Flow fluctuations in small systems

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Workshop on
Foundational aspects of relativistic hydrodynamics
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Outline

- What do we mean by collectivity ?
- Specificities of small systems
- A few recent predictions

Giacalone, Noronha-Hostler, JYO 1702.01730

Particle emission in hydrodynamics

- Particles emitted independently (no correlations) on the freeze-out surface
- The anisotropy of the single-particle momentum distribution (v_n) is driven by the initial density profile.
- There is certainly more, but we can use these two properties as a first definition of *collectivity*.

Property #1: The flow paradigm

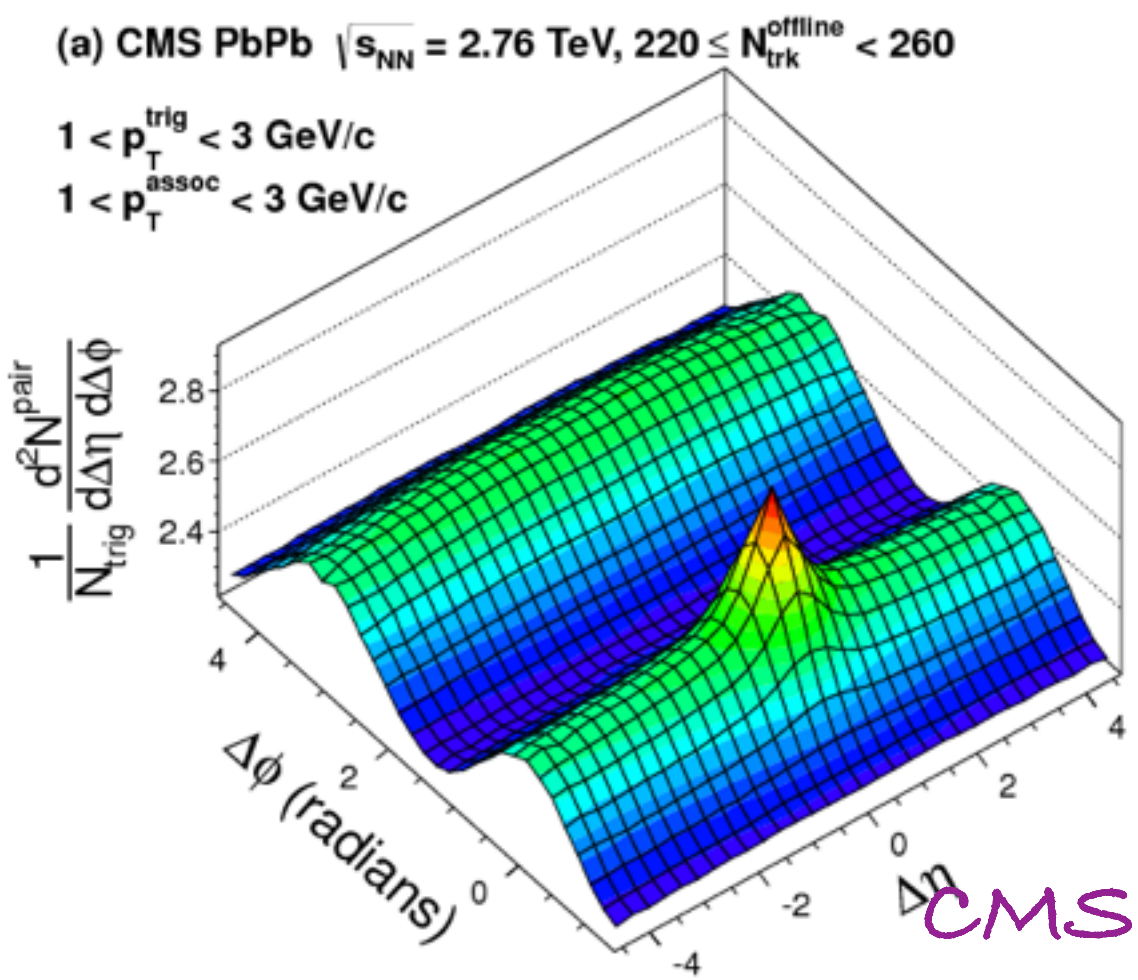
- Particles are emitted independently in every event with momentum distribution f(p)
- f(p) fluctuates event to event
  - azimuthal angle of impact parameter fluctuates
  - more generally: fluctuations in density profile, hot spots..
- Averaging over events generates non-trivial correlations to all orders, e.g., the pair distribution is $\langle f(p_1)\, f(p_2) \rangle$

