Jet measurements in p+Pb and Pb+Pb from ATLAS

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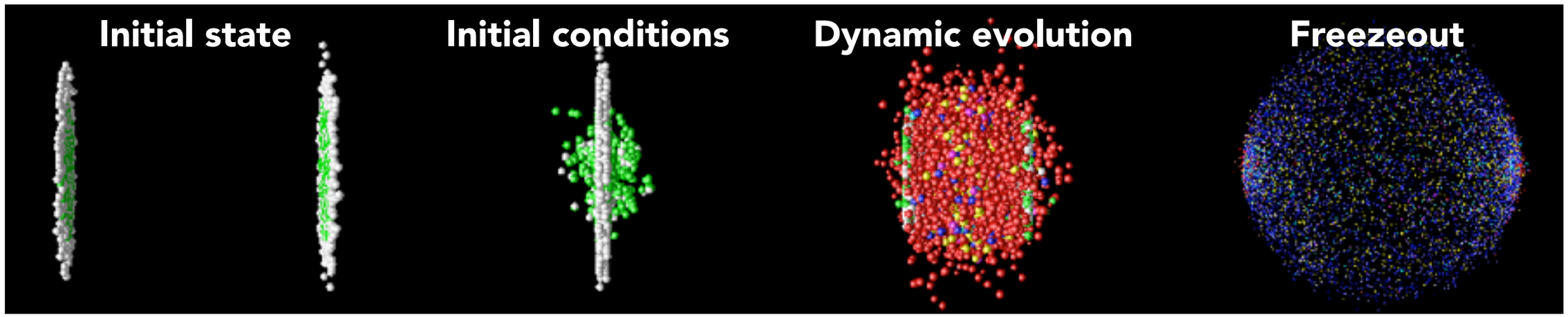
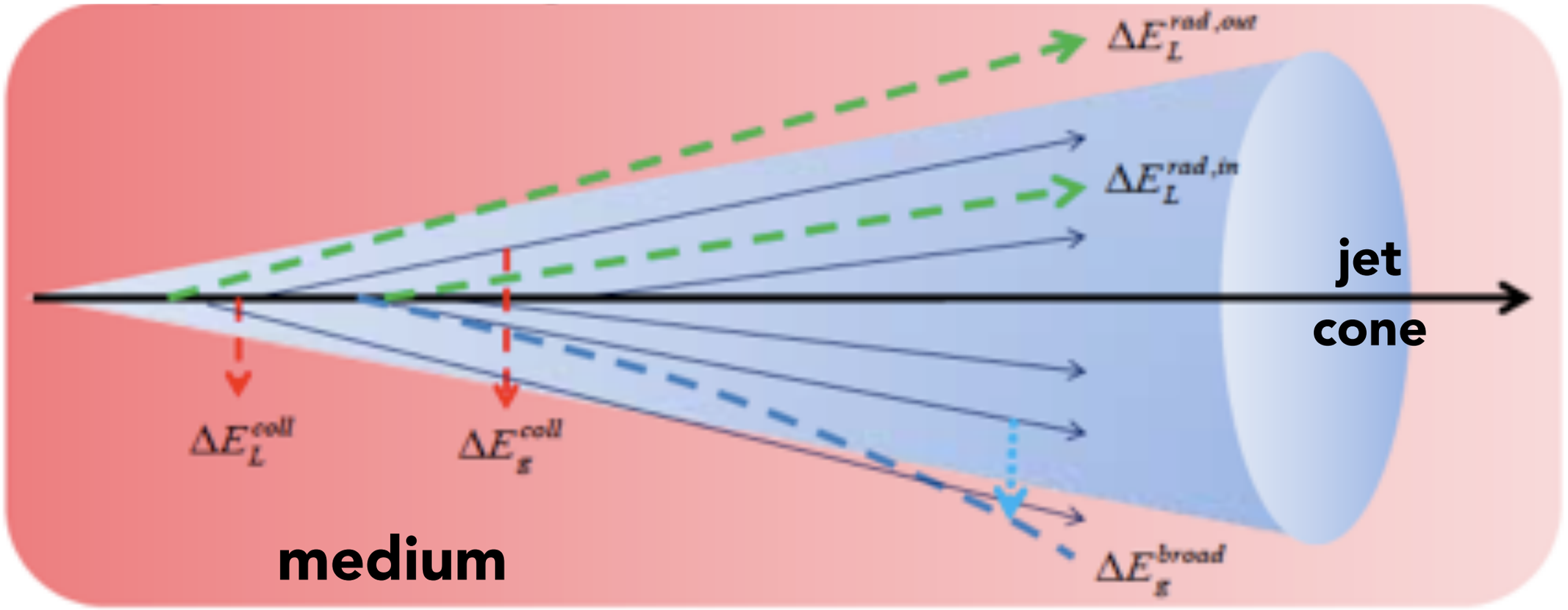
Jets in heavy ion collisions



- Hard work at RHIC and the LHC have still left us with very basic questions to address about the sQGP
- In particular, we need to better understand the initial state (nPDFs) and the initial conditions (which seed the hydro evolution):
  - How are initial PDFs modified by the nucleus?
  - How do we characterize pre-equlibirum physics?
  - What are the constituents of the system at early times?
  - Is the system strongly or weakly coupled at early times?
- Need to understand soft and hard physics to address these questions

How can **jets** help with this?

Jet modifications in the equilibrated medium



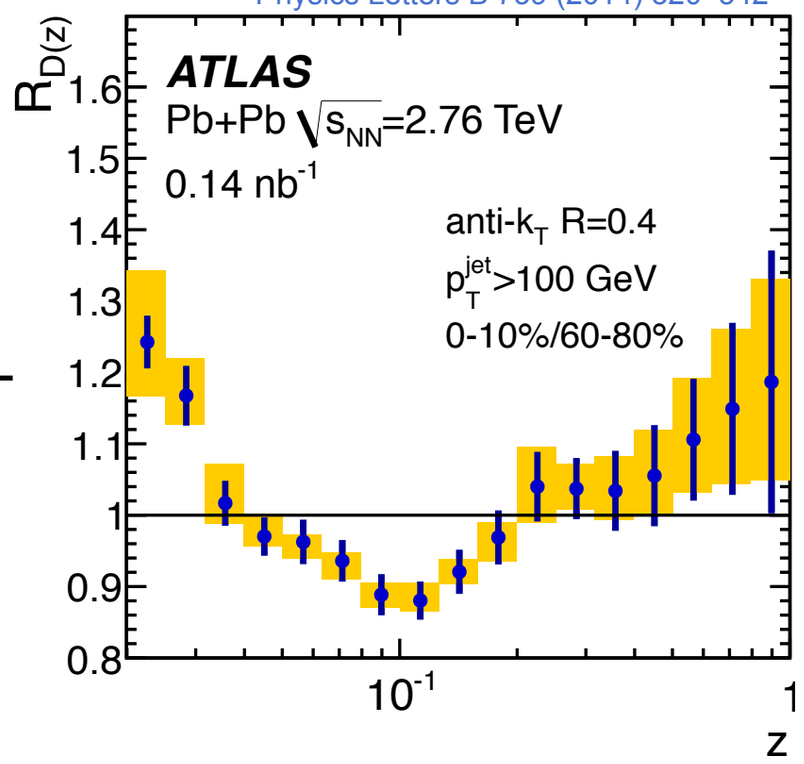
Radiative and collisional processes, with the radiated partons themselves interacting in the medium

Quite complicated - and an evolving story on theory & experimental sides

Increasing interest in flavor dependence (q vs. g) & jet structure

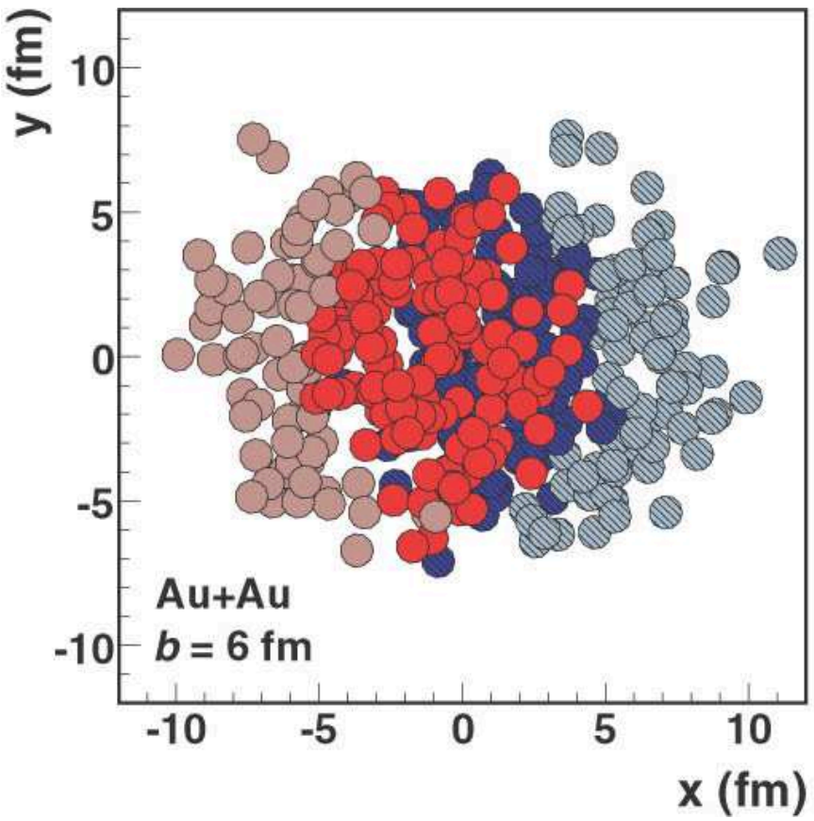
$$\frac{D(z)_{0\text{-}10\%}}{D(z)_{60\text{-}80\%}}$$

Physics Letters B 739 (2014) 320–342



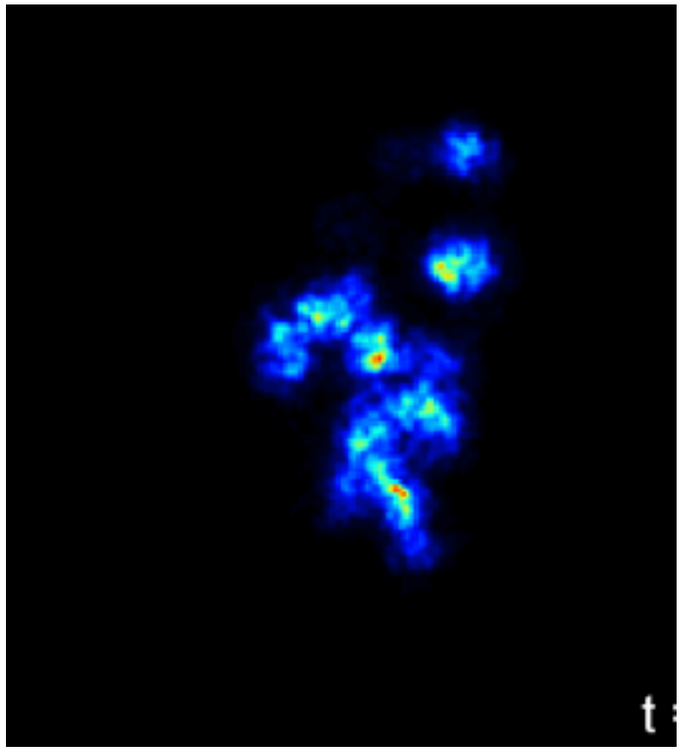
Probes of pre-equilibrium physics?

