QCD phase transition, hydrodynamics, hadronization session (from the experimental point of view)

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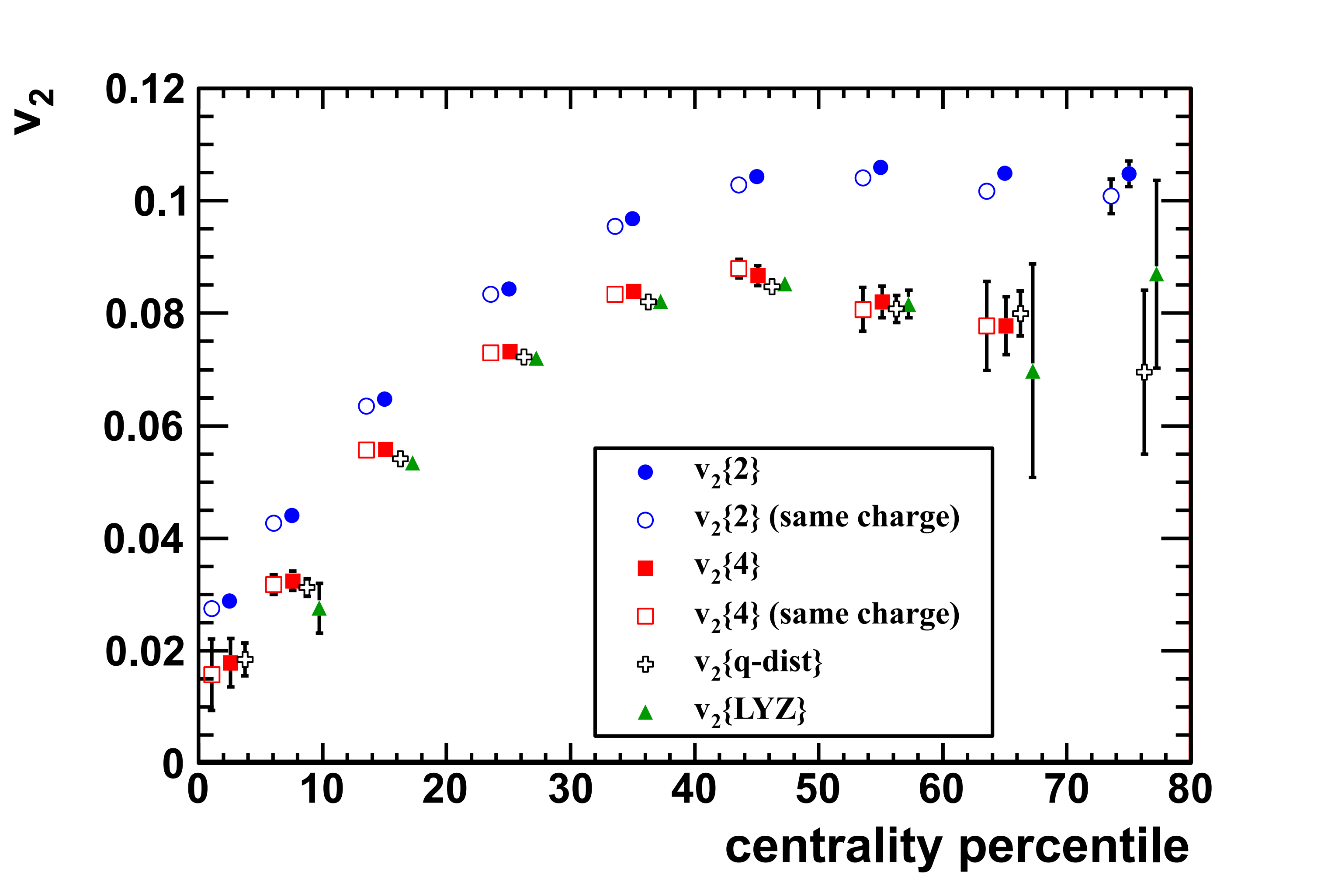
Disclaimer

What you will not see: Not published data; for this you have to wait for them to be presented by the people that performed the analysis!

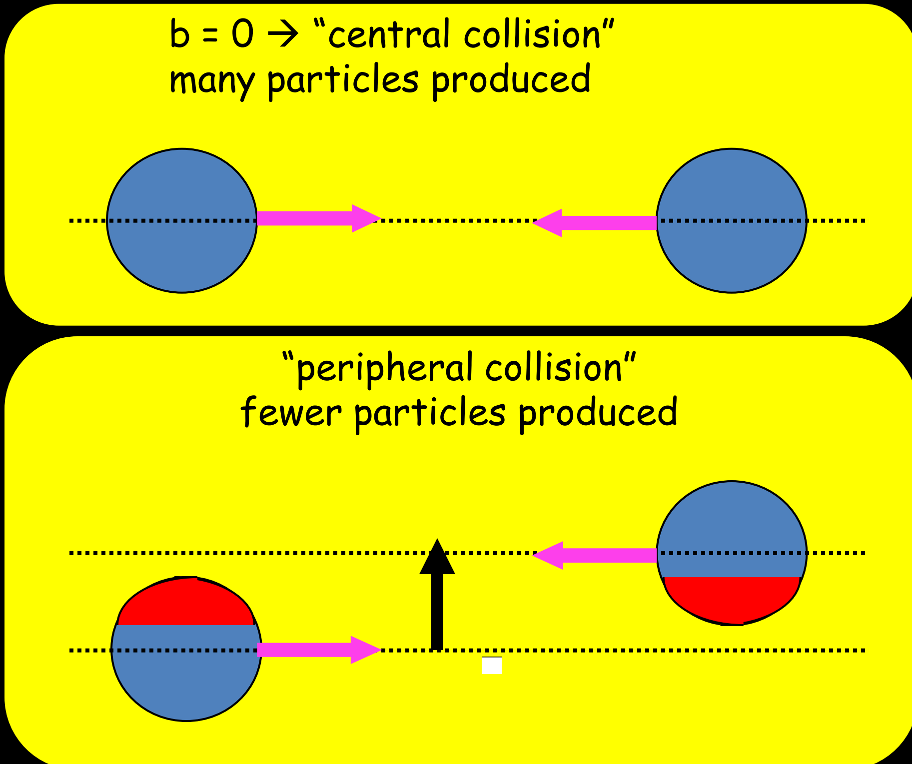
Many thanks to Ante Bilandzic, Mikolaj Krzewicki, Paul Kuijer, Mike Lisa, Ilya Selyuzhenkov, Raimond Snellings, Sergey Voloshin, for the enlightening discussions, feedback and contributions!!!

