Anisotropic flow in nuclear collisions

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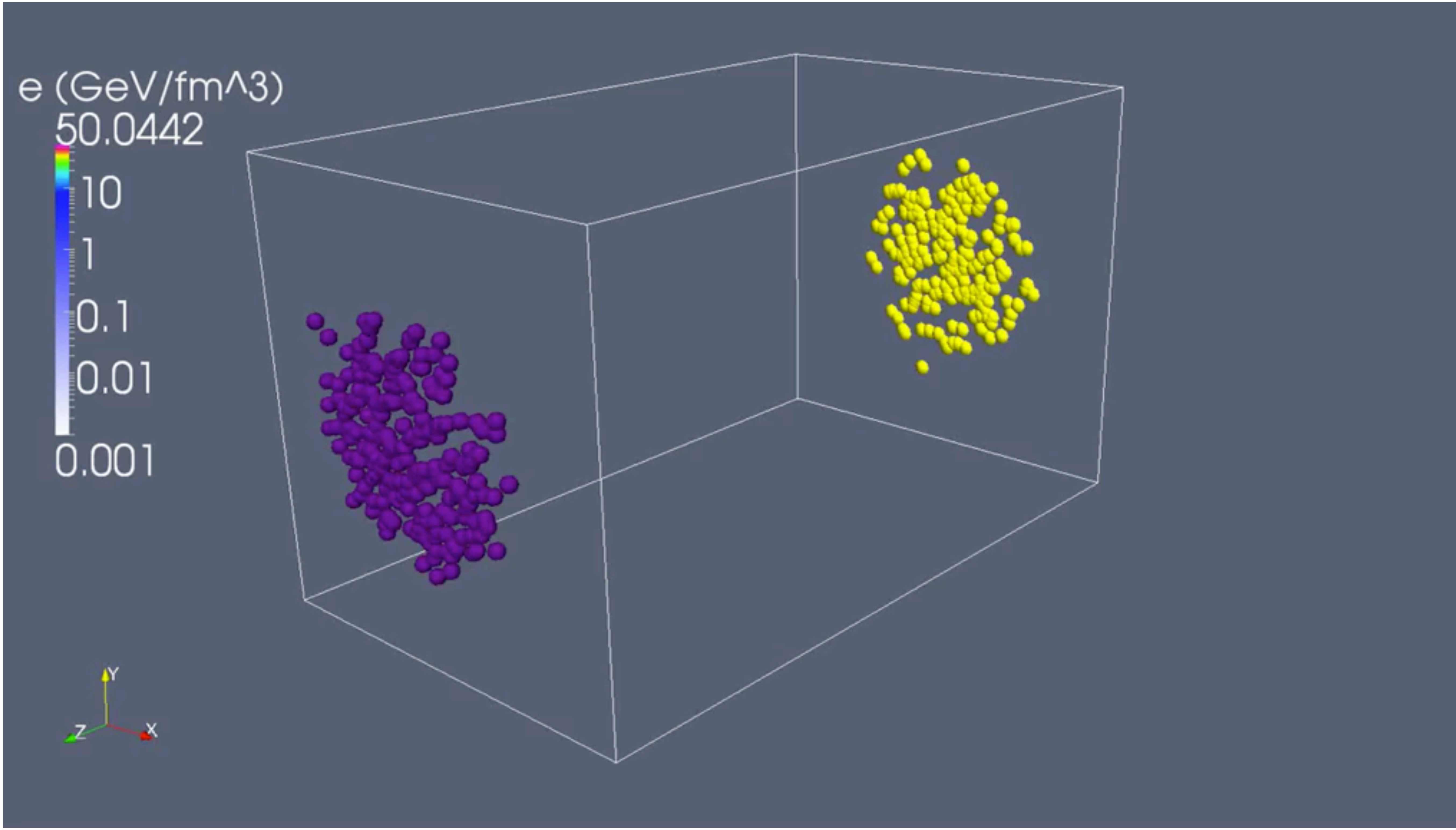
Outline

- Define anisotropic flow, recall traditional problems of comparing data with hydrodynamic calculations.
- Show that higher harmonics can be combined with lower harmonics in a way that eliminates some model uncertainties.
- Discuss what we can learn from this study

Yan JYO 1502.02502

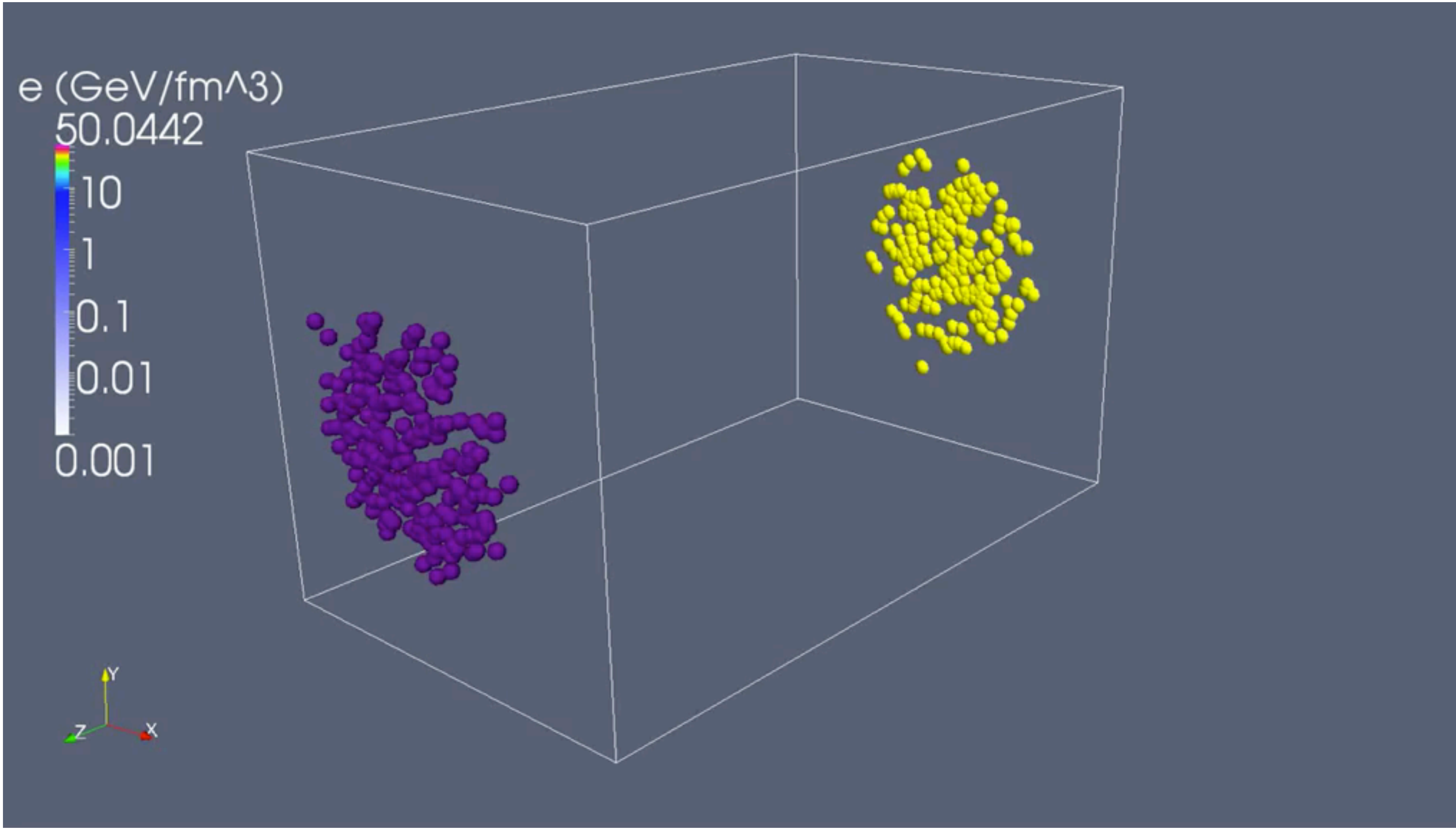
& work in progress with Li Yan and Subrata Pal