Glauber



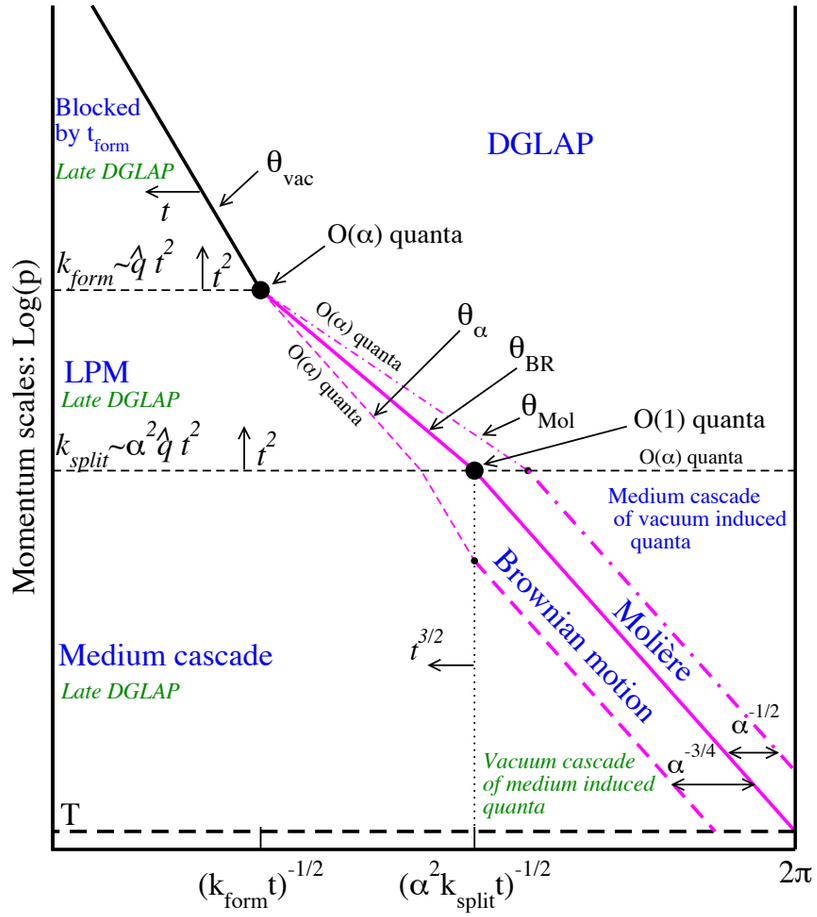
Density fluctuations from initial-state glauber geometry

Schenke et al



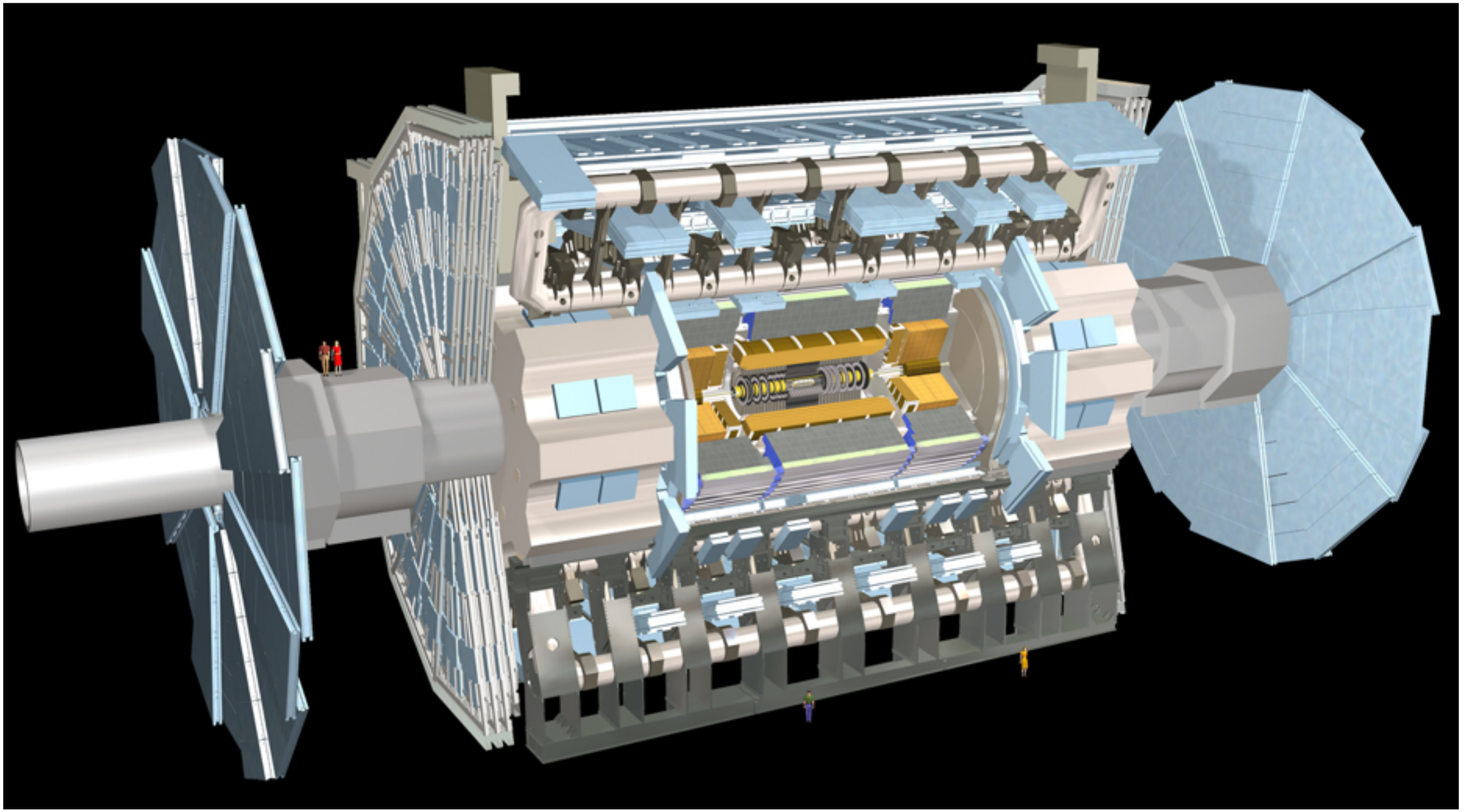
Classical Yang-Mills: hotspots beyond Glauber?

Kurkela & Wiedemann



Are there regimes, manifest in angular distributions of fragments, or $\Delta\phi$ of jets (e.g. d'Eramo et al, or parton cascade) which can elucidate the microscopic properties of the medium at early times?

ATLAS at the LHC



Hermetic electromagnetic and hadronic calorimeters,extending out to $|\eta|<4.9$. Centrality estimated using Forward Calorimeters (FCal, $3.2<|\eta|<4.9$).

Inclusive jet suppression in Pb+Pb

Jets reconstructed with anti-k_t algorithm
R=0.2-0.4, after iterative flow-sensitive UE
background subtraction

UE jets rejected by requiring
a track jet (p_T>7 GeV) or EM cluster (p_T>8 GeV)

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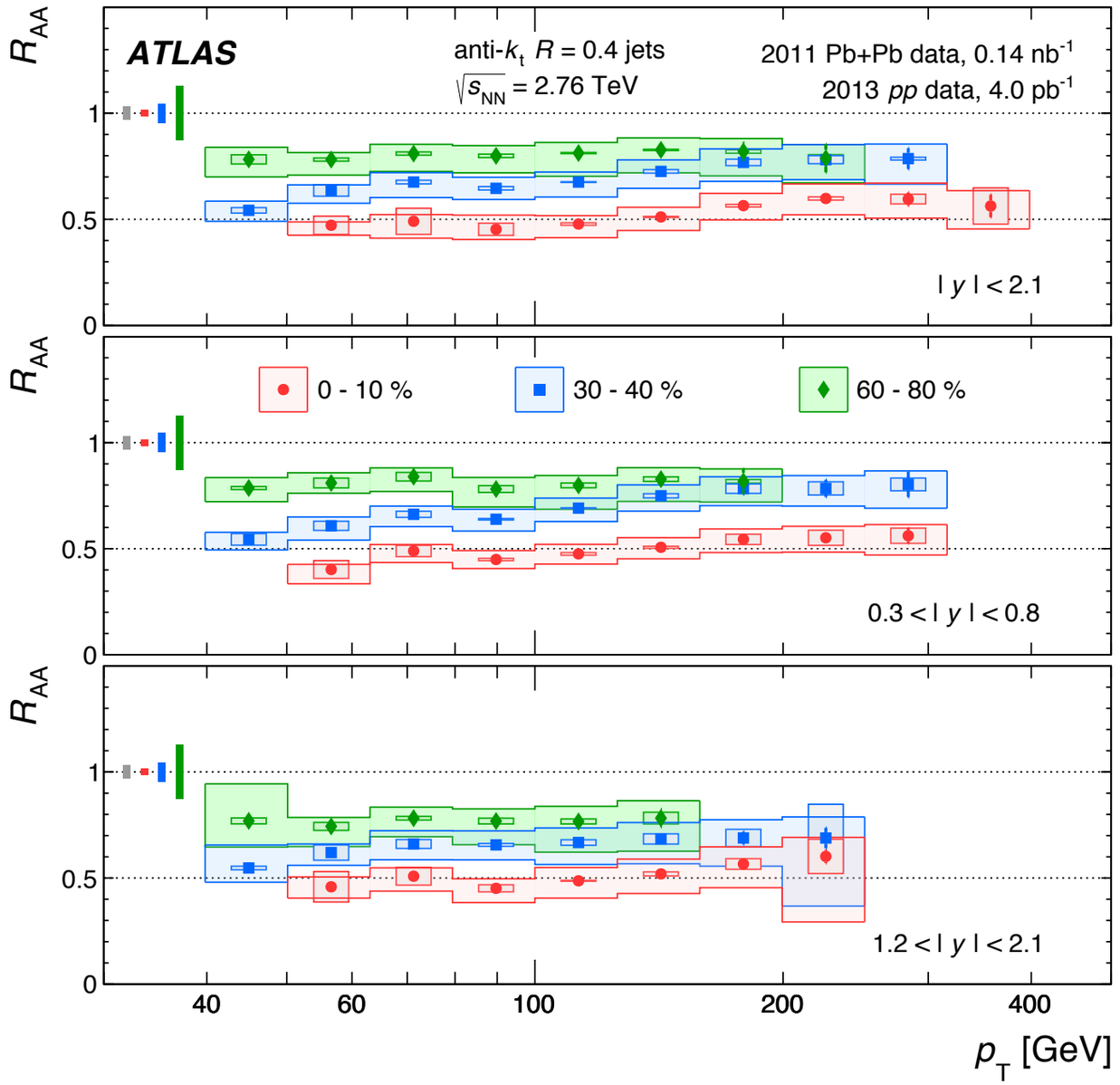
Fully unfolded inclusive jet rates in Pb+Pb, scaled by cross sections from 2013 2.76 TeV pp data (4.0 pb^{-1}): extends accessible p_T range.

arxiv:1411.2357, submitted to PRL



$$R_{\mathrm{AA}} = \frac{\left.\frac{1}{N_{\mathrm{evt}}}\frac{\mathrm{d}^2 N_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\right|_{\mathrm{cent}}}{\langle T_{\mathrm{AA}}\rangle_{\mathrm{cent}} \times \frac{\mathrm{d}^2\sigma^{pp}_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}}$$

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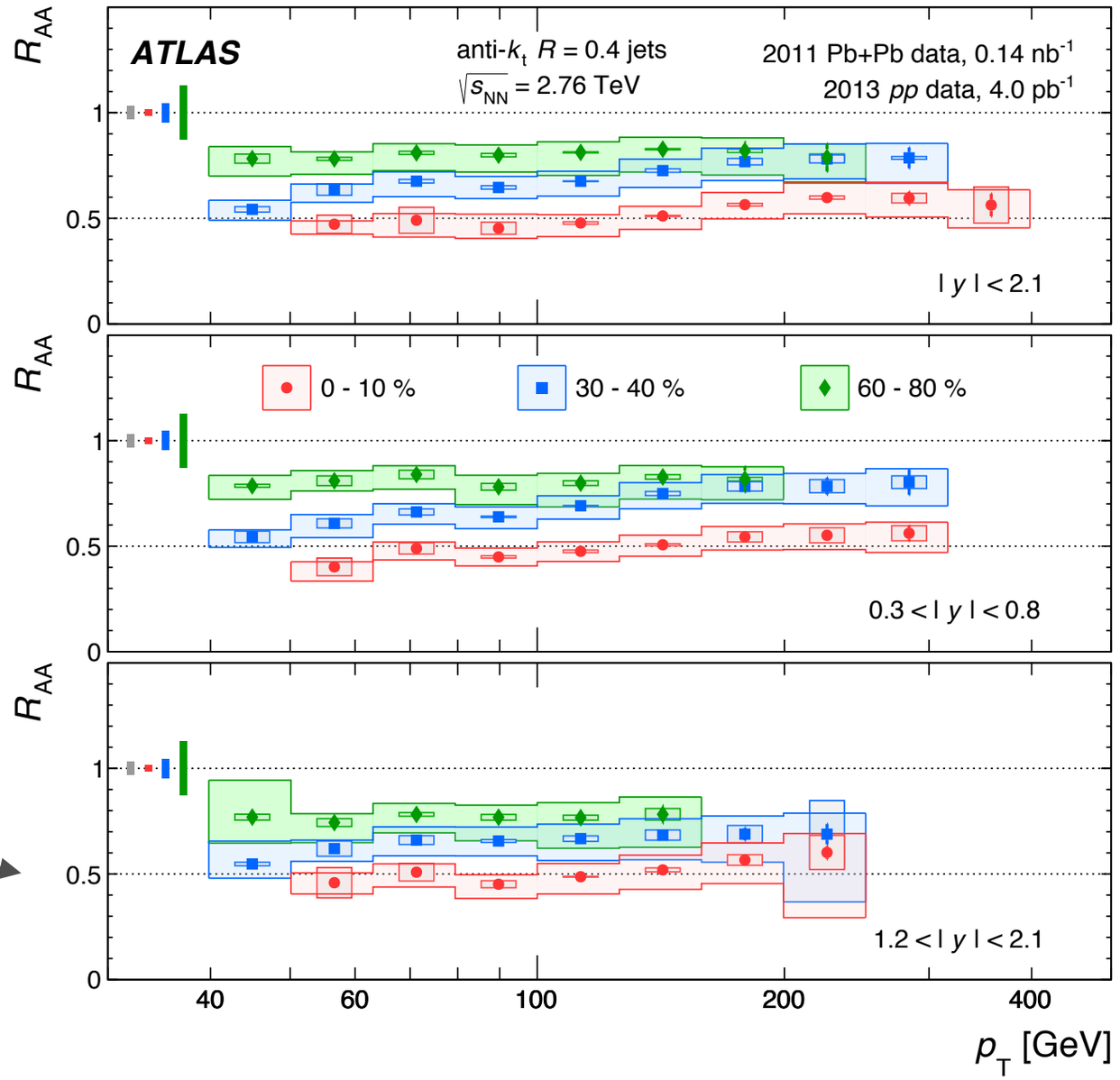
Fully unfolded inclusive jet rates in Pb+Pb, scaled by cross sections from 2013 2.76 TeV pp data (4.0 pb^{-1}): extends accessible p_T range.

