Collective Emotion in Pb-Pb at the LHC

Raimond Snellings

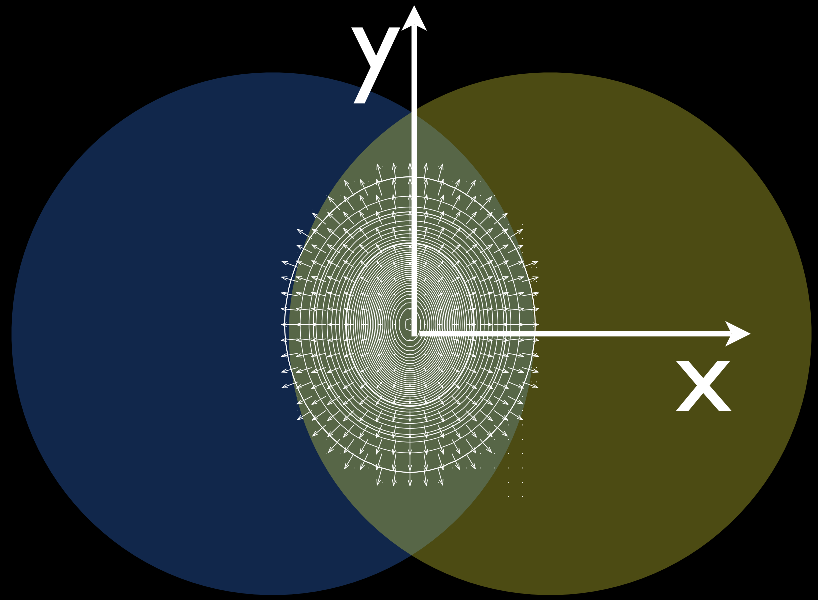
Workshop on Hot & Dense Matter in the RHIC-LHC Era
Tata Institute of Fundamental Research, Mumbai
12-14 Feb, 2008

Outline

- Flow results from RHIC
  - can we quantify the perfect liquid behavior?
- Expectations and capabilities with ALICE at the LHC

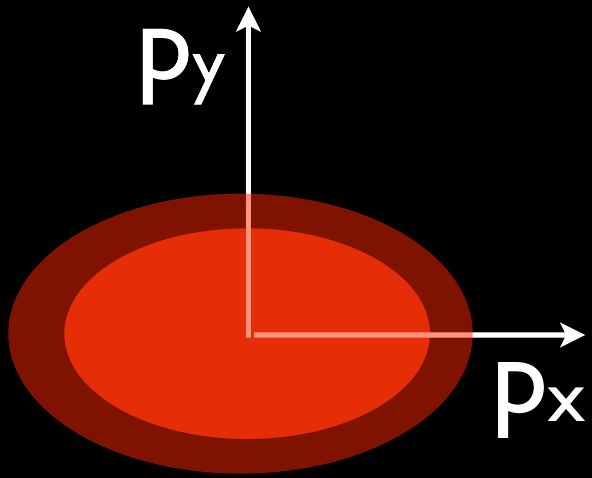
Anisotropic Flow

- In non central collisions coordinate space configuration is anisotropic (almond shape). However, initial momentum distribution isotropic (spherically symmetric)



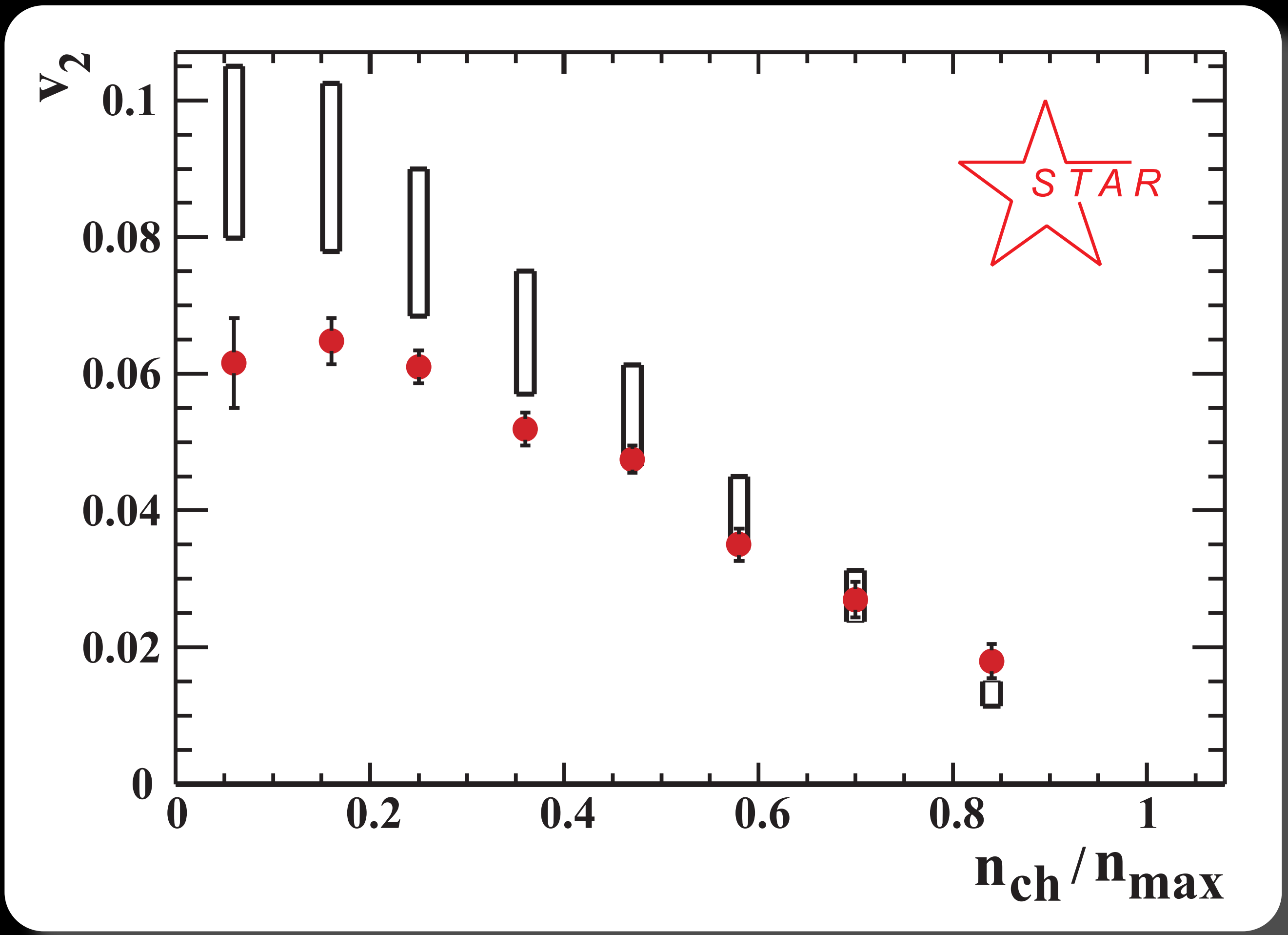
- Only interactions among constituents generate a pressure gradient which transforms the initial coordinate space anisotropy into the observed momentum space anisotropy → anisotropic flow

- Multiple interactions lead to thermalization → limiting behavior hydrodynamics

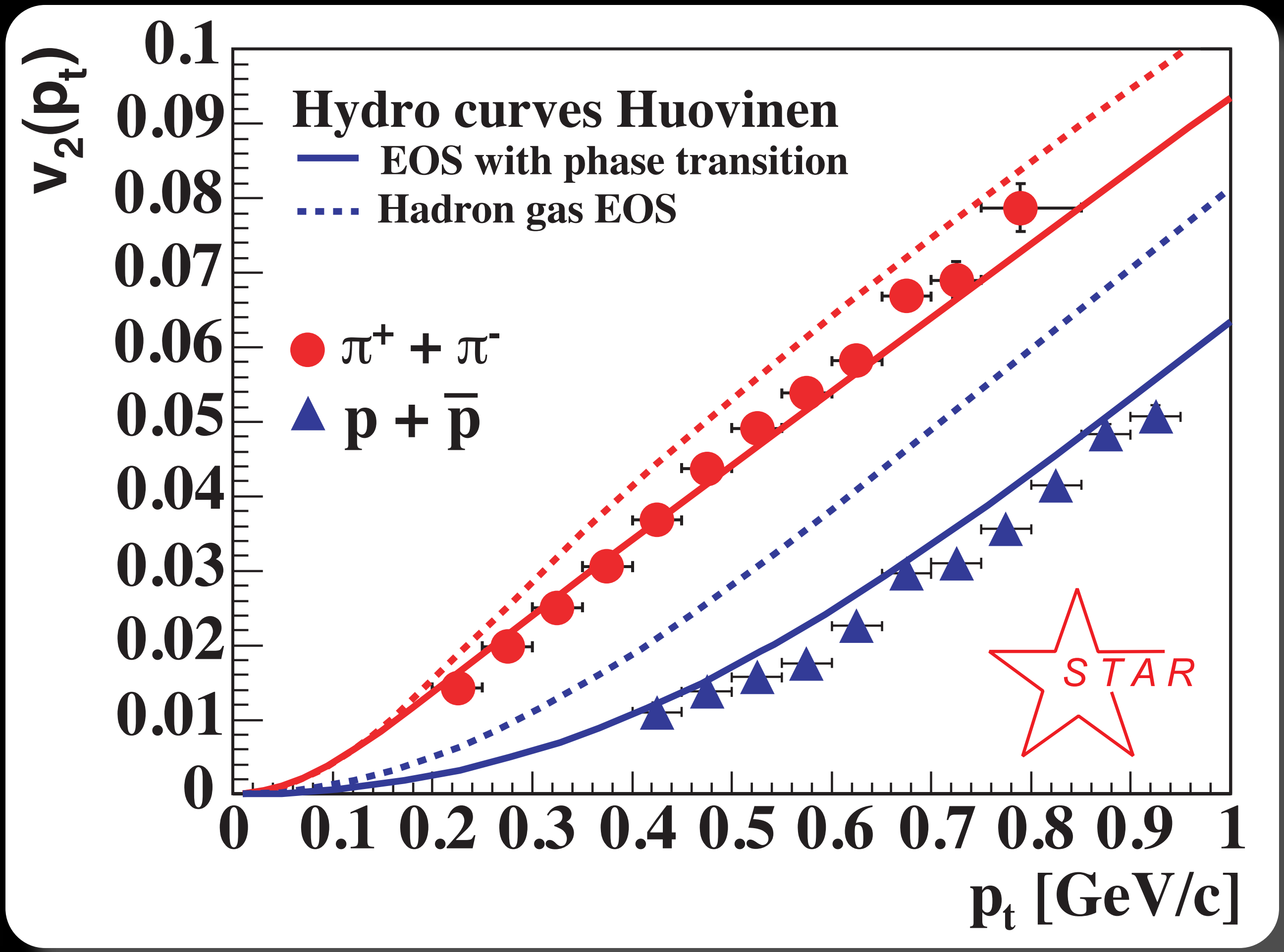


- In addition anisotropic flow allows us to determine the reaction plane and study the medium modification of probes as function of path length (less dependent on reference data from pp and pA and their scaling to AA)

Flow at RHIC



STAR Phys. Rev. Lett. 86, 402–407 (2001)



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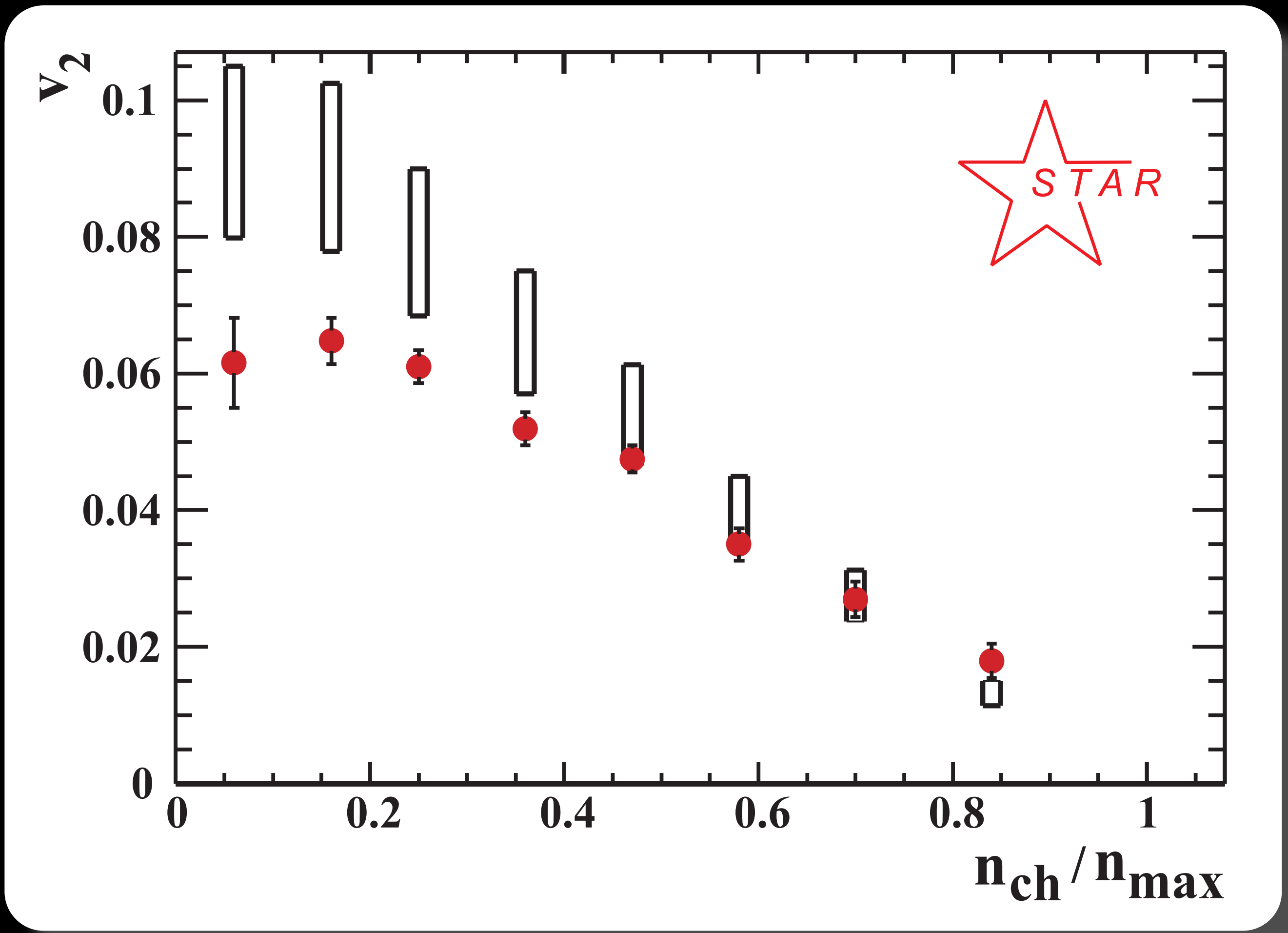
Flow at RHIC



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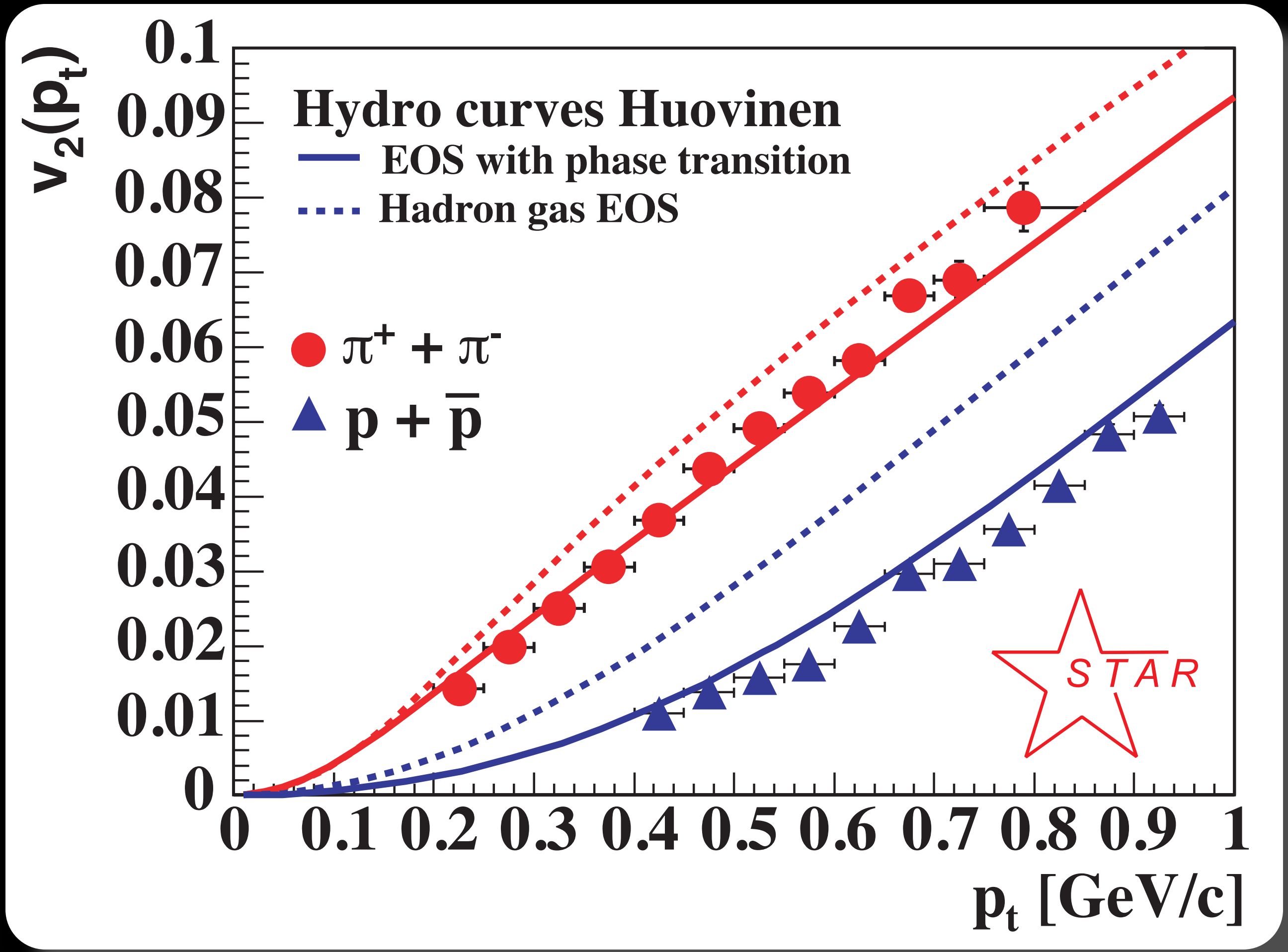
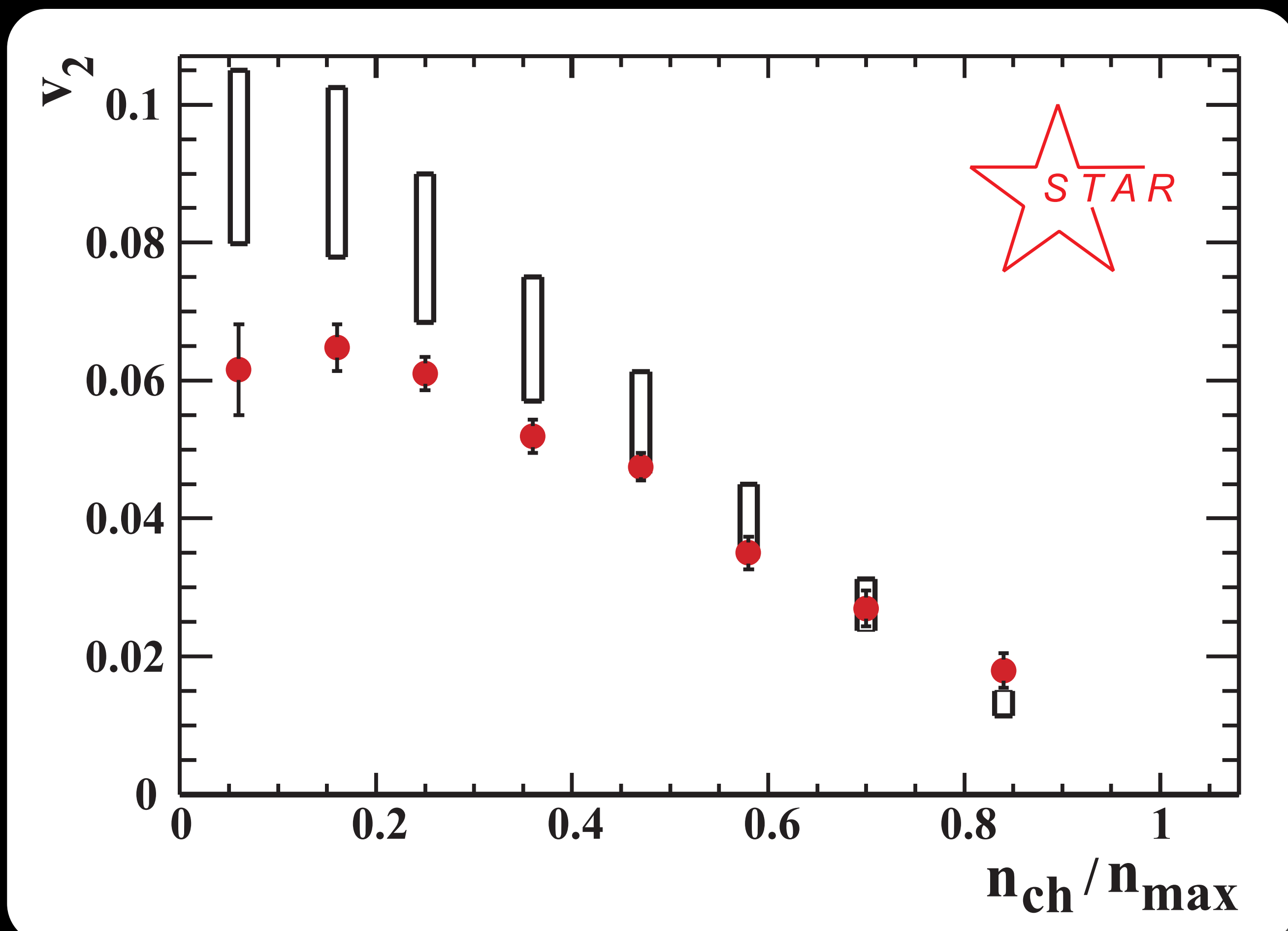


