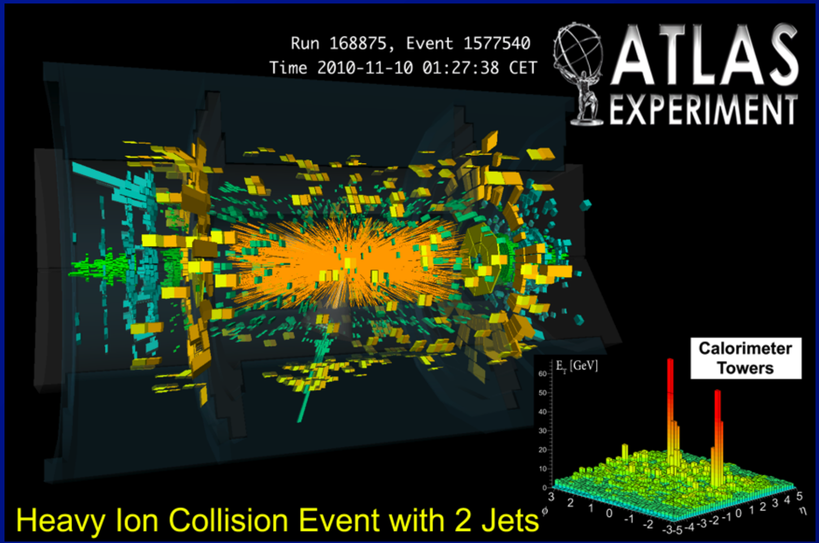
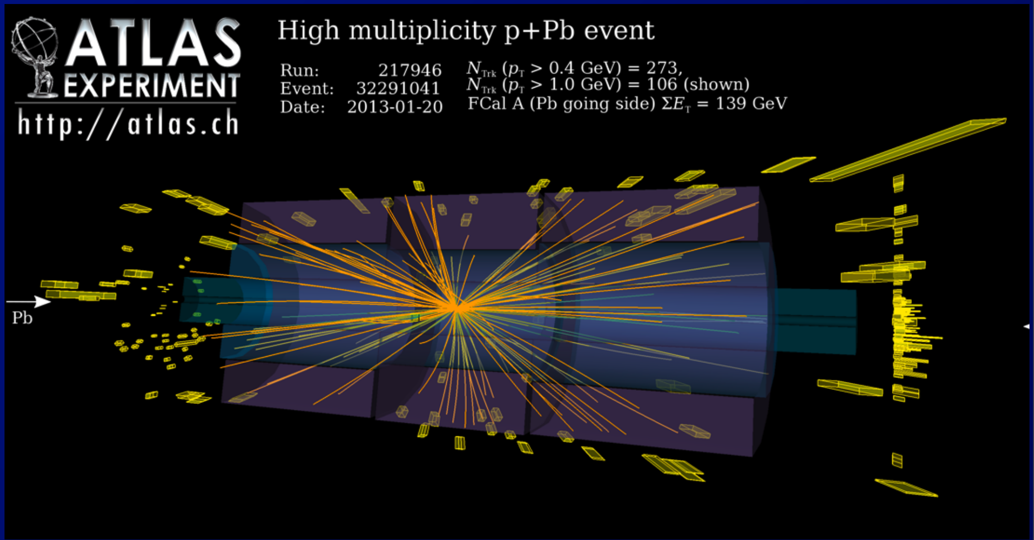
High p_T measurements in Pb+Pb collisions by the ATLAS experiment

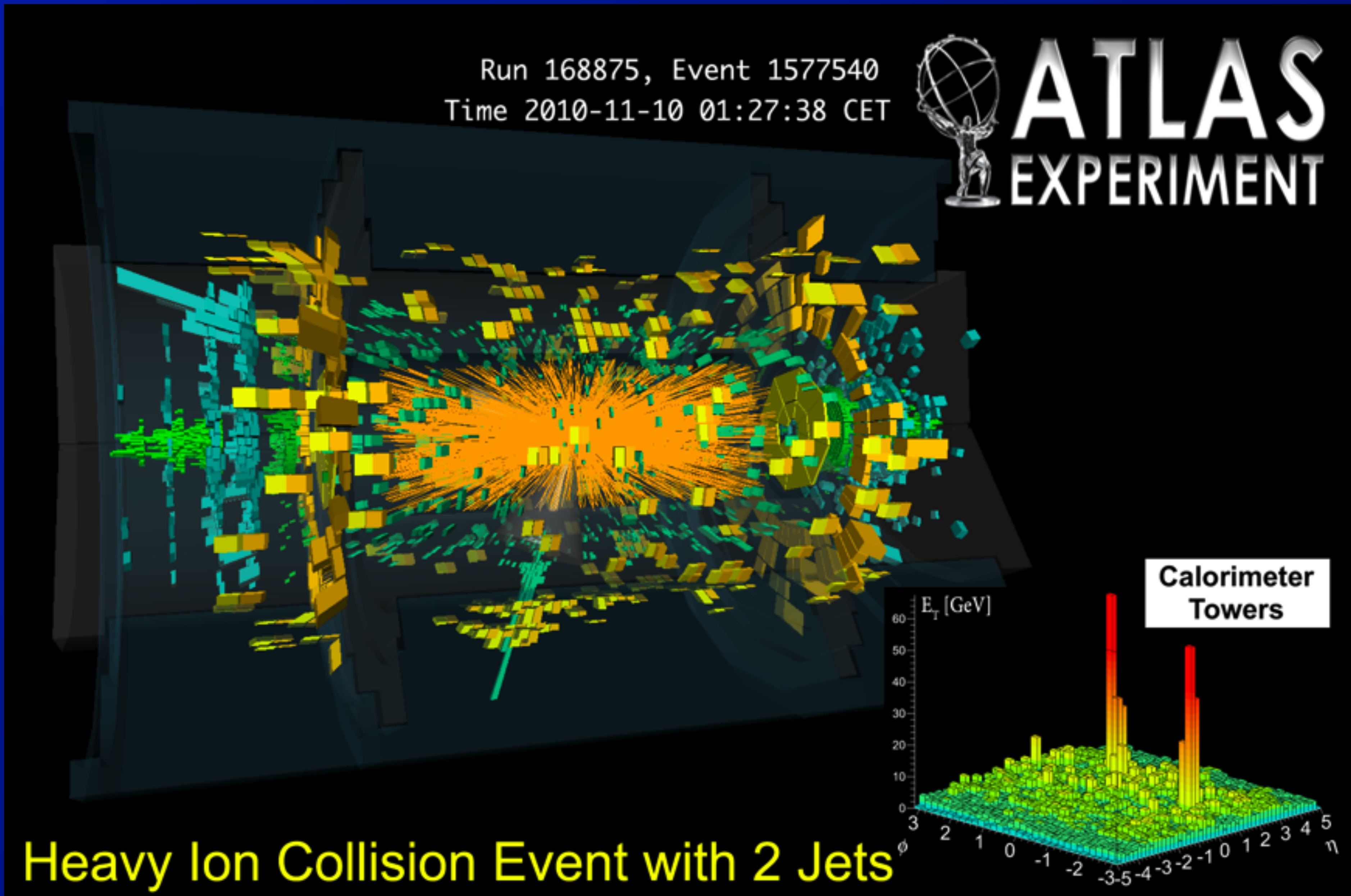
Brian. A Cole

June 16, 2013





Heavy ion collision in ATLAS

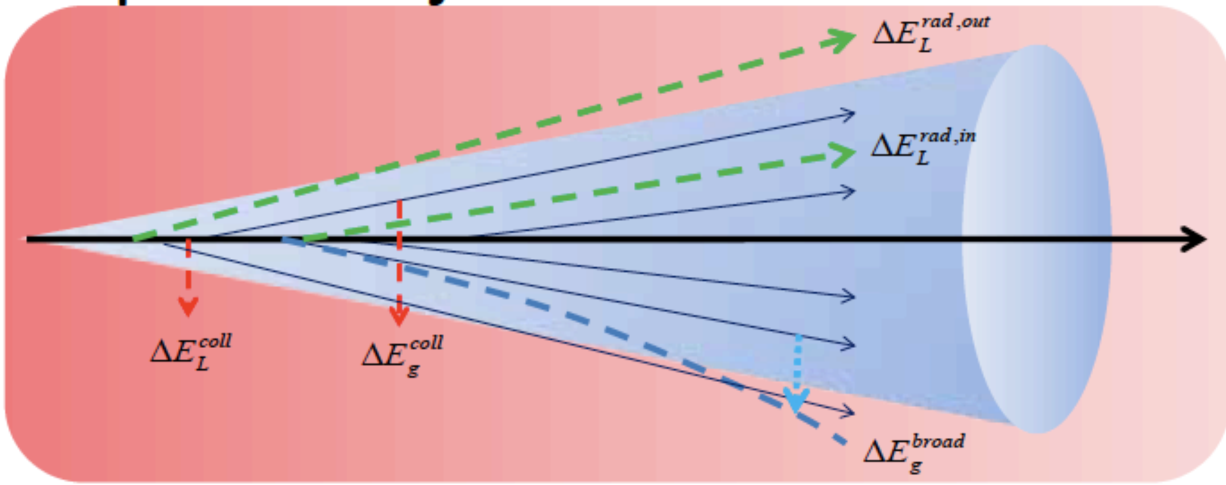


Jet probes of the quark gluon plasma

Jet - QGP interactions schematically

From Quark Matter 2011 talk by Muller, Qiu

A partonic jet shower in medium



Leading parton:

Transfers energy to medium by elastic collisions

Radiates gluons due to scatterings in the medium (*inside* and *outside* jet cone)

Radiated gluons (*vacuum* & *medium-induced*):

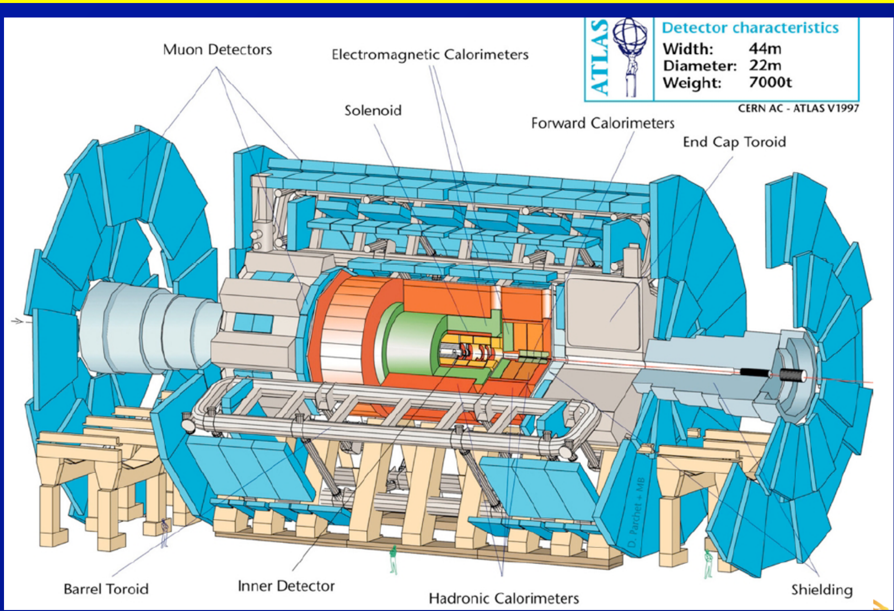
Transfer energy to medium by elastic collisions

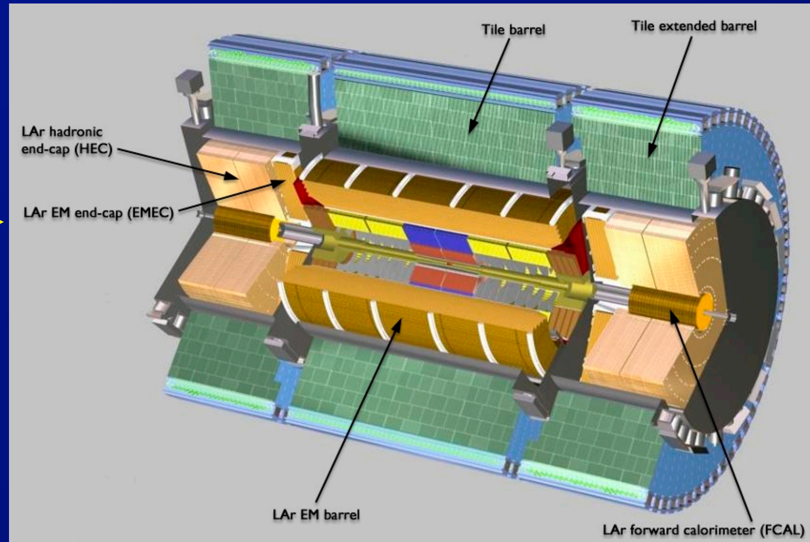
Be kicked out of the jet cone by multiple scatterings after emission

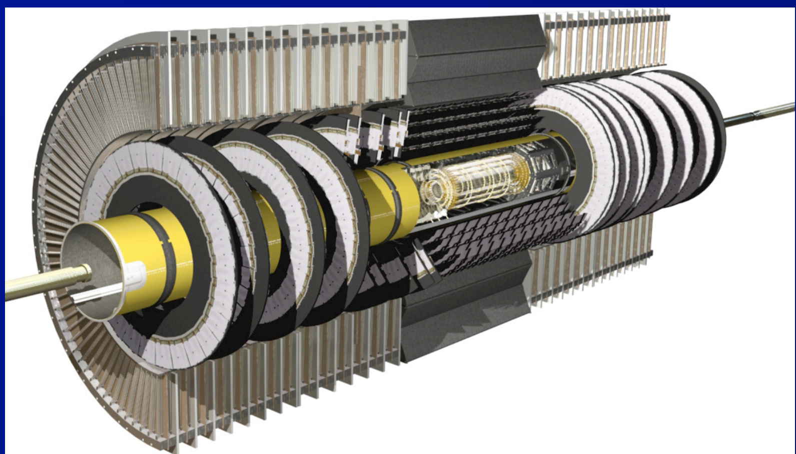
- Complicated theoretical problem
  - Need to go beyond single/di-hadrons in order to test our understanding of the physics

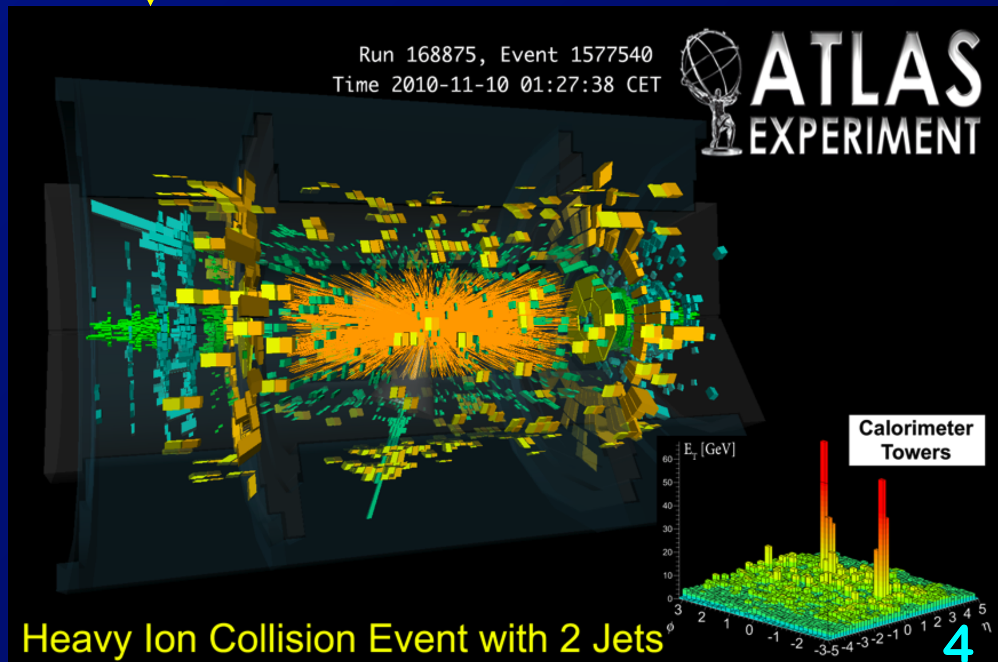
    ⇒only then is precision possible

Pb+Pb Measurements in ATLAS

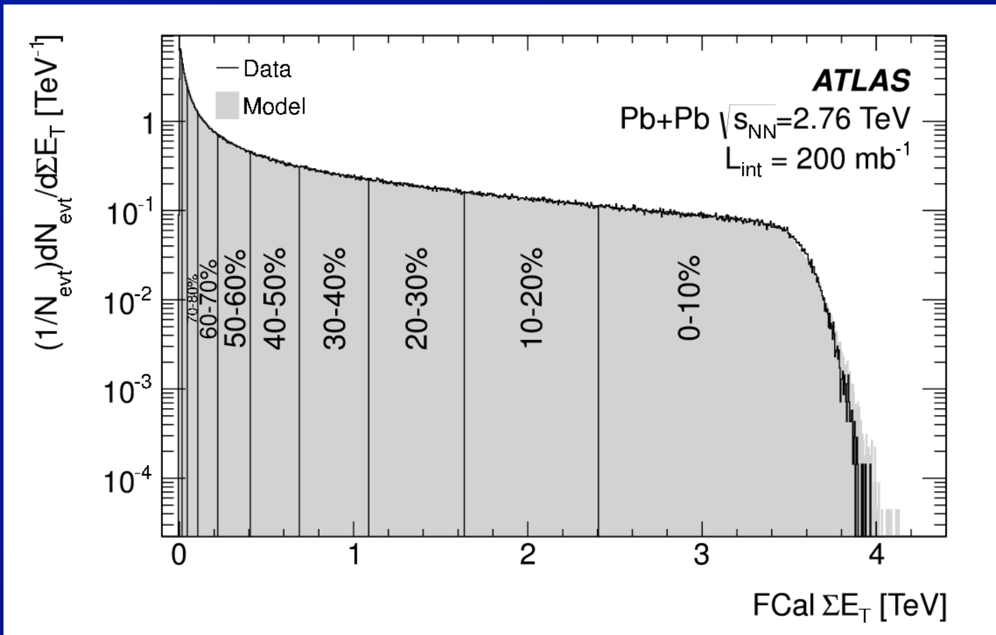








ATLAS: Pb+Pb centrality

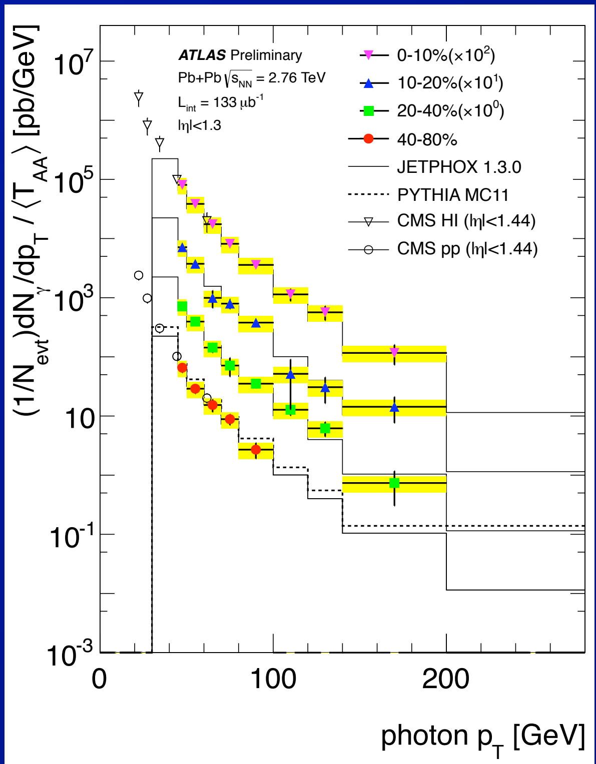


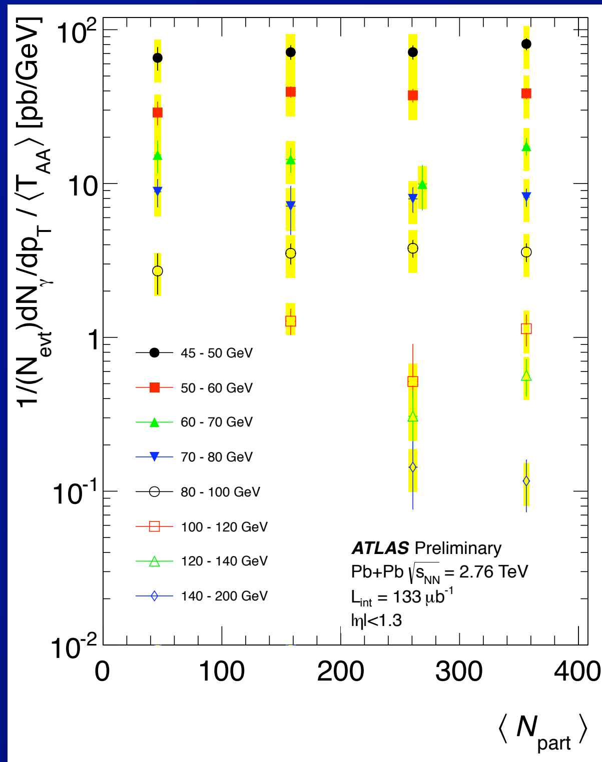
Centrality	$\langle N_{part} \rangle$	$\langle N_{coll} \rangle$
0 – 10%	356 ± 2	1500 ± 115
10 – 20%	261 ± 4	923 ± 68
20 – 30%	186 ± 4	559 ± 41
30 – 40%	129 ± 4	322 ± 24
40 – 50%	86 ± 4	173 ± 14
50 – 60%	53 ± 3	85 ± 8
60 – 80%	23 ± 2	27 ± 4