Nucleus-nucleus collision at the LHC



Hydrodynamic simulation by Chun Shen (Ohio State)

Nucleus-nucleus collision at the LHC



Hydrodynamic simulation by Chun Shen (Ohio State)

The *flow paradigm*

- In each collision, particles are emitted independently: sampled with an *underlying probability distribution* $f(\mathrm{p})$.
- The momentum distribution $f(\mathrm{p})$ fluctuates event to event.
- This naturally explains most correlations seen experimentally — in particular the ridge.

Alver Roland 1003.0194

Luzum 1107.0592

Anisotropic flow

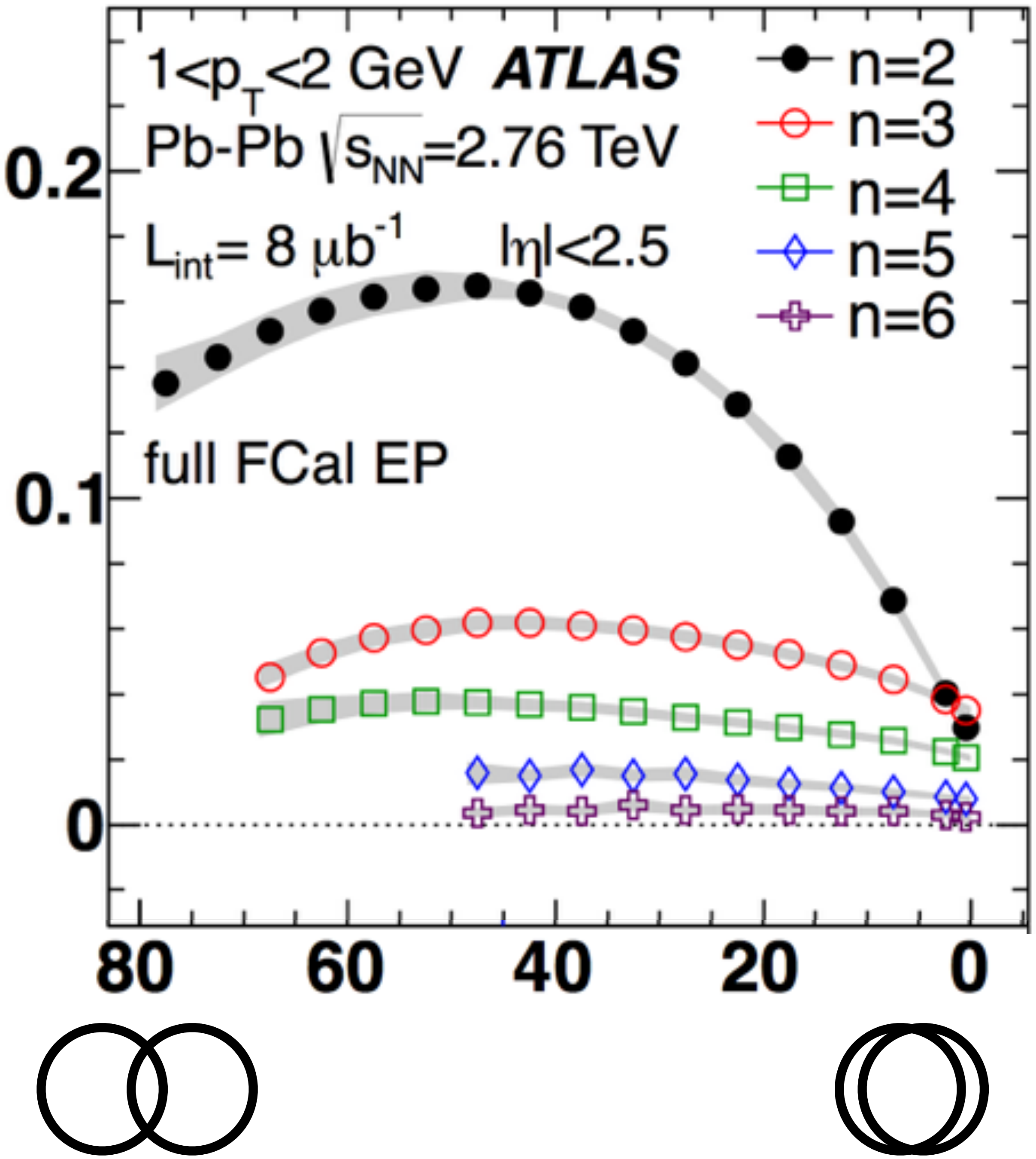
- In a single event, azimuthal symmetry is broken. The φ distribution can be written as

$$f(\varphi)=\sum_n V_n \, e^{-in\varphi}$$

- V_n=Fourier coefficient=anisotropic flow
- $f(\varphi)$ real $\Rightarrow$ $V_{-n}=V_n^*$; normalisation $V_0=1$
- Transformation under rotation

