

Measurements of Longitudinal Decorrelation in small systems with ATLAS

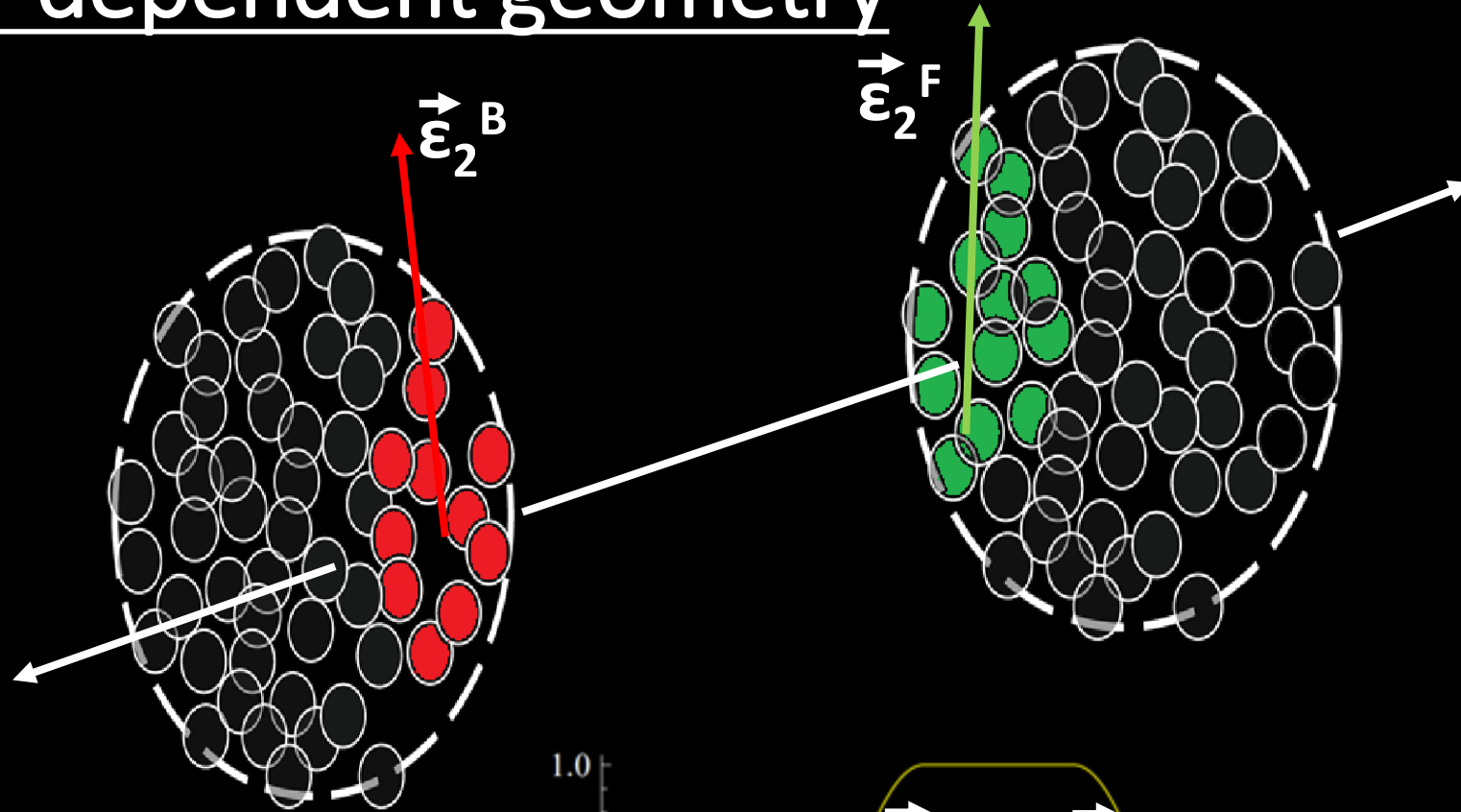


Blair Daniel Seidlitz
Columbia University

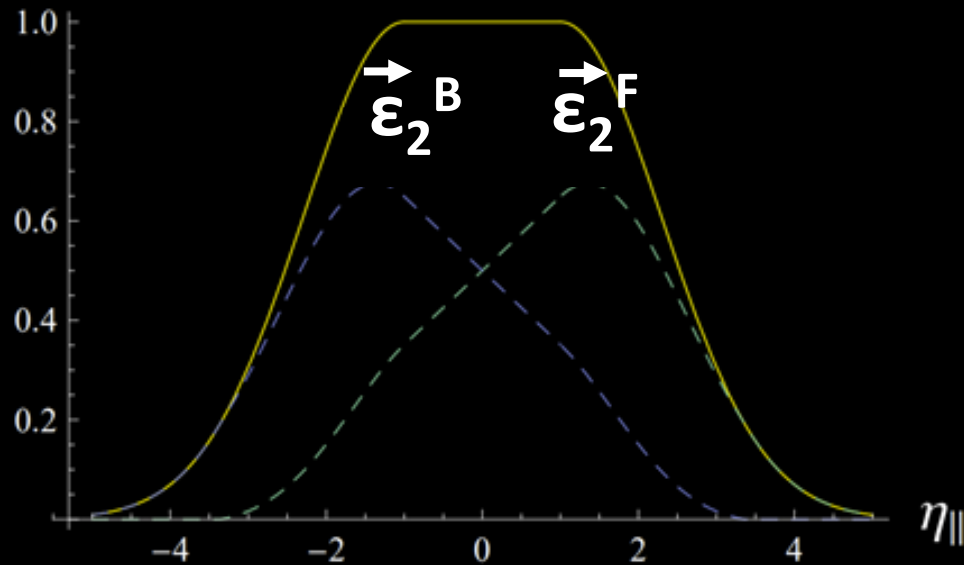


Quark Matter Sept. 5th , 2023

η -dependent geometry



$$\frac{dN}{d\eta}$$



First models of longitudinal decorrelation

Backwards-going participants dominates backwards-going $dN/d\eta$ and backwards-going initial-state geometry ϵ_n^B

ϵ_n^B and ϵ_n^F could be different

Interpolation between geometries at mid rapidity

Fluctuation-driven geometry (e.g. ϵ_3) can vary more

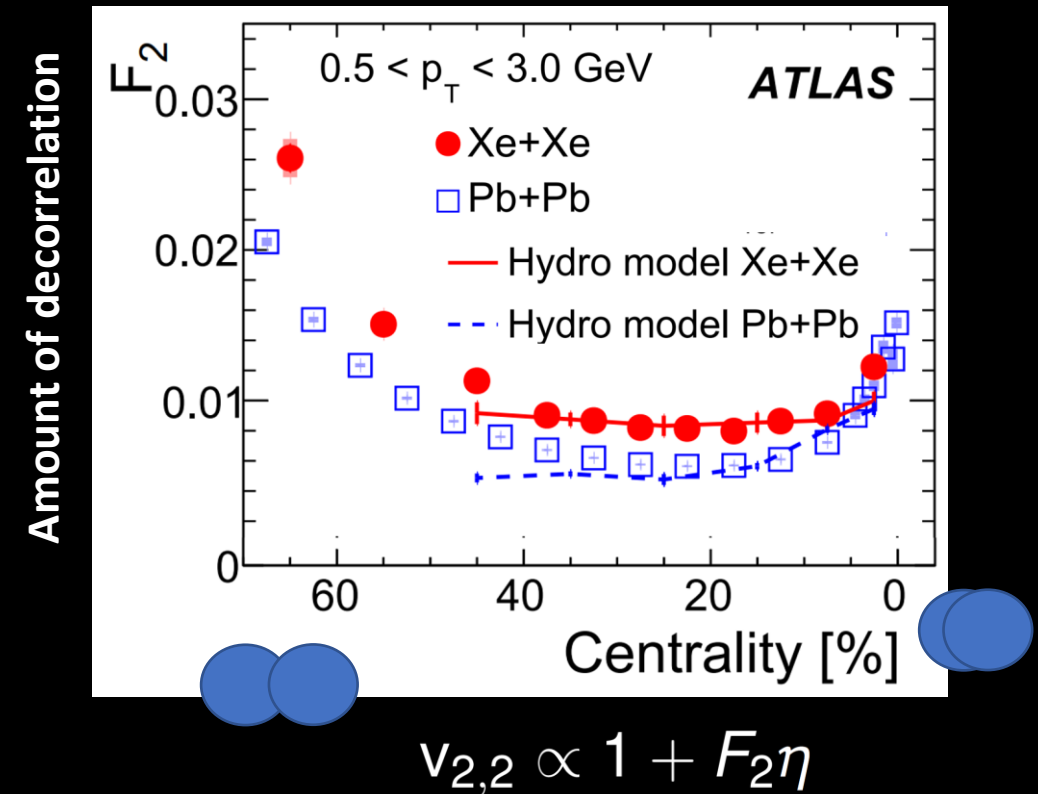
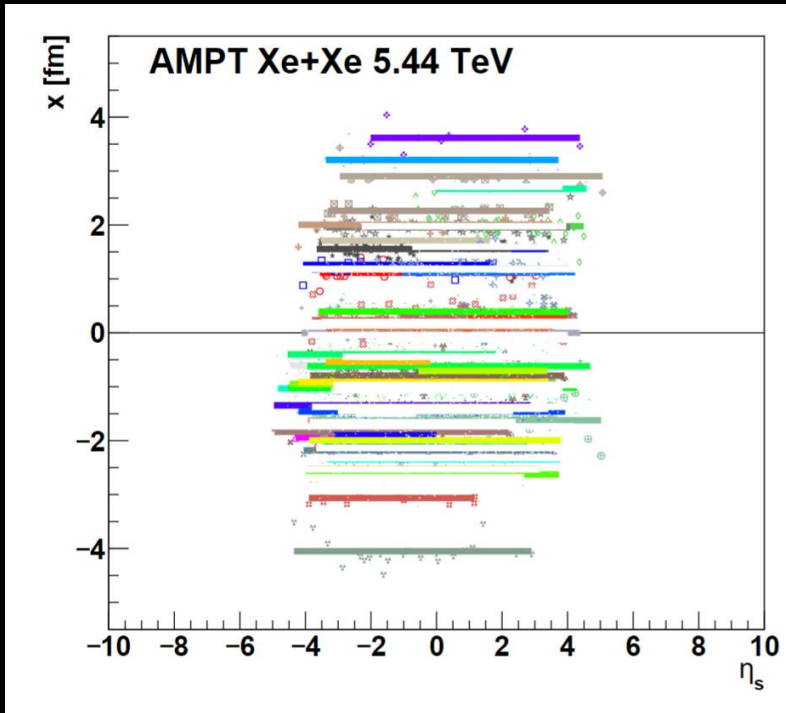
Hydrodynamic expansion gives rise to azimuthally anisotropic final-state momentum

