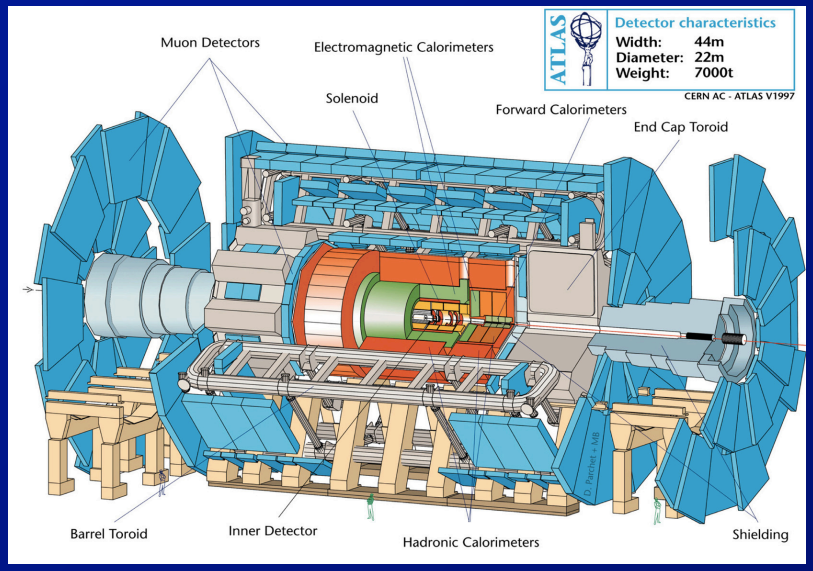
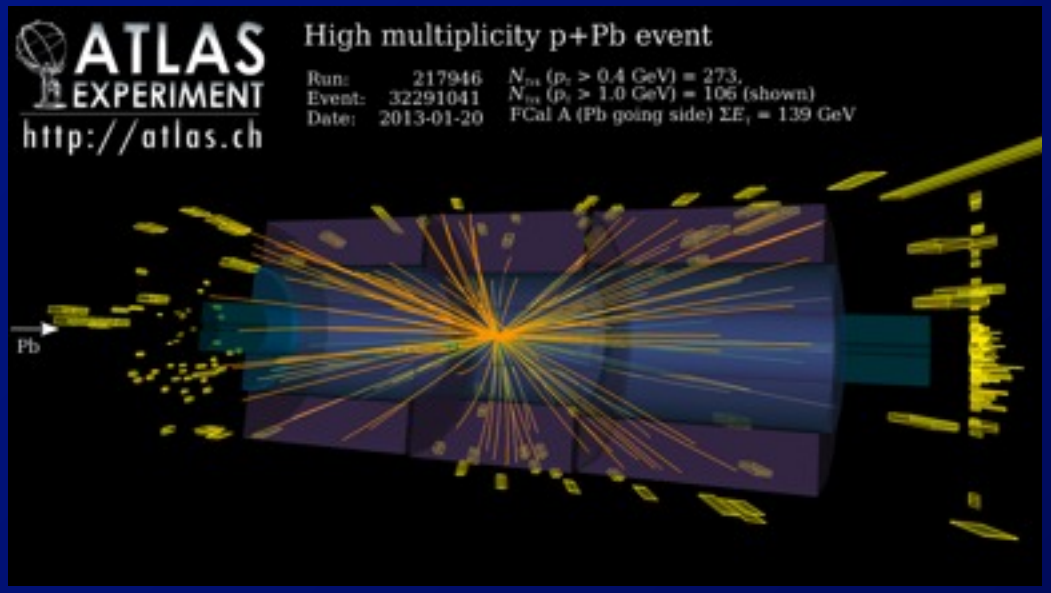
Soft and Hard QCD in proton-nucleus collisions at the LHC

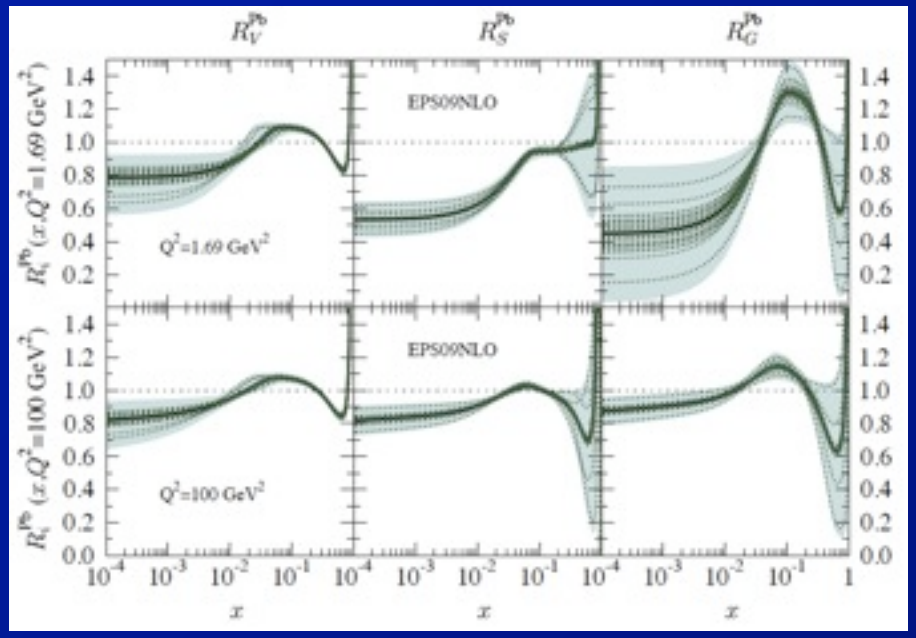
Prof. Brian A. Cole
Columbia University

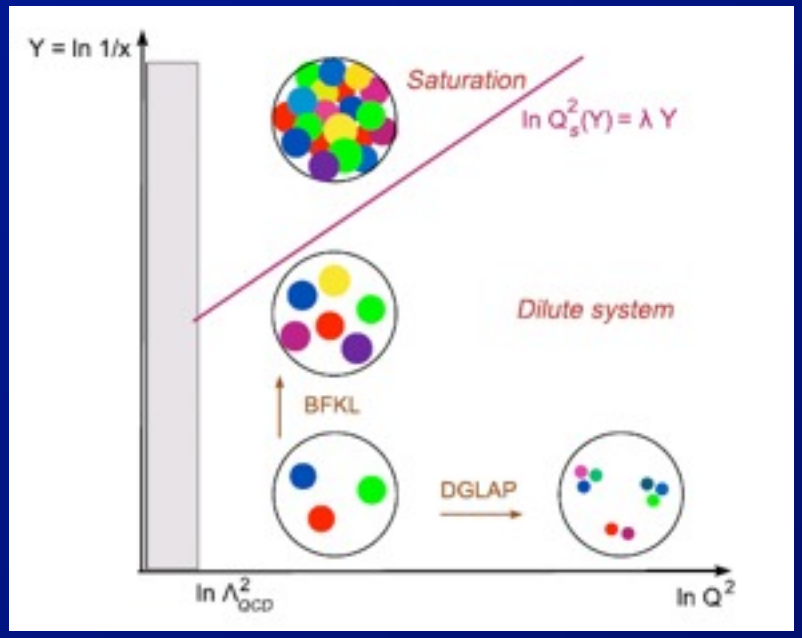
for the ATLAS collaboration





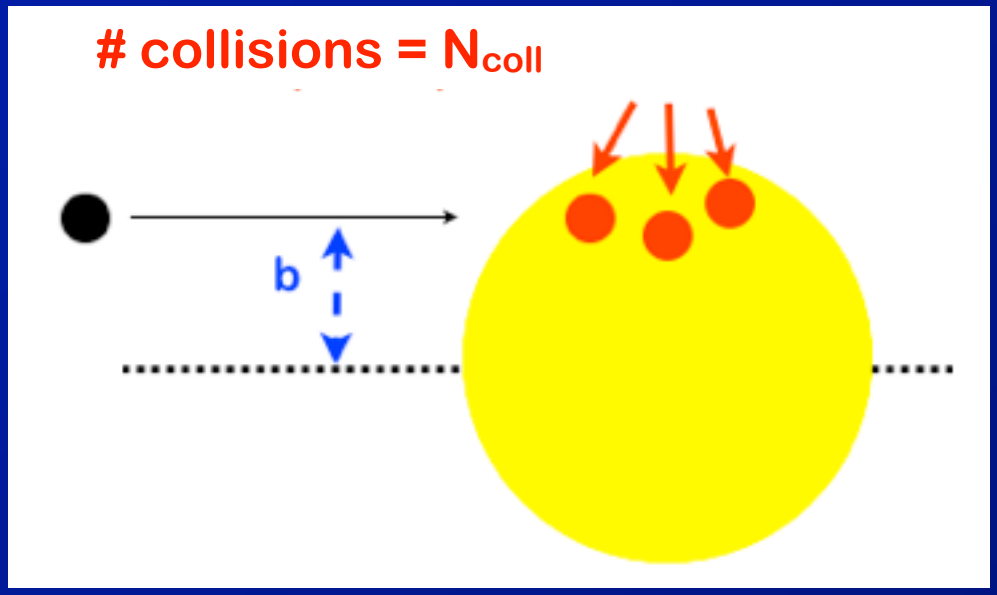
p-A collisions: goals

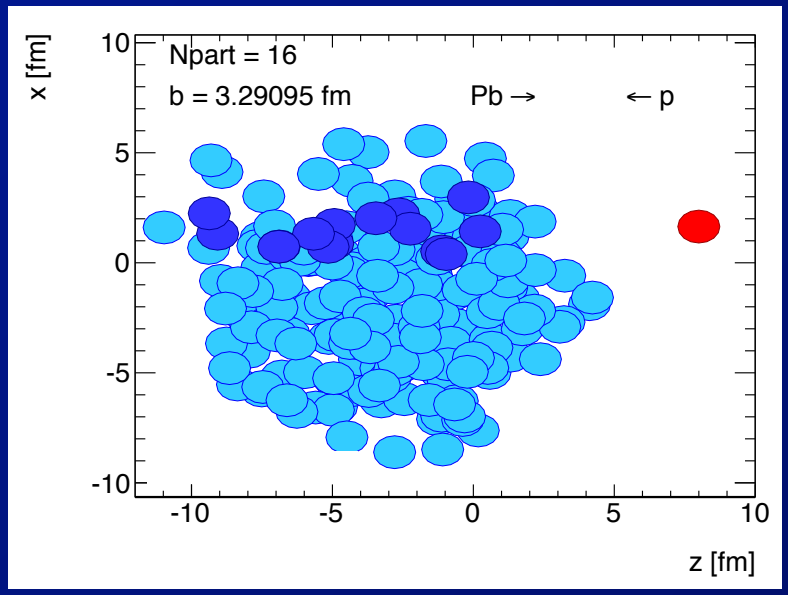




- Probe nuclear PDFs
  - ⇒ But not with precision of DIS
- Study saturation effects at low x
- Probe initial- or final-state parton interactions in nucleus.
  - ⇒probe factorization breaking in hard-scattering processes due to nucleus
- Note: initial goals focused on hard processes …

proton-nucleus collisions: Geometry





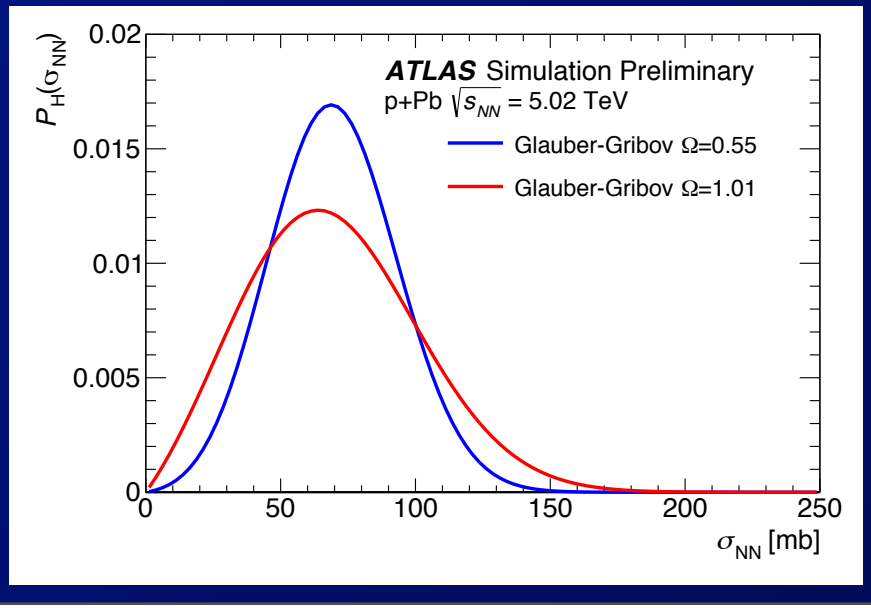
- **p+Pb collisions controlled by geometry**
  - Impact parameter (b)
  - Or number of soft scatterings in the nucleus
    - ⇒Number of participants: $N_{part} = N_{coll} + 1$
- **Can be estimated using Glauber model**
  - Semi-classical, Eikonal model
  - Key parameter is nucleon-nucleon σ_{inel}

Glauber-Gribov model

- Several authors have argued that the Glauber model needs correction @ high energy
  - due to off-shell intermediate states
    - ⇒included in Glauber-Gribov framework
- Particular Glauber-Gribov model:
  - Color-fluctuation model (Strikman et al)
    - ⇒Fluctuations in proton color configuration, frozen during collision, changing σ_{inel},
- Model assumption:

$$P(\sigma_{tot}) = \rho \left(\frac{\sigma_{tot}}{\sigma_{tot} + \sigma_0} \right) \exp\left\{ -\frac{(\sigma_{tot}/\sigma_0 - 1)^2}{\Omega^2} \right\}$$

  - Ω can be estimated from p-p diffraction data:
    - ⇒ Ω = 0.55 - 1



Soft physics

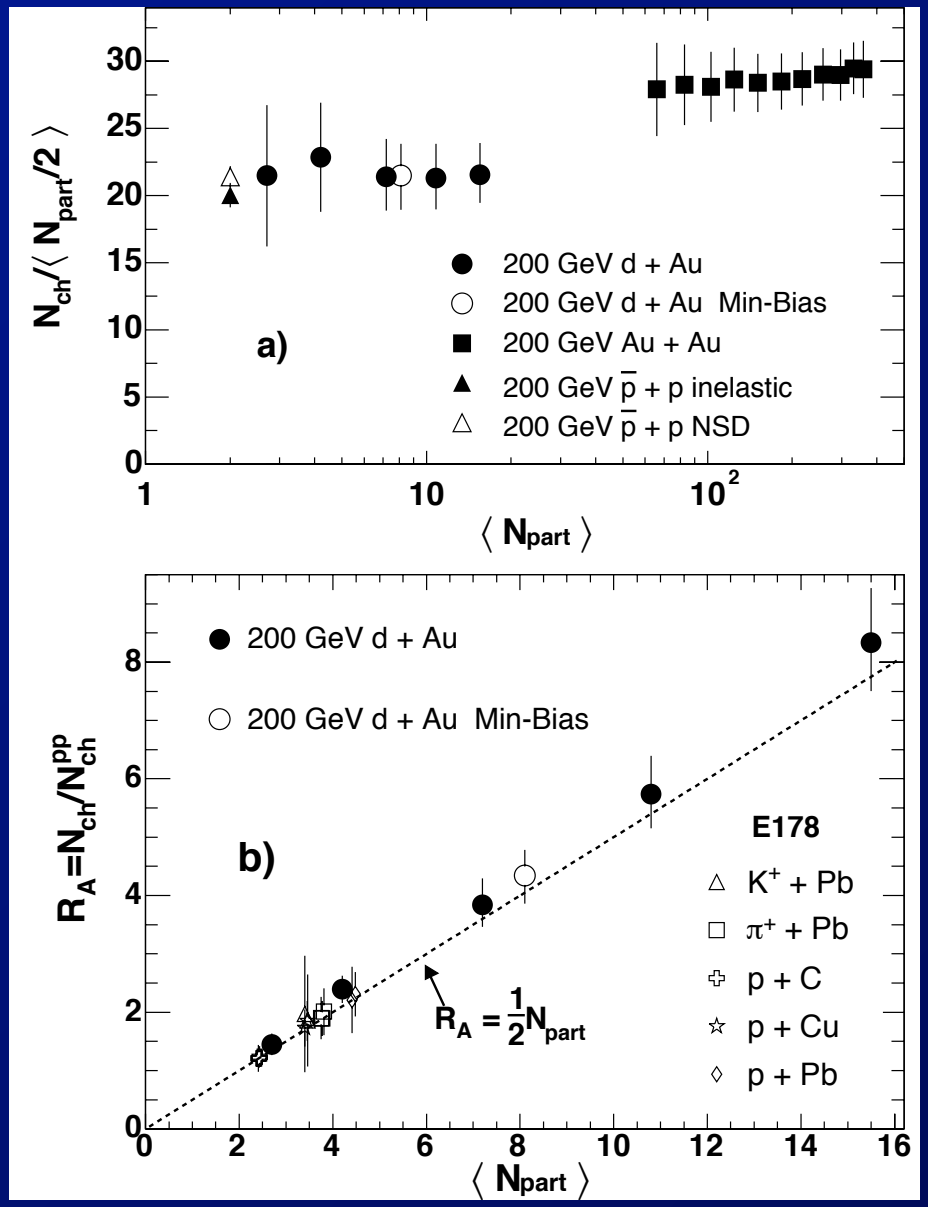
Soft production, N_{part} scaling

- ~ 30 years of soft particle production phenomenology:
  - particle multiplicities in p+A, A+A collisions increase $\propto N_{part}$
  - For fixed-target h+A and d+Au at RHIC.

    ⇒Consequence of the coherence of soft multiple scattering (time dilation)
- New physics at LHC energies

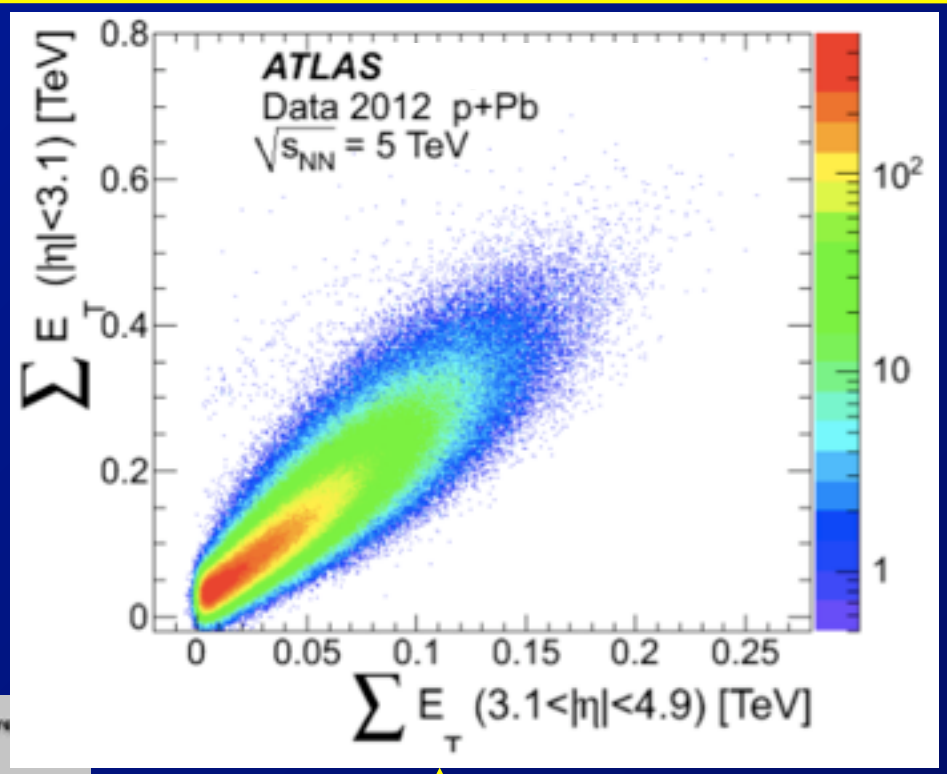
  ⇒e.g. saturation?

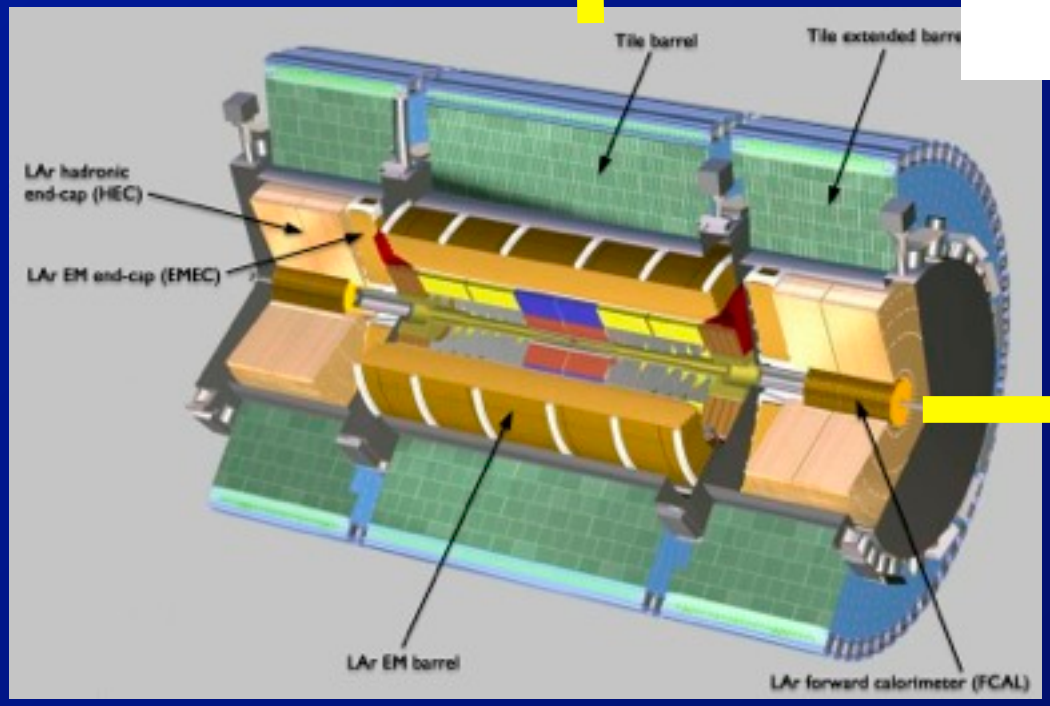
from PHOBOS experiment at RHIC



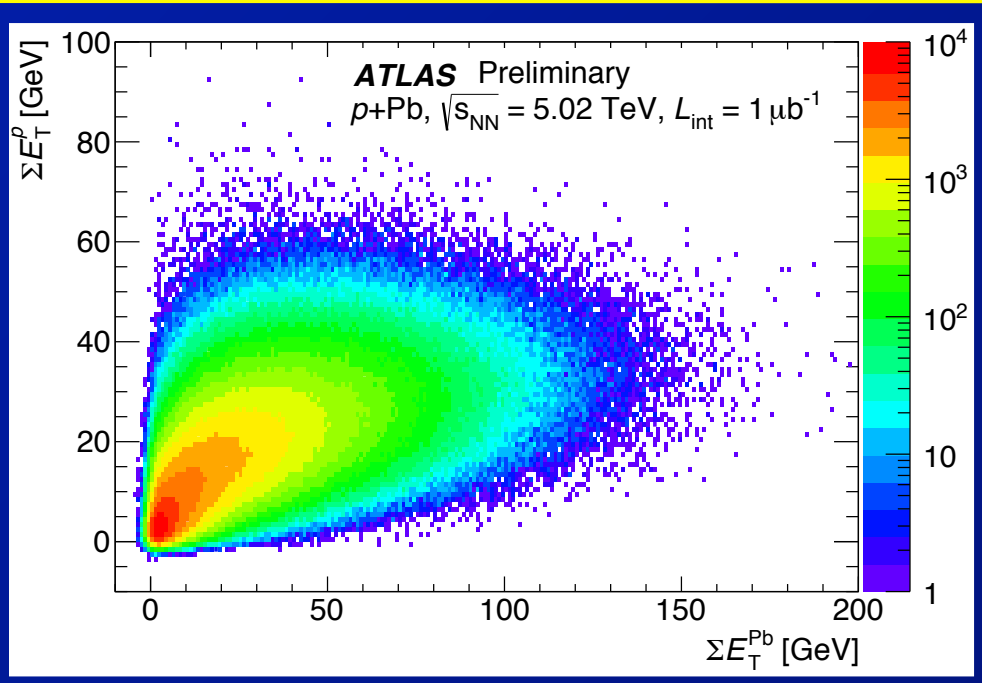
p+Pb E_T measurement

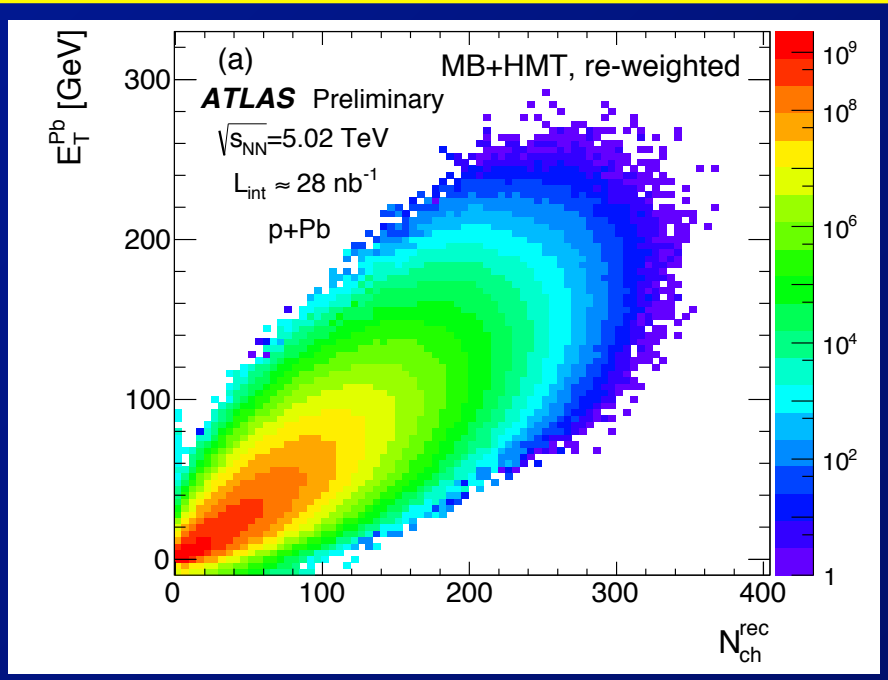
Use extended coverage of the ATLAS calorimeter, measure event ΣE_T instead of multiplicity





