Jet Spectra in pp, pA, and AA Collisions

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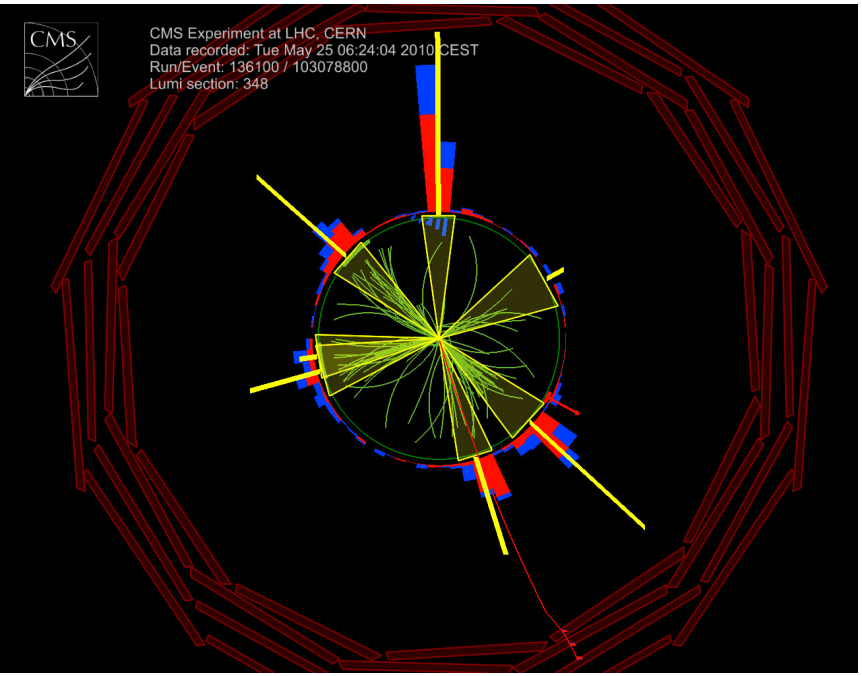
University of Illinois at Chicago

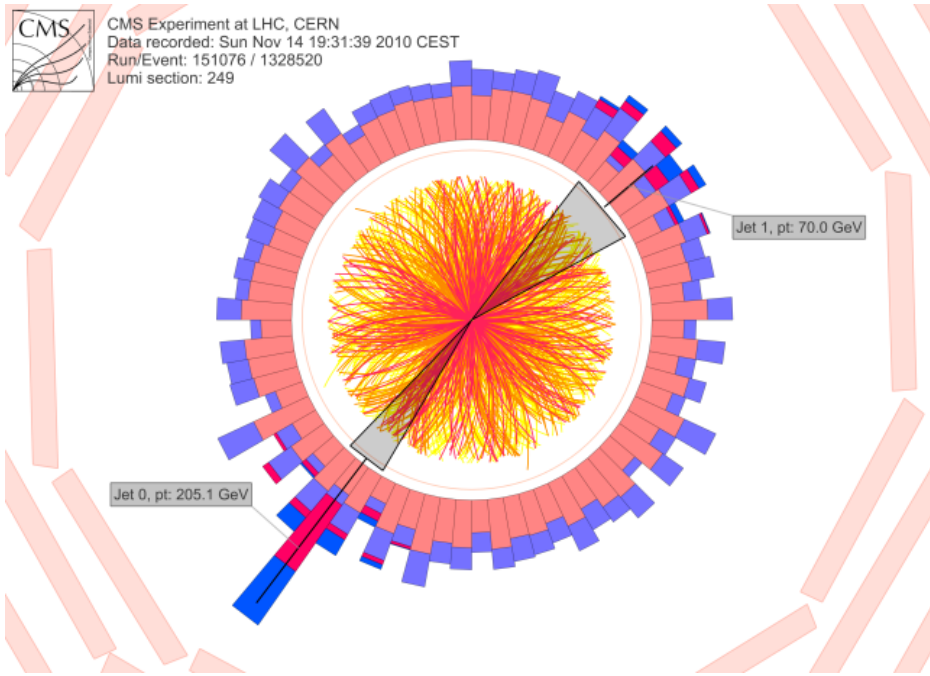
Sept. 26, 2016

Little Bangs, Both Big and Small

7 TeV pp Multijet Event



2.76 TeV PbPb Dijet Event

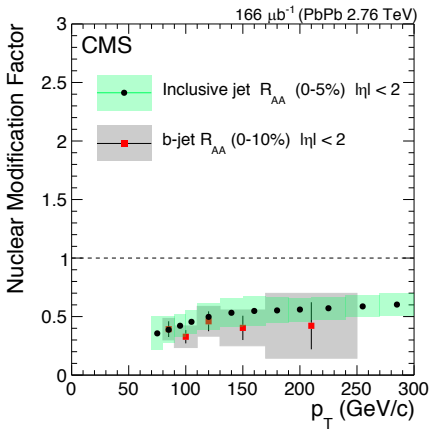


Jets provide direct access to parton kinematics BUT:

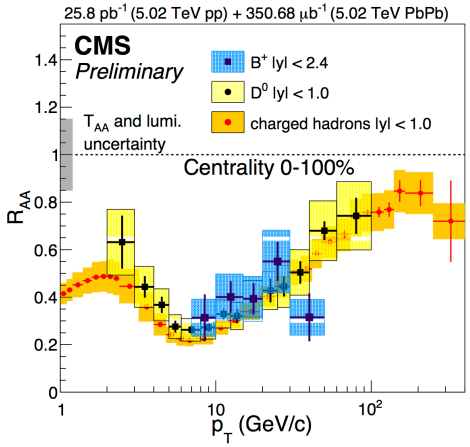
- Generally clearer connections than PbPb
- Multiparton interactions (MPI) smear quark-jet connections
- Full jet evolution still not totally understood
- Jet-Medium interactions obfuscate jet-quark connections
- Large (and flowing!) underlying event

Some Thoughts on **Jets in Pb+Pb**

- The Jet R_{AA} does not seem to depend on:
  - Jet cone size (or even e.g. full jet vs charged jet)
  - Jet flavor (b / c(?) / light), at high-p_T
  - Jet pseudorapidity
  - (Large) Collision species, e.g. Cu+Au & Pb+Pb
  - Depends weakly on jet p_T

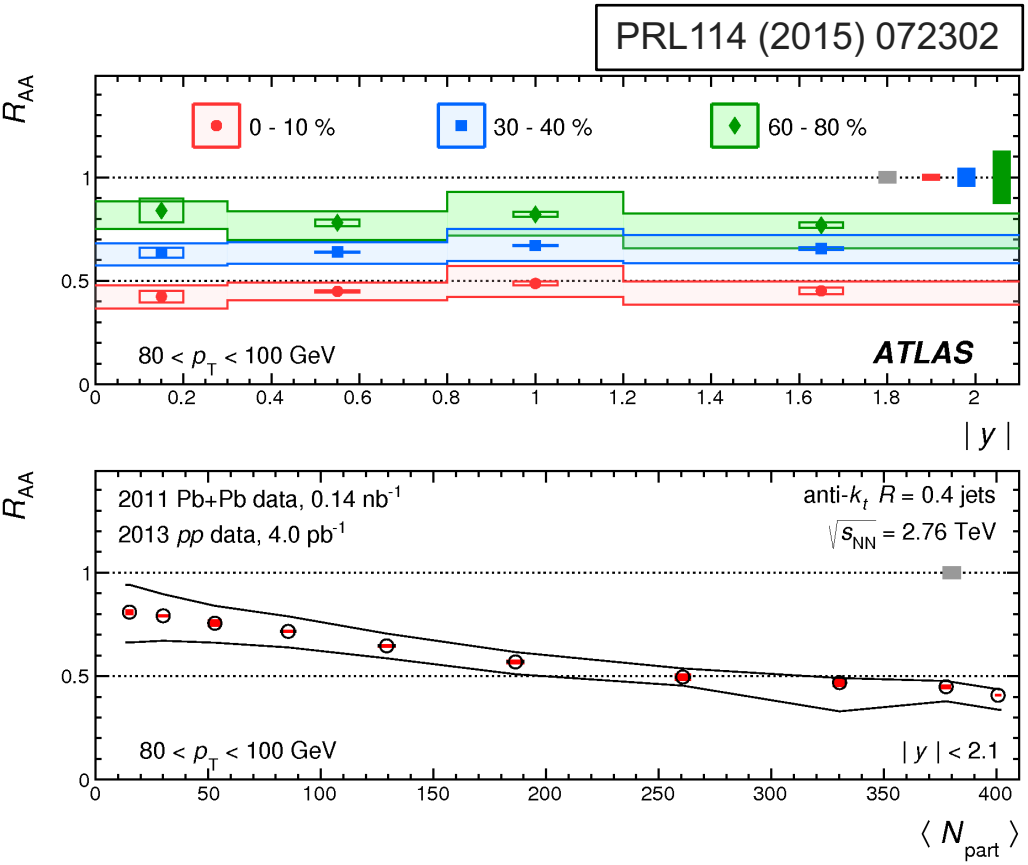


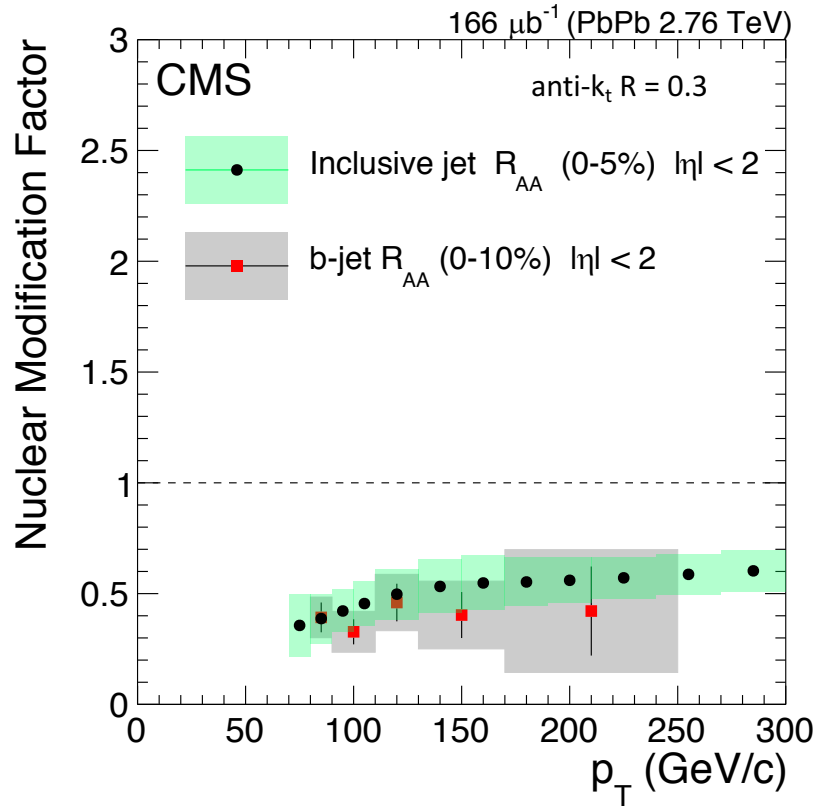
- Is there a tension in the Meson <-> jet correspondence?
  - Meson R_{AA} seems to trend quickly toward unity
  - Jet R_{AA} asymptotes toward unity eventually??



- Large cones (R > 1) needed to recover the jet energy

Inclusive Jets in PbPb Collisions, so far…

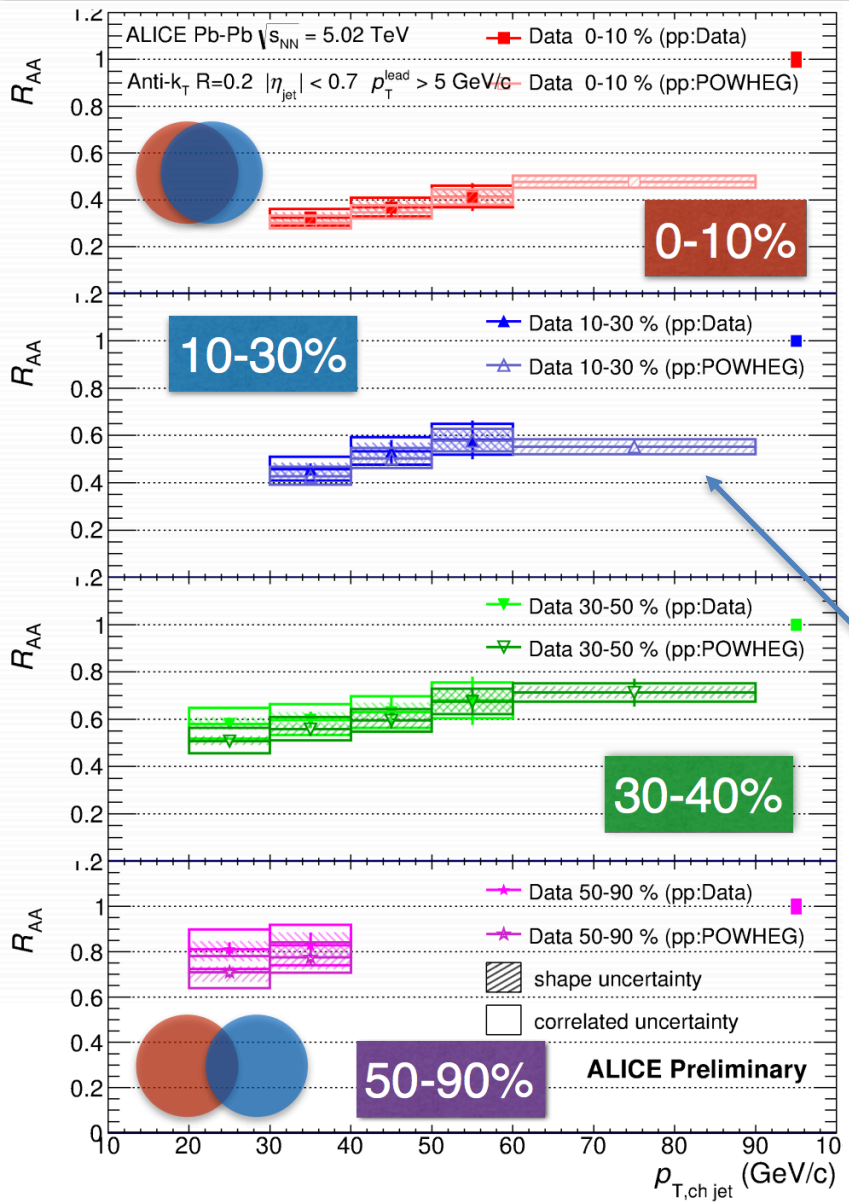


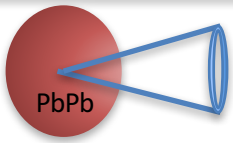


arXiv: 1312.4198, 1609.05383

- Jets are quenched – even out to very large p_T
  - Suppression independent of rapidity and flavor

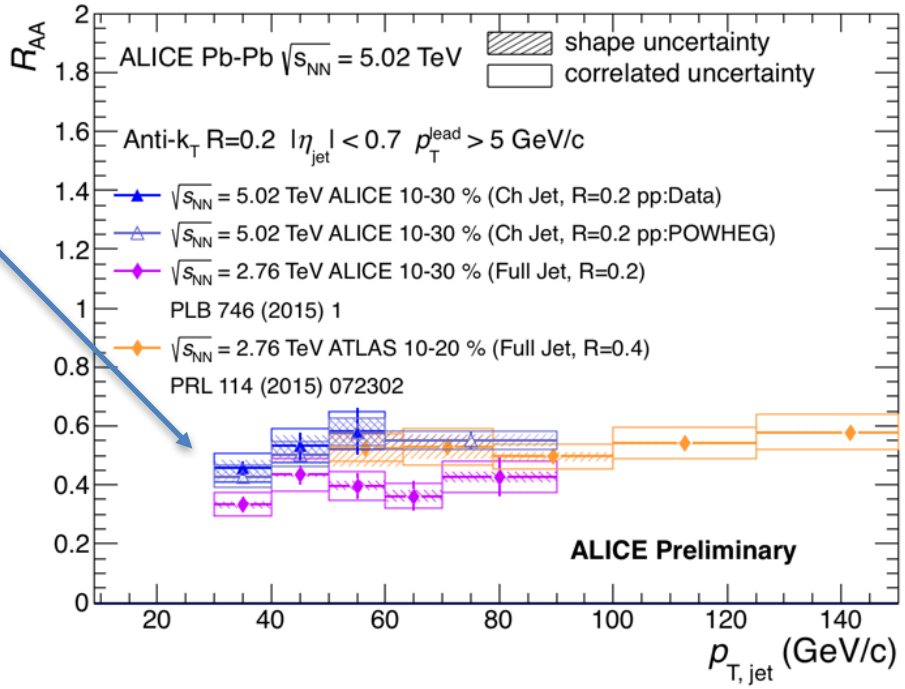
5 TeV Jet R_{AA}





See talk by: Hiroki Yokoyama (Sat. AM)

