COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

ATLAS EXPERIMENT

ATLAS Jet Quenching Measurements from Run 1 at the LHC

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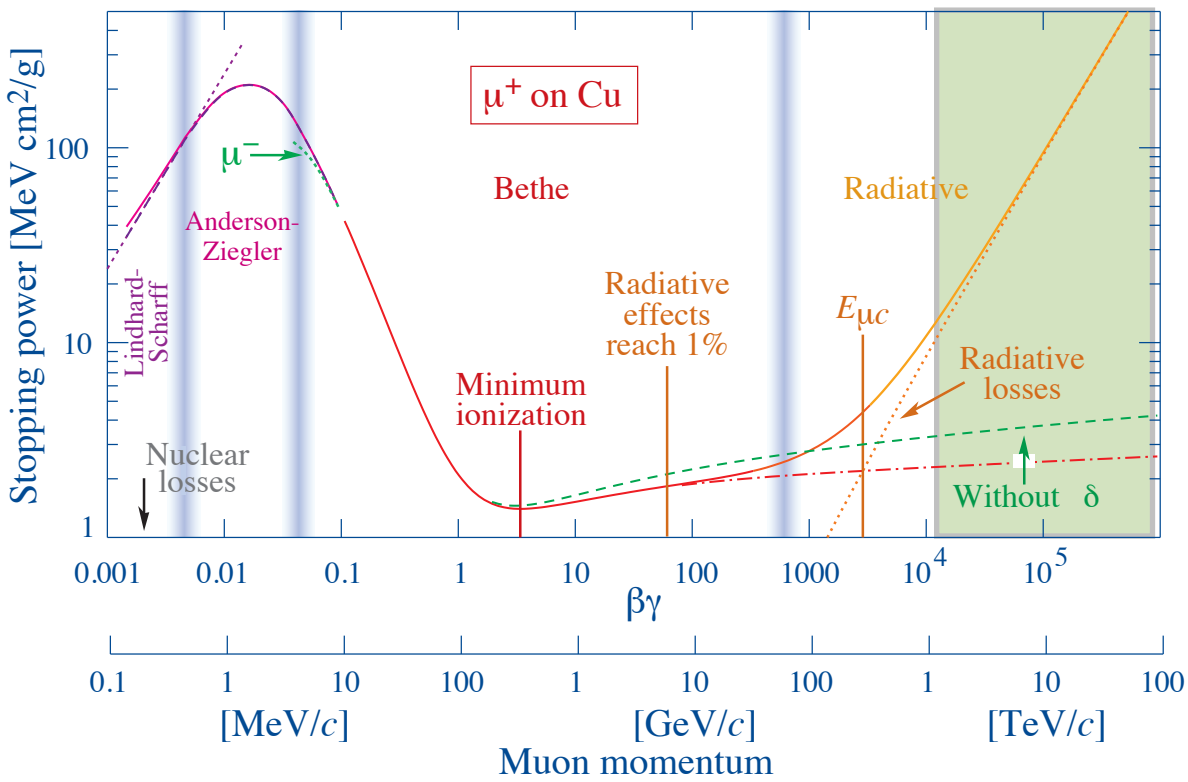
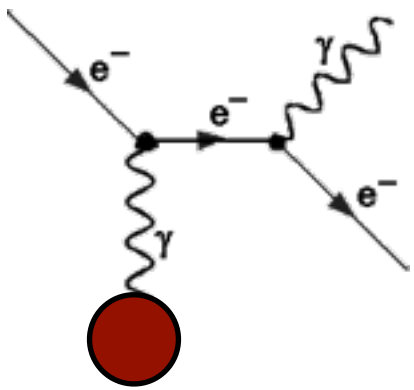
Jet Tomography

- Often stated goal of jet quenching studies is to use jets to probe the structure of the QGP
- Temptation is often to proceed in strict analogy with QED

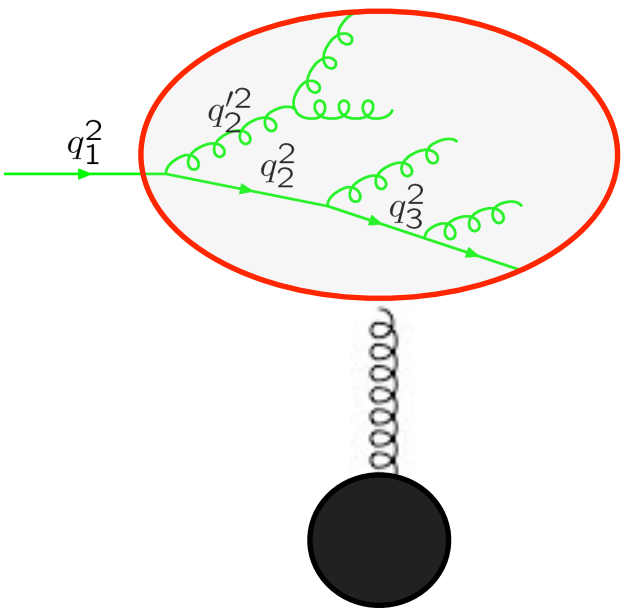




- In QED in radiative regime, interaction characterized by single scale (radiation length)

Jet Tomography

- Know from generations of QCD phenomenology that jets emerge from hard scattering processes with large virtuality and that they radiate copiously as they evolve back on shell
- Pattern of radiation is known as the parton shower
  - Enhancement of higher order radiation (large logs) arising from separation of scales between initial and final jet virtuality
  - Evolution of parton is virtuality ordered
- Jet is a coherent object and emissions are angular ordered



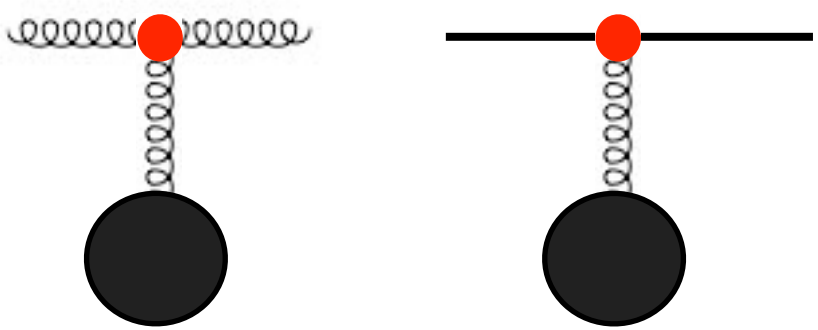
  - E-loss not obviously characterized by single scale, probe has hierarchy of scales…
  - What is the relationship between these scales and those set by the medium?

➡ To what extent does medium resolve jet?

  - Need to understand this well before phenomenon can be used to “measure” the medium scales

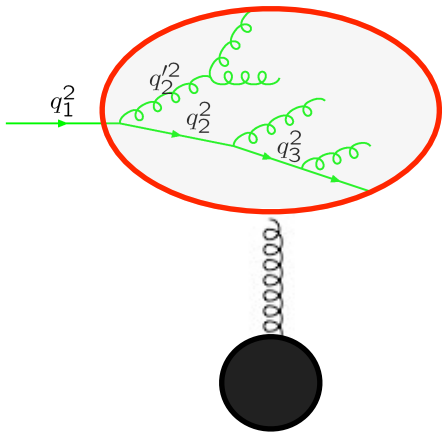
Flavor Dependence of Jet Energy Loss

- Properties of jets, final momentum distribution of hadrons w/in jet, sensitive to whether initial parton is a quark or gluon
  - "Gluon jets" wider, less likely to have high z leading fragment and have larger multiplicity
  - Distinction is only strict in LO picture (or LO+PS)
- May expect gluons to receive 9/4 enhancement in E-loss due to color factor



Detailed analysis of this in the context of PYTHIA
Cole and Spousta,1504.05169 [hep-ph]

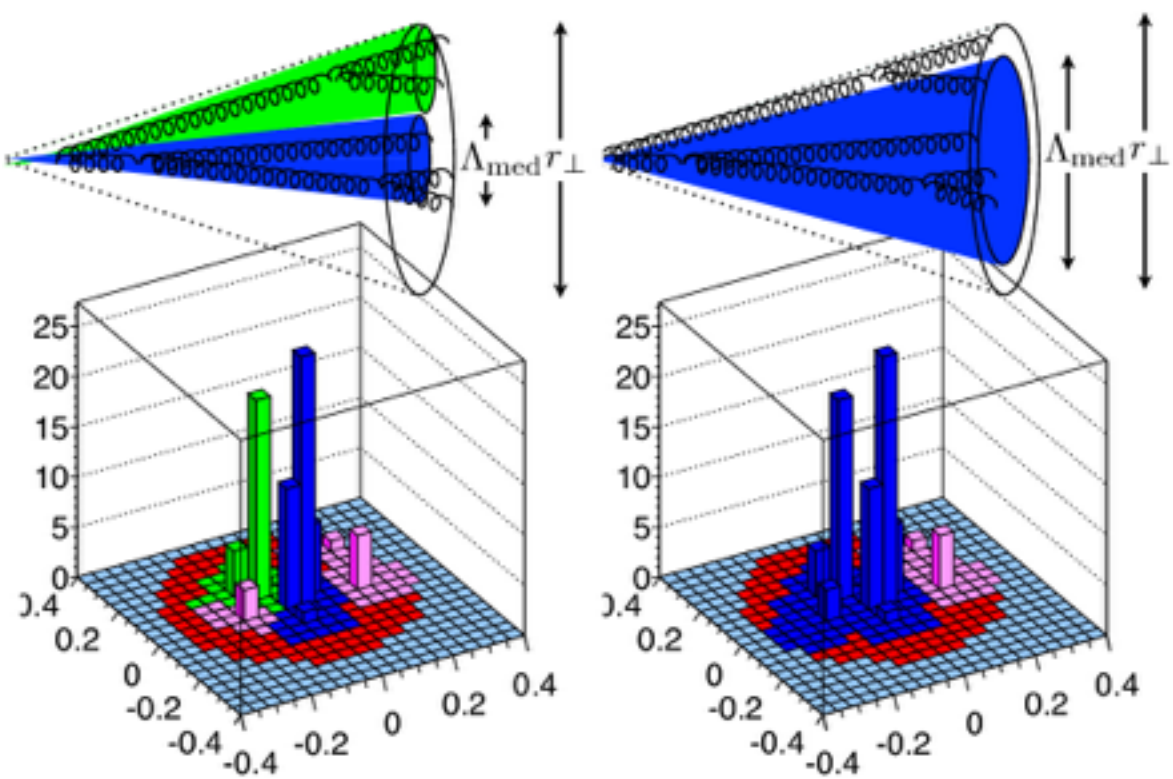
- But if medium resolves jet how much does initial flavor matter?



- Can study this by varying mixture of of *q*/*g* initiated jets

Coherence Approach to Quenched Jets

- Recent theoretical advances in coherence based approach
  - Combined effects of vacuum (virtuality and angular ordered) and in-medium (time ordered, angular anti-ordered) cascades
- Medium resolves jets to some scale ($\Lambda_{\rm med}$)
- Does not see jet substructure on smaller length scales, only total color charge, i.e. coherent substructures



➡ Depending on details of parton shower medium resolves jet into number of effective emitters

- Jets with different parton showers (categorizable by their substructures) are quenched differently

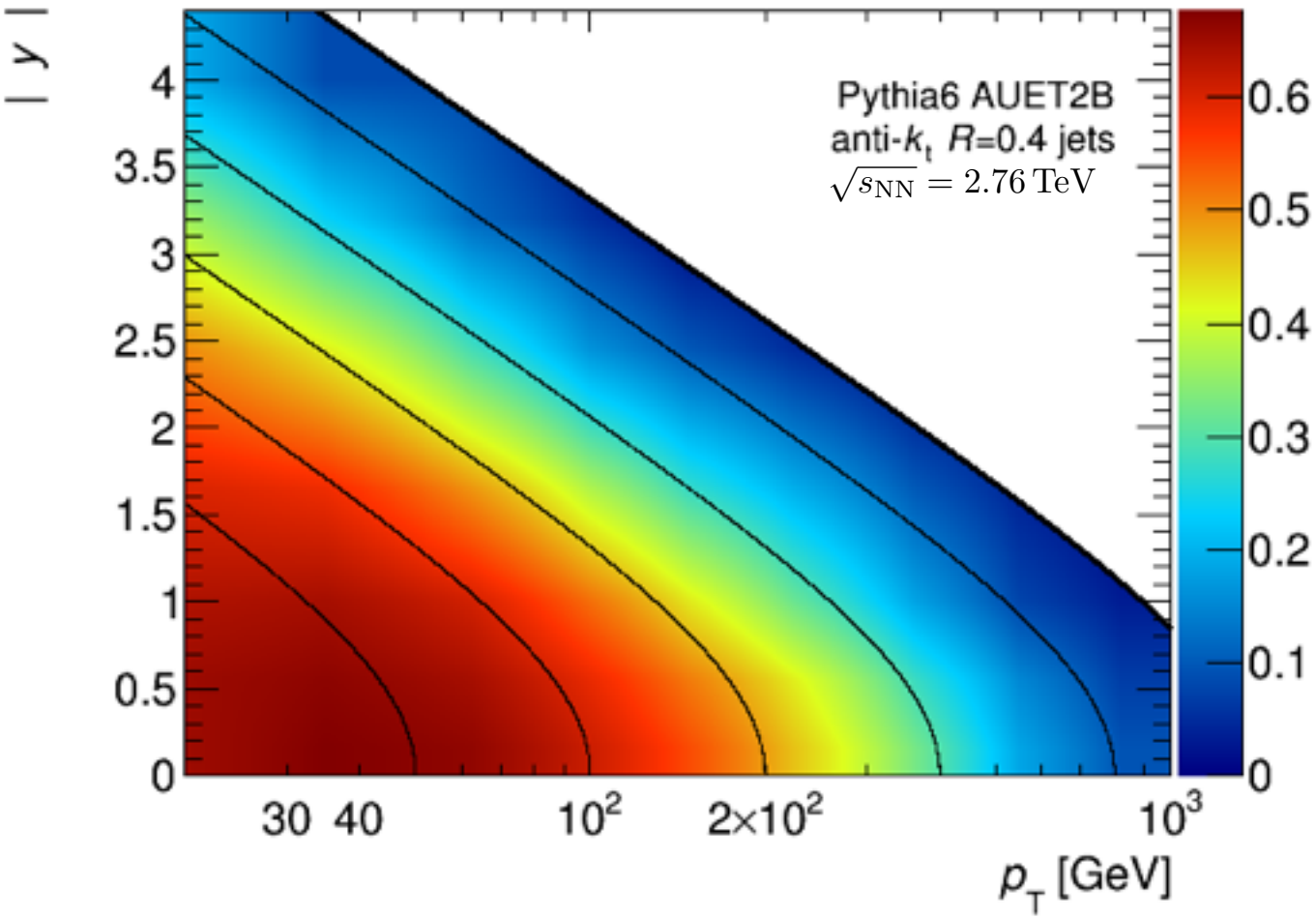
Casalderrey-Solana, Mehtar-Tani, Salgado, and Tywoniuk
Phys.Lett. B725 (2013) 357-360

