Jets from RHIC to LHC and Back Again

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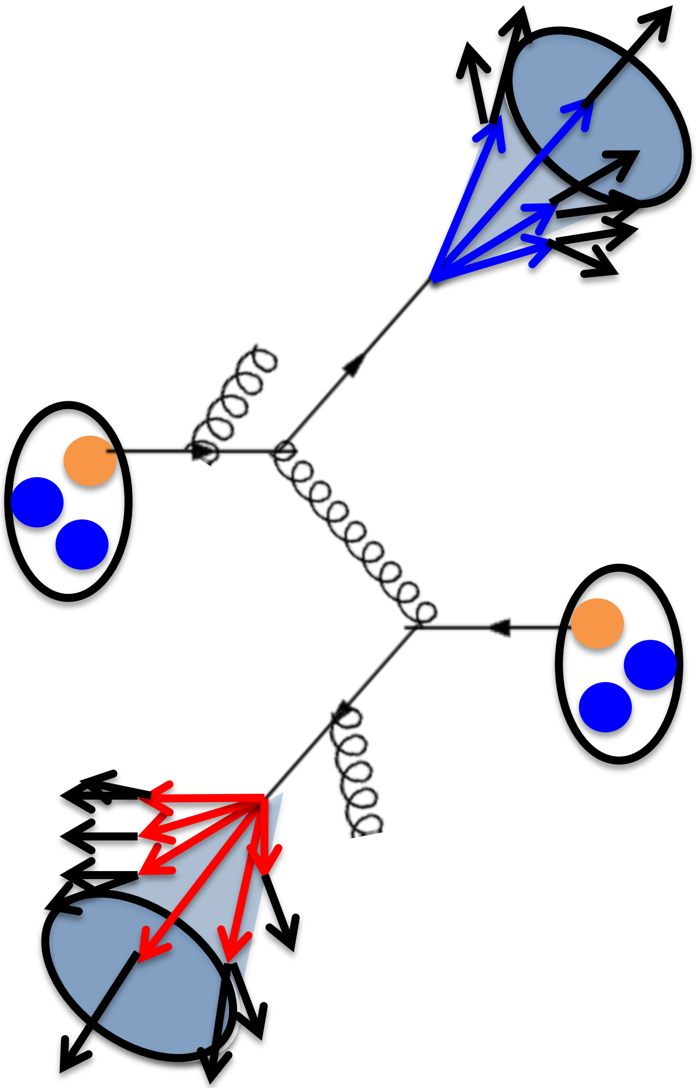
RHIC & AGS
Annual Users' Meeting
From Protons to Heavy Ions, and Back Again
Hosted By Brookhaven National Laboratory

Jet at RHIC



A hard scattered parton will fragment and hadronize into a spray of particles

- We call this a jet

Jets are as tools to understand QCD

- Heavy-ion Collisions
- Spin Physics

Goal of Jets in Heavy-ion Collisions

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

- What are we scattering off of?
  - Point-like at LHC —> lower energy jets at RHIC?
  - 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?

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
- **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**

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

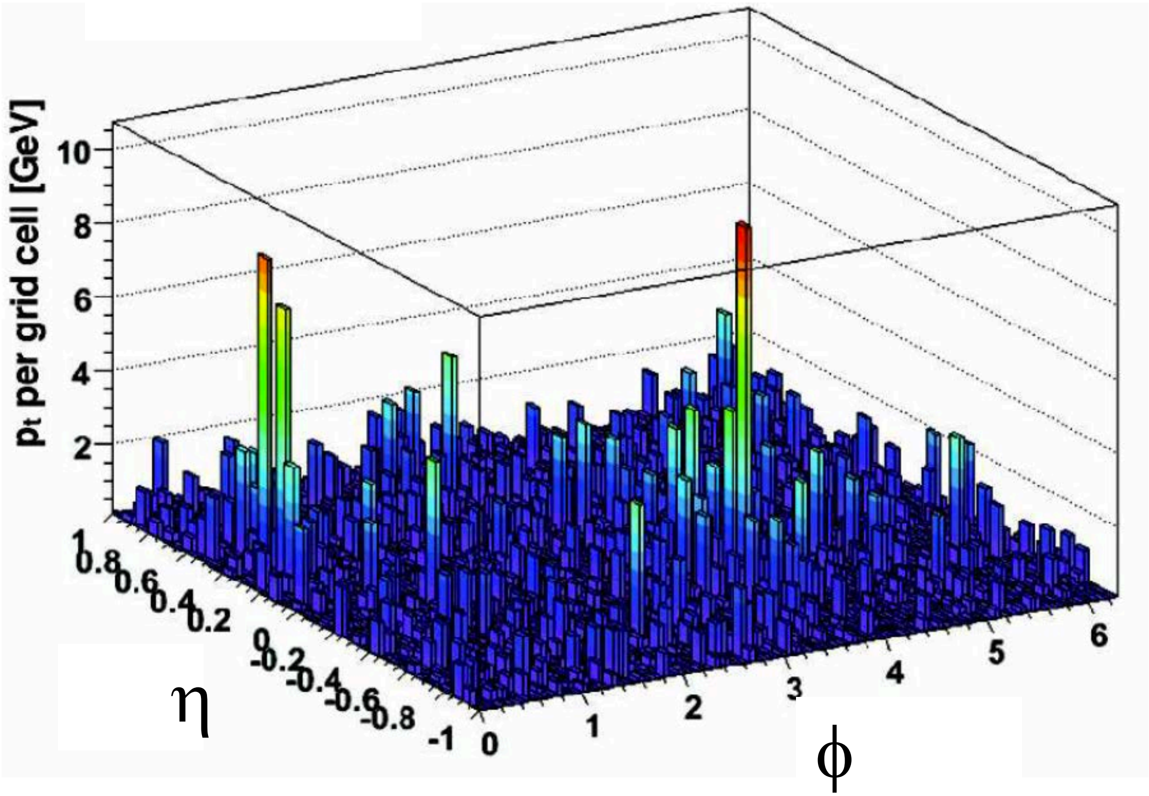
Agreement on definition is necessary to fully understand theory-experiment comparisons

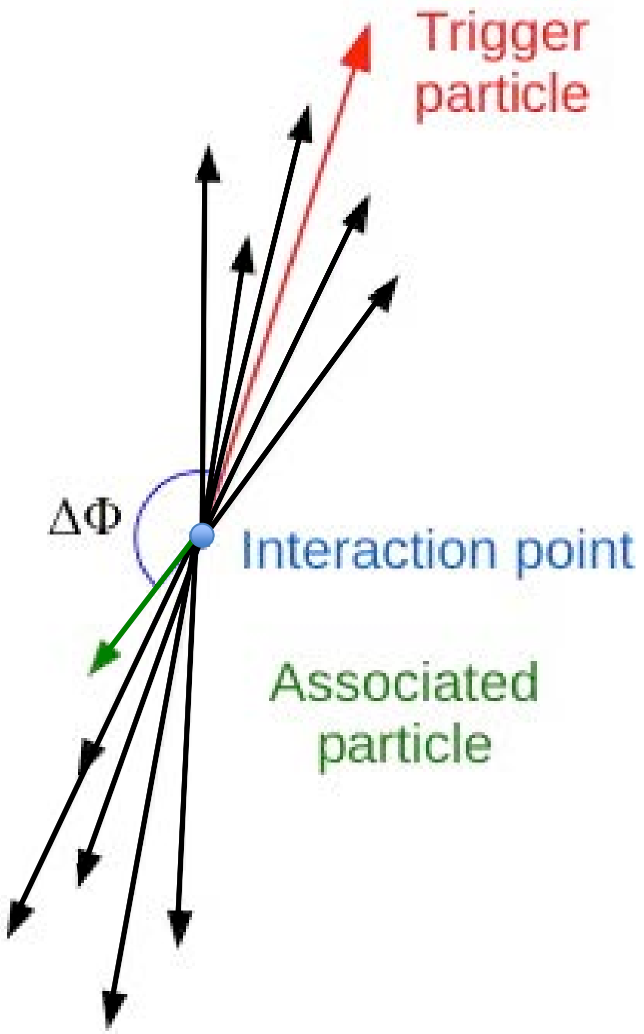
Jet Biases

To select jets from the underlying event **requires some sort of bias**

- This bias is not necessarily bad, but it exists and **must be understood!**
- We want to identify hard QCD processes, does our **selection change what we see of the hard process**?
  - Quark vs gluon flavor dependencies are difficult to disentangle → γ-jet
  - Fragmentation depends on the parton p_T which is correlated to, but not equivalent to the jet p_T
  - Selecting vacuum-like jets will find vacuum-like jets → But the away side fragmentation may be less biased!

Underlying Event (UE) at RHIC



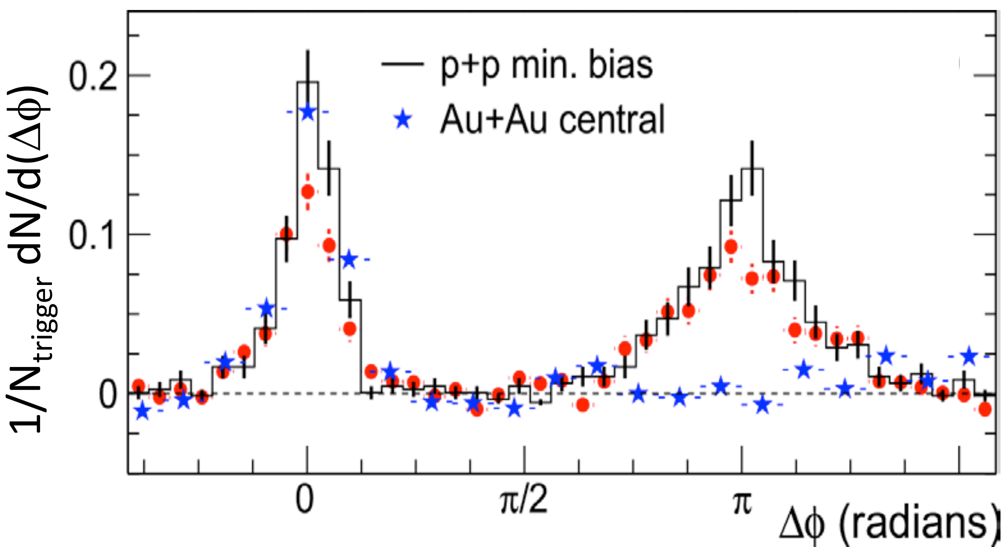


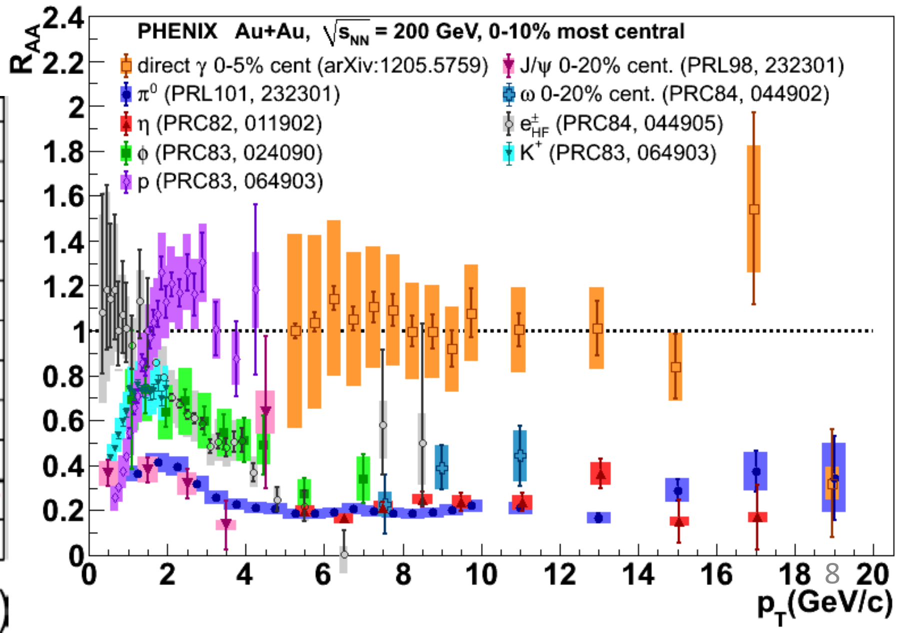
- High p_T hadrons serve as a jet proxy
- Easier to "find" than jets, but care must be taken with the background

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 with Jets in HI Collisions

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

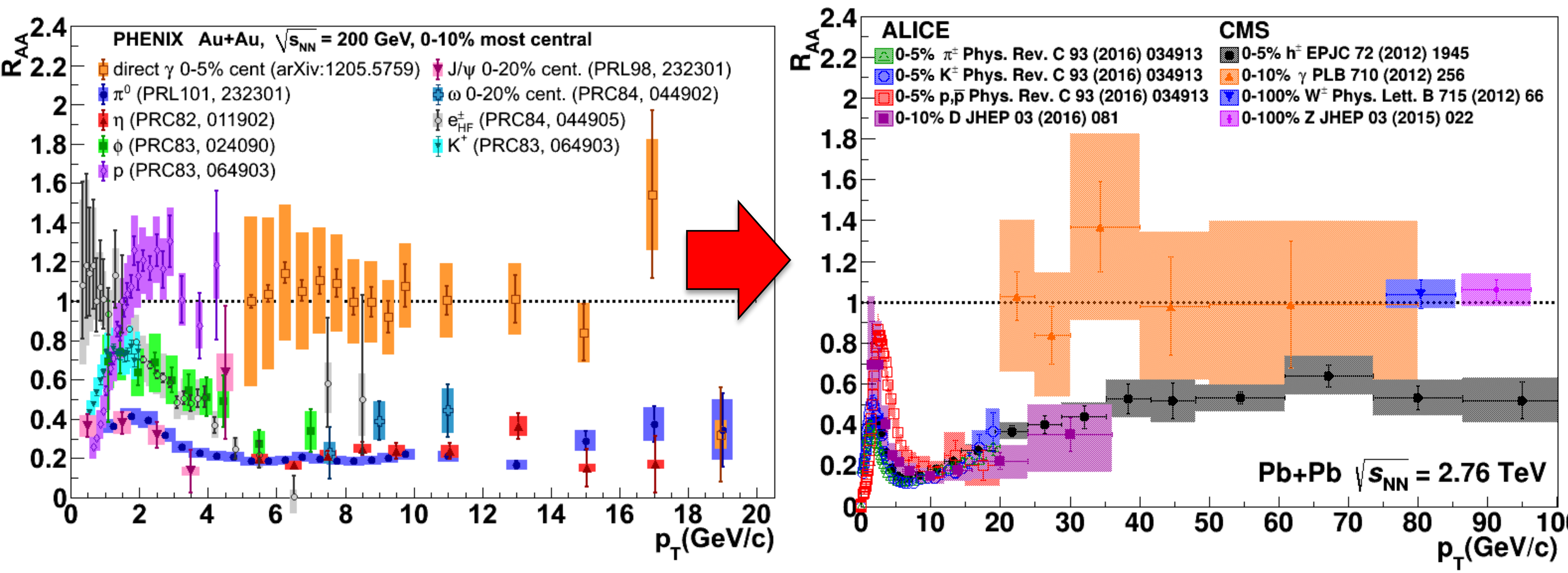
- Jet-finding algorithms cluster the entire event
  - **Combinatorial jets** are created from the soft physics
  - "Hard" **jet kinematics are blurred** by UE contribution
  - Jet Energy Scale and Resolution **(JES, JER) are modified**
- Lower luminosity of pre-LHC era RHIC combined with steeper hard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

