Hydro overview

Jean-Yves Ollitrault, Saclay
August 13, 2012

Outline

Hydrodynamics: the only theory for the strongly-coupled quark-gluon plasma out of equilibrium.
Only well-controlled approach to bulk properties at RHIC & LHC (typically, pions at low transverse momentum)

- Modeling a collision with hydro
- A close look at a hydro event
- Flow in data: a close look at azimuthal correlations
- Current state of the art of hydro models

Modeling a collision with hydro

- Initial conditions for the fluid (talk Kevin Dusling)
- Solve for fluid expansion using equations of ideal or viscous relativistic hydrodynamics
- Transform the fluid into independent particles.
- Further interactions/decays may occur.
- The fluid is continuous: in every event, we can compute accurately single-particle spectra, i.e., the probability distribution of
  - Transverse momentum p_t
  - Pseudorapidity η
  - Azimuthal angle φ

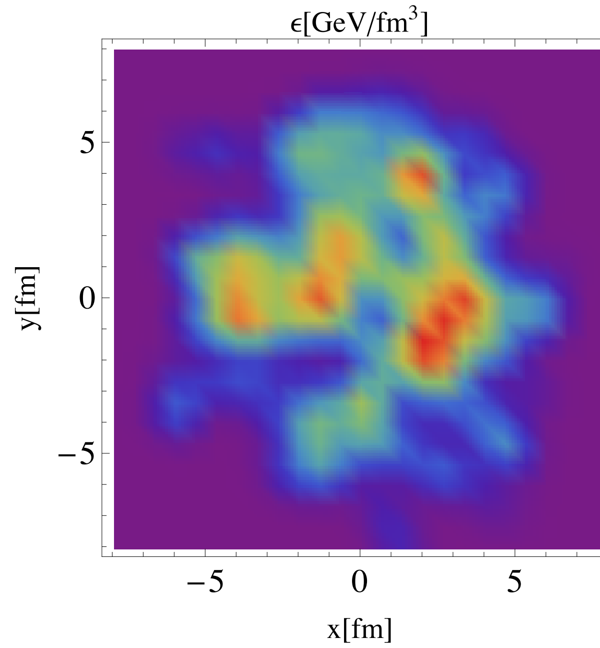
Anisotropic flow in hydro

Fourier expansion of φ *probability distribution* at fixed p_t and η

$2\pi\, dN/d\varphi = 1 + 2 \sum v_n(p_t,\eta) \cos(n(\varphi - \psi_n(p_t,\eta)))$

also written as: $V_n(p_t,\eta) \equiv v_n(p_t,\eta) e^{in\psi_n(p_t,\eta)} = \{e^{in\varphi}\}$

V_n is well defined in hydro (only)



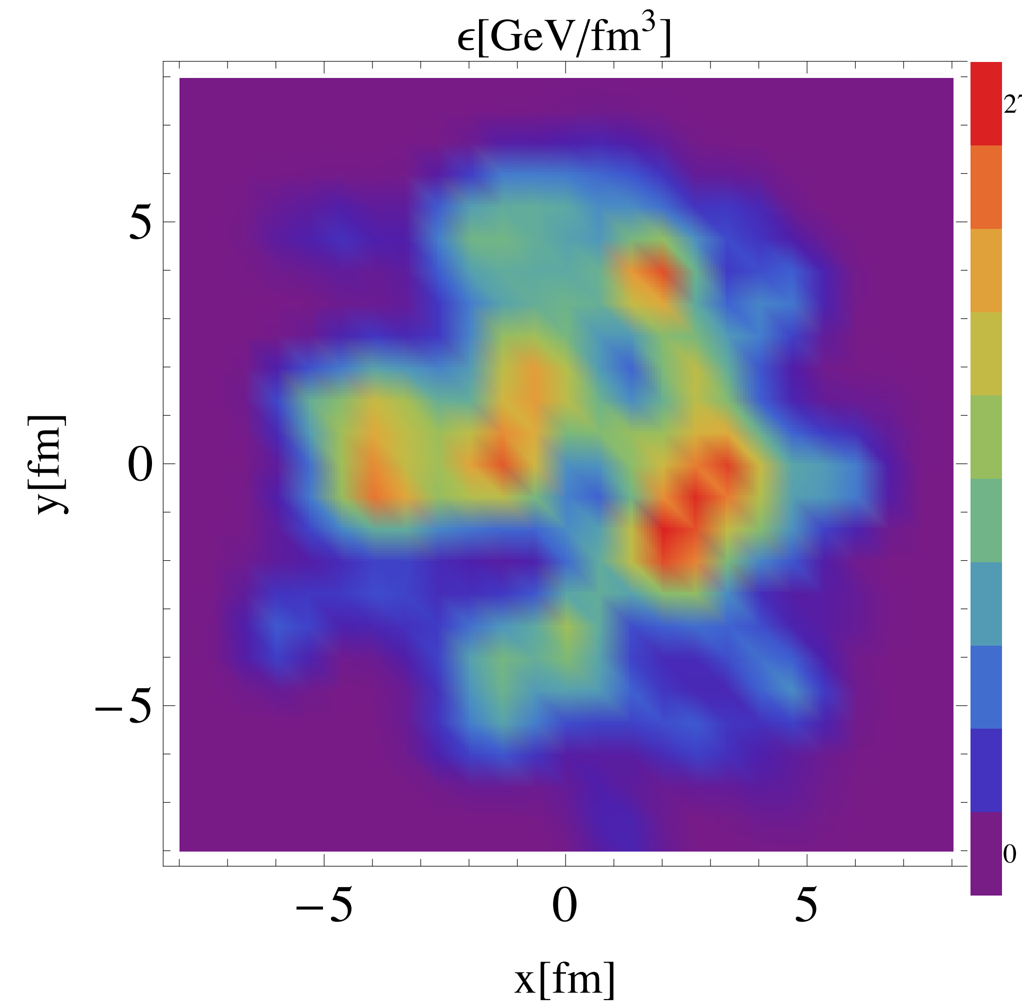
With initial state fluctuations:

- Odd harmonics at midrapidity: V_1 (directed flow) and V_3 (triangular flow) in addition to V_2 (elliptic flow).
- Each harmonic has its own phase ψ_n which may depend on p_t and η

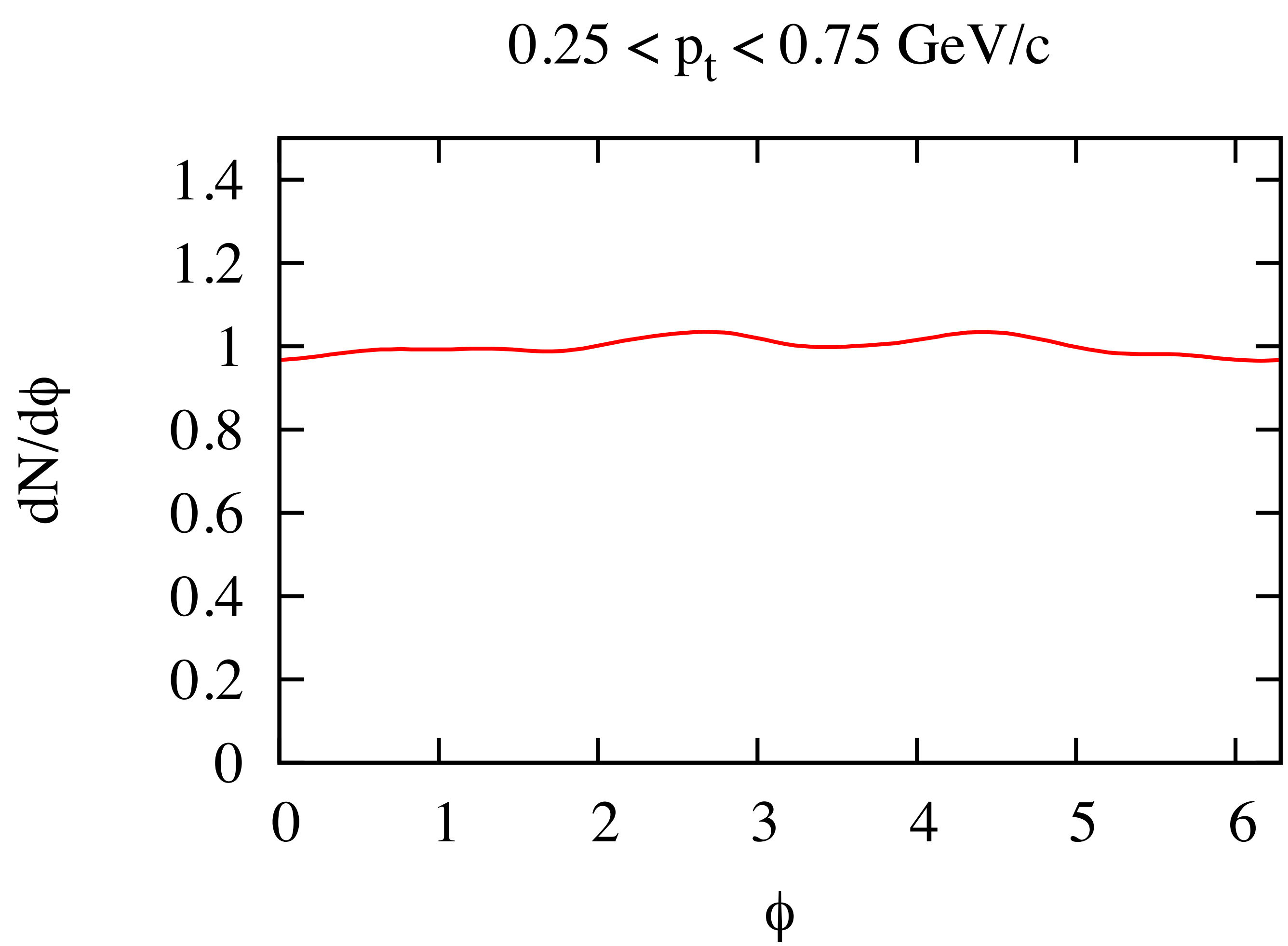
A close look at a hydro event

(thanks to Fernando Gardim!)

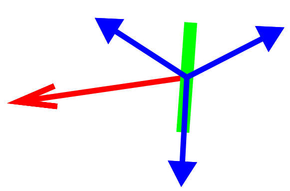
- A random central Au-Au collision at top RHIC energy, initial conditions from NeXus event generator
- These initial conditions are evolved through ideal hydrodynamics.
- Compute distribution of charged particles near midrapidity.
- See how the φ distribution evolves with p_t.



