Connecting the Advances in Precision Jet Physics in Hadronic Reactions to the Interpretation of the Heavy-Ion Jet Data

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Goal of Jet Measurements in HI Collisions

Address the important fundamental questions of **how** and **why** partons lose energy in the QGP?

- What are we scattering off of?
  - Quasi-particles, fields <=> **Microscopy of the QGP**
- Where does the "**lost**" energy go?
  - What is the response of the medium to the jet?
- What is the temperature/density dependence of the energy loss?
  - What is the **Temperature** dependence of the coupling to the QGP?
  - How does it depend on energy scale?

Jets as a QGP Probe

Probe → Any particle that is not in thermal equilibrium with the bulk

- Short QGP lifetime requires auto-generated probes
  - High p_T partons
  - Heavy flavor
  - Prompt γ
- Need a small resolution scale to see the structure of the QGP → High p_T
- Jets are **multi-scale probes**
  - This is both a bug and a feature!
  - Complicates interpretation, but allows us to have information for a wide variety of length scales

Jets as a QGP Probe

- **Production process is known** → calculable by pQCD
  - Production, fragmentation and hadronization of high p_T partons into collimated sprays of particles (jets!) well understood in pp collisions
  - Clustering final state particles → **jet kinematics should be correlated with hard parton kinematics**
- **We understand that** Parton E_{loss} is the dominant effect
  - How do we turn this into a microscope to determine the QGP structure?
  - We need to look at the modifications of the jet structure
  - **Know precisely the scale and direction of the initial parton**

What is a jet?

There is **no unambiguous definition** of what a jet is!

- Comparing observables created with different jets is dangerous
- Sensitivity to the underlying physics depends on:
  - Constituents
  - Jet Resolution Parameter
  - Transverse Momentum Selection
  - Background Removal Technique

Agreement on definition is necessary to fully understand theory-experiment comparisons

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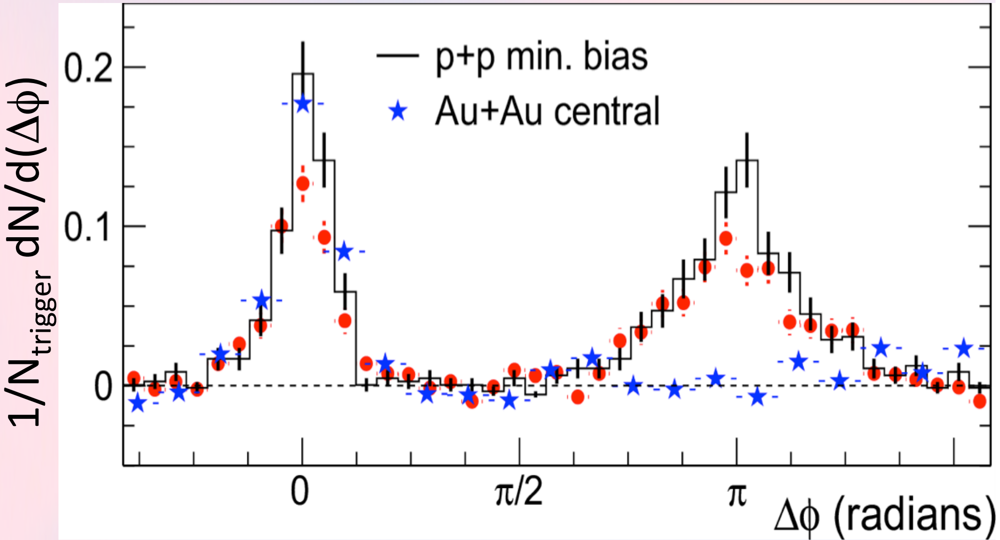
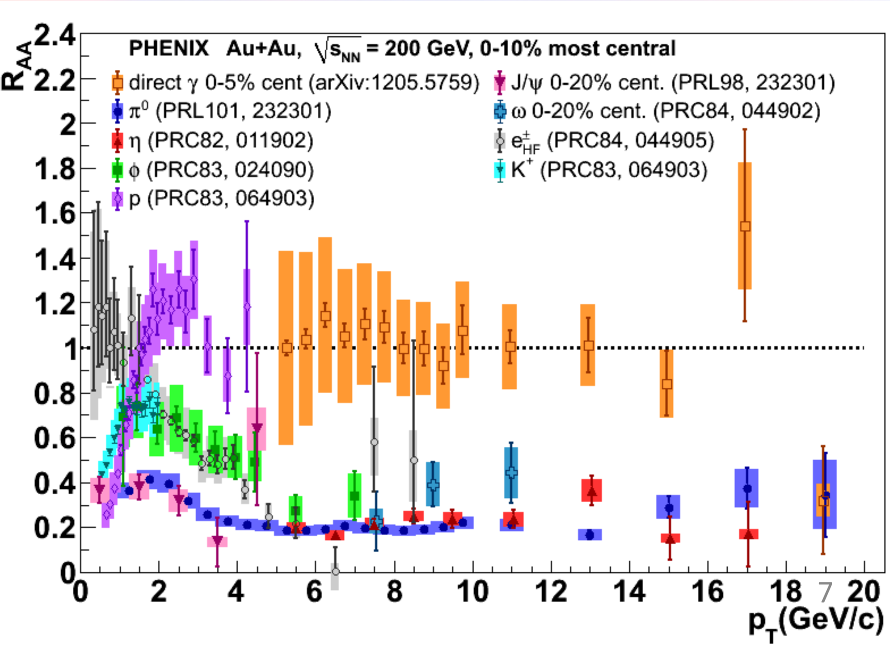
1^{st} Generation Jet Observables

First measurements were dihadron correlations, single particle R_{AA}, I_{AA}, D_{AA}

- **Sensitive to overall jet energy loss**
- Relatively straightforward to calculate
- But limited information on the dynamical details of the jet-medium interaction



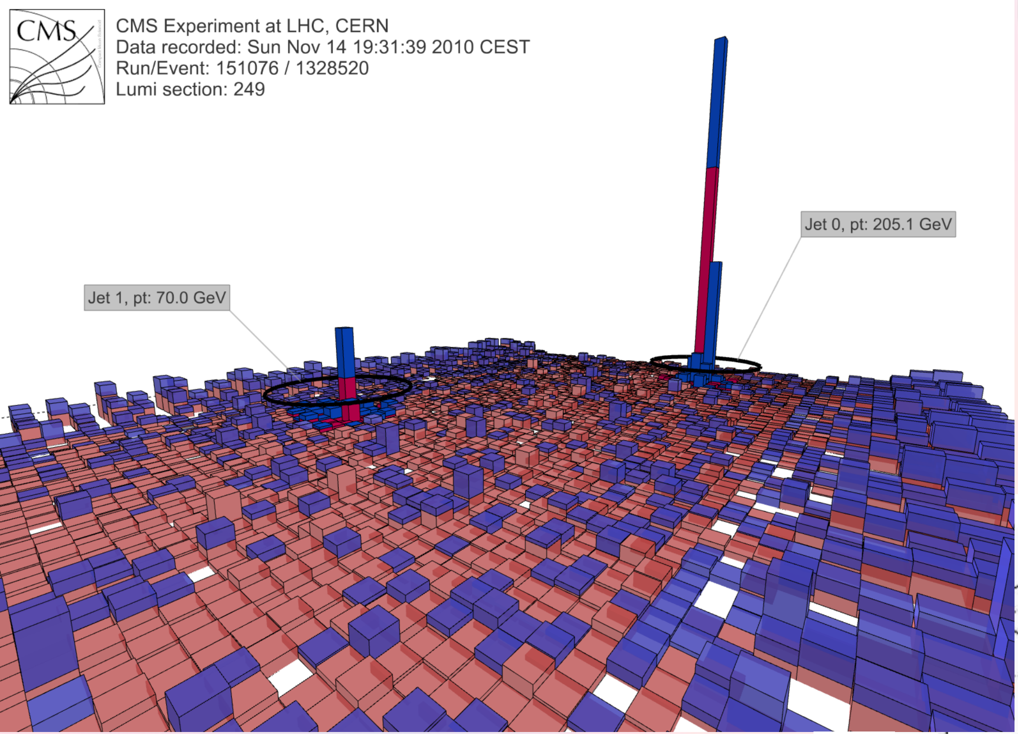


Difficulty Measuring Jets in HI Collisions

The evolution of the field from high p_T hadrons to jets was **complicated by the underlying event**

- Jet-finding algorithms cluster the entire event
  - **Combinatorial jets** are created from the soft physics
  - “Hard” **jet kinematics are blurred** by UE contribution
  - Jet Energy Scale and Resolution **(JES, JER) are modified**
- Lower luminosity of pre-LHC era RHIC combined with steeper hard probe cross-section required significant development of tools
  - **Cross-pollination** between LHC and RHIC was a key factor in the successes in heavy-ion jet measurements!

