

QUARK MATTER 2015

The XXVth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions

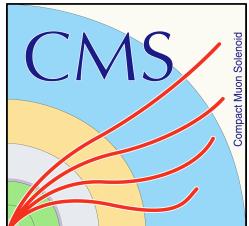
Experimental overview of flow measurements

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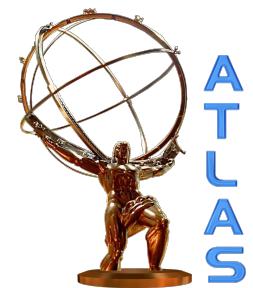
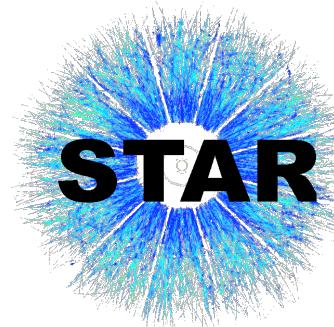


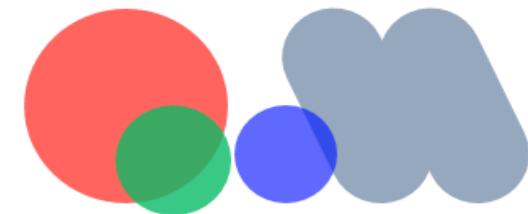
Soumya Mohapatra

COLUMBIA
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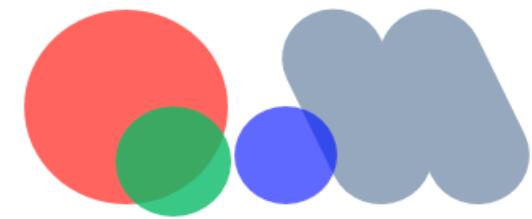
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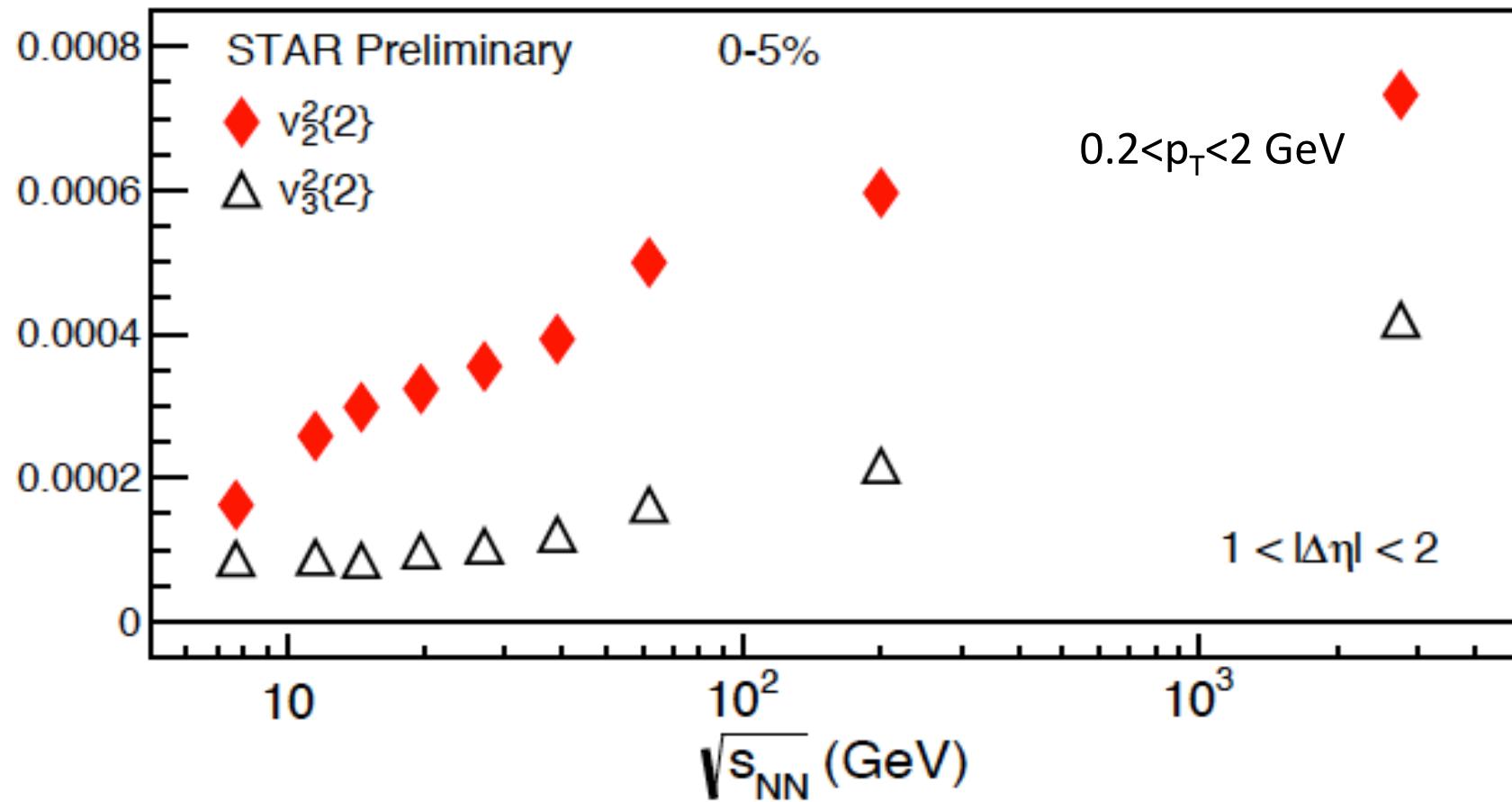


Outline

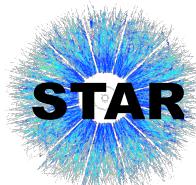
- ✧ Event geometry correlations & fluctuations
 - ✧ Event-shape engineering Focus on new observables.
 - ✧ Flow-correlations
 - ✧ Event-plane fluctuations Detailed understanding of correlations or de-correlations in initial geometry.
 - ✧ Cu+Au collisions
- ✧ Correlations in small systems : $p+A$, $d+A$, $\text{He}+A$
 - ✧ PID results
 - ✧ Higher order cumulants Collective effects!
 - ✧ pp long range correlations (possible collective effects???)
- ✧ Other places where flow measurements will be discussed:
 - ✧ Experimental overview on beam energy scan
 - ✧ Experimental overview on small colliding systems at RHIC
 - ✧ Experimental overview on small colliding systems at LHC
 - ✧ Experimental overview on open heavy flavor

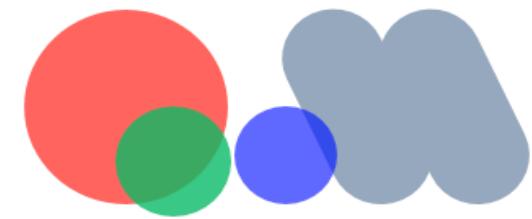


Flow is everywhere



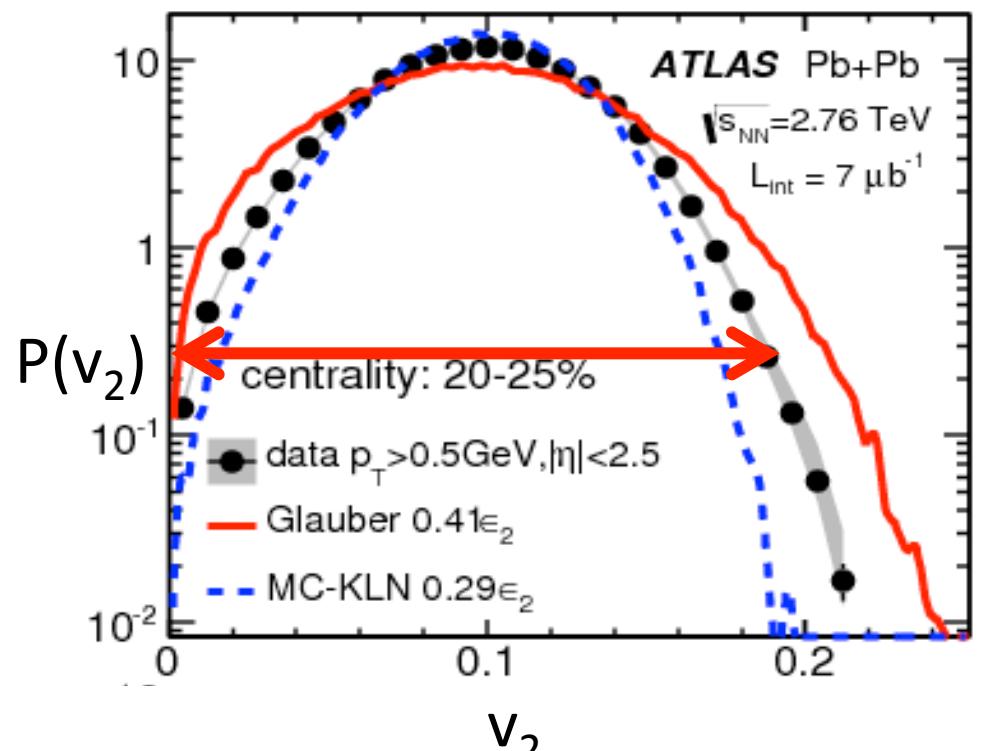
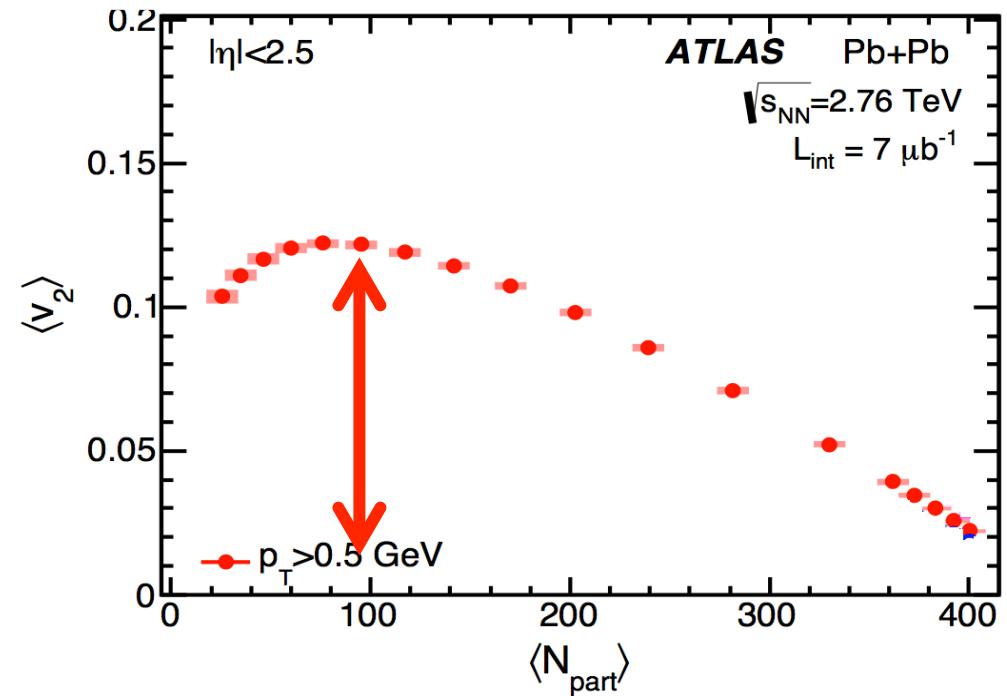
Flow has been studied over vast range of collision energies and colliding systems



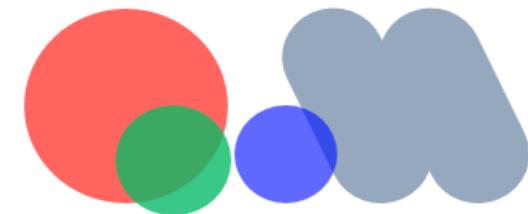


Importance of fluctuations

JHEP11(2013)183

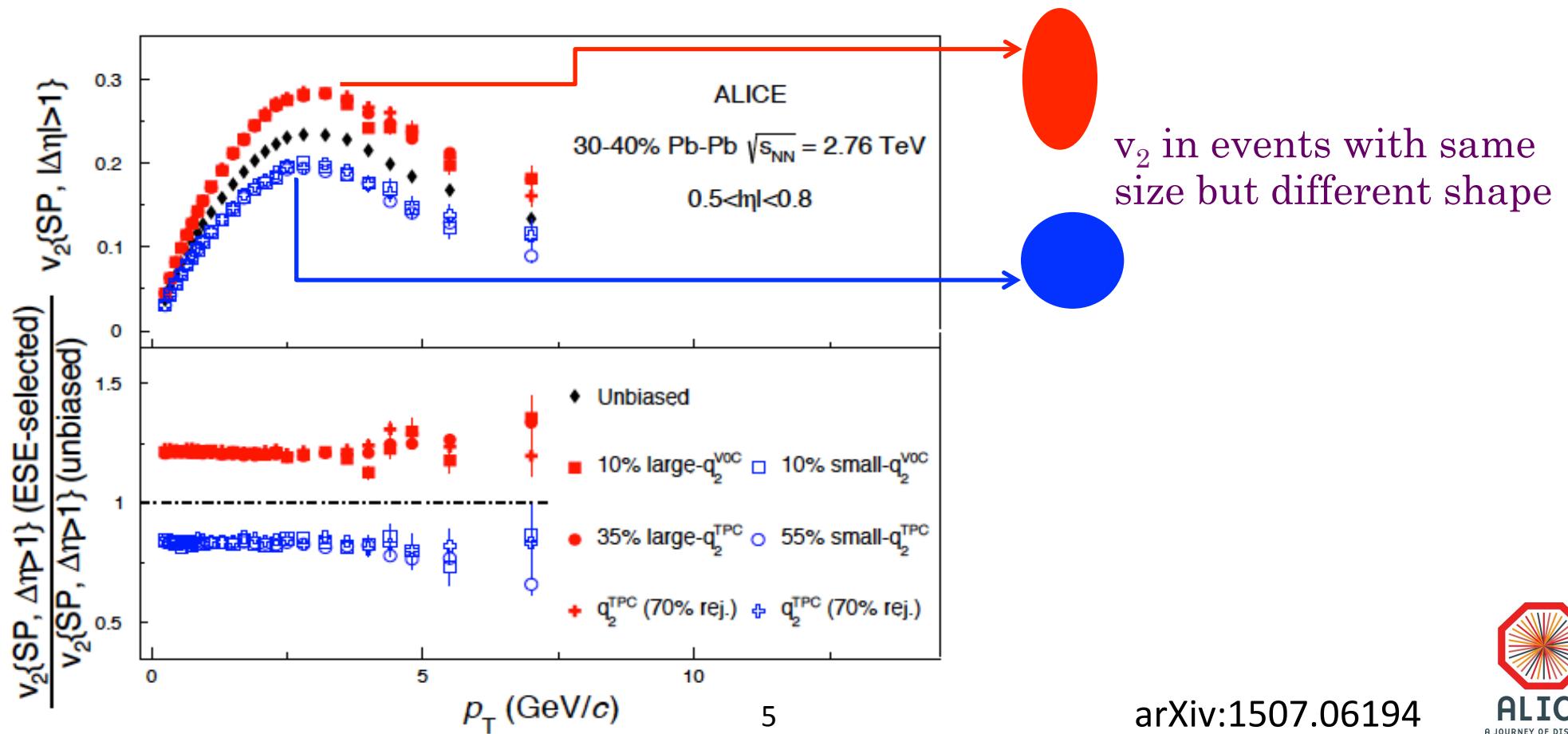


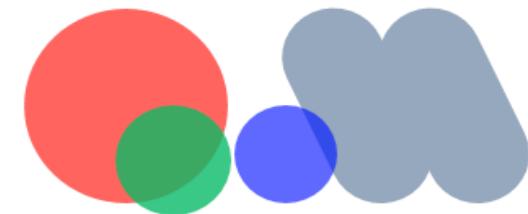
- ❖ Much more variation in v_n within one centrality than variation of mean v_n across all centralities
- ❖ Almost all new flow observables presented in QM15 study effects of, or rely on fluctuations



Event-shape engineering

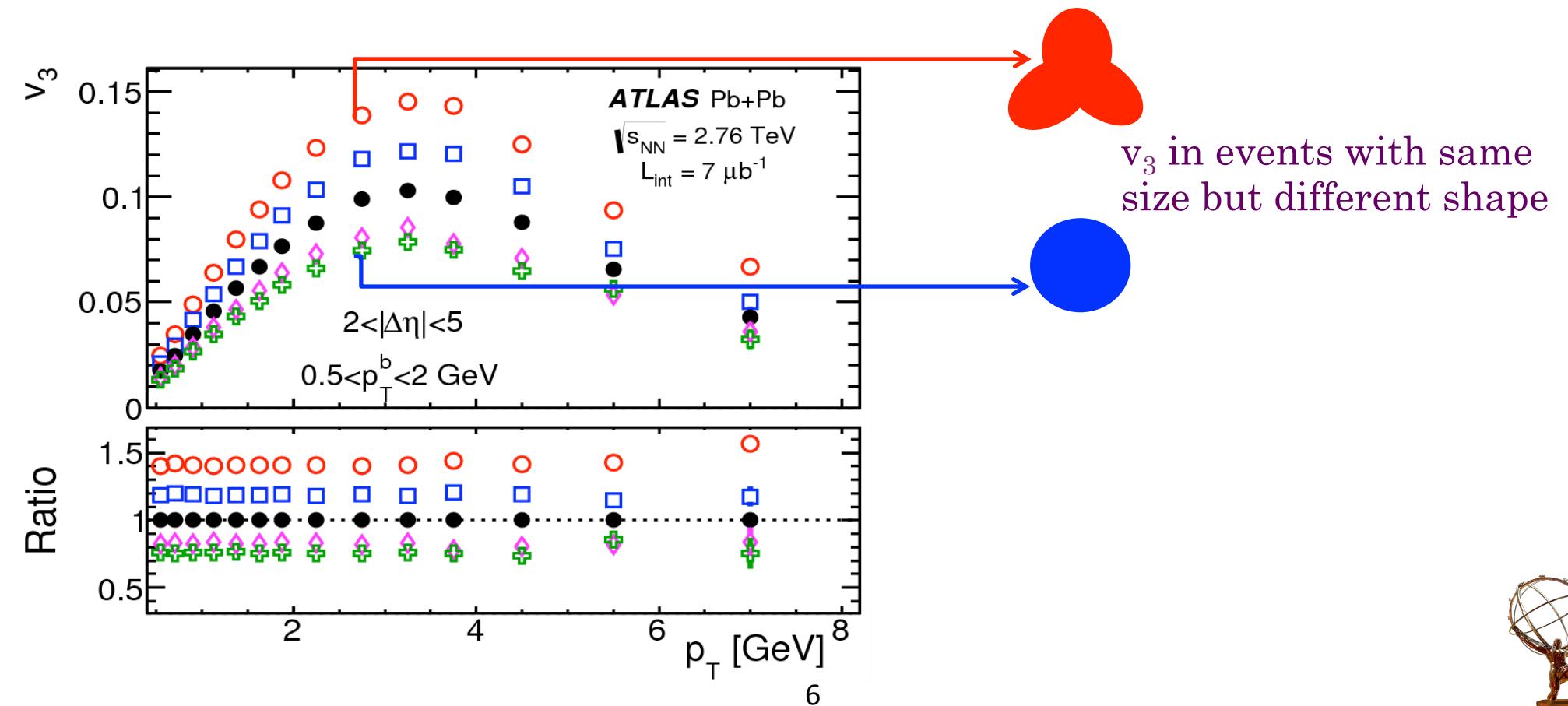
- ❖ Much variation in event geometry at fixed centrality
- ❖ Can not (should not) use centrality as proxy for event geometry
- ❖ Select different geometries at fixed centrality

