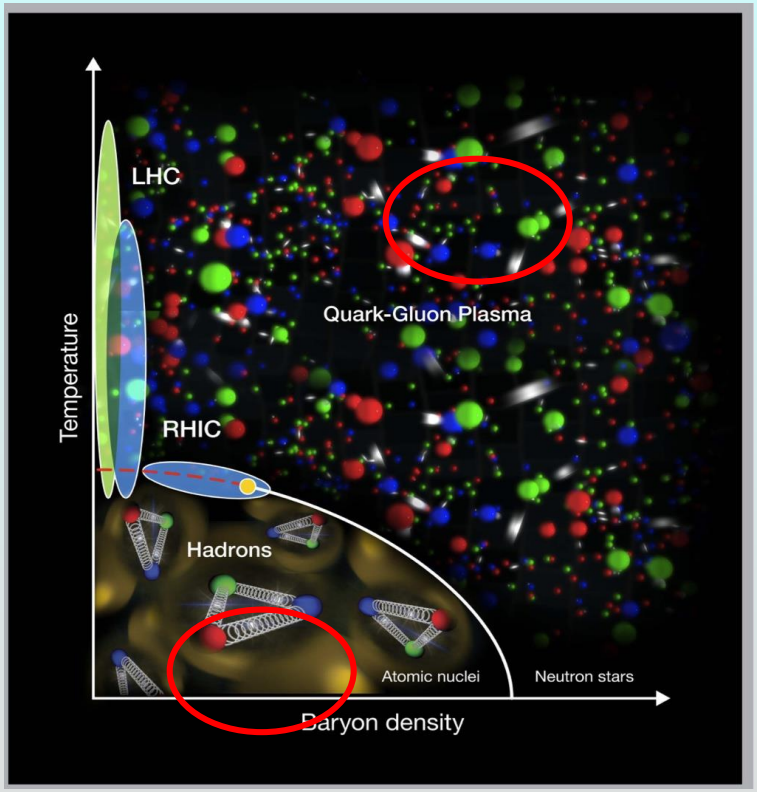
An experimentalist thinks about transport

What can we learn from measuring this:

about studying this?



What should we measure to keep you guys entertained?

… and honest?

Barbara Jacak, UC Berkeley & LBNL - November 16, 2018

outline

- Why this is important & what tools to use
- Energy loss in cold, dense gluonic medium?
- Medium effects on soft particles in jets
- Medium effects on early branching

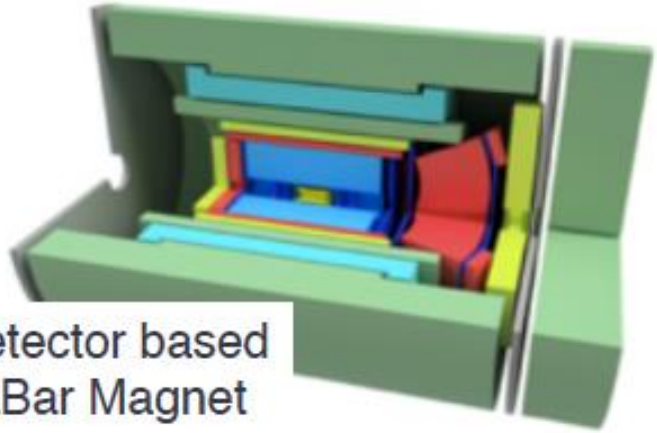
Transport (experimental view)

- **Momentum**
  - **V_n a good tool in A+A, less clear in p+A**
  - **In e+A??? Likely initial state effects only**

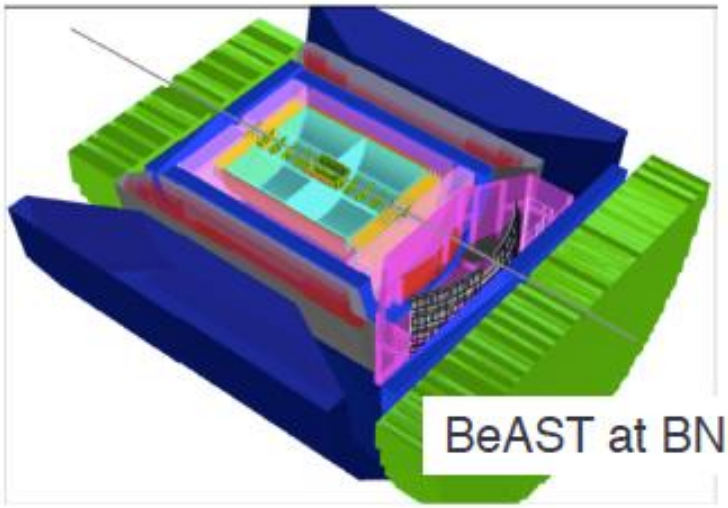
- **Energy**
  - **How much energy is lost to the medium?**
  - **Where does it end up?**

- **Particles**
  - **What does this mean for a cold, dense gluon gas?**
  - **(which is spatially not so large)**
  - ***Look for effects on hadronization by varying A???***

EIC Detector *From Berndt Mueller*



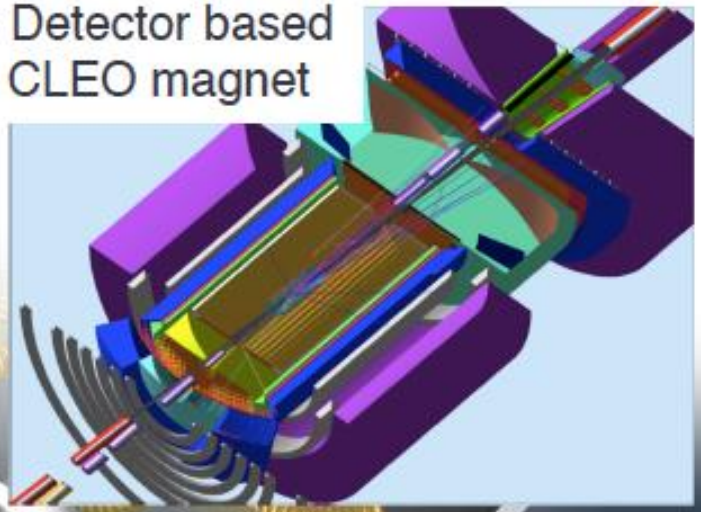
EIC Detector based on BaBar Magnet



BeAST at BNL

Ongoing $1M Generic EIC Detector R&D Program managed by BNL

EIC Detector based on CLEO magnet



SiEIC Detector (ANL)

Experiment Design

- **Currently have ≥ 4 concepts**
  Each is pretty close to "perfect"

- **Need the physics to inform inevitable compromises**
  $, space, rate, sociology…
  This includes the magnitude of effects we are supposed to measure!

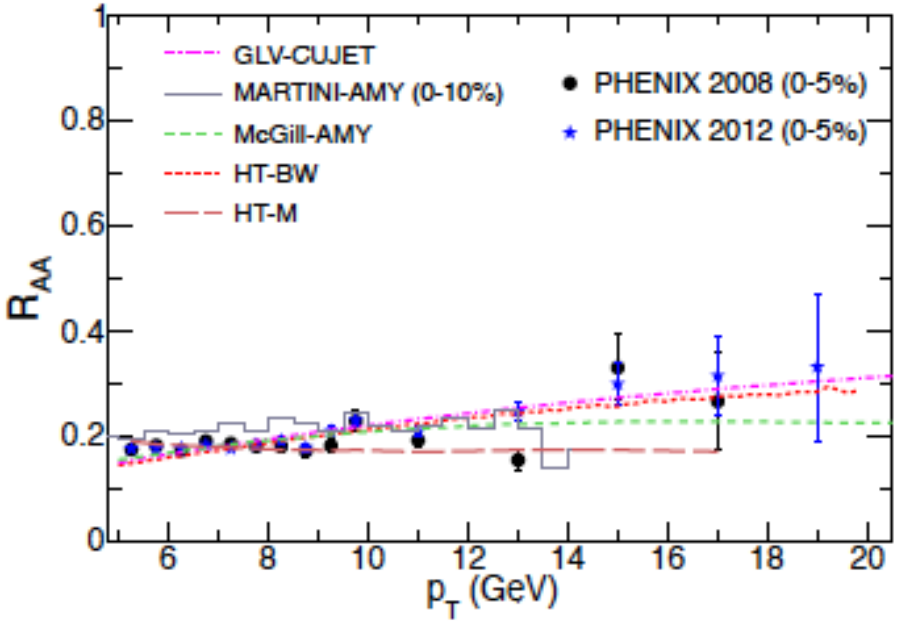
- **Need the physics to guide R&D on detector technology**

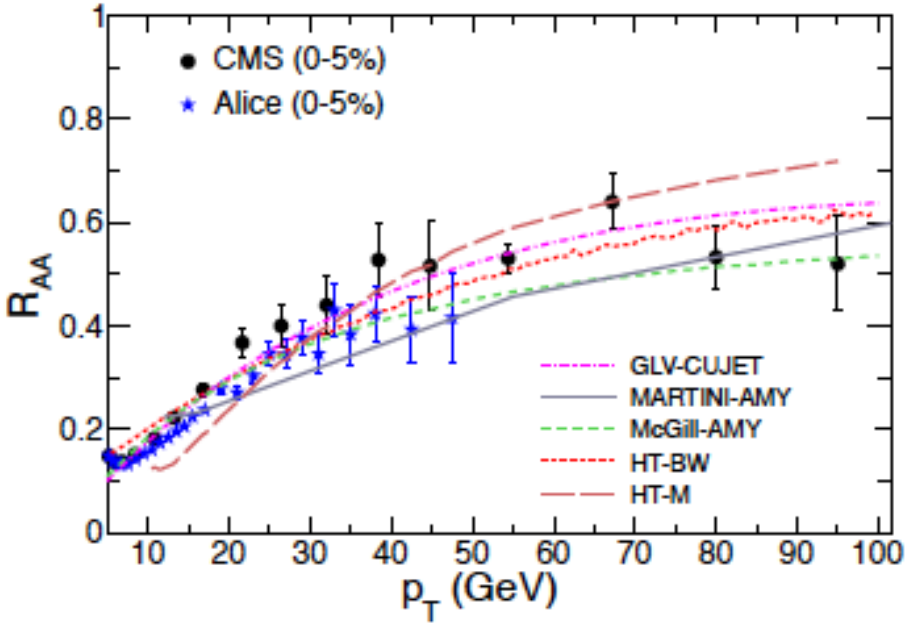
- **Need help from theory (the time is now!)**
  Here is where you keep US honest!

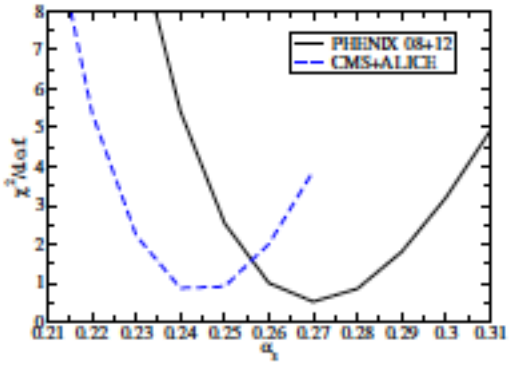
Energy loss observables

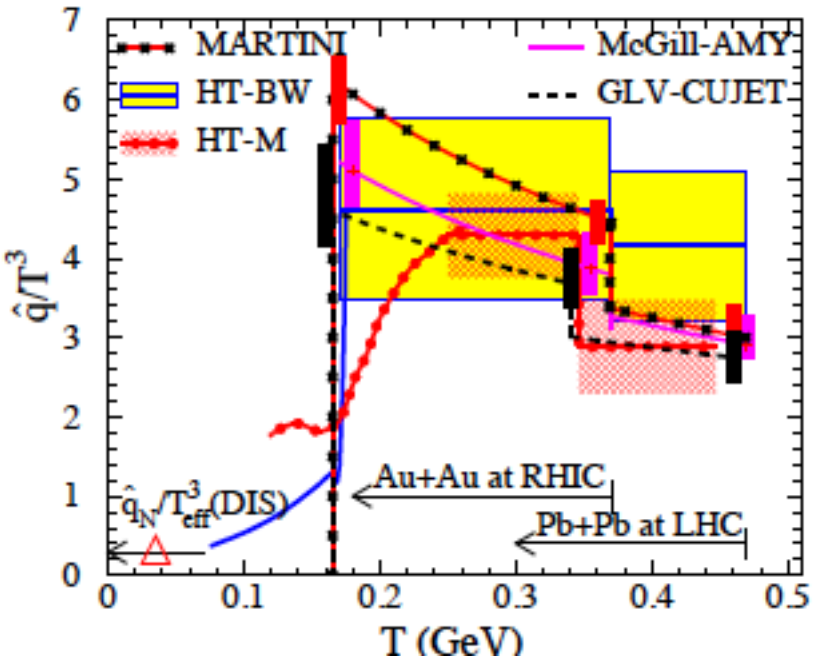
- High pT hadrons
- Jets
- γ – jet

JET collaboration analyzed hadron R_{AA}



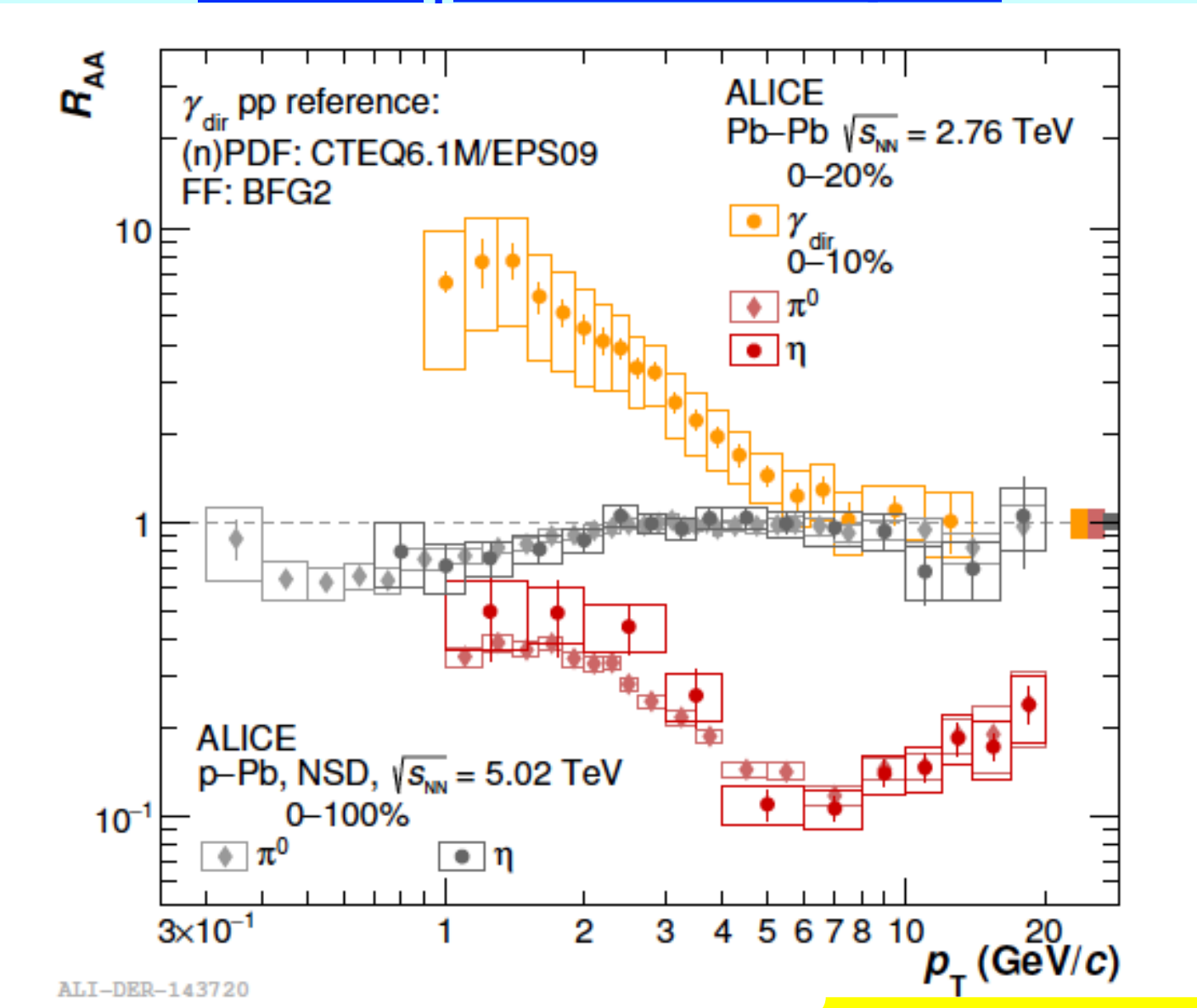






- $\hat{q}$ *large!*
- *decreases w/* $\sqrt{s}$
- *parton exchanges momentum w/medium*

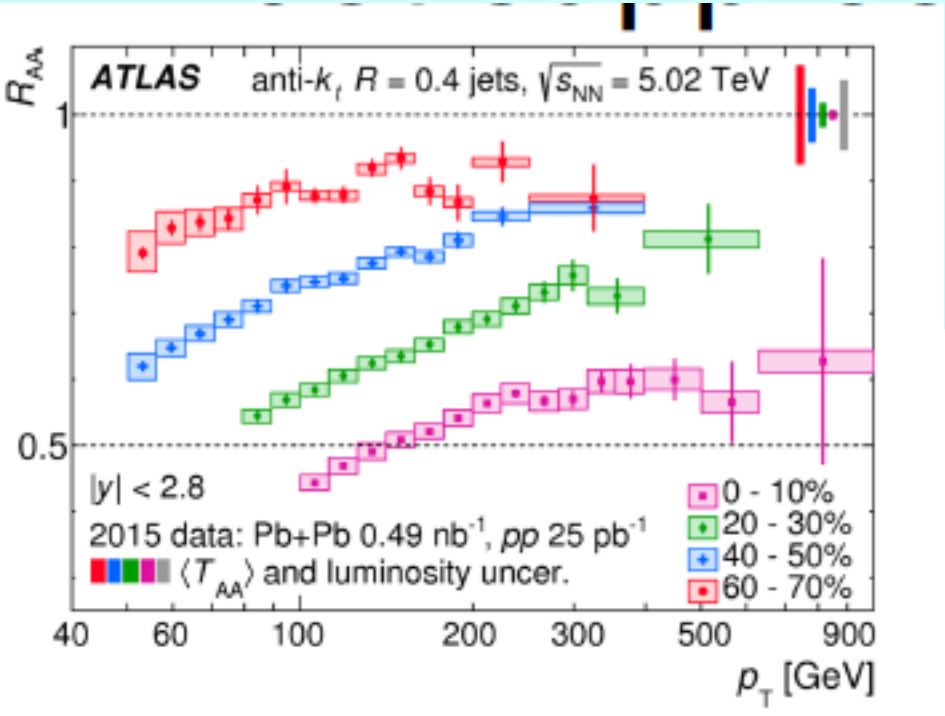
High p_T hadrons in p+A



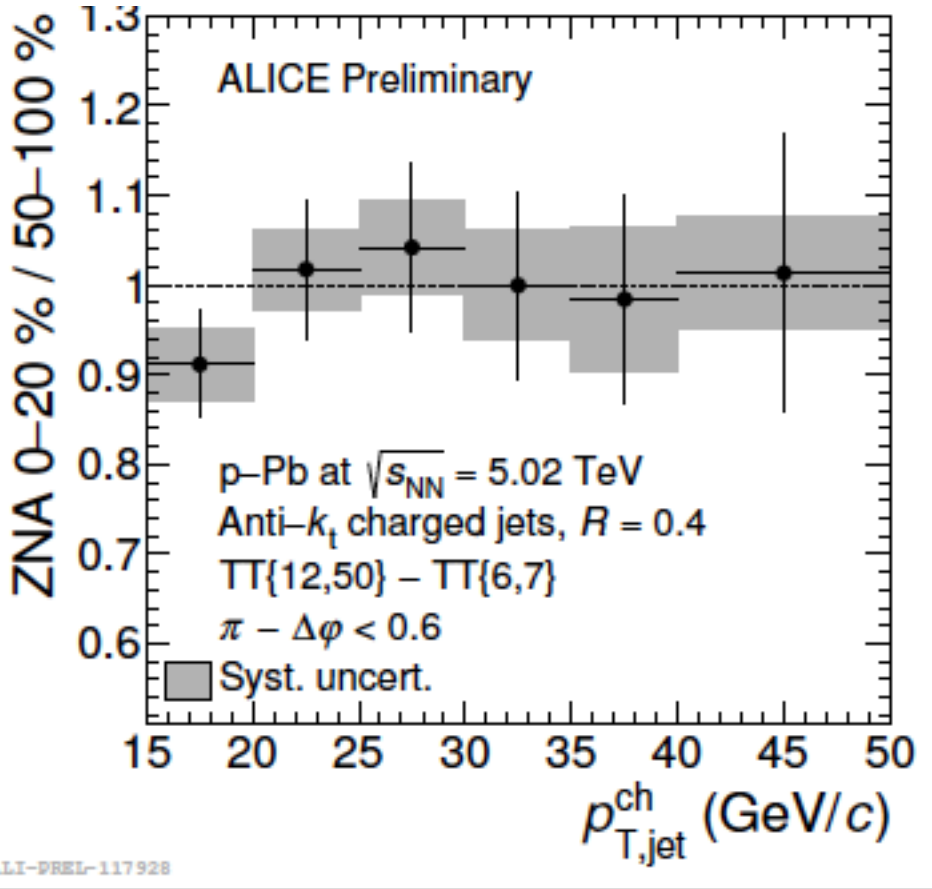
- No evidence of energy loss

At EIC also…?!

