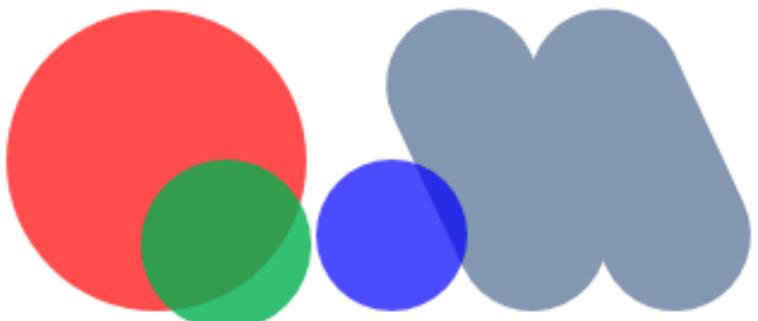


An experimental review of Jets and charged hadrons

Matthew Nguyen



Q: Why jets?

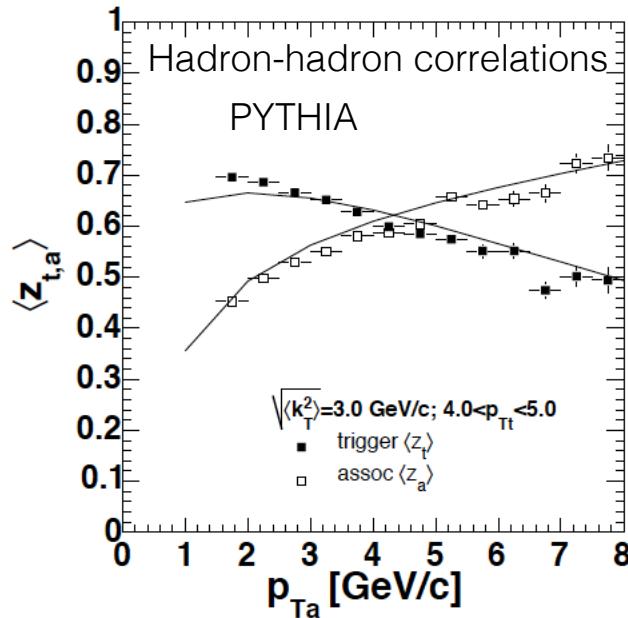
Q: Why jets?

A: To get closer to the parton energy

Q: Why jets?

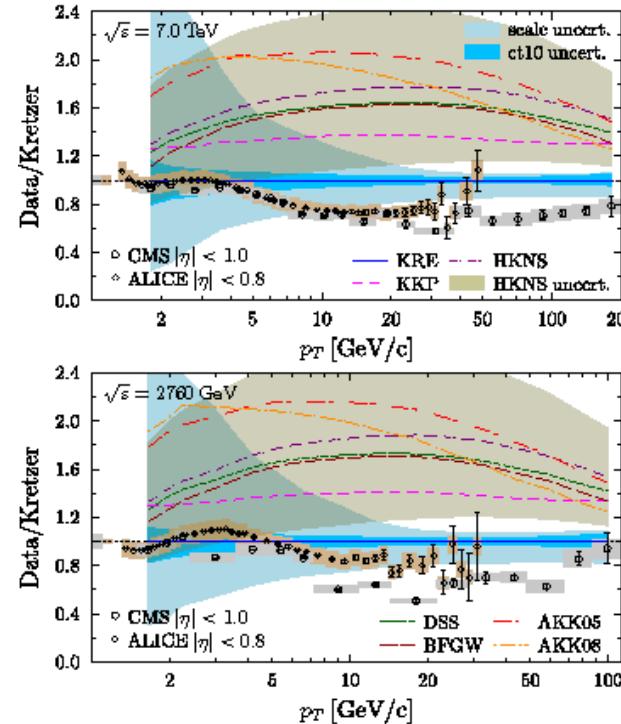
A: To get closer to the parton energy

PHENIX [PRD74 \(2006\) 072002](#)



Avoid (or control)
kinematic biases

d'Enterria, Eskola, Helenius, Paukkunen
[Nucl.Phys. B883 \(2014\) 615-628](#)



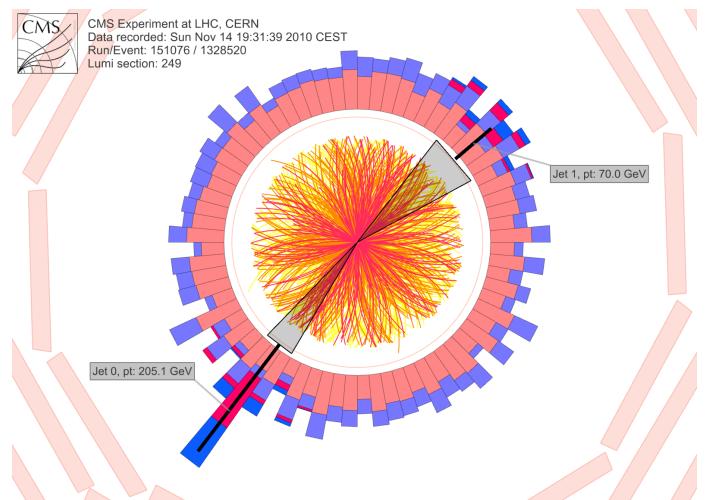
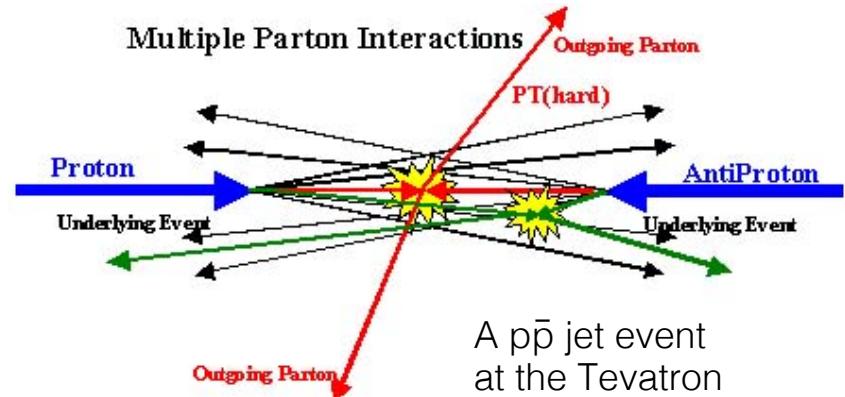
... and the (poorly known)
non-perturbative FFs

But which parton?

- Ambiguous even in pp
 - Multijets, initial and final state radiation
 - Beam remnants, multi-parton interactions

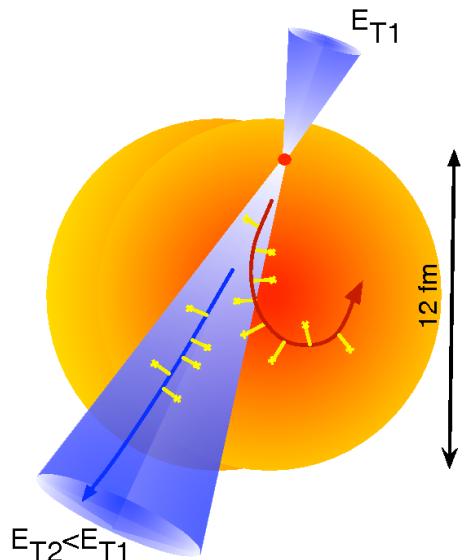
→ Particle-level jets

- A+A
 - Large (flowing) UE
 - Jet-medium interactions

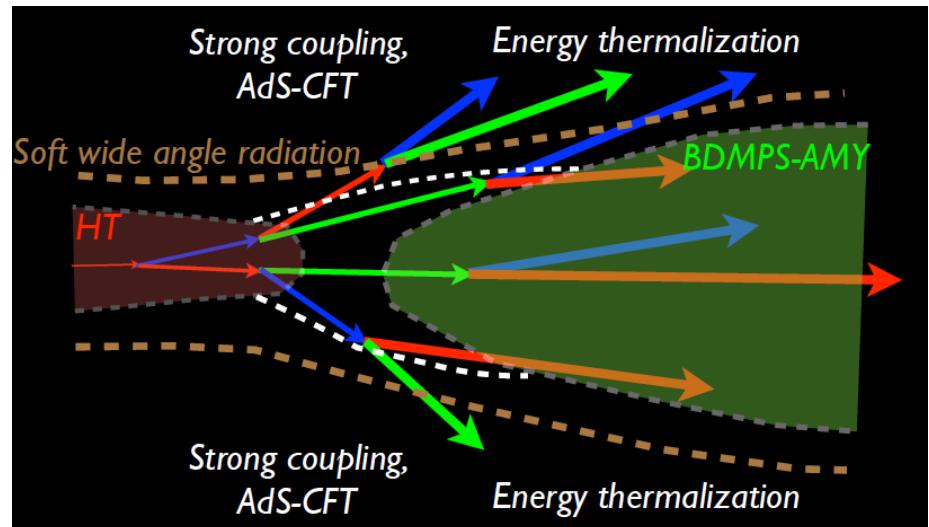


Q: Why probe the QGP w/ jets?

- Novel mechanisms



- Different regimes of applicability, different scales

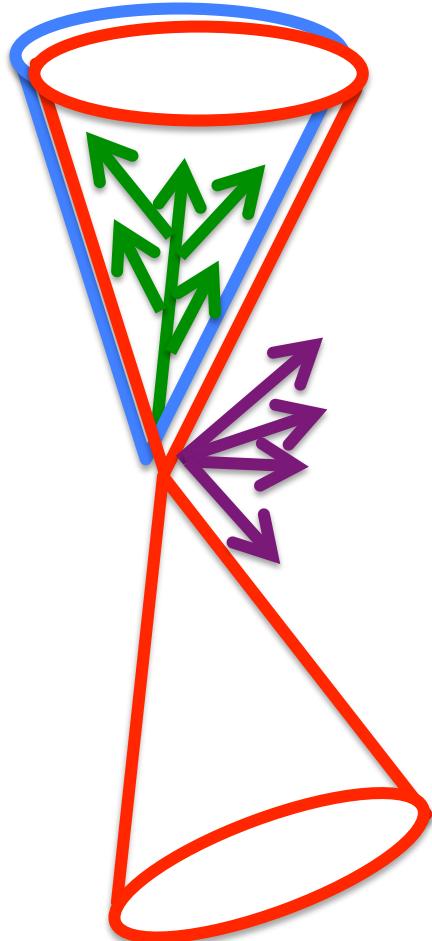


Casalderrey-Solana, Milhano, Weidemann
[J.Phys. G38 \(2011\) 035006](https://doi.org/10.1088/0954-3899/38/3/035006)

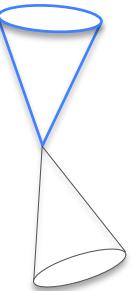
Majumder – Hard Probes 2015

A: To understand the transport properties of the medium in detail, we must understand how parton showers are modified in the QGP to the extent that we can model the entire process

Roadmap

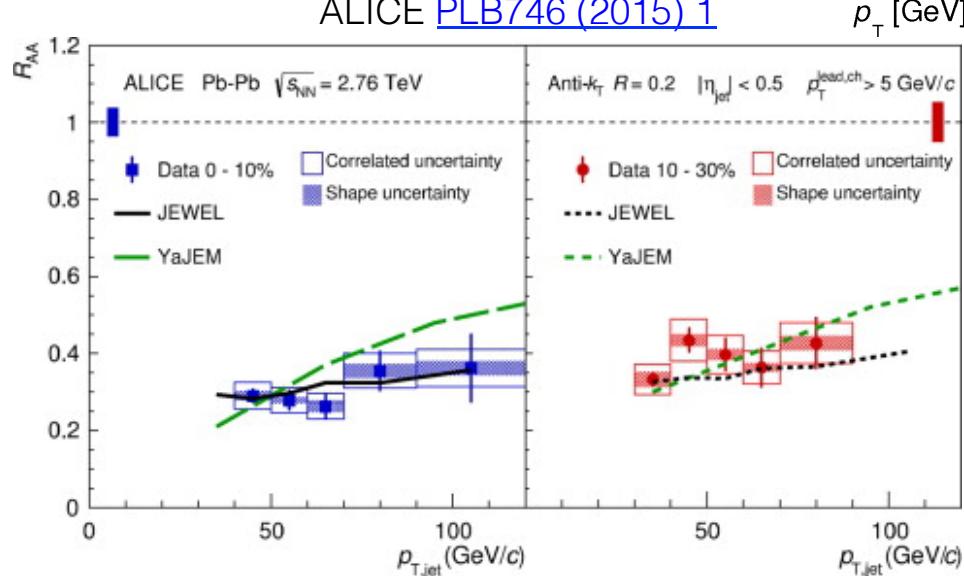
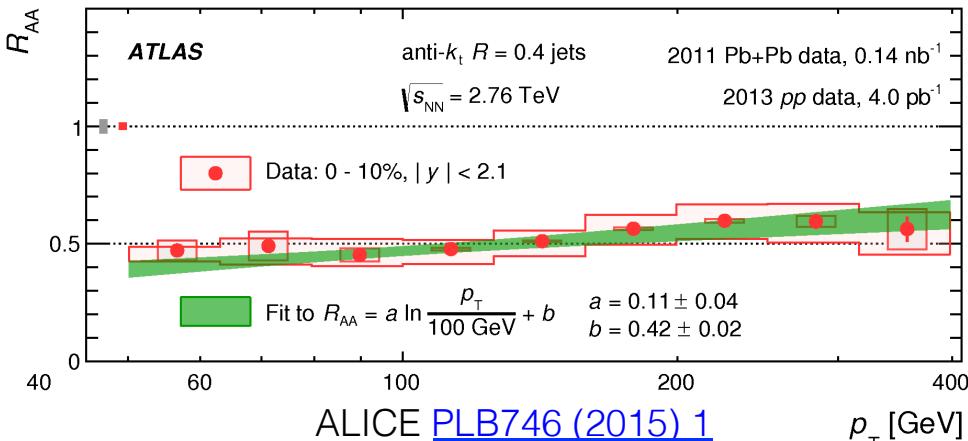


- Single jet: R_{AA} , v_2
- Inter-jet: Dijets, recoil jets
- Intra-jet: ‘FFs’, jet shapes, substructure
- “Detour”: $p(d)+A$
- Extra-jet: Energy flow



Jet spectra: R_{AA}

ATLAS [PRL114 \(2015\) 072302](#)

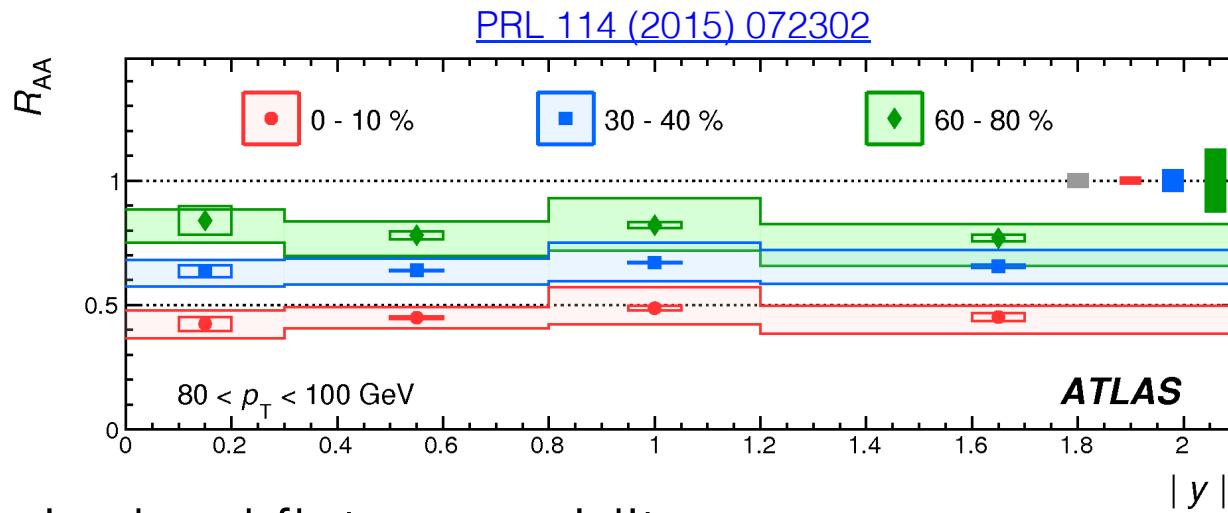


- Flattish $R_{AA} \rightarrow$
 - i.e., not very far from a constant fractional shift*
 - some slope expected from increasing quark-gluon ratio
- ~ Reasonably described by models that get hadron R_{AA}
- Reasonable agreement across experiments given measurement differences (more work needed)

* Not to be equated w/ fractional e-loss if jet-by-jet fluctuations are important (which they are!)

