

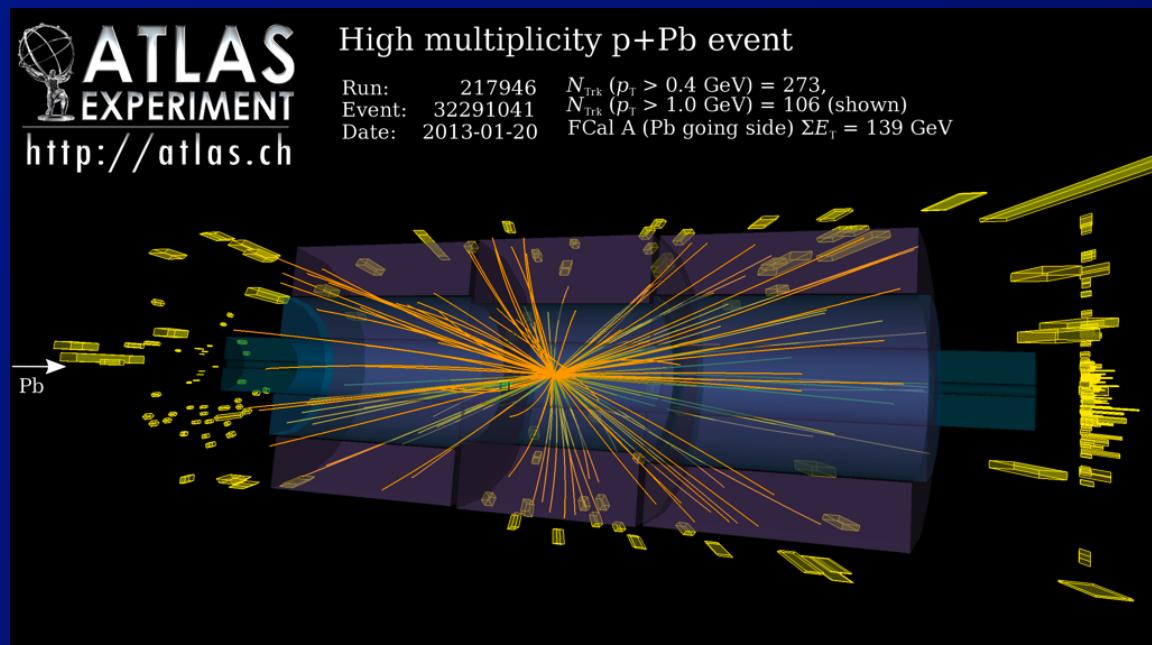
Measurement of long-range azimuthal anisotropies in pp and p+Pb collisions with the ATLAS detector.

Prof. Brian. A Cole
for the ATLAS collaboration

IS 2016 Conference
May 23, 2016



ATLAS



Measurement of long-range azimuthal anisotropies in pp and p+Pb collisions with the ATLAS detector.

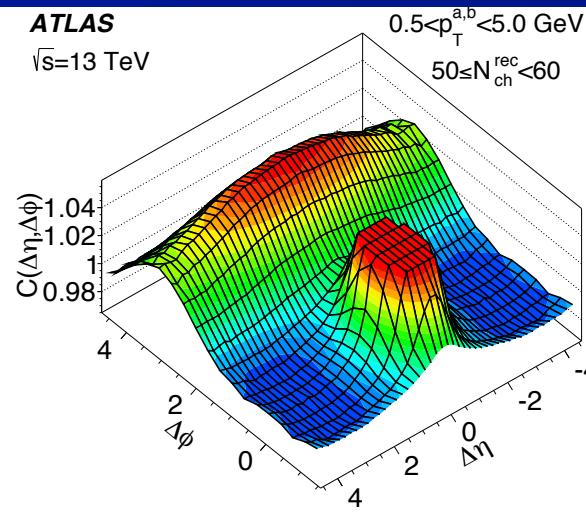
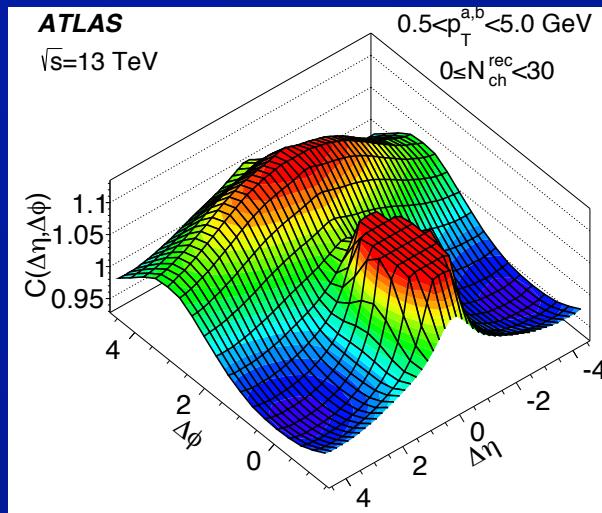
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I want to acknowledge essential contributions to these results by Soumya Mohapatra and Xiao Tu from Columbia University

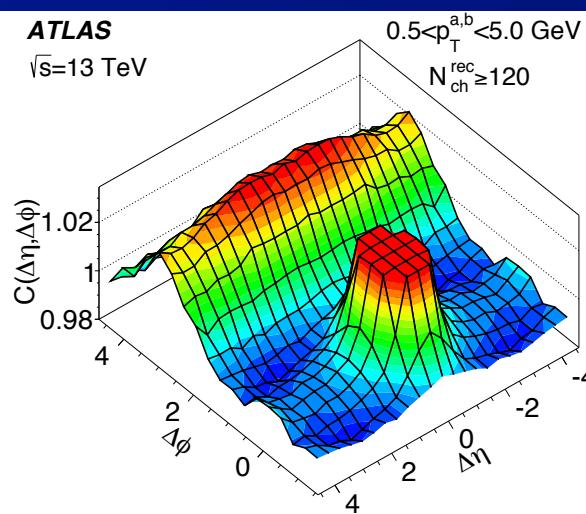
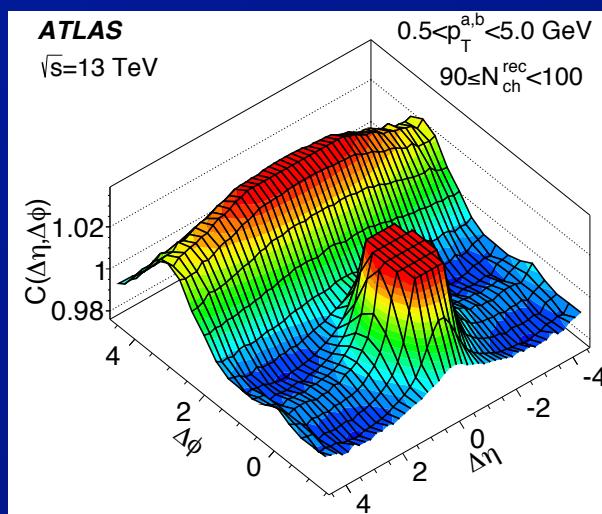


13 TeV 2-particle correlation function



For most of the results here:

$0.5 < p_T < 5$ GeV

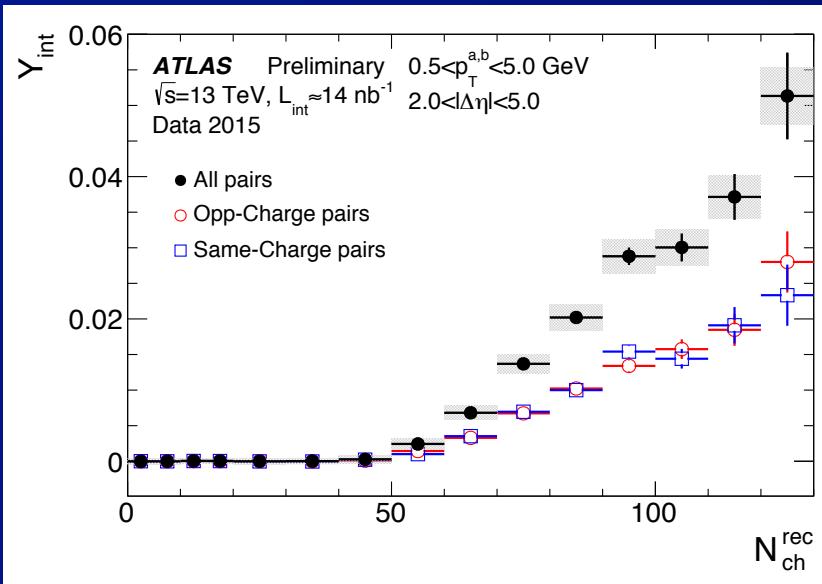
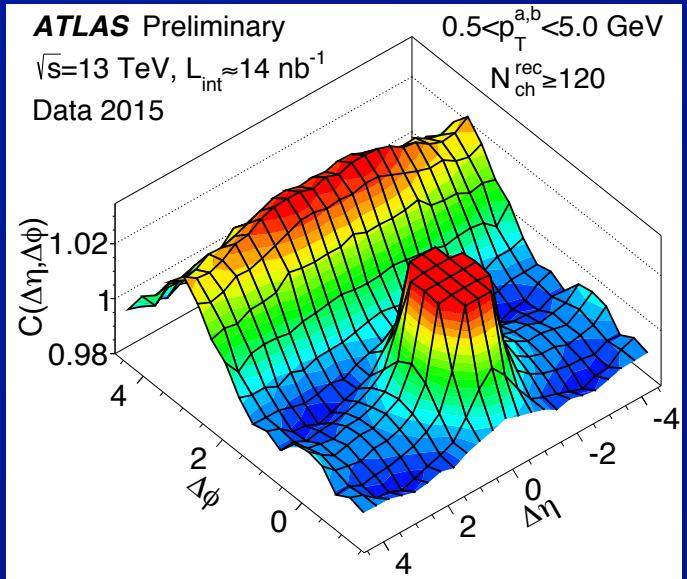


- Surprising nobody, ATLAS observed the ridge in in high-multiplicity 13 TeV p-p collisions
 - And not in low-multiplicity collisions (?)

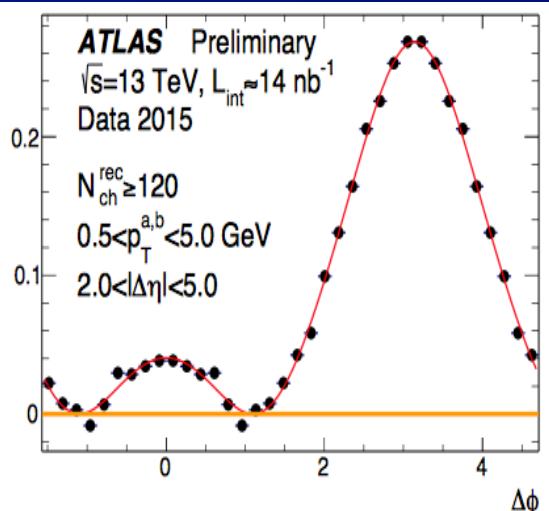
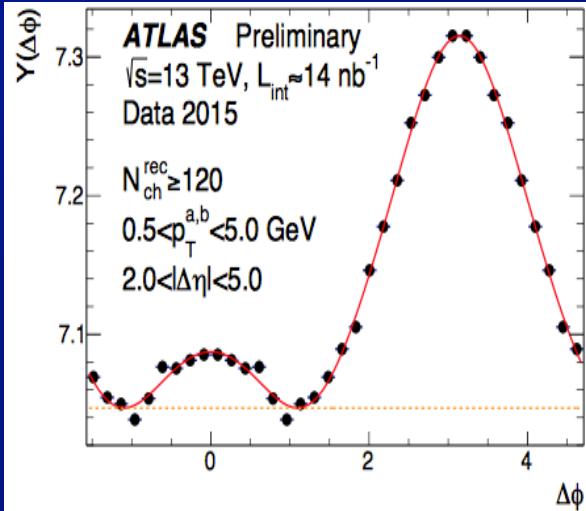
Ridge in 13 TeV p-p collisions

- “Usual” ridge analysis:

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

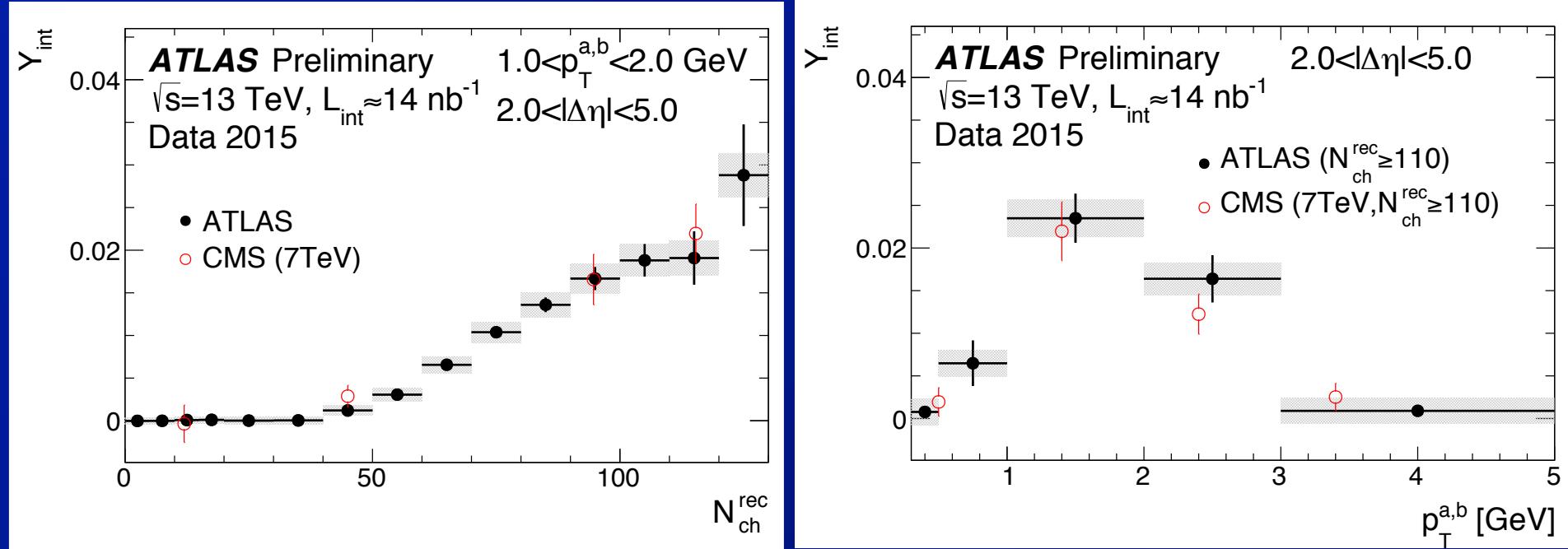


Project
long-range
component
onto $\Delta\phi$,
normalize
to obtain
per-trigger
yield



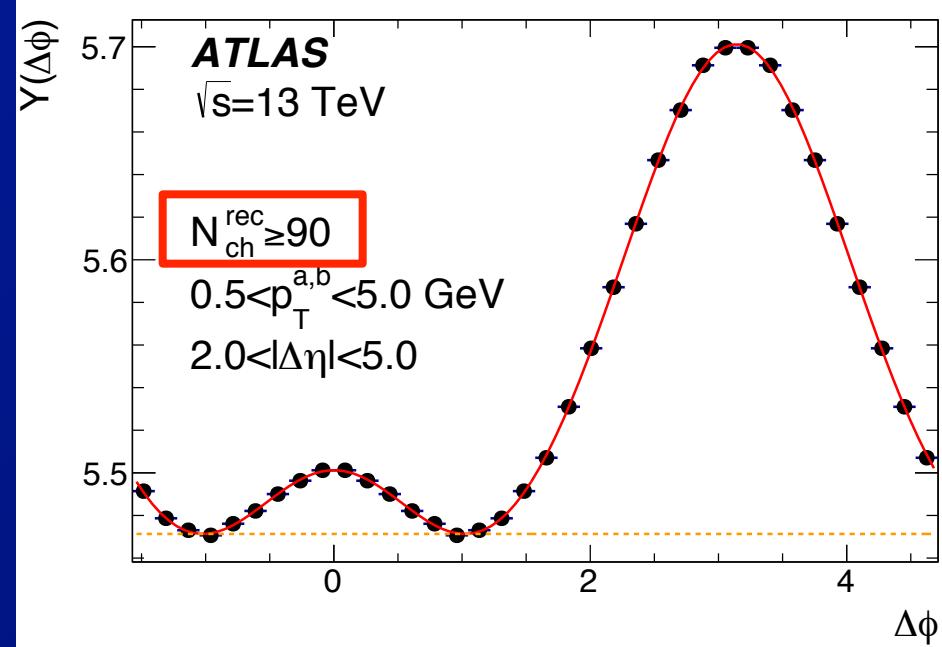
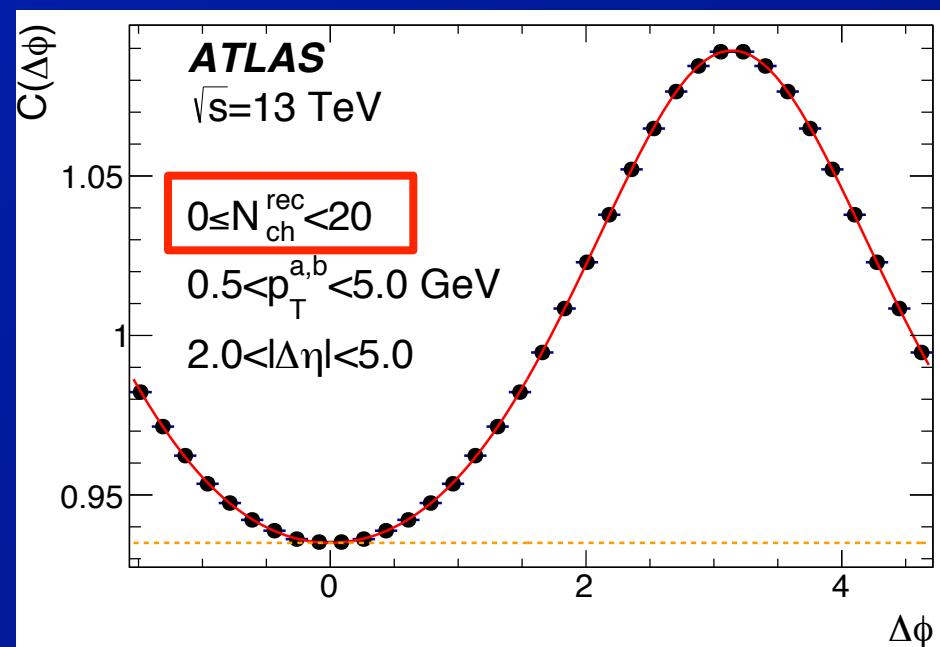
Assume yield
at minimum is
combinatorial
(ZYAM),
subtract flat
combinatorial,
integrate over
 $\Delta\phi$

