Jets Escaping From Quark Soup

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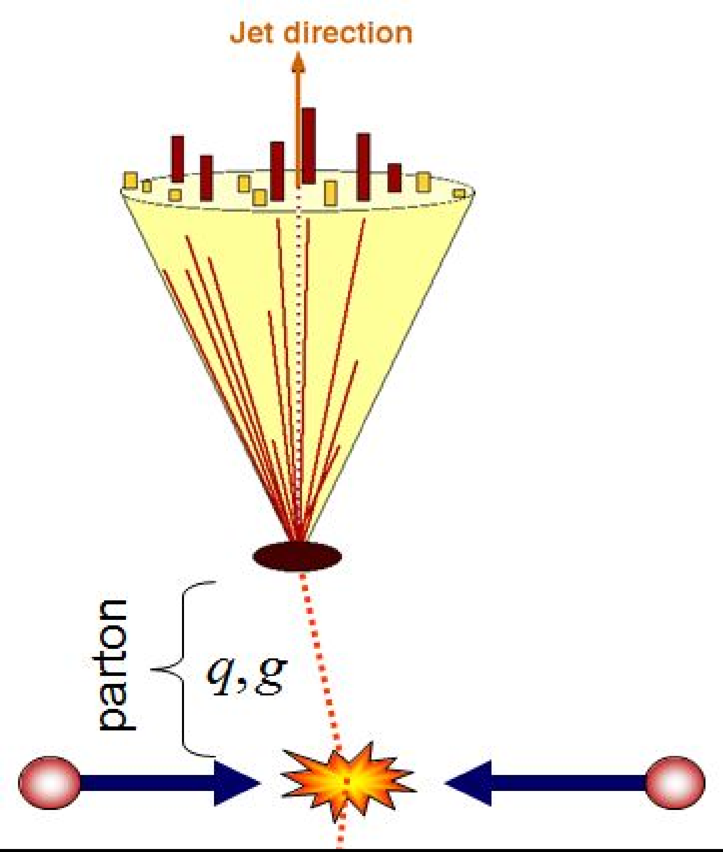
What is a jet?

- 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



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

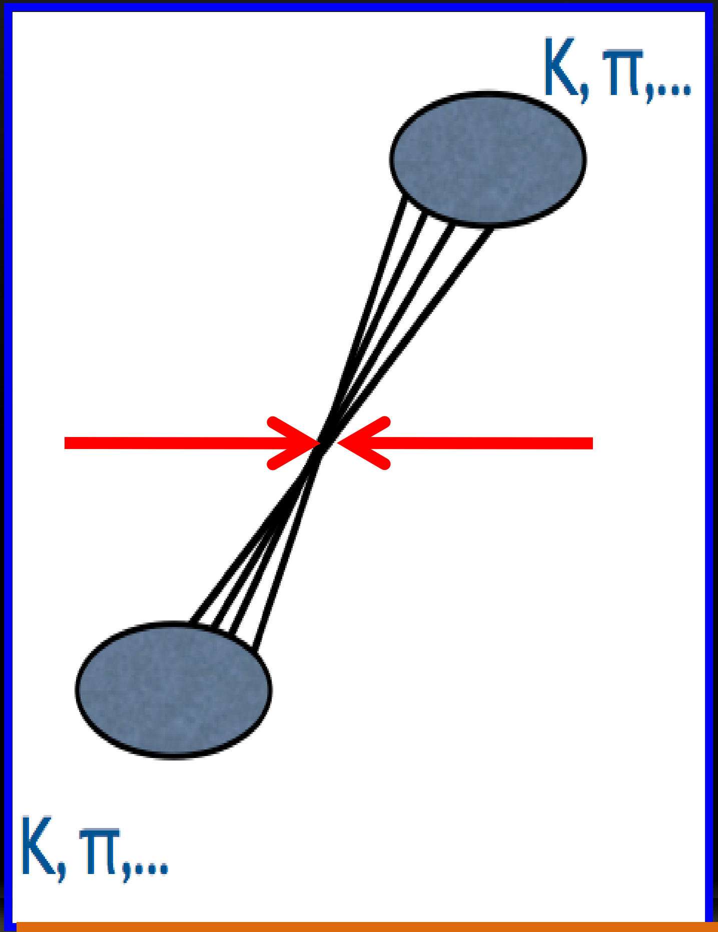
$$\phi = \sum_{i \in jet} \phi_i E_{T,i} / E_T$$

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

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

Briefing: jets at HEP

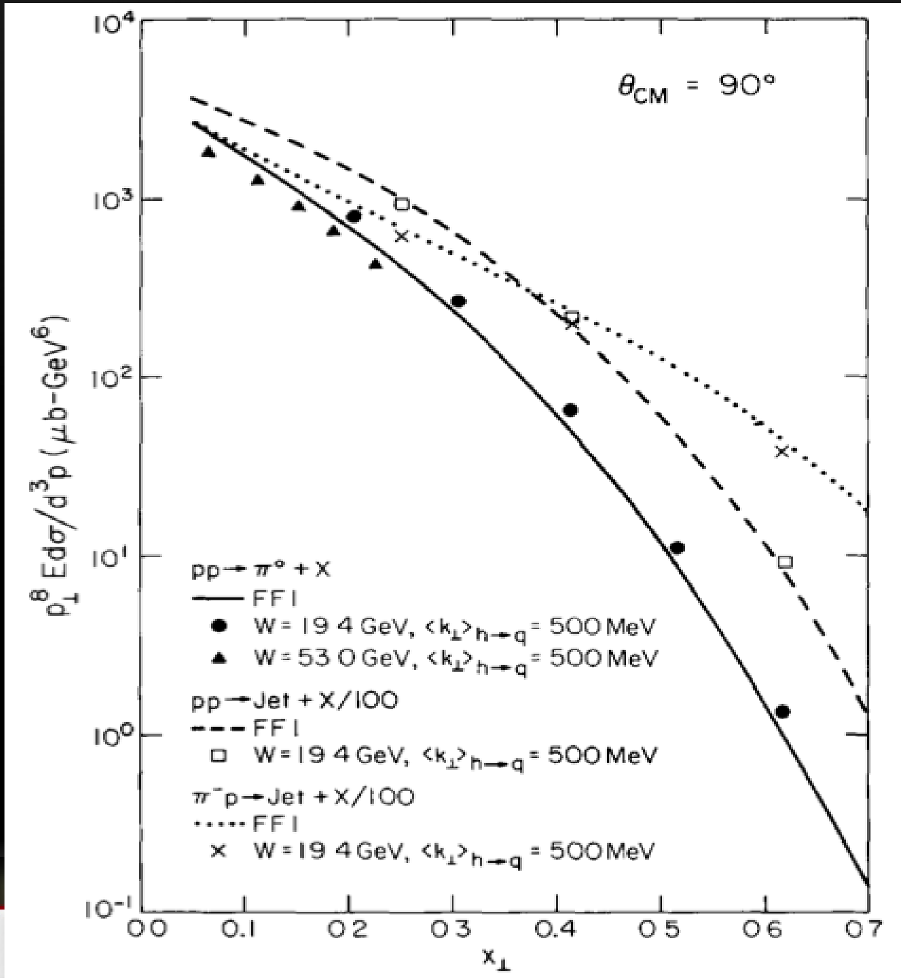
- Sterman & Weinberg('77) defined a two-jet event and made an analytic calculation.



Sterman, Weinberg (1977)

Briefing: jets at HEP

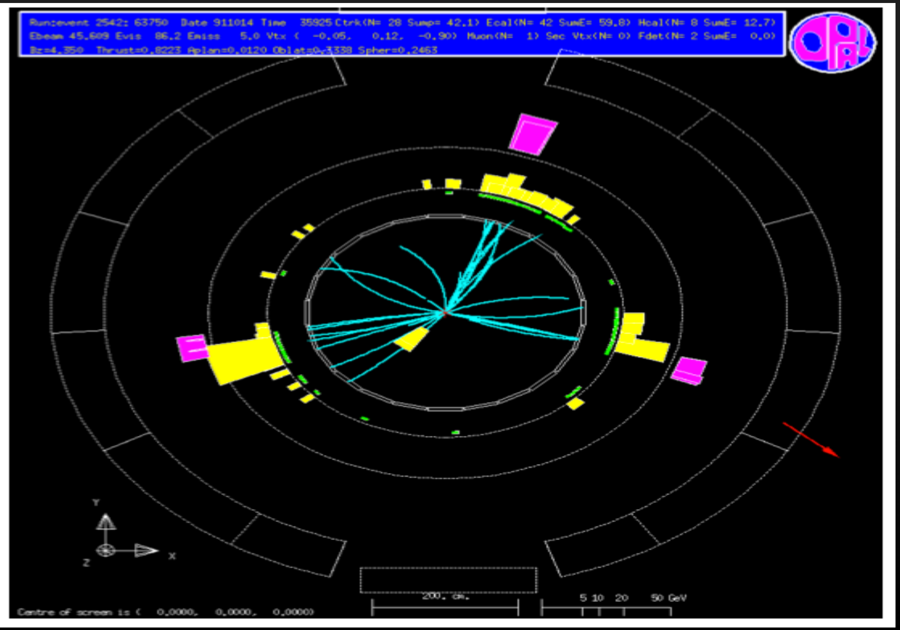
- Feynman, Field, Fox ('77) made a numerical calculation of the inclusive jet production.

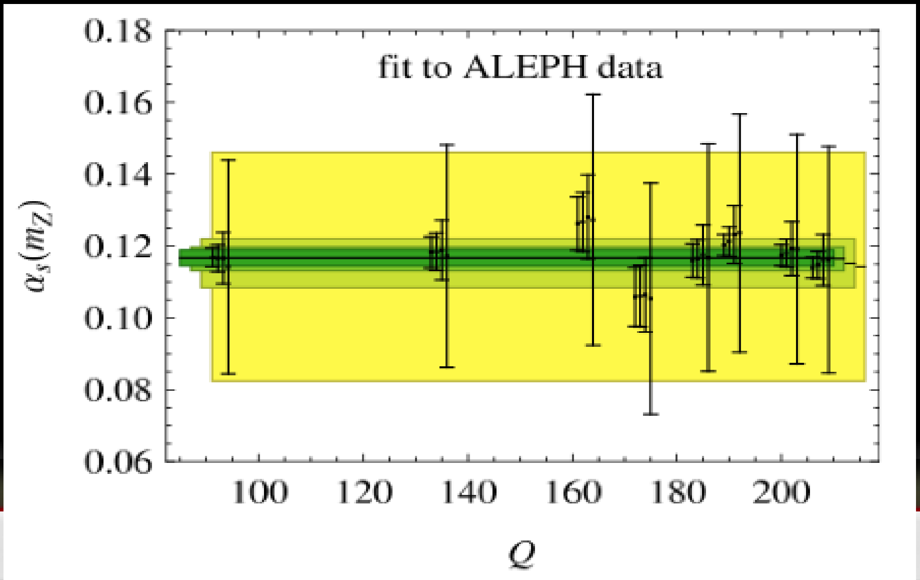


Feynman, Field, Fox (1977)

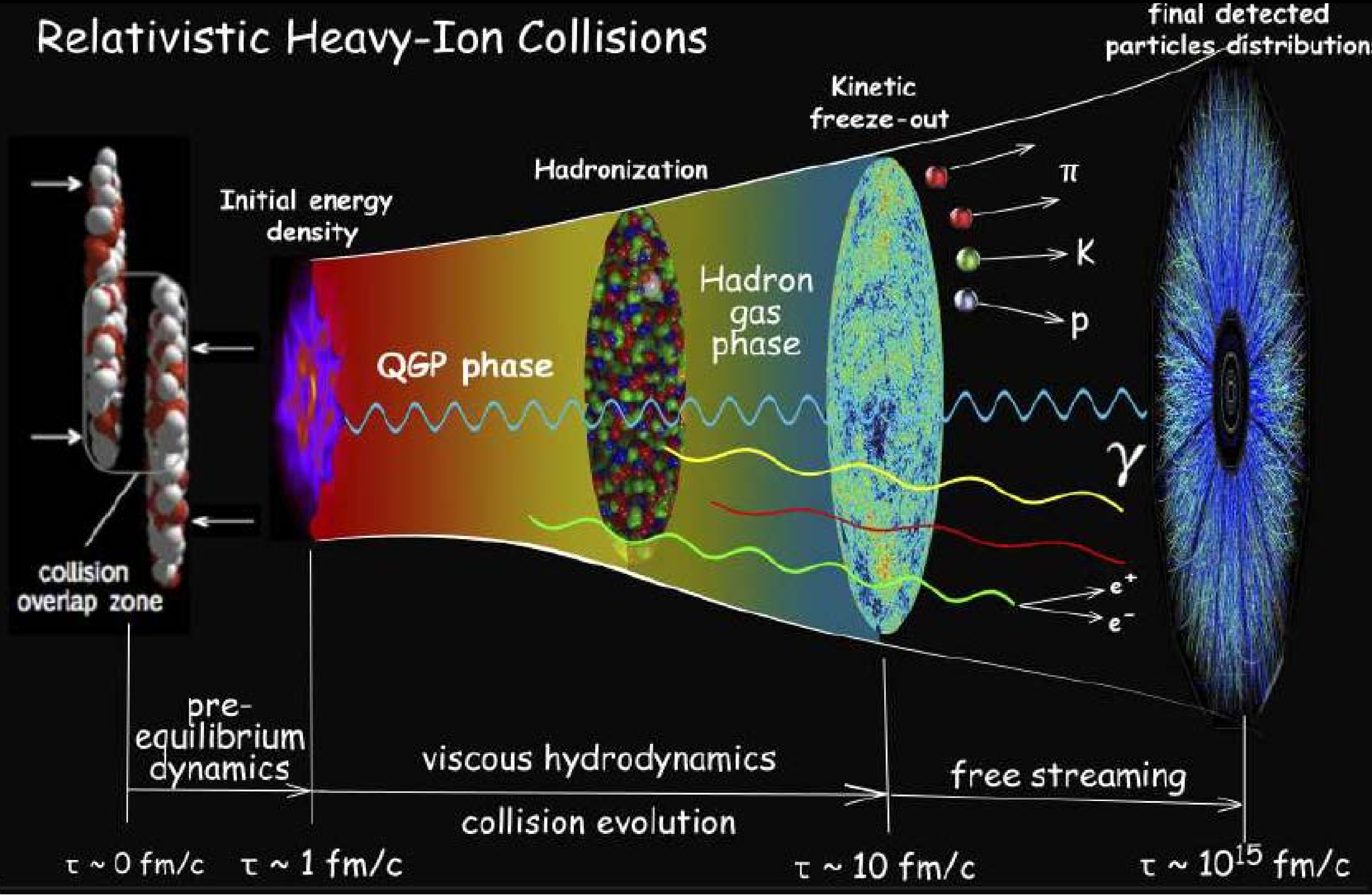
Briefing: jets at HEP

- 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.

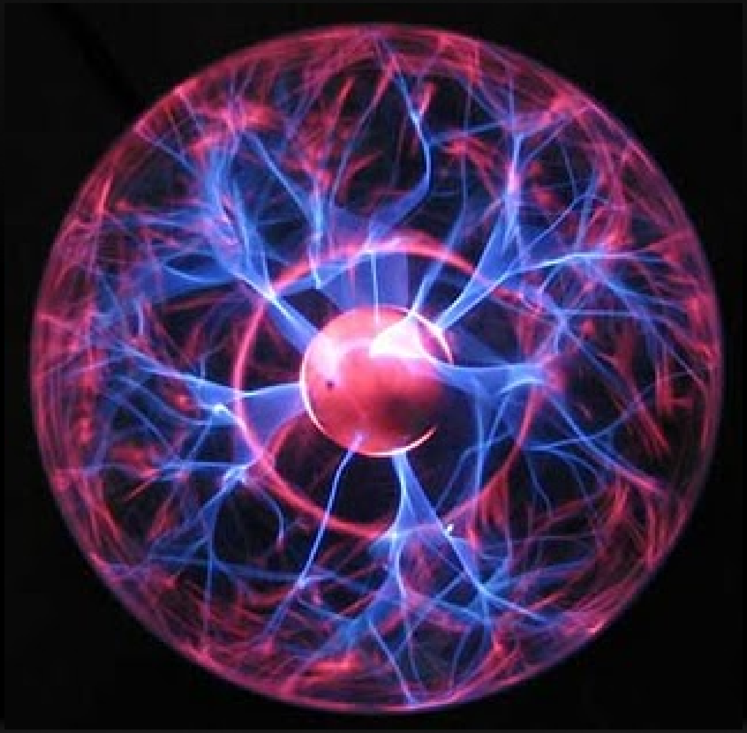


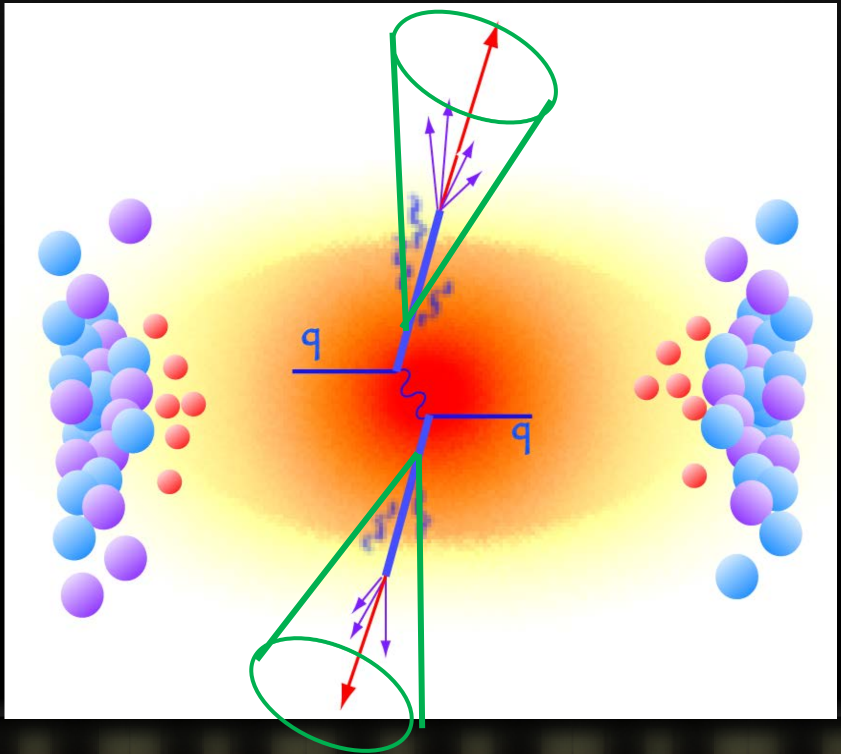


The Little Bang



How will jets be modified in the existence of QGP ?

