Recent heavy ion results from the LHC

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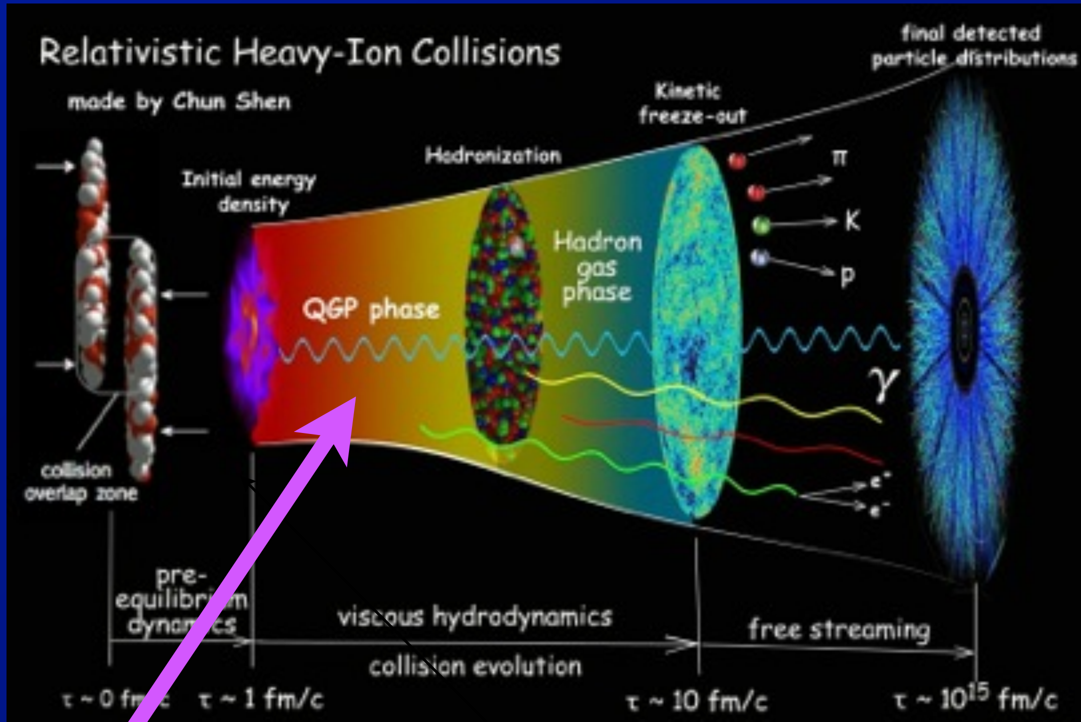
Aspen Winter Conference on
Particle Physics

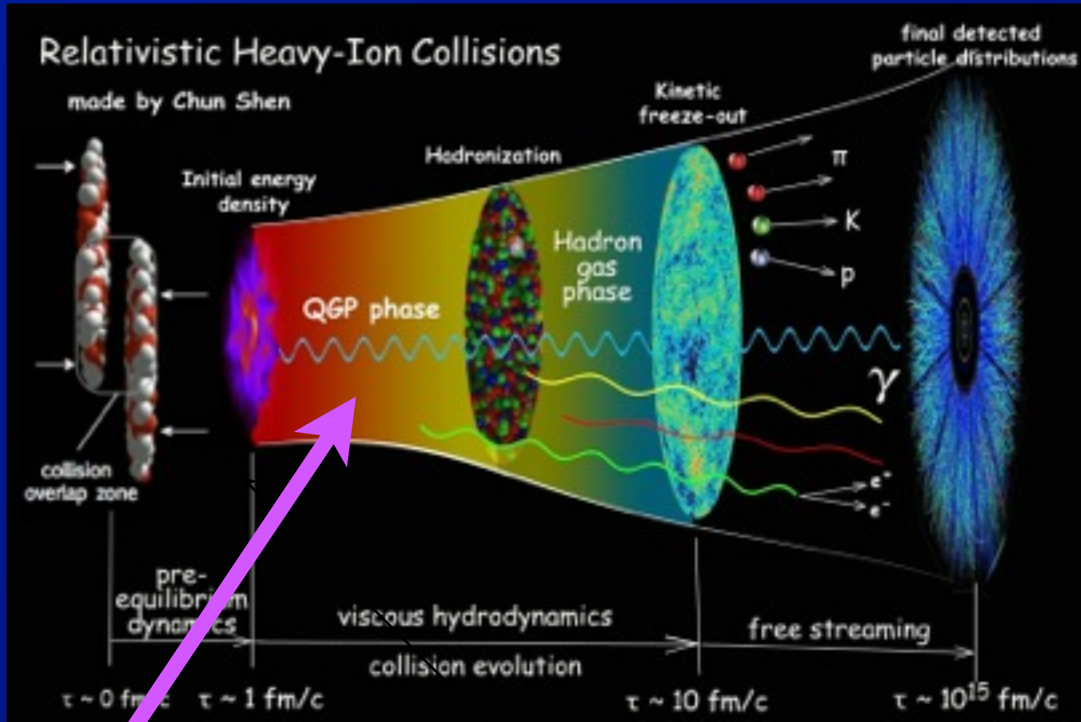
Introduction

(generously)
The Heavy Ion concordance model



- We want to study using probes of different wavelength -- since QGP properties may (should) evolve
  - Long - study collective dynamics
    - ⇒which we know from past data to be strongly coupled
    - ⇒how strongly, and why?
  - Short - study using high-energy quarks and gluons
    - ⇒and their energy loss (quenching) in plasma

Introduction



(generously) The Heavy Ion concordance model

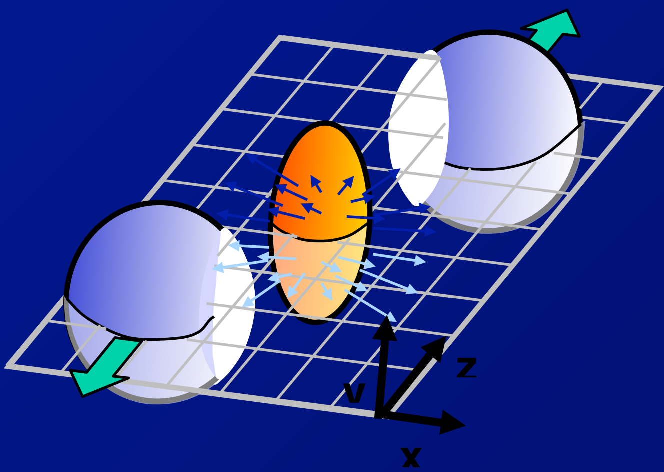
- We want to study using probes of different wavelength -- since QGP properties may (should) evolve
  - Long - study collective dynamics
  - Short - study using high-energy quarks and gluons
- For brevity: in this talk, focus on these two topics

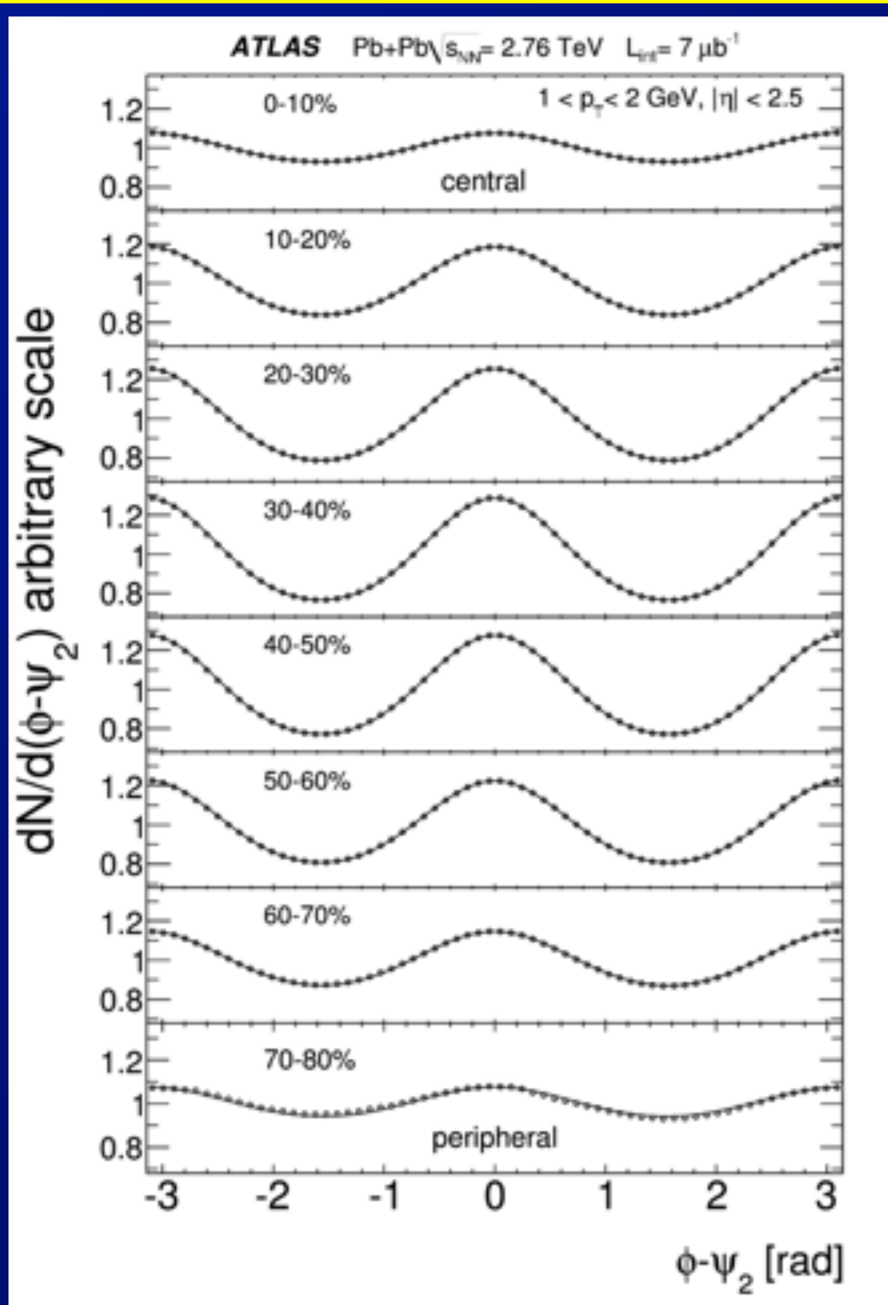
  ⇒Necessarily skipping many interesting results …

Soft probes

Elliptic flow

- **Old news:**
  - See cos(2φ) modulation of produced particle angular distributions
  - ⇒Attributed to collective expansion in collisions with non-zero impact parameter
  - Naturally appears in hydrodynamics
  - ⇒many, many subtleties



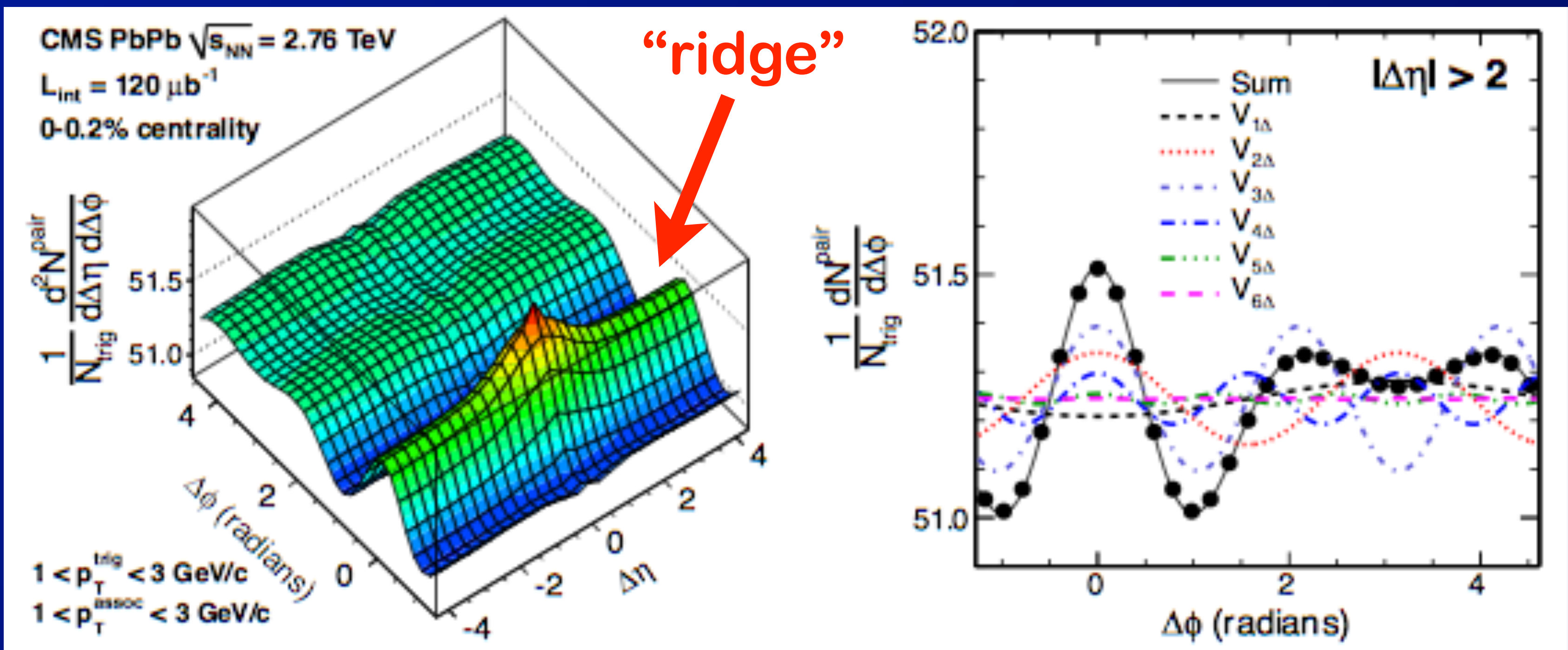


Higher Flow Harmonics

- **Major paradigm shift in the field in last 5 years**
  - Higher flow harmonics arising from initial-state fluctuations (~ which nucleons scatter)