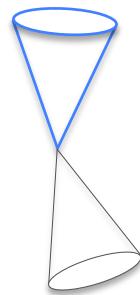


Rapidity dependence of R_{AA}

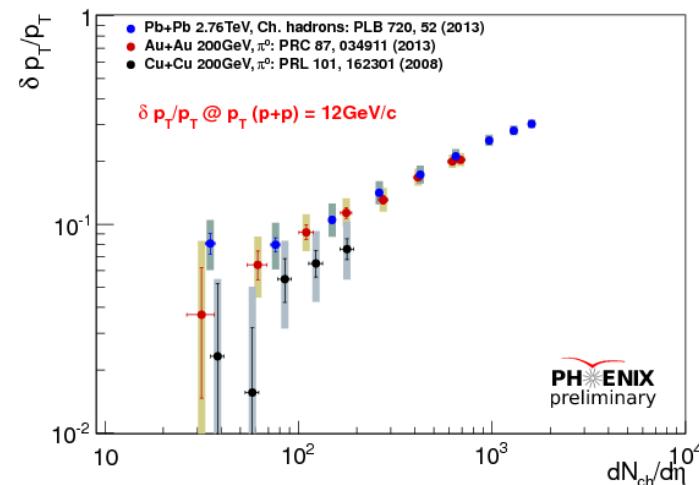
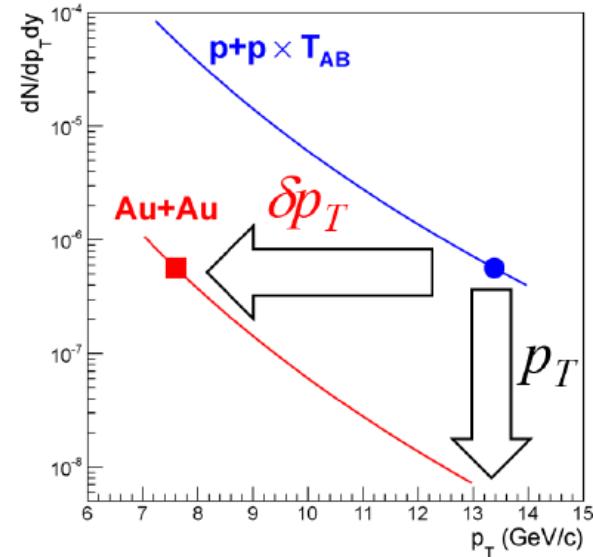


- R_{AA} is dead flat vs. rapidity
- With increasing rapidity:
 - Jet spectrum steepens (R_{AA} should decrease)
 - Quark-to-gluon ratio rises (R_{AA} should increase)
- Fortuitous cancellation?
- Forward jets would offer improved sensitivity
(but difficult to measure) See: Spousta & Cole [arXiv:1504.05169](#)
- Forward jets a focus of CMS HL-LHC upgrades

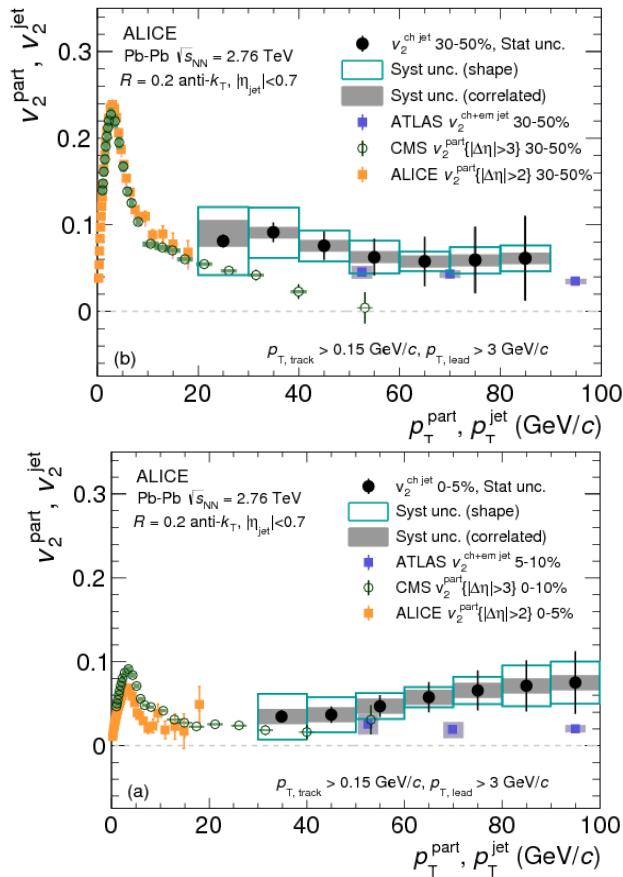
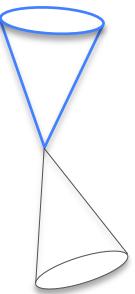
p_T Shift: $\delta p_T/p_T$ (S_{loss})



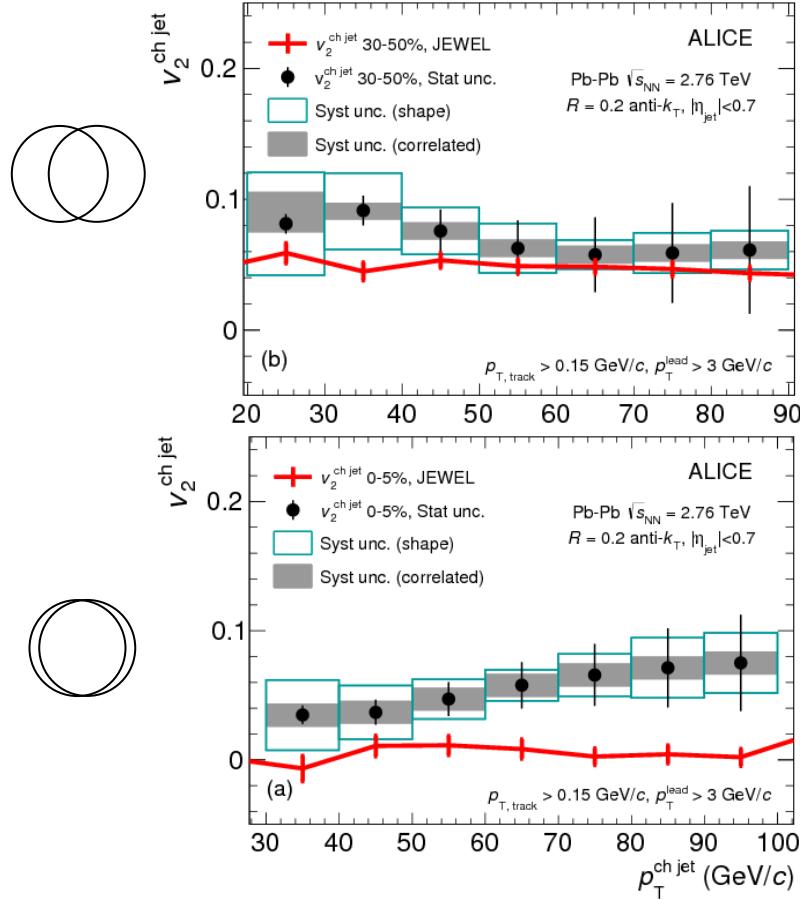
- R_{AA} sensitive to underlying spectral shape
 - p_T shift more useful to compare across \sqrt{s}
 - Scaling:
 - ✓ multiplicity
(or Bjorken energy density)
 - ✗ number of participant nucleons or quarks
- Energy loss mainly driven by energy density



Jet v_2

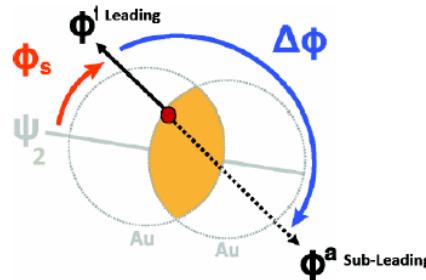
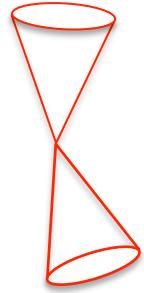


ALICE: [arXiv:1509.07334](https://arxiv.org/abs/1509.07334)
ATLAS: [PRL 111 152301 \(2013\)](https://doi.org/10.1103/PhysRevLett.111.152301)



- Relatively large → up to 10% more jets in-plane than out-of-plane
- Qualitative agreement between ALICE and ATLAS $\langle p_T^{\text{charged jet}} \rangle \approx 0.65 \langle p_T^{\text{full jet}} \rangle$
- Well described by AMPT and by JEWEL

Dijet p_T asymmetry vs. reaction plane



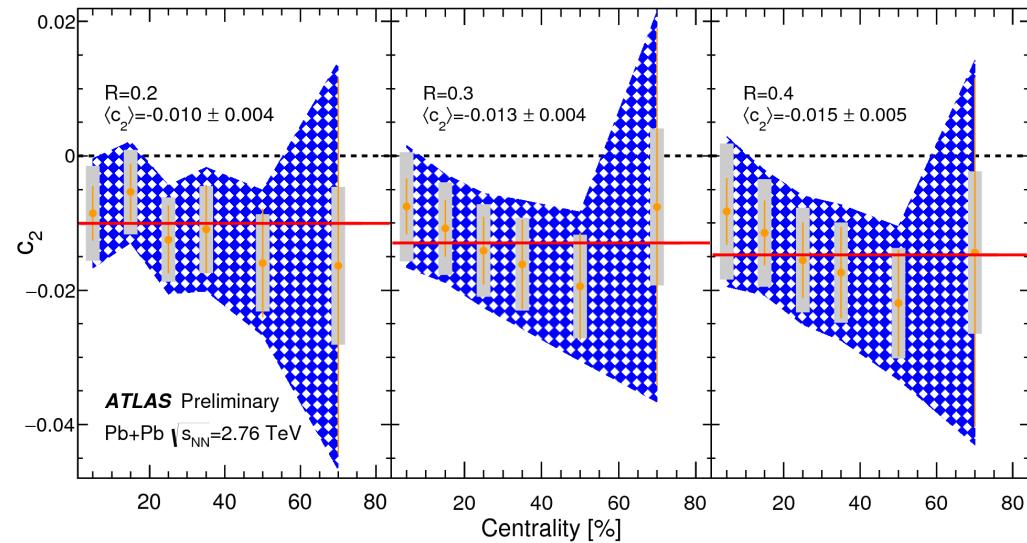
$$\langle A_J \rangle = A_J^0 \left(1 + 2c_2^{\text{obs}} \cos(2(\phi^{\text{lead}} - \Psi_2)) \right)$$

*c*₂ quantifies the EP angle dependence of *A*_J

6

$$A_J = \frac{E_T^{\text{lead}} - E_T^{\text{sublead}}}{E_T^{\text{lead}} + E_T^{\text{sublead}}}$$

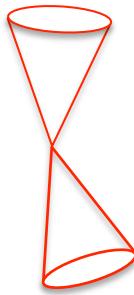
[ATLAS-CONF-2015-021](#)



- Variation of dijet p_T asymmetry small compared to inclusive jet v₂
- What is the correspondence between these two quantities?
- Naïve $\Delta E = \text{const} * L^2 + \text{MC Glauber}$ tuned to match jet R_{AA} and v₂, shows this result is not unexpected^{1,2}
- (Real) model comparisons?

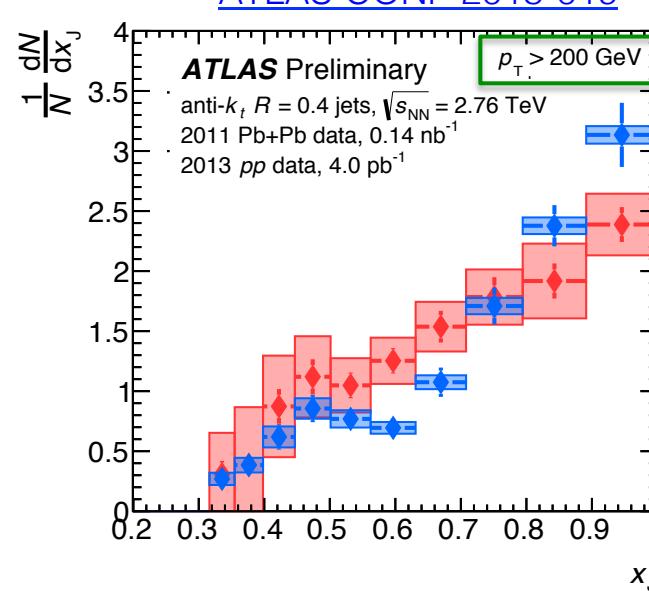
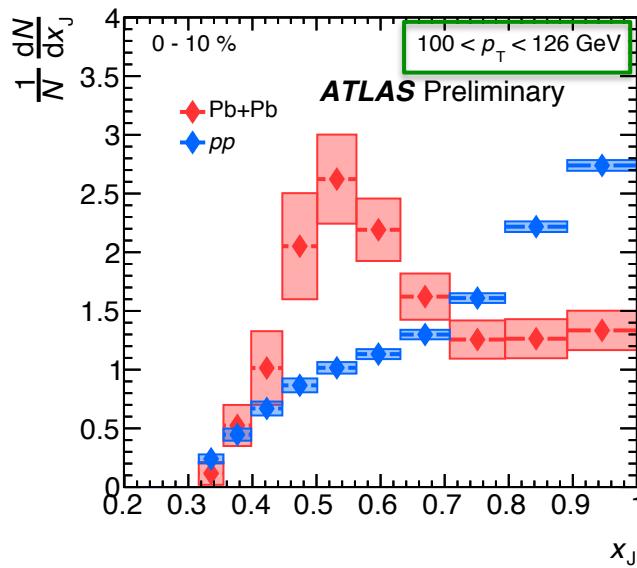
¹Credit: Yetkin Yilmaz

²Blame: This speaker



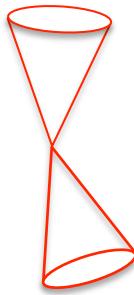
Dijet p_T asymmetry

$x_J = \text{subleading jet } p_T / \text{leading jet } p_T$

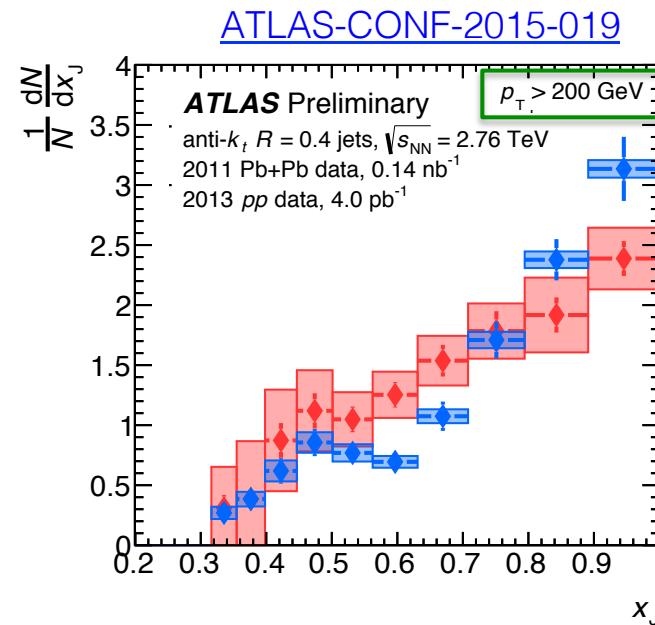
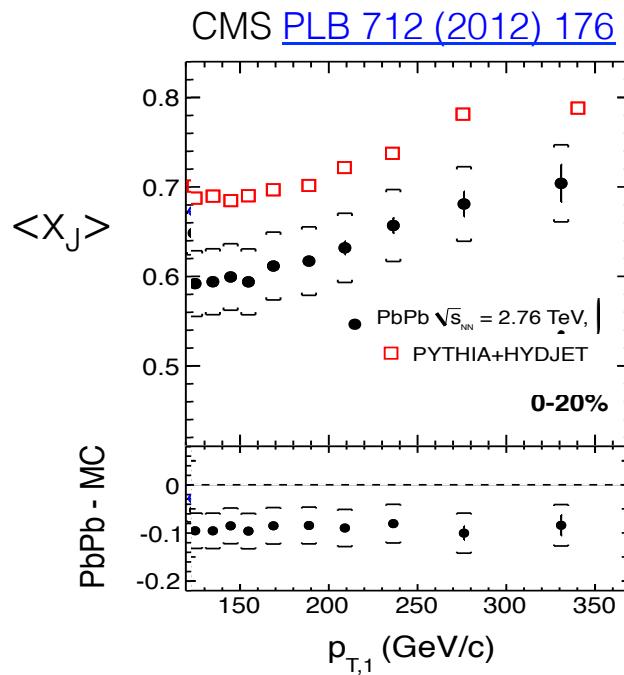


- ATLAS has fully unfolded detector resolution effects for dijet p_T asymmetry
- Difference between Pb+Pb and pp diminishes with leading jet p_T

Dijet p_T asymmetry

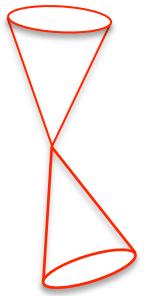


$x_J = \text{subleading jet } p_T / \text{leading jet } p_T$

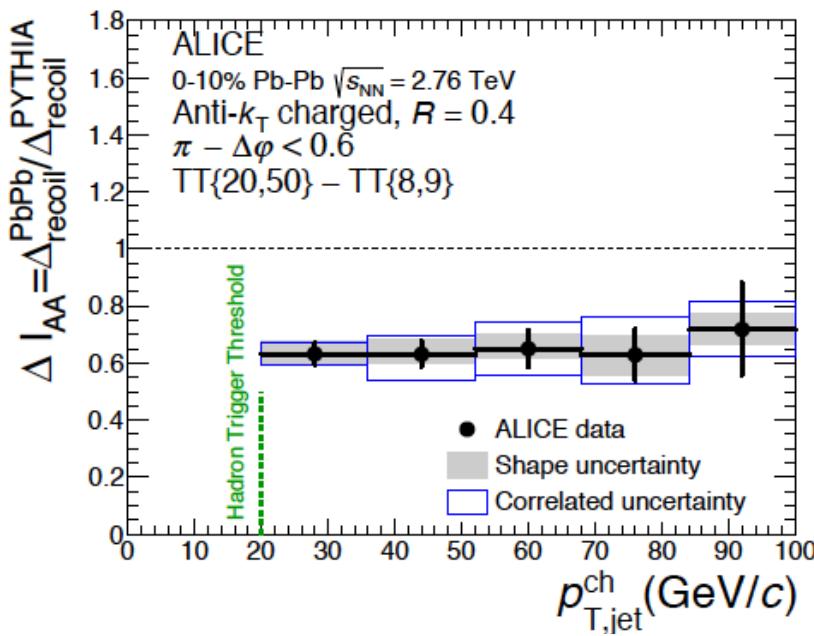


- ATLAS has fully unfolded detector resolution effects for dijet p_T asymmetry
- Difference between Pb+Pb and pp diminishes with leading jet p_T
- Qualitatively different message than CMS → to be followed up

Recoil jets (from hadrons)



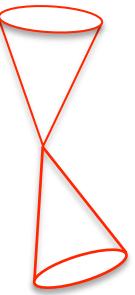
ALICE [arXiv:1506.03984](https://arxiv.org/abs/1506.03984)



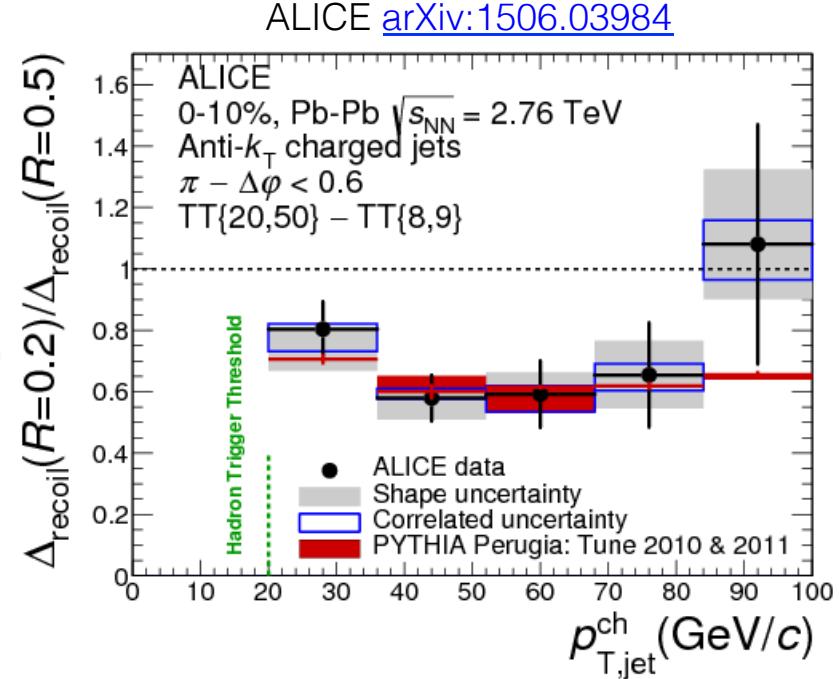
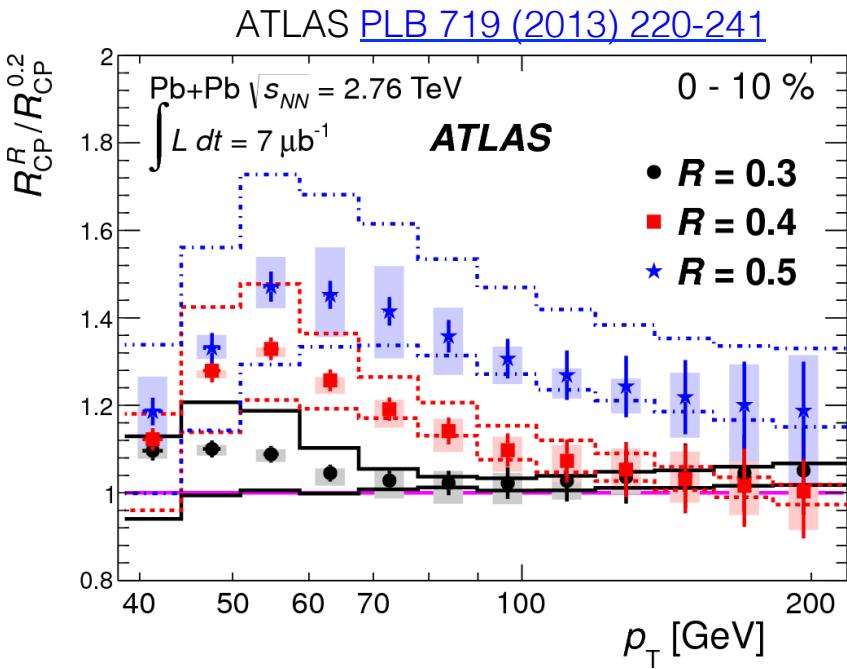
I_{AA} = ratio of recoil jet spectrum
in central PbPb to PYTHIA