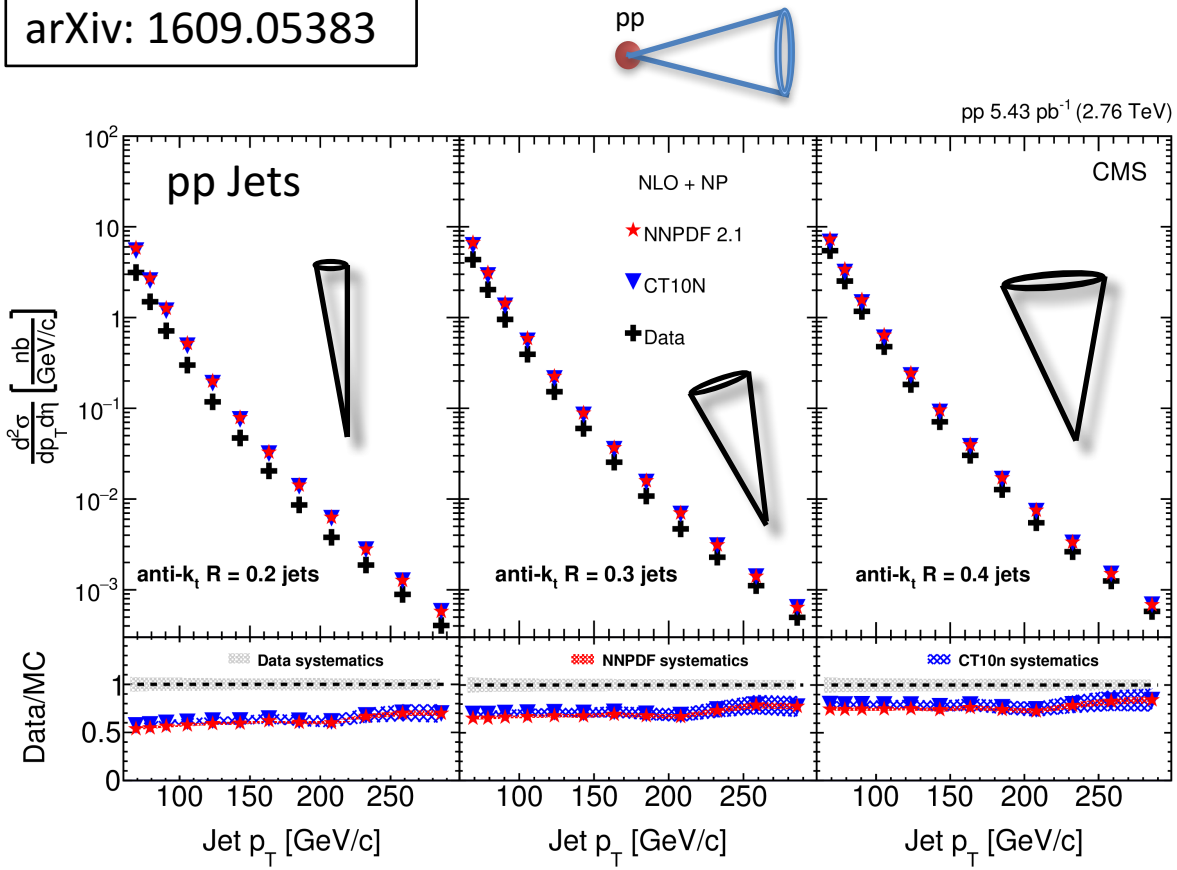
- Finally a true pp reference
- Interplay between full jet, charged jet and cone size seen via comparisons to ATLAS



Jet radius dependence of R_{AA}

arXiv: 1609.05383

See poster by: Raghav Elayavalli



- Dependence on jet radius parameter is negligible
  - Cone-size dependence useful to test both vacuum QCD fragmentation expectations and quenching
  - Quenching affects R=0.2->0.4 similarly
  - Large cone sizes >1.4 needed to fully recover energy (seen in jet-track corr.)

Jet radius dependence of R_{AA}

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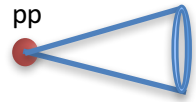

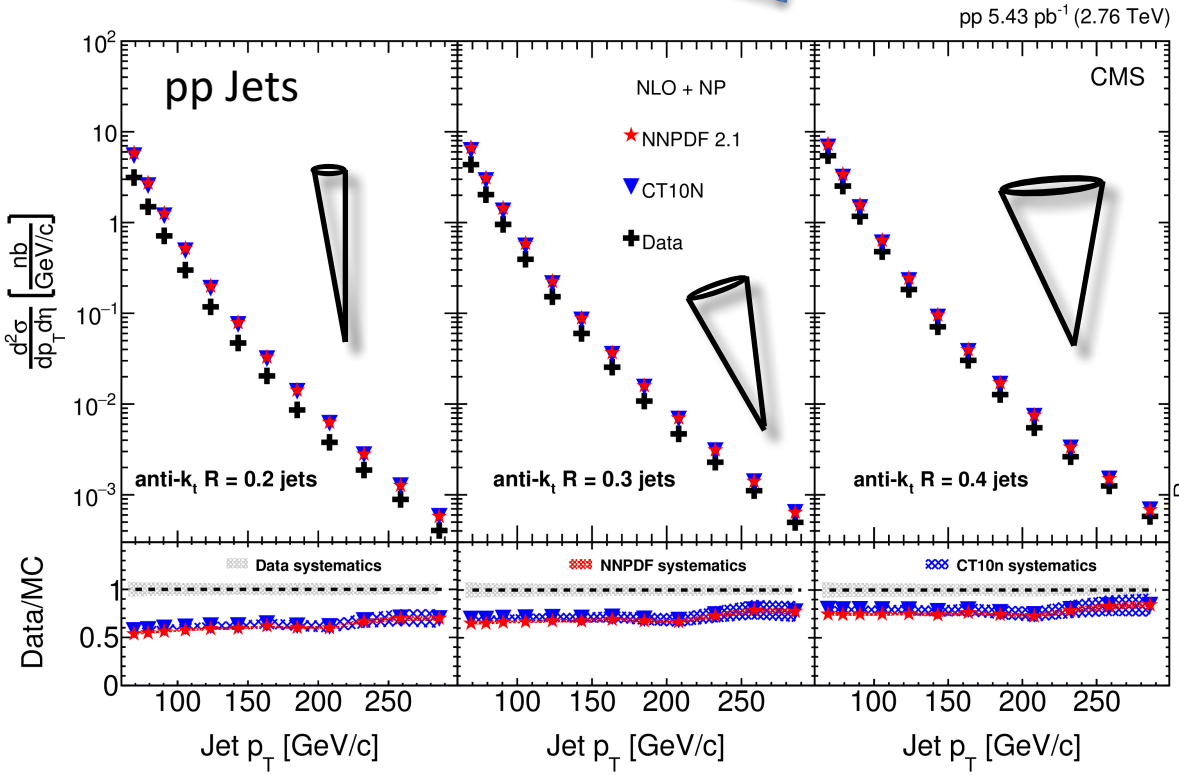

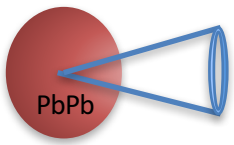

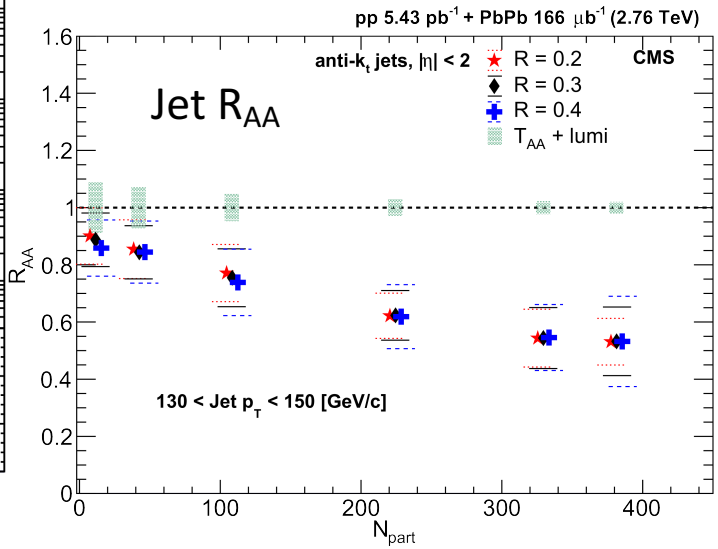

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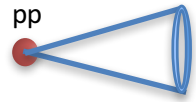

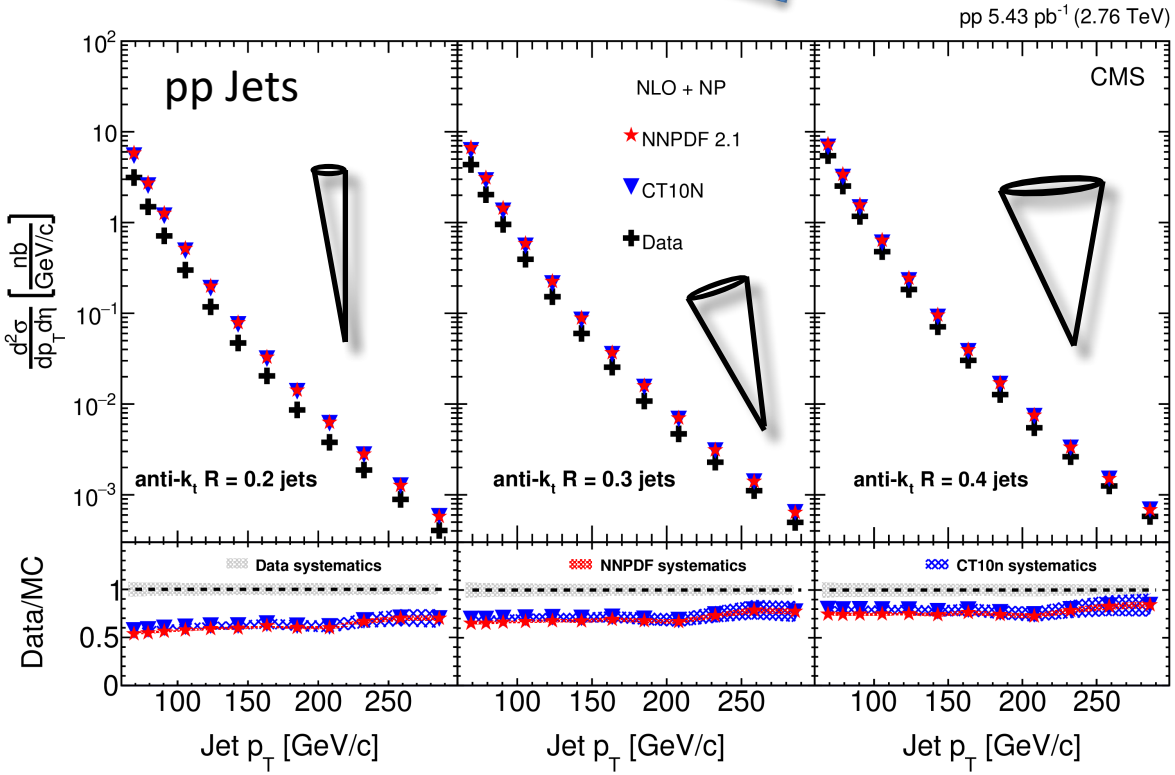

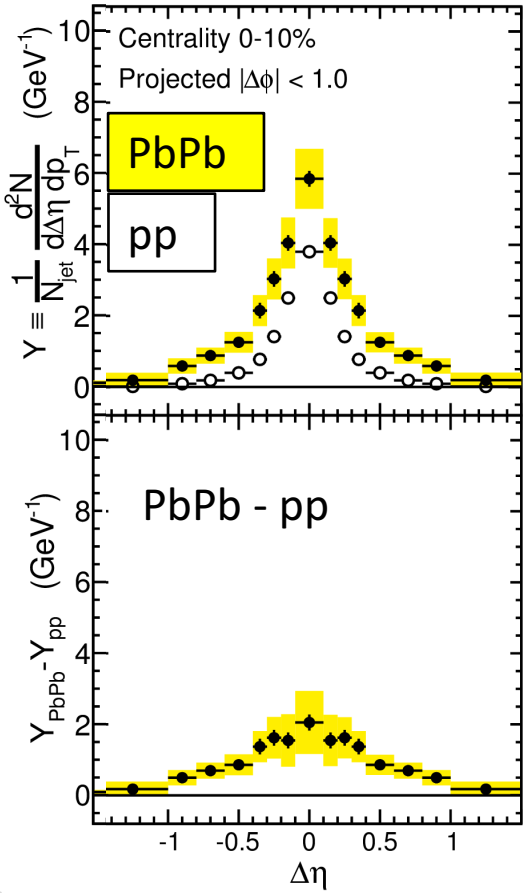

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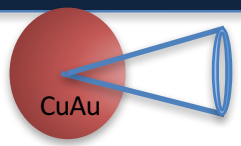
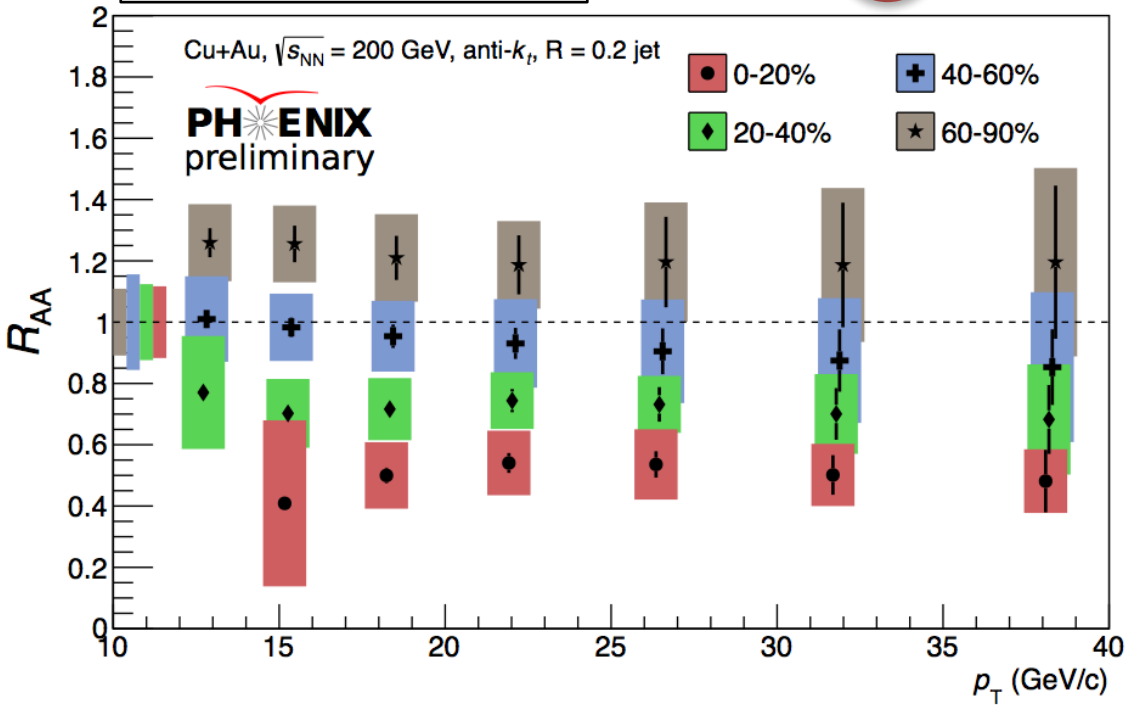
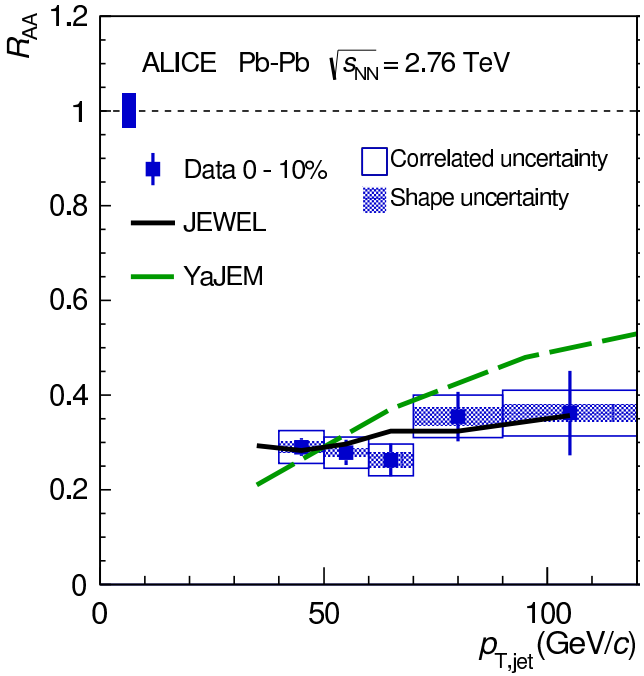
Jets in Cu+Au