Ridge yields: no \sqrt{s} dependence



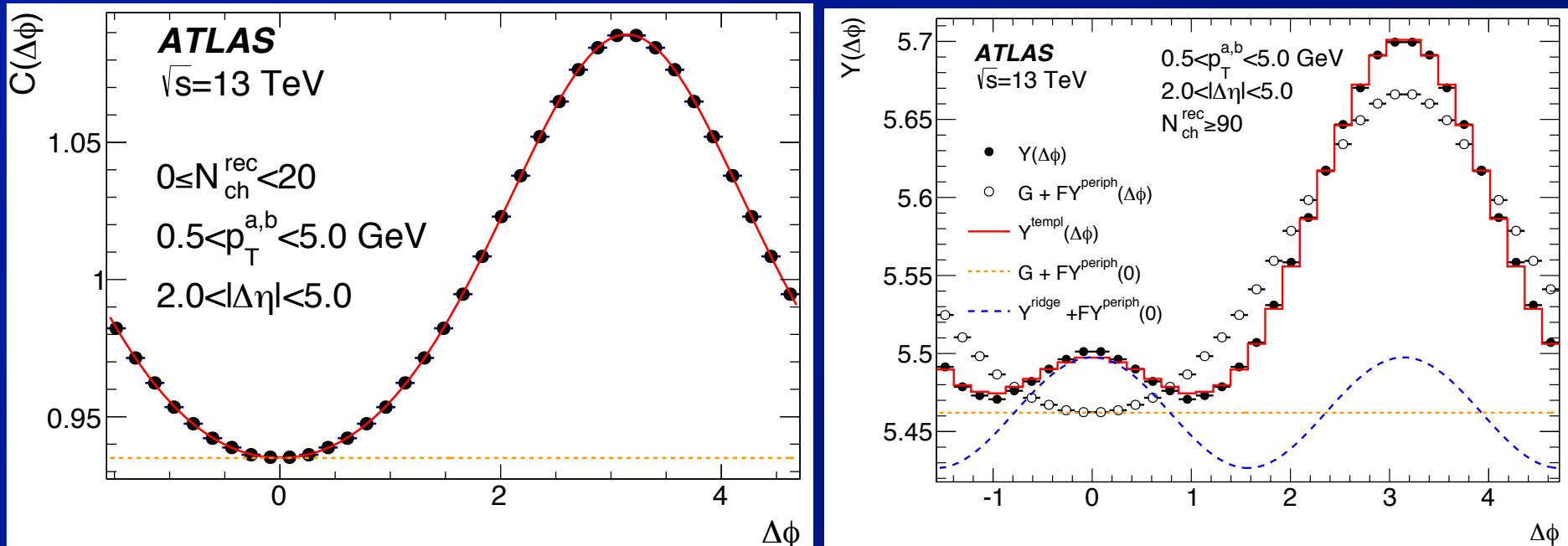
- Surprising us, the per-trigger yields in 13 TeV p-p collisions agreed with the CMS 7 TeV p-p data
 - both in absolute magnitude and in the dependence on multiplicity and p_{T}
- ⇒ Very weak or no dependence of ridge (yield) on center of mass energy in p-p collisions!

p-p ridge interpretation



- **Obvious question:**
 - Is the ridge associated with $\cos(n\Delta\varphi)$ modulation as was observed in p+Pb collisions?
⇒ And if so, do the phenomena have same origin?
- **Technical problem:**
 - ZYAM is clearly “broken” by the concavity seen in the low-multiplicity (AKA “peripheral”) correlation function

Template fitting method



- Simplest possible assumption:
 - Correlation observed in high-multiplicity events is superposition of same “hard” (?) correlation seen in low-multiplicity events + $\cos(2\Delta\varphi)$ modulation
- ⇒ Fit measured $Y(\Delta\varphi)$ distribution to

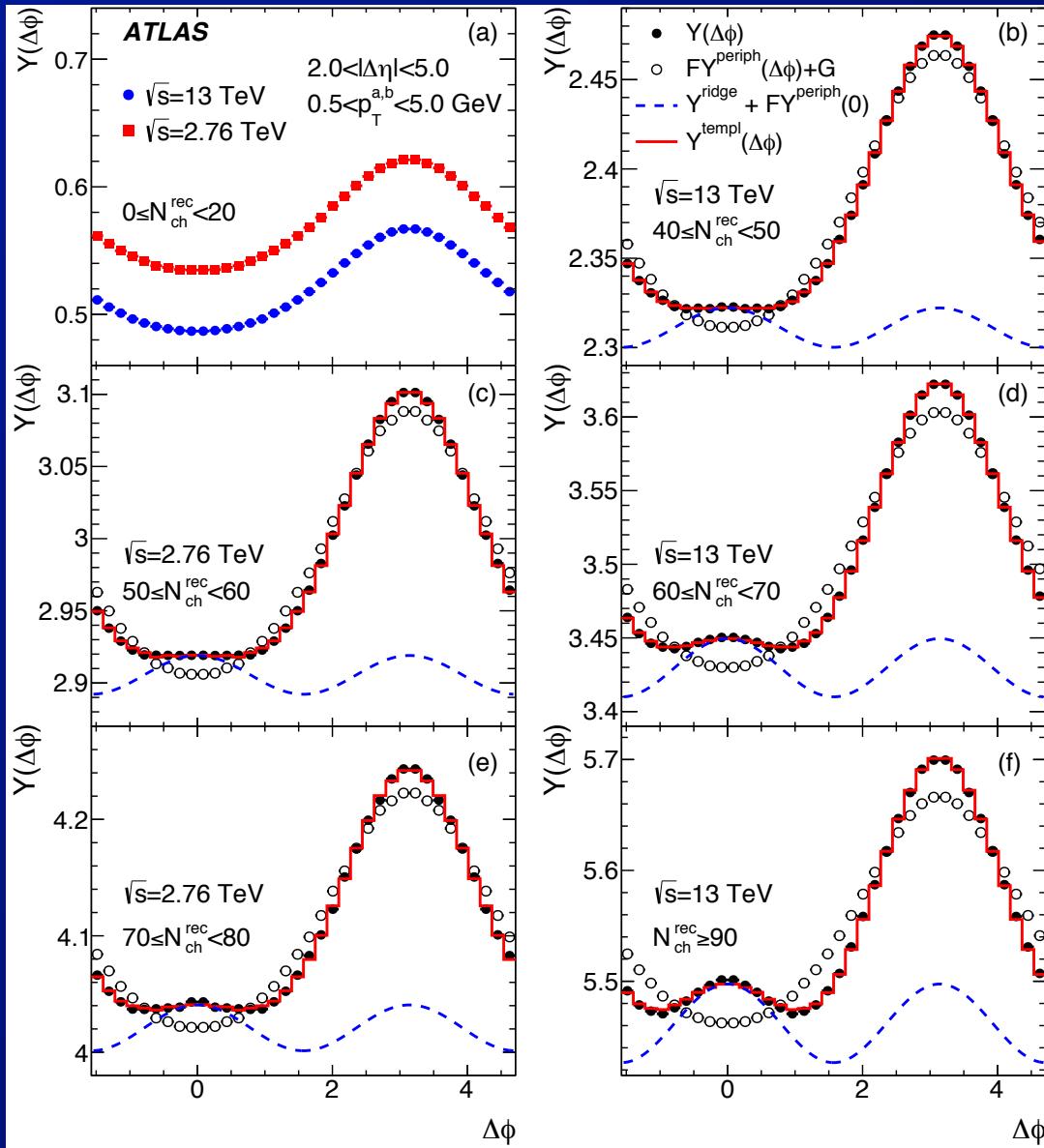
$$Y^{\text{templ}}(\Delta\phi) = F Y^{\text{periph}}(\Delta\phi) + Y^{\text{ridge}}(\Delta\phi),$$

⇒ with

$$Y^{\text{ridge}}(\Delta\phi) = G (1 + 2v_{2,2} \cos(2\Delta\phi))$$

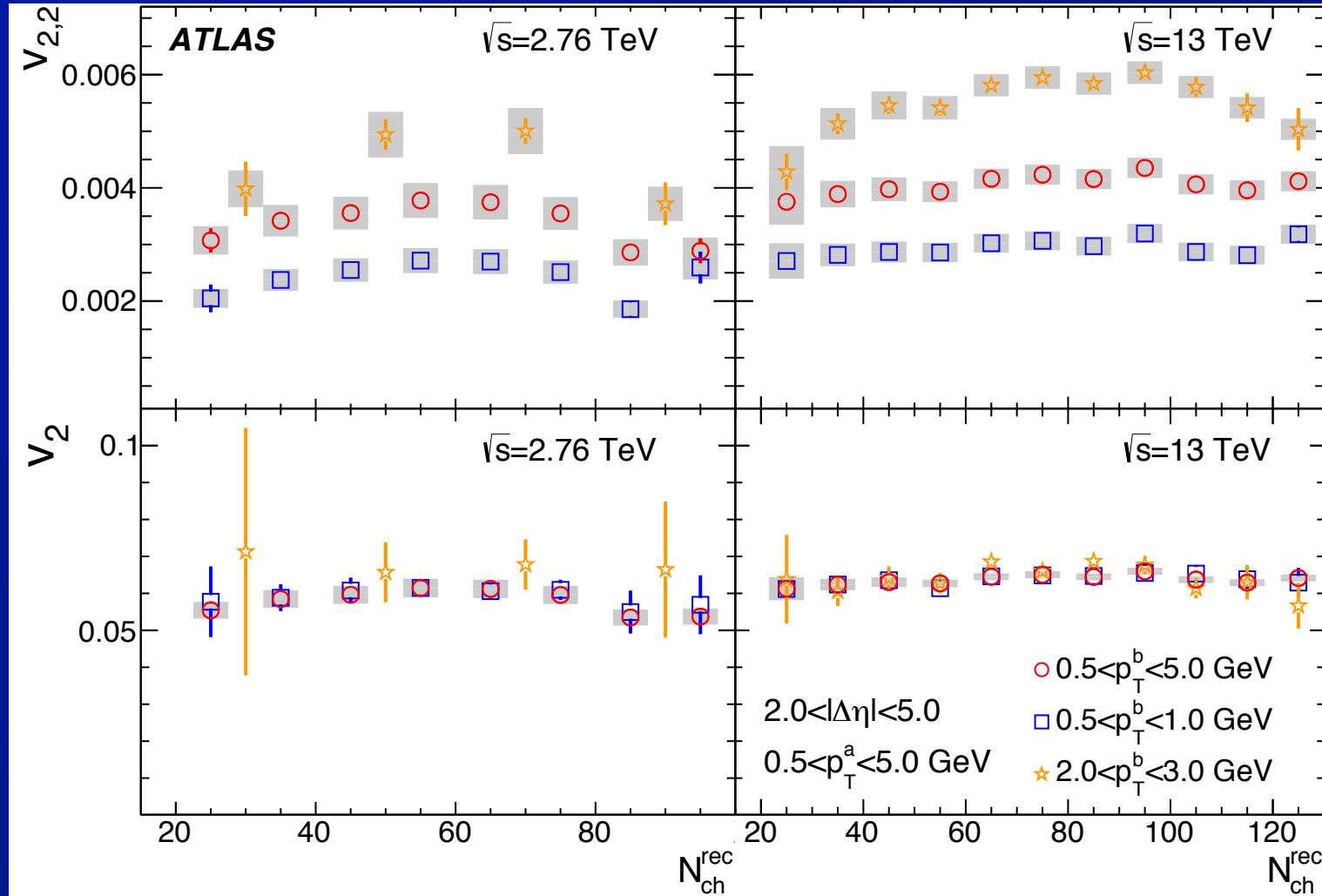
13 TeV 2-particle correlation function

- Template fits provide excellent description of the measured correlations
 - For both 13 TeV and 2.76 TeV p-p collisions
- Template fit also “solves” the failure of ZYAM method
 - ridge observed even in low-multiplicity events



⇒ $\cos(2\Delta\varphi)$ modulation of “underlying event” causes a narrowing of correlation function @ high multiplicity

13 TeV pp Template fit results

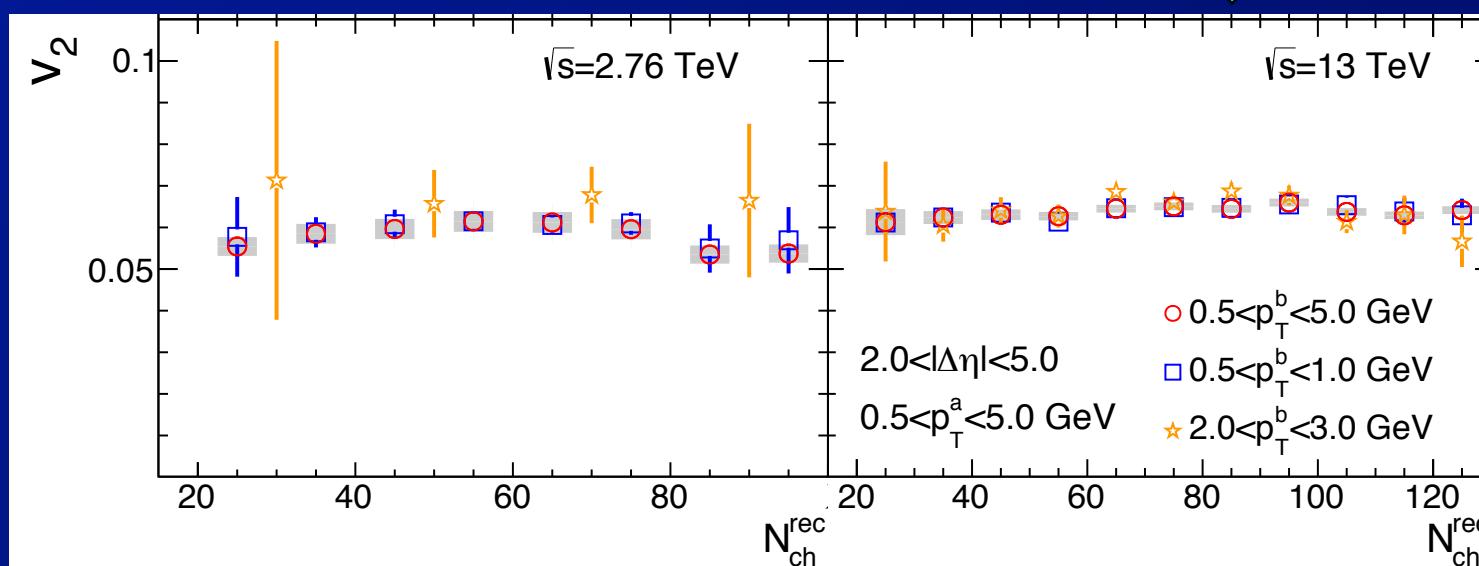
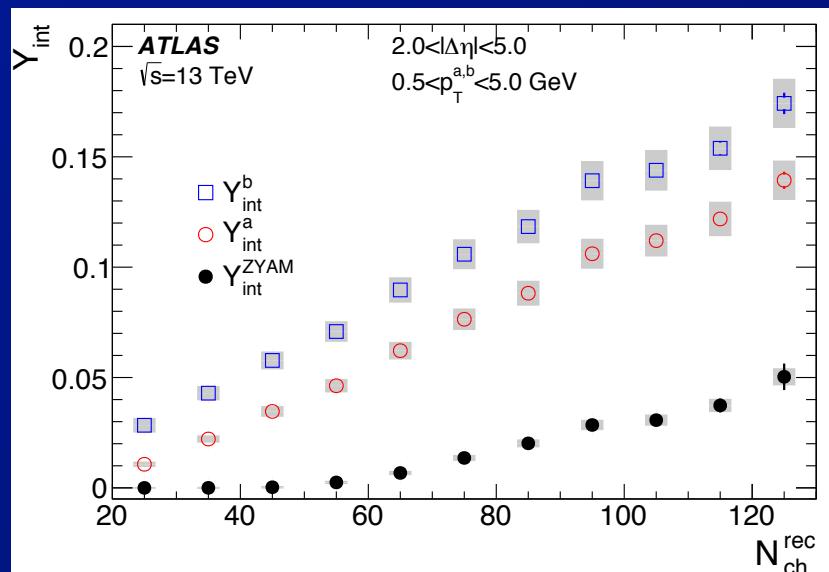
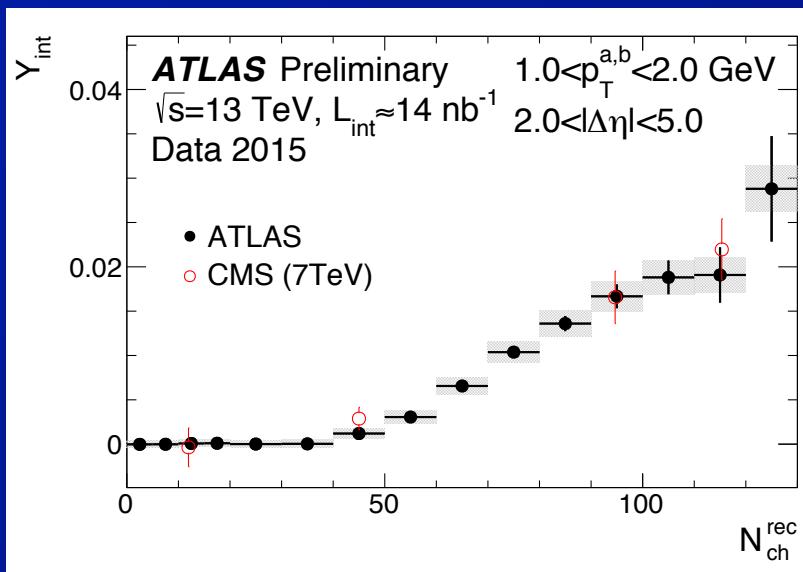


- ⇒ $v_{2,2}$ exhibits factorization
- ⇒ v_2 approximately constant versus multiplicity
- ⇒ v_2 agrees within errors between 2.76, 13 TeV

