Lecture 4: Jet measurements in heavy ion collisions

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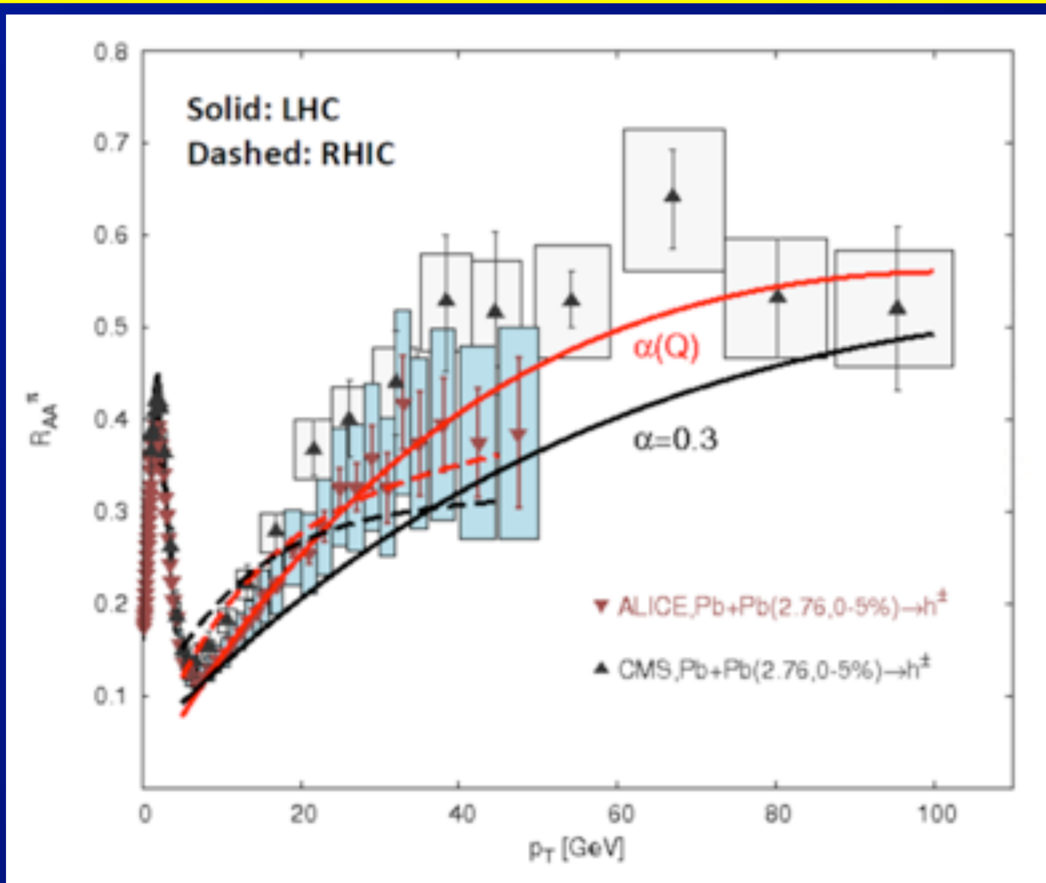
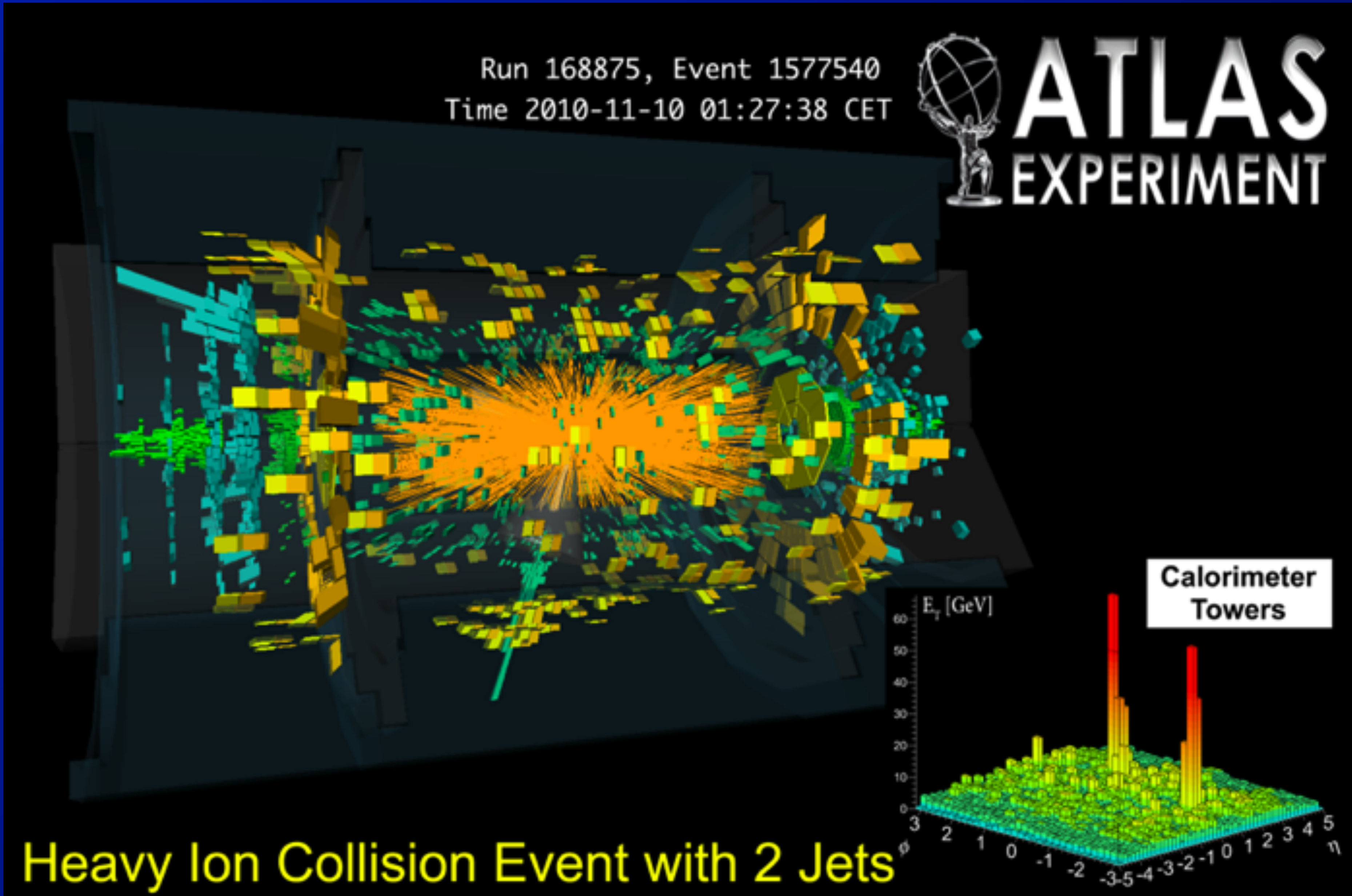
Single hadrons, theory

- Rapid variation in hadron R_{AA} with p_T
  - Expected, but not (easily) seen at RHIC
- But, rapid rise, saturation(?) seen in data
  - In one energy loss calculation (GLV) needs running coupling

    ⇒Which should have been there all along, but theoretically still uncertain

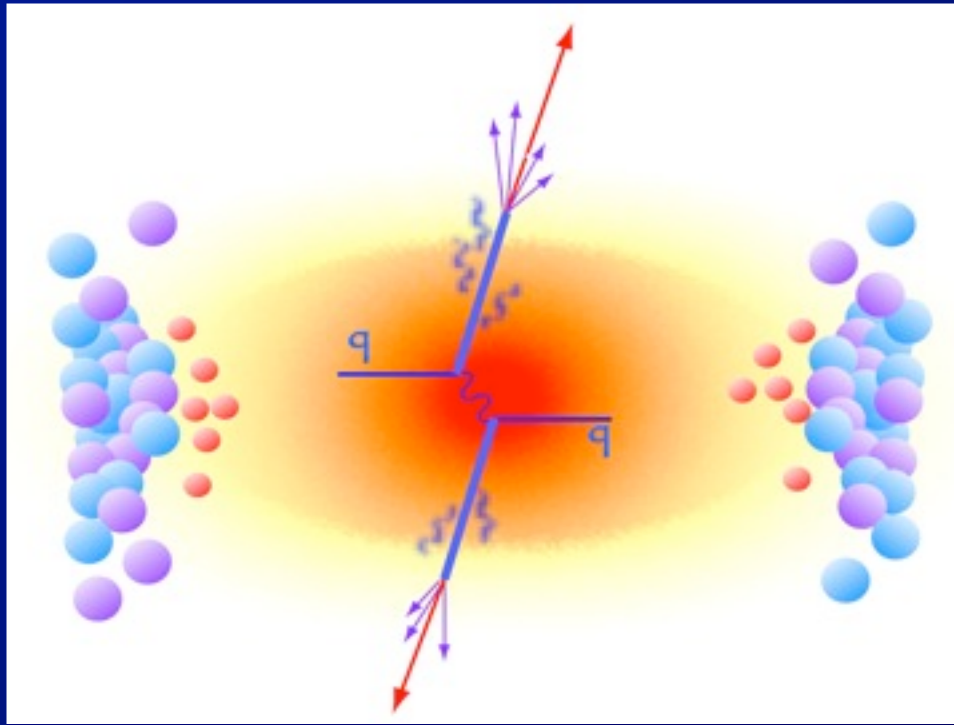


Jet measurements at the LHC



Jet probes of the quark gluon plasma

- Use jets from hard scattering processes to directly probe the quark gluon plasma (QGP)

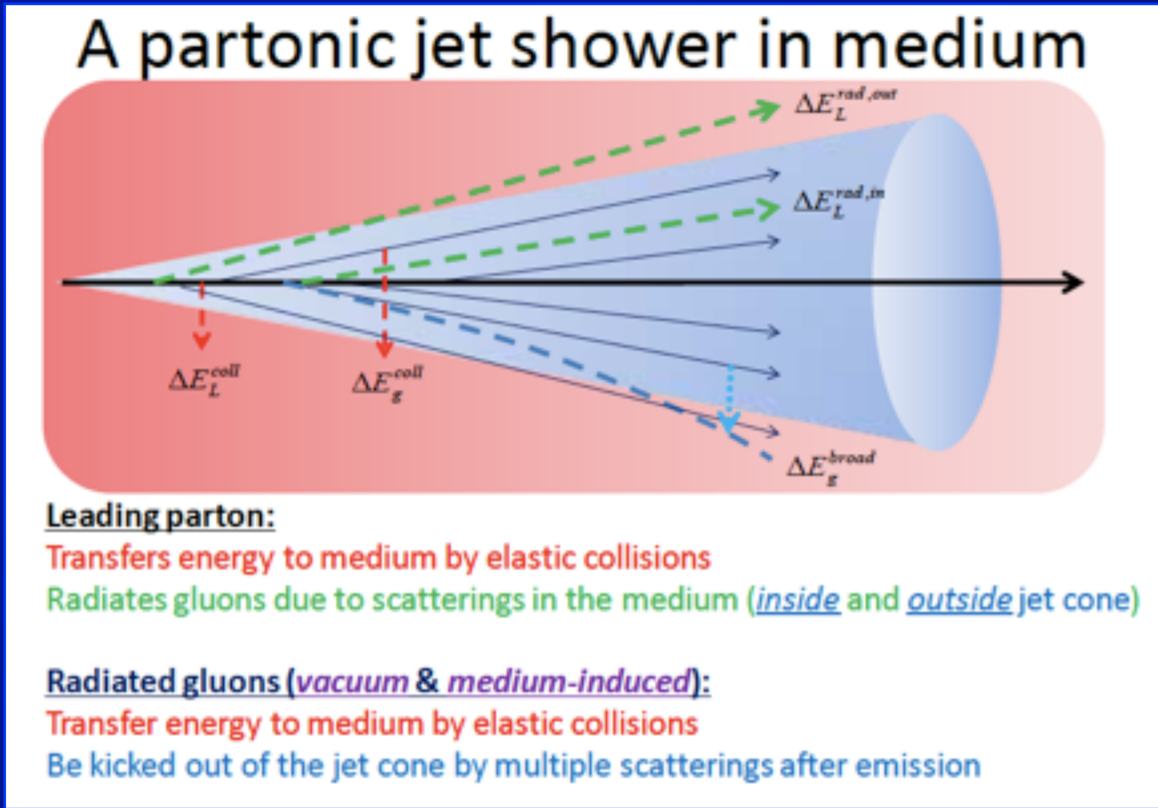


- Key experimental question:
  - ⇒How do parton showers in quark gluon plasma differ from those in vacuum?
- Use vector bosons -- for which the QGP is transparent -- to calibrate hard scattering rates in Pb+Pb collisions.

Jet probes of the quark gluon plasma (2)

Jet - QGP interactions schematically

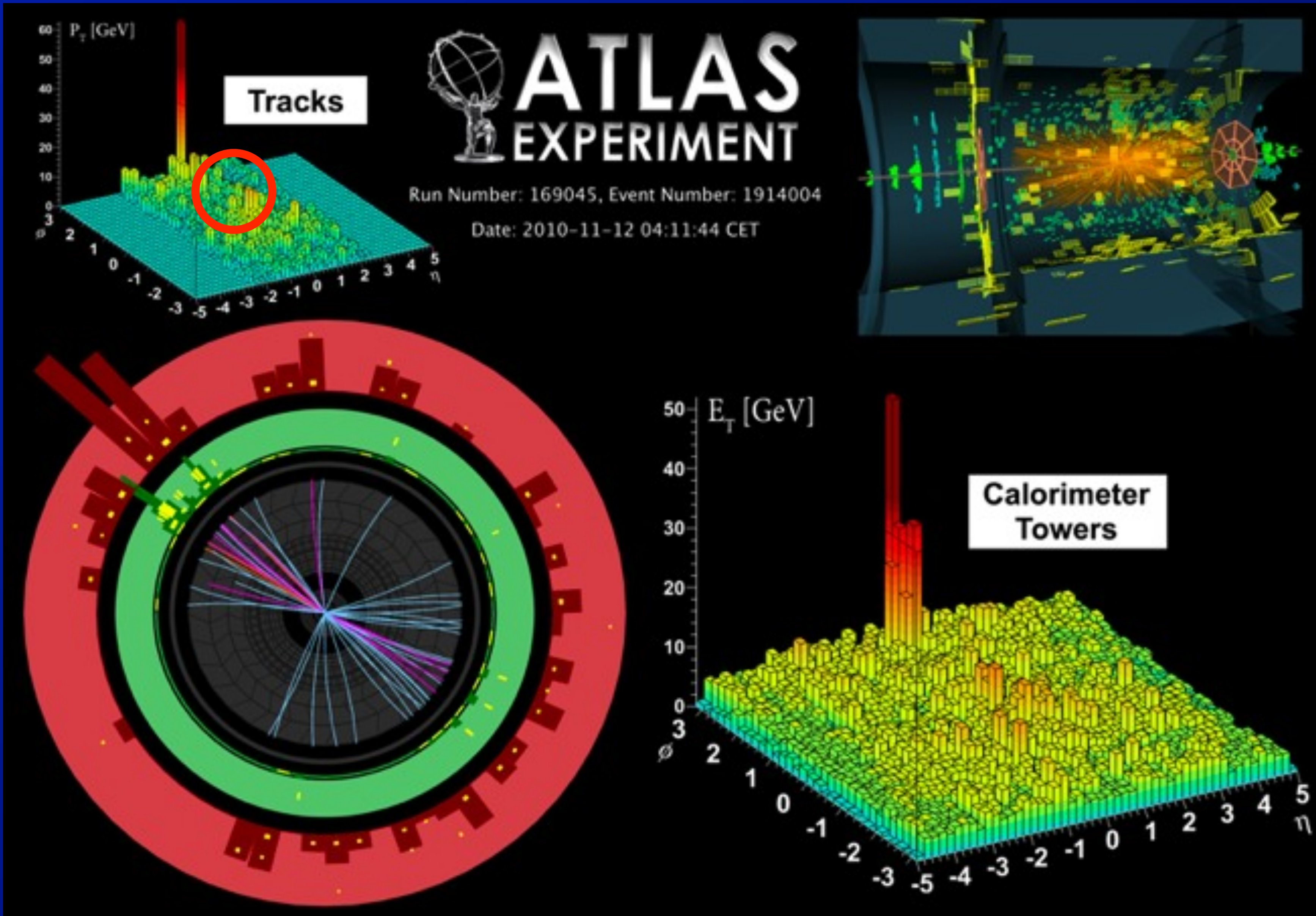
From Quark Matter 2011 talk by B. Muller



- QGP can modify jets in multiple ways:
  1. Collisional energy loss (analog of Bethe-Bloch)
  2. Radiative energy loss (enhanced splitting)
  3. Broadening of parton shower

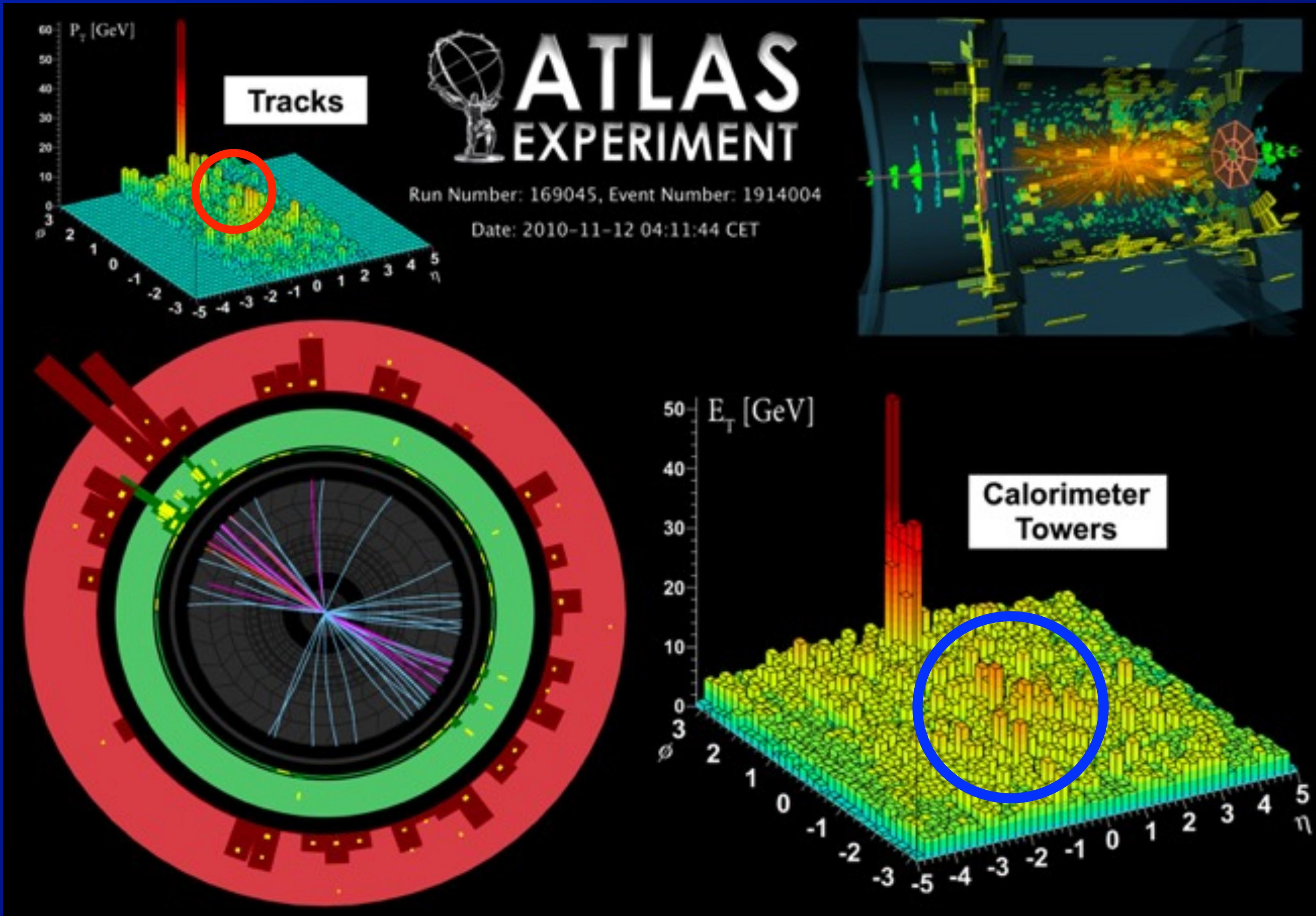
  $\Rightarrow$ 2 & 3 will depend on jet radius

An example Pb+Pb jet event



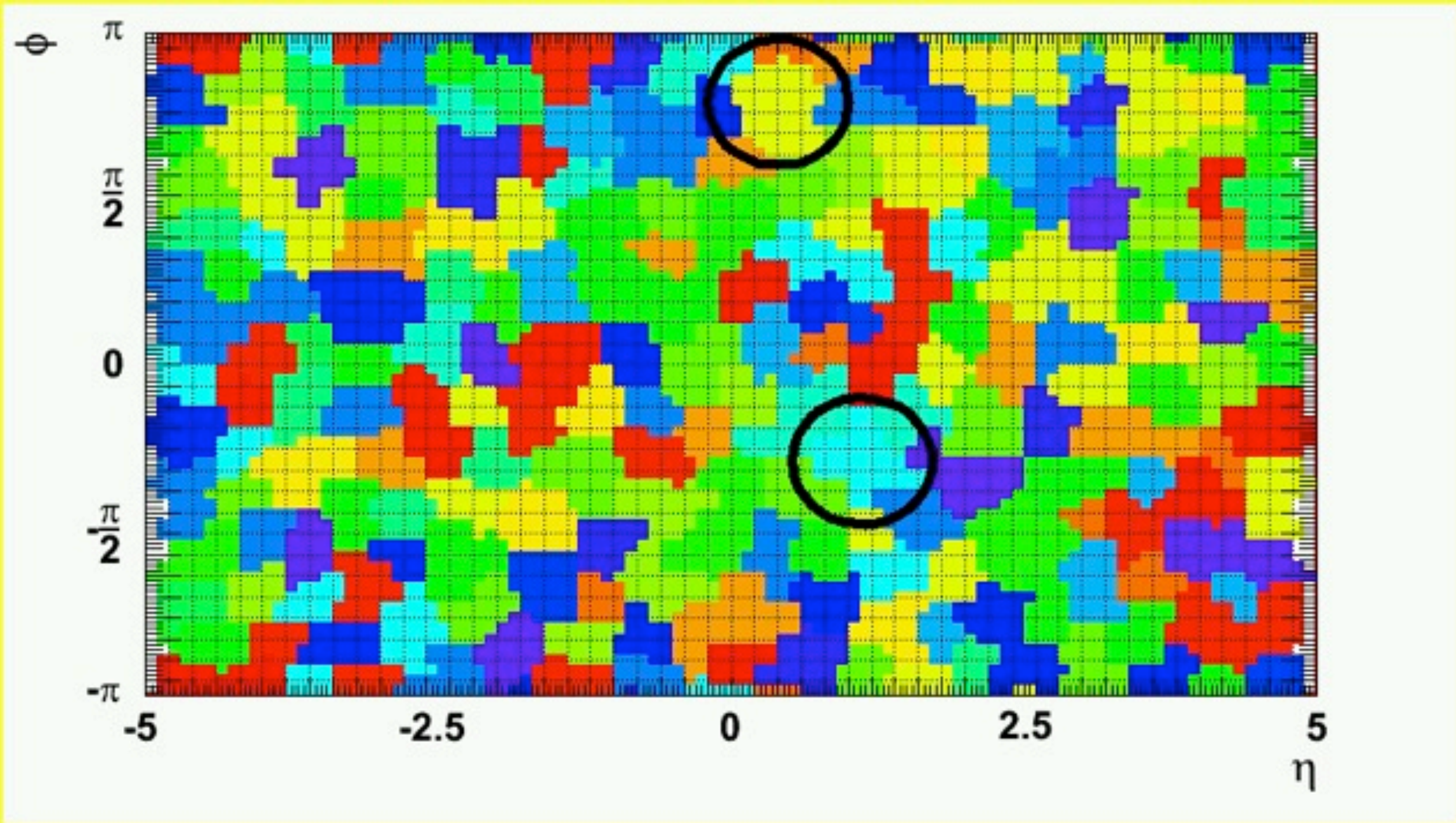
Even more central collision, more asymmetric dijet

An example Pb+Pb jet event



Even more central collision, more asymmetric dijet

The starting point



- Reconstruct (unsubtracted) Pb+Pb event
  - Here, for demonstration, with k_t algorithm
    - ⇒But the kt algorithm is problematic because the background jets "eat" edges of real jets

The underlying event

- ~ universal starting point for UE subtraction
  - $E_{\mathrm{T}}^{\mathrm{subtr}} = E_{\mathrm{T}}^{\mathrm{unsubtr}} - \rho A$

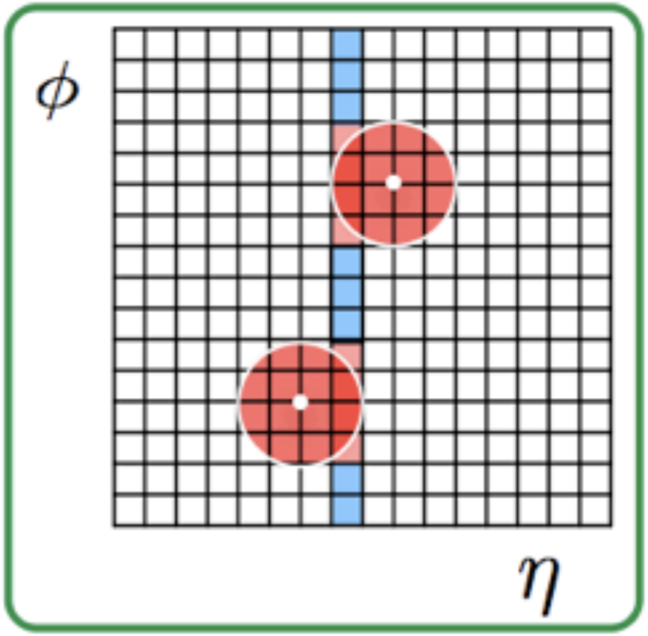
    ➡ But the details are critical
- Important considerations:
  - What kind of objects is subtraction applied to?