R = 0.2, charged jet



See talk by: Sergey Zharko (Sat. AM)





- Cu+Au R_{AA} tells same story as Au+Au or Pb+Pb
  - Suppression slightly reduced from Pb+Pb LHC
  - Cu+Au @ 200 GeV -> Pb+Pb @ 2.76 TeV = add'l 15% suppression?
  - Note R_{AA} convolutes energy loss with spectrum shape

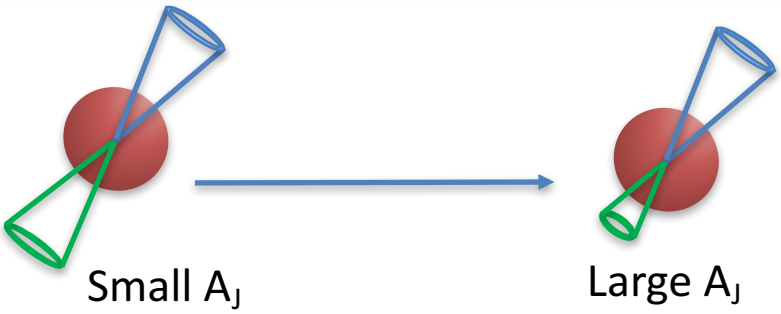
Thoughts on **Dijets in PbPb**

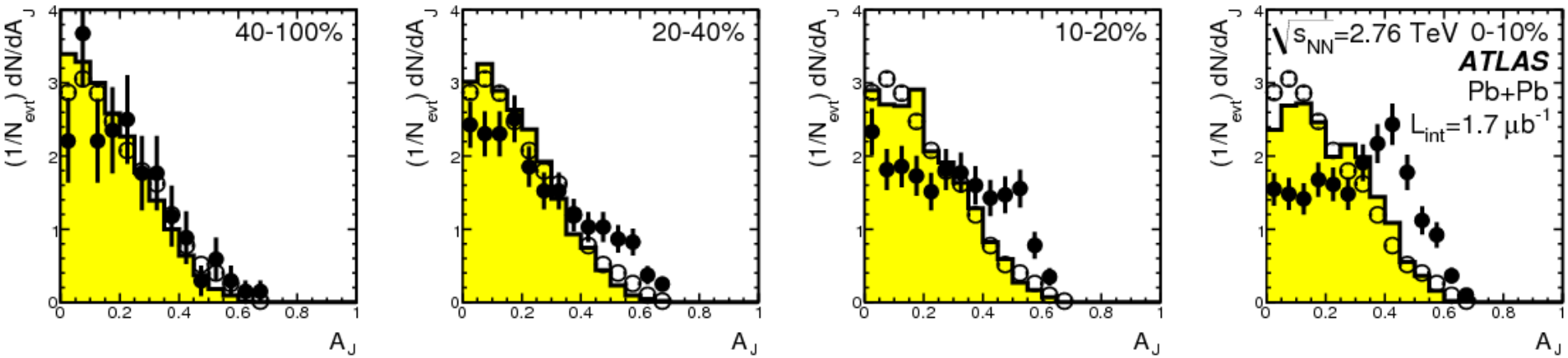
- Classic picture of "leading jet = unmodified jet" may be incorrect at LHC (but probably ok at RHIC!)
  - Better baselines (e.g. EW probes) needed to properly determine full extent of quenching
- Angular spread of jet constituent particles is likely different at LHC and at RHIC
- Have to be very careful when discussing dijet distributions for PbPb – pp or PbPb/pp
  - Quenching smears the relative jet parton p_T

Dijets at the LHC

arXiv: 1011.6182

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



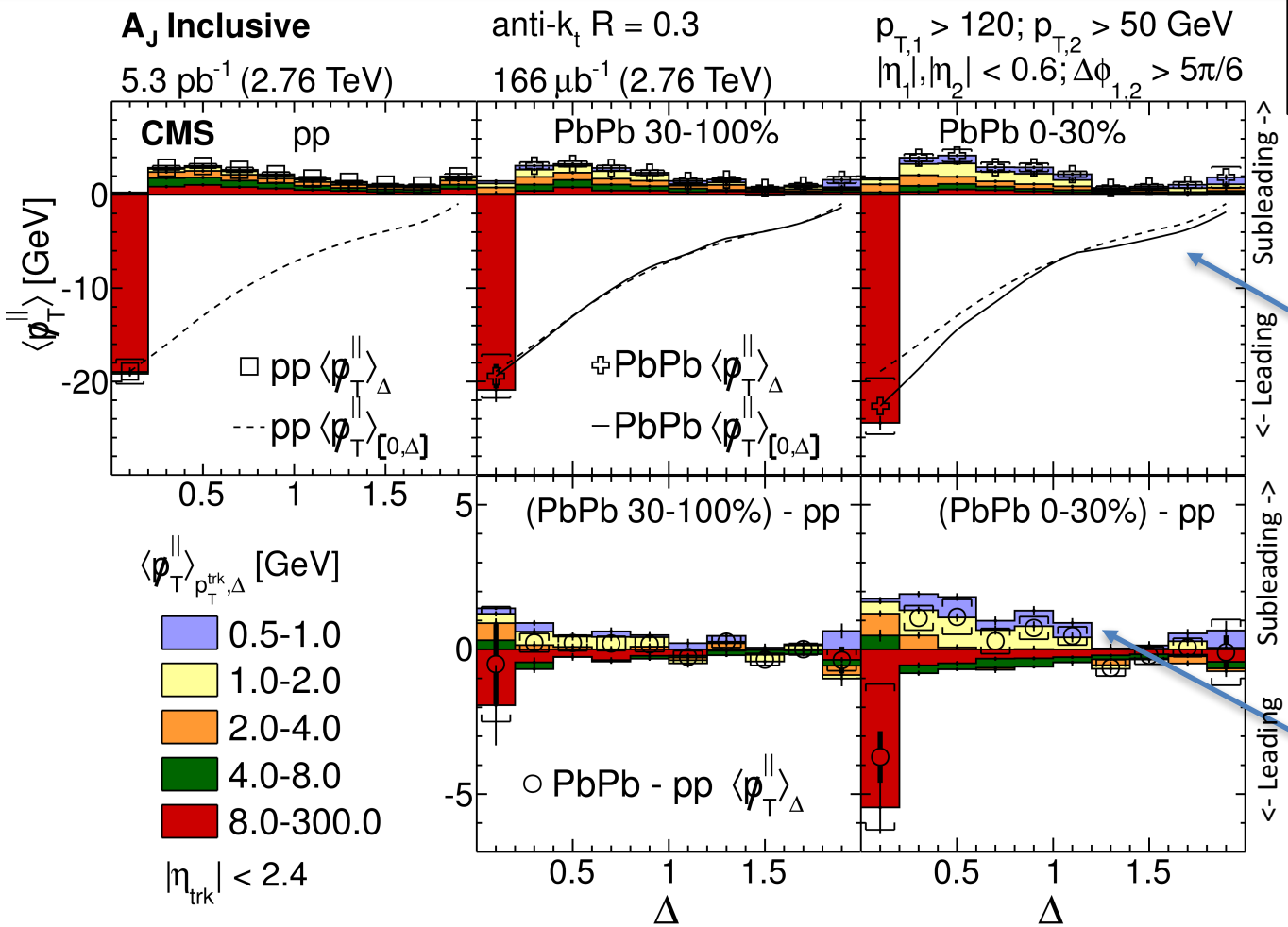


- Centrality-dependent dijet asymmetry observed as early as 2010 at LHC
  - Clear deviation of A_J toward quenching

Di-jets in PbPb Collisions, so far…

Missing Dijet momentum recovered via rings of **Δ**R

arXiv: 1509.09029



Cumulative Energy Recovery per **Δ**

Excess of low-p_T particles at large **Δ**

- Large angles needed to fully recover the energy
  - Typically energy contained in low-p_T particles (< 1 GeV/c)

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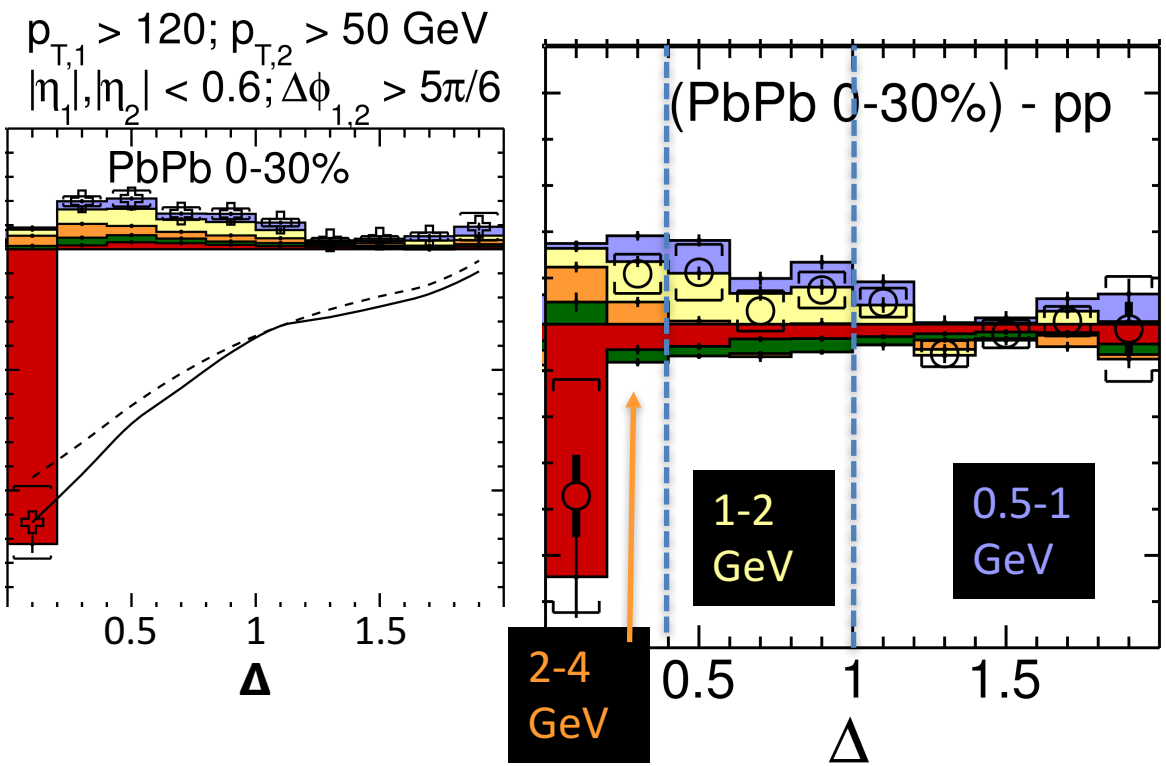


- Shape of energy recovery is similar in pp and PbPb
- Indications that low-p_T particles are ***pushed further from dijet axis*** than high-p_T particles

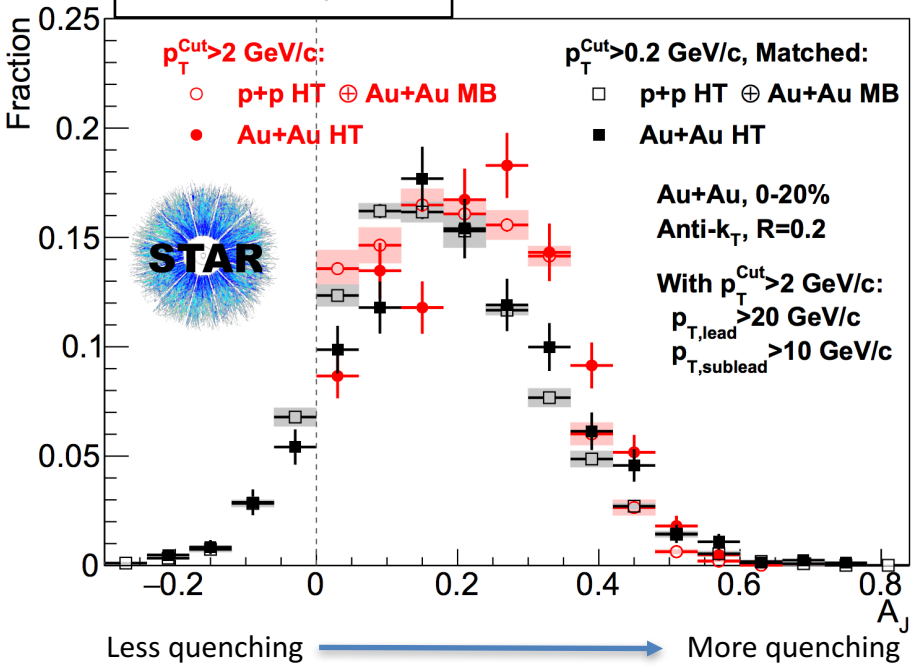
- Large angles needed to fully recover the energy
  - Typically energy contained in low-p_T particles (< 1 GeV/c)

Dijets at RHIC

arXiv: 1609.03878

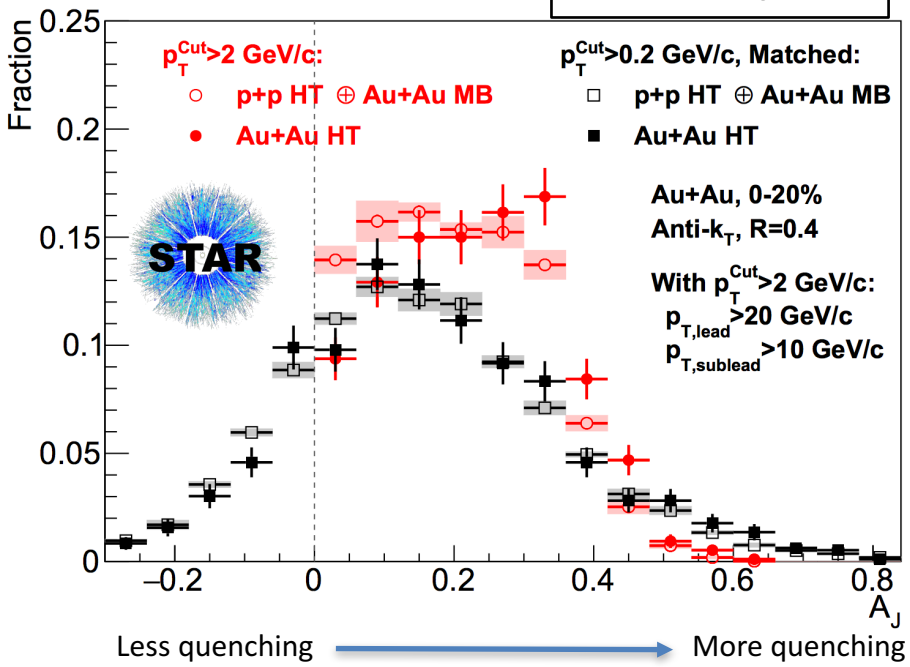
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