Overview of ATLAS Jet Measurements

Measurement	Kinematics		Geometry	
	p_T	y	Centrality	ϕ - ψ_2
Jet suppression	X	X	X	X
Single hadron suppression	X	X	X	X
Fragmentation Functions	X	X	X	
Dijets	X		X	X

Gluon Fractions: Single Jets

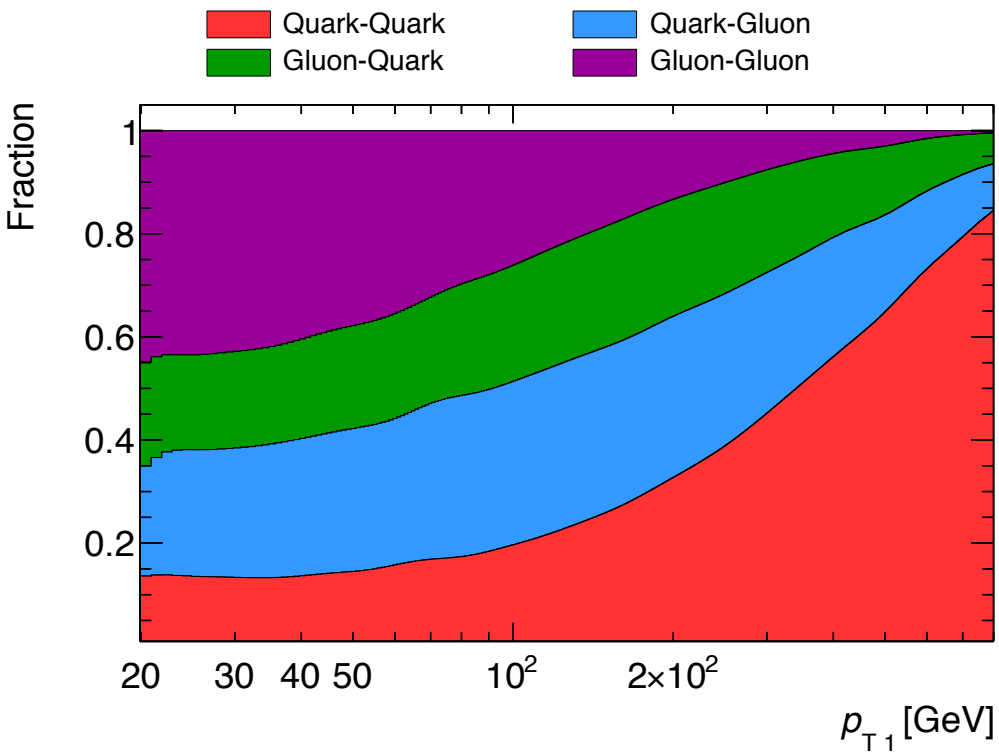
- Flavor of jet defined to be highest p_T parton w/in R of jet

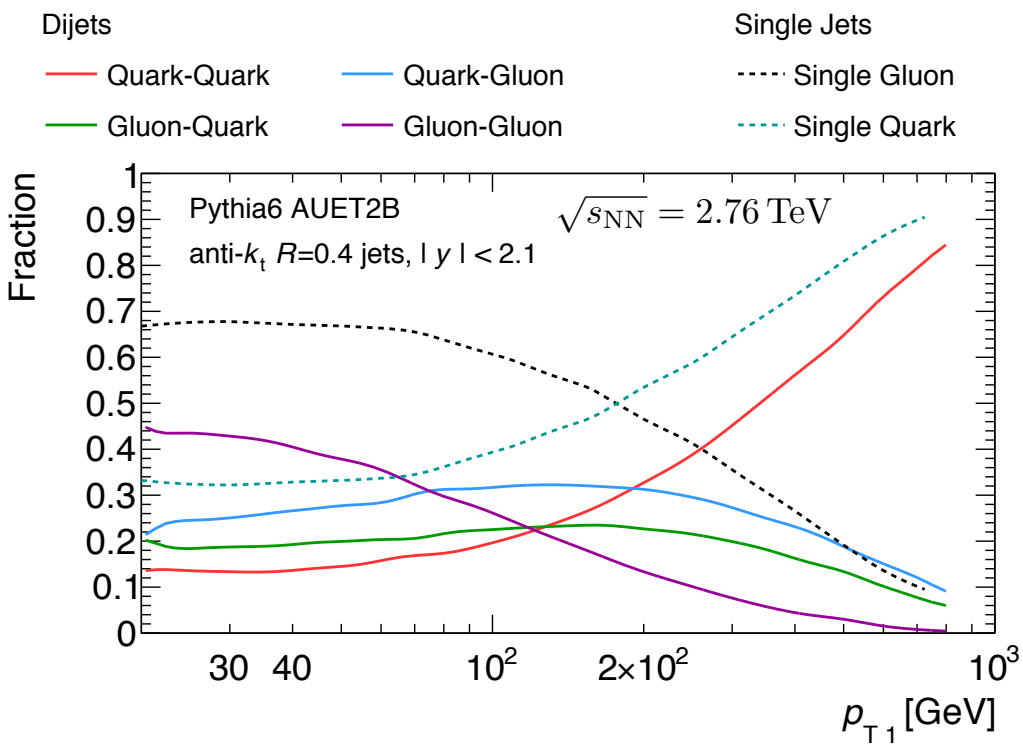


- Note that PDFs and flavor fractions are only indirectly related
  - Fractions extracted from generator which has initial and final state parton showers that may change flavor/kinematics of parton-level jets

- Two generators (e.g. PYTHIA and HERWIG) that have different PS implementations will not necessarily give the same flavor fractions even if they use the same input PDFs
- Also the *tune* of the generator matters, e.g. α_S used in ISR

Gluon fractions: Dijets





- **Naive expectation, Quark-Gluon configuration expected to show largest asymmetry *on average***

Partonic Fragmentation Functions

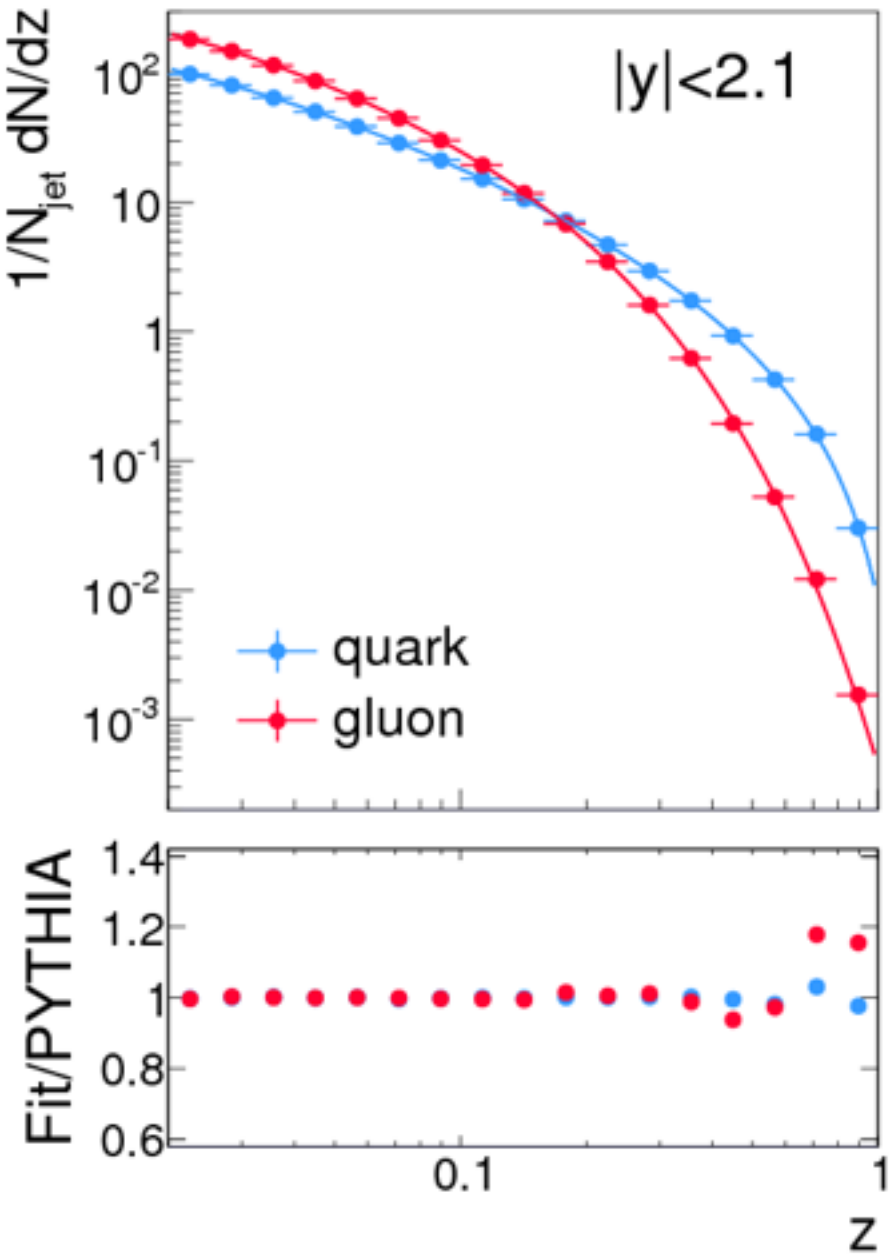
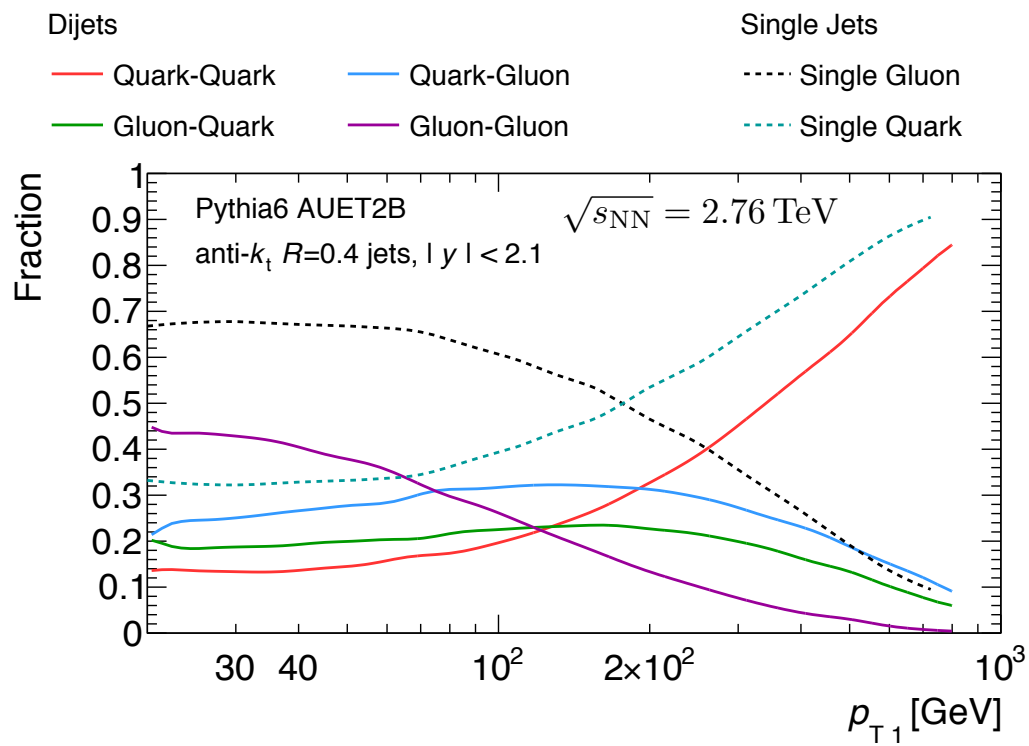
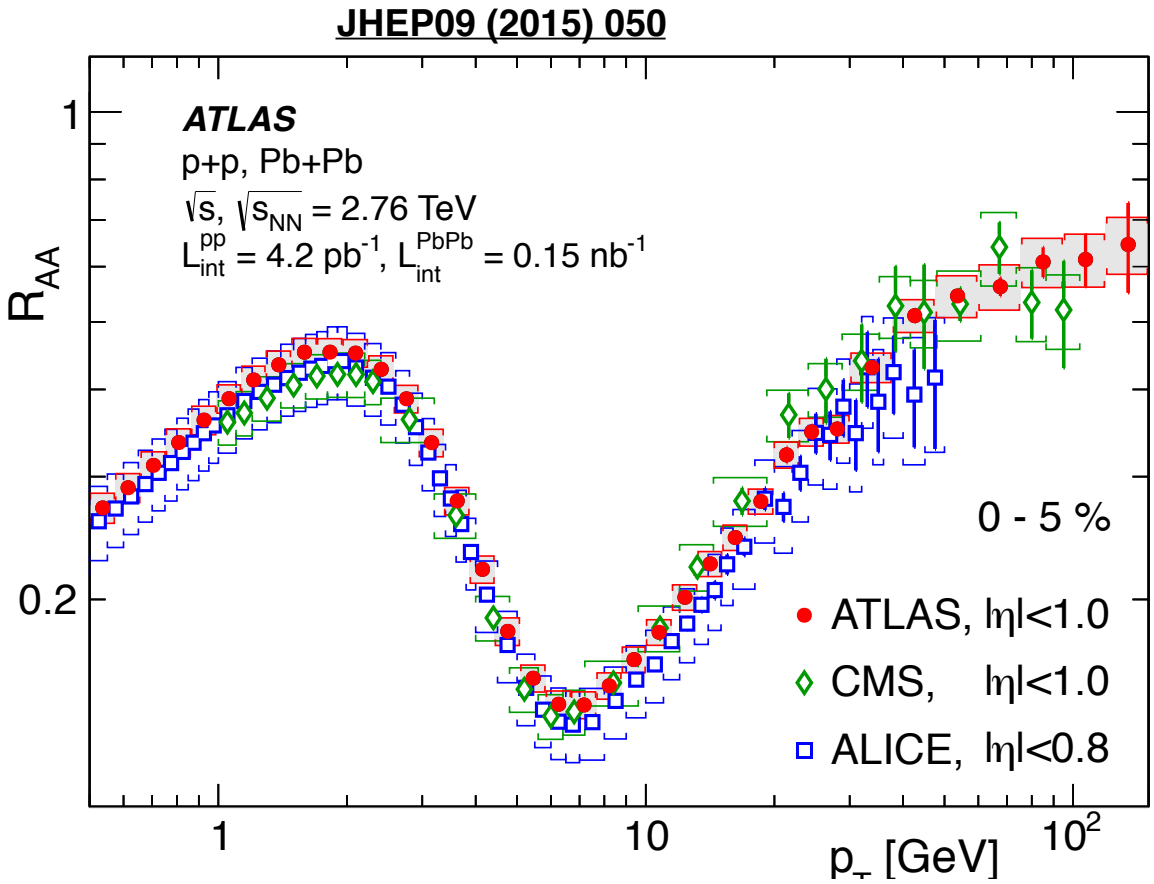


