Distribution of azimuthal momentum anisotropies in event-by-event fluid dynamics

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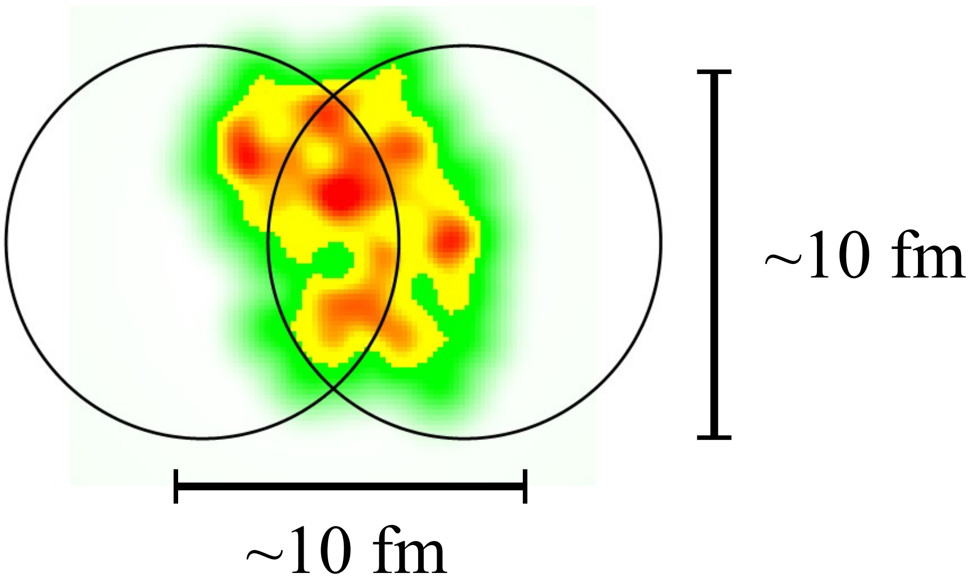
Motivation

- Now, we finally accept that fluid dynamics must be applied event by event (v_3, ridge, etc)



- From the fluid-dynamical point of view, very challenging to describe

→ Hydrodynamics should describe, not only event-averaged observables, but also **distributions** of observables

In this talk

➔ Is there correlation between the initial condition and the momentum anisotropies in an event-by-event level ?

➔ What can we learn from event-by-event distribution of flow? and flow correlations?

➔ Can we find fluid-dynamical signatures for event-by-event **thermalization** ? (not look only at averages)

Fluid dynamics: inputs

$$\partial_\mu T^{\mu\nu} = 0$$

energy-momentum conservation

Transient theory of fluid dynamics

$$\Delta^{\mu\nu}_{\alpha\beta}\tau_\pi D\pi^{\alpha\beta} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} - \frac{4}{3}\pi^{\mu\nu}\theta - \frac{10}{7}\Delta^{\mu\nu}_{\alpha\beta}\sigma^{\alpha}{}_{\lambda}\pi^{\beta\lambda} + \frac{74}{315\eta}\Delta^{\mu\nu}_{\alpha\beta}\pi^{\alpha}{}_{\lambda}\pi^{\beta\lambda},$$

GSD *et al*, PRD85 114047 (2012)

$$\sigma^{\mu\nu} = \Delta^{\mu\nu}_{\alpha\beta}\nabla^\alpha u^\beta$$

$$\theta = \nabla_\mu u^\mu$$

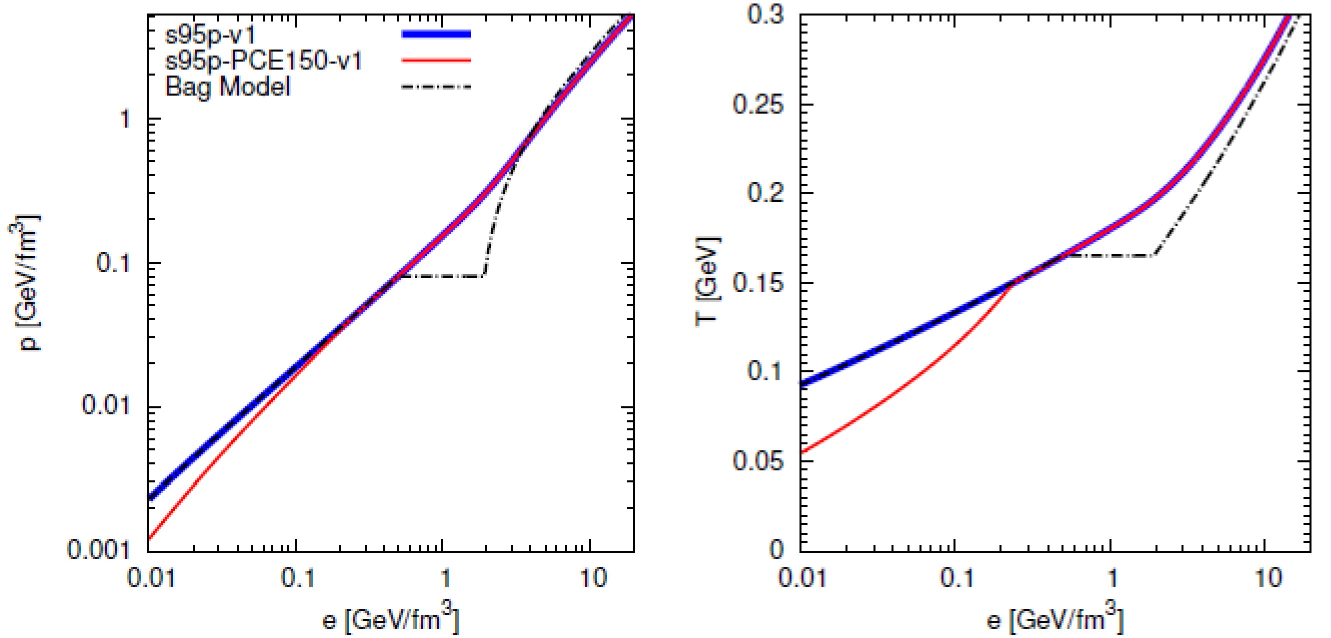
$$\omega^{\mu\nu} = \frac{1}{2}\left(\nabla^\mu u^\nu - \nabla^\nu u^\mu\right)$$

$$\Delta^{\mu\nu}_{\alpha\beta} = \left(\Delta^\mu_\alpha \Delta^\nu_\beta + \Delta^\nu_\alpha \Delta^\mu_\beta - 2/3\Delta^{\mu\nu}\Delta_{\alpha\beta}\right)/2$$

