Jet Measurements in pp and AA

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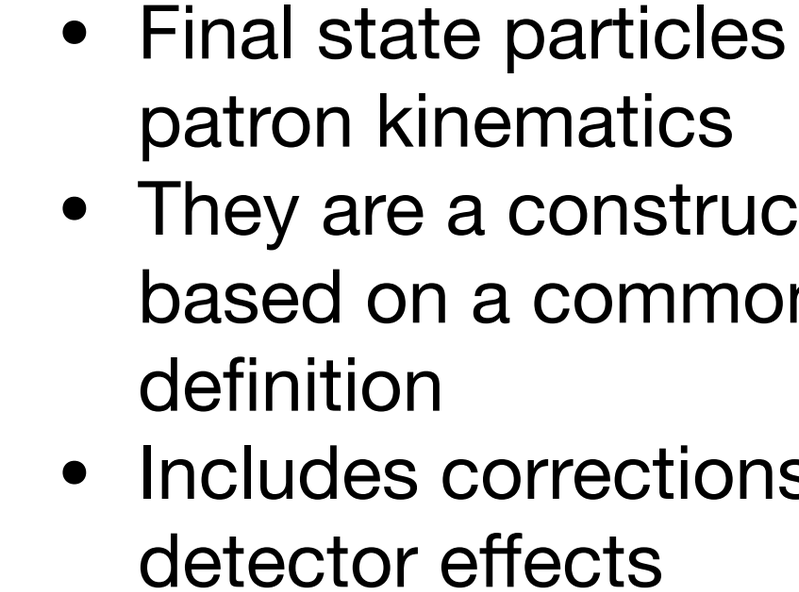
Berkeley, California

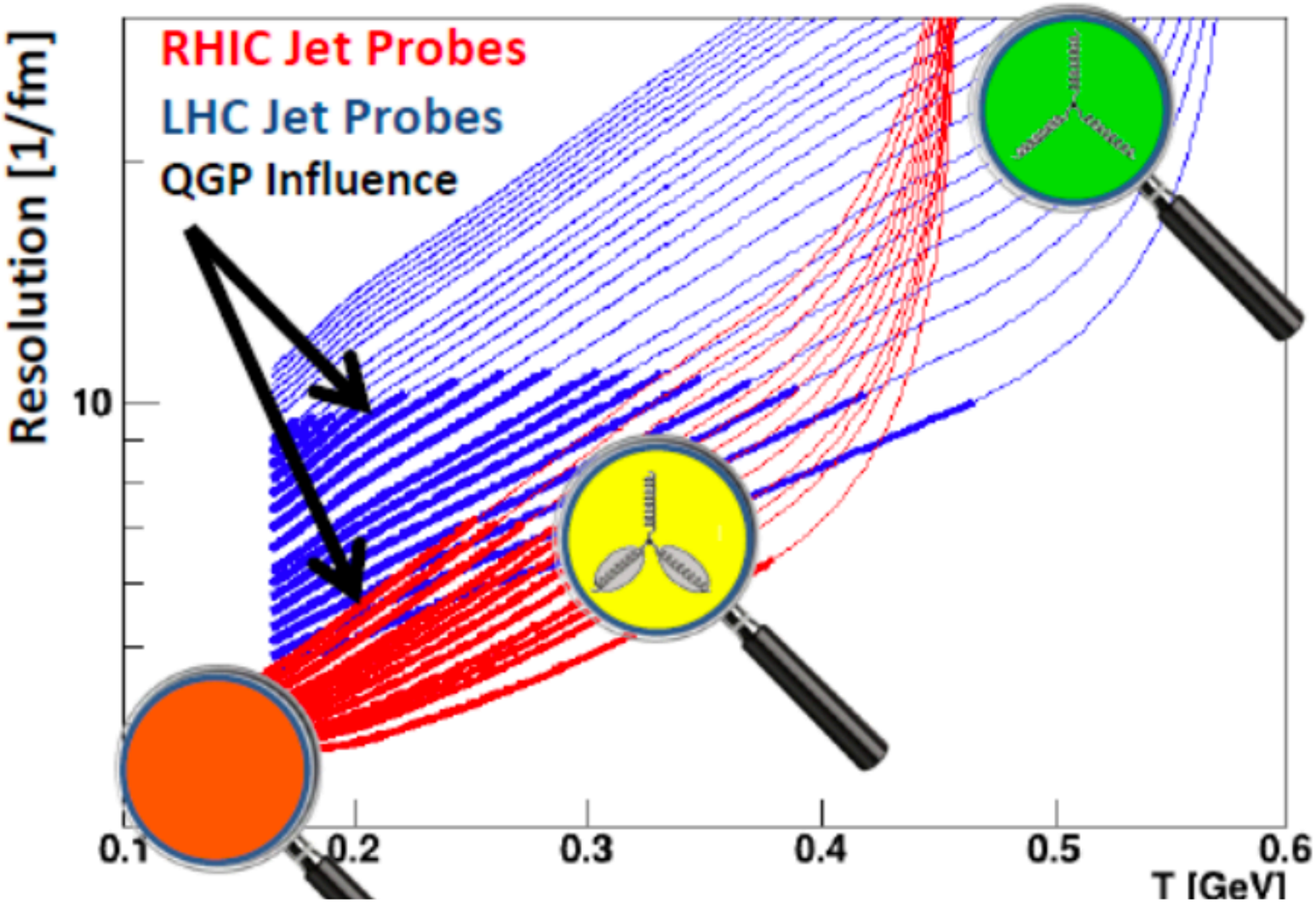
Jets In Data

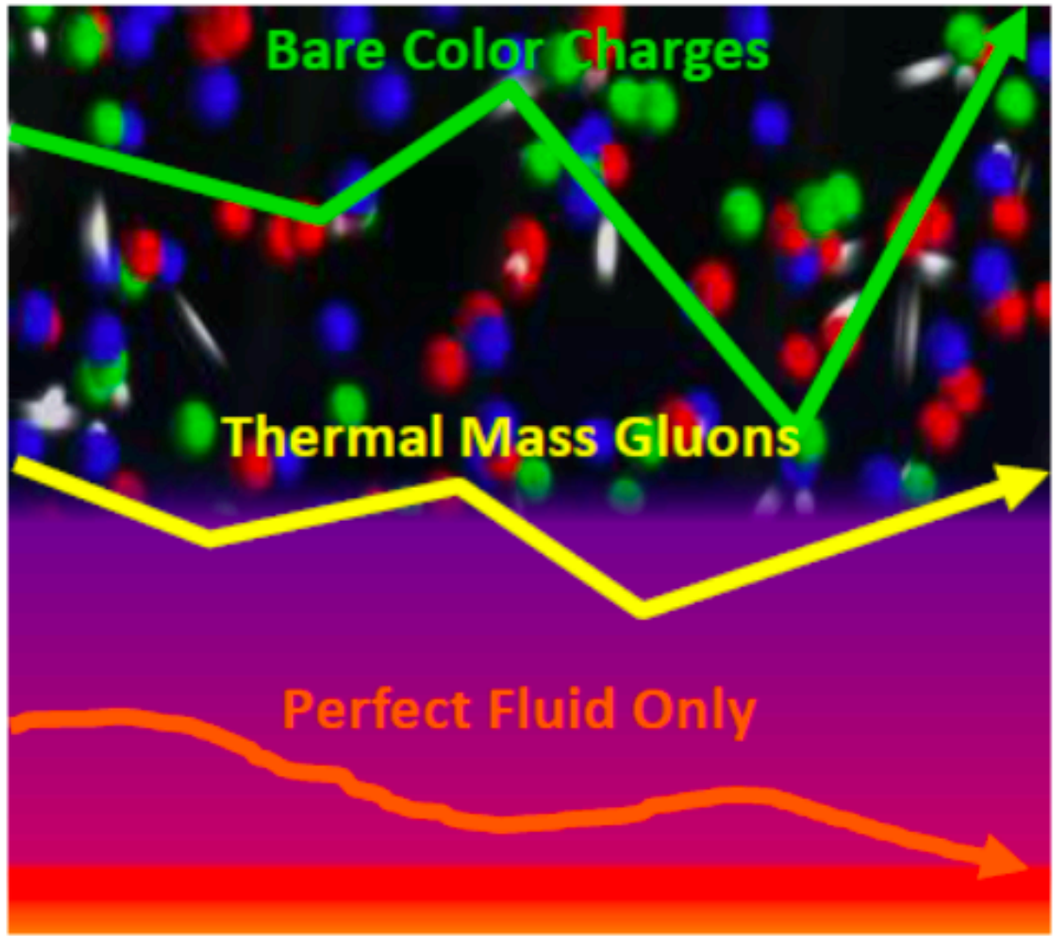
- Final state particles to patron kinematics
- They are a construct - based on a common definition
- Includes corrections for detector effects
- Comes with uncertainties



Salam G, ‘09

Stefan Hoche 1411.4085

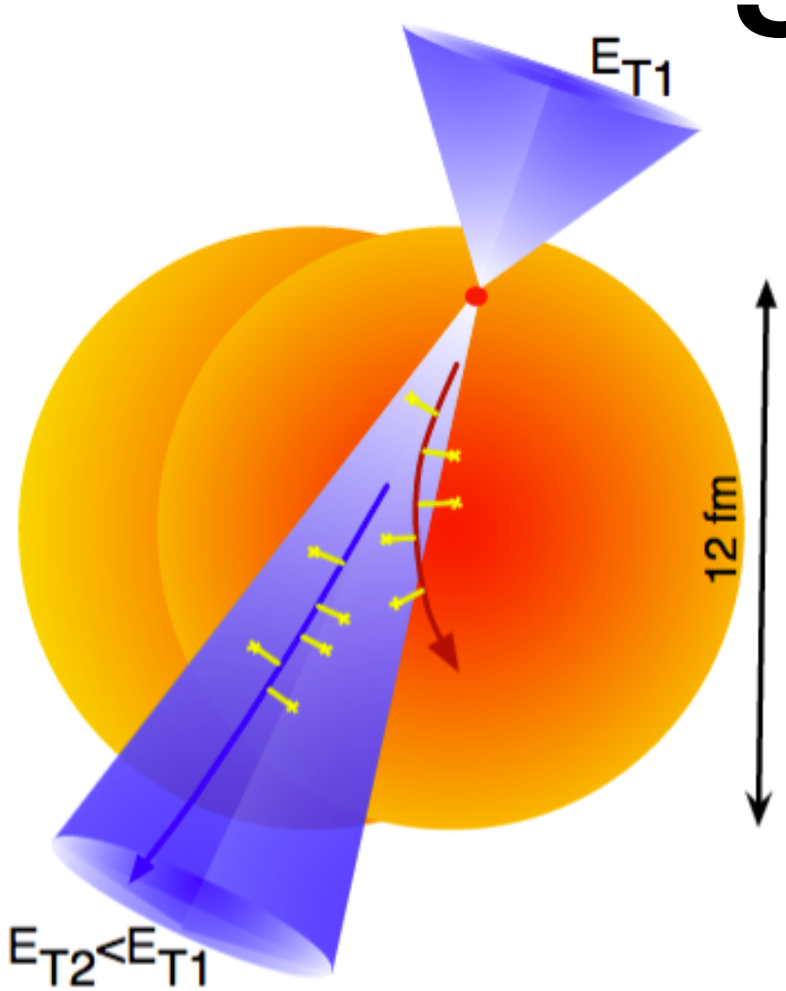


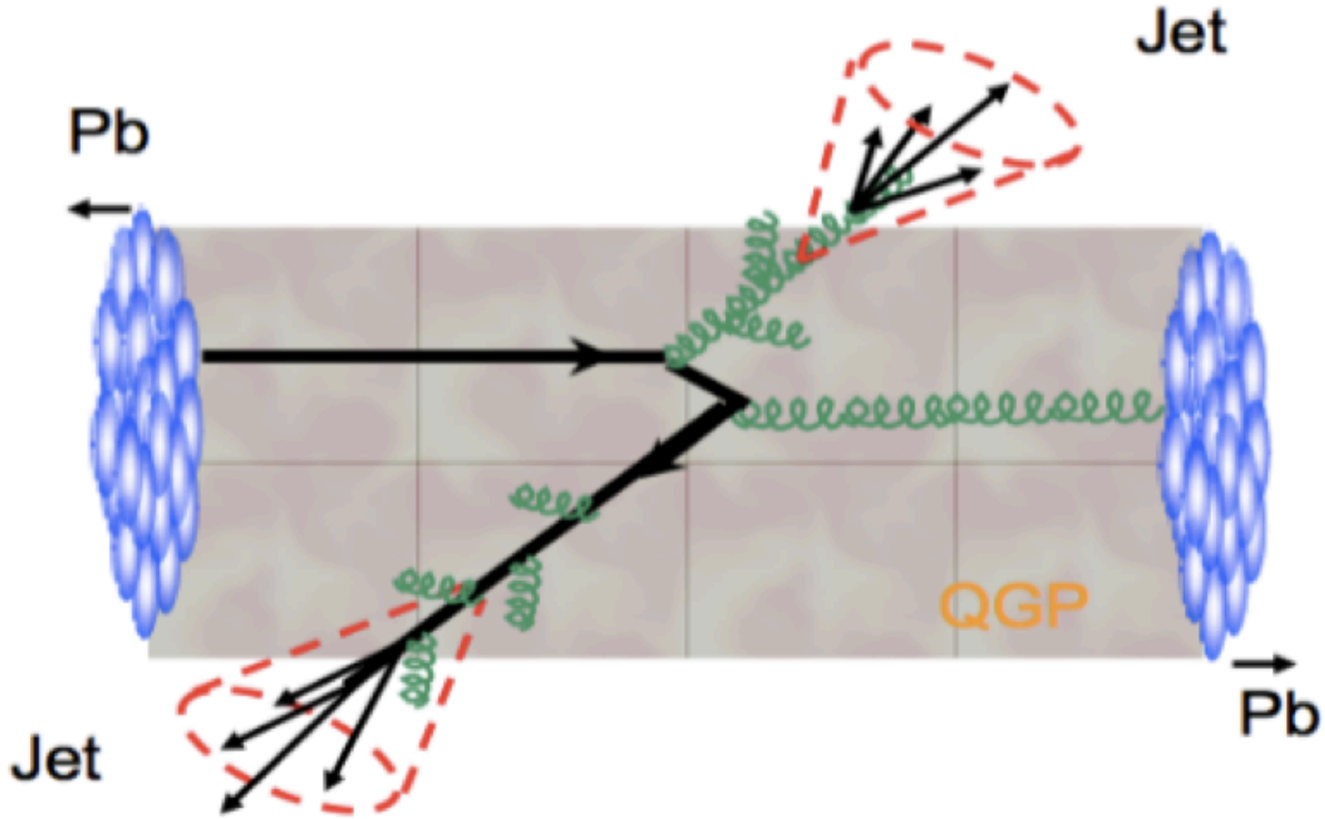


"These studies have shown that the interaction of a jet with the medium does not detectably alter the direction of the jet as a whole and that while the energy loss is substantial, the depleted jets that emerge from the droplet are not substantially modified in other respects."

2015 NP-LRP

Lets start with something simple

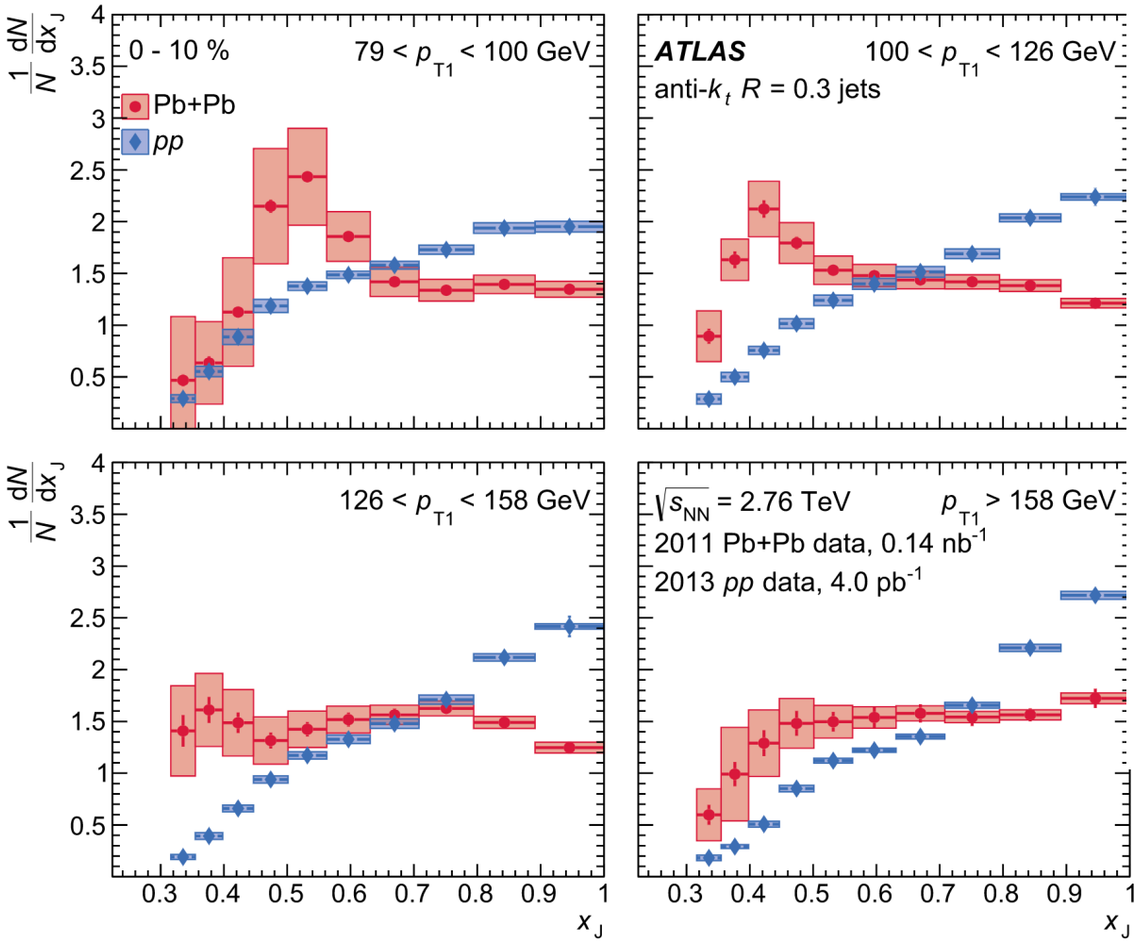




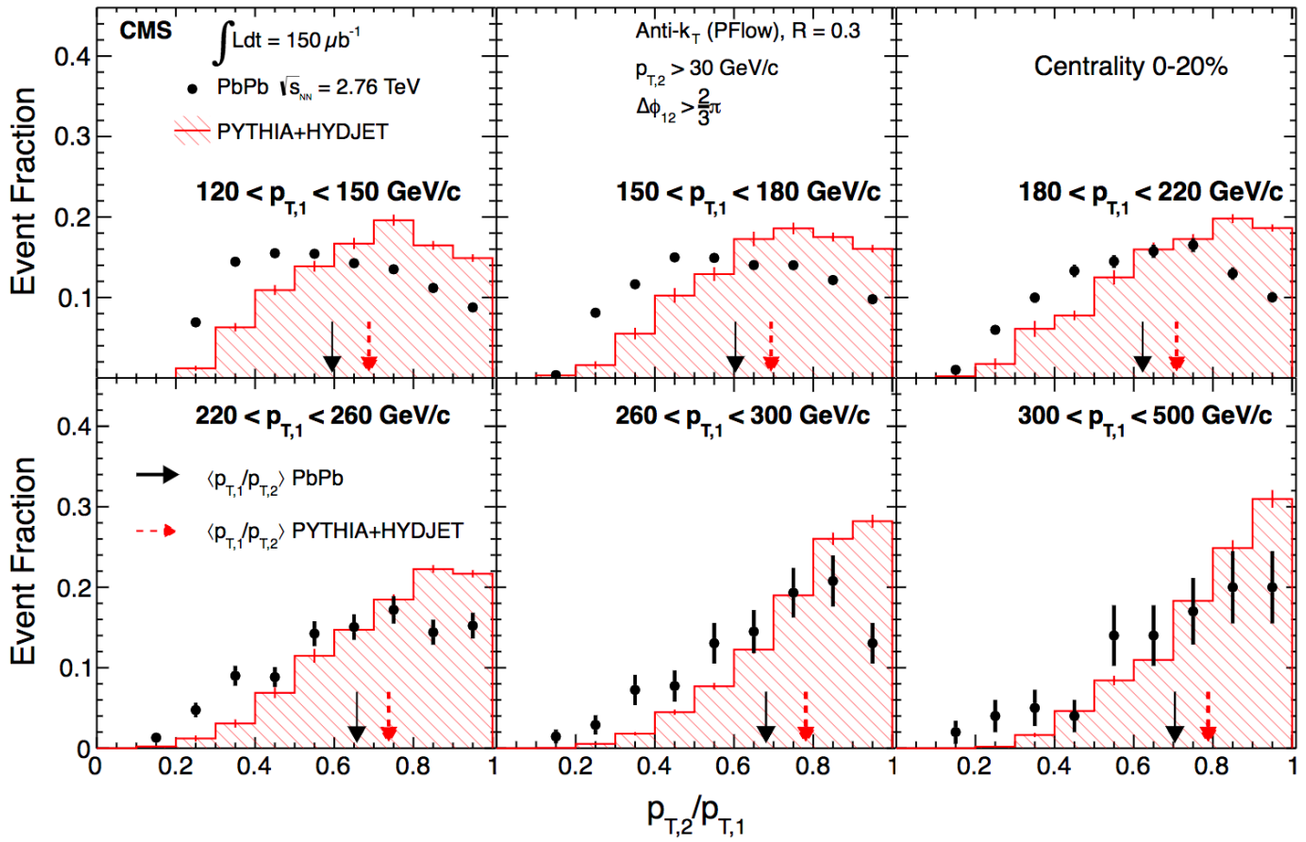
Ensemble distributions based on simple assumptions/expectations from QCD

Dijet Asymmetry

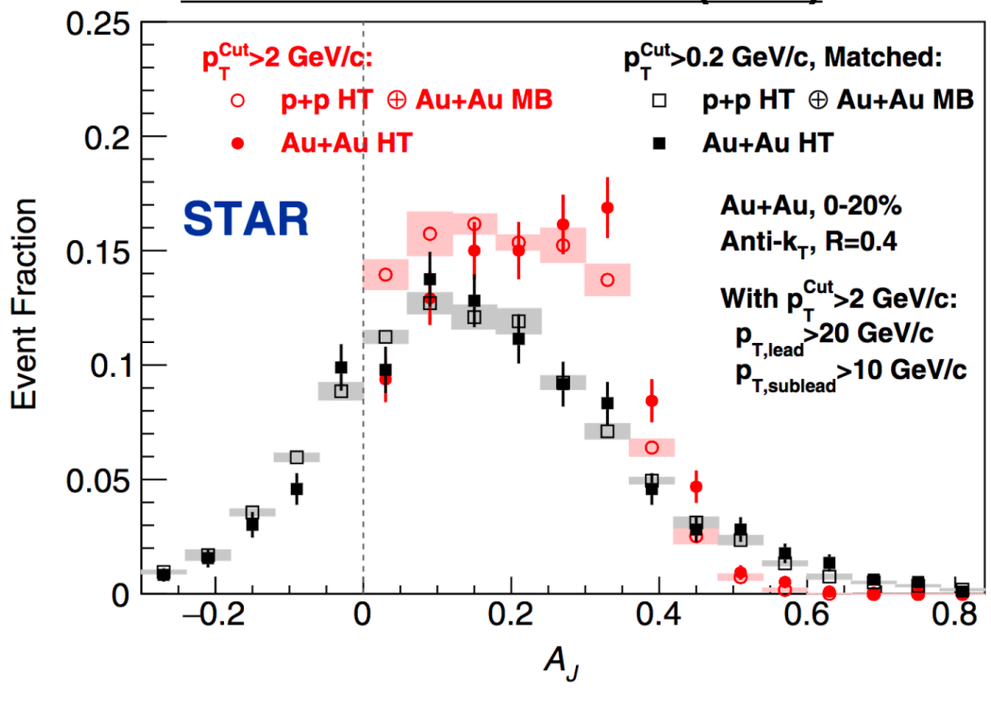
ATLAS - PLB 774 (2017) 379-402



CMS - PLB 712 (2012) 176



STAR - PRL 119 062301 (2017)



- Very clear dependence of asymmetry on centrality
- Medium induced fluctuations interactions leads to asymmetry (JEWEL)

Eur.Phys.J. C76 (2016) no.5, 288

Dijet Asymmetry

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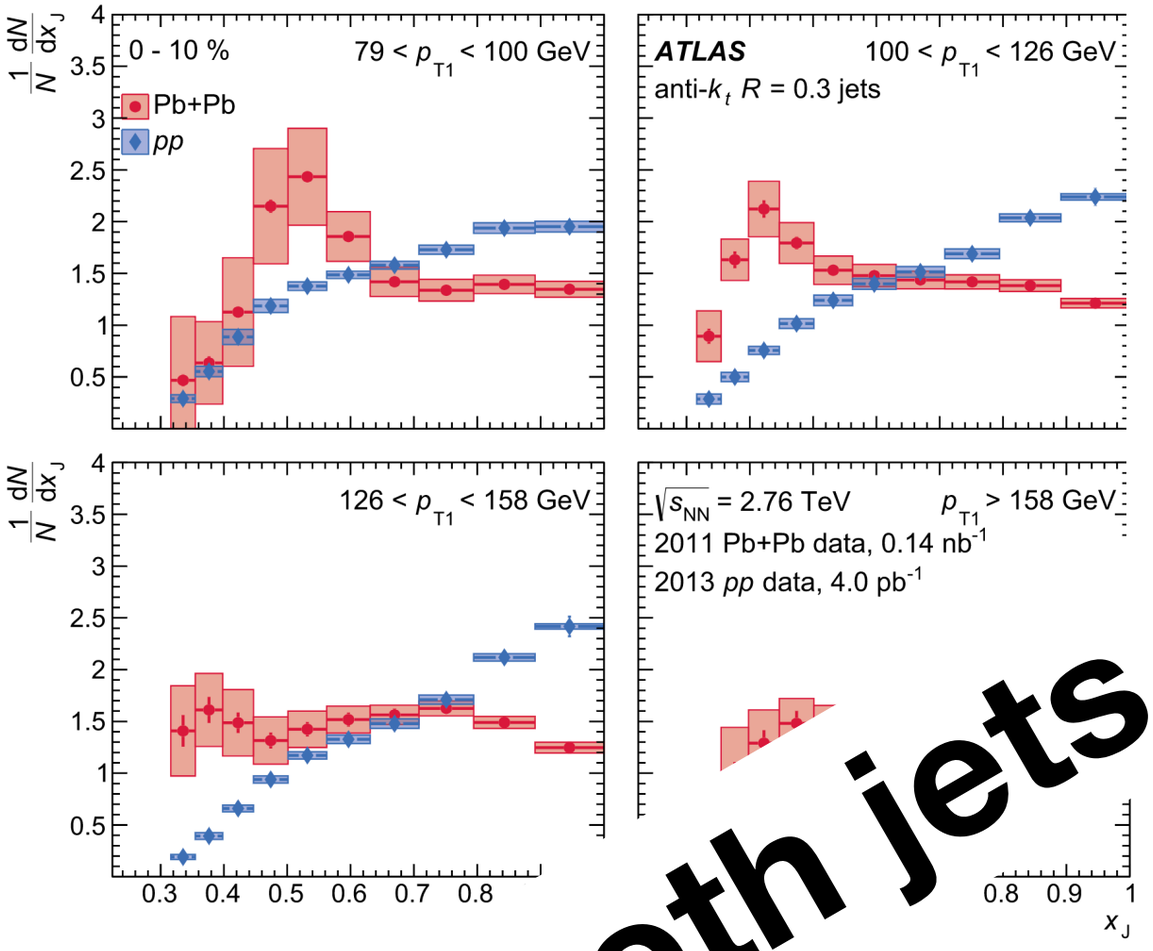

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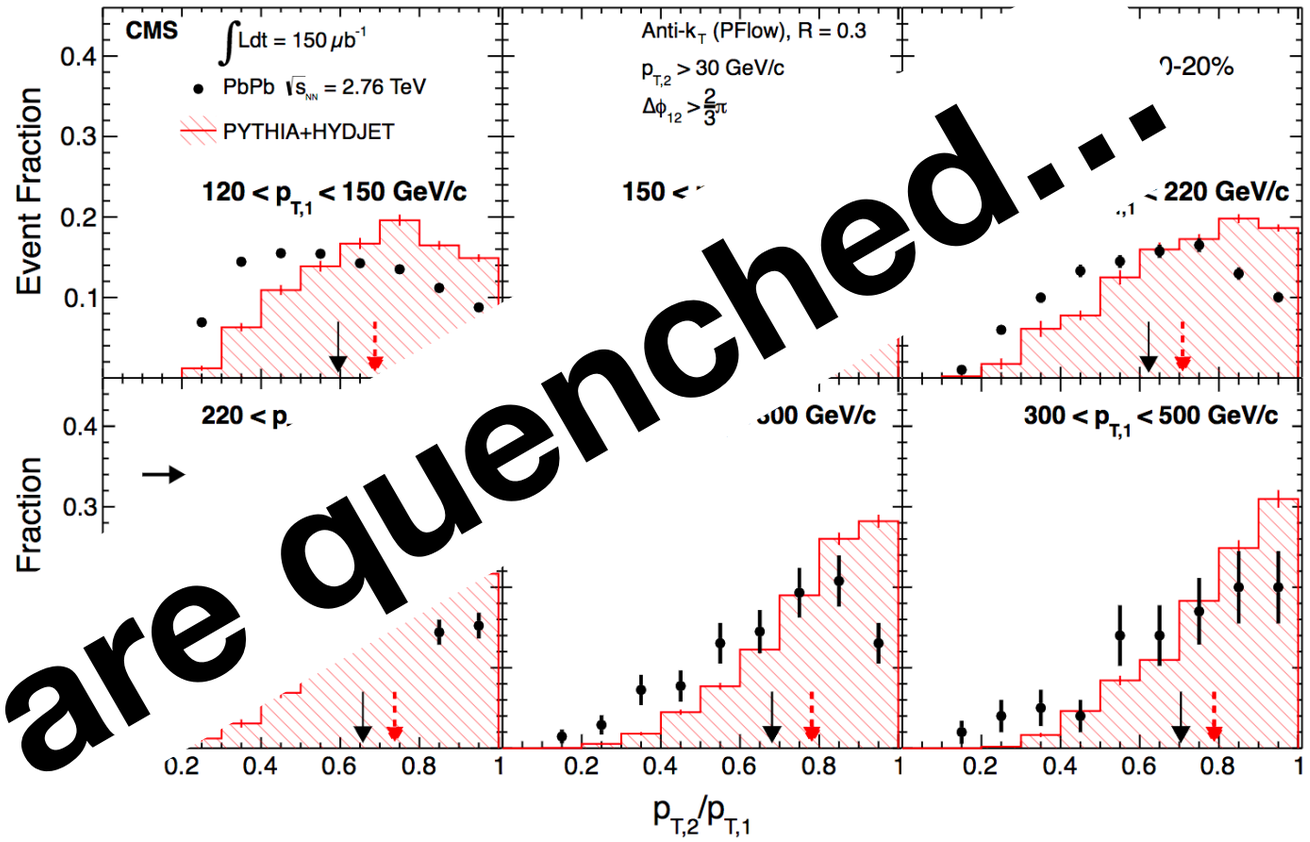

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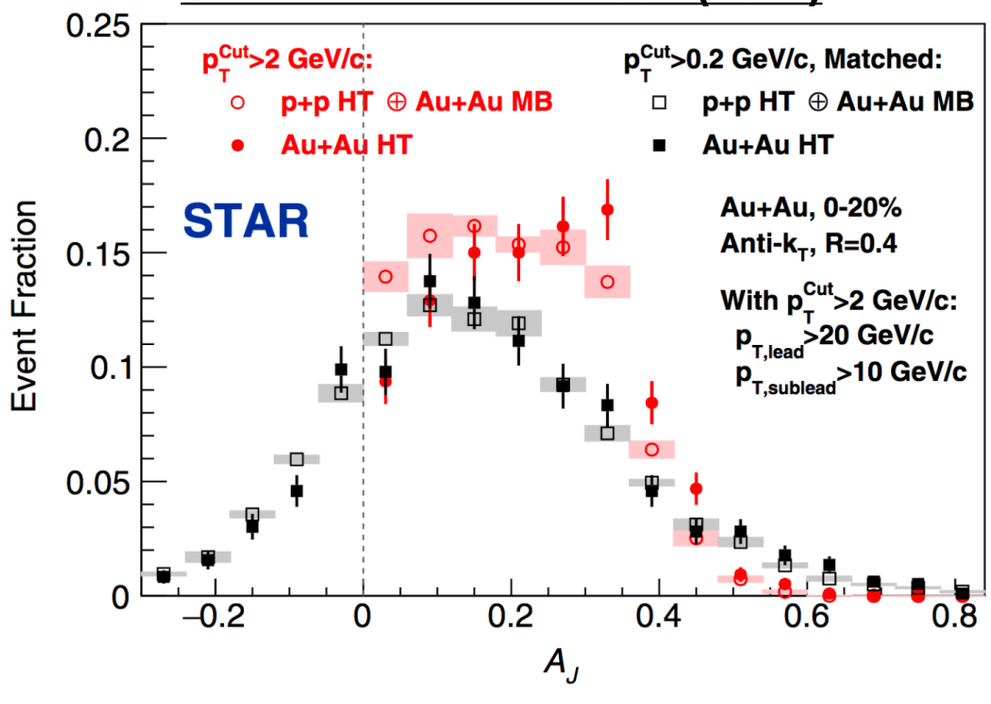


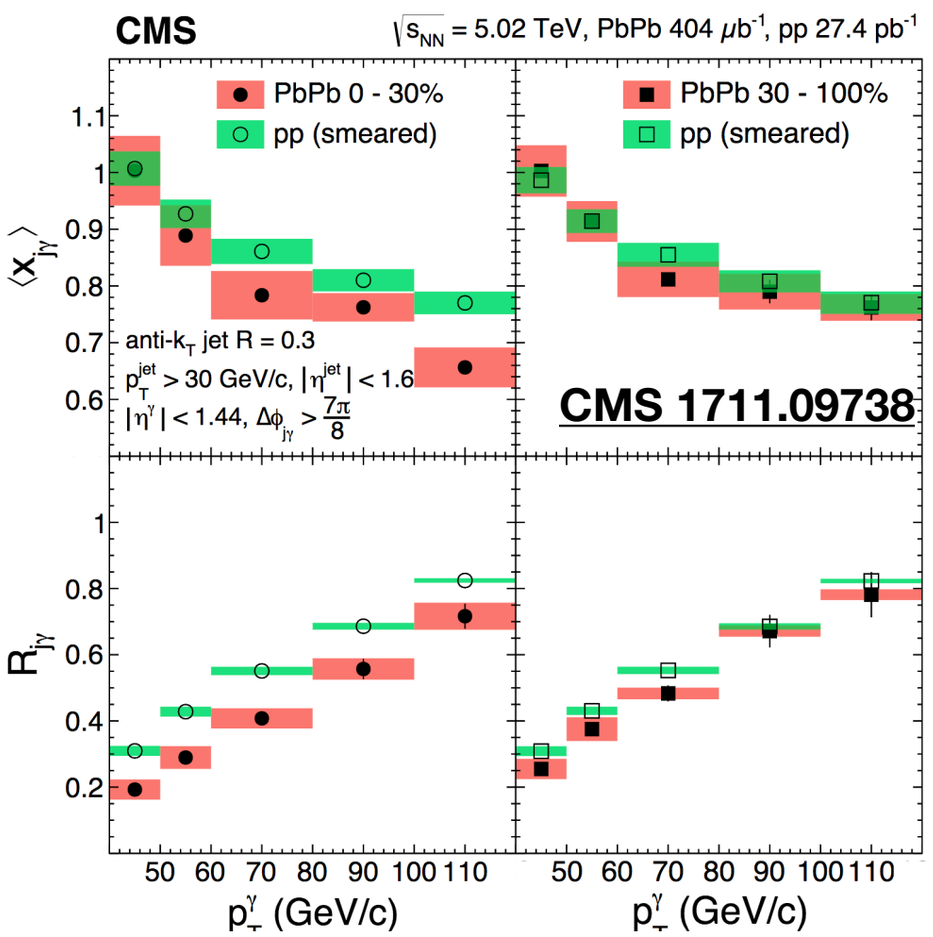
But both jets are quenched...