STAR Phys. Rev. Lett. 87, 182301 (2001)

- Hydro gets the magnitude and species dependence

Flow at RHIC



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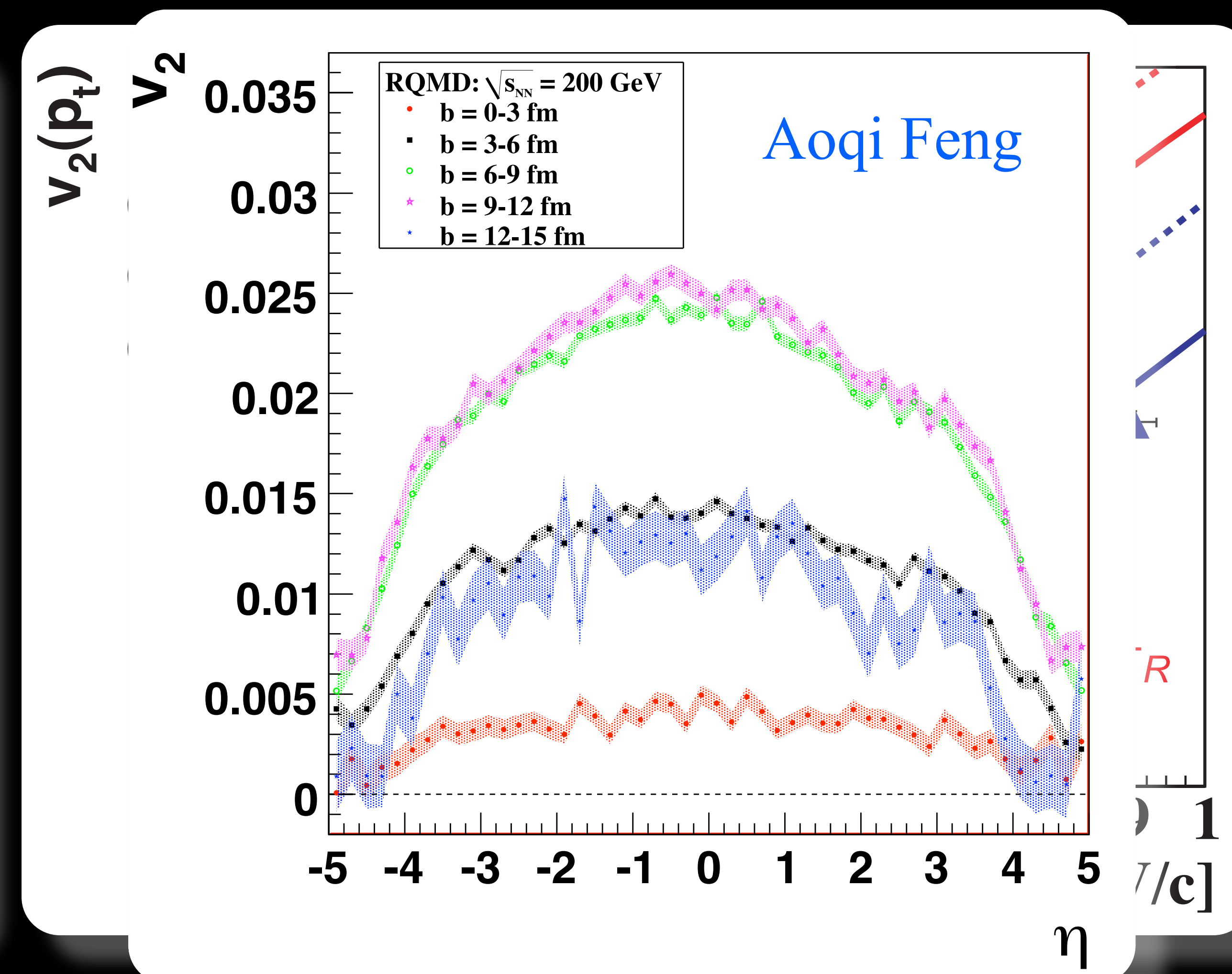
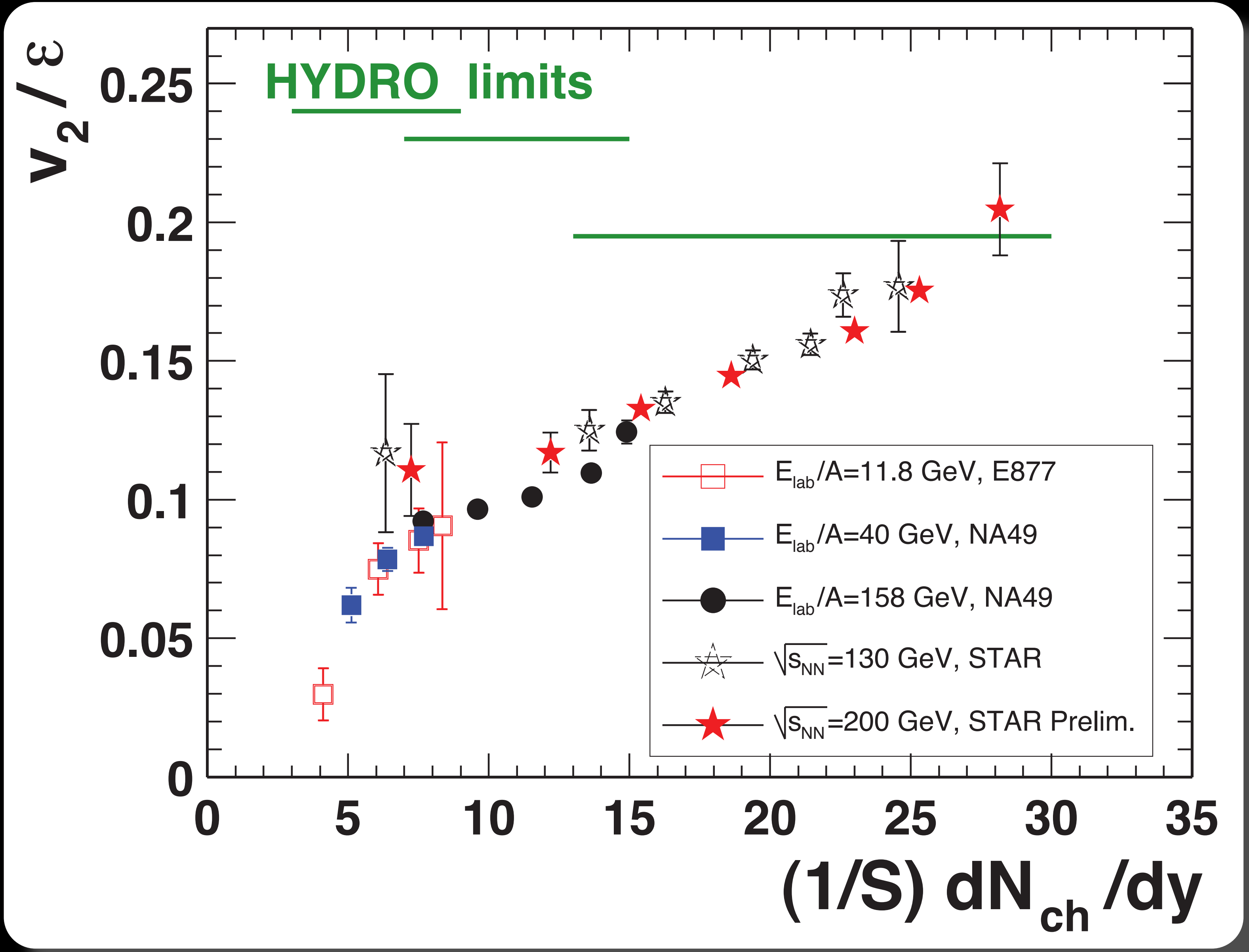


STAR Phys. Rev. Lett. 87, 182301 (2001)

- Hydro gets the magnitude and species dependence
- Cascade calculations are factors 2-3 off

The hydro limit

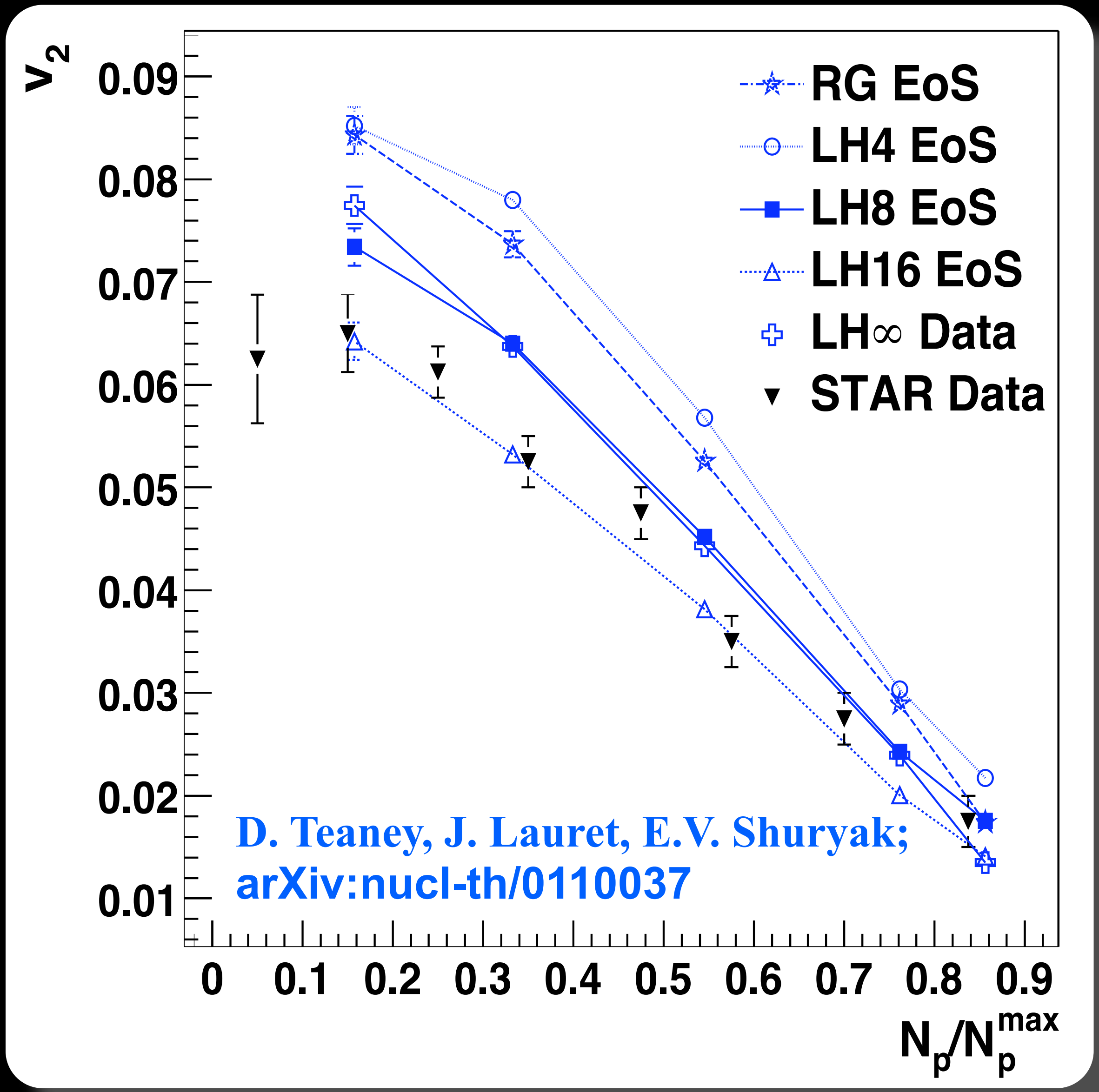


Hydro limits from P.F. Kolb, J. Sollfrank, U.W. Heinz; Phys.Rev.C62:054909,2000.

- At RHIC more central collisions approach the hydro limit

Hydro + cascade

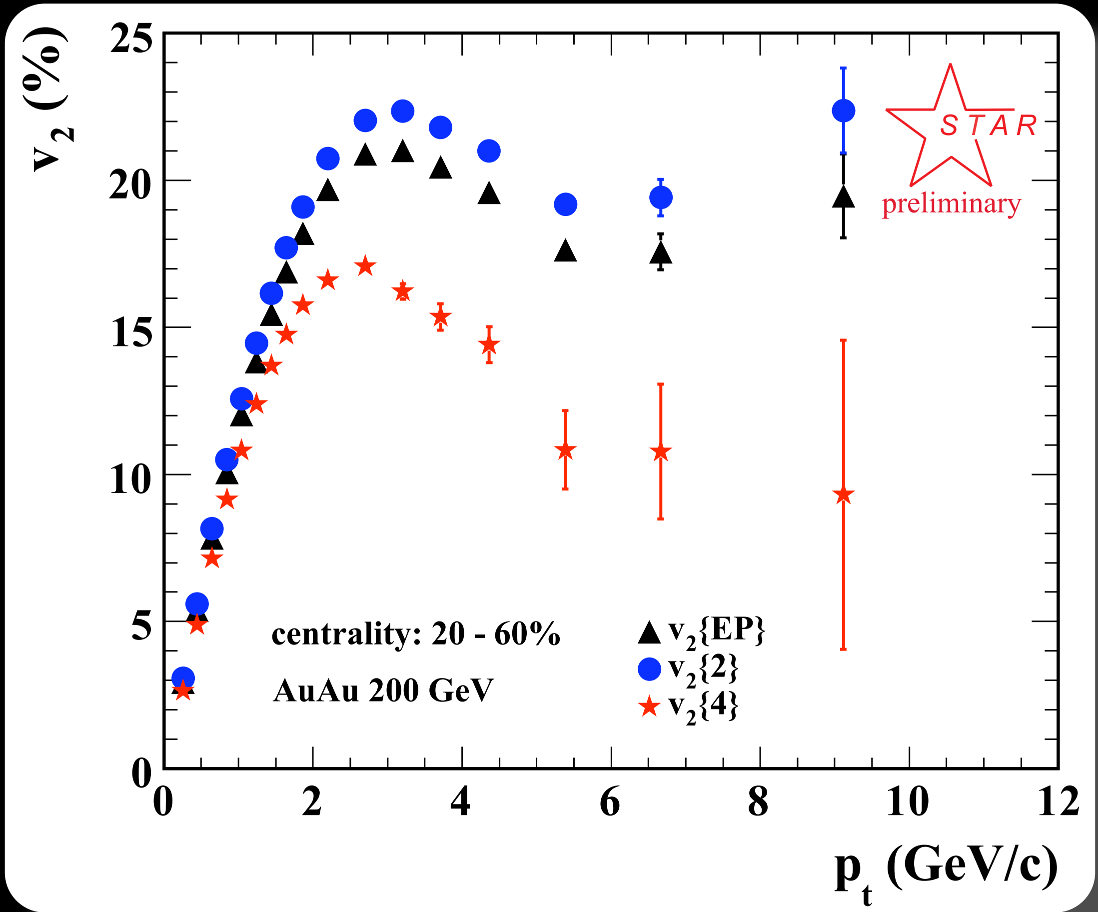
- Centrality (and energy) dependence can be described using ideal hydro + hadron gas (RQMD)
- The centrality dependence of v_2/ε for this scenario should come from the hadronic contribution



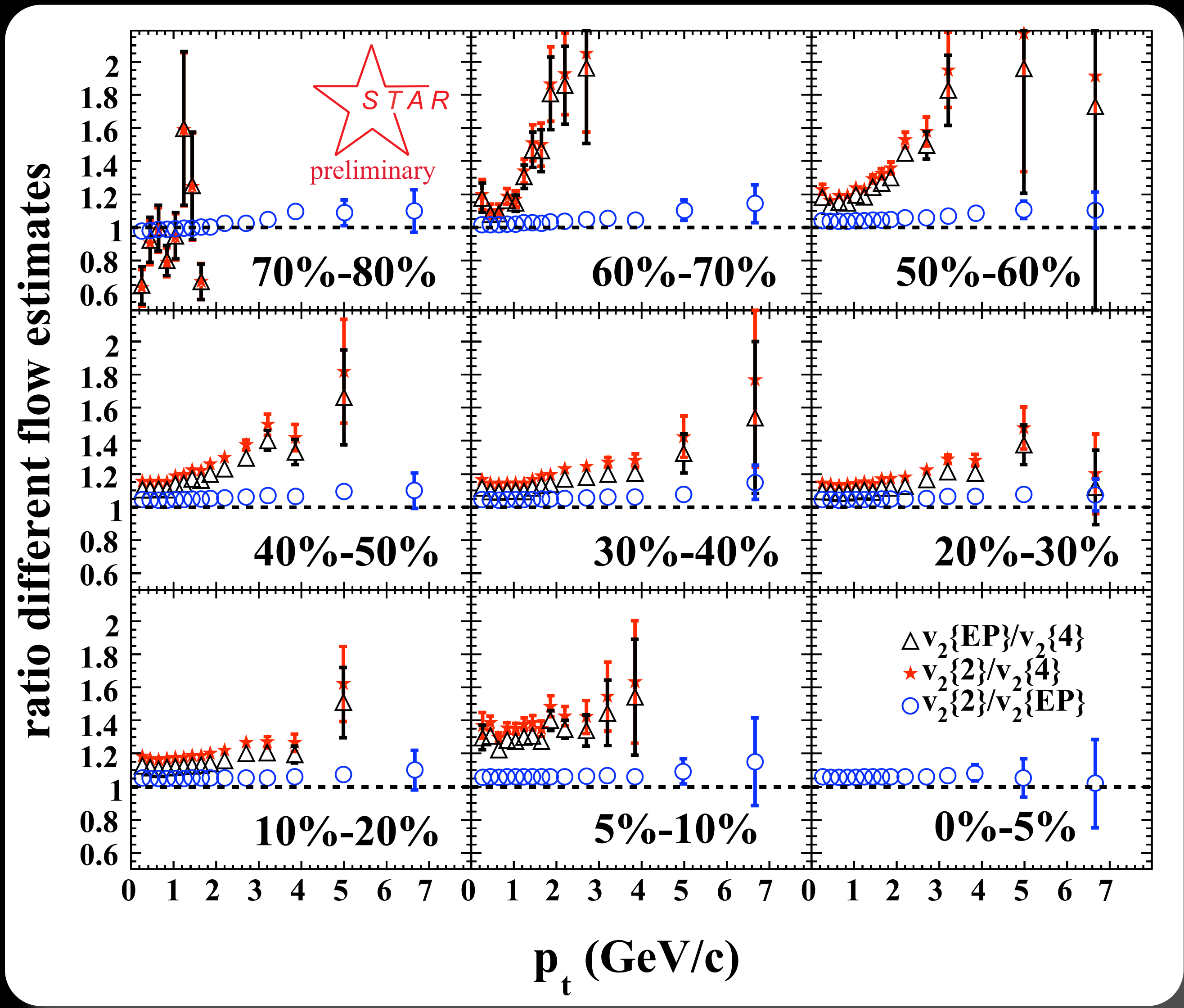
Some uncertainties

- The experimental determination of v_2
  - Event Plane, Cumulants, Lee Yang Zeroes
- The "hydro limit"
  - the EoS
- The initial conditions
  - spatial eccentricity: Glauber, CGC, with/without fluctuations