$$\varphi \to \varphi+\alpha$$
$$V_n \to V_n \, e^{in\alpha}$$

Anisotropic flow at the LHC



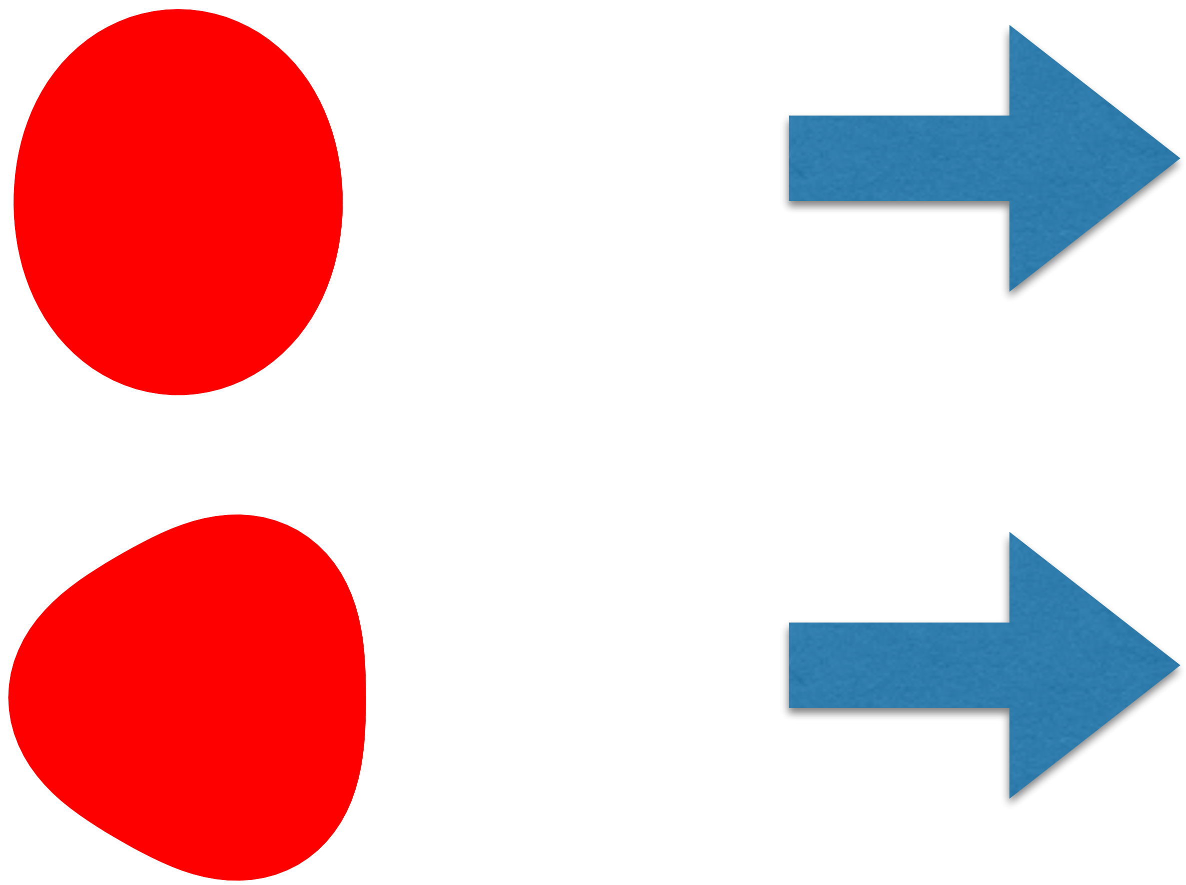
- These are typical (rms) values of $|V_n|$
- Measured up to n=6
- V_2 largest (elliptic flow)
- V_3 next (triangular flow)
- This talk: V_4, V_5, V_6

The origin of elliptic and triangular flow

Initial transverse density profile

Expansion

Final distribution



Elliptic flow V_2

Triangular flow V_3

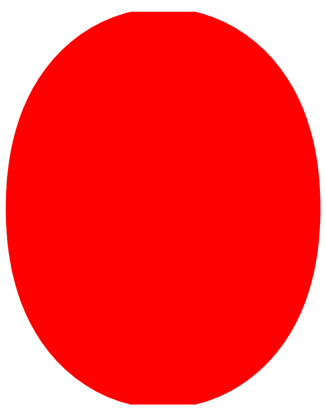
But the initial density is poorly constrained theoretically

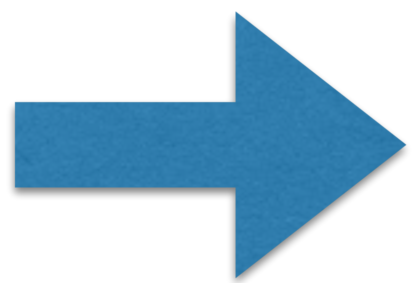
The origin of elliptic and triangular flow

Initial transverse density profile

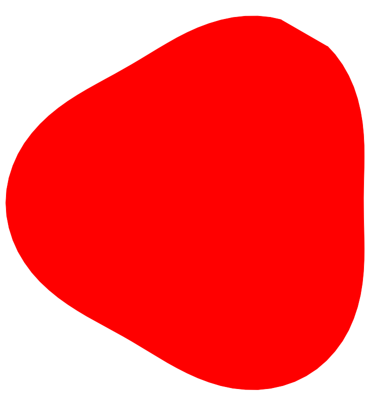
Expansion

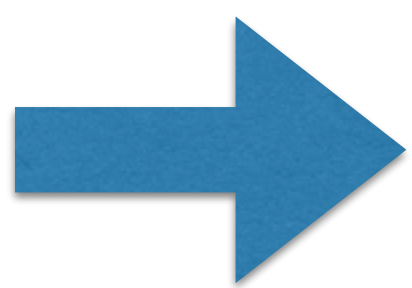
Final distribution





Elliptic flow V_2





Triangular flow V_3

Initial state: major uncertainty in hydro calculations

The origin of higher harmonics

- Rotational symmetry allows a nonlinear coupling with lower-order harmonics

$$V_4 = \chi_4 (V_2)^2 + \ldots$$

- In hydrodynamics, the nonlinear coupling χ_4 is essentially independent of the initial state

Borghini JYO nucl-th/0506045

Teaney Yan 1206.1905

The origin of higher harmonics

- Rotational symmetry allows a nonlinear coupling with lower-order harmonics

$$V_4=\chi_4\,(V_2)^2+\ldots$$
$$V_5=\chi_5\,V_2V_3+\ldots$$
$$V_6=\chi_{62}\,(V_2)^3+\chi_{63}\,(V_3)^2+\ldots$$
$$V_7=\chi_7\,(V_2)^2\,V_3+\ldots$$

- All χ_n : independent of initial state
- and can be measured.

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What can we measure?

- V_n cannot be measured on an event-by-event basis: statistical fluctuations way too large.
- Average over events: $\langle V_n \rangle = 0$ by rotational symmetry.
- Measurements of anisotropic flow are extracted from multiparticle correlations.

