Jet measurements in heavy ion collisions at the LHC

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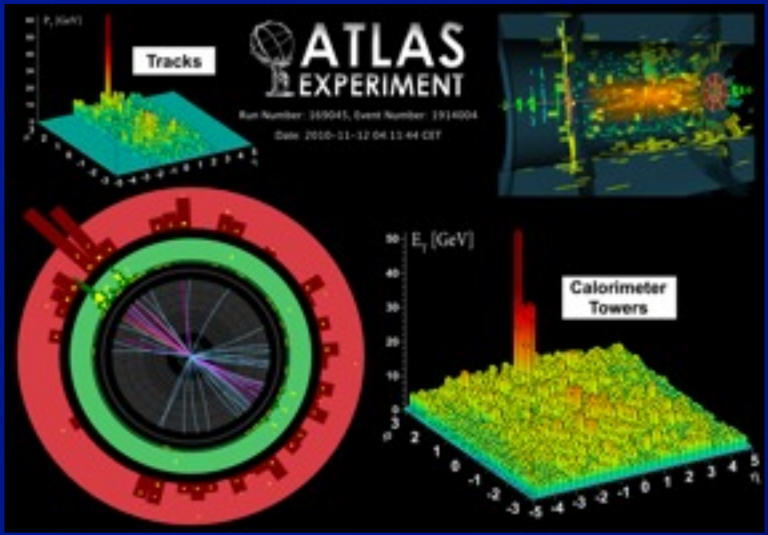
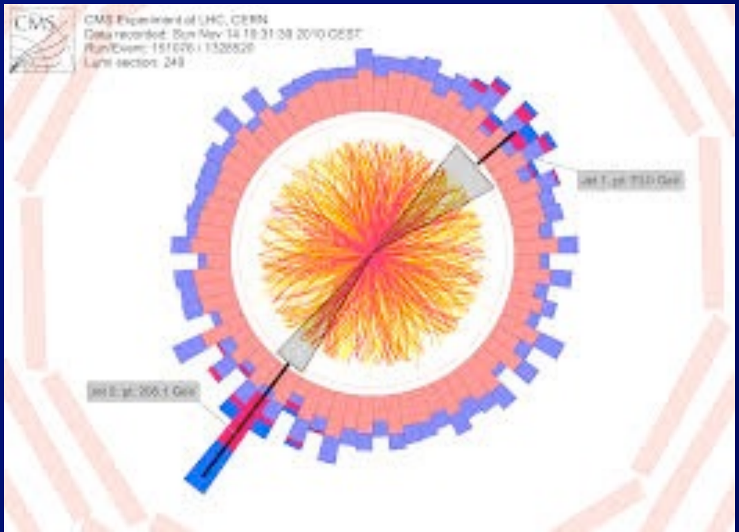
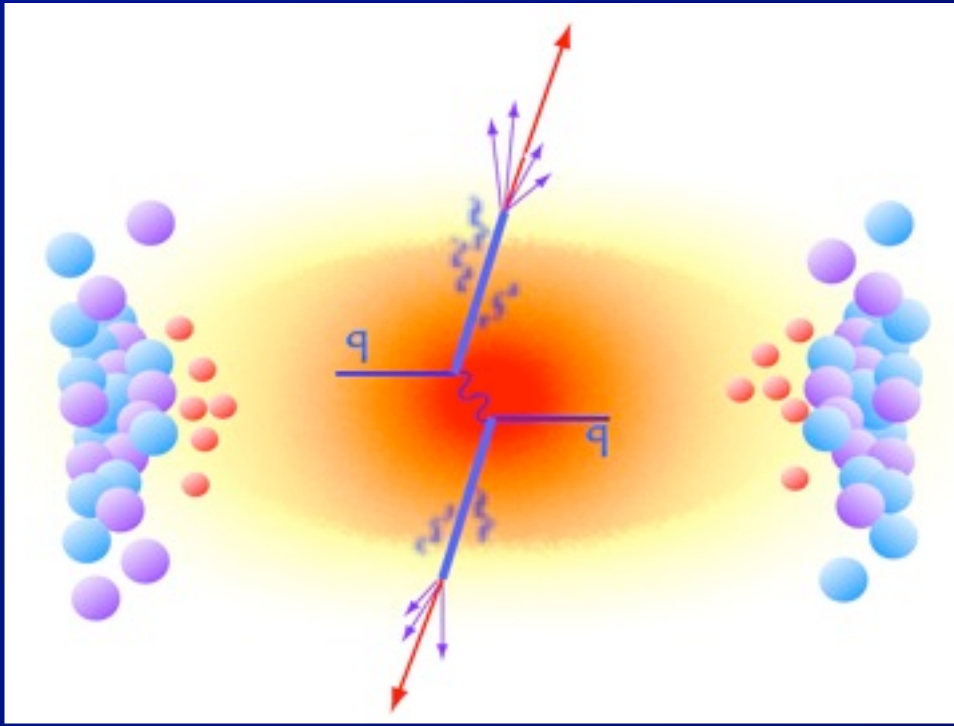
January 22, 2014





Jet probes of the quark gluon plasma



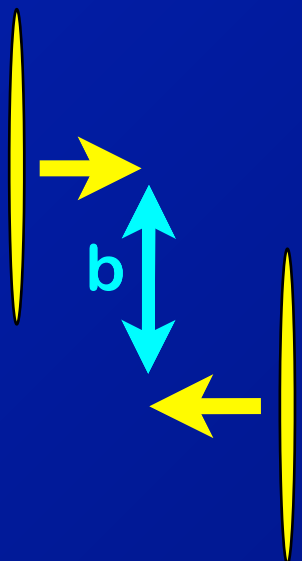
- Use jets from hard scattering processes to directly probe the quark gluon plasma (QGP)

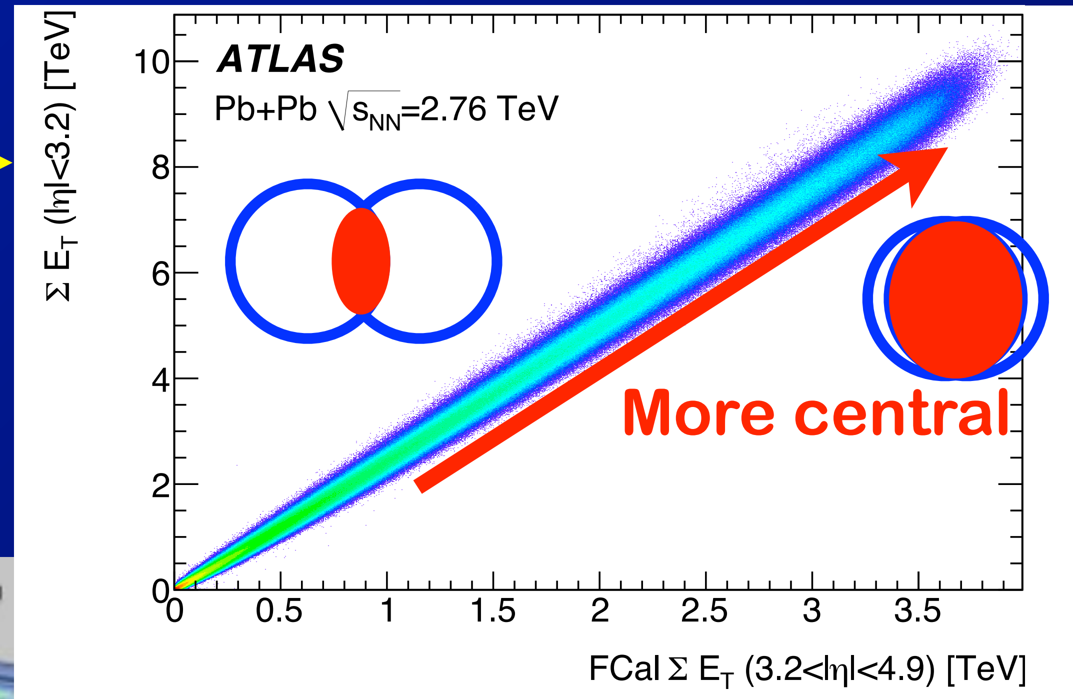
- Key experimental question:
  - ⇒How do parton showers in quark gluon plasma differ from those in vacuum?

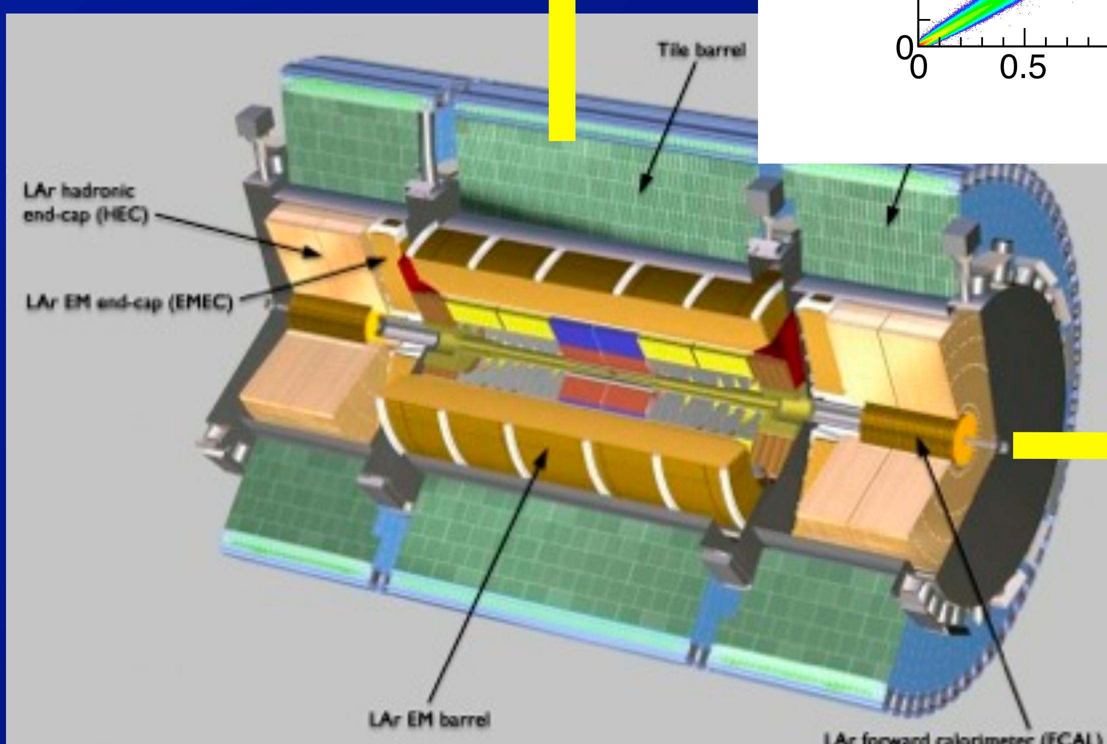
- Use vector bosons -- for which the QGP is transparent -- to calibrate hard scattering rates in Pb+Pb collisions.

