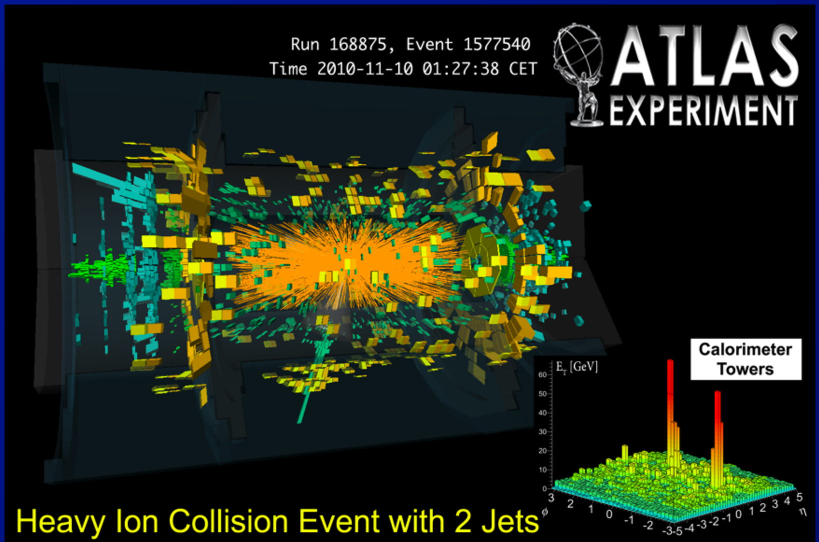
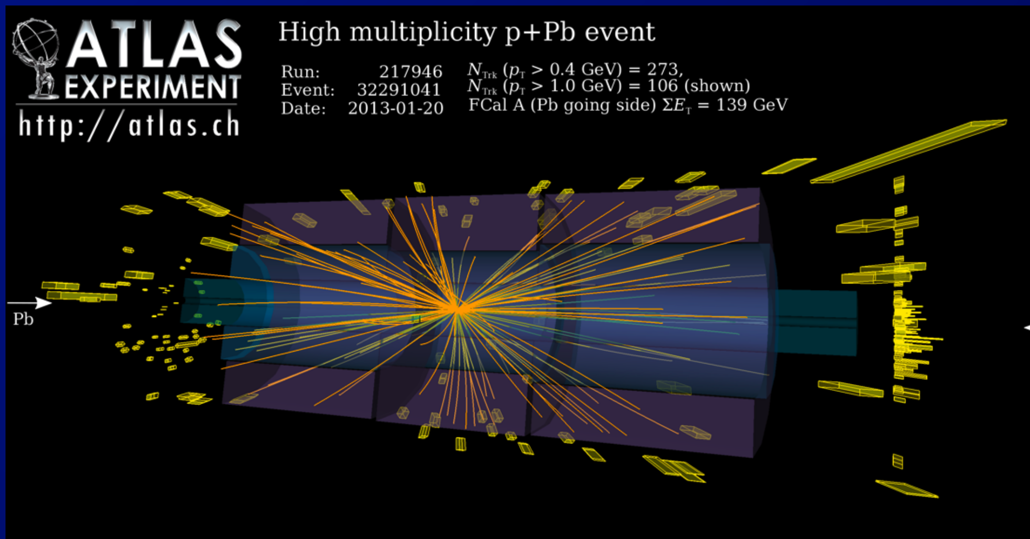
Jet quenching II:
or
What do we know, and how well do we know it?

Brian. A Cole
April 16, 2013



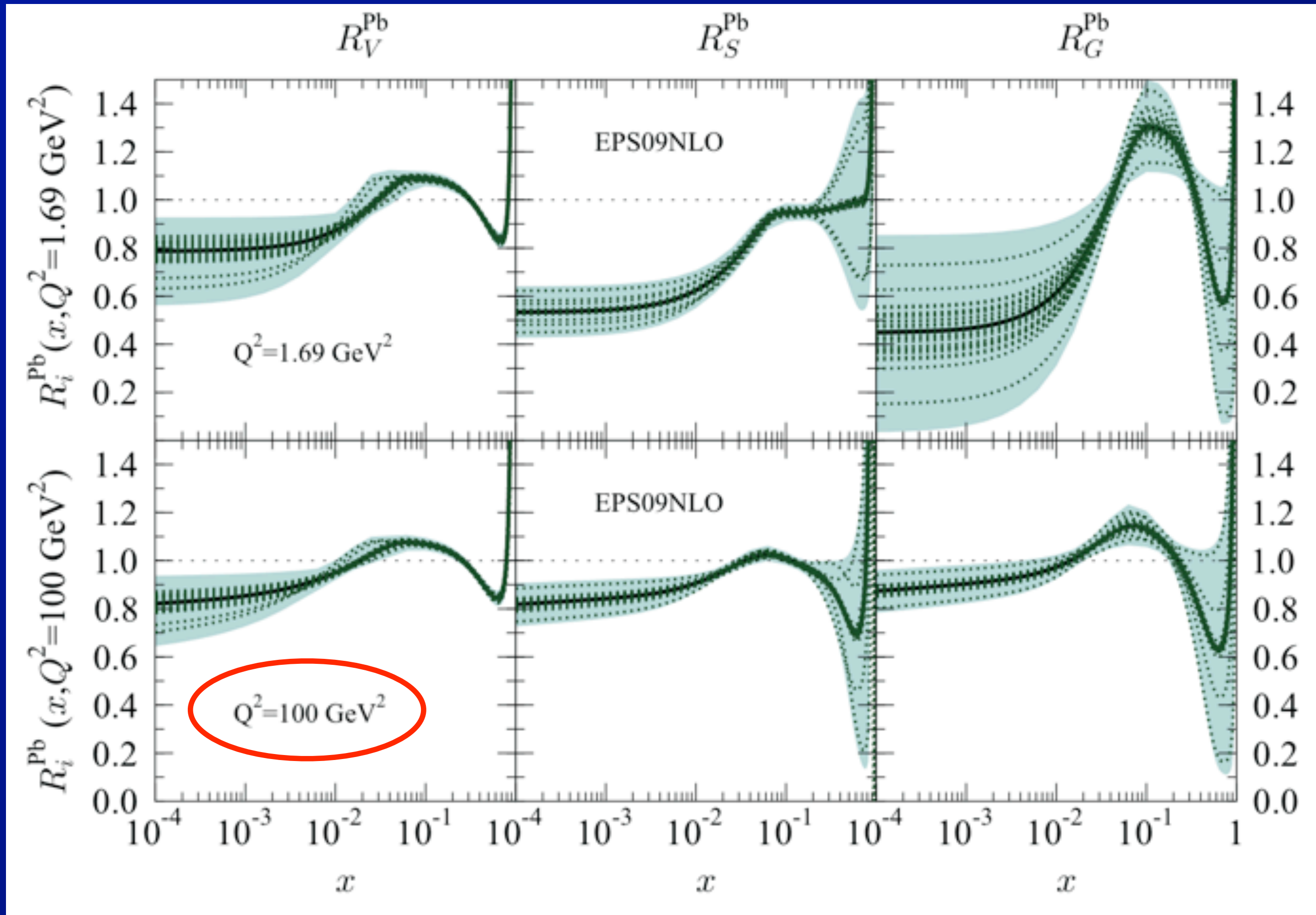


Overview

- From workshop web page:
  - Specific topics we plan to address include:
    - To what extent do we achieve control over initial state effects in light of the new dAu and pPb data?
    - How do the medium properties change from RHIC to LHC?
    - Can we achieve precision by combining the vast amount of data from RHIC and LHC?
    - How does the jet quenching response to fluctuating initial geometry (jet tomography) evolve from RHIC to LHC?
- Discuss:
  - Theory, p+Pb, Pb+Pb constraints on nuclear modifications on hard scattering rates at high p_T.
    - $\Rightarrow$ Single hadron, jet and heavy flavor suppression
  - Jet quenching probes insensitive to PDFs/rates
  - Tomographic measurements

Constraints on initial-state effects

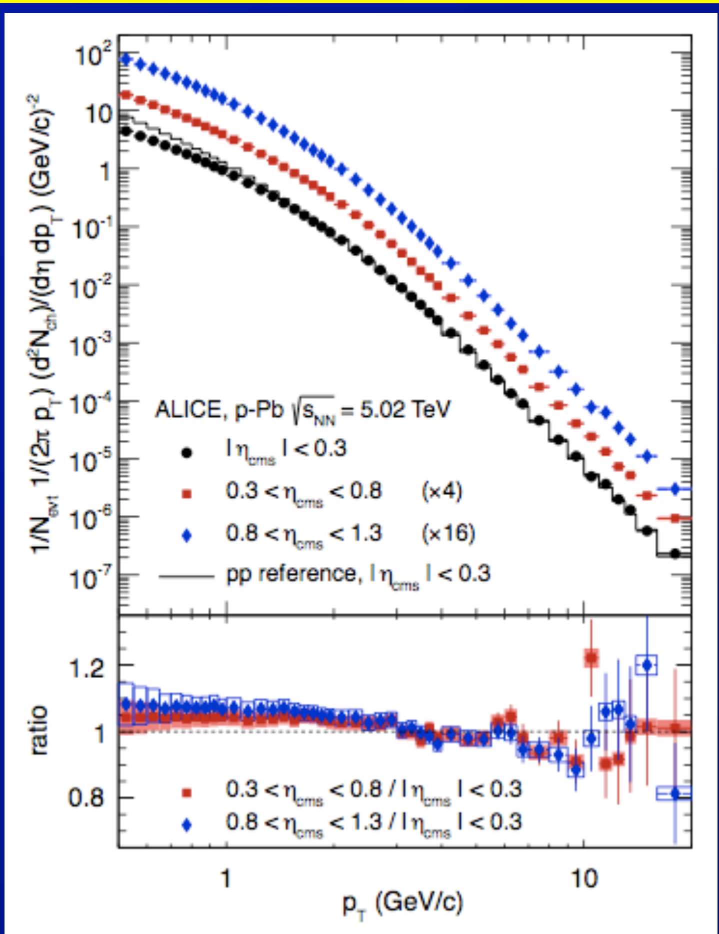
Initial-state effects (not saturation)

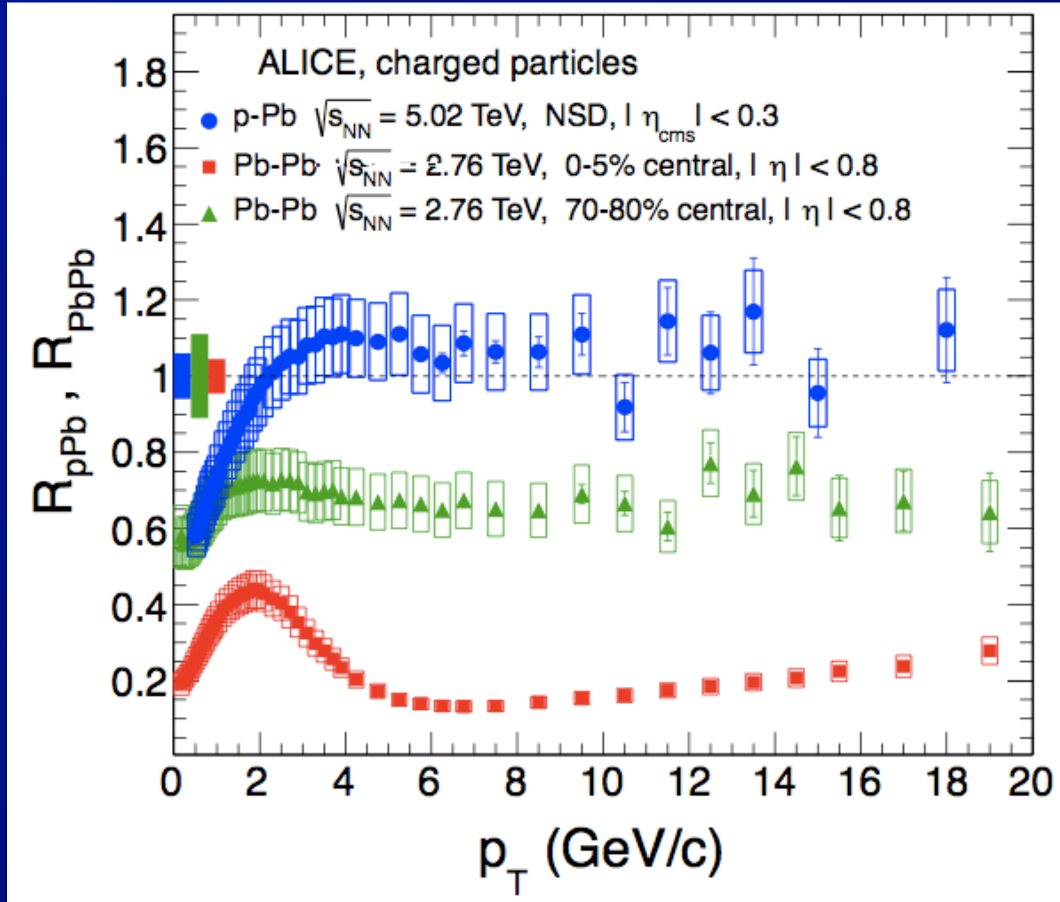


- For Q^2 = 100 GeV^2 ⇒ jet p_T ~ 10 GeV
  - Expect modest low x effects (b dependence?) for high-p_T processes

    ⇒ p+Pb measurements will provide stringent test

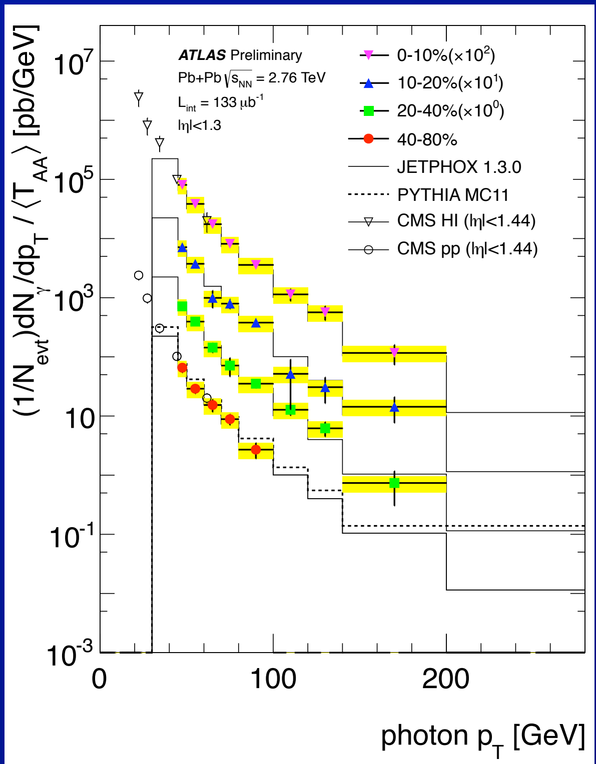
p+Pb inclusive spectra

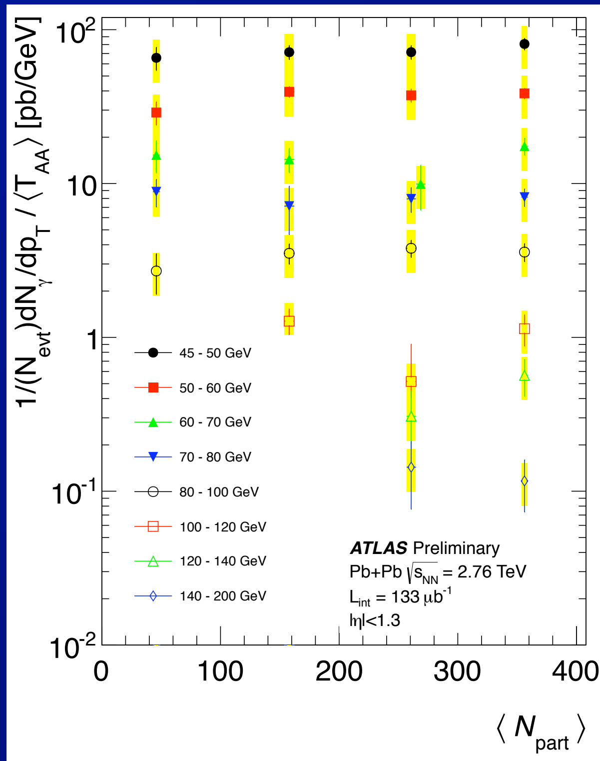


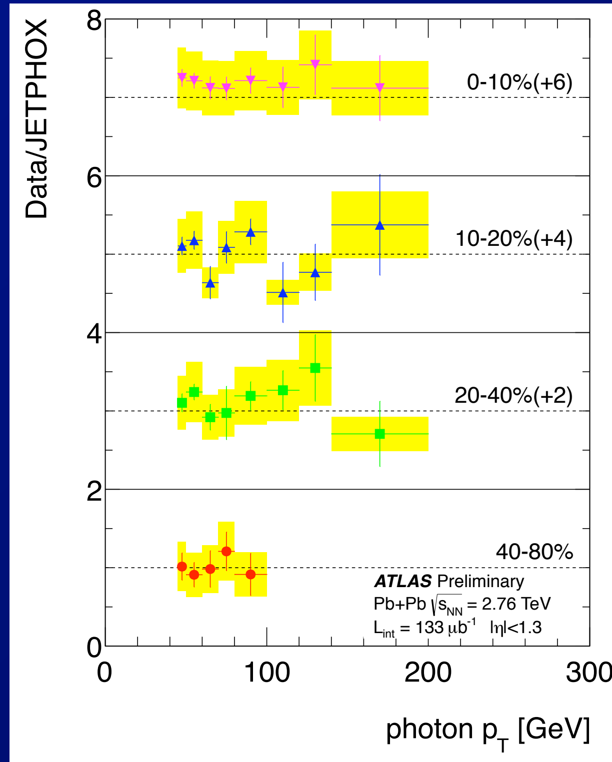


- 1st look at charged particle spectra
  - arXiv:1210.4520, ALICE inclusive, NSD
    - ⇒ R_{pPb} consistent with 1, no suppression at mid-rapidity, also little or no “Cronin”

Pb+Pb: Prompt photon production





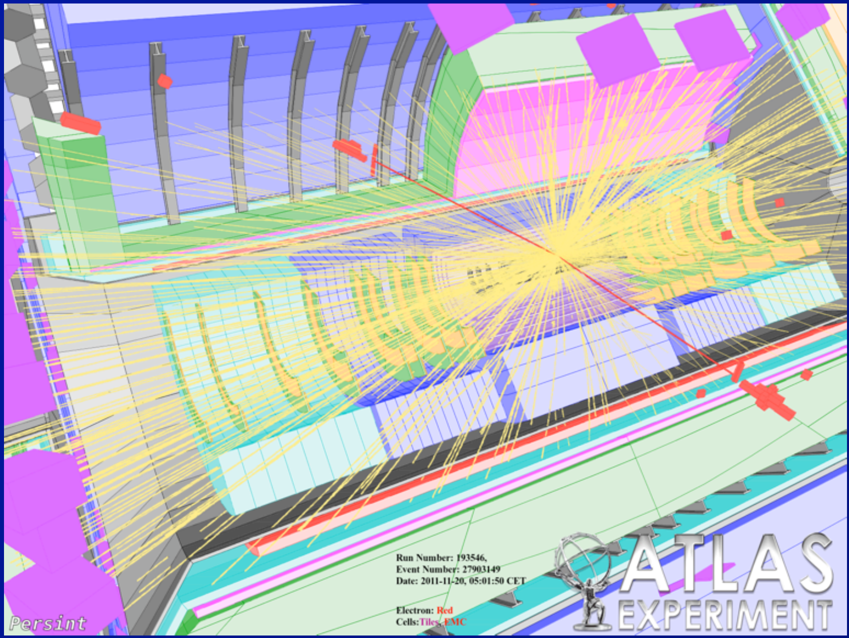


- Photon spectra over $40 < p_T < 200$ GeV
  - well described by JETPHOX multiplied by T_{AA}
  - Yield / T_{AA} ~ independent of centrality

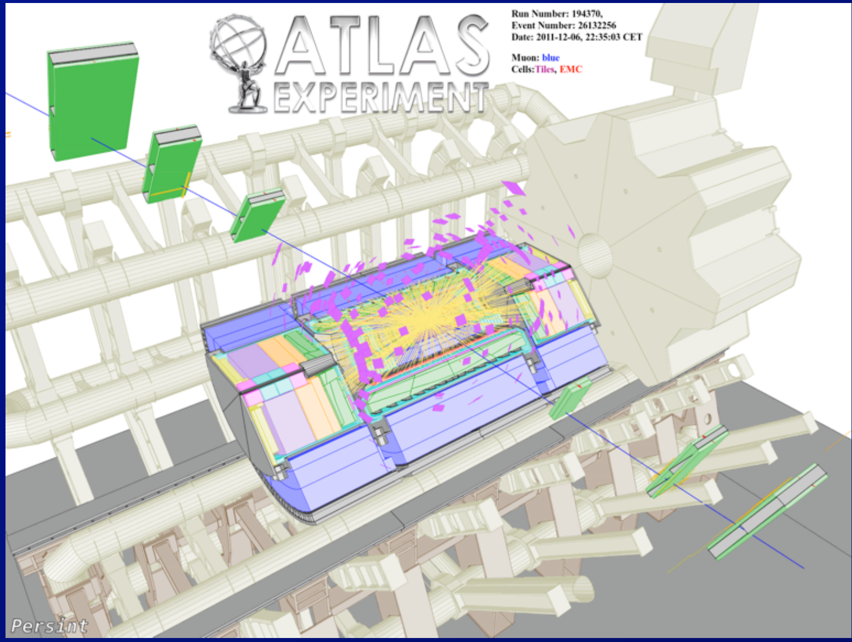
    ⇒ Hard QCD photon production varies with Pb+Pb centrality as expected

