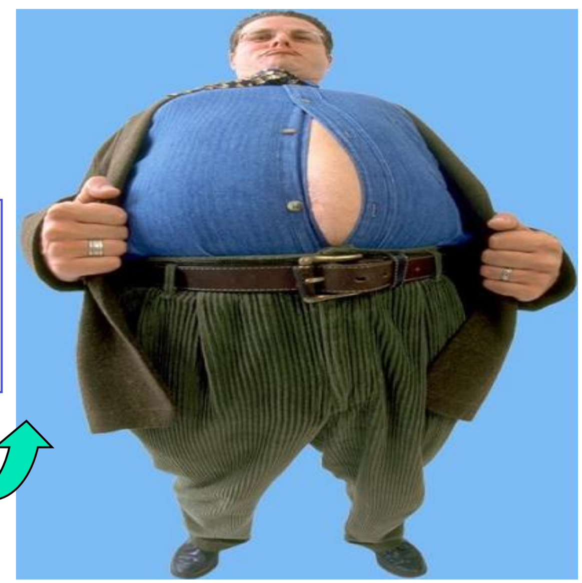
Dai, Vitev, BWZ, in progress

Z^0 + jet

- Disadvantage: small cross section
- Advantage: no final-state effects

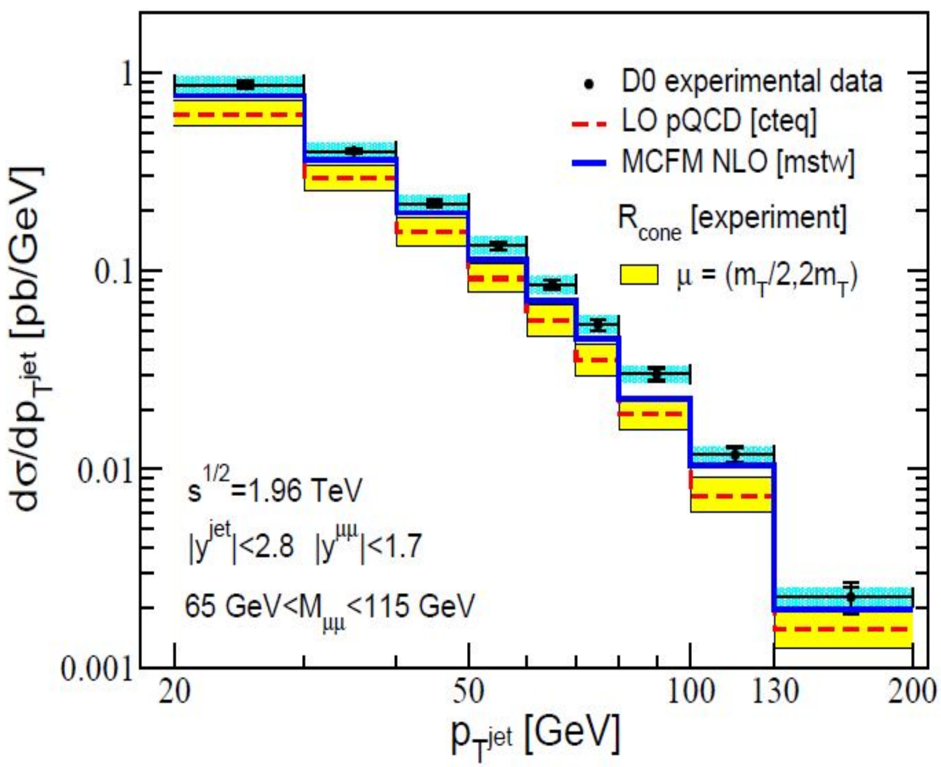
Neufeld, Vitev, BWZ, PRC (2011)

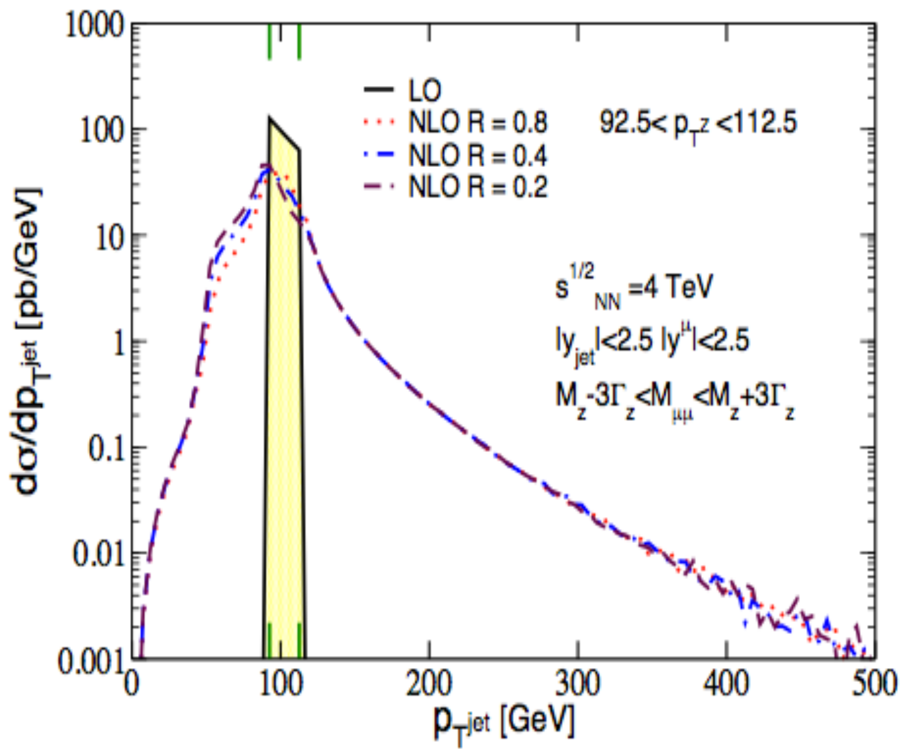
You are so light, I am too heavy.