Alver & Roland 1003.0194

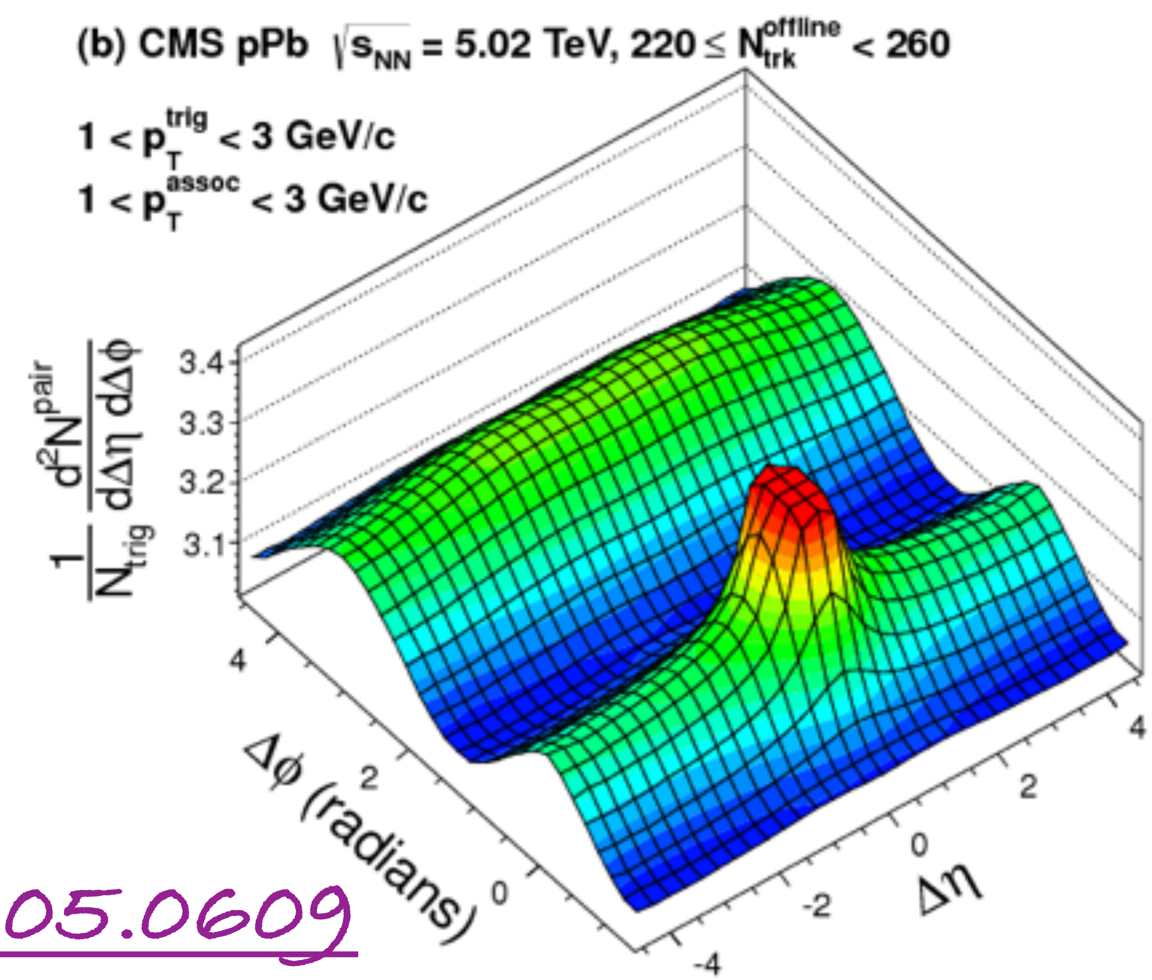
Flow paradigm naturally explains the ridge

- At the expense of an additional symmetry assumption: f(p) is essentially independent of rapidity in every event

Pb+Pb



p+Pb



CMS 1305.0609

Hydro versus CGC

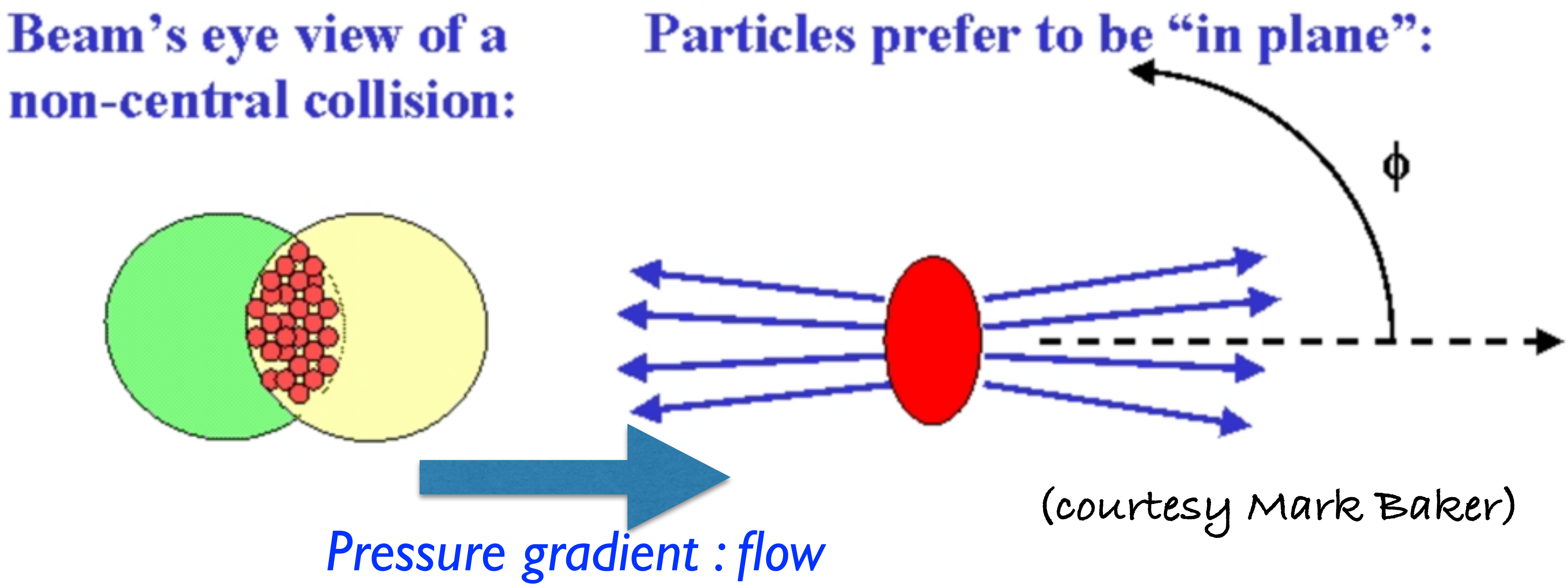
- Note that some alternatives to hydro referred to as CGC strictly comply with this *flow paradigm*.

