COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

ATLAS EXPERIMENT

Jet measurements with the ATLAS detector in Pb+Pb and *p*+Pb collisions

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Hard Probes 2013

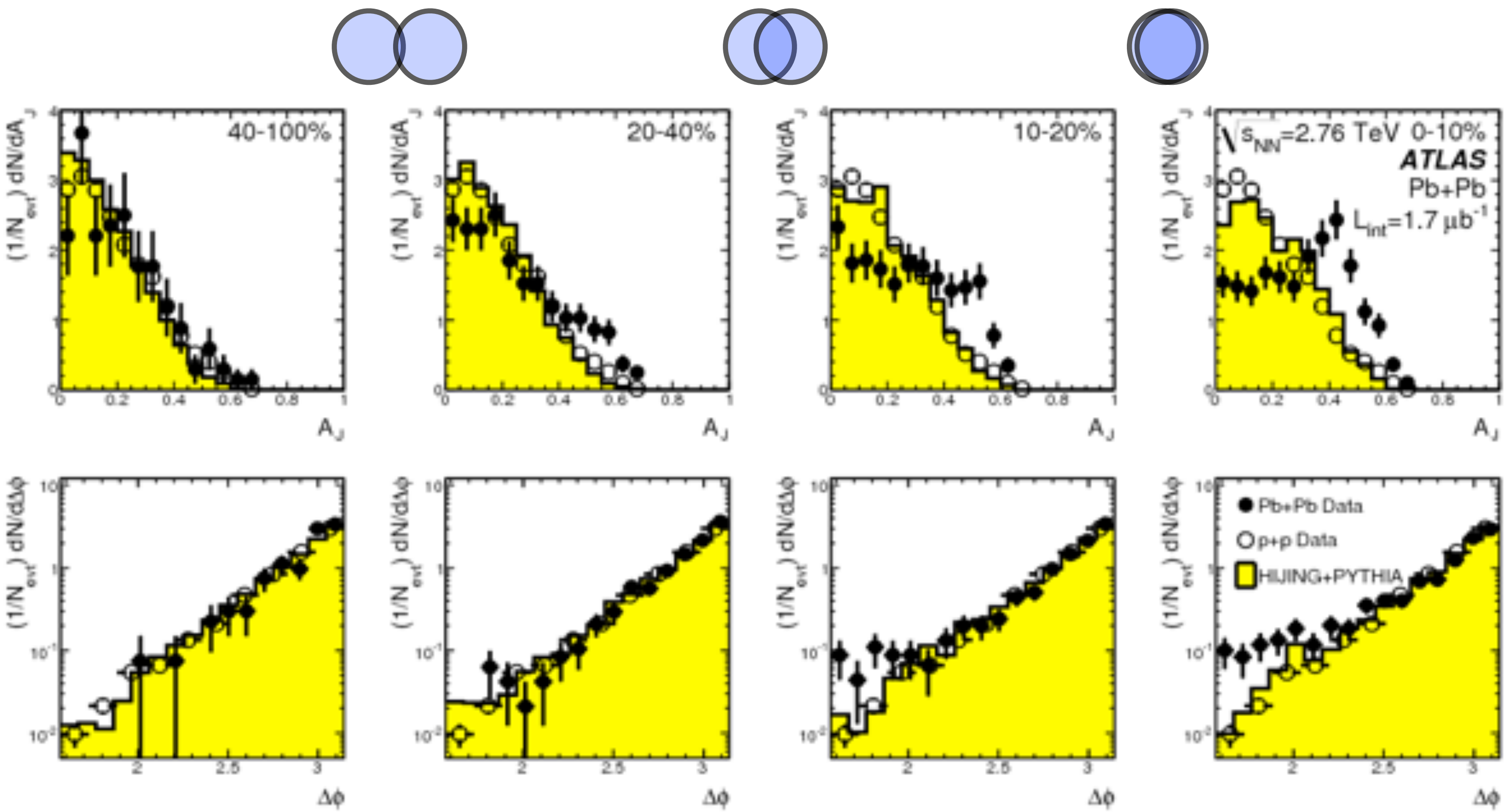
Tuesday, November 5, 2013

Overview

- Present forward-looking summary of jet results from ATLAS in Pb+Pb collisions
  - Not many new results
    - ➡ Azimuthal dependence of quenching
  - Emphasize how each of these measurements contributes to a holistic understanding of quenching mechanism
- New jet results in *p*+Pb
  - Implications for jet quenching in Pb+Pb

Ushering in the LHC Era: Dijet Asymmetry

hep-ex/1210.6182



$$A_J = \frac{E_T^1 - E_T^2}{E_T^1 + E_T^2}$$

$$E_{T1} > 100\ GeV$$

$$E_{T2} > 25\ GeV$$

First direct observation of jet quenching

Significant fraction of events with enhanced dijet asymmetry while simultaneously preserving the back-to-back angular correlation

Ushering in the LHC Era: Dijet Asymmetry

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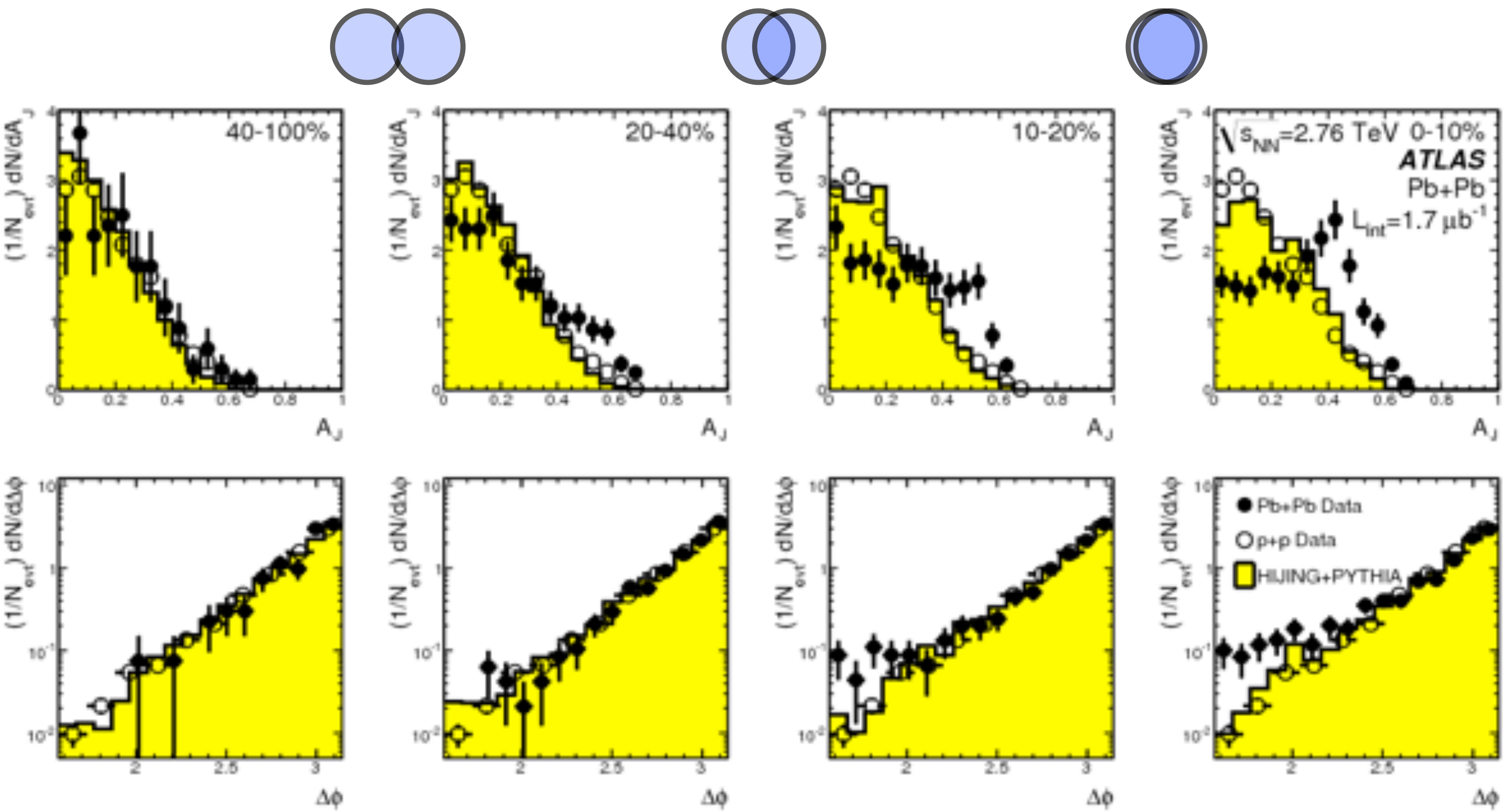

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First direct observation of jet quenching

Significant fraction of events with enhanced dijet asymmetry while simultaneously preserving the back-to-back angular correlation

Puts very tight constraints on models where quenching primarily affects the leading parton