R = 0.2 jets



Less quenching → More quenching

R = 0.4 jets



Less quenching → More quenching

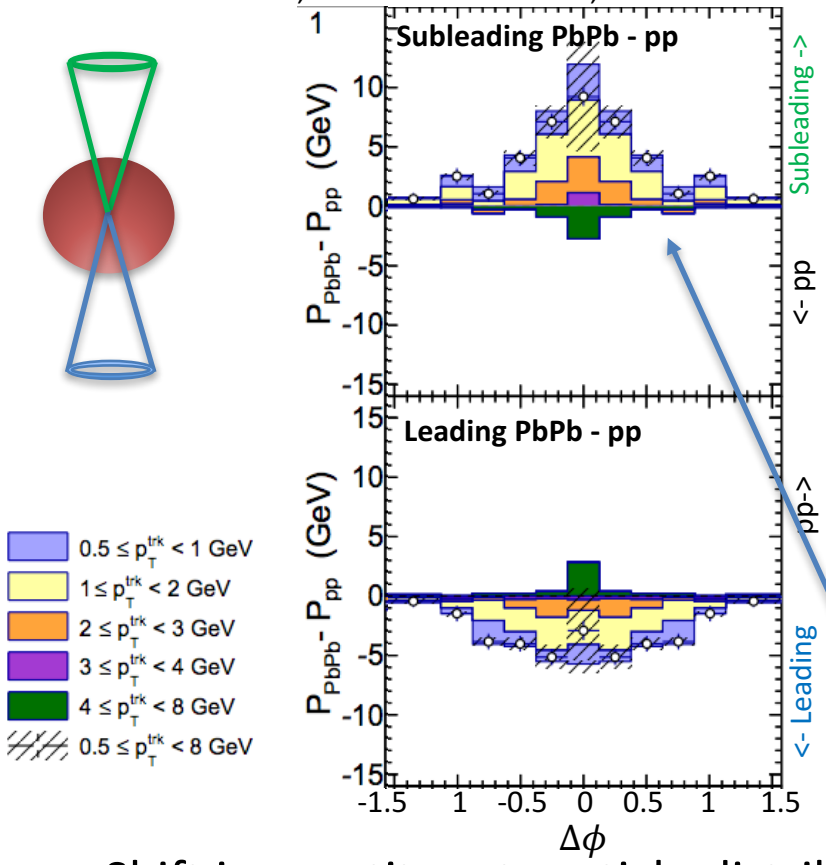
- New STAR measurement of dijet A_J
  - Hints of quenching for R=0.2 jets
  - Quenching *fully recovered by R=0.4*: consistent A_J distributions between pp and AuAu

Jet Track Correlations

arXiv: 1609.02466

See talk by: Dragos Velicanu (Sat. PM)

A_J < 0.22, $p_{T,1}$ > 120 GeV, $p_{T,2}$ > 50 GeV



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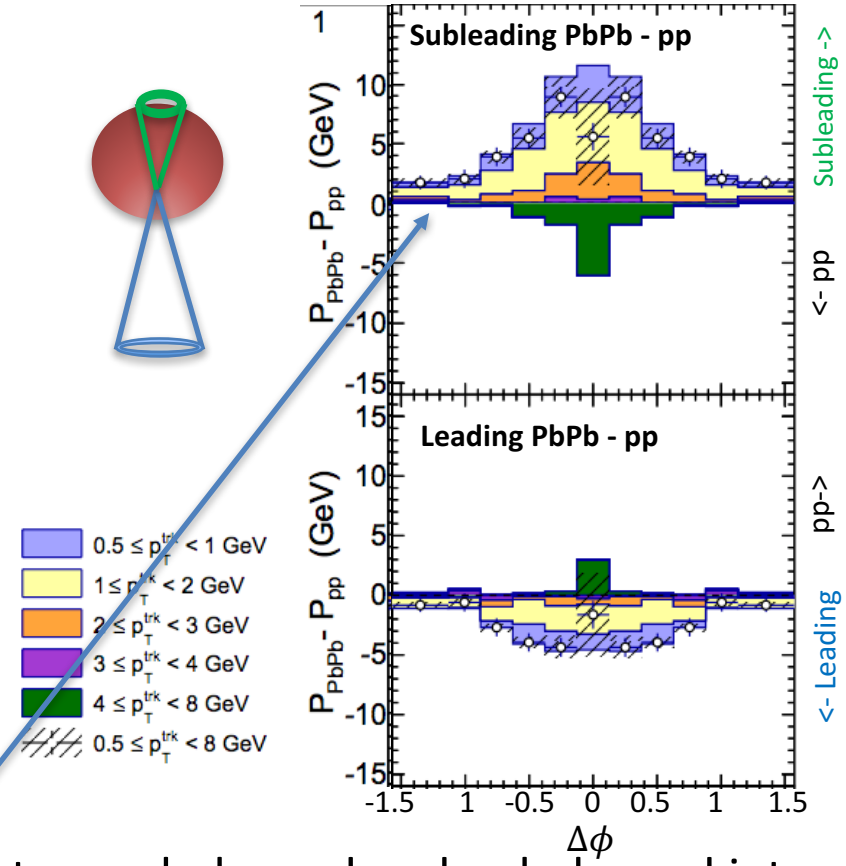

- Shift in constituent particle distribution between balanced and unbalanced jets
  - Subleading jet low-pT constituents pushed farther away for quenched jets
  - Leading jet particle distributions consistent between quenched/unquenched sample

Jet Track Correlations

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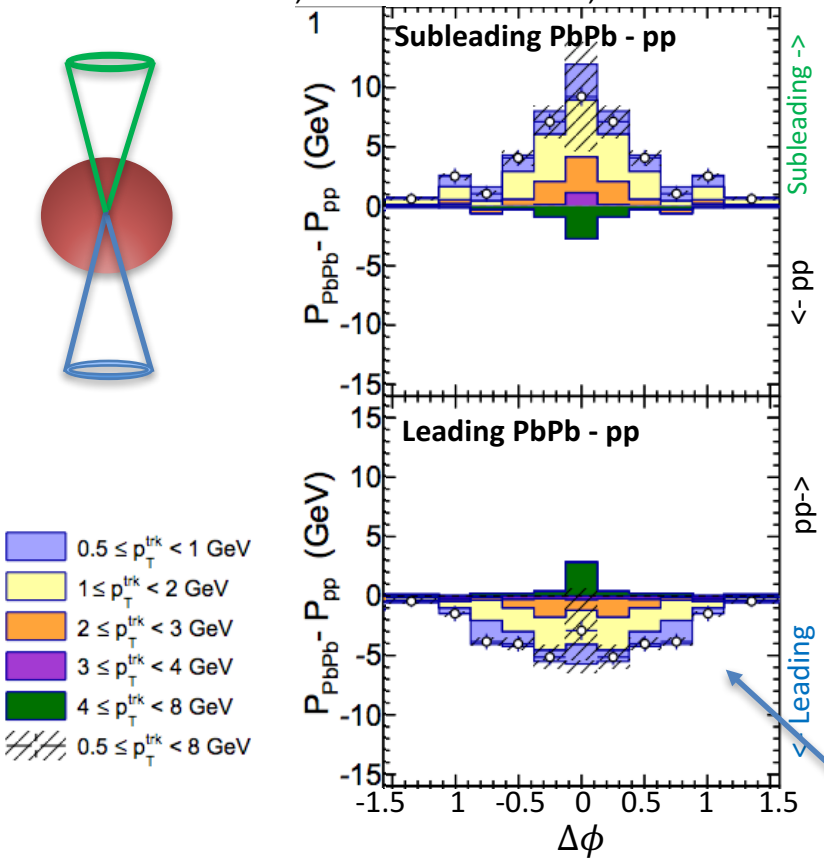

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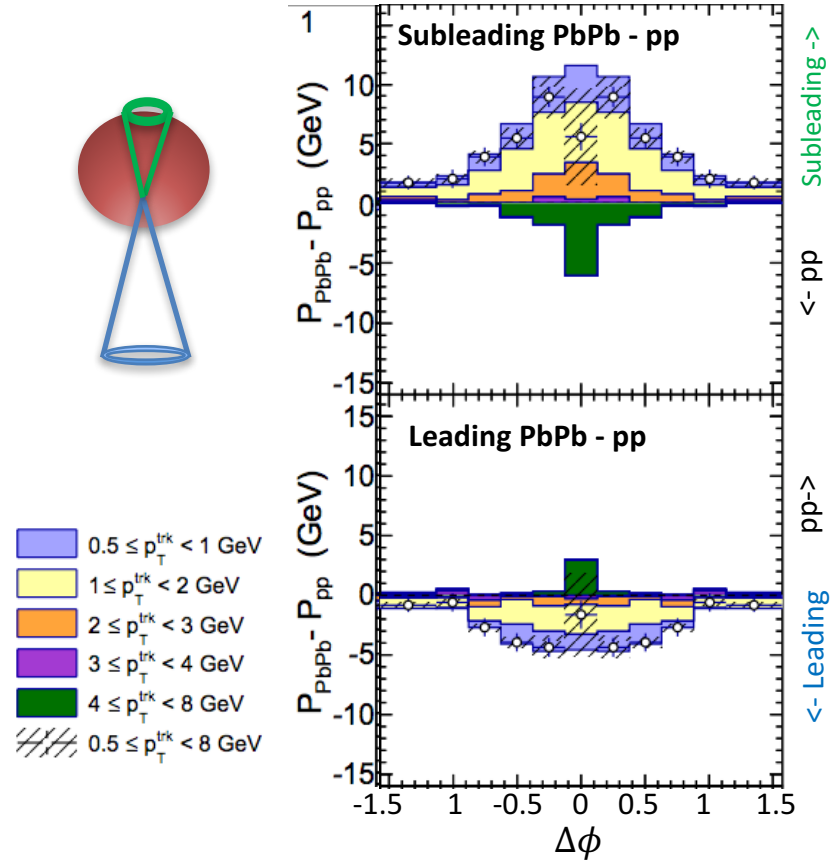

- Leading jet constituents are modified, even for **balanced** dijets (!)
  - Assumption that leading jet is unmodified may not be true at LHC energies
  - Need a ***better reference*** for jet suppression than another jet

Jet Track Correlations

arXiv: 1609.02466

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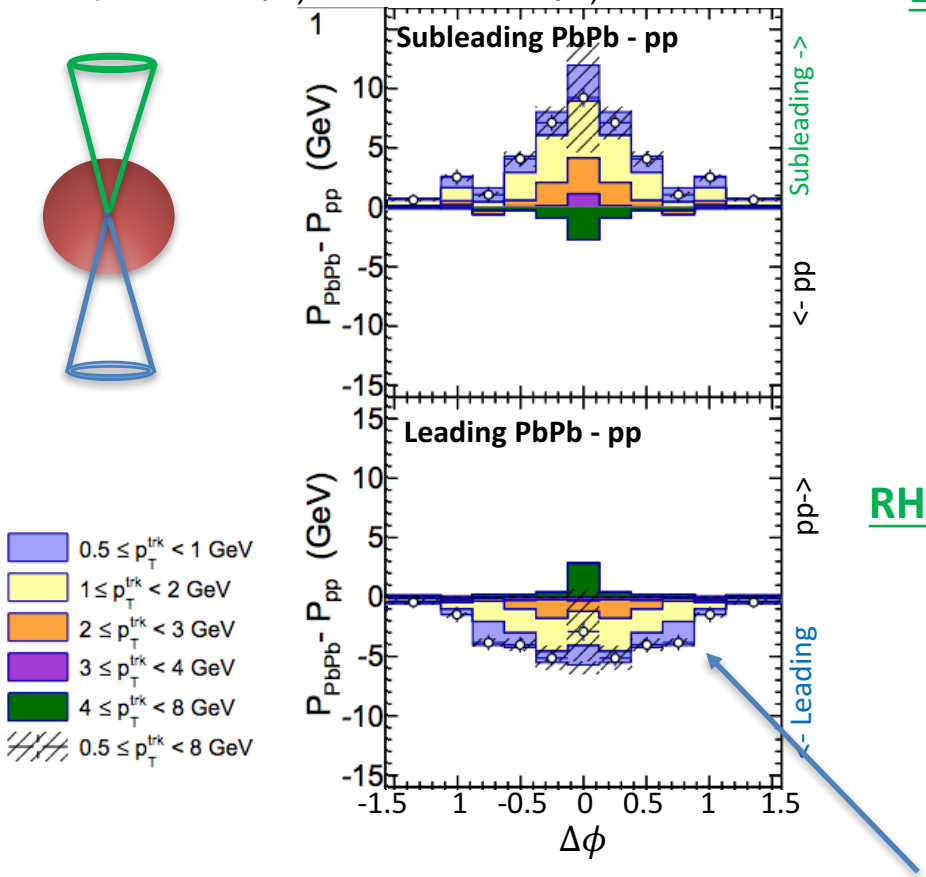
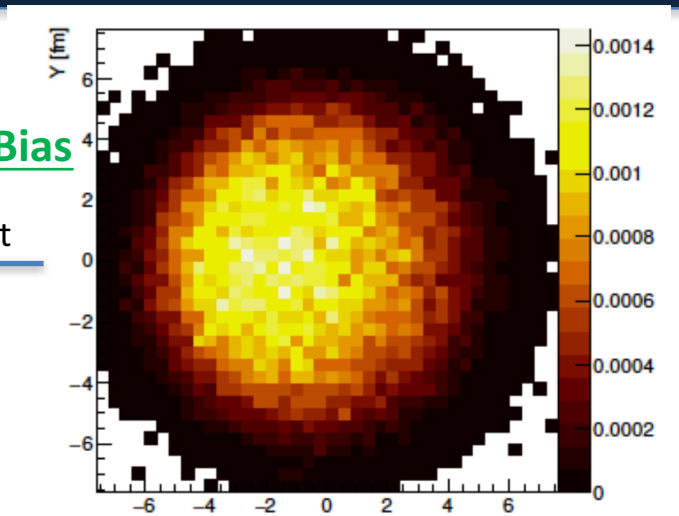