Determining v_2

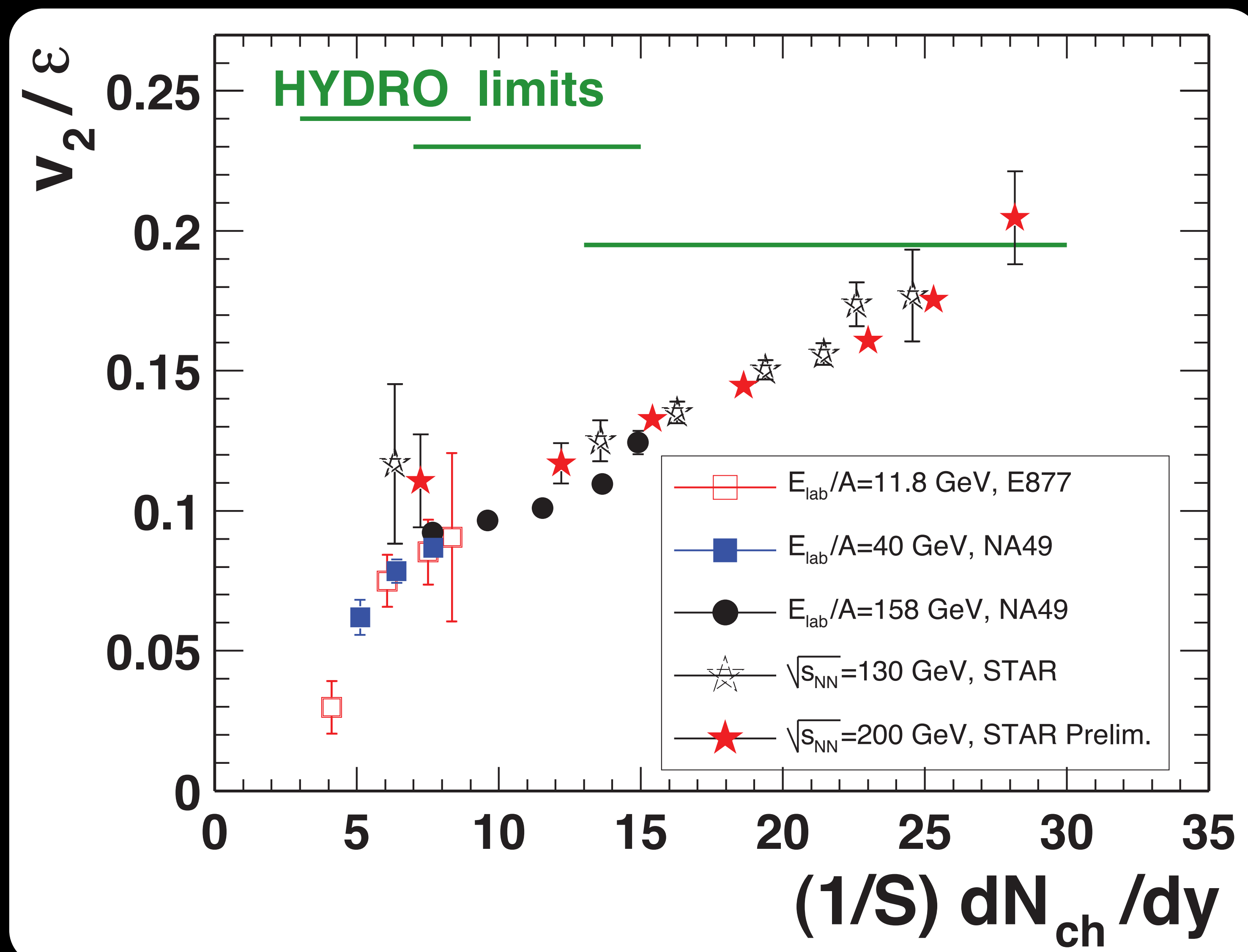


Yuting Bai, PhD thesis



- Reasonably under control for low-p_t and mid-central collisions

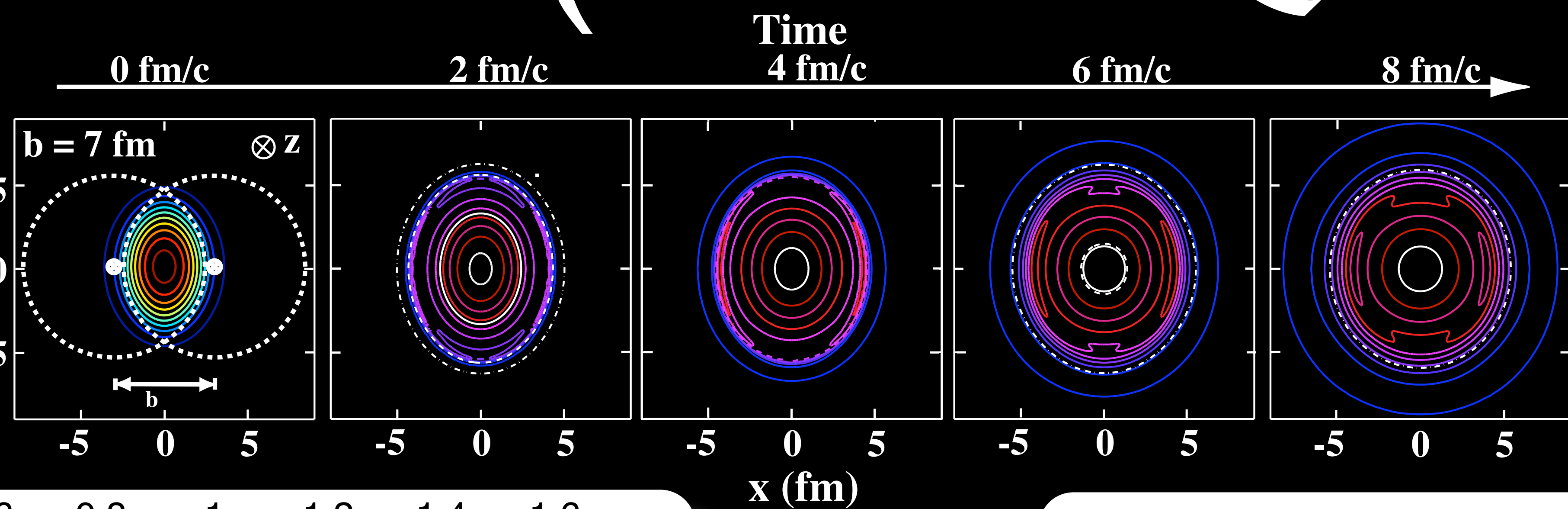
Comparing to theory

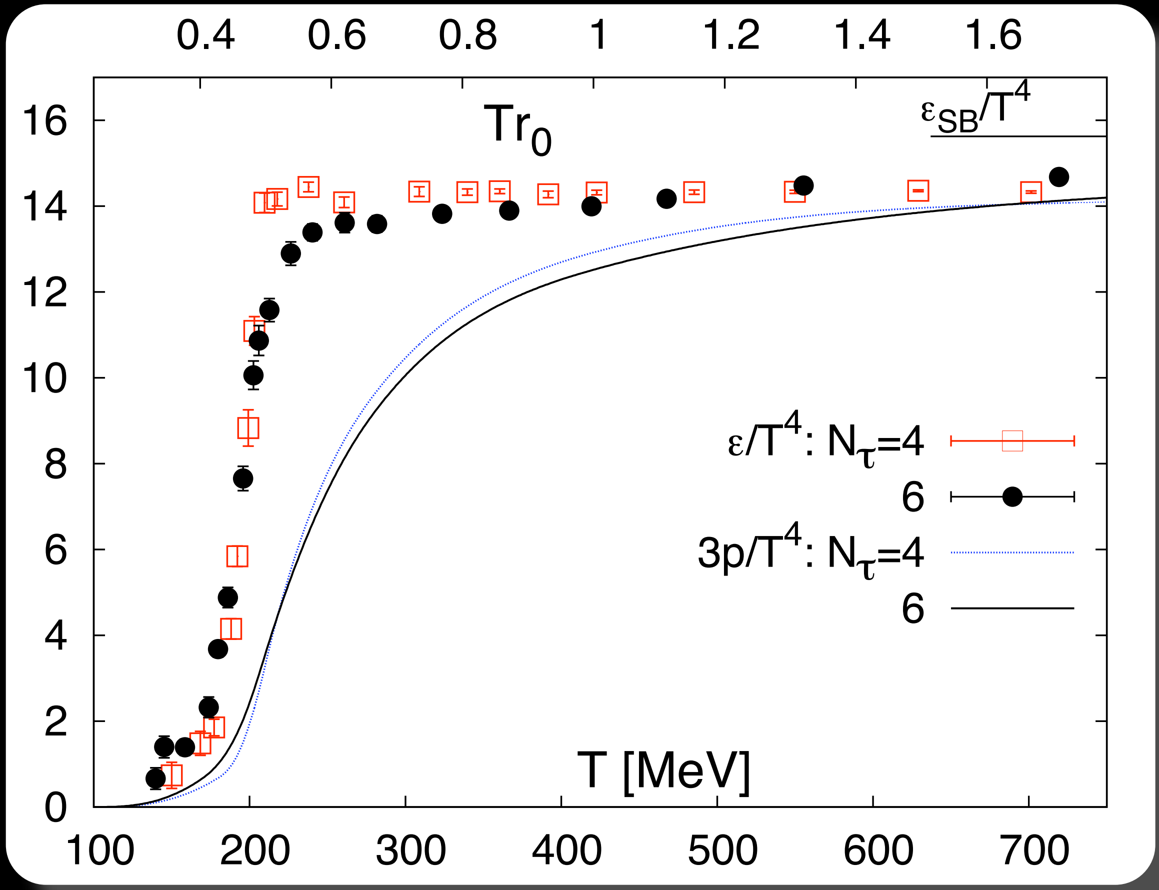


Hydro limits from P.F. Kolb, J. Sollfrank, U.W. Heinz; Phys.Rev.C62:054909,2000.

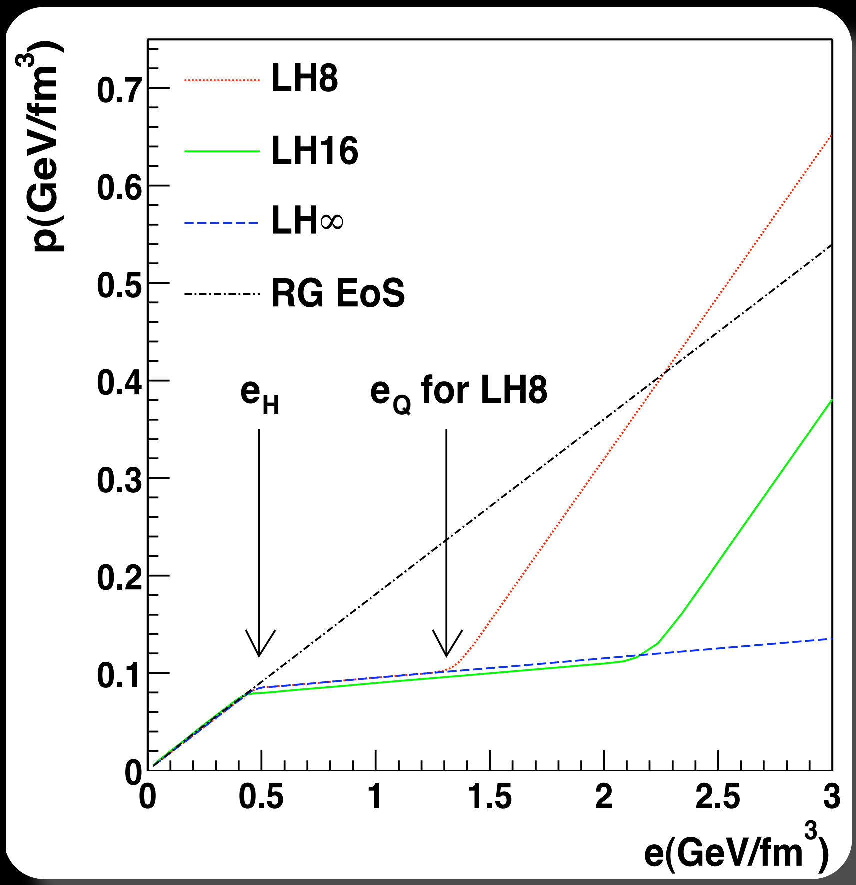
- At RHIC more central collisions approach the hydro limit

The EoS (Lattice QCD)