Elliptic flow measurement



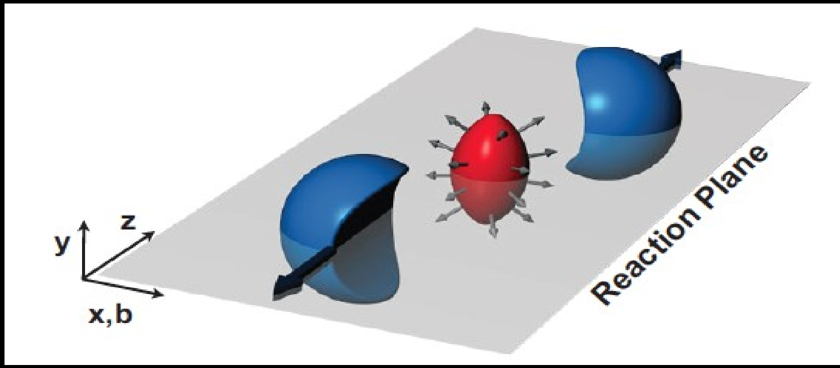
K. Aamodt et al. (ALICE Collaboration), Phys. Rev. Lett. **105**, 252302 (2010)

Why does elliptic flow develop?



- In non central collisions, the coordinate space configuration is anisotropic (almond shape).
  - The initial momentum distribution isotropic (spherically symmetric)
- The interactions among constituents generate a pressure gradient which transforms the initial coordinate space anisotropy into the observed momentum space anisotropy
  - anisotropic flow quantified by v_2
- Evidence of collective motion
- Connection to the equation of state

Reaction plane defined by the beam axis and the impact parameter



$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+2\sum_{n=1}^{\infty} v_n \cos\left[n\left(\phi-\Psi_{RP}\right)\right]\right)$$

$$v_n\left(p_t, y\right)=\left\langle \cos\left[n\left(\phi-\Psi_{RP}\right)\right]\right\rangle$$

S. Voloshin and Y. Zhang, Z. Phys. **C70**, 665 (1996)

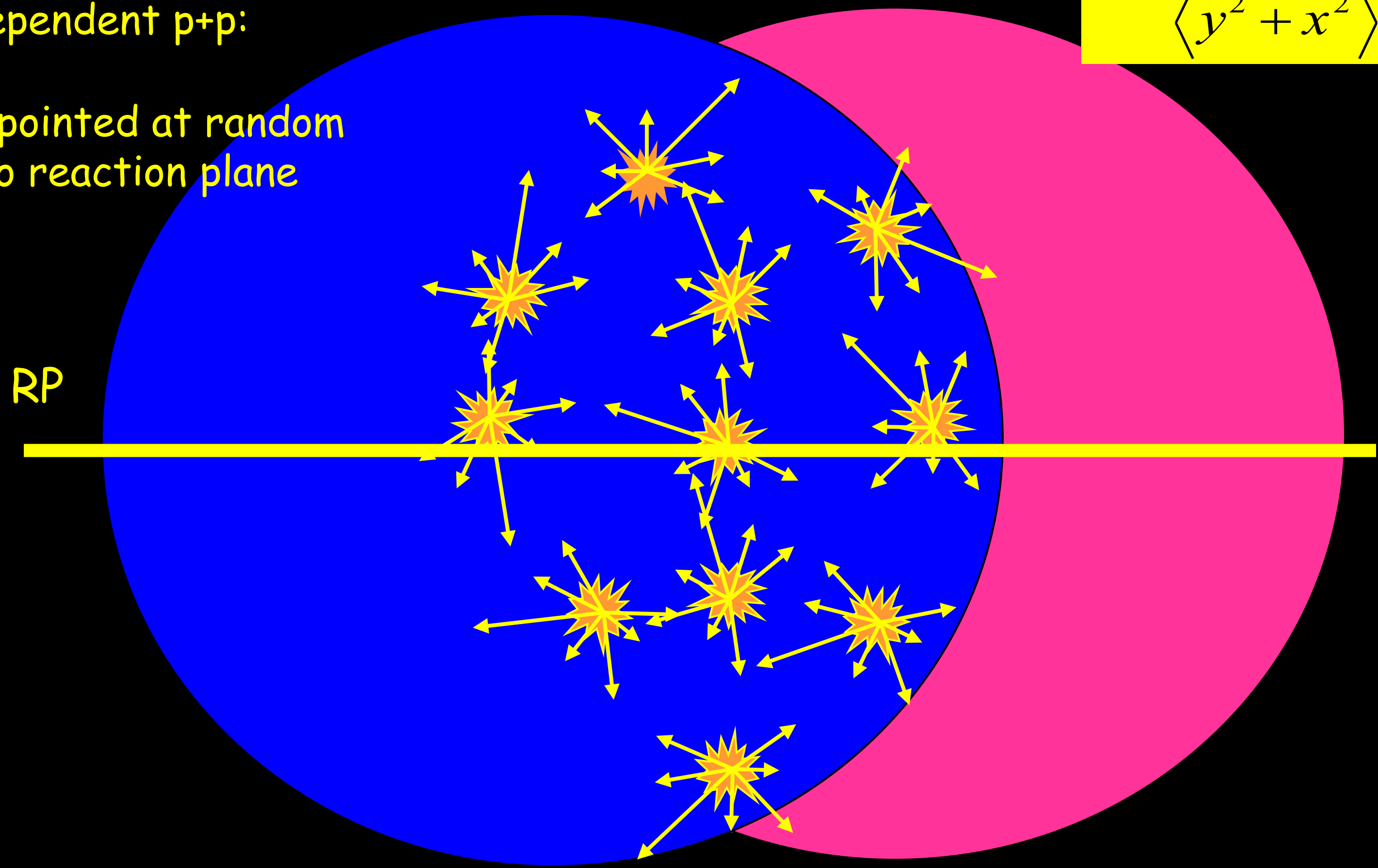
Elliptic flow

Courtesy of Mike Lisa

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

1) Superposition of independent p+p:

momenta pointed at random
relative to reaction plane



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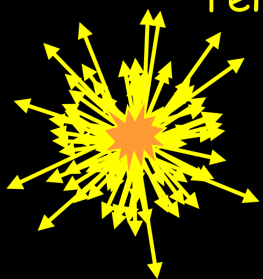
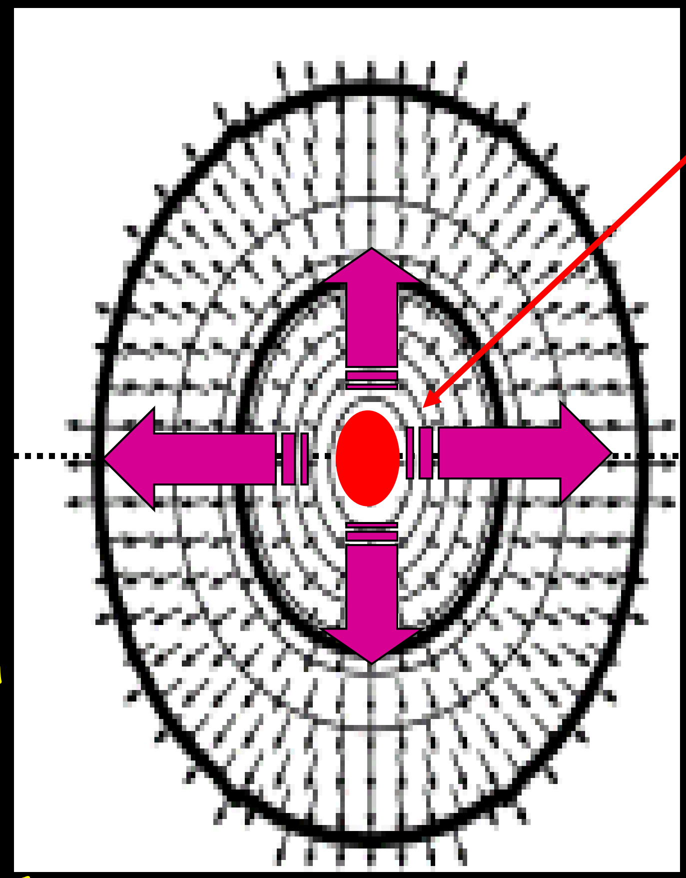


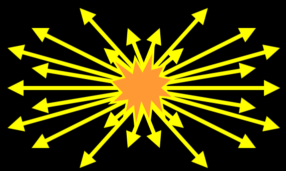


high density / pressure at center

"zero" pressure in surrounding vacuum

2) Evolution as a **bulk** **system**

Pressure gradients (larger in-plane) push bulk "out" → "flow"



more, faster particles seen in-plane

Elliptic flow

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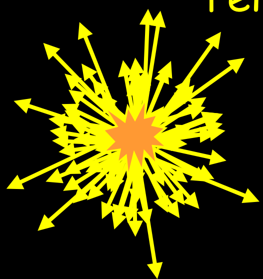

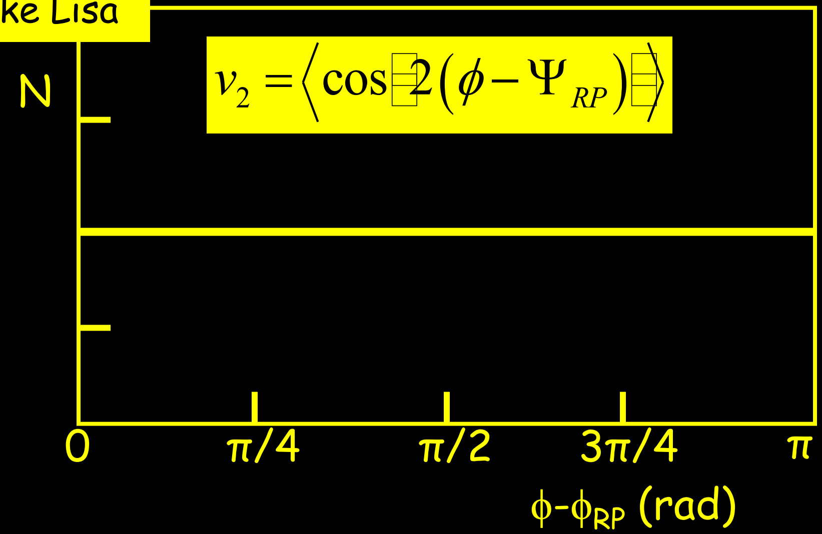

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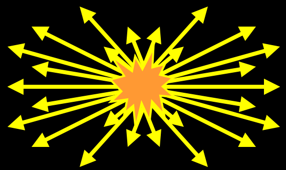

