Big Probes in Little Systems

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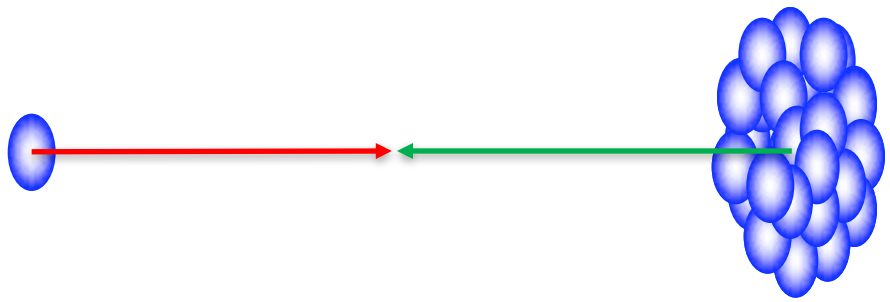
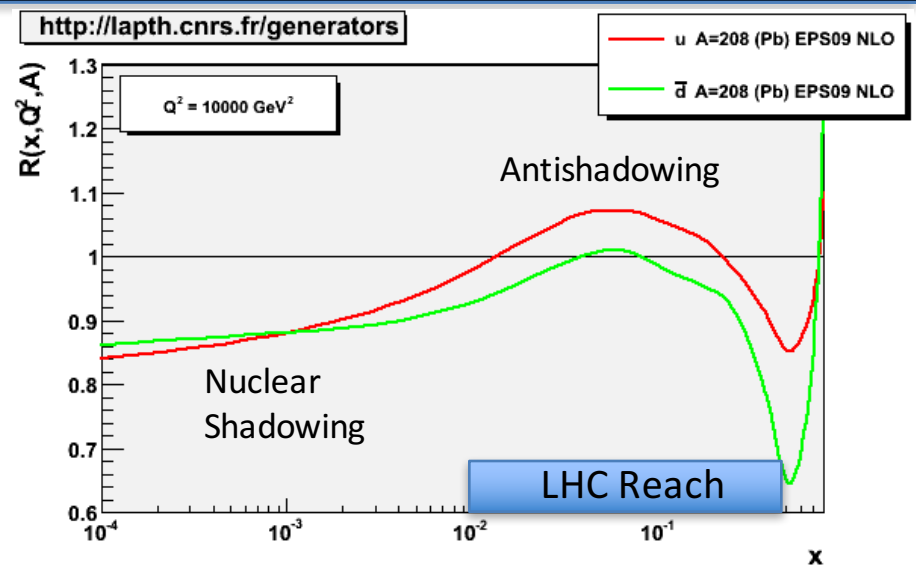
Disclaimers

1. As with all these talks, there is not time to show every applicable result

2. There are (unfortunately) not many jet/W/Z results in small systems at RHIC so LHC analyses are the de-facto focus of this talk

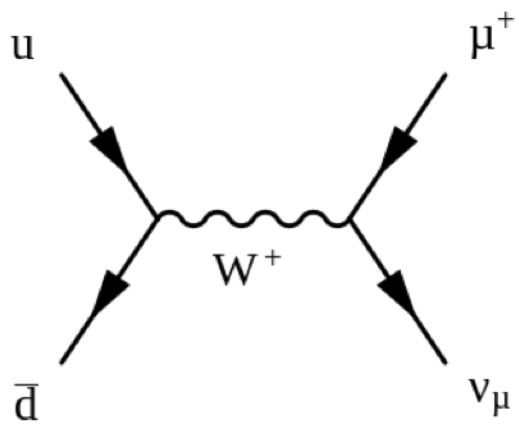
Global Motivations for p(d) + Pb(Au,Cu,etc)





- Probe nuclear PDFs
  - W/Z meas. can constrain nPDFs
  - Dijet rapidity correlated to Bjorken-x
- Can factorize initial state effects from final-state quenching
  - QGP was not expected to be produced in small systems***
  - Nuclear shadowing / antishadowing?
  - Test behavior of small system "centrality" – do Glauber models work in small systems?
- Hard probes (can) connect directly to initial partons

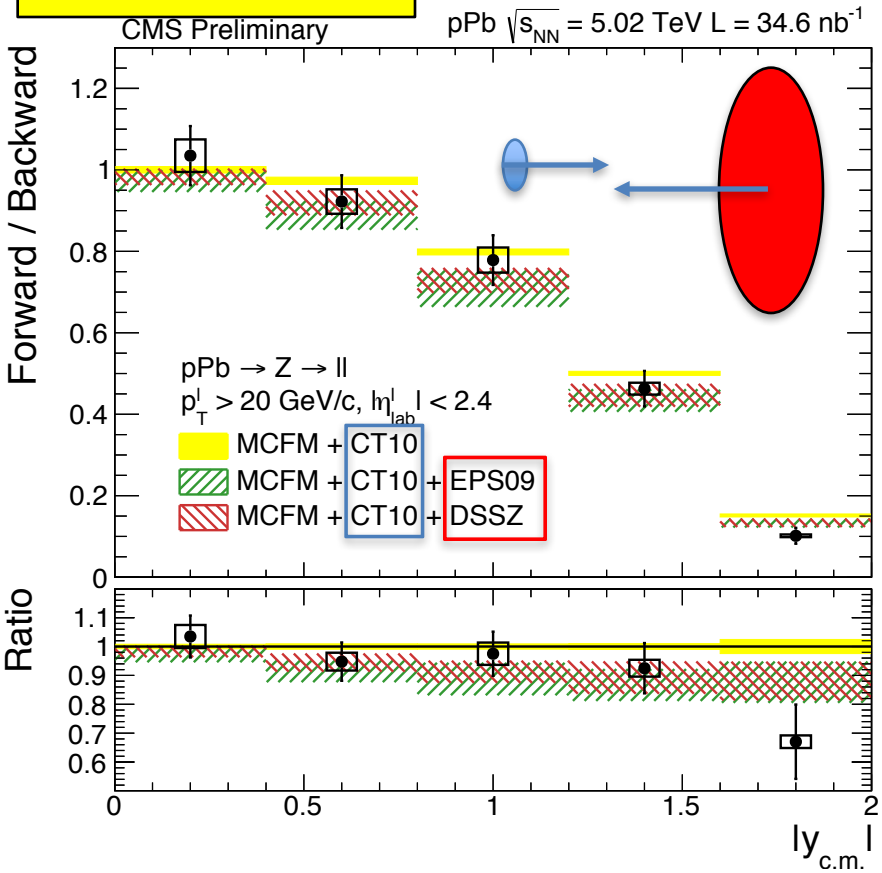
Electroweak Bosons



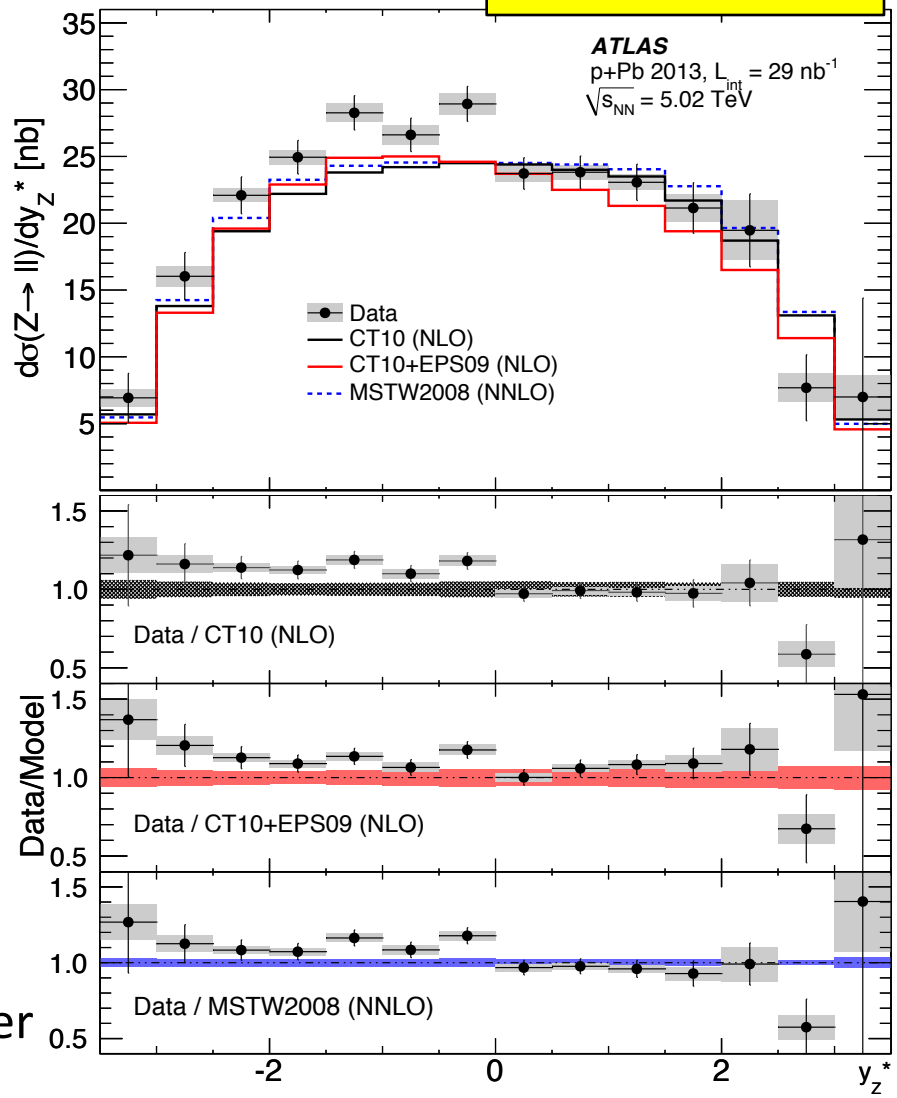
- Unaffected by strong force interactions
- Natively sensitive to initial-state effects
  - W-boson isospin effects probe pn/pp/nn fluctuations
  - Z/W strongly coupled to quark PDFs
- Measurements of forward/backward asymmetry have better nPDF sensitivity
  - R_{FB} = N(+y)/N(-y) = N(p-going) / N (Pb-going)

