Measurement of ridge and v_2 in 13 and 2.76 TeV *pp* collisions with ATLAS

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for the ATLAS collaboration

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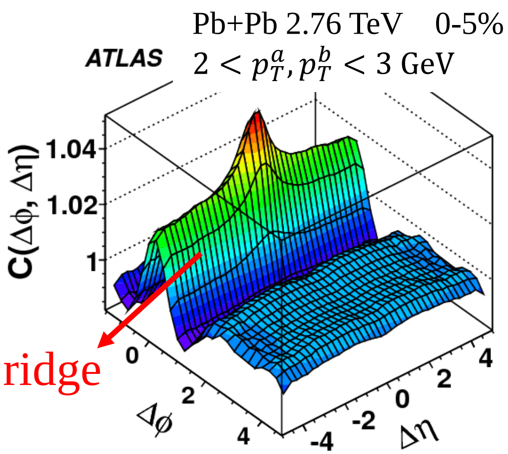
http://arxiv.org/abs/1509.04776

Stony Brook University

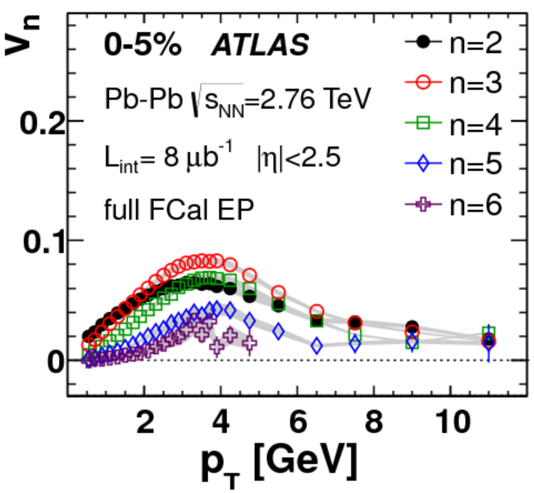
ATLAS EXPERIMENT

2015 KOBE JAPAN

Introduction



The ridge first discovered in A+A collisions.



Single-particle v_n was measured.

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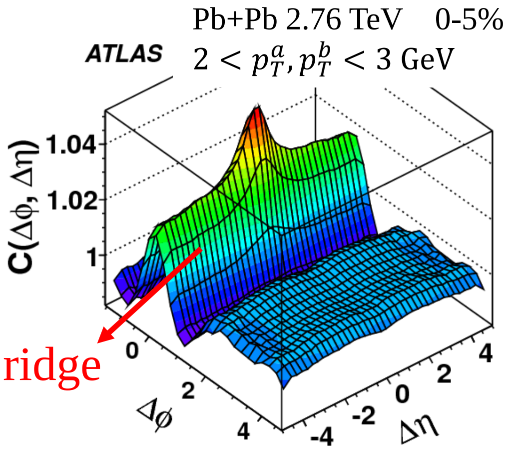

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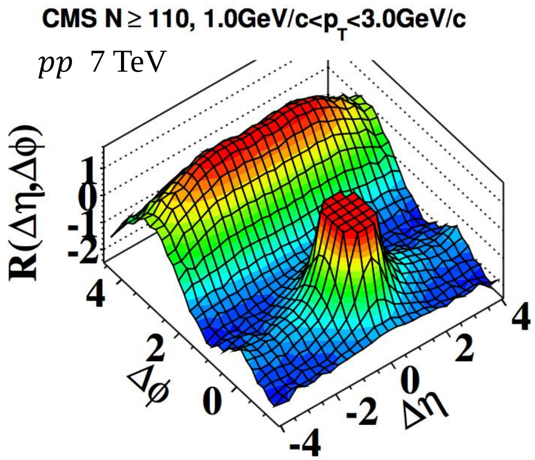
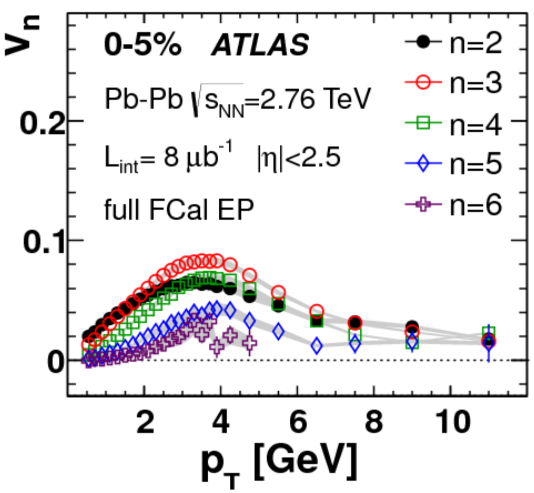


Ridge observed in *pp*.



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Theoretical interpretations

- Flow effects?
- Initial state physics?

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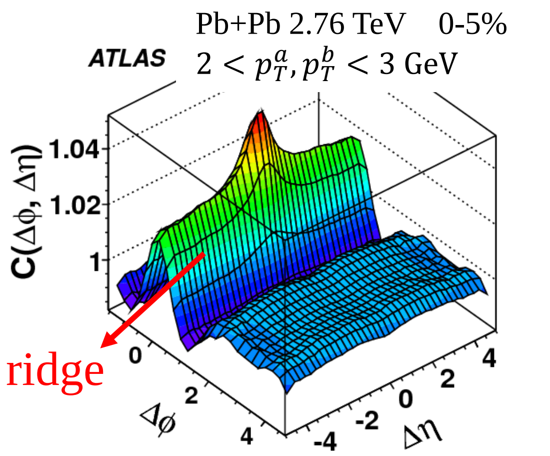

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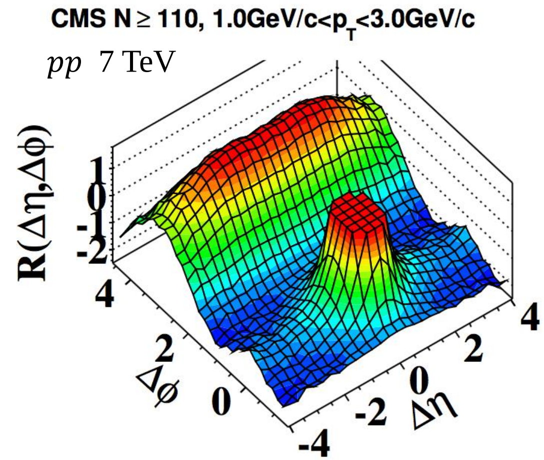

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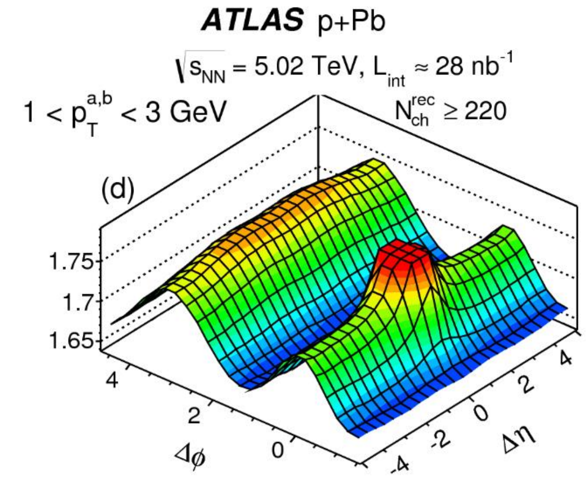
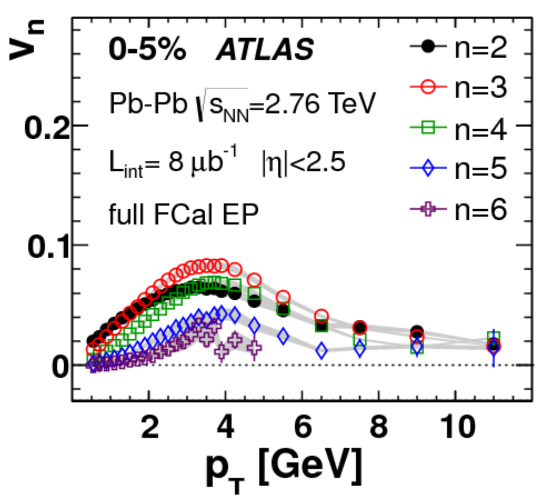


Ridge in p+Pb.



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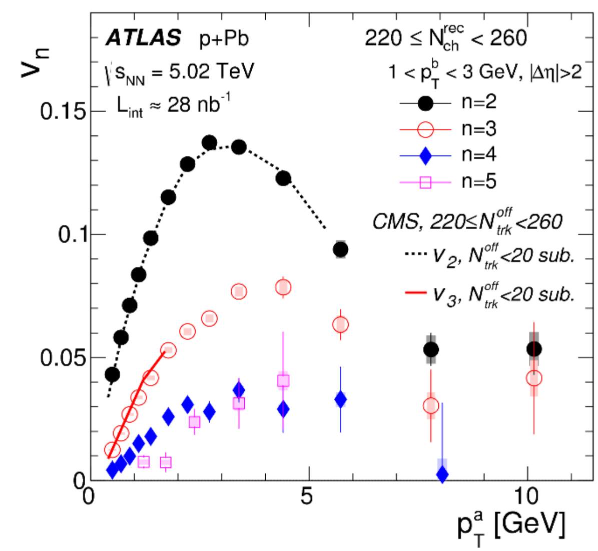

v_n was also measured.

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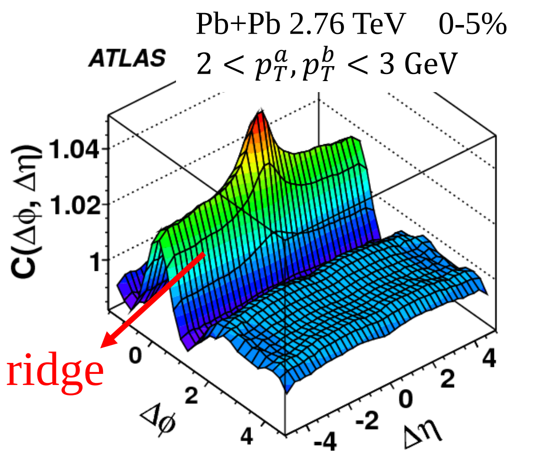

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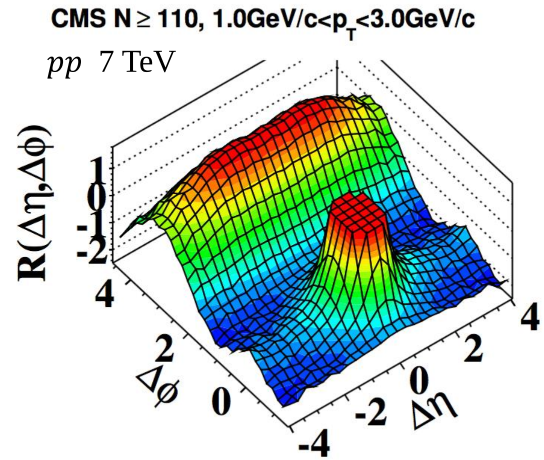

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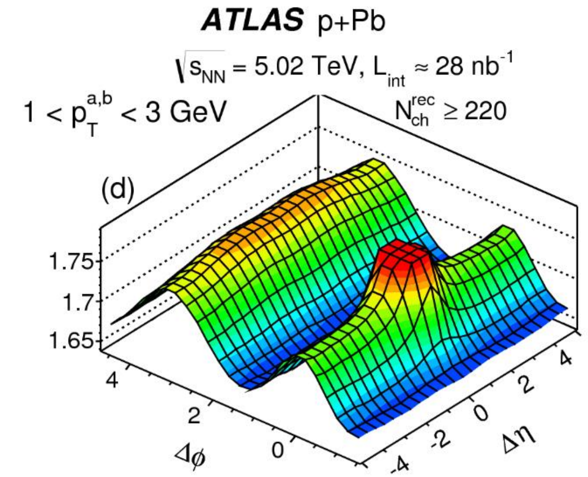
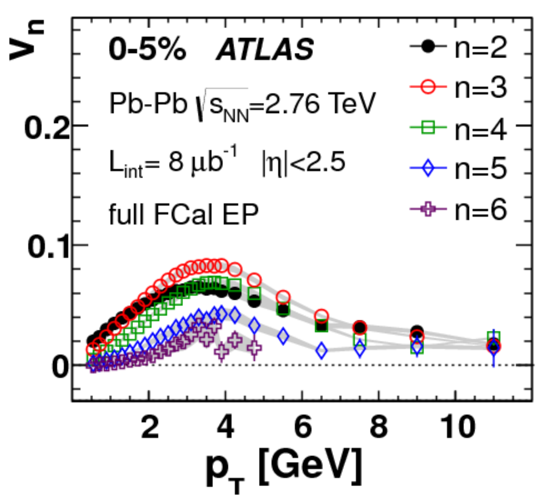


Ridge in p+Pb.