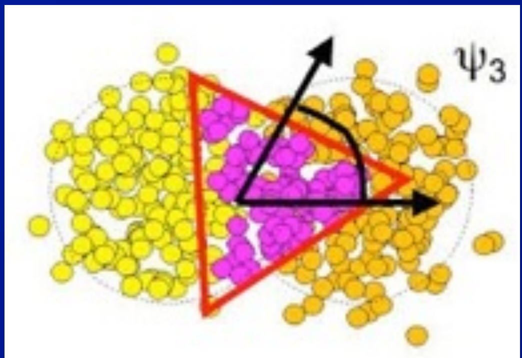
$$\frac{dN}{d\phi dp_T d\eta} = \frac{dN}{2\pi dp_T d\eta}\left(1 + \sum_n 2v_n \cos\left[n(\phi - \psi_n)\right]\right)$$

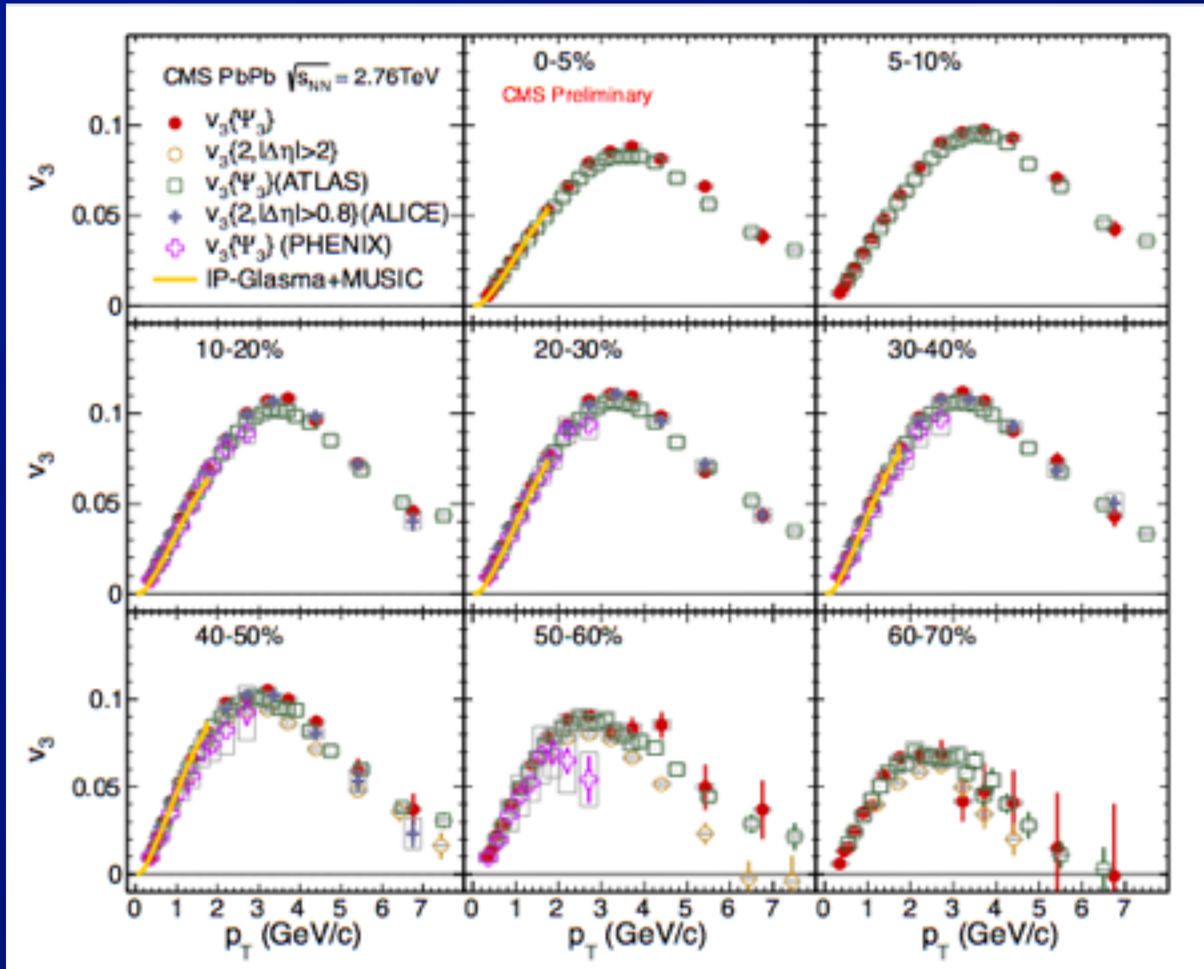
- **Frequently measured using two-particle angular correlations**



"Triangular flow"

- Summary of LHC + PHENIX@RHIC results on measurements of v_3:
  - ⇒Good agreement. Even with RHIC data?!
  - ⇒Note characteristic p_T dependence

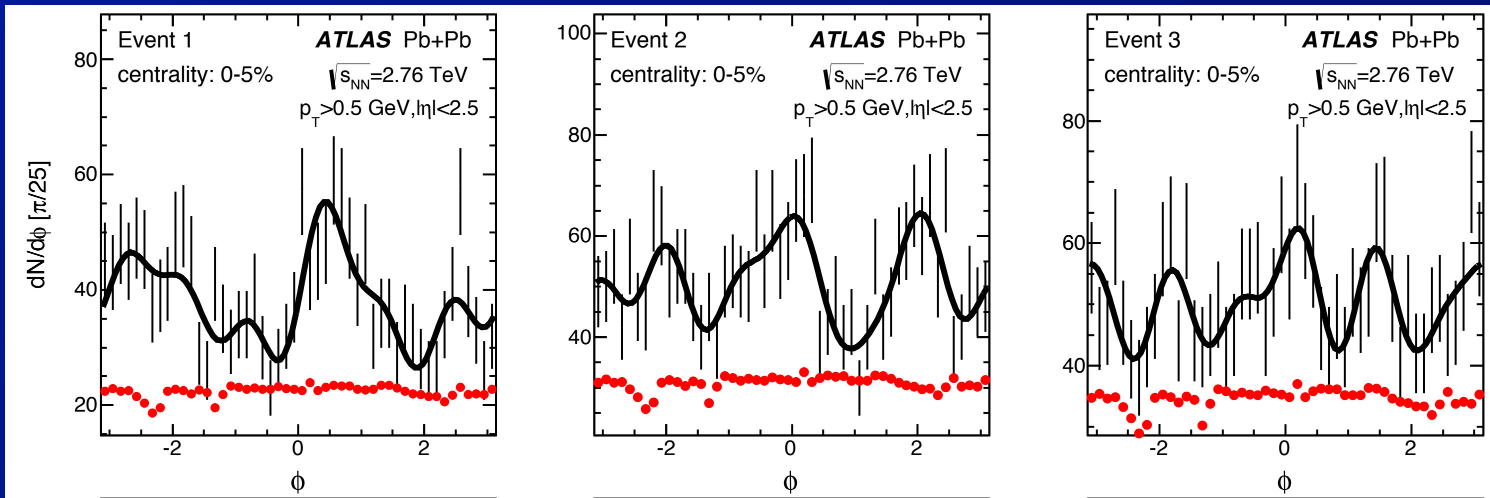




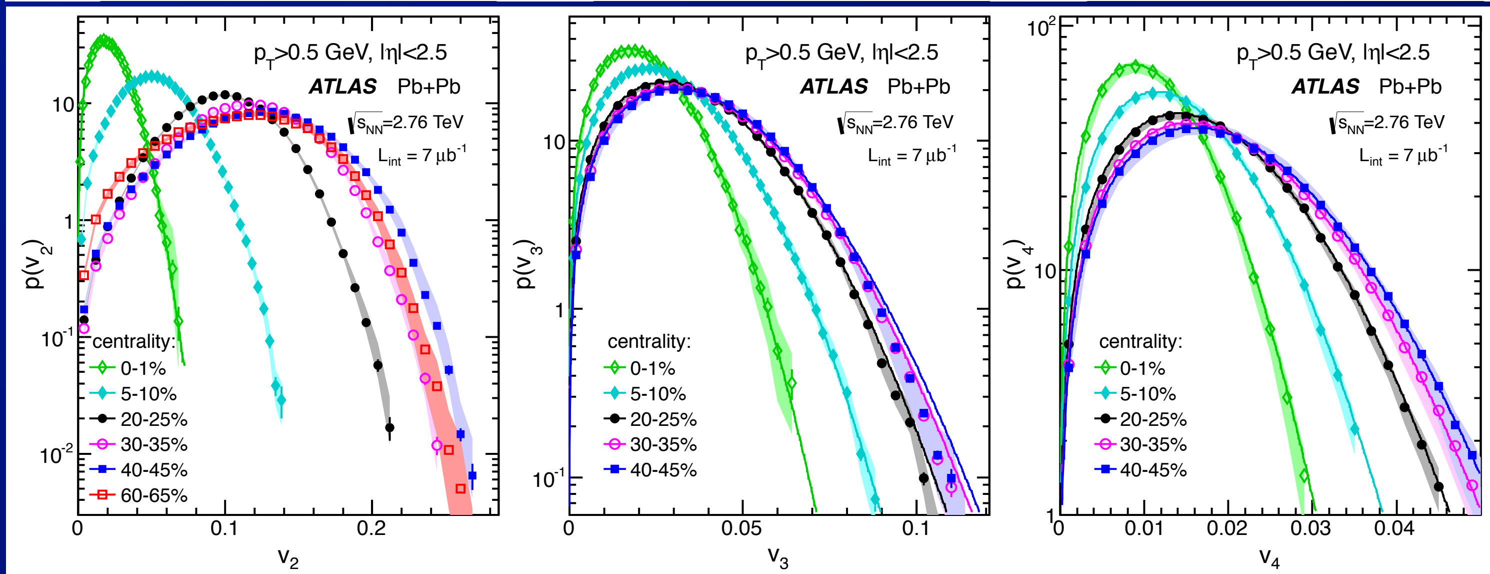
Event-by-event v_n measurements

- **Unique to LHC: large acceptance detectors allow event-by-event v_n measurements**

e.g. single particle φ distributions in 3 events



Distributions of v_2, v_3, v_4 unfolded for experimental resolution

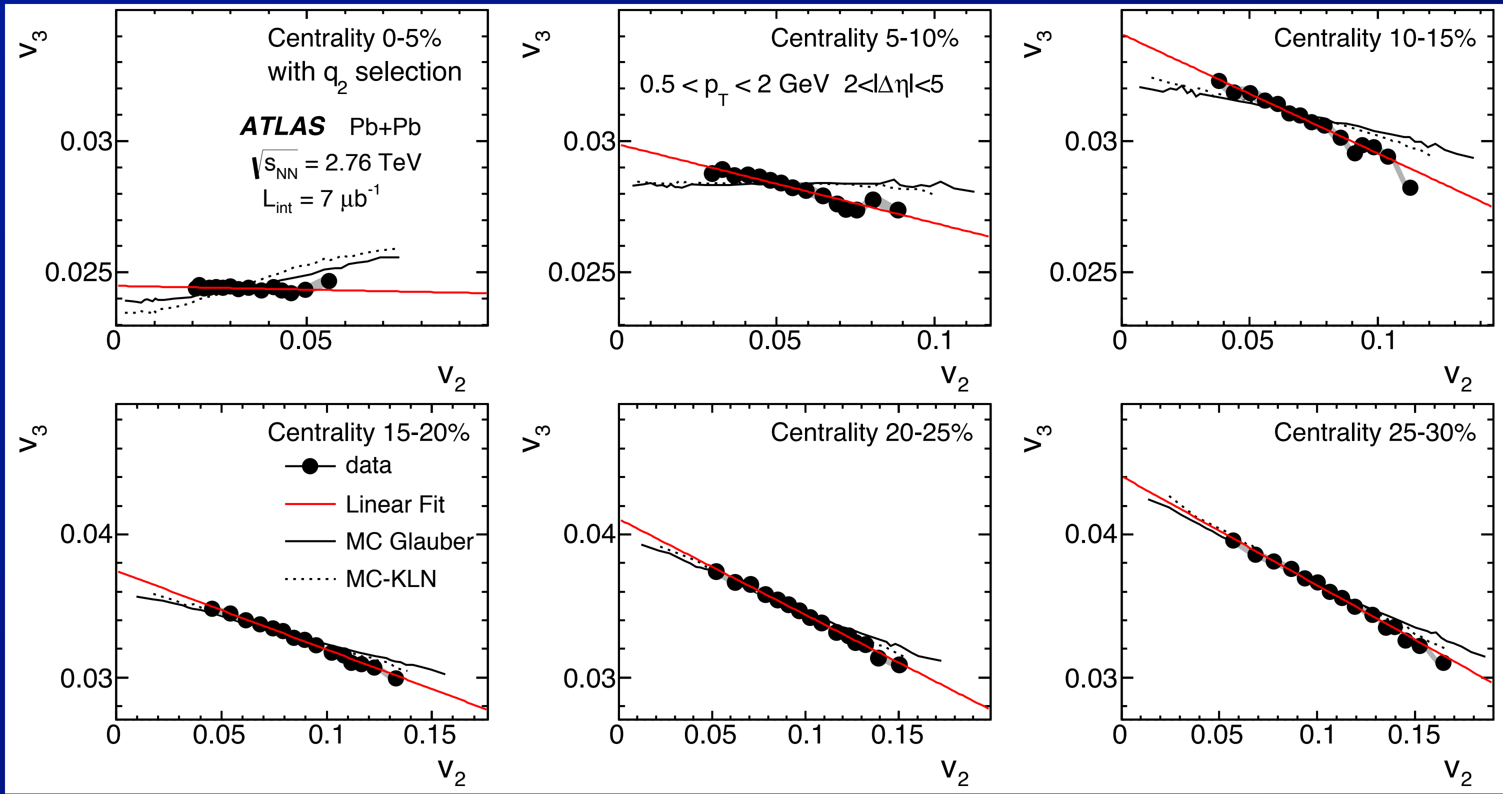


Event-by-event v_n correlations

- Event-by-event v_n method allows direct study of correlations between different harmonics:

e.g. v_3-v_2 for a subset of available centrality intervals

Compared to 2 models



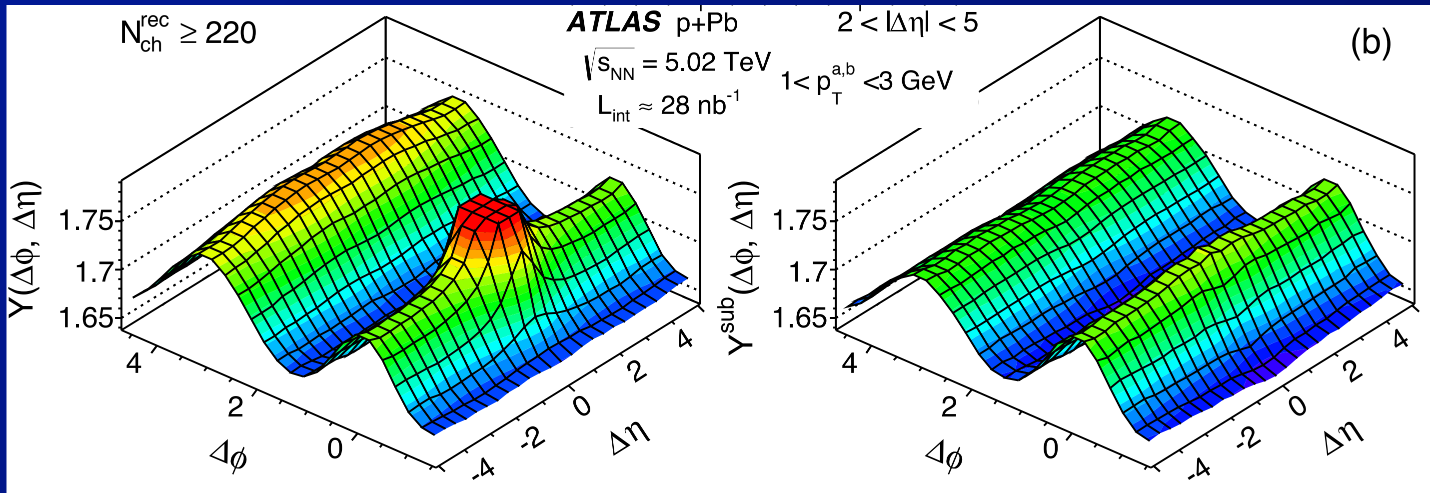
- Such measurements provide a detailed test of models of initial-state fluctuations

  ⇒Also show coupling between harmonics due to non-linear "hydrodynamic" expansion

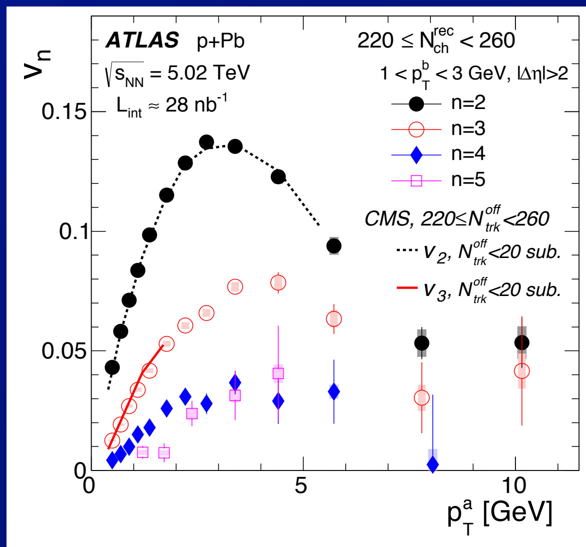
Azimuthal harmonics in p+Pb

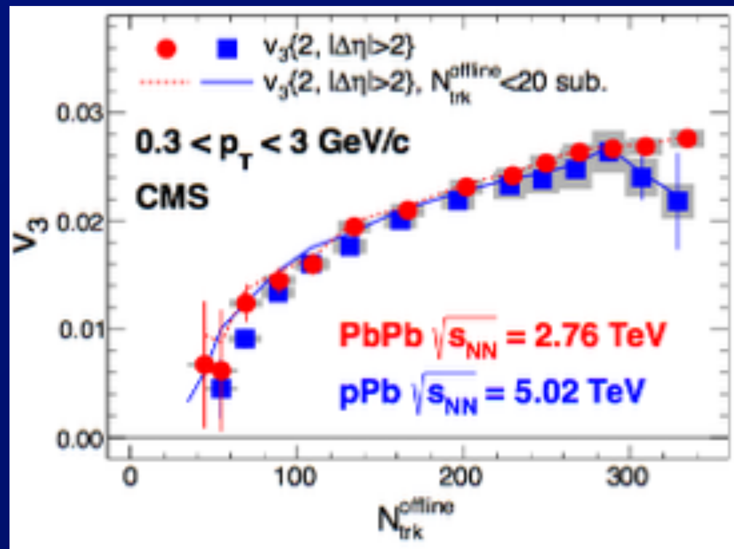
- **Surprising development in last 3 years:**
  - Observation of flow-like harmonics in p+Pb
    - ⇒ similar to that observed in Pb+Pb

2-particle correlation before (left), after (right) subtracting low-multiplicity yield



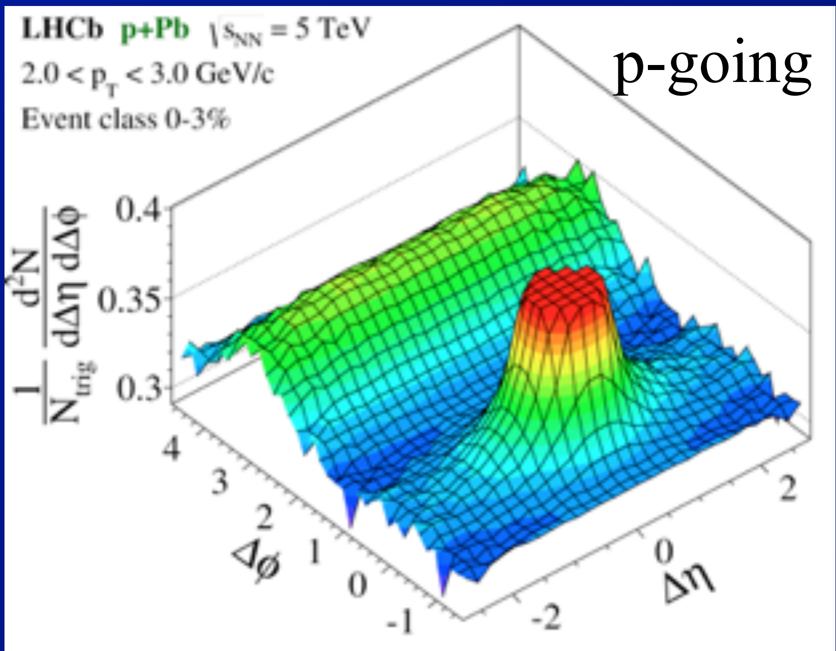
p+Pb v_n values versus pT (left) and multiplicity (right) for v_3 with Pb+Pb comparison

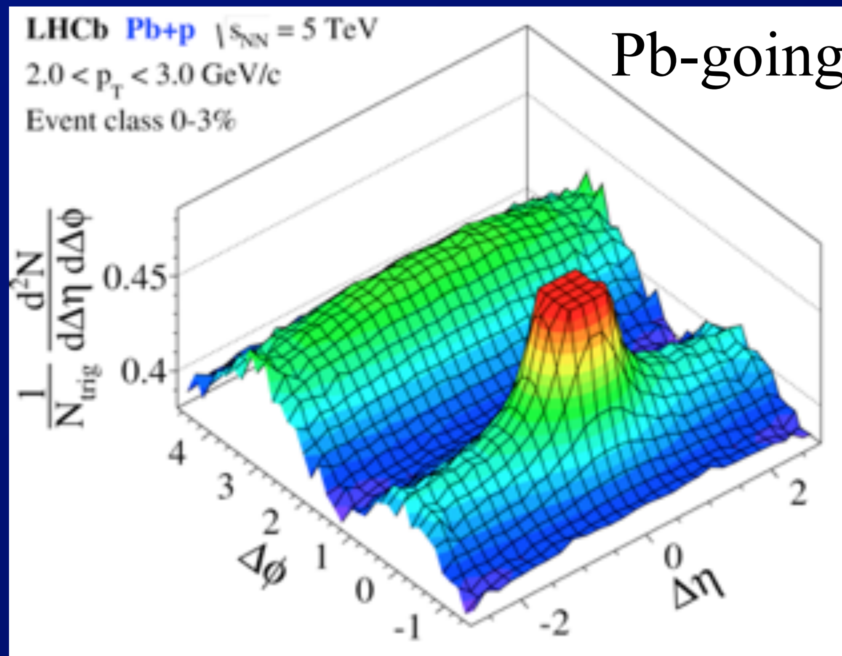




p+Pb forward ridge from LHCb

- Two-particle correlations in forward η
  - clear ridge signal in both proton-going (2<η<4.9) and lead-going (-4.9<η<-2) side.
  - the amplitude is comparable
    ⇒ CMS/ALICE see FB difference up to 10-20%

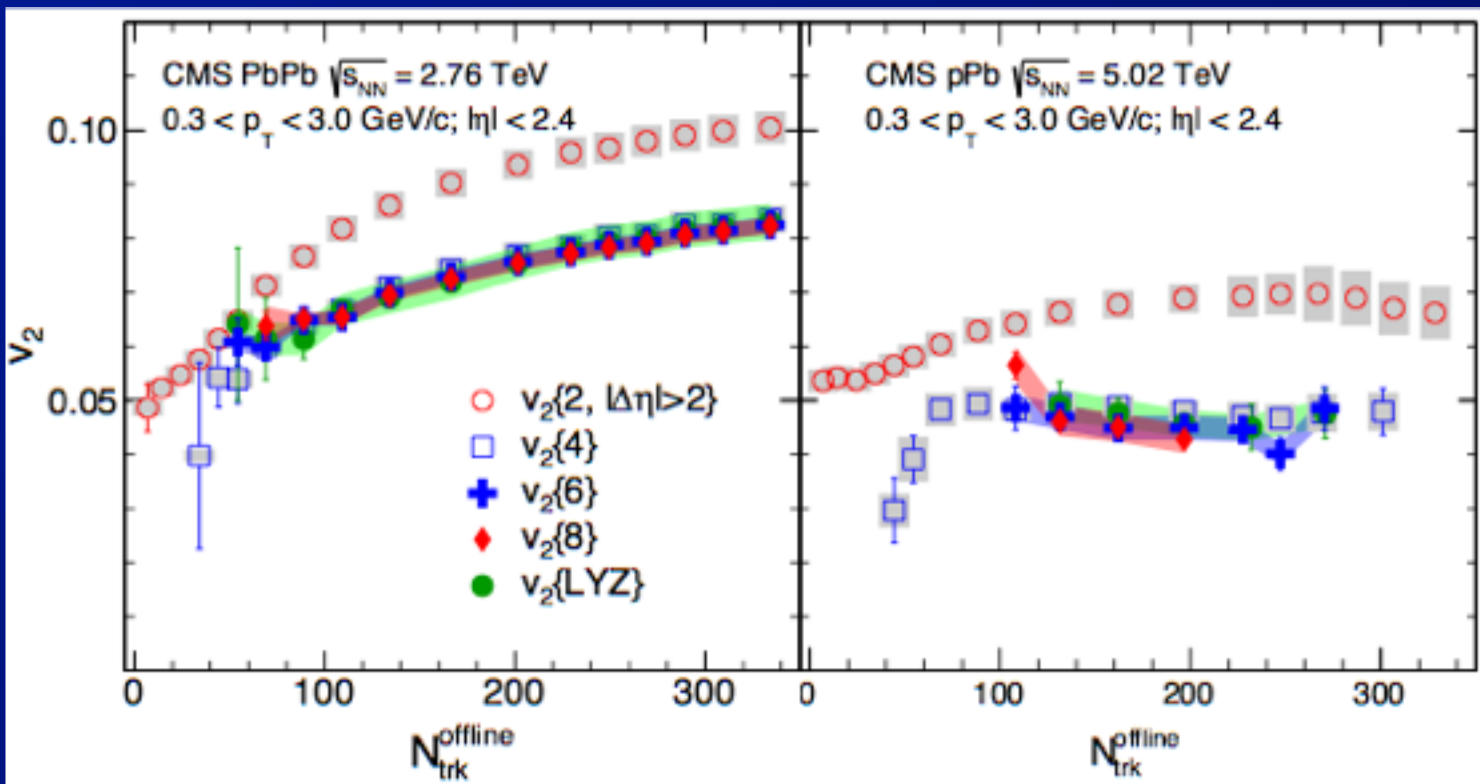




Azimuthal harmonics in p+Pb

- Multi-particle (4, 6, 8) correlations an important test of whether azimuthal harmonics are "global" features
  - as opposed to (e.g.) pQCD-induced correlations
  - studied using cumulants (details skipped for brevity)