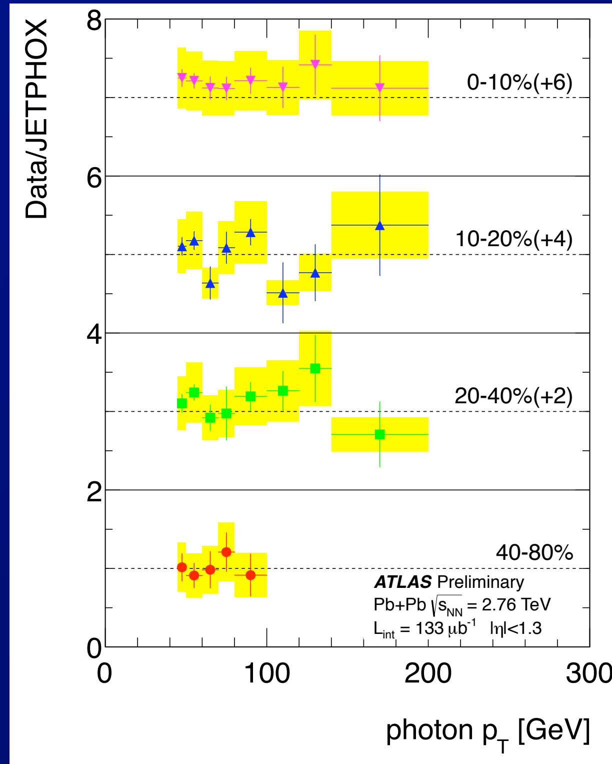
- Pb+Pb collision centrality characterized by ΣE_T in forward calorimeters ($3.2 < |\eta| < 4.9$).
  - Also quantified using number of participants (N_{part})
  - Pb+Pb partonic luminosity expressed in terms of "number of nucleon-nucleon collisions" (N_{coll}) or T_{AA}

    ⇒Calculated using standard Glauber Monte Carlo.

Pb+Pb: Prompt photon production





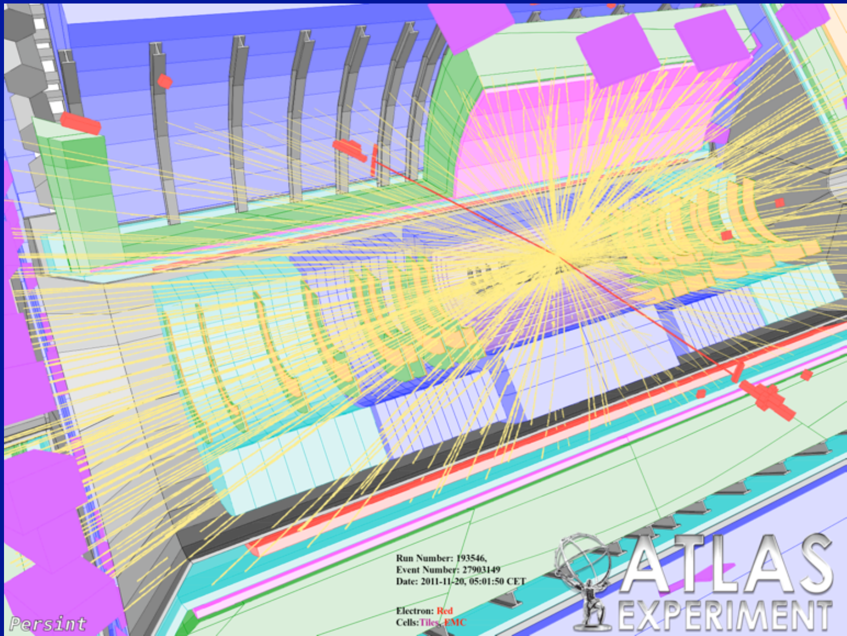


- Photon spectra over $40 < p_T < 200$ GeV
  - well described by JETPHOX multiplied by T_{AA}
  - Yield / T_{AA} ~ independent of centrality

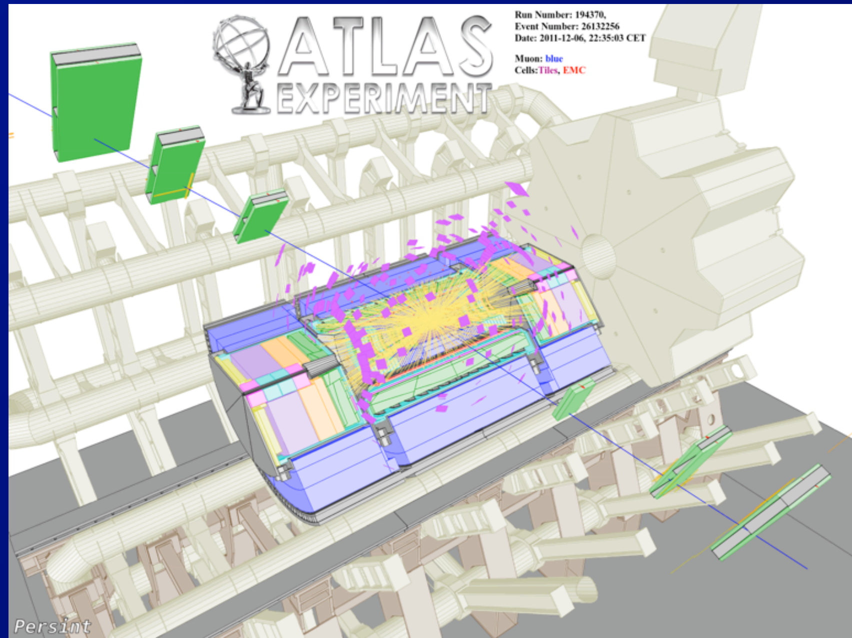
    ⇒ Hard QCD photon production varies with Pb+Pb centrality as expected

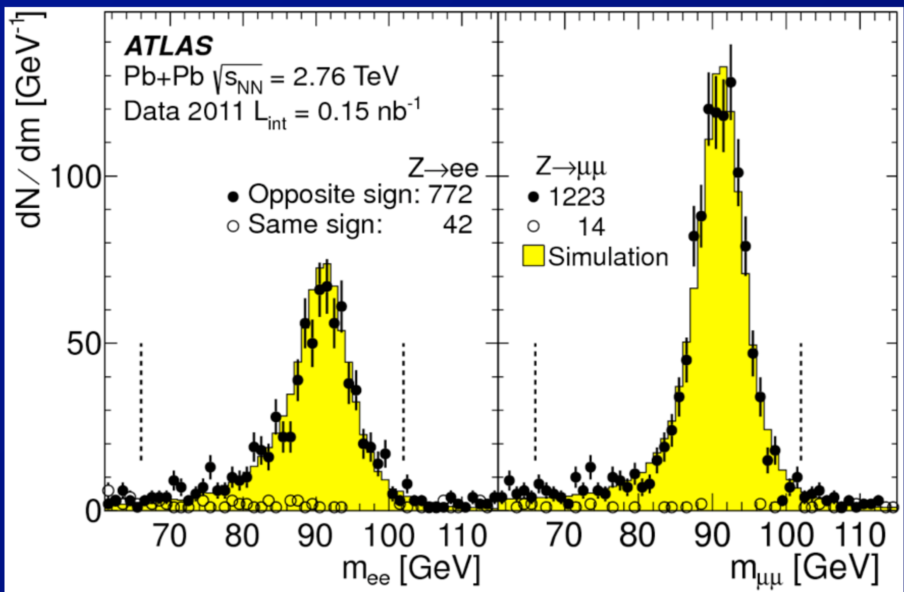
Pb+Pb: Z production

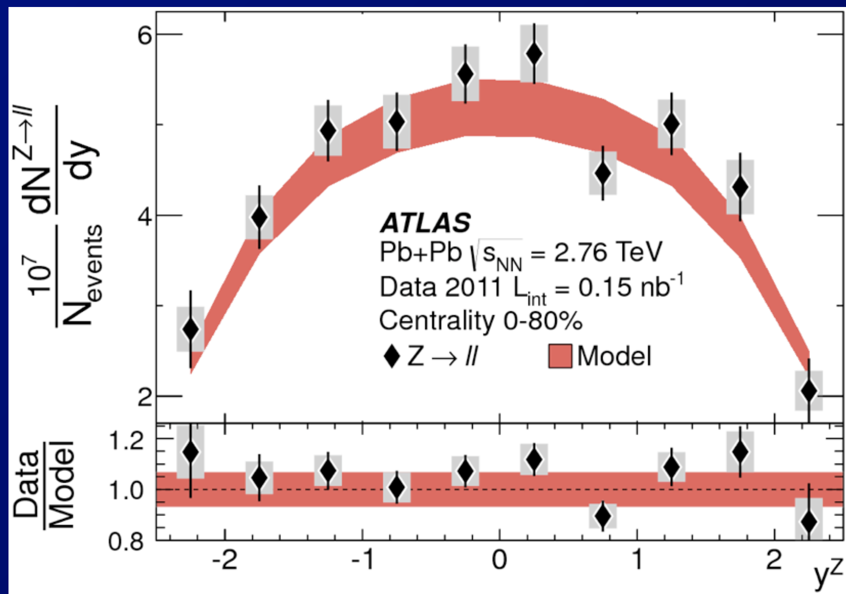
$Z \rightarrow e^+e^-$ event display



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

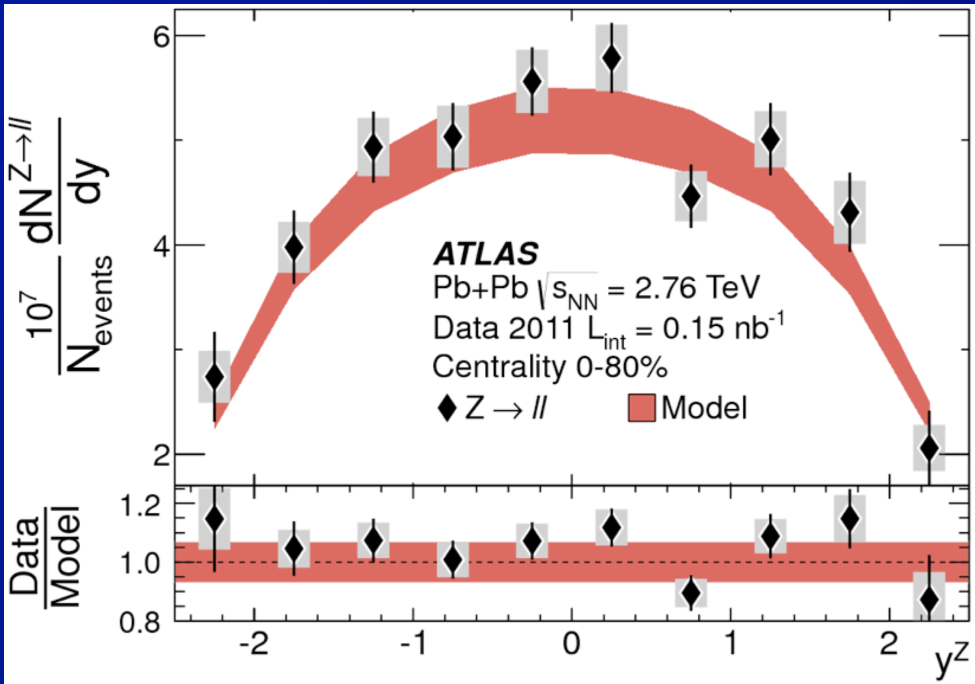


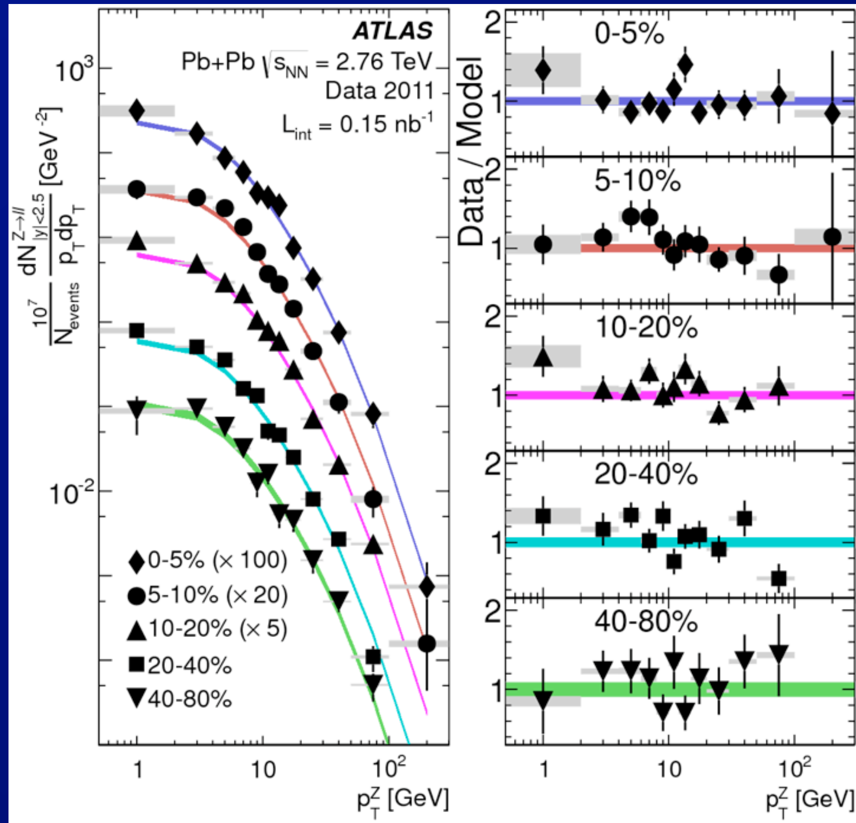




Pb+Pb: Z production (2)

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



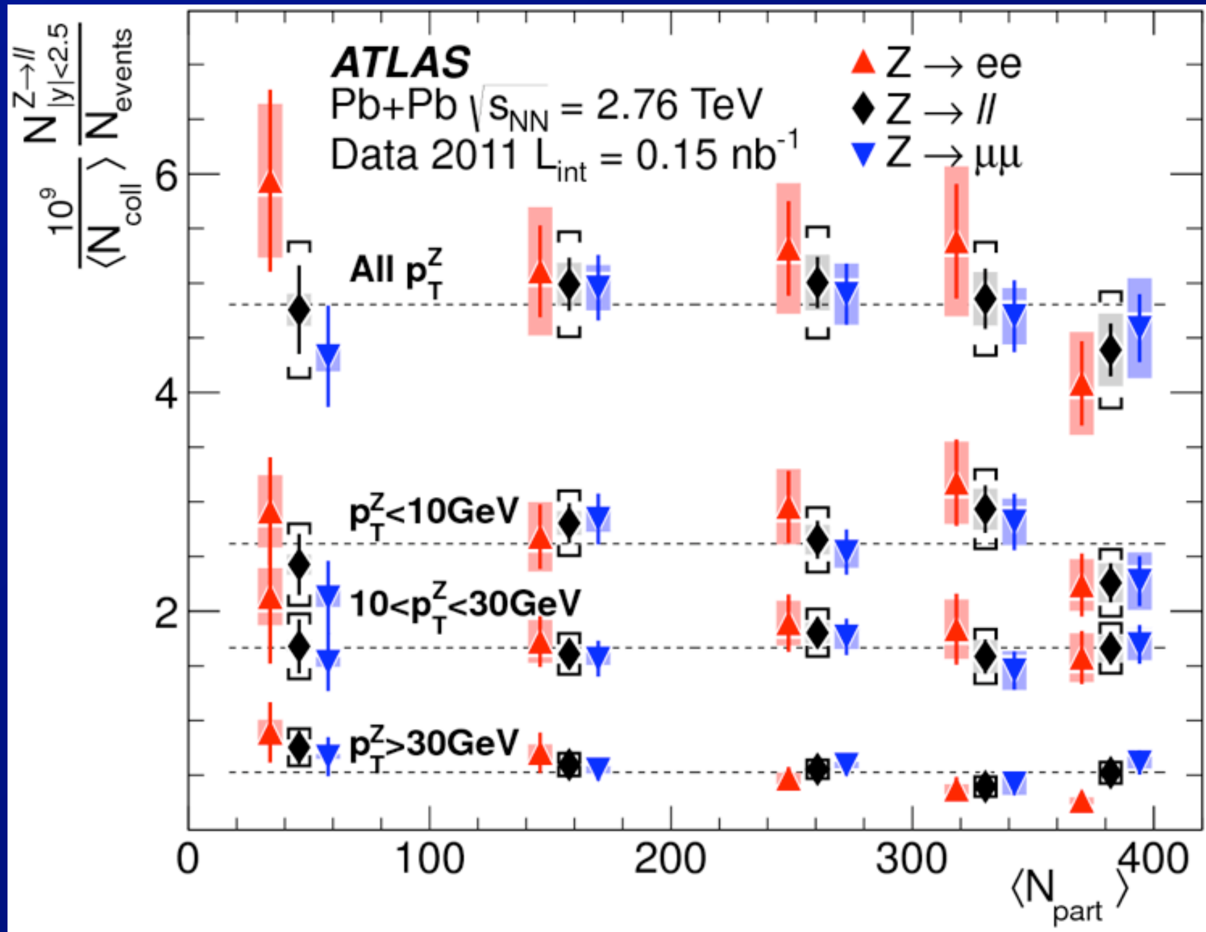


- Compare Pb+Pb Z rapidity distributions (minimum-bias) and pT spectra to PYTHIA scaled to NNLO calculations
  - No nuclear PDFs

    ⇒ Nuclear PDF effects <~ 20%

Pb+Pb: Z production (3)

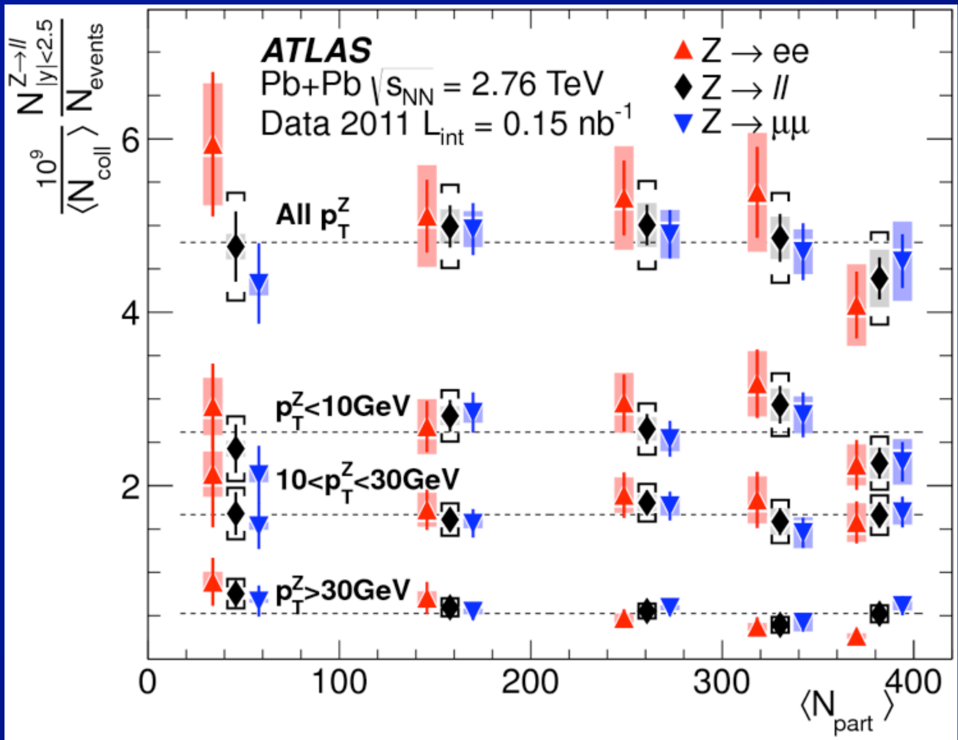
Phys. Rev. Lett. 110, 022301 (2013)