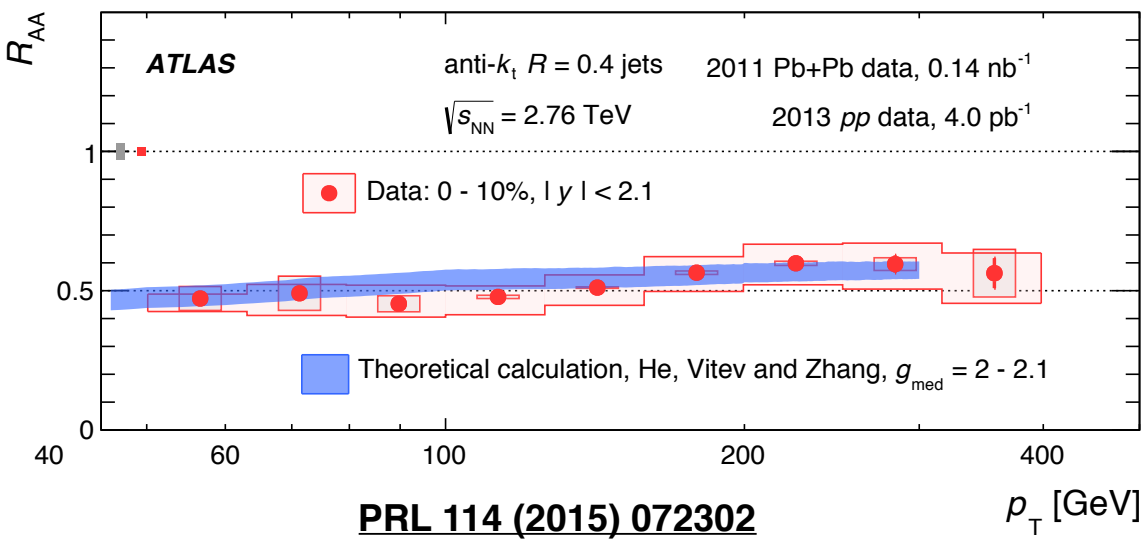
Figure from 1504.05169 [hep-ph]



- **At fixed hadron p_T, expect different mixture of *q*/*g* than for inclusive jets**

Single Jet Observables: p_T Dependence

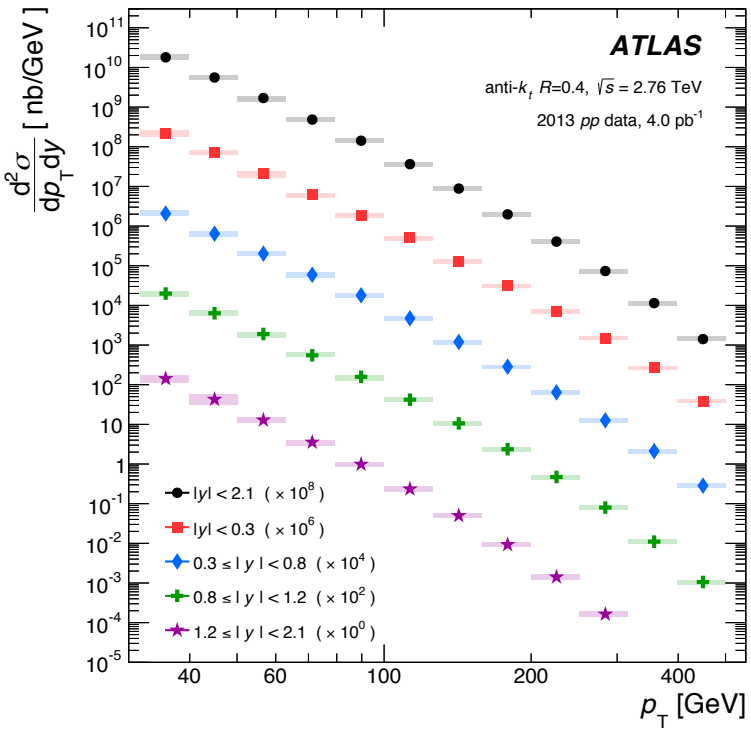


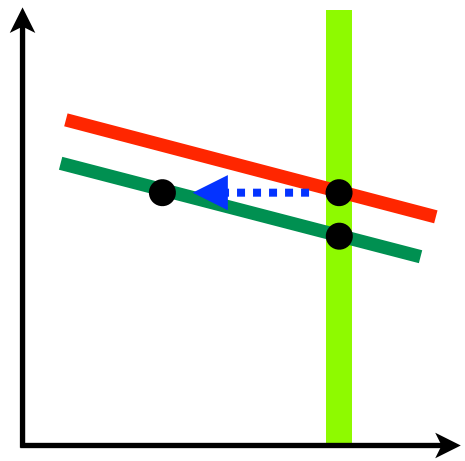


PRL 114 (2015) 072302

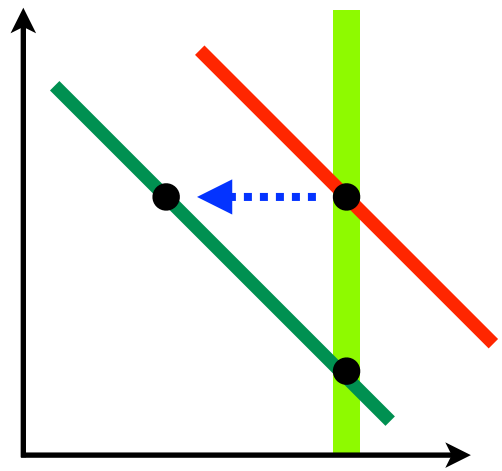
- R_{AA} for charged hadrons
- Can see more of flattening trend in latest ATLAS measurement
- Qualitatively similar to flatness observed in jet R_{AA}

Single Jet Observables: Rapidity Dependence





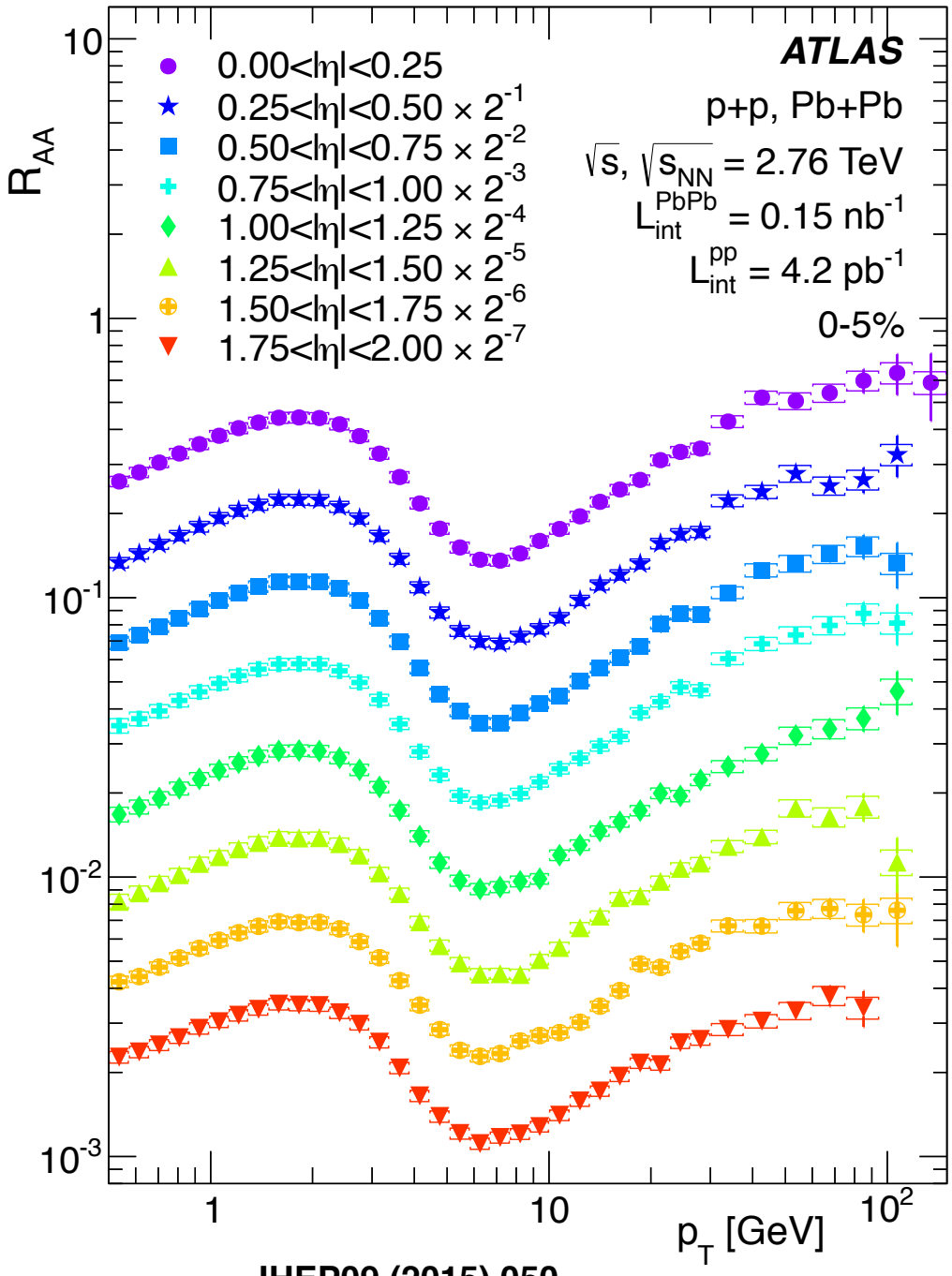
Mid-rapidity



forward rapidity

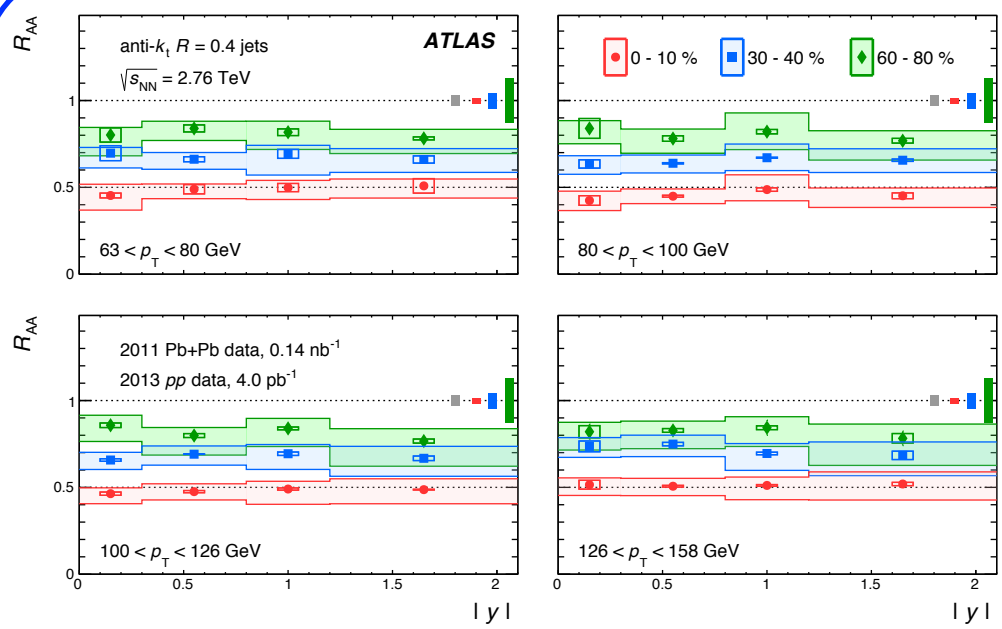
- Increasing rapidity results in a steeper production spectrum (lower R_{AA} at fixed energy loss)
- But higher fraction of quark jets (lower energy loss, higher RAA for fixed spectral slope)