[arXiv:1011.3354](https://arxiv.org/abs/1011.3354)

String models of longitudinal decorrelation

- String-based MC Glauber models of the initial state simulate these effects out of the box
- Popular models (HIJING/AMPT) produce one string per participant
- String-based initial state + hydro has shown good agreement with previous ATLAS results.

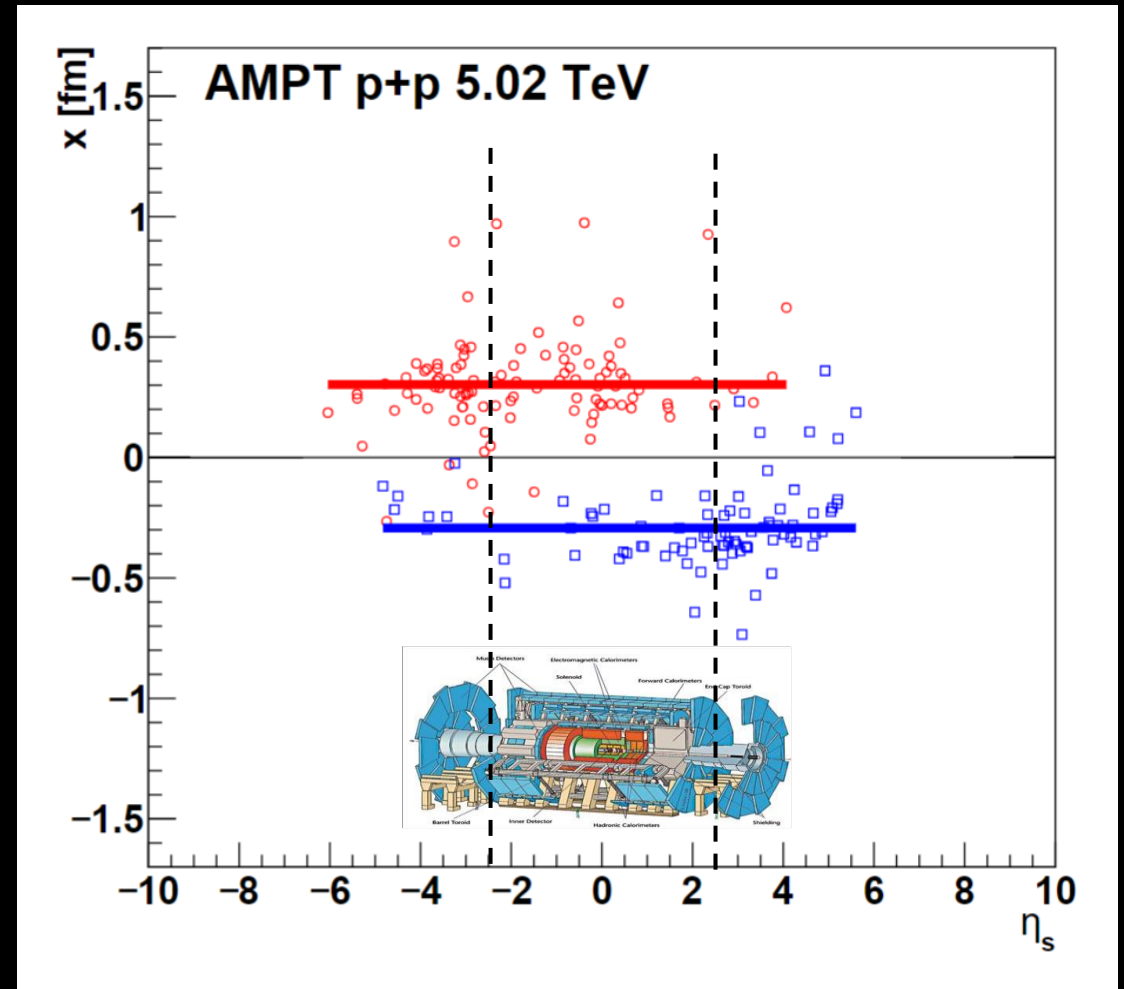
[arXiv:2001.04201](https://arxiv.org/abs/2001.04201)



String models make straightforward prediction in pp

- A string per participant produces a simple model of proton-proton collisions
- Strings span the acceptance of the ATLAS inner detector.
- No variation in geometry
- **No longitudinal decorrelation**

What does data say



Fundamental constraints on nucleon-nucleon collisions

- Constrains the correlation between initial state
 1. Transverse structure and
 2. Longitudinal energy deposition / initial state momentum structure
- Knowledge of the small-system initial-state geometry guards the understanding of many interesting phenomenon such as pre-hydrodynamic evolution
- Longitudinal dependence of correlations is of practical importance when
 - **Comparing experimental results with different acceptances**
 - **Comparing theory and data**

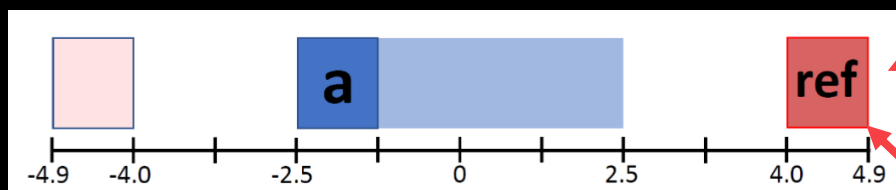
Analysis overview

Systems analyzed

pp 13 TeV Xe+Xe 5.44 TeV

Analysis steps

Step 1: Two-particle correlations between inner detector tracks and forward calorimeter