p+Pb event activity/centrality

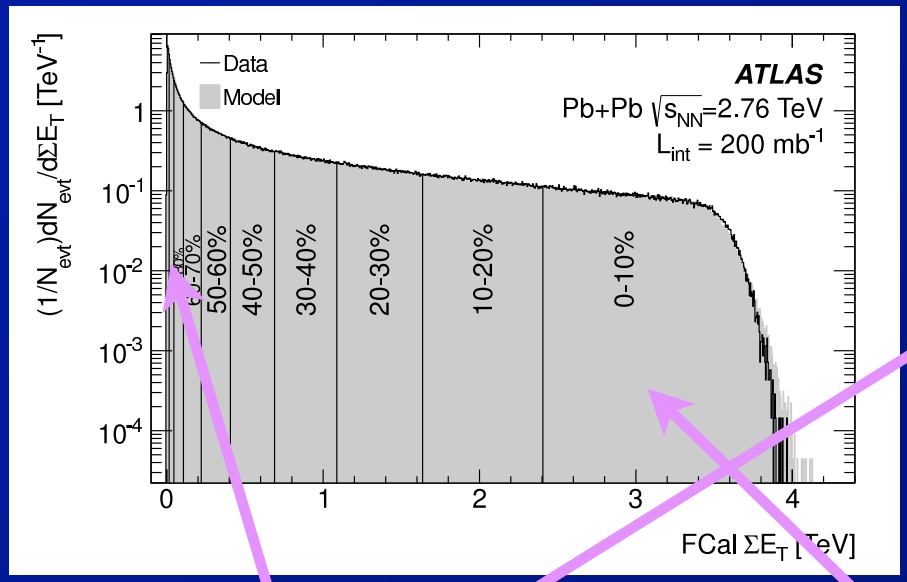




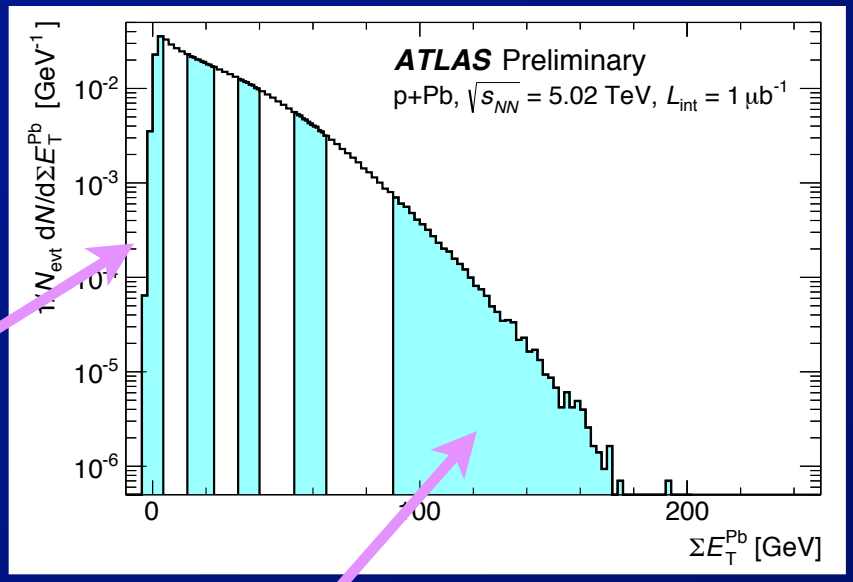
- **Forward (p)-backward (Pb) E_T correlation**
  - ⇒backward direction more sensitive to effects of the proton multiple scattering in nucleus
- **Clear correlation between charged particle multiplicity ($|\eta| < 2.5$) and E_T^{Pb} ($-4.9 < \eta < -3.2$)**
  - But much weaker than in Pb+Pb collisions

Centrality in Pb+Pb, p+Pb

$3.2 < |\eta| < 4.9$



$-4.9 < \eta < -3.2$

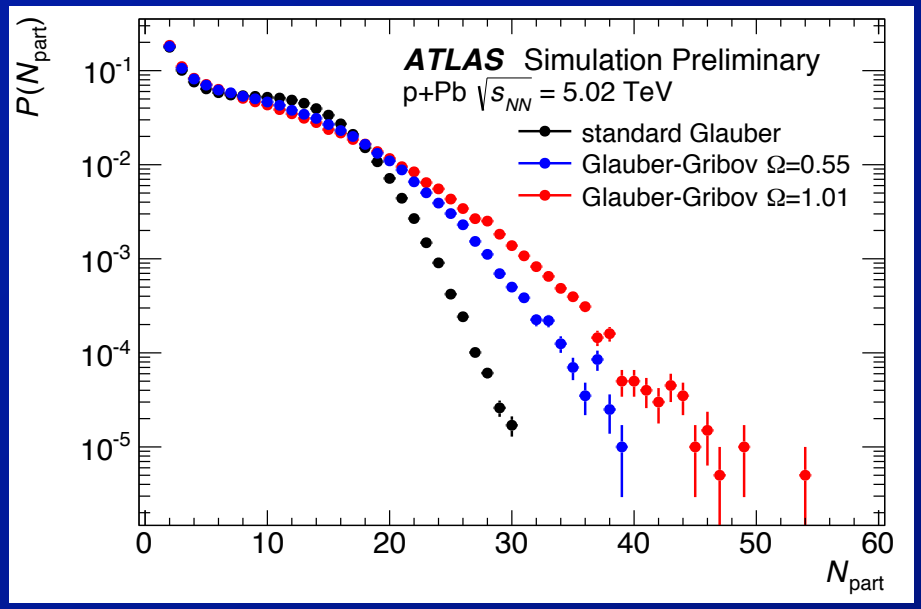


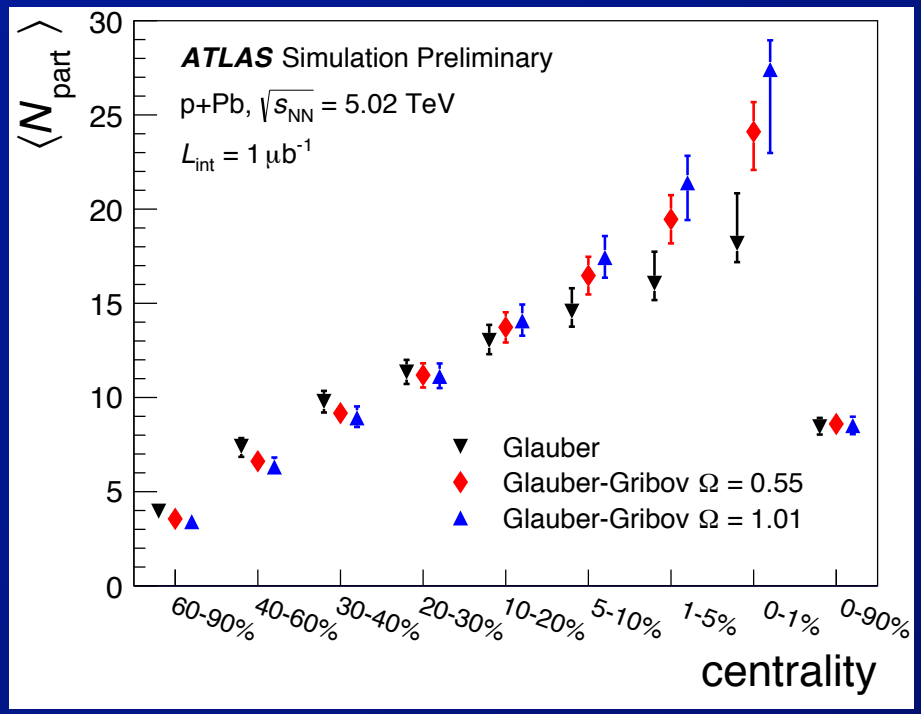
peripheral

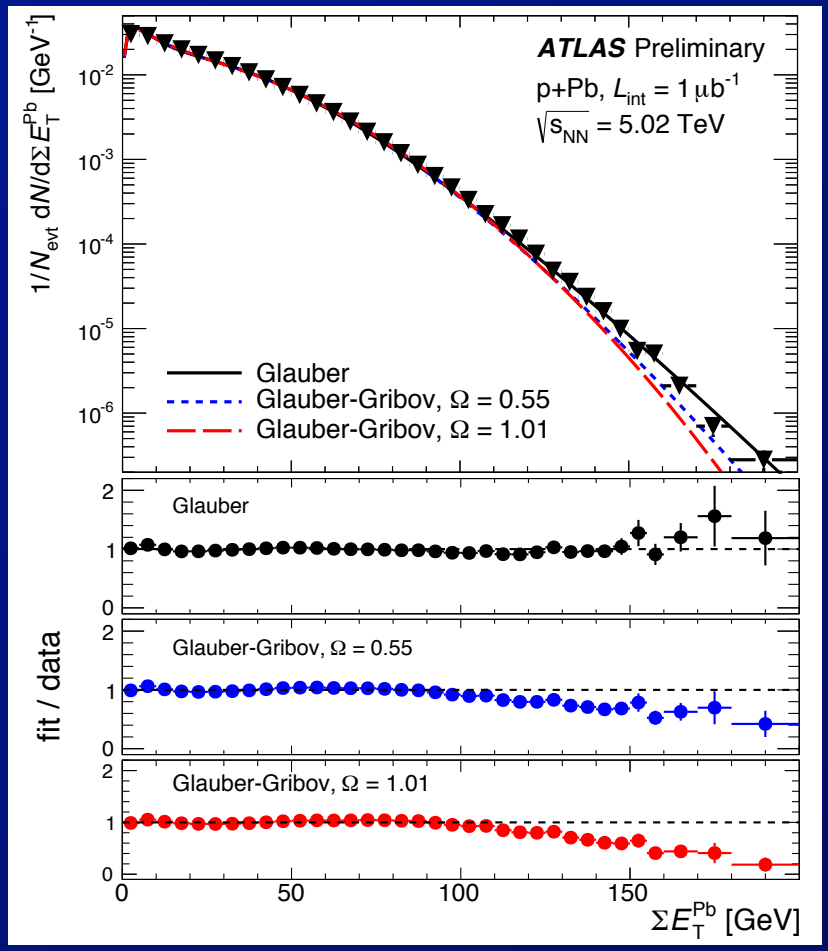
central

- **Measured using forward calorimeter(s)**
  - ⇒In p+Pb, on Pb-going side only
- **Centrality:**
  - percentile divisions of distributions
    - ⇒Smaller → higher E_T, smaller b, more central

p+Pb Glauber (Gribov) analysis



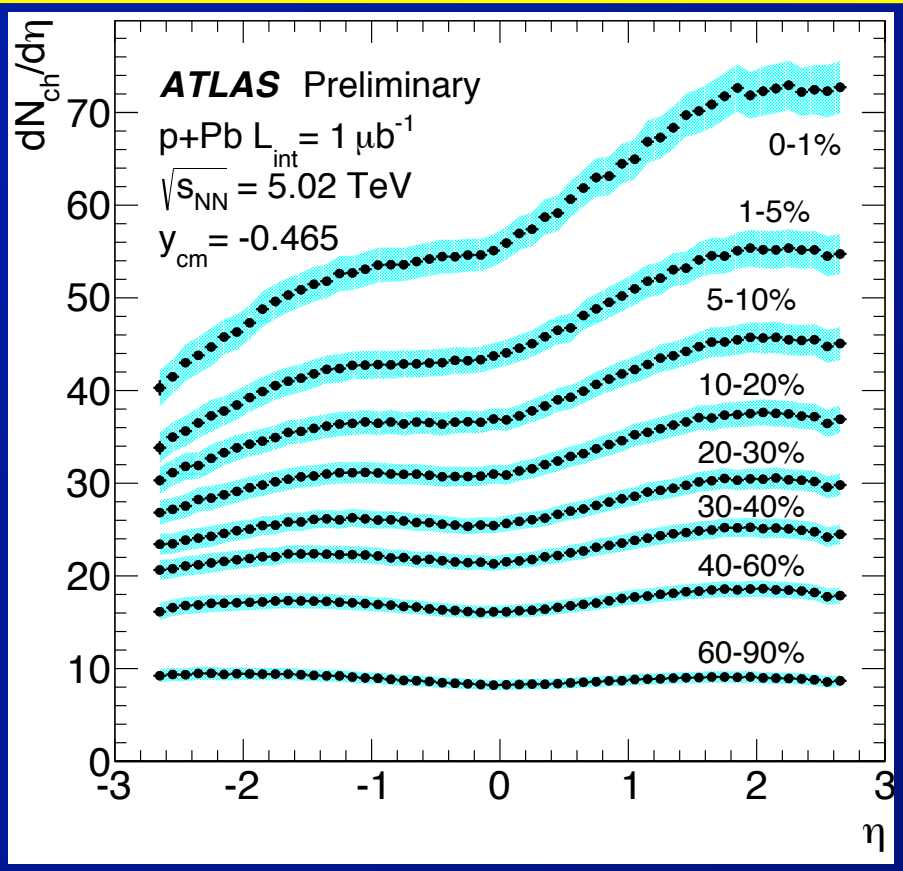


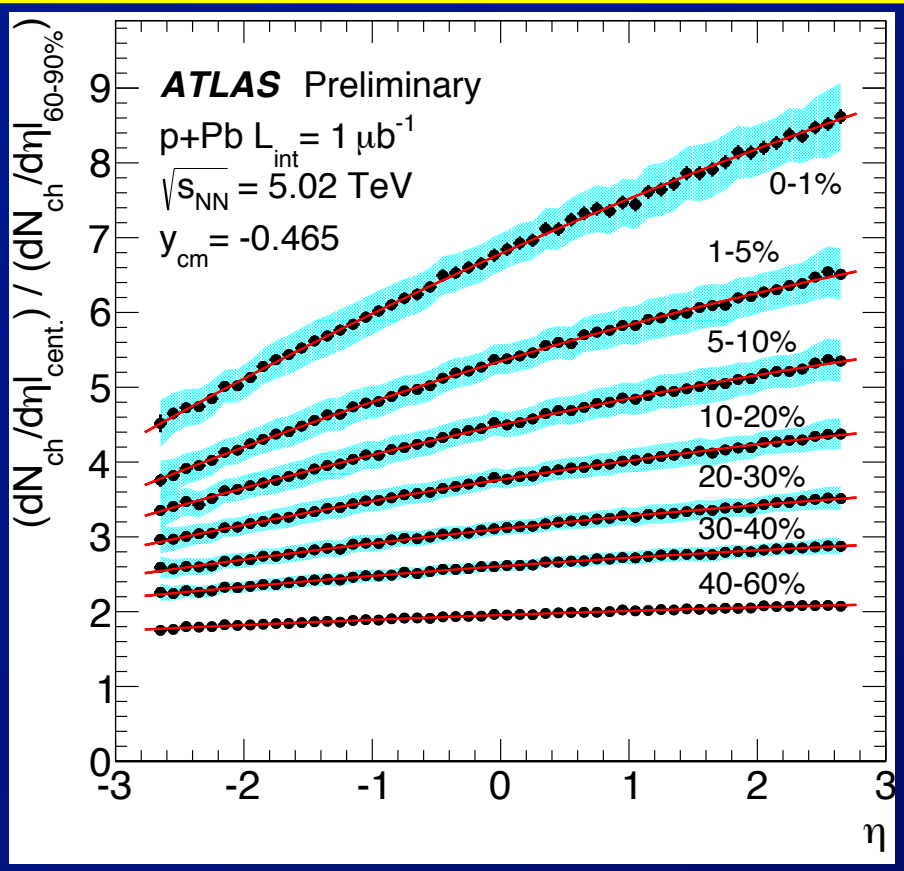


- GG color-fluctuation model significantly broadens $P(N_{part})$

  ⇒changes estimated ⟨Npart⟩ vs centrality

ATLAS p+Pb dN/dη



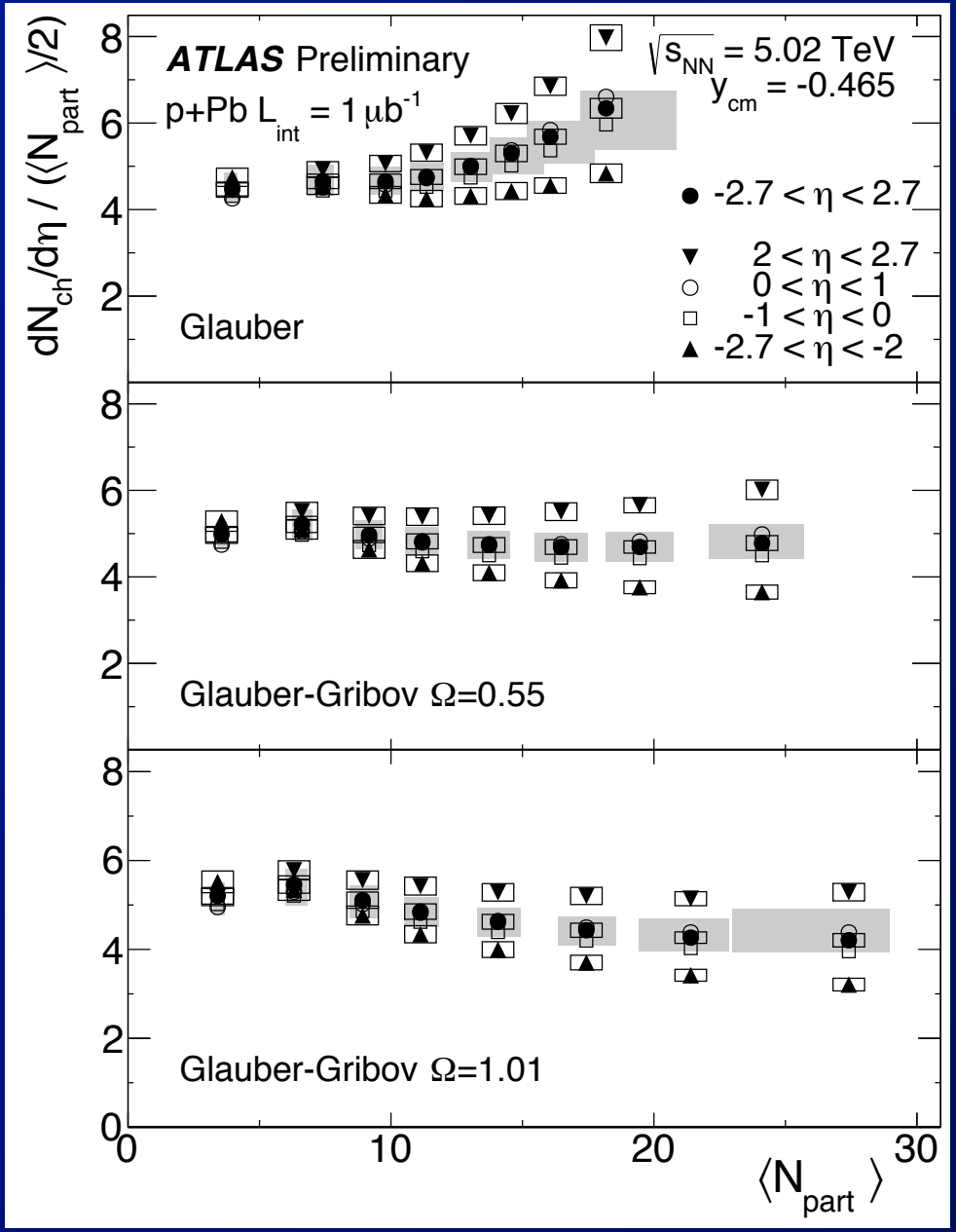


- **Centrality dependence of dN/dη (left) and ratio to most peripheral (right)**
  - **Rapid growth in multiplicity at all η**
    - ⇒ **Especially in the most central bin**
    - ⇒ **But, largest increase is in Pb-going direction**

ATLAS p+Pb dN/dη

- Evaluate per-participant pair multiplicity as a function of N_{part}
  - Pure Glauber shows a rapid growth vs N_{part} in central collisions
  - Glauber-Gribov with $\Omega = 0.55$ compatible with N_{part} scaling

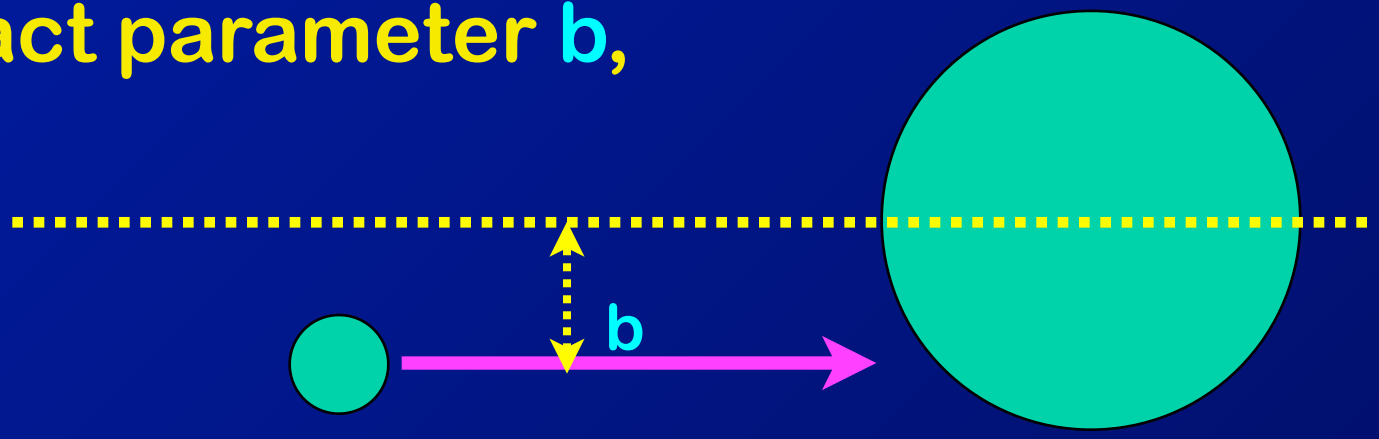
⇒Cannot yet determine whether N_{part} scaling observed at lower energy persists @ LHC



Hard processes

p-A: nuclear geometry

- Starting point, nuclear nucleon density distribution: $\rho(r)$
- Then, assuming straight-line trajectory at impact parameter b,



  - electron or proton passes through "thickness"

$$T(b) = \int_{-\infty}^{\infty} dz\, \rho(\sqrt{b^2 + z^2})$$

- *T(b)* has dimensions $1/L^2$
  - *T(b)* x cross-section = # of something

$\Rightarrow$e.g. $N_{coll} = T(b)\sigma_{inel}$

p-A: nuclear geometry

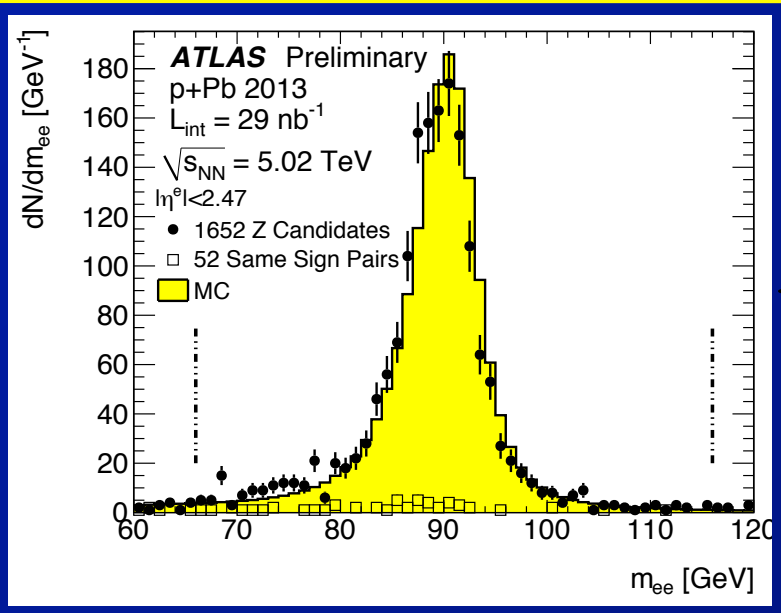
- Then, hard processes occur in p-A collisions at a rate/event:
  - $$E\frac{d^3n^{pA(b)}}{dp^3} = T(b) \times E\frac{d^3\sigma^{pp}}{dp^3}$$
  - Assuming factorization
  - Neglecting nuclear PDF modifications
- Measure deviation from naive expectation

$$\Rightarrow R_{pPb} \equiv \frac{1}{T_{Pb}}\frac{dn_{pPb}/dp_T}{d\sigma_{pp}/dp_T}$$