Pb+Pb global energy flow

Phys. Rev. Lett. 105 (2010) 252303



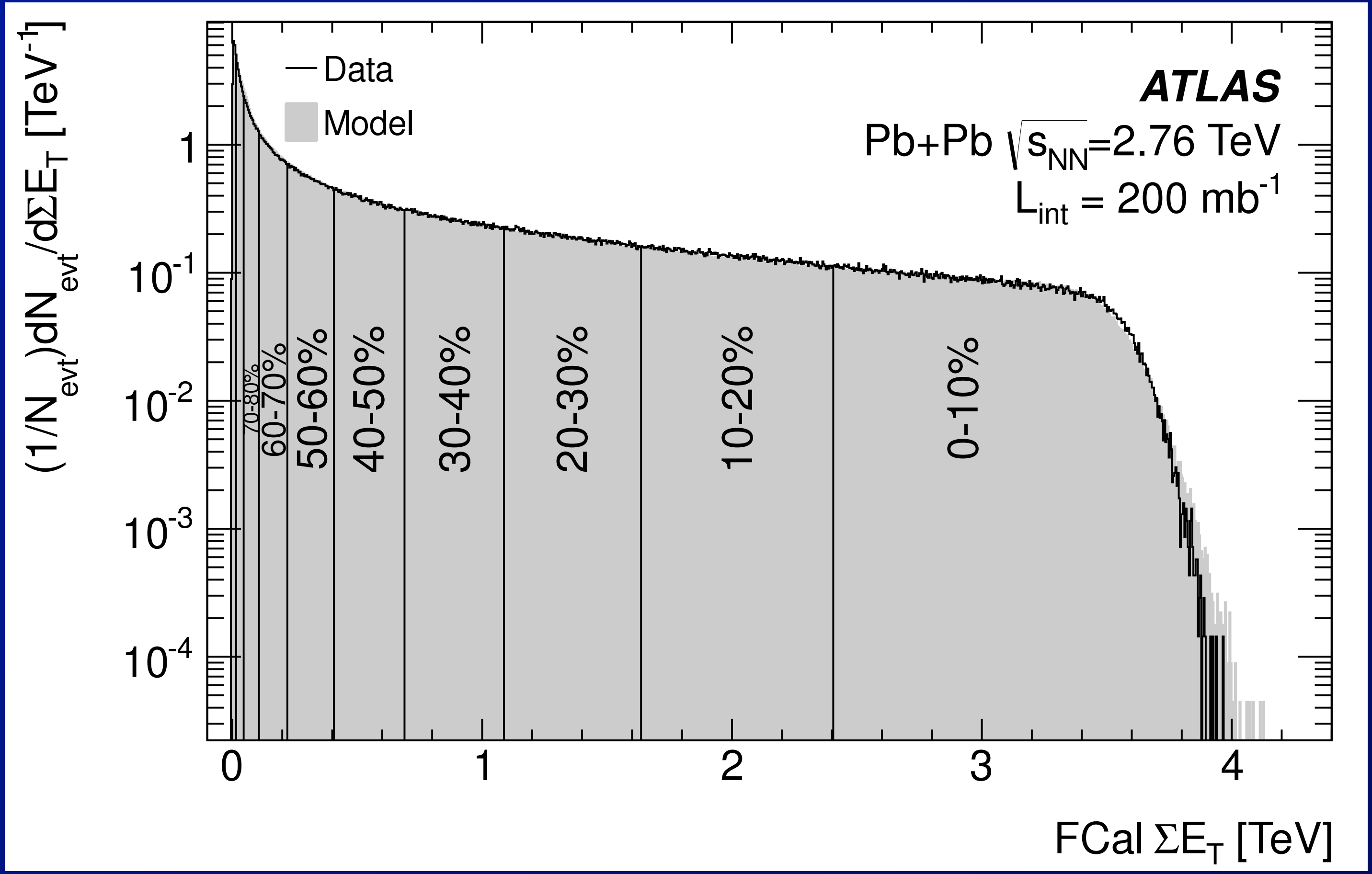




Characterizing Pb+Pb centrality

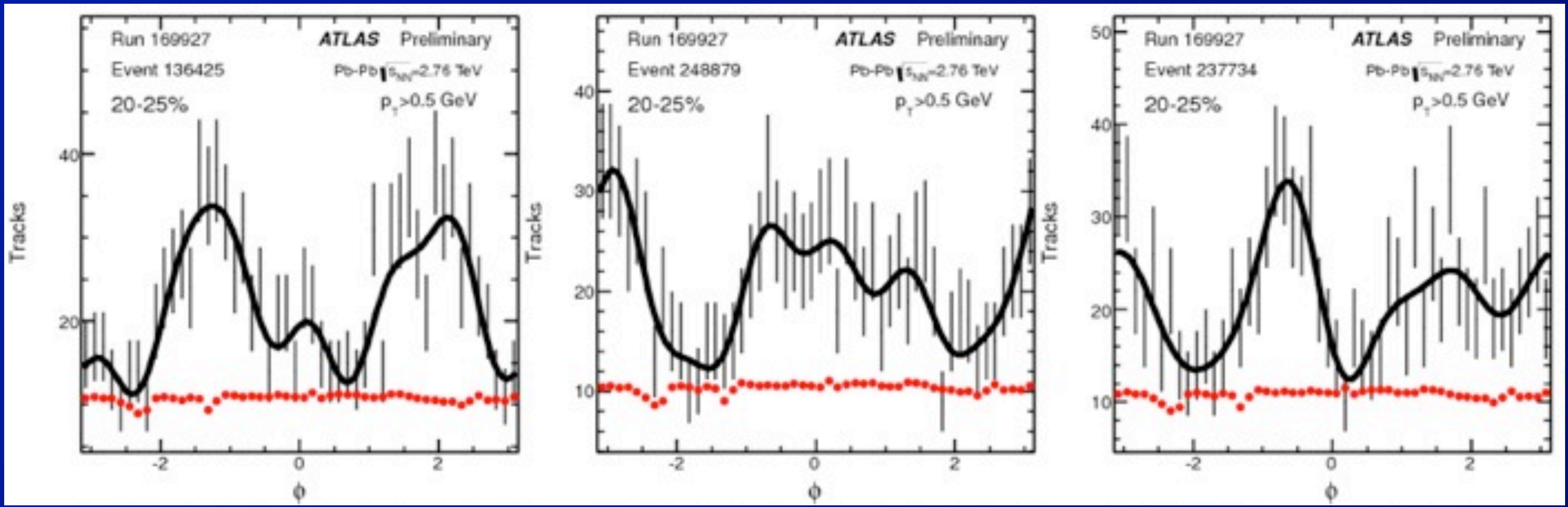
Phys. Lett. B707 (2012) 330-348

Minimum-bias distribution of ΣE_T over $3.2 < |\eta| < 4.9$ (EM scale)



- **Large event-to-event variations in the UE due to the geometry of the collision**
  - "centrality" quoted in terms of percentiles

Event-by-event collective flow



- Underlying event in Pb+Pb collisions have complicated azimuthal structure due to initial-state fluctuations and collective dynamics
  - Typically characterized by Fourier coefficients

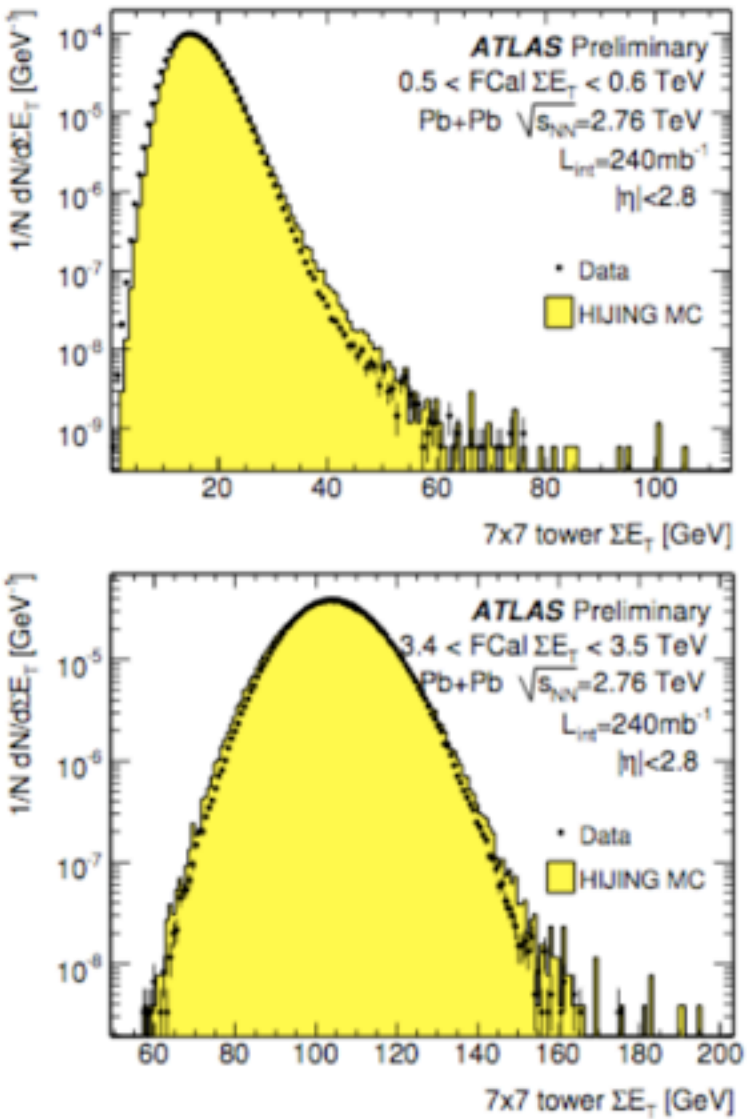
$$\Rightarrow \frac{dN}{d\phi dp_T d\eta} = \frac{dN}{2\pi dp_T d\eta}\left(1 + \sum_n 2v_n \cos\left[n(\phi - \psi_n)\right]\right)$$

  - Measurable event-by-event.

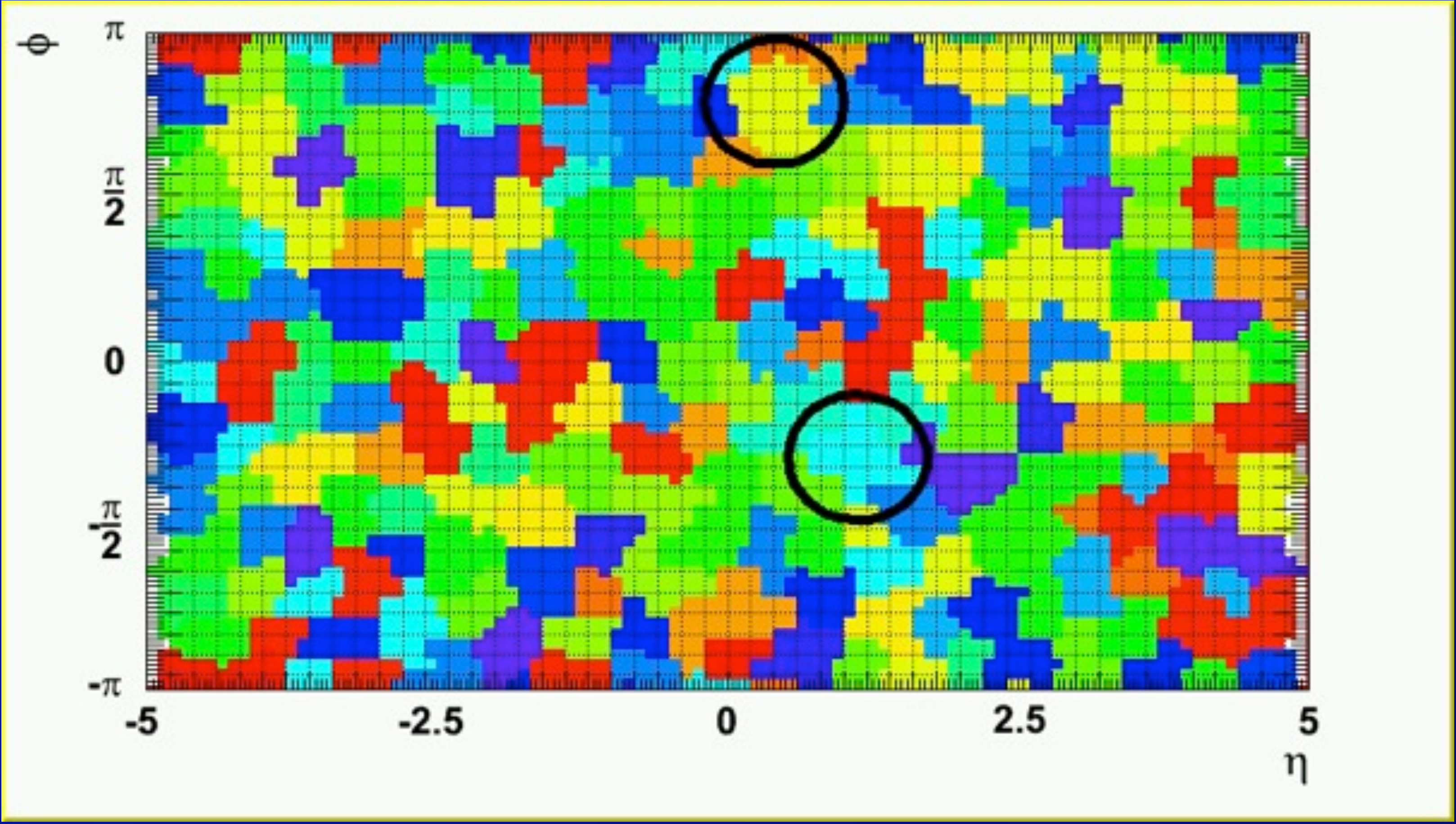
The underlying event (ATLAS)

ATLAS-CONF-2012-045, https://cds.cern.ch/record/1440894

- In minimum-bias Pb+Pb events
  - Sum EM-scale tower E_T over NxN groups of towers (ΣE_T)
  - N chosen to match jet sizes
    - ➡ R = 0.4 ↔ 7x7 ($\pi \times 0.4^2 = 0.50$)
- Distributions shown to right for two different centralities
  - ➡ top: peripheral
  - ➡ bottom: central
- Observe:
  - ➡ Distributions are NOT Gaussian (Gamma dist's)



The starting point



QM2006 poster by N. Grau

- 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
  - $E_T^{\mathrm{subtr}} = E_T^{\mathrm{unsubtr}} - \rho A$

    ➡ But the details are critical

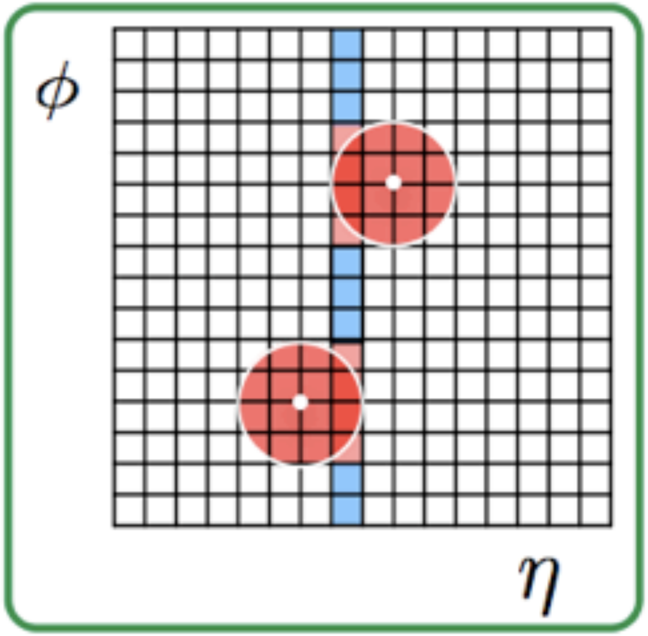
- Important considerations:
  - What kind of objects is subtraction applied to?