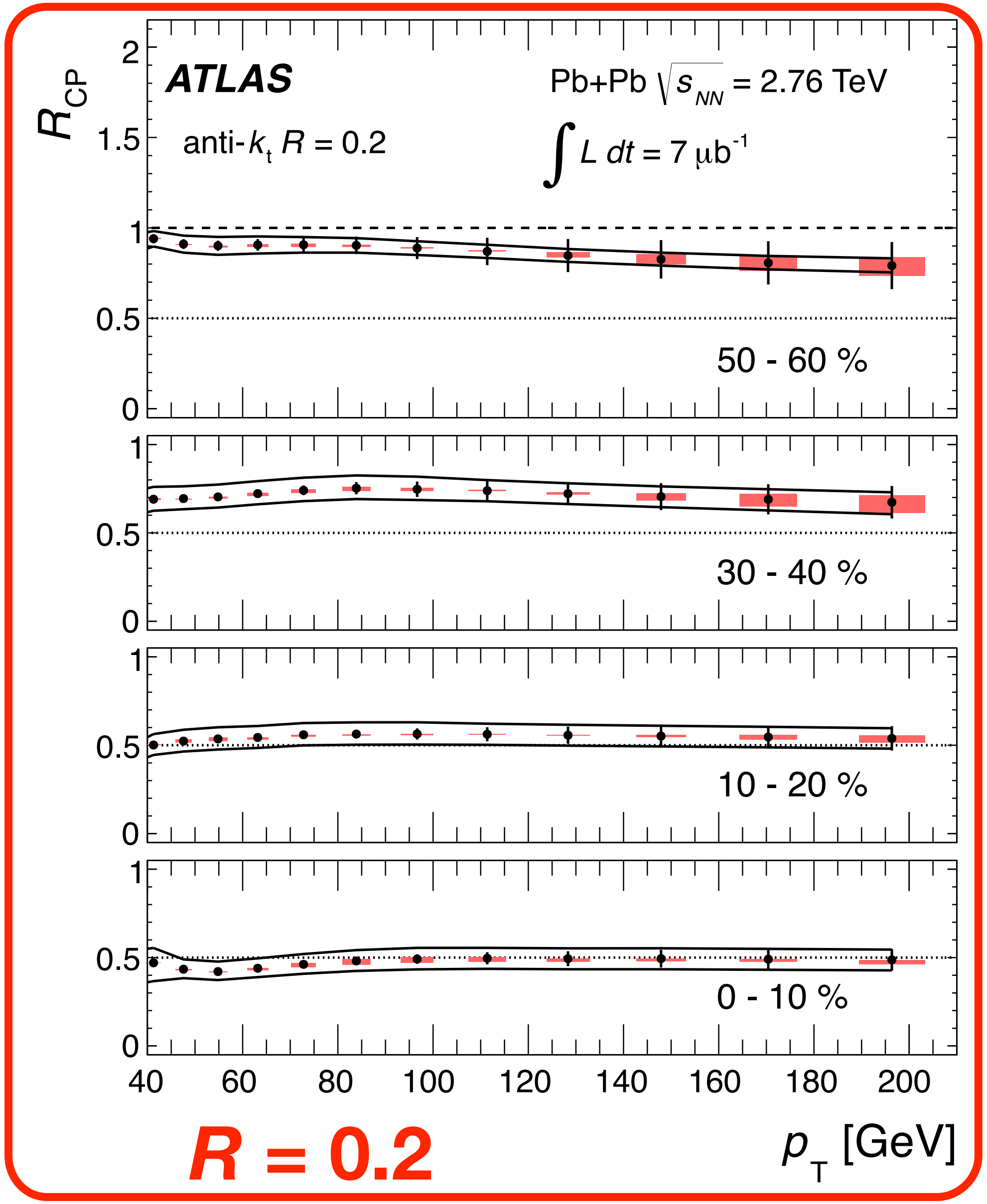
Full parton shower must be considered

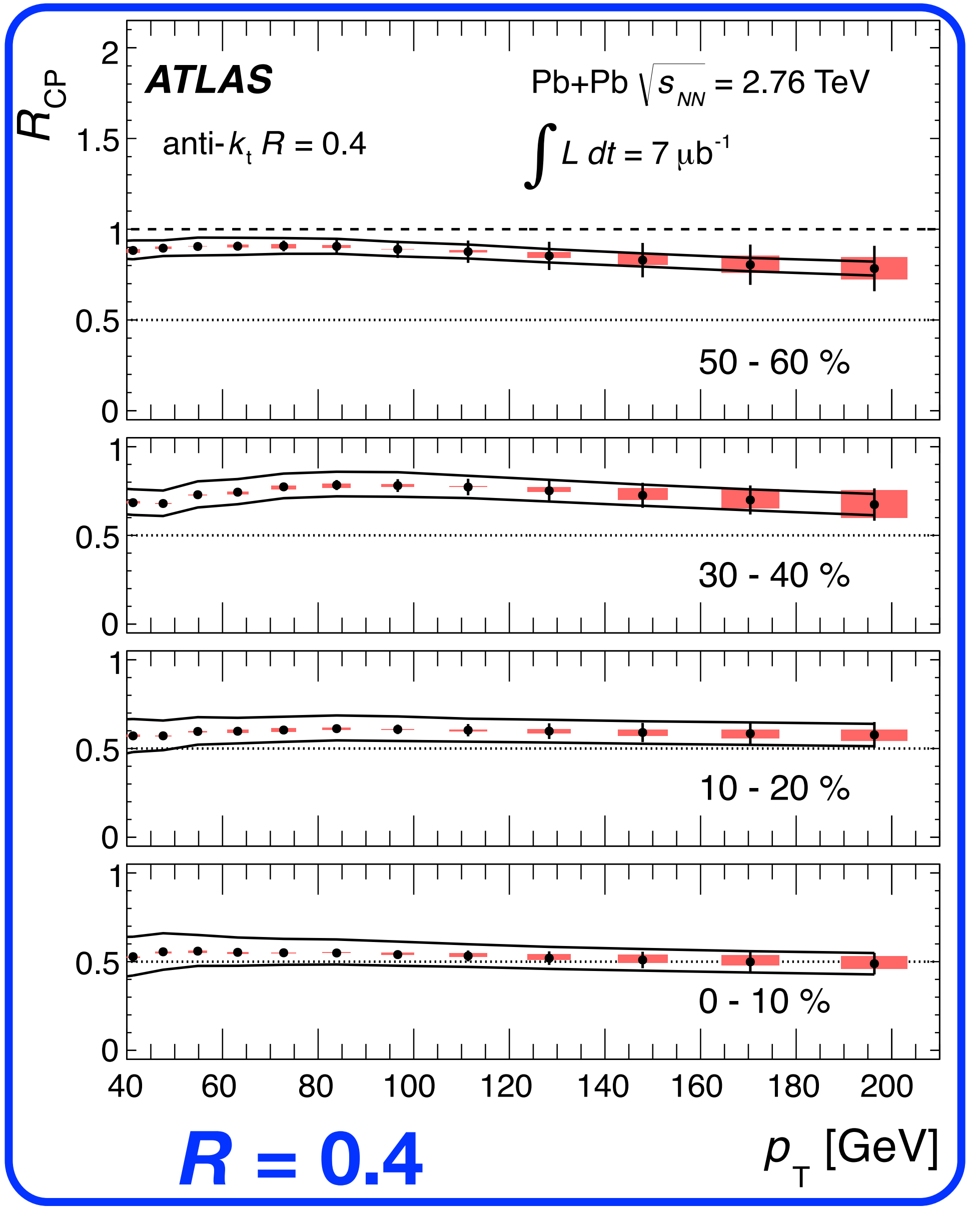
Jet observables at the LHC

- Follow asymmetry observation with a series of measurements using fully reconstructed jets to map out features of quenching mechanism
- Jet kinematics contain information about full parton shower not just the leading parton
- Highly differential studies of inclusive *jet suppression*
  - Big lever-arm in p_T at the LHC
  - Dependence on centrality and $\Delta\phi$
    - Sensitivity to medium properties
  - Dependence on jet size
- *Jet structure* and properties of quenched jets
  - Distribution of particles within jets
  - Distributions of fragment p_T, z and j_T
- *Differential energy loss* through correlations with color neutral probes
  - Different quark/gluon mixture than inclusive jets
  - Distribution of jet p_T recoiling against Z or photon

Inclusive jets: R_{CP} vs p_T in centrality bins

hep-ex/1208.1967

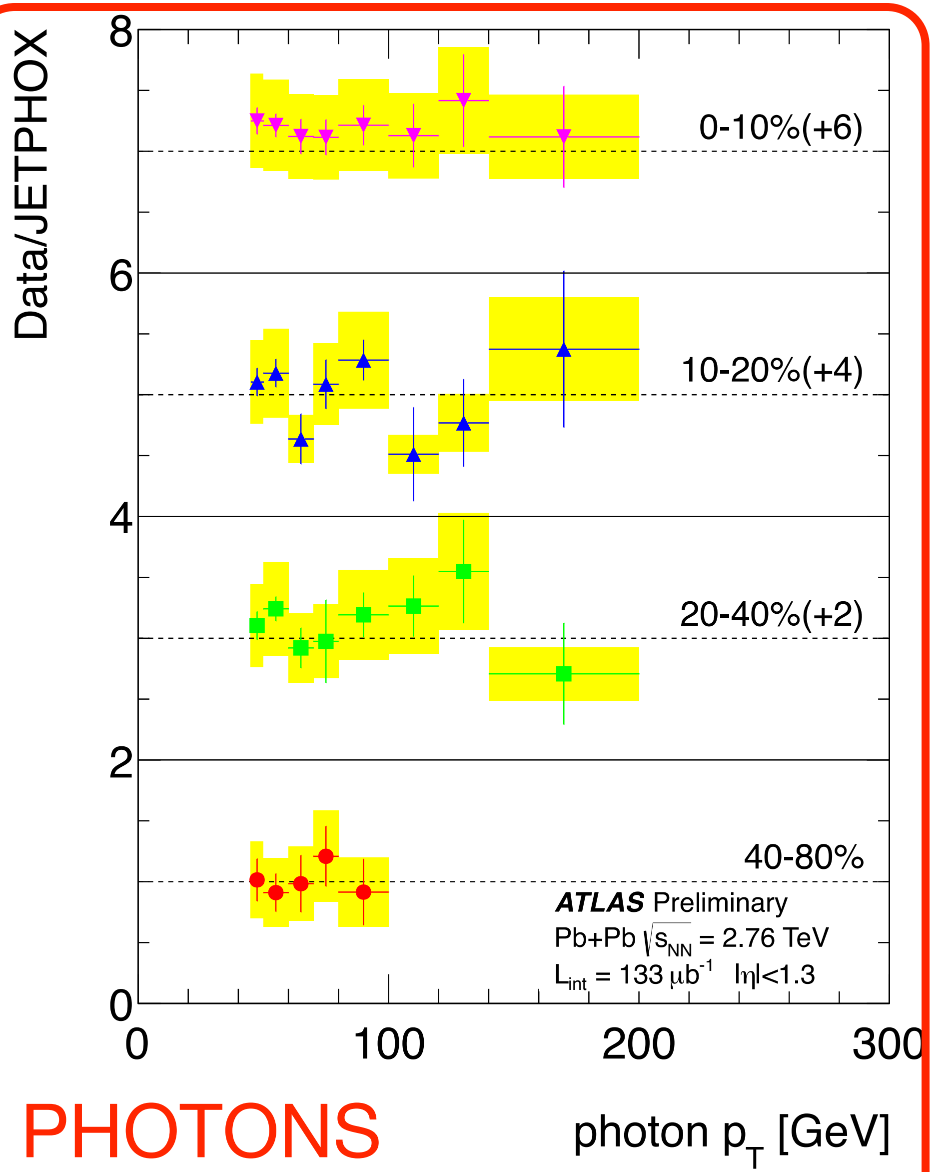




Use 60—80 % as peripheral reference

See parallel talk by M. Rybar on Monday

Isolating initial state effects



PHOTONS

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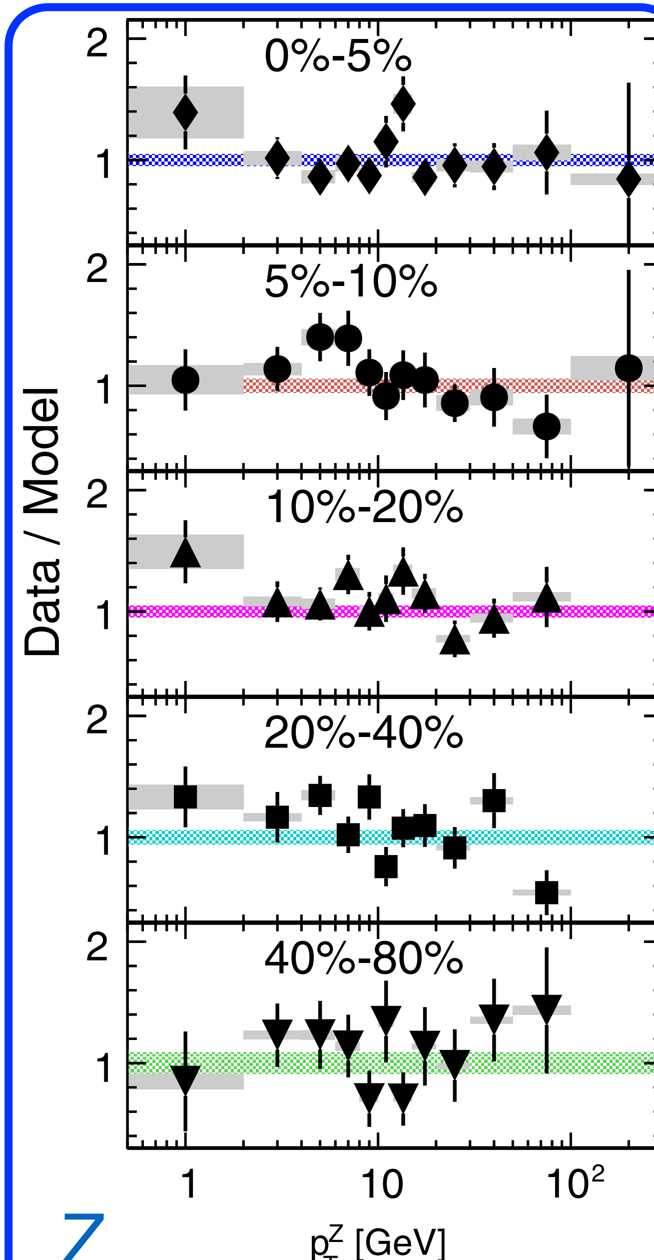