Example : pair correlation

- Pairs of particles in the same event with azimuthal angles φ_1, φ_2.
- Do a statistical average in the event
  $\{e^{in\varphi 1}\, e^{-in\varphi 2}\} = \{e^{in\varphi 1}\}\, \{e^{-in\varphi 2}\}$ (independent)
  $= \quad V_n \quad\quad V_{-n} \quad = |V_n|^2$
- Finally, average over events
  $\langle e^{-in\varphi 1}\, e^{-in\varphi 2}\rangle = \langle |V_n|^2 \rangle \quad > 0$

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Generalization

- Now, 3-particles with azimuthal angles $\varphi_1, \varphi_2, \varphi_3$
- $\{e^{4i\varphi 1}\, e^{-2i\varphi 2}\, e^{-2i\varphi 3}\} = \{e^{4i\varphi 1}\}\, \{e^{-2i\varphi 2}\}\, \{e^{-2i\varphi 3}\}$

$$= \quad V_4 \quad V_{-2} \quad V_{-2}$$

$$= V_4\,(V_2^*)^2$$

- Finally: $\langle e^{4i\varphi 1}\, e^{-2i\varphi 2}\, e^{-2i\varphi 3}\rangle = \langle V_4\,(V_2^*)^2\rangle$
- In principle, one can measure the average value of any product of V_ns, that is, all *moments*.

Bilandzic 1409.5636

Bhalerao Pal JYO 1411.5160

Measuring nonlinear couplings

Start from definition:

$$V_4 = \chi_4 (V_2)^2 + \ldots$$

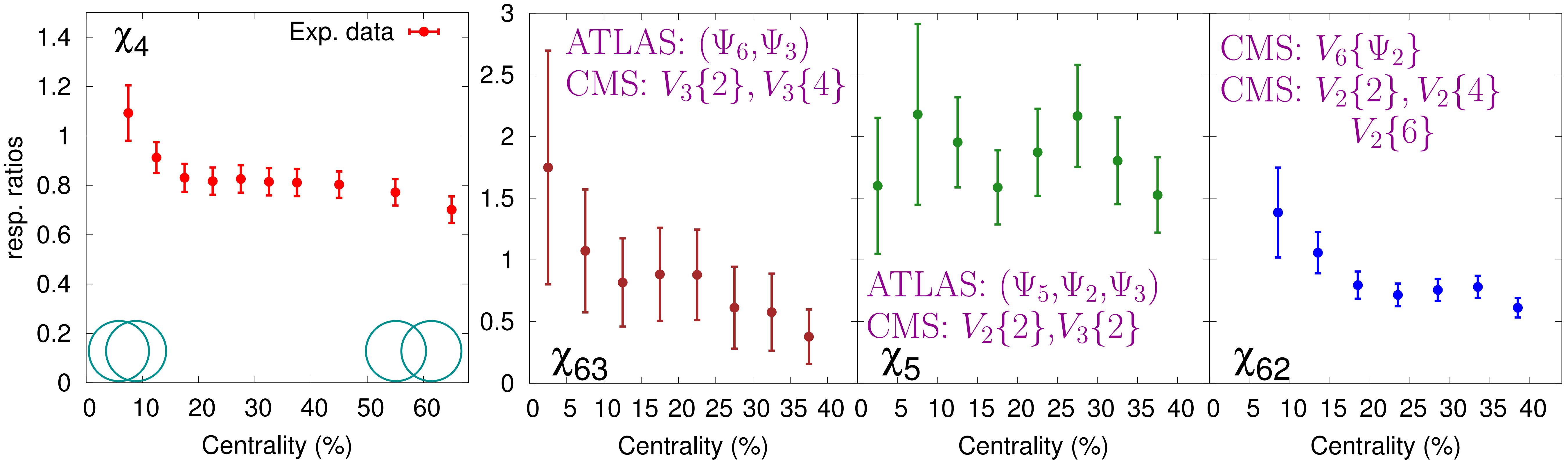
Make both sides invariant under rotations, average over events:

$$\langle V_4 (V_2^*)^2 \rangle = \chi_4 \langle (V_2)^2 (V_2^*)^2 \rangle + \ldots$$

If we neglect the remaining part $+\ldots$, we obtain the nonlinear response χ_4 in terms of moments, which are measured.

Note: $\langle V_4 (V_2^*)^2 \rangle$ is measured with better relative accuracy than $\langle |V_4|^2 \rangle$.

Nonlinear couplings at the LHC



The χ_n are of order unity and vary mildly with centrality, unlike V_n itself.

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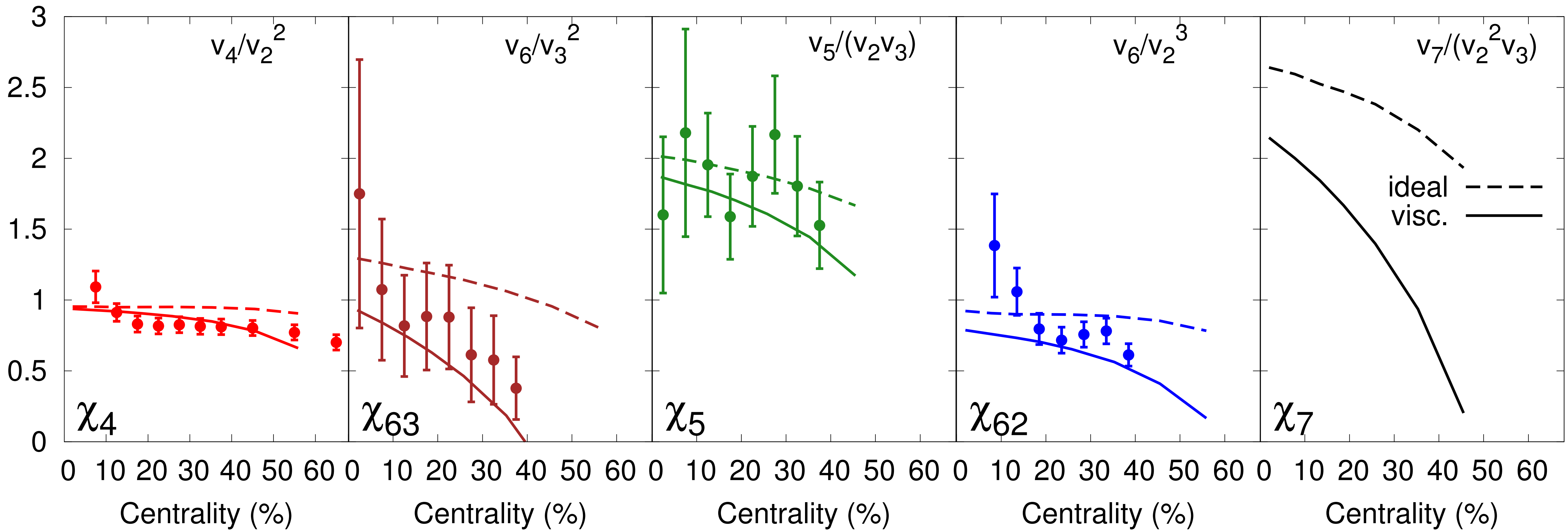
Nonlinear couplings and hydro

- Hydro ≠ experiment: we calculate V_n and χ_n in a single « hydro event ».
- Since χ_n are independent of the initial density profile, we choose a simple smooth profile: e.g., Gaussian for χ_4 and χ_{62}
- Solve relativistic ideal (or viscous) hydrodynamics with an EOS from lattice QCD.
- Transform the fluid into hadrons when it cools down to T_f=150 MeV

Nonlinear couplings and hydro



Both ideal and viscous ($\eta/s=1/4\pi$) results are in the ballpark for all coefficients, all centralities.