Z Boson Forward-Backward Asymmetry

arXiv: 1512.06461



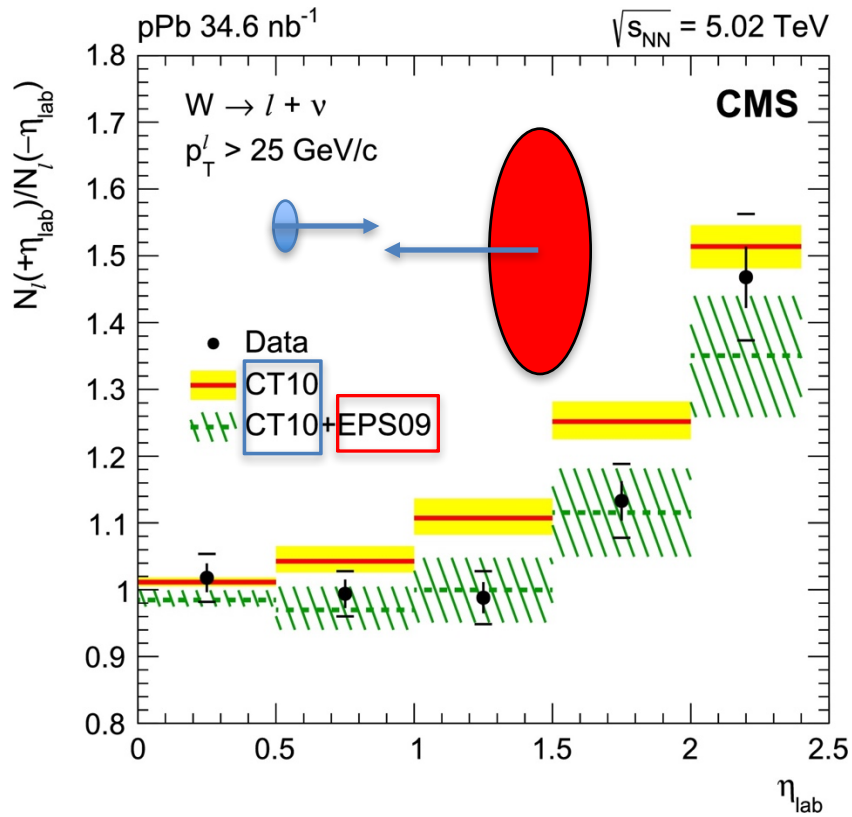
arXiv: 1507.06232



- R_{FB} shown by CMS shows better consistency with nPDFs (DSSZ preferred)
- ATLAS cross-section measurements prefer CT10 + EPS09 from χ^2 tests

W Boson η Asymmetry

arXiv: 1503.05825



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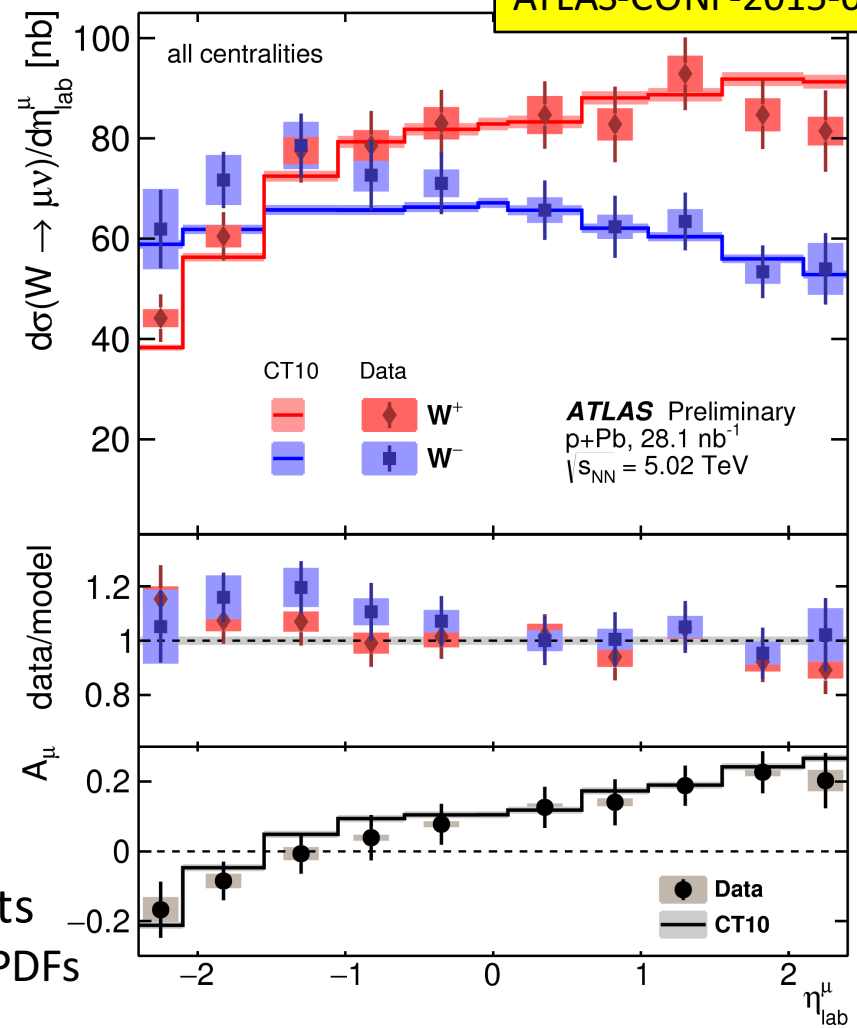
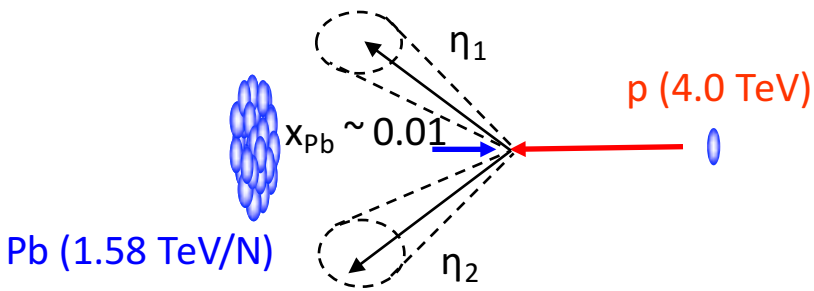


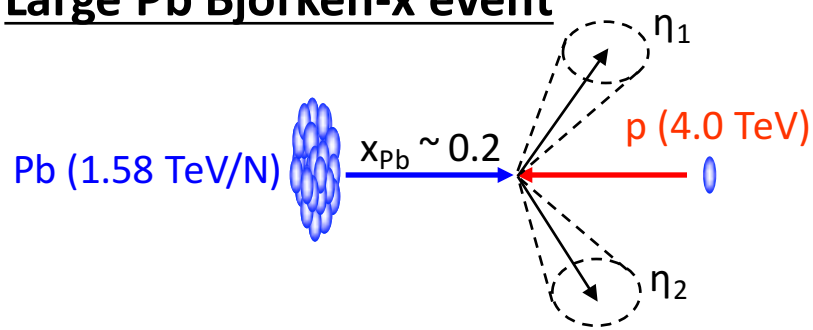
- W-boson asymmetry probes isospin effects
  - Consistent with predictions from EPS09 nPDFs
- ATLAS shows relative consistency with CT10 PDFs, but uncertainties are larger than ~5-10% effects seen from inclusion of nPDFs