Z^0 + jet in h+h

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



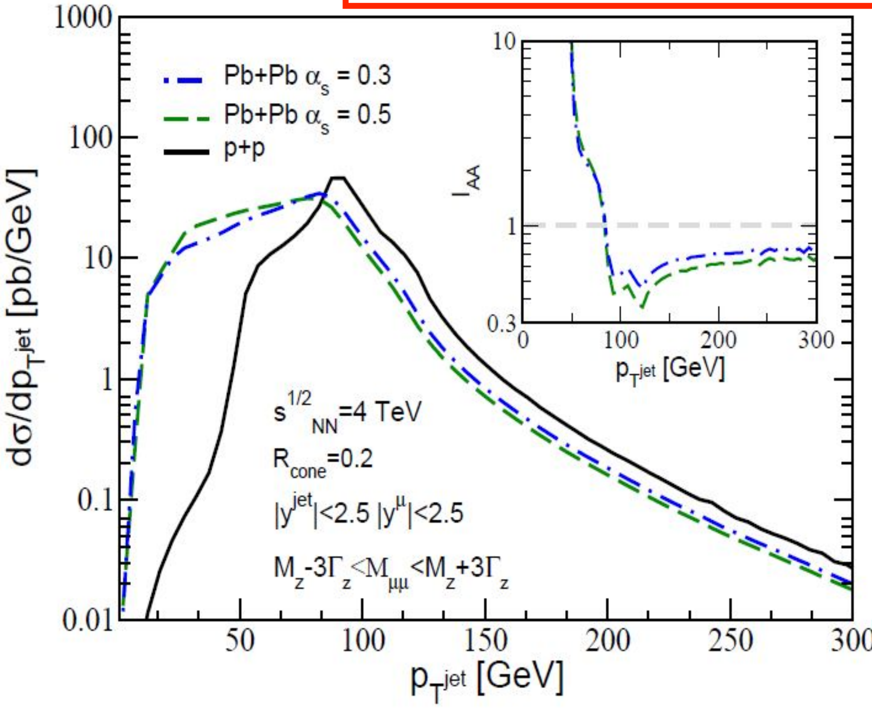


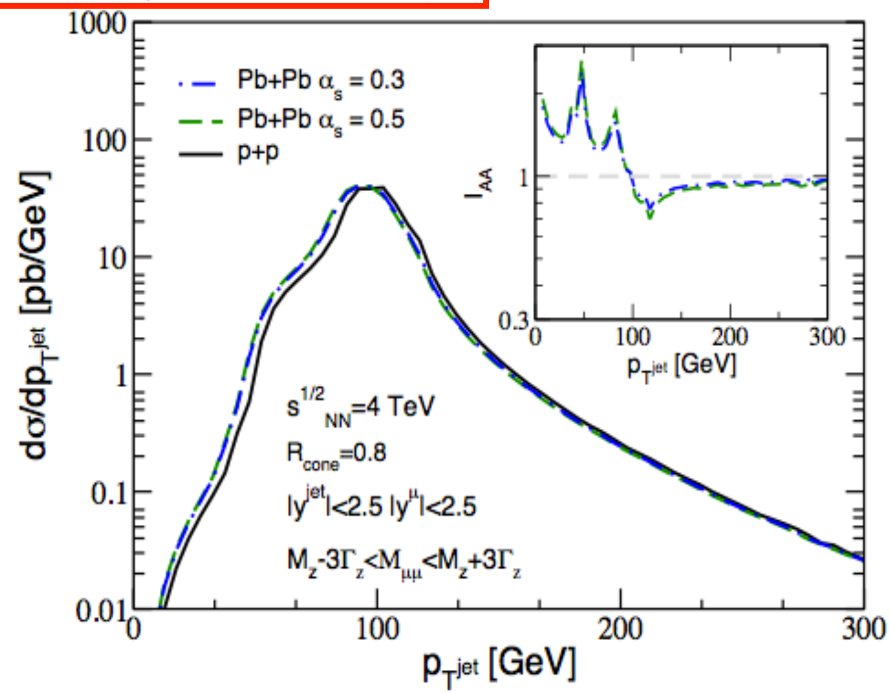
$p_T \in (92.5\text{GeV}, 112.5\text{GeV})$

Z^0 + jet in A+A: Iaa

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

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



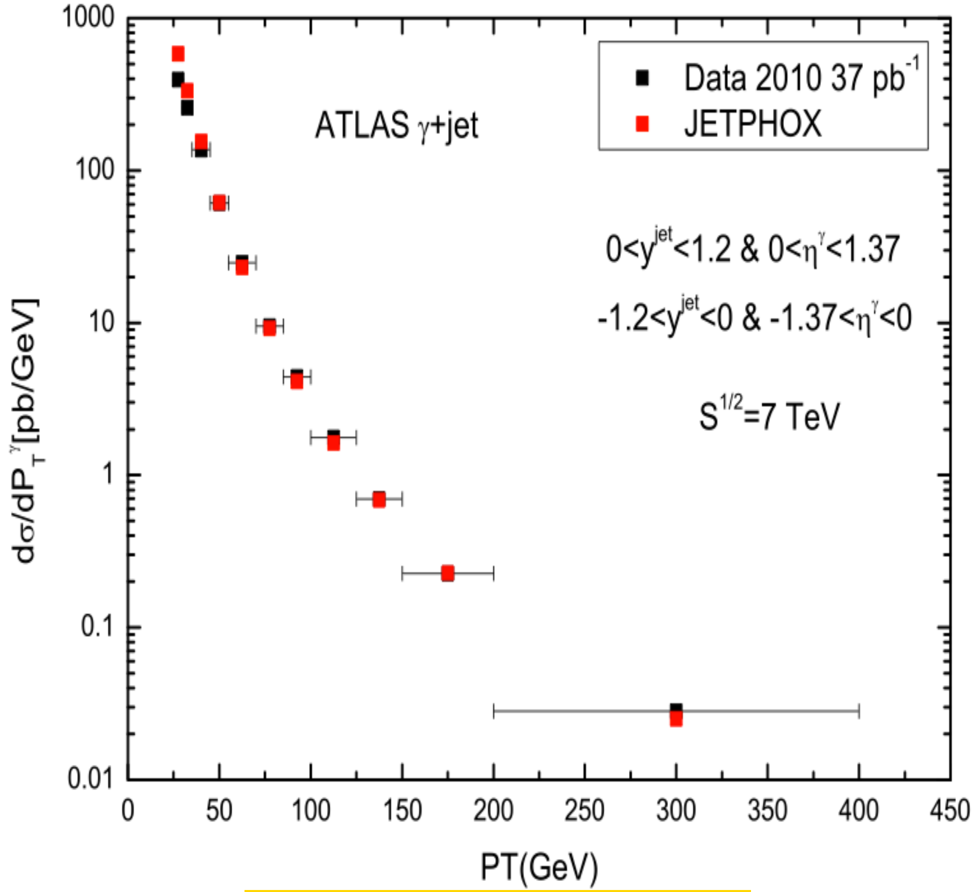


Neufeld, Vitev, BWZ, PRC 83, 034902 (2011).