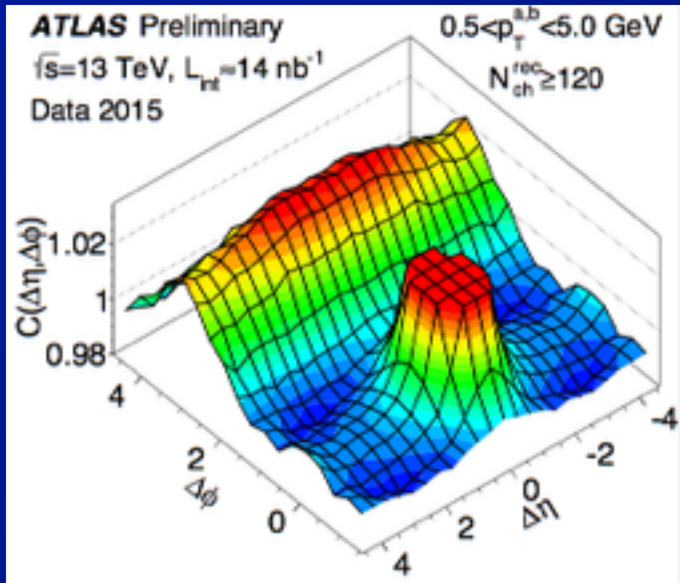
  ⇒ Agreement between 4, 6, 8-particle v_2 values suggests correlation is global in Pb+Pb and p+Pb

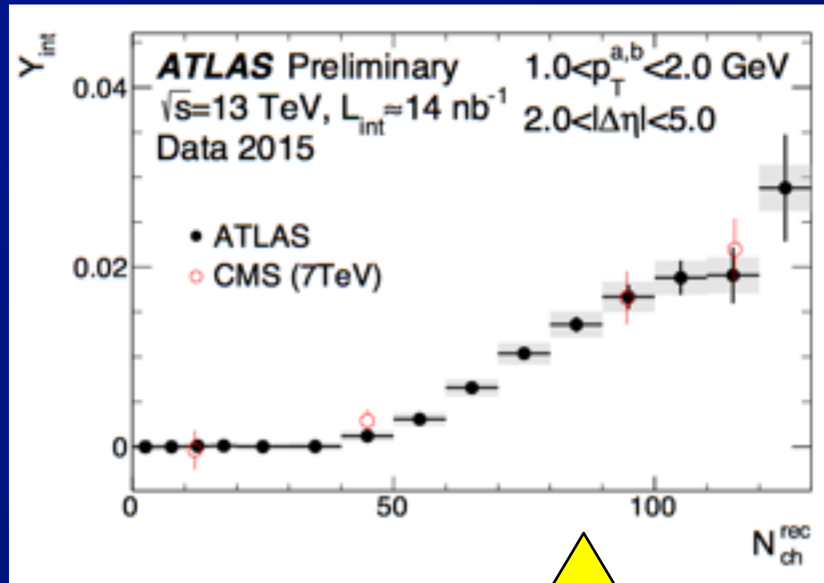


Ridge in 13 TeV p-p collisions

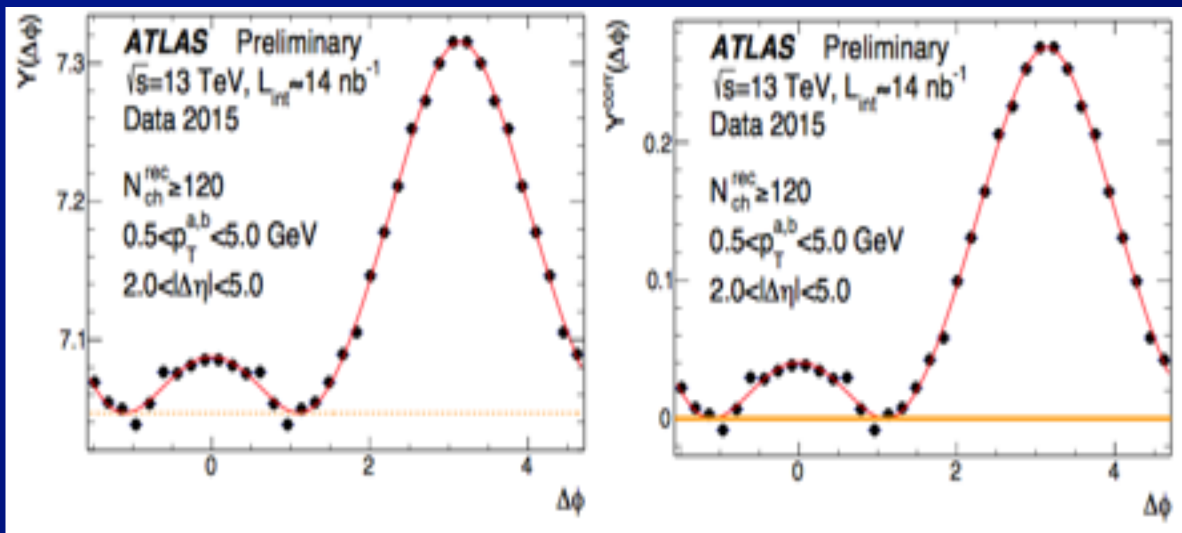
- Usual 2-particle correlation analysis:

Measure 2-particle correlation function vs $\Delta\eta$, $\Delta\varphi$



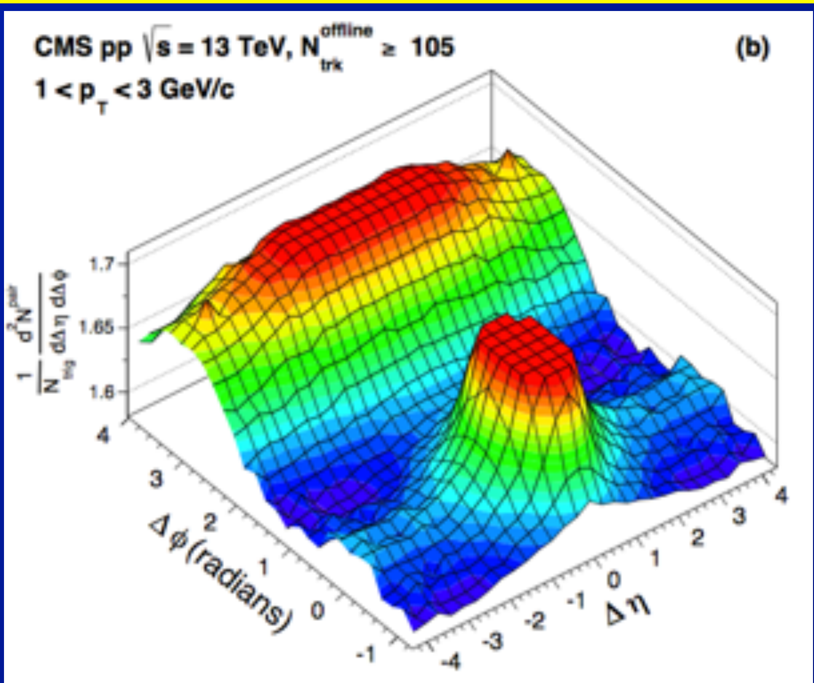


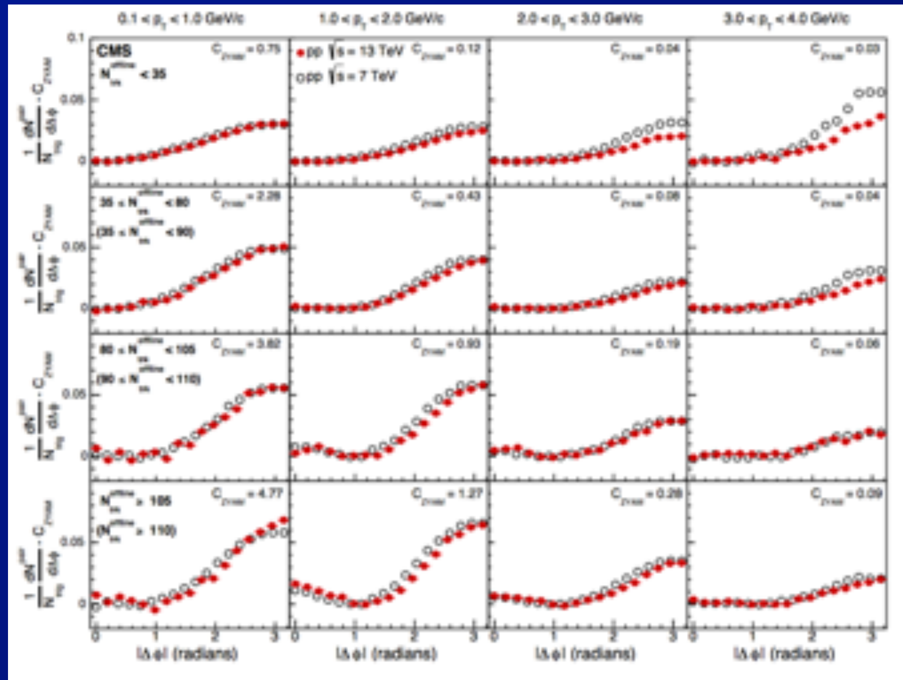
Project long-range component onto $\Delta\varphi$, normalize to obtain per-trigger yield

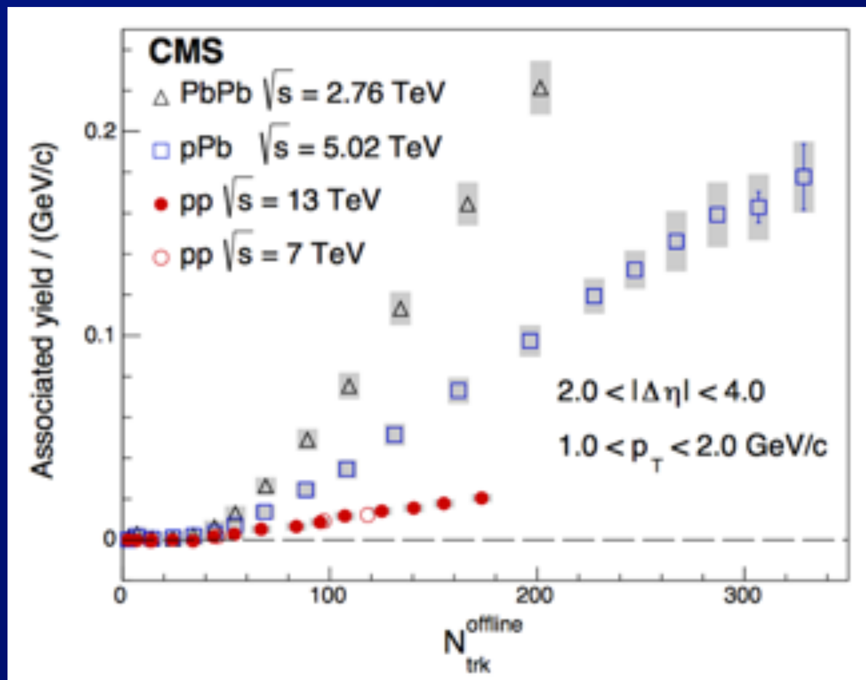


Assume yield at minimum is combinatoric (ZYAM), subtract flat combinatoric, integrate over $\Delta\varphi$