pp: calorimetric clusters

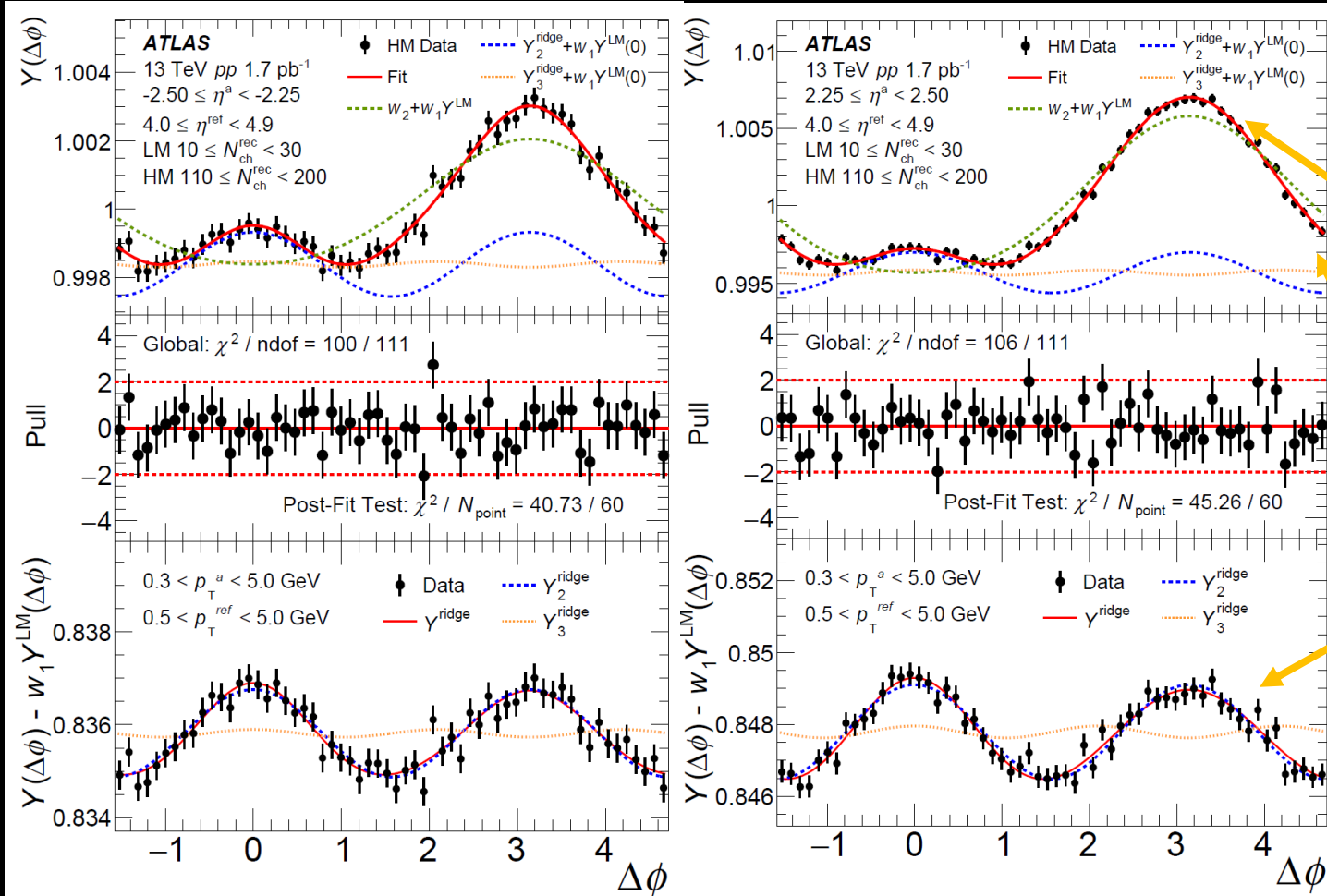
Xe+Xe: calorimetric towers

$$\Delta\phi = \underbrace{\phi^a}_{\eta^a = [-2.5, 2.5]} - \underbrace{\phi^{\text{ref}}}_{\eta^{\text{ref}} = [4.0, 4.9]}$$

Step 2: measure Fourier moments and perform non-flow subtraction as a function of η^a

Step 3: Parametrize decorrelation via the slope of $v_{n,n}(\eta^a)$

Correlation functions and template fits

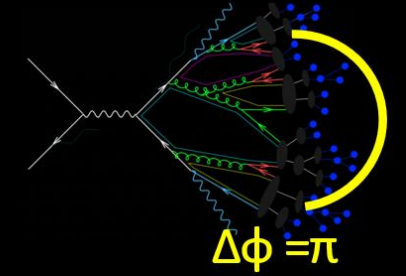


Raw Fourier fit: $a_n(\eta^a)$

$$Y(\Delta\phi, \eta^a) = G \left\{ 1 + 2 \sum_n a_n(\eta^a) \cos(n\Delta\phi) \right\}$$

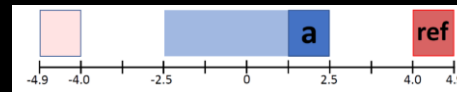
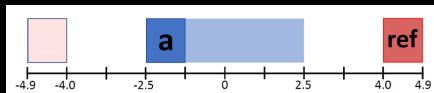
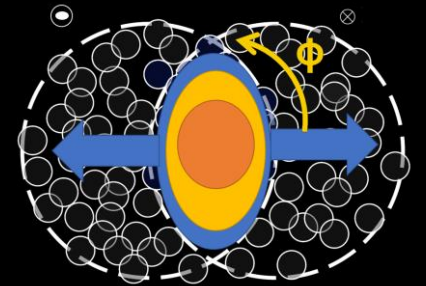
Nonflow

Momentum conservation
Jets & particle decays
Not a global collectivity



Flow

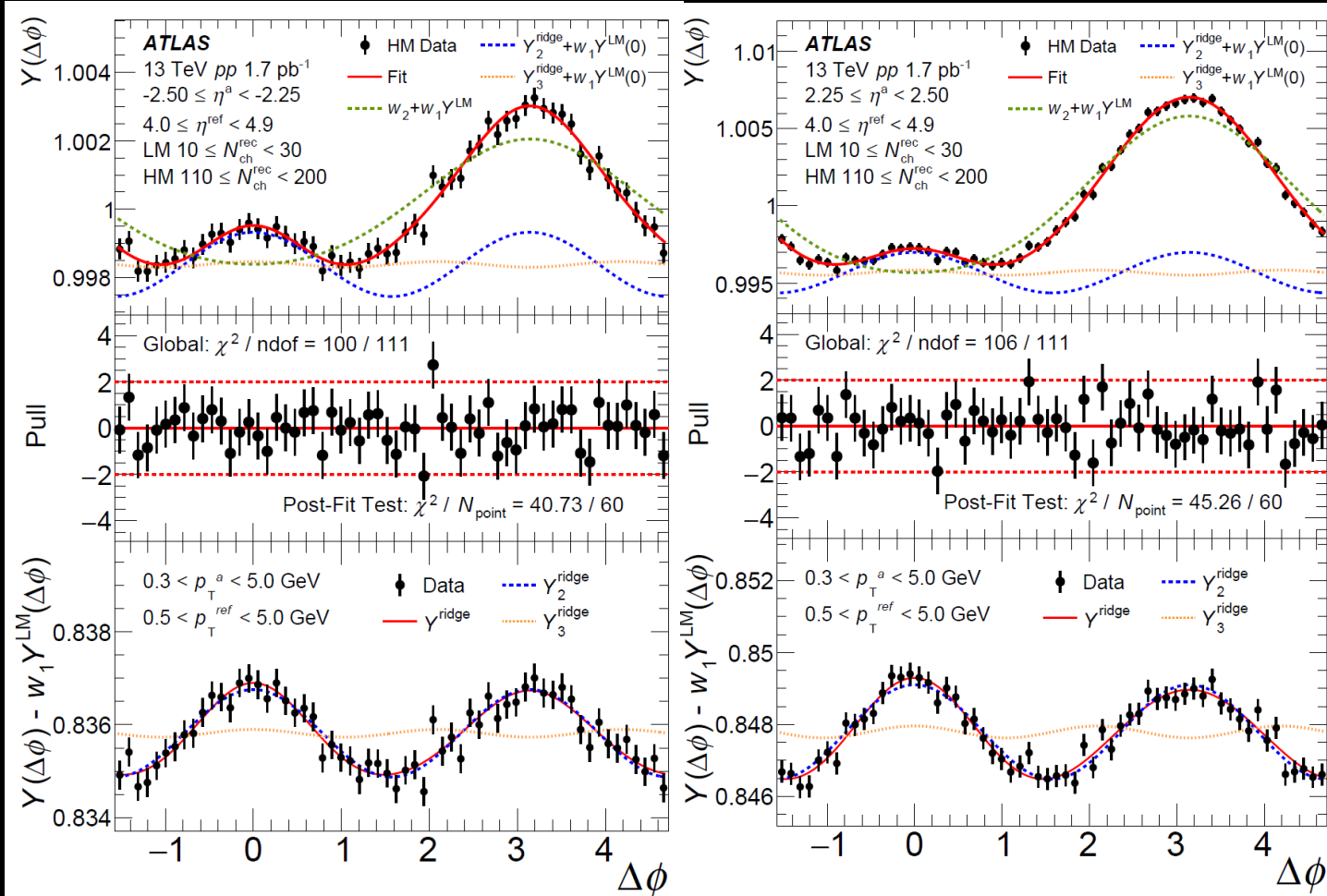
Global modulation
No flow c_1



[arXiv:2308.16745](https://arxiv.org/abs/2308.16745)

Raw Fourier is a combination of flow and nonflow: $a_n(\eta^a)$

Correlation functions and template fits



Template fit: $c_n(\eta^a)$

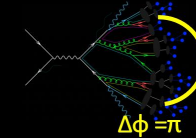
$$Y^{\text{HM}}(\Delta\phi) = w_1 Y^{\text{LM}}(\Delta\phi) + w_2 \left(1 + 2 \sum_{n=2}^4 c_n \cos(n\Delta\phi) \right)$$

Fit:

Low multiplicity correlation

Dominated by nonflow

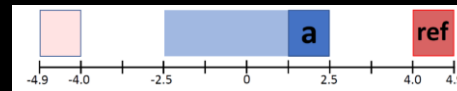
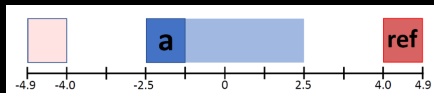
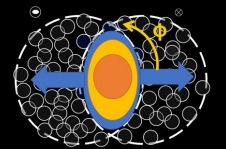
Assumes LM HM nonflow shape