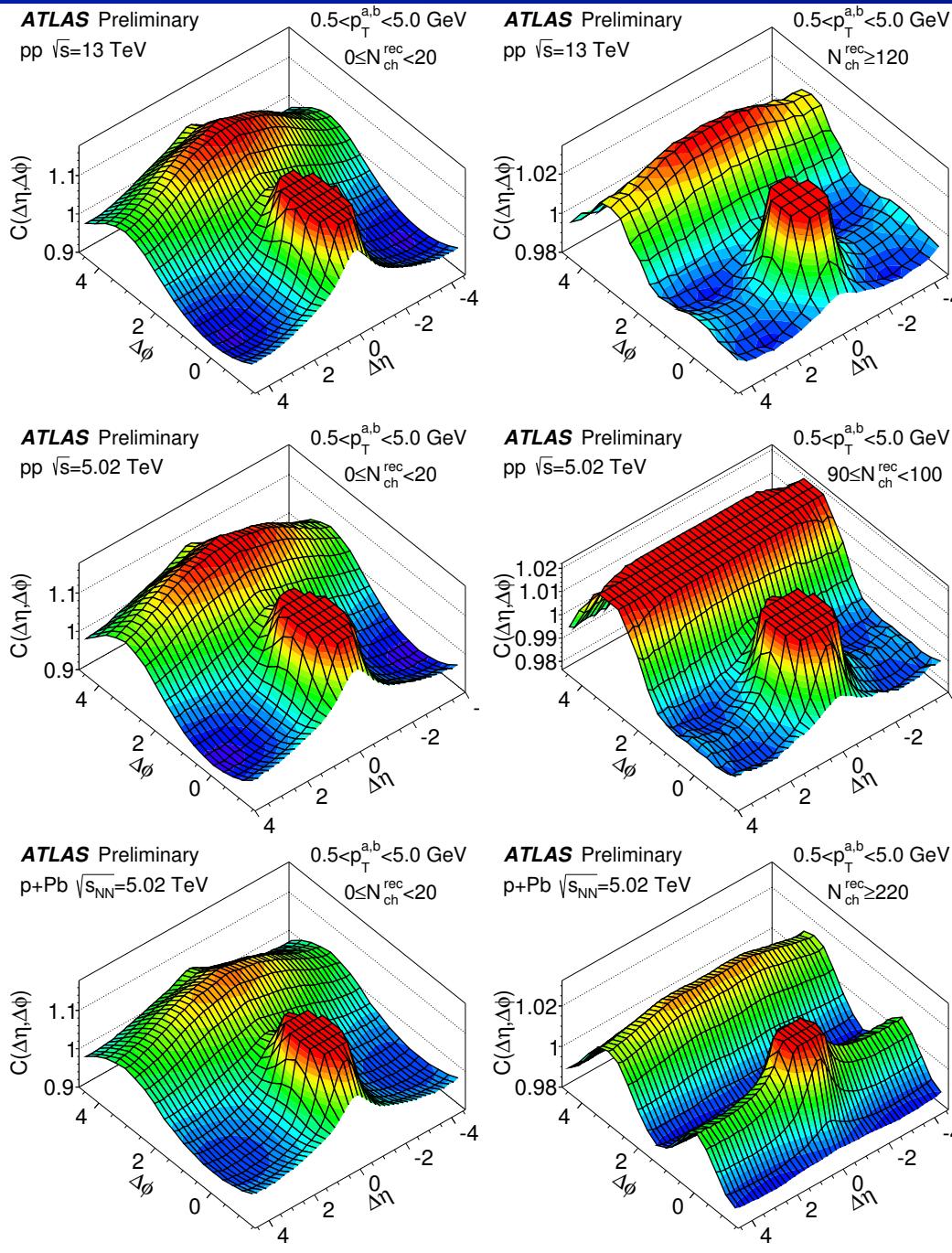
Integrated ridge yields

ZYAM

Template fit

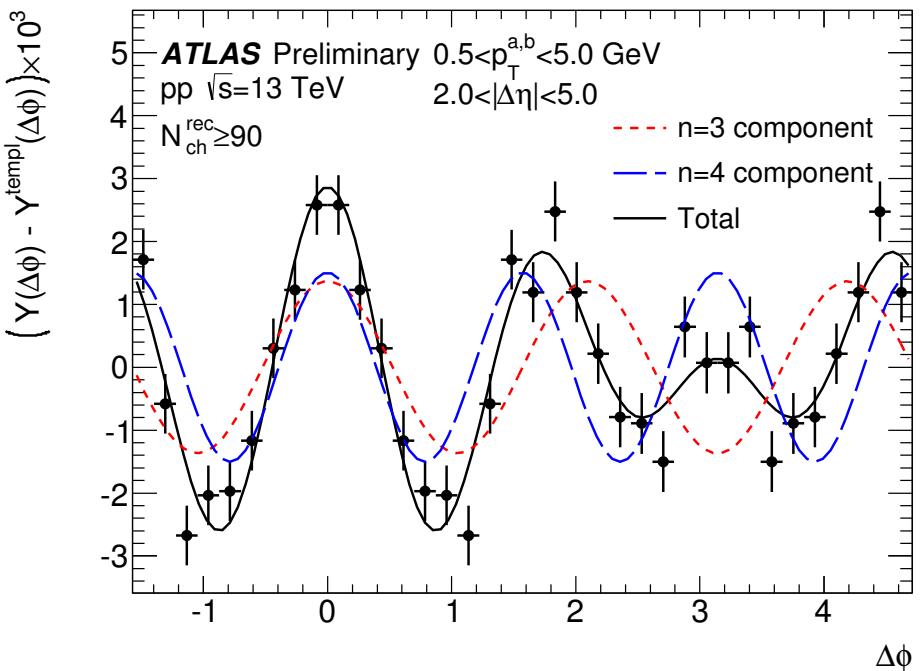
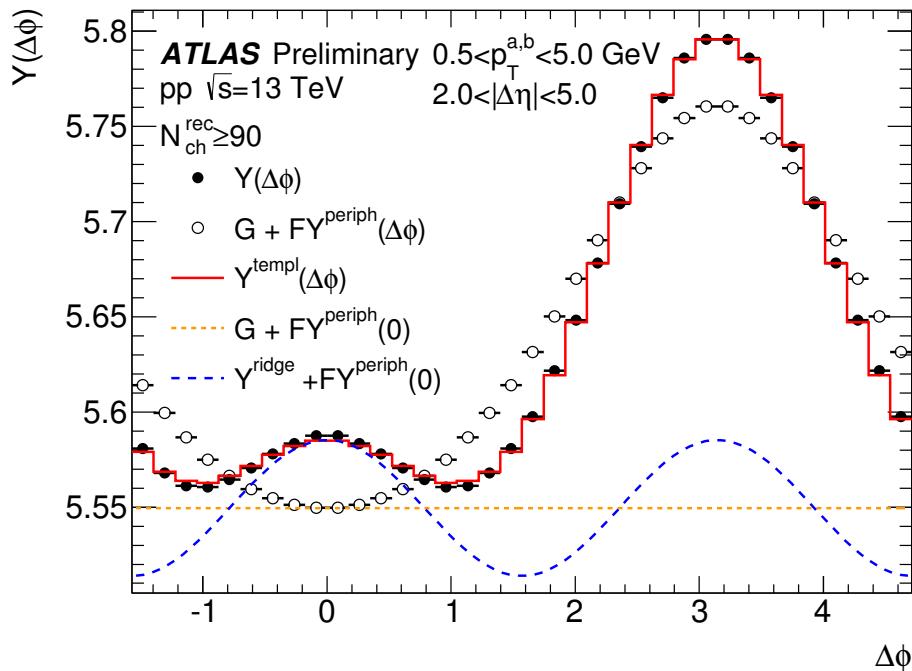


New Results for IS2016



- Update to 13 TeV pp PRL results with additional data from 2015
- 5.02 TeV pp data from 2015 heavy ion run
- Re-analysis of 5.02 TeV p+Pb using template fitting method

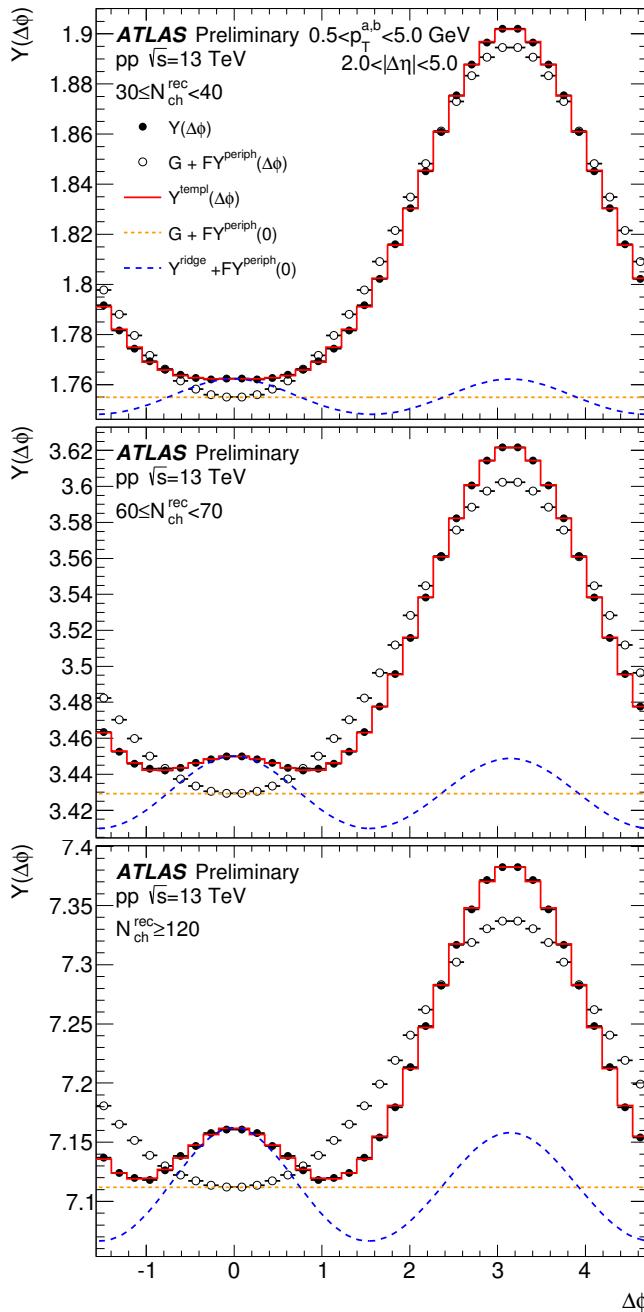
Including v3 and v4



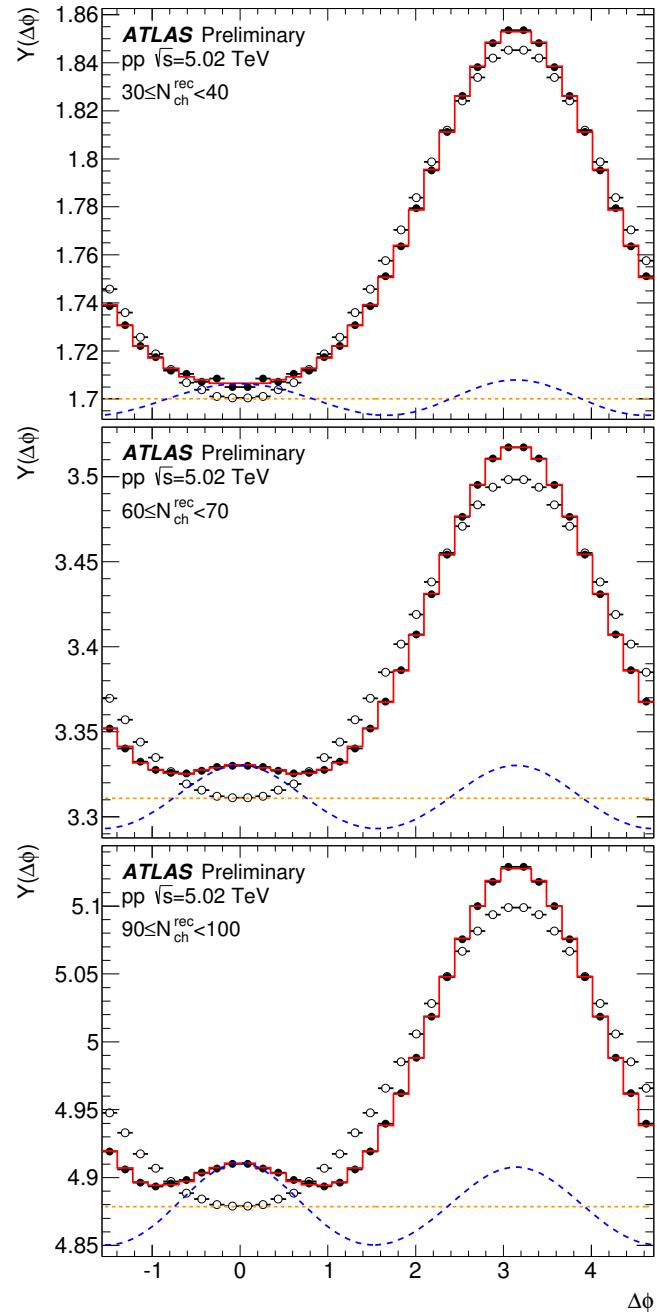
- Subtract template fit including only $\cos(2\Delta\varphi)$ term from the measured correlation functions
 - Observe clear higher harmonics
 - Especially:
 - Enhancement at $\Delta\varphi = 0$ cannot result from changes in shape of the hard component
 - Well described by sum of $\cos(3\Delta\varphi)$ and $\cos(4\Delta\varphi)$

13 and 5.02 TeV pp template fits

13 TeV pp

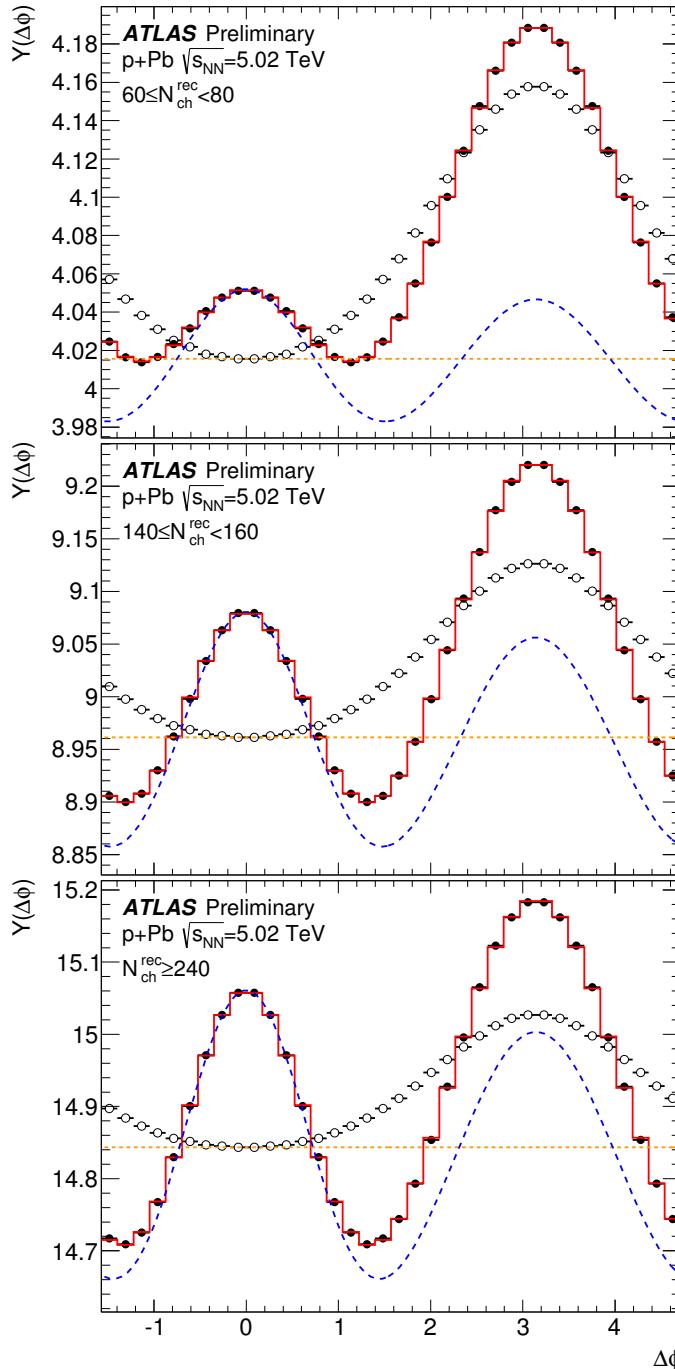
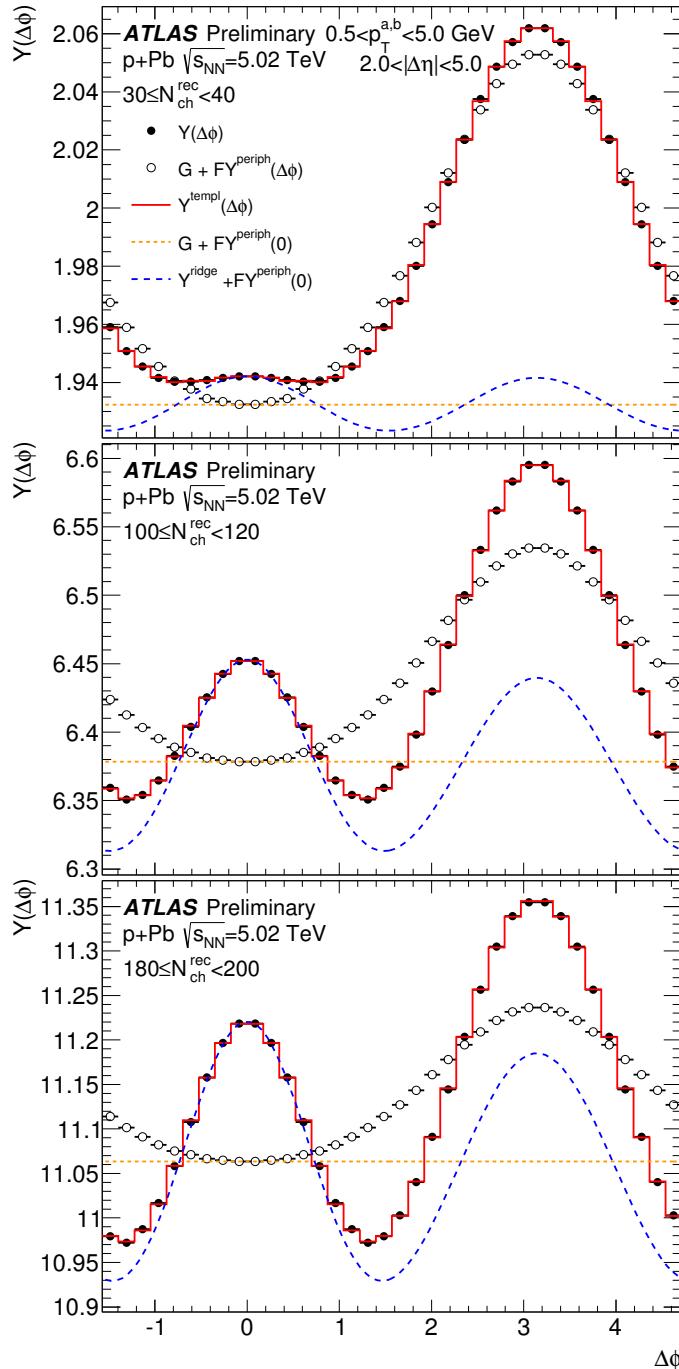


5.02 TeV pp

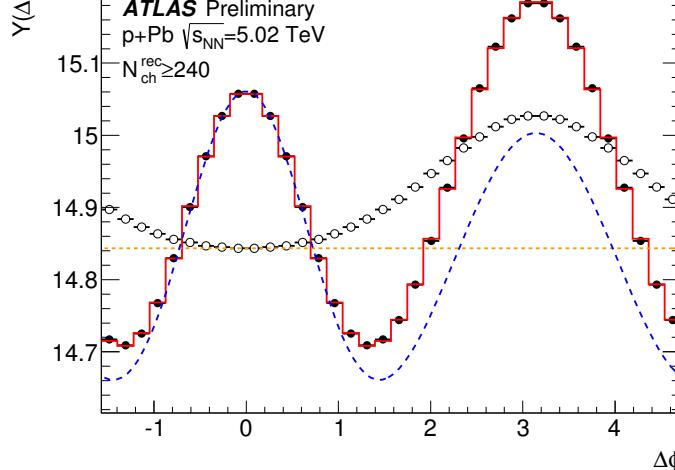
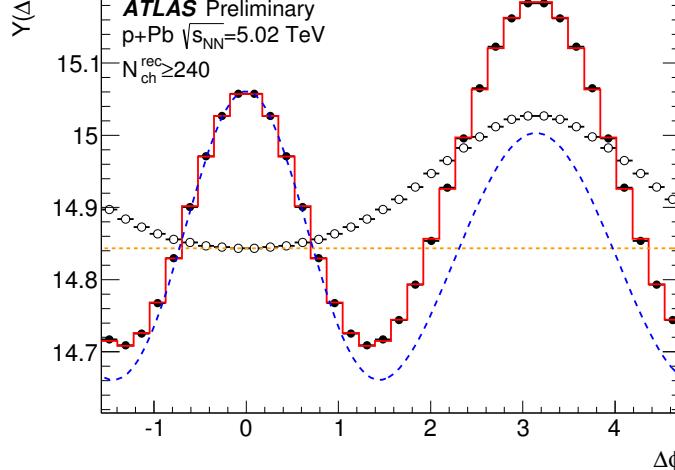
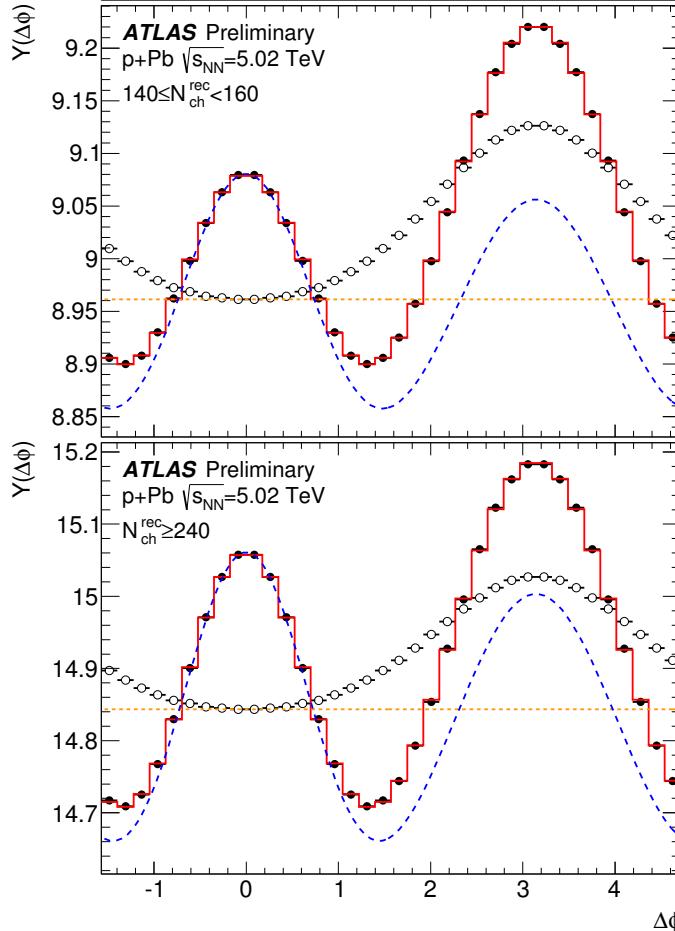
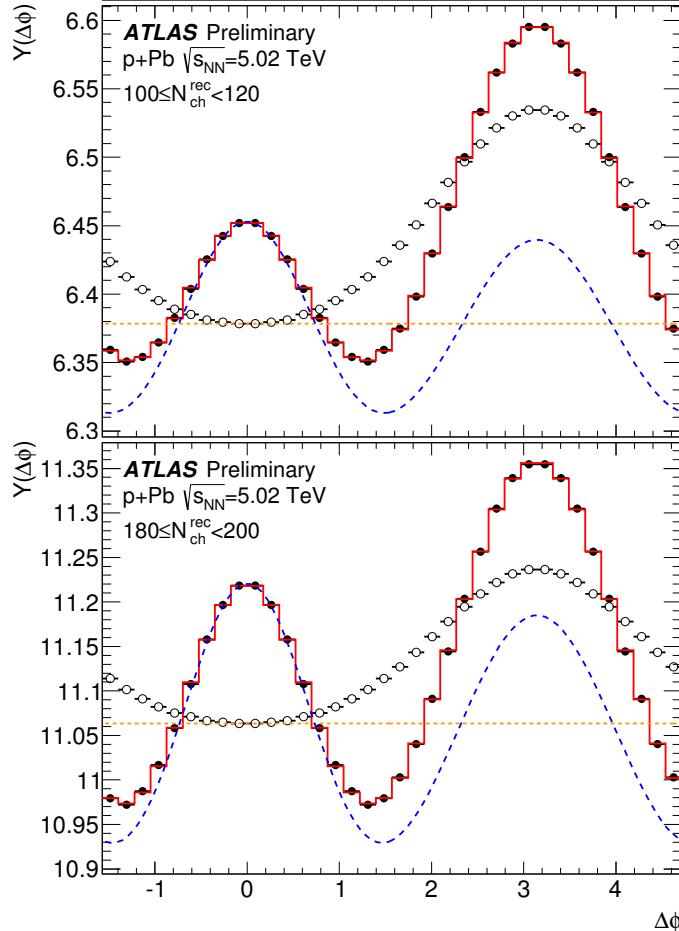