Jet R_{AA}

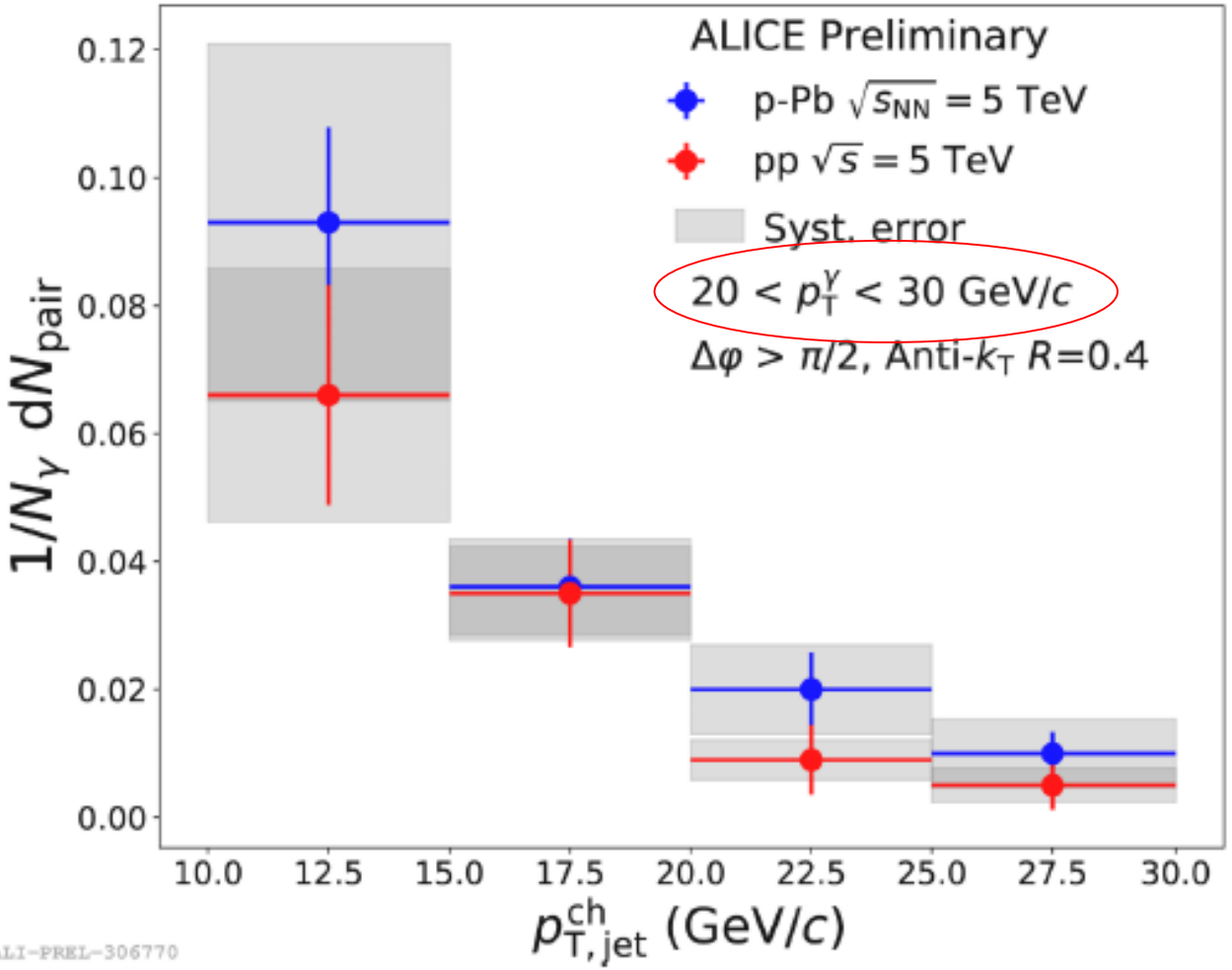


semi-inclusive p_T-differential cross sections of hadron+jet



- **Consistent picture as in the hadrons**
- **Nuclear effects are small**

p+Pb vs. p+p γ-jet



no difference observed in the associated jet spectra

Within ~ 25%

Need better precision !

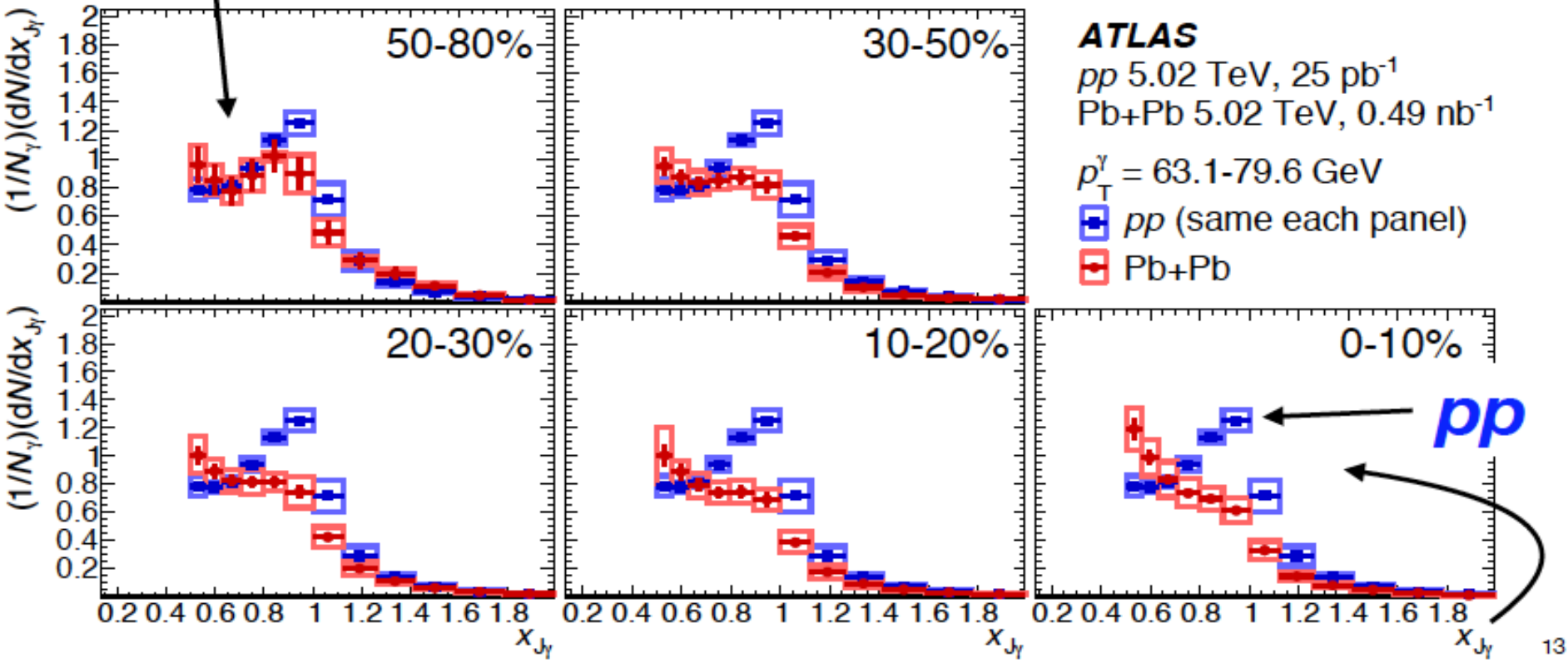
At EIC need better than 10%

In Pb+Pb: p_T balance killed by medium

D. Perepelitza, HP2018

peak returns in ***50-80%*** *Pb+Pb events*

Results: p_T^{γ} = 63.1-79.6 GeV



peaked structure destroyed in ***0-10%*** *Pb+Pb*

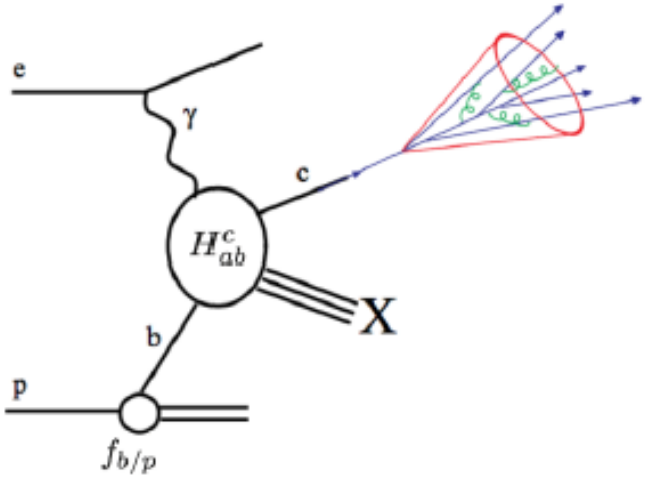
At EIC

Inclusive Jets

- $ep \to \text{jet} + X$, **final lepton unobserved, high p_T**

Boughezal, Petriello, Xing `18,
Hinderer, Schlegel, Vogelsang `18,
Uebler, Schfer, Vogelsang `17,
Abelof, Boughezal, Liu, Petriello, `16

- $ep \to e + \text{jet} + X$, **DIS, high p_T and Q^2**



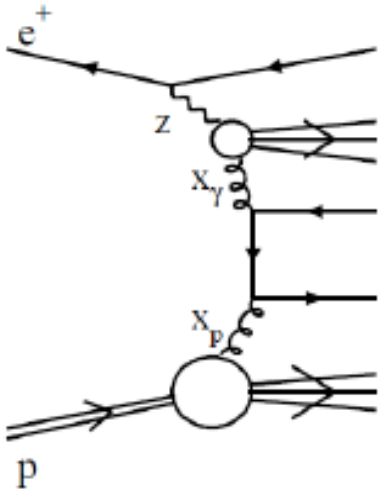
- $ep \to e + \text{jet} + X$, **photoproduction, high p_T and $Q^2 < 1$ GeV^2**

Kyle Lee

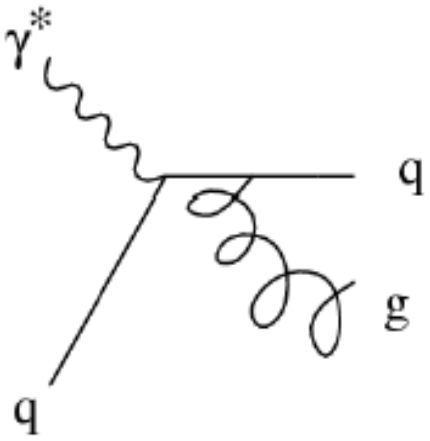
Processes of interest?

Brian Page

Resolved

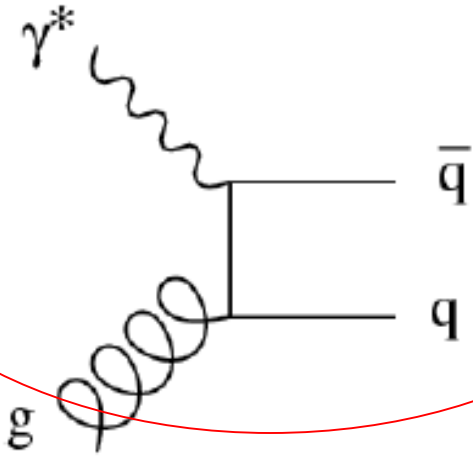


QCD-Compton (QCDC)

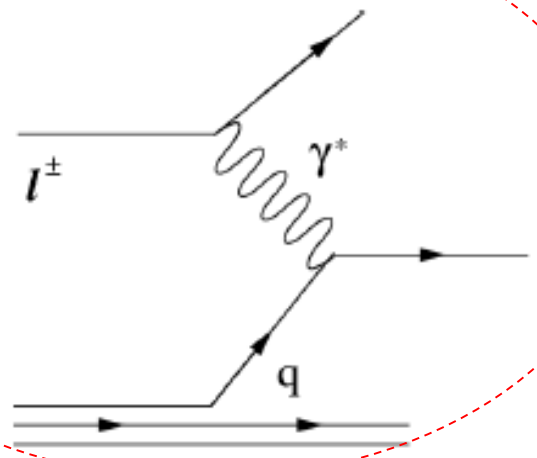


Sea quarks at small x…

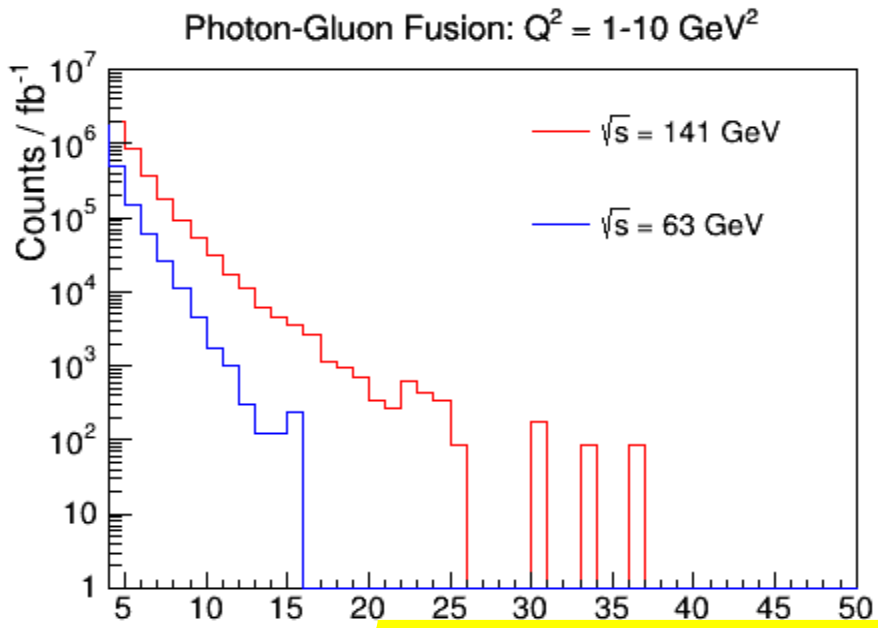
Photon-Gluon Fusion (PGF)