Z

hep-ex/1210.6486

No large NPDF effects

Constrained to ~10%

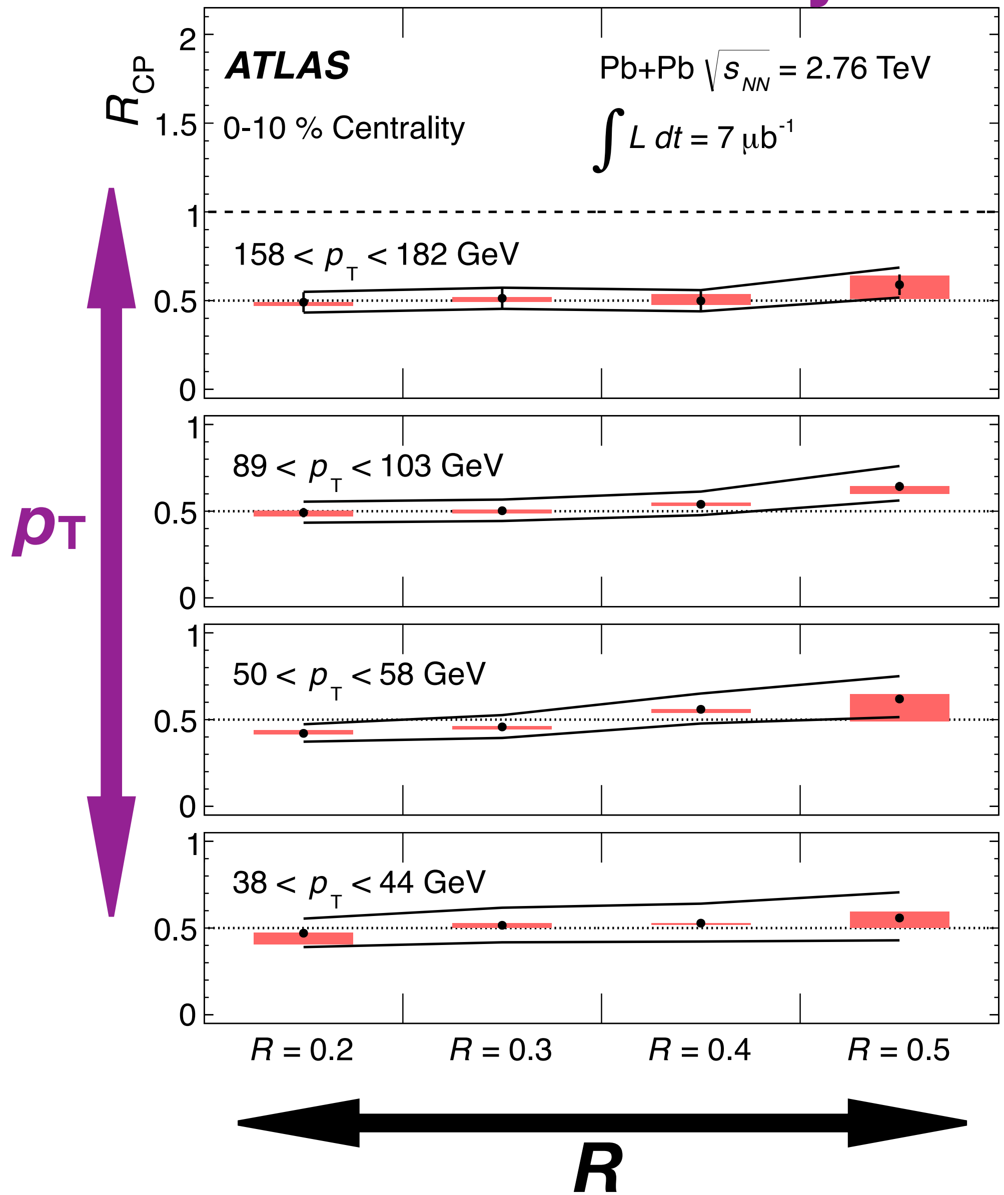
Can be further constrained with future data

Initial state effects not enough to explain measured jet suppression

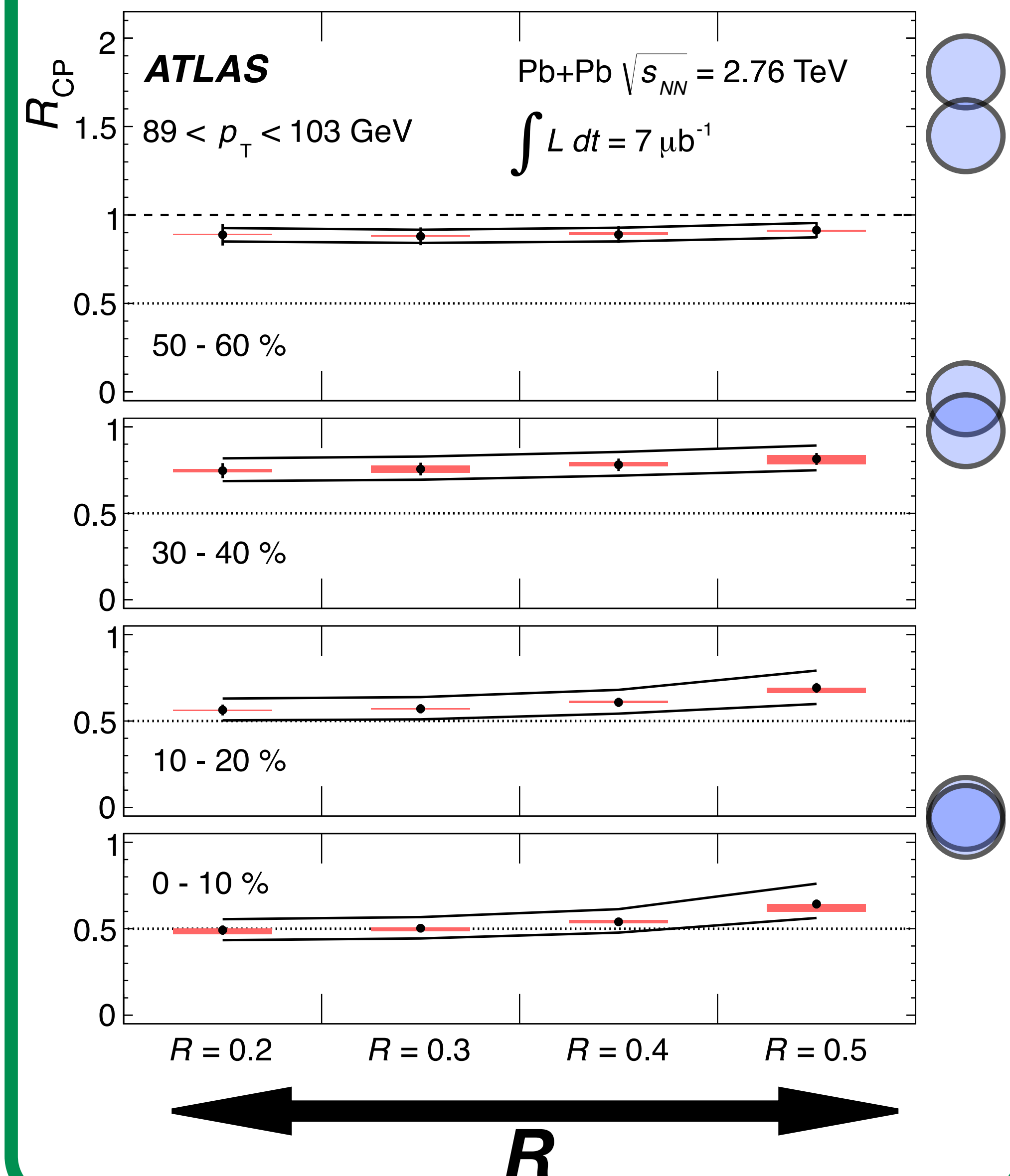
Inclusive jets: R_{CP} vs R

hep-ex/1208.1967

0—10% centrality

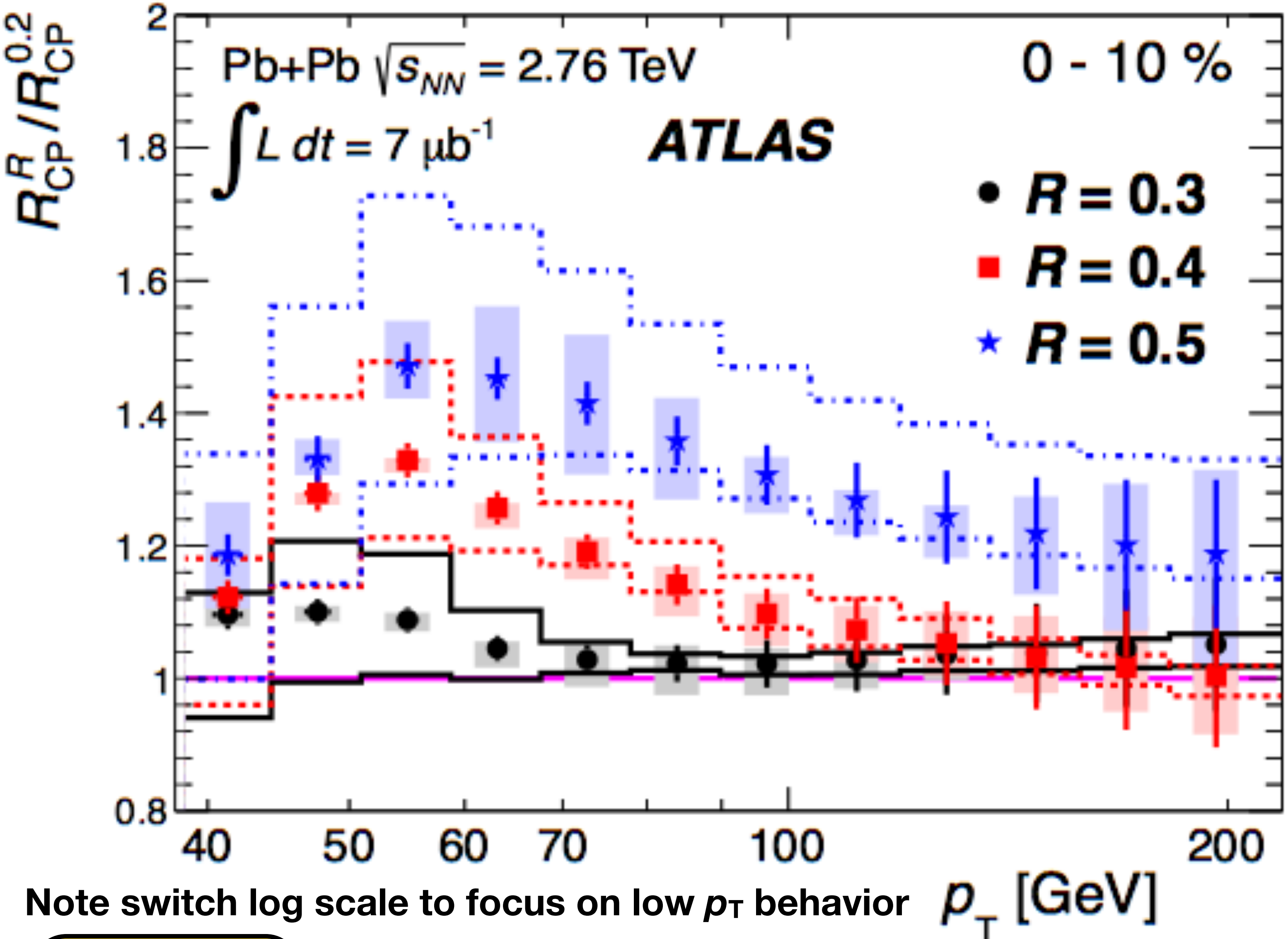


89 < p_T <103 GeV



Quantitative statement of *R* dependence

hep-ex/1208.1967



Ratios of R_{CP} to R_{CP} with R=0.2

Measure *relative* suppression with respect to most suppressed *R* value (*R*=0.2)