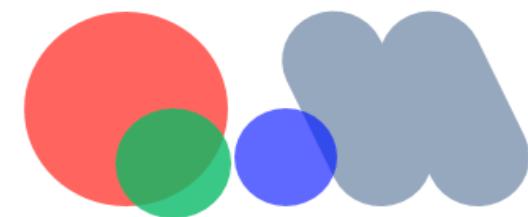




Event-shape engineering

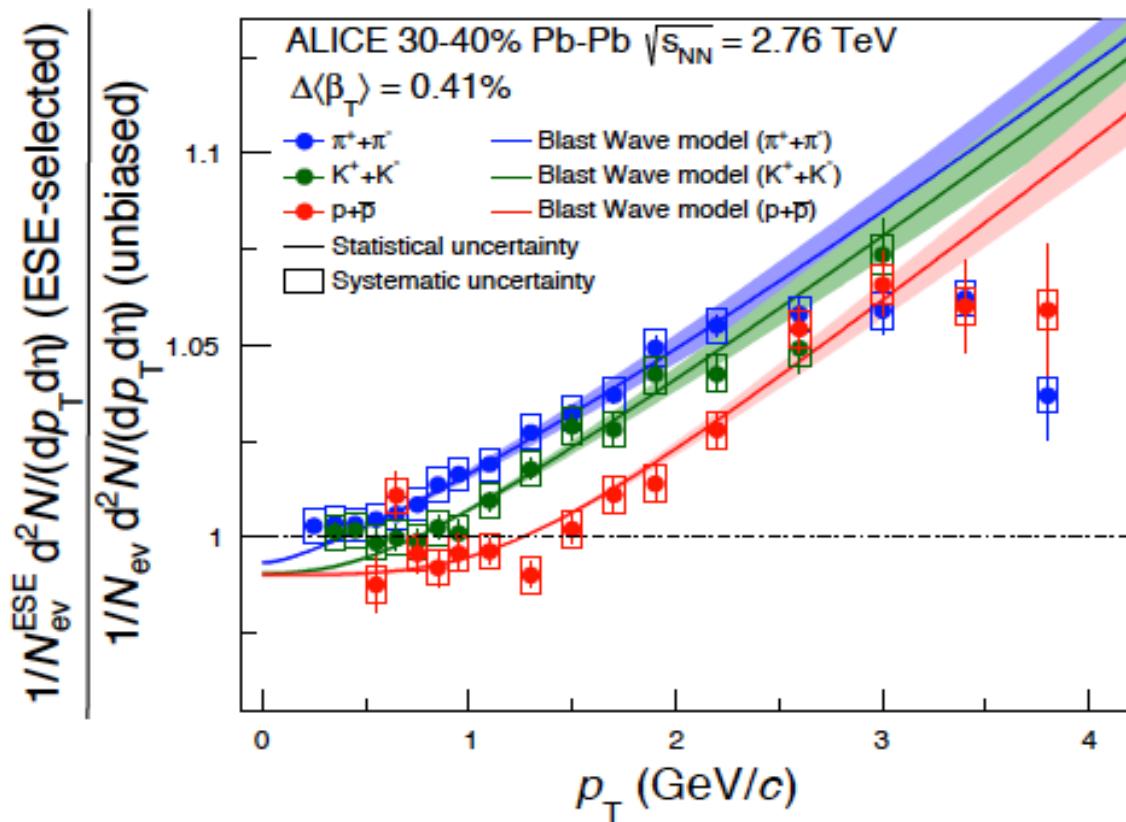
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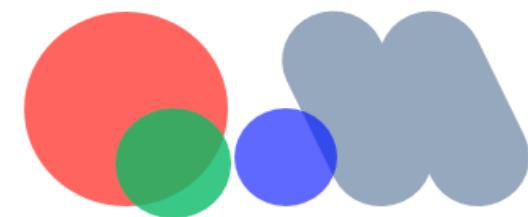




Spectra in shape selected events

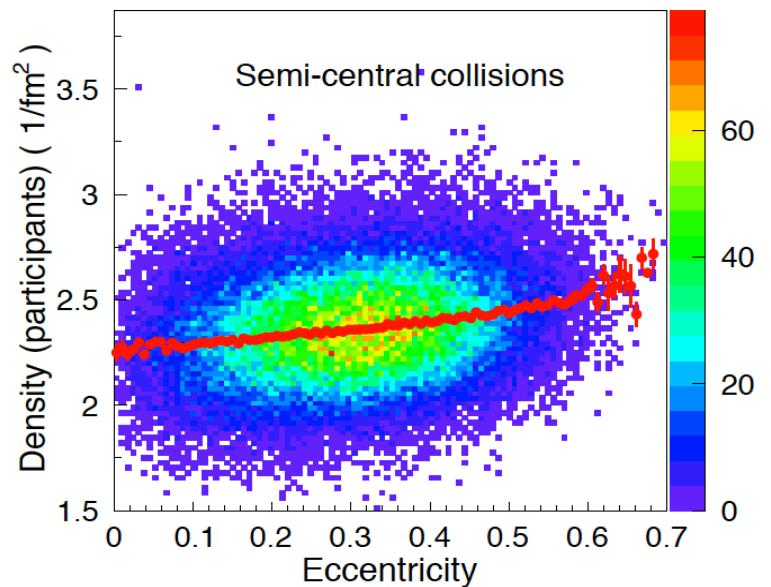
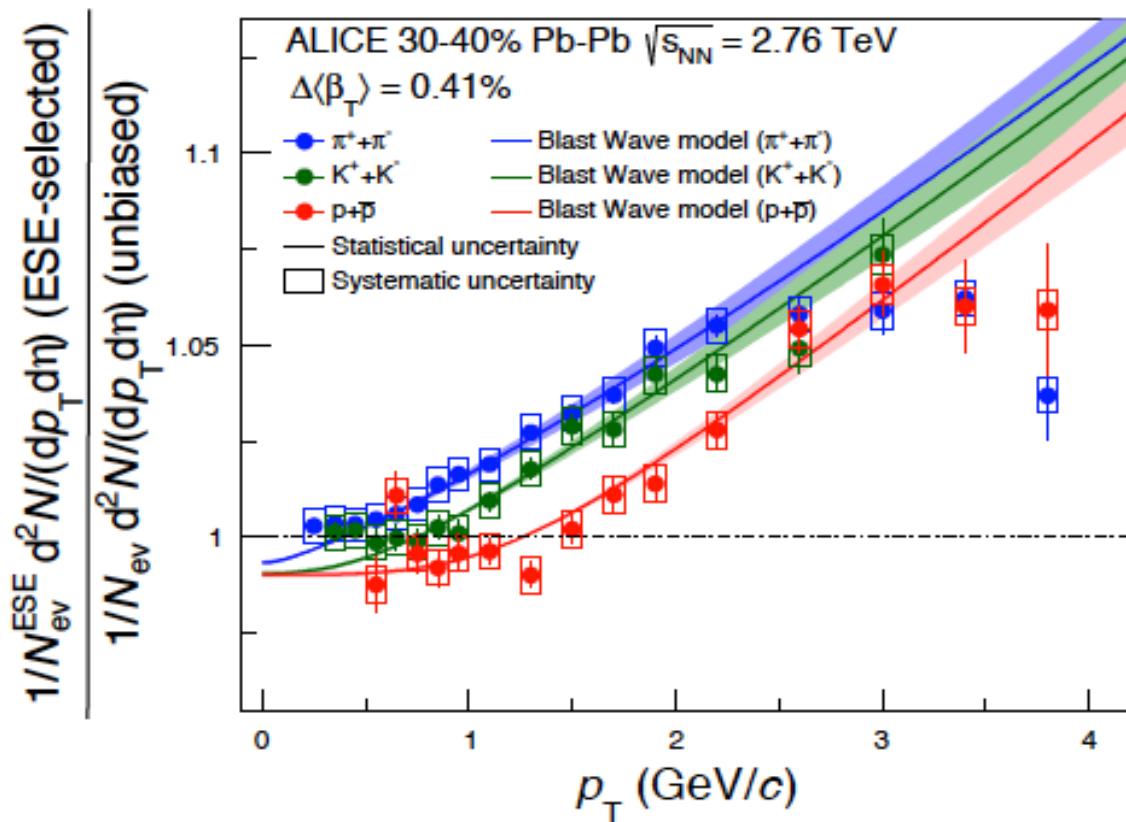
- ✧ Clear modification of spectra seen when selecting on shape
- ✧ More elliptic geometry => Harder spectra! => More radial flow

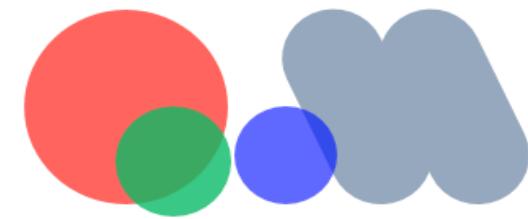




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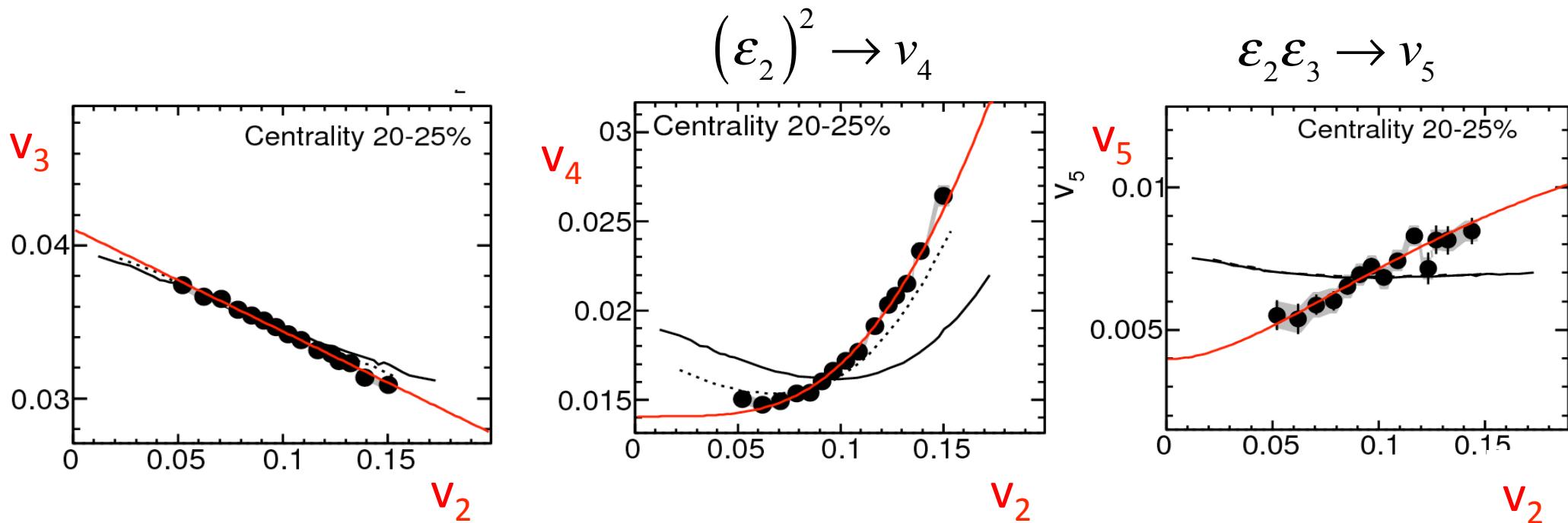


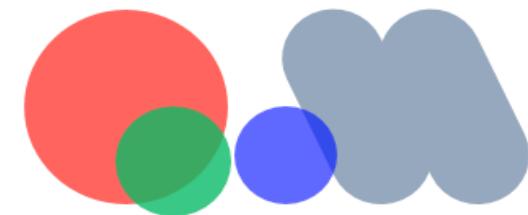


Correlations between flow harmonics



- ❖ Can study correlation between different harmonics via shape selection
- ❖ Understand initial geometry & non-linear hydrodynamic response



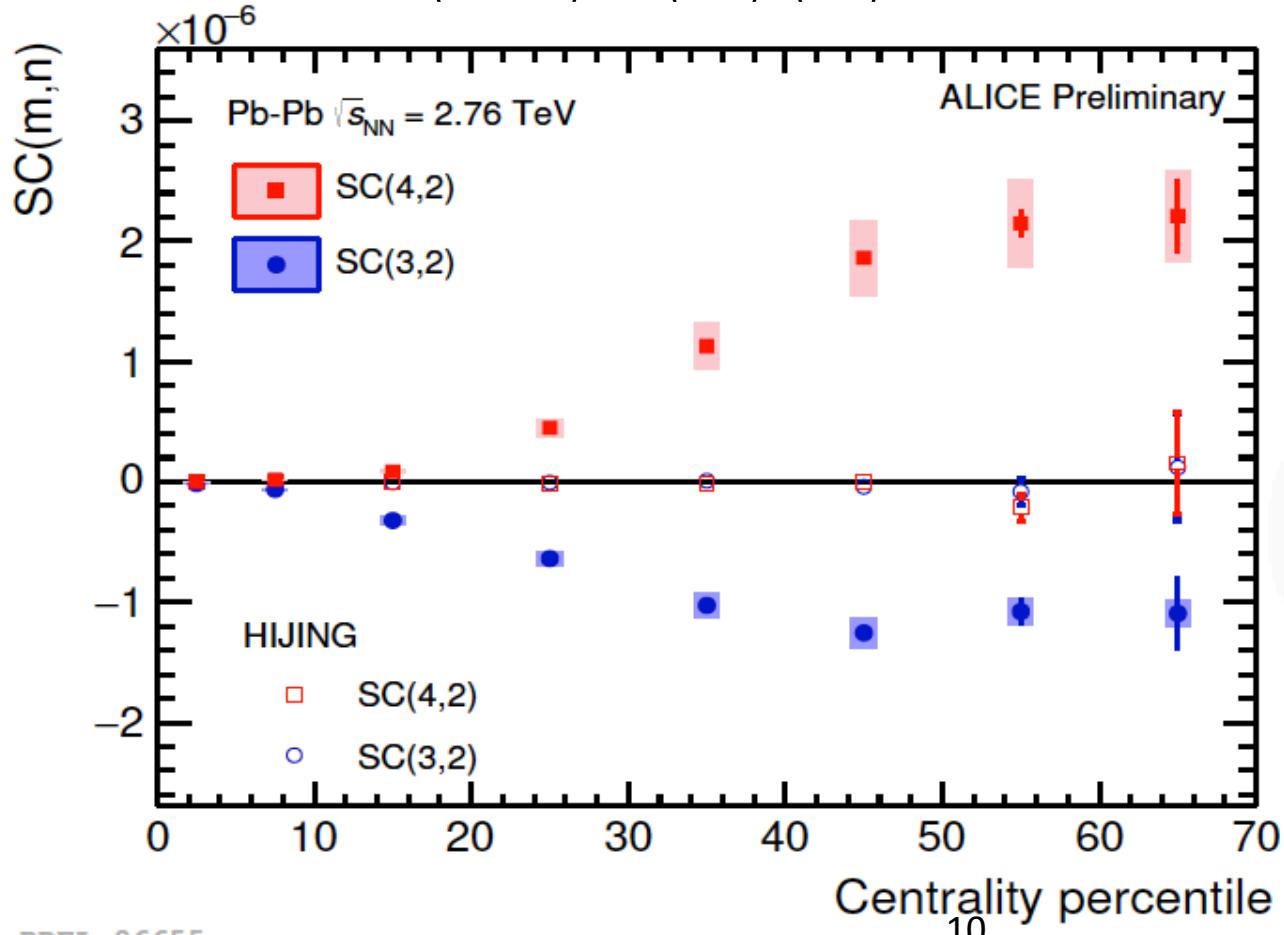


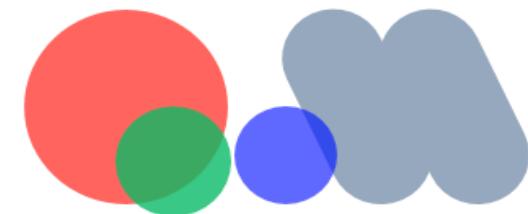
v_n correlations via cumulants

- ❖ Can directly calculate correlations without selecting on geometry
- ❖ Symmetric 2-harmonic 4-particle Cumulants, SC(m,n)

$$SC(m,n) = \left\langle v_m^2 v_n^2 \right\rangle - \left\langle v_m^2 \right\rangle \left\langle v_n^2 \right\rangle$$

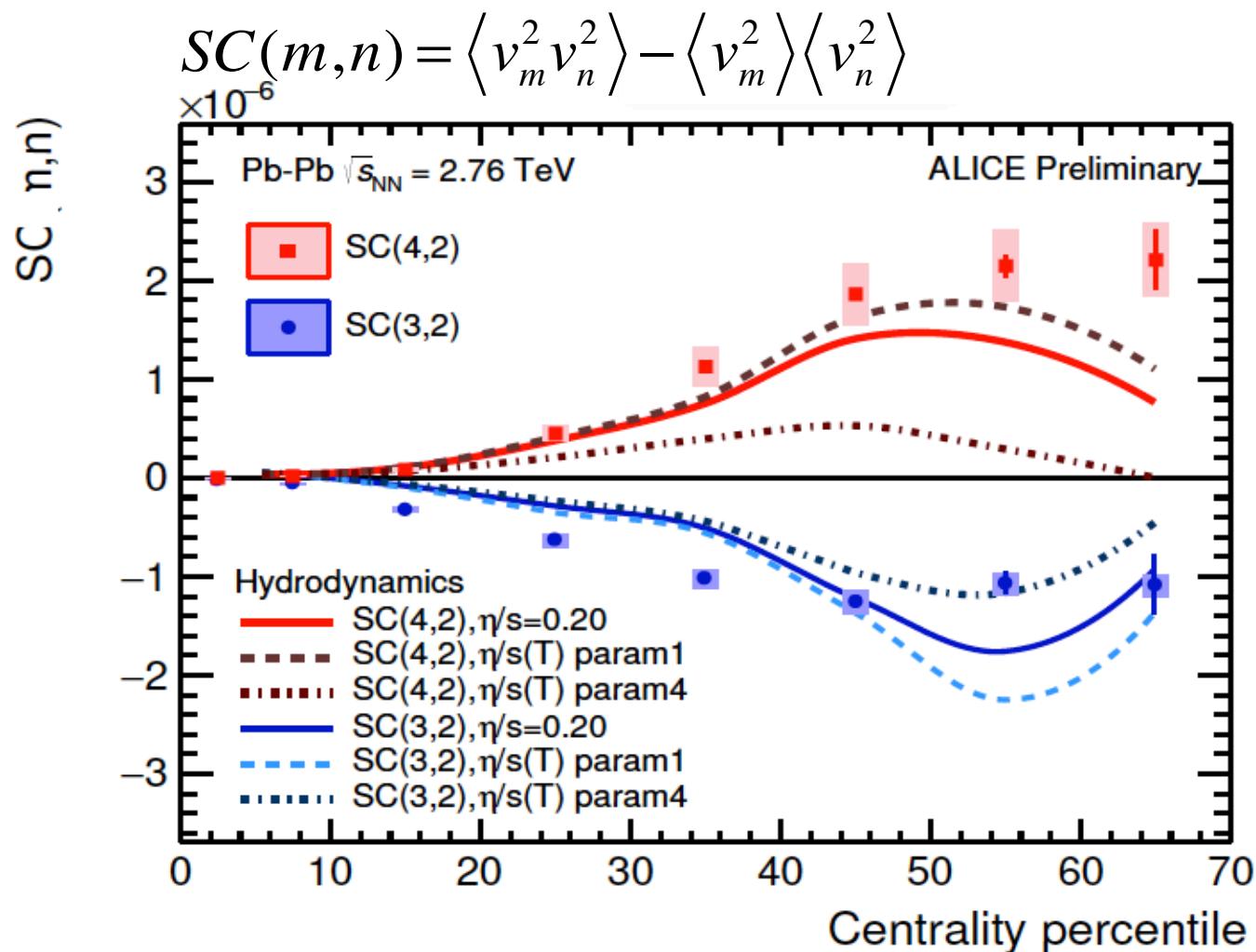
arXiv:1312.3572

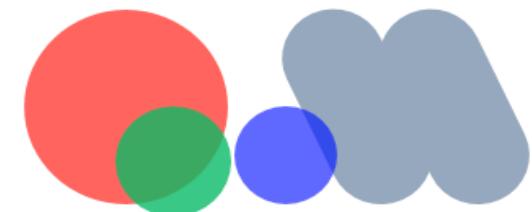




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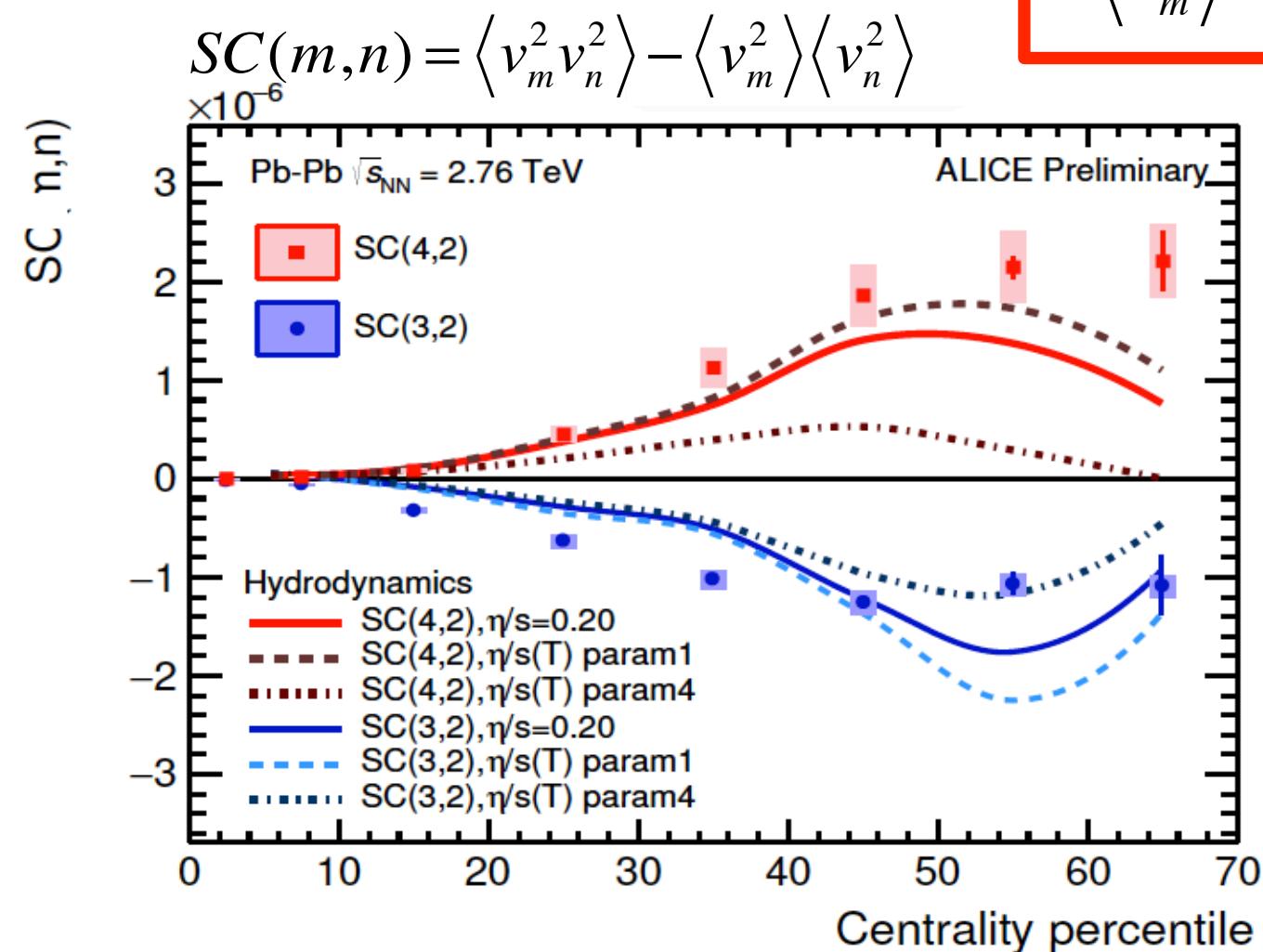