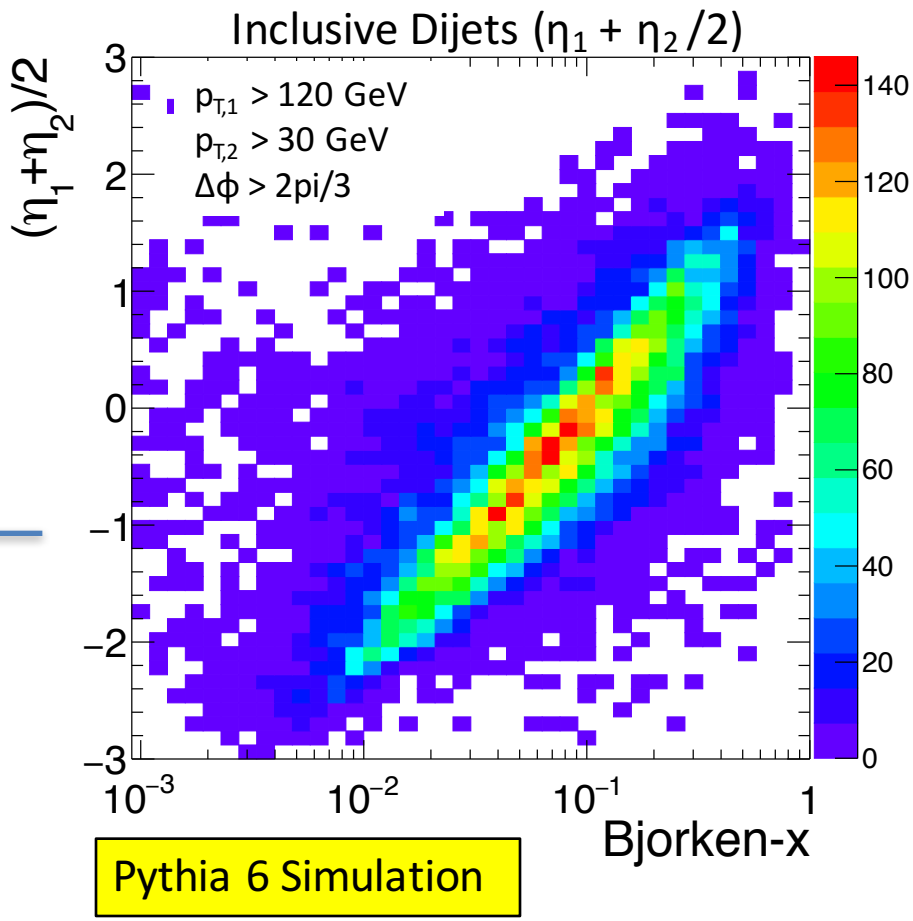
Dijet Production at the LHC

Small Pb Bjorken-x event



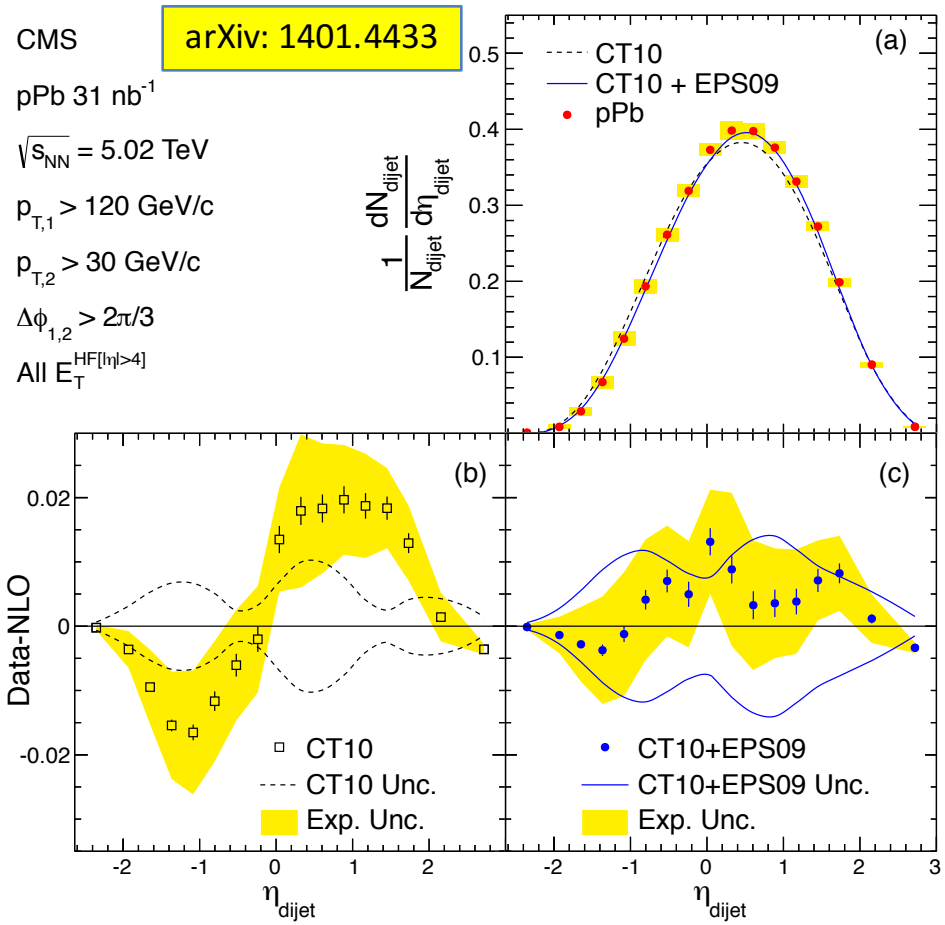
Large Pb Bjorken-x event



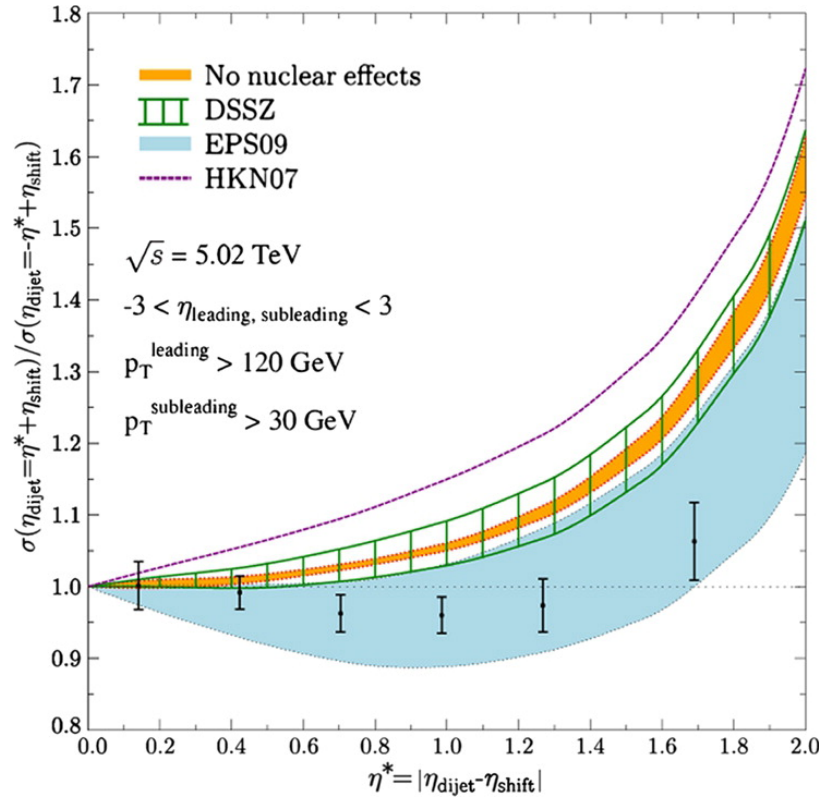


- Dijets provide another opportunity to probe nPDFs
  - Dijet η correlates strongly with Bjorken-x

Dijet Production at the LHC



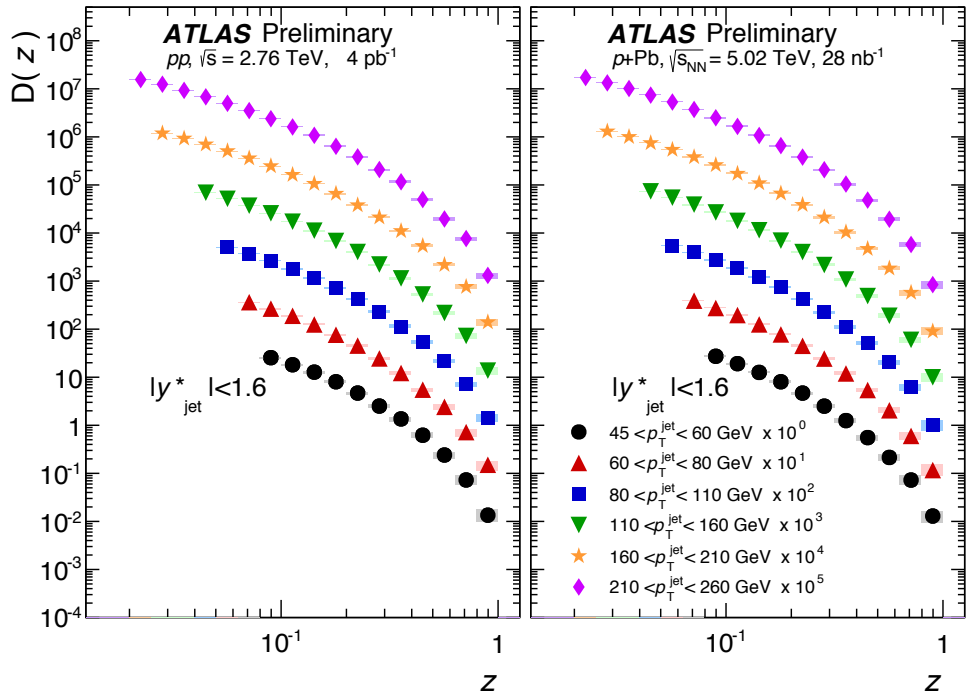
Nucl. Phys. A 931: 331 (2014)



- Dijet pseudorapidity distributions in pPb can only be explained by nPDFs
- Forward to backward ratios compatible ONLY with EPS09
  - Uncertainties on EPS09 can be reduced by 10-20%, especially at large x.

Jet Fragmentation Functions

ATLAS-CONF-2015-022

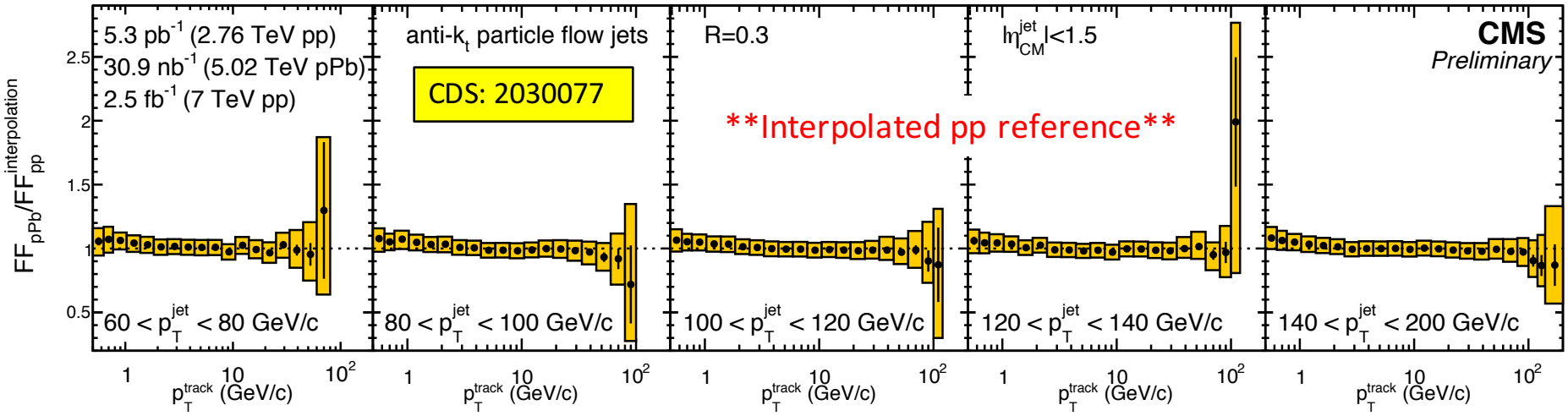


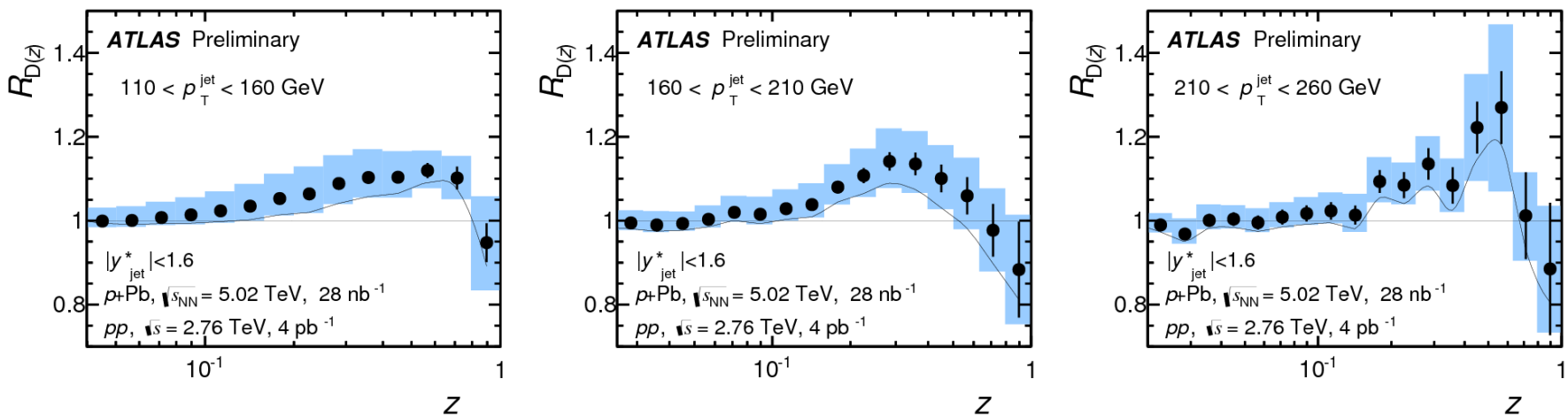
$$\xi = \log\left(\frac{p^{jet}}{p_{||}^{track}}\right) \quad \text{(CMS)}$$

$$z = \frac{p_T^{trk}}{p_T^{jet}} \cos\Delta R \quad \text{(ATLAS)}$$

- Jet Fragmentation functions show relative yields of tracks within jet cones
- Generally shown as function of some ratio of track p_T to jet p_T
- Underlying event subtraction in pPb highly non-trivial
  - Removal of soft underlying event from soft jet fragmentation is fundamentally impossible