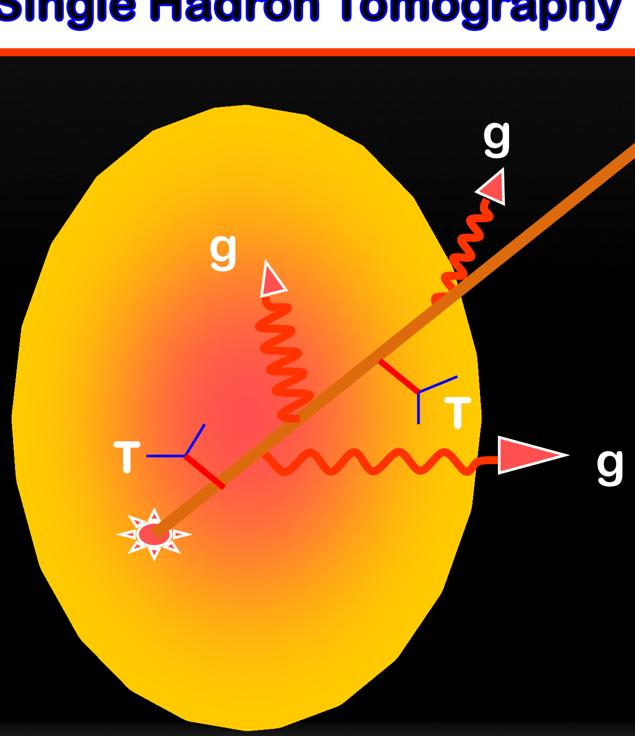


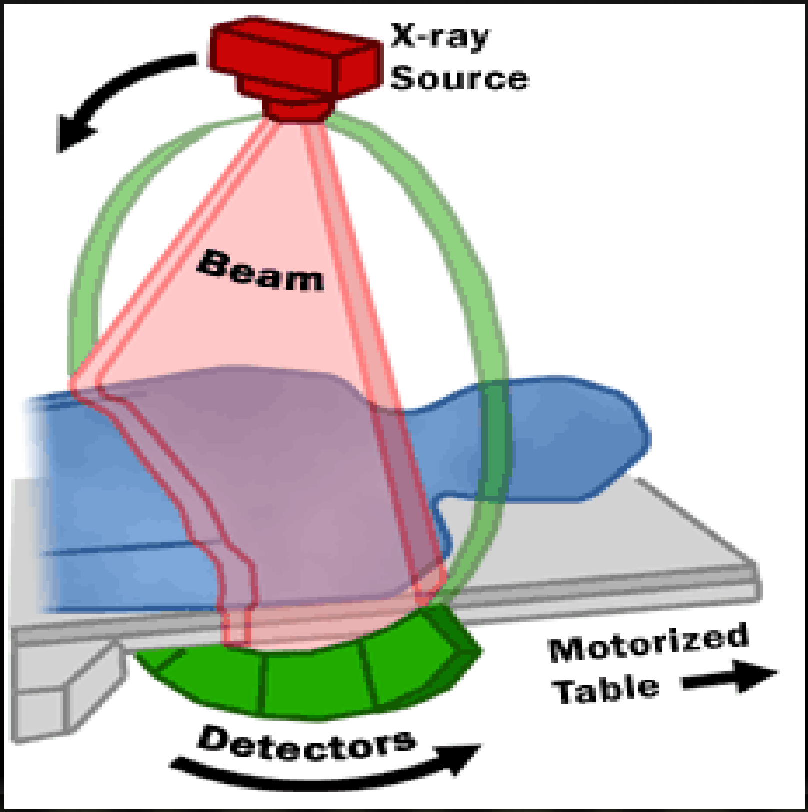


Parton Energy loss as a hard probe

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

Single Hadron Tomography

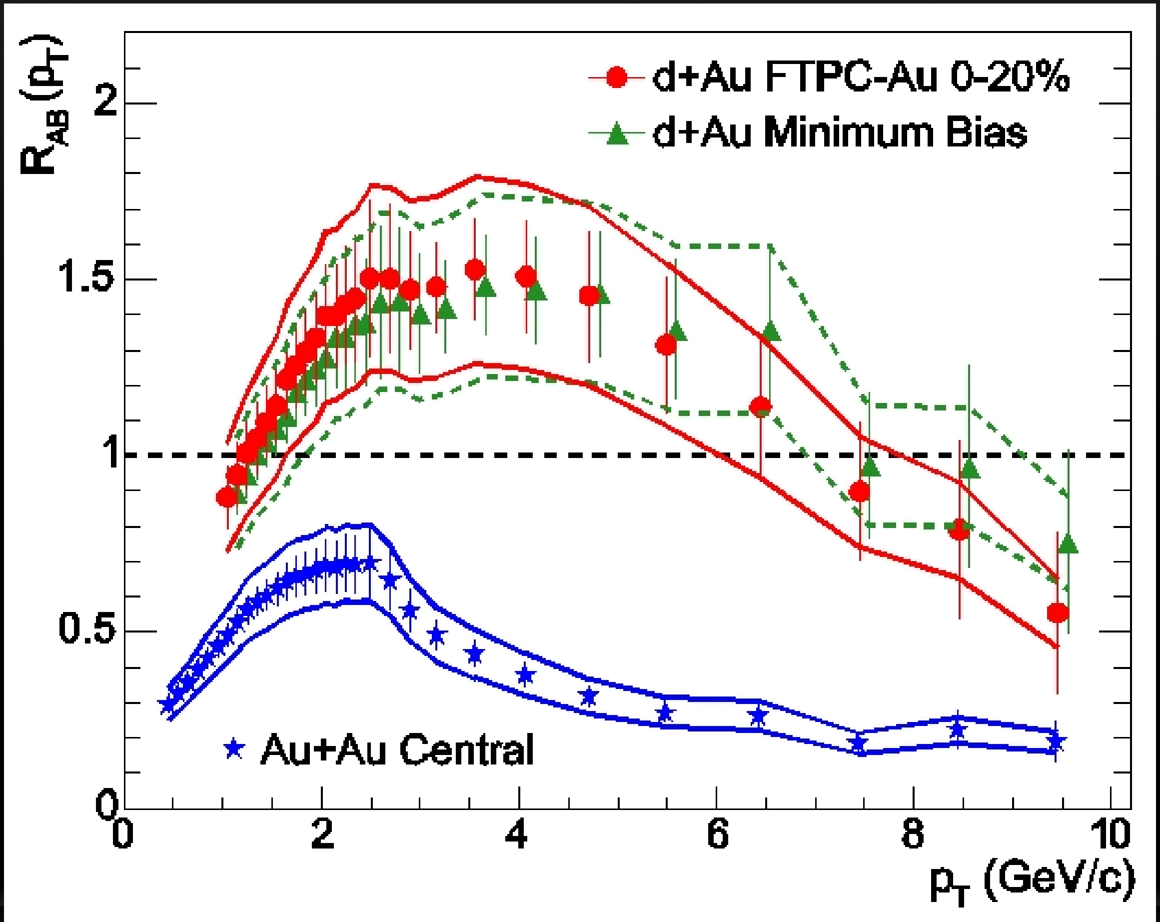




Xin-Nian Wang, M. Gyulassy, PRL68(1992)1480

Jet quenching at RHIC

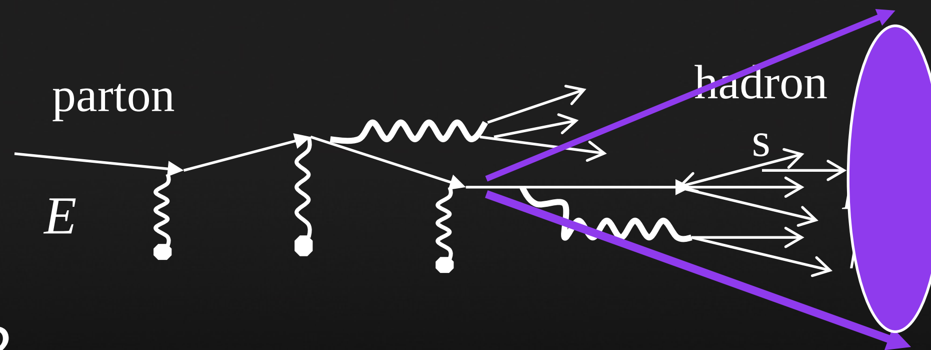
$$R_{AA} = \frac{\text{Yield}_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{\text{Yield}_{pp}}$$

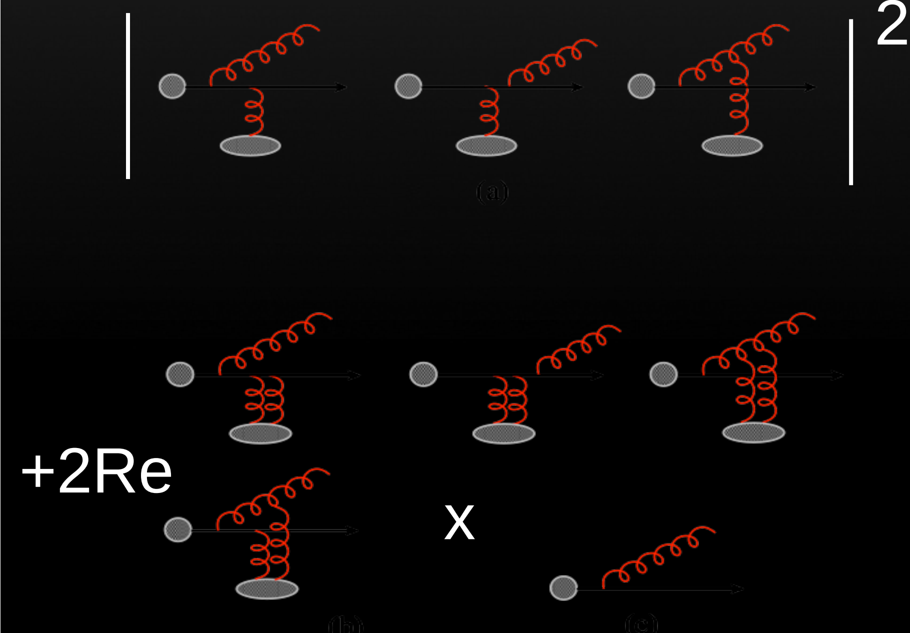


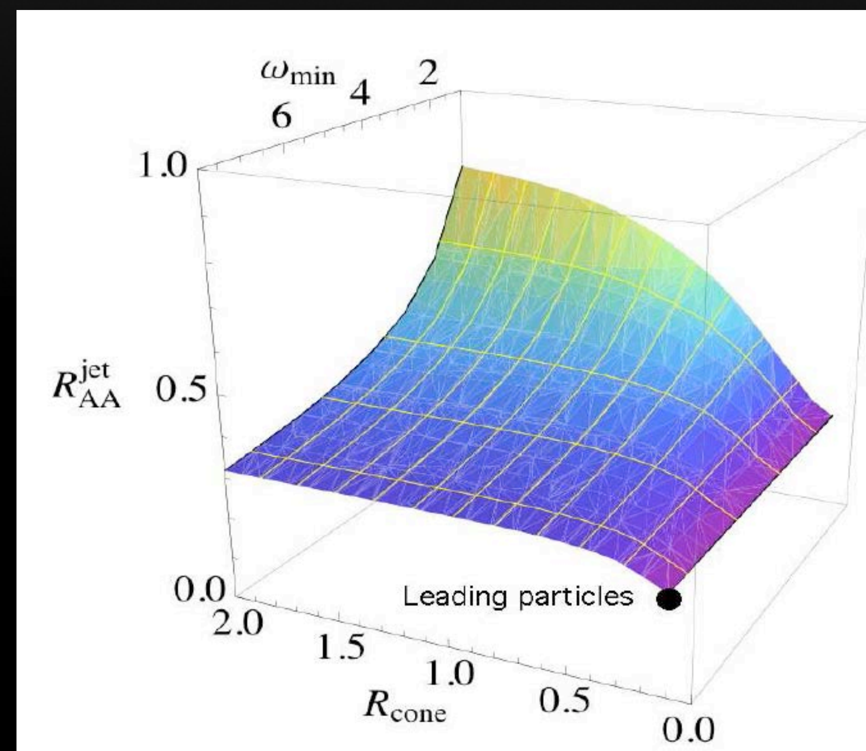
Gyulassy, Vitev, X.N.Wang, BWZ, 《QGP3》p123-191 (2004); nucl-th/0302077.

Eloss: From hadron to jets

Gyulassy-Levai-Vitev







Vitev, Wicks, BWZ, JHEP (2008)

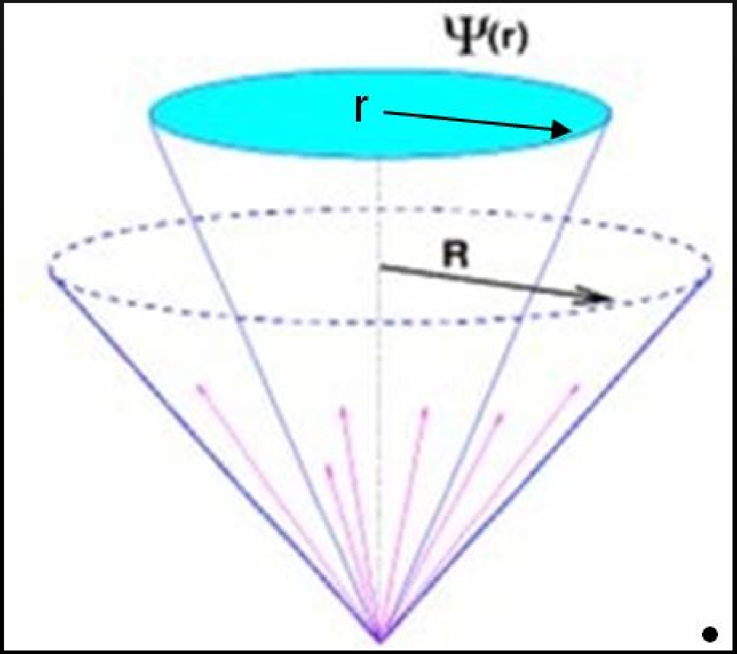
Jets in HIC

Jet shape in HIC

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

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

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

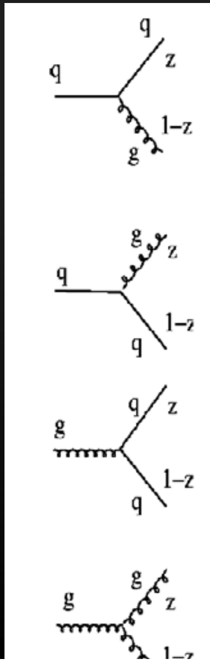


LO & Resummation: p+p

An analytic approach to the energy distribution of jet

Seymour, M. (1998)

Jet shape at LO with the acceptance cut



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

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

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

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

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

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

Collinear divergence requires Sudakov resummation:

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

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

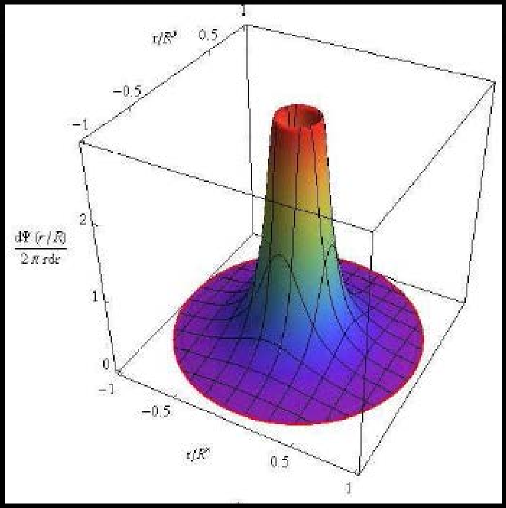
Jet shape p+p: baseline

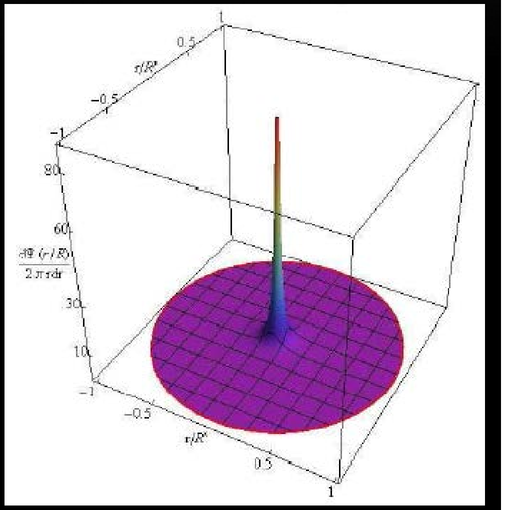
$$\psi(r) = \psi_{\rm coll}(r)\,(P(r)-1) + \psi_{\rm LO}(r) + \psi_{i,{\rm LO}}(r) + \psi_{\rm PC}(r) + \psi_{i,{\rm PC}}(r)\,,$$

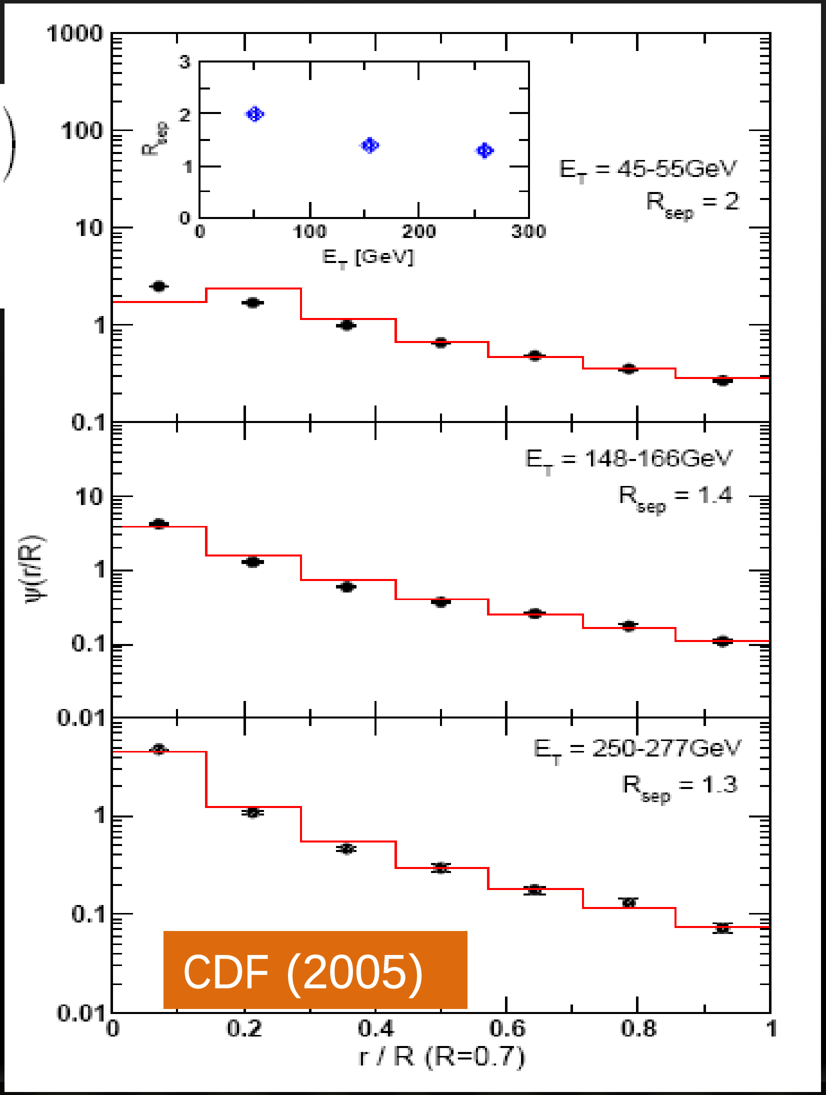
LHC

20 GeV

500 GeV







CDF (2005)

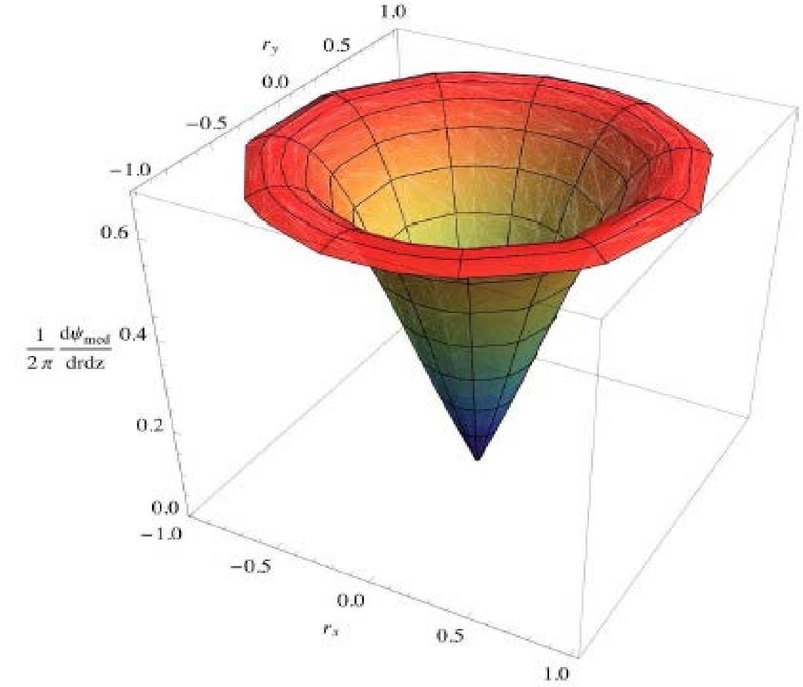
I Vitev, S Wicks, BWZ, JHEP 0811,093 (2008)

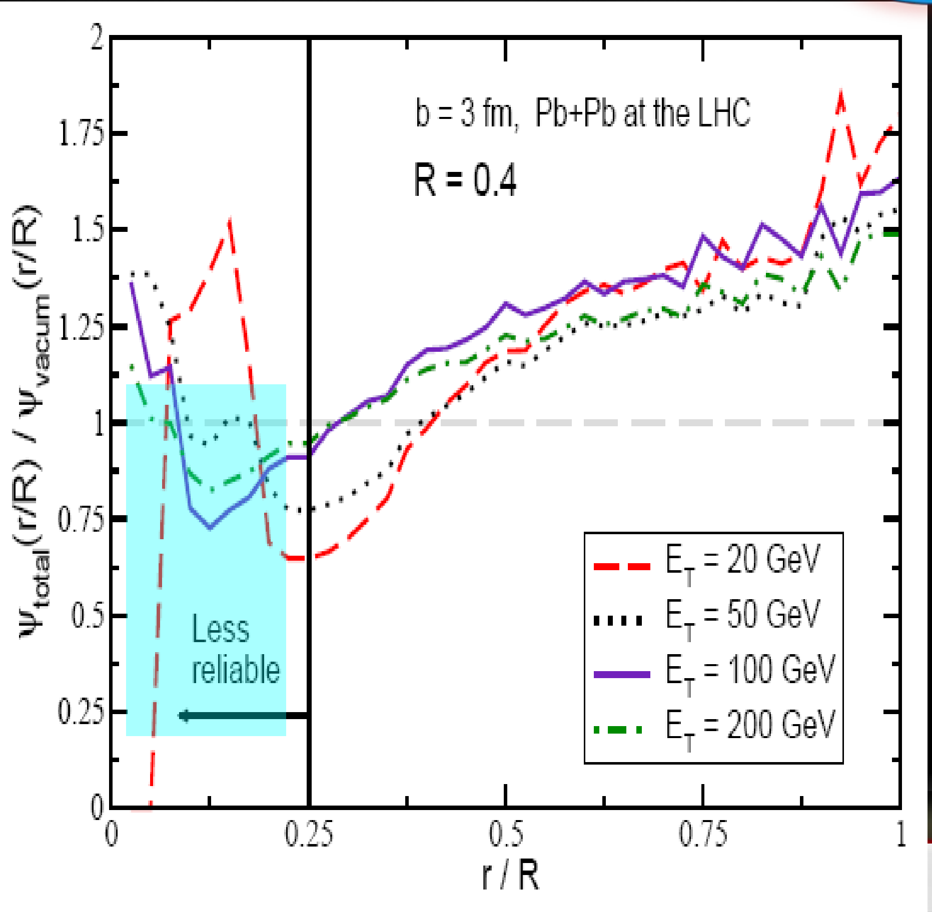
$\sqrt{s} = 1960$ GeV

Total jet shape in HIC

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

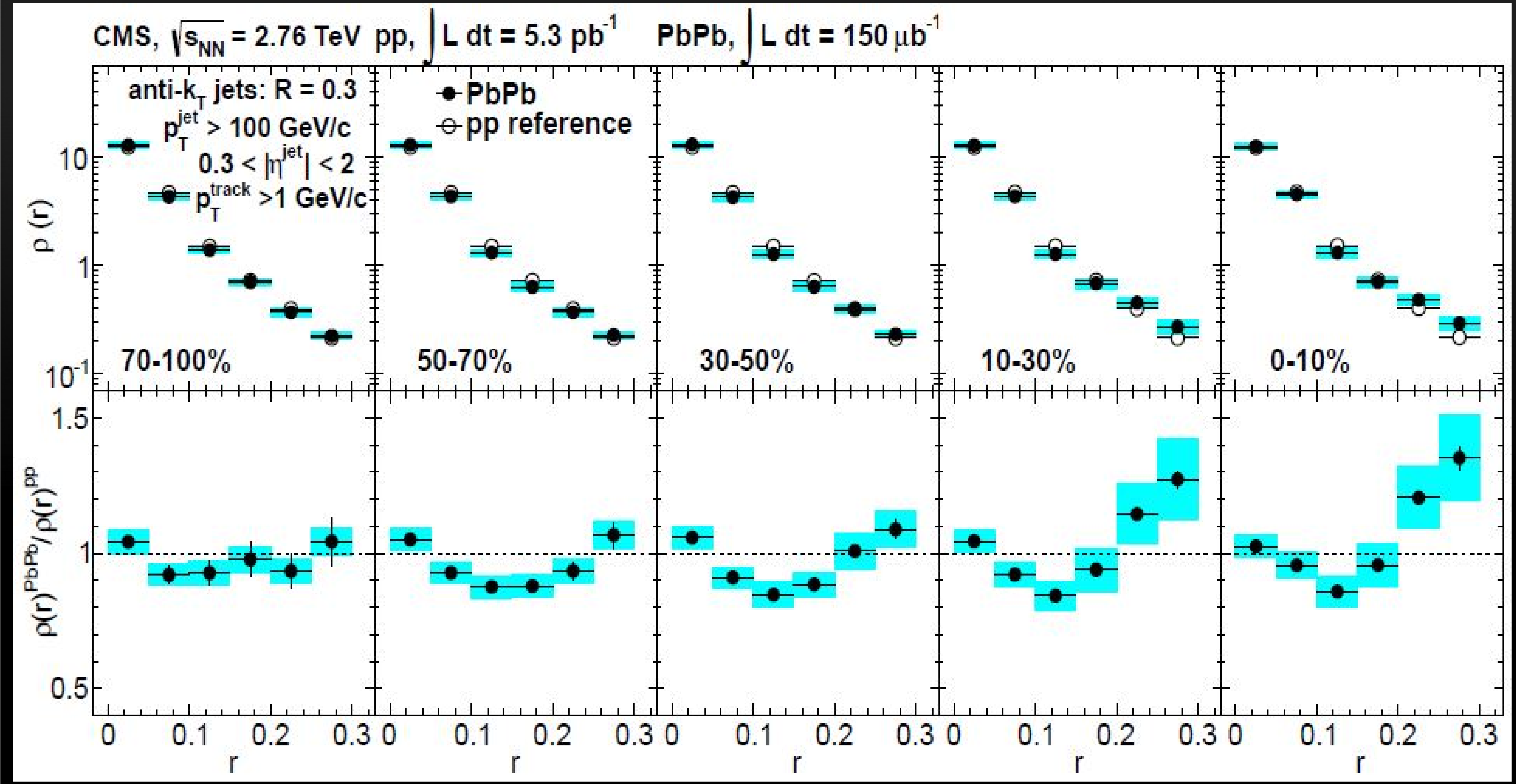
$$\psi_{\rm tot.}(r/R) = \frac{1}{\rm Norm}\int_{\epsilon=0}^{1} d\epsilon \sum_{q,g} P_{q,g}(\epsilon)\frac{1}{(1-(1-f_{q,g})\cdot\epsilon)^3} \times \frac{\sigma_{q,g}^{NN}(R,\omega^{\rm min})}{d^2E'_T dy}\left[(1-\epsilon)\,\psi_{\rm vac.}^{q,g}(r/R) + f_{q,g}\cdot\epsilon\,\psi_{\rm med.}^{q,g}(r/R)\right]$$