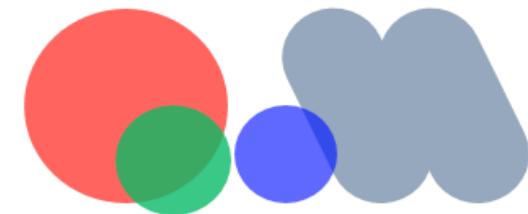


v_n correlations via cumulants

- ✧ Possible alternate observable
Can directly compare to initial geometry

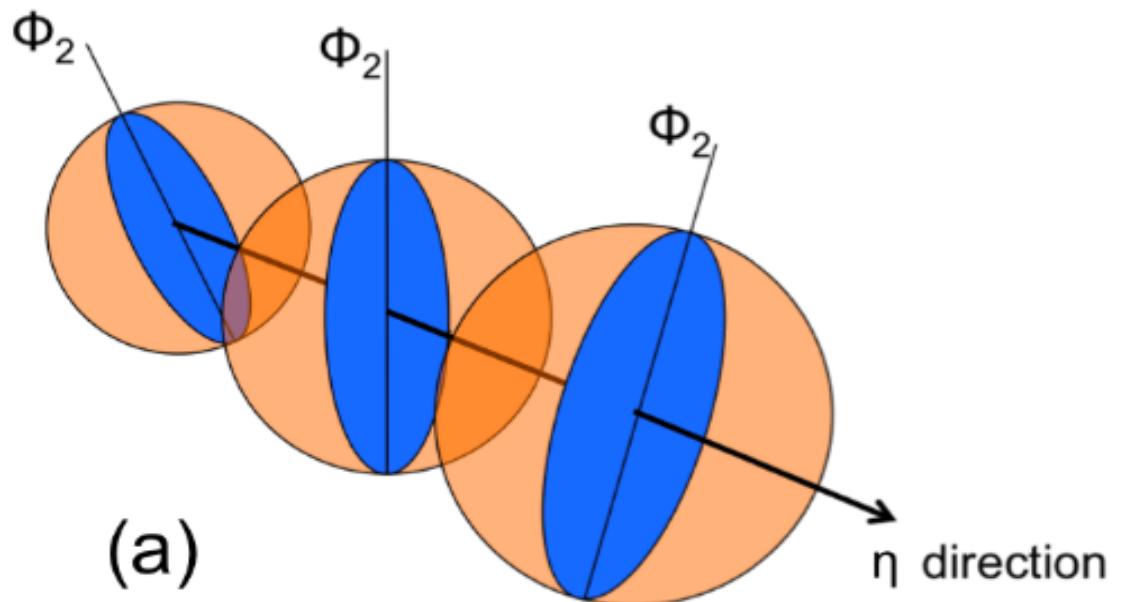
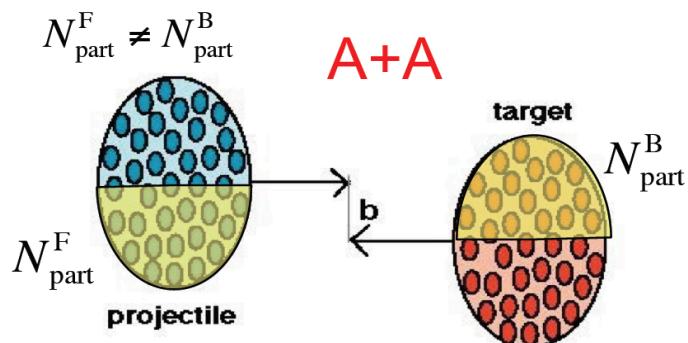
$$\frac{\langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle}{\langle v_m^2 \rangle^{EP} \langle v_n^2 \rangle^{EP}}$$

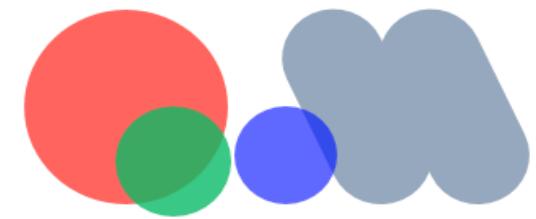




Event-plane rotation

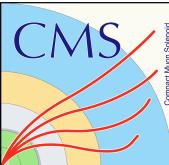
- ✧ Longitudinal geometry fluctuations
- ✧ Forward (backward) eccentricity determined by forward (backward) going participants.
- ✧ Expect rotation of event plane angles from forward to backward rapidity



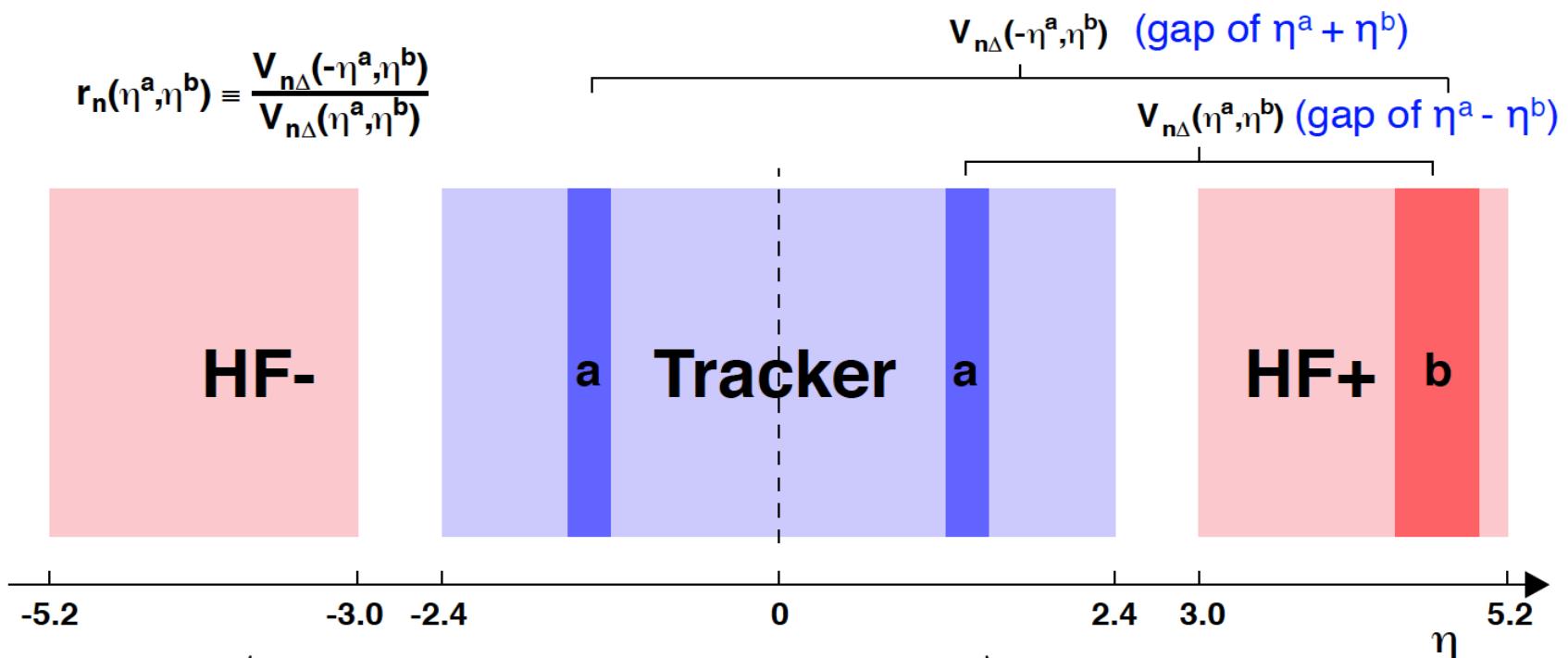


Event-plane rotation

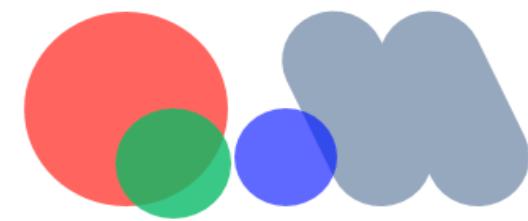
- ❖ Measure EP rotations via two-particle correlations:



$$v_{n\Delta}(\eta^a, \eta^b) = \langle v_n(\eta^a)v_n(\eta^b) \rangle \longrightarrow v_{n\Delta}(\eta^a, \eta^b) = \langle v_n(\eta^a)v_n(\eta^b) \cos(n\Psi_n(\eta^a) - n\Psi_n(\eta^b)) \rangle$$

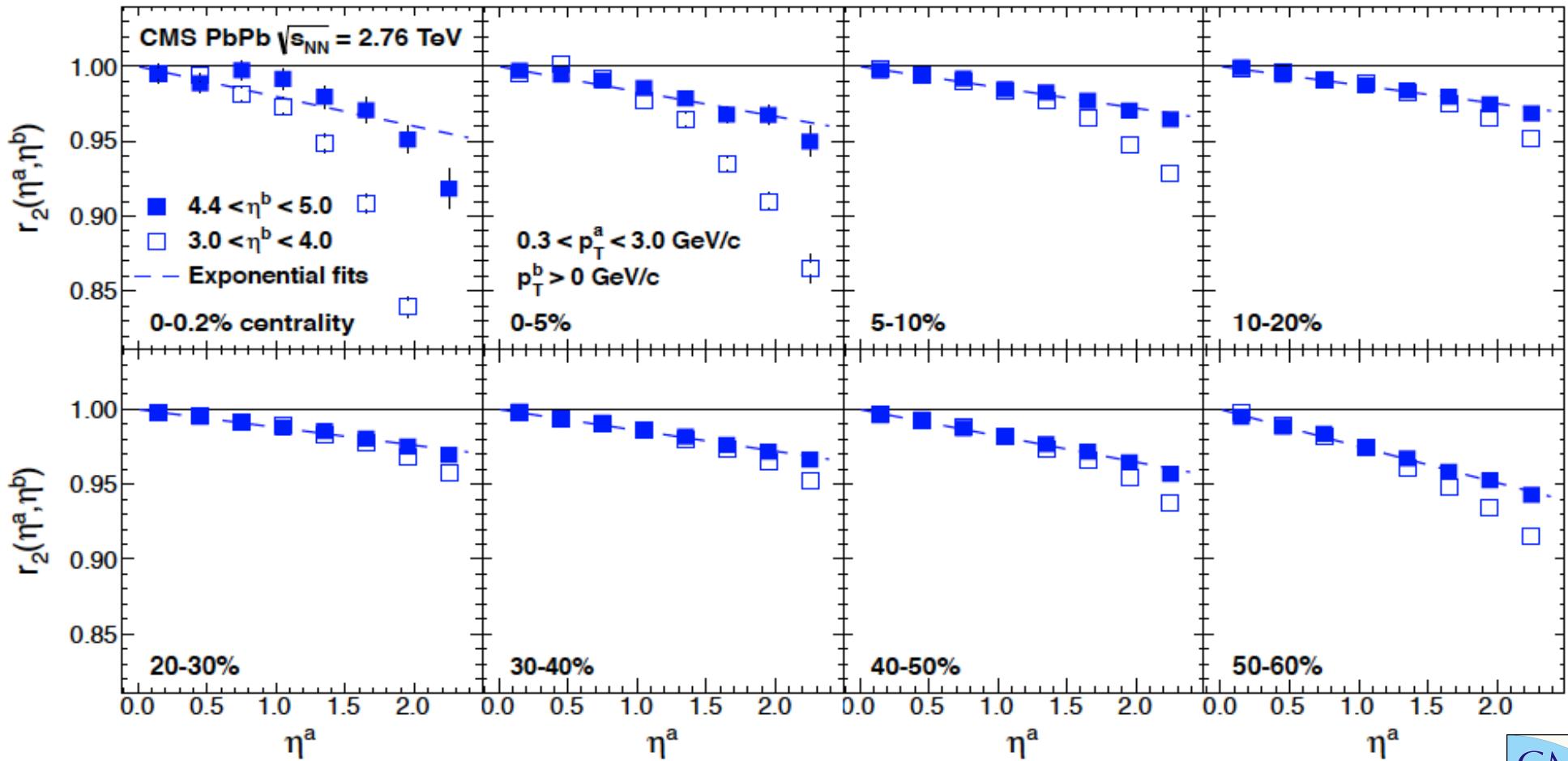


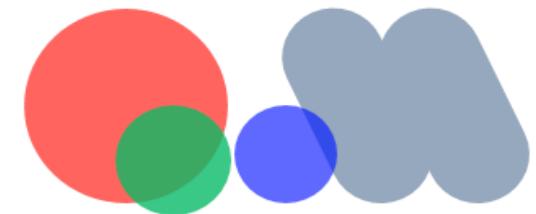
$$r_n(\eta^a, \eta^b) = \frac{\langle v_n(-\eta^a)v_n(\eta^b) \cos[n(\Psi_n(-\eta^a) - \Psi_n(\eta^b))] \rangle}{\langle v_n(\eta^a)v_n(\eta^b) \cos[n(\Psi_n(\eta^a) - \Psi_n(\eta^b))] \rangle} \sim \langle \cos[n(\Psi_n(\eta^a) - \Psi_n(-\eta^a))] \rangle$$



Event-plane rotation: Ψ_2

$$r_n \approx \langle \cos(n\Psi_n(\eta^a) - n\Psi_n(-\eta^a)) \rangle \approx 1 - 2\eta^a F$$

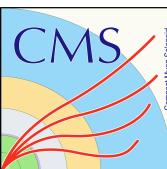
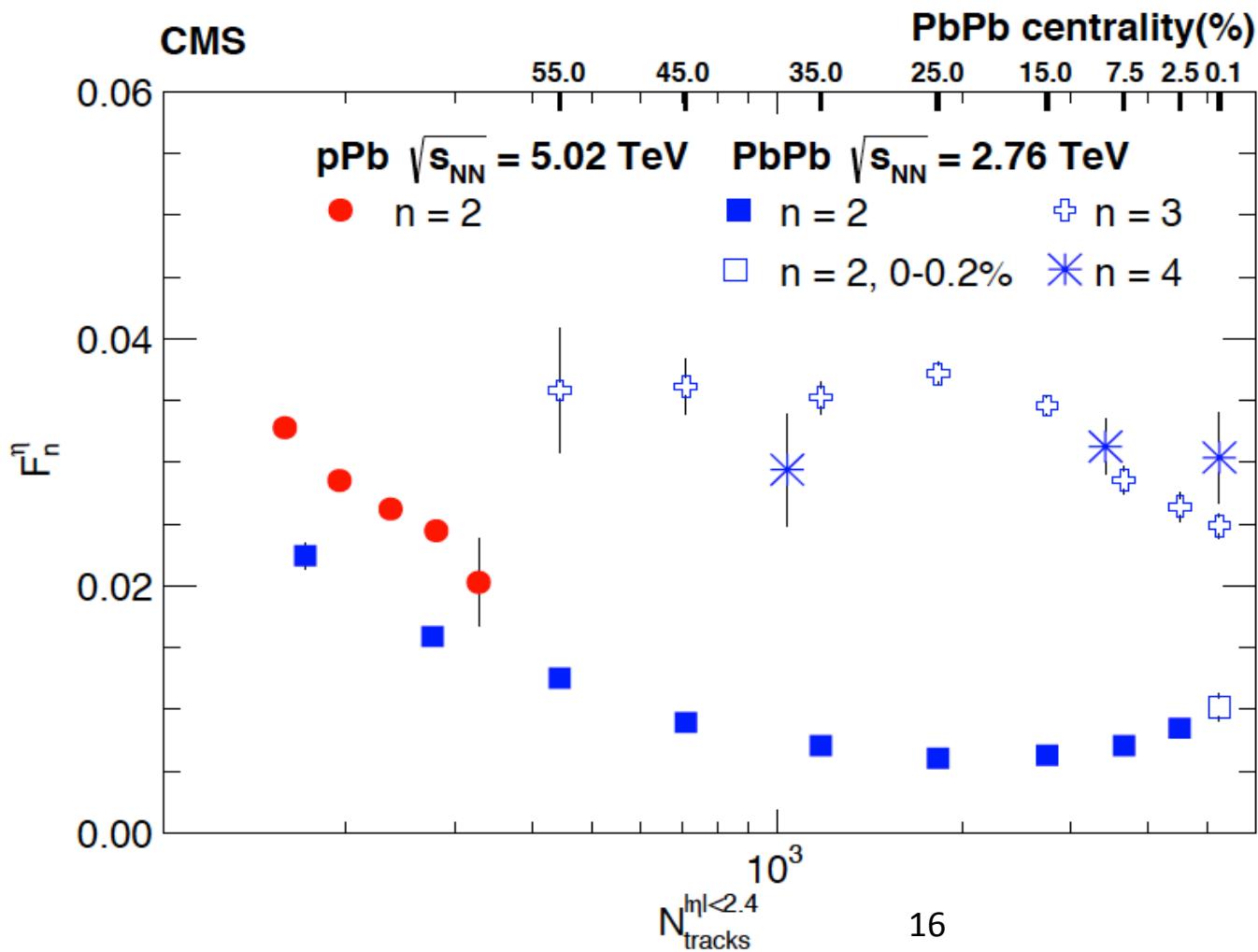


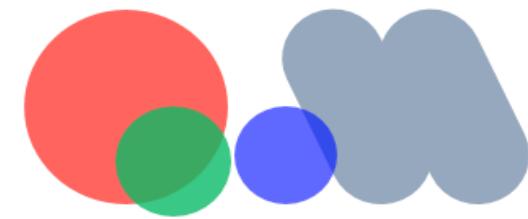


Event-plane rotation: Ψ_n

❖ Effect is larger for higher order and for $p+\text{Pb}$

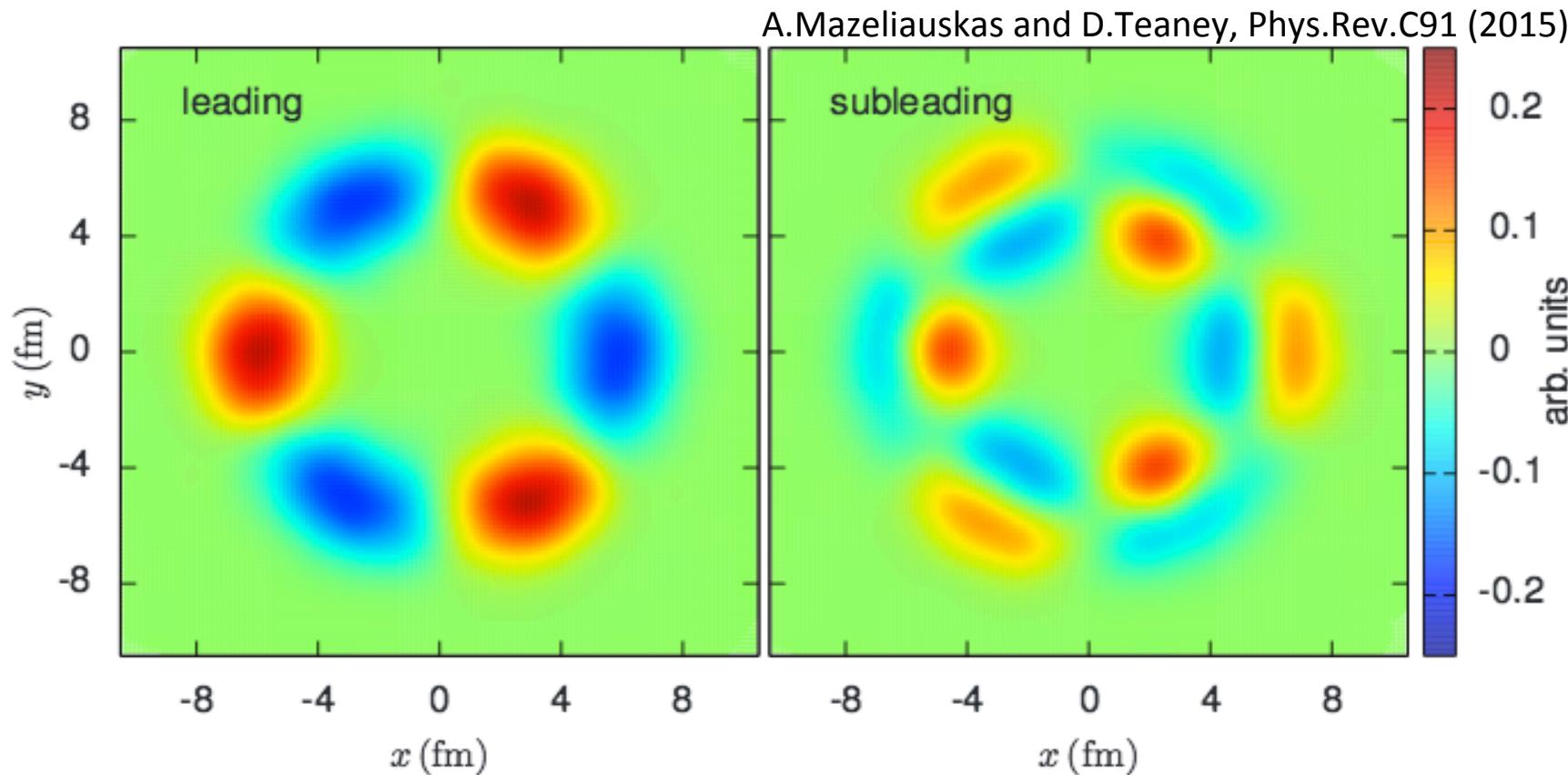
$$r_n \approx \langle \cos(n\Psi_n(\eta^a) - n\Psi_n(-\eta^a)) \rangle \approx 1 - 2\eta^a F \approx \exp(-2\eta^a F)$$