Ridge in 13 TeV p-p collisions







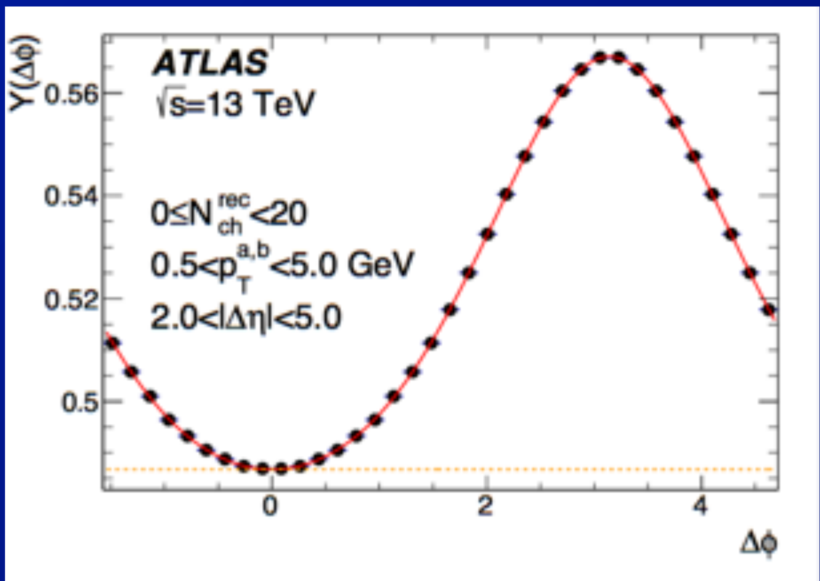
- Similar results obtained (submitted to PRL) by CMS using similar methods:
  - consistent results

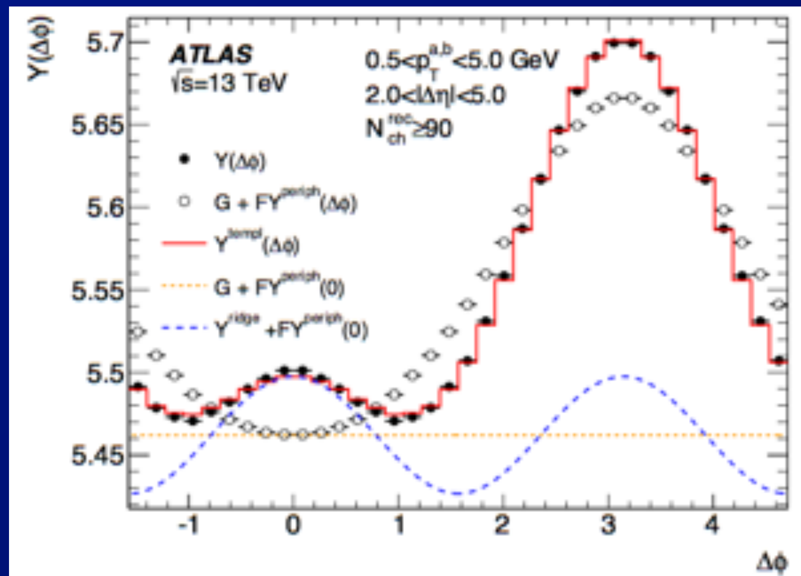
    ⇒ same ridge yields at 7 and 13 TeV for the same event multiplicity

“Flow” in p-p collisions?

- **Critical question:**
  - does the p-p ridge result from cos(nΔφ) modulation?
  - how to better handle the hard contribution?

    ⇒New method from ATLAS: use template fit consisting of low-multiplicity Y(Δφ) + cos(2Δφ) term (to start).





⇒template method works well, describes both the ridge and modifications to the dijet peak

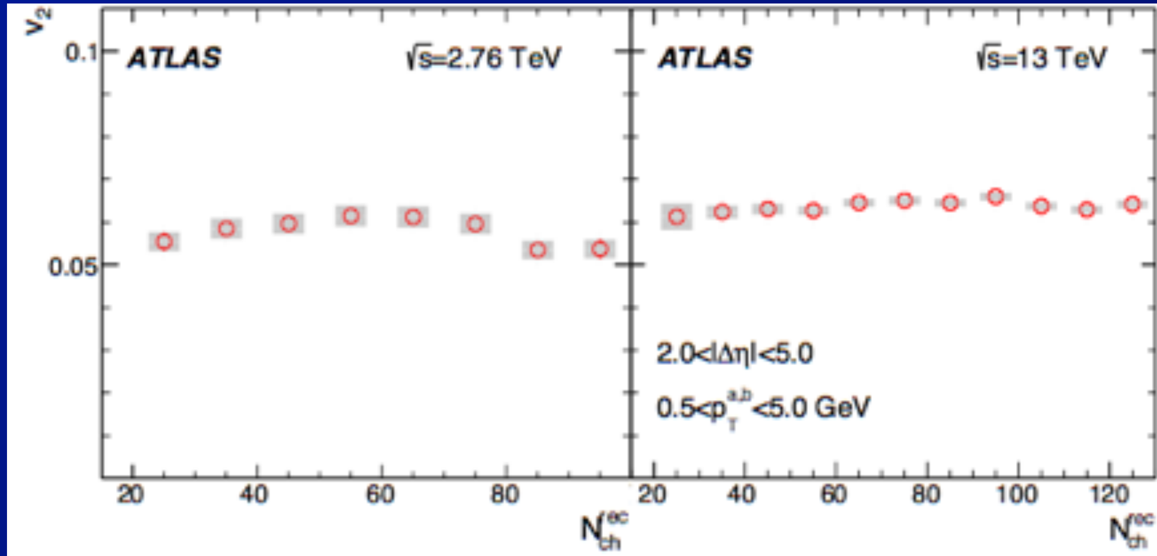
⇒extract the v_2 (relative amplitude of cos(2Δφ) term)

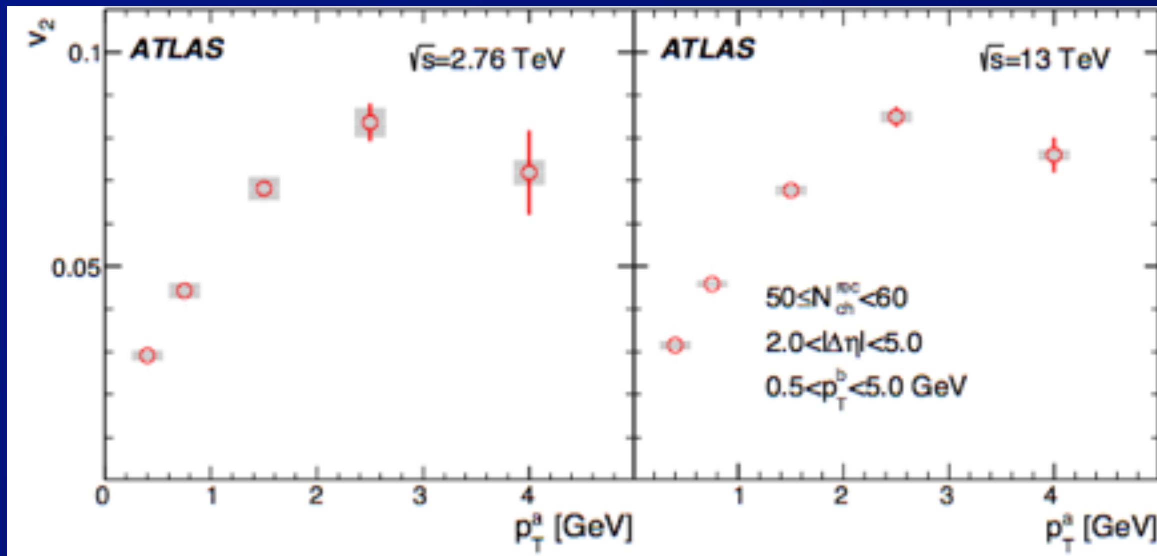
13 and 2.76 TeV p-p v_2 values

- **Surprises:**
  - Observe that v_2 is approximately constant versus multiplicity

  ⇒Growth in ridge yield with N_{trk} ~ trivial
  - v_2 approximately the same at 2.76 and 13 TeV
  - Similar dependence on p_T as in p+Pb

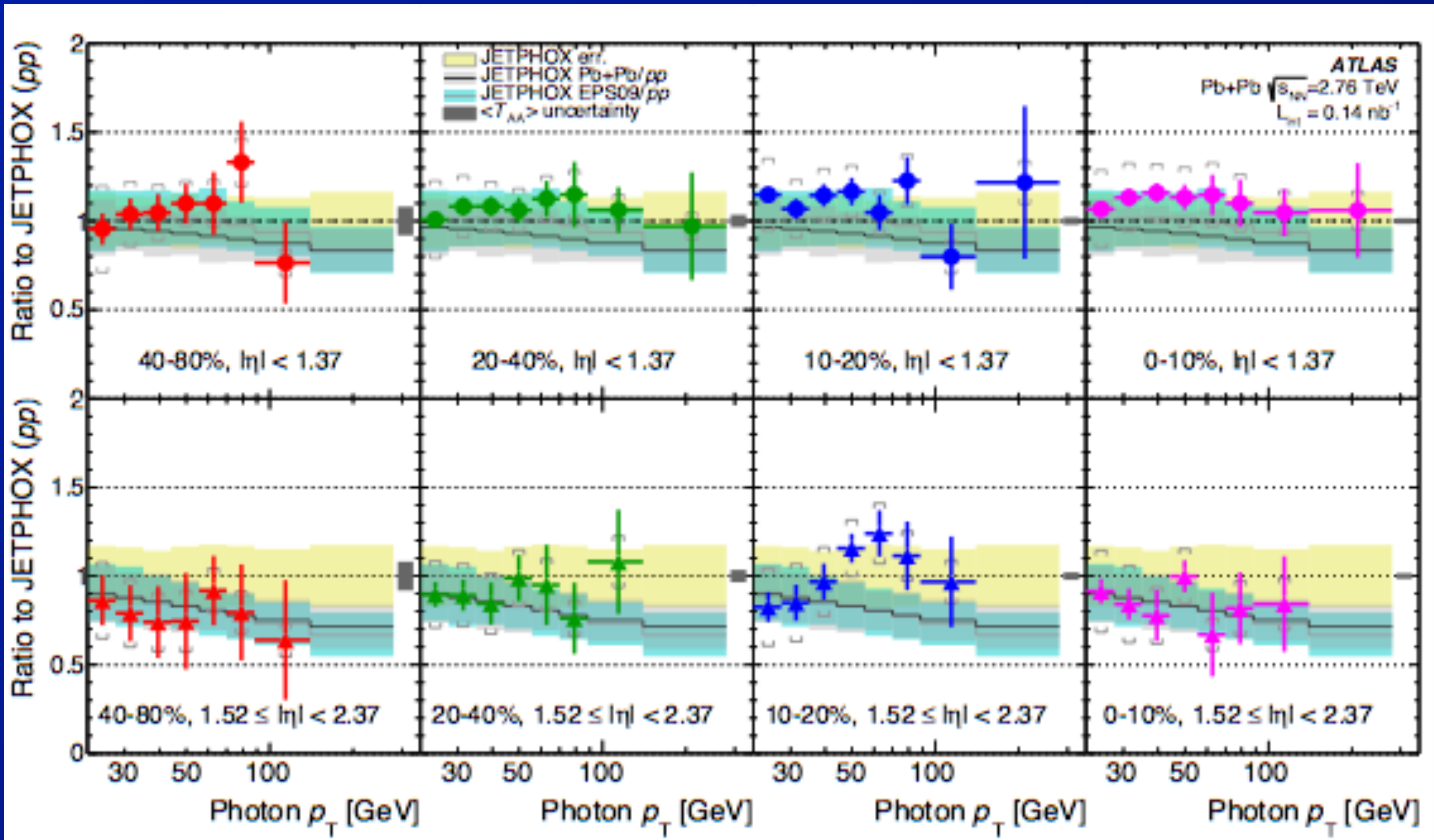
  ⇒Direct comparison awaits p+Pb analysis using same template method.