- Sometimes useful to compare central and peripheral:

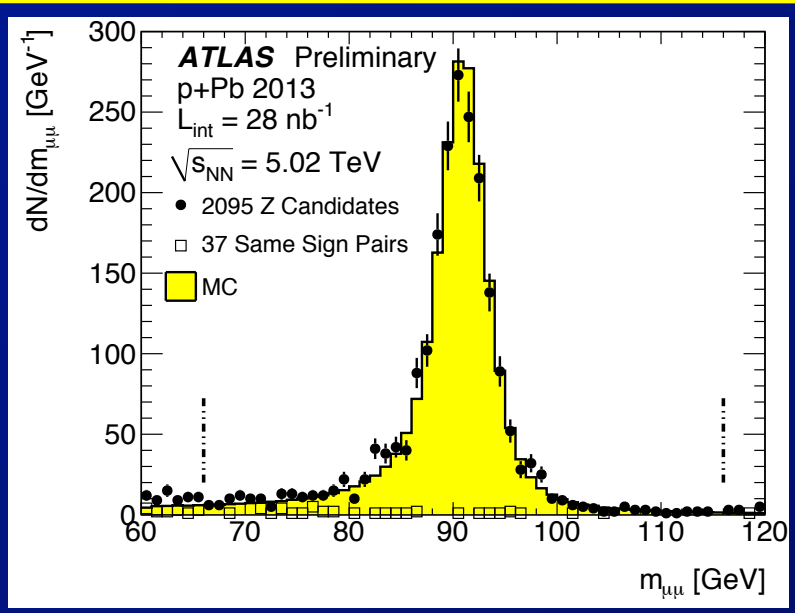
$$\Rightarrow R_{\mathrm{CP}} = \frac{N_{\mathrm{coll}}^{\mathrm{periph}}}{N_{\mathrm{coll}}^{\mathrm{cent}}}\frac{dn/dp_{\mathrm{T}}|_{\mathrm{cent}}}{dn/dp_{\mathrm{T}}|_{periph}}$$

Z production in p+Pb

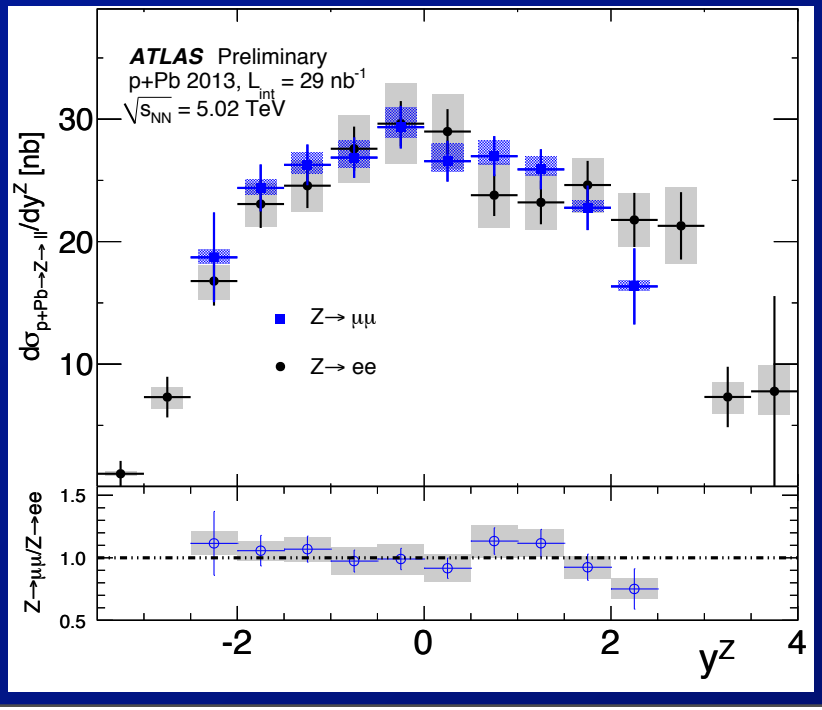


$Z \rightarrow e^+e^-$

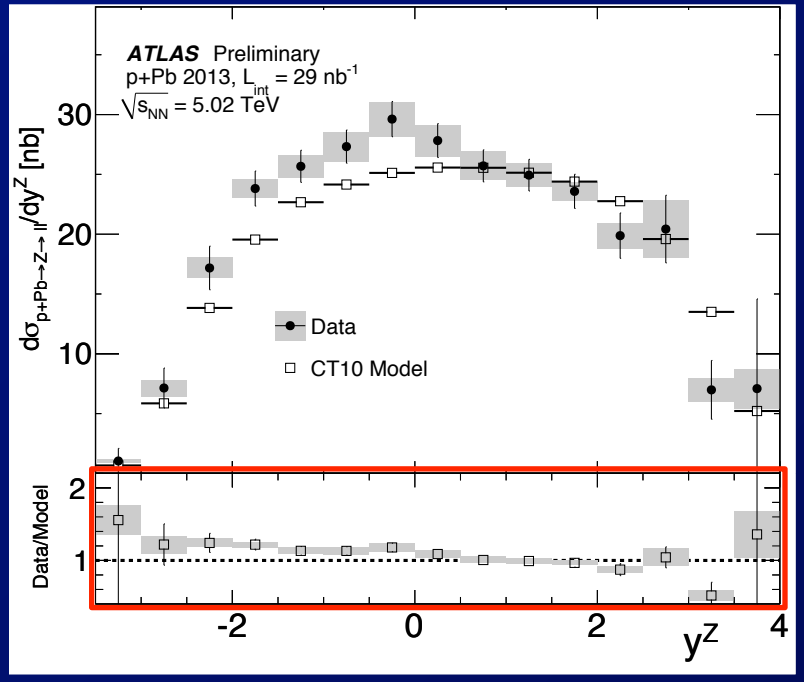
$Z \rightarrow \mu^+\mu^-$



Inclusive cross-sections

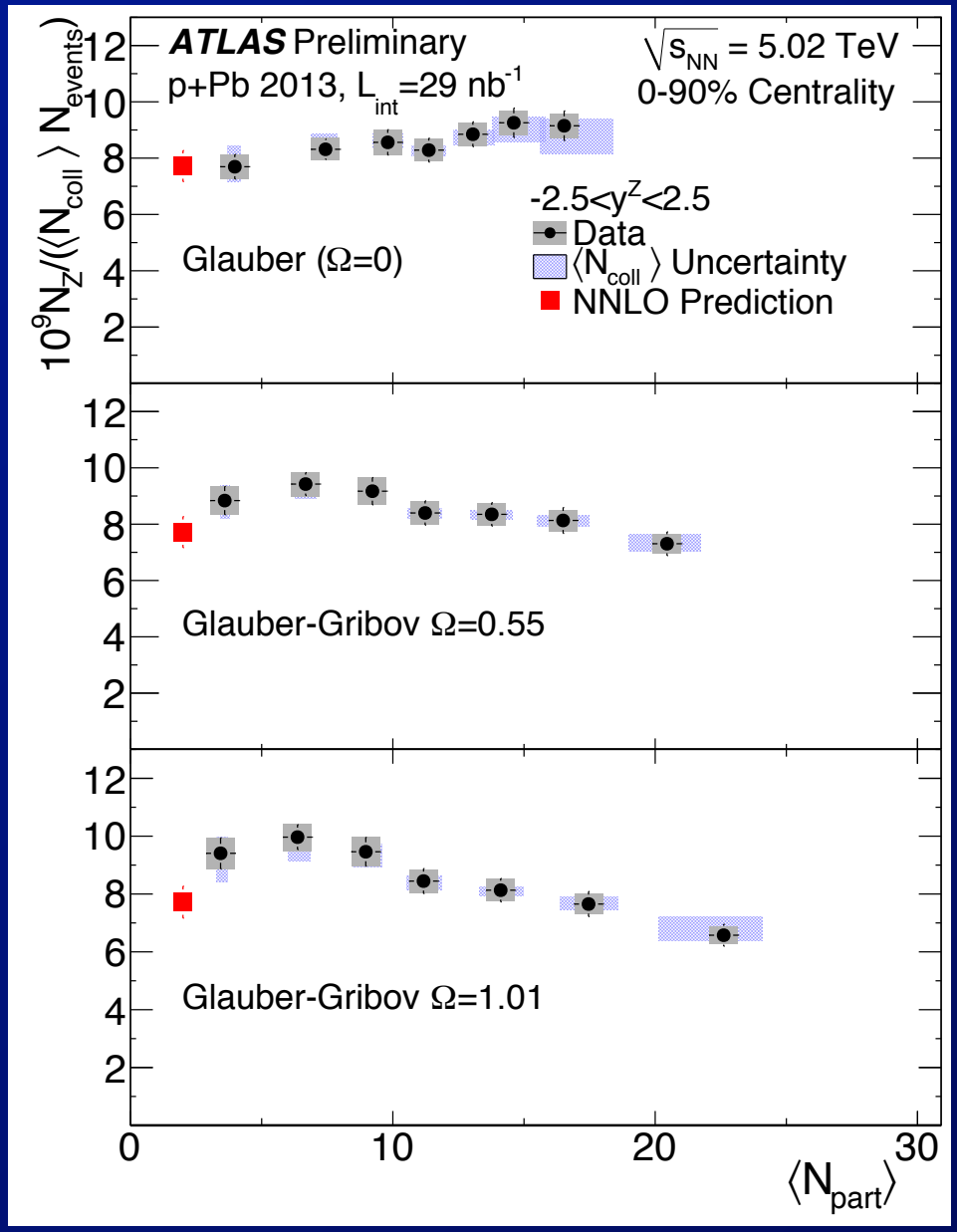


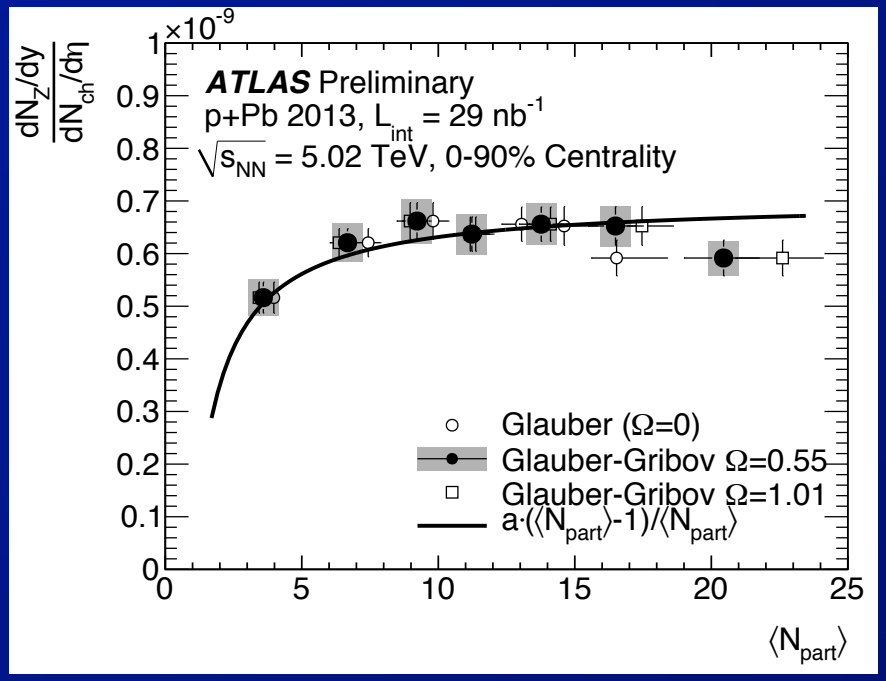
Combined cross-section



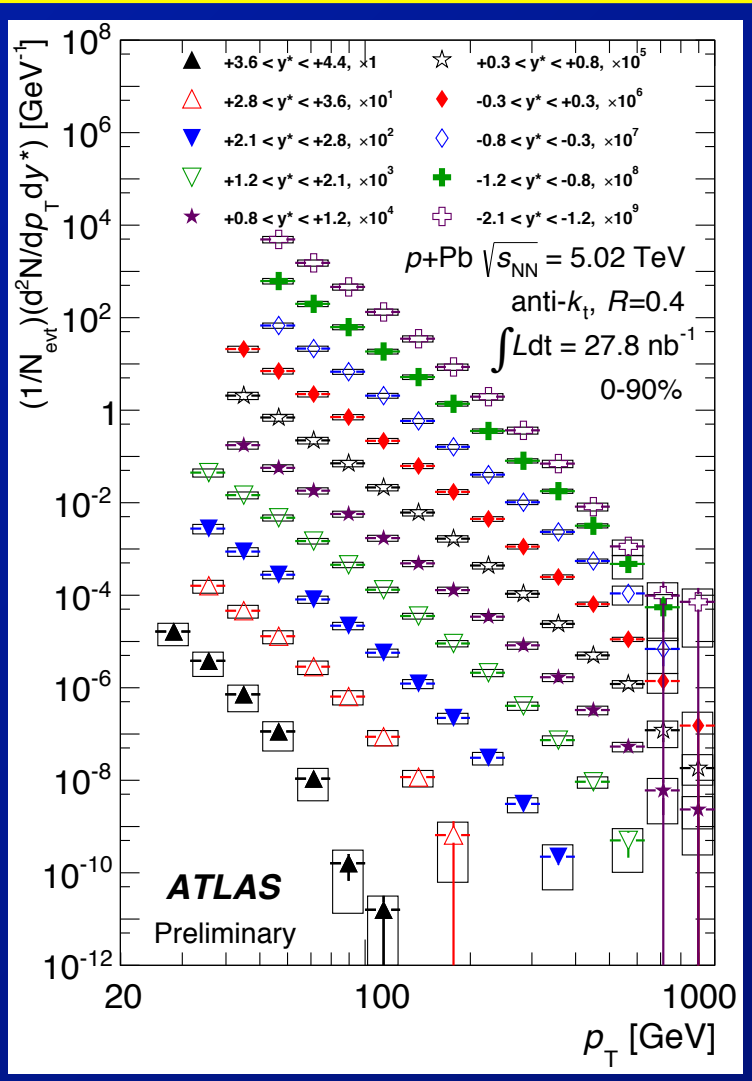
p+Pb Z yields vs centrality

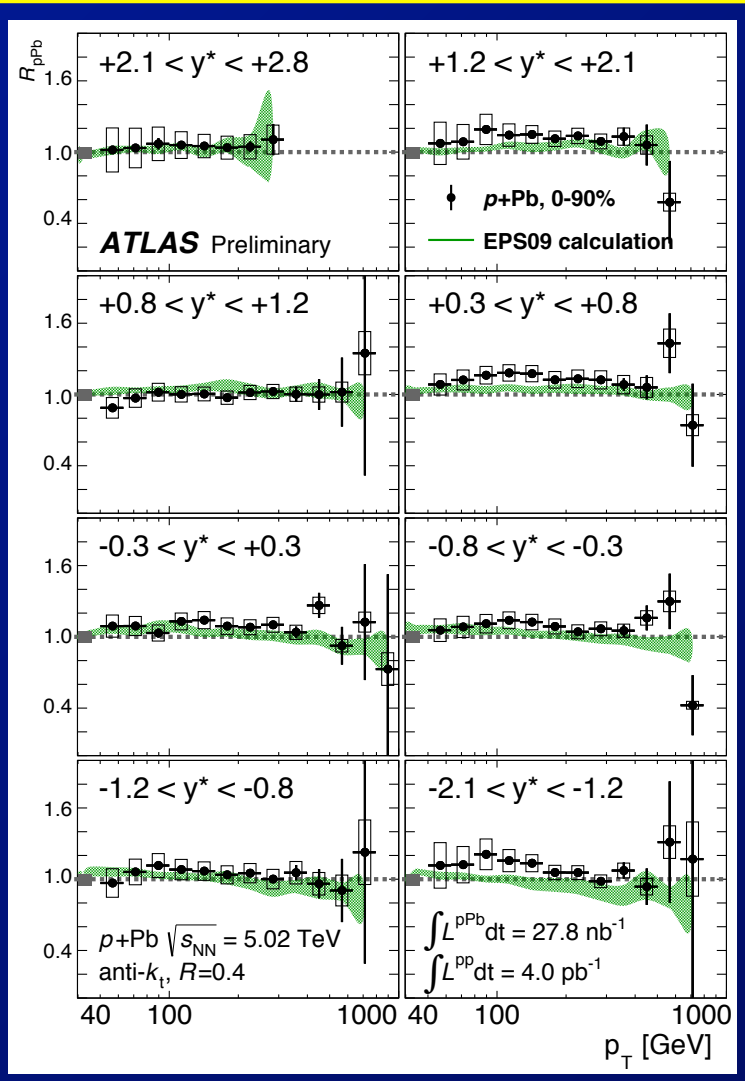
- Evaluate Z yields/N_{coll} vs centrality (N_{part})
  - sensible results for Glauber, GG Ω = 0.55
- Ratio of Z and charged particle yields consistent with $\frac{\langle N_{part}-1\rangle}{\langle N_{part}\rangle}$





p+Pb Jet production





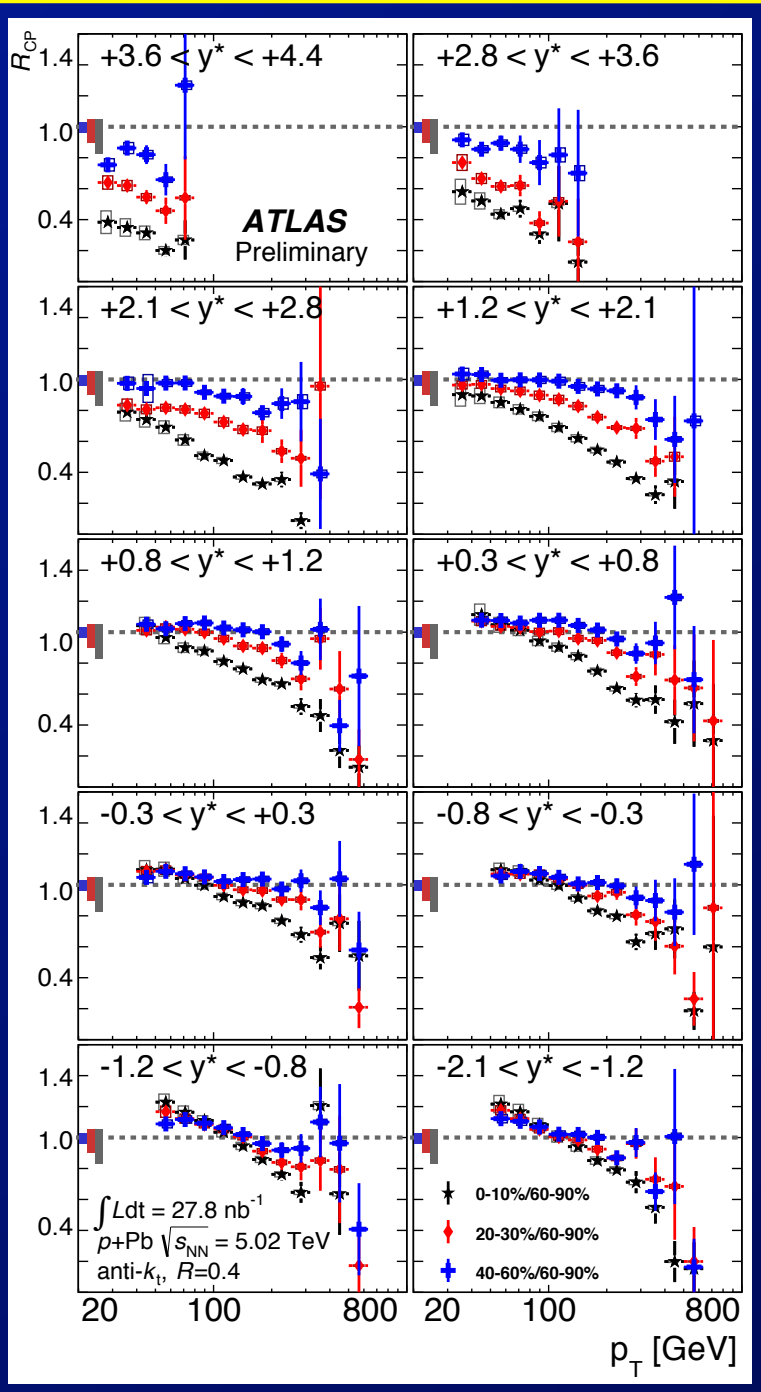
- **Inclusive jet yields (left) and jet R_{pPb} (right)**
  - compared to pQCD w/ EPS09 (Armesto)
    - ⇒Generally good agreement.

Jet R_{CP}

- Inclusive jet production agrees with pQCD
  - Does the centrality dependence make sense?
  - e.g. the Z results above.
- Study R_{CP} using the full ATLAS calorimeter

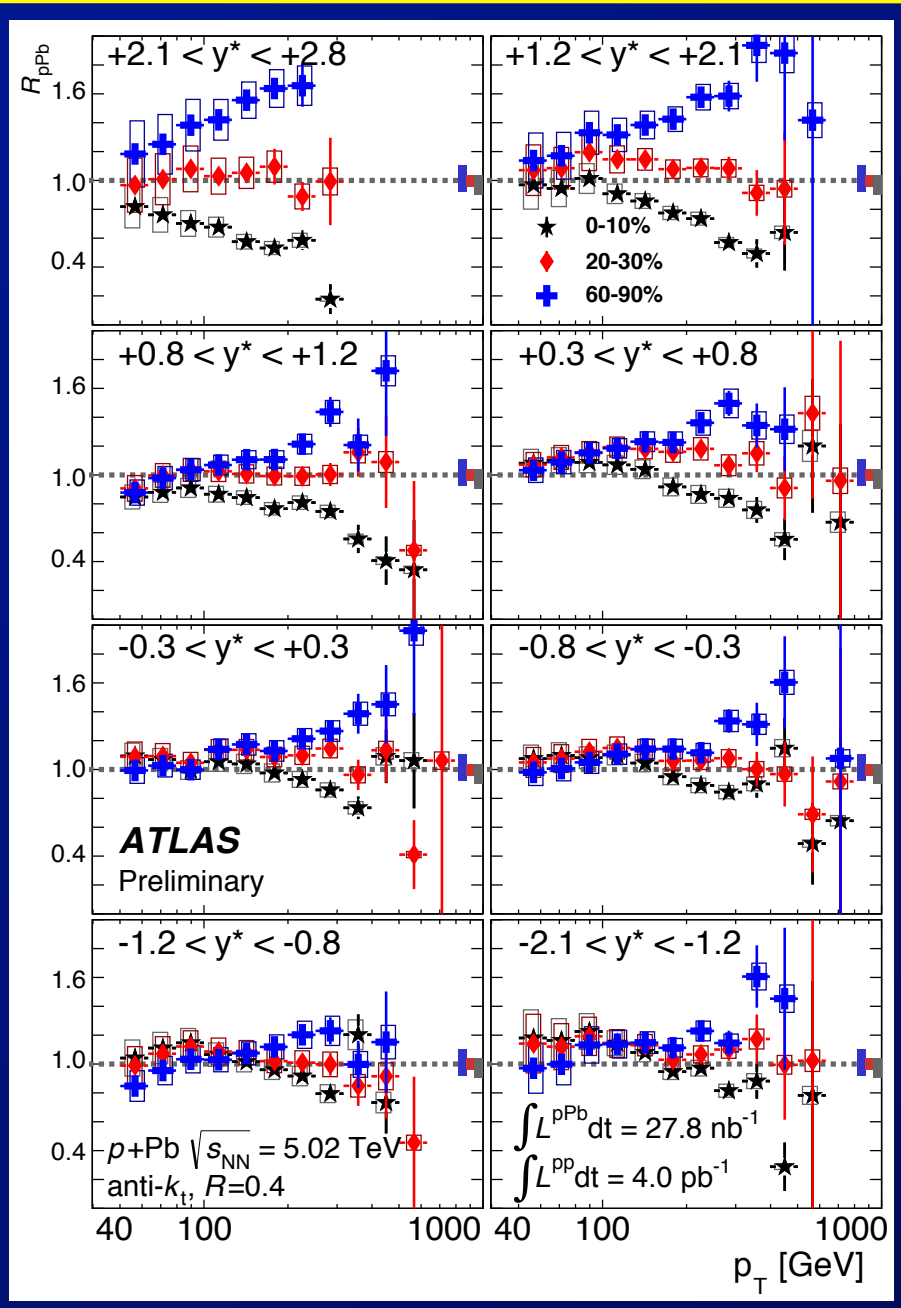
$$R_{\mathrm{CP}} = \frac{N_{\mathrm{coll}}^{\mathrm{periph}}}{N_{\mathrm{coll}}^{\mathrm{cent}}} \frac{dn/dp_{\mathrm{T}}|_{\mathrm{cent}}}{dn/dp_{\mathrm{T}}|_{periph}}$$

- @ moderate pT, mid-rapidity and backward
  - ⇒ Results make sense
- But @ higher p_T, forward
  - ⇒ Strong reduction ??