    ➡ Towers, topoclusters, cells, ...
  - How to estimate UE energy density, ρ ?
  - With what granularity?
  - Event -by-event or event-averaged?

    ➡ But if averaged, need separate measure of μ
  - How to exclude jets, photons, ... from ρ ?

The underlying event (ATLAS)

$$\rho(\eta) = \left\langle \frac{E_{\mathrm{T}}^{i}}{\Delta\eta^{i}\Delta\phi^{i}} \right\rangle_{i \notin \mathrm{jet},\, |\eta^{i}-\eta|<0.05}$$



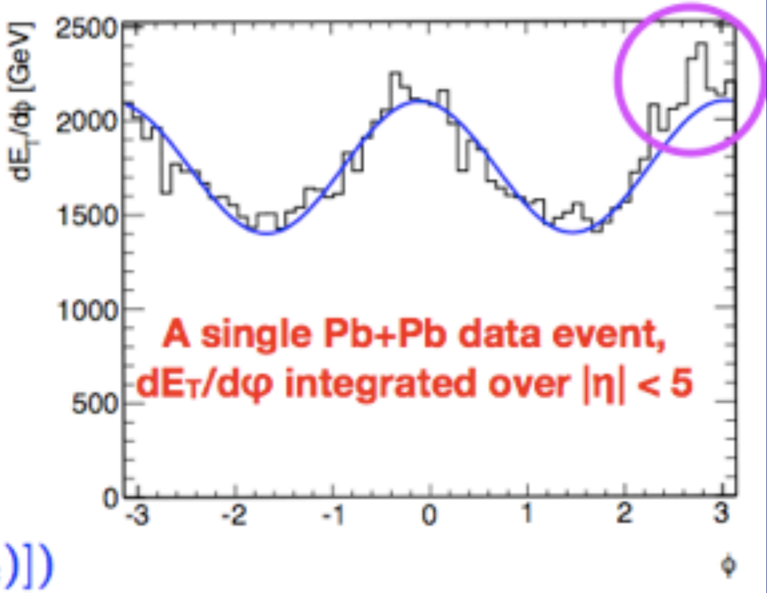
- For each Pb+Pb event:
  - For each calorimeter layer:
    - ➡ Calculate an AVERAGE (not median!) cell E_T density in $\Delta\eta = 0.1$ intervals
    - ➡ Excluding cells that lie within $\Delta R = 0.4$ of seeds
- Then, apply $E_{\mathrm{T}}^{\mathrm{subtr}} = E_{\mathrm{T}}^{\mathrm{unsubtr}} - \rho A$ to each cell within tower constituents of reconstructed jets

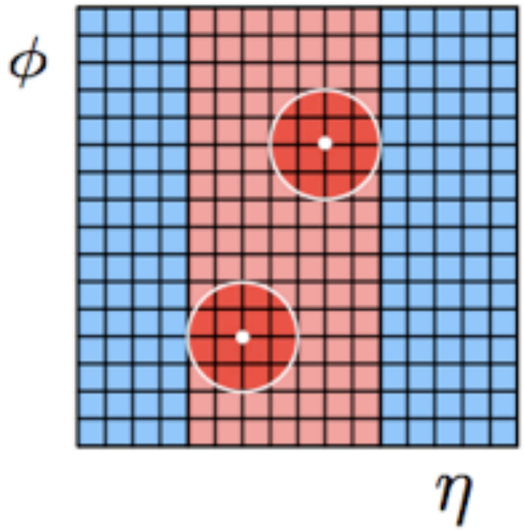
The underlying event (ATLAS)

- Pb+Pb collisions present additional complications
  - collective flow in the UE
    - ➡ as large as ± 20%
    - ➡ fluctuates event to event
- Accounted for in subtraction
  - $\rho^{\mathrm{Pb+Pb}}(\eta, \phi) = \rho(\eta)(1 + 2v_2^{\mathrm{UE}} \cos[2(\phi - \Psi_2)])$
- With amplitude of modulation (v_2) determined event-by-event

$$v_2^{\mathrm{UE}} = \langle E_{\mathrm{T}}^i \cos[2(\phi^i - \Psi_2)] \rangle_{i \notin \mathrm{jet}}$$

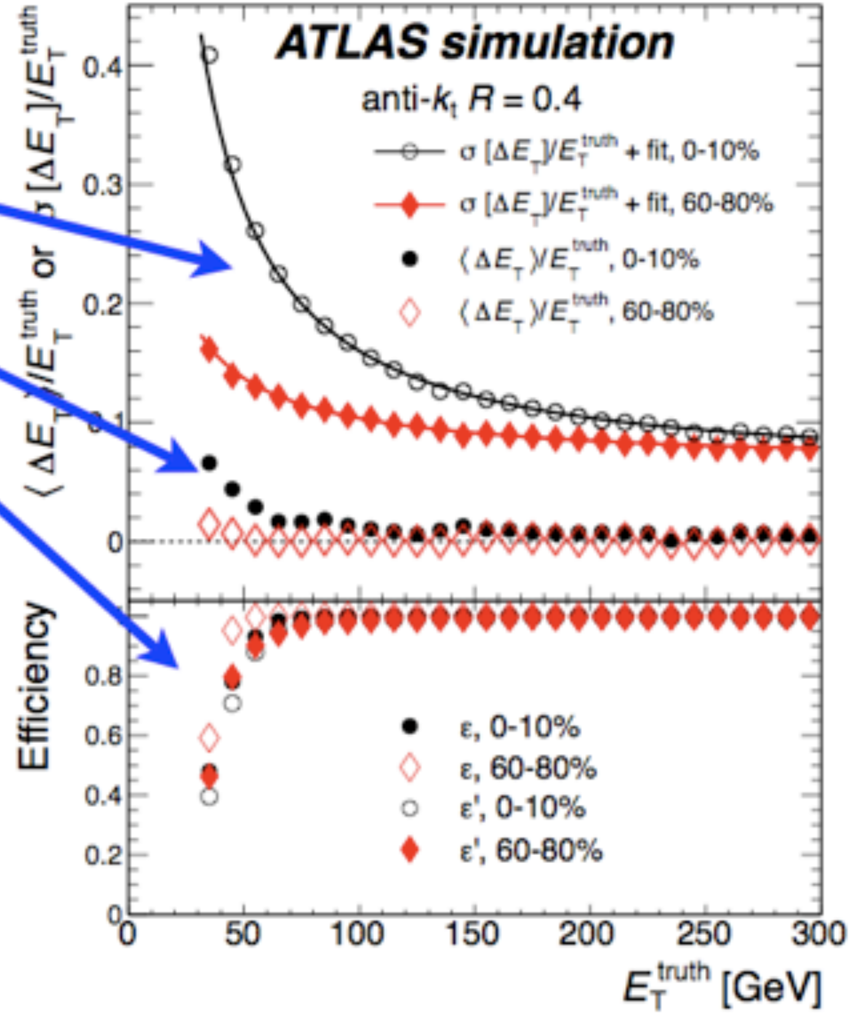
➡ excluding any η interval containing a seed





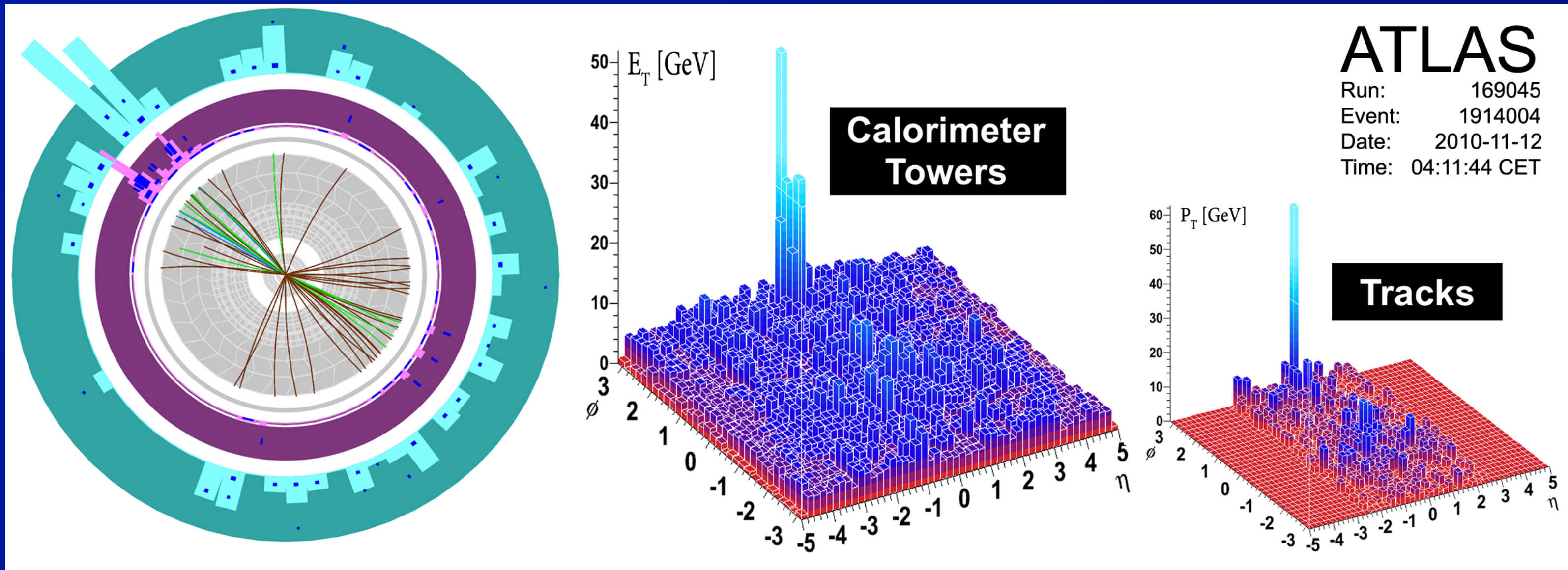
ATLAS jet performance

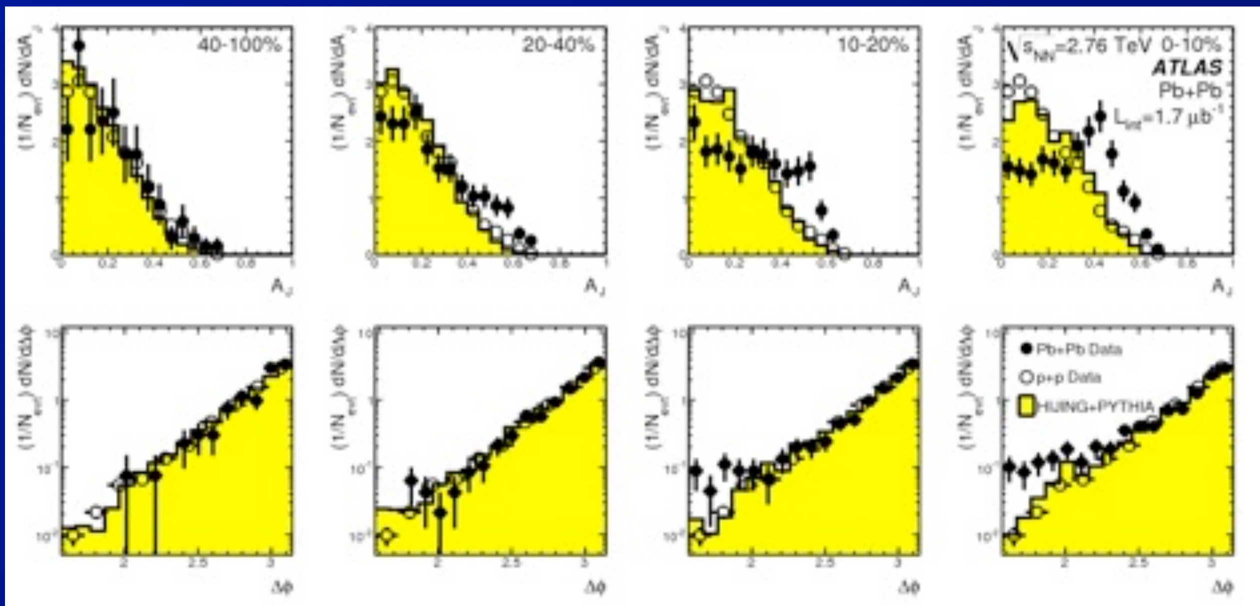
- Three metrics
  - Jet energy resolution
  - Jet energy scale
  - Jet reconstruction efficiency
    - ➡ with (ε') and without (ε) fake rejection
- Of these, we only have control over JES
  - ➡ Sensitive test of background subtraction



- Jet is considered not fake if within R = 0.2:
  - R = 0.4 track jet (rec. from tracks w/ p_T > 4 GeV), photon, or electron with p_T > 7 GeV

ATLAS dijet asymmetry measurement





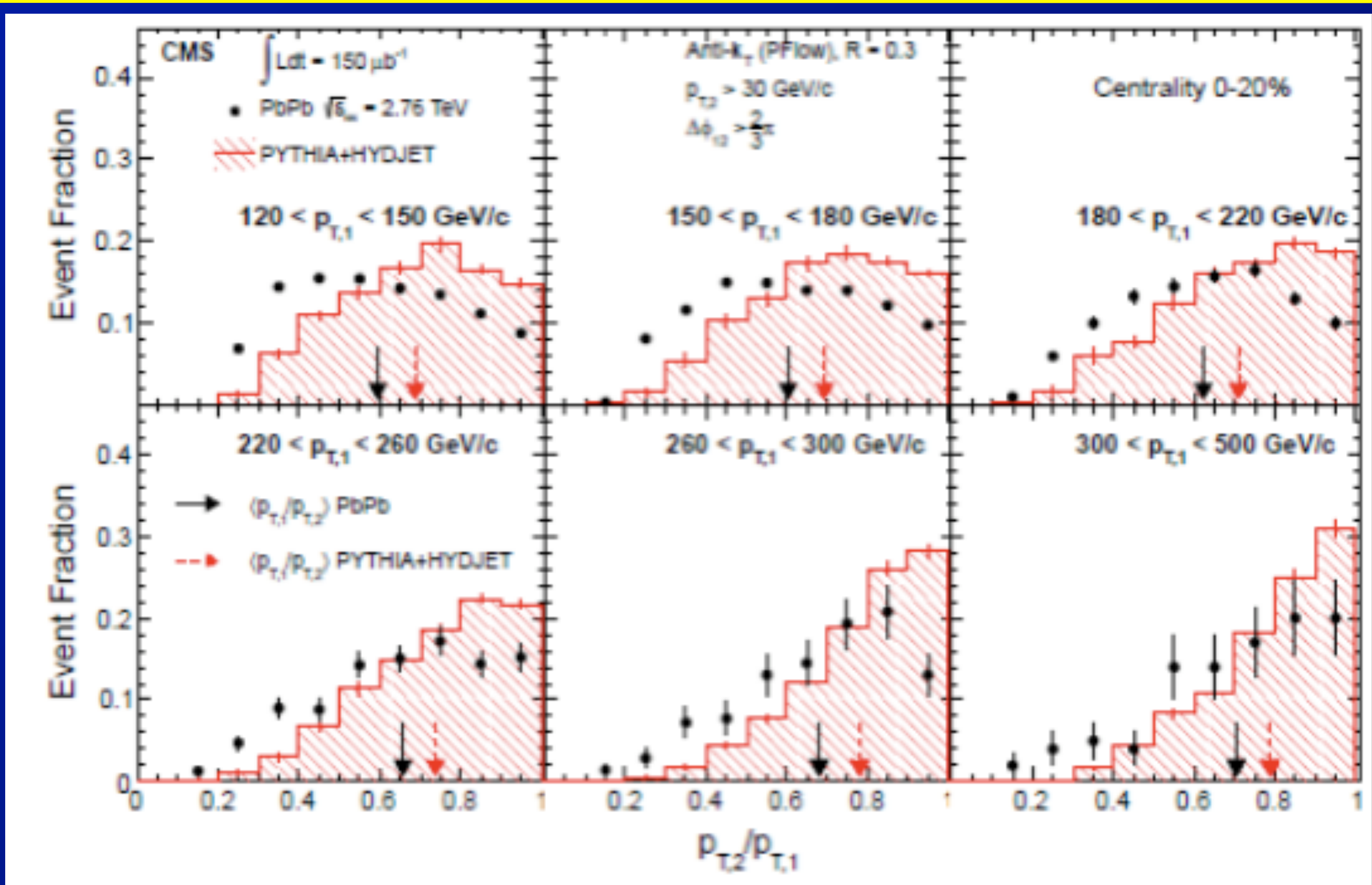
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

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

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

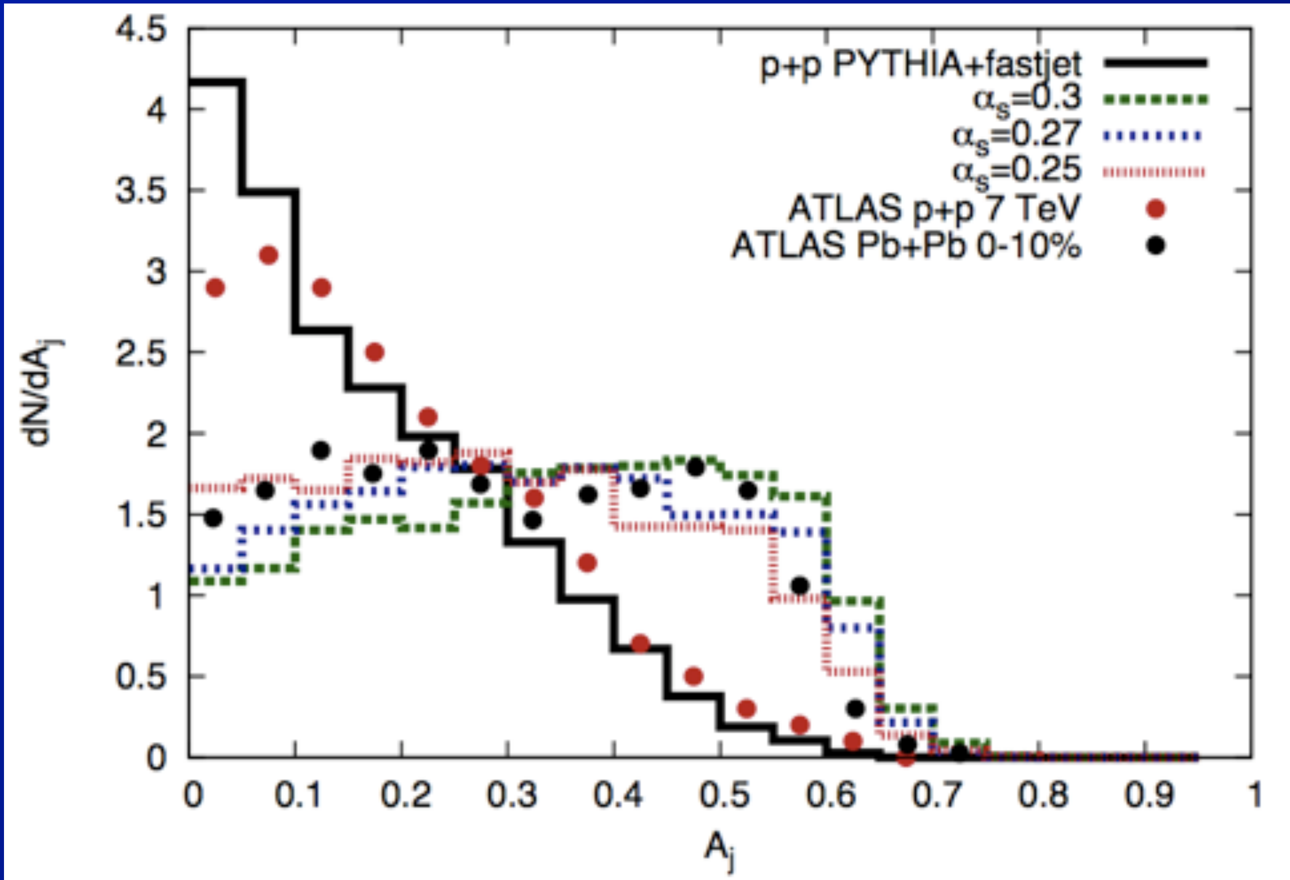
1st indication of medium modifications of jets @ LHC

Dijets: CMS 2011 data



- Clear demonstration that the effects of differential quenching extend to high p_T
  - what is role of jet flavor (quark, gluon, heavy)?
    - ⇒In particular, gg vs qg.