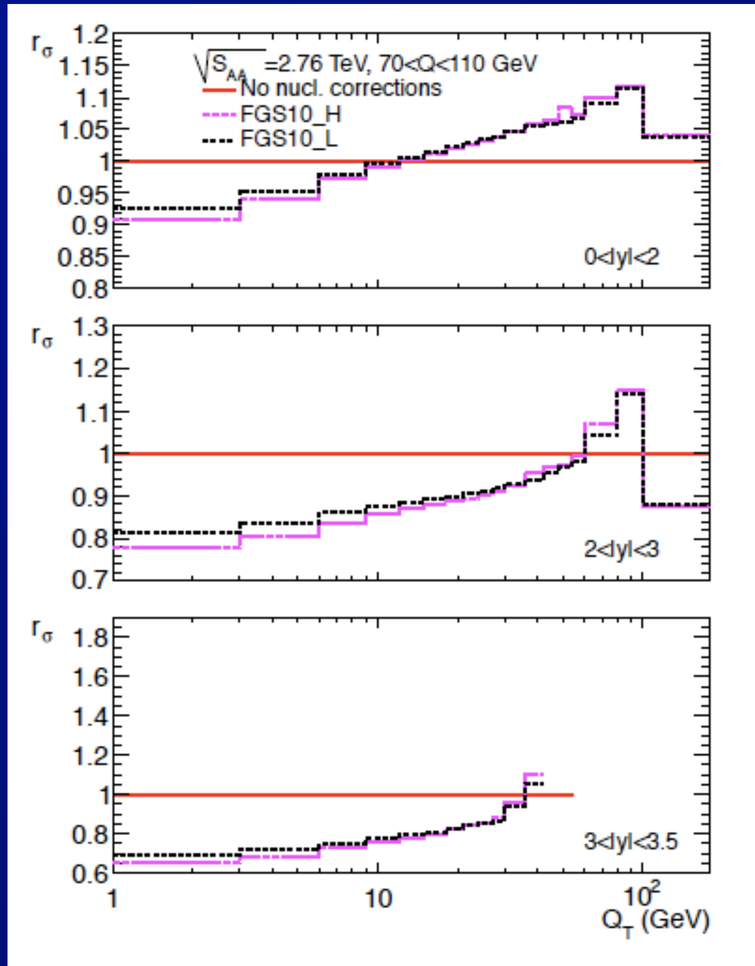


- Check T_{AB}/Ncoll scaling of Z yield in different p_T intervals
  - Slight drop in central yield/Ncoll for p_T < 10 GeV
    - ⇒But not significant given errors. Expected?

Pb+Pb: Z production (4)

Guzey et al, Eur. Phys. J. A49 (2013) 35

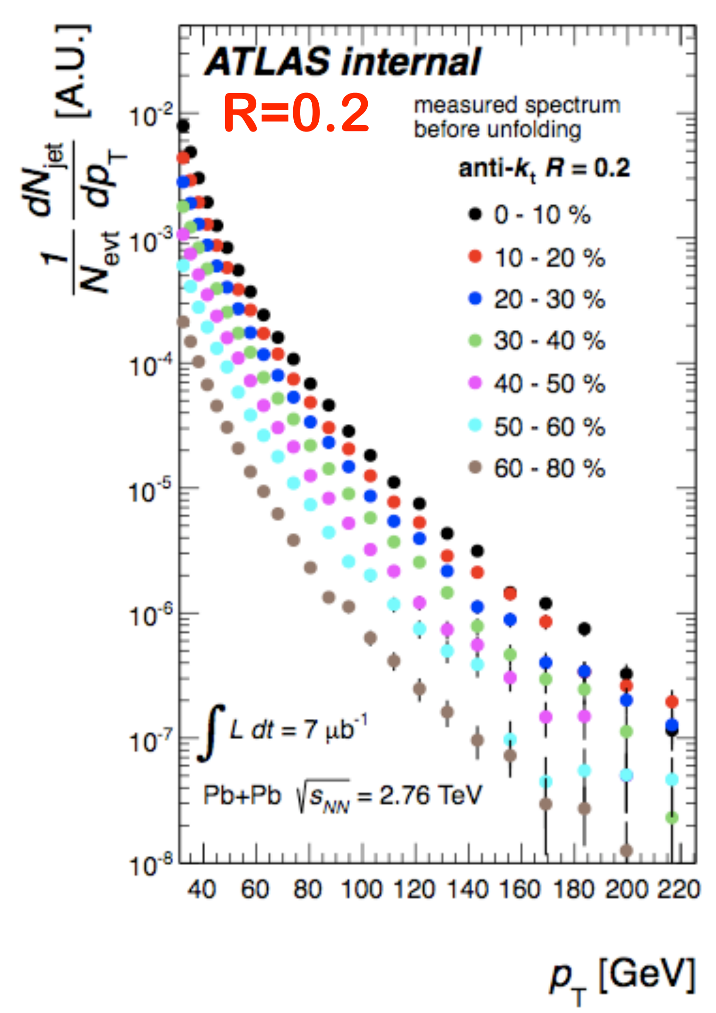


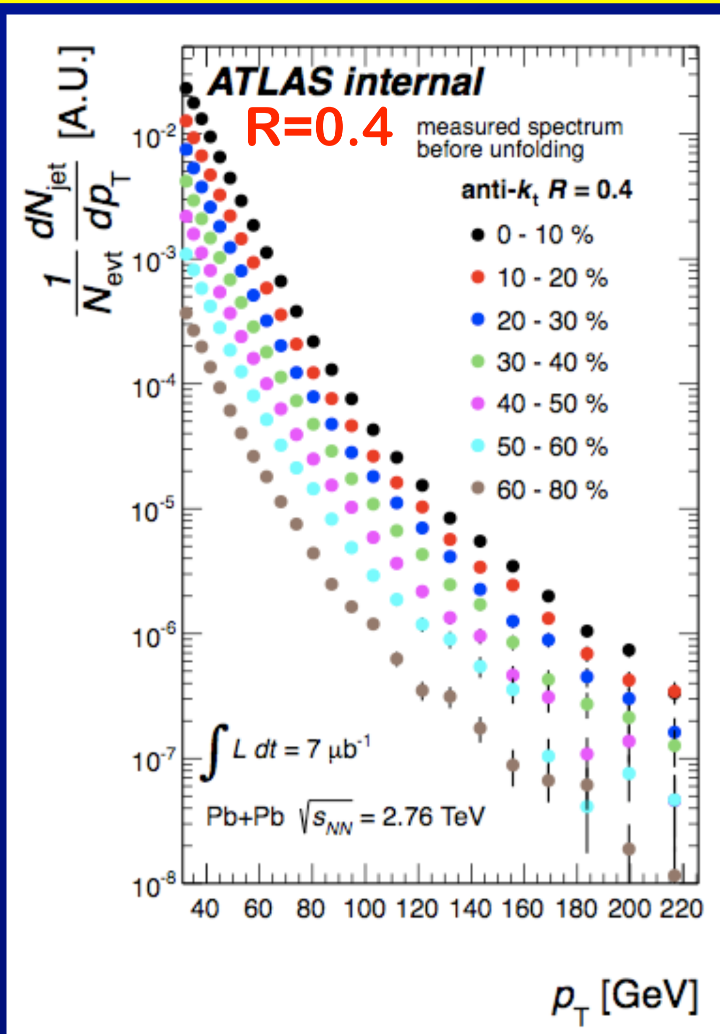


- Predictions of ~ 10% nuclear modifications in Pb+Pb at both low Q_T and high Q_T
  - ⇒Measurements not precise enough to test yet
  - ⇒But maybe with 2013 2.76 TeV p-p data

Jet quenching

Pb+Pb Jet Spectra



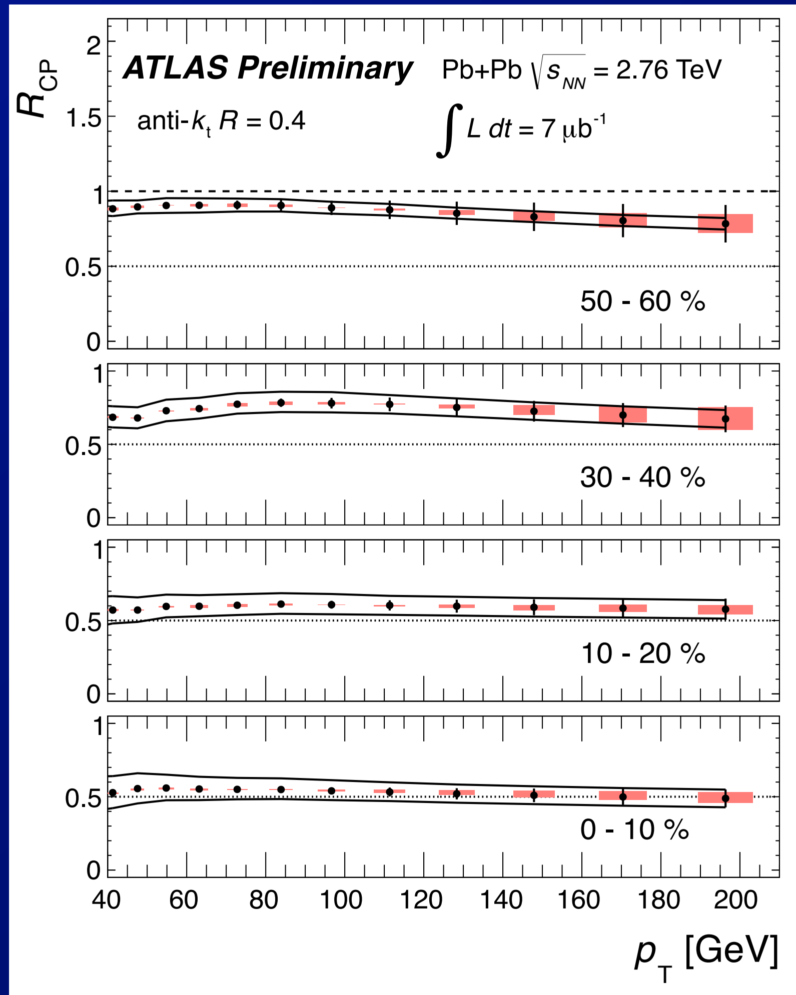


Unfolded (SVD) and efficiency corrected

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

Jet yields: centrality dependence

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



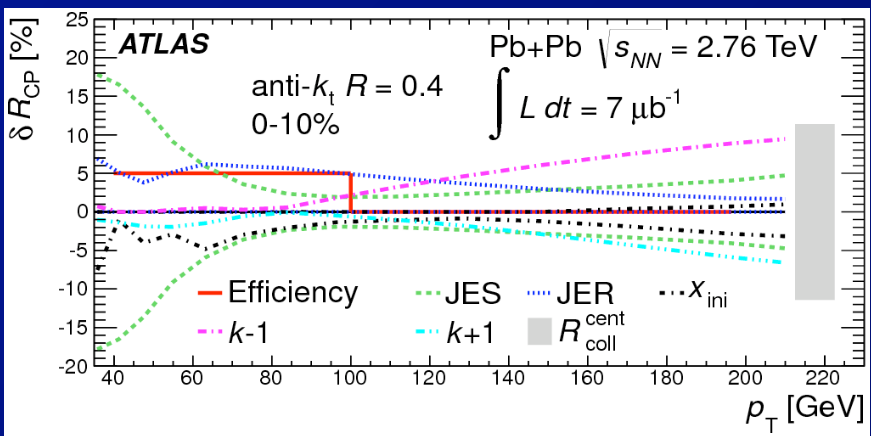
$$R_{CP} = \frac{\frac{1}{N_{coll}}\frac{1}{N_{evt}}\frac{dN}{dp_T}\Big|_{cent}}{\frac{1}{N_{coll}}\frac{1}{N_{evt}}\frac{dN}{dp_T}\Big|_{60-80}}$$

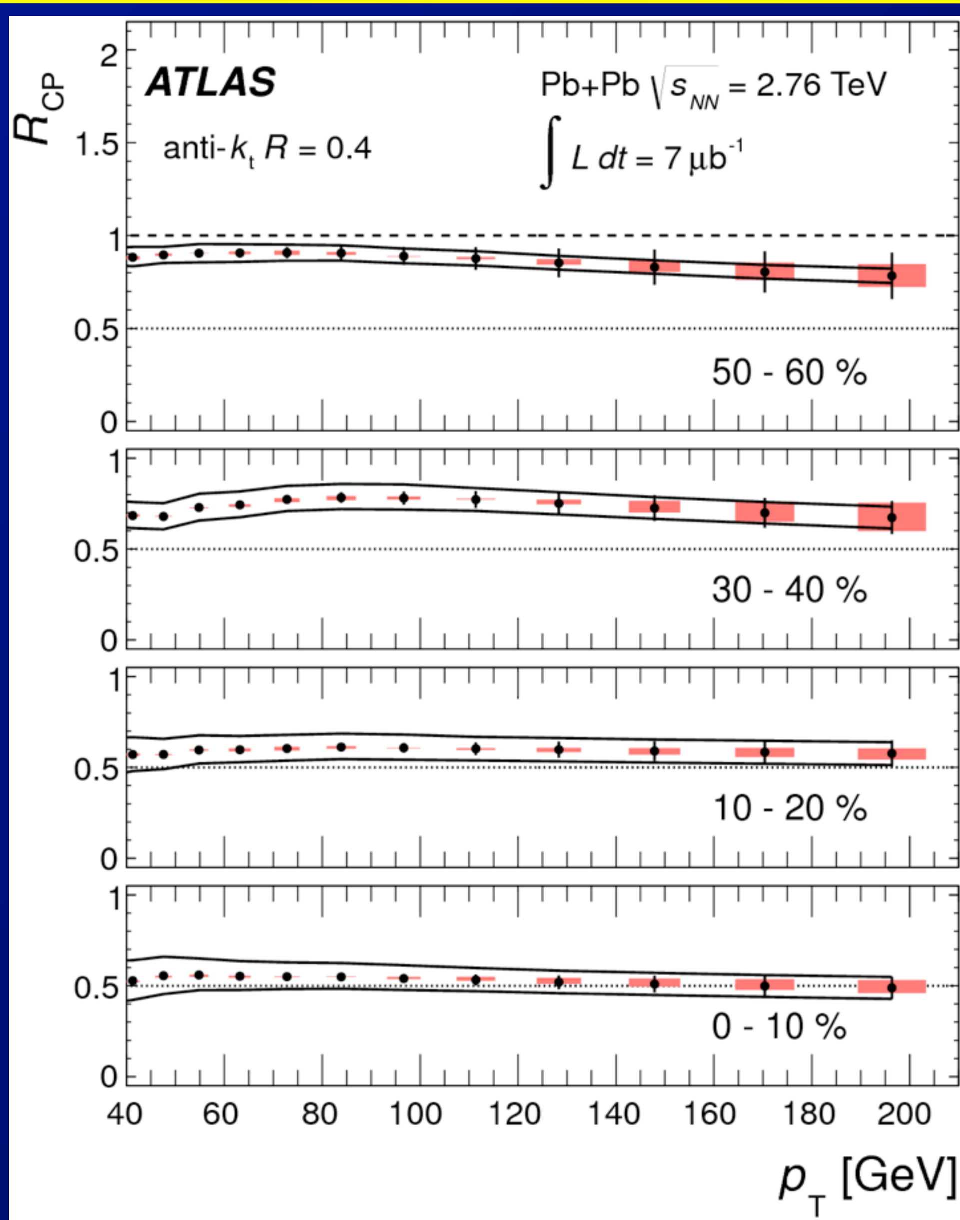
- Overall jet energy scale divides out in ratio

R = 0.4 Jet Rcp

Systematic errors

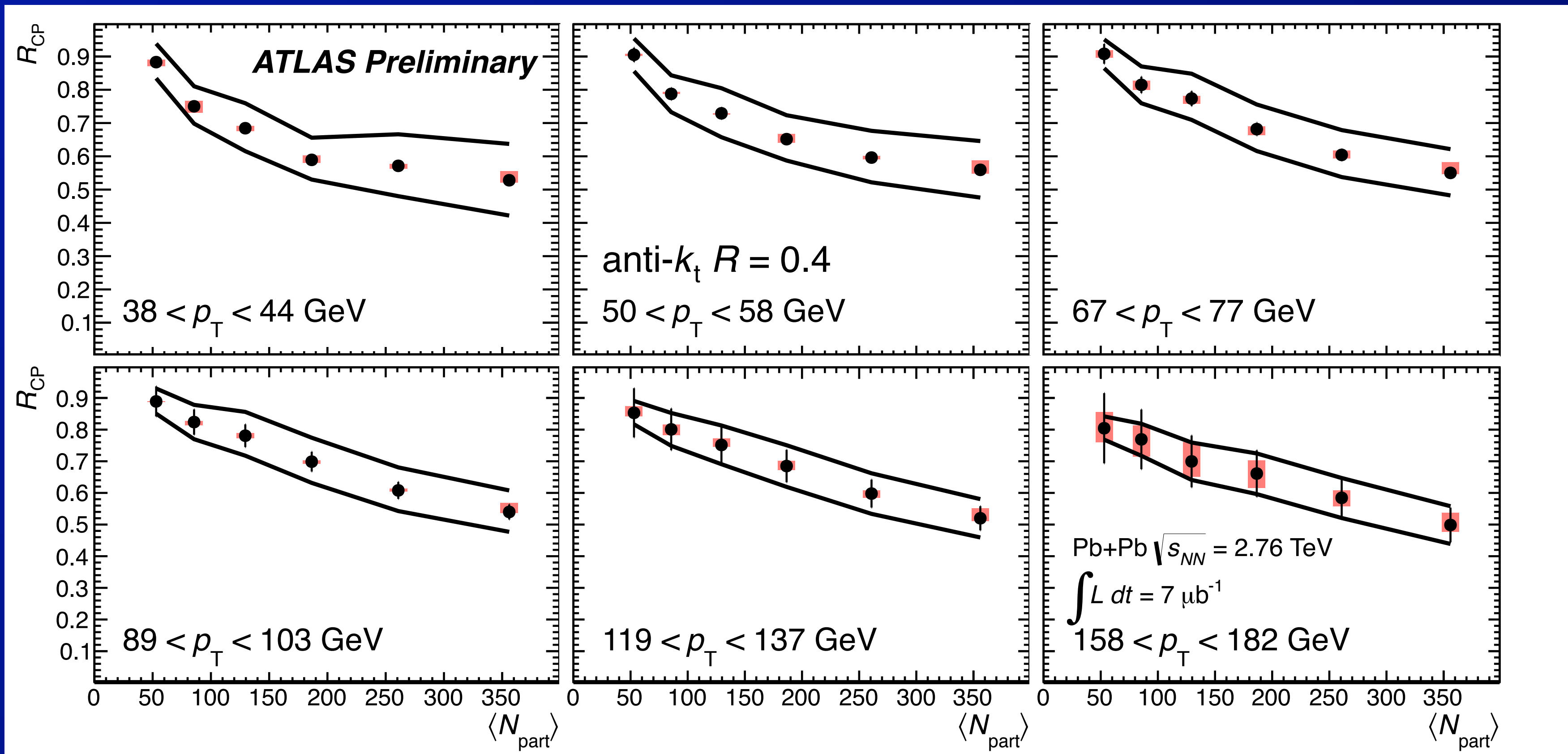
- Black band: fully correlated systematics
- Red boxes: partially correlated systematics
- Error bars:
  - √ of diagonal element of unfolding statistical covariance matrix