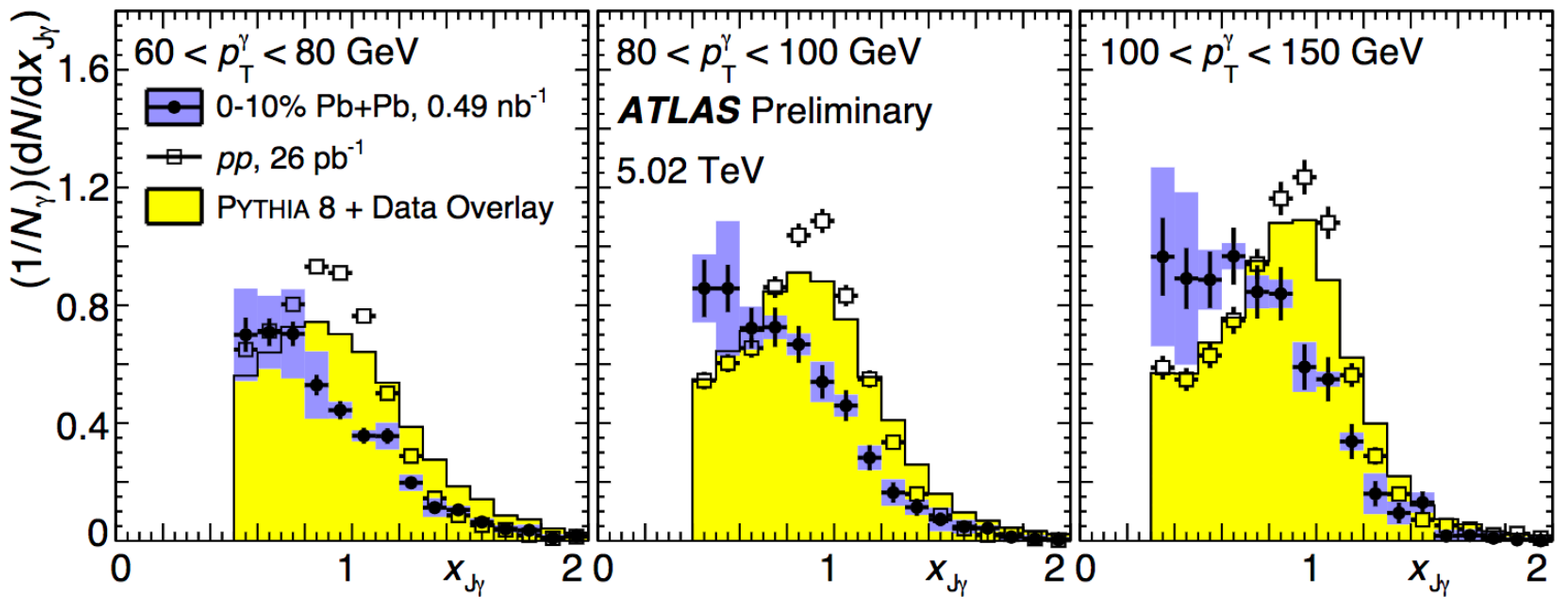
- Very clear dependence of asymmetry on centrality
- Medium induced fluctuations interactions leads to asymmetry (JEWEL)

Eur.Phys.J. C76 (2016) no.5, 288

Compare with Standard Candles

- Photon/Z + Jet Events
- Overall shape reproduced by models
- Room for improvement on pp reference





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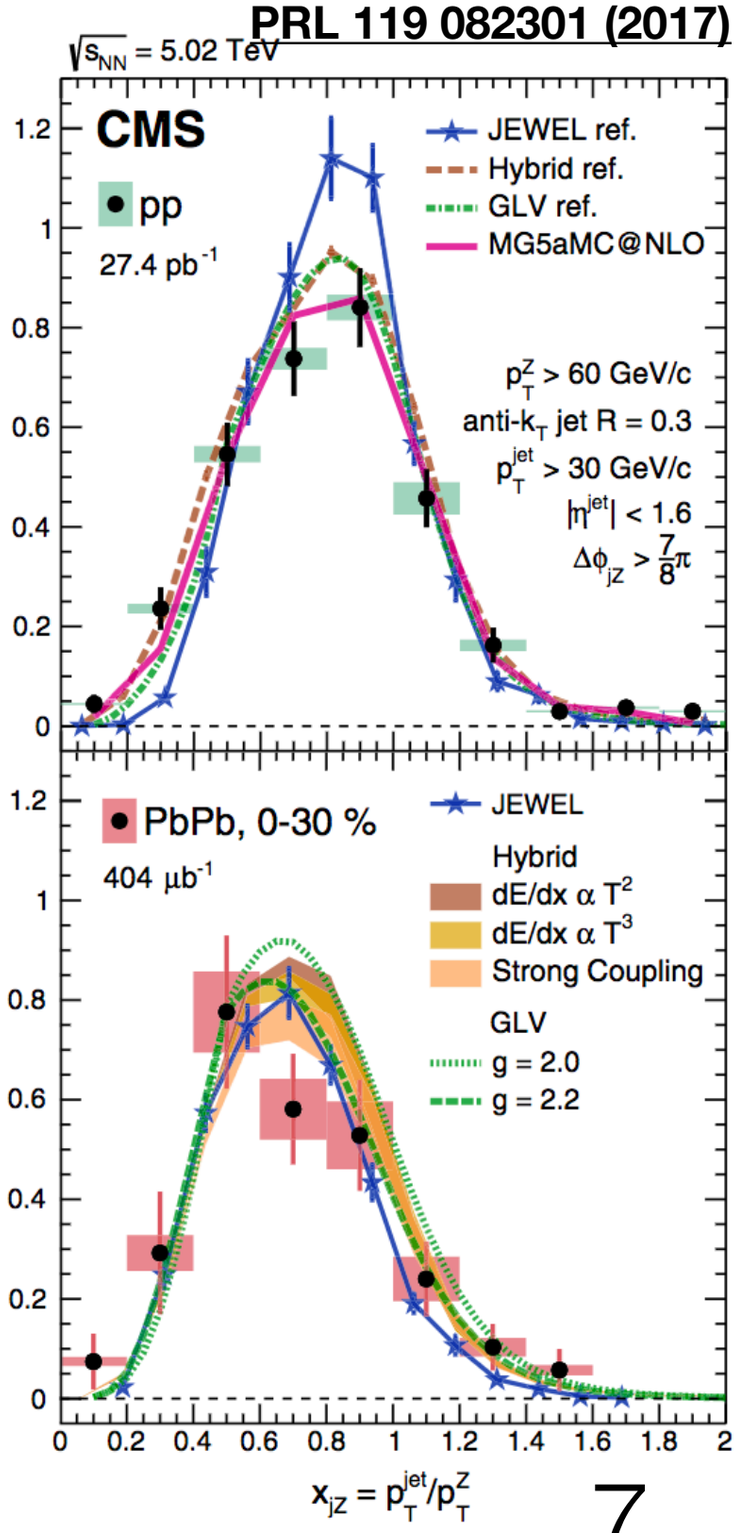
PRL 119 082301 (2017)



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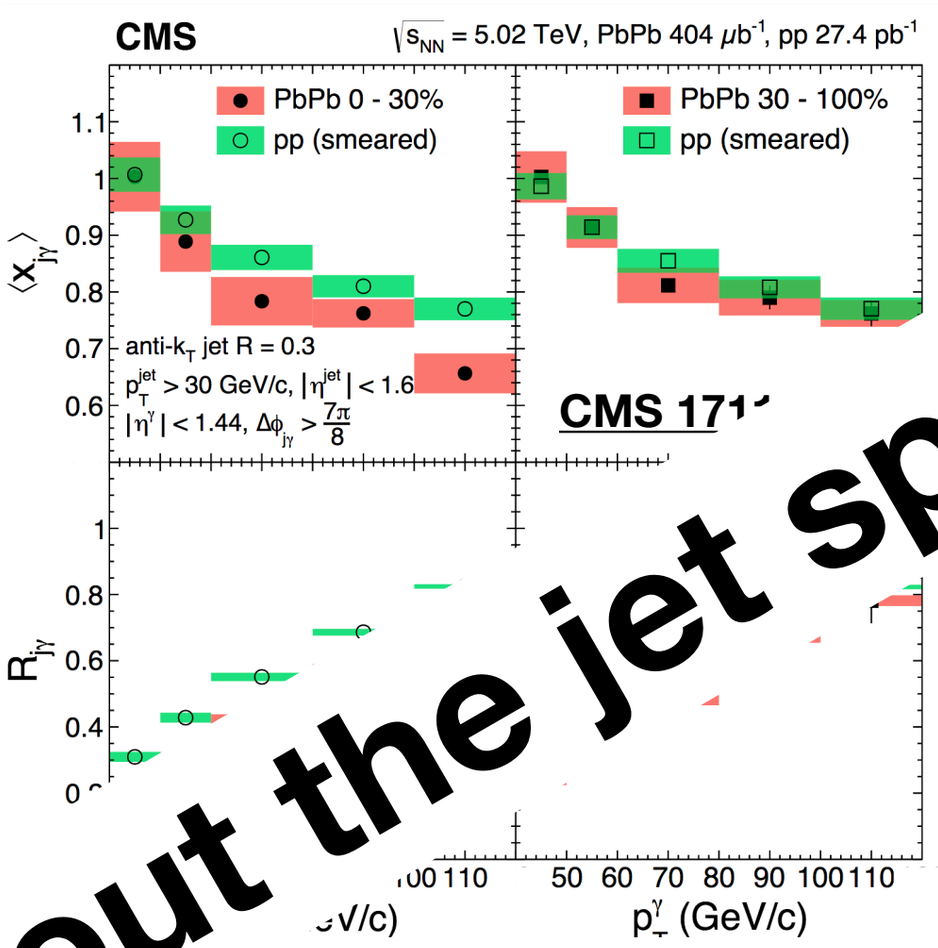

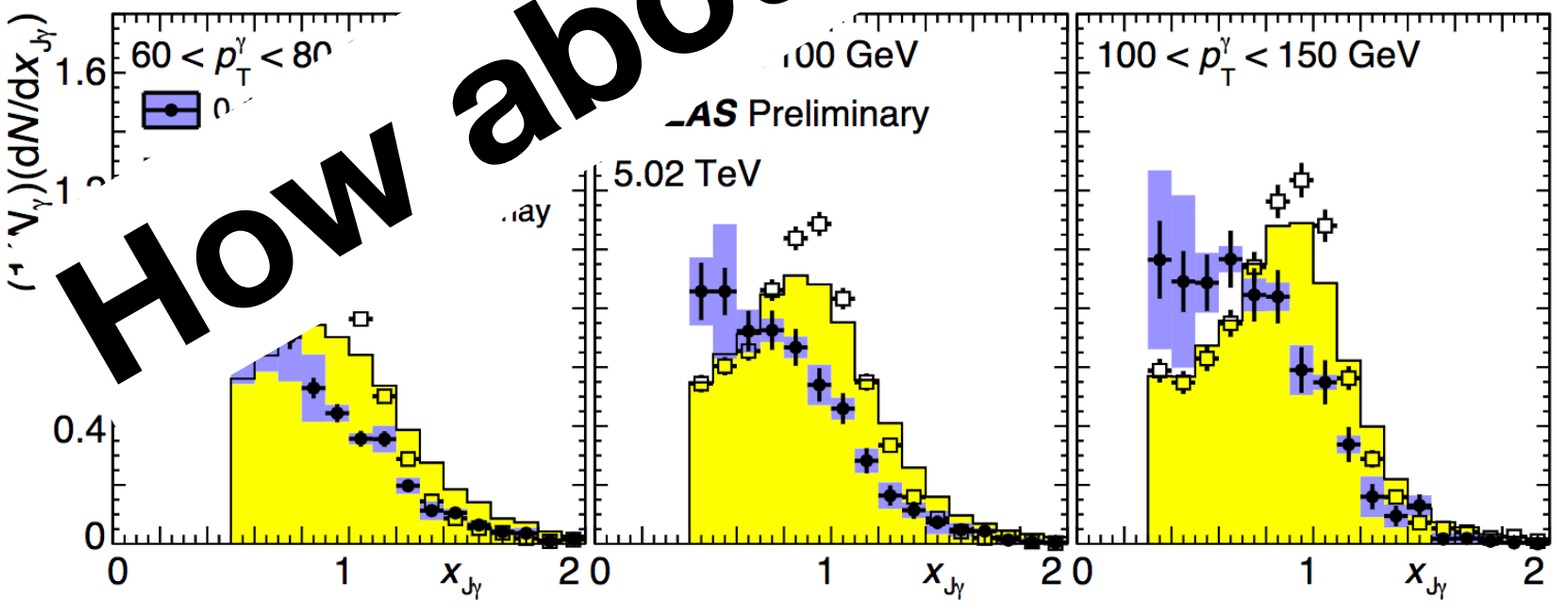

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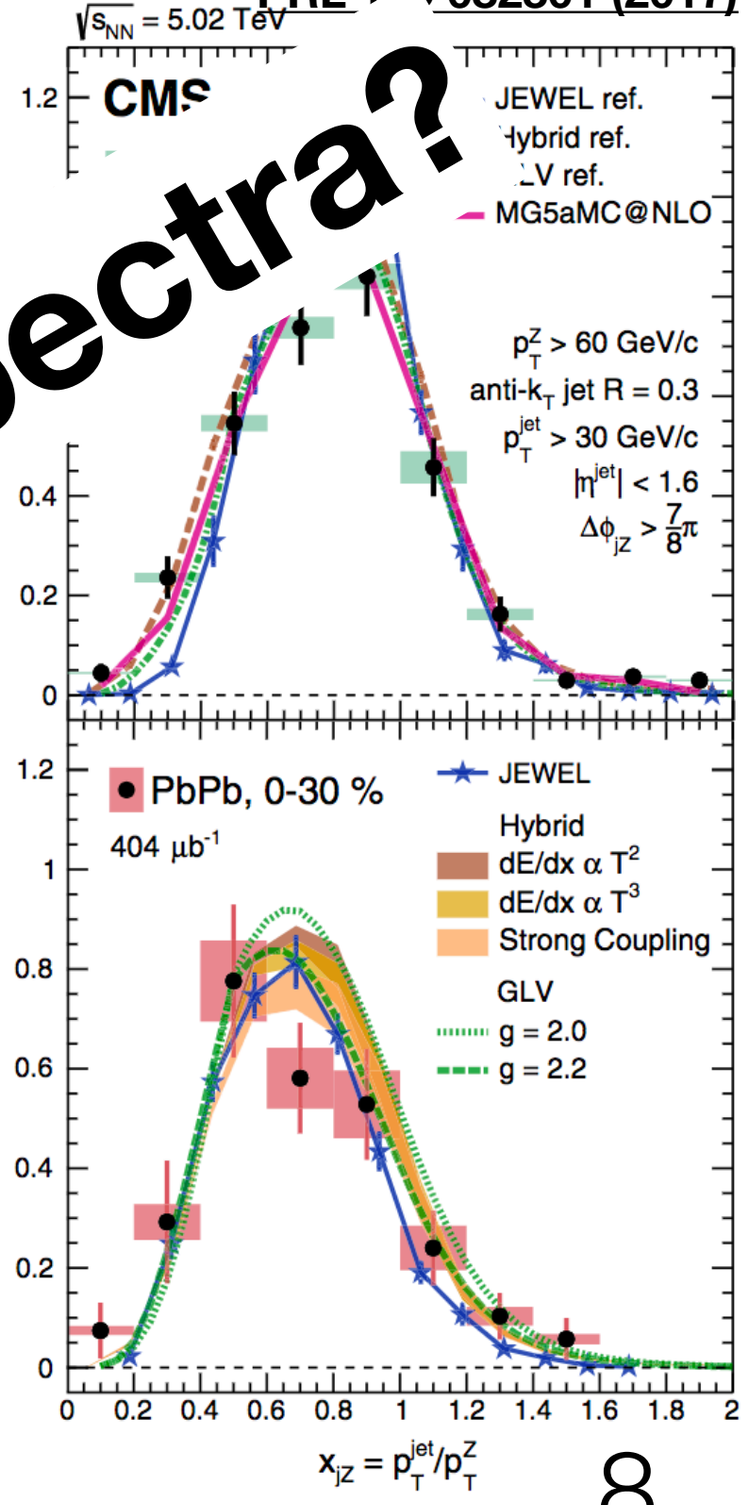
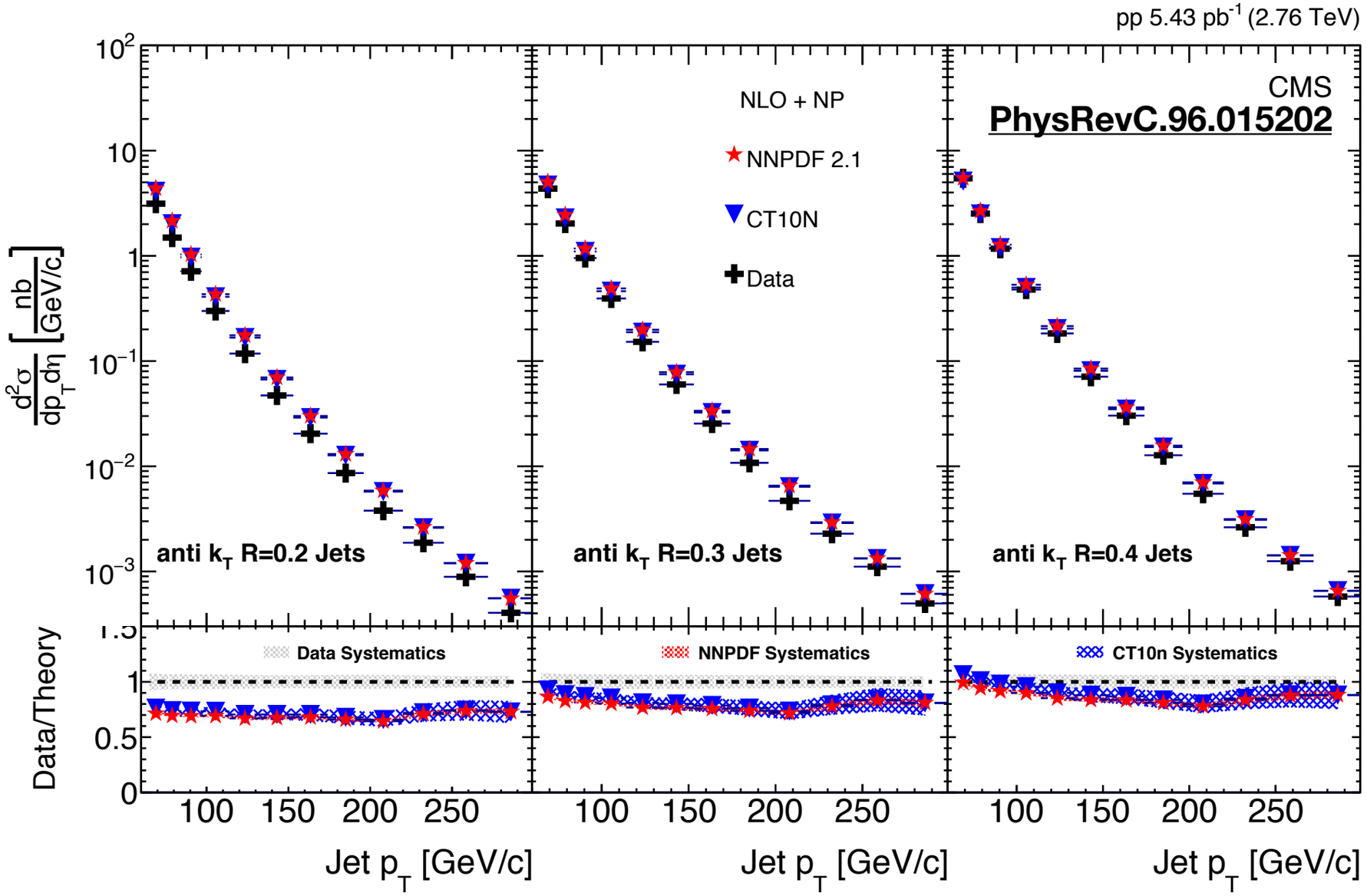
How about the jet spectra?

PRL 119 082301 (2017)

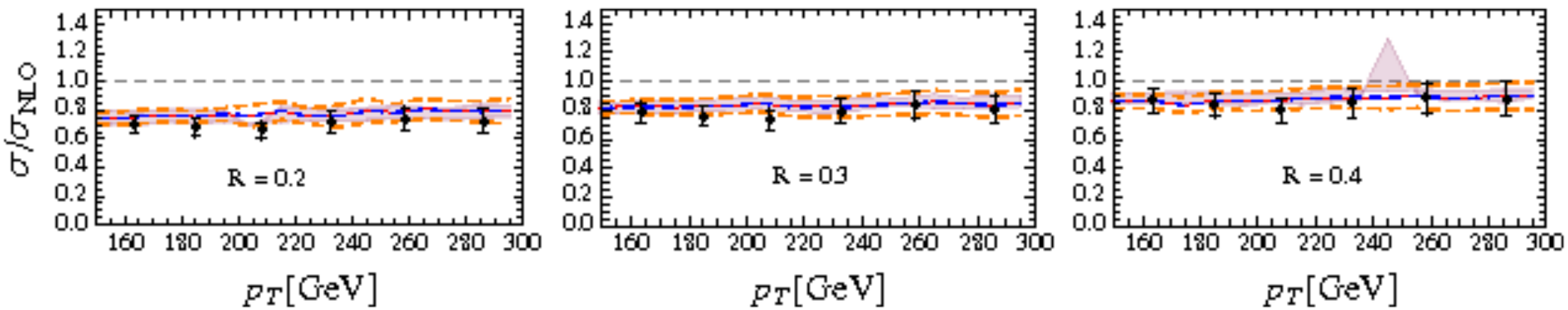


Jet Spectra in PP

- Unfolded Jet Cross section overestimated by NLO+NP
- Resummations in ln r vital
- At NNLO these corrections are quite significant



Xiaohui Liu et.al PRL 119 212001



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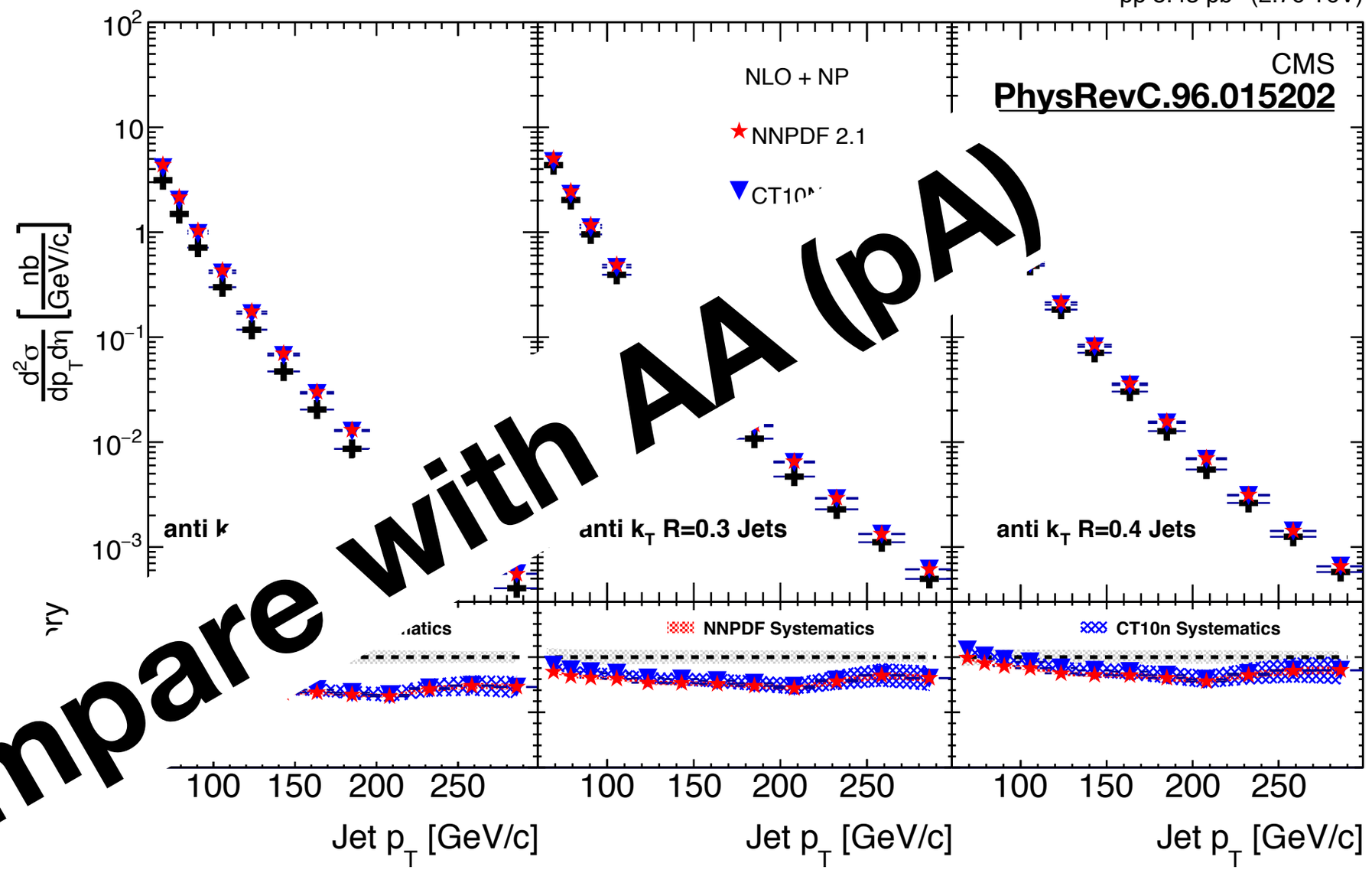
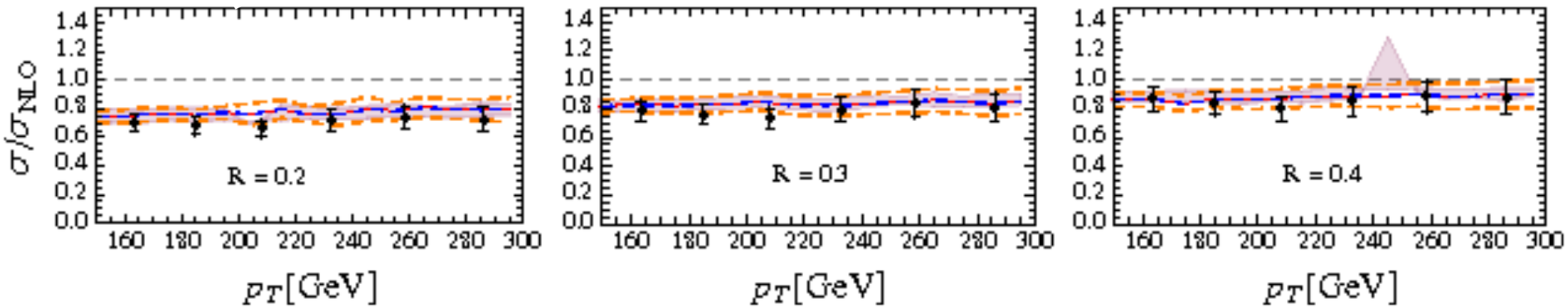
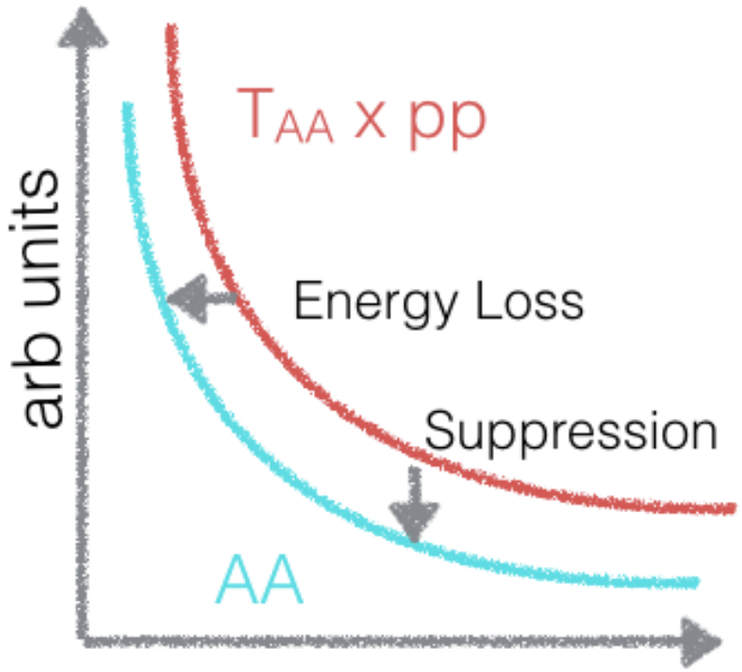


Compare with AA (pA)

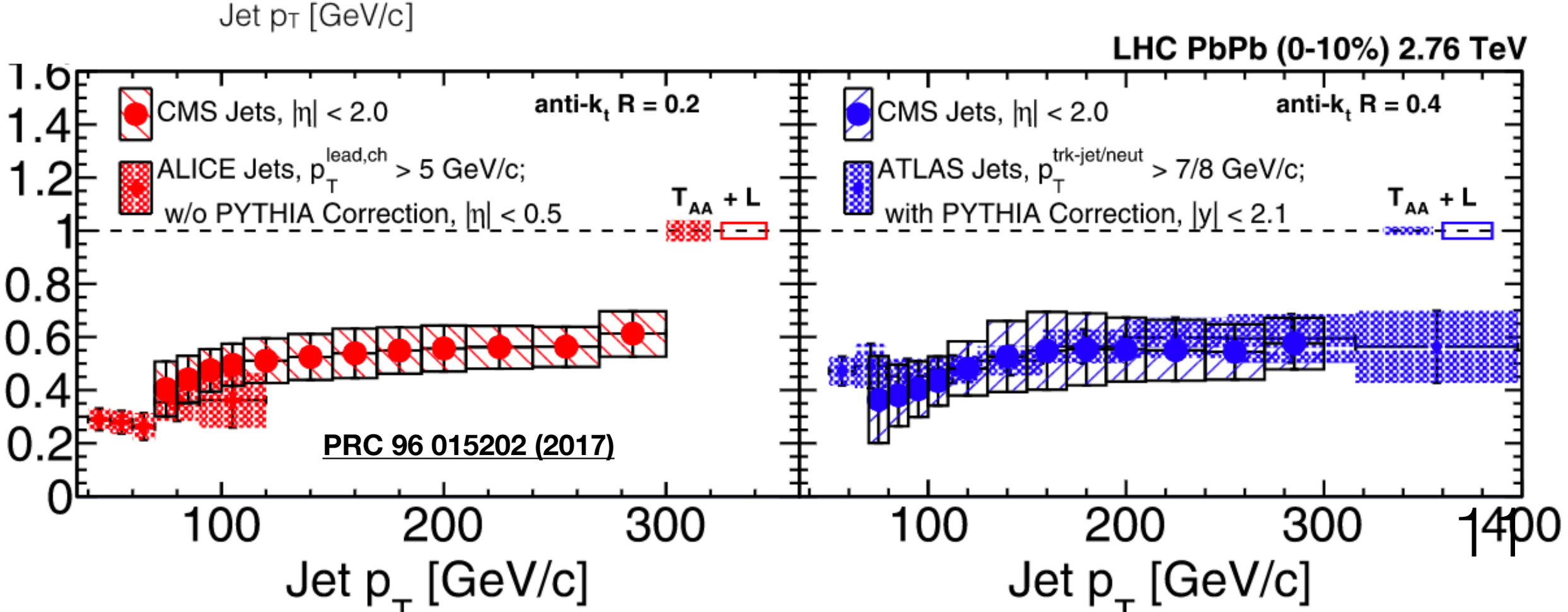
Xiaohui Liu et.al PRL 119 212001



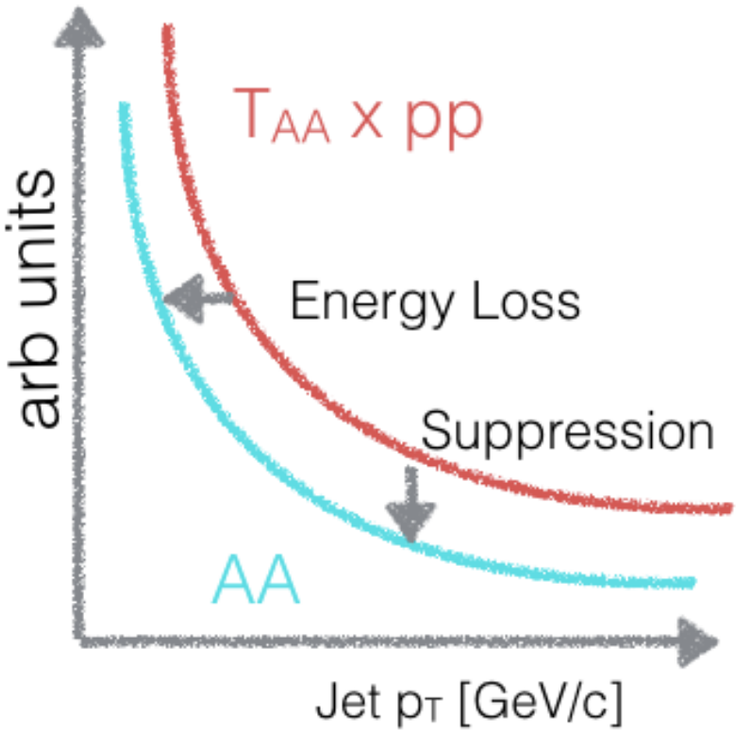
Nuclear Modification in AA



- Glauber model provides us with NBinary to go from pp to AA
- Within exp-uncertainties RAA consistent for R 0.2~0.4

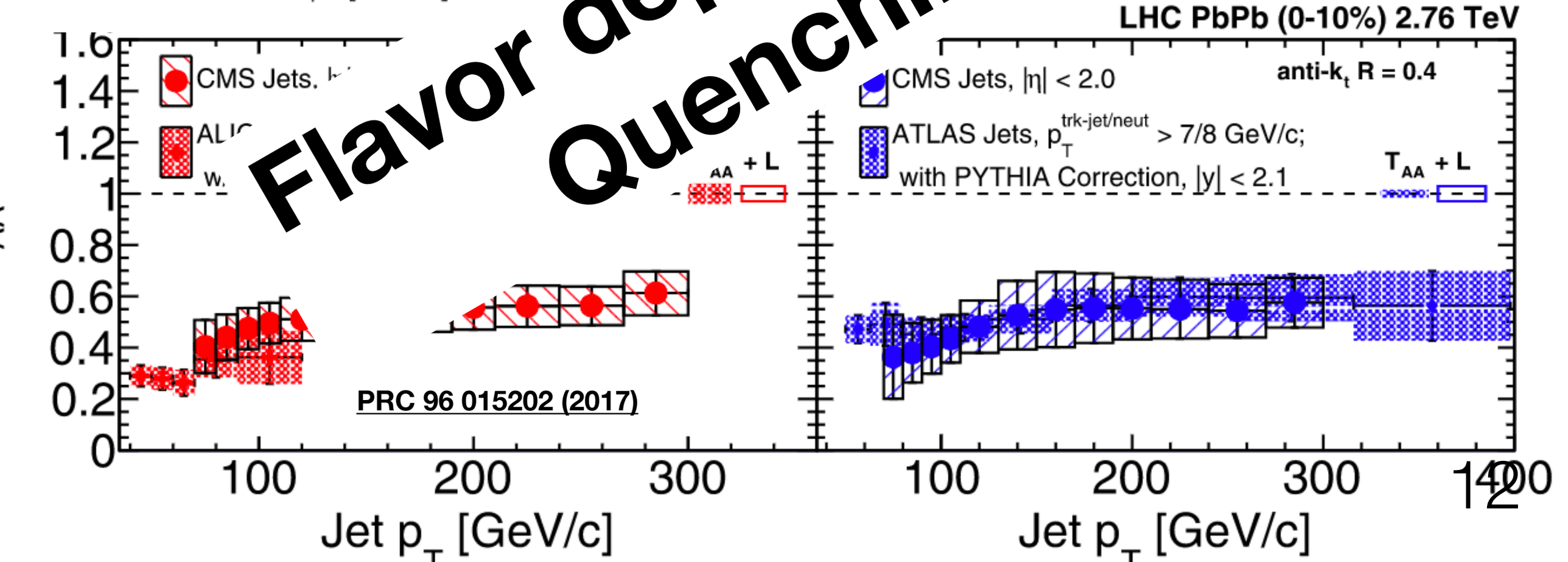


Nuclear Modification in AA



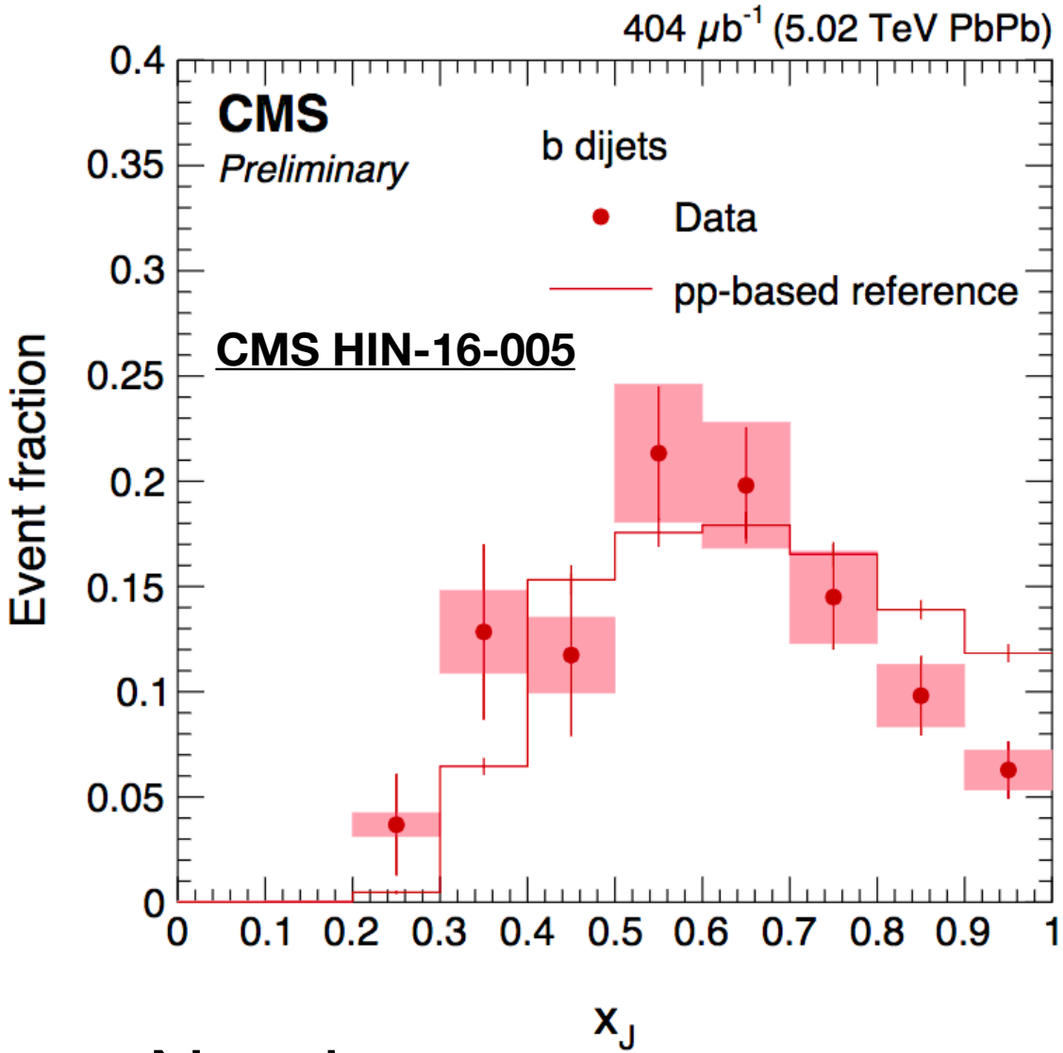
- Glauber model … ith NBinary to …
- Within … …

Flavor dependence on Quenching?