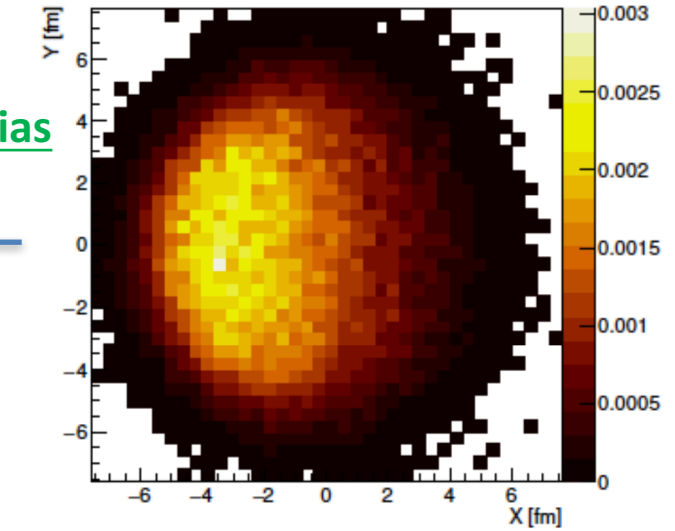
LHC Surface Bias

Leading jet



RHIC Surface Bias

Leading jet



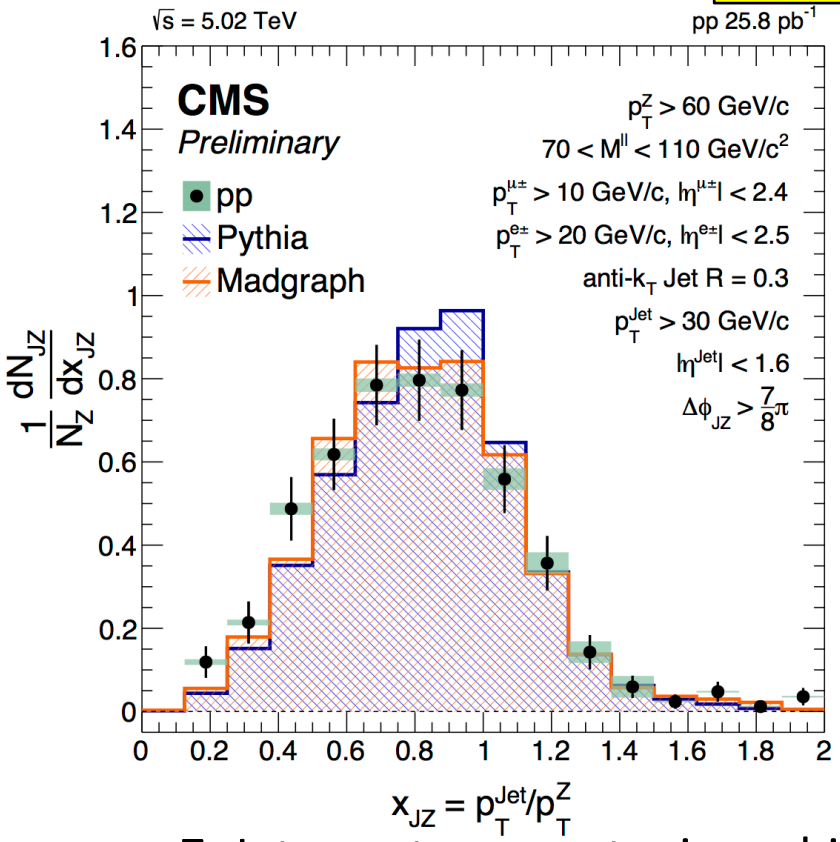
- Leading jet constituents are modified, even for **balanced** dijets (!)
  - JEWEL predicts this phenomenon looking at dijet surface bias

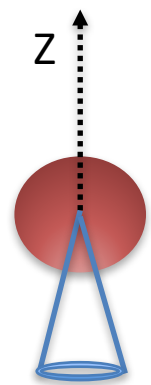
Electroweak Boson References in PbPb

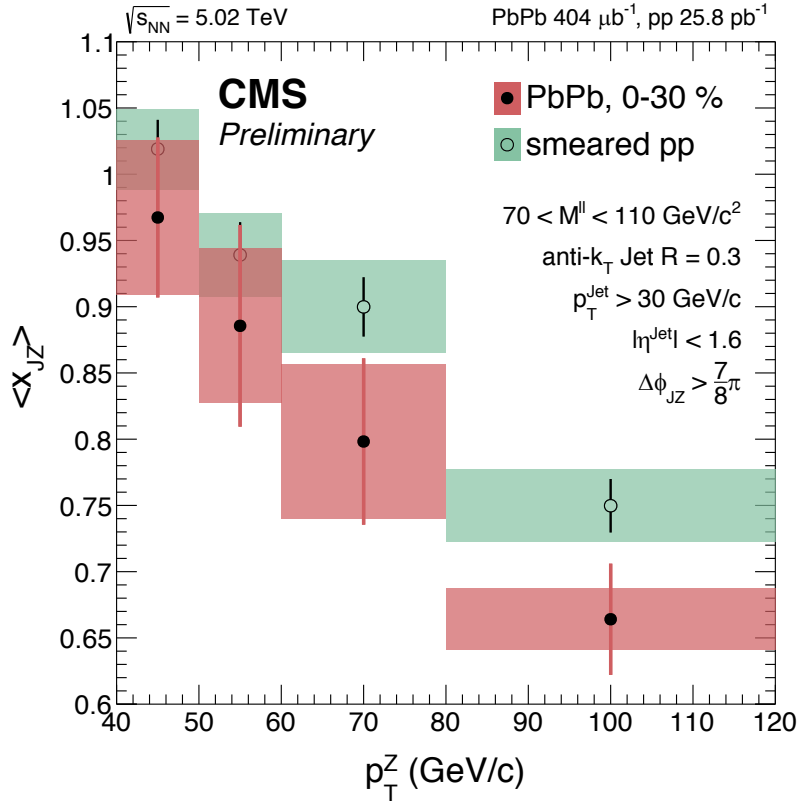
CMS-PAS-HIN-15-013

Z+Jet Energy Modification

See talk by K. Tatar (Sat. PM)



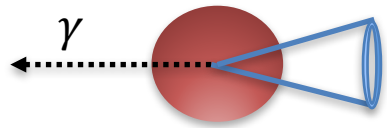




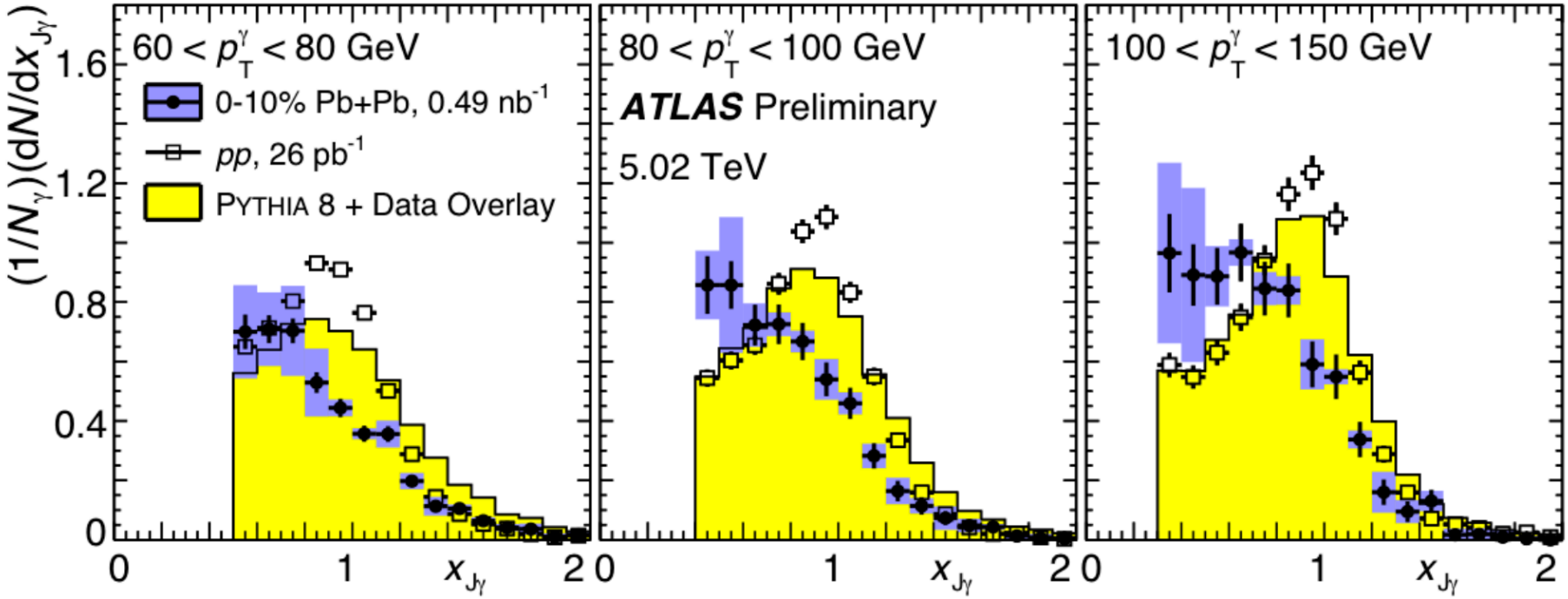
- Z+Jet events suggest minor shift in jet energy relative to Z-boson
  - Increase of Z p_T shifts jet distribution away from 30 GeV cutoff resulting in smaller $\langle X_{JZ} \rangle$
  - Observed effect consistent with jet quenching
- Distributions in pp consistent with MADGRAPH predictions

Electroweak Boson References in PbPb

ATLAS-CONF-2016-110



See talks by:
Chris McGinn (Sat. PM)
Brian Cole (Sat. PM)

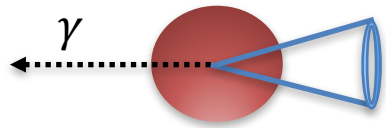


- $\langle X_{J\gamma} \rangle$ in PbPb smaller than in pp
  - Sizeable shift in jet energy for central events
  - Photon p_T dependence is fairly minor

Electroweak Boson References in PbPb

ATLAS-CONF-2016-110

CMS-PAS-HIN-16-002



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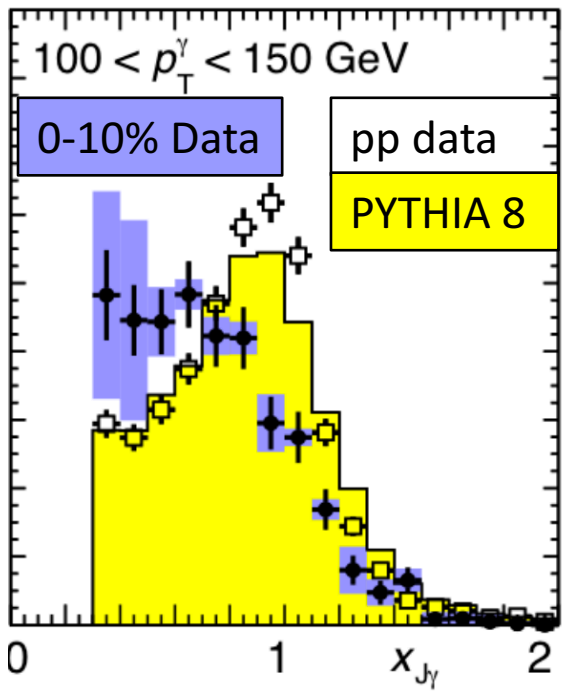
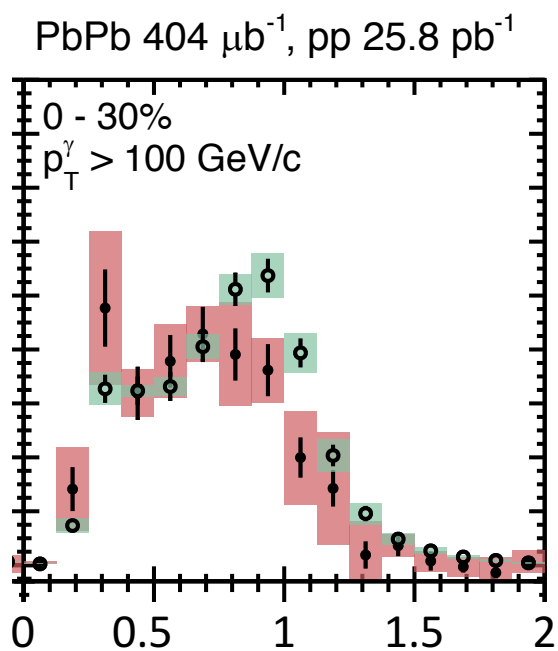
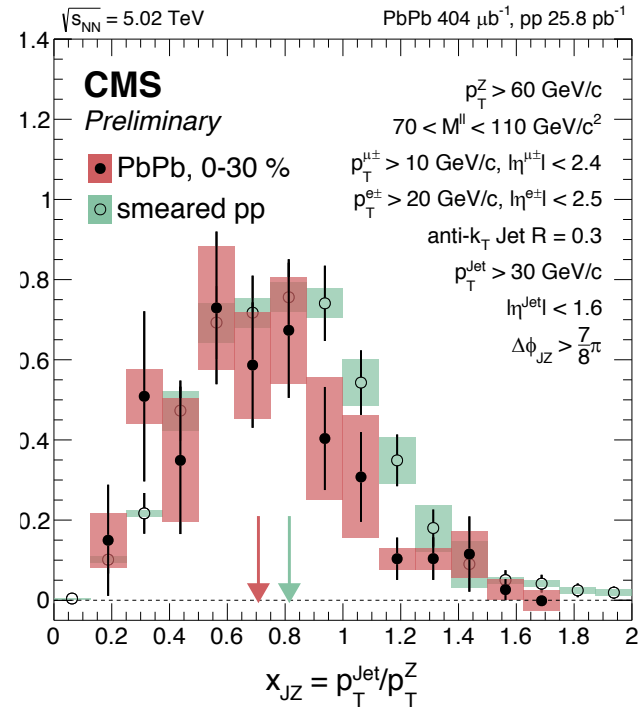




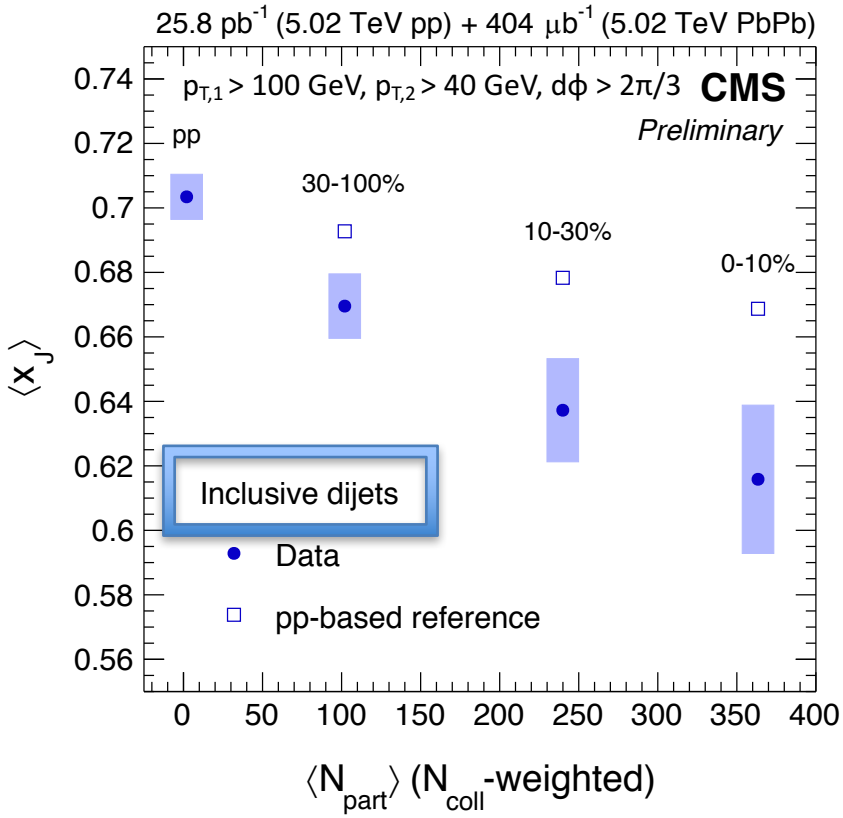


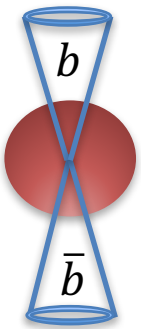
- $\langle X_{J\gamma} \rangle$ in central PbPb reduced from pp
  - Relative shift in quenched jets similar between both new electroweak references: photons and Z-Bosons