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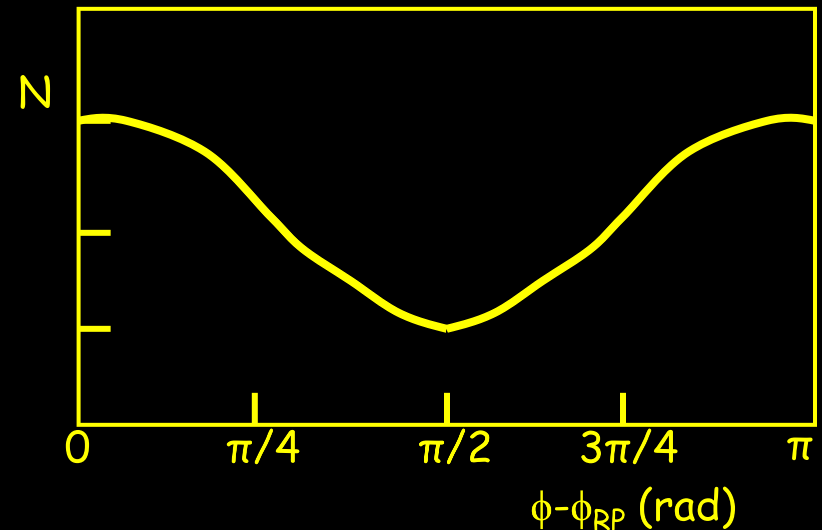
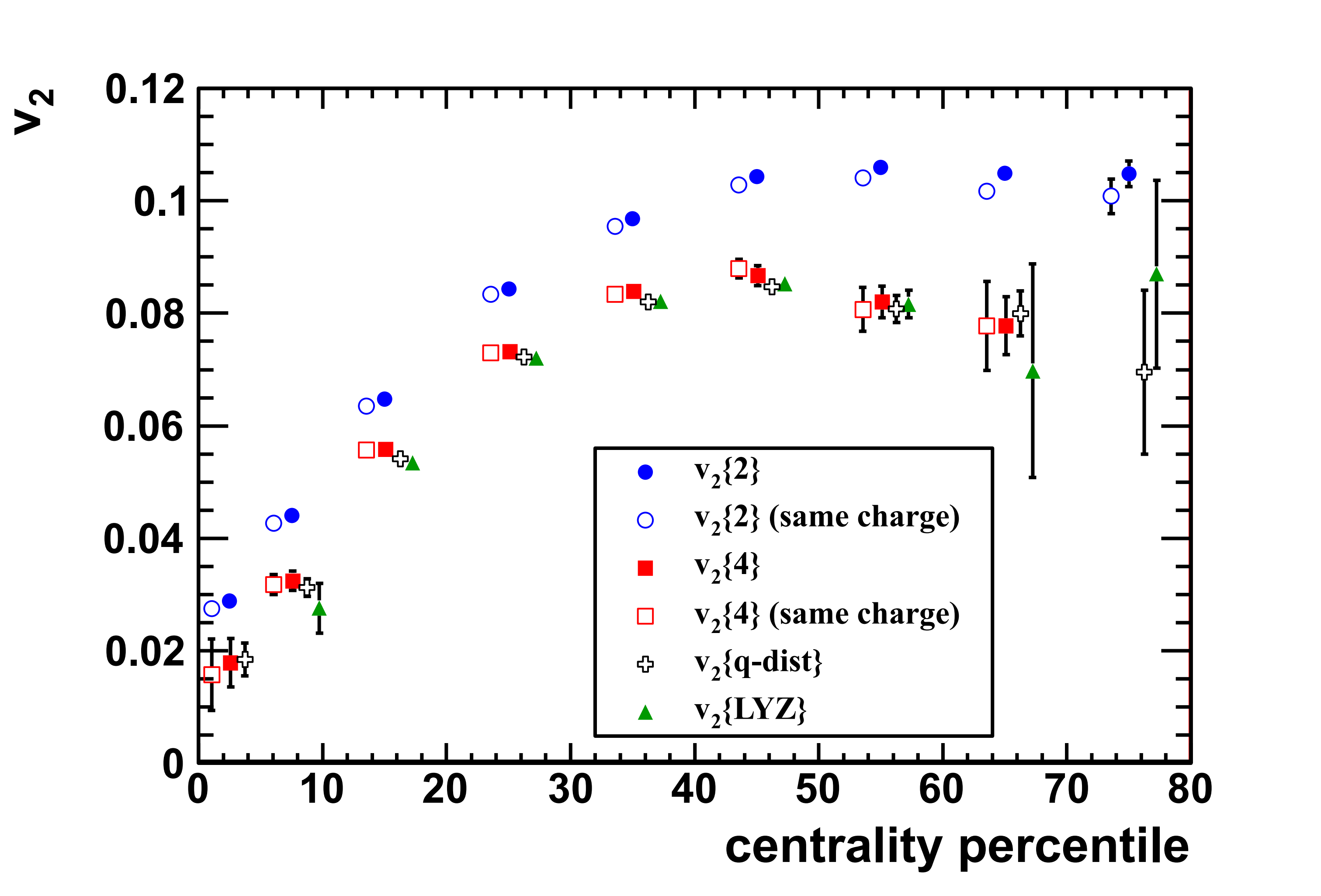


What is the actual value of v_2?



Different methods are affected in a different way by the background. We have to use as many as possible!

Non-flow contributions

- Correlations not connected to the reaction plane (resonances, jets, HBT,…)
- Suppression using multi-particle correlation techniques, η-gap analyses, different charge combinations,…

2-particle correlations

$$c_n\{2\} = \langle v_n^2 \rangle + \delta_2$$

4- (multi-) particle correlations

$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2\langle\langle 2 \rangle\rangle^2 =$$

$$= \langle v_n^4 \rangle + 4\langle v_n^2 \rangle \delta_2 + 2\delta_2^2 - 2\left(\langle v_n^2 \rangle + \delta_2\right)^2 + \delta_4 =$$

$$= -\langle v_n^4 \rangle + \delta_4$$

$$\delta_2 \propto 1/M \Rightarrow v_n >> 1/M^{1/2}$$

$$\delta_4 \propto 1/M^3 \Rightarrow v_n >> 1/M^{3/4}$$

- For a typical Pb-Pb collision at LHC energies in 30-40% centrality, M ~ 425
  - v_n >> 4.8% for the 2-particle correlation technique
  - v_n >> 1.1% for the 4-particle correlation technique

A. Bilandzic, R. Snellings, S. Voloshin, Phys. Rev. **C83**, 044913 (2011)

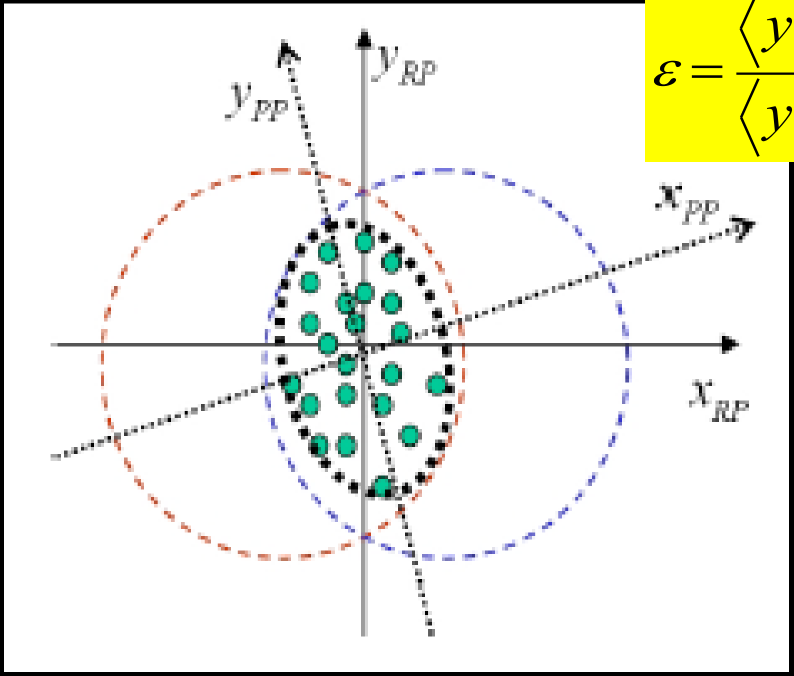
Flow fluctuations

- Originating from the fluctuations in the initial collision geometry.
  - The participant plane Ψ_{PP}, that fluctuates from event to event