Still one term missing ... $\Delta^{\mu\nu}_{\alpha\beta}\pi^{\alpha}_{\lambda}\omega^{\beta\lambda}$

$$\tau_\pi = 5\frac{\eta}{\varepsilon + P}$$

Input - EoS



➔Lattice parametrization by Petreczky/Huovinen, arXiv:0912.2541

➔Chemical Freeze-out at 150 MeV (s95p-PCE150-v1)

➔Hadron Resonance Gas includes all hadronic states up to 2 GeV

Input - Initial Condition

- Event-by-event IC: Monte Carlo Glauber (Hannu's; ~**2400 events**)

$$s(x,y) = W \sum_{i=1}^{N_{\mathrm{part,bin}}} \exp\left\{-\left[(x-x_i)^2 + (y-y_i)^2\right] / (2\sigma^2)\right\}$$

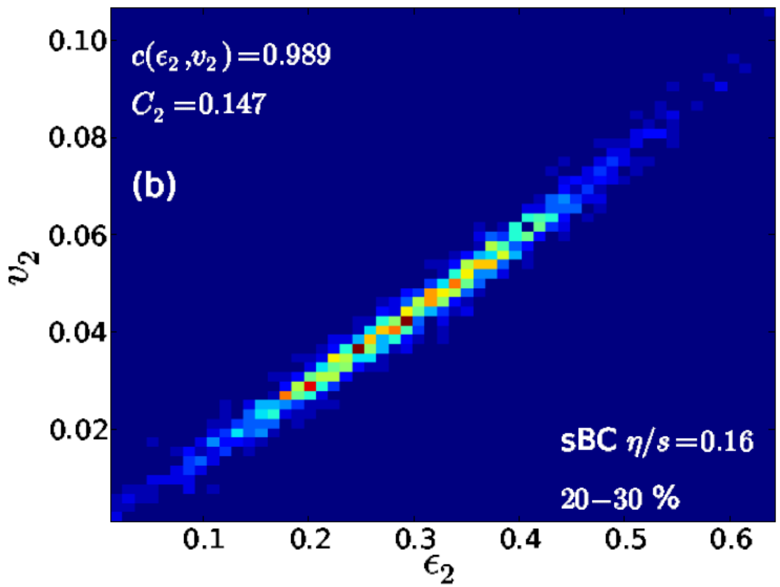
Npart: sWN and **Nbin: sBC**

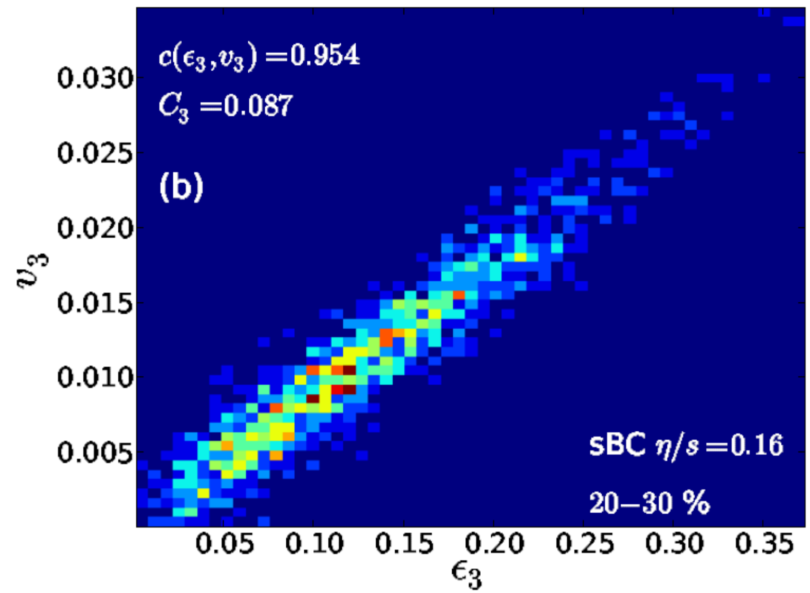
- Initial conditions in local thermal equilibrium; no initial velocity
- $\tau_0 = 0.5 - 1.0$ fm

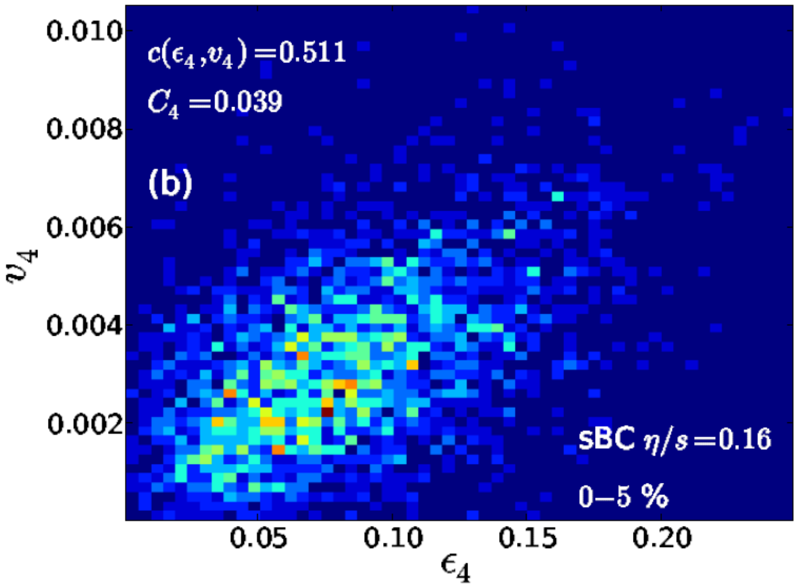
Input - Freezeout

- Standard Cooper-Frye (Israel-Stewart *ansatz*), T_f=100 MeV
- Decays included – no re-scatterings