Underlying Event LHC vs RHIC

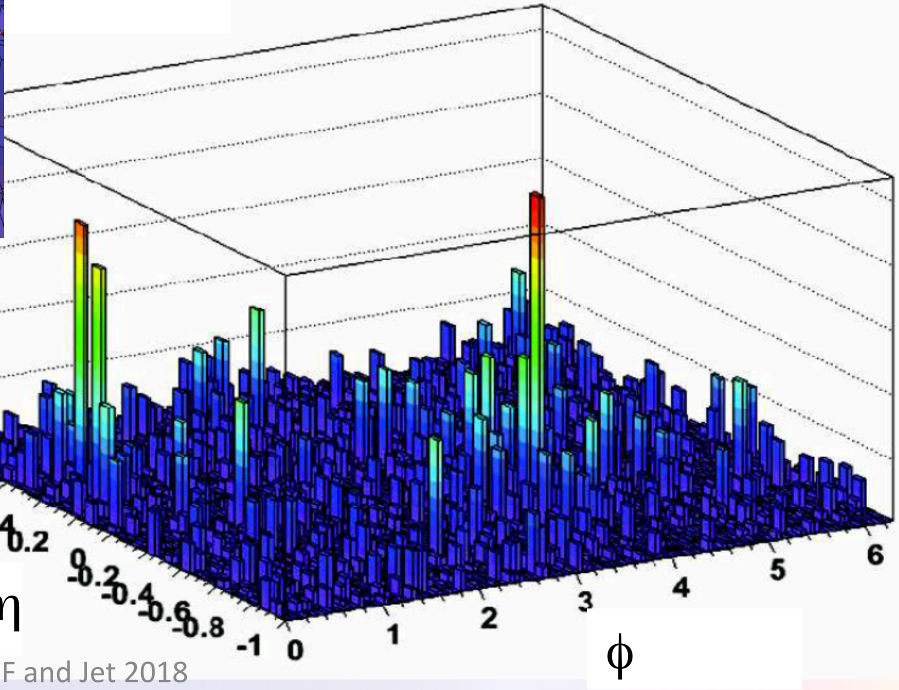


Hard parton cross section increases faster than QGP Temperature

- Simplifies dividing hard from soft

Allowed a wealth of new observables to be measured at the LHC

- Including Jet structure

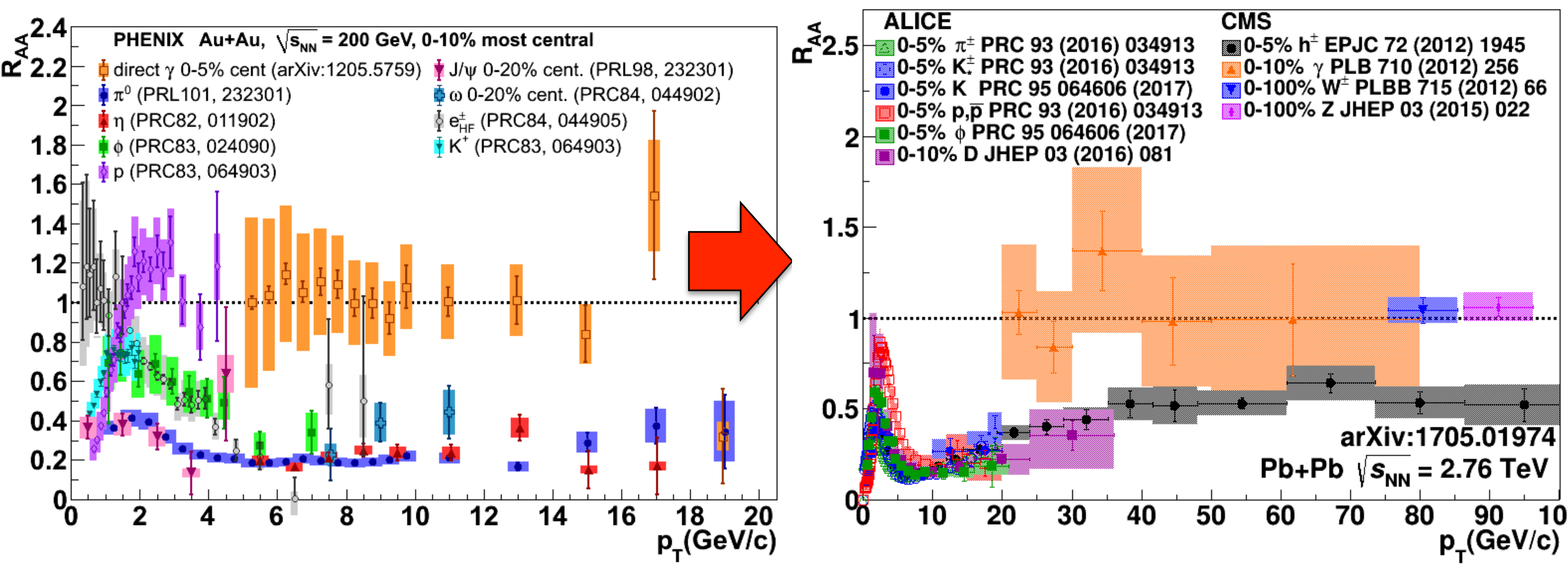


1^{st} Generation Jet Observables

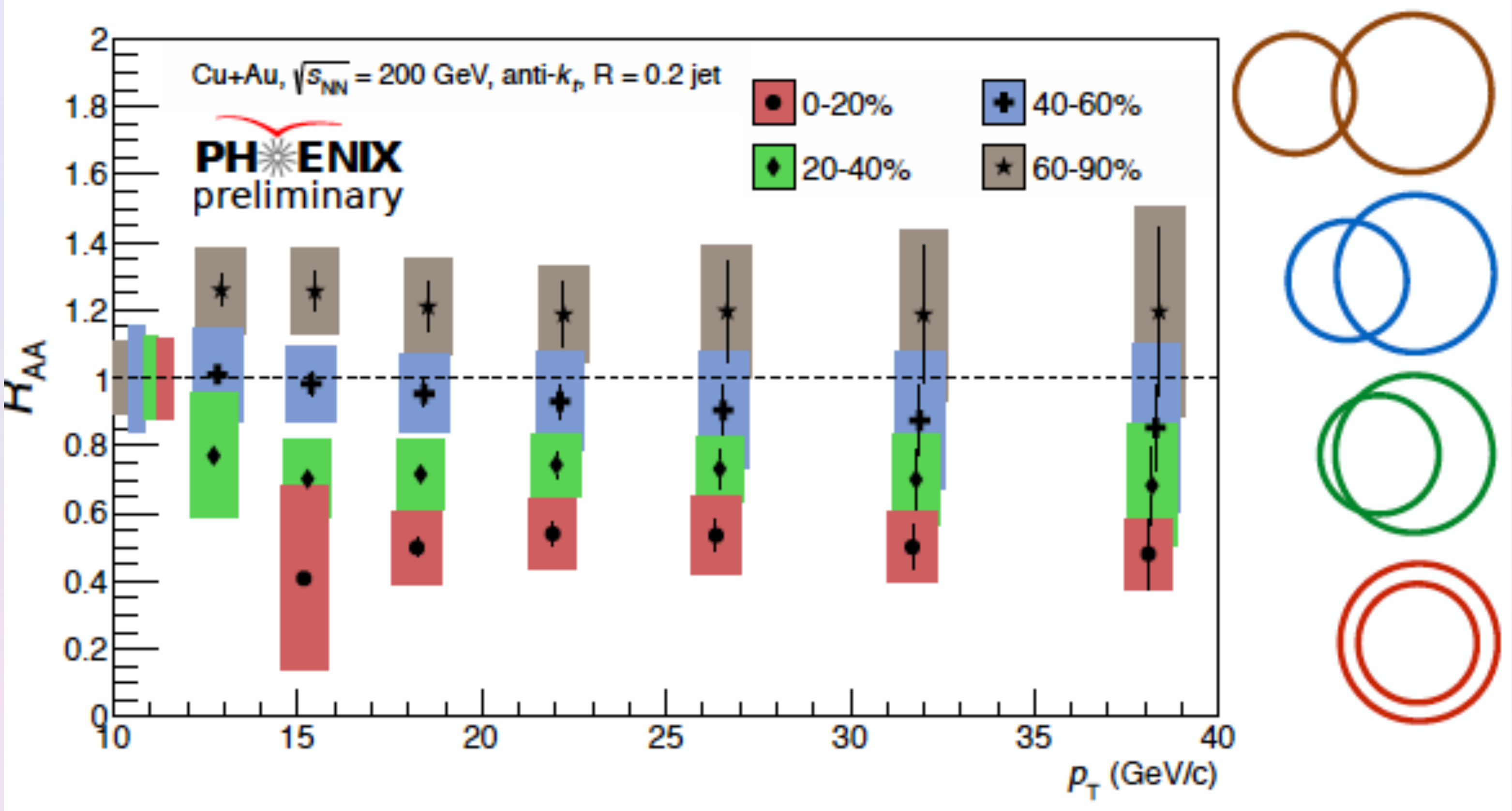
Hadron observables repeated with greater kinematic range

- EM probes still show R_{AA} ~1
- High pT hadrons are suppressed
- Lowest value of R_{AA} a little less at the LHC

arxiv:1705.01974

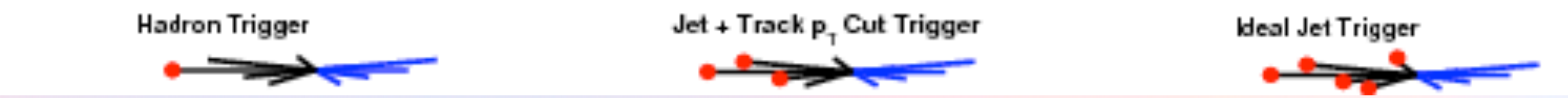


Nuclear Modification Factor of Jets at RHIC

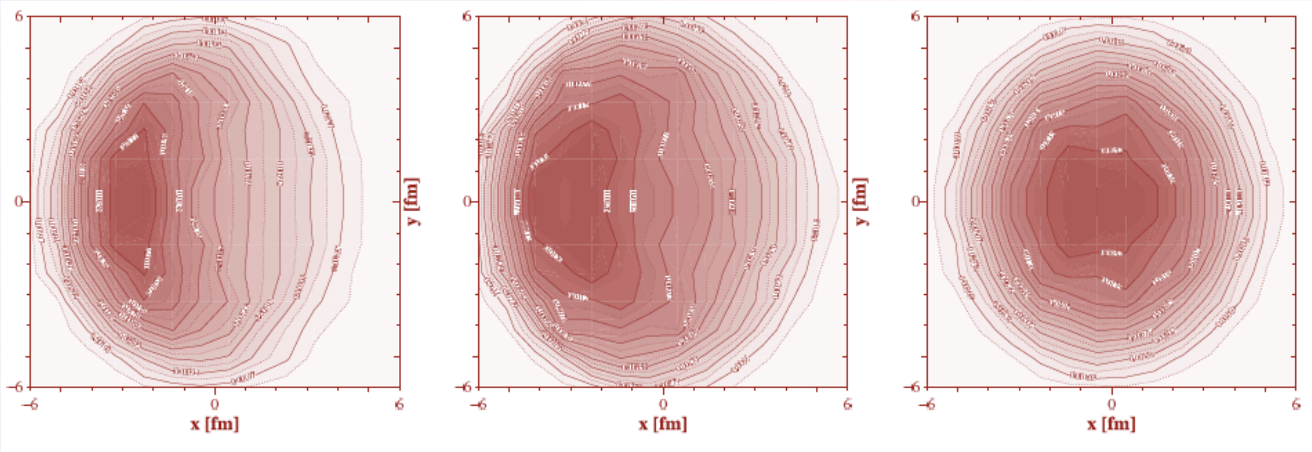


- R_{AA} of jets in HI collisions at 200 GeV → similar magnitude as hadrons

Surface Bias versus probe



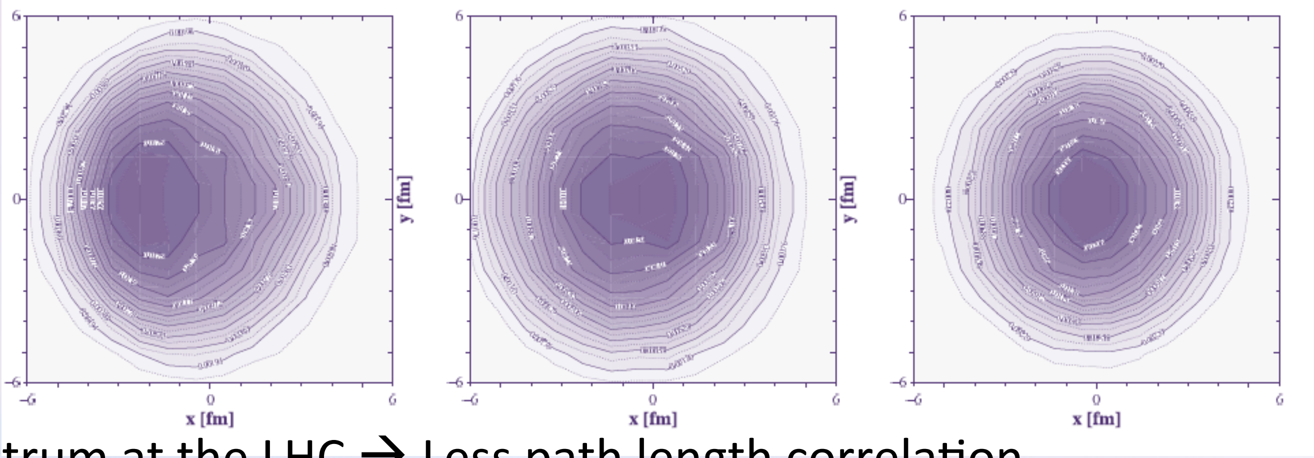
RHIC



Renk
arXiv:1210.1330v1

Using different jet definitions → **selectively probe** different regions of the geometry

LHC

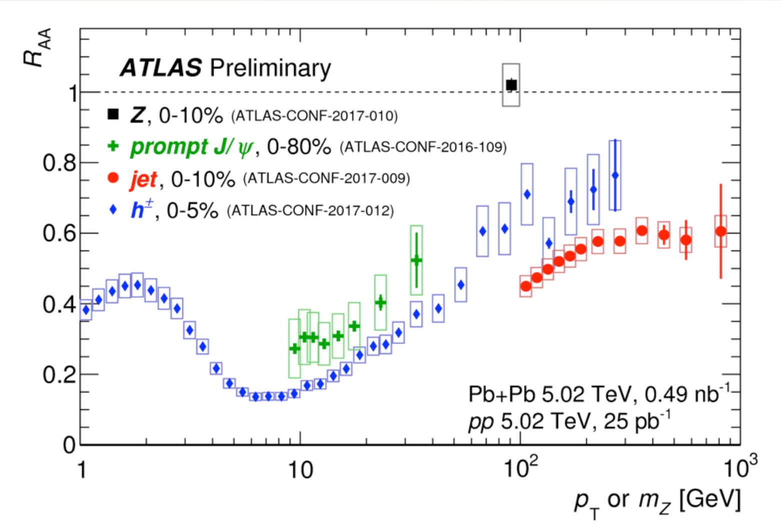


Harder spectrum at the LHC → Less path length correlation

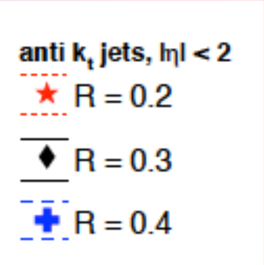
1^{st} Generation Jet Observables

- Hadron observables repeated with reconstructed jets
  - Correlation with hard parton kinematics is stronger