- Template fit now includes v_3 and v_4 terms
⇒ Data well described by fits in all multiplicity intervals

p+Pb template fits



- Template fits also work well in p+Pb collisions



Treatment of “peripheral” sample

- Clear that the v_2 persists to lowest multiplicities:

$$Y^{\text{periph}}(\Delta\phi) = Y^{\text{hard}}(\Delta\phi) + G_0 \left(1 + 2v_{2,2}^0 \cos(2\Delta\phi) \right)$$

- “Usual” treatment of the peripheral sample:

- Apply ZYAM to extract the “hard” component

⇒ But, if peripheral sample has v_2 , that is also included

- Effectively subtract $Y^{\text{hard}}(\Delta\phi) + G_0 \left(1 + 2v_{2,2}^0 \cos(2\Delta\phi) \right)$

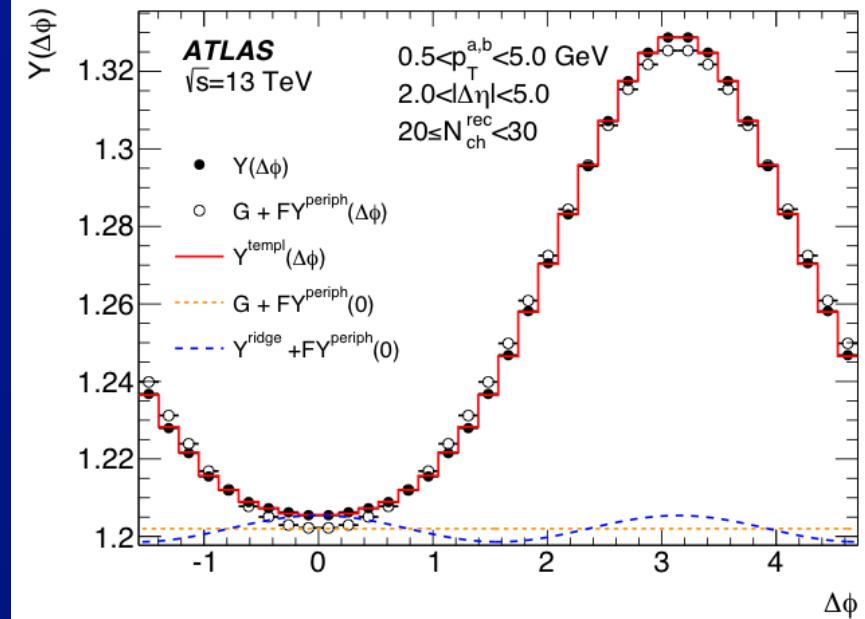
⇒ Bias the v_2 extracted from other multiplicity interval

- However, if no subtraction is applied to Y^{periph} :

- Effectively subtract $Y^{\text{hard}}(\Delta\phi) + G_0 \left(1 + 2v_{2,2}^0 \cos(2\Delta\phi) \right)$

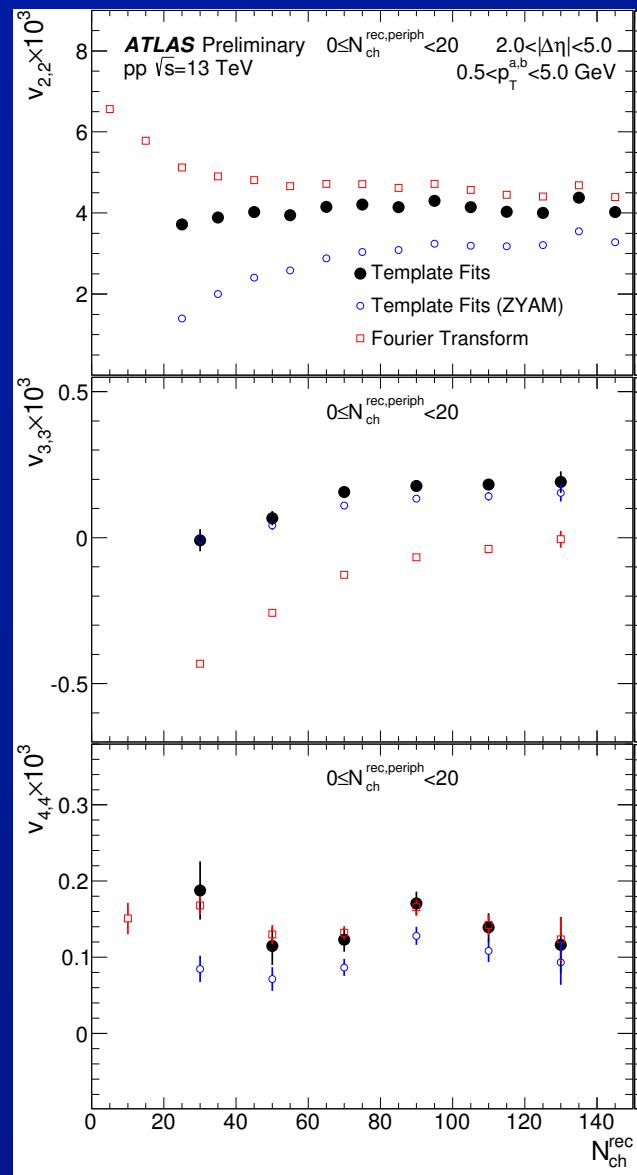
⇒ Bias the “G” in $Y^{\text{ridge}}(\Delta\phi) = G \left(1 + 2v_{2,2} \cos(2\Delta\phi) \right)$

⇒ But much smaller bias on $v_{2,2}$, none if $v_{2,2}$ constant

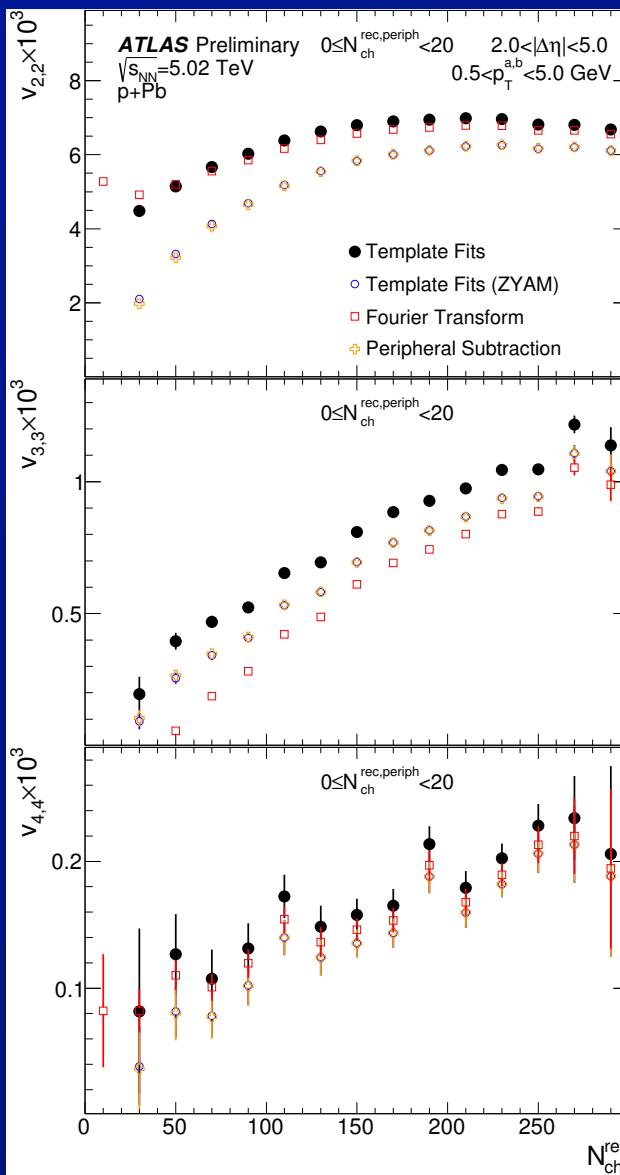


p+Pb template fit $v_{n,n}$

13 TeV pp

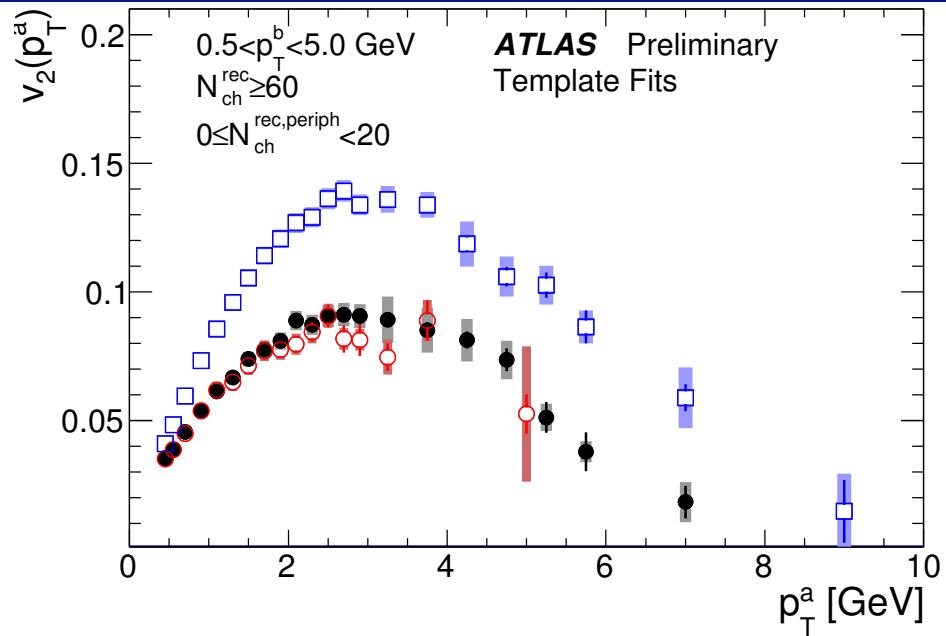
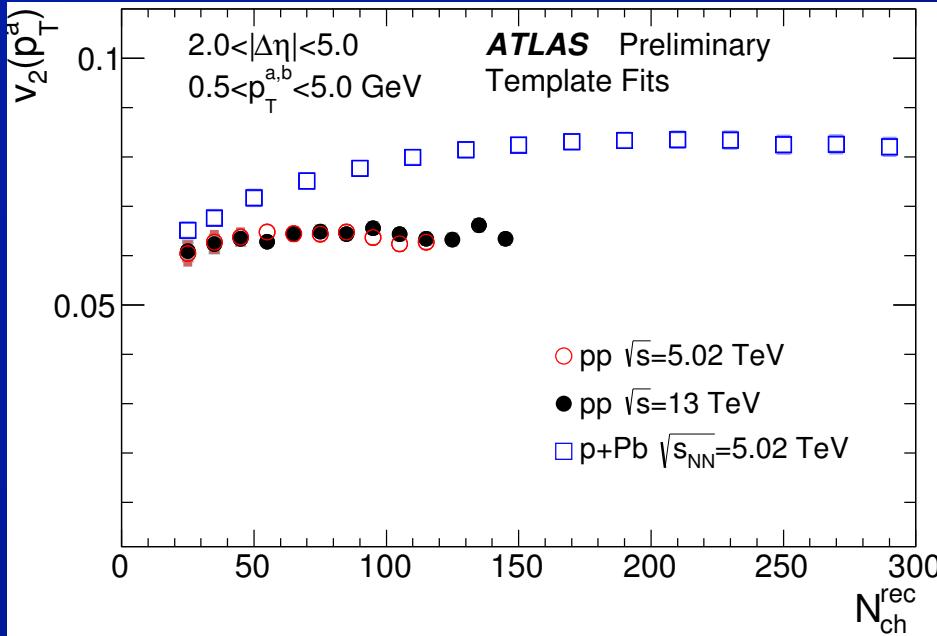


5.02 TeV p+Pb



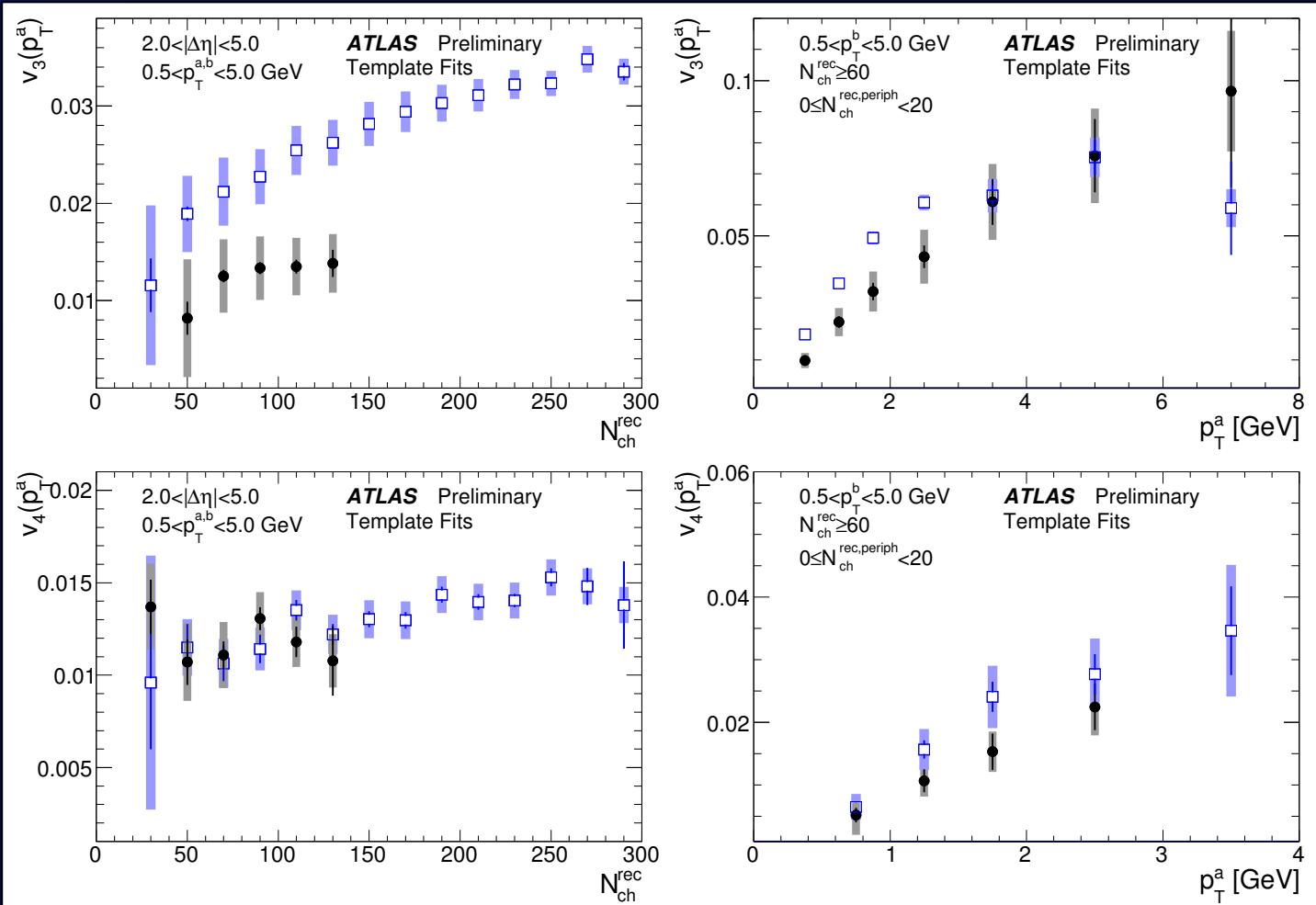
- Template fit $v_{n,n}$ values using both methods of treating peripheral bin
 - Also compared to peripheral subtraction used previously in p+Pb
- ⇒ Template fits produce higher $v_{2,2}$ especially @ low multiplicity
- ⇒ Smaller effect of peripheral ZYAM for $v_{3,3}$ and $v_{4,4}$

Comparison of v_2 values



- Comparing 5.02 and 13 TeV pp
 - Agree ~everywhere
⇒ Consistent with PRL results for 13 TeV and 2.76 TeV
- Comparing pp and p+Pb
 - pp and p+Pb ~consistent @ low multiplicity, but p+Pb increases while pp remains constant