Single Jet Observables: Rapidity Dependence



JHEP09 (2015) 050

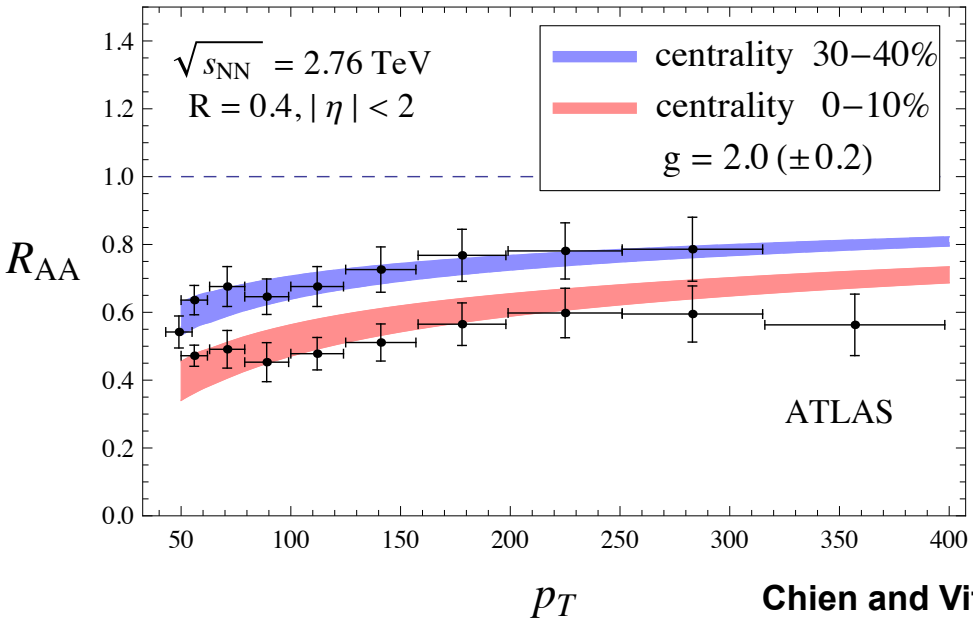
- **Neither shows large variation with rapidity suggestion effects mostly cancel**

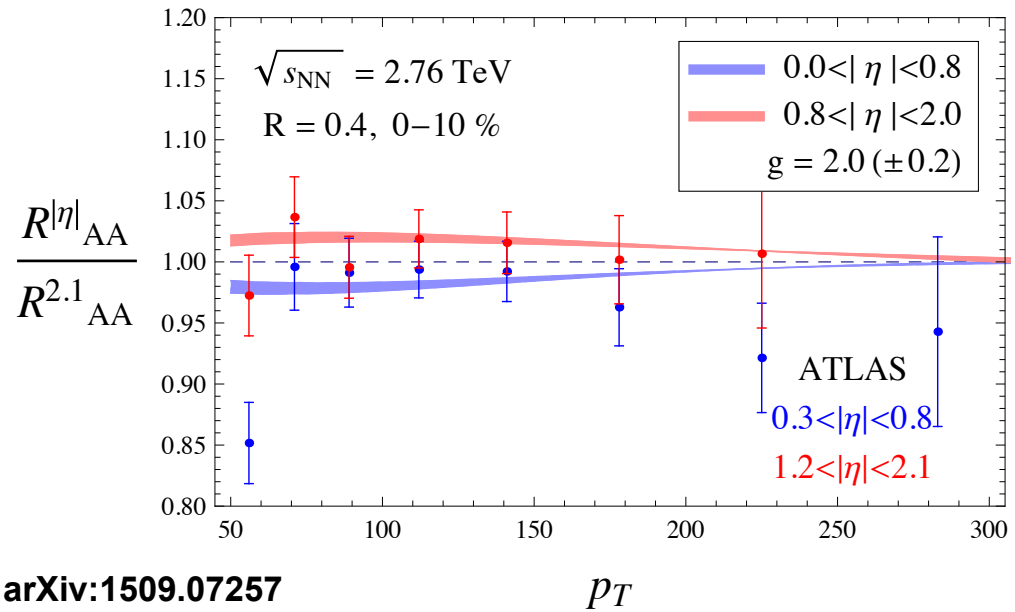


PRL 114 (2015) 072302

Single Jet Observables: Rapidity Dependence

- p_T, centrality and y dependence of R_{AA} well described by recent calculations

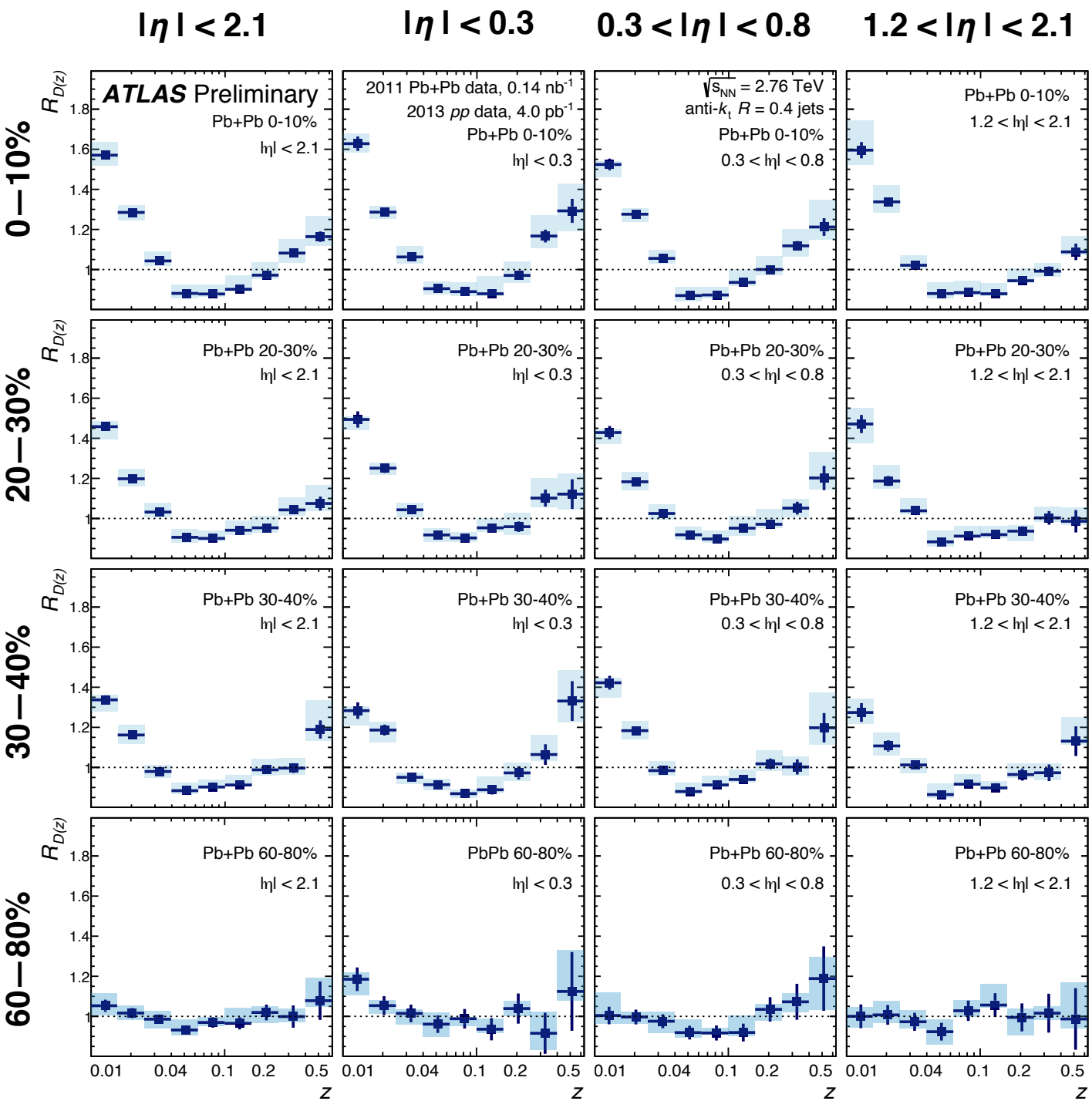




Chien and Vitev, arXiv:1509.07257

- R_{AA} larger at forward rapidity ⇒ increasing quark fraction wins out over increasing steepness of spectrum

Jet Structure: Rapidity Dependence

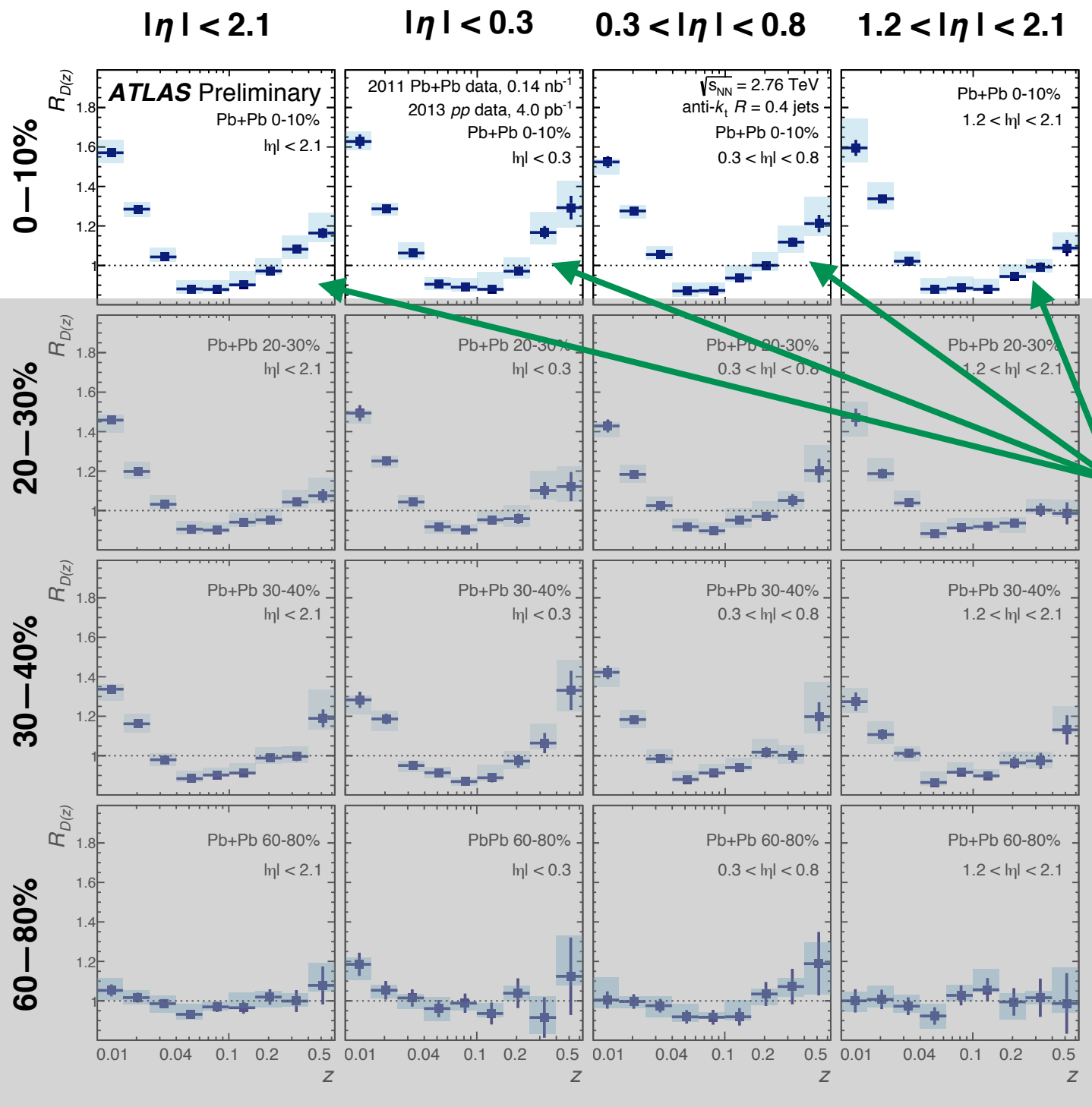


New fragmentation measurement

- **Includes *pp* reference using high stat. 2013 run**
  - ➡ **Significant improvement in ratios at high z**

ATLAS-CONF-2015-055

Jet Structure: Rapidity Dependence



New fragmentation measurement

- Includes *pp* reference using high stat. 2013 run
  - ➡ Significant improvement in ratios at high z
- Modifications at high *z* observed to be significant for first time

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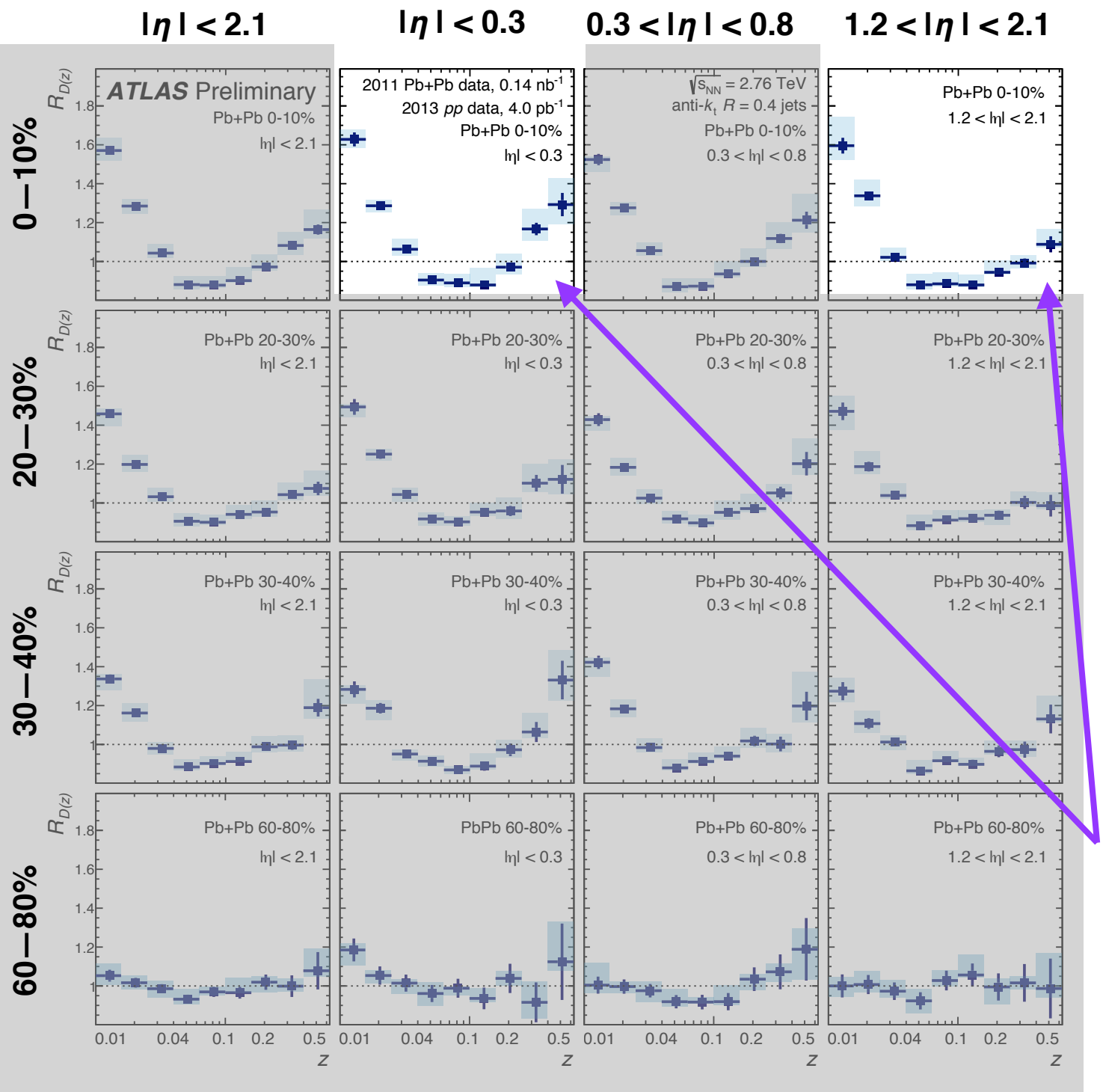
Jet Structure: Rapidity Dependence



