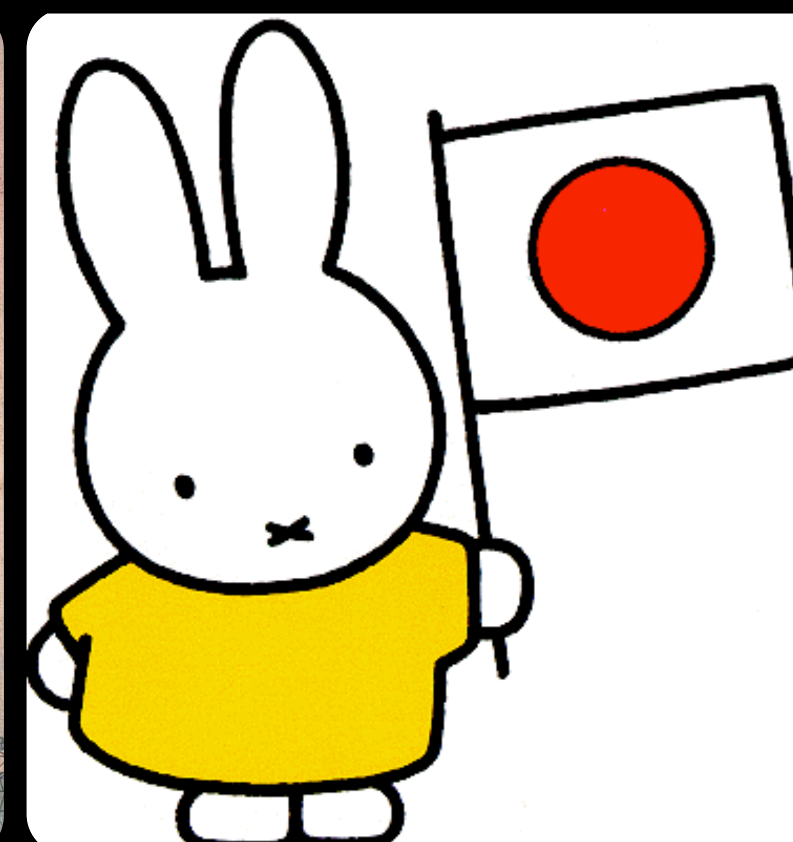
Anisotropic Flow: from RHIC to the LHC

Raimond Snellings NIKHEF



ATHIC Asian Triangle Heavy Ion Conference

The 2nd Asian Triangle Heavy Ion Conference

13th - 15th October, 2008

University of Tsukuba, Tsukuba, Japan

NIKHEF

arXiv:0809.2949 [nucl-ex]

Collective phenomena in non-central nuclear collisions

October 6, 2008 Draft

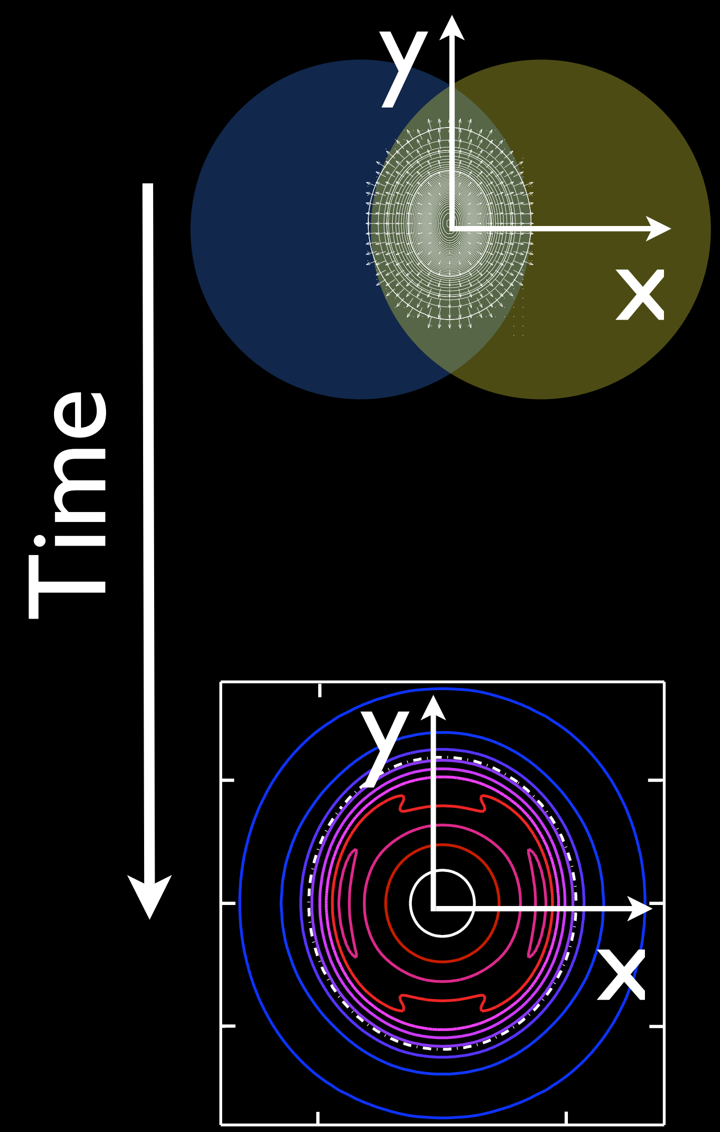
Sergei A. Voloshin, Arthur M. Poskanzer, and Raimond Snellings