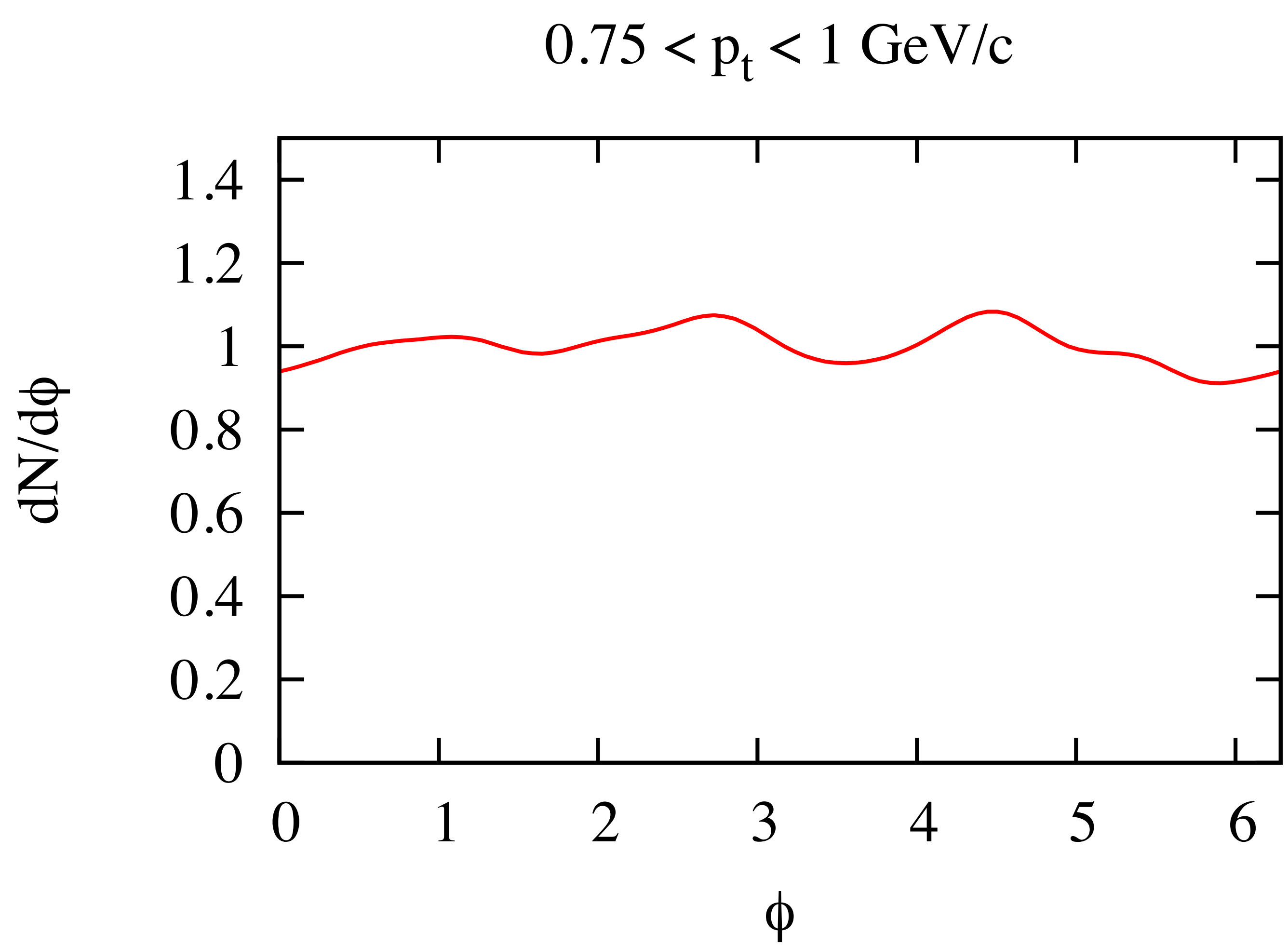
A close look at a hydro event



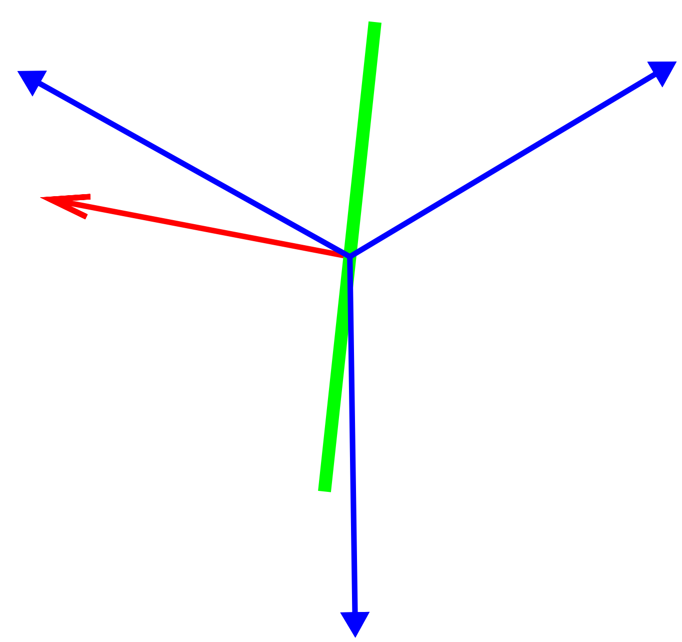
Fourier decomposition → magnitude and directions of directed, elliptic and triangular flows, all at the % level at low p_t.



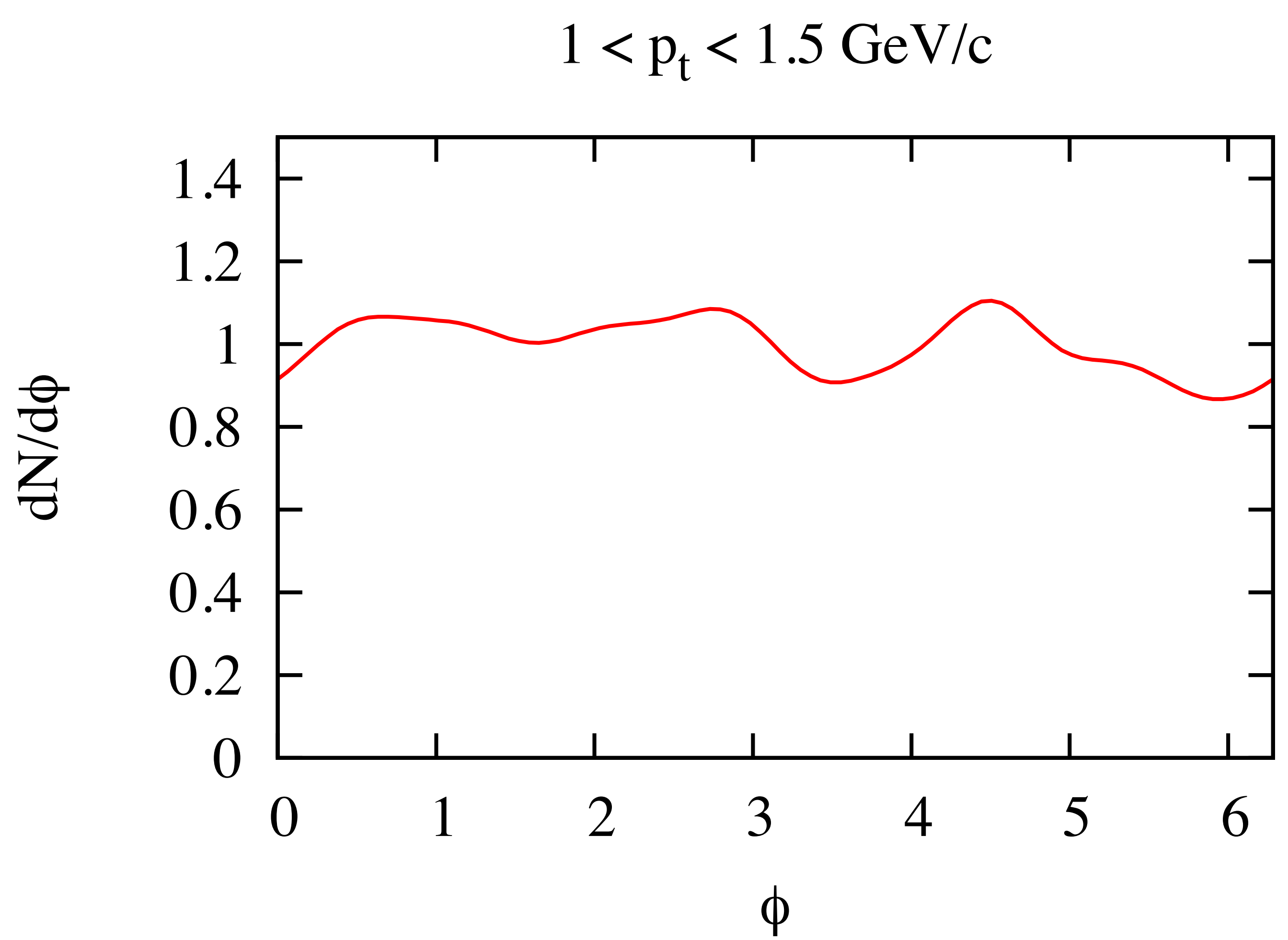
A close look at a hydro event

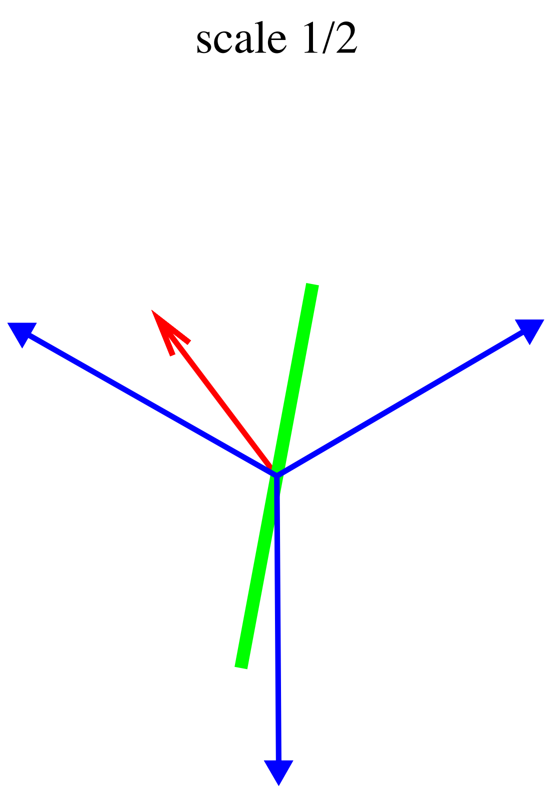


As p_t increases, anisotropic flow increases.
ψ_2 and ψ_3 change mildly ,
ψ_1 rotates more strongly