1^{st} Generation Jet Observables

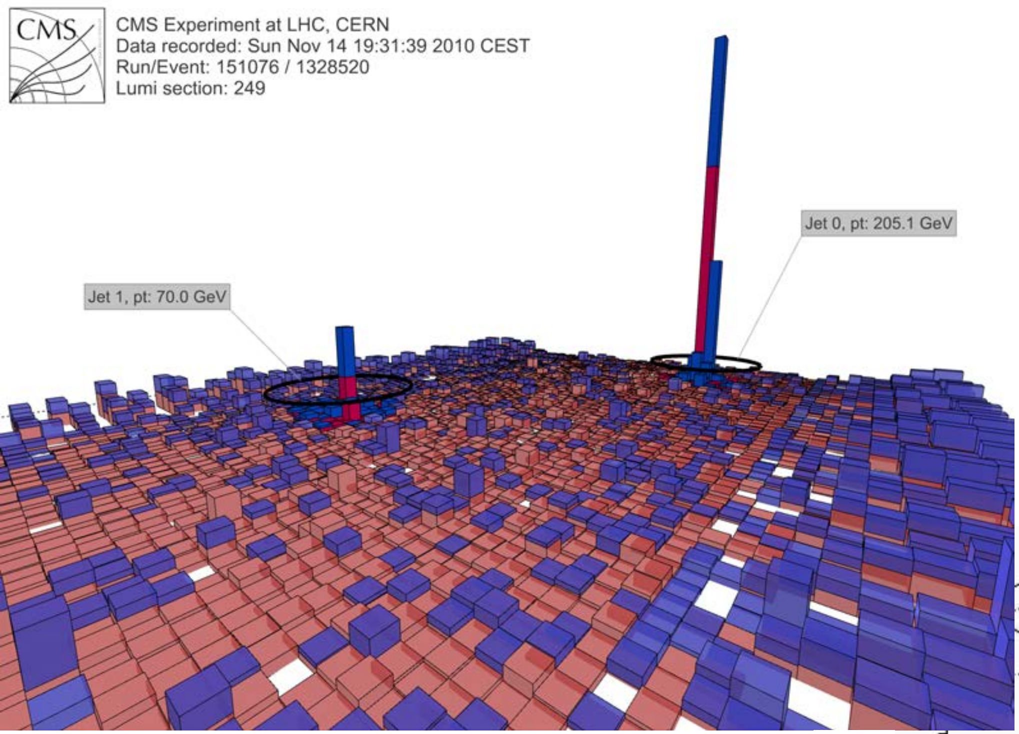
Hadron observables repeated with greater kinematic range

- 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

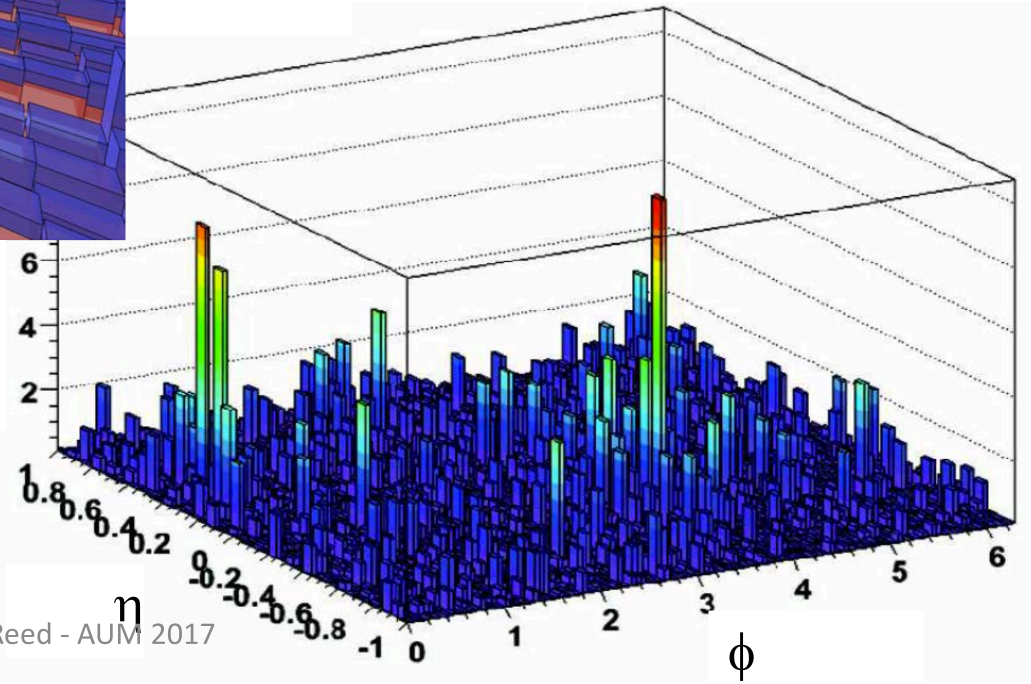


Underlying Event LHC vs RHIC



Hard parton cross section increases faster than QGP Temperature

- Simplifies dividing hard from soft



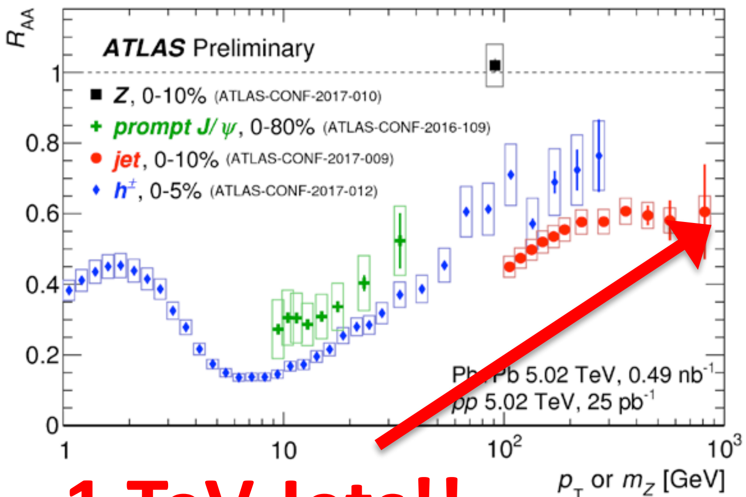
Allowed a wealth of new observables to be measured at the LHC

- Including Jet structure

1^{st} Generation Jet Observables

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

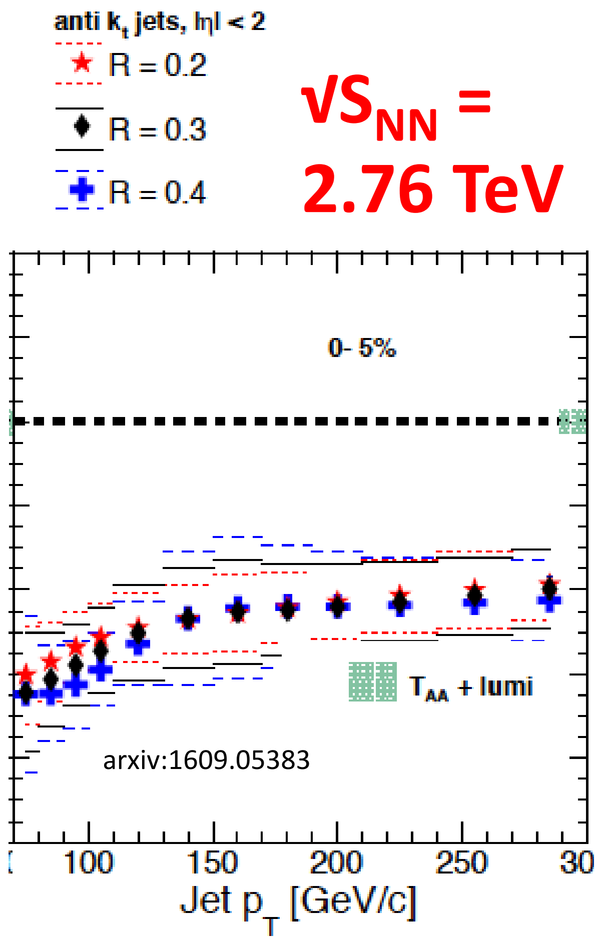
$\sqrt{S_{NN}}$ = 5.02 TeV



1 TeV Jets!!

Wow!!

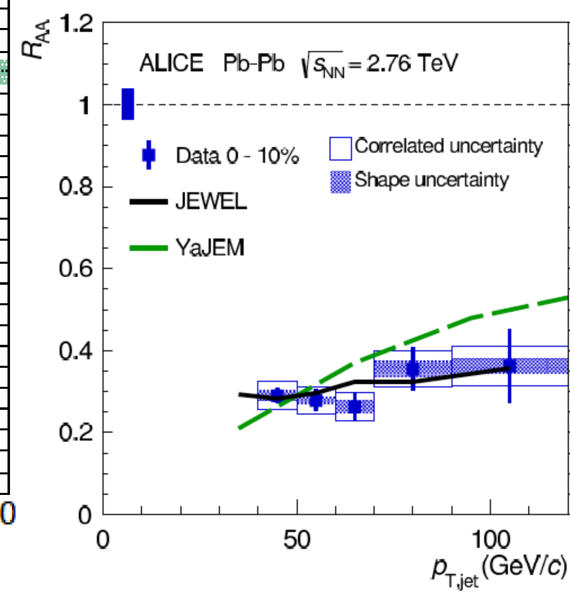
Results for inclusive jets and inclusive hadrons are very similar at high p_T



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

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)

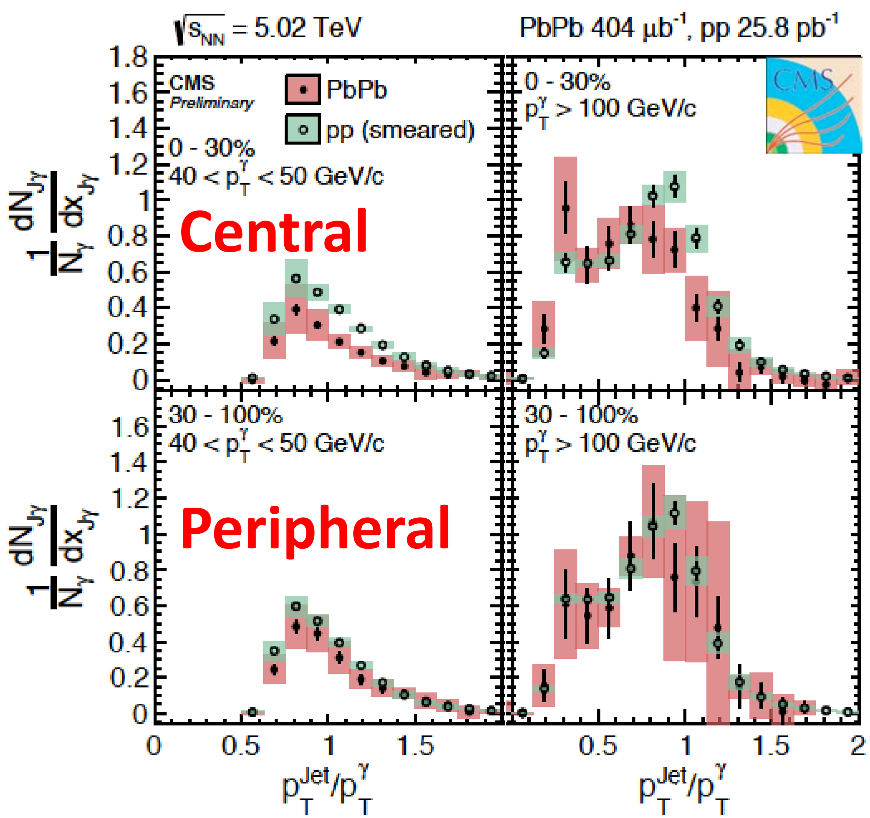
Measurements of Dijet correlations

- 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
$\Delta\phi J\gamma$ > 7p/8



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

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

HIN-16-002

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!

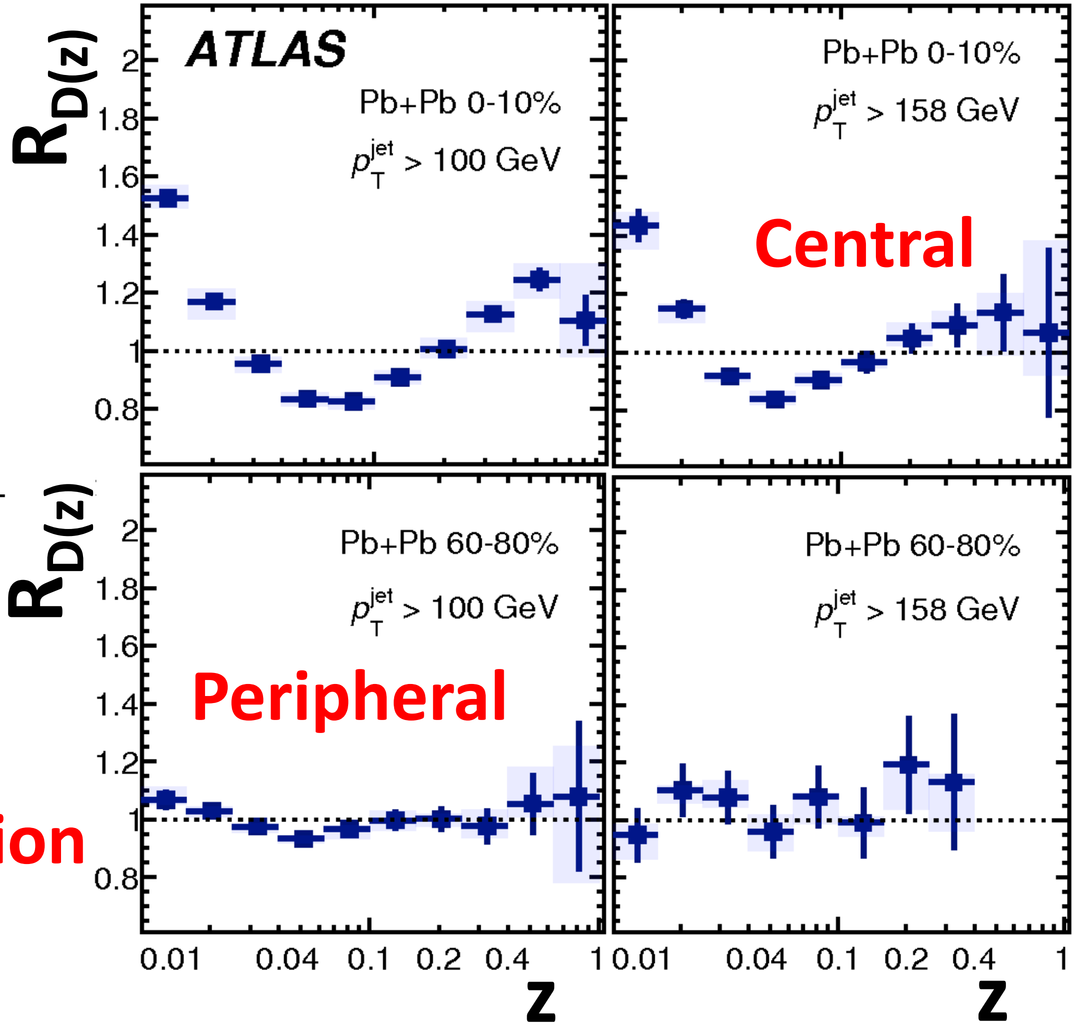
Jet Structure modification

Fragment yield in central collisions is (GeV):

