Probing p_{T}-dependent flow vector fluctuations

Zimanyi School 2020 - Review

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THE VELUX FOUNDATIONS
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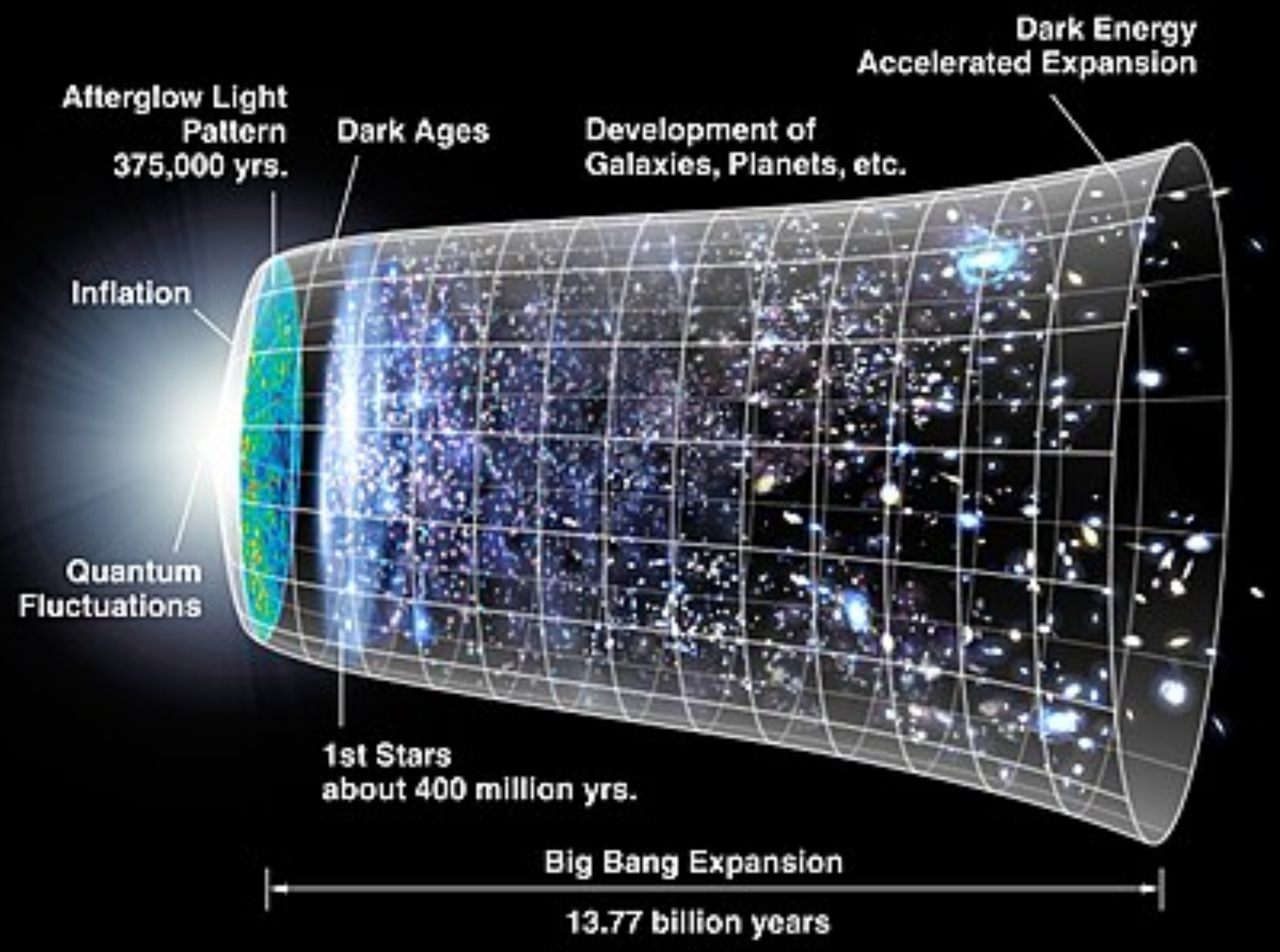
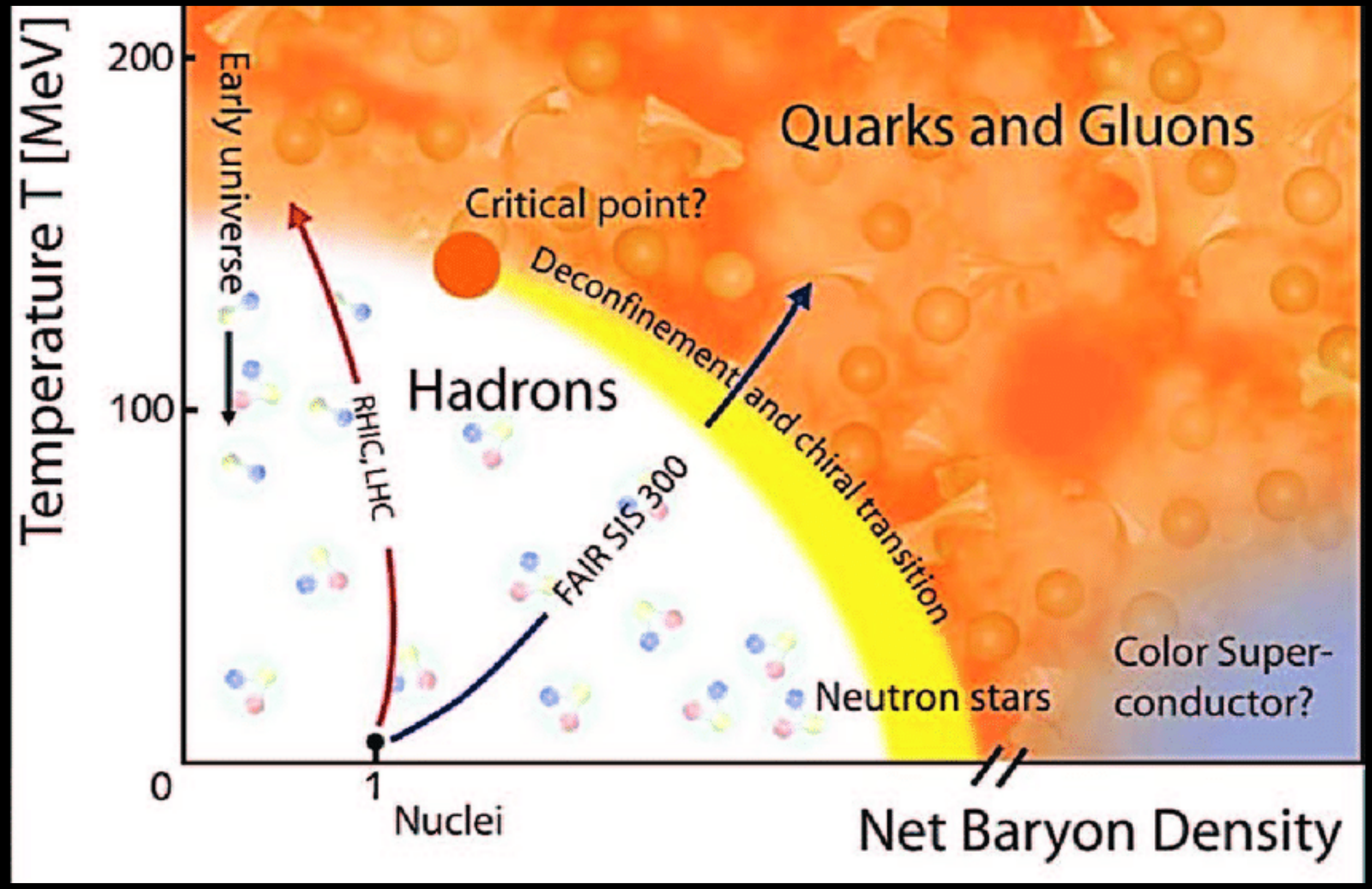
Quark-Gluon Plasma