Large (~2x suppression) observed in the most central events, consistent with previous ATLAS measurements of central/peripheral ratios

Constant in more peripheral bins, Significant rise at higher p_T in central events.

arxiv:1411.2357, submitted to PRL



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Centrality & rapidity dependence

Varying collision centrality varies path length in medium: with increasing centrality strong and clear modification in magnitude of suppression

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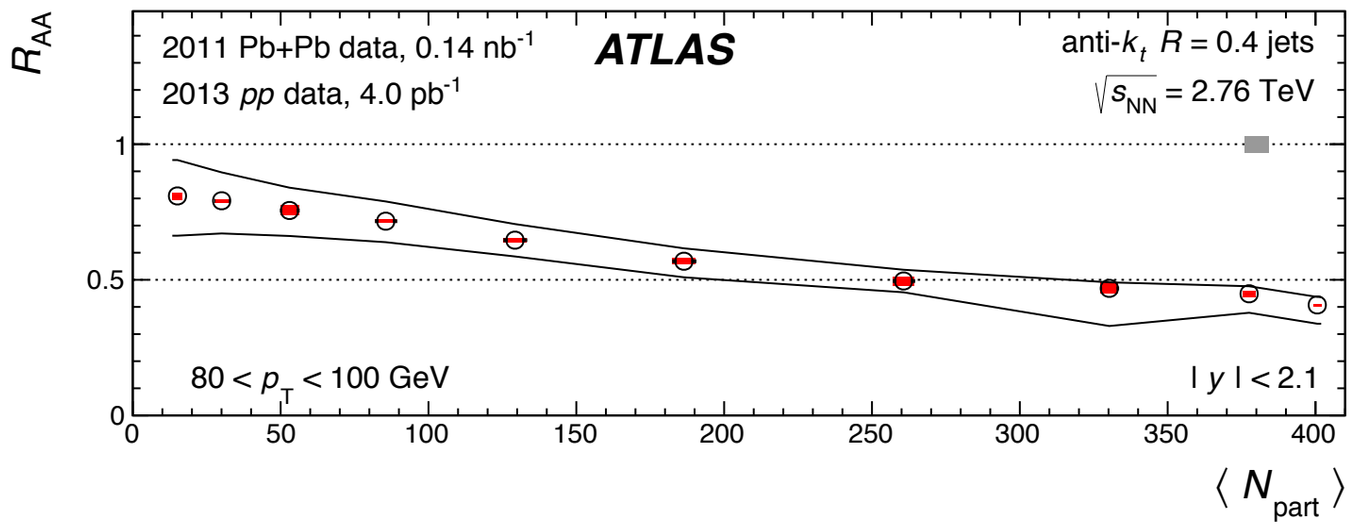
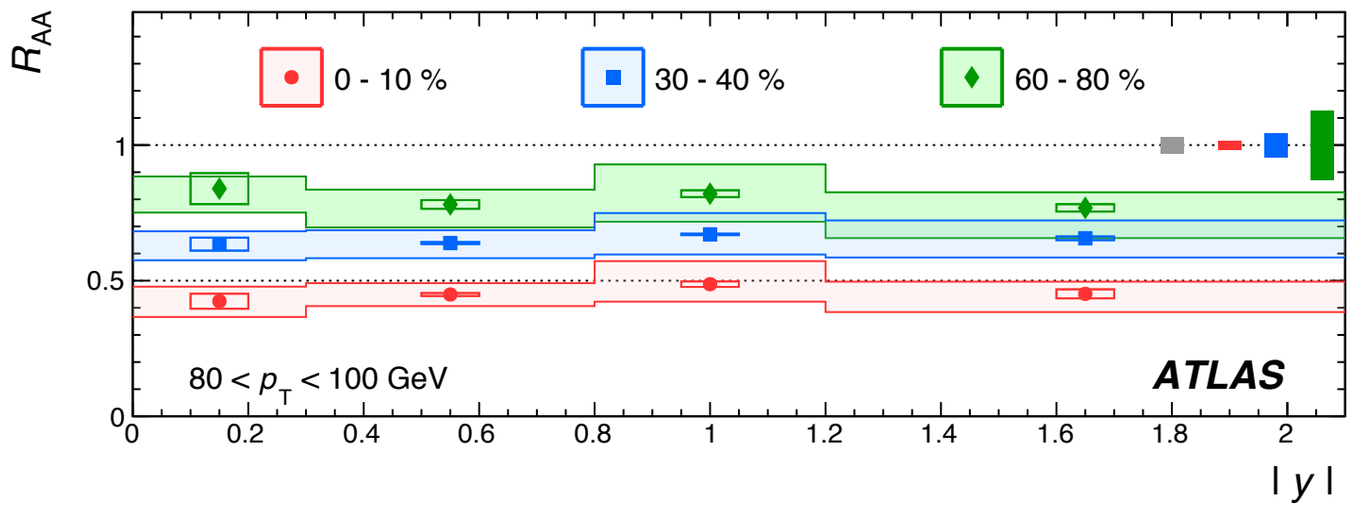
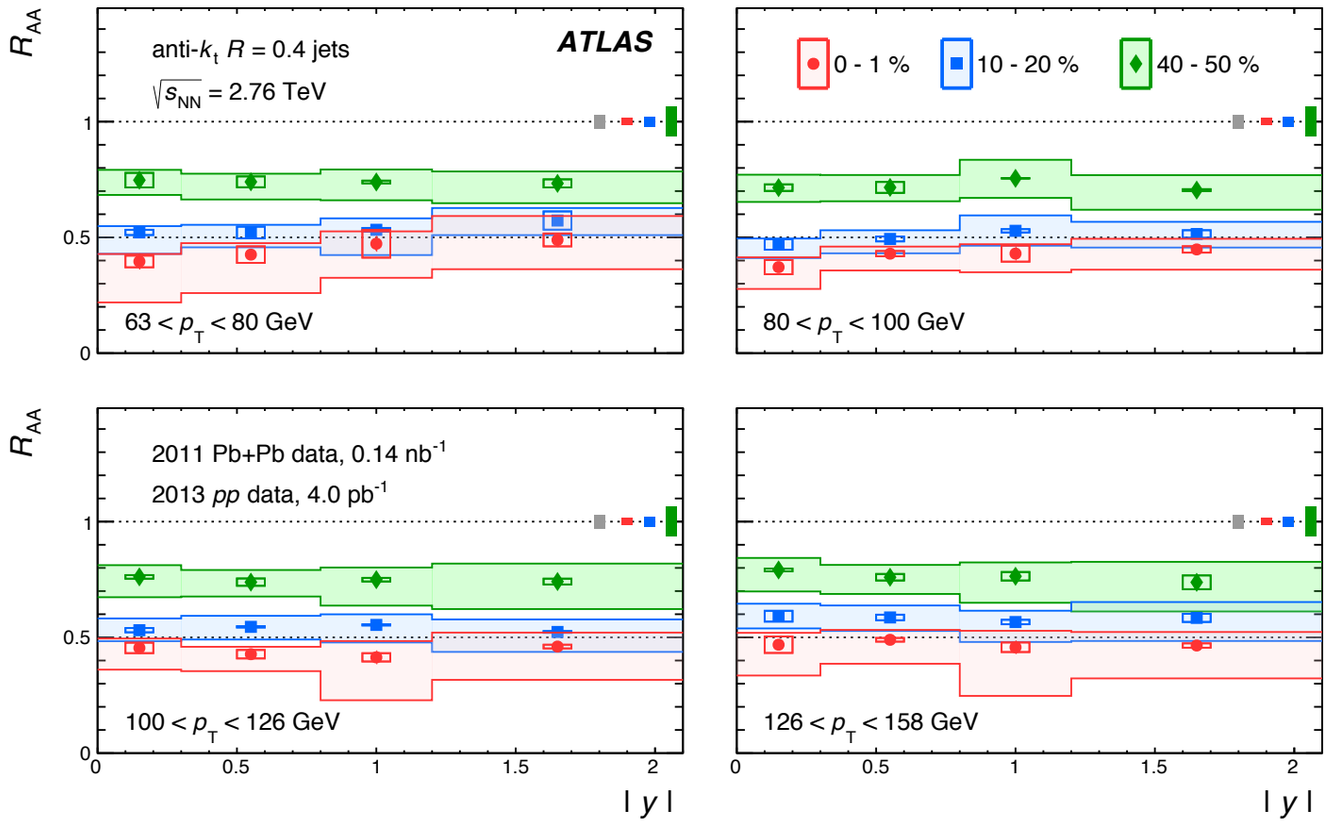


No observed difference in suppression with rapidity of the jet, even for different centrality selections



Rapidity dependence

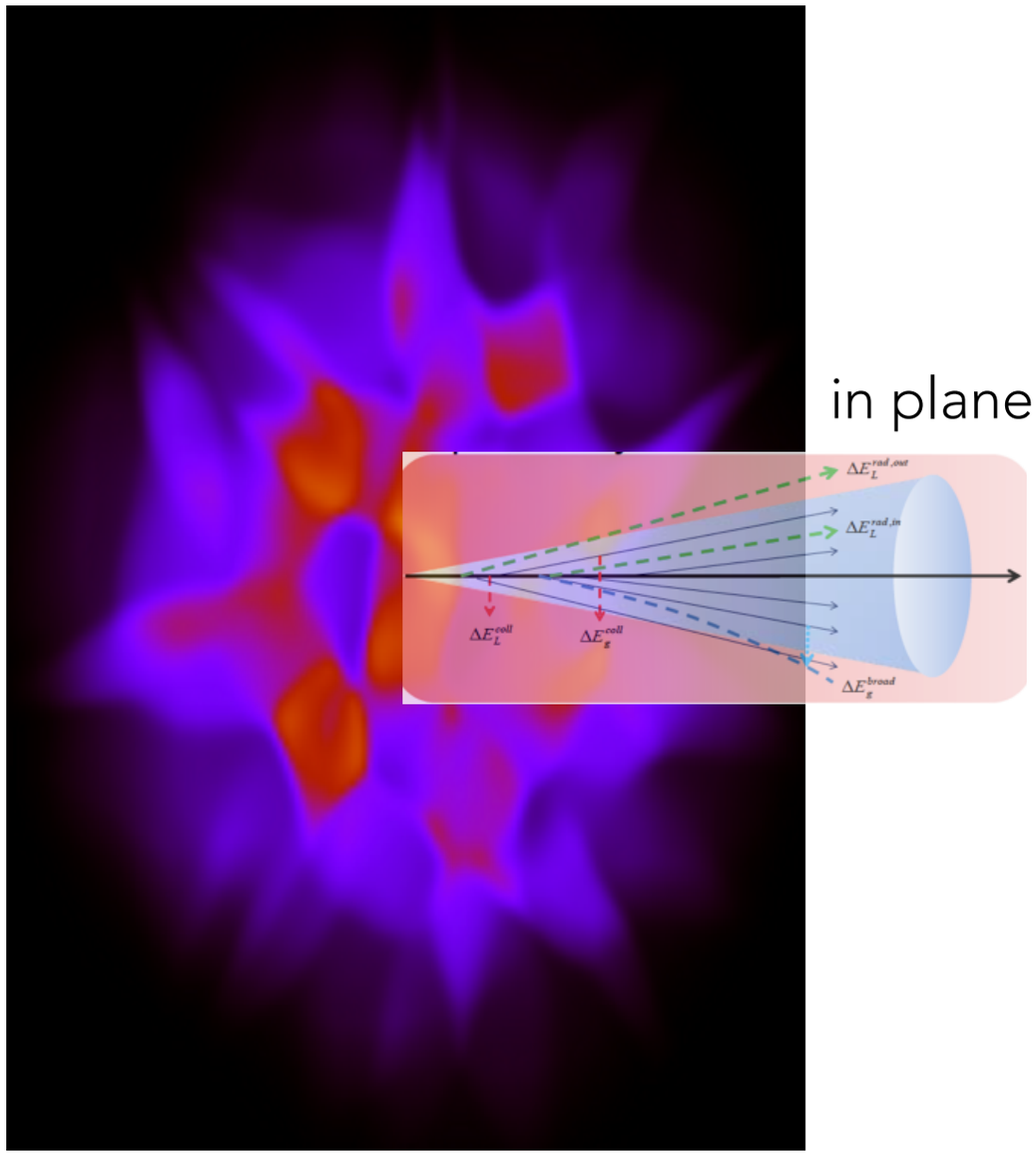
- Might expect multiple contributions to rapidity dependence of R_{AA}, some directly related to initial state
  - **Steeper spectrum** in forward rapidities
  - **nPDFs** could enhance/decrease jets resulting from different x_1,x_2 combinations
  - **Quark vs. gluon** composition of jets should also vary, and they could have different quenching patterns
  - **Different path length**: potentially longer for more forward jets
- In this context, lack of observed variation seems quite surprising