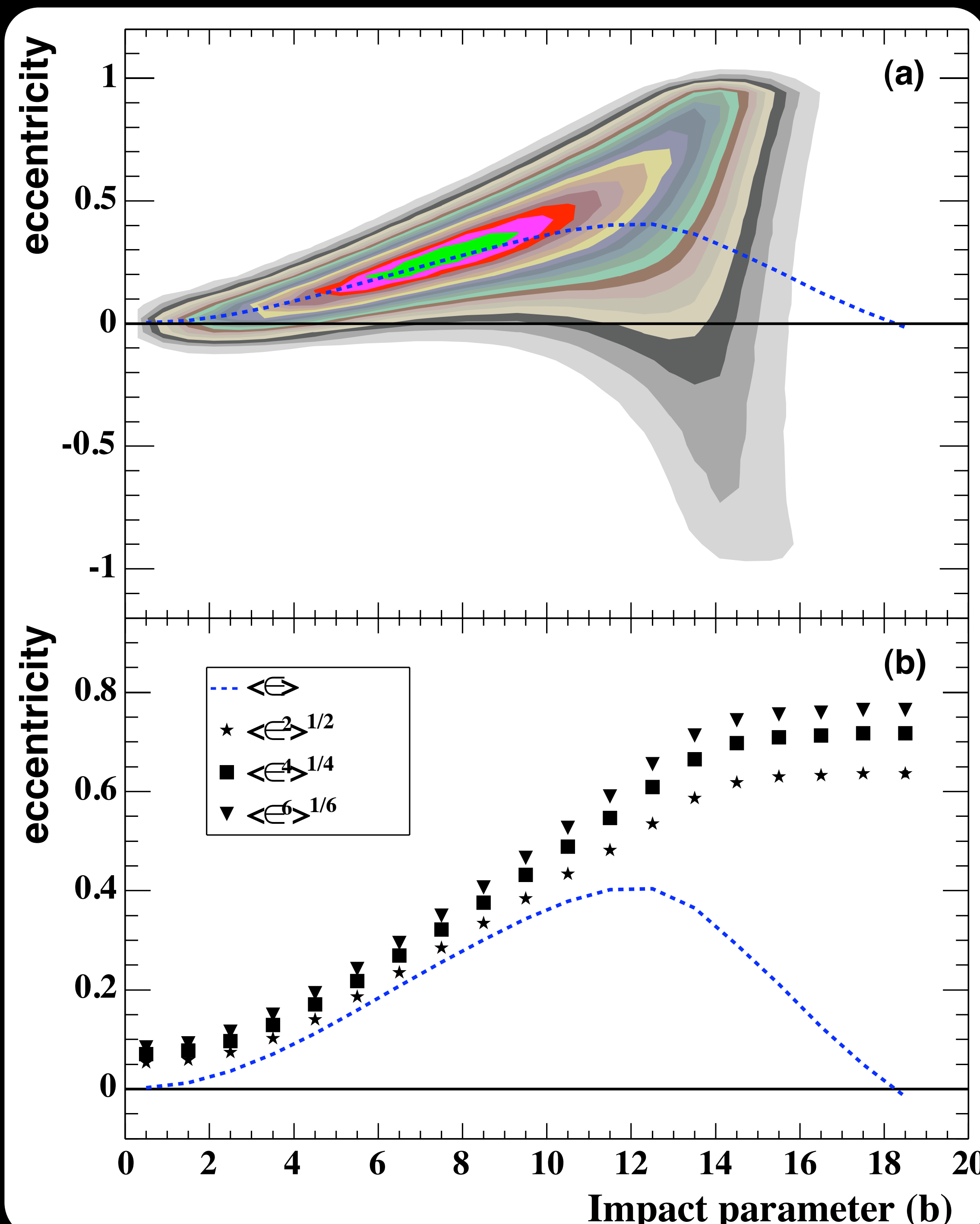


D. Teaney, J. Lauret, E.V. Shuryak;
arXiv:nucl-th/0110037



- EoS best studied quantity in lattice QCD

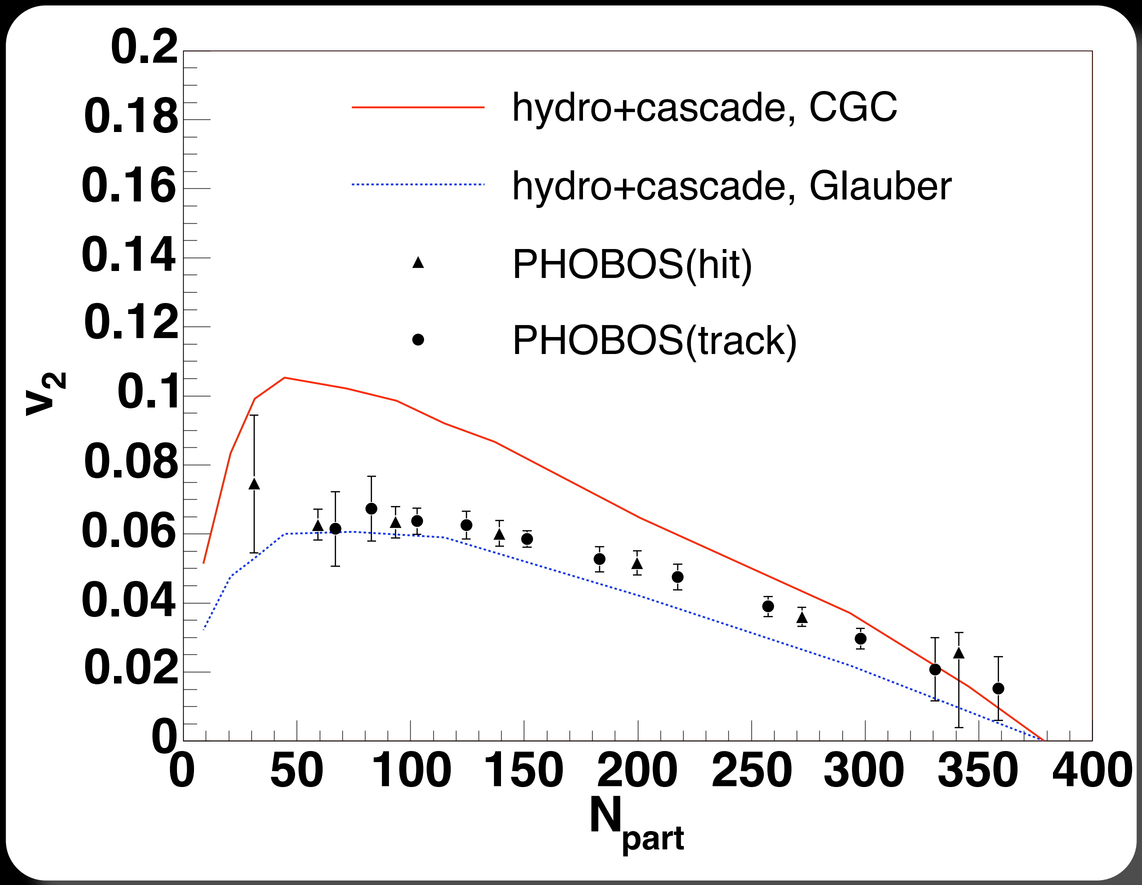
eccentricity fluctuations



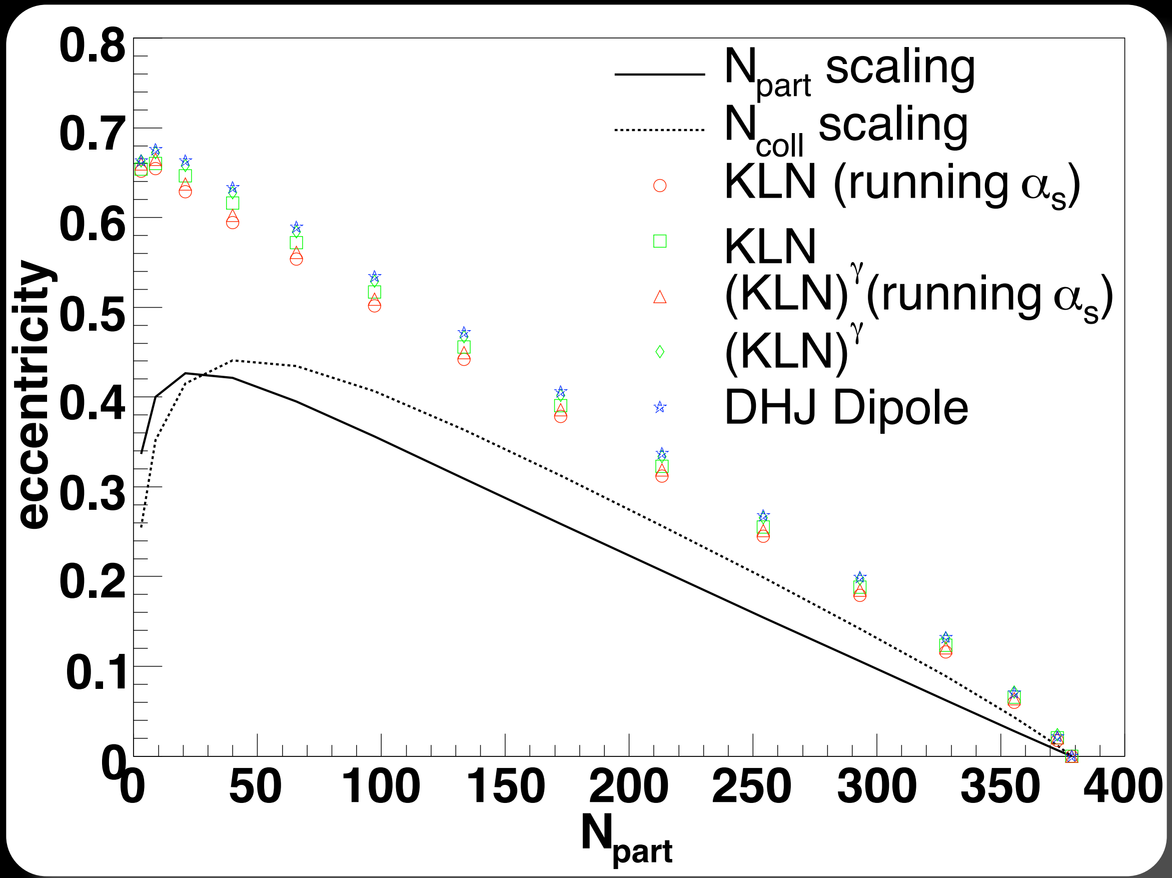
M. Miller and RS, arXiv:nucl-ex/0312008

- Cumulant analysis $v_2\{2\}$-$v_2\{4\}$ give a bound on fluctuations and nonflow < 10% uncertainty for mid central collisions (see also talk from Paul Sorensen)
- $v_2 \propto \varepsilon$ (we do not assume this proportionality to be constant as function of energy or centrality)
- eccentricity fluctuations do change the centrality dependence of v_2/ε

Comparing to theory: the initial condition: ε



T. Hirano et al., J.Phys.G34:S879-882,2007

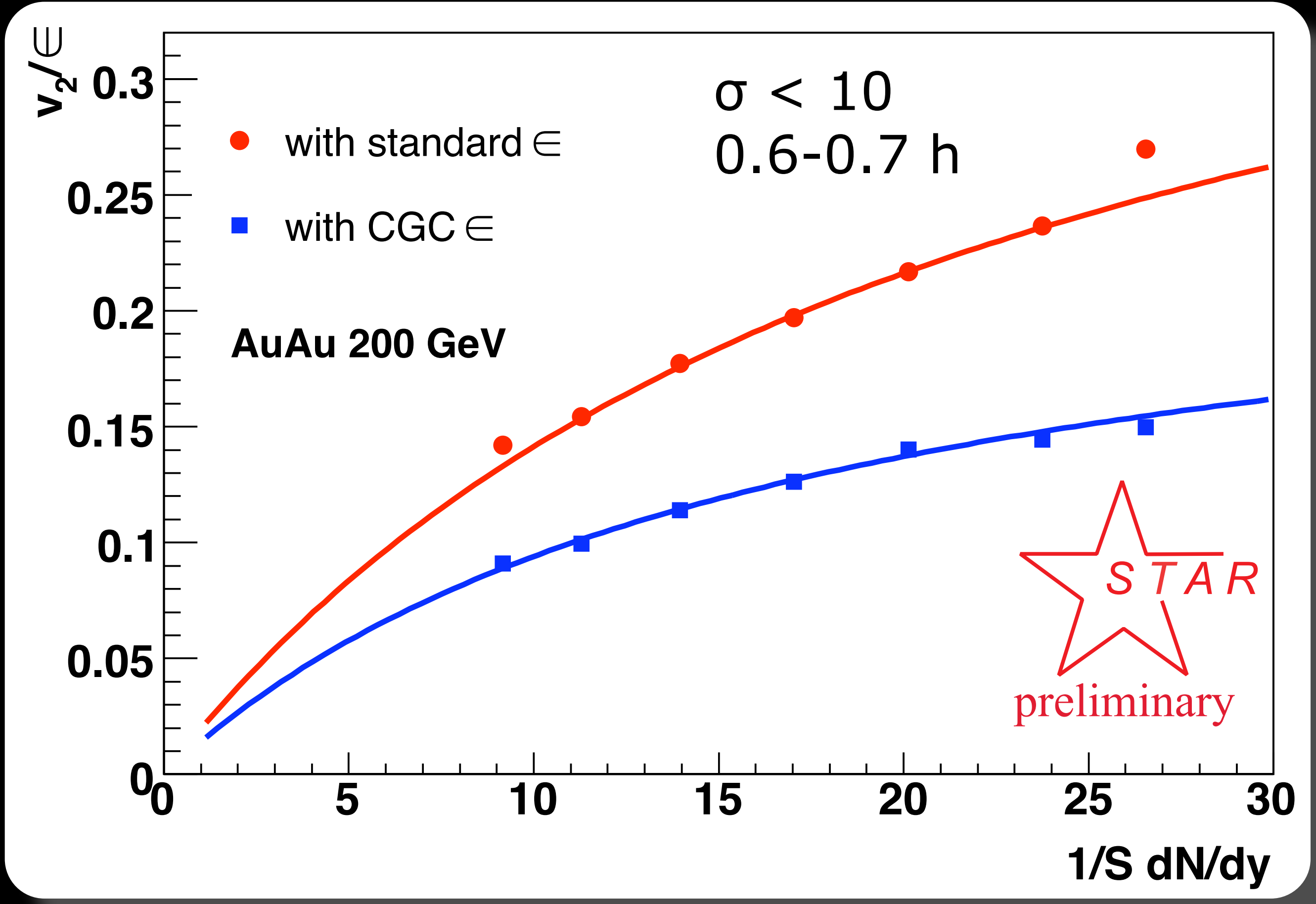


H-J. Drescher et al., Phys.Rev.C74:044905,2006

- Not a direct observable

Estimate the EoS

- Try to use the data to constrain the hydro limit!
- Use relativistic Boltzmann calculations to calculate how v_2 approaches hydro as function of cross section and density
- Based on these calculations the v_2/ε dependence has been parameterized as function of K



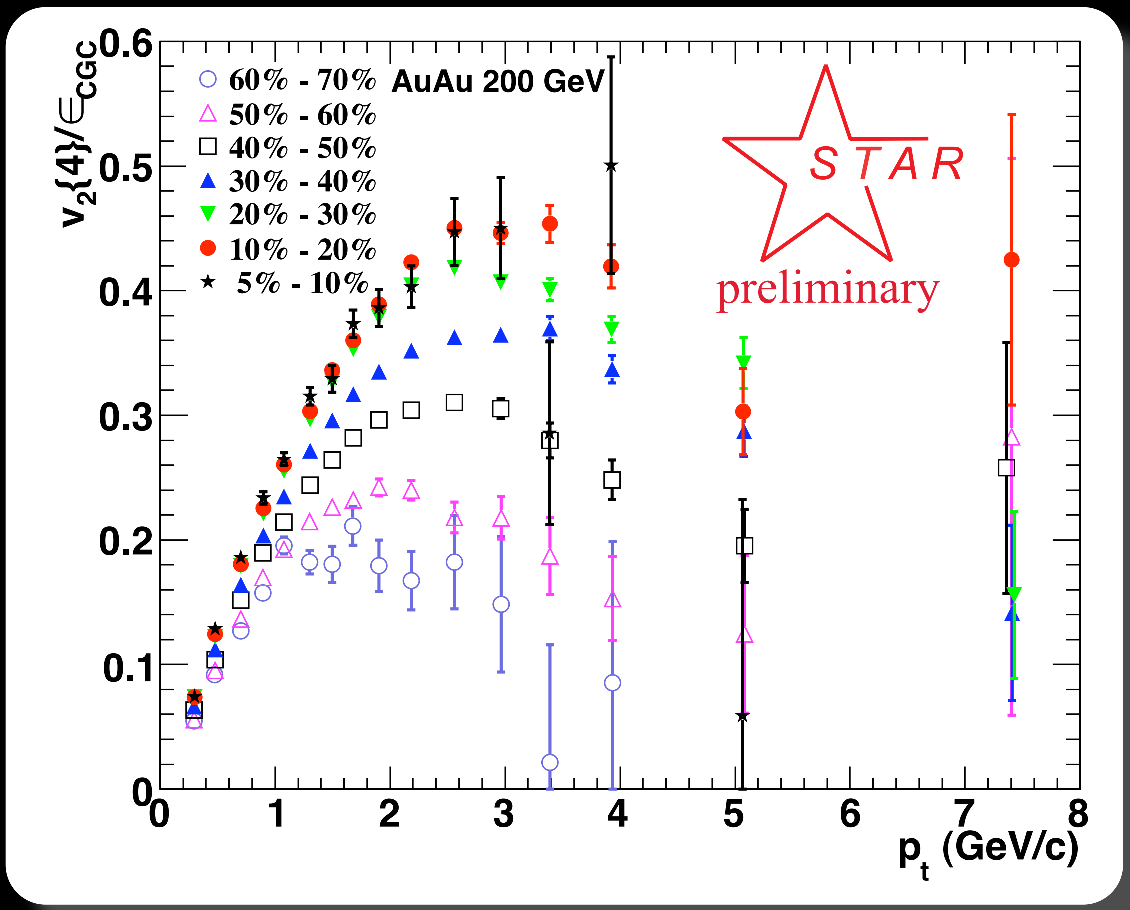
R.S. Bhalerao, J-P. Blaizot, N. Borghini and J-Y. Ollitrault; Phys.Lett.B627:49-54,2005.

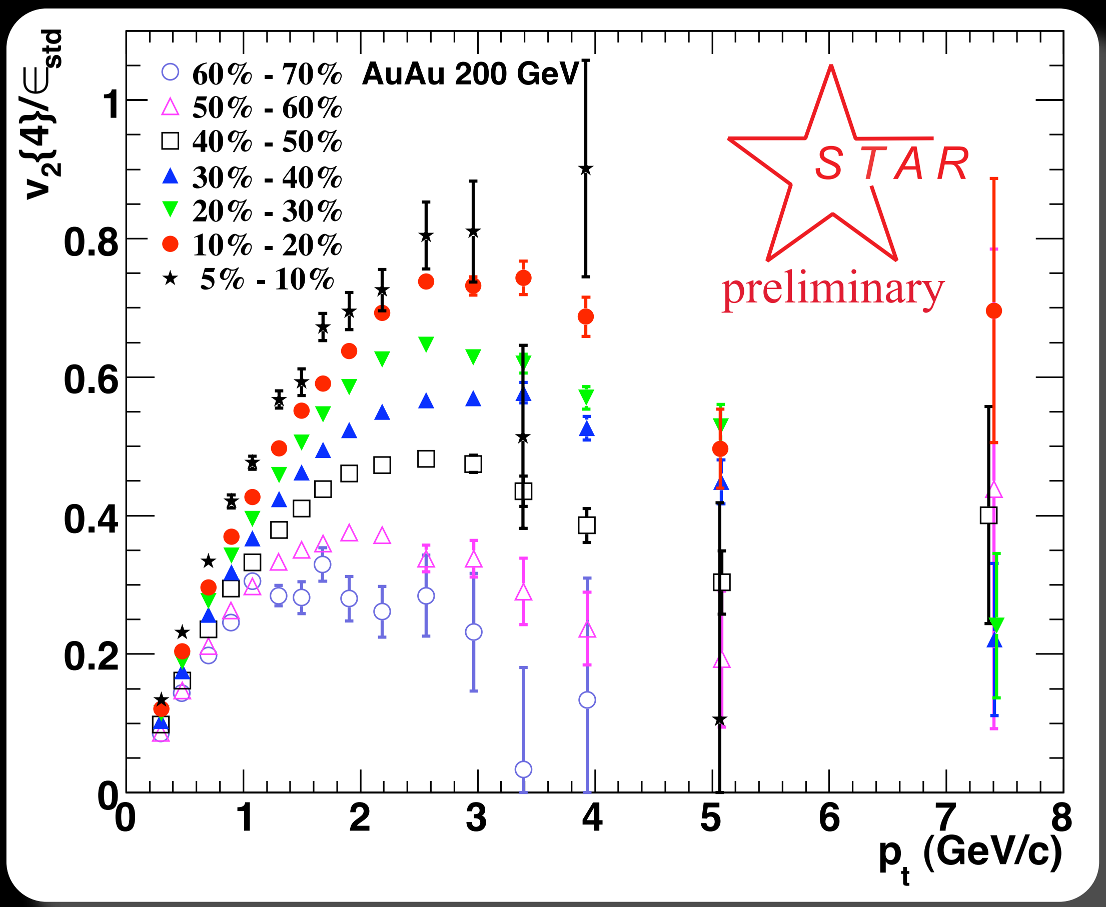
C. Gombeaud and J-Y. Ollitrault; arXiv:nucl-th/0702075

H-J. Drescher, A. Dumitru, C. Gombeaud and J-Y. Ollitrault; Phys.Rev.C76:024905,2007.

$v_2/\varepsilon = h/(1+1.4K)$
h: hydro limit
Knudsen number: $K = \lambda/R$
The number of collisions per particle:
$1/K = (\sigma/S)(dN/dy)c_s$
σ = partonic cross section

Flow increases



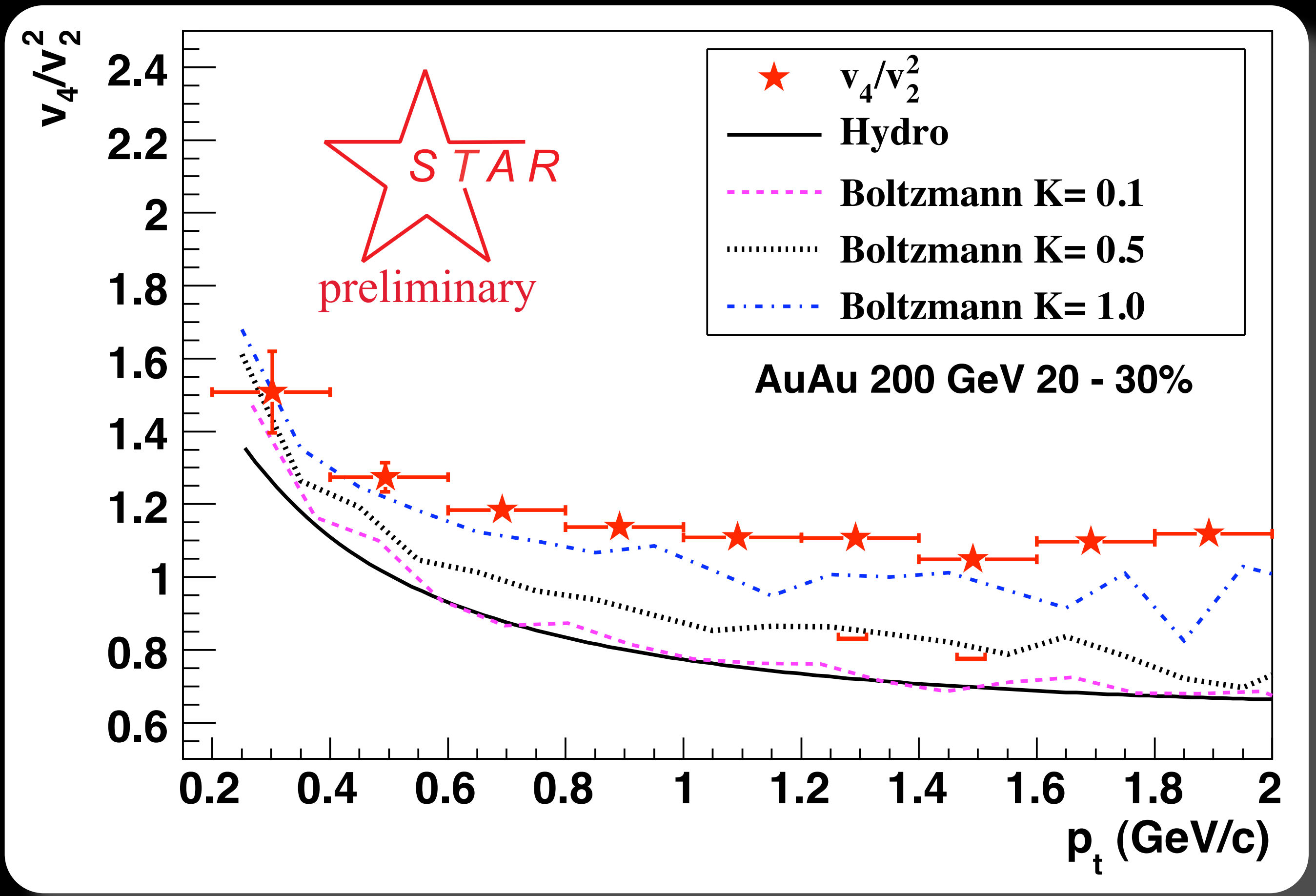


Yuting Bai, PhD thesis

- $v_2\{4\}/\varepsilon_{std}$ increases with centrality over large p_t range ($v_2\{2\}$ did not allow for this study due to strong nonflow at high-p_t)
- peak position of $v_2\{4\}$ moves to higher transverse momentum with increasing centrality