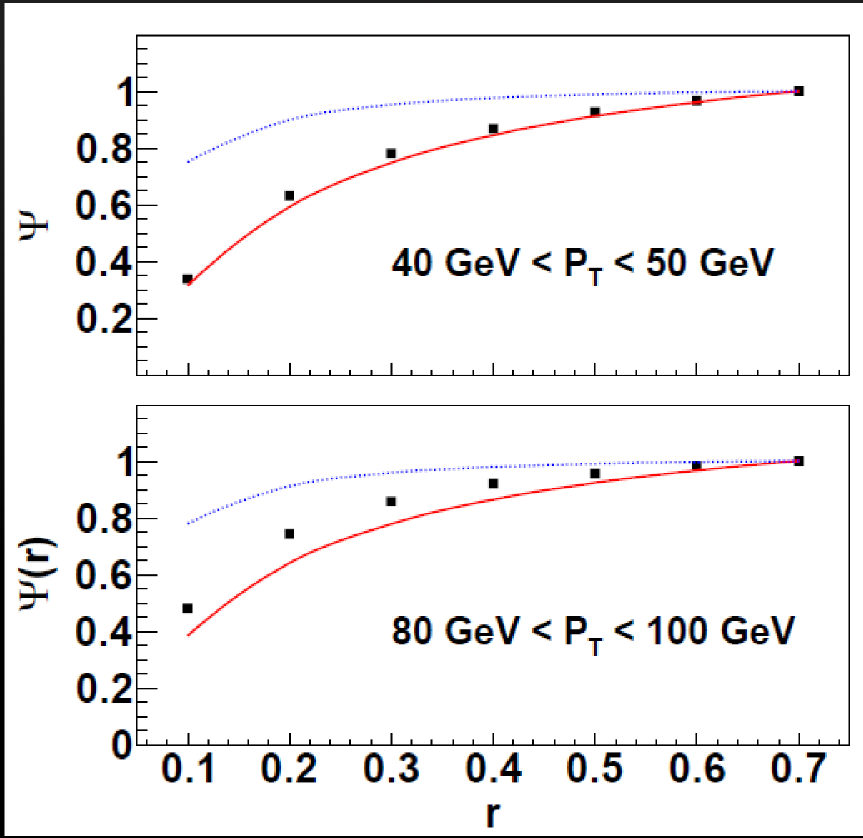
I Vitev, S Wicks, BWZ (2008)

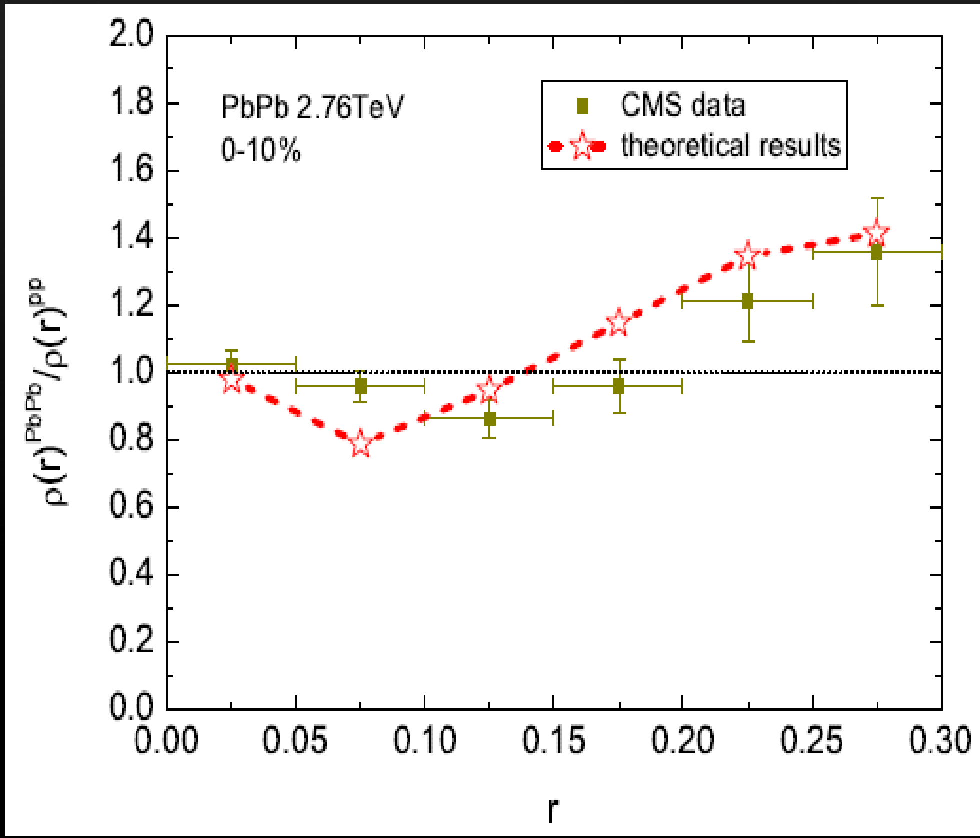
Jet shapes measured at LHC



CMS, arXiv:1310.0878

Jet shapes: NLL+NLO





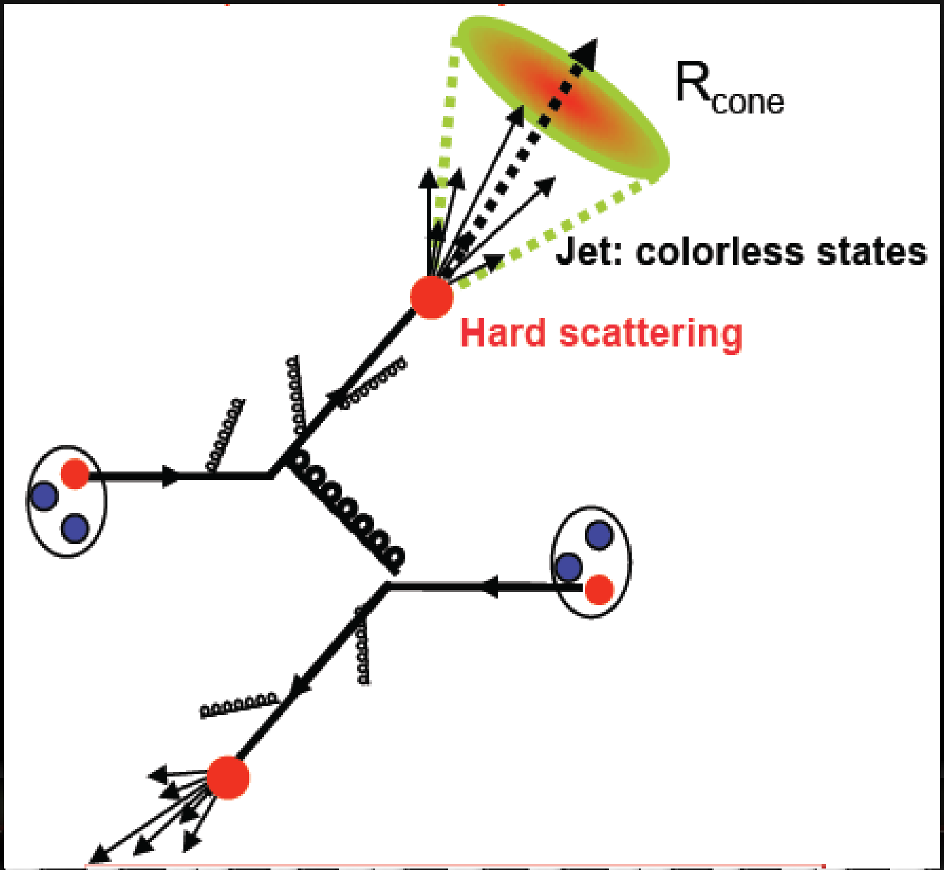
H-N Li, Z Li, C P Yuan,

PRL (2011); PRD (2012)

S Chen, Z Li, BWZ,

in progress

Inclusive jet cross section in HIC



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

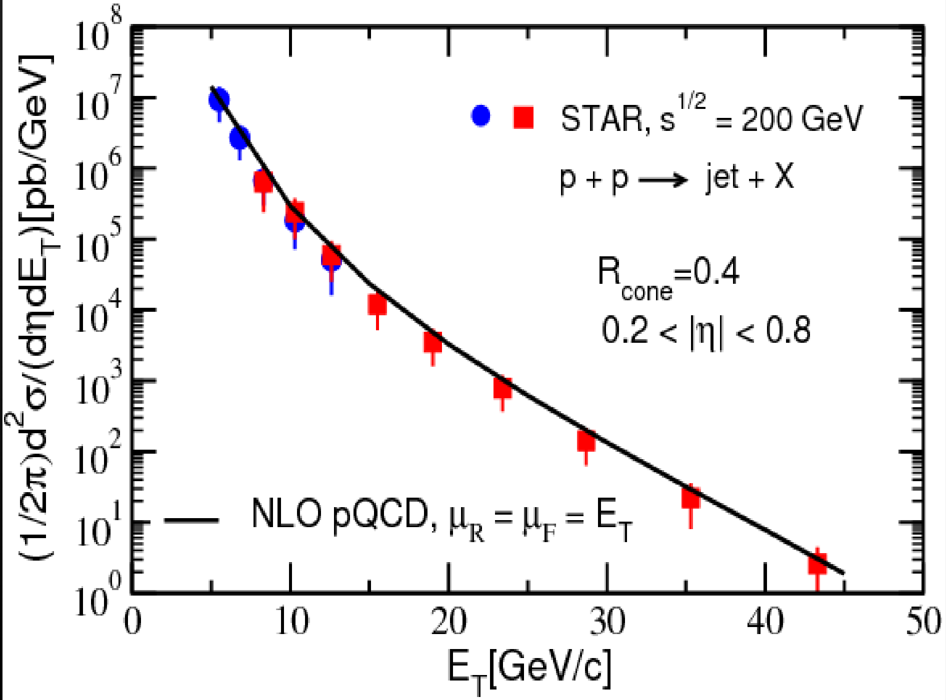
$$S_2 = \sum_{i=1}^{2} S(i) = \sum_{i=1}^{2} \delta(E_{T_i} - E_T)\delta(y_i - y)$$

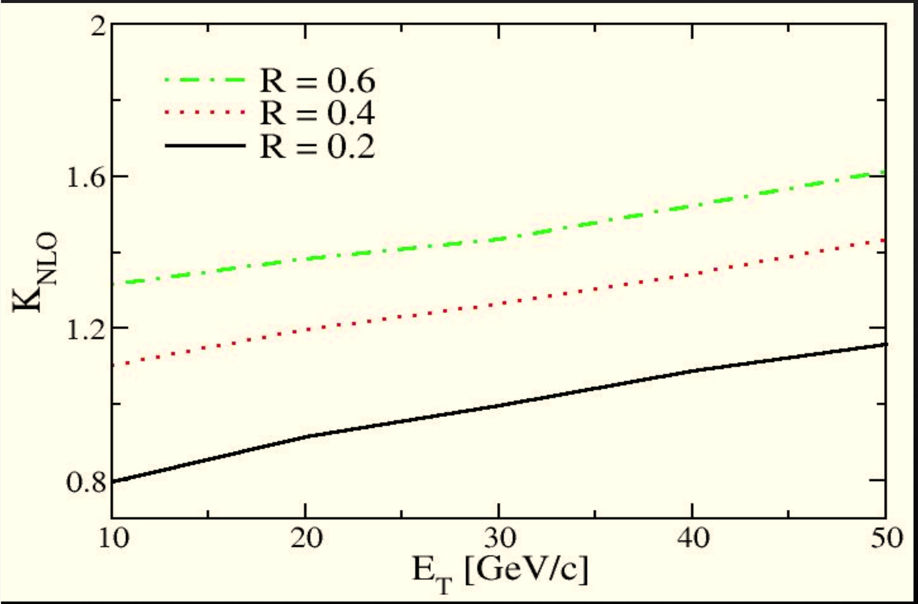
2 --→ 3

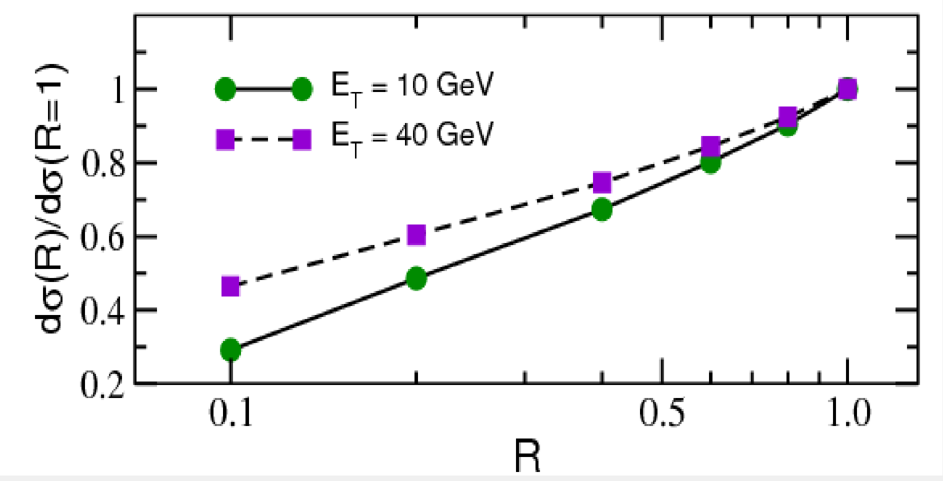
$$S_3 = \sum_i \delta(p_i - p_J)\delta(y_i - y_J) \prod_{j(j\neq i)} \theta\left(R_{ij} > \frac{p_i + p_j}{\max(p_i,p_j)} R\right) + \sum_{i,j(i<j)} \delta(p_i + p_j - p_J)\delta\left(\frac{p_i y_i + p_j y_j}{p_i + p_j} - y_J\right)\theta\left(R_{ij} < R_{\rm rc}\right)$$

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

Inclusive jet in p+p at NLO

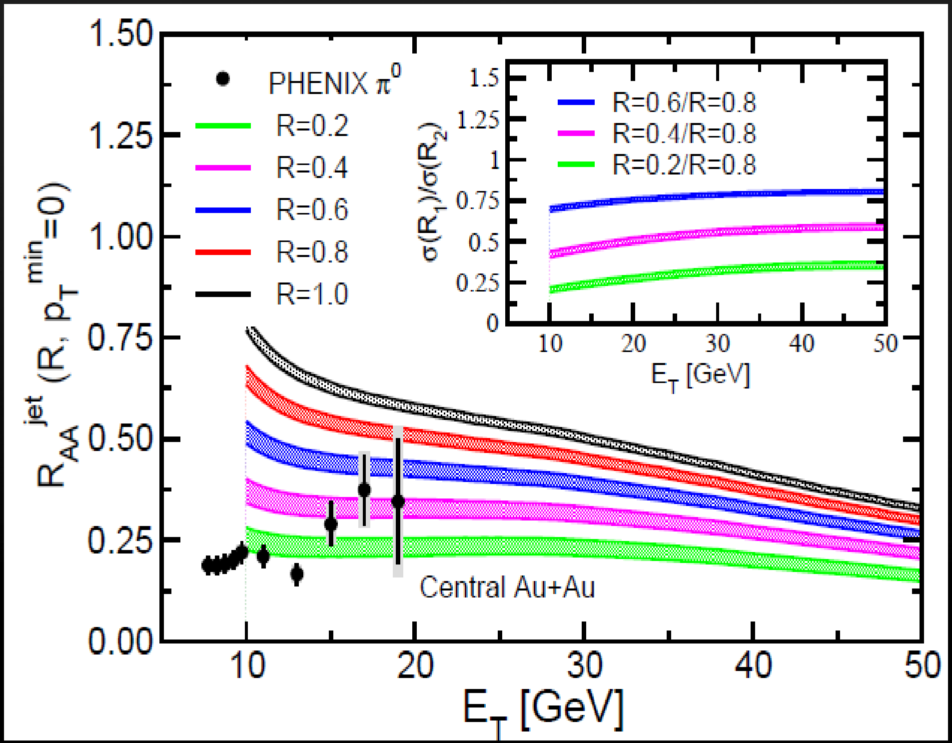




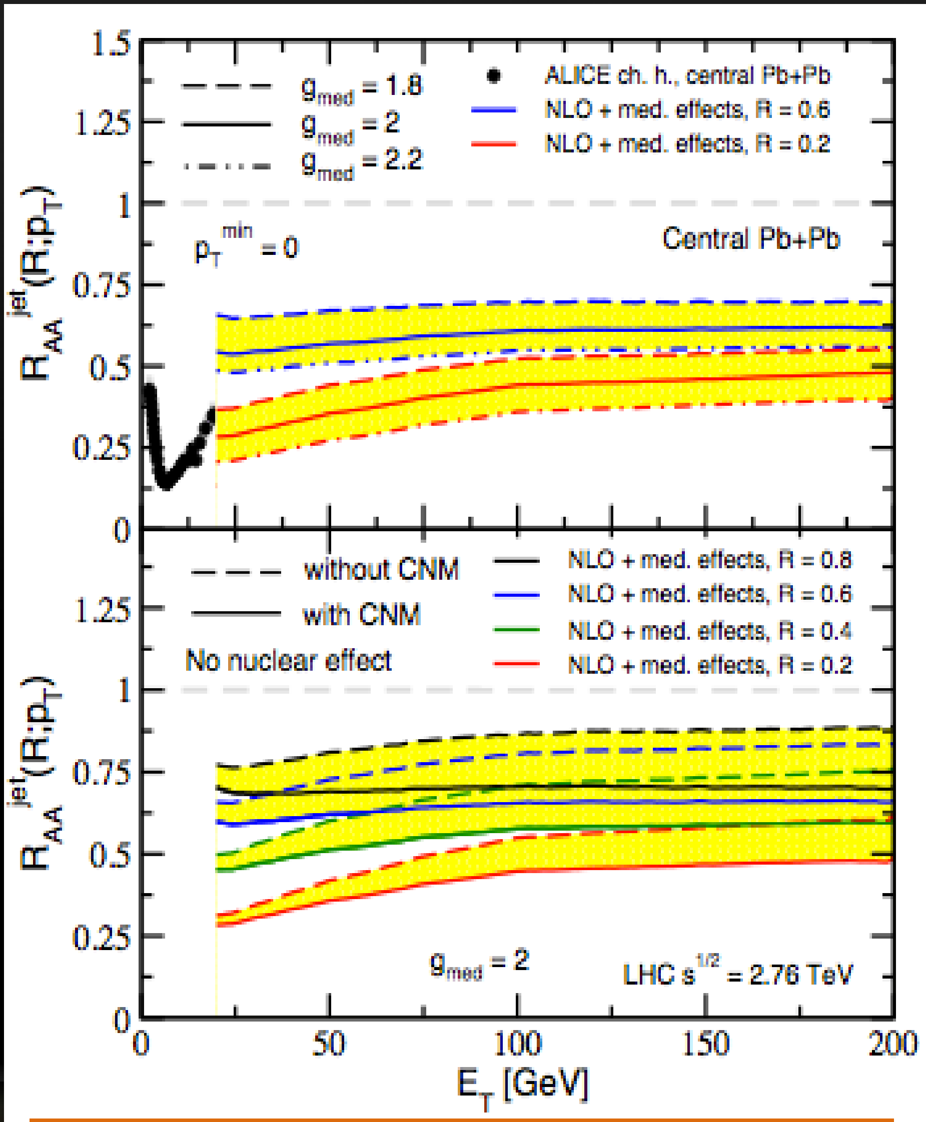


- Very good agreement between data and theory is achieved;
- K_{NLO}=NLO/LO can be smaller than 1 at small cone radius.

Inclusive jets in A+A at RHIC



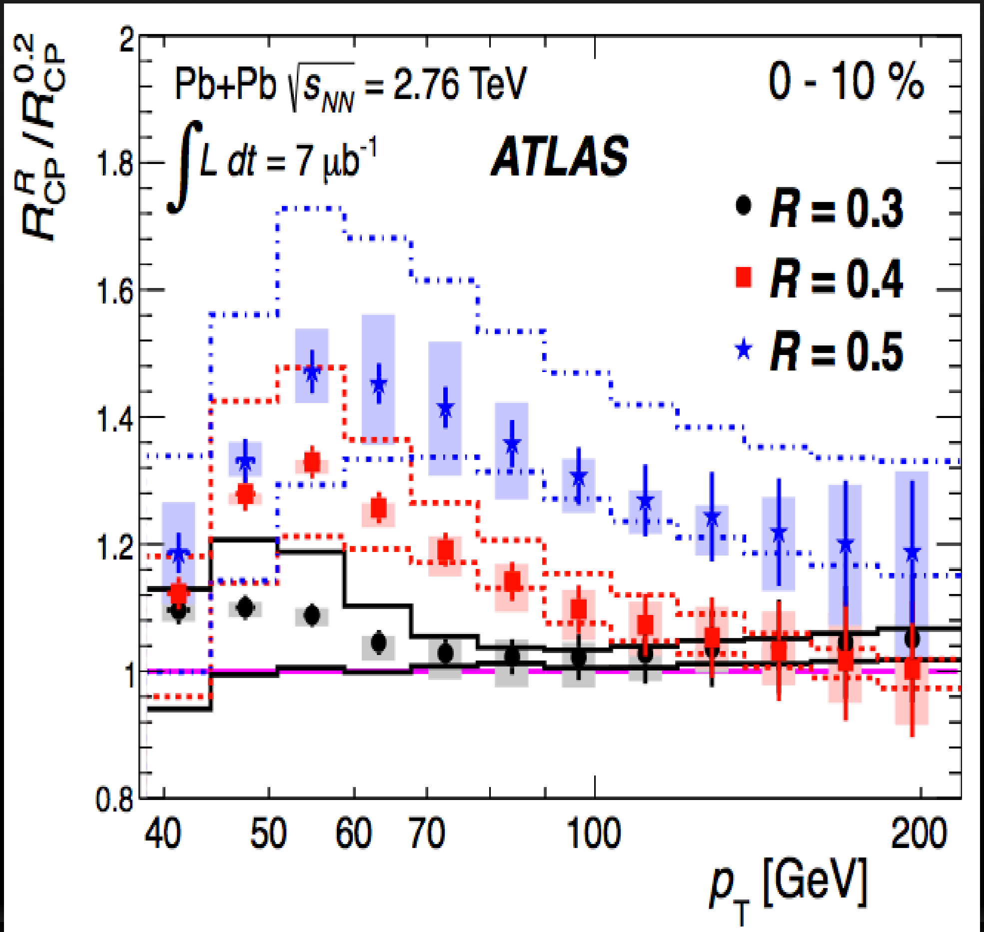
I Vitev, BWZ， PRL (2010).