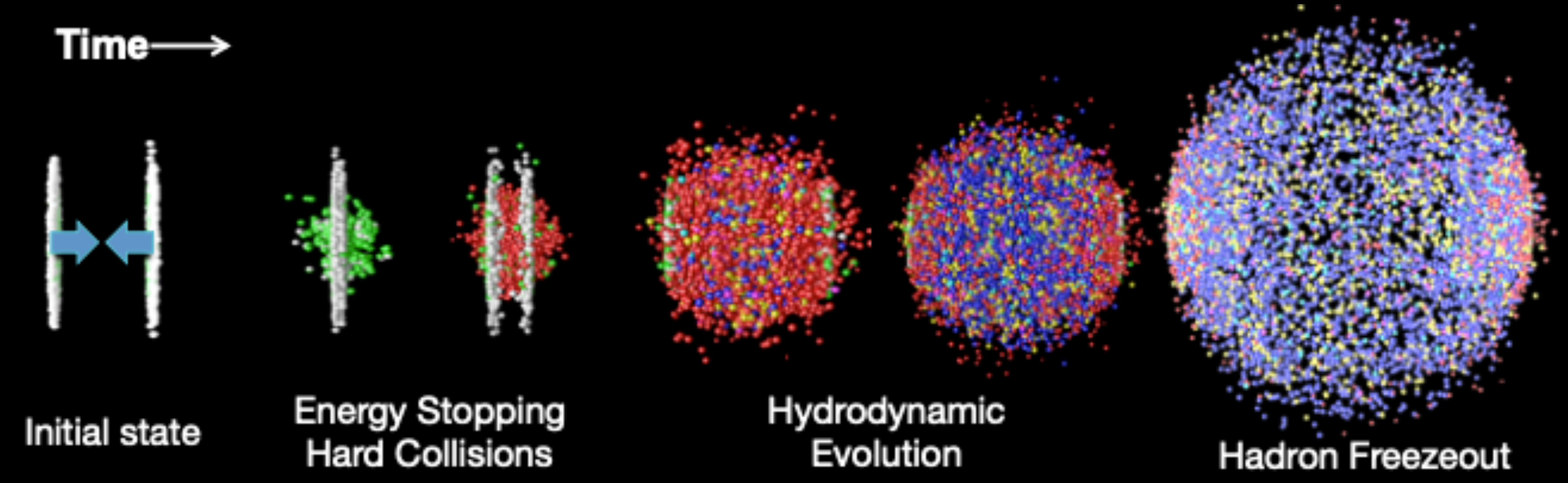
- Early universe dominated by hot, dense matter
- Deconfined state of quarks and gluons → Quark-gluon plasma (QGP)
- QGP is recreated in experiments with heavy-ion collisions (“little bangs”)
- Experiments at the LHC probe high-temperature/low baryon chemical potential region