Correlation with the initial state





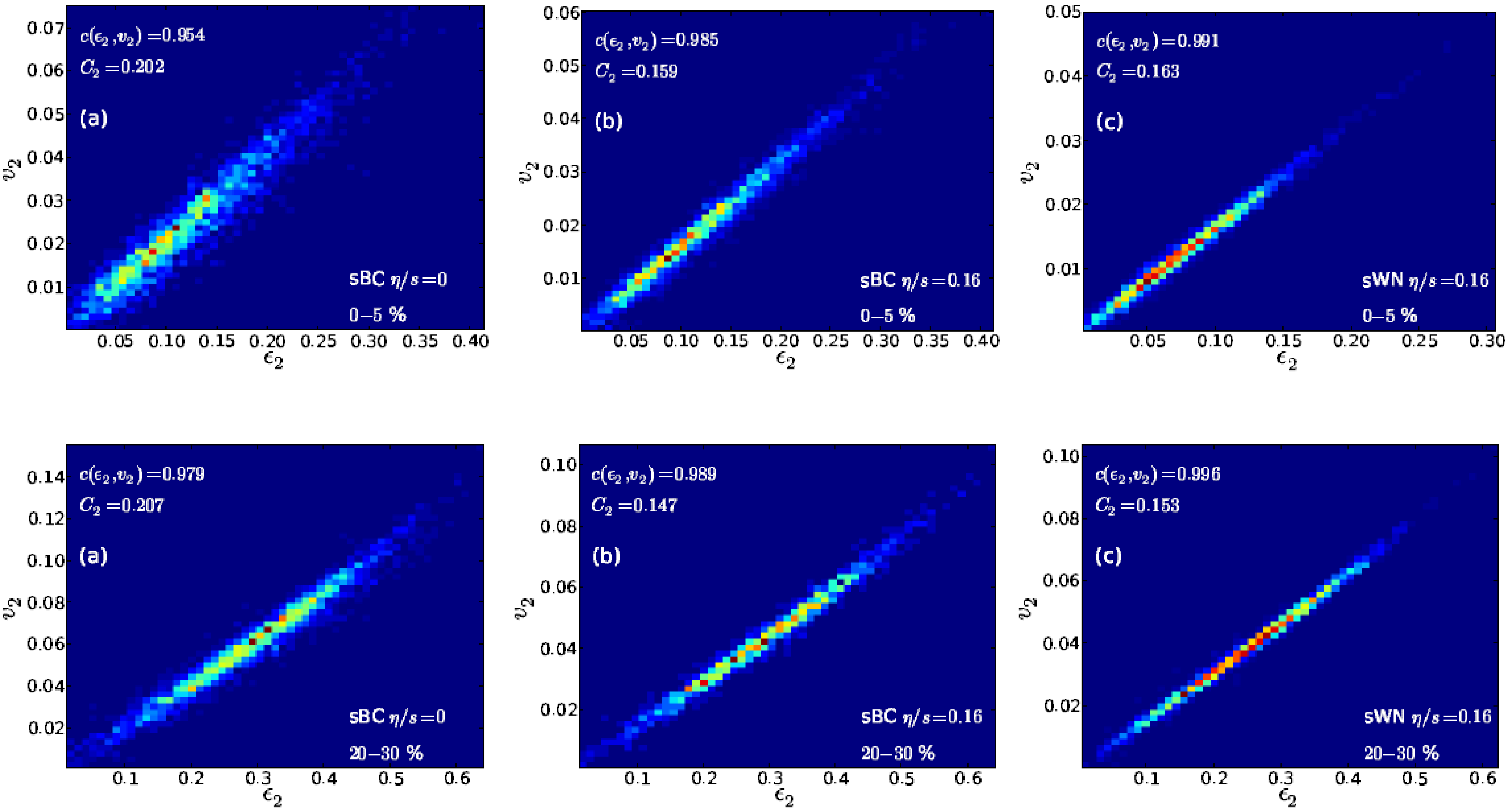


$$c(a, b) = \left\langle \frac{(a_i - \langle a \rangle)(b_i - \langle b \rangle)}{\sigma_a \sigma_b} \right\rangle$$