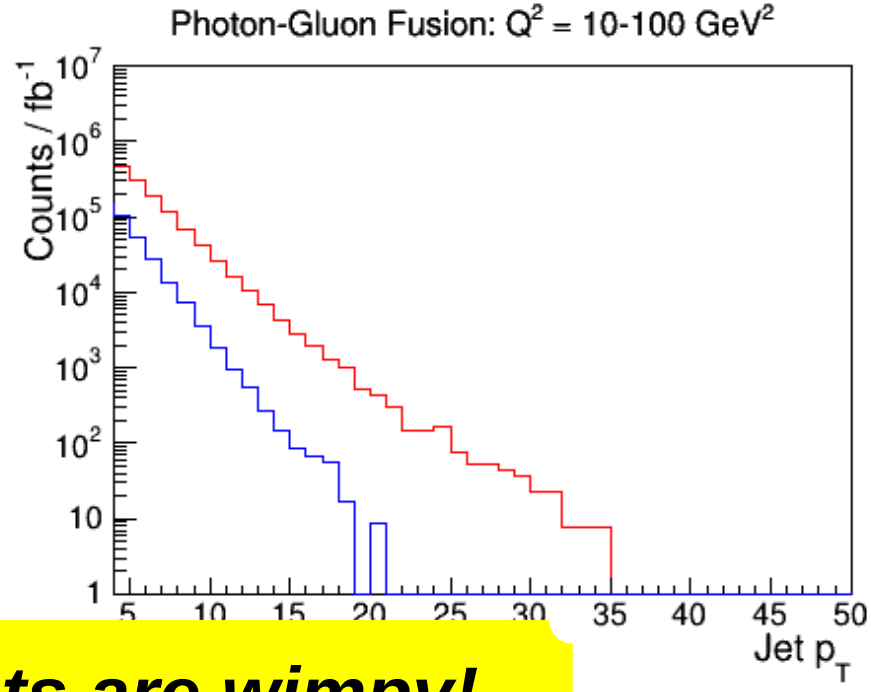


DIS

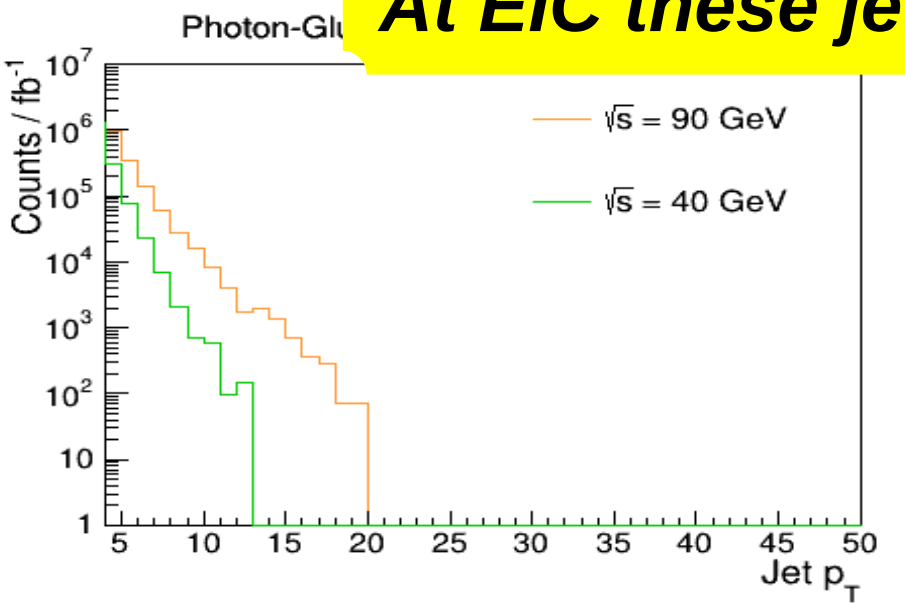


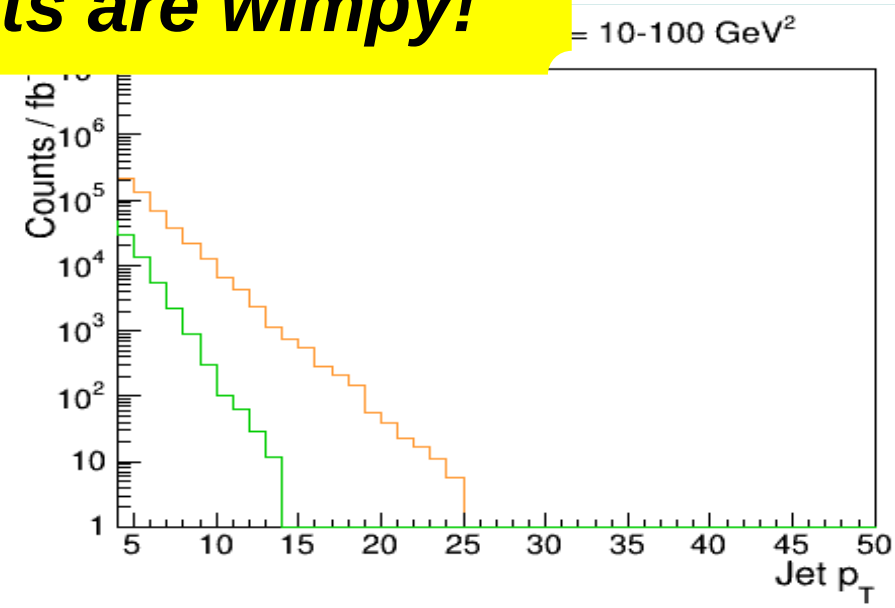
Photon-gluon fusion jet p_T



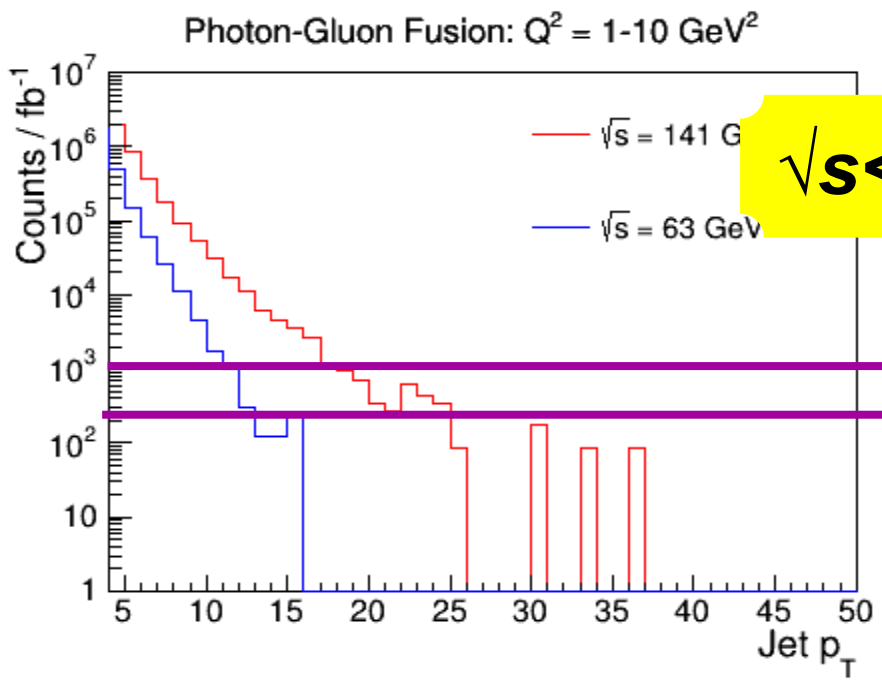


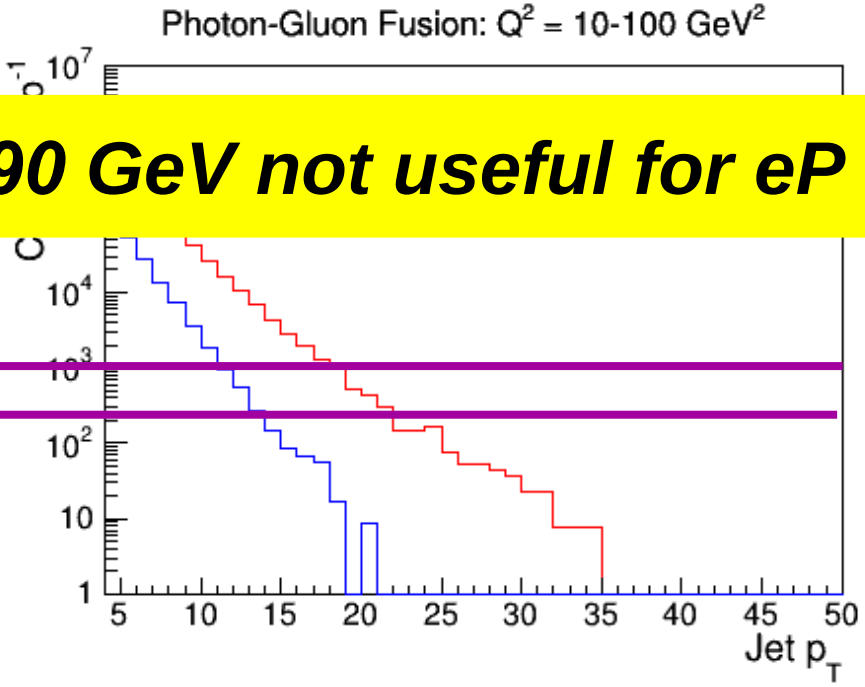
At EIC these jets are wimpy!



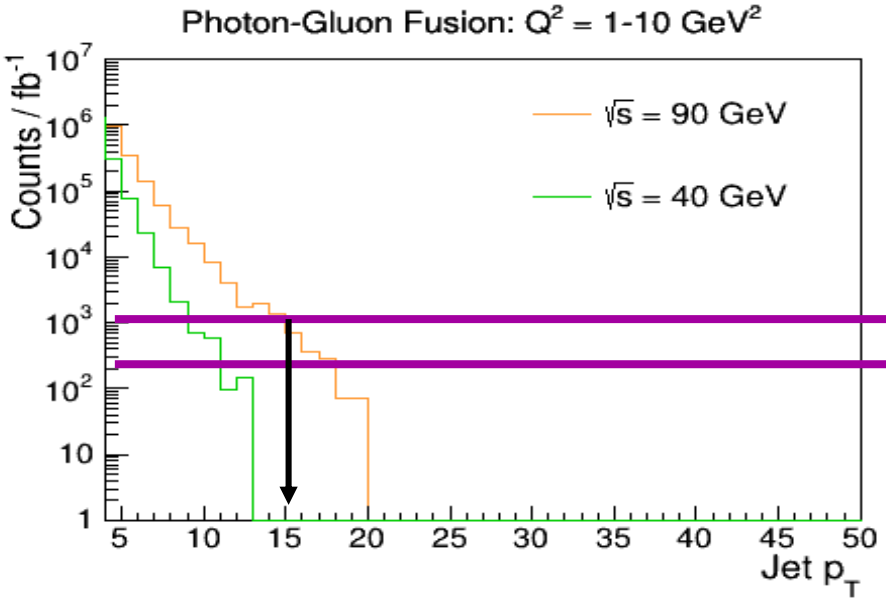


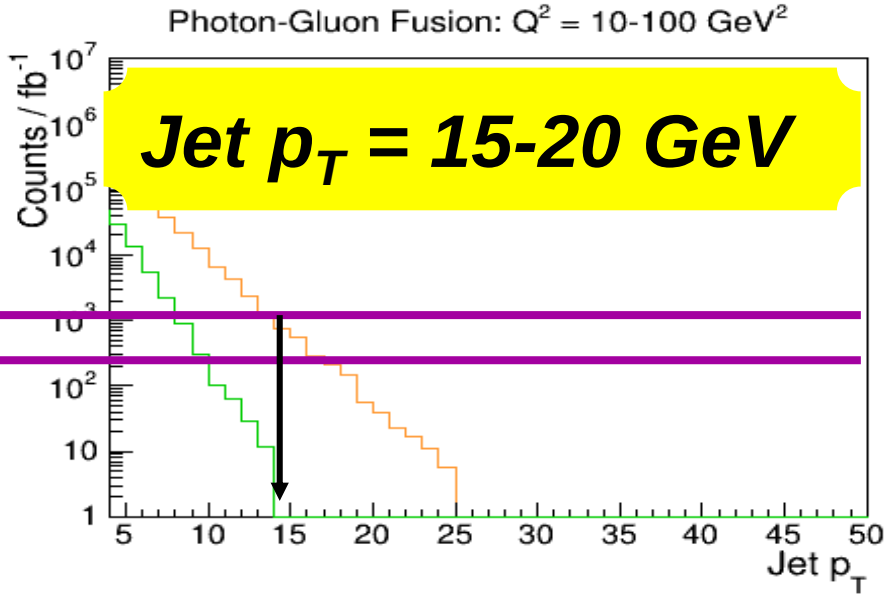
Integrated $\mathcal{L}$ = 2-10 fb^{-1}; rate = Page/2





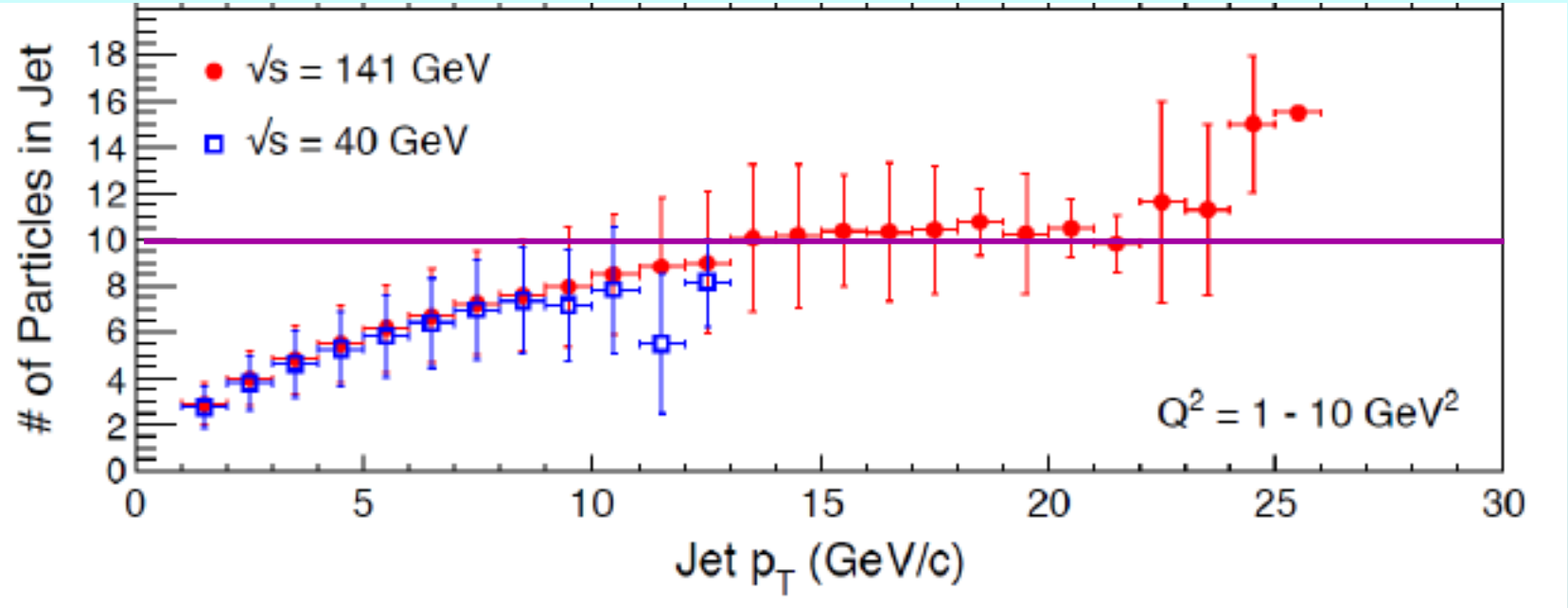
√s<90 GeV not useful for eP





Jet p_T = 15-20 GeV

To reconstruct those jets



only ~10 particles in the jet,
so need excellent tracking efficiency + calorimetry

Homework: find rates for the other processes
(e.g. dijets look feasible & interesting – E. Aschenauer)

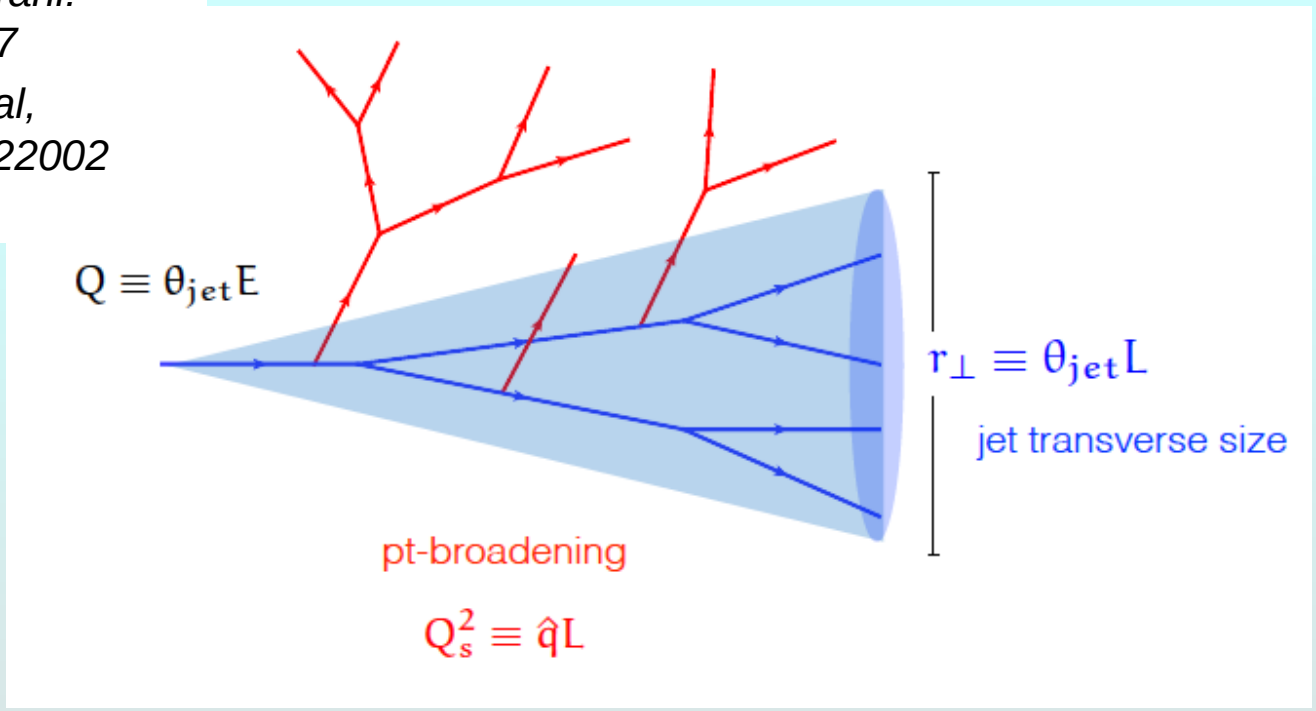
Next…

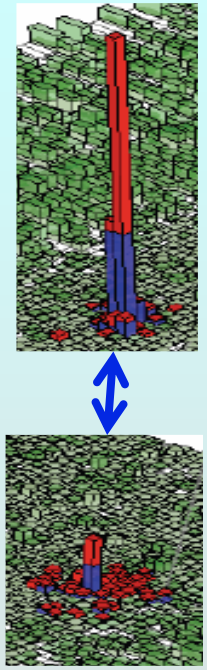
Look inside the jets

Medium modification of jets

Y. Mehtar-Tani: 1602.01047

Blaizot, et al, PRL114, 222002 (2015)





High energy jets fragment mostly outside the plasma

radiate gluons as they transit plasma, producing secondary showers with enhanced splitting

Lower energy jets start to fragment in medium

What to measure?