Viscous marginally better than ideal.

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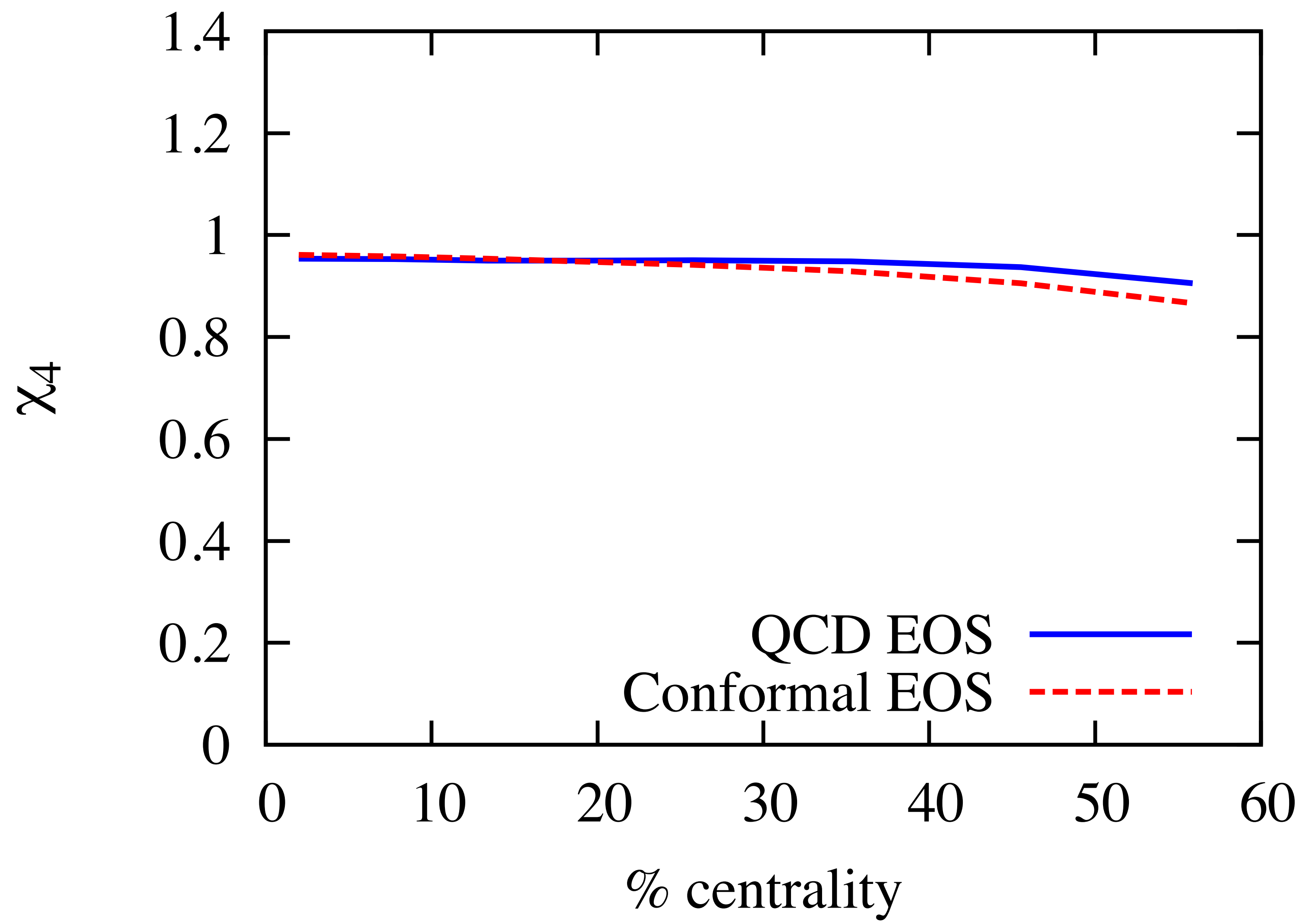
What do nonlinear couplings tell us?

- They are insensitive to the initial state, but what about other parameters?
- Equation of state
- Viscosity of the quark-gluon plasma
- Freeze-out temperature
- Viscous « corrections » at freeze-out
[note that viscosity enters in 2 different places in hydrodynamic calculations]