Y He, Vitev, BWZ, PLB (2012)

Inclusive jet in Pb+Pb: Exp.

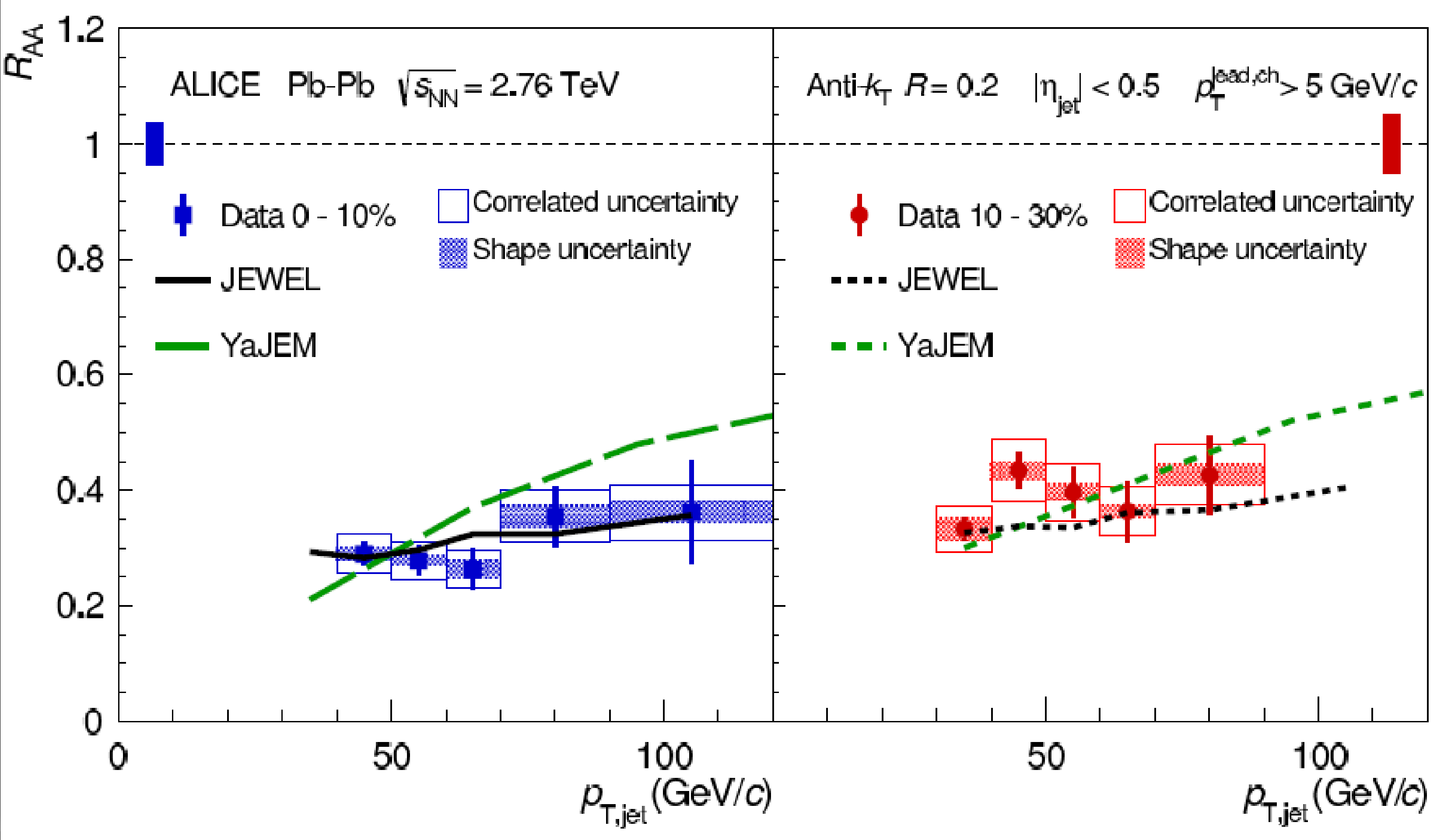
- The jet radius dependence of Raa on inclusive jets has been confirmed by ATLAS measurements most recently.



ATLAS, PLB (2013)

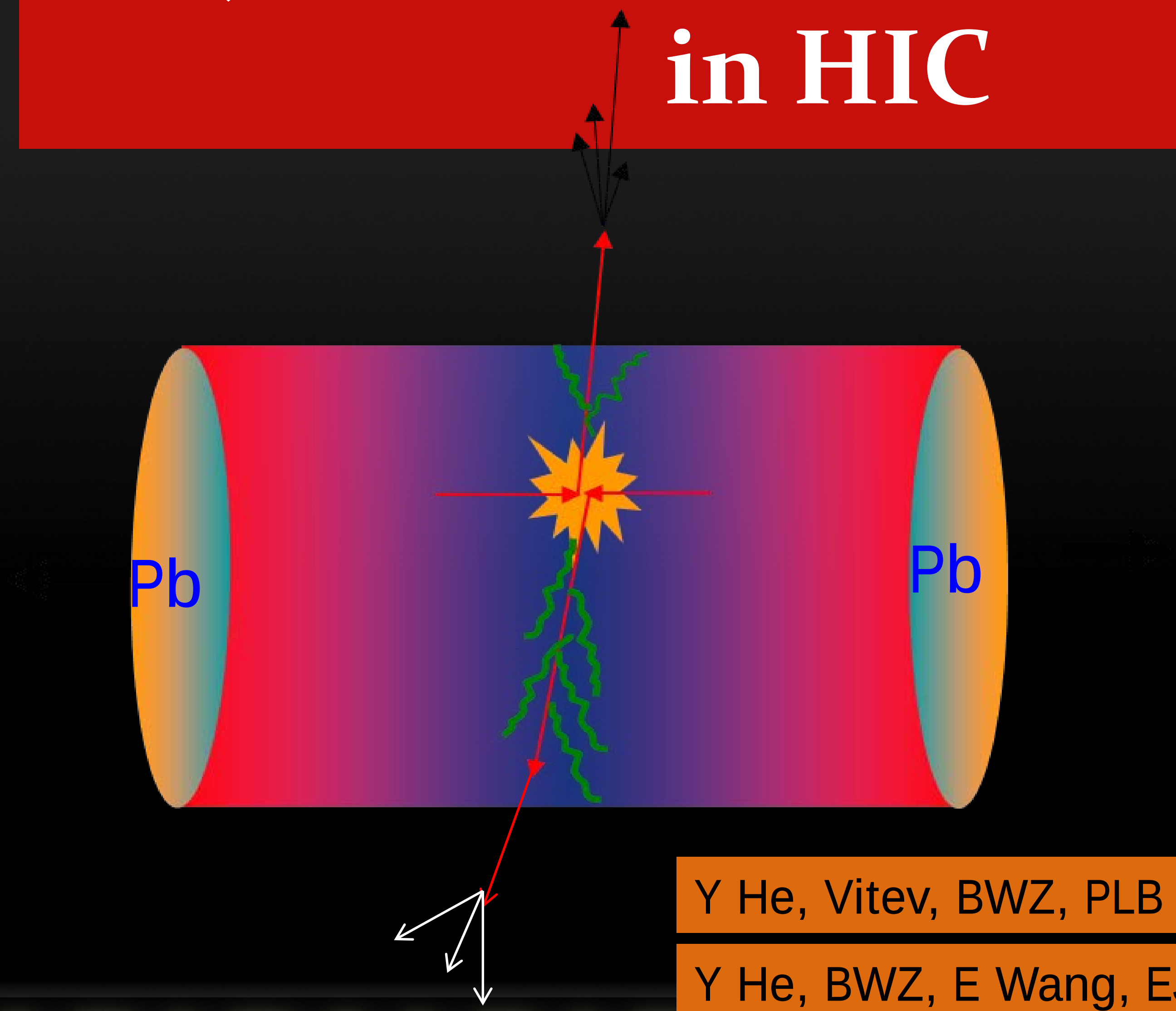
Inclusive jet in Pb+Pb: Exp.

- Inclusive jet Raa has also recently measured by ALICE.



ALICE, arXiv: 1502.01689

Dijet momentum imbalance in HIC



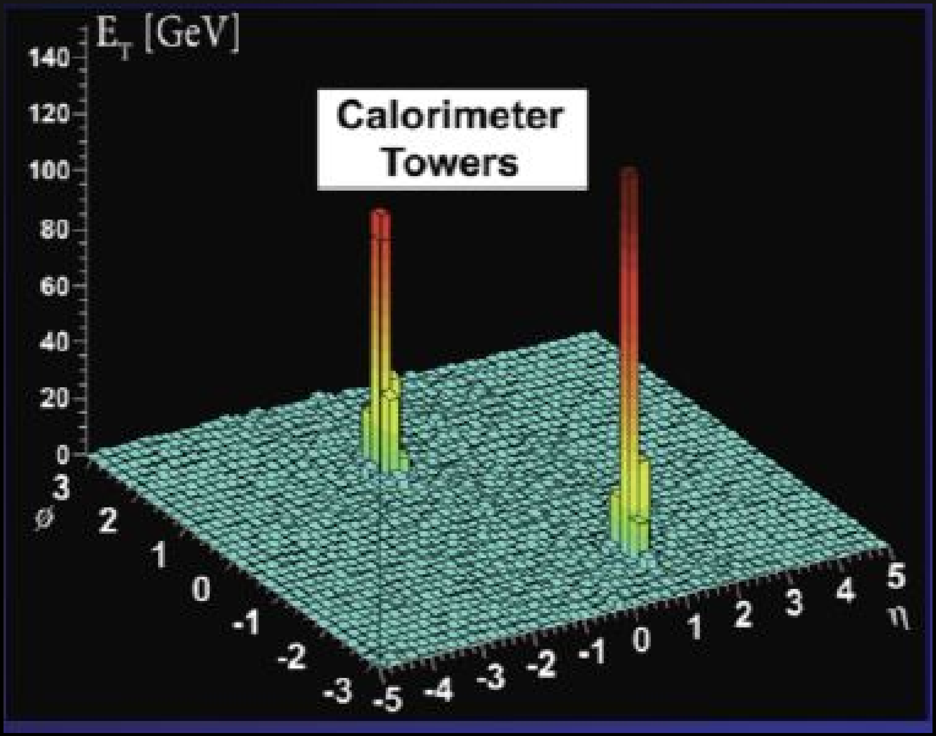
Y He, Vitev, BWZ, PLB (2012)

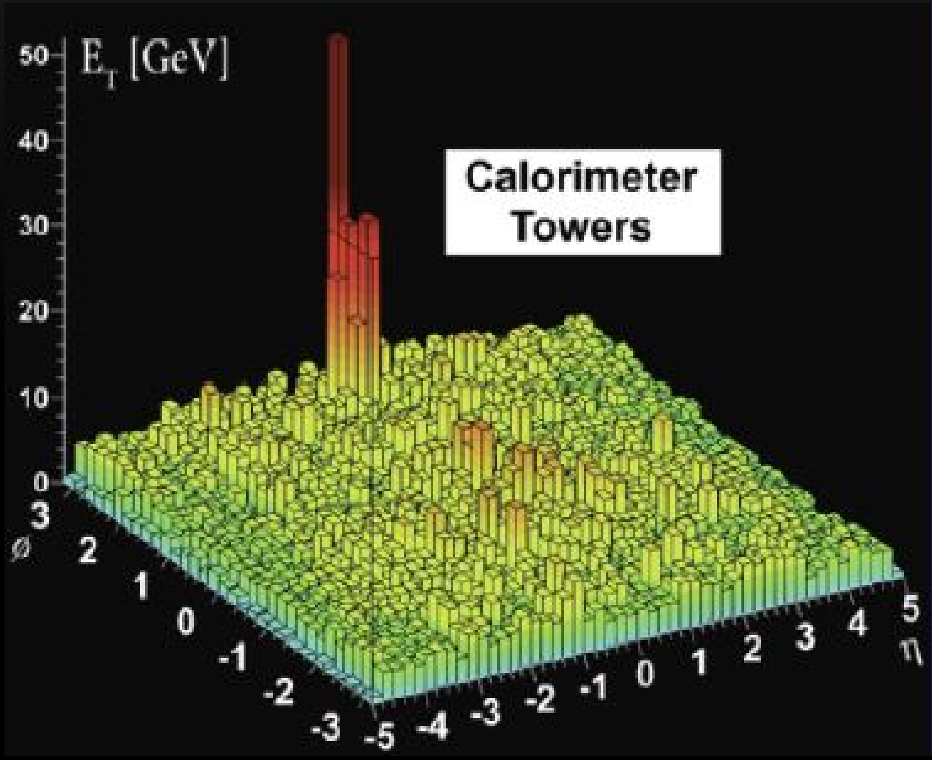
Y He, BWZ, E Wang, EJPC (2012)

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。

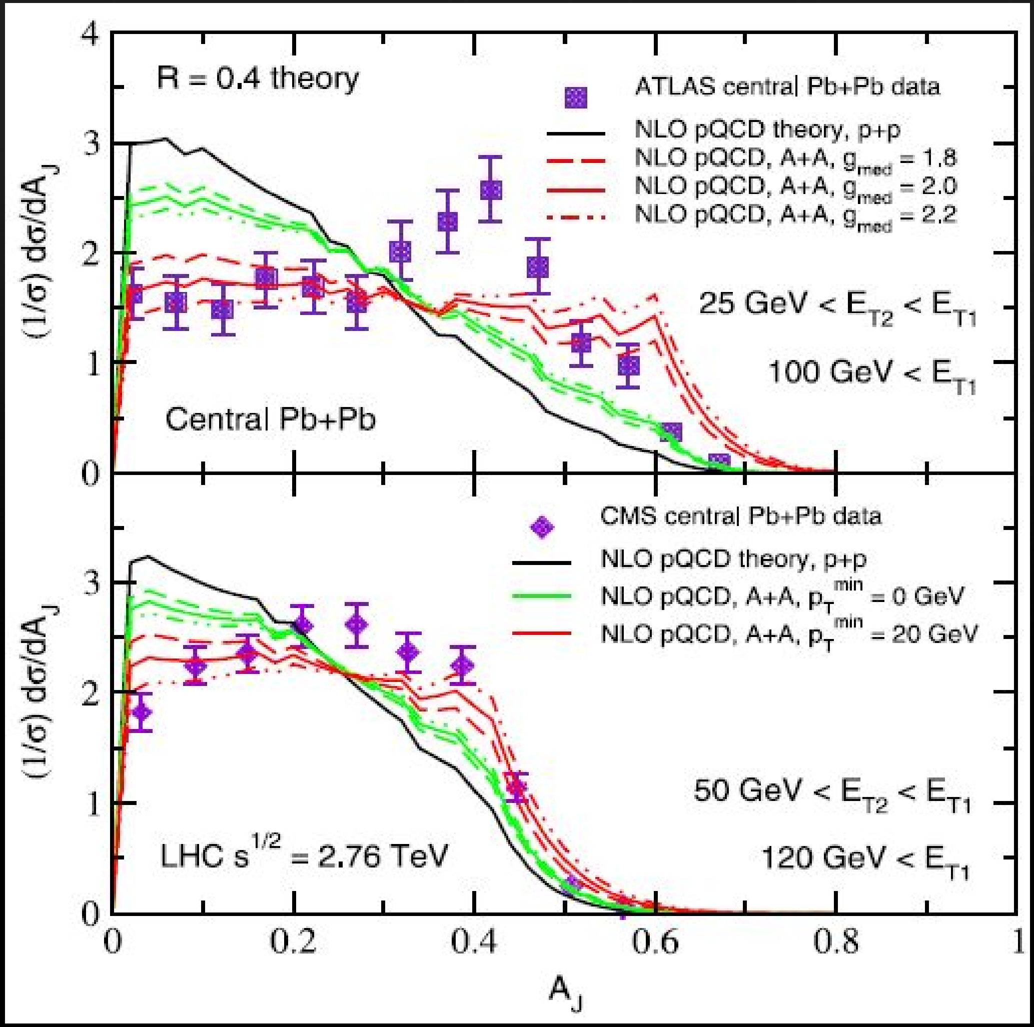




ATLAS, arXiv:1011.6182, PRL (2011); CMS, arXiv: 1102.1957, PRC(2012)

Dijet in Pb+Pb at LHC

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



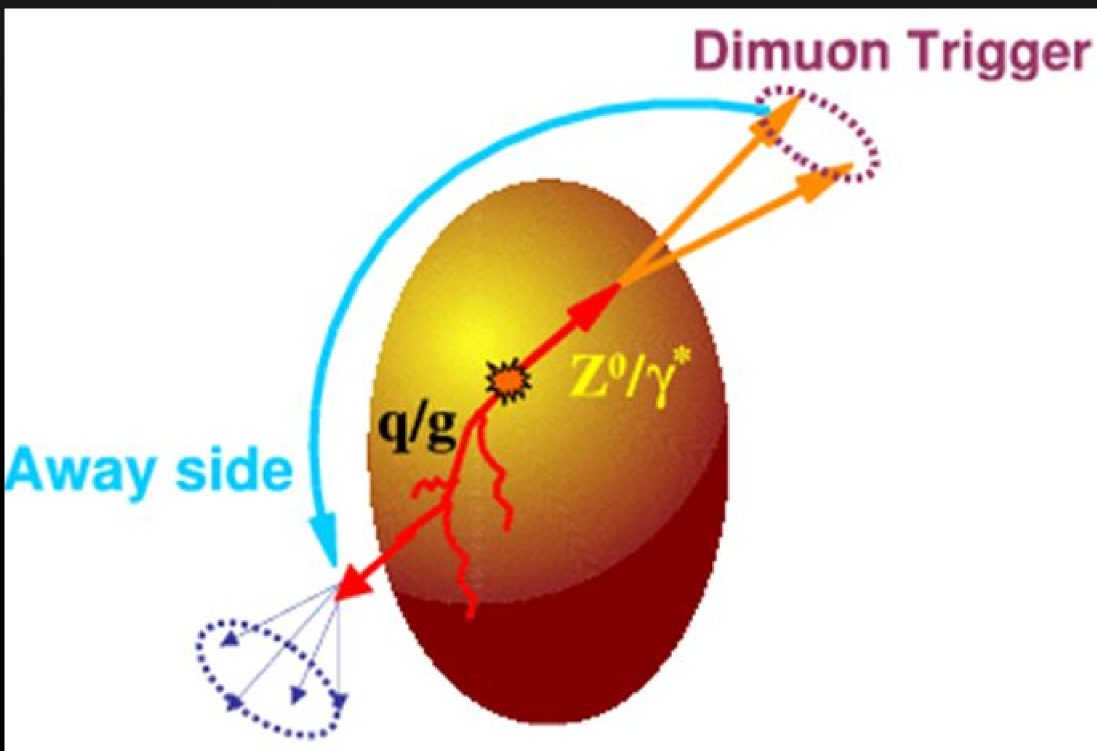
Y He, Vitev, BWZ, PLB (2012)

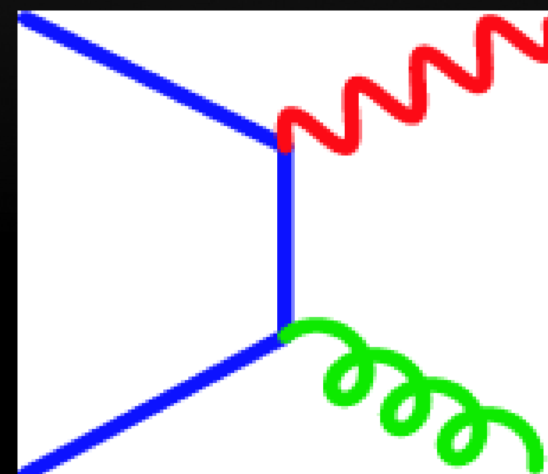
G Qin, B Muller, PRL (2011)

ATLAS, arXiv:1011.6182, PRL (2011);

CMS, arXiv: 1102.1957, PRC (2012) .

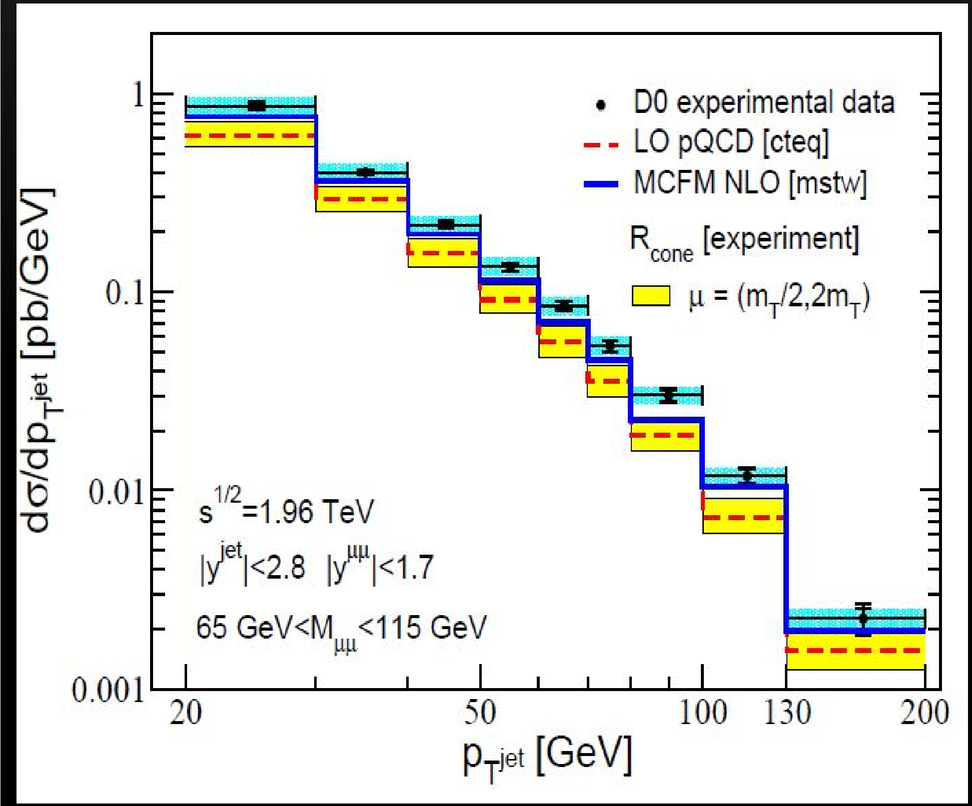
Tagged jet production in HIC

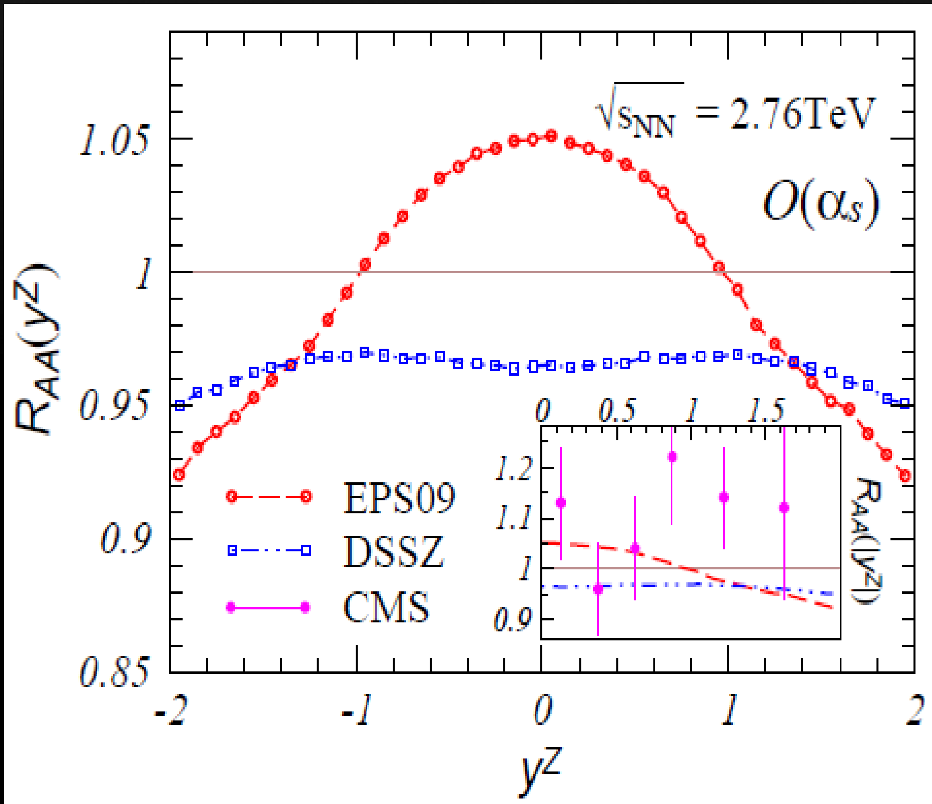




Zº in pp and PbPb

- pQCD gives a good description of the data at the LHC and DO.
- The CNM effects for Z boson is small.