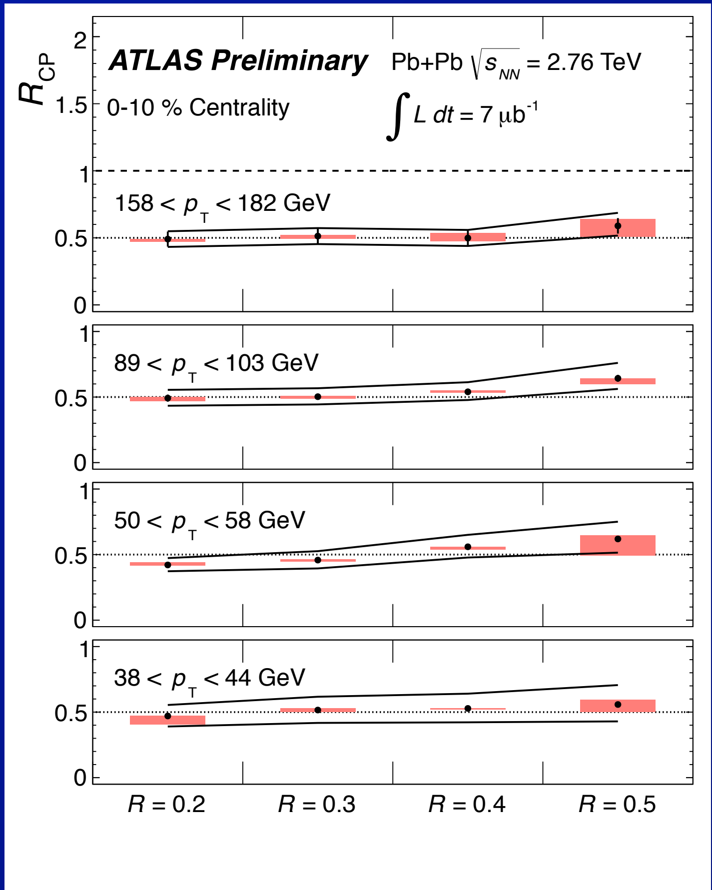
Phys. Lett. B 719 (2013) 220-241

Centrality dependence of jet R_{cp}

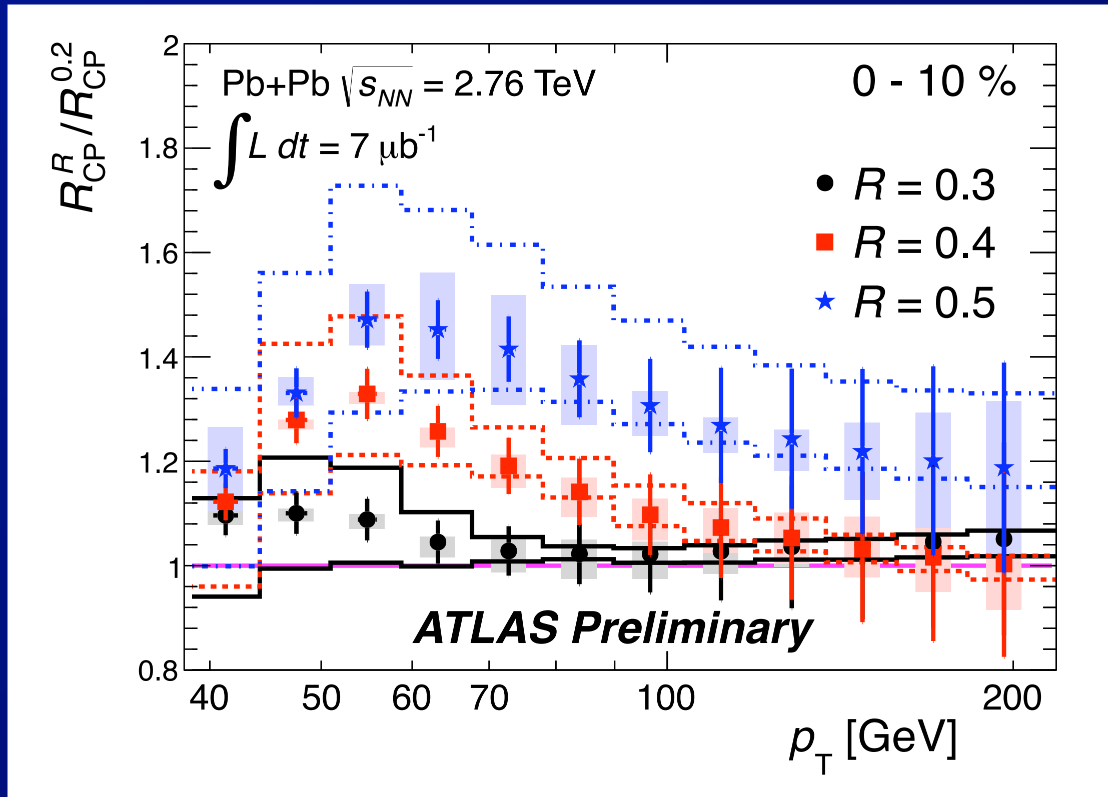


- Study centrality evolution for fixed jet p_T
  - R_{cp} vs N_{part}
    - ⇒Smooth turn on of jet suppression between peripheral and central collisions.

Jet radius dependence of R_{cp}



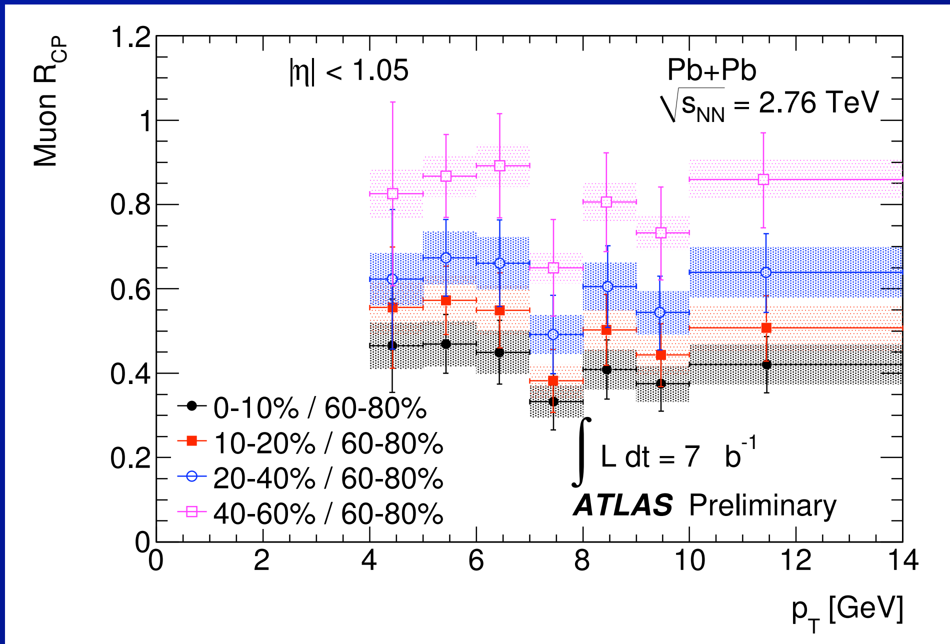
Significant cancellation of correlated errors

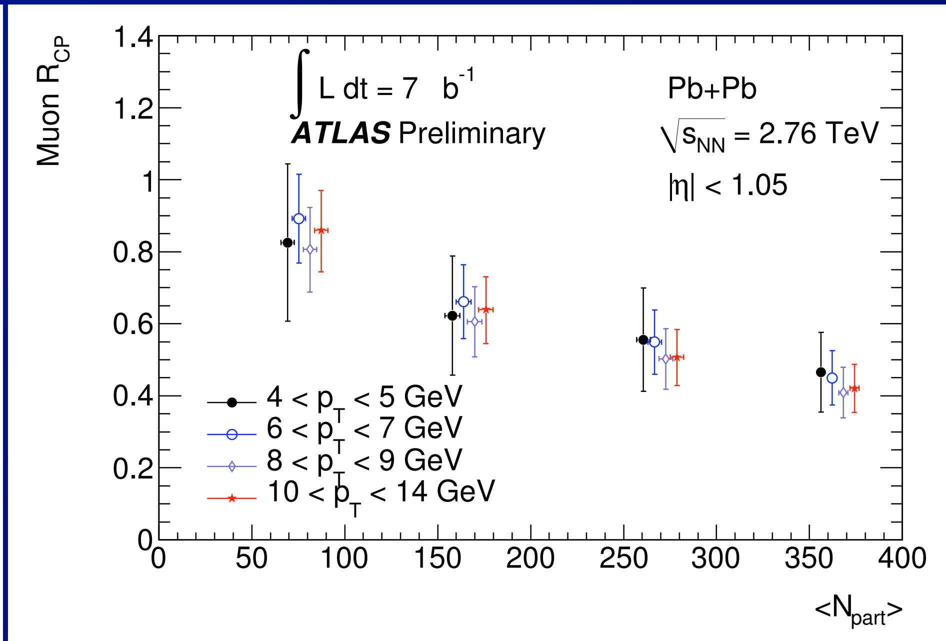


- Evaluate jet radius dependence of R_{cp}
  - Modest but significant variation of R_{cp}
  - Less suppression for larger R

    ⇒An indication of jet broadening?

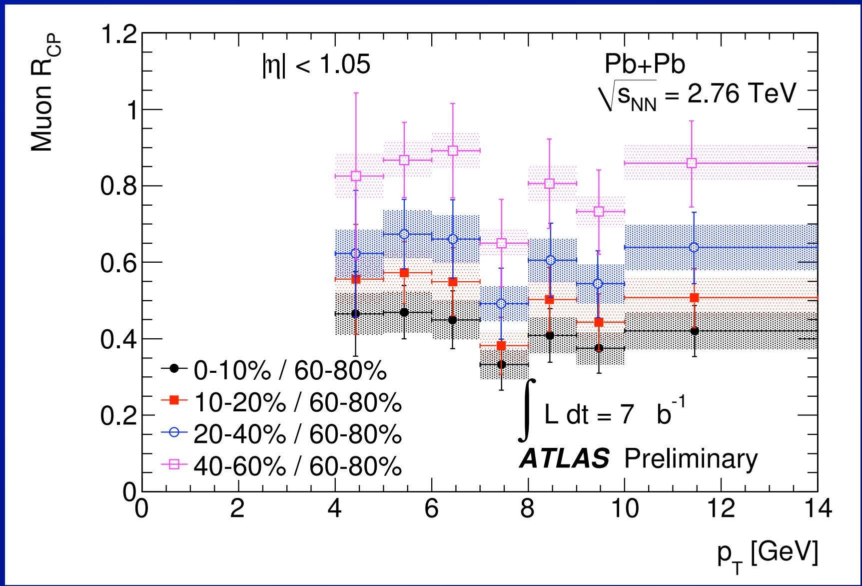
Single muons from heavy quark decays

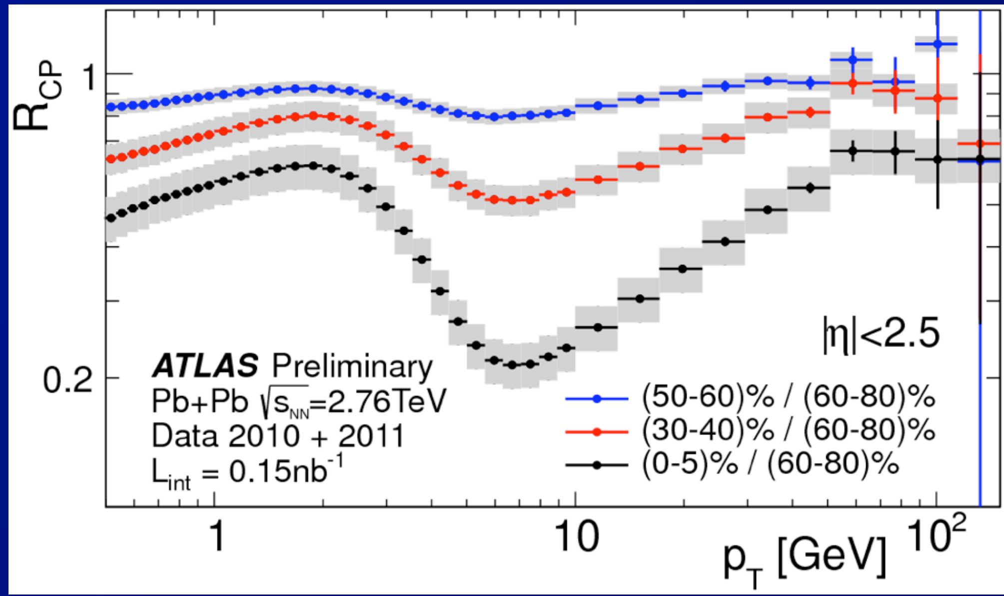




- In measured p_T range, muons primarily from charm and bottom decays.
  - J/ψ contribution ~ 1%
- Evaluate R_{cp} using 60-80% peripheral reference
  - ⇒ Factor of 2.5 suppression in 0-10% relative to 60-80%
  - ⇒ Independent of muon p_T within errors
  - ⇒ Evolution with N_{part} consistent between p_T bins

Single muons, charged comparison



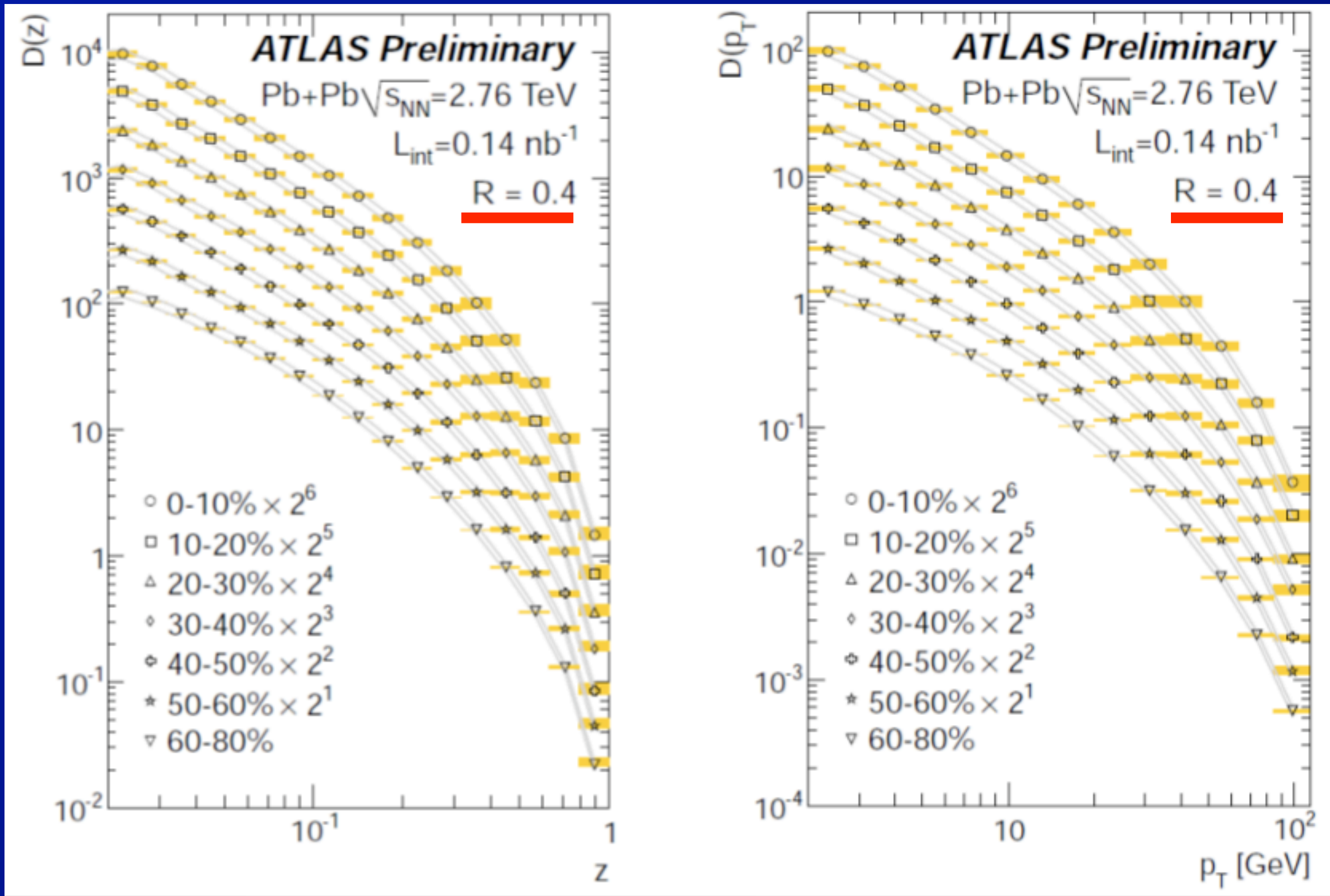


- See less suppression of heavy flavor decay muons than single hadrons @ lower p_T
  - But, both muon and hadron p_T poorly correlated with jet momentum.

    ⇒Jets

    ⇒ b-tagged jets, especially at lower p_T (to come)

Inclusive jet fragmentation

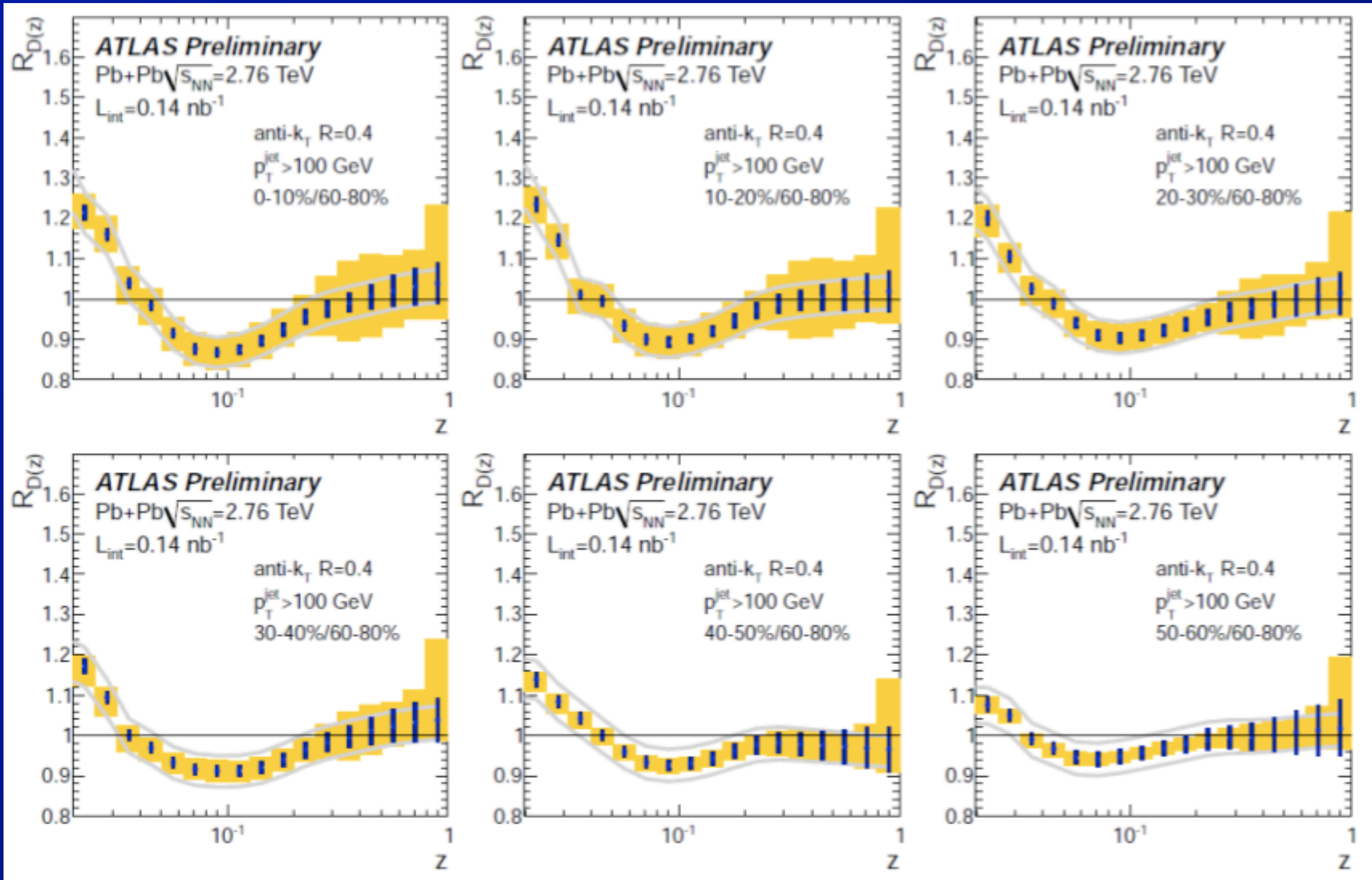


Unfolded for jet and charged particle resolution

$$D(z) = \frac{1}{N_{jet}} \frac{dN_{chg}}{dz}, z = \vec{p}_{chg} \cdot \vec{p}_{jet} / \left|\vec{p}_{jet}\right|^2$$