    ➡ 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 ?

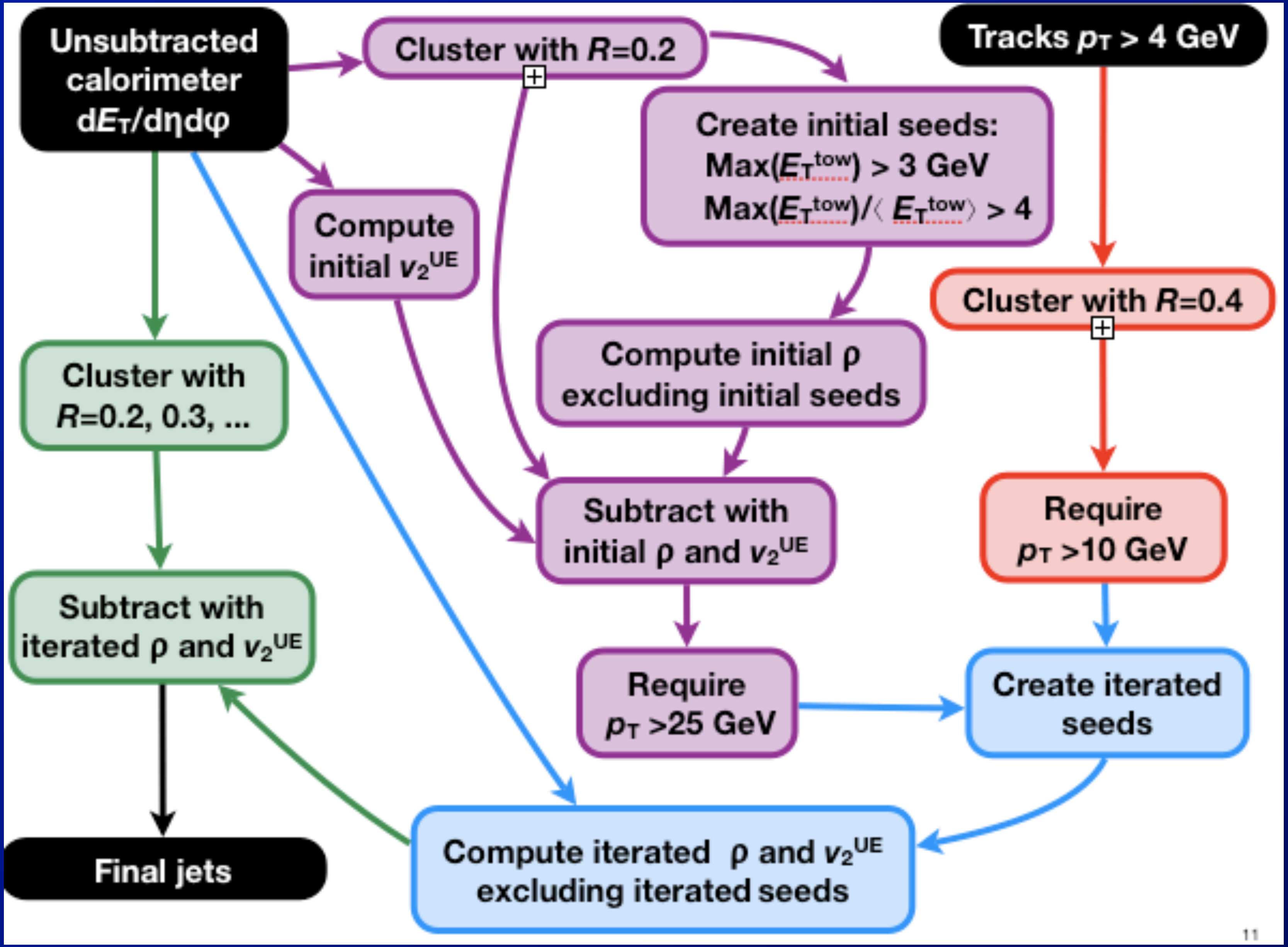
The underlying event (ATLAS)

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



- 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

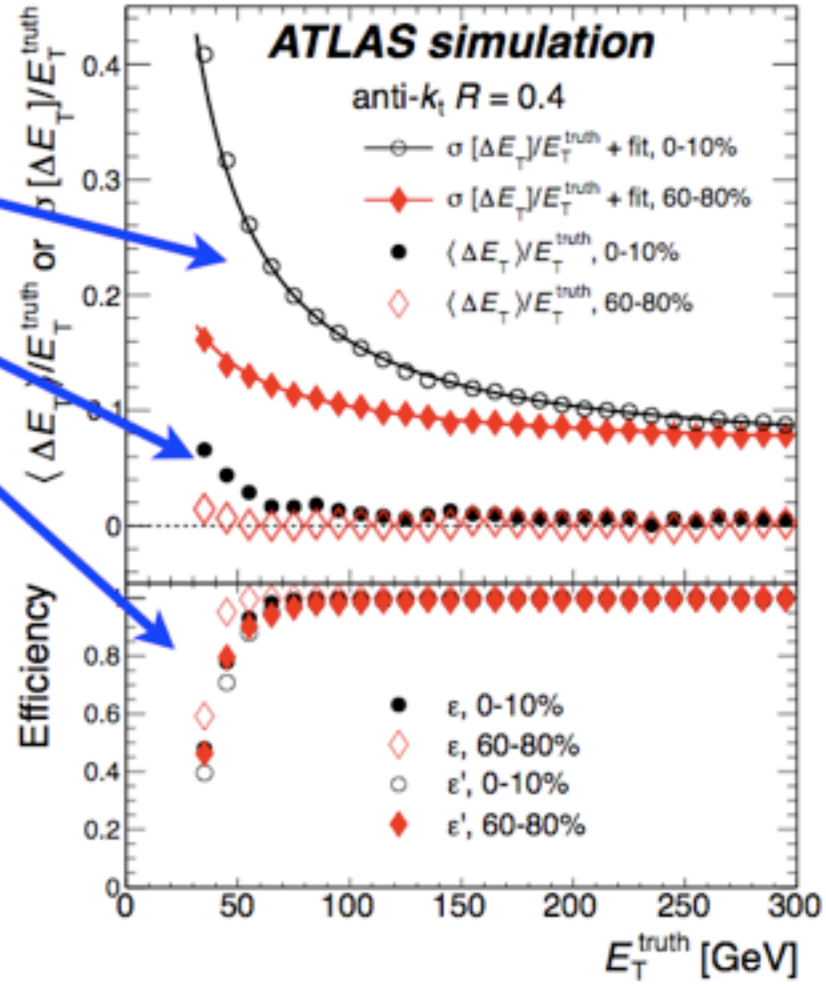
ATLAS jet reconstruction (2010)



ATLAS Pb+Pb jet performance (2010)

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

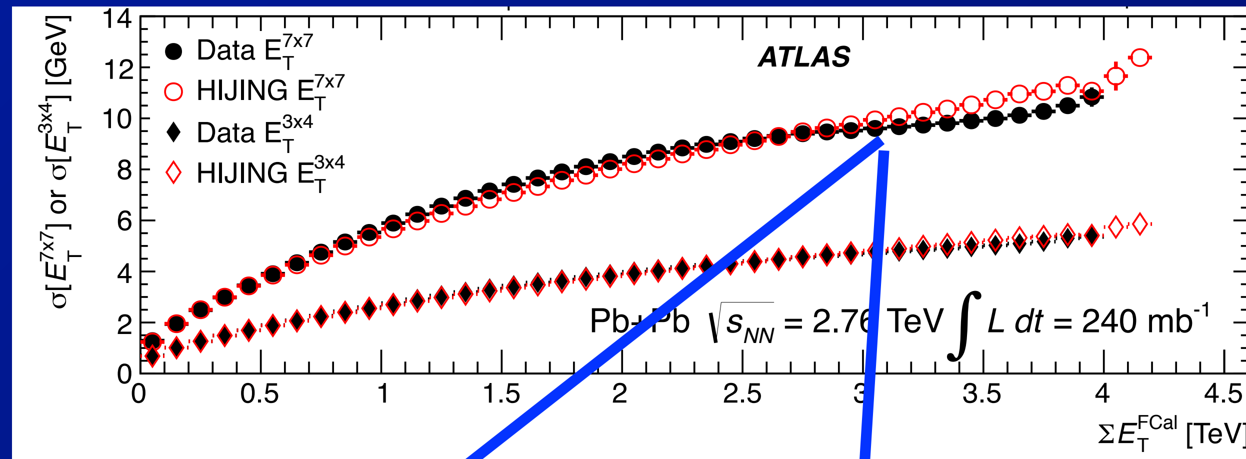
- Three metrics
  - Jet energy resolution
  - Jet energy scale
  - Jet reconstruction efficiency
    - ➡ with (ε') and without (ε) fake rejection
- Of these, we only have control over JES
  - ➡ Sensitive test of background subtraction



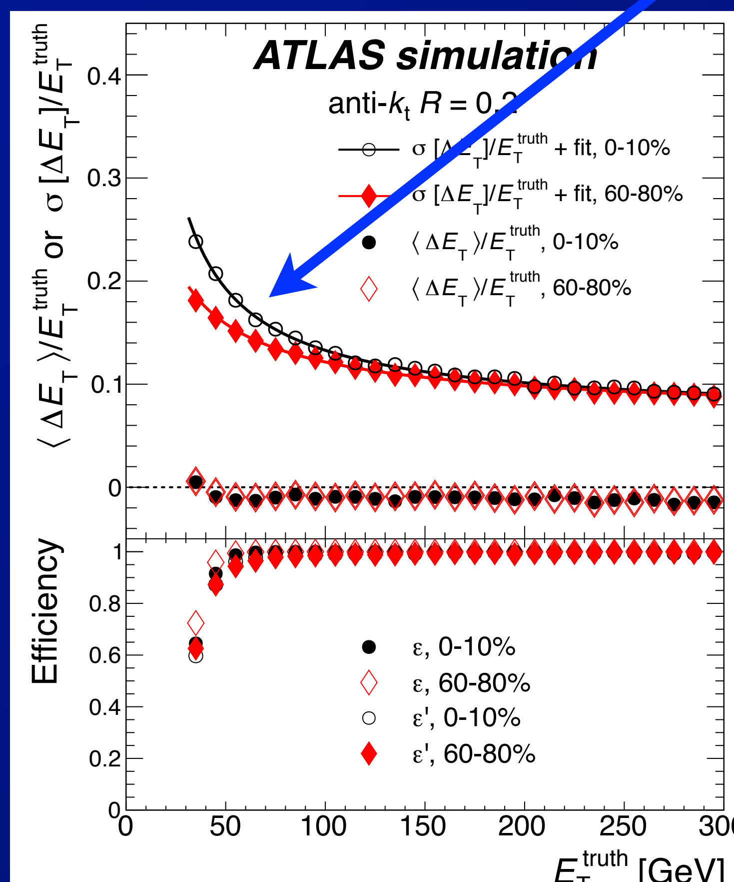
- Jet is considered not fake if within R = 0.2:
  - R = 0.4 track jet (rec. from tracks w/ p_T > 4 GeV), photon, or electron with p_T > 7 GeV

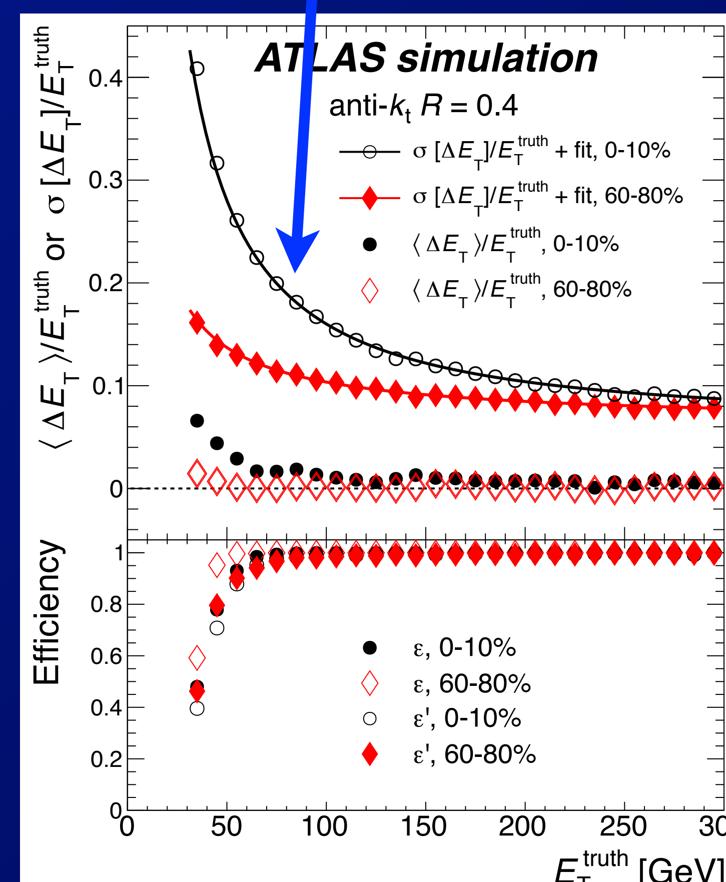
ATLAS jet performance (2010 data)