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

Increasing Jet p_T

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



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

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

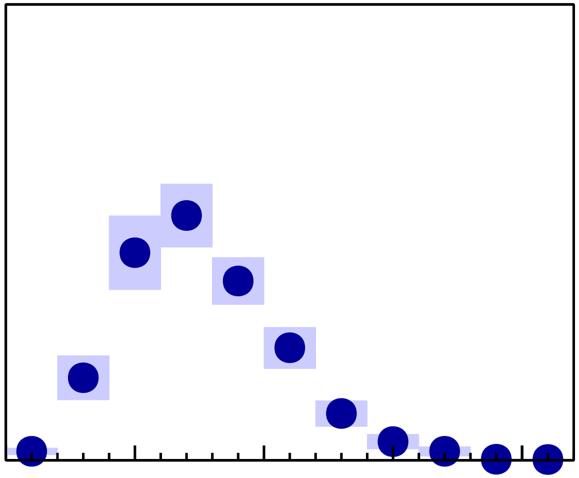
Difference in fragmentation does not have much p_T dependence

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

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

Jet 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**

There should be a relationship virtuality <-> jet mass

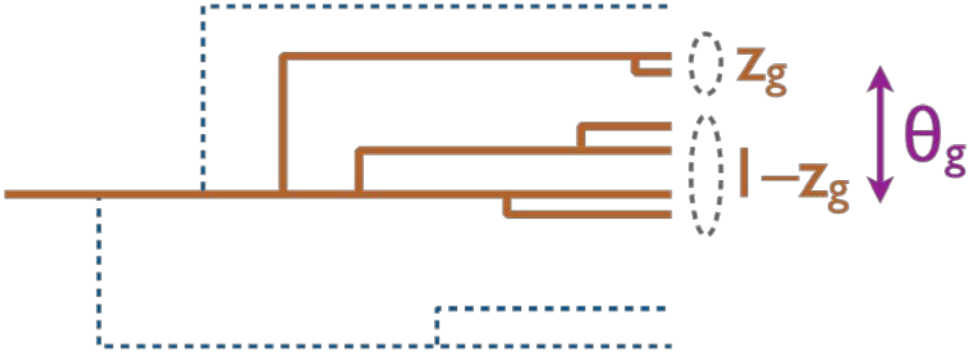
- Perhaps this gives us another jet characterization

Groomed Momentum Sharing z_g

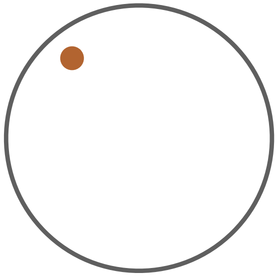
Soft Drop: Remove wide angle soft radiation

Catagorizing stuff

Hard versus soft



Based on declustering an angular-ordered tree



With β=0 + 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

J. Thaler ALICE Jet Workshop (2015)

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

Groomed Momentum Sharing z_g

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**

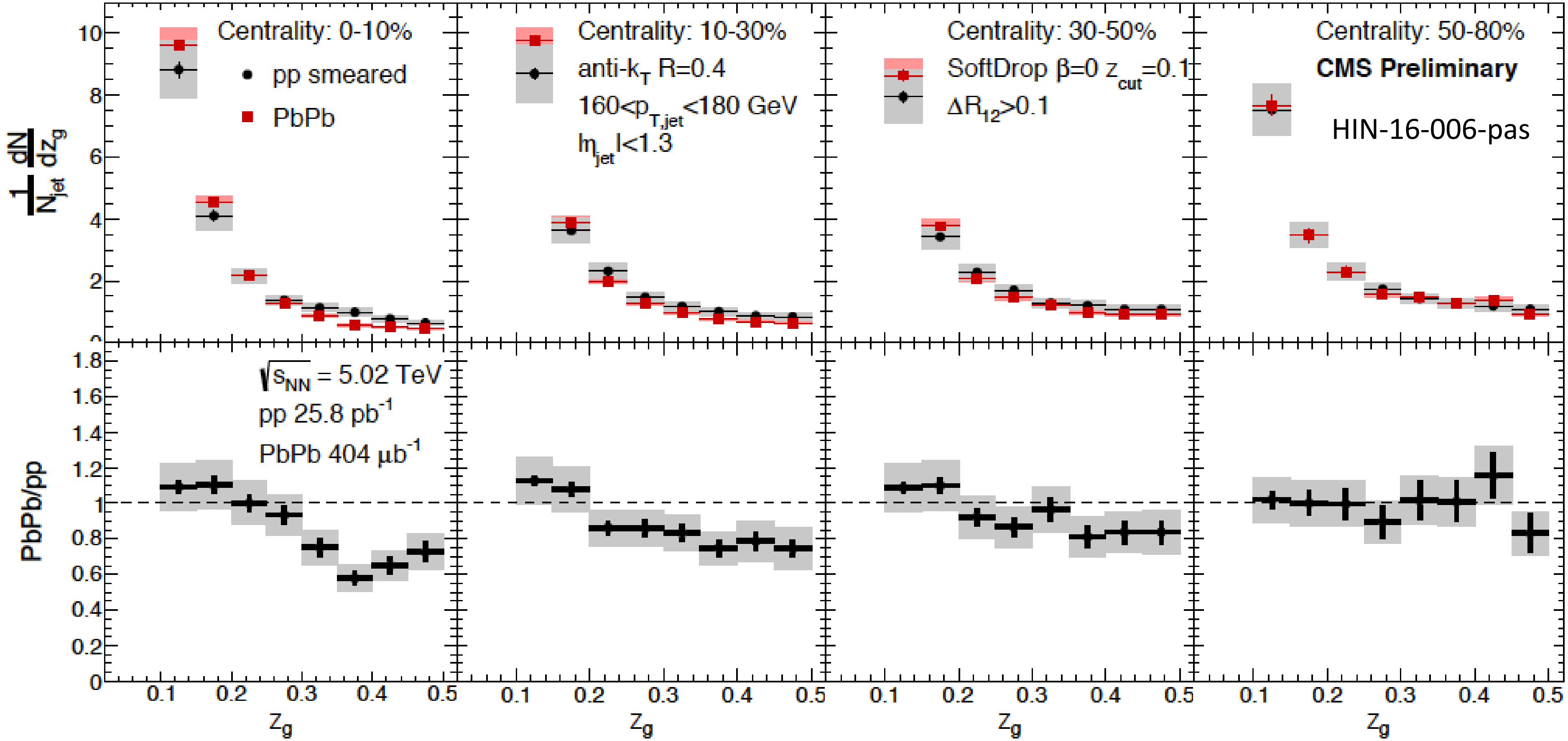
In vacuum:

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

P_i: AP splitting functions

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

Groomed Momentum Sharing z_g



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?

LHC/Early RHIC Conclusions

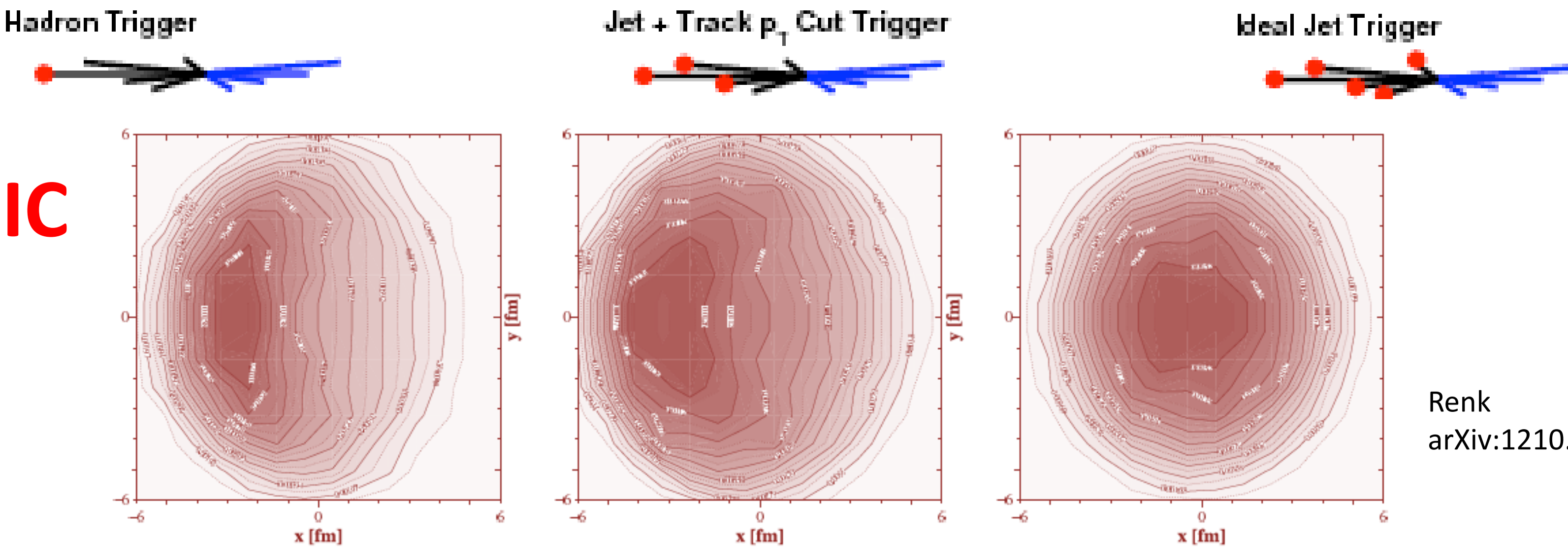
Results at the LHC indicate a very similar story to RHIC energies, jets are:

- **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

Surface Bias versus probe

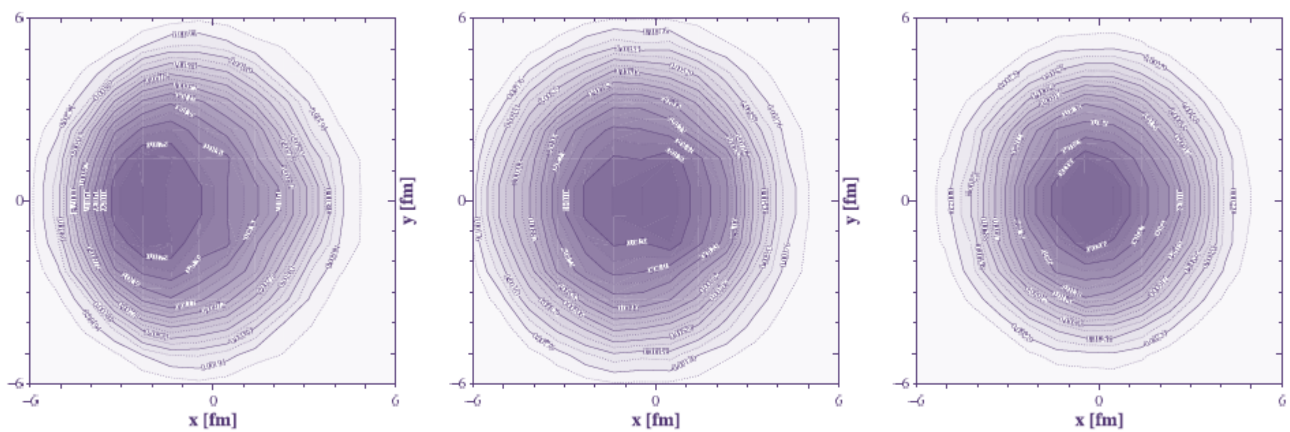


RHIC

Renk
arXiv:1210.1330v1

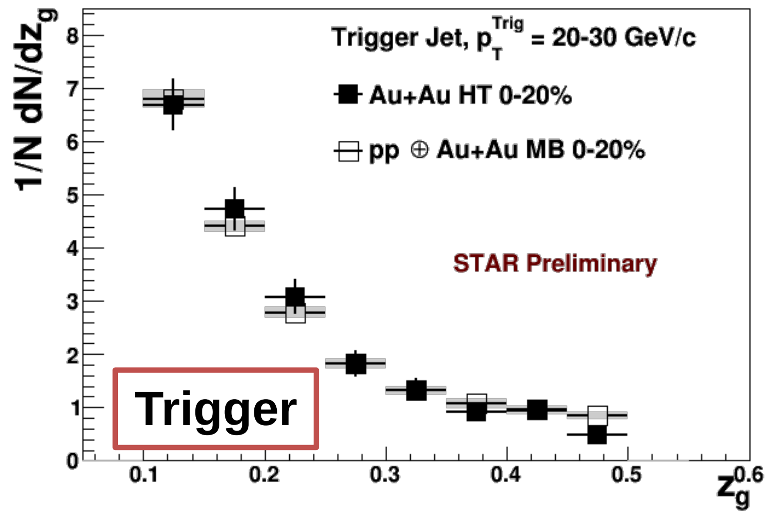
Using different jet definitions → **selectively probe** different regions of the geometry