$$\langle v_2^2 \rangle = \langle v_2 \rangle^2 + \sigma_v^2$$

$$\langle v_2^4 \rangle = \langle v_2 \rangle^4 + 6\sigma_v^2 \langle v_2 \rangle^2$$

$$\langle v_2^6 \rangle = \langle v_2 \rangle^6 + 15\sigma_v^2 \langle v_2 \rangle^4$$



$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

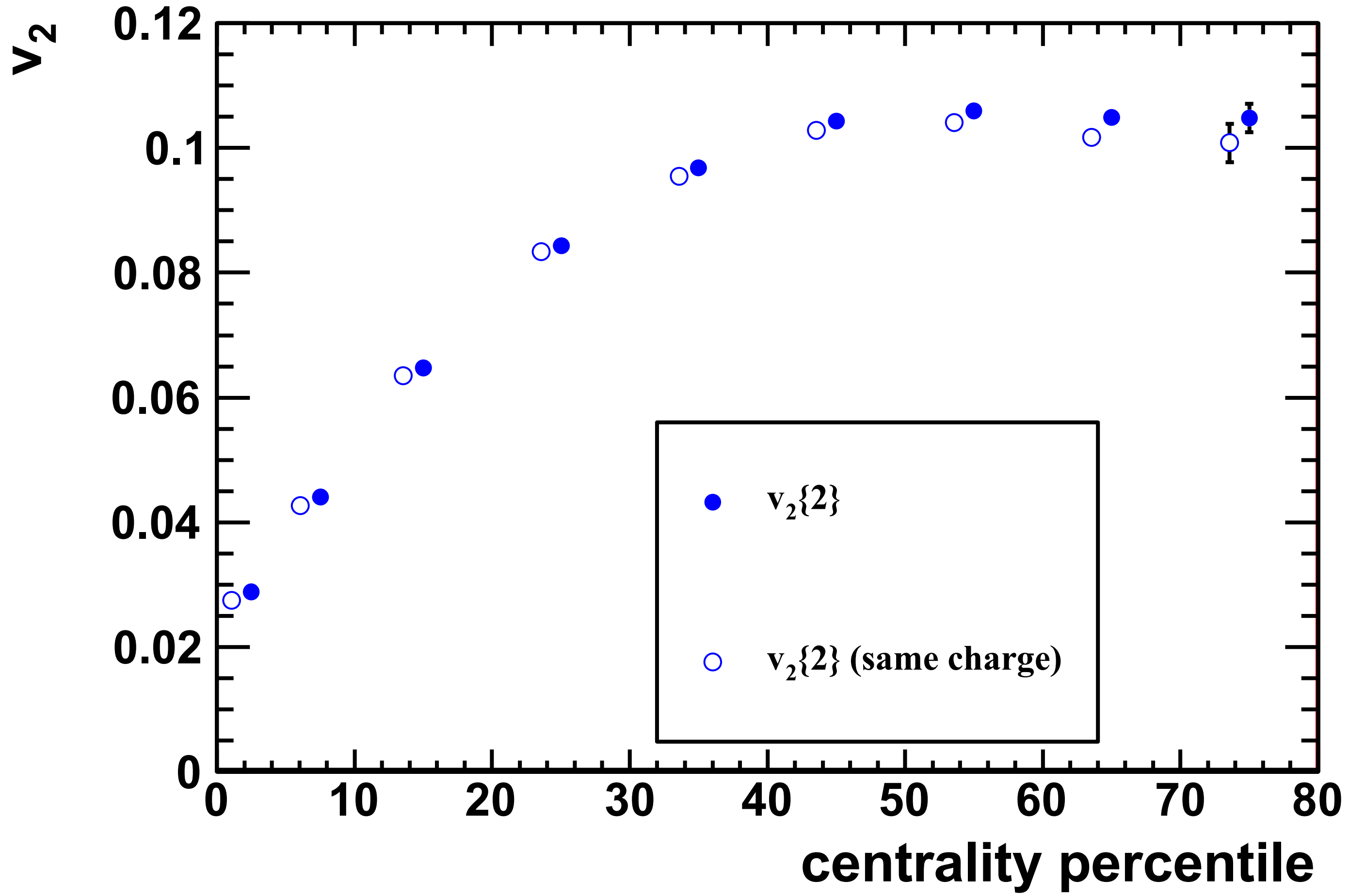
$$v_2\{2\} = \sqrt{\langle v_2^2 \rangle} = \ldots = \langle v_2 \rangle + \frac{1}{2}\frac{\sigma^2}{\langle v_2 \rangle}$$

$$v_2\{4\} = \sqrt[4]{2\langle v_2^2 \rangle^2 - \langle v_2^4 \rangle} = \ldots = \langle v_2 \rangle - \frac{1}{2}\frac{\sigma^2}{\langle v_2 \rangle}$$

$$v_2\{6\} = \sqrt[6]{\frac{1}{4}\left(\langle v_2^6 \rangle - 9\langle v_2^2 \rangle \langle v_2^4 \rangle + 12\langle v_2^2 \rangle^3\right)} = \ldots = \langle v_2 \rangle - \frac{1}{2}\frac{\sigma^2}{\langle v_2 \rangle}$$