Data-driven evaluation of underlying event fluctuations



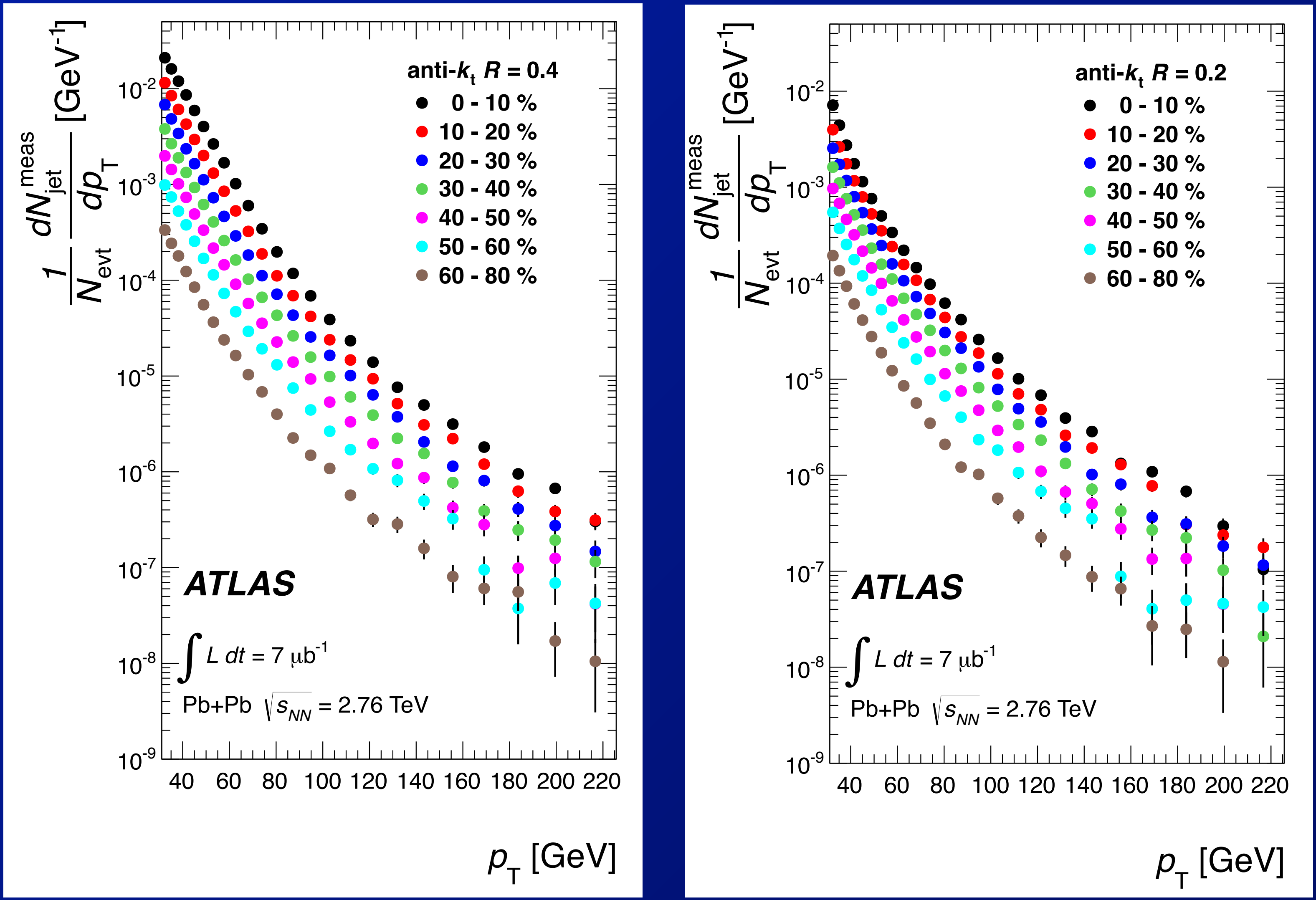
HIJING MC evaluation of performance





Pb+Pb Jet Spectra (2010)

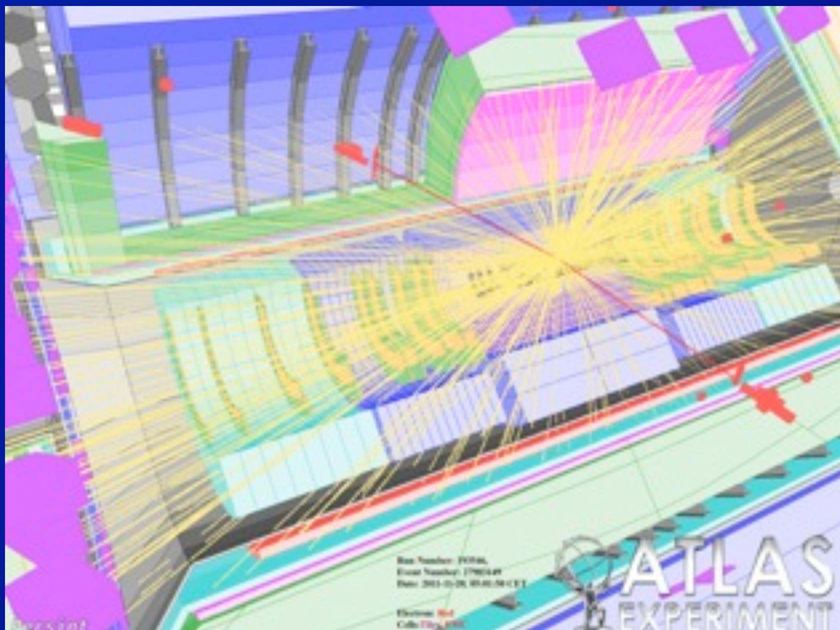
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HION-2011-02/



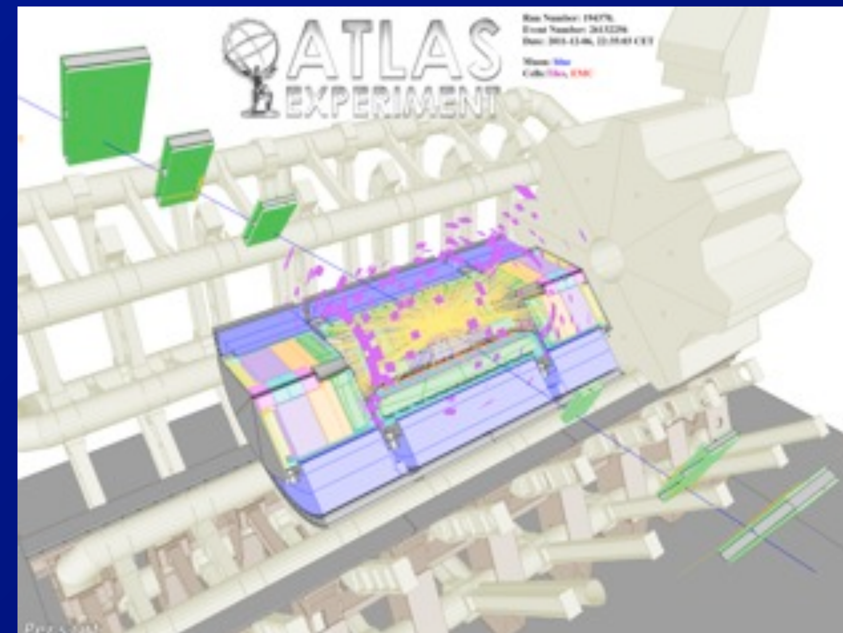
- **For these results, no absolute normalization**
  - **awaiting absolute jet energy scale uncertainty**