|y| dependence for wide range in centrality and p_T

Path length dependence

out of plane

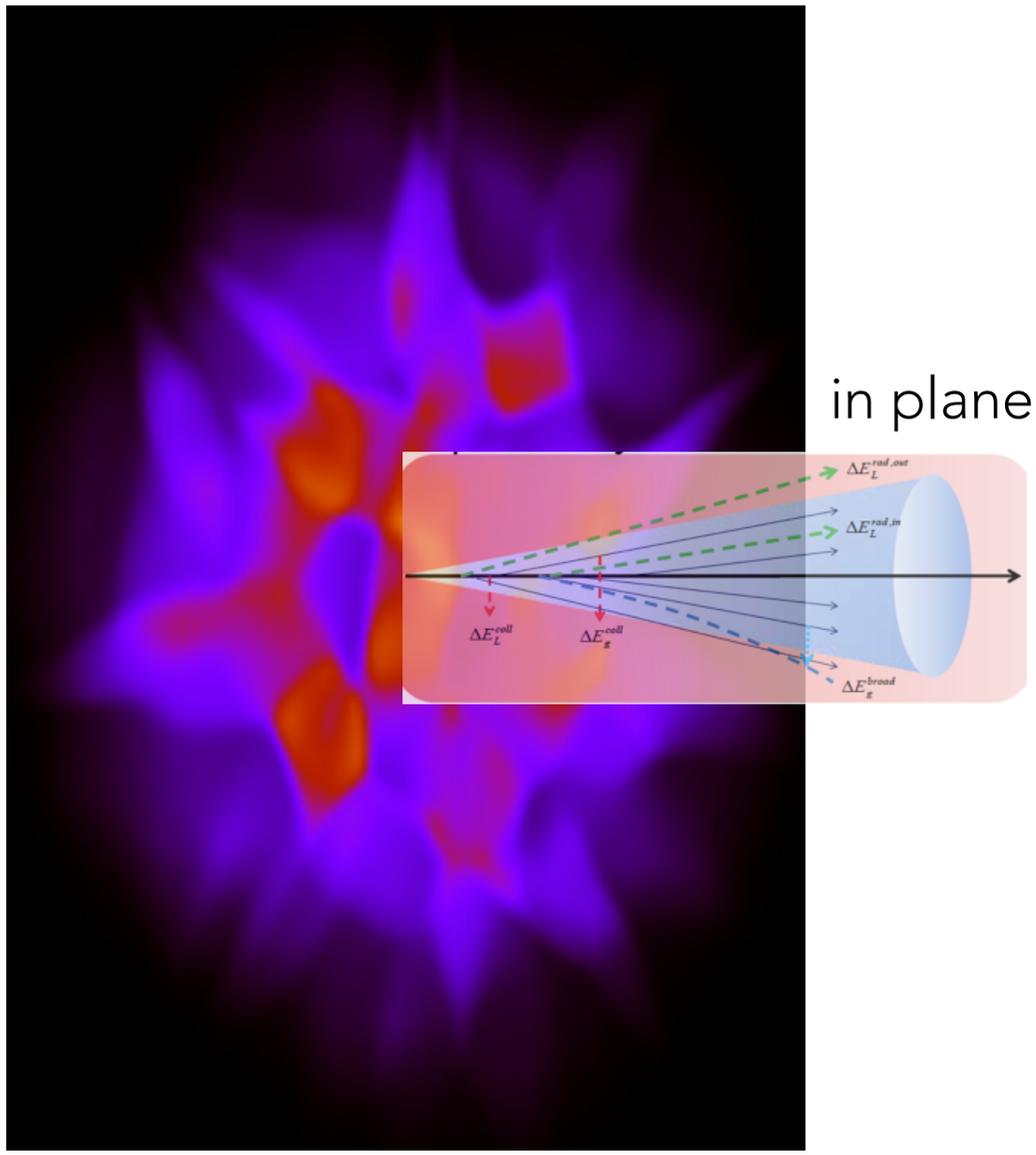


Jets propagate through the expanding medium we study in detail using flow harmonics

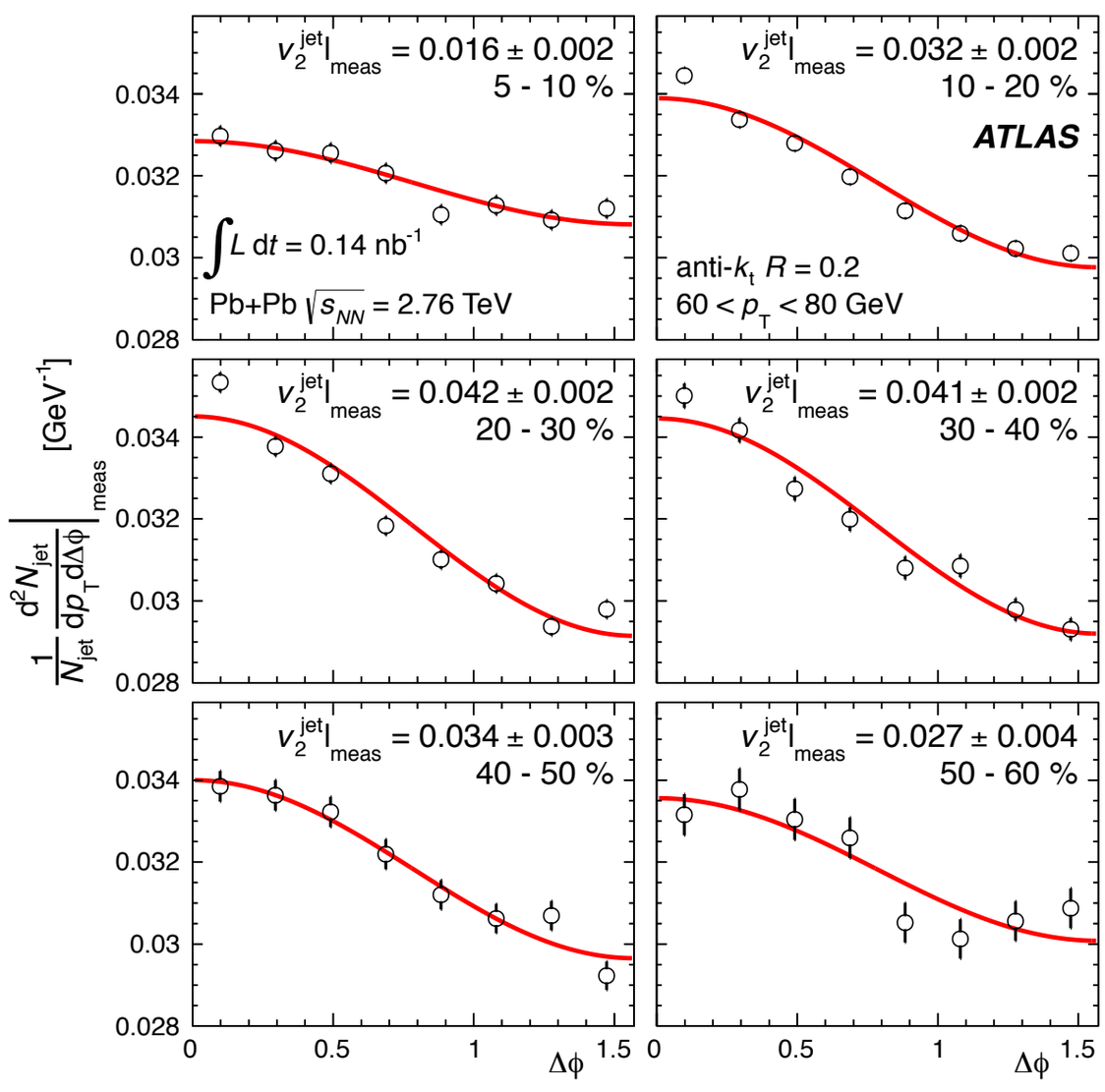
Expect jets to be sensitive to the direction of their emission relative to the event plane: path-length dependence of jet quenching

Path length dependence

out of plane



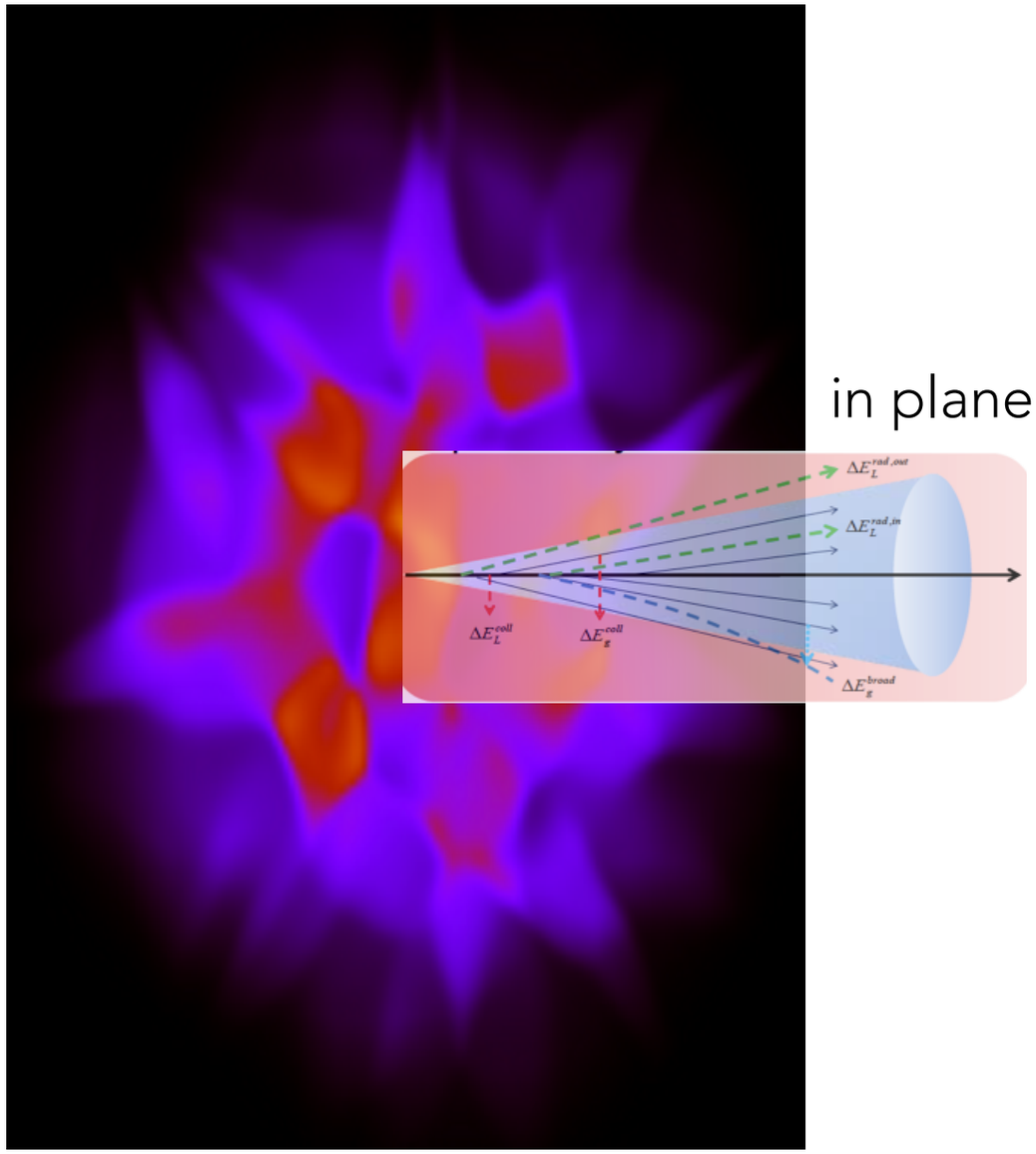
Phys. Rev. Lett 111, 152301 (2013)