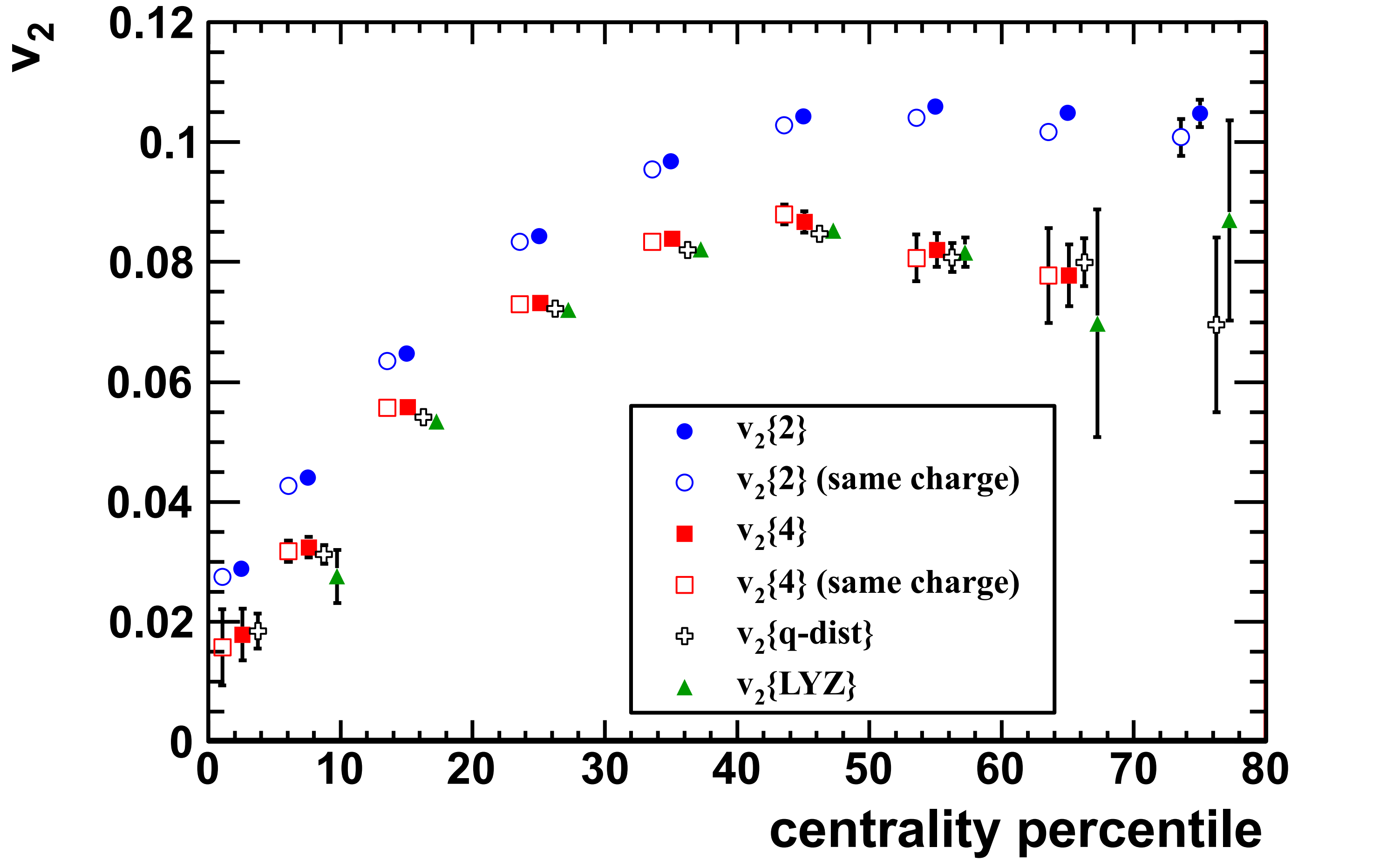
2-particle correlations

Biased by non-flow and by flow fluctuations (+)



Multi-particle correlations

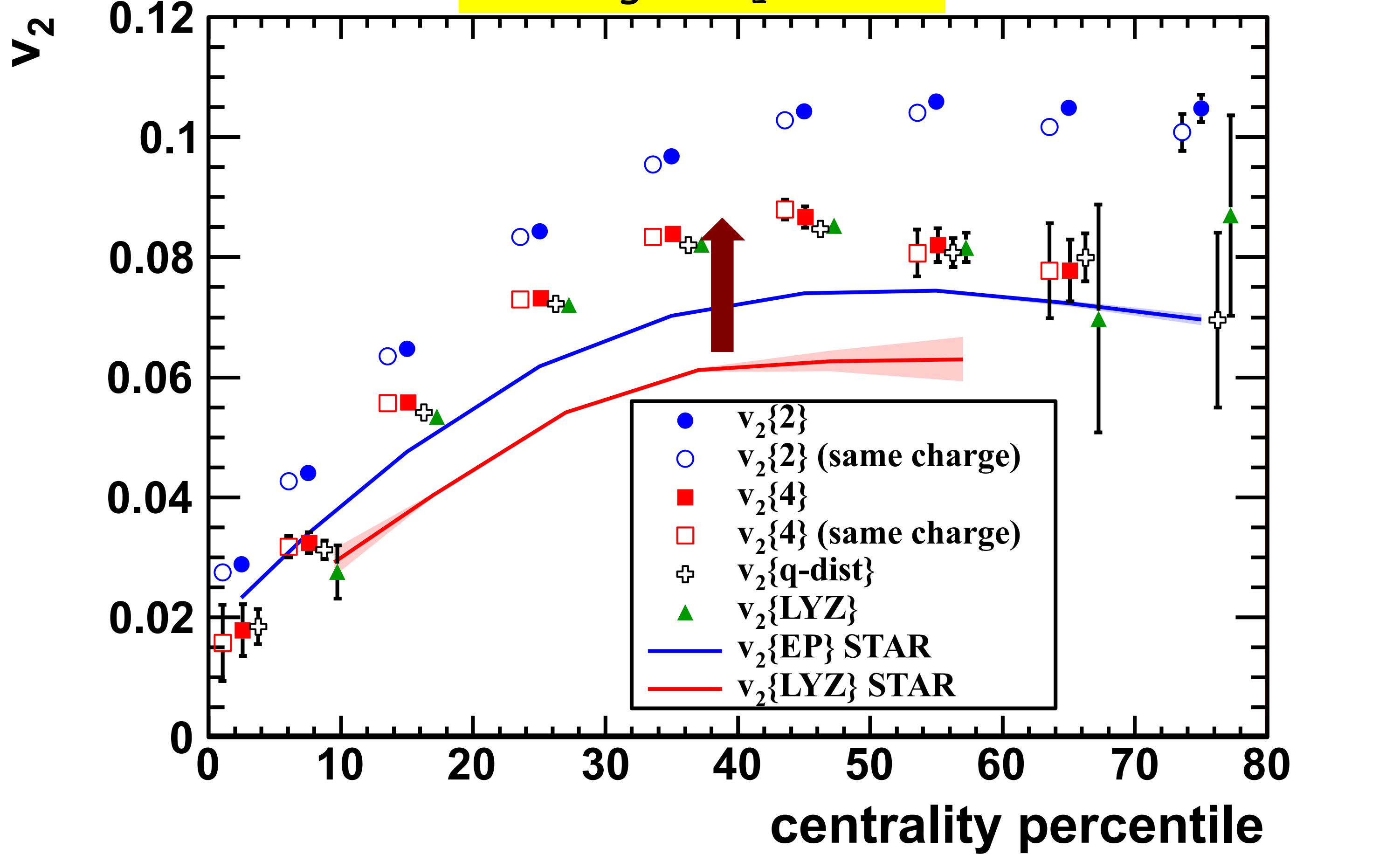
Suppresses non-flow (2p) but biased by flow fluctuations (-)