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

Inclusive jet fragmentation (2)

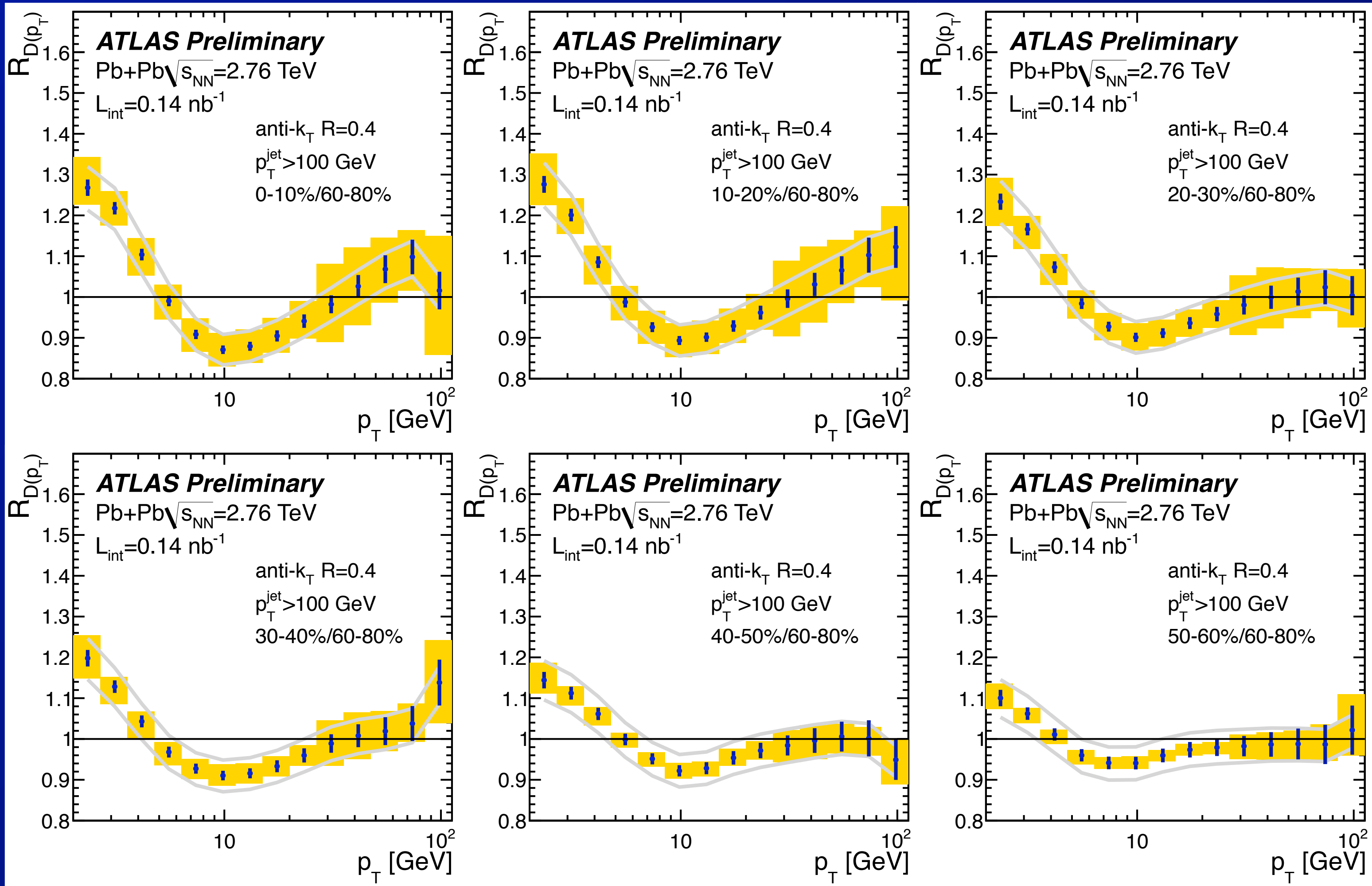


R = 0.4

- First observation of modified parton shower in inclusive jets

  ⇒Not only seeing “left over” unquenched jets.

Inclusive jet fragmentation (3)

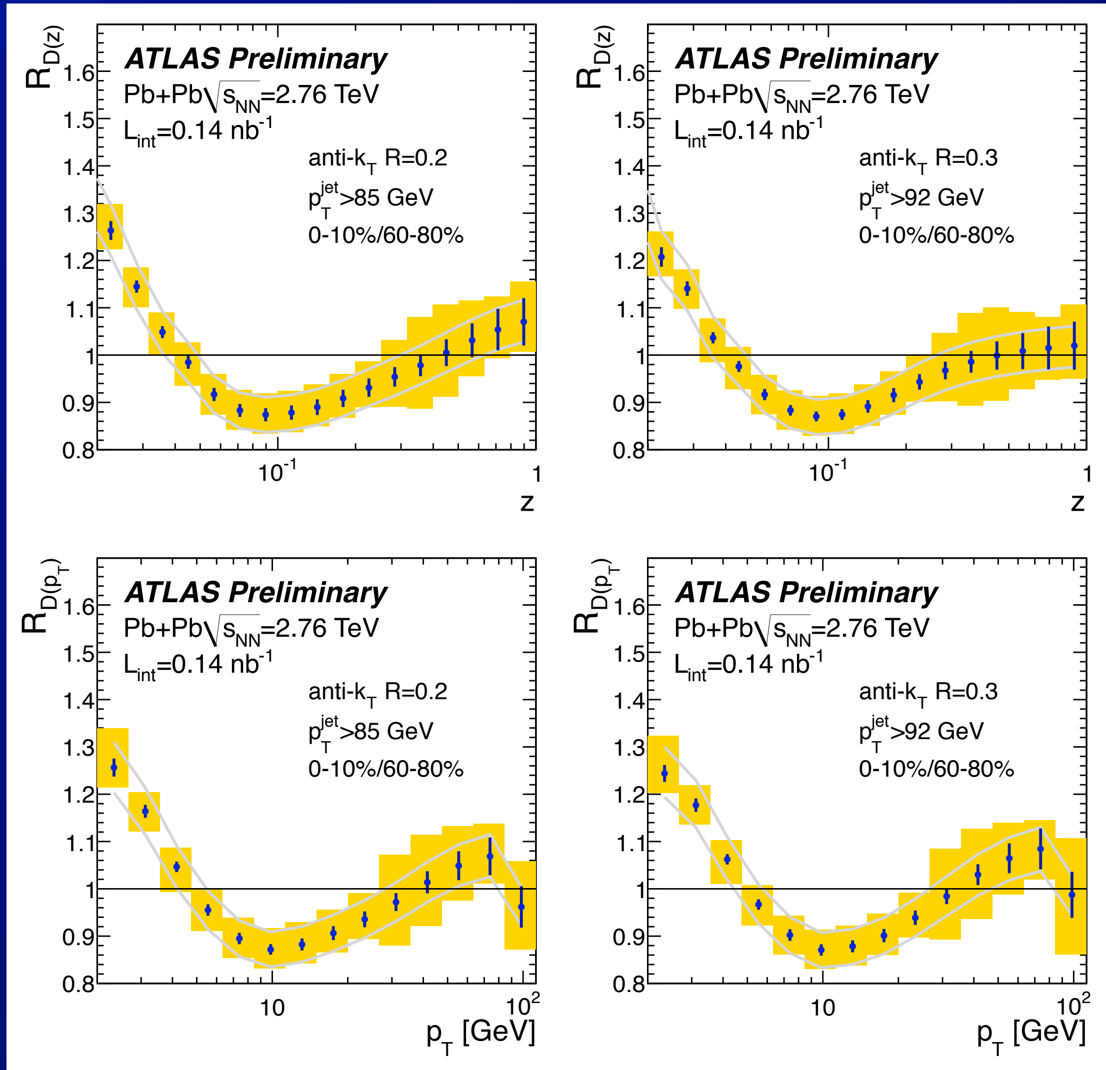


- Check that the modification is not due to the measurement of jet $p_T \Rightarrow D(p_T)$

  $\Rightarrow D(p_T)$ shows similar modifications

Jet fragmentation: R dependence

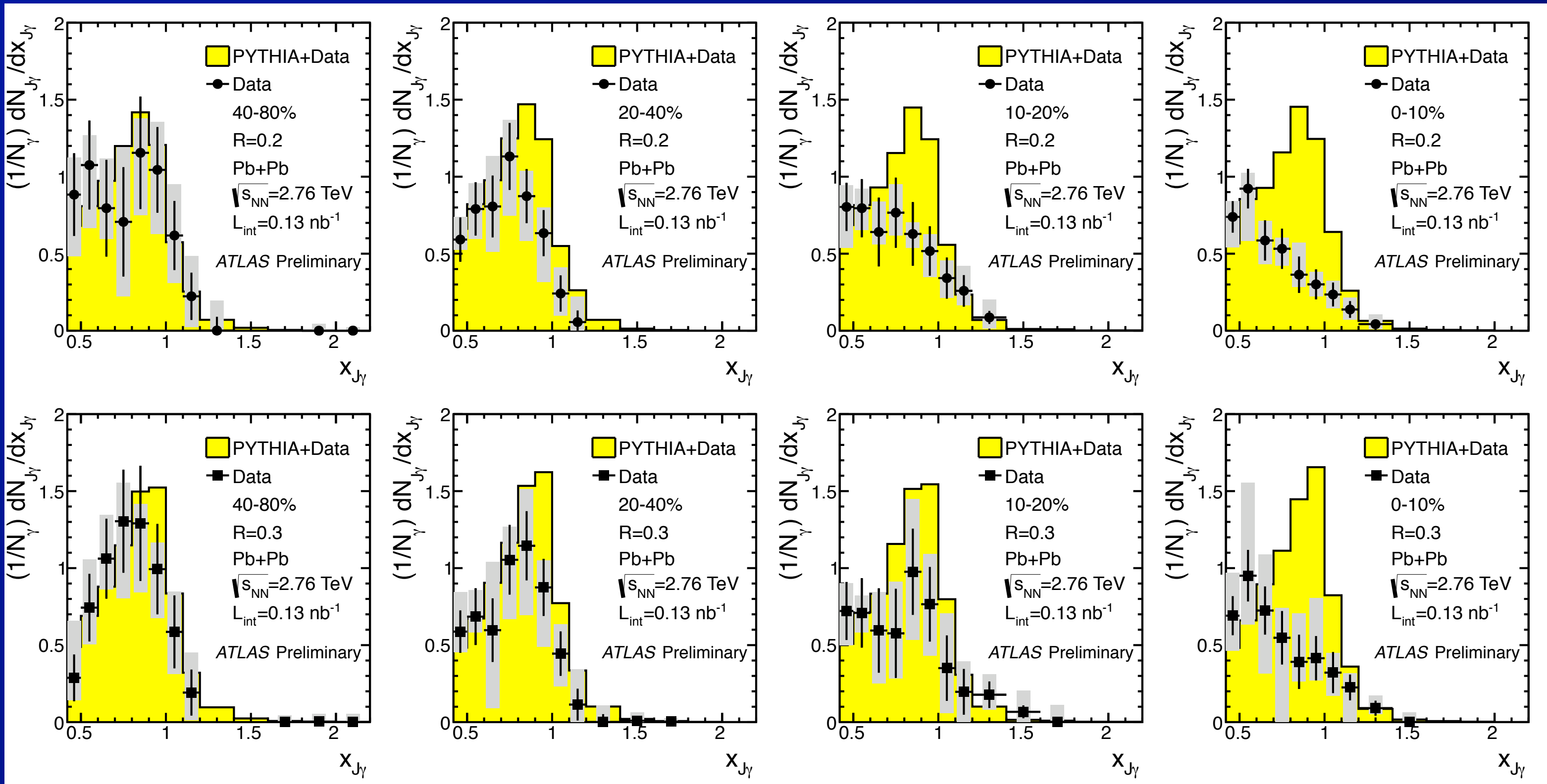
- Check that the modification is not due to underlying event fluctuations
  - Use different jet sizes:
    - ⇒R = 0.2, 0.3
  - Same R = 0.4 for hadrons



- Obtain the same results as for R = 0.4 jets
  - ⇒Observed modifications are robust

γ-jet momentum balance

Peripheral → central



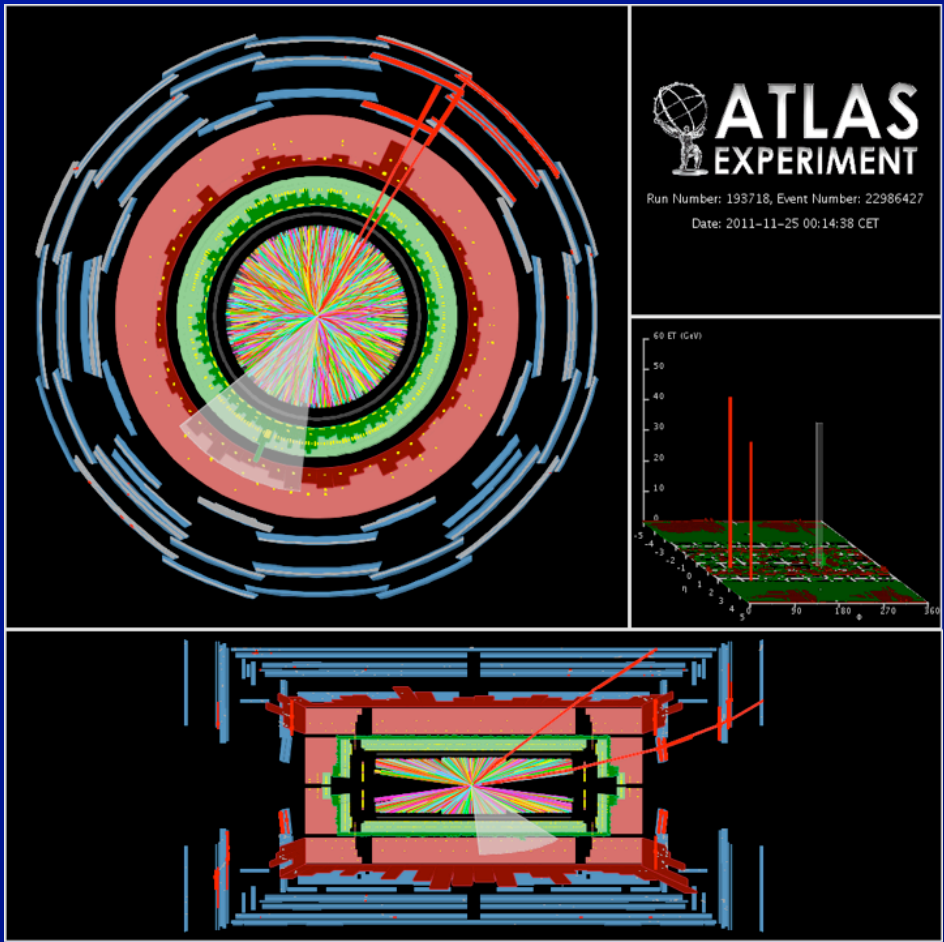
R = 0.2

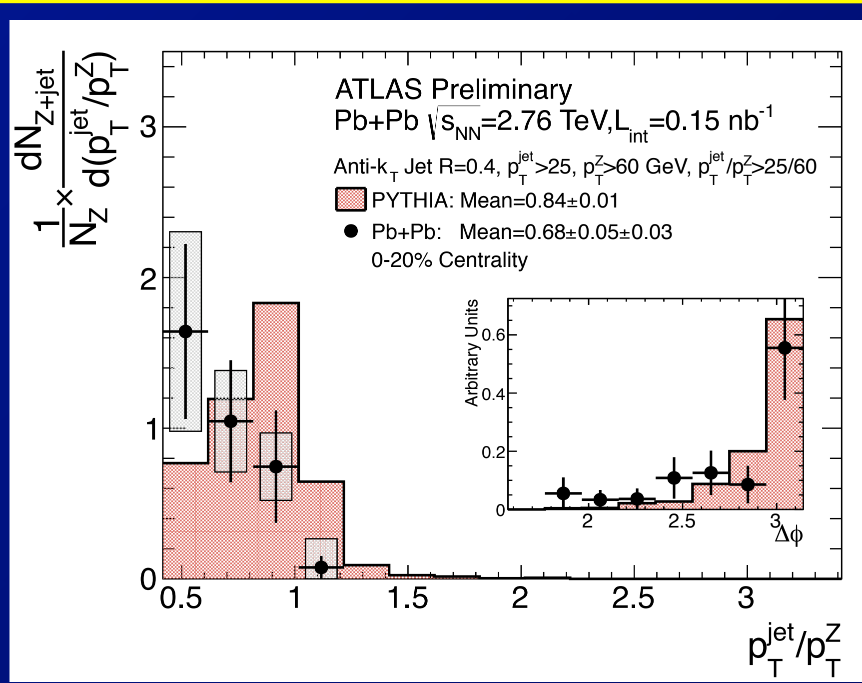
R = 0.3

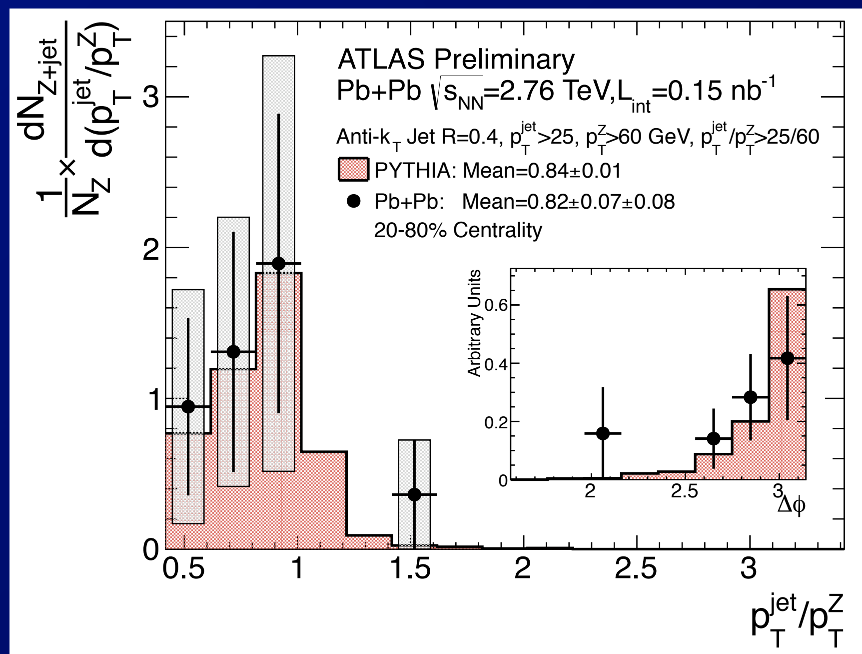
- Plot distribution of $x_J = p_T^{\text{jet}} / p_T^{\gamma}$
  - photon background pairs subtracted
  - unfolded for jet energy resolution