Dusling Mace Venugopalan 1705.00745

$$\frac{d^m N}{d^2\mathbf{p_{i\perp}}\cdots d^2\mathbf{p_{m\perp}}} = \prod_{i=1}^{m}\int d^2\mathbf{b_i}\int\frac{d^2\mathbf{k_i}}{(2\pi)^2}W_q(\mathbf{b_i},\mathbf{k_{i\perp}})$$

$$\cdot\int d^2\mathbf{r_i}e^{i(\mathbf{p_{i\perp}}-\mathbf{k_{i\perp}})\cdot\mathbf{r_i}}\left\langle\prod_{j=1}^{m}D\left(\mathbf{b_j}+\frac{\mathbf{r_j}}{2},\mathbf{b_j}-\frac{\mathbf{r_j}}{2}\right)\right\rangle. \quad (1)$$

Property #2: Initial spatial anisotropy as the seed of anisotropic flow



An elliptic density profile produces elliptic flow
A triangular density profile produces triangular flow…

Specificities of small systems

- *Nonflow* correlations, breaking the flow paradigm, are larger.
- Initial anisotropies are solely produced by fluctuations (in p+p and p+Pb) and these fluctuations are larger in small systems.

Nonflow

- Particles sometimes come in clusters (jets, resonance decays).
- The probability that two arbitrary particles come from the same cluster scales like 1/(# of clusters).
- Hence, nonflow contribution to a 2-particle correlation typically scales like $1/N_{ch}$ and is larger for small systems.
- Nonflow both present at short $\Delta\eta$ (short range) and large $\Delta\eta$ (away-side)

Methods to suppress nonflow

- Rapidity gap: eliminates short-range nonflow. Usually implemented in 2-particle correlations $v_n\{2\}$

PHENIX nucl-ex/0305013

- Cumulants: higher-order correlations: $v_n\{4\}$, $v_n\{6\}$.

Borghini et al nucl-th/0007063 nucl-th/0105040

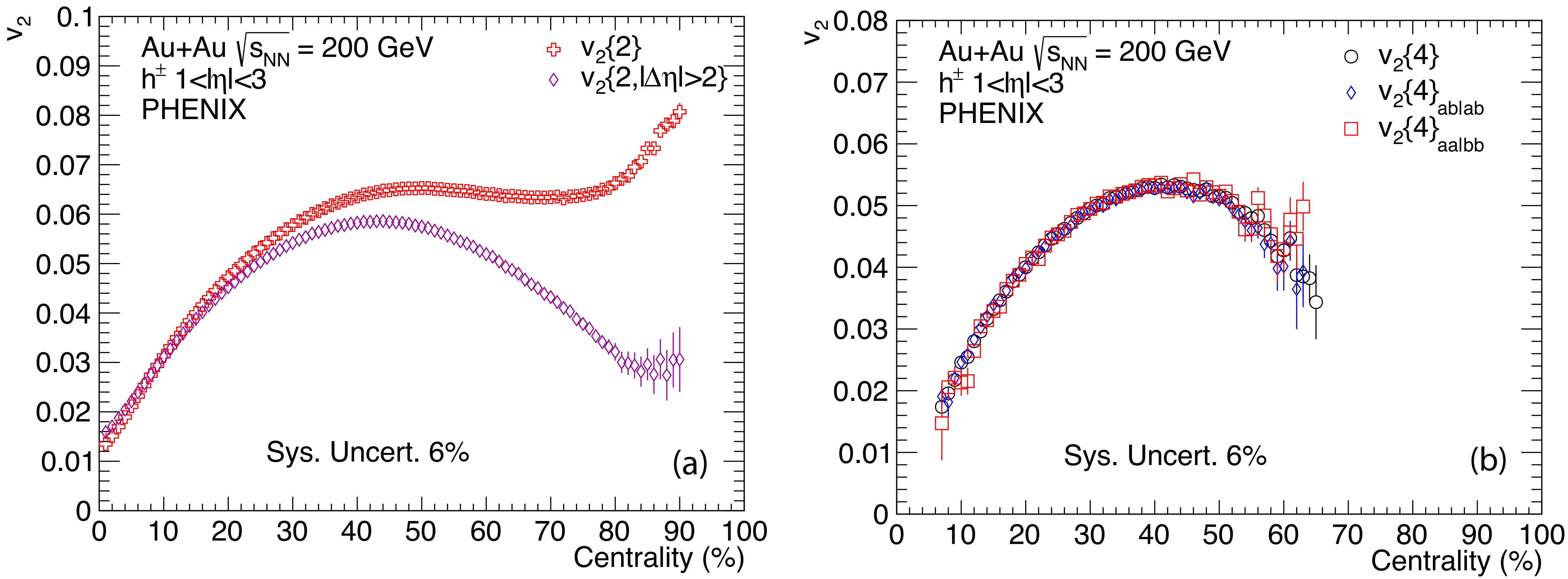
Bilandzic et al 1010.0233

- Note that flow depends on rapidity and comparing $v_n\{2\}$ with gap and $v_n\{4\}$ without gap is not apples-to-apples.