Jet yields vary systematically with angle relative to event plane: induces a v_{2jet}

Path length dependence

out of plane



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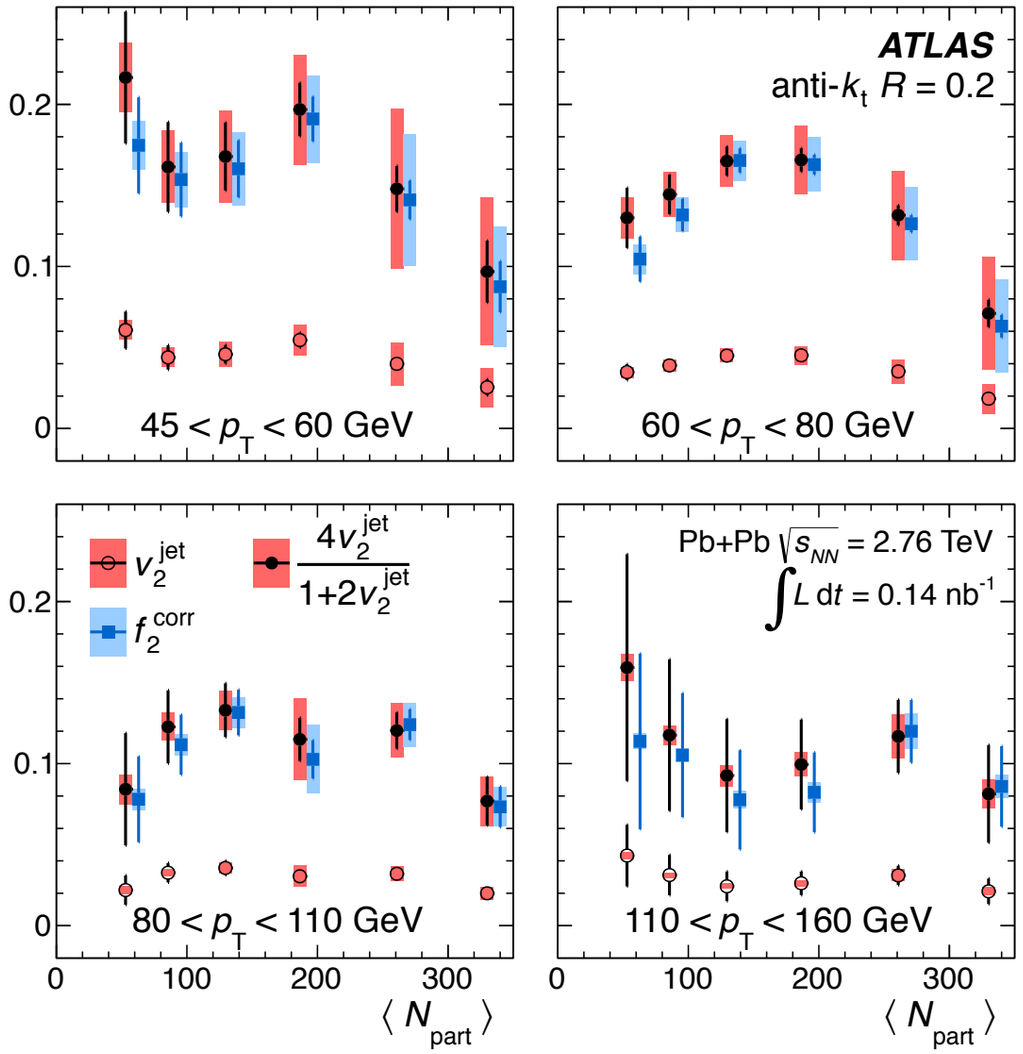


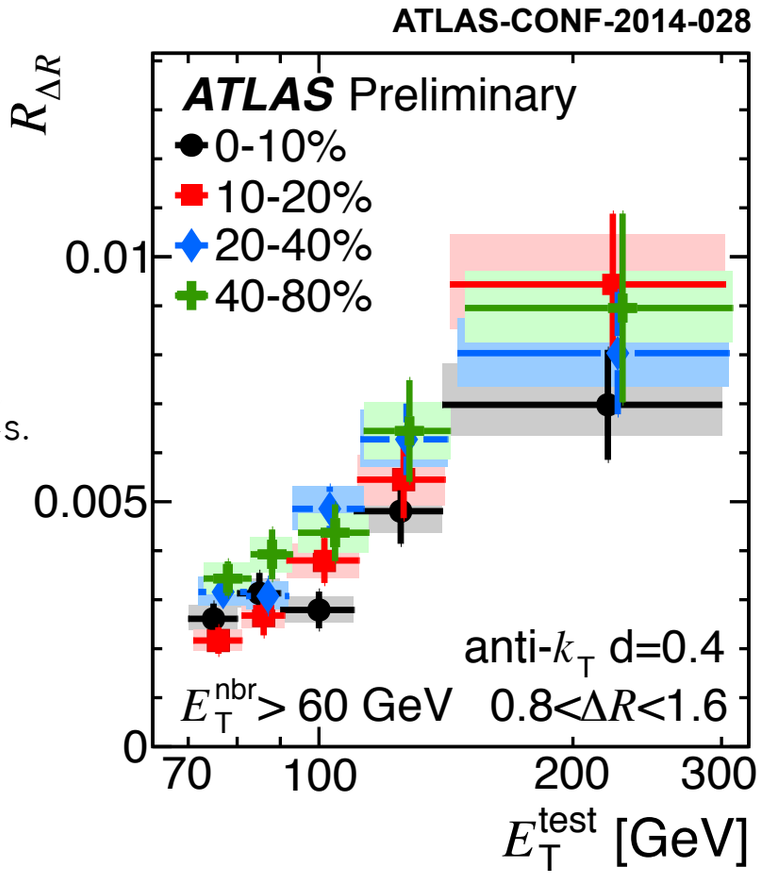
Information in phi modulation nearly exhausted by
the extracted v_2^{jet} even when data shown as a pure suppression ratio
$f_2 = 1 - R_{AA}(\text{out})/R_{AA}(\text{in})$: little room for higher harmonics

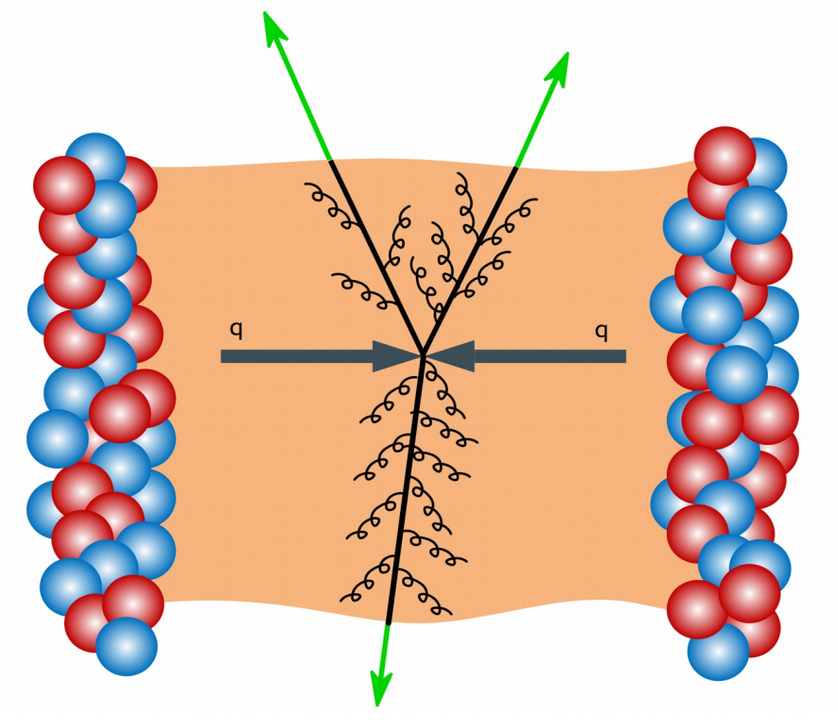
Nearby jets in Pb+Pb

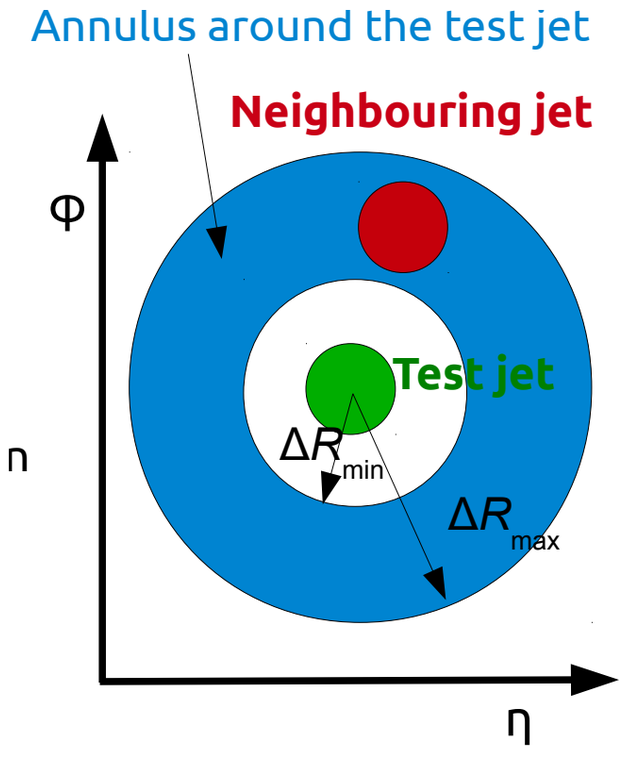
Measurement of jets in annulus ΔR=(0.5-0.8)-1.6 (depending on jet radius R=0.2-0.4) nearby inclusive jets, after subtracting combinatoric background w/ min. bias data. Based on technique (arxiv:1207.4957) used by D0 to measure α_s. Provides insight into medium modification of parton shower.

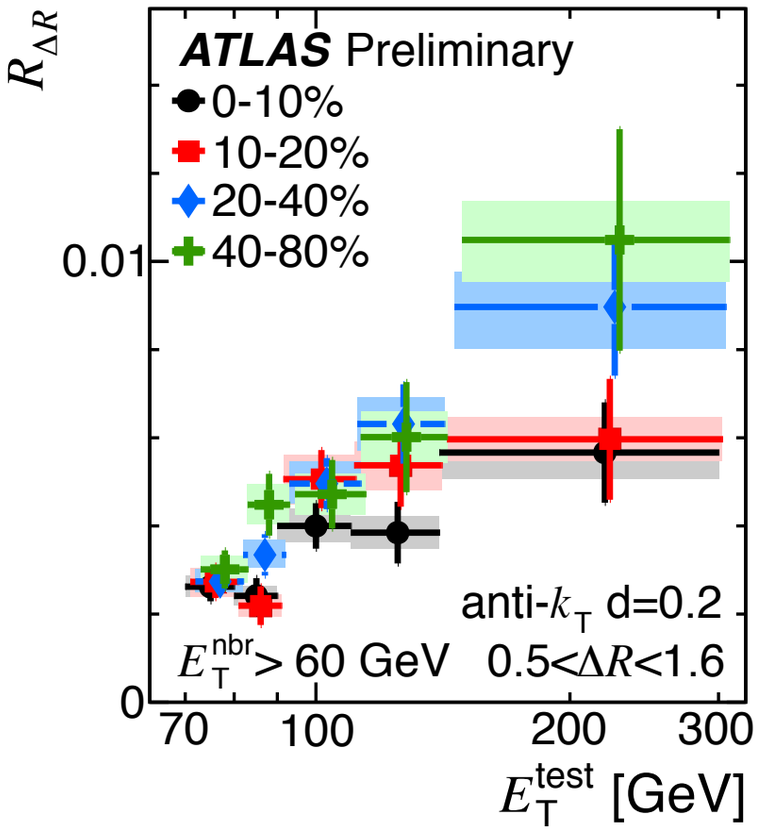
Nearby jets suppressed with increasing centrality →

$$R_{\Delta R} = \frac{1}{\mathrm{d}N_{\mathrm{jet}}^{\mathrm{test}}/\mathrm{d}E_{\mathrm{T}}^{\mathrm{test}}} \sum_{i=1}^{N_{\mathrm{jet}}^{\mathrm{test}}} \frac{\mathrm{d}N_{\mathrm{jet},i}^{\mathrm{nbr}}}{\mathrm{d}E_{\mathrm{T}}^{\mathrm{test}}}(E_{\mathrm{T}}^{\mathrm{test}}, E_{\mathrm{T,min}}^{\mathrm{nbr}}, \Delta R)$$





