Parton transport in medium

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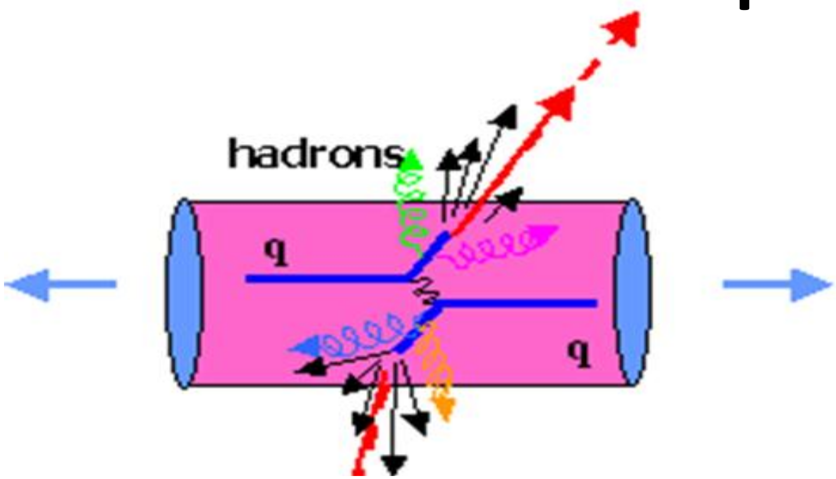
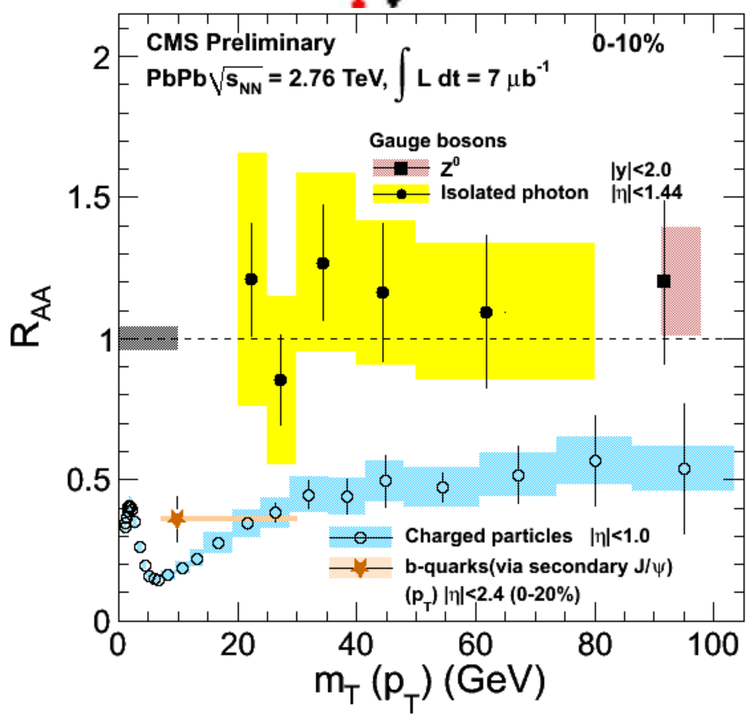
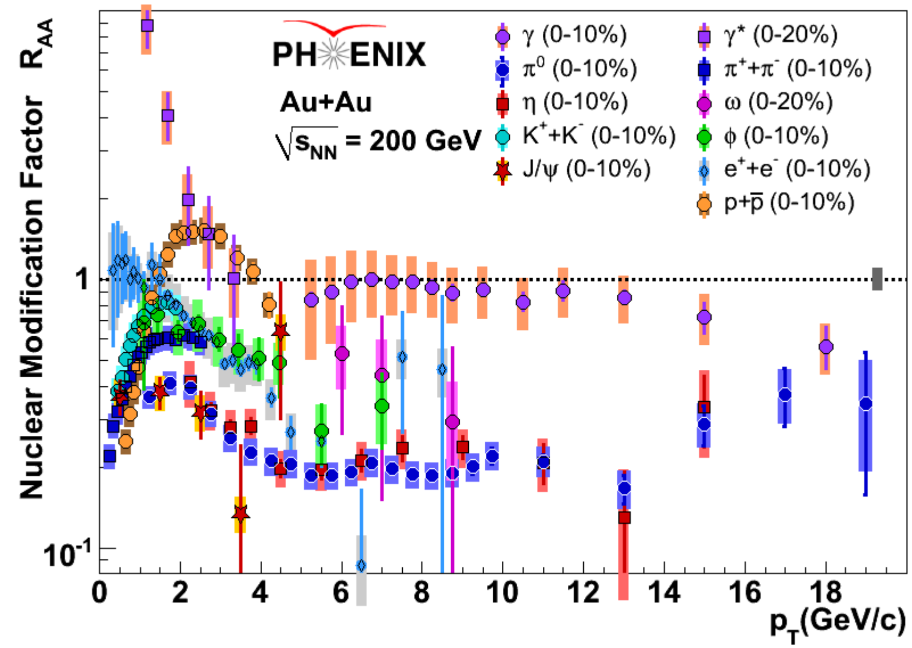
Jet quenching





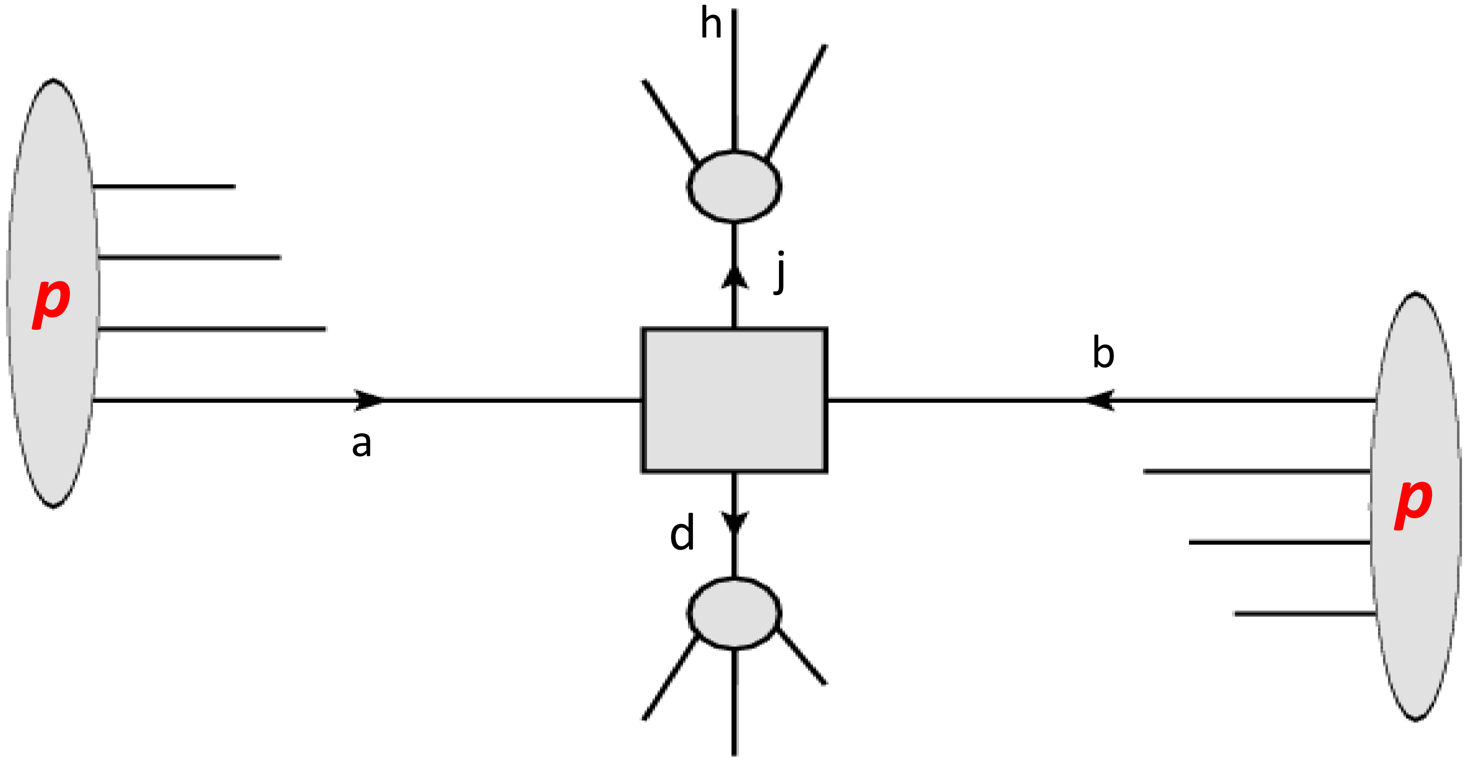


$$R_{AA} = \frac{1}{N_{coll}} \frac{dN_{AA}/dp_T dy}{dN_{pp}/dp_T dy}$$

Hadrons are suppressed in Au+Au

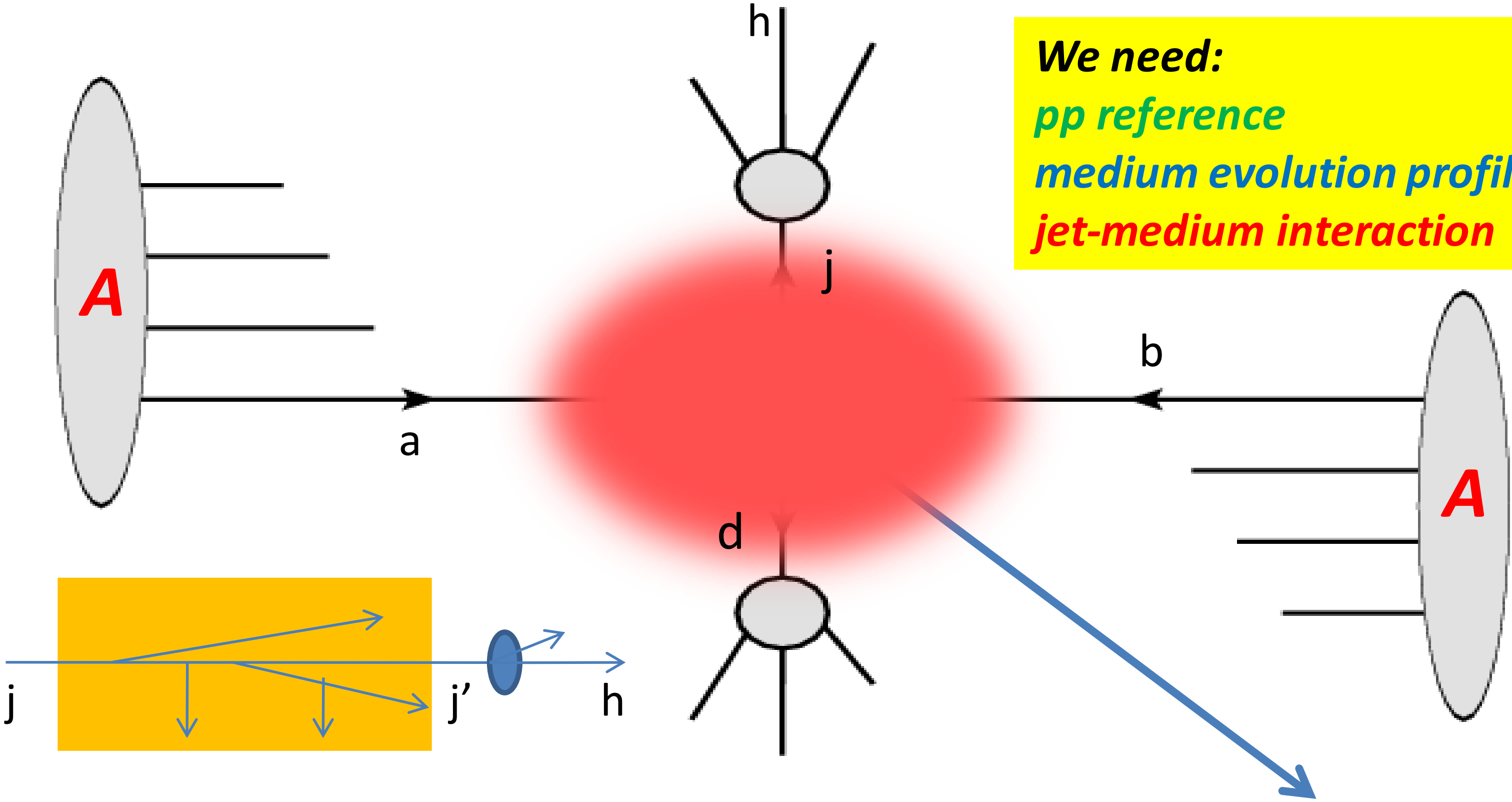
No suppression for photons and EW bosons