Dijet asymmetry: Theory comparisons



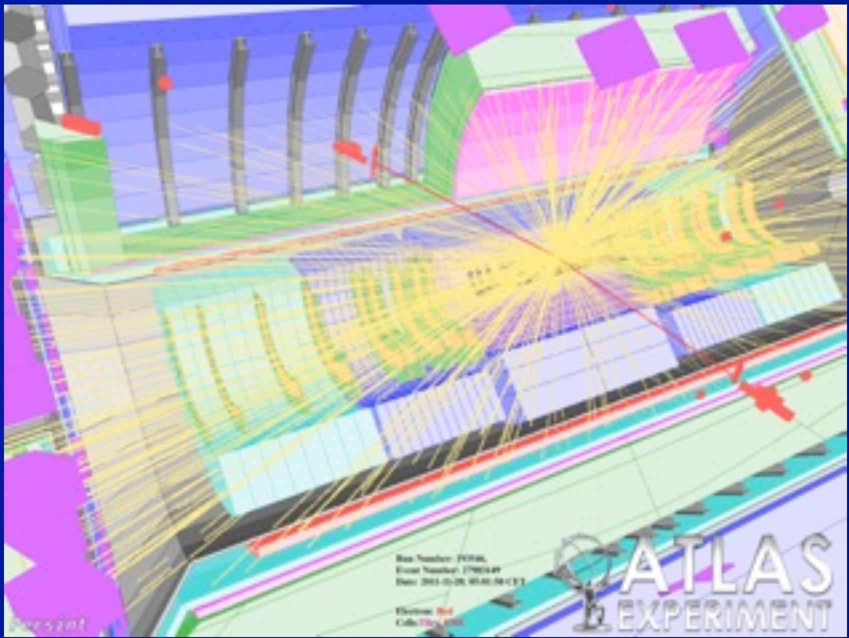
Young et al, arXiv 1103.5769 [nucl-th]

AMY energy loss formalism

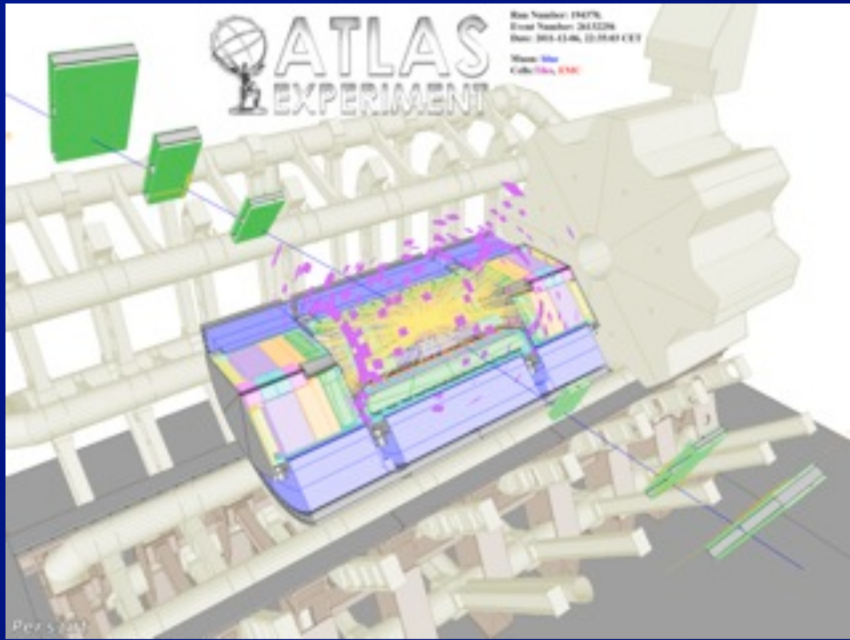
- AMY energy loss with 1 free parameter (α_s)
  - Good description of modified asymmetry distribution
    - ⇒Decisive test of energy loss calculations
    - ⇒1st step towards quantitative probe of jet + sQGP interactions using jets

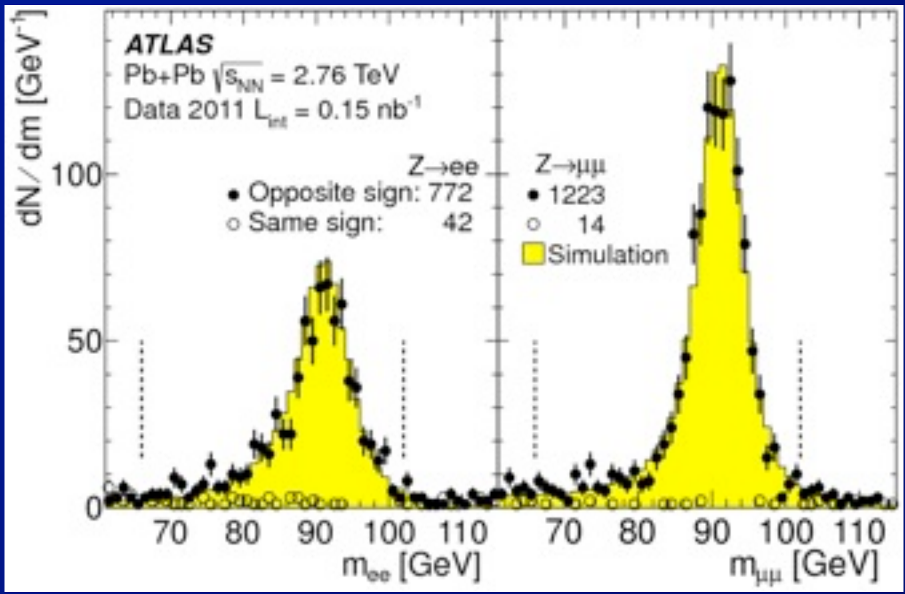
Hard scattering rate control: Z

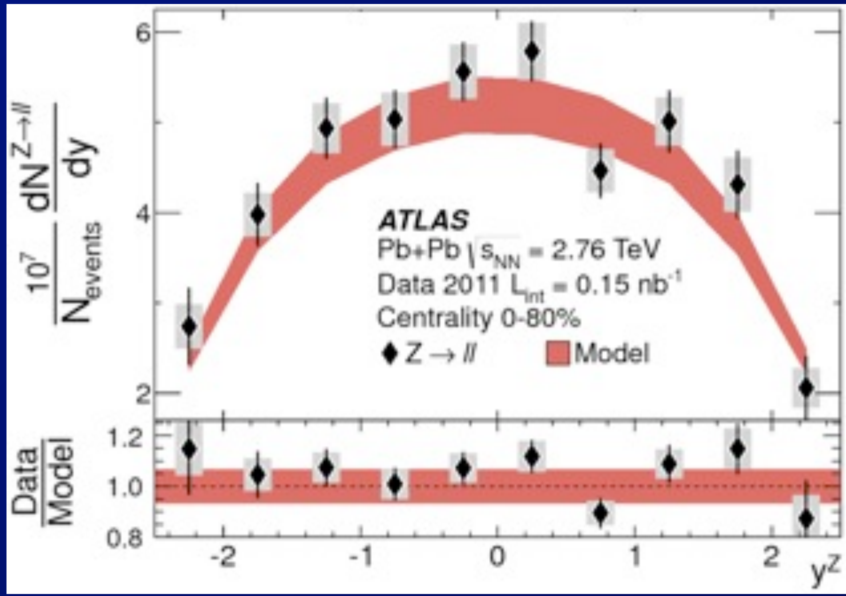
$Z \rightarrow e^+e^-$ event display



$Z \rightarrow \mu^+\mu^-$ event display

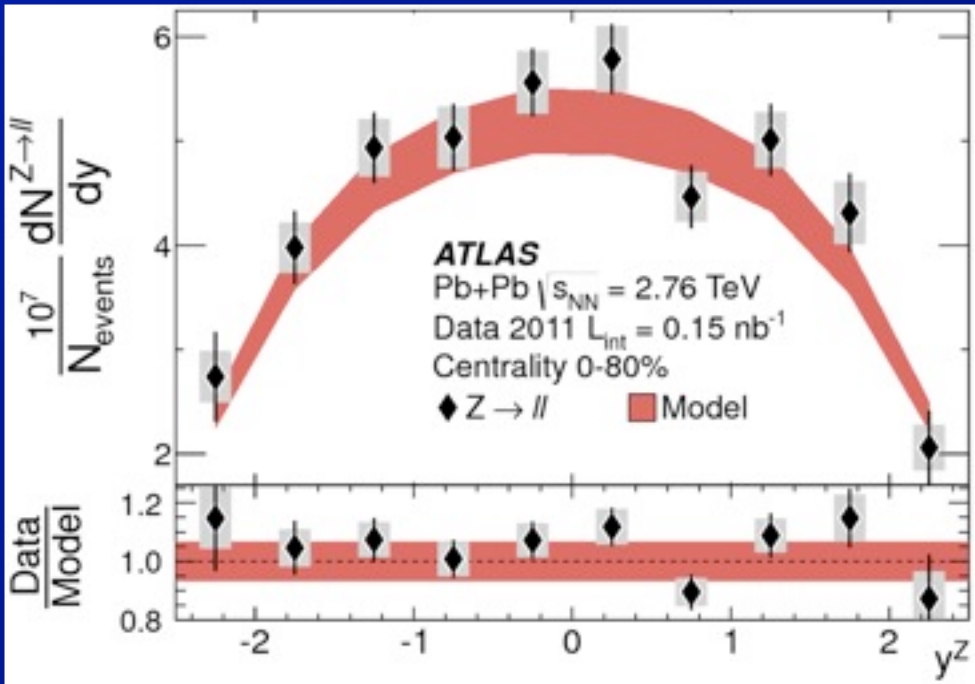


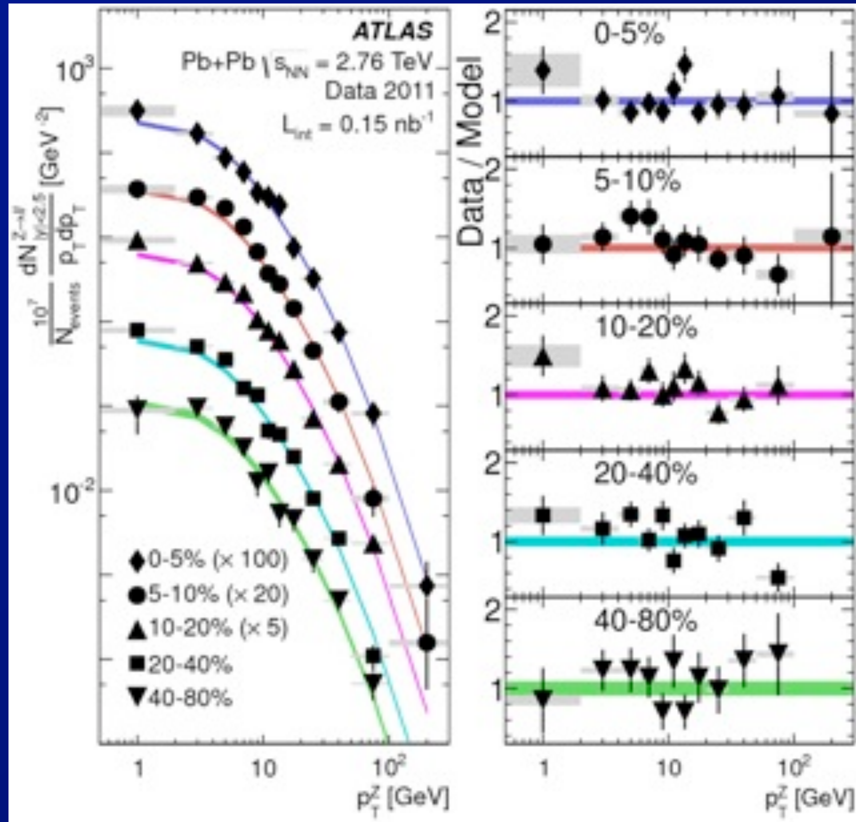




Hard scattering rate control: Z

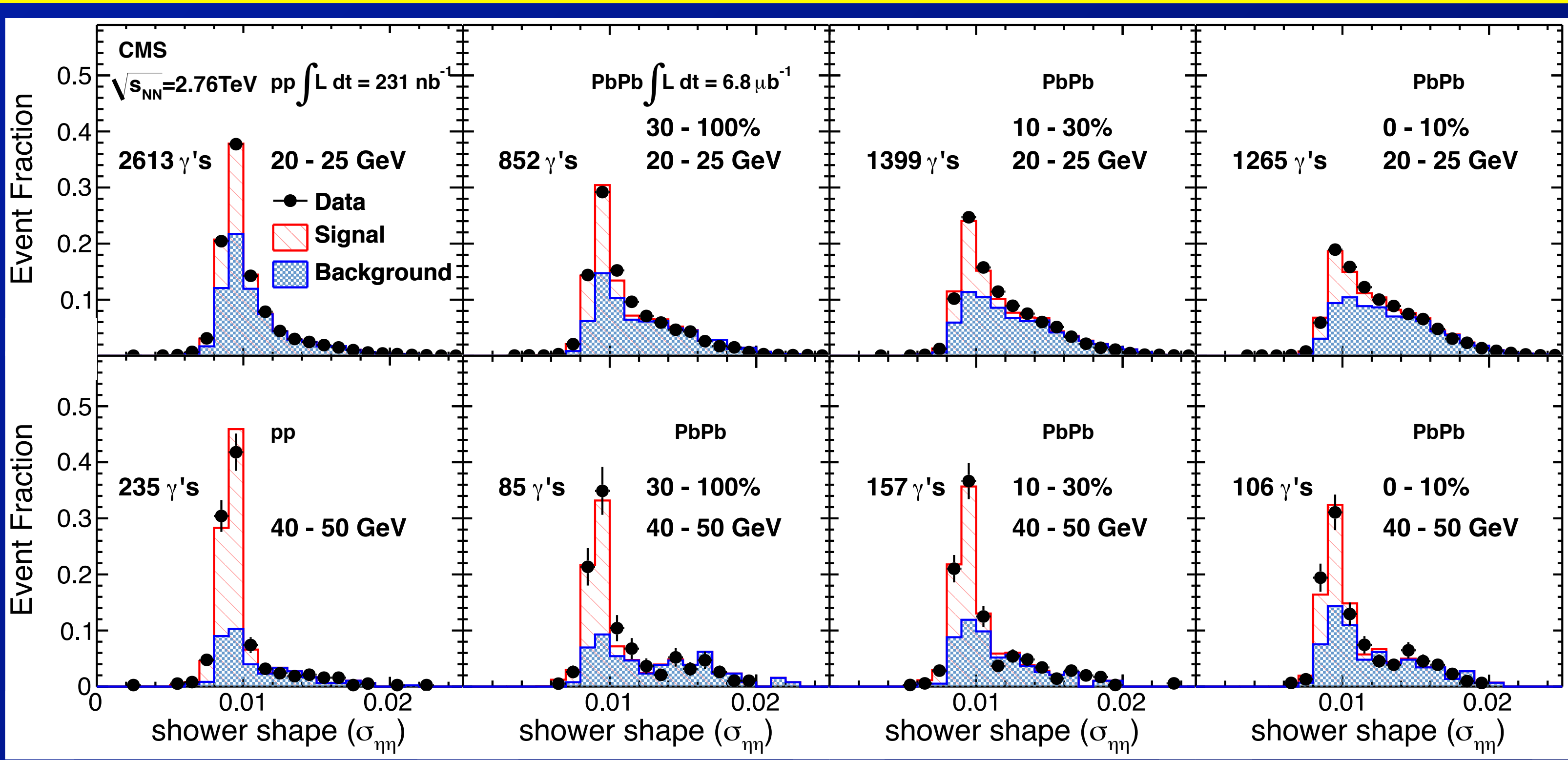
Phys. Rev. Lett. 110, 022301 (2013)





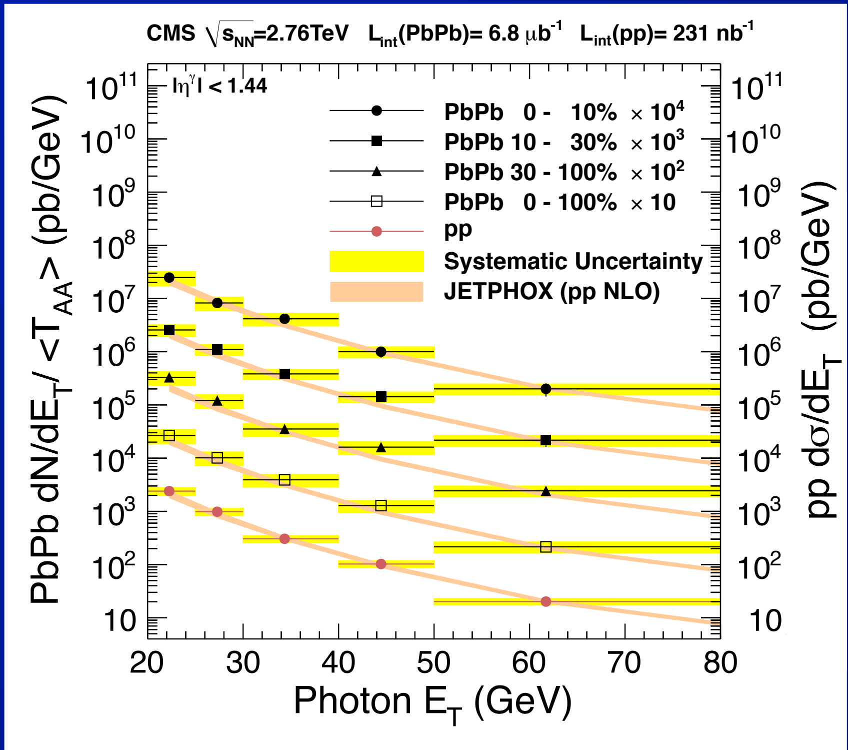
- Compare Pb+Pb Z rapidity distributions (minimum-bias) and p_T spectra to PYTHIA scaled to NNLO calculations
  - Pb+Pb Z production rates consistent with MC
    ⇒hard scattering rates under control

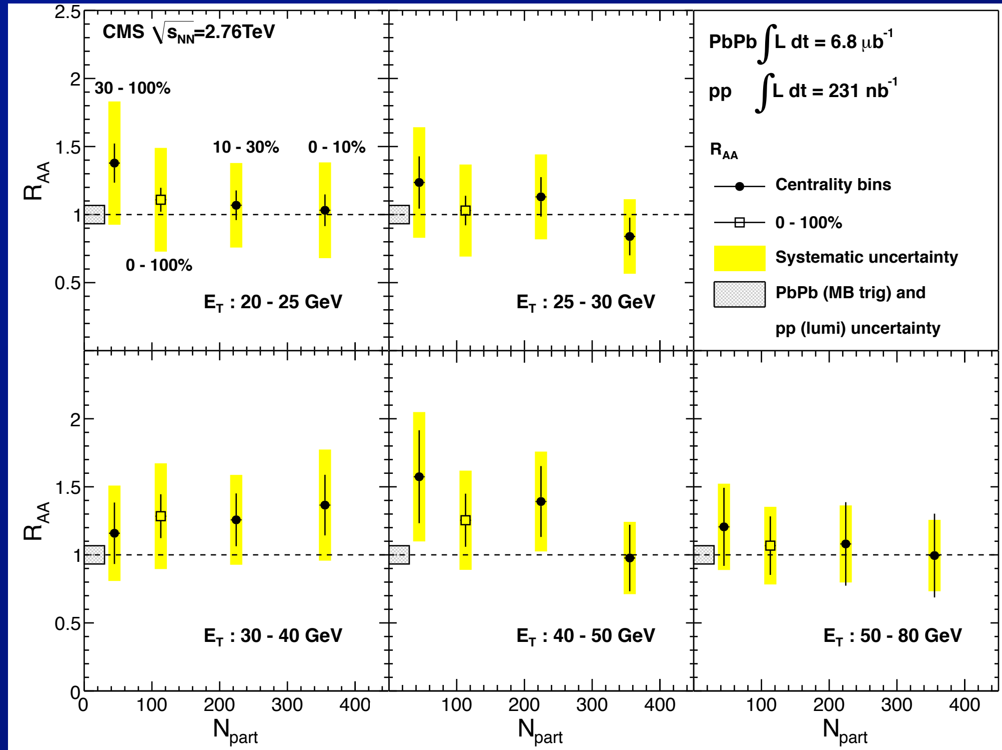
CMS: photon identification



- With high-energy calorimeters, cannot separate π^0, η decay photons
  - Instead, use the shape of the shower and isolation to separate photons from π^0, η
    - ⇒Very different analysis from PHENIX (e.g.)

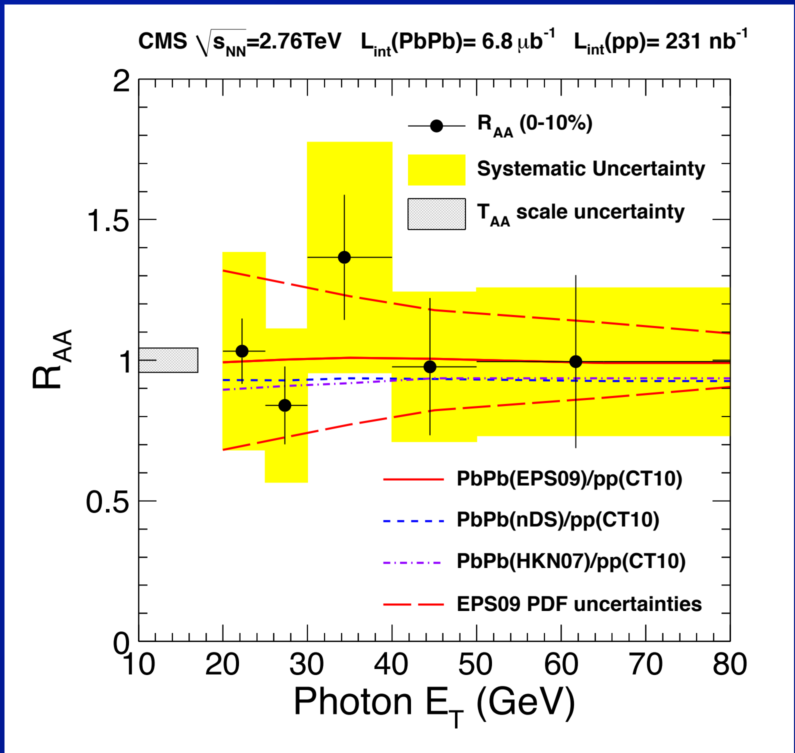
CMS: photon yields, R_{AA}

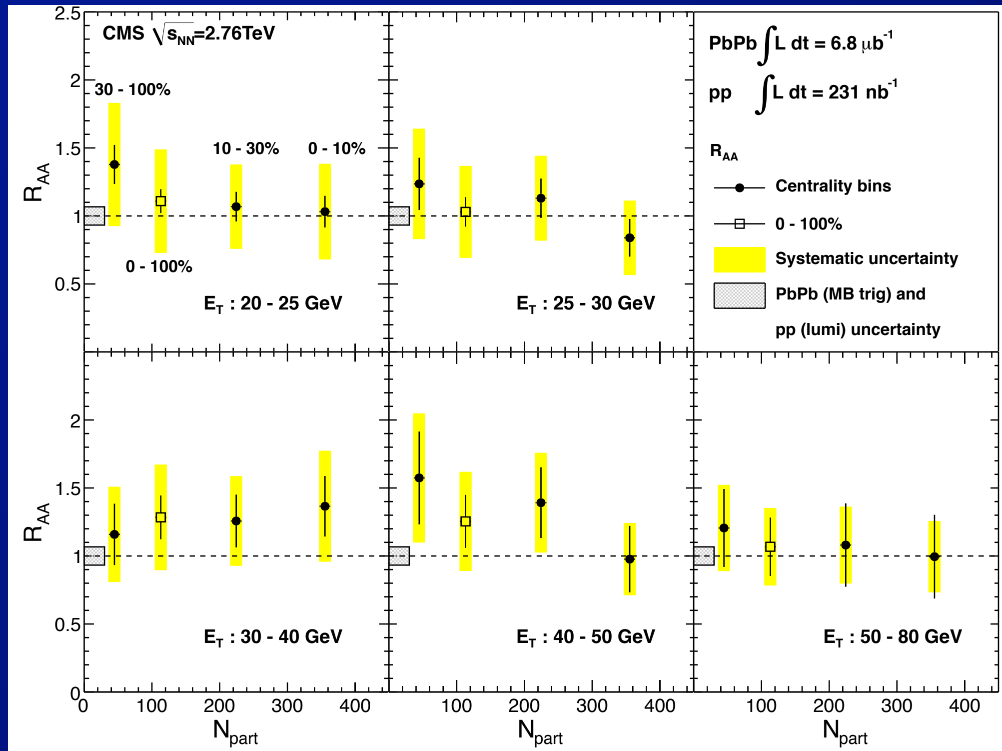




- **Left:**
  - comparison between p-p and Pb+Pb photon spectra and JETPHOX calculation
- **Right:**
  - photon R_{AA} -- consistent with 1