  ⇒Substantial change in γ-jet balance

Pb+Pb Z-jet measurement





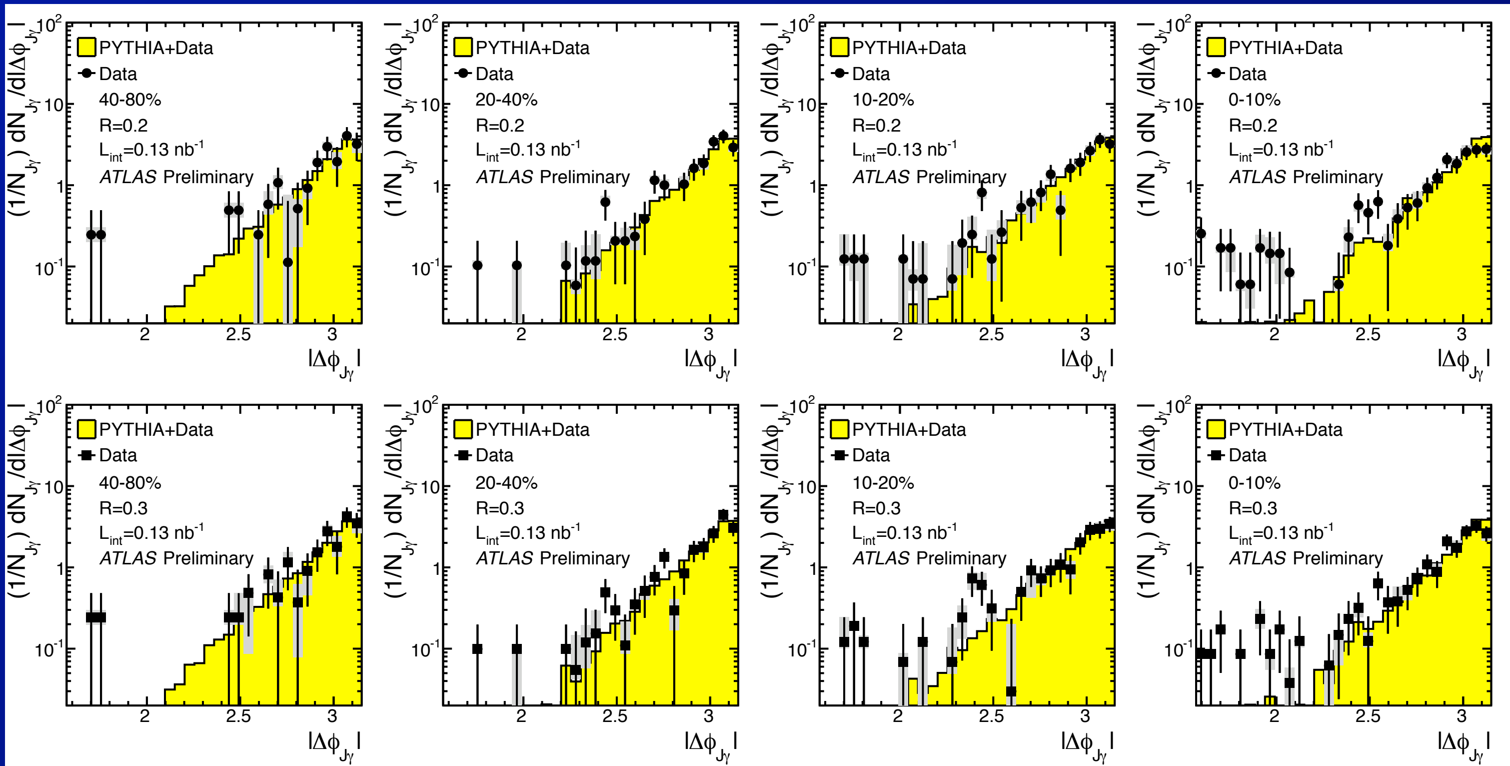


- Z-jet measurements have less background than γ-jet, but smaller rate

  ⇒1st results

γ-jet angular distribution

Peripheral → central

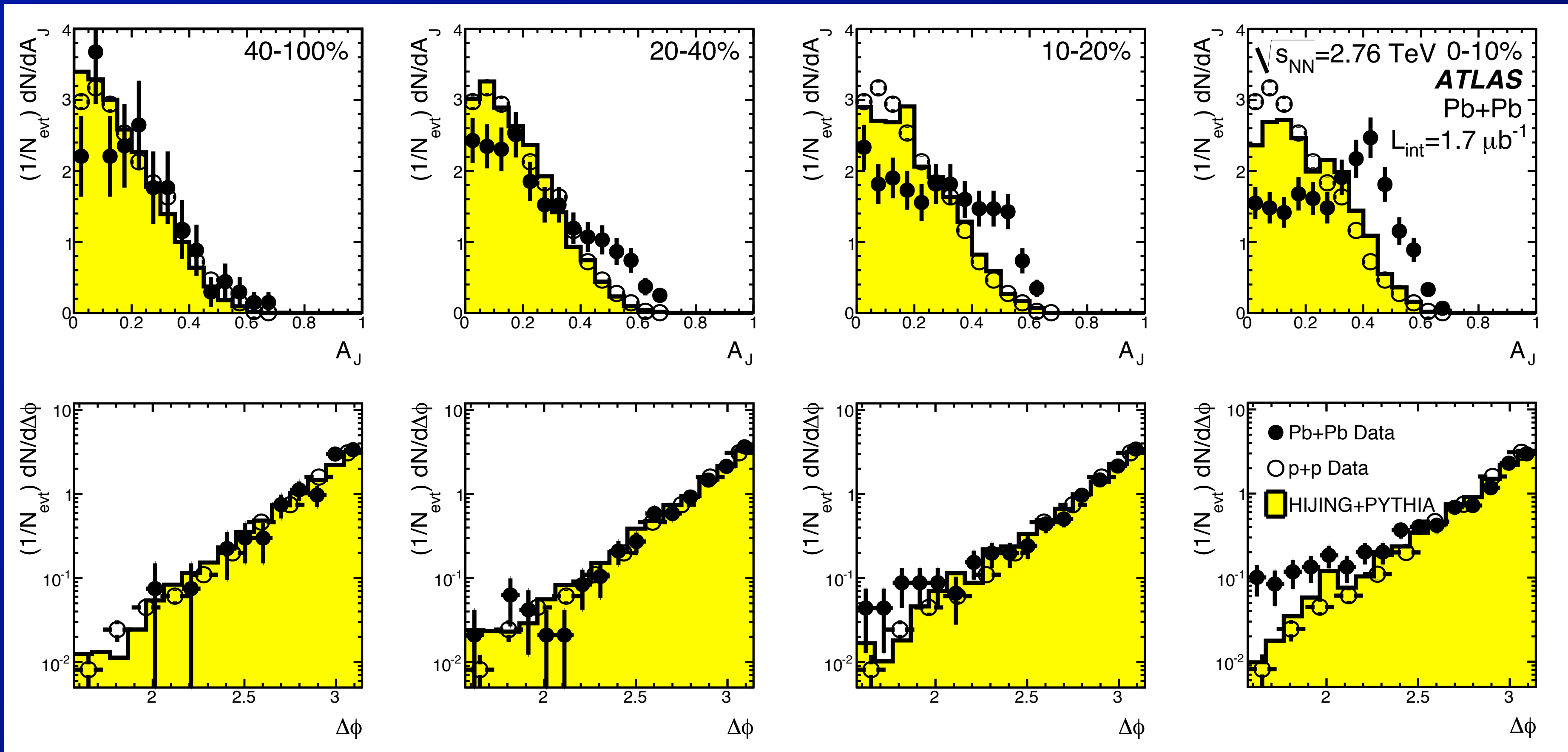


R = 0.2

R = 0.3

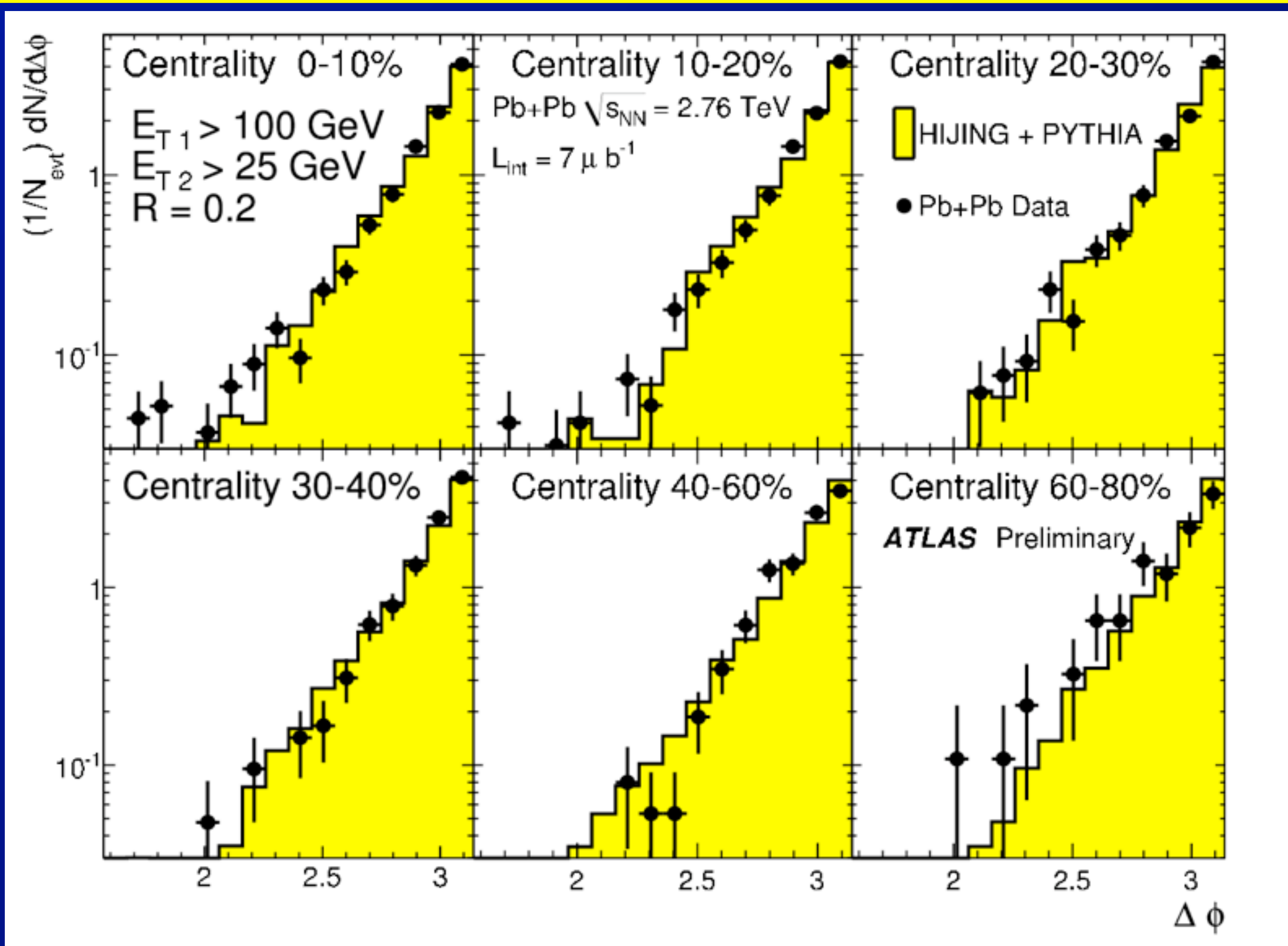
- Take leading jet in hemisphere opposite photons with $60 < p_T < 90$ GeV
  - Jets with $p_T > 25$ GeV, R = 0.2 and 0.3
    - ⇒Distribution of Δφ peaked at π
    - ⇒For following, apply cut $|\Delta\phi - \pi| < 7\pi/8$

Di-jet asymmetry & acoplanarity



- For more central collisions, see:
  - Change in distribution of dijet asymmetry
  - While no change in the distribution of Δφ
    - ⇒Except for combinatoric pairs in central

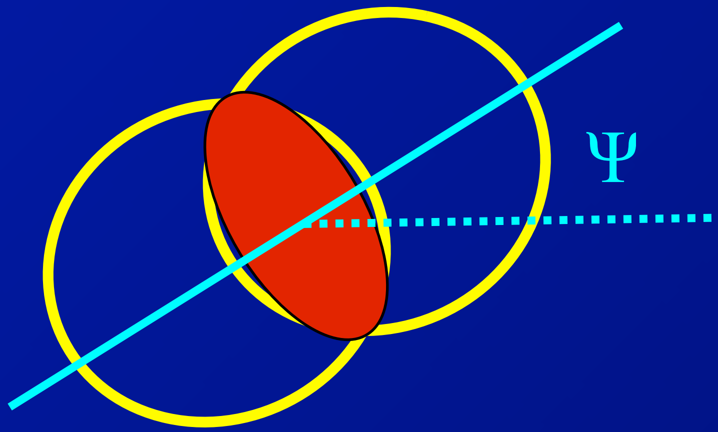
Dijet acoplanarity, R = 0.2



- Look at dijet acoplanarity w/ R = 0.2 jets
  - ⇒ small UE effects
  - ⇒ <NO> broadening

Tomography

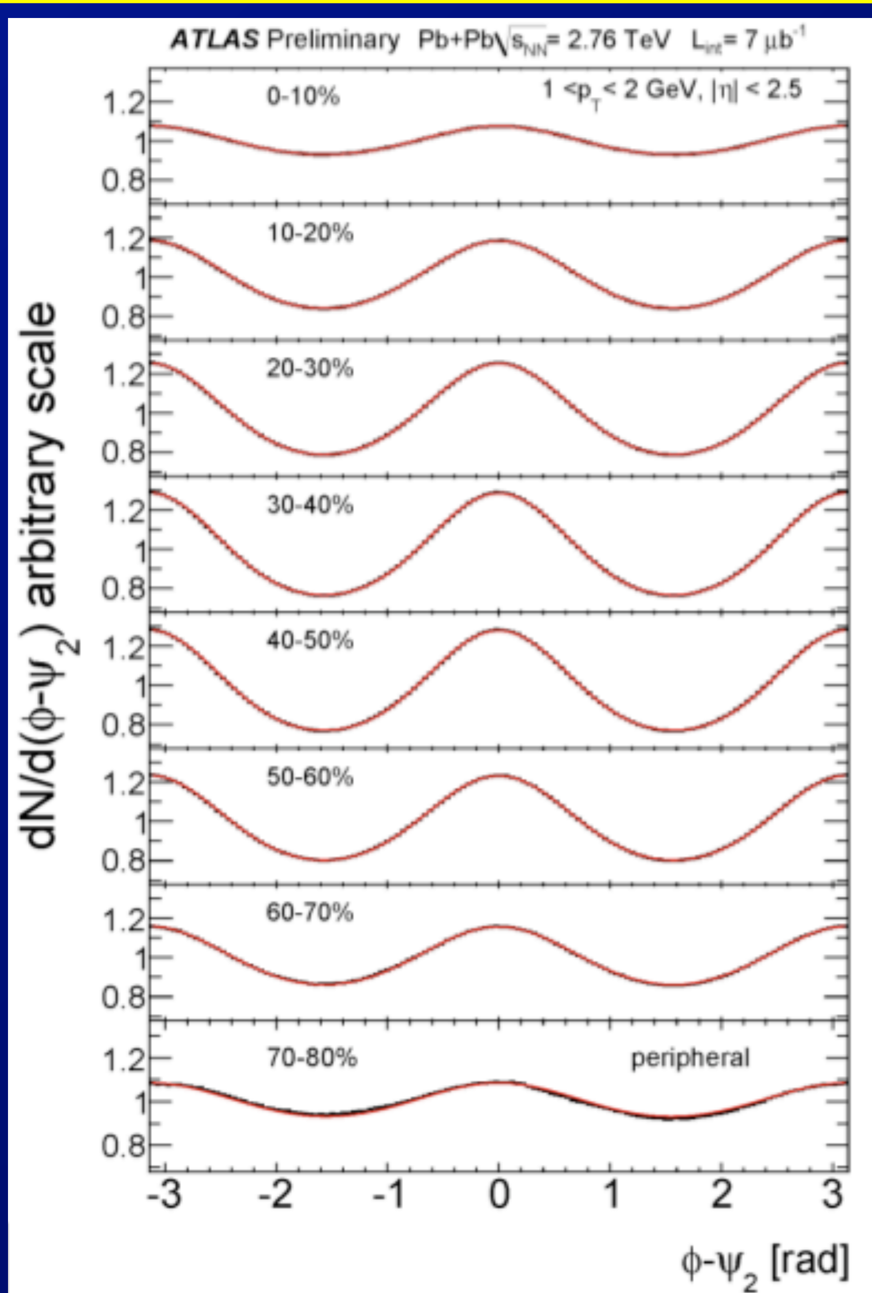
Collective Motion: Elliptic Flow



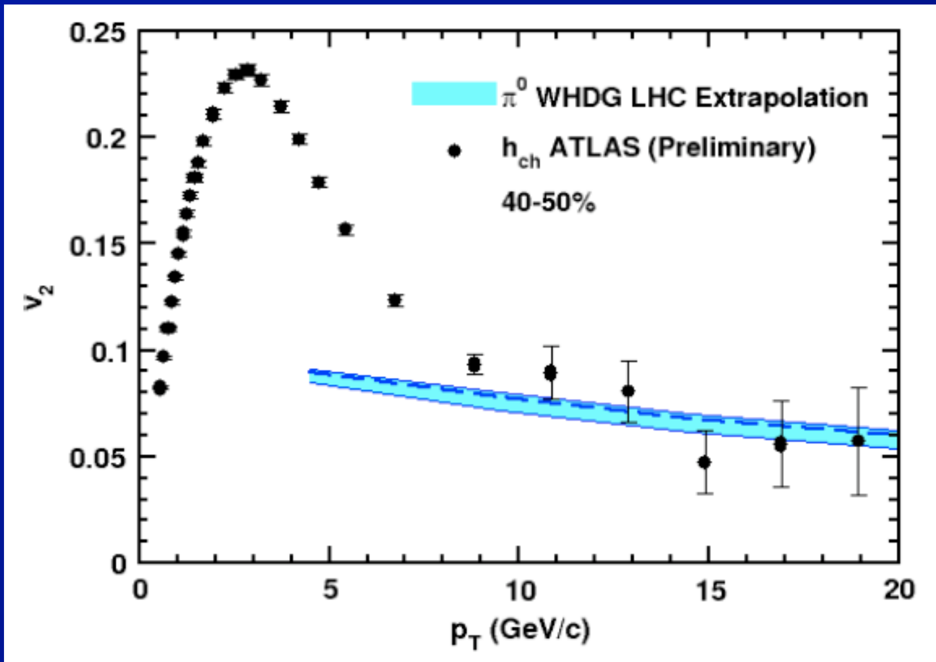
- Characterize the modulation in terms of 2nd Fourier coefficient

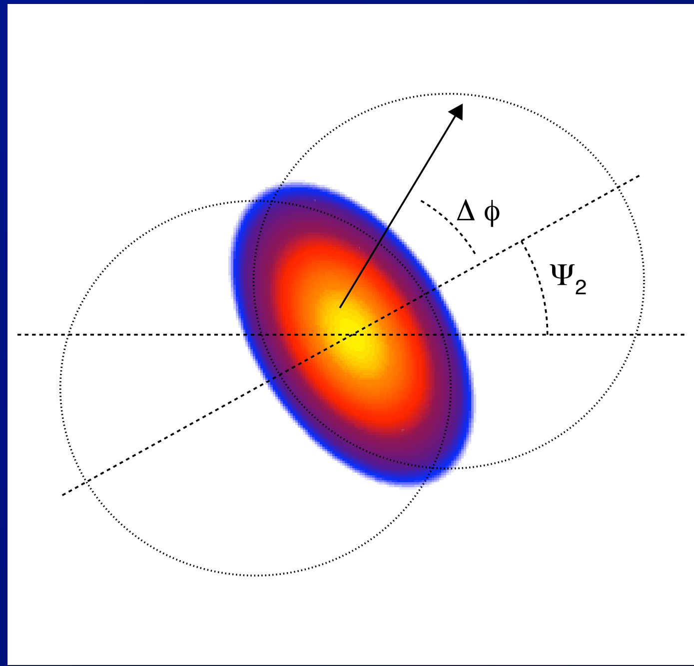
$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos\left(2[\phi - \psi_{\mathrm{evt}}]\right)$$

  - v_2 describes "efficiency" of QGP in transferring spatial anisotropy to momentum anisotropy