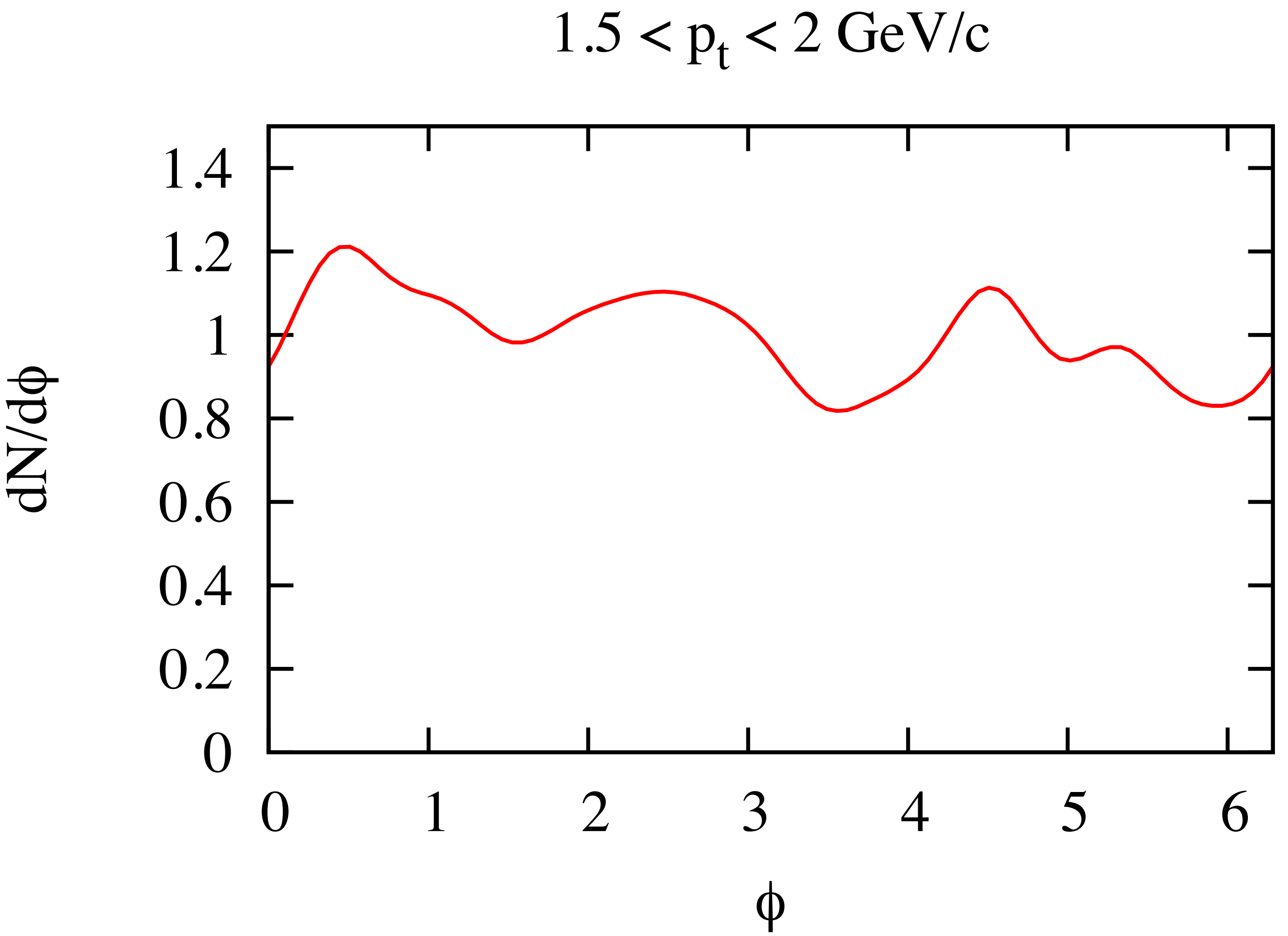


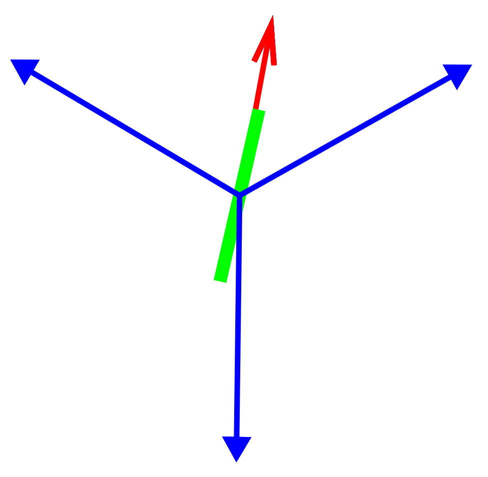
A close look at a hydro event



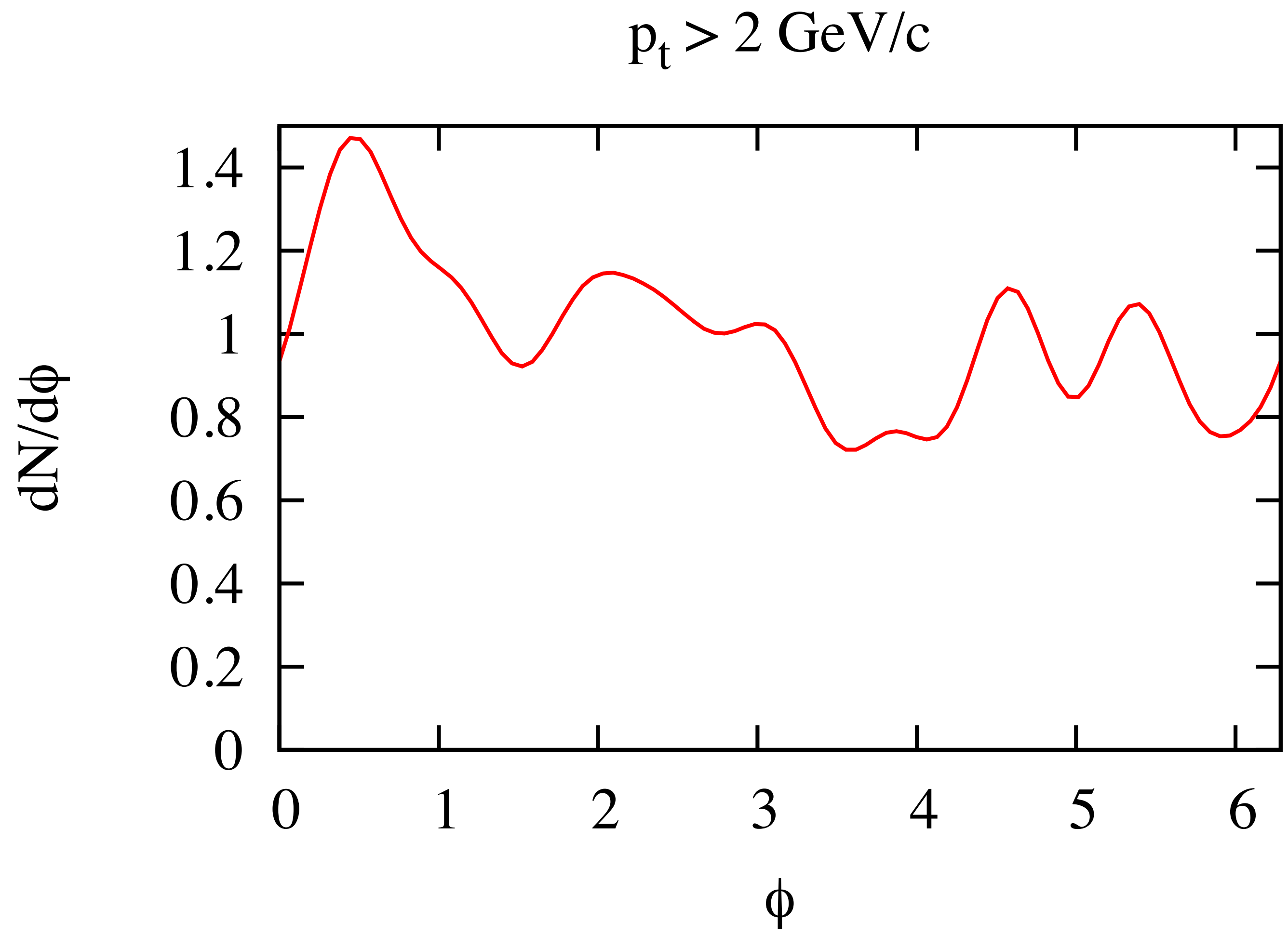


A close look at a hydro event

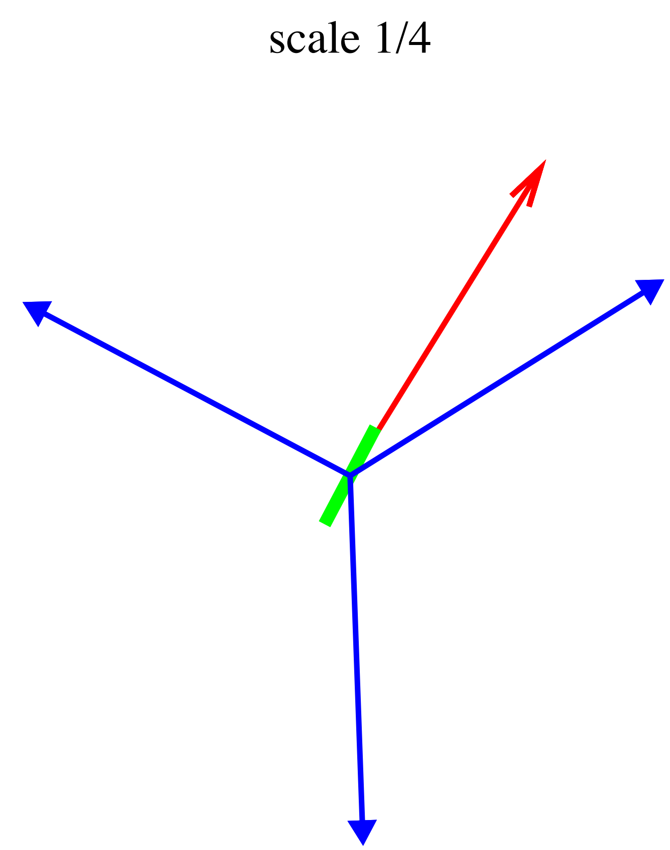




A close look at a hydro event



ψ_1 rotates by π between low p_t and high p_t, because the total transverse momentum $\int p_t\, v_1 e^{i\psi_1} \sim 0$.



Flow in data

- *Anisotropic flow is not an observable*
- The number of particles in a single event is too small to measure $V_n(p_t,\eta)$, or even the integrated v_n
  statistical error is typically 50% for event-by-event v_2, 100% for event-by-event v_3.
- Anisotropic flow can only be measured through event-averaged azimuthal correlations between particles.
- LHC experiments have recently measured the full 2-particle correlation matrix

$$V_{n\Delta}(t,a) \equiv \langle \cos n(\varphi_t - \varphi_a) \rangle = \langle e^{in(\varphi_t - \varphi_a)} \rangle$$

versus p_t of trigger and associated particles.