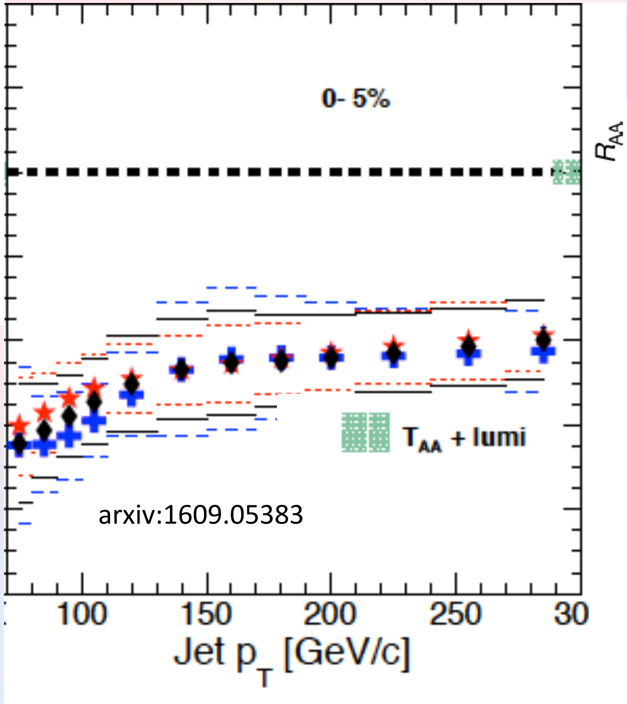
$\sqrt{S_{NN}}$ = 5.02 TeV



Results for inclusive jets and inclusive hadrons are very similar at high p_T



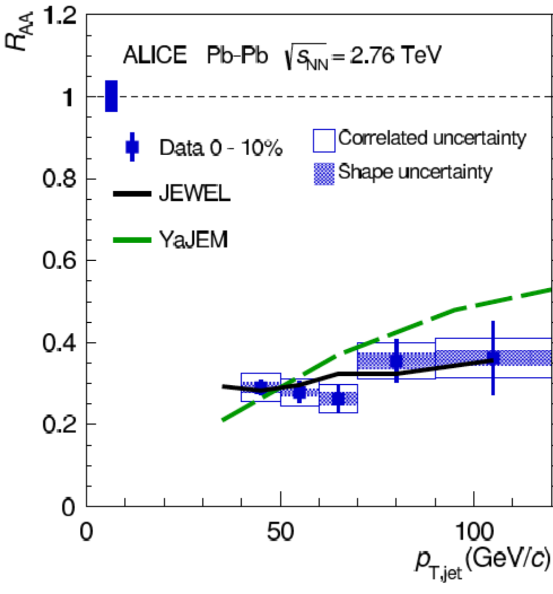
$\sqrt{S_{NN}}$ = 2.76 TeV



arxiv:1609.05383

Be careful, these jets are not the same!

$\sqrt{S_{NN}}$ = 2.76 TeV



2nd Generation Jet Observables

Measurements of boson-reconstructed jet correlations

- **“Golden” probe** as boson (Z/γ) kinematics are more closely correlated with the parton kinematics than the jets
- Z/γ do not interact with the QGP→ **energy scale is unaltered**
- **Mostly quark** jets (~80% depending on p_T, etc)

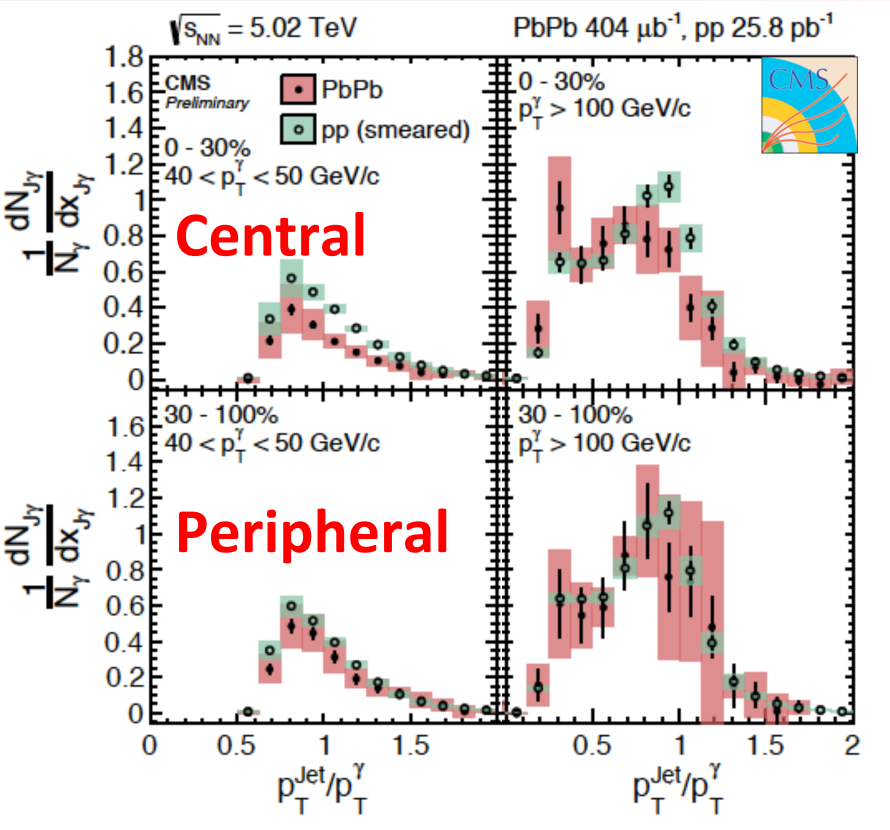
Measurements of Dijet correlations

- Among the first LHC HI jet results - A_J

Jet-to-Photon p_T Balance

Increased $p_{T,jet}$ →

Anti-k_T Jet R = 0.3 $p_{T,jet} > 30$ GeV/c $|\eta_{jet}|<1.6$
$\Delta\phi_{J\gamma} > 7\pi/8$



Central

Peripheral

HIN-16-002

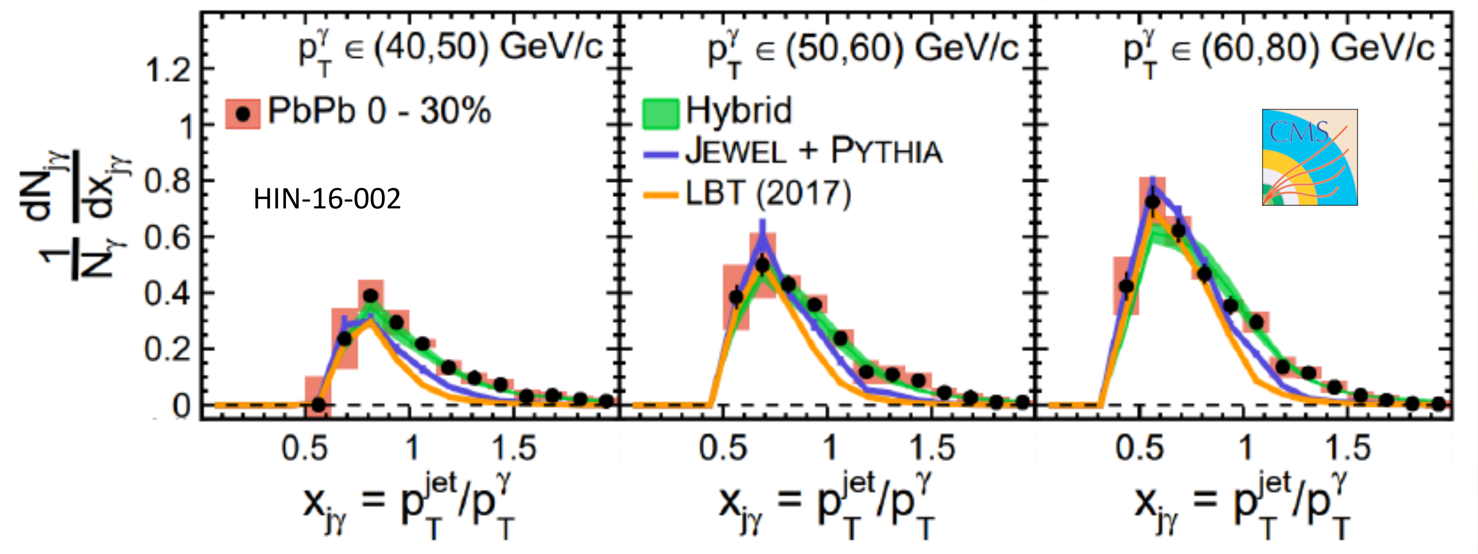
- Jets lose more energy in AA vs pp
  - Centrality dependence
  - p_T dependent

Energy is lost, are the jets modified? → How and **why**

Jet-to-Photon p_T Balance

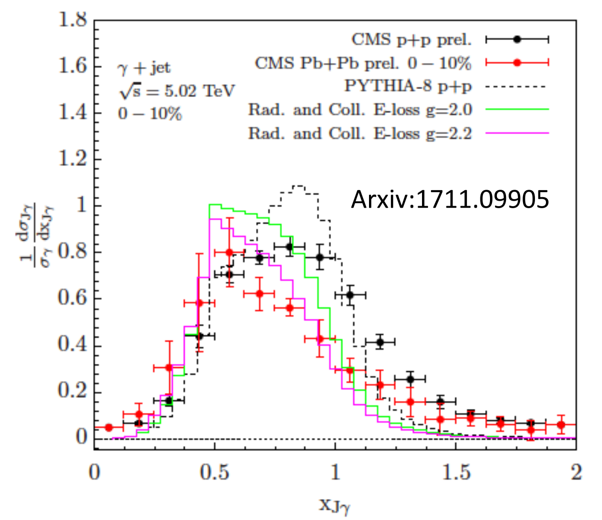
Increased $p_{T,\gamma}$ →

arXiv:1711.09738



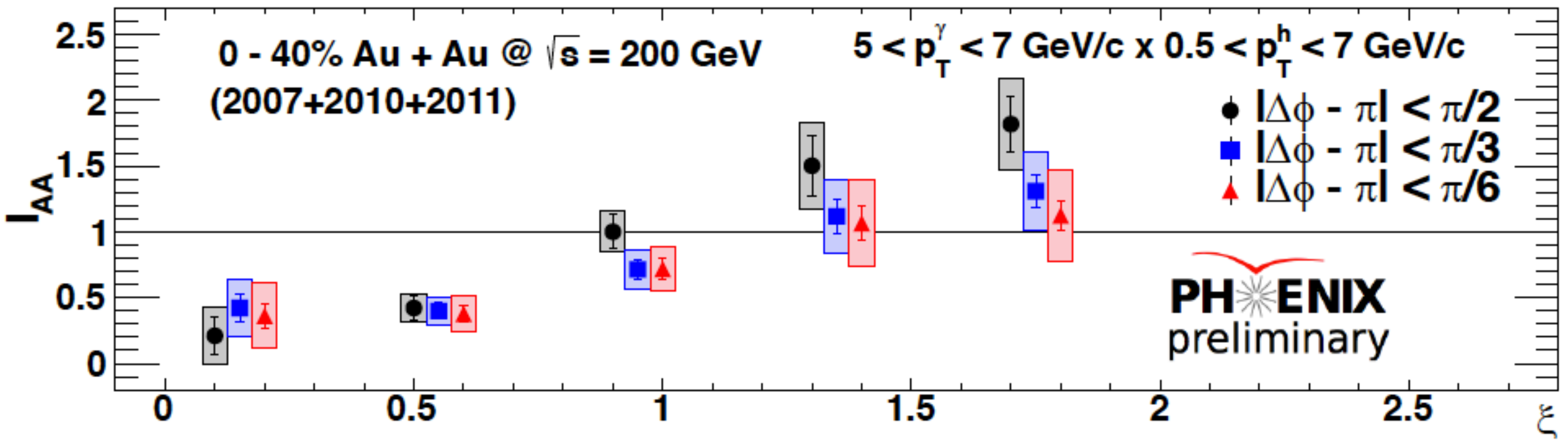
Anti-k_T Jet R = 0.3
$p_{T,jet} > 30$ GeV/c $|\eta_{jet}|<1.6$ $\Delta\phi_{J\gamma} > 7\pi/8$