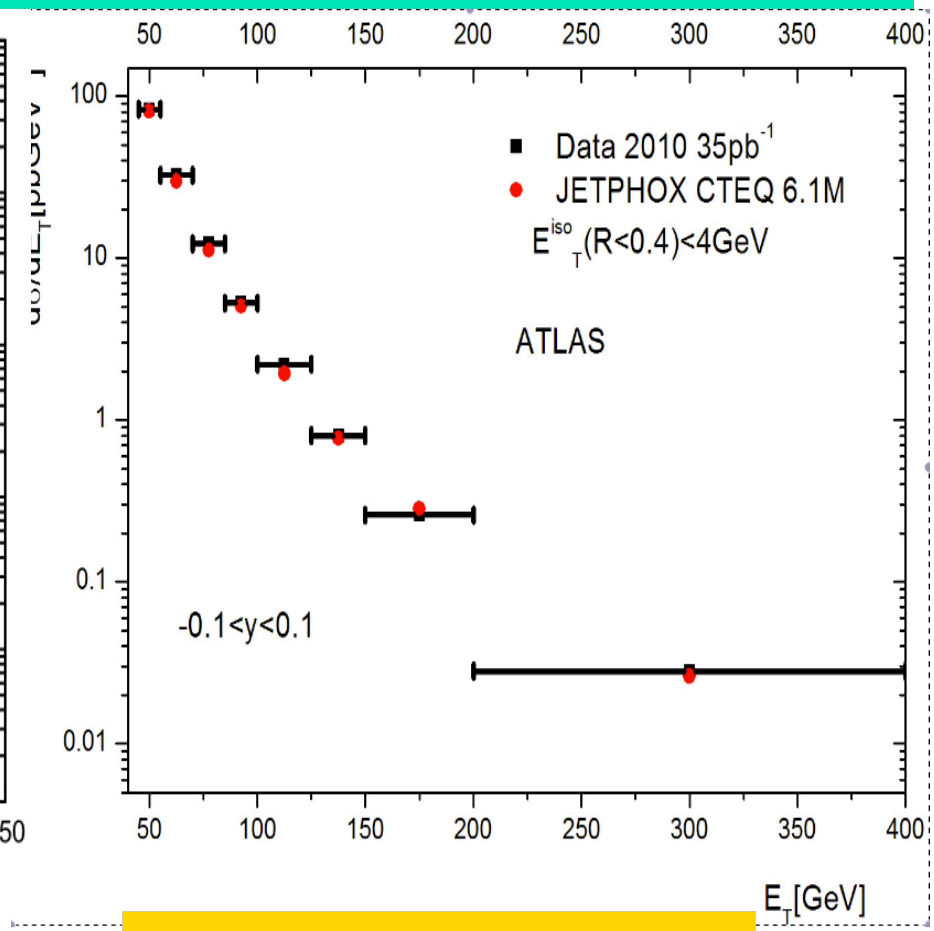
$p_T \in (92.5\text{GeV}, 112.5\text{GeV})$

Photon + jet: p+p

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



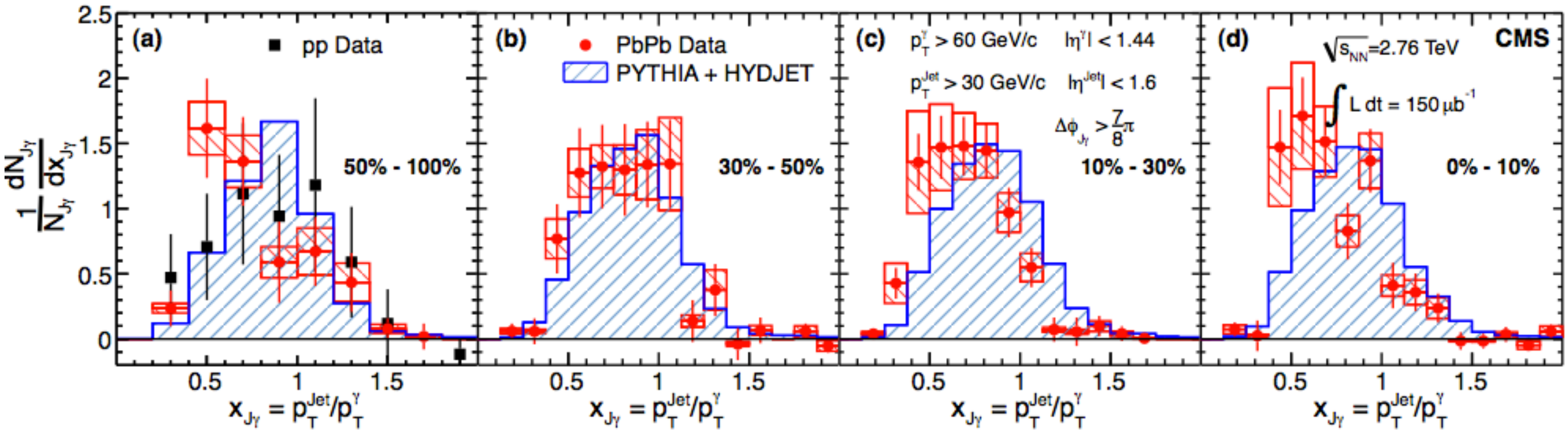
ATLAS, 1203.3161



ATLAS, 1012.4389

Photon + jet: Pb+Pb

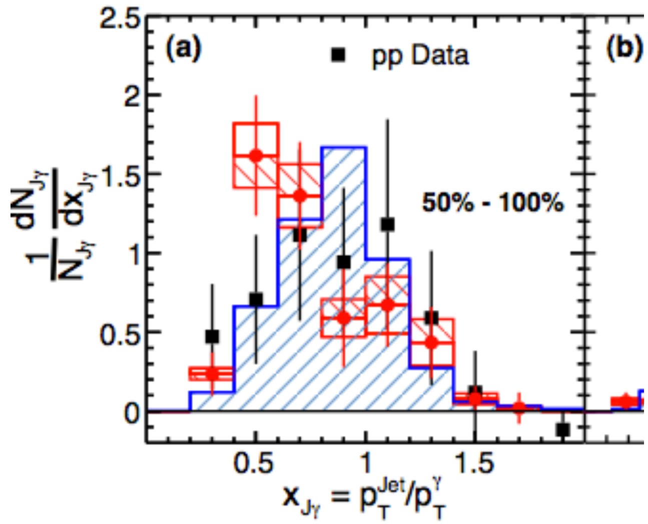
- Latest results of photon tagged jet in HIC have been given by CMS