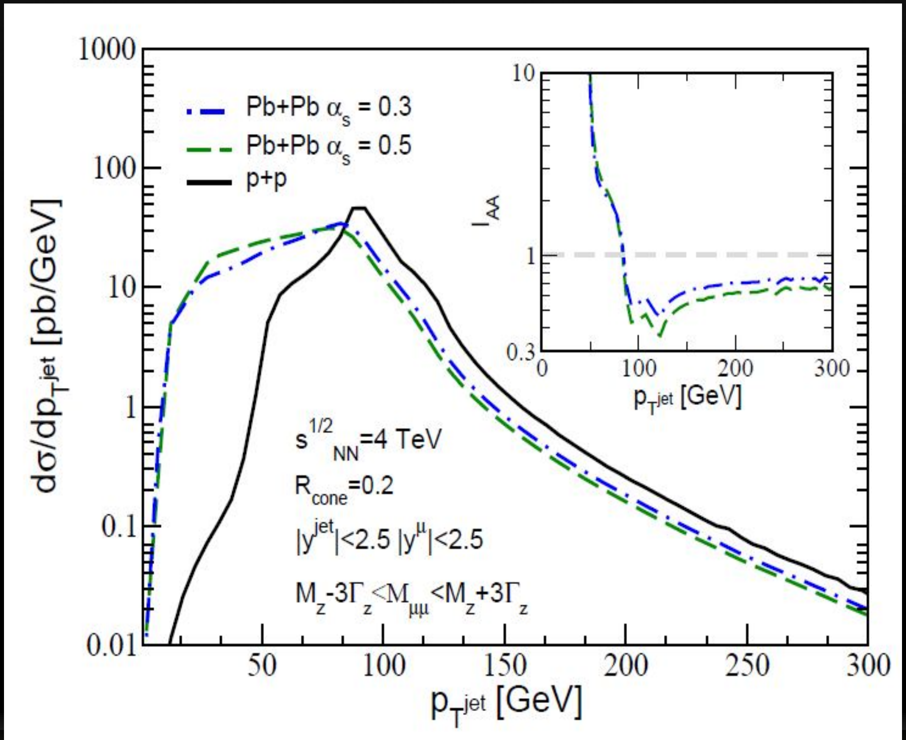
Neufeld, Vitev, BWZ, PRC (2011).

Ru, BWZ, Cheng, et al, JPG (2015).

Zº + 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 (2011).

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

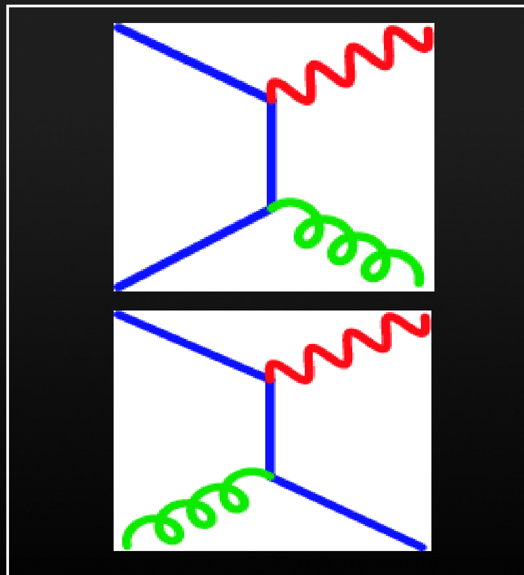
Prompt photon in pp collisions

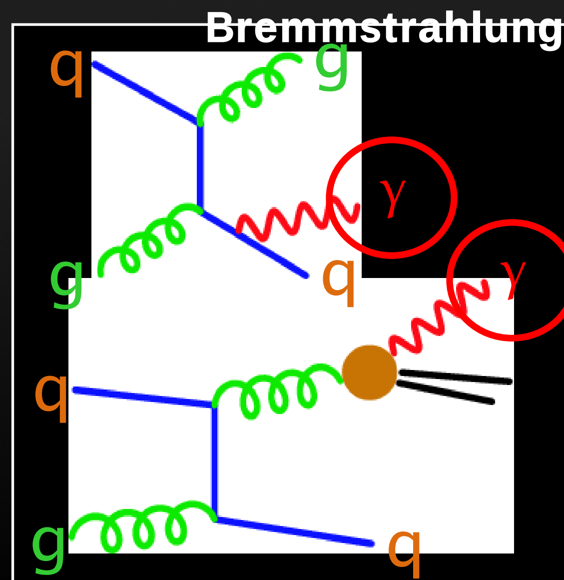
LO

Annihilation

$\alpha\alpha_s$

Compton





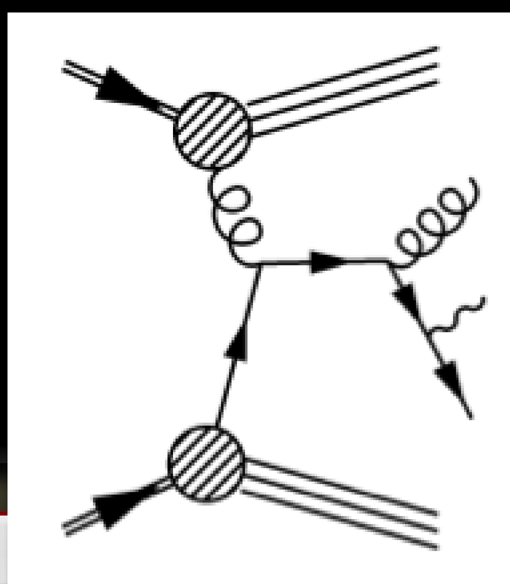
$$\alpha_s(Q) \propto \ln^{-1}(\frac{Q^2}{\Lambda^2})$$

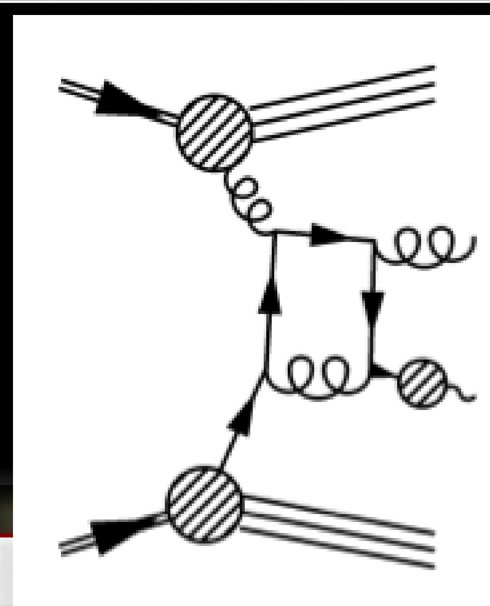
$$D_{\gamma/c}(z, Q^2) \propto \ln(\frac{Q^2}{\Lambda^2})$$

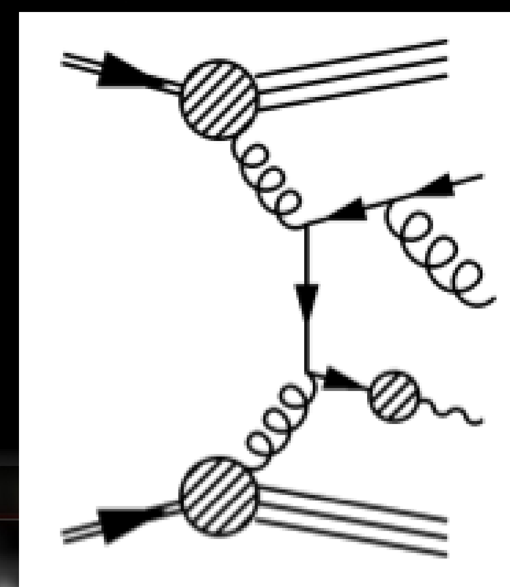
$$\alpha\alpha_s^2 D_{\gamma/c} \propto \alpha\alpha_s$$

NLO

$\alpha\alpha_s^2$

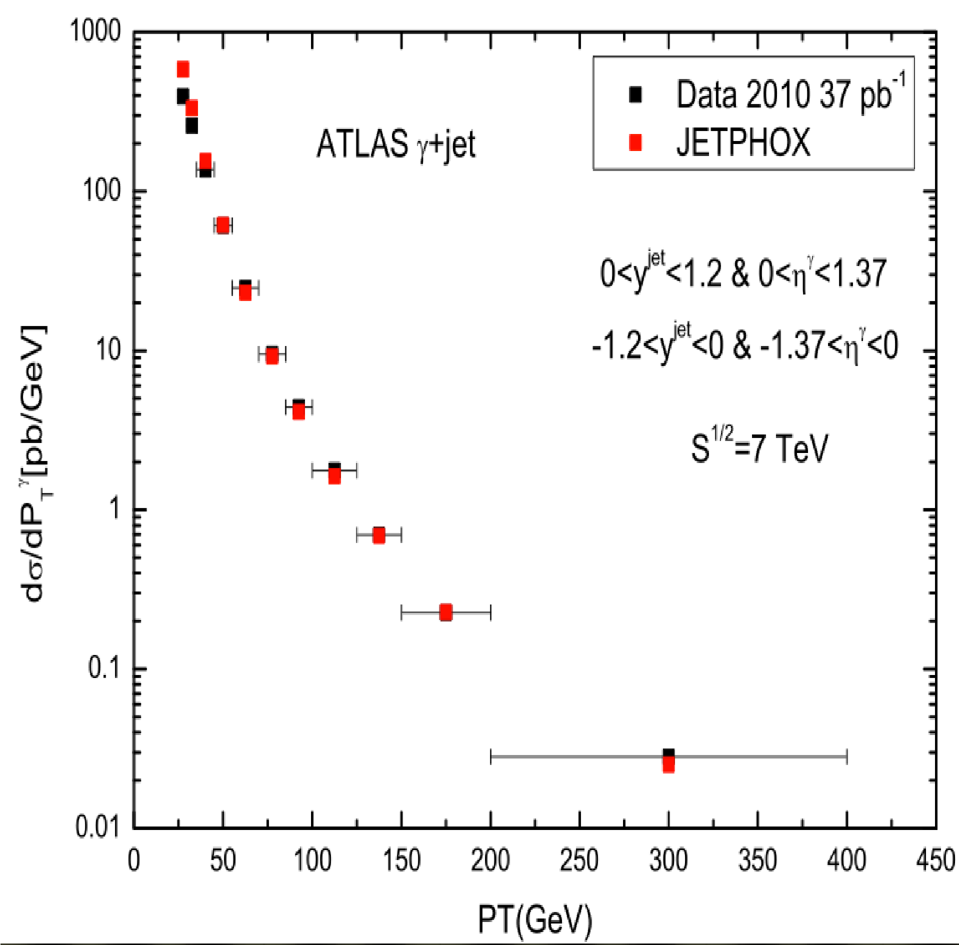


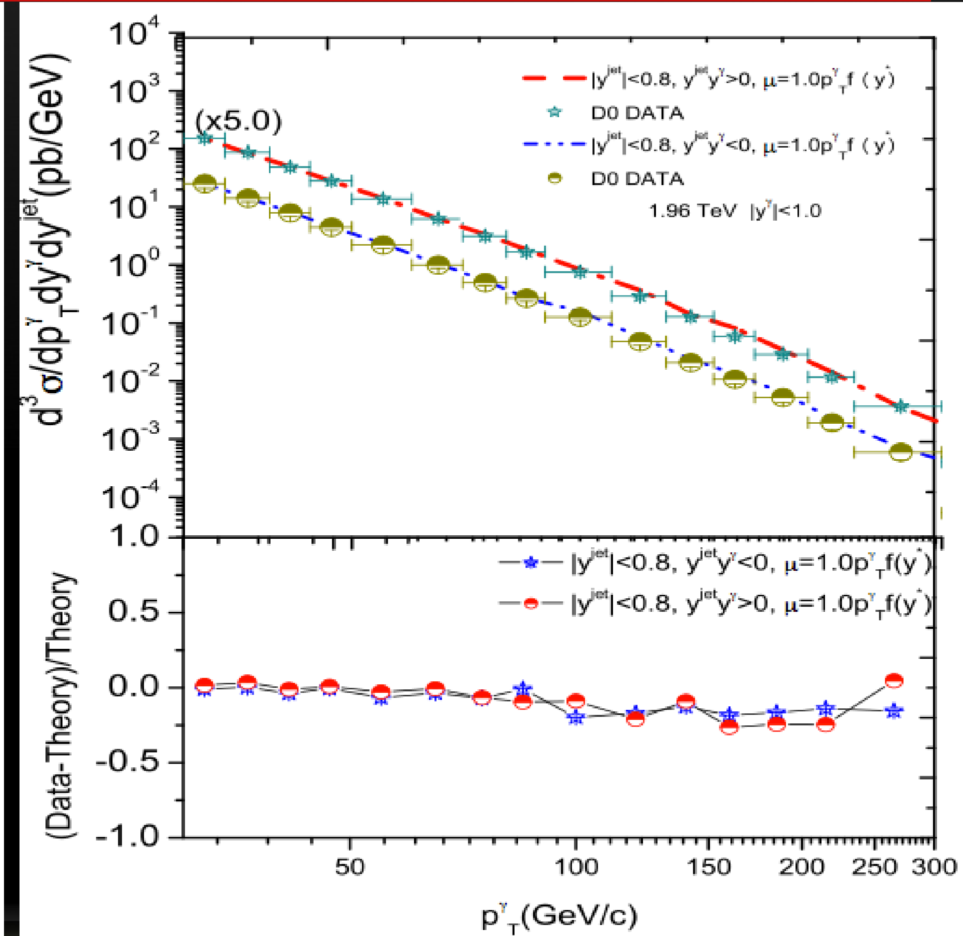




Photon + jet in p+p at NLO

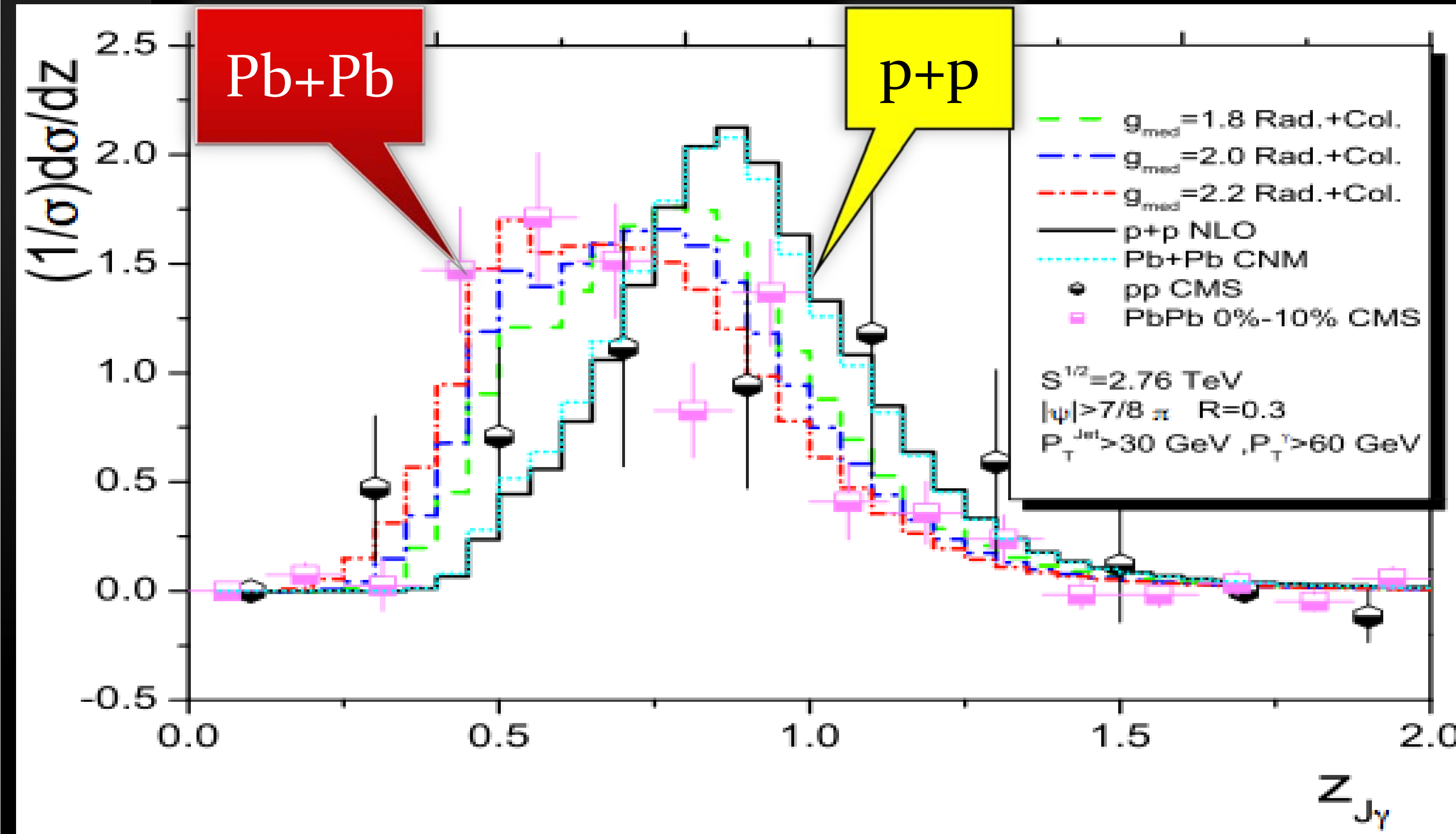
- A good baseline for photon+jet in hadron-hadron production has been given by the NLO pQCD.





W Dai, I Vitev, BWZ, PRL (2013)

Asymmetry in photon + jet



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

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

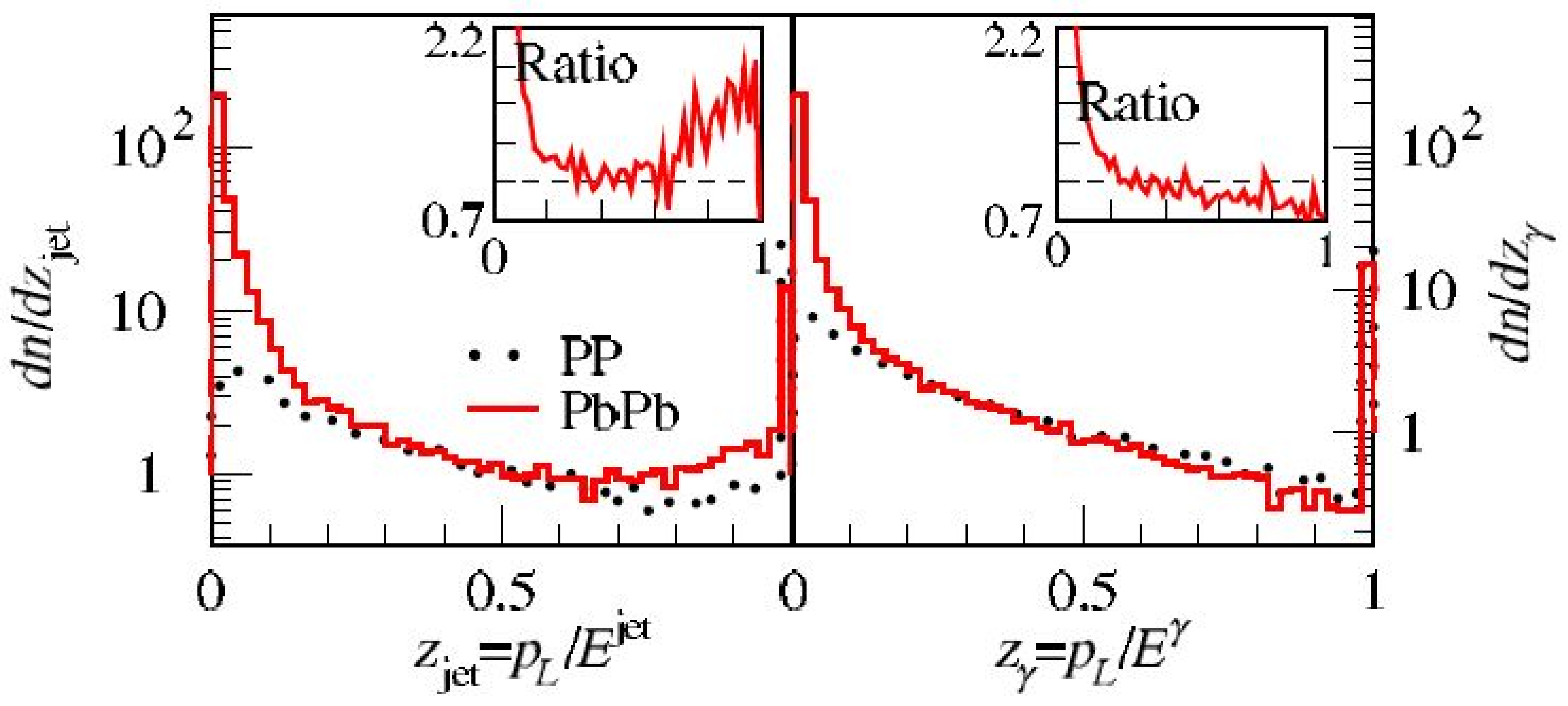
CMS, PLB(2013)