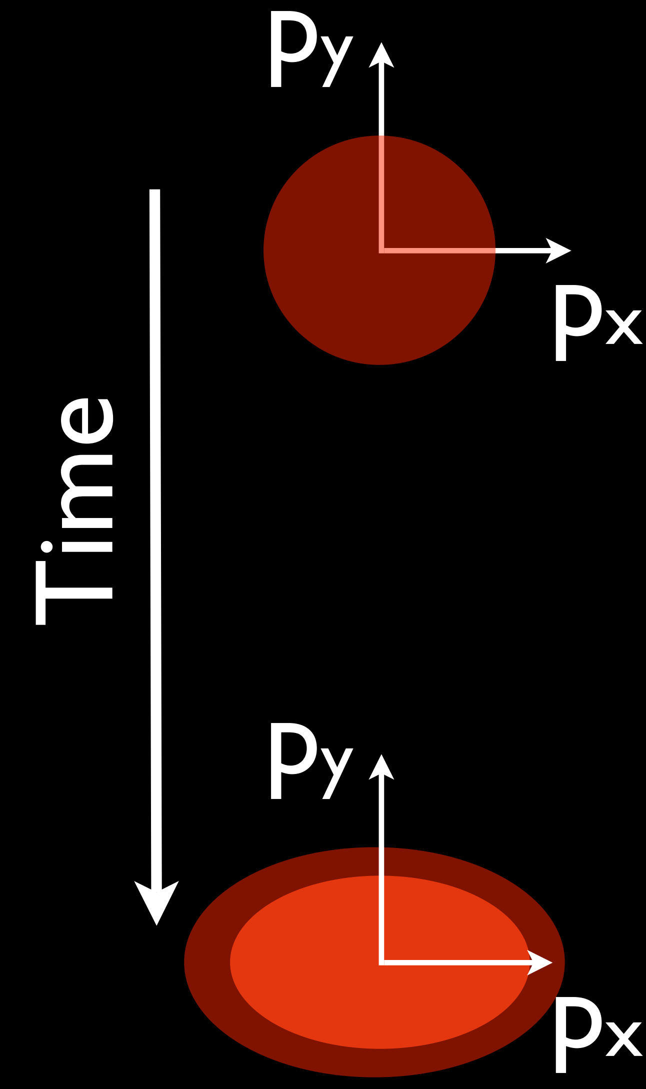
Abstract Recent developments in the field of anisotropic flow in nuclear collision are reviewed. The results from the top AGS energy to the top RHIC energy are discussed with emphasis on techniques, interpretation, and uncertainties in the measurements.