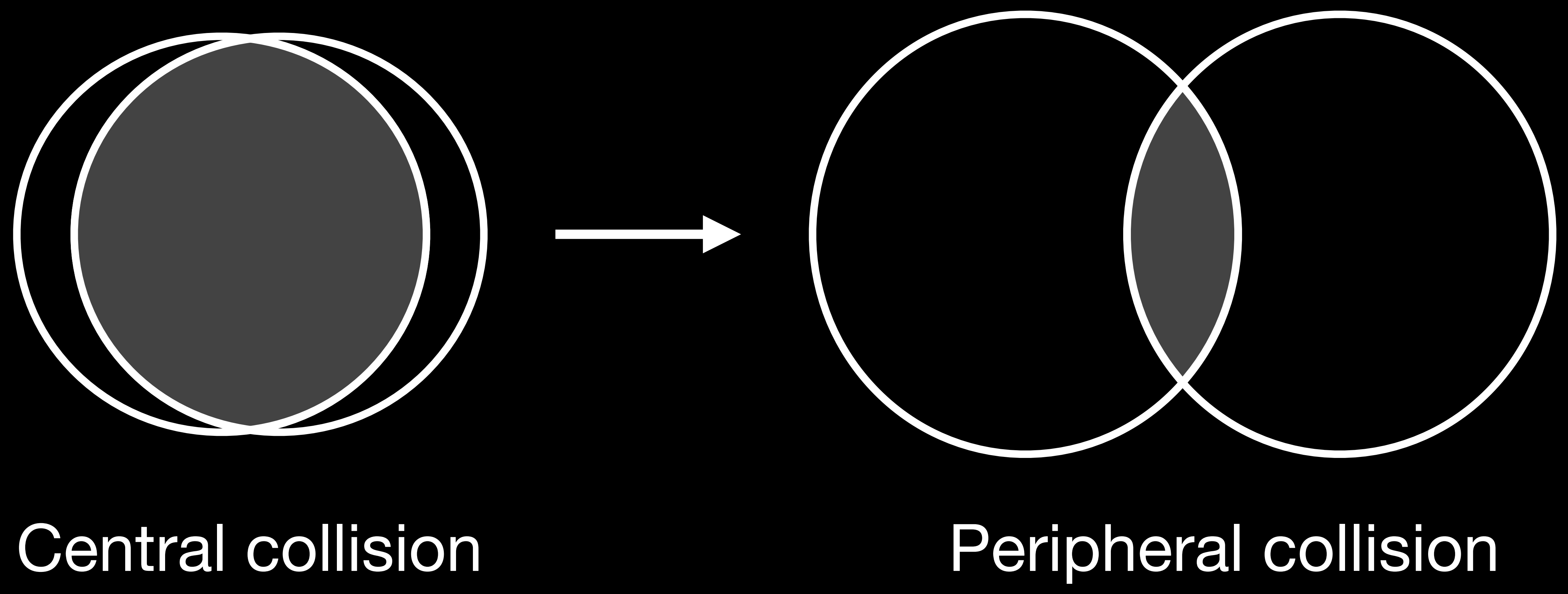




Heavy-ion collisions

- After thermalization time $\tau \sim 1$ fm/c → System described by hydrodynamics
- Experiments seek to determine initial conditions (IC) and the QGP properties
    - Shear viscosity η/s and bulk viscosity ζ/s
- Hydrodynamic models can constrain IC and η/s, ζ/s
- Strong interactions transfer initial geometric anisotropy into final state momentum-space azimuthal anisotropy
    - Anisotropic flow, an observable sensitive to IC, η/s, ζ/s





Anisotropic flow

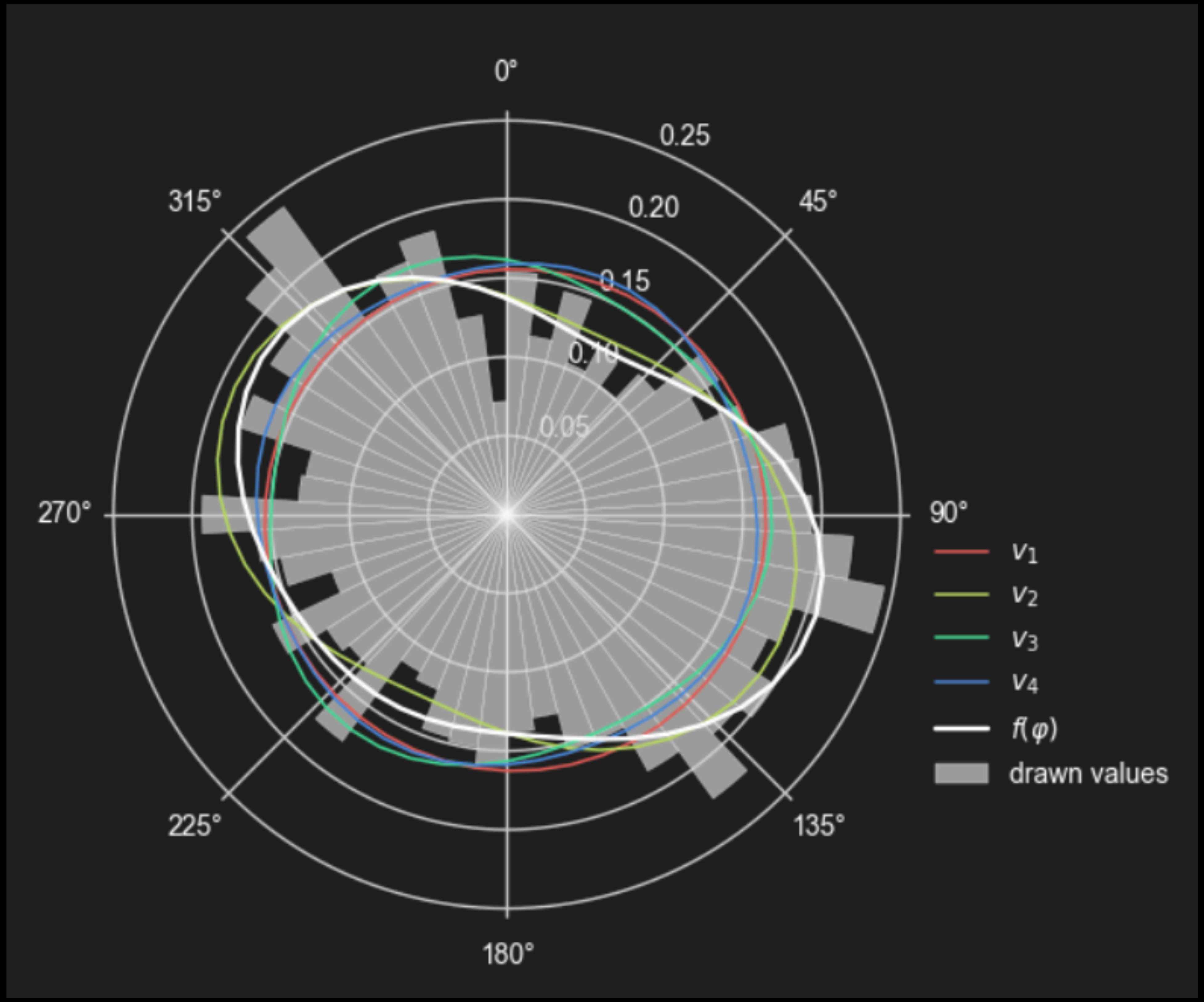
- Fourier expansion of azimuthal distribution of emitted particles:

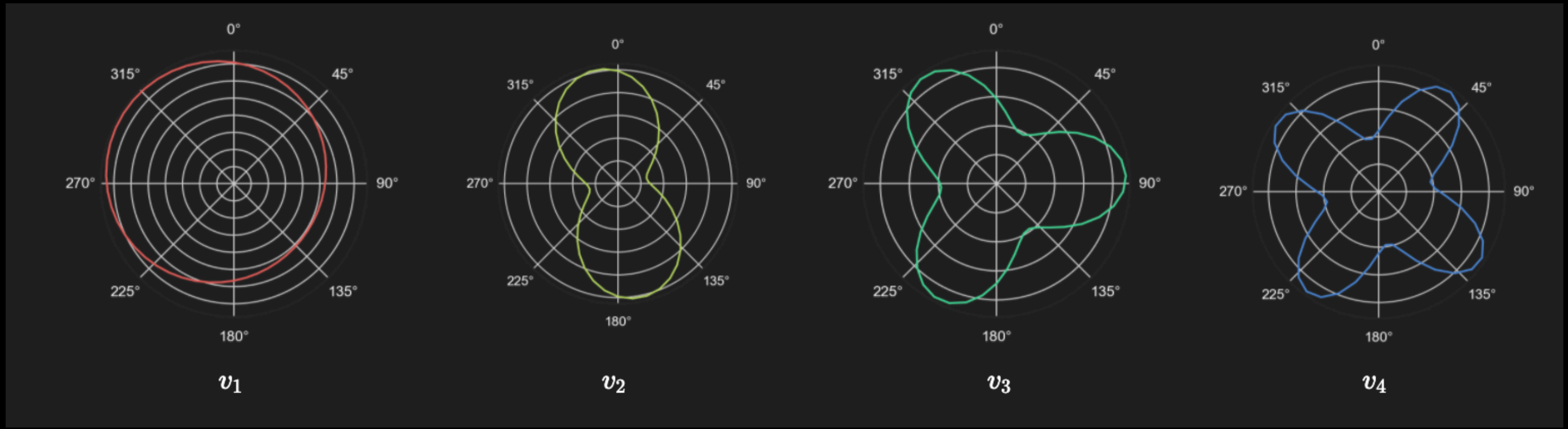
$$\frac{dN}{d\varphi} \propto f(\varphi) = \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} V_n e^{in\varphi}\right]$$

- Complex flow vector $V_n = v_n e^{in\Psi_n}$
- with magnitude:

$$v_n = \langle \cos n[\varphi - \Psi_n] \rangle$$

- and flow angle Ψ_n



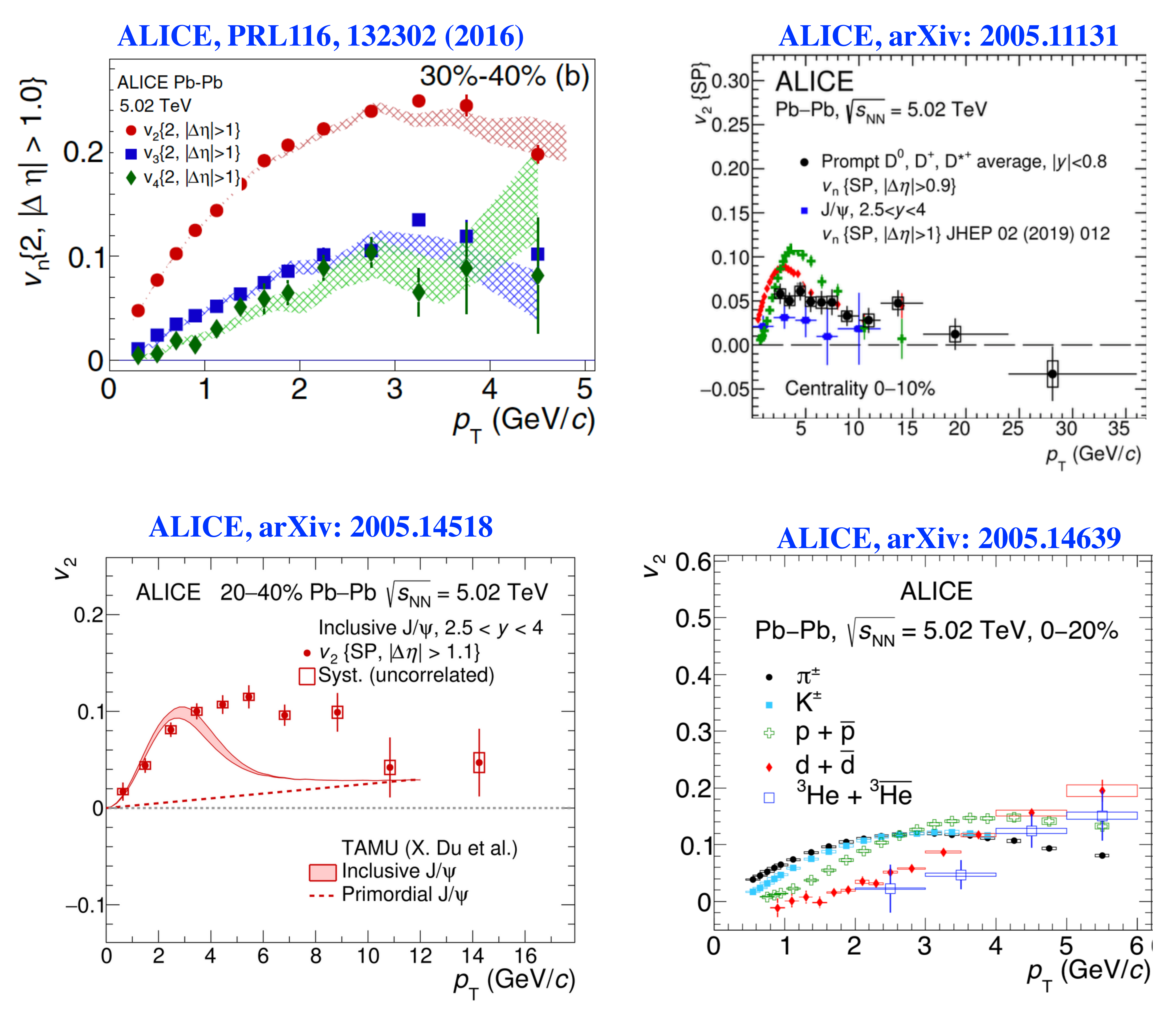


Flow measurements

- Measurements of flow coefficients v_n
  - Typically measured with two-particle correlations with cumulant / scalar-product method