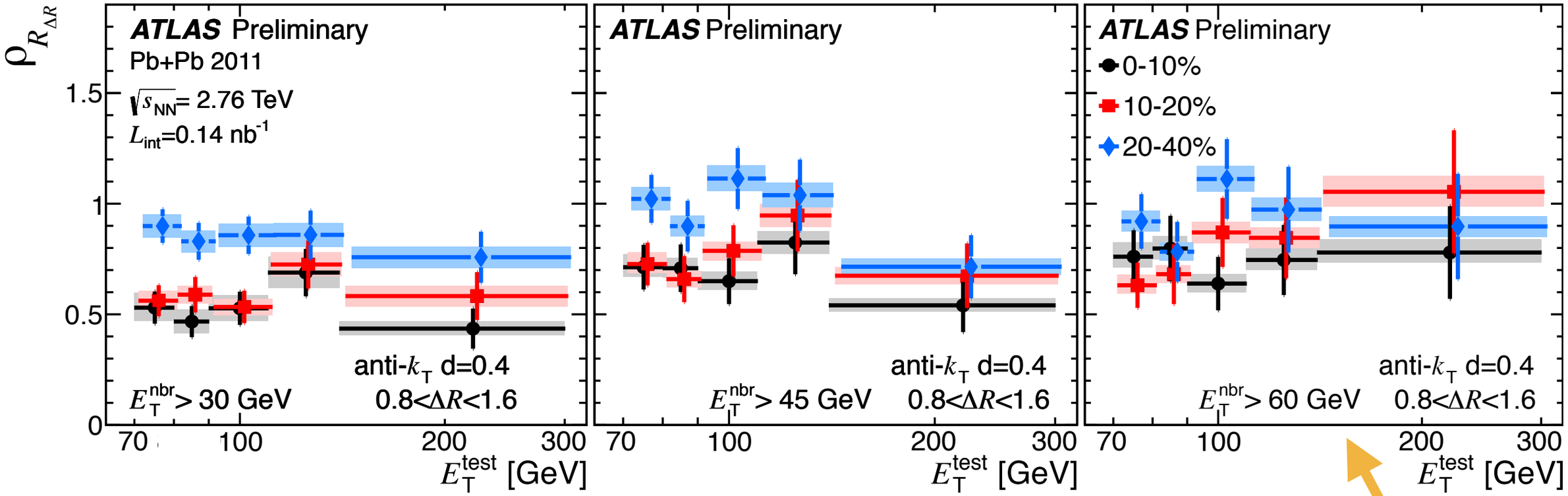




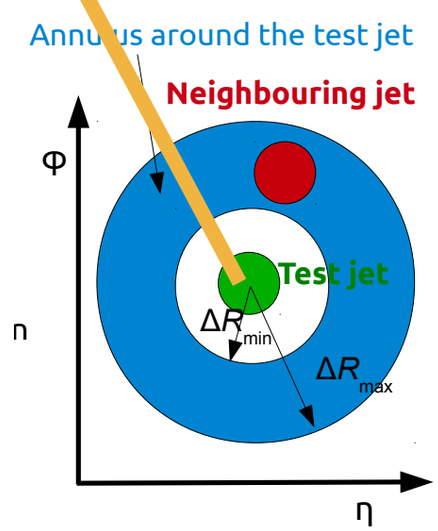
"test" = trigger, "neighbor" = associated

Central-peripheral ratios

$$\rho_{R_{\Delta R}} = R_{\Delta R}|_{\text{cent}} / R_{\Delta R}|_{40-80}$$



Relative yield of neighboring jets between central and peripheral events shows overall suppression with increasing centrality, for E_T^{nbr} ranges, no trend with **increasing E_T^{test}**



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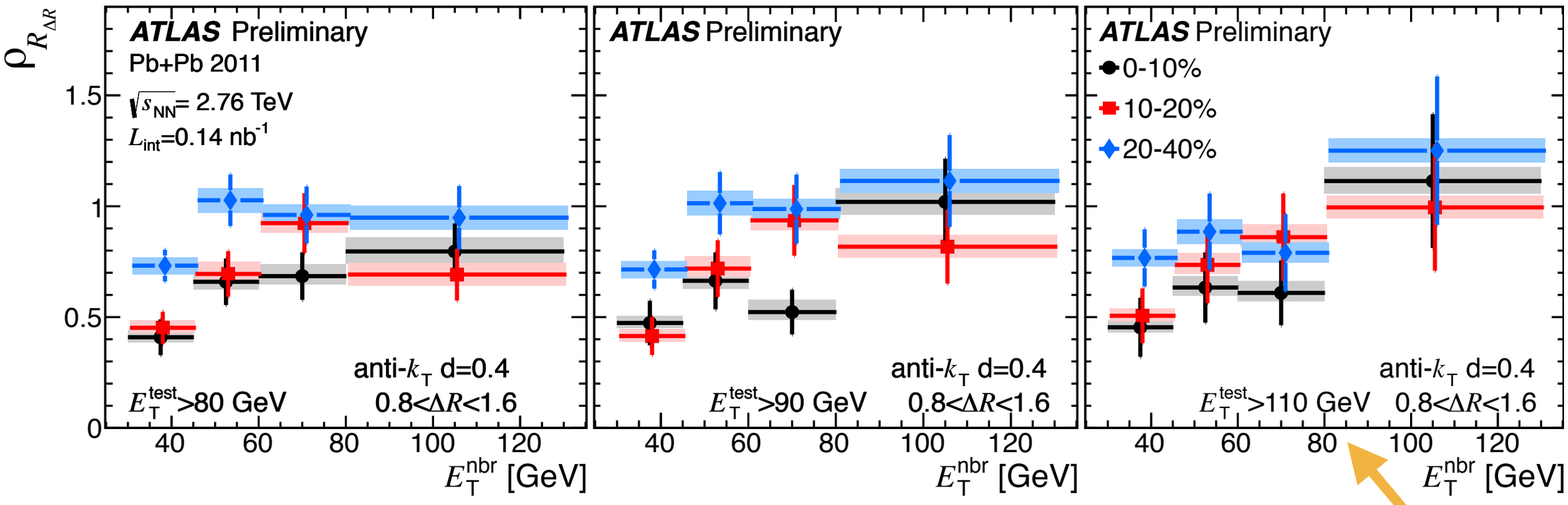
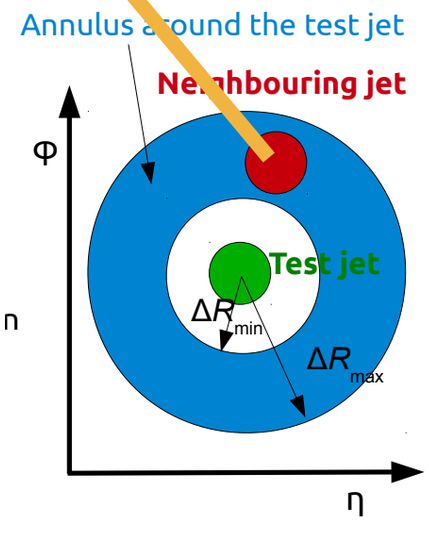


A decrease in suppression seen with **increasing E_T^{nbr}**:

As the two jets have more similar E_T,

perhaps they are suppressed in a similar way?



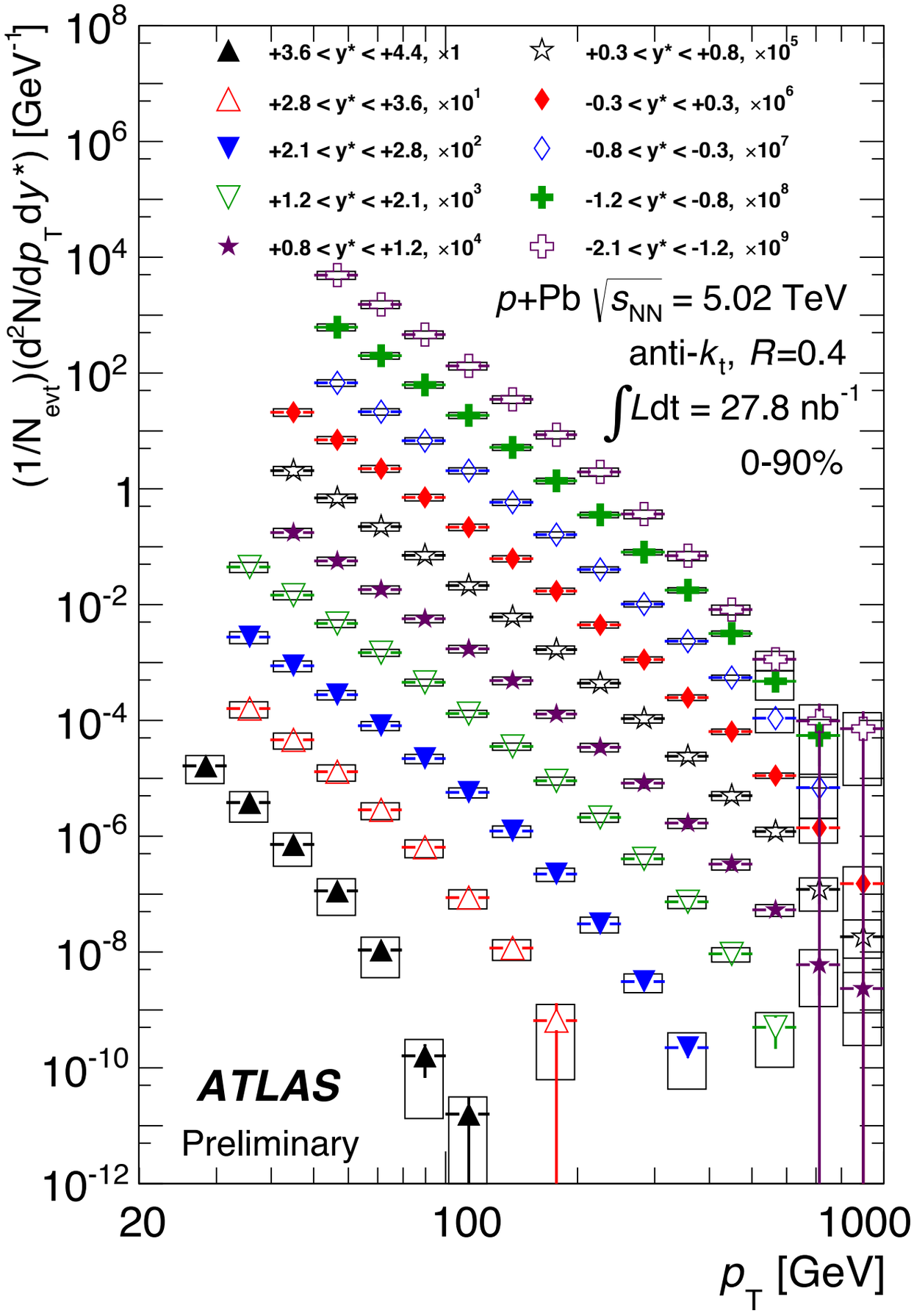
Multi-jet observables potentially sensitive to details of geometry and energy loss, including fluctuations

Jets in p+Pb

- Some indications of hot, dense matter observed in p+Pb collisions ("double ridge")

- Strong energy loss not expected, due to much shorter transverse path length in p+Pb than in Pb+Pb
  - No overall suppression relative to *pp* has been observed for hadrons or jets

- ATLAS has measured jets in p+Pb over a very wide kinematic region and as a function of centrality
  - Kinematic regions selected where efficiency & unfolding corrections are smallest