Elliptic Flow

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\phi \rangle$$

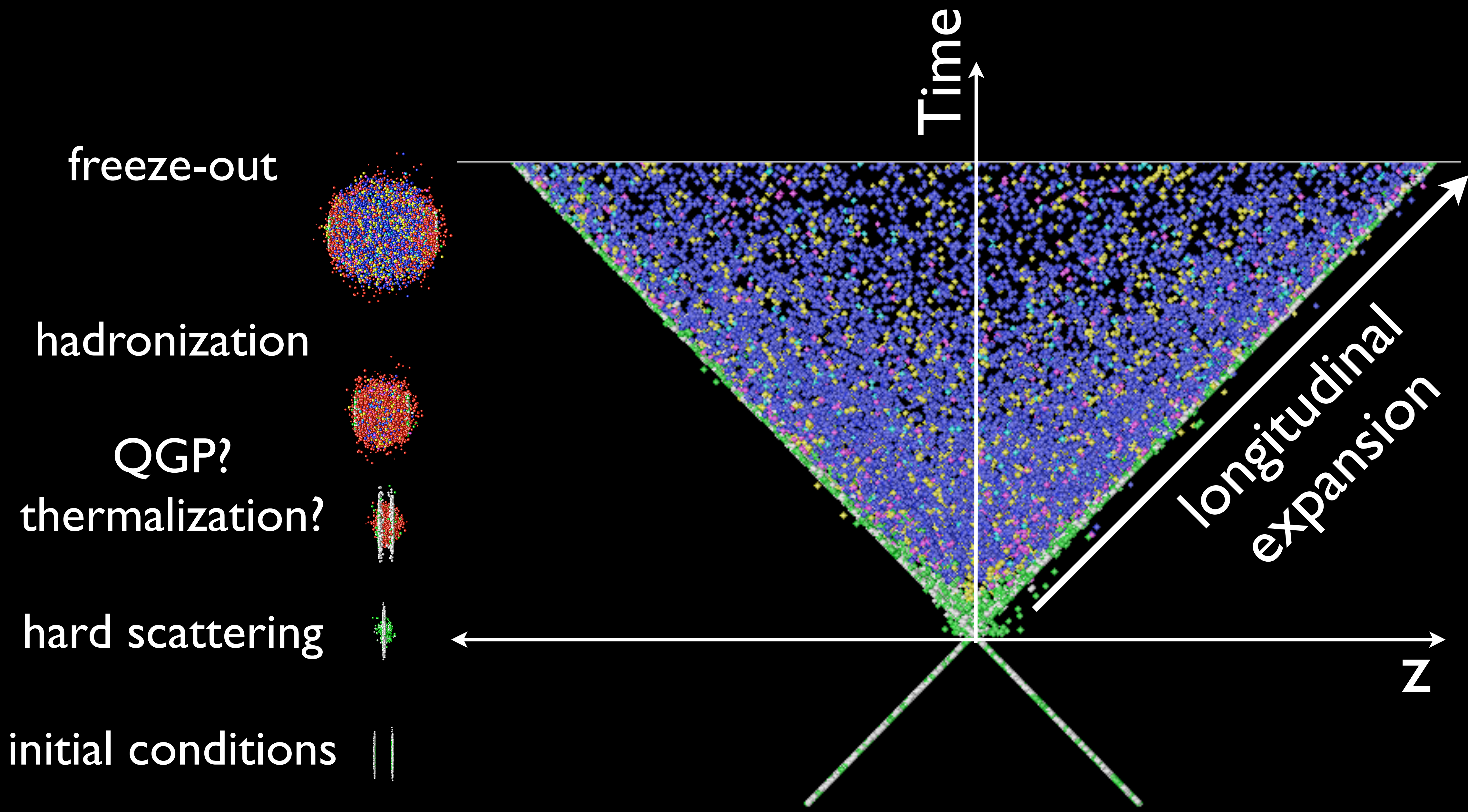
- A unique hadronic probe of the early stage
  - In non central collisions coordinate space configuration is anisotropic (almond shape). However, initial momentum distribution isotropic (spherically symmetric)
  - Interactions among constituents generate a pressure gradient which transforms the initial coordinate space anisotropy into the observed momentum space anisotropy → anisotropic flow
  - self-quenching → sensitive to early stage