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

Dai, Vitev, BWZ, PRL(2013)

photon + jet with LBT

$$p \cdot \partial f(p) = -C(p)$$

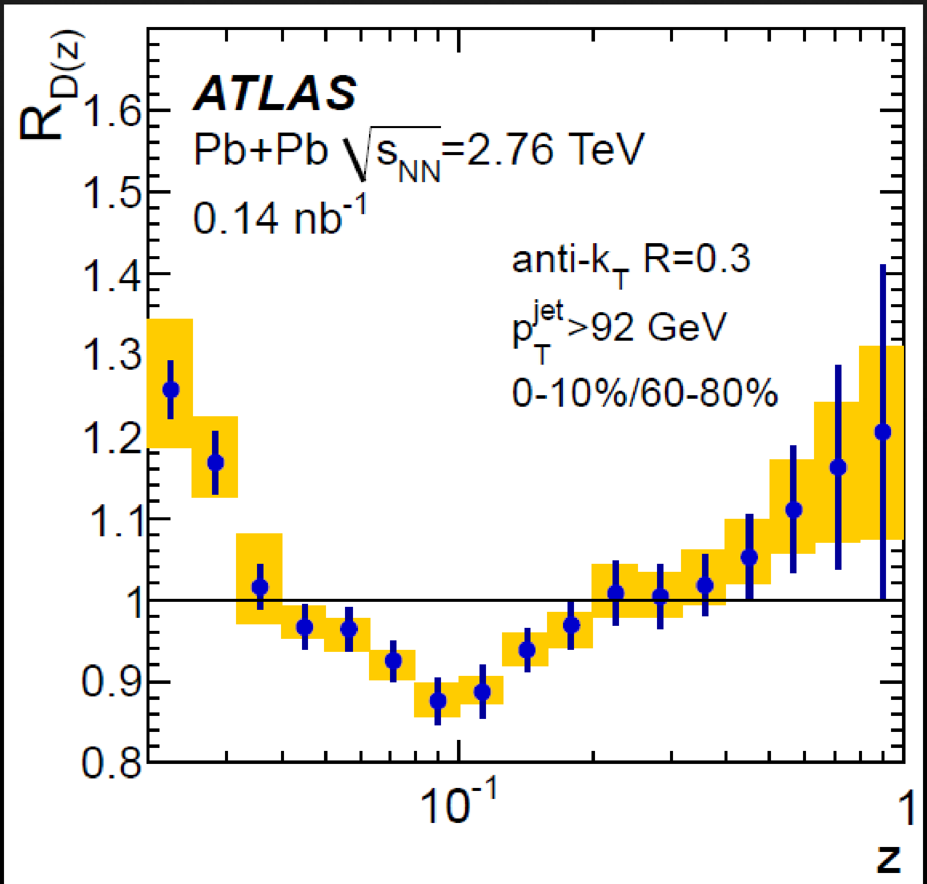


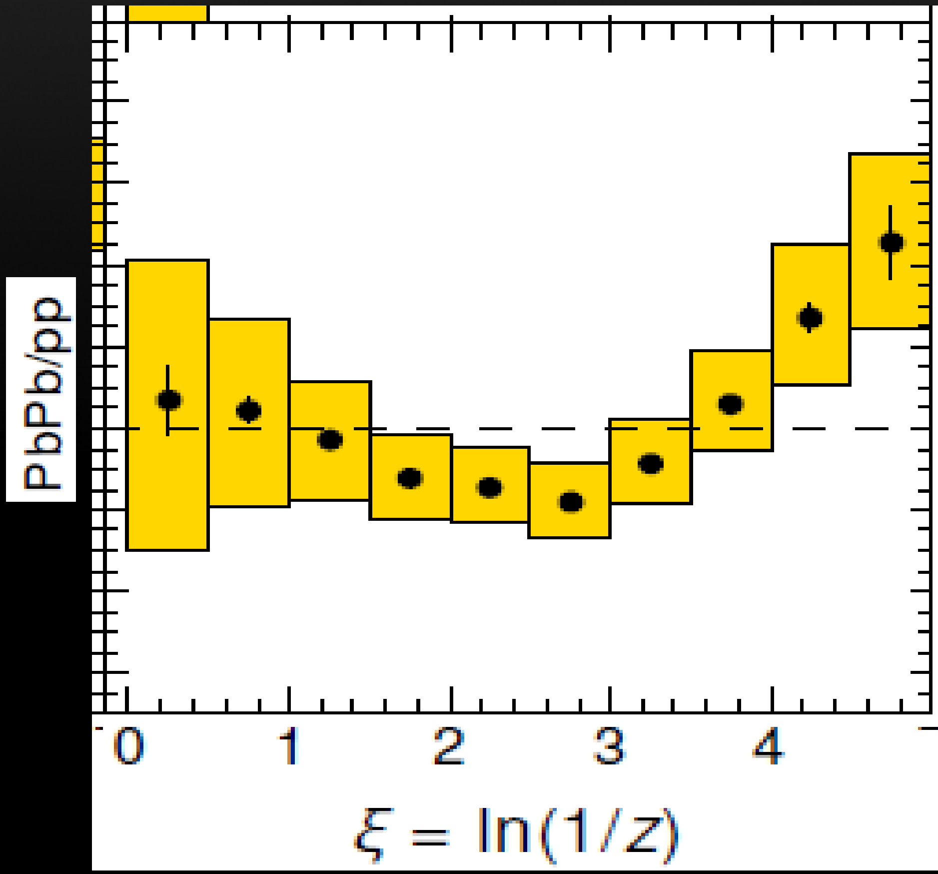
Xin-Nian Wang, Yan Zhu, PRL (2013)

Jet Fragmentation Function

$$D(z) \equiv \frac{1}{N_{\rm jet}} \frac{{\rm d}N_{\rm ch}}{{\rm d}z}$$

$z = p_T^h / p_T^{jet}$





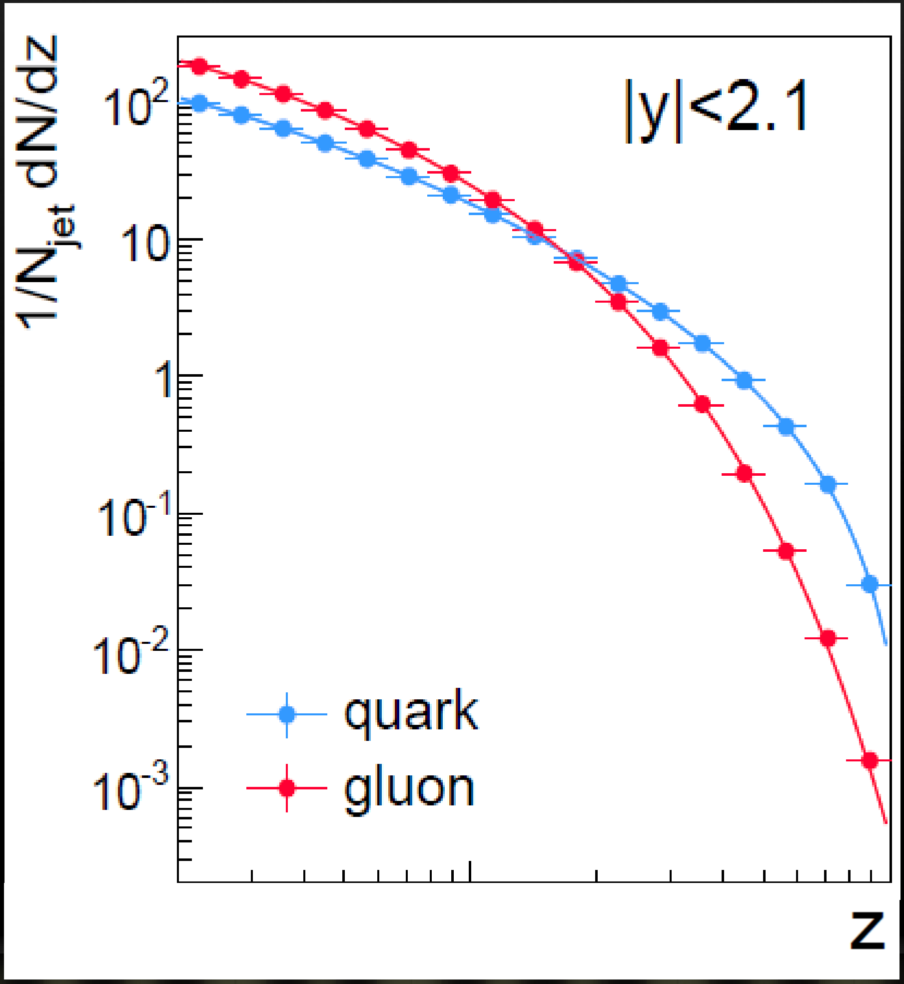
ATLAS, 1406.2979

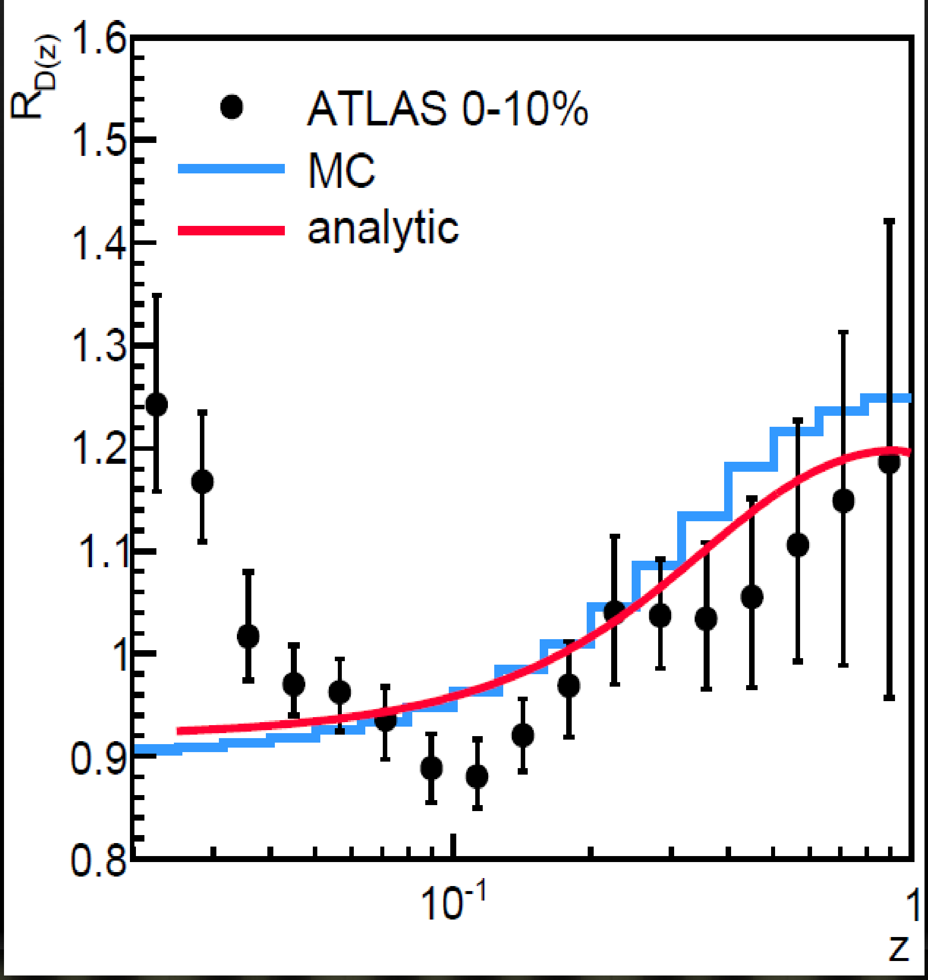
CMS, 1406.0932

Jet FF: Quark VS Gluon

$$D(z) \equiv \frac{1}{N_{\rm jet}} \frac{{\rm d}N_{\rm ch}}{{\rm d}z}$$

$z = p_T^h / p_T^{jet}$

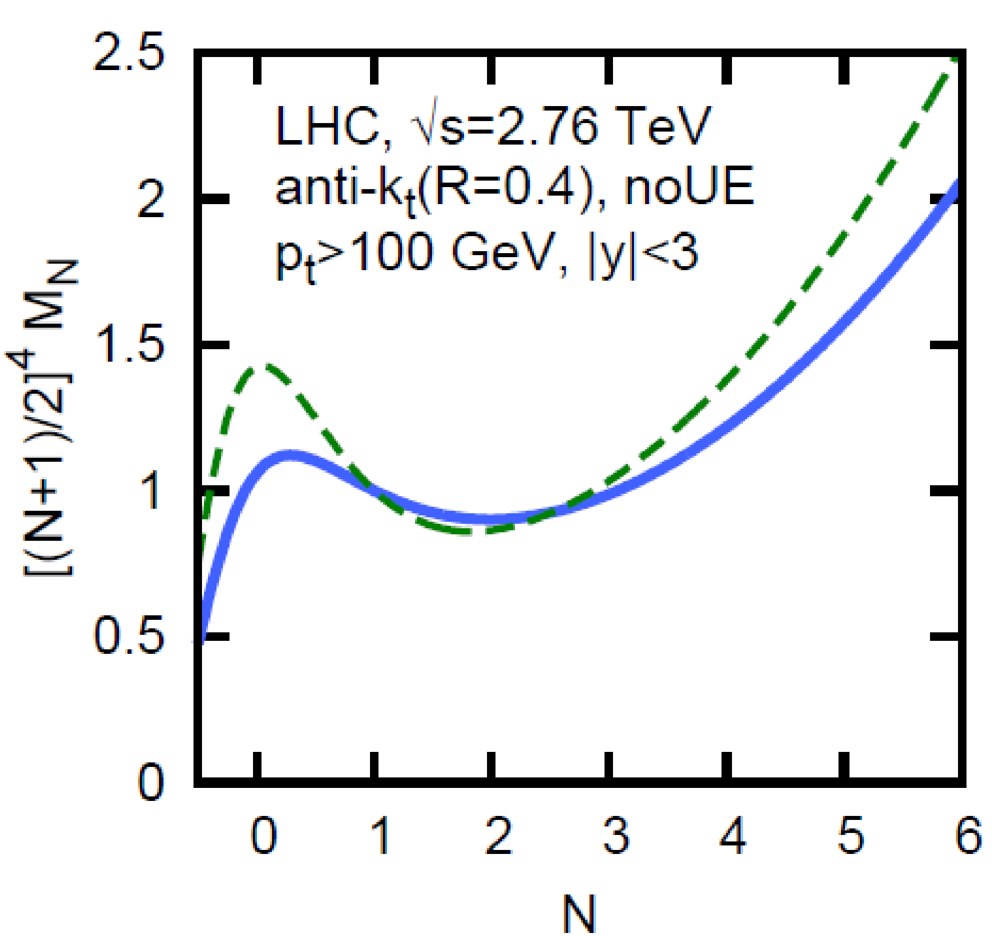




M Spousta, B Cole, 1504.05169

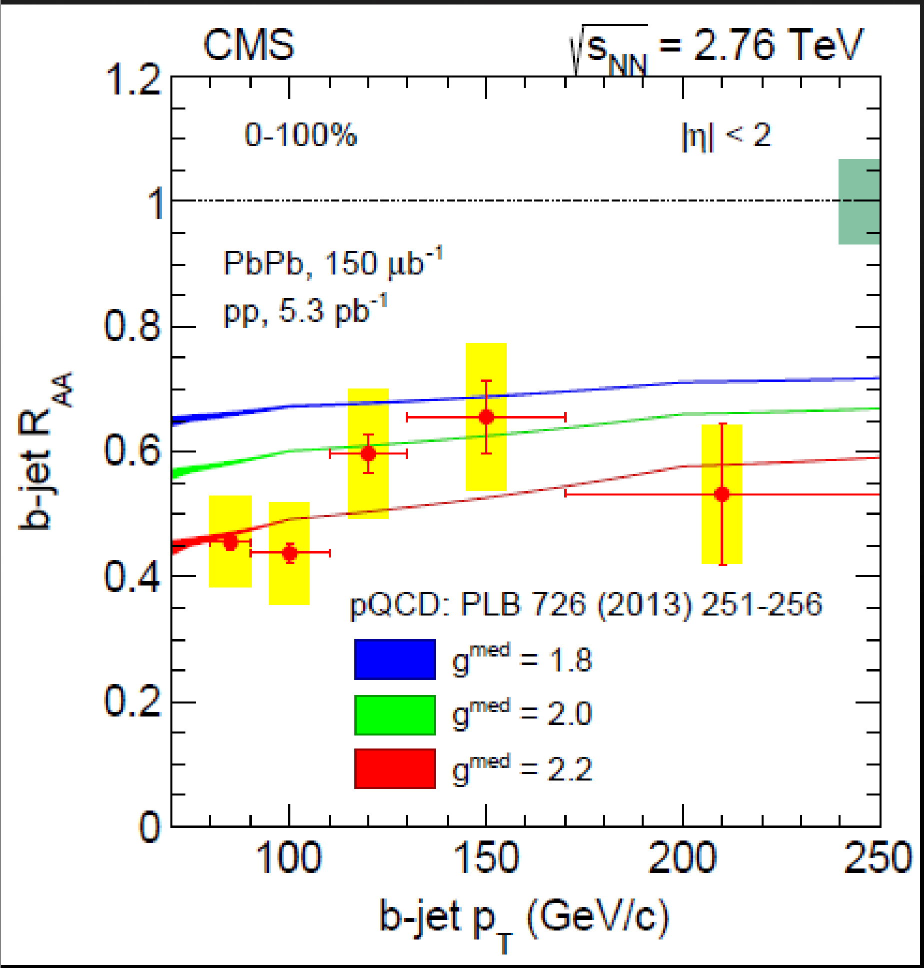
Jet FF Moments

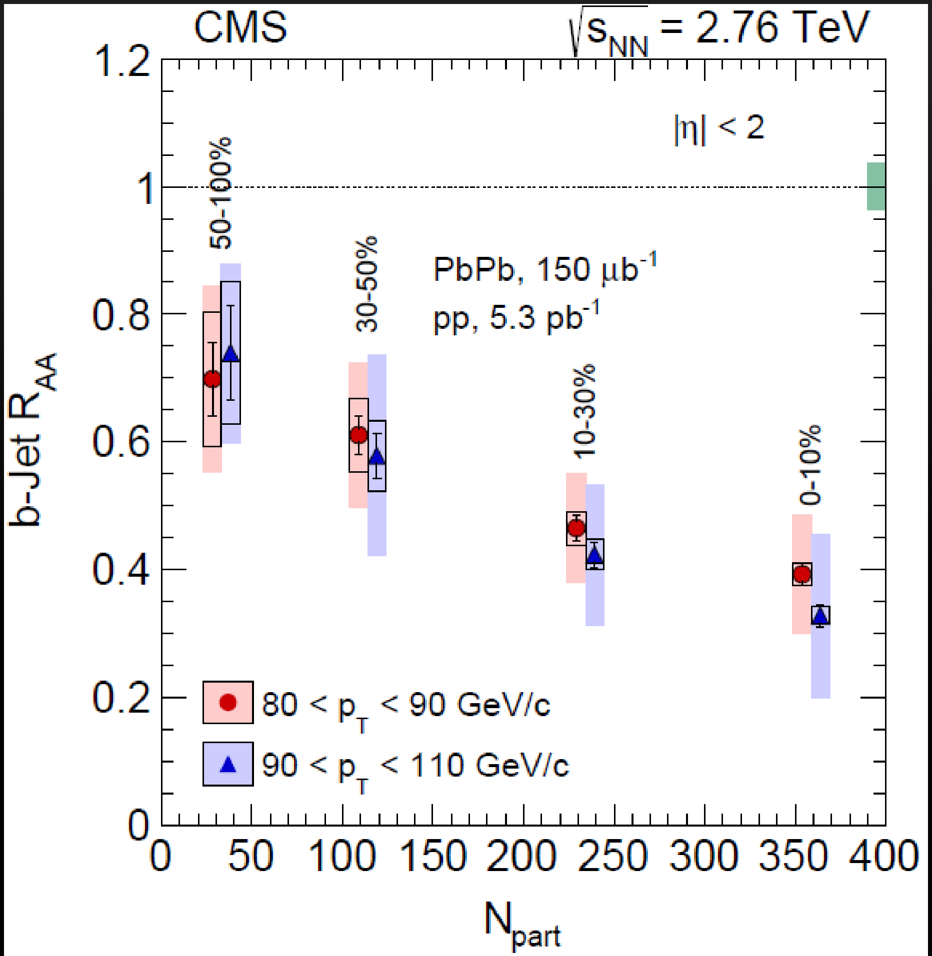
$$M_N = \frac{1}{N_{\text{jet}}} \int_0^1 z^N \frac{dN_h}{dz}\, dz$$



Cacciari, Quiroga-Arias, Salam, Soyez, 1209.6086

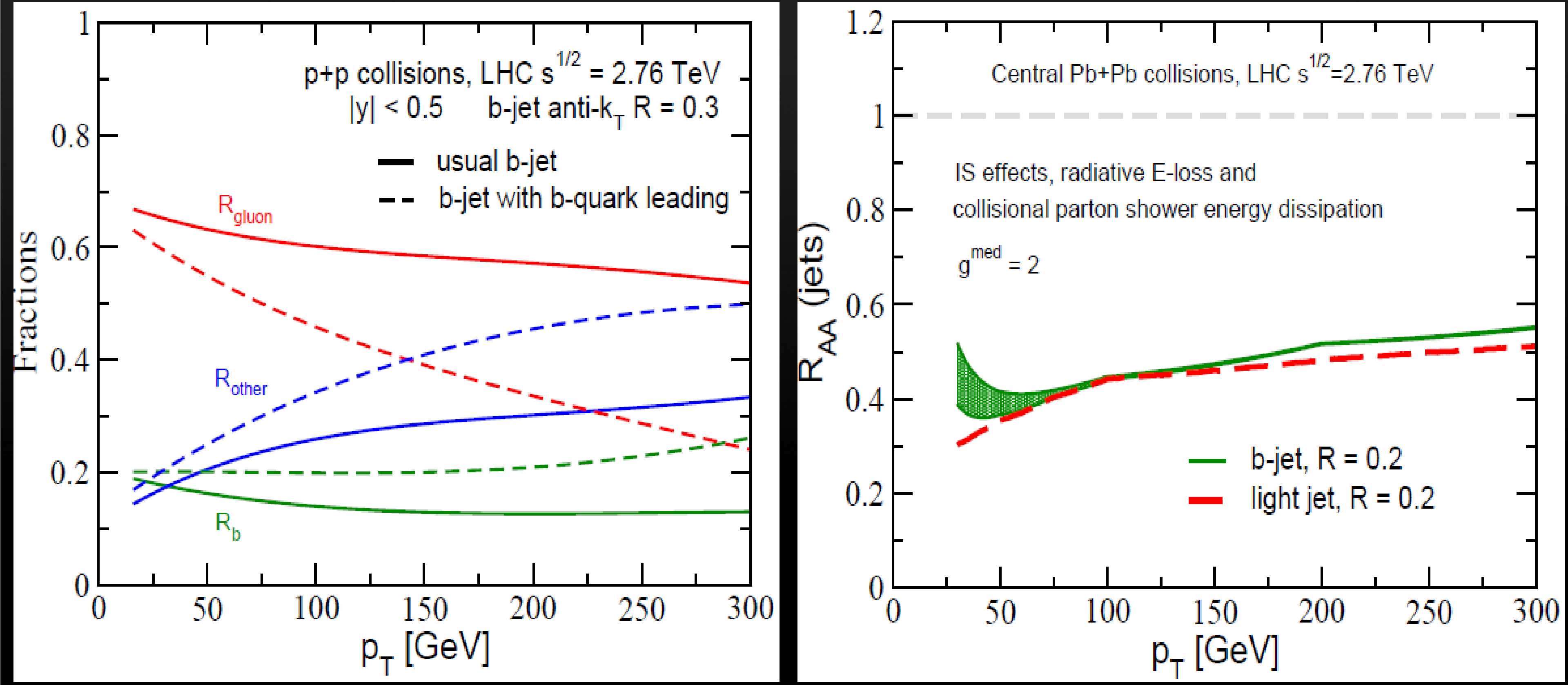
b-tagged Jet in HIC (1)