$v_{2,3}$ **linearly correlated**

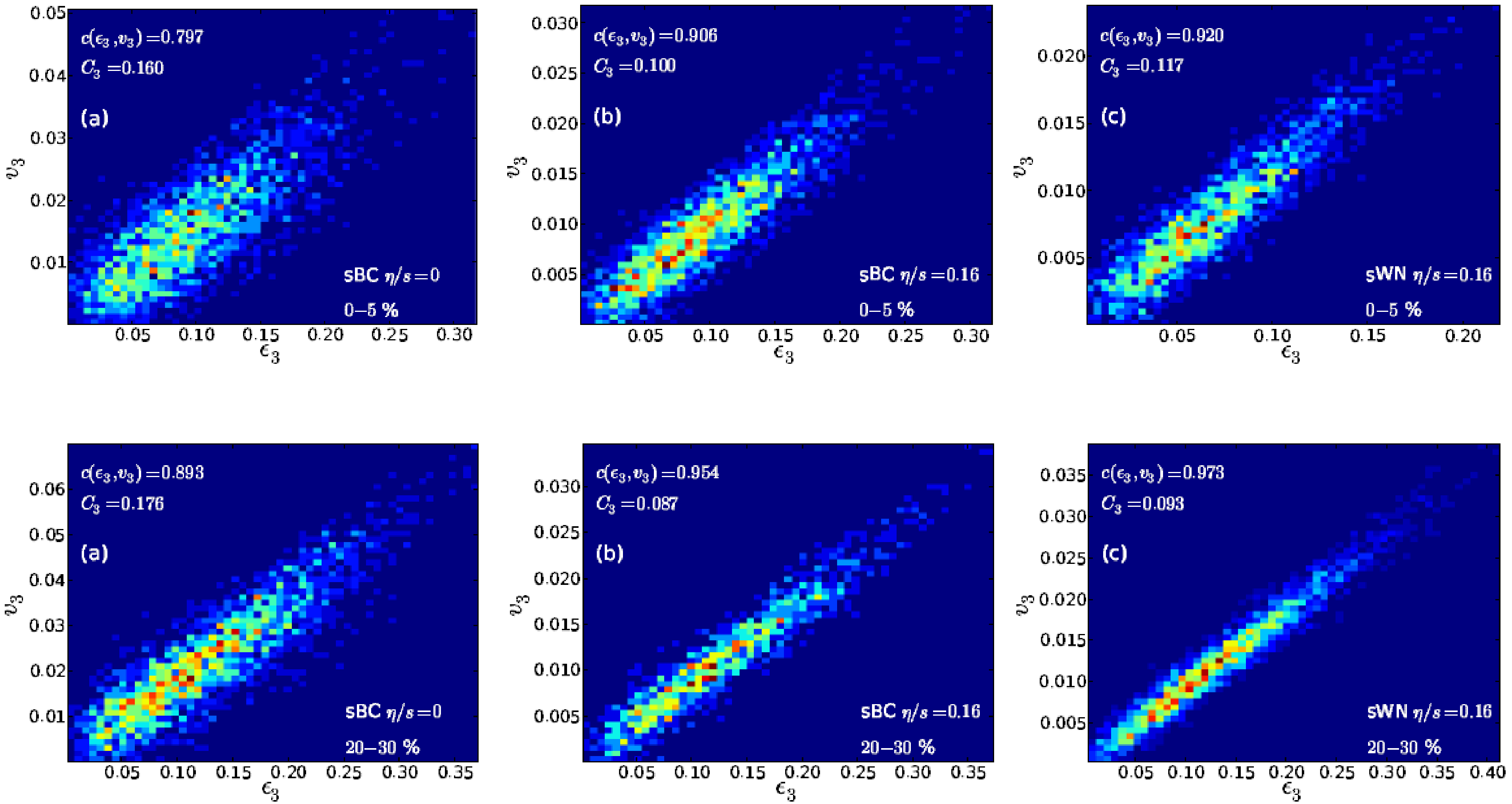
v_4 **not linearly correlated**

v_2 and ε_2 – 0-5%, 20-30%



Strong linear correlation

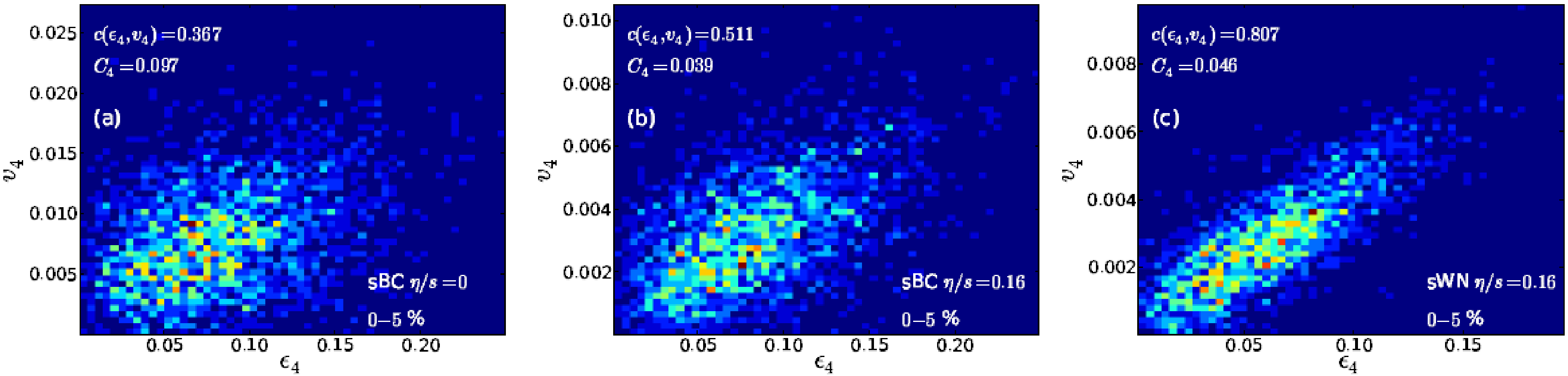
v_3 and ε_3 – 0-5%, 20-30%



Strong linear correlation

v_4 and ε_4 – 0-5%

20-30% – no linear correlation



no linear correlation

linear correlation

Depends on initial condition and viscosity

Conclusions so far (n=2,3)

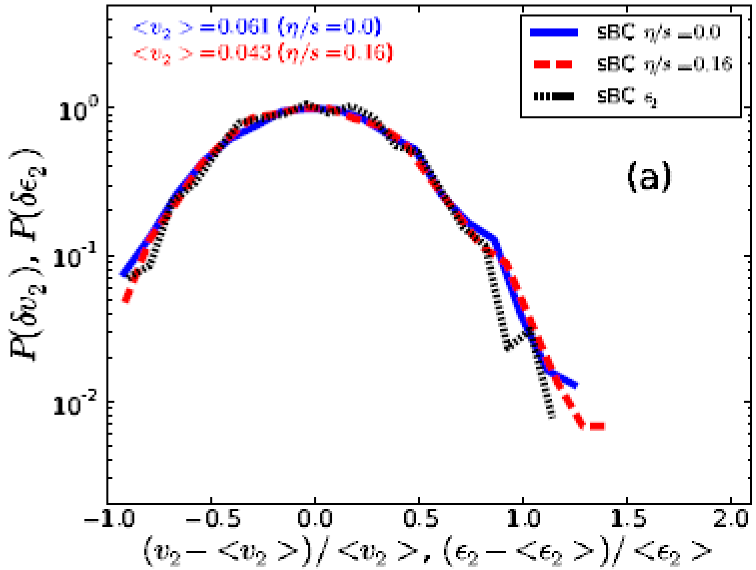
- Only the **event-averaged** v_n carries information about the fluid

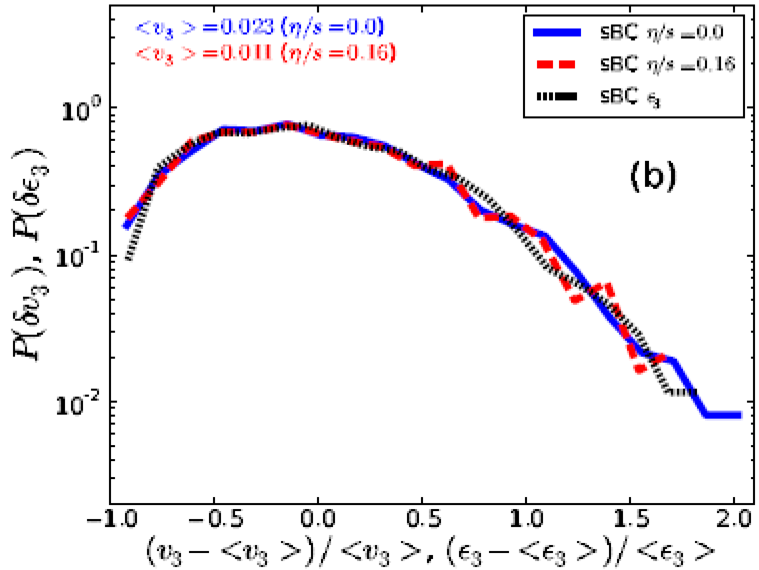
- The rest of the distribution is solely determined by the **initial eccentricity fluctuations**