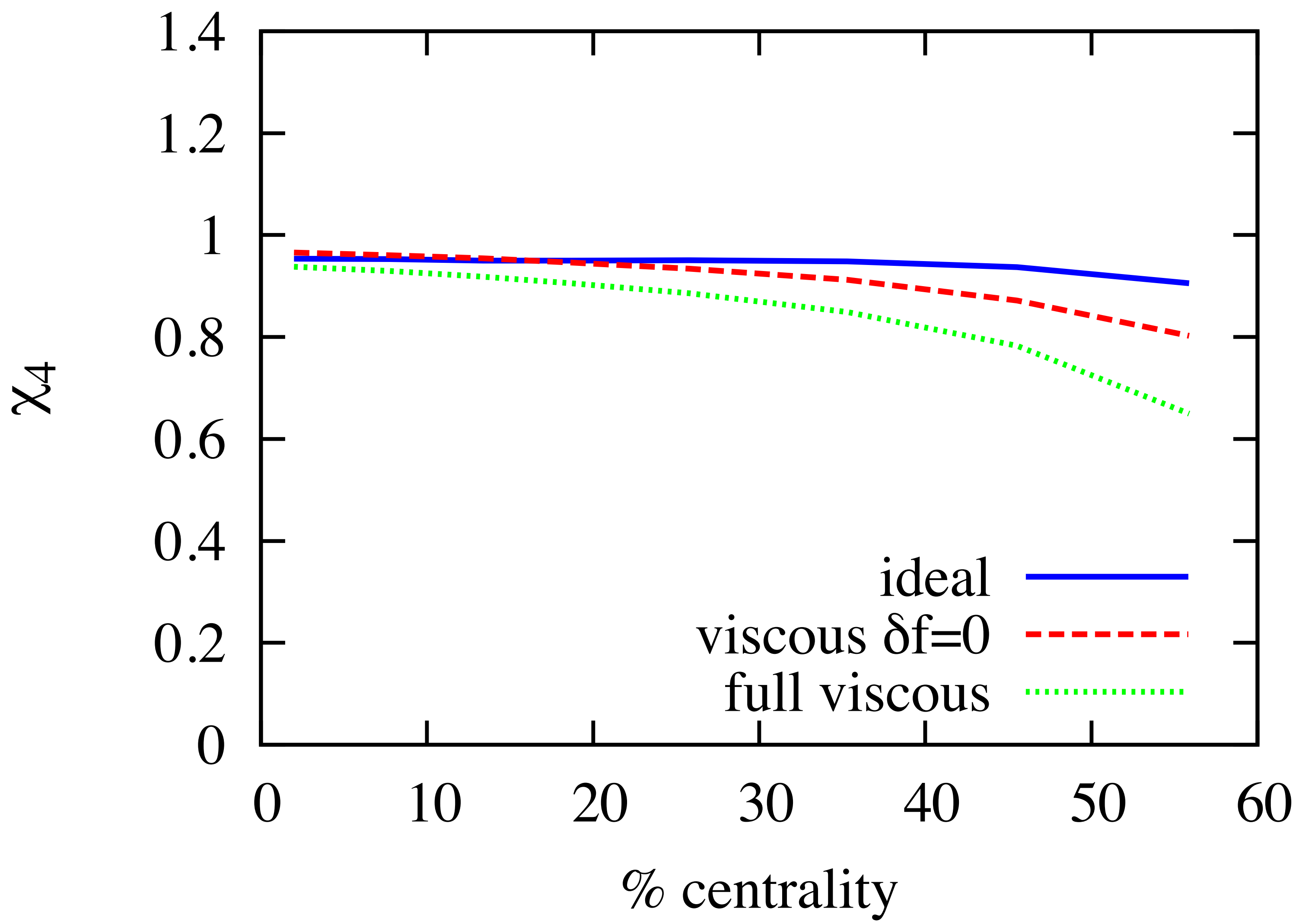
Sensitivity to equation of state



EOS from lattice QCD versus conformal ε=3P:

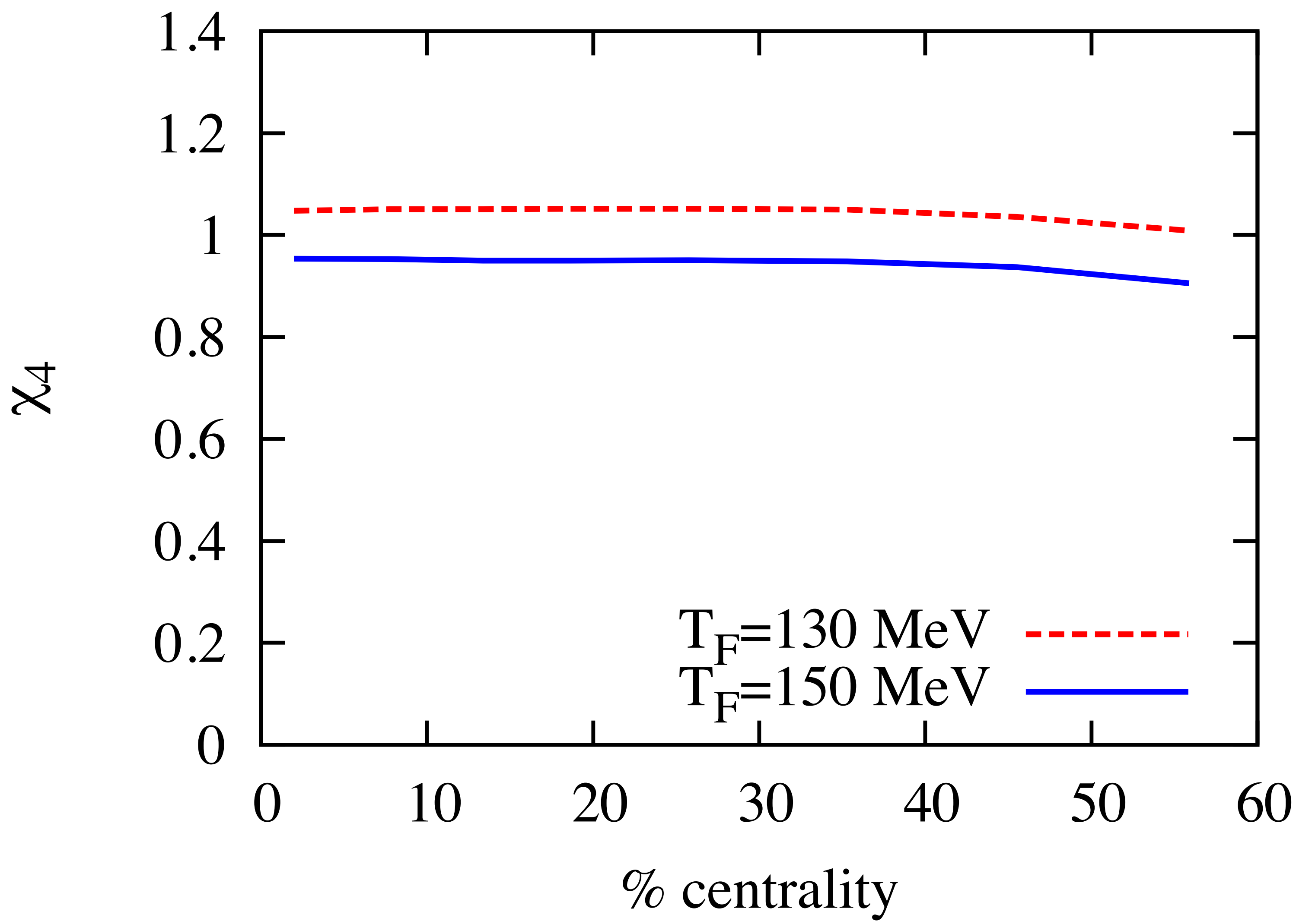
nonlinear coupling surprisingly insensitive to EOS.