General idea of jet quenching calculation



$$d\sigma_h = f_a \otimes f_b \otimes d\sigma_{ab\to jd} \otimes D_{h/j}$$

General idea of jet quenching calculation



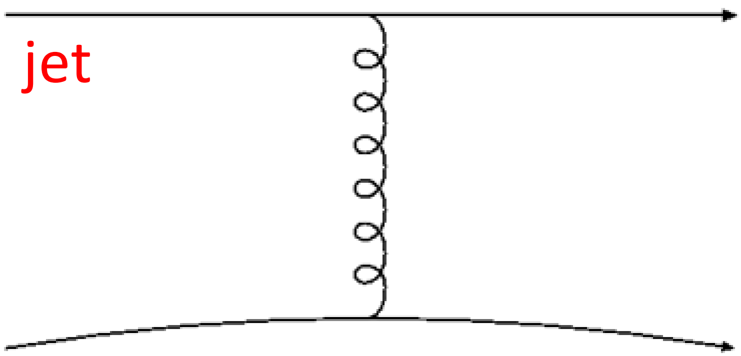
We need:
pp reference
medium evolution profile
jet-medium interaction

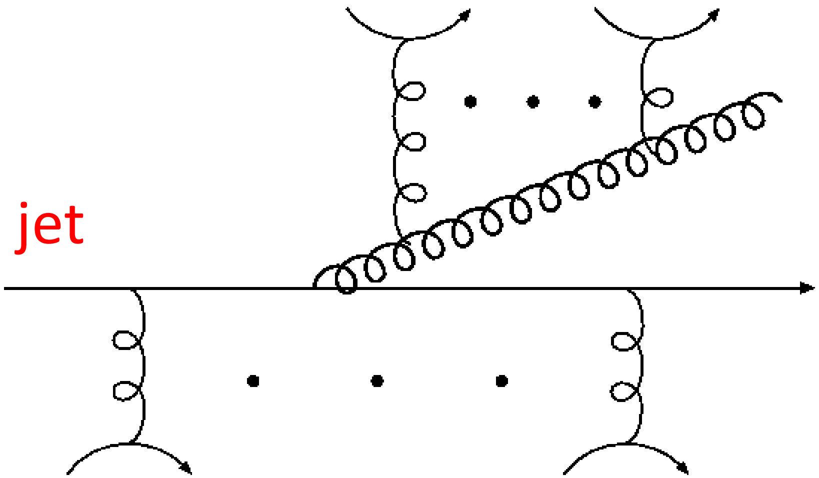
$$d\sigma_h = f_a \otimes f_b \otimes d\sigma_{ab\to jd} \otimes \tilde{D}_{h/j}$$

$$d\sigma_h = f_a \otimes f_b \otimes d\sigma_{ab\to jd} \otimes P_{j\to j'} \otimes D_{h/j'}$$

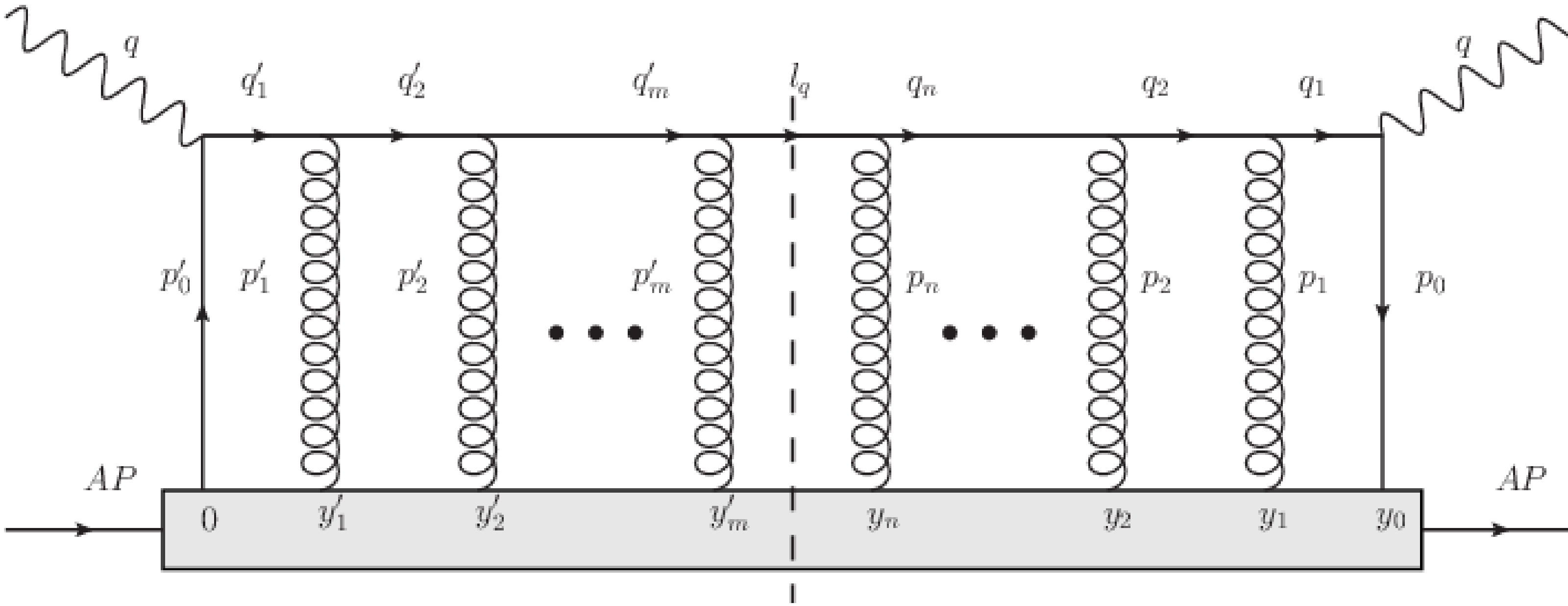
The central job for jet quenchers

$$P_{j\to j'}(\hat{q}, \hat{e}, T, \vec{u}, L, E, m, \ldots)$$





Transport coefficients



$$\frac{\partial \phi}{\partial L^-} = \left[D_{L1} \frac{\partial}{\partial l_q^-} + \frac{1}{2} D_{L2} \frac{\partial^2}{\partial^2 l_q^-} + \frac{1}{2} D_{T2} \nabla^2_{l_{q\perp}} \right] \phi(L^-, l_q^-, \vec{l}_{q\perp})$$

$$\hat{e} = \frac{dE}{dt} = D_{L1},\ \hat{e}_2 = \frac{d(\Delta E)^2}{dt} = \frac{D_{L2}}{\sqrt{2}},\ \hat{q} = \frac{d(\Delta p_T)^2}{dt} = 2\sqrt{2} D_{T2}$$

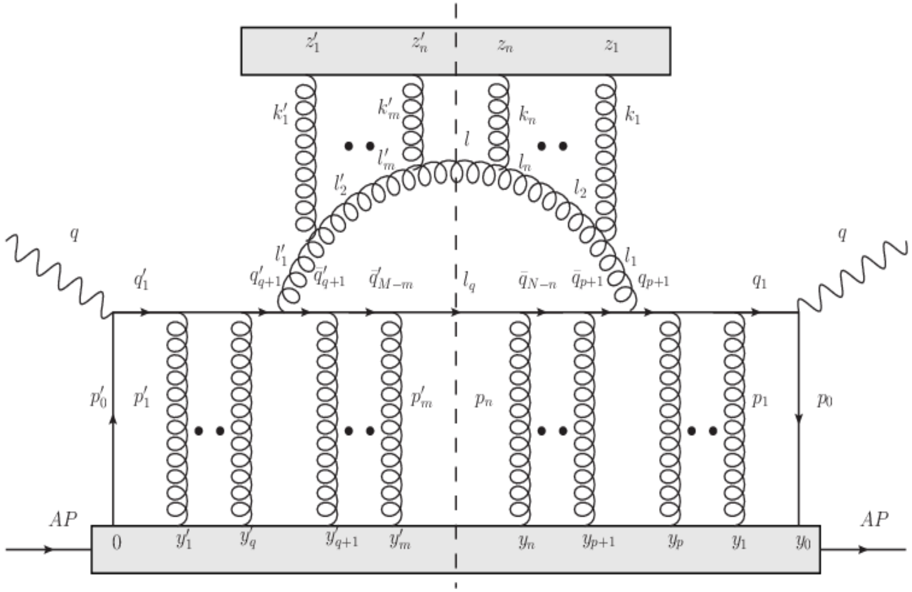
GYQ, Majumder, arXiv:1205.5741

q=(λ^2, 1, λ)Q, scattered gluons (λ^2, λ, λ)Q

Radiative energy loss

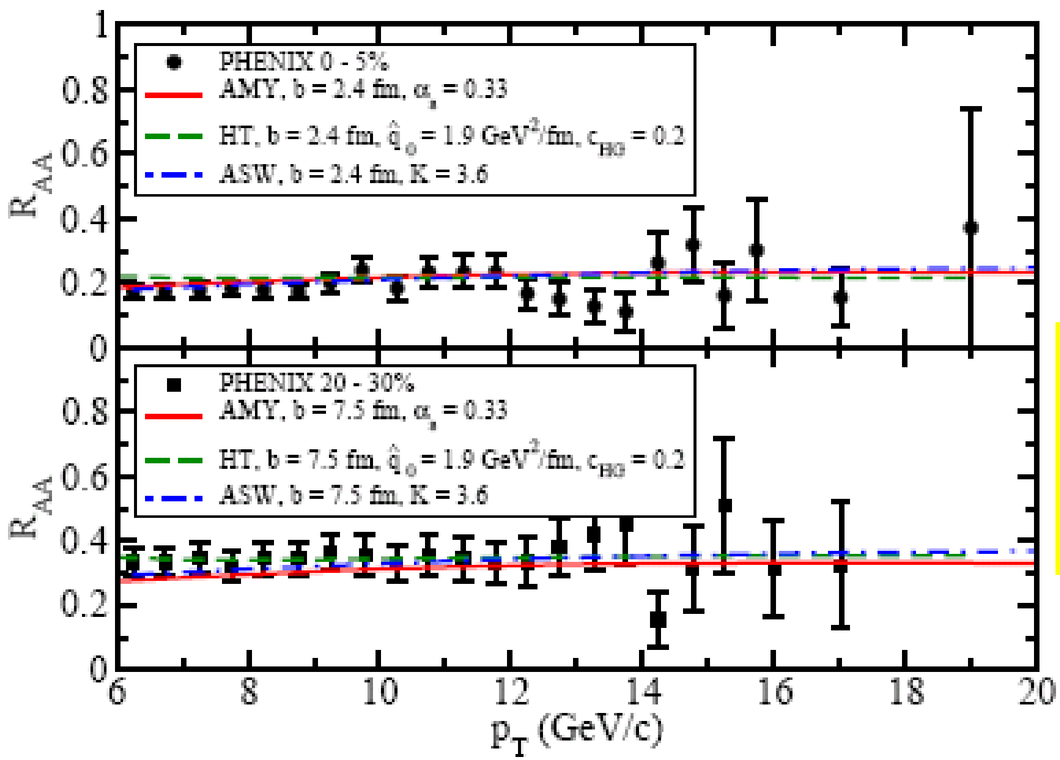
- ***Modeling the medium***
  - *Static scattering centers (BDMPS, Zakharov, GLV, ASW)*
  - *HTL perturbative plasma (AMY)*
  - *General nuclear medium, soft scattering assumed (Higher Twist)*
- ***Resummation schemes***
  - *Resume all possible numbers of soft interactions (BDMPS, AMY)*
  - *Path integral representation of parton transport(Zakharov, ASW)*
  - *Order by order in number of scatterings per emission (GLV)*
- ***Evolution scheme***
  - *Poisson independent emissions (BDMPS, GLV, ASW)*
  - *Transport rate equations (AMY)*
  - *Modified DGLAP (Higher Twist)*

BDMPS: Baier Dokshitzer Mueller Peigne Schiff;
ASW: Armesto Salgado Wiedemann;
AMY: Arnod Moore Yaffe;
GLV: Gyulassy Levai Vitev;
HT: Guo Wang Majumder



The longitudinal scattering may play a role in medium-induced radiation *(GYQ, Majumder, work in progress)*