- **Jet fragmentation function – *large angle radiation*?**
  γ - hadron correlations
  D(z) of jets

- **Groomed jet splitting functions: z_g - *early (angular ordered) splitting modifications?***

- **Jet mass, girth, etc. – *rearrangement of fragments inside the jet due to medium interactions?***

At LHC

Study modification of parton shower

Gives info about the dynamics of hot QCD matter

Tools :

Jet fragmentation function (FF)

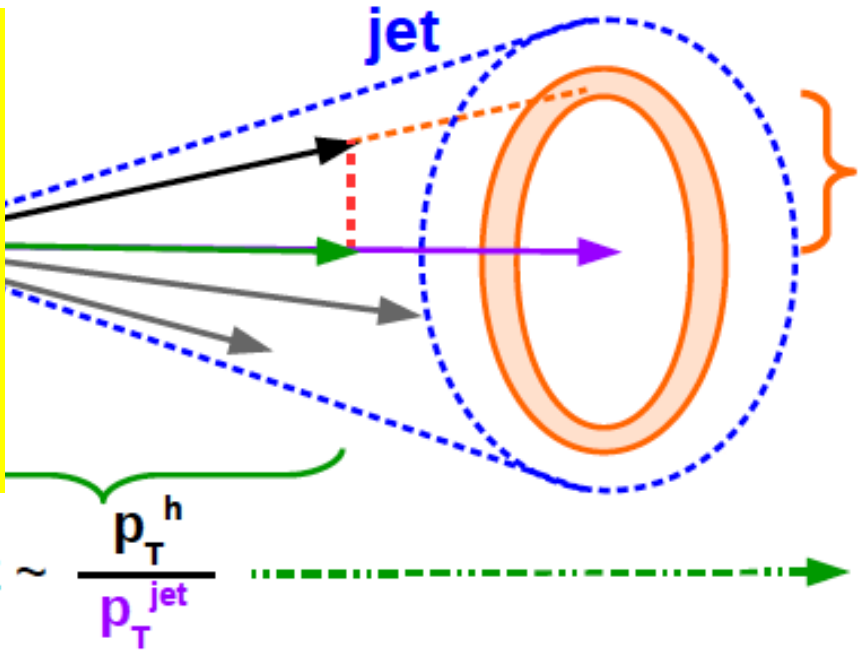
- Longitudinal distribution of momentum

Jet shapes (JS)

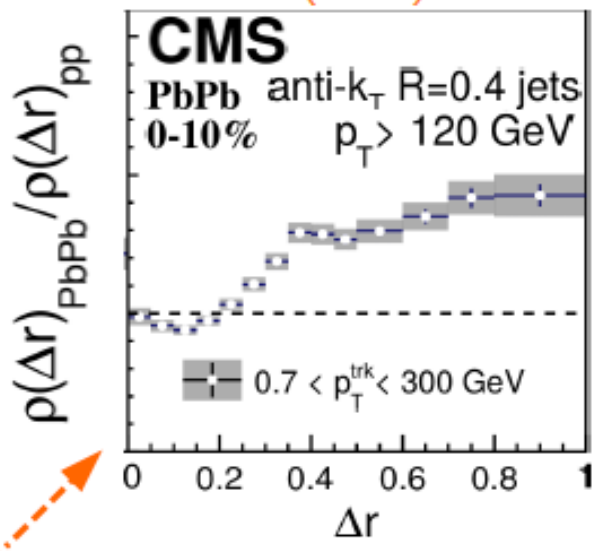
- Distribution of jet energy in transverse direction

FF and JS provide different, but complementary info

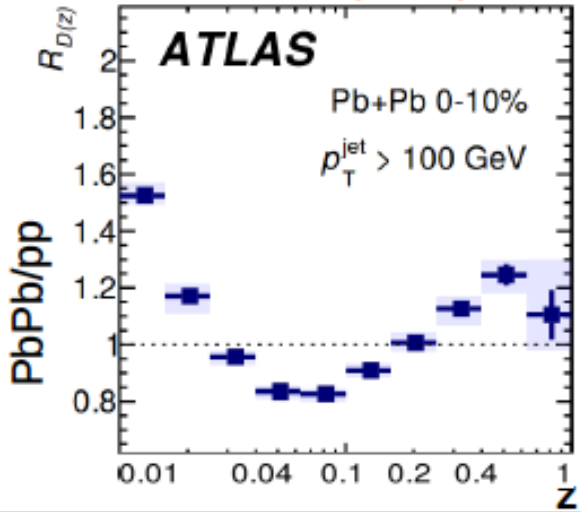
Use these data to quantify QGP transport properties



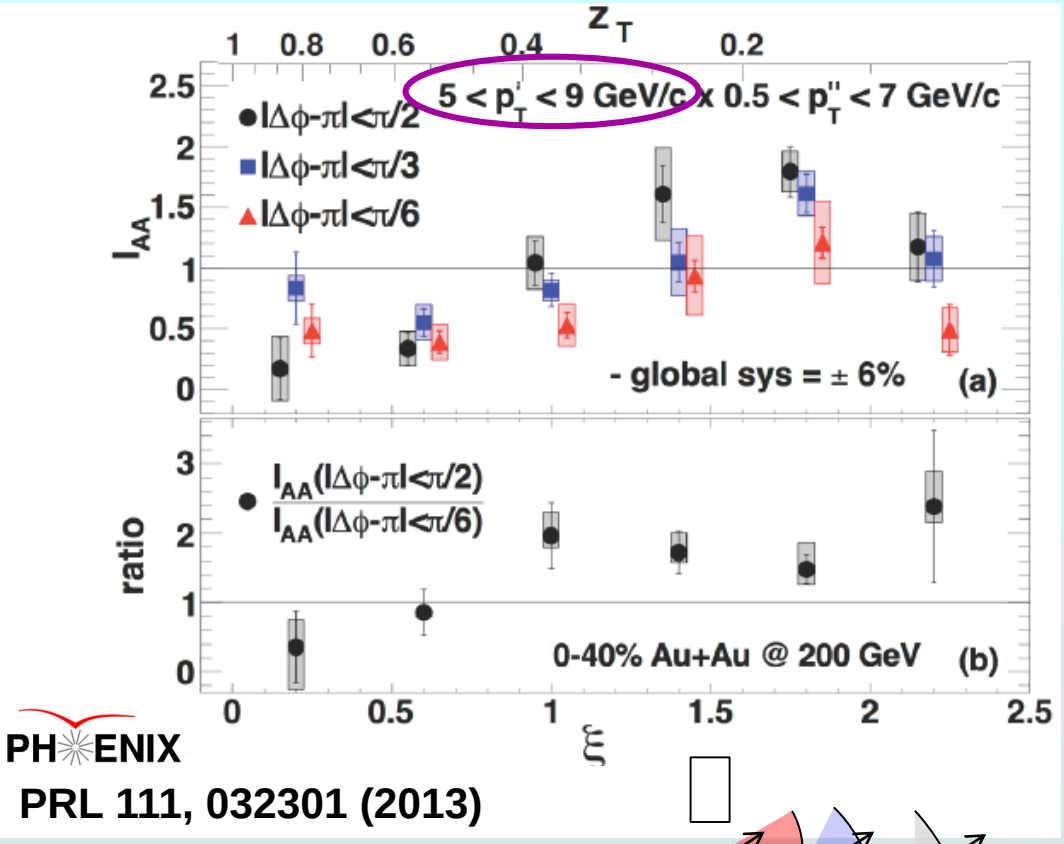
JHEP 05 (2018) 006

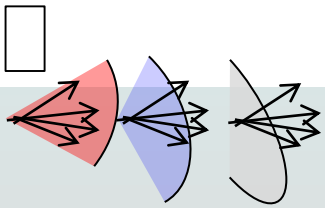


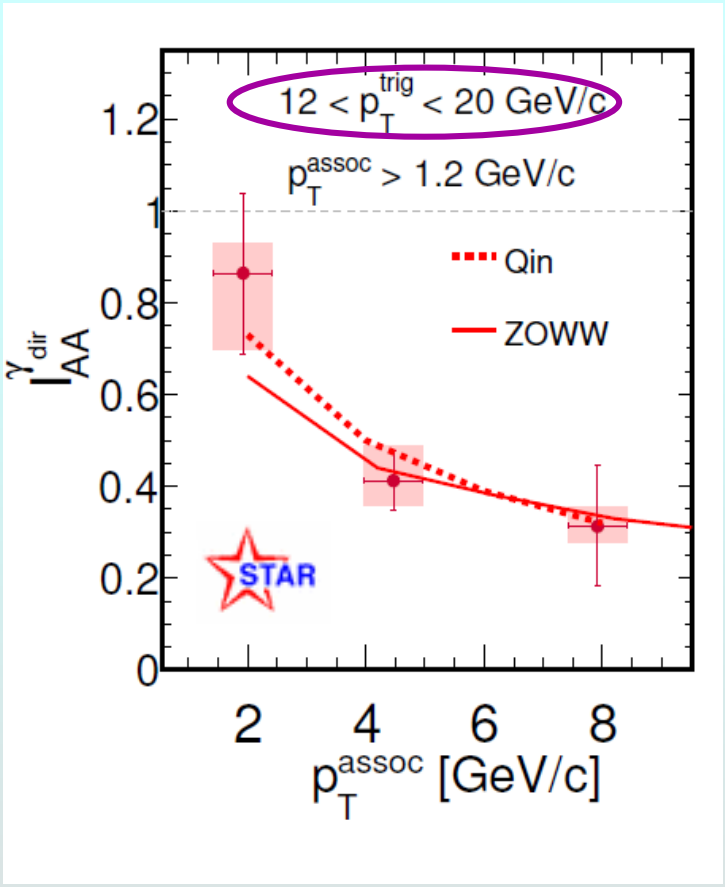
EPJC 77 (2017) 379



Fragmentation function via γ-h at RHIC

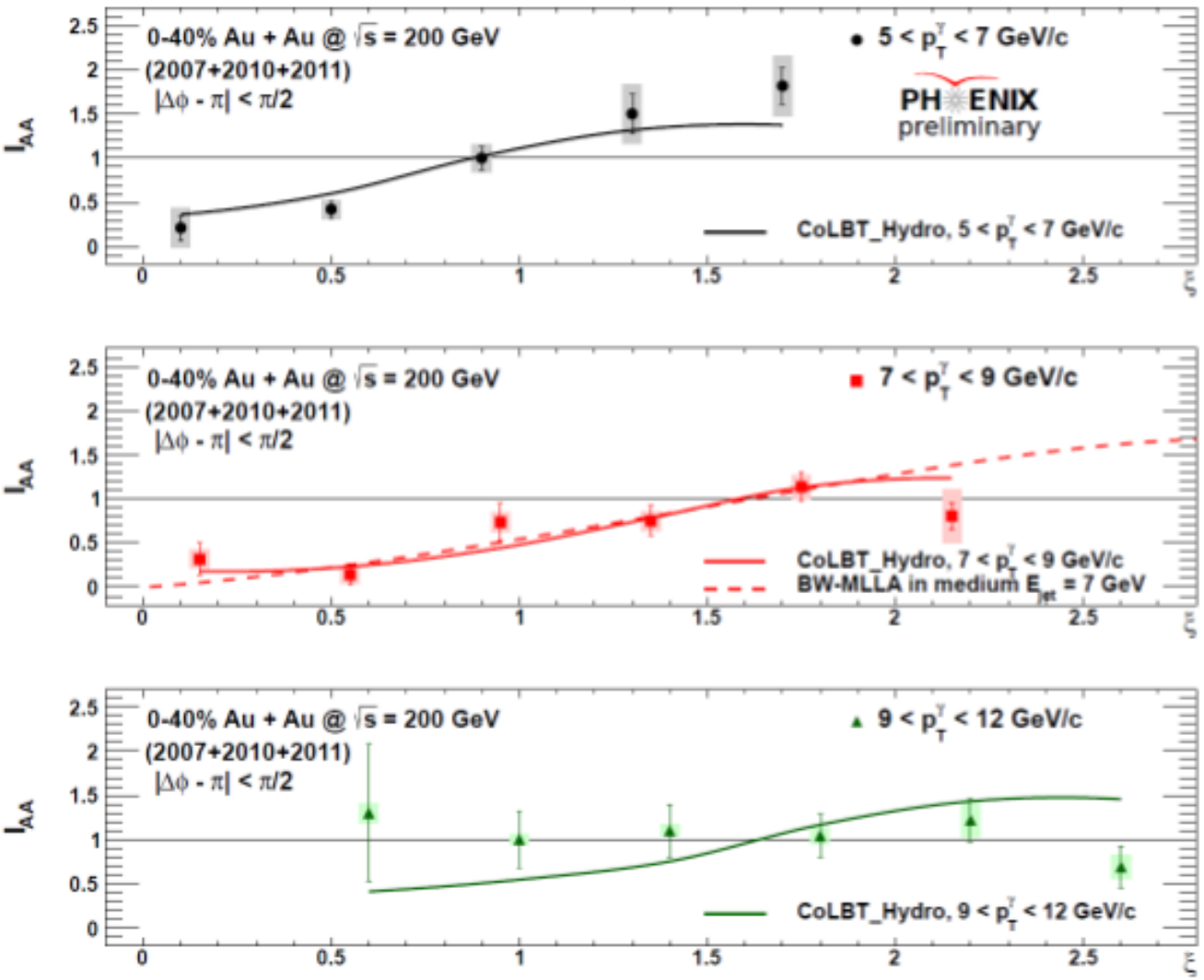






- Enhanced production of jet-correlated soft particles at large angles for soft γ triggers
- Parton energy dependence?

LBT reproduces the data

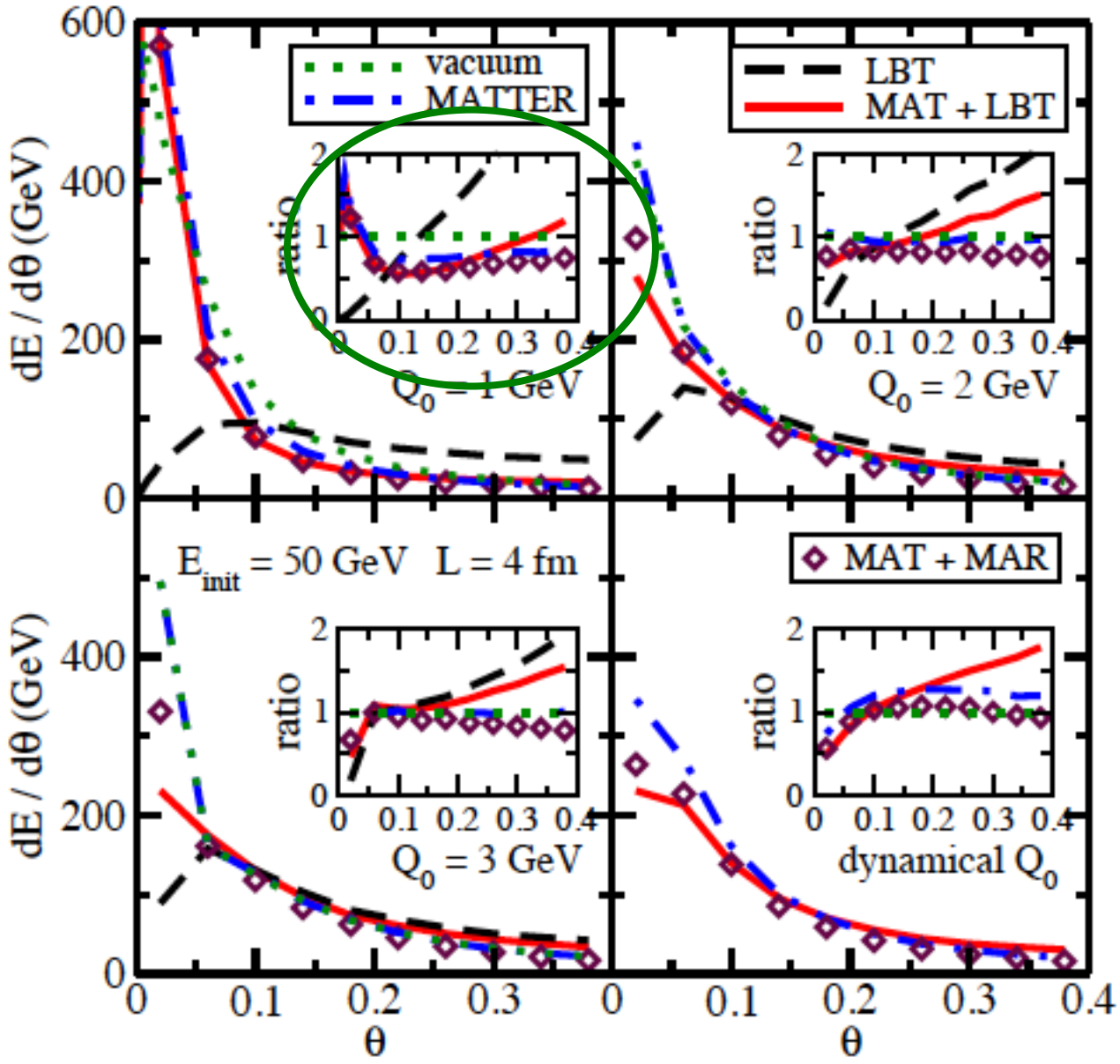


- Theory predictions including the effect of jet-induced medium excitations shows agreement with data
- Transition from suppression to enhancement does not seem to occur at a fixed ξ

Y. He, T. Luo, X. N. Wang and Y. Zhu, arXiv: 1503.03313v2 (2015)
N. Borghini and U. Wiedemann, arXiv: hep-ph/0506218 (2005)

JETSCAPE

arXiv:1705.00050

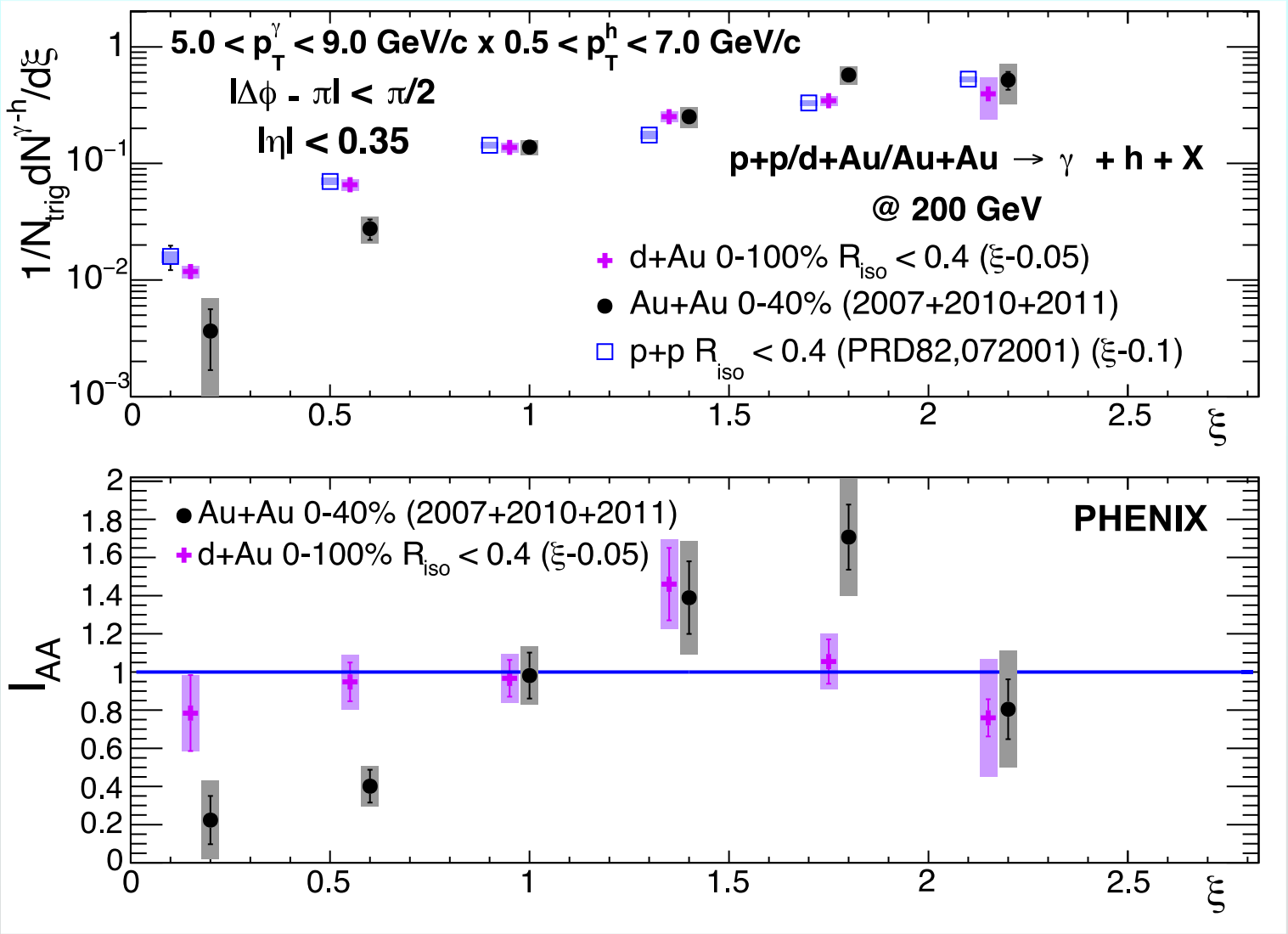


Collinear emission: core narrows

+

Scattering w/medium: large angle emission

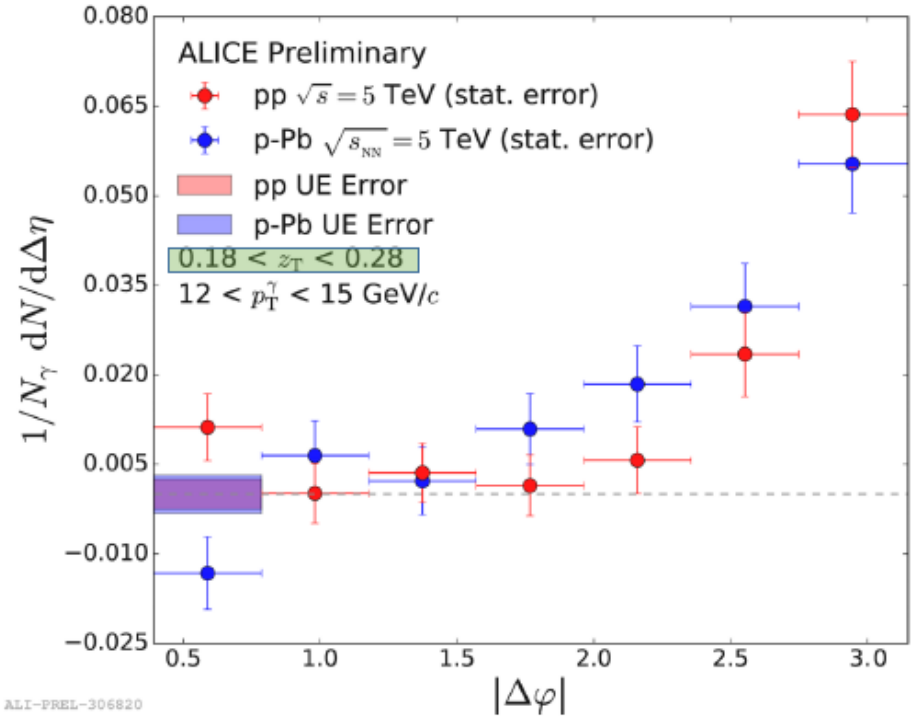
What happens in d+A?