Sensitivity to viscosity



Moderate effect of viscosity, mostly through the viscous correction to phase-space distribution at freeze-out

Sensitivity to freeze-out temperature

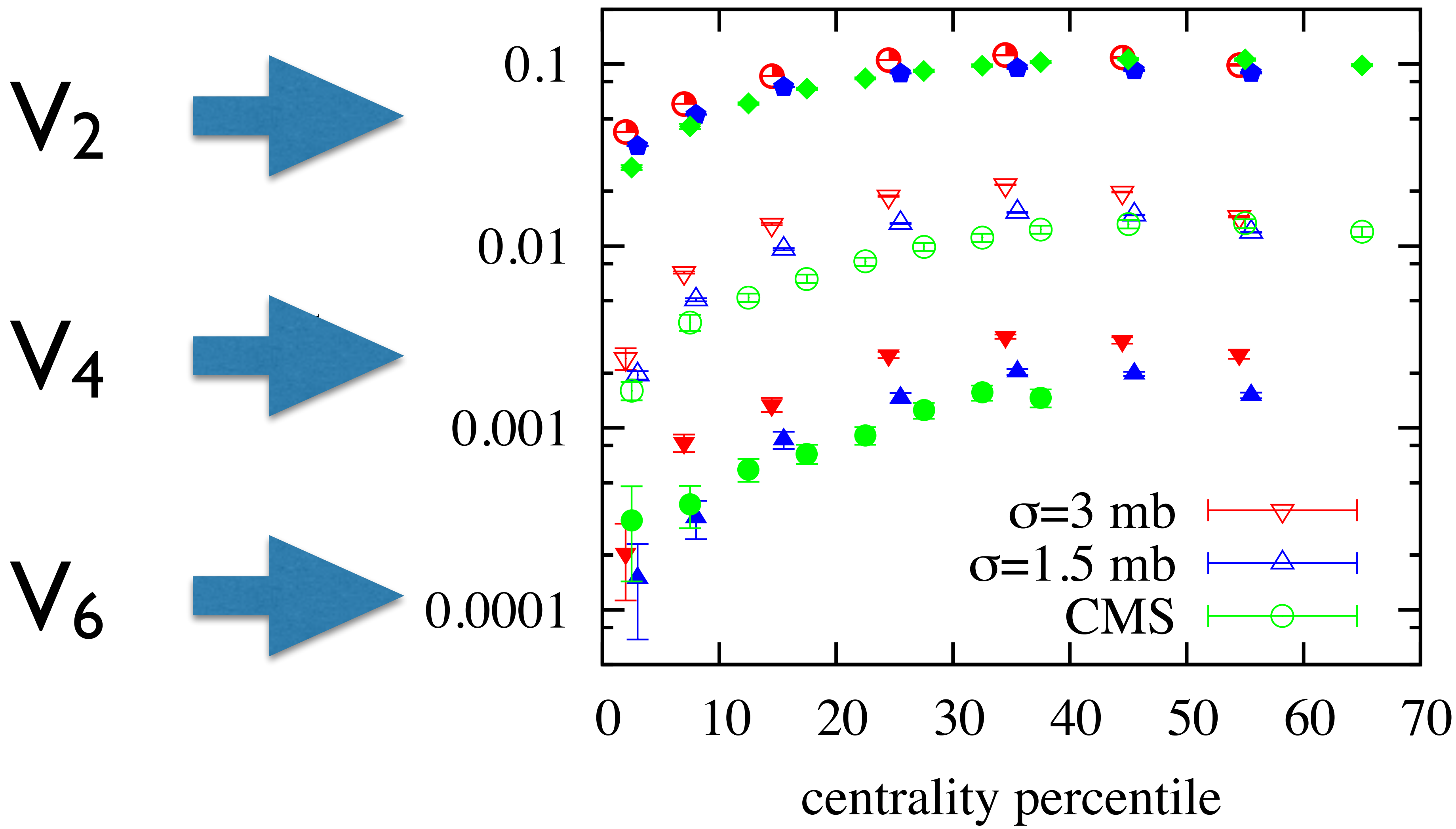


If the system expands for a longer time, the nonlinear couplings increase. Still a modest effect.

Transport calculations

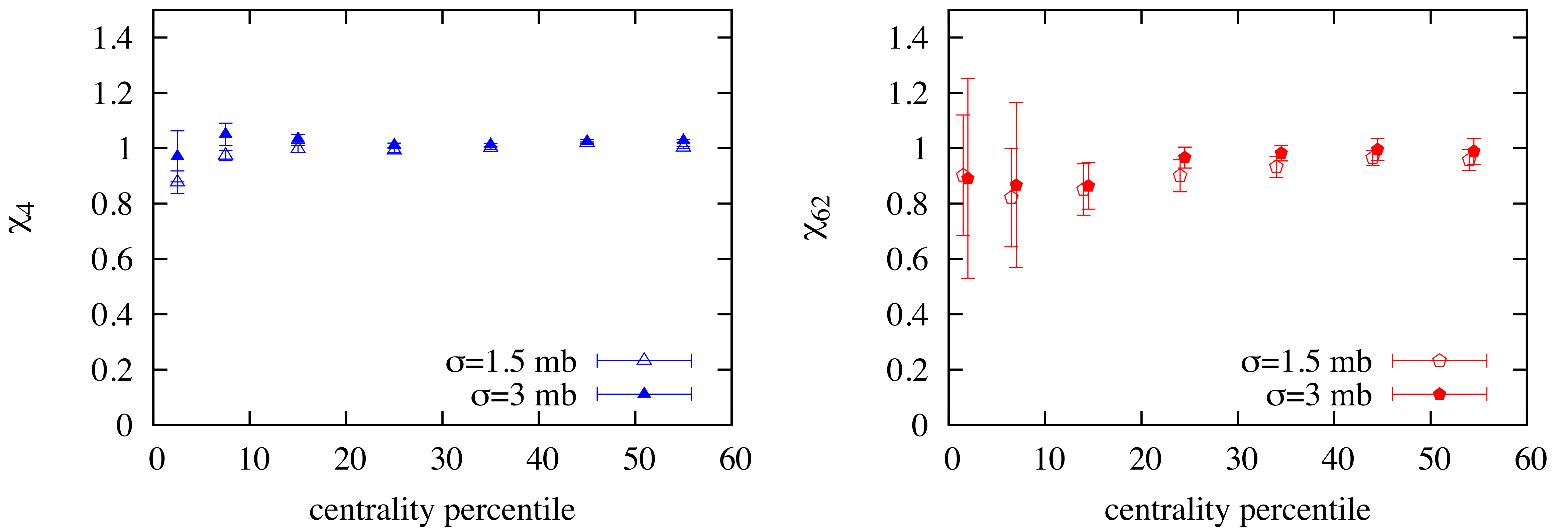
- Late stages where the system falls out of equilibrium seem to be the most important and are not correctly modeled in hydro.
- Therefore we carry out transport (AMPT) calculations where one follows trajectories and collisions until the last.
- Free parameter : parton-parton elastic cross section σ