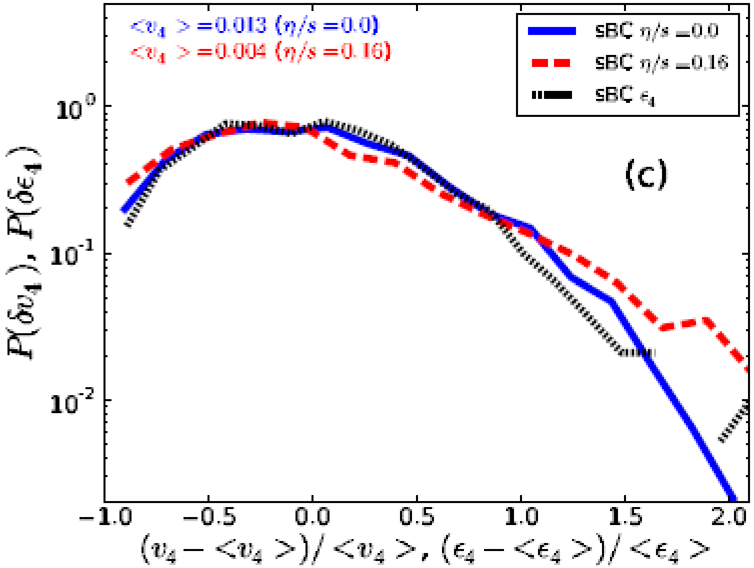
lets see how this shows up in v_n distributions

Distributions of v_2, v_3, and v_4

Effect of viscosity (RHIC)







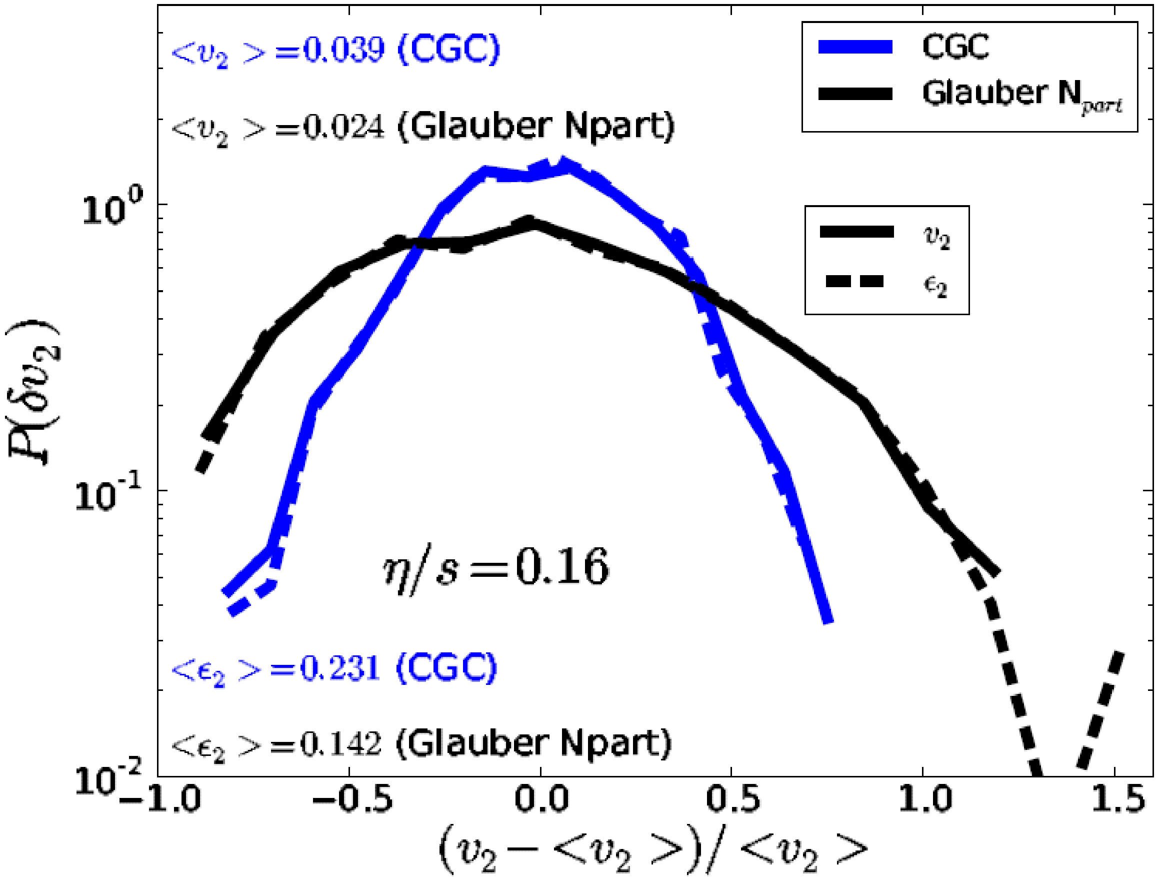
$$\delta v_n \equiv \frac{v_n - \langle v_n \rangle_{\rm ev}}{\langle v_n \rangle_{\rm ev}}$$

no sensitivity to viscosity!

follows initial condition!

Distributions of v_2

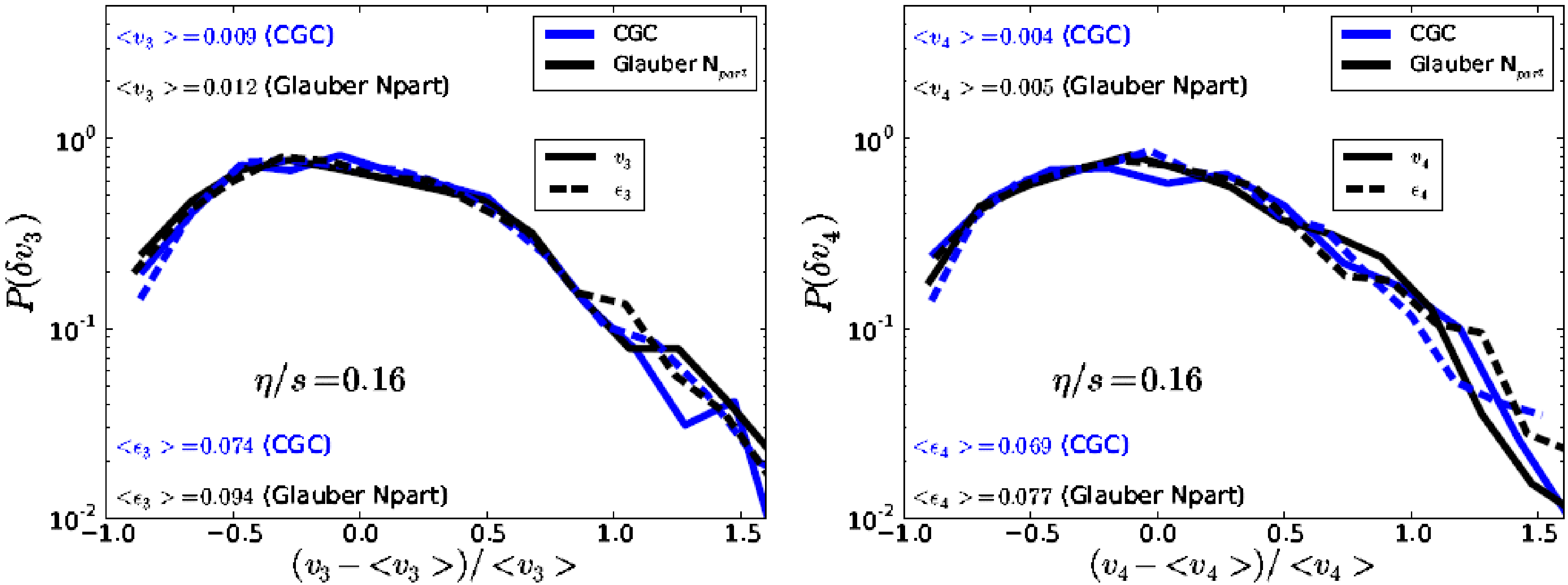
CGC mcKLN vs Glauber (LHC)