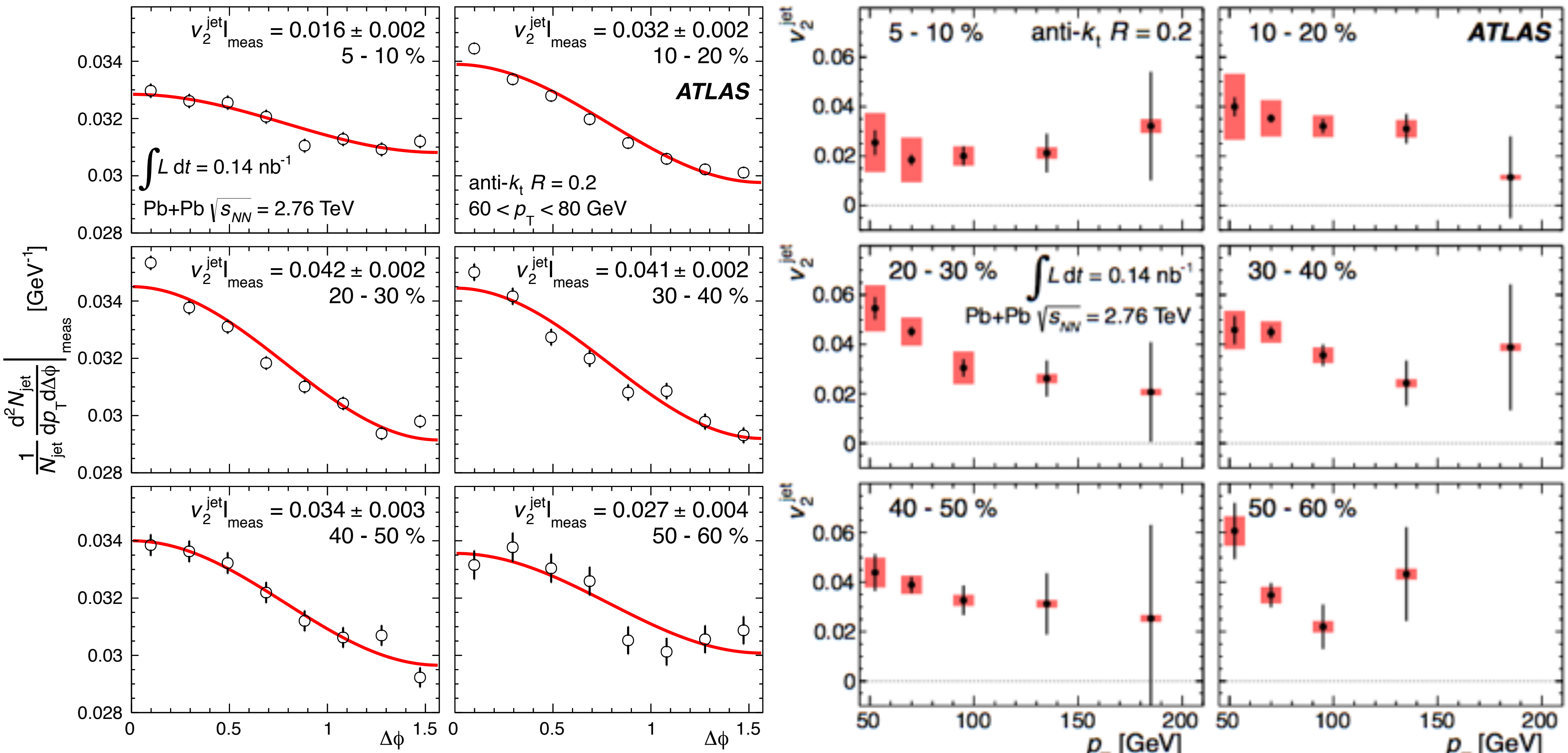
Variation with R is significant

Note switch log scale to focus on low p_T behavior

See parallel talk by M. Rybar on Monday

- **Many systematics cancel, correlated between different *R***
- **Statistical correlation between different *R* values included and propagated through unfolding**

Jet suppression and collision geometry

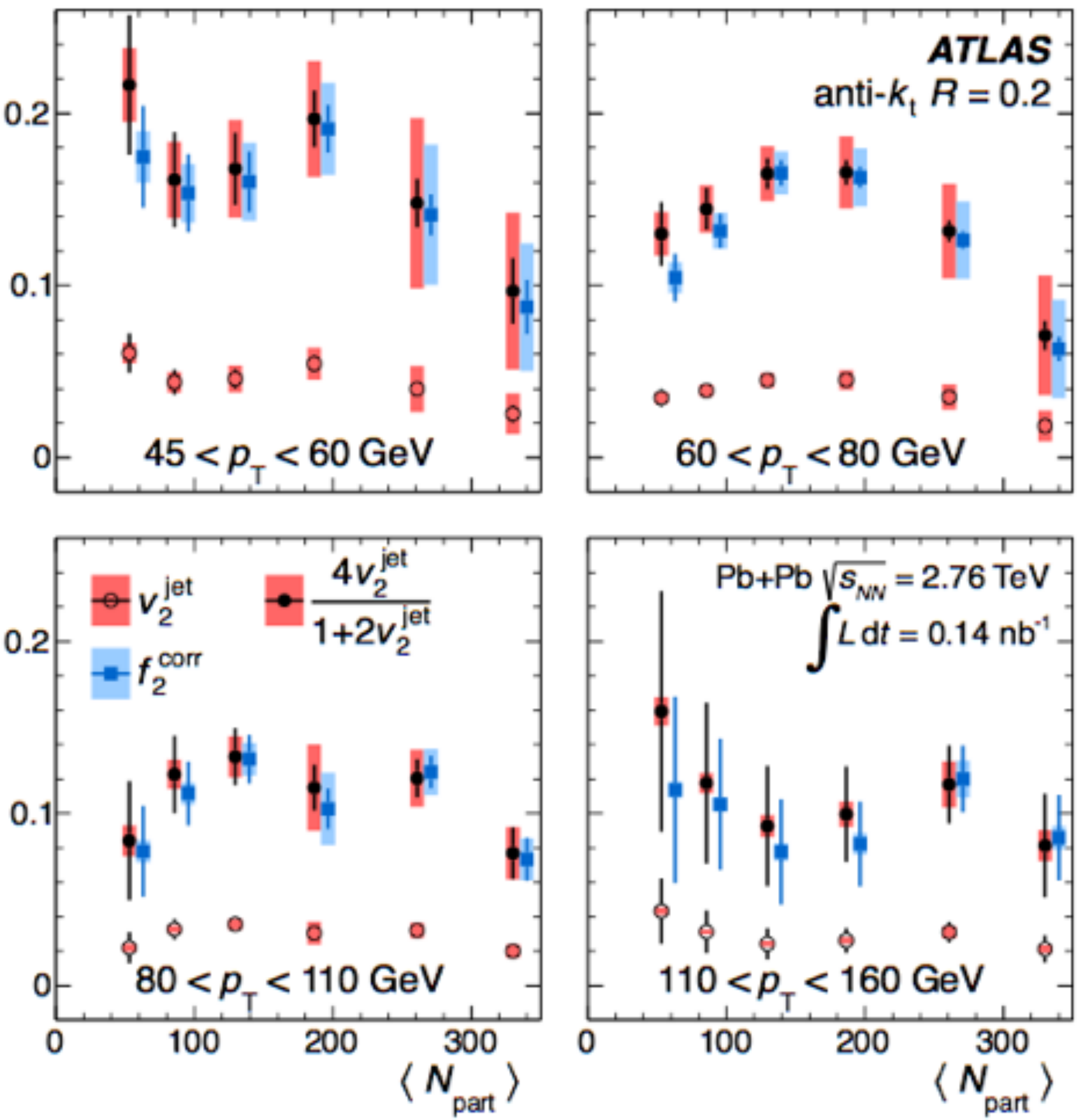


[hep-ex/1306.6469](hep-ex/1306.6469)

- **Jets in the direction of the event plane are less suppressed**
- **cos(2$\Delta\phi$) modulation of yield of 1-5%**