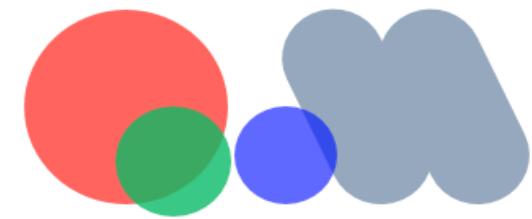




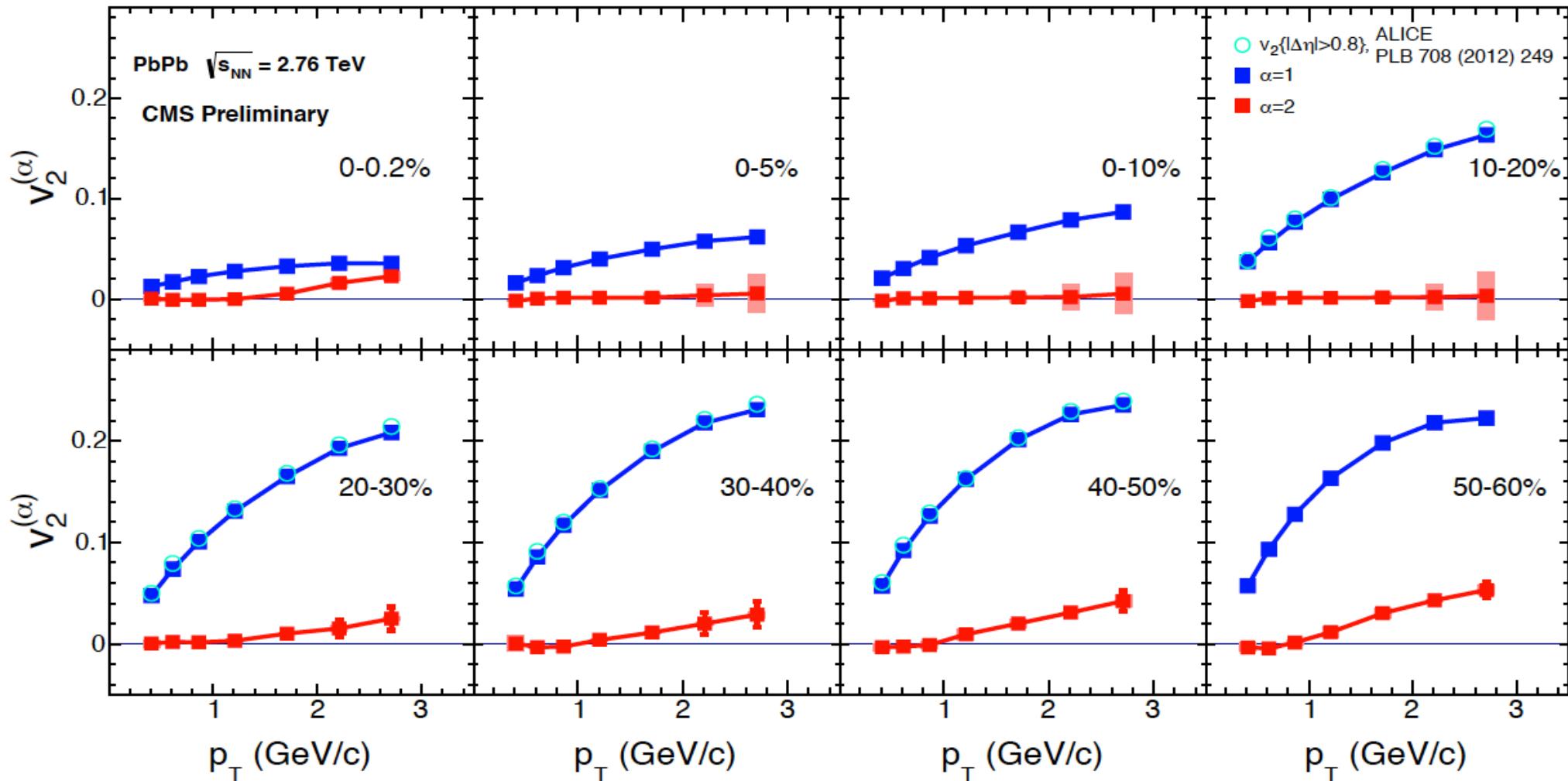
Principal component analysis

- ✧ Multiple radial modes in the initial geometry drive the v_n
- ✧ The hydro response to the radial modes can be different leading to breakdown of factorization



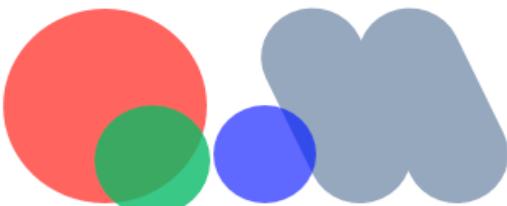


Principal component analysis : v_2 in $Pb+Pb$

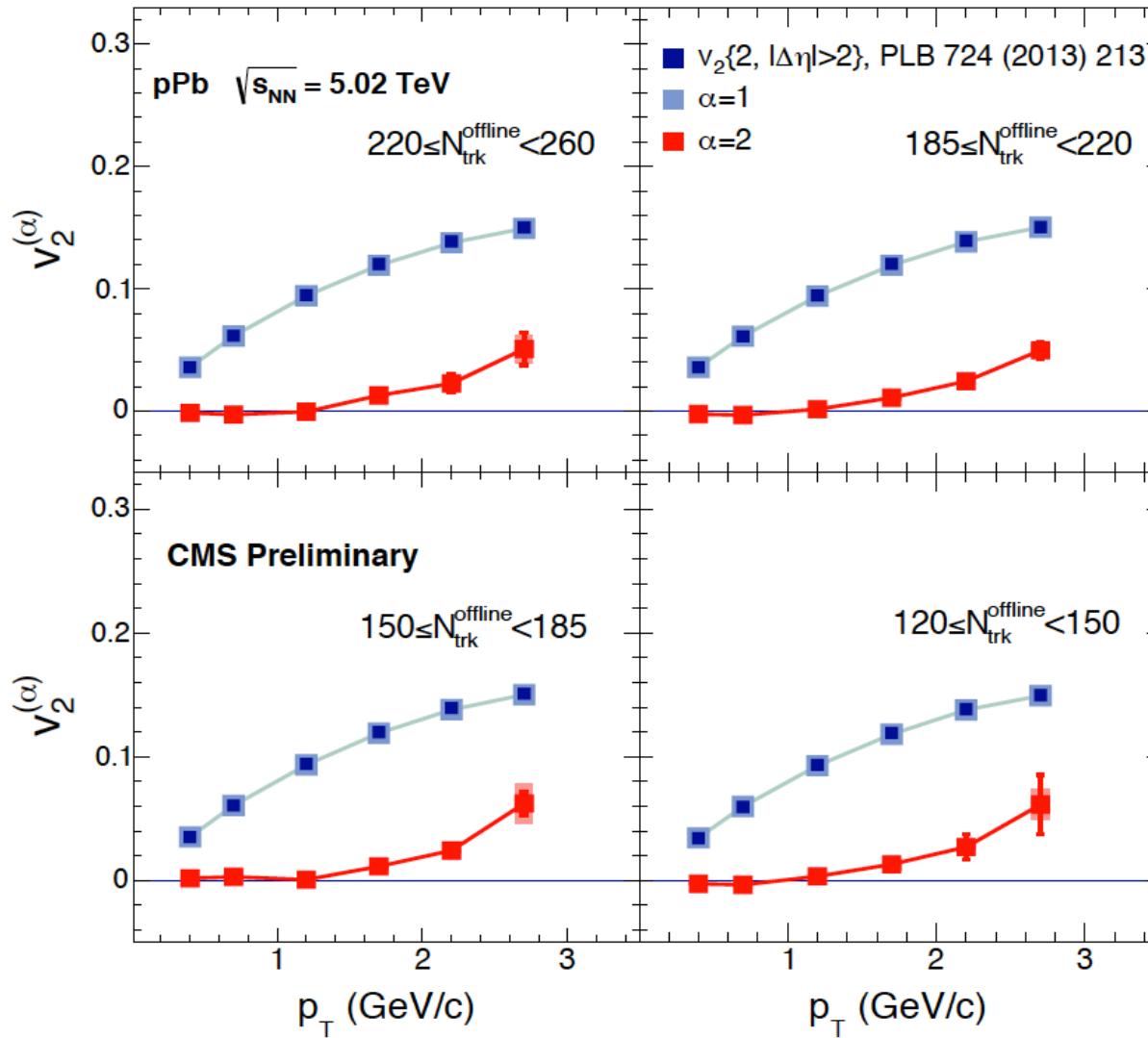


- ❖ Leading and sub-leading mode for v_2 in $Pb+Pb$ shown
- ❖ Leading mode is quite dominant, except in most central collisions

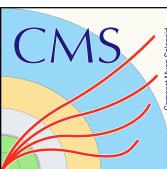


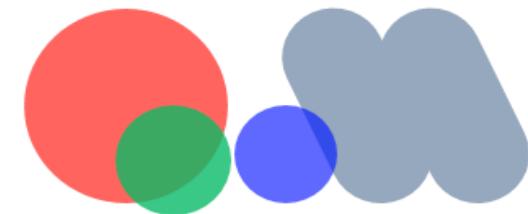


Principal component analysis: v_2 in $p+Pb$



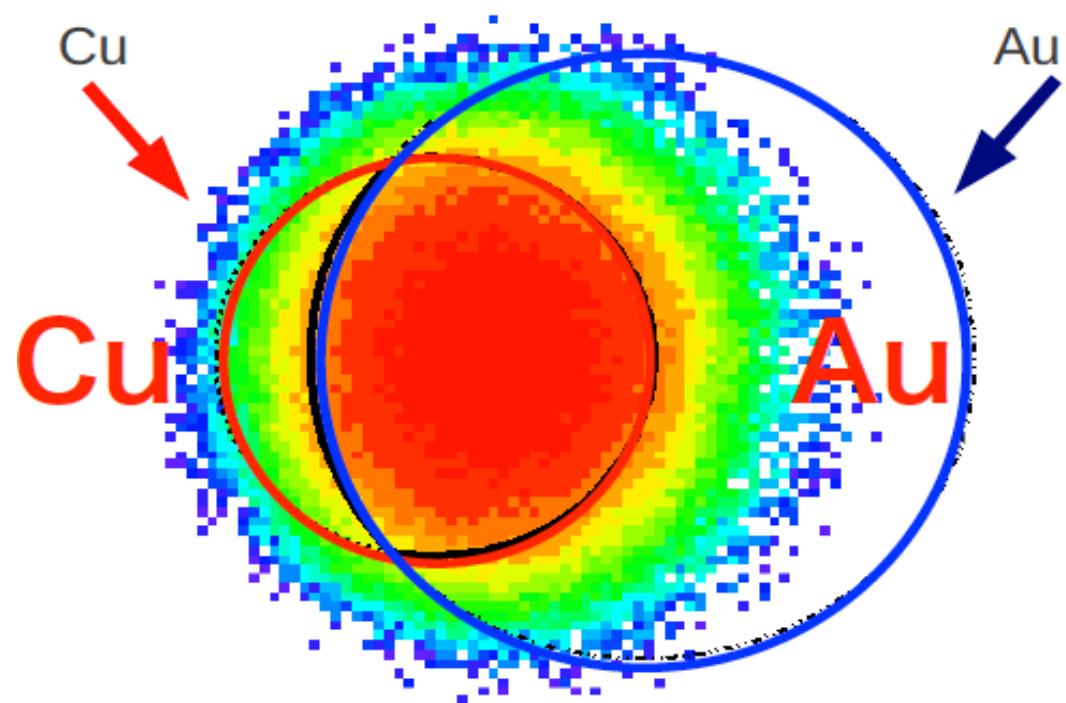
- ❖ The leading flow mode, $\alpha=1$, practically identical to the v_2 measured using two-particle correlations
- ❖ The sub-leading flow mode, $\alpha=2$, is essentially equal to zero at small p_T and increases up to 4-5% going to the high- p_T



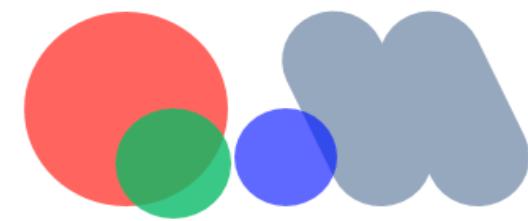


Asymmetric Collisions

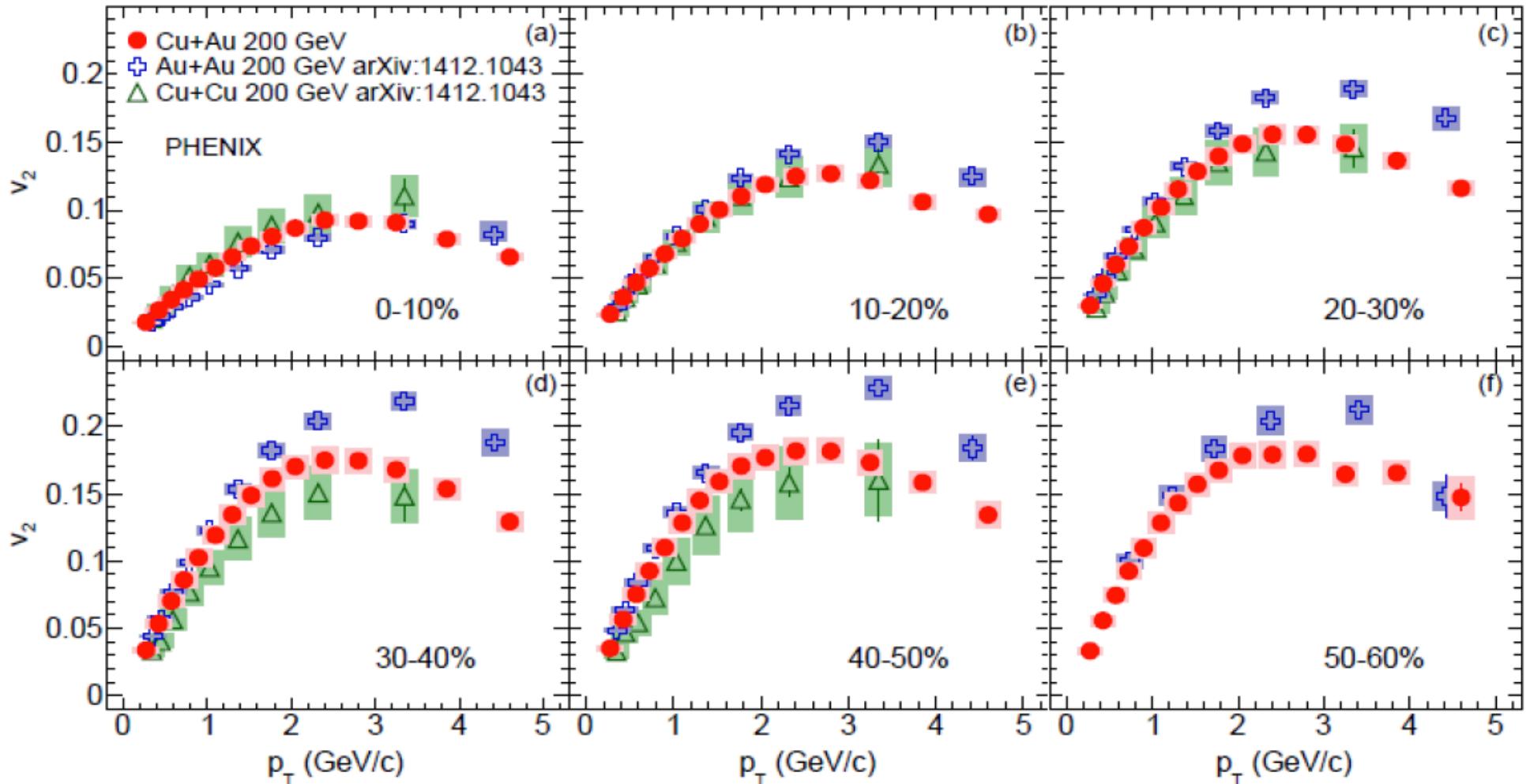
- ❖ Pick collisions with deformed geometry.
- ❖ Or collide systems that have asymmetric average geometry



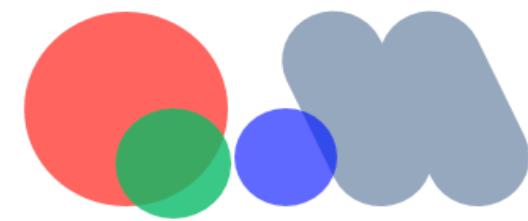
Participant density (log-z scale)



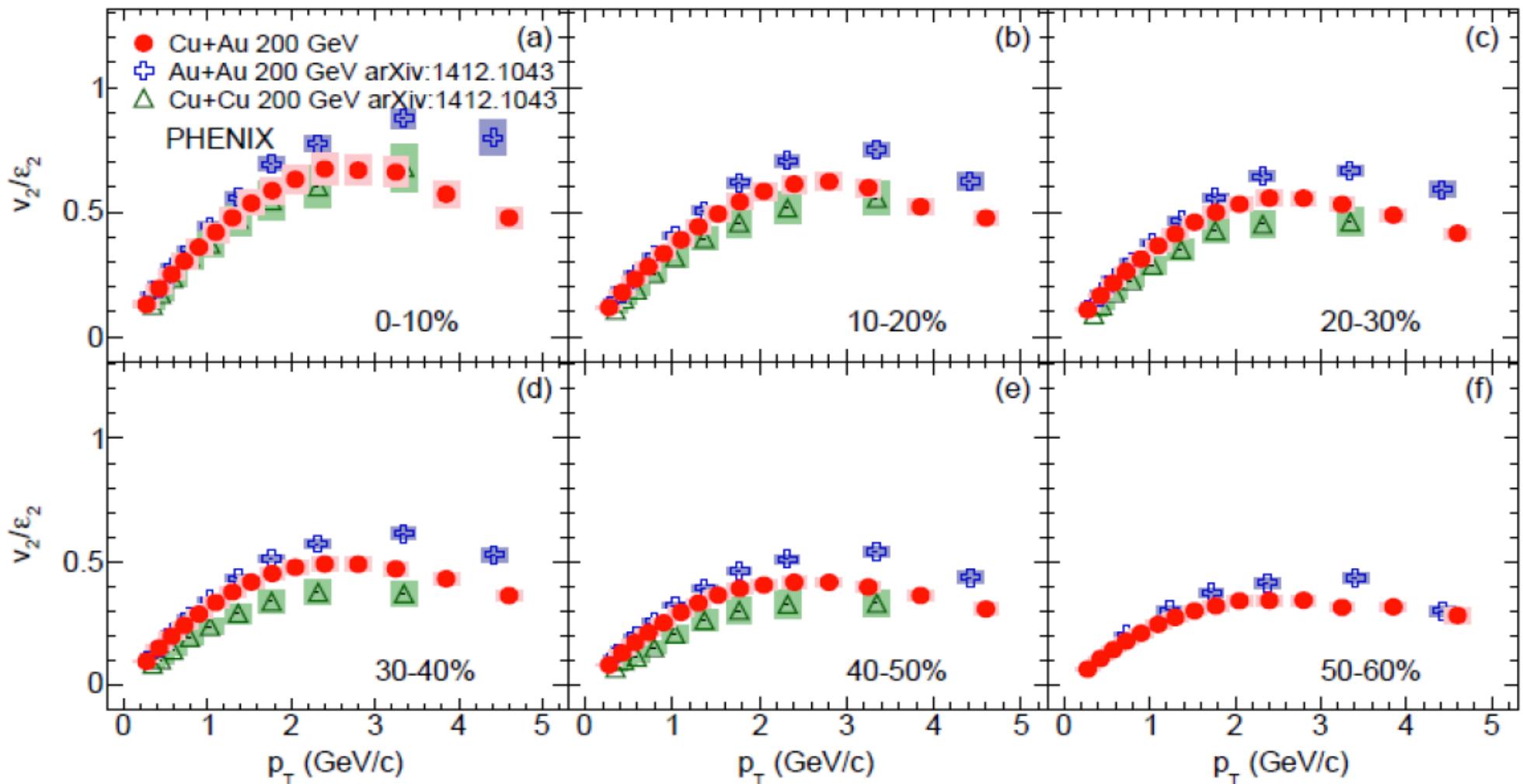
Cu+Au v_2



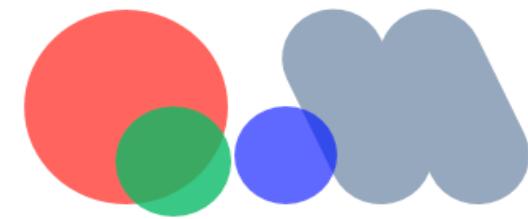
✧ Cu+Au v_2 falls between Cu+Cu and Au+Au