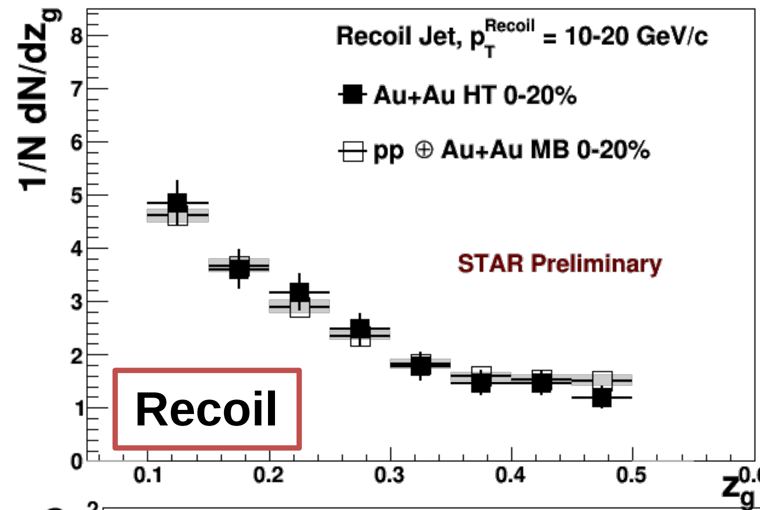
LHC



Harder spectrum at the LHC → Less path length correlation

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



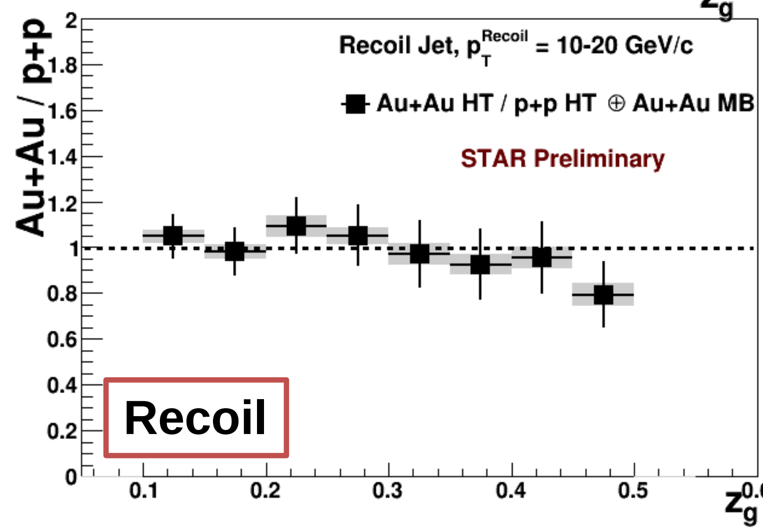


No significant splitting modification on near- or away-side

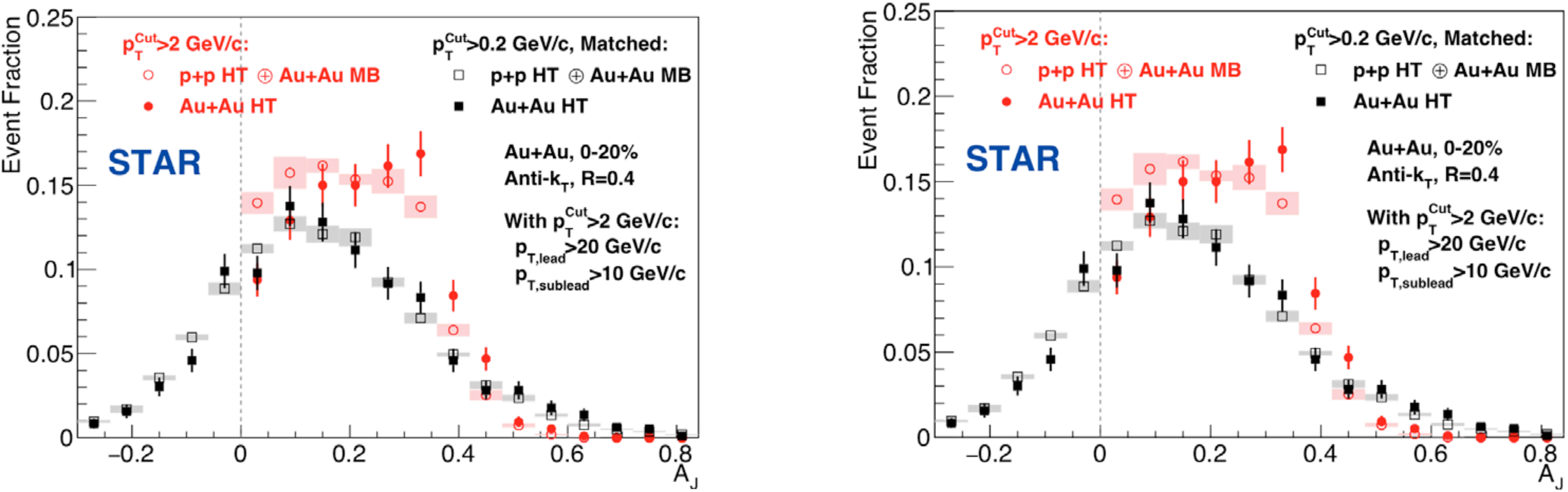
- But A_J is modified!

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

- Discussion with theory!



Di-Jet Momentum Imbalance



R = 0.4 → increase in A_J imbalance vs p+p with constituents p_T > 2 GeV/c

R = 0.4 → pT > 0.2 GeV/c the **imbalance becomes the same** within errors

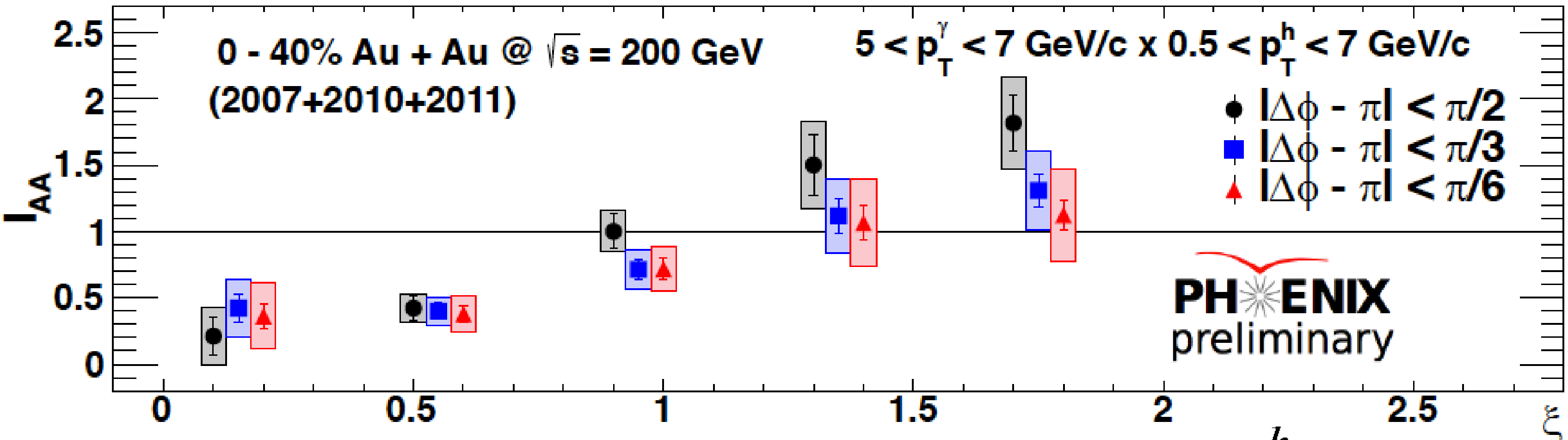
R = 0.2 → **Balance is not recovered**

Indicate at RHIC energies → possible to recover lost E for selection of jets

- Low p_T + Broadened

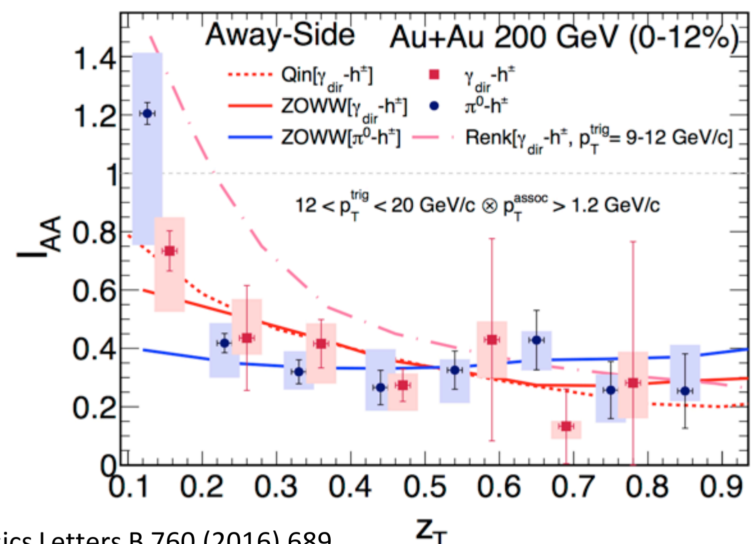
First step towards Jet Geometry Engineering

γ-hadron



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

- 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



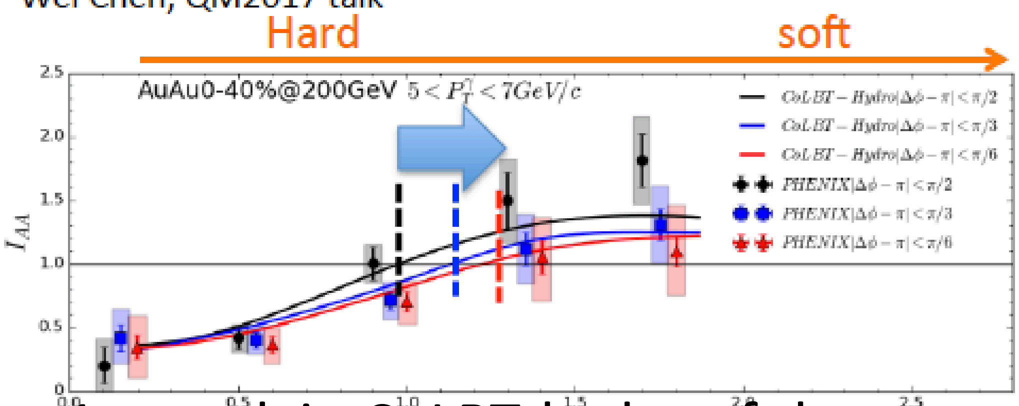
Physics Letters B 760 (2016) 689

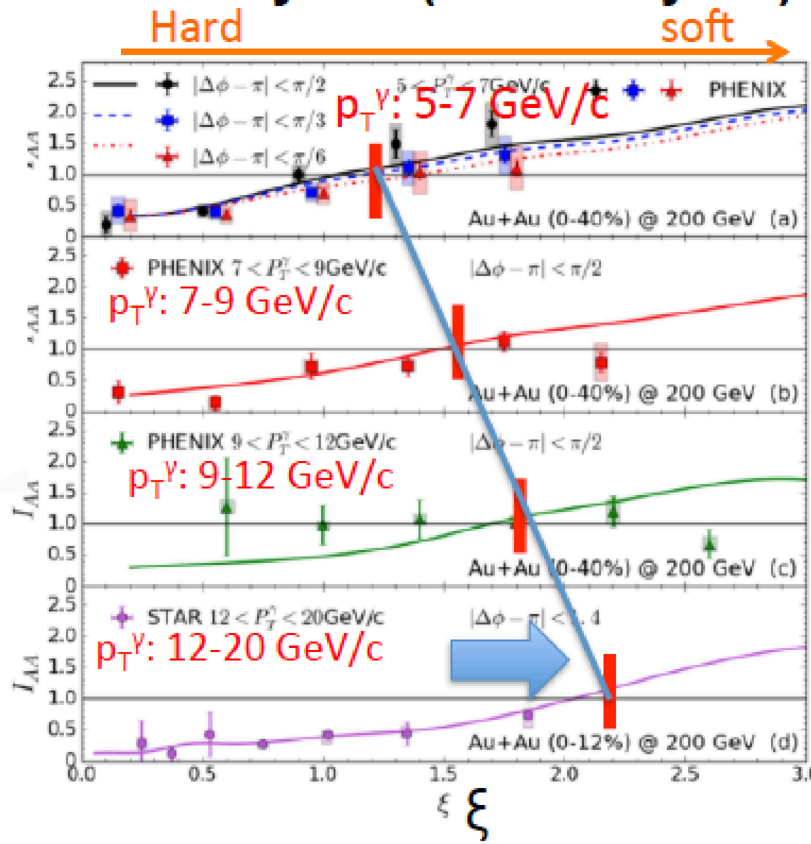
γ-hadron

W. Chen, et al. arxiv:1704.03648

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

Wei Chen, QM2017 talk





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

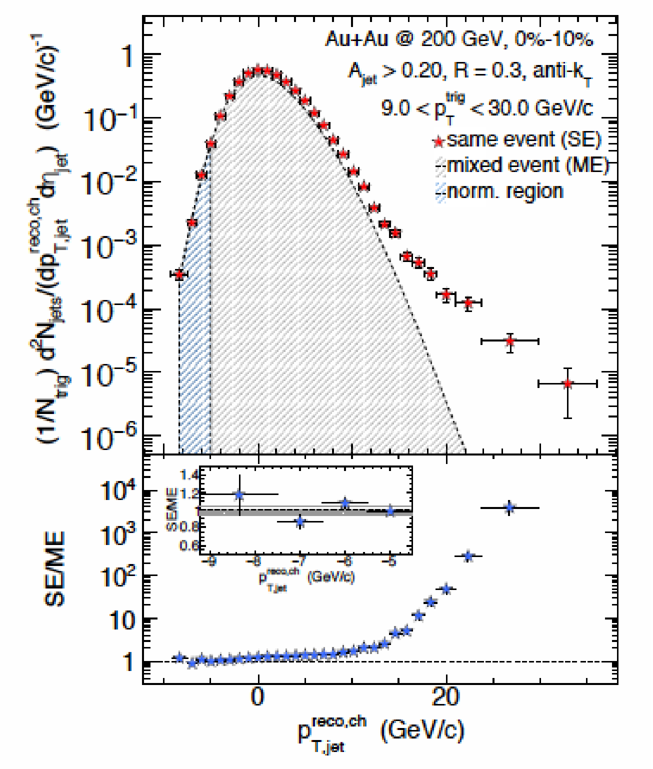
- Suppression of leading hadrons due to E_{loss}
- Enhancement of soft hadrons due to jet-induced medium excitation

Similar effect from low to high p_T^{γ} ?

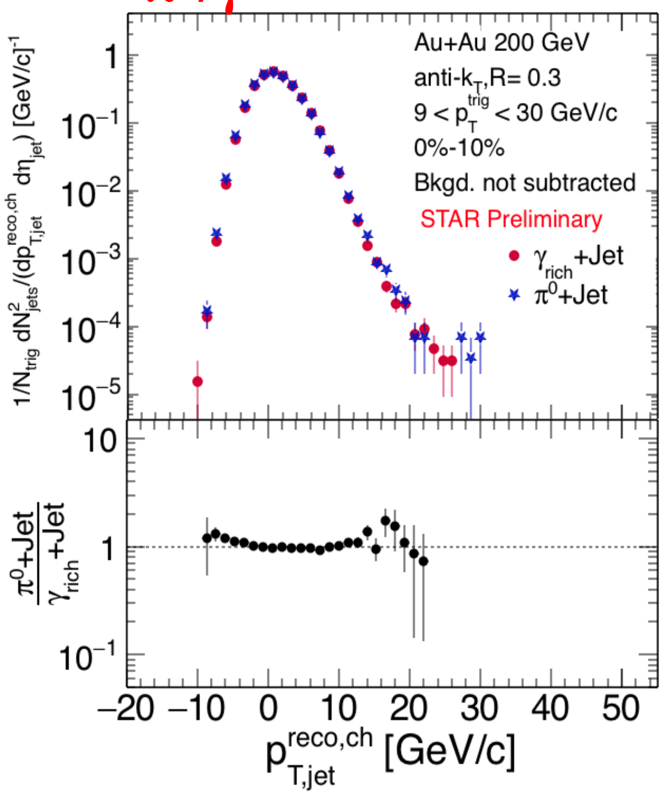
Important for jet tomography!