Higher harmonics

- Ratio v_4/v_2^2 is sensitive to the degree of thermalization
- The Boltzmann curves are from the same calculation as used for v_2/ε, which for most central collisions reached K~ 0.5
- Measured ratios indicate that ideal hydro limit is not reached



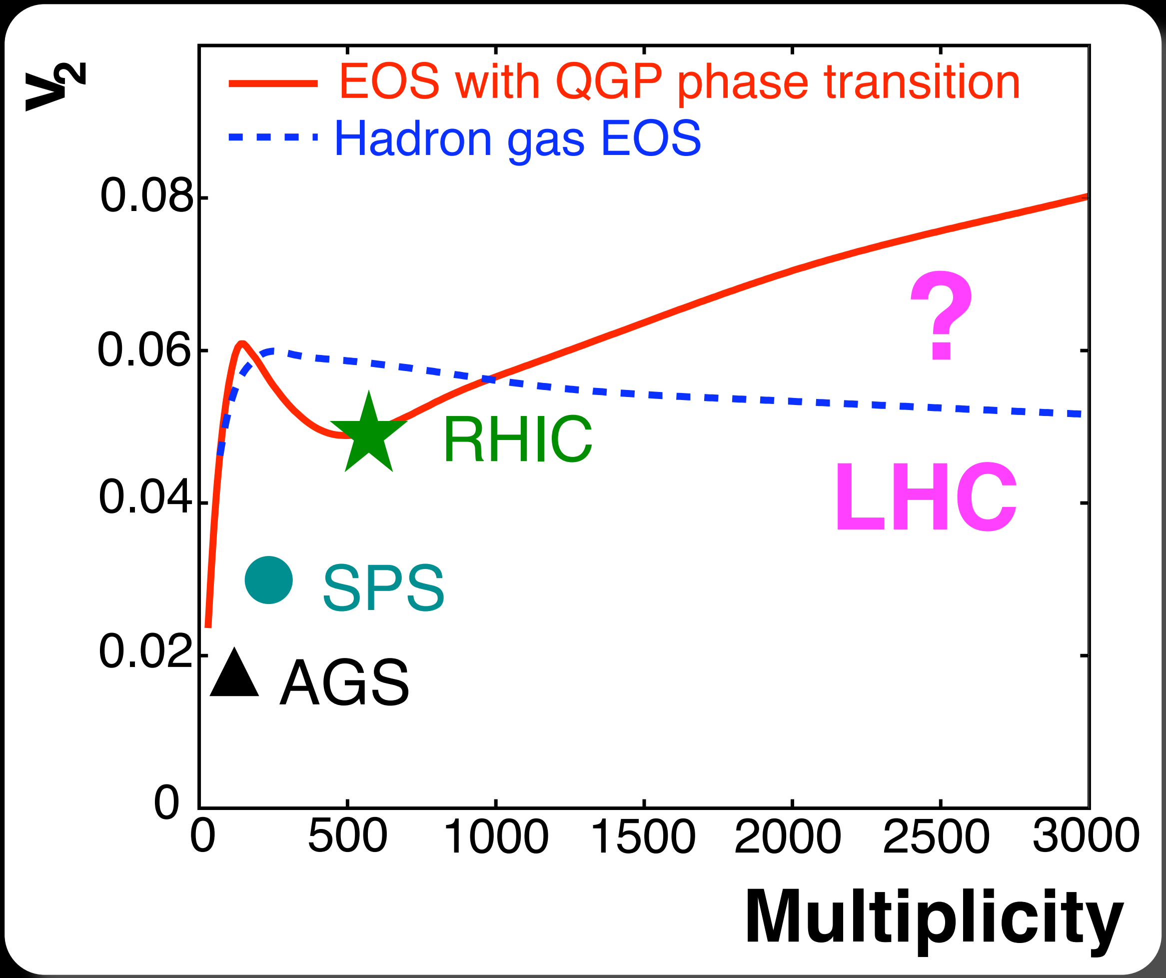
Yuting Bai PhD thesis, Jocelyn Mlynarz

Boltzmann curves J-Y. Ollitrault

flow at RHIC: status

- The observed centrality and energy dependence of elliptic flow as well as v_4/v_2^2 are not in agreement with ideal hydro behavior and point to incomplete thermalization, deviations can be described by:
  - Ideal hydrodynamics + fluctuations ?
  - Ideal hydrodynamics + hadron cascade
  - Viscous hydrodynamics ?
  - Boltzmann kinetic theory (top RHIC energy reaches 60-70% of the hydro limit)

Day one at the LHC



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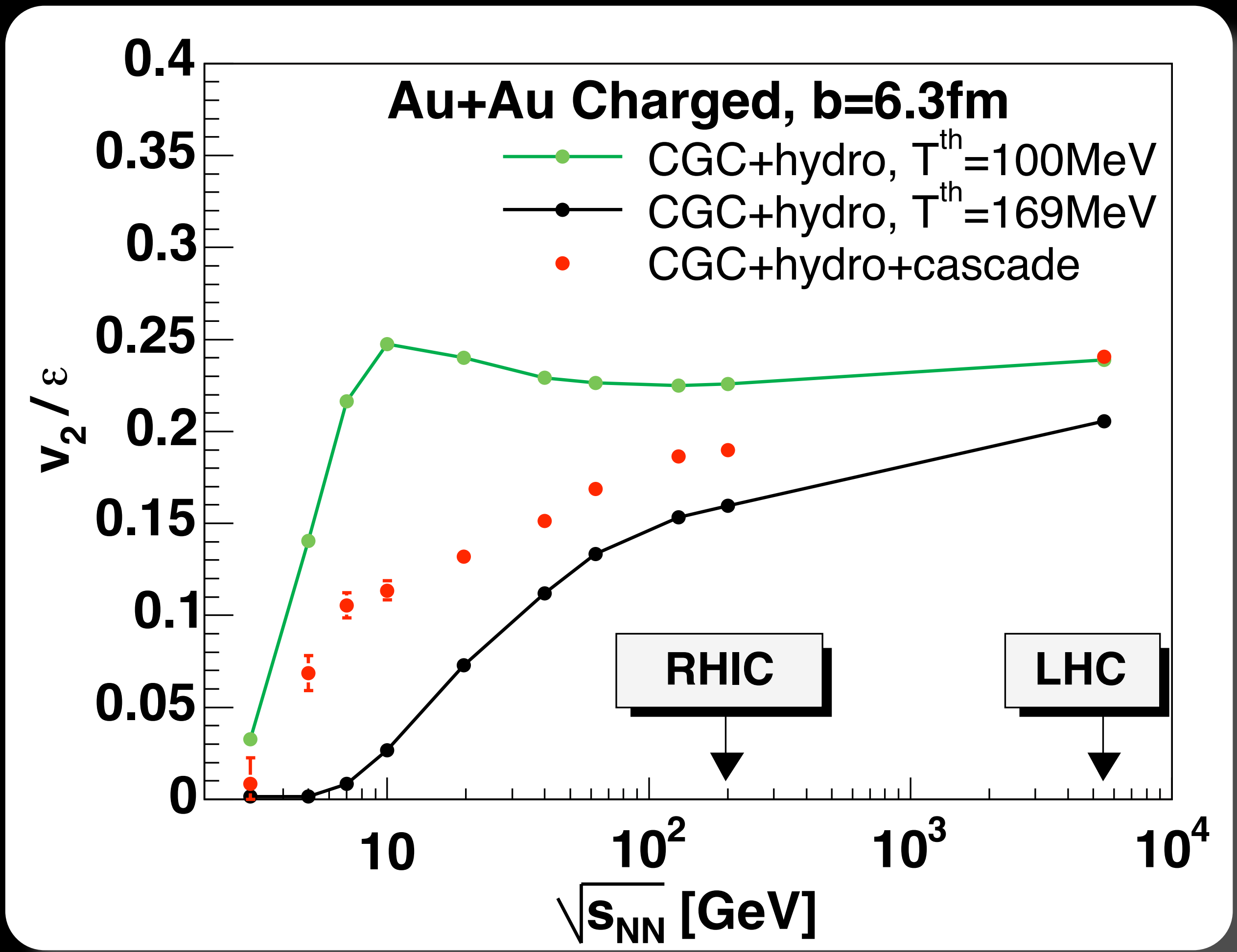
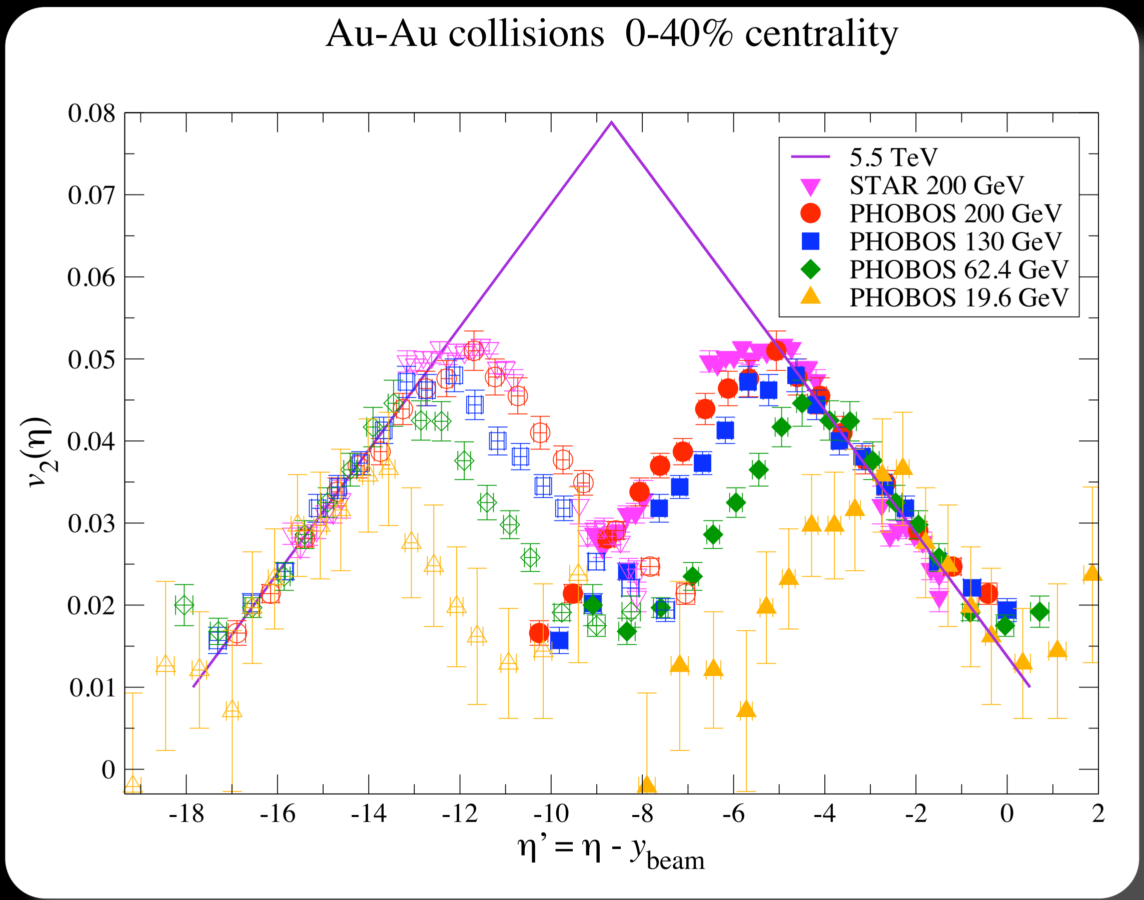
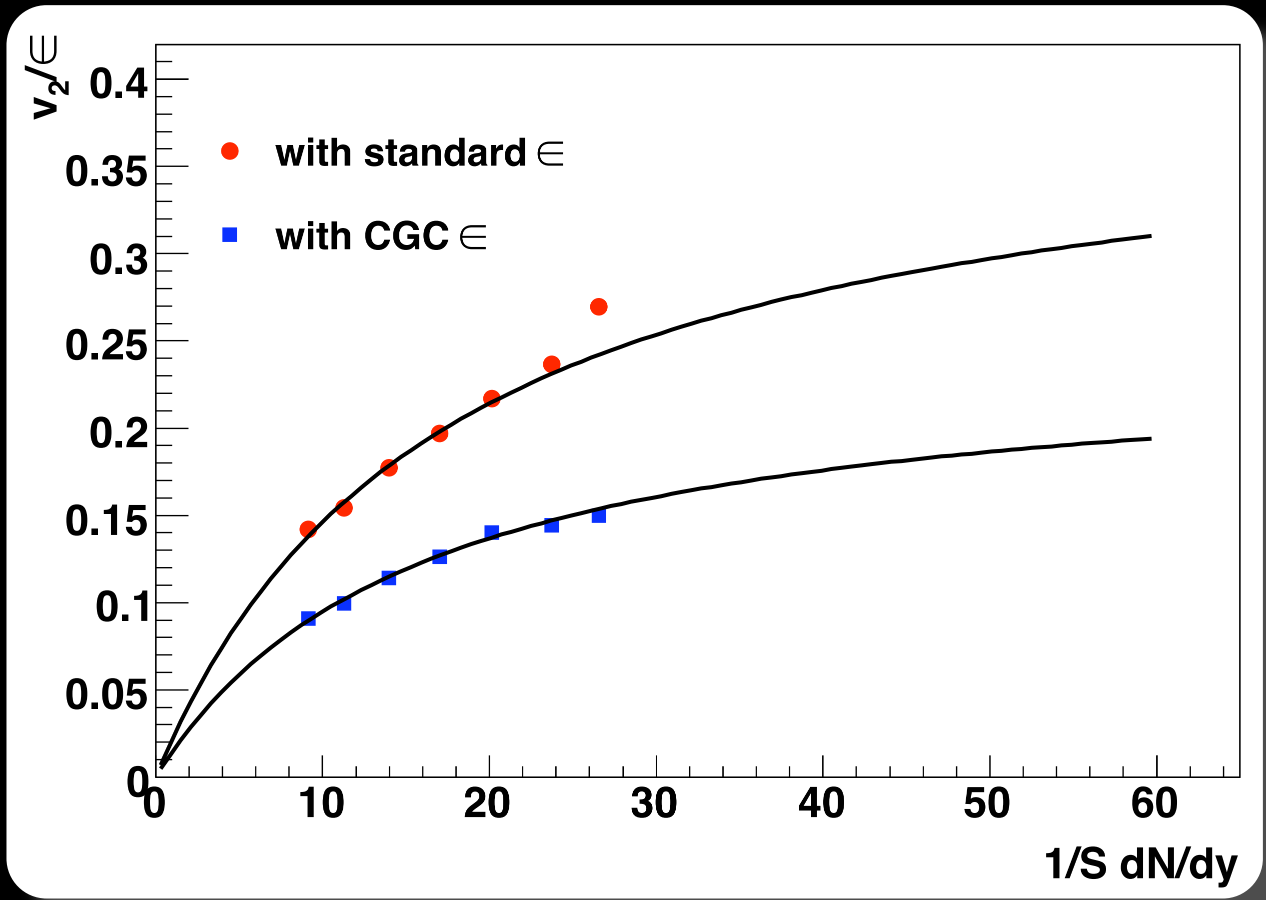