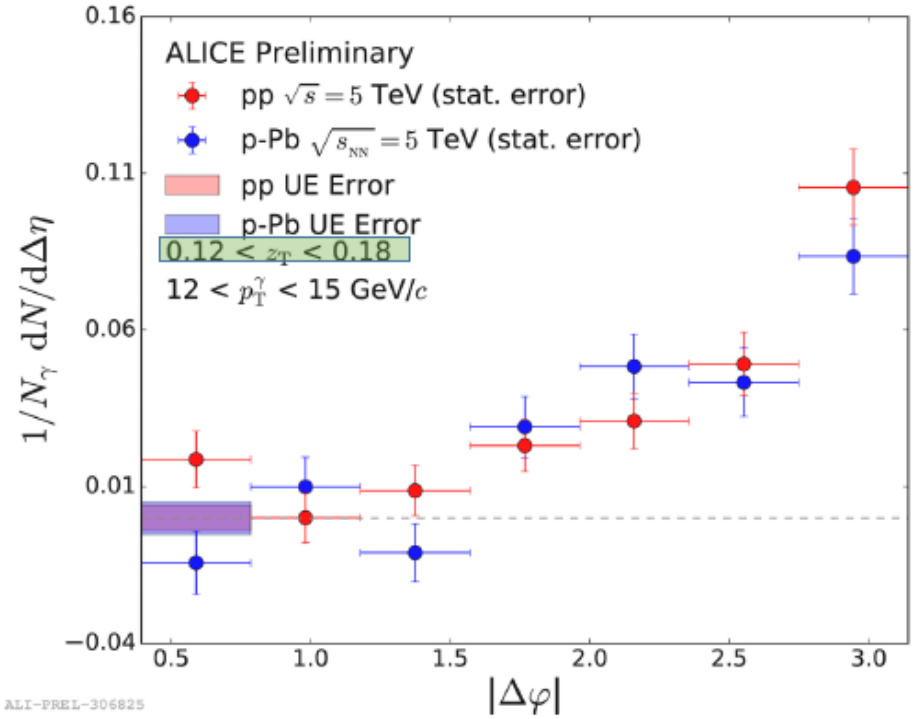


- d+Au looks like pp

γ-hadron at the LHC

Isolated 12-15 GeV photon – hadron correlations

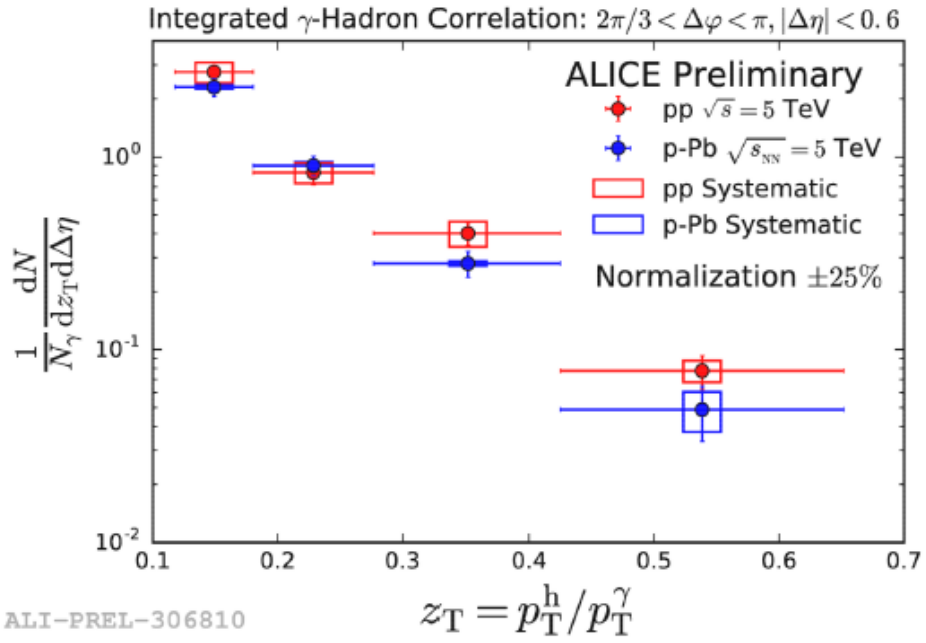


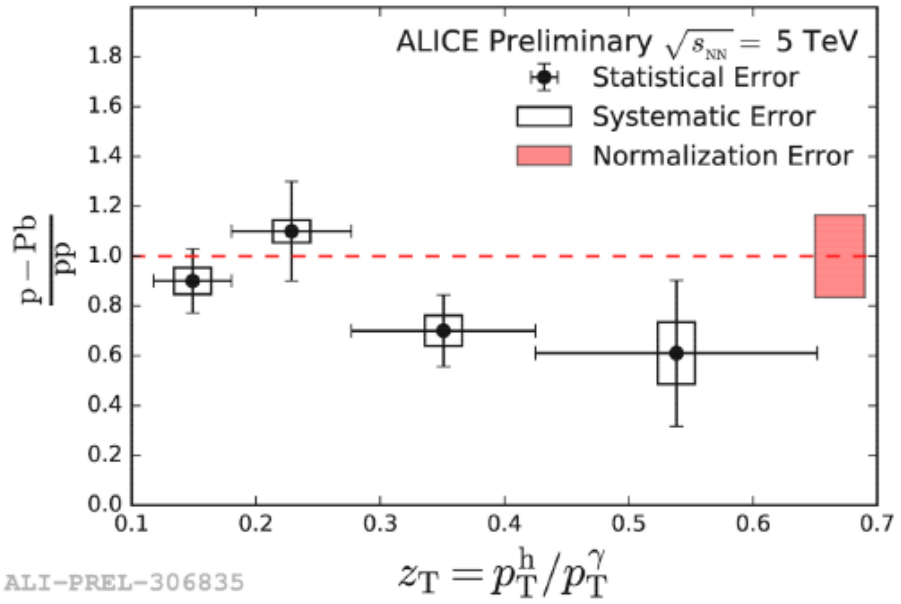


as a function of z

Miguel Arratia, HP2018

Fragmentation functions

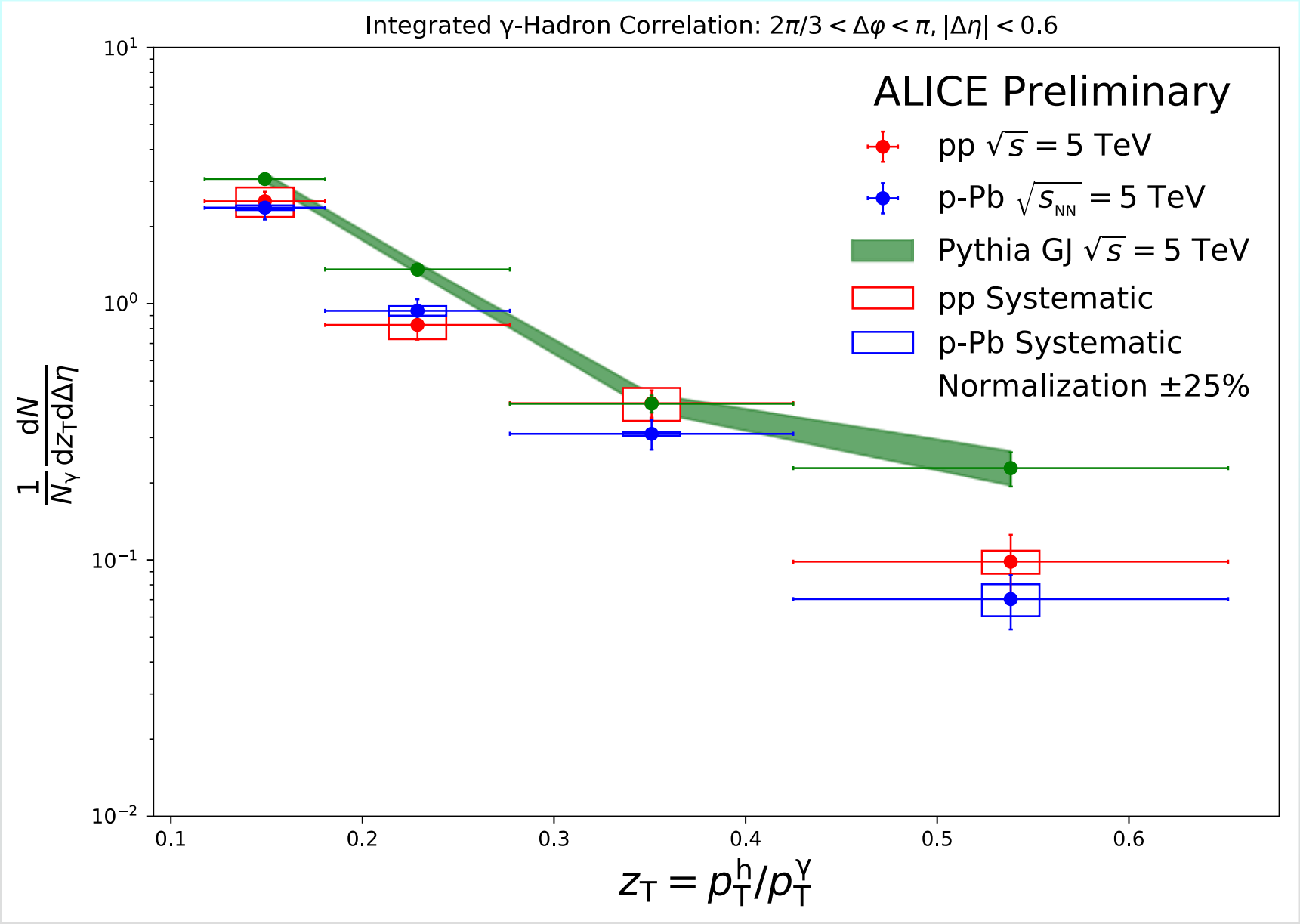




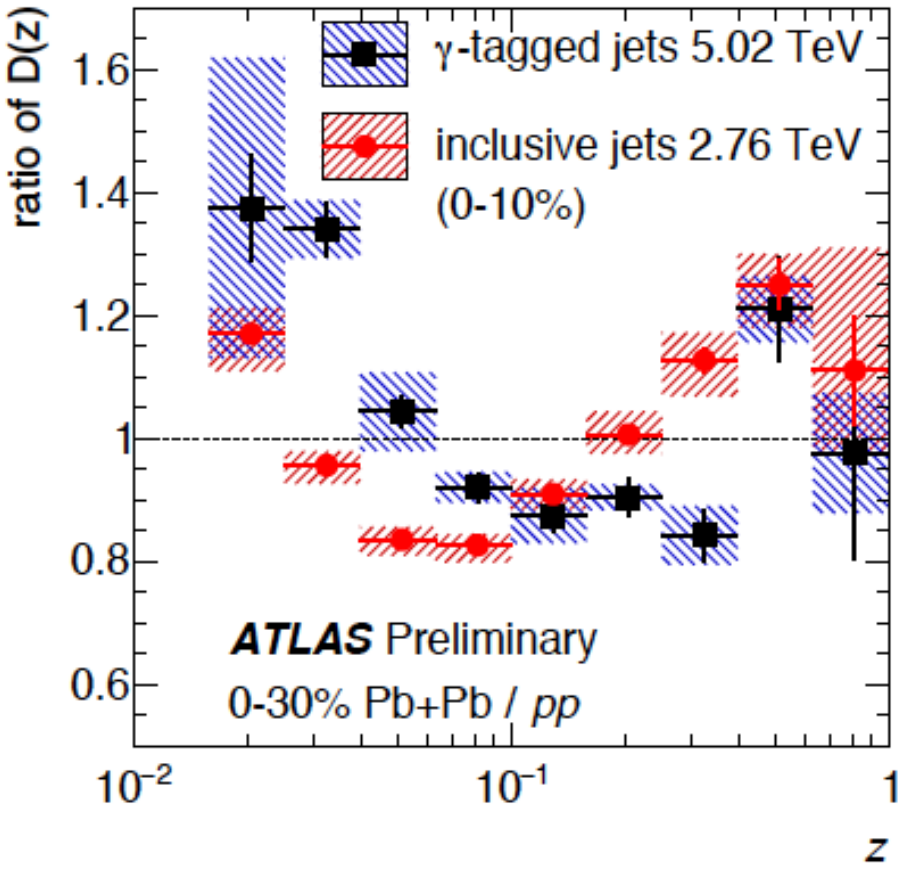
Miguel Arratia, HP2018

- **p+Pb looks a lot like pp**
- **Again, higher precision is needed**
- ***What effect of dense gluon medium at EIC??***

Compare to Pythia γ-jet simulation



Note from ATLAS



how much of this can be attributed just to flavor?

… and how much to selection effects?

(bias against strongly modified jets w/ ***inclusive selection****, but not with* ***photon tag****?)*

Situation at the EIC

- Does cold, dense gluon medium modify jets????
- Look inside reconstructed jets
- Easier:

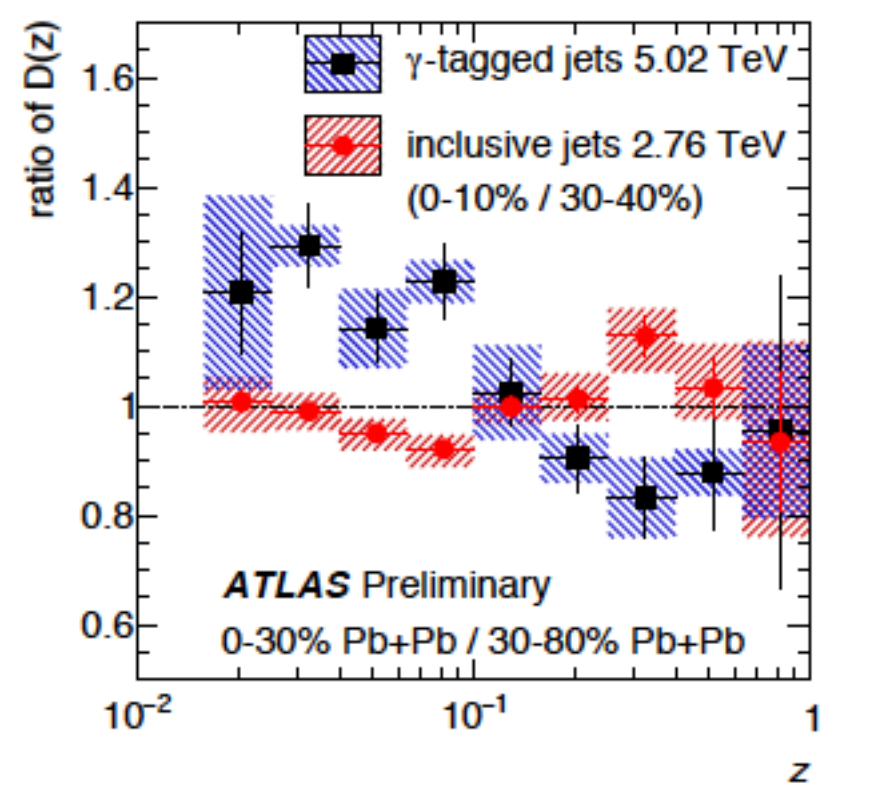
  low underlying event allows larger R jets

  smaller background -> easier to interpret
- Harder:

  . modification is likely small (how small?)

  . Photon tag absent
- Use DIS jets instead??