How does this compare to RHIC?

Pb-Pb @ the LHC vs Au-Au @ RHIC

30% higher v_2 @ LHC

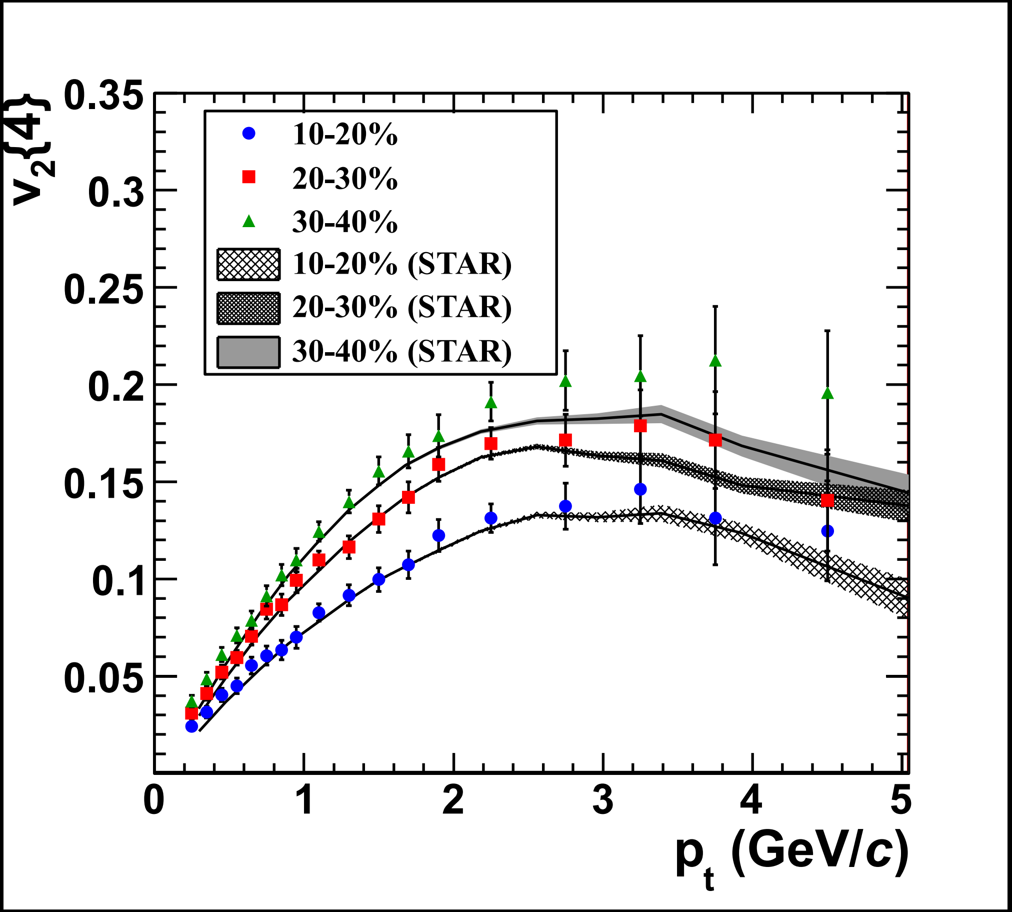


Similar trend but v2 is higher!

Where does this increase come from?