distributions are different, but still follow the initial condition

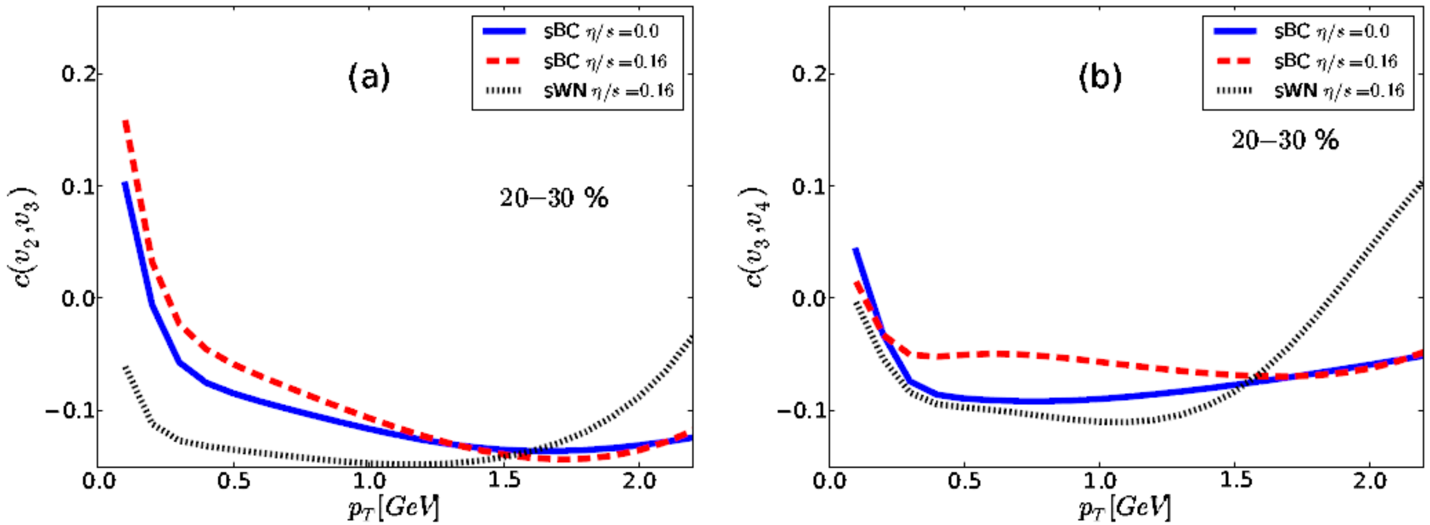
Distributions of v_3 and v_4

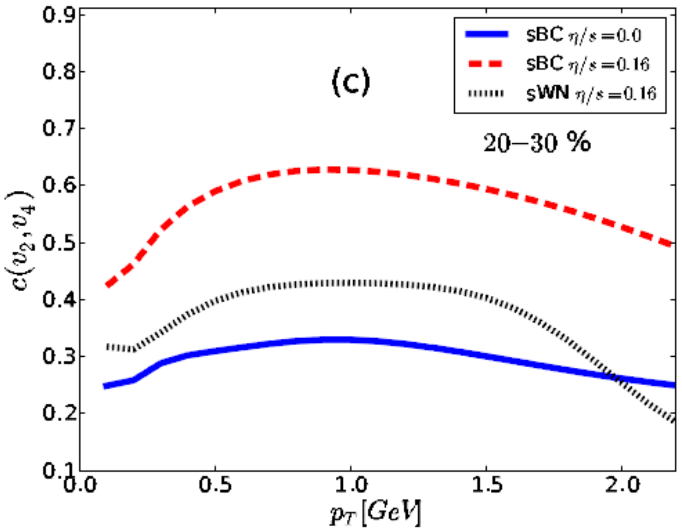
CGC mcKLN vs Glauber



n=3,4 fluctuations are the same for all initial conditions

(v_n, v_m) linear correlations (RHIC)





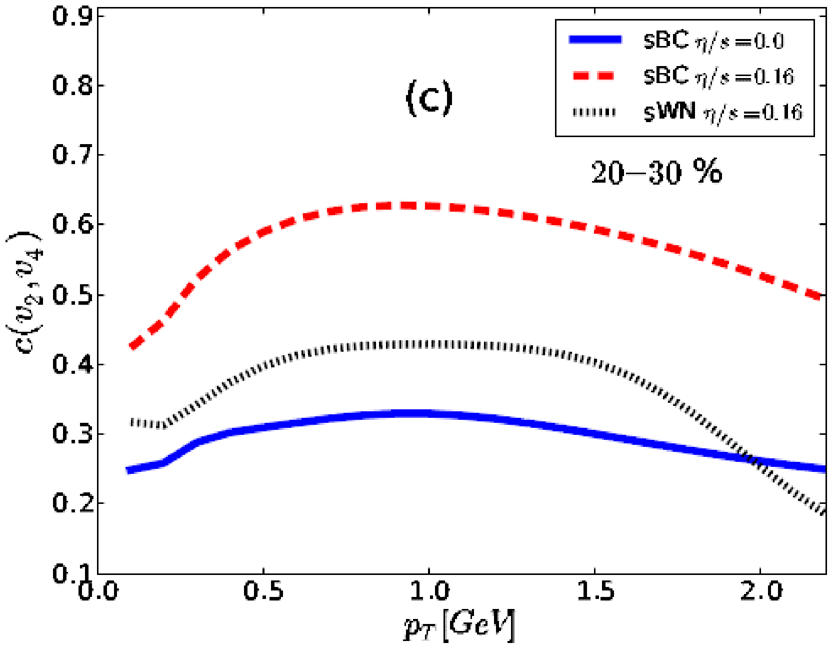
$$c\,(a,b) = \left\langle \frac{(a_i - \langle a\rangle)\,(b_i - \langle b\rangle)}{\sigma_a \sigma_b} \right\rangle$$

c ~ 1 linear correlation

c ~ 0 no linear correlation

c ~ -1 linear anti-correlation

(v_2 ,v_4) correlation



Huge effect of viscosity and of eccentricity correlations

Good observable to constraint the validity of event by event fluid dynamics

Summary

➔ We found **strong EbyE linear correlation** between eccentricities and momentum anisotropy