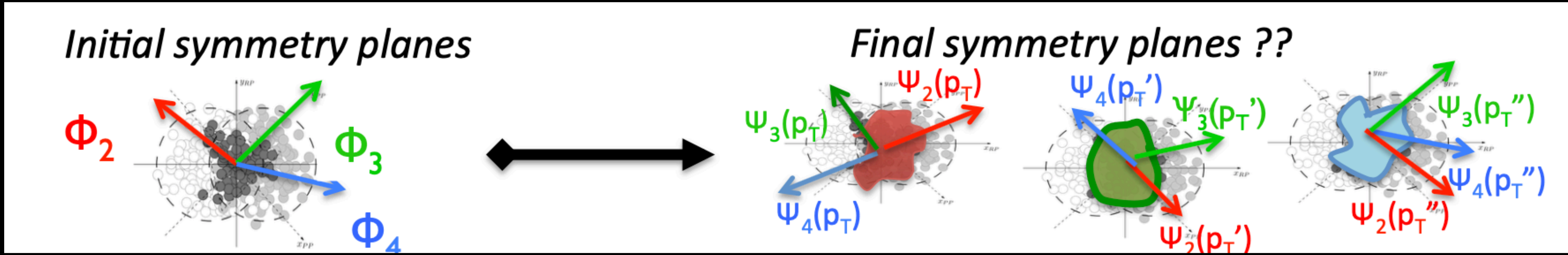
$$v_n(p_\mathrm{T}) = \frac{\langle\langle \cos n[\varphi_1(p_\mathrm{T}) - \varphi_2^{Ref}]\rangle\rangle}{\sqrt{\langle\langle \cos n[\varphi_1^{Ref} - \varphi_2^{Ref}]\rangle\rangle}}$$

- The flow measurements provide tight constraints on the initial conditions and also the QGP properties
- However, the nature of fluctuations determines that the reality might not be as simple as what the above equation shows :(



Revisit of standard two-particle correlations

- Measurements of flow coefficients v_n
  - Typically measured as $v_n\{2\} = \dfrac{\langle v_n(p_{\mathrm{T}})\ v_n \cos n[\Psi_n(p_{\mathrm{T}}) - \Psi_n]\rangle}{\sqrt{\langle v_n^2\rangle}}$
  - What is actually measured?
- Hydrodynamic model predicted additional flow angle and magnitude fluctuations!
- If these effects are present in data, but not in models → Apples to pears comparison
- Quantifying additional fluctuations necessary for correctly estimating QGP properties



p_{T}-dependent flow vector fluctuations

- Anisotropy of azimuthal distribution

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} V_n e^{in\varphi}$$

May fluctuate with p_{T} in both angle and magnitude

- Flow vector $V_n = v_n e^{in\Psi_n}$

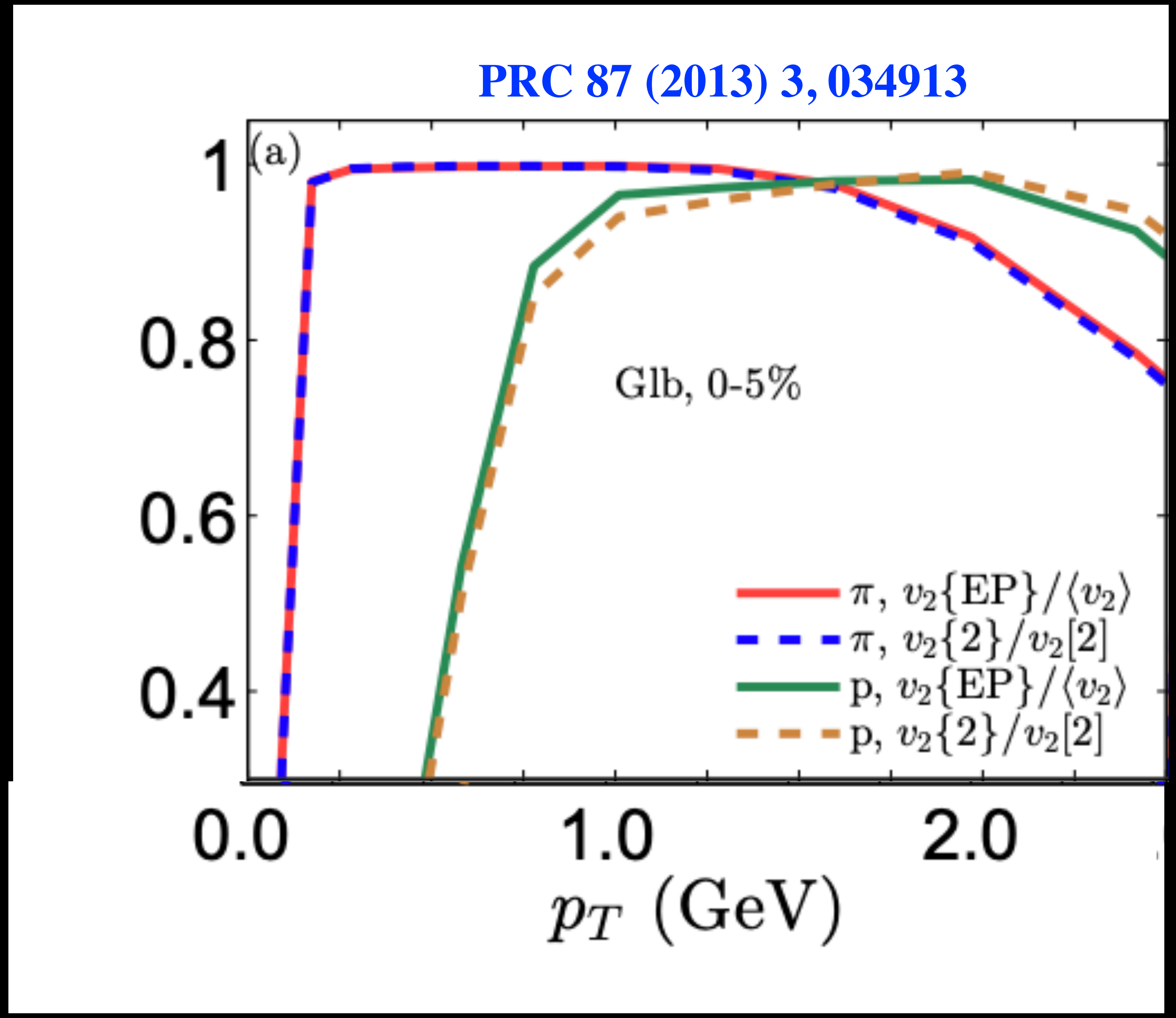
- How to measure these fluctuations?

$$\frac{v_n\{2\}}{v_n[2]} = \frac{\langle v_n(p_{\mathrm{T}}^a)\, v_n \cos n[\Psi_n(p_{\mathrm{T}}^a) - \Psi_n]\rangle}{\sqrt{\langle v_n(p_{\mathrm{T}}^a)^2\rangle}\sqrt{\langle v_n^2\rangle}}$$

Flow angle fluctuations

Flow magnitude fluctuations

- If $v_2\{2\}/v_2[2] < 1$, it indicates presence of flow vector fluctuations



p_T-dependent flow vector fluctuations

- Flow vector fluctuations include both flow angle and flow magnitude fluctuations