Free Flow moments

Assumes LM HM flow is equal

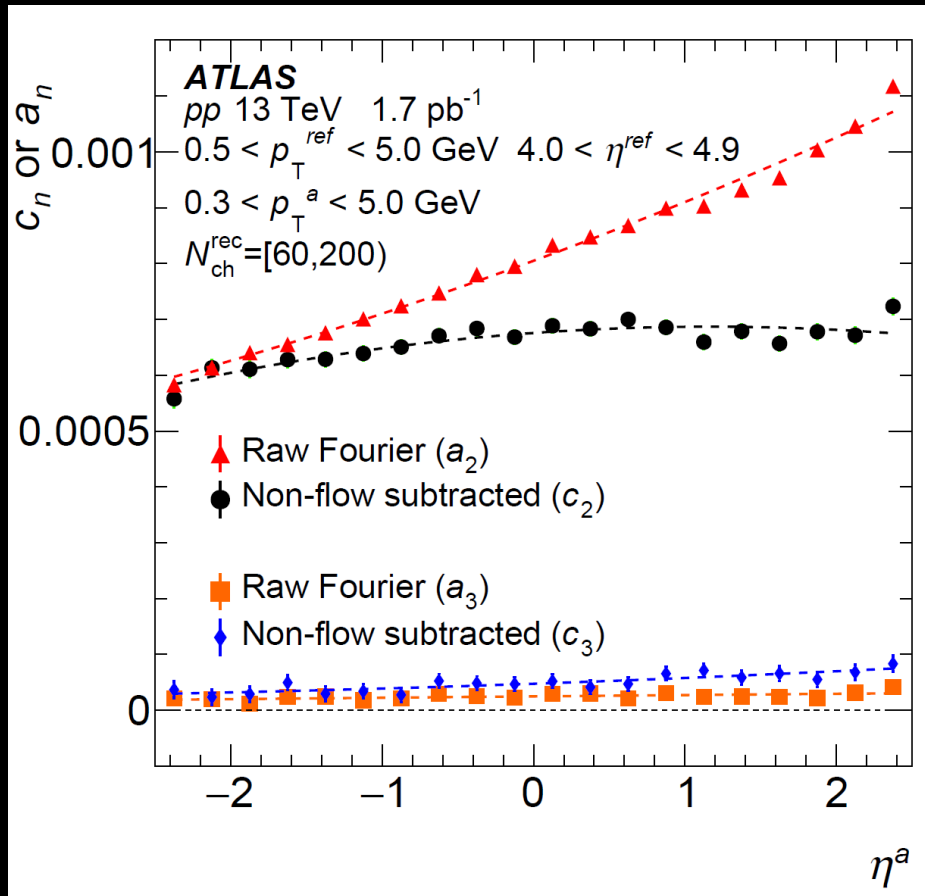
No flow c_1



[arXiv:2308.16745](https://arxiv.org/abs/2308.16745)

With assumptions, template fit removes nonflow: $c_n(\eta^a)$

$v_{2,2}(\eta^a)$ and non-flow subtraction



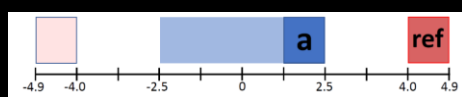
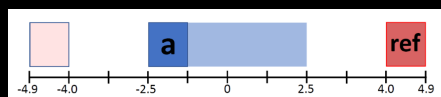
Nonflow a_2
is positive

Raw Fourier a_2 : large $da_2/d\eta$
 Non-flow subtraction: : small $dc_2/d\eta$ with
 a large subtraction for small gaps and a
 small correction for large gaps

Nonflow a_3
is negative

3rd moment has opposite hierarchy!
Raw Fourier a_3 : small $da_3/d\eta$
Non-flow subtraction: : larger $dc_3/d\eta$

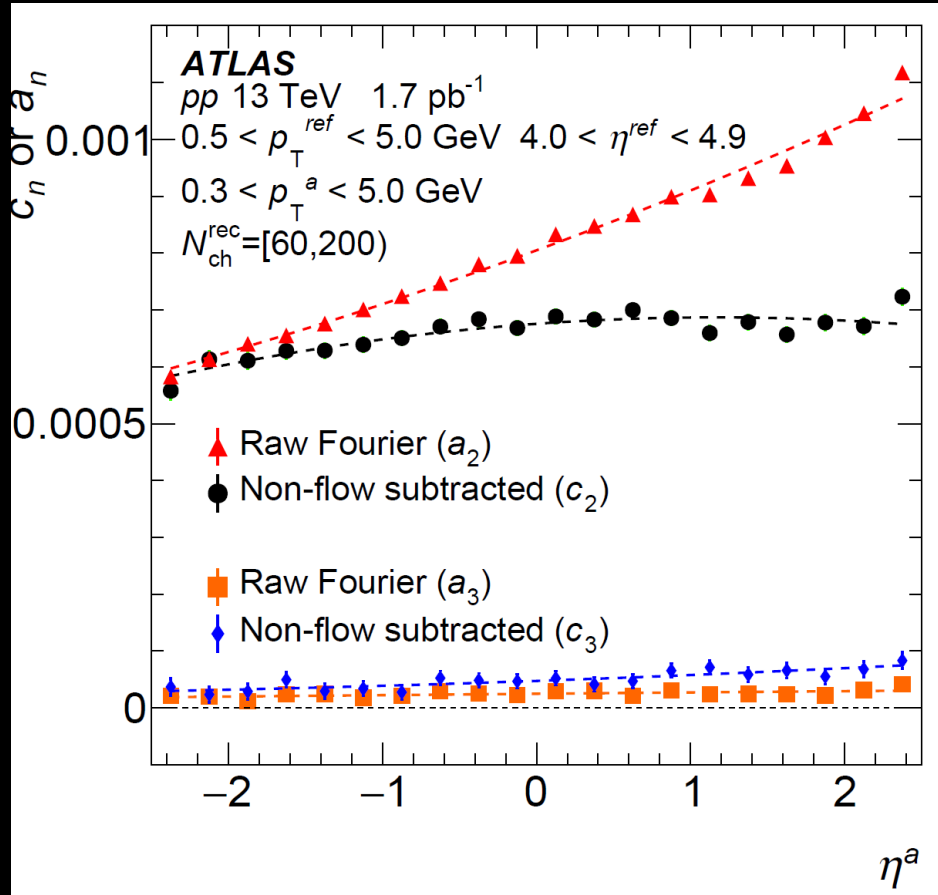
[arXiv:2308.16745](https://arxiv.org/abs/2308.16745)



Nonflow is a large background for decorrelation measurements

Parametrize dependence of correlation coefficients

[arXiv:2308.16745](https://arxiv.org/abs/2308.16745)



We characterize the η^a behavior of the correlation coefficients with a fit function,

$$A(1 + F_n \times (\eta^a) + S_n \times (\eta^a)^2)$$

Decorrelation observable

- F_n is the linear fractional change in the correlation coefficient and is the parameter of interest.

Other parameters in the fit

- A is the mid-rapidity flow and is not of interest
- S_n is an η^a -even function and does not represent decorrelation and is not of interest.
- Data is described by the function well

Past observable

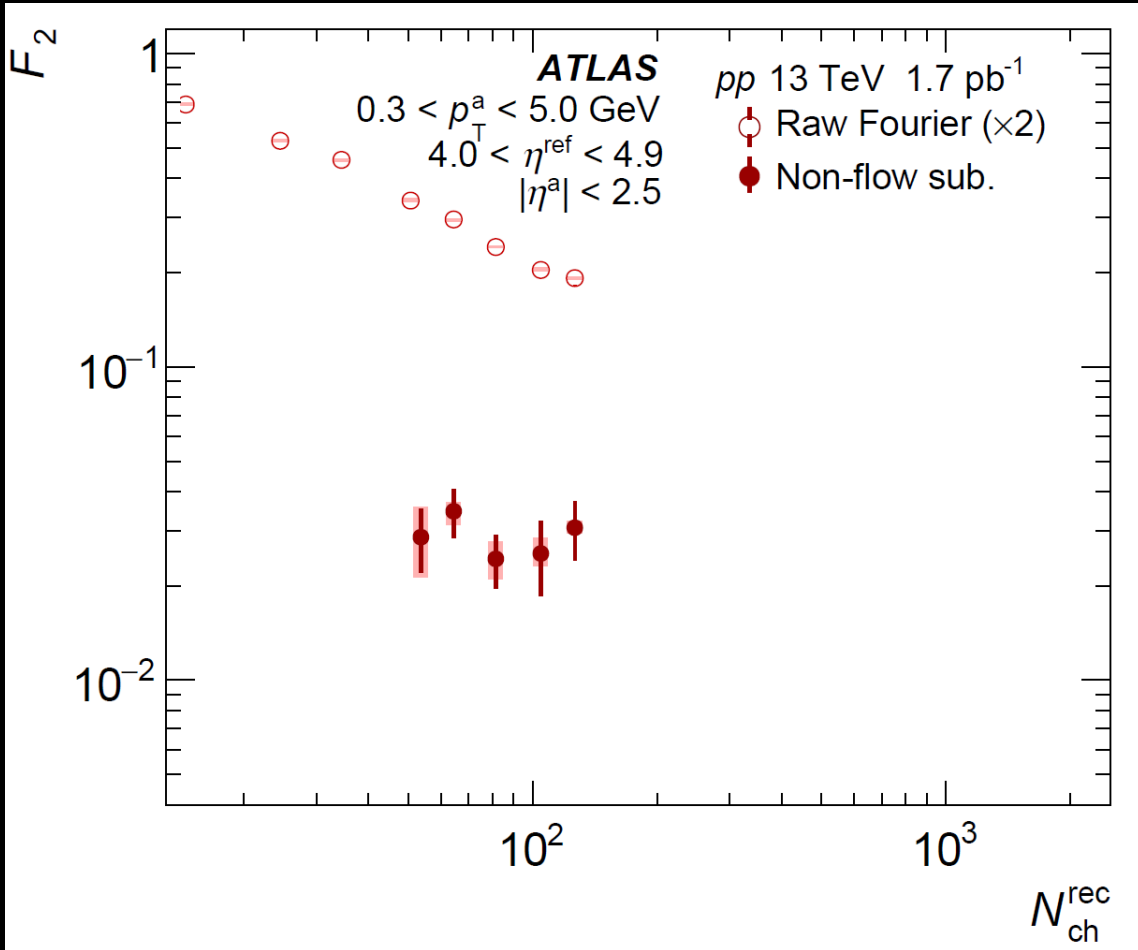
$$r_n(|\eta^a|) = \frac{c_n(-|\eta^a|)}{c_n(|\eta^a|)}$$