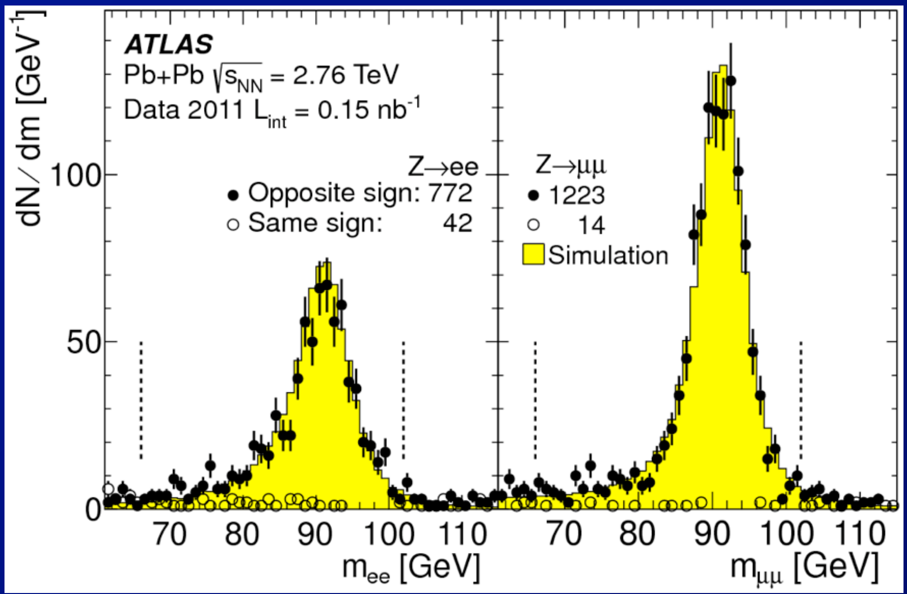
Pb+Pb: Z production

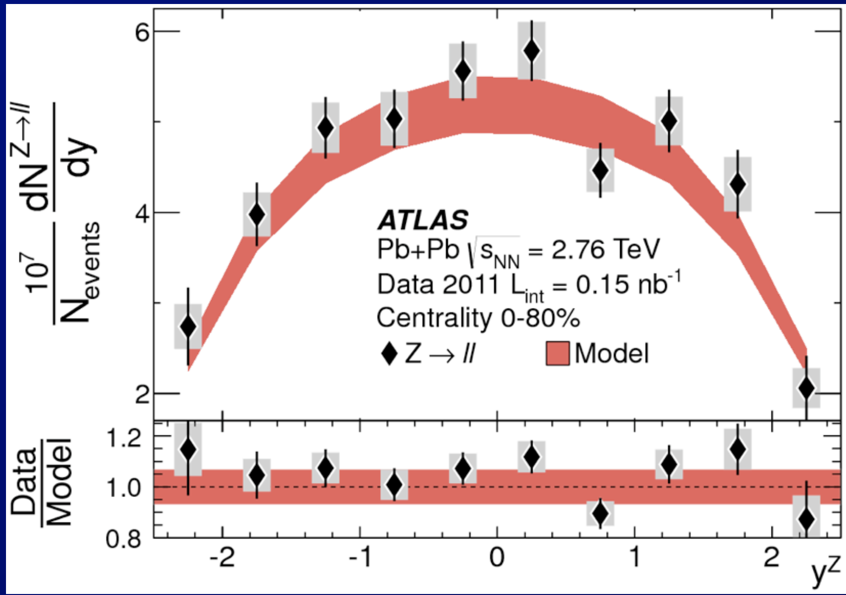
$Z \rightarrow e^+e^-$ event display



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

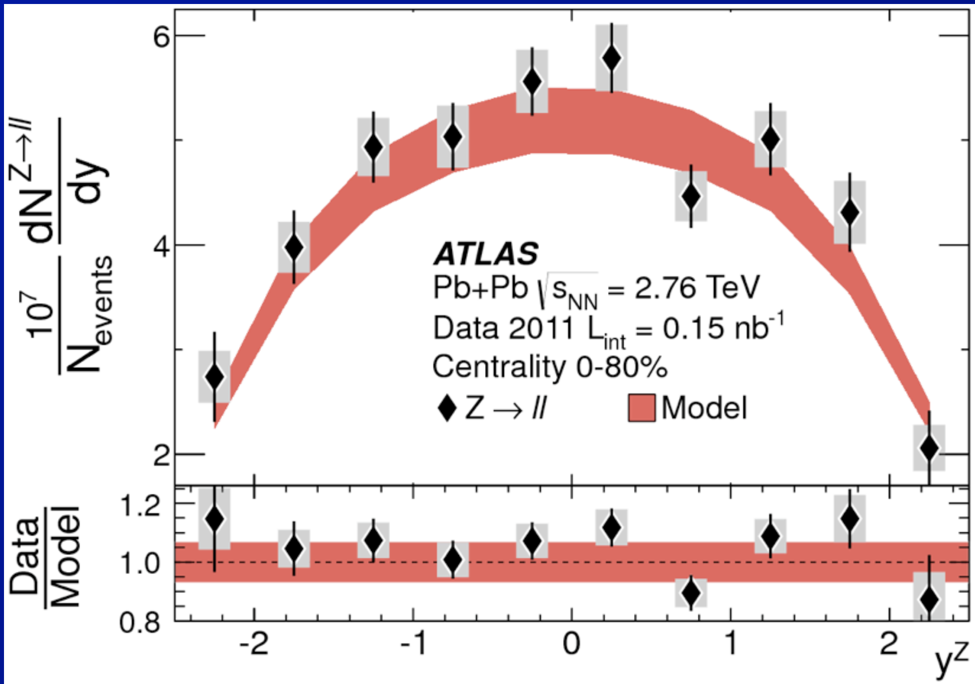


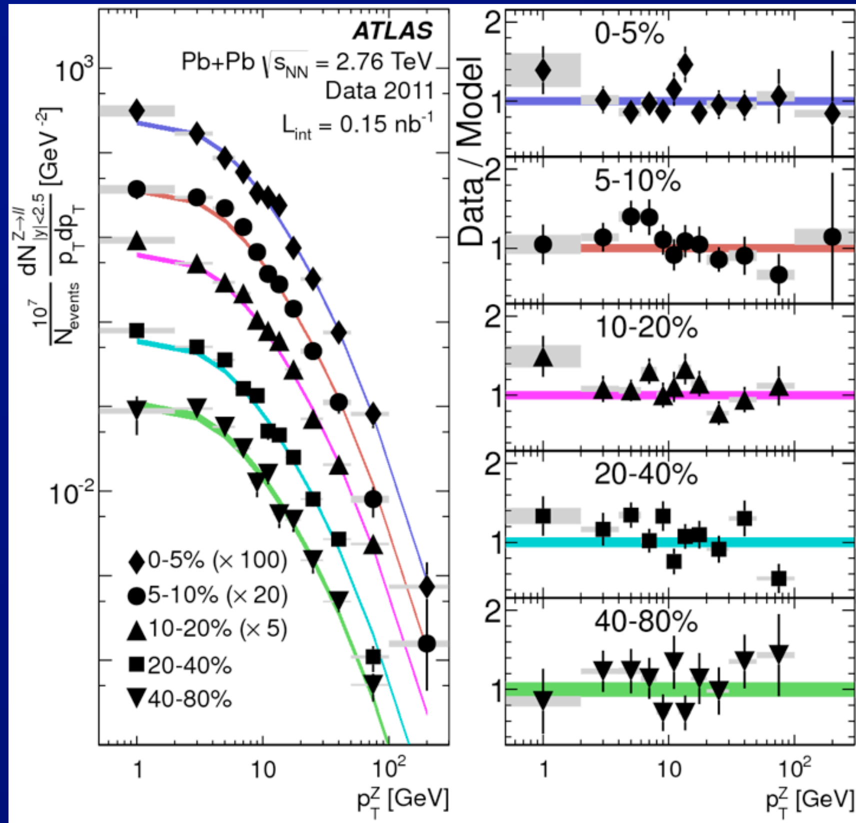




Pb+Pb: Z production (2)

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

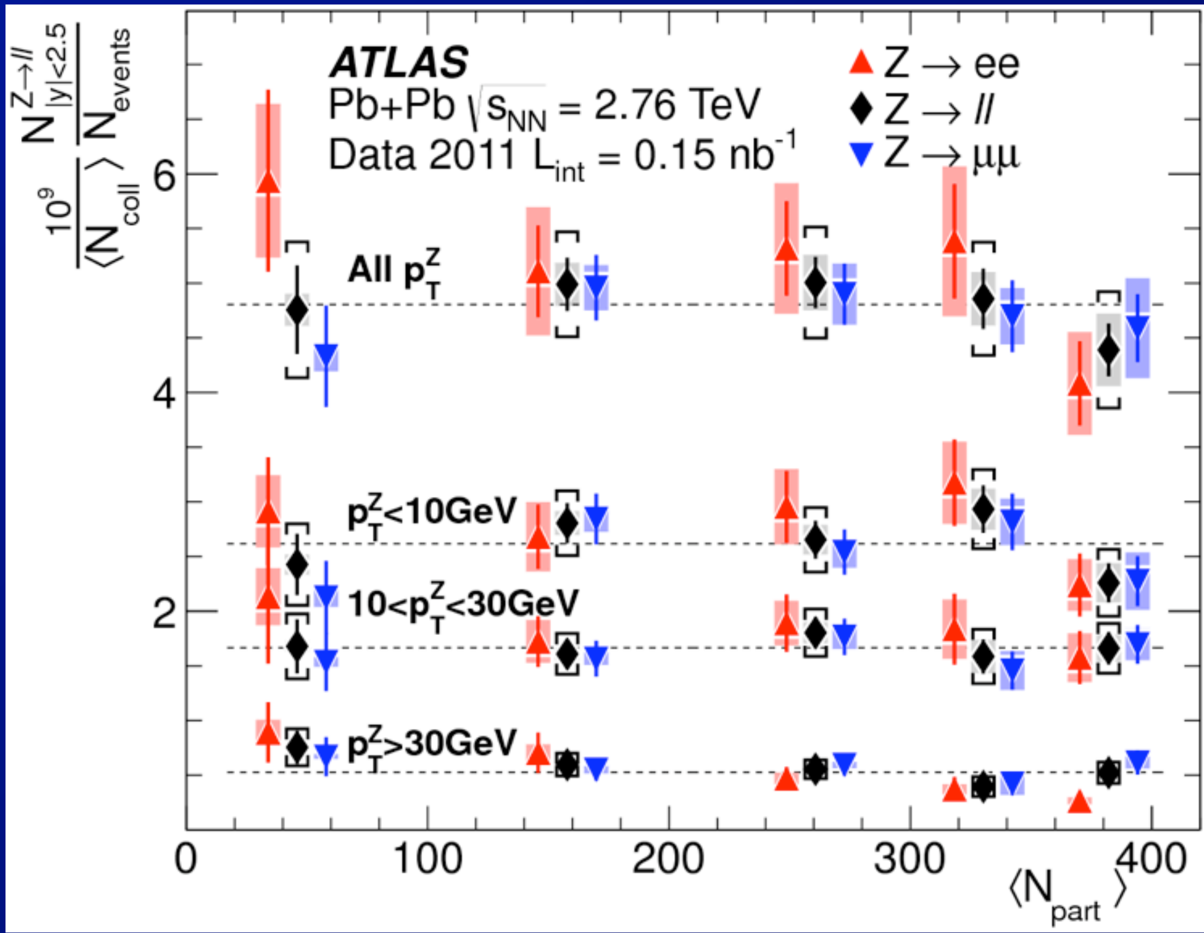




- Compare Pb+Pb Z rapidity distributions (minimum-bias) and pT spectra to PYTHIA scaled to NNLO calculations
  - No nuclear PDFs
    - ⇒ Nuclear PDF effects <~ 20%

Pb+Pb: Z production (3)

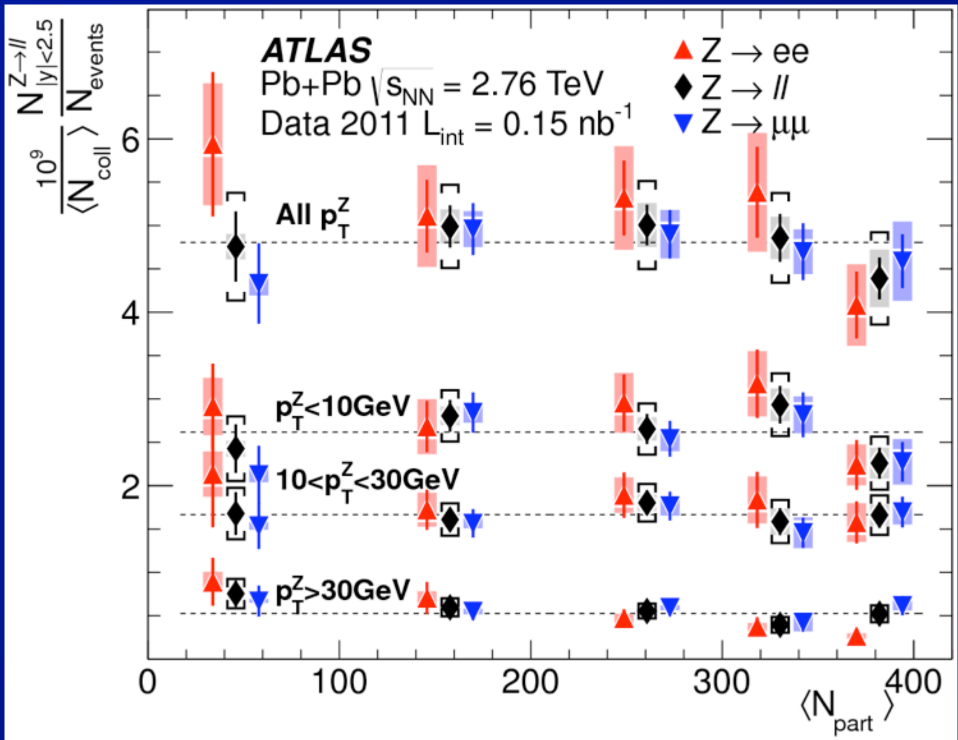
Phys. Rev. Lett. 110, 022301 (2013)

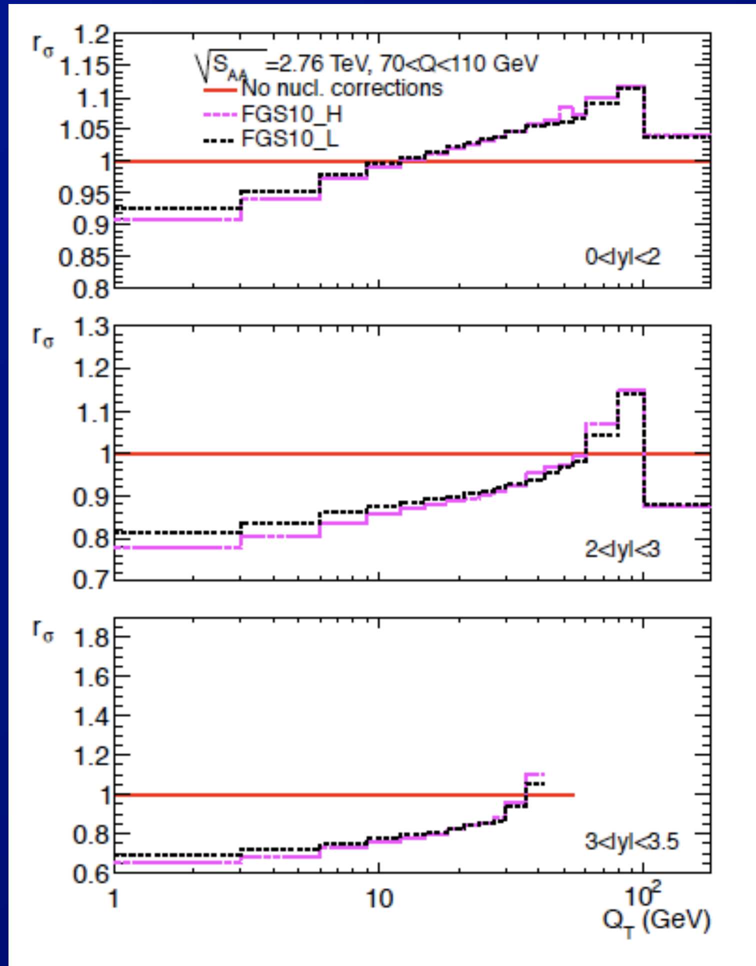


- Check Ncoll scaling of Z yield in different p_T intervals
  - Slight drop in central yield/Ncoll for p_T < 10 GeV
    - ⇒But not significant given errors. Expected?

Pb+Pb: Z production (4)

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

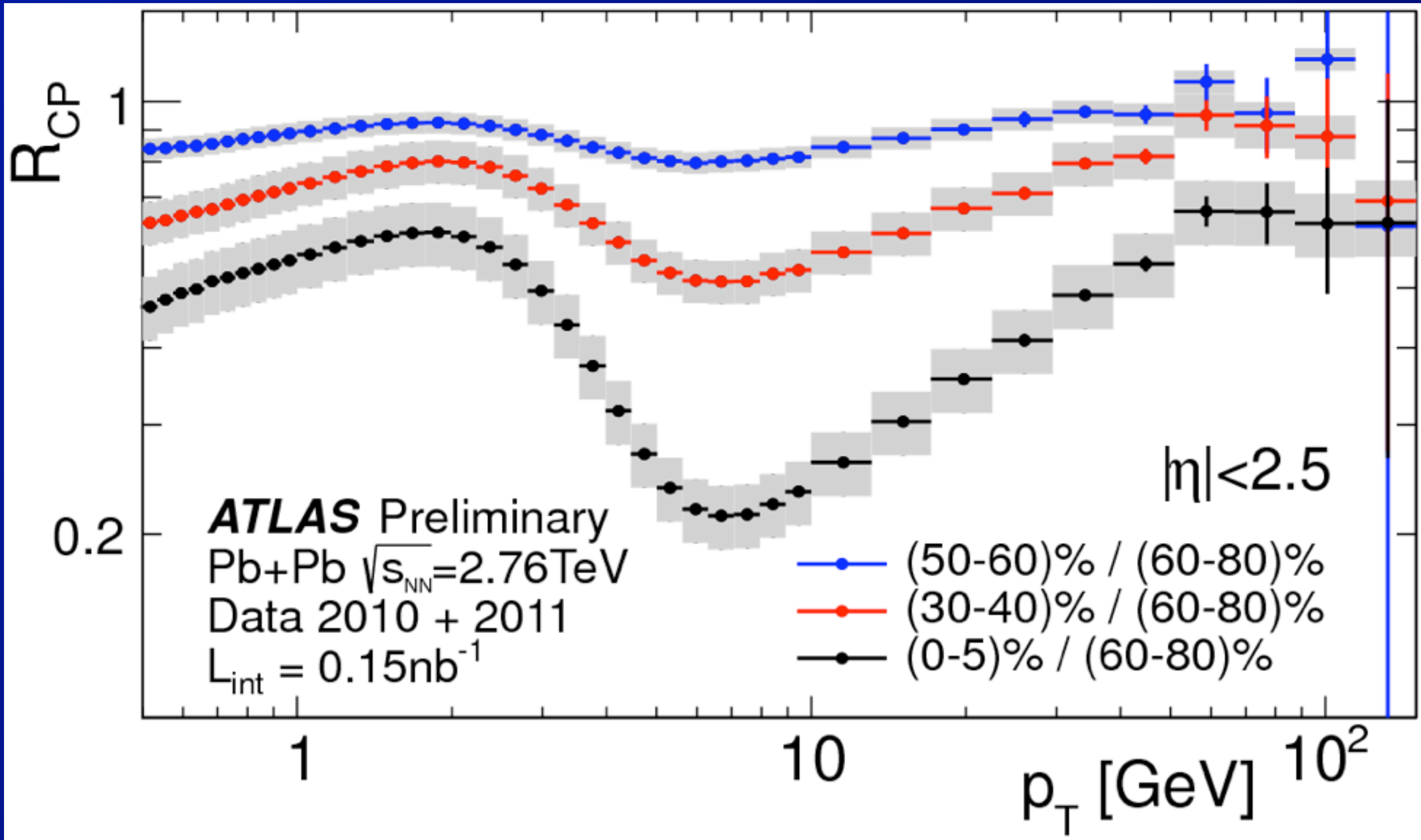




- Predictions of ~ 10% nuclear modifications in Pb+Pb at both low Q_T and high Q_T
  - ⇒Measurements not precise enough to test yet
  - ⇒But maybe with 2013 2.76 TeV p-p data

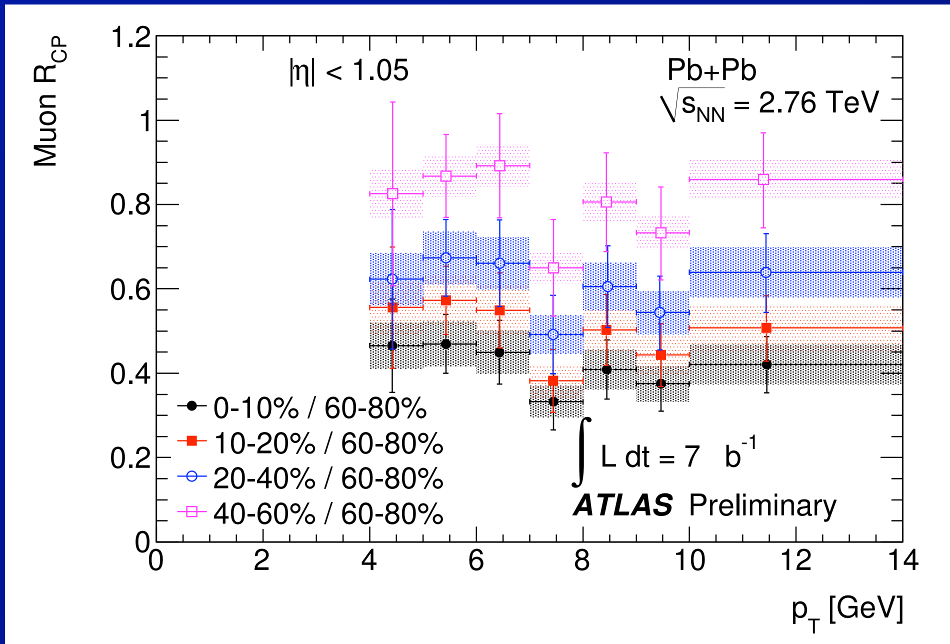
Single hadron, heavy flavor (muon), jet suppression