Application to inclusive hadrons



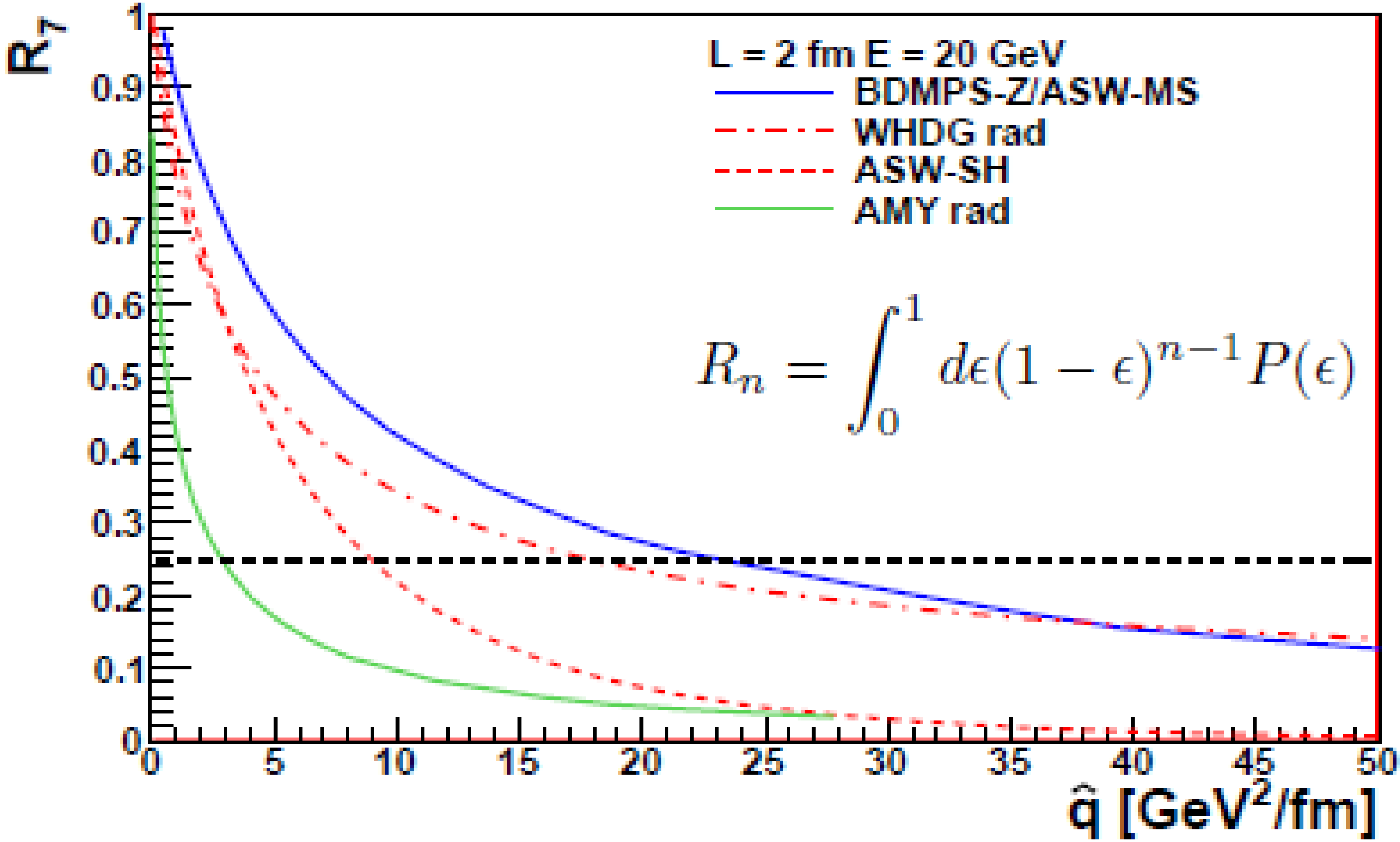
Bass, Gale, Majumder, Nonaka, GYQ, Renk, Ruppert, PRC, 2009

R_{AA} can be described well
But,
a factor of 5 difference in $\hat{q}$

$\hat{q}(\vec{r},\tau)$ scales as	ASW $\hat{q}_0$	HT $\hat{q}_0$	AMY $\hat{q}_0$
$T(\vec{r},\tau)$	10 GeV^2/fm	2.3 GeV^2/fm	4.1 GeV^2/fm
$\epsilon^{3/4}(\vec{r},\tau)$	18.5 GeV^2/fm	4.5 GeV^2/fm	
$s(\vec{r},\tau)$		4.3 GeV^2/fm	

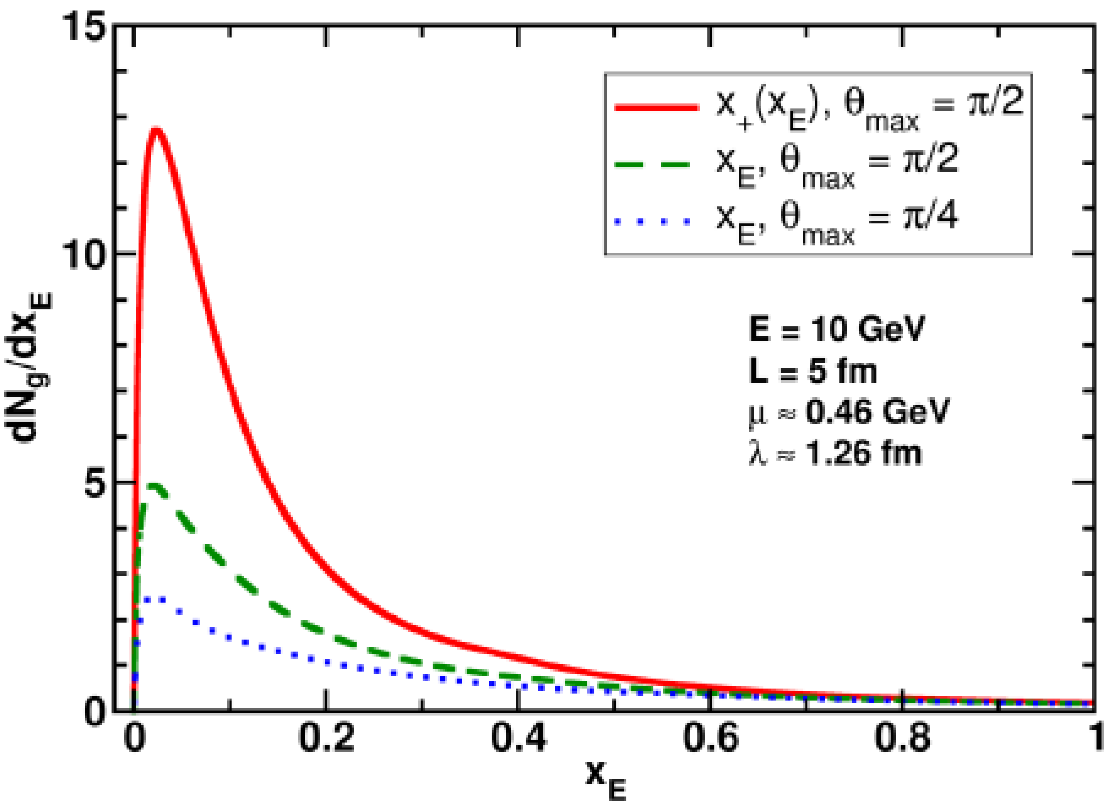
Comparison of Jet Quenching Formalisms for a Quark-Gluon Plasma "Brick"

Nestor Armesto,[1] Brian Cole,[2] Charles Gale,[3] Willam A. Horowitz,[4,5] Peter Jacobs,[6] Sangyong Jeon,[3] Marco van Leeuwen,[7] Abhijit Majumder,[4] Berndt Müller,[8] Guang-You Qin,[8] Carlos A. Salgado,[1] Björn Schenke,[3,9] Marta Verweij,[7] Xin-Nian Wang,[10,6] and Urs Achim Wiedemann[11]



arXiv: 1106:1106

Sensitivity to kinematic approximation



All formalisms invoke the collinear approximation (sensitivity to this approx. is model specific)

For WHDG, sensitivity to both the maximum angle of radiation and the choice of Feynman or Bjorken-x

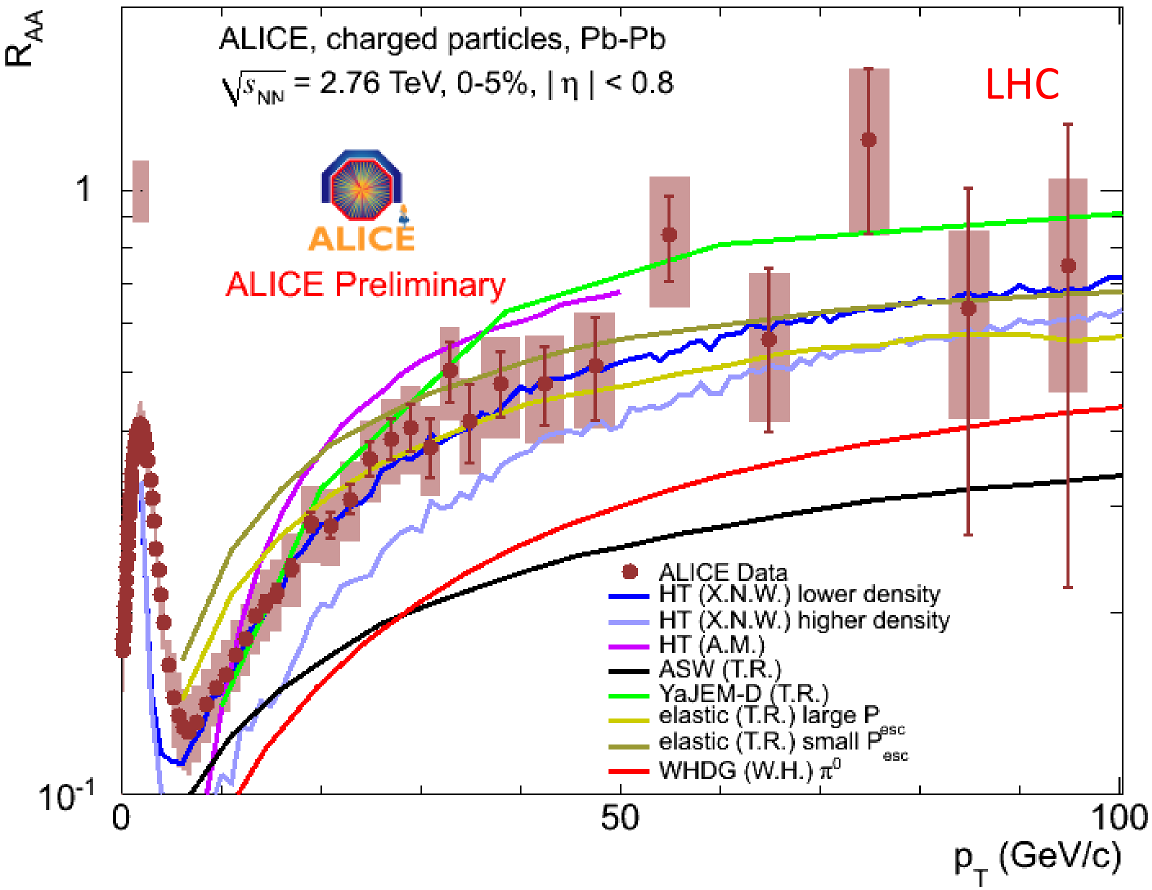
$$x_+ = \frac{1}{2} x_E \left(1 + \sqrt{1 - \left(\frac{k_T}{x_E E}\right)^2}\right)$$

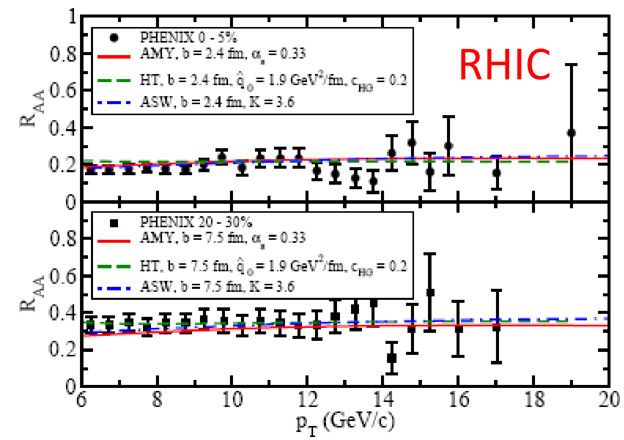
$$x_E = x_+ \left(1 + \left(\frac{k_T}{x_+ E^+}\right)^2\right),$$

arXiv: 1106:1106
Horowitz, Cole, PRC, 2009

Nee to include both soft collinear and hard large-angle medium-induced radiation and match between them (NLO)