Recent progress: cumulants with gaps

Jia Zhou Trzupek 1701.03830

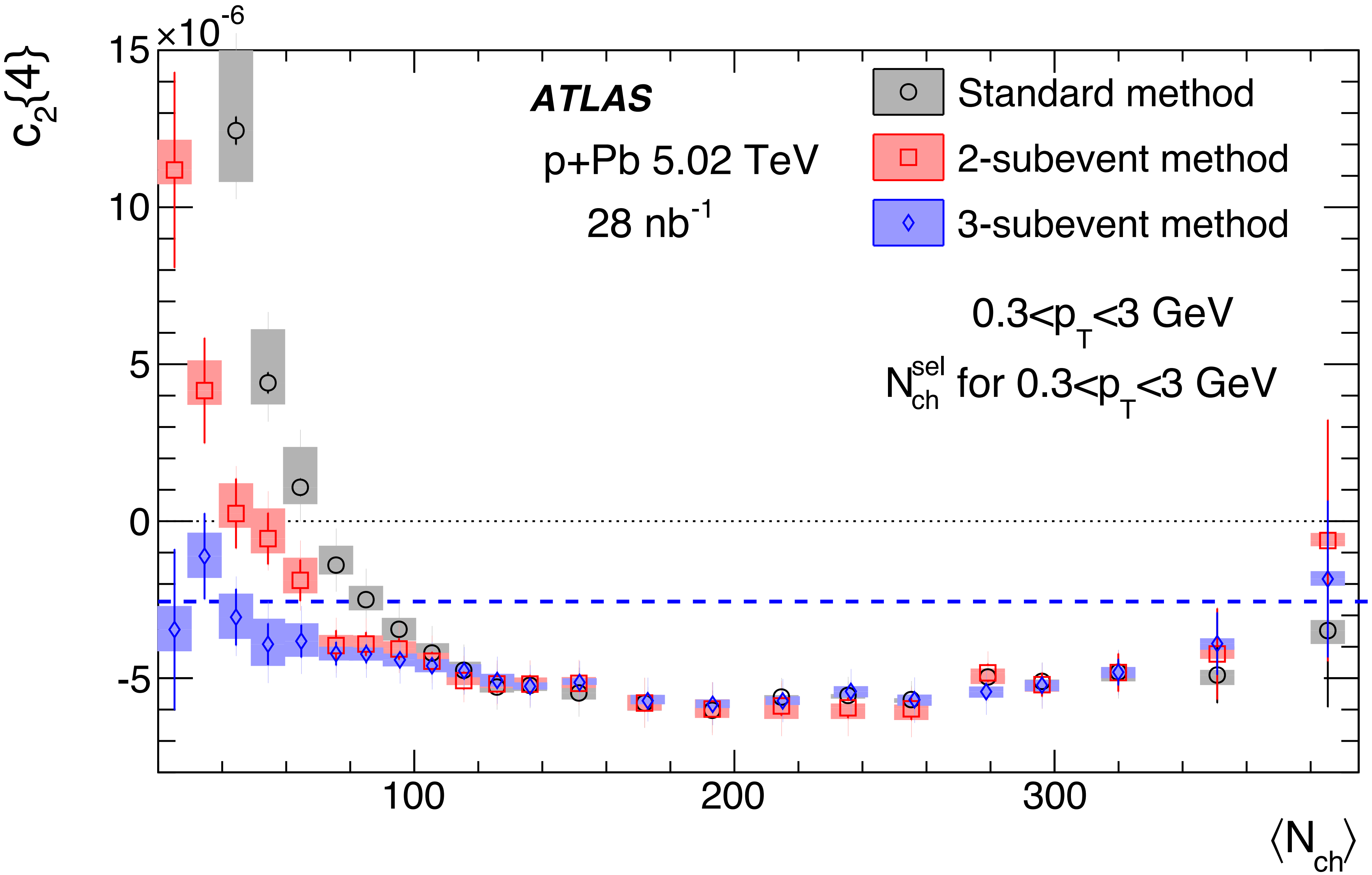
Di Francesco et al 1612.05634



PHENIX 1804.10024

In Au+Au, rapidity gaps matter for $v_2\{2\}$, not $v_2\{4\}$.