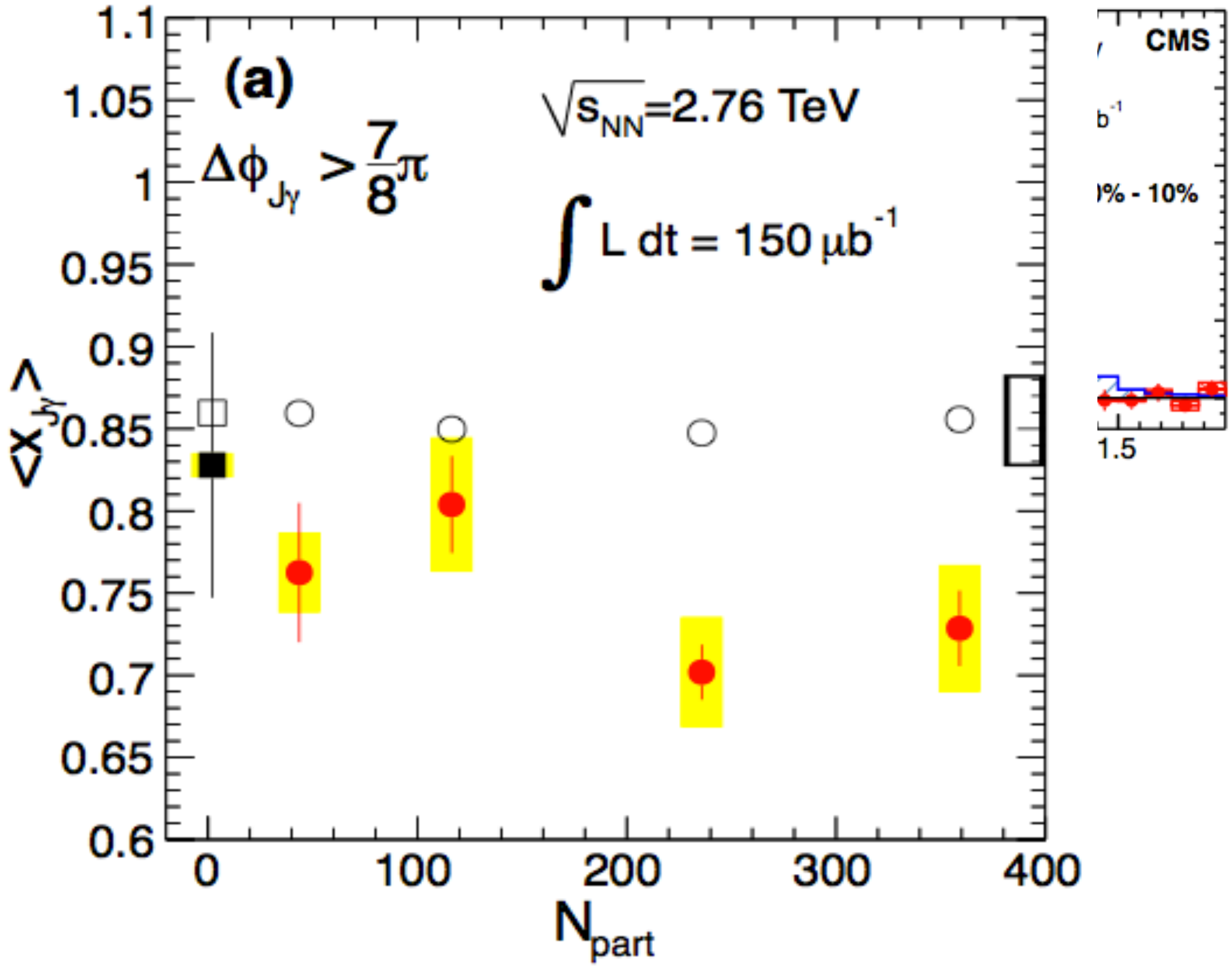


CMS, 1205.0206

Photon + jet: Pb+Pb

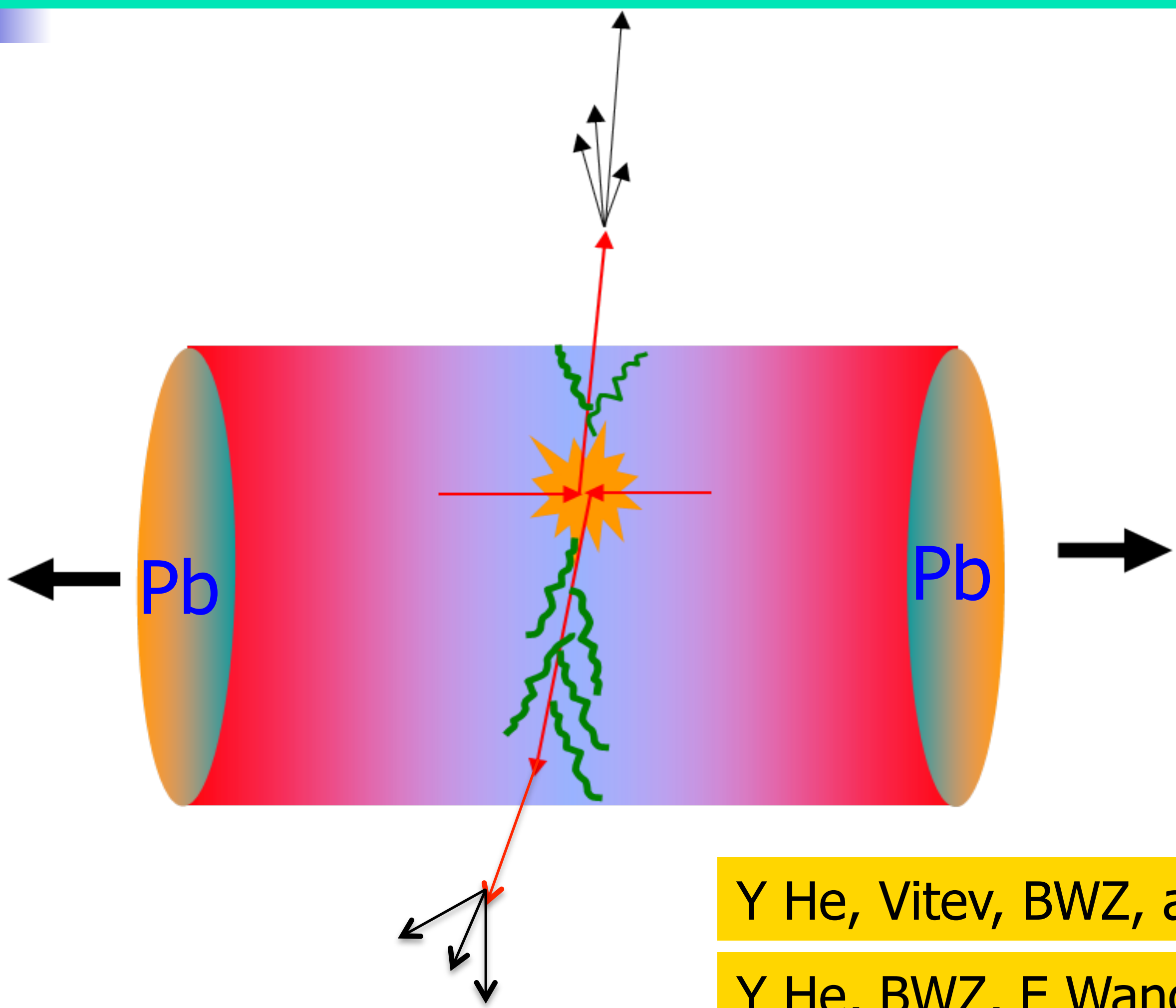
- Latest results of photon tagged jet in HIC have been given by CMS