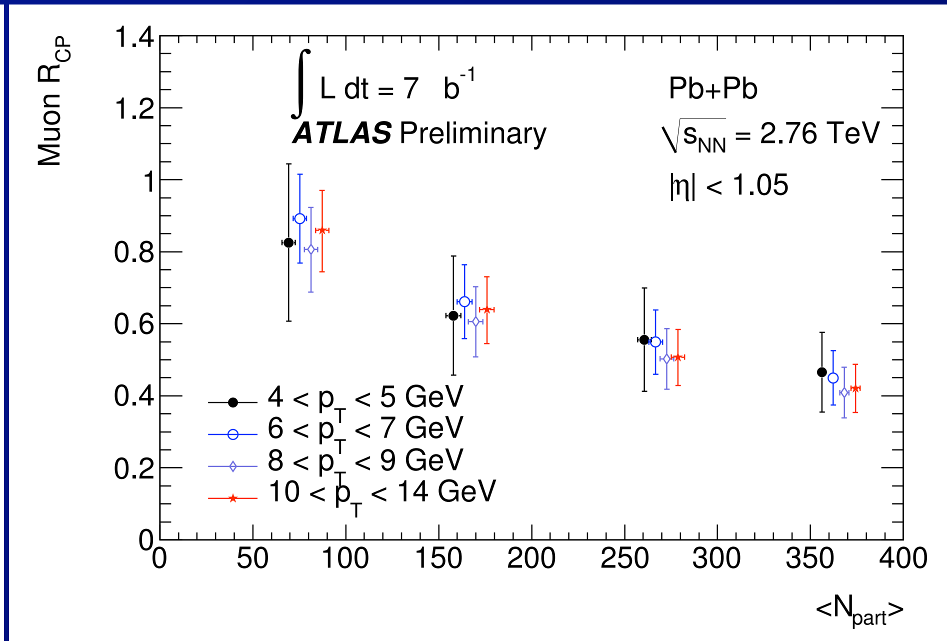
Charged particle R_{cp}



- Similar to ALICE, CMS results
  - R_{cp} ~ 0.6 for p_T > 60 GeV
    - ⇒ (change in) slope for pT > 50 GeV important

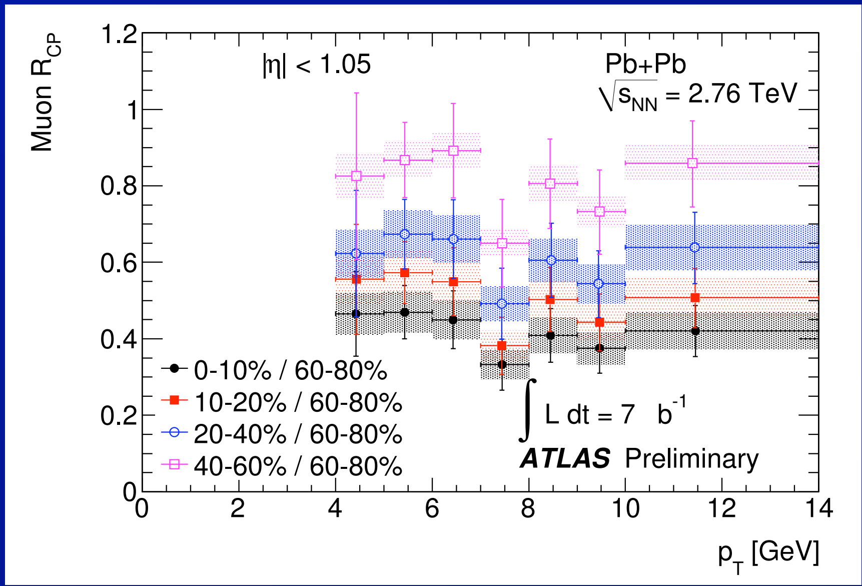
Single muons from heavy quark decays

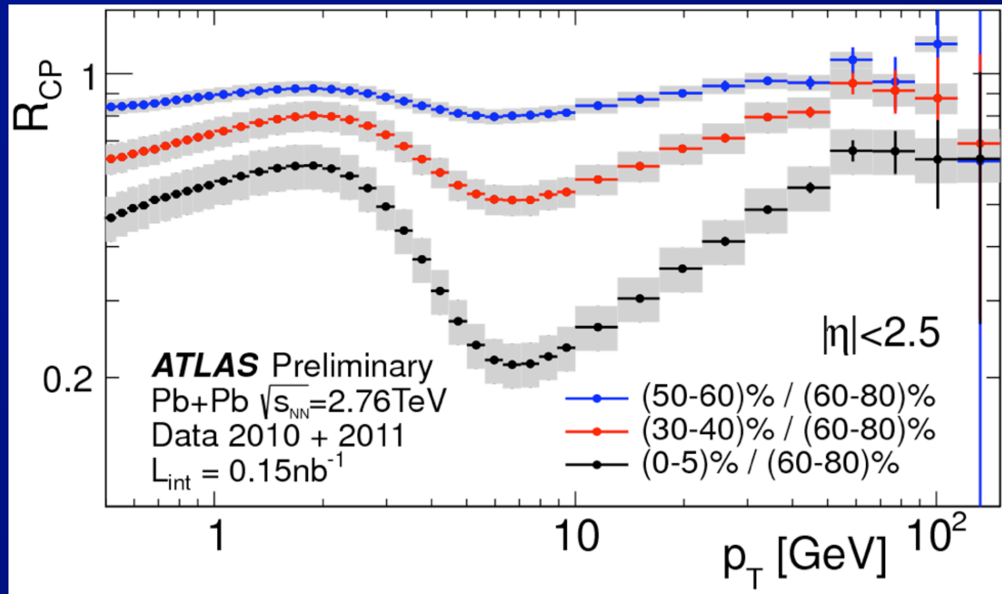




- In measured p_T range, muons primarily from charm and bottom decays.
  - J/ψ contribution ~ 1%
- Evaluate R_{cp} using 60-80% peripheral reference
  - ⇒ Factor of 2.5 suppression in 0-10% relative to 60-80%
  - ⇒ Independent of muon p_T within errors
  - ⇒ Evolution with N_{part} consistent between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

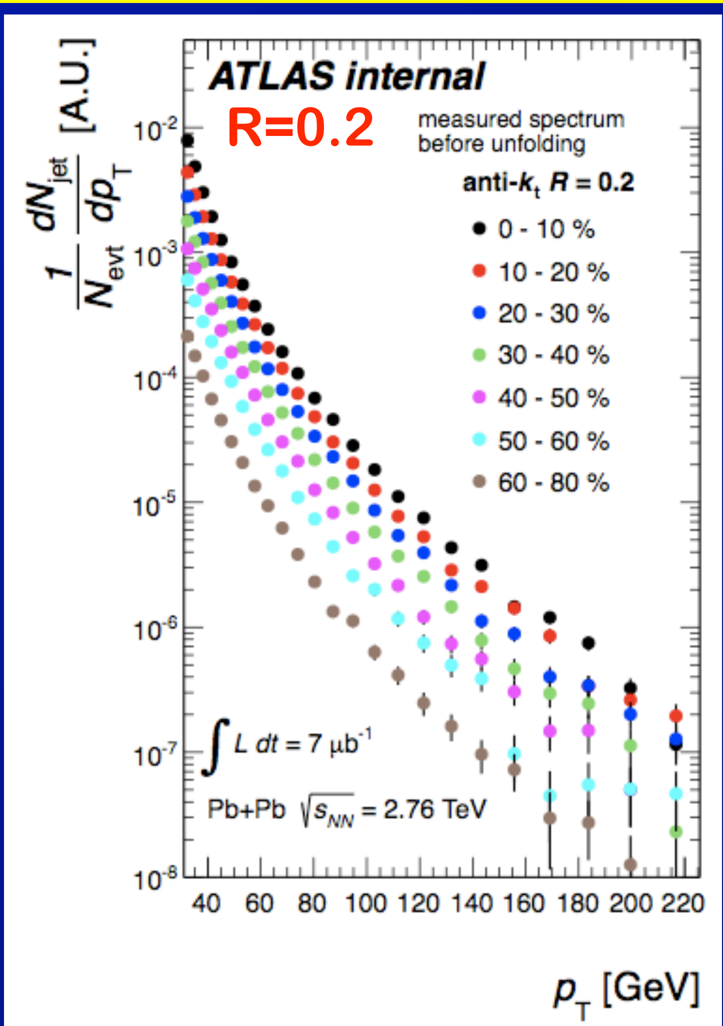
Single muons, charged comparison

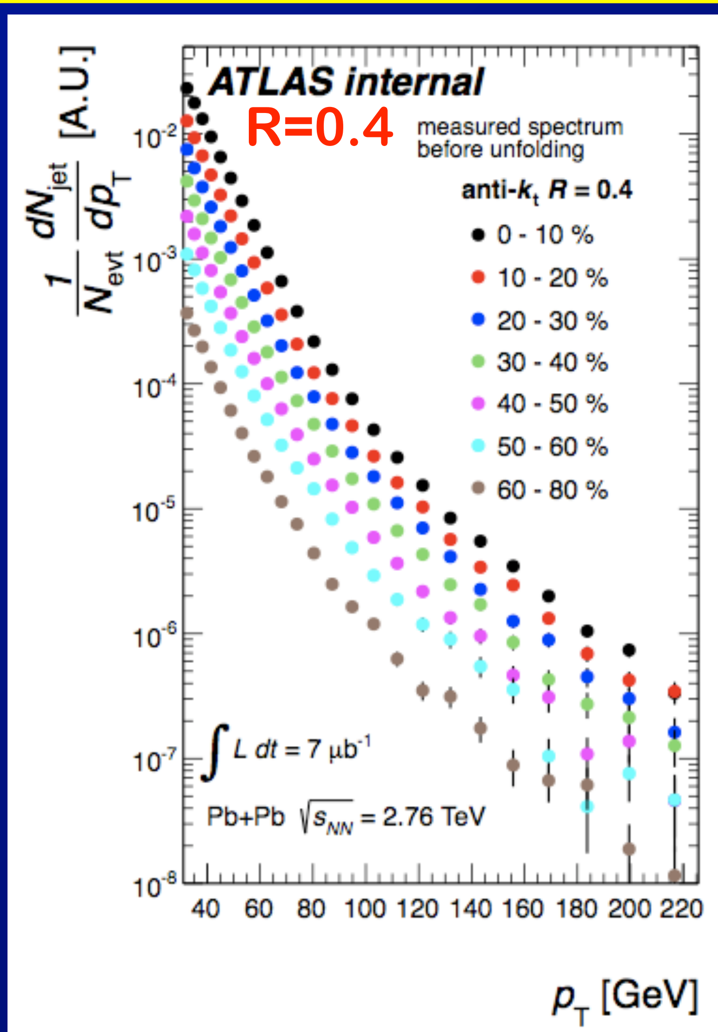




- **See less suppression of heavy flavor decay muons than single hadrons @ lower p_T**
  - But, both muon and hadron p_T poorly correlated with jet momentum.
    - ⇒ Single jets (below)
    - ⇒ b-tagged jets, especially at lower p_T (to come)

Pb+Pb Jet Spectra





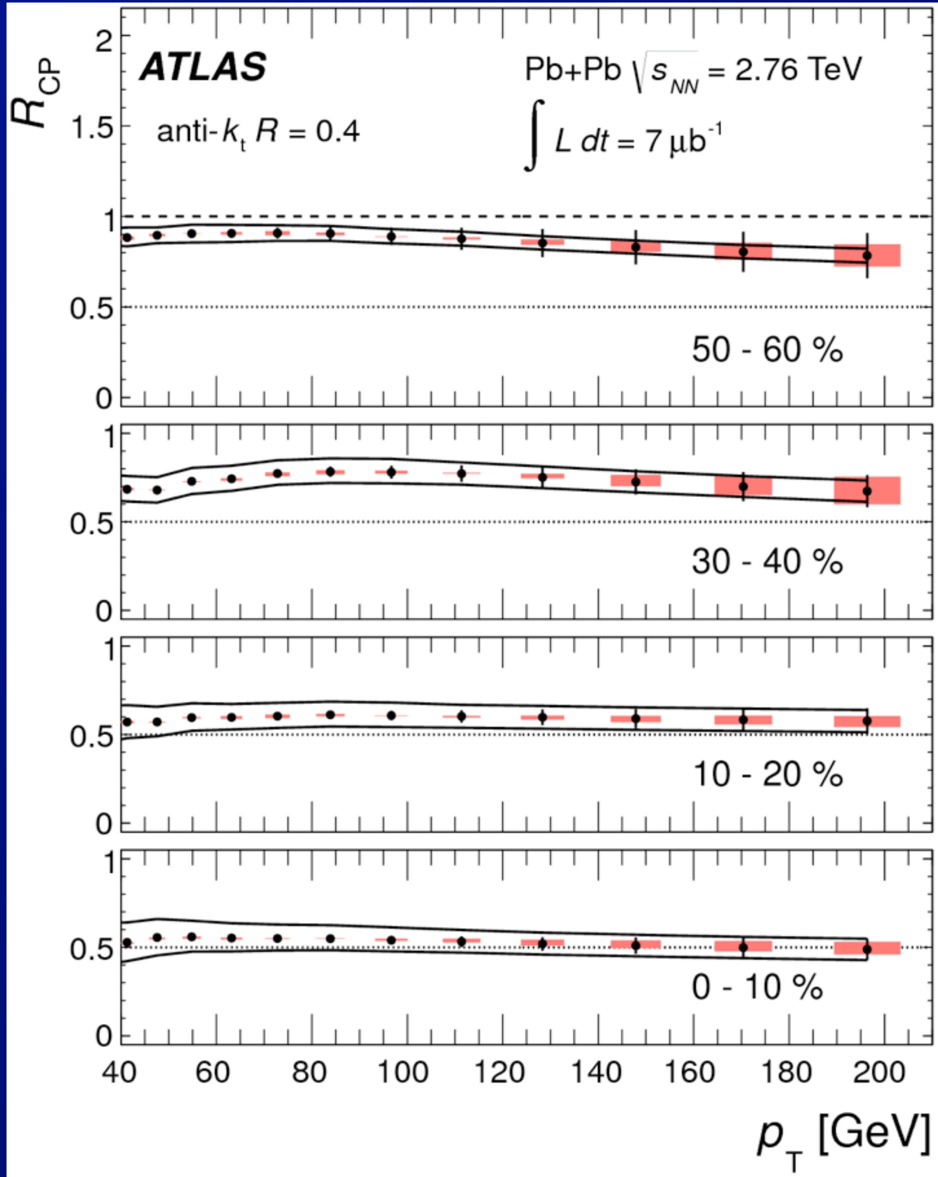
Unfolded (SVD) and efficiency corrected

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

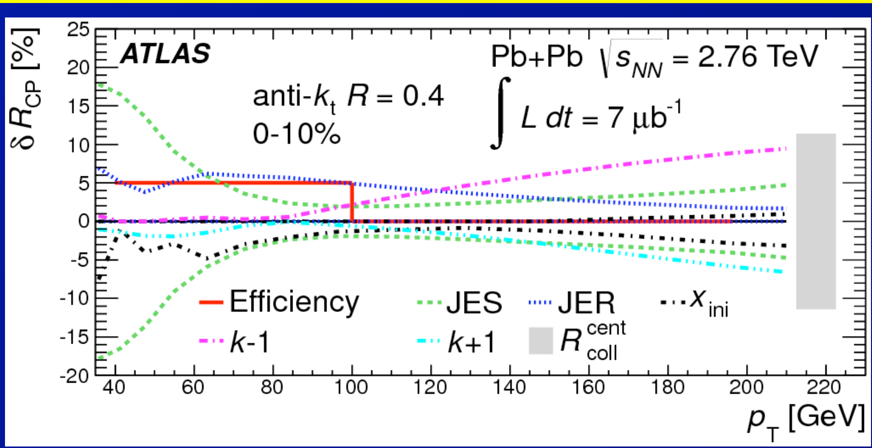
R = 0.4 Jet R_{cp}

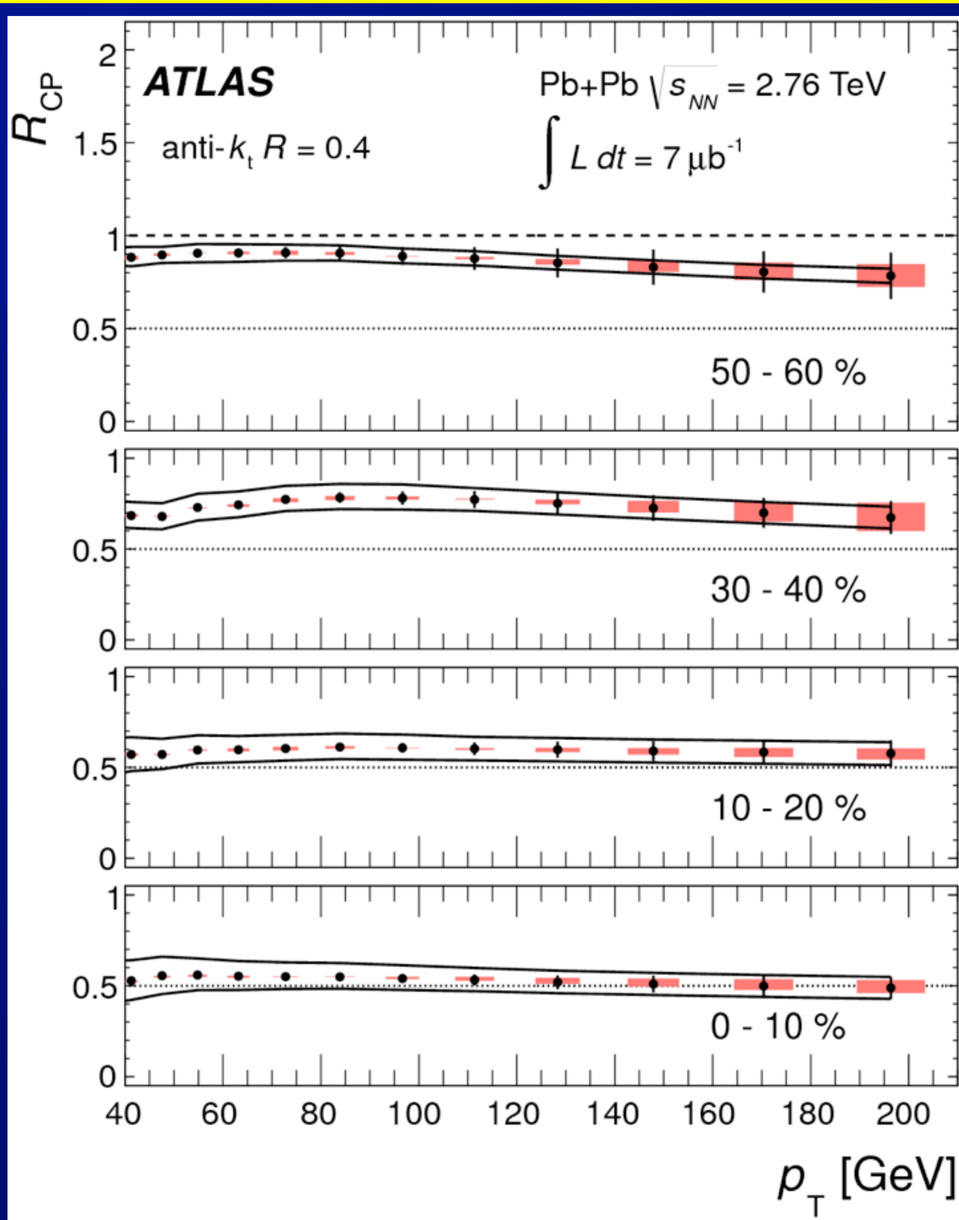
Phys. Lett. B 719 (2013) 220-241

- Systematic errors
  - Black band: fully correlated systematics
    - ➡ all points move up/down together
    - ➡ JES, JER, efficiency, x_{ini}, R_{coll}
  - Red boxes: partially correlated systematics
    - ➡ unfolding
- Error bars: square root of diagonal elements of covariance matrix
- No significance to horizontal width of error bars



R = 0.4 Jet R_{cp} Uncertainties





- **All systematic uncertainties decrease w/ high-statistics 2011 data**
  - Better control of unfolding
  - Better constraint on jet energy resolution, jet energy scale

    ⇒MC, cross-checks

Jet yields: centrality dependence

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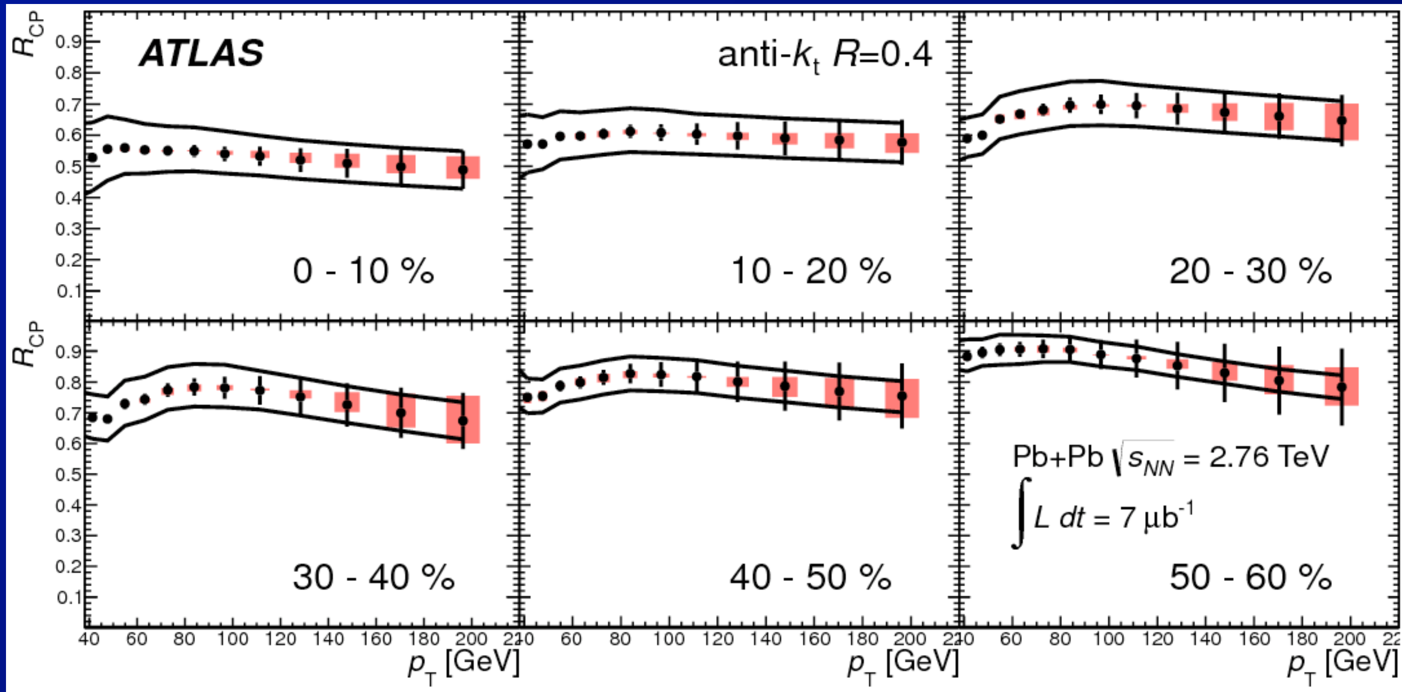
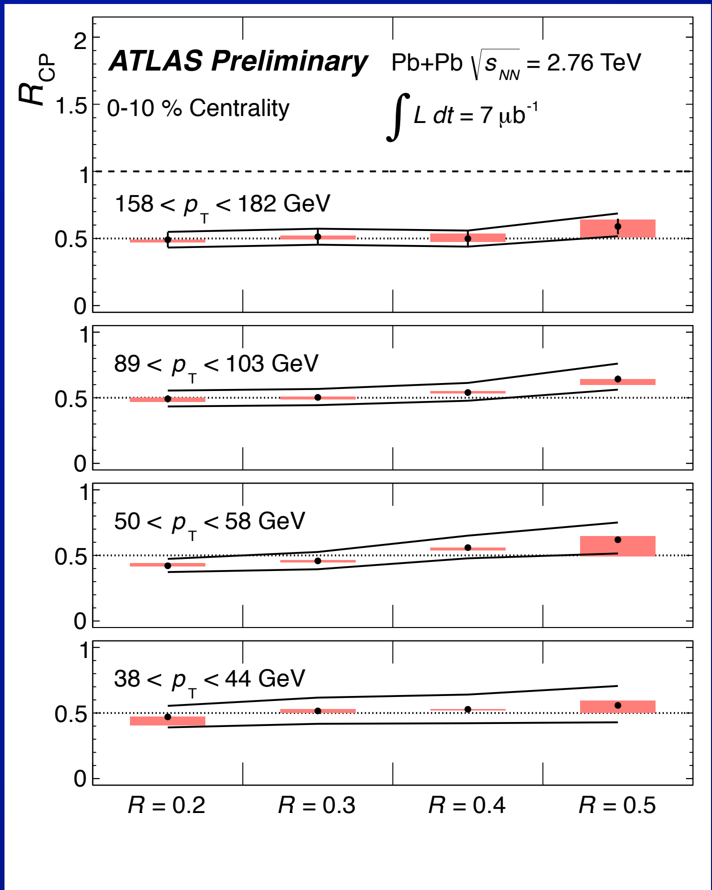