T. Hirano et al., J.Phys.G34:S879-882,2007

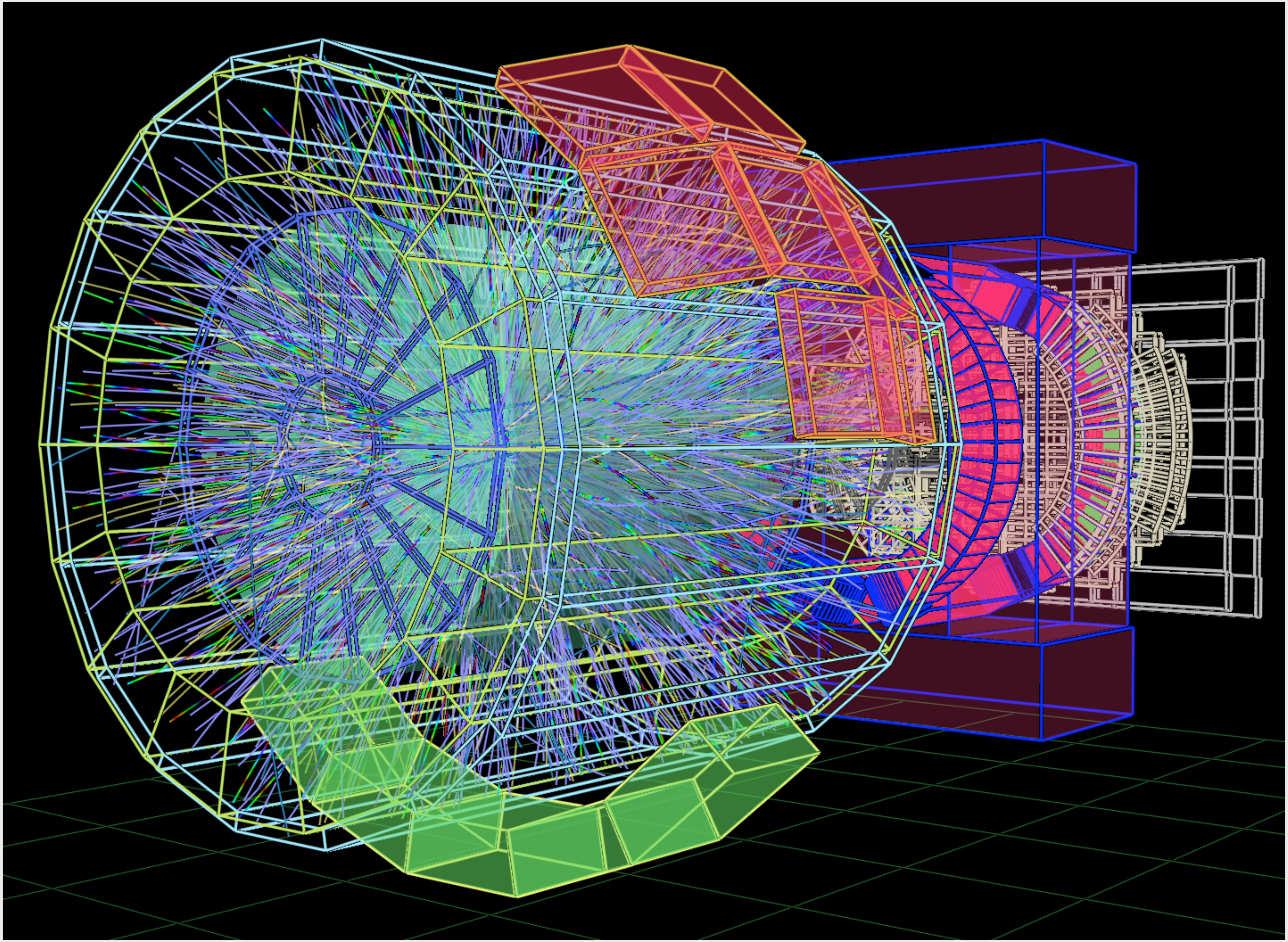
- Most models predict stronger flow

Day one at the LHC





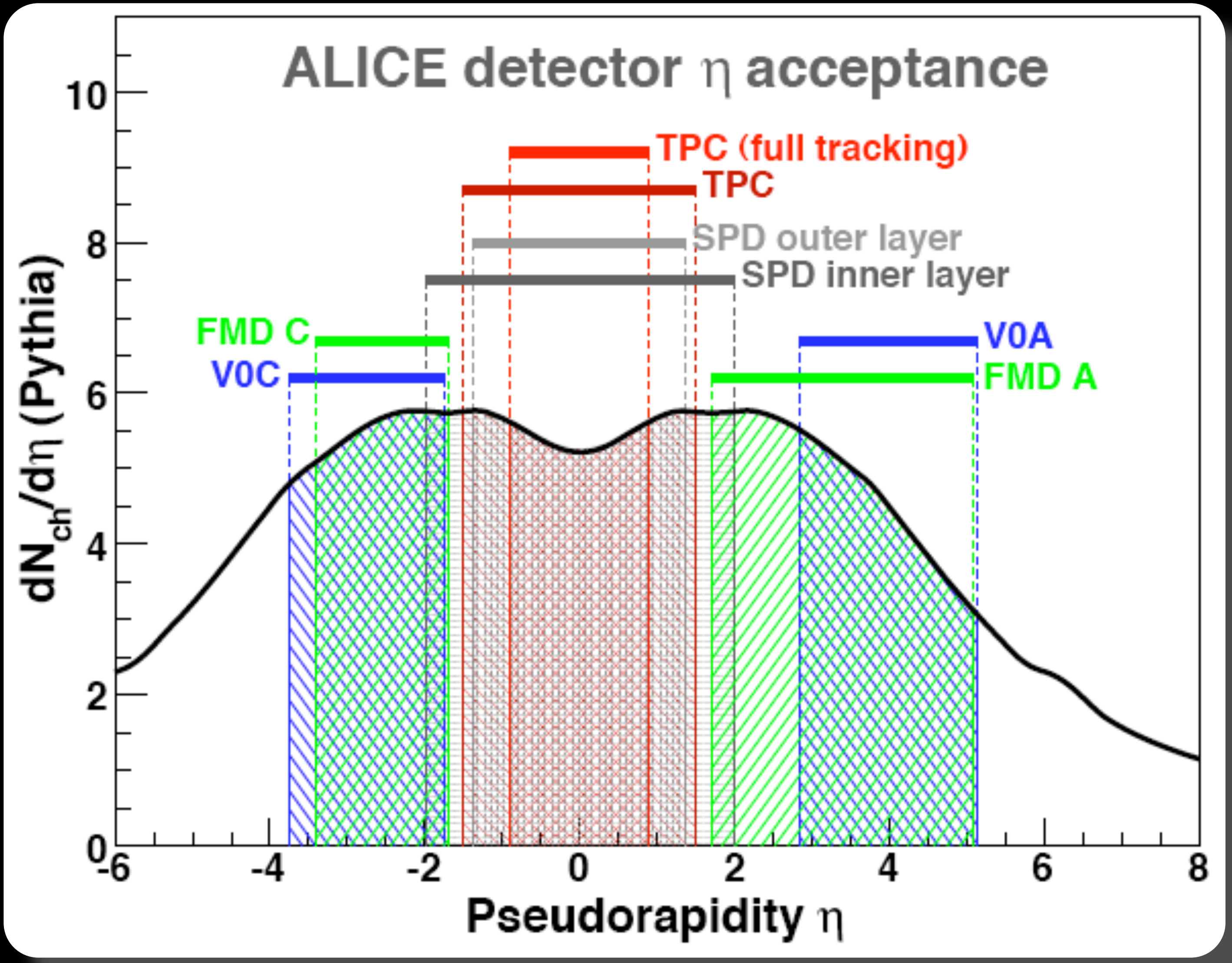
- Extrapolations predict stronger flow
- sQGP $\longrightarrow$? wQGP smaller flow



The ALICE detector

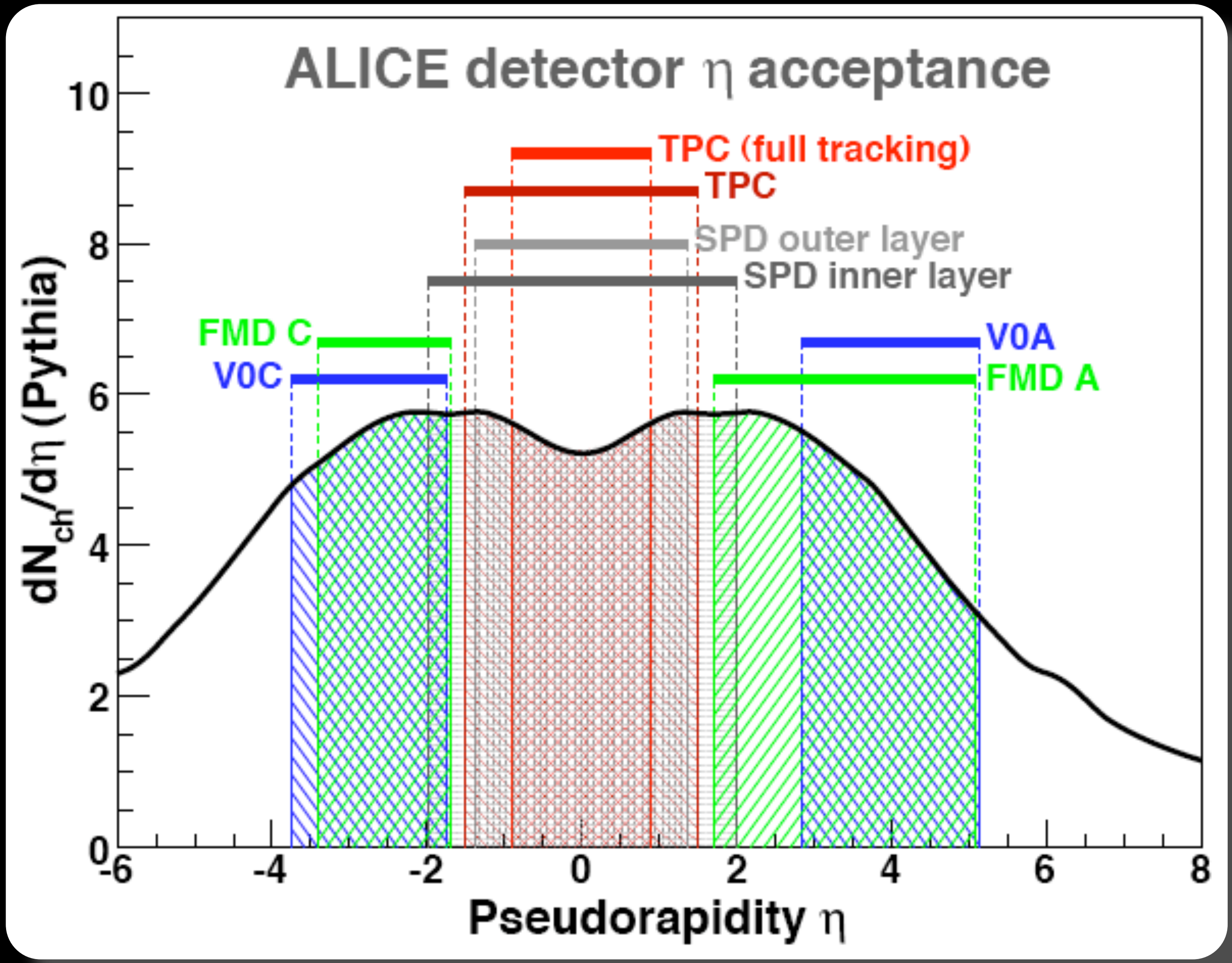
The ALICE detector

- good η coverage



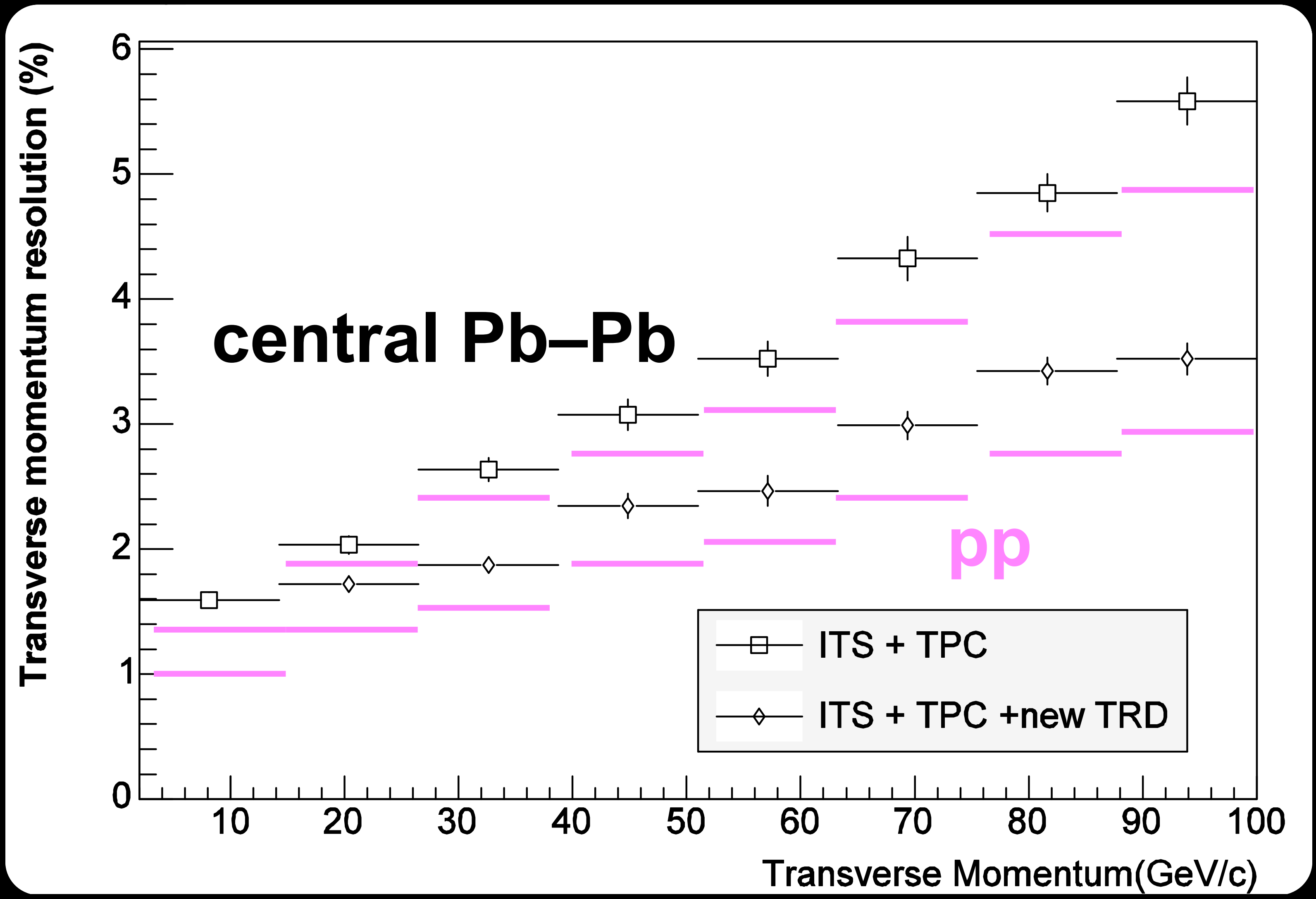
The ALICE detector

- good η coverage
- ZDCs



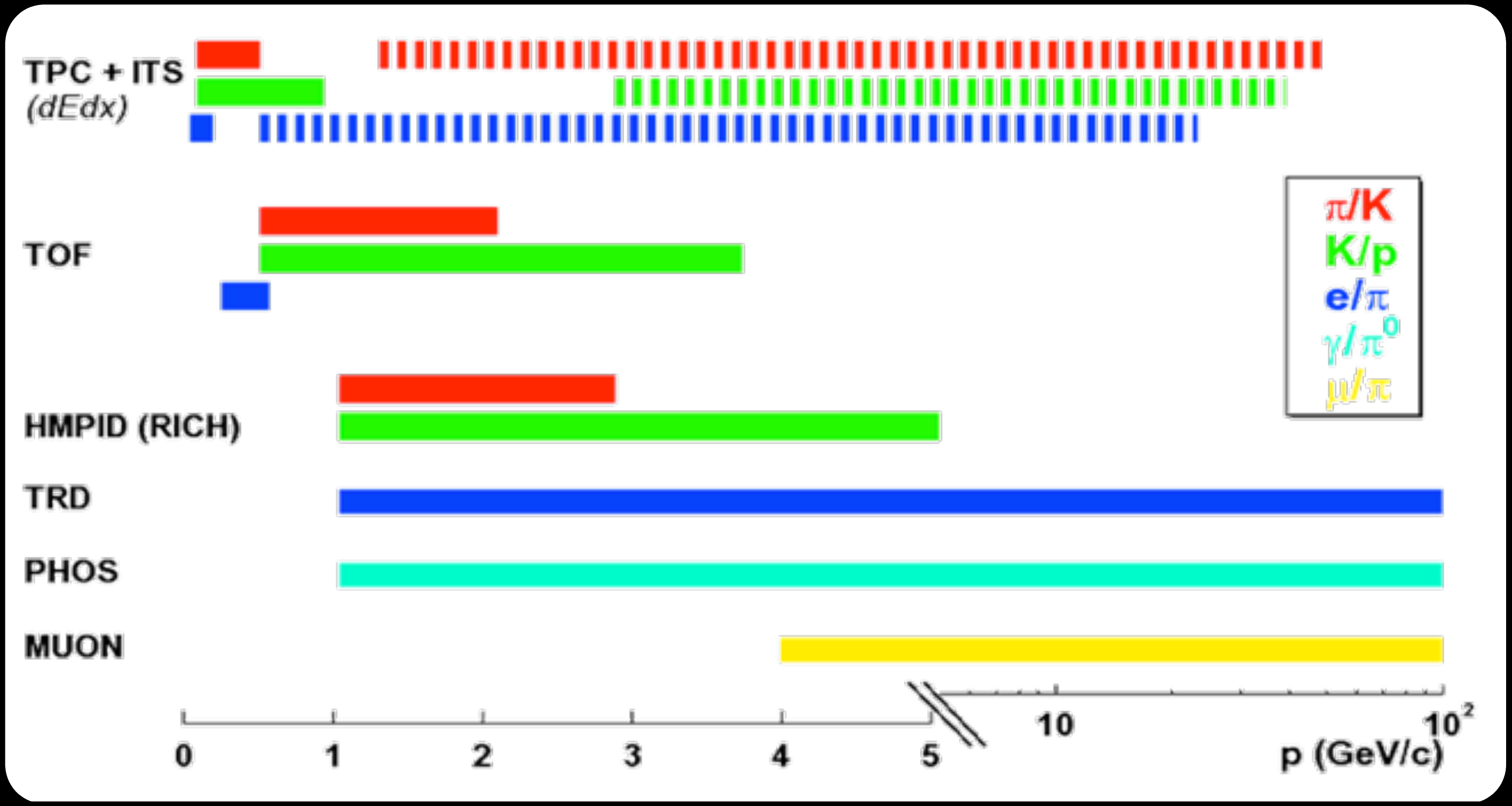
The ALICE detector

- good η coverage
- ZDCs
- p_t resolution



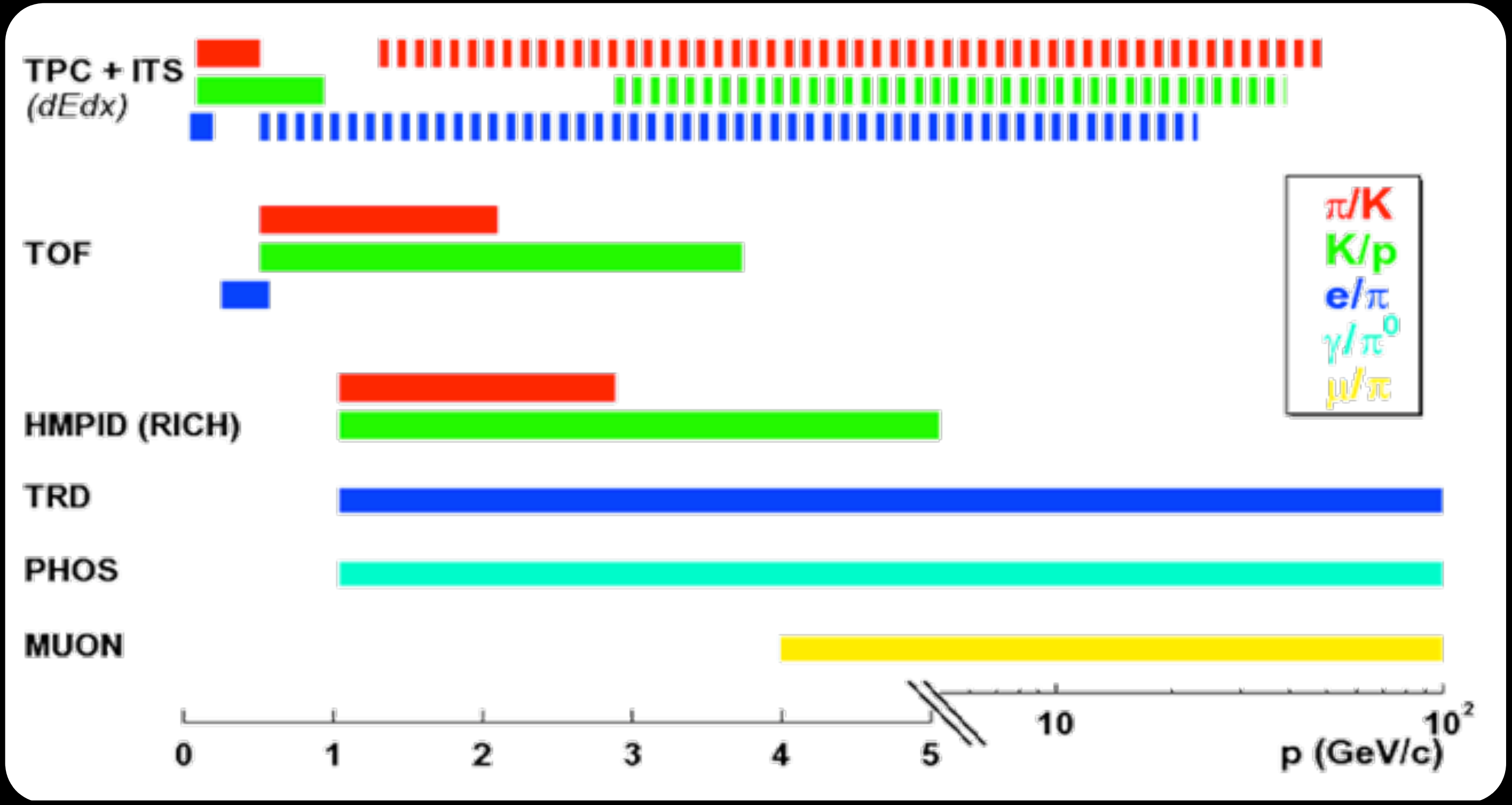
The ALICE detector

- good η coverage
- ZDCs
- p_t resolution
- pid range



The ALICE detector

- good η coverage
- ZDCs
- p_t resolution
- pid range
- abundant jet and heavy quark production