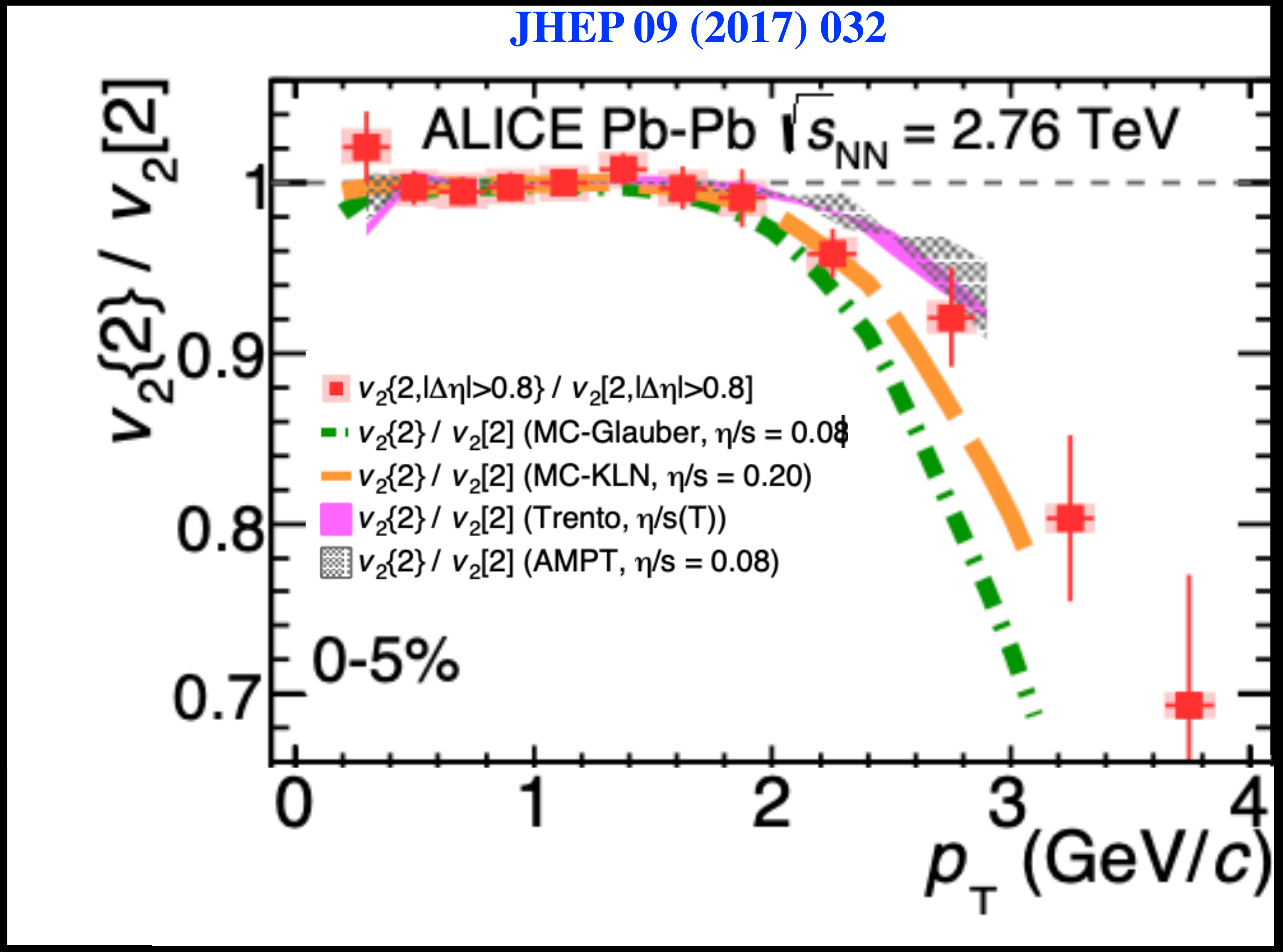
$$\frac{v_n\{2\}}{v_n[2]} = \frac{\langle v_n(p_T^a)\, v_n \cos n[\Psi_n(p_T^a) - \Psi_n]\rangle}{\sqrt{\langle v_n(p_T^a)^2\rangle}\sqrt{\langle v_n^2\rangle}}$$

Flow angle fluctuations

$$\langle \cos n[\Psi_n(p_T^a) - \Psi_n]\rangle < 1$$

Flow magnitude fluctuations

$$\langle v_n(p_T^a)\, v_n\rangle < \sqrt{\langle v_n(p_T^a)^2\rangle}\sqrt{\langle v_n^2\rangle}$$



- $v_2\{2\}/v_2[2] < 1$ was observed in Pb-Pb collisions at $\sqrt{S_{NN}} = 2.76$ TeV in ALICE, it indicated presence of flow vector fluctuations