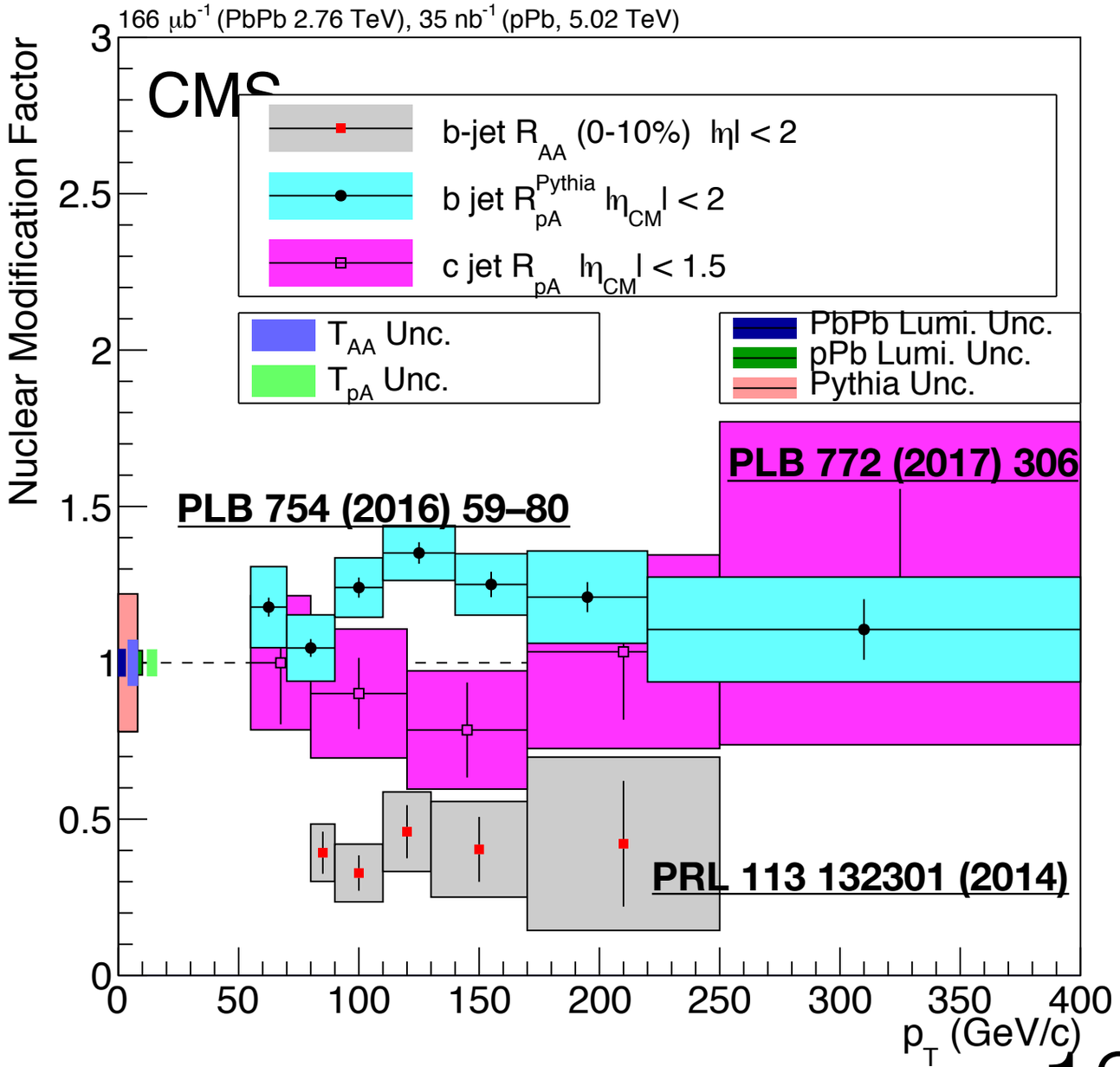


Heavy Flavor Jets

- b/c jets selected via secondary vertices and BDTs
- Similar RpA/RAA for Inc and heavy flavor jets



- Need measurements at low pT where we know mass matters!



Recap - I
What we know so far?

- Proton-proton
  - Jet Spectra can be nicely described at NLO+NLL
  - Boson+Jet distributions also reproducible by MC/TH
- Heavy Ions
  - Di-jet Asymmetry and RAA highlight partonic energy loss
  - RAA/RpA experimentally comparable for Inc and heavy-flavor jets (in current kinematic reach)

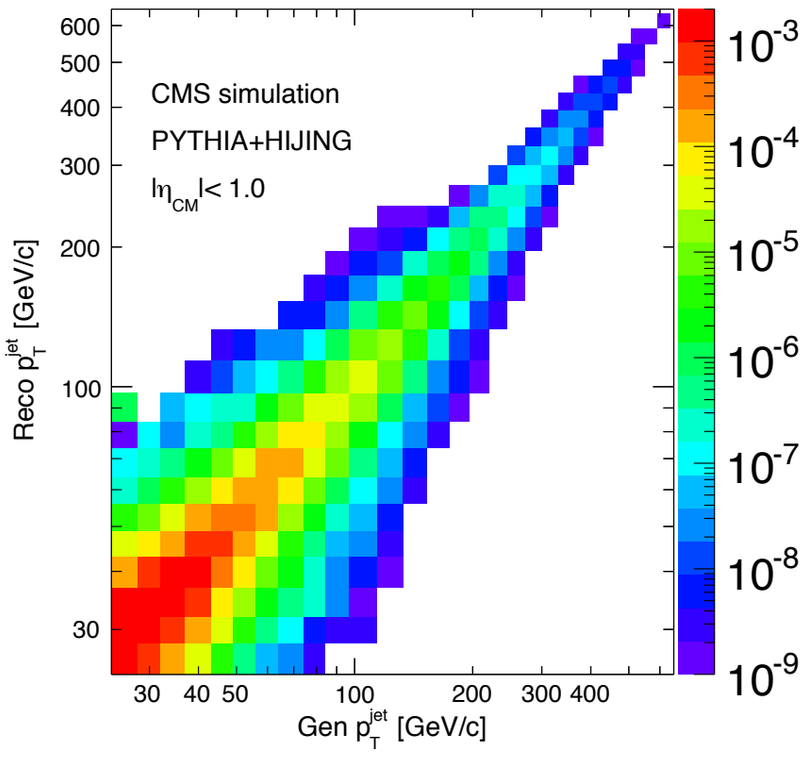

DETOUR

“PP Reference”

- Experimental need to compare expected medium modification with vacuum (no modification)
- Two common methods -
  - Unfolding
  - Resolution Smearing

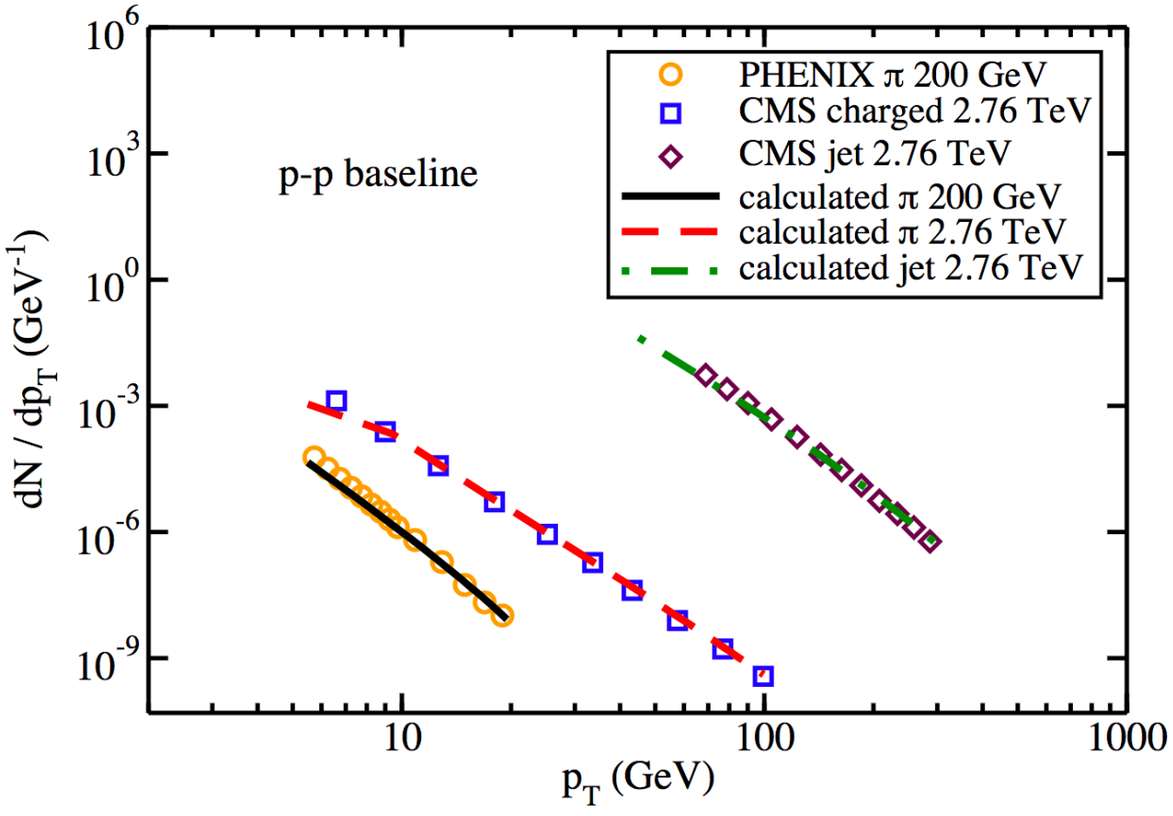
unfolding

- Inverting response matrix
- Trusting the prior



Smearing

- Varies Exp-Exp and Meas-Meas
- Cant compare with Theory

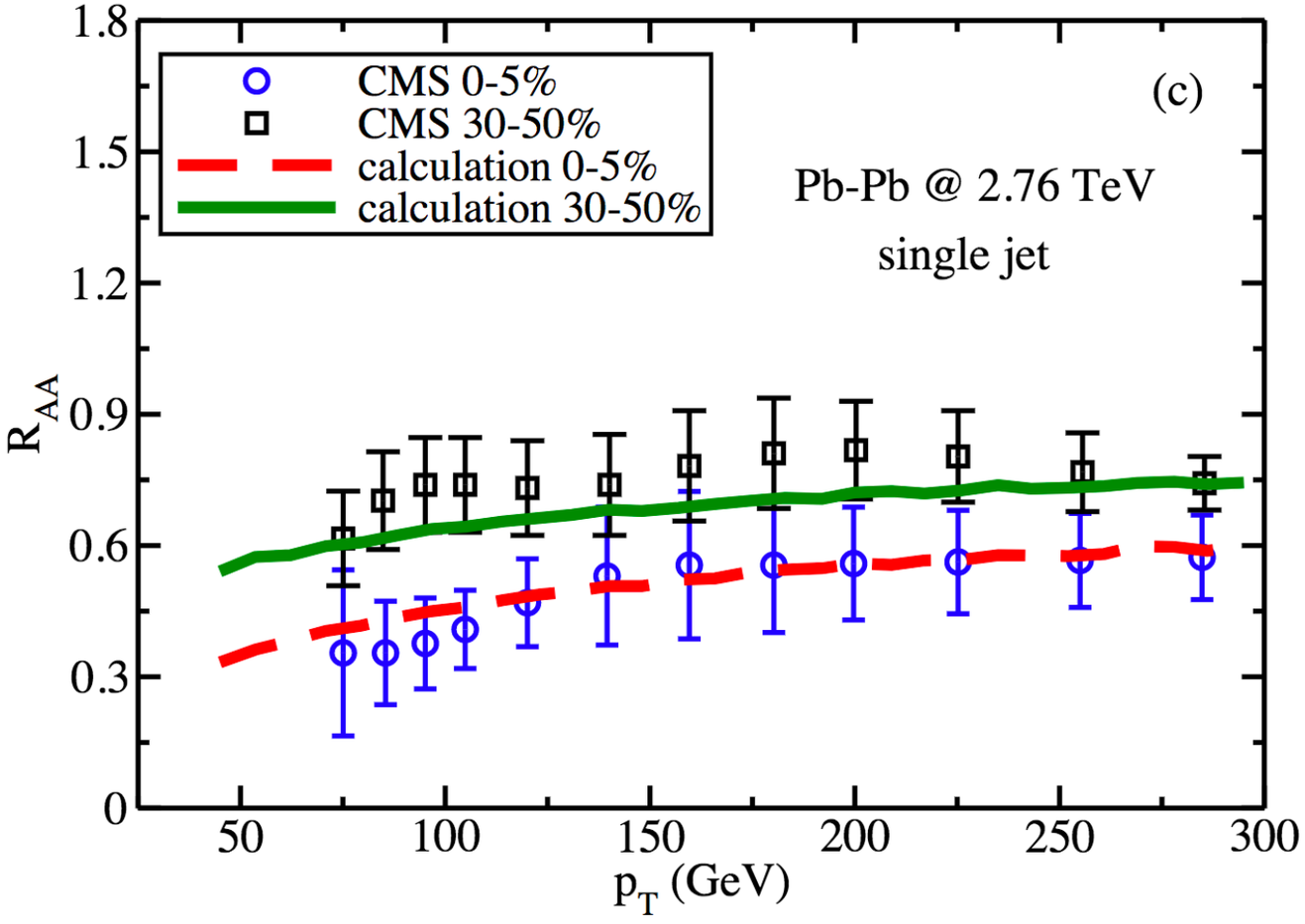


PP Spectra

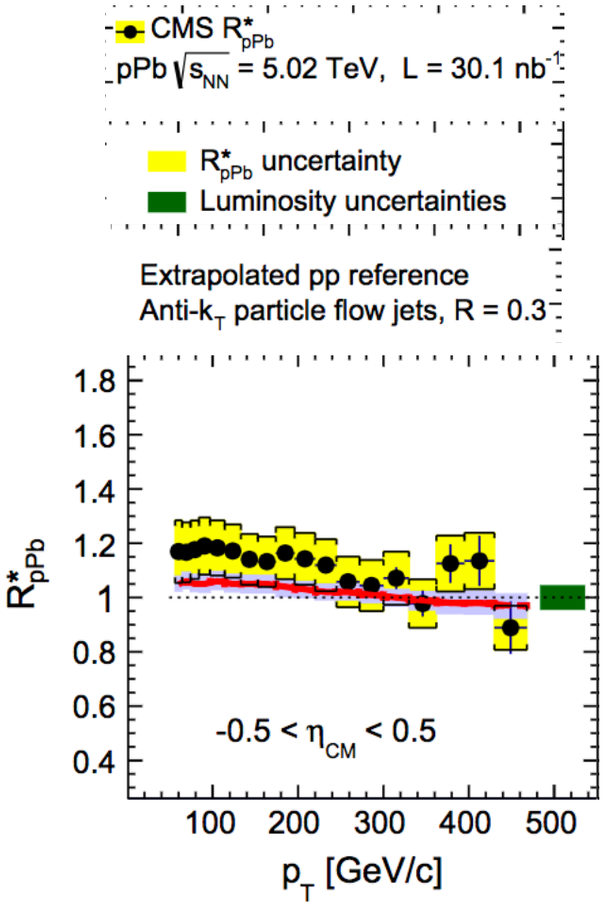
Cao S, and Majumder A1712.10055

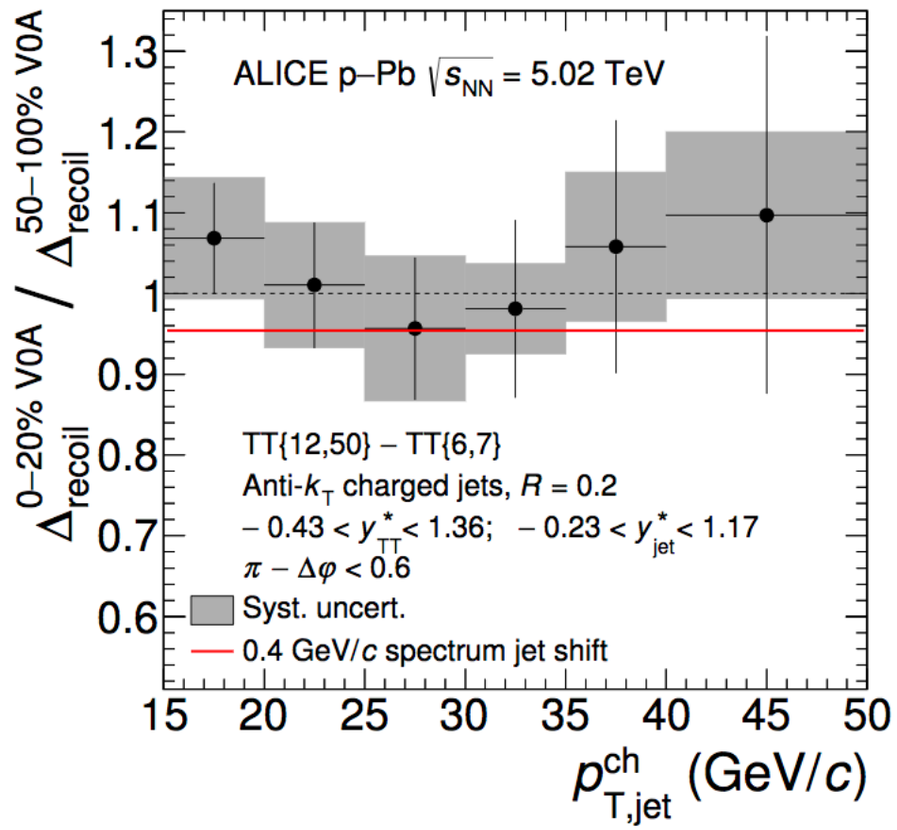
RAA ->

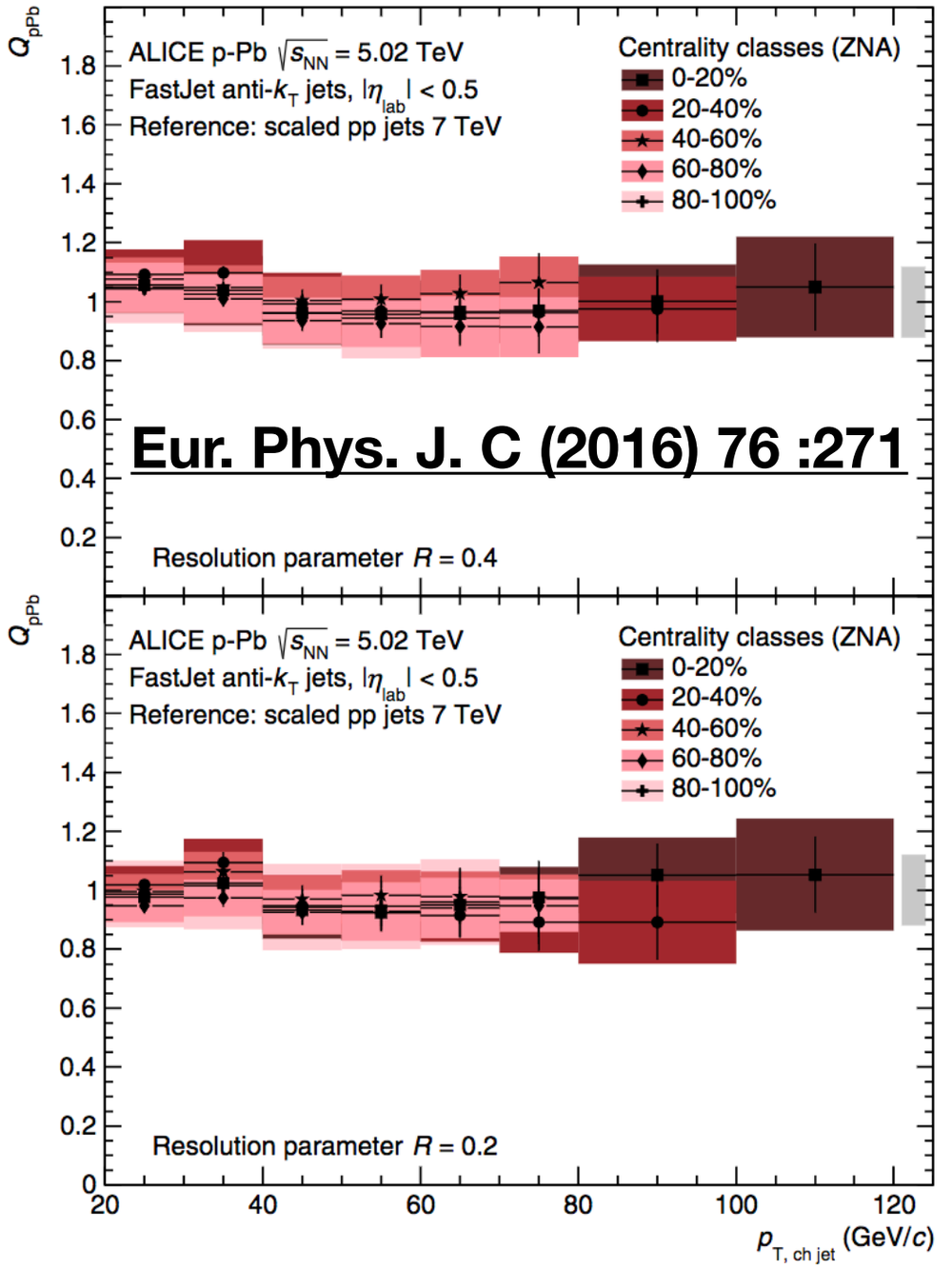
- Very good to see reference comparison
- See Shanshan and Tau's talk for more details



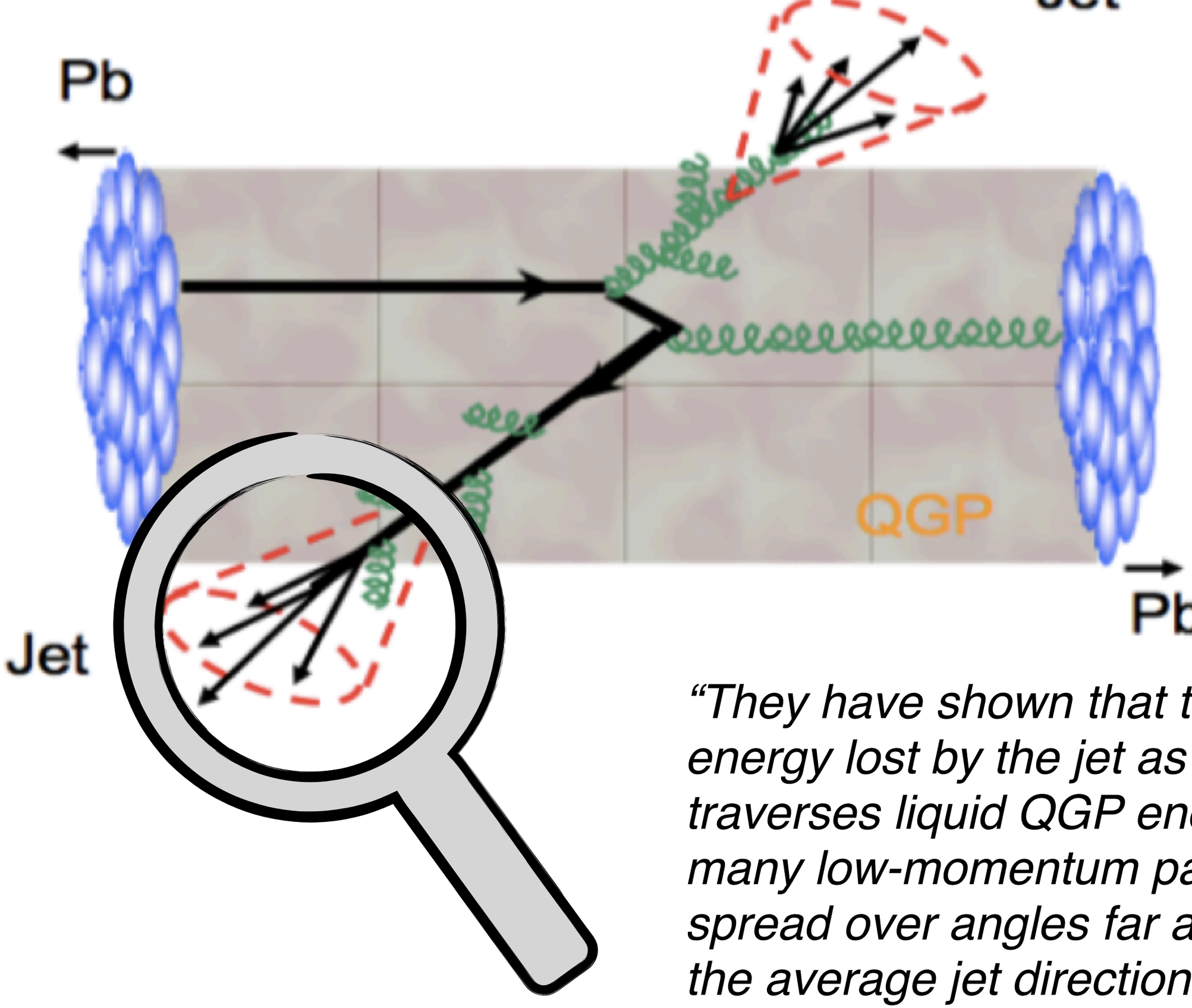
“Cold” Nuclear Matter vs Jets







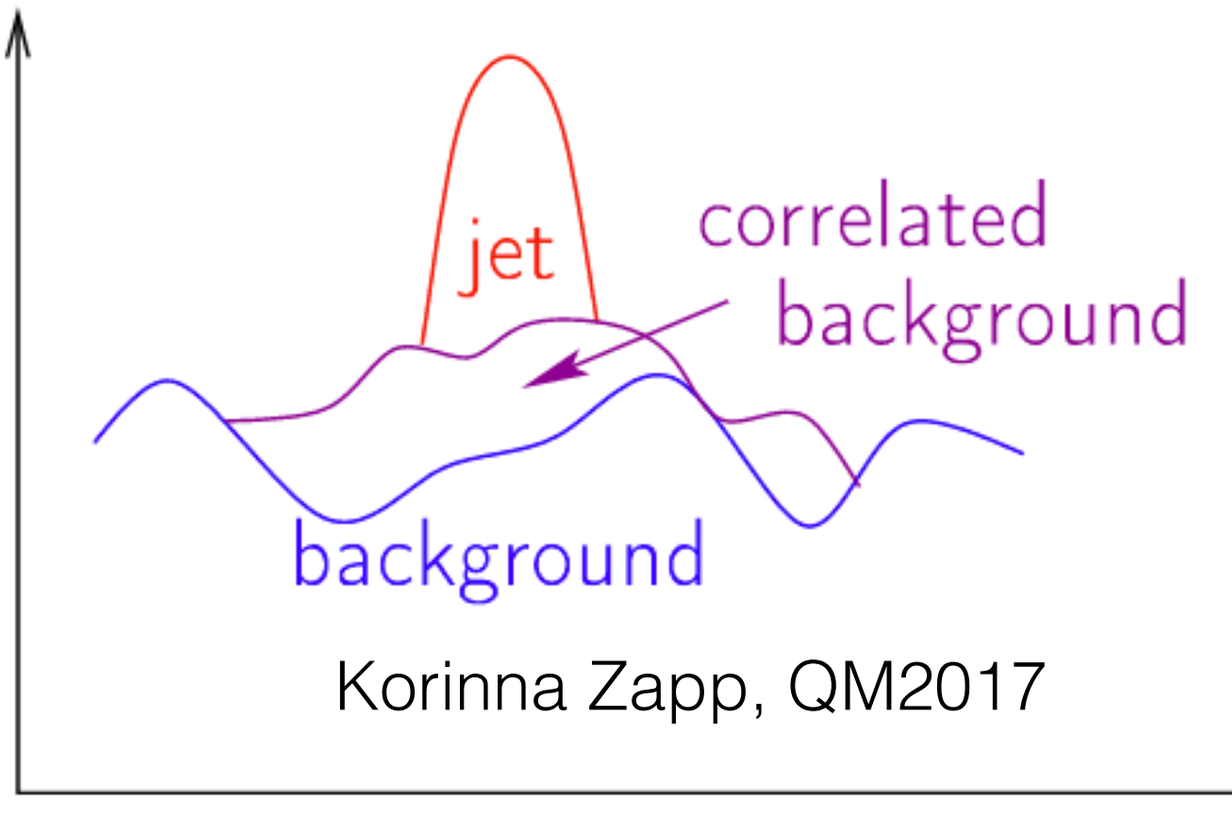
- Question on Centrality?
- EPS09 does reasonably well - lack of cold nuclear matter effects
- Jet Quenching is a final state effect



"They have shown that the energy lost by the jet as it traverses liquid QGP ends up as many low-momentum particles spread over angles far away from the average jet direction, i.e., as a little bit more QGP."

2015 NP-LRP

Effect of Background, Nuclear Modifications, fragmentation functions, Jet Structure/shapes

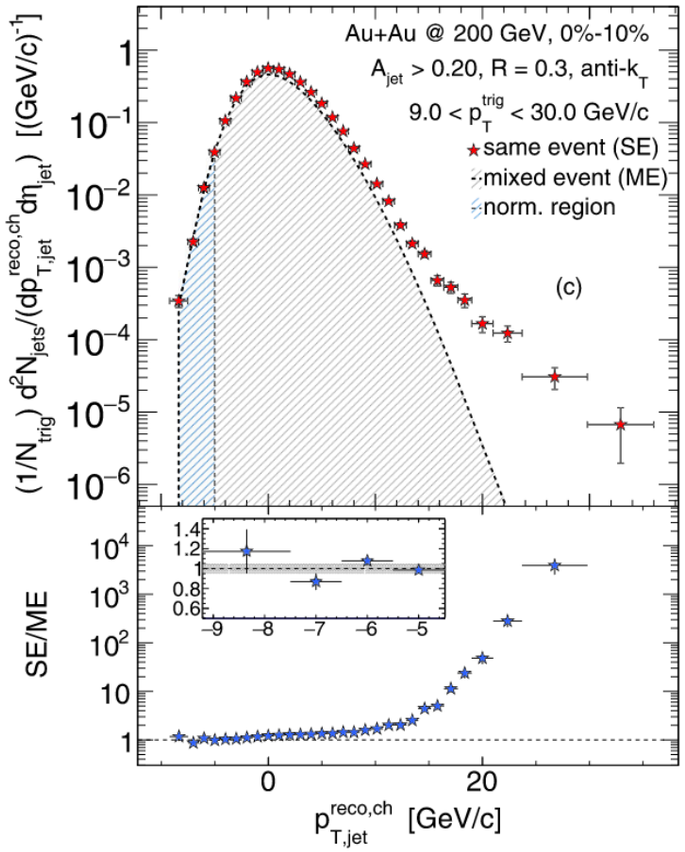


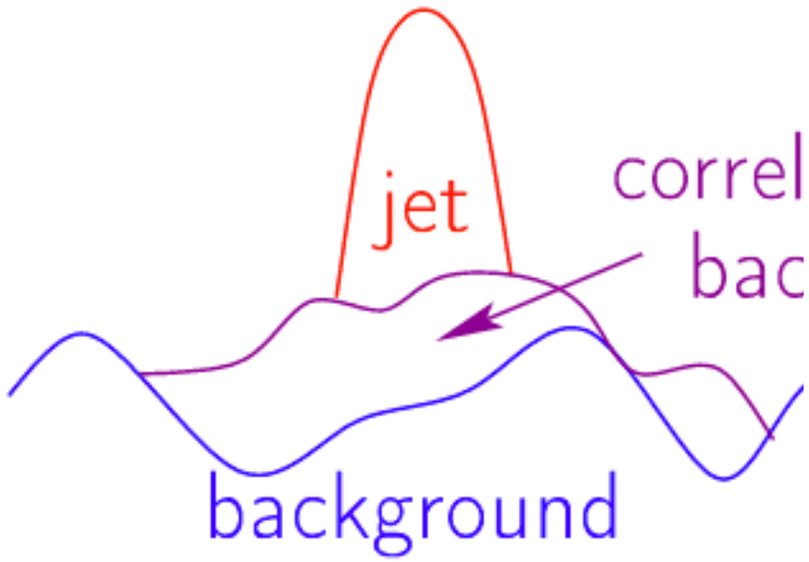
Korinna Zapp, QM2017

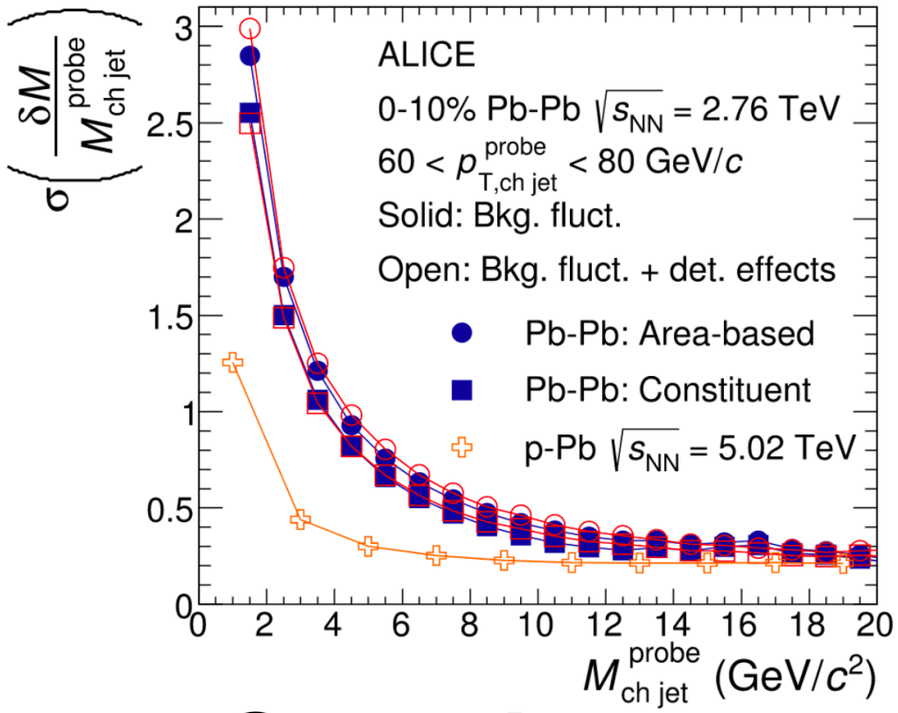
Known
Unknown

" There are known knowns. These are things we know that we know. There are known unknowns. That is to say, there are things that we now know we don't know. But there are also unknown unknowns. These are things we do not know we don't know."