CMS: photon yields, R_{AA}



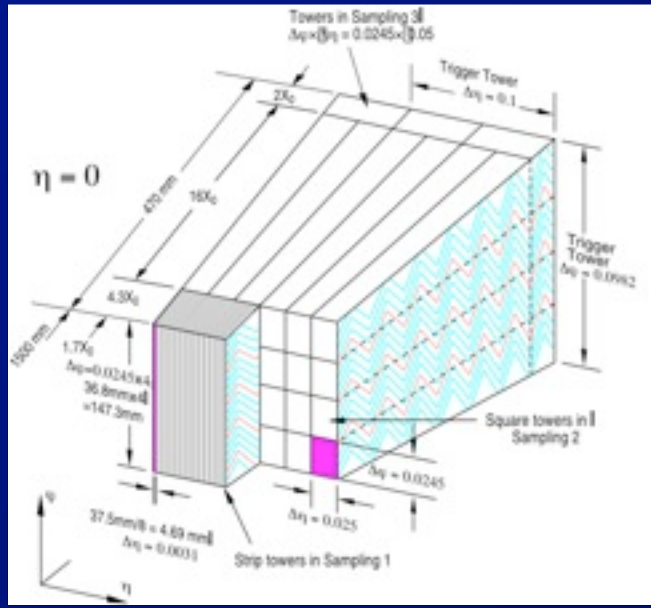


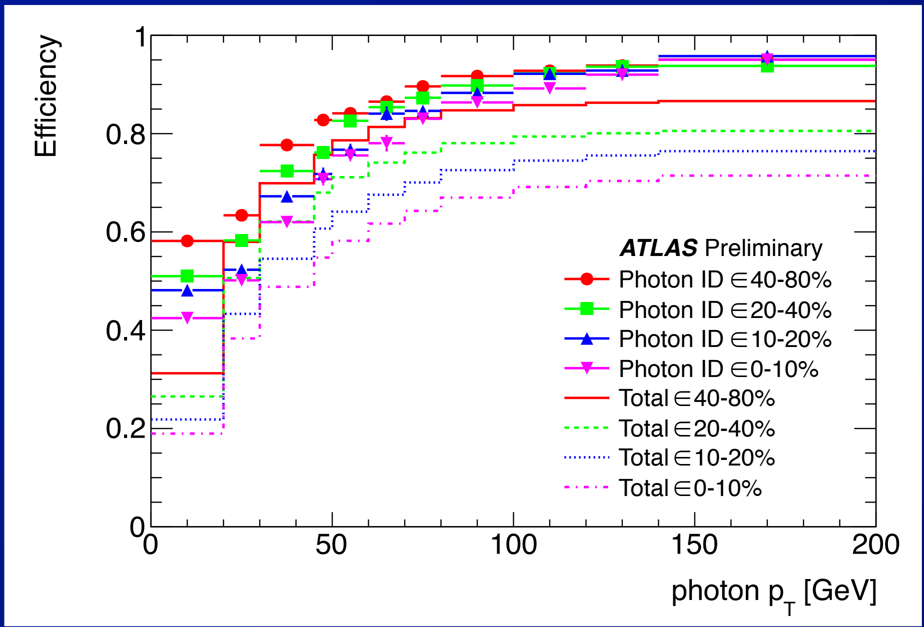
- **Left:**
  - Central R_{AA} with different pQCD calculations using different nuclear parton distributions
    ⇒ All nuclear PDF effects within systematics

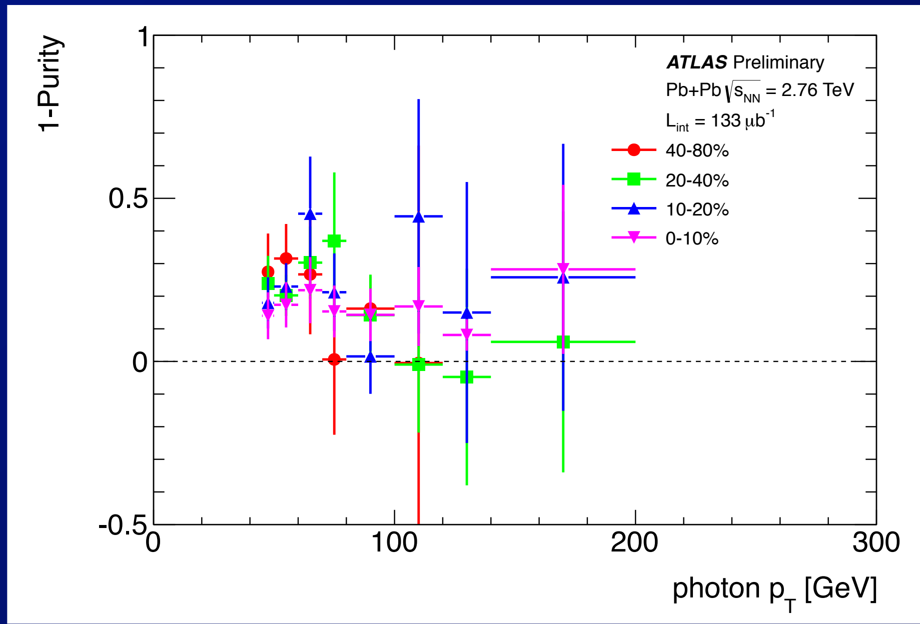
Prompt photon production

- Transverse segmentation of ATLAS EM calorimeter allows rejection of photons from π^0, η decay
- Also use isolation cuts

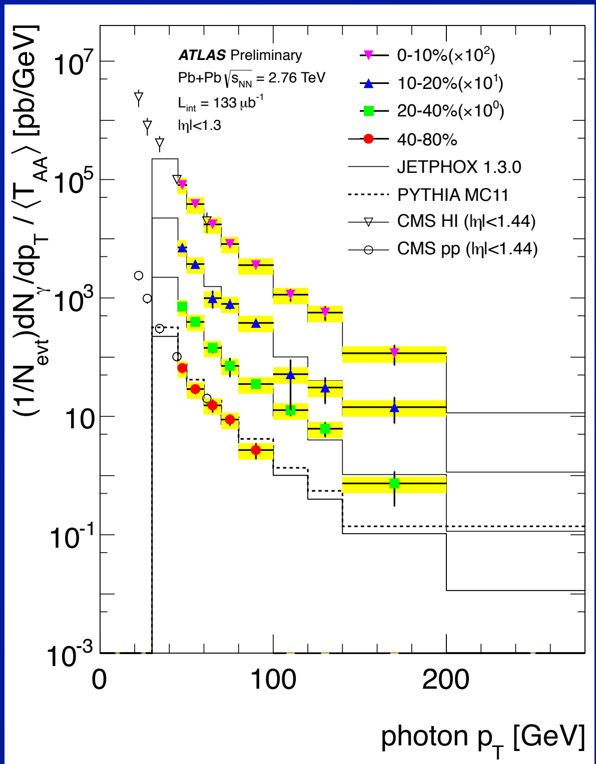
  $\Rightarrow$ Purity > 70%

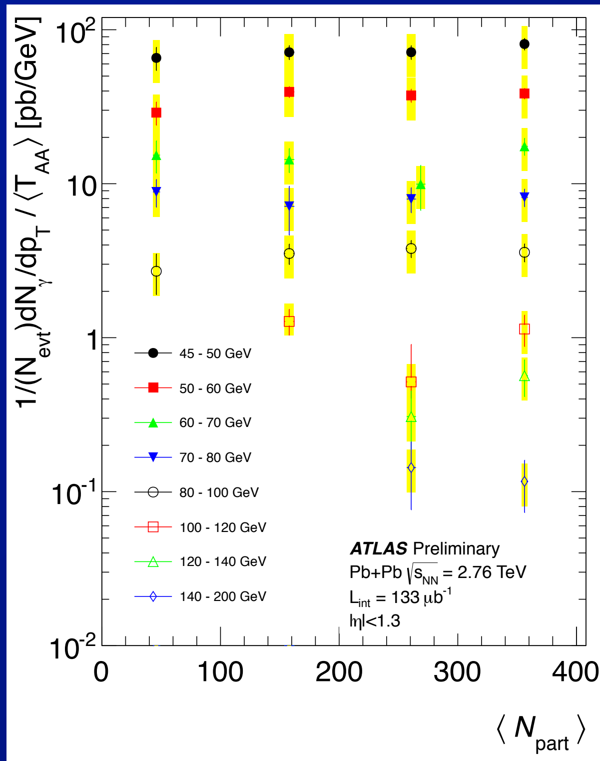


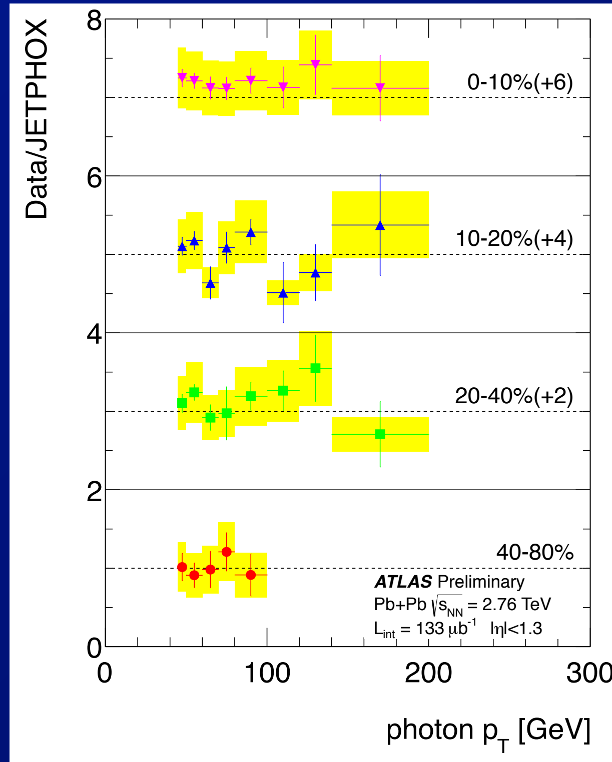




Prompt photon production (2)



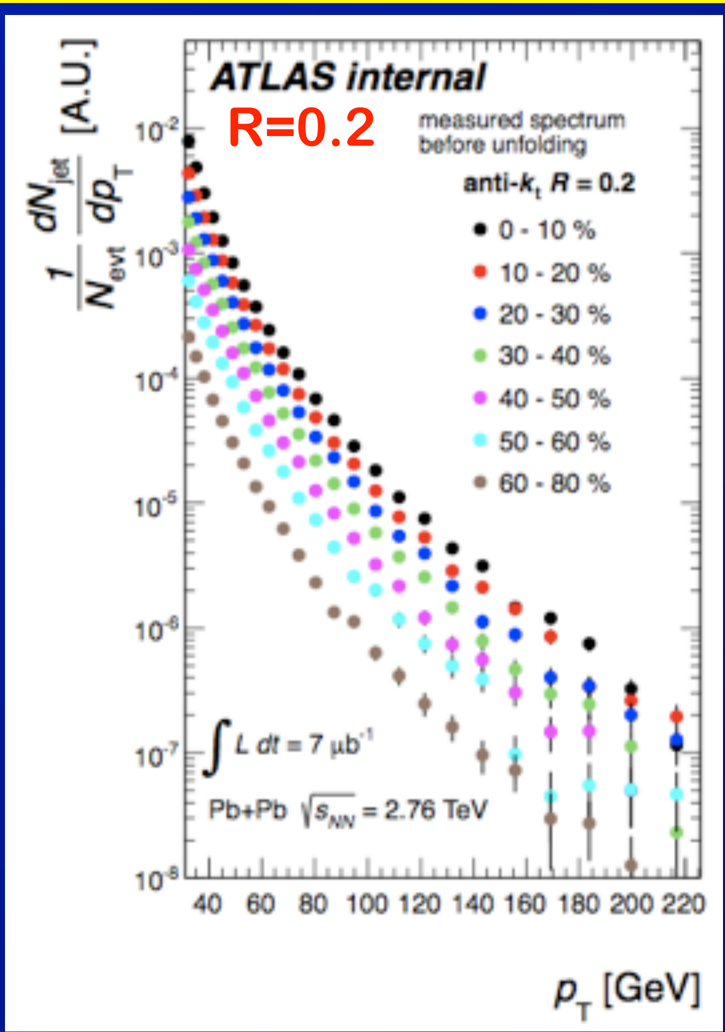


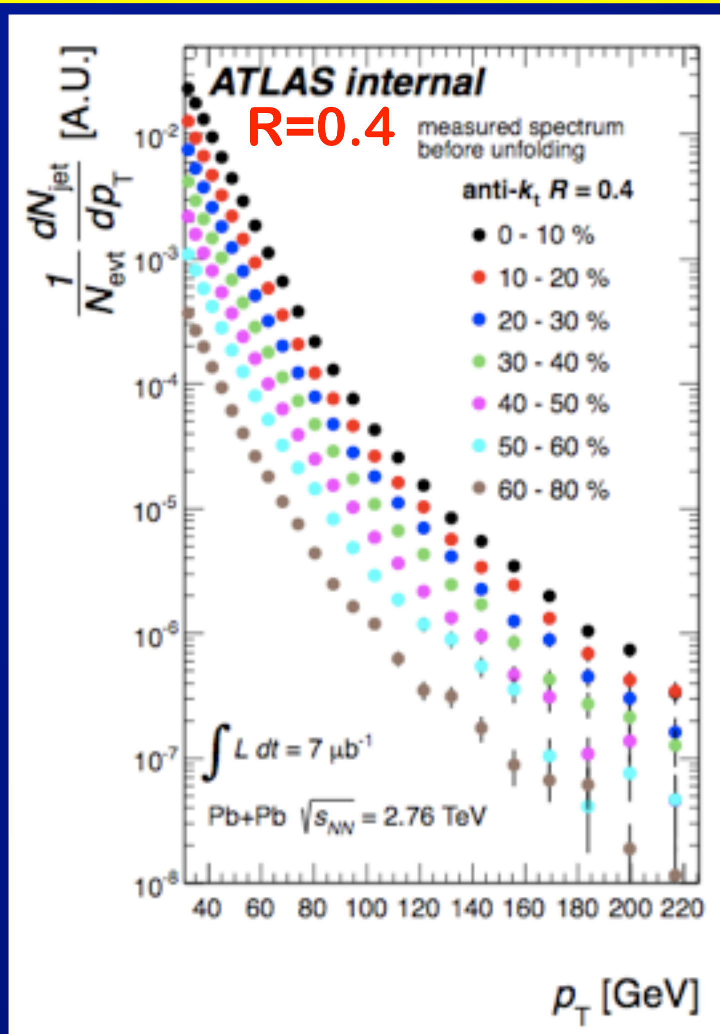


- Photon spectra over $40 < p_T < 200$ GeV
  - well described by JETPHOX multiplied by T_{AA}
  - Yield / T_{AA} ~ independent of centrality

⇒Hard QCD photon production varies with Pb+Pb centrality as expected

Pb+Pb Jet Spectra





Unfolded (SVD) and efficiency corrected

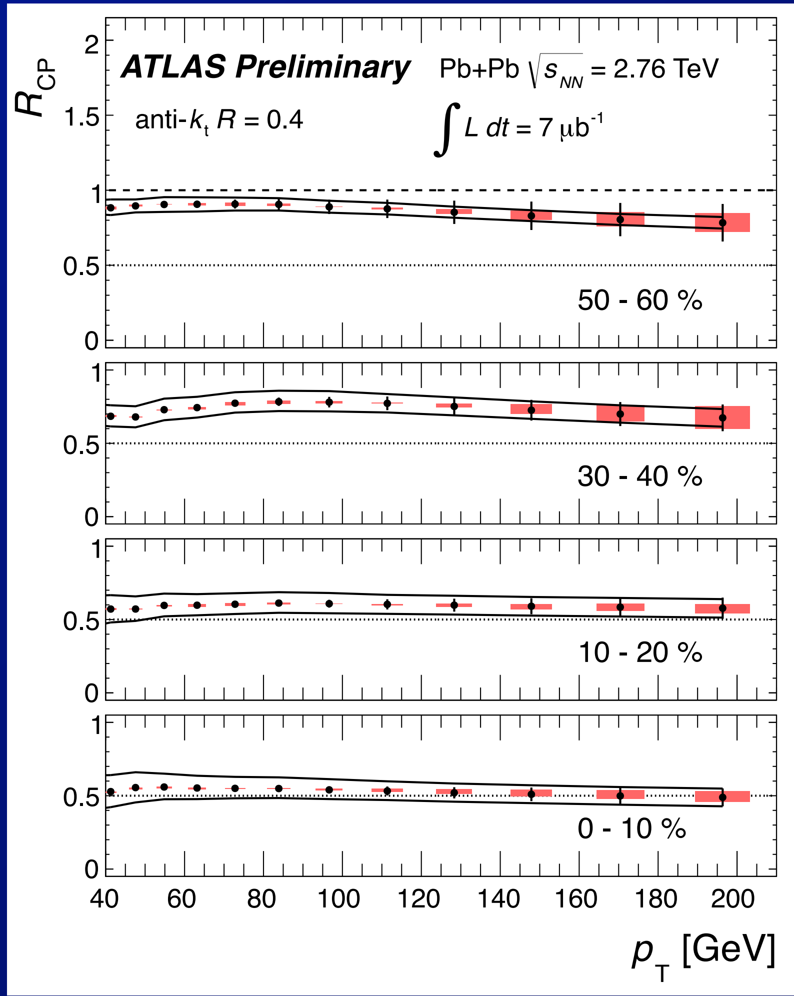
- For these results, no absolute normalization
  - awaiting absolute jet energy scale uncertainty

Jet yields: centrality dependence

- If factorization holds jet yields should vary with centrality ∝ N_{coll}
- Compare yields between centrality bins using "R_{cp}"

$$R_{CP} = \frac{\frac{1}{N_{coll}}\frac{1}{N_{evt}}\frac{dN}{dp_T}\Big|_{cent}}{\frac{1}{N_{coll}}\frac{1}{N_{evt}}\frac{dN}{dp_T}\Big|_{60-80}}$$

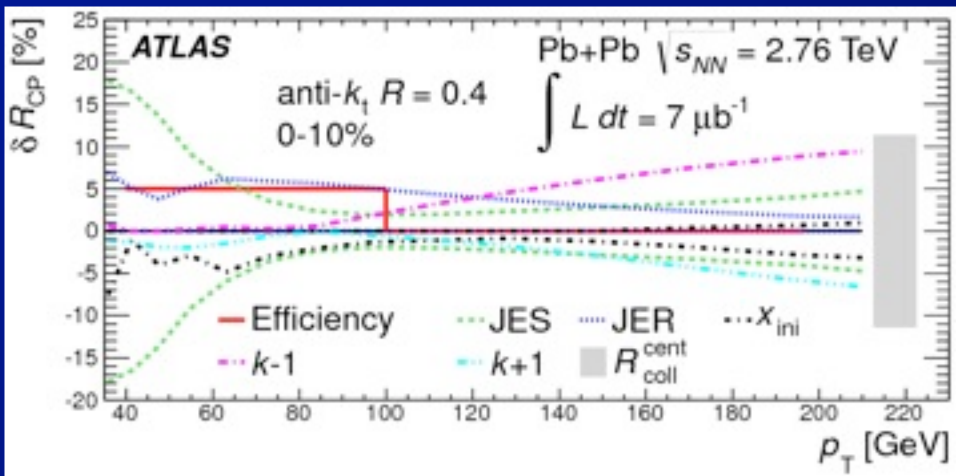
  – Overall jet energy scale divides out in ratio

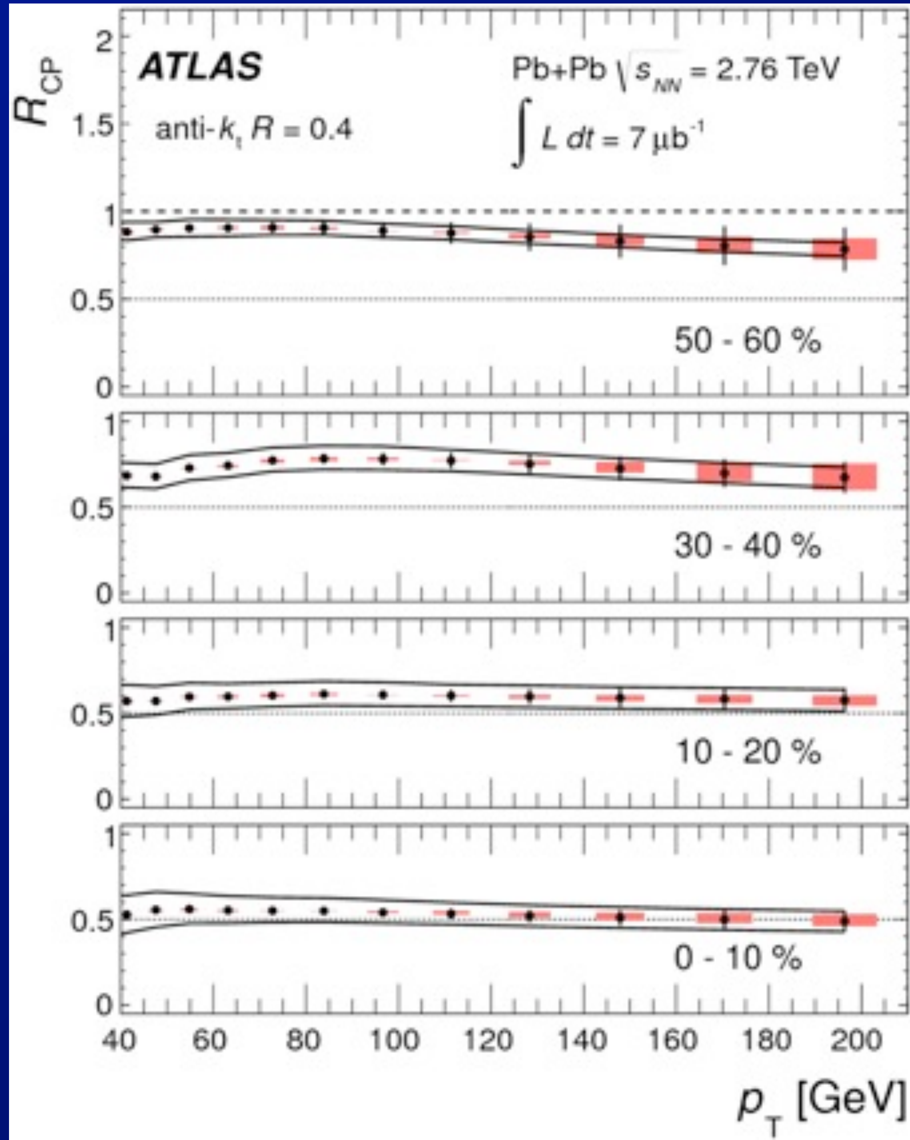


R = 0.4 Jet Rcp

Systematic errors

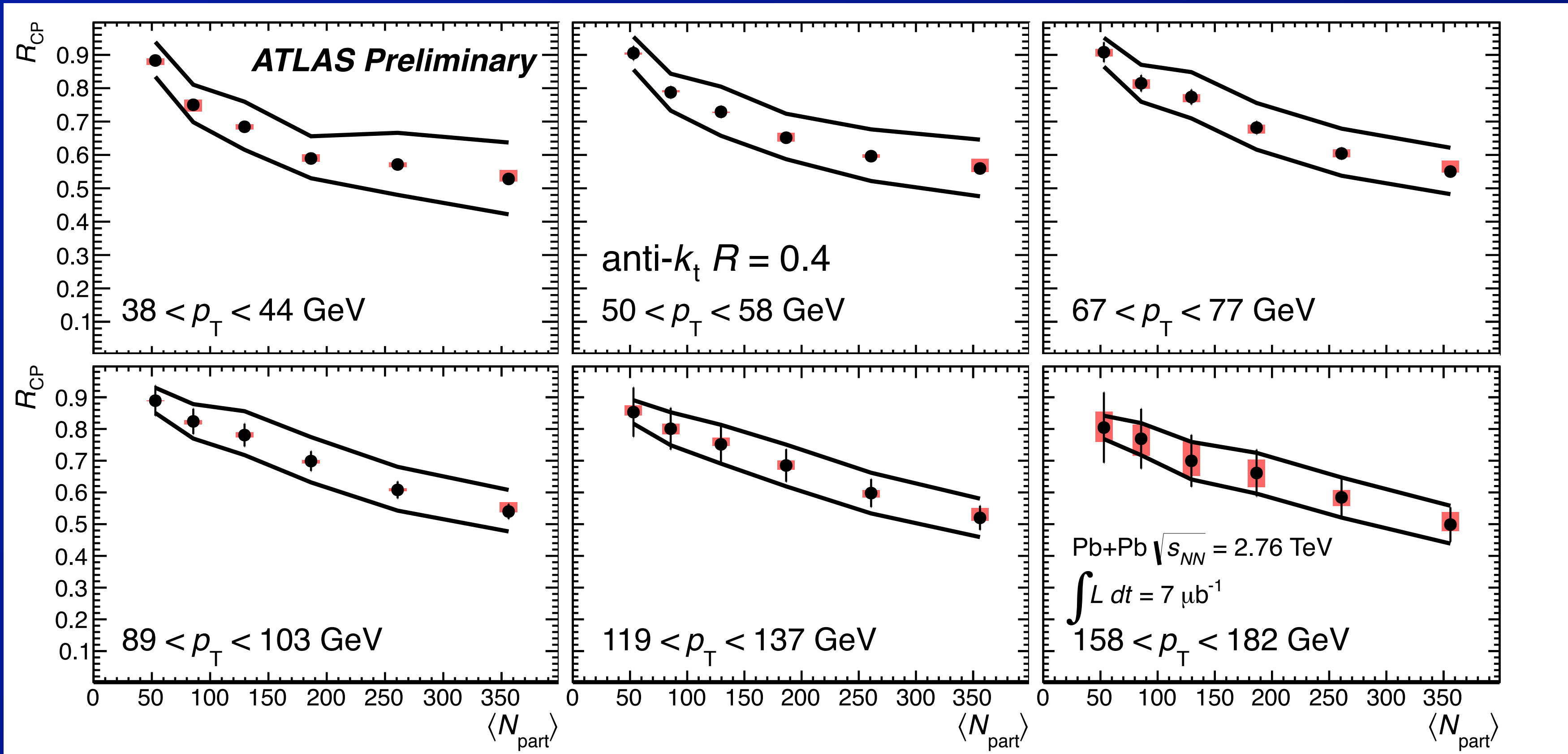
- Black band: fully correlated systematics
- Red boxes: partially correlated systematics
- Error bars:
  - – √ of diagonal element of unfolding statistical covariance matrix