- Charged jets opposite a high p_T hadron (20-50 GeV/c)
- Low p_T hadron trigger class jets used for UE subtraction
- Selects a particular population of jets
 - Near-side fragmentation bias (similar to hadron-hadron)
 - Surface / unquenched bias
- Biases evolve with $p_{T,\text{jet}}$

R dependence: inclusive vs. recoil



$$\langle p_T^{\text{charged jet}} \rangle \equiv 0.65 \langle p_T^{\text{full jet}} \rangle$$



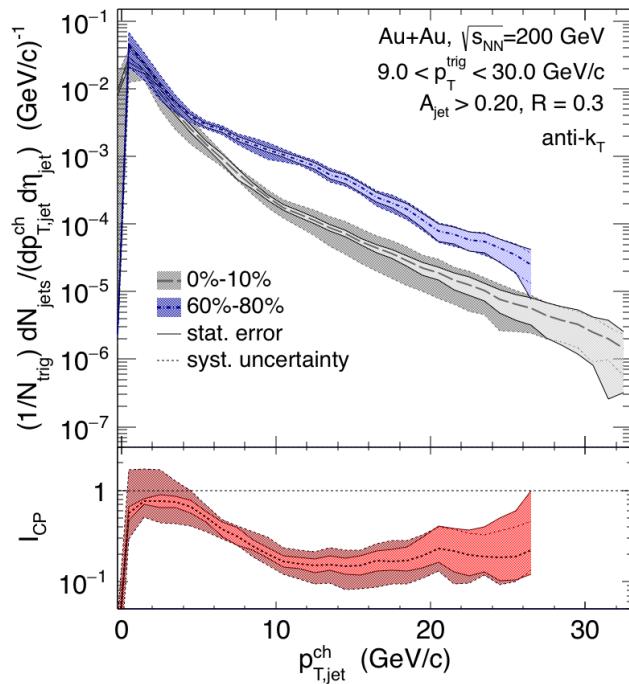
Shift of inclusive jet spectrum with R different for peripheral and central PbPb

Shift of recoil spectrum with R similar for pythia and central PbPb

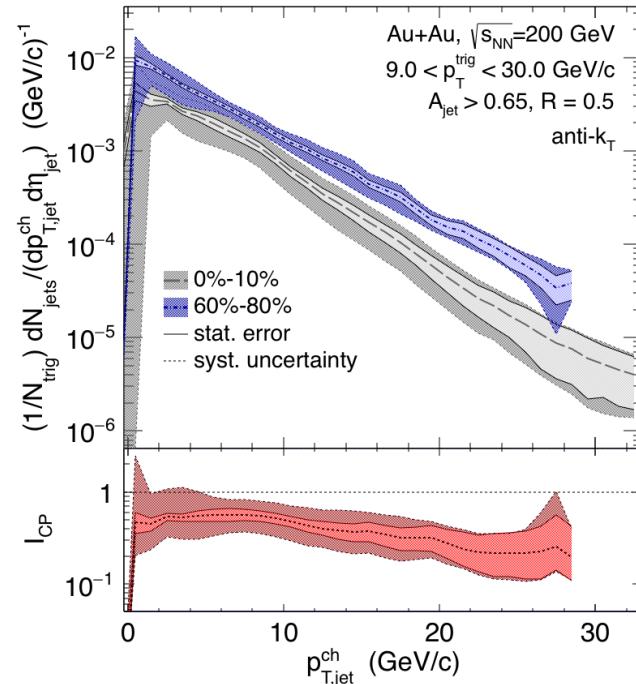
- A different population of jets is selected in the two cases
- Interesting interplay between jet selection and pathlength

Recoil jets at RHIC

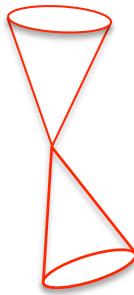
R=0.3



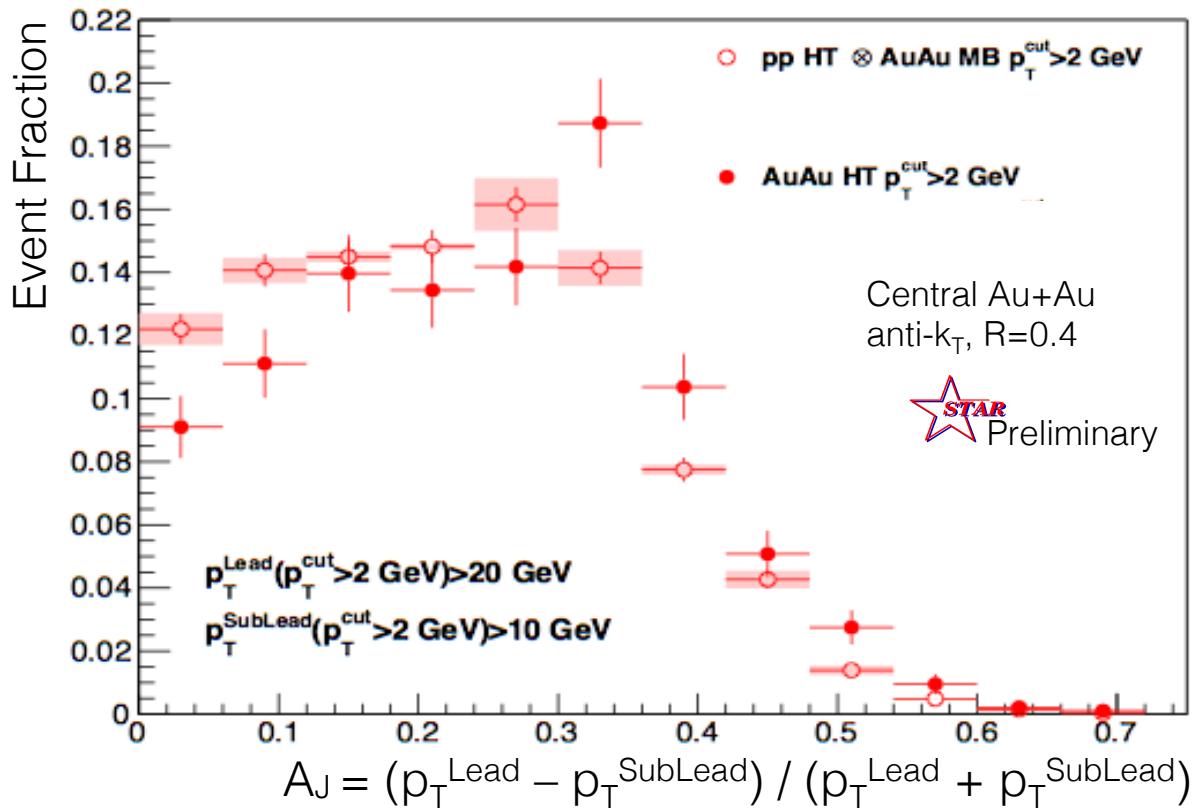
R=0.5



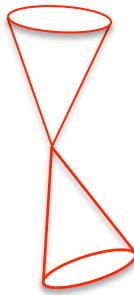
- Similar measurement to ALICE, except
 - I_{CP} instead of I_{AA}
 - 9-30 GeV/c charged hadrons instead of 20-50 GeV/c
- STAR does see a reduced suppression with increasing cone size
- Caution: trigger condition may sample different pathlengths for different \sqrt{s}
- Nevertheless, difference between RHIC and LHC is intriguing



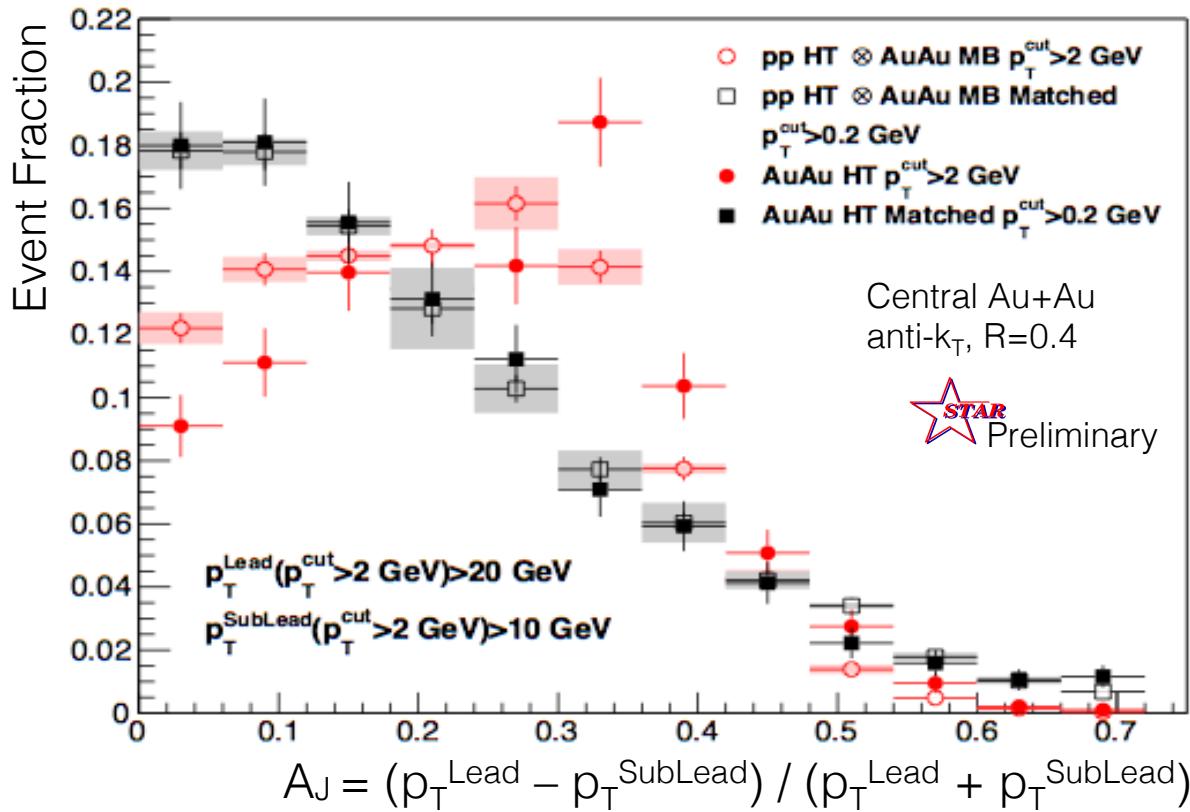
Dijet imbalance at RHIC



- With constituent cut of 2 GeV/c anomalous imbalance is observed



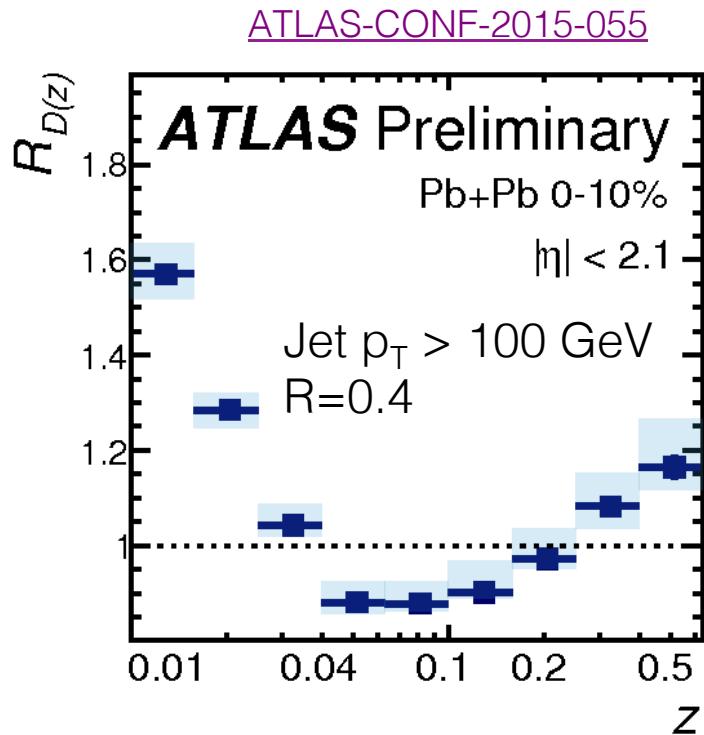
Dijet imbalance at RHIC



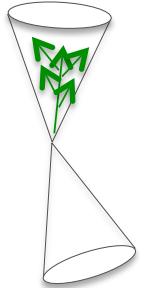
- With constituent cut of 2 GeV/c anomalous imbalance is observed
- For matched dijets w/o constituent cut, imbalance disappears!
- Is this a very particular population of jets or is quenching very different at RHIC and LHC energies (or both)?

Looking inside jets

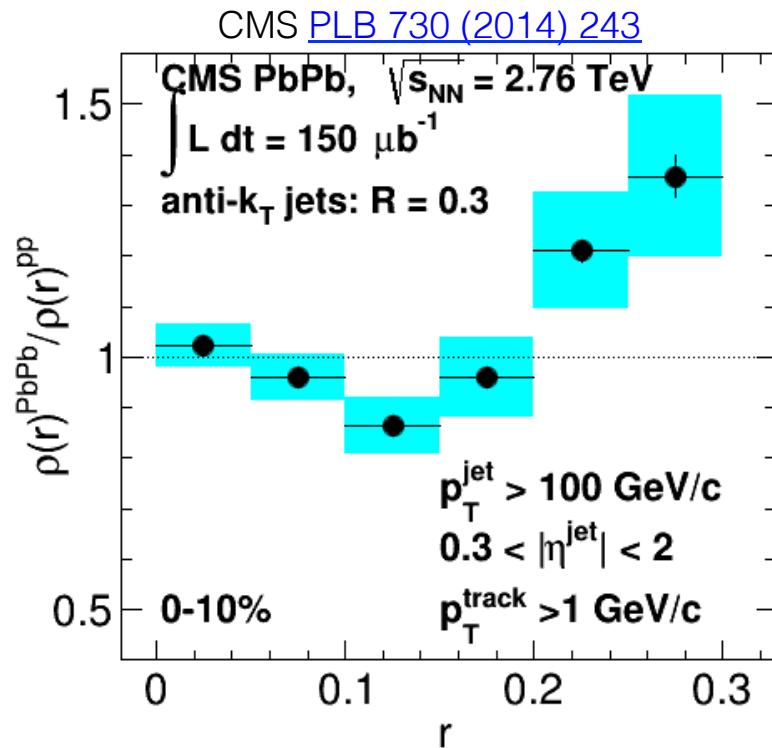
Jet fragmentation (longitudinal)



$$\rho(r) = \frac{1}{\delta r} \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \frac{\sum_{\text{tracks} \in (r_a, r_b)} p_{\text{T}}^{\text{track}}}{p_{\text{T}}^{\text{jet}}}$$

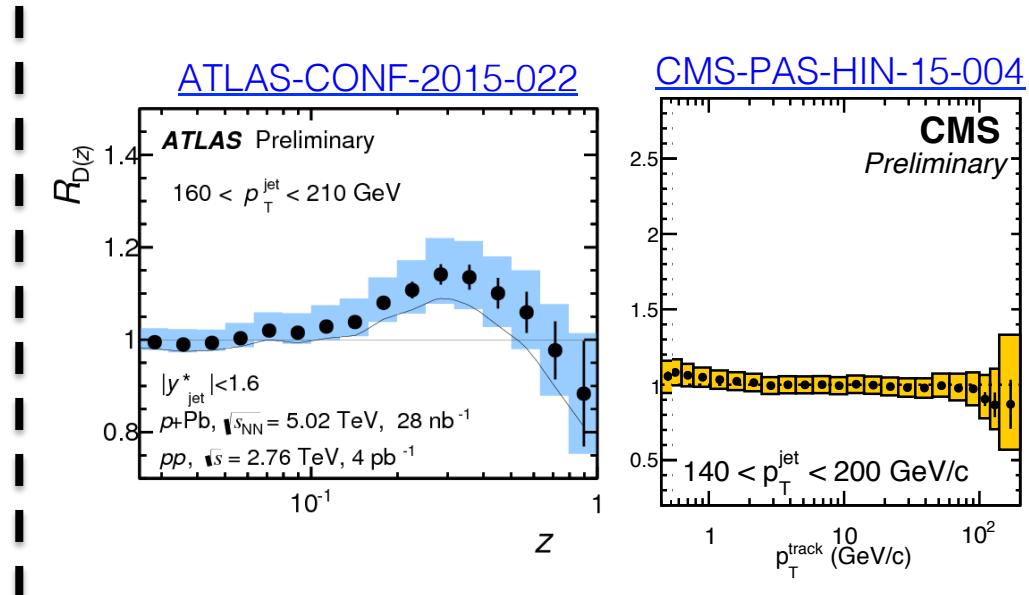
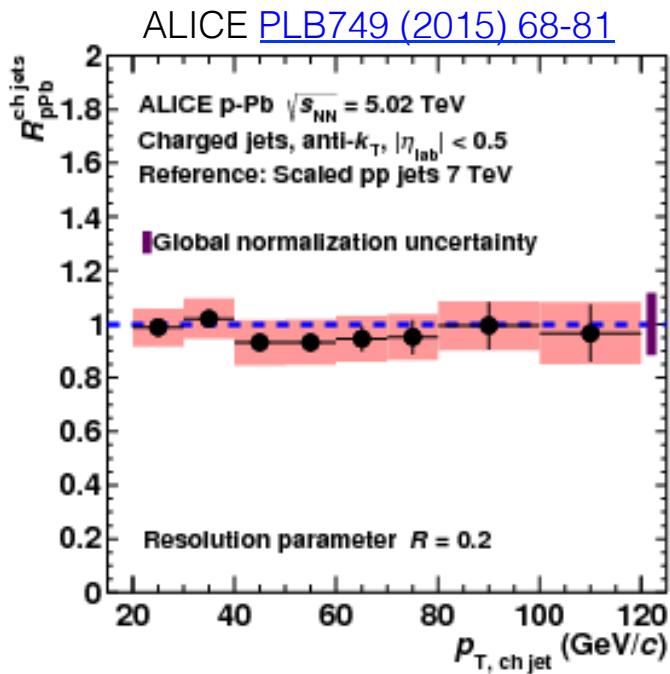