LHC opens a new era





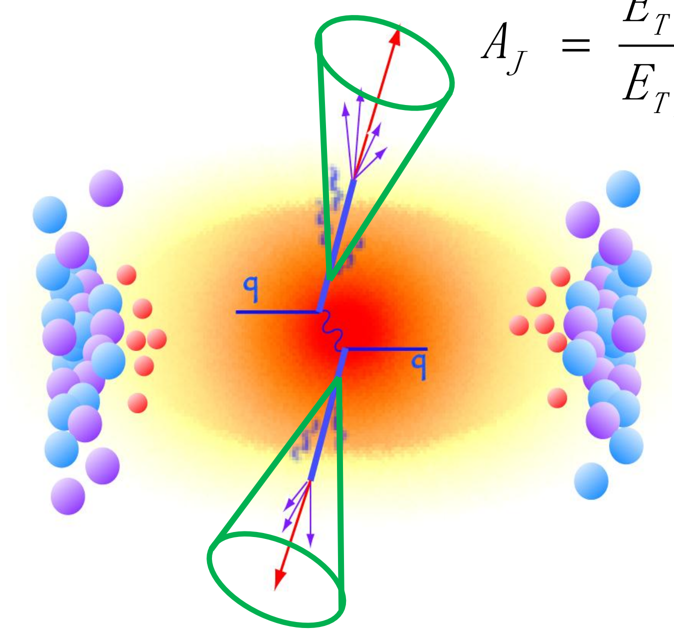
Horowitz and Gyulassy: NPA 2011
Renk, et. al. PRC 2011
Majumder and Shen: arXiv:1103.0809
Chen et. al. PRC 2011

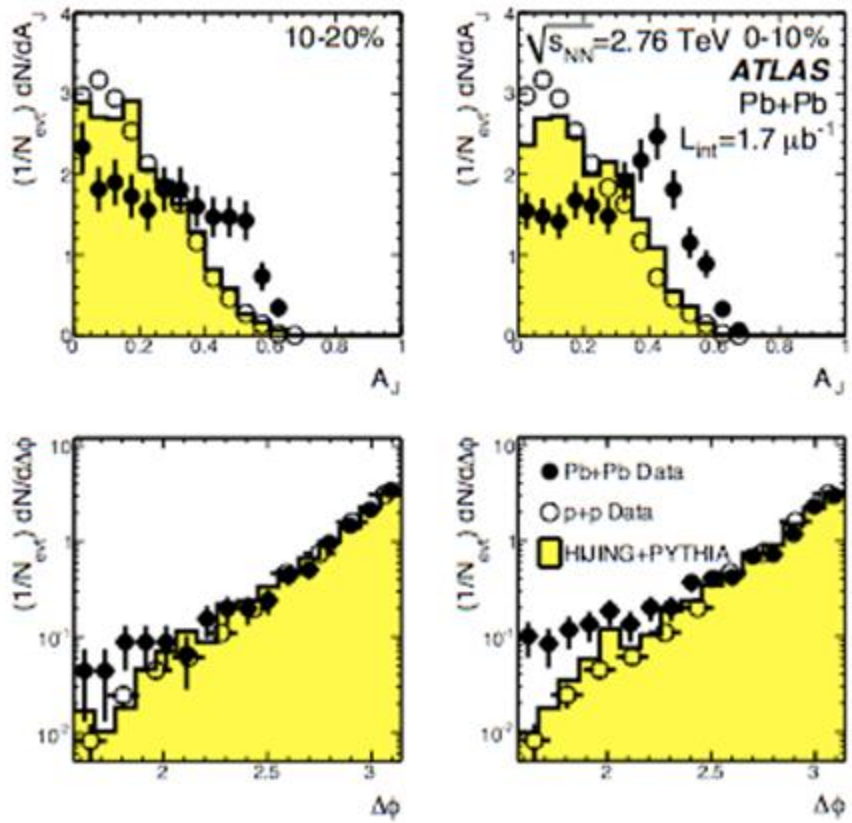
Models correctly reproduce the rising and saturation of R_{AA}. Refinements on model are ongoing: running coupling, finite size effect, virtuality …

New development: full jets

- *To capture both leading and sub-leading fragments, providing more discriminating power*
- *Require running jet finders*
- *Need reliable tools to disentangle jets from background*

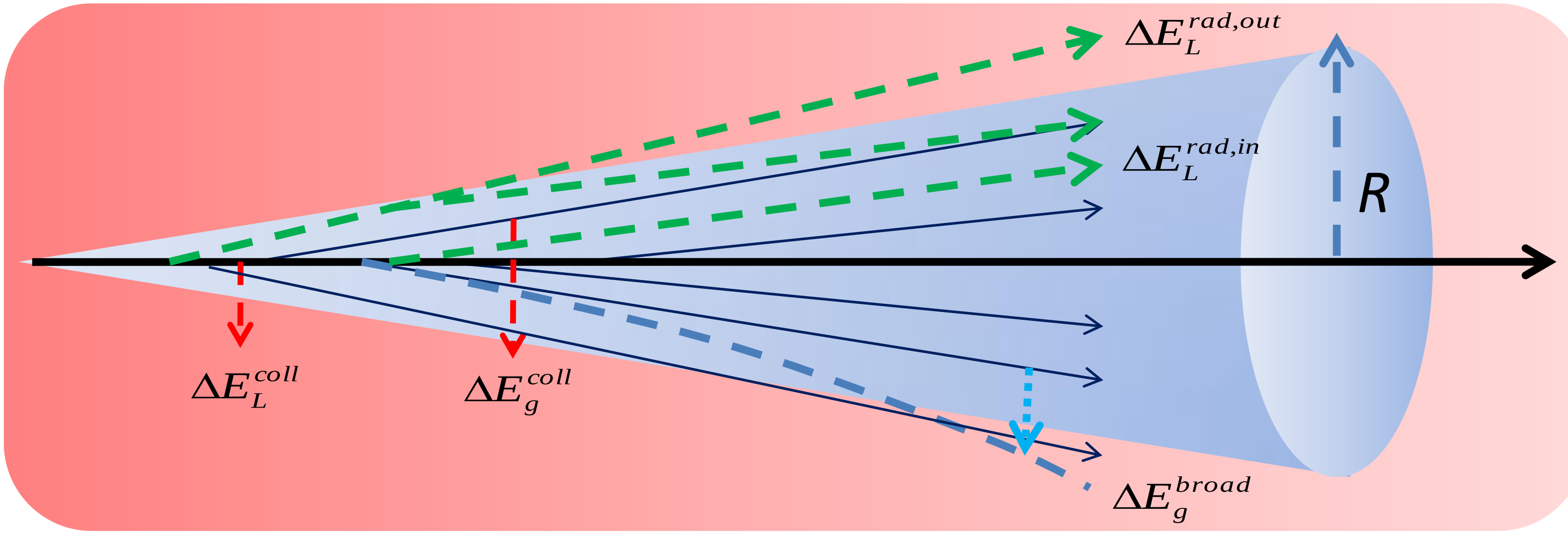
$$A_J = \frac{E_{T,1} - E_{T,2}}{E_{T,1} + E_{T,2}}$$





Strong energy imbalance but angular distribution largely unchanged

Jet shower evolution in medium



Leading parton:

Transfers energy to medium by elastic collisions

Medium-induced gluon radiation (inside and outside jet cone)

Radiated gluons (vacuum & medium-induced):

Transfer energy to medium by elastic collisions

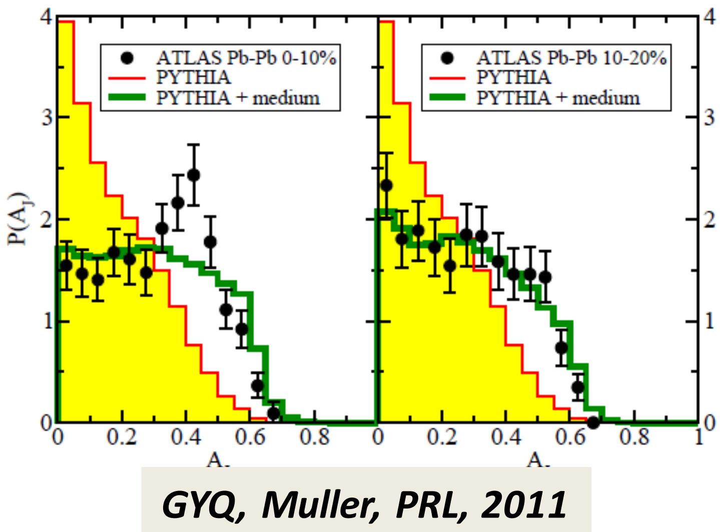
Be kicked out of the jet cone by multiple scatterings after emission

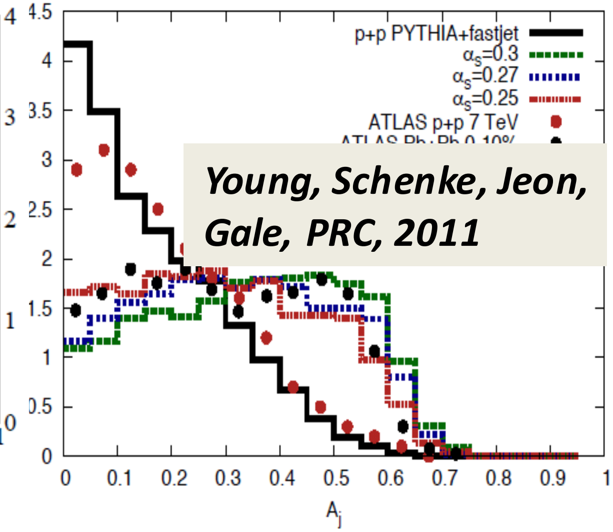
$$E_L(t) = E_L(t_i) - \int \hat{e}_L dt - \int \omega d\omega dk_\perp^2 dt \frac{dN_g^{med}}{d\omega dk_\perp^2 dt}$$

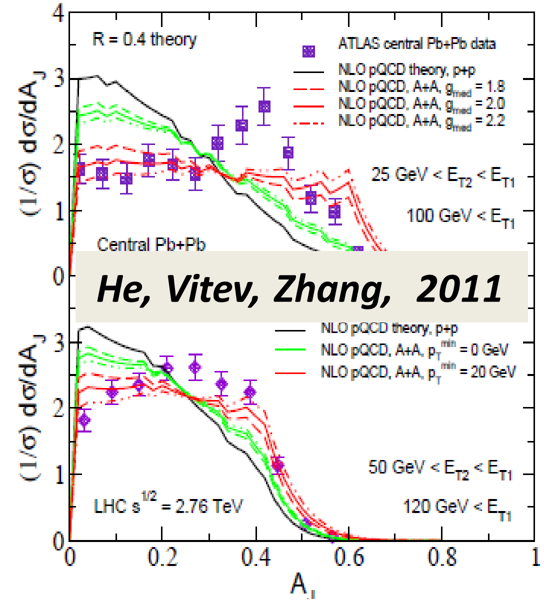
$$\frac{df_g(\omega, k_\perp^2, t)}{dt} = \hat{e}\frac{\partial f_g}{\partial \omega} + \frac{1}{4}\hat{q}\nabla_{k_\perp}^2 f_g + \frac{dN_g^{med}}{d\omega dk_\perp^2 dt}$$