Theoretical interpretations

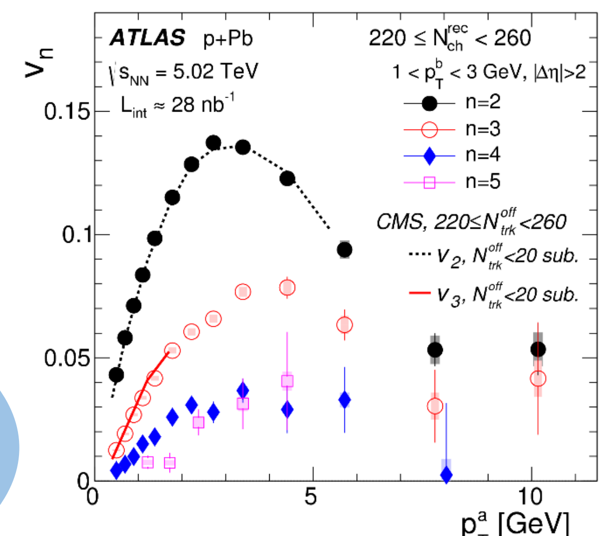
- Flow effects?
- Initial state physics?



Single-particle v_n was measured.

To shed light on competing theories, more studies needed:

- Single-particle v_n;
- Energy dependence.



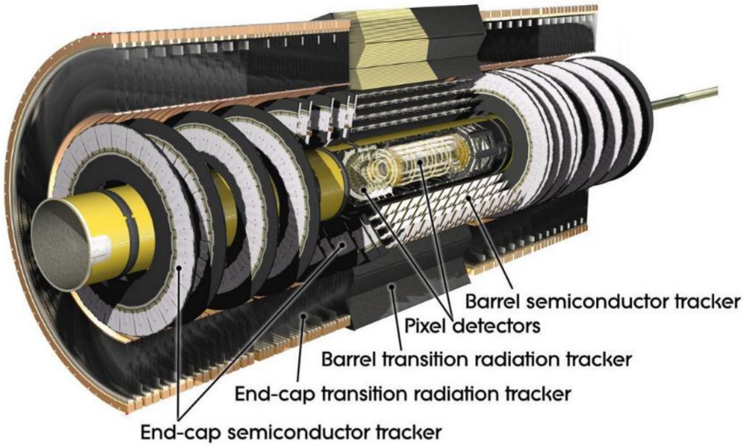
v_n was also measured.

Data set

- ATLAS *pp* 2.76 and 13 TeV data

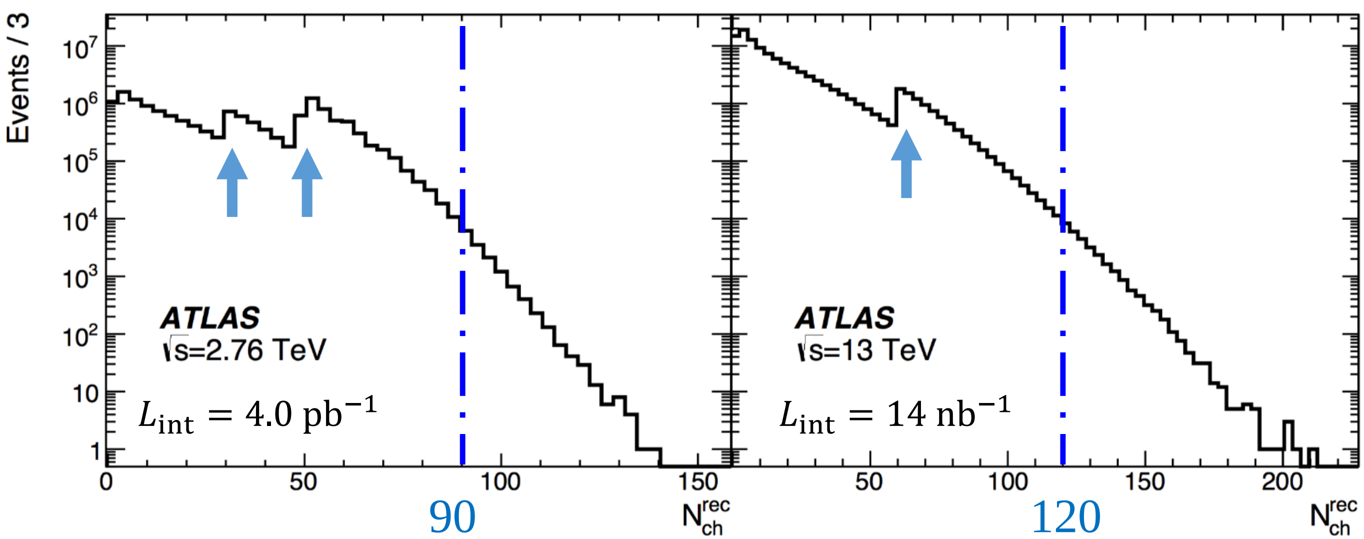
- Charge particle tracks reconstructed in Inner Detector:
  - $|\eta| \leq 2.5$
  - $p_{\mathrm{T}} > 0.3$ GeV

$$C(\Delta\eta, \Delta\phi) = \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}$$

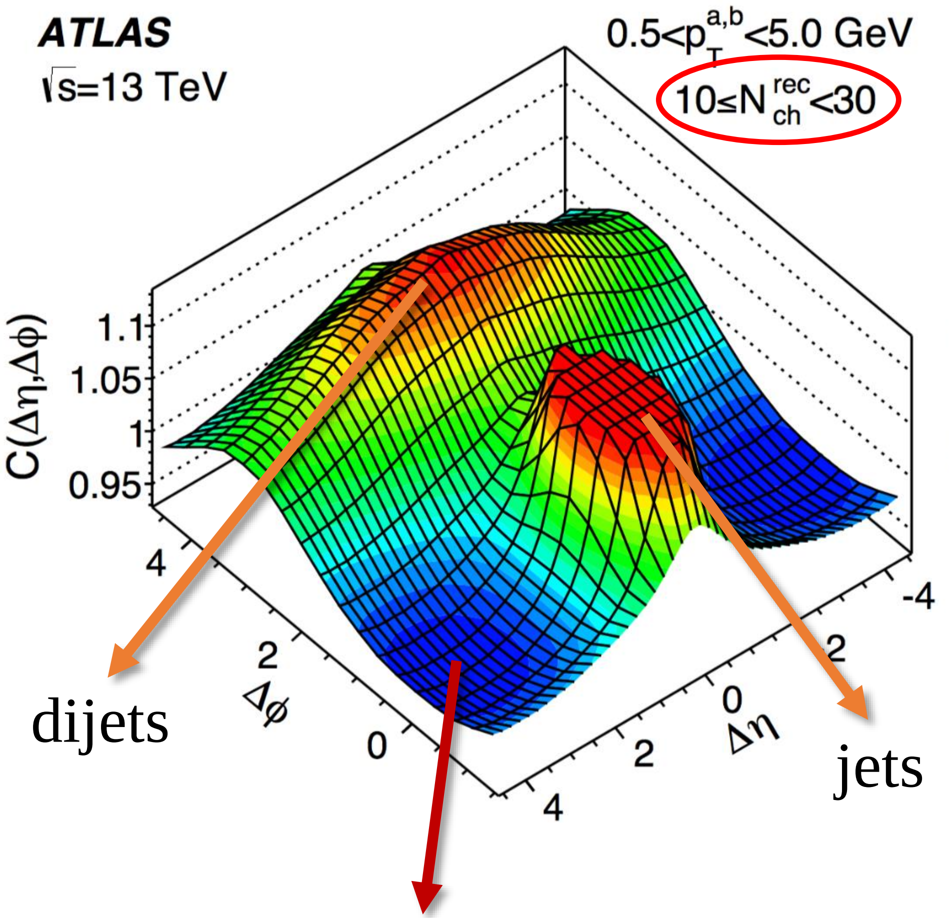


ATLAS Inner Detector

- High-Multiplicity track triggers used to increase statistics.

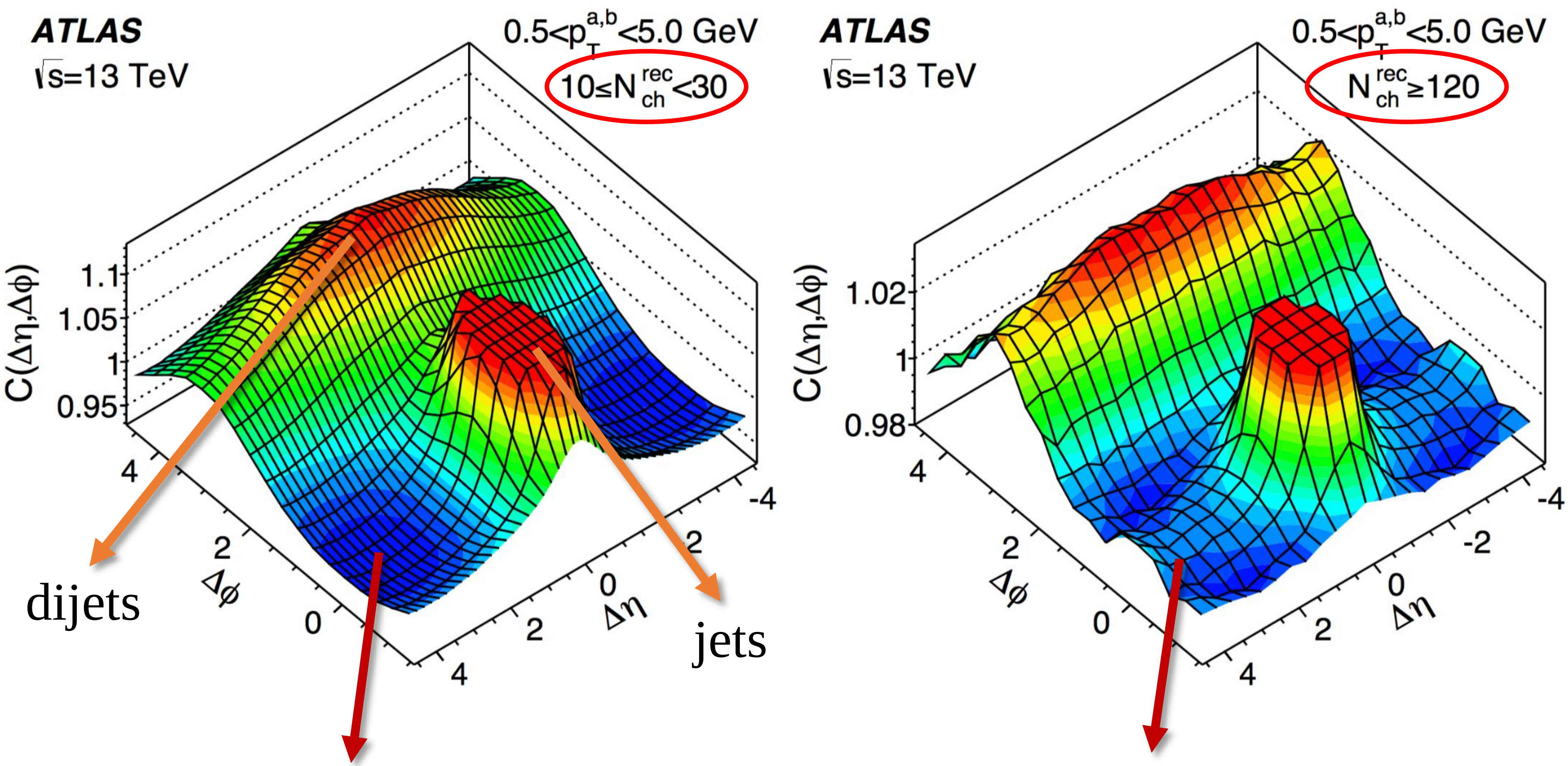


$C(\Delta\eta, \Delta\phi)$ in 13 TeV pp



Long-range correlation shape is concave-up on near-side: no ridge.

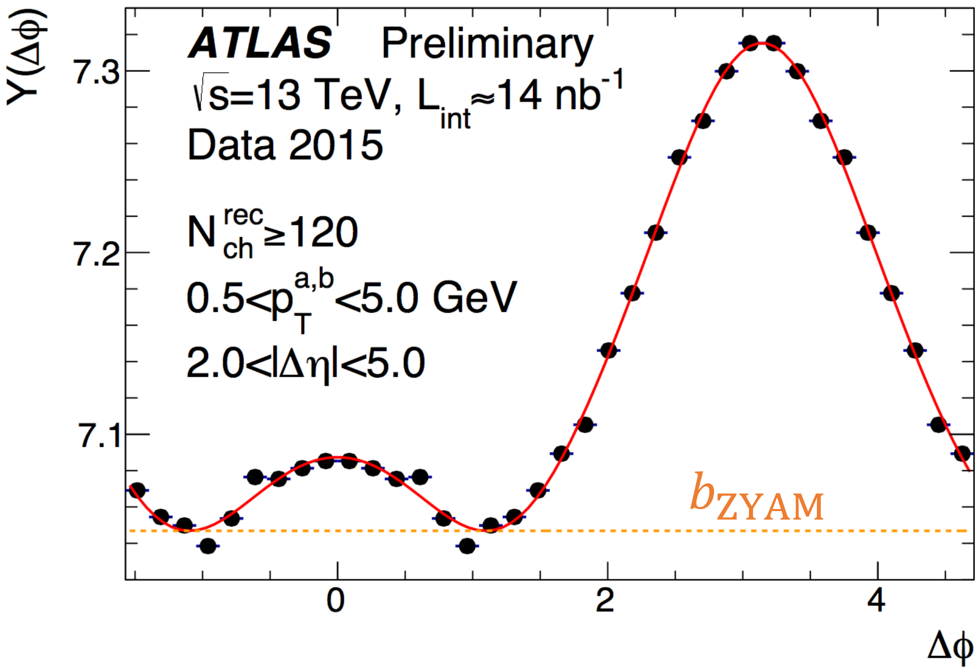
$C(\Delta\eta, \Delta\phi)$ in 13 TeV *pp*



Long-range correlation shape is concave-up on near-side: no ridge.