γ/h-Triggered Recoil Jets in A+A

Hadrons



π^0/γ



Purity of γ_{dir} :

p+p ~**40%**

Au+Au(0-10%) ~**70%**

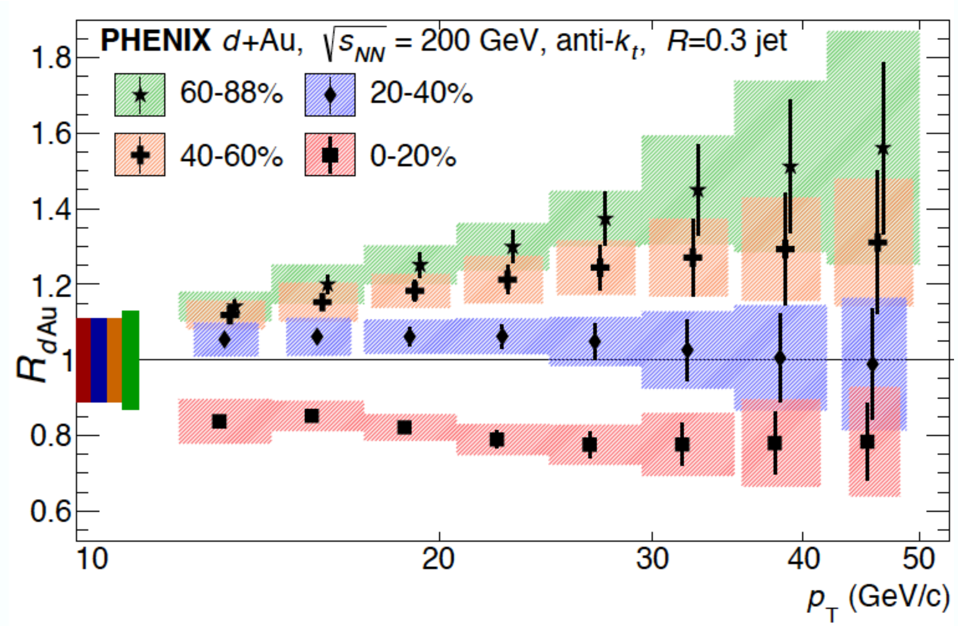
RHIC advantage that → Cross over from **π^0 to γ_{dir} dominated** at high pT

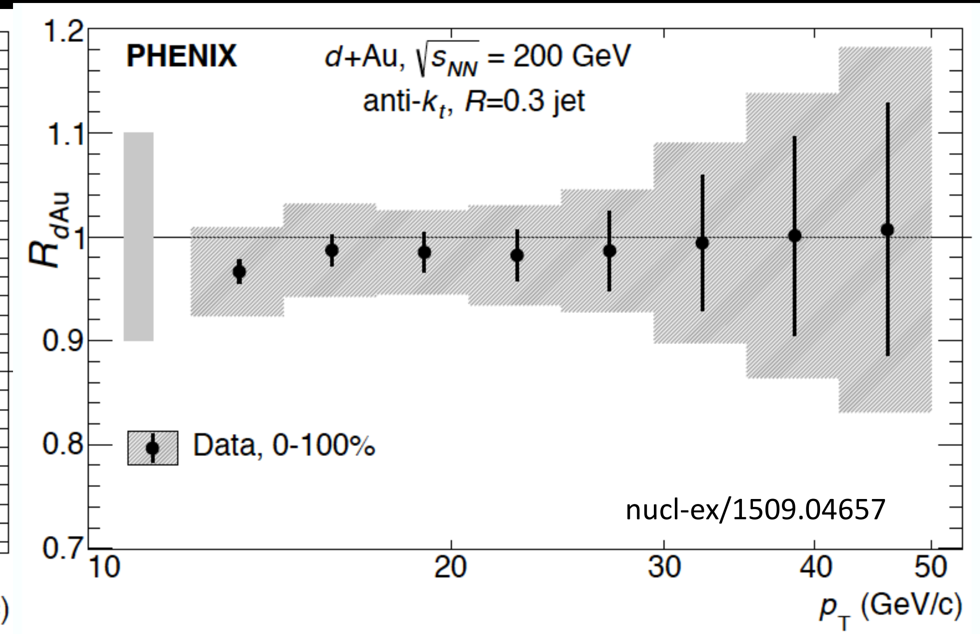
- Not true for LHC

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

- Ideal comparison with the LHC!

Understanding CNM + System Size

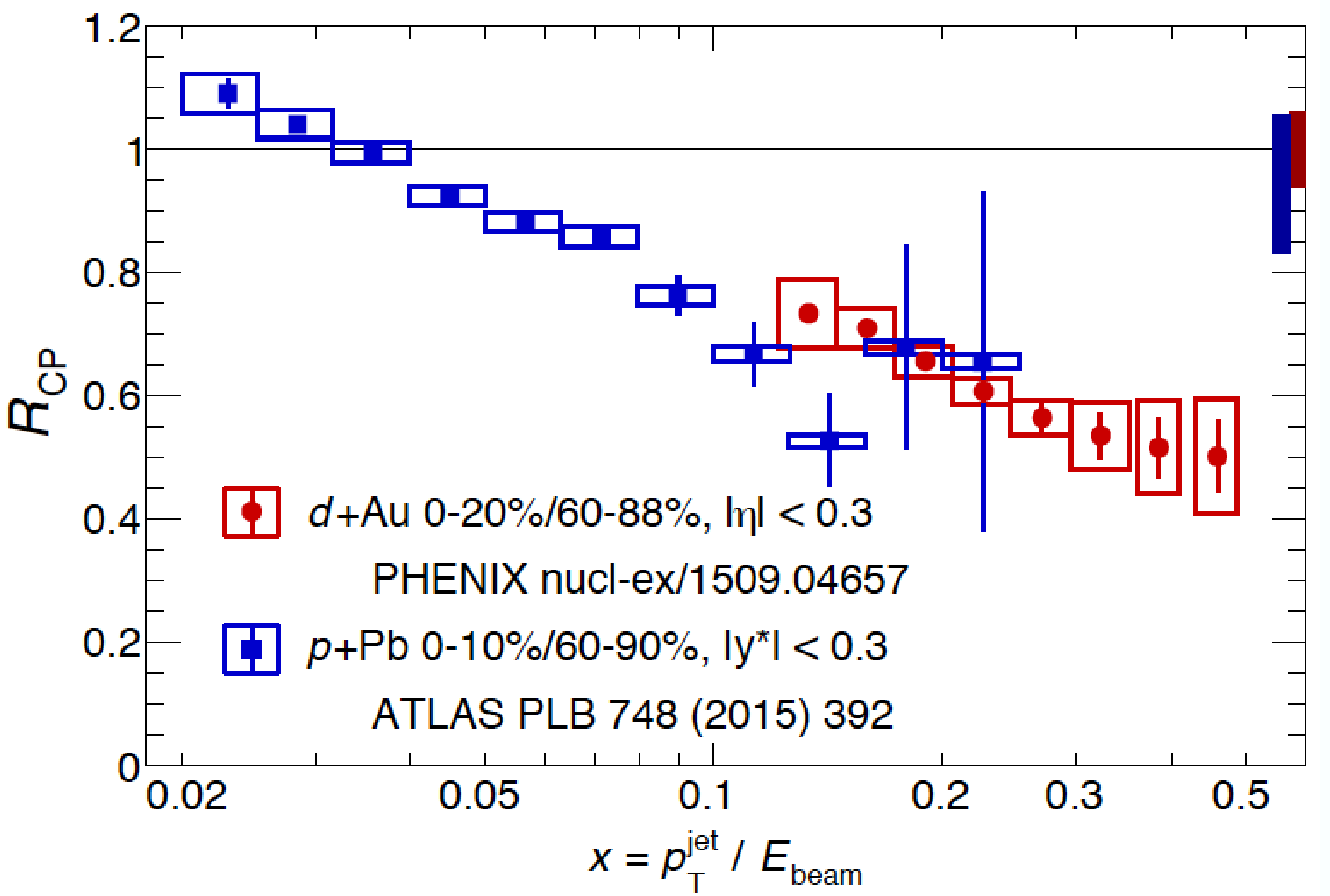




In order to understand AA results, we need to study CNM and system-size effects

- Jet production unmodified in d+Au→ multiplicity in Au going direction is modified in jet events
  - Jet events re-rearranged in centrality → min-bias R_{dAu} = 1 by construction

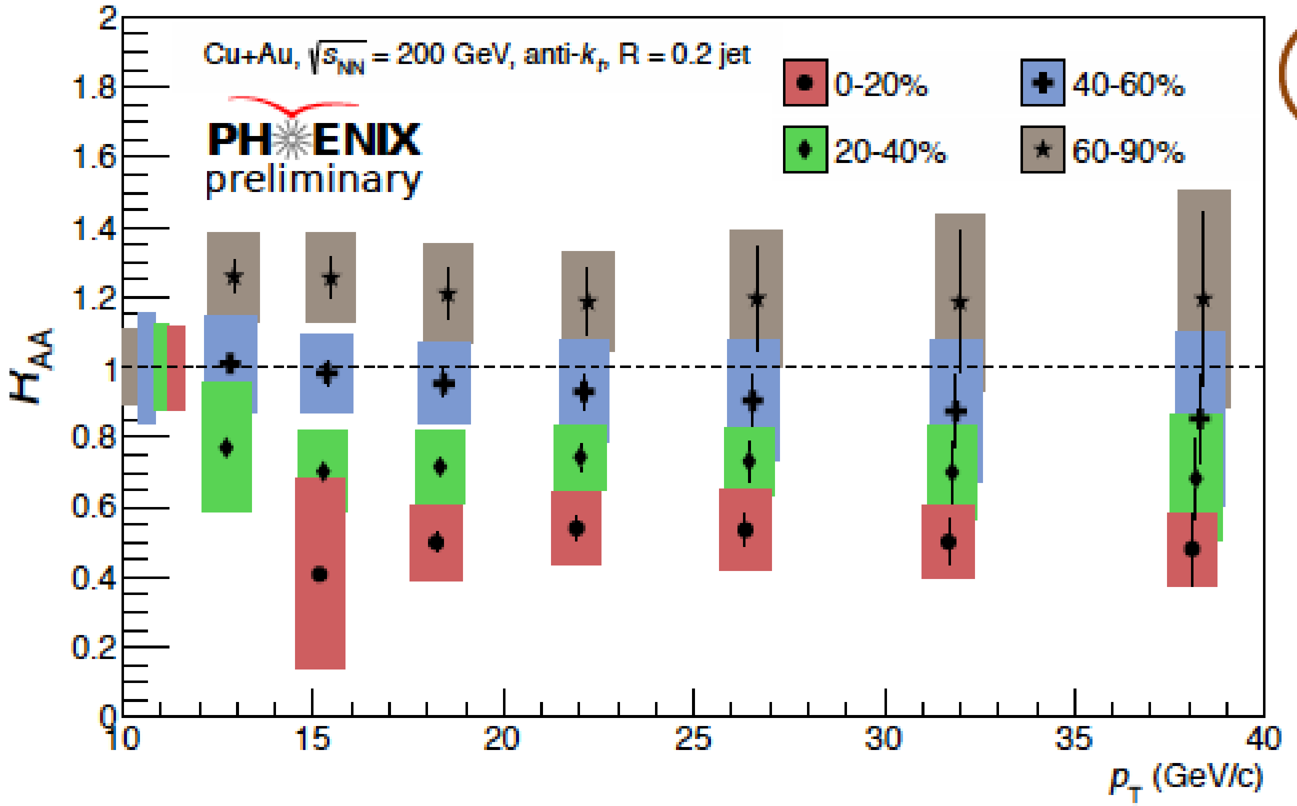
RHIC and LHC Scaling

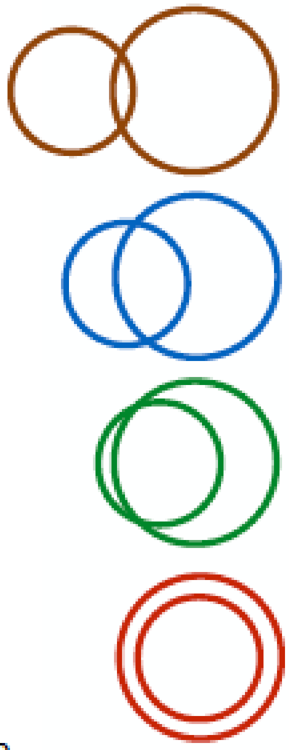


Same (universal) hadron physics at RHIC and the LHC?

Shrinking proton produces less multiplicity?

Nuclear Modification Factor of Jets at RHIC



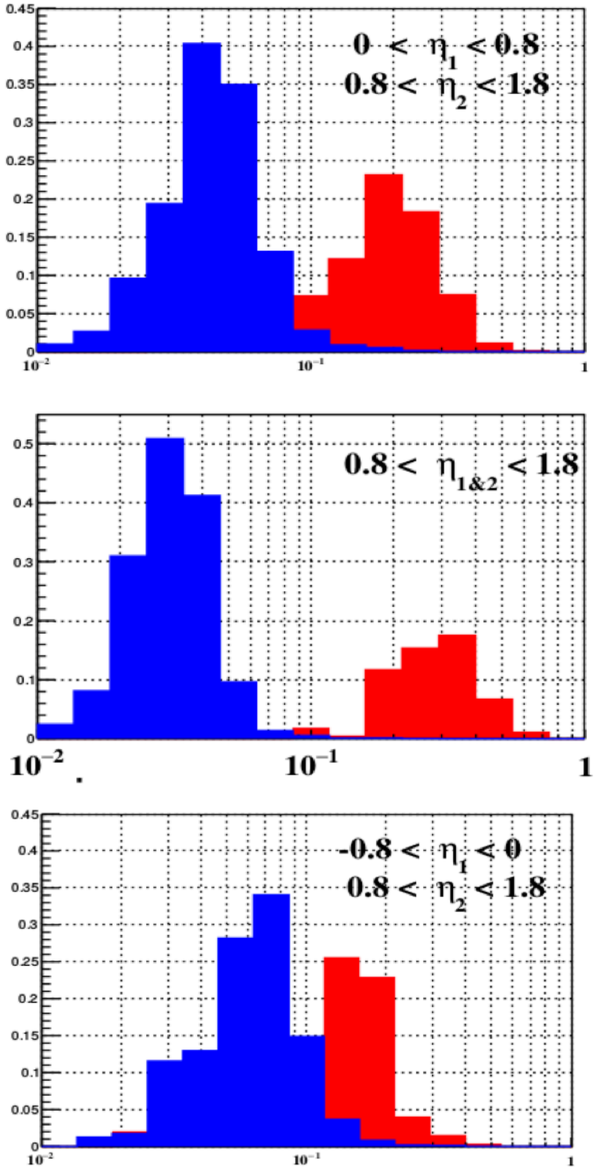


- R_{AA} of jets in HI collisions at 200 GeV → similar magnitude as hadrons

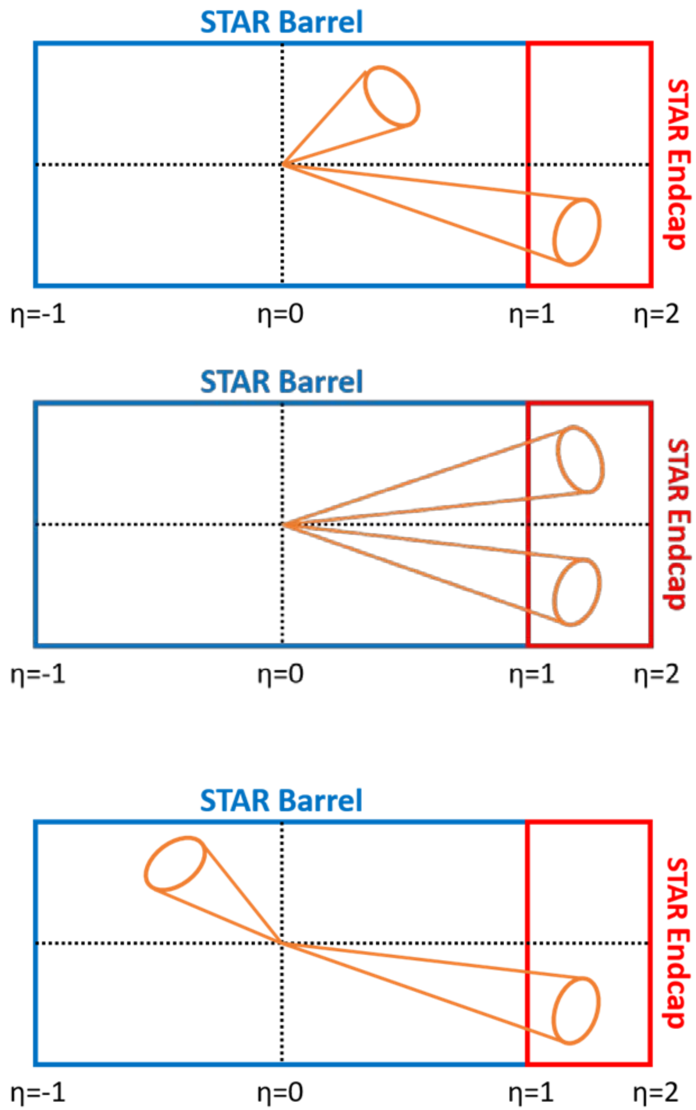
Proton-proton Jets at RHIC

- RHIC is the only polarized collider in the world!
- Used to study the spin structure of the proton
  - We want to understand the contributions due to:
    - Valence Quarks
    - Sea Quarks and Gluons
  - Use jets (and dijets)
- Techniques for UE removal developed at the LHC also used in the RHIC spin program