Jet Fragmentation Functions





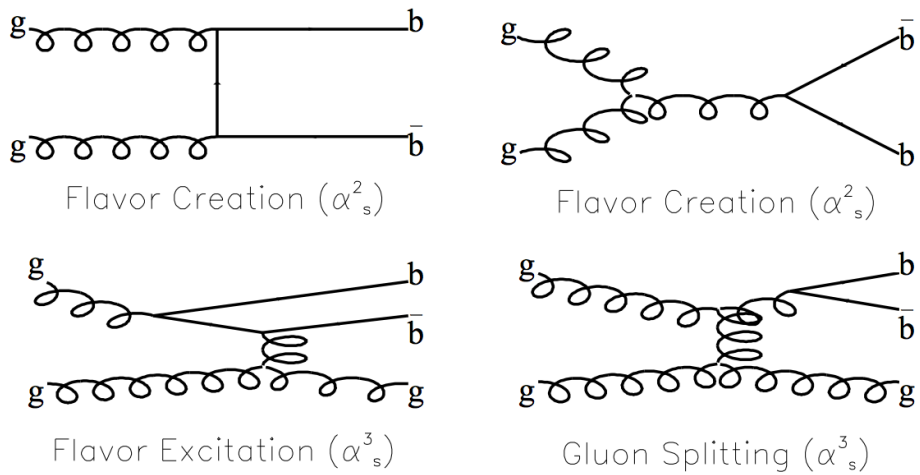
- Ratio of fragmentation functions in pPb to pp shown
  - No modification of jet fragmentation in pPb seen w.r.t. pp
  - Underlying event removed in both cases

ATLAS-CONF-2015-022

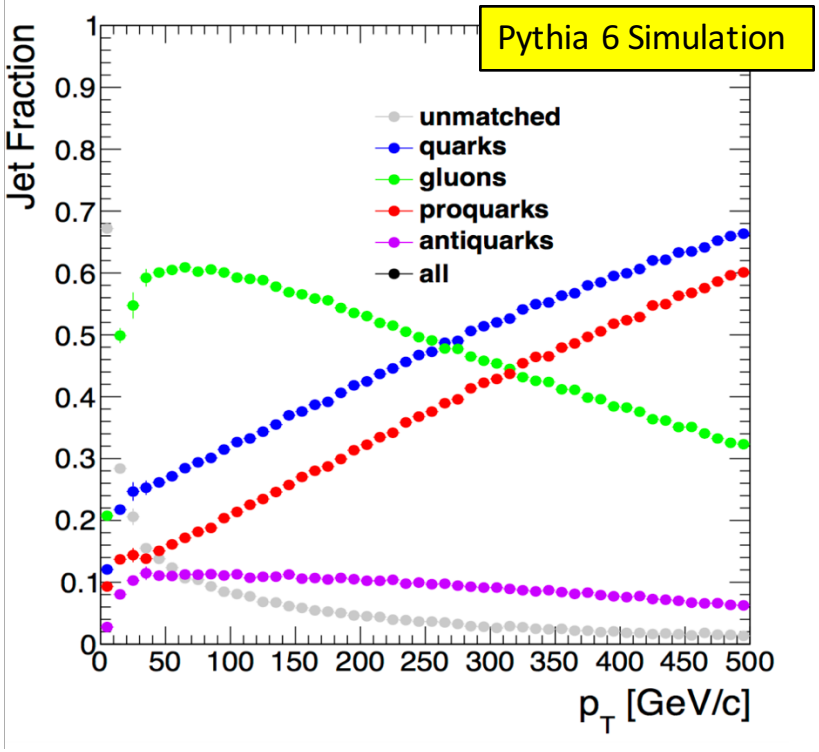
Flavored Jets

arXiv: hep-ex/0412006

B-jet production types (gg prod. only)

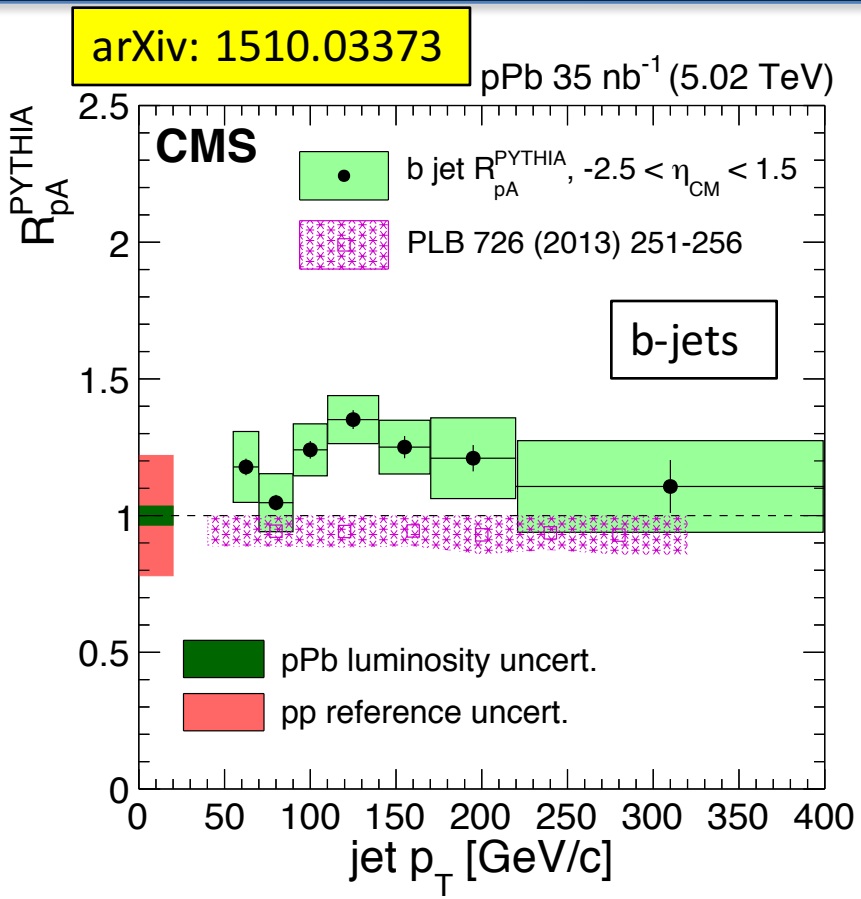


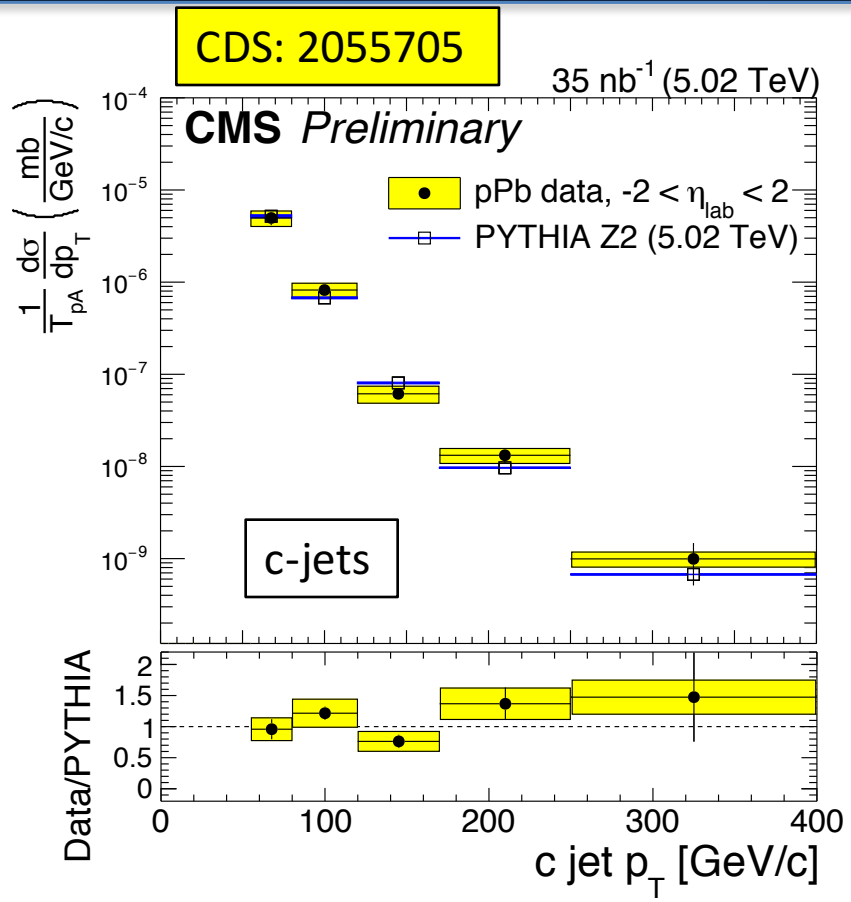
Inclusive-jets (large quark component)



- Flavored jets have the advantage of providing
  - Direct access to heavy-flavored quarks
  - Exclusive probes of the ***gluon*** nPDFs
- Disadvantaged by contamination of gluon splitting events