Donald Rumsfeld (US Sec. of Defense; Feb 12, 2002)





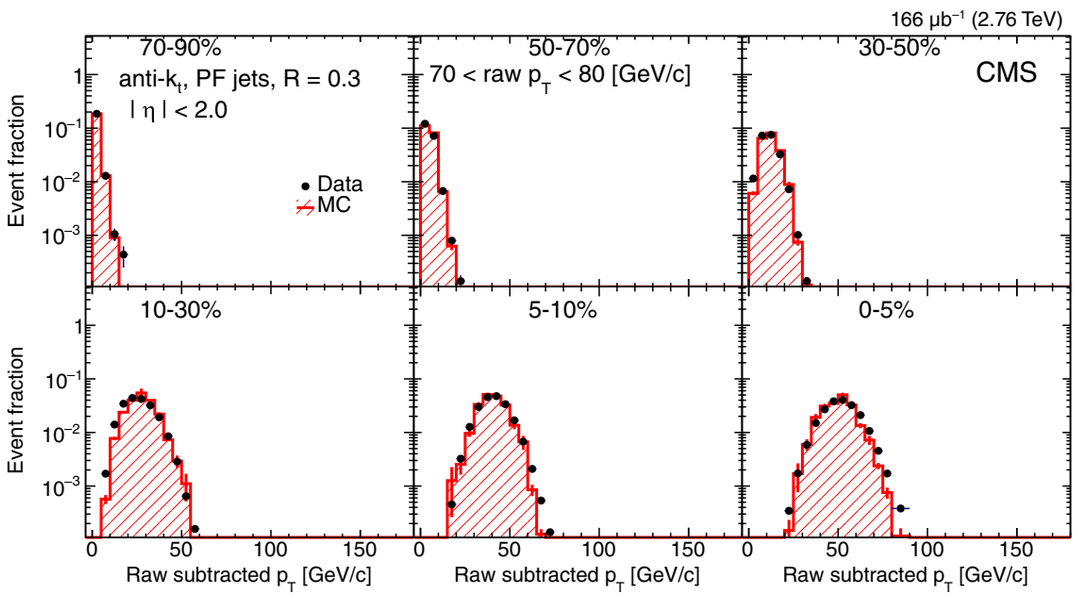


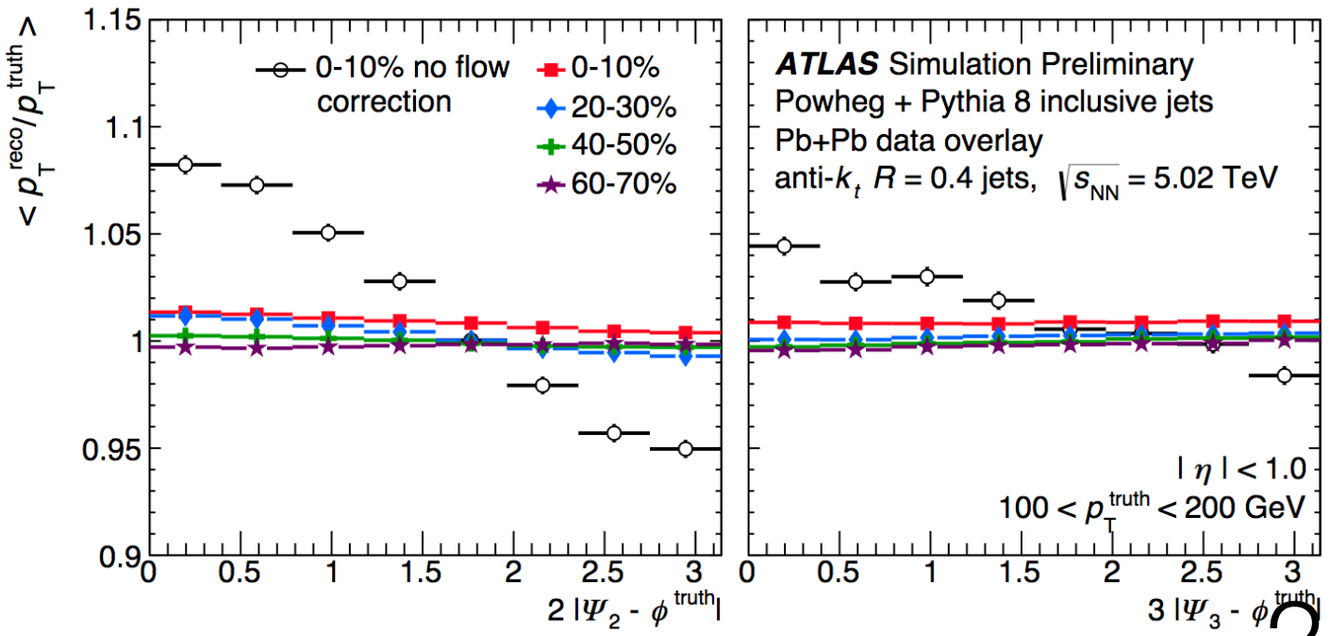
Constituents

Fluctuations

Korinna Zapp, QM2017

Flow modulation



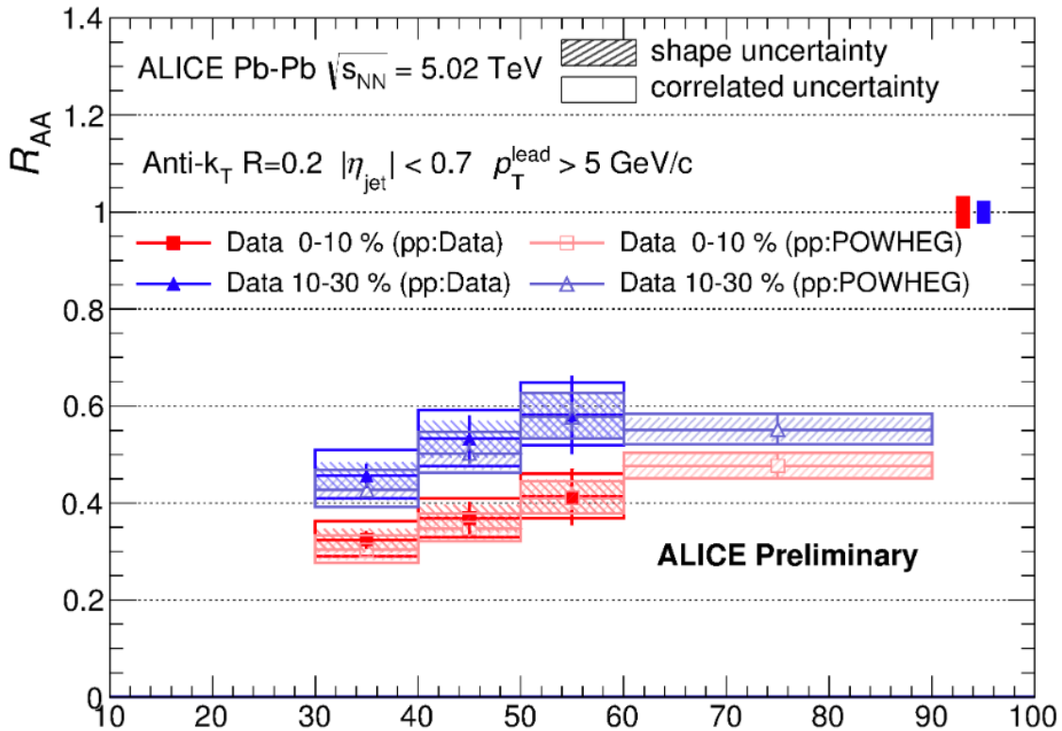


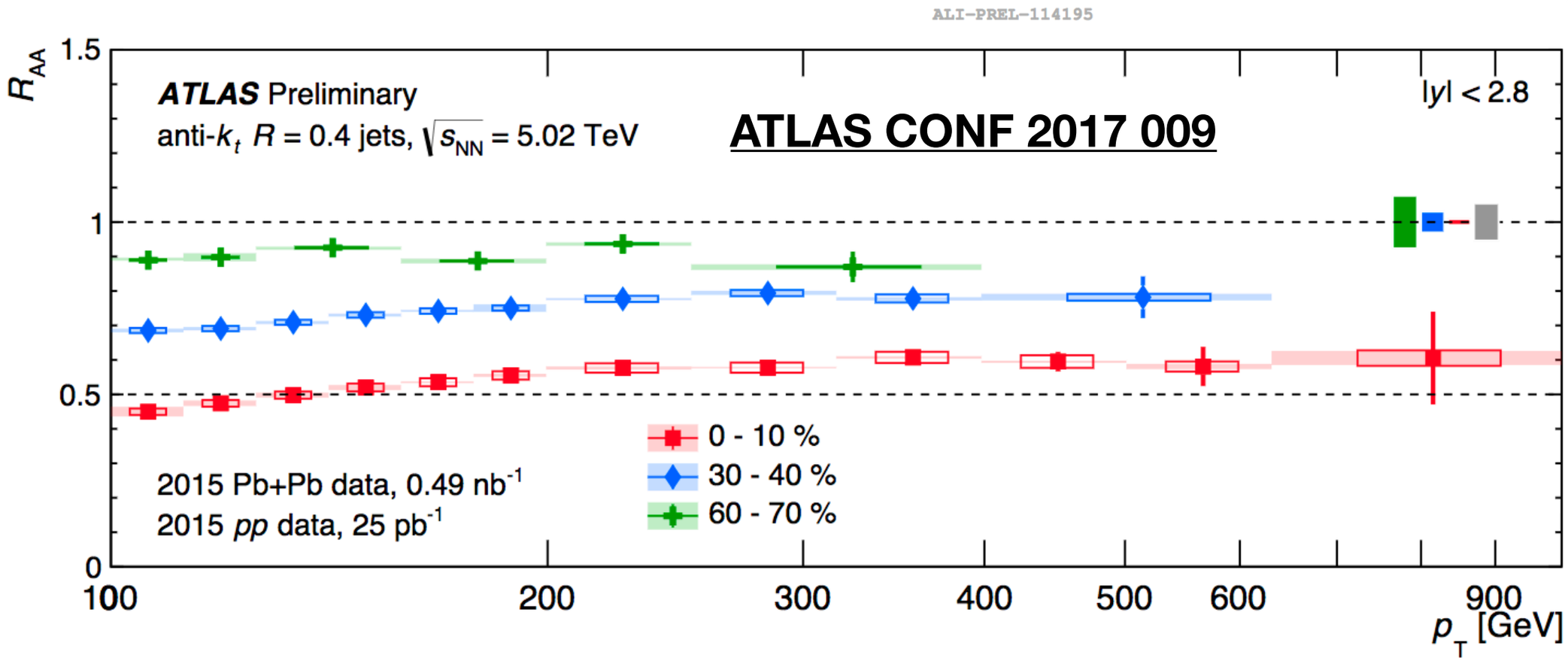
PRC 96 015202 (2017)

ATLAS CONF 2017 009

Back to RAA but at different sqrt-s

- Quenching a 1TeV Jet!
- What are we learning from RAA (alone), across different center of mass energies?





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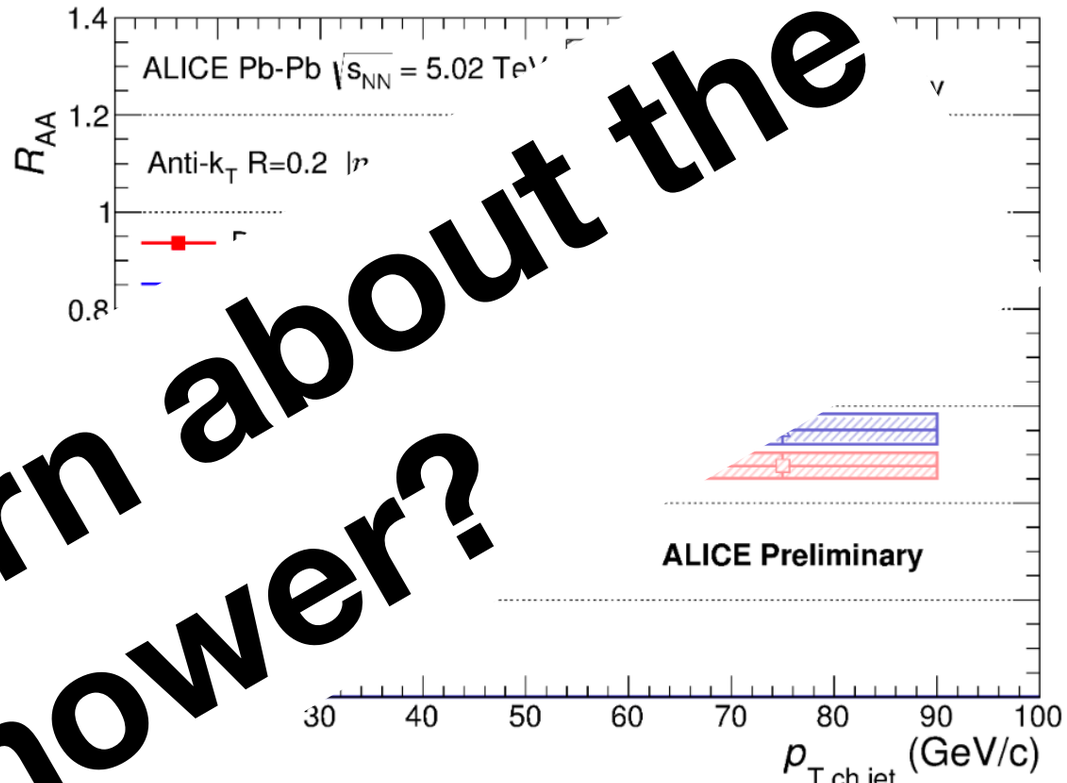
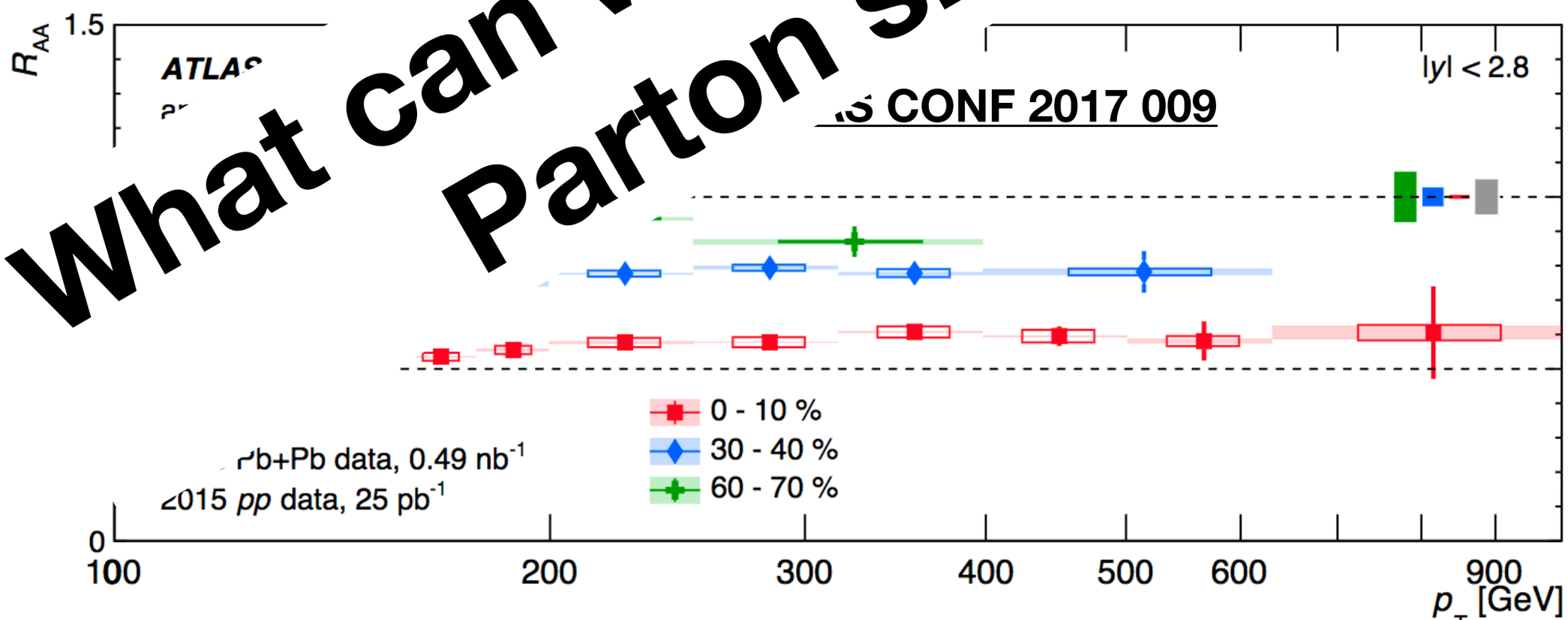
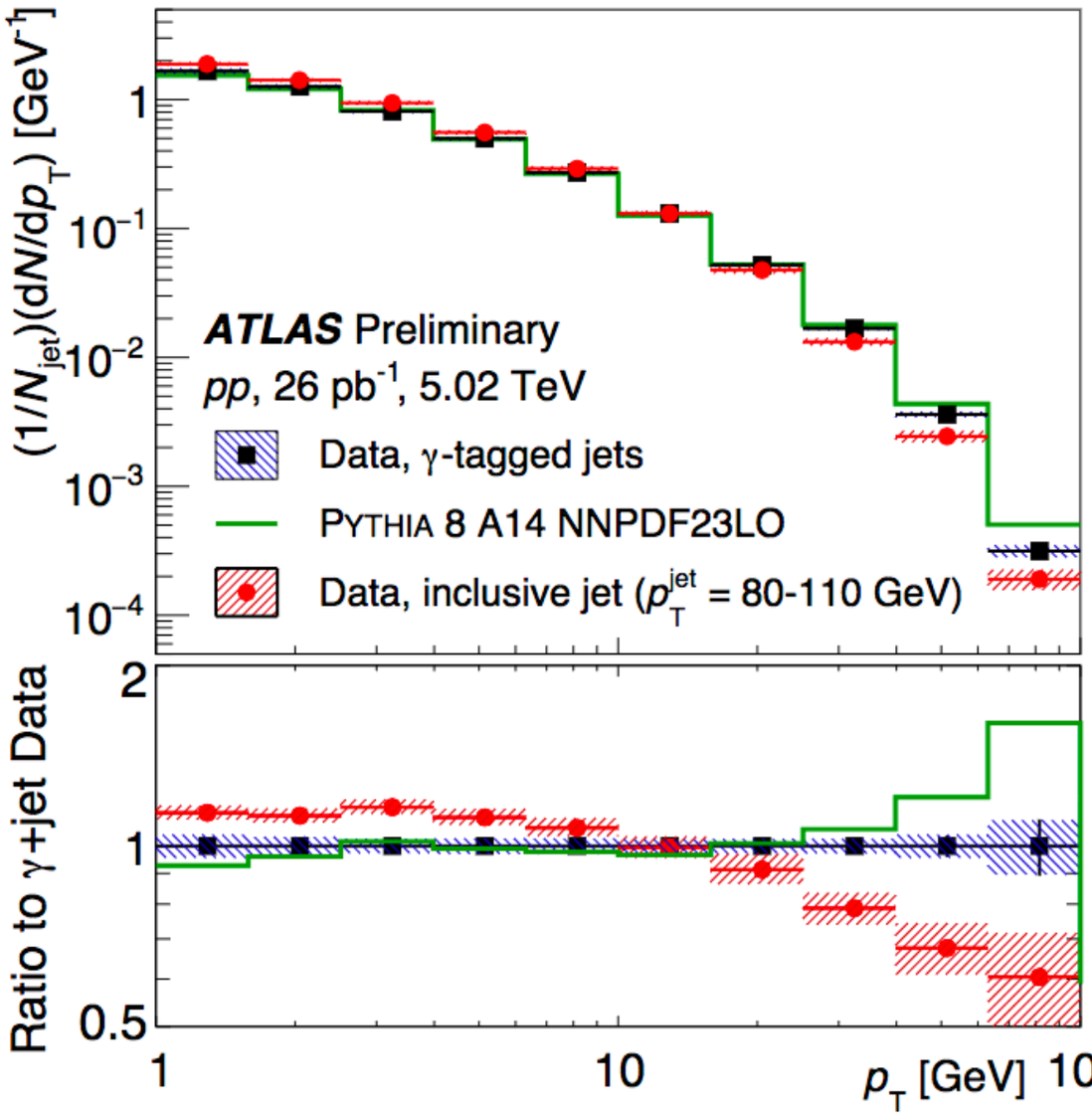
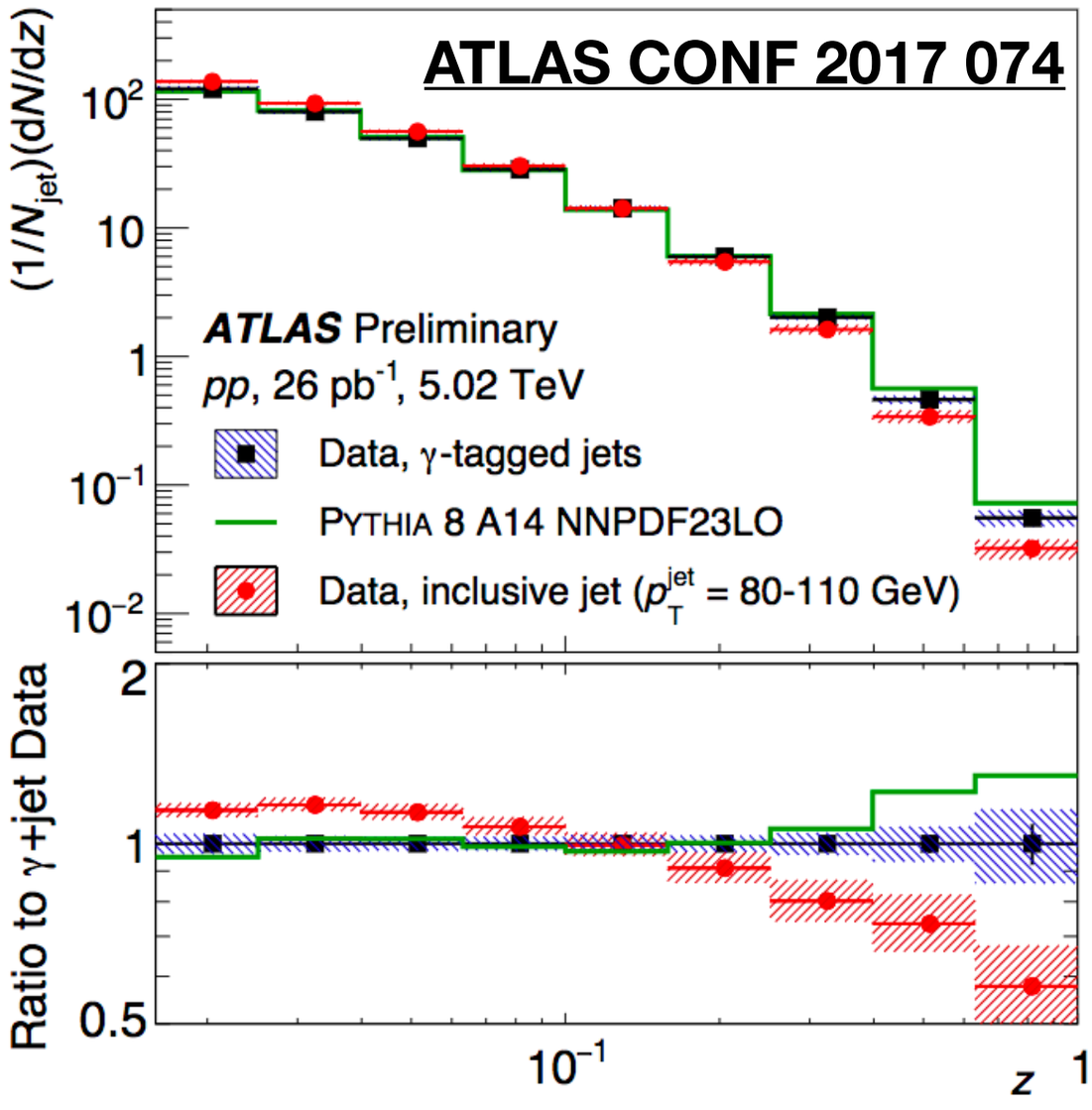




What can we learn about the Parton shower?

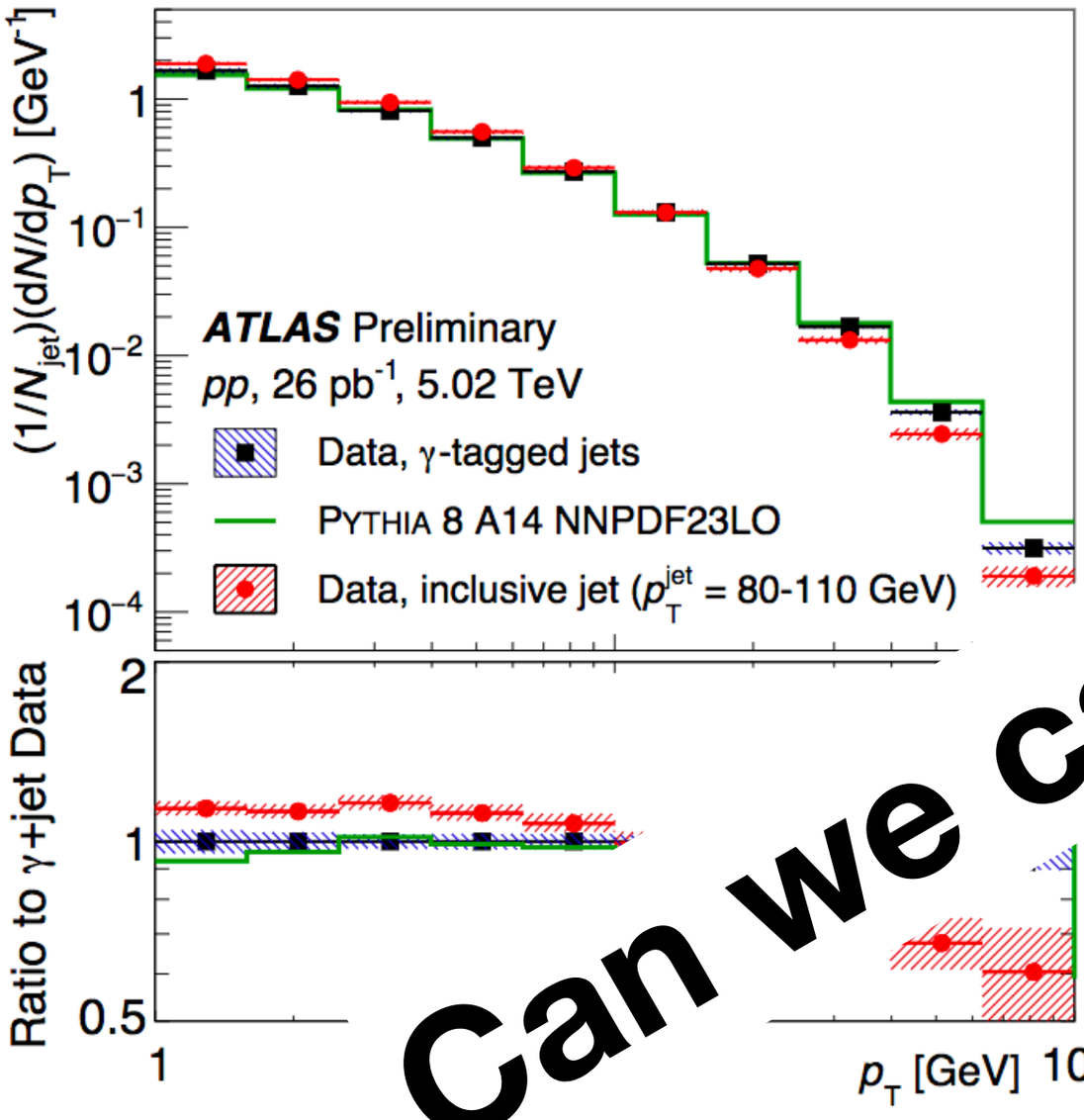
Fragmentation Function - PP

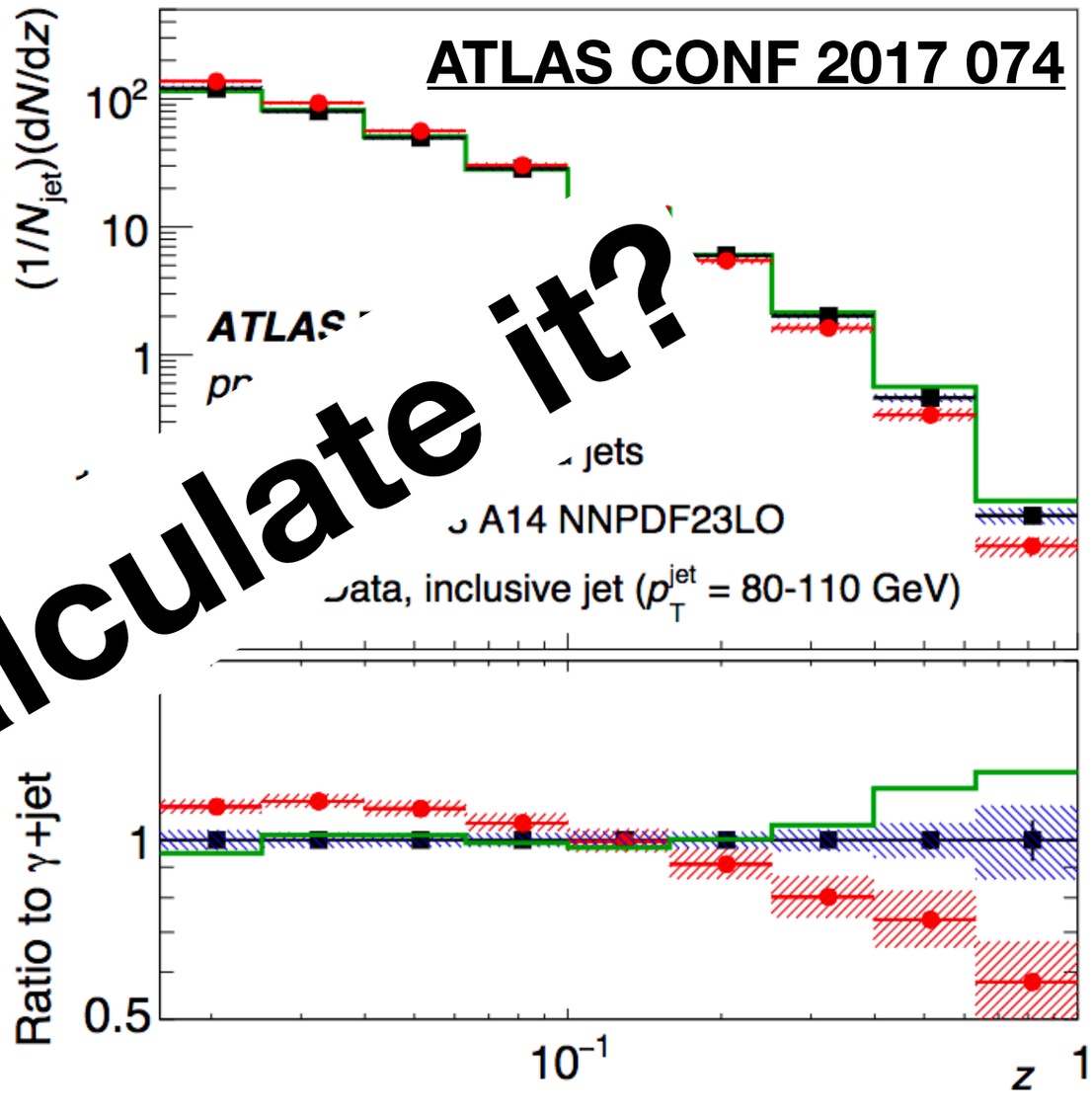




- Accessibility to a large boson+jet sample crucial to have a knob on jet flavor to more quark jets
- QCD color factor - Quark jets fragment more harder compared to gluons

Fragmentation Function - PP





Can we calculate it?

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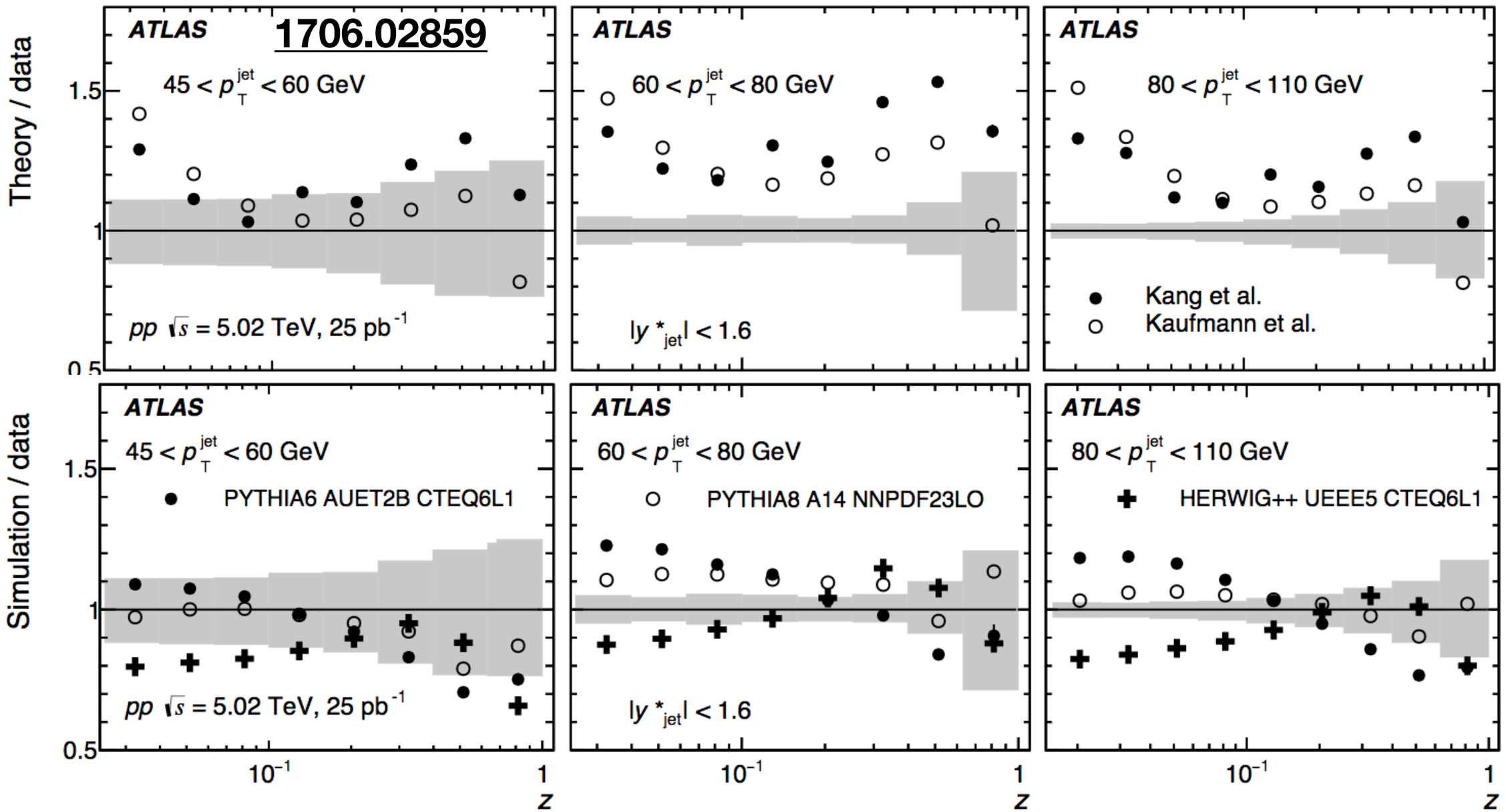
- QCD color factor - Quark jets fragment more harder compared to gluons

Can we simulate/calculate it?



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- Theoretical calculations have room for improvements

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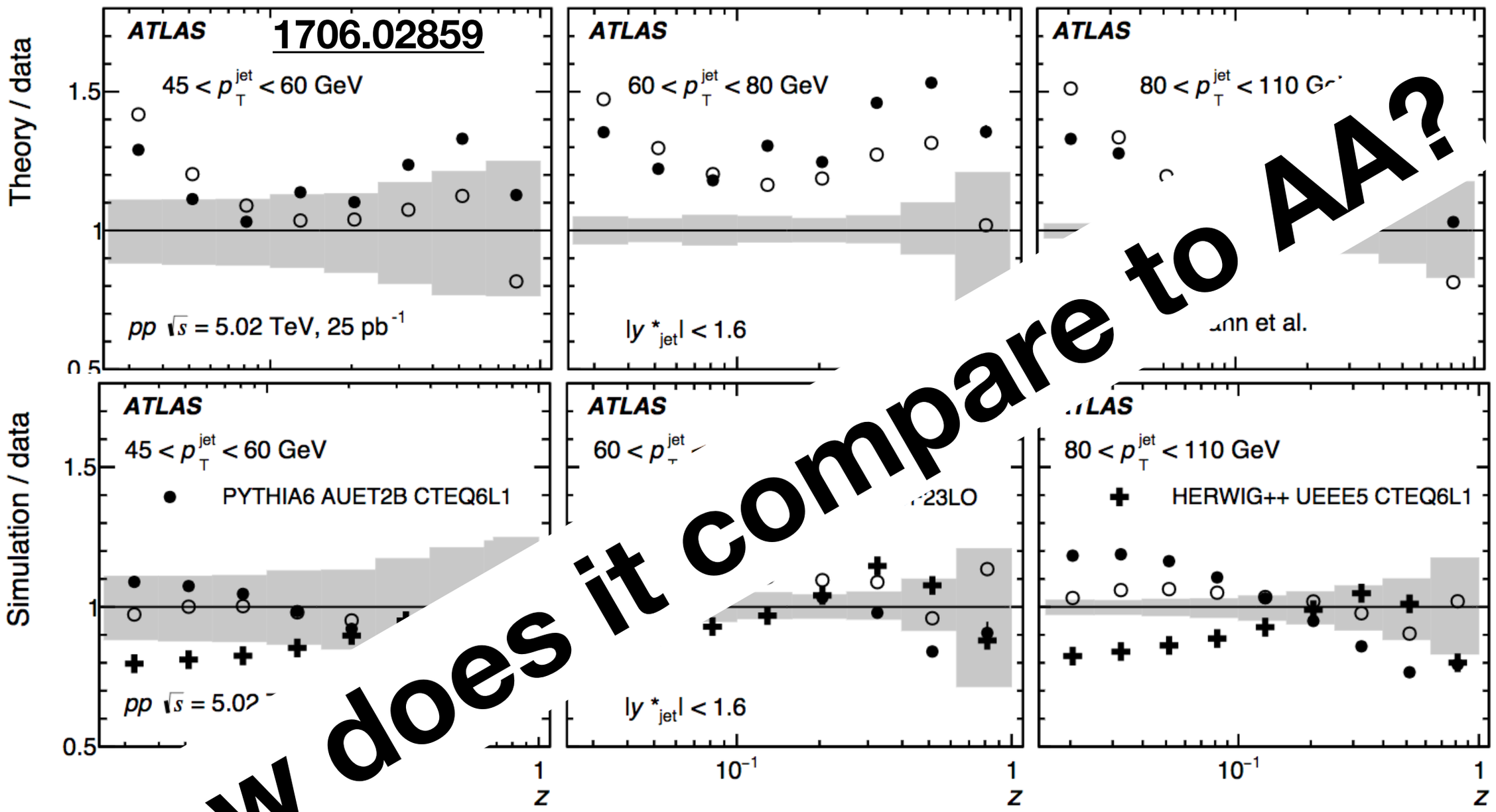

How does it compare to AA?