  . Need your advice



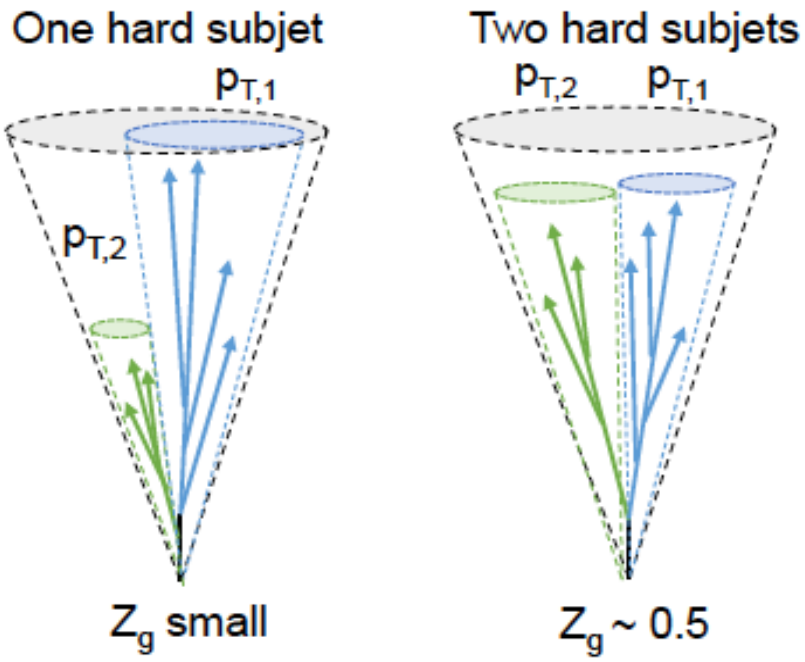
Jet substructure

- Undo the stepwise clustering of energy/particles into a jet

- "groom" the jet to remove the softest stuff
  pro: lets you look at the early splittings
  con: the soft stuff is very interesting

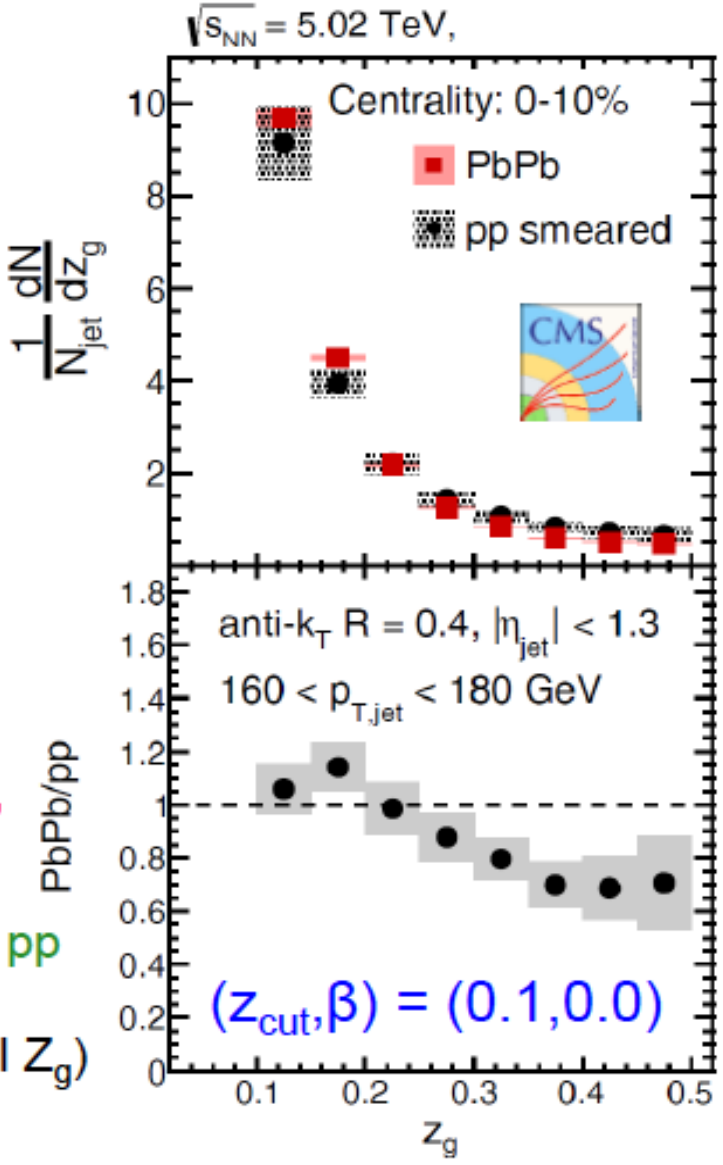
- Have a number of observables, I will talk about z_g and jet mass

Momentum Sharing of Subjets



$$Z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$

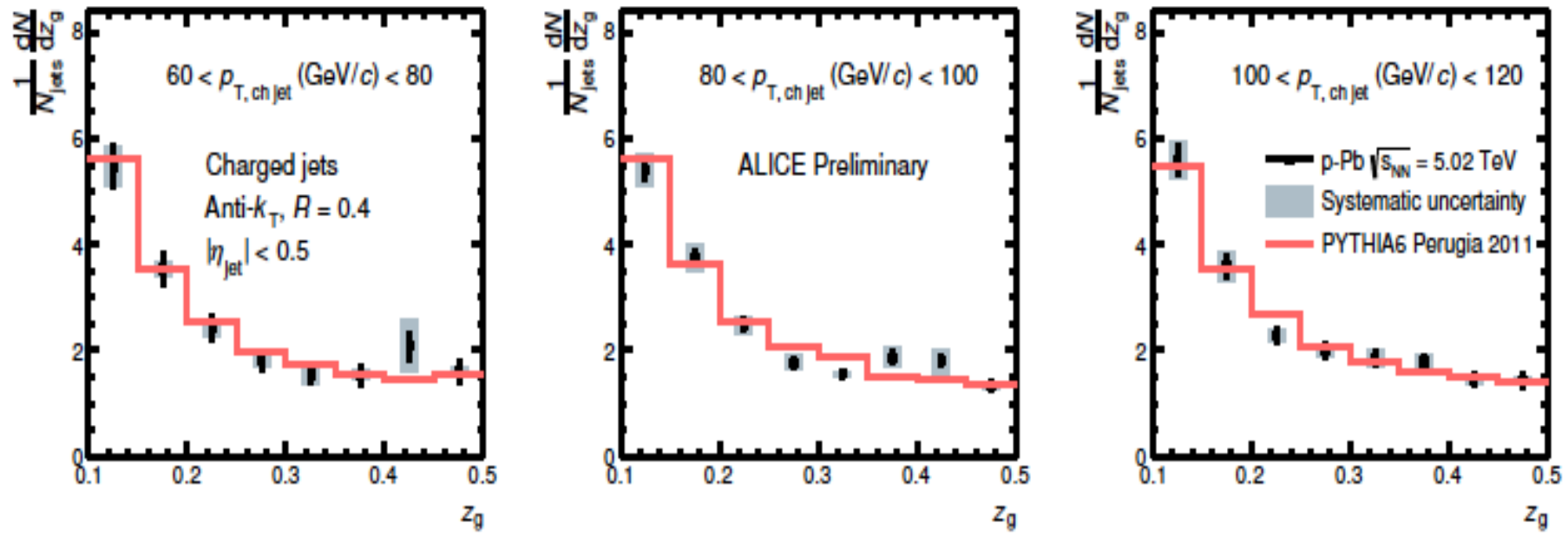
"Flat Grooming"



- Quark and gluon Z_g distributions are very similar in pp
- Jets with **two hard subjets** (large Z_g) **"relatively"** more suppressed than jets with a single core (small Z_g)

Dhanush Hangal | PRL 120 (2018) 142302

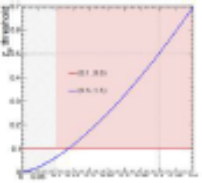
z_g in p+A



- p + Pb looks like PYTHIA (i.e. like pp)

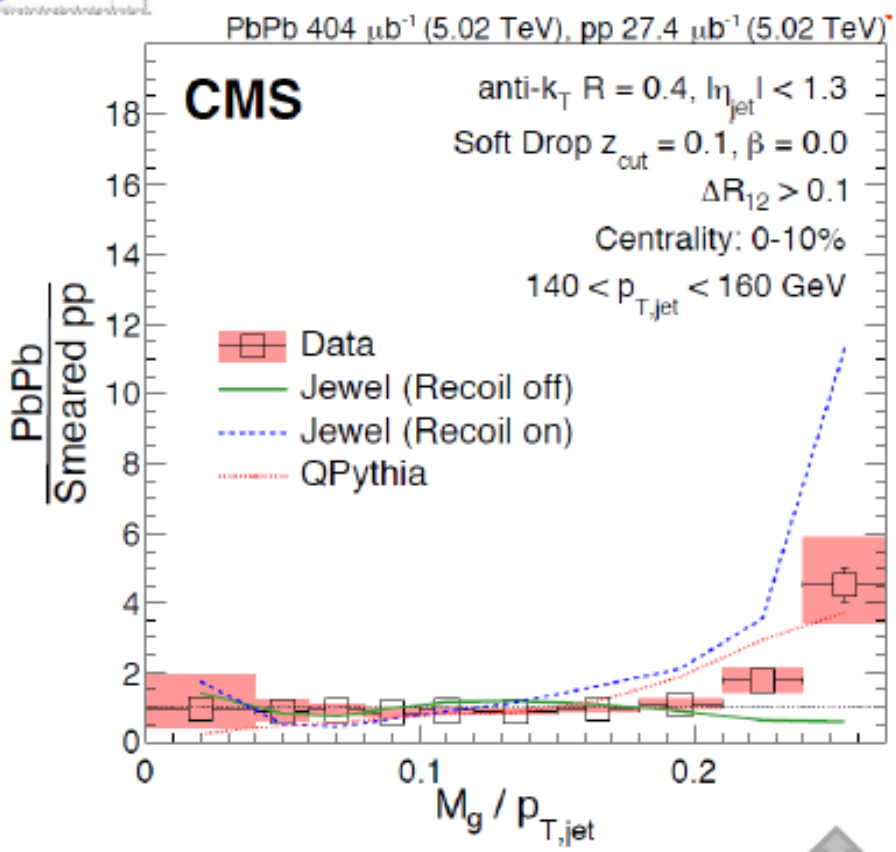
Will the dense gluon system probed by e+A affect the first splitting????

Groomed Jet Mass



$(z_{cut},\beta) = (0.1,0.0)$ $\Delta R>0.1$

"Flat Grooming"

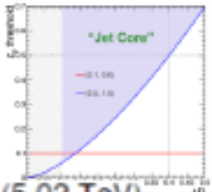


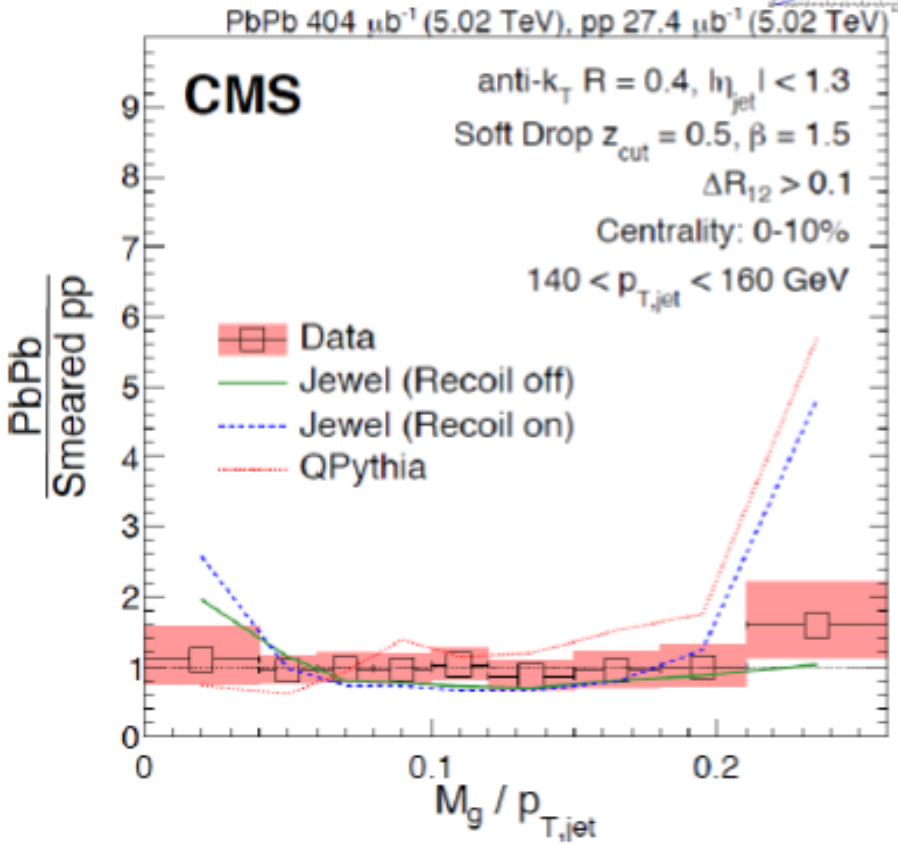
- Enhancement at large mass with flat grooming

arXiv:1805.05145

$(z_{cut},\beta) = (0.5,1.5)$ $\Delta R>0.1$

"Jet Core"

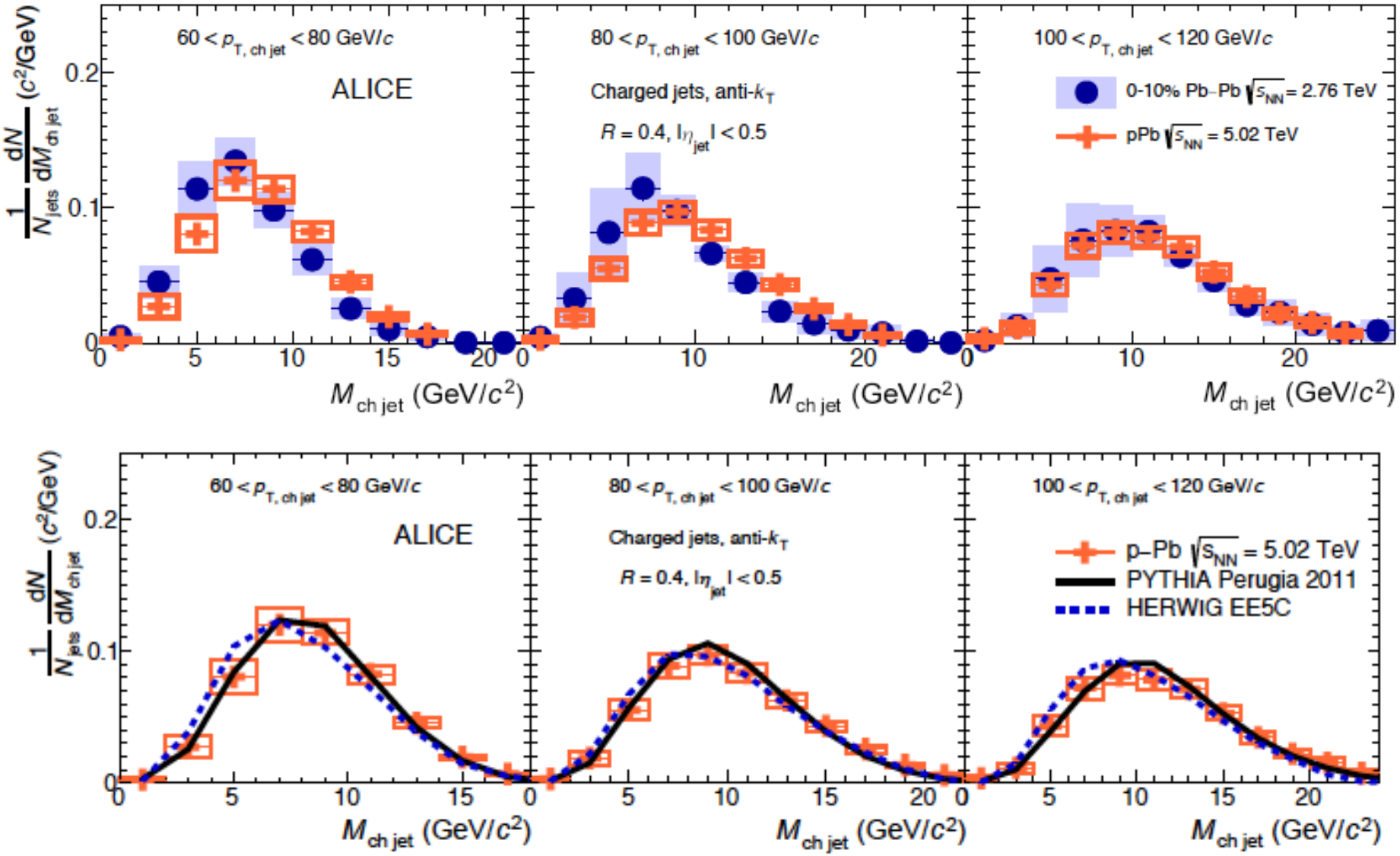




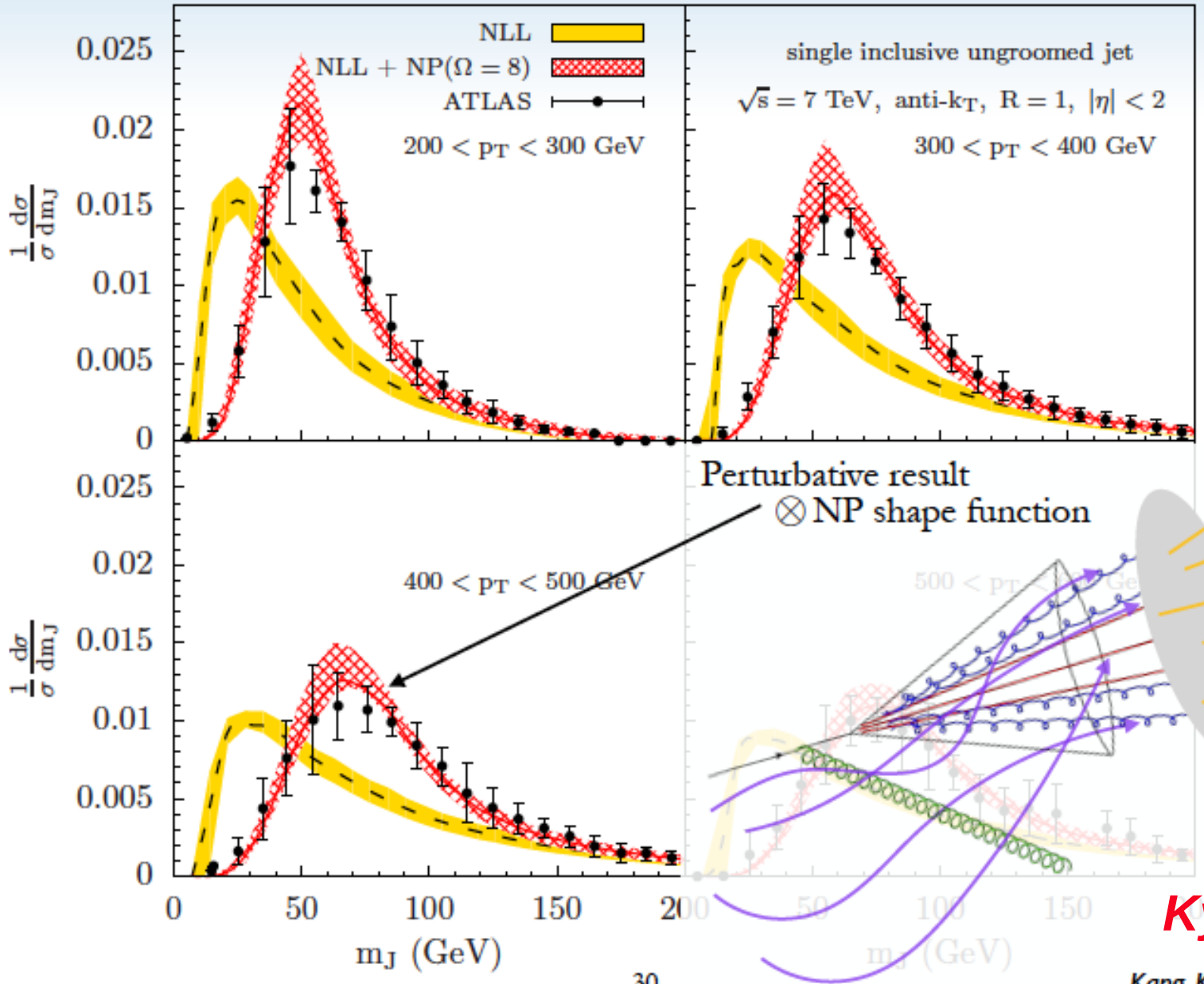
- "More aggressive grooming"
- Smaller or no significant modification of the "jet core"