Long-range structure becomes flat: ridge develops.

Ridge yield

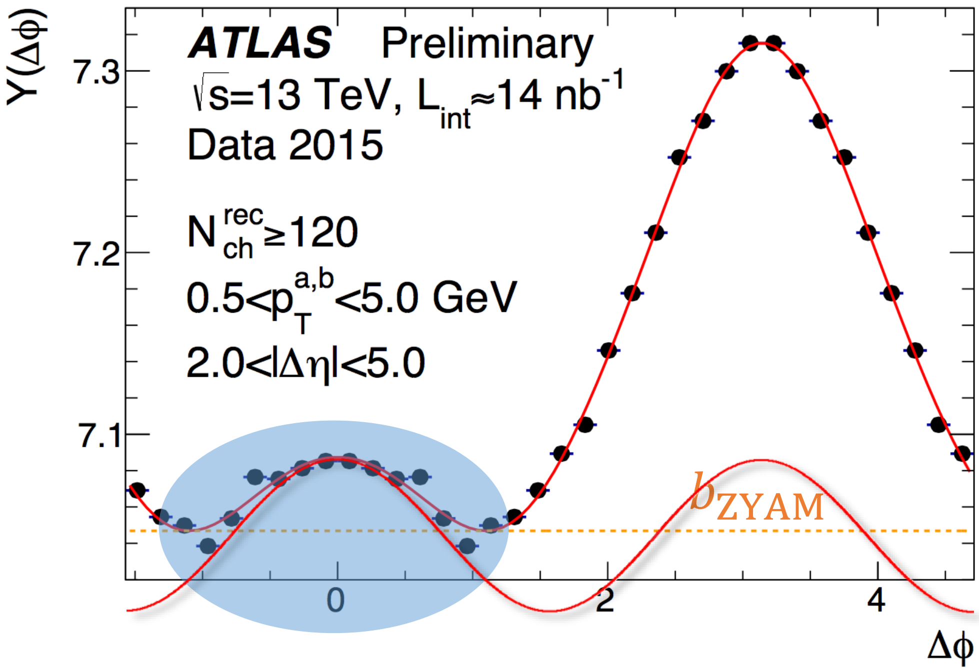


- To quantify the strength of the ridge yield:

$$Y(\Delta\phi) = \left(\frac{\int B(\Delta\phi)\, \mathrm{d}\Delta\phi}{N^a \int \mathrm{d}\Delta\phi}\right) C(\Delta\phi)$$

N^a total number of trigger number

Ridge yield



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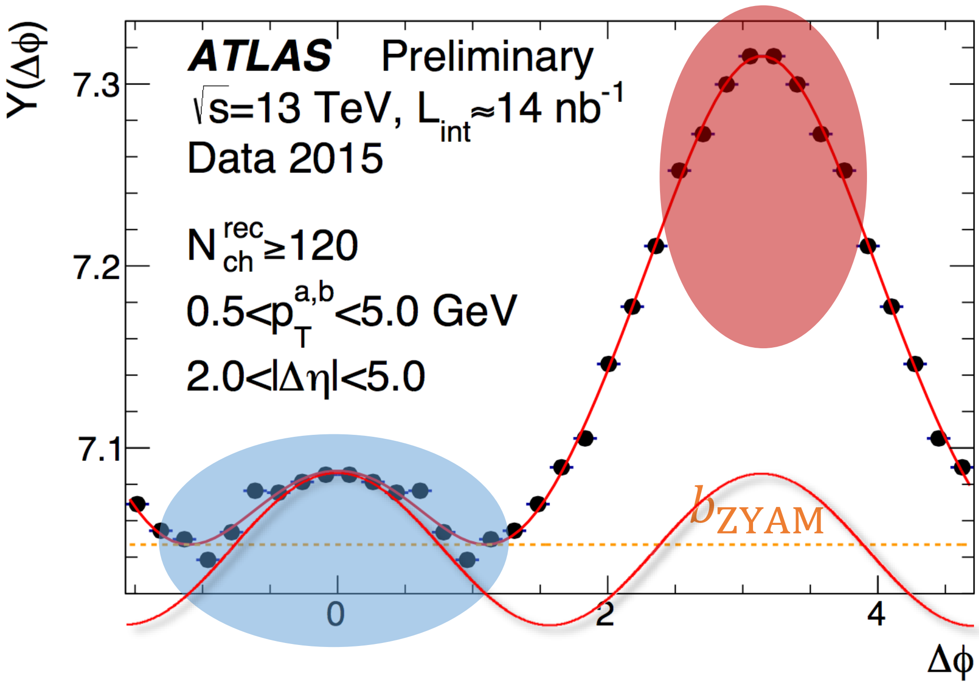
- ZYAM method estimates ridge yield in near-side (presented in EPS 2015);
- ZYAM assumes pairs under pedestal b_{ZYAM} are uncorrelated;
- Due to the modulation of LRC in near-side, ridge yield may be underestimated.

Ridge yield



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- ZYAM method estimates ridge yield in near-side (presented in EPS 2015);
- ZYAM assumes pairs under pedestal b_{ZYAM} are uncorrelated;
- Due to the modulation of LRC in near-side, ridge yield may be underestimated.

- Due to dominance of dijet, ZYAM cannot estimate LRC in away-side.

- New method needed!

Template fitting: two approaches

- Peripheral subtraction $Y^{\mathrm{LRC}} = Y^{\mathrm{cent}} - F\,Y^{\mathrm{peri}}$
- To determine *F*:
  - Scale jet yield in near-side;
  - Template fitting (used in this analysis).

Assumption: shape of away-side jet is independent of N_{ch}^{rec}.

Both ways give consistent results!

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- Decompose yield in peripheral $Y^{\mathrm{peri}} = \boldsymbol{N_0^{\mathrm{peri}}} + N_0^{\mathrm{peri}}\, v_{n,n}^{\mathrm{peri}} \cos(n\,\Delta\phi) + Y_{\mathrm{jet}}^{\mathrm{peri}}$
- First term represent uncorrelated pairs, second term is LRC in peripheral;
- The key is whether including the pedestal N_0^{peri} or not!

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- First term represent uncorrelated pairs, second term is LRC in peripheral;
- The key is whether including the pedestal N_0^{peri} or not!

- Expand Y^{LRC} and Y^{cent}. Denote $F\,N_0^{\mathrm{peri}}/N_0^{\mathrm{cent}} \equiv \alpha$;
- Exclude pedestal

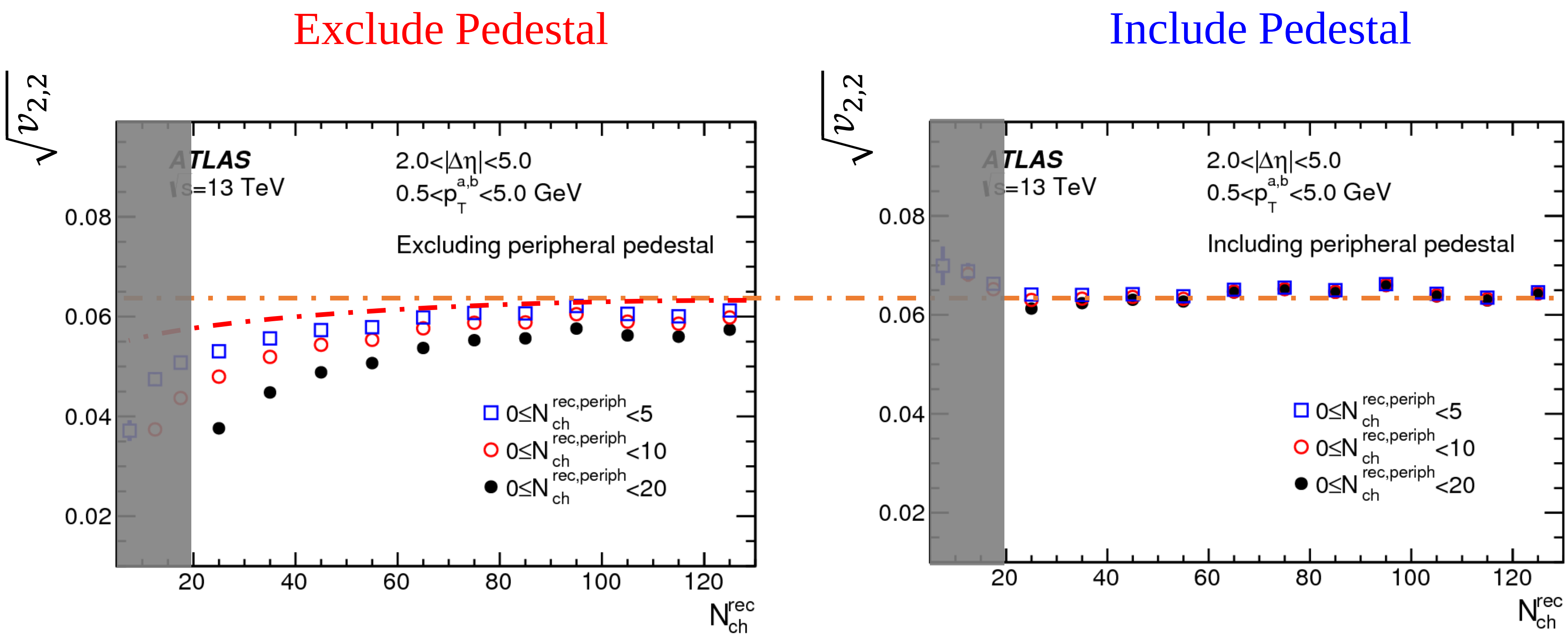
$$v_{n,n}^{\mathrm{LRC}} = v_{n,n}^{\mathrm{cent}} - \alpha\, v_{n,n}^{\mathrm{peri}}$$

- Include pedestal

$$v_{n,n}^{\mathrm{LRC}} = \frac{v_{n,n}^{\mathrm{cent}} - \alpha\, v_{n,n}^{\mathrm{peri}}}{1-\alpha}$$

Only differentiate by a scale factor $1-\alpha$!

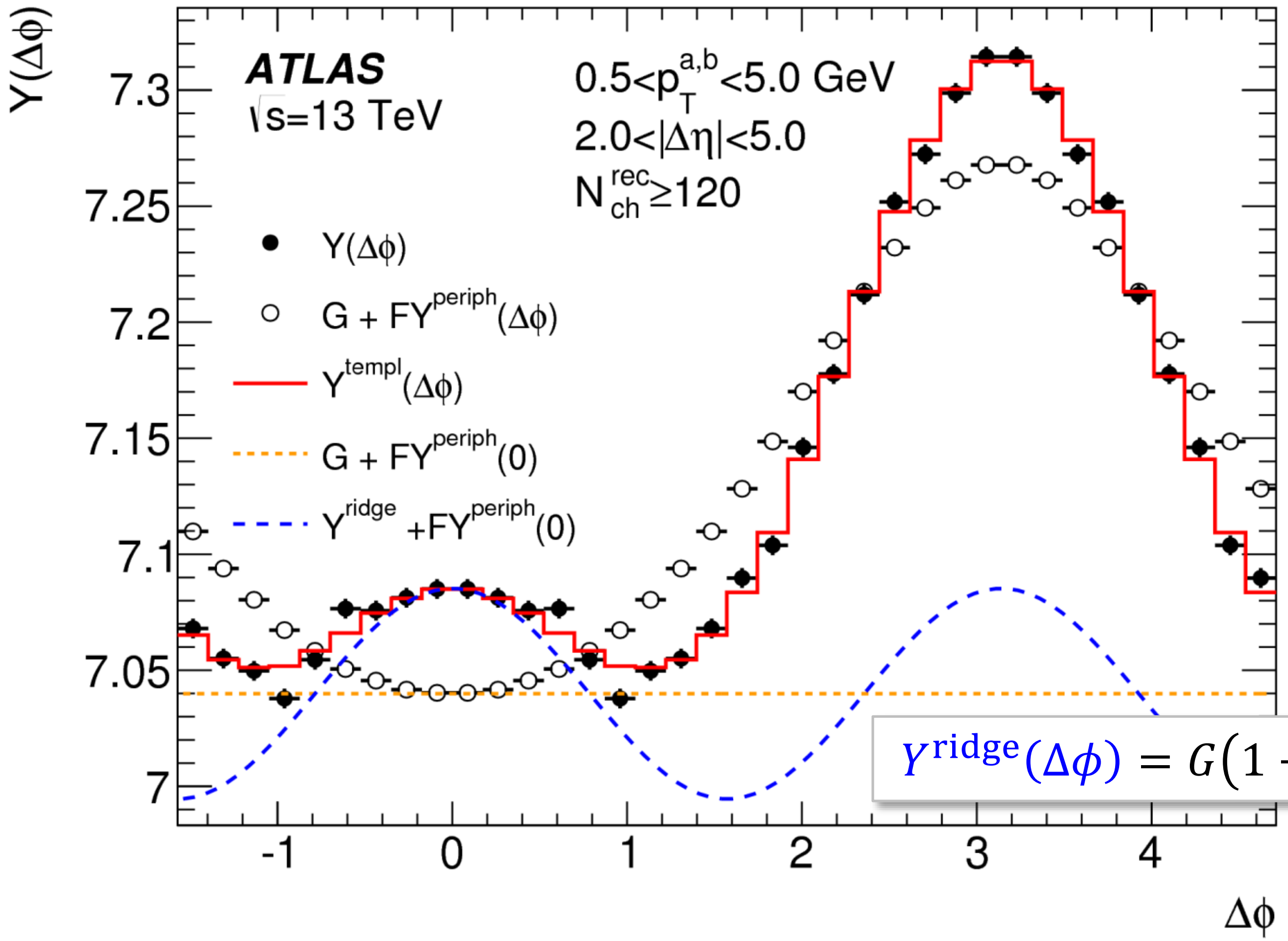
Comparison of two template fit methods



- Two methods represents two limits, however, they give similar LRC signal for $N_{ch}^{rec} \geq 20$. The true value of $v_{2,2}$ lies between two bounds.
- In this analysis, default results are from including pedestal, for $N_{ch}^{rec} \geq 20$.