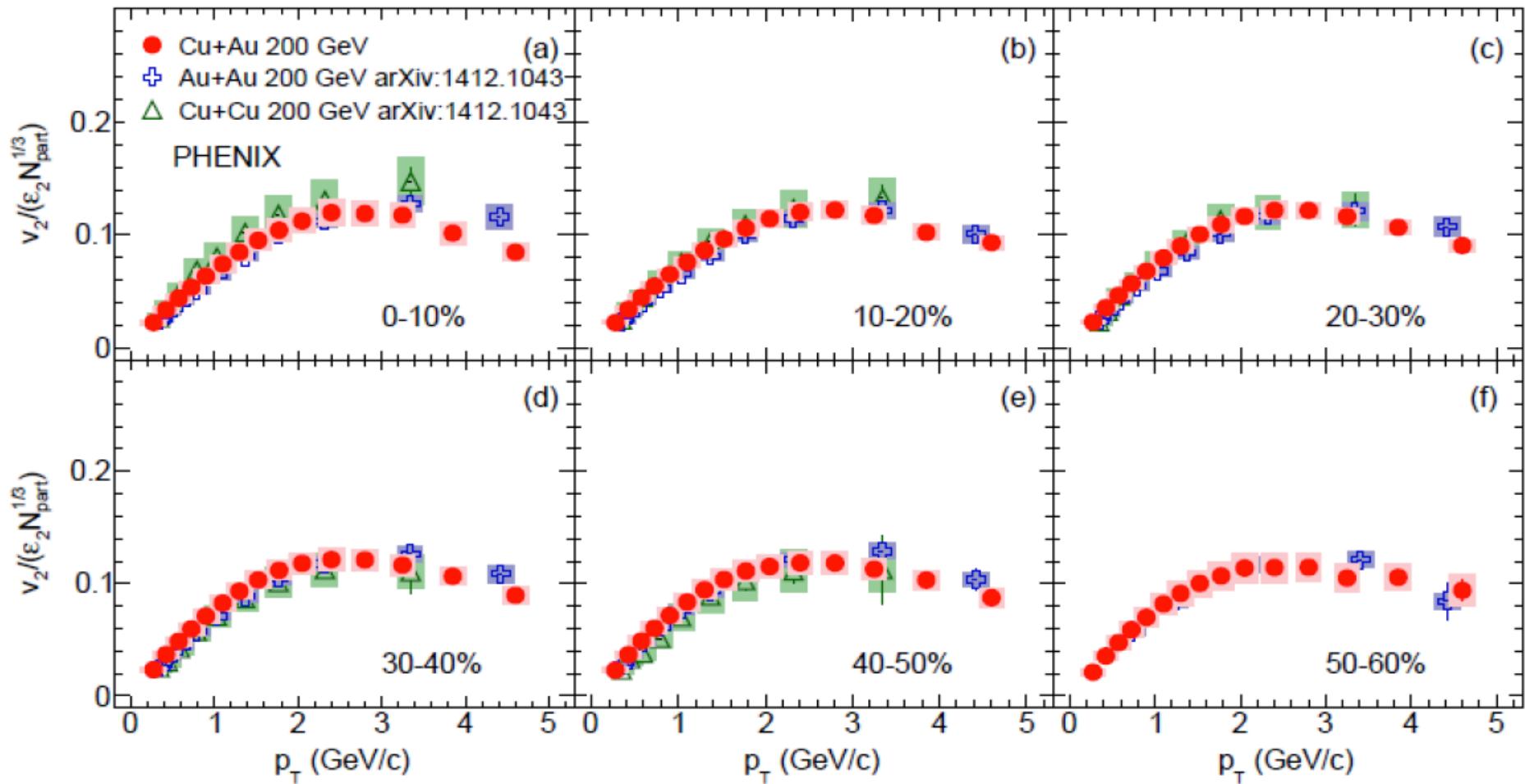
Cu+Au ν_2



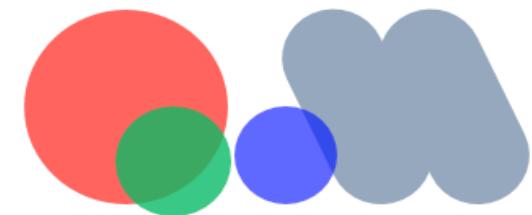
❖ Scaling by ε_2 orders the v_2 by system size.



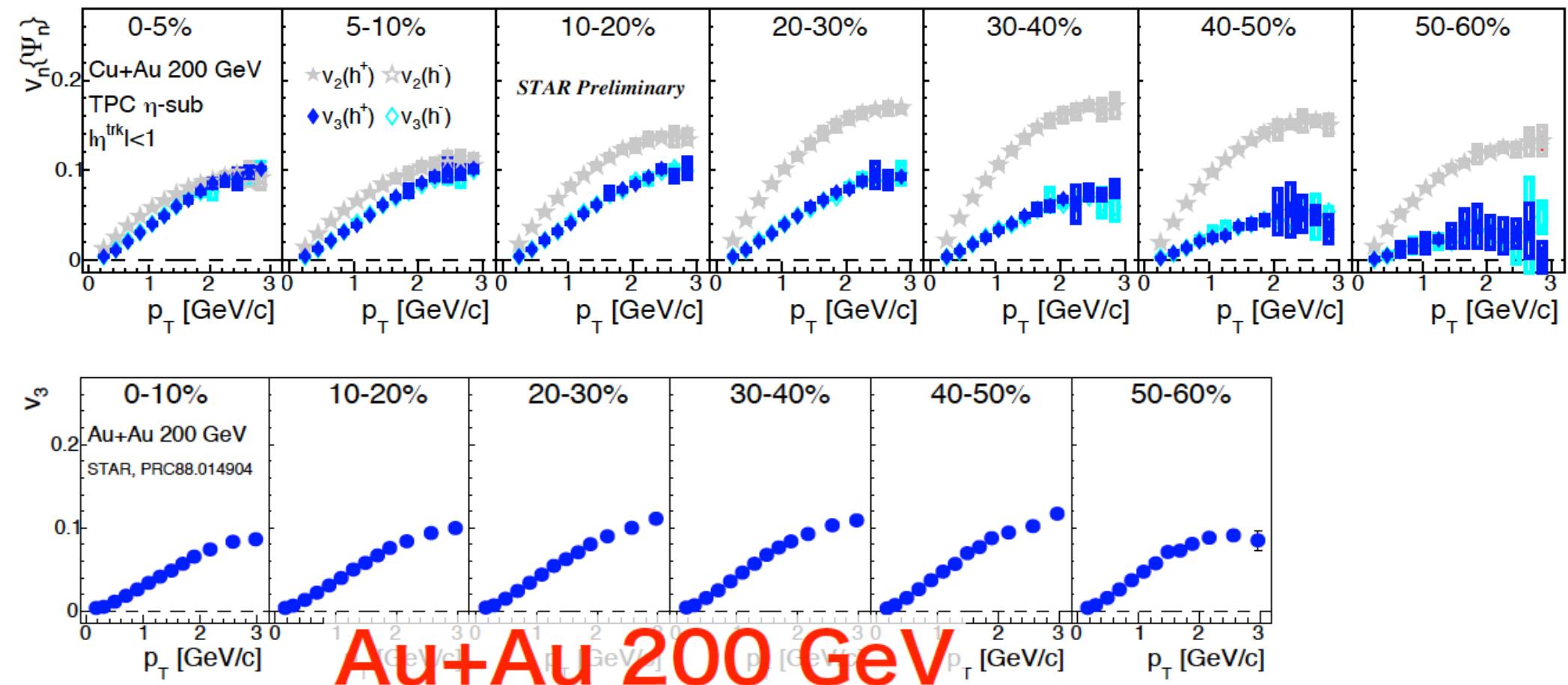
Cu+Au V₂



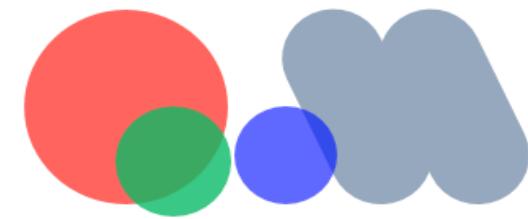
❖ Empirical scaling seen across all systems and centralities.



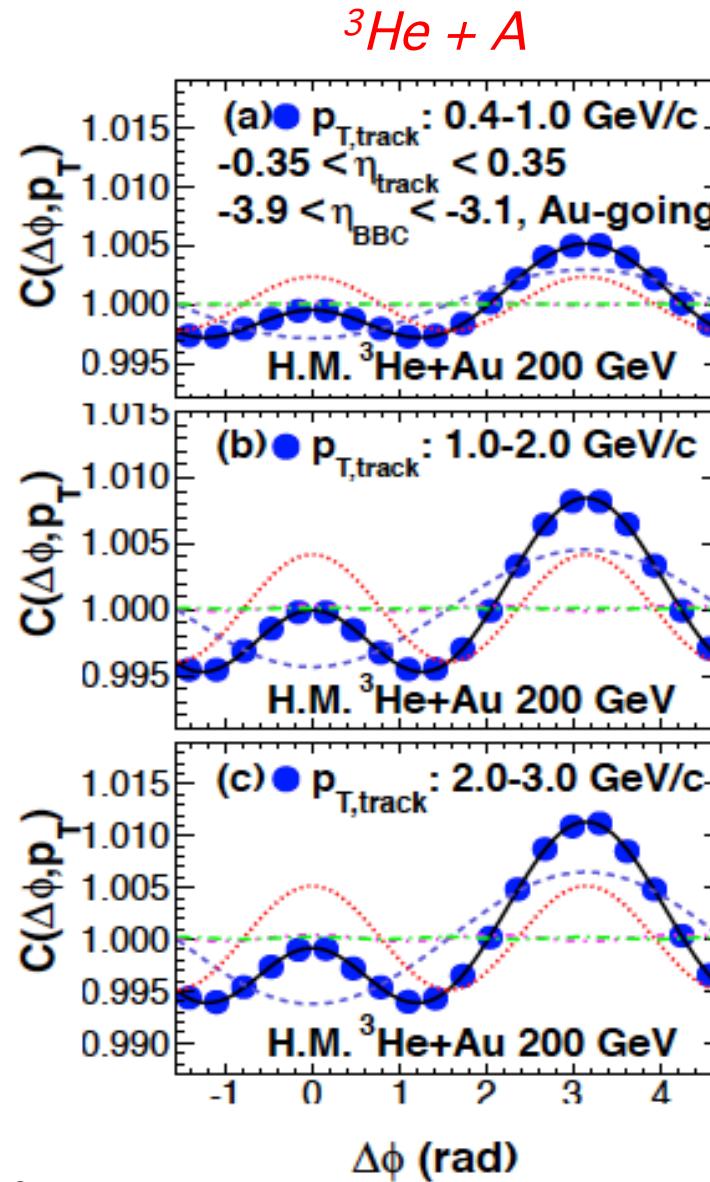
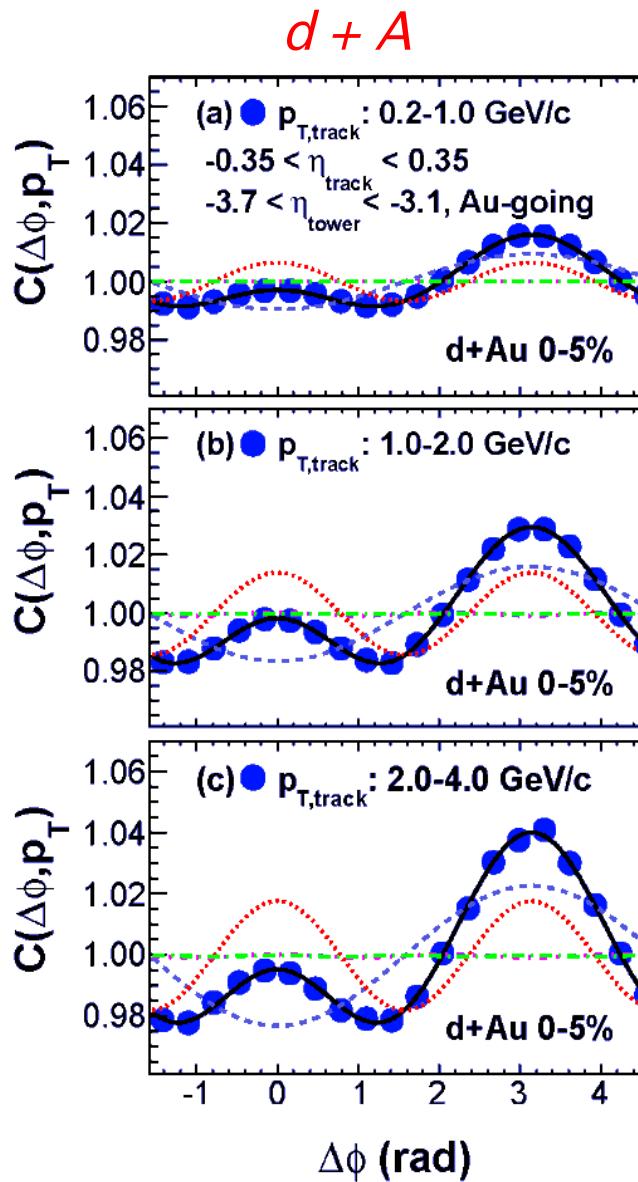
Cu+Au ν_3

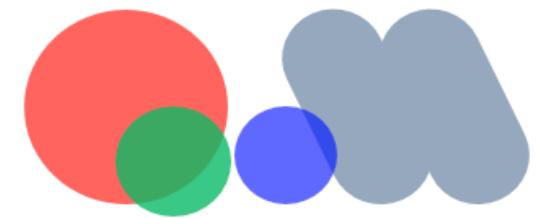


- ✧ Stronger centrality dependence of v_3 compared to Au+Au

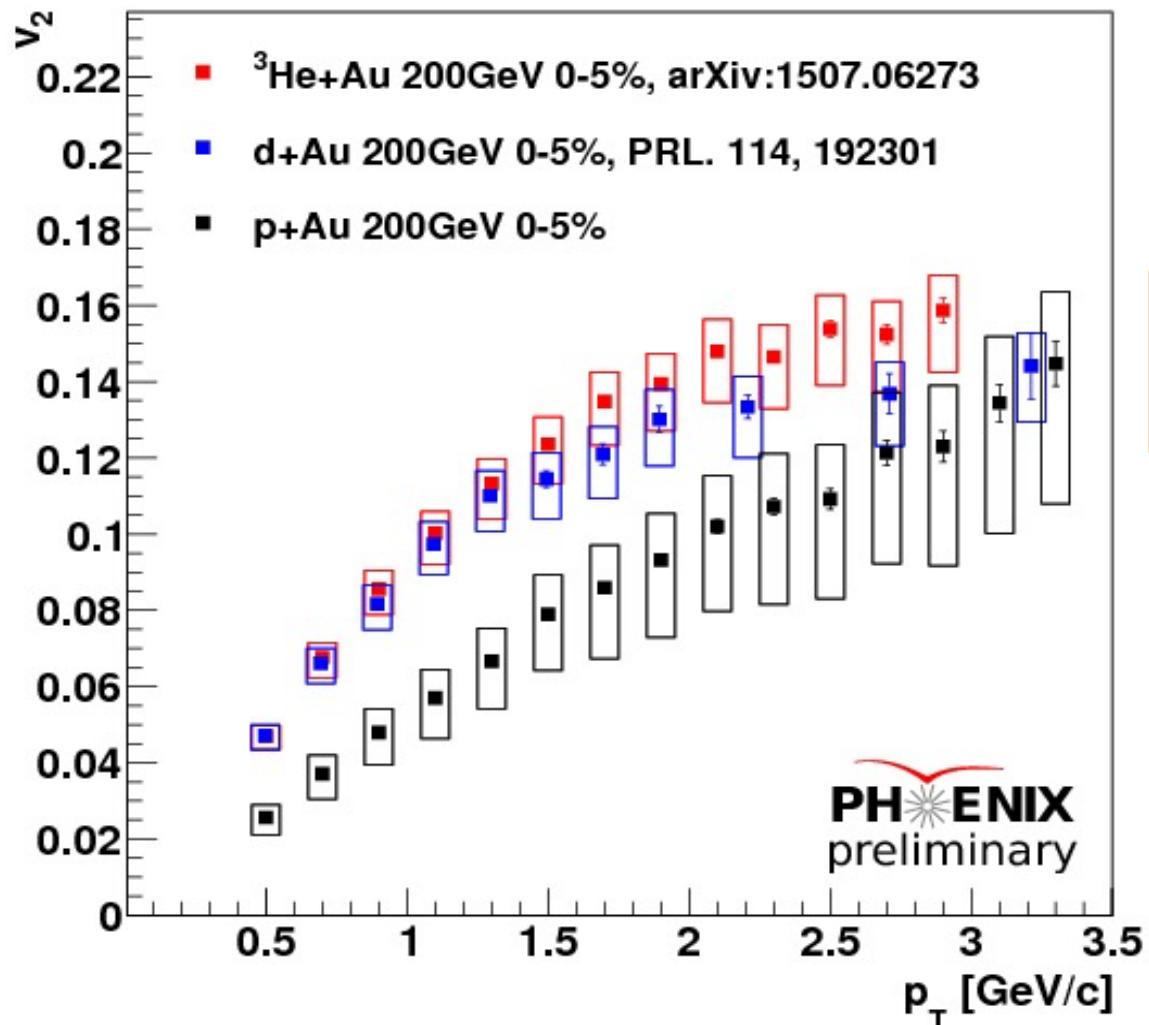


Flow in $p/d/{}^3He + A$



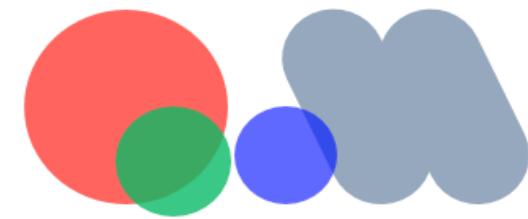


Flow in $p/d/{}^3He + A$

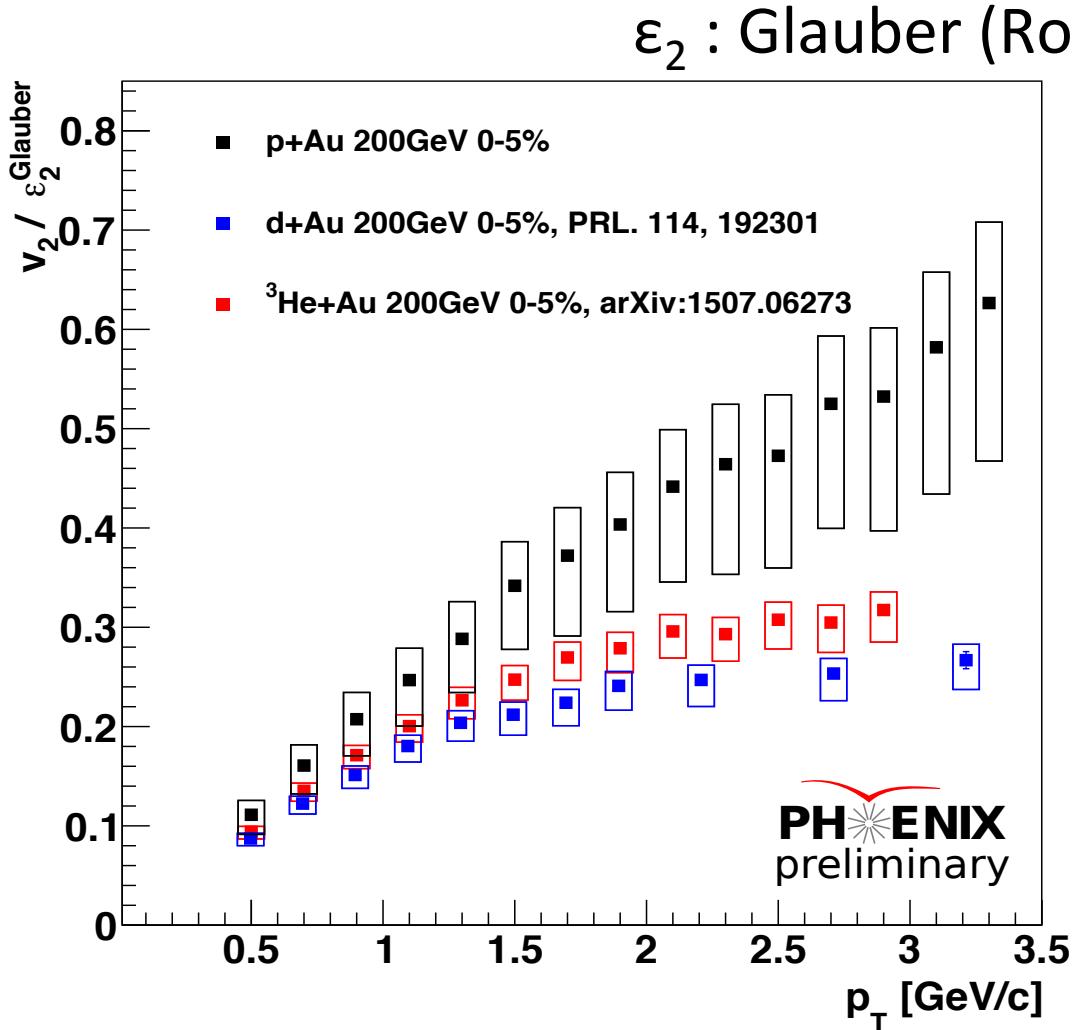


$$v_2^{pAu} < v_2^{dAu} \leq v_2^{{}^3HeAu}$$

Ordering expected from initial state eccentricities
(smallest ε_2 in $p + \text{Au}$)