Flavored Jets

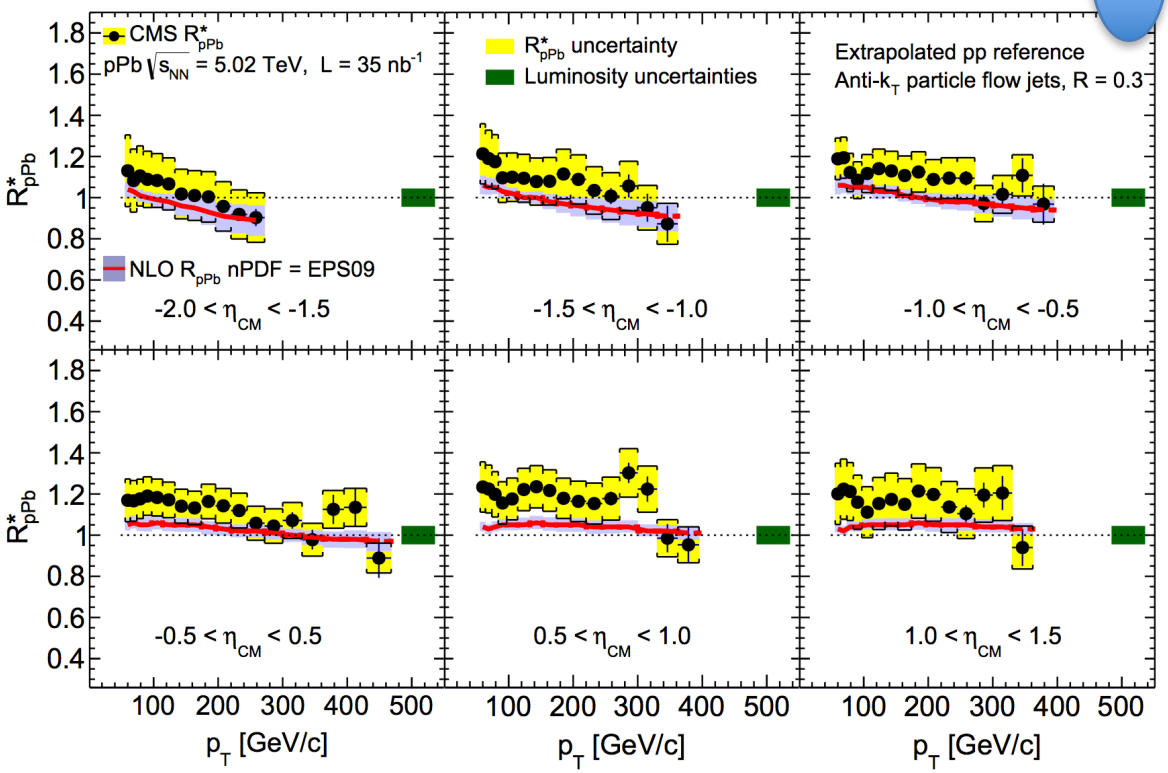




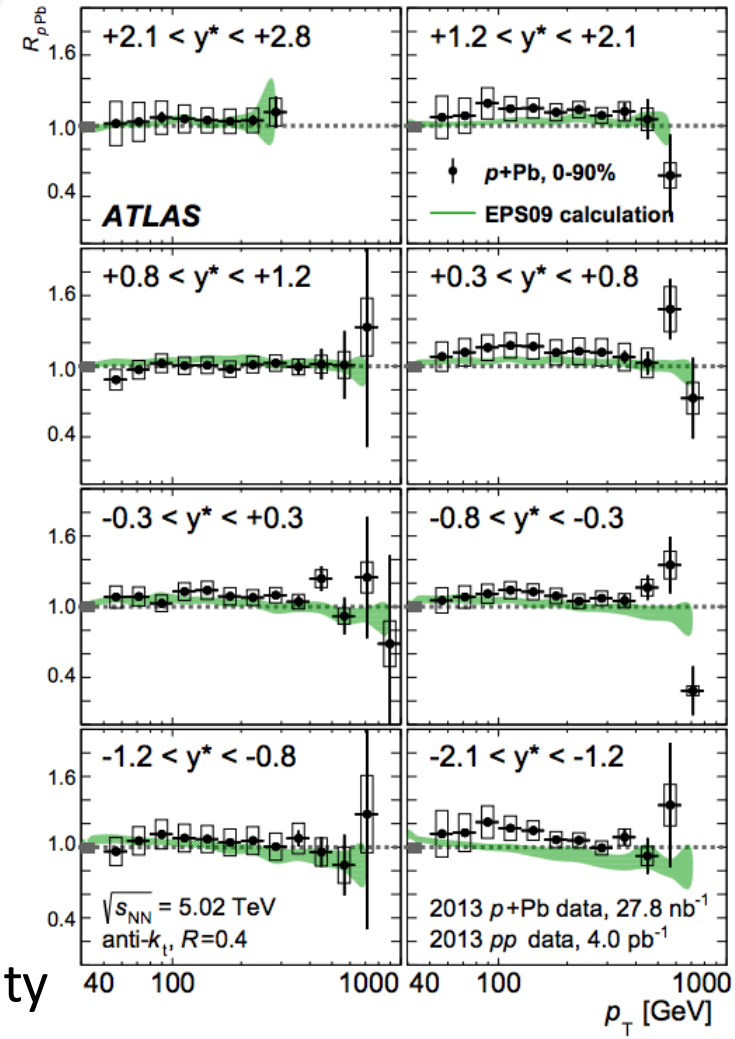
- b-Jet and c-Jet R_{pA}^{Pythia} find no discrepancy from unity
- Flavored jet measurements tell a similar story as the inclusive jets
  - Favors pQCD models where mass-dependent effects are negligible at jet p_T >> b-quark mass

Inclusive Jet Production at the LHC

CMS, arXiv:1601.02001



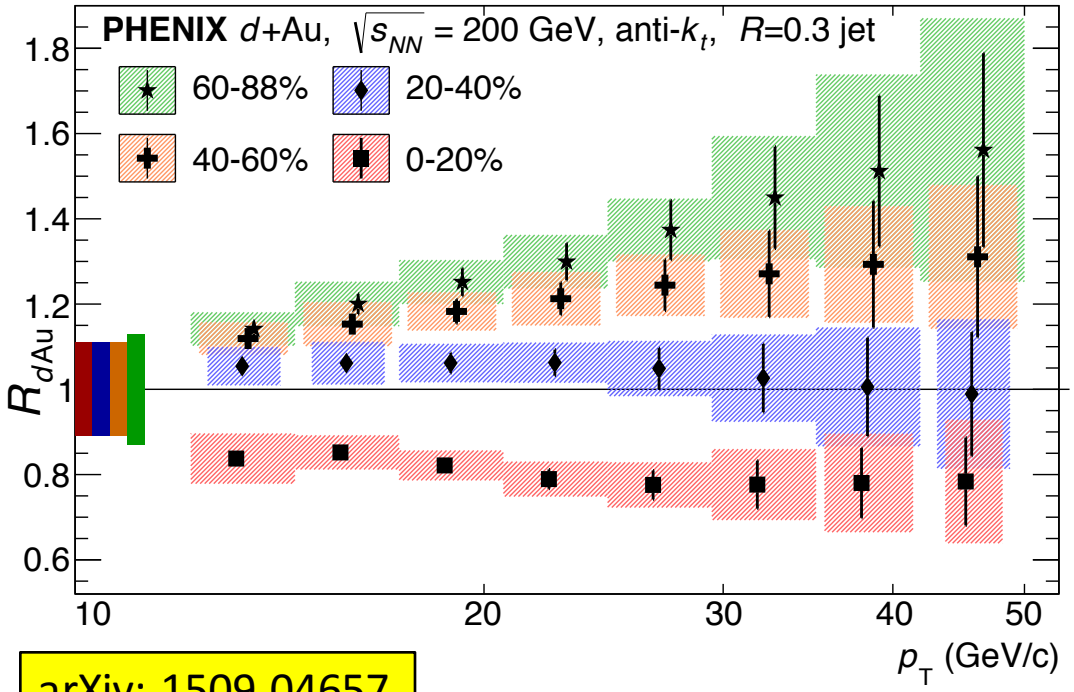
ATLAS, arXiv:1412.4092



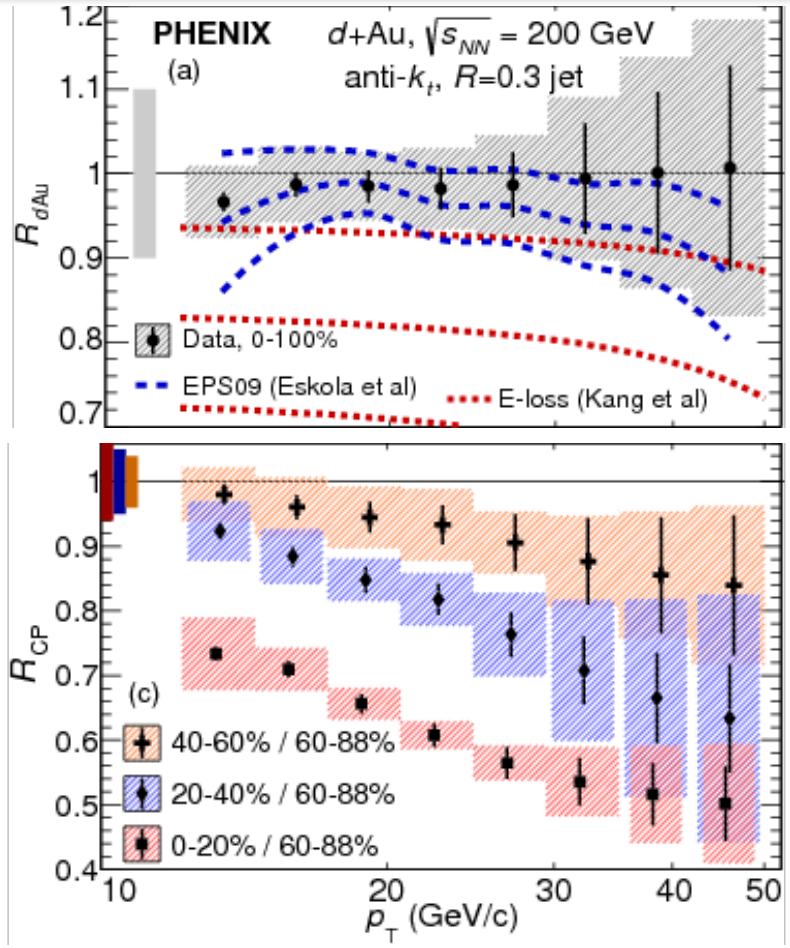
- ATLAS and CMS inclusive-jet measurements see no suppression/enhancement
- CMS measurements are as a function of η_{CM}, ATLAS as function of y* = proton-beam rapidity