CMS, 1205.0206

Dijet production in HIC at NLO

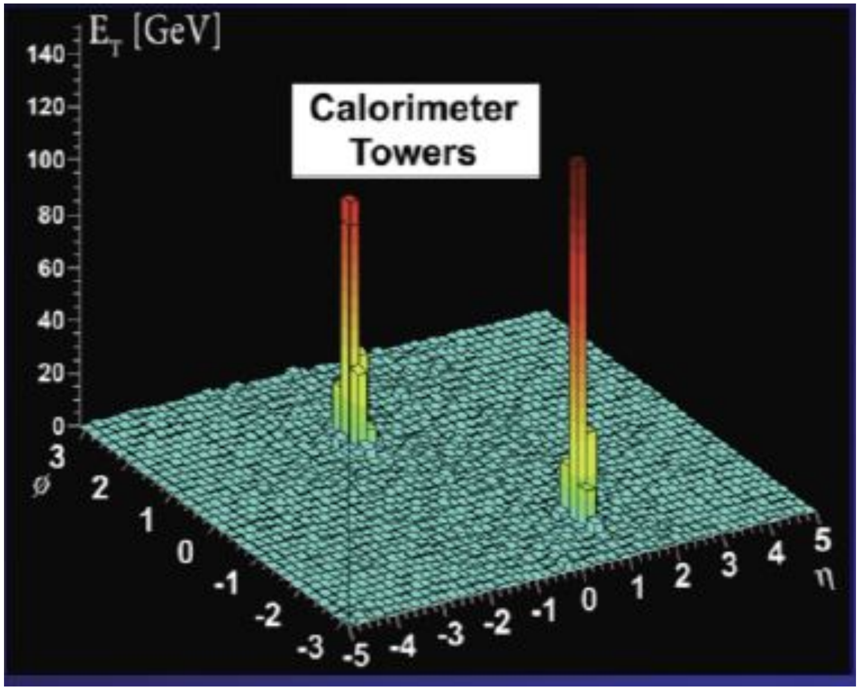


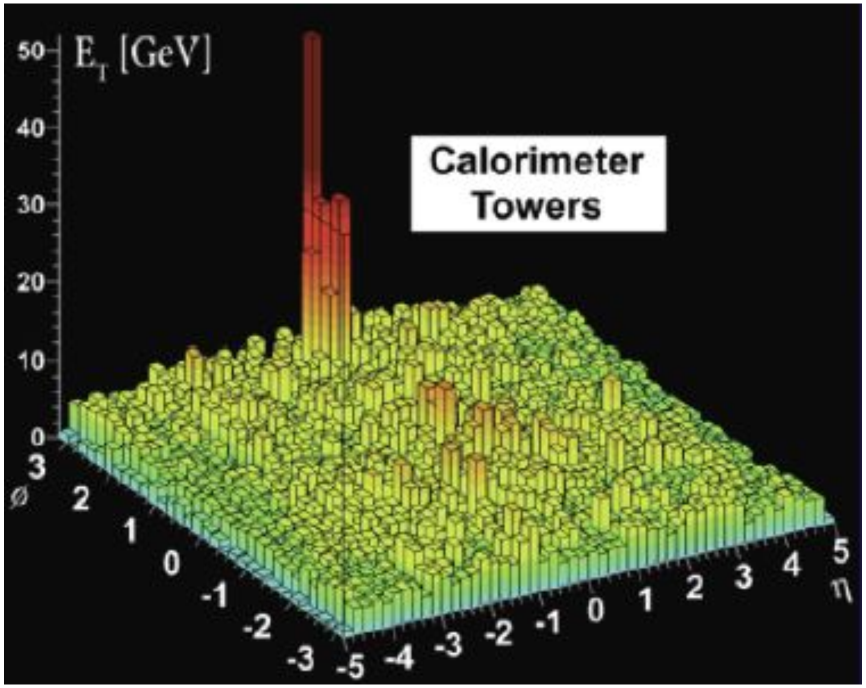
Y He, Vitev, BWZ, arXiv:1105.2566

Y He, BWZ, E Wang, EPJC (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。

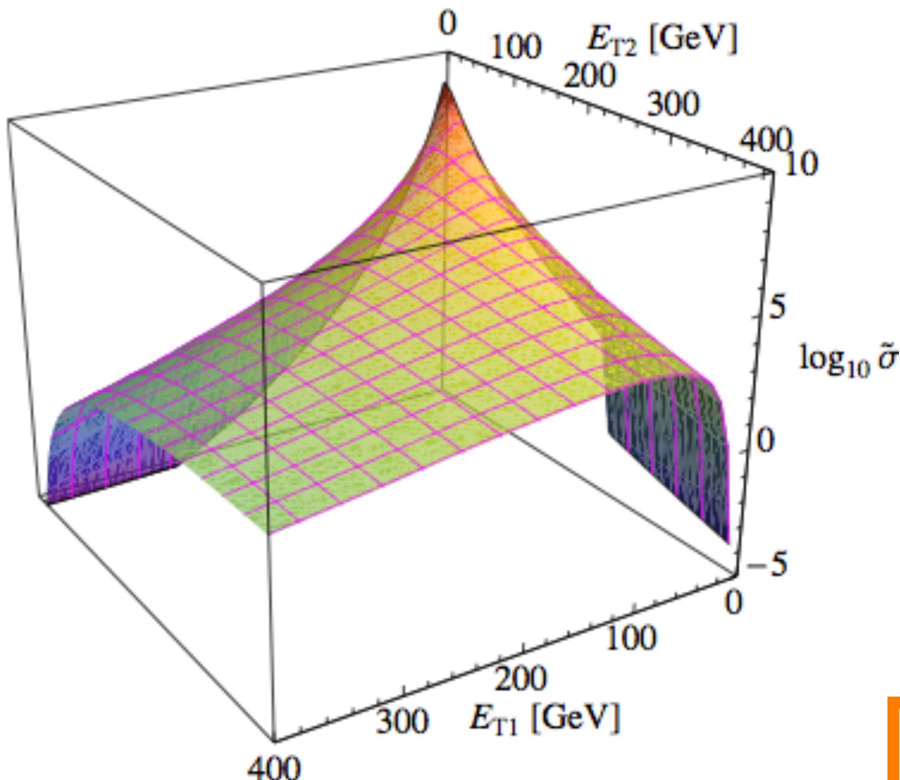


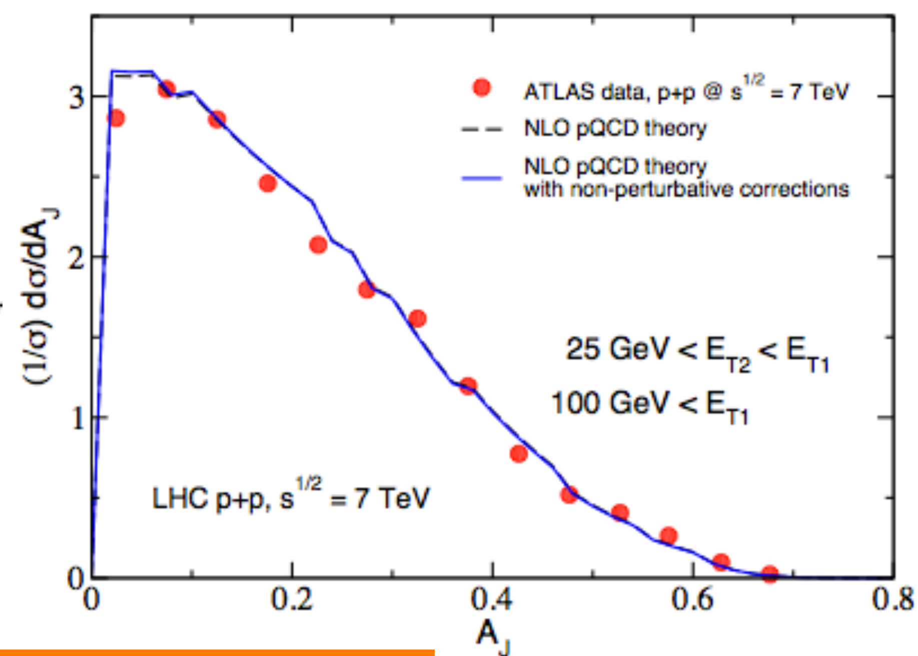