Flow analysis methods

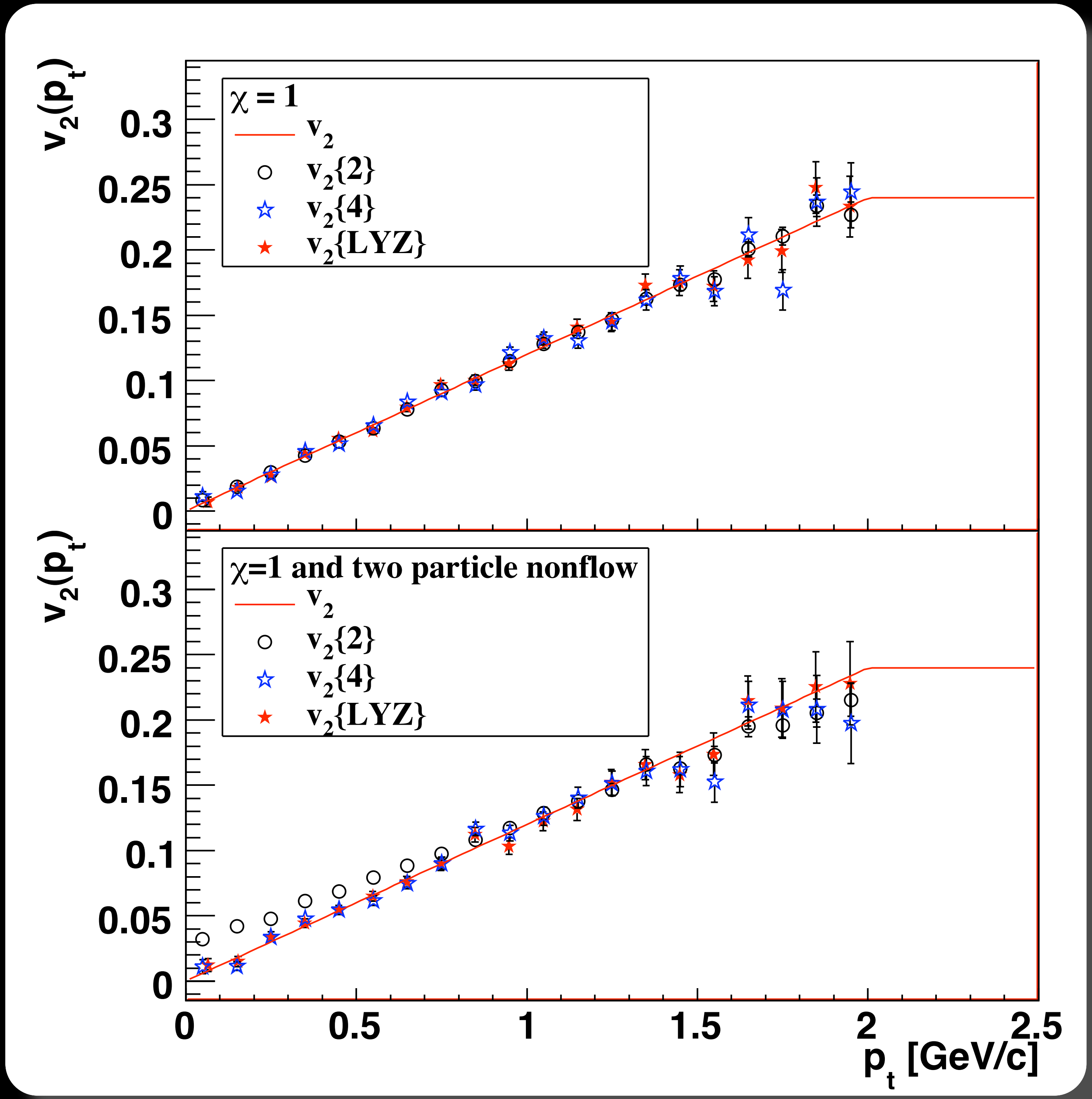
- Event plane method
- Cumulants
- Lee Yang Zeroes
- Lee Yang Zeroes + event plane

Flow analysis methods

input $\langle v_2 \rangle$ no nonflow	0,0625	
$\langle v_2\{2\} \rangle$	0,0626	+/- 0,0003
$\langle v_2\{4\} \rangle$	0,0624	+/- 0,0005
$\langle v_2\{LYZ\} \rangle$	0,0626	+/- 0,0005

input $\langle v_2 \rangle$ + nonflow	0,0625	
$\langle v_2\{2\} \rangle$	0,0764	+/- 0,0004
$\langle v_2\{4\} \rangle$	0,0627	+/- 0,0007
$\langle v_2\{LYZ\} \rangle$	0,0629	+/- 0,0007

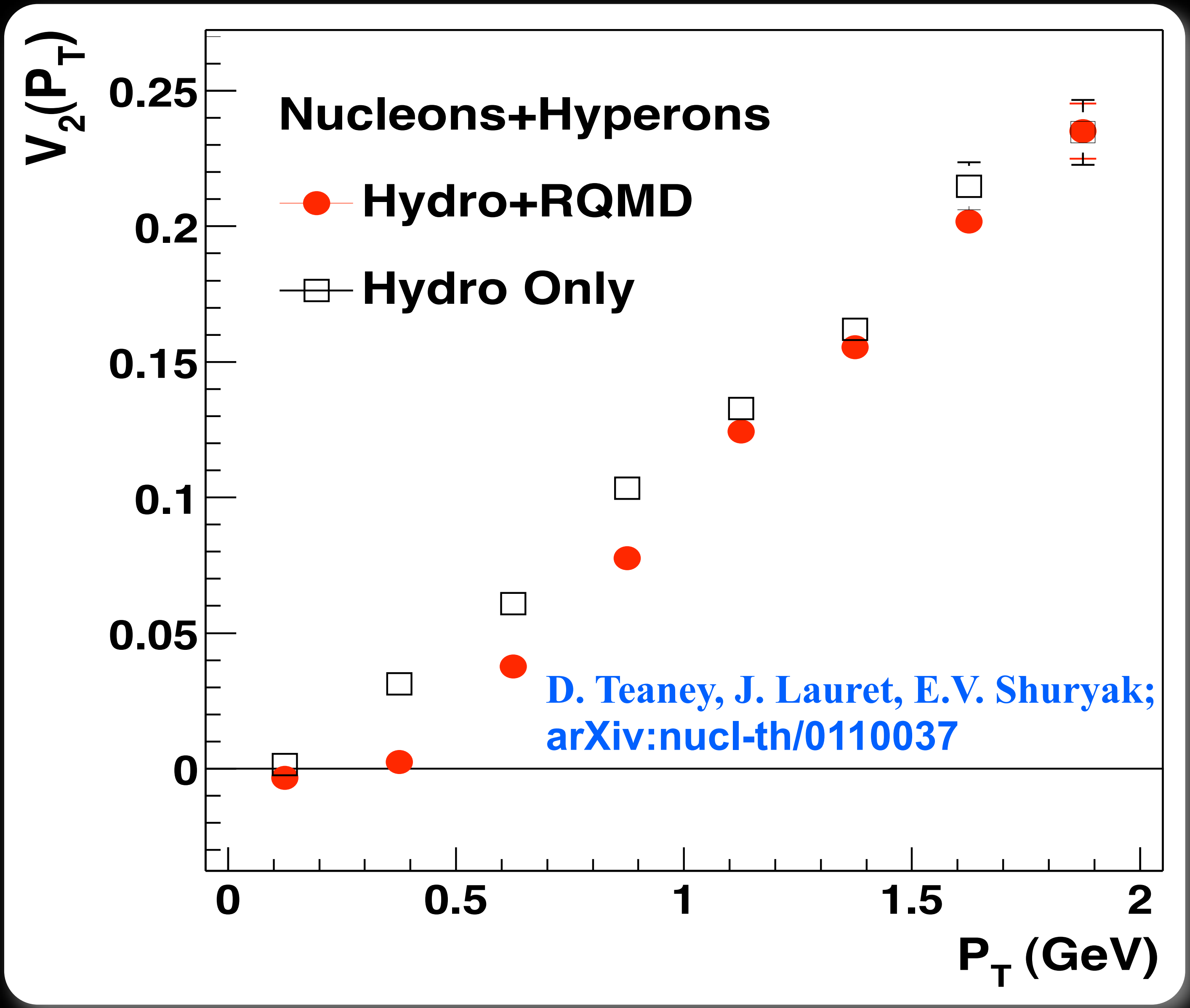
- It Matters!



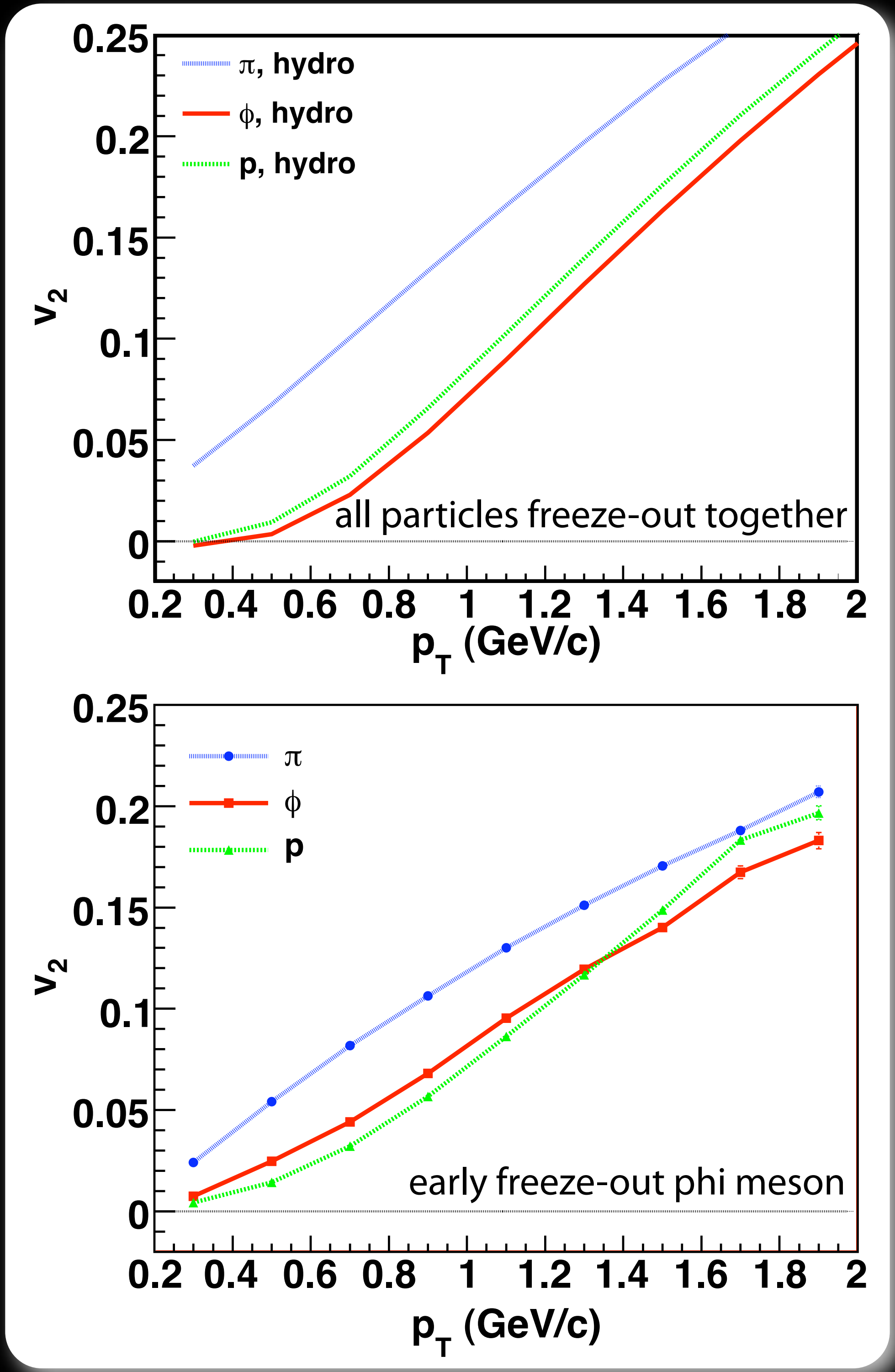
A. Bilandzic, N. van der Kolk, J-Y Ollitrault and RS; arXiv:0801.3915

Heavier particles

- Heavier particles are more sensitive to the EoS (QGP + hadronic)
- Heavier particles which freeze out early (small cross sections) provide sensitivity how important the contribution from the hadronic phase is



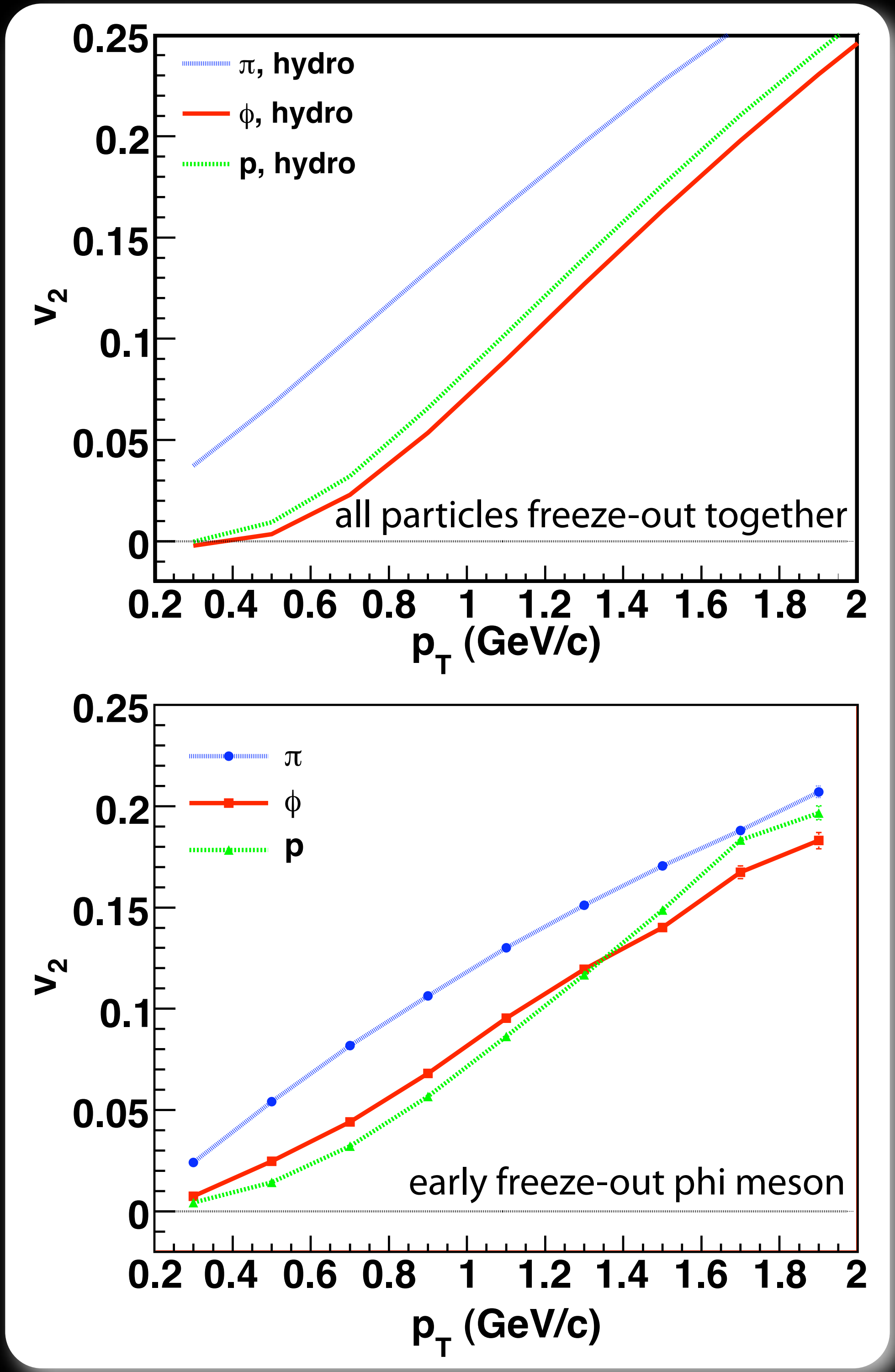
ϕ meson v_2



T. Hirano et al., arXiv:0710.5795

ϕ meson v_2

- Particles which decouple earlier should break mass dependence



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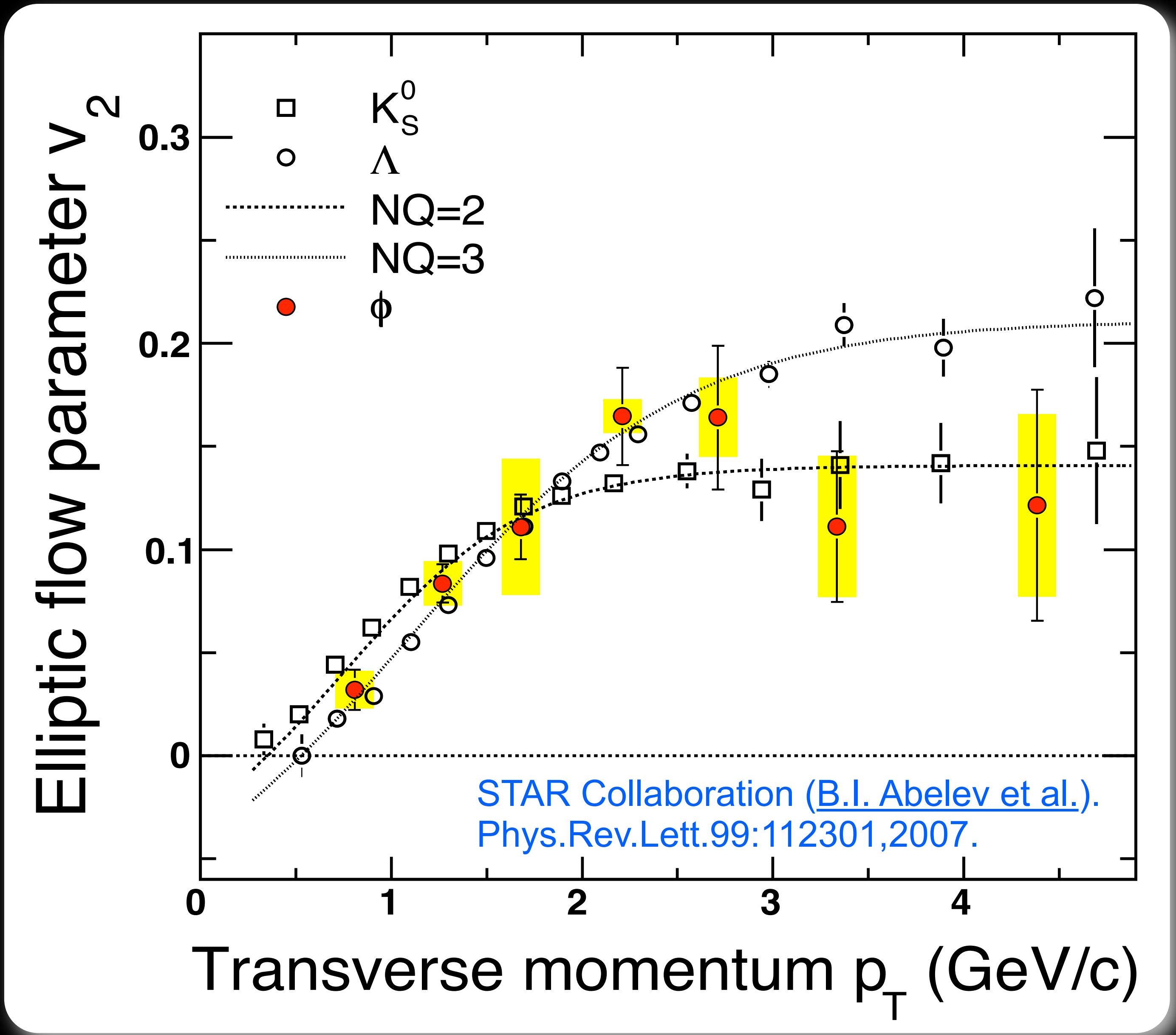
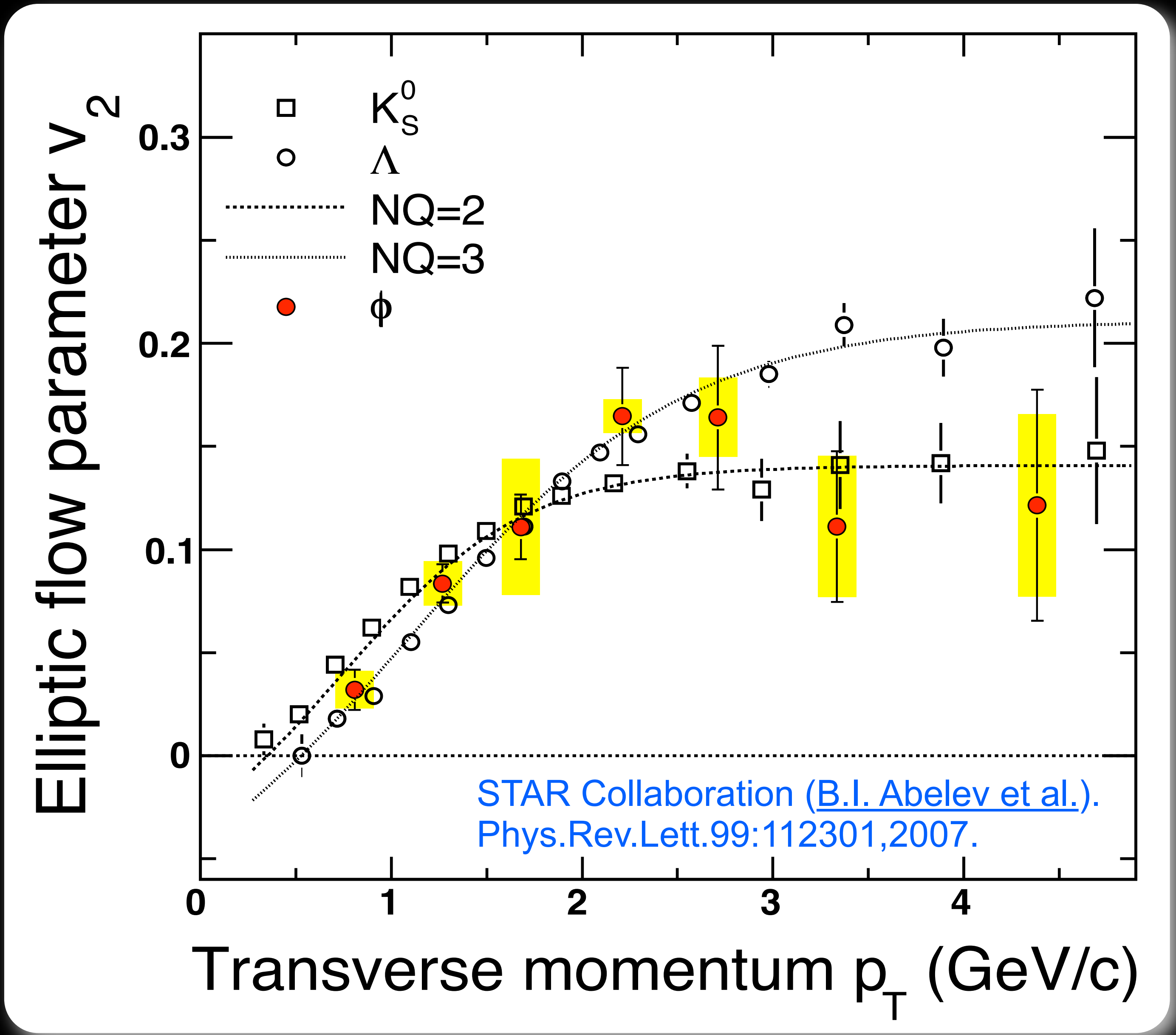
Φ meson v_2