Template fitting results

$$Y^{\mathrm{templ}}(\Delta\phi) = Y^{\mathrm{ridge}}(\Delta\phi) + FY^{\mathrm{periph}}(\Delta\phi)$$

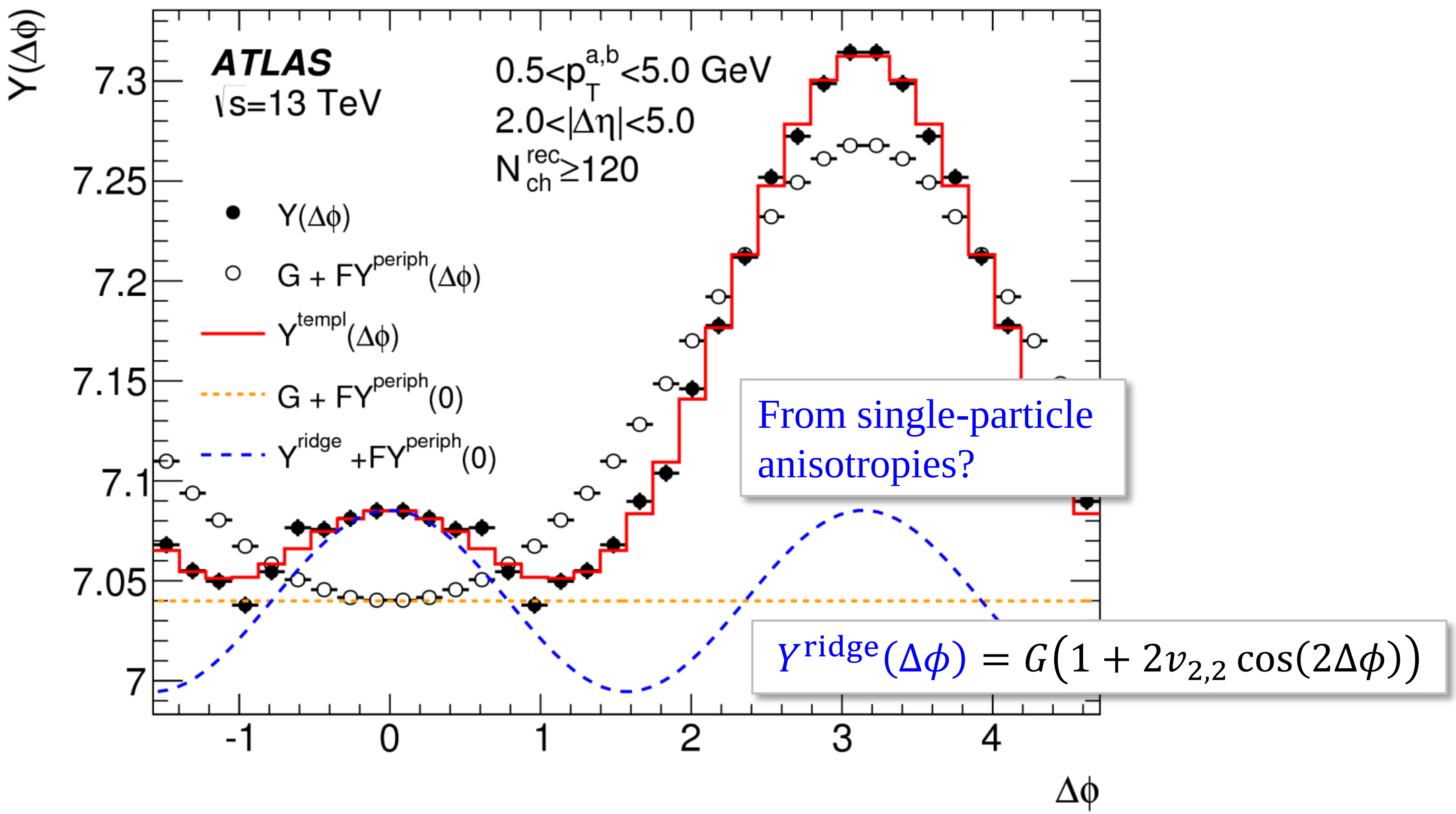


$$Y^{\mathrm{ridge}}(\Delta\phi) = G\left(1 + 2v_{2,2}\cos(2\Delta\phi)\right)$$

- Template fitting works quite well: compare red curve Y^{templ} and black bullets Y.

Template fitting results

$$Y^{\mathrm{templ}}(\Delta\phi) = Y^{\mathrm{ridge}}(\Delta\phi) + FY^{\mathrm{periph}}(\Delta\phi)$$



- Template fitting works quite well: compare red curve Y^{templ} and black bullets Y.

Single-particle anisotropies v_2

- In Pb+Pb and *p*+Pb collisions, the long-range structures in two-particle correlation arise from single particle anisotropies

$$\text{Singles:} \quad \frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos n(\phi - \Phi_n)$$

$$\Rightarrow \quad \text{Pairs:} \quad \frac{dN}{d\Delta\phi} \propto 1 + \sum_n 2v_n^a v_n^b \cos n(\Delta\phi)$$

- If this is also true in *pp*, then the measured $v_{2,2}$ should factorize as:

$$v_{2,2}\left(p_{\mathrm{T}}^a, p_{\mathrm{T}}^b\right) = v_2(p_{\mathrm{T}}^a) v_2\left(p_{\mathrm{T}}^b\right)$$

$$\Rightarrow \quad v_2(p_{\mathrm{T}}^a) = v_{2,2}\left(p_{\mathrm{T}}^a, p_{\mathrm{T}}^b\right) / \sqrt{v_{2,2}\left(p_{\mathrm{T}}^b, p_{\mathrm{T}}^b\right)}$$

- Expectation: $v_{2,2}\left(p_{\mathrm{T}}^a, p_{\mathrm{T}}^b\right)$ depends on both p_{T}^a and p_{T}^b, but the ratio $v_2(p_{\mathrm{T}}^a)$ should be independent of reference p_{T}^b.

Factorization of $\boldsymbol{v_{2,2}}$

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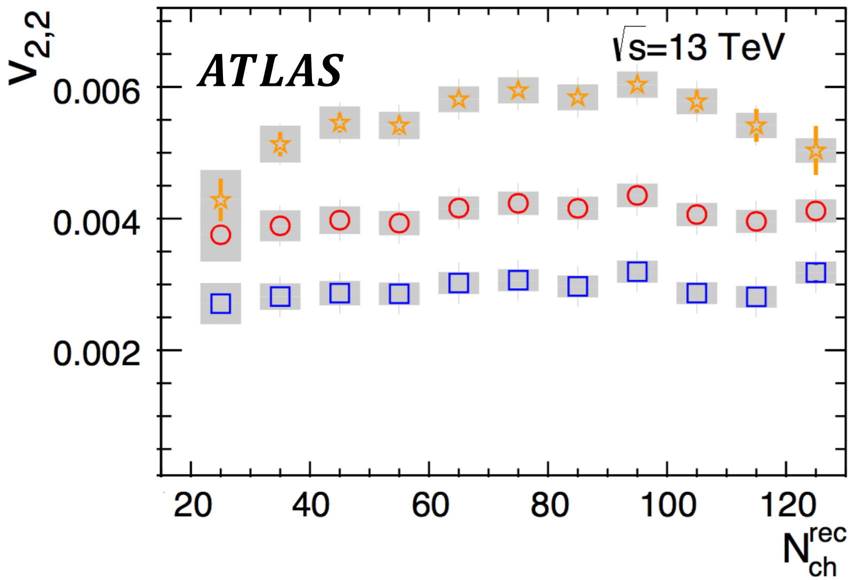
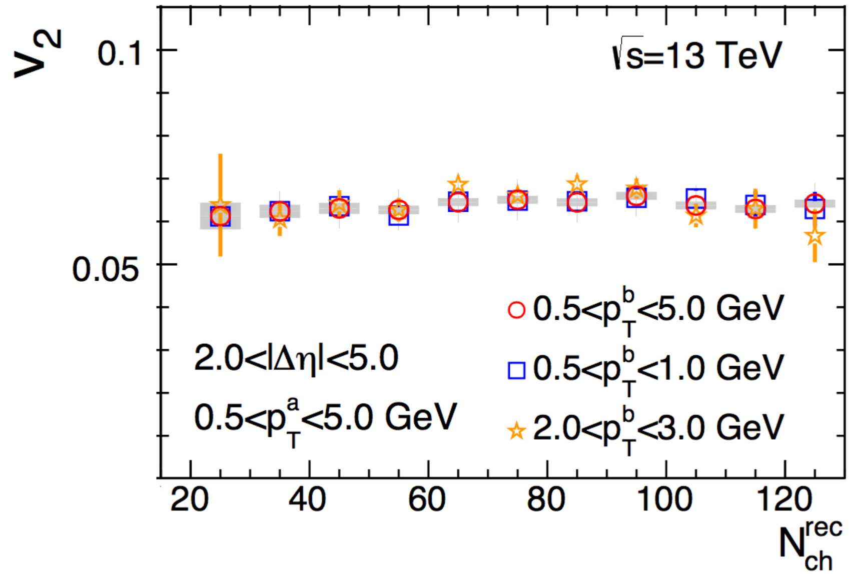
Factorization of $v_{2,2}$



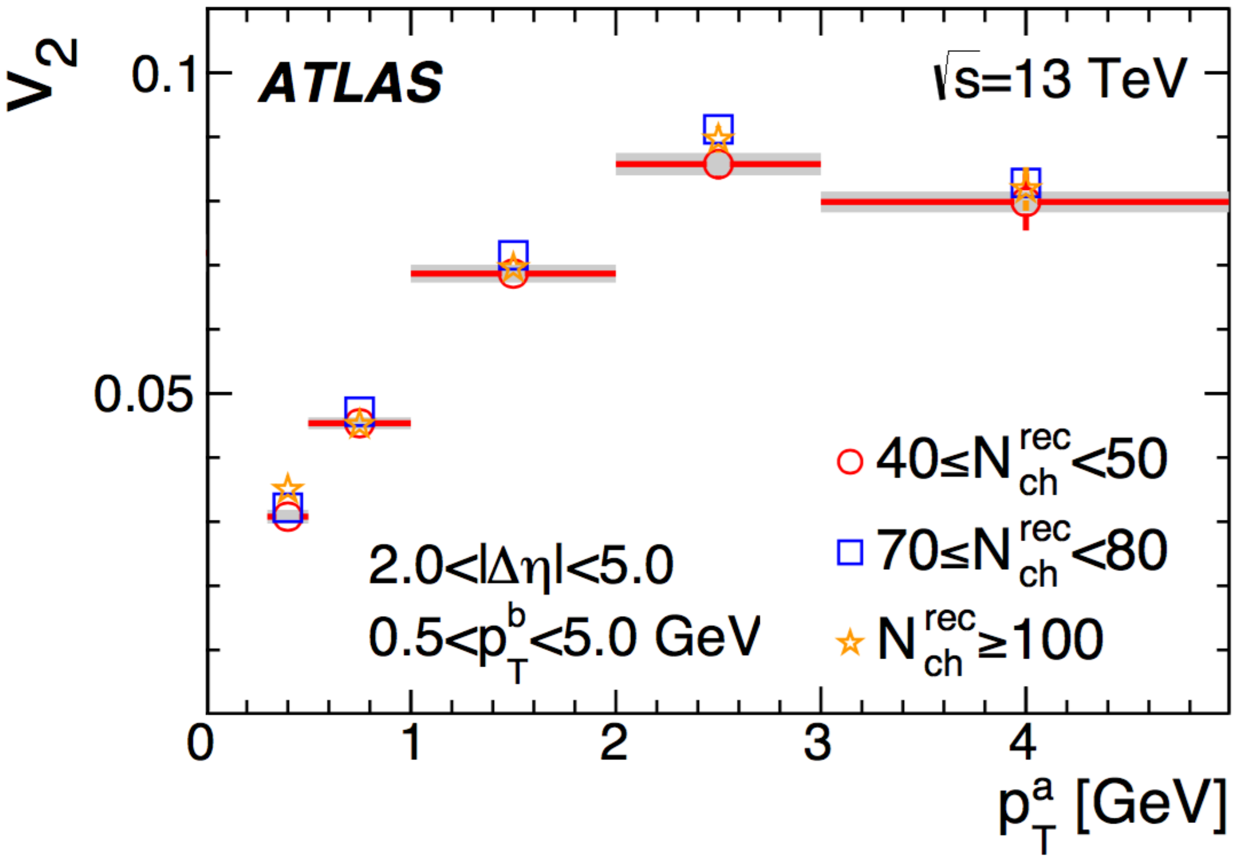


- $v_{2,2}$ is dependent of p_T^b.
- v_2 is independent of p_T^b.