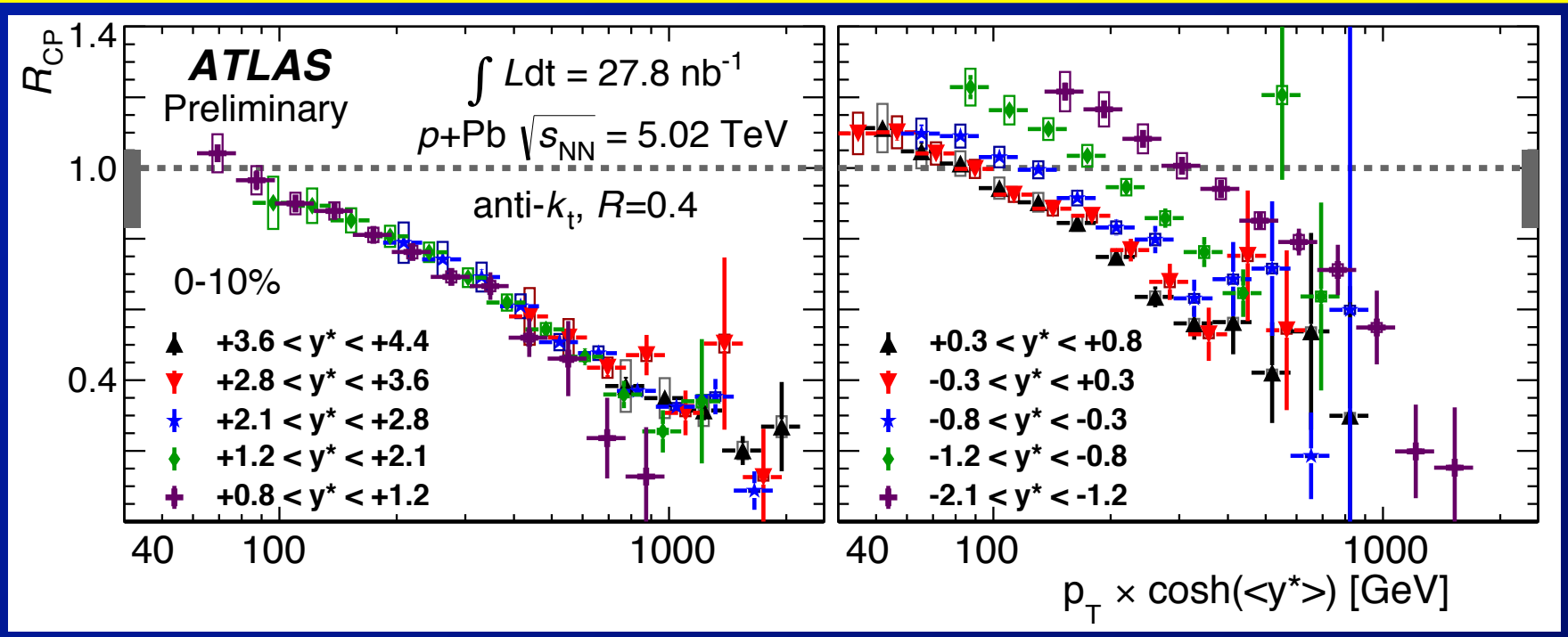


Jet R_{pPb}

- If inclusive R_{pPb} ~ 1 and R_{CP} shows such effects, necessarily
  - peripheral enhancement
  - central suppression
    - ⇒Exactly what we observe in the R_{pPb}
    - ⇒?!??
- This was also observed in preliminary PHENIX jet measurement.



Plot vs jet energy

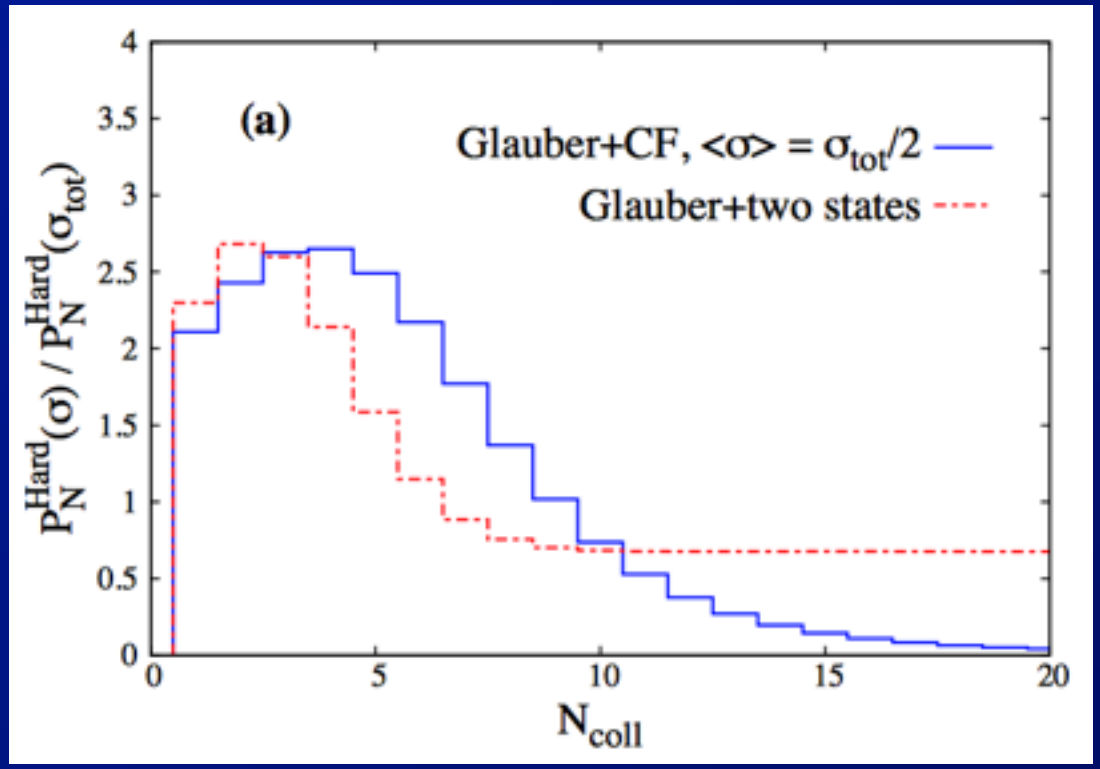


- When plotted vs $E = p_T \cosh(y)$:
  - forward results fall on a single curve.
  - But not mid-rapidity or backward
    - ⇒Suggests that the forward centrality variation is due to the x_p of the parton from the proton

p+Pb jets: geometric explanation?

Alvioli, Frankfurt, Strikman arXiv:1402.2868

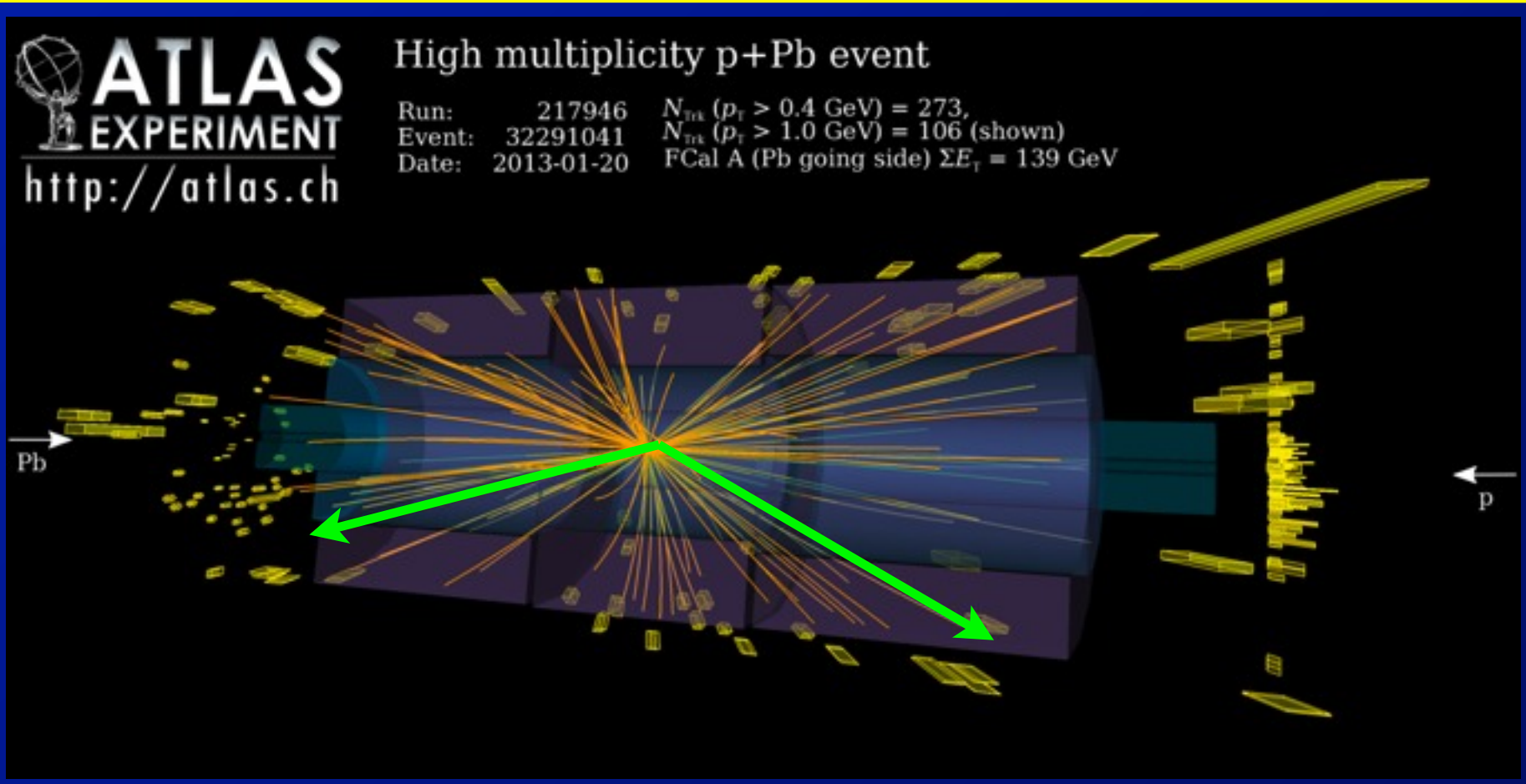
- Proton spatial configuration (size) depends on x of quark entering hard scattering
  - ⇒protons w/ large(r) *x* partons have a reduced soft cross-section



- Calculation:
  - Reduced cross-section for proton shifts N_{coll} distribution to smaller values
    - ⇒Suggestive, but conditional probabilities are "backwards" compared to data …
    - ⇒Calculation analogous to data underway.

Soft physics reprise: two-particle correlations

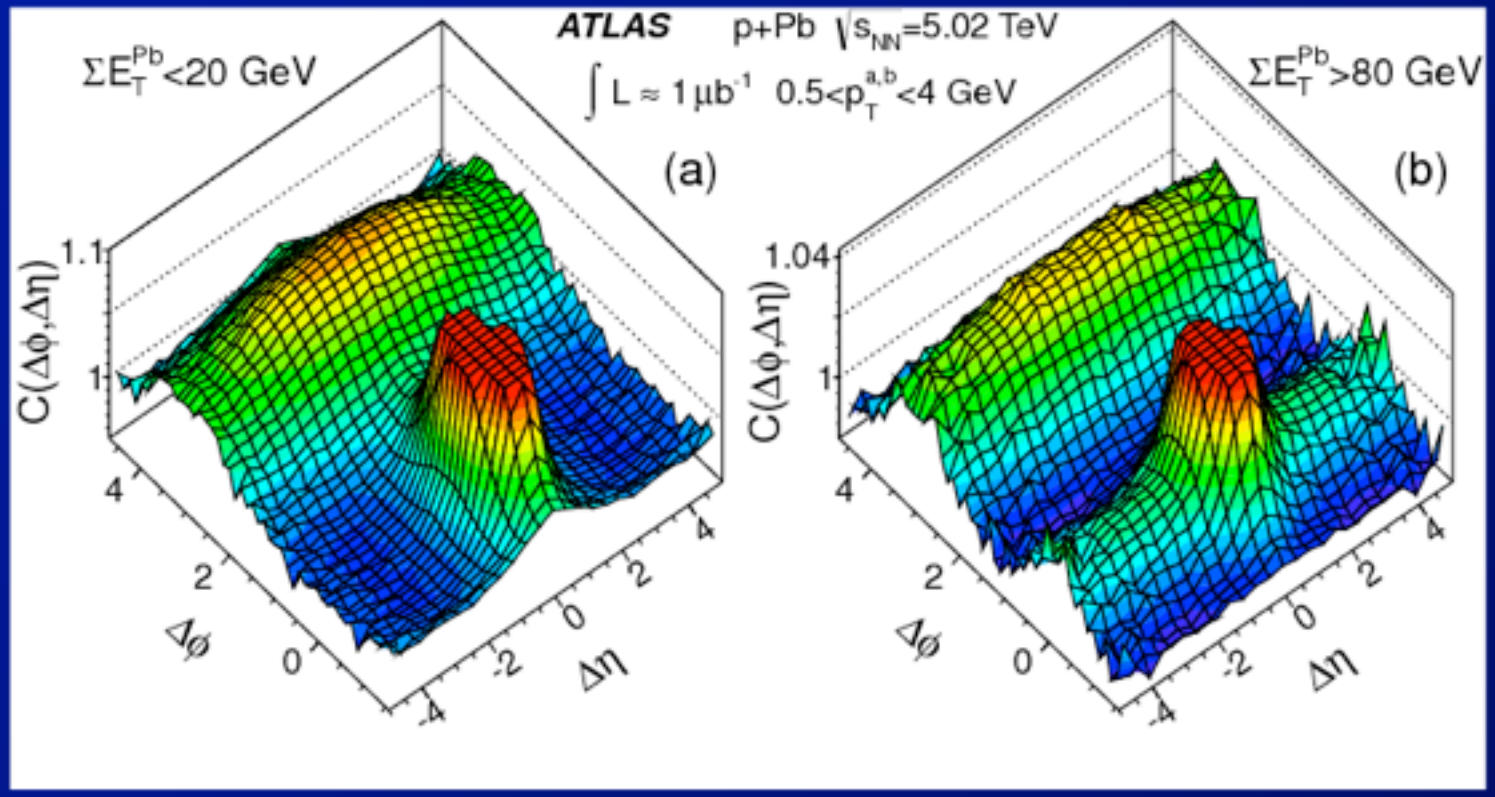
proton-lead collisions @ LHC



- Study angular correlations between pairs of particles to look for saturation, other effects.
  - $C_2 \equiv \frac{N_{\rm pair}(\Delta\eta, \Delta\phi)}{N_1 \; N_2}$
  - in chosen (lower) p_T bins

ATLAS 2-particle correlations

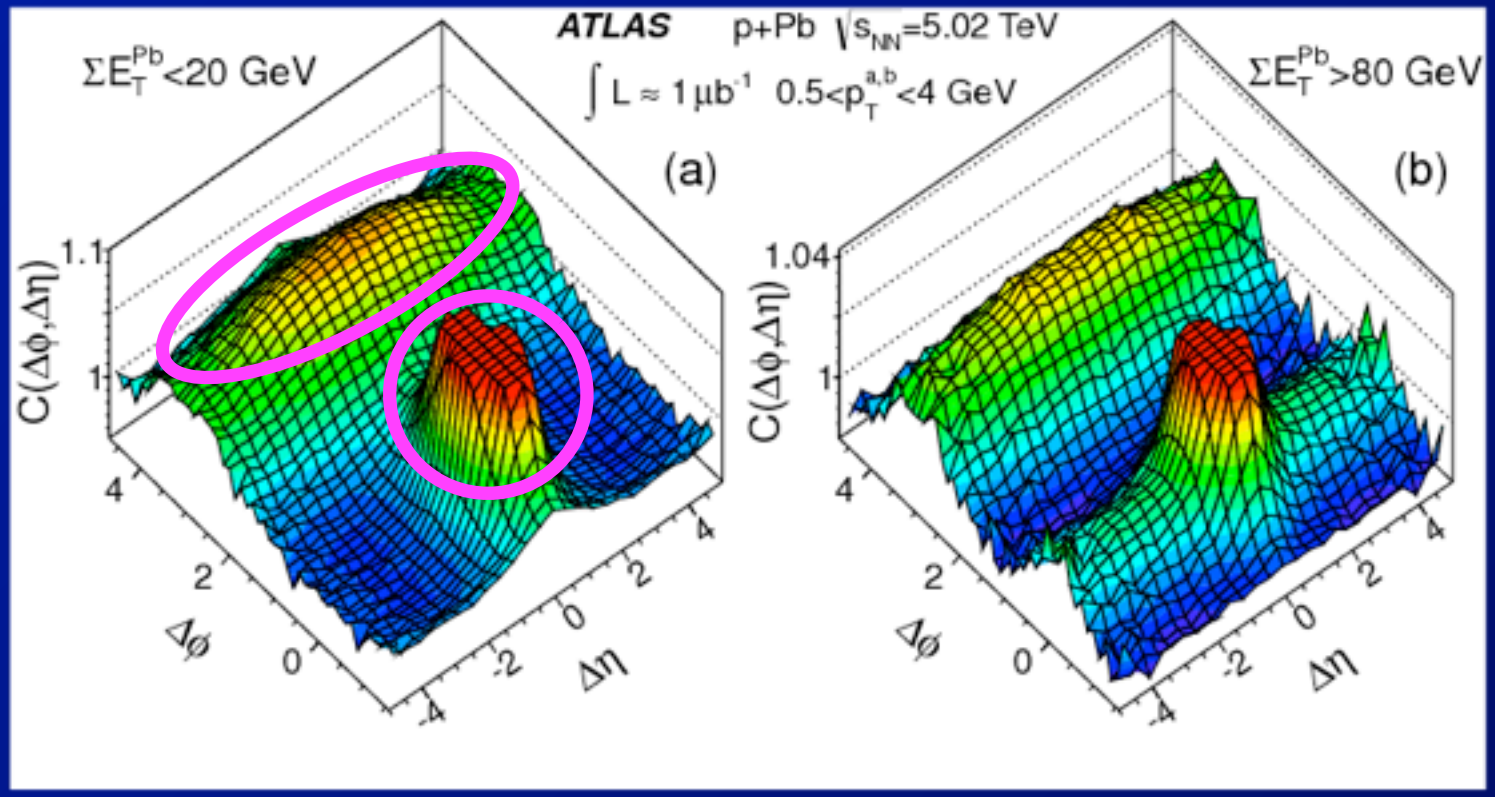
"low multiplicity" "high multiplicity"



- Study azimuthal (Δφ) and longitudinal (Δη) correlations between pairs of particles
  - ⇒usual correlations in low-multiplicity events
  - ⇒additional "ridge" in high-multiplicity events

ATLAS 2-particle correlations

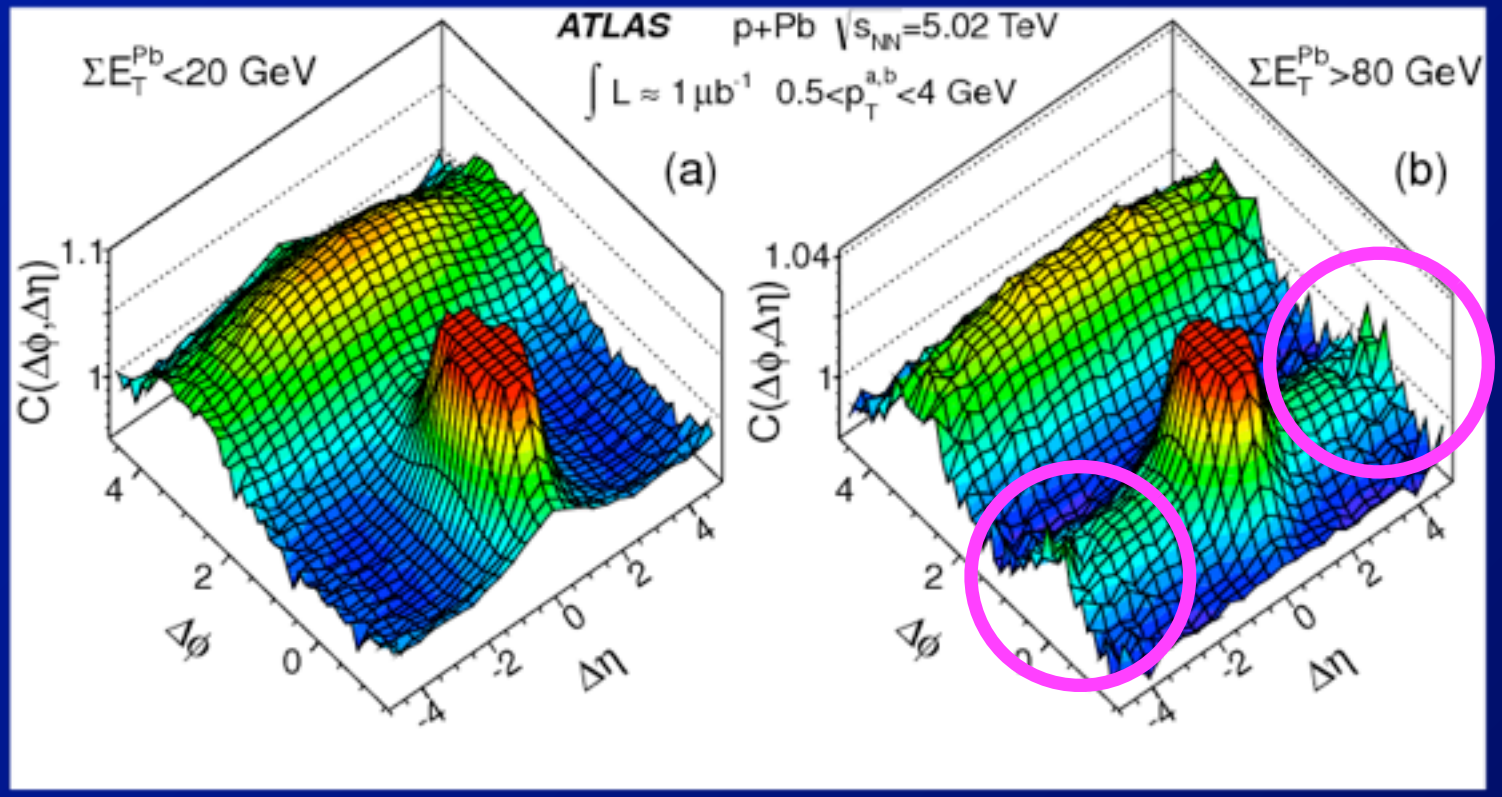
"low multiplicity" "high multiplicity"



- Study azimuthal (Δφ) and longitudinal (Δη) correlations between pairs of particles
  - ⇒usual correlations in low-multiplicity events (jets)