- Good data-theory agreement from all models
  - **Medium recoil?**
  - Process dominated by the jet energy scale (pQCD-like)



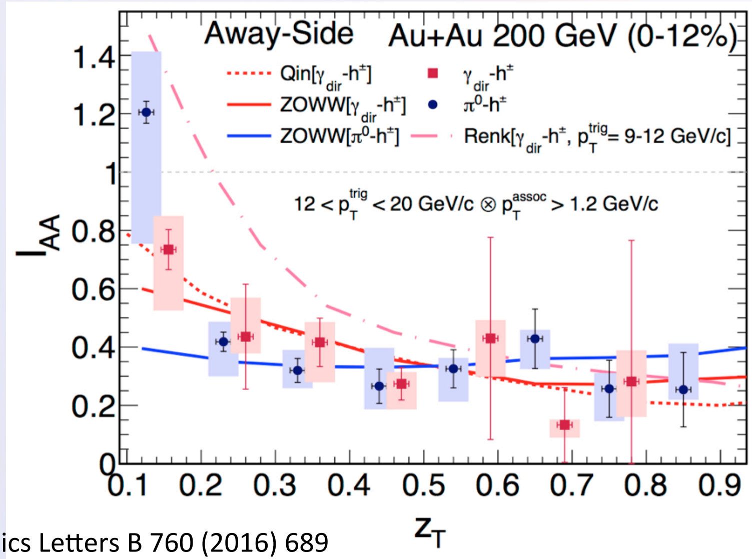
Arxiv:1711.09905

γ-hadron (I_{AA})



$$\zeta = \ln(1/z_T) \quad z_T = \frac{p_T^h}{p_T^\gamma}$$

- Lost E → redistributed to soft, large angle particles
- Transition not at fixed ζ - medium response in addition to redistribution of lost energy
- The modified fragmentation function is not a universal function of z_T

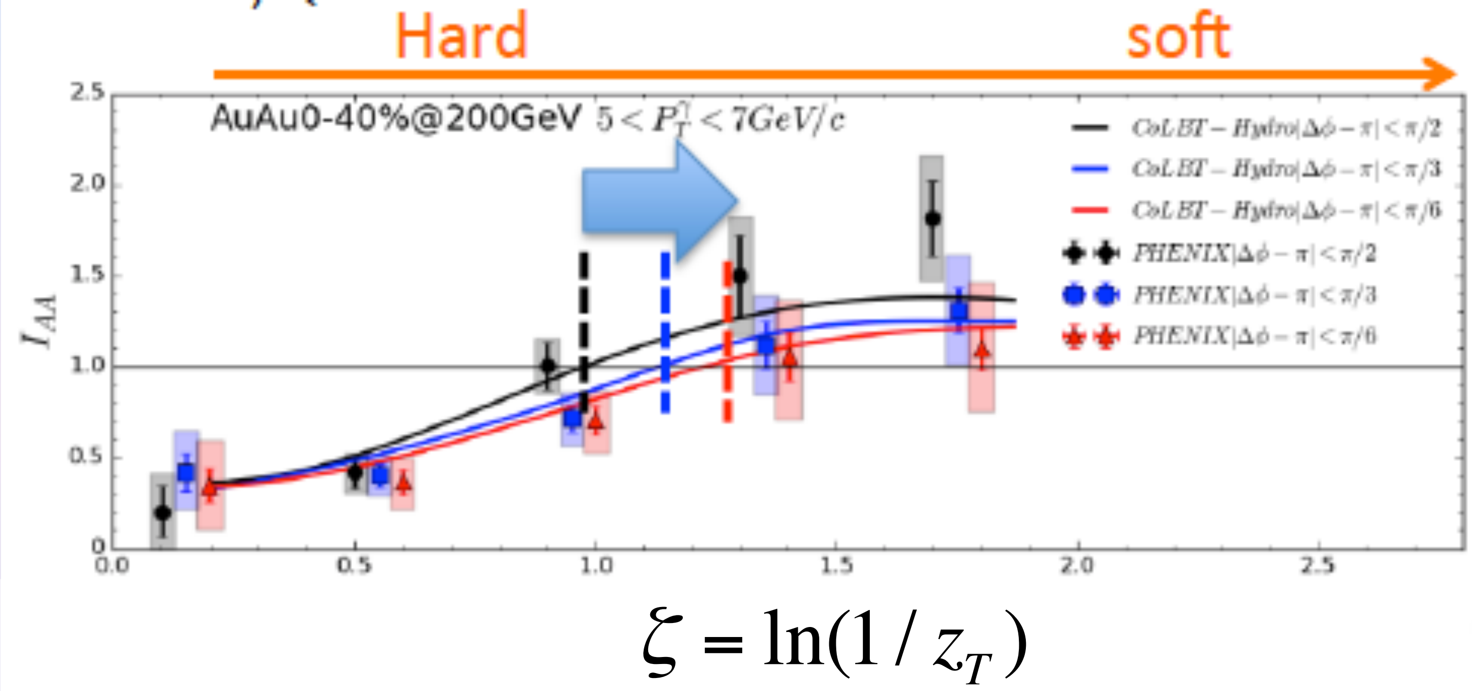


Physics Letters B 760 (2016) 689

γ-hadron (I_{AA})

W. Chen et al arxiv: 1704.03648

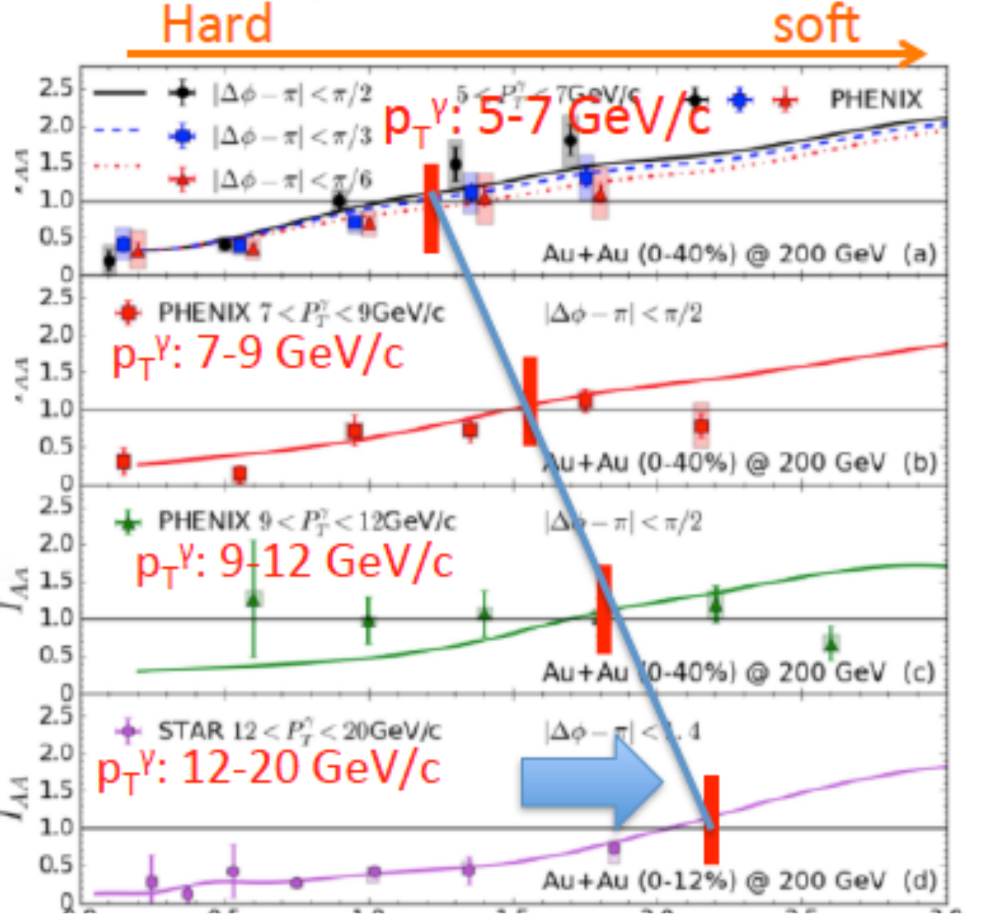
Coupled Linear Boltzmann Transport and 3+1D hypdro (CoLBT-hydro)



1st study in CoLBT-hydro of the medium modification of γ-hadron correlations in HI at RHIC

- Suppression of leading hadrons due to E_{loss}
- Enhancement of soft hadrons due to jet-induced medium excitation

γ-hadron



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1st study in CoLBT-hydro of the medium modification of γ-hadron correlations in HI at RHIC

- Suppression of leading hadrons due to E_{loss}
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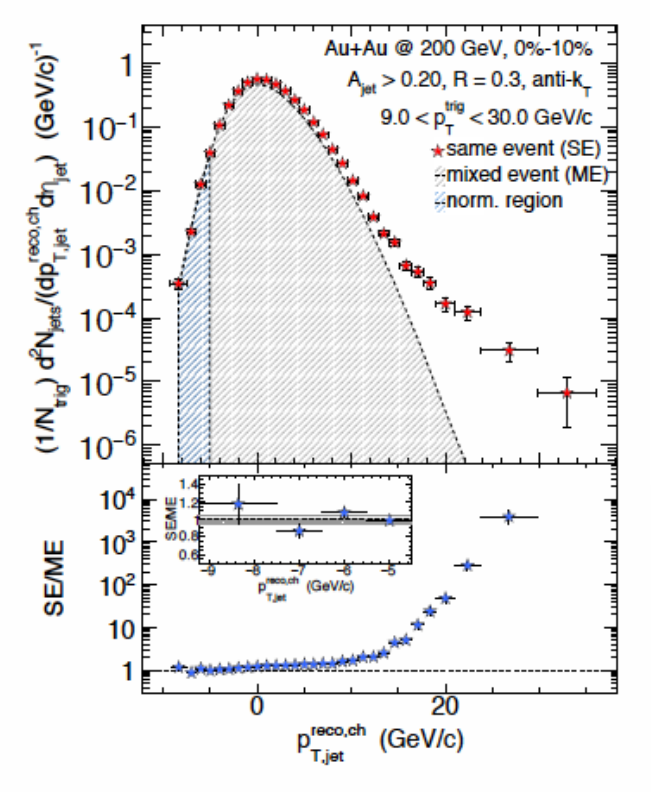
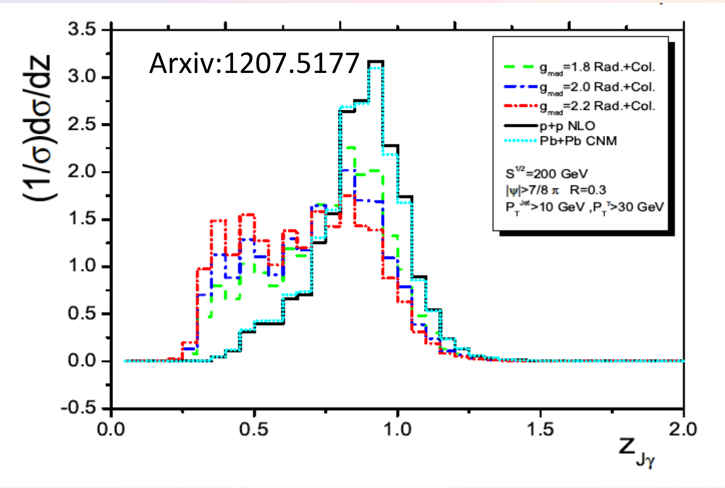
Important for jet tomography!

h-Triggered Recoil Jets in A+A

Hadrons




Arxiv:1207.5177

It would be great to have more predictions at RHIC energies!

RHIC advantage that → Cross over from π^0 **to γ_{dir} dominated** at high p_T

- Not true for LHC

Stay tuned → γ jet results from RHIC will be available shortly

- Ideal comparison with the LHC!

3rd Generation Jet Observables

With increased jet statistics and precision detectors, the structure of jets can be measured

- Helps to answer the **How** and **Why** questions of energy loss
- Also indicates where the lost energy goes

Observables like:

- Fragmentation functions
- Sub-jet analyses
- Z_g (Groomed Momentum Sharing)
- Jet mass (virtuality)
- Heavy flavor jets → Now possible in HI collisions!