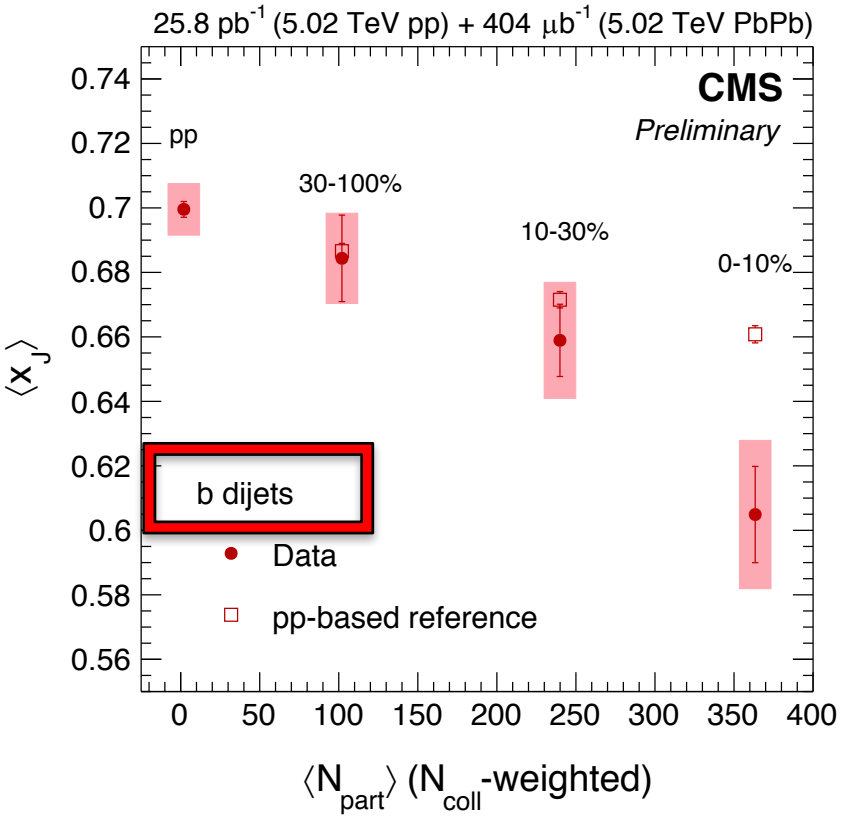
Di-b-jets

CMS-PAS-HIN-16-005

See talk by: Cheng-Chieh Peng (Sun. AM)



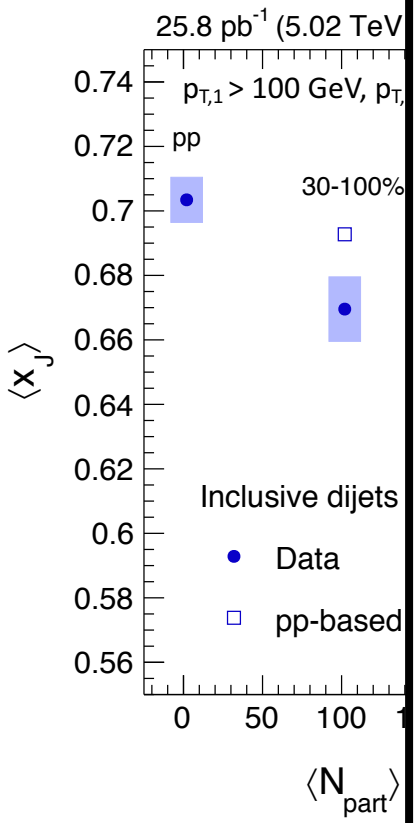


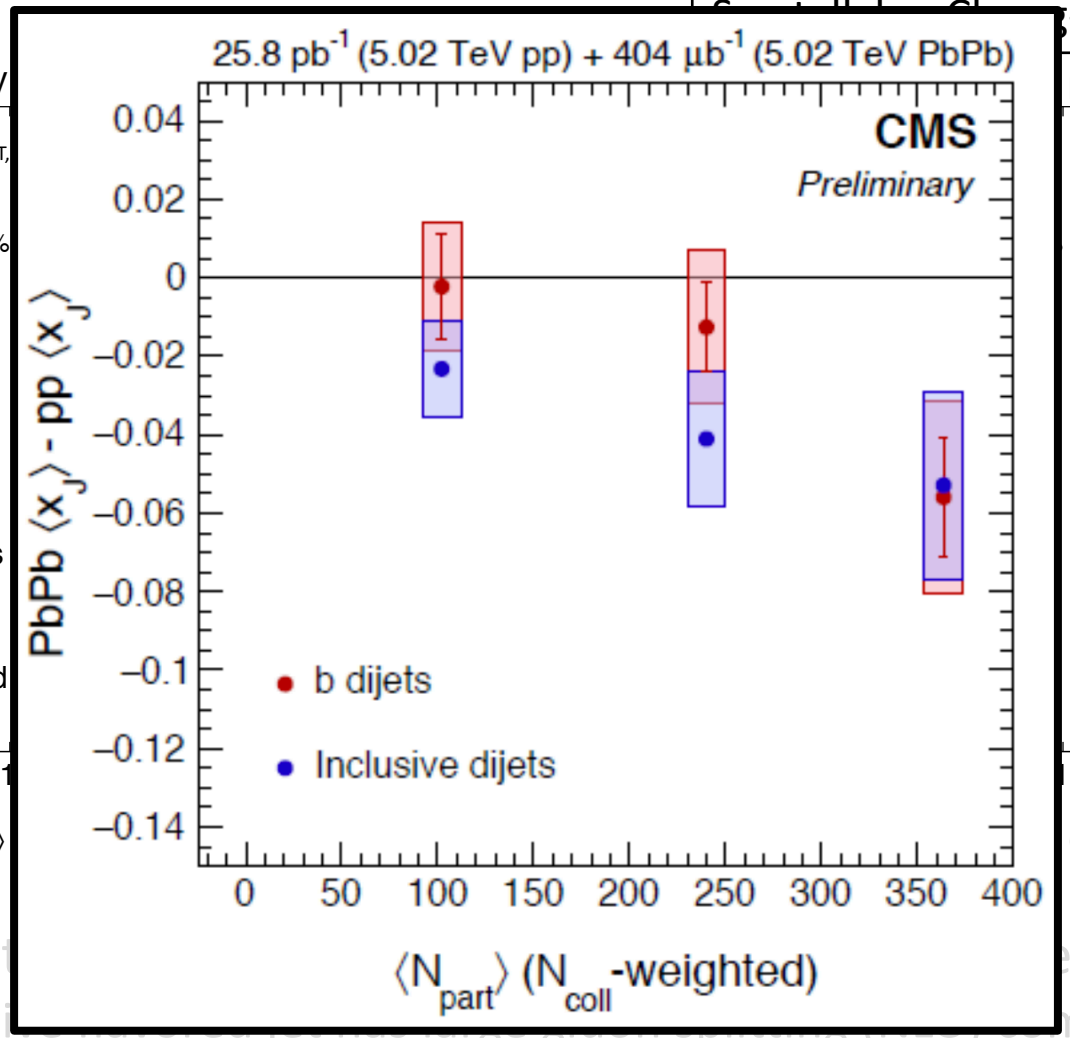


- Investigate properties of **leading order** heavy-flavor jet production
  - Inclusive flavored jet has large gluon splitting (NLO) component
- Observe modification consistent with inclusive-jet measurements

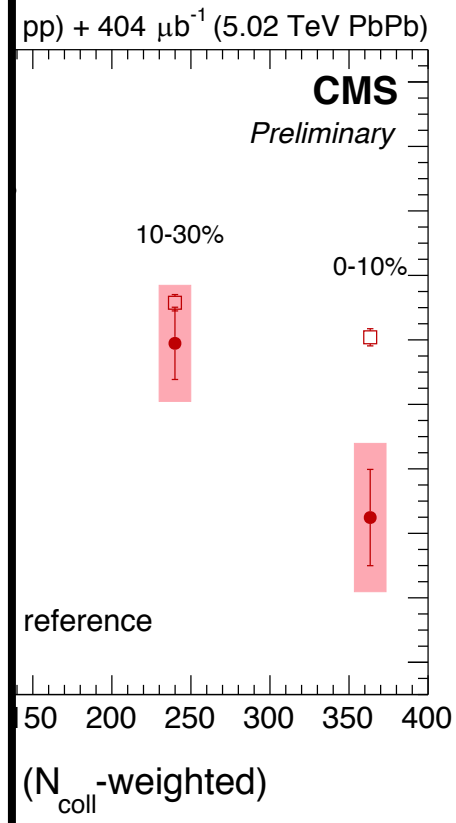
Di-b-jets

CMS-PAS-HIN-16-005





-Chieh Peng (Sun. AM)



- Investigat… …et production
  - Inclusi… …mponent
- Observe modification consistent with inclusive-jet measurements

Thoughts on Jets in pA

- Centrality definitions in pA can be biased by assuming Glauber scaling works properly
  - Jets in particular can dramatically affect centrality classification

$\langle N_{trk} \rangle =$  + 

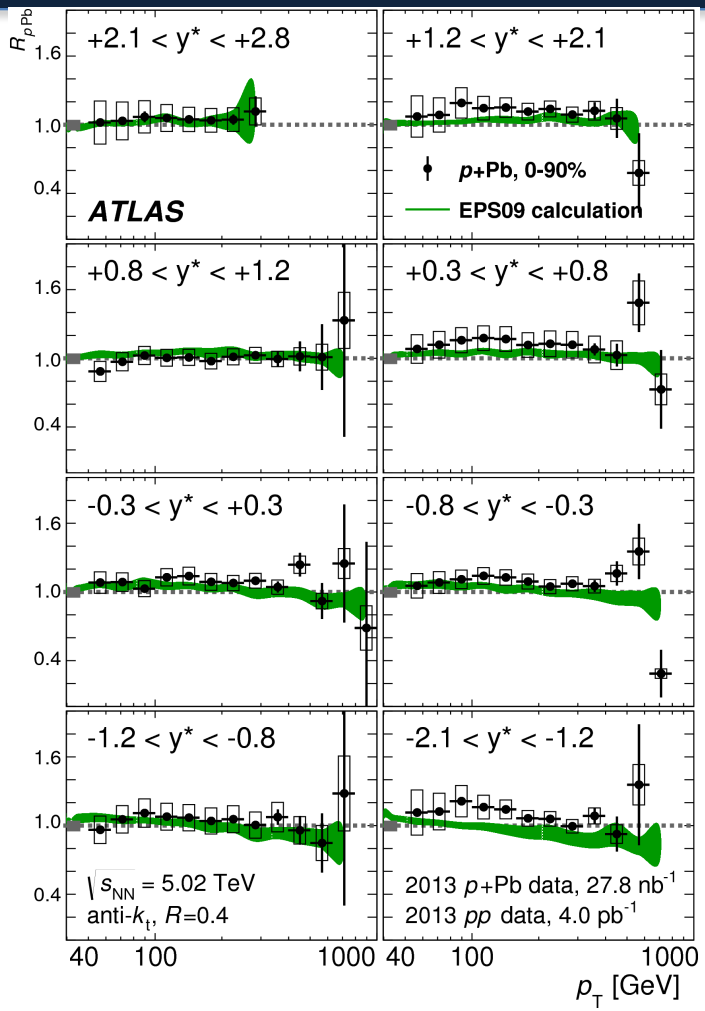
"Central" medium light fragmentation

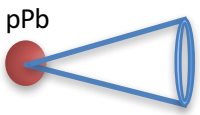
"Peripheral" medium heavy fragmentation

  - Would be good to see Q_{PbPb} studies to confirm/validate the ALICE centrality estimation procedure

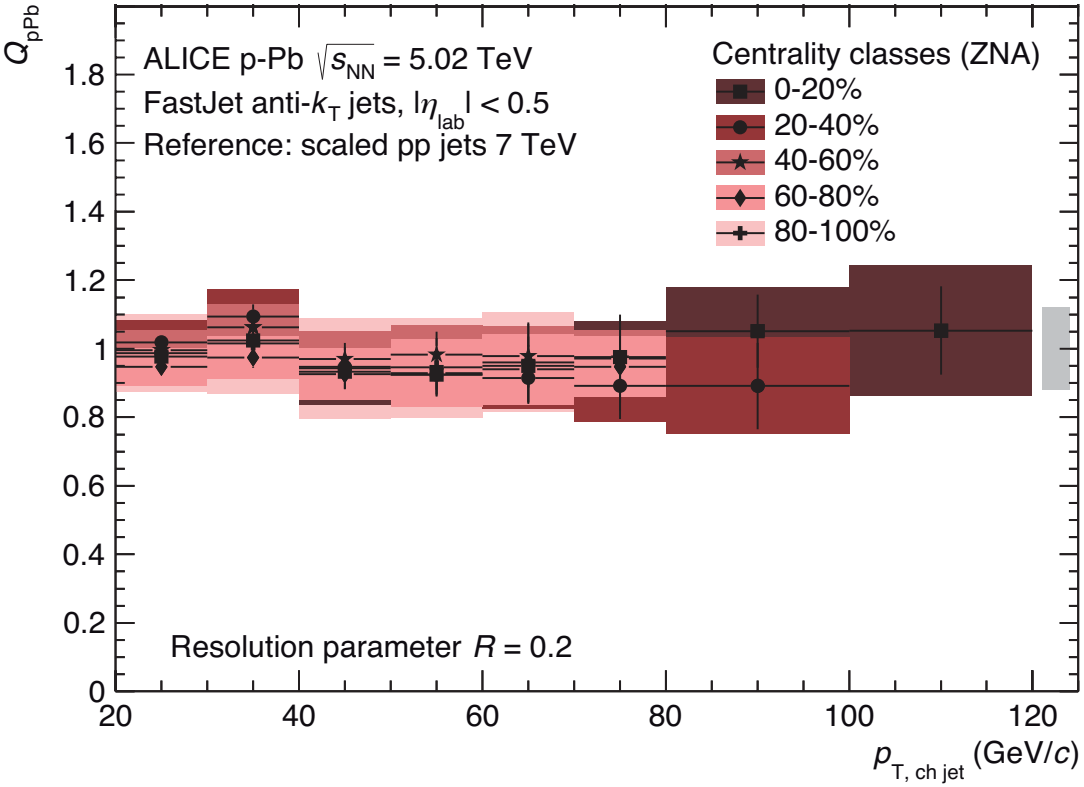
- New pp data allows tight nPDF constraints using dijets large regions of Q^2-x phase space
  - Would be great to check di-b-jets in pPb = gluon nPDF

Jets in pA Collisions, so far…



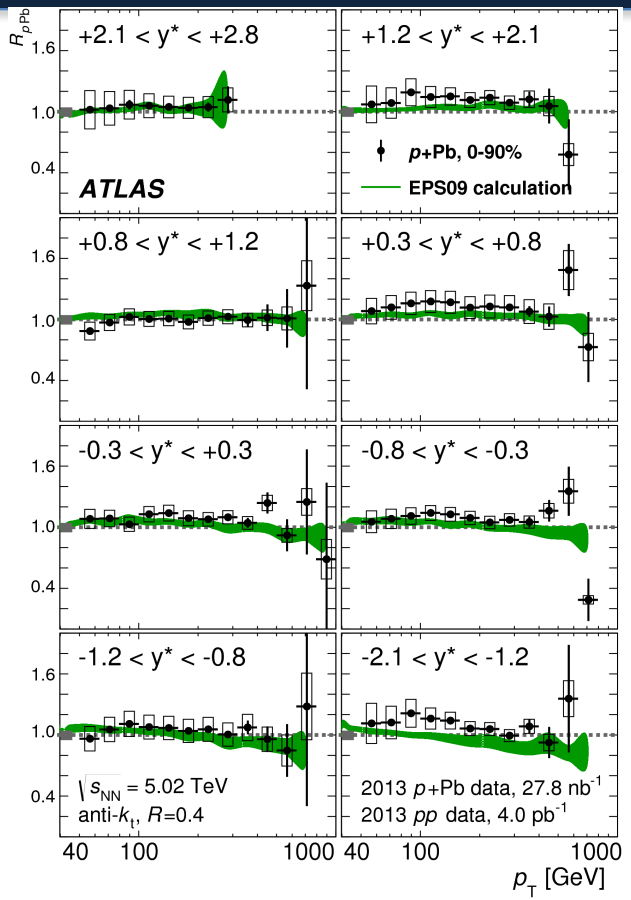


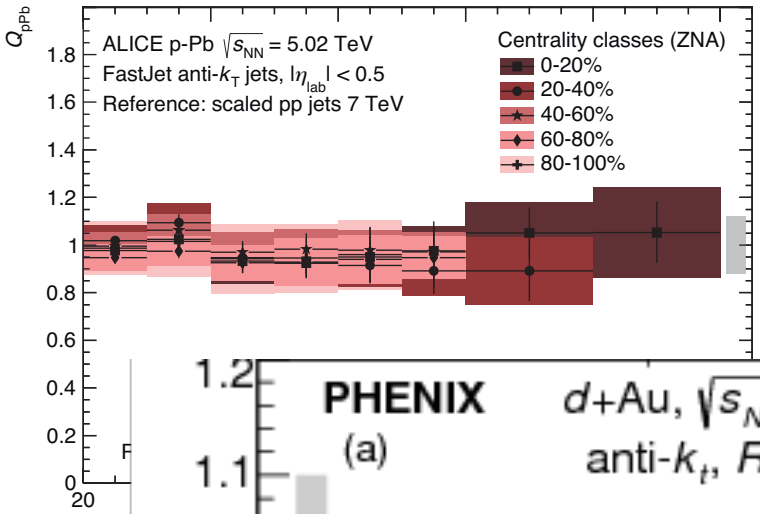
arXiv: 1412.4092, 1603.03402



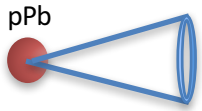
- pPb jets are ***not*** quenched
  - No large initial state effects observed, even vs flavor