- **Consider systematics:**
  - Based on previous slides, γ, Z measurements constrain initial conditions to <~ 20%

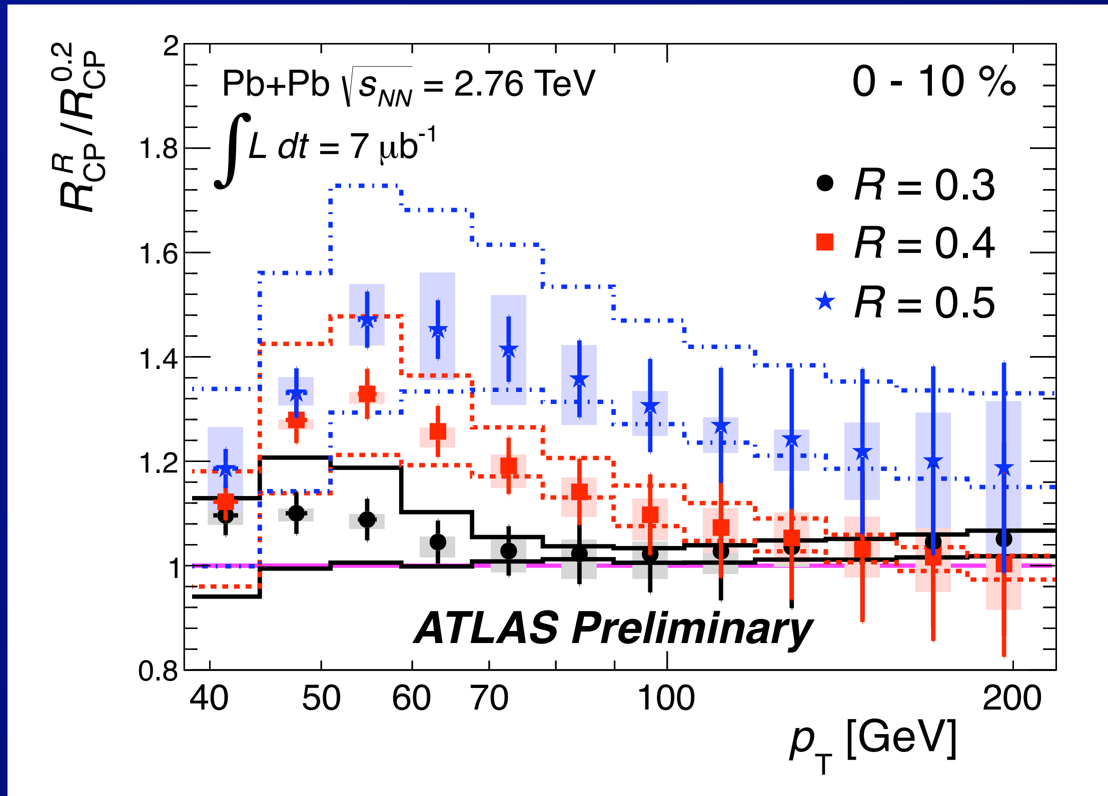
    ⇒ Will be reduced by p-Pb measurements
  - ~ 15% systematic uncertainties in R_{cp}

    ⇒ Reduced in 2011 data, in R_{AA}

Jet radius dependence of R_{cp}



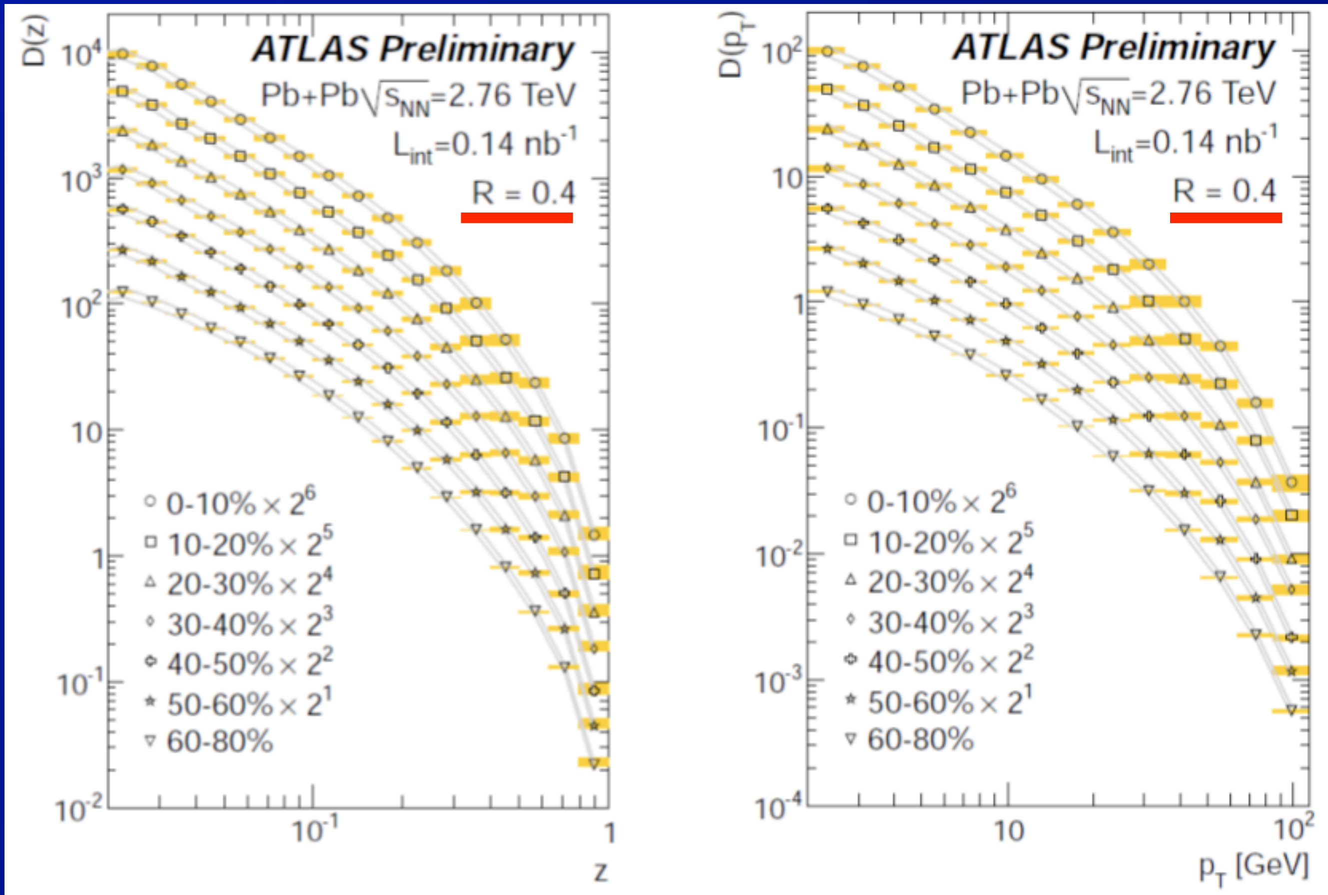
Significant cancellation of correlated errors



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

Probes insensitive to nuclear PDFs, hard-scattering rates

Inclusive jet fragmentation

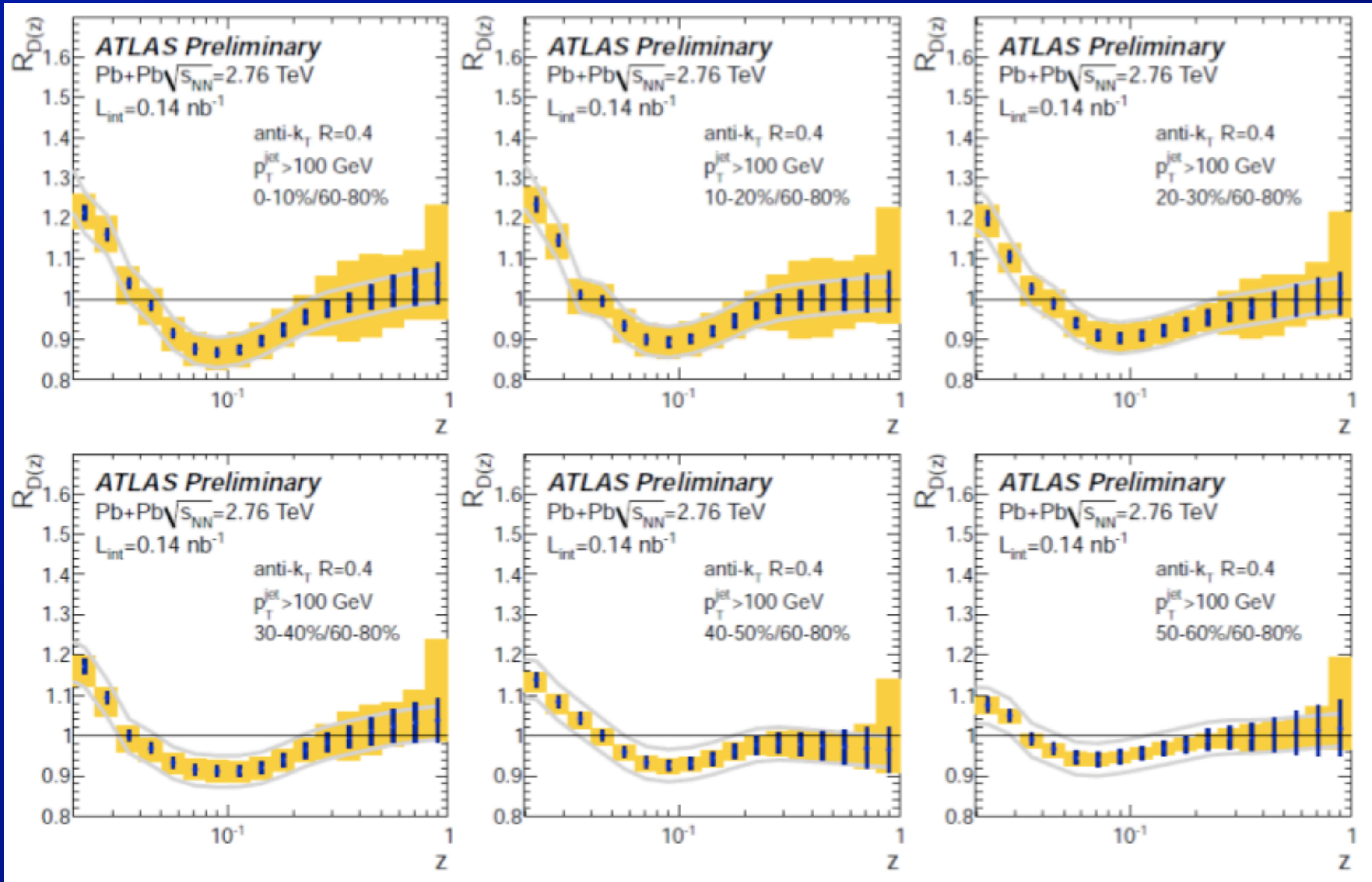


Unfolded for jet and charged particle resolution

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

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

Inclusive jet fragmentation (2)

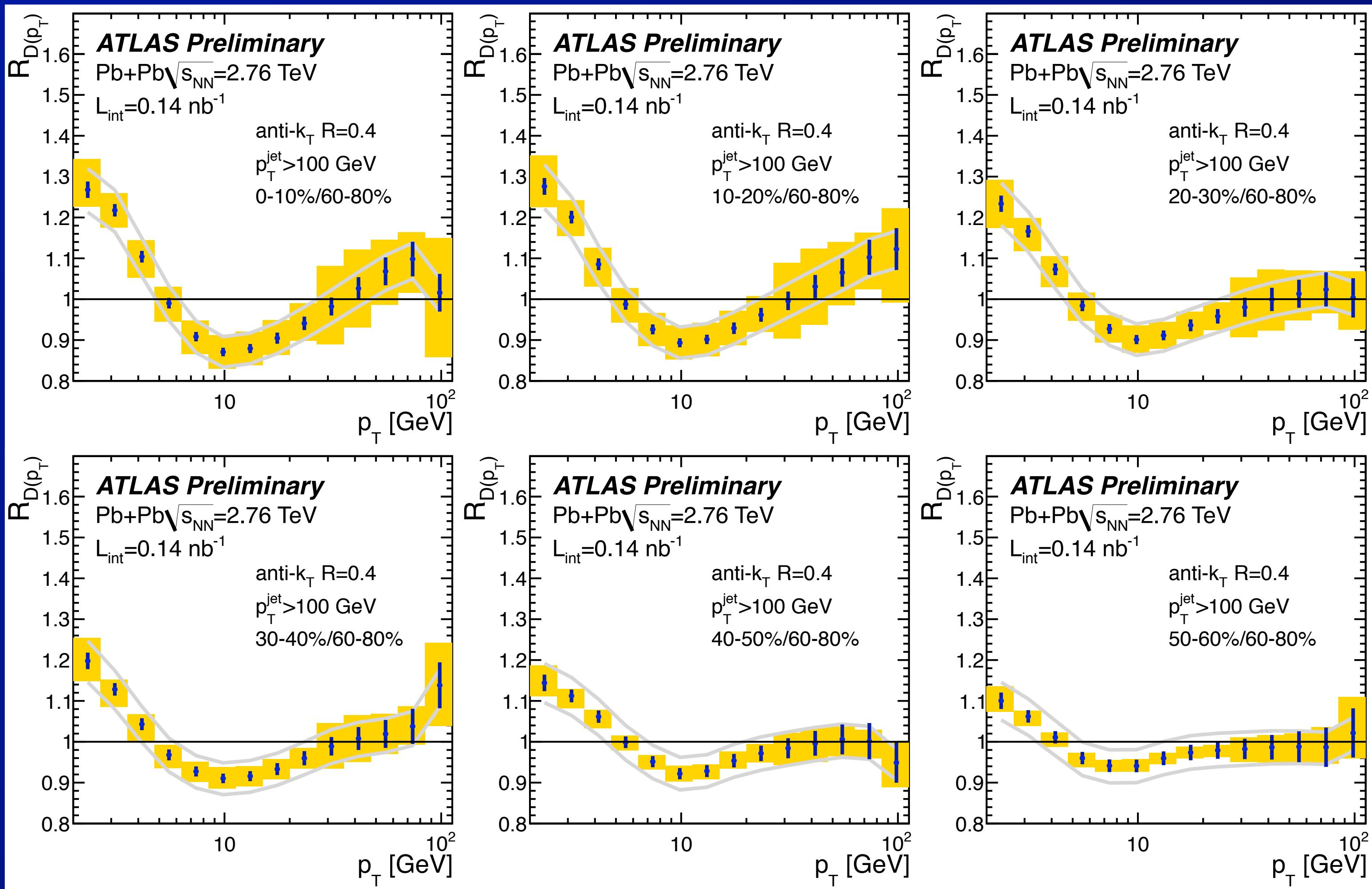


R = 0.4

- First observation of modified parton shower in inclusive jets

  ⇒Not only seeing “left over” unquenched jets.

Inclusive jet fragmentation (3)



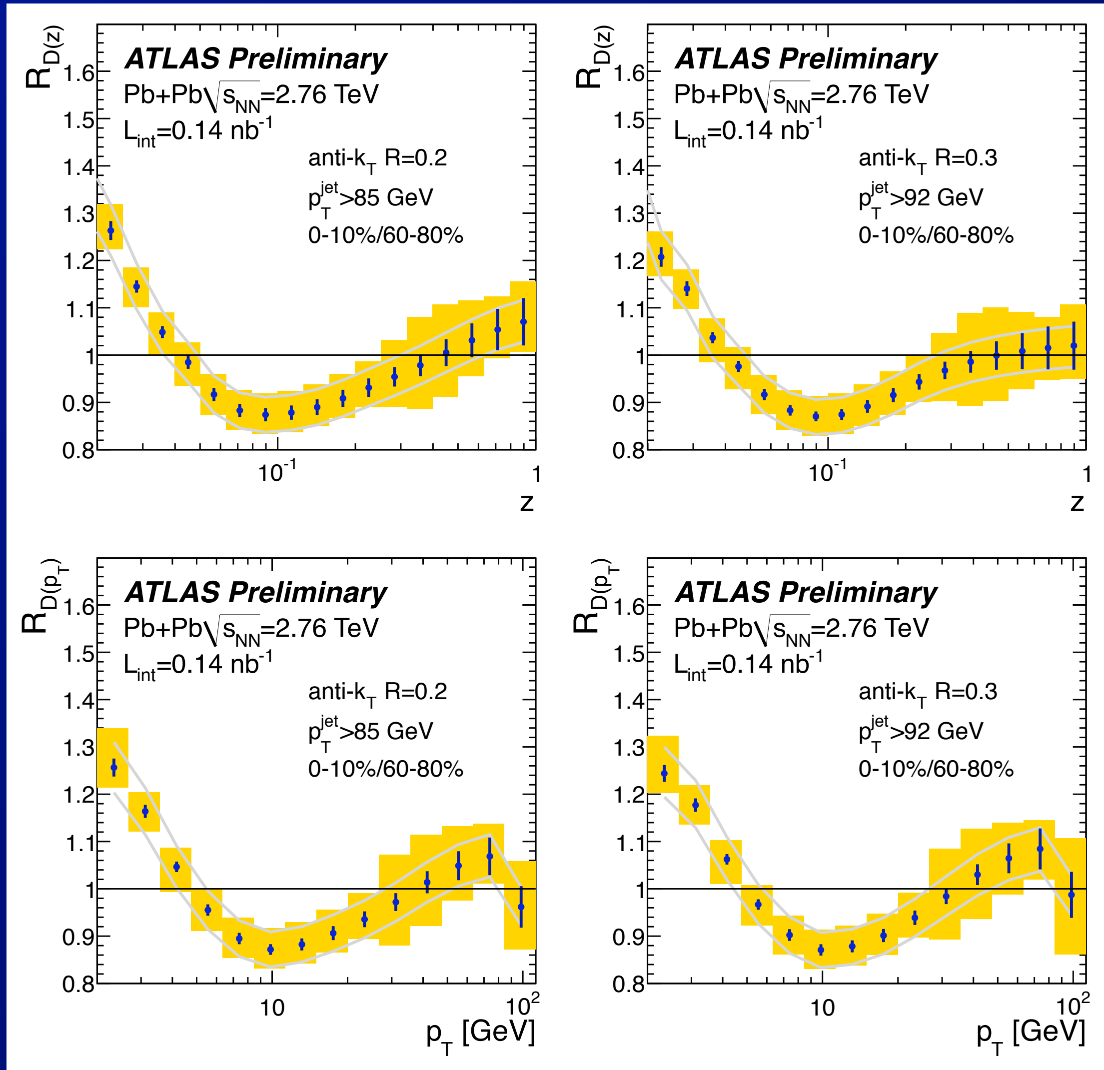
- Check that the modification is not due to the measurement of jet $p_T \Rightarrow D(p_T)$