Dhanush Hangal

Jet mass


60 < $p_{T,\text{ch jet}}$ < 80 GeV/c
80 < $p_{T,\text{ch jet}}$ < 100 GeV/c
100 < $p_{T,\text{ch jet}}$ < 120 GeV/c
ALICE
Charged jets, anti-k_T
R = 0.4, $|\eta_{\text{jet}}| < 0.5$
0-10% Pb–Pb $\sqrt{s_{NN}}$ = 2.76 TeV
pPb $\sqrt{s_{NN}}$ = 5.02 TeV
p–Pb $\sqrt{s_{NN}}$ = 5.02 TeV
PYTHIA Perugia 2011
HERWIG EE5C
$\frac{1}{N_{\text{jets}}}\frac{dN}{dM_{\text{ch jet}}}$ (c^2/GeV)
$M_{\text{ch jet}}$ (GeV/c^2)

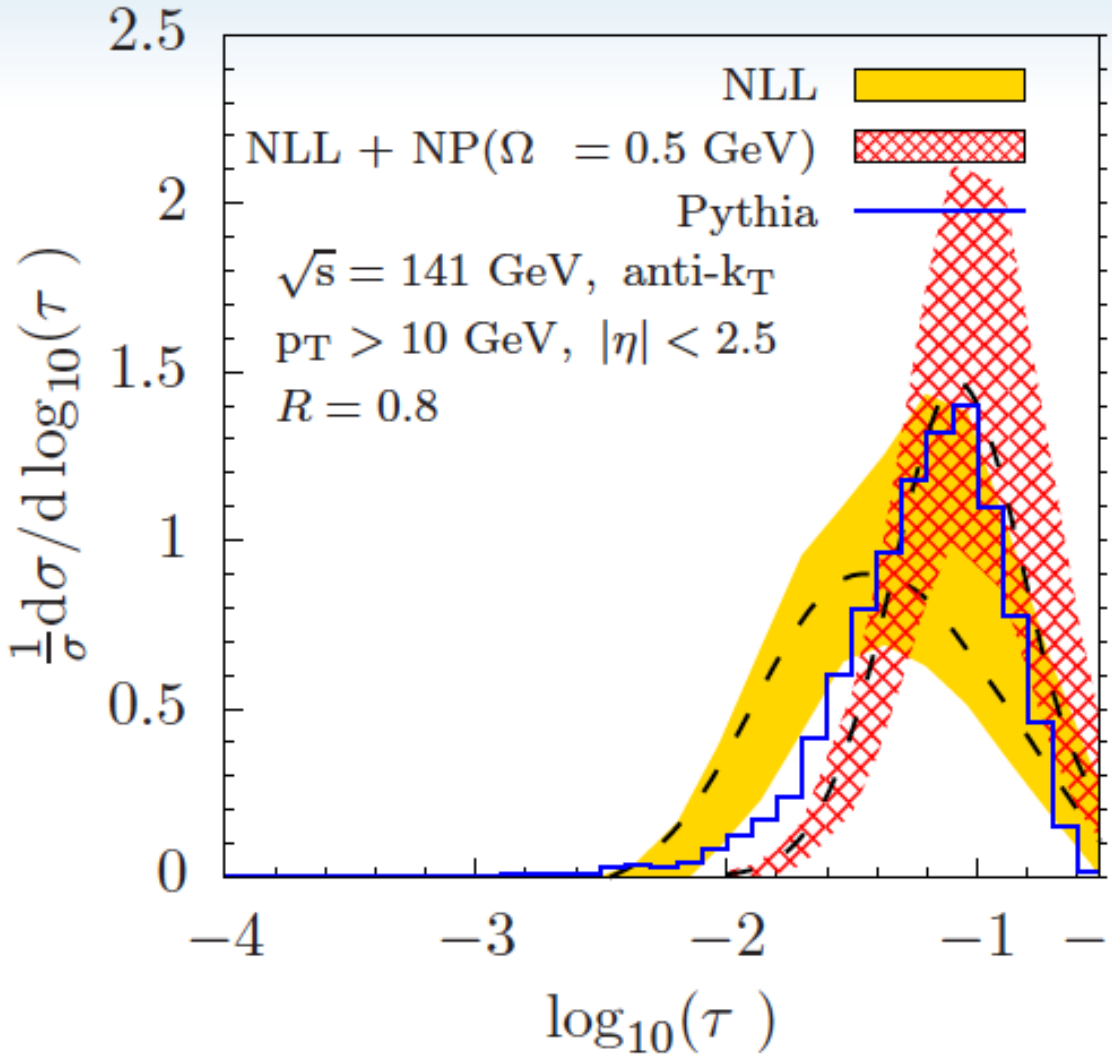
Phenomenology



Kyle Lee

Kang, KL, Liu, Ringer `18

Shift from hadronization effects



- Even without grooming, EIC results only require a small shift to agree with the Pythia result. ($\Omega \approx \Lambda_{QCD}$)
- NP effects mostly from hadronization.

Non-perturbative effects

In collaboration with Elke Aschenauer and Brian Page

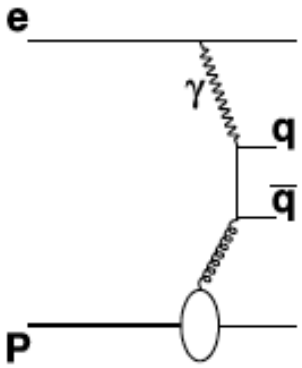
Conclusions

- **Jets at EIC will be soft (like at RHIC)**
- **p+A collisions suggest that jet modifications will be (very?) small**
- **Mapping early splitting as a function of A in eA would be valuable (and probably doable…)**
- **DIS jets could be interesting in eA**
- **Dijets offer a way to study the photon structure at EIC**

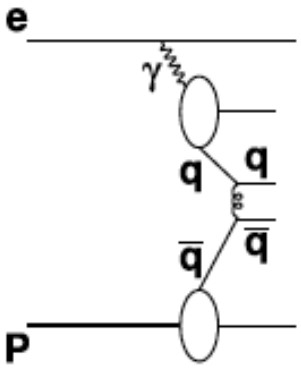
- **Backup**

Photon Parton Structure

In high energy ep collision, two types of processes lead to the production of di-jets:



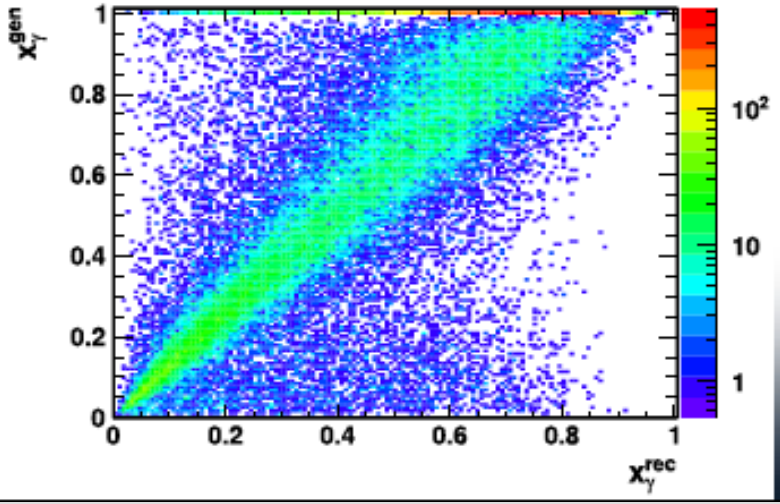
direct: point-like photon

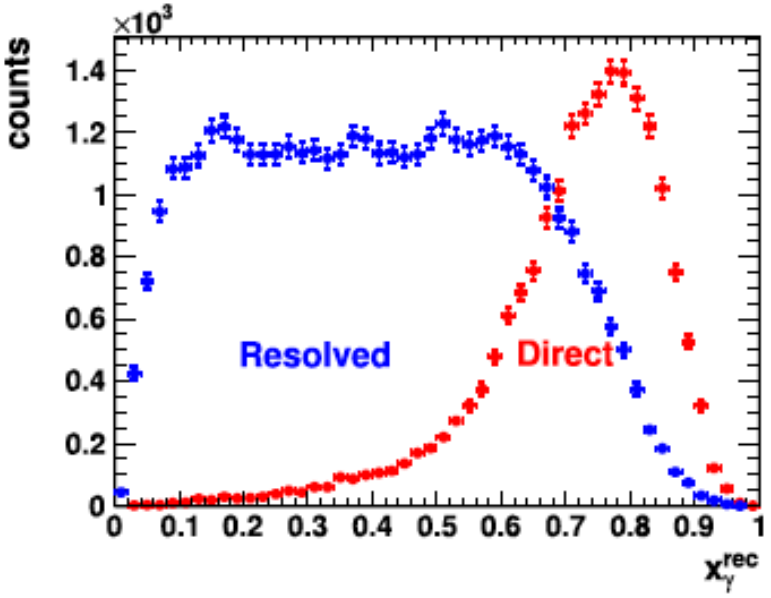


resolved: hadronic photon

- **Di-jets@EIC ideal probe to constrain (un)polarised Photon-PDFs**
  - **Direct/resolved contributions can be separated** reconstructing xγ

$$x_\gamma^{rec} = \frac{1}{2E_e y}(p_{T1}e^{-\eta_1} + p_{T2}e^{-\eta_2})$$





Chu, Aschenauer, Lee, Zheng; arXiv: 1705.0883

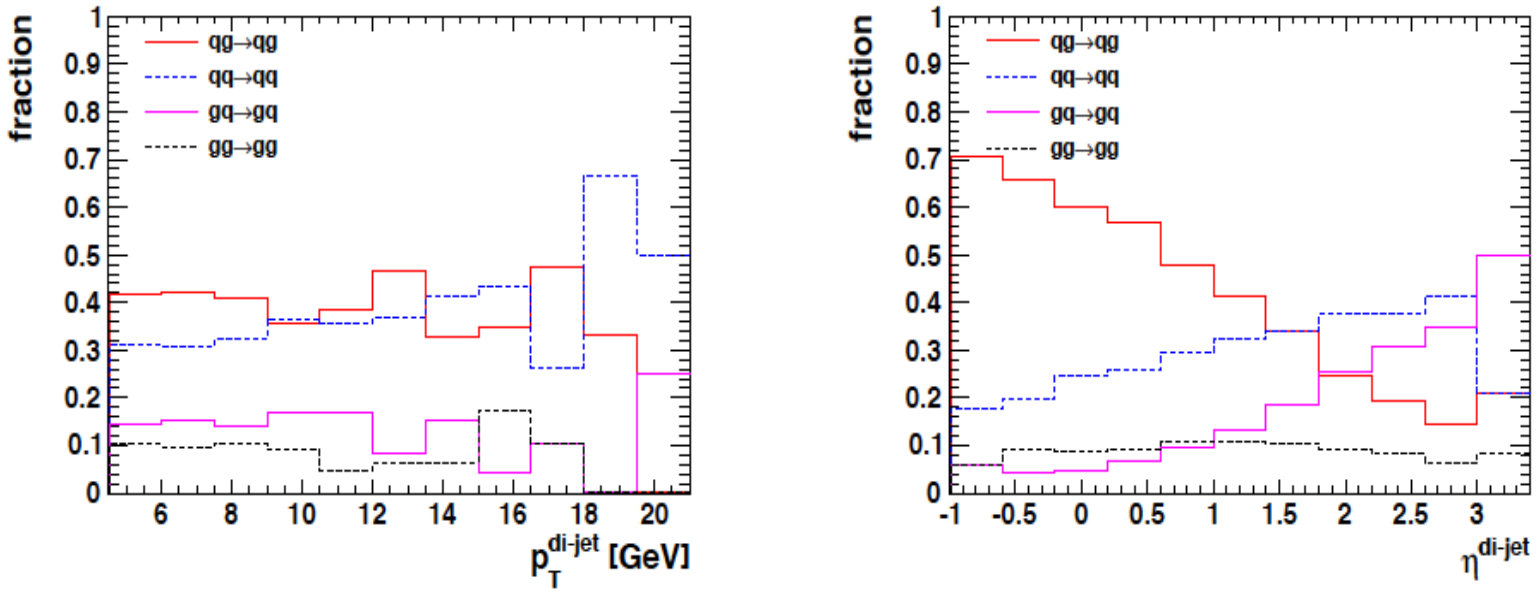


FIG. 7. [color online] Left: the fraction of the major subprocesses of the resolved process dependence on $p_T^{\text{di-jet}}$. Right: the fraction distribution dependence on $\eta^{\text{di-jet}} = \frac{\eta^{\text{jet1}}+\eta^{\text{jet2}}}{2}$.

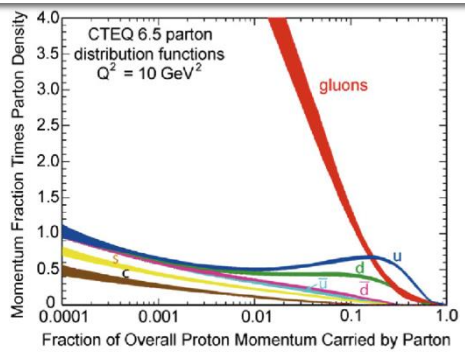
How can system thermalize quickly?

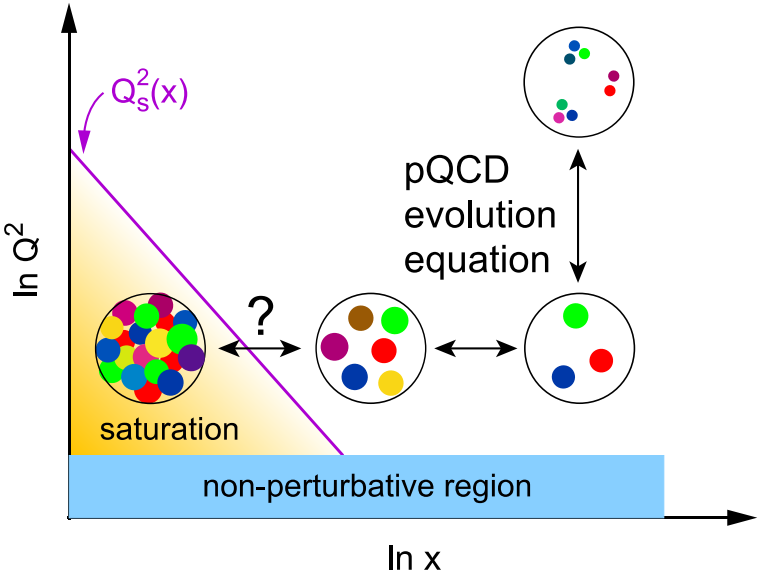
- **One of the key questions for hot QCD**
  But it's very hard to measure directly!

- **To pin down physics of many-body QCD in hot dense matter:**
  How is the deposited energy transported?
  Heavy vs. light quark probes
  How are jets quenched?

  - **How important is coherent scattering?**
  - **Parton interactions in hot, dense QCD and cold, dense QCD should be similar**

What is deep in the nucleus?





What tames the low-x rise?

- New evolution eqn.s @ low x & moderate Q^2
- Saturation Scale $Q_S(x)$ where gluon emission and recombination comparable

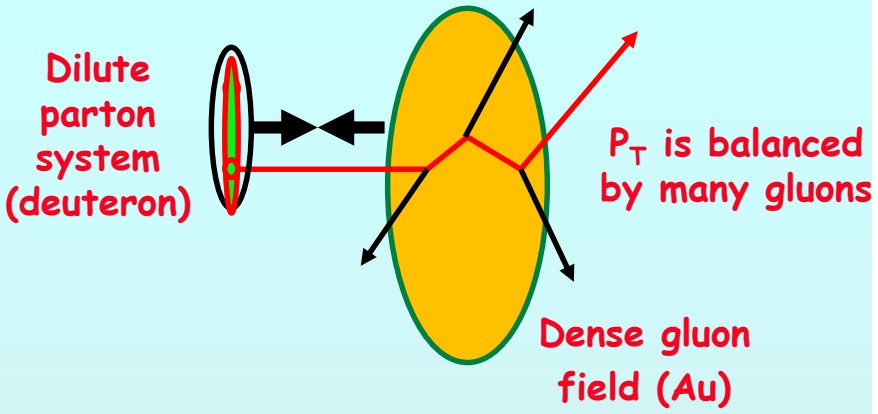
gluon emission = gluon recombination

At Q_S

First observation of gluon recombination effects in nuclei:
➔leading to a collective gluonic system!

First observation of g-g recombination in different nuclei
→ Is this a universal property?
→ Is the Color Glass Condensate the correct effective theory?

See hints at RHIC for saturation of gluons

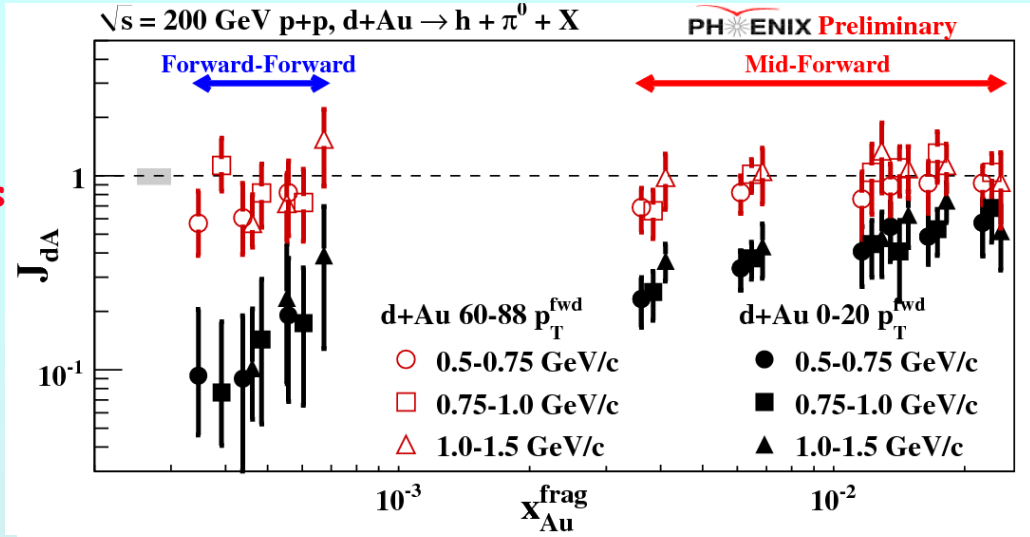


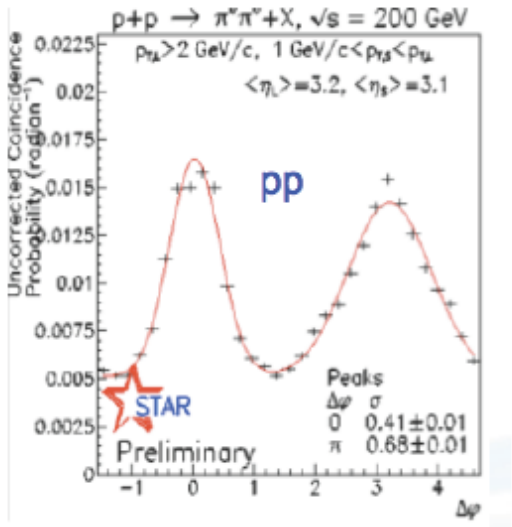
Saturated gluon field is easier to equilibrate???