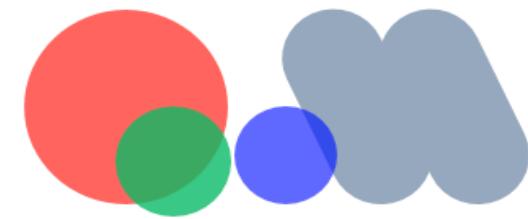


Eccentricity scaling

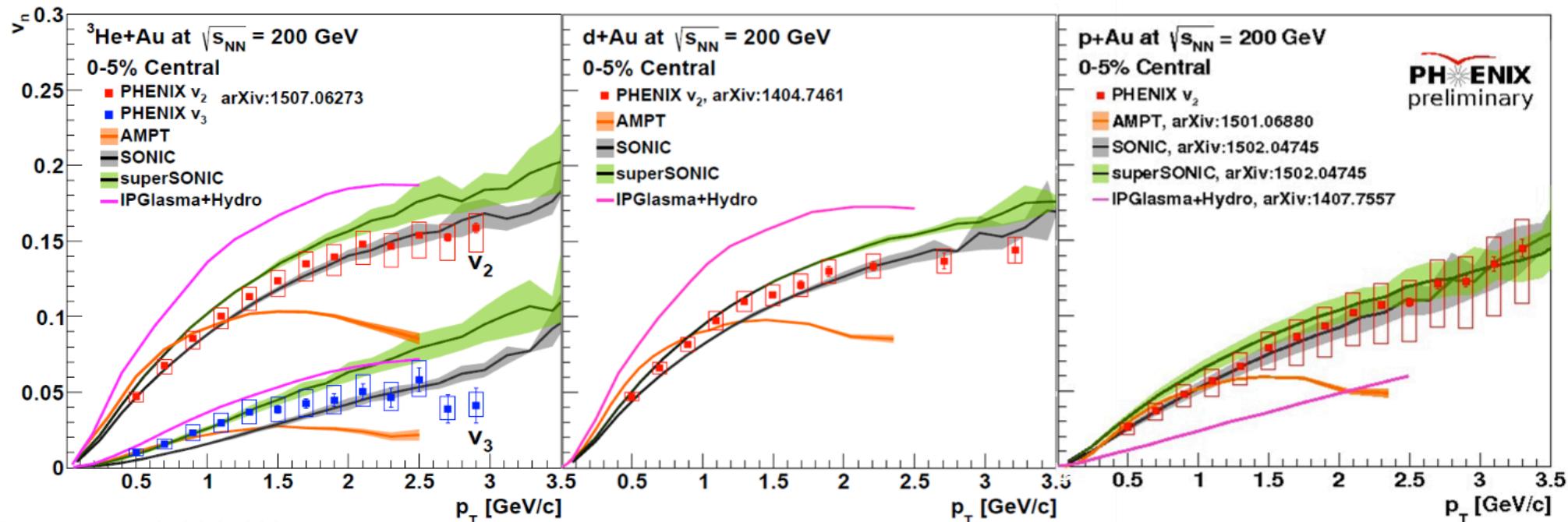


$$\frac{v_2^{dAu}}{\varepsilon_2^{dAu}} < \frac{v_2^{^3HeAu}}{\varepsilon_2^{^3HeAu}} < \frac{v_2^{pAu}}{\varepsilon_2^{pAu}}$$

- ❖ The ordering now changes and p +Au becomes largest due to round nucleon assumed in Glauber calculation.
- ❖ Small system with shorter lifetime would not fully reflect initial geometry information

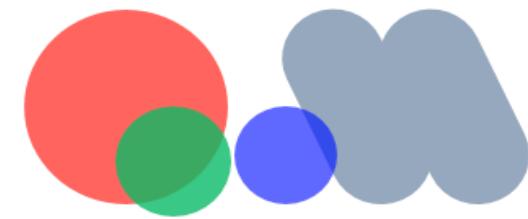


v_2 and v_3

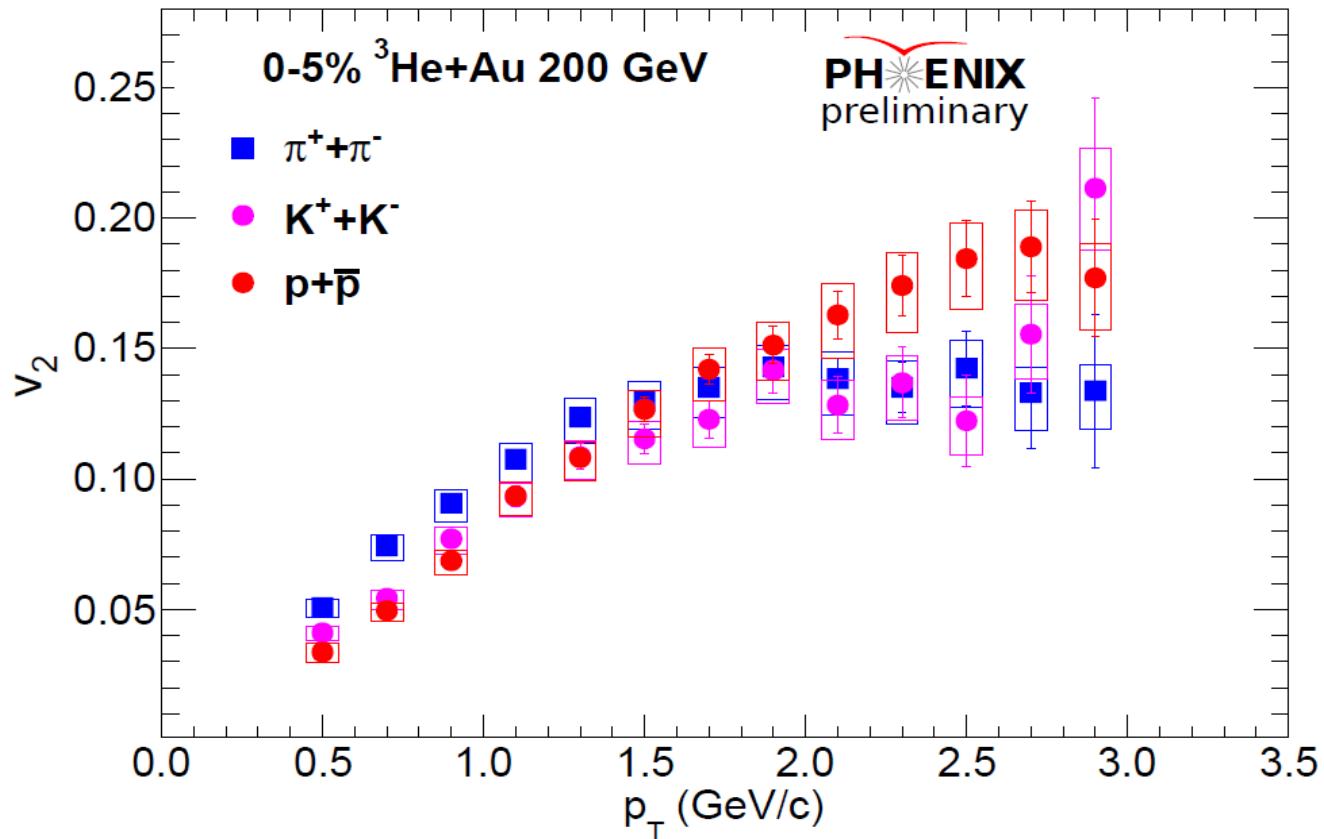


AMPT: arXiv:1501.06880 SONIC: arXiv:1502.04745 IP+Hydro:arXiv:1407:7557

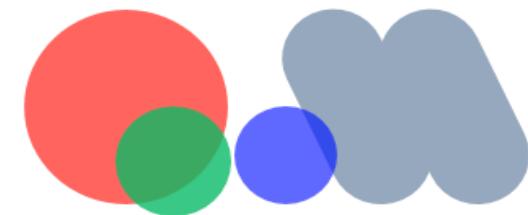
- ❖ The v_2 in 0-5% $^3\text{He}+\text{Au}$ and 0-5% $d+\text{Au}$ collisions are very similar
- ❖ SONIC reasonably well reproduces the v_n



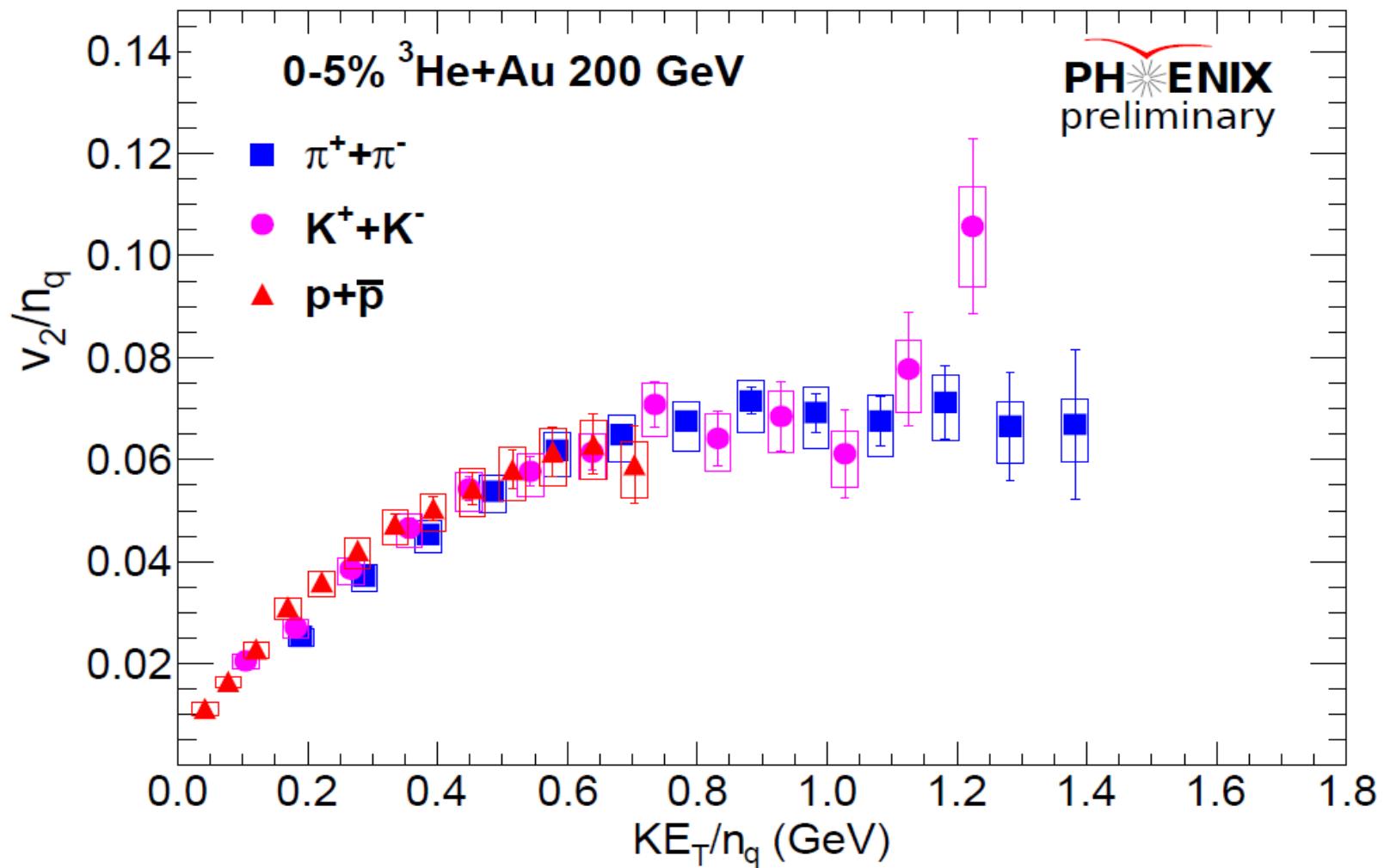
${}^3\text{He} + \text{Au}$: Identified particle v_2



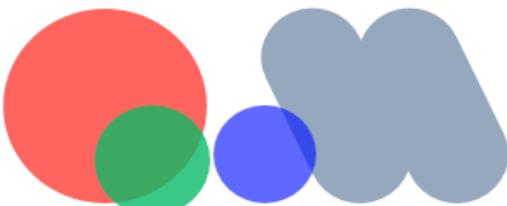
- ✧ At $p_T < 1.5$ GeV/c: mass ordering : $v_2(\text{proton}) < v_2(\text{kaon}) < v_2(\text{pion})$
- ✧ At $p_T > 2.0$ GeV/c: difference for meson and baryon
- ✧ Similar to that in Au+Au collisions



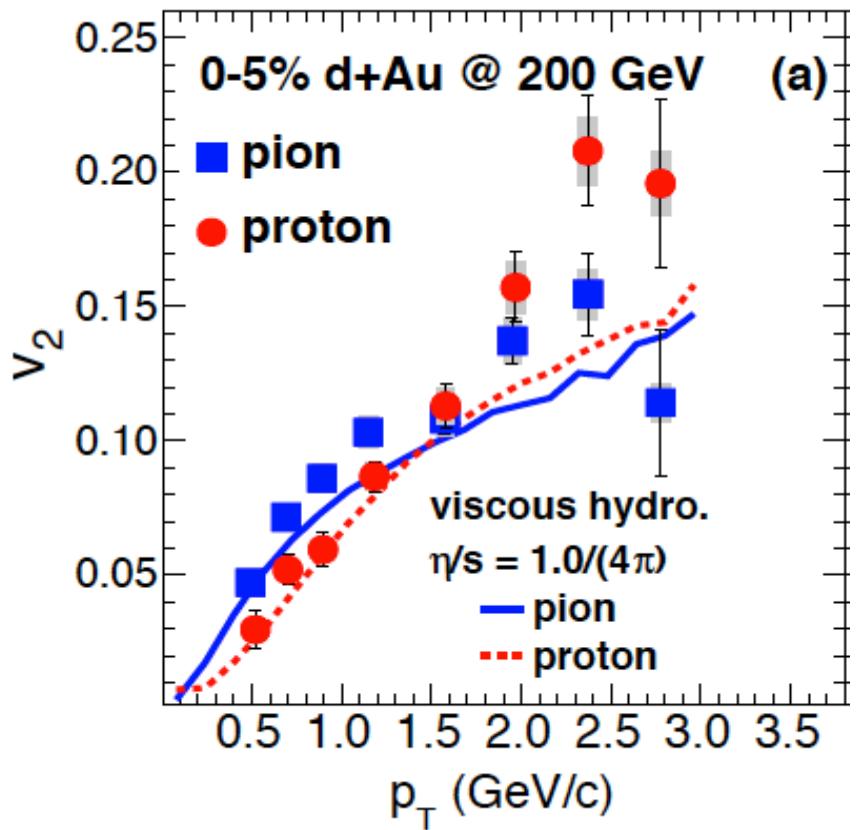
$^3\text{He} + \text{Au} : n_q$ scaling



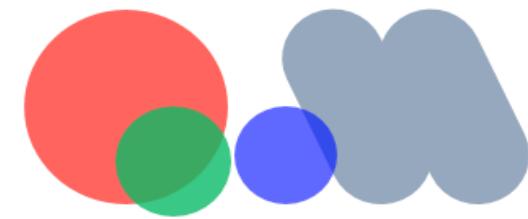
❖ n_q scaling observed in A+A collisions is also seen in the small $^3\text{He} + \text{Au}$ system



d+Au : Identified particle v_2



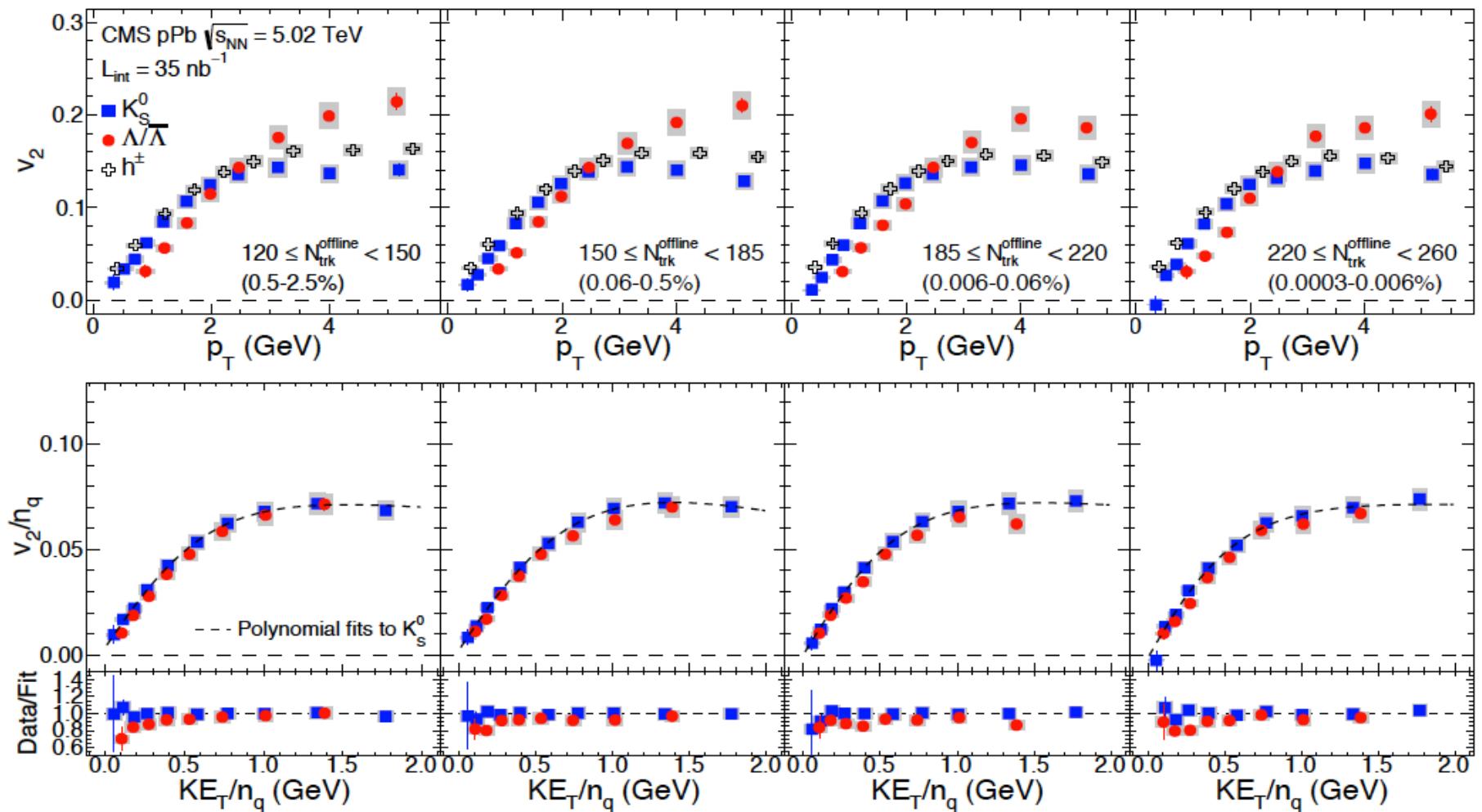
❖ Mass ordering seen



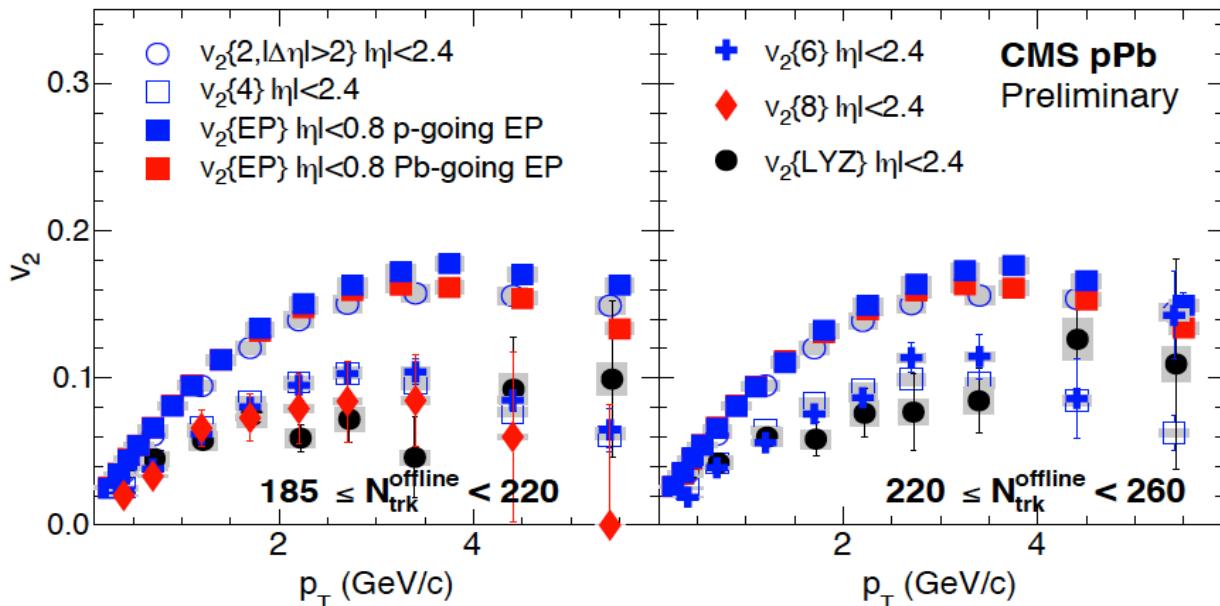
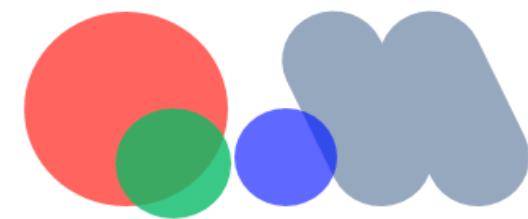
$p+A : Identified particle v_2$