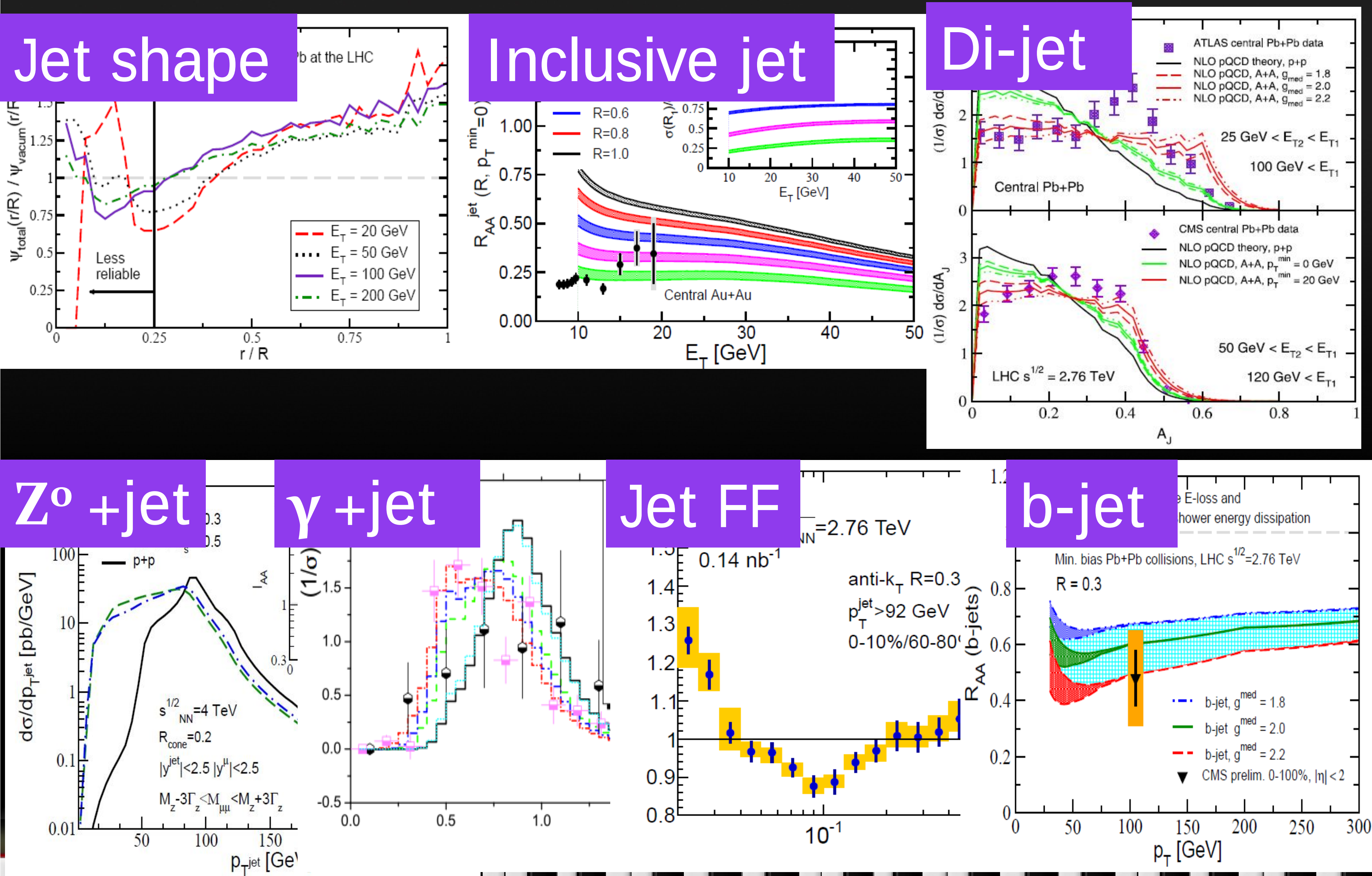
CMS, PRL (2014)

b-tagged Jet in HIC (2)



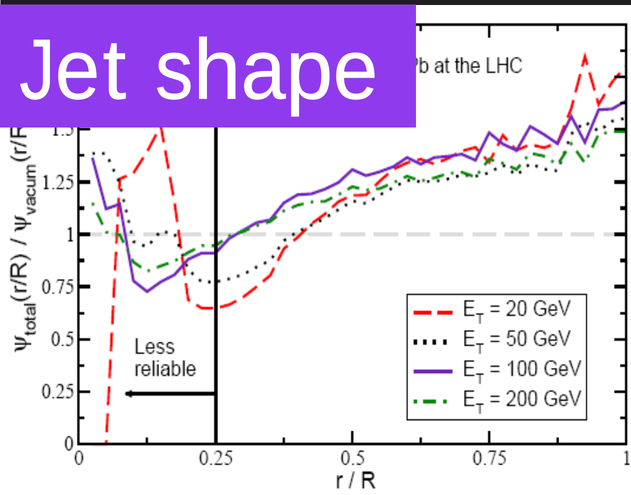
Huang, Kang, Vitev, PLB (2013)

Recap: a world of jets

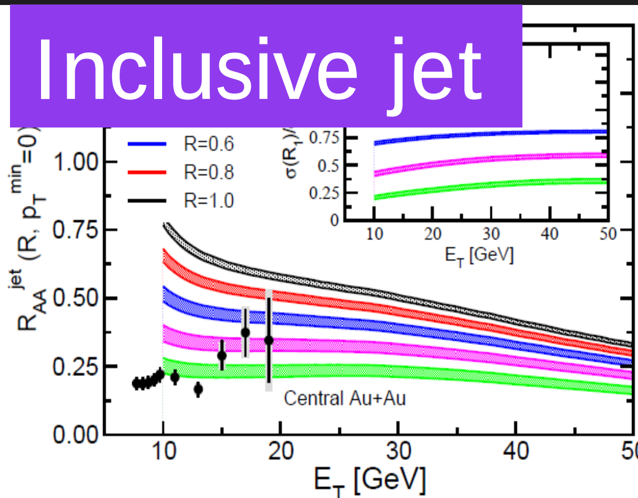


Recap: a world of jets

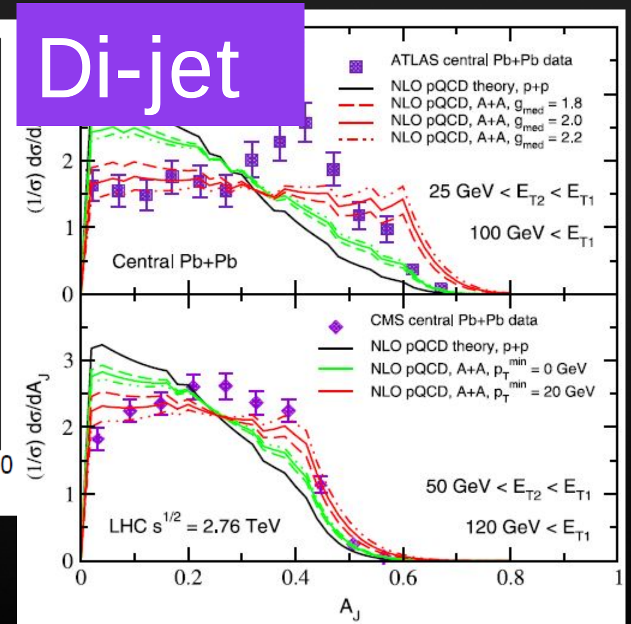
Jet shape



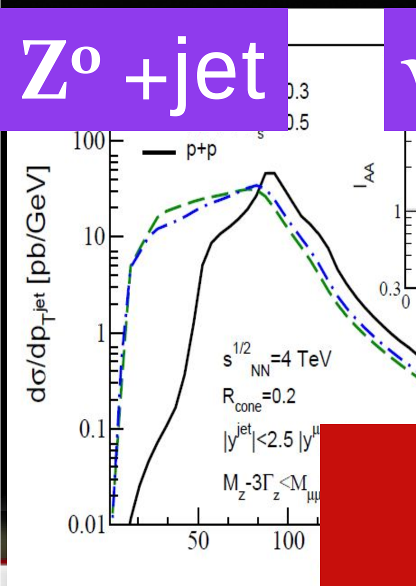
Inclusive jet



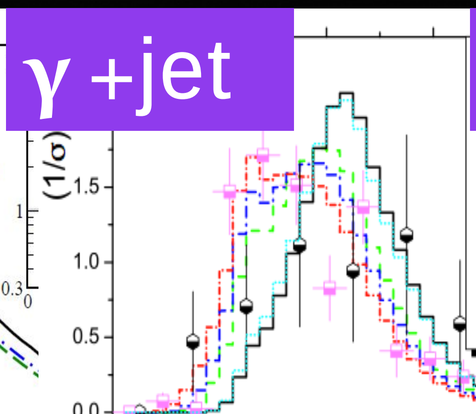
Di-jet



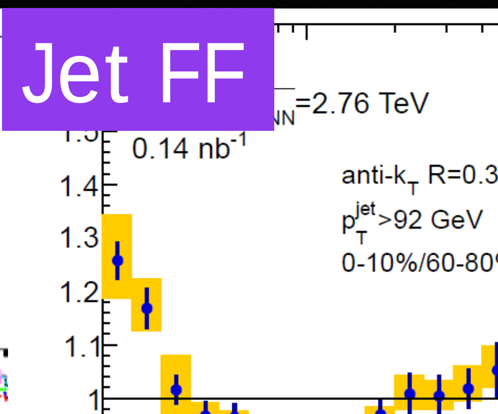
Zº +jet



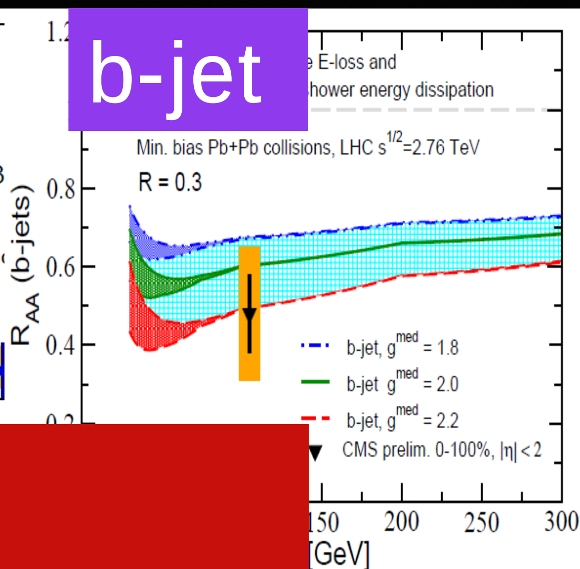
γ +jet



Jet FF



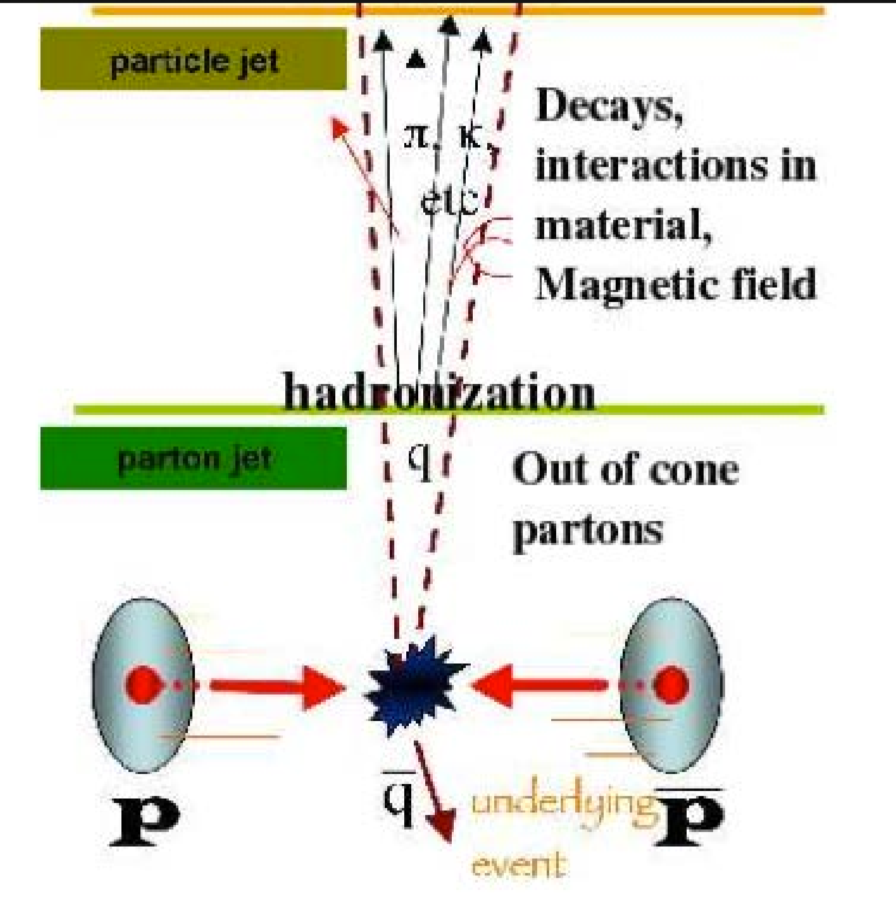
b-jet

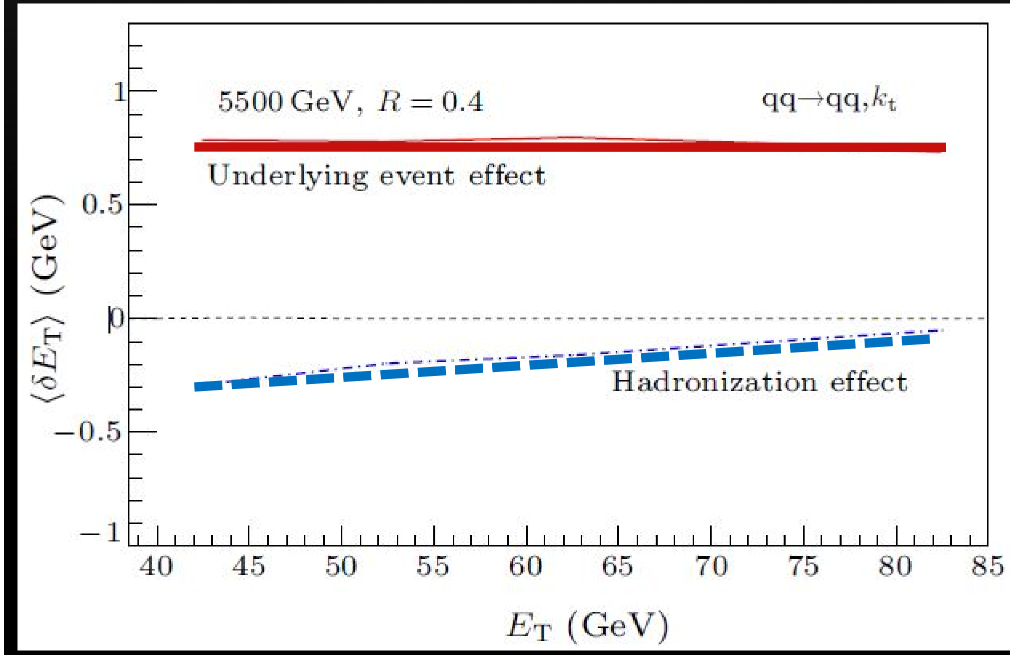


Thank you!

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)

Sudakov resummation

Jet shapes for a quark and a gluon are:

$$\psi_q(r) = \frac{C_F\alpha_s}{2\pi}\frac{2}{r}\left(2\log\frac{1-z_{min}}{Z} - \frac{3}{2}\left[(1-Z)^2 - z_{min}^2\right]\right),$$

$$\psi_g(r) = \frac{C_A\alpha_s}{2\pi}\frac{2}{r}\left(2\log\frac{1-z_{min}}{Z} - \left(\frac{11}{6} - \frac{Z}{3} + \frac{Z^2}{2}\right)(1-Z)^2 + \left(2z_{min}^2 - \frac{2}{3}z_{min}^3 + \frac{1}{2}z_{min}^4\right)\right) + \frac{T_R N_f\alpha_s}{2\pi}\frac{2}{r}\left(\left(\frac{2}{3} - \frac{2Z}{3} + Z^2\right)(1-Z)^2 - \left(z_{min}^2 - \frac{4}{3}z_{min}^3 + z_{min}^4\right)\right)$$

Collinear divergence Requires Sudakov resummation

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

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

Sudakov form factors:

$$P_q(r > z_{min}R) = \exp\left(2C_F\log\frac{R}{r}f_1\left(2\beta_0\alpha_s\log\frac{R}{r}\right) - \left[\frac{3}{2}C_F - CR^2 - c_q^>(z_{min})\right]\times f_2\left(2\beta_0\alpha_s\log\frac{R}{r}\right)\right),$$

$$P_g(r > z_{min}R) = \exp\left(2C_A\log\frac{R}{r}f_1\left(2\beta_0\alpha_s\log\frac{R}{r}\right) - \left[\frac{1}{2}b_0 - CR^2 - c_g^>(z_{min})\right]\times f_2\left(2\beta_0\alpha_s\log\frac{R}{r}\right)\right).$$

$$P_q(r < z_{min}R) = P_q(r > z_{min}R; r = z_{min}R)\times\exp\left(-\left[\frac{3}{2}C_F - c_q^<(z_{min})\right]\times f_2\left(2\beta_0\tilde{\alpha}_s\log\frac{z_{min}R}{r}\right)\right),$$

$$P_g(r < z_{min}R) = P_g(r > z_{min}R; r = z_{min}R)\times\exp\left(-\left[\frac{1}{2}b_0 - c_g^>(z_{min})\right]\times f_2\left(2\beta_0\tilde{\alpha}_s\log\frac{z_{min}R}{r}\right)\right).$$

Tagged jet production in HIC

photon + jet

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

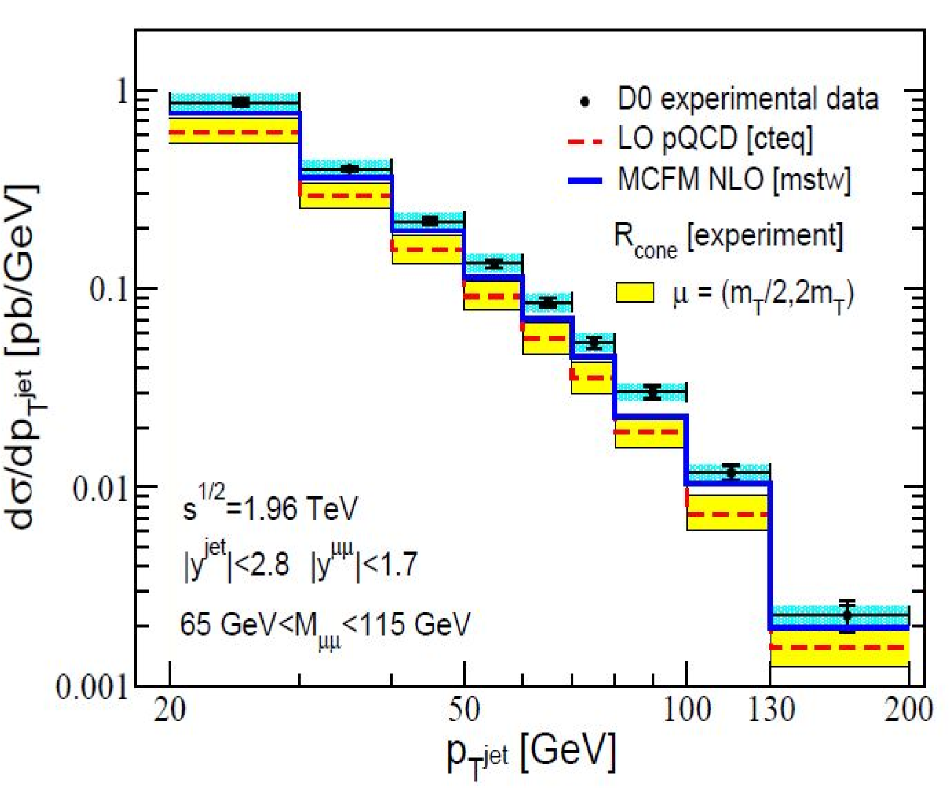
Z^0 + jet

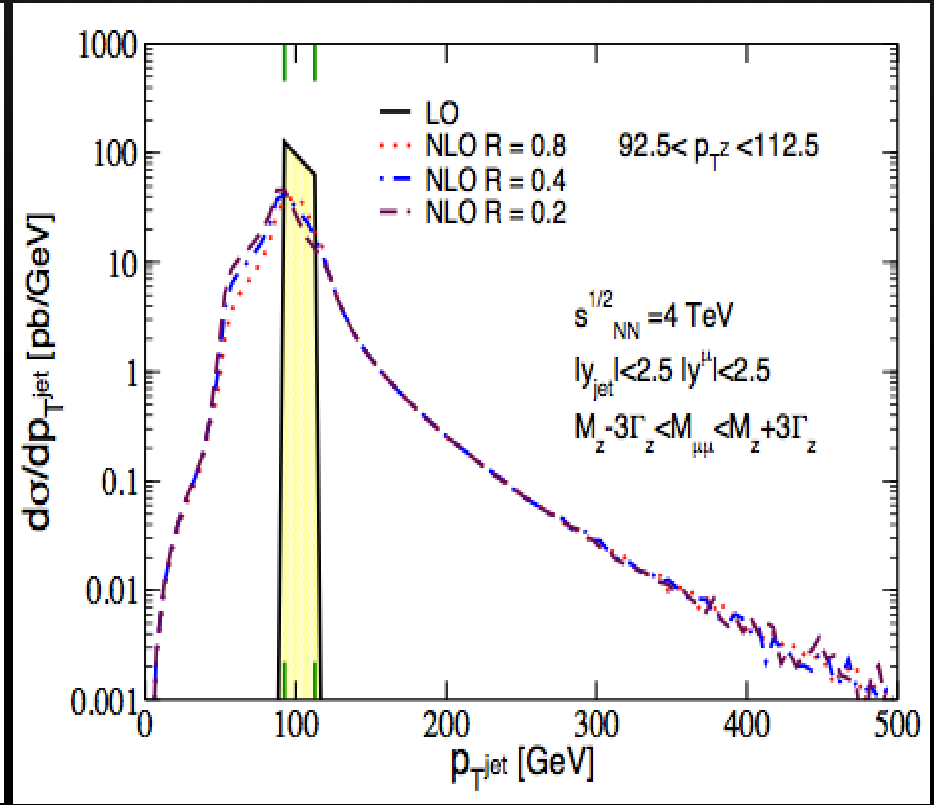
- Disadvantage: small cross section
- Advantage: no final-state effects

You are so light, I am too heavy.