See parallel talk by M. Rybar on Monday

Jet suppression and collision geometry

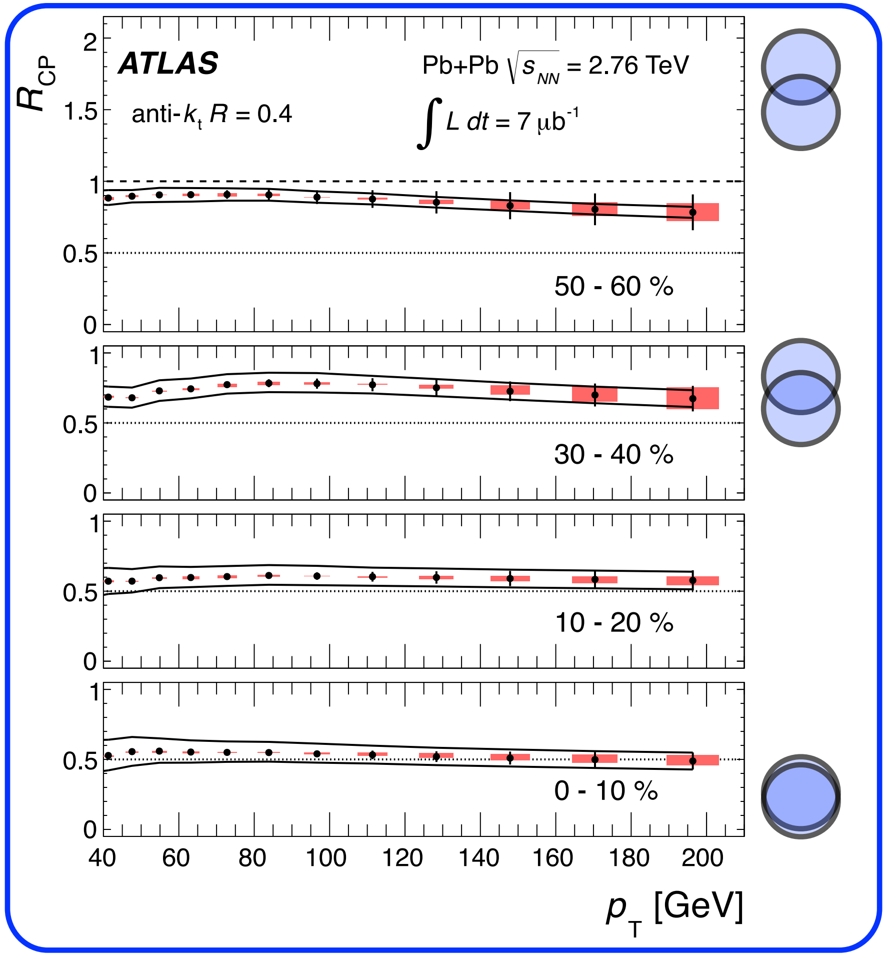


hep-ex/1306.6469

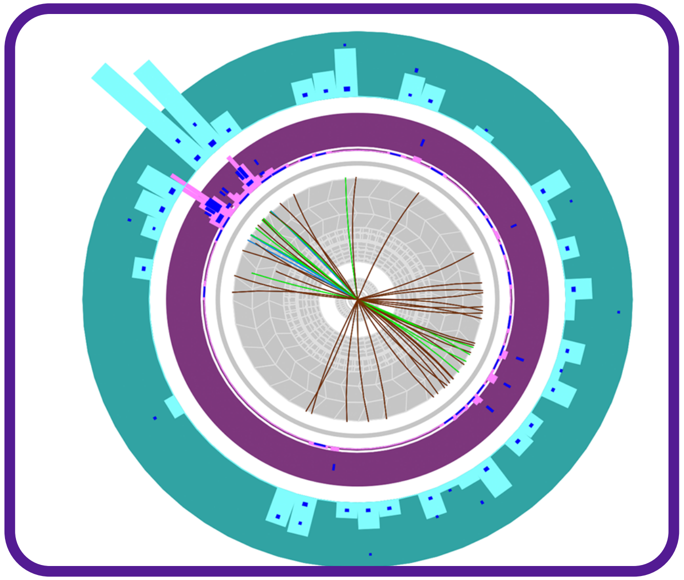
- Compare ratio of yields at $\Delta\phi$=0 and $\pi/2$ to expectation from pure second harmonic modulation
- Almost no room for different modulation modulation (e.g. $\cos^2 2\Delta\phi$) which may be expected from non-linear path length dependence
- Need calculation with full realistic geometry

- In HI we have event-by-event fluctuations in both the parton shower and the jet interactions with the medium

➡ <u>Key question</u>: Is quenching driven by average energy loss effects or by significant event-by-event variation not well represented by the average?



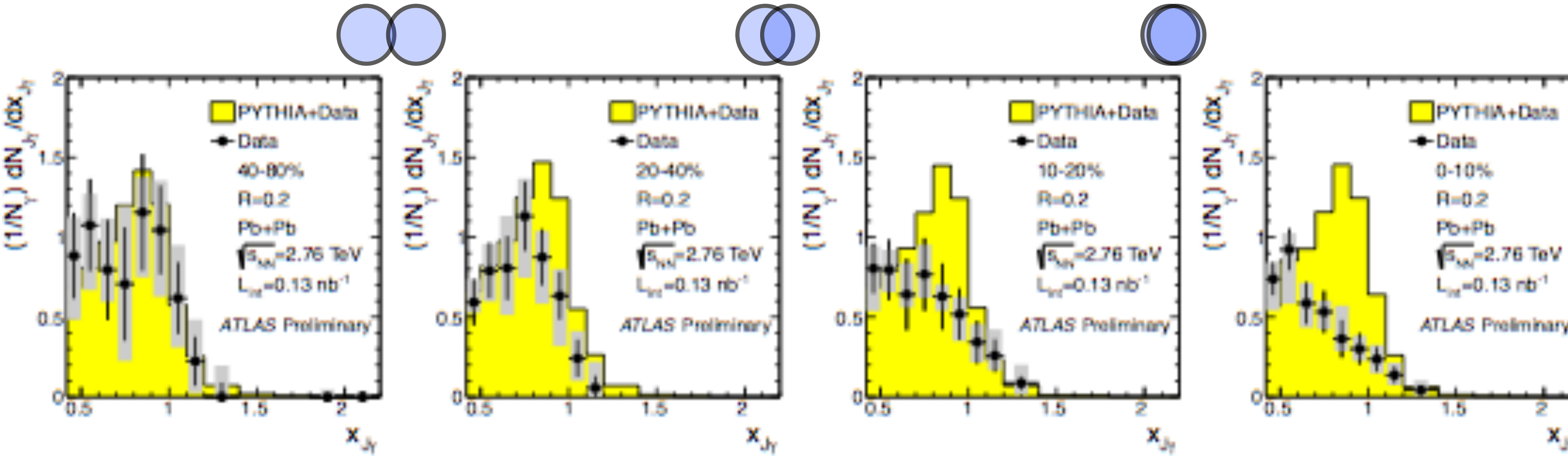
- Use suppression measurement with simple quenching models to give estimate of average energy loss
- Contrast with asymmetry observation : jets often lose more than 50% of their energy



Asymmetry: Differential Energy Loss

- γ/Z— jet correlations provide clean probe since γ and Z (or leptonic decay products) do not suffer energy loss
  - ➡ Do NOT expect jets recoiling against γ/Z to have same p_T as γ/Z
  - - Effects like initial state parton shower cause broadening of distribution
  - - Focus on $x_J = p_T^{\text{jet}} / p_T^{\gamma/Z}$
- Unmodified x_J and A_J distributions in are different γ— and Z— jet events
  - - Large virtuality required to produce Z
  - ➡ Potentially provide different handles on energy loss since intrinsic distributions are different

γ-jet: $x_{J\gamma}$ Distributions



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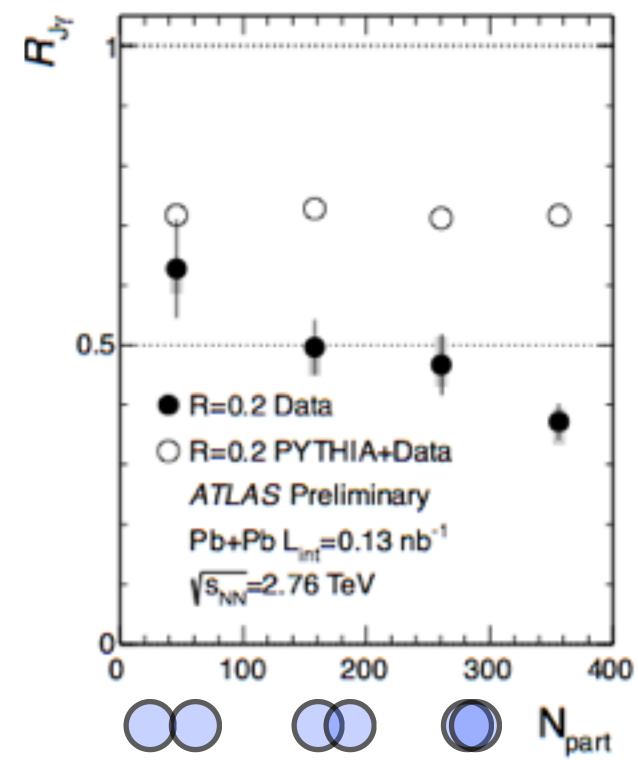

- Distributions are normalized ***per photon***
  - Includes cases where recoiling jet is out of kinematic range or quenched entirely
- Not just a shift in distribution but affects entire shape
  - ➡ Again see average vs fluctuation-driven energy loss contrast

Z—jet correlations

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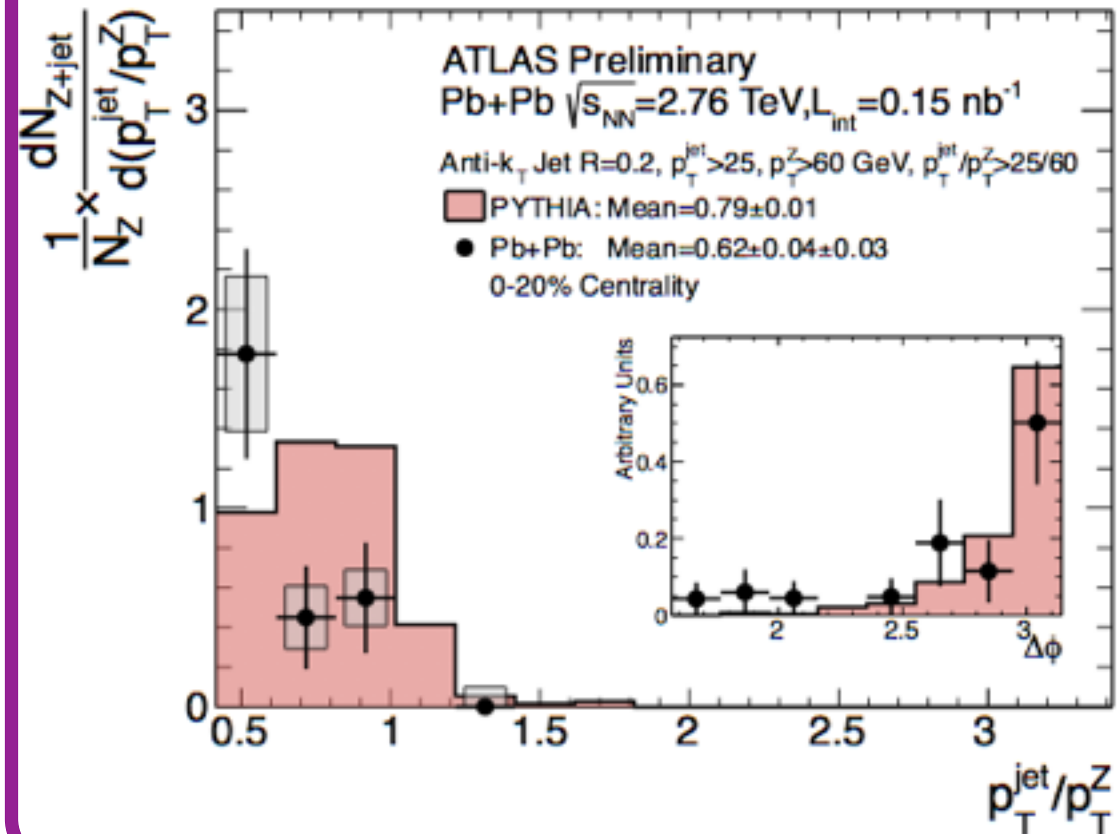
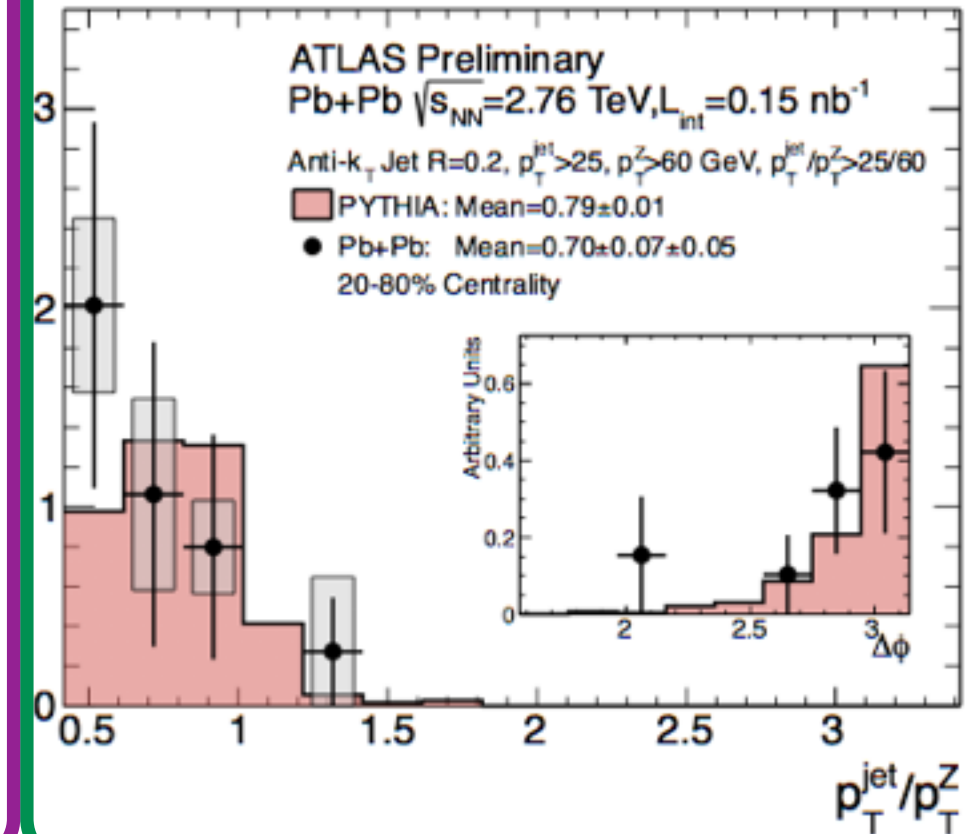
0—20% centrality