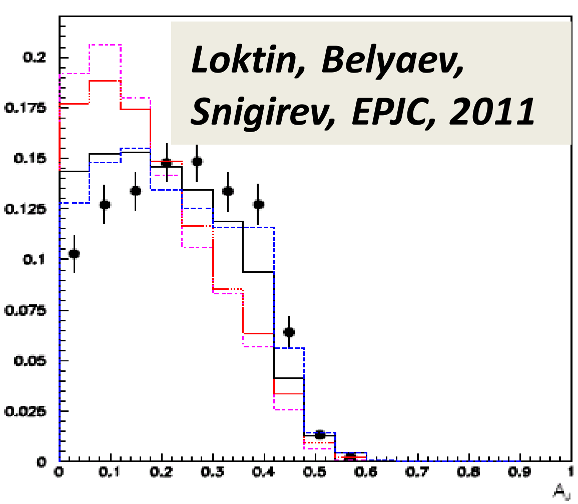
GYQ, Muller, PRL, 2011

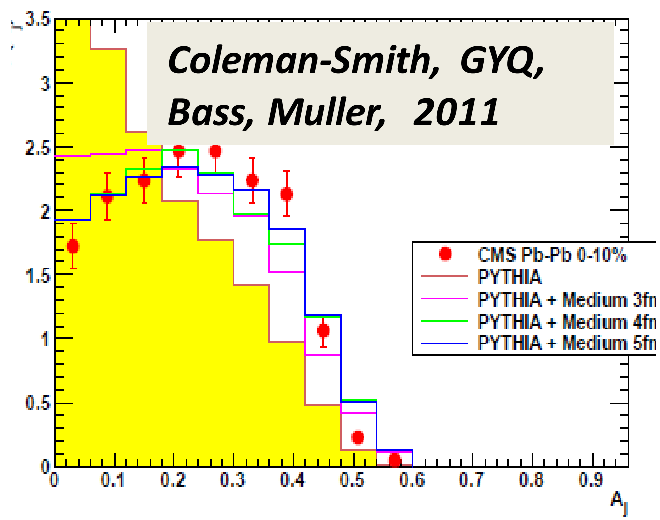
Theory postdictions for dijet asymmetry

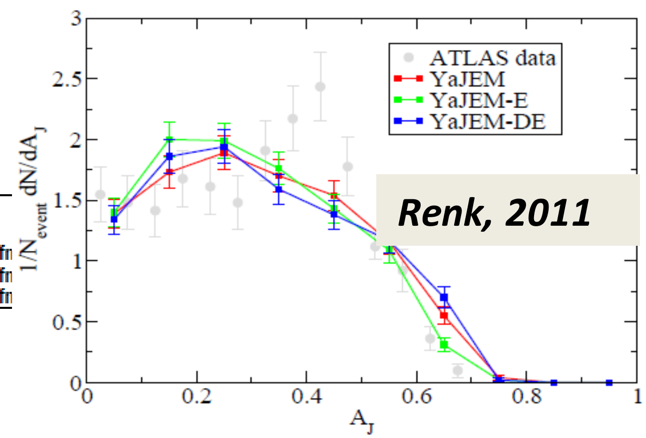








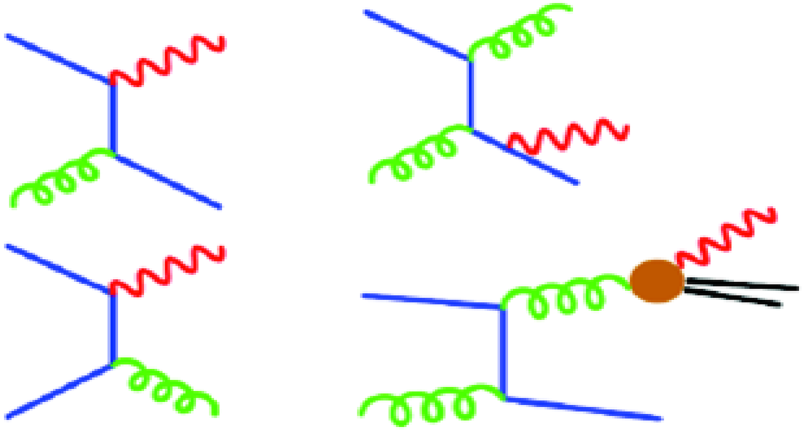


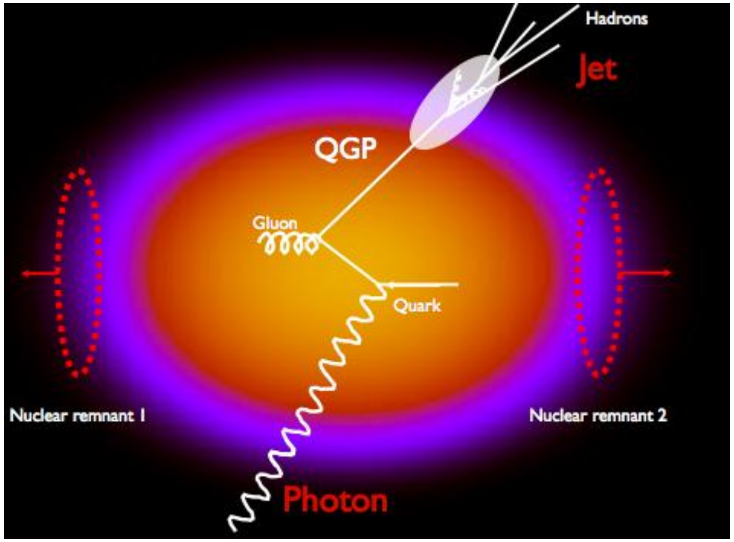


Photons and electroweak probes

- ***Mainly produced from initial hard collisions***
- ***No final state interaction once produced***
- ***Baseline for jet quenching***

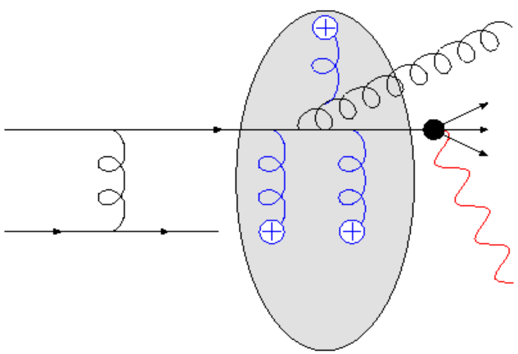
- ***Photon-tagged jets:***
  - *Provide better control of the initial jet information (p_T, direction)*
  - *Remove a lot of bias (deep-falling spectrum, surface emission)*
  - *"Golden" channel for studying jet-medium interaction*
  - *Potential for tomographic tool for studying QGP*



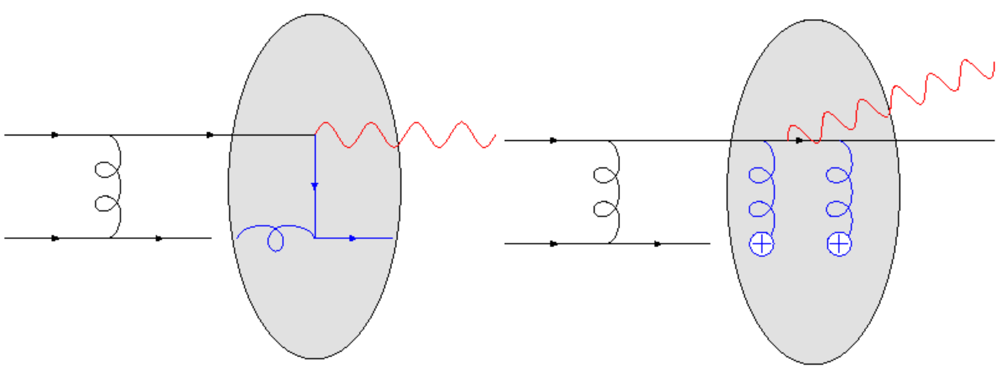


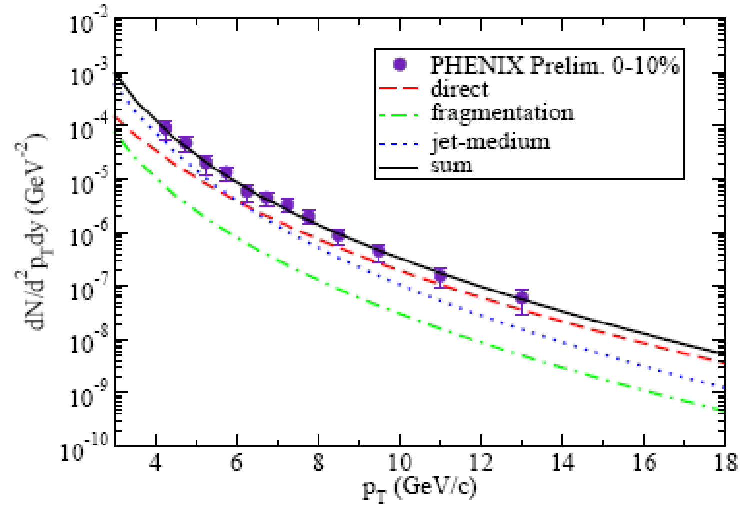
Photon production

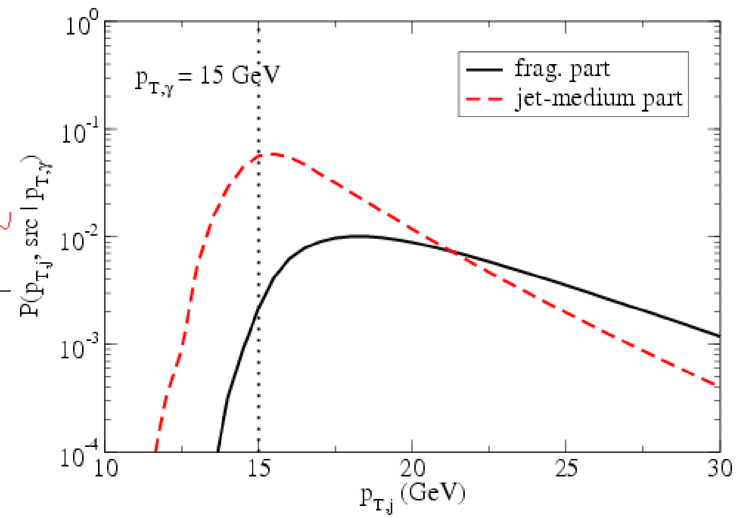
- ***Sizable contribution from jet-medium photons at intermediate p_T***
- ***Different photon-trigged jets have different distribution and shapes***



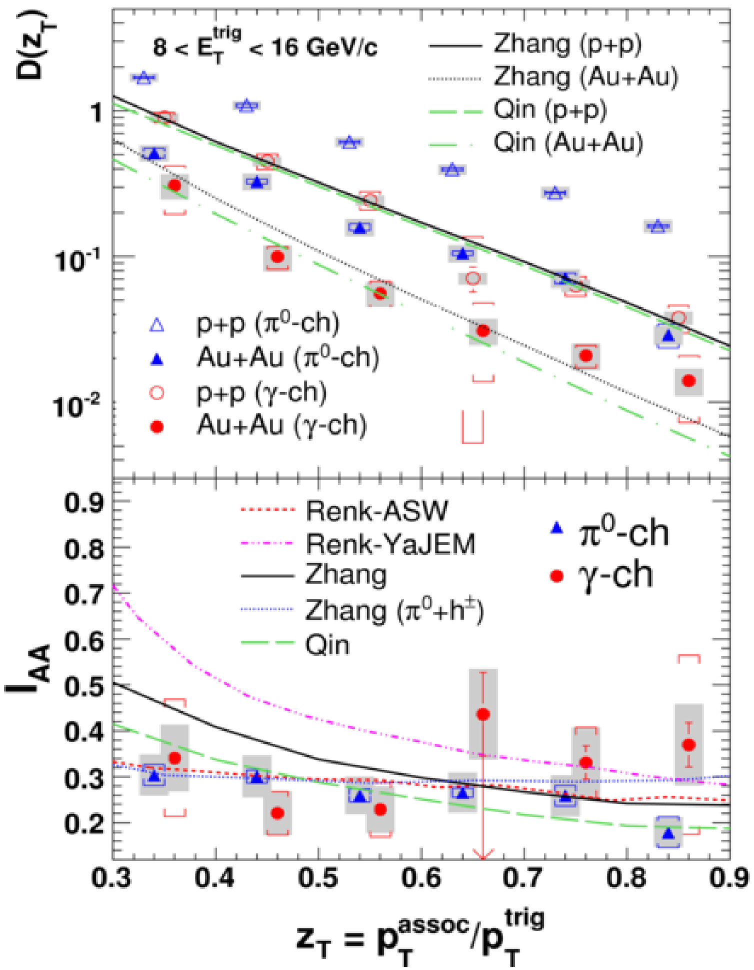
GYQ, Ruppert, Gale, Jeon, Moore, PRC, EPJC, 2009