$v_{2,2}$ can be factorized into single-particle v_2.

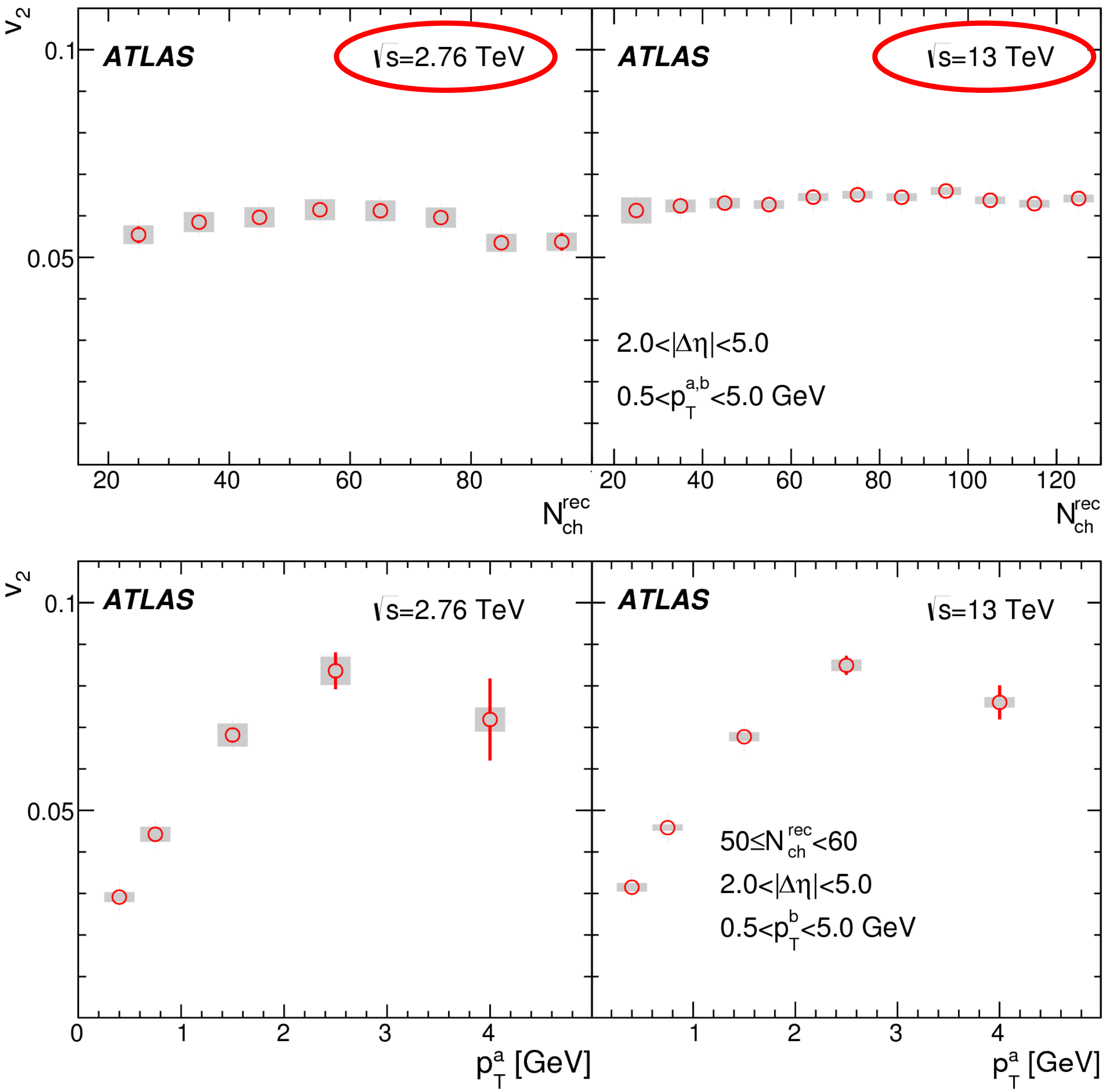
- Expectation: $v_{2,2}(p_T^a, p_T^b)$ depends on both p_T^a and p_T^b, but the ratio $v_2(p_T^a)$ should be independent of reference p_T^b.

p_T dependence of v_2



- v_2 increases with p_T at lower p_T;
- Reaches a maximum between 2 and 3 GeV;
- Decreases at higher p_T.

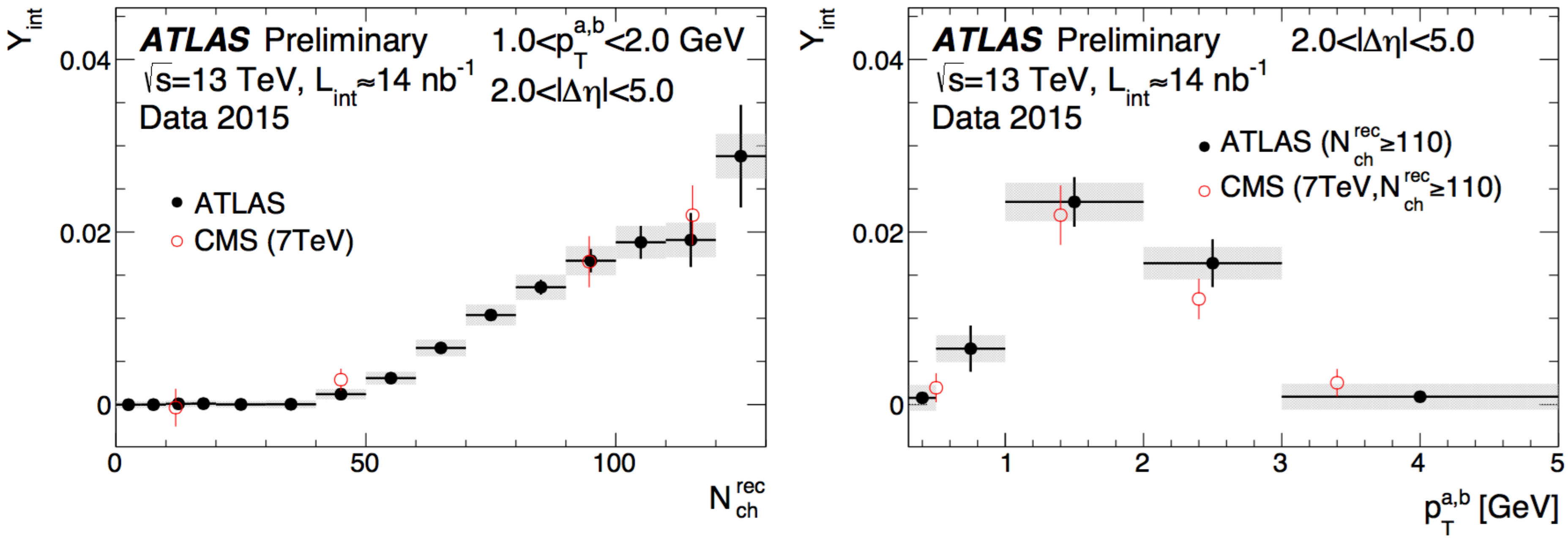
Energy dependence of v_2



v_2 has a very weak energy dependence.

Energy dependence of integrated yield

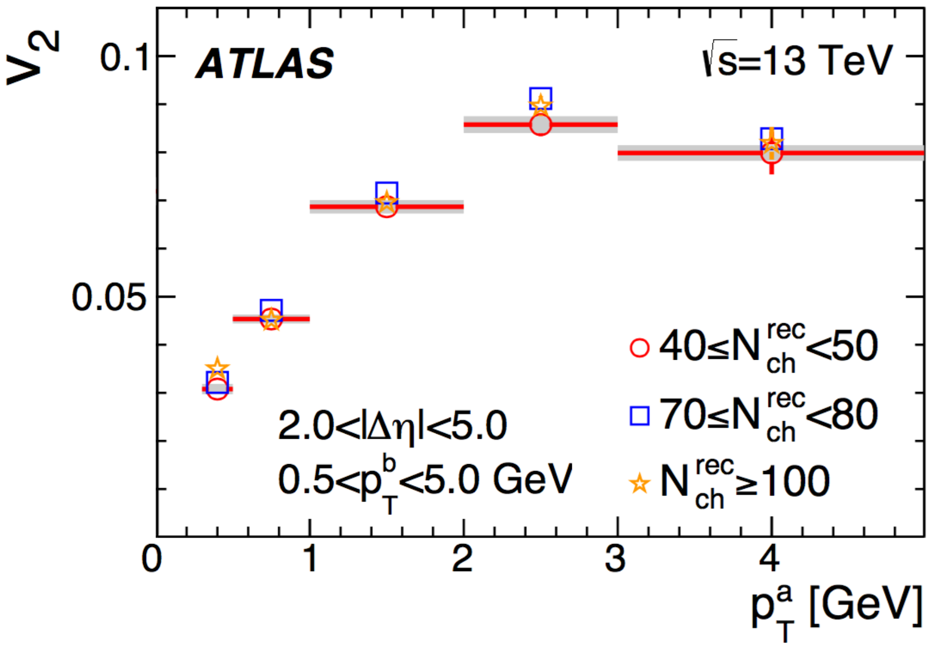
$$Y_{\mathrm{int}} = \int_{-\Delta\phi_{ZYAM}}^{\Delta\phi_{ZYAM}} \mathrm{d}\Delta\phi\,\left(Y(\Delta\phi) - b_{\mathrm{ZYAM}}\right)$$



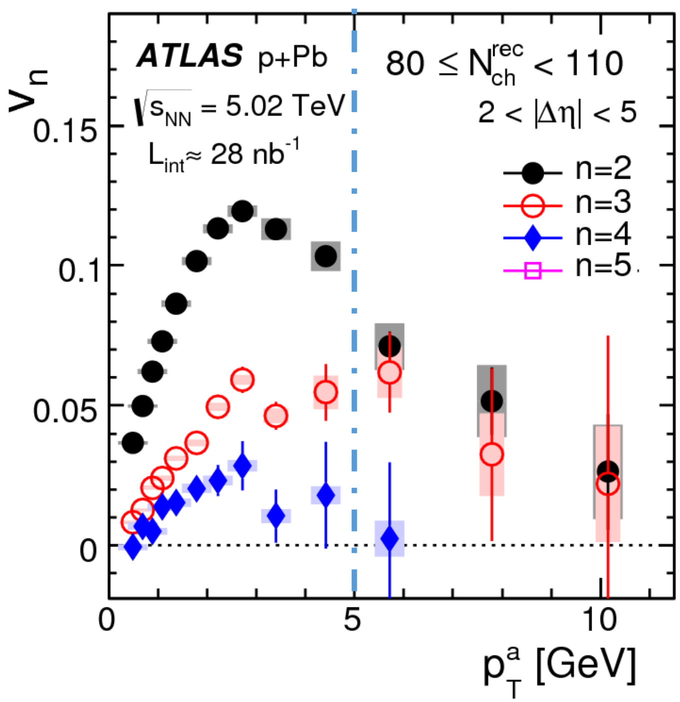
Integrated yield has a very weak energy dependence.

Different collision systems

pp



p+Pb



- v_2 have similar trend, but 30% smaller in *pp*;
- Suggesting a similar physical mechanism?