20—80% centrality



Mostly proof of principle due to low statistics but hints at potential of the measurement when more data comes

General trend compatible with photon-jet results

Jet structure: centrality dependence

Ratio = D $_{0-10\%}$ ***/ D*** $_{60-80\%}$

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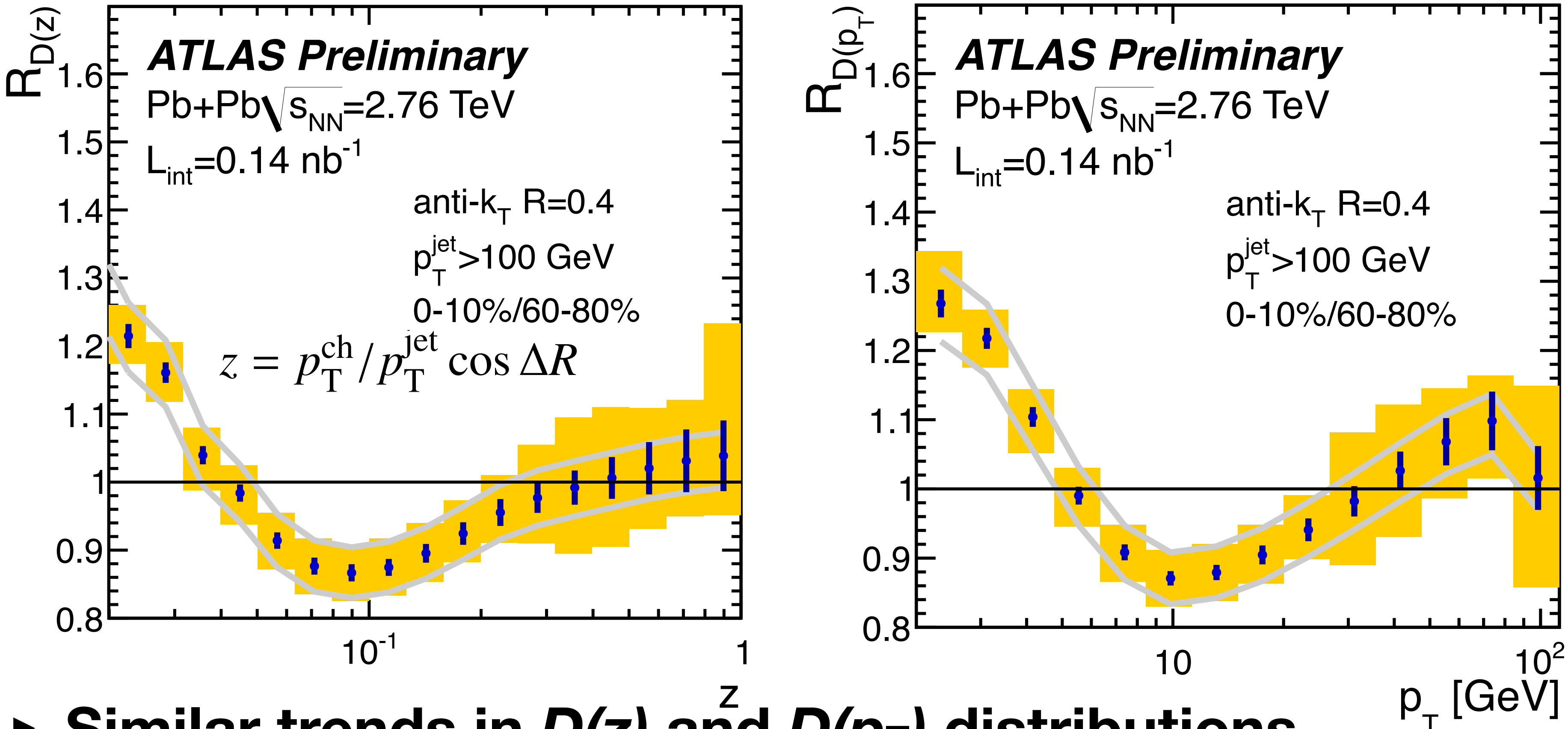


- **Similar trends in *D(z)* and *D(p_T)* distributions**
- ***D(p_T)* does not have quenching effect in denominator**
  - **Slightly cleaner interpretation**
- **Note: no "normalization" constraint**
  - **Enhancement in one region of *z*/p_T does not imply suppression in another**

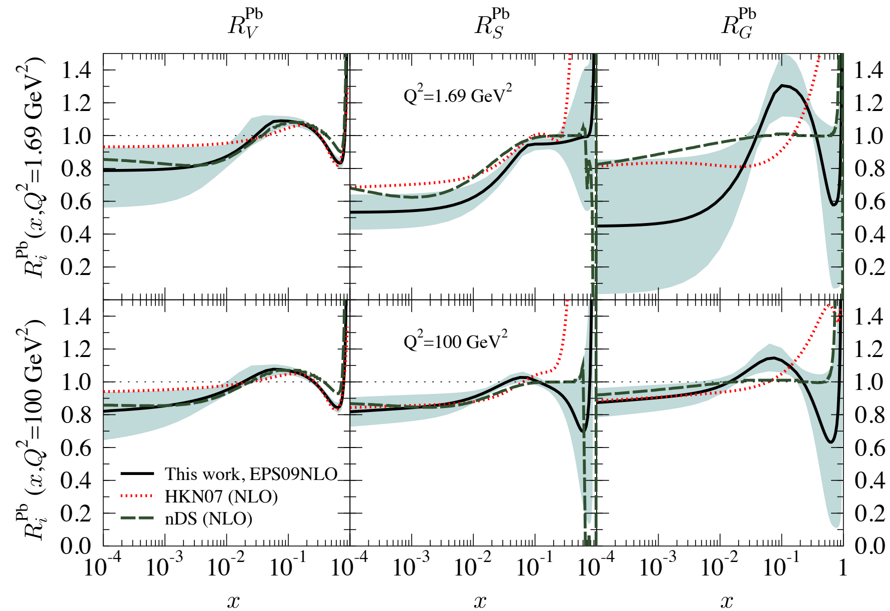
Conclusions: Pb+Pb

- Typical- vs fluctuation- driven quenching paradigm
  - How can measurements and calculations be more discriminating?
- Large quenching effects still preserve dijet $\Delta\phi$ correlations
  - Rigorous approach considering full parton shower needed to describe LHC data
- *R* dependence of single jet suppression suggests some medium induced radiation recovered by going using larger jet definition
  - Need to be precise about energy being radiated away at “large angles”
  - Can such calculations also describe excess at low z/p_T in fragmentation functions?
- Path length dependence needs serious investigation
  - How does *L* dependence survive integration over realistic geometry?

Towards *p*+Pb

- **Nuclear PDFs are <u>not</u> simple superposition of nucleon PDFs**

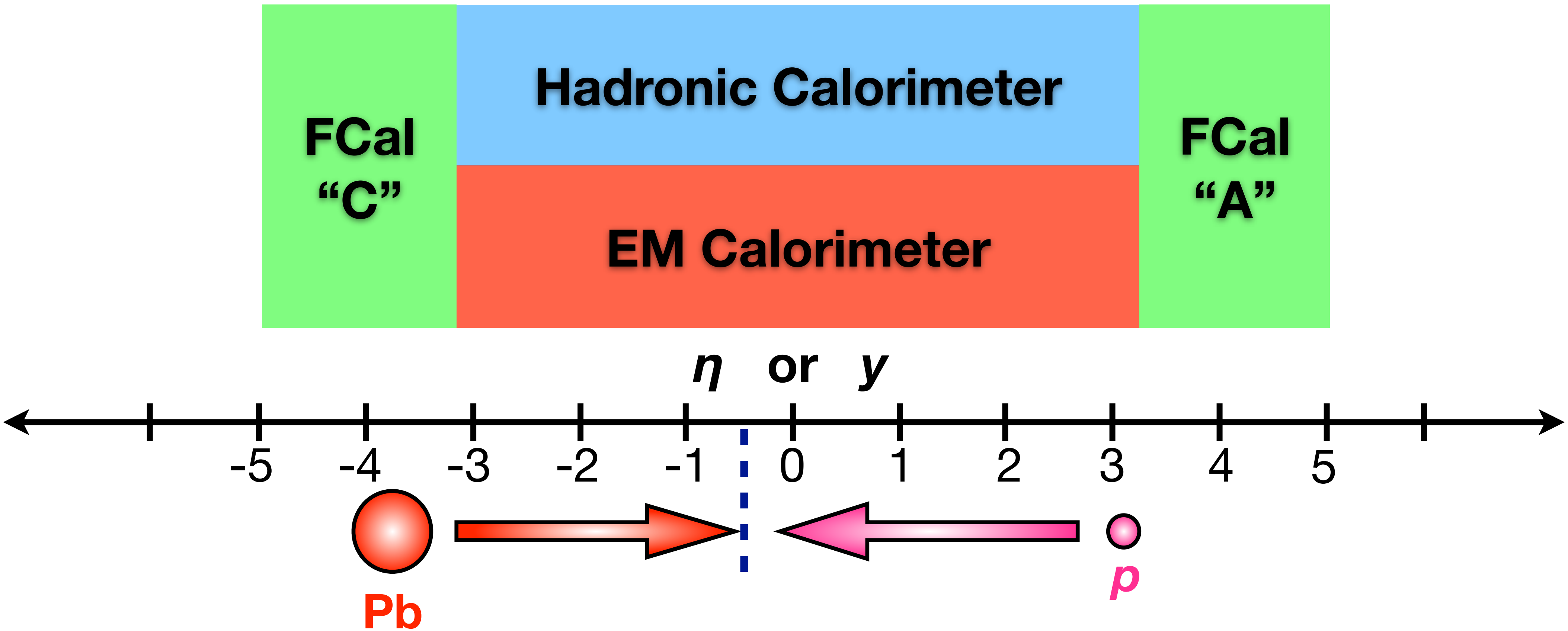
$$R_A = \frac{f_A(x,Q^2)}{Af_N(x,Q^2)} \neq 1$$