Hard probes

Pb+Pb photon yields

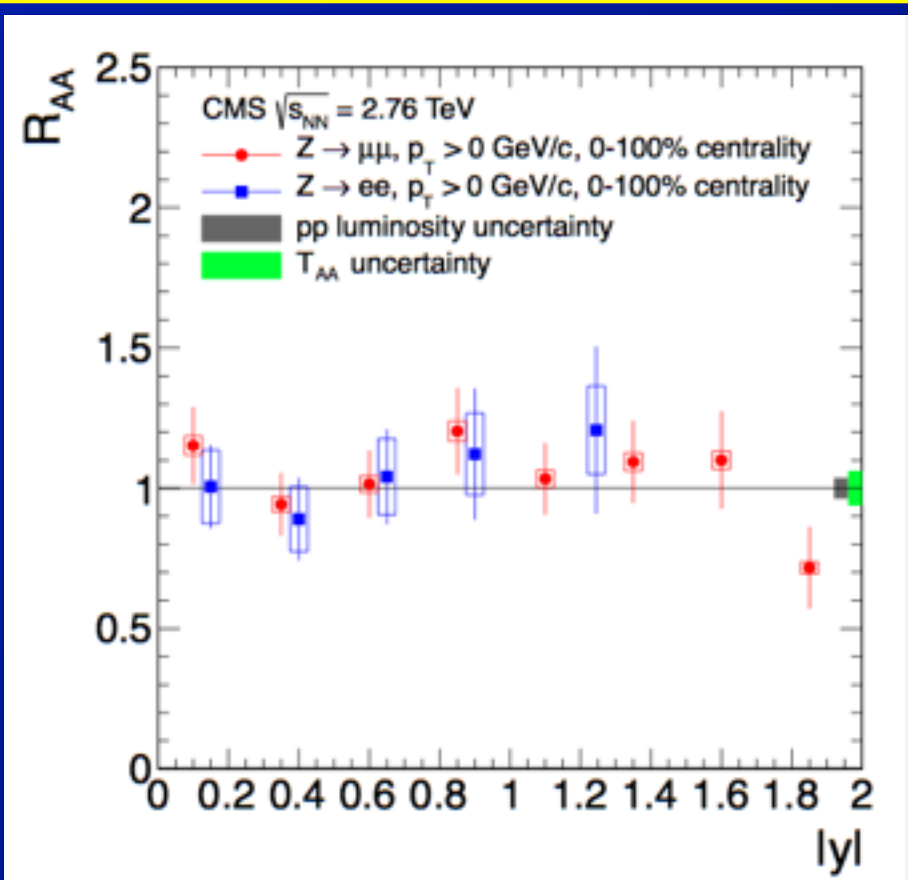


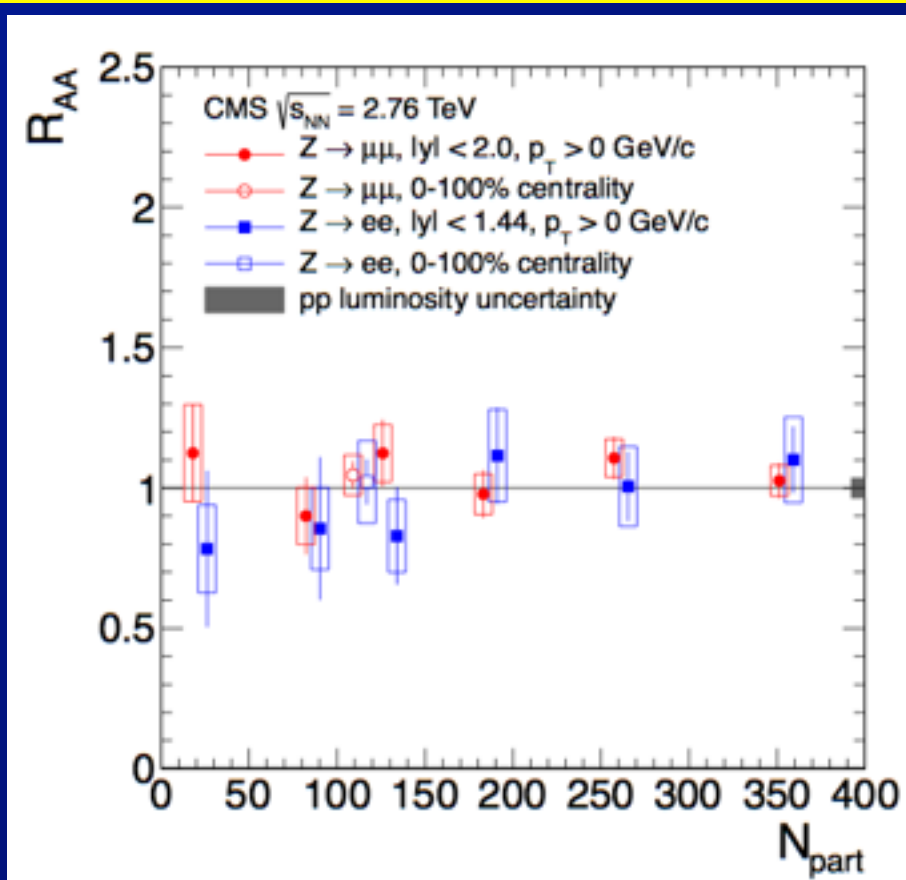
|η|<1.37

1.52<|η|<2.37

- Ratios of isolated, direct photon yields/T_{AA} to NLO pQCD calculation for p-p (JETPHOX1.3)
  - Also shown, JETPHOX for Pb+Pb: iso only, EPS09 NPDF
    - ⇒Hard scattering rates under control
    - ⇒Not yet sensitive to nuclear PDF effects in Pb+Pb

Pb+Pb Z production



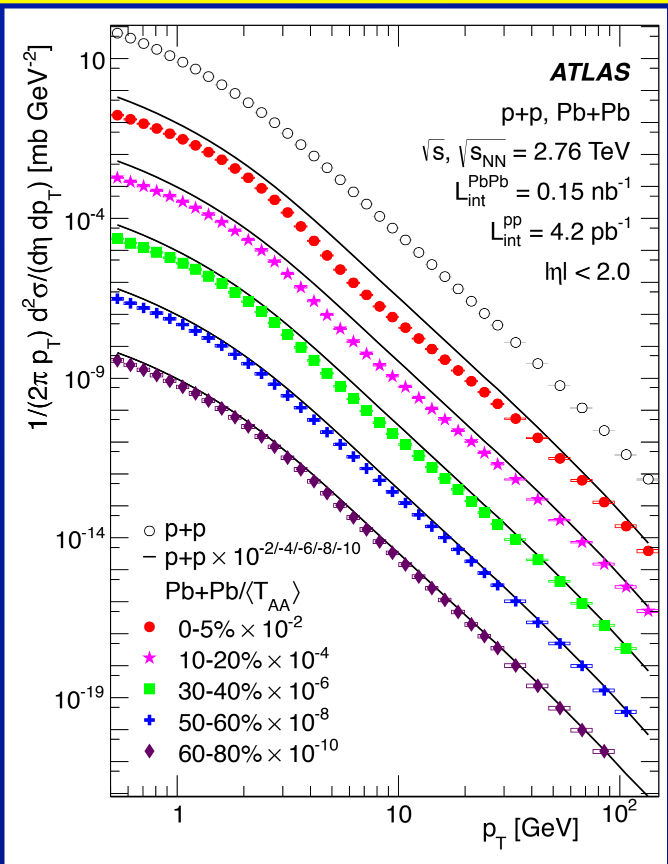


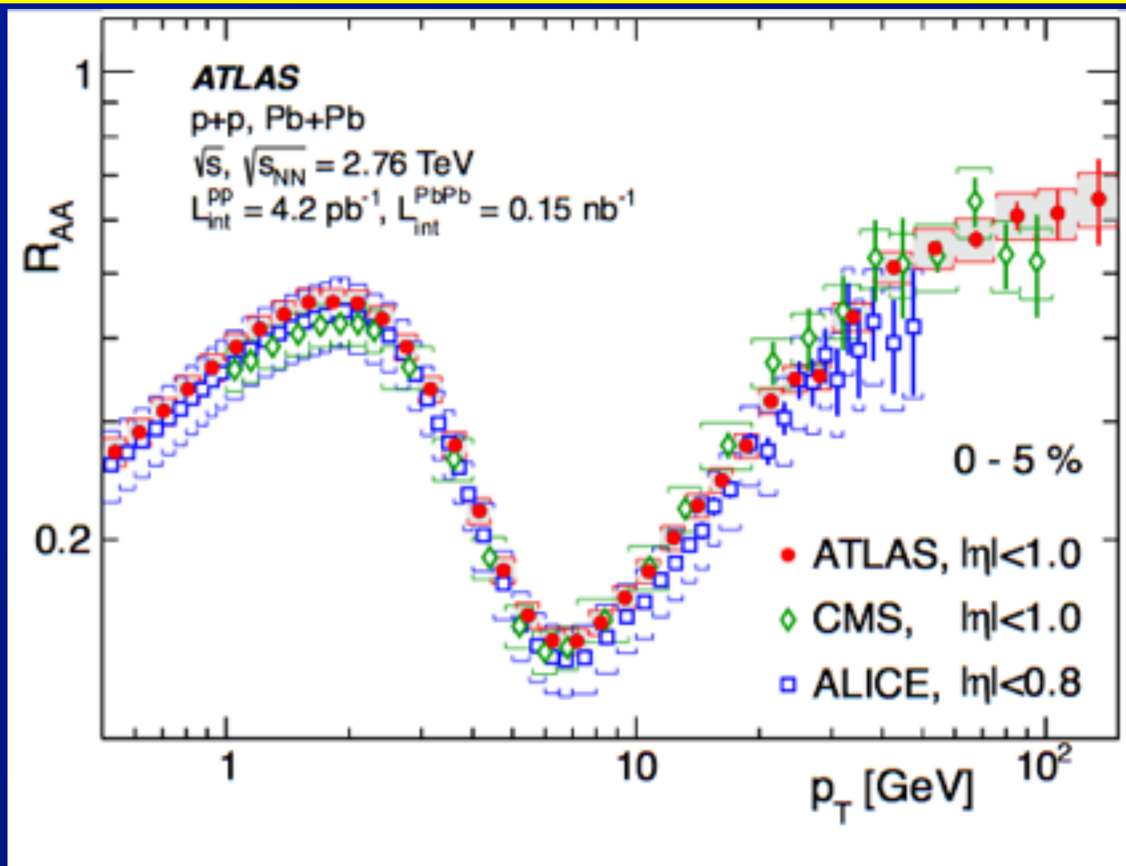
- Z R_{AA} consistent with unity
  - Similar observation from ATLAS
- Same conclusion by ATLAS and CMS for W^{+-}

⇒ Hard scattering rates in Pb+Pb collisions "understood"

⇒ Nuclear PDF effects will eventually (soon?) be important.