Jet yield in minimum-bias p+Pb relative to pp

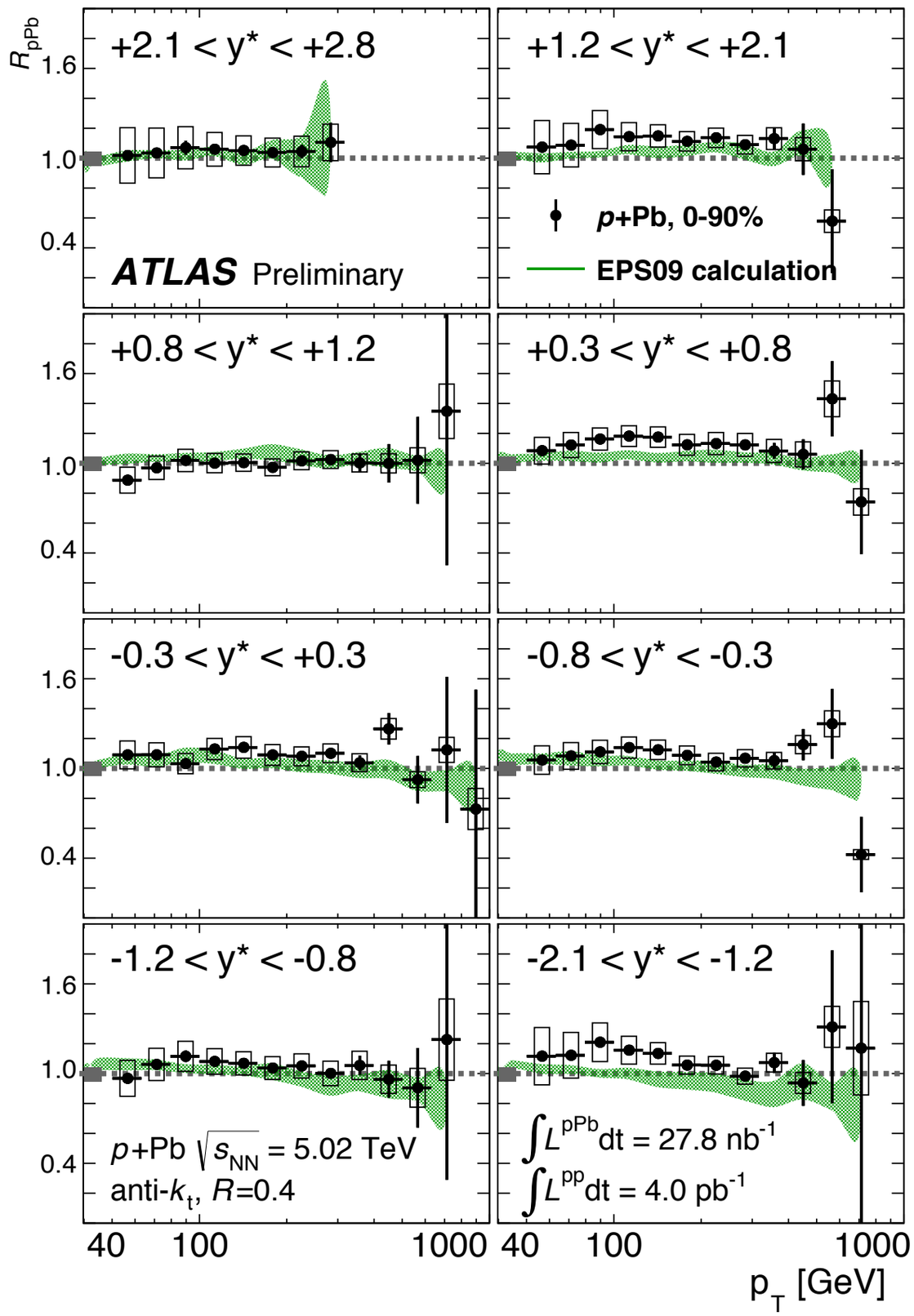
Also using the 2013 p+p data set, interpolated to 5.02 TeV using x_T scaling.

Use of y* (rapidity in CM frame) to account for CM boost in p+Pb relative to p+p

At all rapidities, no suppression seen, with perhaps a small systematic enhancement over pp.

Consistent with EPS09 calculation (green region)

Forward



Backward

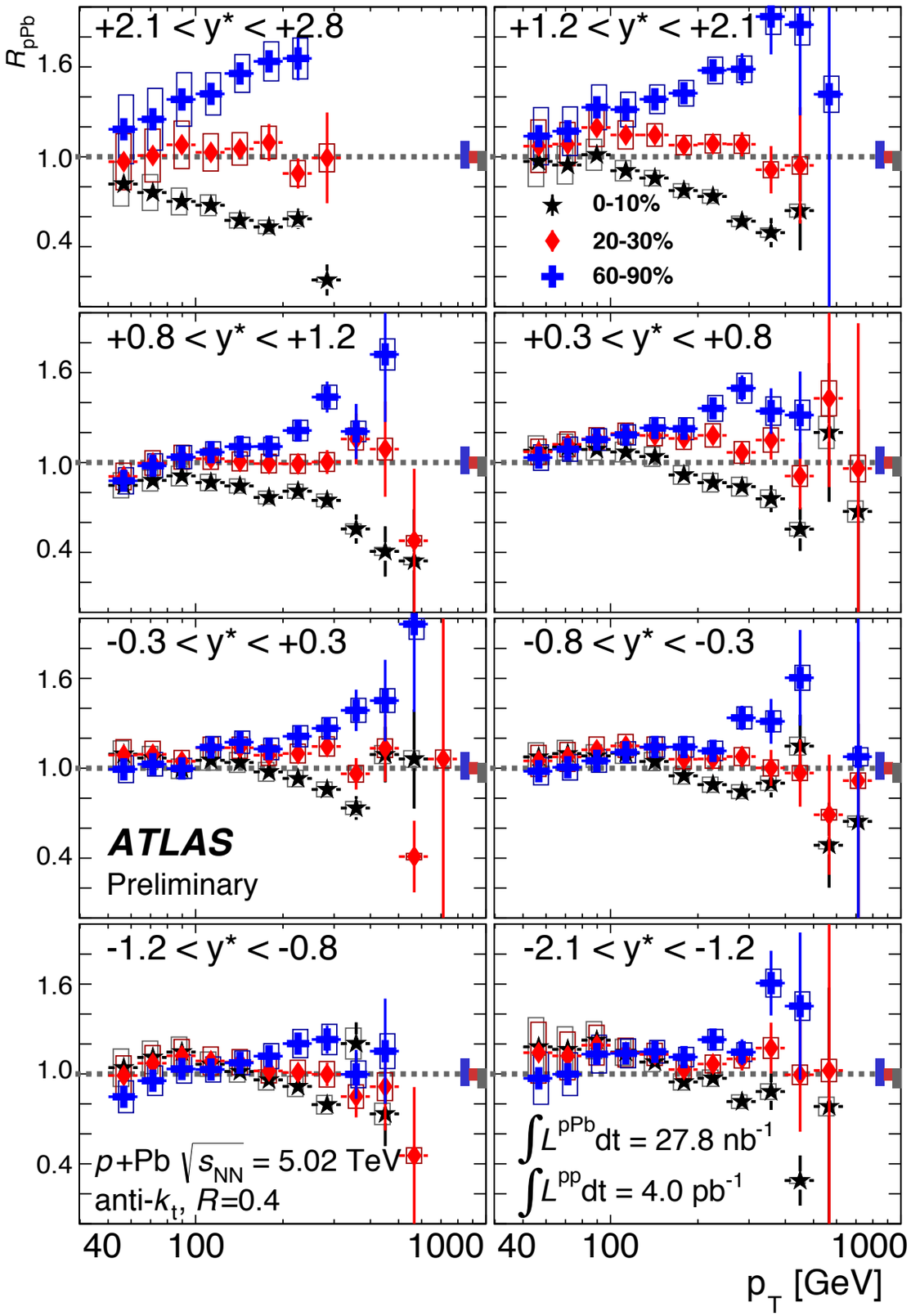
Jet yield in centrality-selected p+Pb relative to pp

Centrality intervals selected, based on Pb-going FCal (& standard Glauber)

Jets are **suppressed**
in more **central** events,
but **enhanced** in **peripheral** events!