Forward Di-jet Topologies @ 200 GeV

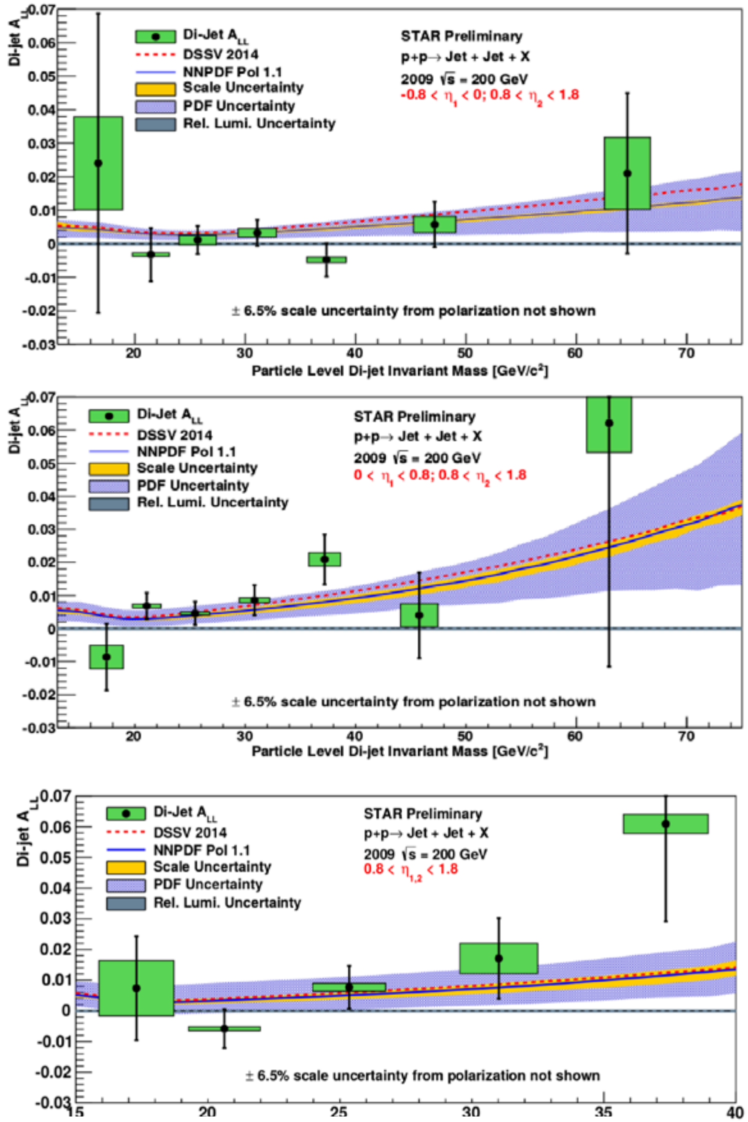


X (p_{parton}/p_{proton})



- STAR Endcap → new di-jet topologies
- Forward jets probe lower values of X

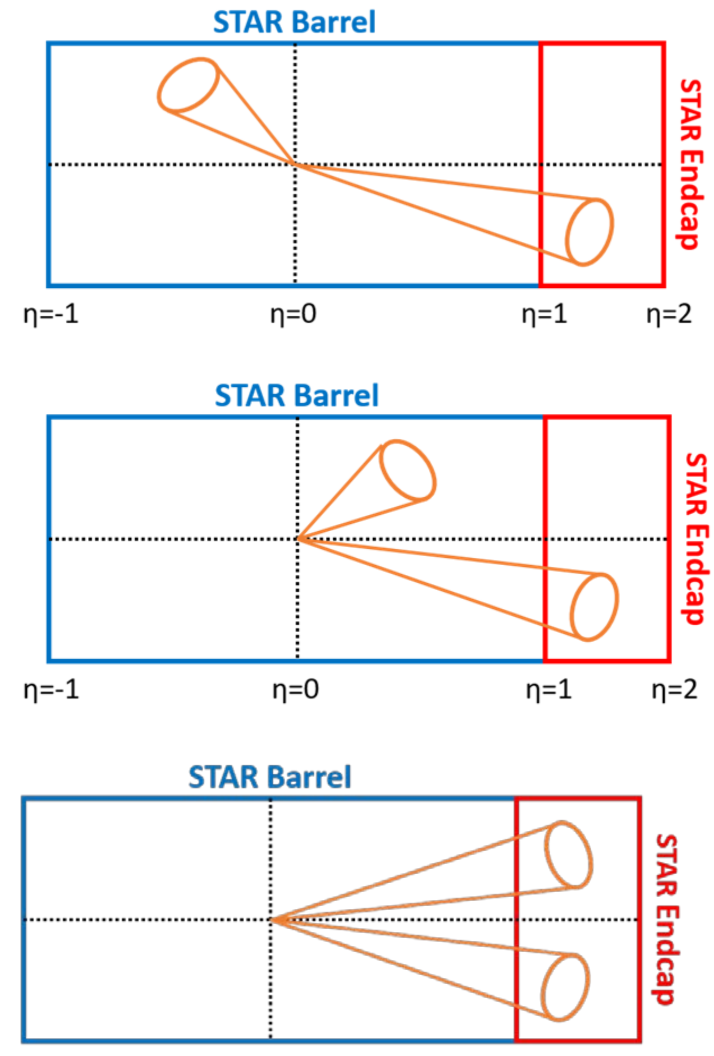
Forward Di-jet A_{LL}



Dijet mass

Small x

Large x



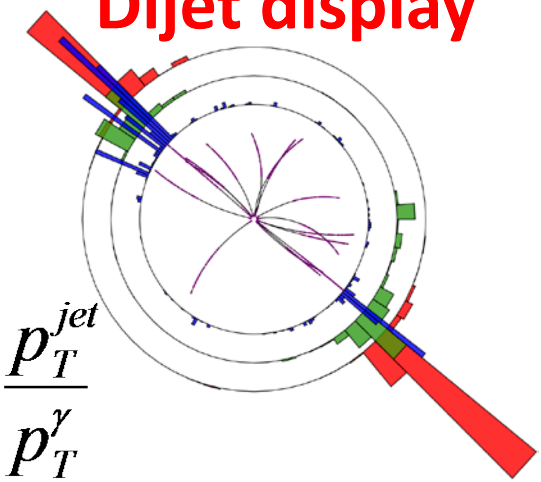
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{a,b,c} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \cdot \hat{a}_{LL}^{f_a f_b \to f_c X} \otimes D_{f_c}^h}{\sum_{a,b,c} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \otimes D_{f_c}^h}$$

Future Detectors → sPHENIX

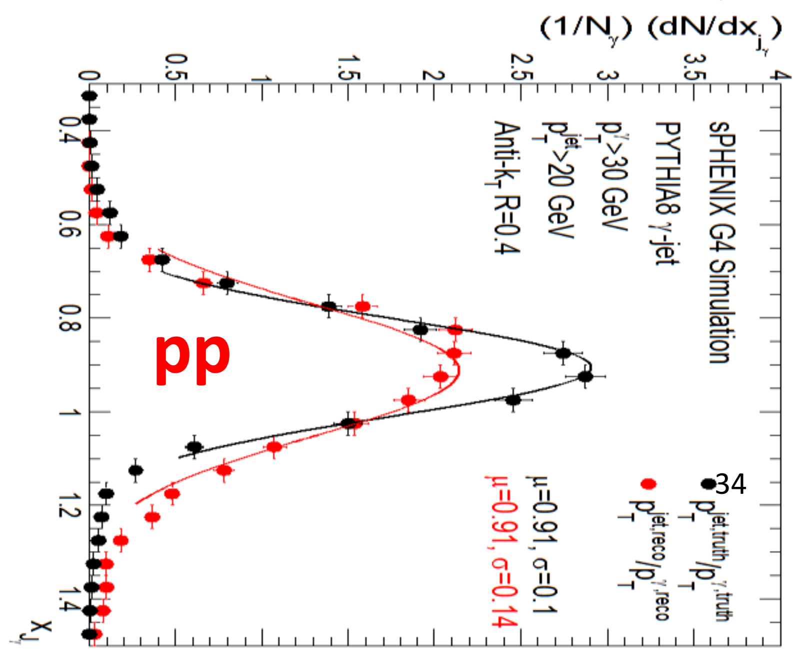
Planned operation - Minimum bias Au+Au at 15 kHz for |z| < 10 cm: 47 billion (2022) + 96 billion (2024) + 96 billion (2026) = **Total 239 billion events**

- sPHENIX received CD0, preparing for CD1 review
- Prototype testing validates simulated results
- HCal+EMCal → Hermetic Jet Energy
- Tracking → HF jets!

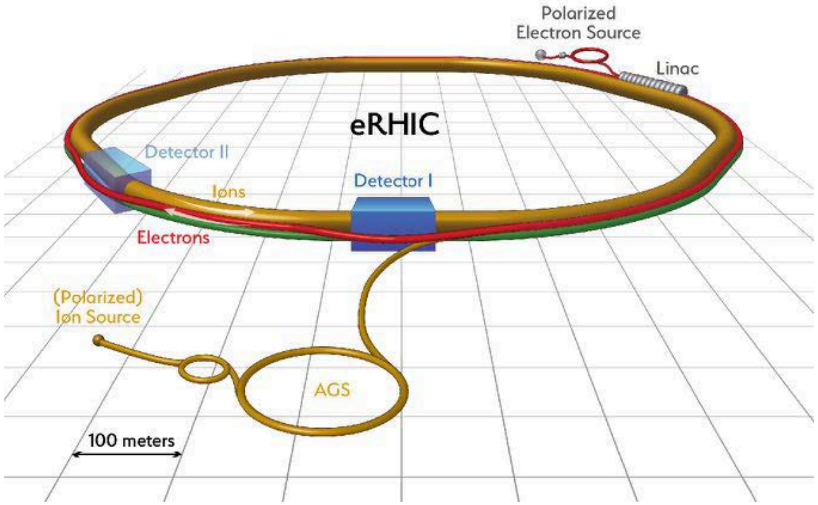
Dijet display



$$X_{J\gamma} = \frac{p_T^{jet}}{p_T^{\gamma}}$$



Electron-Ion Collider



- EIC → Understanding the glue that binds us all
  - Precision understanding of QCD
- Bring the HI and Spin jet communities together to face the new challenges in QCD physics

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 (RAA, IAA, fragmentation function

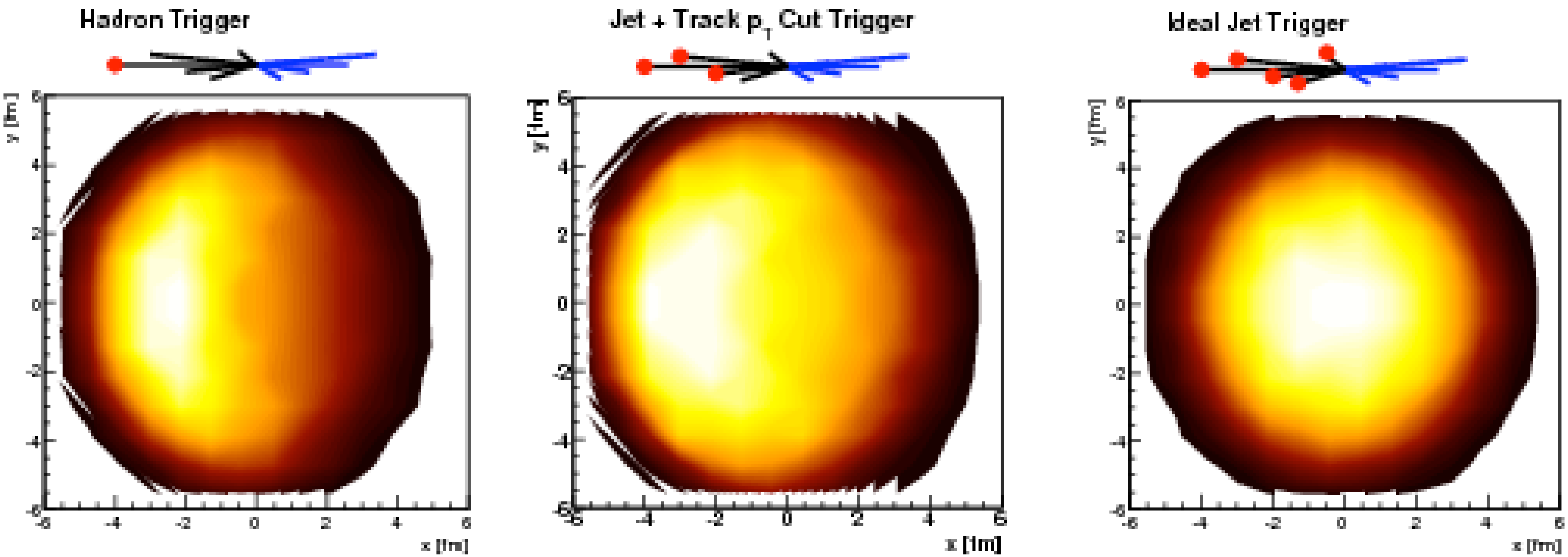
We should use γ-jet observables to compare across energies and experiments

- This is the path forward to precision heavy-ion collisions
- Theory input into most differential observables is important
  - JETSCAPE
- Spin and HI jet communities are complementary → Need to understand pp jets → Face the same challenges!

RHIC and LHC are complementary → need both for understanding!

For further discussion, see arxiv:1705.01974

Back-Up



Renk
arXiv:1210.1330v1

- d

Jet-to-Z boson p_T Balance

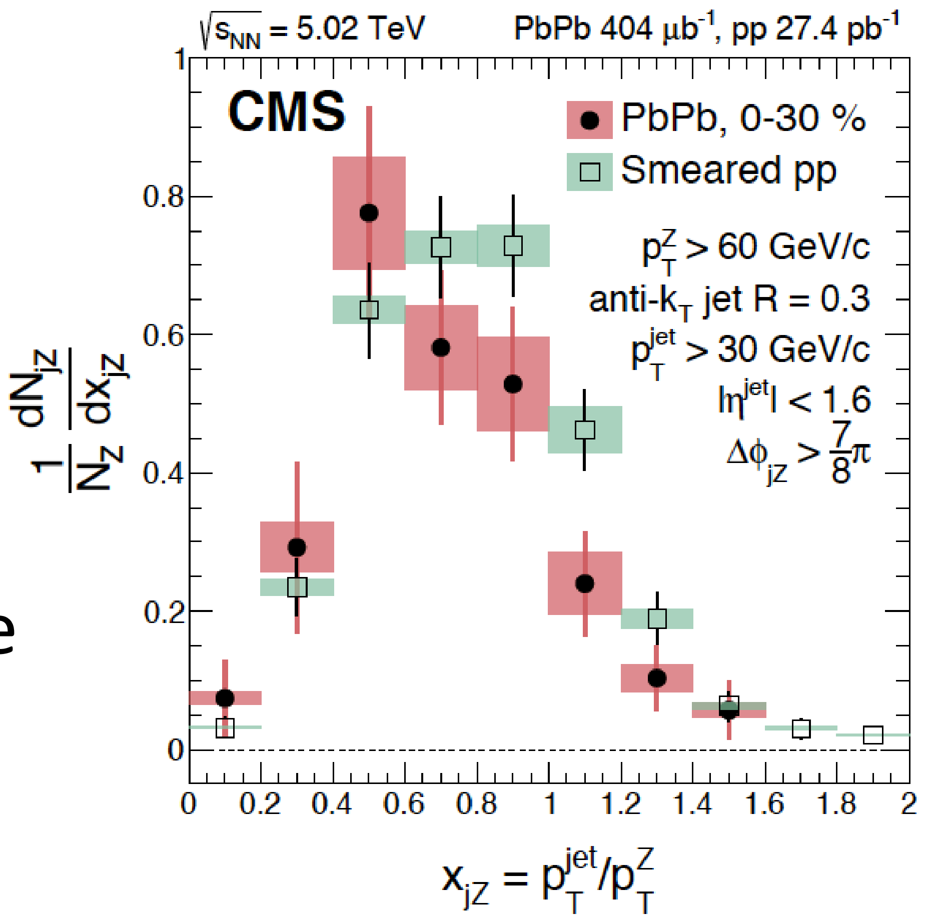
Repeated with Z bosons!