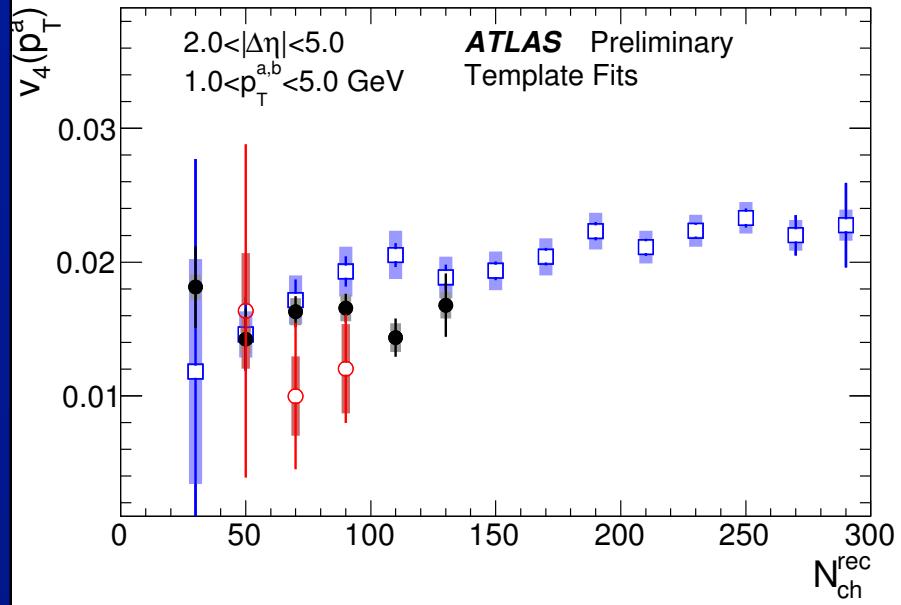
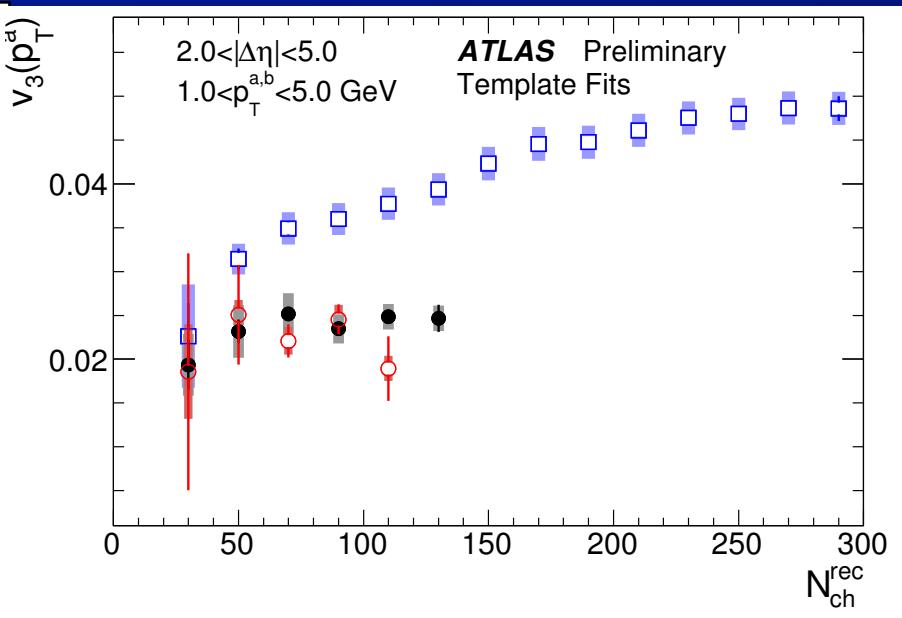
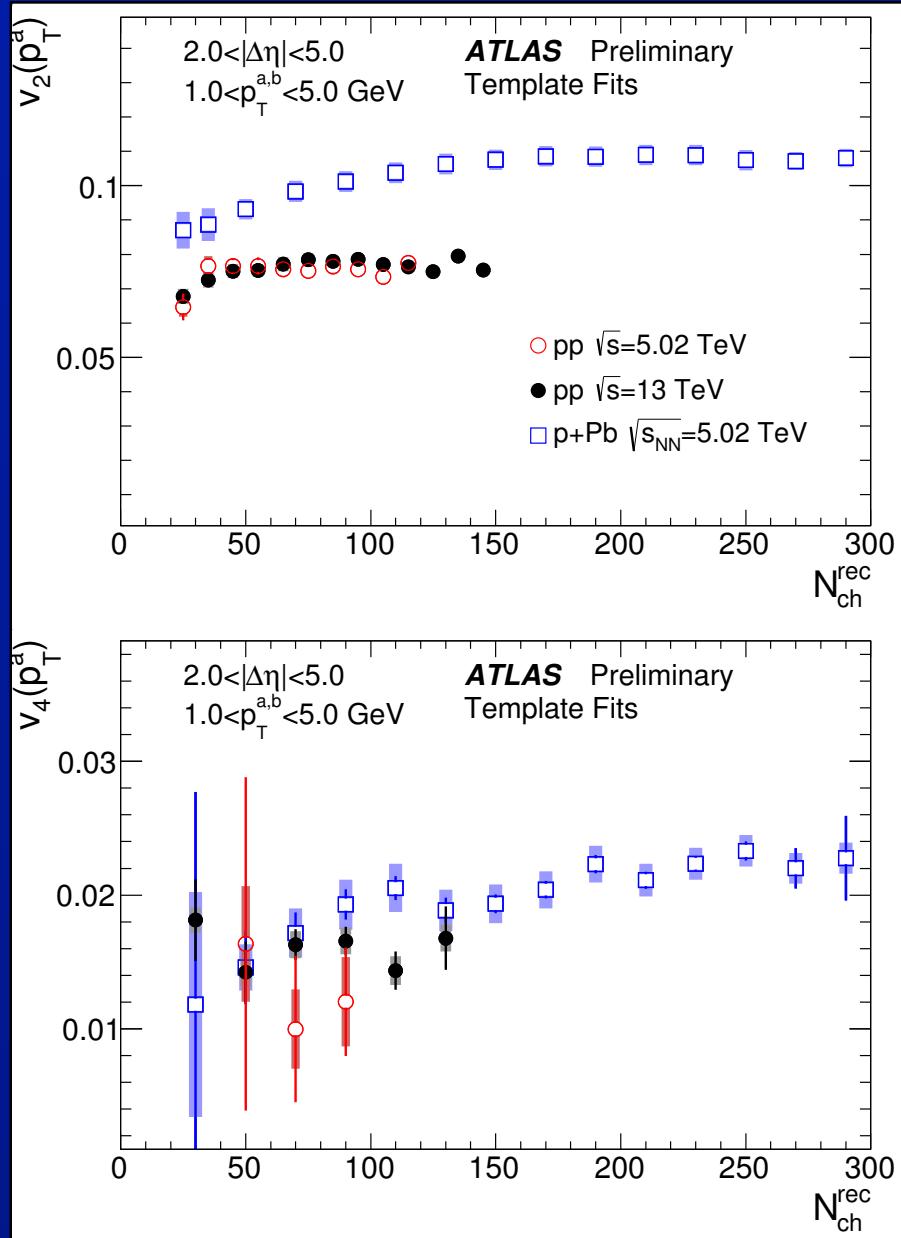
Comparison of v_3 , v_4 values



• Observe

- 13 TeV pp v_3 and v_4 constant versus multiplicity while p+Pb v_3 rises (v_4 ?)
- ⇒ similar to v_2 observation
- v_3 p_T dependence suggests (hard) bias @ high p_T

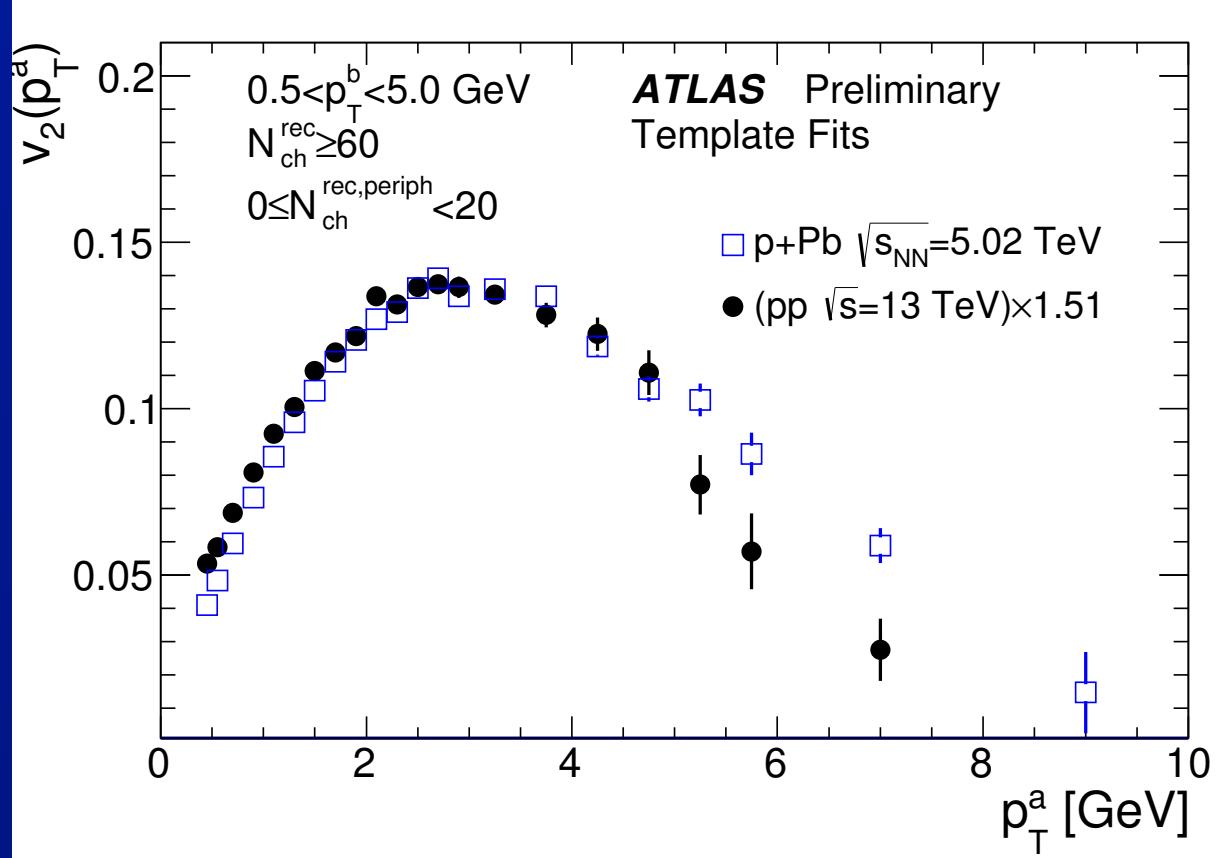
Using a higher p_T range



- Can also extract v_3 , v_4 in 5.02 TeV pp collisions
 - agrees with 13 TeV pp results

Compare pp, p+Pb $v_2(p_T)$

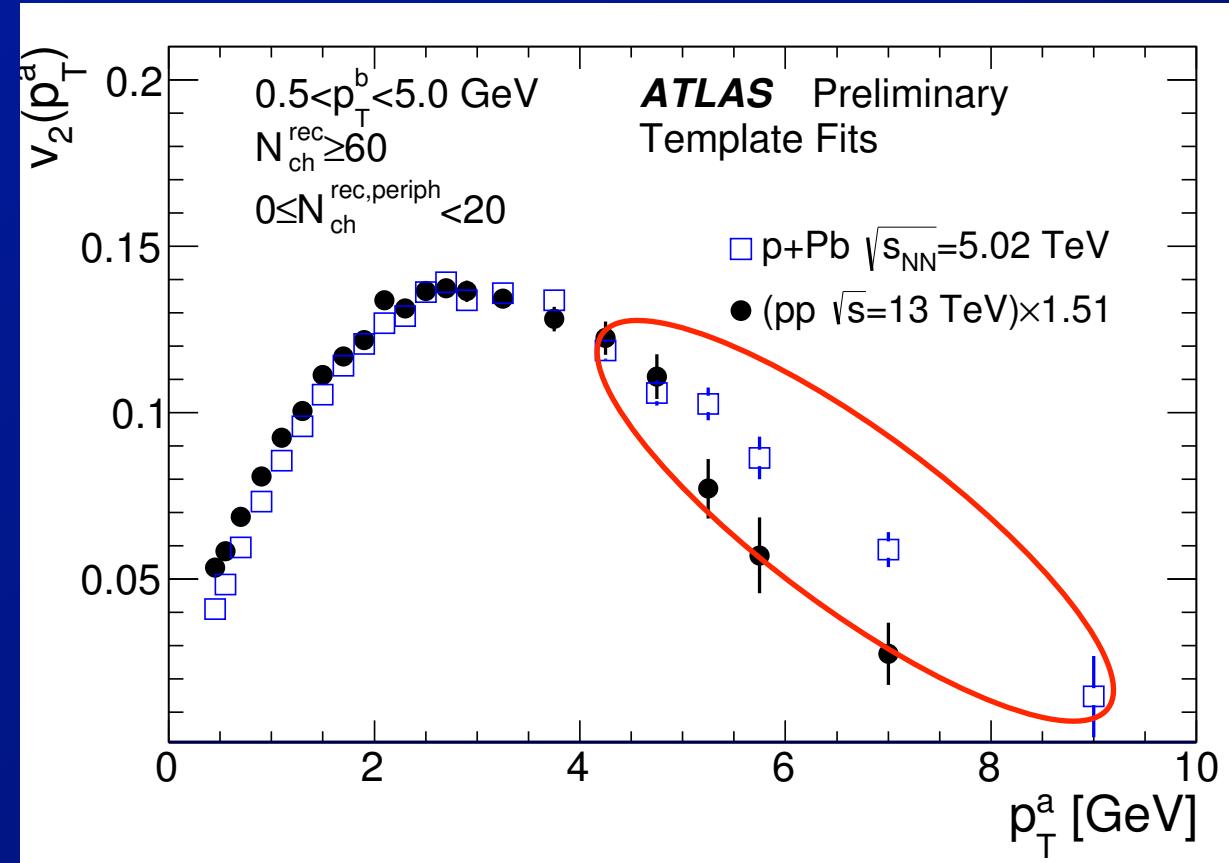
- Compare $v_2(p_T)$ after multiplying pp values by empirical factor of 1.51
 - Generally, good agreement
- ⇒ pp and p+Pb v_2 have ~same trends vs p_T



Compare pp, p+Pb $v_2(p_T)$

- Compare $v_2(p_T)$ after multiplying pp values by empirical factor of 1.51

– Generally, good agreement
 ⇒ pp and p+Pb v_2 have ~same trends vs p_T



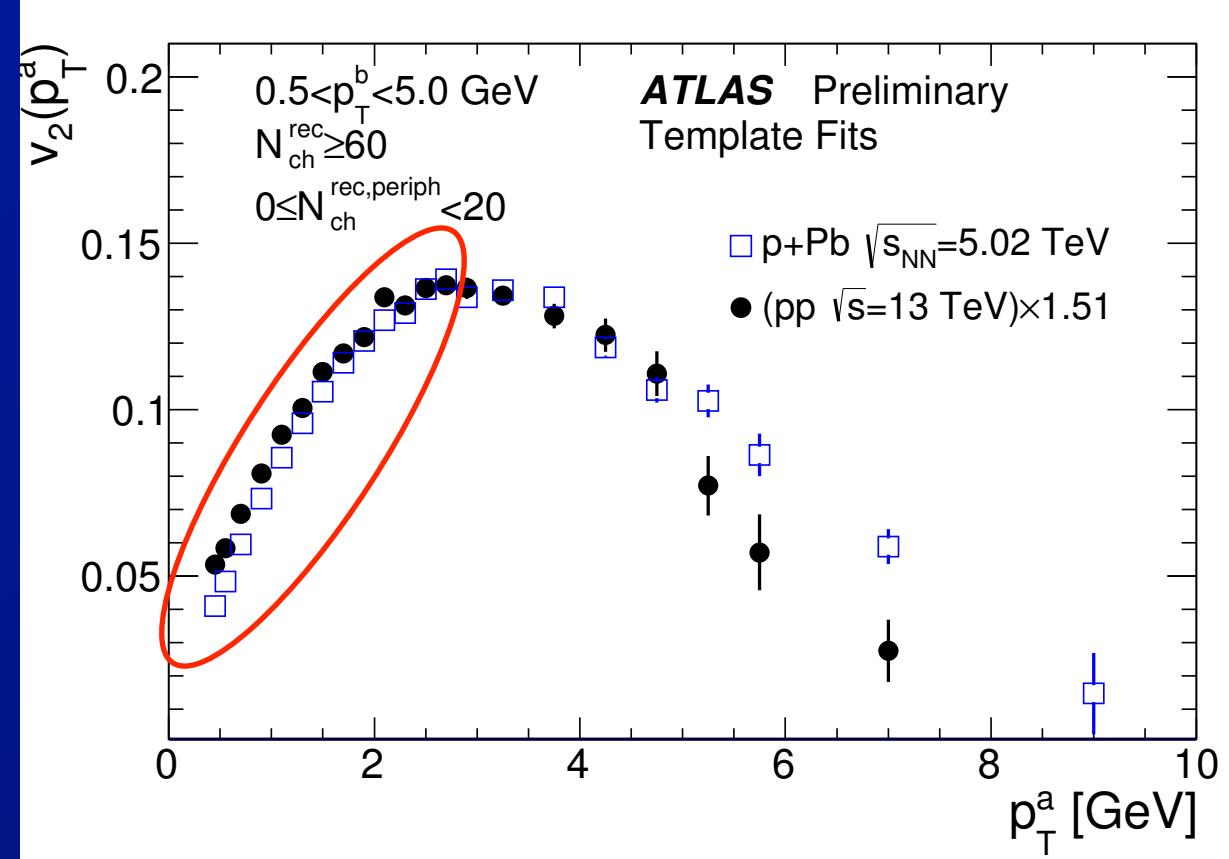
- But:
 - Differences @ high p_T due to growth in the width of the pp “hard” $\Delta\varphi$ distribution with multiplicity for $p_T > 5-6$ GeV
 ⇒ In a way it’s comforting to see the expected pQCD effects show up, but only at higher p_T

Compare pp, p+Pb $v_2(p_T)$

- Compare $v_2(p_T)$ after multiplying pp values by empirical factor of 1.51

- Generally, good agreement

⇒ pp and p+Pb v_2 have ~same trends vs p_T



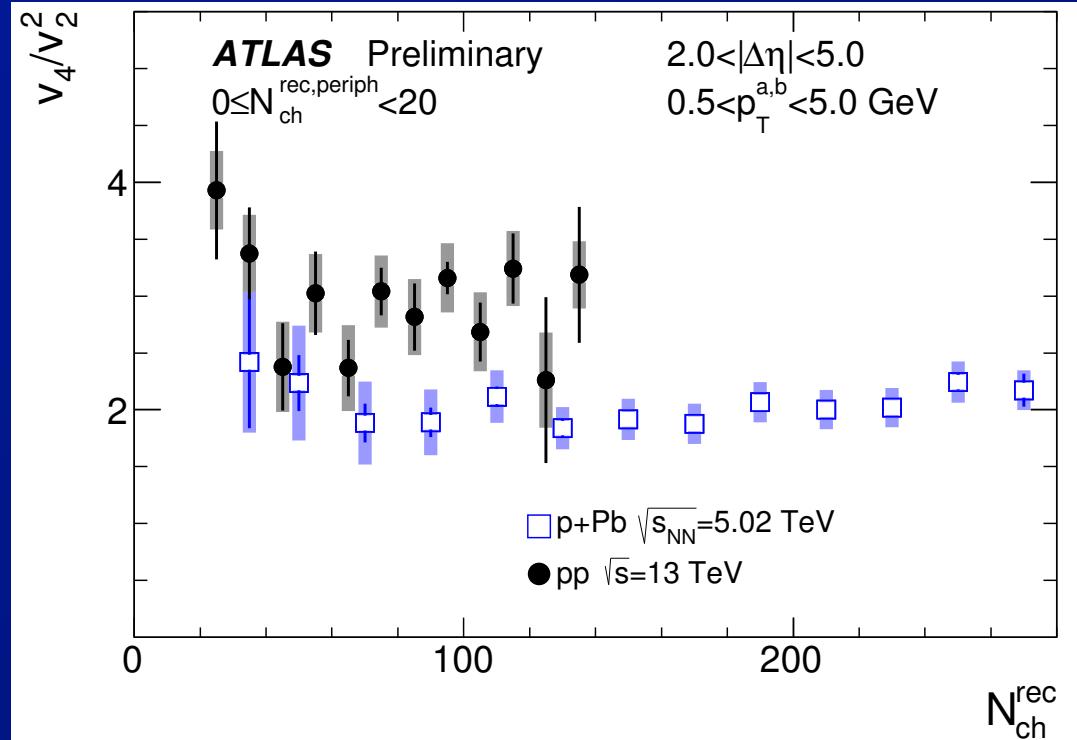
- But:
 - Subtle differences in the slope & intercept at low- p_T
- ⇒ not yet understood.