- We end up at the standard PYTHIA-HERWIG sandwich
- Theoretical calculations have room for improvements

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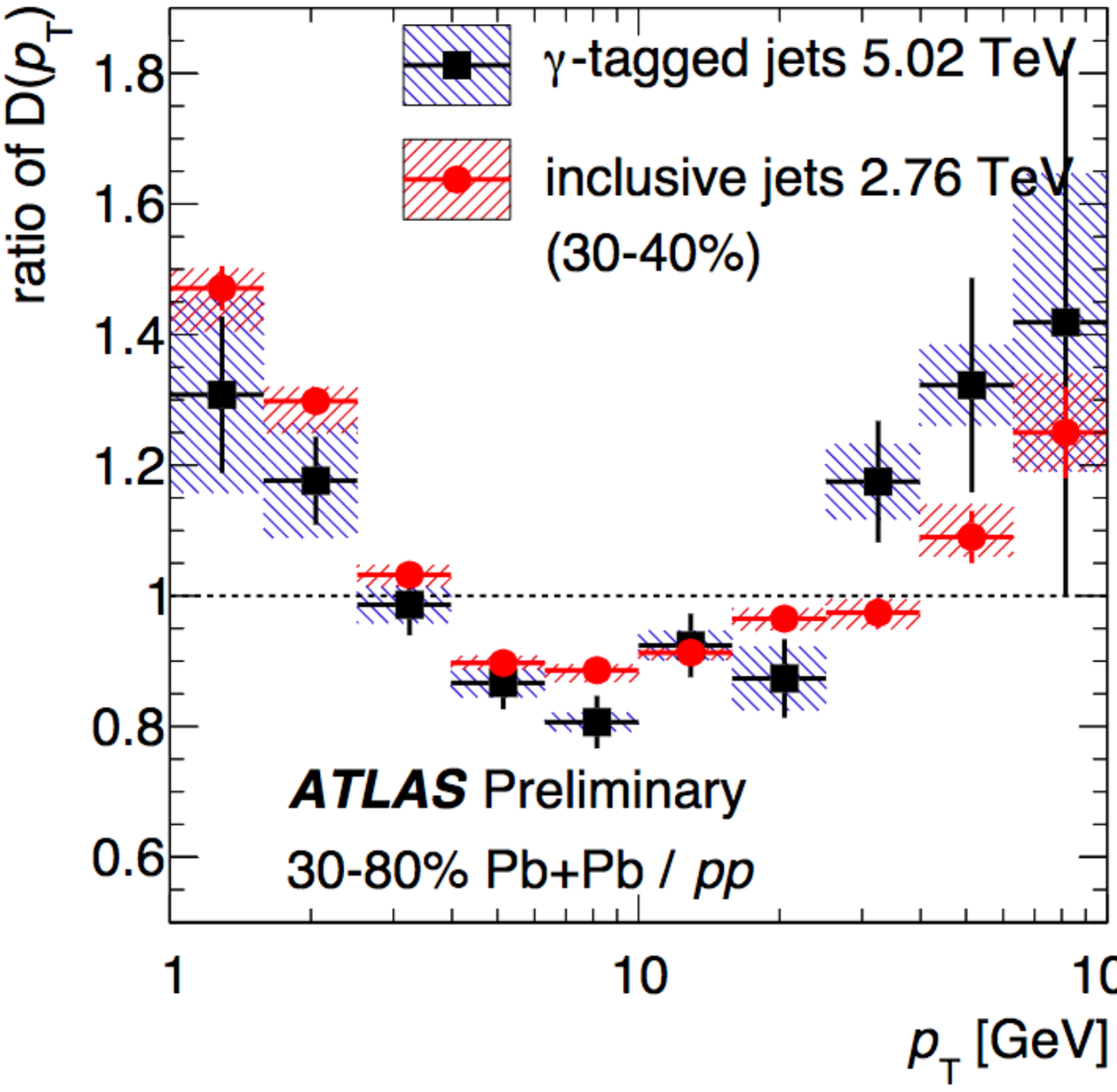

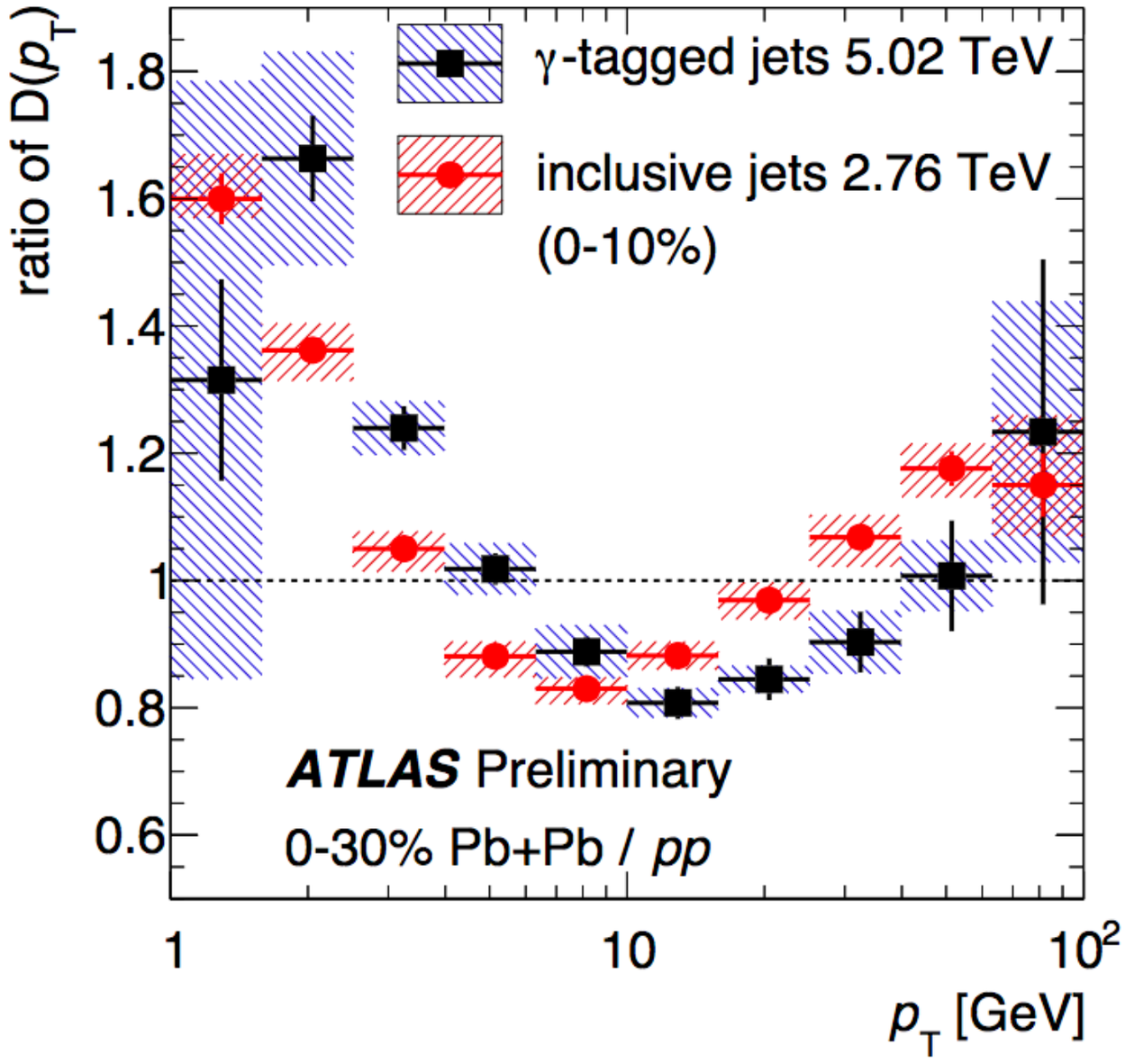

- Significant but small-ish modification of FF
- Inclusive compared to y-jet, mostly quark jets (expected)

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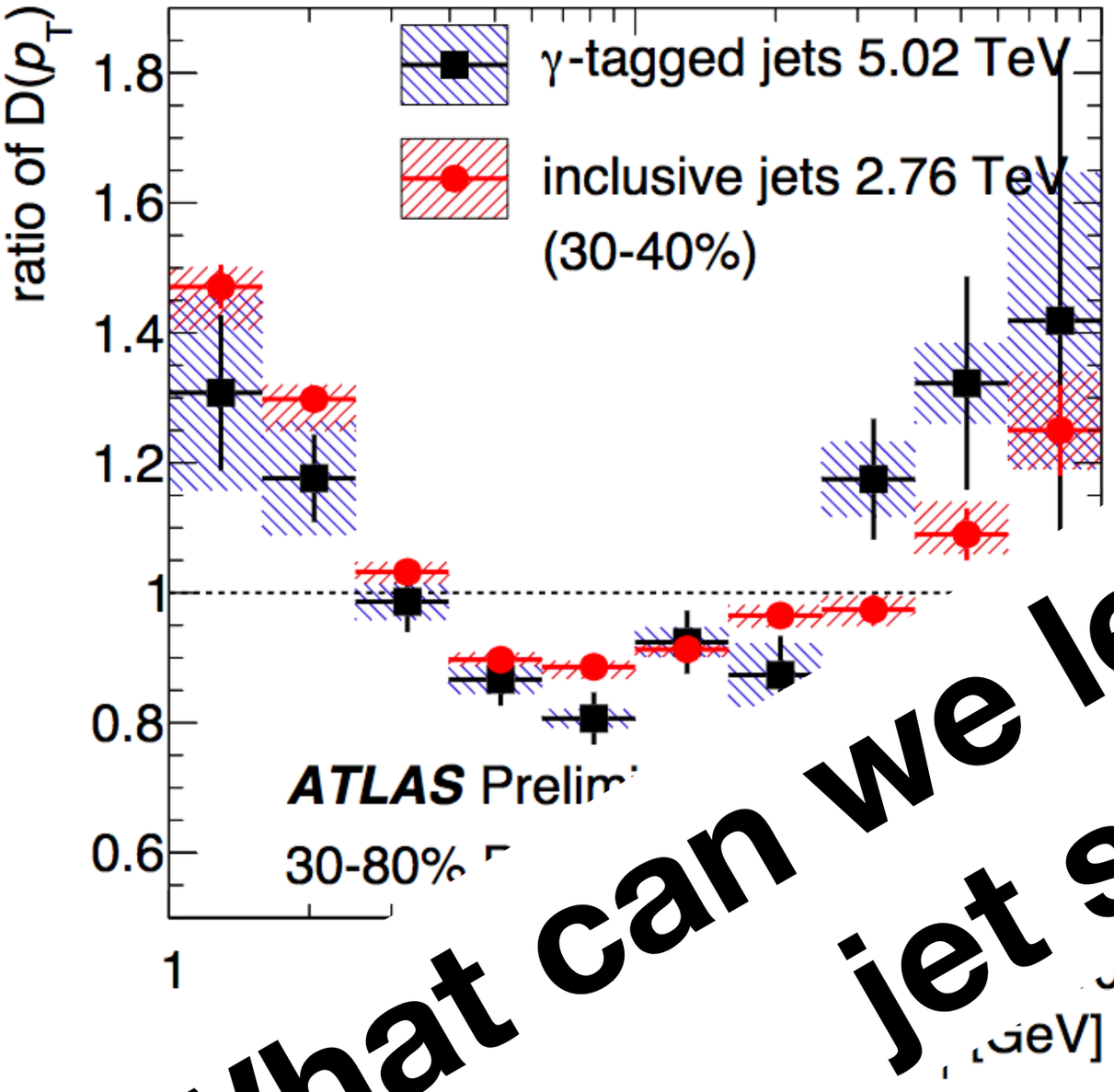
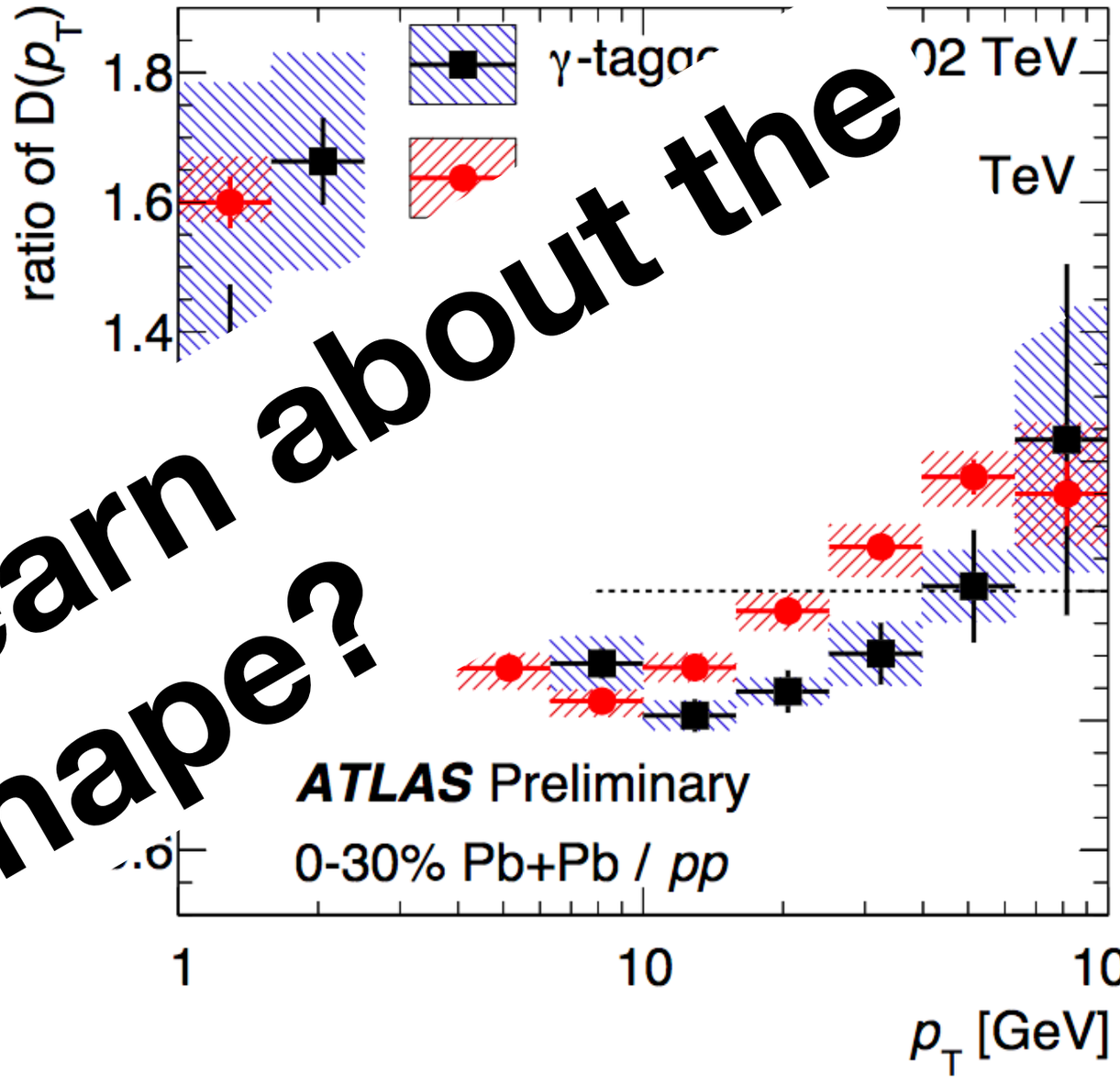




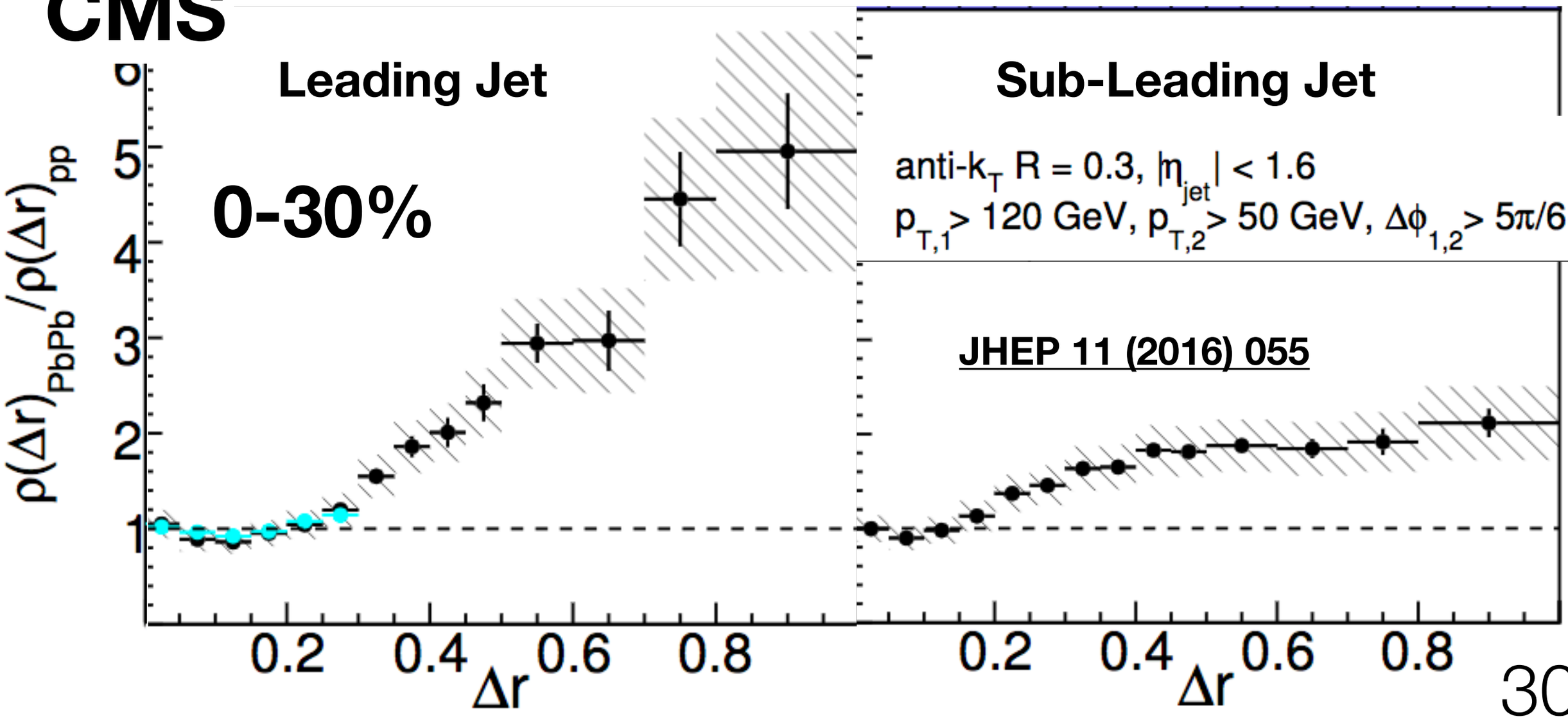
What can we learn about the jet shape?

- Significant but small-ish modification of FF
- Inclusive compared to y-jet, mostly quark jets (expected)

Standard Jet Shapes - AA/pp

- ETA-Reflection background
- In-jetcone : sub-leading jet broader
- Out-jetcone : leading hemisphere has more activity compared with pp

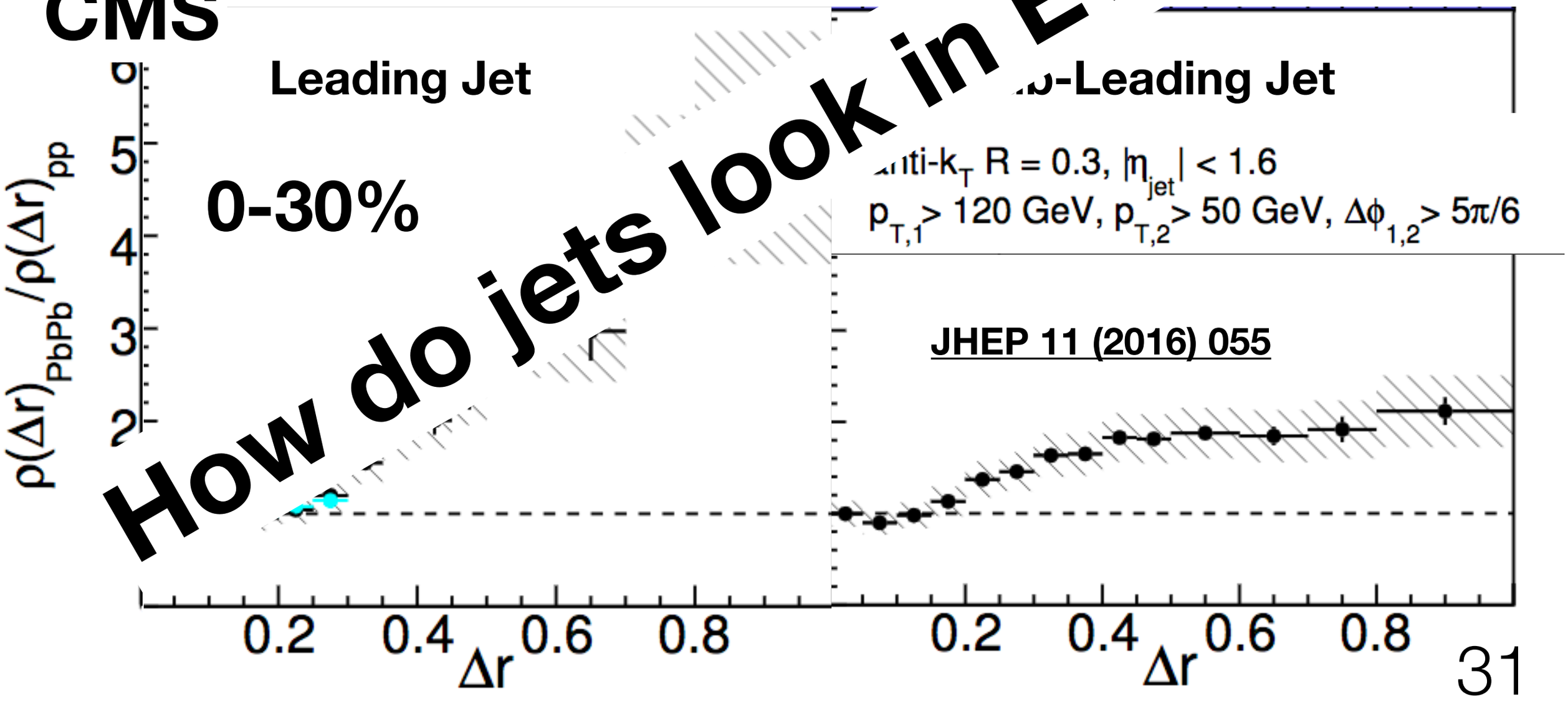
CMS



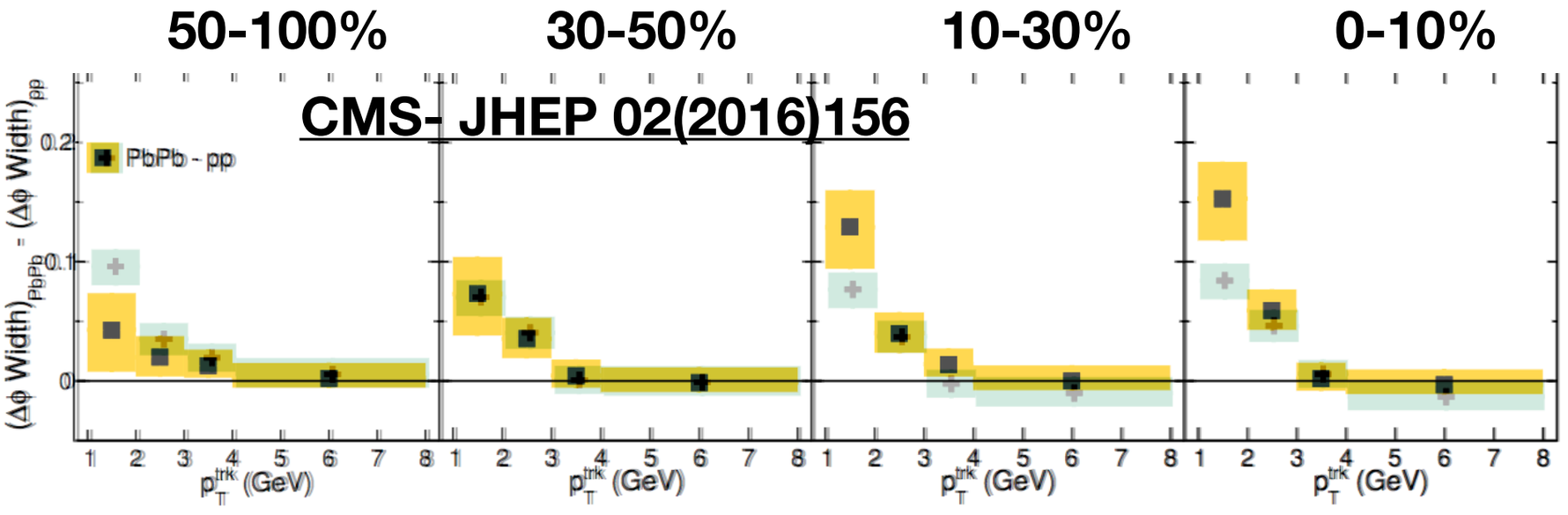
Standard Jet Shapes - AA/pp

- ETA-Reflection background
- In-jetcone : sub-leading jet broader
- Out-jetcone : leading hemisphere has more a
  compared with pp

How do jets look in ETA-PHI?



Jet-Track correlations

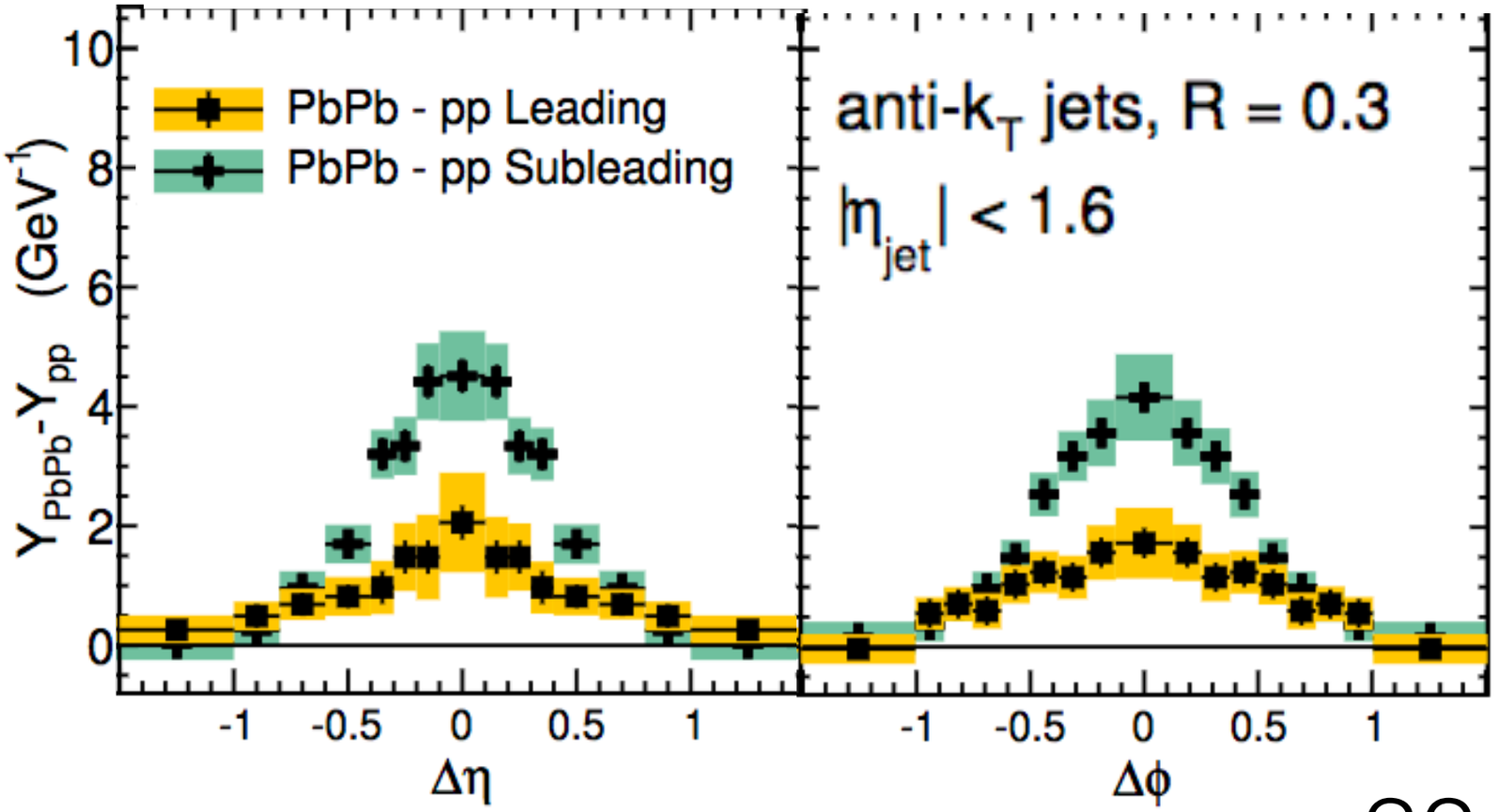


$p_{T,\,jet1} > 120$ GeV

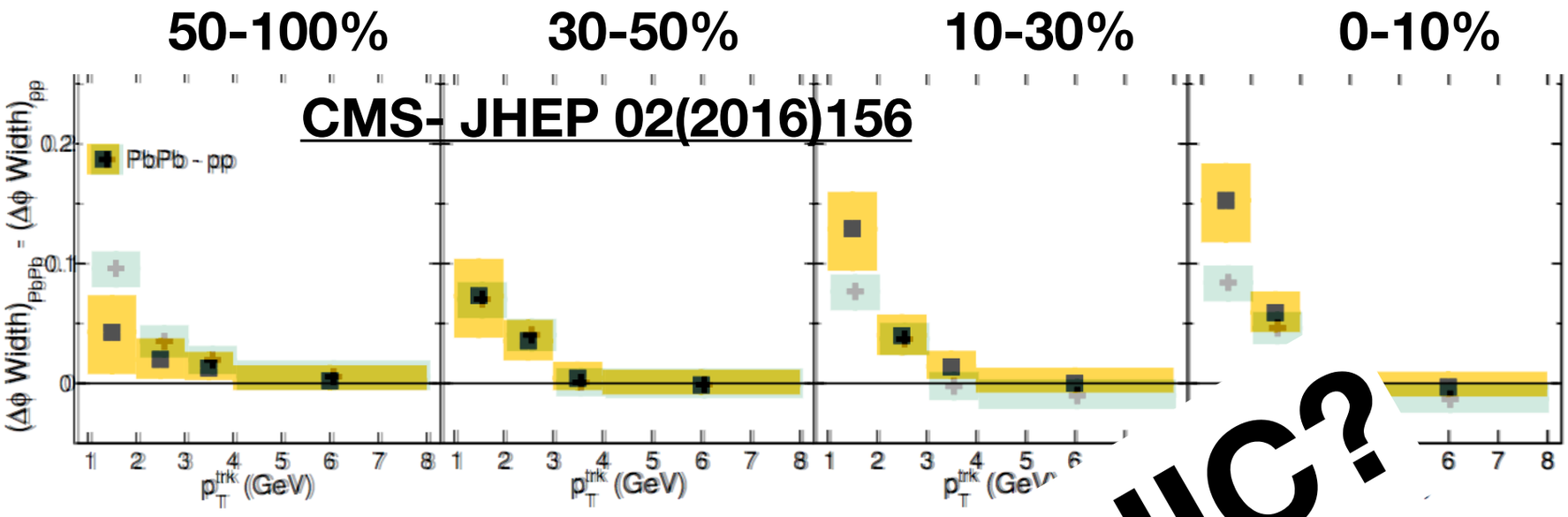
$p_{T,\,jet2} > 50$ GeV

$|\Delta\phi_{1,2}| > 5\pi/6$

- Similar jet shapes in both eta/phi
- Mild Centrality dependence for leading Jets



Jet-Track correlations

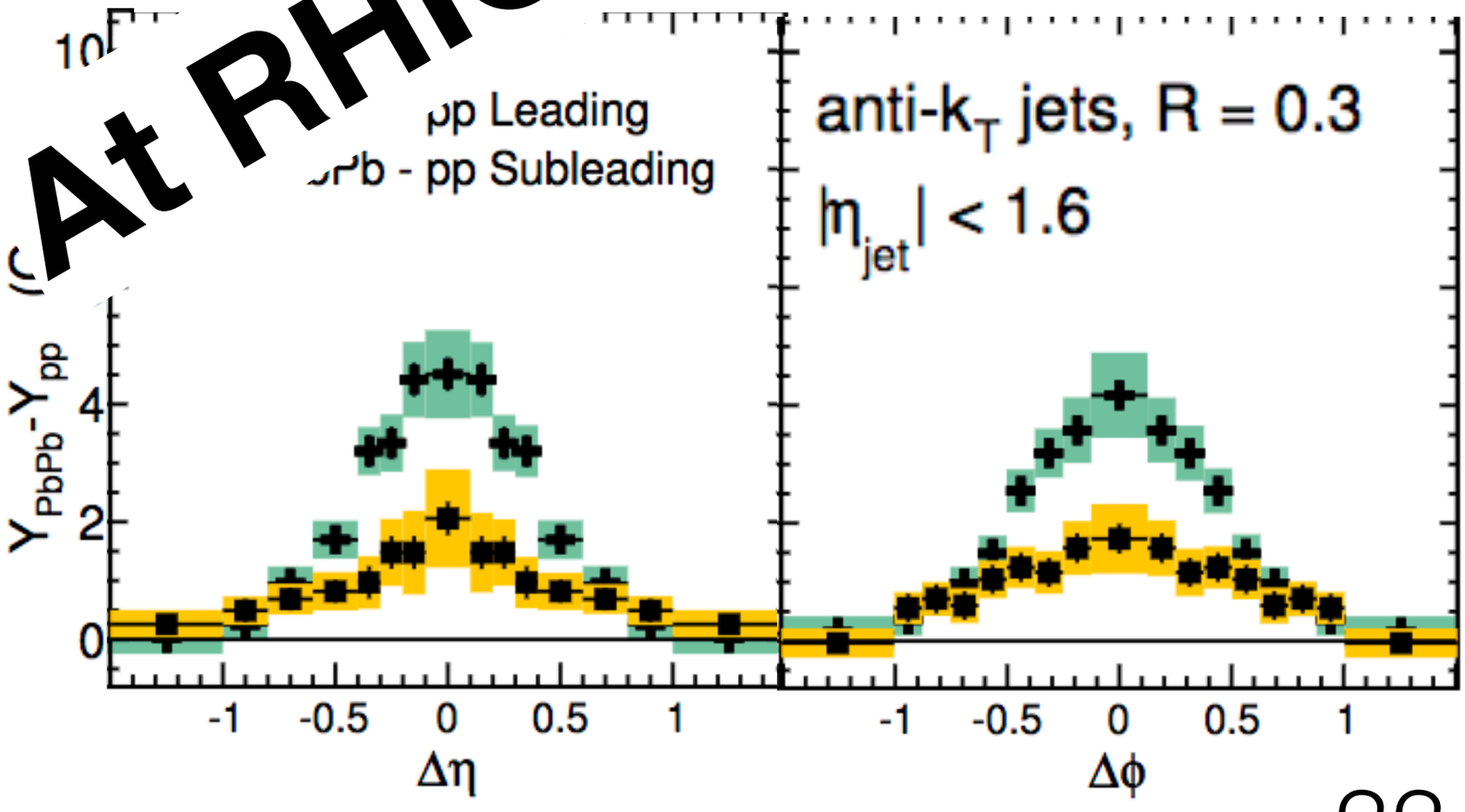


$p_{T,\,jet1} > 120$ GeV

$p_{T,\,jet2} > 50$ GeV

$|\Delta\phi_{1,2}| > 5\pi/6$

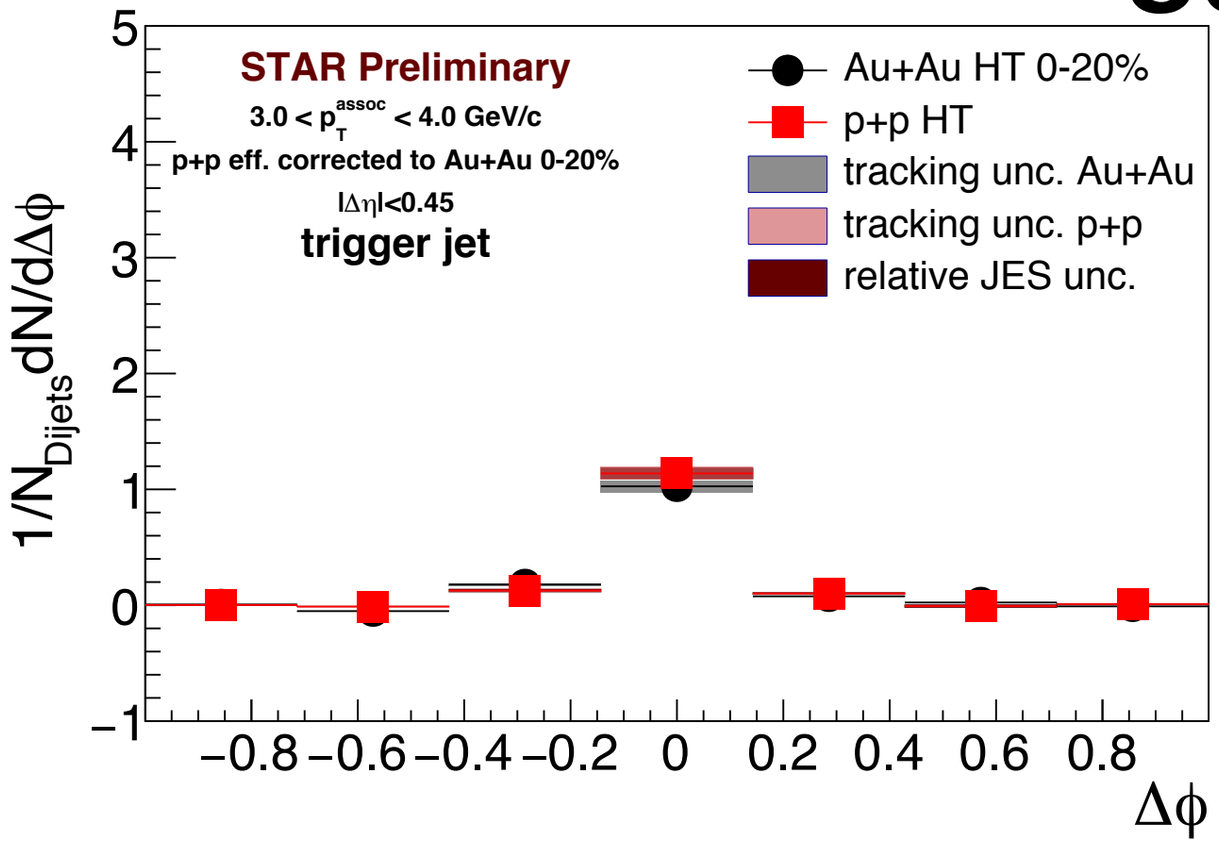
At RHIC?