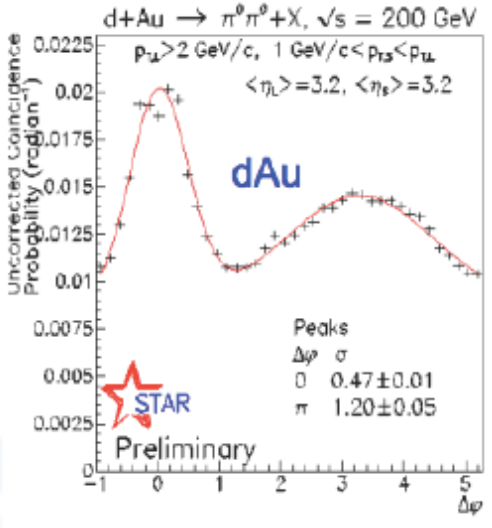
QCD Compton scattering to find out (q+g -> q+γ):

no final state effects on γ!

Being measured now…

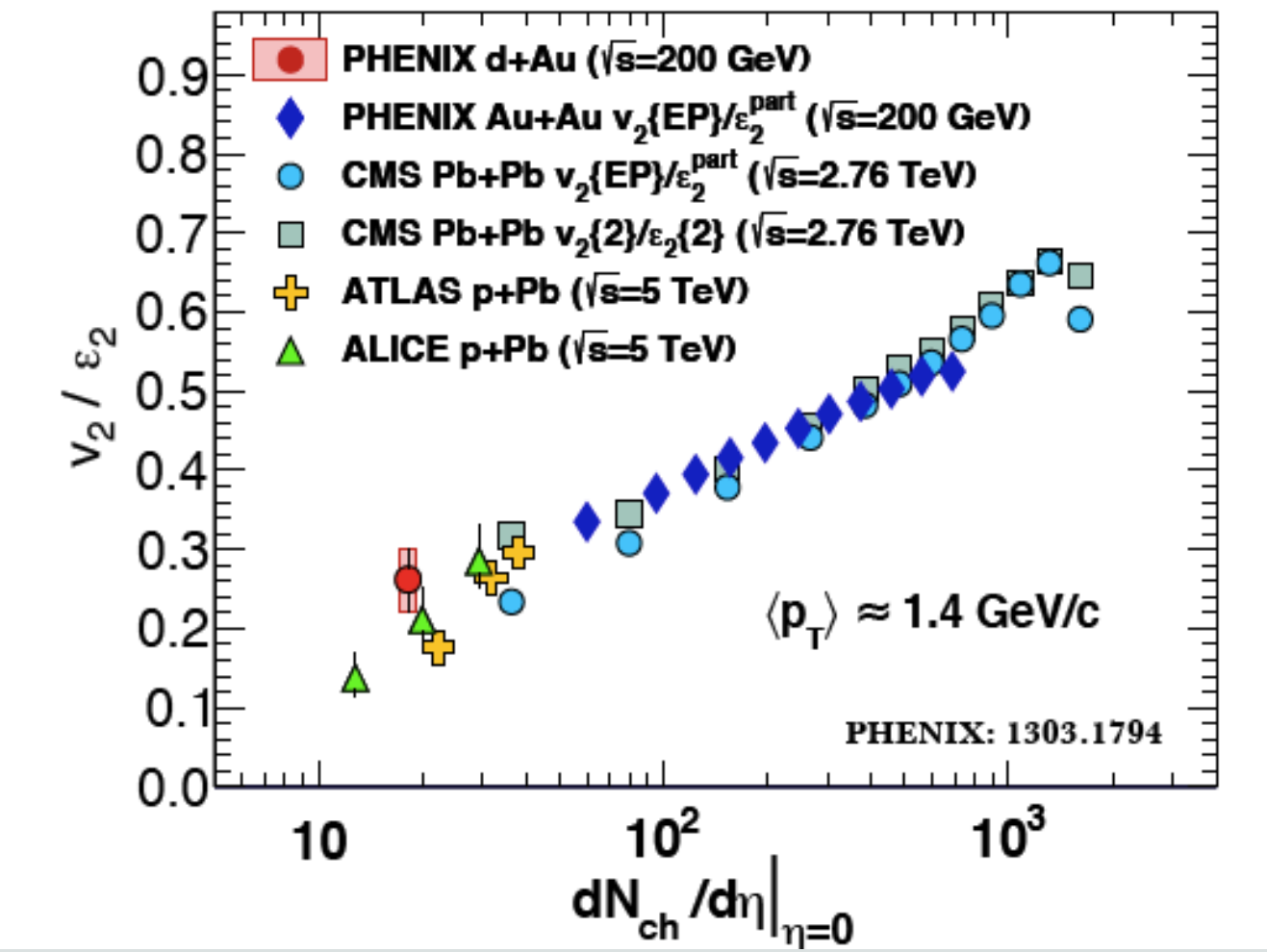






But – incoming parton dynamics are still confusing (the probe loses energy)

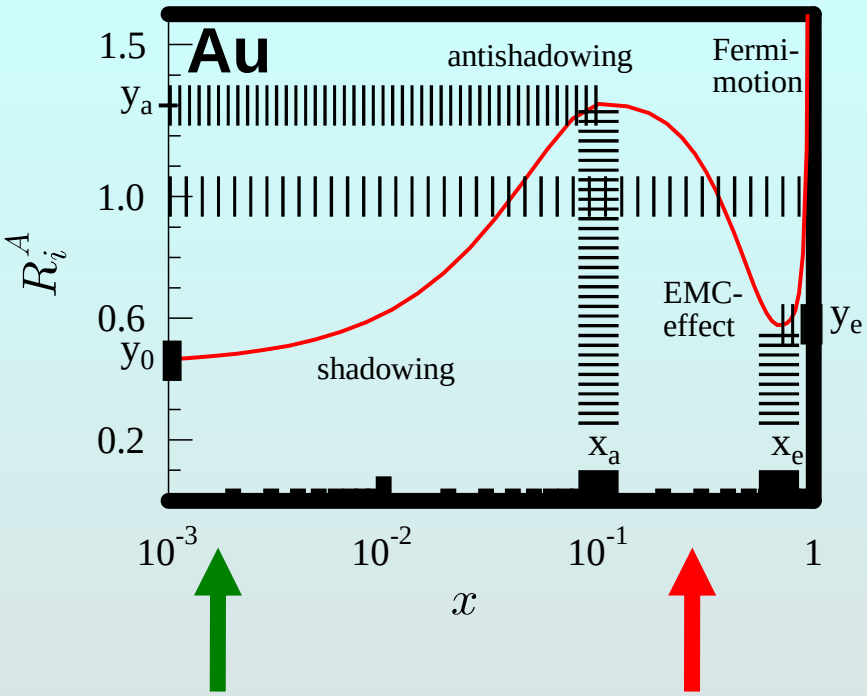
Small systems: drop of QGP even there?



p/d + A show same trend as A + A

hydrodynamics in small systems?!

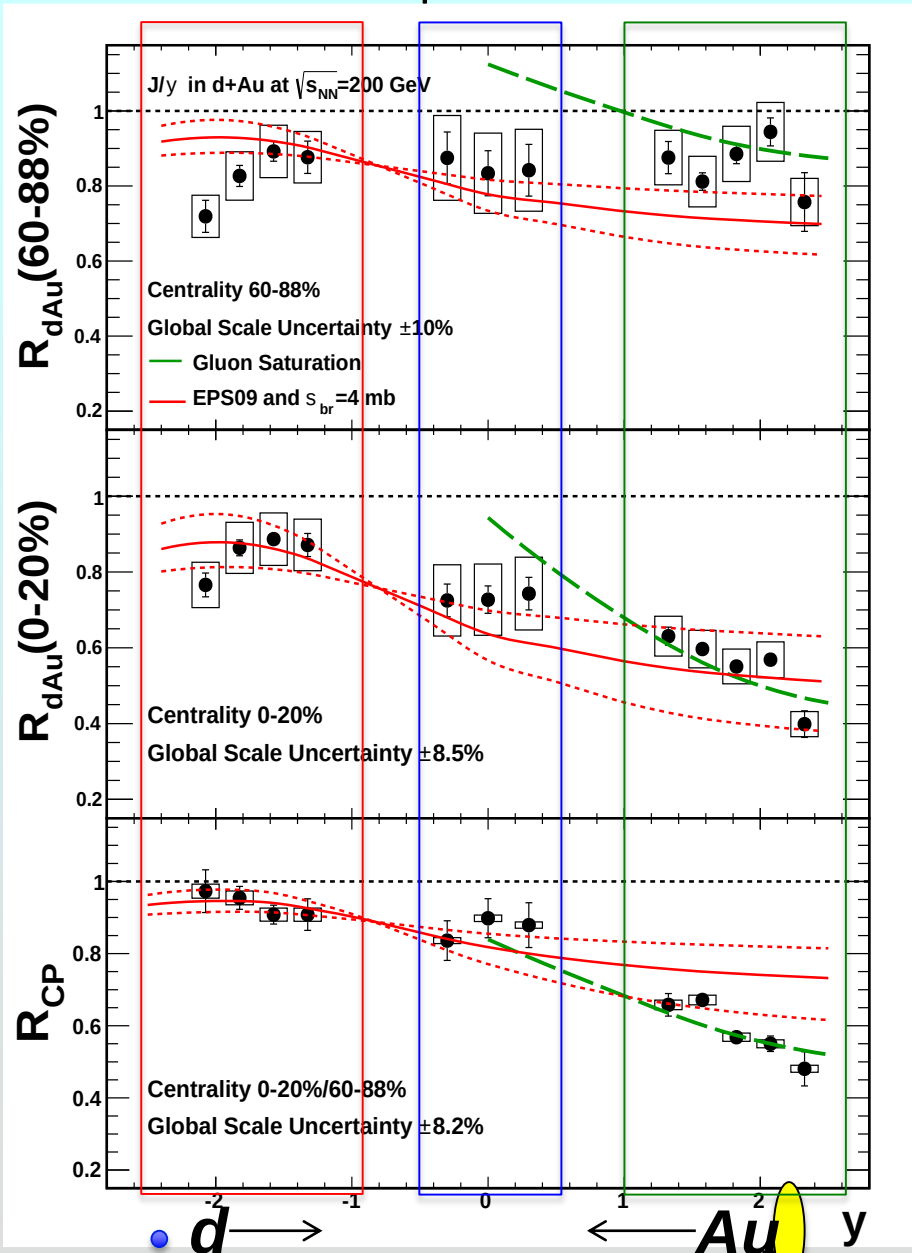
Initial State: what's where?



Forward
+ y
d-going

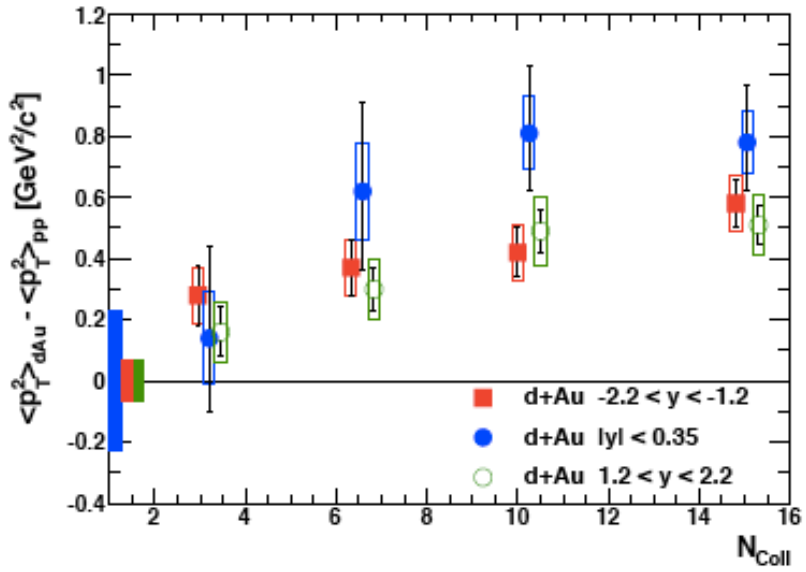
Backward
- y
Au-going

d+Au -> J/ψ from PHENIX

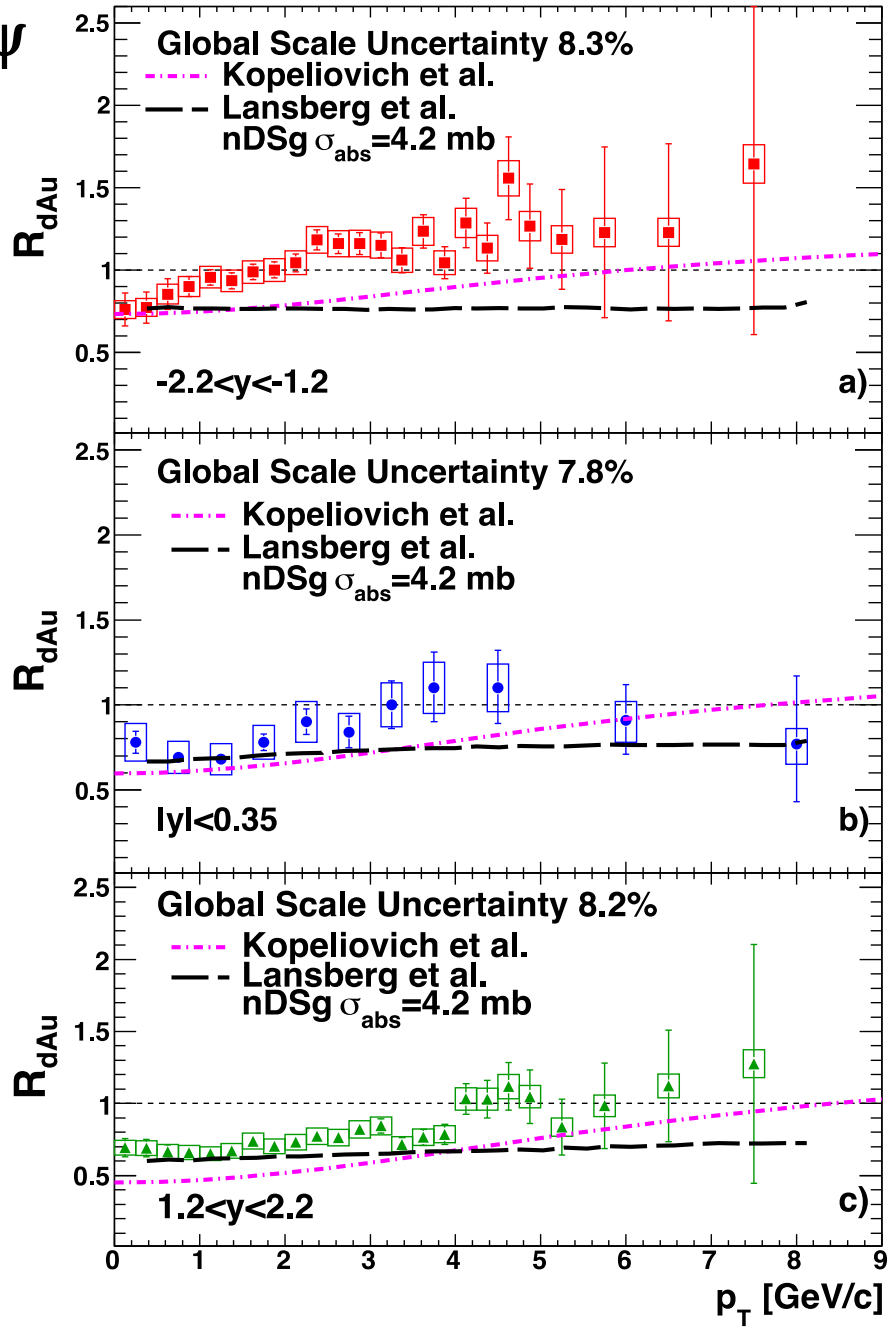


Shadowing, breakup & Cronin effect

PRC87, 034911 (2013)



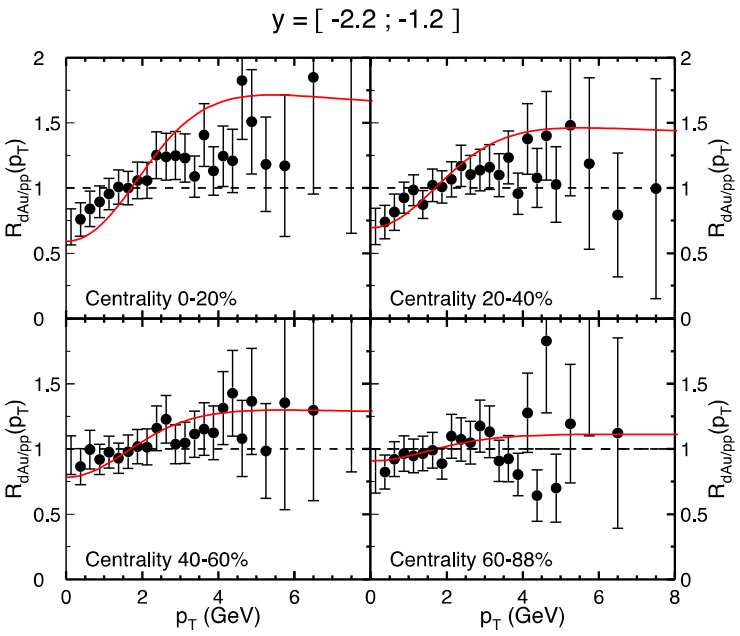
J/ψ

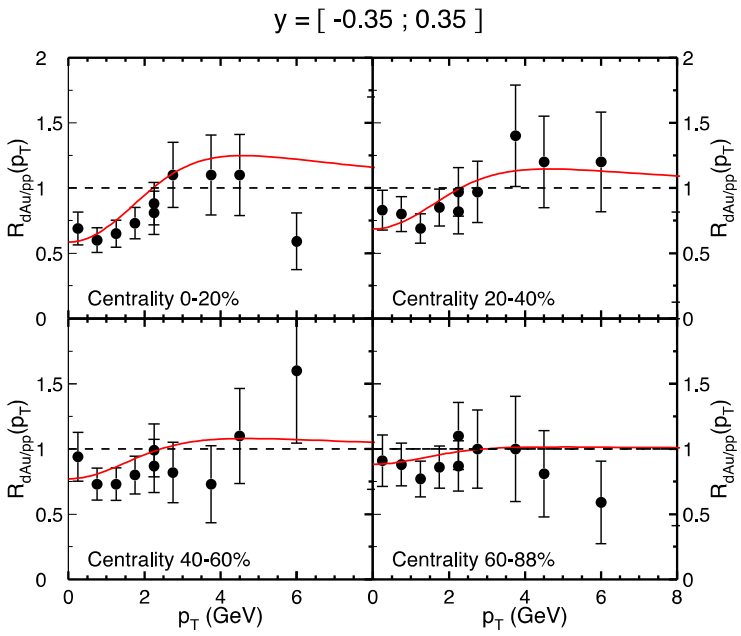


- p_T broadens (multiple scattering) w/N_{coll}; effect stronger at y=0
- J/ψ suppressed to higher p_T @ mid & forward y (lower x in Au);
- R_{dA}>1 at high p_T backward (Cronin effect in Au nucleus)
- p_T, y, centrality dependence was not reproduced by the models

but

Arleo, et al 1304.090





coherent parton energy loss and p_T broadening from multiple scattering in the nucleus is consistent with data!

$\hat{q}_0 = 0.075$ GeV^2/fm