3rd Generation Jet Observables

With increased jet statistics and precision detectors, the structure of jets can be measured

- Helps to answer the **How** and **Why** questions of energy loss
- Also indicates where the lost energy goes

One open question is which picture of jet quenching is correct

- Parton showers in the QGP are not changed compared to the vacuum
- Parton showers in the QGP are modified, thus more channels in the jet formation process are available
- Need multiple observables with different scale dependencies that are well understood
  - Constrain parton kinematics and flavor as much as possible!

Jet Structure modification

Fragment yield in central collisions is (GeV):

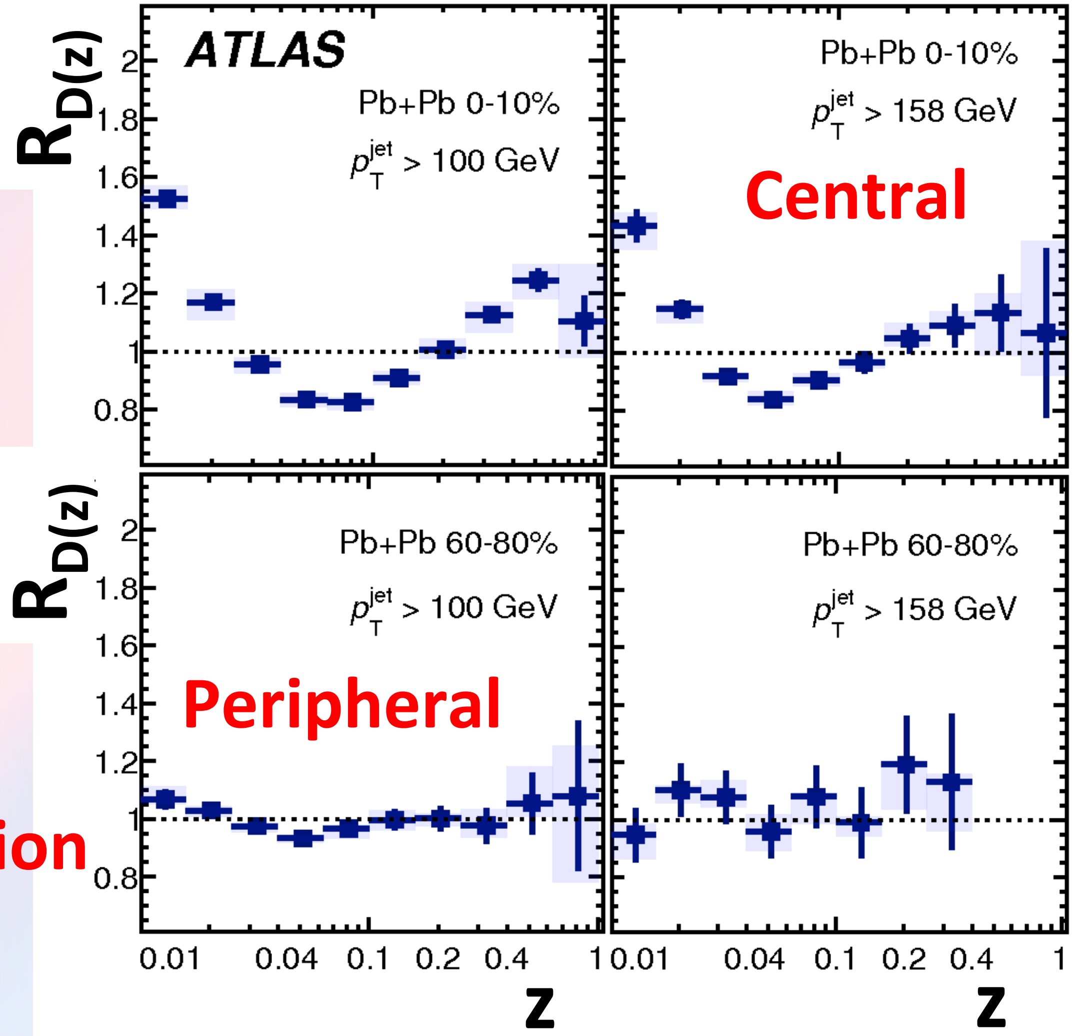
- Enhanced $1 < p^{ch}_T < 4$
  Reduced $4 < p^{ch}_T < 25$
  Enhanced $p^{ch}_T > 25$

$$z = \frac{p_T^{track} \cos \Delta R}{p_T^{jet}} \qquad D(z) \equiv \frac{1}{N_{jet}} \frac{dN_{ch}}{dz}$$

$$R_{D(z)} \equiv \frac{D(z)_{PbPb}}{D(z)_{pp}}$$

Increasing Jet p_T

$\sqrt{S_{NN}}$ = 2.76 GeV

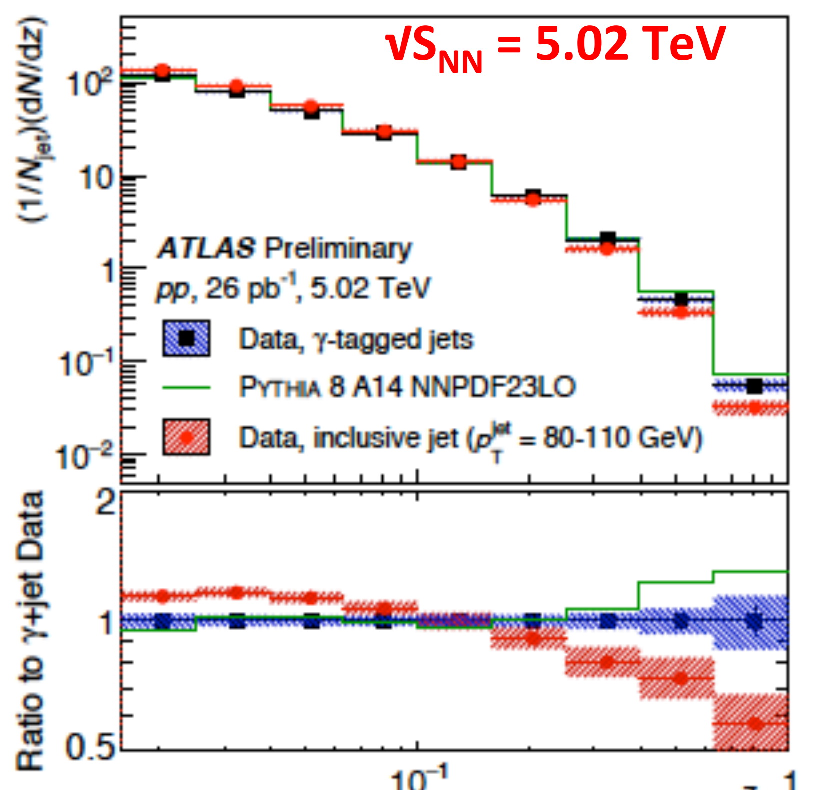


Difference in fragmentation does not have much p_T dependence

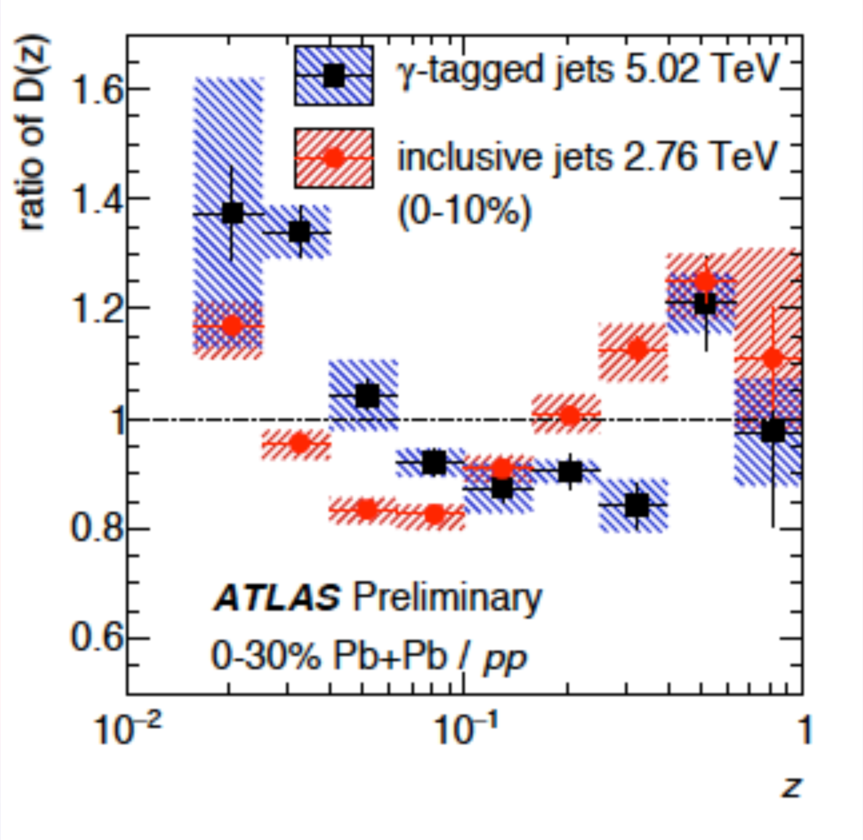
2014 Pb-Pb data 0.14 nb^{-1}
2013 pp data 4.0 pb^{-1}

Eur. Phys. J. C 77 (2017) 379

Jet Structure modification with γ!

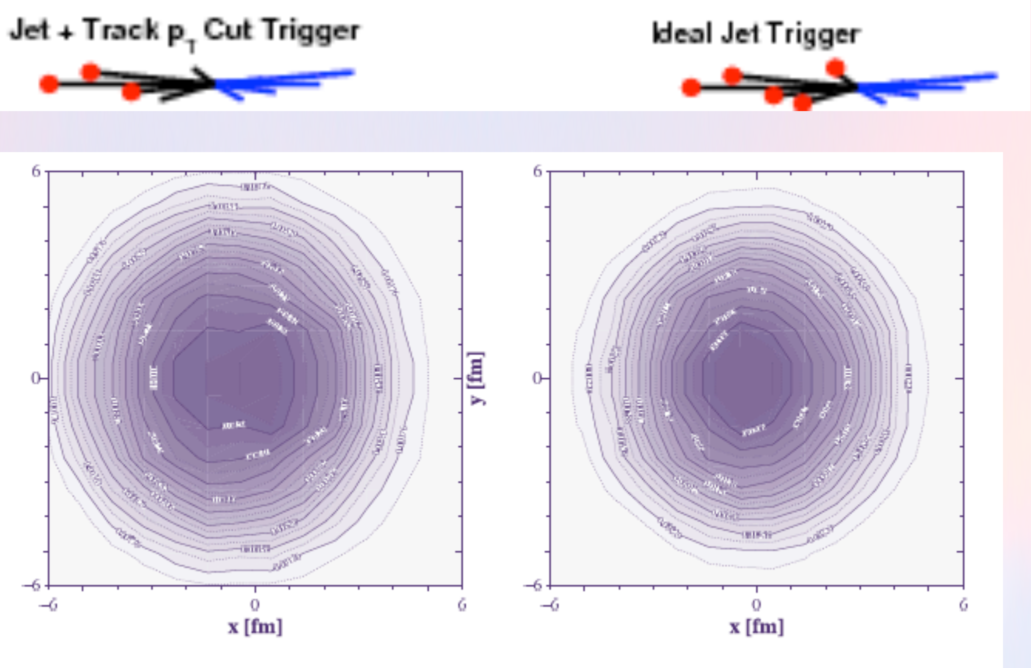


ATLAS-CONF-2017-074



- Photon-jet structure measurements allow determination to be tightly correlated with the parton
  - Dominated by quark jets → Removes flavor dependent fragmentation effects
  - Flavor difference causes the majority of the difference between inclusive and γ-tagged

Jet Structure modification with γ!