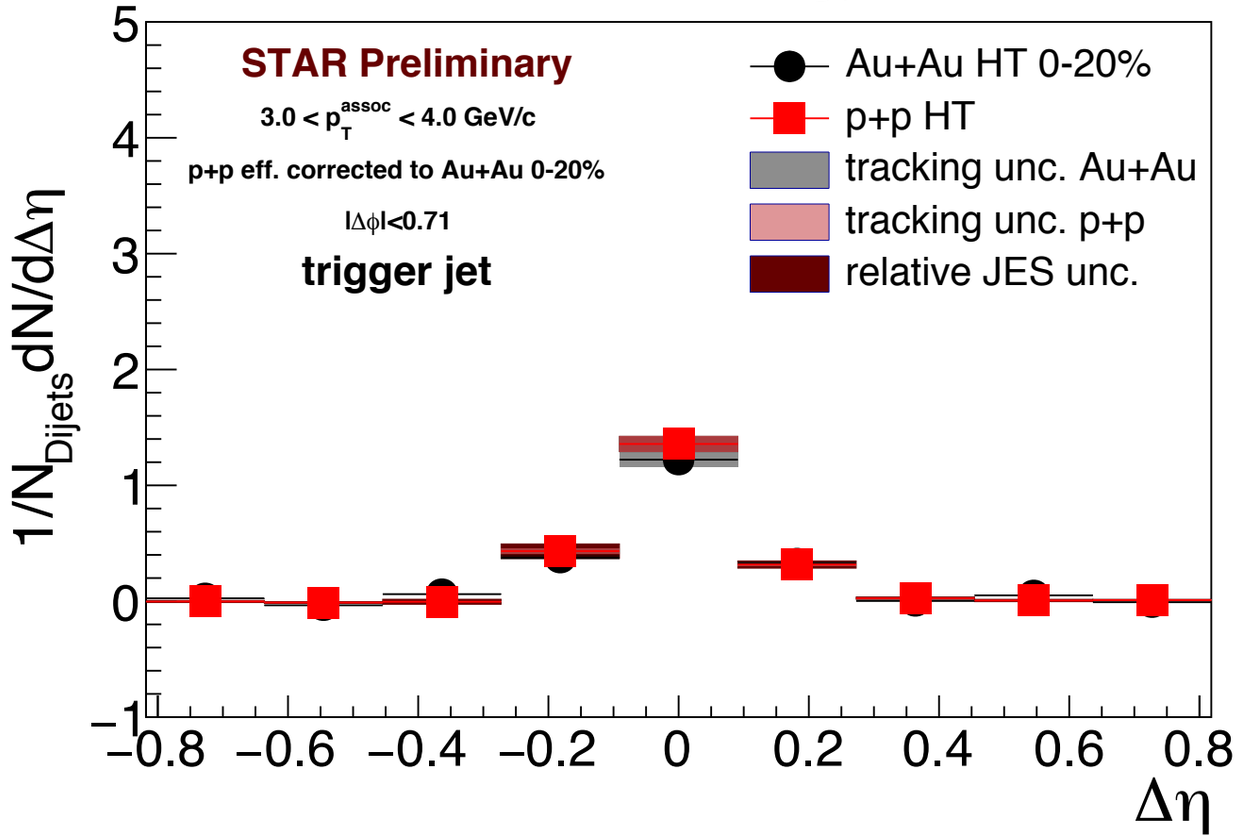


- Similar jet shapes in both eta/phi
- Mild Centrality dependence for leading Jets

Trigger Jet

Nick Elsey, DNP 2017



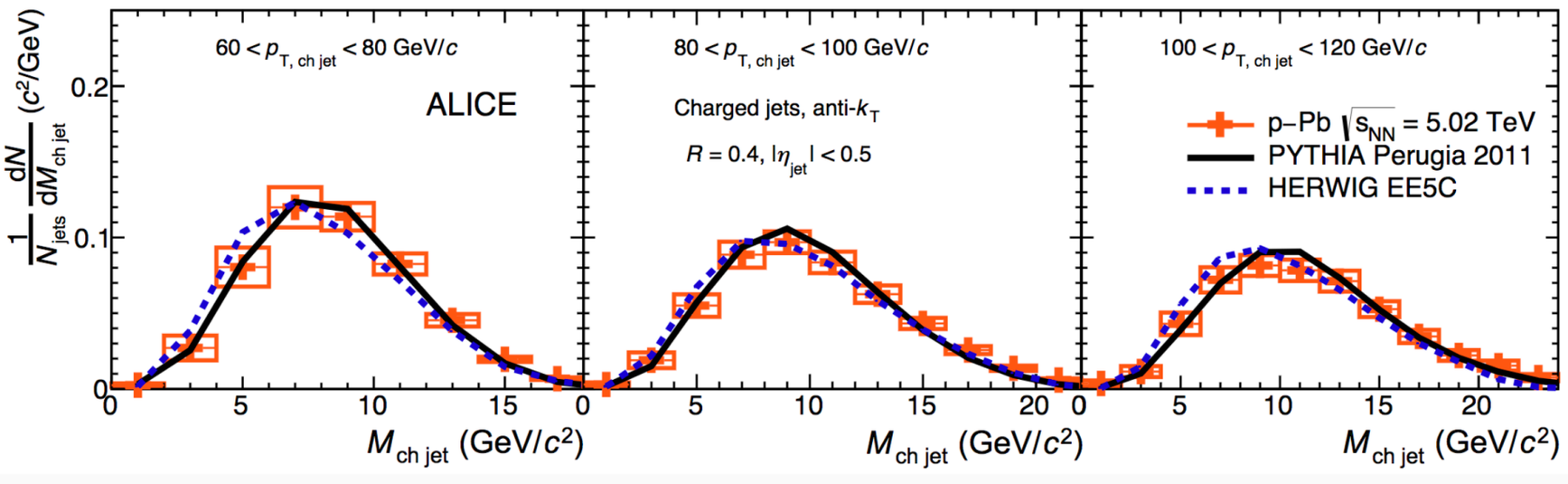


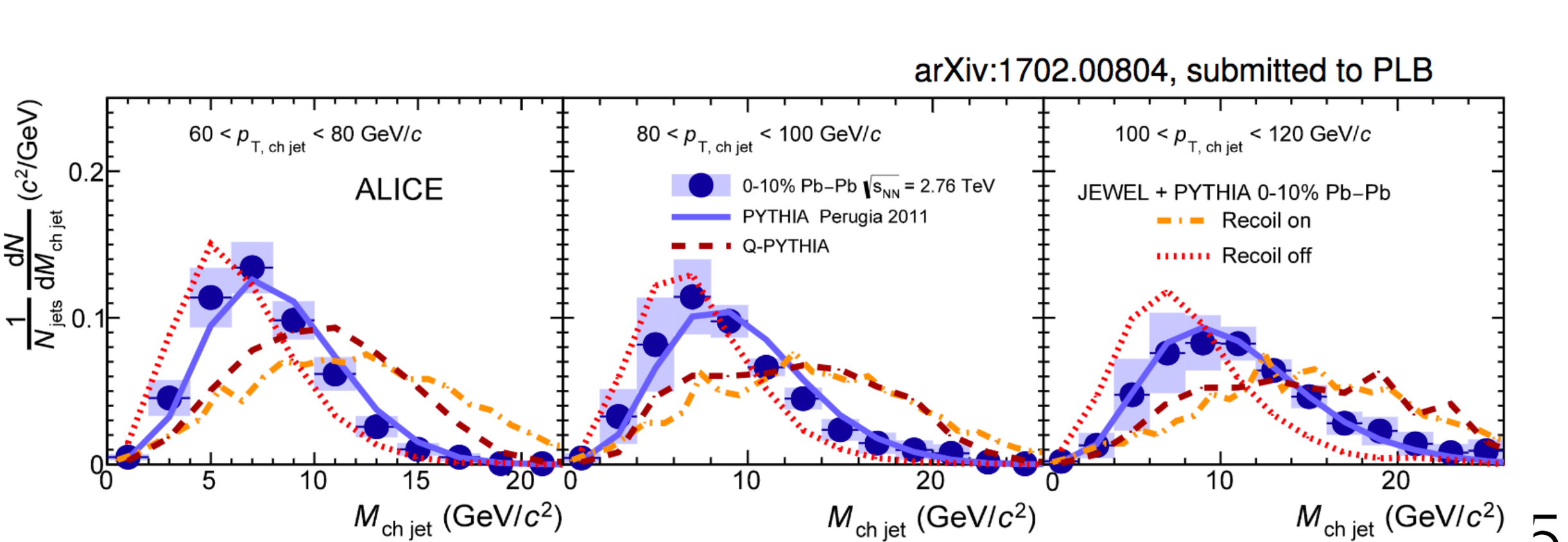
"At the same time, many attributes of the jets that emerge from QGP are described very well at weak coupling, for example, the fact that they have quite similar fragmentation patterns and angular shapes as jets that form in vacuum. This makes us optimistic that jets encode information about the structure of QGP over a wide range of length scales."

2015 NP-LRP

Invariant Jet Mass

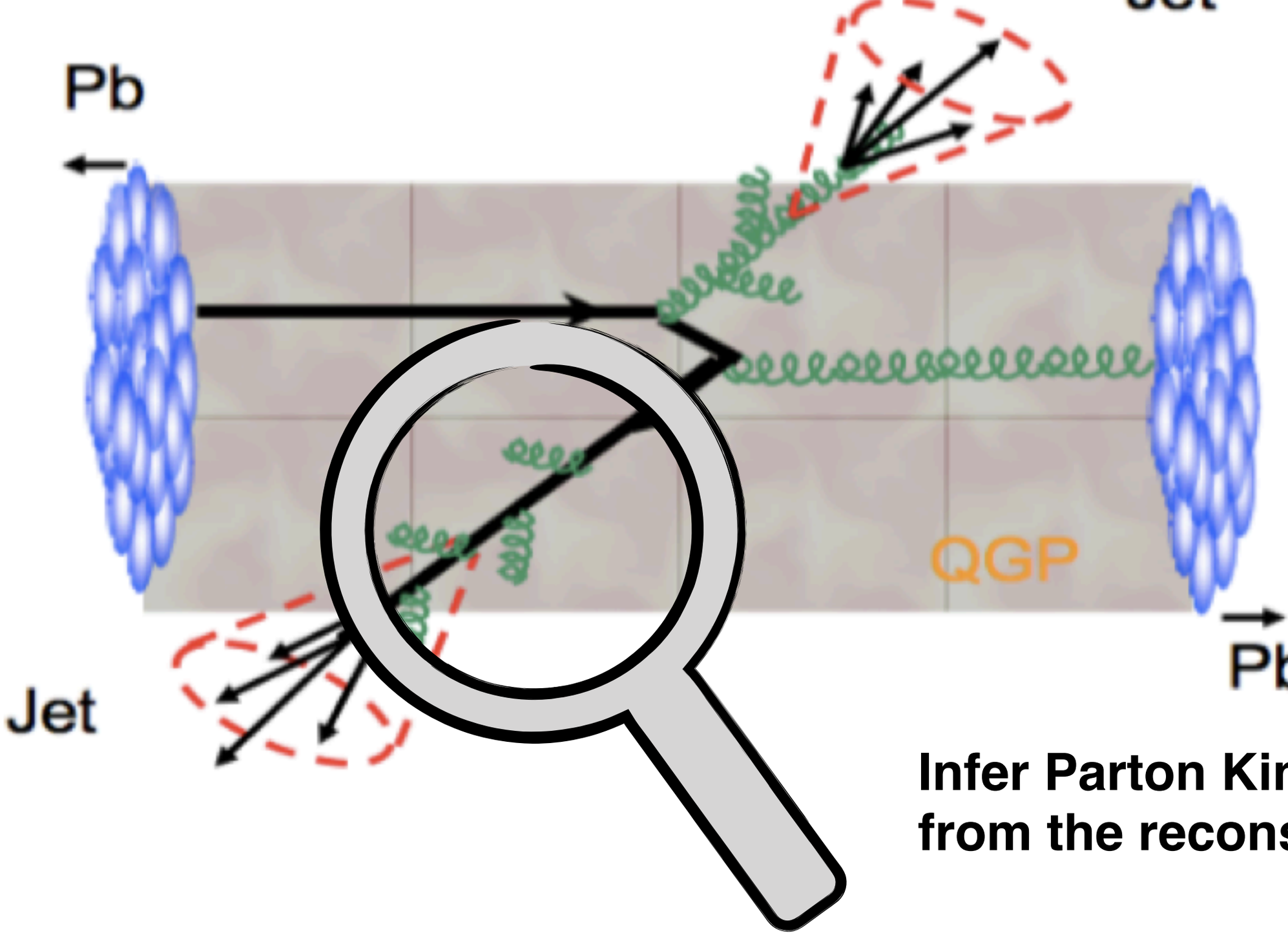
- M ~ z theta^2
- Area based and constituent subtraction gives similar results
- Unfolded - AA jet mass distributions different compared to MC





Recap - II
Jet Shape/Fragmentation

- Proton-proton
  - Take advantage of small MPI/UE (compared to AA)
    - MC/Theory, close but not there yet
- Heavy Ions (AA)
  - Expected changes to Jet Shape and Fragmentation
  - Jets appear to be more collimated at the core



Infer Parton Kinematics from the reconstructed Jet

"Jets provide tools of great potential for microscopy because their modification as they travel through QGP is influenced by the structure of the medium at many length scales."

Tools from HEP

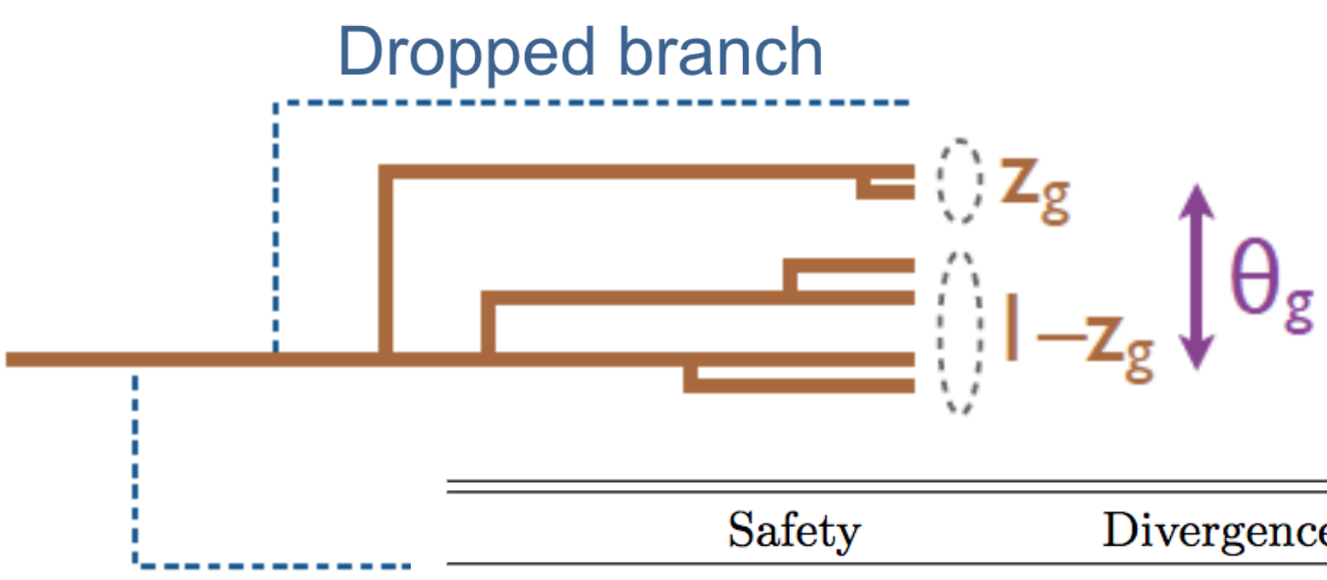
Grooming -> Splitting

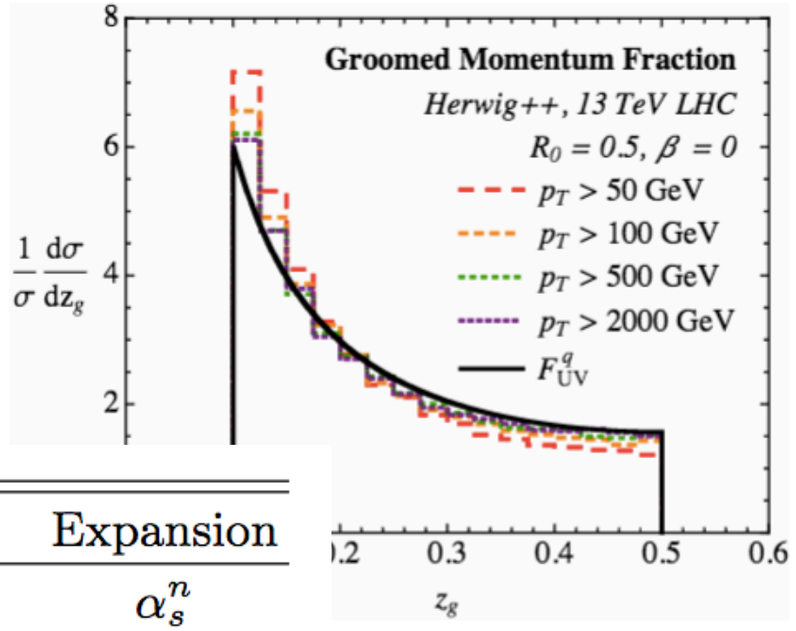
z_g (groomed shared momentum fraction) :

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

z_{cut} = 0.1, β= 0

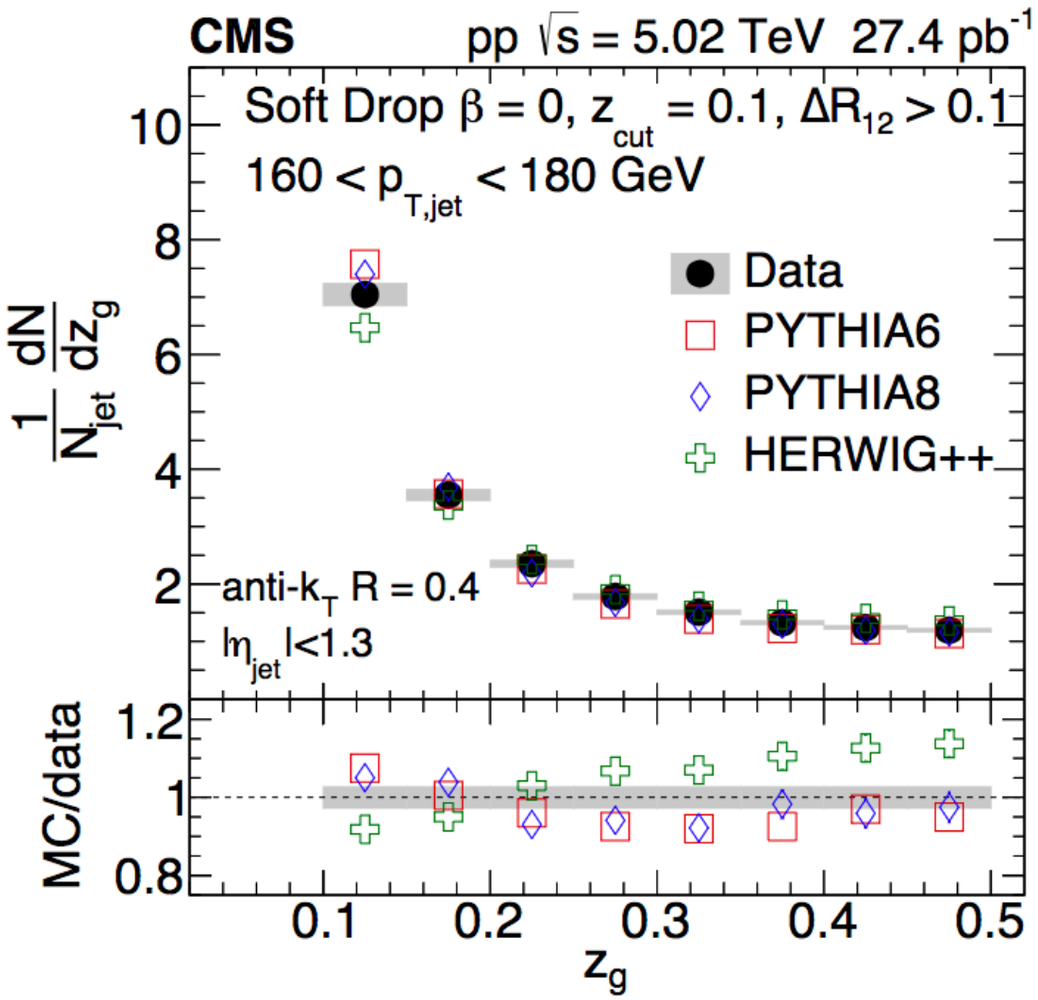
Modifications to subjet splitting in the HIN environment: what can we expect?

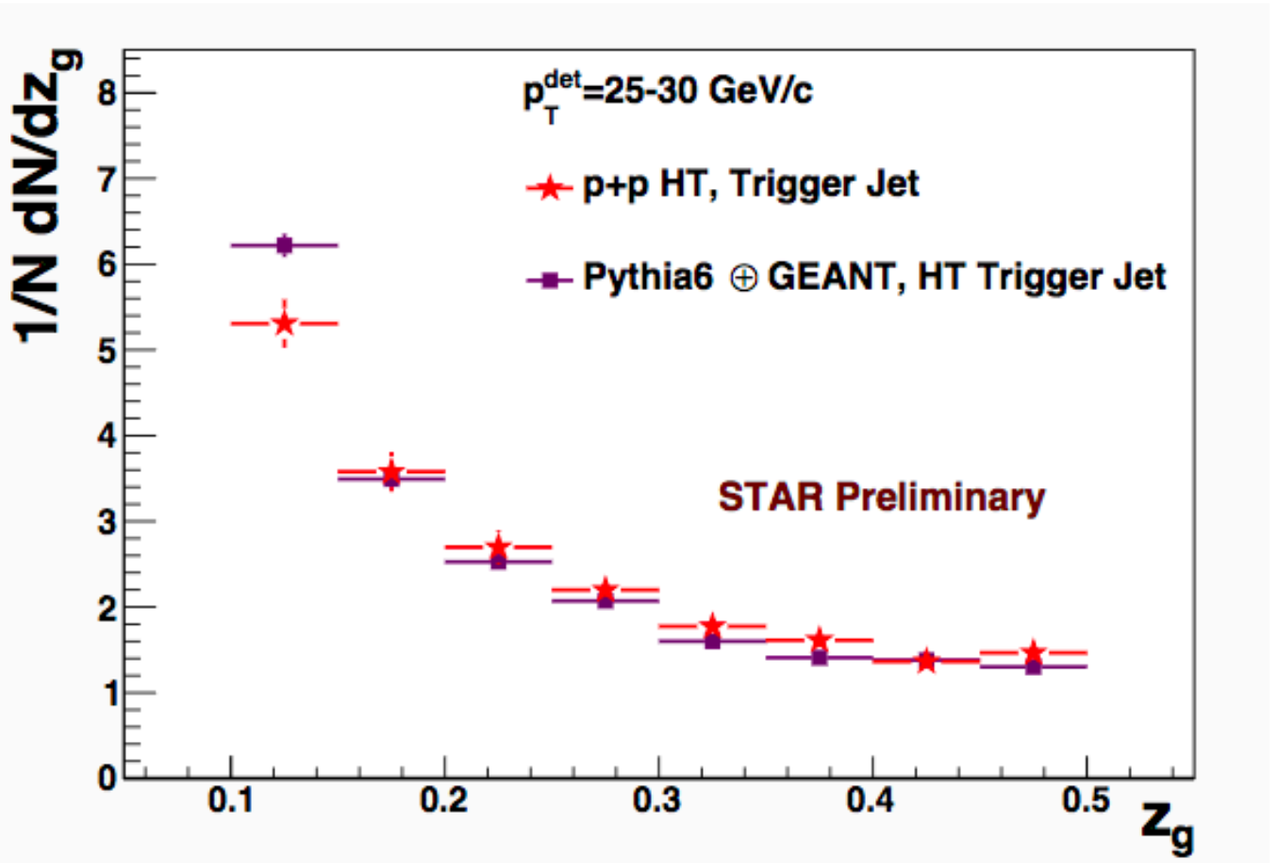


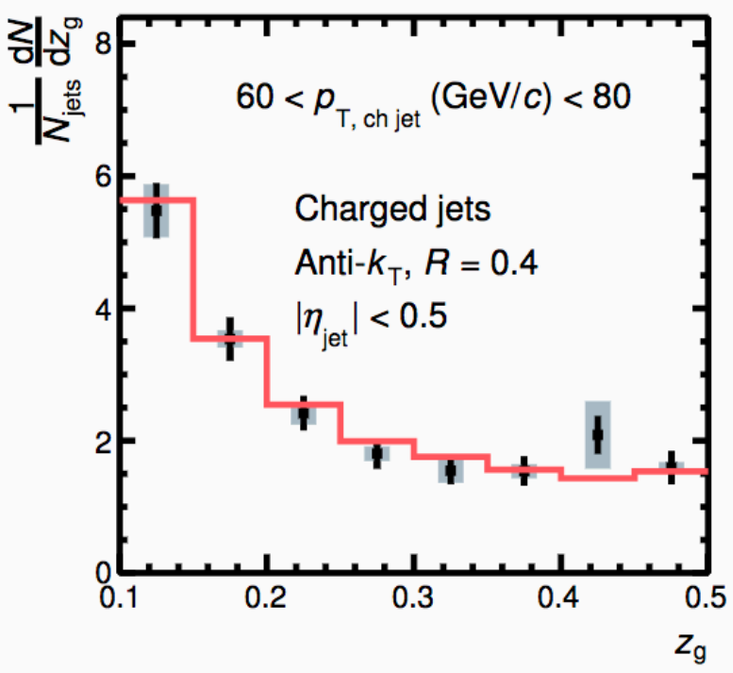


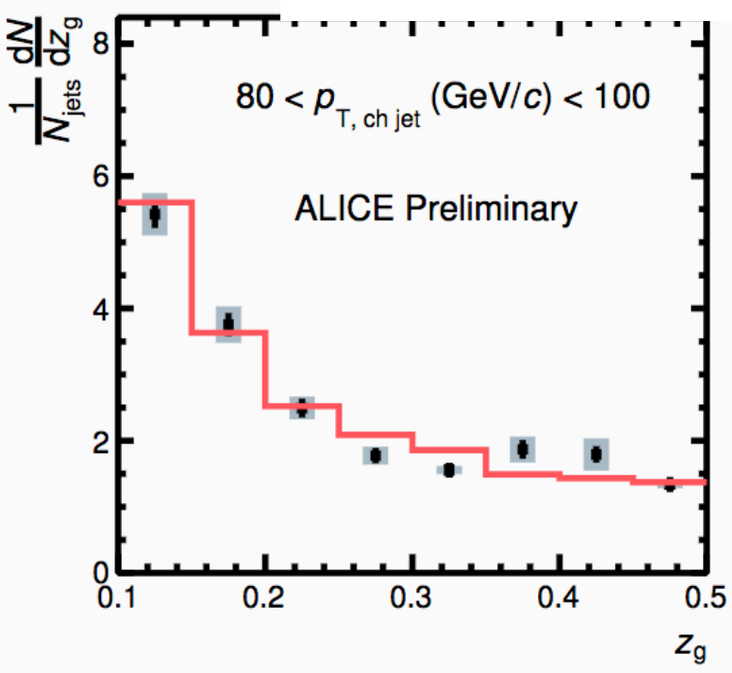
	Safety	Divergences	Expansion
$\beta < 0$	IRC	None	α_s^n
$\beta = 0$	IRC via FF	Collinear Only	α_s^{n-1}
$\beta > 0$	Sudakov	Collinear & Soft-Coll.	$\alpha_s^{n/2}$