Phys. Lett. B 719 (2013) 220-241

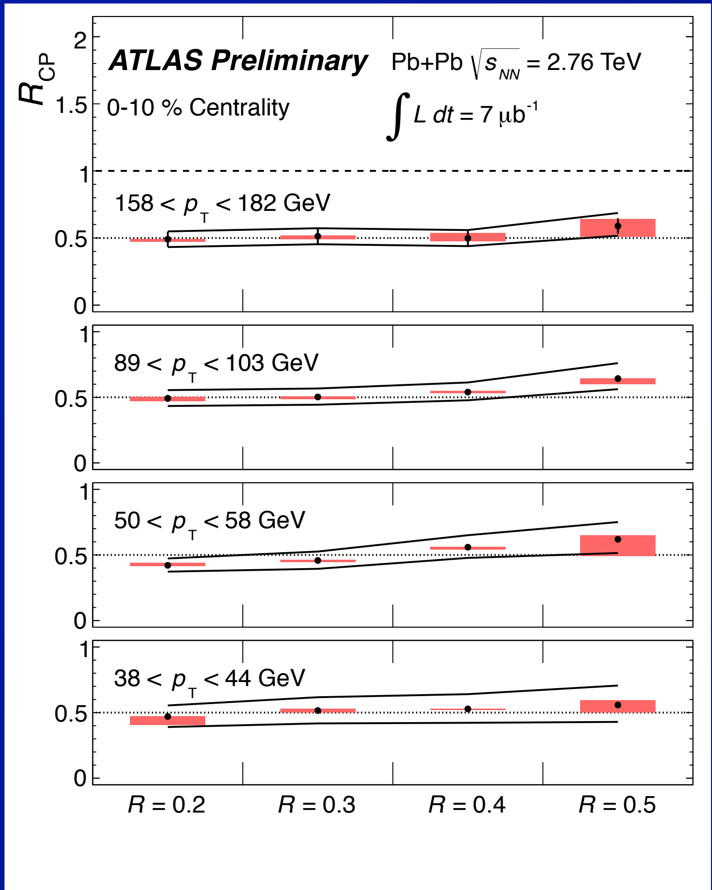
Centrality dependence of jet R_{cp}



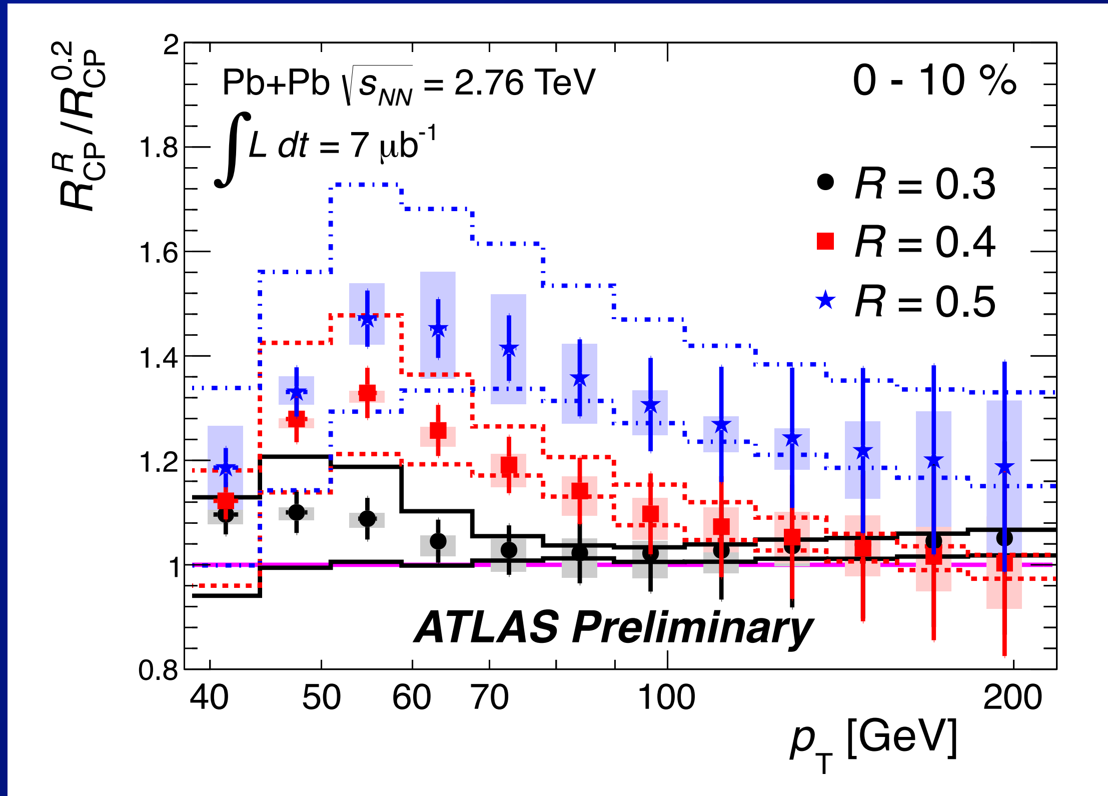
- Study centrality evolution for fixed jet p_T
  - R_{cp} vs N_{part}

    ⇒Smooth turn on of jet suppression between peripheral and central collisions.

Jet radius dependence of R_{cp}

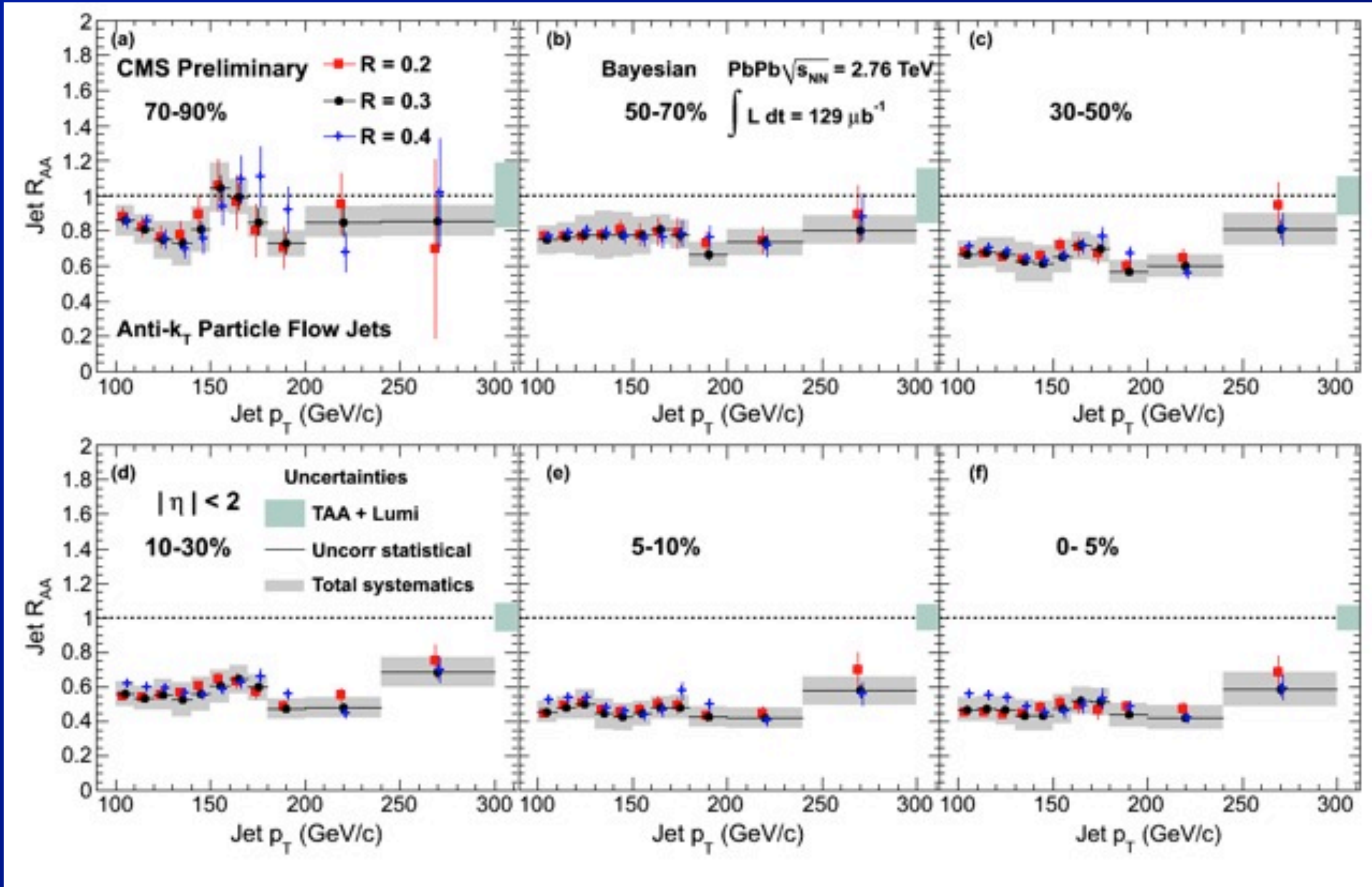


Significant cancellation of correlated errors



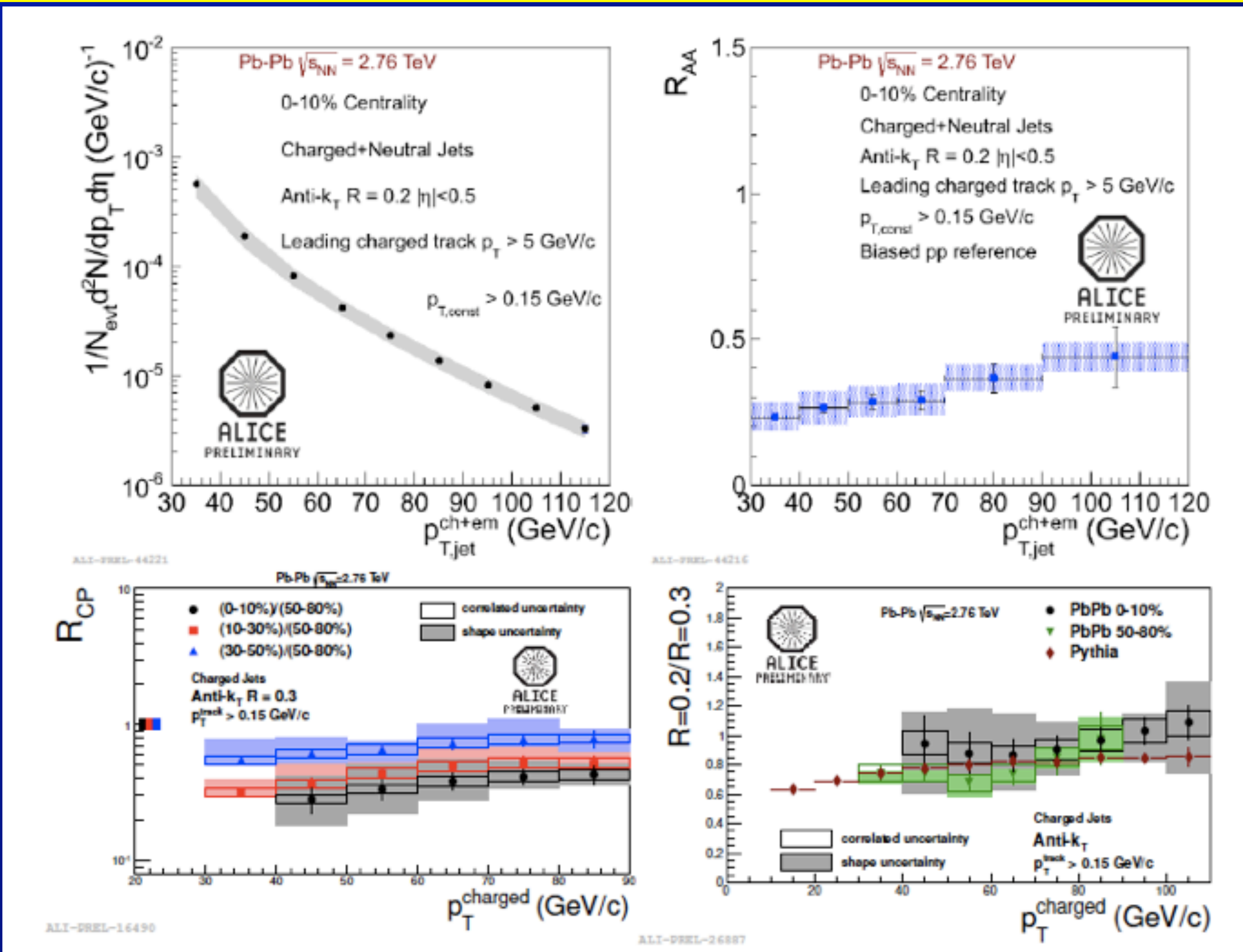
- Evaluate jet radius dependence of R_{cp}
  - Modest but significant variation of R_{cp}
  - Less suppression for larger R
    - ⇒An indication of jet broadening?

CMS jet R_{AA}

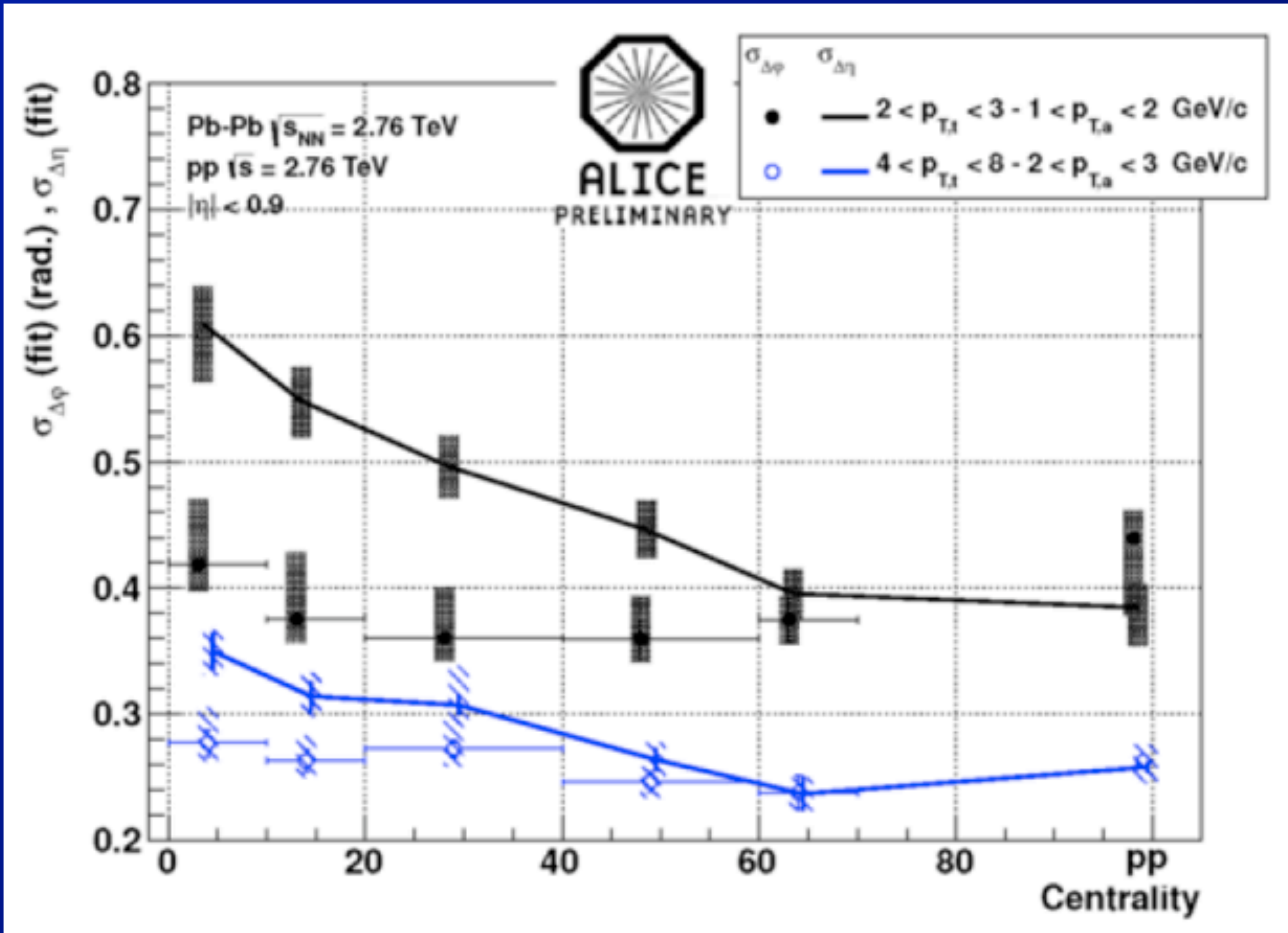


- **First results on jet R_{AA} @ LHC**
  - ⇒ Consistent behavior with ATLAS R_{cp}

ALICE: jet suppression



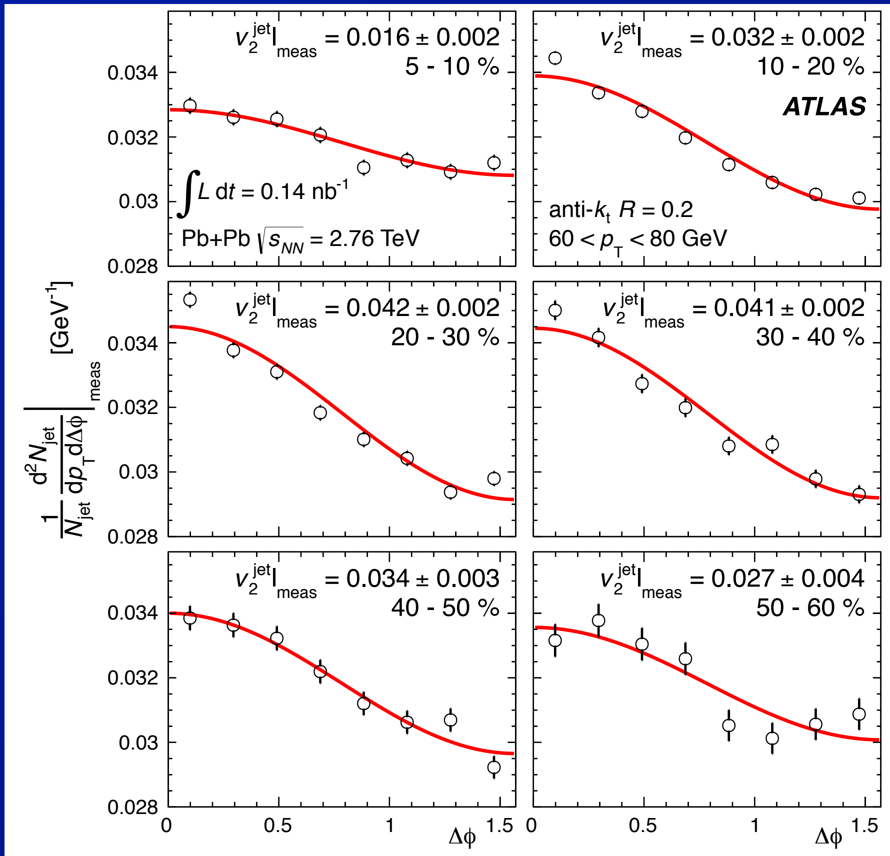
ALICE: jet shapes

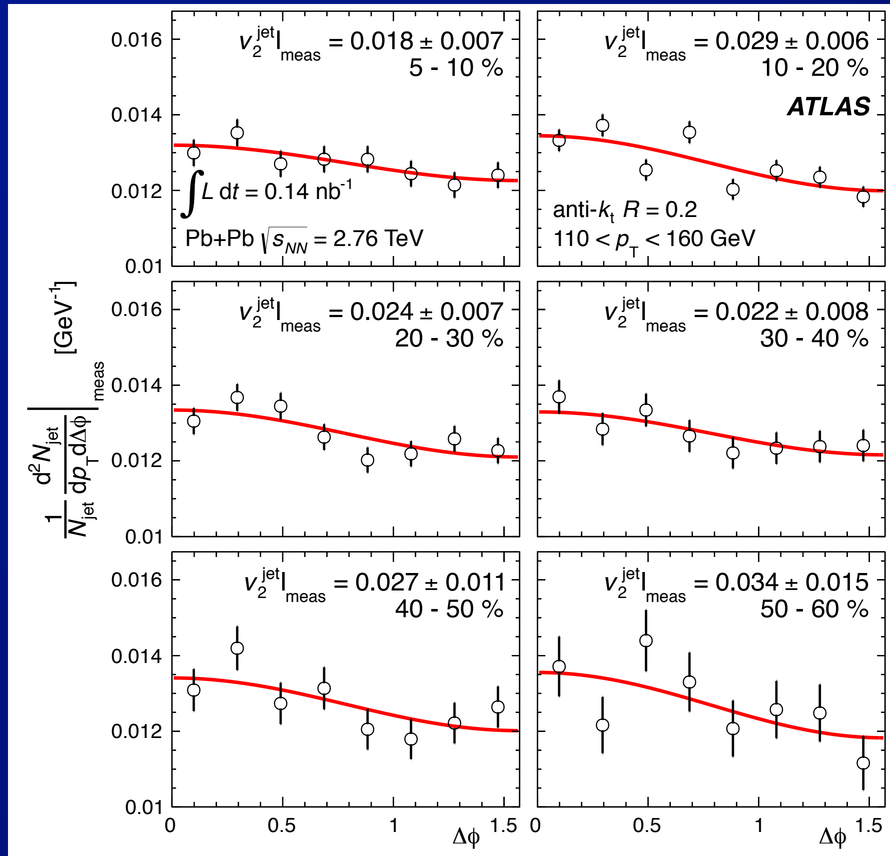


- More evidence for jet broadening @ low hadron p_T

Differential jet suppression

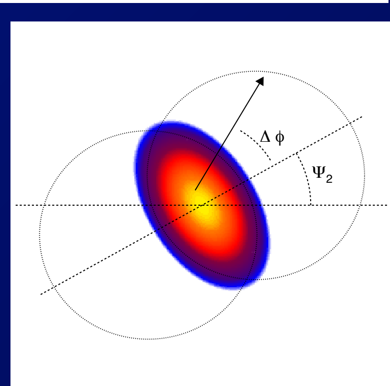
60 < p_T < 80 GeV **110 < p_T < 160 GeV**