Jet shape (transverse)



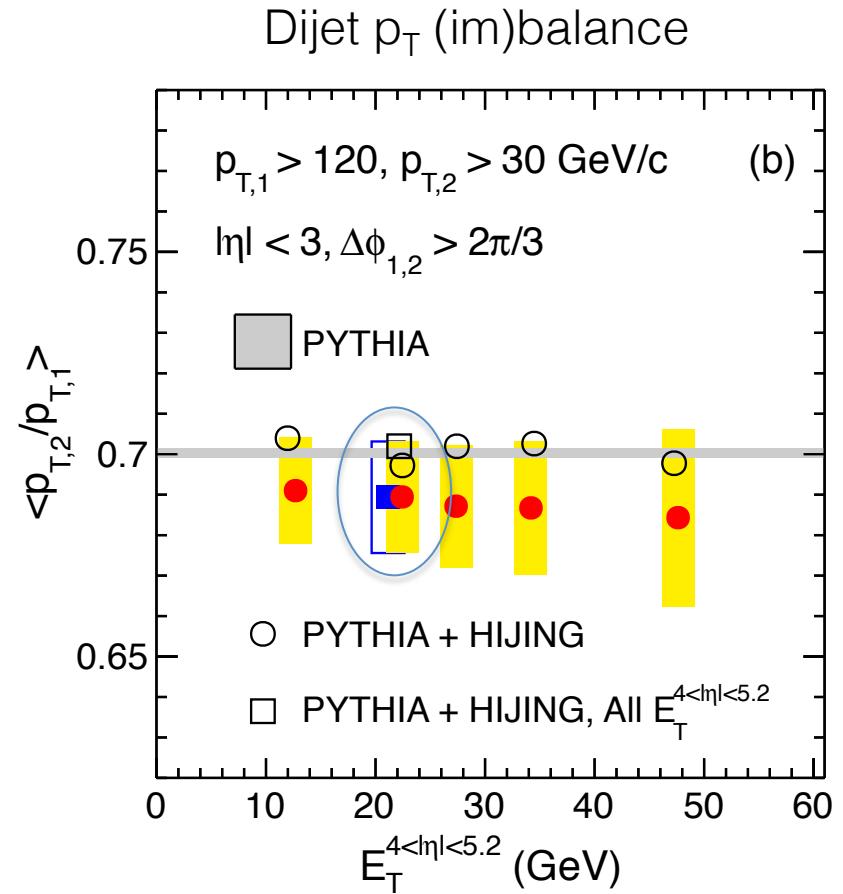
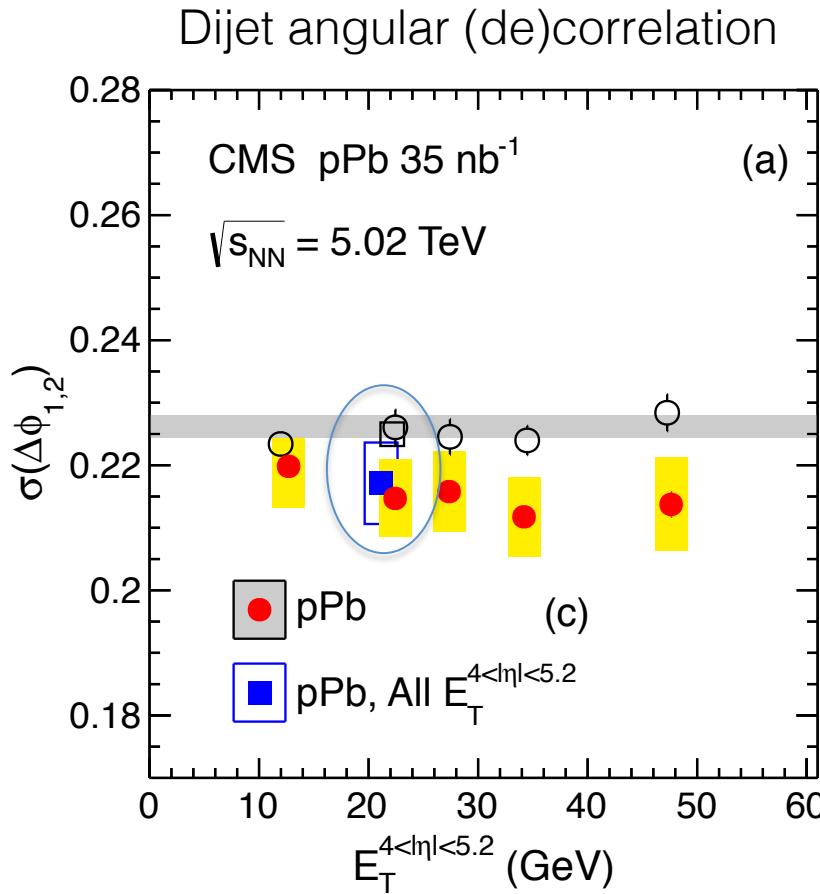
- Excess at low p_T and large angle clearly a feature of jet quenching
- Modest modification of jet structure at small angle & medium to high p_T
- To what extent is this due to quenching changing the q/g fraction?

Jet production and fragmentation in p+A



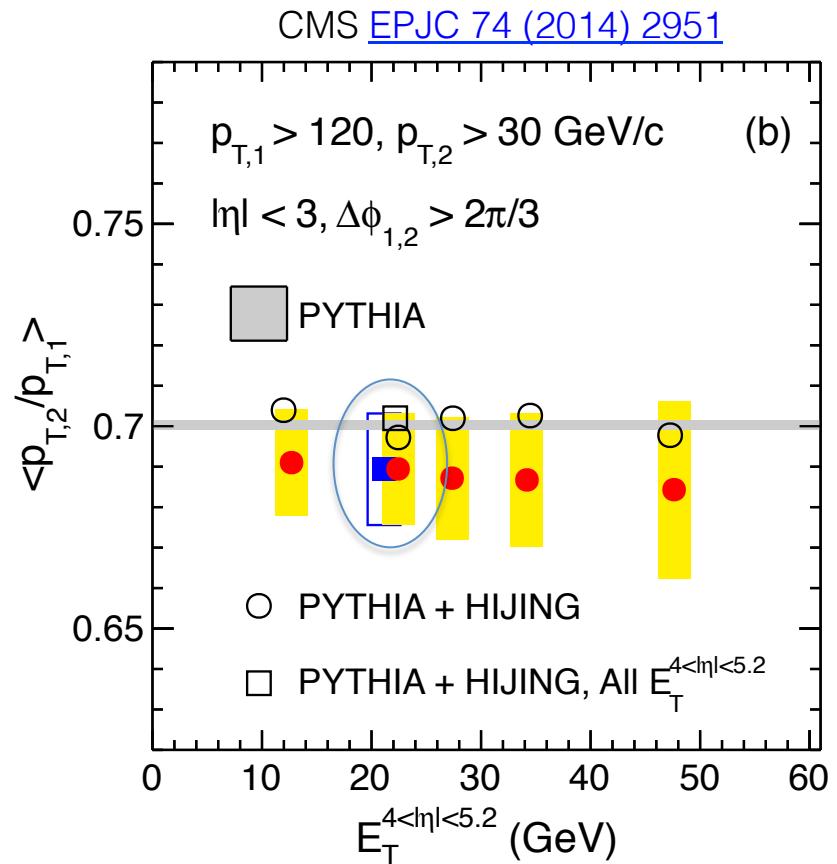
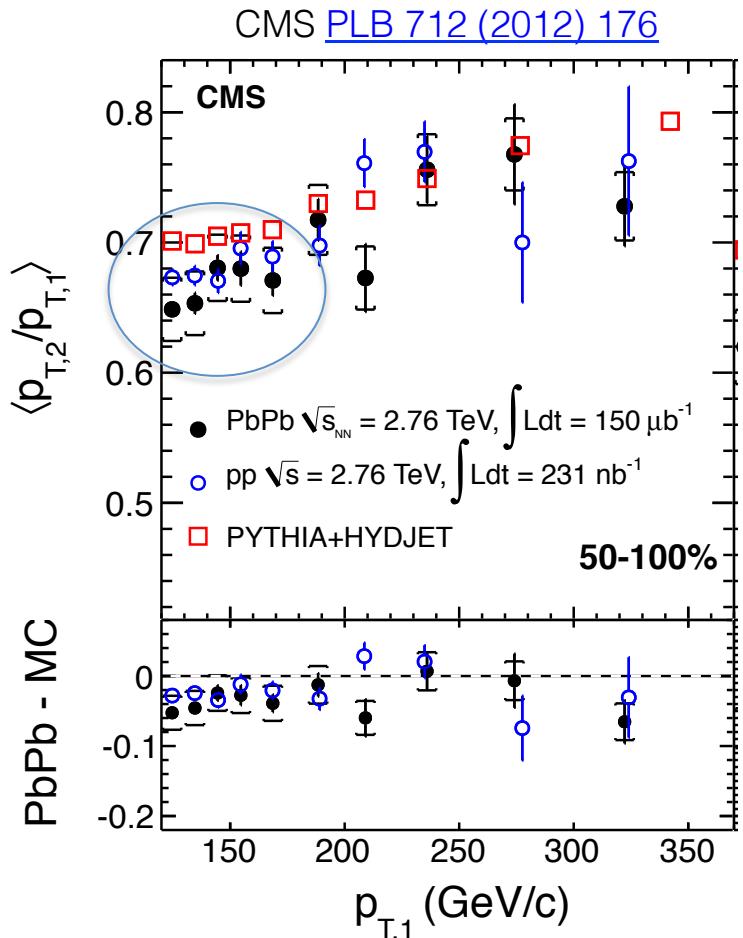
- Jet spectra not very modified (w/i errors), all expt's agree
- The jury is still out on jet fragmentation → urgent need for 5 TeV pp reference data (w/ matching parton luminosity)

Jet quenching in p+A?



No sign yet of angular decorrelation or anomalous p_T imbalance

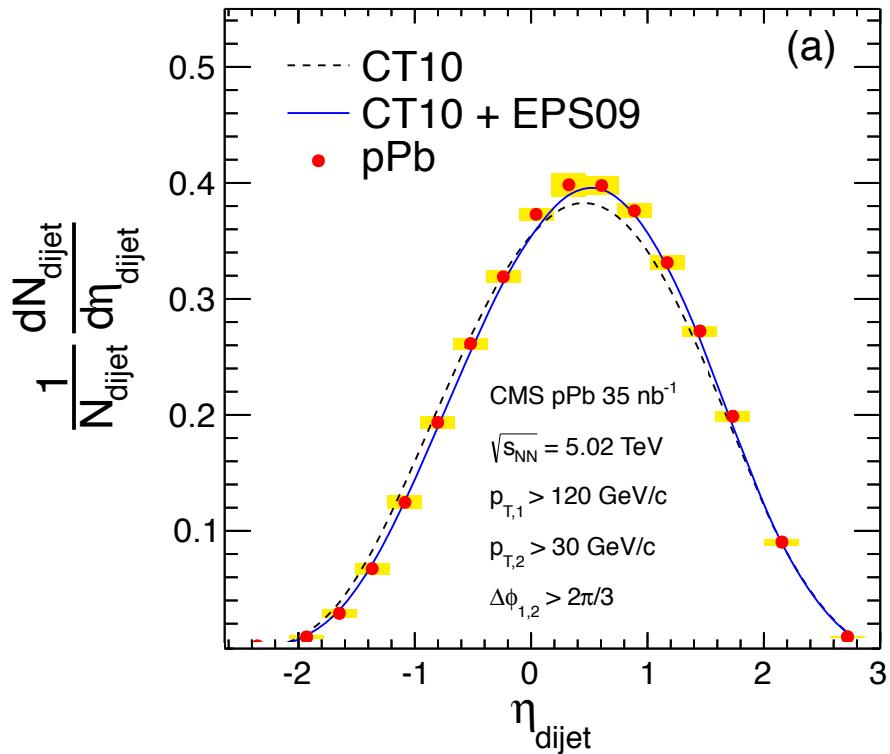
Jet quenching in p+A?



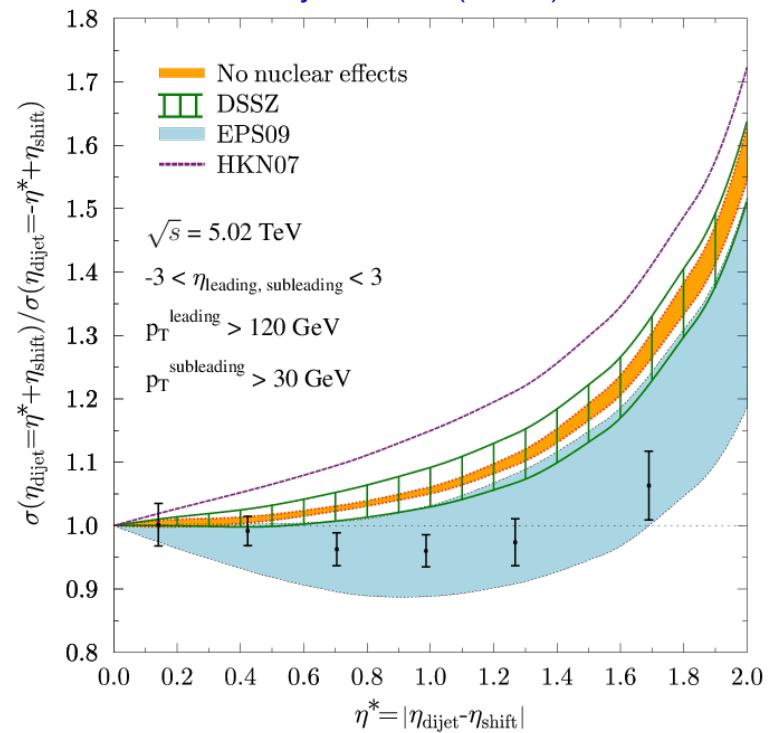
- Already in 50-100% dijet asymmetry is not *much* different than in pPb ($dE_T/d\eta$ per participant in min. bias pPb more like 70-100% PbPb)
- More data will help map out turn off (or not) of final state effects in PbPb

Nuclear PDFs from p+A

CMS [EPJC 74 \(2014\) 2951](#)

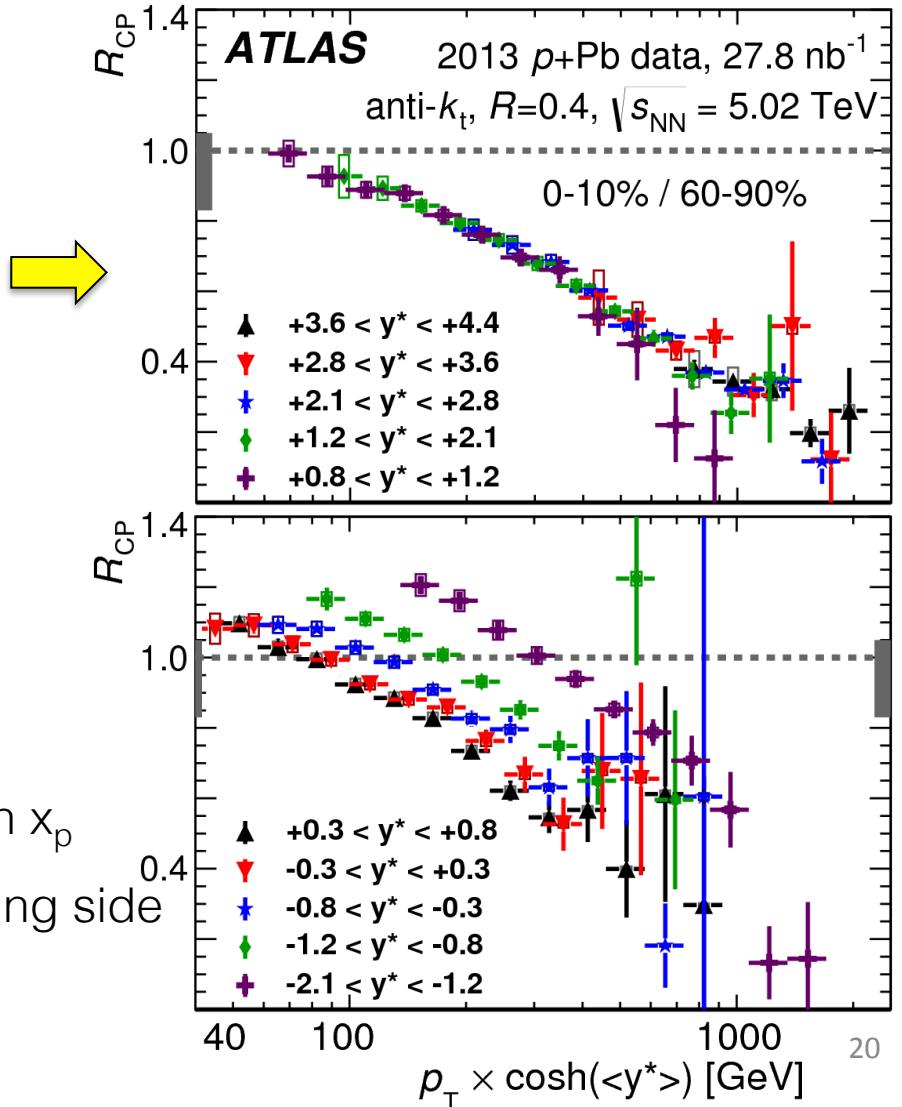
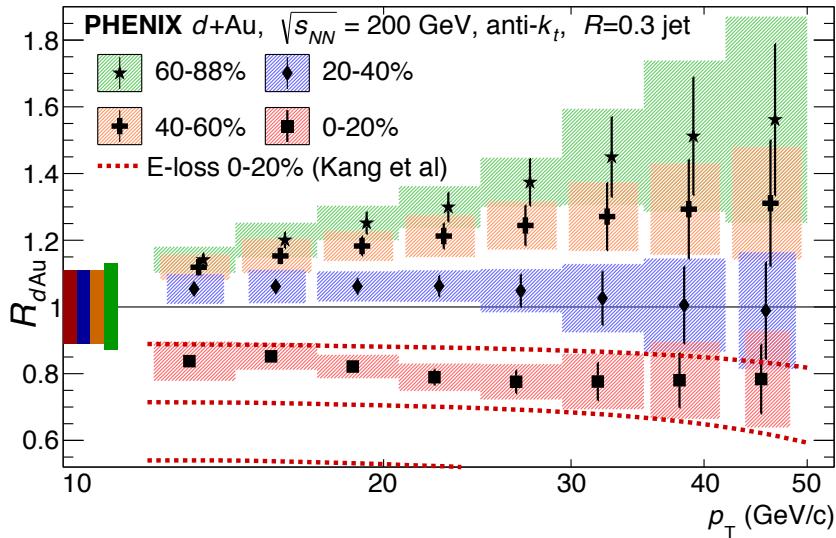