➔ **Distributions of v_n can provide robust constraints on initial condition models**

➔ Correlation functions between different v_n's can be a good signature of **event-by-event fluid-dynamical behavior**

BACK UP

We use the event plane method

We compute v_n as:

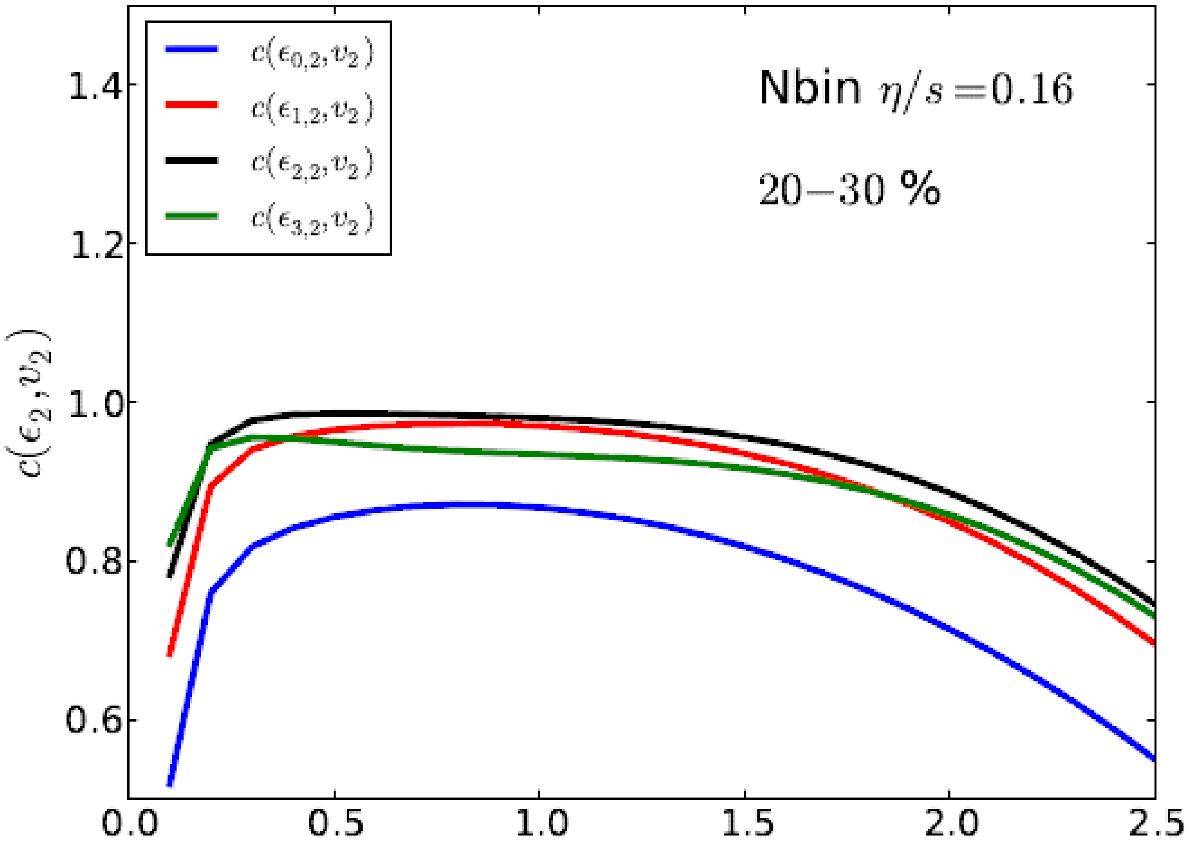
$$v_n e^{in\Psi_n} \equiv \langle e^{in\phi} \rangle$$

$$\psi_n \equiv \frac{1}{n} \arctan \frac{\langle p_T \sin n\phi \rangle}{\langle p_T \cos n\phi \rangle}$$

We compute ε_n as:

$$\varepsilon_{p,n} \equiv \frac{\langle r^p \cos\left[n\left(\phi - \psi_{PP}\right)\right]\rangle_\varepsilon}{\langle r^p \rangle_\varepsilon} \qquad \varepsilon_n \equiv \varepsilon_{2,n}$$