$$\approx 1 - 2F_n|\eta^a|$$

F_n is the fractional change in $v_{2,2}$ per a unit rapidity
 it characterizes longitudinal decorrelation effects well

Results in 13 TeV pp

[arXiv:2308.16745](https://arxiv.org/abs/2308.16745)



Raw Fourier (x2)

- combination of flow and nonflow
- Nonflow yields a huge fake decorrelation signal of raw $F_2 = 0.09$ -0.4 which varies heavily with multiplicity

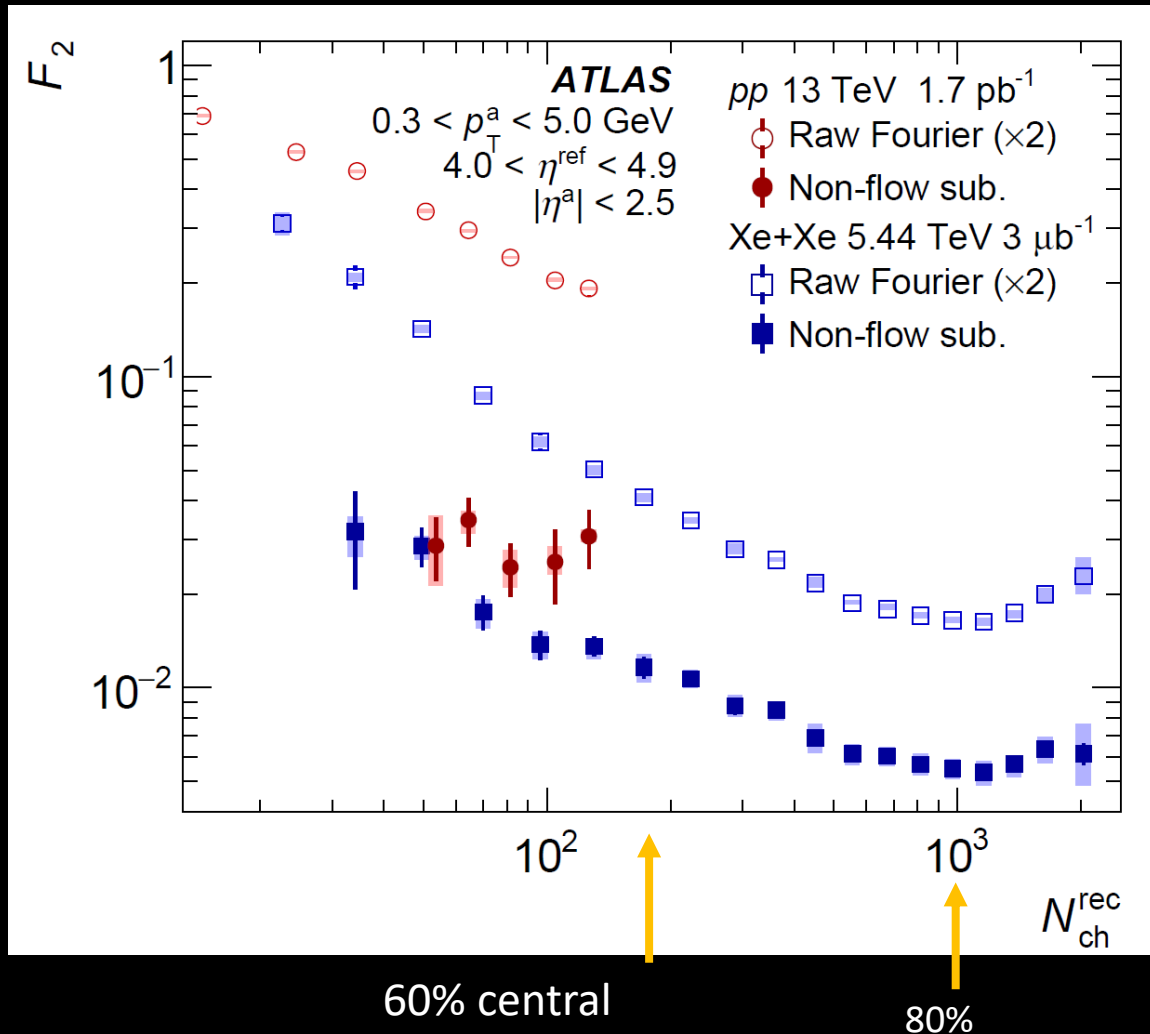
Nonflow subtracted F_2 (solid markers)

- Much smaller, $F_2 = 0.02$ -0.03, which is multiplicity independent

Little change in longitudinal dynamics as a function of multiplicity

Results in Xe+Xe

[arXiv:2308.16745](https://arxiv.org/abs/2308.16745)



Raw Fourier (x2)

- Consistent with past results in large systems from **ATLAS** and others for centrality > 60%

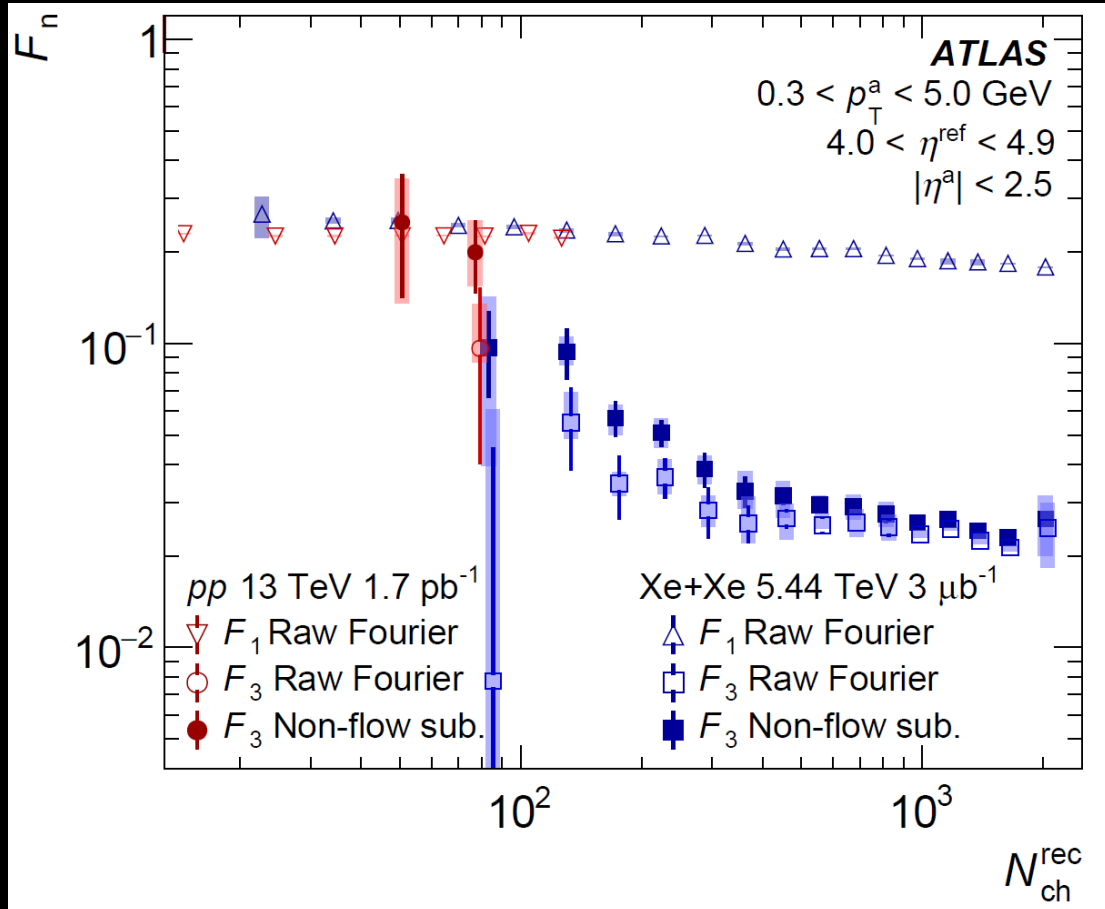
Nonflow subtracted F_2

- Nonflow subtraction removes 40-70% of raw decorrelation in peripheral.
- Decorrelation of ~ 0.03 observed in most peripheral ~ 80 -90% centrality
- But we also observe 30% nonflow effect for more than 50% central
 - Template fit assumption-violating effects such as modification to nonflow shape may cause an overestimate of nonflow effects.
 - but with current available techniques is a significant background in all 2PC and event-plane measurements of decorrelation.