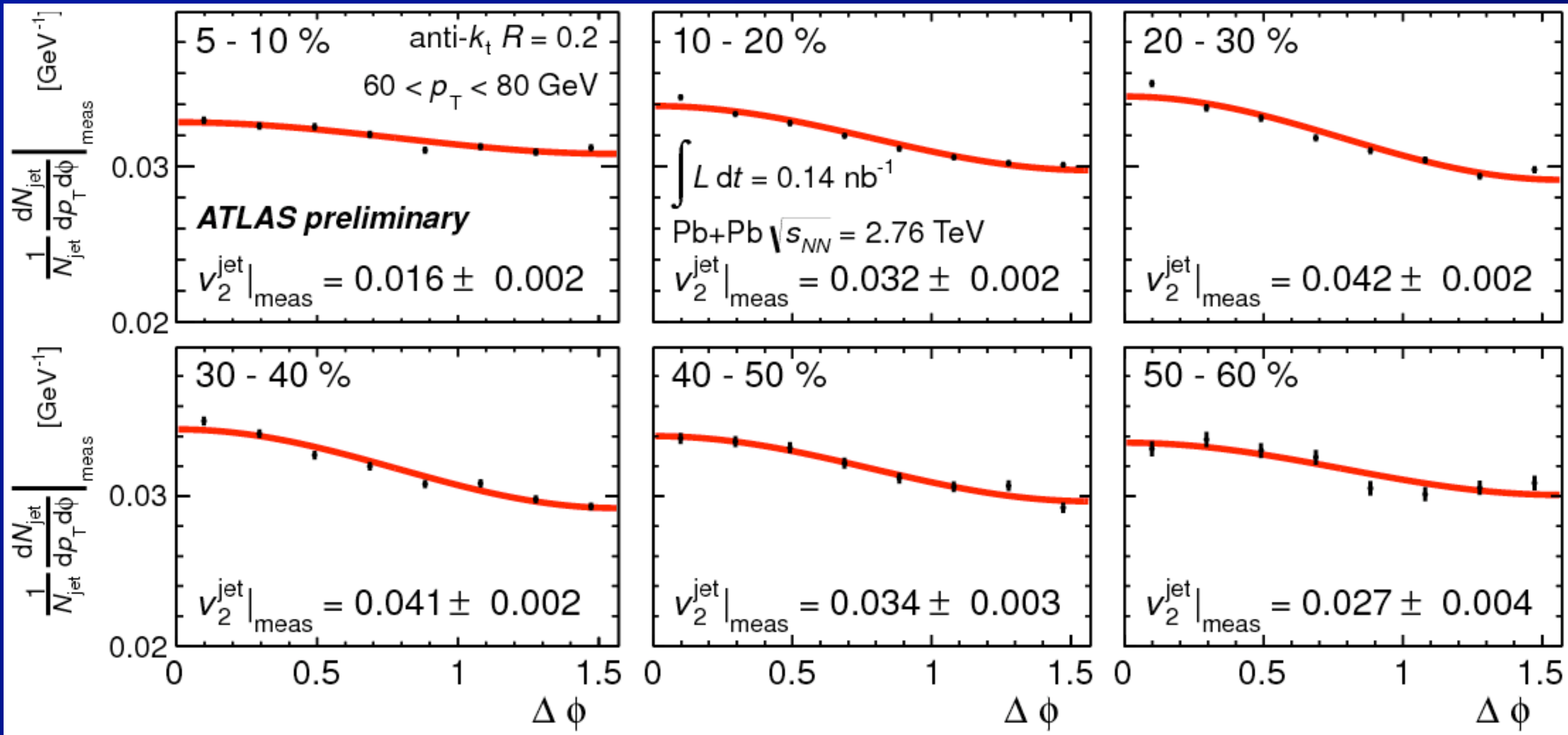
ATLAS: Charged particle $v_2(p_T)$



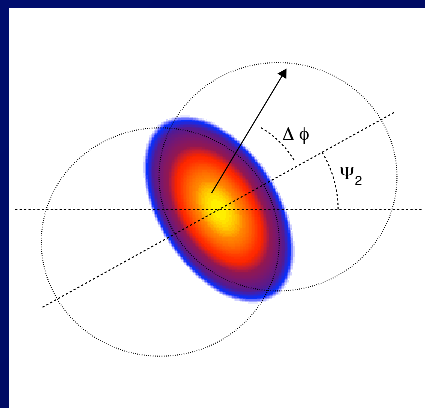


- Evolution from flow at low p_T to differential jet quenching at higher p_T
  - WHDG energy loss describes $v_2(p_T)$ for $p_T > 10$
  - Flow/other dominates for p_T <~ 8 GeV?

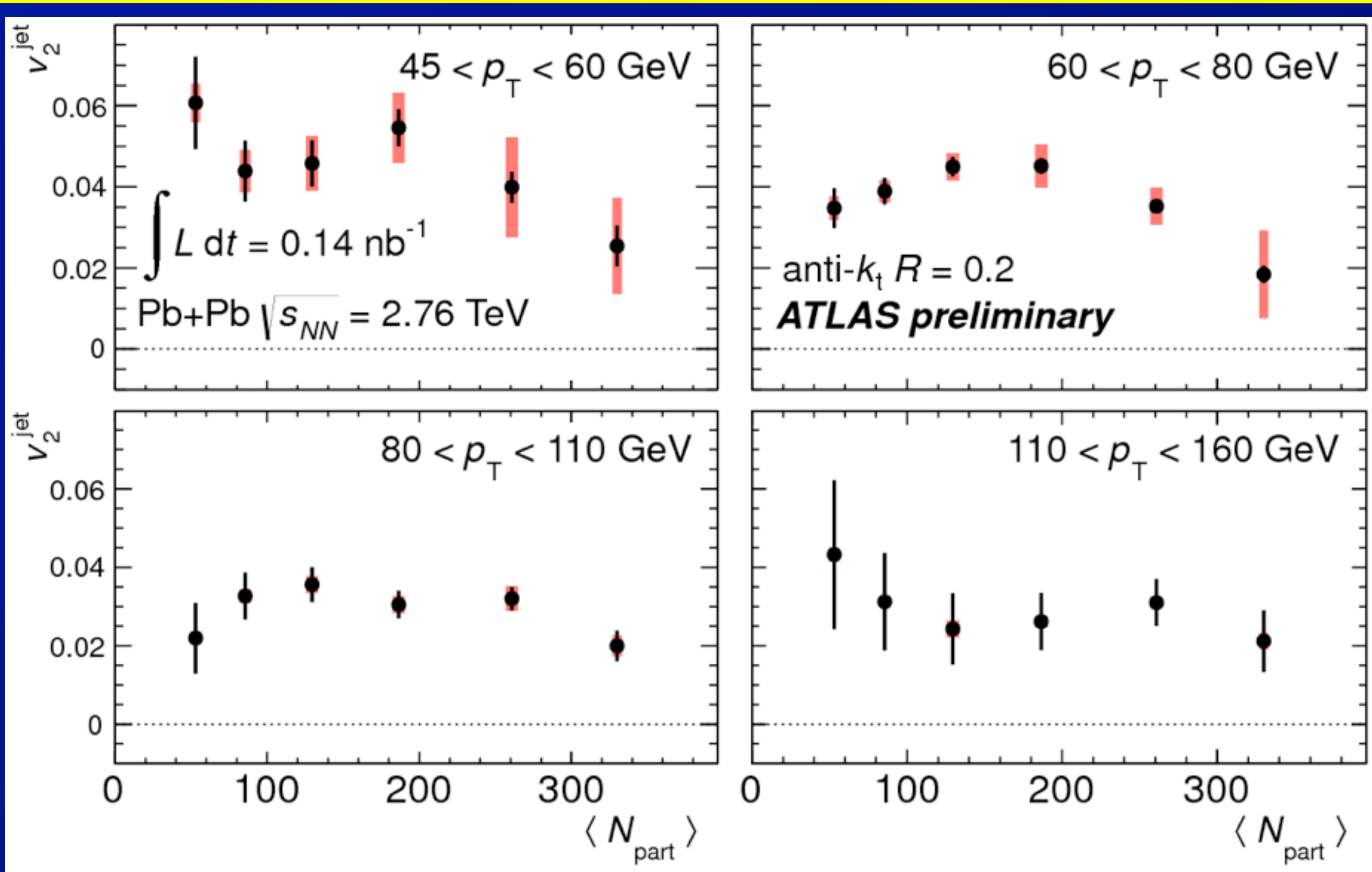
Differential jet suppression



- Measure jet yields in 8 bins of $\Delta\phi$ with respect to the elliptic event plane
  - Here for R = 0.2 jets, 60 < p_T < 80 GeV
    - ⇒UE subtraction corrected for elliptic flow modulation in calorimeter

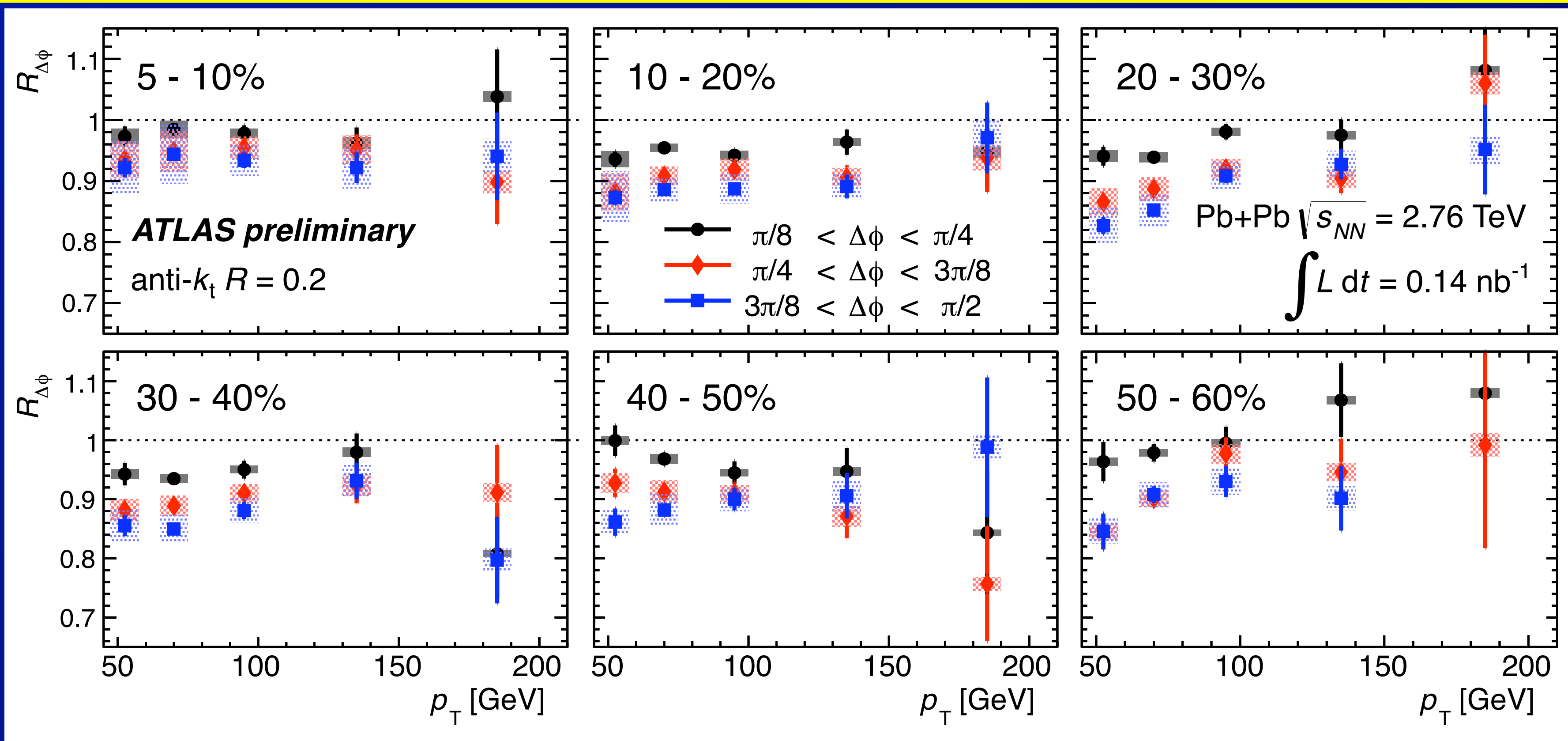


Differential jet suppression



- Observe non-zero jet v_2 for (R = 0.2) p_T values > 100 GeV
  - ⇒jet quenching clearly sensitive to initial geometry out to very high p_T

Differential jet suppression



- Evaluate ratio of jet yields in different Δφ bins 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

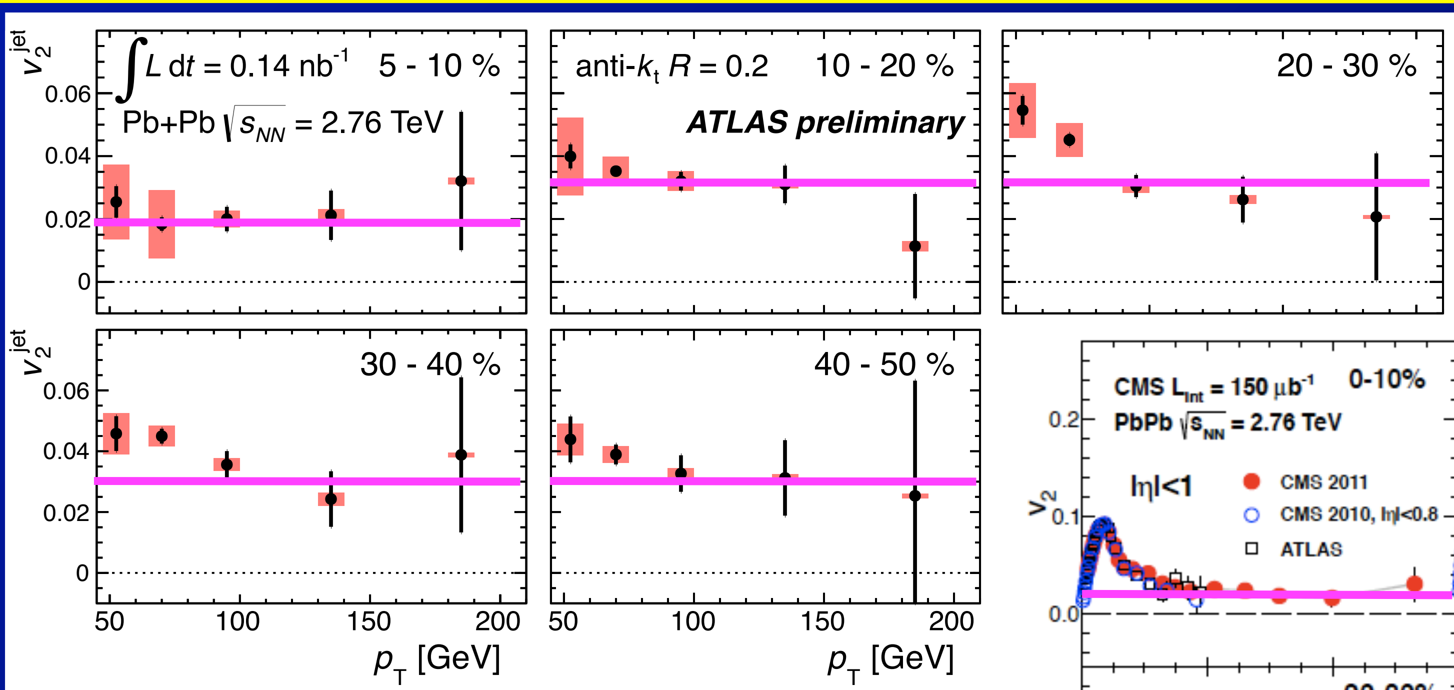
Summary, conclusions

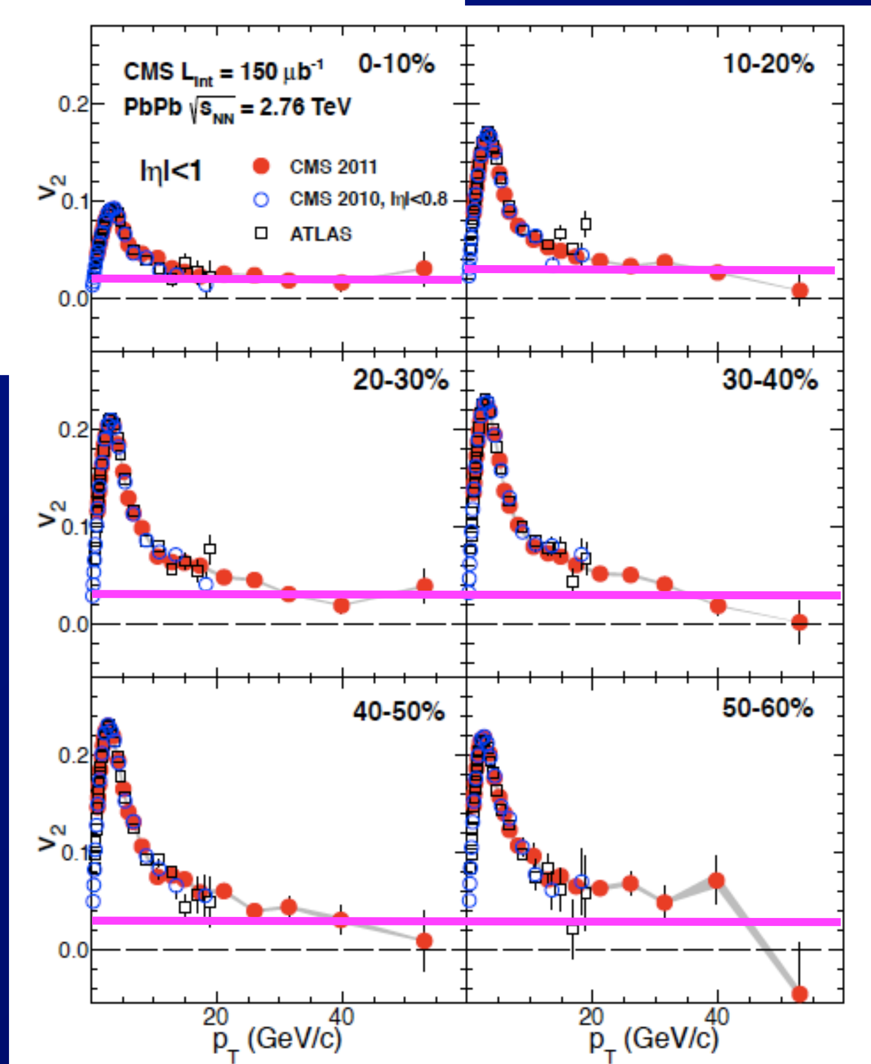
Jet probes of the quark gluon plasma

- We are well along on "first generation" of jet quenching measurements at the LHC.
  - See energy loss of jets via single jets, dijets, gamma-jet.
  - See modifications of parton shower via jet fragmentation measurements.
    - ⇒Modifications in the angular structure are not as well constrained experimentally
  - See geometry of initial state via differential jet quenching measurements.
  - See heavy quark quenching indirectly
    - ⇒More directly with ALICE D measurements
    - ⇒But b-tagged jets (@ p_T not >> m) to be done
- How to go from where we are to more rigorous, quantitative understanding?