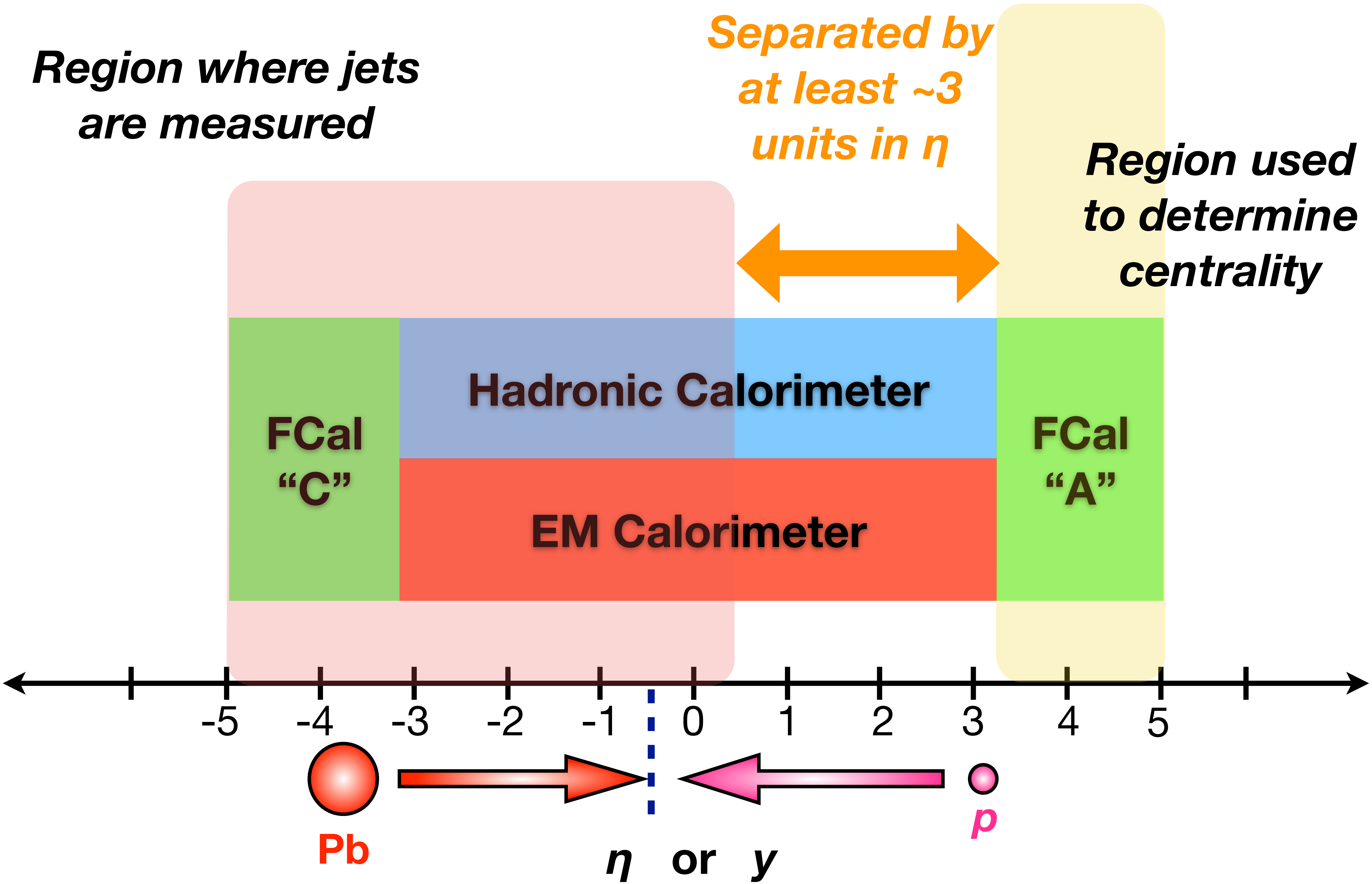
  - **What is partonic nature of these modifications?**
  - **Possible explanations for (anti-) shadowing in terms of saturation physics**
  - **Less clear for EMC**

- **Measurements of photon/Z yields rule out NPDFs as sole source of jet suppression**
- **If we want precise measurements of quenching effects we need to know (very precisely) how much suppression is coming from initial NPDF effects**
  - ➡ **Especially impact parameter dependence**
- **Can perform precision measurements in *p*+Pb using hard probes over a huge range in phase space and put strong constraints on this**

Inclusive jet production in p+Pb collisions



Inclusive jet production in *p*+Pb collisions



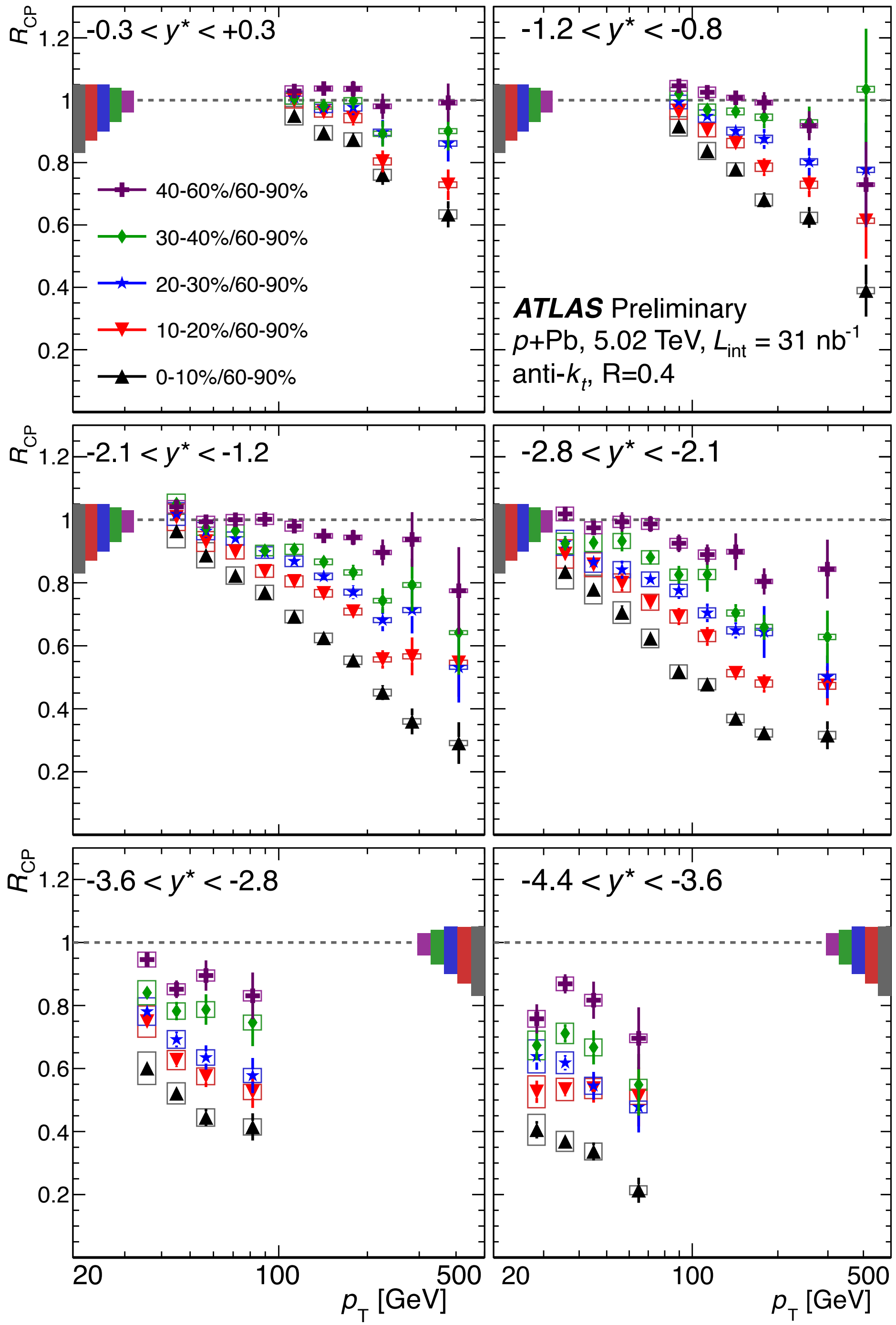
Inclusive jet production in p+Pb collisions

- Measurement uses 2013 p+Pb data from both beam orientations 31 nb^{-1}
- In R_{CP}, 60—90 % bin used as peripheral reference
- Jet p_T spectra measured as a function of centrality and rapidity in CM frame, y^*
  - Measuring $-4.4 < y^* < 0.3$
- Measurement performed with bin-by-bin unfolding in p_T range where correction factors are centrality independent
- Energy within jets in FCal is excluded from centrality determination

See parallel talk by D. Perepelitsa on Thursday

Jet R_{CP} in p+Pb

More forward (p-going)



Jets suppressed by up to a factor of three

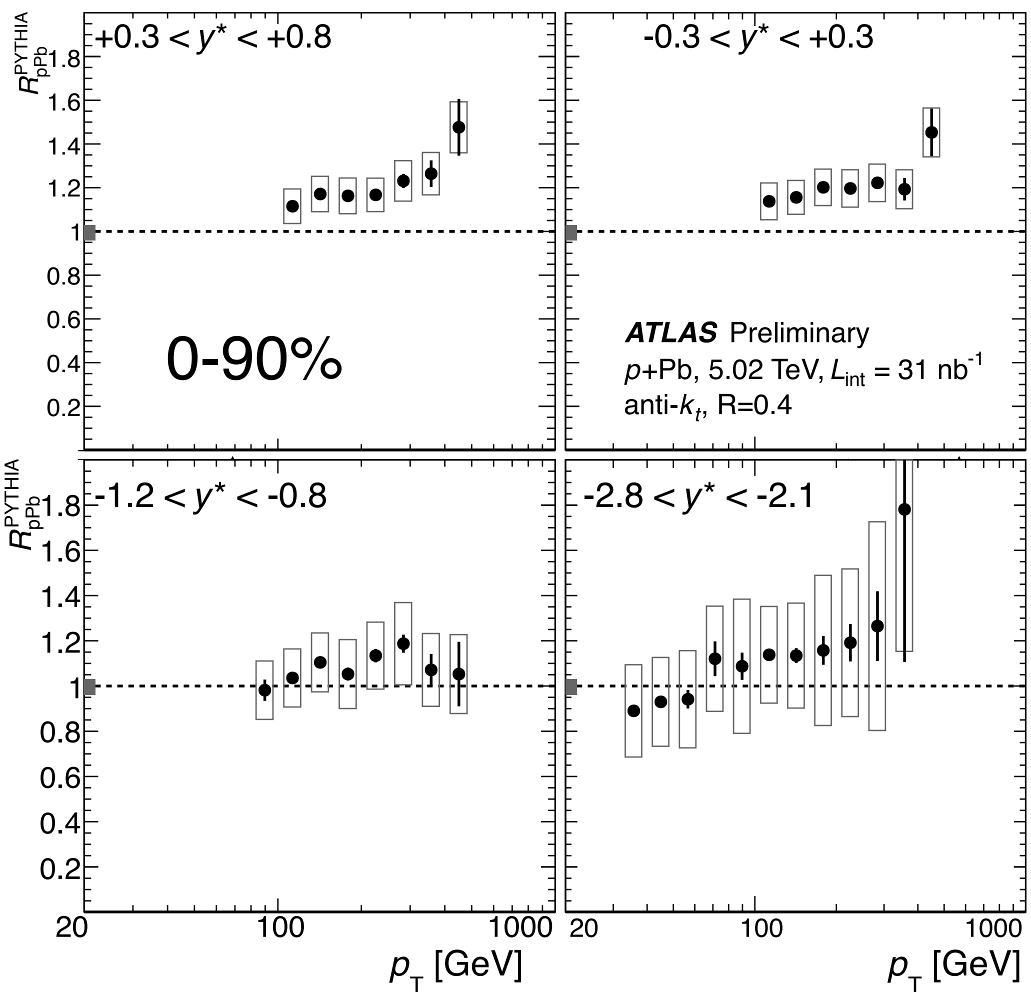
Suppression increases with p_T and y^*

Peripheral is 60 — 90 %

Colored bands are N_{coll} uncertainties

$R_{pPb}^{\mathrm{PYTHIA}}$: minimum bias averaged

- **No *pp* data available at this energy**
  - **Rescaling of measured *pp* jet cross sections possible**
- **For now use PYTHIA as reference for absolute suppression**



$$R_{p\mathrm{Pb}}^{\mathrm{PYTHIA}} = \frac{\frac{1}{N_{\mathrm{evt}}} \frac{1}{\langle T_{\mathrm{A}} \rangle} \left. \frac{\mathrm{d}N_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*} \right|_{\mathrm{cent}}}{\left. \frac{\mathrm{d}\sigma_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*} \right|_{\mathrm{PYTHIA}}}$$