- Similar interpretation
- Very little background for finding the Z unlike for γ

Boson-jet observables advantages:

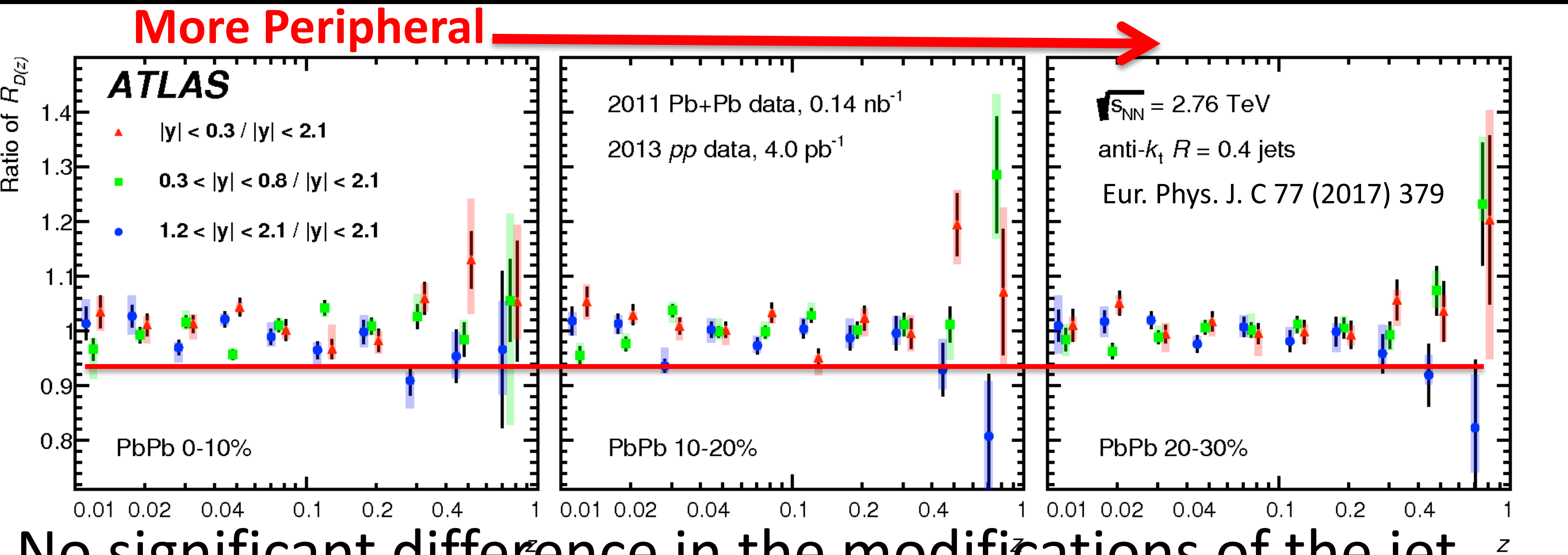
- RHIC/LHC comparisons are closer to apples-to-apples

Arxiv:1702.01060



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

Jet Structure modification



No significant difference in the modifications of the jet structure are observed

- As a function of rapidity
  - From $100 < p_{T,jet} < 398$ GeV
  - Except at high z → hint of reduction of the enhancement for more forward jets is observed

Jets are modified, but that modification is relatively similar?

Pushing to Lower X: Higher Energy

$$x_1 = \frac{1}{\sqrt{s}}\left(p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4}\right)$$

$$x_2 = \frac{1}{\sqrt{s}}\left(p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4}\right)$$

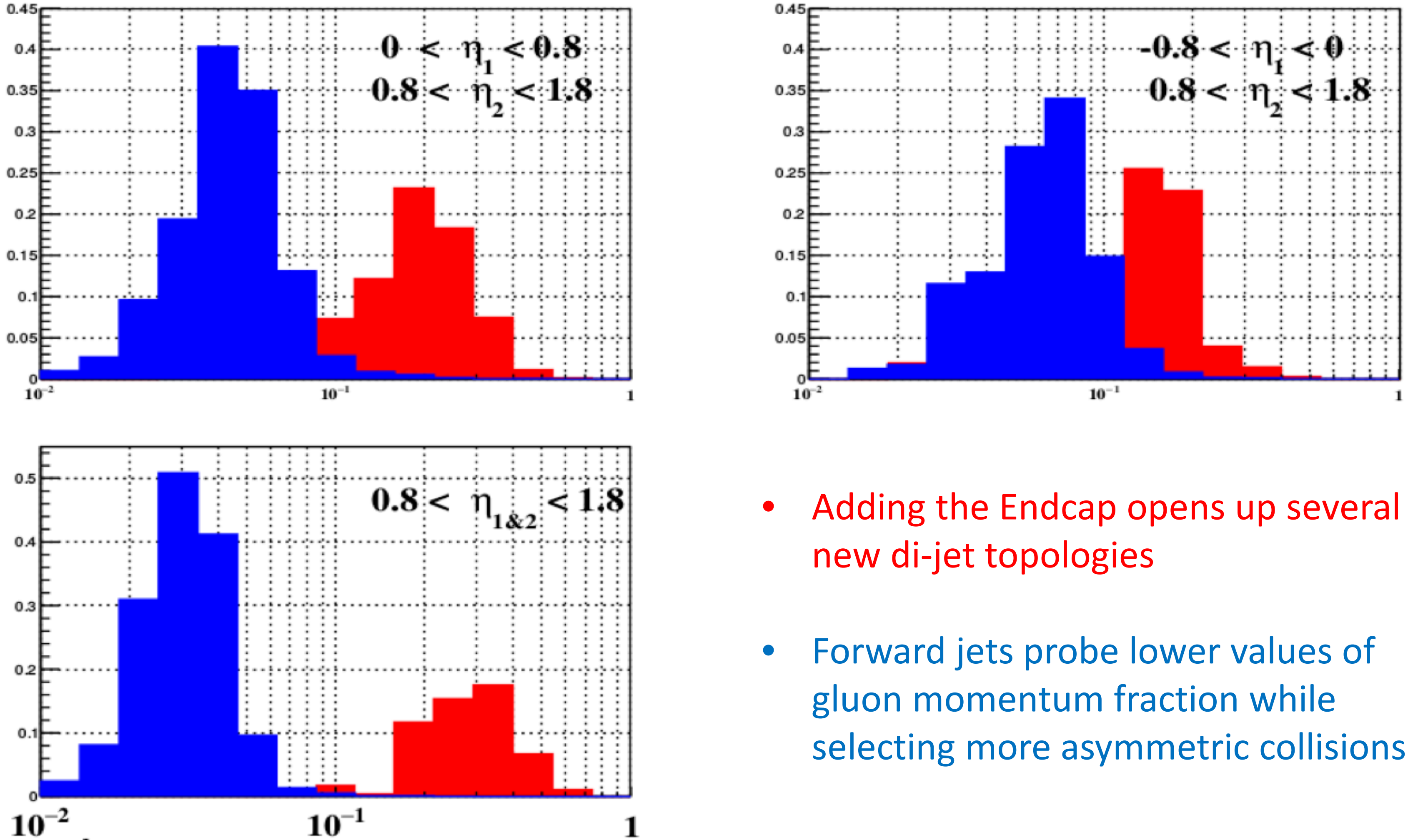
$$M = \sqrt{x_1 x_2 s}$$

$$\eta_3 + \eta_4 = \ln\frac{x_1}{x_2}$$

$$\left|\cos\theta^*\right| = \tanh\left|\frac{\eta_3 - \eta_4}{2}\right|$$

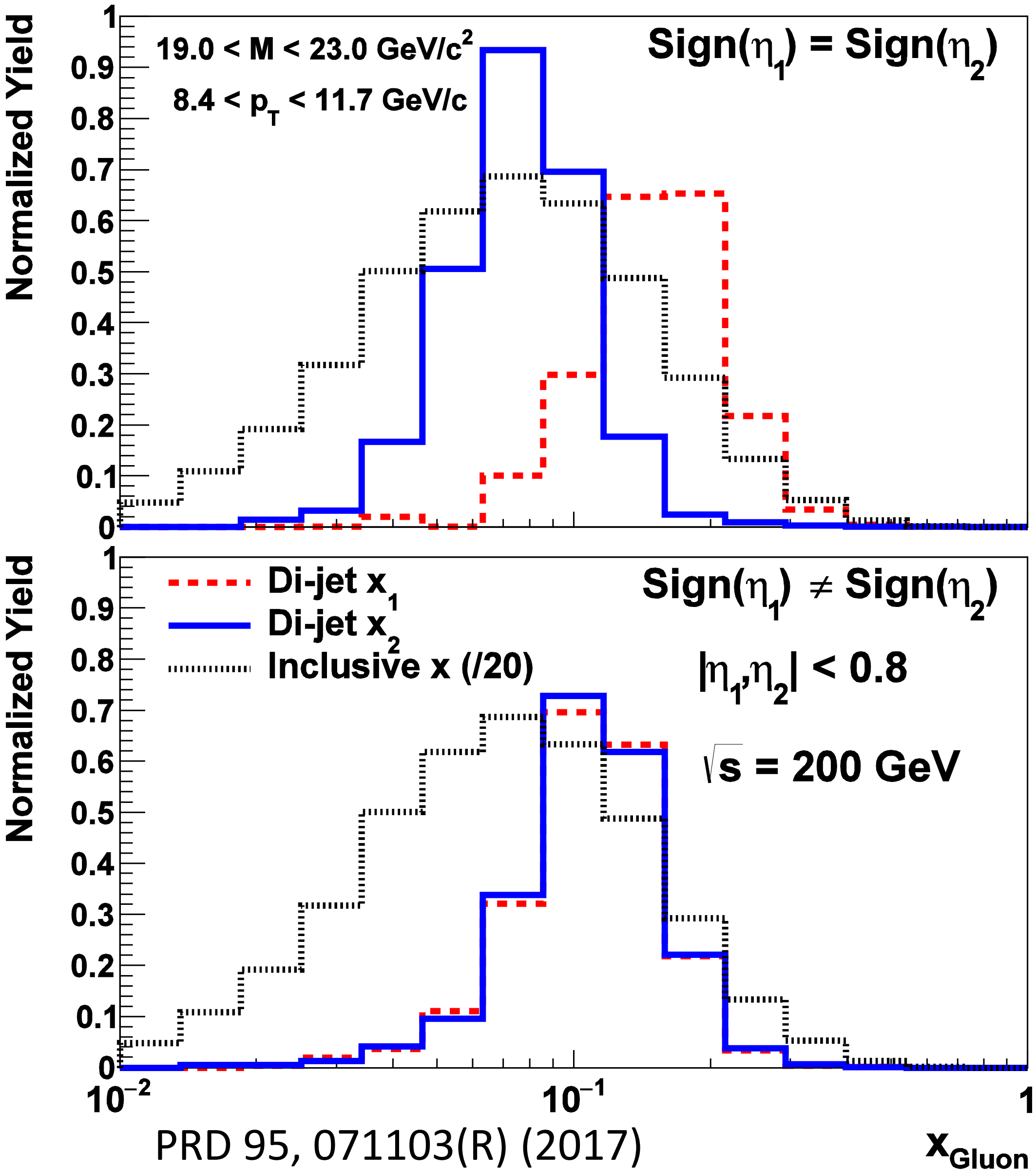
- RHIC has placed strong constraints on ΔG in the range x > 0.05 but lower x regions are relatively unexplored
- There are two knobs to turn which can provide access to lower x: higher energies and forward rapidities
- Can see that moving to higher center of mass energies will push down to lower x values

Forward Di-jet Topologies @ 200 GeV



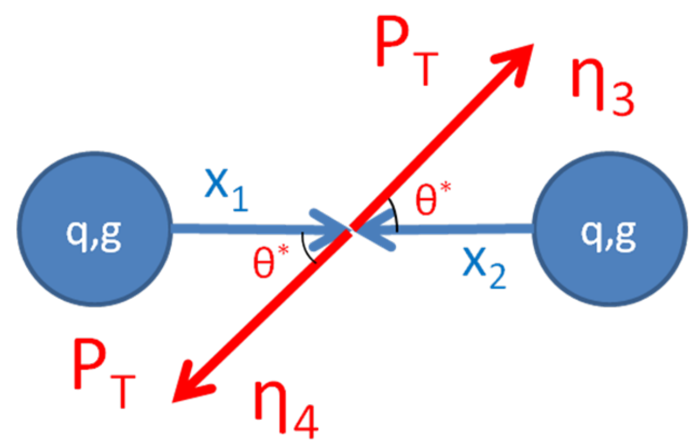
- Adding the Endcap opens up several new di-jet topologies
- Forward jets probe lower values of gluon momentum fraction while selecting more asymmetric collisions

Correlation Measurements

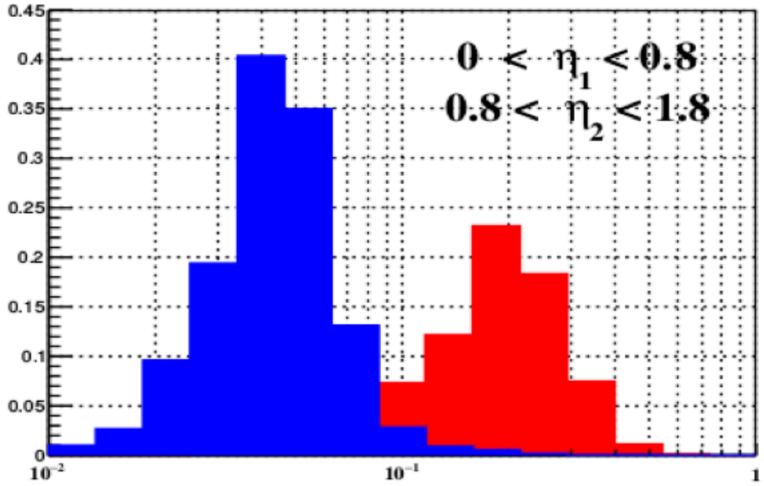


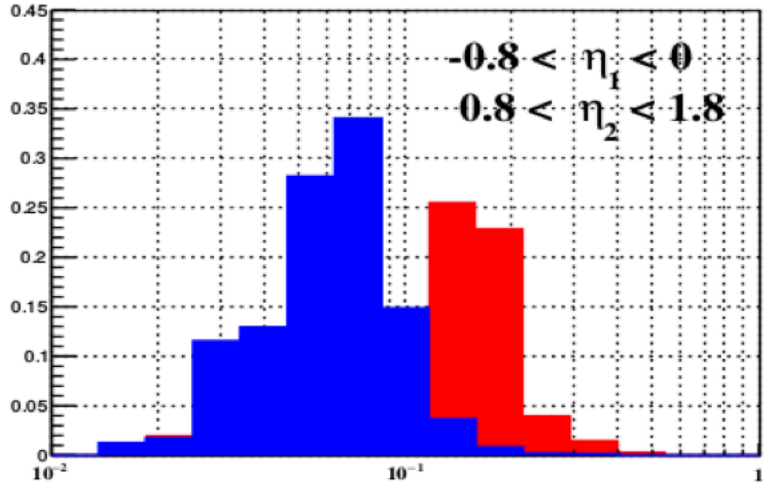
PRD 95, 071103(R) (2017)