Backup

Jet $v_2(p_T)$

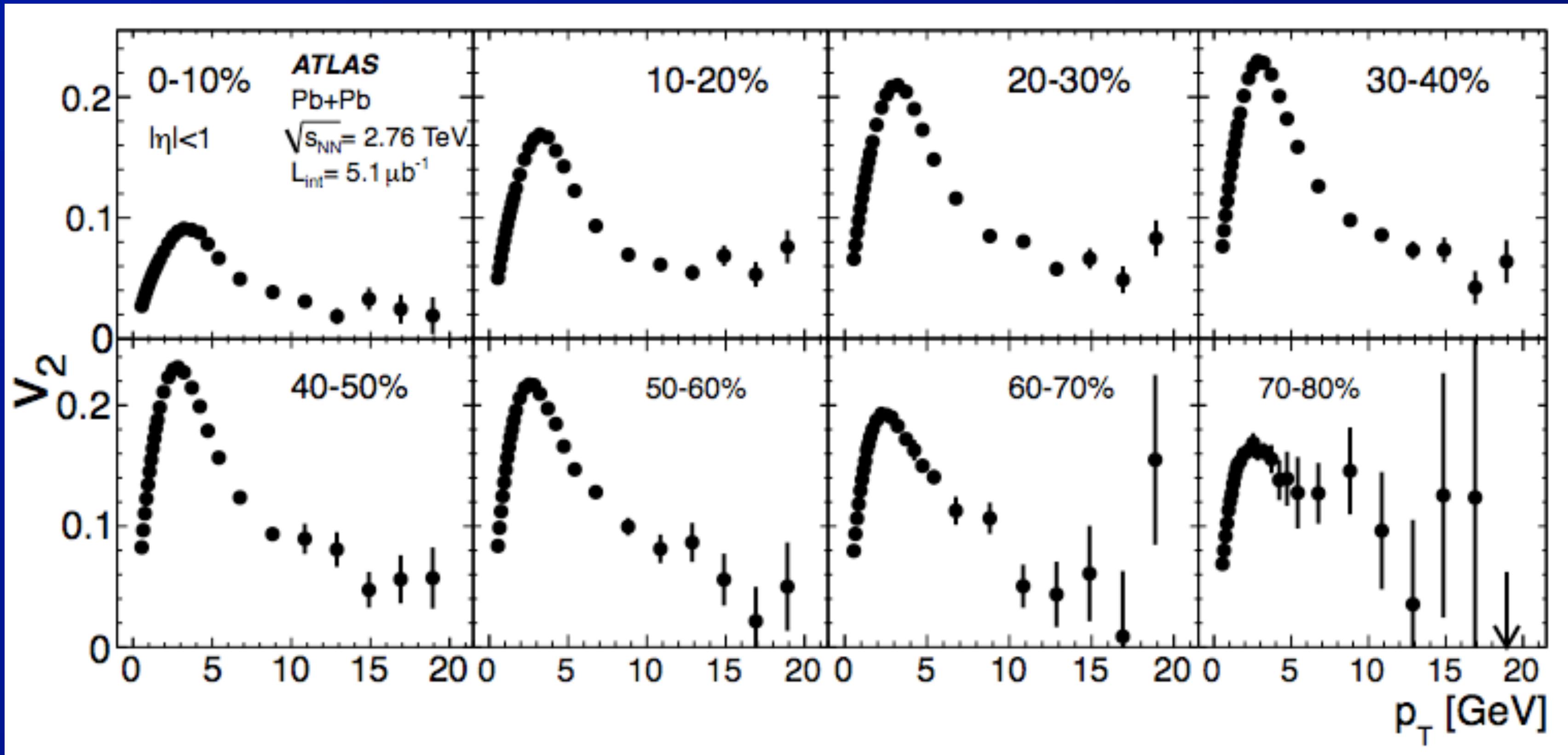




- Do rough comparison of jet, charged v2 at high p_T
  - plot 0.02 for 0/5-10%
  - plot 0.03 for > 10%

  ⇒As good as could be expected

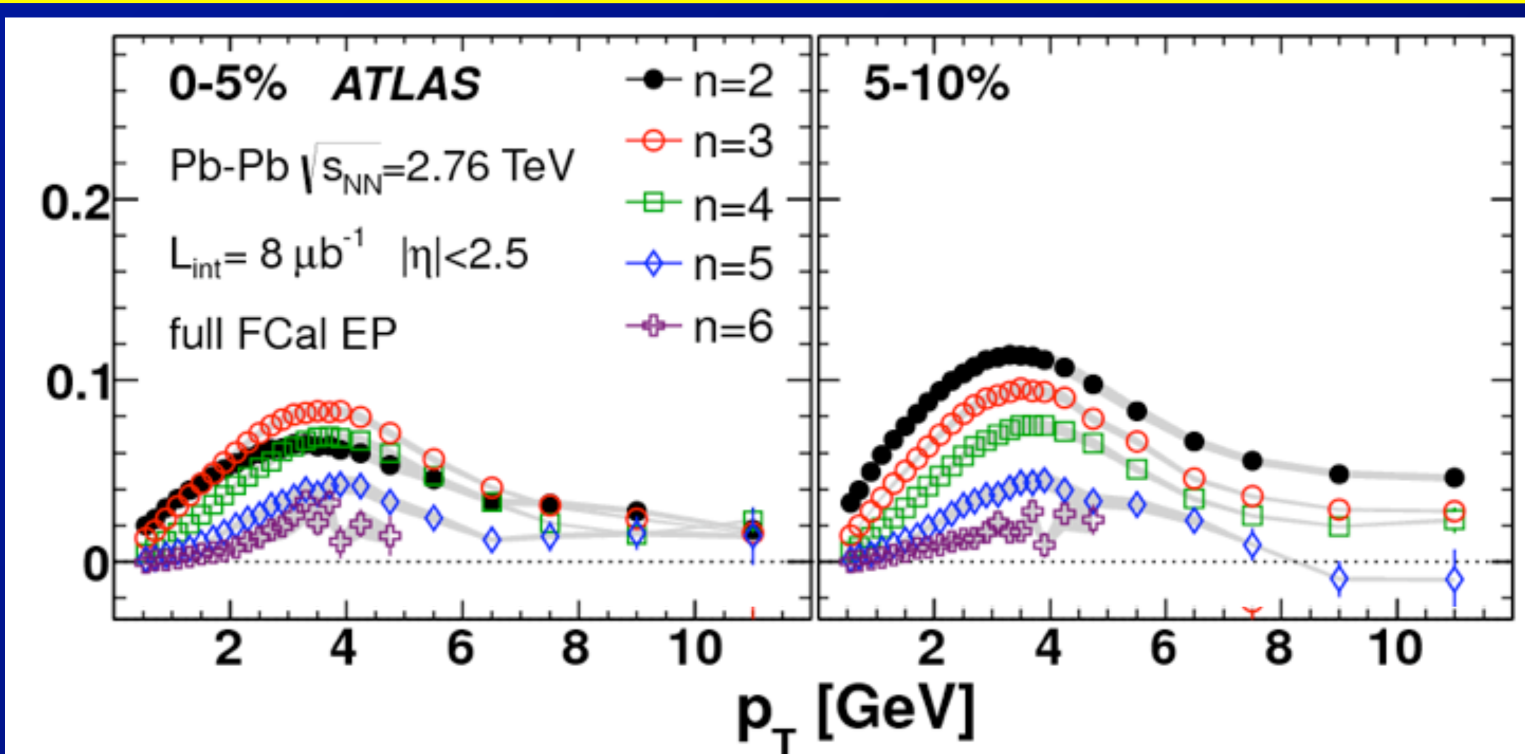
ATLAS: Charged particle $v_2(p_T)$



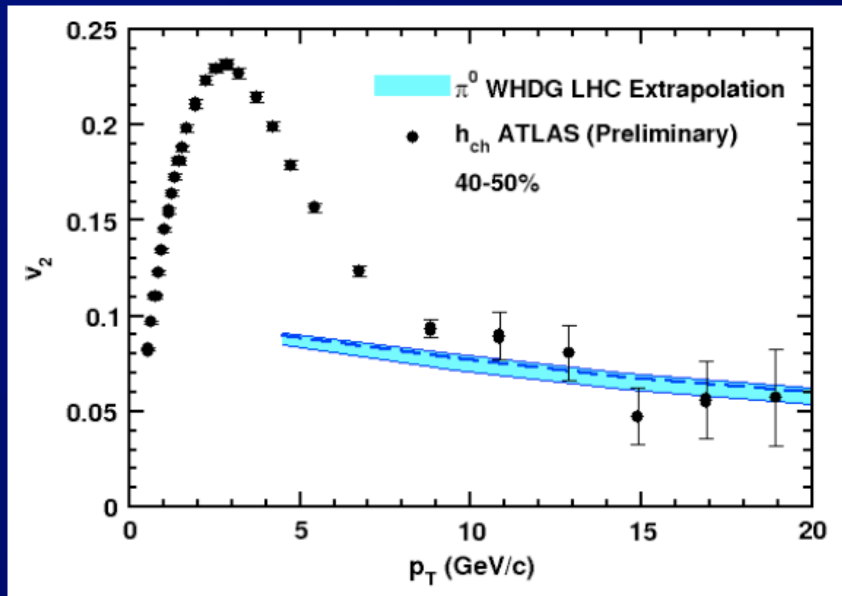
- **Single hadron $v_2(p_T)$:**
  - Evolution from flow (p_T < 6-7 GeV)
  - to quenching (p_T >~ 10 GeV)

    ⇒ Consistent with conclusions from similar analyses in PHENIX

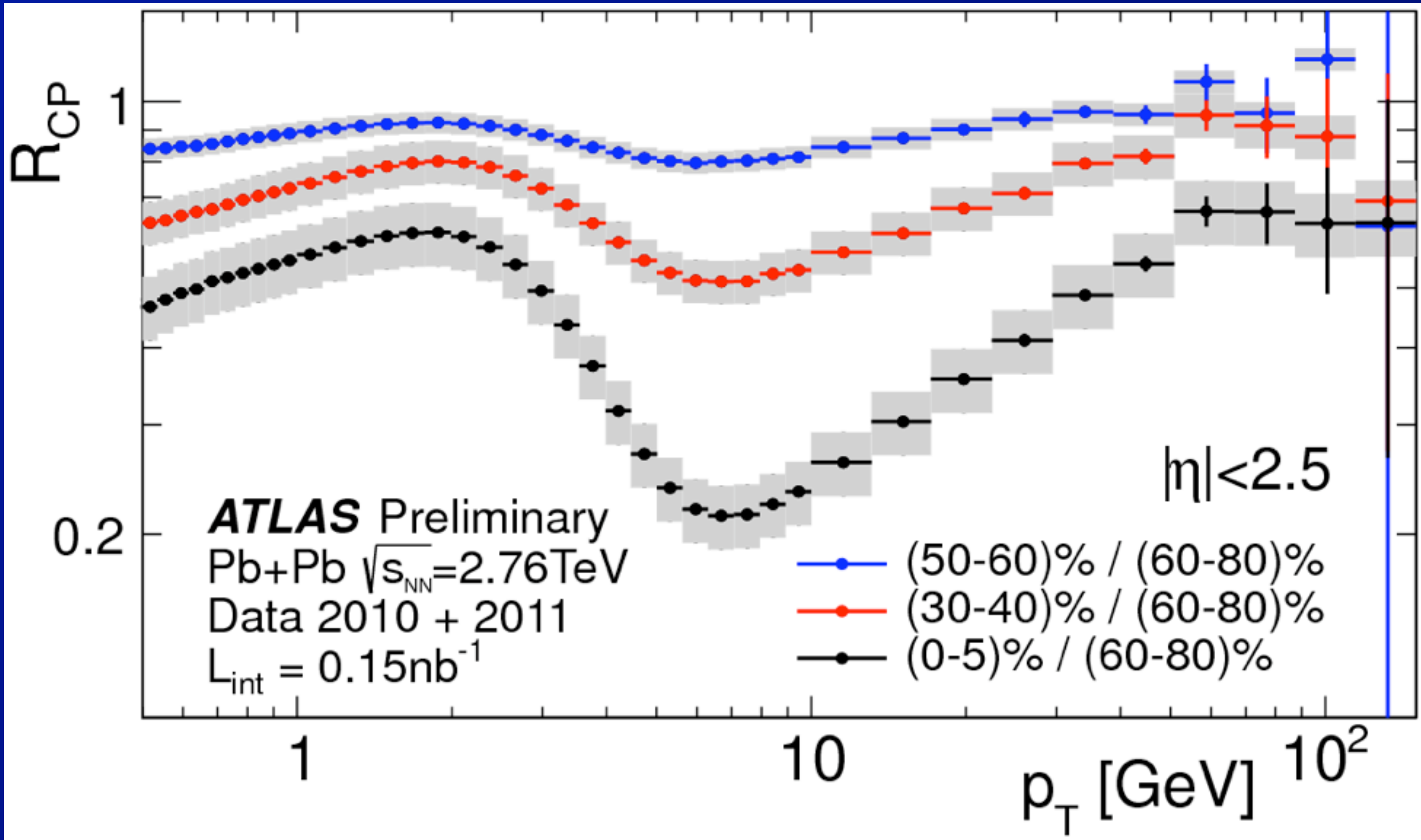
n > 2 collective flow @ high(er) p_T



- For 0-5%, 5-10%
  - get non-zero, ~ flat v_n's in region where v_2 is due to quenching?
    - ⇒Suggestive, but not conclusive.



Charged particle R_{cp}



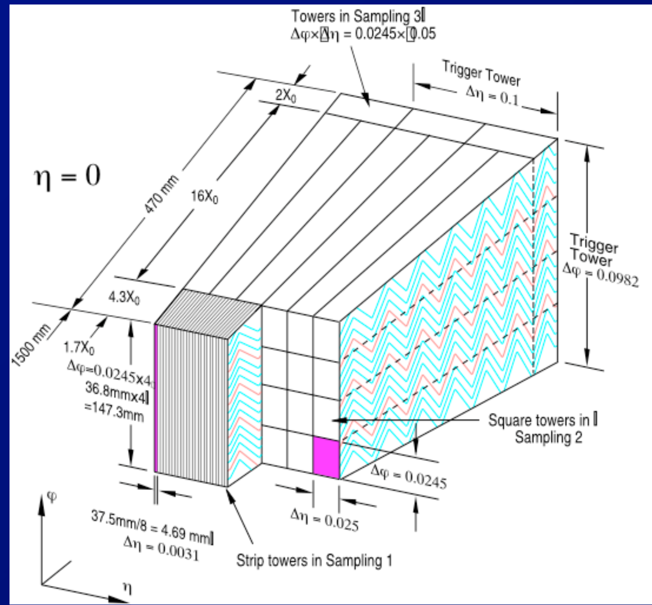
- Similar to ALICE, CMS results
  - R_{cp} ~ 0.6 for p_T > 60 GeV

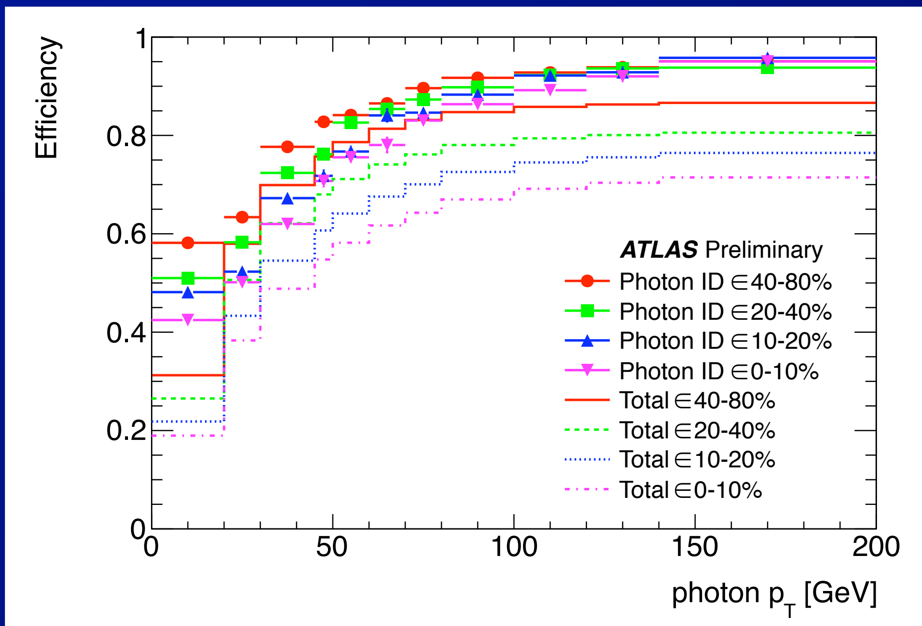
    ⇒ (change in) slope for pT > 50 GeV important

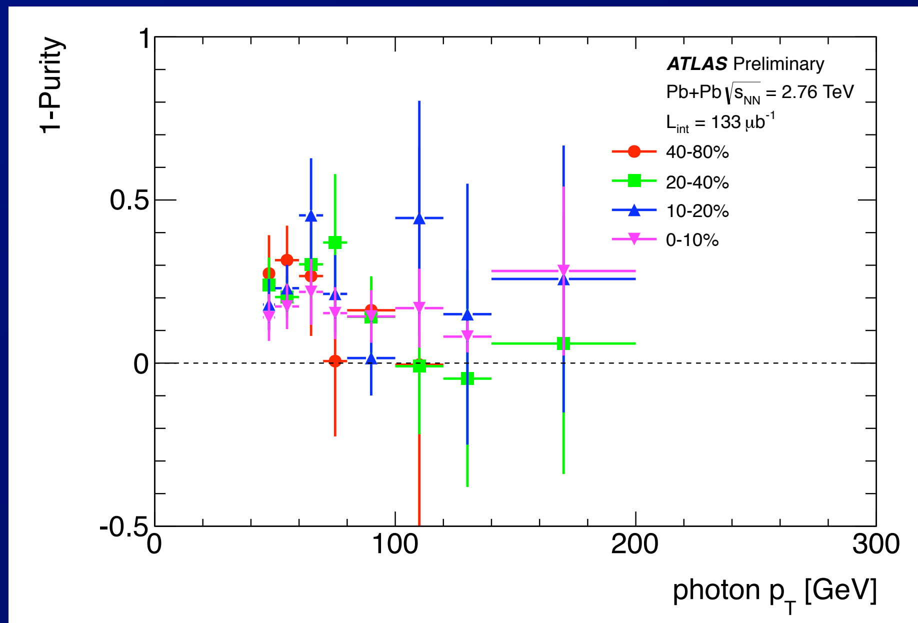
Prompt photon production

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

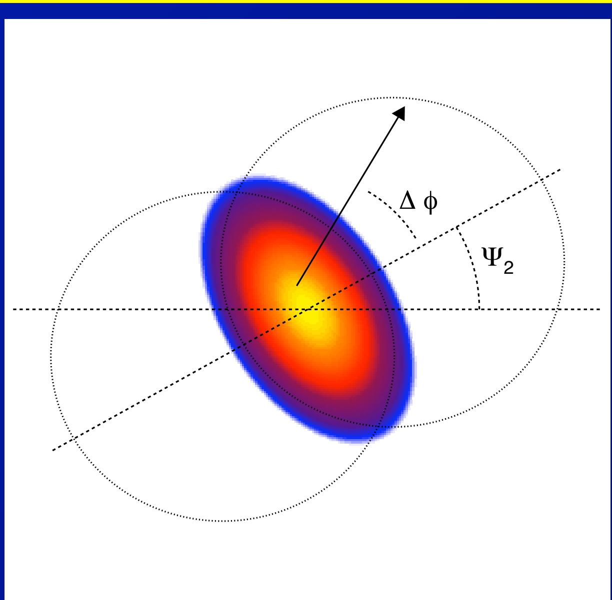
  $\Rightarrow$ Purity > 70%

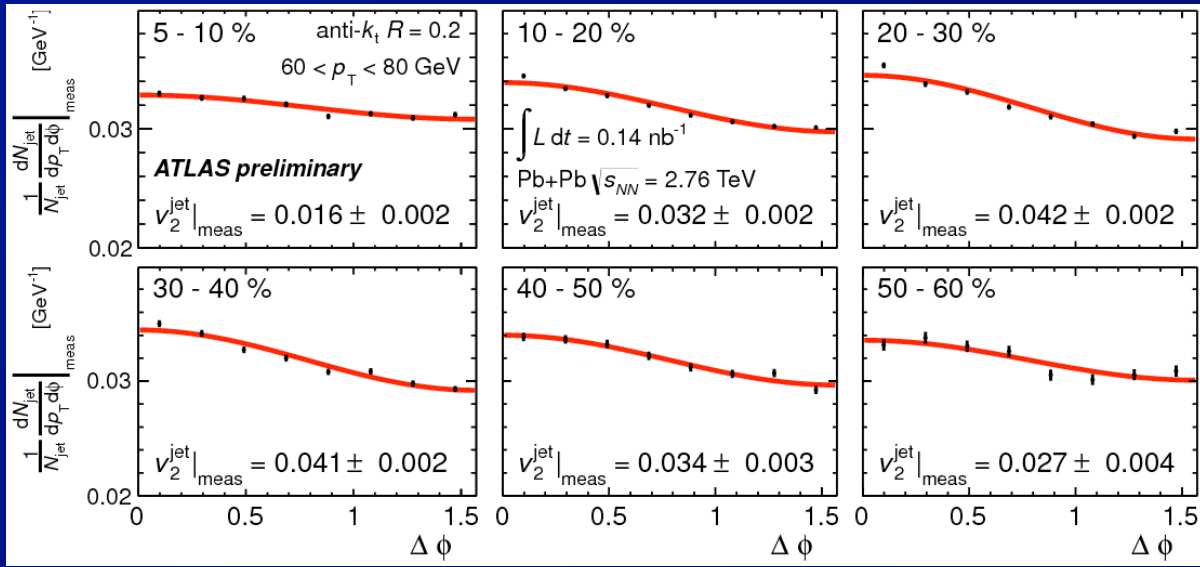






Differential jet suppression





- **Measure:**
  - Jet v_2