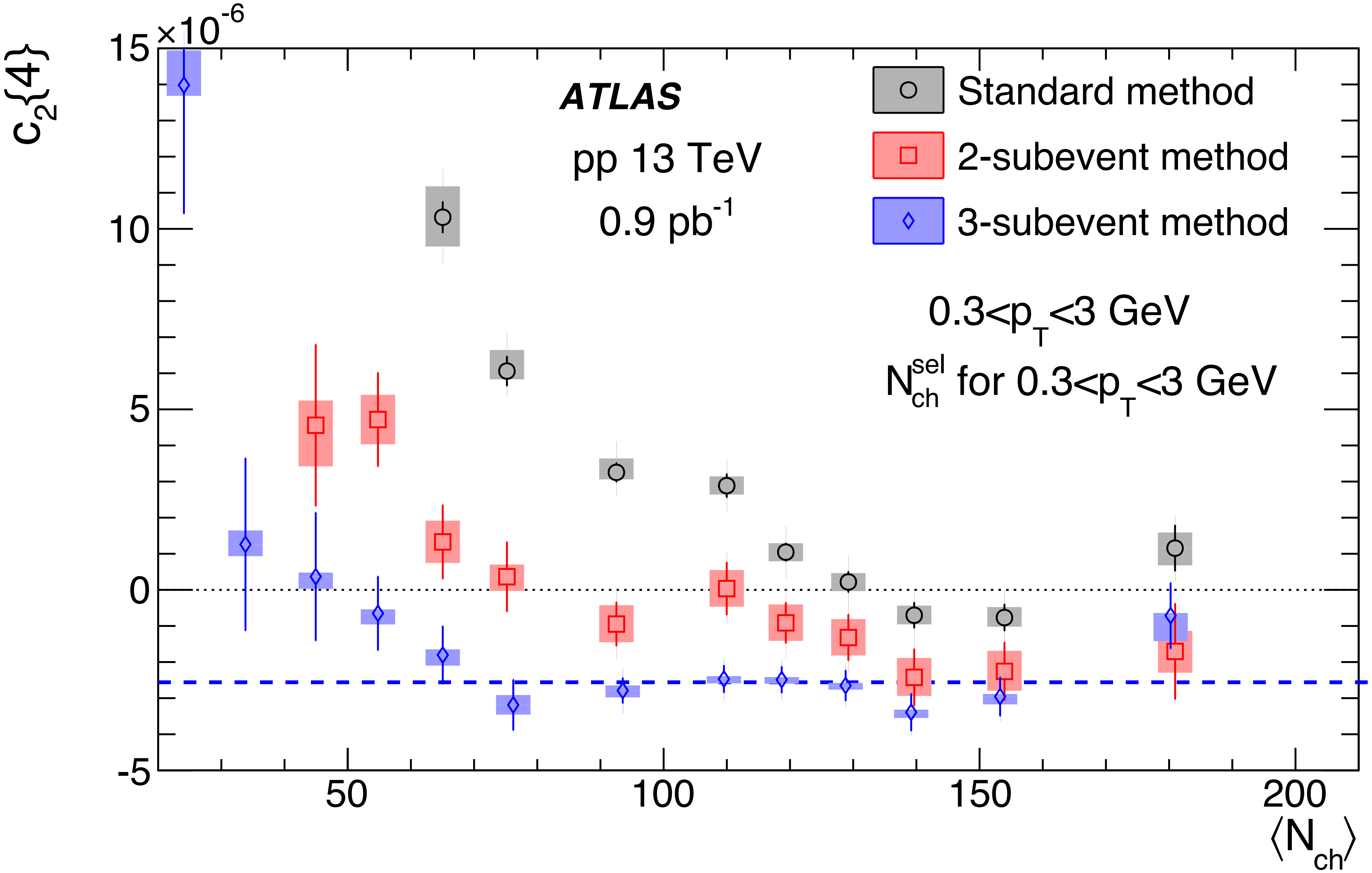
Recent progress: cumulants with gaps



ATLAS 1708.03559

In p+Pb, $v_2\{4\}$ depends somewhat on the gap

Recent progress: cumulants with gaps



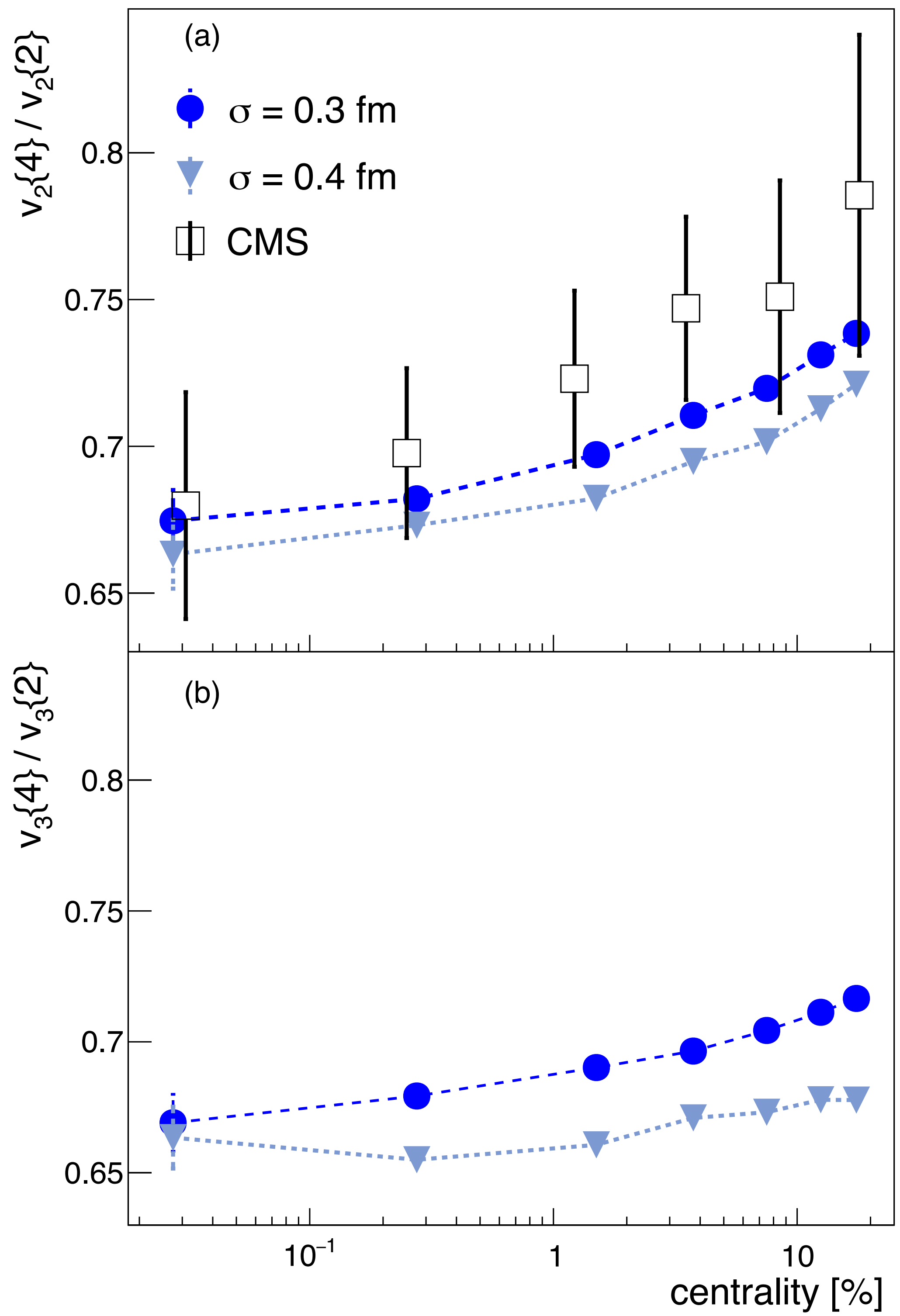
ATLAS 1708.03559

In p+p, a gap changes everything

Anisotropy fluctuations

- Small fluctuations are often Gaussian (central limit theorem).
- This also applies to ε_n fluctuations
  Voloshin, Poskanzer, Aihong Tang, Gang Wang 0708.0800
- =Transverse, 2-dimensional Gaussian fluctuations usually dubbed *Bessel-Gaussian*
- Such fluctuations imply $v_n\{4\}=v_n\{6\}=\ldots=0$ in small systems (no mean v_2 in reaction plane)
- Small systems have large fluctuations, and this results in non-Gaussianities.