Paukkunen, Eskola, Salgado
[Nucl.Phys. A931 \(2014\) 331-336](#)



- Nuclear effects distort the dijet rapidity distribution
- Relative normalization insensitive to jet reconstruction systematics
- Best constraint yet on the nuclear glue from the LHC
- With Run 2: dijet η vs dijet mass to probe both x_p/x_{Pb} and Q^2

Centrality dependence of hard probes in p+A



- Unexpected “centrality” dependence
- R_{CP} scales w/ jet energy for forward jets
- Forward (p-going): jet energy \sim Bjorken x_p
- Anti-correlation btwn x_p and E_T on A-going side

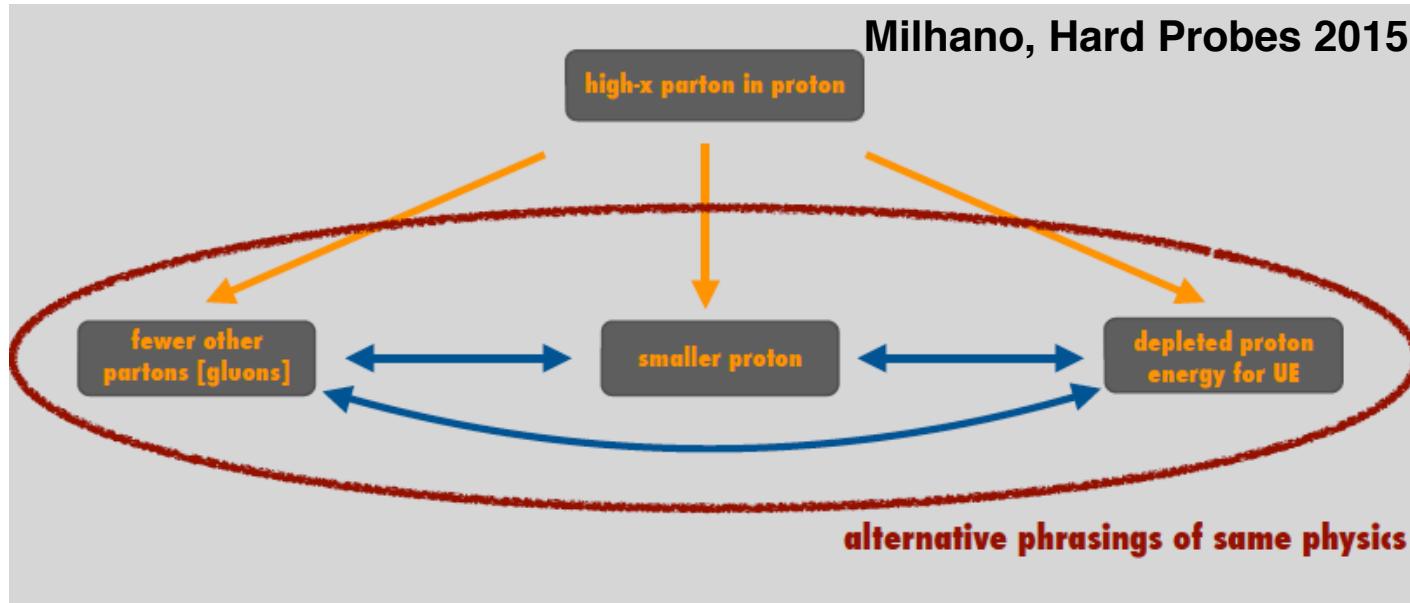
ATLAS [PLB 748 \(2015\) 392-413](#)

PHENIX [arXiv:1509.04657](#)



Centrality dependence of hard probes in p+A

- Several proposed mechanisms/models

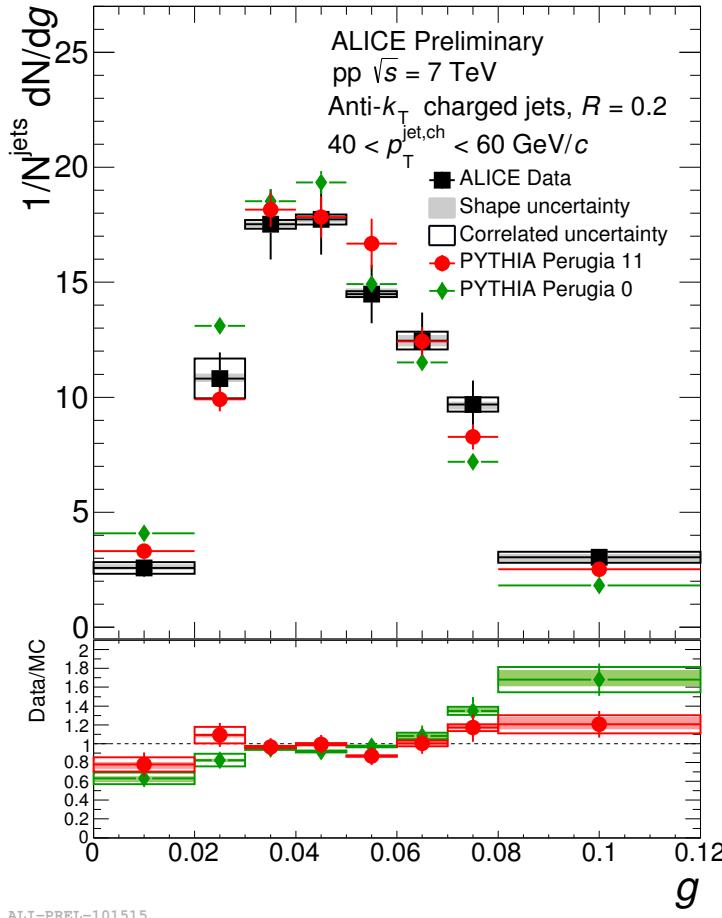


- Based on measurements in pp, not a trivial consequence of energy conservation [ATLAS-CONF-2015-019](#)
- Can we measure energy loss in “central” p+A or study the impact parameter dependence of nPDFs in a well-controlled manner?
- Underscores one of the physics cases for an Electron-Ion Collider



Jet substructure

pp @ 7 TeV

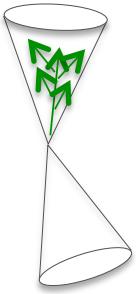


$$g = \sum_{i \in \text{jet}} \frac{p_T^i}{p_T^{\text{jet}}} |r_i|$$

r_i is distance between constituent i and jet axis

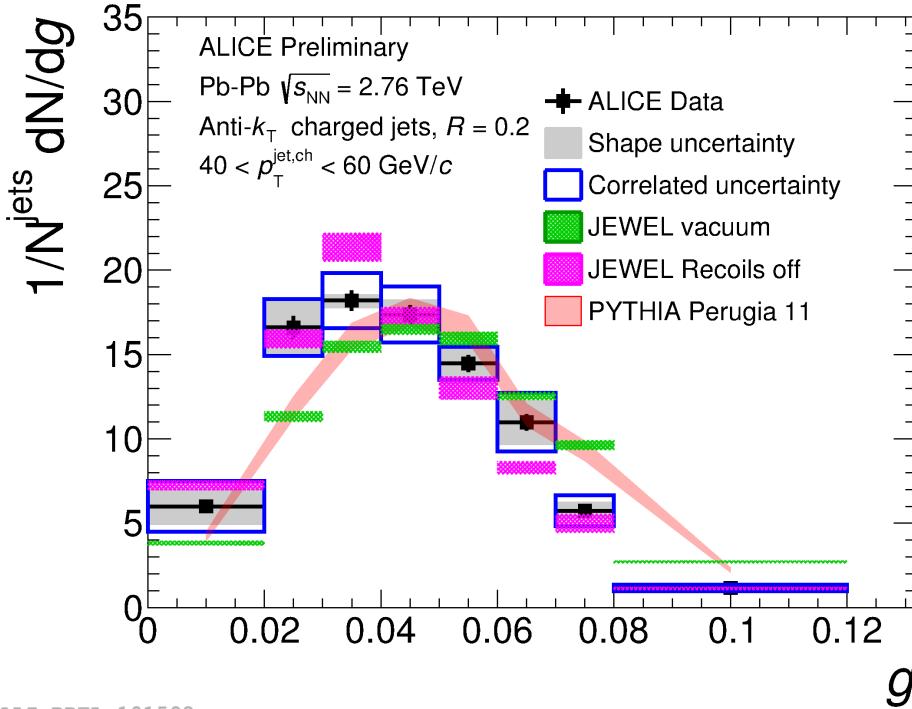
- Radial moment (girth) is a p_T -weighted width of the jet: collimated jets have lower g
- Reasonably well described by recent PYTHIA Perugia tune

Also measured by ALICE: dispersion $p_T D$, and leading-subleading track



Jet substructure

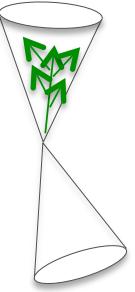
Pb-Pb @ 2.76 TeV



ALI-PREL-101592

$$g = \sum_{i \in \text{jet}} \frac{p_T^i}{p_T^{\text{jet}}} |r_i|$$

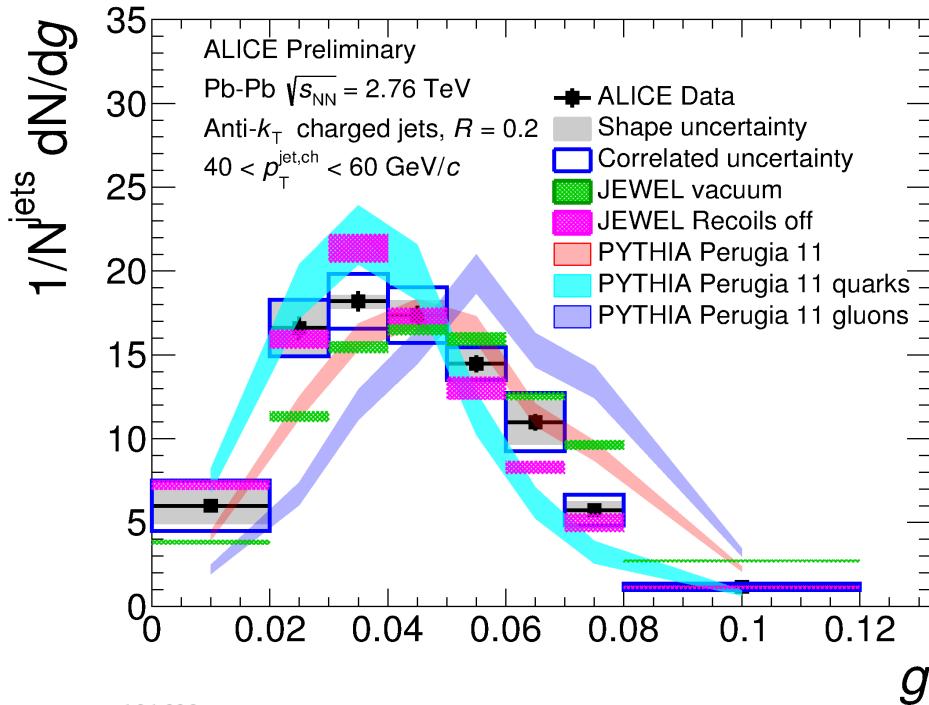
r_i is distance between constituent i and jet axis



- Jets shift towards lower g
i.e., more collimated
- Similar trend in JEWEL
(recoil turned off)

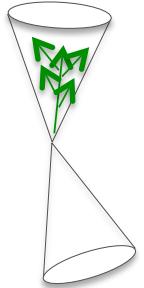
Jet substructure

Pb-Pb @ 2.76 TeV



ALI-PREL-101608

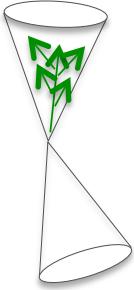
- Collimation or preferential gluon quenching (or both)?
- Substructure observables should discriminate not only quenching mechanisms, but flavor selection effects (and their interference)



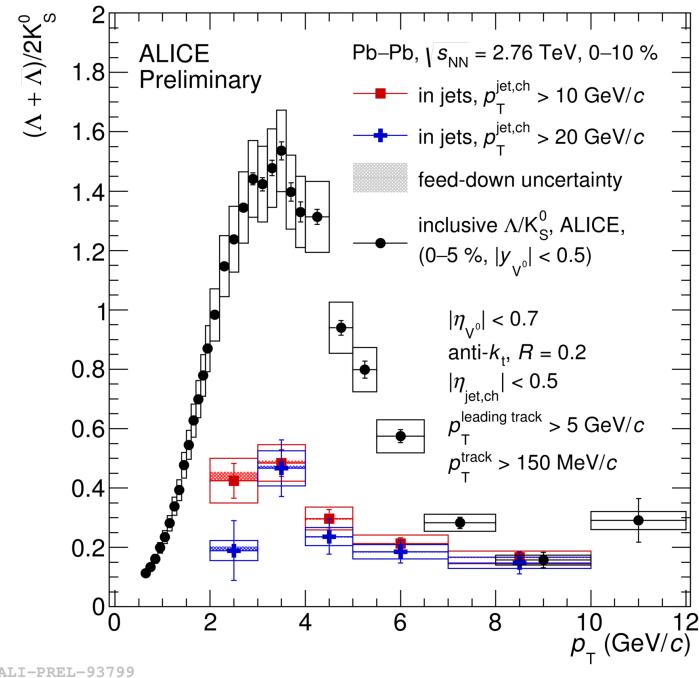
$$g = \sum_{i \in \text{jet}} \frac{p_T^i}{p_T^{\text{jet}}} |r_i|$$

r_i is distance between constituent i and jet axis

- Jets shift towards lower g
i.e., more collimated
- Similar trend in JEWEL (recoil turned off)
- PbPb jets more quark-like



Jet hadrochemistry



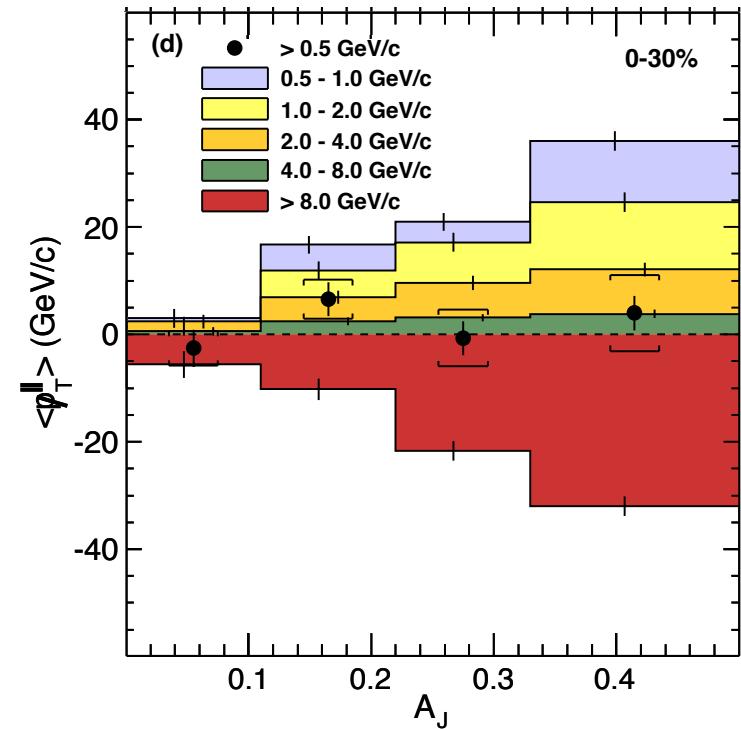
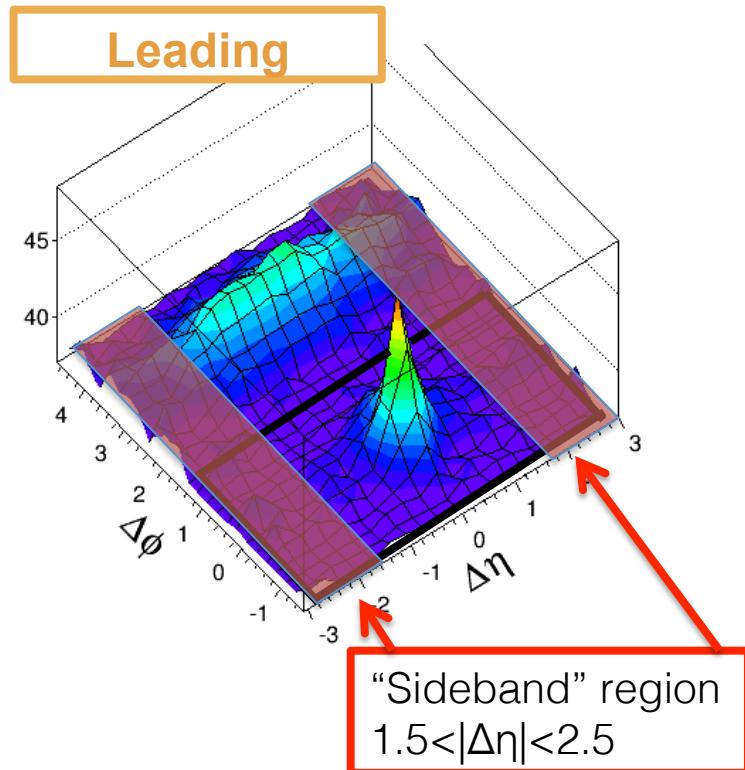
- No strong modification of jet hadrochemistry (baryon/meson) in jets
- Clean separation between fragmentation and recombination regimes



Quenched energy flow

Two approaches used by CMS:

- Jet track correlations
- Missing p_T^{\parallel}



Also, top-down approach of ATLAS via “neighboring jets”