Anisotropic flow in transport theory



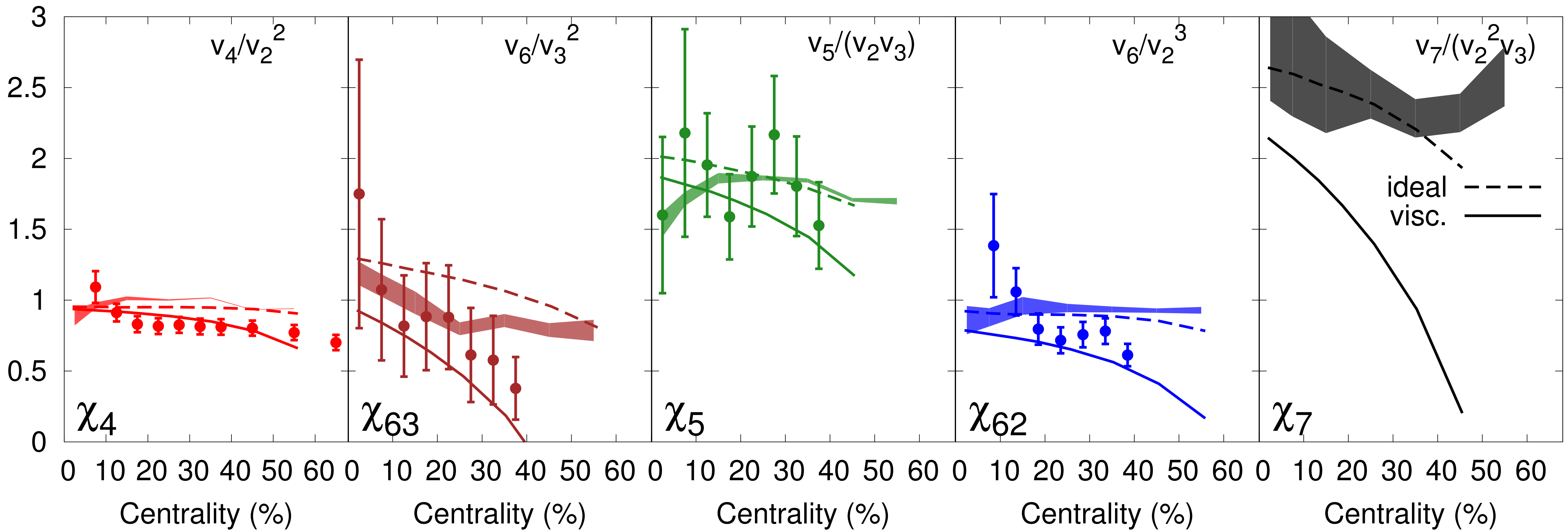
anisotropic flow increases with interaction strength as expected

Nonlinear coupling in transport theory



sensitivity to σ cancels out in the nonlinear couplings

Transport versus hydro versus data



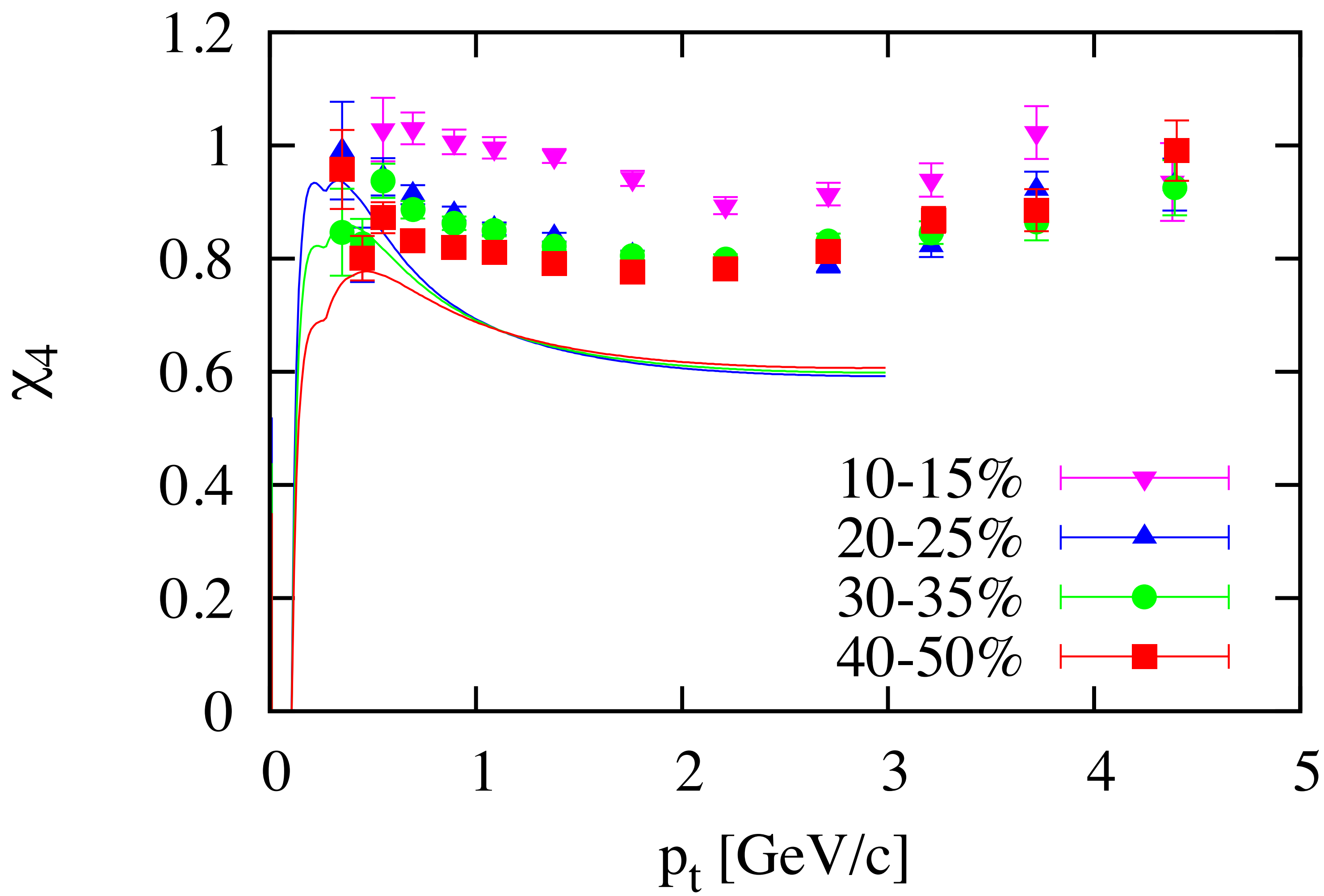
Shaded bands: AMPT results with σ=1.5 mb
In fairly good agreement with ideal hydro results and data.

Conclusions

- Nonlinear response coefficients: first examples of quantities that can be both measured and calculated in hydro, and without any dependence on the « initial state ».
- Hydro does a good job in predicting their magnitude and centrality dependence.
- This success of hydro is embarrassingly robust with respect to model parameters.
- Nonlinear couplings might contain nontrivial information about the late stages of the evolution (hadronization & freeze-out)

More

Transverse momentum dependence



(CMS data)

Essentially constant as a function of transverse momentum