Non-Gaussianities in p+Pb



Giacalone et al [1702.01730]

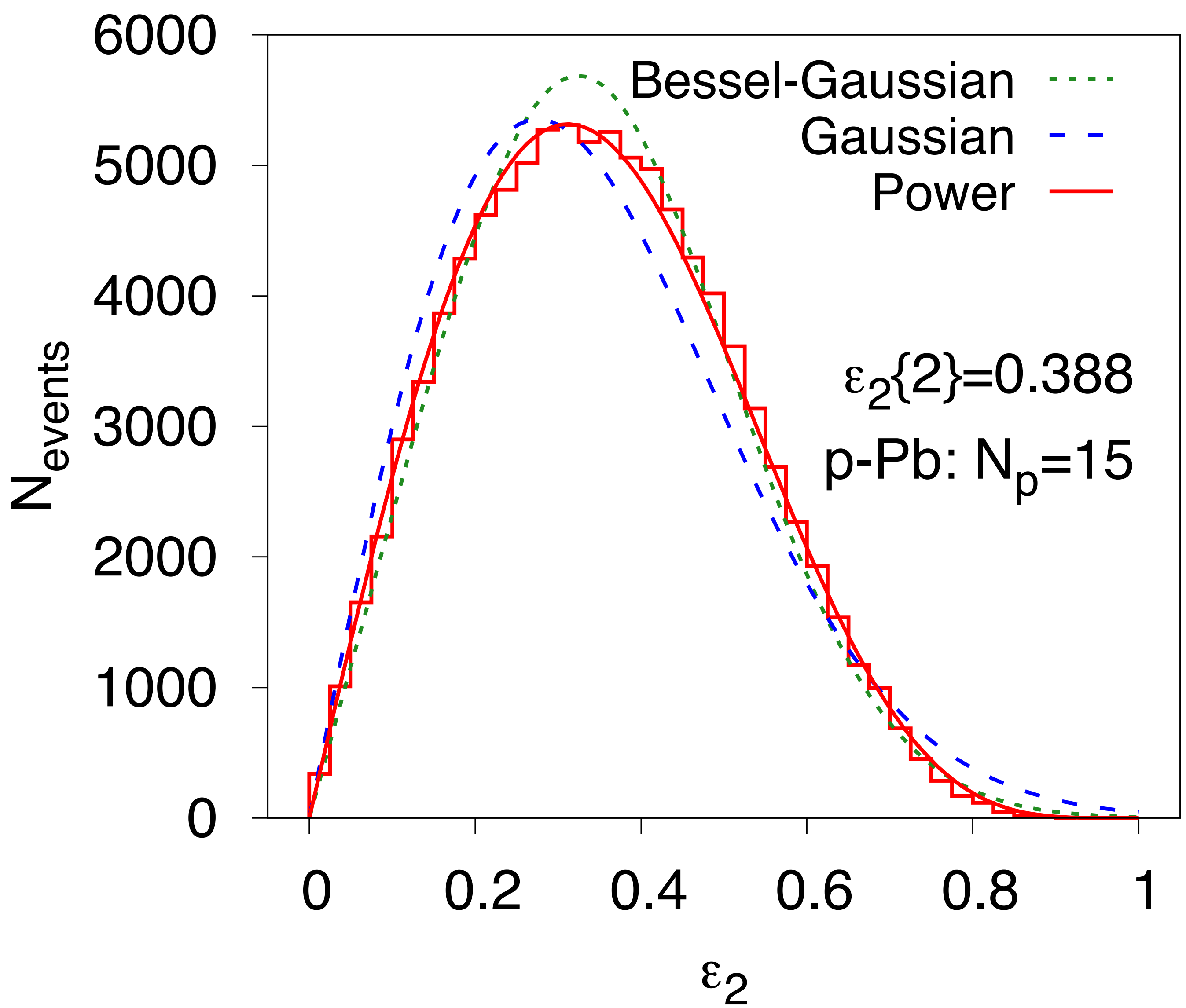
Monte Carlo simulations based on the Trento model of initial conditions (essentially a Monte Carlo Glauber)

Moreland Bernhard Bass [1412.4708]

No hydro here: We assume that v_n is proportional to ε_n in every event.

A generic prediction is that non Gaussianities increase as a function of centrality %: smaller systems are less Gaussian. Seen by CMS.