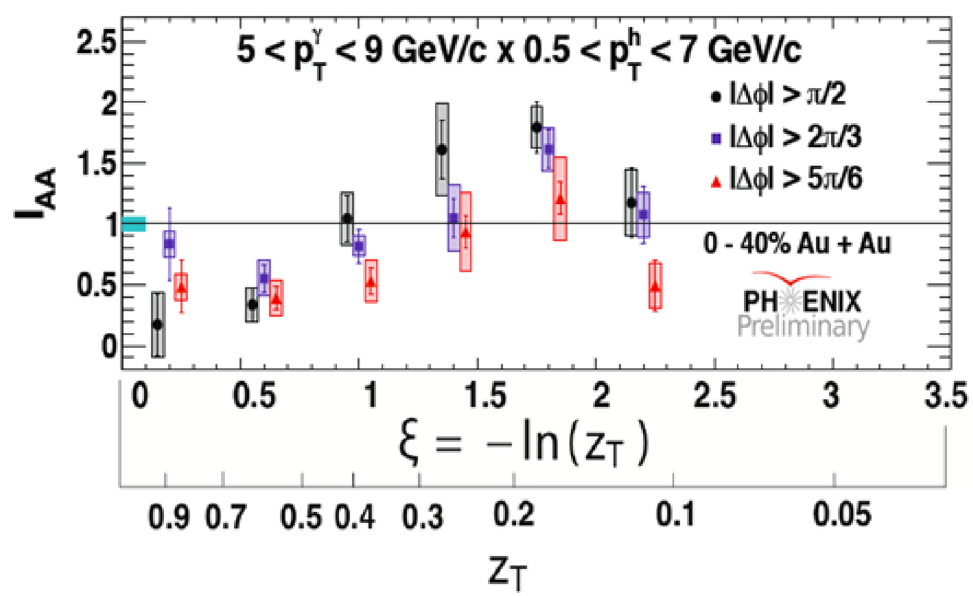




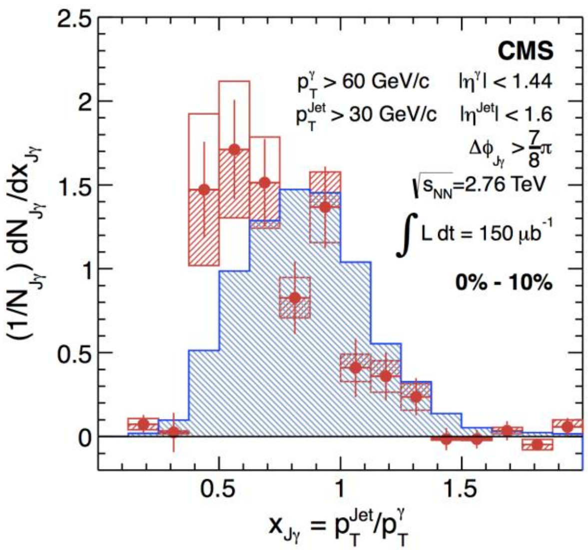
Photon-hadron correlations

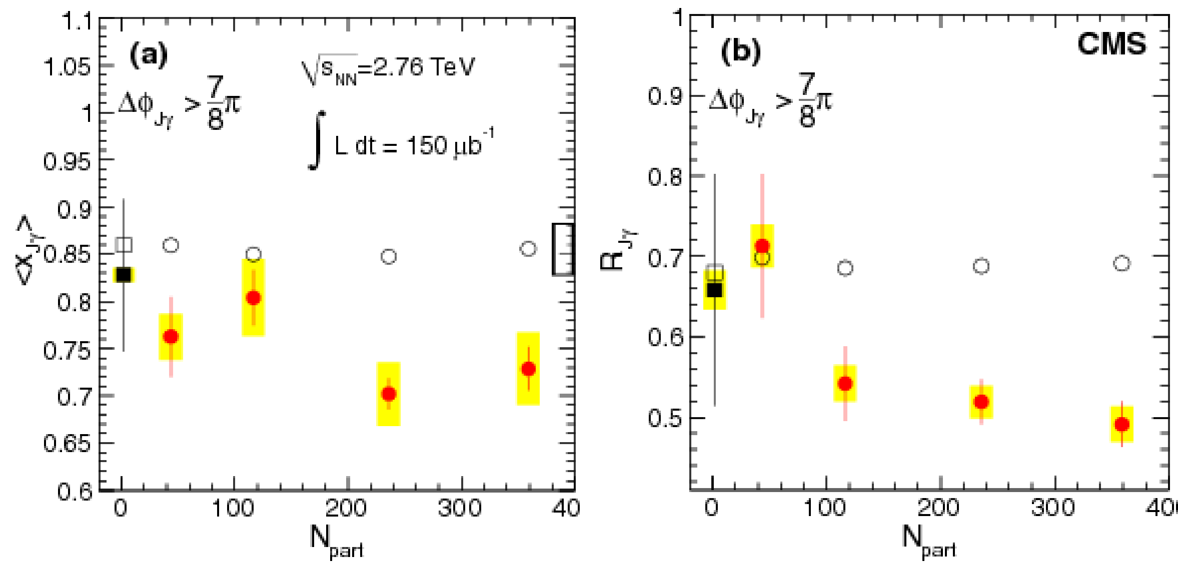


- *Photon-triggered FF is an approx. of medium-modified FF*
- *Suppression at high z_T and enhancement at low z_T*
- *Consistent with the picture of jet energy loss and redistribution of lost energy from jet*



γ-full jet correlations

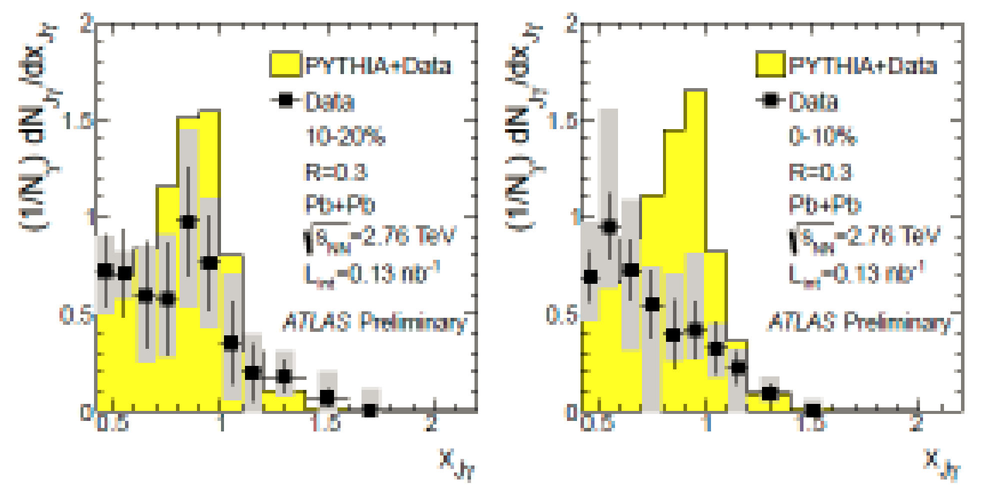




The distribution shift towards smaller x_J

More quenching towards central collisions

Missing pair probability (the integral is smaller for ATLAS)

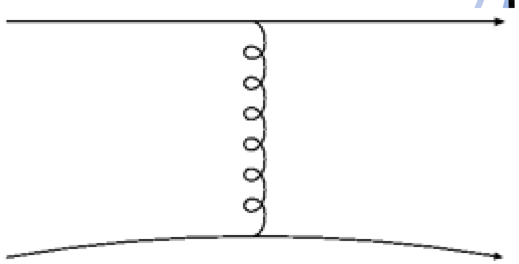


In-medium jet transport

Generate pp events from PYTHIA

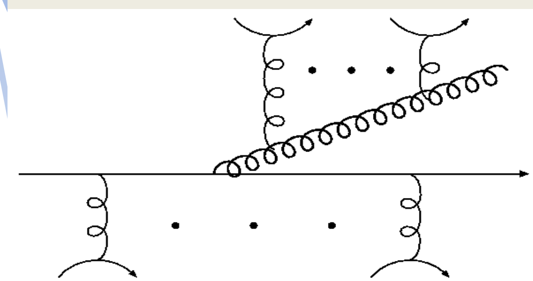
MC simulation of in-medium jet transport

Collisional/elastic energy loss



Drag $\hat{e}$ and diffusion $\hat{e}_2$, $\hat{q}$

Radiative energy loss



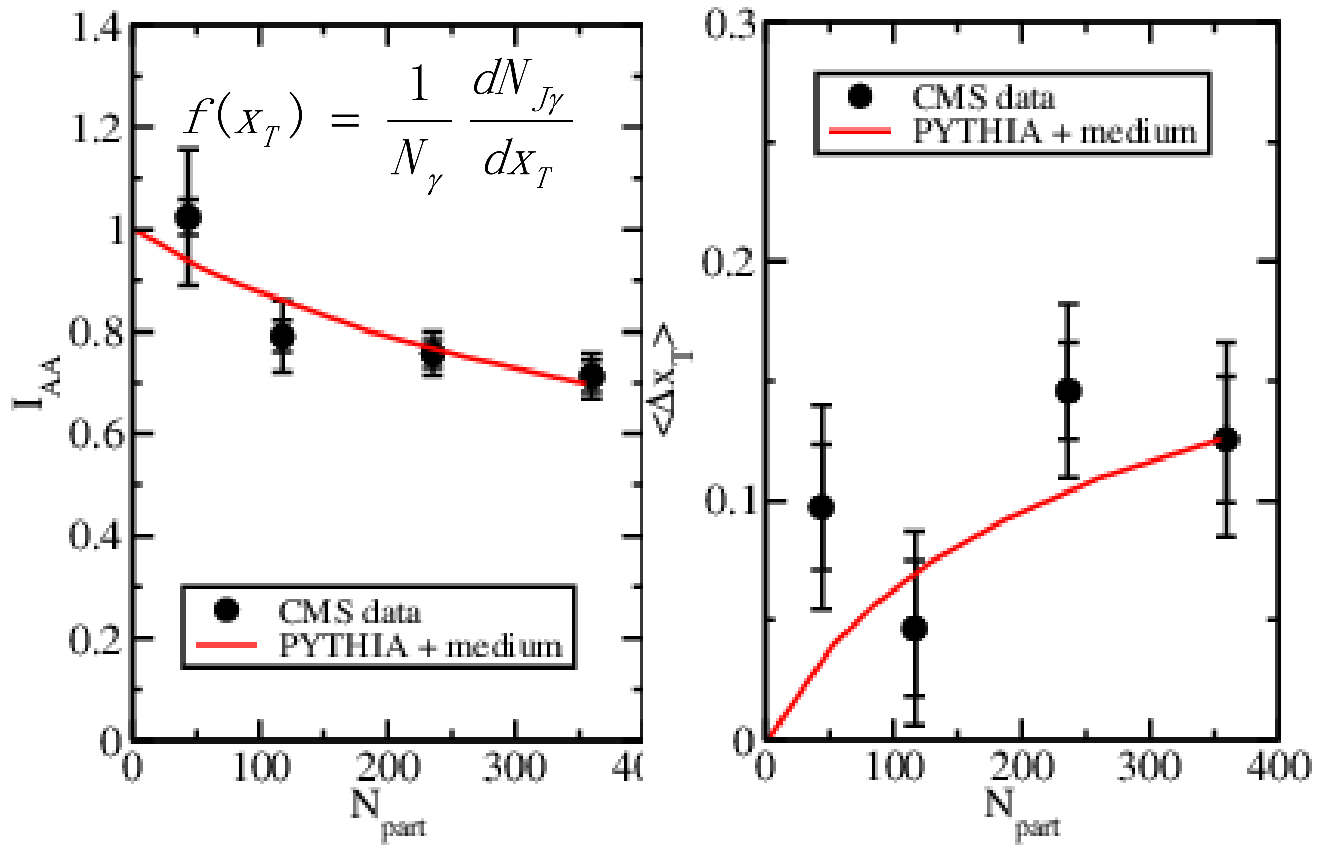
$$\frac{dN_g}{d\omega dk_\perp^2 dt} = \frac{2\alpha_s x P(x) \hat{q}(t)}{\pi \omega k_\perp^4} \sin^2\left(\frac{t - t_i}{2t_{form}}\right)$$

Higher Twist

Reconstruct jets using FASTJET(anti-kt algorithm)

Medium modification of γ-jet

- **Fit one data point I_{AA} = 0.7 in 0-10% PbPb collisions**
- **Larger medium modification on tagged jets for more central collisions (smaller yield & large energy loss)**