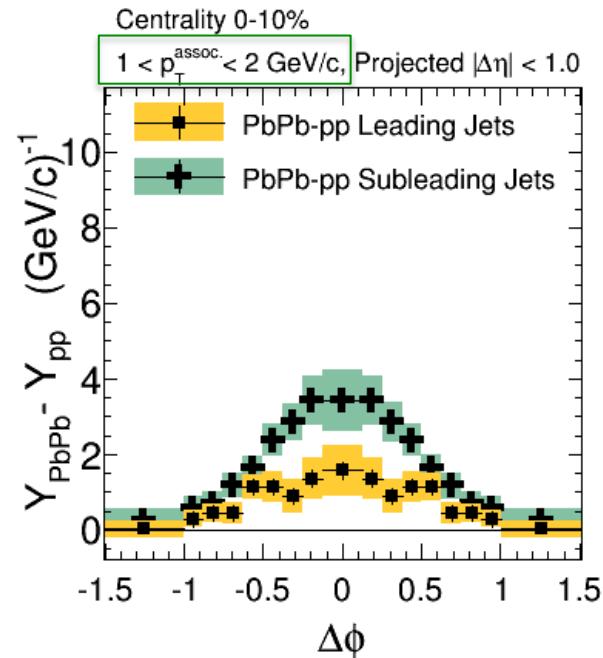
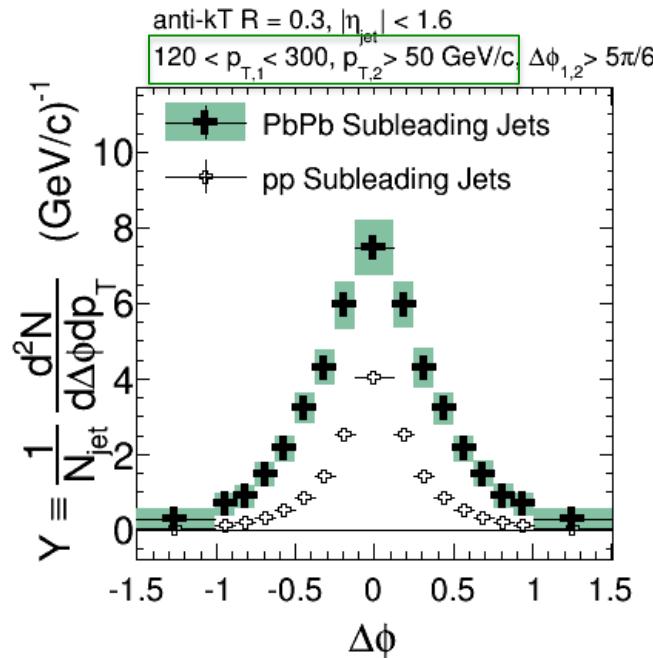
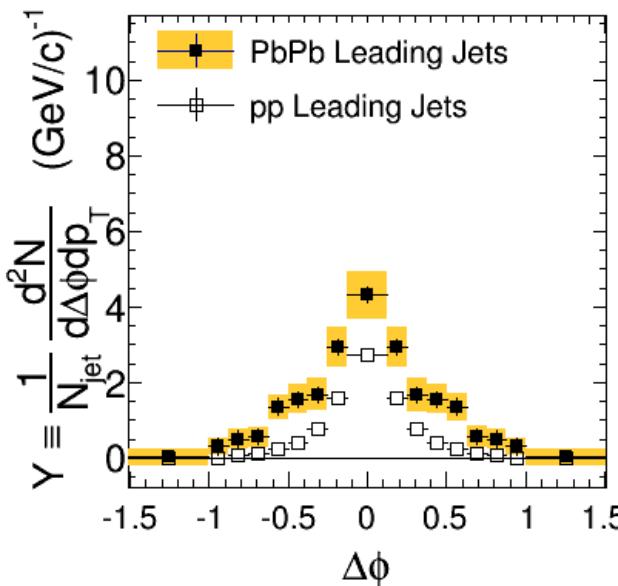
Angular (re)distribution

Jet-track correlations

CMS Preliminary

PbPb $166 \mu\text{b}^{-1}$ (2.76 TeV)

pp 5.3 pb^{-1} (2.76 TeV)

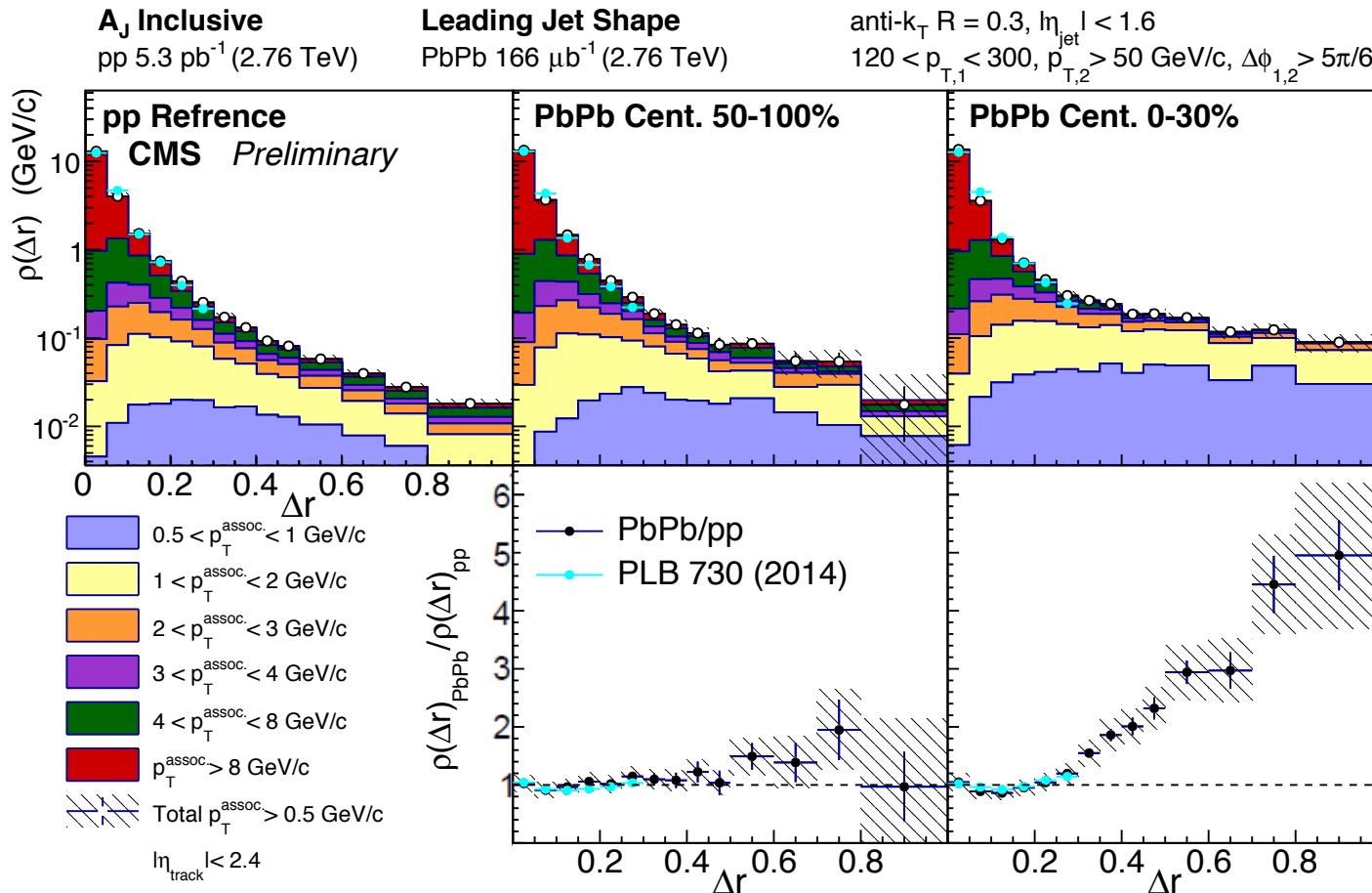


- Broad angular distribution of low p_T jet ‘fragments’
- Also seen for leading jets
- Departure from a pure surface bias picture

$$\rho(r) = \frac{1}{\delta r} \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \frac{\sum_{\text{tracks} \in (\mathbf{r}_a, \mathbf{r}_b)} p_{\text{T}}^{\text{track}}}{p_{\text{T}}^{\text{jet}}}$$



Jet shapes to large angle

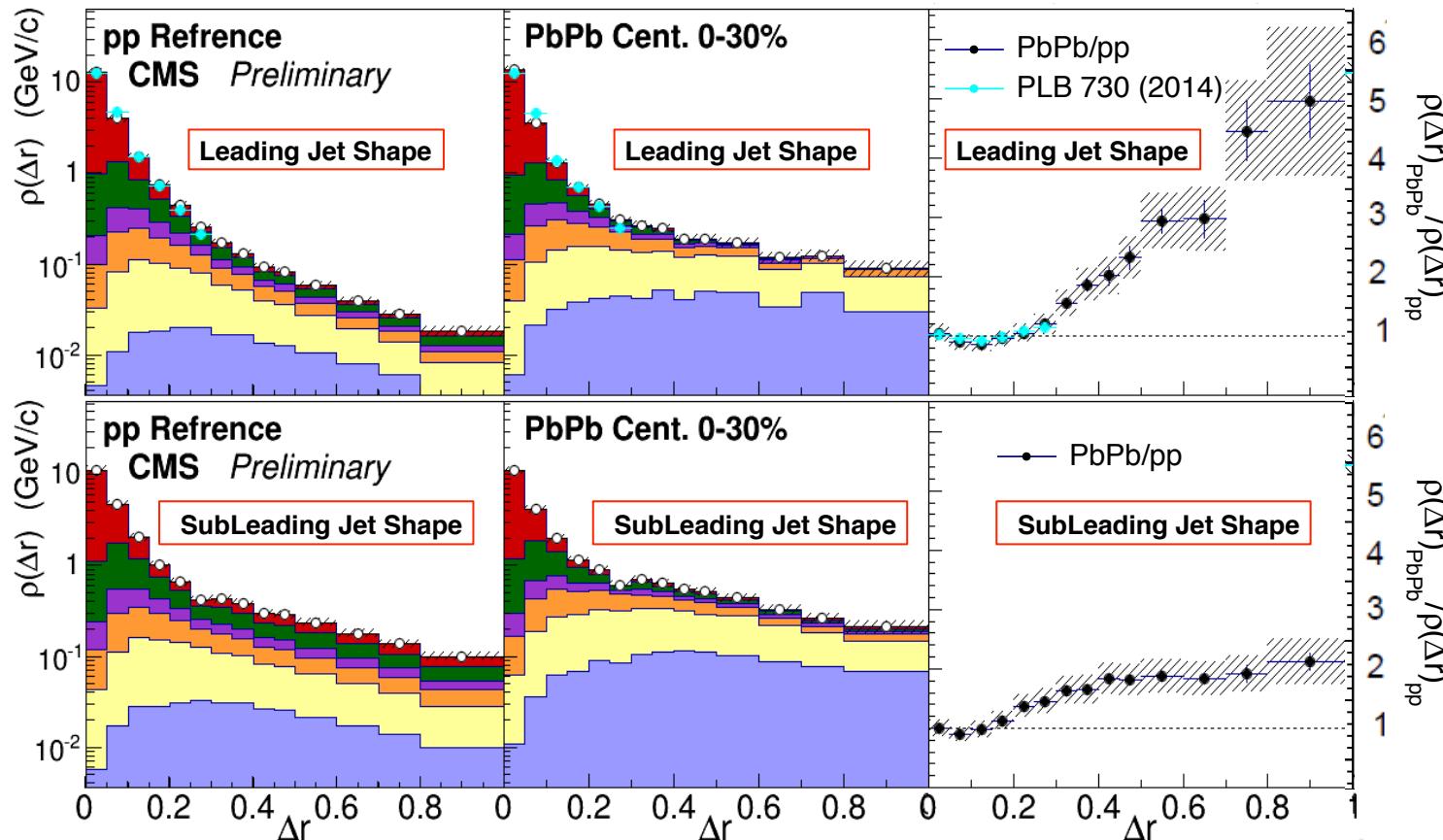


- Radial profile of jet (+ radiation + nearby jet) momentum out to 1 unit of Δr!
- Sizable modification of momentum flow, ratio increasing with angle

$$\rho(r) = \frac{1}{\delta r} \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \frac{\sum_{\text{tracks} \in (r_a, r_b)} p_{\text{T}}^{\text{track}}}{p_{\text{T}}^{\text{jet}}}$$



Jet shapes to large angle Leading vs. subleading

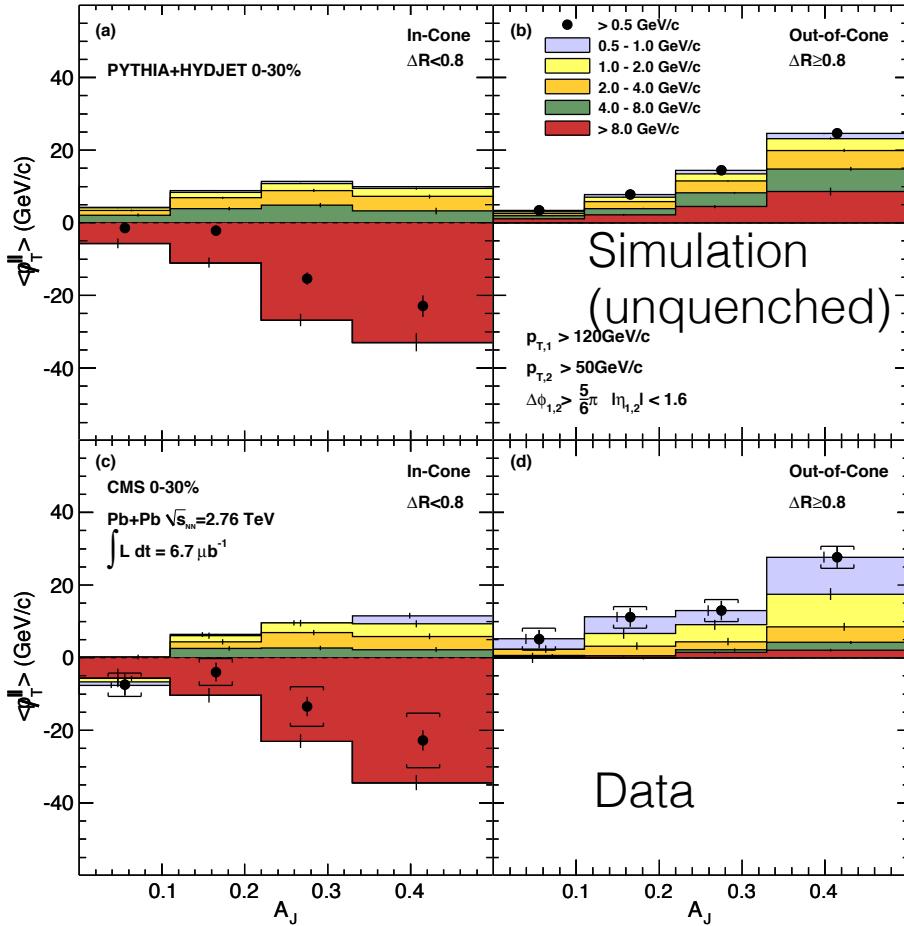


- At first glance subleading jet looks less modified than leading in PbPb
- Driven by the difference between leading and subleading in pp
→ Handle reference comparisons with care



Missing p_T^{\parallel} : In/out of cone

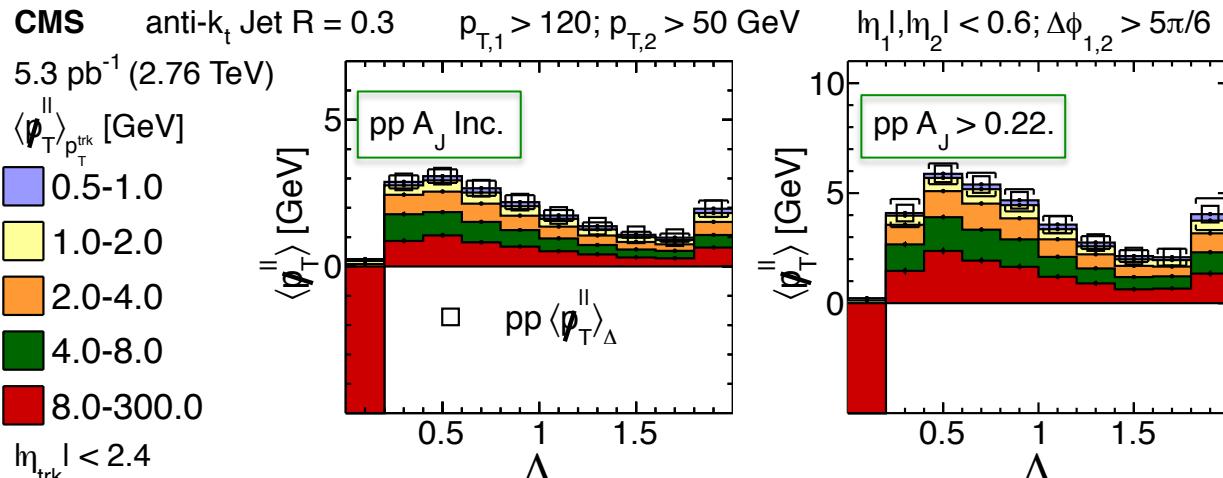
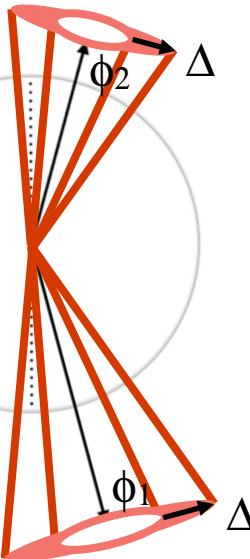
CMS [PRC 84 \(2011\) 024906](#)



- Take-home message (ca. 2011): Dijet balance only recovered at low p_T and large angle
- But what does large angle mean, if pp shows a similar pattern?