New fragmentation measurement

- Includes *pp* reference using high stat. 2013 run
  - ➡ Significant improvement in ratios at high z
- Modifications at high *z* observed to be significant for first time
- Jet p_T and η dependence
  - Unmodified distributions for quark and gluon jets very different
- Modifications at high *z* weaker at larger η
  - Higher quark fraction?

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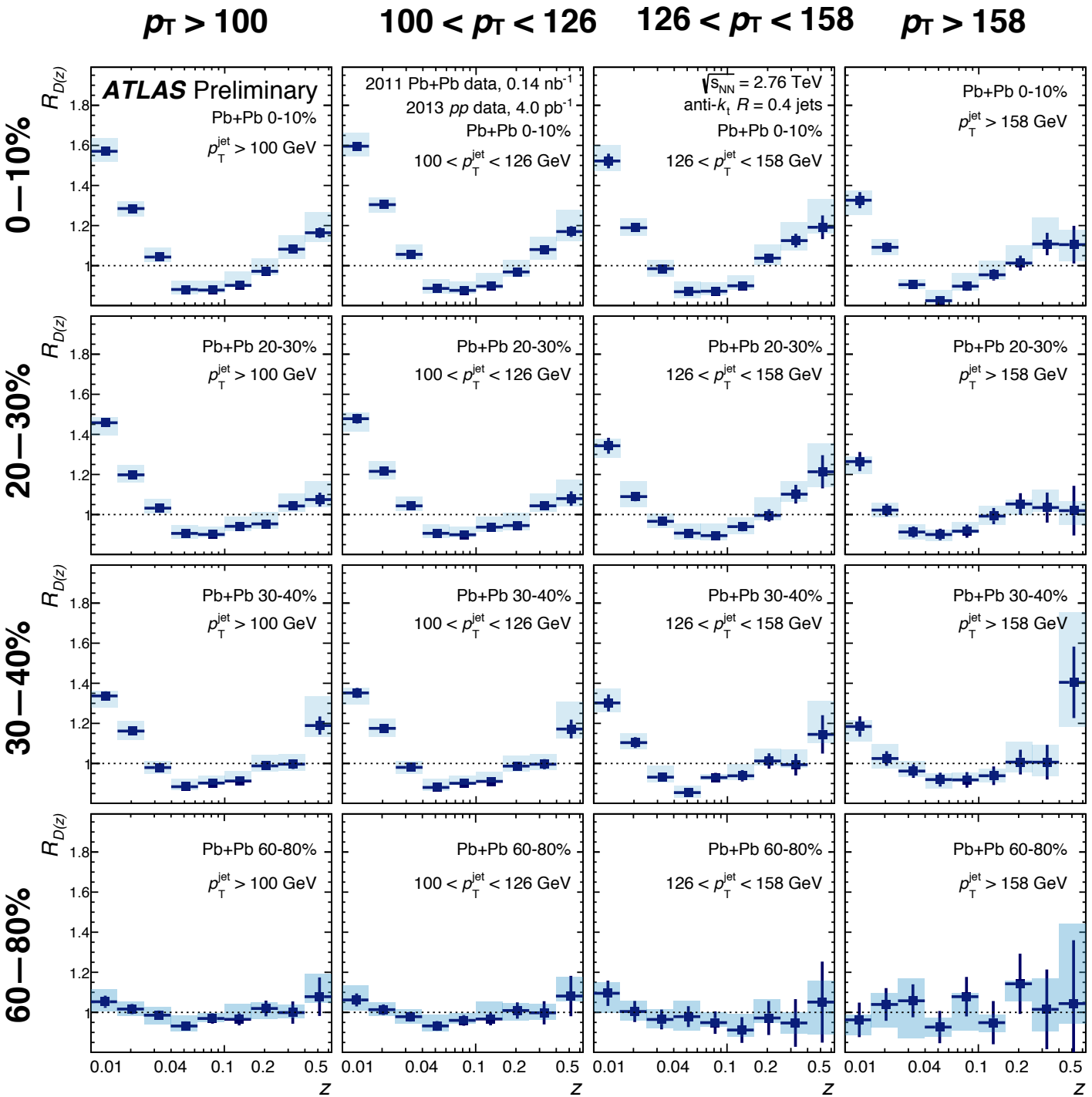
Jet structure : p_T dependence



- **Modifications at high z are less strong at larger p_T**

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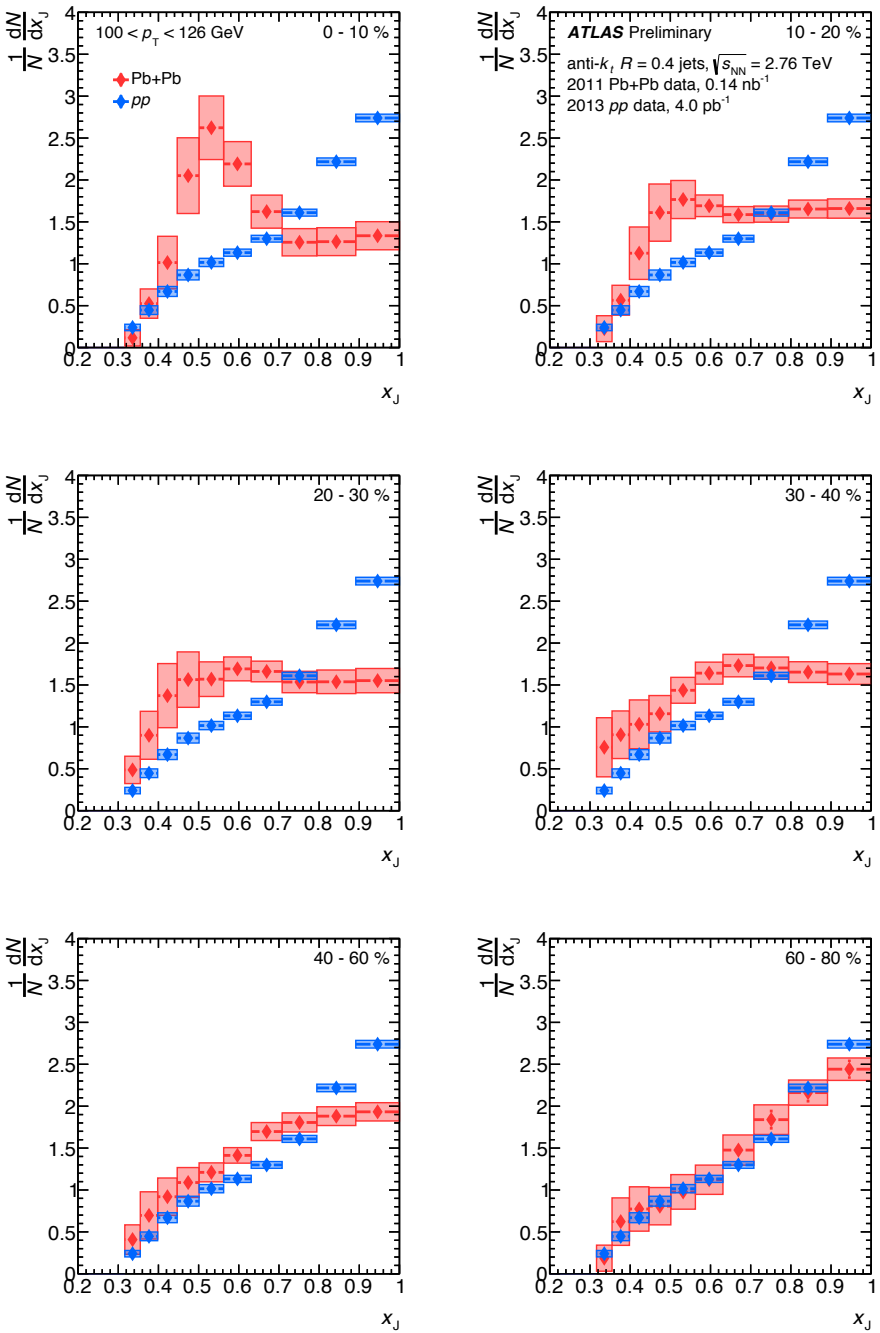
Jet Energy loss: Dijet asymmetry

$100 < p_{T1} < 126$ GeV, $x_J = p_{T2} / p_{T1}$

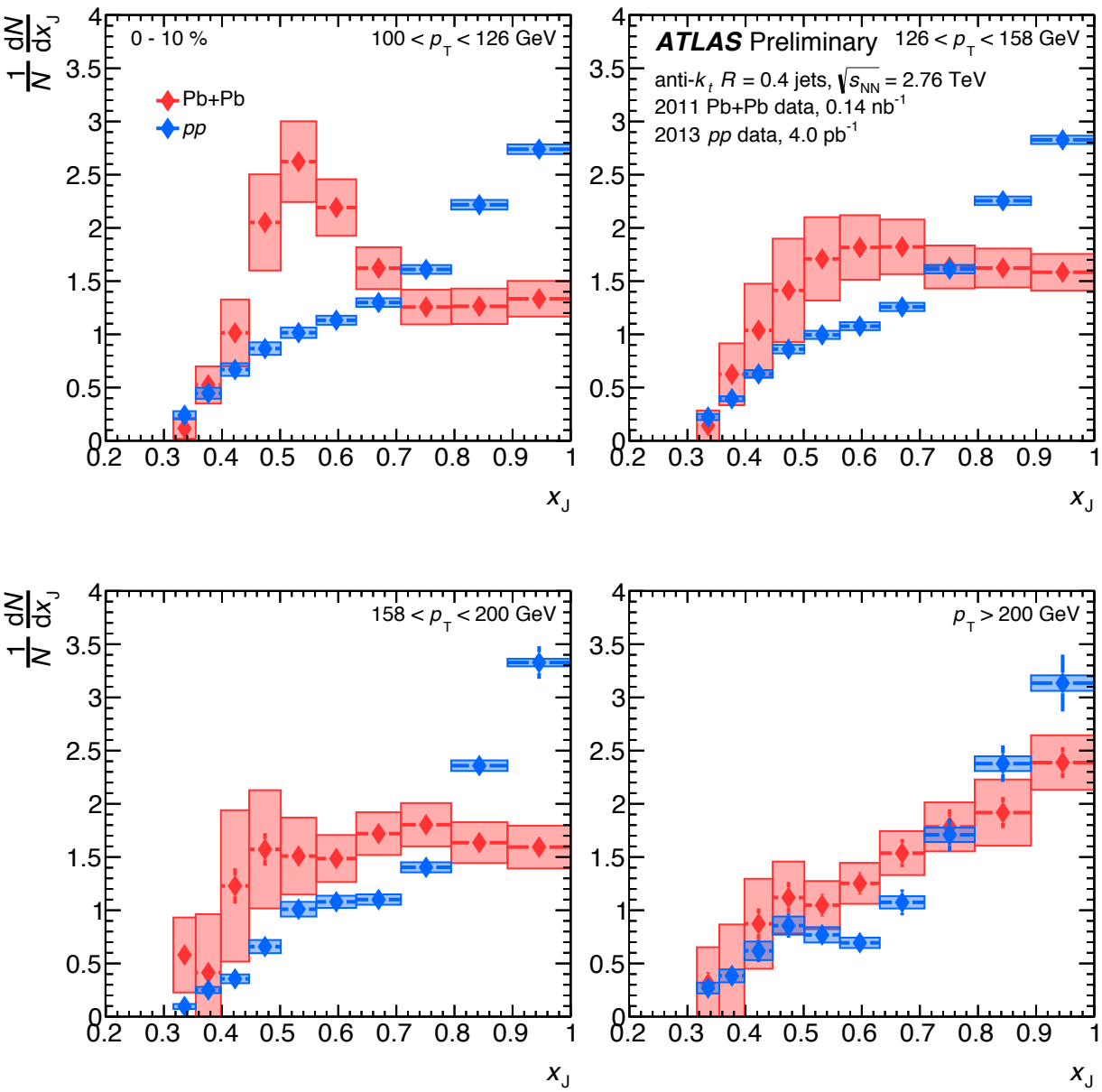


- Fully unfolded in two-dimensional p_{T2} - p_{T1} space and projected onto x_J
  - Can be directly compared to theory
- In *pp* collisions, most probable dijet configuration is x_J~1, balanced dijets
- In central Pb+Pb collisions most probable configuration for dijets is for one jet to have HALF as much energy as the other
  - ➡ Qualitative change in dijet behavior general feature of central HI collisions