pp and p+Pb v_4/v_2^2

- ATLAS E-by-E measurements in Pb+Pb have shown non-linear hydrodynamic coupling between v_4 and v_2

⇒ non-linear v_4 varies as v_2^2

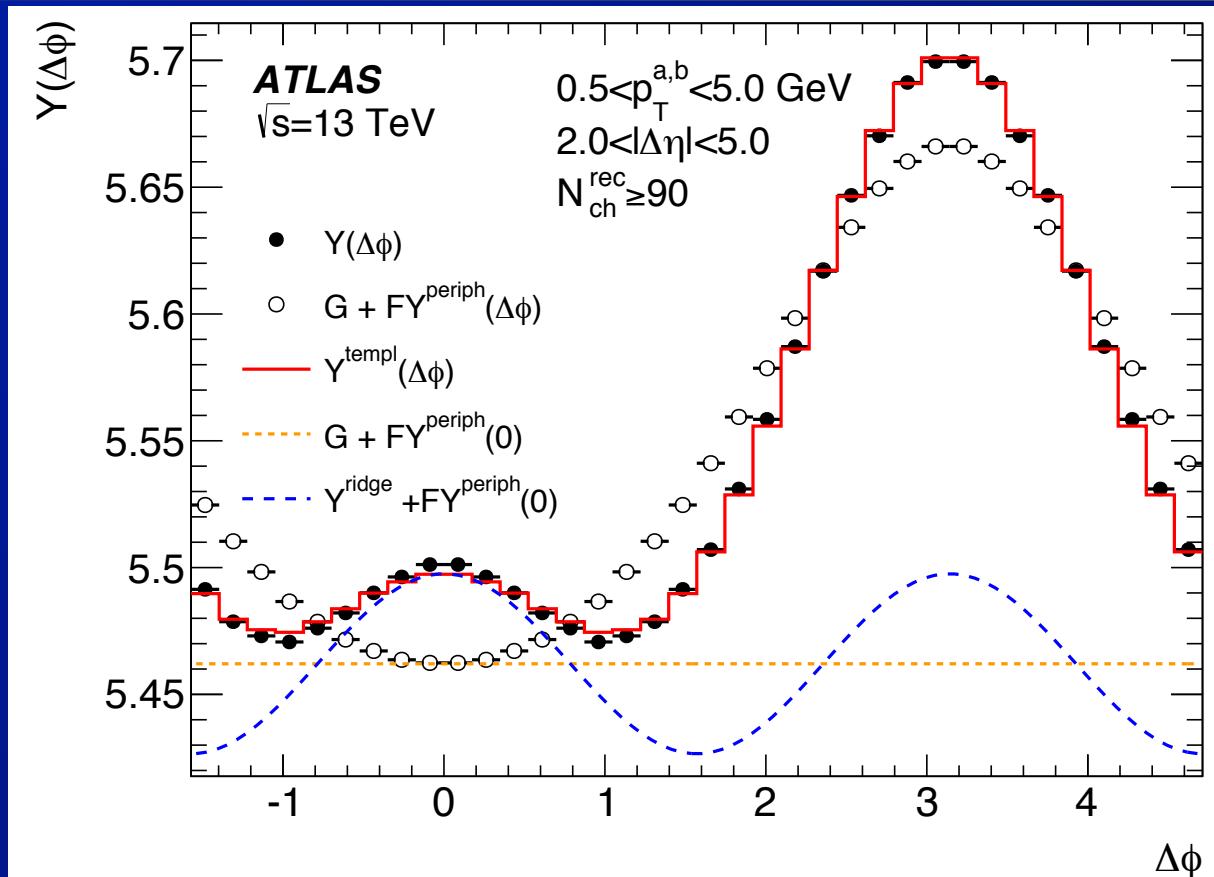
- Look at v_4/v_2^2 in pp and p+Pb collisions
 - in p+Pb, though v_2 and v_4 both vary with multiplicity
⇒ the ratio is constant.
 - not surprisingly, in pp the ratio is also constant
⇒ but is higher than in p+Pb collisions
⇒ Naively: stronger non-linear coupling in pp



Summary

- Review of 13 and 2.76 TeV pp results from PRL
 - ⇒ Observation of $\cos(2\Delta\varphi)$ modulation in pp collisions
 - ⇒ Constant as a function of multiplicity
 - ⇒ No difference between 2.76 and 13 TeV
- New results from analyses of 13 TeV and 5.02 TeV pp and 5.02 TeV p+Pb data
 - Observe $\cos(3\Delta\varphi)$, $\cos(4\Delta\varphi)$ modulation in pp collisions
 - ⇒ pp v_n constant versus multiplicity
 - ⇒ pp v_n agree between 5.02 and 13 TeV
 - Template fitting method yields somewhat higher v_n values in p+Pb collisions, especially @ low multiplicity
 - ⇒ p+Pb v_n values similar to pp for low multiplicity, but increase with multiplicity
 - pp and p+Pb v_2 values have similar p_T dependence
 - pp and p+Pb v_4/v_2^2 constant vs multiplicity, pp higher

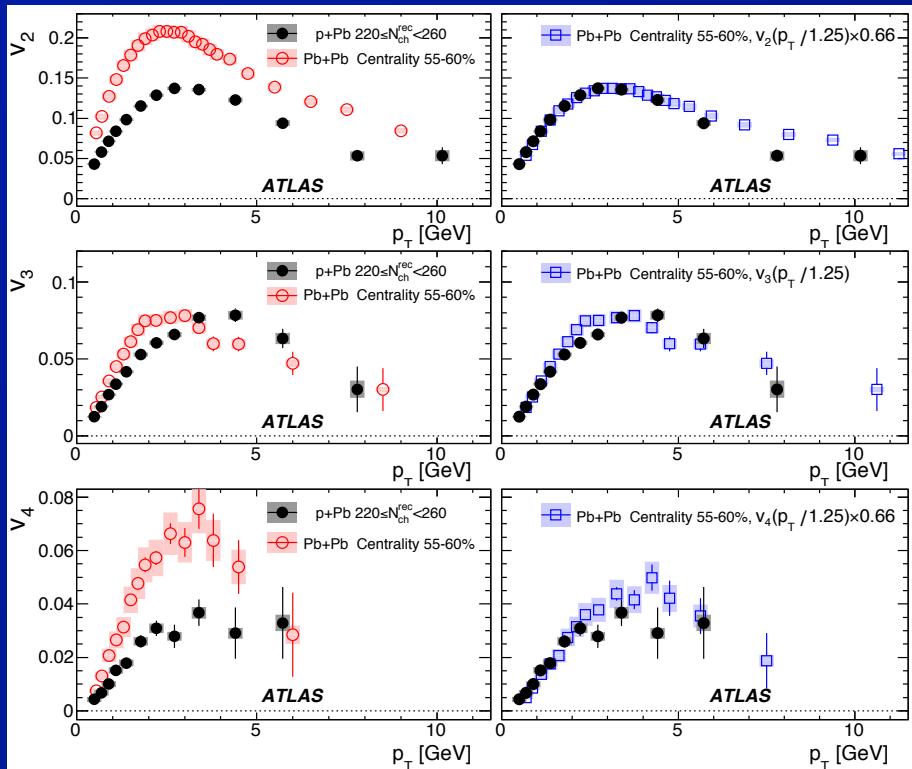
Important



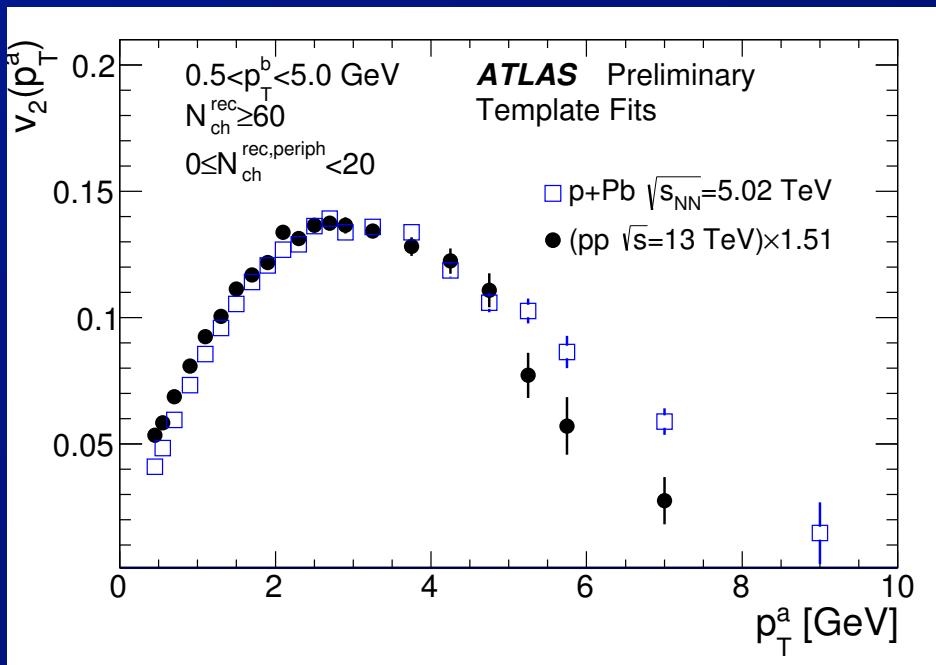
- Modulation in “underlying event” changes the shape of 2-particle correlation
 - makes Y/C_2 near $\Delta\phi = \pi$ substantially narrower
⇒ Modification of global properties of pp collisions
⇒ Not in PYTHIA! In fact, PYTHIA has opposite trend

pp, p+Pb, Pb+Pb

ATLAS, Phys. Rev. C 90, 044906

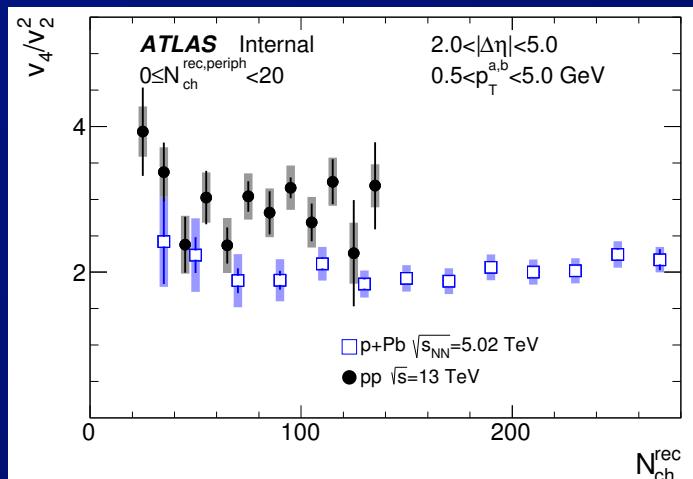
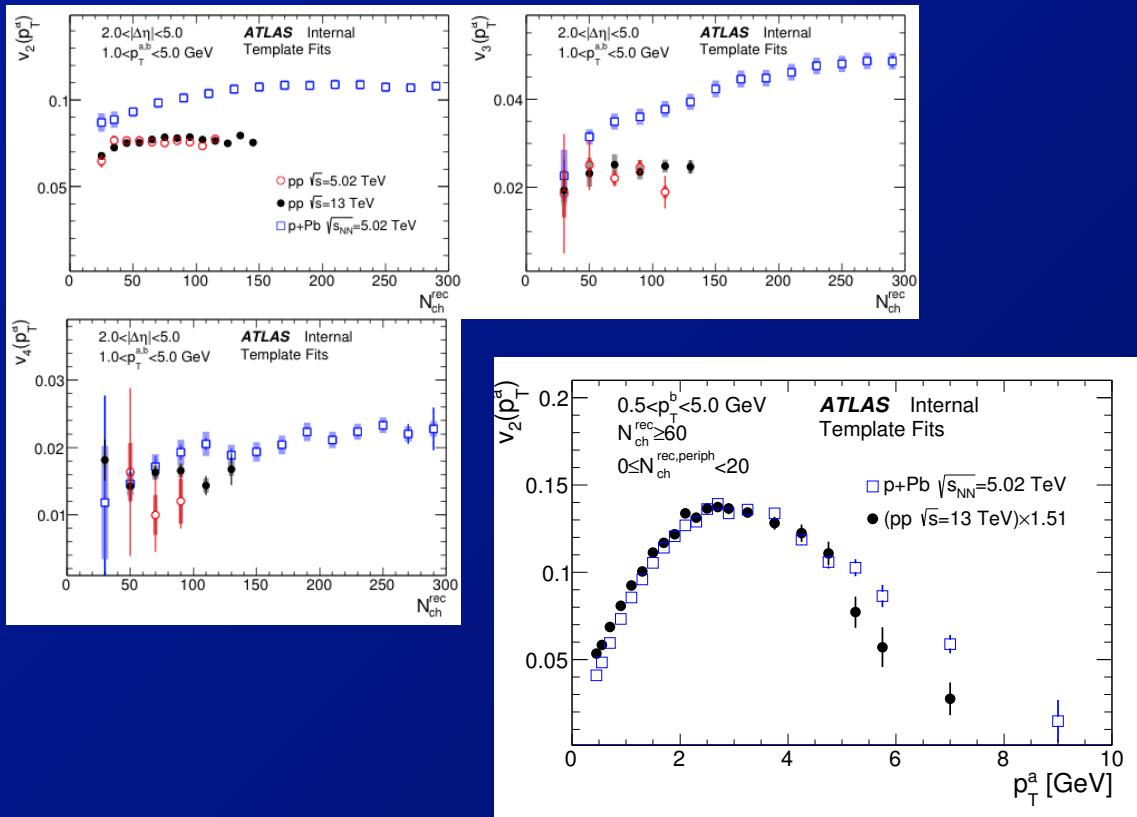
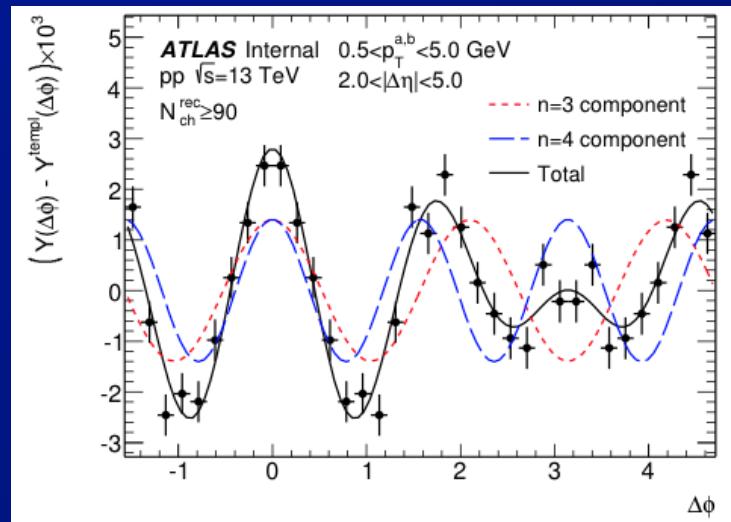
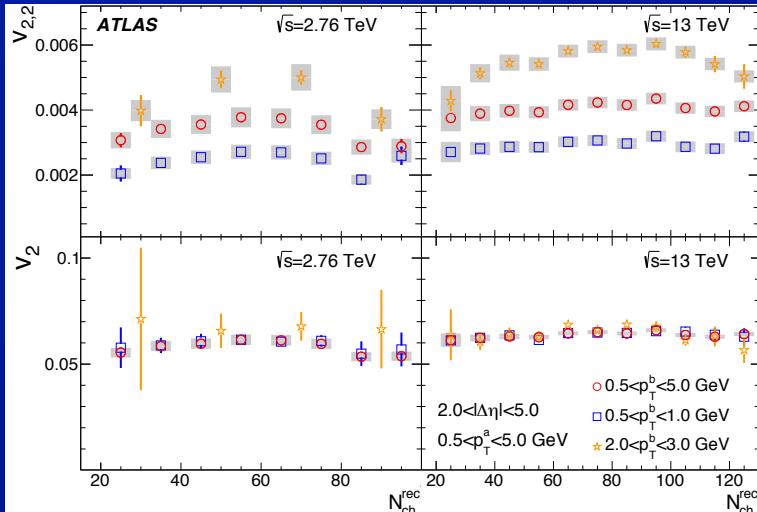


ATLAS, this talk



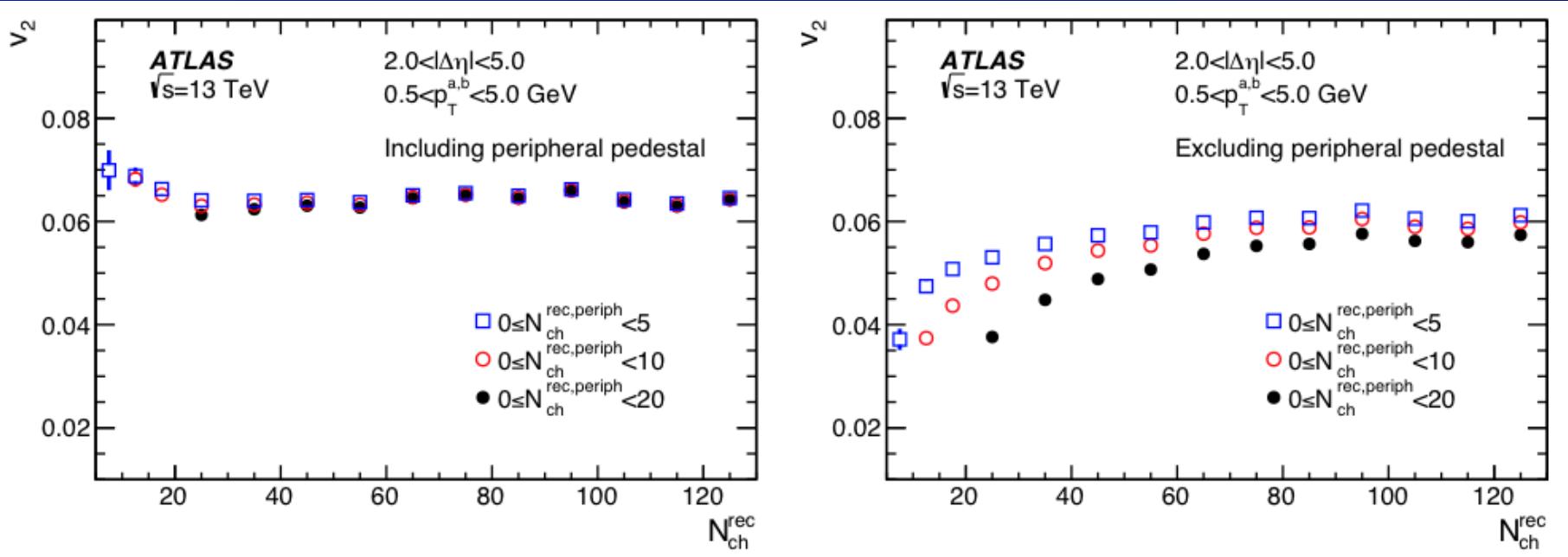
- Previous p+Pb measurements:
⇒ p+Pb and Pb+Pb $v_2(p_T)$ exhibit “scaling”
- Now:
⇒ pp and p+Pb exhibit scaling
- Inference left to the reader ...