ATLAS, arXiv:1011.6182, PRL (2011); CMS, arXiv: 1102.1957, PRC(2011)

Dijets in p+p at NLO

- Dijet yield gives a broad distribution at NLO.
- Dijet asymmetry is described very well by NLO pQCD.



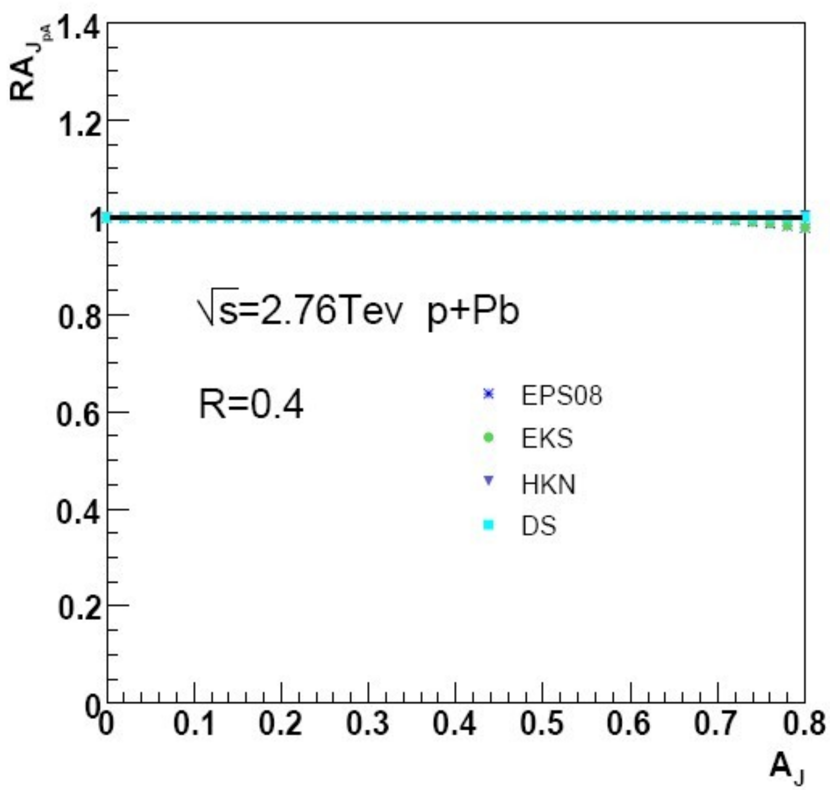


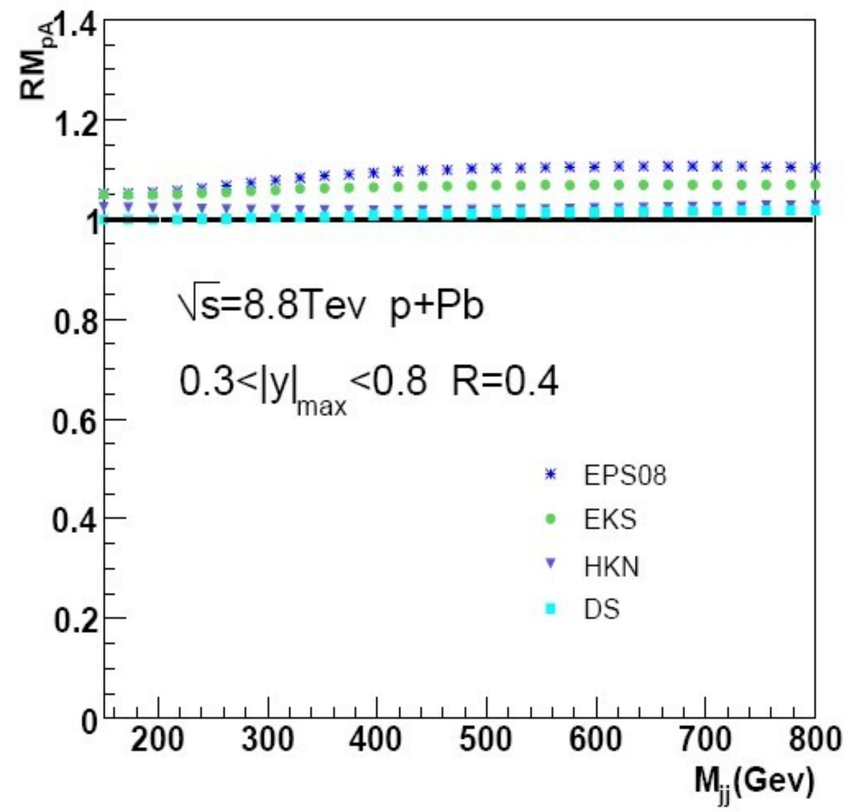
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