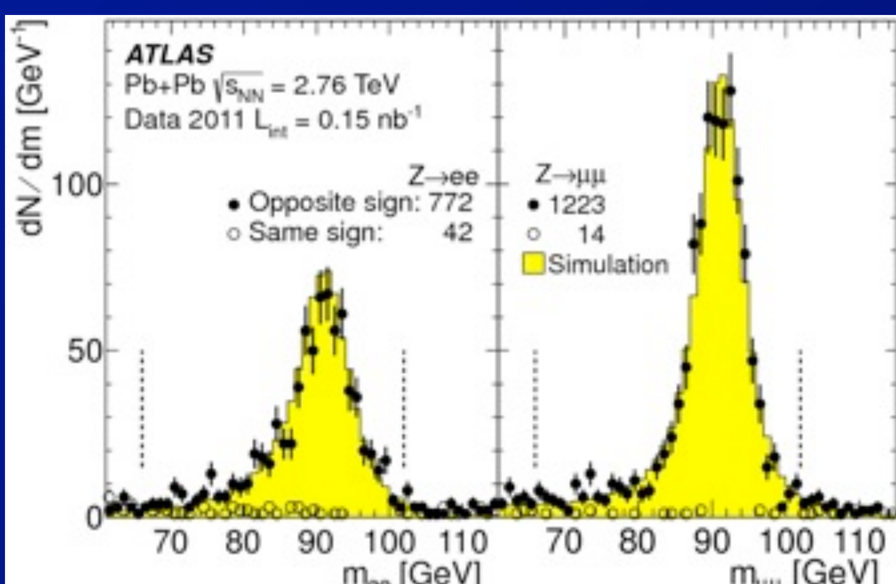
Hard scattering rate control: Z

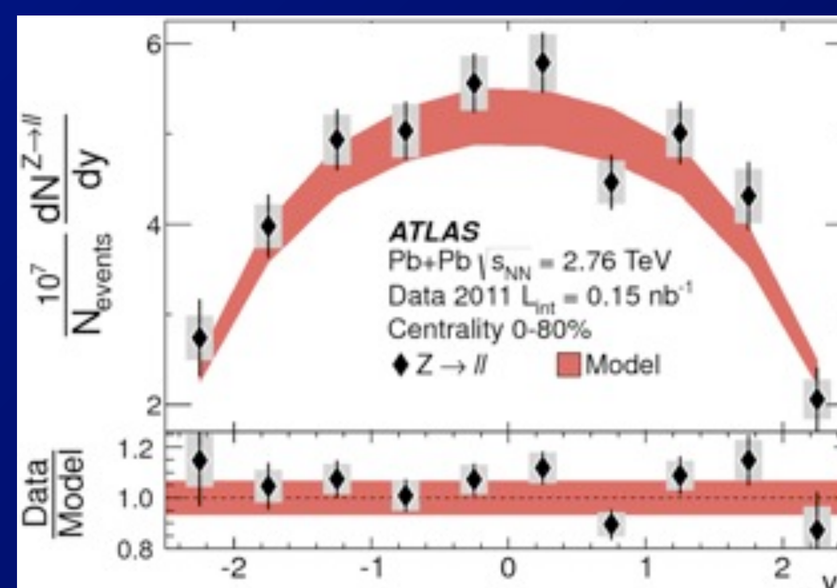
$Z \rightarrow e^+e^-$ event display



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

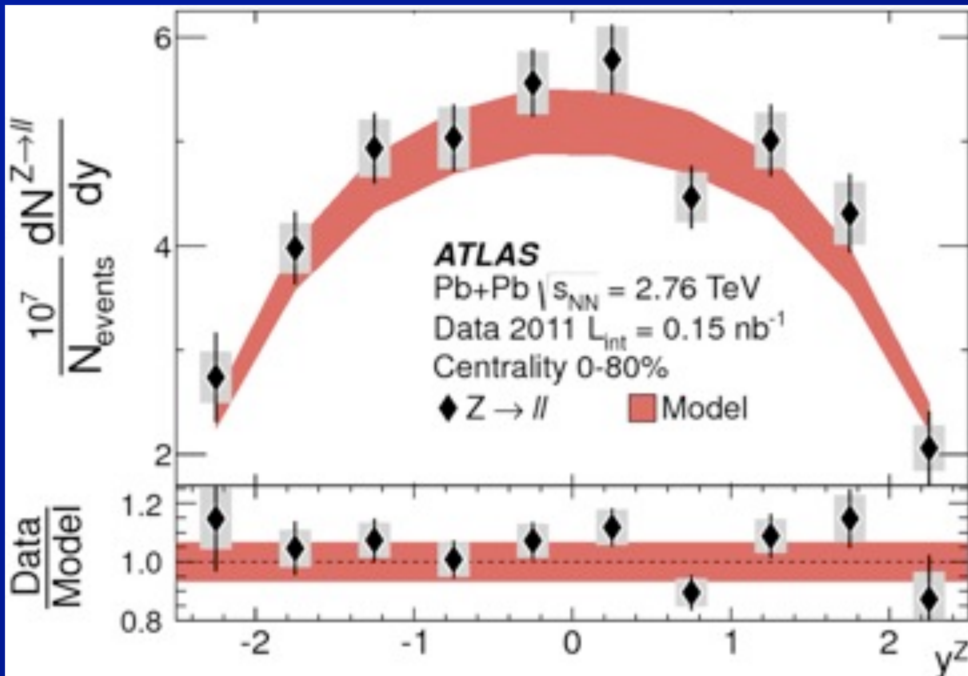


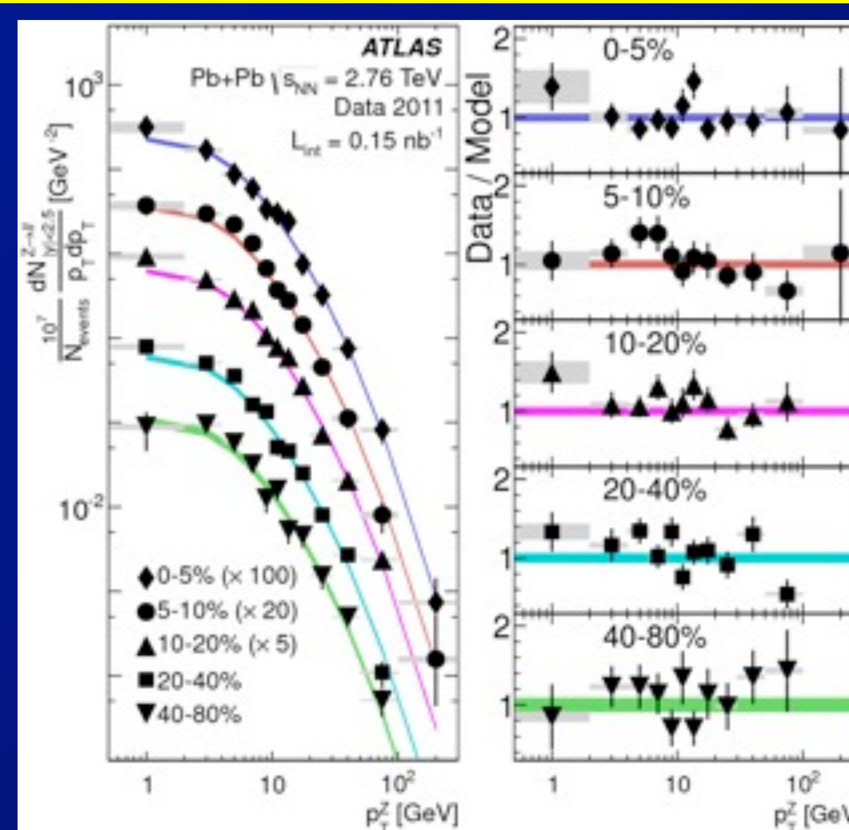




Hard scattering rate control: Z

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





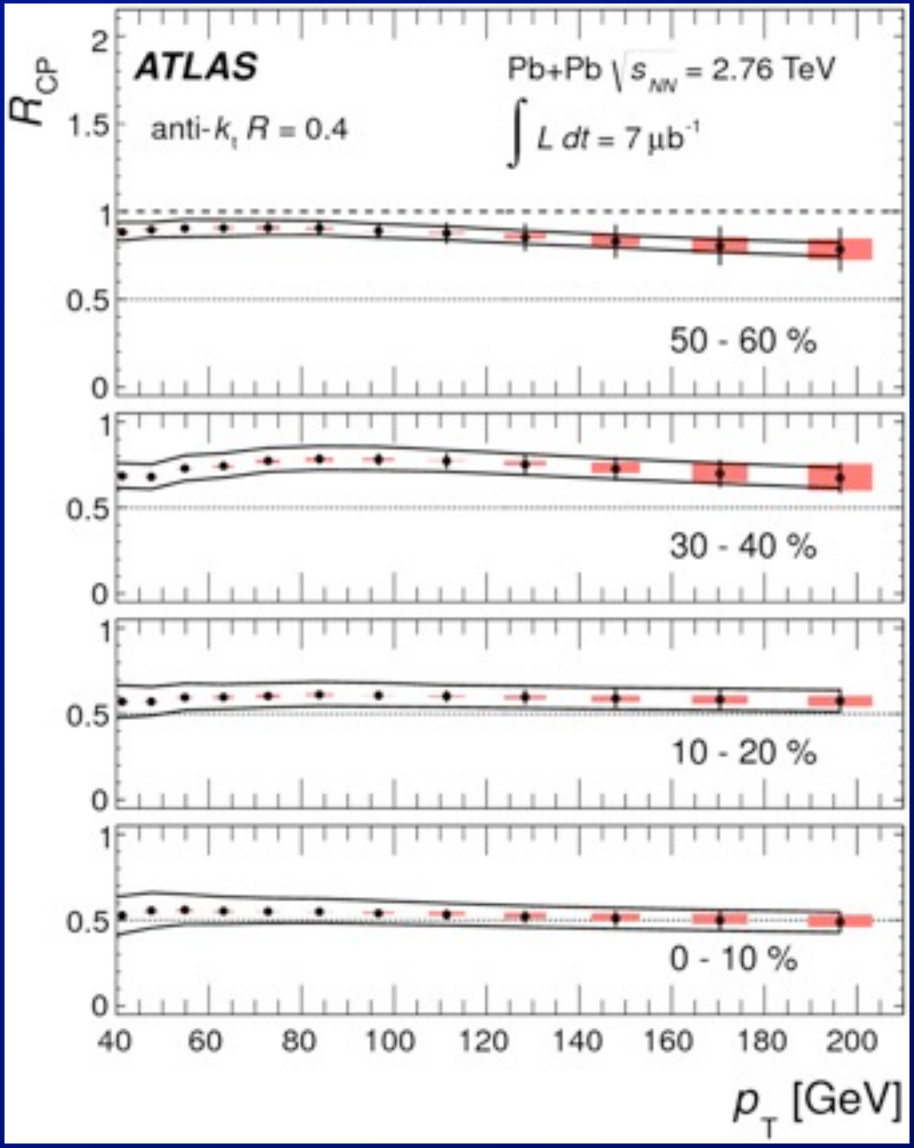
- Compare Pb+Pb Z rapidity distributions (minimum-bias) and pT spectra to PYTHIA scaled to NNLO calculations
  - No nuclear PDFs

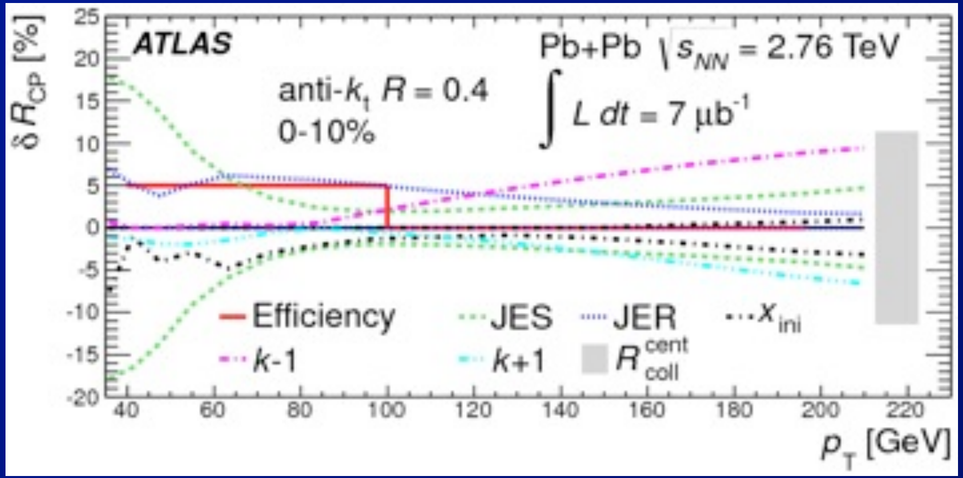
    ⇒ Nuclear PDF effects <~ 20%

Jet suppression: central/peripheral

- Ratio of jet yields between different centrality bins and peripheral collisions
  - corrected for "trivial" geometric factors

    ⇒Observe a factor of two suppression in jet yield ($|\eta| < 2.1$)





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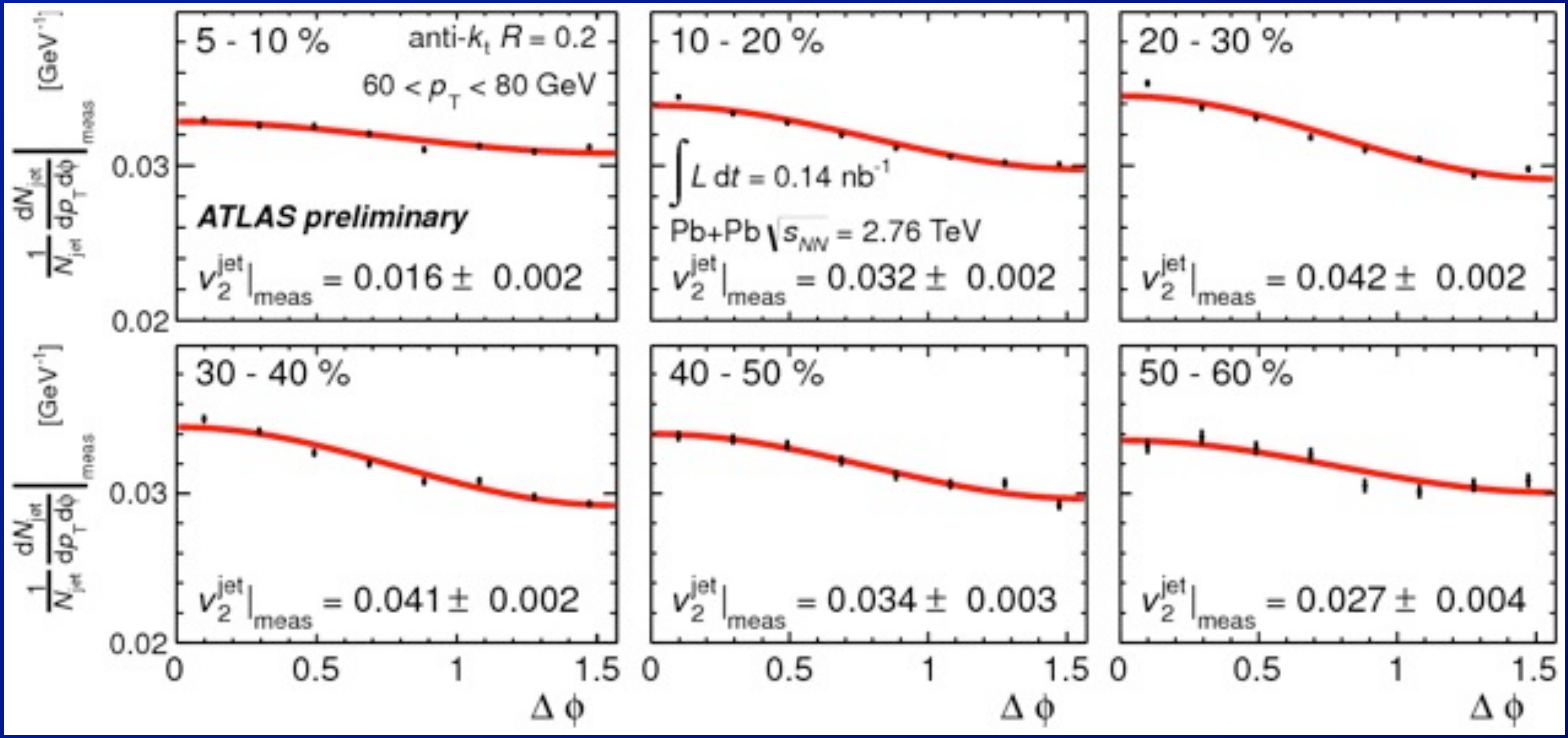
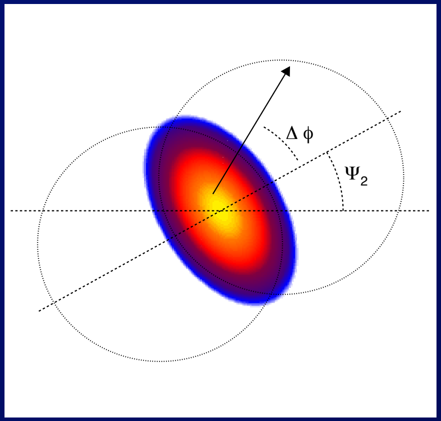
Differential jet suppression

Phys. Rev. Lett 111, 152301 (2013)

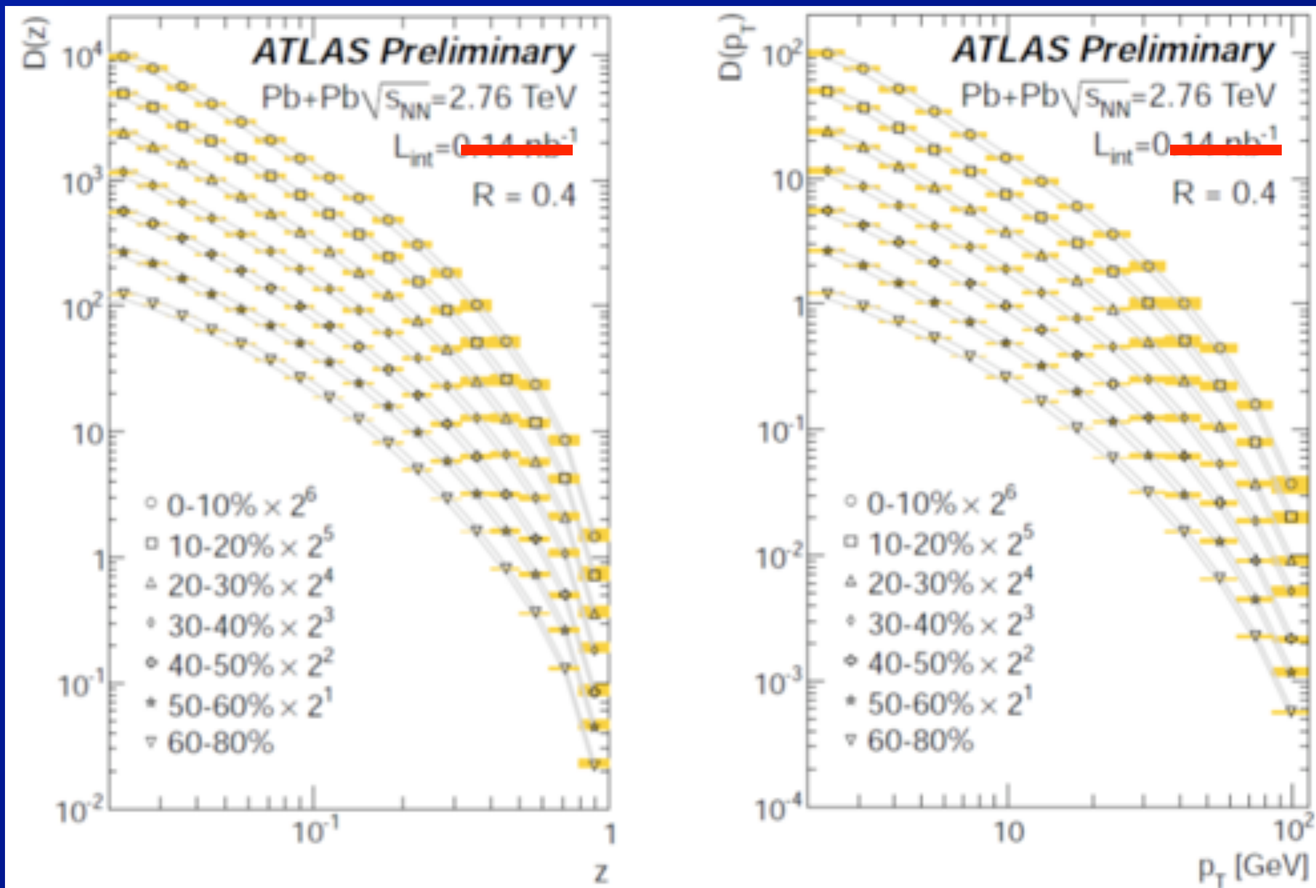


- Measure jet yields in 8 bins of $\Delta\phi$ with respect to the elliptic event plane
  - Here for R = 0.2 jets, $60 < p_T < 80$ GeV
    - ⇒UE subtraction corrected for elliptic flow modulation in calorimeter