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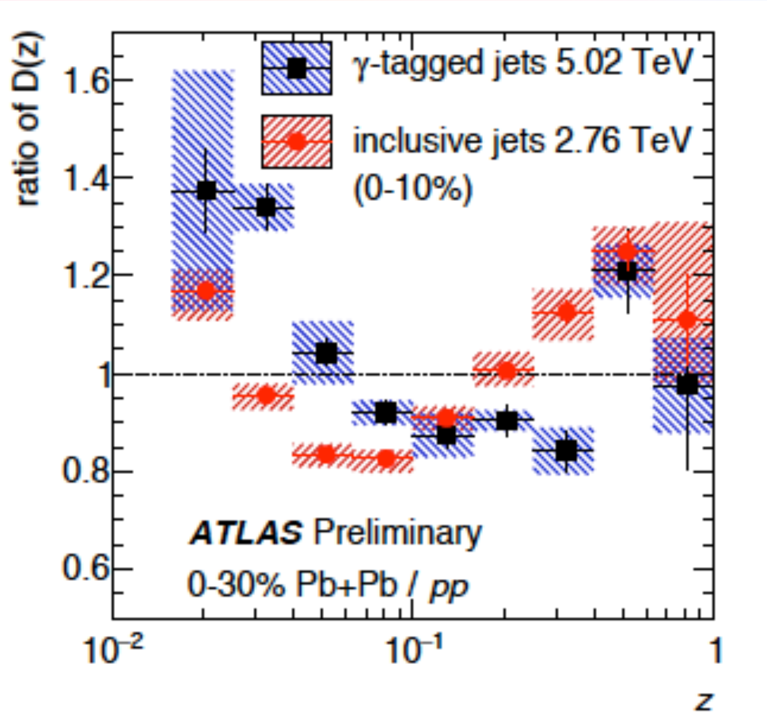
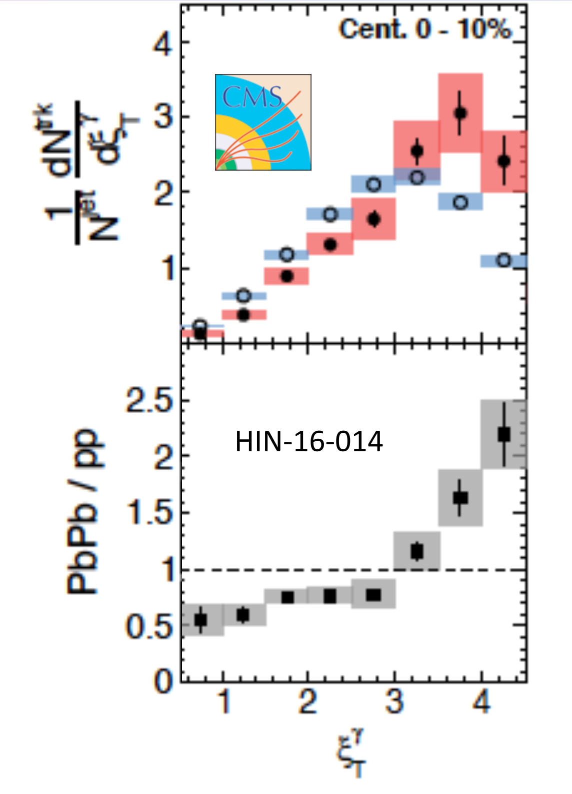


- Jet finders will impose a bias when selections are made on the jet kinematics
  - Preferentially select surface biased jets
  - γ-jet analyses are less biased as the γ does not interact with the QGP

Unfolding and Other Issues



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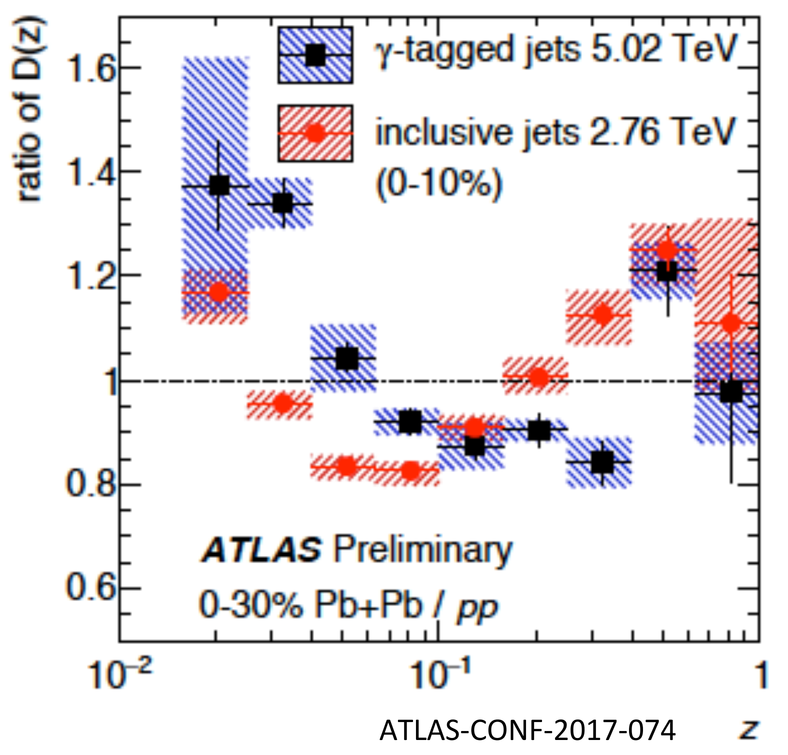


ATLAS-CONF-2017-074

- Atlas results are unfolded
  - Detector effects that wash out features removed
  - Unfolding is tricky, but required for direct comparisons
- CMS results are compared to smeared pp
  - This means the energy scales will not be the same (JES/JER are effected by detector effects), effects such as jet finding efficiency may also be difficult to disentangle

Unfolding and Other Issues

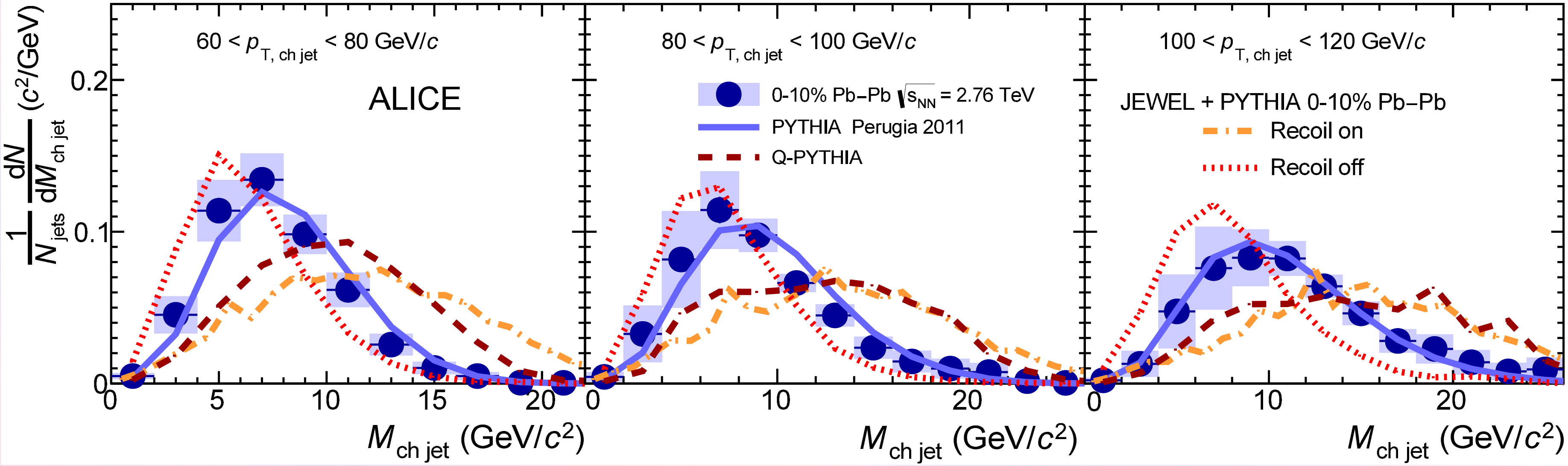
In order to understand our results, we need to make **apples-to-apples** comparisons between experiment and between theory and experiment

- **Different jets are different!** We need to be careful with respect to constituent cuts, resolution parameters, p_T ranges, η ranges
- Comparing unfolded results to not-unfolded results will result in **errors in interpretation**
- Unfolding is tricky, it would be good to confirm results by folding theory for the comparisons
- Experimentalists need to be better about **providing detector performance** to our theory colleagues

If we compare different results, we should not be surprised that they are different!

Jet Mass

$\sqrt{s_{NN}}$= 2.76 TeV



No difference is observed between PYTHIA and data from Pb+Pb collisions for $60 < p^{ch}_{T,jet} < 120$ GeV/c

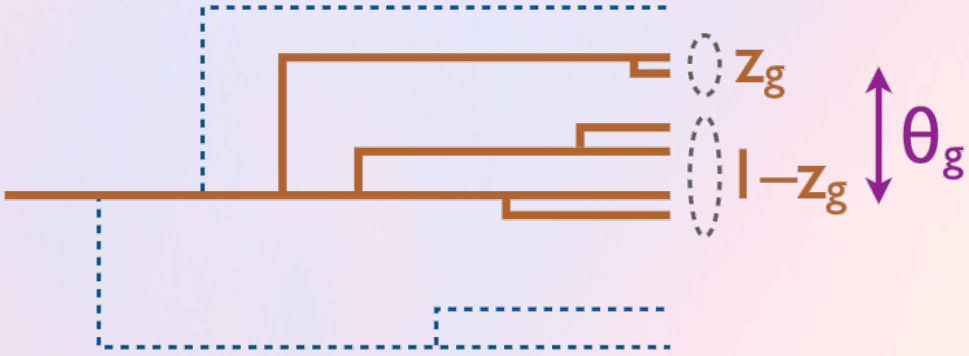
- **No modification indicated**
- Should be sensitive to soft radiation

There should be a relationship virtuality <-> jet mass

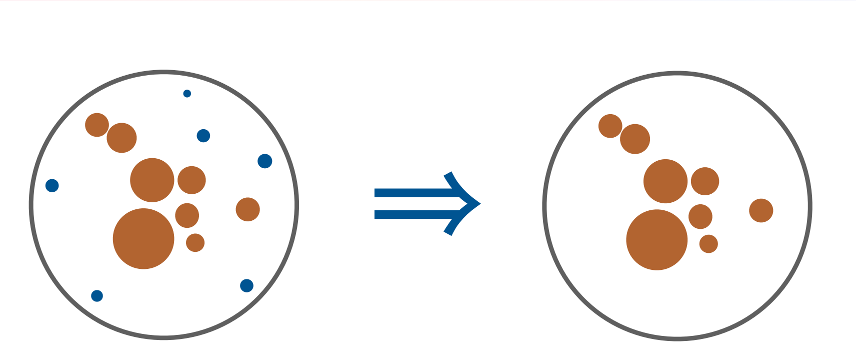
- Perhaps this gives us another jet characterization

Jet Grooming – A New Tool

Soft Drop: Remove wide angle soft radiation in a controlled way



Based on declustering an angular-ordered tree

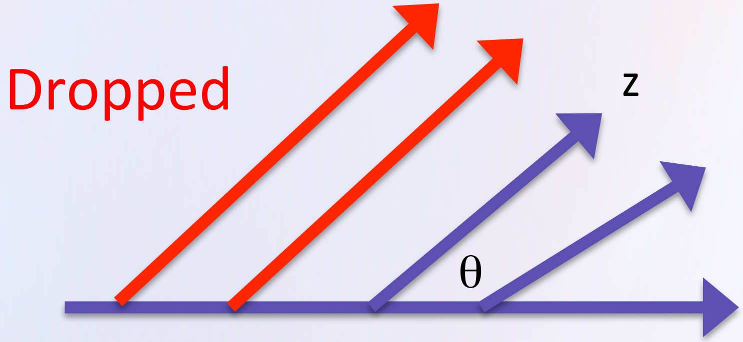


Soft Drop Condition:

$$z > z_{\text{cut}}\, \theta^{\beta}$$

energy threshold

angular exponent



J. Thaler ALICE Jet Workshop (2015)

Larkoski et al., PRD 91, 111501 (2015)

Jet Grooming – A New Tool

Jet structure observables using particles → sensitive to ill constrained hadronization dynamics

- This plays a role for the small jets favored in HI analyses as well!
- Observables built from jet-like structures may be more robust → **Connection to fundamental QCD**

In vacuum:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}z_g} \propto \overline{P_i}(z_g) + \cancel{\mathcal{O}(\alpha_s^2)}$$