Dijet in HIC: CNM

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

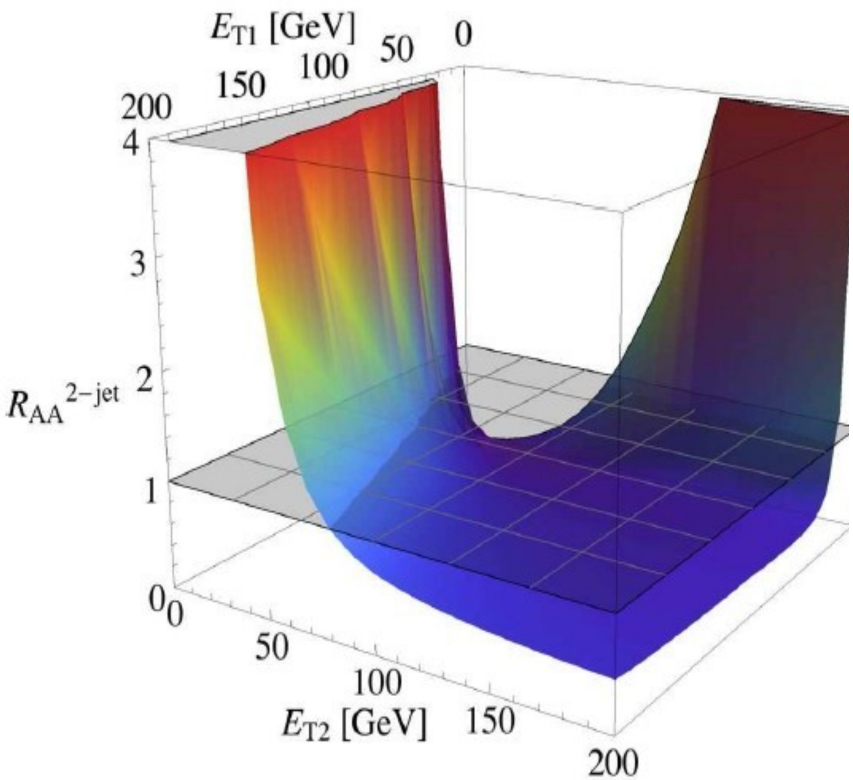
$$M_{jj}^2 = 2p_T^2[1 + cosh(y_1 - y_2)]$$

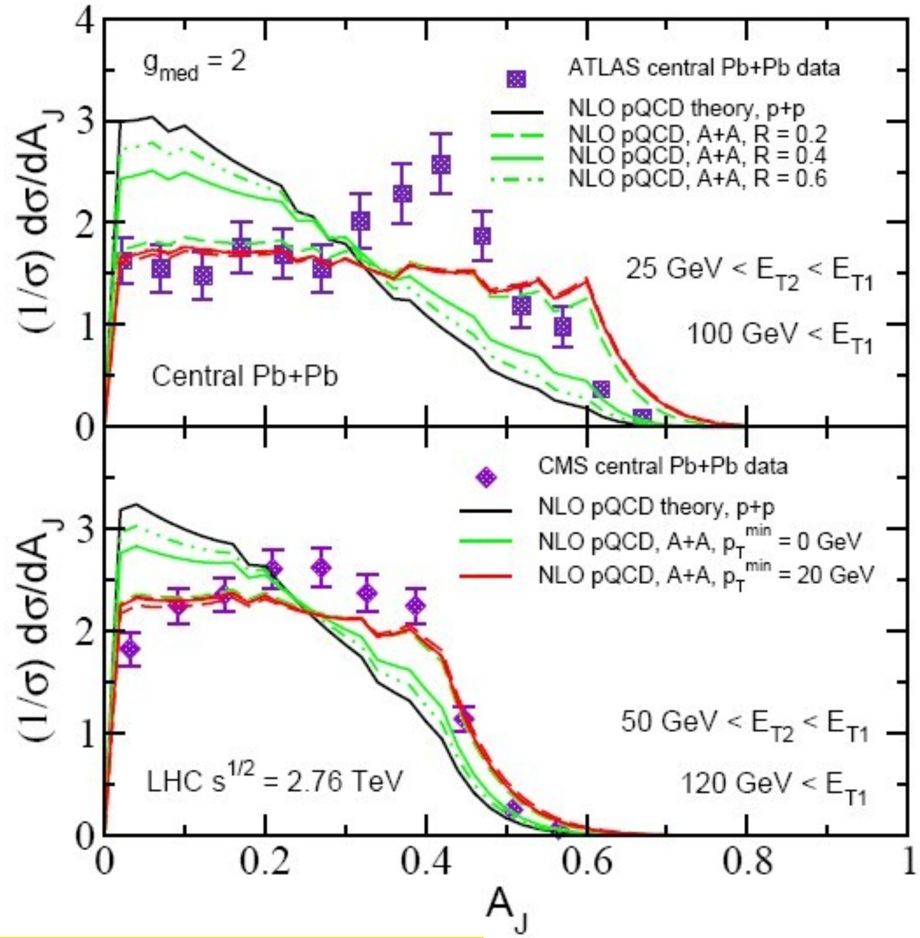




Y He, BWZ, E Wang, EPJC (2012)