  $\Rightarrow D(p_T)$ shows similar modifications

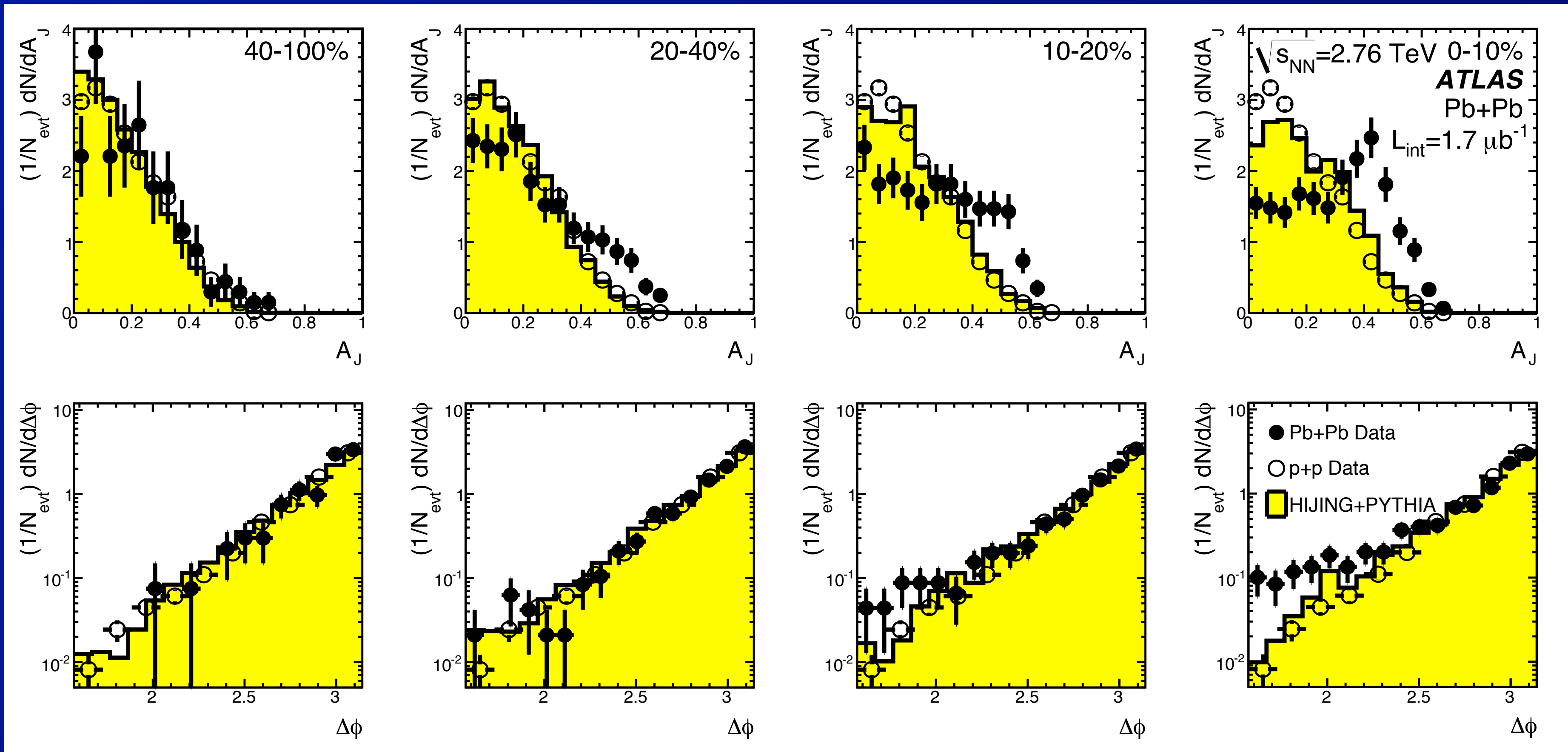
Jet fragmentation: R dependence

- 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

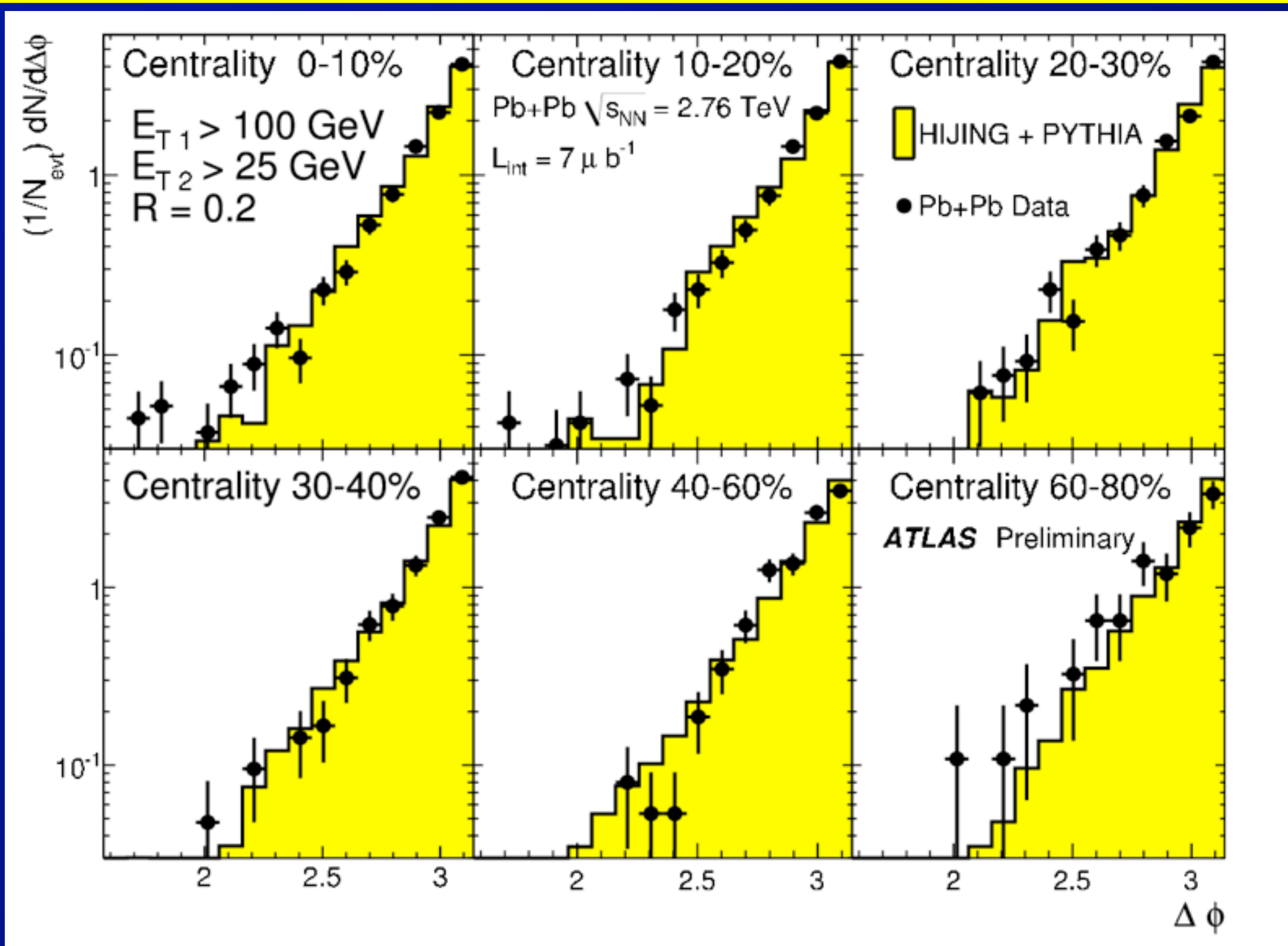


Di-jet asymmetry & acoplanarity



- 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

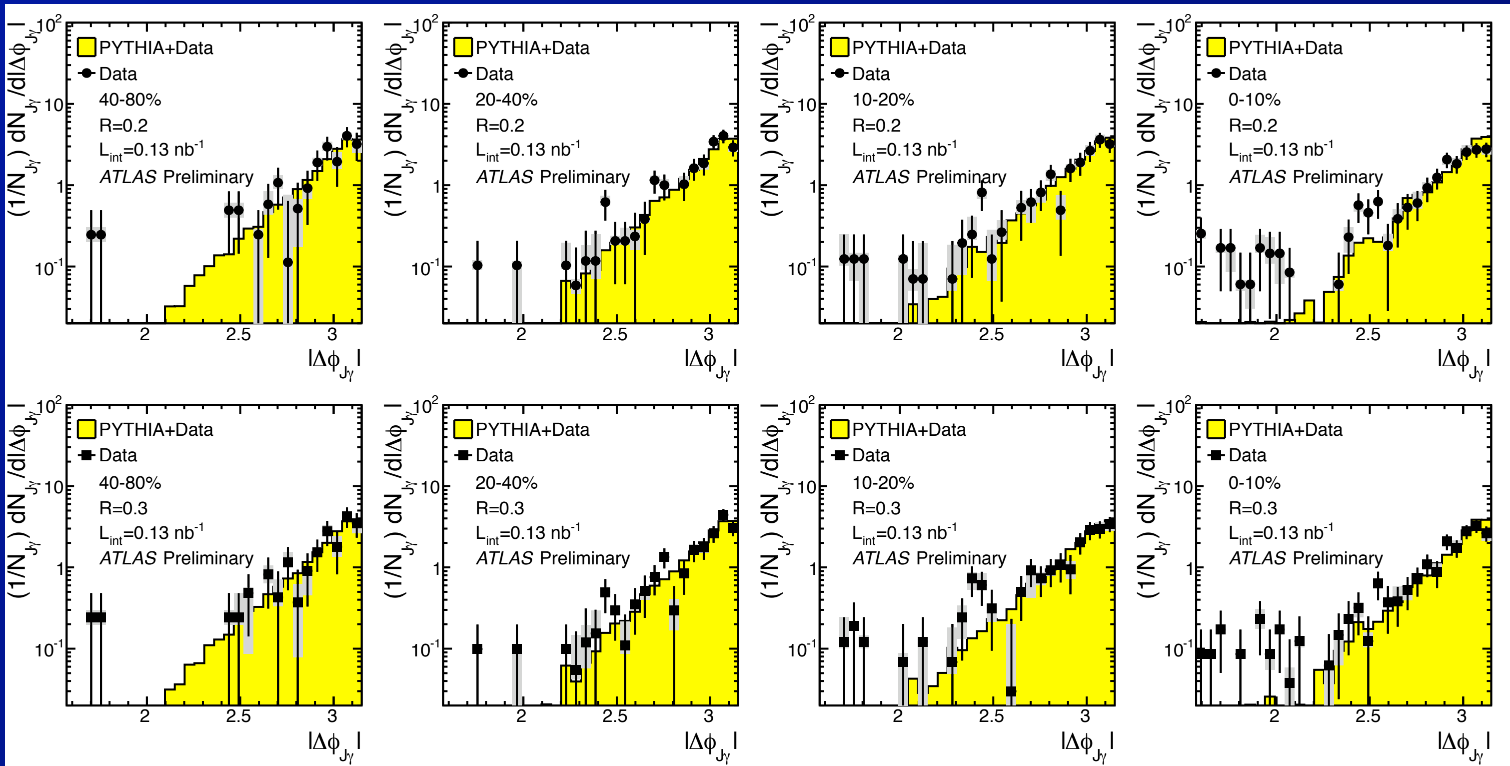
Dijet acoplanarity, R = 0.2



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

γ-jet angular distribution

Peripheral → central



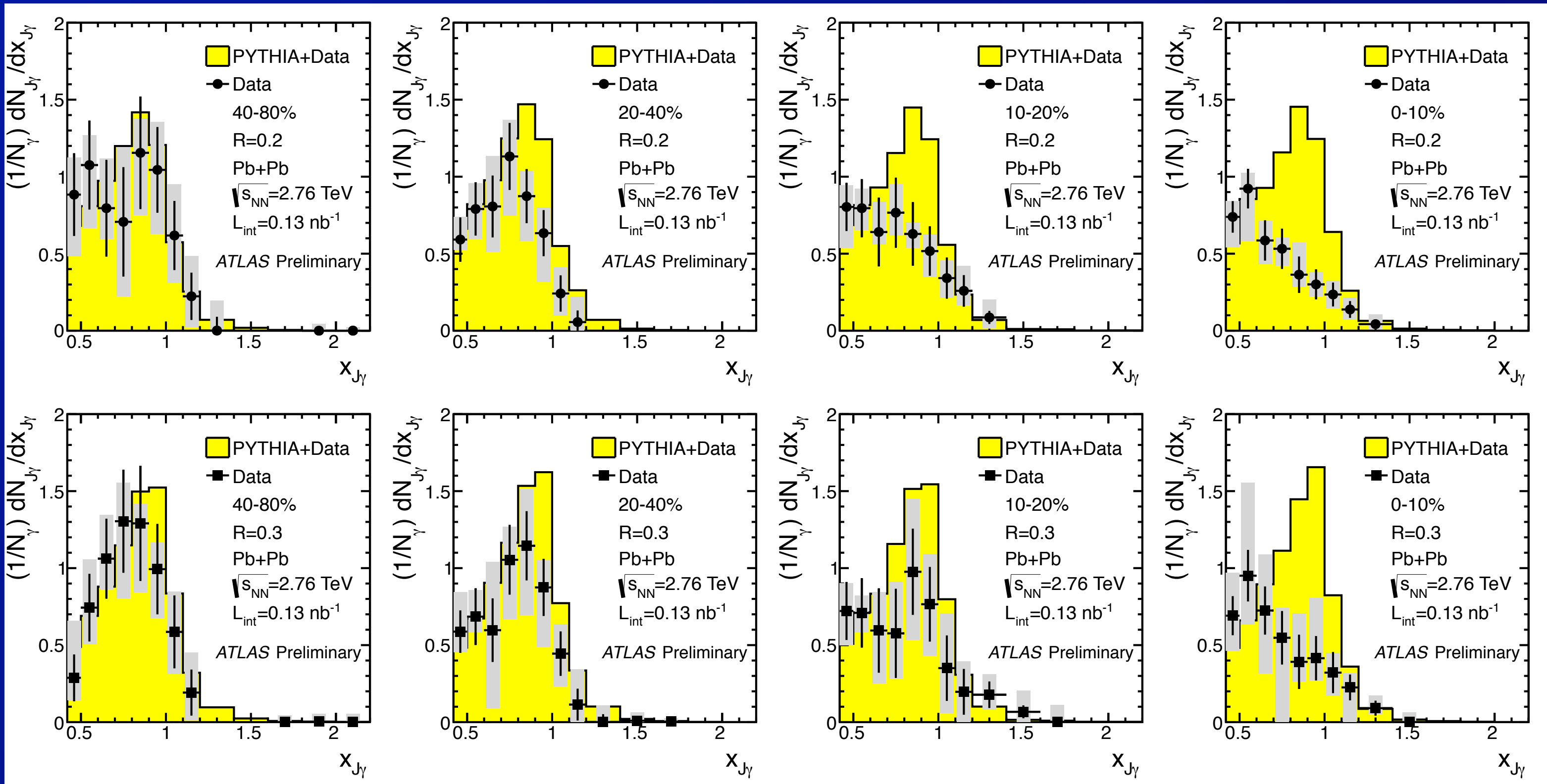
R = 0.2

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 $|\Delta\phi - \pi| < 7\pi/8$

γ-jet momentum balance

Peripheral → central



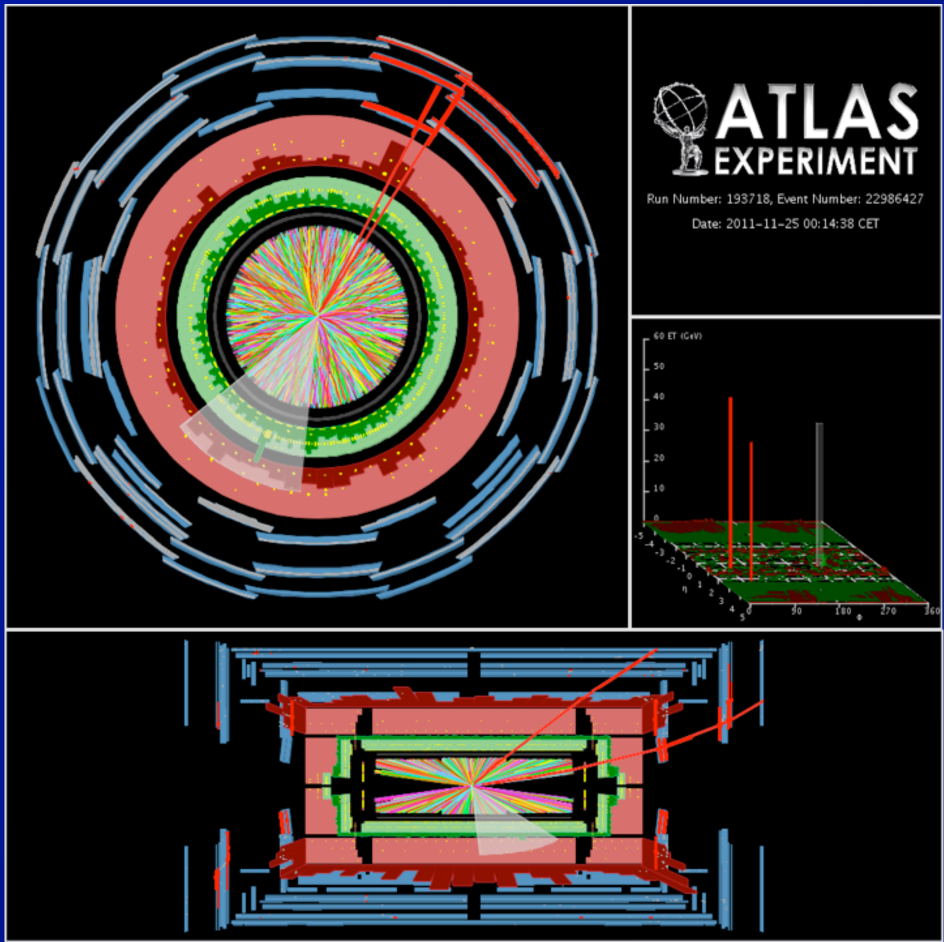
R = 0.2

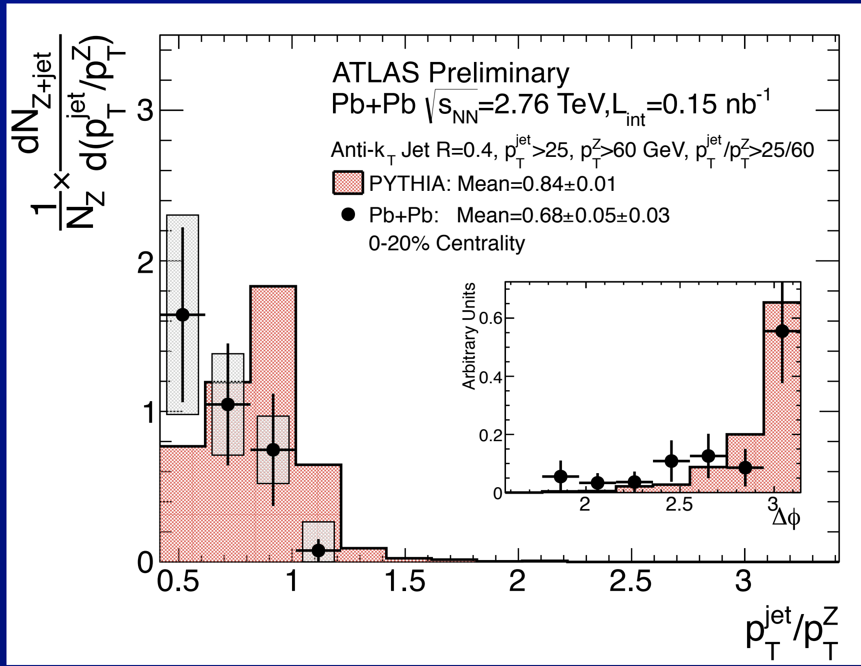
R = 0.3

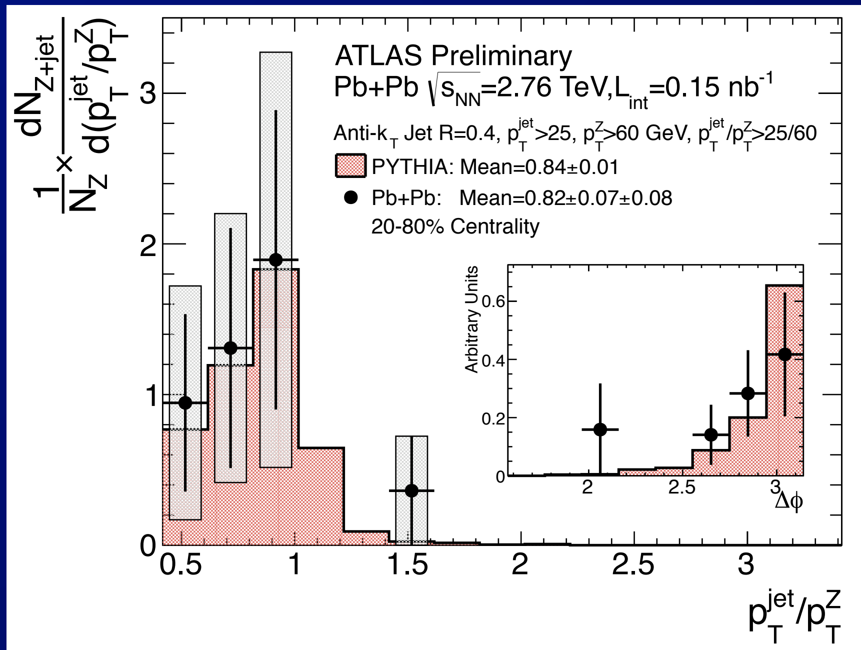
- Plot distribution of $x_J = p_T^{\mathrm{jet}} / p_T^{\gamma}$
  - photon background pairs subtracted
  - unfolded for jet energy resolution