Reminiscent of neutral pion measurements in PHENIX

Forward



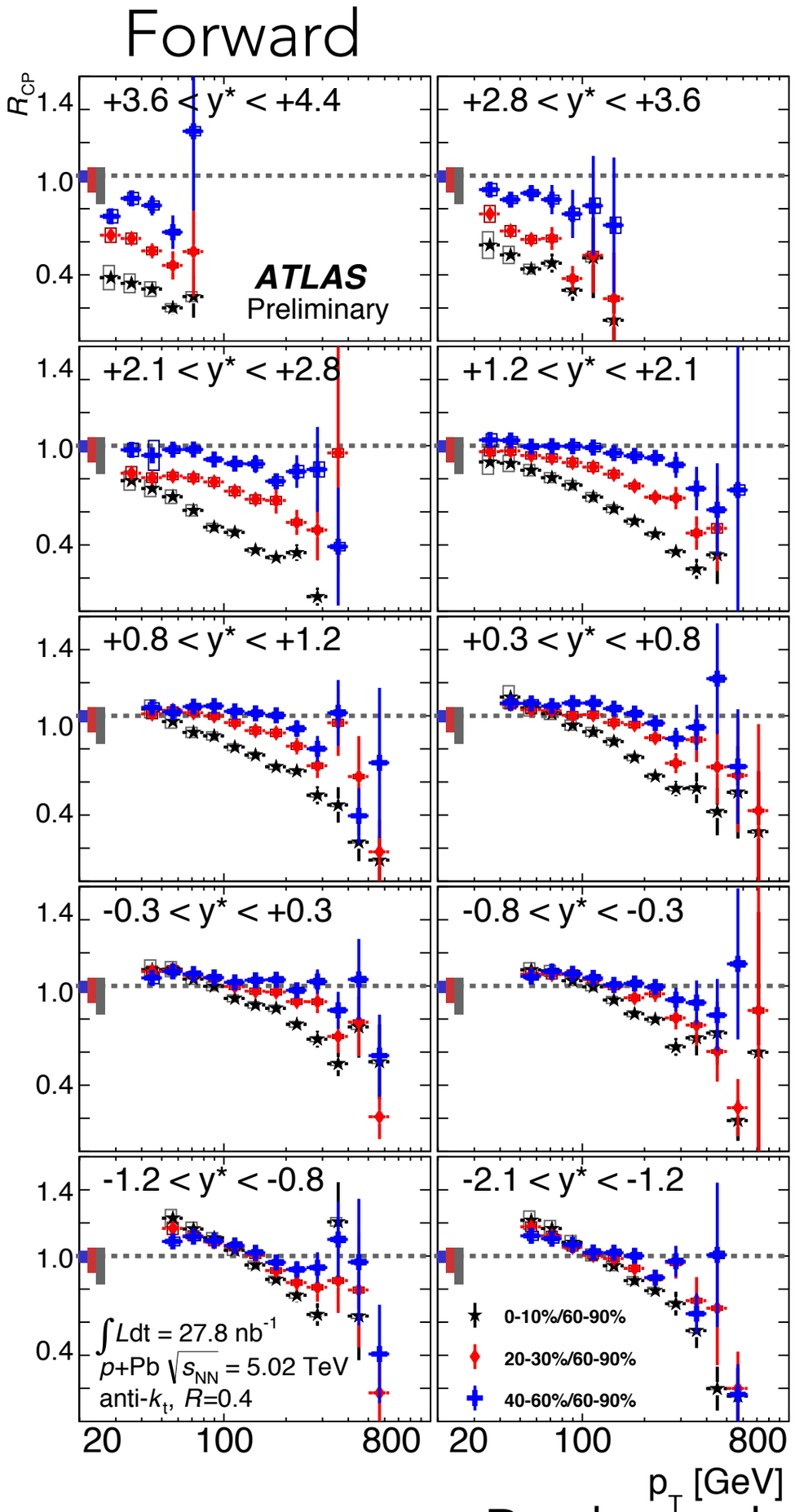
Backward

Jet yield in central p+Pb relative to peripheral p+Pb

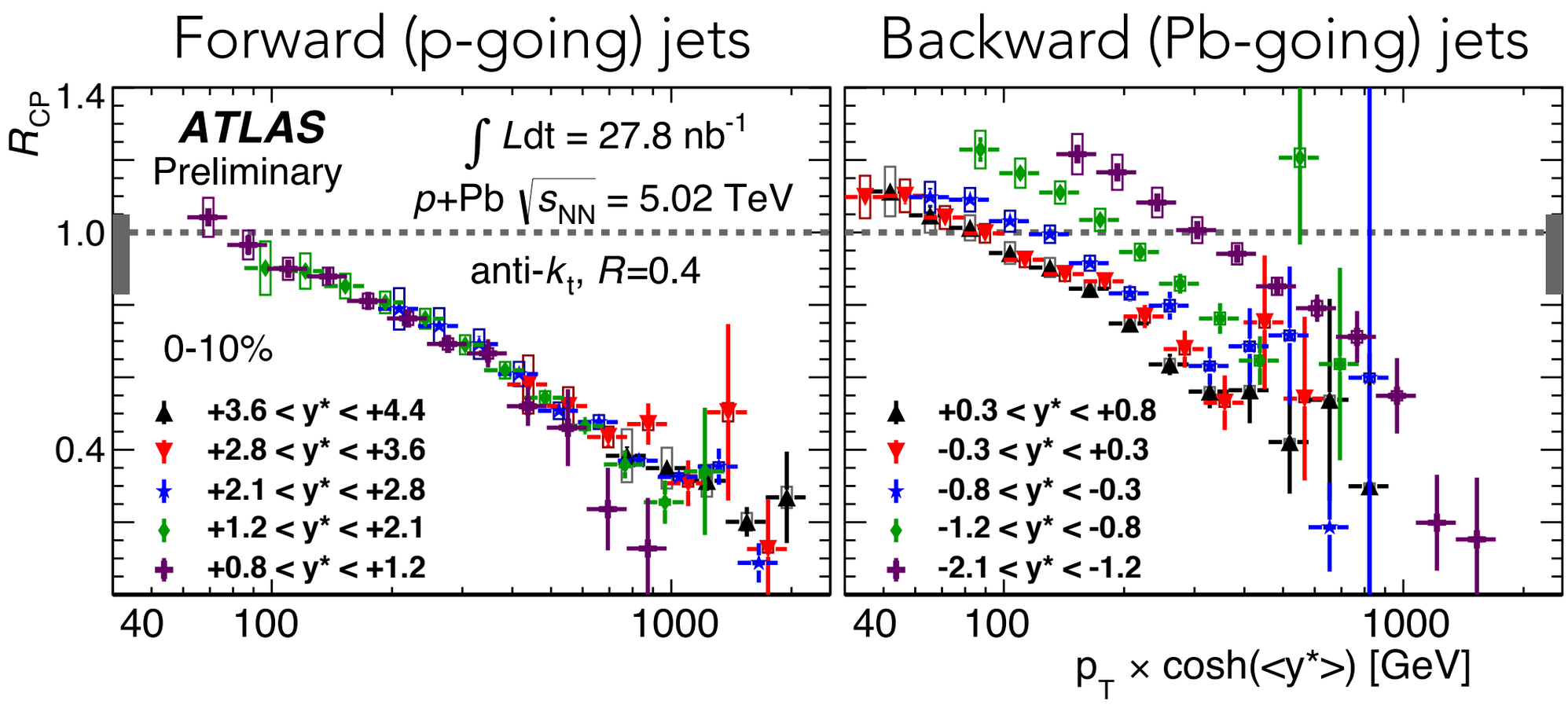
Jet yields in a central selection divided by T_{pPb}, relative to same ratio in the 60-90% selection (closest to *pp*): ***"R_{CP}"***

Based on R_{CP}, strong suppression observed in forward (proton-going) rapidities, increasing w/ centrality, and in the forward-going direction

Mysterious given overall scaling for minimum bias!



What controls the relative suppression in p+Pb?



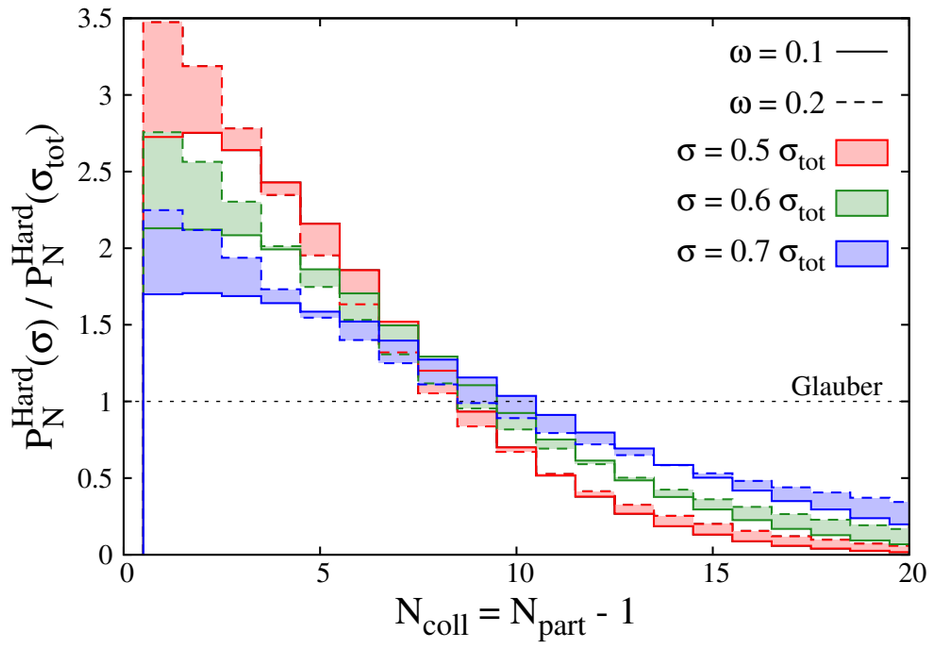
An **unexpected scaling** has been observed for the central/peripheral ratios by plotting the R_{CP} in all rapidity selections as a function of **jet momentum: $p=p_T$ x cosh(y*)**:

Unifies observations of relative jet suppression at all p_T and at forward rapidities (no obvious scaling in Pb direction).

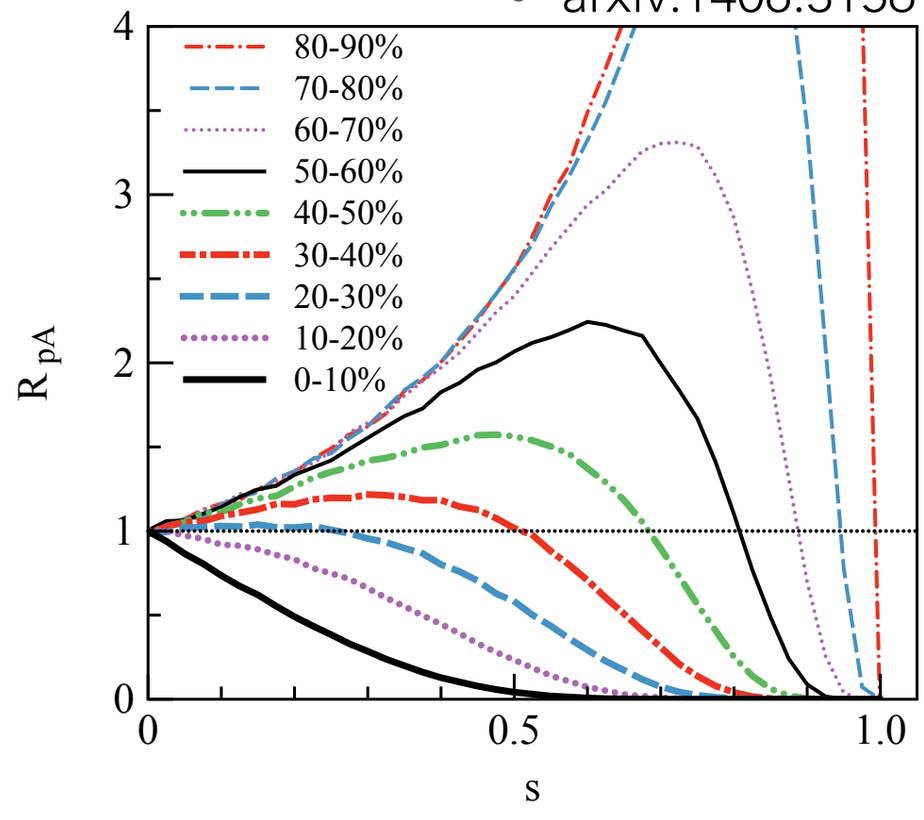
Possible explanations

- Alvioli et al (arxiv:1402.2868, 1409.7381)
  - High-*x* processes involve **smaller proton** configurations
  - Reduces cross section for soft processes, shifts events from central bins to peripheral bins
- Bathe, Bzdak, Skokov (arxiv:1408.3156)
  - Schematic explanation based on "exclusion" of partons in high *x* processes: after making a high *x* jet, do not participate in subsequent evolution
  - Reduces multiplicity, but not cross section, for each NN collision
  - Shifts events from more central to more peripheral bins
  - Similar effect as Alvioli et al. but different cause

arxiv:1409.7381



- arxiv:1408.3156



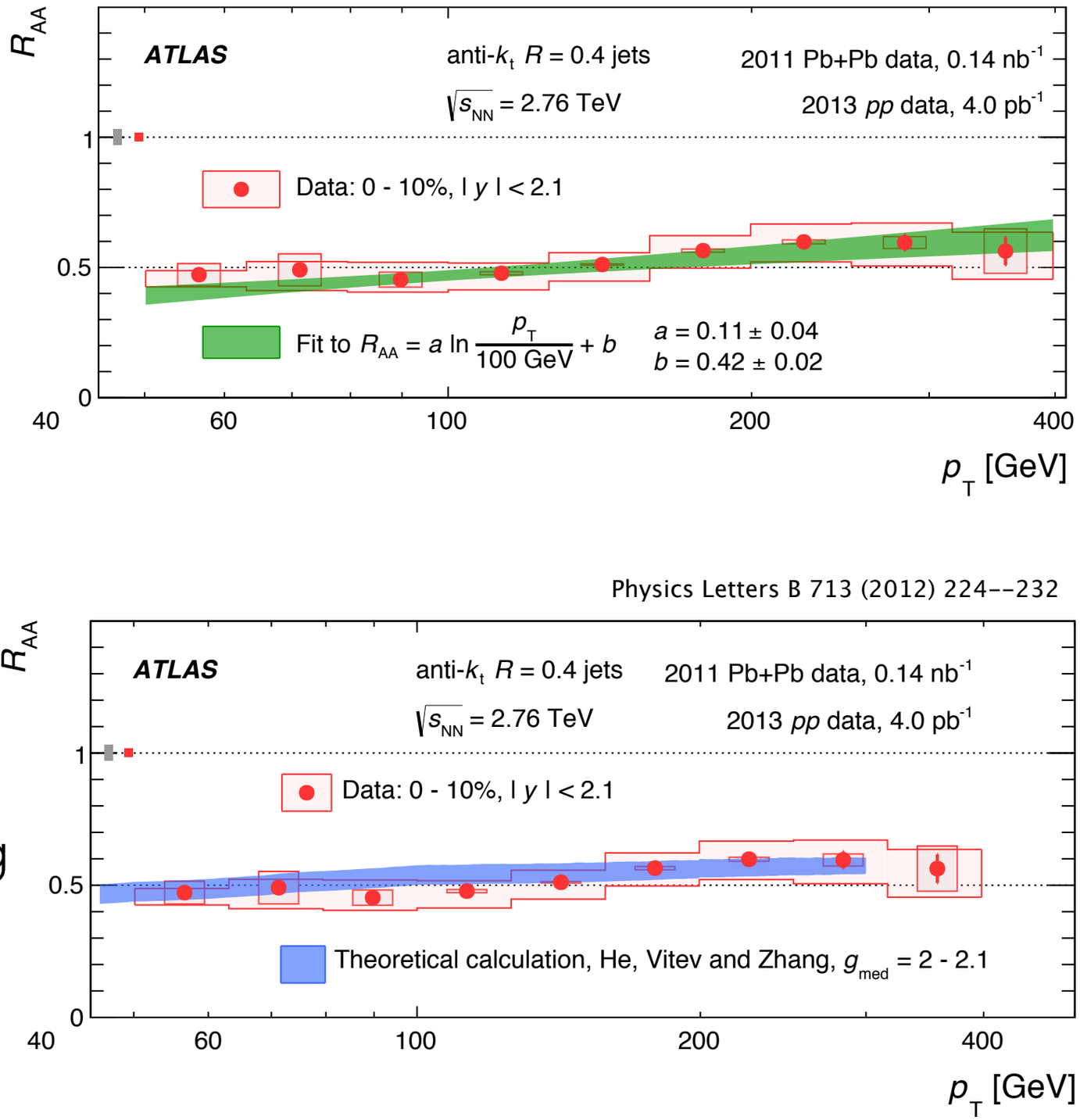
Summary

- Measurements of jets using the ATLAS calorimeter in Pb+Pb, p+Pb and p+p collisions
  - Fully corrected, unfolded using several different techniques
- Suppression measured in Pb+Pb for
  - Fully inclusive jets - rapidity dependence sensitive to changing quark/gluon jet mixture
  - Jet v_2 and nearby jets - sensitive to path length through hot, dense matter, and possible fluctuations (hotspots, etc.)
- p+Pb shows no overall suppression in minimum bias, but a surprising centrality dependence relative to pp and peripheral events
  - Strong differences between scaled jet rates in central and more peripheral event classes
  - Surprising scaling with jet momentum
  - Proposed explanations bear directly on fluctuations of the space-time configurations of the nucleon in the initial collision
- With increasing precision of LHC Run 2, and further input from theory, jets will become even more powerful tools for probing the medium over a large range of time scales, including early times.

Extra slides

Rise at high p_T

Careful fit to 0-10% |y|<2.1 suppression vs. pT, accounting for correlations, shows significant rise



Consistent with theoretical predictions from He et al, assuming a jet-medium coupling strength g_{med} = 2-2.1