Qualitatively different behavior in the shared N_{ch} range for pp and Xe+Xe

Other moments

[arXiv:2308.16745](https://arxiv.org/abs/2308.16745)



F_3

- similar qualitative features as 2nd
- Nonflow bias F_3 down but smaller bias because F_3 is generally larger
- Agreement between Xe+Xe within statistical uncertainties for low N_{ch}

F_1

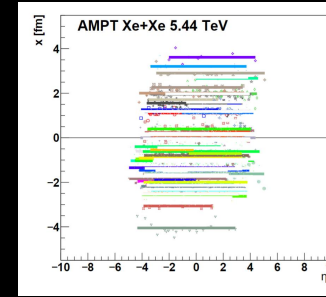
- Completely dominated by nonflow not allowing for subtraction with current methods.
- Very little multiplicity dependence because there is little change in flow/nonflow composition

Comparisons to AMPT: Xe+Xe

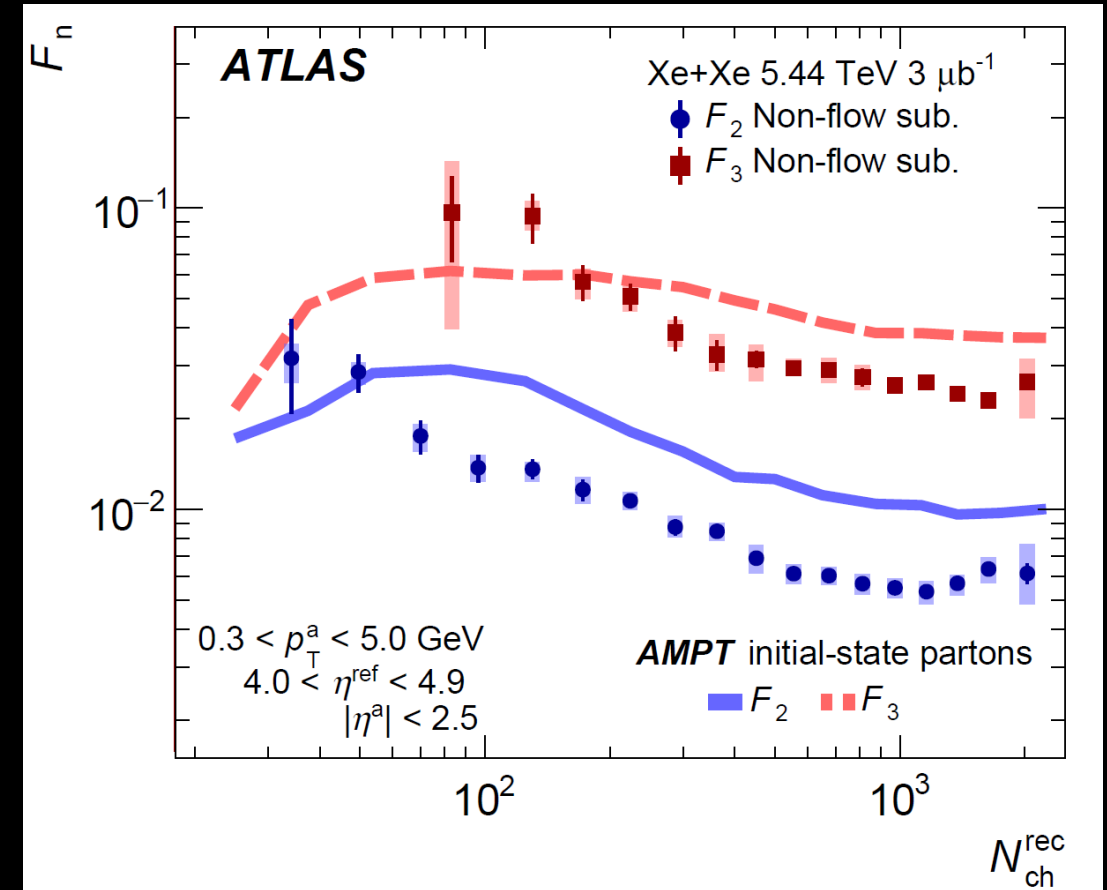
- AMPT initial state geometric decorrelation F_n is shown and is calculated as follows

$$\vec{\epsilon}_2(\eta^a) \cdot \vec{\epsilon}_2(\eta^{ref}) = A(1 + F_n \eta^a + S_n \eta^{a2})$$

- We observe qualitative agreement with AMPT in Xe+Xe in central and mid central collisions
 - within a factor of 2
- A qualitative change in behavior towards smaller decorrelation at low multiplicities is present in AMPT and does not appear in the data.
- This may also indicate the need for sub-nucleonic degrees of freedom.



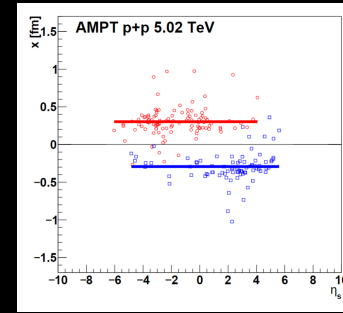
[arXiv:2308.16745](https://arxiv.org/abs/2308.16745)



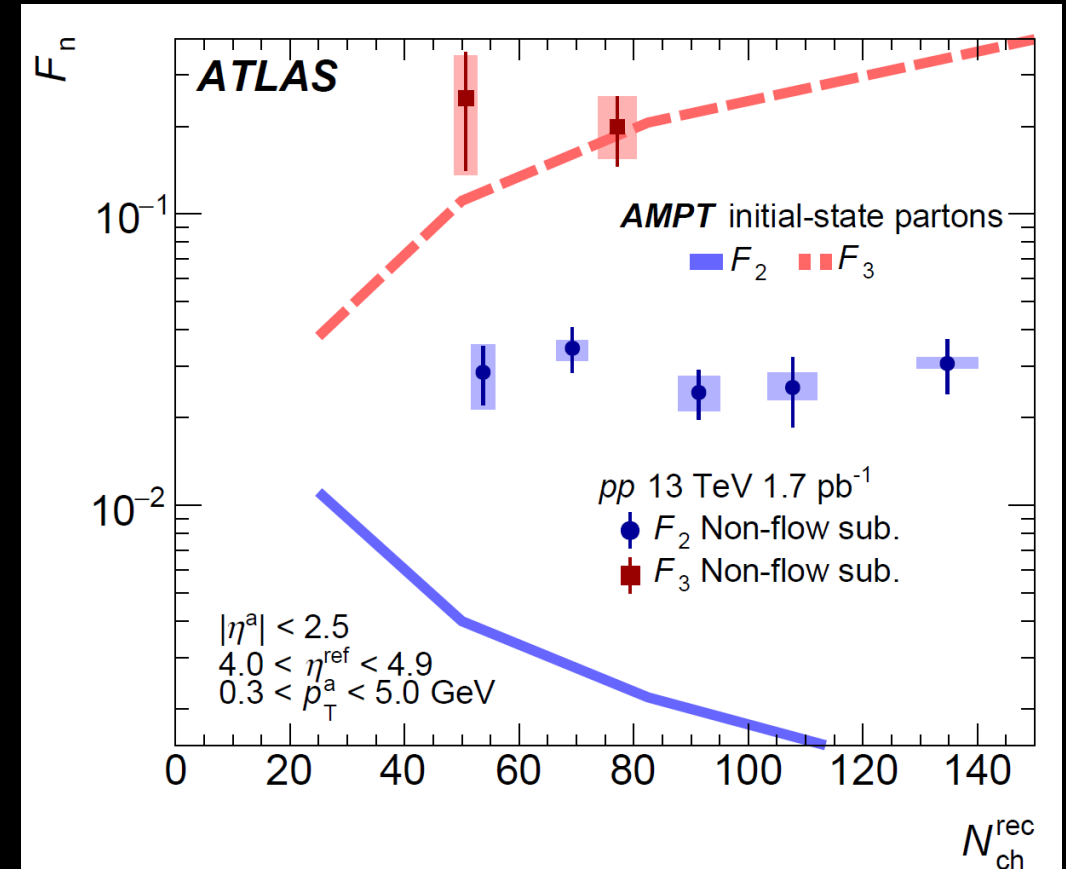
Data indicates sub-nucleonic structure is required to describe peripheral AA and pp