Pb+Pb Inclusive jet fragmentation

ATLAS-CONF-2012-115, https://cds.cern.ch/record/1472936

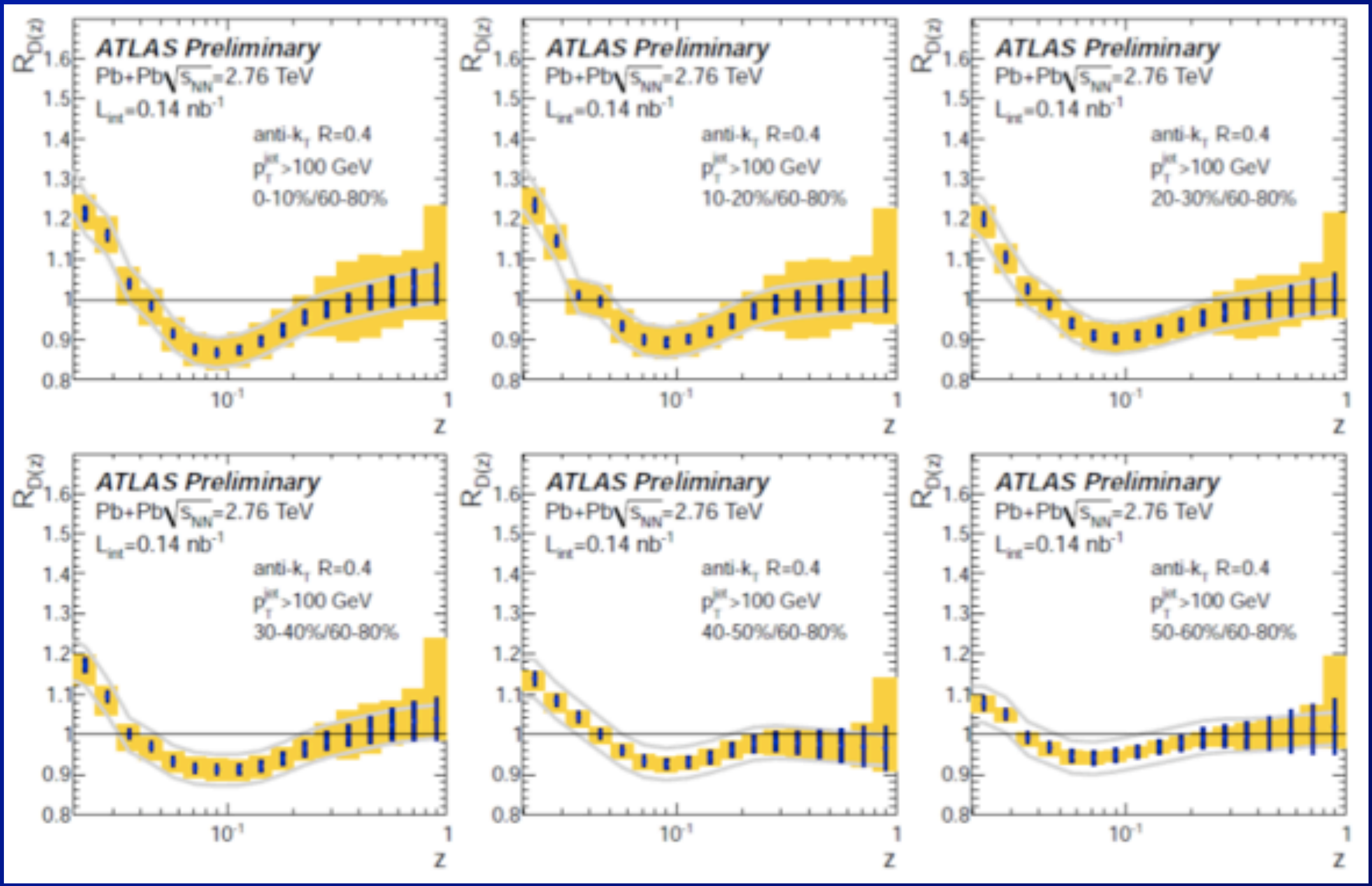


Unfolded for jet and charged particle resolution

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

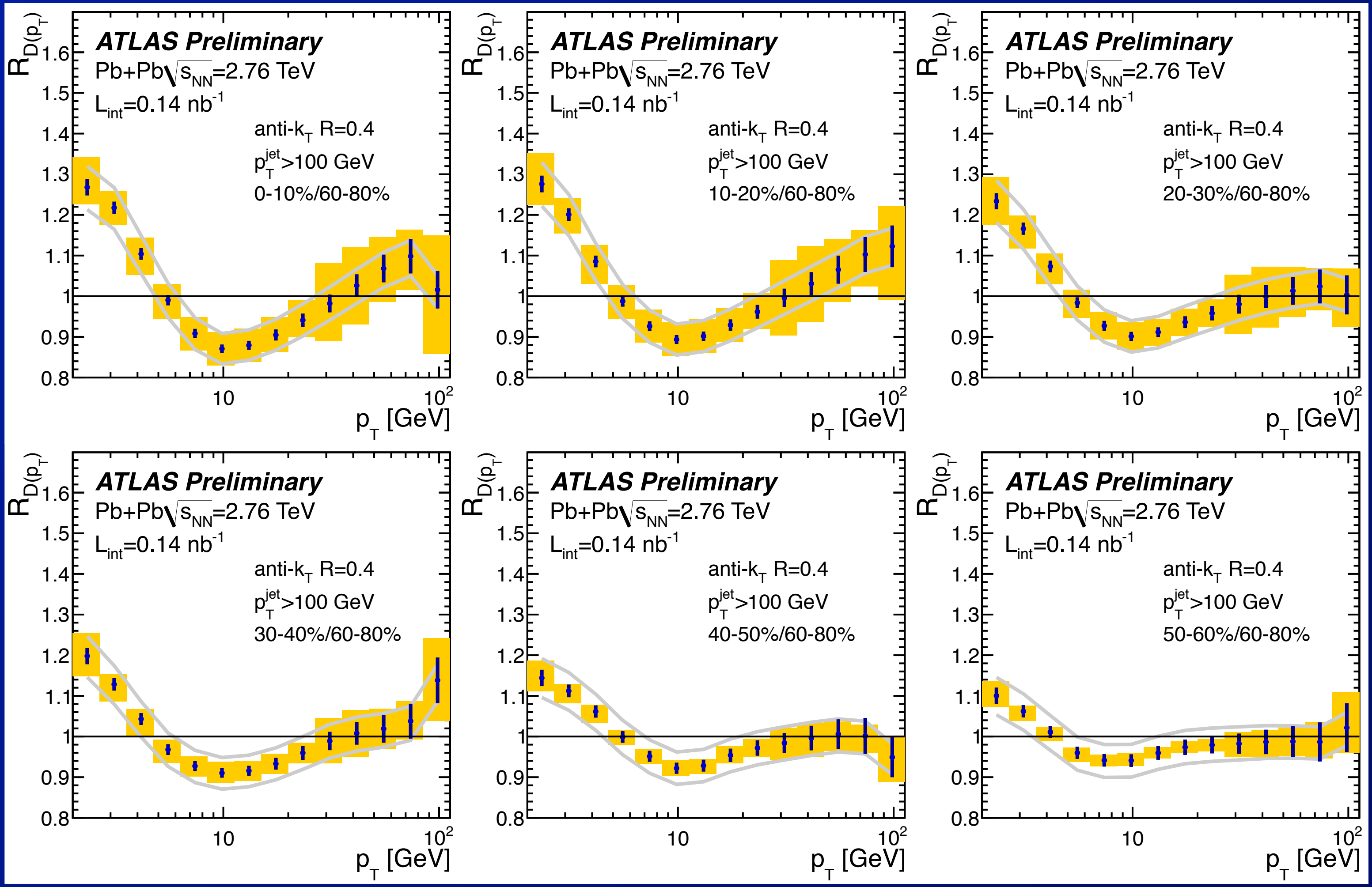
$$D(p_T) = \frac{1}{N_{jet}} \frac{dN_{chg}}{dp_T}$$

Inclusive jet fragmentation (2)



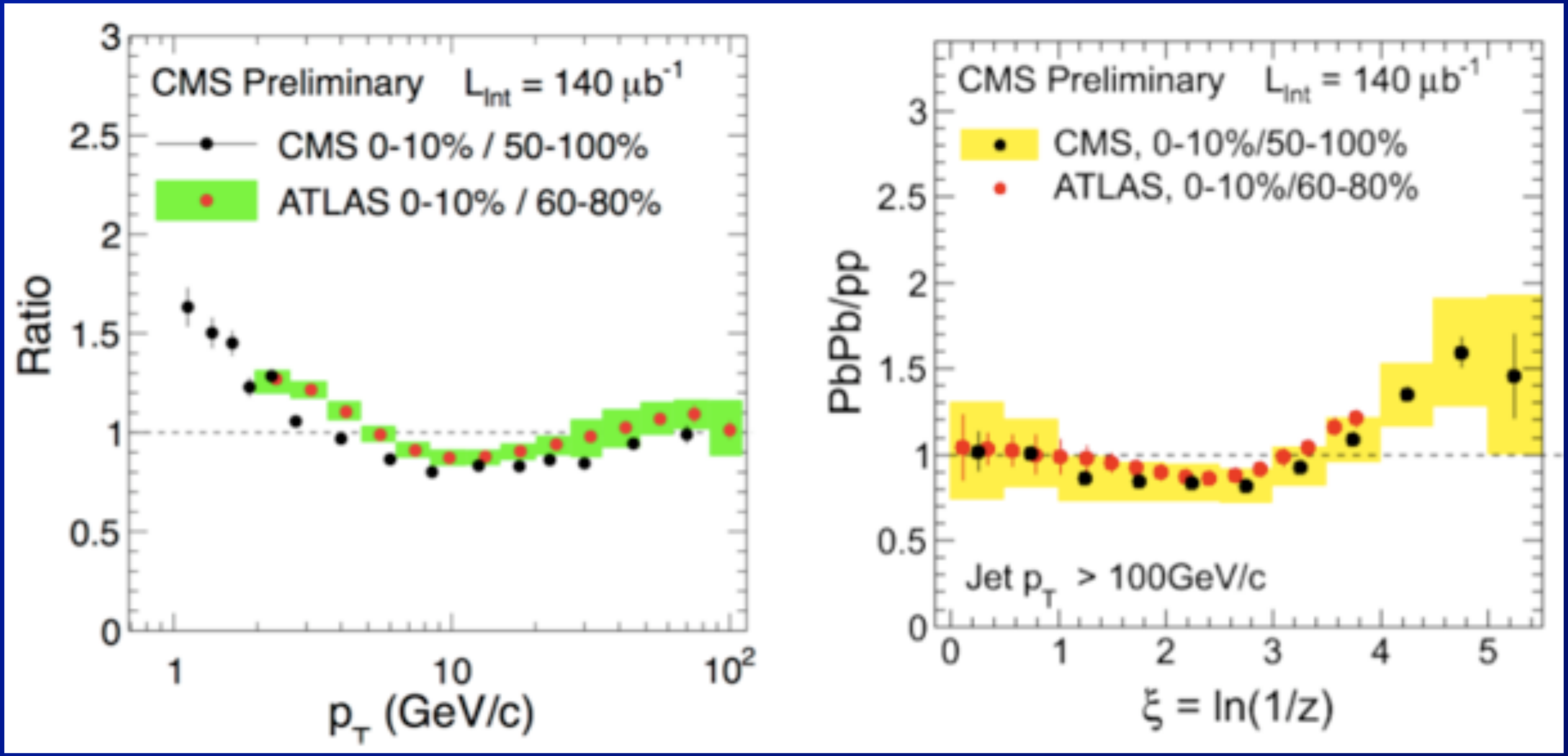
- Ratio of fragmentation functions between different centrality bins and peripheral (60-80%)