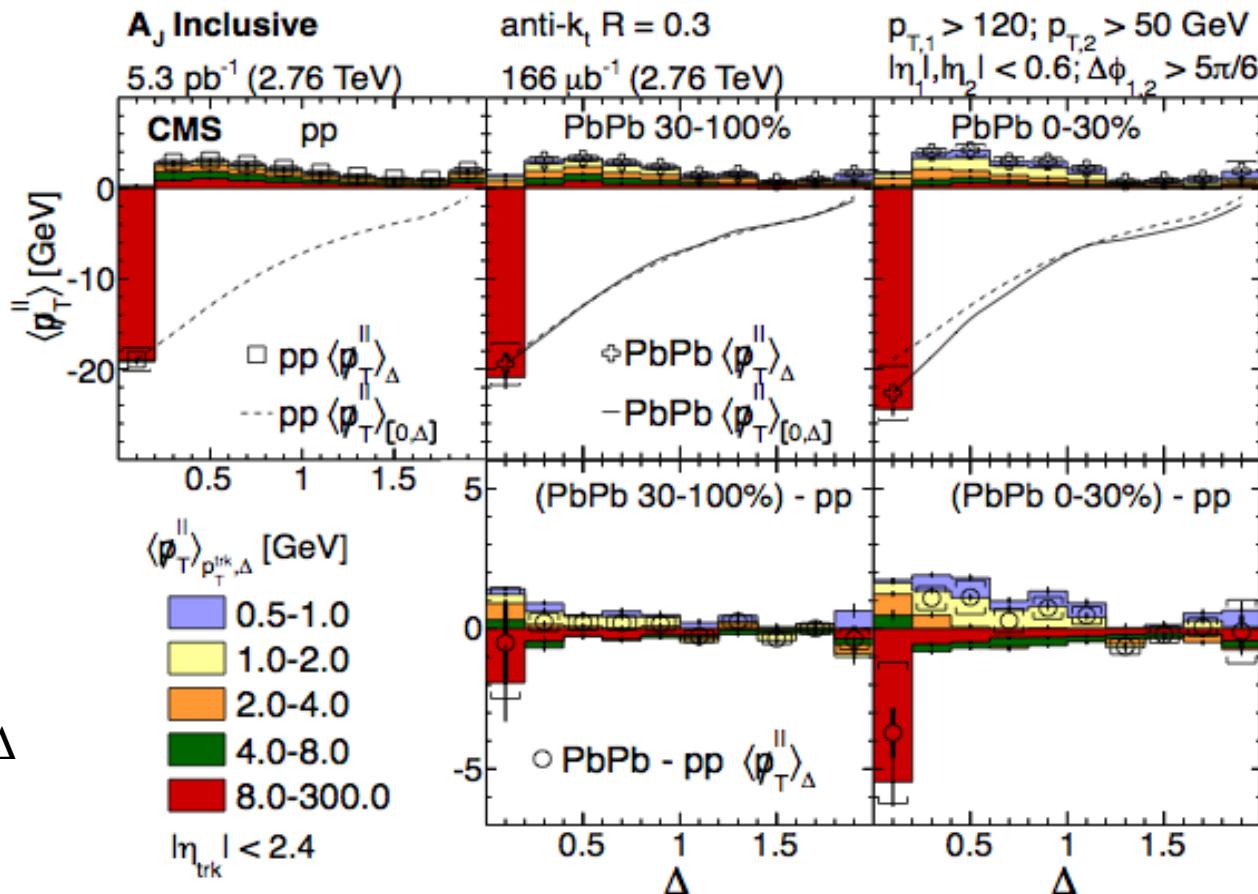
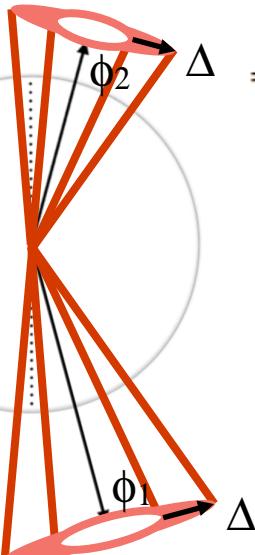
Missing $p_T \parallel$ in pp



- Large angle balance already present in pp, depends on jet selection
- Large A_J selection enhances large angle radiation (e.g., harder 3rd jet)
- What is the more useful reference for asymmetric dijets in PbPb?



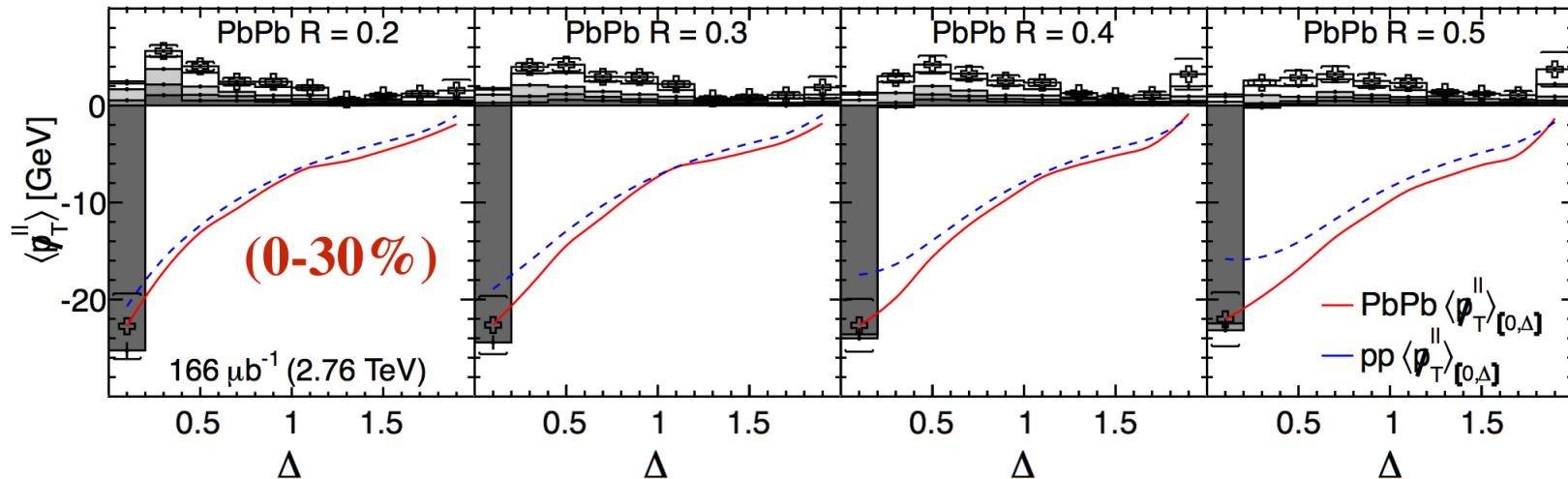
Missing $p_T \parallel$: pp vs. PbPb



- Familiar shift of energy to lower p_T “fragments”
- No large angular redistribution of total energy flow w.r.t. to pp



Missing p_T^{\parallel} : R dependence



- Changing R selects a different population of jets
→ structure of missing p_T changes,
incorporating nearby radiation into jets
- Still, only modest change to cumulative balance
compared to pp
- ... Incidental or fundamental?

So where does the energy go?



Q: Does the quenched energy go to large angle?

A: Well, the core appears more collimated, but yes it must, otherwise we would recover all the dijet imbalance provided we sum over all constituents in the cone (which is at least not true at the LHC)

Q: Ok, so where exactly does it go?

A: Compared to what? So far we don't have a comparison sample of jets with the same initial parton energy.
High statistics γ +jet will go a long way here.
Confronting models will be key.

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High statistics γ +jet will go a long way here.

Confronting models will be key.

Take home message: Beware of take home messages



Thanks for your attention!

And thanks for useful discussions, plots, etc:
François Arleo, Oliver Busch, Zvi Citron, Leticia Cunquero,
Olga Evdokimov, Ali Hanks, Peter Jacobs, Chris McGinn, Hannu
Paukkunen, Dennis Perpelitsa, Hallie Trauger and Yetkin Yilmaz

Backup

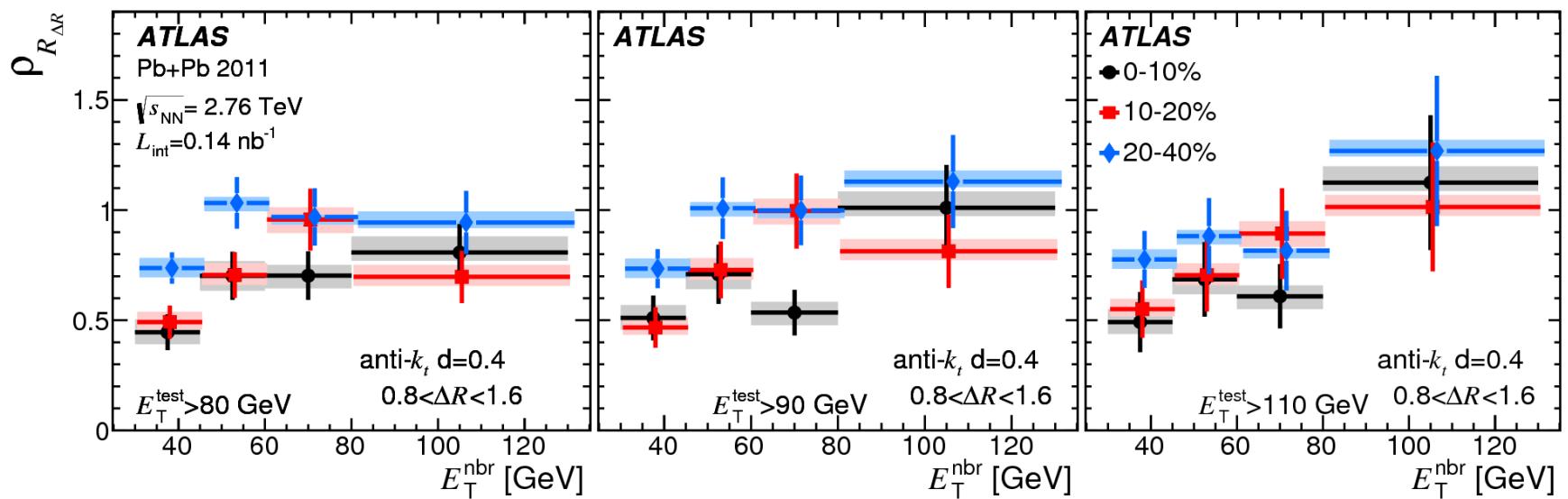
(My) conclusions (so far)

- Jets are now fully part of the HI toolbox
- Overall spectra modification and reaction plane dependence more or less under control, but...
 - Inter-experiment consistency only somewhat established
 - Better sensitivity to flavor dependence is desirable
- Intra-jet structure only lightly modified
... but more so at low p_T / collision energy?
- Interesting results on large angle energy flow
- Ditto for nuclear effects in small systems
- But do we really understand our reference(s)?
 - High-luminosity pp a no-brainer
 - High statistics γ +jet should shed some light
- For complex observables urgent need for (more) full event modeling on top of realistic pQCD / hadronization

What does the future hold?

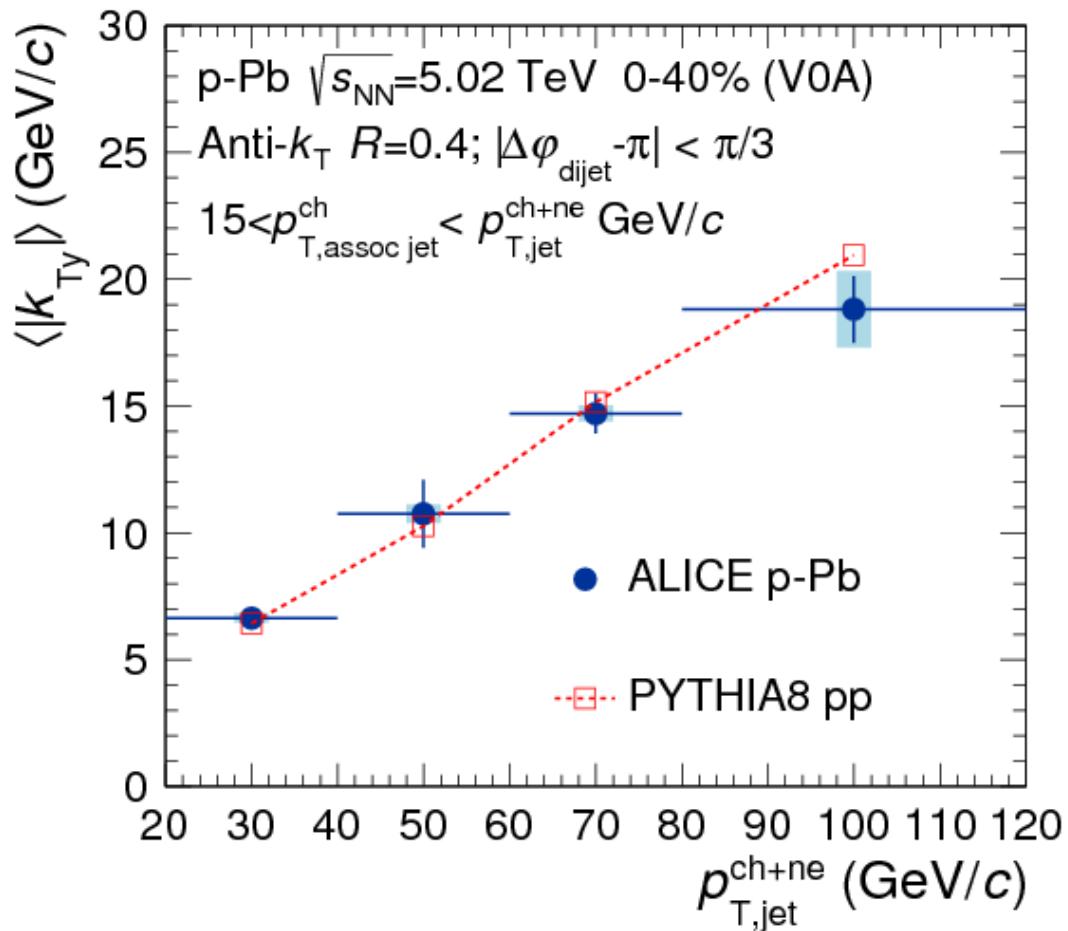
- Near/medium term : High statistics data
 - Full exploitation of recoded & upcoming RHIC data, recently exceeding luminosity expectations
 - LHC Run 2 (3) promising 10x (100x) the stats
→ Repeat all measurements, but for γ +jet
- Medium/long term: Upgrades
 - A high-rate ALICE detector
 - Phase 1 & 2 upgrades of ATLAS and CMS
- Long term: Future facilities
 - A jet (and upsilon) detector at RHIC
 - An EIC that can really pin down nPDFs?

ATLAS neighboring jets

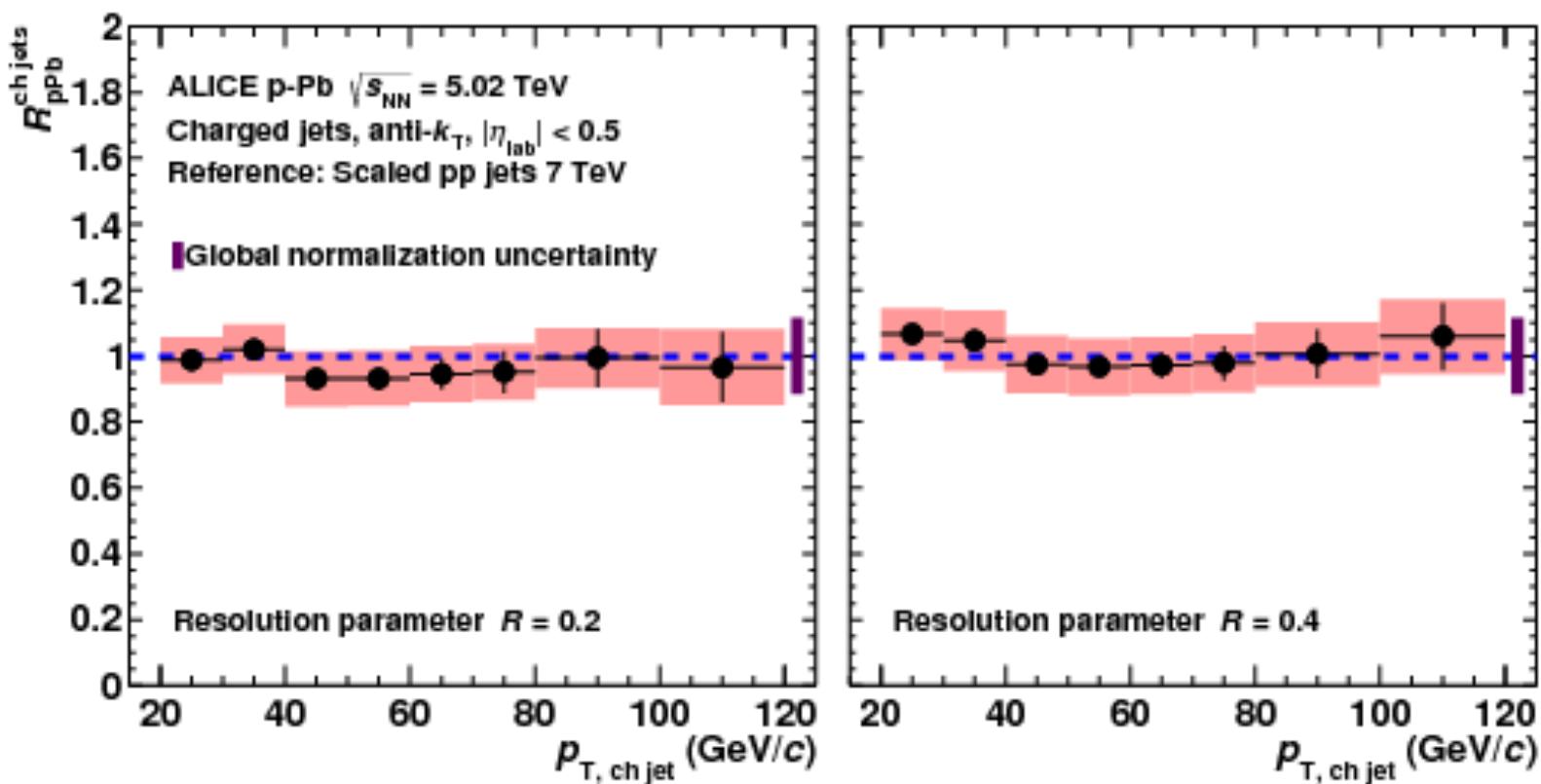


[arXiv:1506.08656](https://arxiv.org/abs/1506.08656)