Inclusive Jet Production at RHIC

(Centrality estimated by Au-going forward energy)



arXiv: 1509.04657

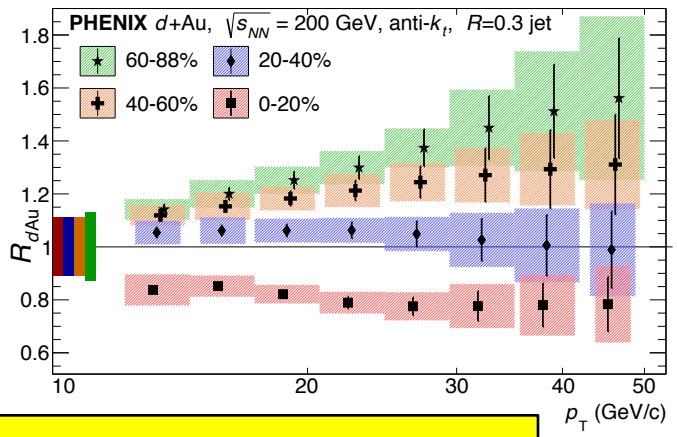


- Centrality dependency found in jet production at RHIC
  - Effect from centrality calculation using forward calorimetry?
  - 30-40% shift expected based on ALICE V0A centrality study

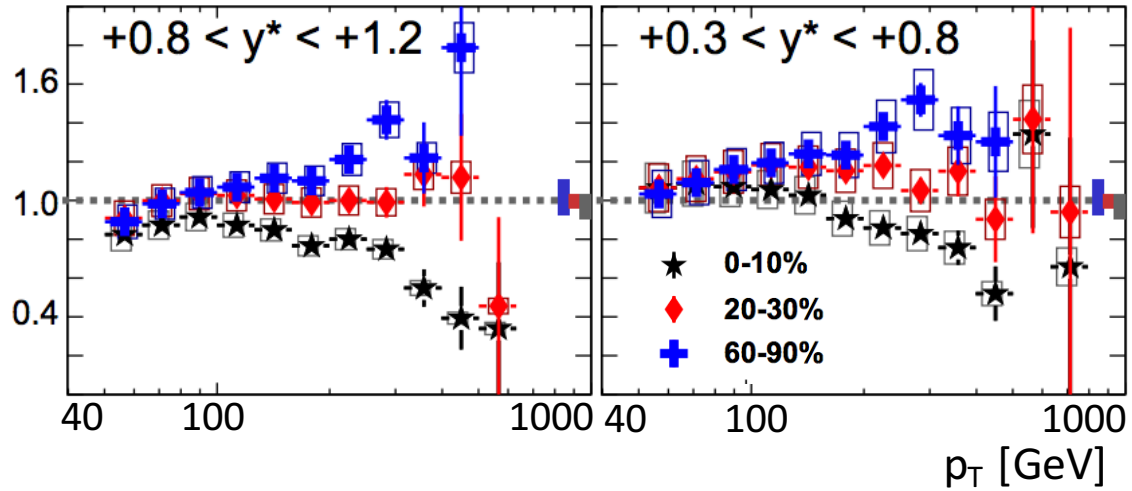
An R_{pA} Centrality Dependence?

(Centrality calculated by Au (Pb)-going forward energy)

ATLAS, arXiv:1412.4092



PHENIX, arXiv:1509.04657

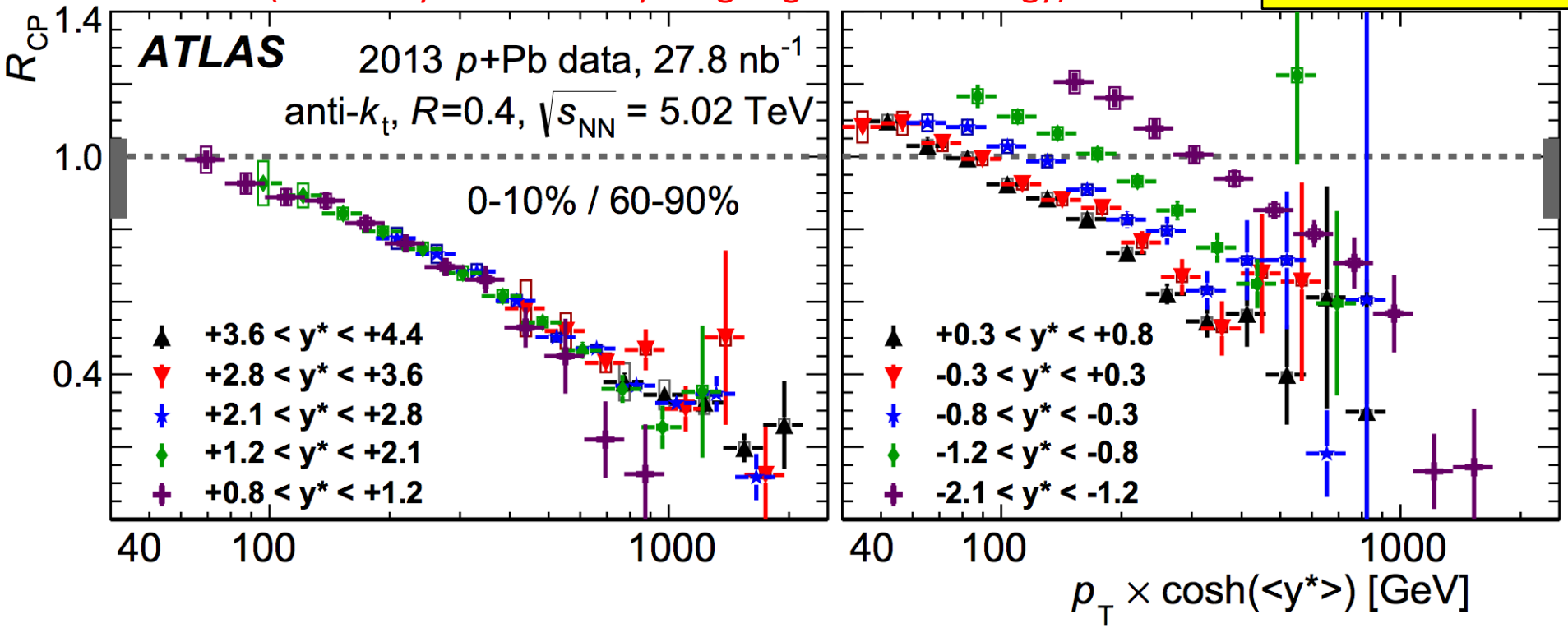


- Centrality-dependent results observed with ATLAS have similar magnitude as those seen by PHENIX
- Centrality determined in both cases by collected forward energy in Au (Pb)-going direction
  - Universal enhancement of peripheral jets?
  - Centrality bias? Kinematic biases?

Inclusive Jet Production at the LHC

(Centrality calculated by Pb-going forward energy)

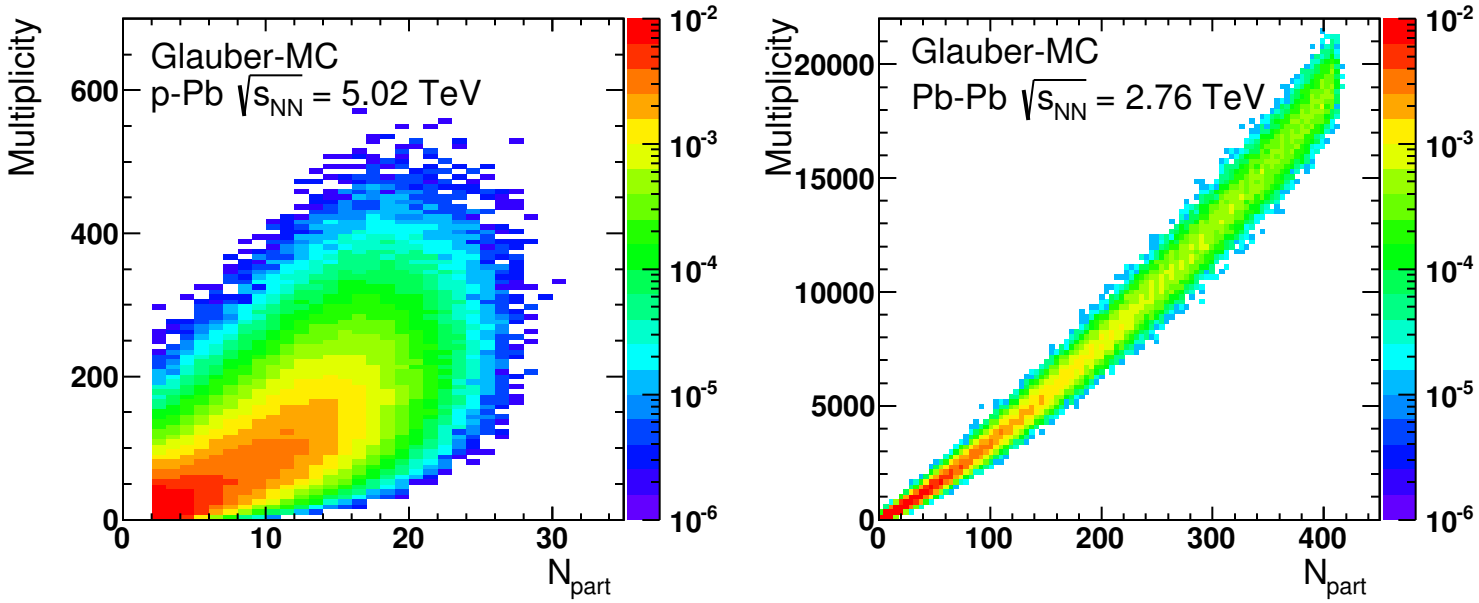
arXiv:1412.4092



- Universal scaling observed for R_{CP} as a function of p_T *x cosh(<y*>)* ≈ jet energy
  - Only observed on the proton-going side of the detector
- Indicative of an effect based on kinematic recoil?
  - Forward-going jets may affect centrality selection