- Particles which decouple earlier should break mass dependence
- Experimental results for the φ meson do not show a clear different behavior compared to non strange particles (above Λ v_2 up to 2 GeV/c)



Φ meson v_2

- Particles which decouple earlier should break mass dependence
- Experimental results for the φ meson do not show a clear different behavior compared to non strange particles (above Λ v_2 up to 2 GeV/c)
  - perhaps the φ mesons do not freeze out earlier
  - need beter data!



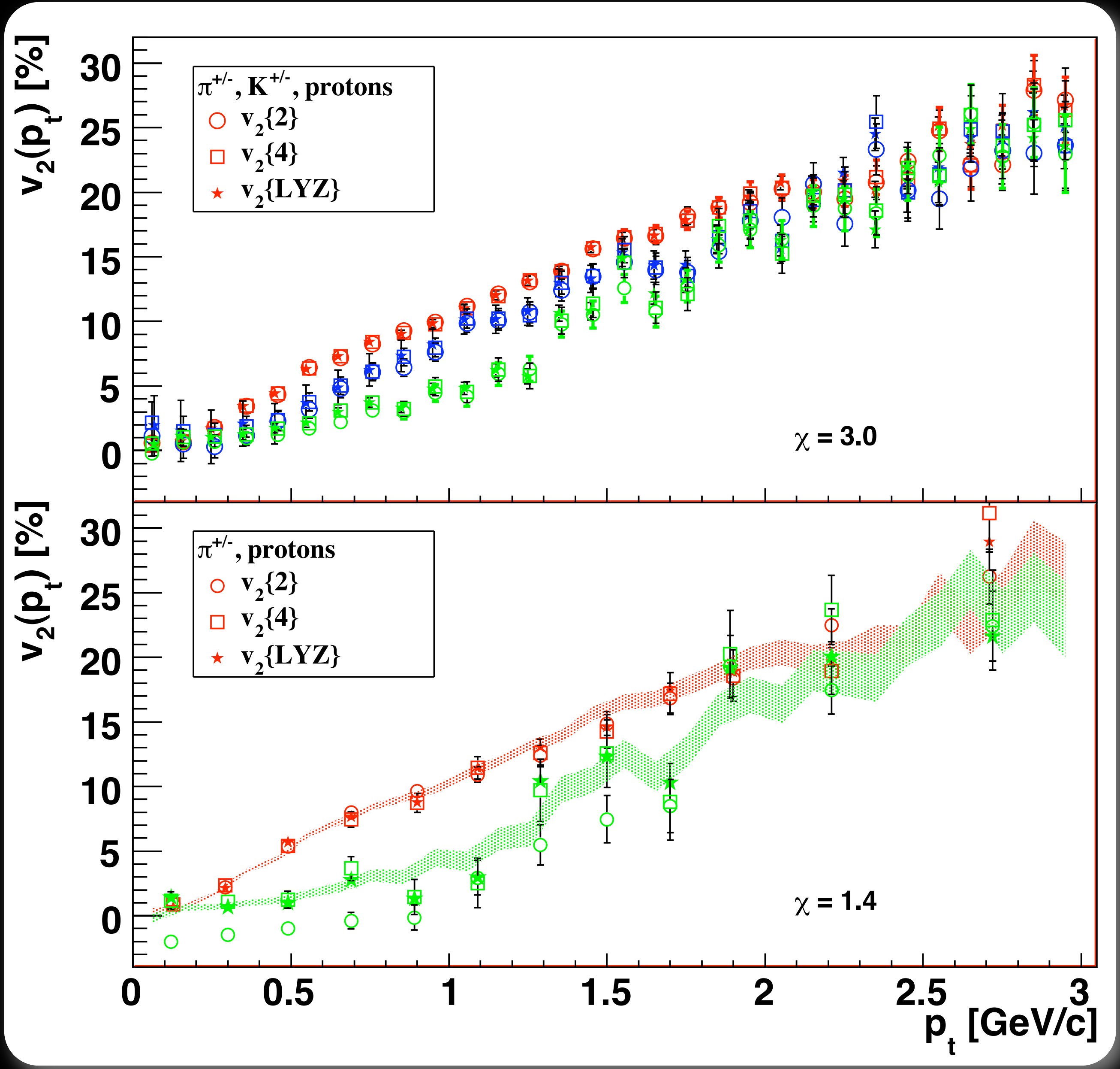
Identified Particle Flow

- The different methods can be used for identified particle flow as well

- Model: hydro calculations used with single thermal freeze-out (done with THERMINATOR)

W. Broniowski M. Chojnacki W. Florkowski A. Kisiel; arXiv:nucl-th/0611069

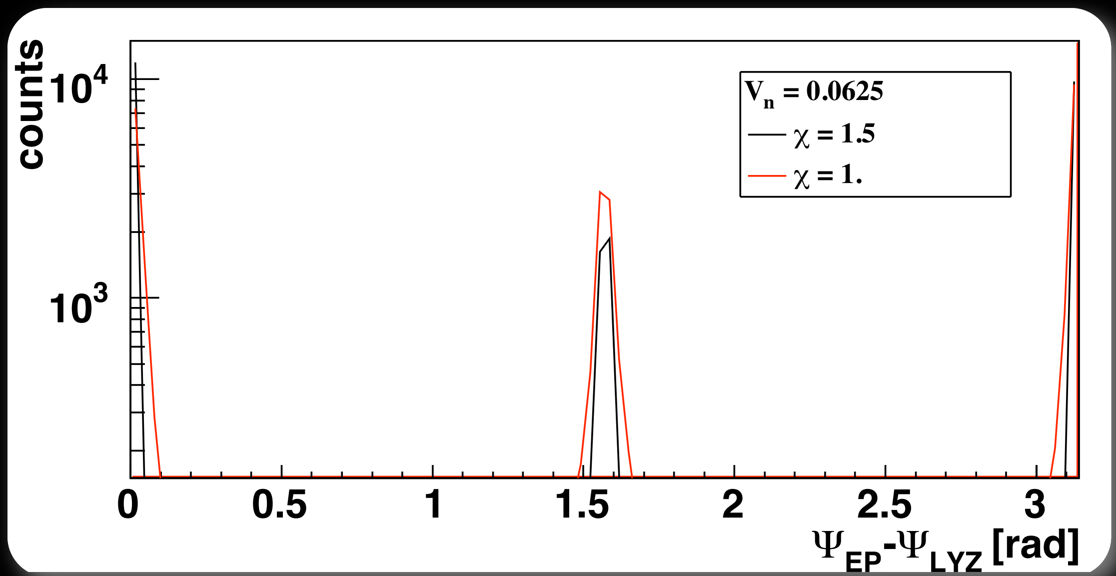
- When the flow and/or multiplicity decreases nonflow effects start to become important

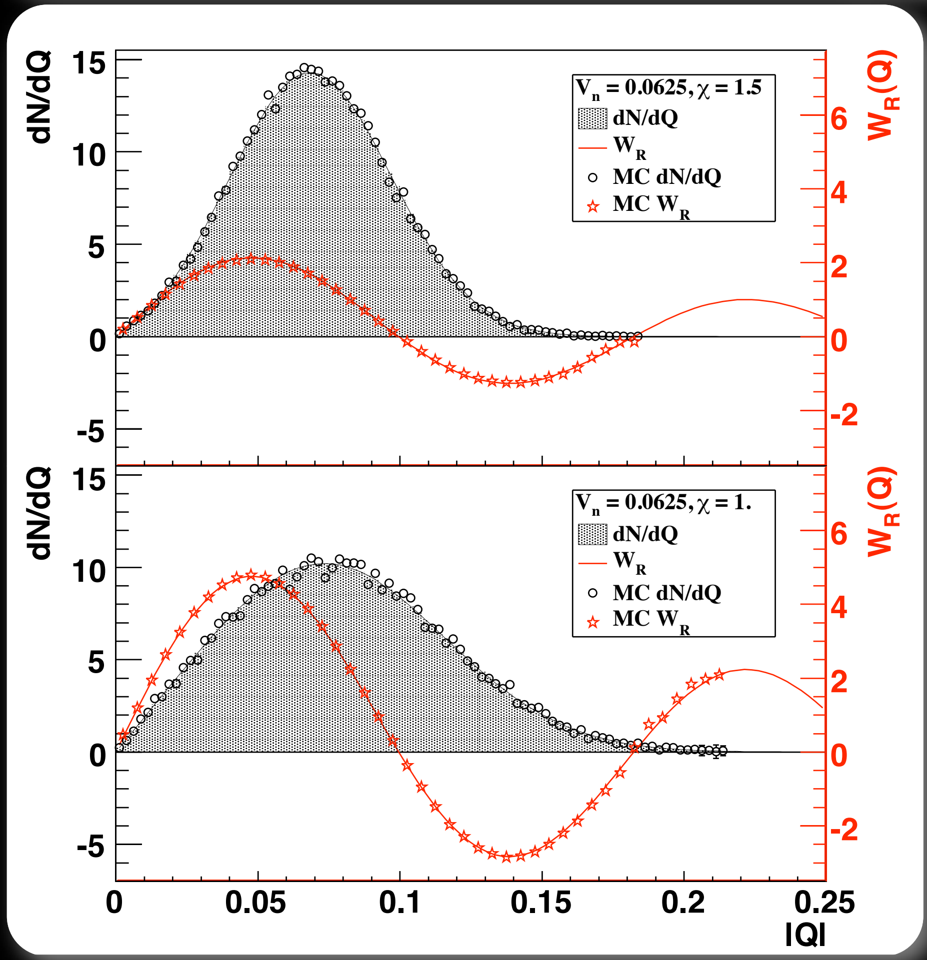


A. Bilandzic, N. van der Kolk

Lee-Yang Zeroes + EP

- Event plane method (nonflow ☹)
- Cumulants (removes nonflow ☺, no event plane ☹)
- Lee Yang Zeroes (removes nonflow to all orders ☺, no event plane ☹)
- Lee Yang Zeroes + event plane (☺ ☺)
  - Gives the event plane for many other observables
  - Nonflow removed using weights for each event depending on the magnitude of the Q vector →





A. Bilandzic, N. van der Kolk, J-Y Ollitrault and RS; arXiv:0801.3915

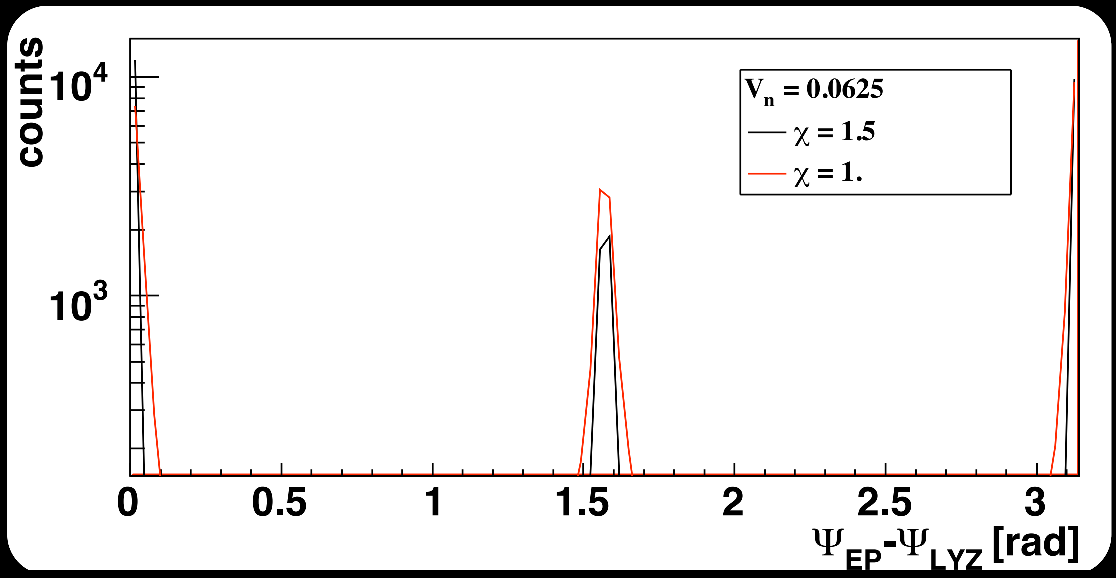
Outlook

- With the main uncertainties being addressed flow measurements start to constrain the EoS and transport coefficients
- Day 1 ALICE flow measurements provide the leverage to confirm/rule out the different models
- In addition flow allows to determine the reaction plane (without nonflow using recent LYZ RP!)
  - parton energy loss of light and heavy quarks
  - much more ... very rich program!

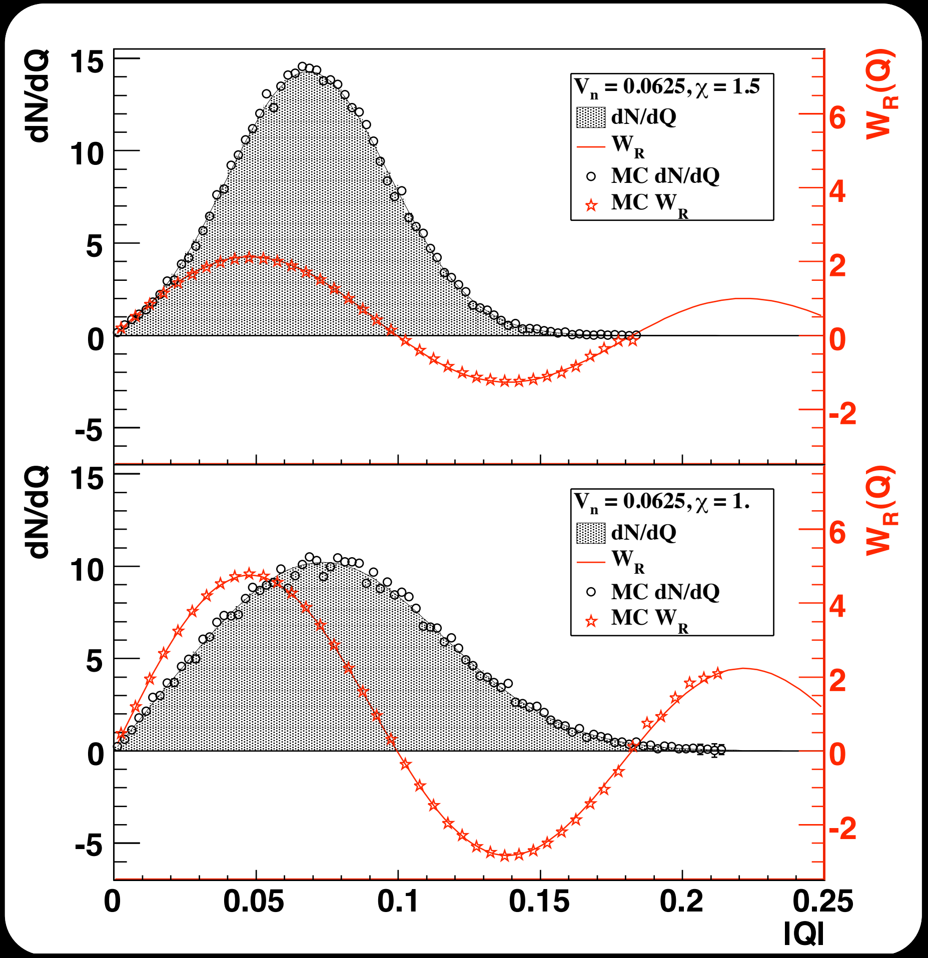
Thanks!

Lee-Yang Zeroes + EP

- New development
- Gives estimate of the reaction plane (same as event plane method) →



- Nonflow removed using weights for each event depending on the magnitude of the Q vector →



$$\mathbf{Q} = (Q_x, Q_y)$$

$$Q_x = Q\cos(n\Psi_R) \equiv \sum_{j=1} w_j \cos(n\phi_j)$$

$$Q_y = Q\sin(n\Psi_R) \equiv \sum_{j=1} w_j \sin(n\phi_j),$$

$$\frac{dN}{dQ} = \frac{2\chi^2 Q}{V_n^2} \exp\left(-\chi^2\left(\frac{Q^2}{V_n^2}+1\right)\right) I_0\left(\frac{2\chi^2 Q}{V_n}\right).$$

A. Bilandzic, N. van der Kolk, J-Y Ollitrault and RS; arXiv:0801.3915

Anisotropic Flow

- In non central collisions coordinate space configuration is anisotropic (almond shape). However, initial momentum distribution isotropic (spherically symmetric)
- Only interactions among constituents (mean free path small) generate a pressure gradient which transforms the initial coordinate space anisotropy into the observed momentum space anisotropy → anisotropic flow
- Multiple interactions lead to thermalization → limiting behavior hydrodynamic flow
- In addition allows us to determine the reaction plane and correlate observables which probe the medium as function of path length