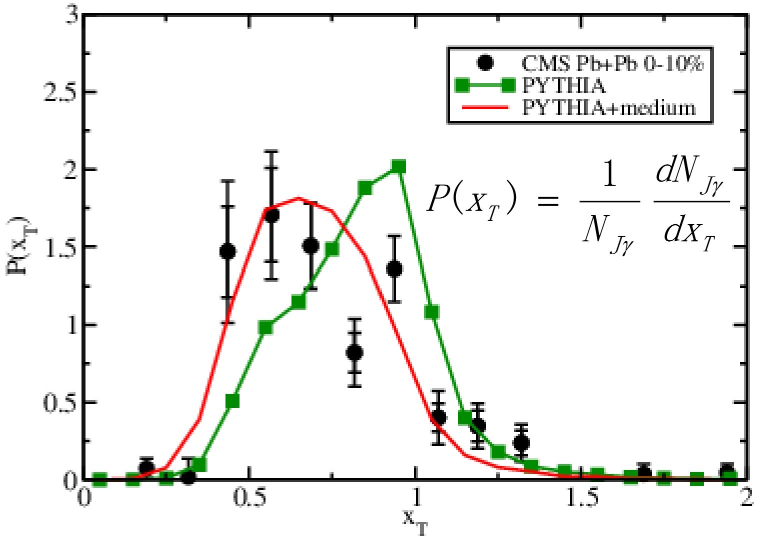


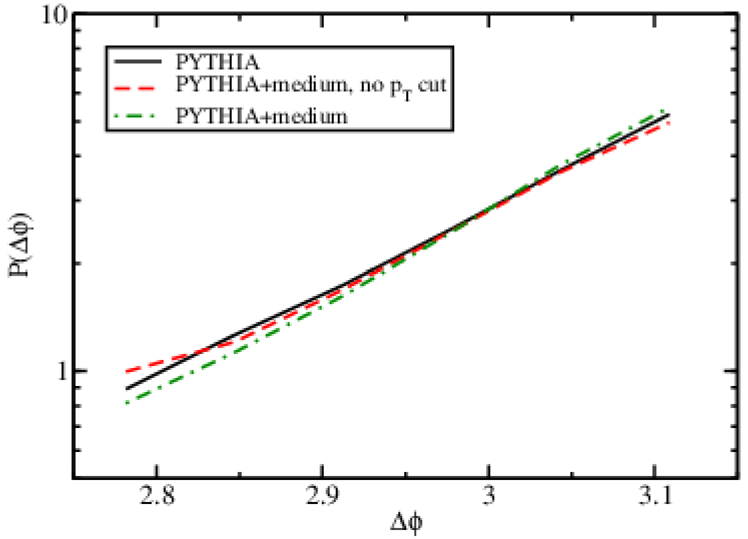
$$I_{AA} = f_{AA}(x_T) / f_{pp}(x_T) \quad \langle \Delta x_T \rangle = \langle x_T \rangle_{pp} - \langle x_T \rangle_{AA}$$

$$\hat{q} \approx 2\hat{e}_2 \approx 4T\hat{e} \propto T^3$$

Energy imbalance & angular separation

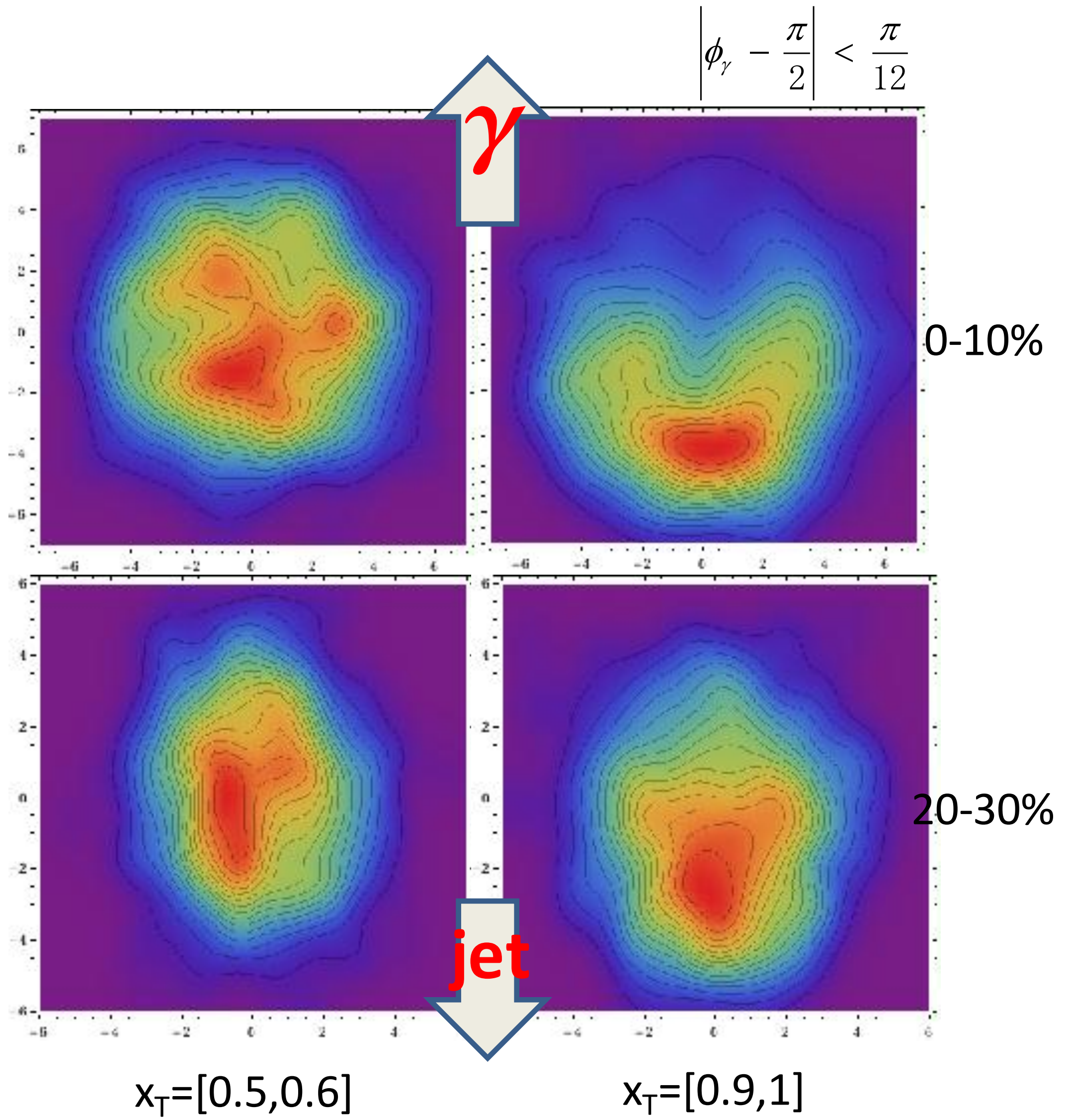
- *The effect of medium modification is to shift $P(x_T)$ to the left (smaller x_T)*
- *No significant change in angular separation distribution (compared to modification on $P(x_T)$*
- *Broadening effect cutoff by the pt cut on the tagged jets and constraint on angular separation when selecting gamma-jet events*





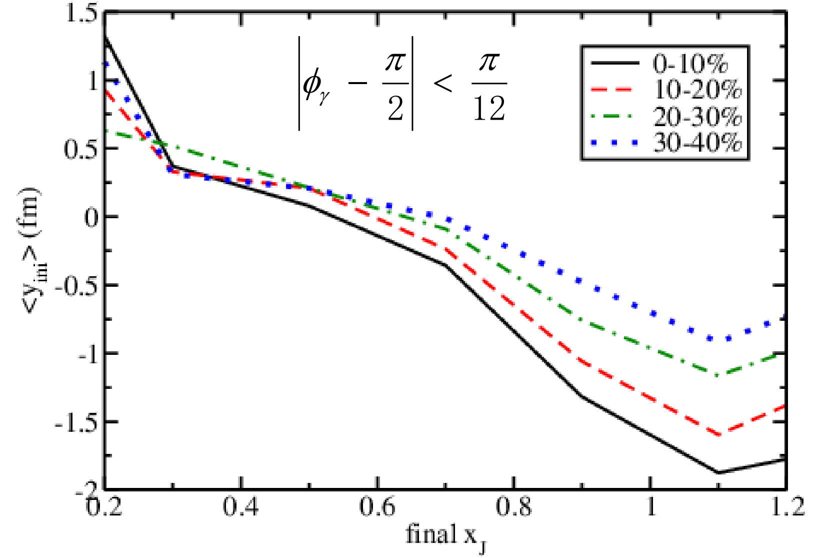
γ-jet tomography

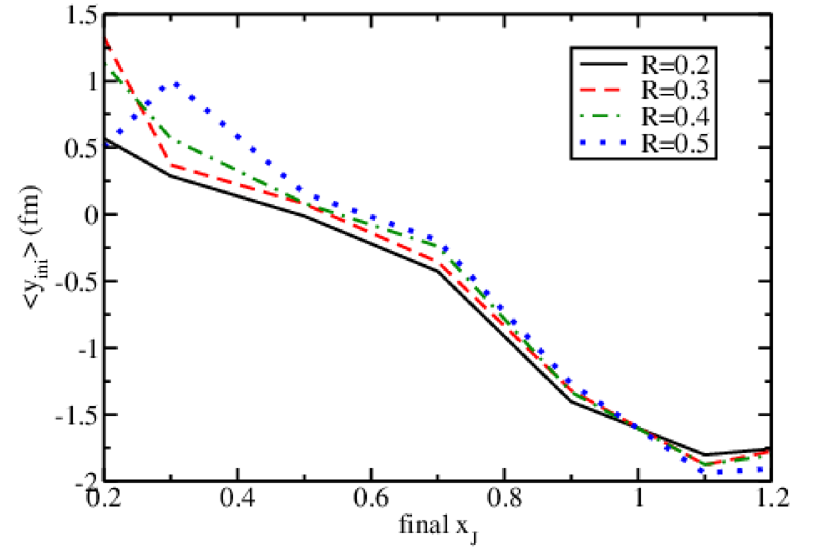
- **Larger x_T jets are more produced at the surface of the medium**
- **Smaller x_T jets have traveled large distance of medium**
- ***Different average x_J probe different path lengths***
- ***Combined with different directions, probe different areas of the collision zone***



γ-jet tomography

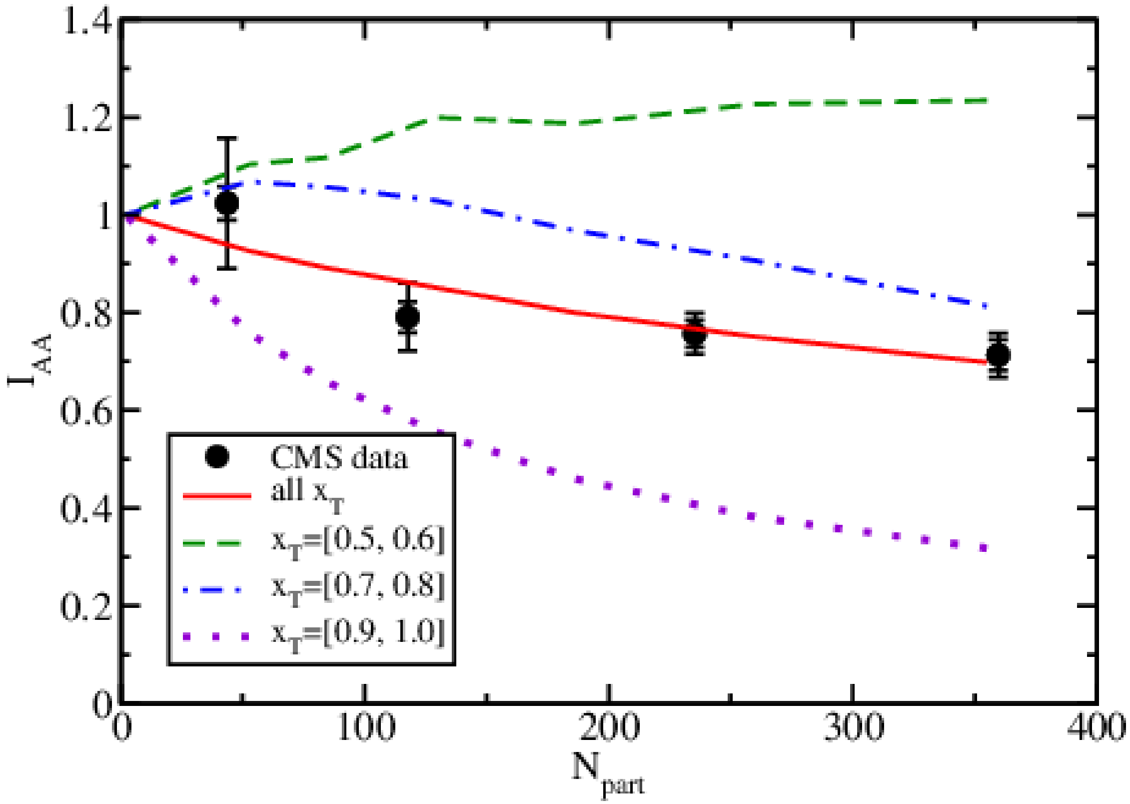
- *The trigger γ propagates in-plane (+y) direction, and the away-side jet propagate roughly (-y) direction*
- *Smaller x_T jets travel a few fm longer distance than larger x_T*
- *The effect is larger for more central collisions*
- *Weak dependence on jet size (larger for larger size)*