P_i: AP splitting functions

- ~ independent of a_s
- ~ independent of p_T (in UV limit)
- ~ independent of quark/gluon jet

Groomed Momentum Sharing z_g

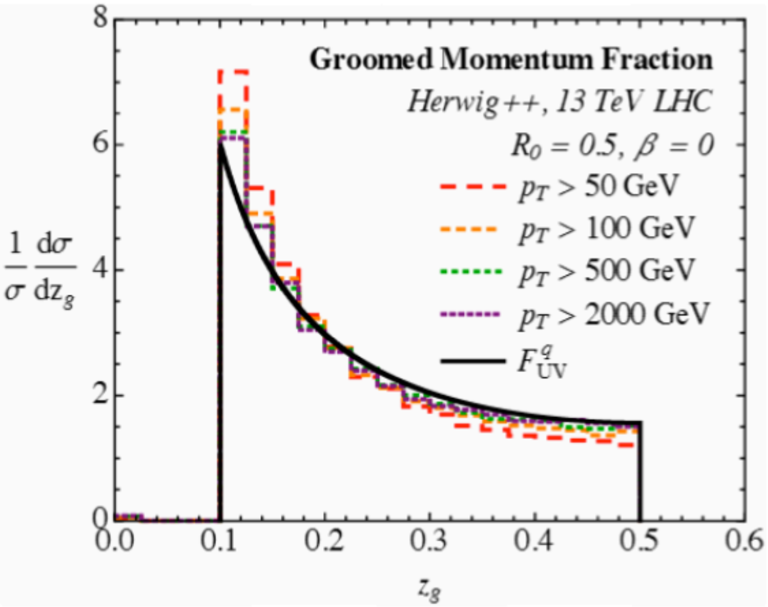
Soft Drop Condition:

$$z > z_{\text{cut}}\,\theta^{\beta}$$

energy threshold

angular exponent

Larkoski et al.,
PRD 91, 111501 (2015)



Use Cambridge/Aachen:

"Groomed Momentum Sharing"

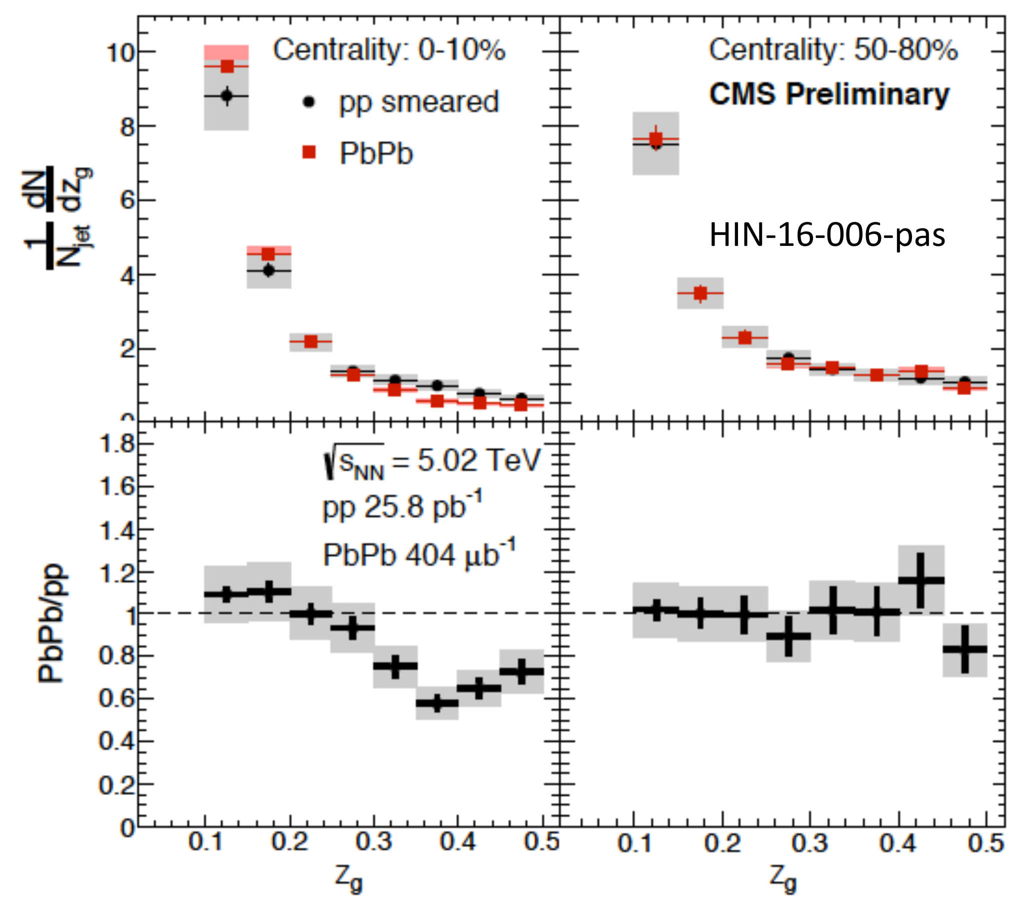
$$z_g = \frac{\min\left(p_{T1}, p_{T2}\right)}{p_{T1} + p_{T2}}$$

Relative z of the softer prong

Z_g relatively independent of jet p_T, quark vs gluon

- Experimental background removals may make interpretation complicated
- Can we use the "groomed away" object?

Groomed Momentum Sharing z_g

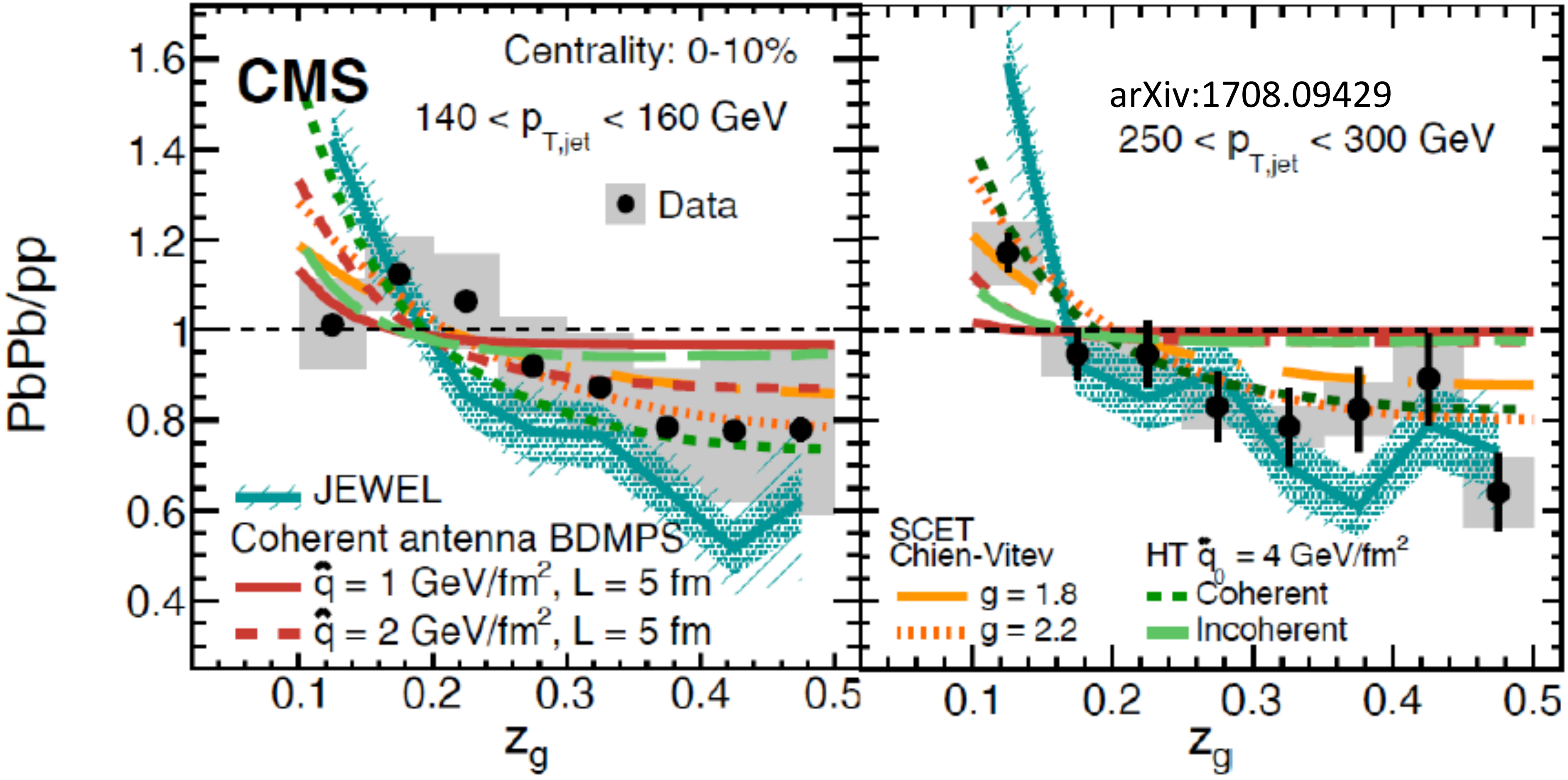


HIN-16-006-pas

Difference seen as less "balanced" subjets → not understood

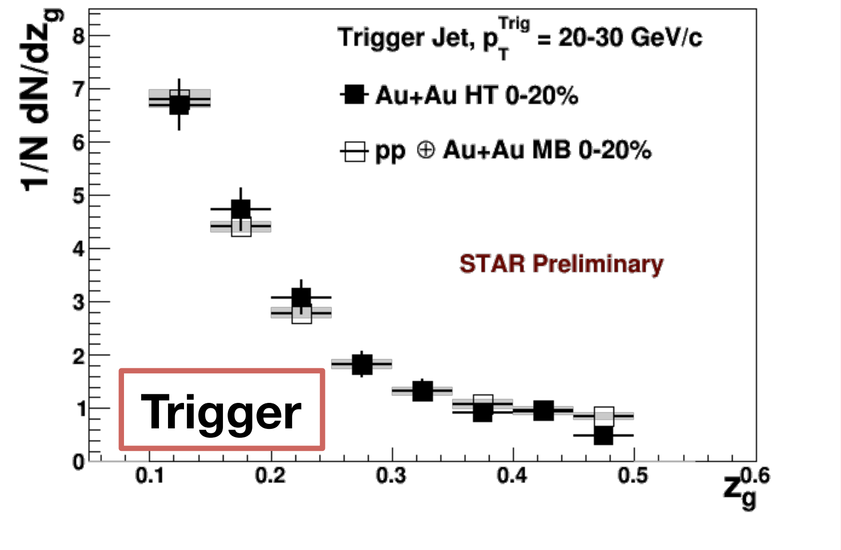
- Observable is insensitive to q/g → Modification greater than this?
- Color coherence in how an angularly-tight collection of partons interacts with the medium?