ALICE 1109.2501
CMS 1201.3158
ATLAS 1203.3087

Correlation matrix in hydro

- In a single event, particles are emitted independently:

$$V_{n\Delta}(t,a)=\{e^{in(\varphi_t-\varphi_a)}\}= \{e^{in\varphi_t}\} \{e^{-in\varphi_a}\}=V_n(t)V_n^*(a)$$

- The correlation matrix factorizes, which implies

$$| V_{n\Delta}(t,a) | = \sqrt{V_{n\Delta}(t,t)V_{n\Delta}(a,a)}$$

Correlation matrix in hydro

- After averaging over hydro events,

$$V_{n\Delta}(t,a) = \langle V_n(t) V_n^*(a) \rangle$$

- The correlation matrix no longer factorizes, but
  - Diagonal elements are positive: $V_{n\Delta}(t,t) = \langle |V_n(t)|^2 \rangle$
  - Non-diagonal elements measure the linear correlation between $V_n(t)$ and $V_n(a)$ and satisfy a triangular inequality, (instead of equality implied by factorization)

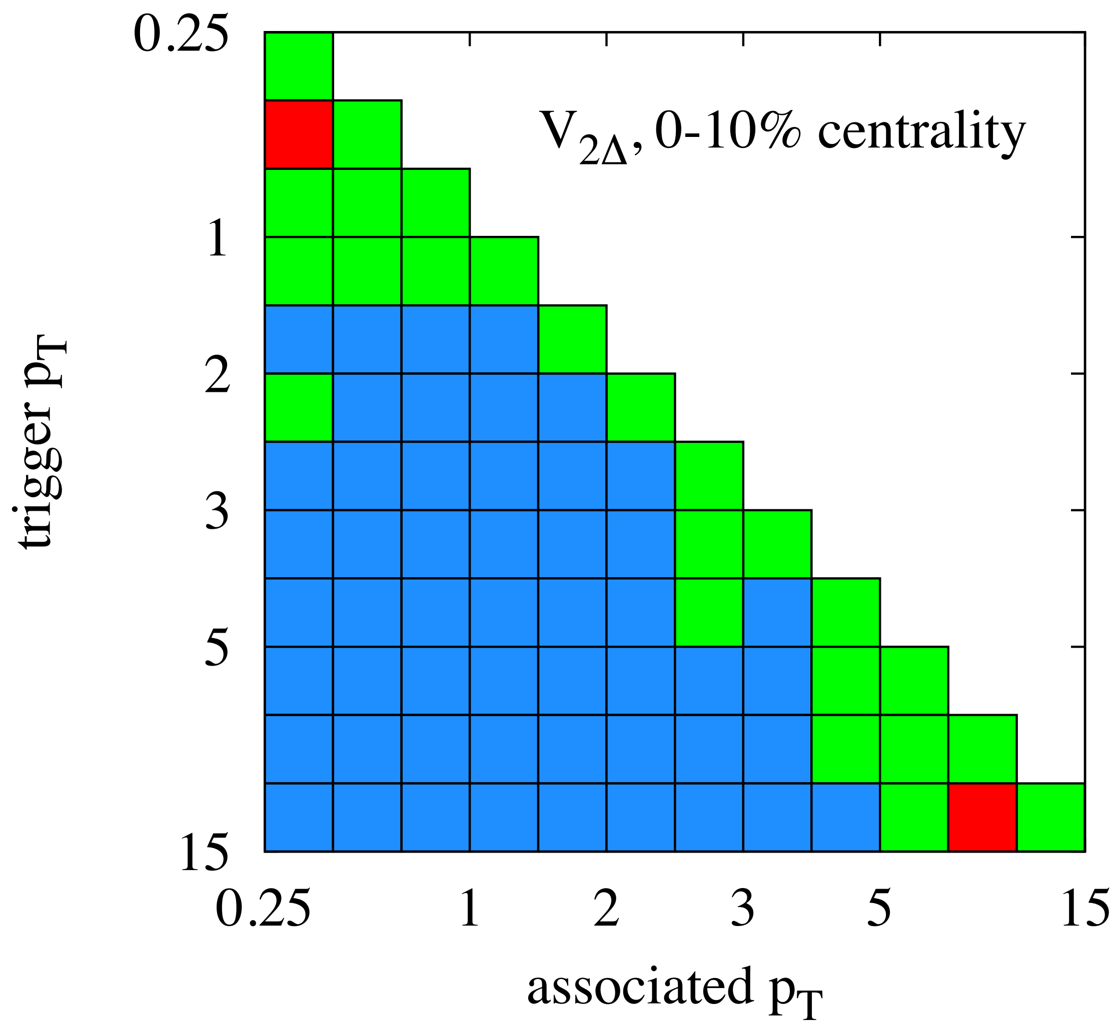
$$| V_{n\Delta}(t,a) | \leq \sqrt{V_{n\Delta}(t,t) V_{n\Delta}(a,a)}$$

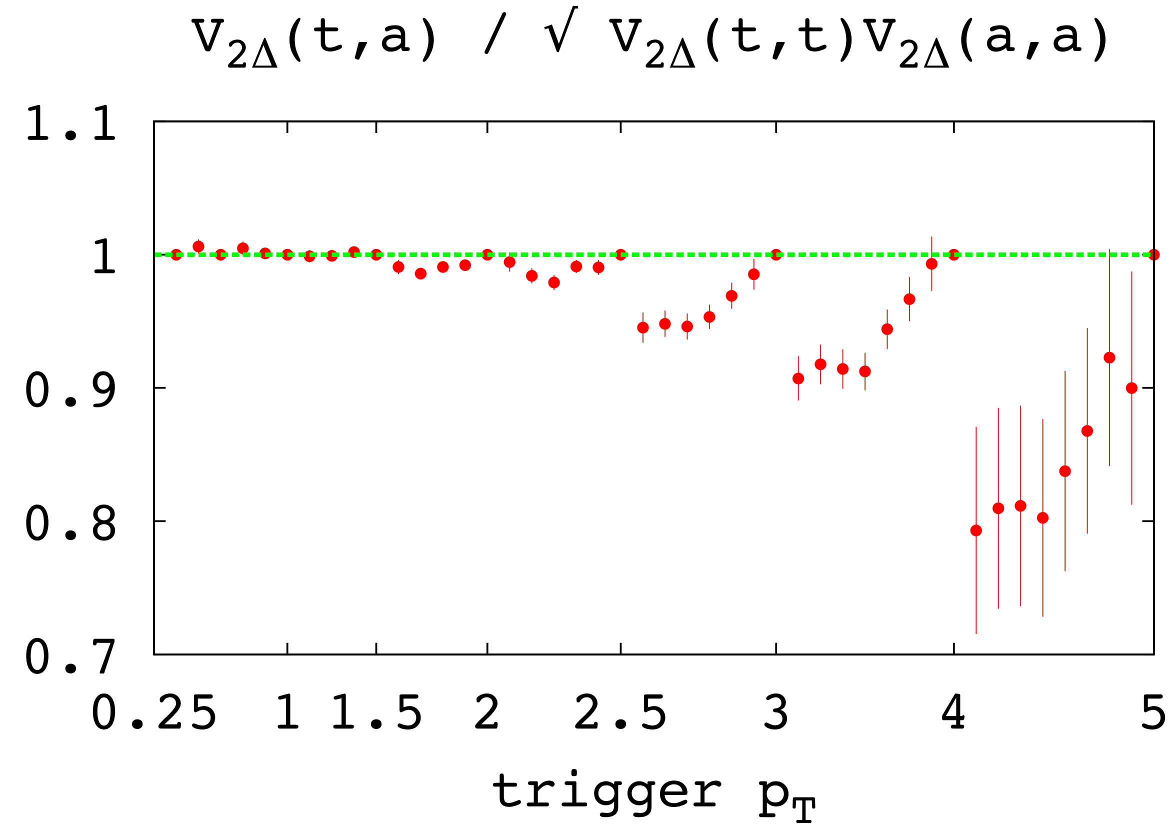
(Gardim, Grassi, Hama, Luzum, JYO, in preparation)

Are data compatible with flow?

- Do data for $V_{n\Delta}$ show
  - Factorization?
  - Strict inequality, i.e. flow fluctuations?
  - Breaking of inequalities (i.e. nonflow)?
- I use ALICE data for 0-10% Pb-Pb collisions.

Is $V_{2\Delta}$ compatible with elliptic flow?





Colors mean:

Factorization OK

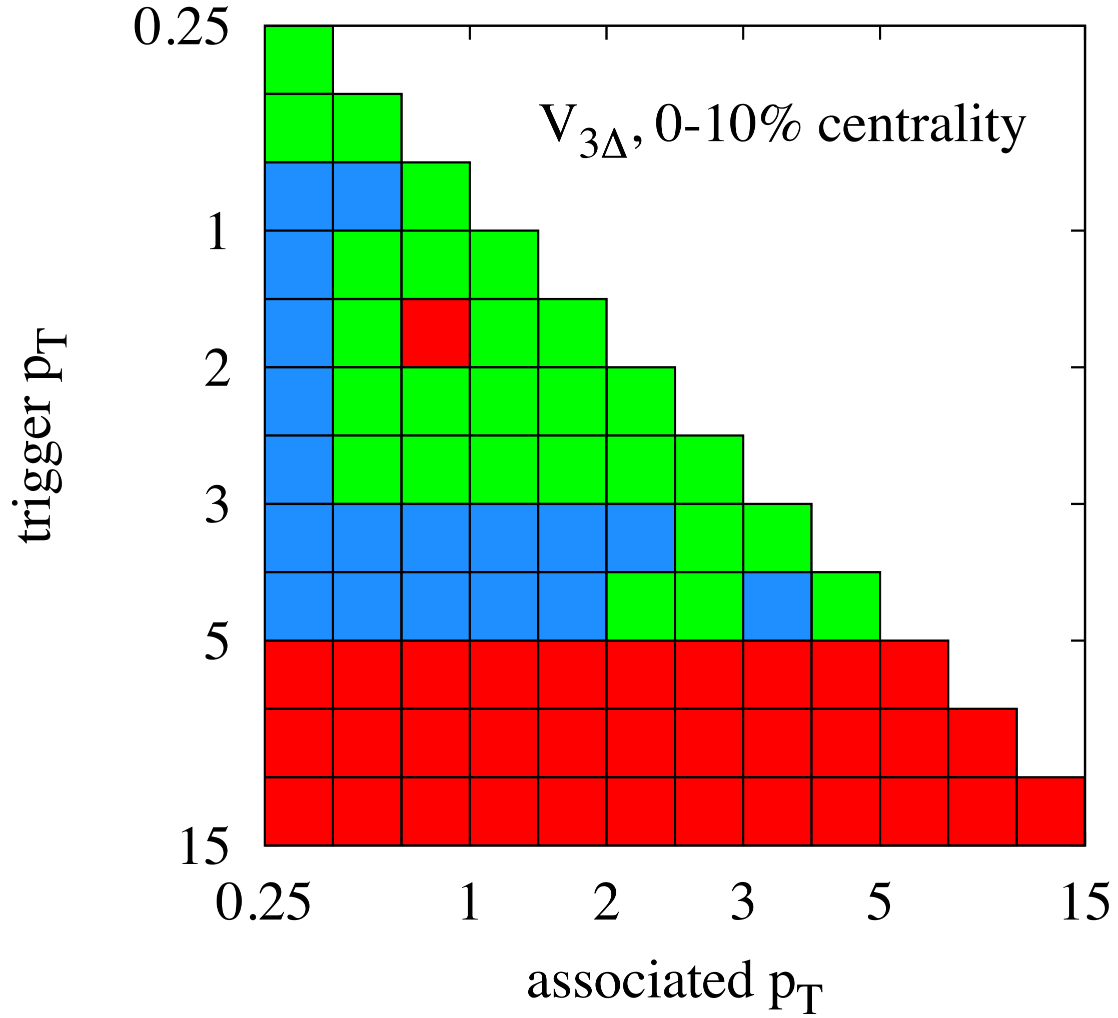
Strict inequality

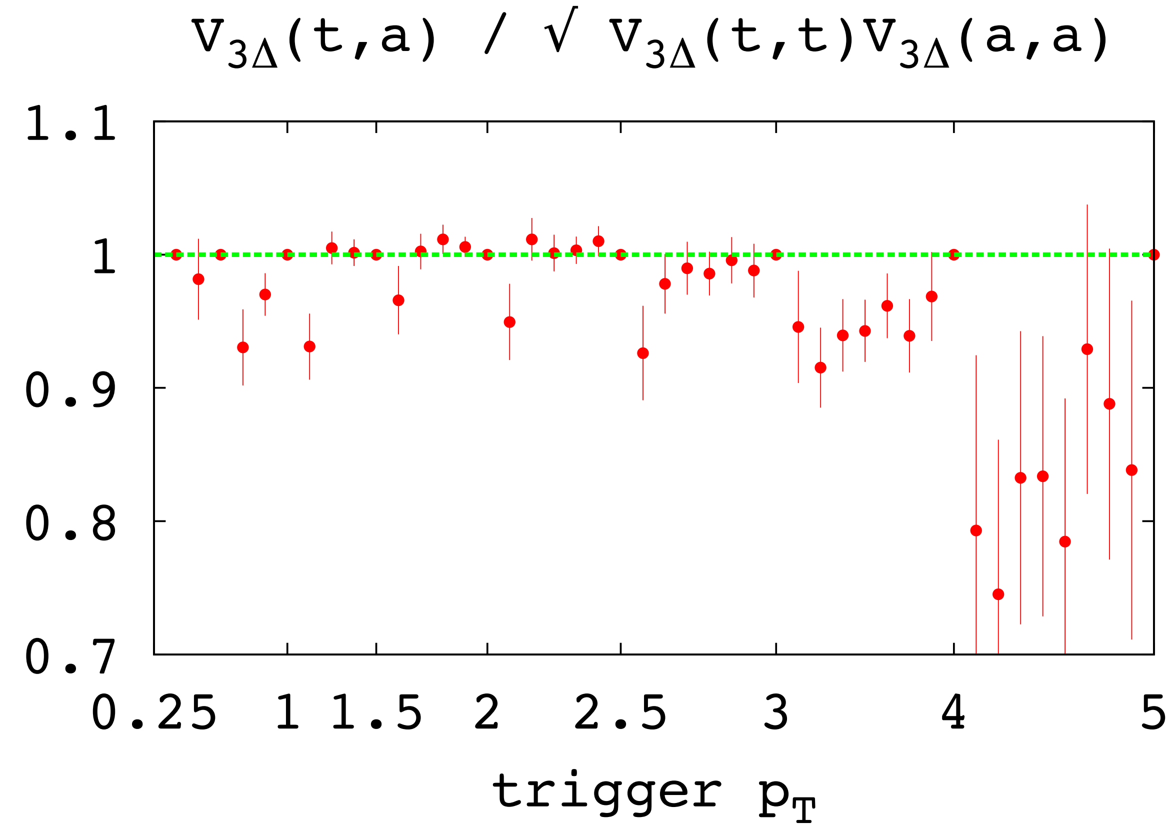
Nonflow

Data everywhere compatible with flow, with evidence of flow fluctuations

Is $V_{3\Delta}$ compatible with triangular flow?

Alver and Roland 1003.0194





Colors mean:

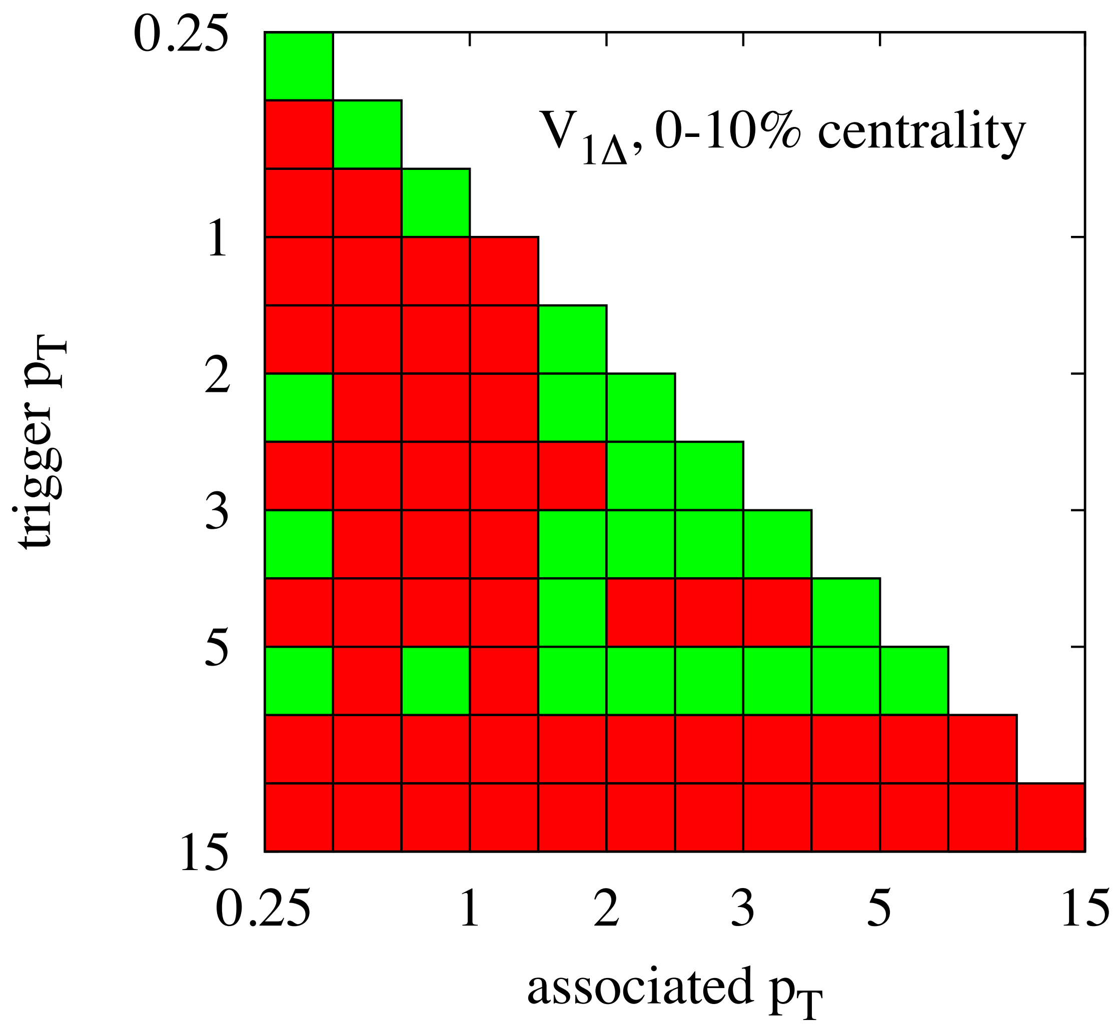
Factorization OK

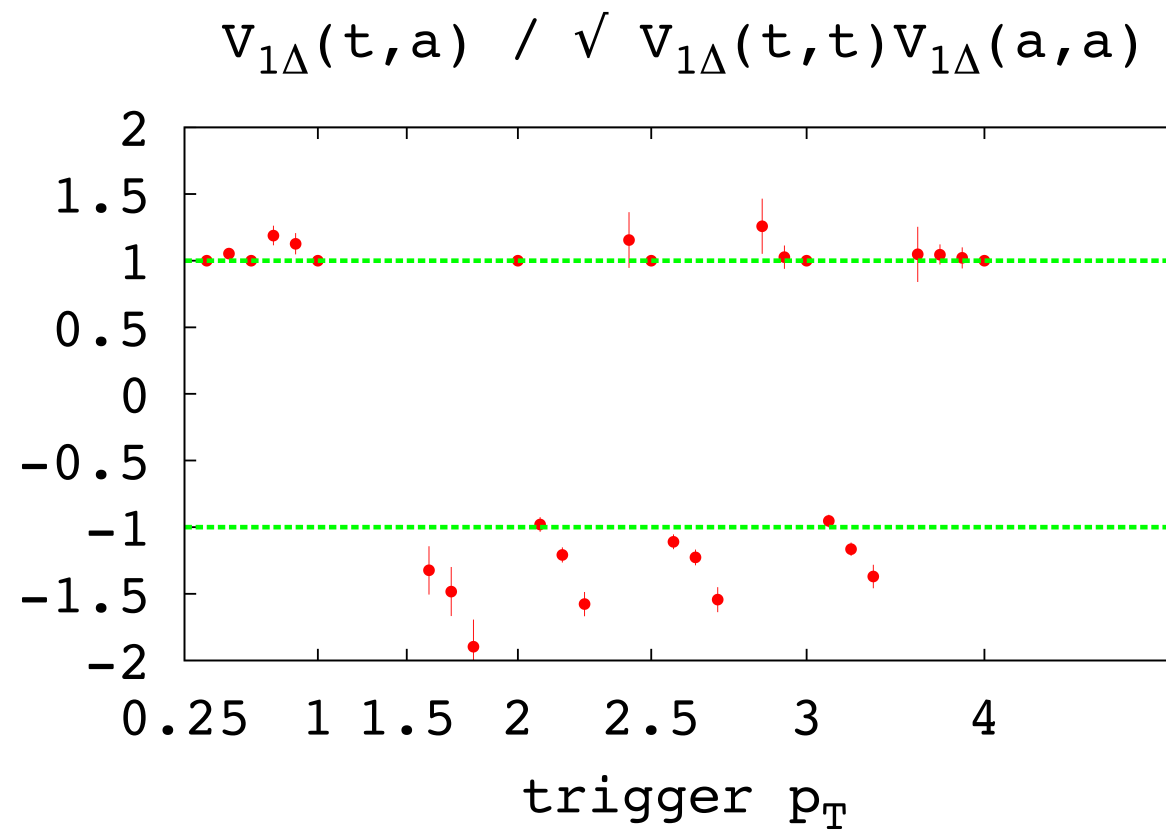
Strict inequality

Nonflow

Evidence for nonflow at high p_t. Can be explained by away-side jet

Is $V_{1\Delta}$ compatible with directed flow?