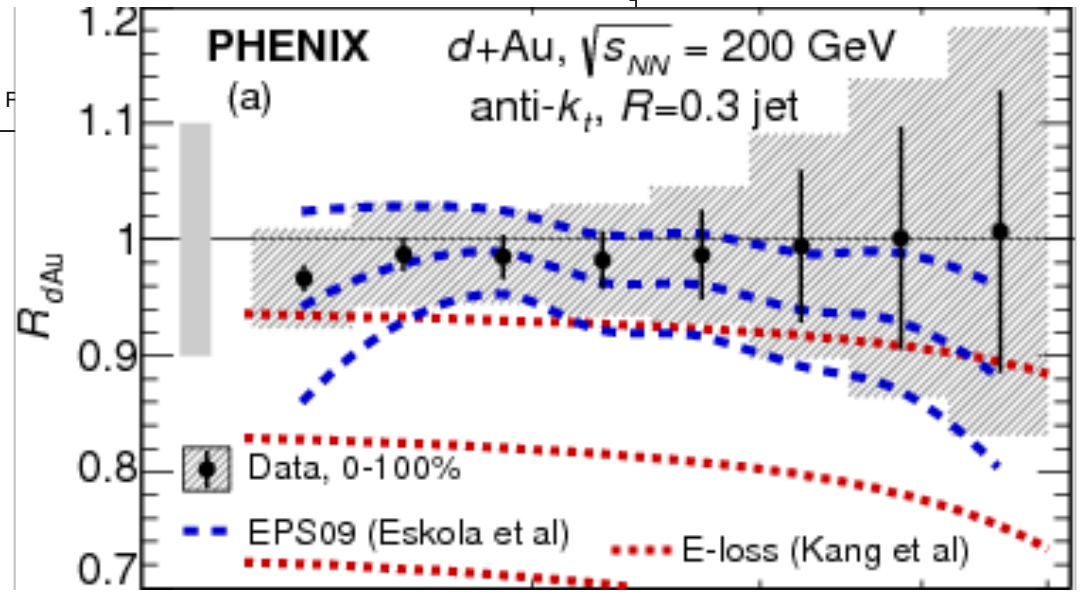
Jets in pA Collisions, so far…





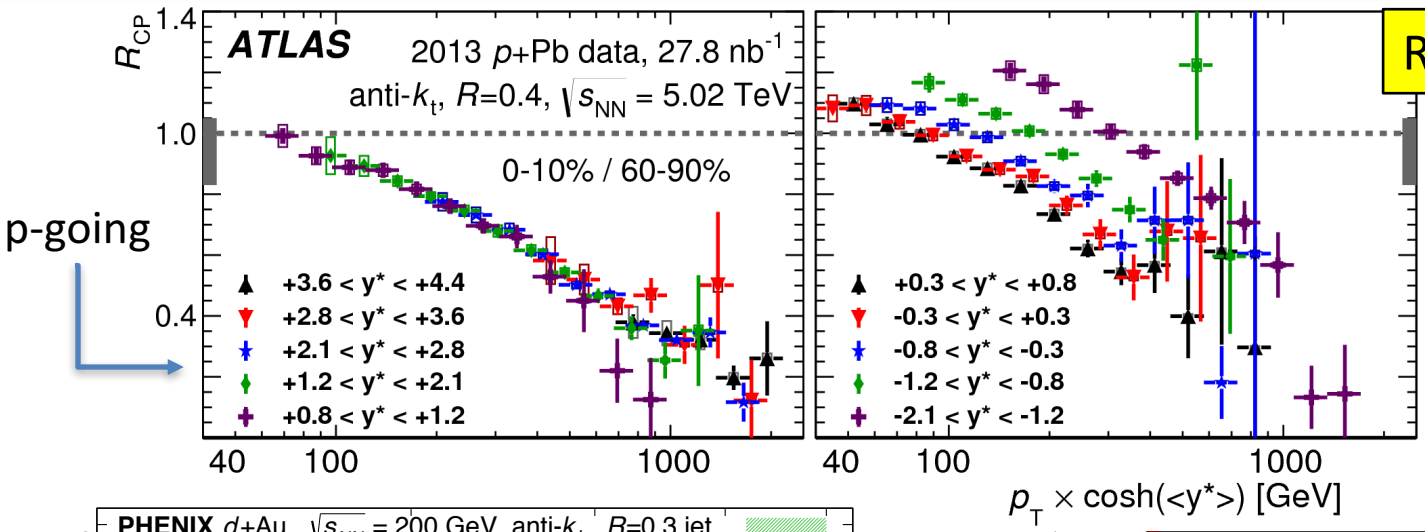
arXiv: 1509.04657





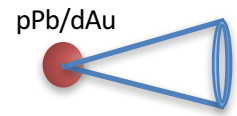
- pPb jets are ***not*** quenched
  - Same story observed at RHIC energies

Jets in pA Collisions, so far…

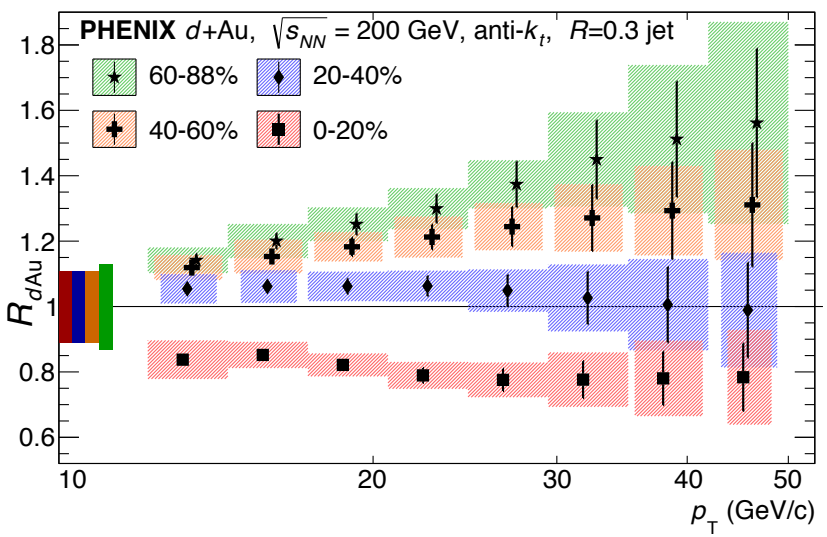


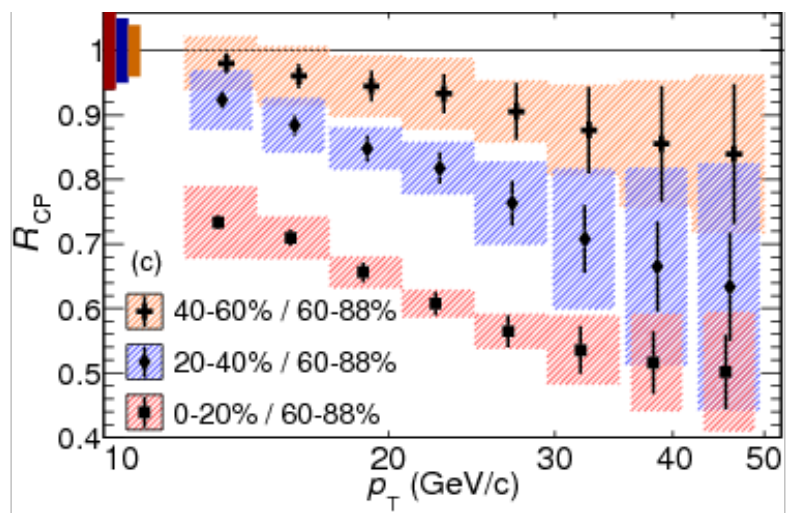
R_{CP} in pPb and dAu

p-going



Pb-going



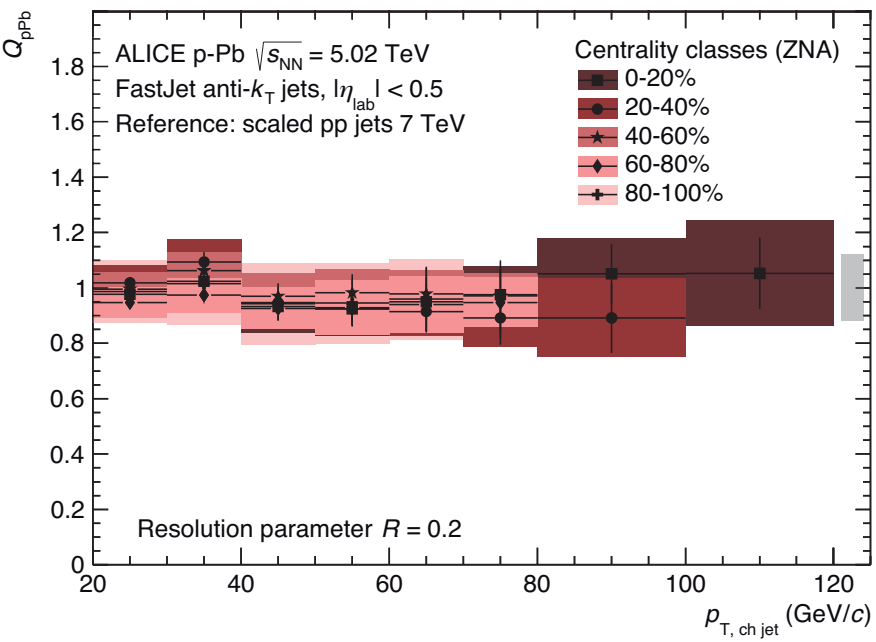


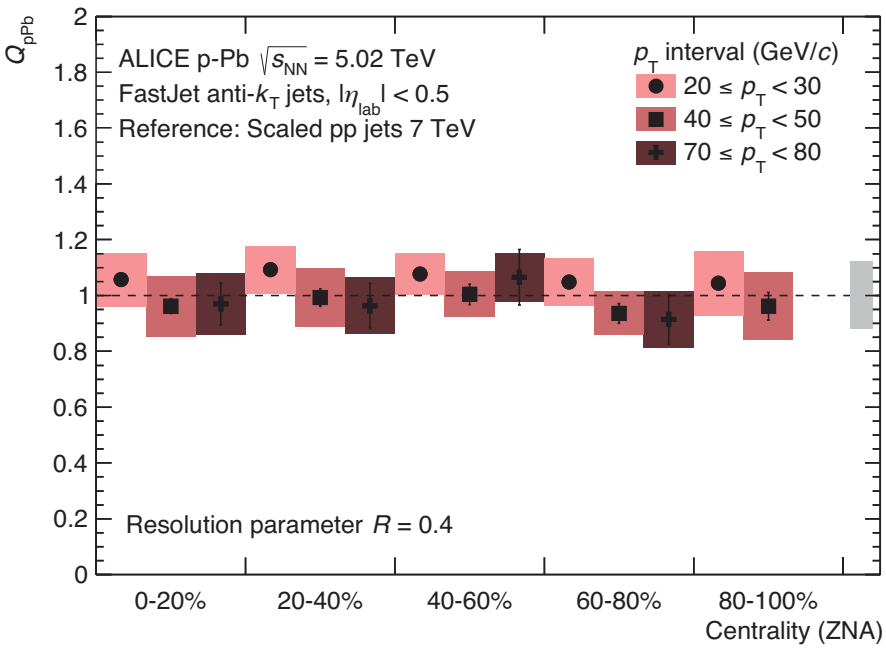
- Centrality dependence is a bit of a mystery
  - R_{CP} values hugely "suppressed" at high-p_T -> centrality bias?

ALICE pPb Inclusive Jet Result

arXiv:1603.03402

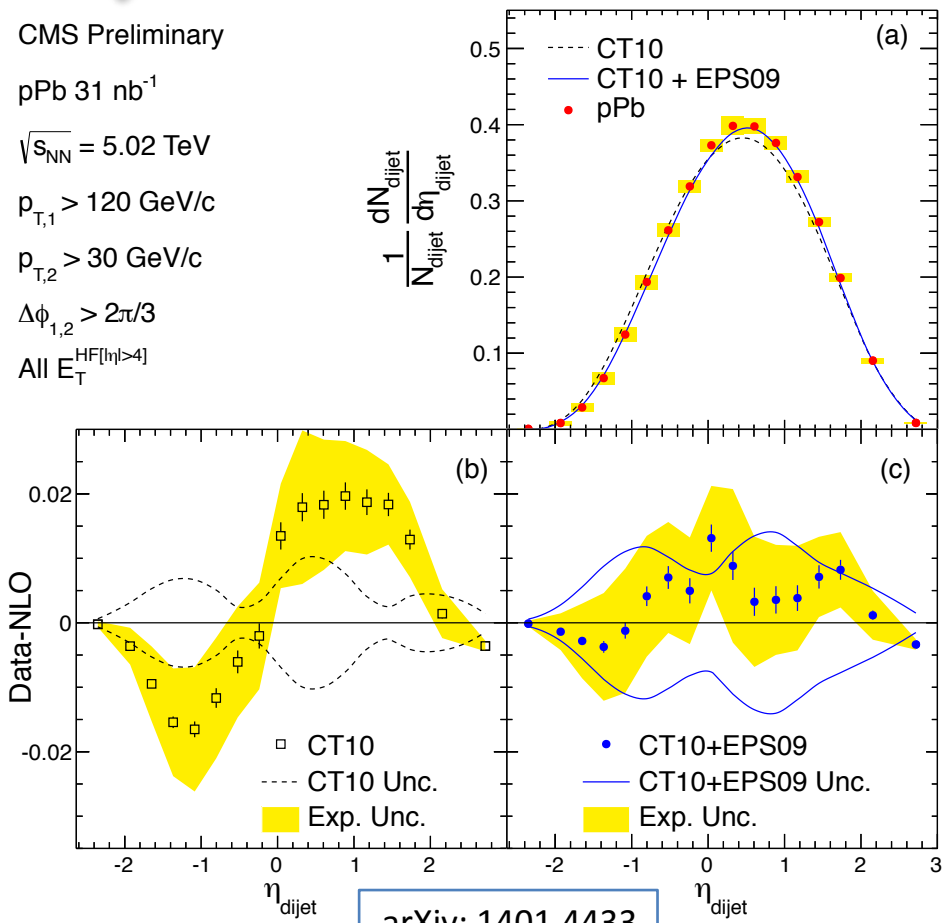
(Centrality calculated in bins of ZDC energy + scaled <N_{coll}>)