Small System Centrality Detour

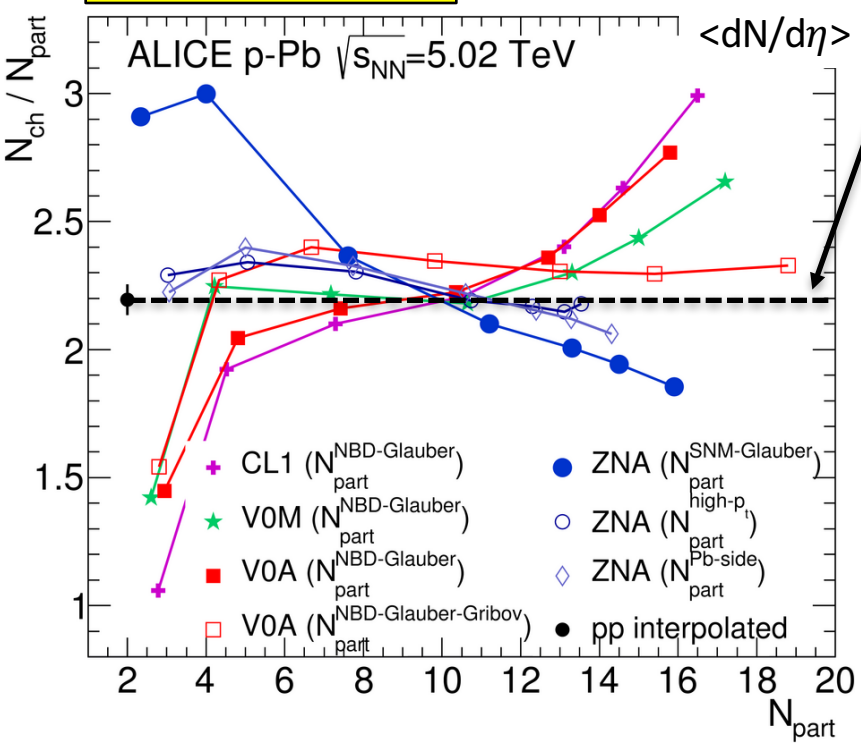
arXiv: 1412.6828



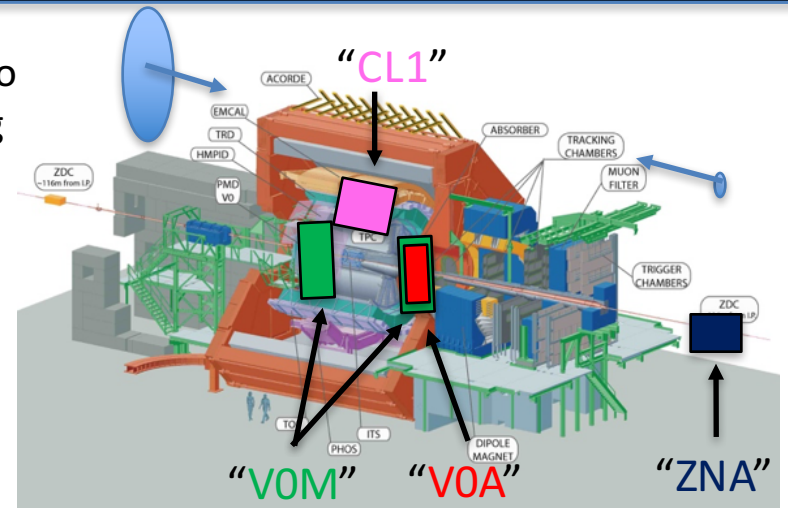
- The usual suspects for centrality determination are no longer immediately valid
- $\langle N_{part} \rangle$ and multiplicity correlate only weakly to impact parameter
- (Relatively) large fluctuations and presence of hard probes can dramatically affect centrality binning (especially in peripheral bins)

Small System Centrality Detour

arXiv: 1412.6828



Perfect <N_{part}> to <dN/dη> scaling

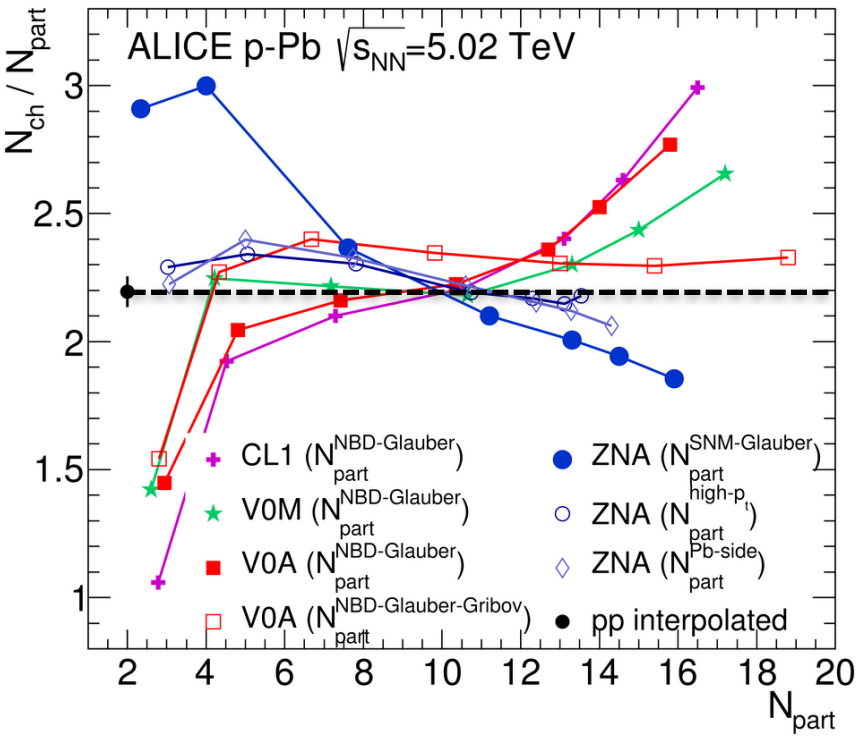


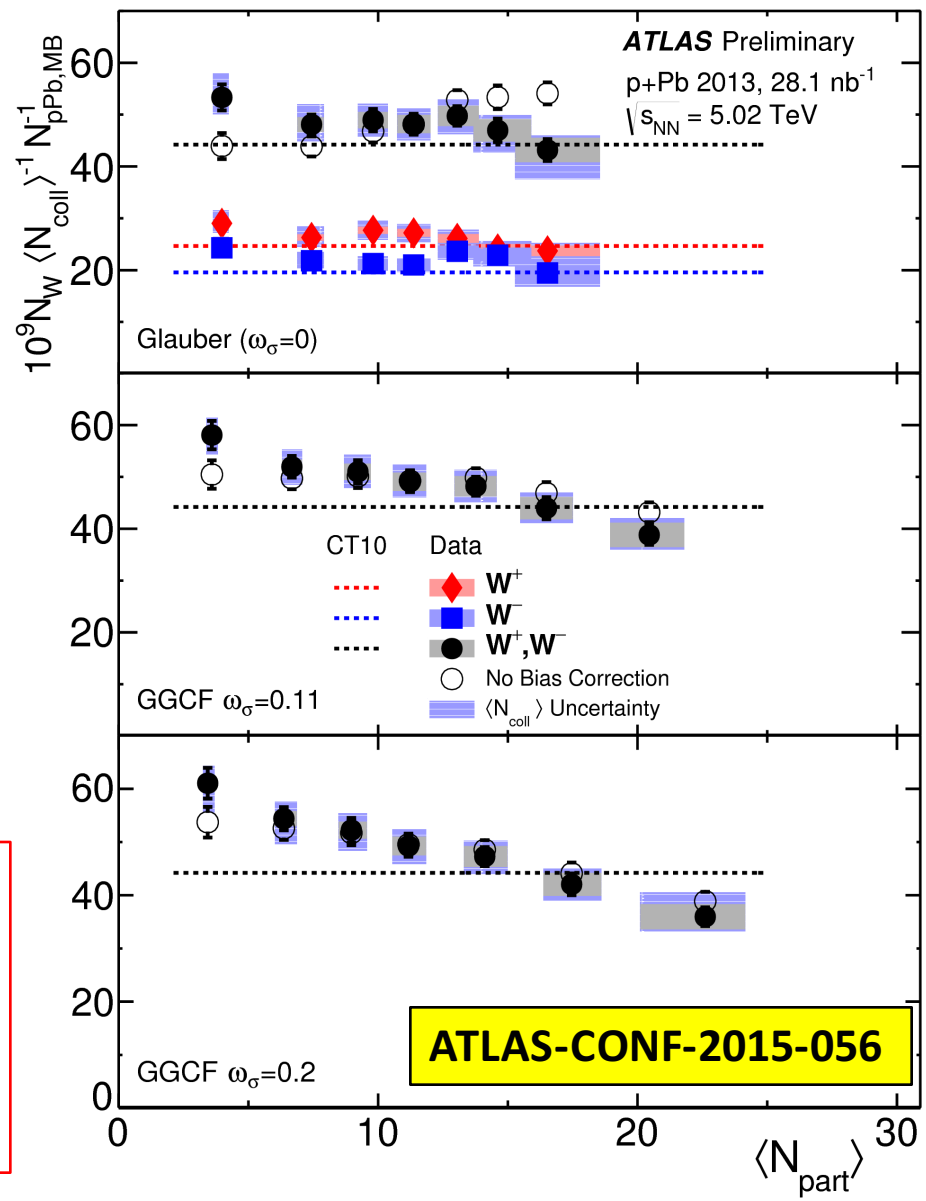
Centrality Classes obtained by different subdetectors in legend, then linked to <Npart> through various assumptions

- <Ncoll> heavily skewed by fluctuations due to small numerical values
  - <Npart> ≈ 8, <dN/dη> ≈ 17
- Carefully calibrated centrality definitions are needed
  - Simple Glauber models are not good enough! Fluctuations are too significant!!