Visual summary



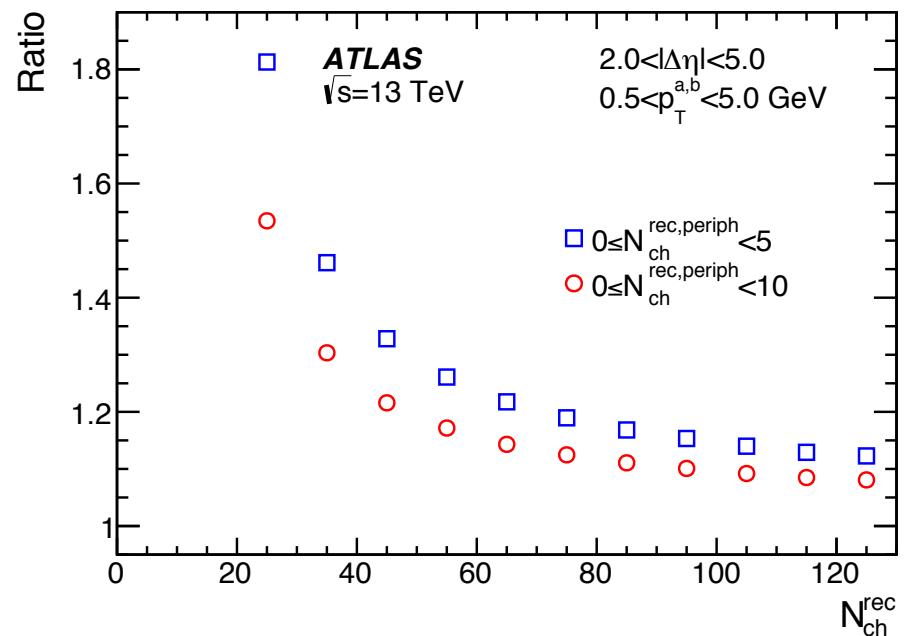
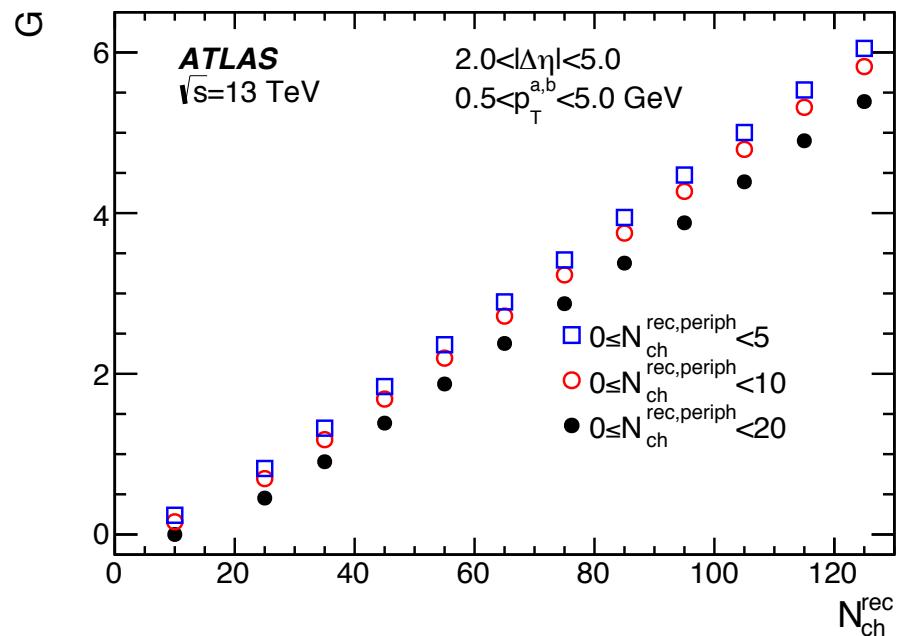
Backup slides

Sensitivity to “peripheral” bin



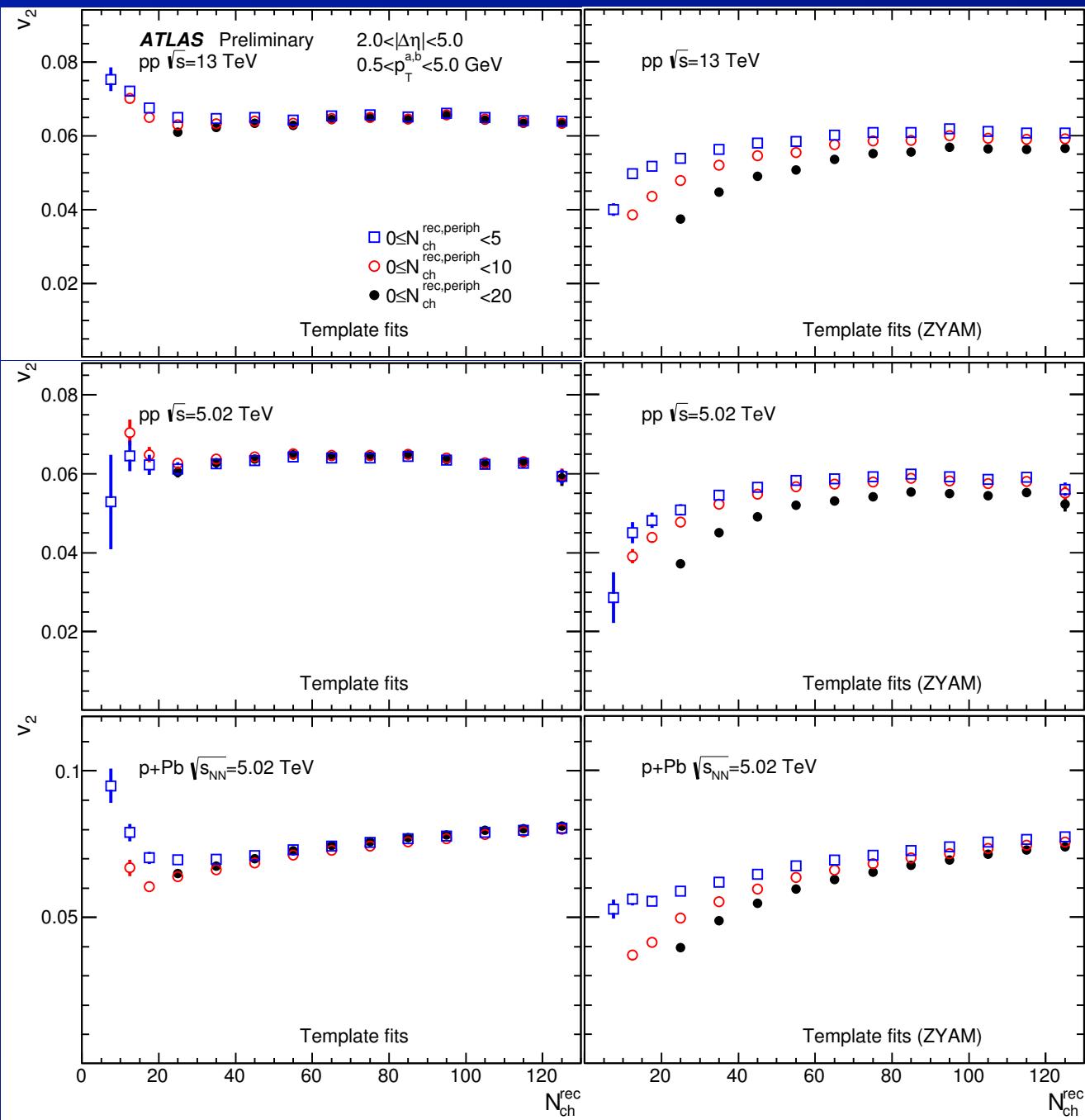
- When using the template fitting method and no ZYAM subtraction on the peripheral reference:
⇒ We see very little dependence of v_2 on the multiplicity range for the reference
- Not so when ZYAM subtracting the reference
⇒ Where v_2 is forced to go to zero at the reference multiplicity (range).

Template fit G parameter

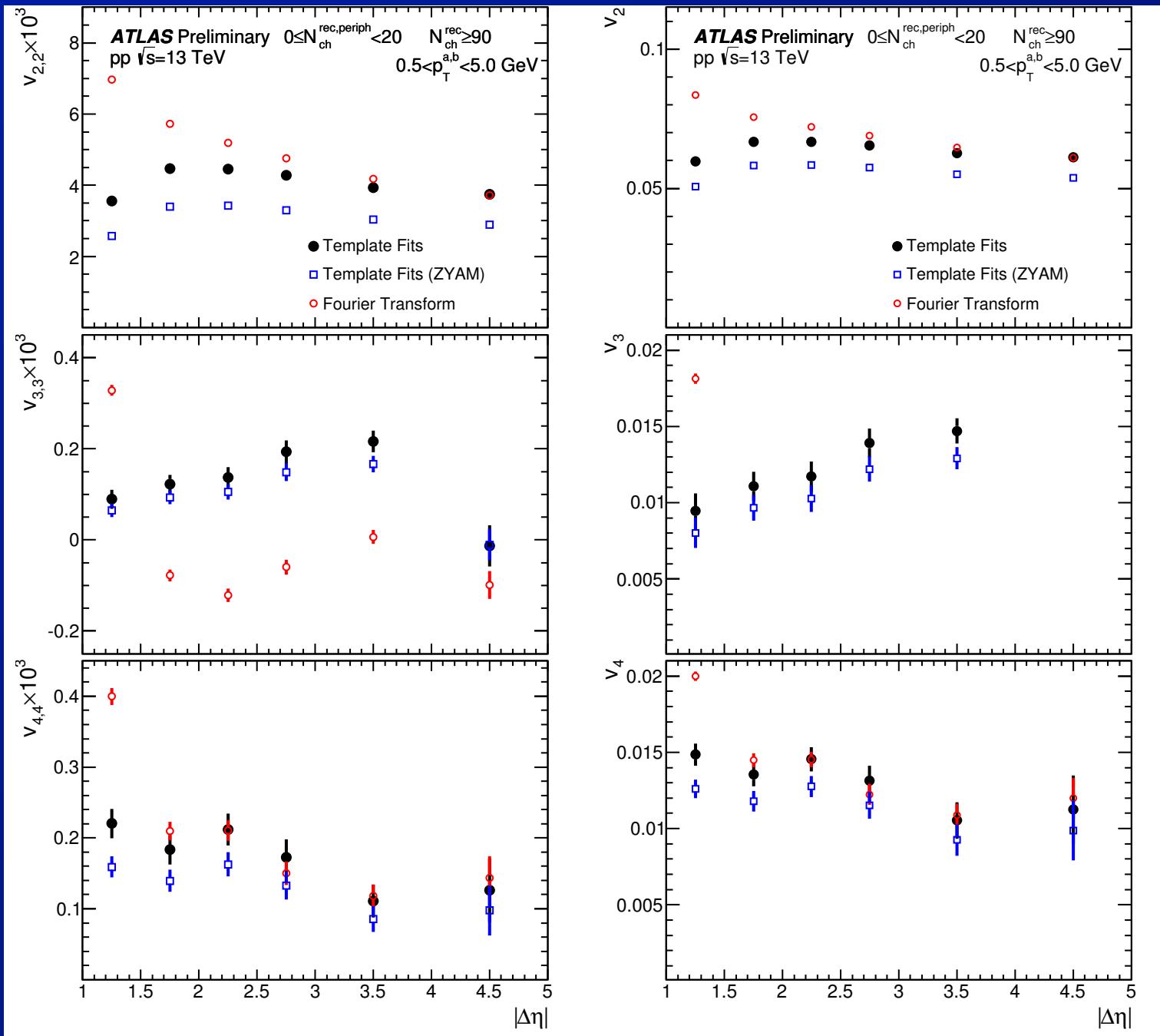


- The ridge yield scaling parameter increases approximately linearly with multiplicity
- Changing the choice of peripheral reference causes G to shift up or down.

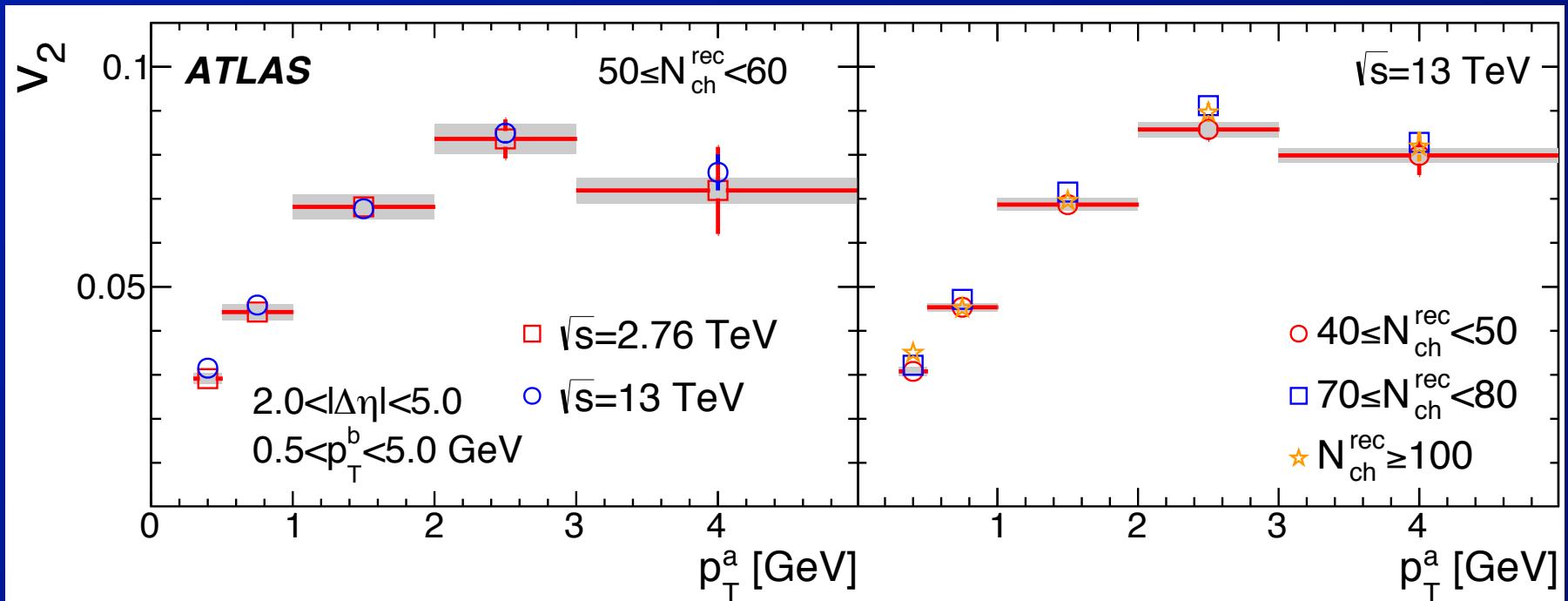
Sensitivity to peripheral reference (new)



$v_{n,n}$ and v_n $\Delta\eta$ dependence

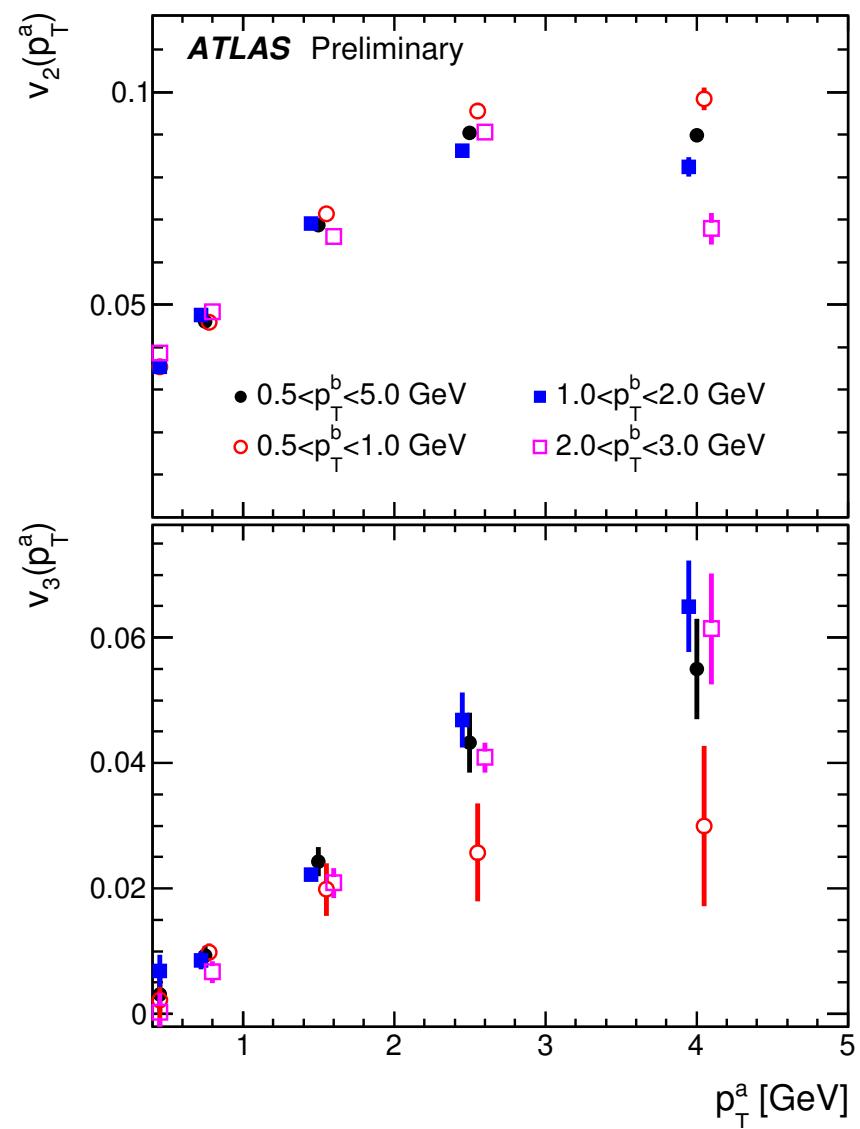
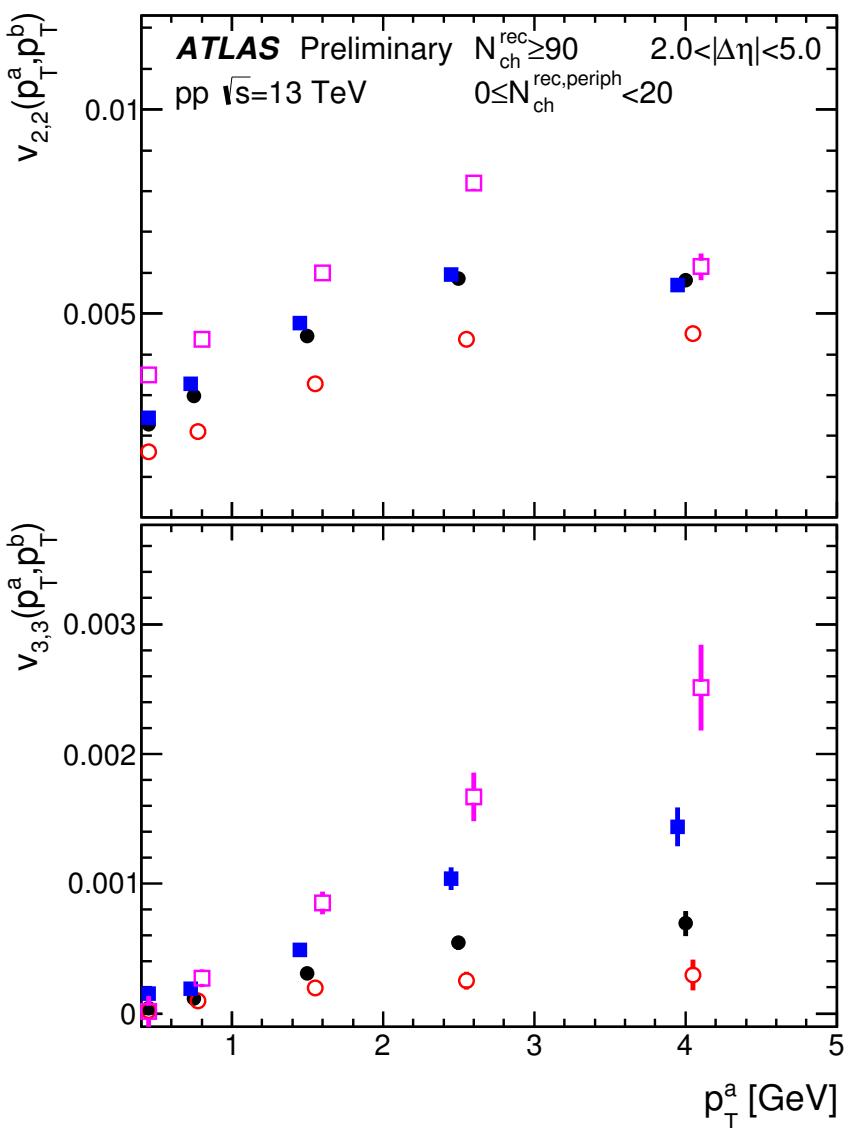