Summary

- Ridge observed in high-multiplicity *pp* collisions at 13 and 2.76 TeV;

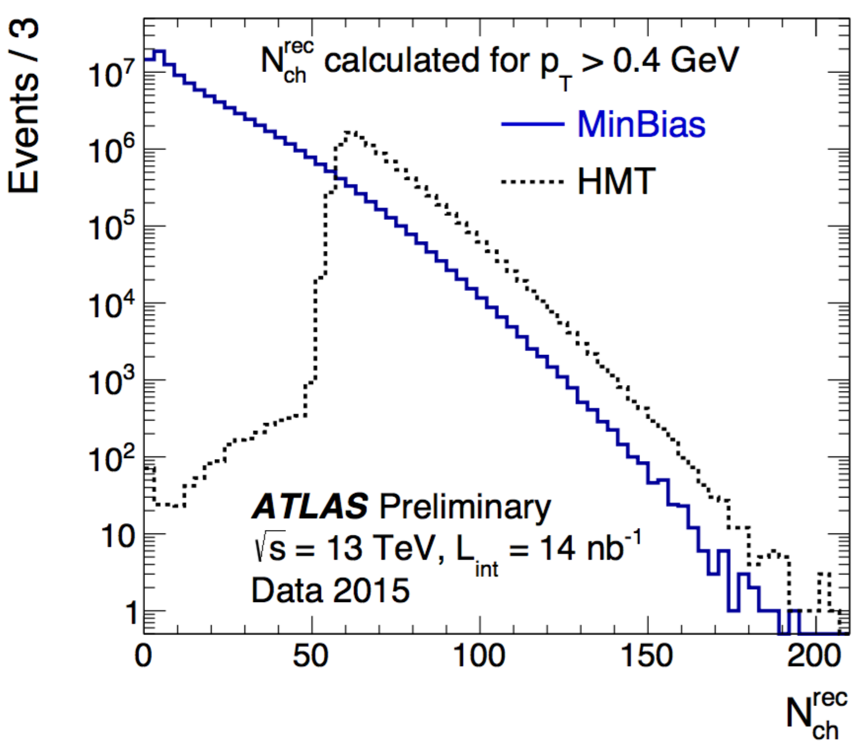
- Template fitting is applied to extract LRC modulated by $v_{2,2}$;
- $v_{2,2}$ can be factorized into single particle v_2;

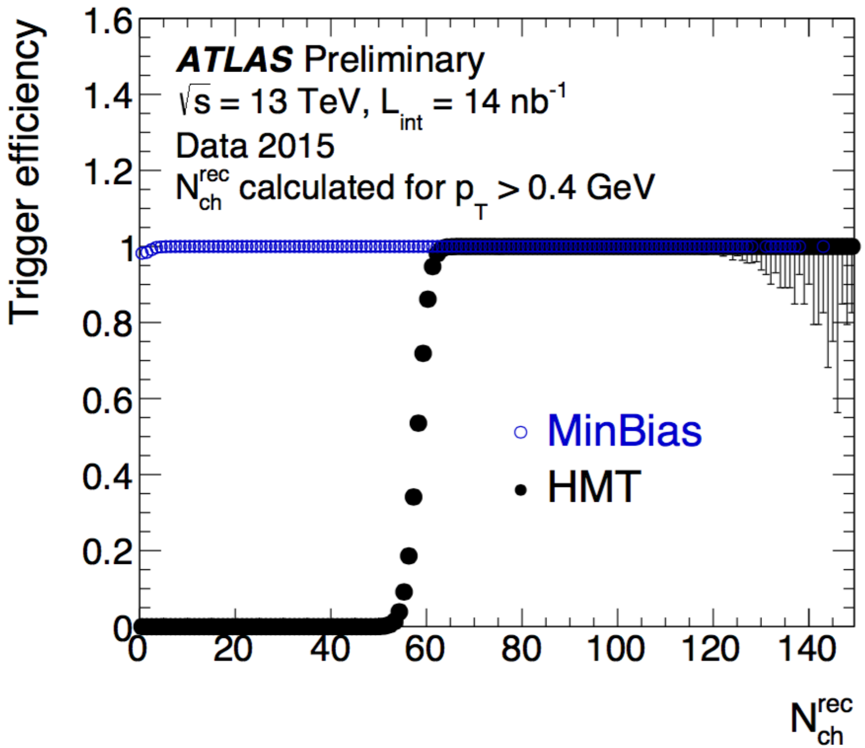
- v_2 has a very weak N_{ch}^{rec} dependence;
- v_2 has a very weak energy dependence;
- v_2 has a similar trend as *p*+Pb.

Back-up

More about the data set

- 13 TeV data were collected in low-luminosity runs for which the collision rate per crossing, μ, varied between ~0.002 and ~0.04;
- The major high-multiplicity track trigger
  - At least one counter on each side of the MBTS;
  - At least 900 hits in the SCT;
  - At least 60 HLT-reconstructed tracks having $p_T > 0.4$ GeV.





Systematics for $v_{2,2}$ at $\sqrt{s} = 13$ TeV

	Syst Uncertainty	Value for $v_{2,2}$	Comment
1	Choice of peripheral bin	10% : $N_{\mathrm{ch}}^{\mathrm{rec}}<30$ 5-2% :$30<N_{\mathrm{ch}}^{\mathrm{rec}}<60$ 2% : $N_{\mathrm{ch}}^{\mathrm{rec}}>60$	$N_{\mathrm{ch}}^{\mathrm{rec}}$ dependent
2	Tracking Efficiency	0.5%	
3	Pileup	0.25%	
4	MC Closure	2% for $p_{\mathrm{T}}>0.5$GeV 6% for $p_{\mathrm{T}}<0.5$GeV 1.5×10^{-4} (absolute)	Larger of the three numbers for each $p_{\mathrm{T}}^{\mathrm{a}}$
5	Pair Acceptance	4×10^{-5}	Absolute error (not %)

- Choice of Peripheral Bin: vary the peripheral reference bins N_{ch}^{rec};
- Tracking Efficiency: repeat the analysis when varying the efficiency to its upper and lower extremes;
- Pileup: fraction of events with pileup vertex close to the primary vertex;
- MC Consistency: $v_{2,2}$ introduced by away-side jet in PYTHIA (no genuine long-range correlation);
- Pair Acceptance: $v_{2,2}$ calculated from the mixed events.

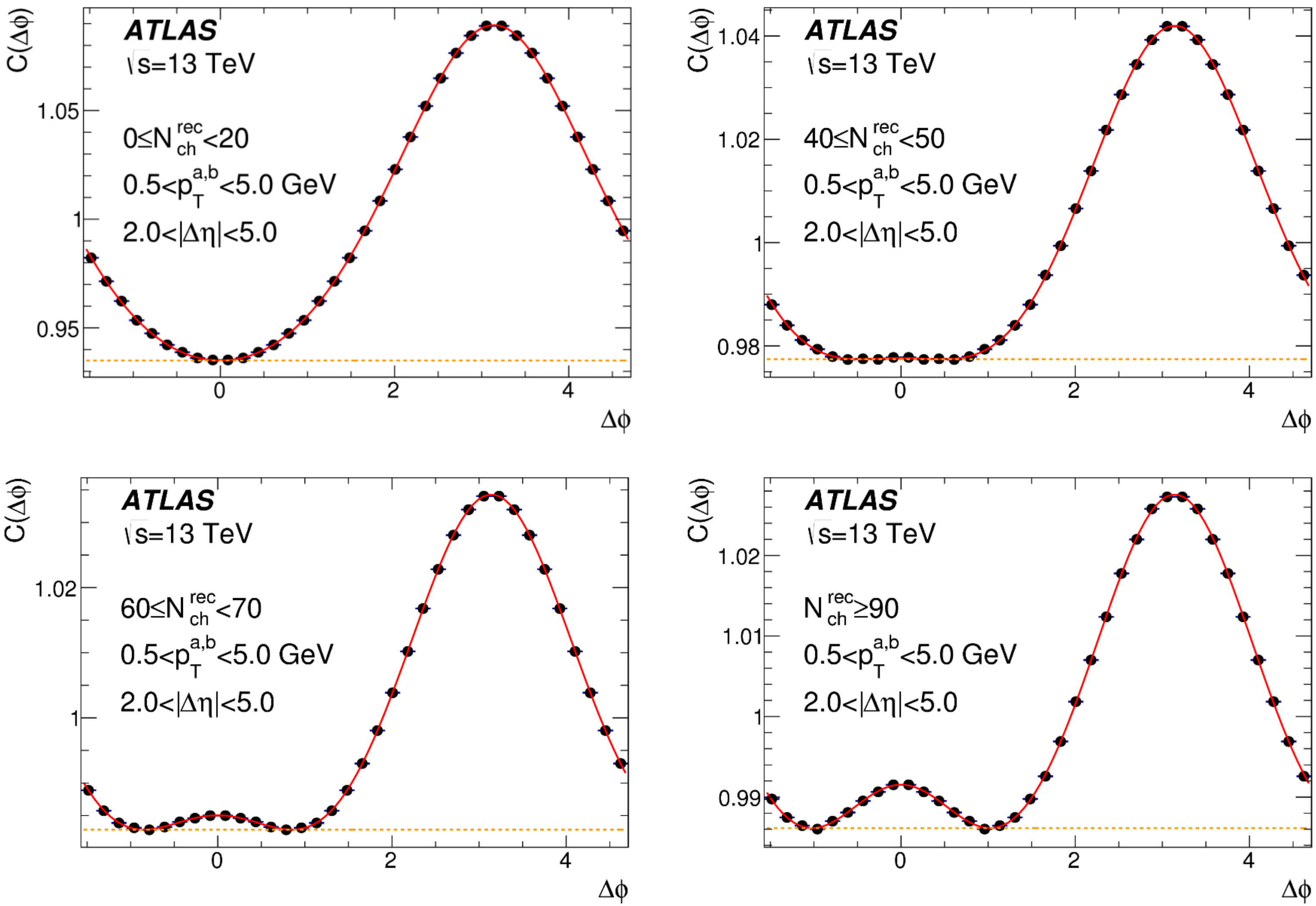
Systematics for $v_{2,2}$ at $\sqrt{s} = 2.76$ TeV

	Syst Uncertainty	Value for $v_{2,2}$
1	Tracking Efficiency	0.8%
2	MC Closure	2%
3	Pair Acceptance	1%
4	Choice of peripheral bin	6%
5	Pileup	5%

- Choice of Peripheral Bin: vary the peripheral reference bins N_{ch}^{rec};
- Tracking Efficiency: repeat the analysis when varying the efficiency to its upper and lower extremes;
- Pileup: fraction of events with pileup vertex close to the primary vertex;
- MC Consistency: $v_{2,2}$ introduced by away-side jet in PYTHIA (no genuine long-range correlation);
- Pair Acceptance: $v_{2,2}$ calculated from the mixed events.

1D Correlation functions $C(\Delta\phi)$ at 13 TeV

$$C(\Delta\phi) = \frac{\int_2^5 d|\Delta\phi| S(\Delta\phi, |\Delta\eta|)}{\int_2^5 d|\Delta\phi| B(\Delta\phi, |\Delta\eta|)}$$



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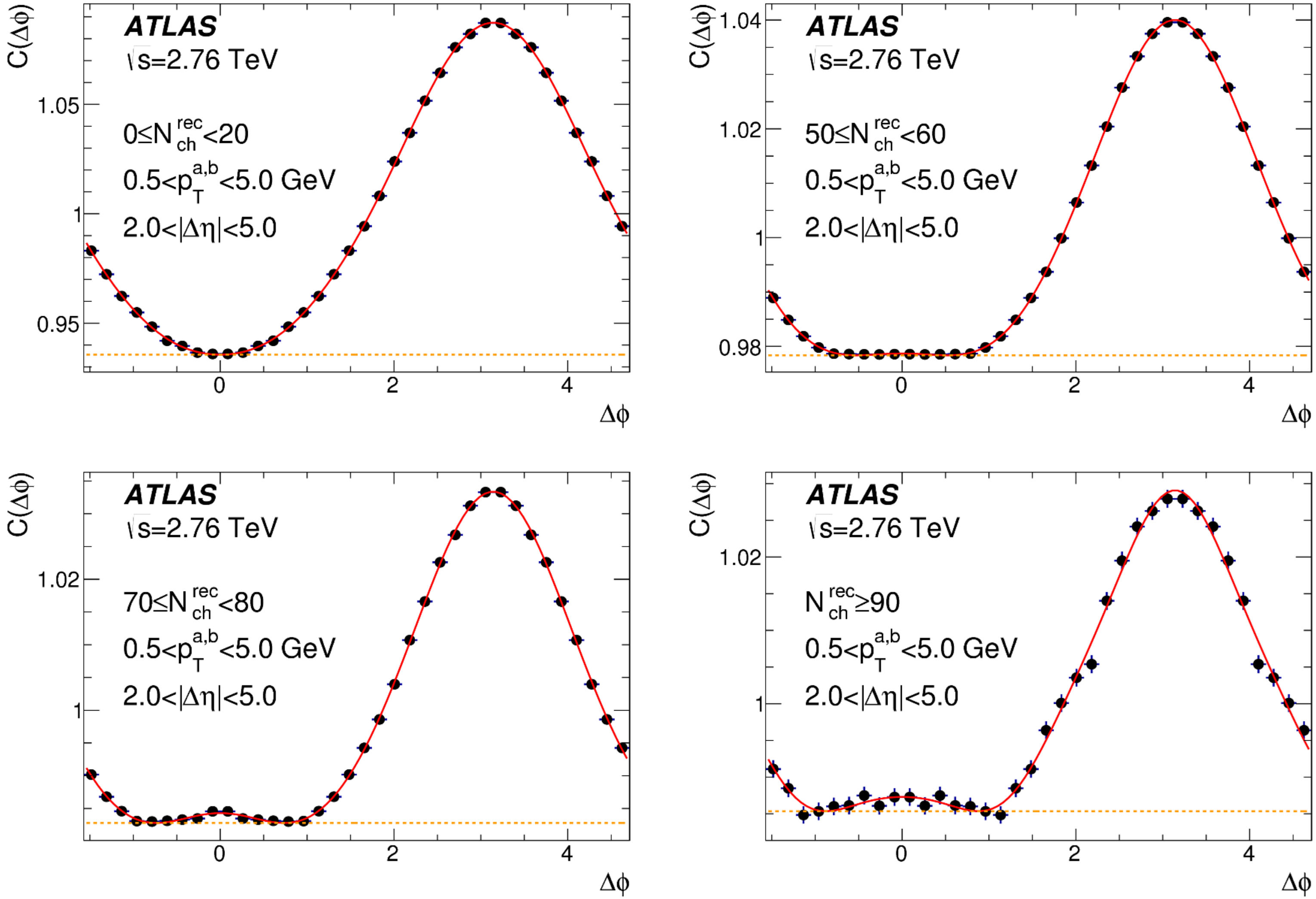
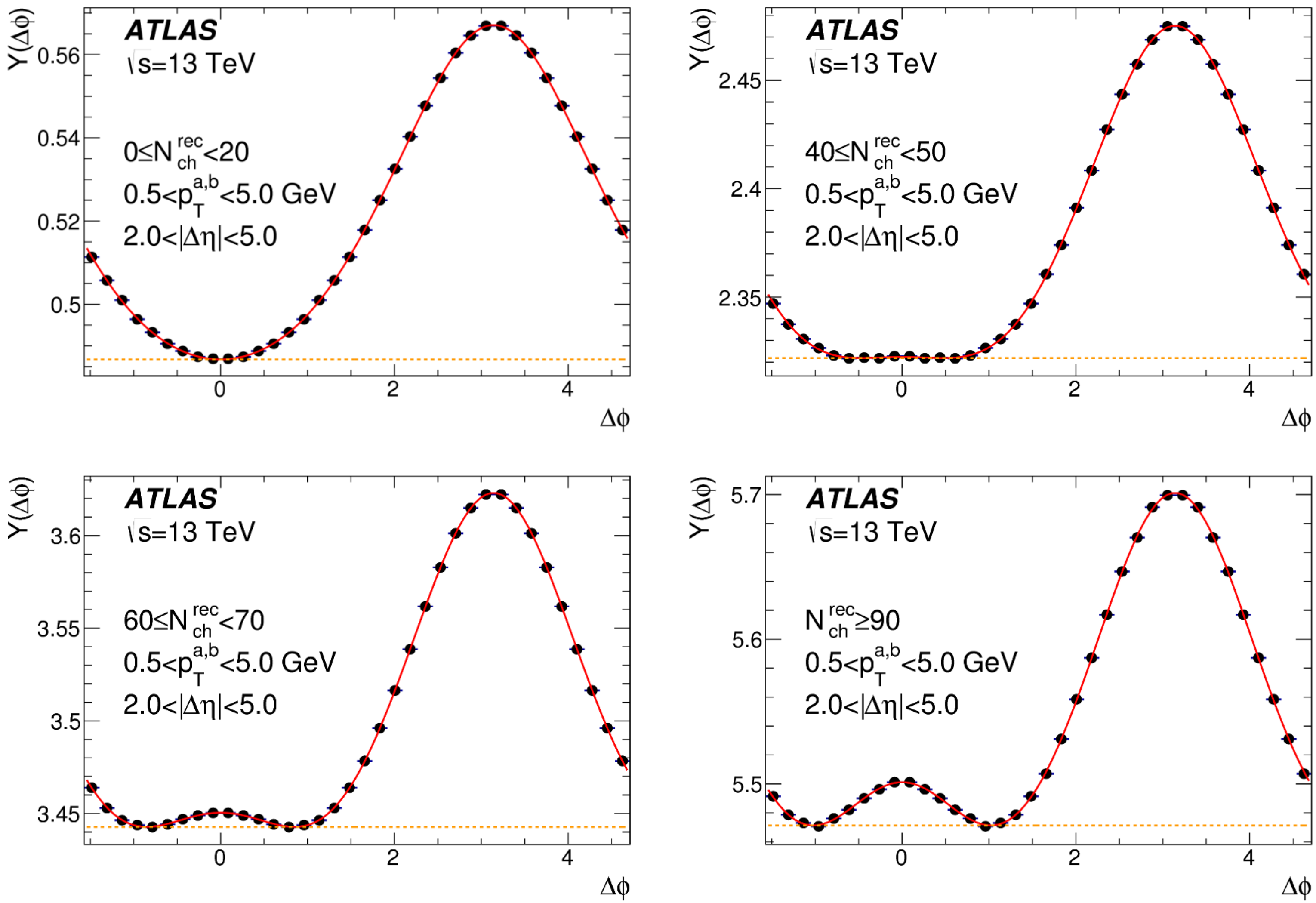