ATLAS-CONF-2015-052

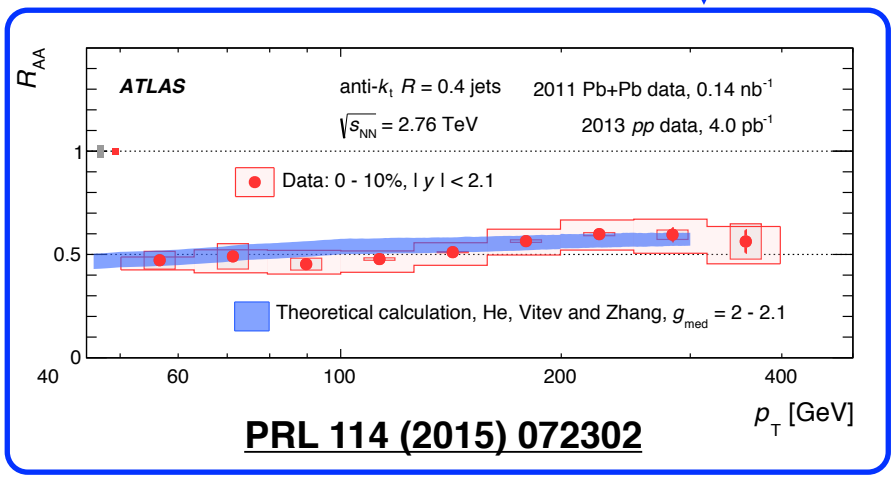
Dijets: p_{T1} and Possible Flavor Dependence

For dijets, *qq/gg/qg* composition of pairs changes with p_{T1}



ATLAS-CONF-2015-052

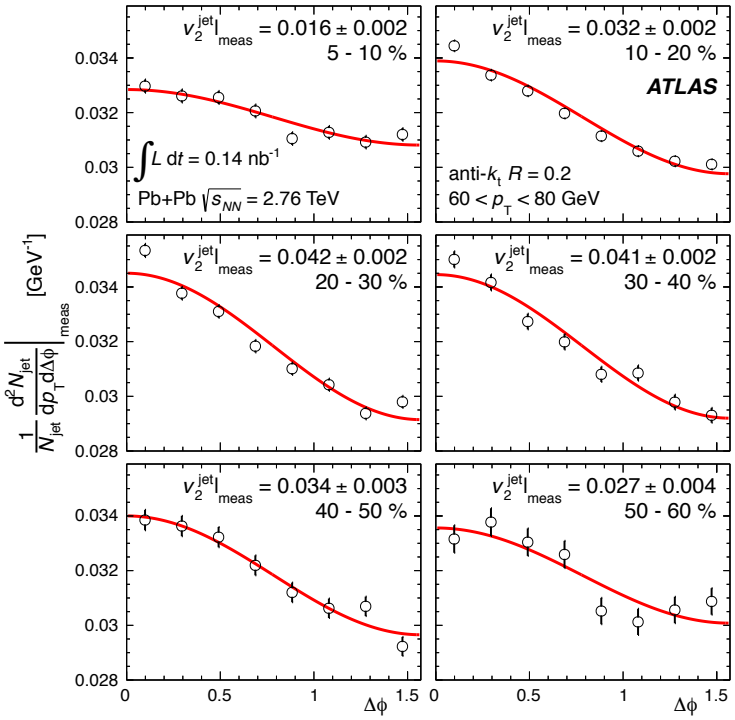
p_{T1} evolution more abrupt than for single jets, e.g. R_{AA} shows very weak p_T dependence



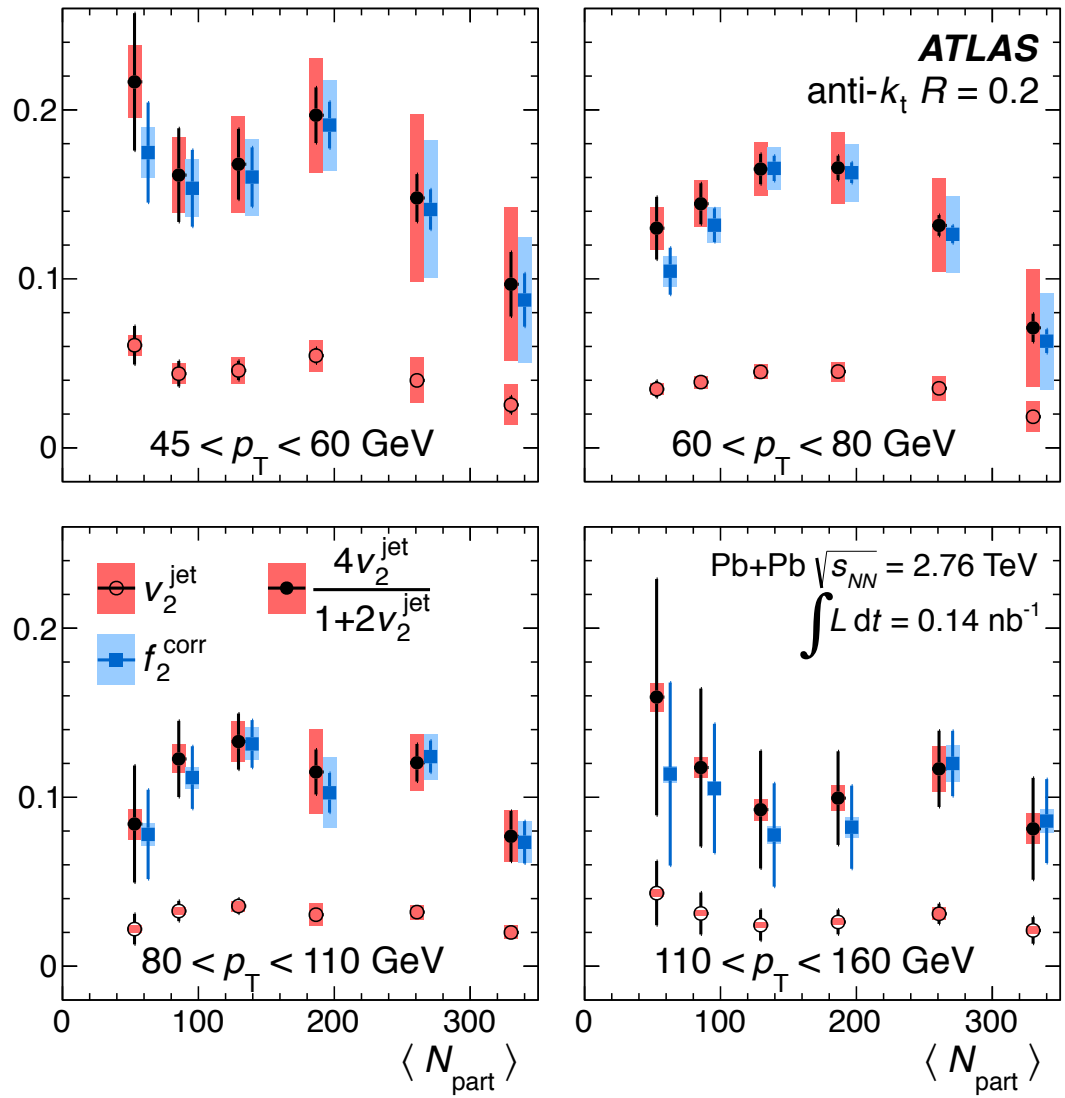
PRL 114 (2015) 072302

Much less modification at higher p_T

Single Jets : Geometry Dependence



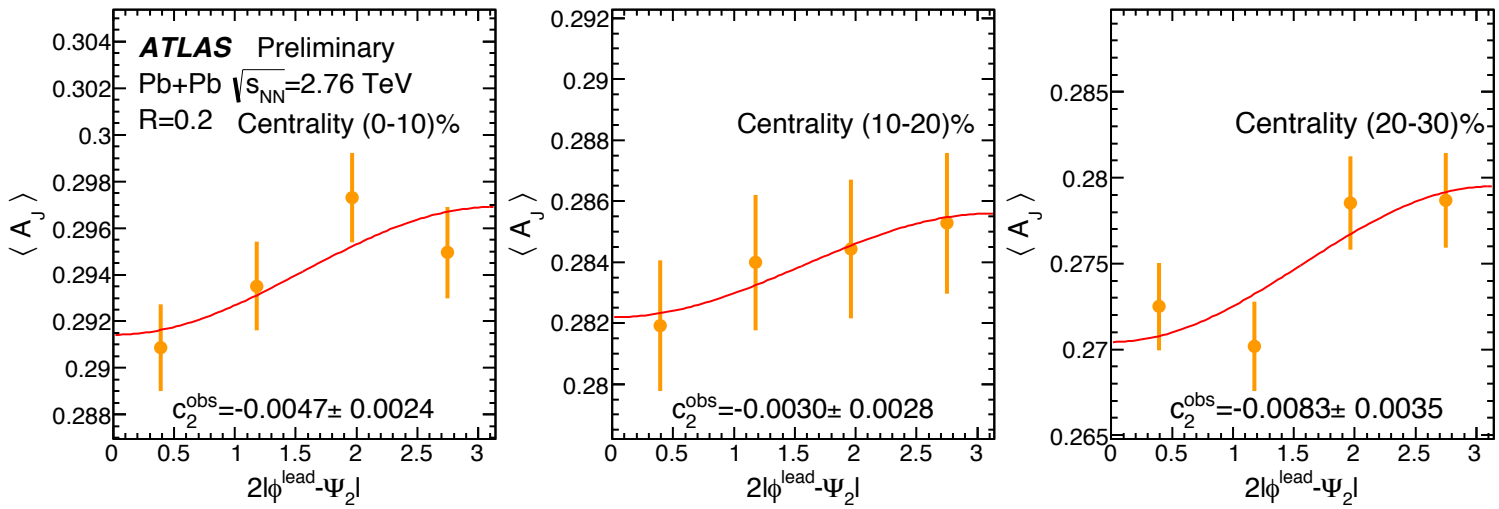
- **Jet yields observed to depend on angle wrt second order event plane : $\Delta\phi = \phi - \psi_2$**

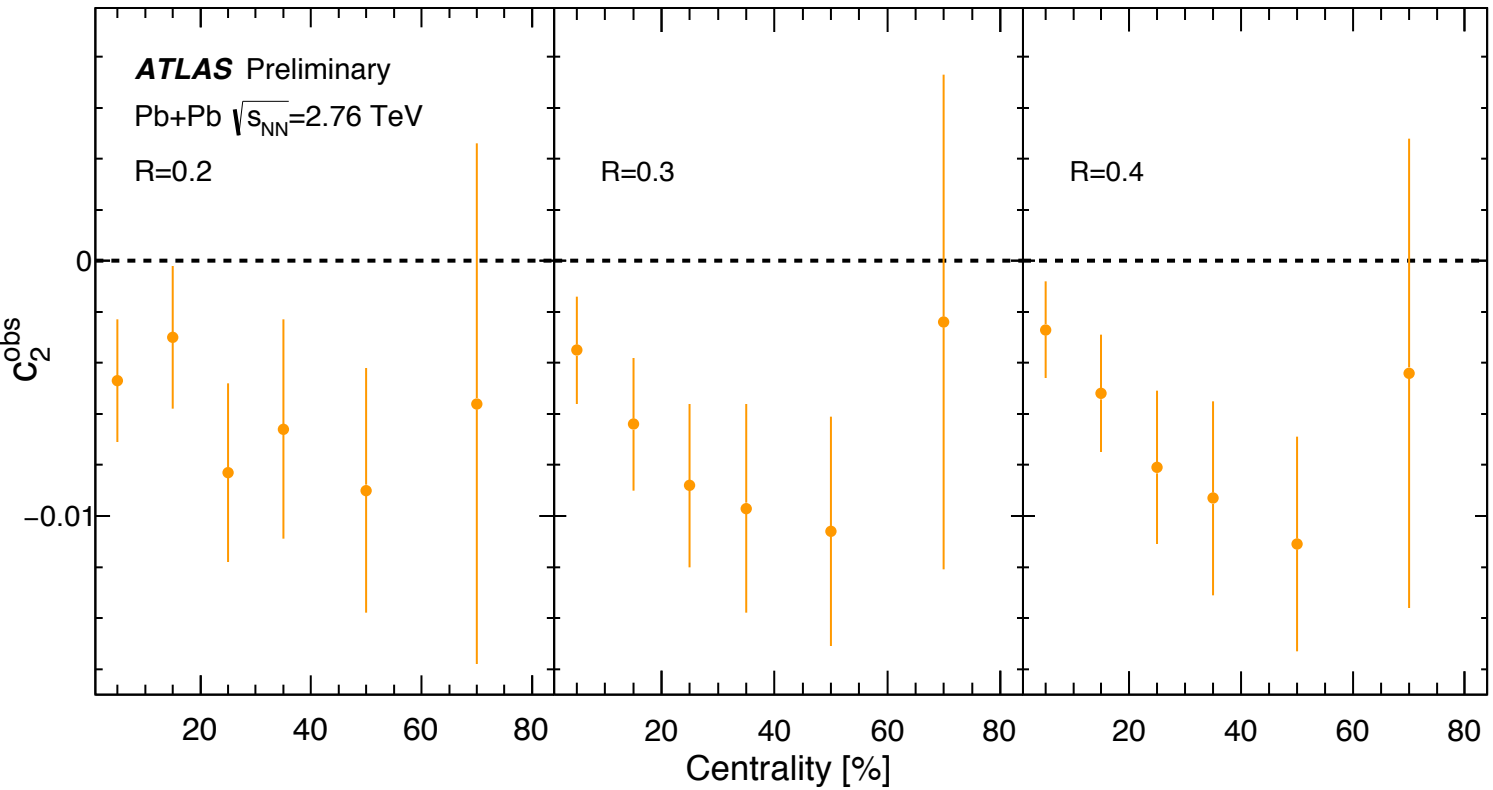


- **In/out-of-plane differences consistent with second harmonic modulation which is consistent w/ simple assumptions of L^2 E-loss and expanding medium**