Factorisation ratio

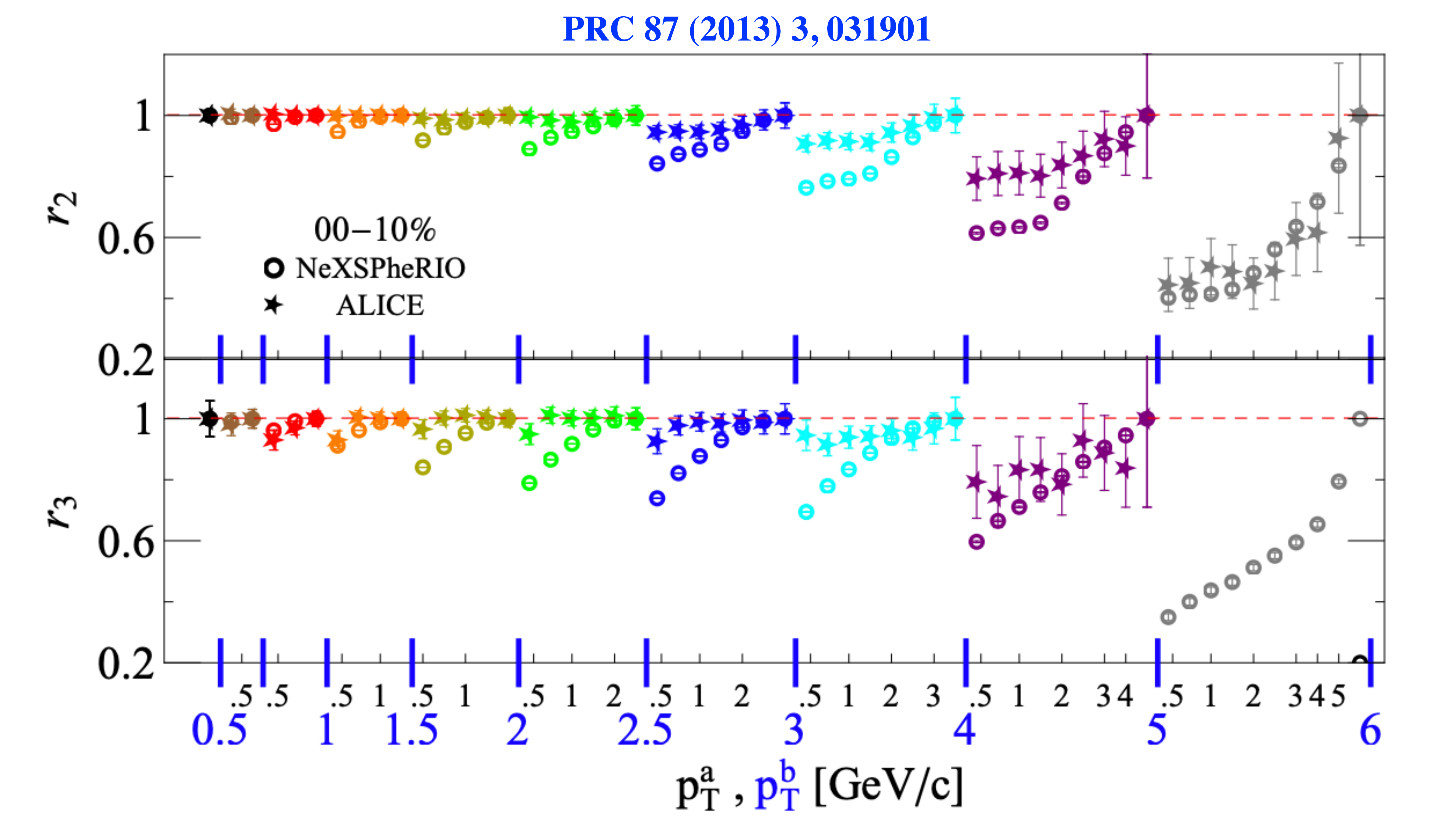
- Another probe of the decorrelation of the flow vector

$$r_n = \frac{\langle v_n(p_T^a) v_n(p_T^b) \cos n[\Psi_n(p_T^a) - \Psi_n(p_T^b)] \rangle}{\sqrt{\langle v_n(p_T^a)^2 \rangle \langle v_n(p_T^b)^2 \rangle}}$$

- Provides detailed information on the structure of the correlation at different transverse momenta
- When $r_n < 1$, factorisation is broken
- Even present in ideal hydrodynamic system

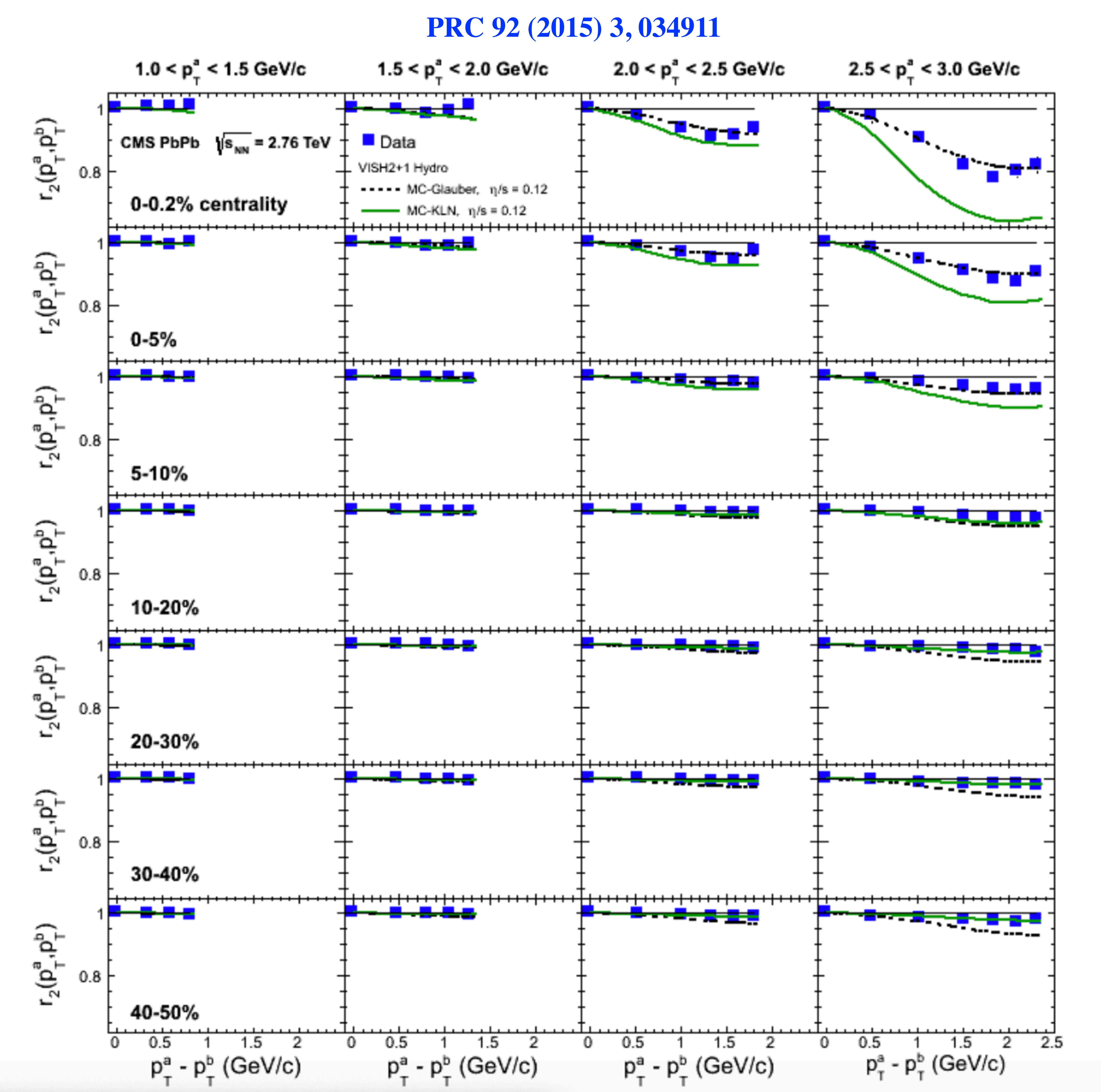
Factorization:

$$V_{n\Delta}(p_T^a, p_T^b) \stackrel{?}{=} v_n(p_T^a) \times v_n(p_T^b)$$



Factorisation ratio

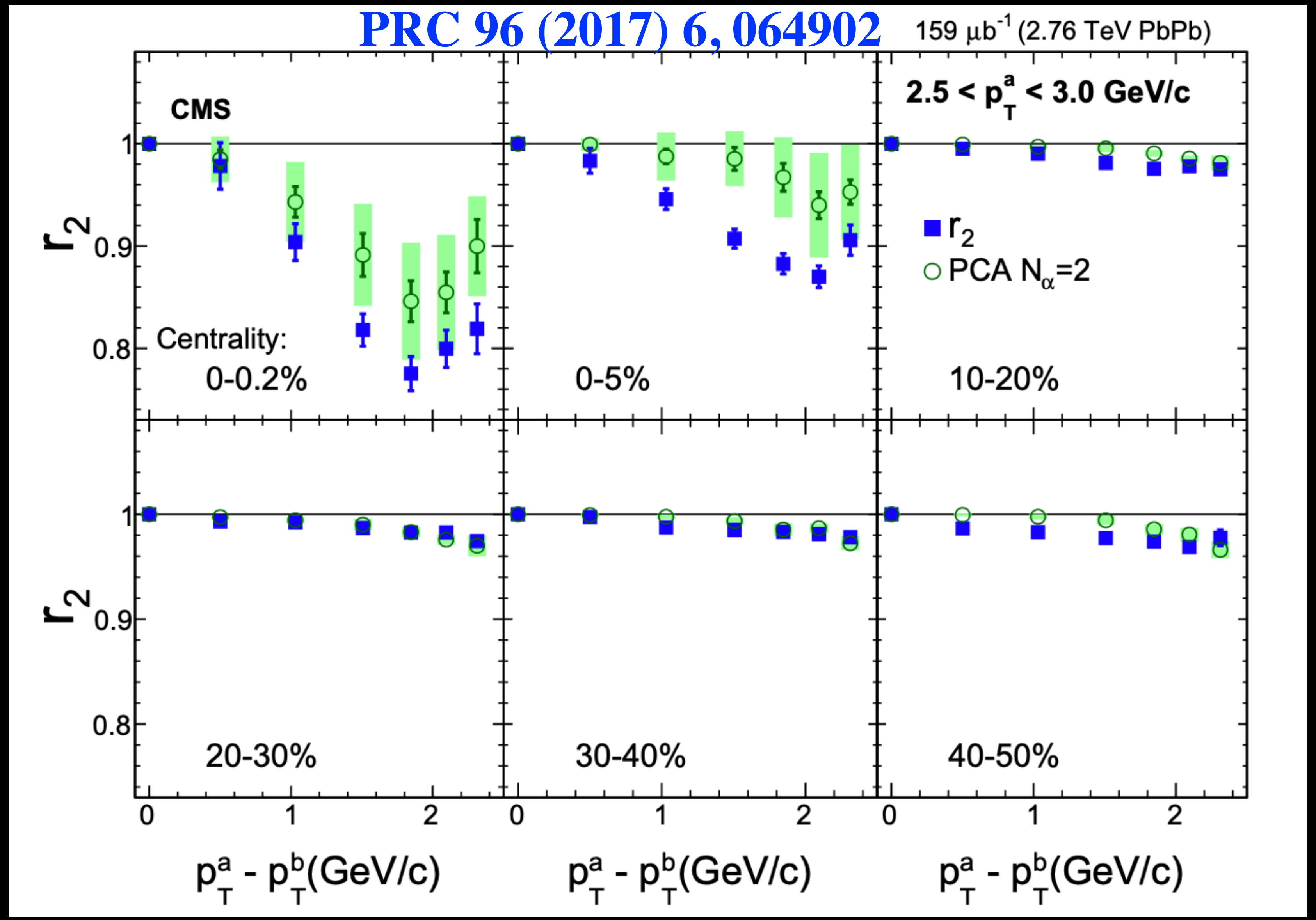
- $r_2 < 1$ observed in Pb-Pb collisions at $\sqrt{S_{\rm NN}} = 2.76$ in CMS
- Indicates the presence of $p_{\rm T}$-dependent flow vector fluctuations
- Deviation from unity increases with the difference $|p_{\rm T}^a - p_{\rm T}^b|$
- If $p_{\rm T}^b$ is taken from a wider kinematic range $r_n = v_n\{2\}/v_n[2]$



p_{T}-dependent flow vector fluctuations

- Many methods to describe flow vector fluctuations

- Principal component analysis (PCA) can describe fluctuations with leading and subleading flow modes



However:

- Not clear if due to fluctuations of flow angle or flow magnitude or both effects

- ***<u>How can we disentangle the two contributions and quantify each of them?</u>***

Flow angle and magnitude fluctuations?

- How can we separate the two effects?
    - Ongoing analysis, will come soon
- Crucial to examine theoretical models and properly extract QGP properties

Flow vector fluctuations

$$\frac{v_n\{2\}}{v_n[2]} = \frac{\langle v_n(p_T^a)\ v_n \cos n[\Psi_n(p_T^a) - \Psi_n]\rangle}{\sqrt{\langle v_n(p_T^a)^2\rangle}\sqrt{\langle v_n^2\rangle}}$$

$$\langle \cos n[\Psi_2(p_T^a) - \Psi_2]\rangle$$

Flow angle fluctuations

$$\frac{\langle v_n(p_T^a)\ v_n\rangle}{\sqrt{\langle v_n^2(p_T^a)\rangle}\sqrt{\langle v_n^2\rangle}}$$

Flow magnitude fluctuations

Summary

- Flow vector fluctuations observed in central collisions in both hydrodynamic calculations and data
- Comparison between data and models gives new understanding of initial conditions and QGP properties
- Question remains whether these effects are due to flow angle fluctuations or flow magnitude fluctuations, or both?
- Answering this question will help improve theoretical models and allow us to more correctly estimate QGP properties