ATLAS 2-particle correlations

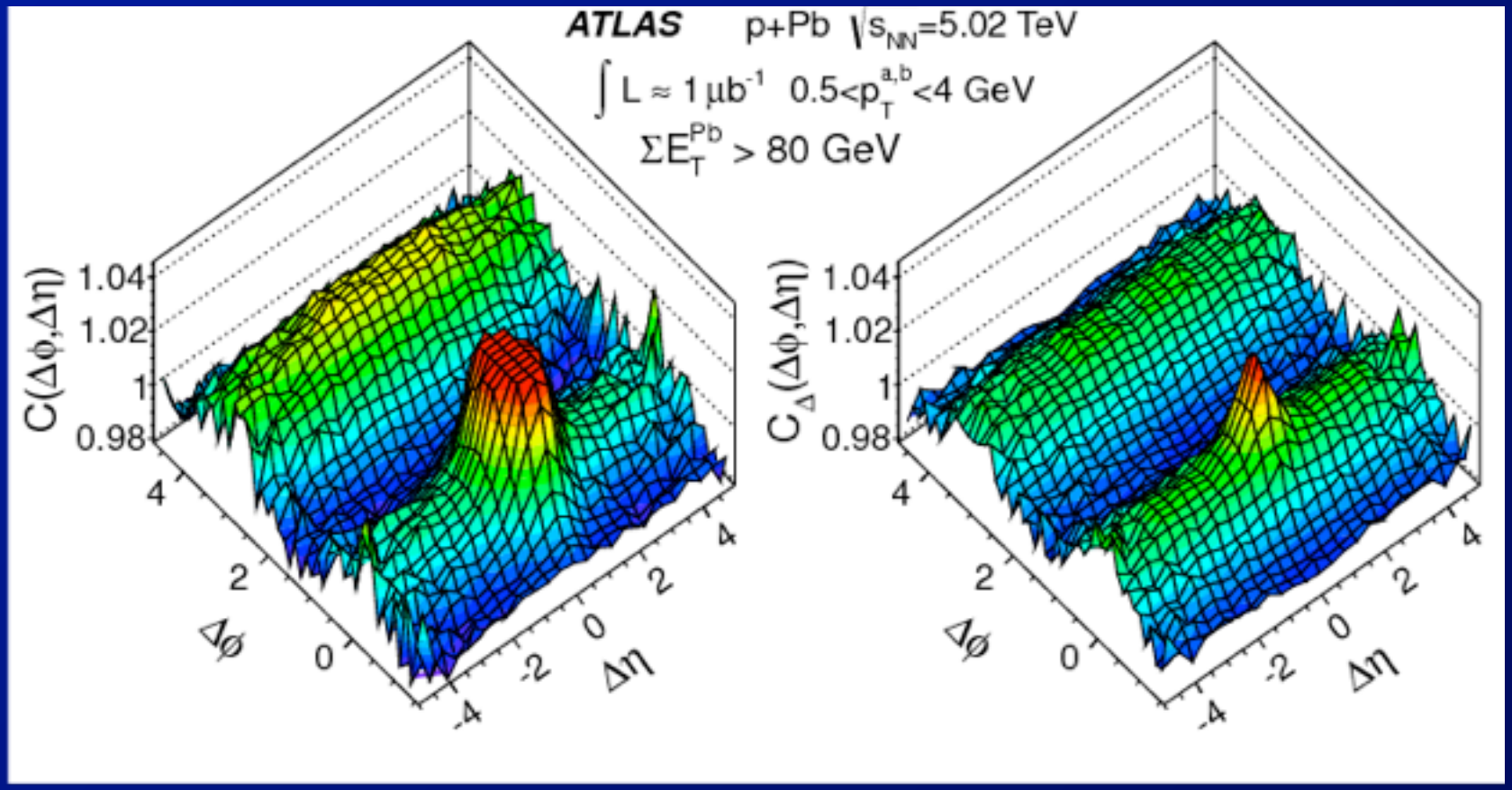
"low multiplicity" "high multiplicity"



- Study azimuthal ($\Delta\varphi$) and longitudinal ($\Delta\eta$) correlations between pairs of particles
  - ⇒usual correlations in low-multiplicity events
  - ⇒additional "ridge" in high-multiplicity events

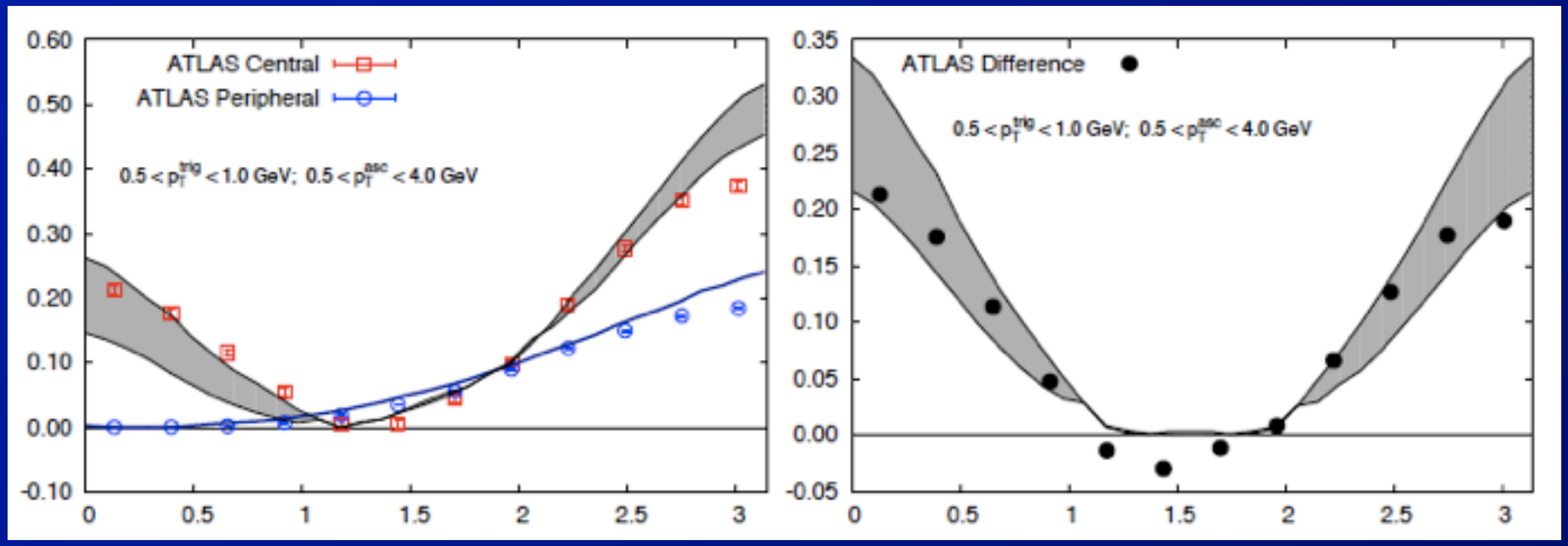
2-particle correlations, subtracted

- Use the peripheral p+Pb data to subtract uninteresting part of the correlation



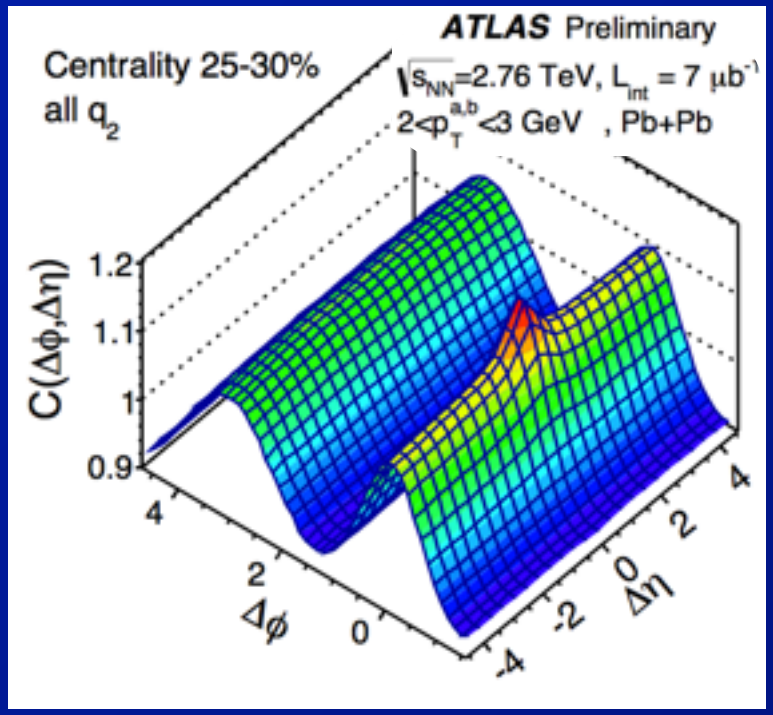
⇒Result looks remarkably similar to Pb+Pb!

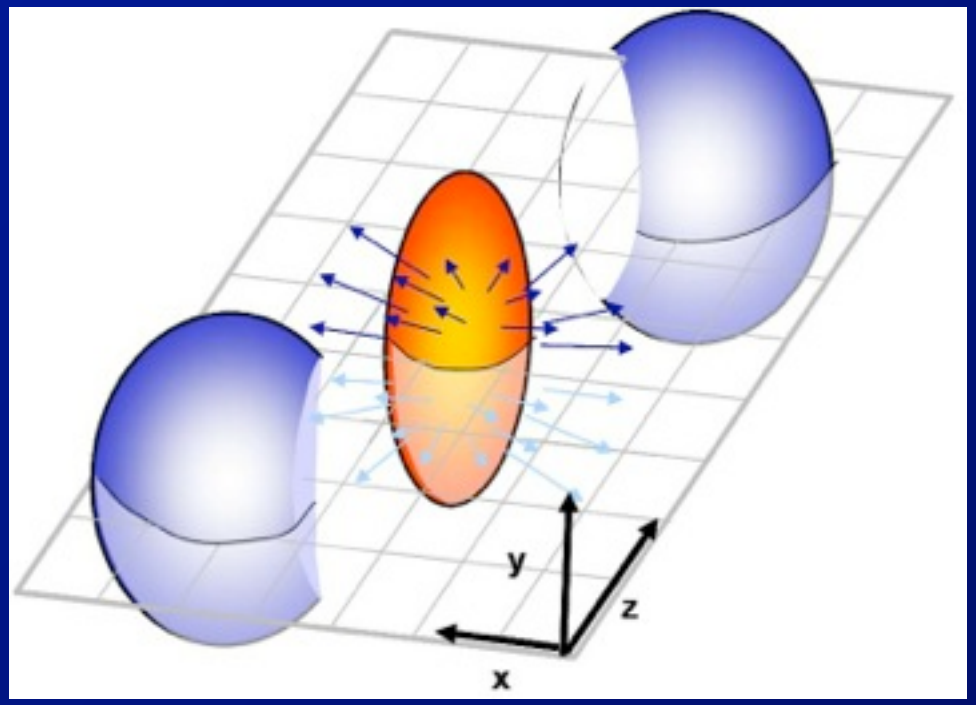
Explained by saturation?



- Theoretical calculations of the effects of saturation in the color glass condensate framework can reproduce the ATLAS data.
  - ⇒But, alternatively, ...

Pb+Pb elliptic flow





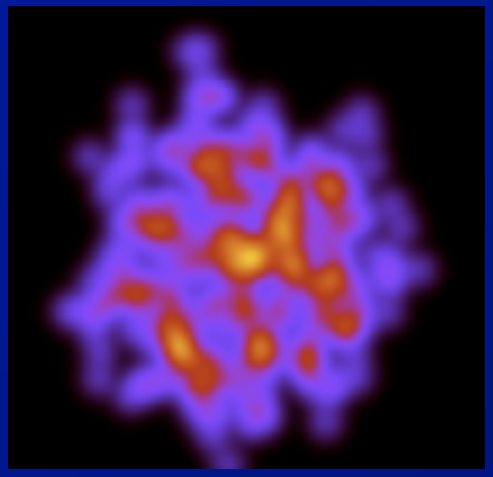
- **Elliptic flow in Pb+Pb collisions arises from strong coupling, low viscosity (η/s) of the quark-gluon plasma**
  - **Behaves like a (nearly ideal) fluid under pressure**
    - ⇒**Modulation due to asymmetric velocity boost from pressure acting in long and short directions**

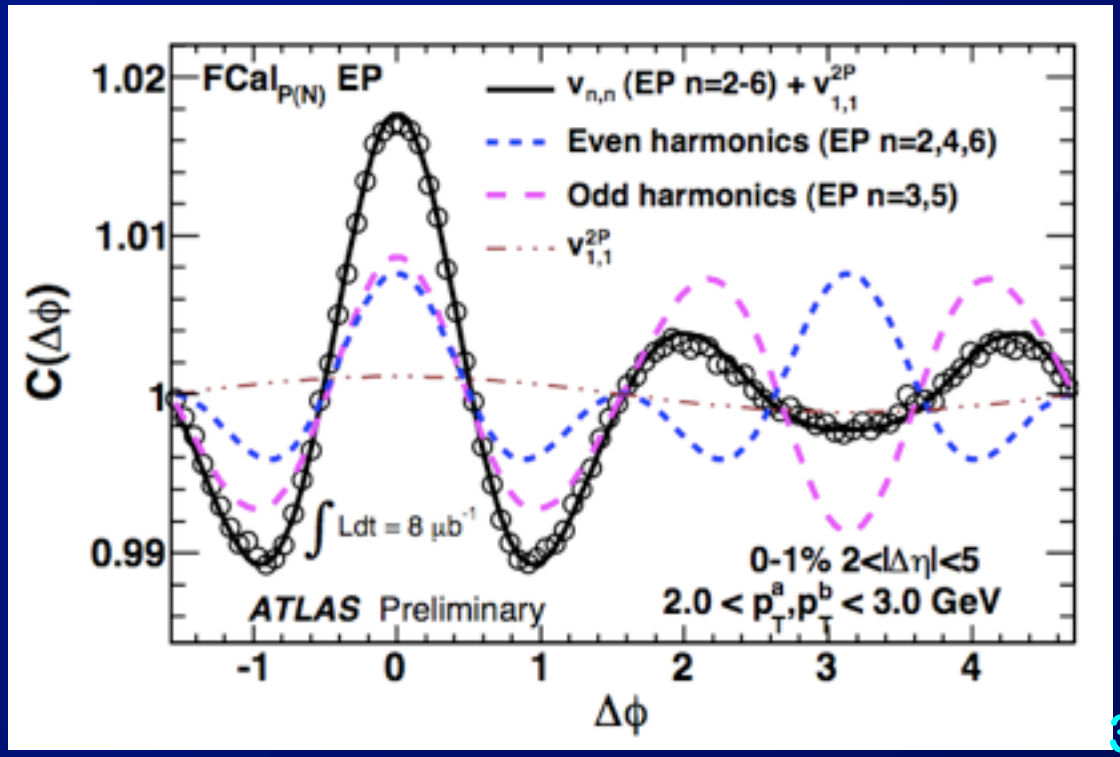
Higher Flow Harmonics

- Major paradigm shift in the field in last 3 years
  - Higher flow harmonics arising from initial-state fluctuations in transverse positions of participants

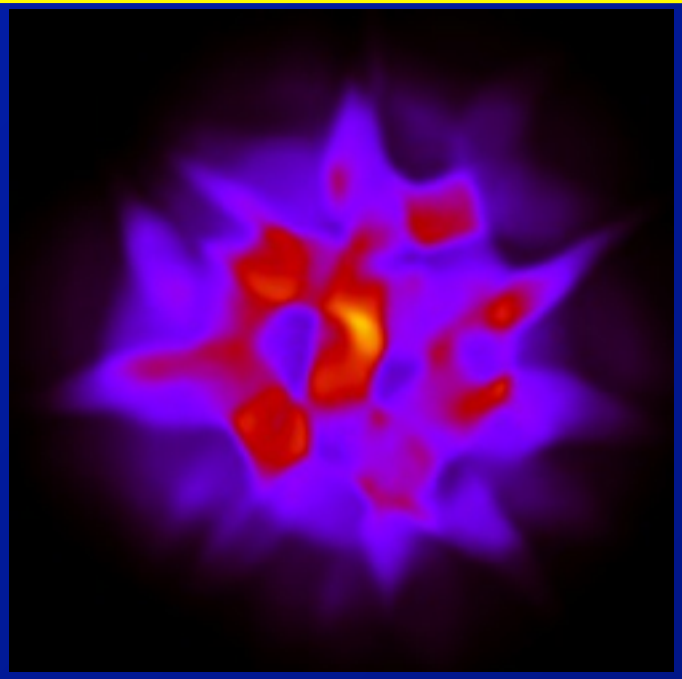
$$\frac{dN}{d\phi dp_T d\eta} = \frac{dN}{2\pi dp_T d\eta}\left(1 + \sum_n 2v_n \cos\left[n(\phi - \psi_n)\right]\right)$$

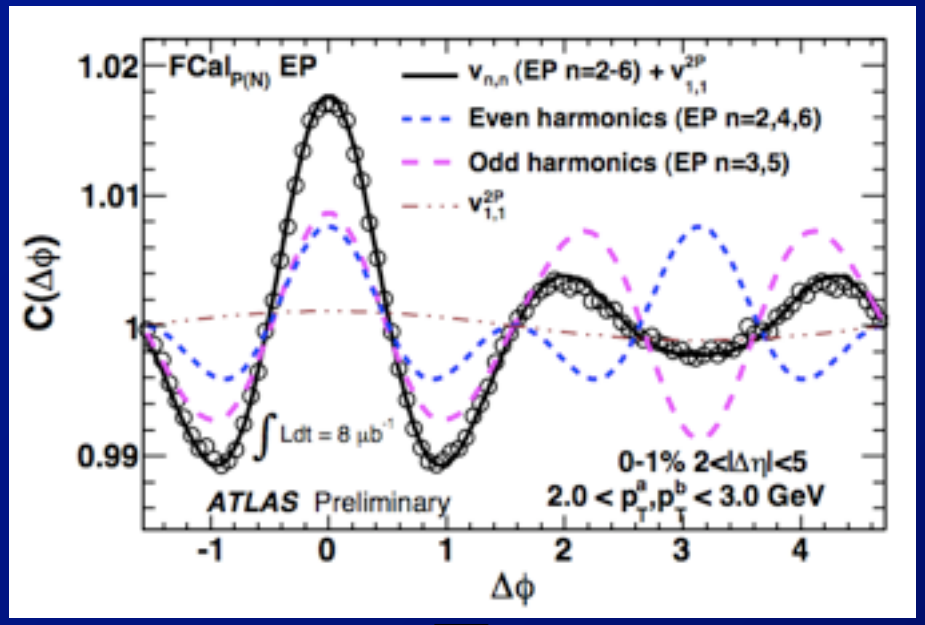
- Frequently measured using pairs of particles



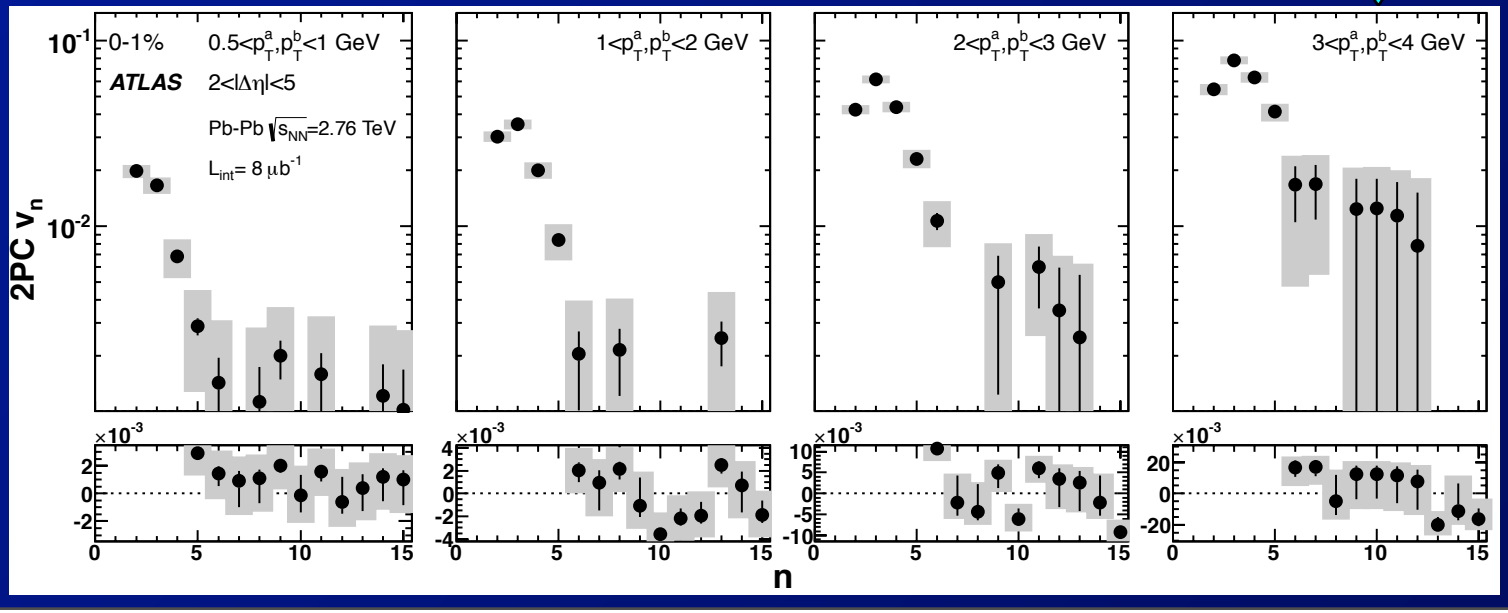


Fluctuations, Fourier amplitudes



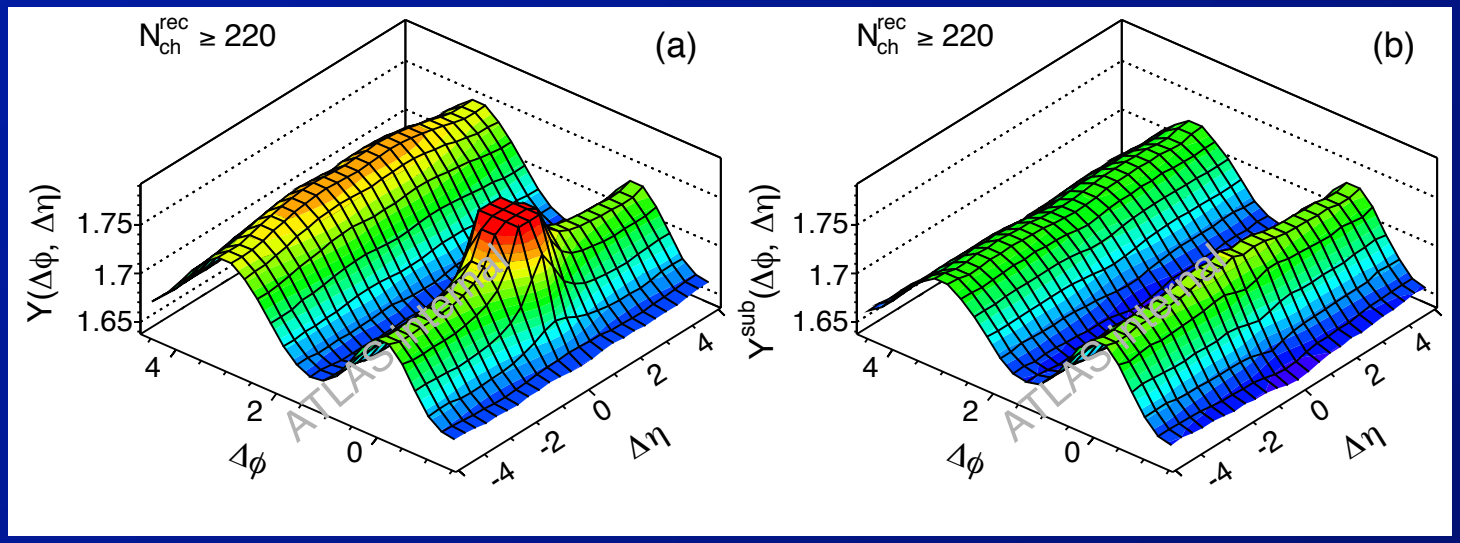


Increasing momenta

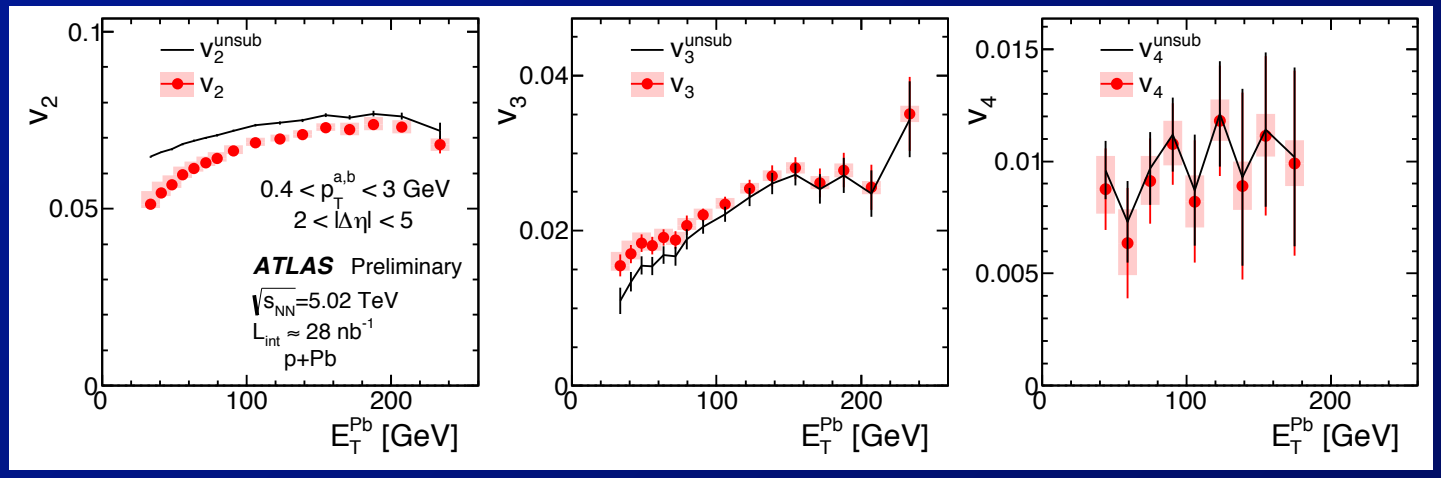


p+Pb v_n using 2013 data

- Use minimum-bias + high-multiplicity trigger data

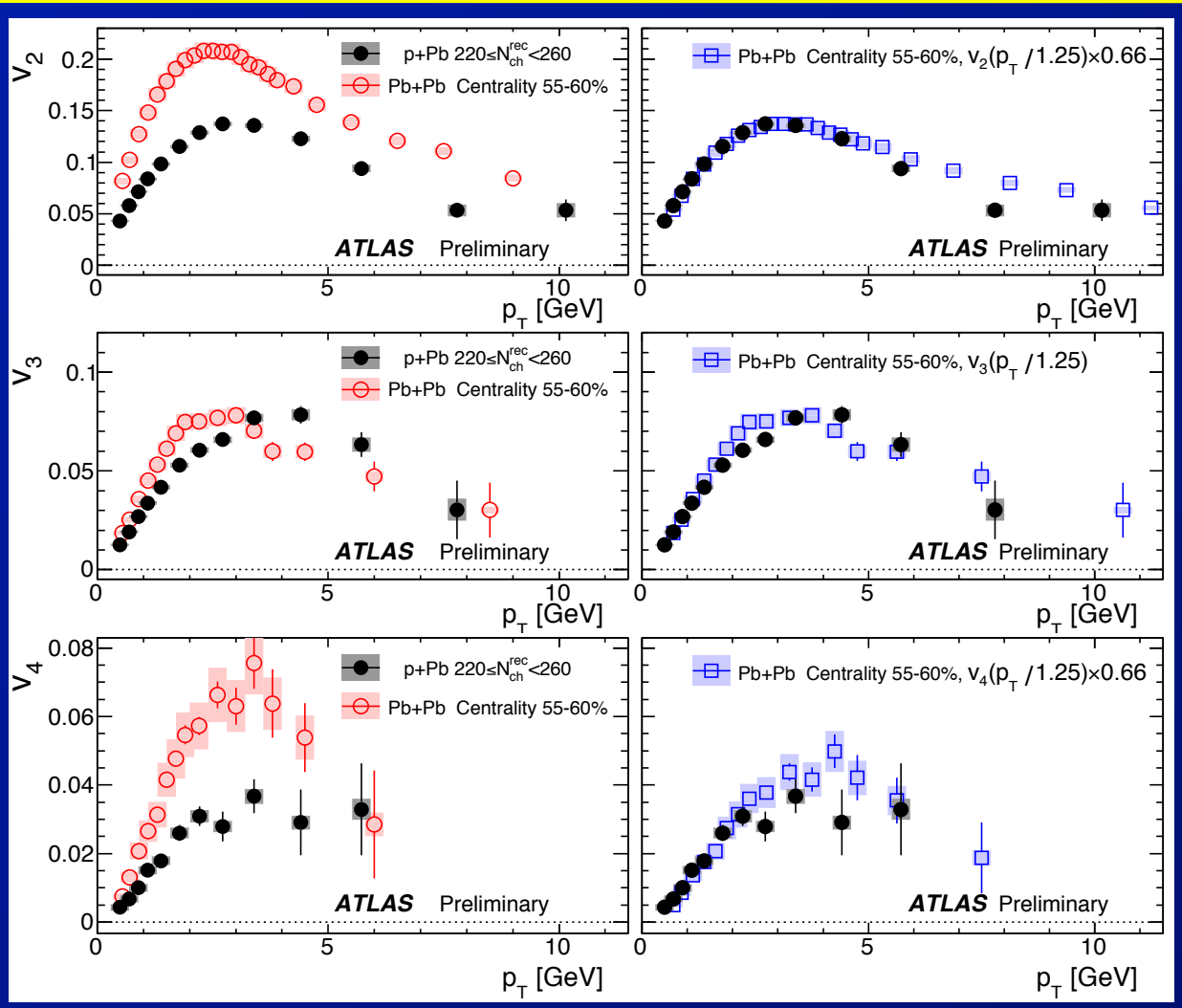


- Observe significant values for v_2, v_3, v_4, even v_5



- Weakly varying with centrality (ΣE_T)