Per-trigger-particle yield $Y(\Delta\phi)$ at 13 TeV

$$Y(\Delta\phi) = \left(\frac{\int B(\Delta\phi)\,\mathrm{d}\Delta\phi}{N^{a}\int \mathrm{d}\Delta\phi}\right) C(\Delta\phi)$$



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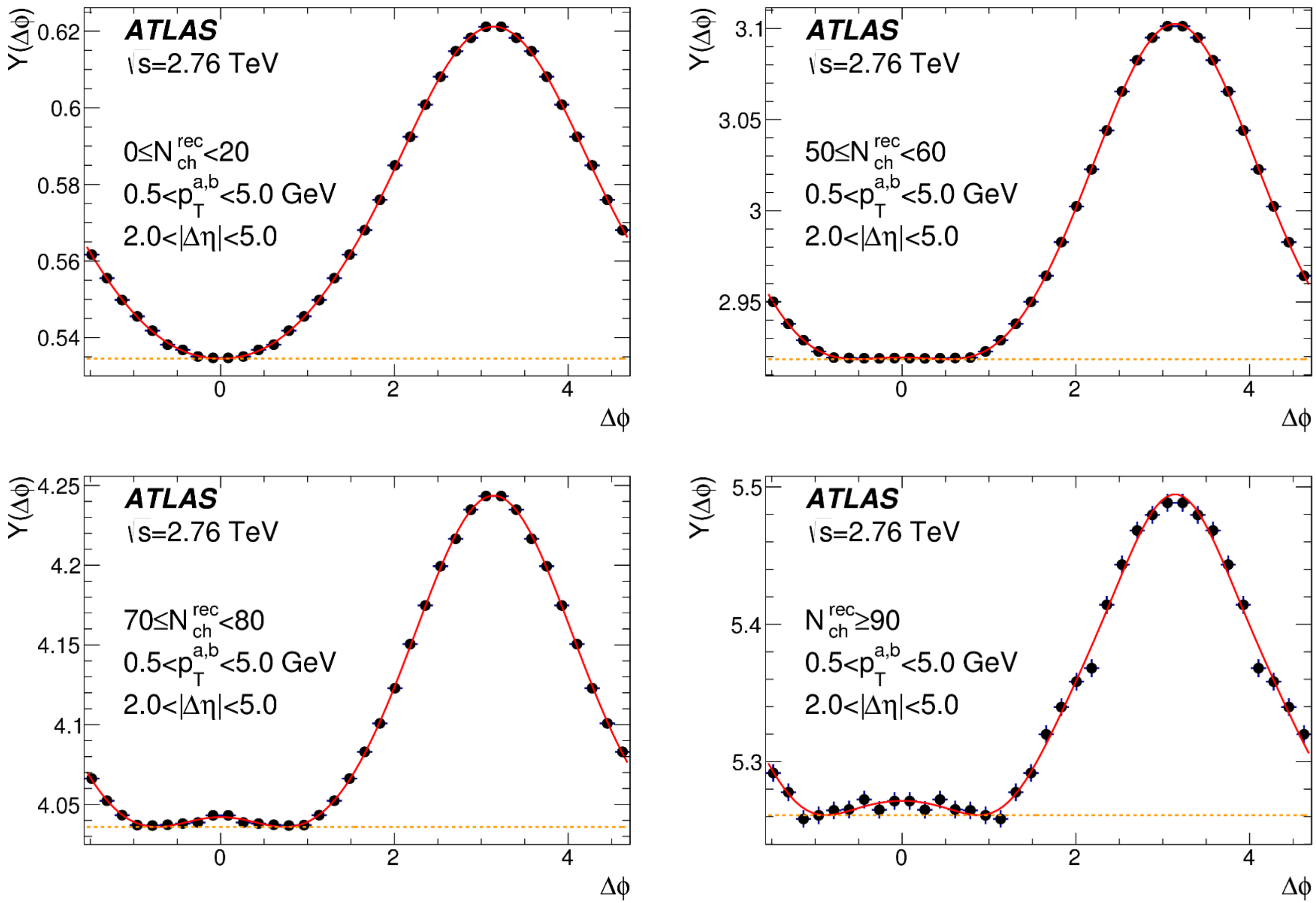
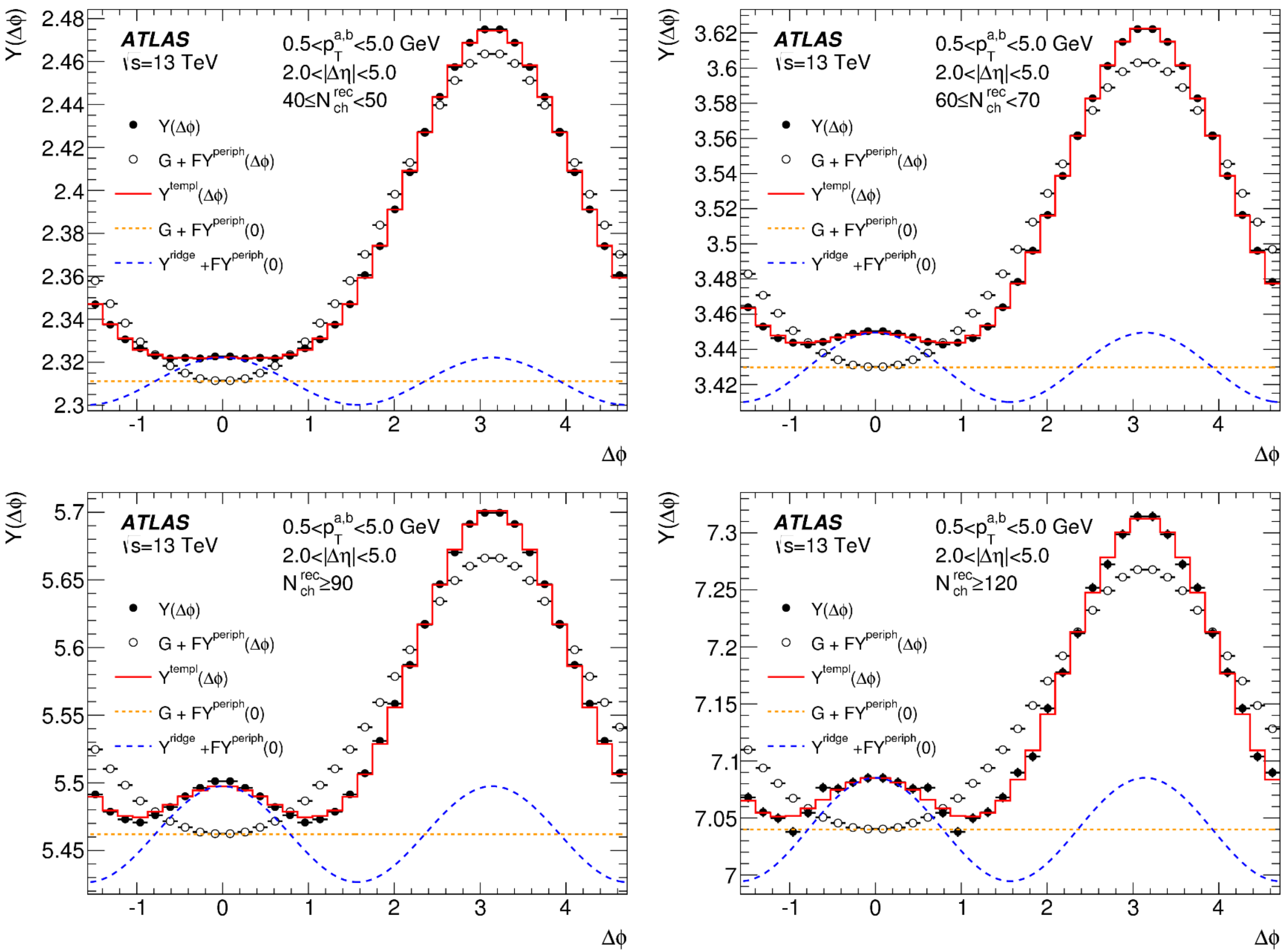