Small System Centrality Detour

arXiv: 1412.6828





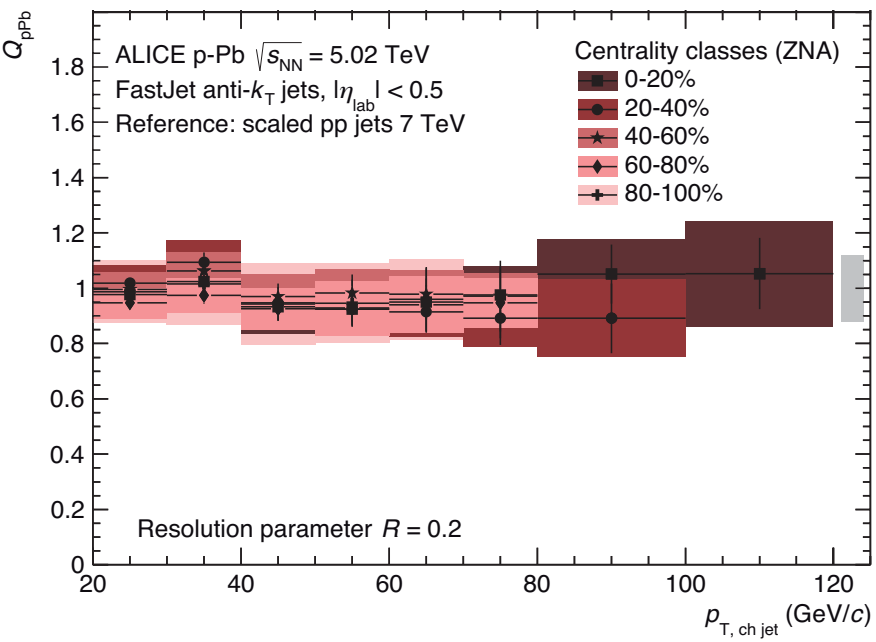
ATLAS-CONF-2015-056

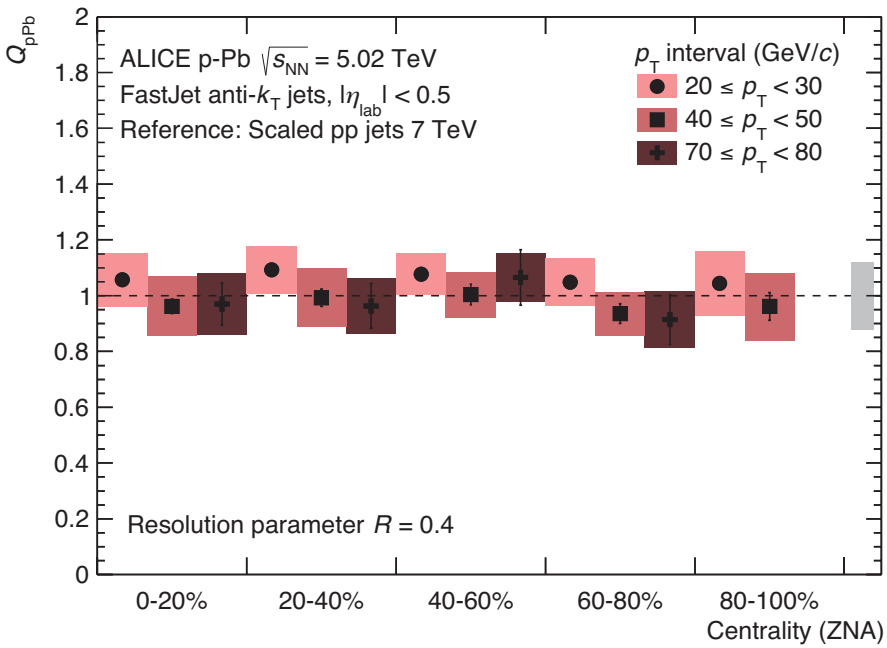
- ATLAS shows further issues with Glauber via W-boson meas.
  - Addition of color fluctuations seem to worsen the problem!

ALICE Inclusive Jet Result

arXiv:1603.03402

(Centrality calculated in bins of ZDC energy + scaled <Ncoll>)

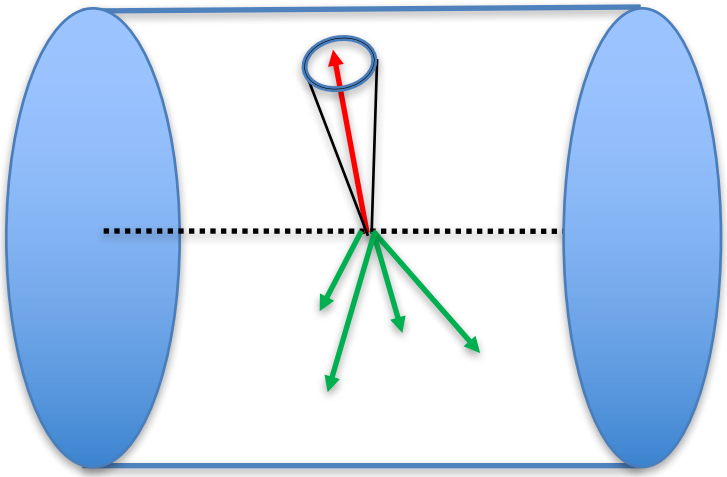




- ALICE measure a different jet R_{pA} centrality dependence than PHENIX and ATLAS
  - Centrality definition based on ZDC + normalized multiplicity in the forward calorimeter ("Hybrid" method)
- Observe virtually no centrality dependence of jet R_{pA}, consistent with inclusive-centrality measurements

Possible culprits for Centrality Bias

1. A reshuffling of the centrality bins based on multiplicity biases
   - Midrapidity jet events preferentially transport energy **out of the forward region**
   - Central events misclassified as "peripheral" events

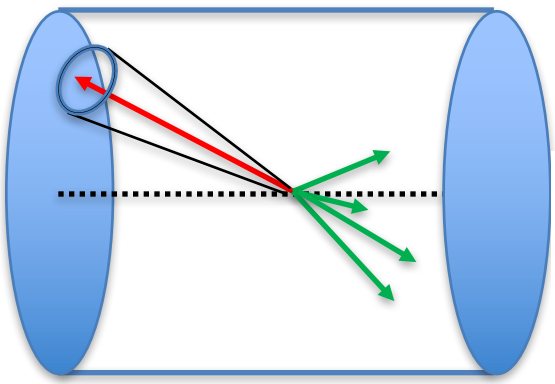


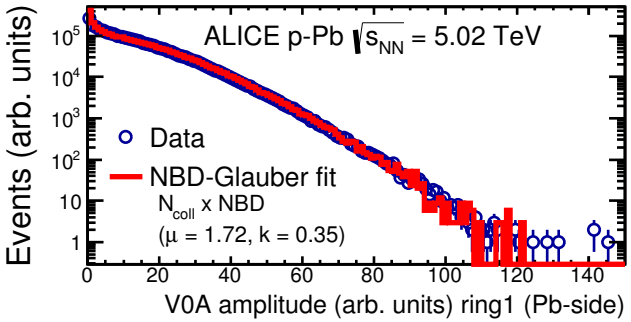
Reclassification leads to enhancement of peripheral RpA and suppression of central RpA (seen in PHENIX & ATLAS)

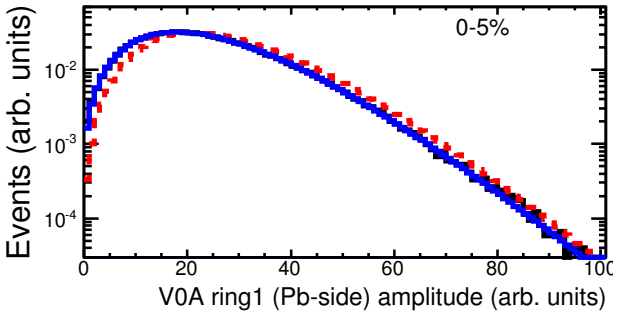
Possible culprits for Centrality Bias

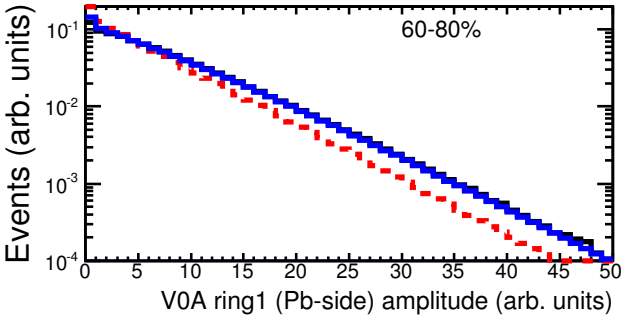
2. Forward jet recoil contaminates centrality selection using bins of forward calorimeter energy
   - Affects shape of centrality distribution such that central events are redefined as peripheral

arXiv: 1412.6828





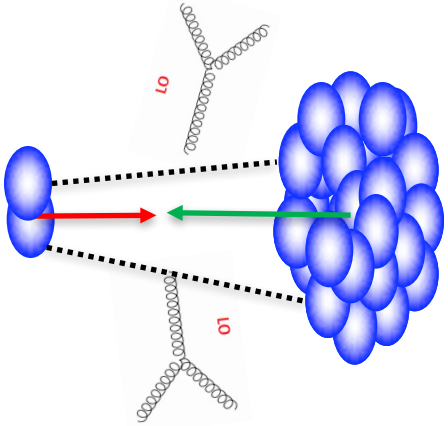




Because fits to Glauber MC are not great (from jet recoil bias), <Ncoll> estimation overnormalizes central events and undernormalizes peripheral events

Possible culprits for Centrality Bias

3. Centrality models must be adjusted to account for multiple interactions (especially in d+Au)
   - Includes beam remnant rescatterings
   - "Proton broadening" fluctuations could cause similar bias



Glauber models do not take into account extended nucleon-nucleon interactions (assumes a single IP)

Conclusions

- Electroweak probes further constrain nPDF effects in p+Pb
  - Favor CT10 + EPS09 PDFs and nPDFs
- Jet R_{pA} and Frag. Function analyses indicate consistency with pp (for inclusive centrality)

- Centrality is a fickle beast in small systems
  - Underscores the need for very carefully calibrated (and clear!) centrality definitions

BACKUP

Further Clarification in Centr. Bias #2

1. Forward jet production reclassifies peripheral events as "central" events by increasing energy in Pb-going direction

2. Centrality distribution changes shape and is still fit to Glauber distributions

3. "50-100%" now really includes 30-40% centrality events

4. Average Ncoll from Glauber is too small to adequately scale peripheral events and too large for central events

If Glauber MC is used to determine Ncoll of "selected" 50-100% events, <Ncoll> is too small for most events!

- Only truly decoupled measurements of multiplicity (i.e. ZDC measurements) can be thought of as directly correlated to impact parameter

ALICE Hybrid Centrality Model

- Hybrid because:
  - The ZNA energy is used to classify events
  - $\langle N_{coll} \rangle$ is obtained by scaling the min bias value (=7.9) by the relative yield of high-p_T particles
- Assumptions involved:
  - ZNA is unaffected by midrapidity biases
  - Yield of charged high-p_T particles at midrapidity is proportional to N_{coll}
- Tested by looking at $dN/d\eta$ density vs N_{part}, where N_{part} is calculated assuming various models

Analyses

- PHENIX
  - Jets in d+Au (http://arxiv.org/pdf/1509.04657v2.pdf)
- STAR
  - (None) Only Au+Au jet results
- CMS
  - Dijets in pPb (http://arxiv.org/abs/1401.4433)
  - Z-boson in pPb (http://arxiv.org/abs/1512.06461)
  - W-boson in pPb (http://arxiv.org/abs/1503.05825)
  - Jet FF in pPb (http://cds.cern.ch/record/2030077)
  - B-jet in pPb (http://arxiv.org/abs/1510.03373)
  - C-jet in pPb (http://cds.cern.ch/record/2055705)
- ALICE
  - Centrality dependence of jets in pPb (http://arxiv.org/abs/1603.03402v1)
  - Dijets in pPb (http://arxiv.org/abs/1503.03050v2)
  - Centrality dependence of particle prod. in pPb (http://arxiv.org/pdf/1412.6828v2.pdf)
- ATLAS
  - Z boson in pPb (http://arxiv.org/abs/1507.06232)
  - Jet prod in pPb (http://arxiv.org/abs/1412.4092)
  - W in pPb (http://cds.cern.ch/record/2055677)
  - Jet FF in pPb (http://cds.cern.ch/record/2029373)