Compare p+Pb, Pb+Pb v_n



Right panels adjust p+Pb p_T scale by 4/5 to account for difference in $\langle p_T \rangle$ (Teany et al)

Pb+Pb v_2 and v_4 multiplied by 0.66 to match p+Pb

- Compare p+Pb and Pb+Pb

  ⇒Good agreement between p+Pb and Pb+Pb when including p_T and v_2, v_4 rescaling

Summary (soft)

- Analysis of centrality/geometry p+Pb collisions requires understanding Glauber-Gribov effects
  - In particular, impact of event-to-event fluctuations in the proton configuration
- Multiplicity measurements show growth in $dN/d\eta$ with ΣE_T^{Pb} over the full η range
  - But much faster at backward (Pb-going)
- Interpretation of multiplicity vs N_{part} depends on choice of geometry model
  - But Glauber-Gribov, $\Omega = 0.55$ more consistent with previous measurements.
    - ⇒Important to constrain description of cross-section fluctuations using p-p diffraction data
- Clear evidence for collective dynamics similar to that observed in Pb+Pb in p+Pb collisions

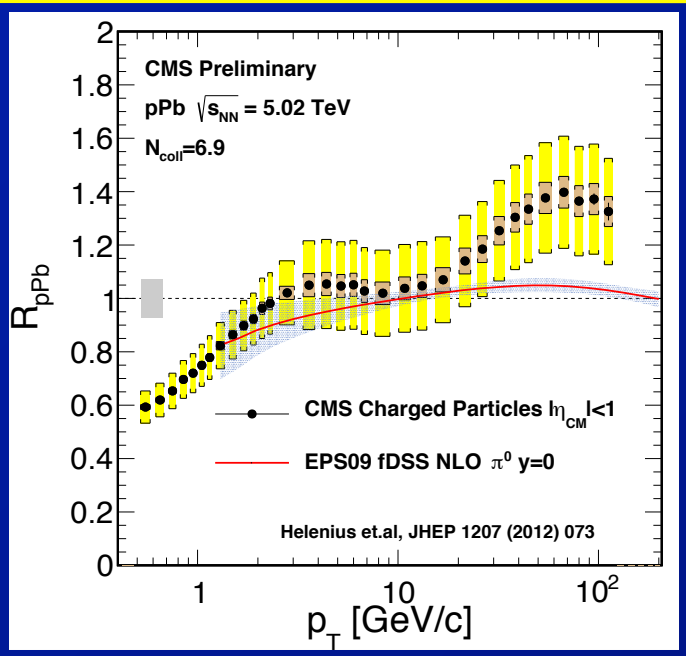
Summary (2)

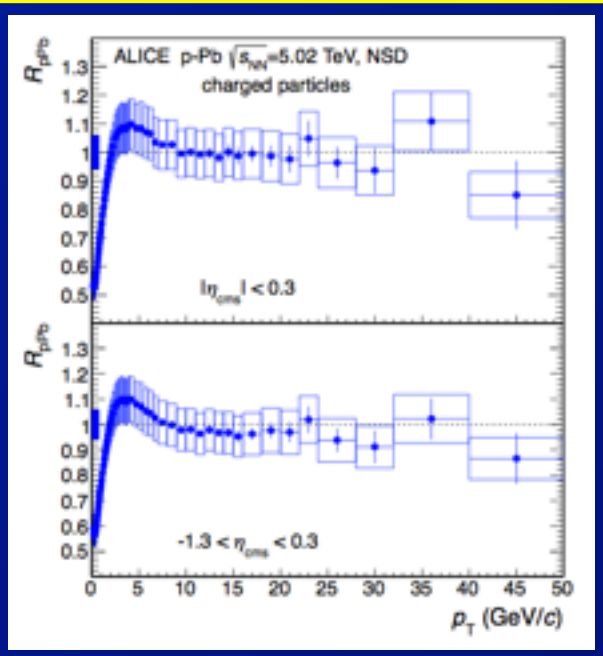
- Inclusive Z cross-section shows ~ 20% excess relative to pQCD (not including NPDF)
- Z/N_{chg} ratio vs centrality makes sense
  - For all geometric models
- Inclusive jet R_{pPb} shows little/no nuclear effect
  - consistent with pQCD + EPS09.
- Centrality-dependent R_{CP}, R_{pPb} shows strong reduction in jet yield in central collisions
  - At high pT, more forward rapidities
  - variation scales with jet energy
- Suggestion that observed behavior can result from correlation between proton configuration and x_p

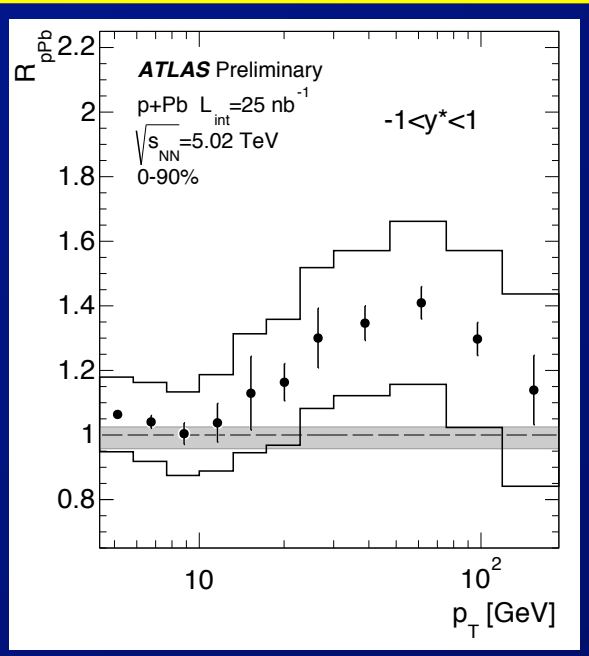
  ⇒Probing the structure of the proton not nucleus?

Backup

p+Pb charged particle R_{pPb}





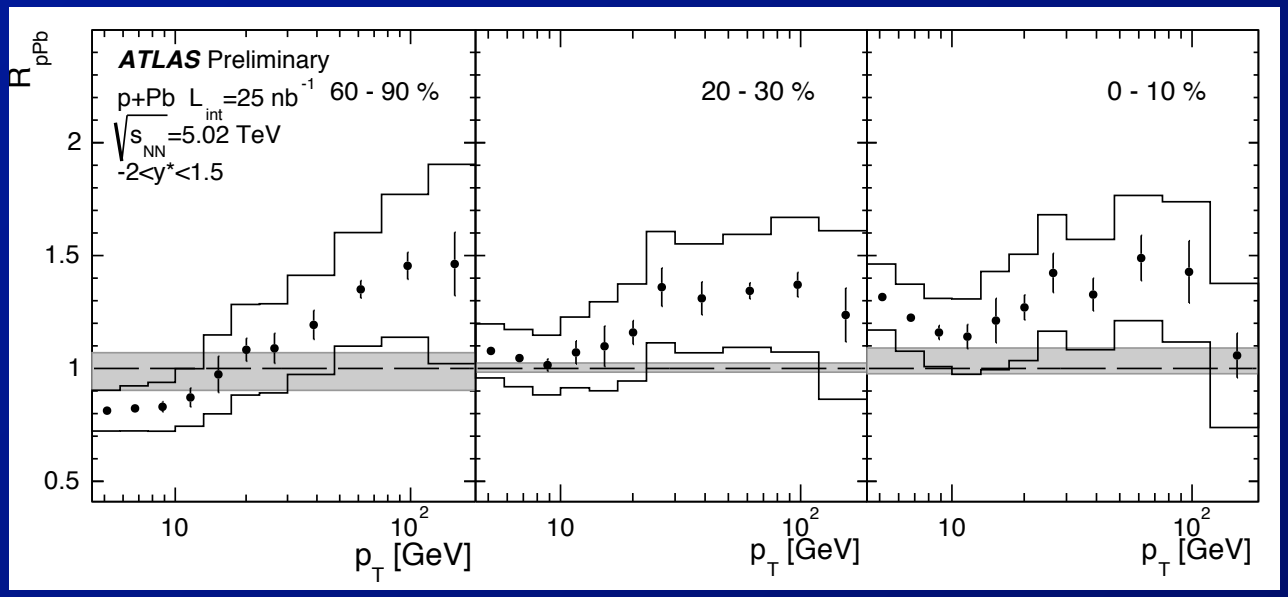


- **Puzzle from the Hard Probes 2013 conference:**
  - CMS observes unexpected enhancement in high-p_T charged particle yield in p+Pb relative to p+p
  - Recently submitted paper from ALICE shows no such effect (over narrower p_T) range
  - Preliminary result from ATLAS at QM2014 shows an enhancement similar to result from CMS

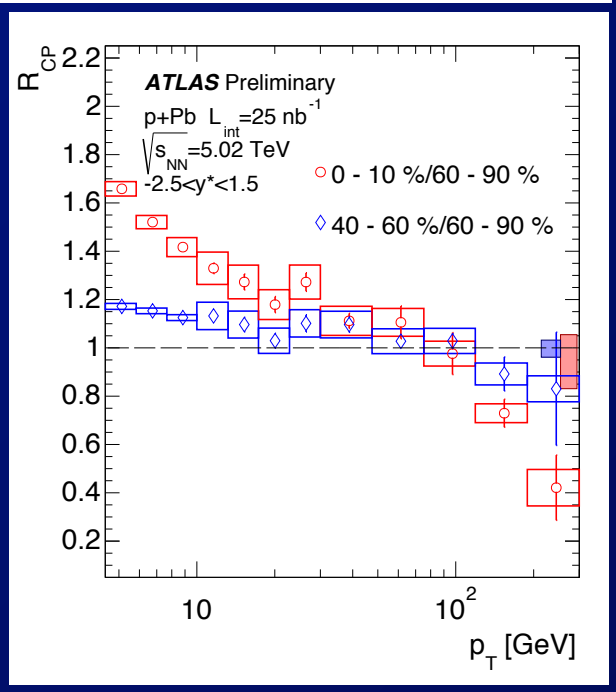
  ⇒Experimental disagreement? Explanation?

p+Pb charged particle R_{pPb}

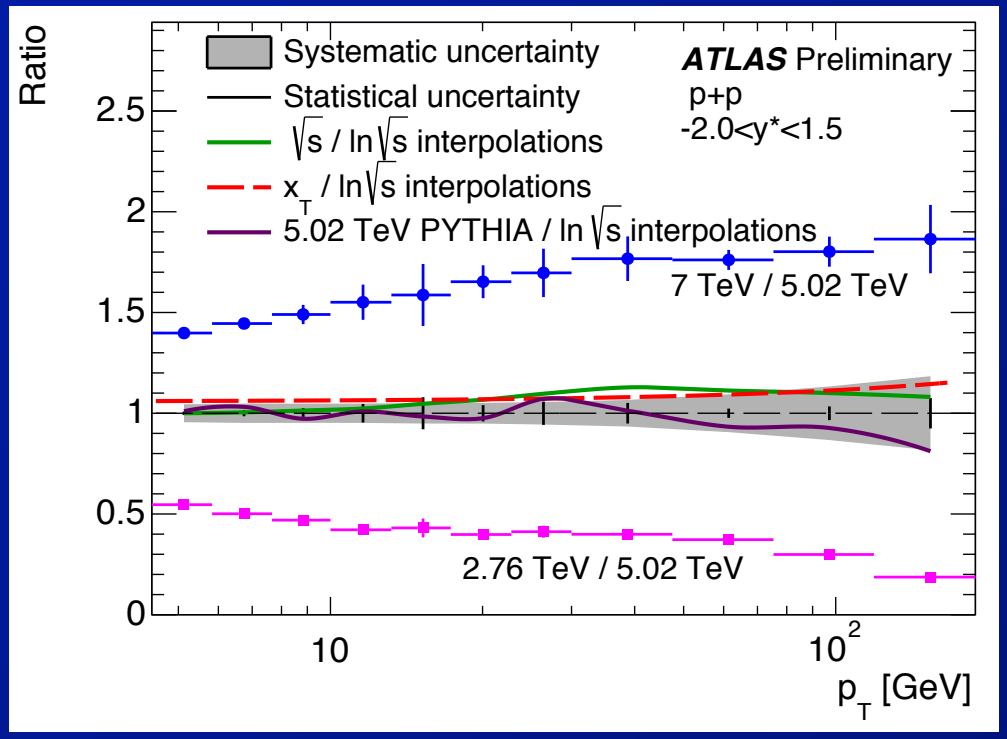
- Enhanced R_{pPb} seen in all centrality bins.

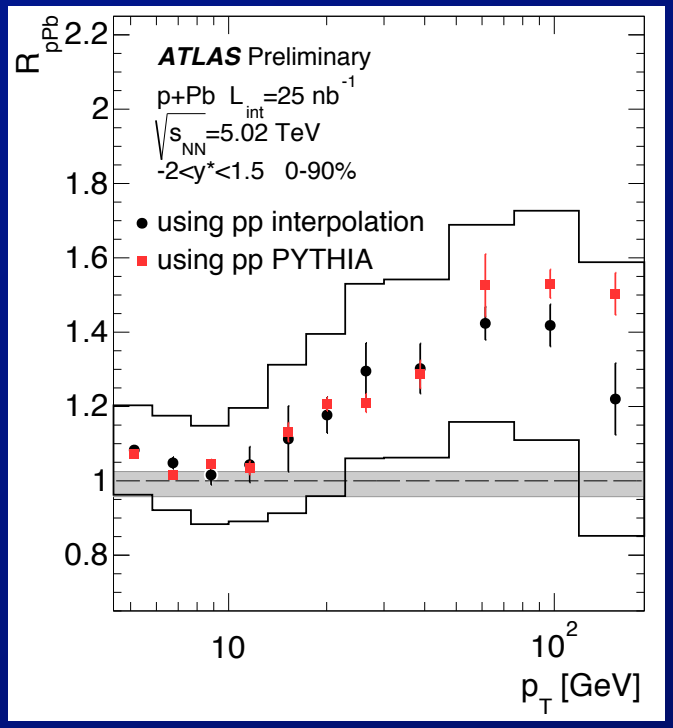


- R_{CP} (integrated over y*) shows similar features as the jet R_{CP}



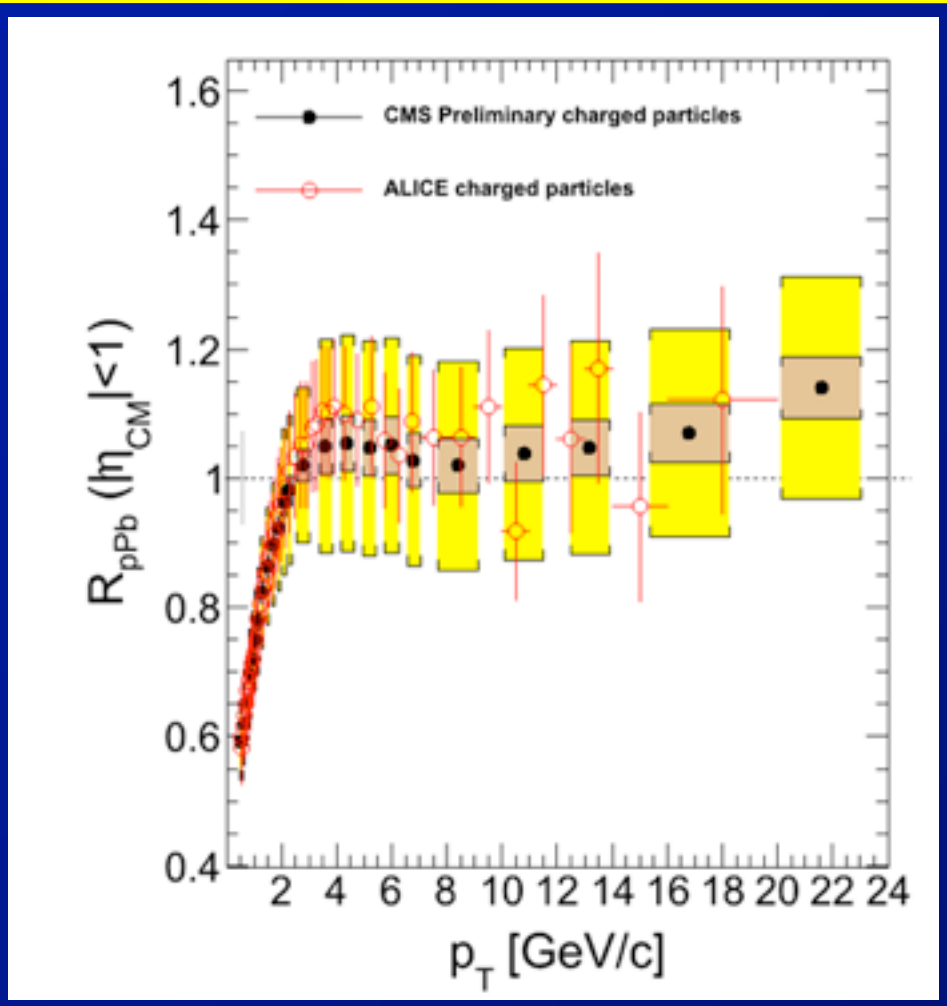
p+Pb charged particle R_{pPb}

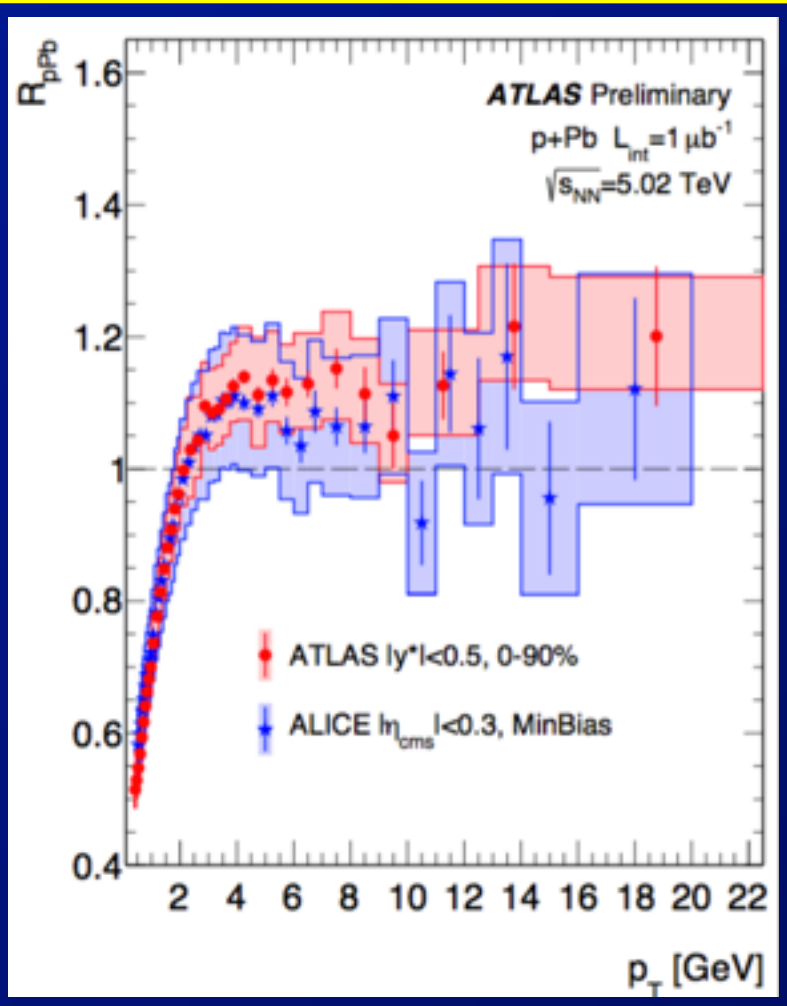




- p-p charged particle cross-section measured at 2.76 TeV, 7 TeV, interpolated to 5.02 TeV
  - Three different interpolation methods tested
- R_{pPb} measured using PYTHIA baseline shows same result obtained with interpolated p-p.