Comparisons to AMPT: pp

- F_2 : AMPT predicts an order of magnitude lower F_2 which is N_{ch} dependent
- Our results disfavor models with a small number of long color strings in the initial state and highlights the need for sub-nucleonic degrees of freedom.
- AMPT F_3 which is fluctuation driven agrees better with the data



[arXiv:2308.16745](https://arxiv.org/abs/2308.16745)

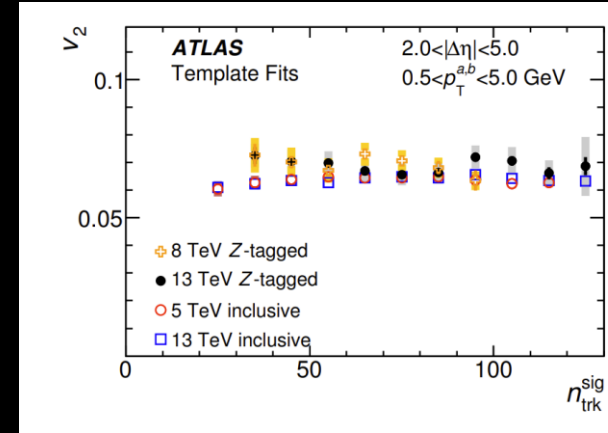


Much larger F_2 in data than AMPT: disfavors a few long strings as initial state

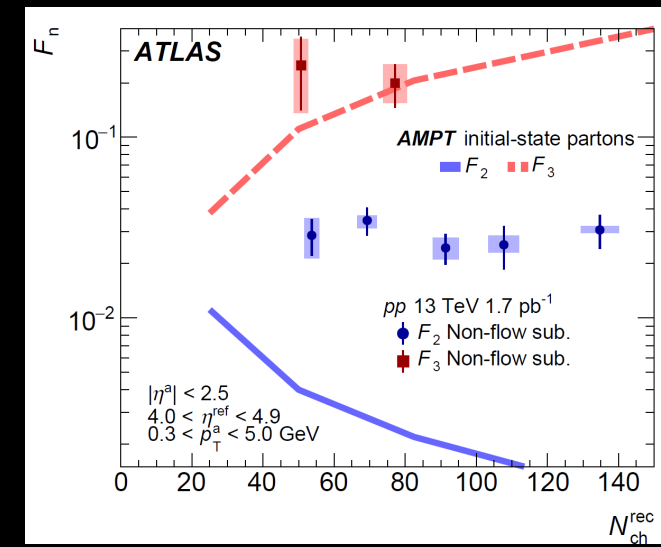
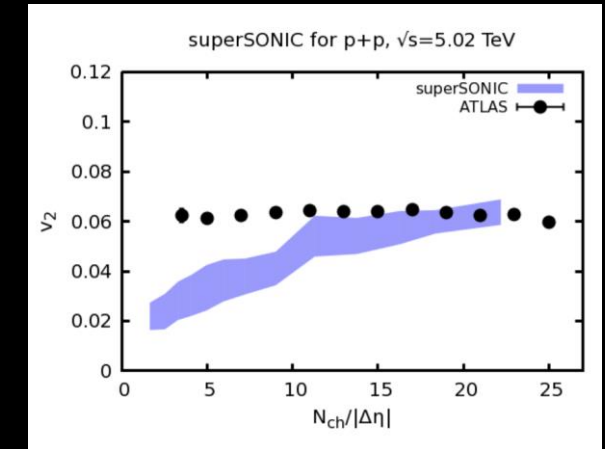
The pp initial-state

- We observe little N_{ch} dependence in longitudinal dynamics in pp
- It has been observed little N_{ch} dependence in transverse dynamics
- I think this collection of data suggests that treating the proton as **cs a few independent constituent quarks (nucleon-like) with Glauber-like participation** is ill-suited to describe details of the initial state in pp collisions.

[arXiv:1906.08290](https://arxiv.org/abs/1906.08290)



[arXiv:1701.07145](https://arxiv.org/abs/1701.07145)



What's next: a new (precision) world

- In the push towards precision in collectivity, backgrounds such as nonflow cannot just be ignored.
- For decorrelations, in data (here) and models ([arXiv:2012.06689](https://arxiv.org/abs/2012.06689)) show impacts, even in central collisions.
- New observables, less sensitive to nonflow, must be adopted.
- Multi-particle decorrelation observables may achieve this.
- These are extremely statics hungry and are challenging in pp (I've tried!) and future observables must take this into account.

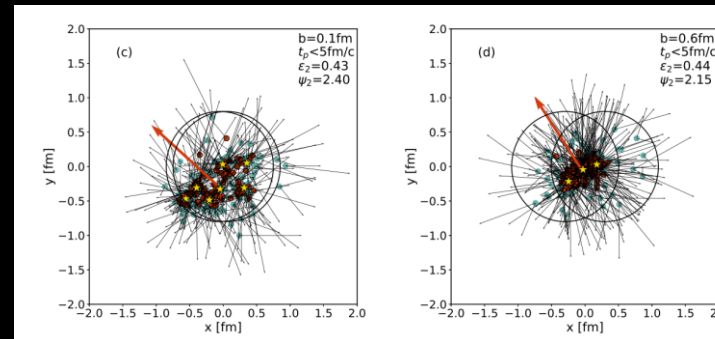
- Part of a push towards a full precision-oriented description of collective QCD physics
- Discriminate between final and initial state effects

- Recent work show very large initial-state azimuthal anisotropic decorrelation

- [arXiv:2201.08864](https://arxiv.org/abs/2201.08864)
- [arXiv:2109.03512](https://arxiv.org/abs/2109.03512) (pure hydro)

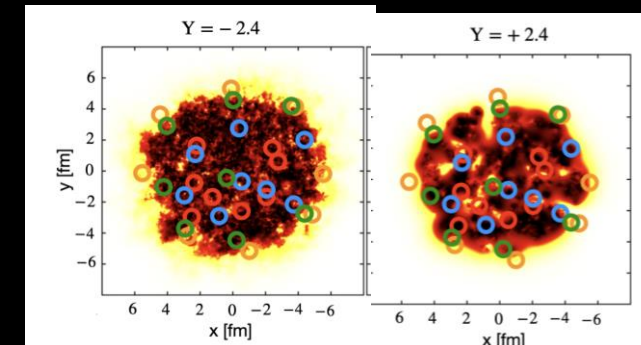
[arXiv:2104.05998](https://arxiv.org/abs/2104.05998)

AMPT+PYTHIA Zhang et al.



[arXiv:2201.08864](https://arxiv.org/abs/2201.08864)

IP-Glasma+MUSIC+UrQMD



★ Constituent quark collision

↑ ψ_2

● Parton: loc. ↑ Vel.

Conclusion

- First measurement of longitudinal decorrelation in pp collisions
 - The magnitude is similar to peripheral Xe+Xe
 - Multiplicity independent (with non-flow subtraction).
- First measurement of decorrelation in peripheral AA collisions
 - When single nucleon-nucleon collision multiplicities are reached, the Xe+Xe nonflow-subtracted F_2 agrees with nonflow subtracted F_2 in pp .
 - Results indicate that nonflow *may* be a significant background at all multiplicities
- AMPT comparisons shows need for sub-nucleonic degrees of freedom