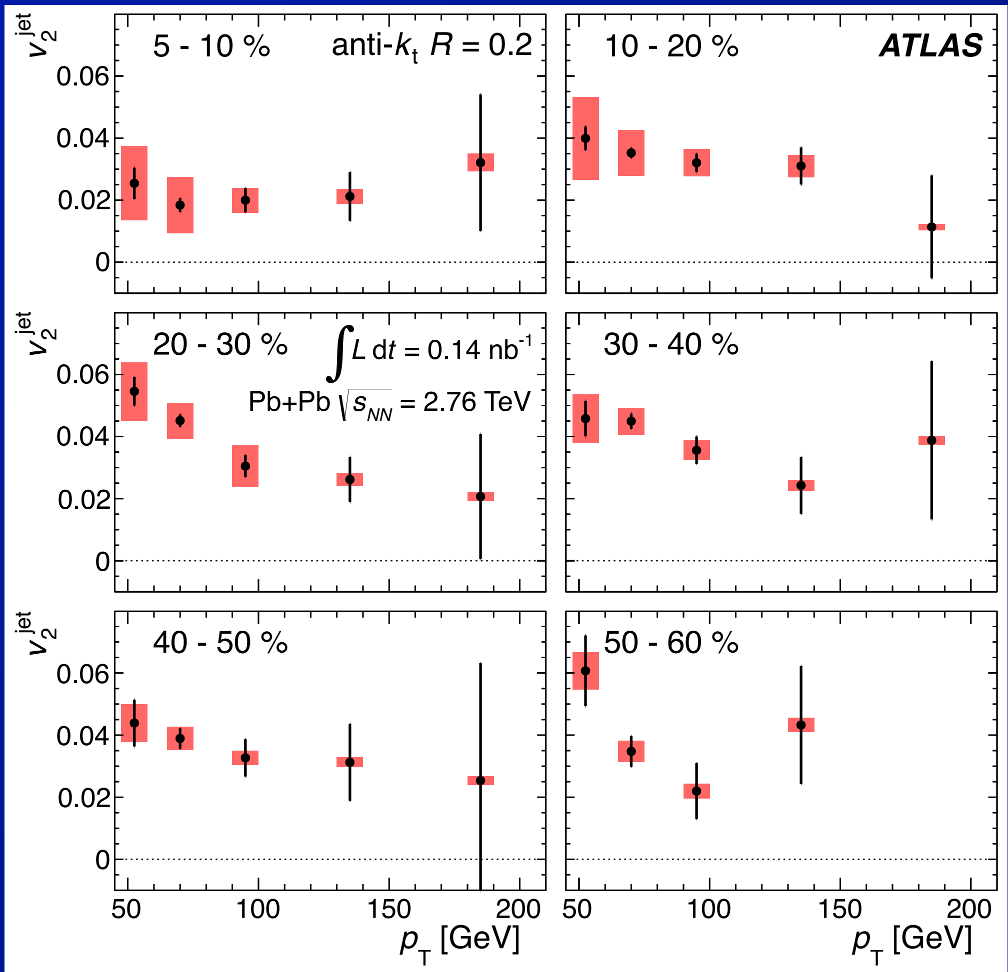


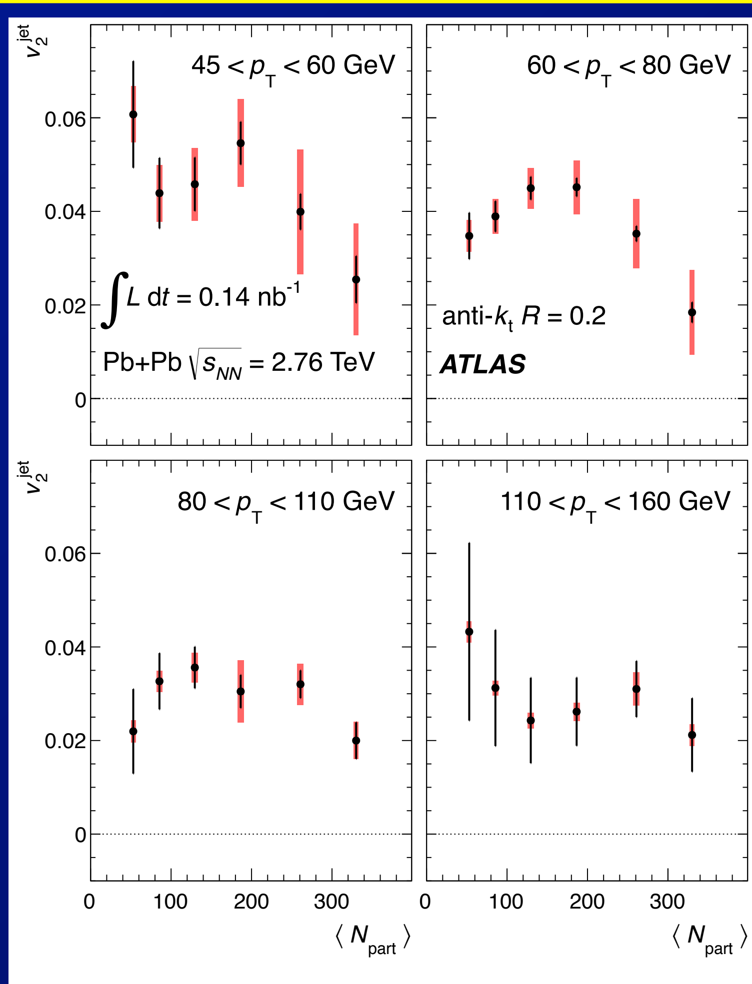
- **Measure jet yields in 8 bins of $\Delta\phi$ with respect to the elliptic event plane**
  - Here for R = 0.2 jets

⇒ See modulation for jet p_T > 100 GeV



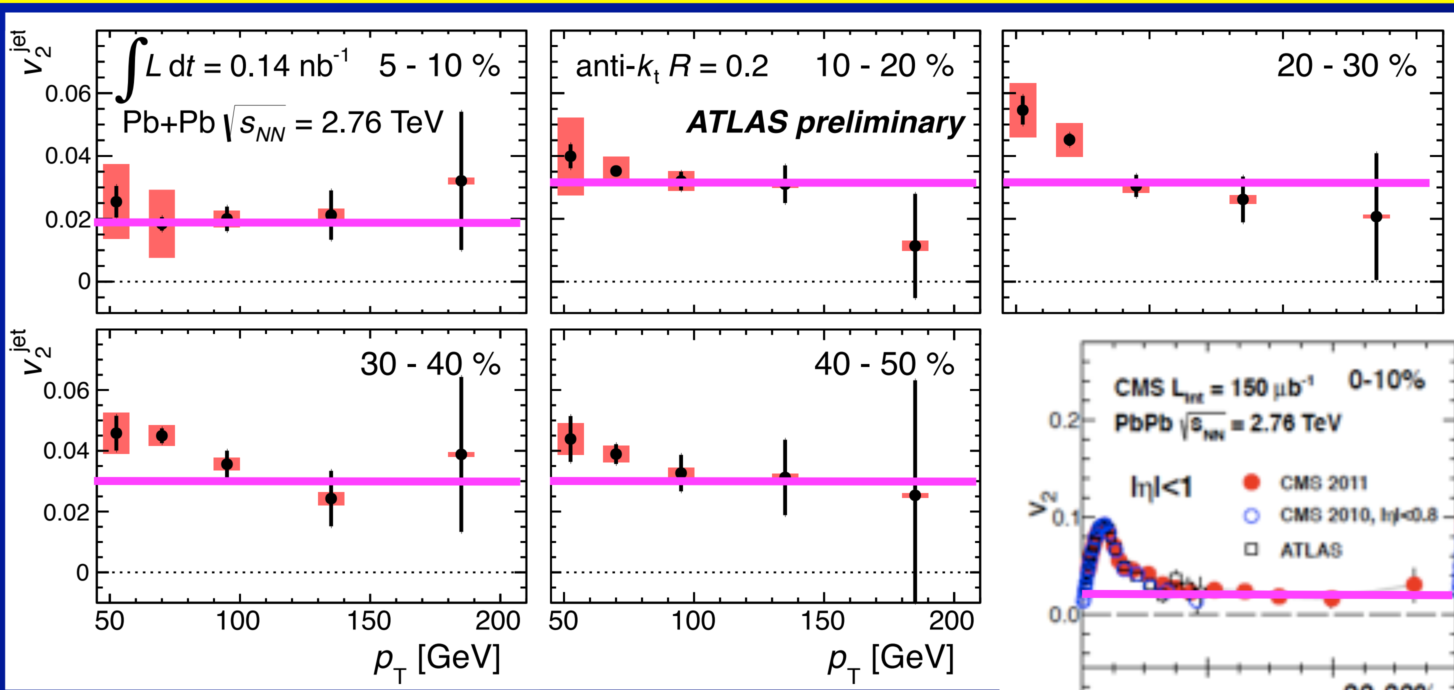
Differential jet suppression

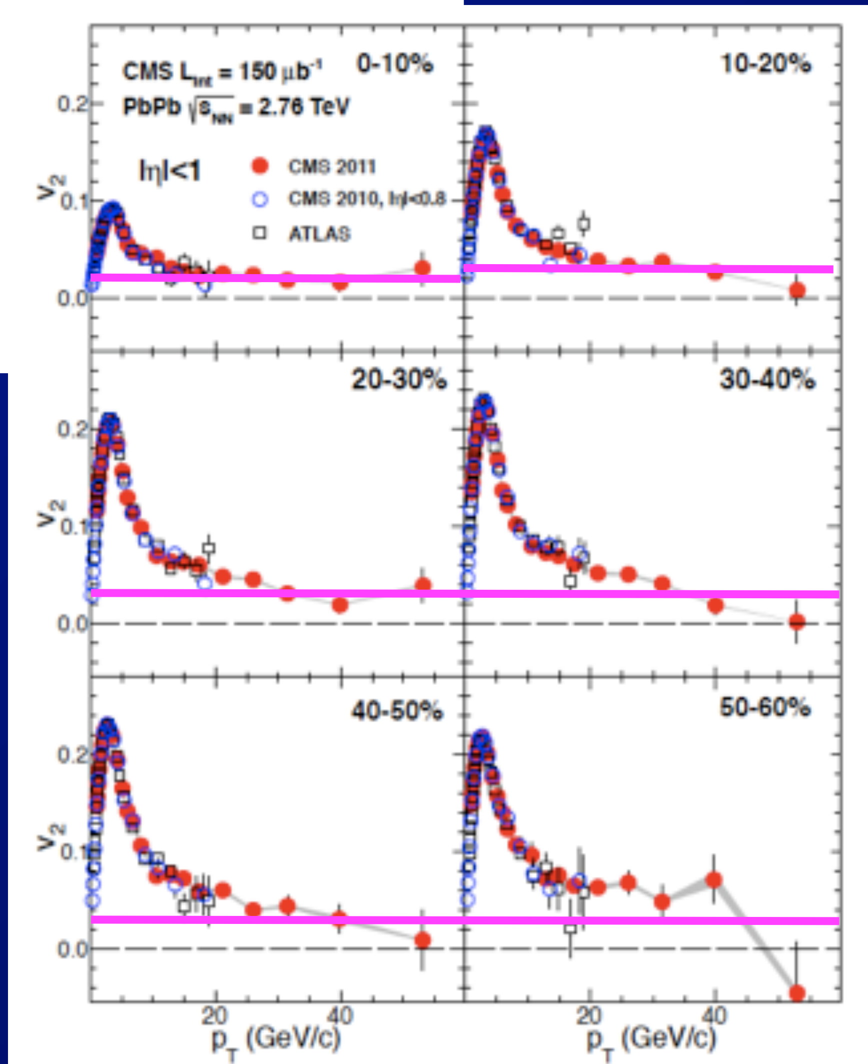




- Jet $v_2(p_T)$ ~ flat at high p_T
- Characteristic centrality dependence
  - ⇒Peripheral -- no quenching
  - ⇒central -- no eccentricity

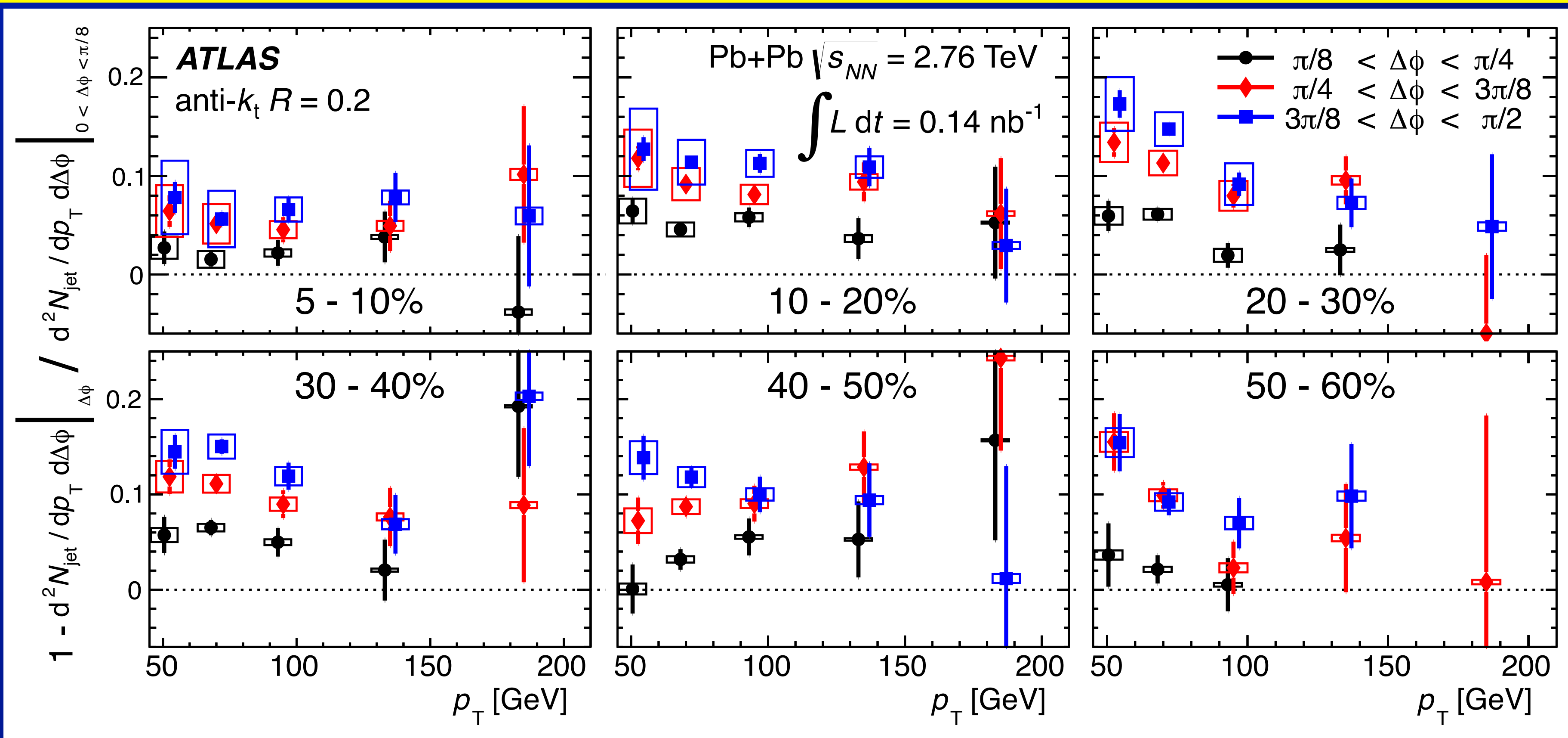
Jet $v_2(p_T)$





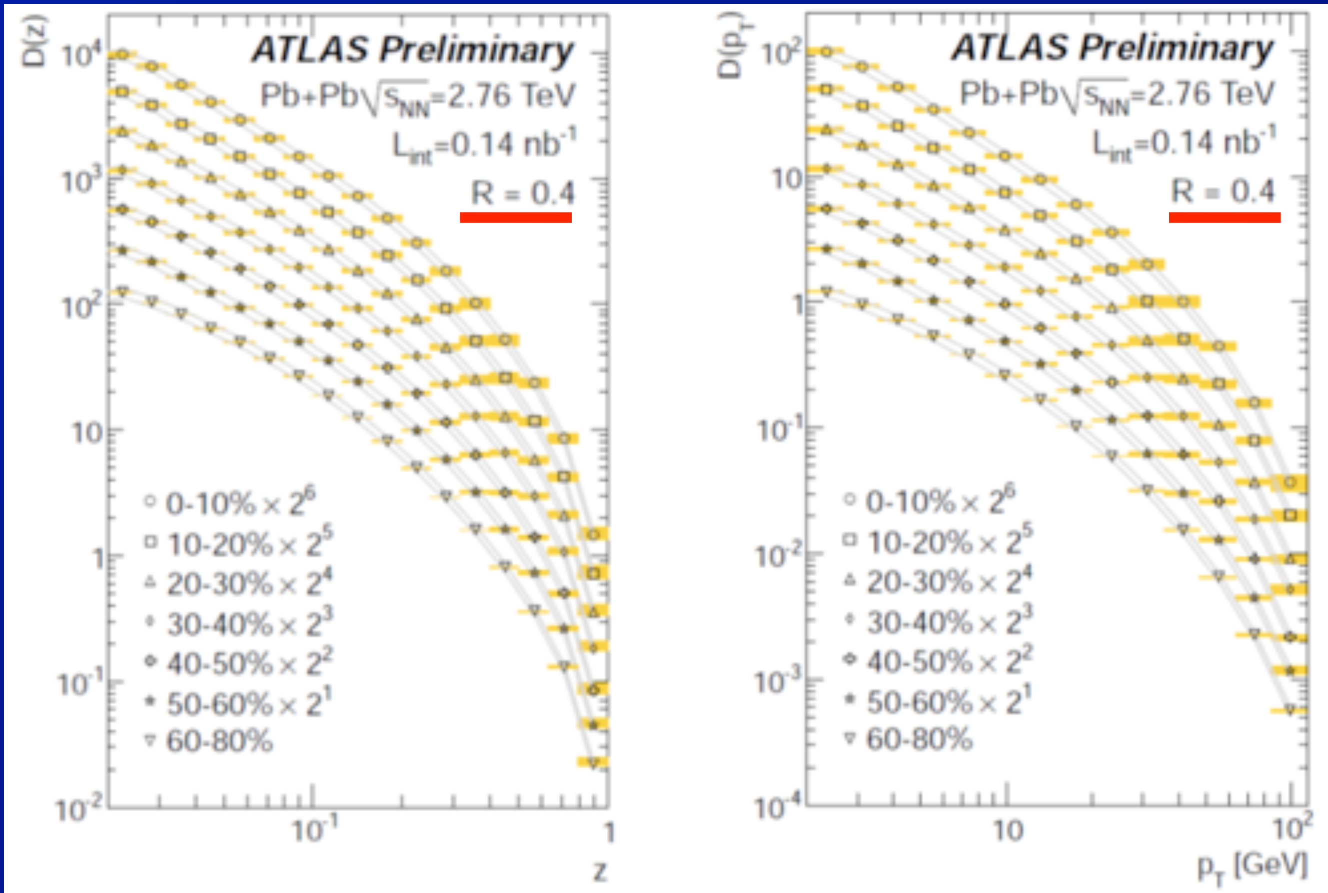
- Do rough comparison of jet, charged v2 at high p_T
  - plot 0.02 for 0/5-10%
  - plot 0.03 for > 10%
    - ⇒ As good as could be expected

Differential jet suppression



- **Evaluate fractional change in jet yields vs Δφ relative to the yield in 0 < Δφ < π/8.**
  - $R_{AA}(\Delta\phi)/R_{AA}(0\text{-}\pi/8)$
    - ⇒ **~15% change in single jet suppression between in-plane, out-of-plane @ high p_T**

Inclusive jet fragmentation

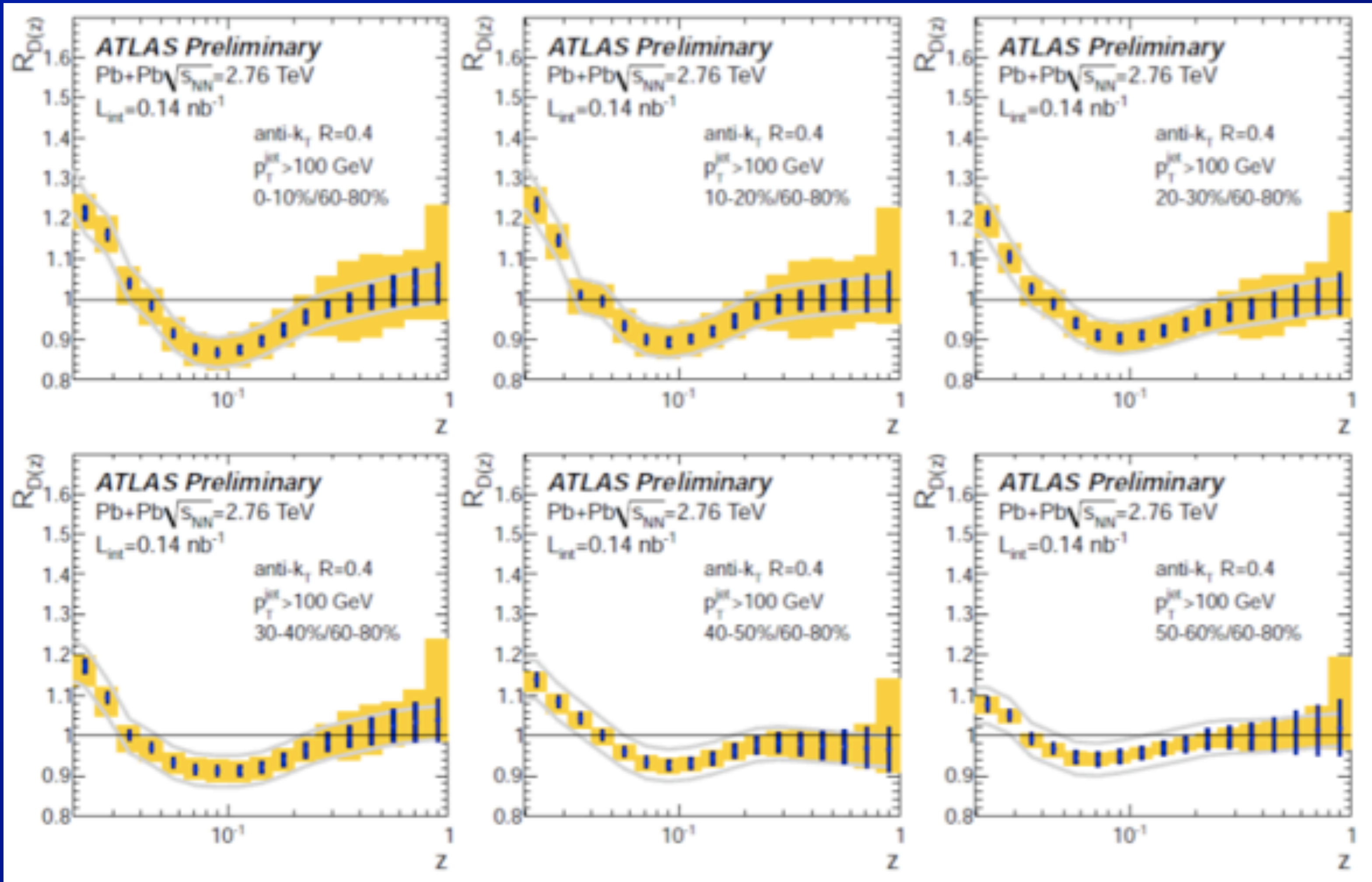


Unfolded for jet and charged particle resolution

$$D(z) = \frac{1}{N_{jet}}\frac{dN_{chg}}{dz}, z = \vec{p}_{chg}\cdot\vec{p}_{jet}/\left|\vec{p}_{jet}\right|$$

$$D(p_T) = \frac{1}{N_{jet}}\frac{dN_{chg}}{dp_T}$$

Inclusive jet fragmentation (2)