Colors mean:

Factorization OK

Strict inequality

Nonflow

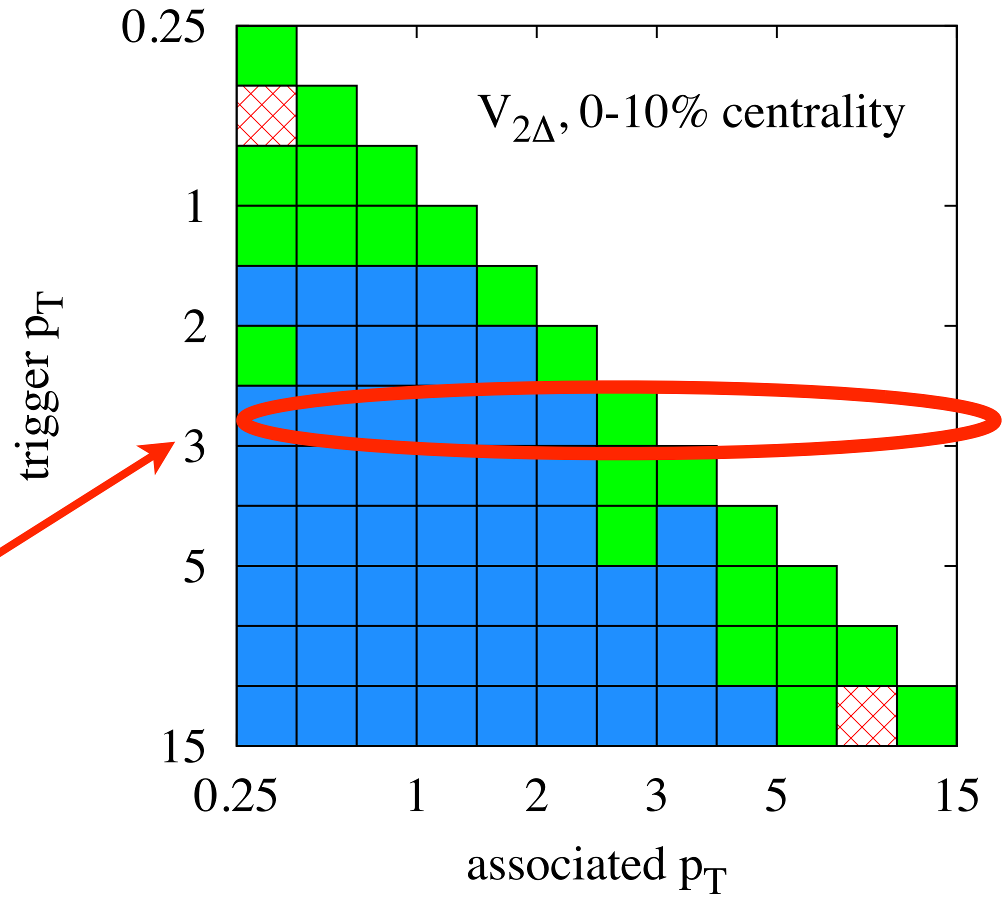
Clear evidence for nonflow= additional correlation from global momentum conservation

talk J. Jia, 4A

Poster E. Retinskaya

Hydro versus data

- Eventually, hydro should address the full structure of correlations.
- We are not there yet...
- Most comparisons so far: limited to measurements of single-particle $v_n(p_t)$: typically, a single particle correlated with all particles in an "event-plane" detector.
- Amounts to averaging the correlation matrix over a line



Initial conditions

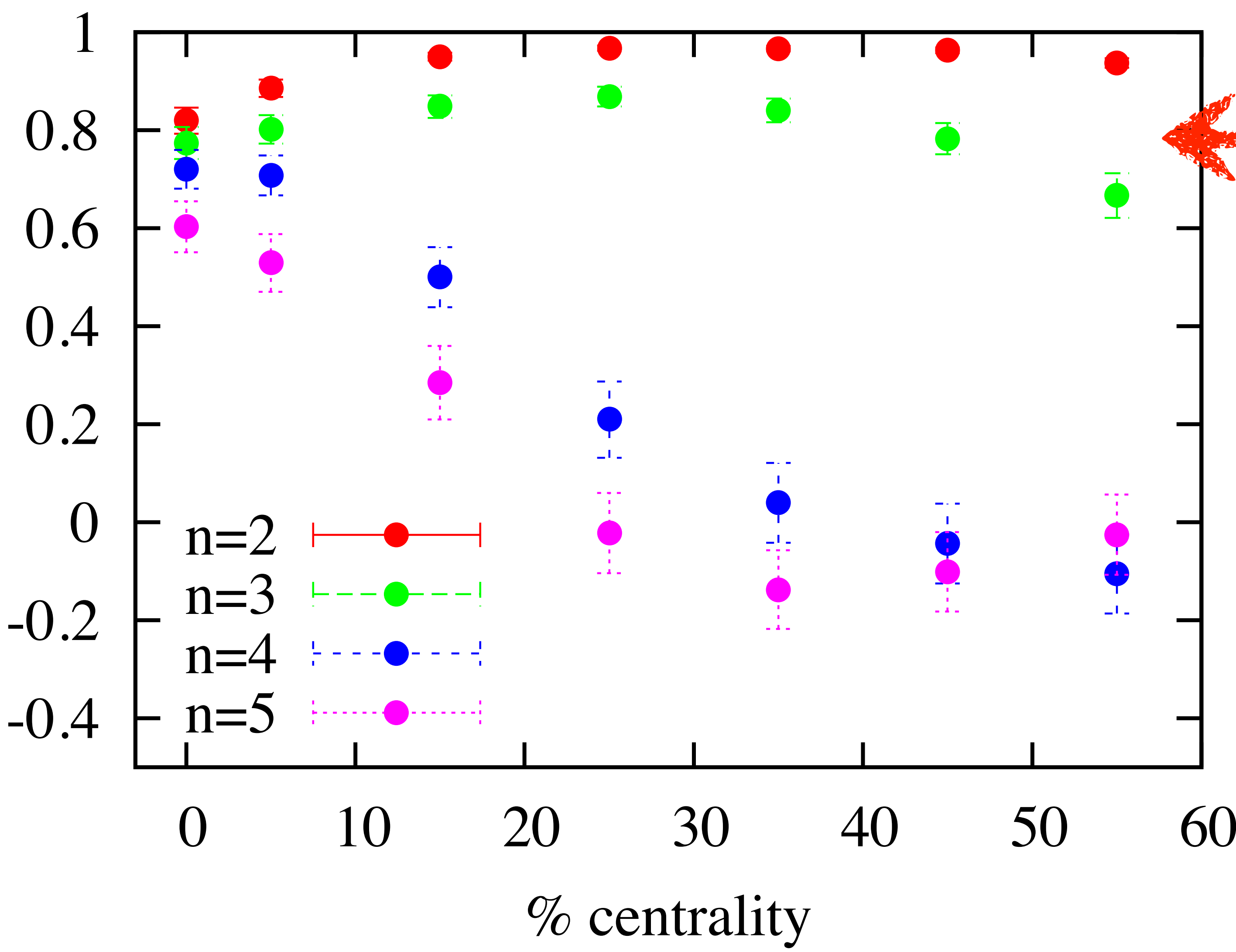
- The dominant uncertainty in hydro/data comparison is the uncertainty in initial conditions.
  The KLN model, aka CGC, has a larger eccentricity than the Glauber model, therefore it predicts a larger elliptic flow.
- New observables (e.g. v_3) are sensitive to fluctuations, which also come with uncertainties:
  - The scale and magnitude of fluctuations are poorly constrained (K. Dusling, earlier in this session)
  - The hydro response to initial density is not as well understood for higher harmonics as for elliptic flow (next slide)

Hydro response

How is the final particle distribution correlated with the initial density profile in the same Fourier harmonic?

Define $\varepsilon_n \equiv -\{r^n e^{in\varphi}\}/\{r^n\}$, where {...}=average over initial density

Petersen et al 1008.0625



Linear correlation between initial ε_n and final V_n (both complex) in ideal hydro

from Gardim et al 1111.6538

(see also Qiu & Heinz 1104.0650)

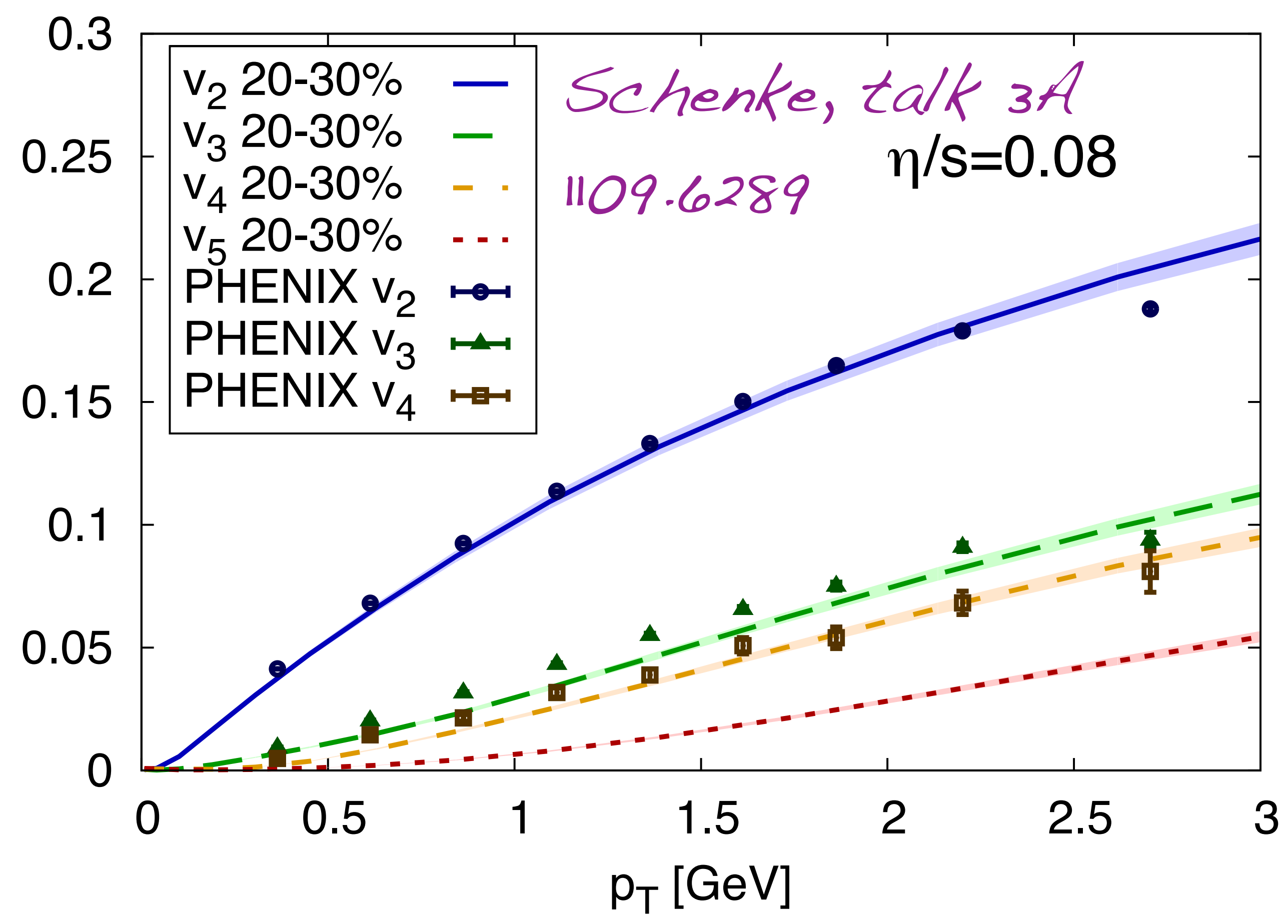
Strong for v_2 and v_3

v_4 and v_5 need more work

(Talks Li Yan, 1A; F. Gardim, 6D)

QGP viscosity (Huichao Song today)

- Viscosity of hot QCD still unknown
- Higher harmonics have a larger sensitivity to the shear viscosity η
- But they also depend on initial conditions (Luzum, talk 2A)
- The fact that a particular model matches data does not mean it has the correct η/s
  (see poster 52, F. Grassi)
- Bulk viscosity: talk by T. Schaefer (3A)