Thank you

Additional material for future comparisons

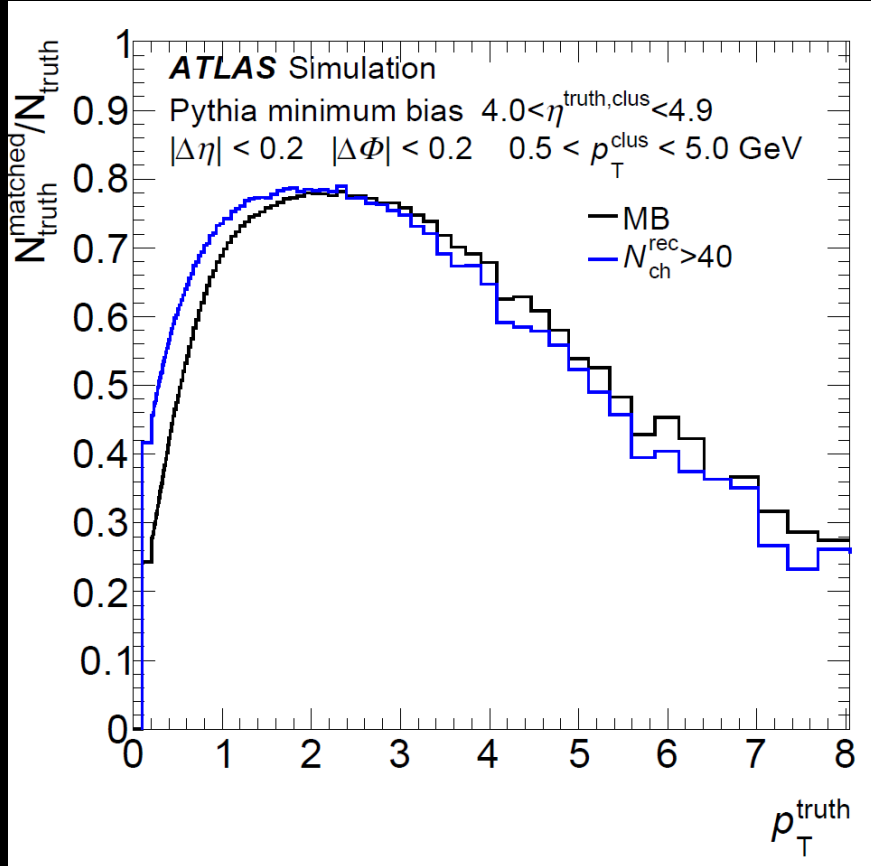
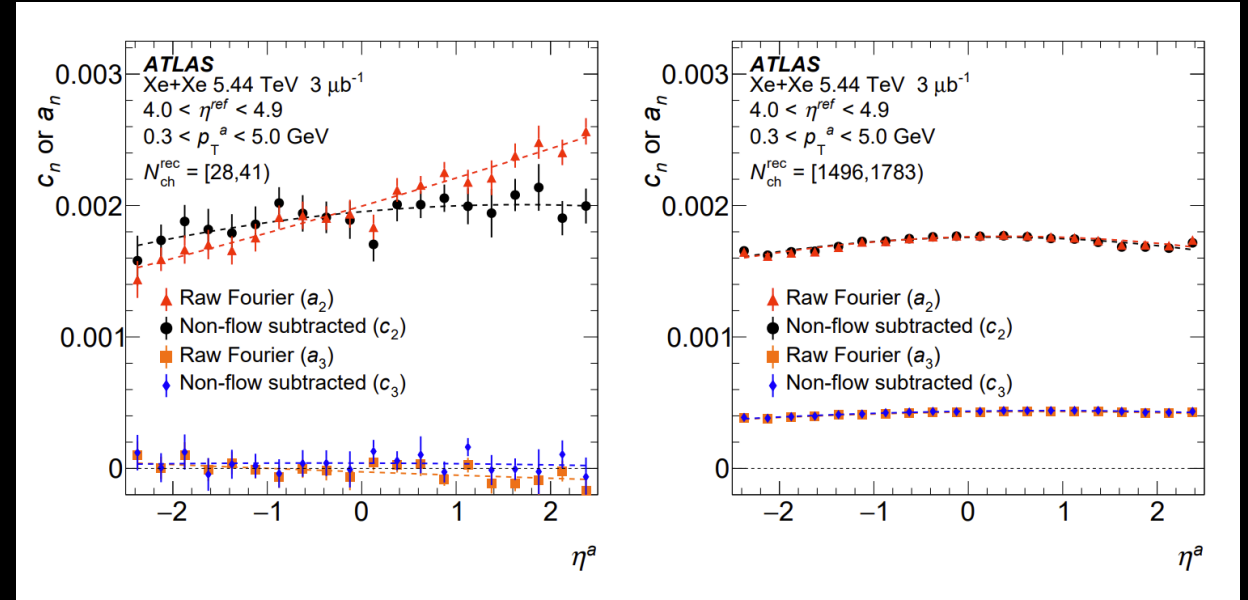
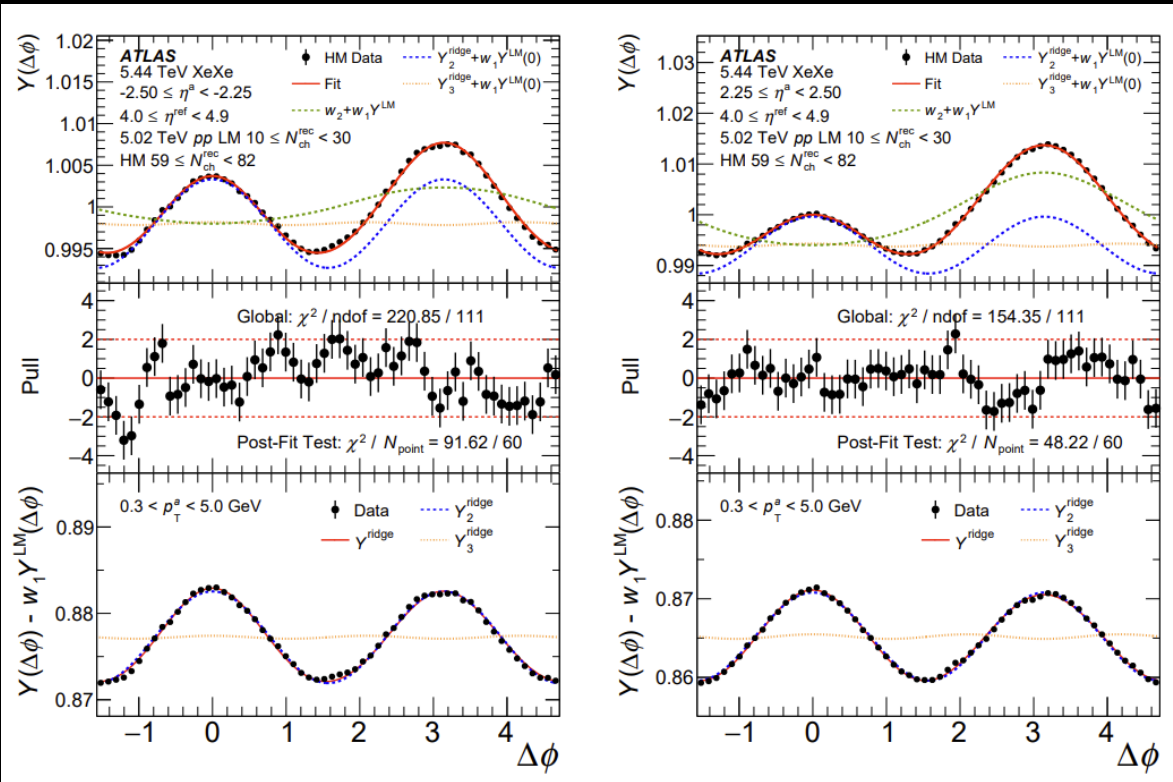


Table 1: Average centrality percentile of events in the given $N_{\text{ch}}^{\text{rec}}$ bin for the Xe+Xe analysis.

$N_{\text{ch}}^{\text{rec}}$	Average centrality percentile
[18, 28]	$> 76.6\%$
[28, 41]	$> 76.6\%$
[41, 59]	$76.6\% \pm 1\%$
[59, 82]	$72.6\% \pm 1\%$
[82, 112]	$68.1\% \pm 1\%$
[112, 150]	$63.6\% \pm 1\%$
[150, 196]	$59.2\% \pm 1\%$
[196, 254]	$54.8\% \pm 1\%$
[254, 323]	$50.2\% \pm 1\%$
[323, 404]	$45.8\% \pm 1\%$
[404, 500]	$41.3\% \pm 1\%$
[500, 612]	$36.8\% \pm 1\%$
[612, 740]	$32.3\% \pm 1\%$
[740, 889]	$27.8\% \pm 1\%$
[889, 1061]	$23.2\% \pm 1\%$
[1061, 1261]	$18.6\% \pm 1\%$
[1261, 1496]	$13.9\% \pm 1\%$
[1496, 1783]	$9.0\% \pm 1\%$
[1783, 2500]	$3.6\% \pm 1\%$


Figure 6: The number of selected truth particles *matched* to selected topoclusters divided by all selected truth particles. The selected truth particles are those with the p_T of the respective bin of this figure as well as $4.0 < \eta^{\text{truth}} < 4.9$. The selected topoclusters have $4.0 < \eta^{\text{clus}} < 4.9$ and $0.5 < p_T^{\text{clus}} < 5.0$ GeV. A truth particle and topocluster are considered matched if the pair $|\Delta\eta|$ and $|\Delta\phi|$ are both less than 0.2. This result shows which truth particles enter the topocluster correlation performed in the two-particle correlation. PYTHIA8 was used for this study with the same topocluster reconstruction as the data analysis and two selections of the PYTHIA8 events are shown, with no multiplicity selection and one with $N_{\text{ch}}^{\text{rec}} > 40$.

Correlation functions and moments: Xe+Xe



Template fit corrections

The template fit can be corrected for the violation of **N_{ch} -independent flow decorrelation assumption**

$$F_n^{\text{HM}} \approx F_n^{\text{temp}} + \rho \frac{c_n^{\text{LM}} | \eta^a=0}{c_n^{\text{HM}} | \eta^a=0} (F_n^{\text{LM}} - F_n^{\text{temp}})$$


Template fit F_2

N_{ch} -independent
non-flow shape



First moment is all
non-flow



N_{ch} -independent
mid-rapidity flow



F_n at $N_{\text{ch}}=0-20$ is
all non-flow



N_{ch} -independent
flow decorrelation