⇒Substantial change in γ-jet balance

Pb+Pb Z-jet measurement



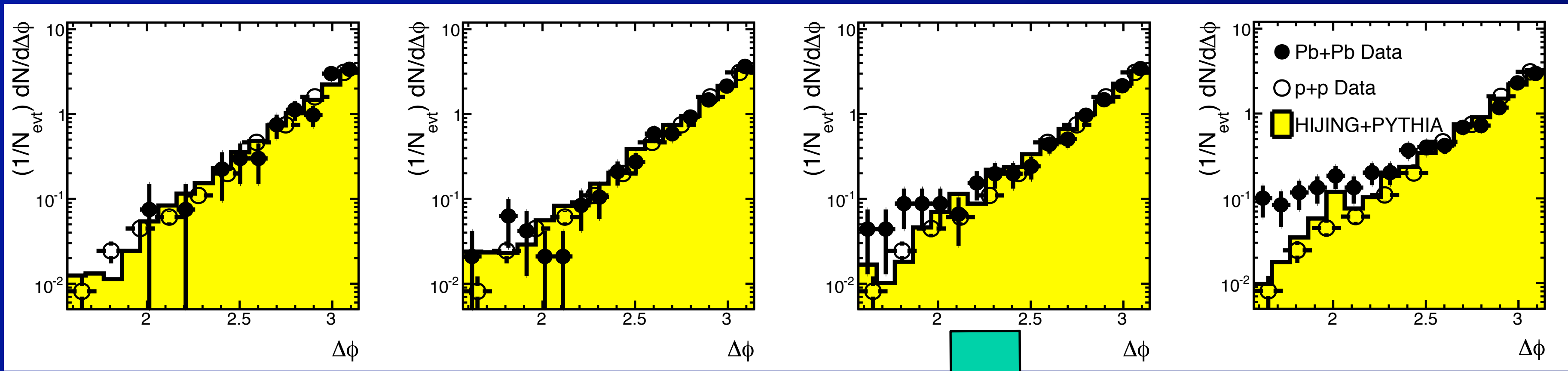




- Z-jet measurements have less background than γ-jet, but smaller rate

⇒1st results

Dijet (and gamma-jet) acoplanarity



Virtuality matters

Virtuality Q^2 of the parton in the medium controls physics of radiative energy loss:

$$Q^2(L) \approx \max\left(\hat{q}L, \frac{E}{L}\right)$$

medium ↑ $\hat{q}L$ vacuum ↑ $\frac{E}{L}$

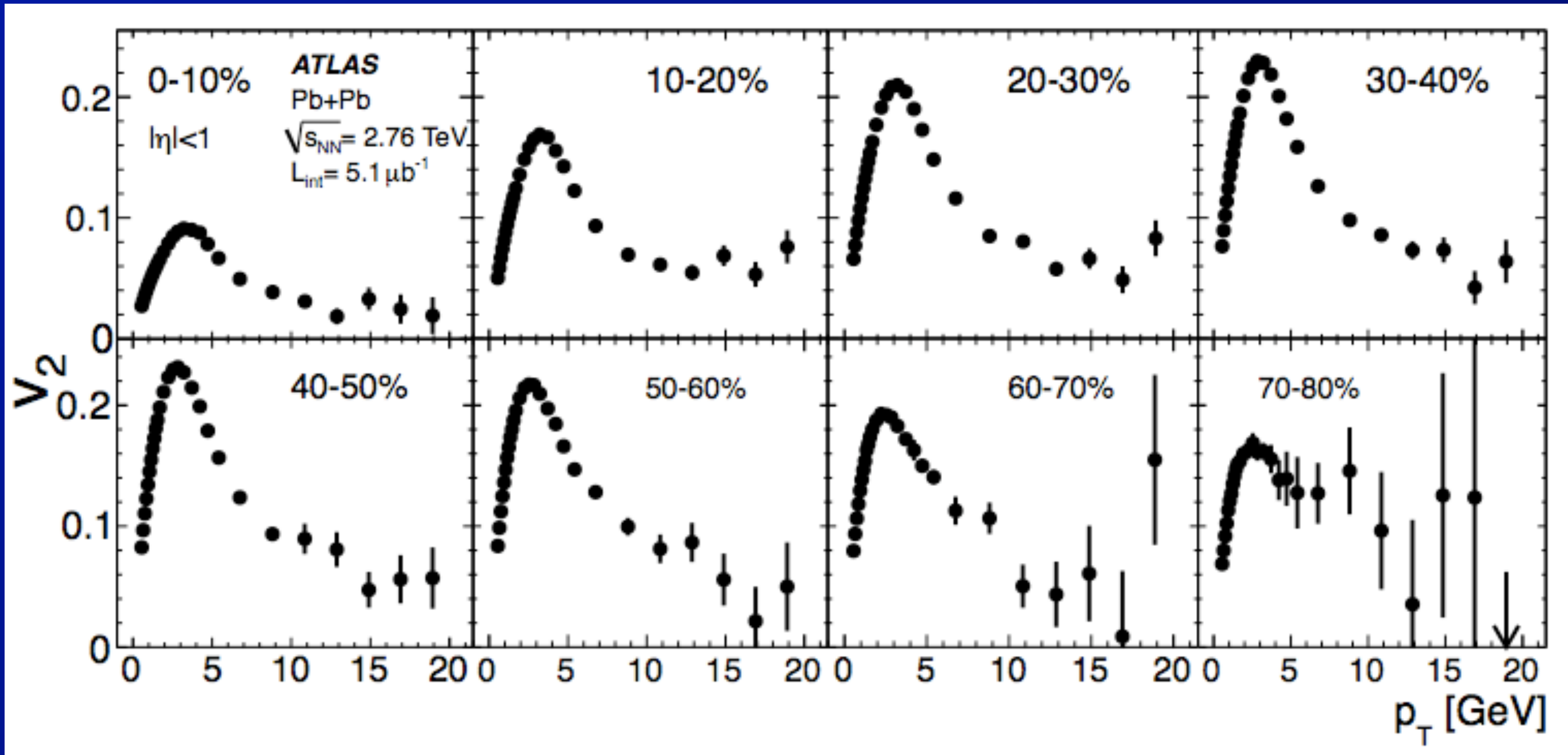
Weak coupling scenario

RHIC: 20 GeV parton, $L = 3$ fm	LHC: 200 GeV parton, $L = 3$ fm
$\hat{q}L \approx 4.5\,\mathrm{GeV}^2 \gg \frac{E}{L} \approx 1.5\,\mathrm{GeV}^2$	$\hat{q}L \approx 9\,\mathrm{GeV}^2 < \frac{E}{L} \approx 13\,\mathrm{GeV}^2$
Virtuality of primary parton is medium dominated and small enough to “experience” the strongly coupled medium	Virtuality of primary parton is vacuum dominated and only its gluon cloud “experiences” the strongly coupled medium

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

Tomography

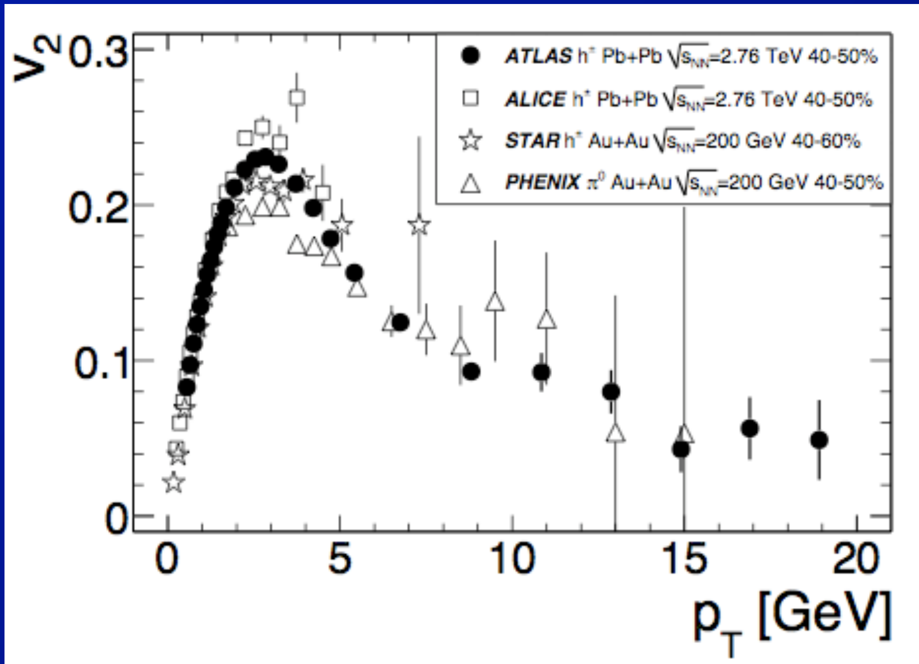
ATLAS: Charged particle $v_2(p_T)$

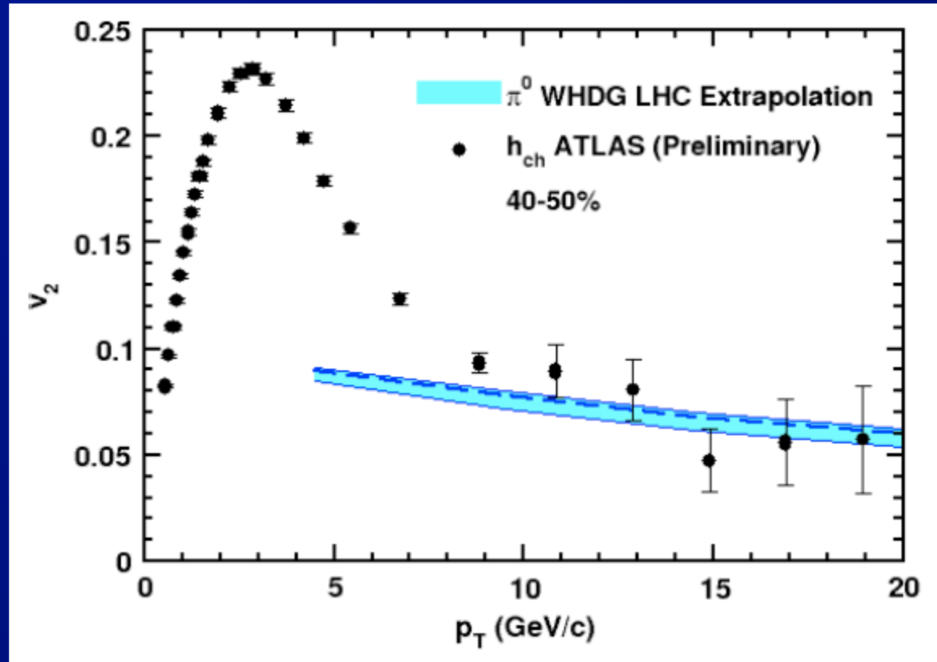


- **Single hadron $v_2(p_T)$:**
  - Evolution from flow (p_T < 6-7 GeV)
  - to quenching (p_T >~ 10 GeV)

    ⇒ Consistent with conclusions from similar analyses in PHENIX

ATLAS: Charged particle $v_2(p_T)$

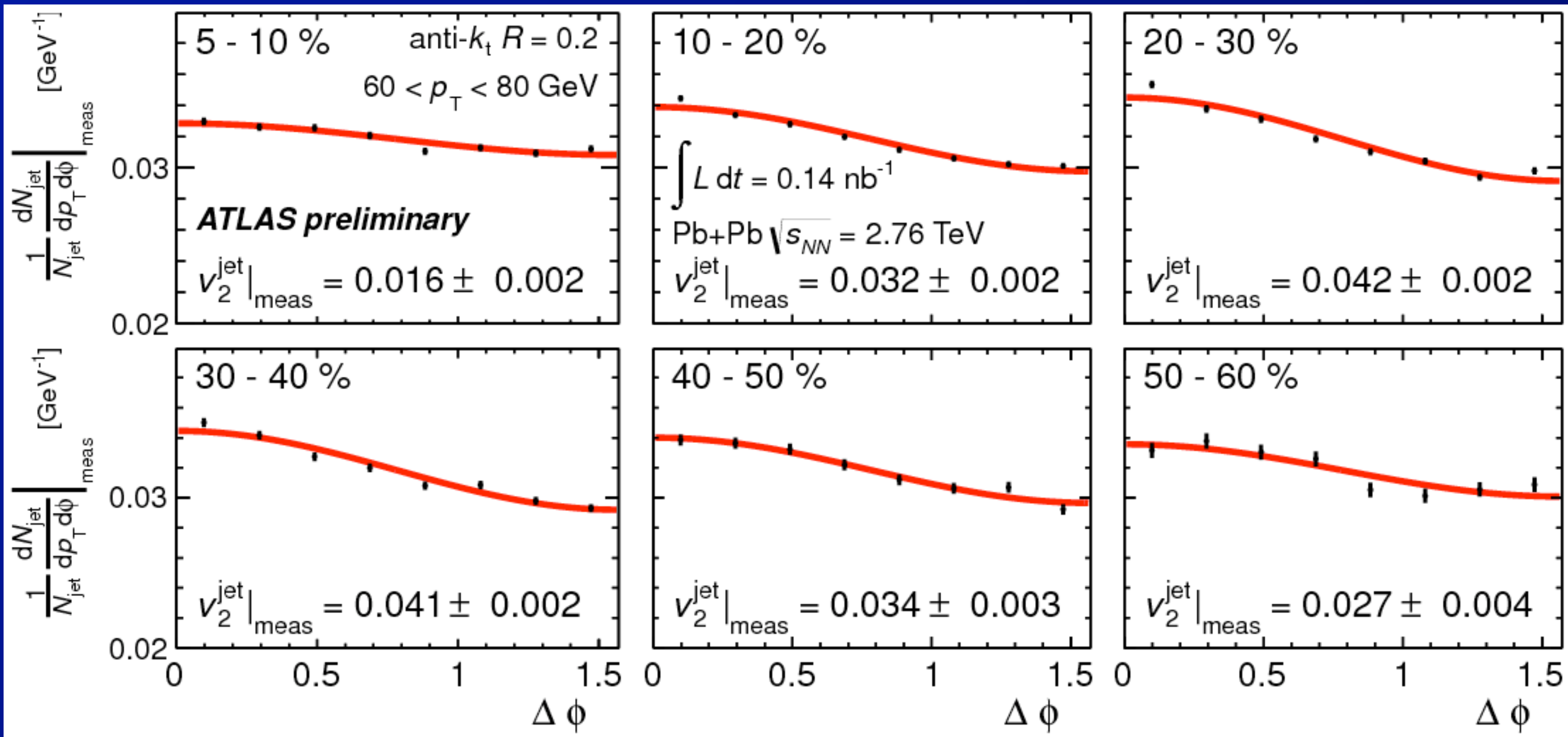




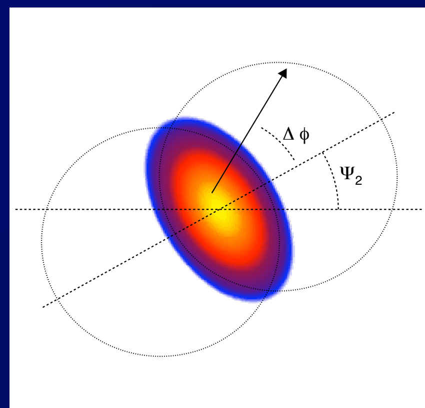
- Surprising agreement between RHIC and LHC $v_2(p_T)$, but beware “apples and oranges”
  - Charged (ATLAS, STAR), π^0 (PHENIX)
- WHDG energy loss describes $v_2(p_T)$ for $p_T > 10$

⇒ Flow dominates for p_T <~ 8 GeV

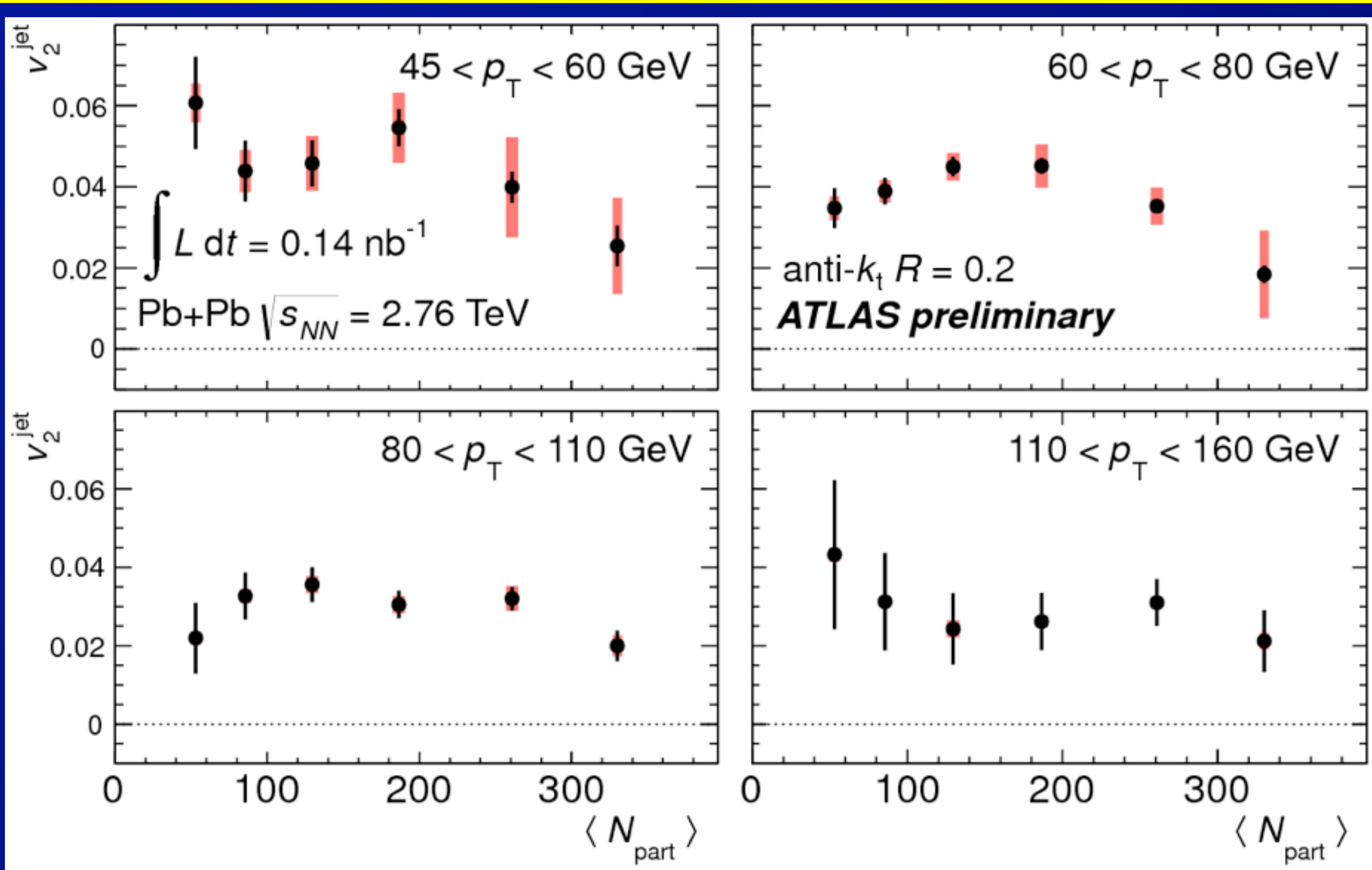
Differential jet suppression



- Measure jet yields in 8 bins of Δϕ 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