Pb+Pb Charged Particle Production

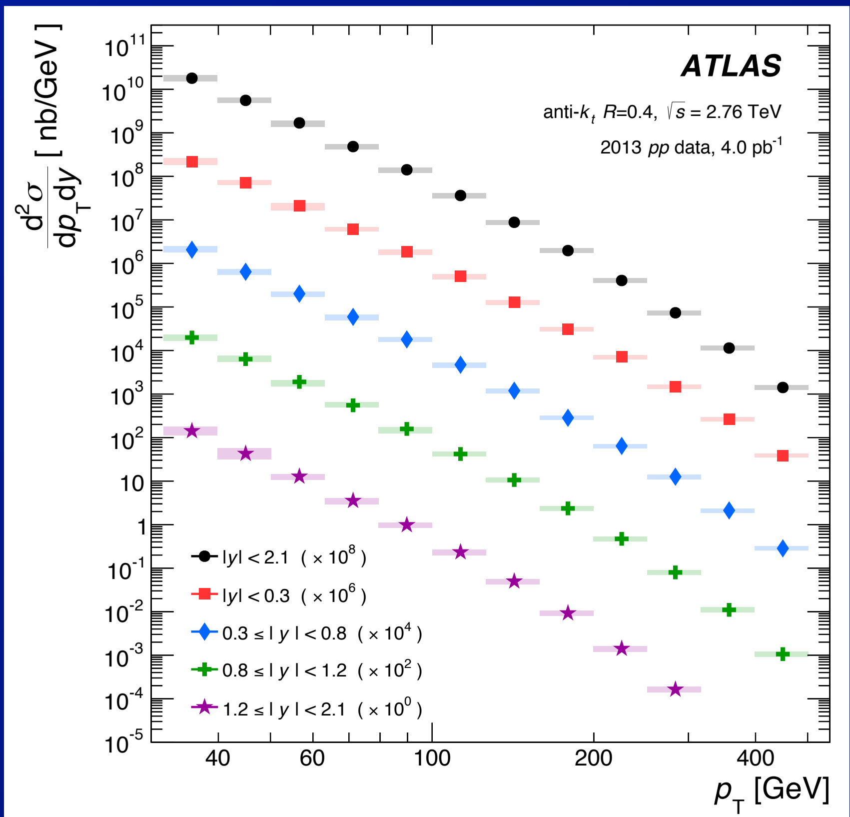


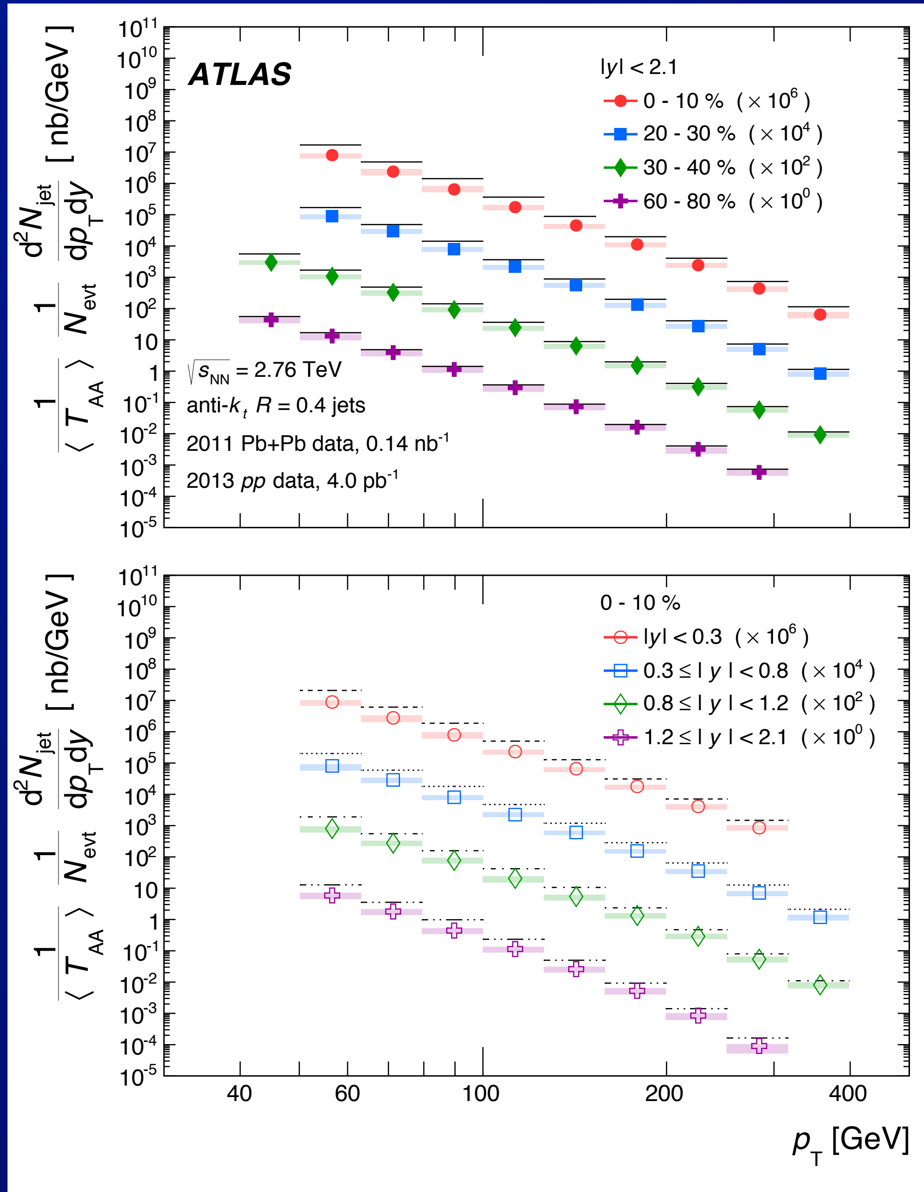


- **Charged particle spectra show a p_T-dependent suppression associated with jet quenching**
  - modified at $p_T \lesssim 4$ GeV by radial expansion of the plasma
    - ⇒theoretical analyses of jet quenching have, until recently, focused primarily on charged particle measurements
    - ⇒But charged particles are insensitive to details ⇒ jets

Jet spectra: p+p and Pb+Pb

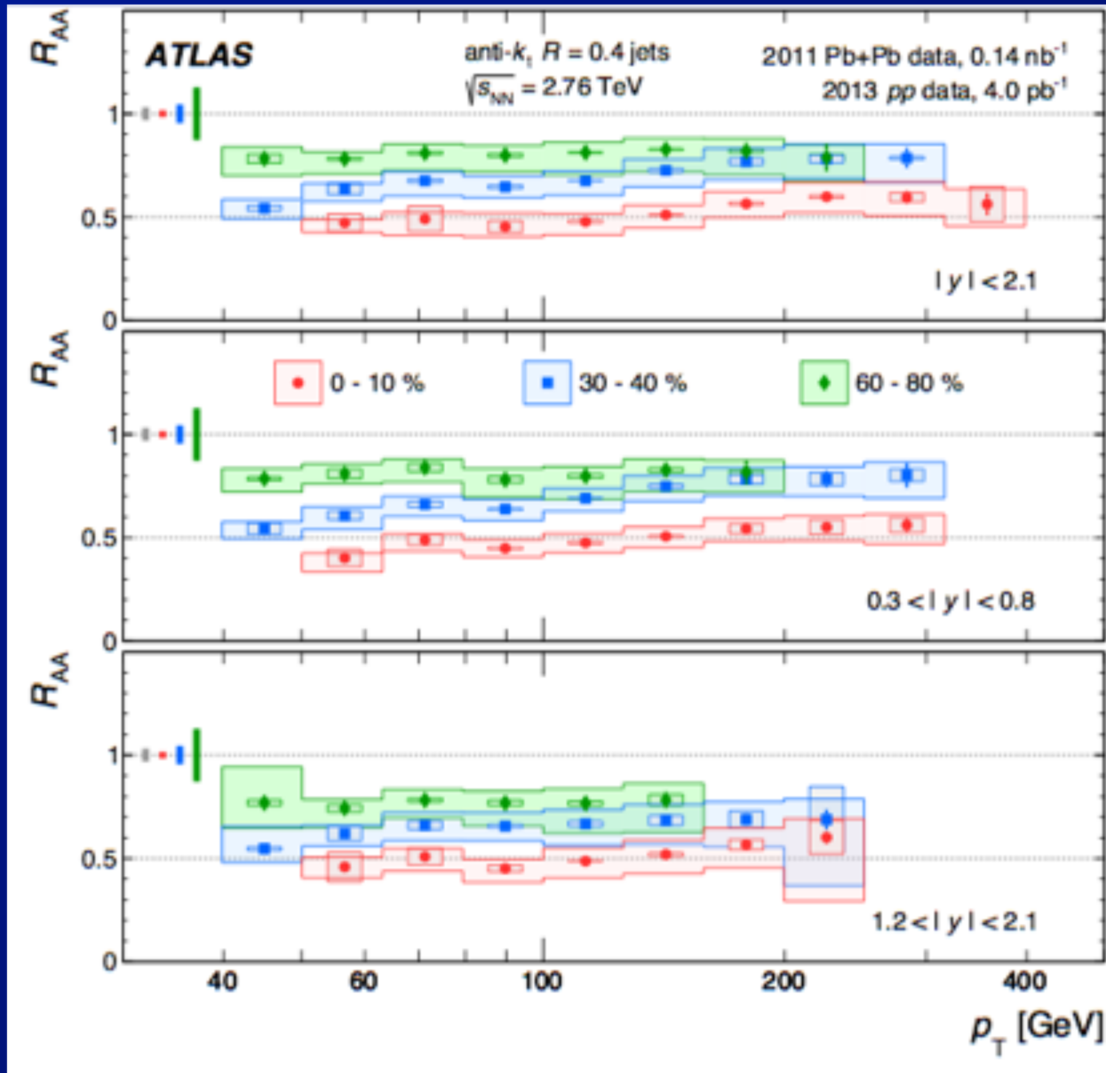
- Absolutely normalized R = 0.4 anti-k_t jet spectra:
  - 2013 2.76 TeV p+p (left)
    - ⇒ cross-section
  - 2011 Pb+Pb (right)
    - ⇒per-event yields





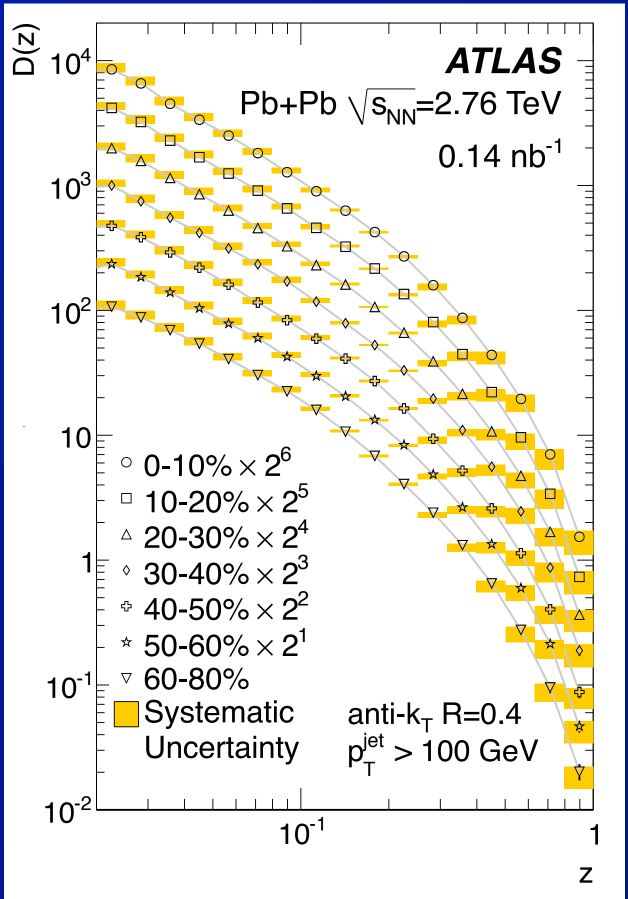
Pb+Pb Jet production

- R_{AA} vs p_T and y
  - in sub-set of centrality bins
  - ⇒ Fully unfolded
- Observe
  - Jet yield suppressed by ~ x2 in central Pb+Pb collisions
  - ⇒ up to jet p_T of 400 GeV
  - Slow increase with increasing jet p_T
  - No apparent rapidity dependence

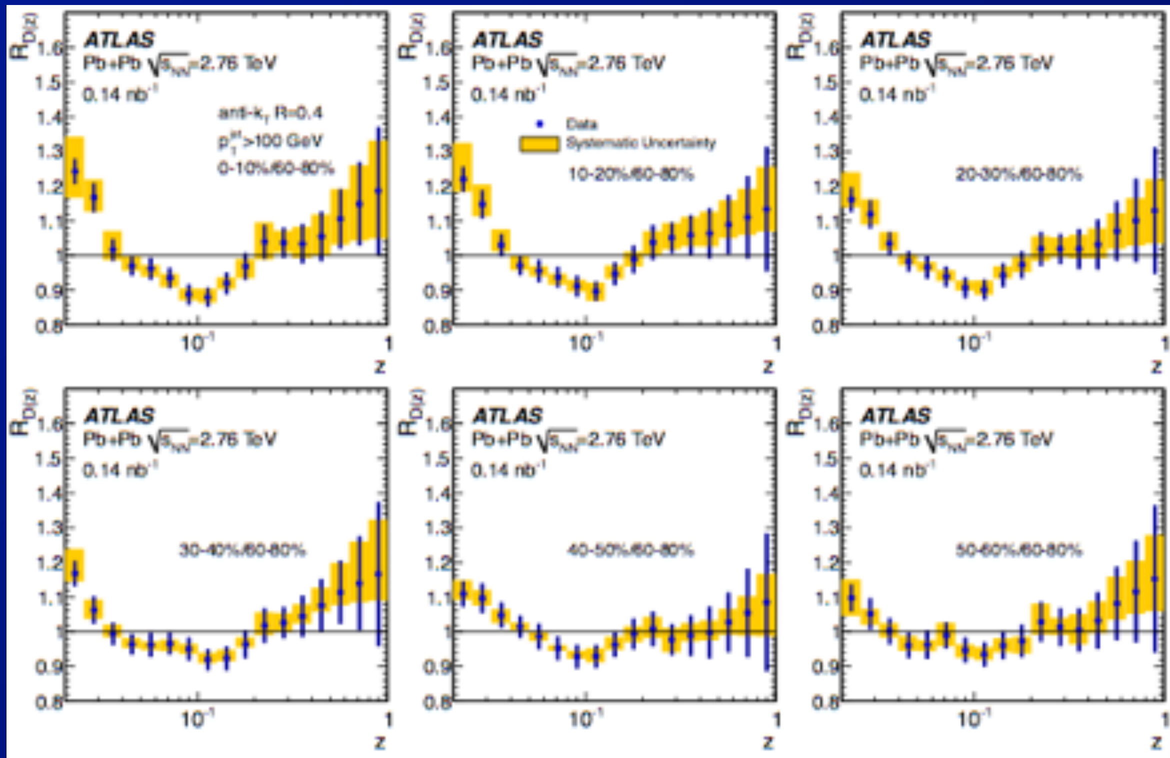


⇒ Non-trivial, as suppression depends on steepness of the jet spectrum, quark/gluon fraction -- both of which change vs rapidity