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

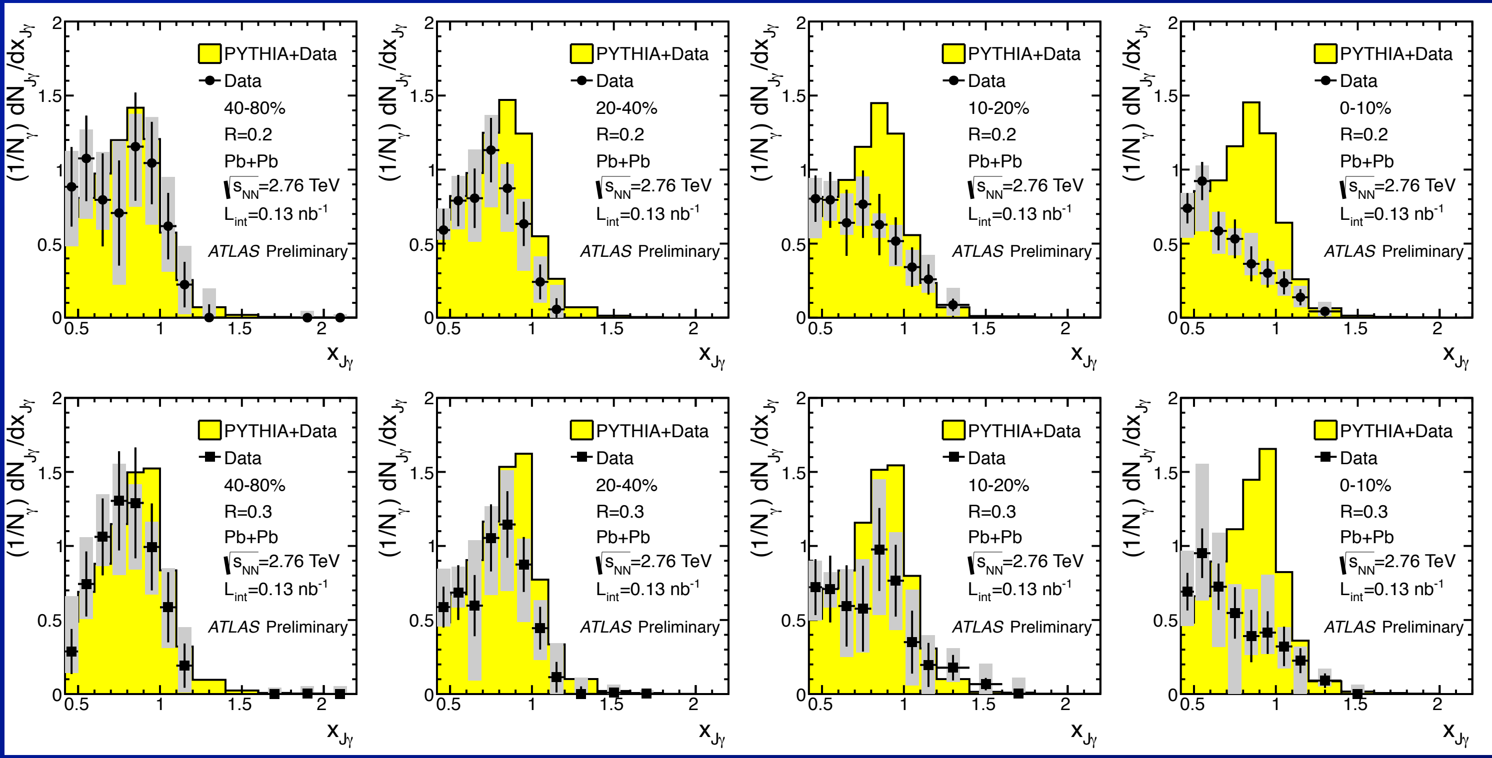
ATLAS & CMS jet fragmentation



- First direct handle on the p_T dependence of modifications of the parton shower.
  - ⇒How much of the modification results from changes in the quark/gluon fraction?
  - ⇒ η dependence (q/g fraction)?

γ-jet momentum balance

Peripheral ⟶ central



R = 0.2

R = 0.3

ATLAS-CONF-2012-121, https://cds.cern.ch/record/1473135

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

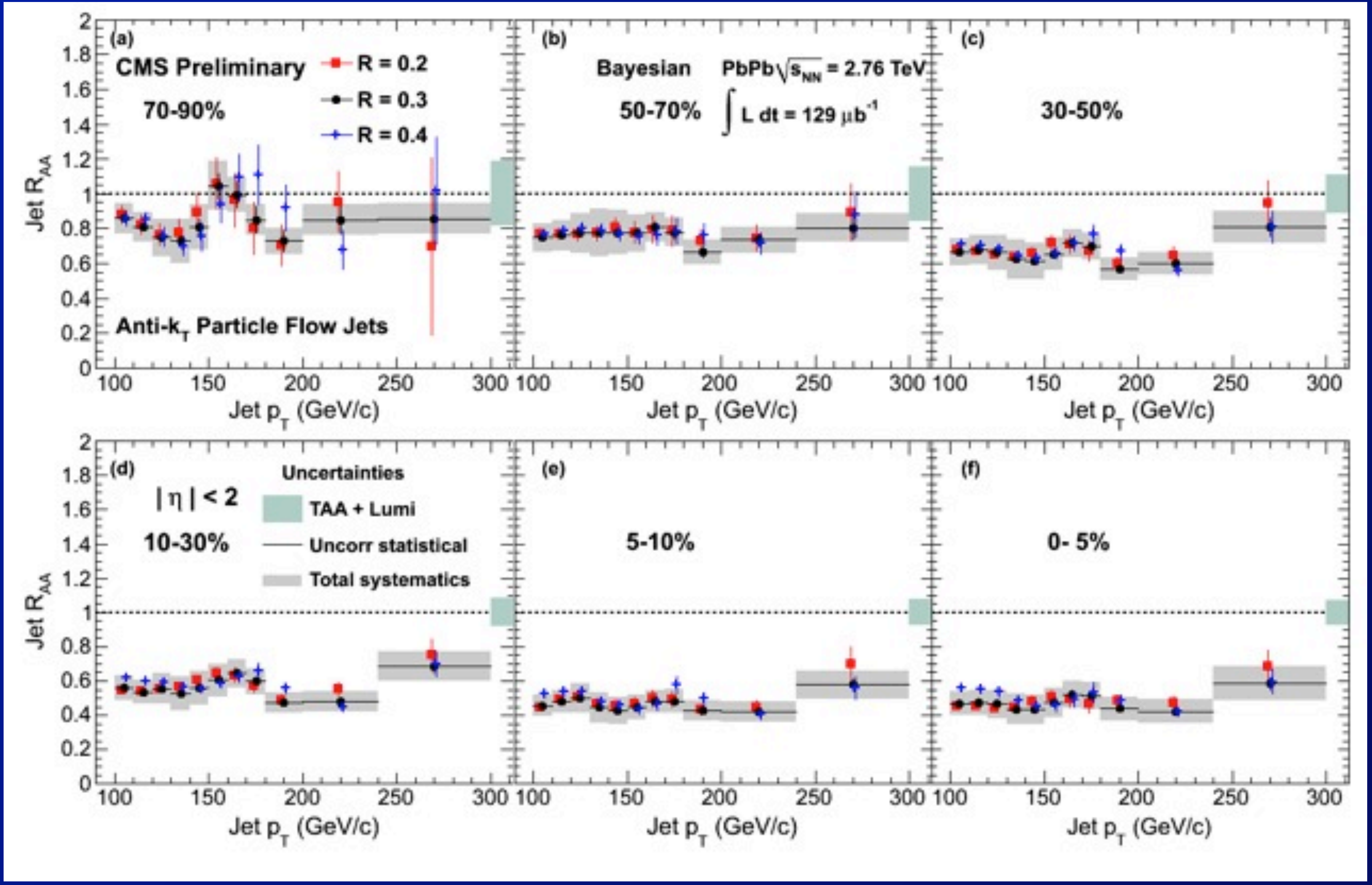
    ⇒Substantial change in γ-jet balance

Summary, thoughts

- Several measurements (more to be shown in following talk) showing that parton showers are modified in the quark gluon plasma.
  - Complete (and unique) theoretical explanation still not yet available.
    - ⇒Do not yet have a validated and tuned event generator capable of describing the data.
- Tools for handling the UE in Pb+Pb collisions and high pile-up p-p are not (yet?) converging
    - ⇒Problems are similar, not the same.
    - ⇒Do we care?
- Flavor tagging in Pb+Pb collisions will be difficult until we understand quenching.
    - ⇒But, gamma-jet, W/Z-jet measurements allow us to change the q/g mixture. Good place to start.

Backup

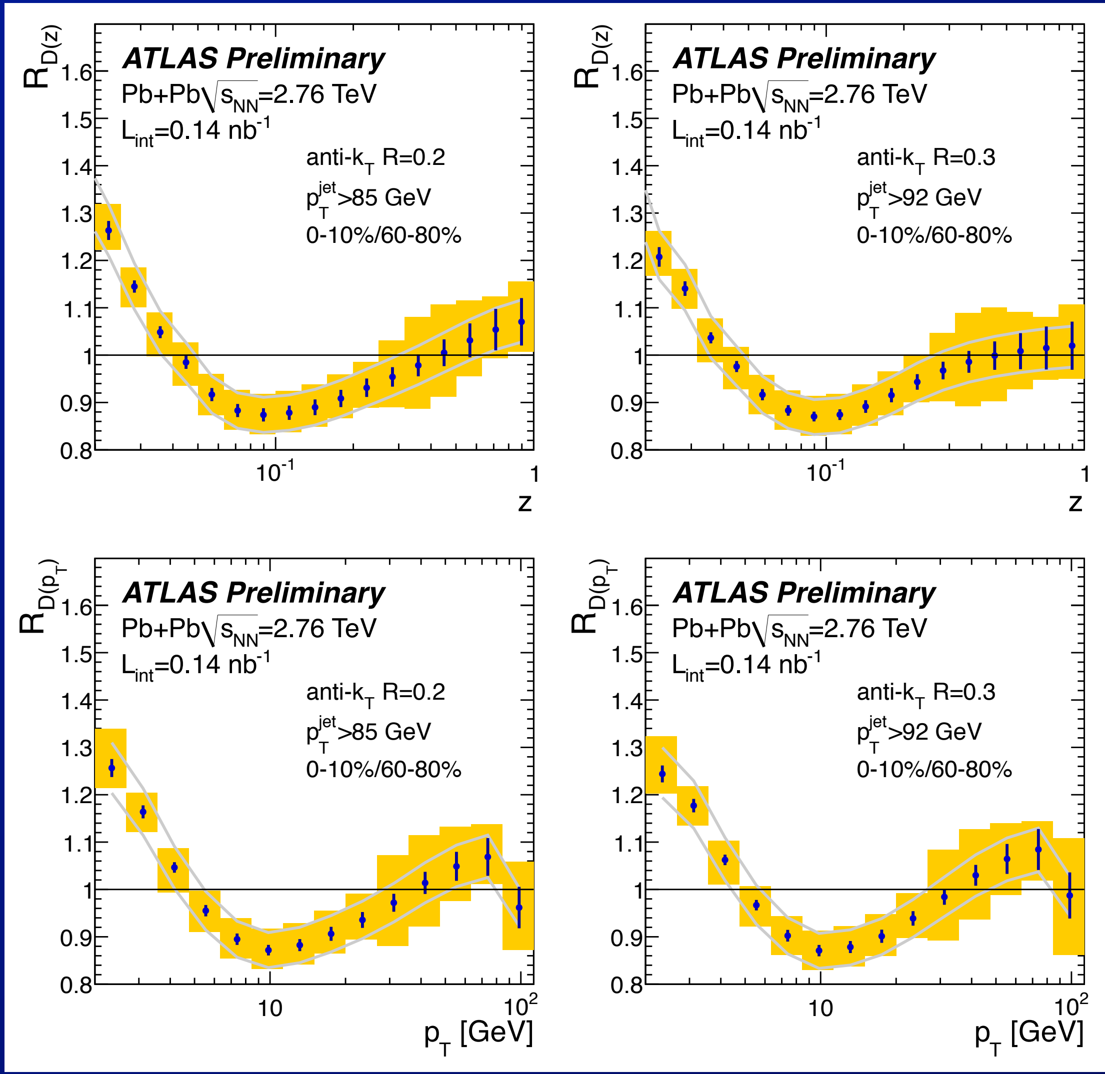
CMS jet suppression, R_{AA} (pp ref.)