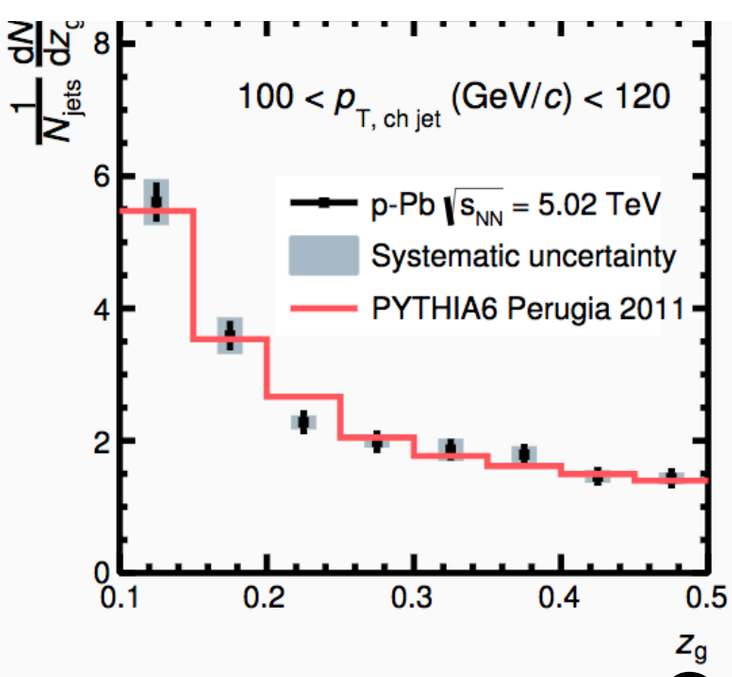
PP (pPb) - vacuum like





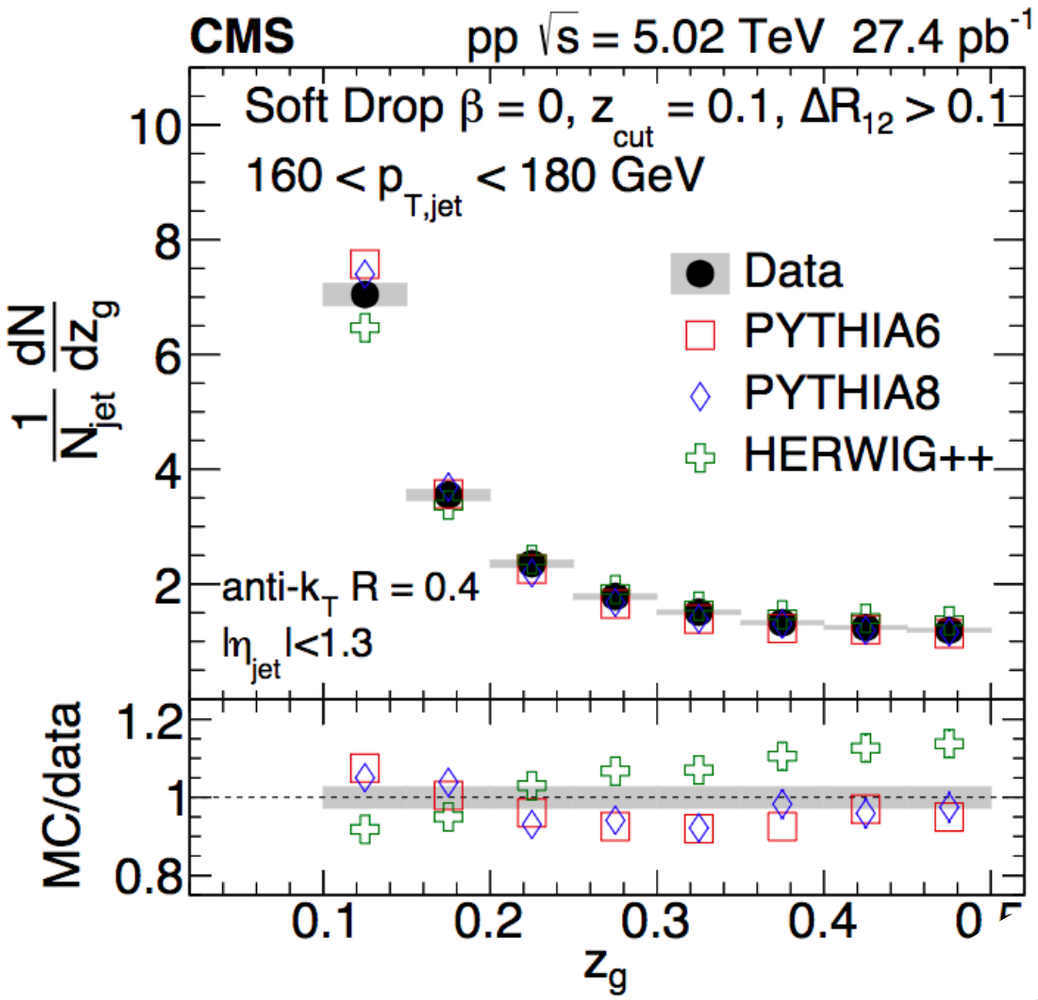


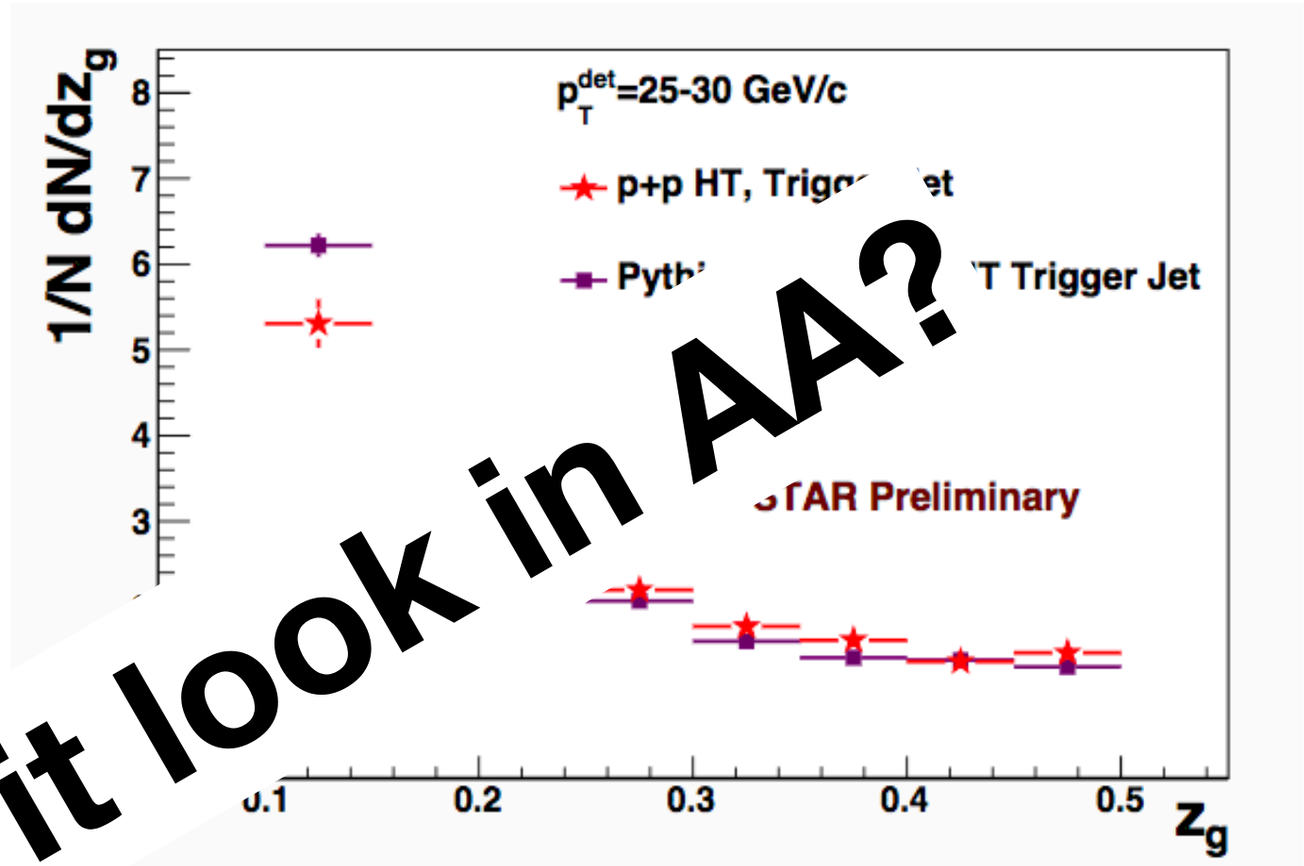




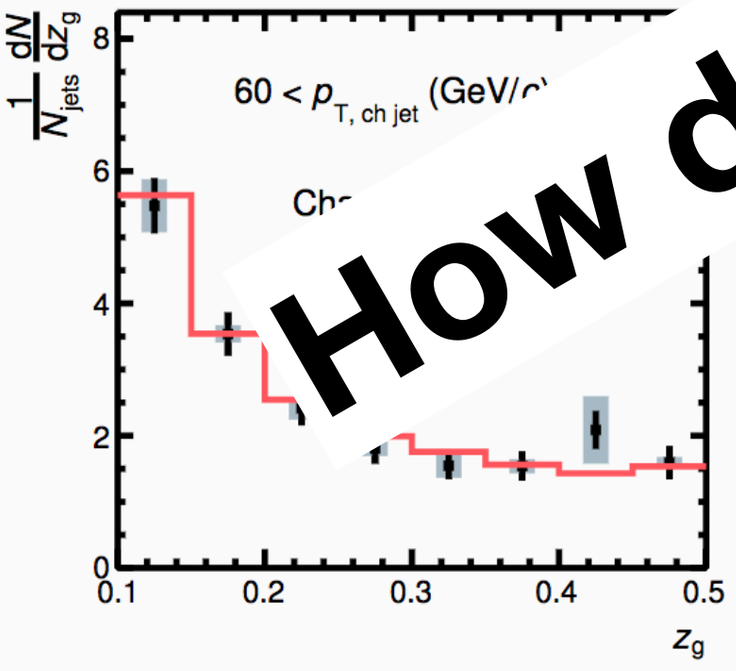
ALI-PREL-120123

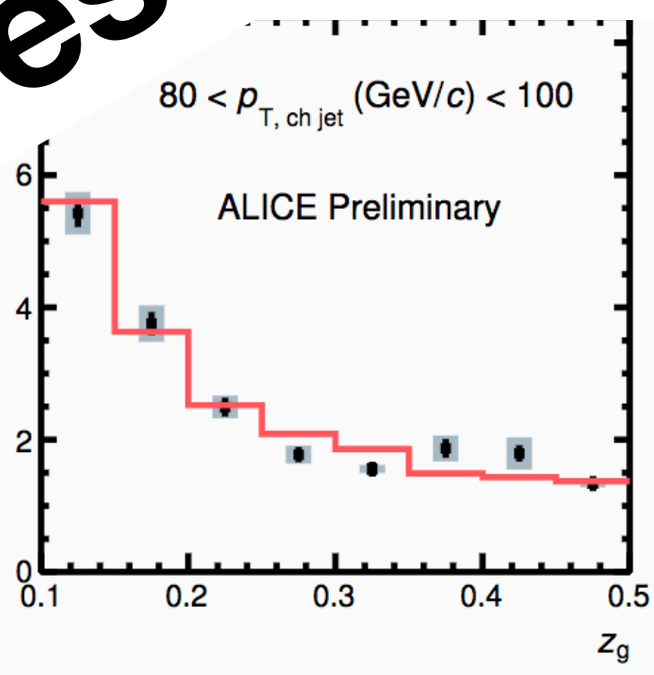
PP (pPb) - vacuum like

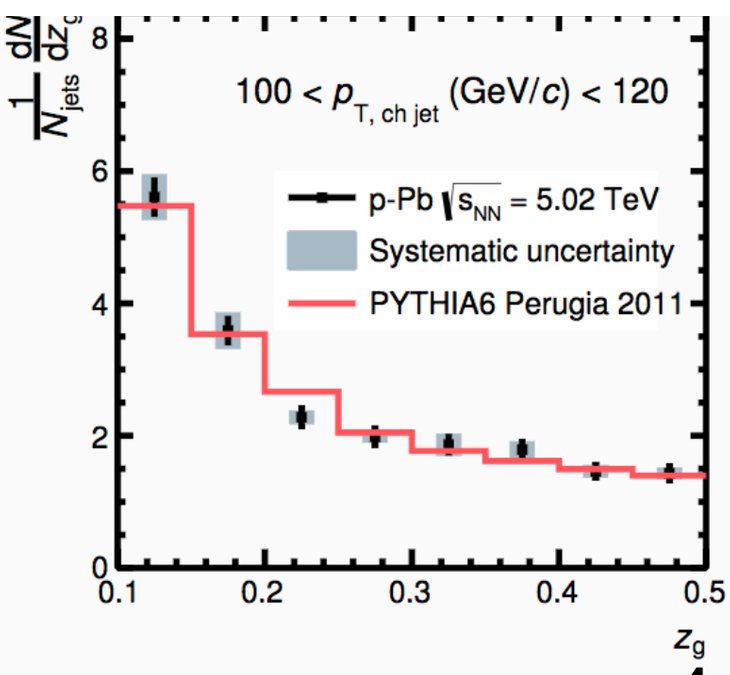




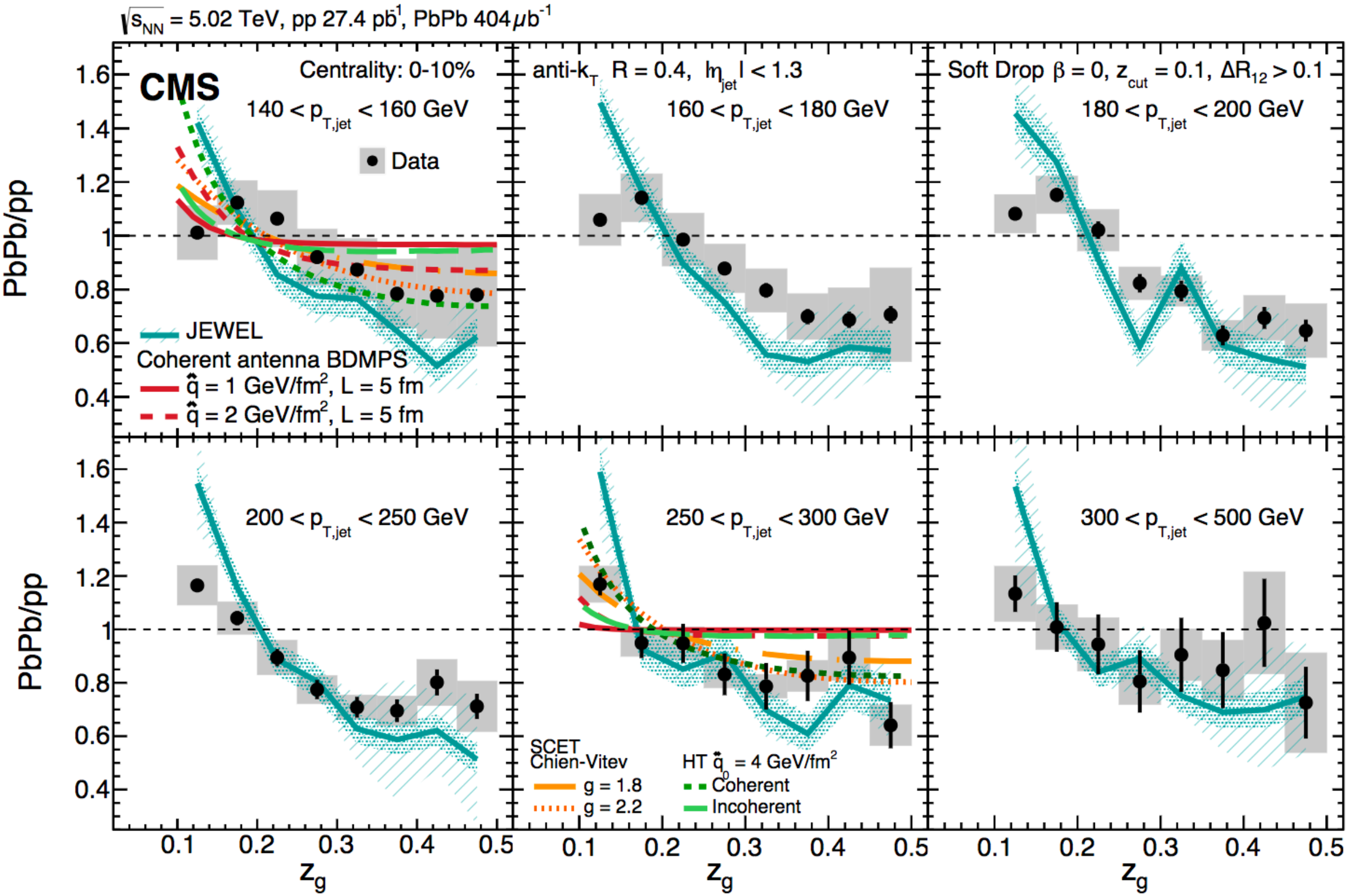
How does it look in AA?



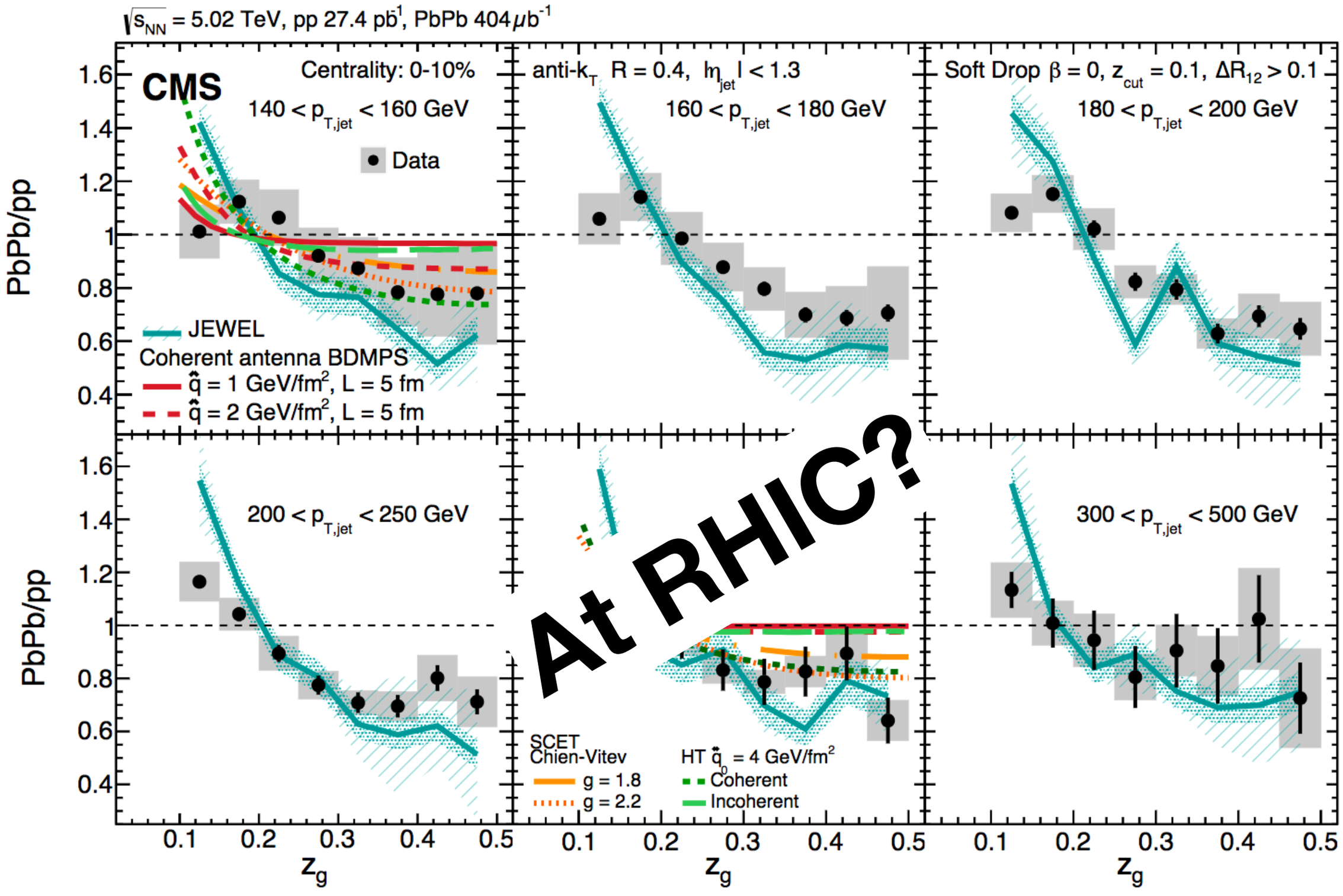




ALI-PREL-120123



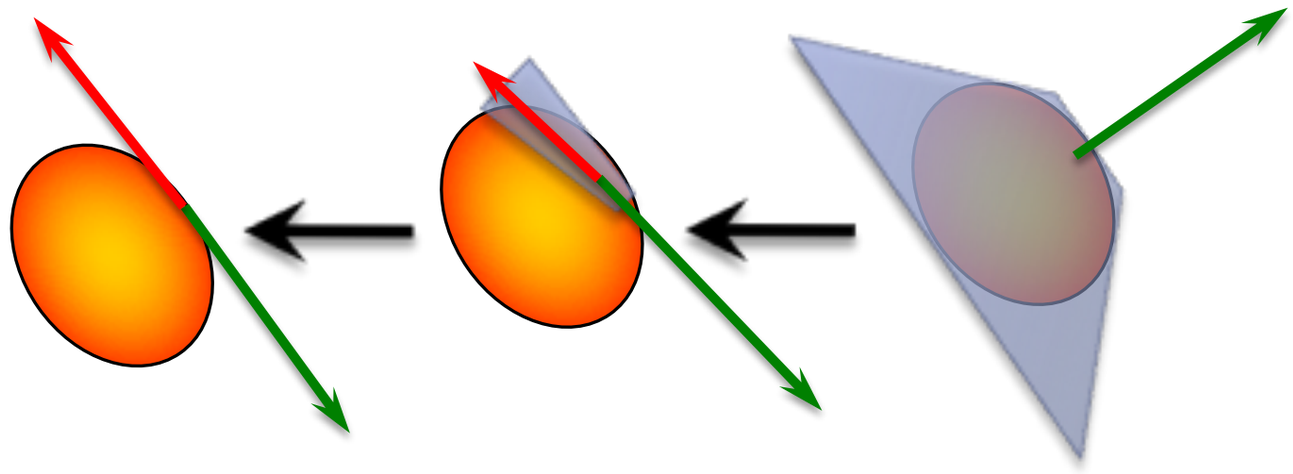
- More Asymmetrically split (special selection) jets in AA
- Slight momenta dependence
- Not Unfolded (pp - smeared reference)

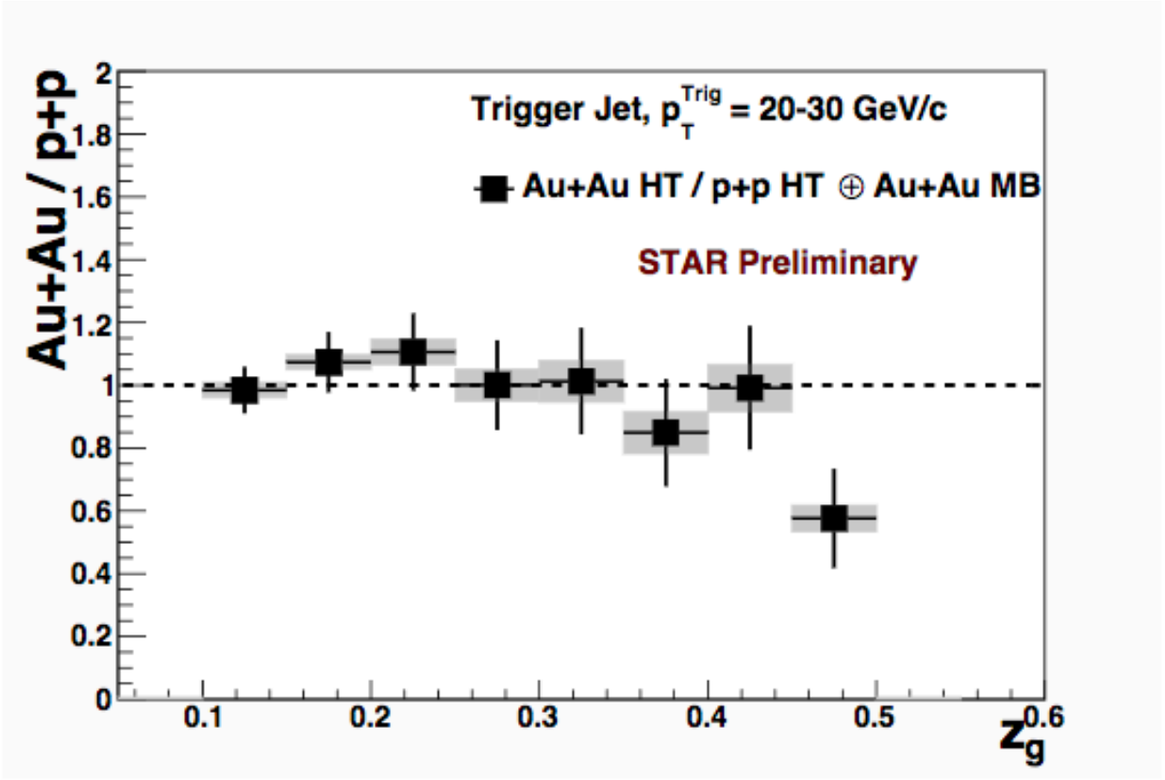


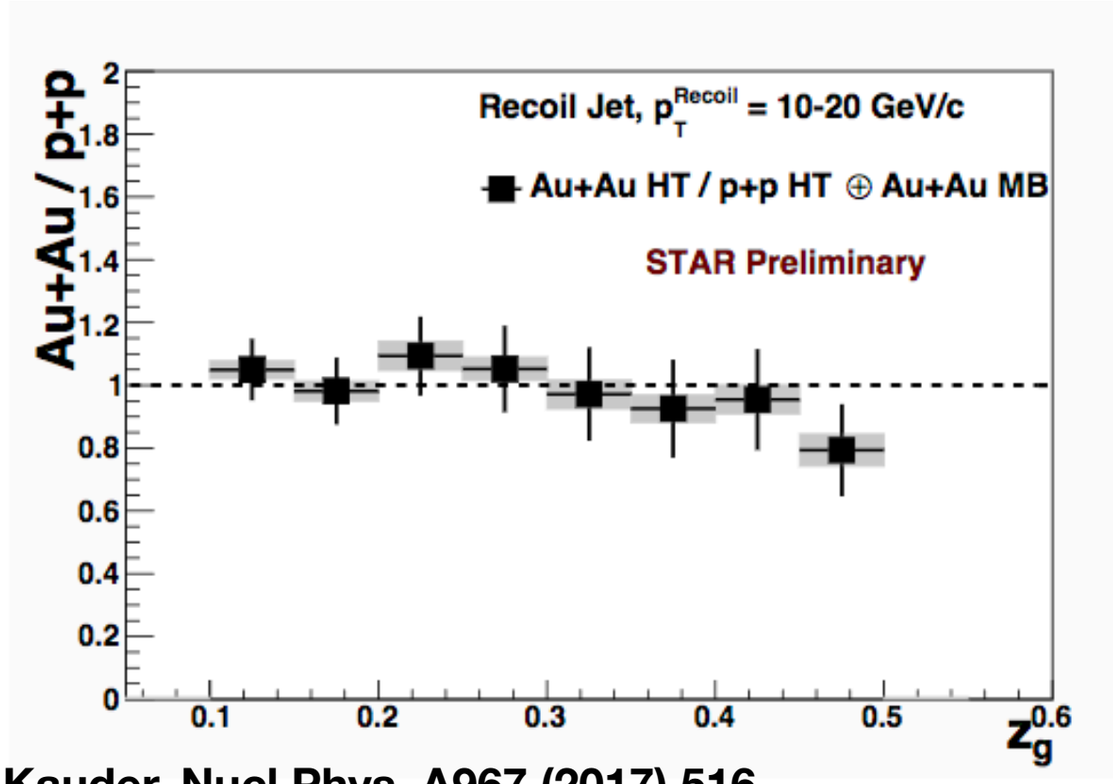
- More Asymmetrically split (special selection) jets in AA
- Slight momenta dependence
- Not Unfolded (pp - smeared reference)

Splitting Functions at STAR

- Data shows no modification in AA compared to pp
- These jets are special - hot tower selection
- Exciting opportunity for jet-geometry engineering



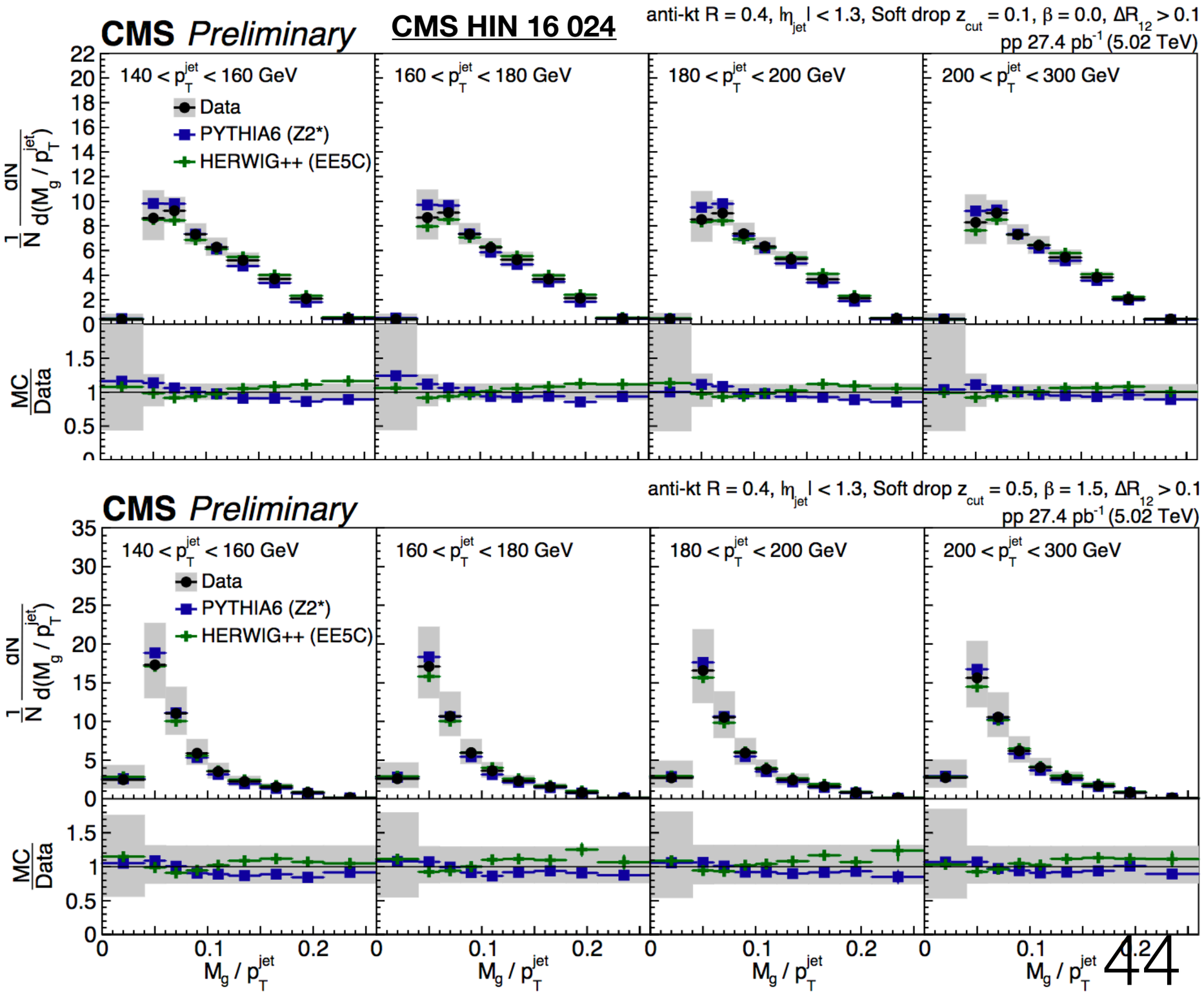




K Kauder, Nucl.Phys. A967 (2017) 516

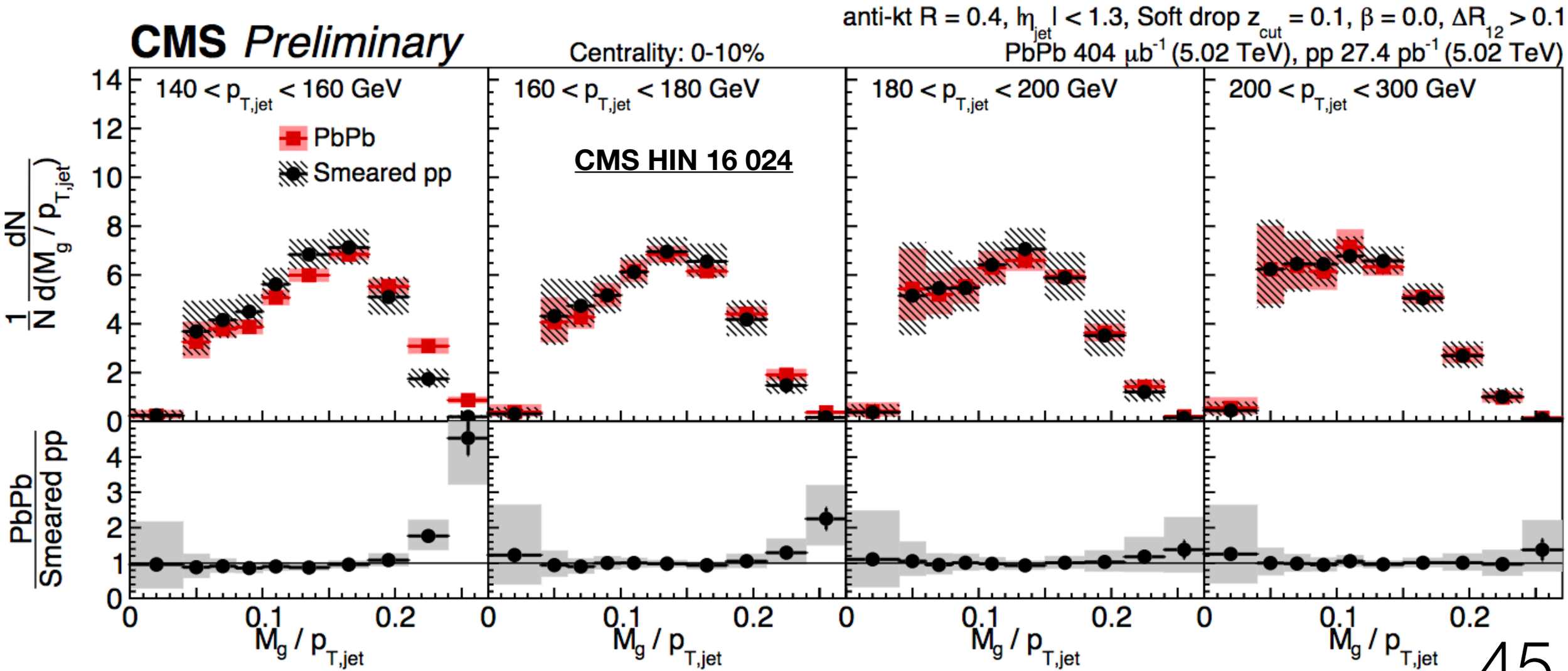
Groomed Jet Mass - PP

- groomed M/ pT ~ tau
- Comparing different grooming techniques
- PYTHIA-HERWIG Sandwich :)
- Not Unfolded…



Groomed Jet Mass - AA

- Jet Core seems to be unmodified for high pT jets
- Low pT - more collimated core, compared with pp ref

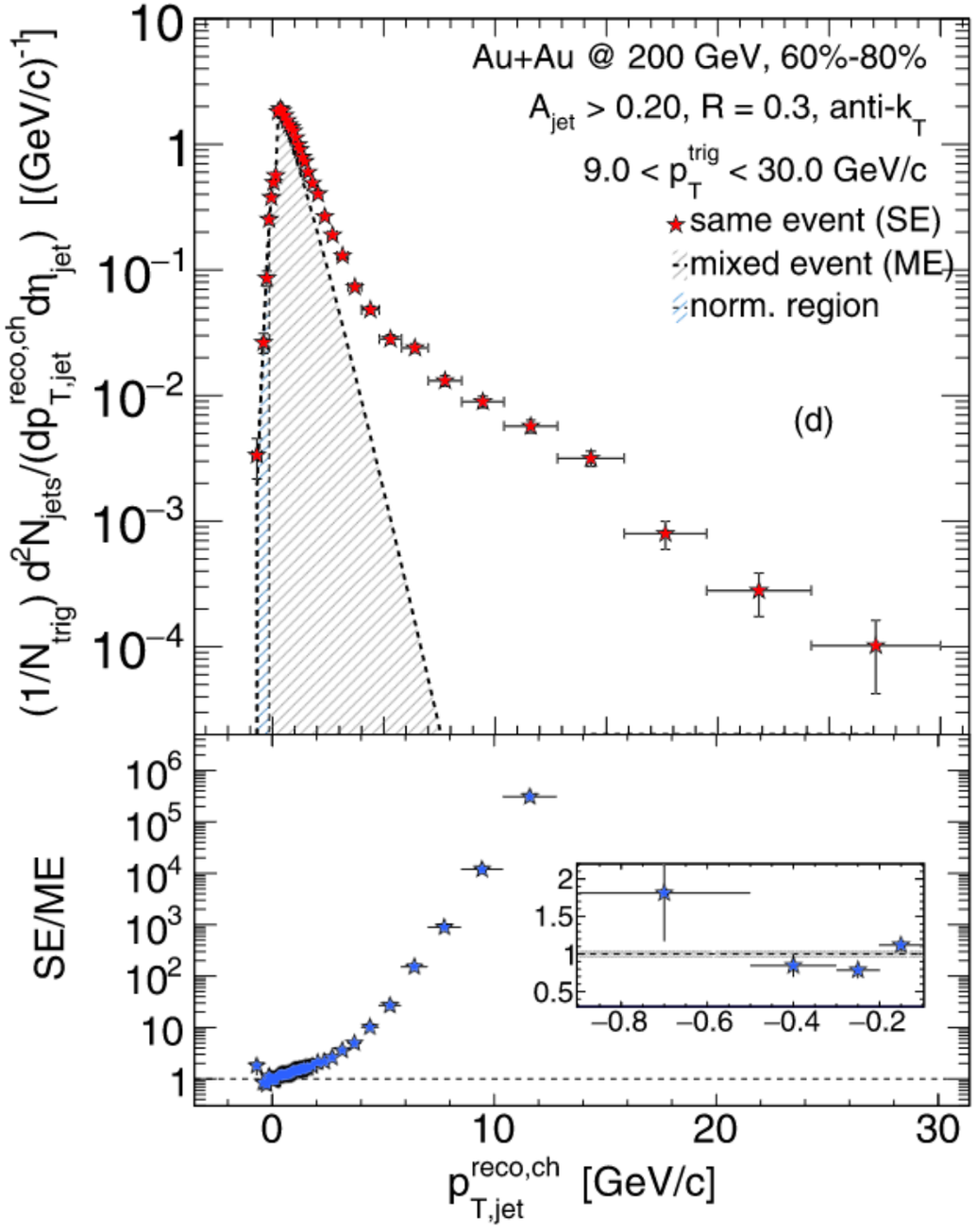


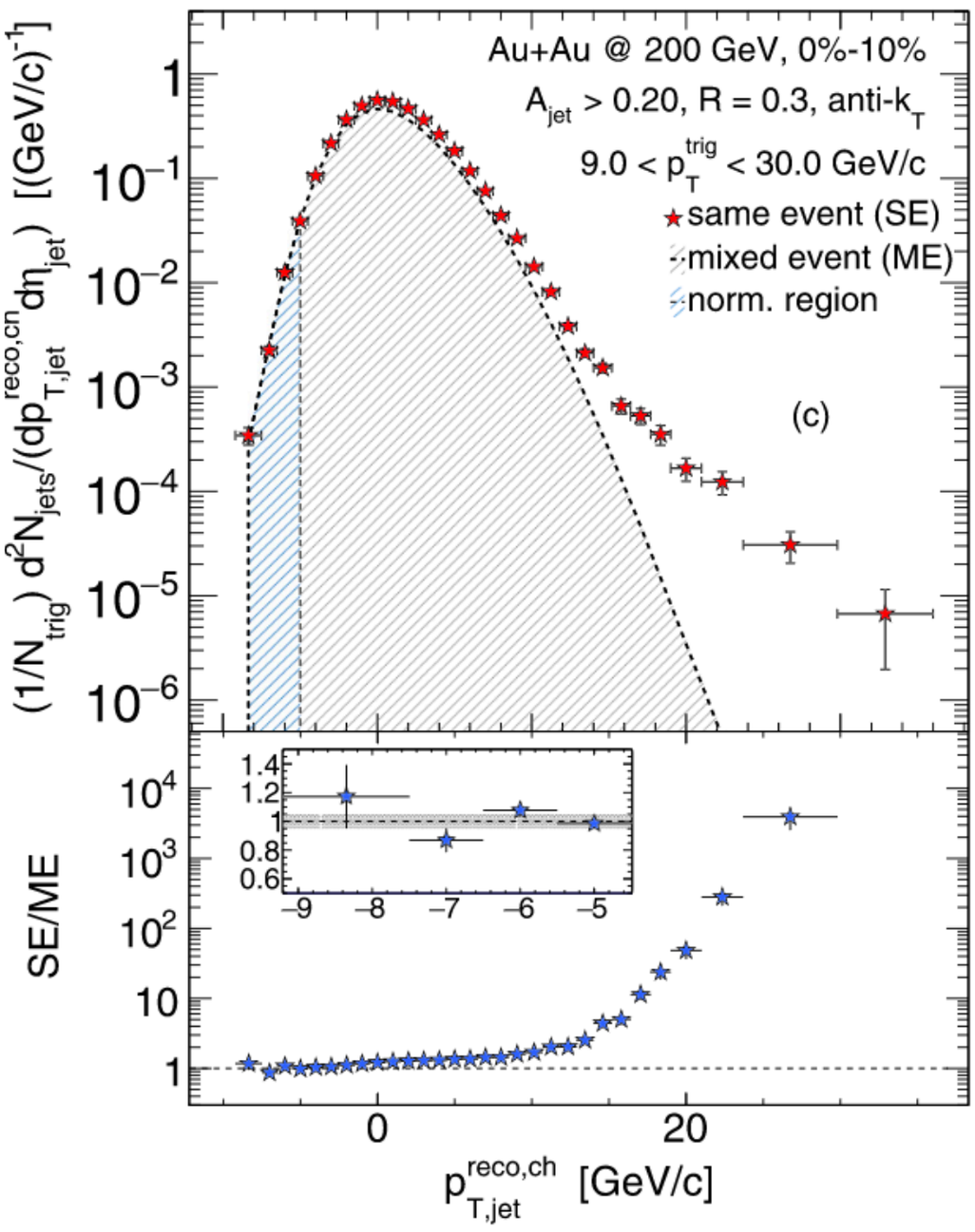
Conclusions

- As outlined in the LRP - Use Jets to probe QGP at various resolution/length scales
- Inclusive jets in pp @ LHC and RHIC are relatively well understood
- Heavy Ion Jets undergo significant energy loss due to the medium
  - Collimated Core ; Enhanced periphery
  - Starting to learn more about the Parton shower
- Exciting time with high statistics datasets at both LHC/RHIC - Utilize Bias!
- Lots of opportunities for new measurements!