Pb+Pb fragmentation functions

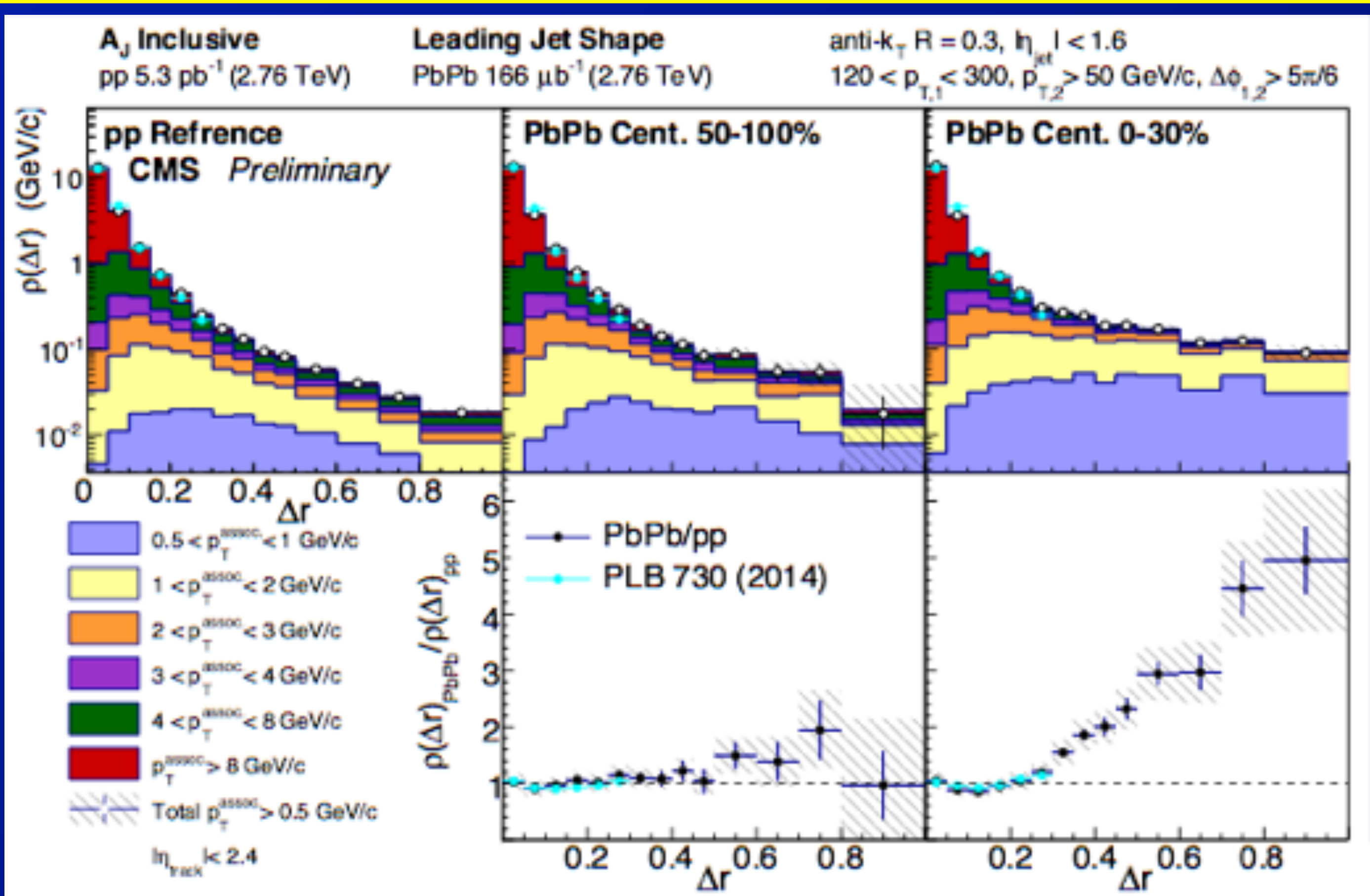


$$D(z) = \frac{1}{N_{jet}} \frac{dN_{chg}}{dz} \qquad z = \vec{p}_{chg} \cdot \vec{p}_{jet} / \left|\vec{p}_{jet}\right|^2$$



- **Measure differential, per-jet yield of charged particles within R = 0.4 of p_T > 100 GeV jets**
  - **evaluate ratios to peripheral (cancel some systematics)**
    - **⇒Complicated pattern of modification at low, high, and intermediate z.**

Pb+Pb Jet shape



Results shown for leading R = 0.3 jets with 120 < p_T < 300 GeV in dijet pairs

- **Direct measurement of fragment angular distribution**

$$\rho(r) \equiv \frac{1}{N_{jet}} \sum_{jets} \left(\frac{\sum_{r_{trk} \in \Delta r} p_T^{trk}}{\Delta r \, p_T^{jet}} \right)$$

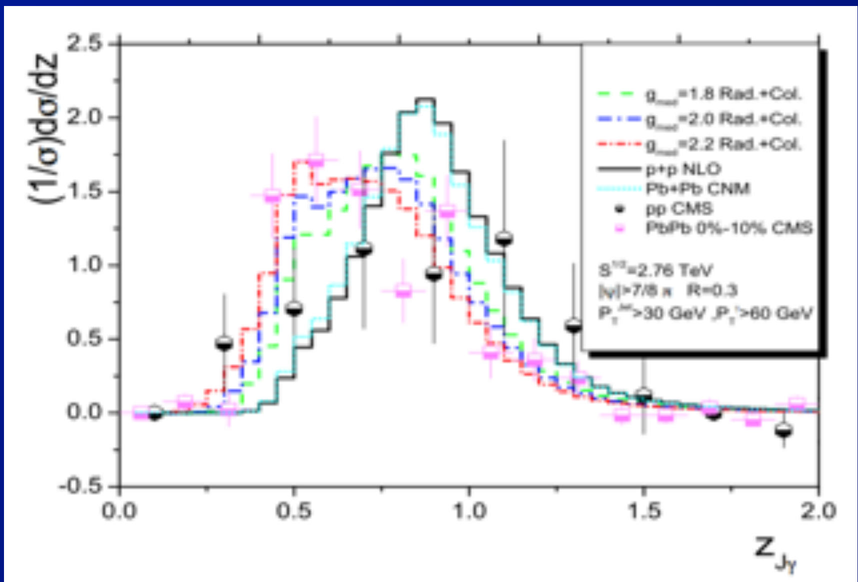
  – Pb+Pb/pp ratio shows excess energy at large angles relative to unquenched jets of same energy

  ⇒Lost energy flows to larger angles

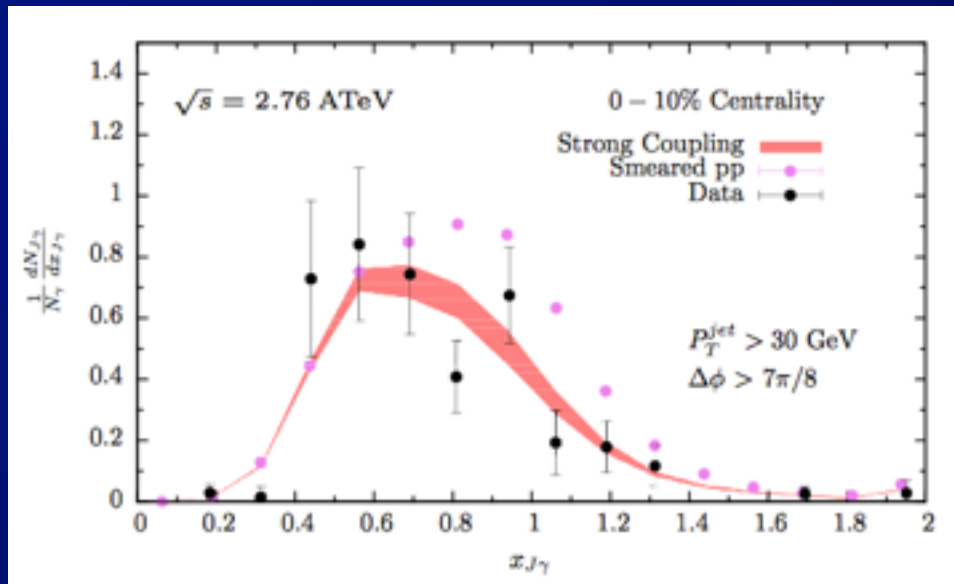
Pb+Pb Gamma-jet balance

- γ-jet measurements are considered vital for understanding jet quenching
  - Though rates are a serious limitation
    - ⇒ expect ~ x10 increase in statistics from 2015 Pb+Pb run
- Run 1 results from CMS compared to two different energy loss calculations (post-dictions):
  - beware inversion of symbol colors, different normalization

Weak coupling, Vitev et al, 10.1103/PhysRevLett.110.142001



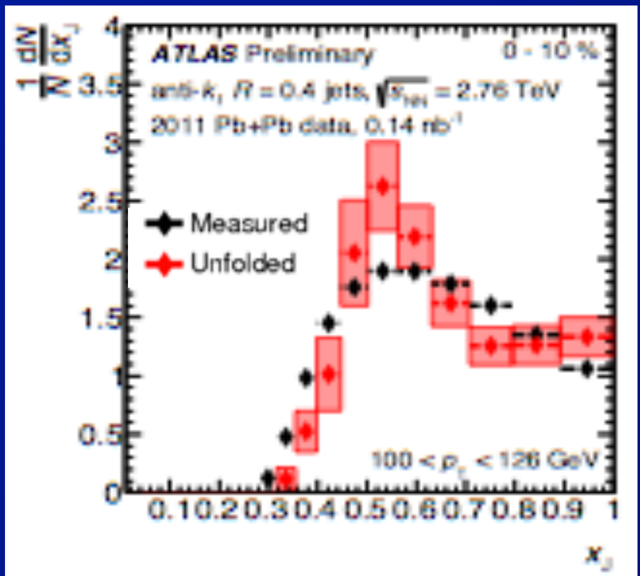
Hybrid strong & weak coupling, Casalderrey-Solana et al, arXiv:1508.00815

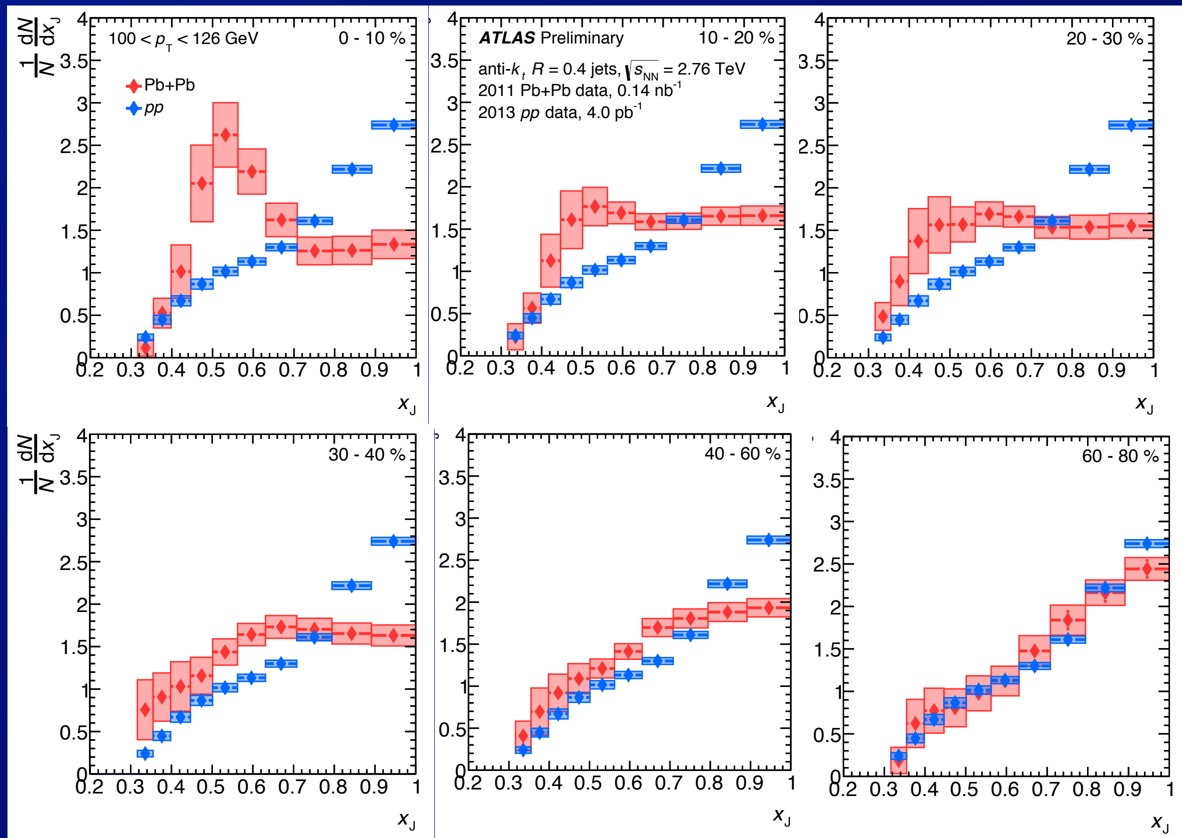


Dijet asymmetry with unfolding

- Jet energy resolution important in Pb+Pb measurements
  - Centrality-dependent UE contributions
- ATLAS presented results for Pb+Pb dijet asymmetry using 2-dimensional unfolding at Quark Matter 2015

  ⇒Should provide better tests of energy loss models





dijet $x_j = x_2/x_1$ distribution before, after unfolding in 0-10% centrality bin

Summary

- A brief overview of LHC heavy ion program focused on two major topics:
  - Long λ: Collective flow
  - Short λ: High p_T probes, jet quenching
- Collective flow
  - There has been a continual evolution in detail and sophistication of Pb+Pb measurements
    - ⇒e.g. event-by-event measurements
    - ⇒driven by and driving theoretical progress
  - Observation of flow-like behavior in p+Pb and p+p collisions has taken us all by surprise
    - ⇒Is it really (final-state) collective flow as in Pb+Pb?
    - ⇒Or an initial-state effect?
      - » Not yet clear, but similarity with Pb+Pb is striking

Summary (2)

- High-p_T probes, jet quenching
  - Measurements of electroweak bosons show that we understand hard scattering in Pb+Pb collisions.

    ⇒We aren't (yet) sensitive to nuclear PDF effects
  - Hadron and (better) jet R_{AA} measurements directly probe energy loss of the parent partons

    ⇒ quantitative/theoretical analysis of jet data needed
  - Fragmentation function measurements show complicated pattern of modifications

    ⇒ no comprehensive understanding yet (early)
  - Measurements of angular distribution show energy flows to large angles

    ⇒as expected, but detailed theoretical analysis and better/ more differential data needed
  - dijet and gamma-jet measurements important

    ⇒ statistics (Run 2) and jet response potential limitations