Dijet in HIC at NLO

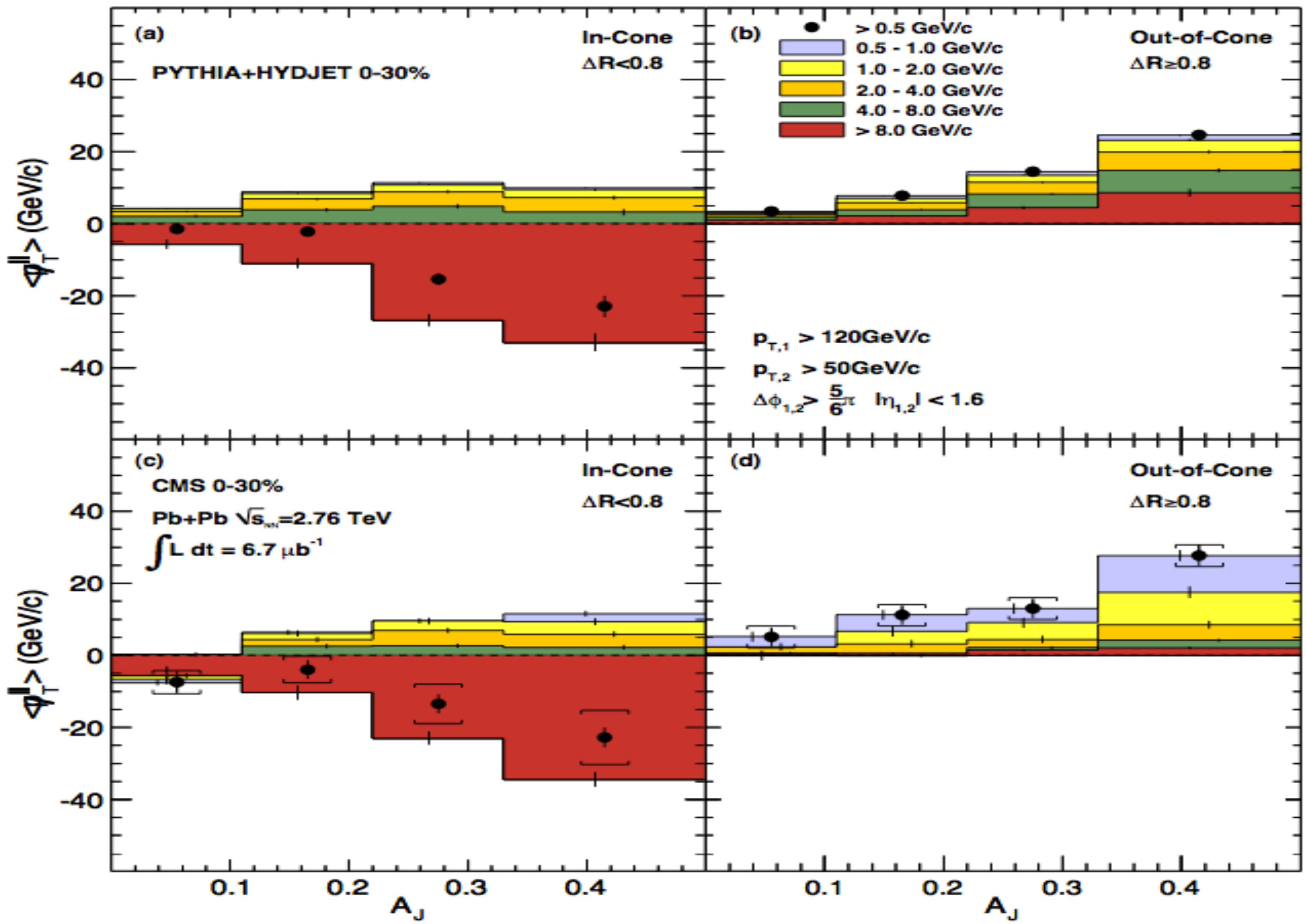




Y He, Vitev, BWZ, arXiv:1105.2566

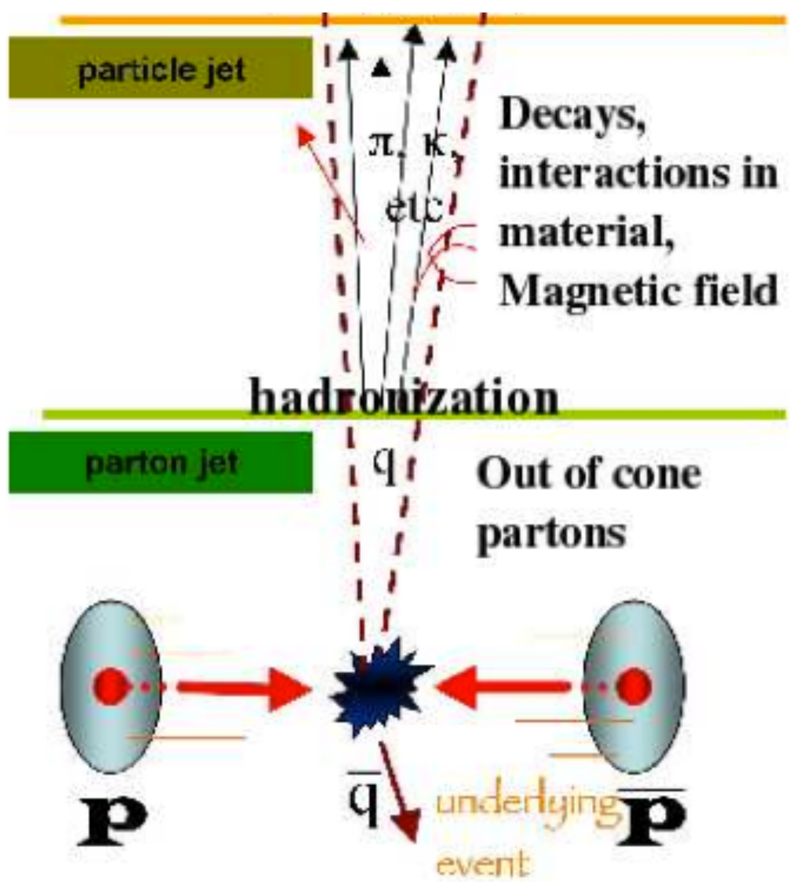
Dijet in HIC by CMS

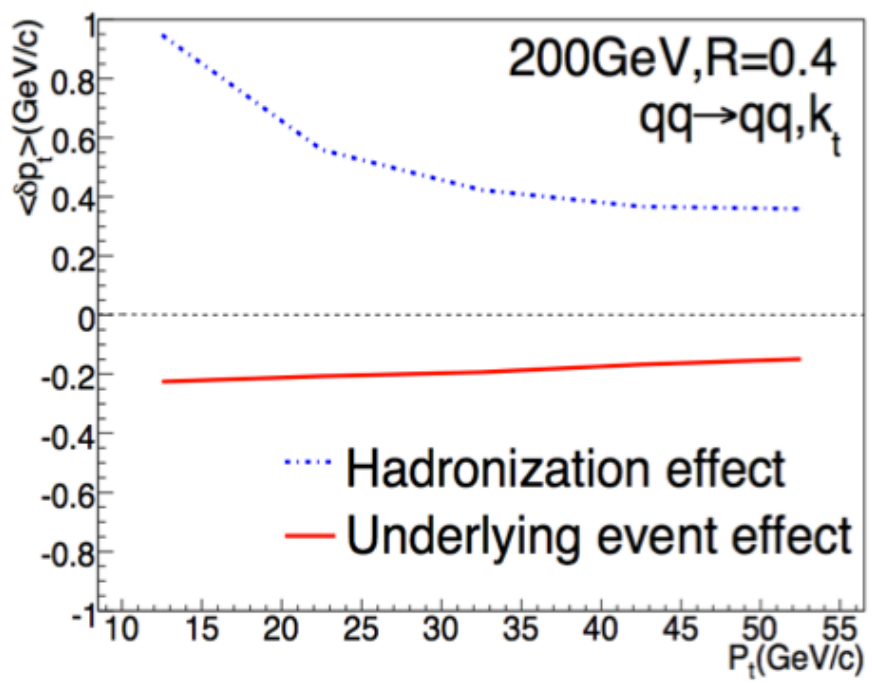
$$\not{p}_T^{\parallel} = \sum_i -p_T^i \cos\left(\phi_i - \phi_{\text{Leading Jet}}\right)$$



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)

Summary

- An entirely new frontier of HIC —— jet observables: jet shapes, inclusive jets, tagged jets, dijets, …

非常感谢！

Thank you!

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

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

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