CMS arXiv:1409.3392v2

K^0_s and Λ particles

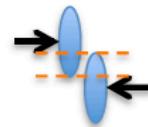
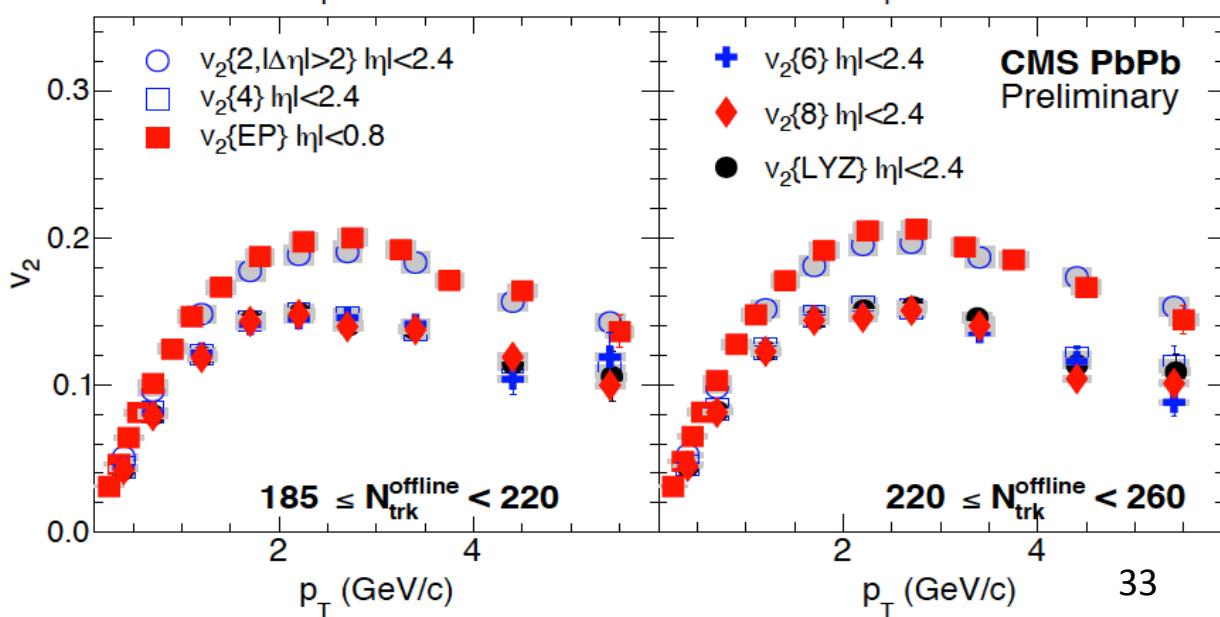


Higher order cumulants in $p+Pb : p_T$ dependence

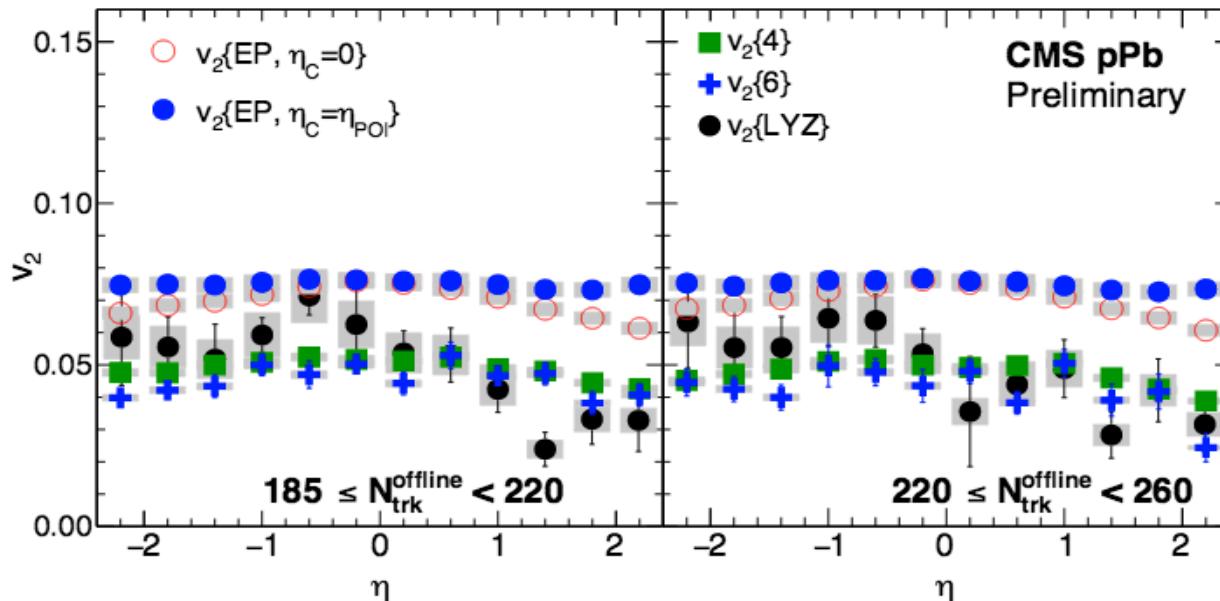
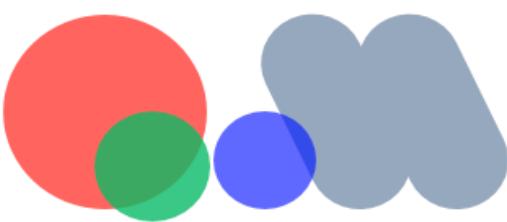


$v_2\{\{\text{EP}\}>\} > v_2\{4\}$

$v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\text{LYZ}\}$

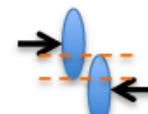
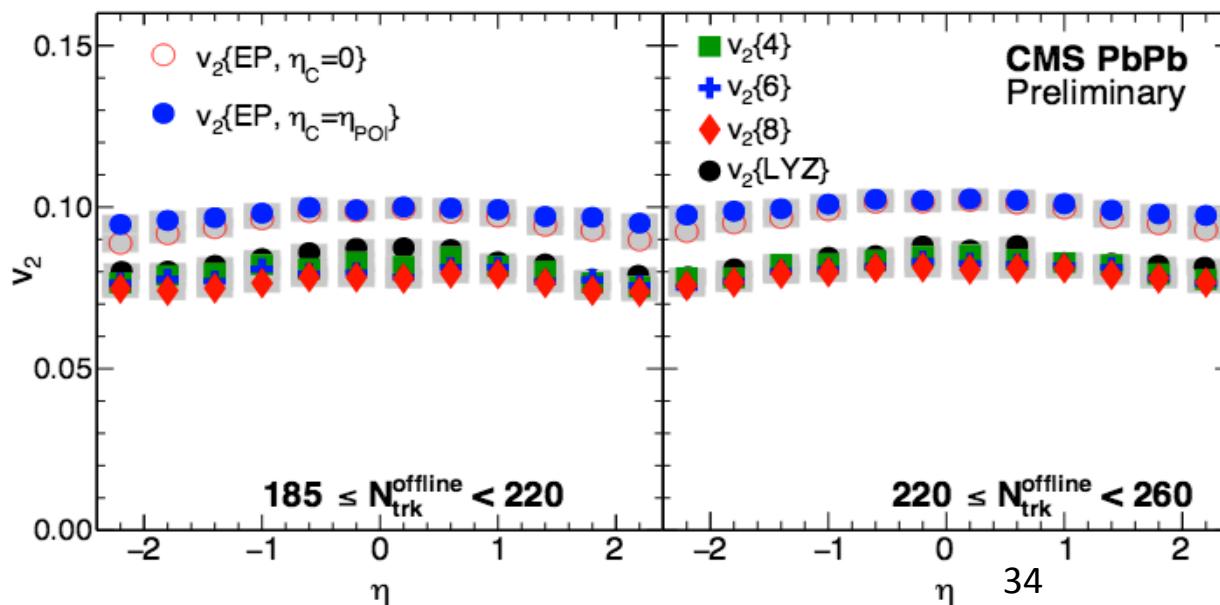


Higher order cumulants in $p+Pb : \eta$ dependence



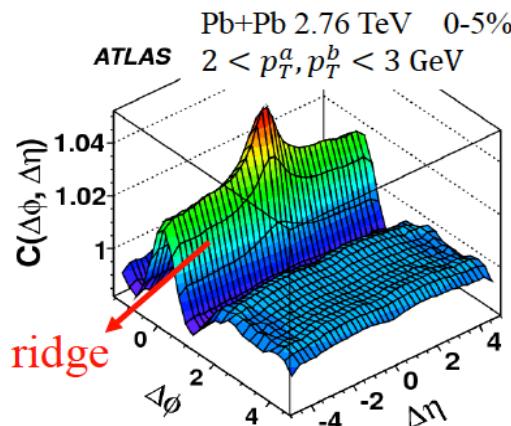
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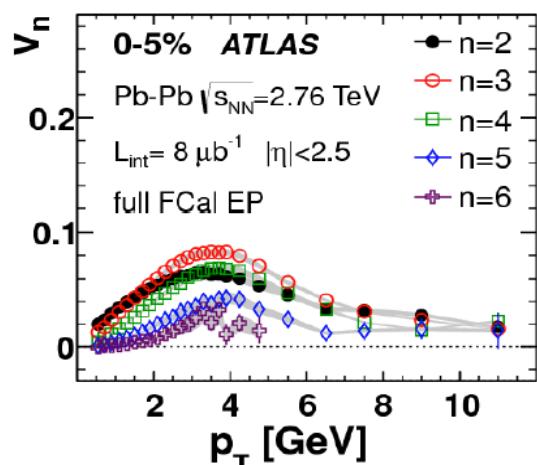


Cumulant and pid results
are strongly supportive
of hydro

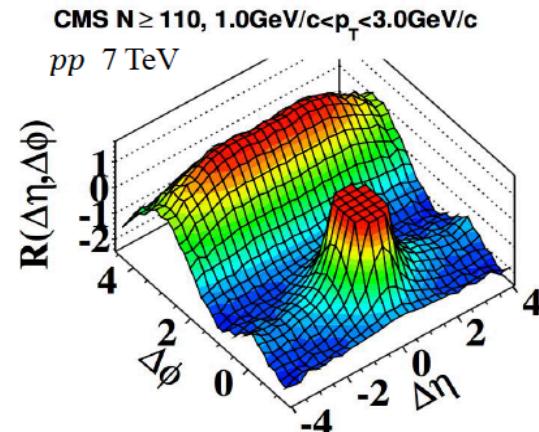
pp Long-range correlations



The ridge first discovered in A+A collisions.



Single-particle v_n was measured.



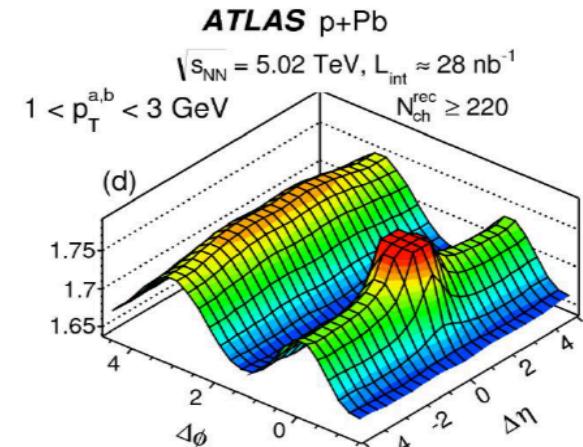
Ridge observed in pp.

Theoretical interpretations

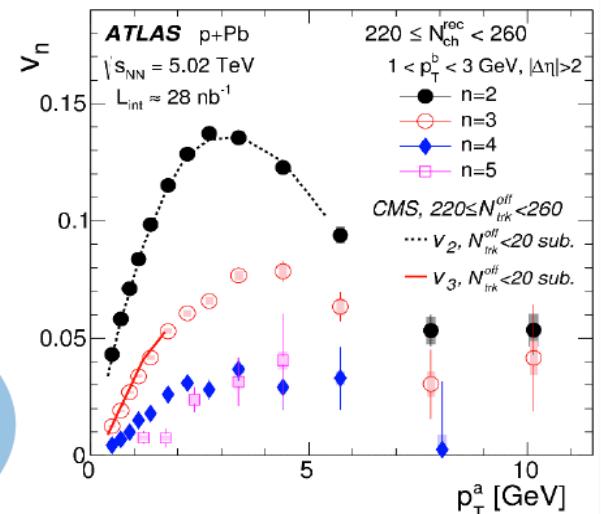
- Flow effects?
- Initial state physics?

To shed light on competing theories, more studies needed:

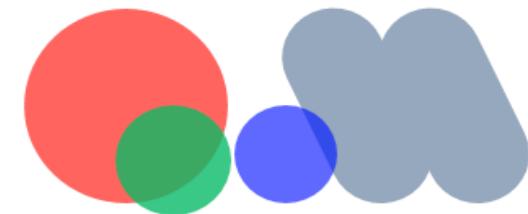
- Single-particle v_n ;
- Energy dependence.



Ridge in p+Pb.

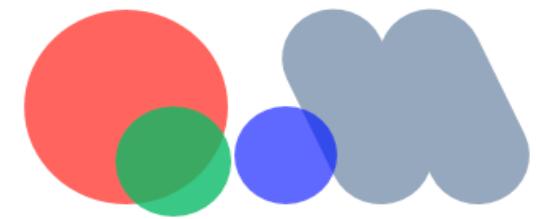


v_n was also measured.



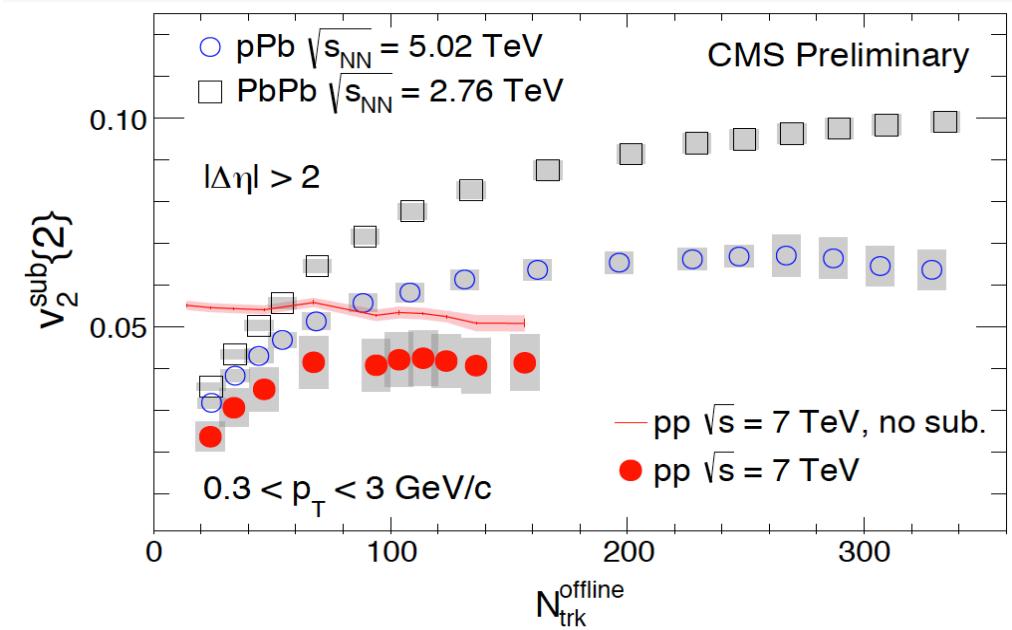
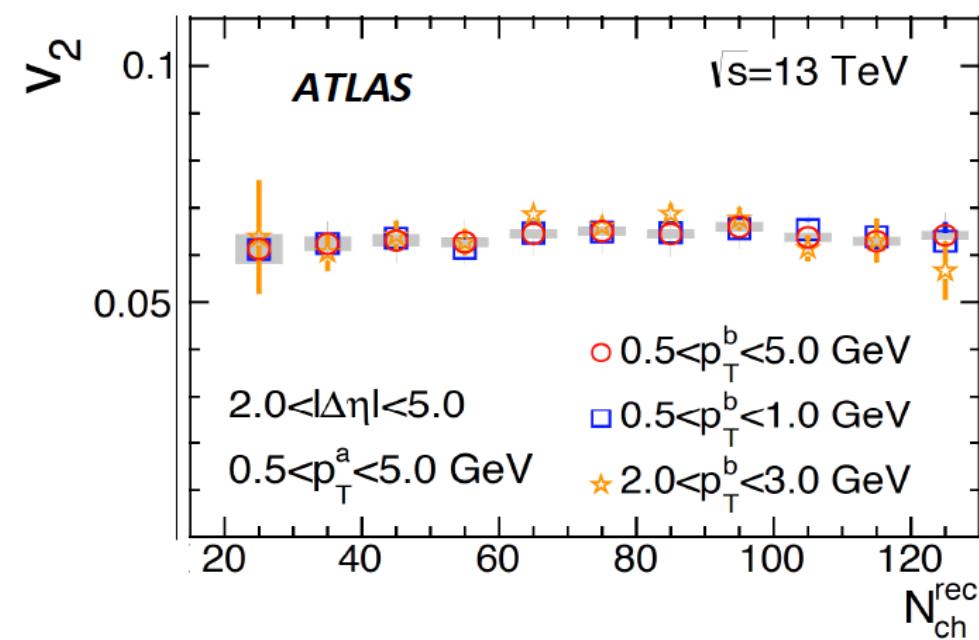
Summary

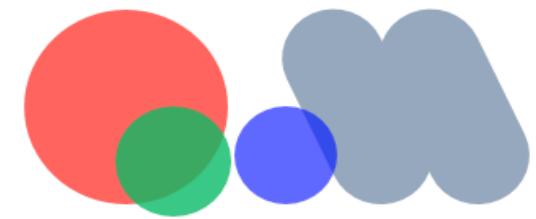
- ✧ Rich set of new observables to study flow fluctuations
 - ✧ Event-shape engineering
 - ✧ Flow-correlations
 - ✧ Event-plane de-correlations
 - ✧ Principal component analysis
 - ✧ Cu+Au collisions
- ✧ Correlations in small systems : $p+A$, $d+A$, $\text{He}+A$
 - ✧ PID results
 - ✧ Higher order cumulants
 - ✧ pp long range correlations (collective or not??)Strongly supportive of hydro
- ✧ Other talks where flow measurements will be discussed:
 - ✧ Experimental overview on beam energy scan
 - ✧ Experimental overview on small colliding systems at RHIC
 - ✧ Experimental overview on small colliding systems at LHC
 - ✧ Experimental overview on open heavy flavor