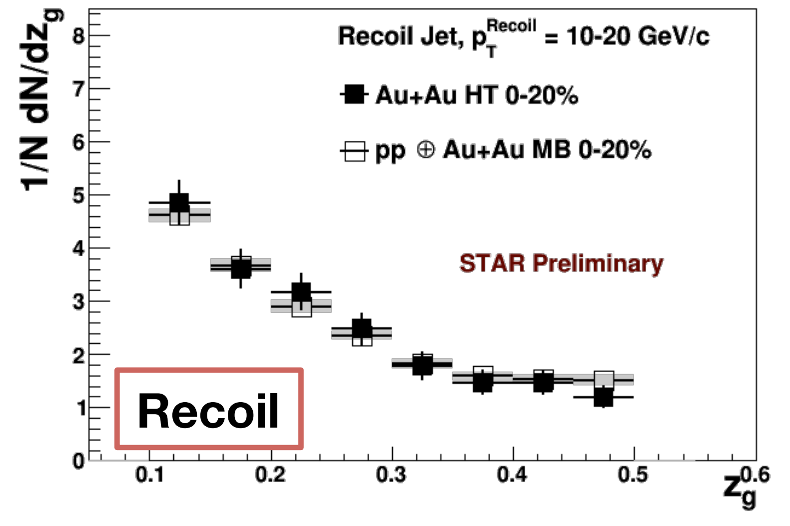
Groomed Momentum Sharing z_g



Different mechanisms for the modification, need additional observables to separate models

Di-jets z_g in Au+Au and p+p



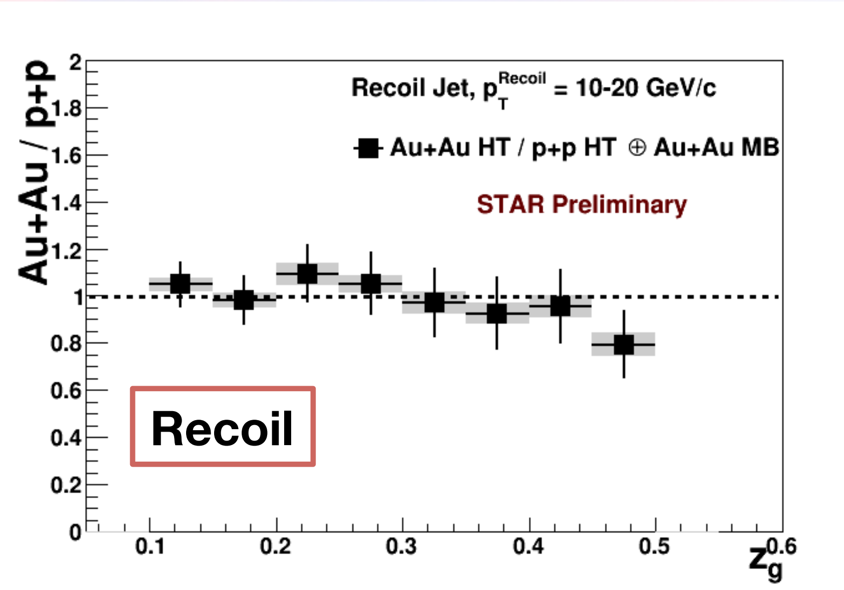


No significant splitting modification on near- or away-side

- But A_J is modified!

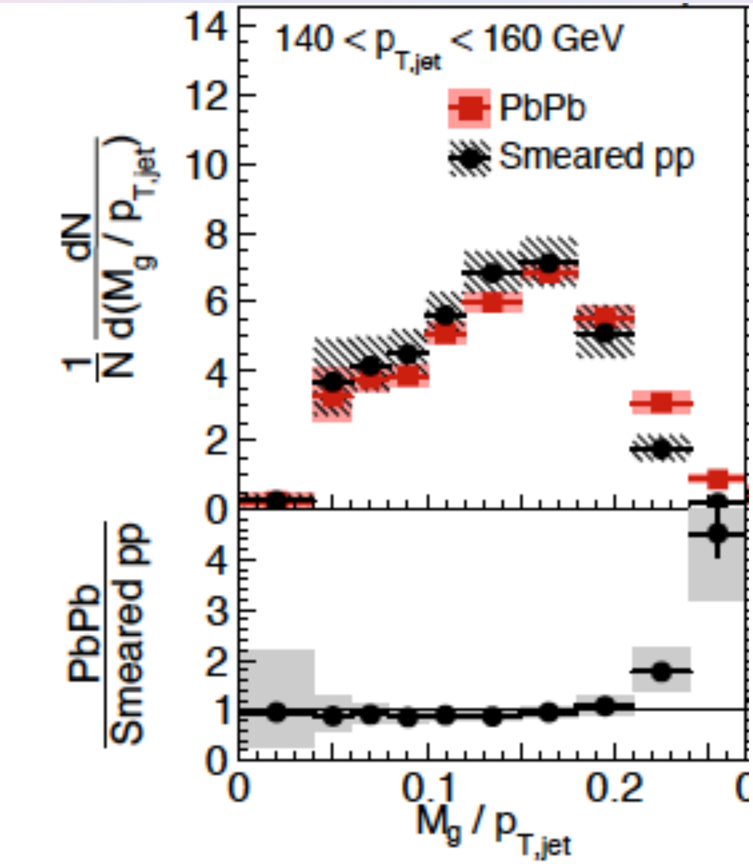
Contrast to LHC modification → Time of split, kinematics, dilution?

- Discussion with theory!
- We need to compare LHC/RHIC data to determine density effects

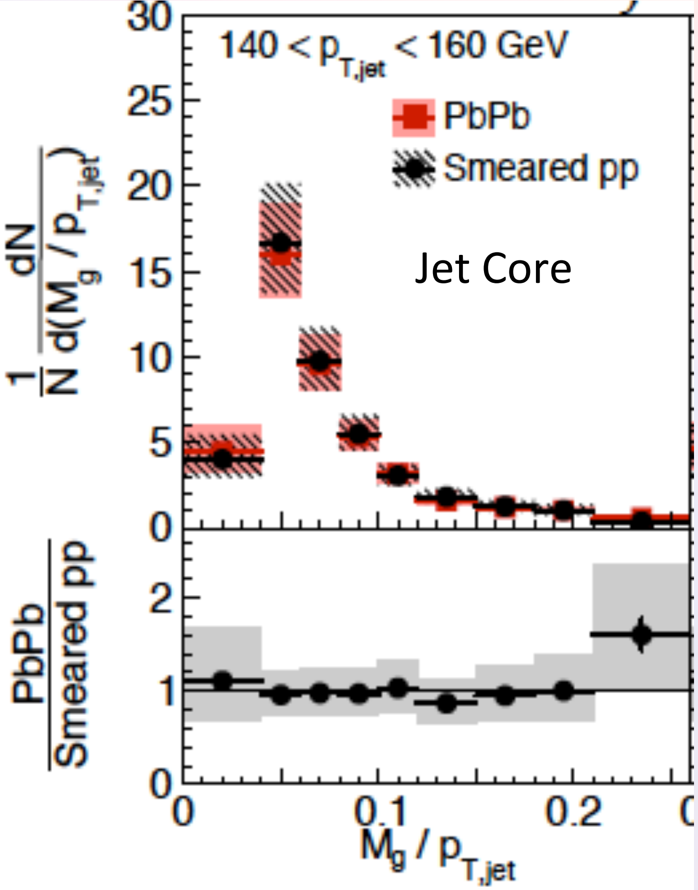


Groomed Jet-Mass (0 – 10% Central)

Anti-k_T R = 0.4 $|\eta_{jet}| < 1.3$, $z_{cut} = 0.1$, $\beta = 0$, $\Delta R_{12} > 0.1$



Anti-k_T R = 0.4 $|\eta_{jet}| < 1.3$, $z_{cut} = 0.5$, $\beta = 1.5$, $\Delta R_{12} > 0.1$



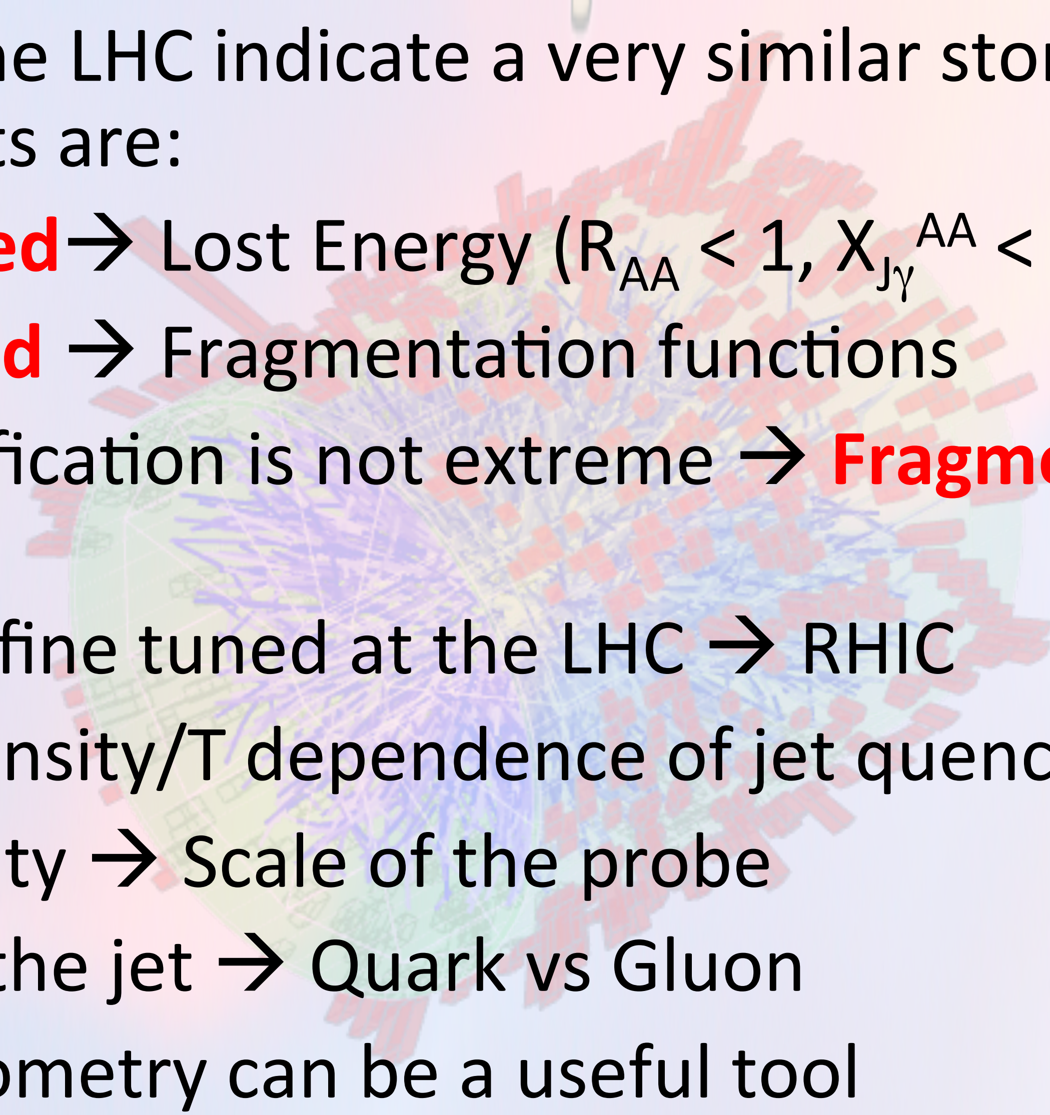
Selecting jet core via strong grooming shows no difference

- Similar to STAR A_J measures
- Difference with "gentle" grooming not significant

HIN-16-024

$$z > z_{cut}\theta^{\beta}$$

LHC/Early RHIC Conclusions



Results at the LHC indicate a very similar story to RHIC energies, jets are:

- **Suppressed**→ Lost Energy ($R_{AA} < 1$, $X_{J\gamma}^{AA} < X_{J\gamma}^{pp}$)
- **Broadened** → Fragmentation functions
- The modification is not extreme → **Fragmentation functions**

Techniques fine tuned at the LHC → RHIC

- Energy density/T dependence of jet quenching
- p_T/virtuality → Scale of the probe
- Flavor of the jet → Quark vs Gluon
- Event Geometry can be a useful tool

Conclusions and Outlook

Techniques for measuring jets in heavy-ion collisions have advanced considerably in the last few years

- More statistics → **Kinematic Reach**
- More observables → **Differential measures**
- Mature background removal techniques → **Reduced systematics**

Current understanding from RHIC and LHC

- Jets are suppressed in HI collisions
- Jets are broadened
  - But the jets seem to be relatively vacuum-like
- Modification shifts energy from high p_T constituents to low p_T

Now we need to turn these **qualitative observations** into **quantitative statements** in order to answer our fundamental questions

- Requires theory input → MC with p/E exchange between jet and medium!

Conclusions and Outlook

Observables→**calculable by QCD** key to answering fundamental questions

- Not enough to see a difference in pp and AA!
- A good jet quenching theory needs to be able to describe an inclusive, triggered and structure observable (R_{AA}, I_{AA}, fragmentation functions)

We should use γ-jet observables to compare across energies and experiments

- This is the path forward to precision heavy-ion collisions
- Theory input into most differential observables is important
- The explosion of new observables can be helpful, but is not constrained
  - Unfolded vs smeared reference, background subtraction, kinematic selections

RHIC and LHC are complementary → need both for understanding!

For further discussion, see arxiv:1705.01974