Modification for different x_T jets

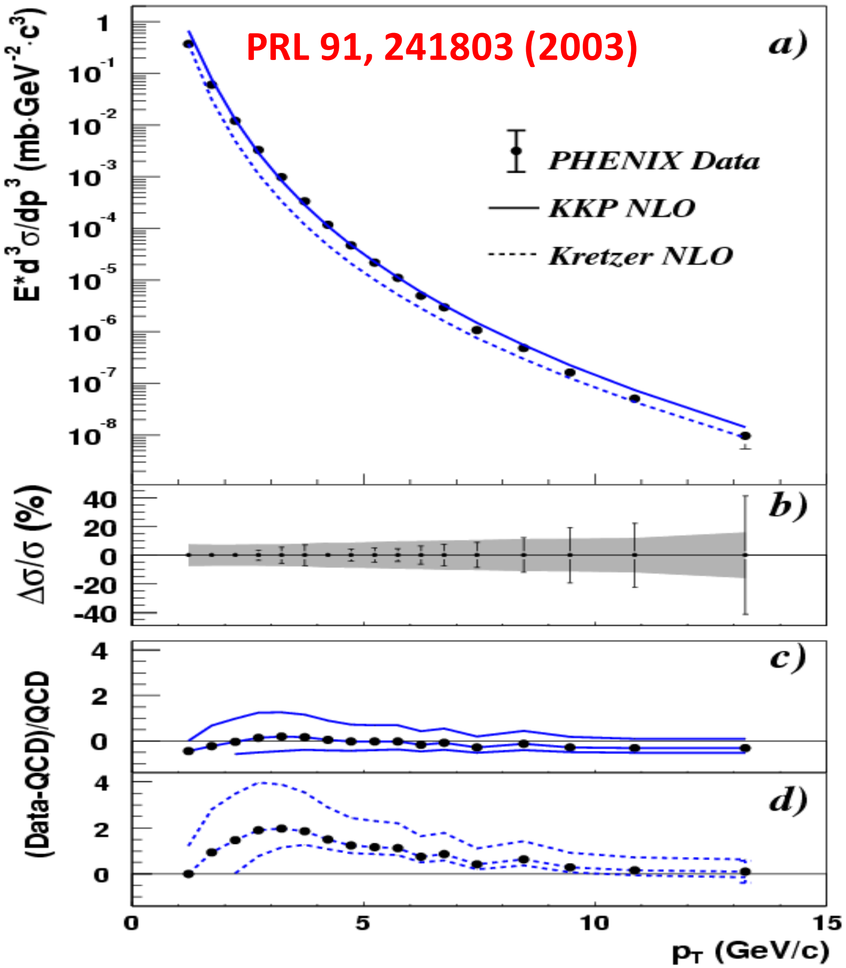
- **Combined with the distribution of tagged jet distribution $f(x_T)$**
- **Stronger suppression and centrality dependence for larger x_T jets**
- **Less suppression (or enhancement) for smaller x_T jets**

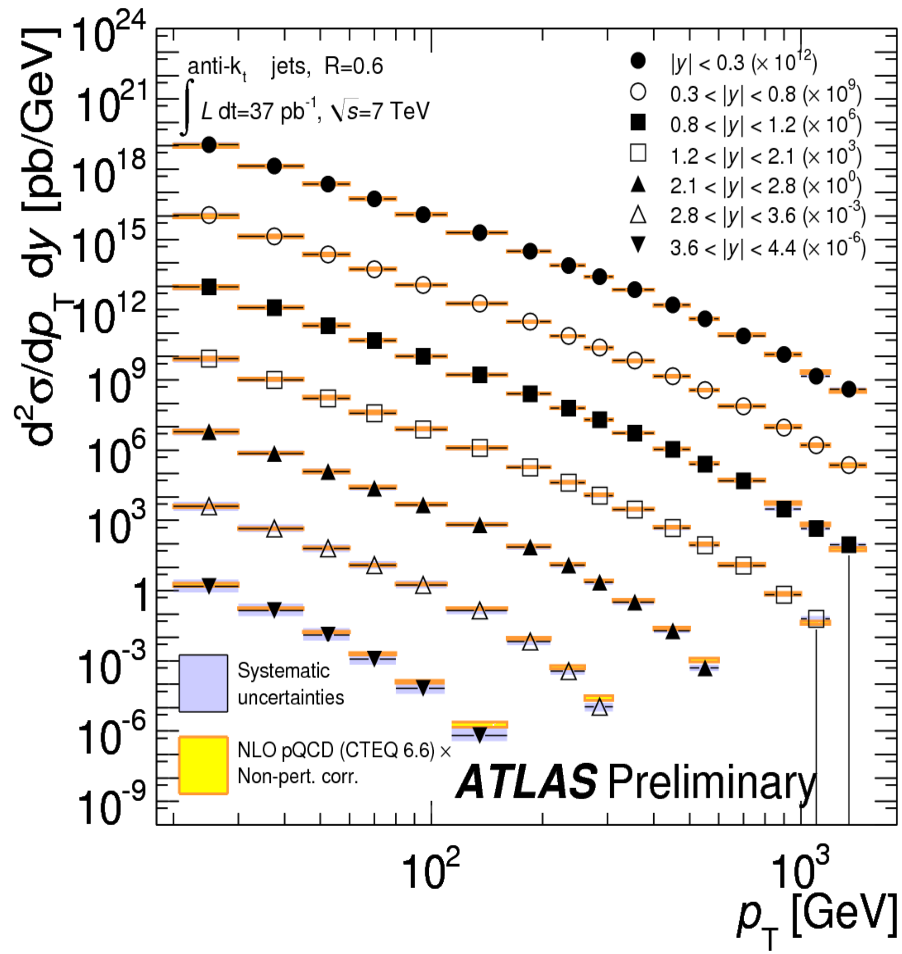


Summary

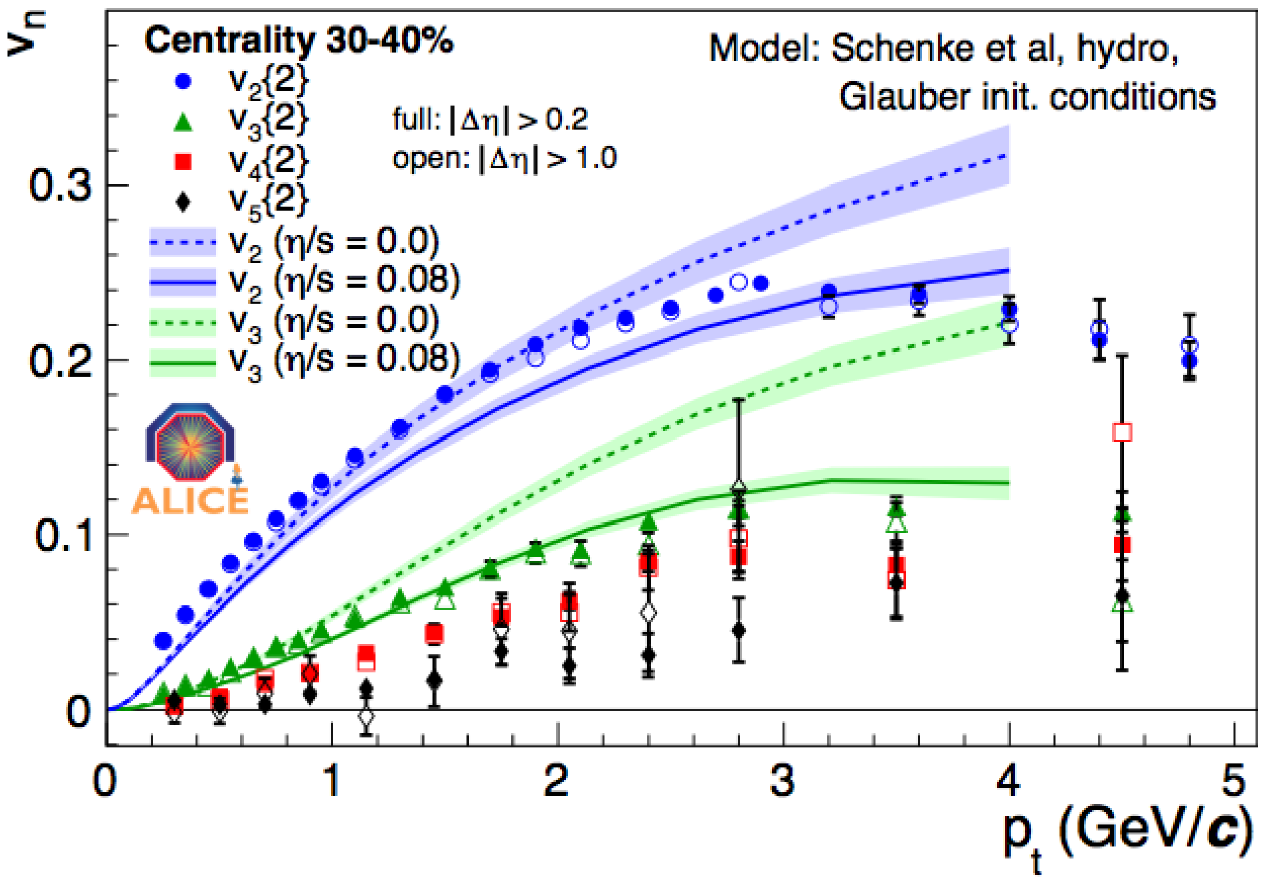
- *Jet-medium interaction provides useful tools to study QGP*
- *Leading parton energy loss in a strongly interacting plasma can be described by pQCD energy loss models*
- *Full jet observables and correlation measurements provide more detailed information*
- *Photon-tagged jets provide good potential for tomographic study of quark gluon plasma.*
- *Need consistent description of multiple observables simultaneously*
- *Medium response to jet transport (energy/momentum deposition)*

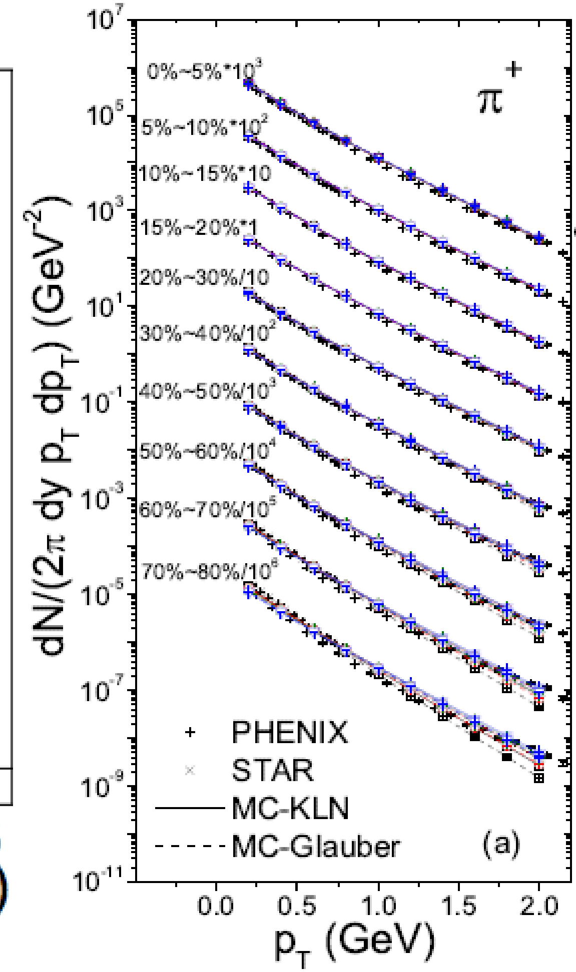
pQCD works for pp reference!





The medium: successful hydro





Utilize viscous hydrodynamics and parton and hadron cascade models for a complete description of all stages of the expanding medium

Song, Bass, Heinz, Hirano, Shen, 2011

MC tools in the market

Simulate full HIC events:

HIJING: Wang, Gyulassy, 1991; Deng, Wang, Xu, 2010

HYDJET++/PYQUEN: Lokhtin, Snigirev, 2006

BAMPS: Z. Xu, C. Greiner, PRC, 2005

Embedding the parton shower in a medium
Obtain the information for the full jet shower evolution
Suitable for hadron observables and full jet observables.

Simulate only jet evolution:

JEWEL: Zapp, Ingelman, Rathsman, Stachel, Wiedemann, 2009; Zapp, Stachel, Wiedemann, 2009

MARTINI: Schenke, Gale, Jeon, PRC, 2009

Q-PYTHIA/Q-HERWIG: Armesto, Cunqueiro, Salgado, 2009; Armesto, Corcella, Cunqueiro, Salgado, 2009

YaJEM: Renk, PRC, 2008, 2009

VNI/BMS: Coleman-Smith *et al*, 2011

CUJET: Buzzatti, Gyulassy, 2011

Compare γ and Z^0/γ^*-tagged jets