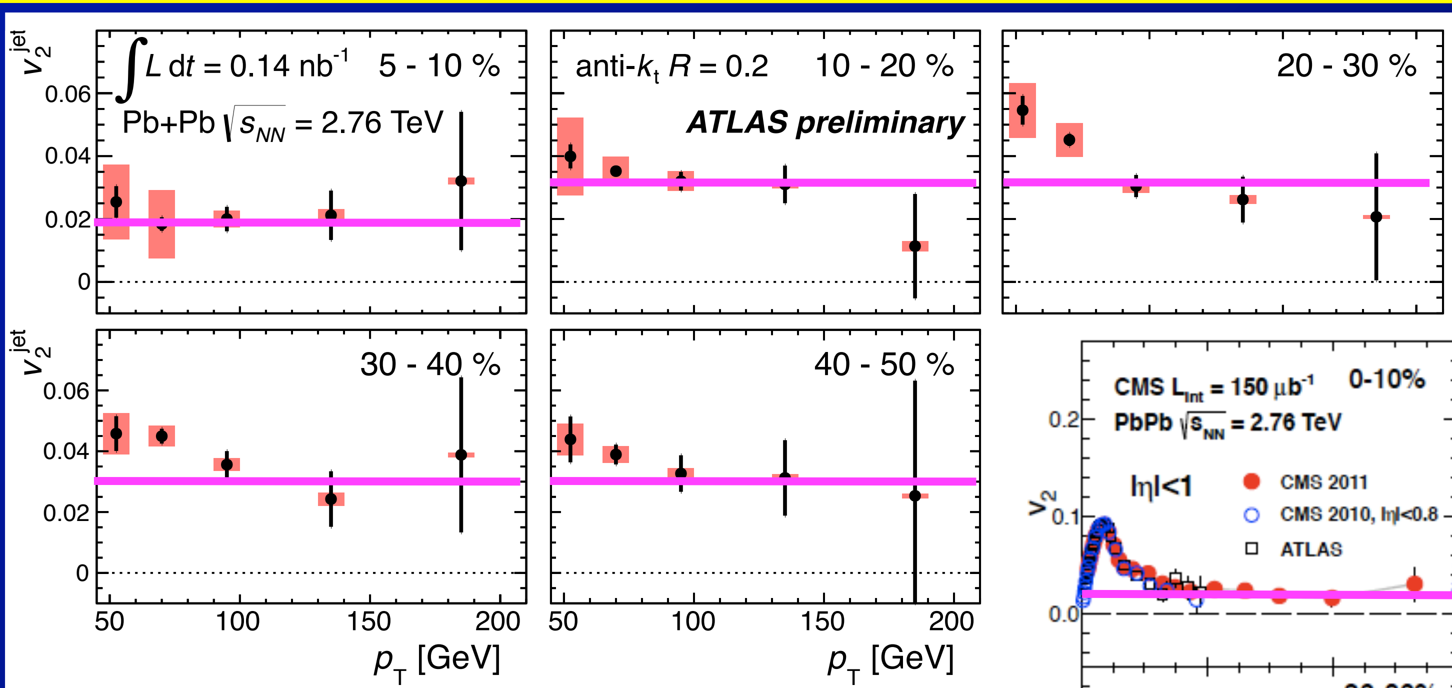


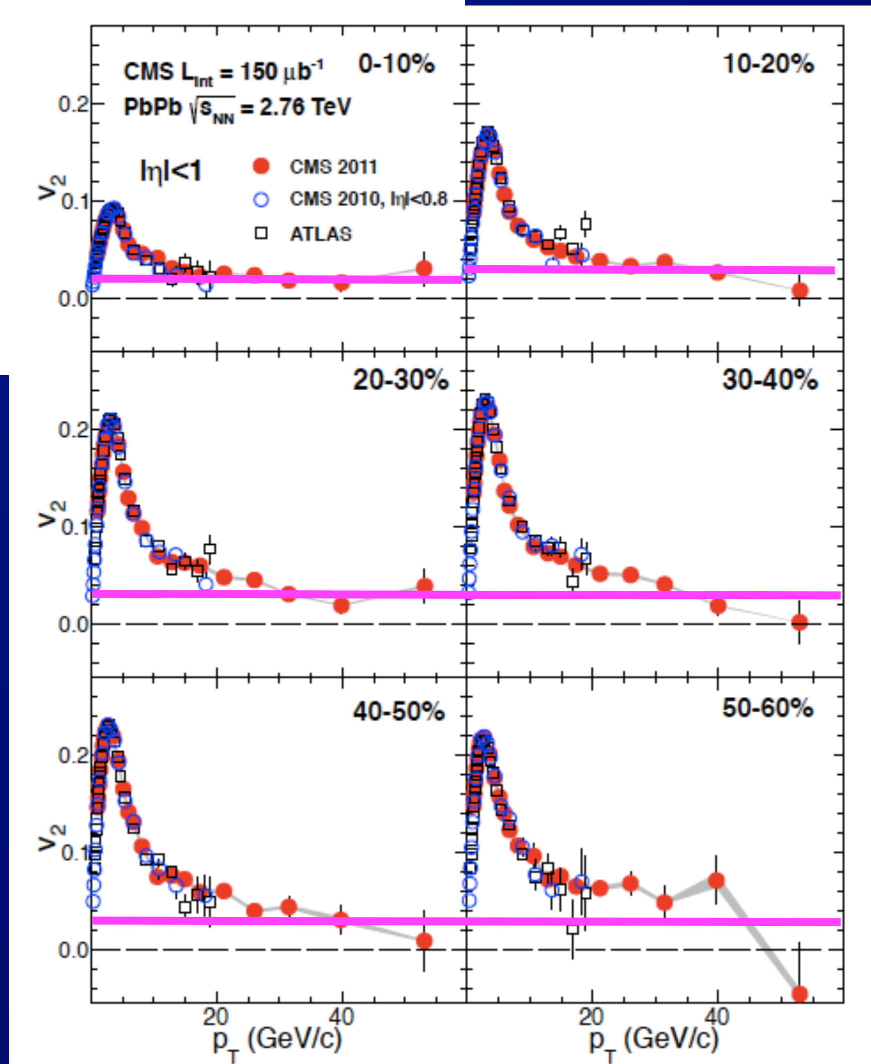
Differential jet suppression



- 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

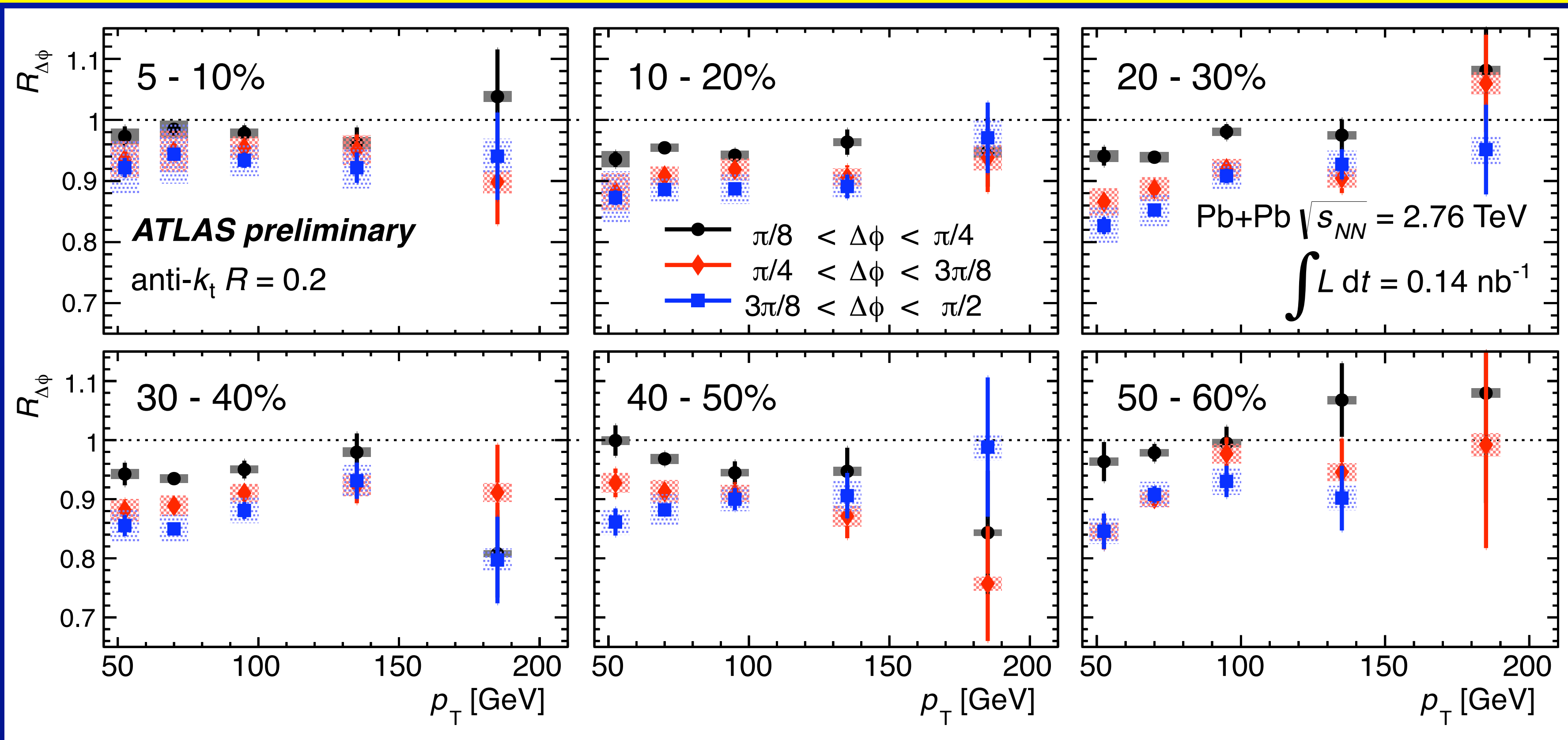
Jet $v_2(p_T)$





- 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



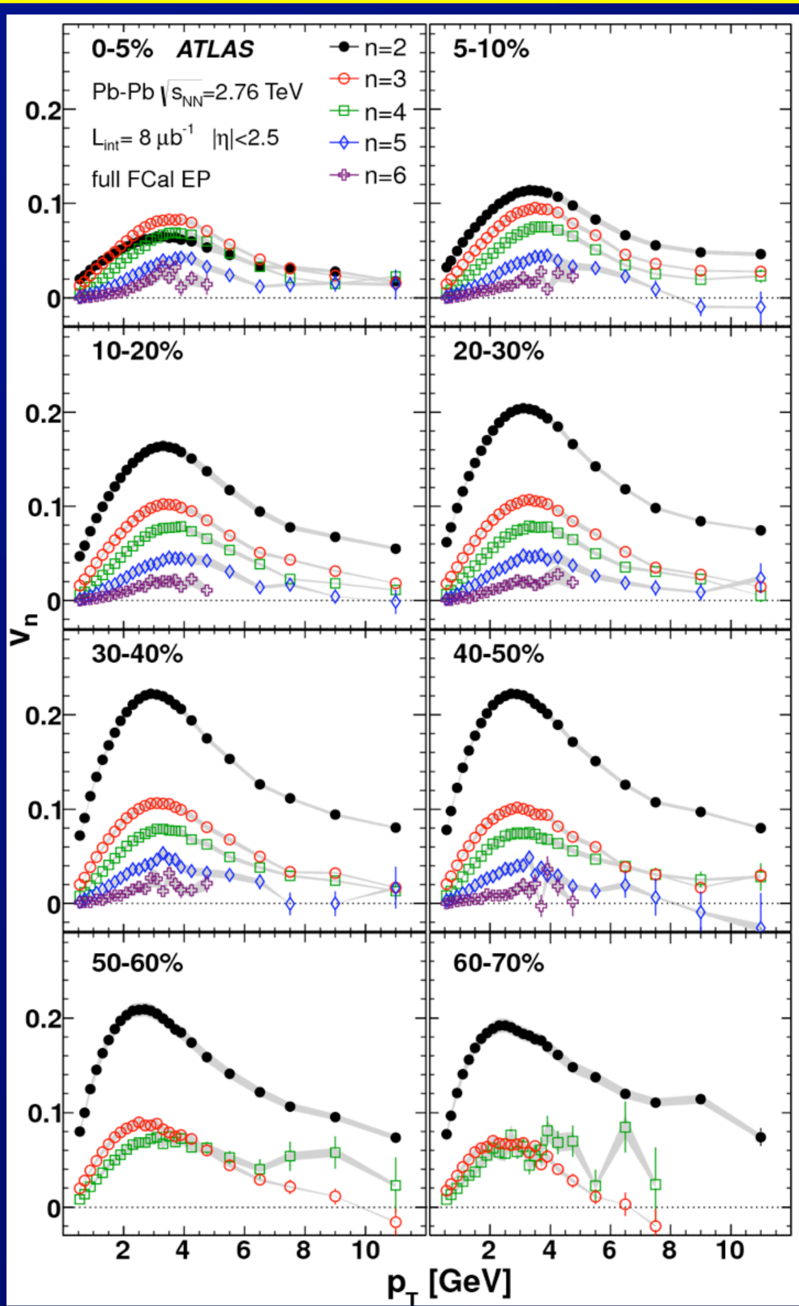
- Evaluate ratio of jet yields in different Δϕ bins to the yield in $0 < \Delta\phi < \pi/8$.
  - $R_{AA}(\Delta\phi)/R_{AA}(0\text{-}\pi/8)$

    ⇒ ~15% change in single jet suppression between in-plane, out-of-plane @ high p_T

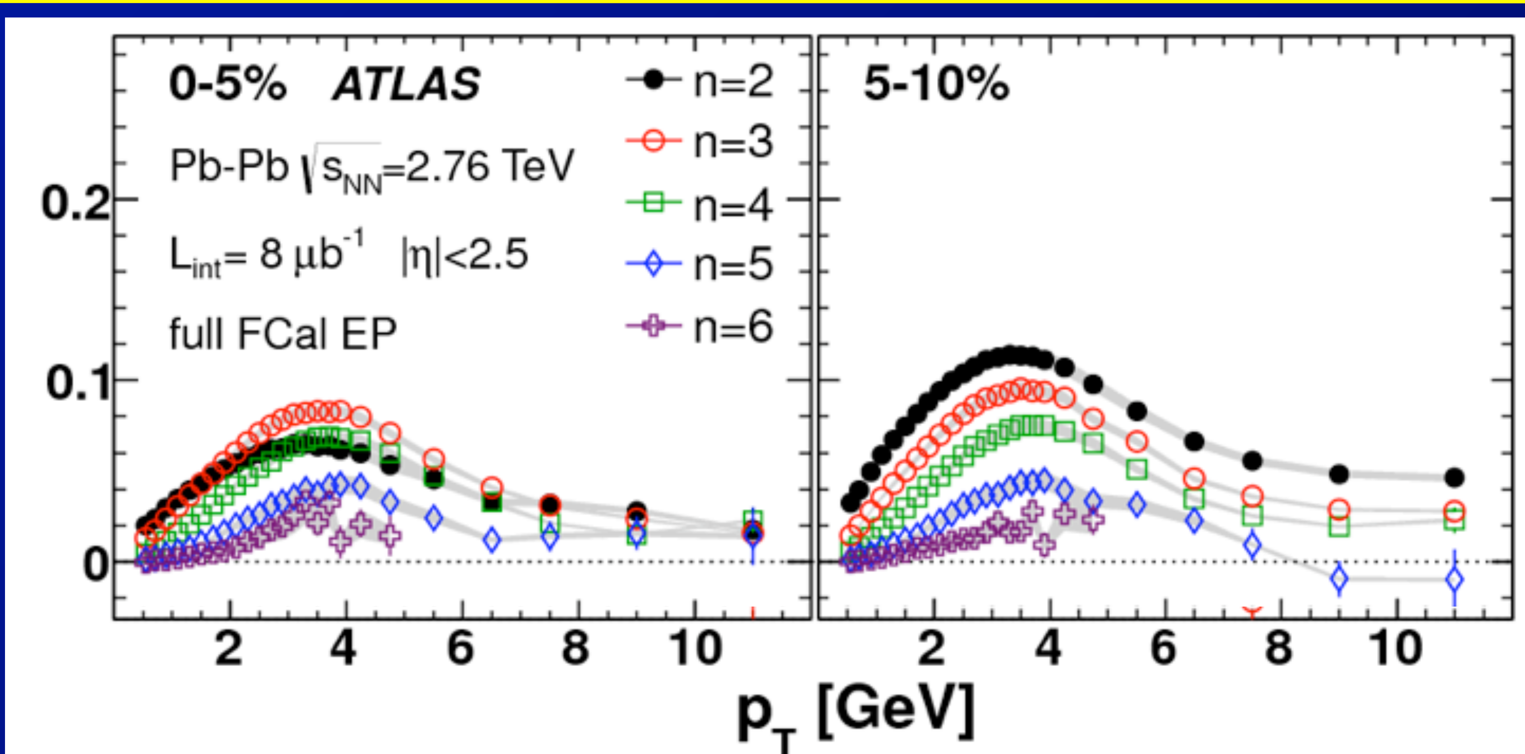
n > 2 collective flow @ high(er) p_T

Phys. Rev. C86 (2012) 014907

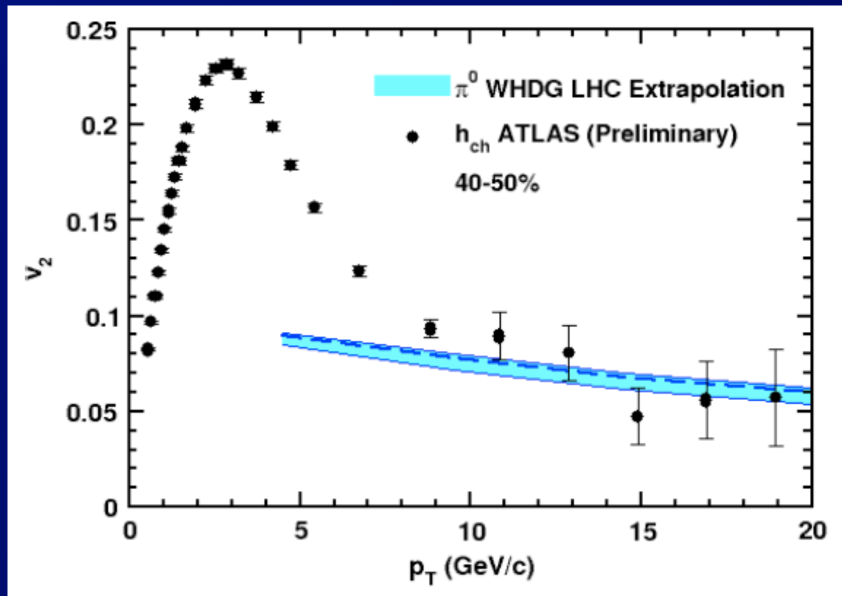
- Full set of event plane $v_n(p_T)$ results
- Observe non-zero v_n for p_T > 10 GeV in central collisions



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.



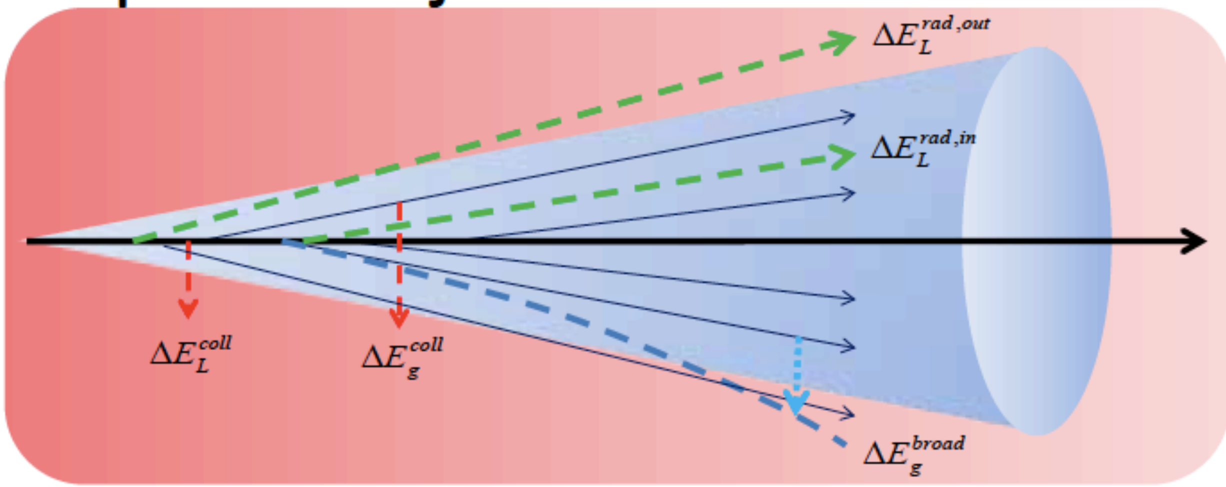
Summary, ruminations

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)

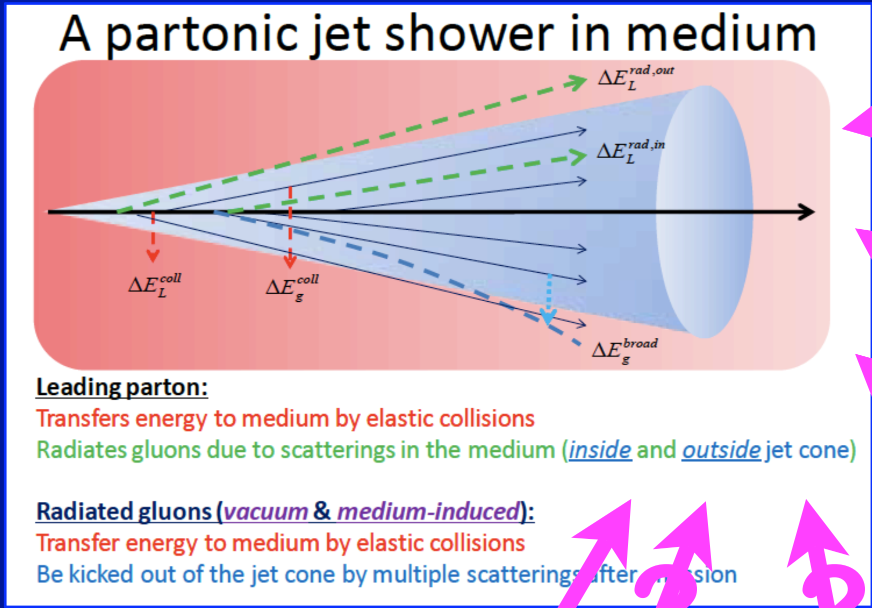
Radiated gluons (*vacuum* & *medium-induced*):

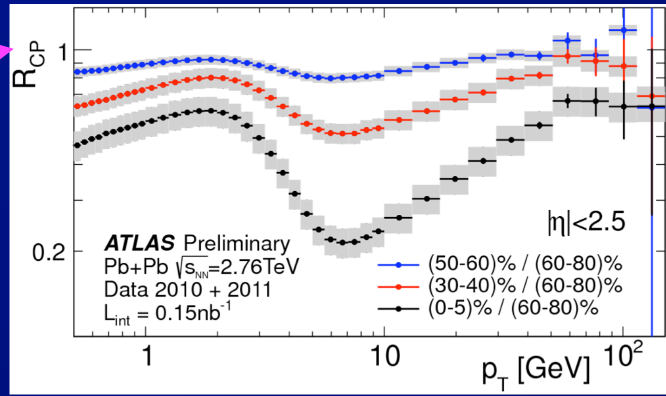
Transfer energy to medium by elastic collisions

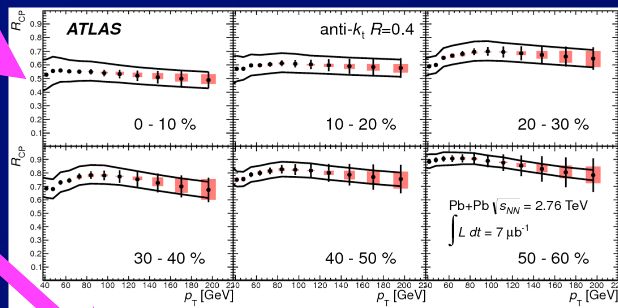
Be kicked out of the jet cone by multiple scatterings after emission

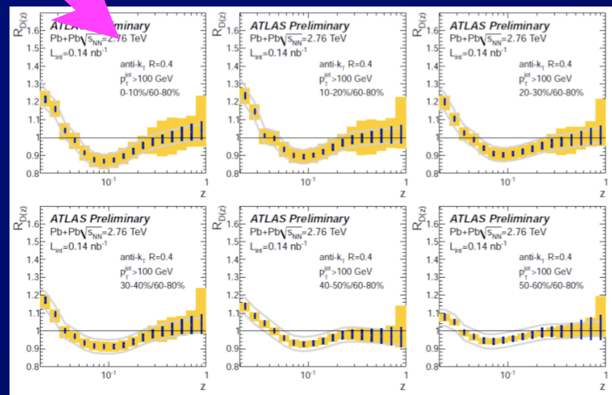
- Complicated theoretical problem
- Addressing complicated measurements
  - Need to be patient (but not too patient), but:
    - ⇒Are we asking, answering right questions?