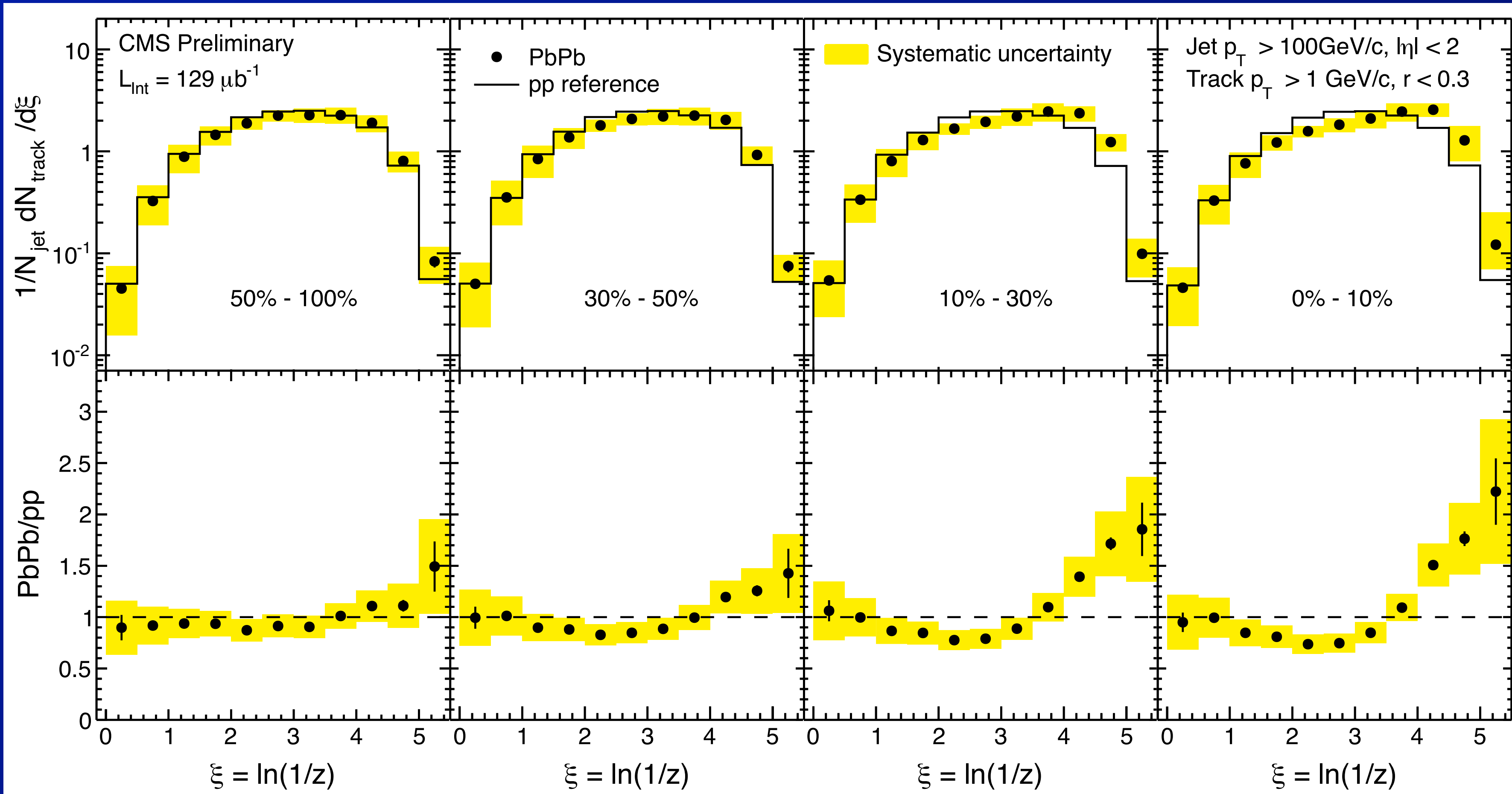


R = 0.4

- First observation of modified parton shower in inclusive jets

  ⇒Not only seeing "left over" unquenched jets.

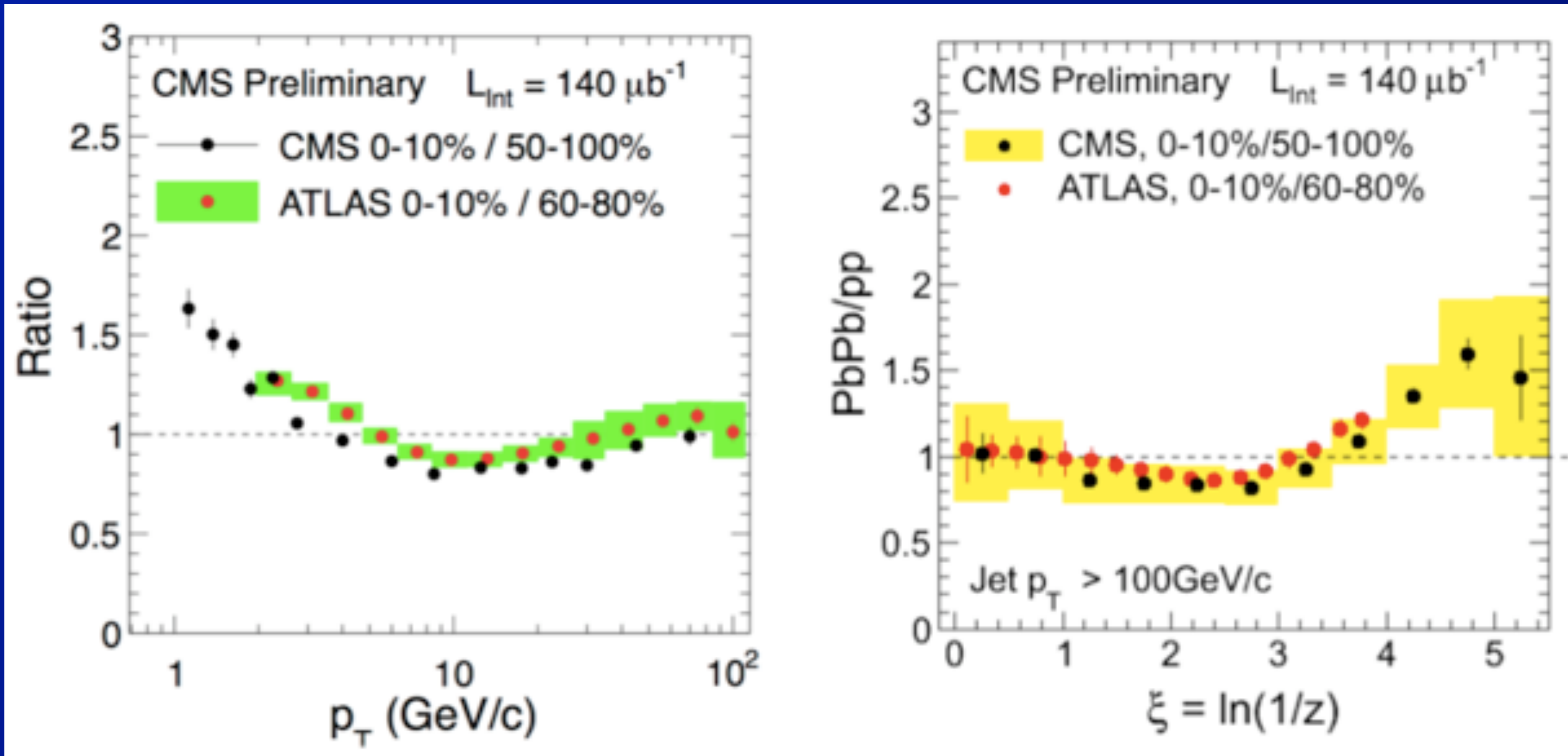
CMS fragmentation



- Measured using MLLA variable not z
- Compared to p-p not peripheral

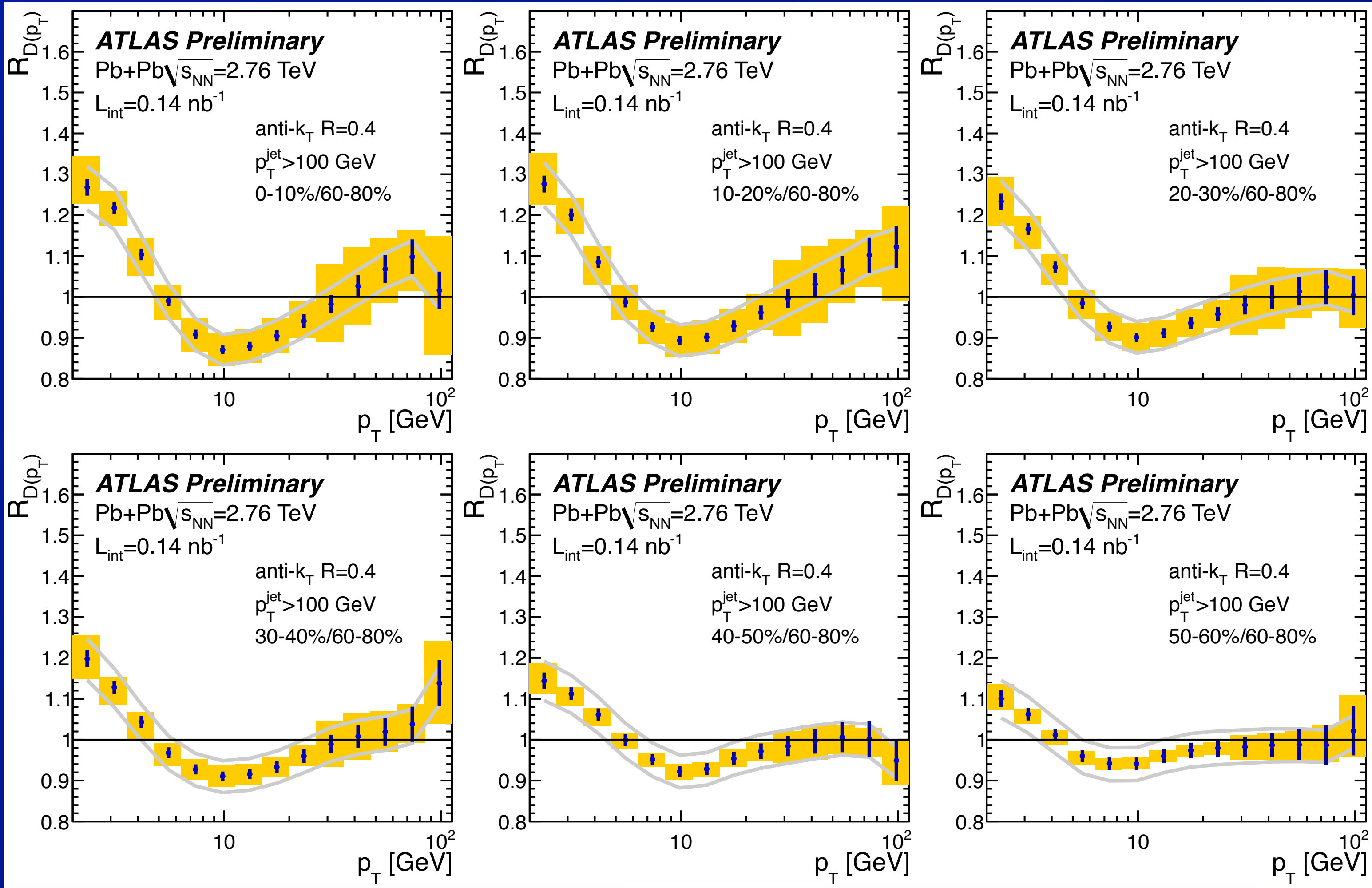
  ⇒ But same modifications as observed by ATLAS

Inclusive jet fragmentation



- First direct handle on the p_T dependence of modifications of the parton shower.
  - ⇒Important to determine whether modification is p_T or z dependent.
  - ⇒How to determine whether low-p_T enhancement is from PS or from medium?

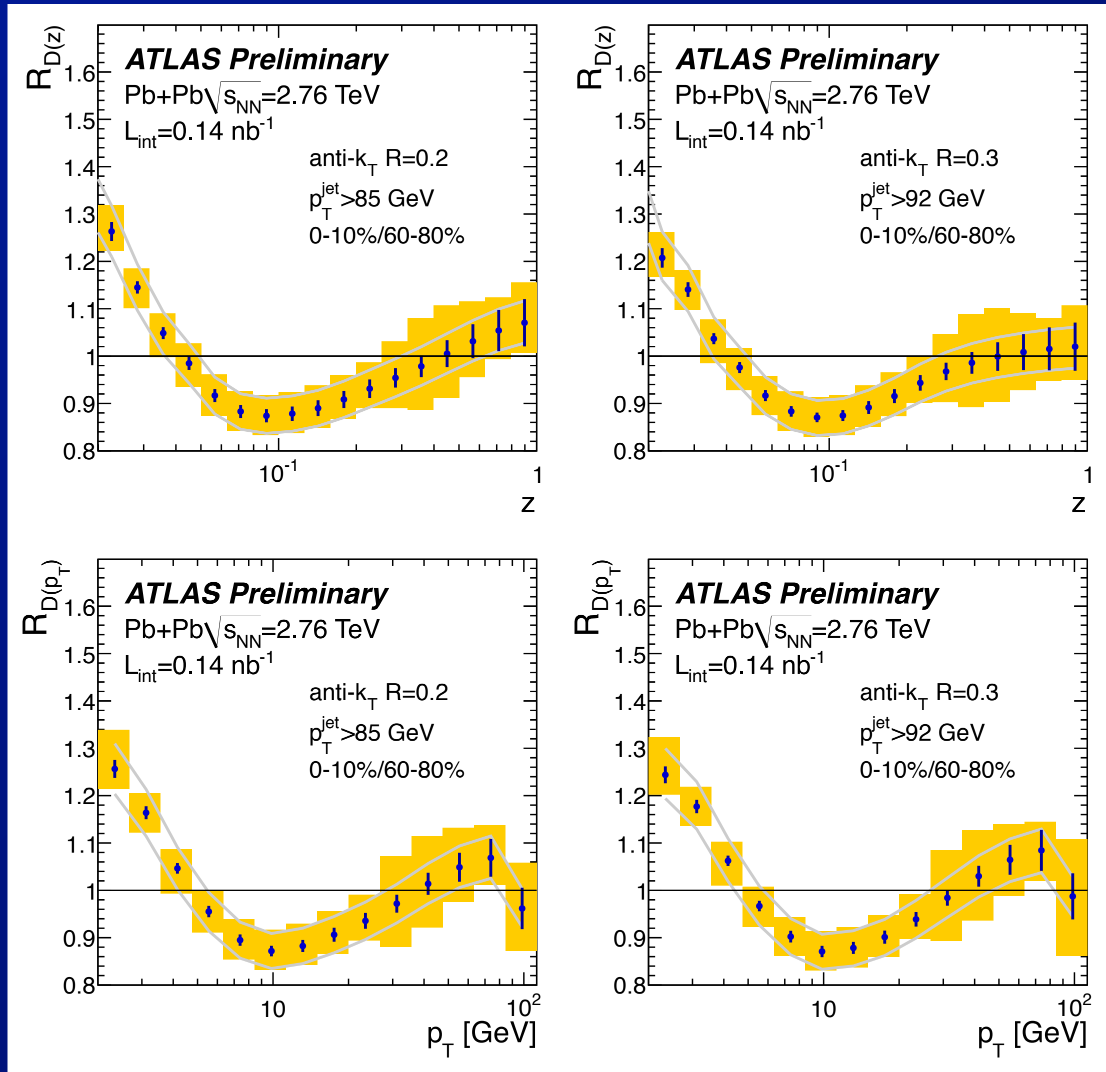
Inclusive jet fragmentation (3)



- Check that the modification is not due to the measurement of jet $p_T \Rightarrow D(p_T)$
  - $\Rightarrow D(p_T)$ shows similar modifications

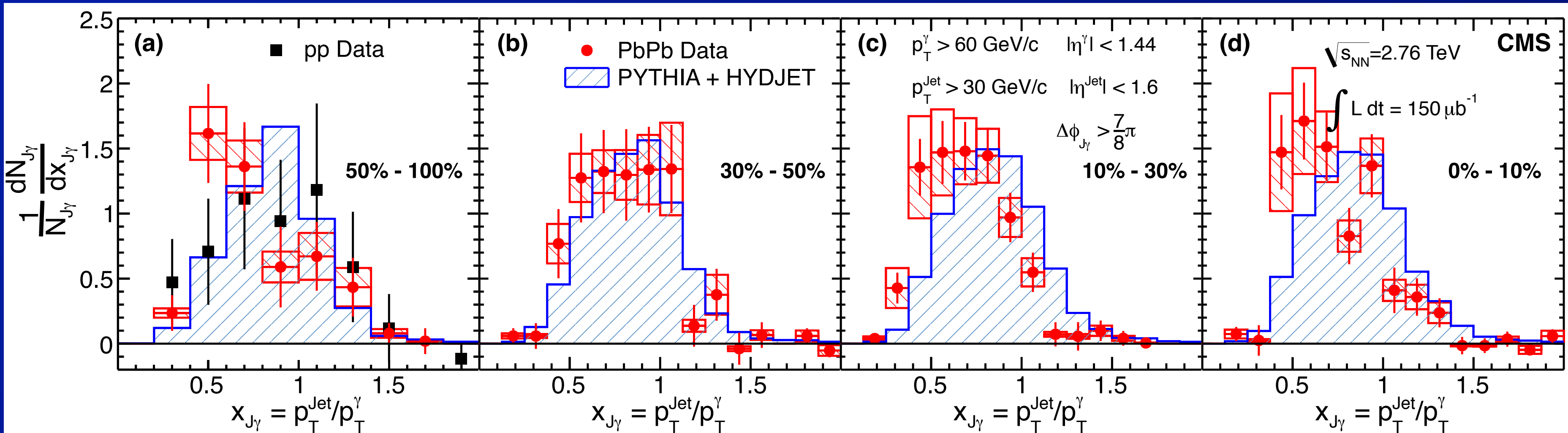
Jet fragmentation: R dependence

- Check that the modification is not due to underlying event fluctuations
  - Use different jet sizes: R = 0.2, 0.3
- Obtain the same results as R = 0.4



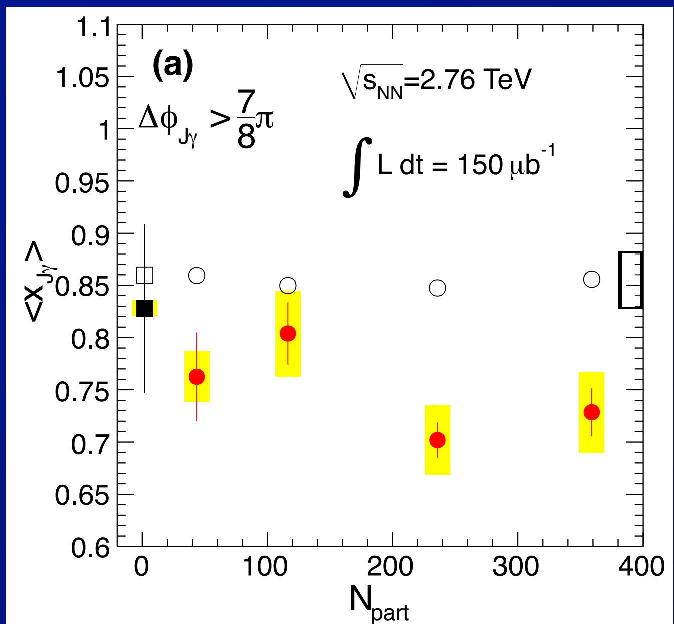
⇒Observed modifications are robust

CMS: gamma-jet

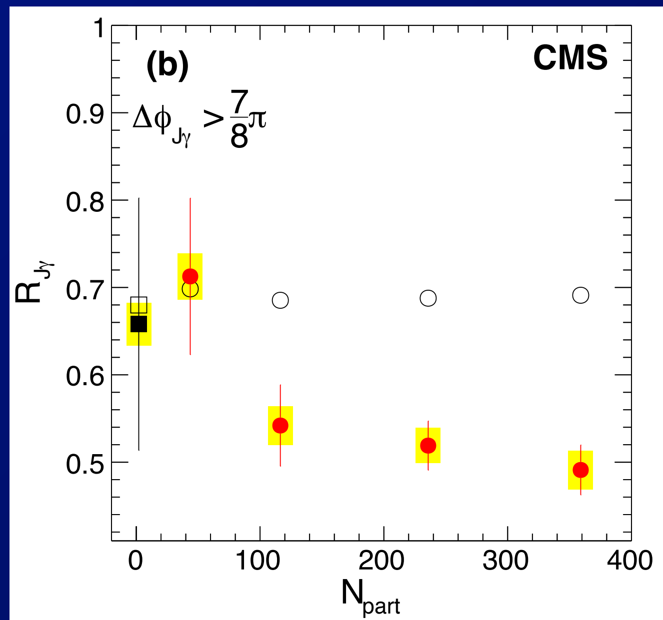


- Observe a shift in the distribution of jet energy to photon energy fraction. Quantify:

mean fraction

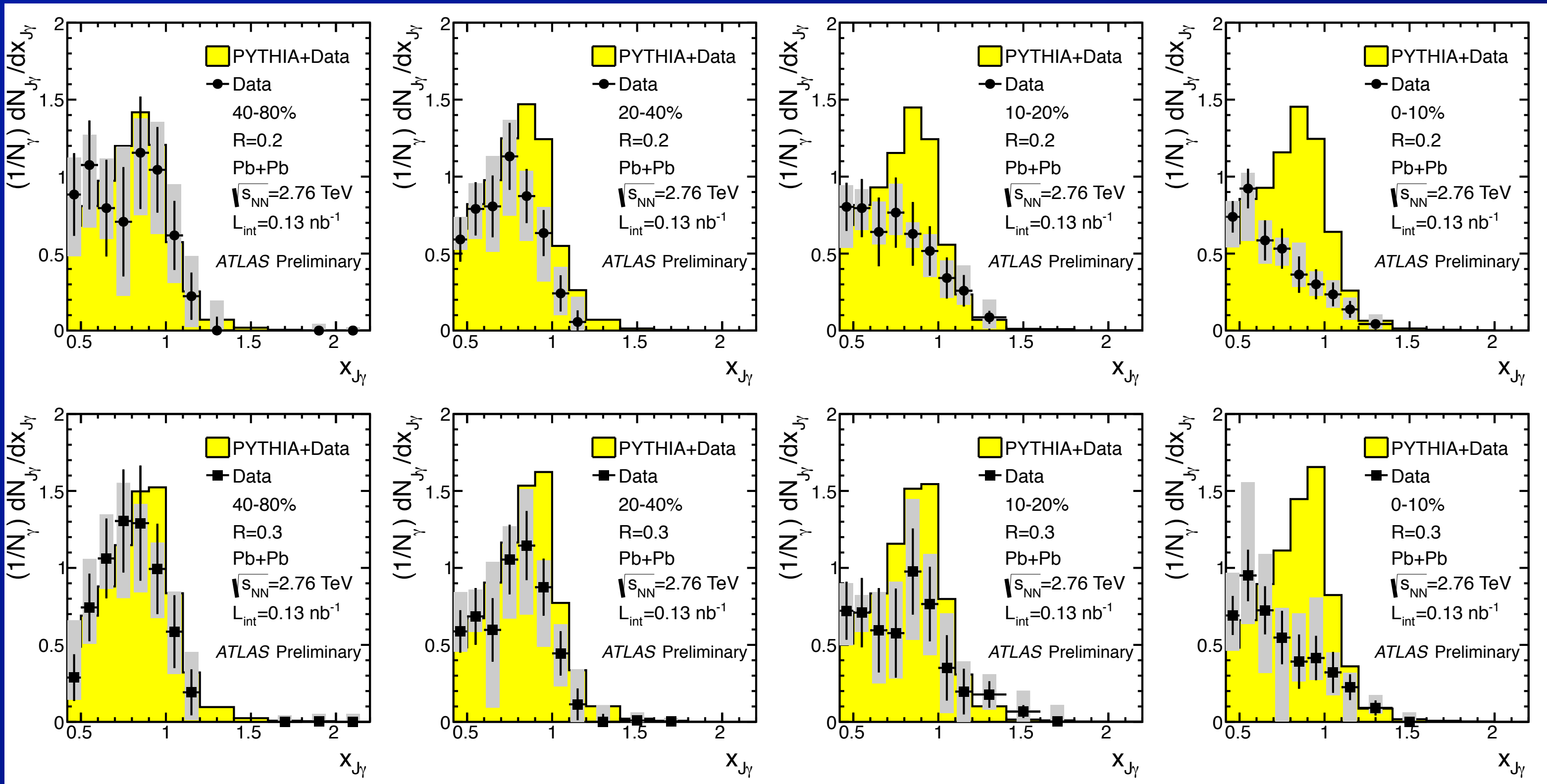


Jet fraction



γ-jet momentum balance

Peripheral ⟶ central



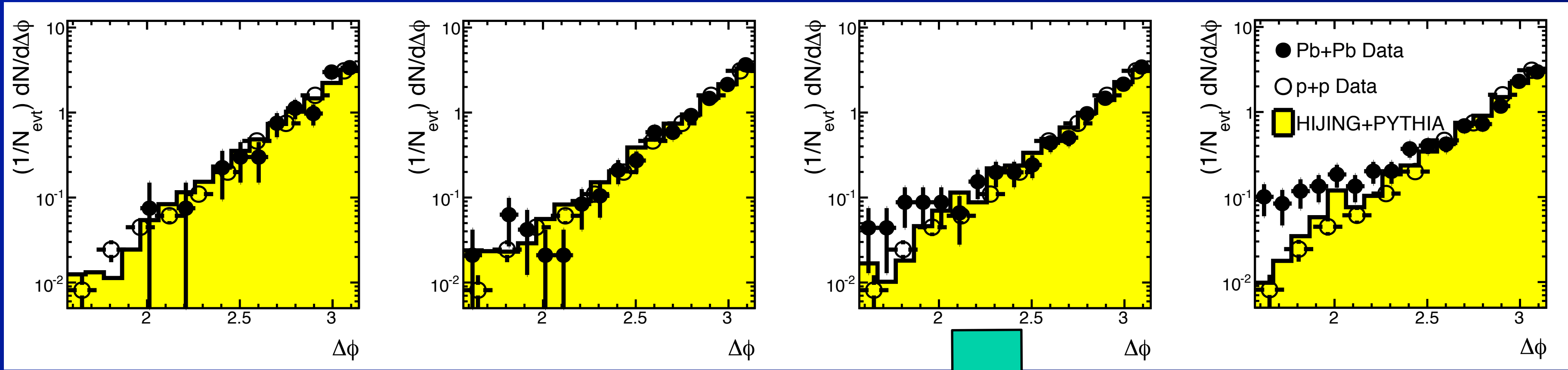
R = 0.2

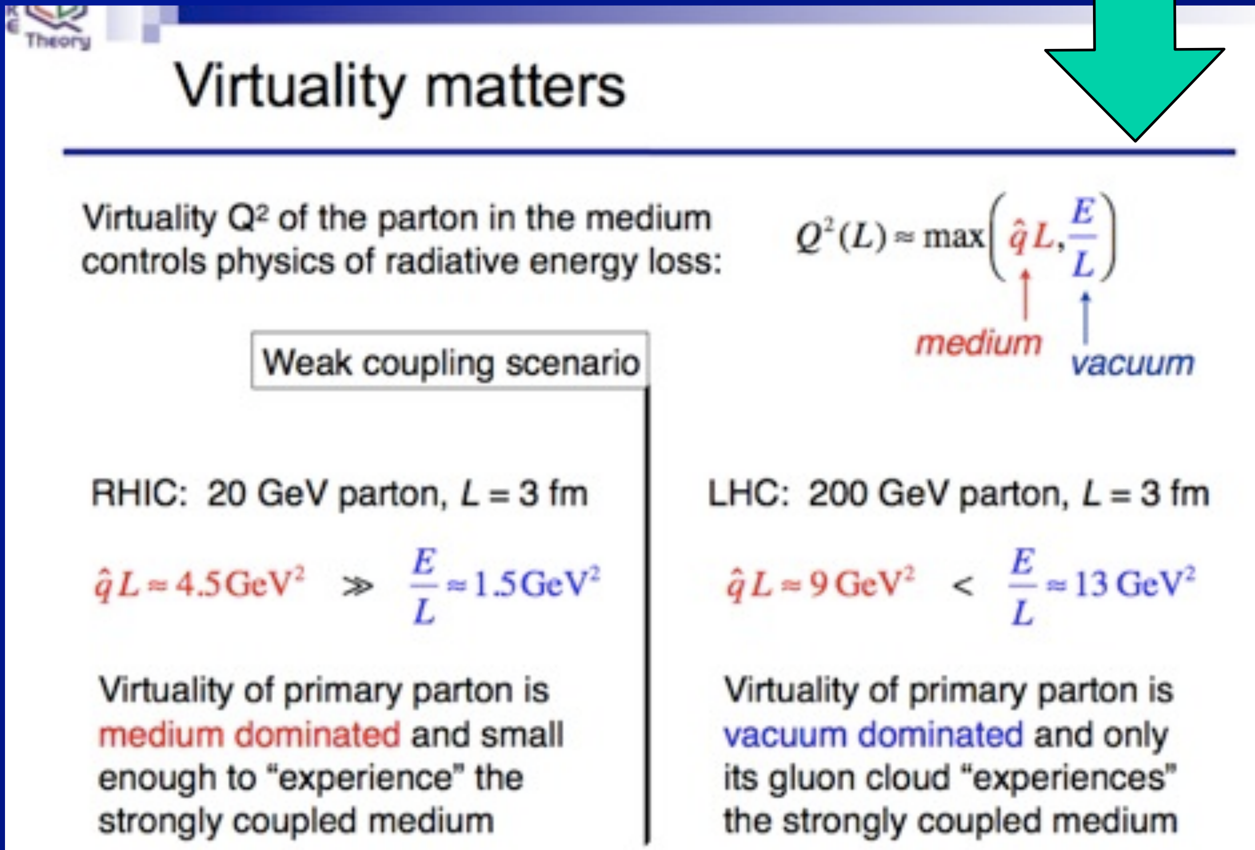
R = 0.3

- Plot distribution of $x_J = p_T^{\text{jet}} / p_T^{\gamma}$
  - photon background pairs subtracted
  - unfolded for jet energy resolution

⇒Substantial change in γ-jet balance

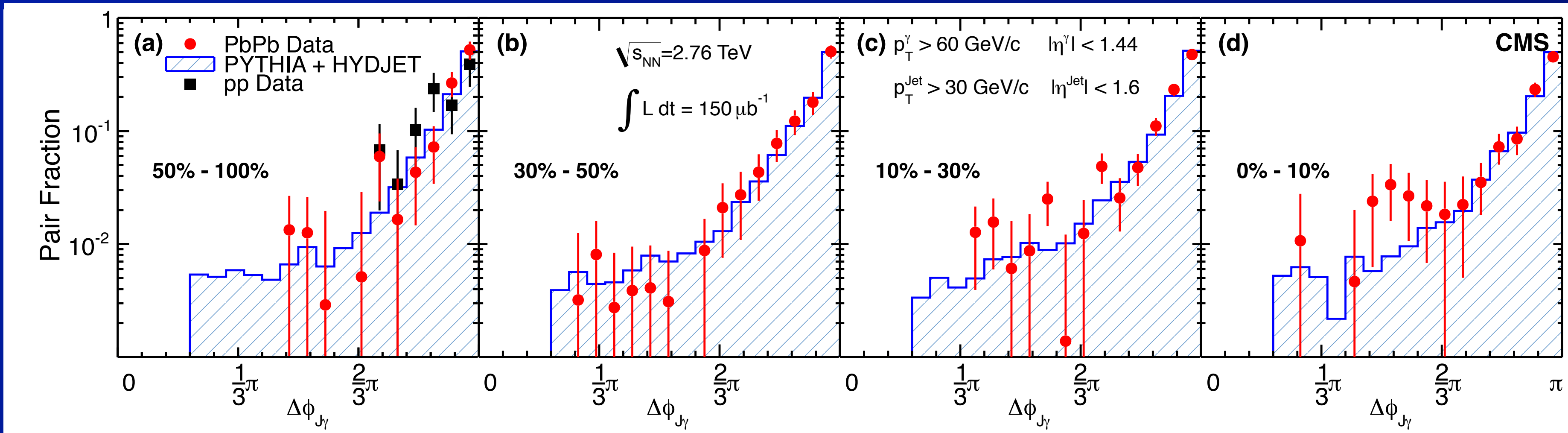
Dijet (and gamma-jet) acoplanarity



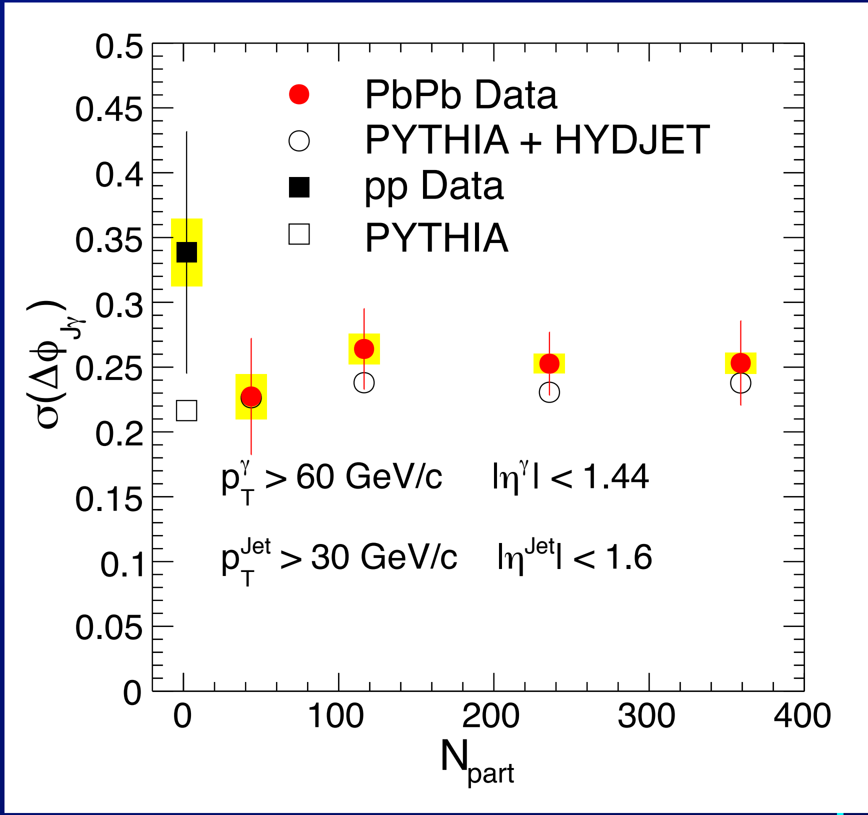


Is the lack of k_T broadening in the presence of significant quenching a death knell for "leading parton" models of energy loss?

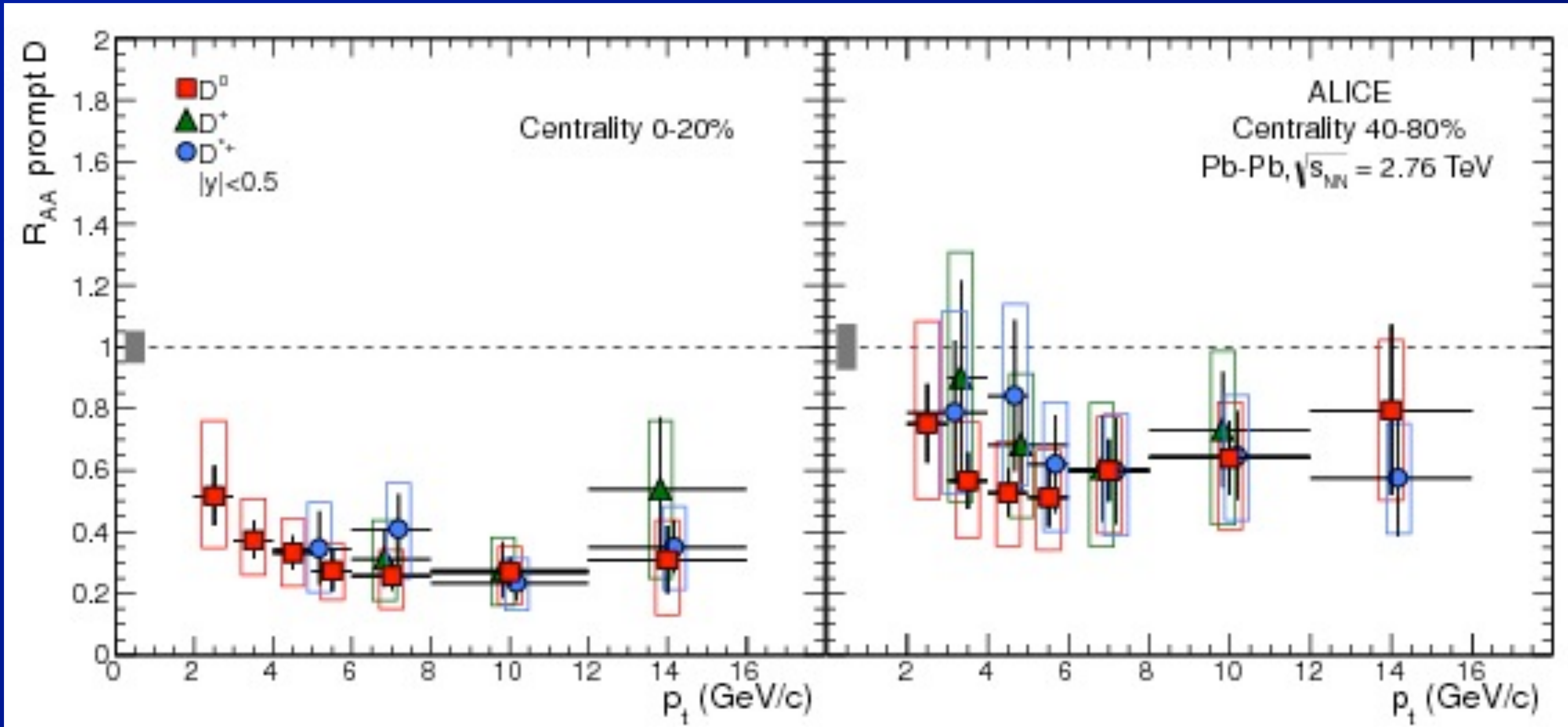
CMS: gamma-jet acoplanarity



- No broadening of gamma-jet ΔΦ distribution

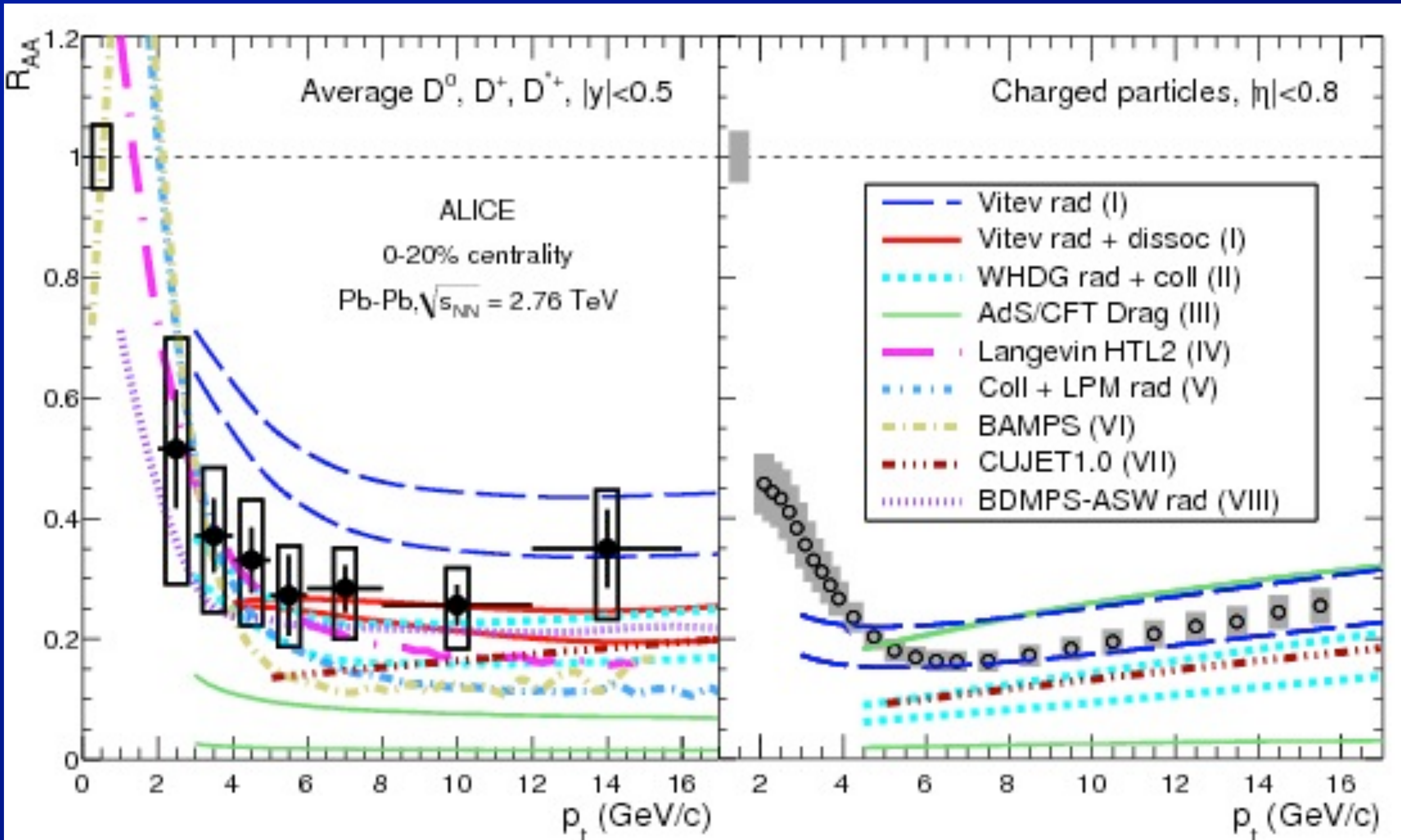


Heavy flavor: D meson R_{AA}



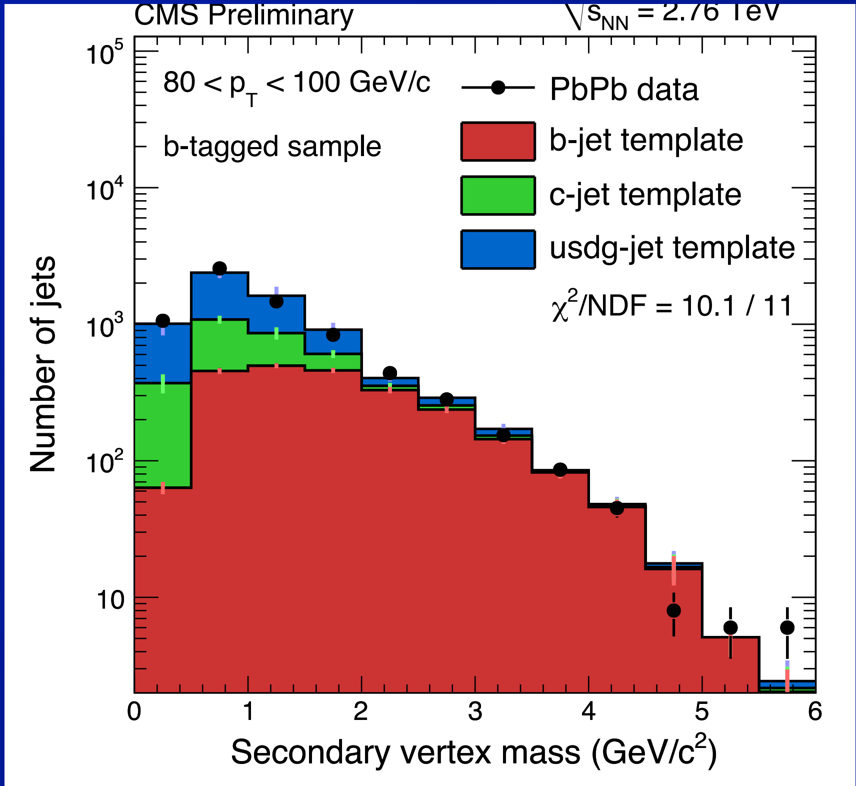
- Direct measurement of charm suppression in a p_T range where charm mass matters
  - unlike semi-leptonic measurements which mix charm and bottom

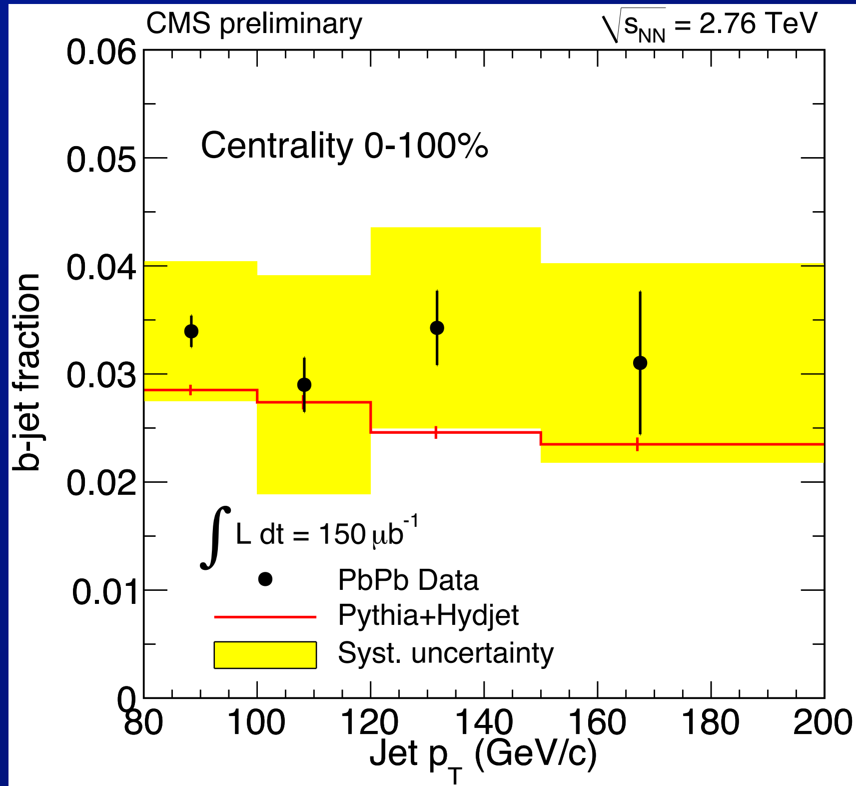
Heavy flavor: D meson R_{AA} and models



- **No single calculation can describe both inclusive hadrons and D mesons.**
  - **WHDG closest, somewhat low on hadrons**

CMS b-tagged jets





- CMS tags jets with secondary decay vertex
  - Then use a template fit to extract b-jet fraction.
    - ⇒Method that is common in LHC experiments
- High-pT b jet fraction consistent with PYTHIA and/or p-p (not shown)

Summary

- Jet measurements are starting to fulfill the promise of providing a new set of tools for studying/understanding jet quenching
  - Alternatives to single hadron measurements
    - ⇒More closely related to parton kinematics
  - Direct measurements of modifications
    - ⇒Observing modified parton showers
- Ultimately, combination of hadron/heavy flavor/jet measurements together will provide more constraints on jet quenching theory than any one of these individually
  - Still much to learn about systematics
  - Still learning how to take advantage of jets
    - ⇒Expect rapid progress over next few years