May even see slight enhancement at mid-rapidity

But no significant suppression especially at forward rapidities

No significant slope with p_T

Shaded bands are N_{coll} uncertainties

R_{pPb}^{PYTHIA} : centrality dependence

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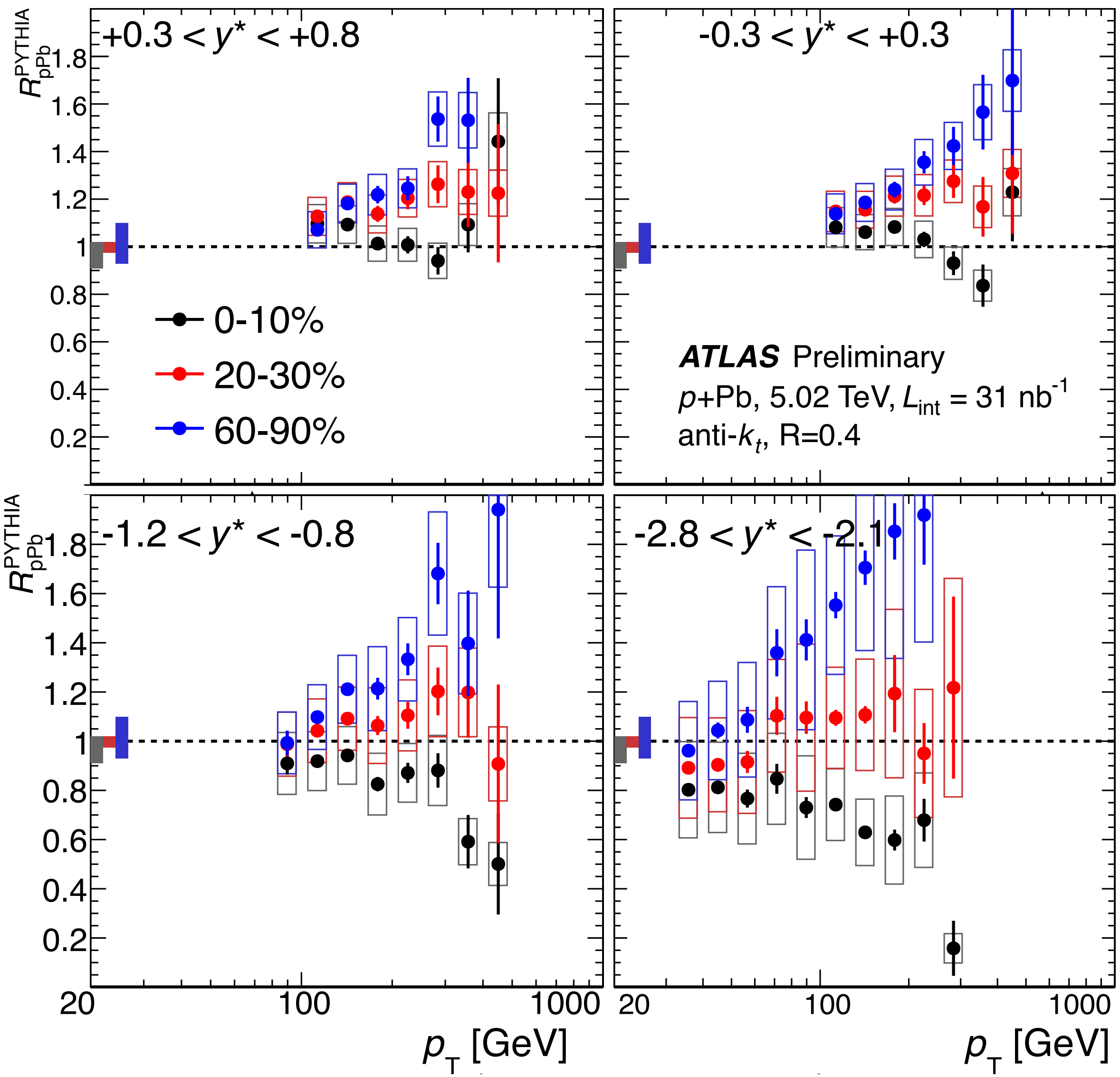
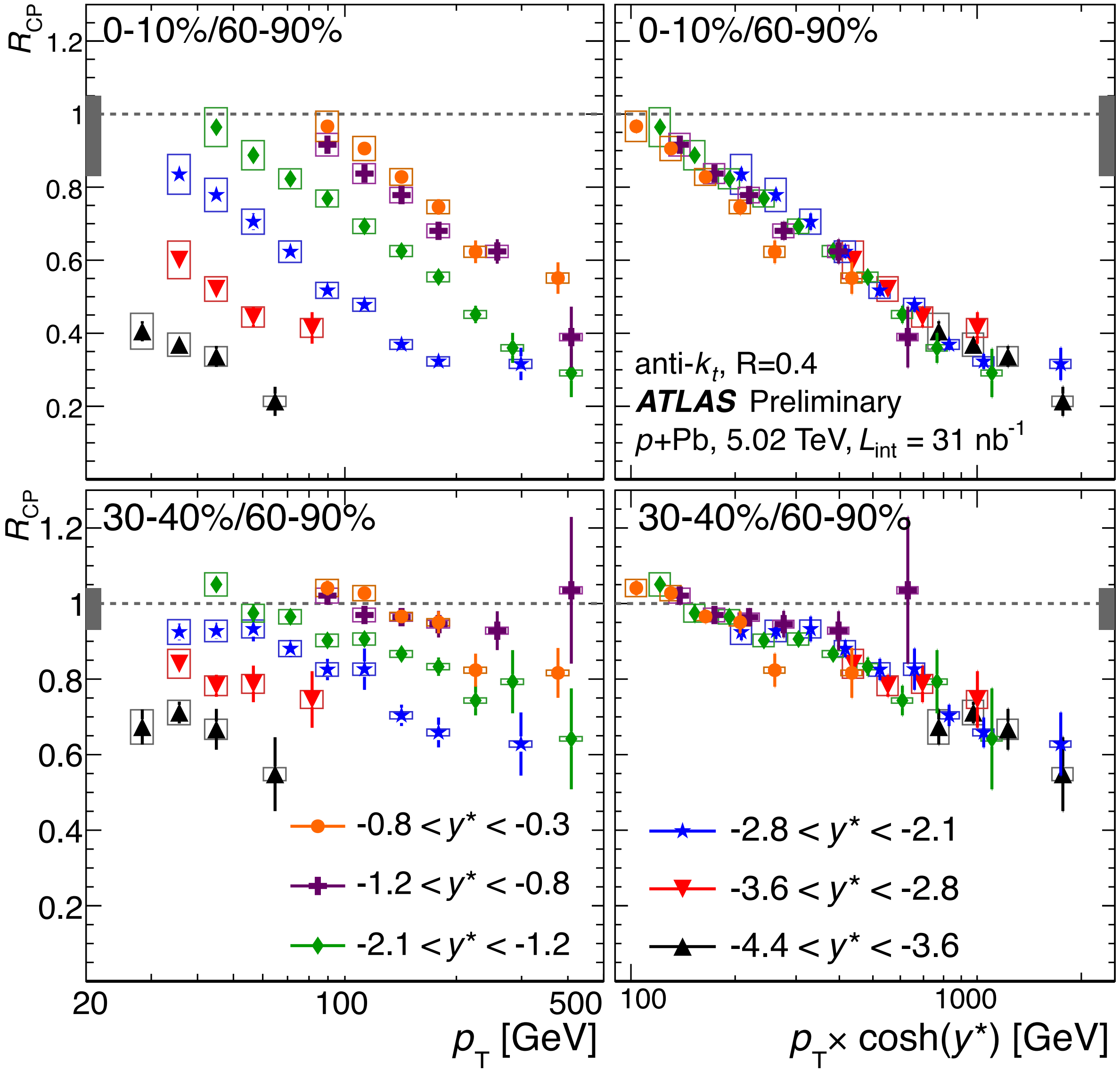
R_{CP} suppression driven by suppression in central and (compensating) enhancement in peripheral



- **Reminiscent of PHENIX result in dAu**
  - **Effect never explained**
- **Does not conform to traditional intuition that peripheral should look like *pp***

Jet R_{CP}

Each y^* bin shows similar suppression when plotted as a function of $p_T \cosh(y^*)$



- Nearly logarithmic $p_T \cosh y^*$
  - ➡ What is setting the scale for this behavior?
- Slope increasingly negative in more central collisions

Issues with Glauber?

- Clear that community has to come to grips with inadequacies of simple Glauber
- However, suppression results are robust
  - Glauber issues can change overall normalization but cannot introduce p_T dependence
  - Extending to Glauber-Gribov further decreases R_{CP}
  - Same Glauber has been used for multiplicity and charged particle R_{pPb} and gives sensible results describing soft and intermediate p_T particle production

See P. Steinberg's overview on Monday

Conclusions: *p*+Pb

- Strong correlation between hard ($q^2 > (100\ \text{GeV})^2$) and soft (UE) particle production
  - In collinear factorized QCD these processes should factorize
  - Correlation not obviously describable by known mechanism
- Case 1: Suppression is the result of a correlation between hard and soft processes affects centrality variable
  - Is correlation due to kinematic constraints?
    - Suppression scales with jet energy
    - Effect significant well away from kinematic limit
  - Is correlation a feature of proton wave function?
    - Likely selecting valence quarks in the proton
  - Know that in *pp* collisions, hard scattering processes are accompanied by larger underlying event
    - Goes in opposite direction as *p*+Pb effect
    - To what extend are these related?
- Case 2: CNM effects cause suppression in central collisions and enhancement in peripheral collisions
  - Correlation enters through centrality dependence of CNM effects

Implications for jet quenching

- Expect effect to be much weaker in AA collisions
  - Averaging over forward/backward
  - Centrality variable has significant contributions from nucleons that do not participate in hard scattering
- Calculations of rates for hard probes often include significant non-negligible CNM effects
- Are we seeing such effects in *p*+Pb?
  - If so how does this explain peripheral “enhancement”?
    - Energy loss in “thin medium” calculations have discussed issue of suppression of vacuum radiation
    - Can we rule this out?
- Clear we cannot proceed with initial strategy for using *p*+Pb to understand quenching
  - Precision NPDF determination

➡ However we have an interesting new phenomenon to study!