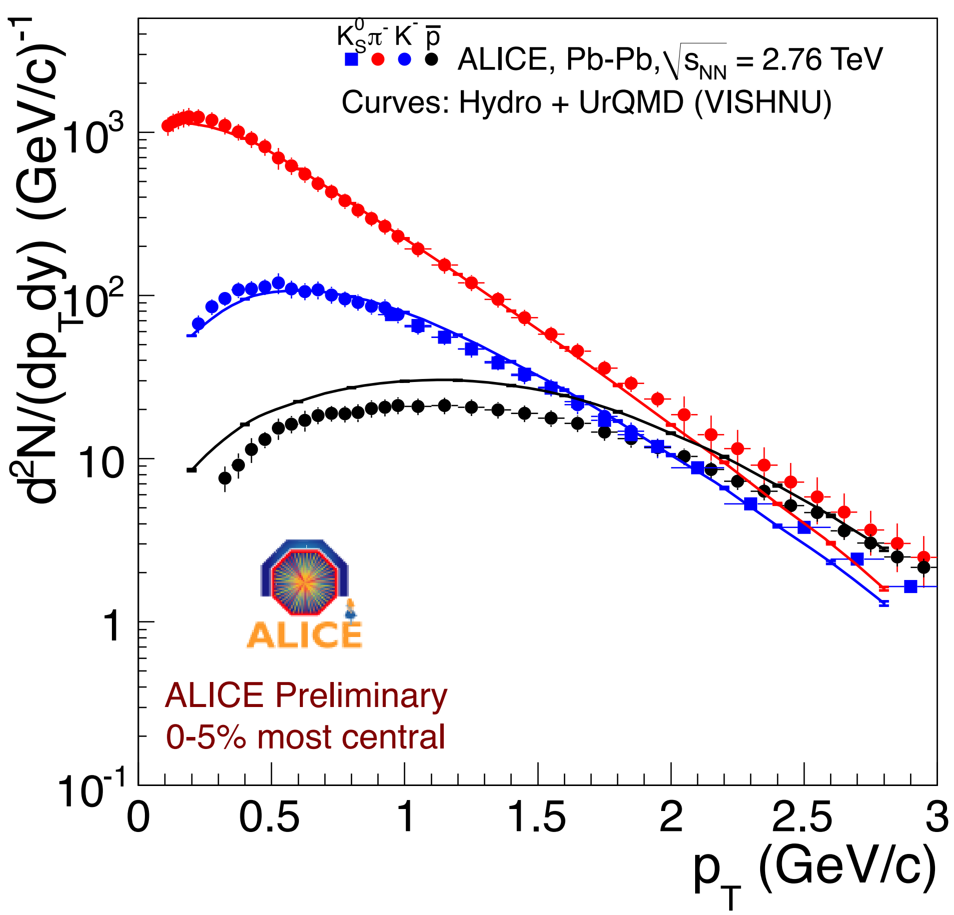


Hadronic phase

Interactions are not as strong among hadrons than among quarks and gluons. Viscosity may be too large for hydro to apply.

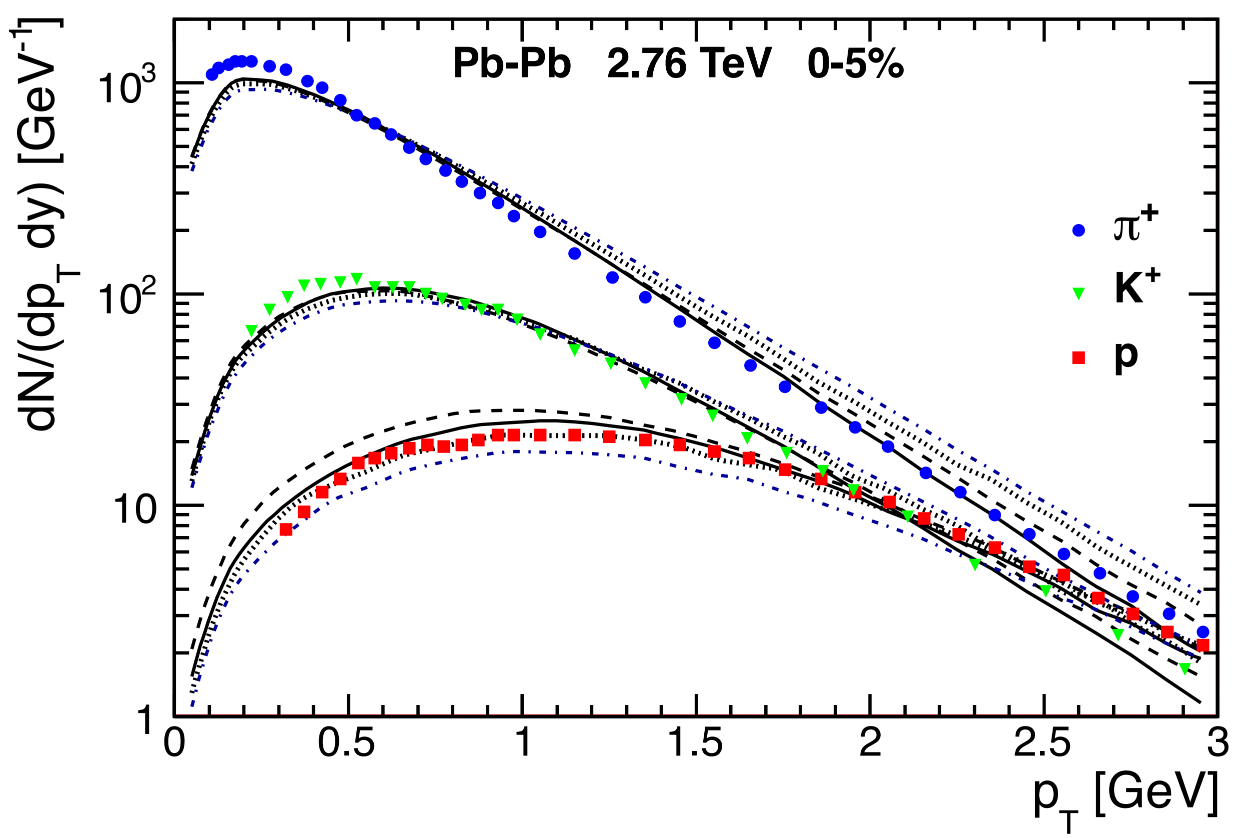
Replacing hydro with a *hadronic afterburner* helps reproducing *identified* hadron spectra and v2

Song 1103.2380



Bulk viscosity in hydro has qualitatively the same effect

Bozek & Wyskiel 1203.6513



Author/Presenter	QM2012	arXiv	initial fluctuations	3+1d	viscous	afterburner
Huichao Song	1D	1207.2396			✓	✓
Teaney/Yan	1A	1206.1905			✓	
Chun Shen	1A	1202.6620			✓	
Sangyong Jeon	2A		✓	✓	✓	✓
Matt Luzum	2A				✓	
Piotr Bozek	2C	1204.3580	✓	✓	✓	
Björn Schenke	3A	1109.6289	✓	✓	✓	
Dusling/Schaefer	3A	1109.5181			✓	
Chiho Nonaka	3A	1204.4795	✓	✓	✓	
Ryblewski/Florkowski	3D	1204.2624		✓		
Longgang Pang	4D	1205.5019	✓	✓		
Hannah Petersen	VA	1201.1881	✓	✓		✓
Fernando Gardim	6D	1111.6538	✓	✓		
Zhi Qiu	29	1208.1200	✓		✓	
Gardim/Grassi	52	1203.2882	✓	✓		
Katya Retinskaya	57	1203.0931			✓	
Hirano/Murase	255	1204.5814	✓	✓		✓
Holopainen/Huovinen	284	1207.7331	✓			
Asis Chaudhuri		1112.1166	✓		✓	
Iurii Karpenko		1204.5351		✓		✓
Yu-Liang Yan		1110.6704		✓		✓
Josh Vredevoogd		1202.1509		✓	✓	
Ron Soltz		1208.0897			✓	✓
Rafael Derradi de Souza		1110.5698	✓	✓		

Other upcoming hydro-related talks/posters at QM2012

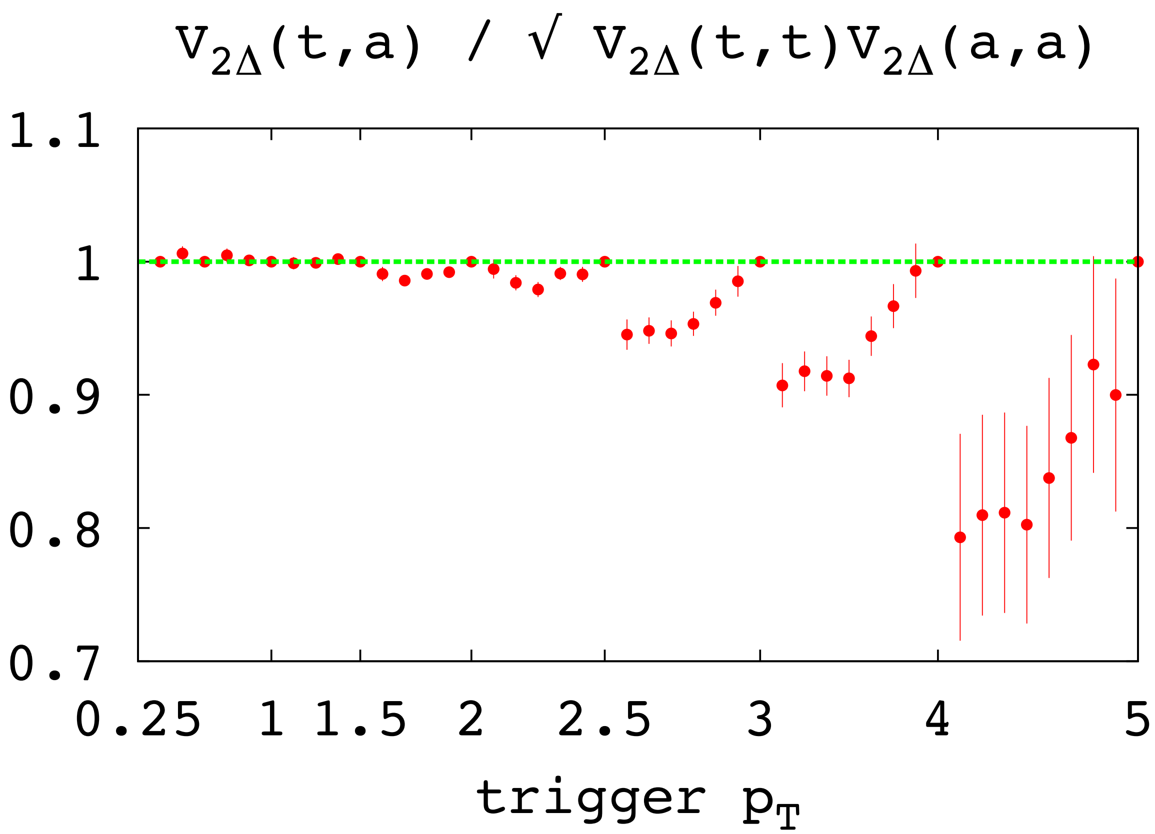
Author/Presenter	QM2012	arXiv
Gabriel Denicol	1A	1202.4551
Kapusta/Stephanov	6D	1112.6405
Andrej El	7E	1206.3465
Laszlo Csernai	23	1112.4287
Amaresh Jaiswal	48	1204.3779
Ioannis Bouras	80	1208.1039
Flörchinger/Wiedemann	97	1108.5535
Harri Niemi	248	
Mate Csanad	295	1205.5965
Gavin/Moschelli	296/354	1205.1218
Jaki Noronha-Hostler	304	
Pilar Staig	365	
Akihiro Monnai	388	1204.4713
Philipe Mota	615	