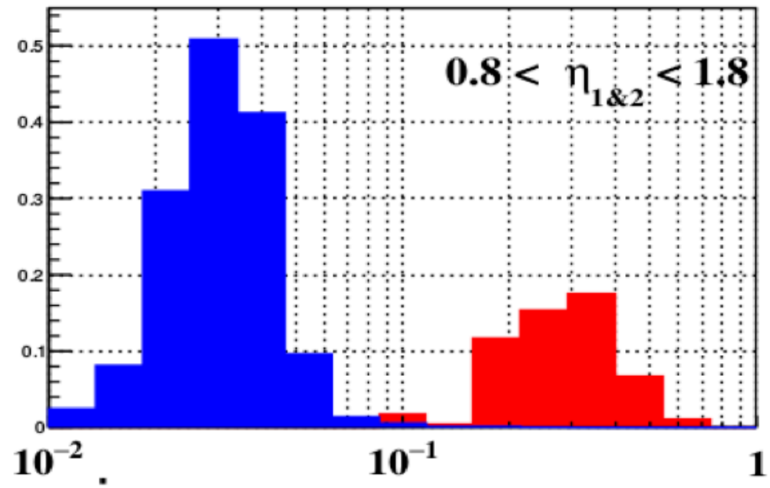
- Correlation measurements capture more information about the hard scattering
- Di-jet measurements provide better resolution on the gluon momentum fraction



Forward Di-jet Topologies @ 200 GeV







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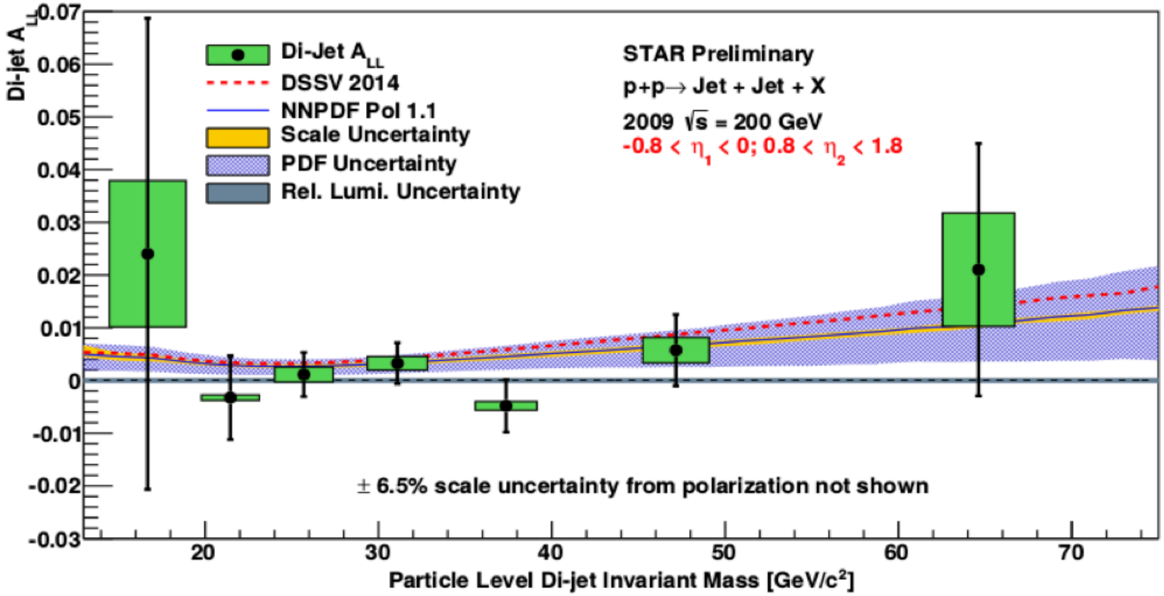
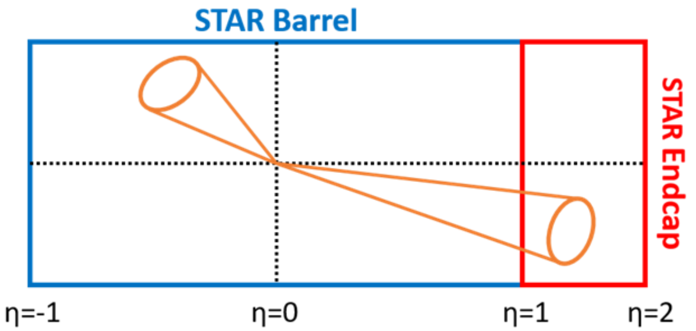
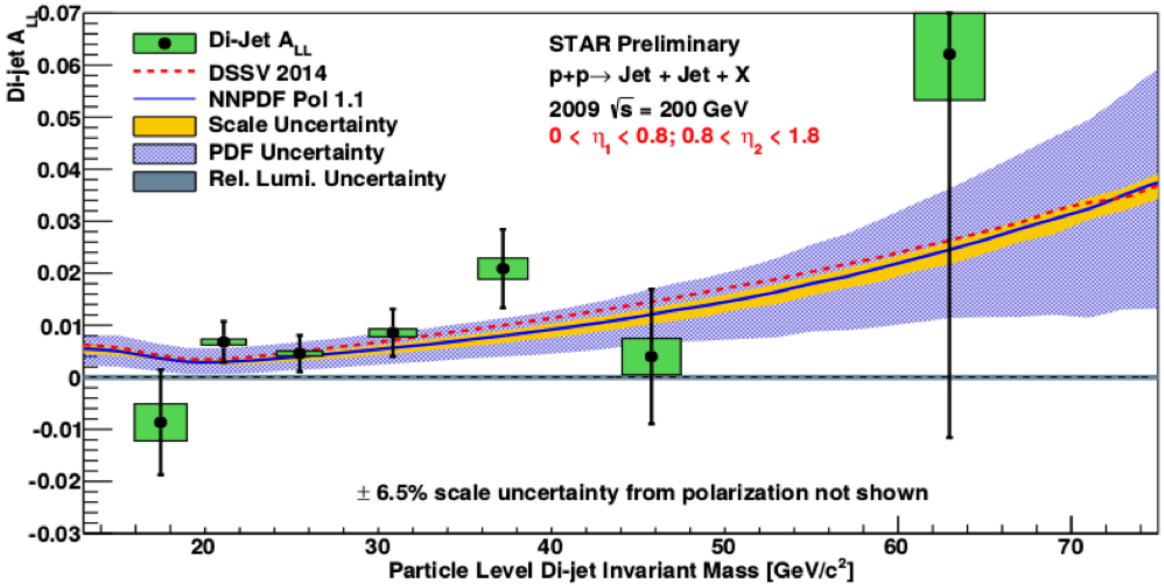
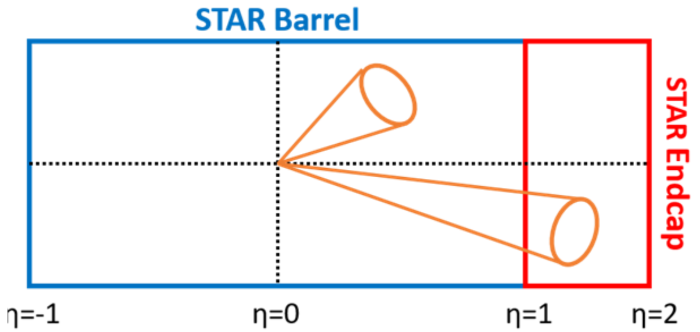
Forward Di-jet A_{LL}

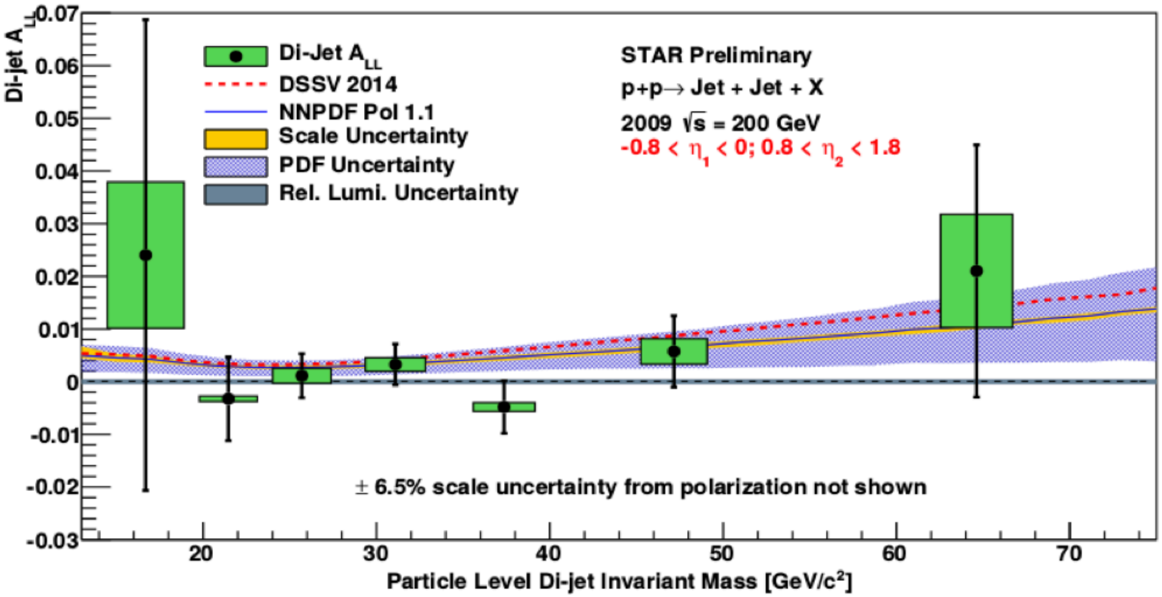


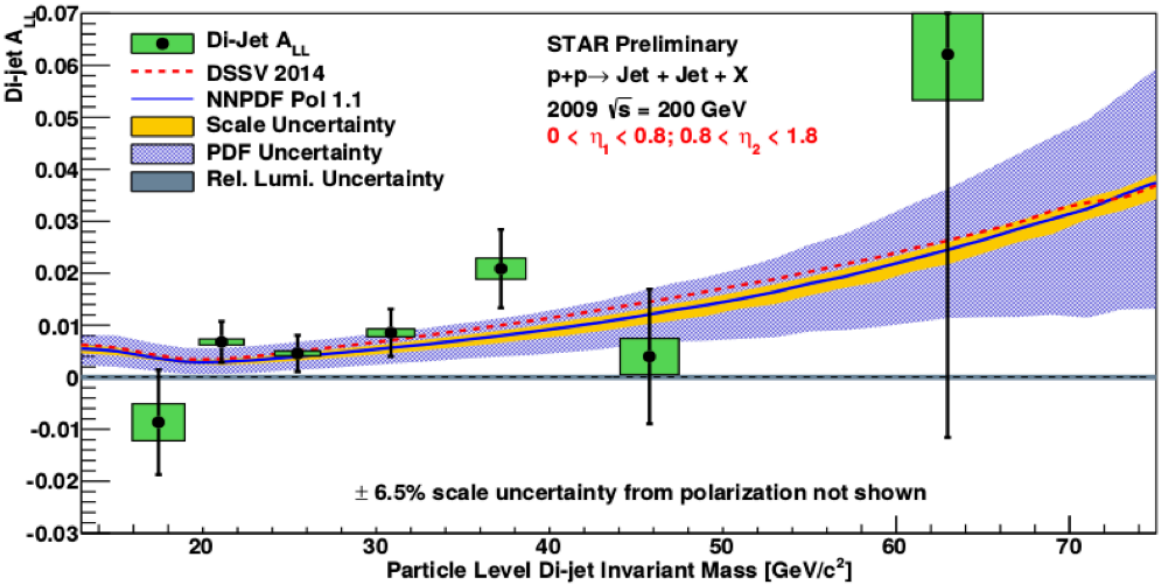






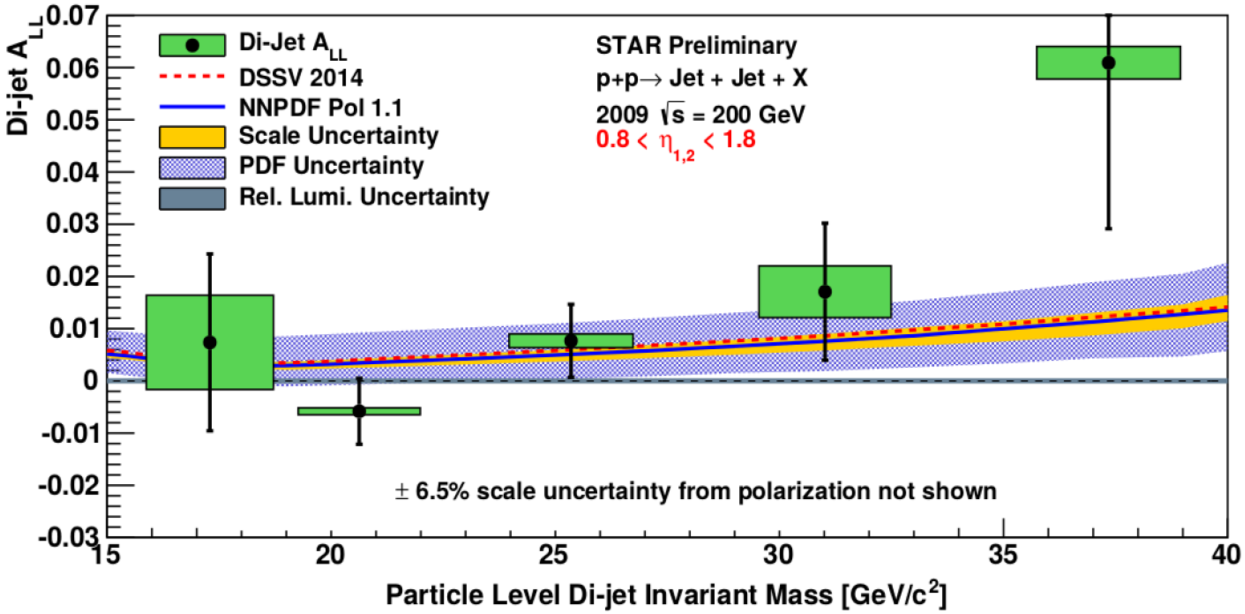
Forward Di-jet A_{LL}





- Di-jet A_{LL} shown for two Barrel-Endcap topologies
- These forward di-jets will access gluons with lower momentum fraction than mid-rapidity results
- Results compared to DSSV14 and NNPDFpol1.1 expectations
- Systematic uncertainties will shrink in final result

Forward Di-jet A_{LL}



- Di-jet events with both jets in the Endcap probe the lowest gluon momentum fractions
- The cross section drops for forward jets making this measurement statistically challenging