Dijets: Geometry Dependence

$A_J = (p_{T1} - p_{T2}) / (p_{T1} + p_{T2})$ (not unfolded)





Very small, but significant anti-correlation between EP angle and $\langle A_J \rangle$

$\langle A_J \rangle$ smaller for dijets in the direction of EP which see shorter path lengths

Shows second harmonic modulation

Constrains extent to which asymmetry determined by geometry

ATLAS-CONF-2015-021

Radiative Corrections to qhat

- **Resummation of radiative corrections yields *anomalous dimension for qhat***
- **Implies anomalous dimension for path length dependence**

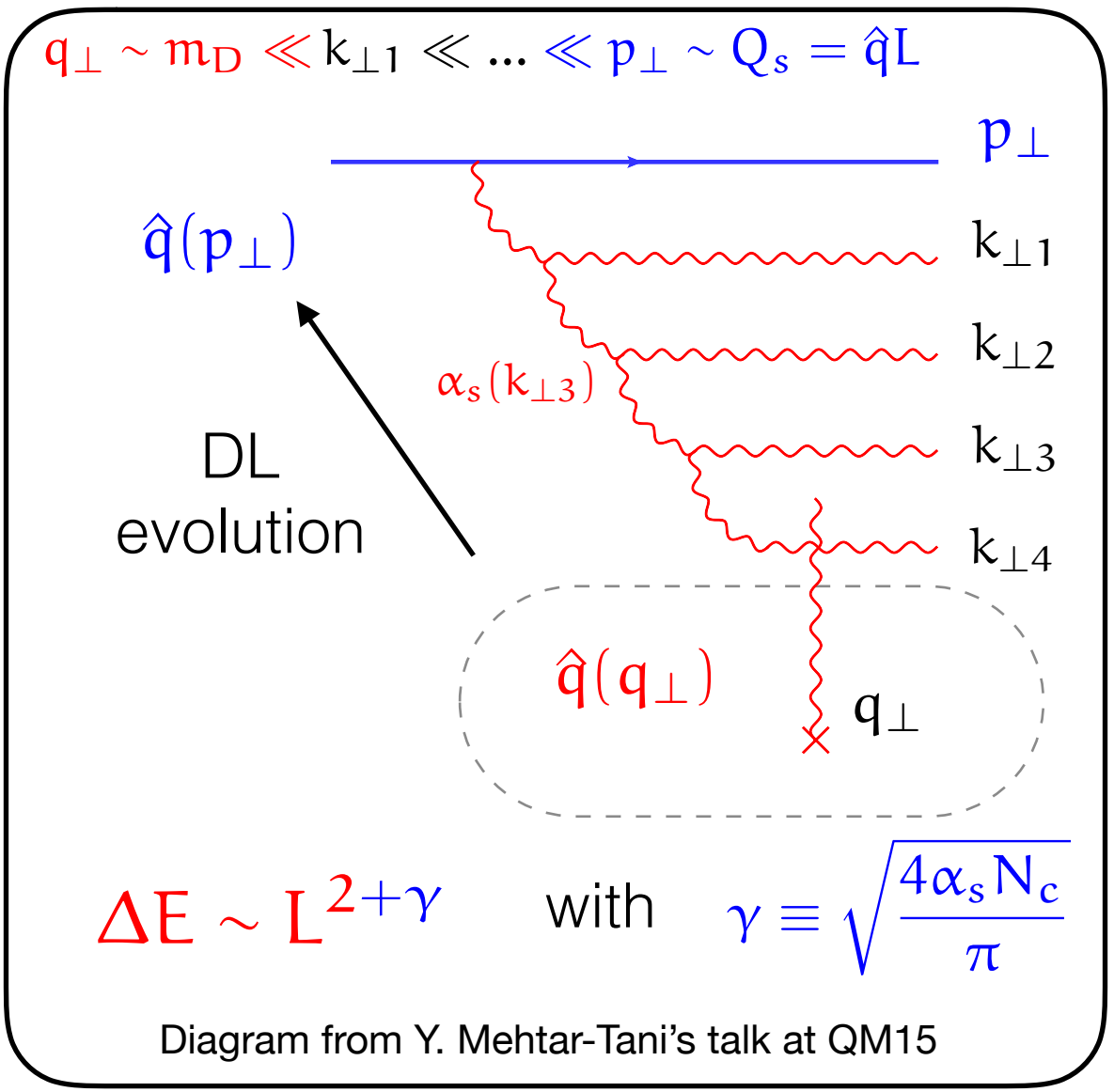


Diagram from Y. Mehtar-Tani's talk at QM15

- **Analysis predicts a path length dependence between pQCD radiative energy loss (L^2) and AdS strong coupling (L^3)**

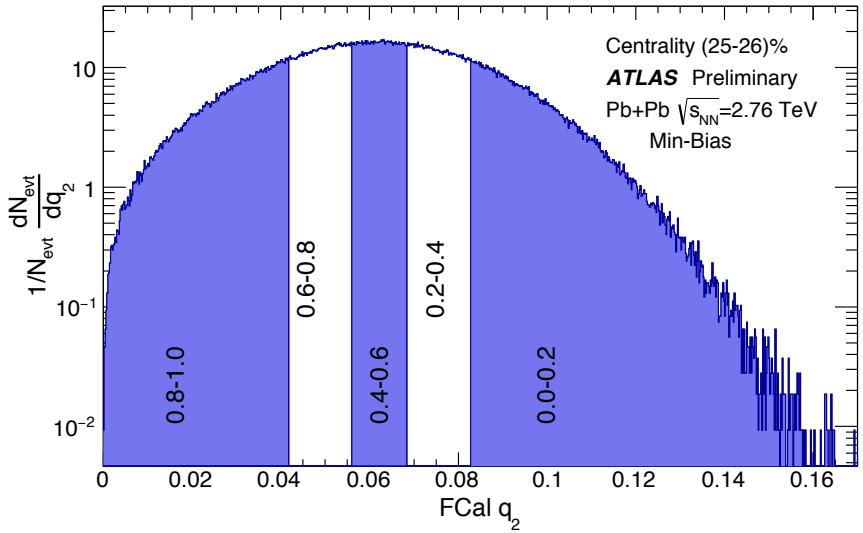
➡ **Tantalizing possibility to connect strong and weak coupling limits**

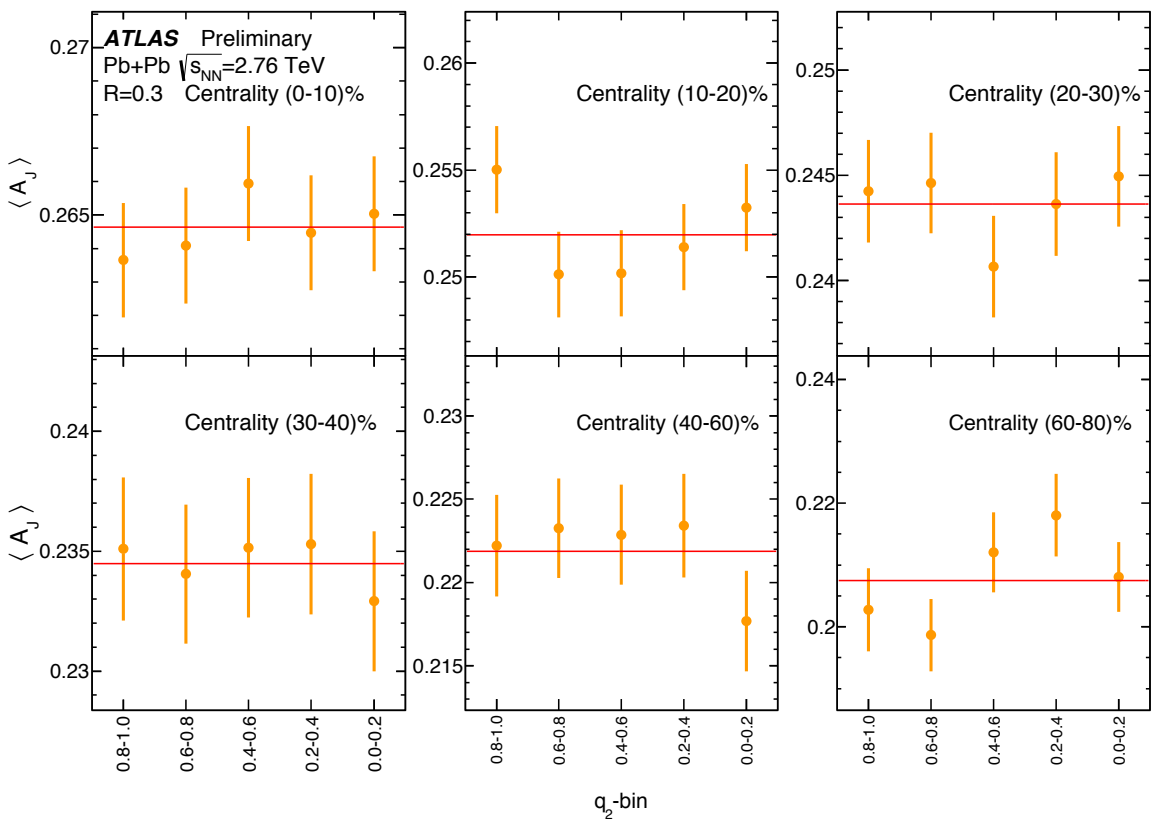
- **Can we observe effect of anomalous dimension through**
  - **More precise measurements?**
  - **Selection on kinematics to enhance contribution?**

Geometry and Jet Quenching : Next Steps

LHC Run 1 results showed improvments in determination of event-by-event geometry

Classify events both by centrality and ellipticity : $|q_2|$





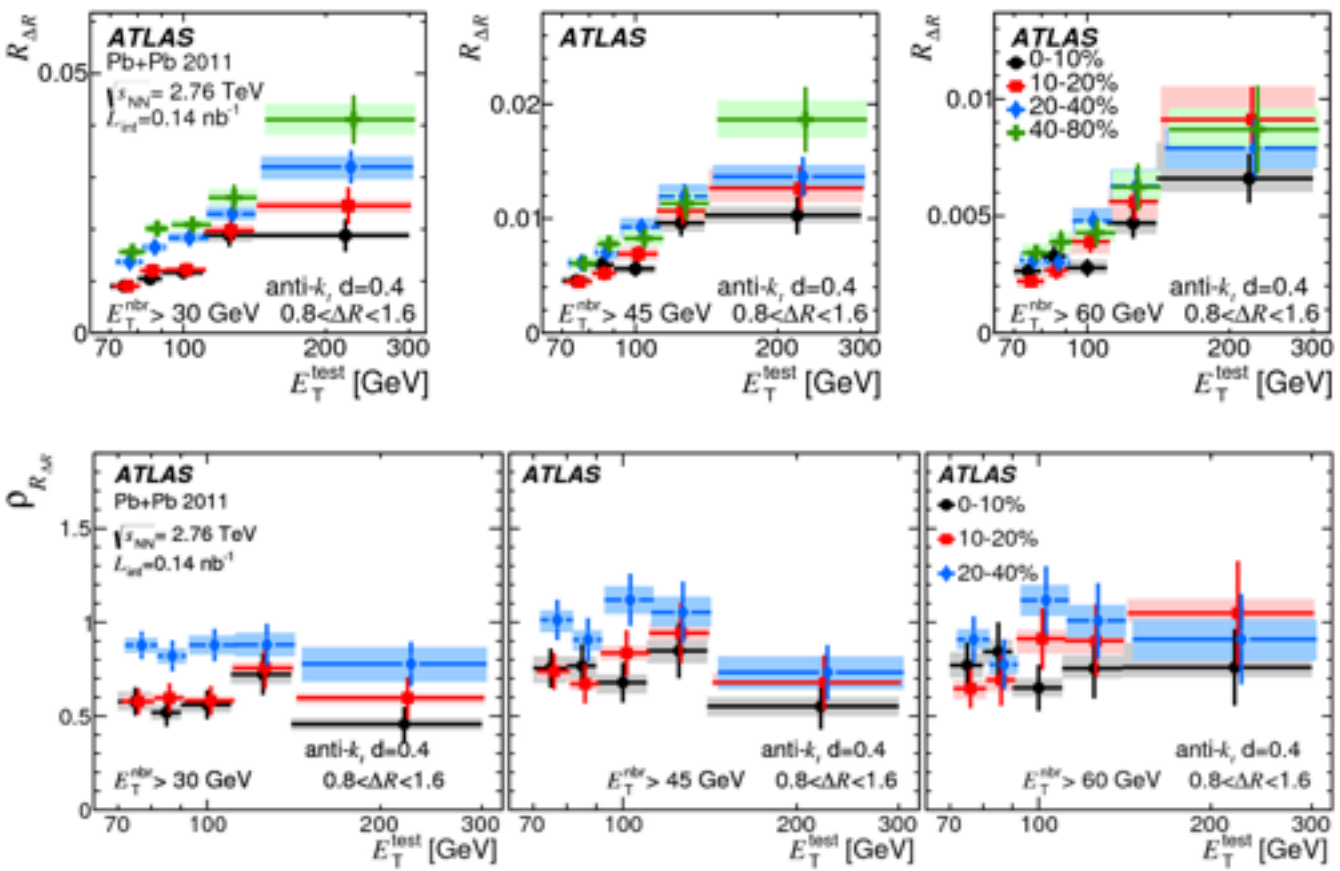
Running out of statistics for this in run 1…

<A_J> also has very small signal …

ATLAS-CONF-2015-021

Multi-jets in Heavy Ion Collisions

- **LHC run 2 should benefit much higher rates of complicated radiation patterns**
  - **Nearby jets see similar path lengths and density fluctuations**
  - **Have correlated color structure**
  - **k_t / opening angle of splitting sets scale to probe medium**



- **First measurement of conditional yields of nearby jets performed by ATLAS could benefit hugely/be expanded**
- **Conditional yields are suppressed in central collisions**

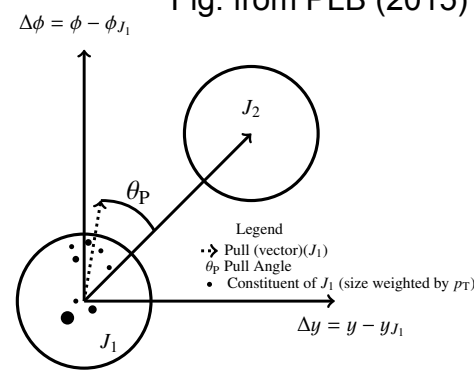
Observing Coherence Effects with Jet Pull ?