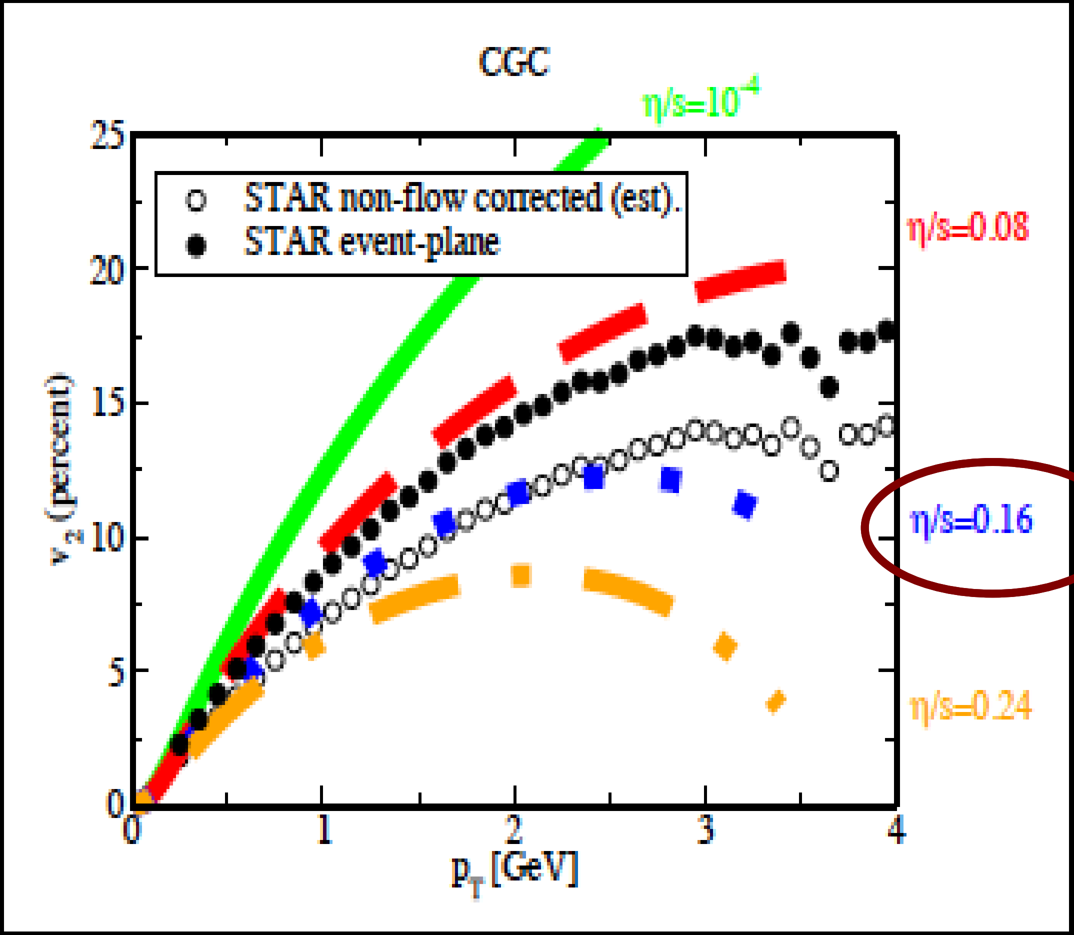
- Either from an increase in the differential (i.e. vs p_T) flow,
- or due to an increase of the average transverse momentum of the charged particles

Remarkable agreement between the ALICE and STAR differential flow values for every centrality bin!!!



Towards the characterization of the medium…

- Hydro calculations meet data for the first time @ RHIC
- Experimental data favor η/s ~ 2 the KSS bound
  - lower bound for a perfect liquid (KSS): 1/4π
- Perfect liquid @ RHIC?
- Can be further constrained by looking at identified particles and higher harmonics



Shear viscosity: measure of the resistance of the "fluid"

M. Luzum, P. Romatschke, Phys. Rev. ***C78***, 034915 (2008)

So how perfect is our perfect liquid @ the LHC?

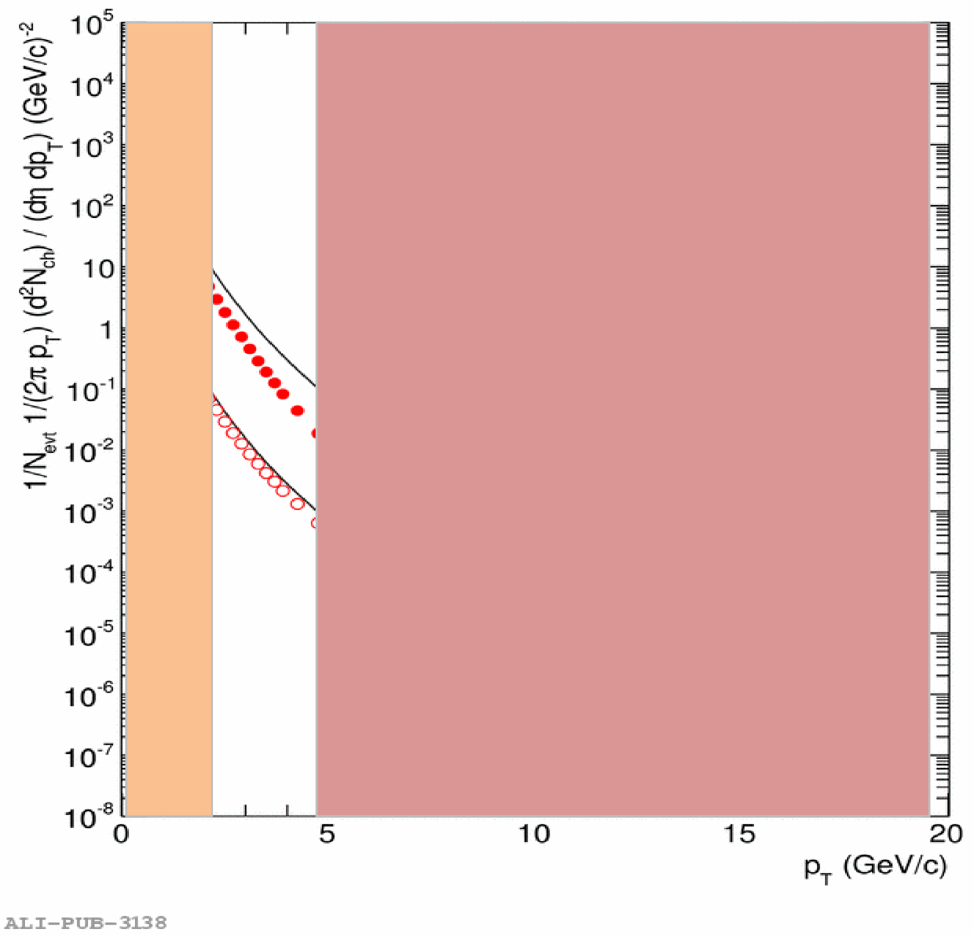
- Do hydro models des
- What would be the r
- For this, we need to
  - higher harmonics (v3, v4, v5, …),
  - flow of identified particles
- Can we do this?

Yes we did! Stay tuned!!!

THANK YOU!

BACKUP

Why soft physics?



- The domain which constitutes the soft sector is "arbitrary" defined as: particles with $p_T < 2$ GeV/c
  - small momentum transfer
  - dominates the particle production
  - follow the participant scaling
- The hard sector:
  - interactions at the partonic level
  - scaling with the number of binary collisions

- Energy/entropy density?
- Thermalization ?
- Space-time extent?
- transport coefficients – η/s?
- Equation of state - cs