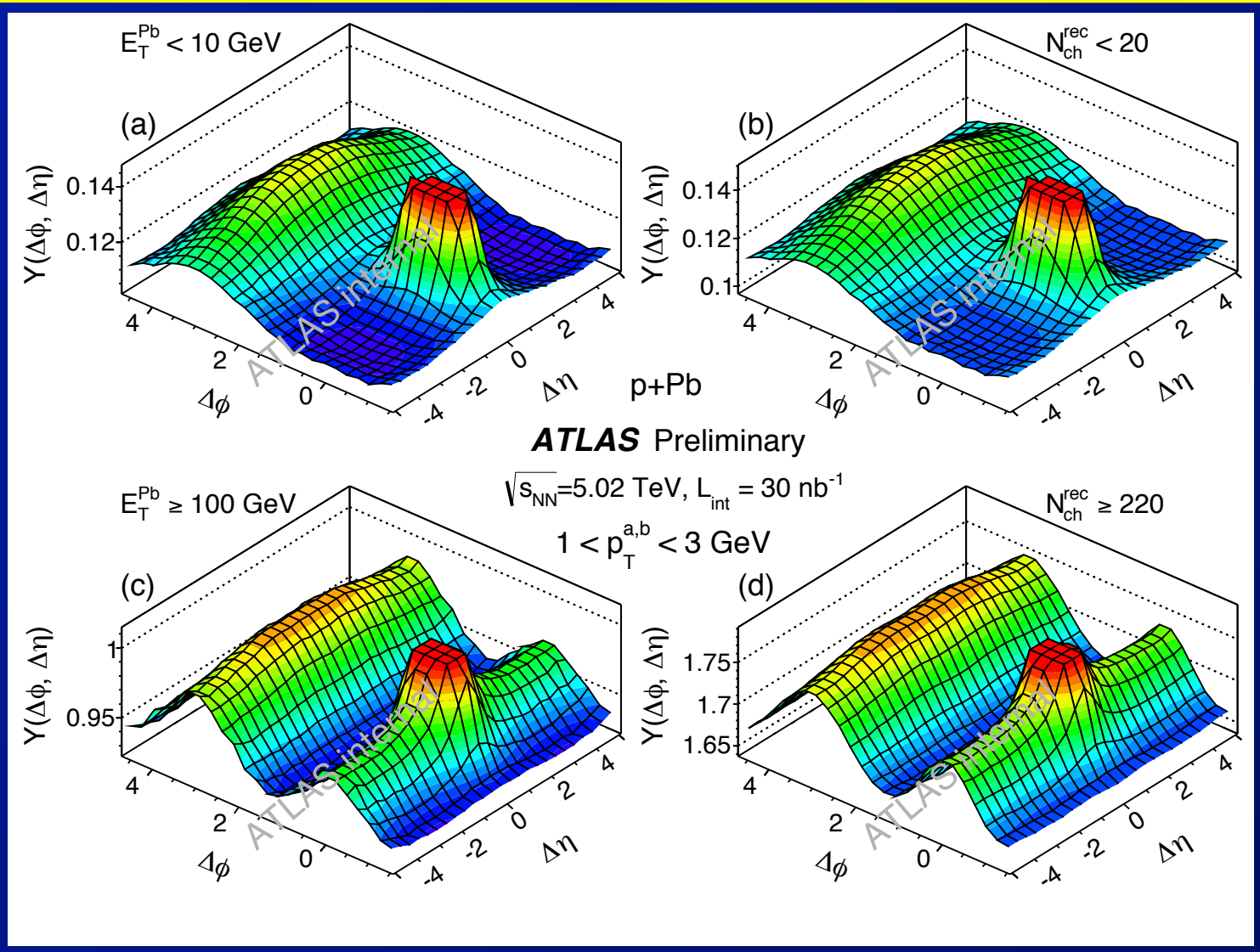
Charged particle R_{pPb}





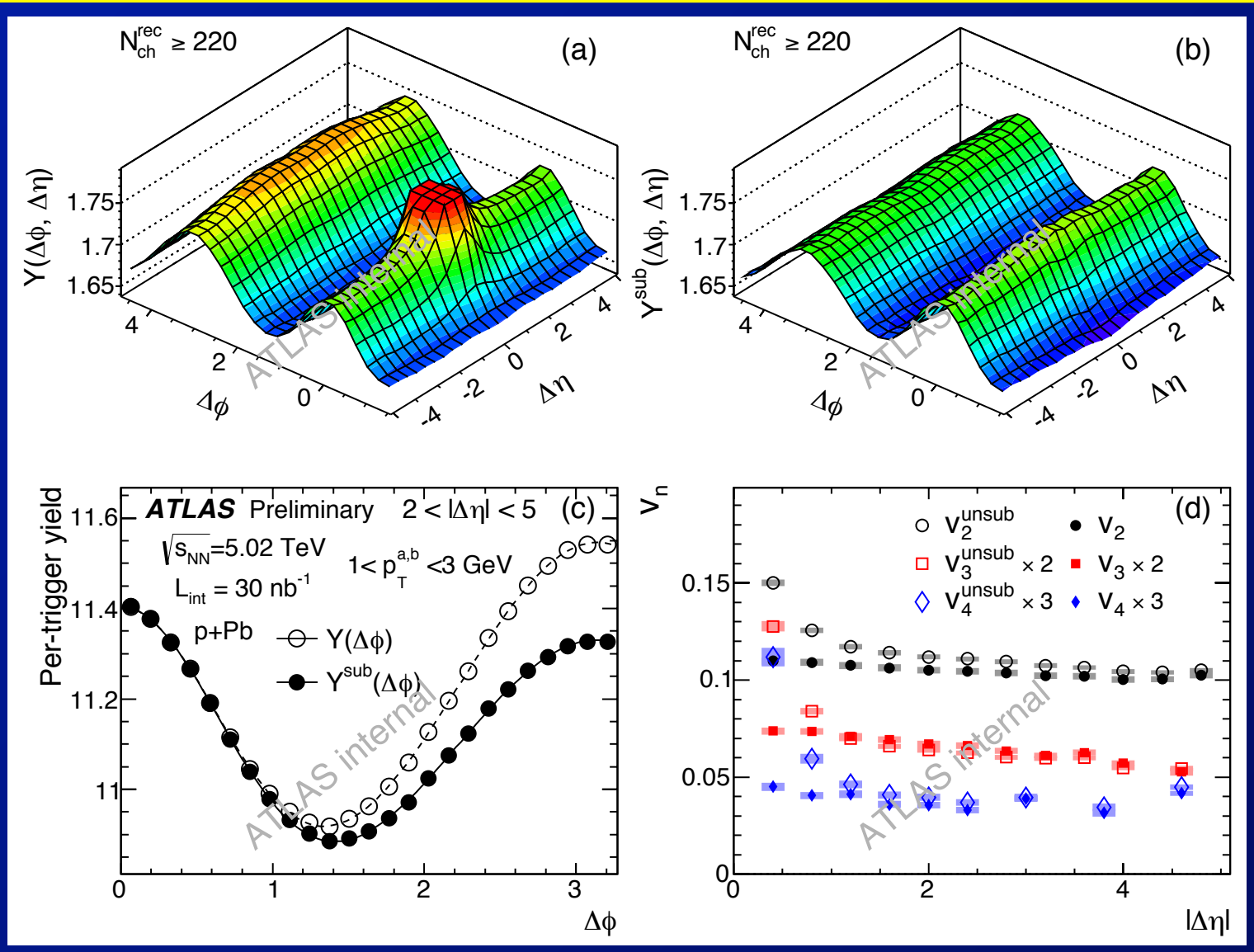
- **Good agreement on (almost) minimum-bias charged particle RpPb**
  - ⇒ **Beware differences in event selection**

p+Pb 2-particle correlations



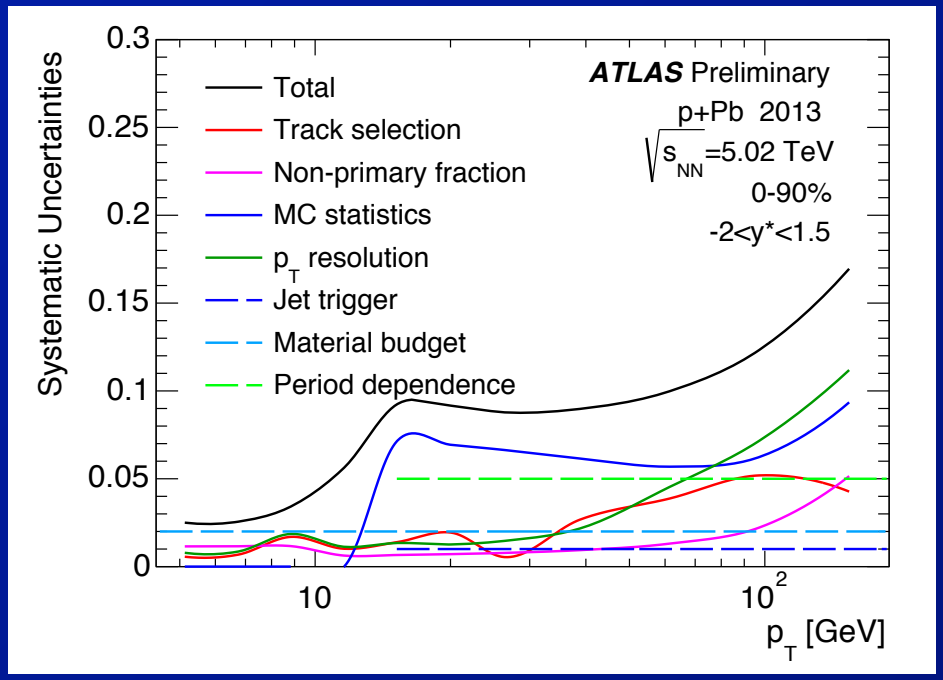
- Good statistical precision on development of the ridge(s) out to high event multiplicities

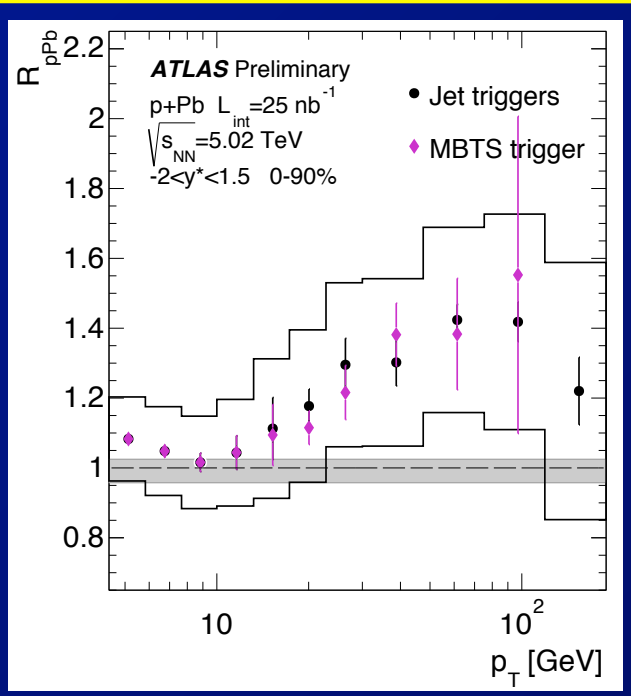
Peripheral subtraction

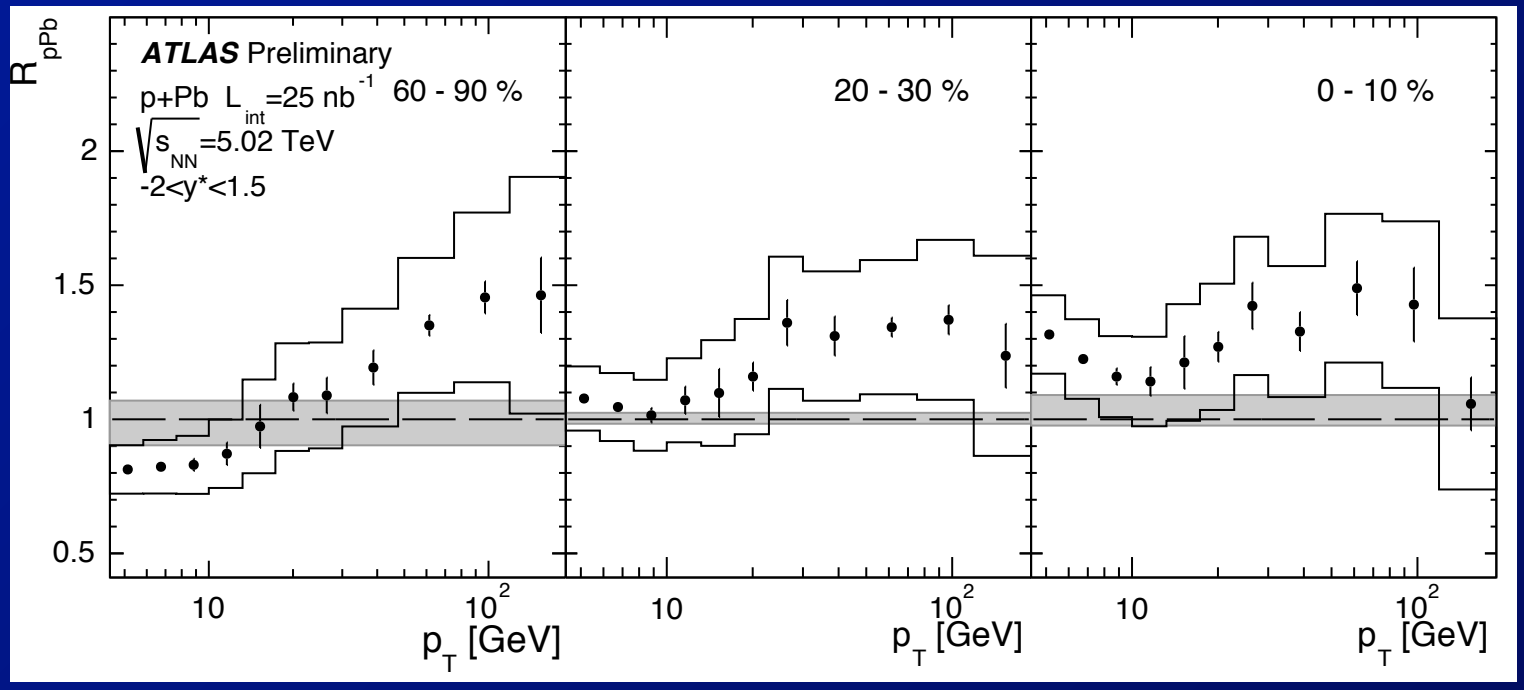


- Apply peripheral subtraction to remove recoil contribution

Charged R_{pPb}

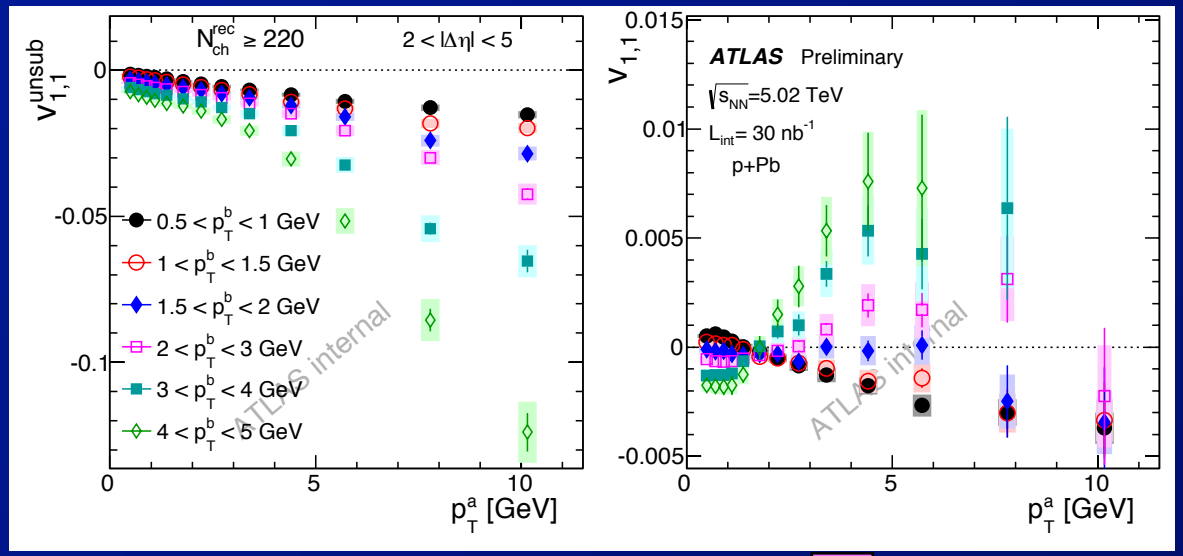


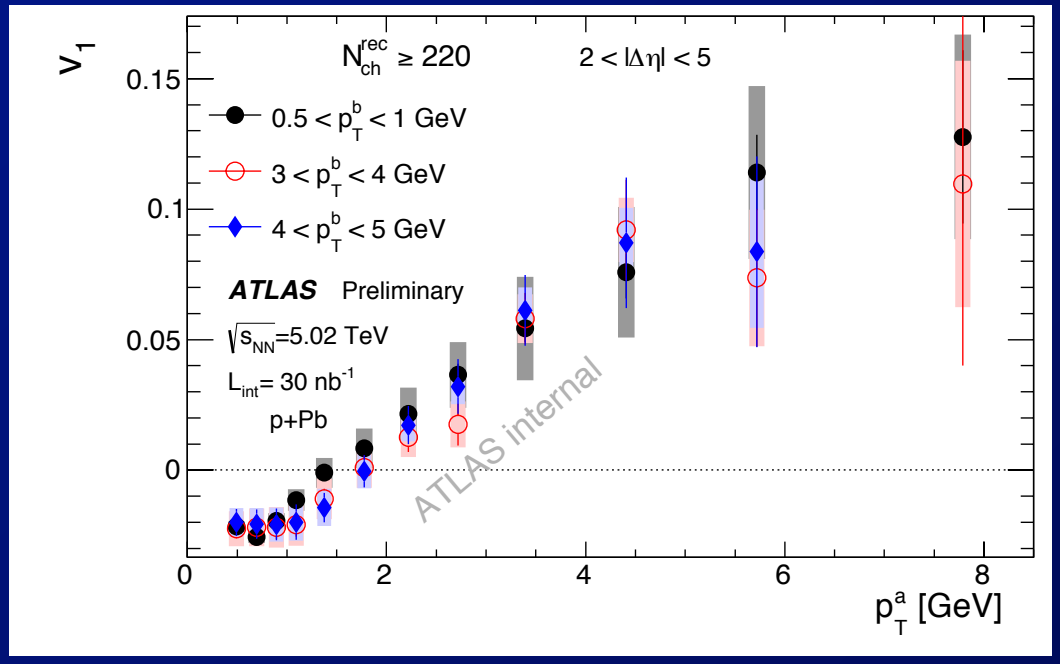




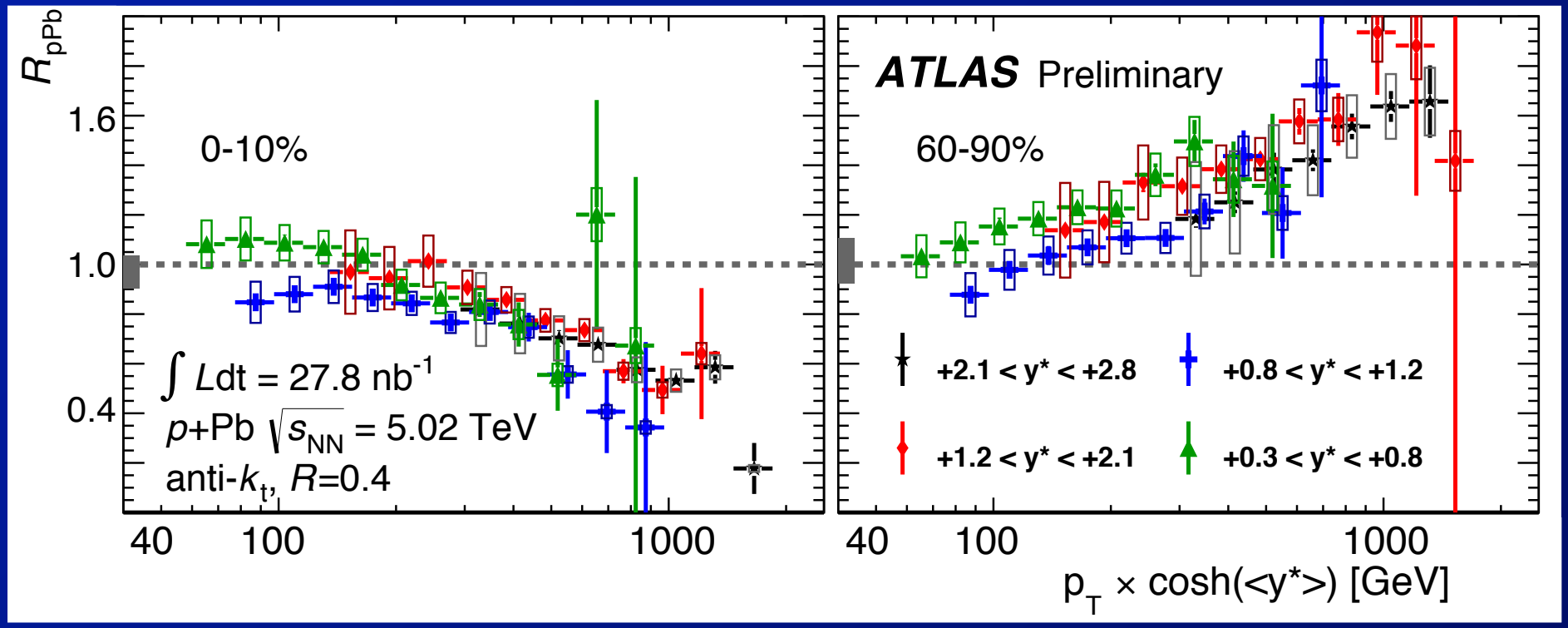
p+Pb v1

- Observe non-zero v_{11} in p+Pb collisions
  - Similar to Pb+Pb, changes sign with increasing p_T
  - Extract v_1 using same procedure applied to Pb+Pb
    - ⇒Observe that v_1 factorizes
    - ⇒Evolution from negative v_1 below ~ 2 GeV to positive above



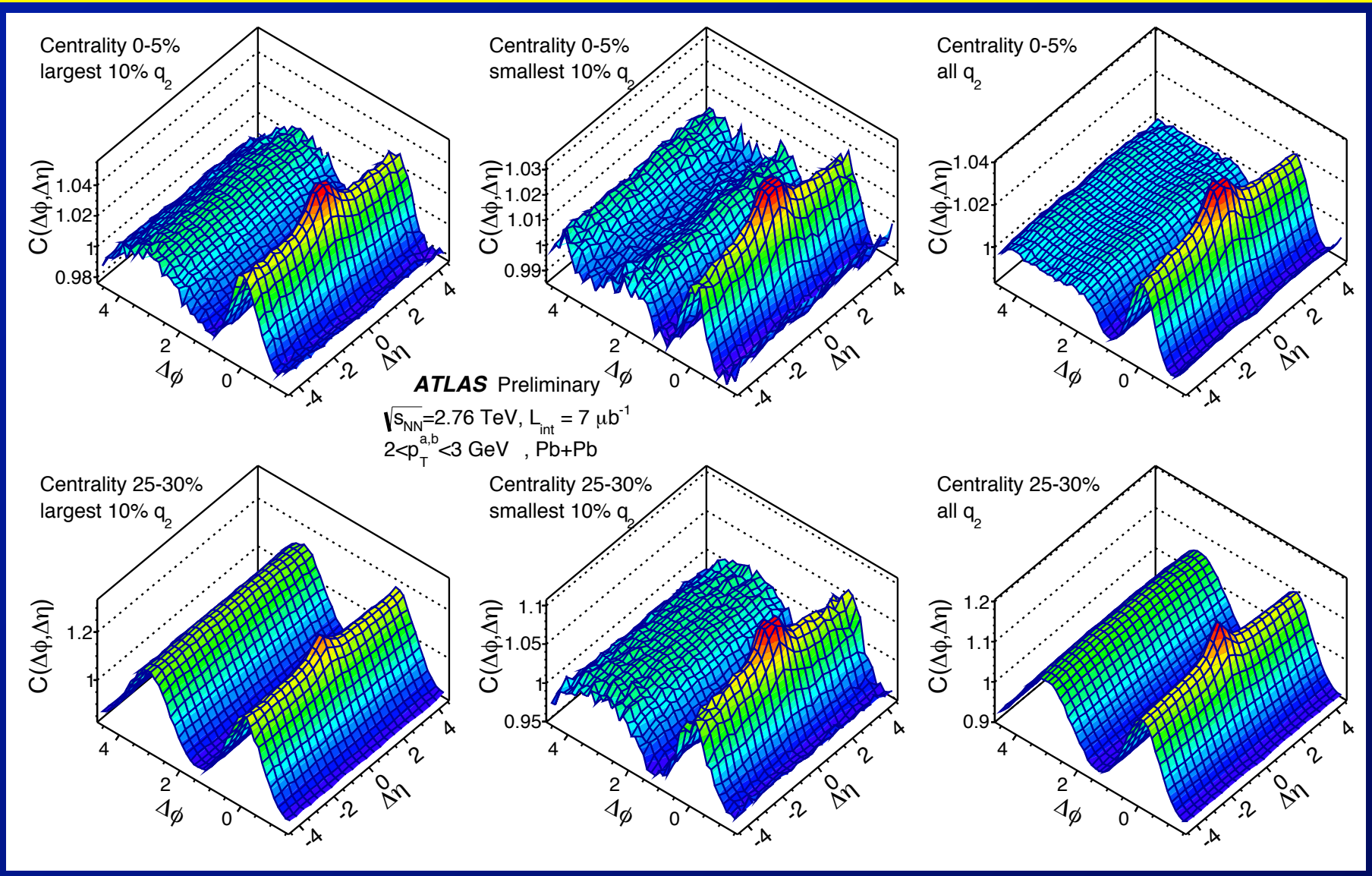


p+Pb R_{pPb} scaling

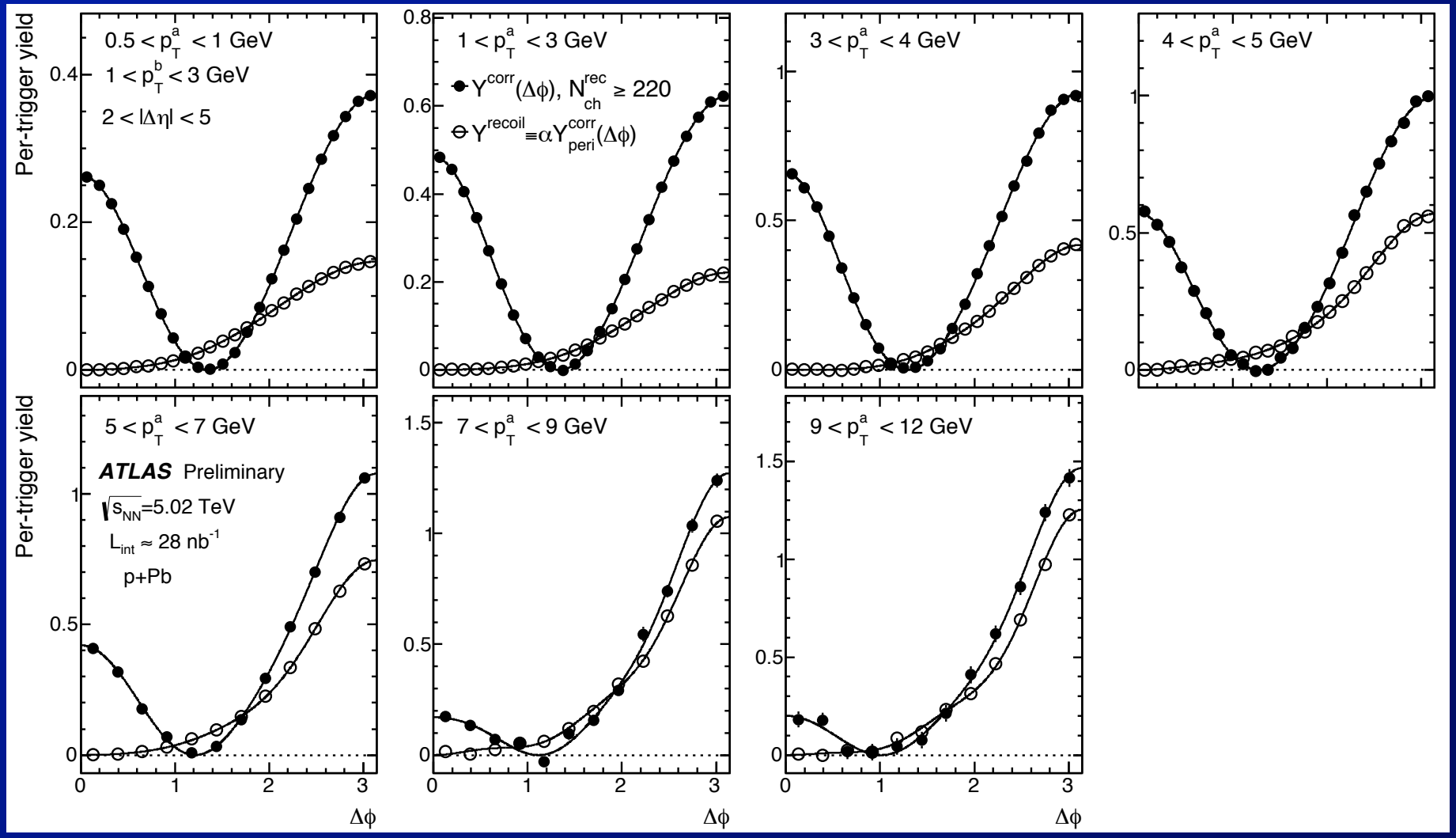


- scaling with p_T cosh(y) less clean in R_{pPb}
  - Errors larger, p-p interpolation, p+Pb y shift, …
    - ⇒ but still present for both peripheral and central collisions