13 TeV pp Template fit results

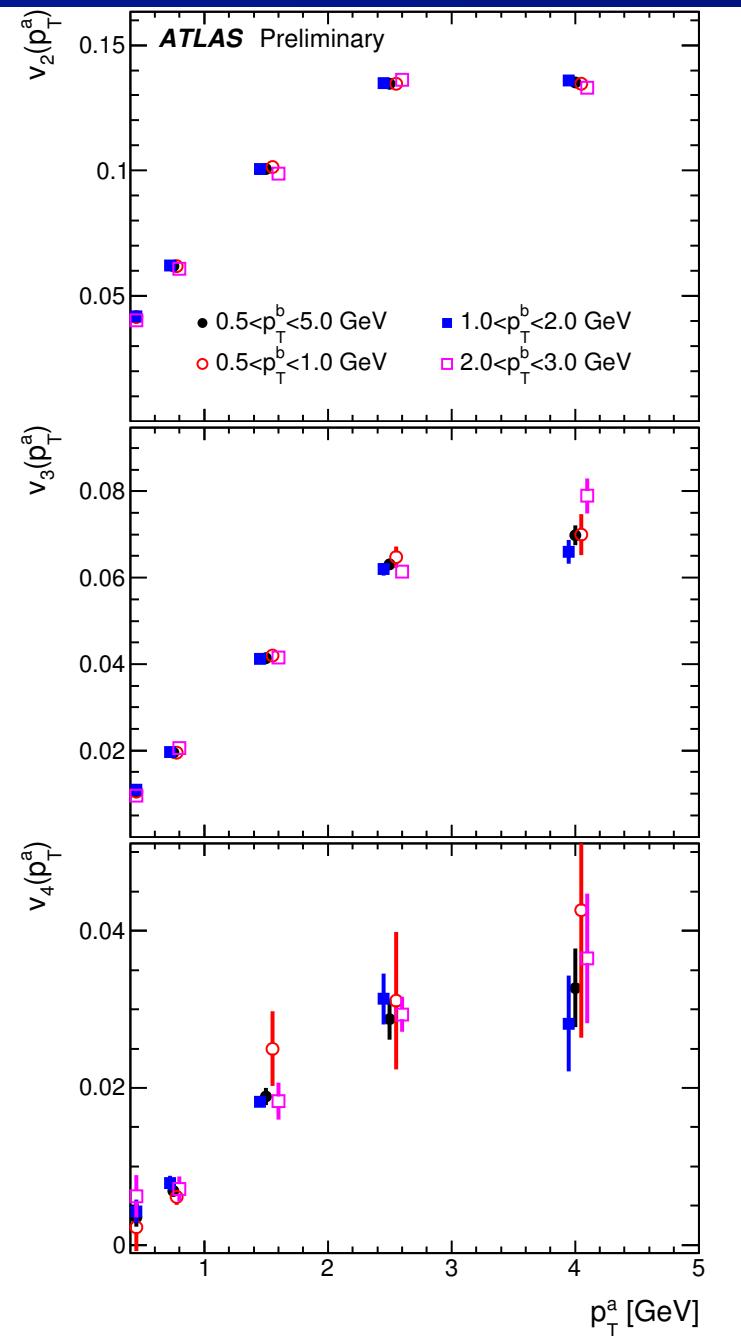
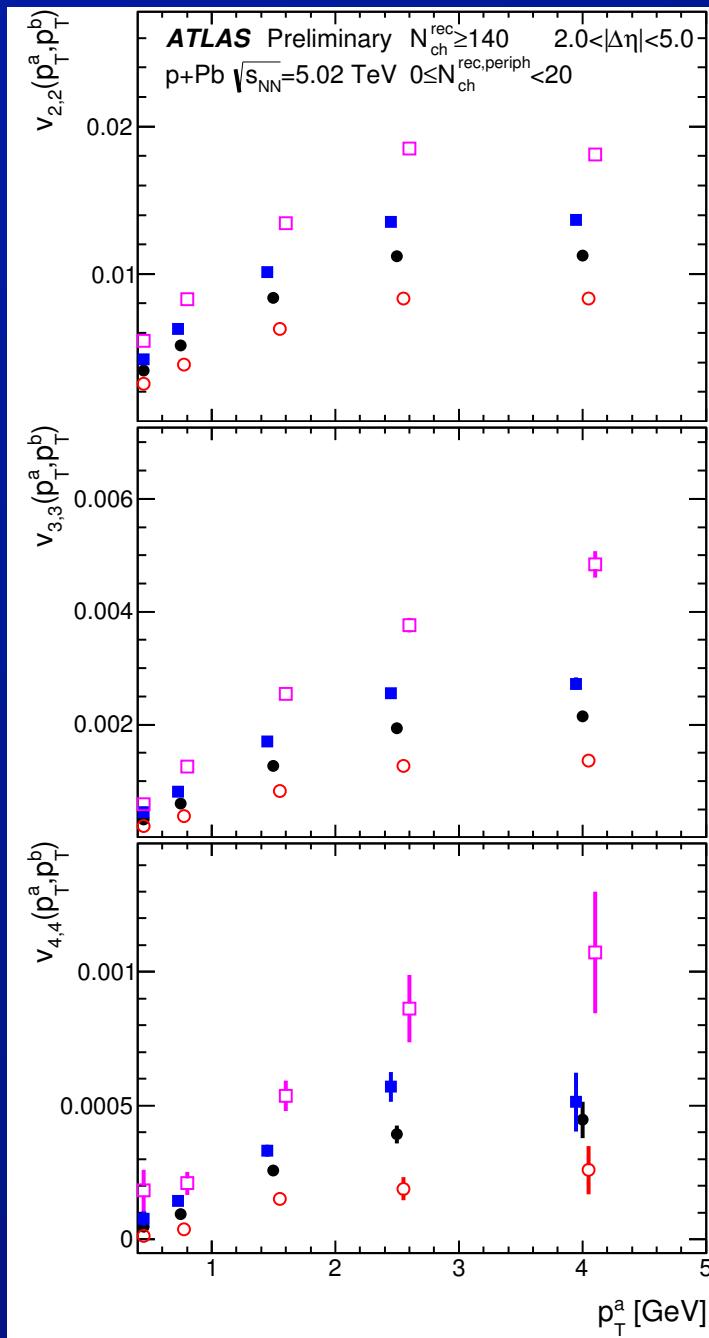


- Observe:
 - $v_2(p_T)$ agrees between 2.76 and 13 TeV
→ p_T integrated agreement not “accidental”
 - same for different multiplicity intervals
 - p_T dependence qualitatively similar to that seen in $p+Pb$ and (even) $Pb+Pb$ collisions

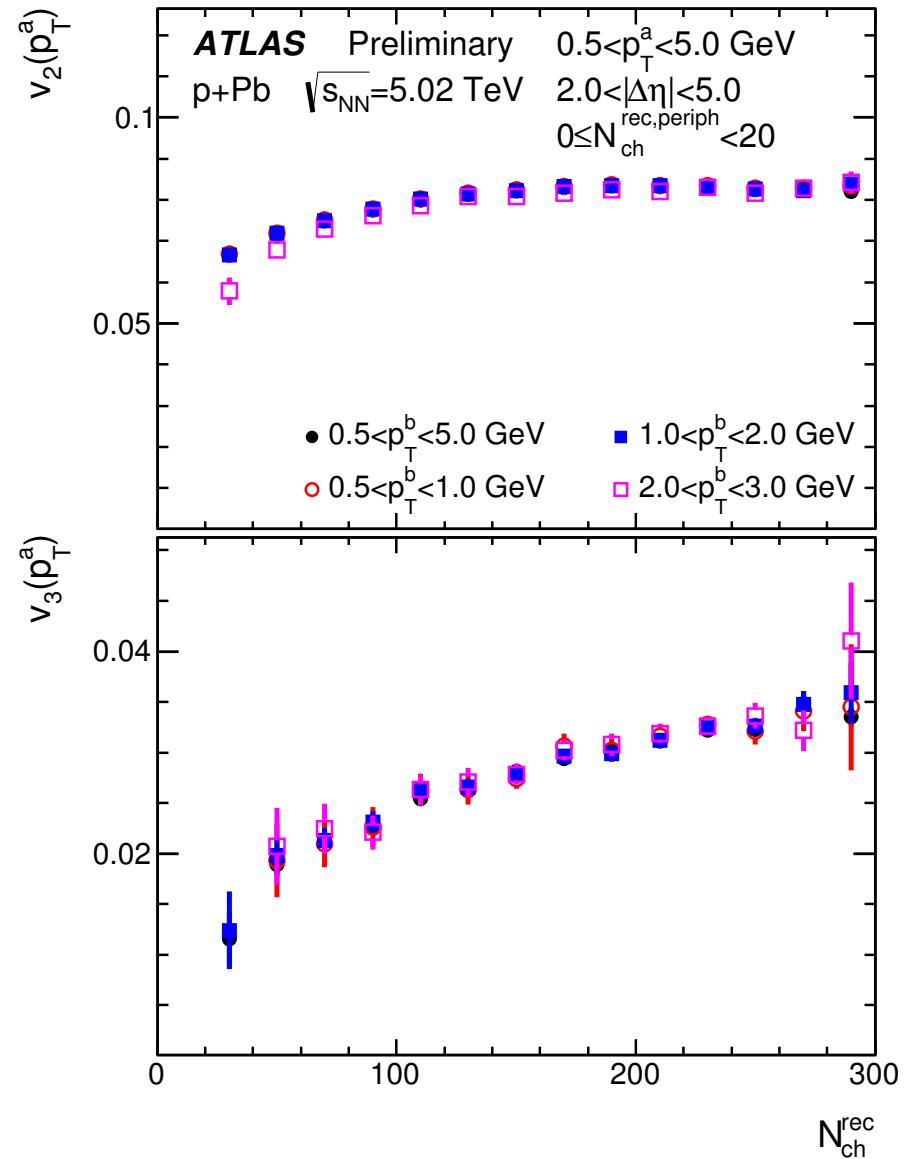
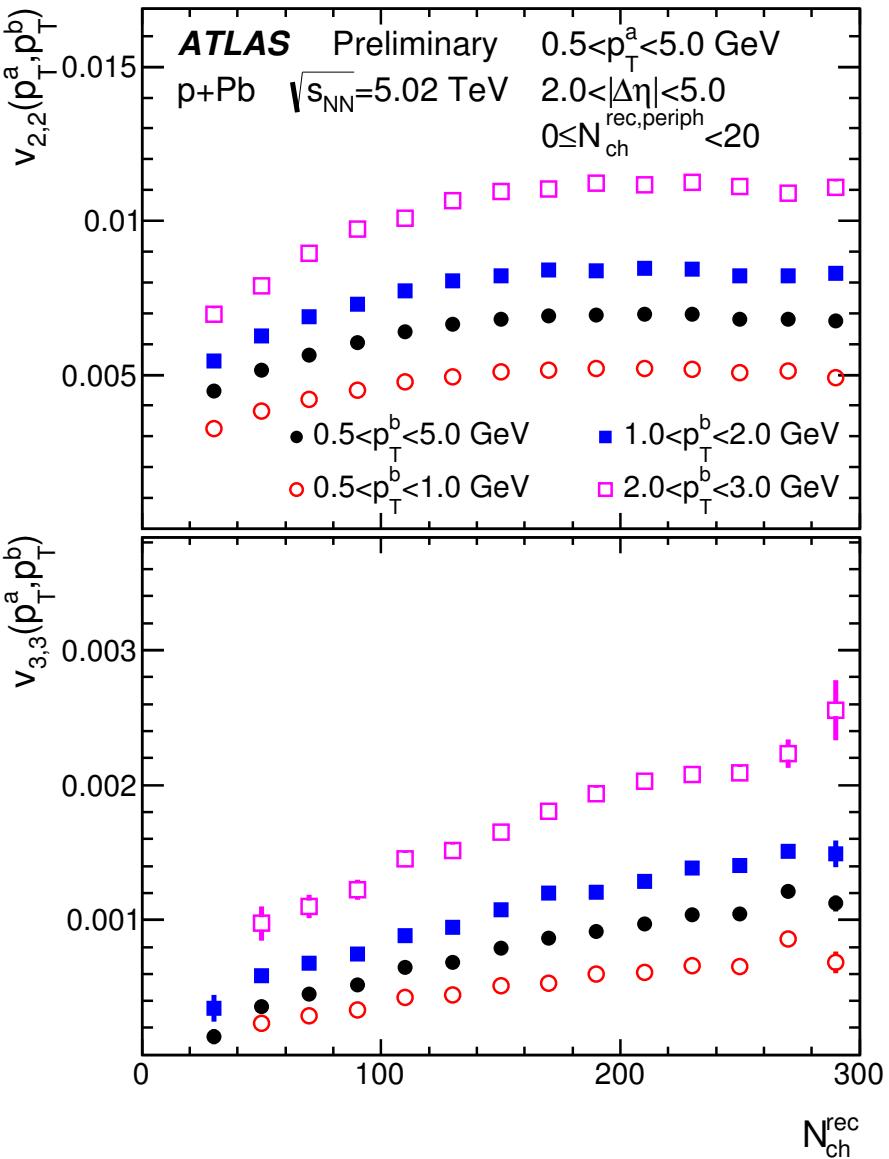
$v_{n,n}$ factorization vs p_T : 13 TeV p-p



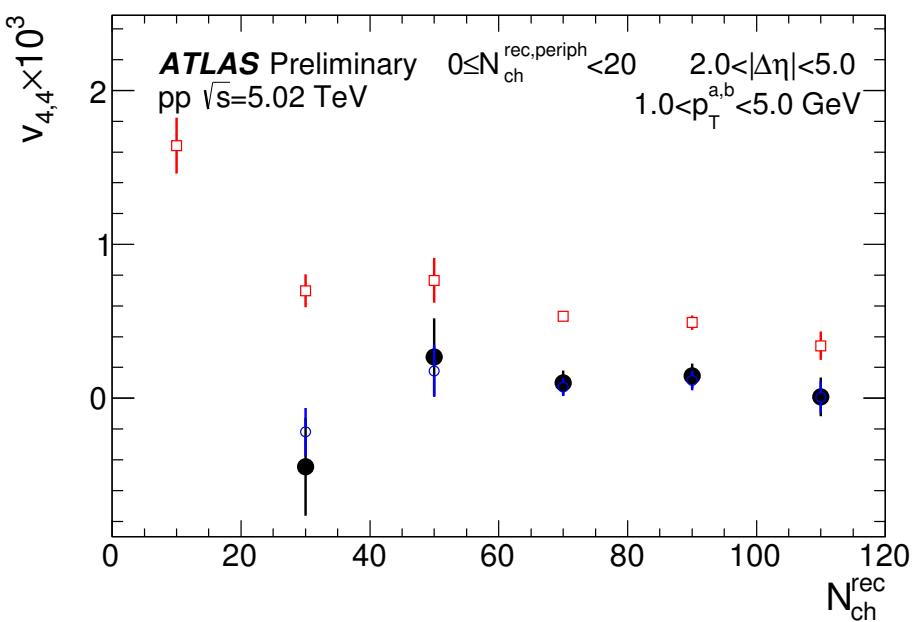
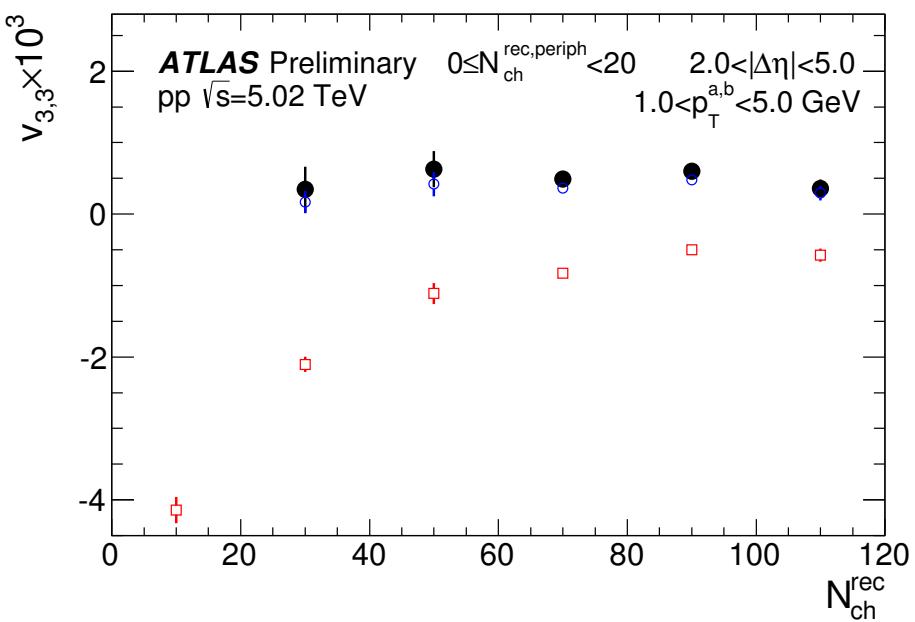
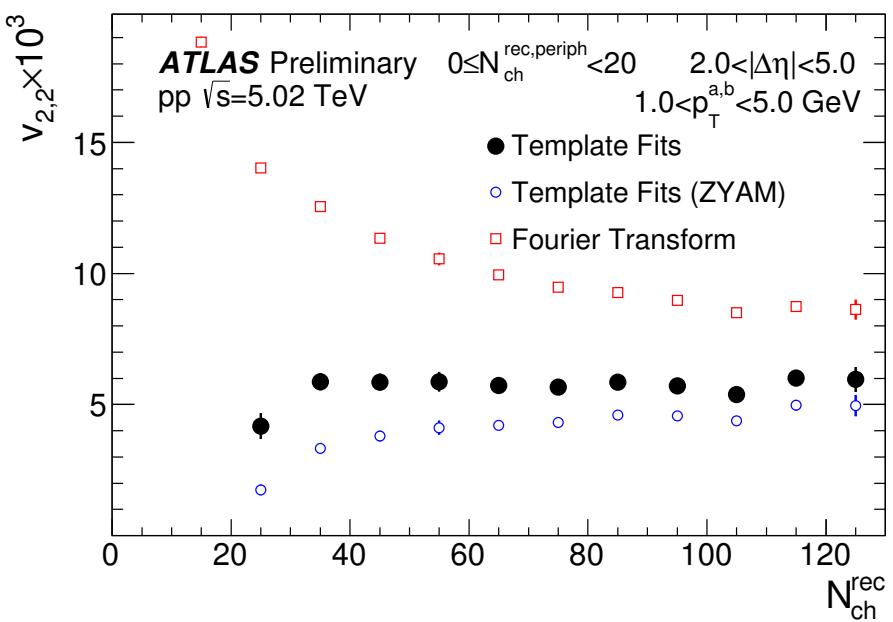
$v_{n,n}$ factorization vs p_T : p+Pb



$v_{n,n}$ factorization vs mult. : p+Pb



5.02 TeV p-p $v_{n,n}$



Full set of 13 TeV pp template fits (PRL)