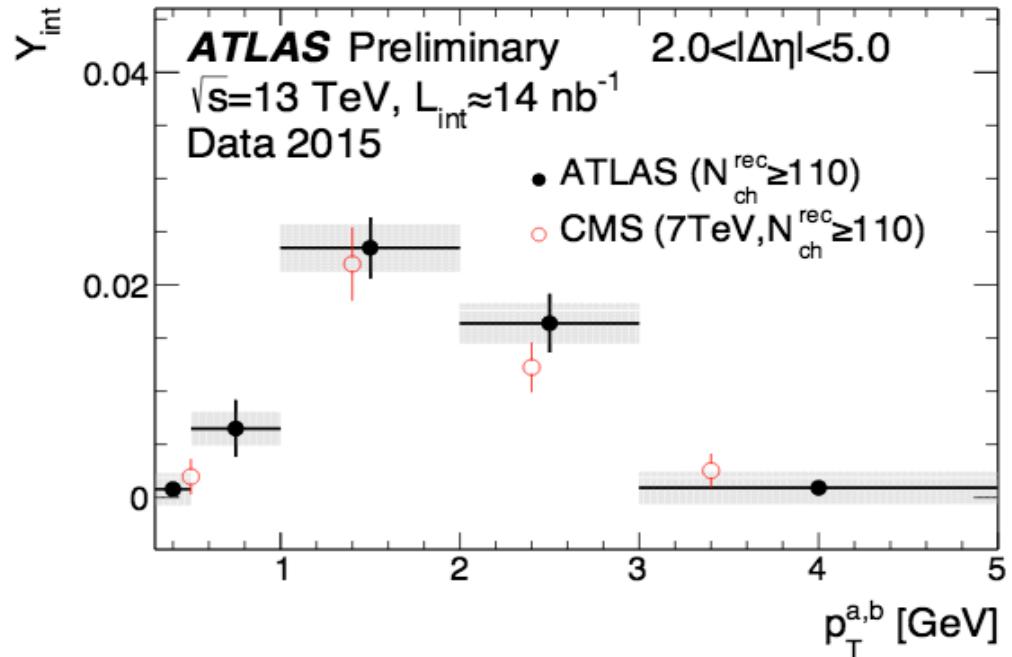
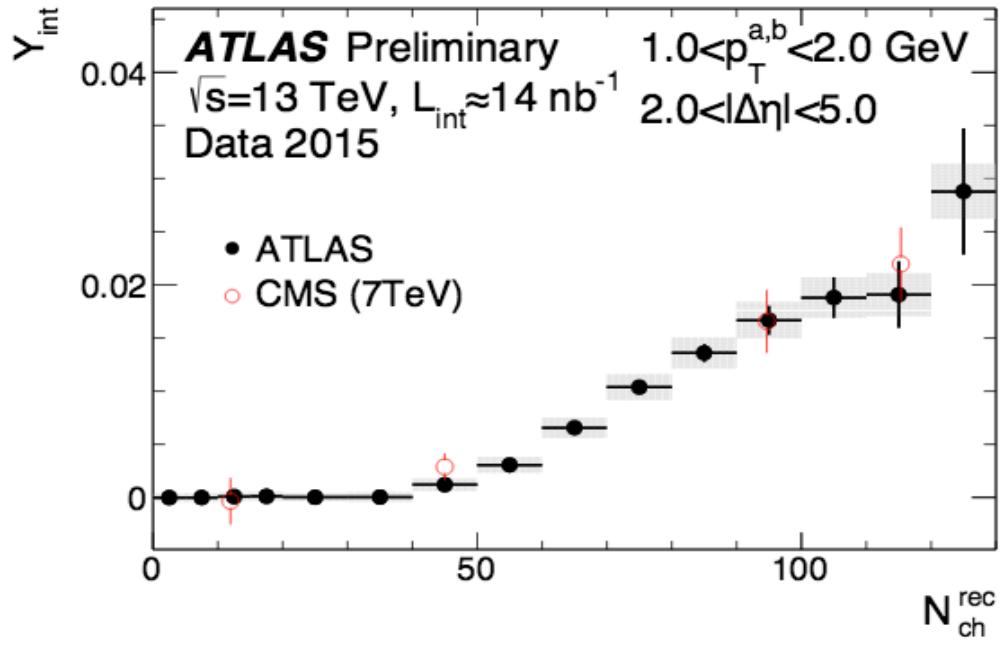
pp Long-range correlations

- ❖ Single particle harmonics v_2 (v_3) extracted by ATLAS and CMS
- ❖ Using different assumptions

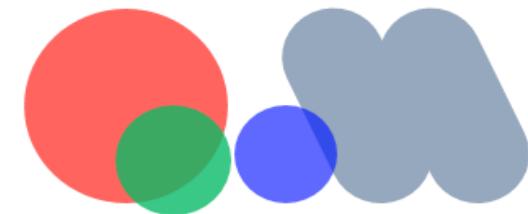




Yields in ATLAS and CMS

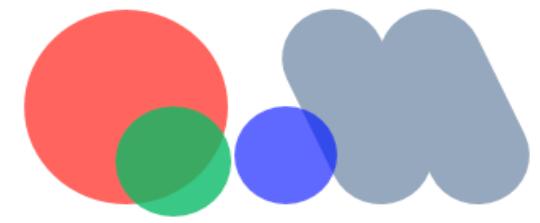


Both experiments get consistent in ZYAM Yields!

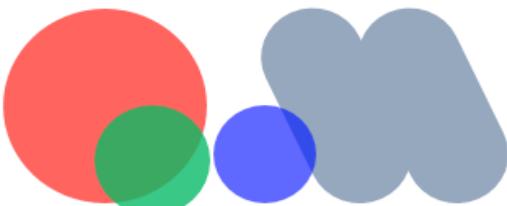


Summary

- ✧ Rich set of new observables to study flow fluctuations
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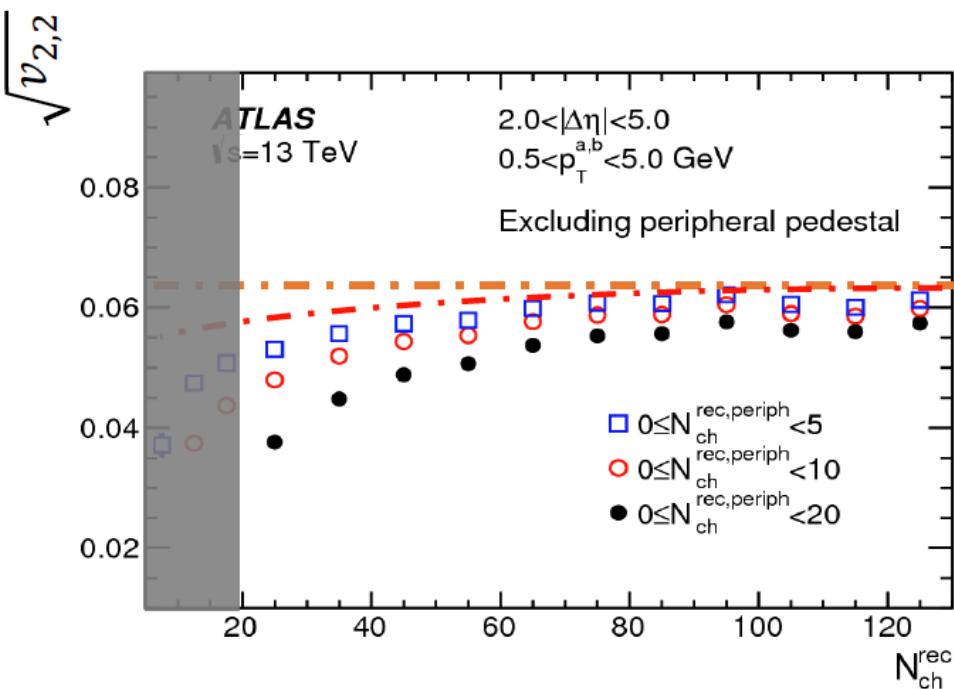


BACKUP

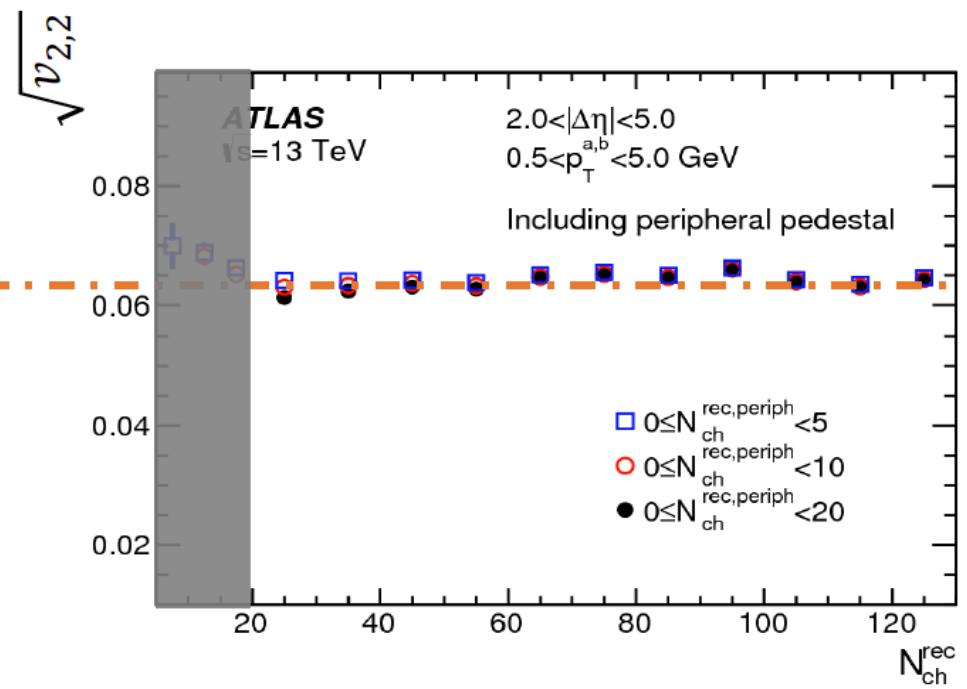


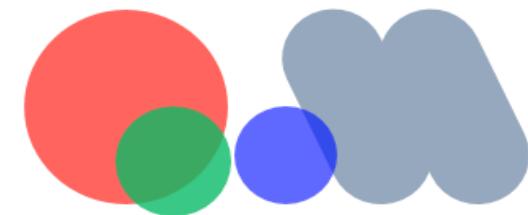
Comparison of the two template fit methods

Exclude Pedestal

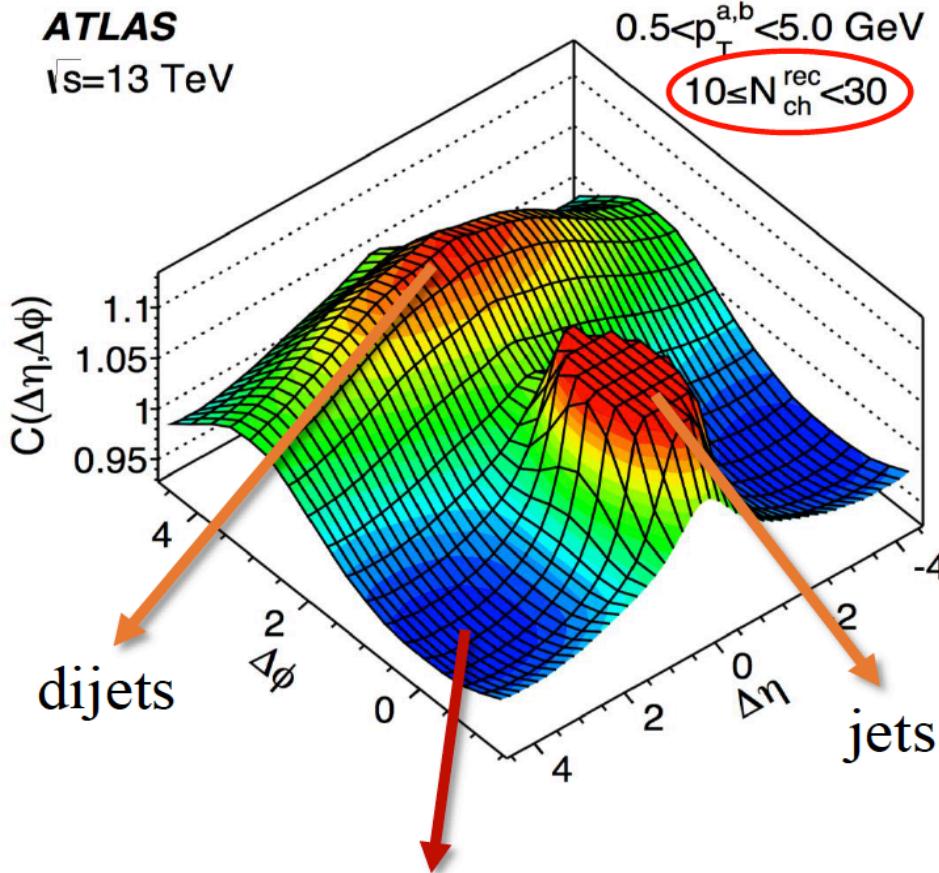


Include Pedestal

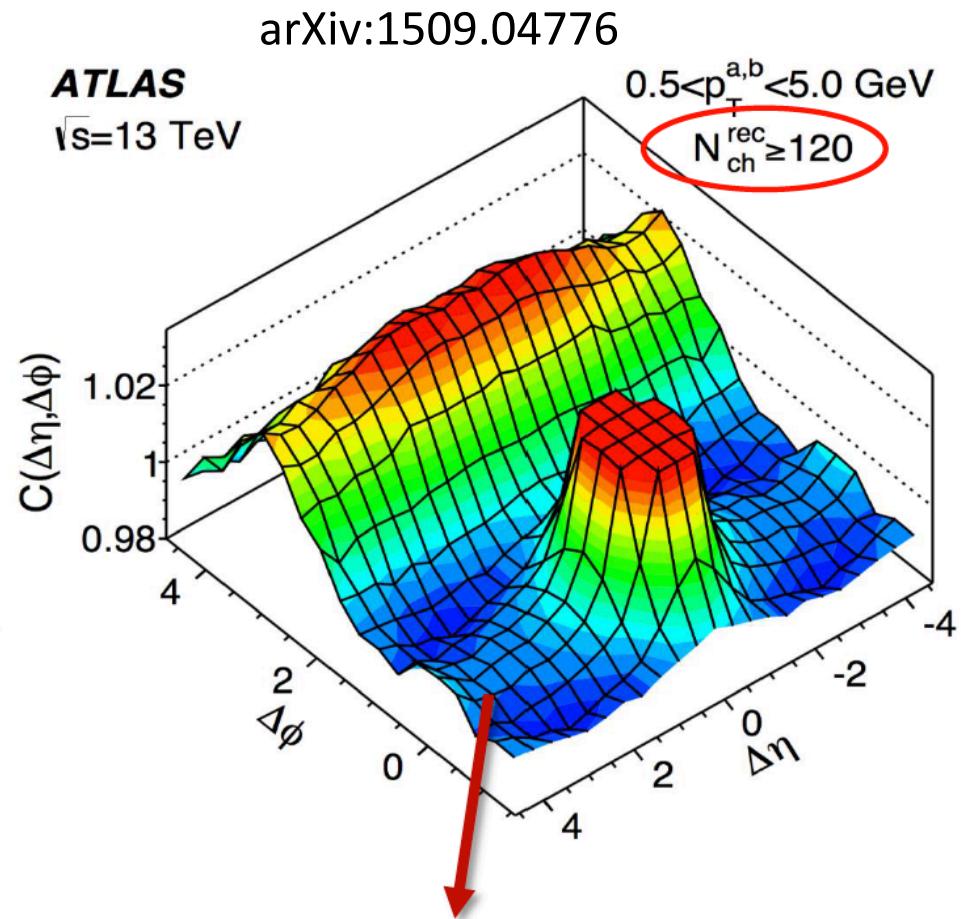




pp Long-range correlations



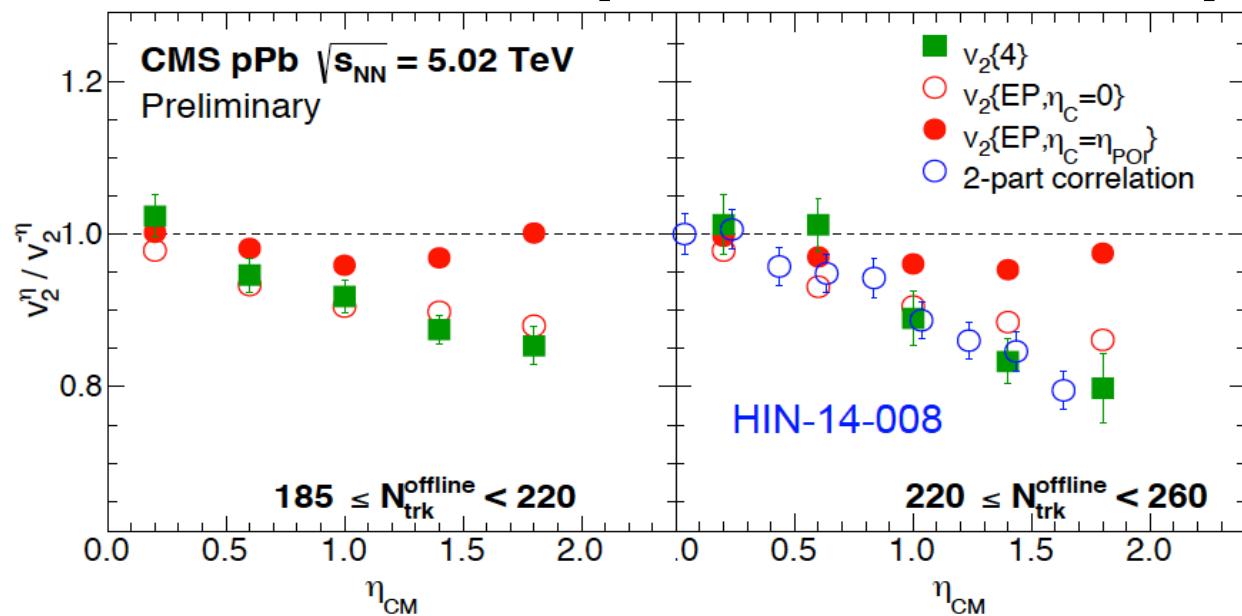
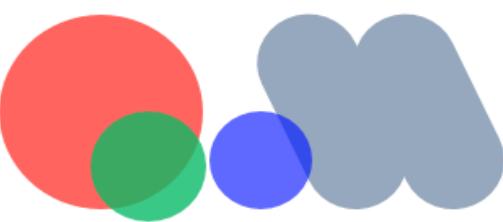
Long-range correlation shape is concave-up on near-side: no ridge.



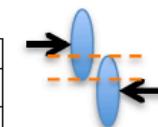
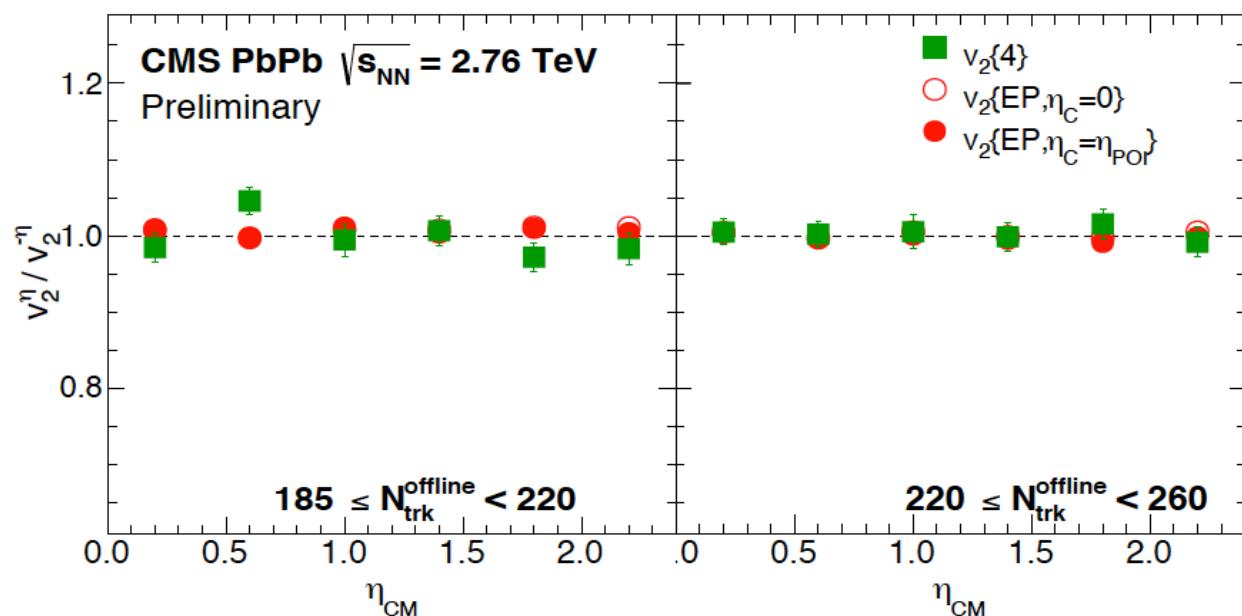
Long-range structure becomes flat: ridge develops.

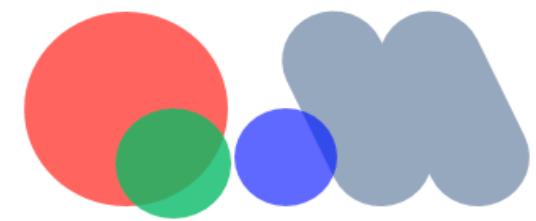
Experimental overview on small colliding systems at LHC

Higher order cumulants in $p+Pb : \eta$ dependence



- $v_2\{4\}$, $v_2\{\text{EP}, \eta_C=0\}$, $v_2\{\text{2-part}\}$ consistent
- Accounting decorrelation reduces asymmetry





Spectra in shape selected events

- ✧ Clear modification of spectra seen when selecting on shape
- ✧ More elliptic geometry => Harder spectra! => More radial flow