Perspective

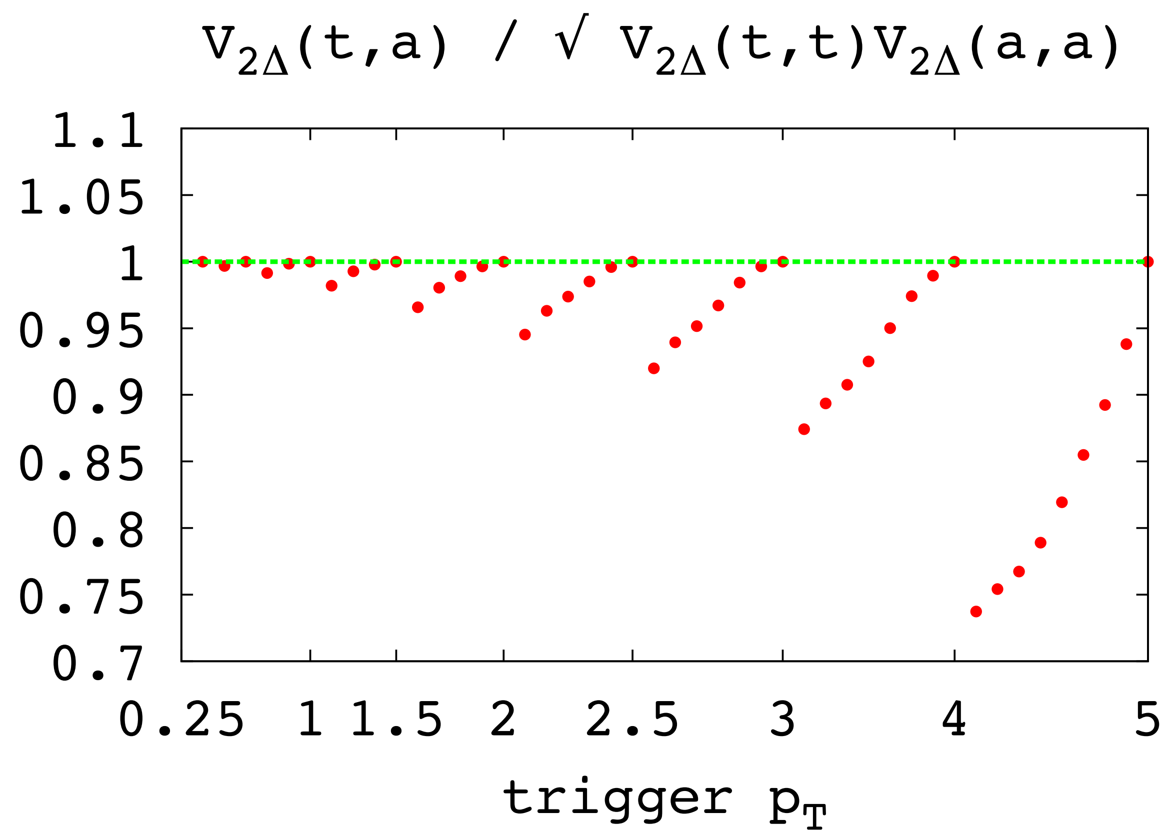
- 2000: Hydro explains the large elliptic flow
- 2010: Hydro might also predict all other harmonics!
  Alver & Roland 1003.0194
- 2011: Predictions for new observables and LHC
- 2012: We need to understand all correlations
  - p_t dependence
  - rapidity dependence: *long-range* correlations, but how long?
    (Bozek et al, 1011.3354; Xiao et al, 1208.1195)
  - Higher-order correlations
    (ATLAS collaboration, 1208.1427 Qiu &Heinz 1208.1200)
  - Beyond independent particles: fluctuations and correlations in hydro
    (talks Bozek 2C, Stephanov 6D)

Backup slides

Factorization also breaks down in hydro



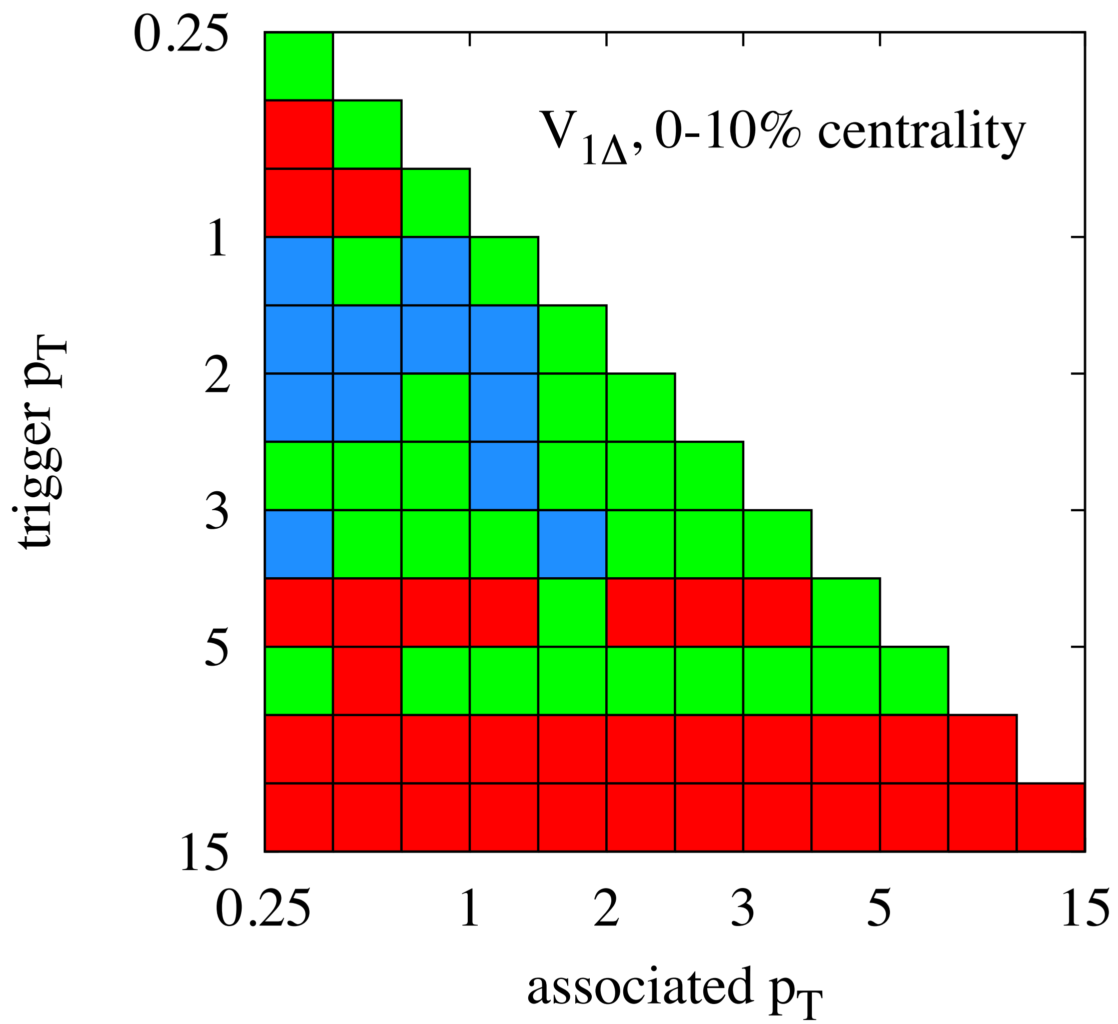
data
Pb-Pb 2.76 TeV
0-10% centrality



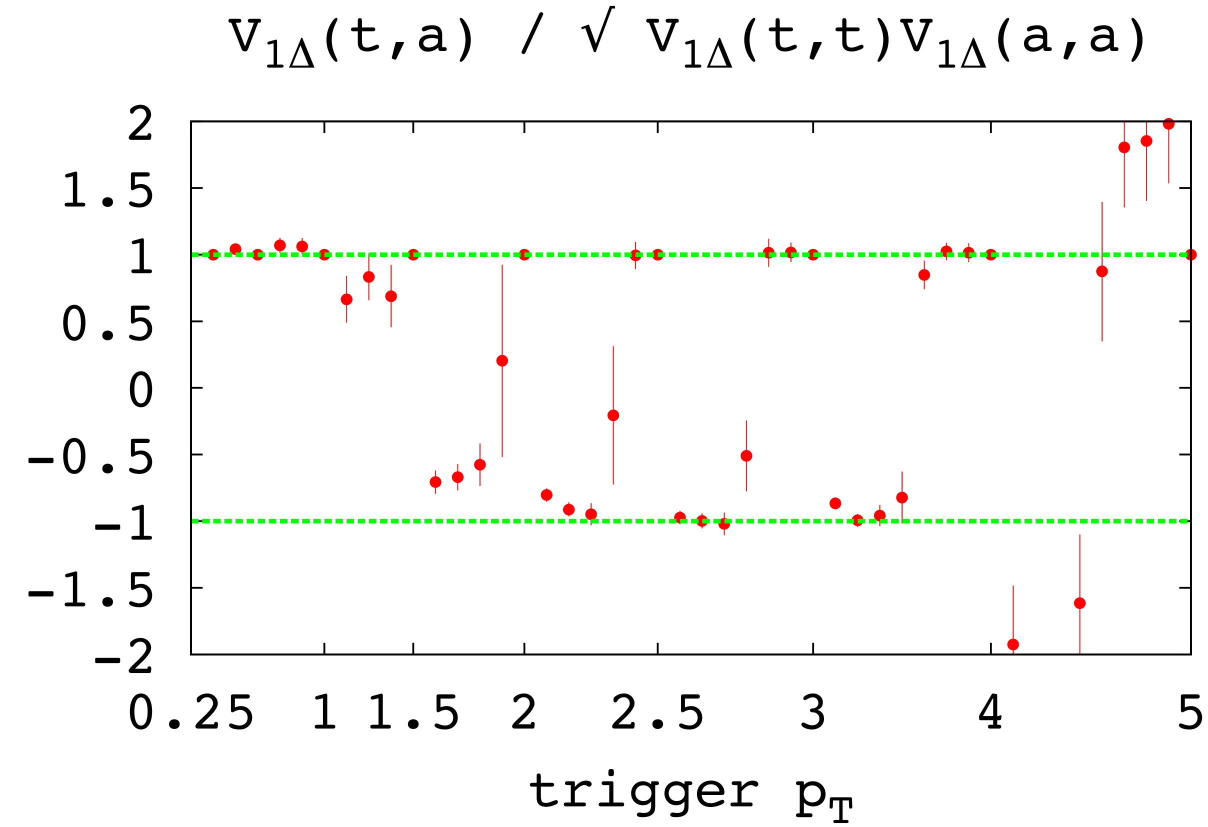
hydro
Au-Au 200 GeV
20-30% centrality

Gardim, Grassi, Luzum, JYO, in preparation

$V_{1\Delta}$ corrected for momentum conservation



Colors mean:
Factorization OK
Strict inequality
Nonflow



Data compatible with directed flow after subtraction of momentum conservation.
Note that v_1 changes sign versus p_t
(Poster Ekaterina Retinskaya)