Template fit at 13 TeV

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



Template fit at 2.76 TeV

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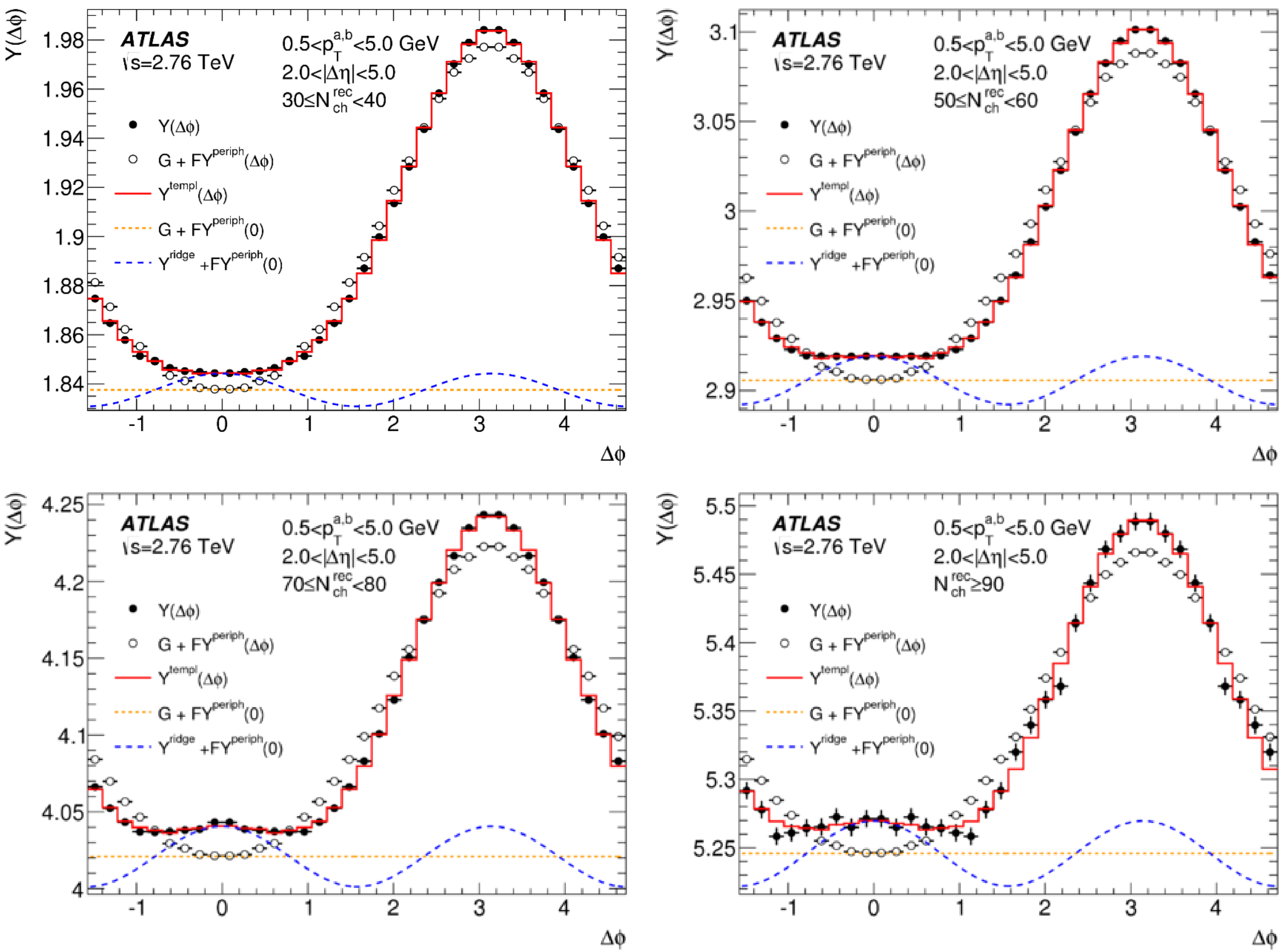
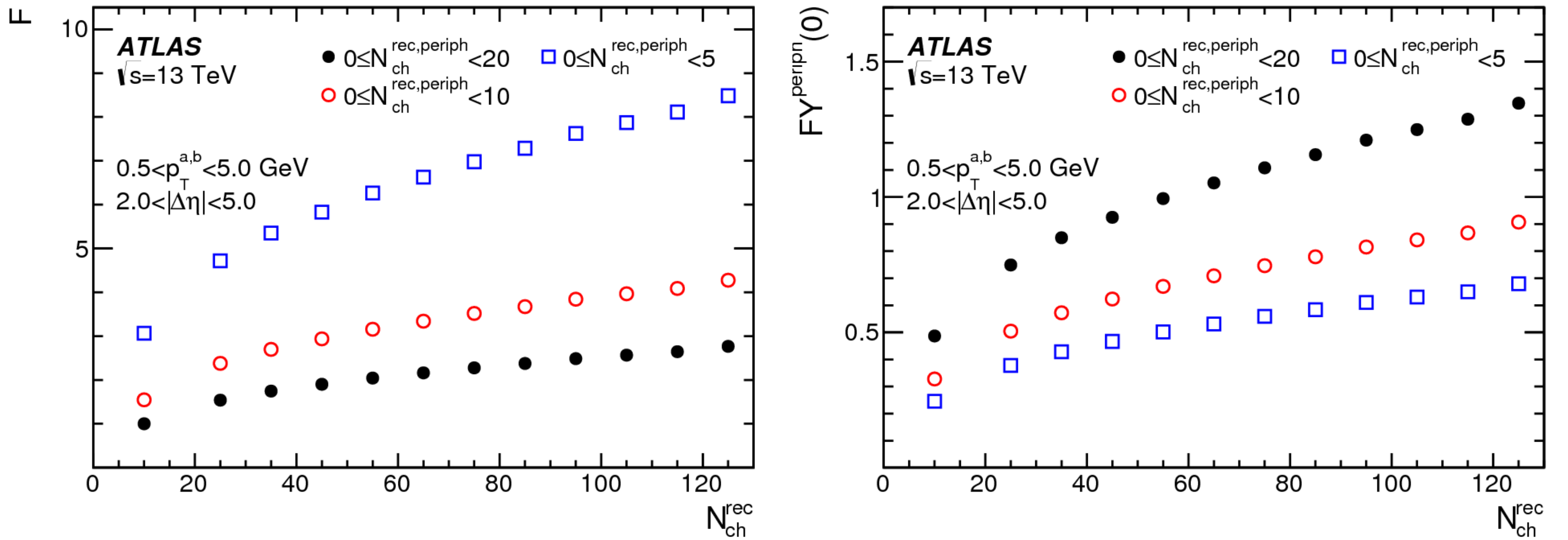
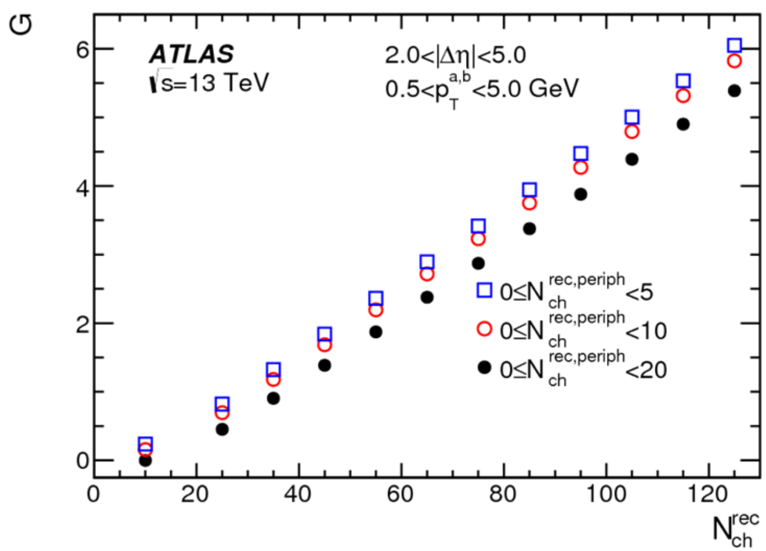


Parameters from template fits





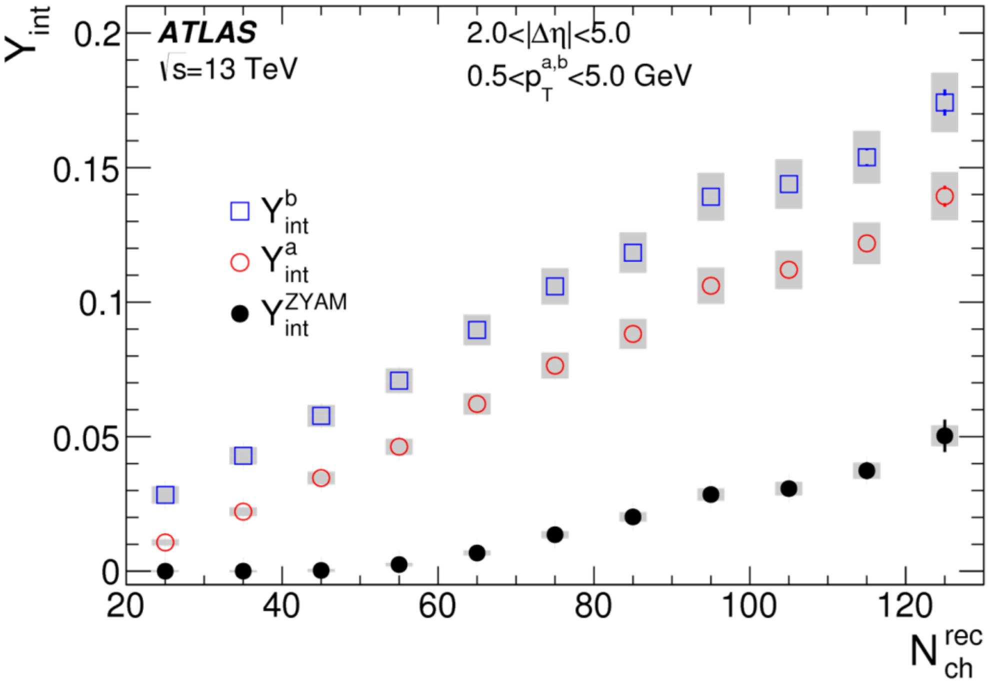
$$Y^{\text{templ}}(\Delta\phi) = FY^{\text{periph}}(\Delta\phi) + Y^{\text{ridge}}(\Delta\phi)$$

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

two free parameters: F and $v_{2,2}$

G is fixed by $\int_0^\pi d\Delta\phi\; Y^{\text{templ}} = \int_0^\pi d\Delta\phi\; Y$

p_{T} dependence of integrated yields



- Results using template fit method from this *pp* analysis.
- Results using template fit method from previous *p*+Pb analysis.
- Results using ZYAM method.

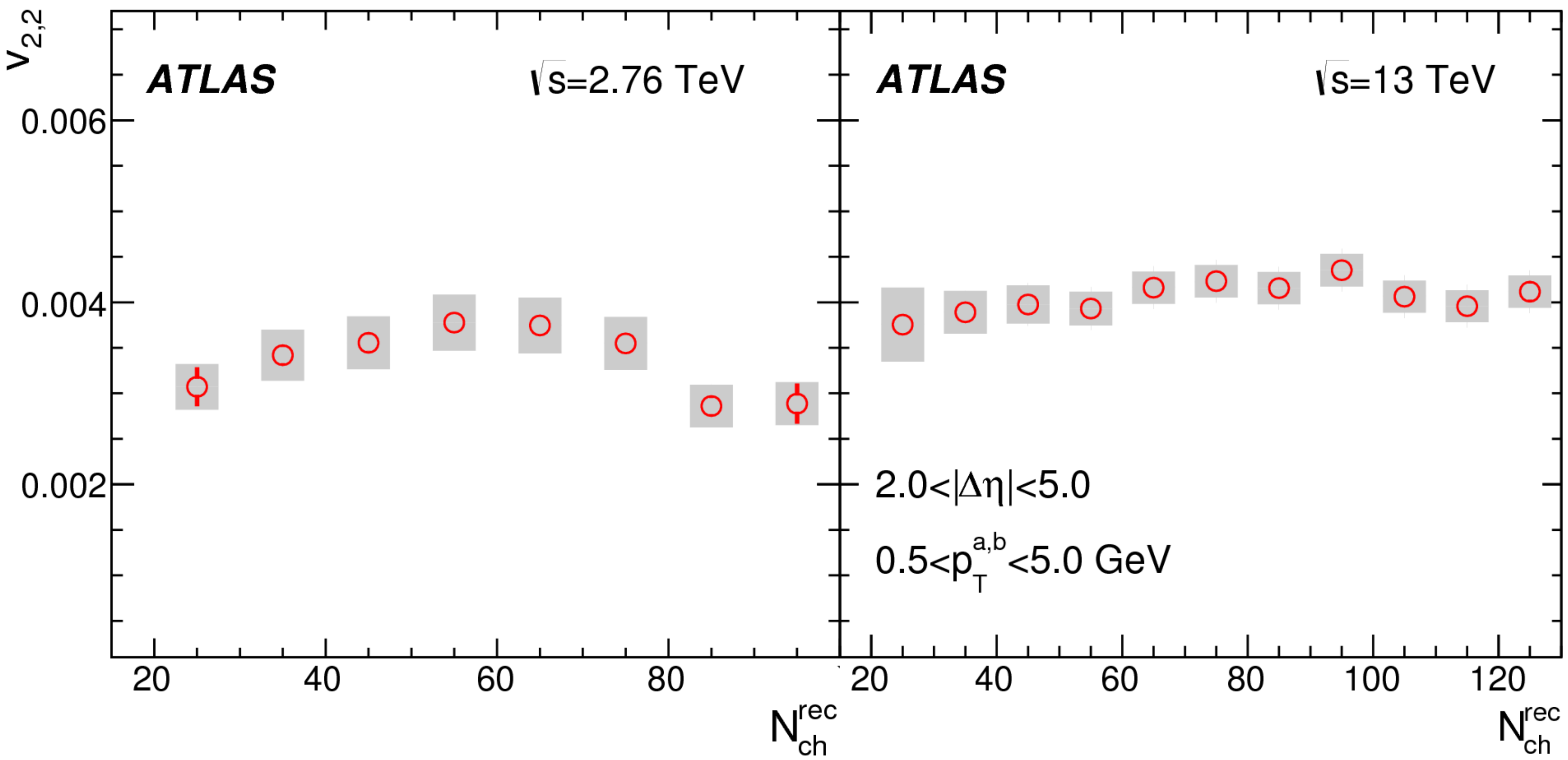
- Due to the modulation of v_n, estimation of b_{ZYAM} is biased: ZYAM method underestimates integrated yield;
- Assuming no flow in the peripheral will give a lower bound of Y_{int};
- Assuming same magnitude of flow in the peripheral will give a upper bound of Y_{int}.

Details about the template fitting procedure

- If there is $v_{2,2}$ in peripheral:

$$Y^{\mathrm{peri}}(\Delta\phi) = N_0^{\mathrm{peri}}\left(1 + 2v_{2,2}^{\mathrm{peri}}\cos(2\Delta\phi)\right) + Y_{\mathrm{jet}}^{\mathrm{peri}}(\Delta\phi)$$

Energy dependence of $v_{2,2}$



This is the last slide