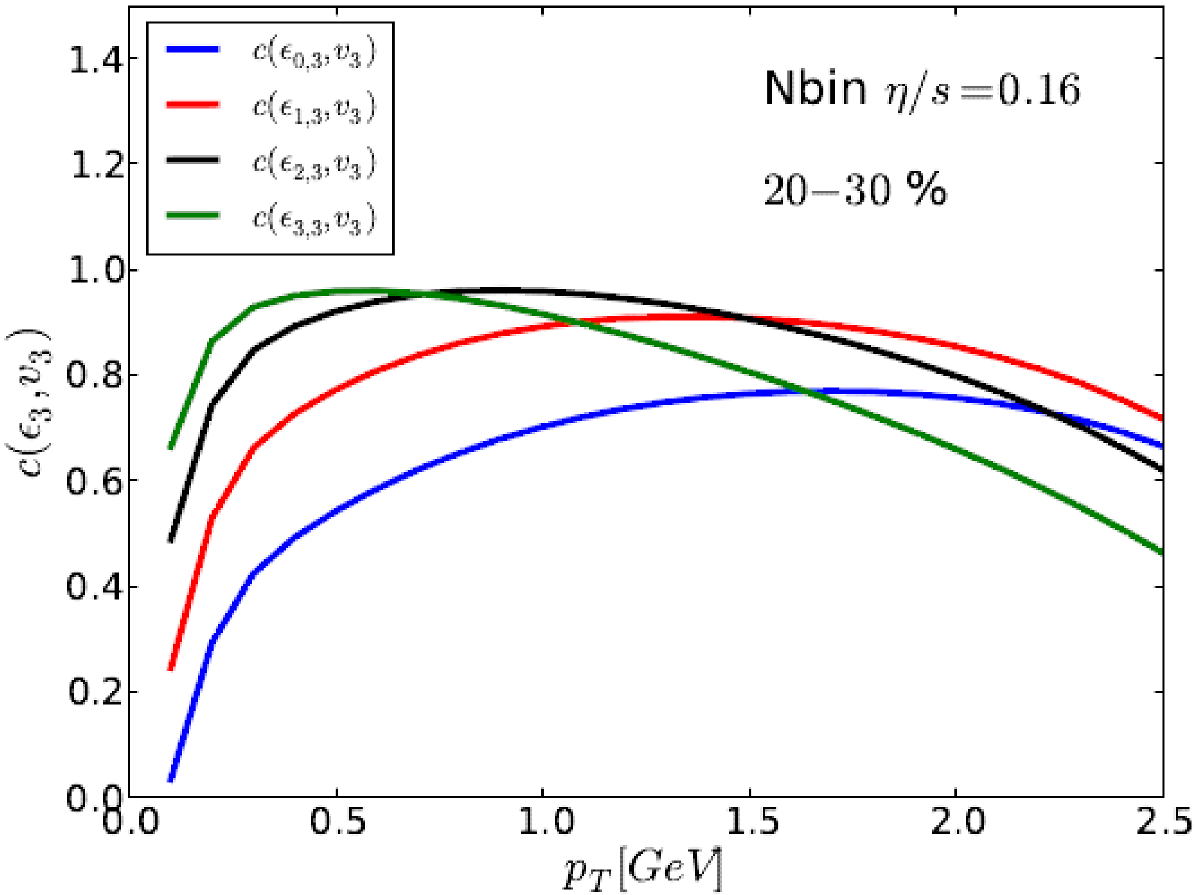
Correlation with eccentricities – v_2



- high-p_T and low-p_T v_n's correlate with different $\varepsilon_{p,n}$'s

$$\varepsilon_{p,n} \equiv \frac{\langle r^p \cos\left[n\left(\phi - \psi_{PP}\right)\right]\rangle_\varepsilon}{\langle r^p \rangle_\varepsilon} \quad \varepsilon_n \equiv \varepsilon_{2,n}$$

Correlation with eccentricities – v_3

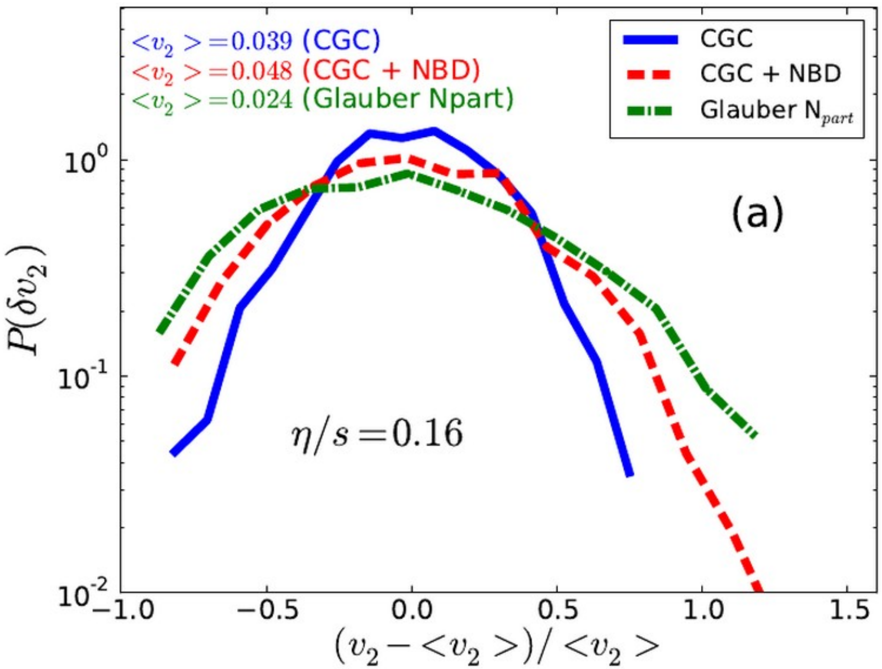


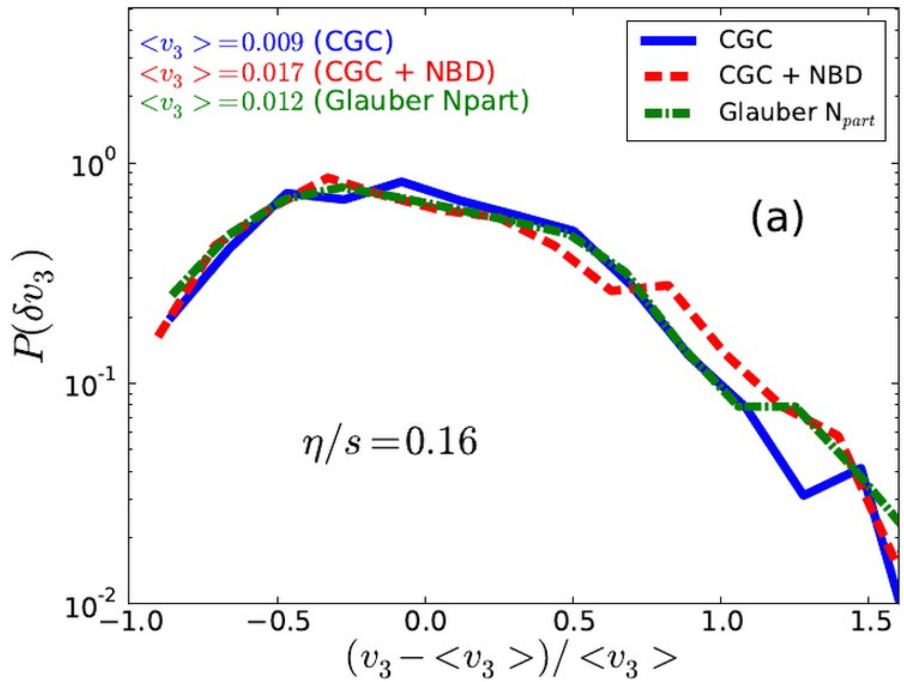
- high-p_T and low-p_T v_n's correlate with different $\varepsilon_{p,n}$'s

$$\varepsilon_{p,n} \equiv \frac{\langle r^p \cos\left[n\left(\phi - \psi_{PP}\right)\right]\rangle_\varepsilon}{\langle r^p \rangle_\varepsilon} \quad \varepsilon_n \equiv \varepsilon_{2,n}$$

Also, inclusion of multiplicity fluctuations

Goes in the correct direction ...





Work in progress

(v_n, v_m) linear correlations