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

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

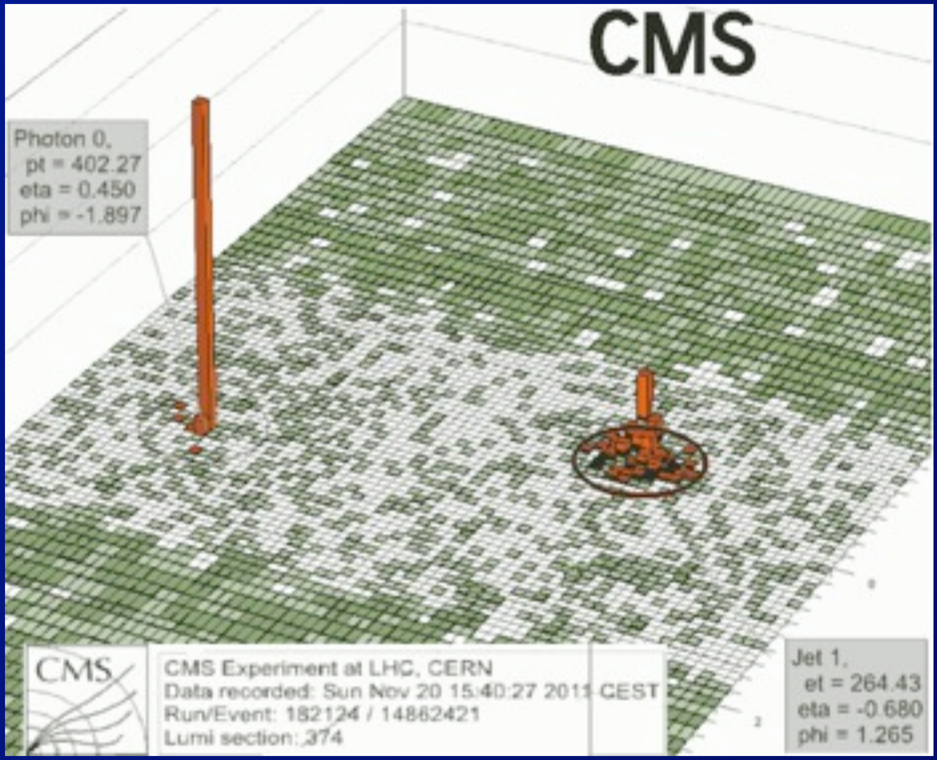


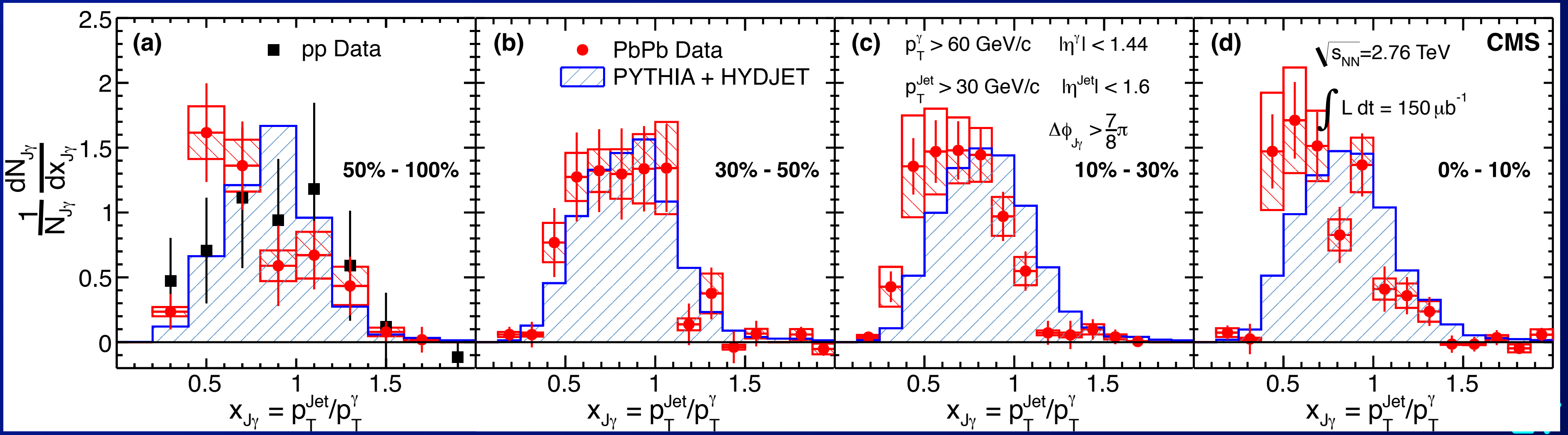
⇒Observed modifications are robust

CMS gamma-jet

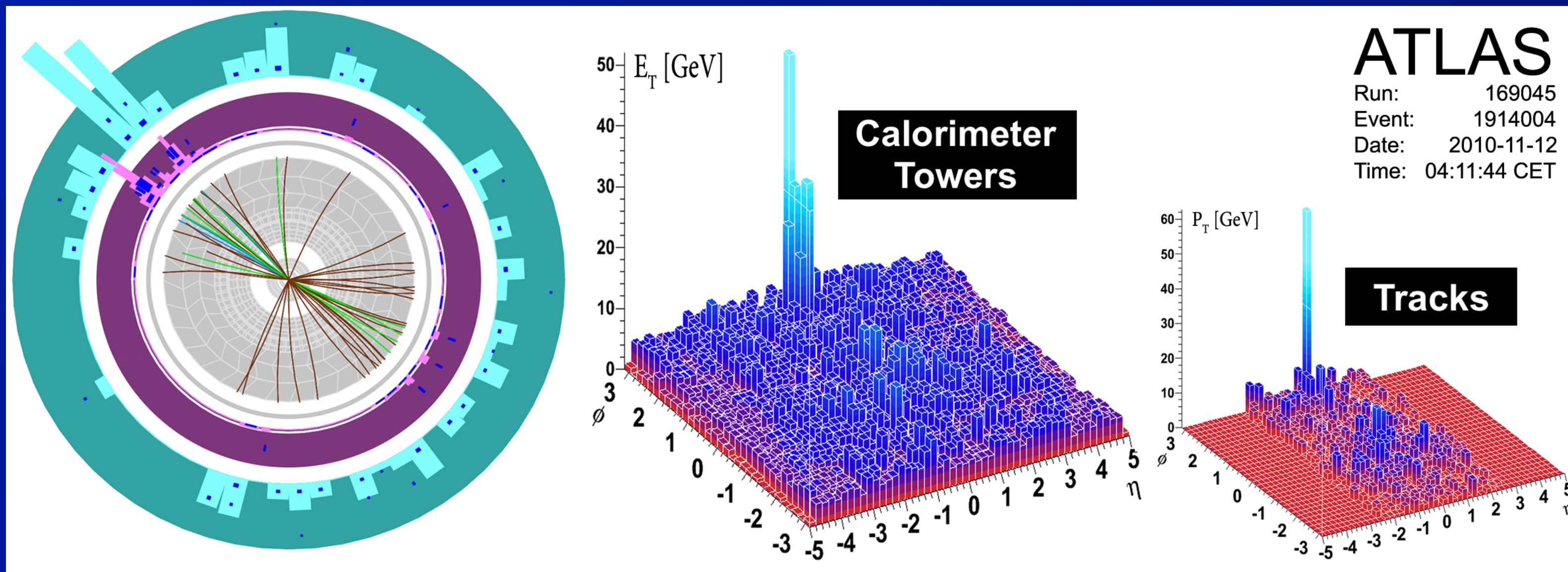
- Analogous to dijet measurement but with “clean” photon
  - See clear shift in fraction of photon energy carried by jet

  ⇒ But beware, photon is not proxy for unquenched jet (p-p)





ATLAS dijet asymmetry measurement



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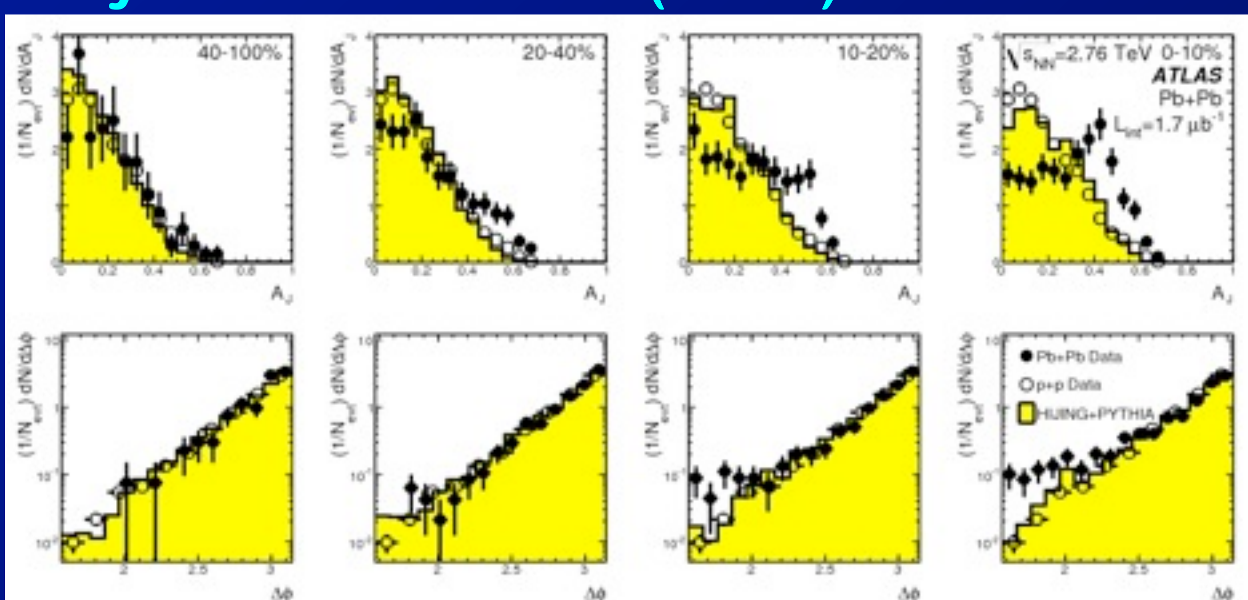
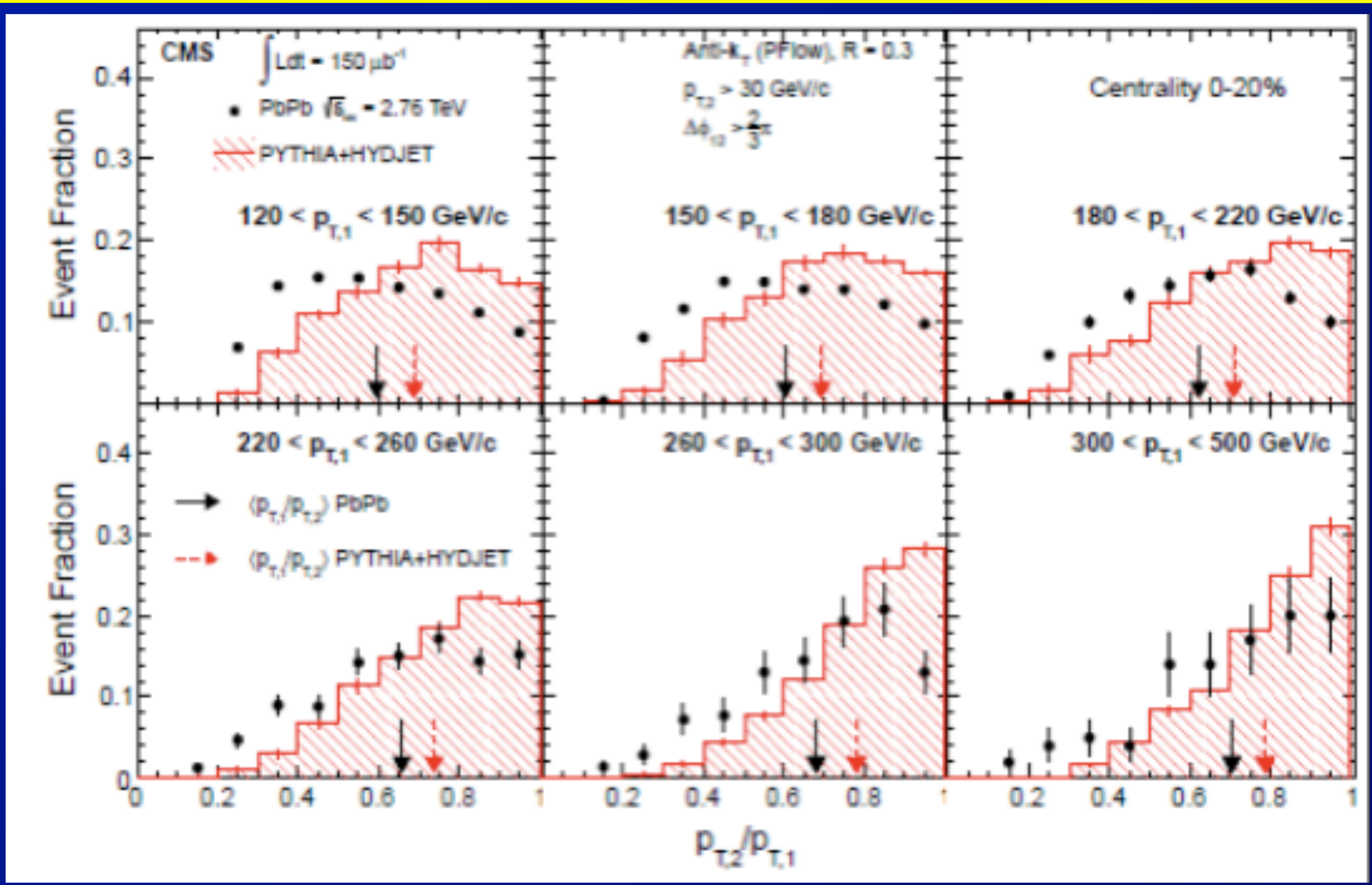


$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

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

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

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.