- **Observable sensitive to color flow: jet pull vector**

$$\vec{v}_p^J = \sum_{i \in J} \frac{p_{\mathrm{T}}^i |\vec{r}_i|}{p_{\mathrm{T}}^J} \vec{r}_i.$$

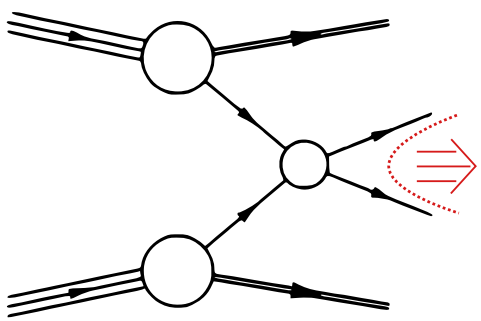
  - **Example here is for distinguishing b bbar final states**

Fig. from PLB (2015) 475-493



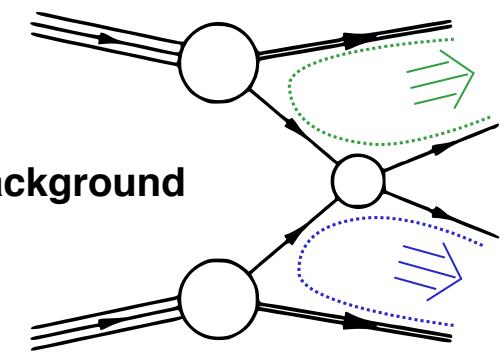
$pp \to H \to b\bar{b}$

Signal



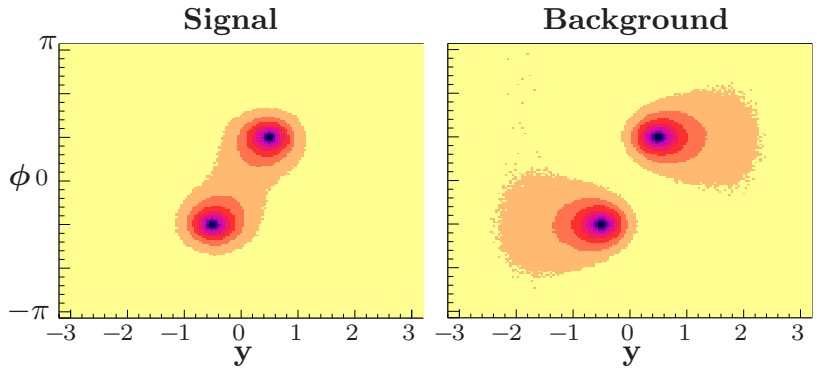
$pp \to g \to b\bar{b}$

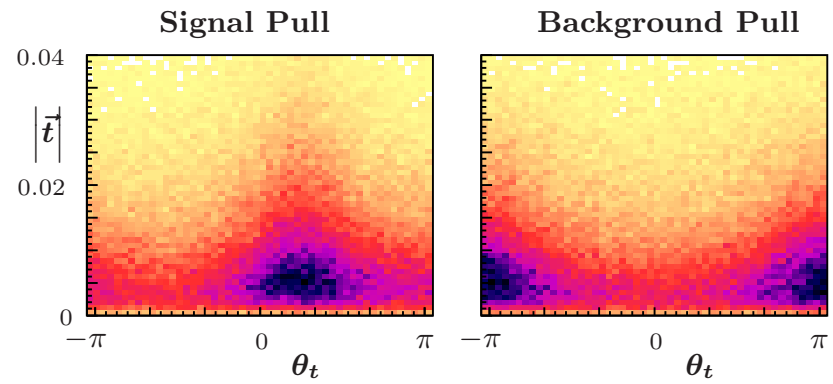
Background



Particle production on axis connecting jets

Color connection between jet and beam remnants





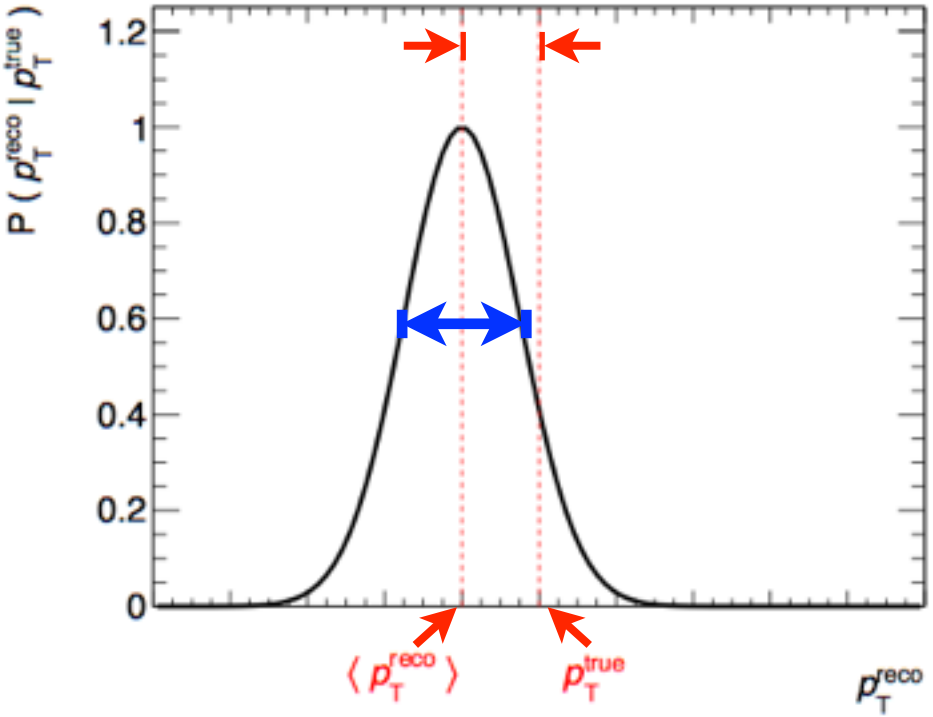
Gallicchio and Schwartz, Phys.Rev.Lett. 105 (2010) 022001

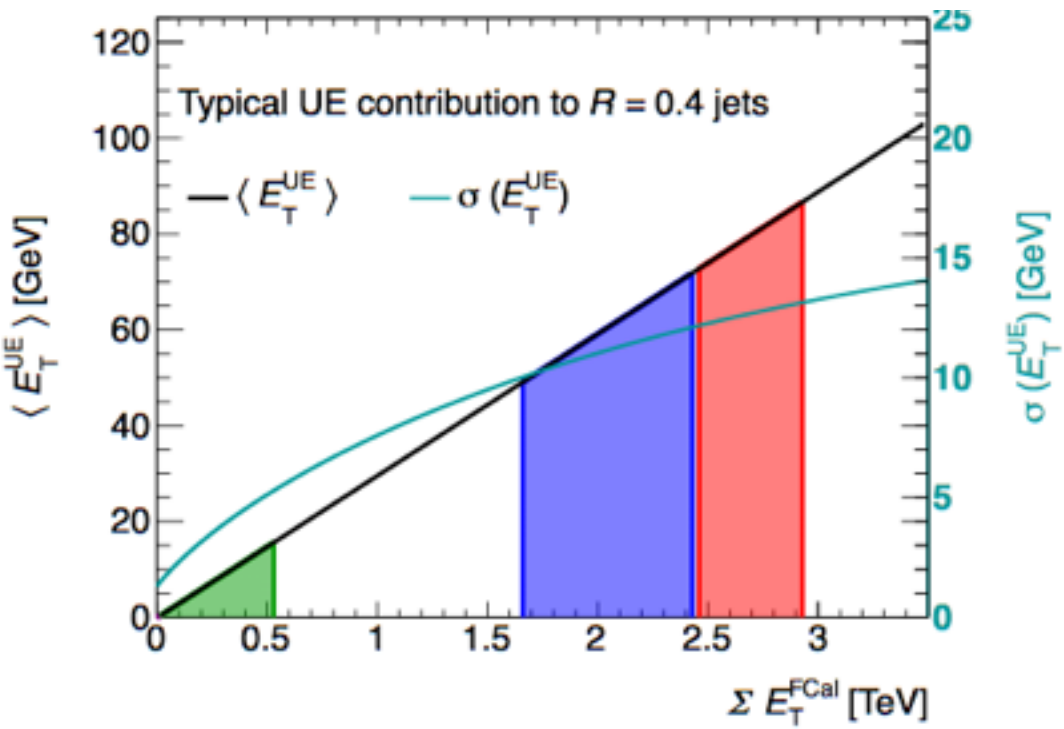
Summary

- See stronger quenching effects in kinematic regions where they are expected from underlying flavor fractions
  - Aspects of this puzzle (e.g. R_{AA}) already well described by theoretical calculations
- Needs full theoretical treatment to sort this out
  - Can be improved using new experimental results
    - Updated NPDF input from LHC measurements
    - Comparisons to unfolded x_J distributions ⇒ additional benchmark
- Flavor just one way of selecting jets with different parton showers
  - Measuring quenching observables for jets tagged by substructure properties could also address this
  - Multi-jets and observables sensitive to color flow also promising
  - Both get at role of decoherence in energy loss
- See geometric dependence consistent w/ L^2 path length dependence
  - Can we see deviations in Run 2?

Extras

Key Experimental Challenge: Jet Response





Jet energy scale (JES):

shift in mean response

Jet energy resolution (JER):

width of response distribution

Receive contributions both from UE and from detector

JES/JER convenient measures of response

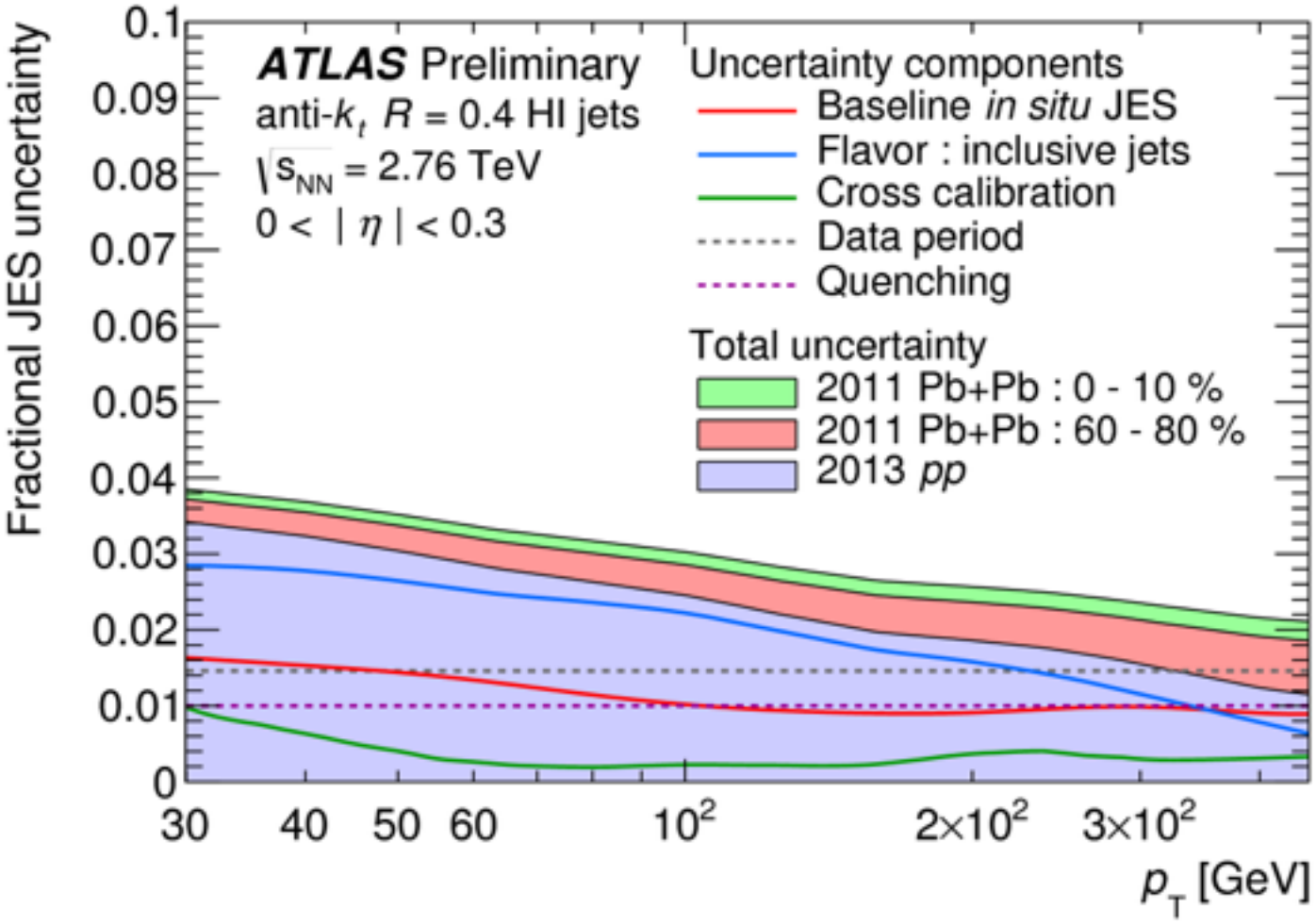
How well known they are often dominant systematic

In ATLAS use "data overlay" generator jets embedded in real HI events

UE contributions to jets described ~exactly

Key Experimental Challenge: Jet Response

Determine JES uncertainty on MC response through data-driven studies (*in situ* contribution)



"Data period" uncertainty **arises from fact that *pp* an Pb+Pb data taken in different years and calorimeter response may have changed**

Will not be present in run 2 since *pp* reference run was taken ~concurrently !

Residual contributions from fact that response is different for quark and gluon jets and may be different for quenched jets