Zº + jet in h+h

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

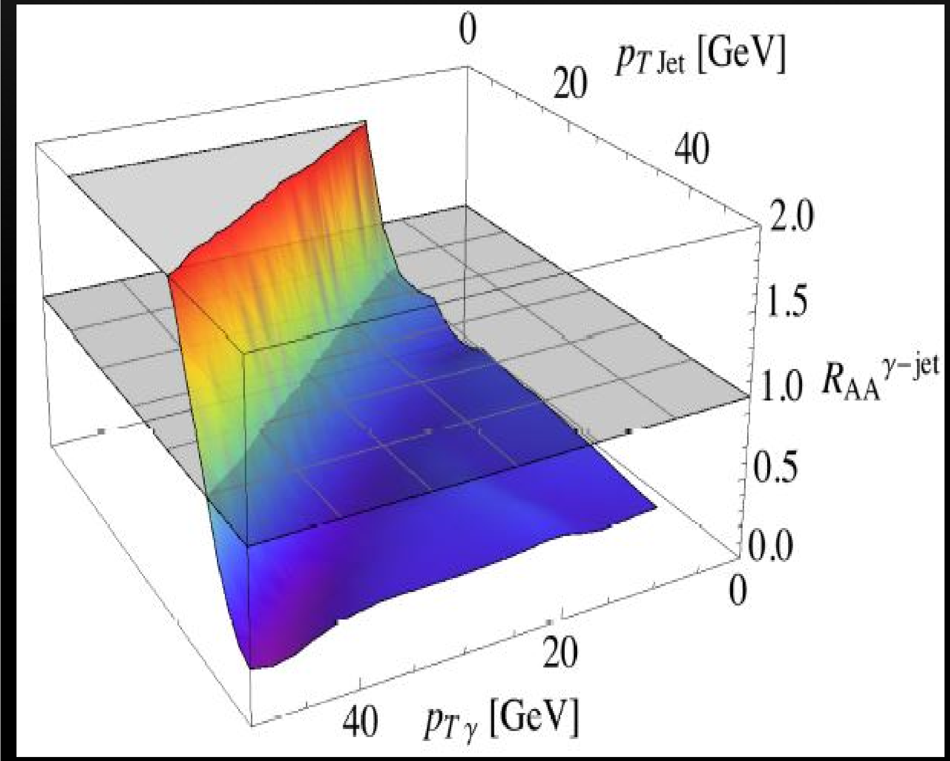


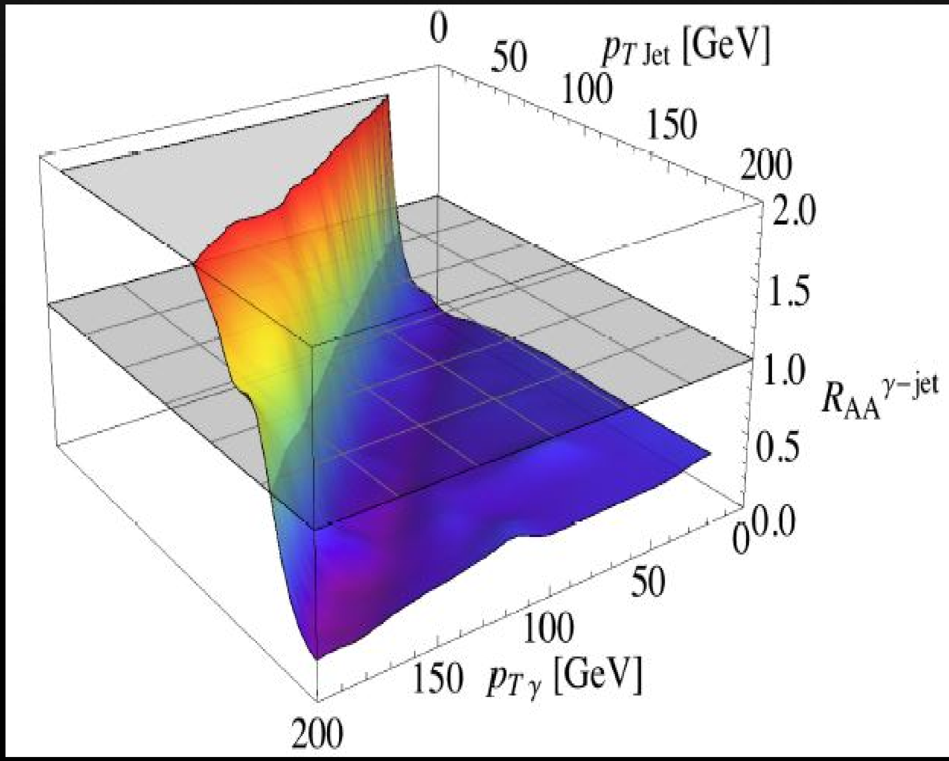


$p_T \in (92.5\text{GeV}, 112.5\text{GeV})$

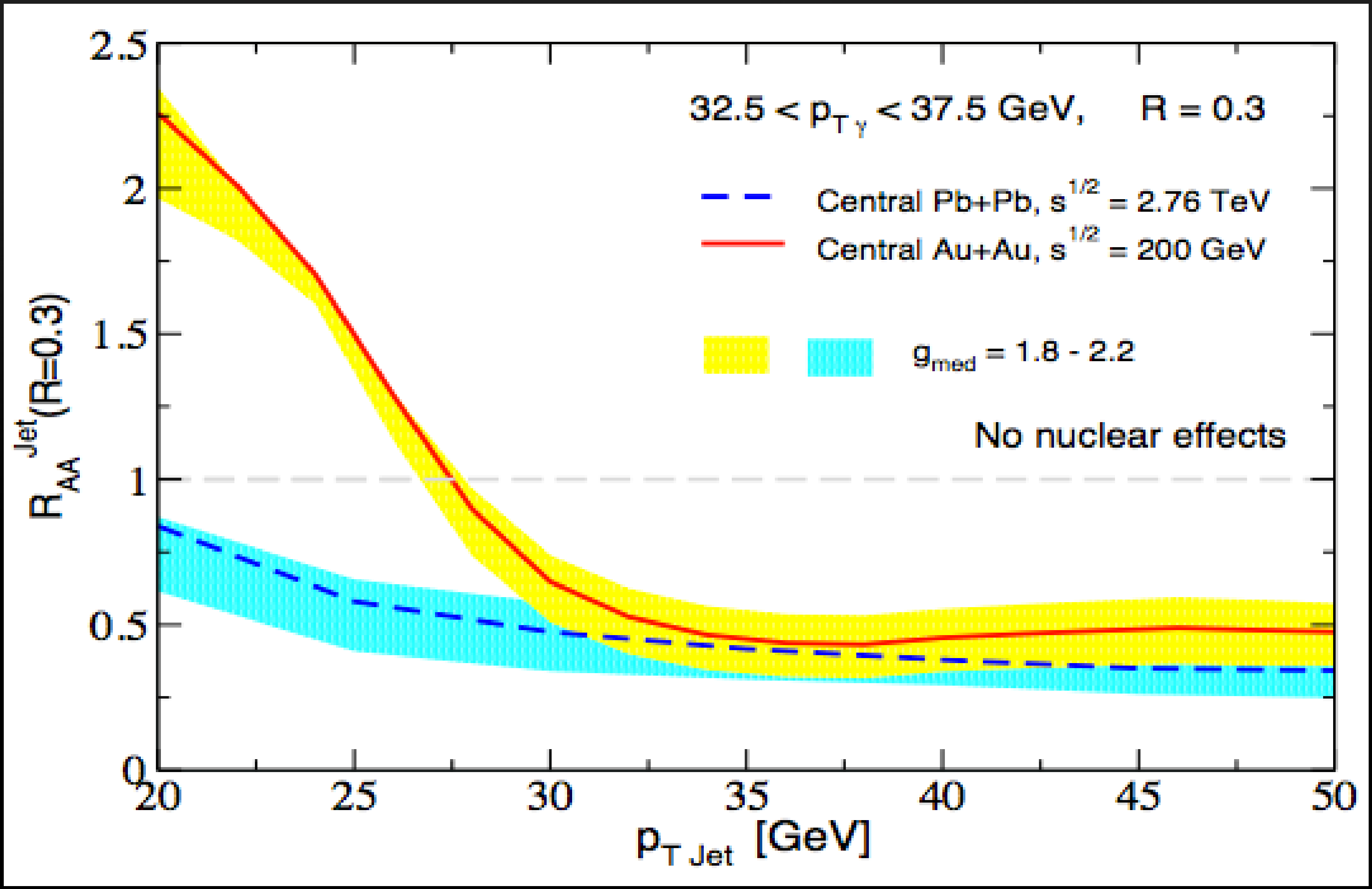
Photon + jet in A+A (II)

- Direct comparison between RHIC and LHC is possible for this exclusive channel.





photon + jet in A+A (I)

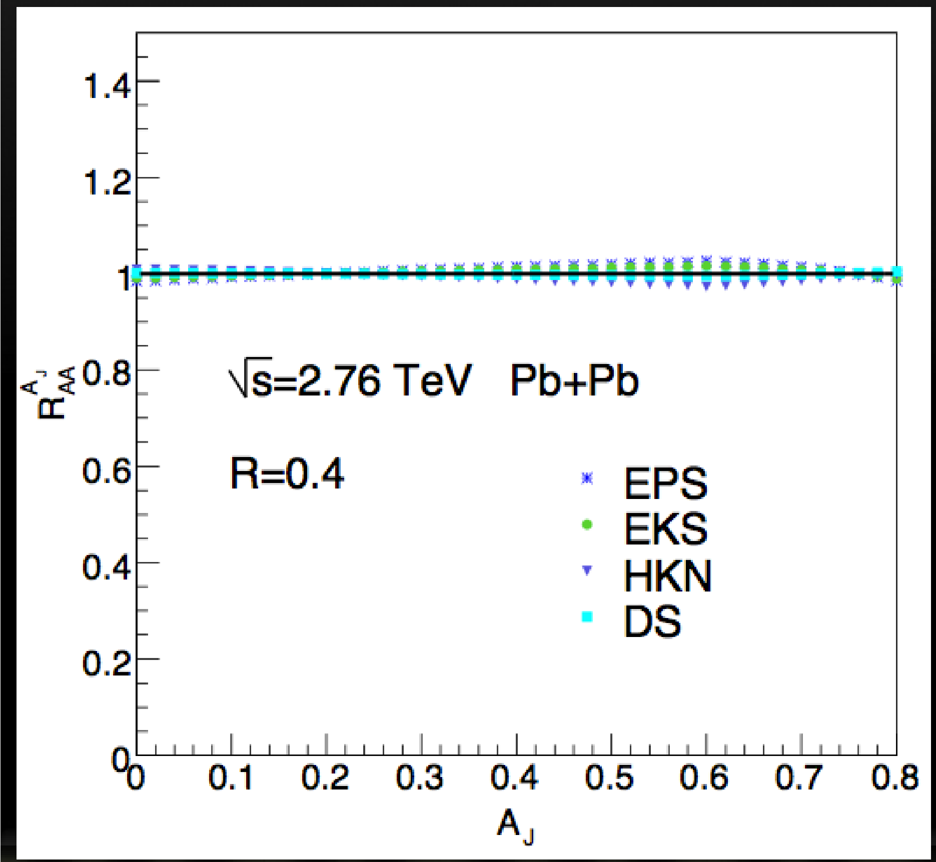


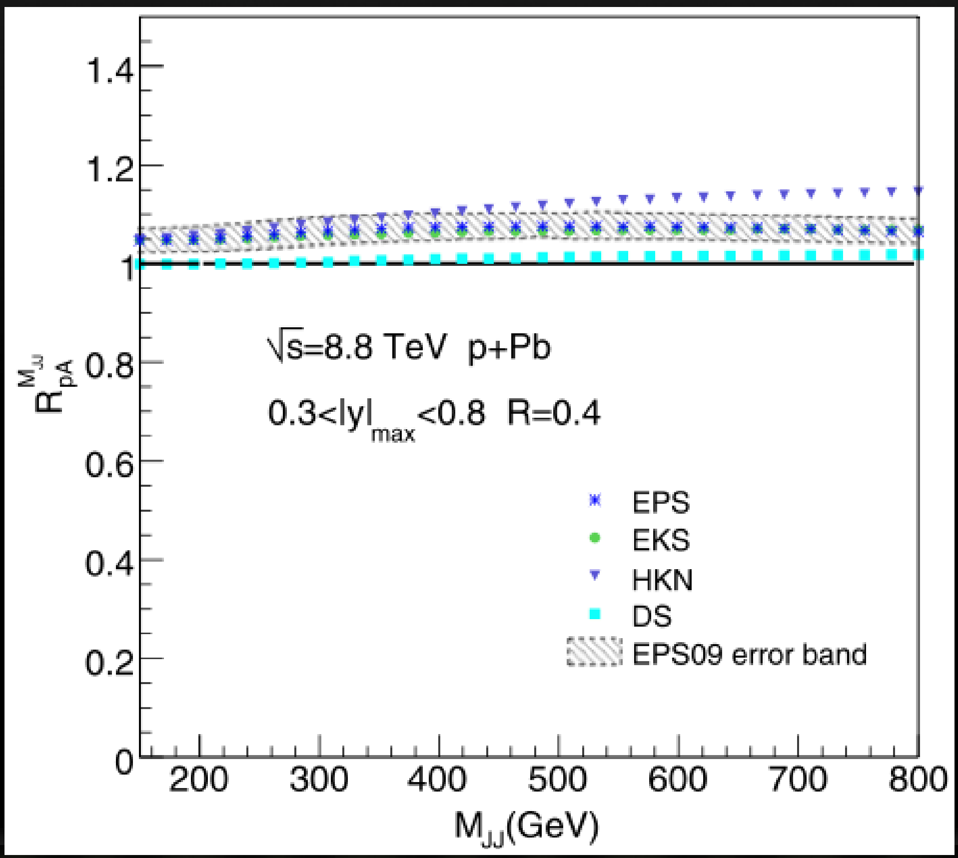
W Dai, Vitev, BWZ, PRL 110, 142001(2013)

Dijet in HIC: CNM

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

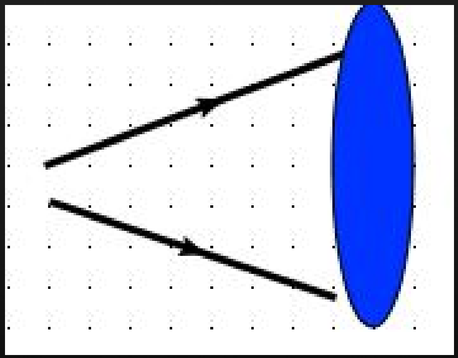
$$M_{jj}^2 = 2p_T^2[1 + cosh(y_1 - y_2)]$$

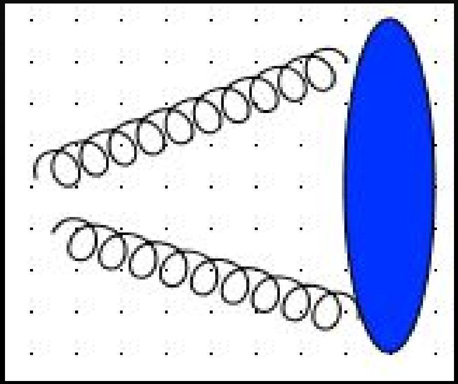


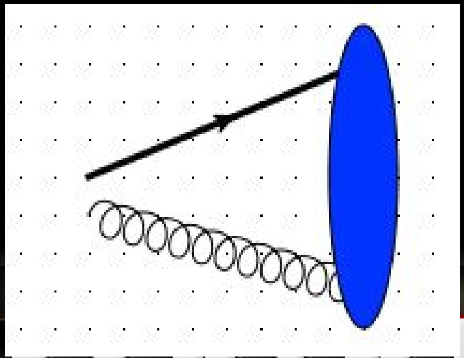


Y He, BWZ, E Wang, EPJC (2012)

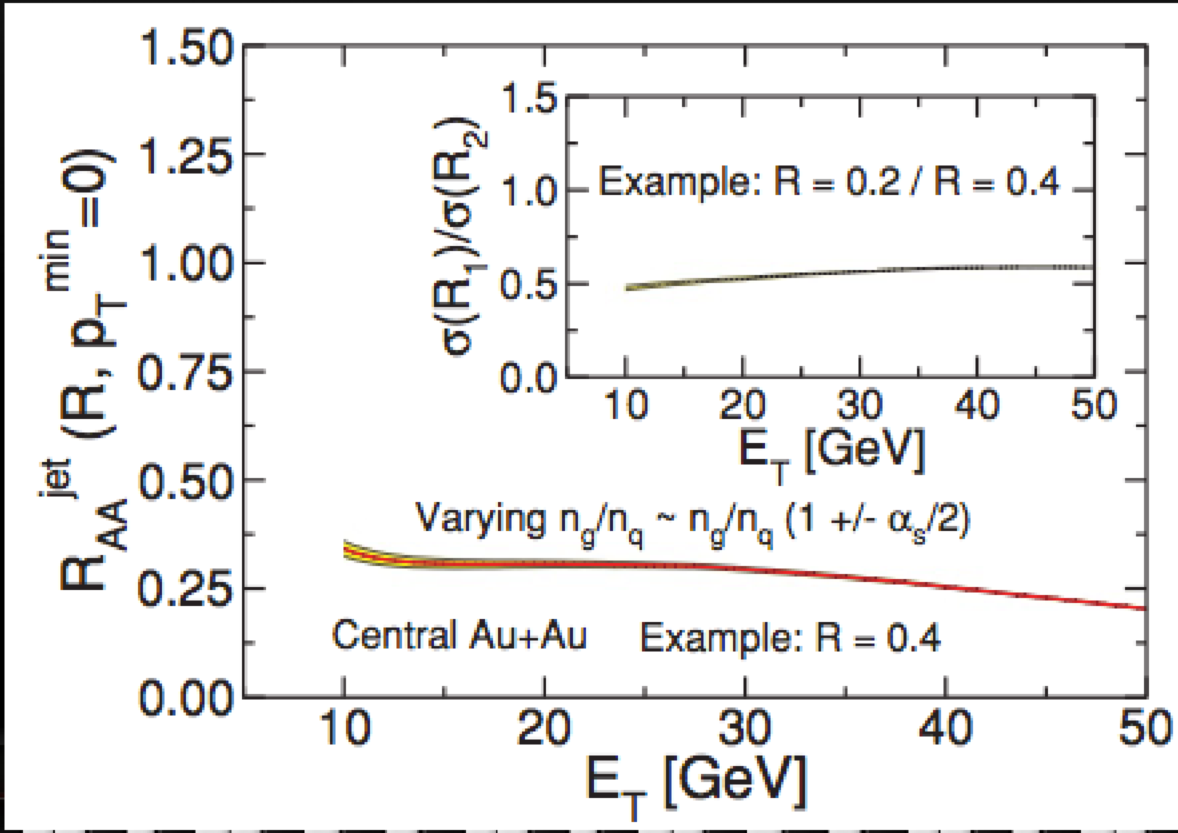
Quark jet and Gluon jet



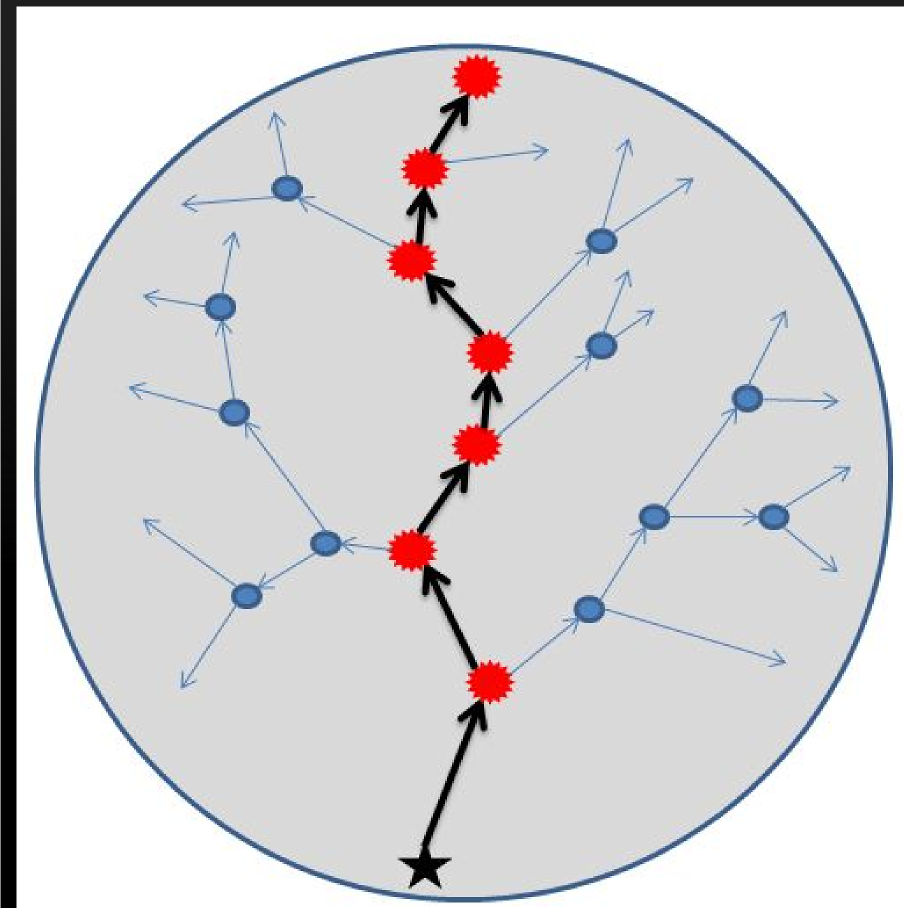


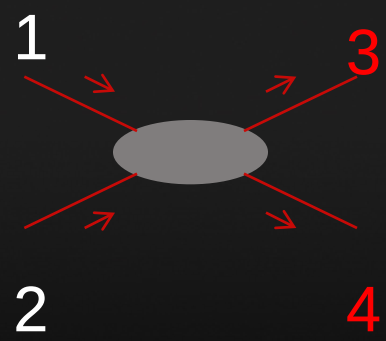


$$n_q = \frac{d\sigma^{q\ \mathrm{jet}}}{dp_T} \Big/ \frac{d\sigma^{\mathrm{jet}}}{dp_T}, \quad n_g = \frac{d\sigma^{g\ \mathrm{jet}}}{dp_T} \Big/ \frac{d\sigma^{\mathrm{jet}}}{dp_T}$$



LBT model of parton ELoss





leading parton---thermal parton scattering

recoiled parton---thermal parton scattering

Linearized Boltzmann jet transport

neglect scatterings between recoiled medium partons.

It’s a good approximation when the jet induced medium excitation δf<<f.