Anisotropy fluctuations



Li Yan JYO 1312.6555

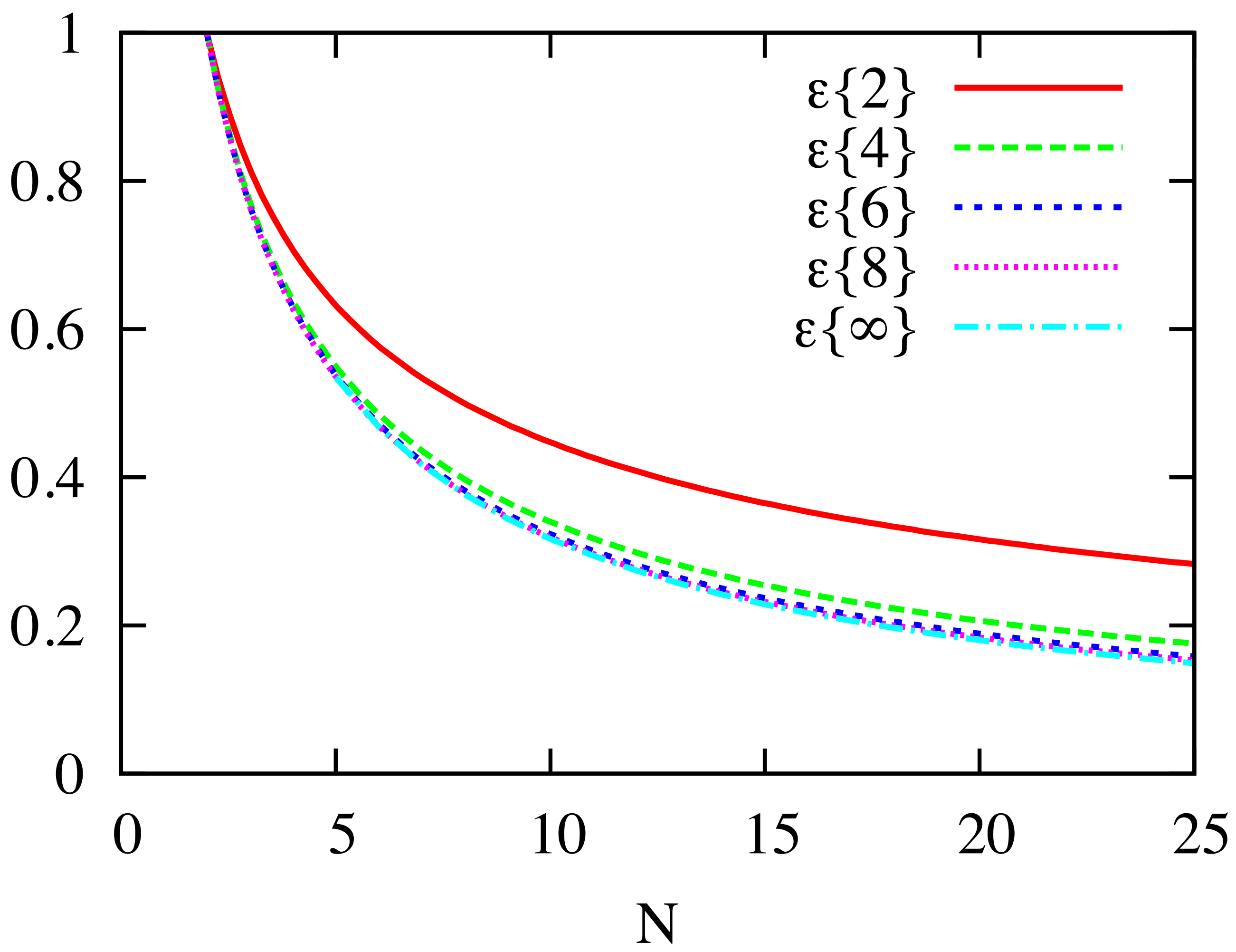
New *Power* Parametrization of the distribution of ε_n in the form

$$P(\varepsilon_n)=\varepsilon_n(1-\varepsilon_n^2)^{\alpha}$$

Takes into account the bound $\varepsilon_n < 1$

A single parameter α fixes the width.

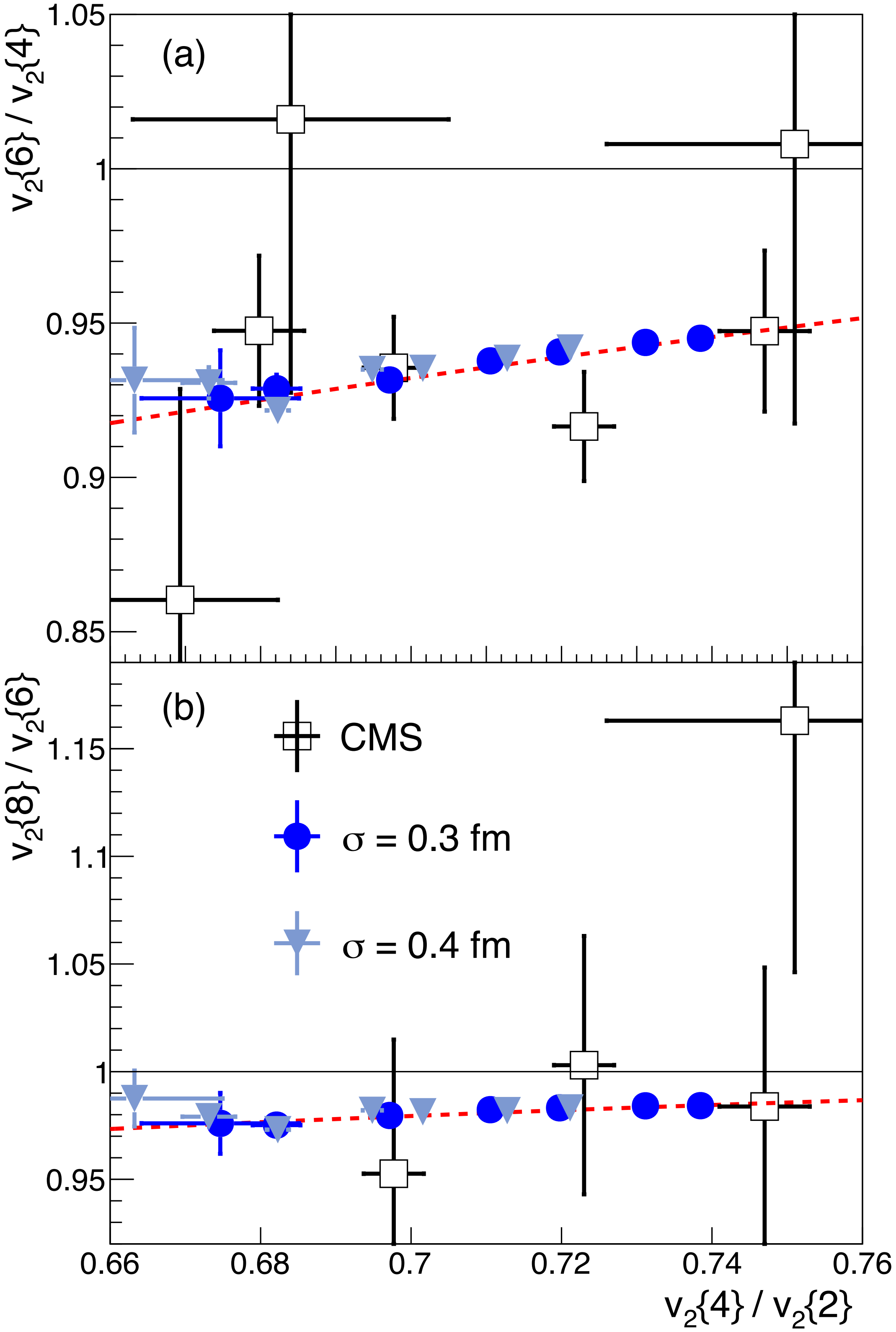
Higher-order Cumulants



(number of pointlike sources)