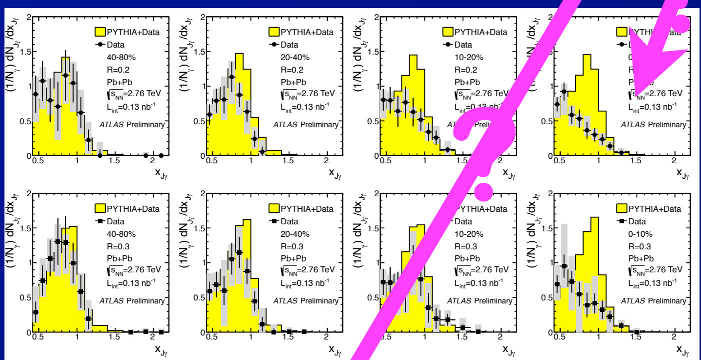
Jet probes of the quark gluon plasma

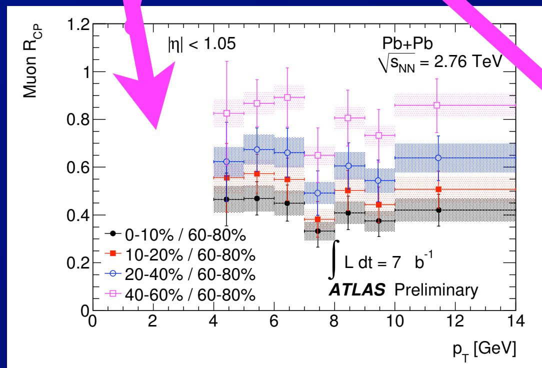


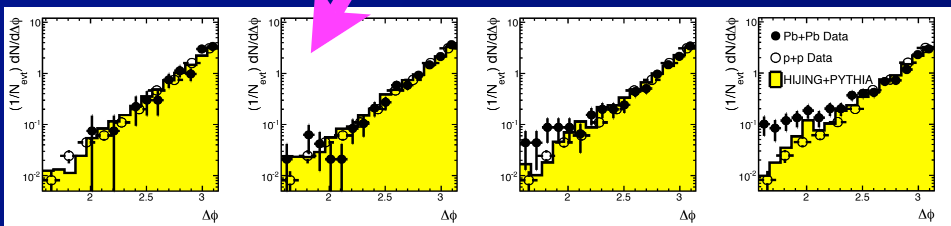




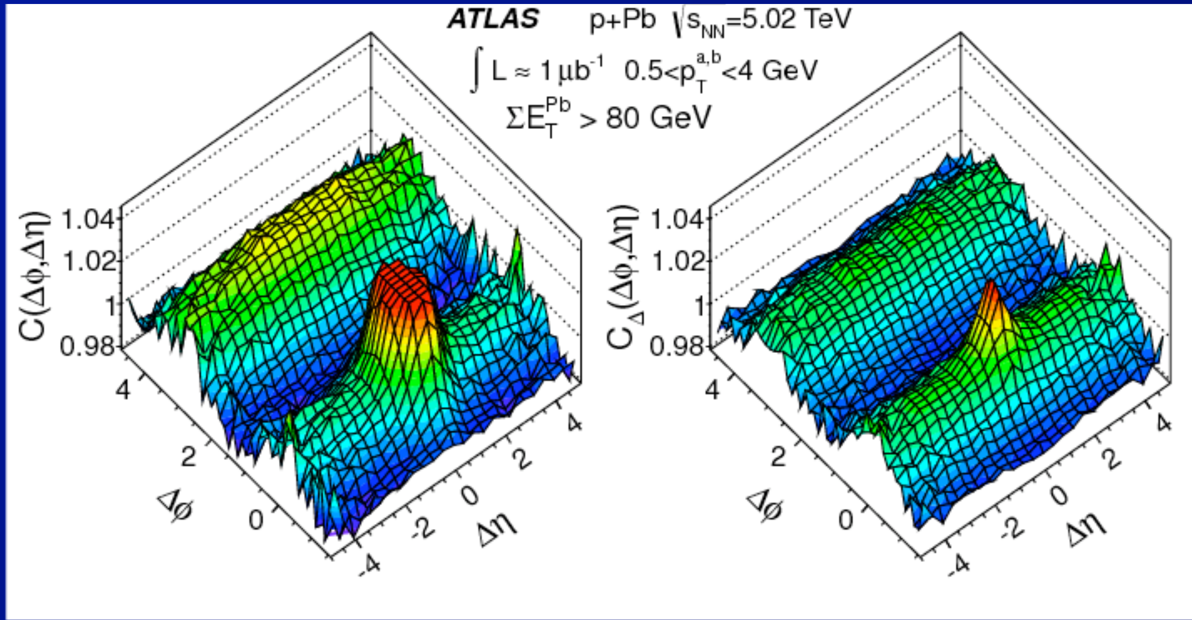








p+Pb ridges, who ordered that?

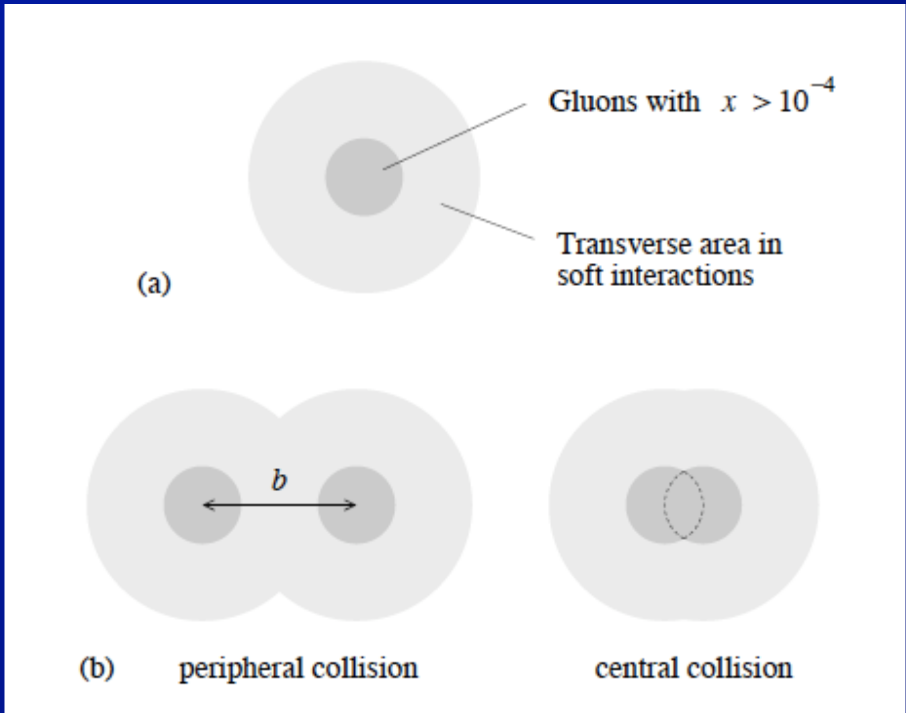


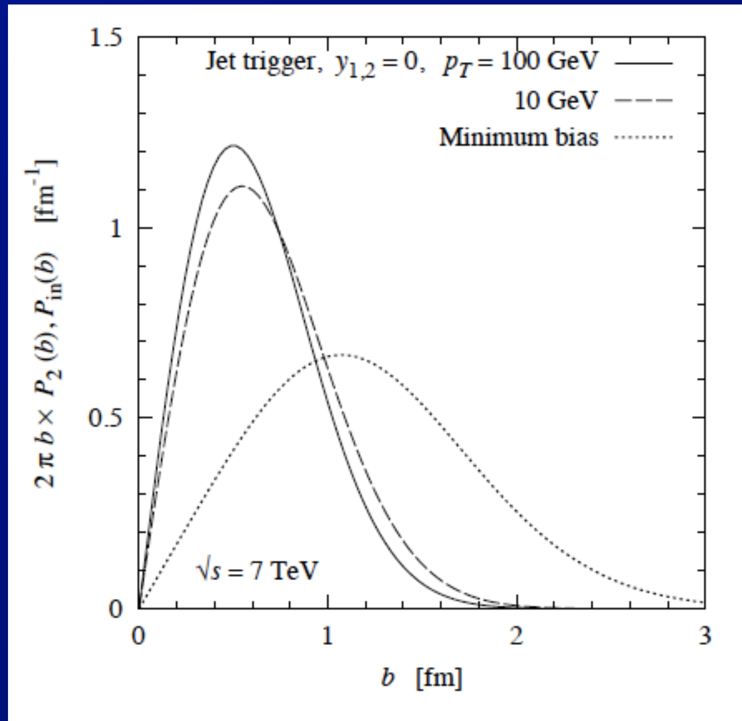
- What are the implications of ridge(s) for understanding jet quenching in Pb+Pb?
  - Improved understanding of initial conditions?
  - Yet more evidence of strong coupling?
  - Potential pre-equilibrium effects that we don't know (yet) know how to control?

  ⇒ Need to understand connection between ridges & hard scattering (if any) in p+Pb.

Wither the Glauber model ...

Frankfurt, Strikman, Weiss, Phys. Rev. D83:054012,2011





- Impact parameter dependence to physics in p-p collisions?
  - ⇒ Implications for d+A, p+A

Wither the Glauber model … (2)

M. Alvioli, M. Strikman, arXiv:1301.0728

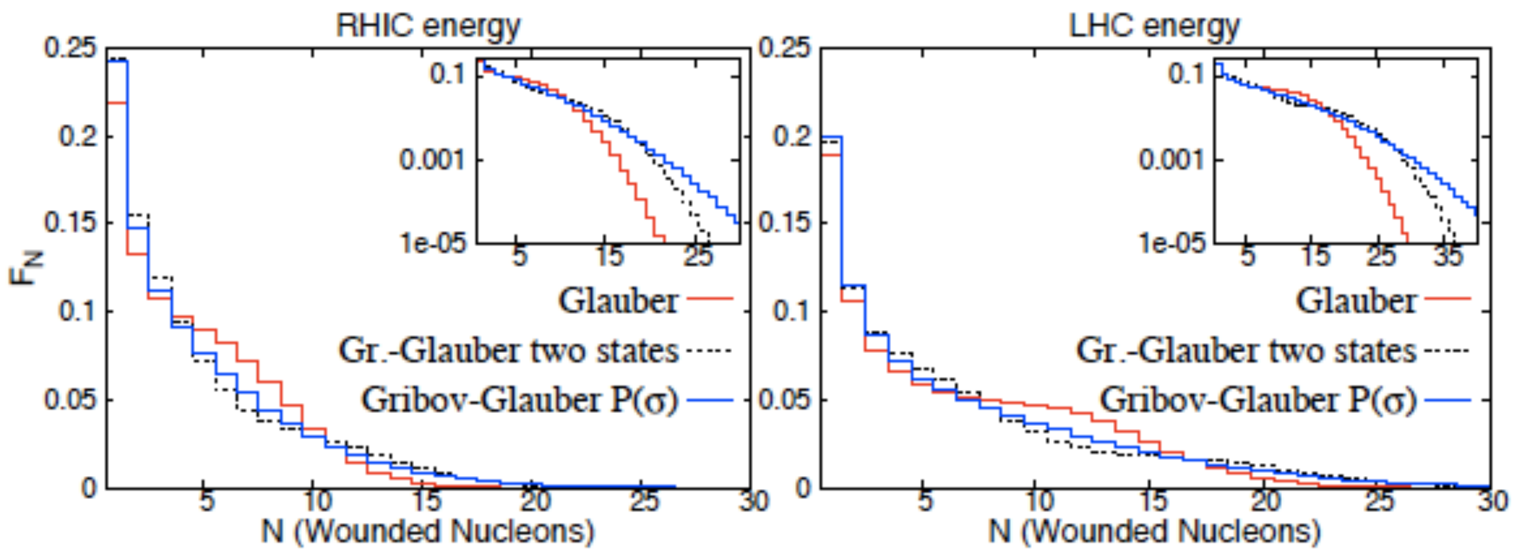
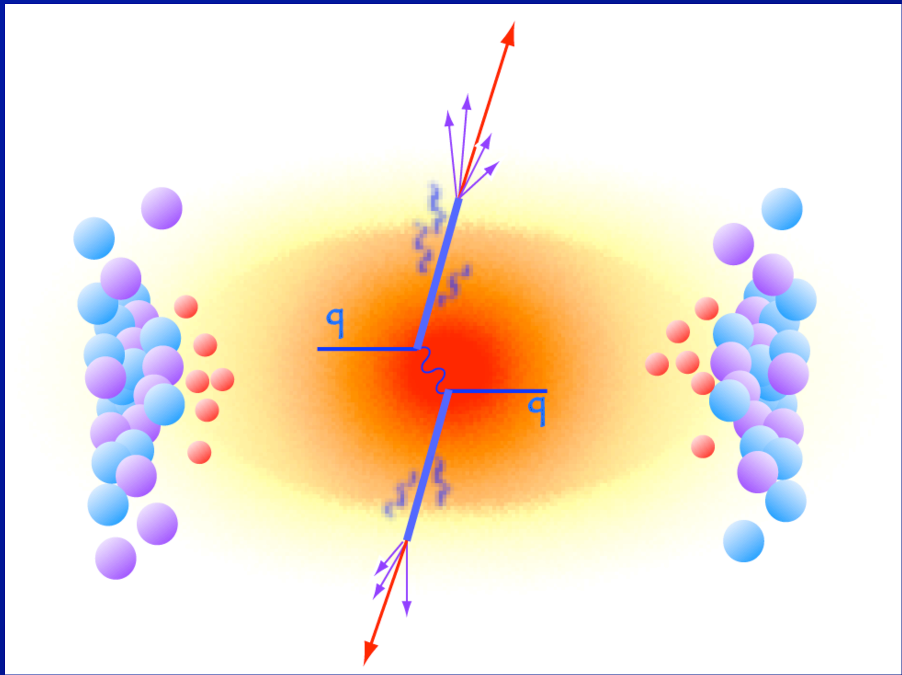


Figure 3: Effect of the event-by-event fluctuating values of σ_{tot}, for RHIC (left panel) and LHC energies (right panel) on the number of wounded nucleons, calculated as $F_N = \int db\, P_N(b)/\sigma_{in}^{hA}$. Red curves show the results obtained with the usual Glauber calculation with fixed cross section, black curves correspond to calculations with the two-component σ_{tot} model and blue curves correspond to calculations with fluctuating cross section with $P_h(\sigma_{tot})$ distribution. The insets show the same quantities in logarithmic scale.

- The Glauber model works well … until it doesn't
  - ⇒ d/p-A may force us to go beyond Glauber.

Backup

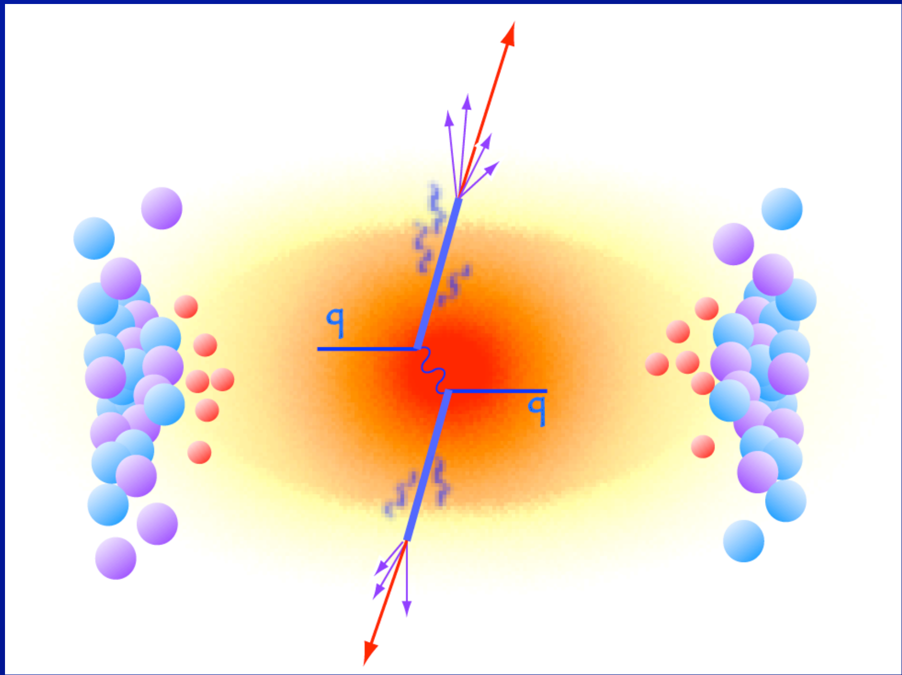
20.1th century view of jet quenching



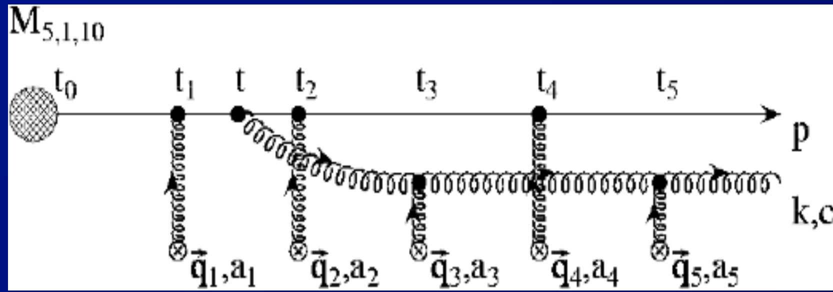
e.g. opacity expansion a la GLV

- High-p_T quarks or gluons propagate through and scatter in the QGP
  - with collisional and radiative energy loss
  - interference between vacuum and medium-induced radiation + LPM interference of multiple emissions
  - Fragmentation in vacuum

20.1th century view of jet quenching



e.g. opacity expansion
a la GLV



- High-p_T quarks or gluons propagate through and scatter in the QGP
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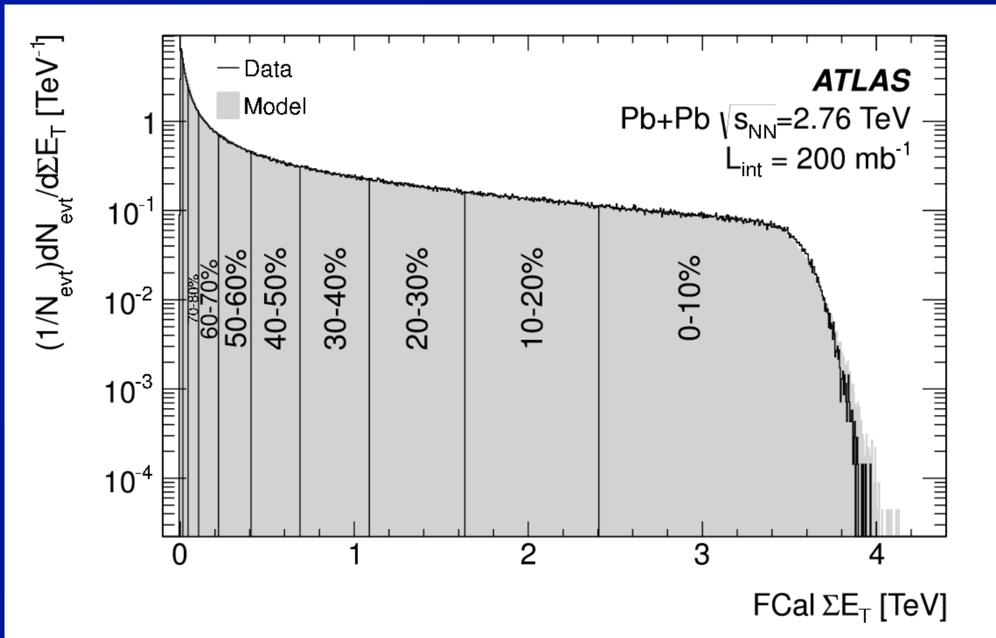
ATLAS: Pb+Pb centrality

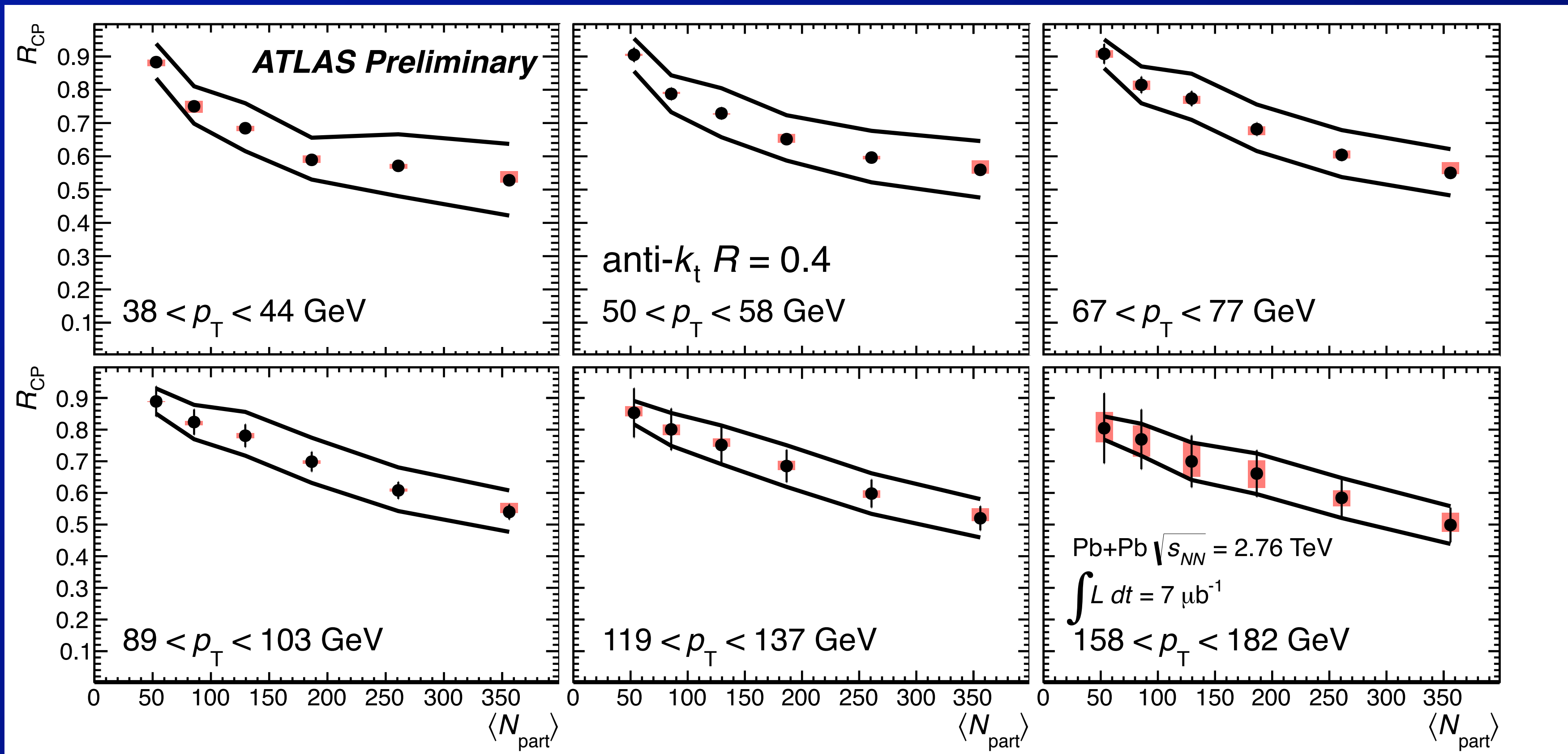


Centrality	$\langle N_{\rm part} \rangle$	$\langle N_{\rm coll} \rangle$
0 – 10%	356 ± 2	1500 ± 115
10 – 20%	261 ± 4	923 ± 68
20 – 30%	186 ± 4	559 ± 41
30 – 40%	129 ± 4	322 ± 24
40 – 50%	86 ± 4	173 ± 14
50 – 60%	53 ± 3	85 ± 8
60 – 80%	23 ± 2	27 ± 4

- 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.

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.