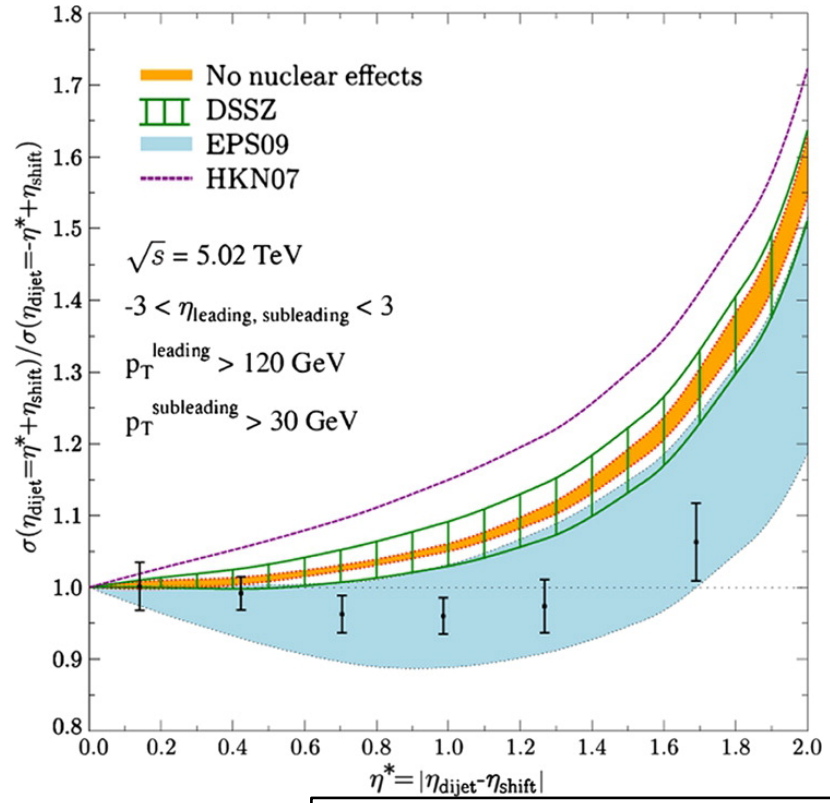
- ALICE measure a different jet R_{pA} centrality dependence than PHENIX and ATLAS
  - Centrality definition based on ZDC + normalized multiplicity in the forward calorimeter ("Hybrid" method)
- Observe virtually no centrality dependence of jet R_{pA}, consistent with inclusive-centrality measurements
- Note limited pseudorapidity region: $|\eta_{lab}|<0.5$ not heavily modified

Di-jets in pA Collisions, so far…



arXiv: 1401.4433

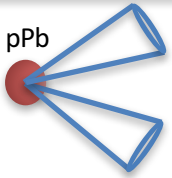
Dijet Pseudorapidity Distributions in pPb



Nucl. Phys. A 931: 331 (2014)

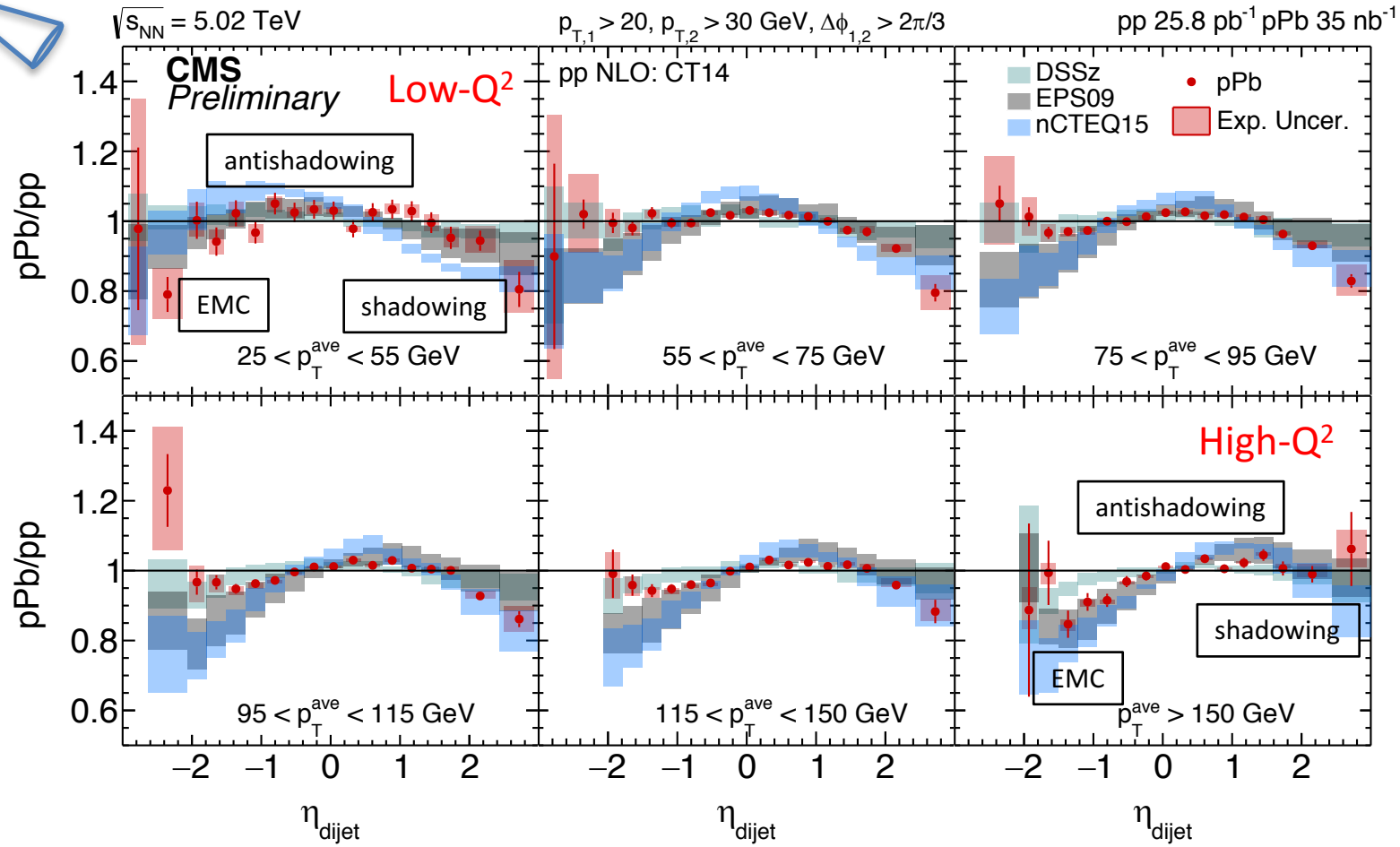
- New tool for constraining nuclear PDFs
  - Strong dijet pseudorapidity ←→ Bjorken-x correlation
  - Forced to use NLO simulation – 5 TeV pp data not yet available at publication time

nPDF constraints with dijets



CMS-PAS-16-003

See talk by: Yen-Jie Lee (Sun. AM)



- Gluon distributions constrained by dijet pseudorapidity distributions
  - Deviations in EMC region from EPS09 -> good agreement with DSSZ

Summary

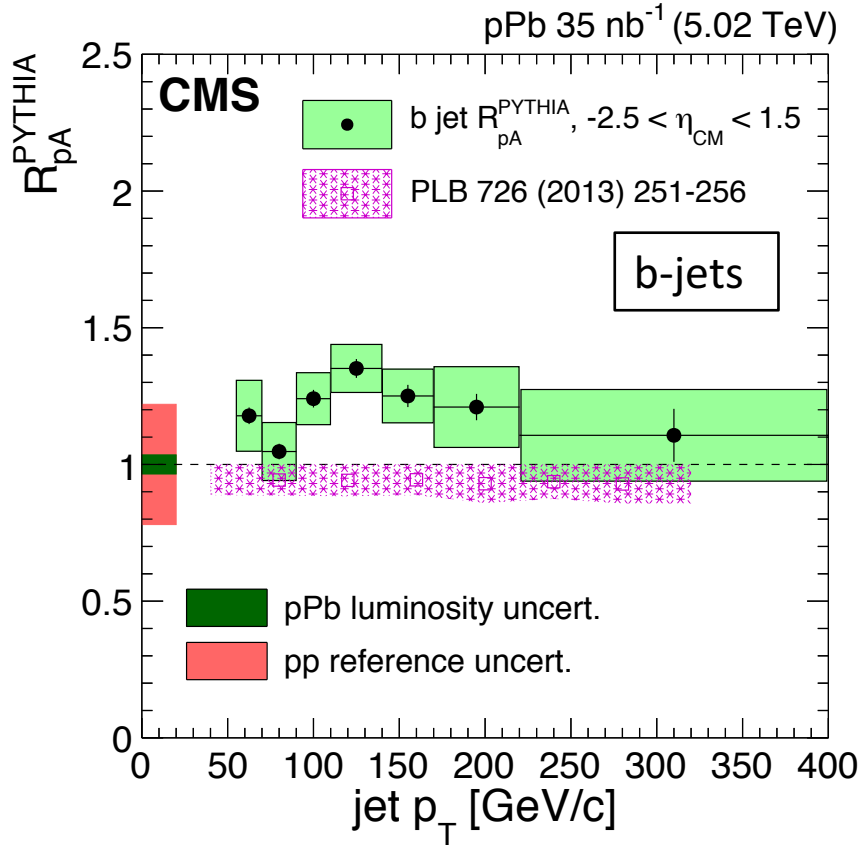
- Can we use ***new references*** to control energy-loss baselines?
  - Consistent picture shown by Electroweak, Flavored, Virtuality Probes: Jet quenching only very apparent at most central events
  - EW + R_{AA} + Theory suggest $<\Delta E>$ ~ 10-15 GeV at 100 GeV jets
- Can we go ***searching for quenched energy***?
  - Quenched energy pushed out to ~1.4 in ΔR, contained in particles of p_T < 2 GeV at LHC, but fully recovered by ΔR~0.4 at RHIC
- Can we ***gain control of centrality*** in small systems?
  - Centrality needs to be carefully calibrated – prefer centrality definitions without Glauber MC and using ZDC
- Can we ***further constrain nPDFs*** using jets?
  - Yes – especially with new 5 TeV pp data. Adding new constraint to the gluon nPDFs using hadron colliders at large x

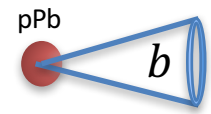
BACKUP

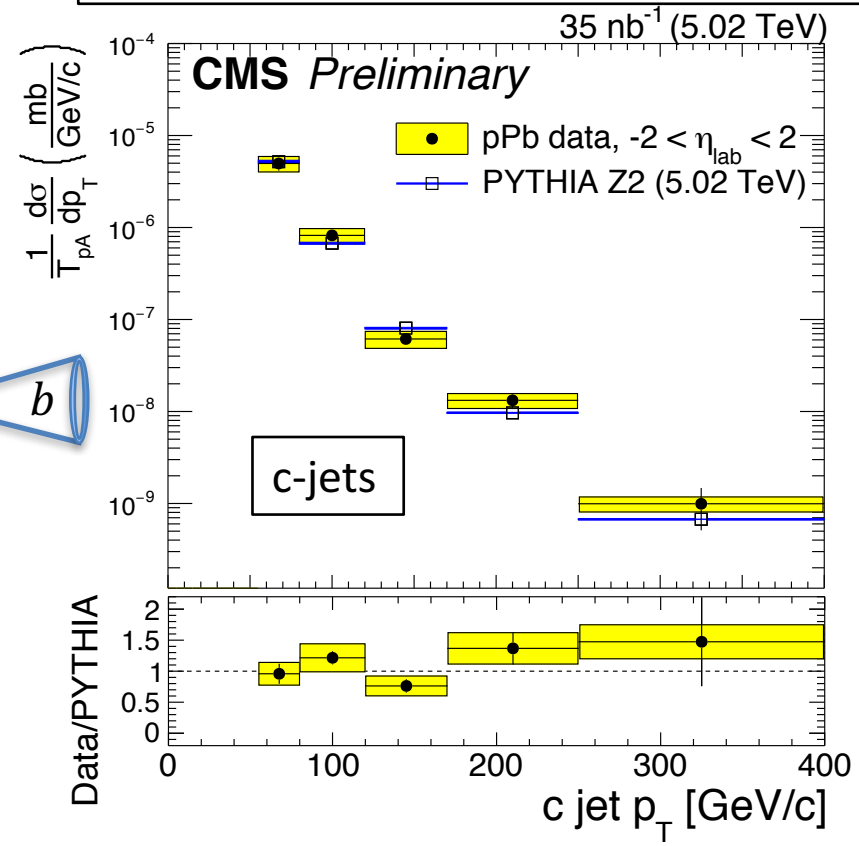
Flavored Jets in pA Collisions

arXiv: 1510.03373 | CDS: 2055705

See talk by: Cheng-Chieh Peng (Sun. AM)





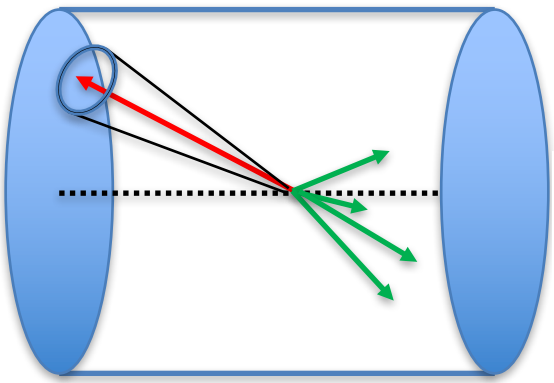


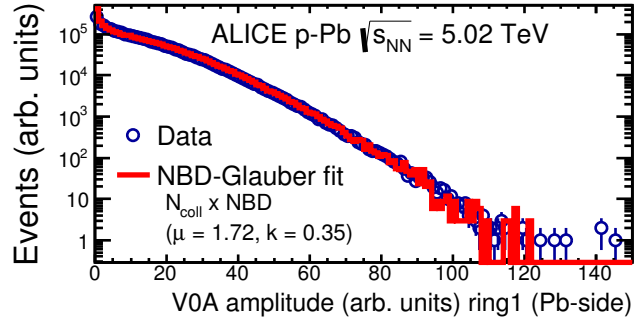
- b-Jet and c-Jet R_{pA}^{Pythia} find no discrepancy from unity
- Flavored jet measurements tell a similar story as the inclusive jets
  - Favors pQCD models where mass-dependent effects are negligible at jet p_T >> b-quark mass

Possible culprit for Centrality Bias

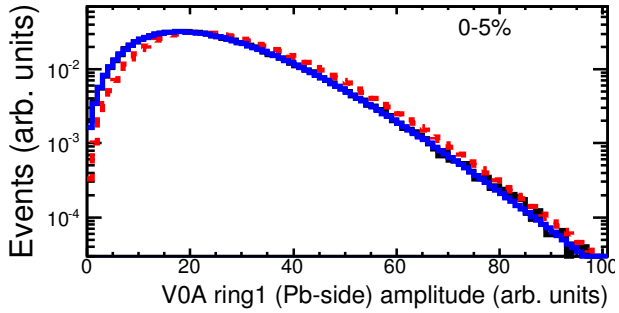
Forward jet recoil contaminates centrality selection using bins of forward calorimeter energy

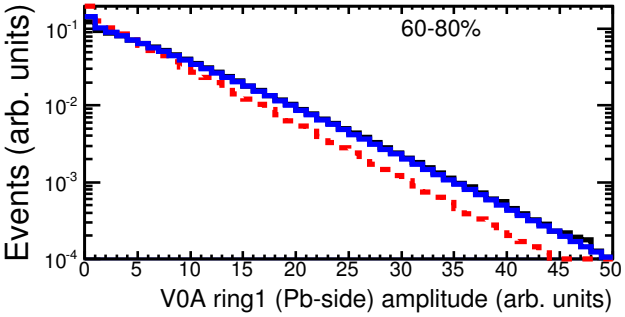
- Affects shape of centrality distribution such that central events are redefined as peripheral





arXiv: 1412.6828





Because fits to Glauber MC are not great (from jet recoil bias), <Ncoll> estimation overnormalizes central events and undernormalizes peripheral events

Analyses

- CMS
  - Updated Jet RAA (1609.05383)
  - Bjet Pairs in PbPb (HIN-16-005)
  - Z-Jet & Photon Jet (HIN-15-013, HIN-16-002)
  - Finalized jet-track correlations (1609.02466)
  - Dijets in pPb @ 5 TeV with updated pp ref (HIN-16-003)
- ATLAS
  - 2.76 TeV Dijet Asymmetry (1011.6182)
  - 2.76 TeV Jet RAA (1411.2357)
  - 5 TeV pPb jet RpA (1412.4092)
  - 5 TeV Photon-Jet Asymmetry (Preliminary)
- ALICE
  - Inclusive charged jet RAA @ 5 TeV (Preliminary)
  - Jet RpA @ 5 TeV (1603.03402)
- PHENIX
  - d+Au jet RpA (1509.04657)
  - Jets in Cu+Au (Preliminary)
- STAR
  - Dijet A_J in Au+Au and pp at 200 GeV (1609.03878)