- The Power distribution predicts a near degeneracy of higher-order cumulants in small systems, even though anisotropy is solely due to fluctuations
- Once v{4}/v{2} is known, the small lifting of degeneracy between higher-order cumulants is precisely predicted

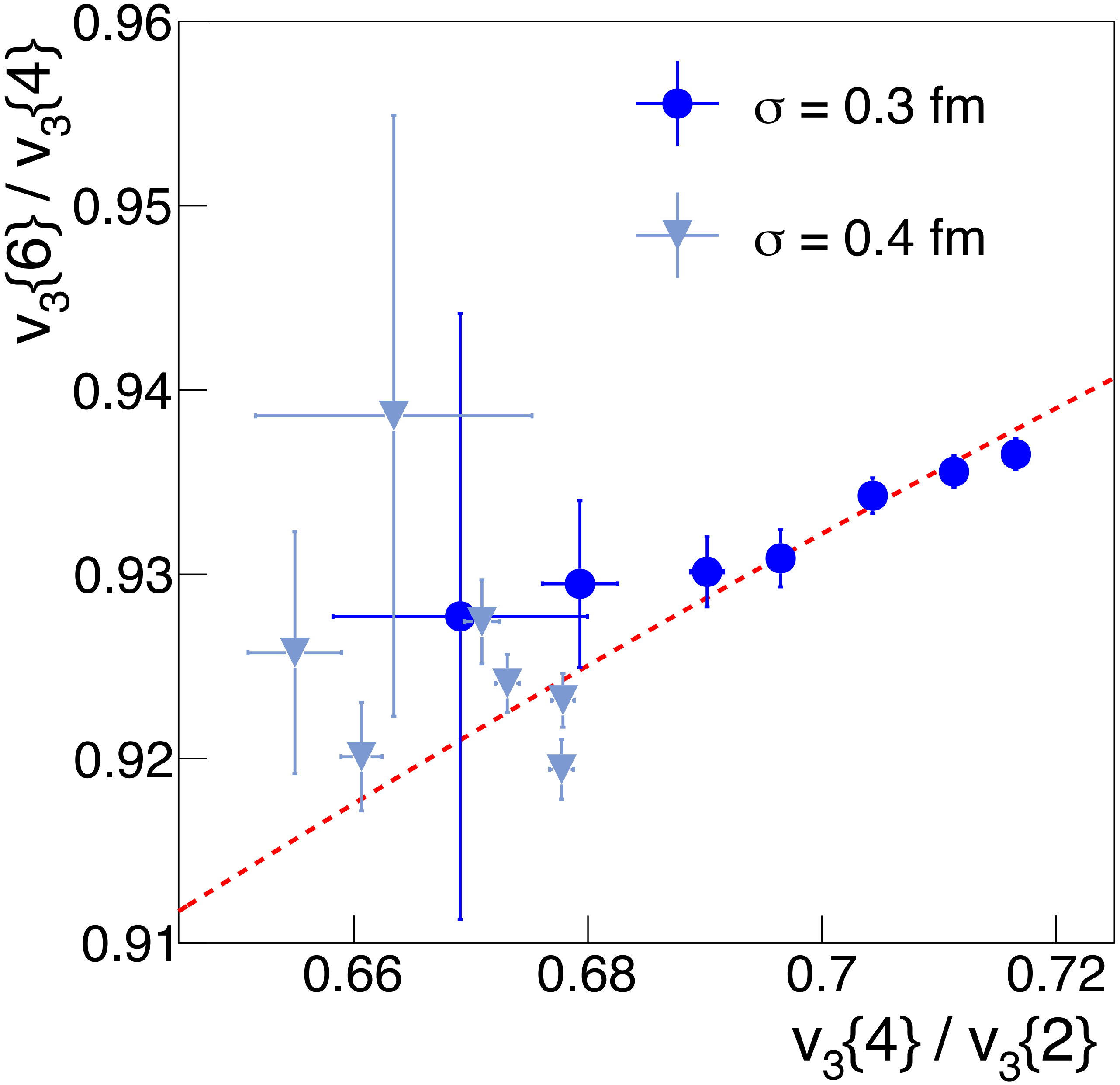
Higher-order Cumulants



- Monte Carlo simulations of the initial state (Trento model) agree with the analytic prediction from the Power distribution
- CMS preliminary data also in good agreement

Giacalone et al 1702.01730

Higher-order Cumulants



- Also works for triangular flow (higher order cumulants not yet measured in p+Pb)

Giacalone et al 1702.01730

Conclusions

- Long range correlations naturally explained by independent particle emission from a fluctuating source (flow paradigm). This also applies to the CGC framework.
- Assuming that anisotropic flow is a linear response to the initial anisotropy allows one to make accurate, quantitative predictions for higher-order cumulants, which can be tested against data.

Backup slides

The fluctuations of elliptic flow

- One can measure much more than the rms value of v_2. Also higher order moments and cumulants

$$v_2\{2\}=(\langle v_2^2\rangle)^{1/2}$$
$$v_2\{4\}=(2\langle v_2^2\rangle^2-\langle v_2^4\rangle)^{1/4}$$
$$v_2\{6\}=((\langle v_2^6\rangle-9\langle v_2^4\rangle\langle v_2^2\rangle+12\langle v_2^2\rangle^3)/4)^{1/6}$$

- $v_2\{4\} < v_2\{2\}$ if v_2 fluctuates
- $v_2\{4\}=v_2\{6\}$ if fluctuations are 2-dim. Gaussian.