Pb+Pb q_2-selected 2-particle correlations



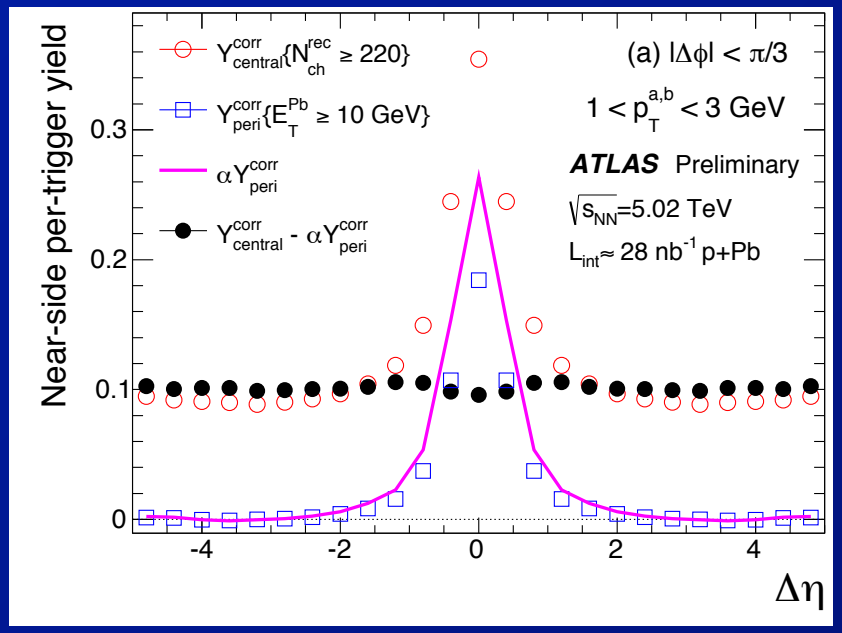
p+Pb 2-particle Δφ vs p_T

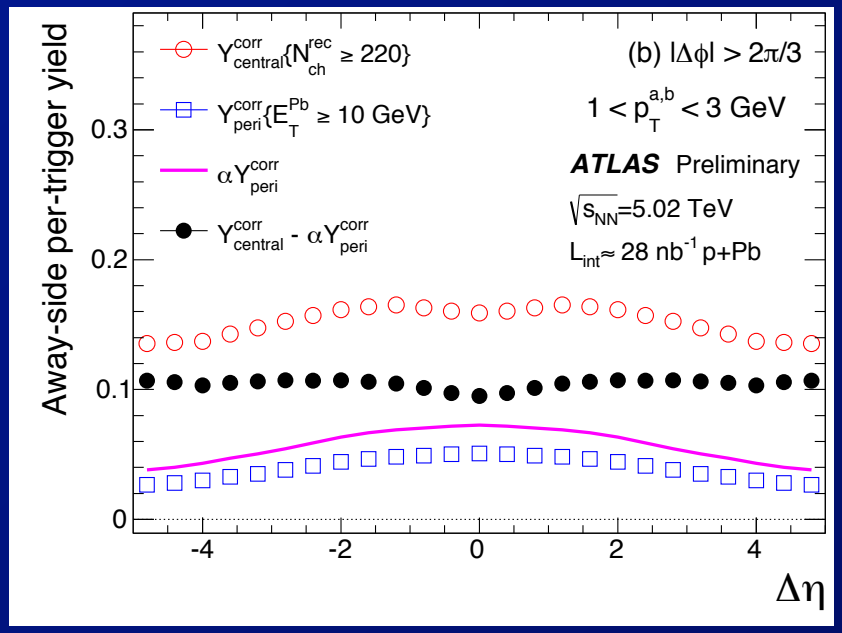


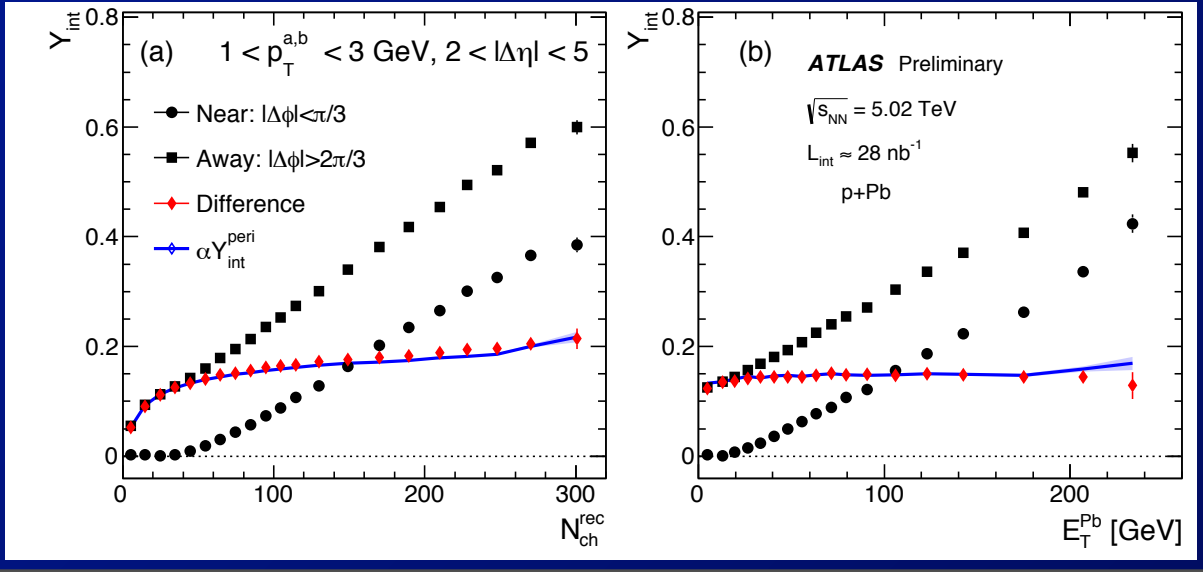
- Clearly see the symmetric ridges even for p_T > 9 GeV!

Peripheral subtraction

- Scale up the peripheral conditional yield to match more central bin in the jet peak



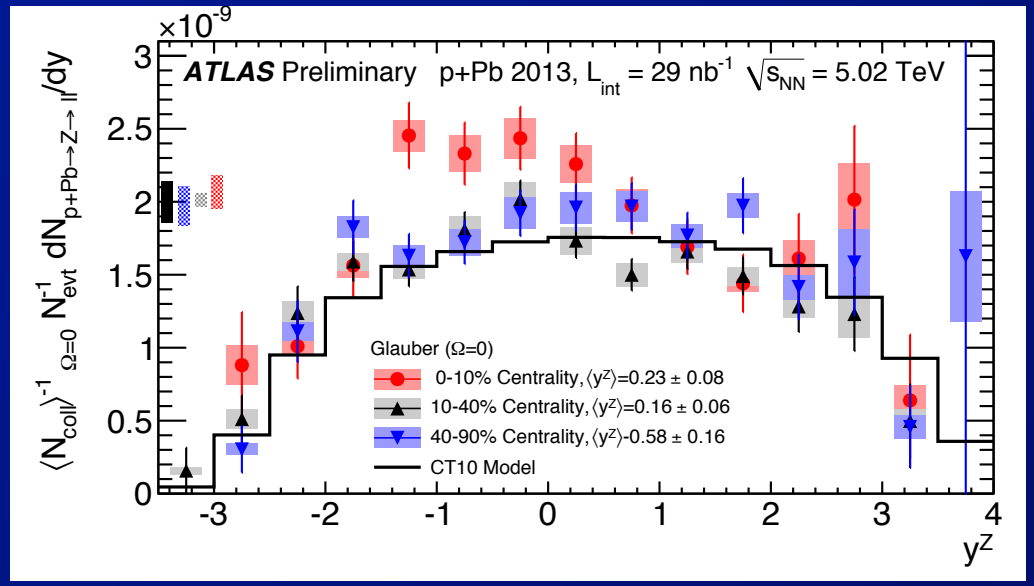




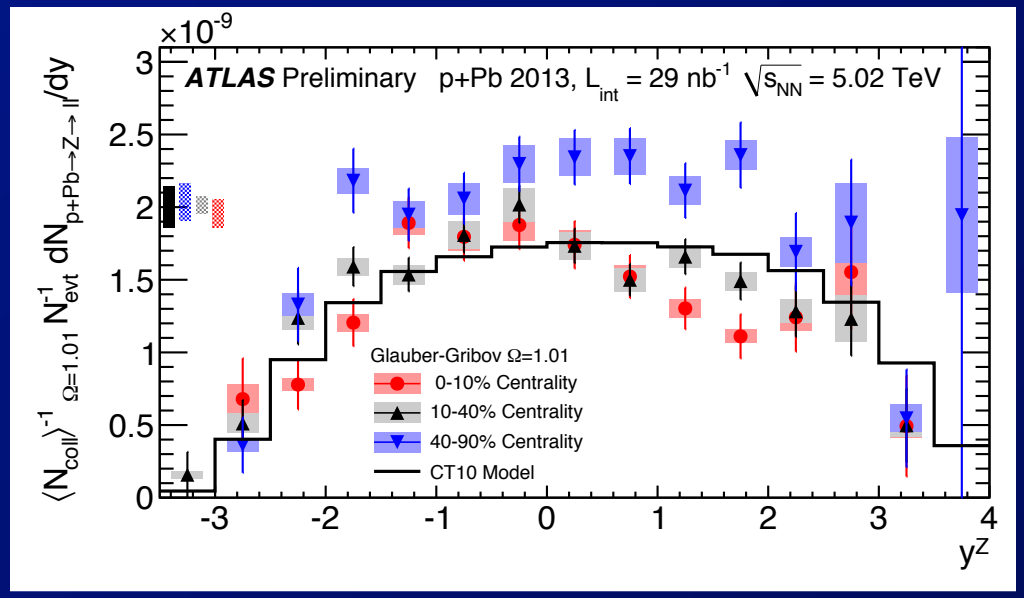
p+Pb Z spectra: centrality dependence

- Plot $1/N_{coll}$ dN/dy in different p+Pb centrality bins
  - Top: Glauber
  - Bottom: Glauber-Gribov CF, $\Omega = 0.55$
    - ⇒Observe centrality dependence
    - ⇒Interpretation depends on the geometric model

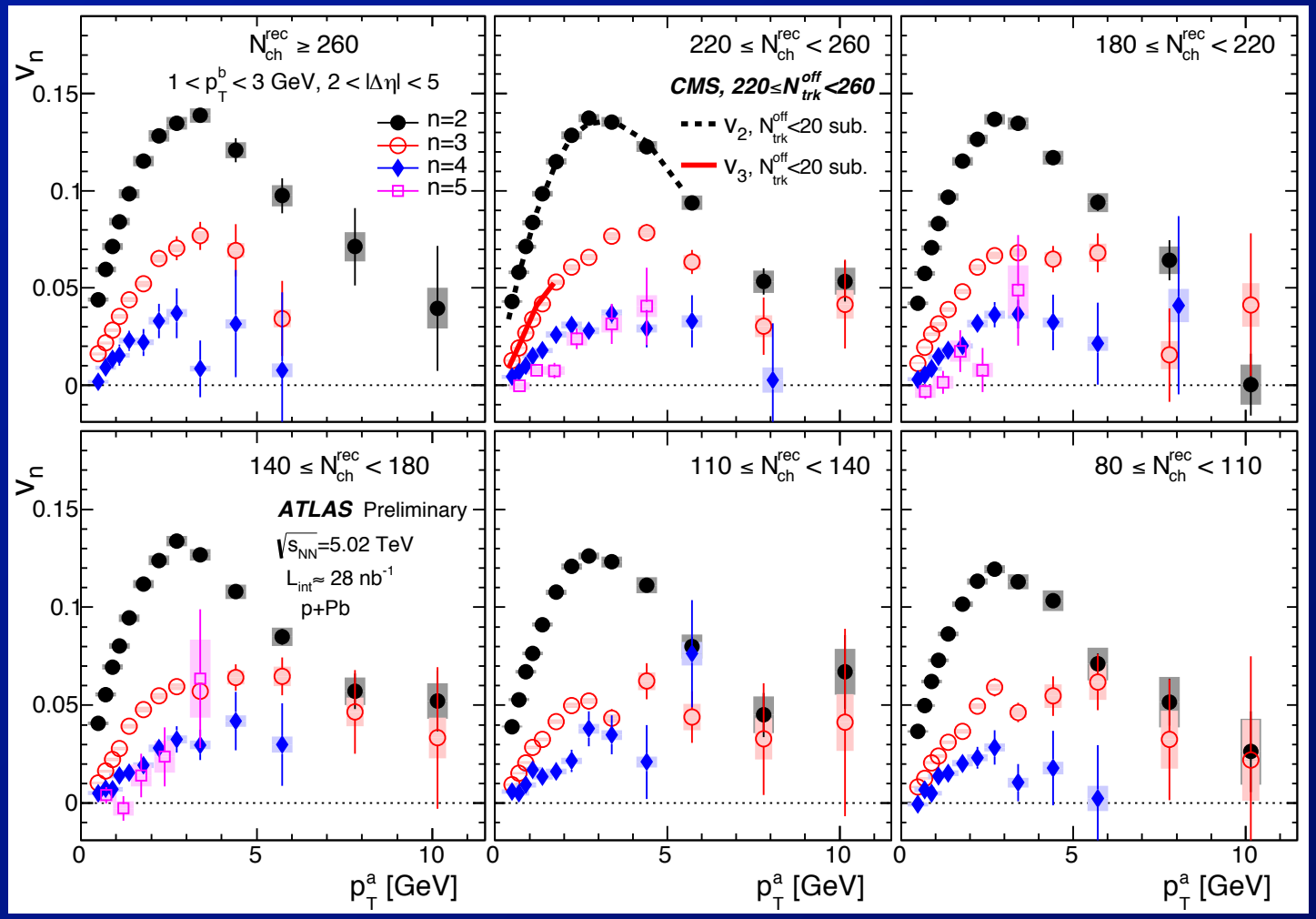
Glauber



Glauber-Gribov $\Omega = 0.55$

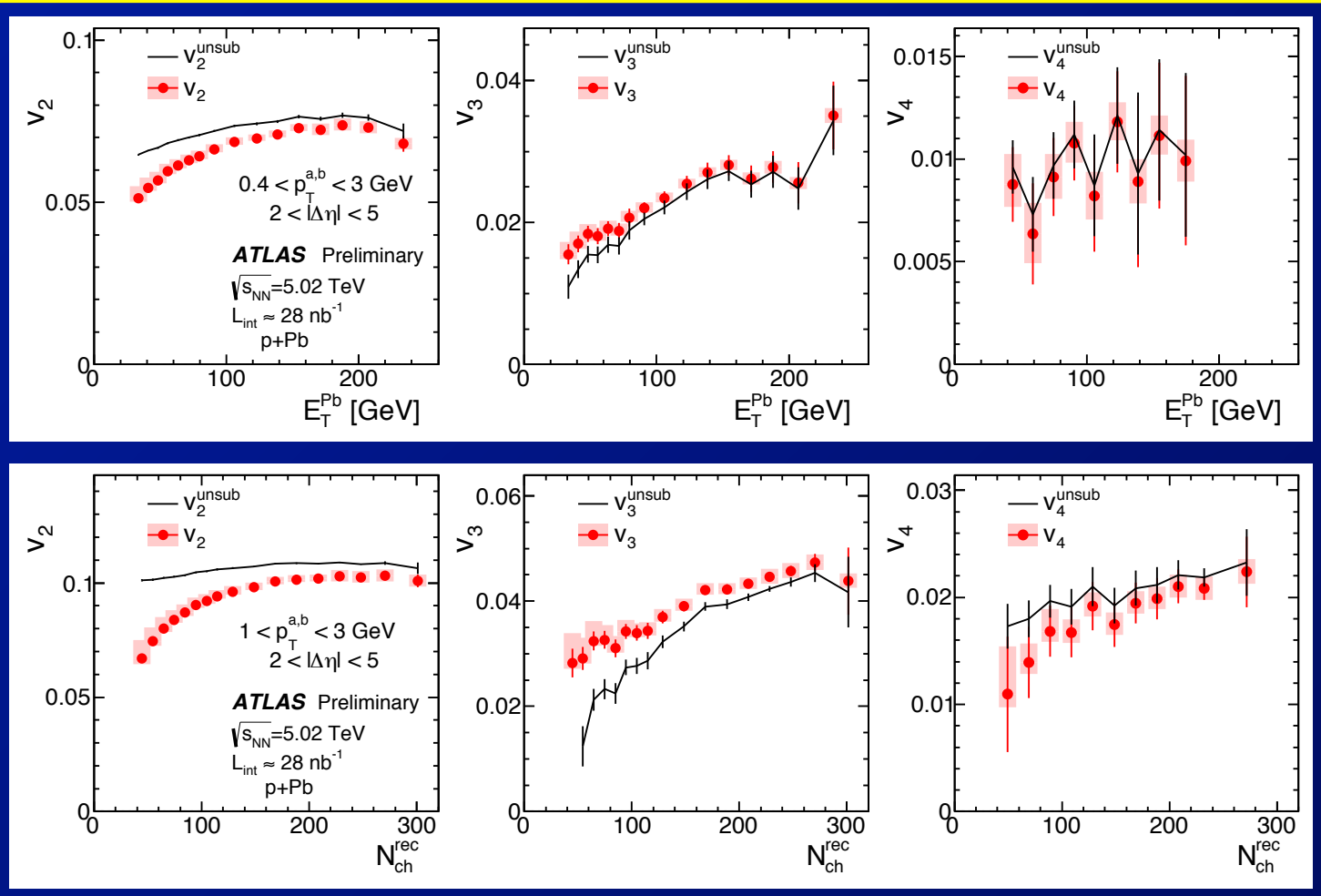


p+Pb 2-particle $v_n(p_T)$



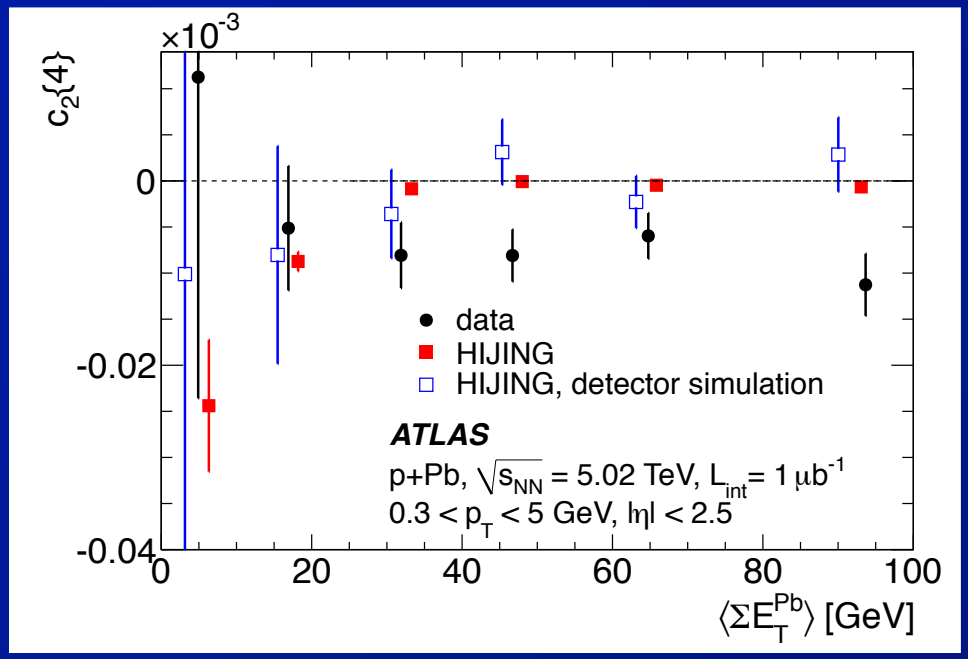
- **Observe significant values for n = 2,3,4,5**
  - **For n = 2,3 to 10 GeV**
    - ⇒ **Why to such high p_T?**

Event activity dependence

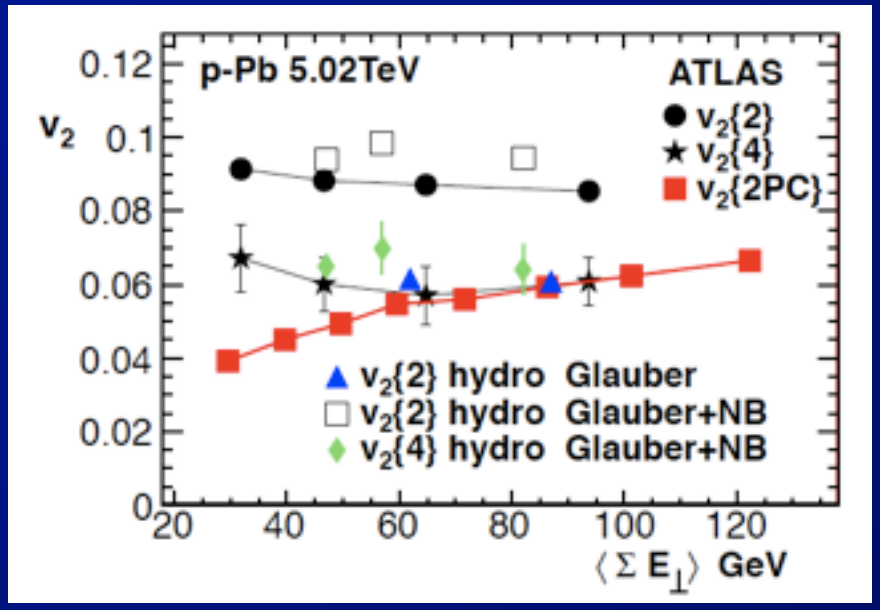


- Compare two ways of selecting event activity
  - Yield similar results
    - ⇒ Weak dependence on v_2, v_3, v_4 with activity
    - ⇒ Ridge yield scales w/ multiplicity but not v_n

p+Pb multi-particle correlations



hydrodynamic calculations by Bozek, Broniowski arXiv: 1304.3044



- 4-particle correlations using cumulants
  - $c_2\{4\}$ negative for global flow-like correlation
    - ⇒First demonstration of multi-particle behavior of the ridge(s)