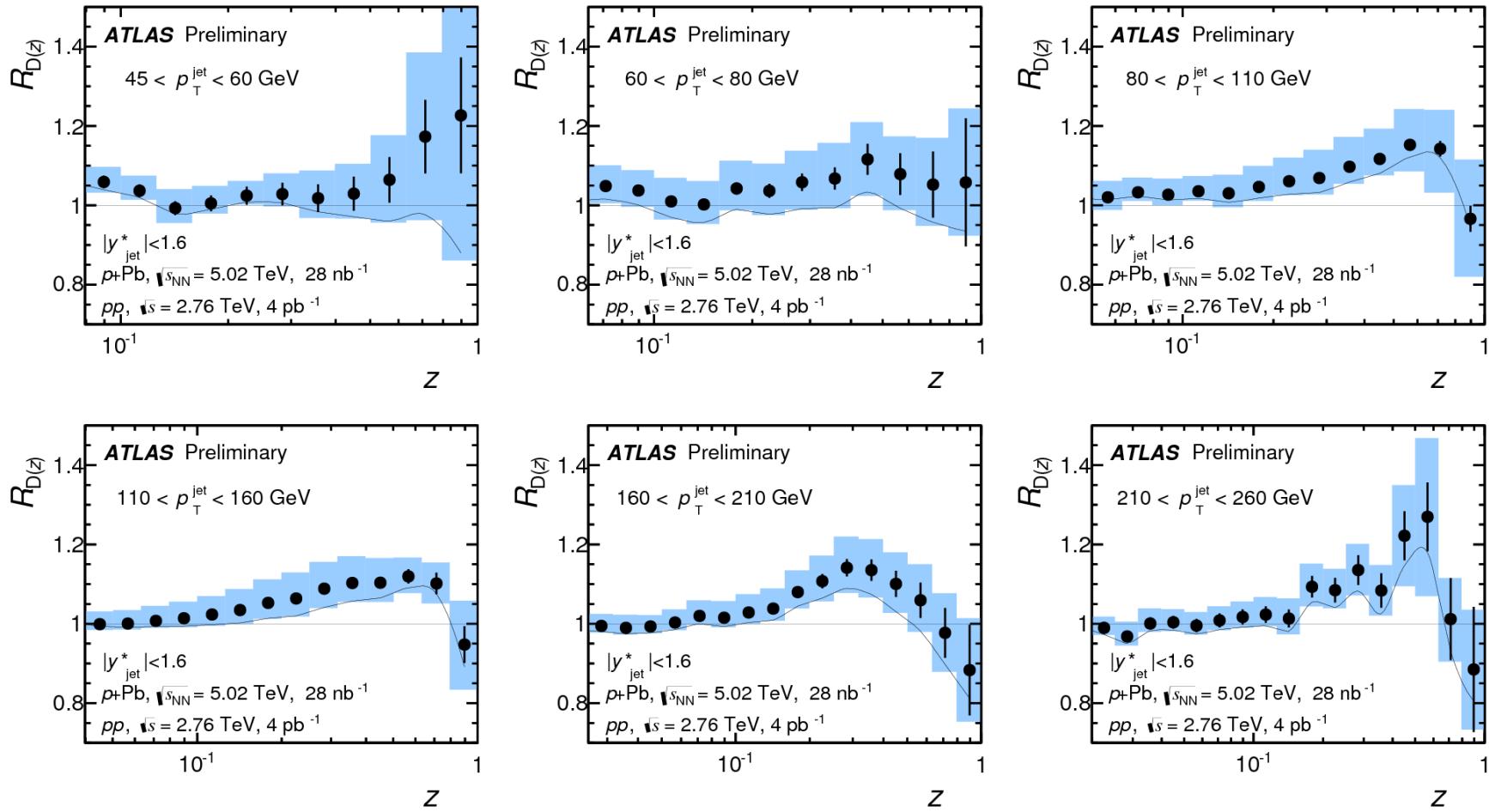
ALICE dijet in pPb



ALICE charged jets in pPb

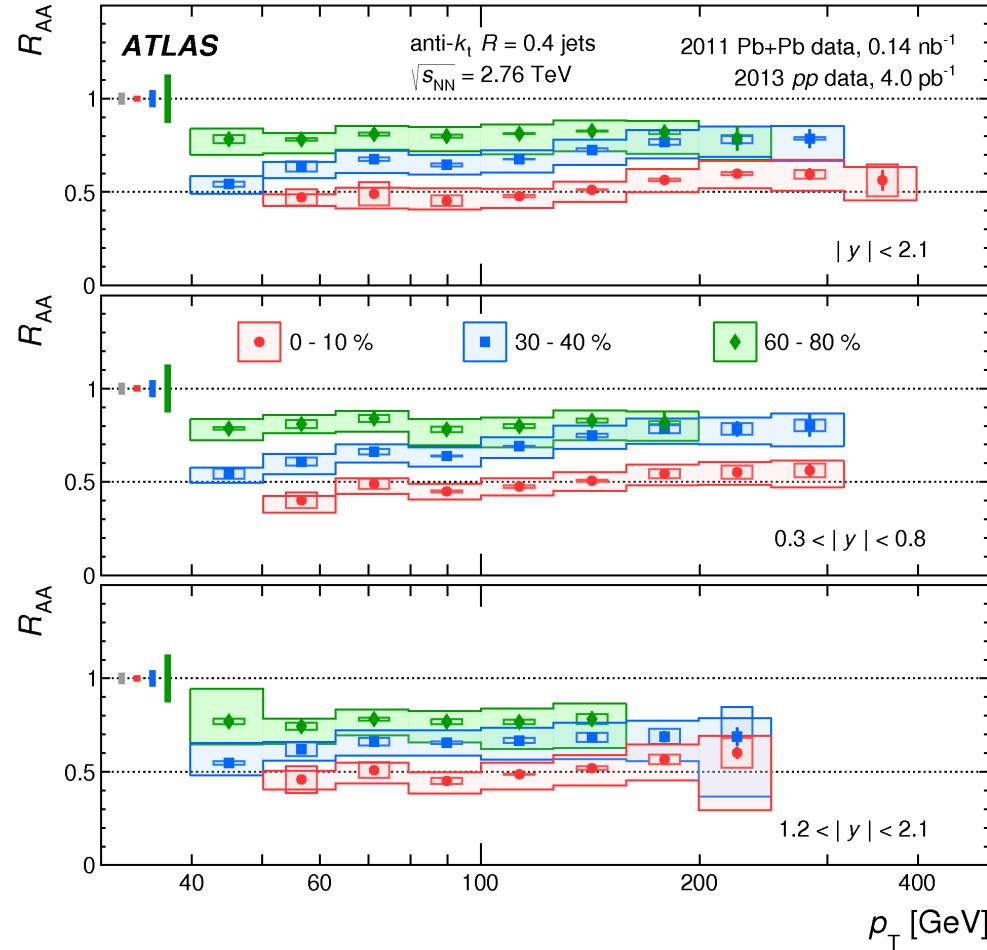


ATLAS pPb jet fragmentation

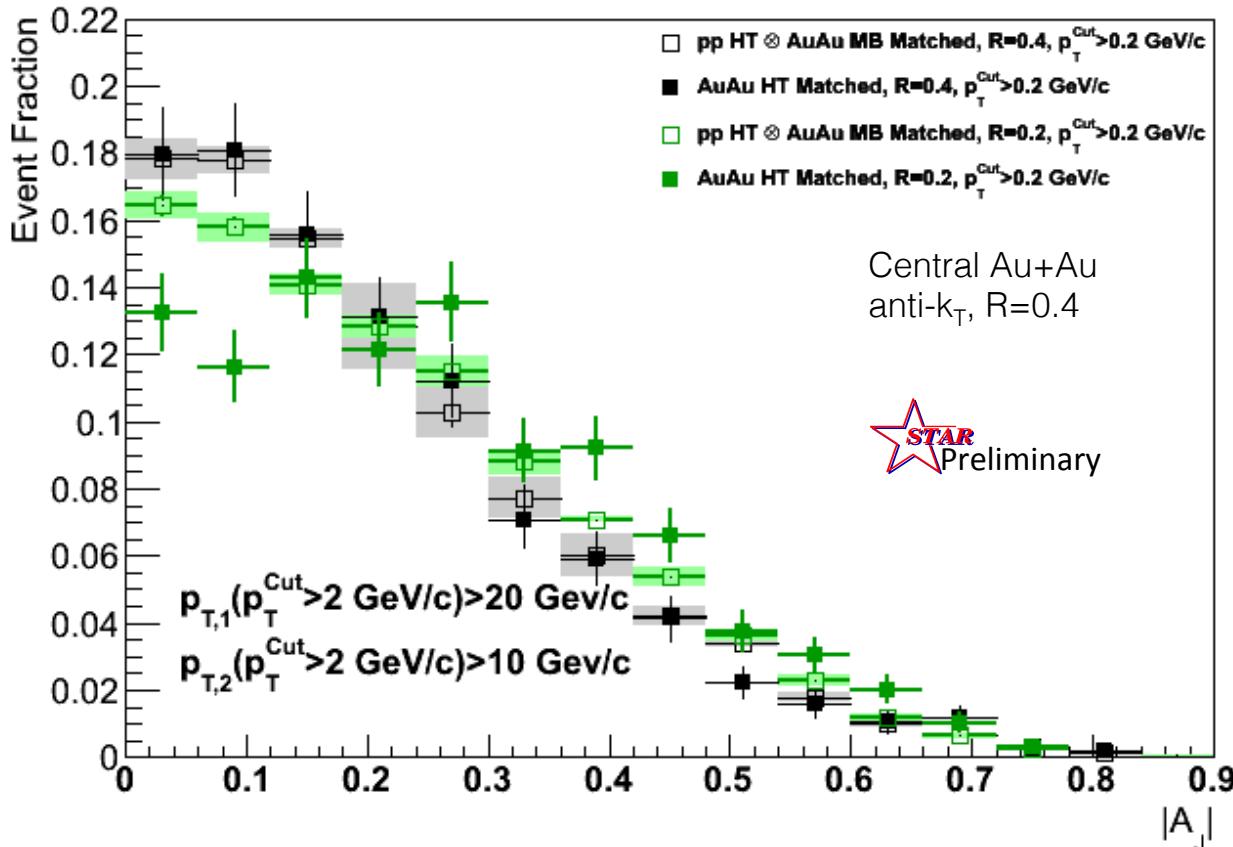


[ATLAS-CONF-2015-022](#)

Rapidity dependence of R_{AA}



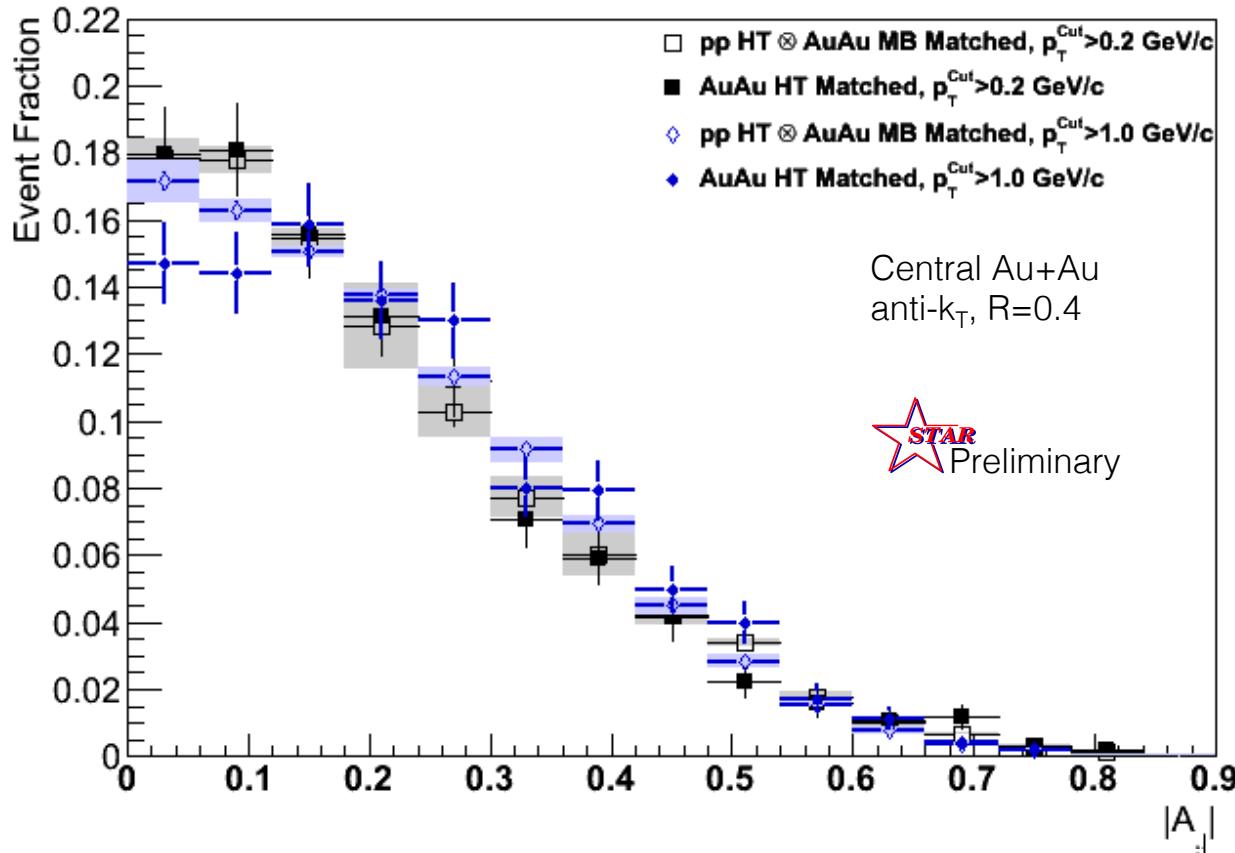
Jet broadening – match to R=0.2



For the same R=0.4, $p_{T,1} > 20$, $p_{T,2} > 10$ GeV jets,
balance can not be restored within R=0.2 → Broadening

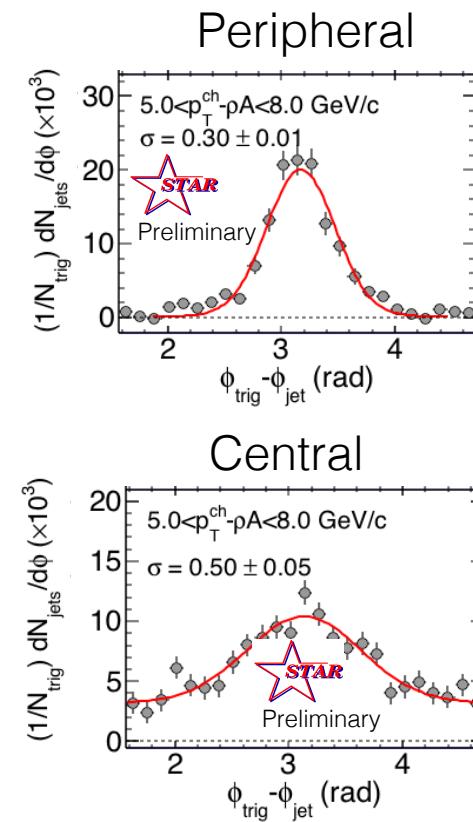
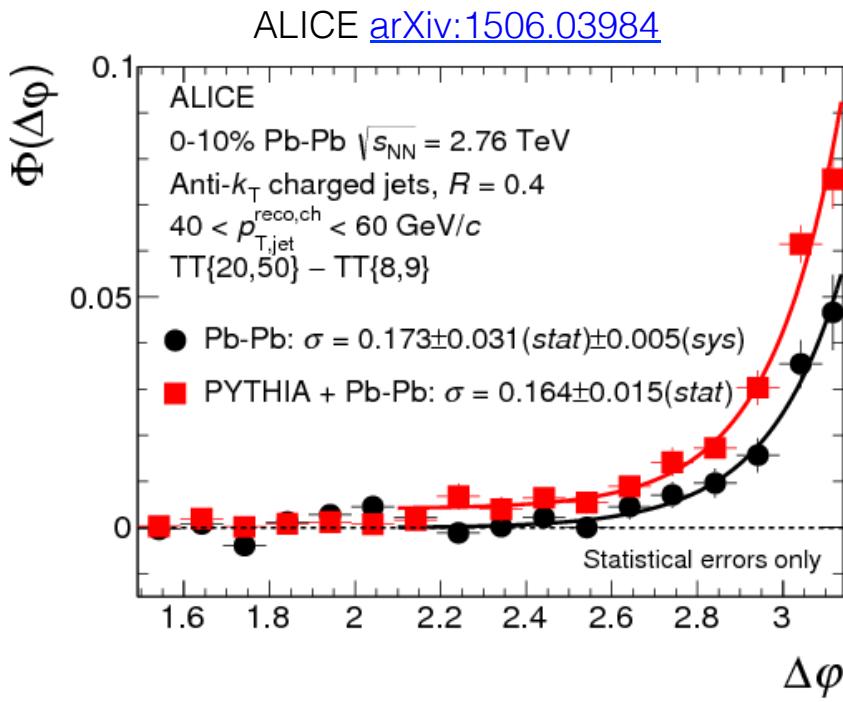
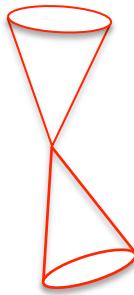
Jet softening – match to

$p_T^{\text{Cut}} = 1\text{GeV}/c$



$p_T^{\text{Cut}} = 1\text{GeV}/c$ not sufficient to restore balance
 → signs of jet softening between 1 and 2 GeV/c

Dijet angular decorrelation?



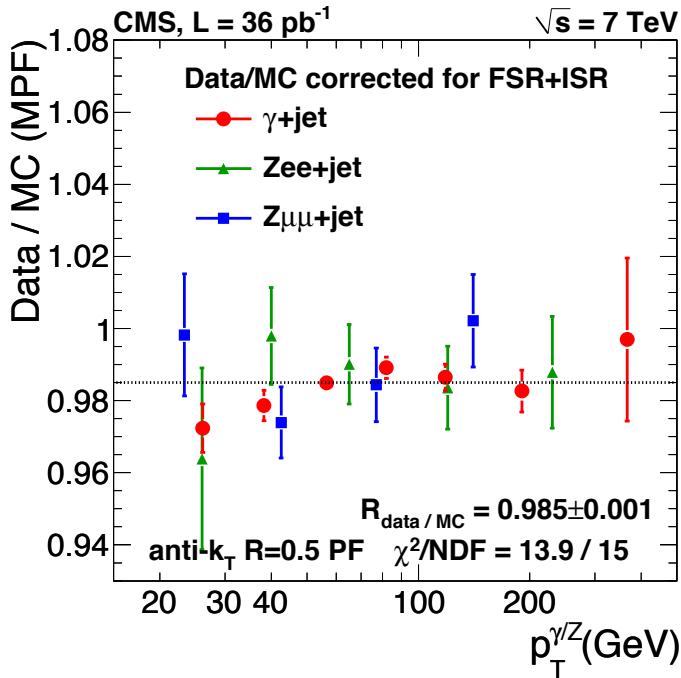
No azimuthal decorrelation observed
Similar message from CMS and ATLAS

STAR does see a broadening*
(*Not yet fully corrected)

Is something fundamentally different at RHIC and LHC energies?

Jet calibration in heavy ions

CMS JINST 6 P09001 (2011)



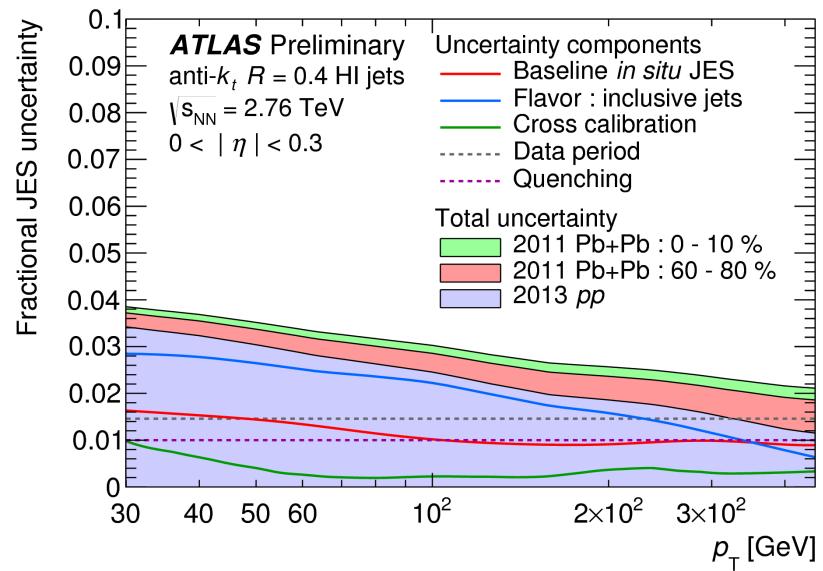
In-situ calibrations in pp

- Relative scale: dijets
- Absolute scale: $\gamma/Z+\text{jet}$

Precision jet measurements **are** feasible in heavy ions

Also ALICE underlying event fluctuations: [JHEP 1203 \(2012\) 053](#)

[ATLAS-CONF-2015-016](#)



Extension to PbPb

- In-situ calibrations via *cross-calibration*
- Moderate add'l uncertainty due to quenching