Backup

Semi-Inclusive Hadron-Jet

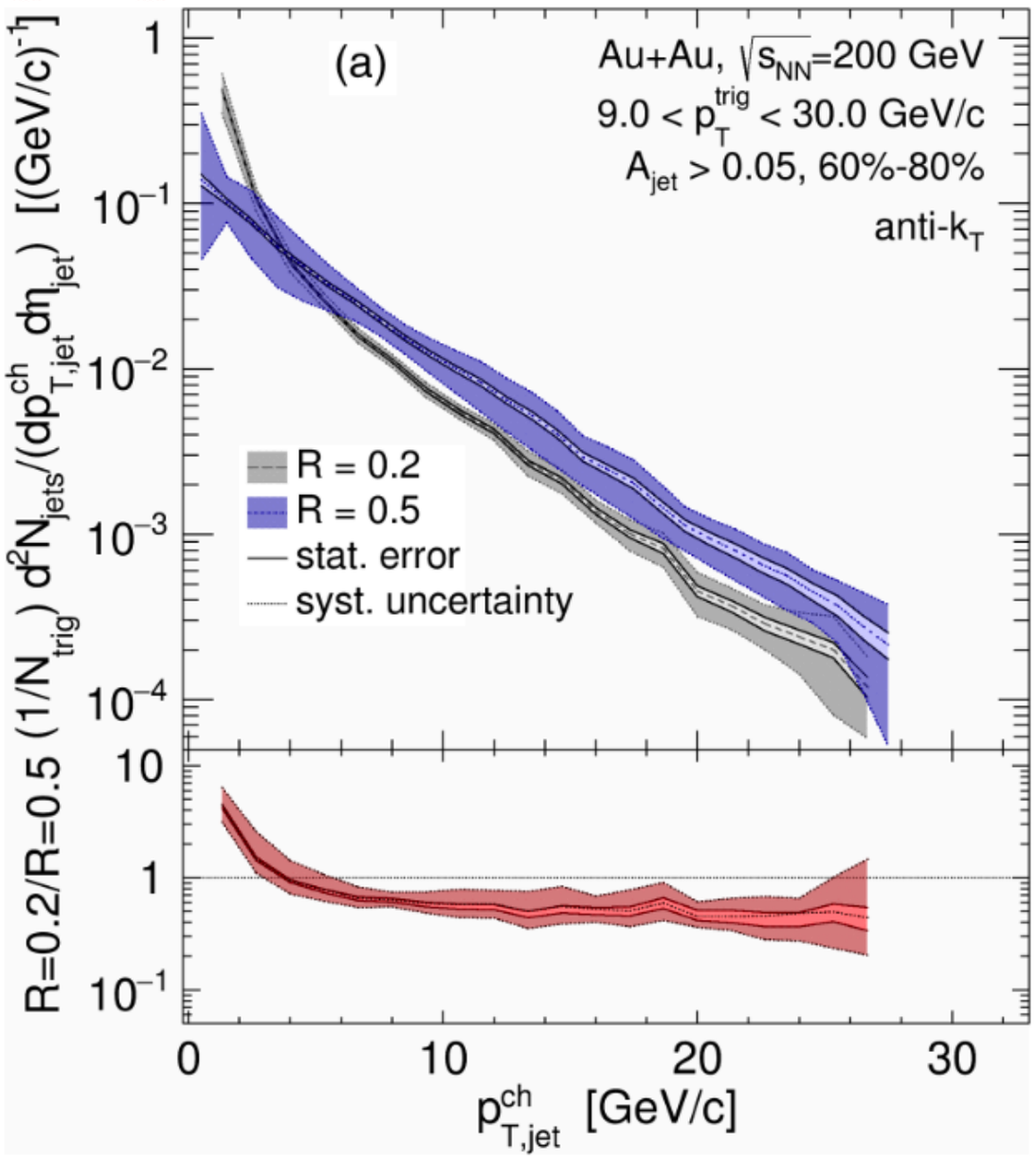


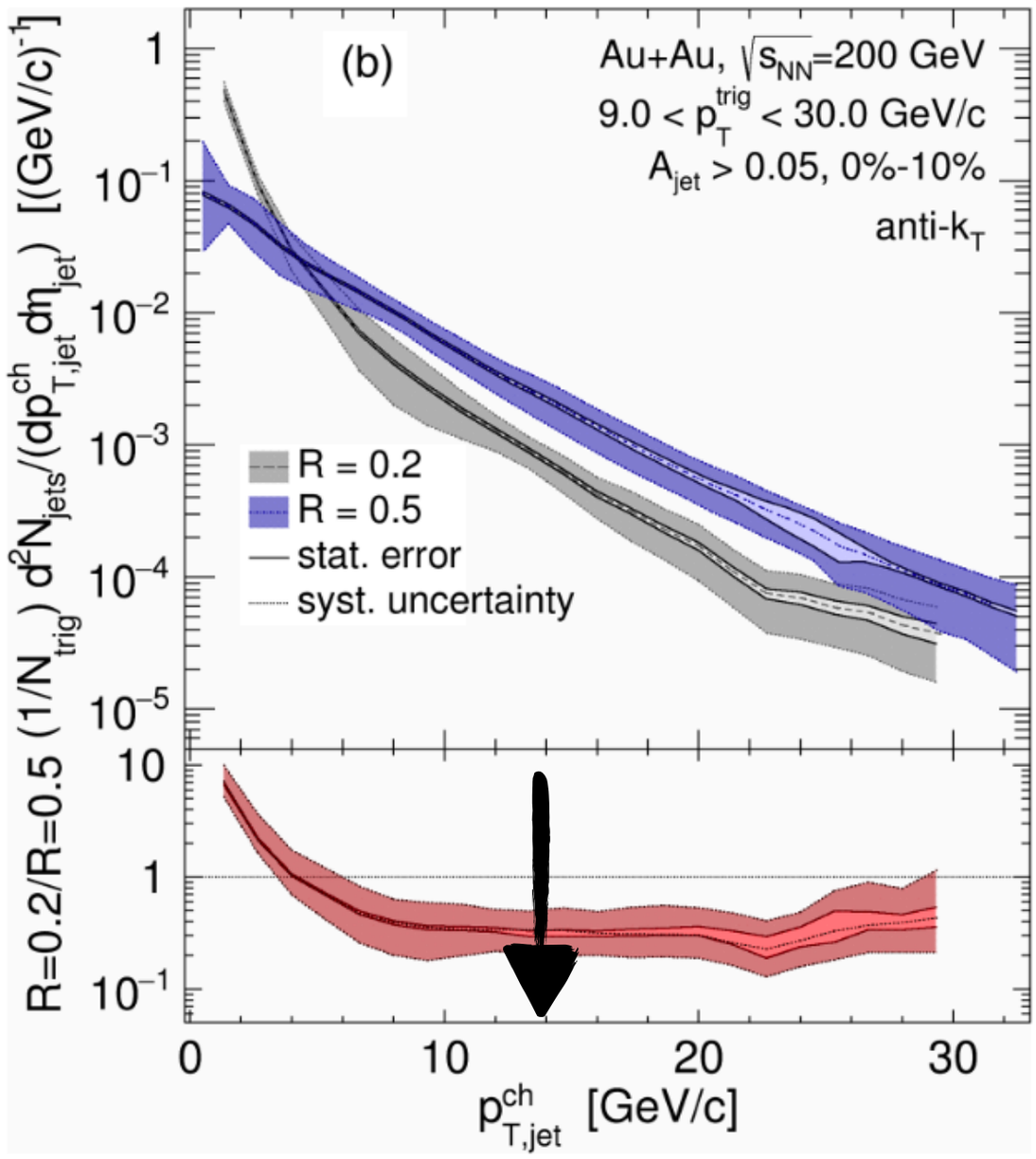


PRC 96 (2017) 024905

- Statistical definition of background for a given observable
- Takes into account fluctuations (courtesy of mixed events)

Jet Shape via spectral study





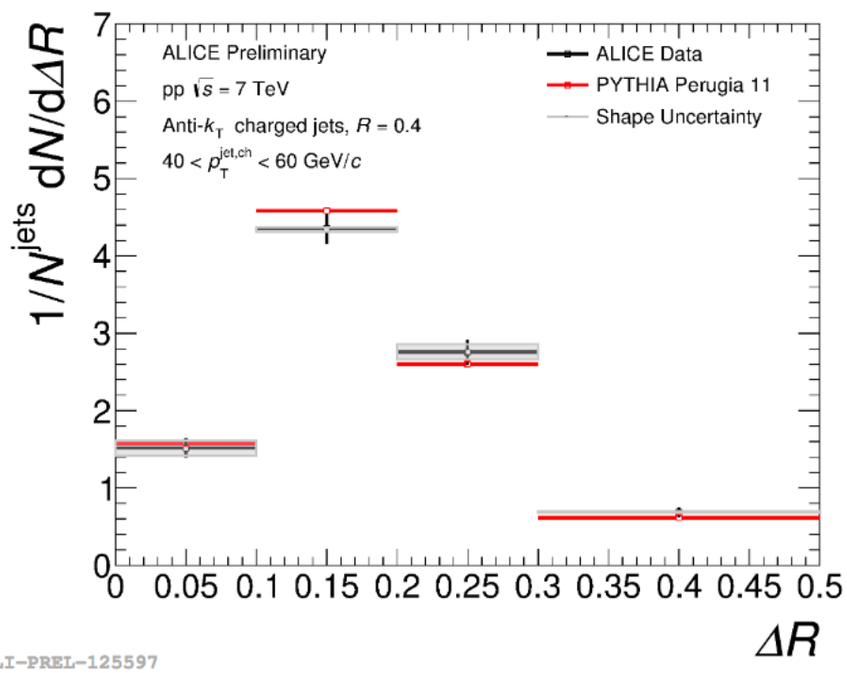
PRC 96 (2017) 024905

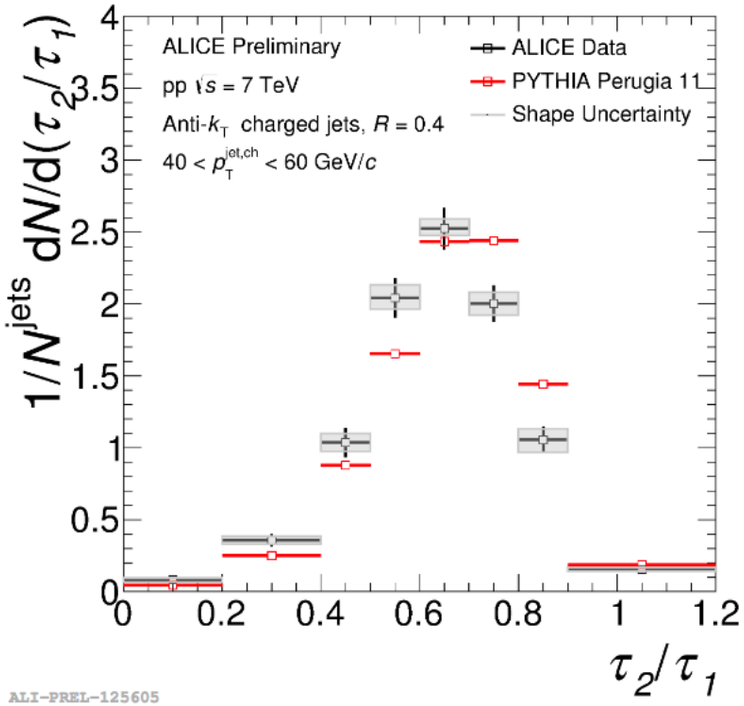
- Larger the radii - flatter the spectra
- Clear dependence on centrality - Statistically independent background subtraction

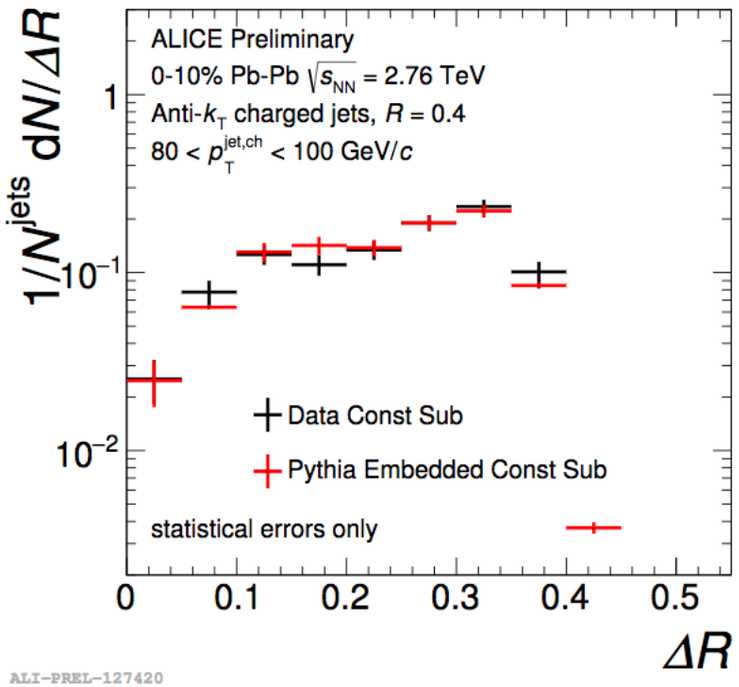
Subjettiness

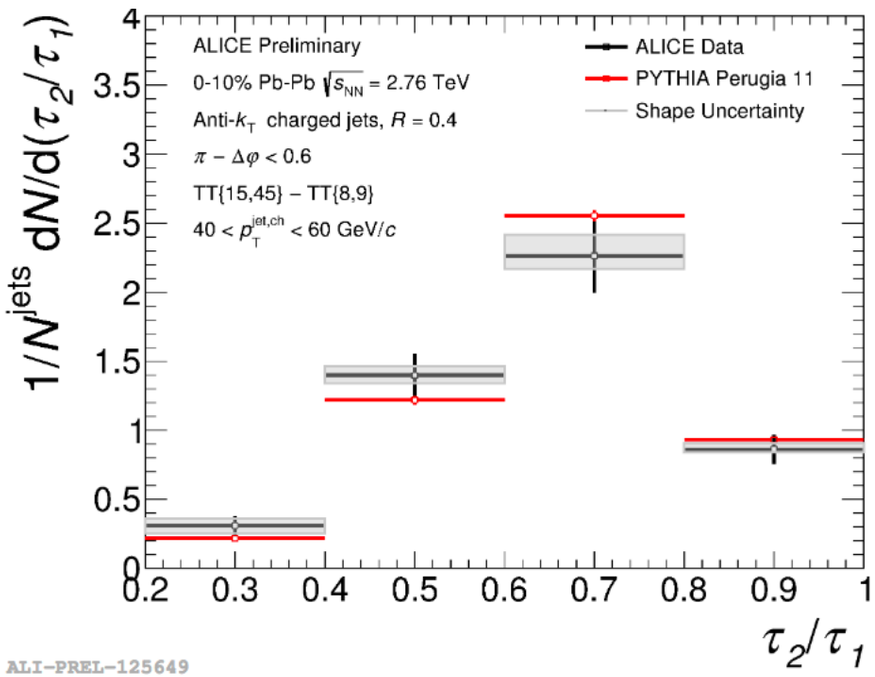
Utilized in HEP for boosted ID

- N-Subjettiness - Similar between pp and AA
- Delta R between subjects - differences between pp and AA
- Unfolded w/ PYTHIA response (different fragmentation)

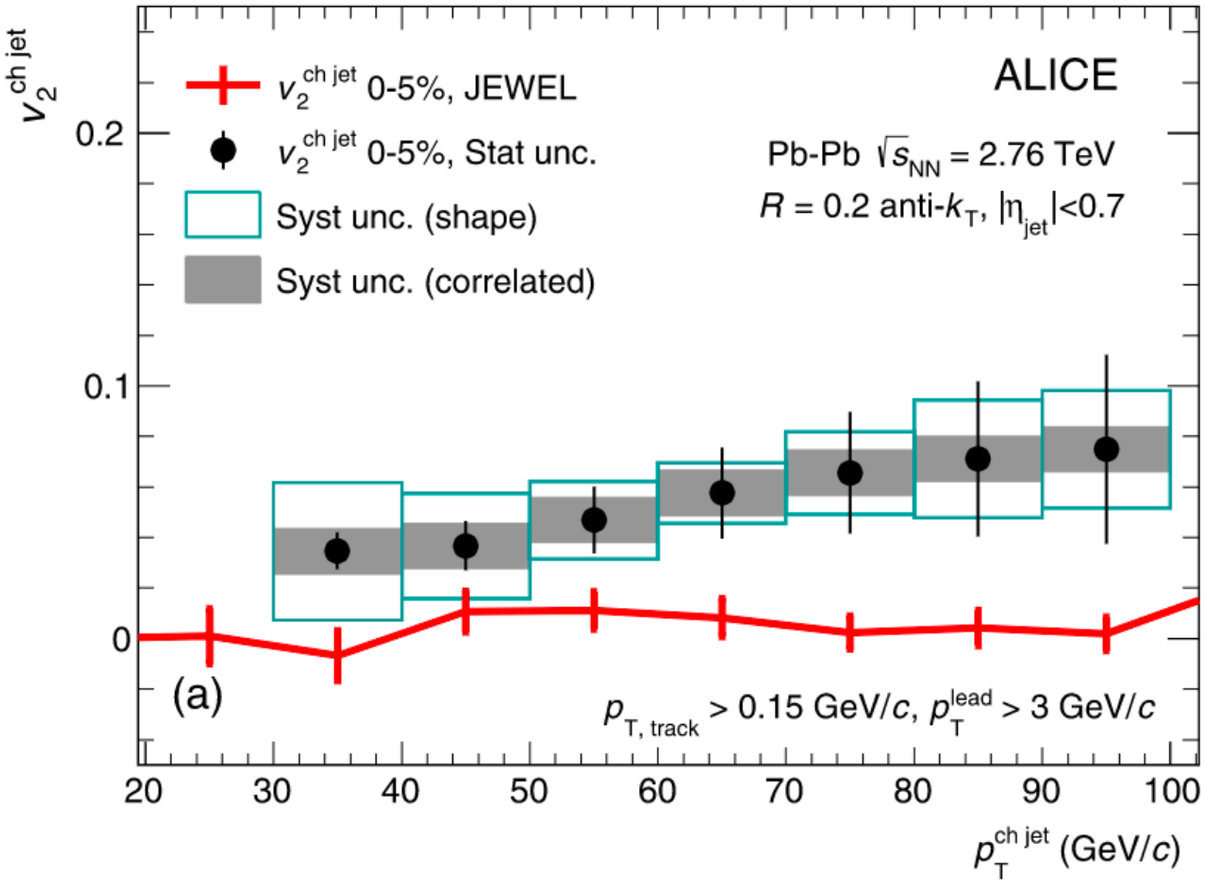


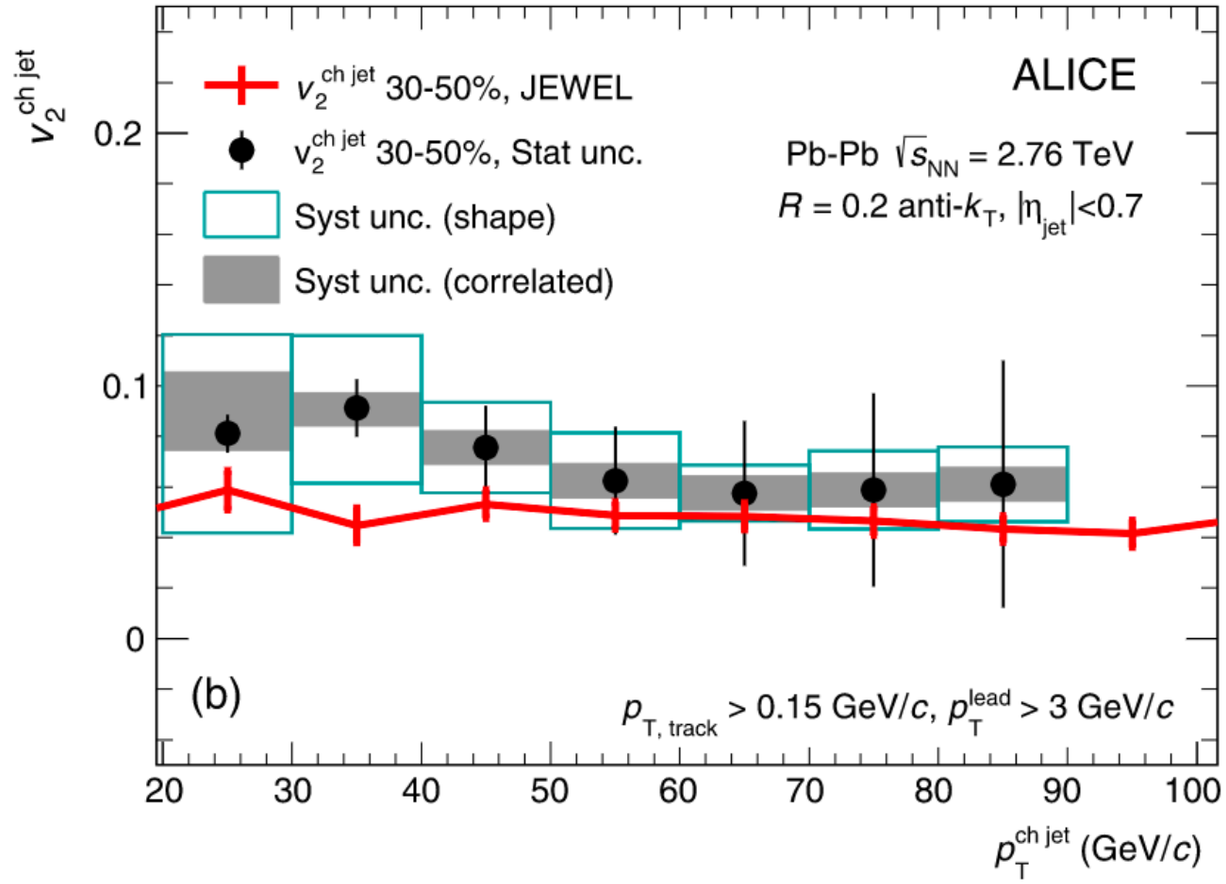






Flowing Jets

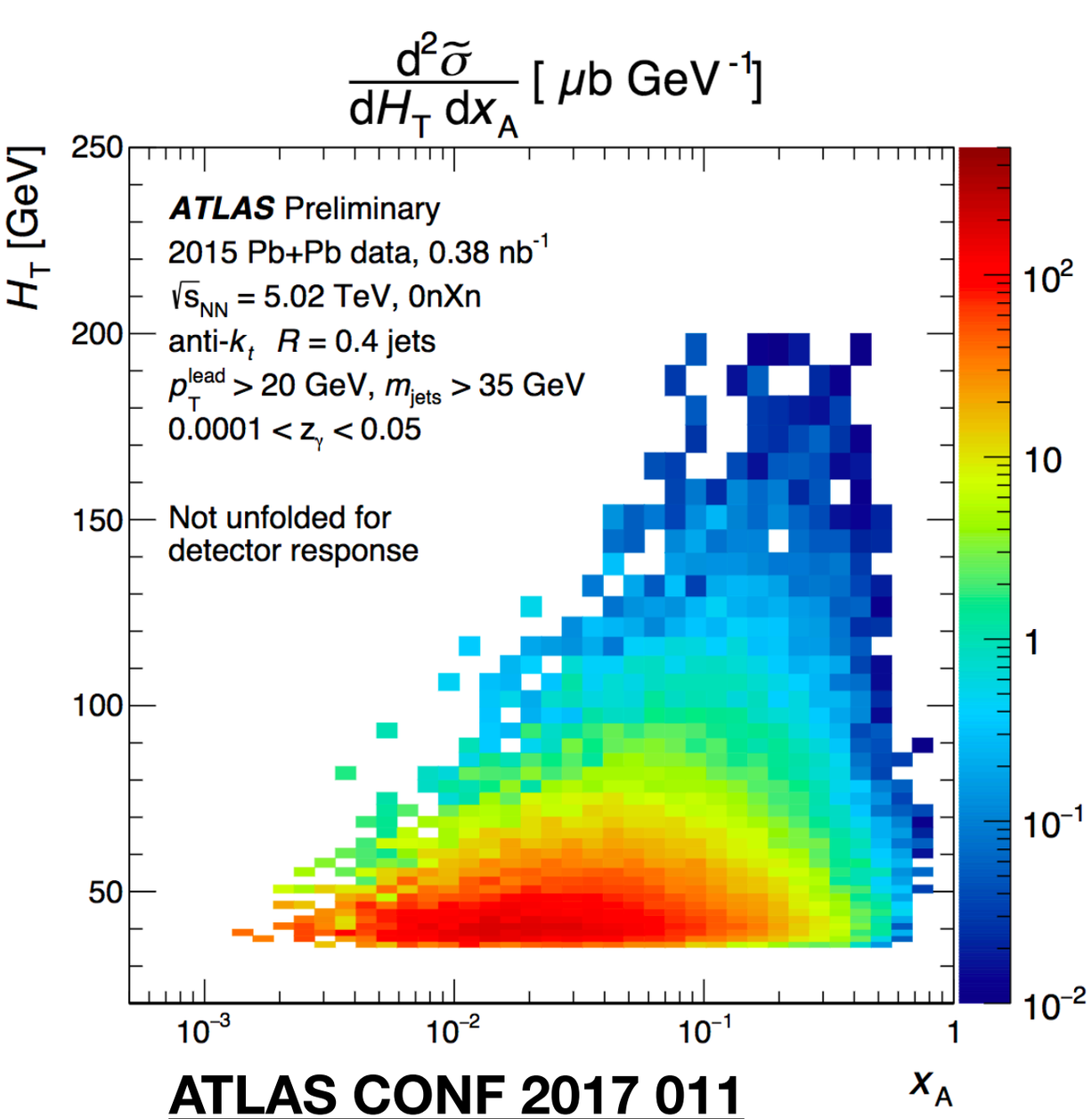


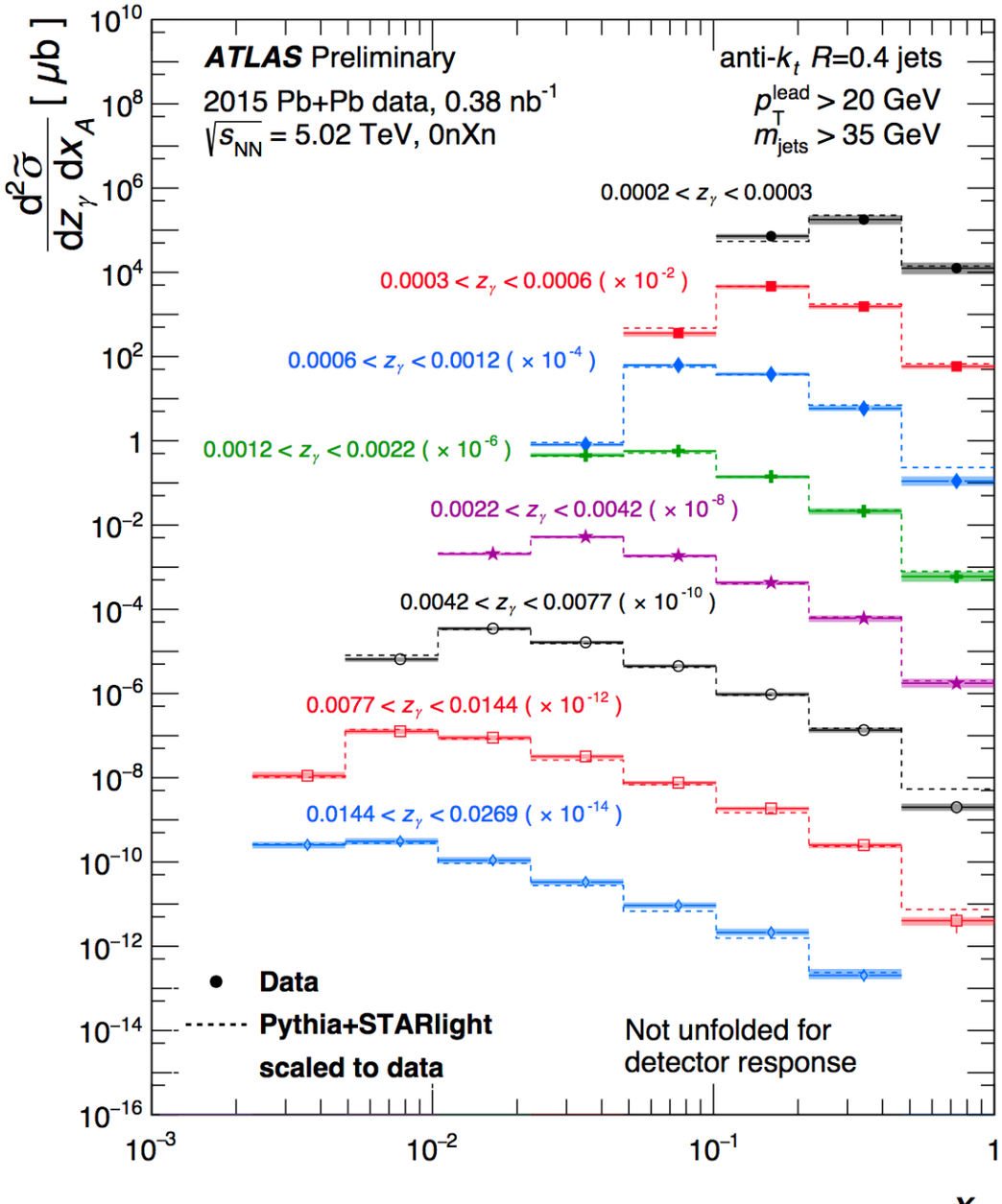


- Jet v2 relatively linear > 0

Jets from UPC

- Very interesting measurement!





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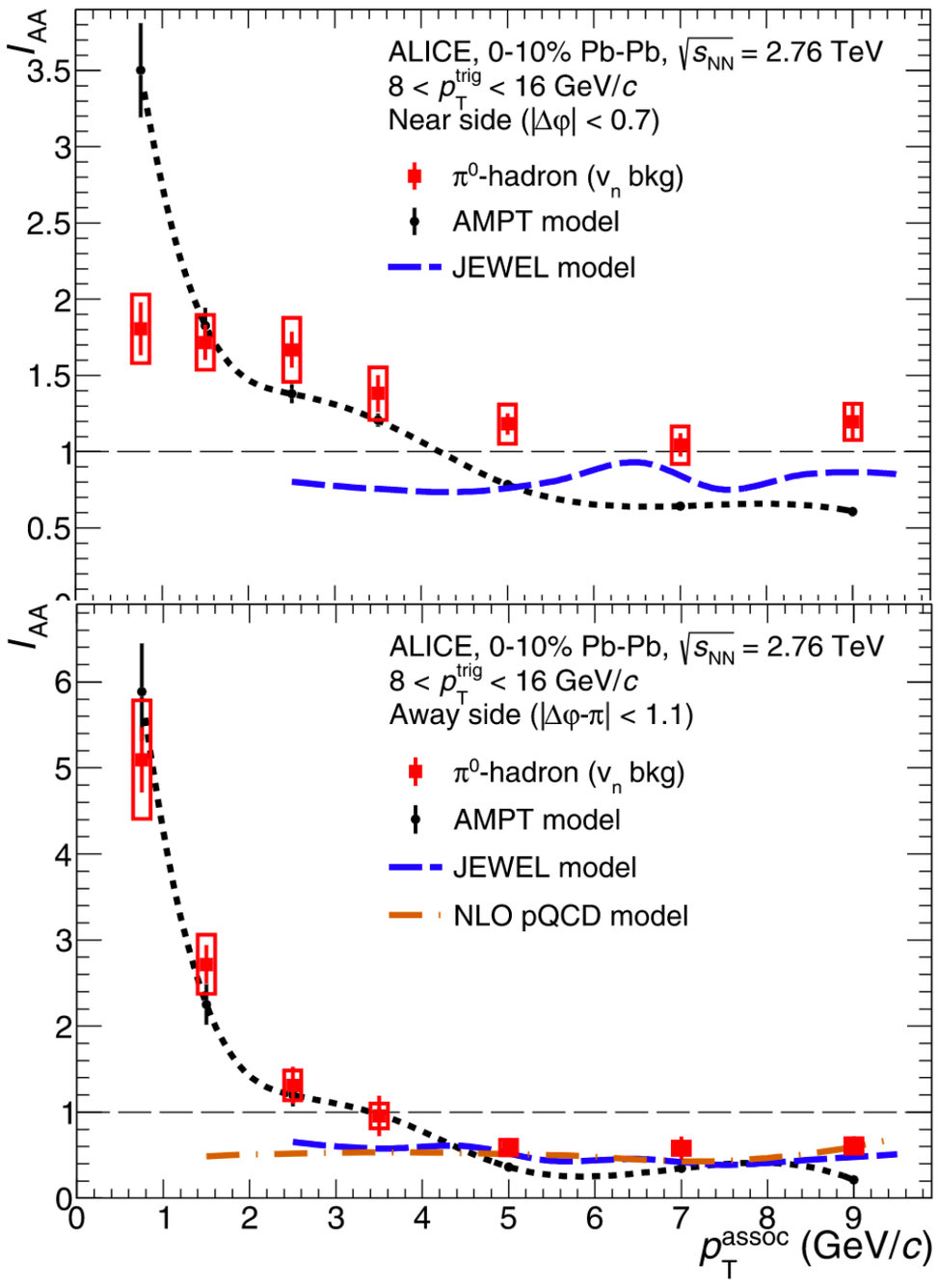
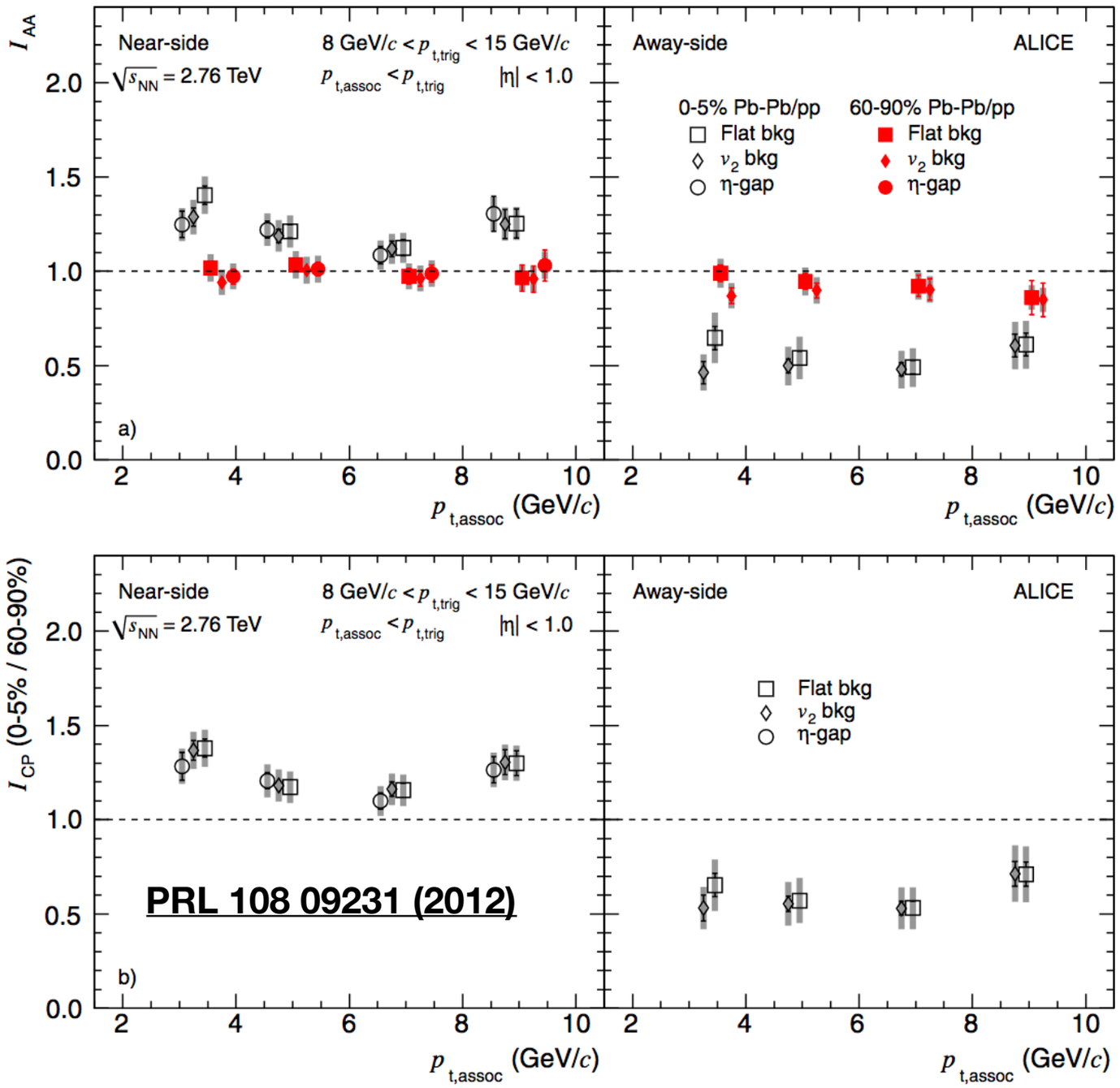
IAA (Effect of EP)





Where does the energy go?