see talk ShinIchi Esumi and Maya Shimomura

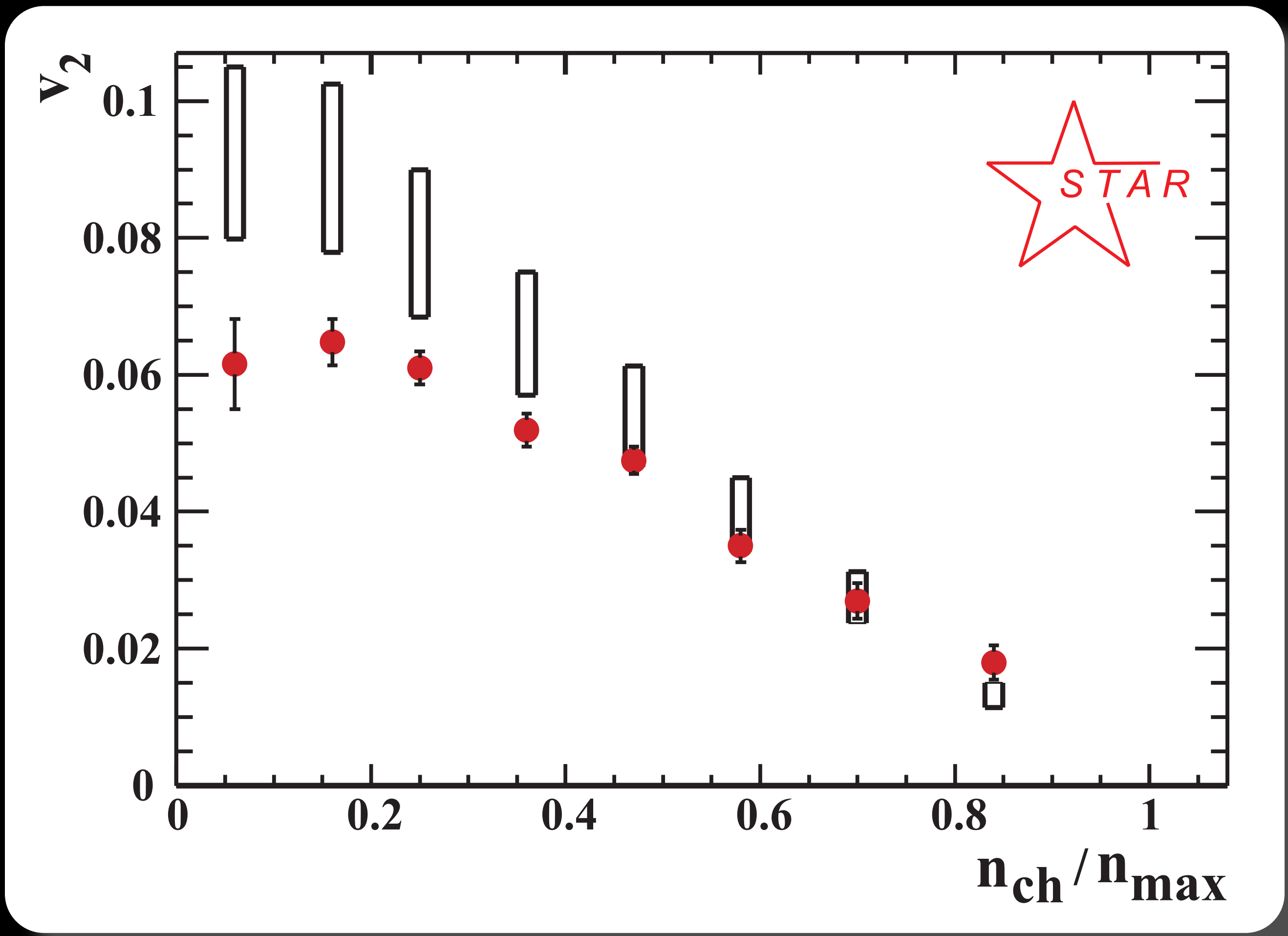
Schematic Time Evolution



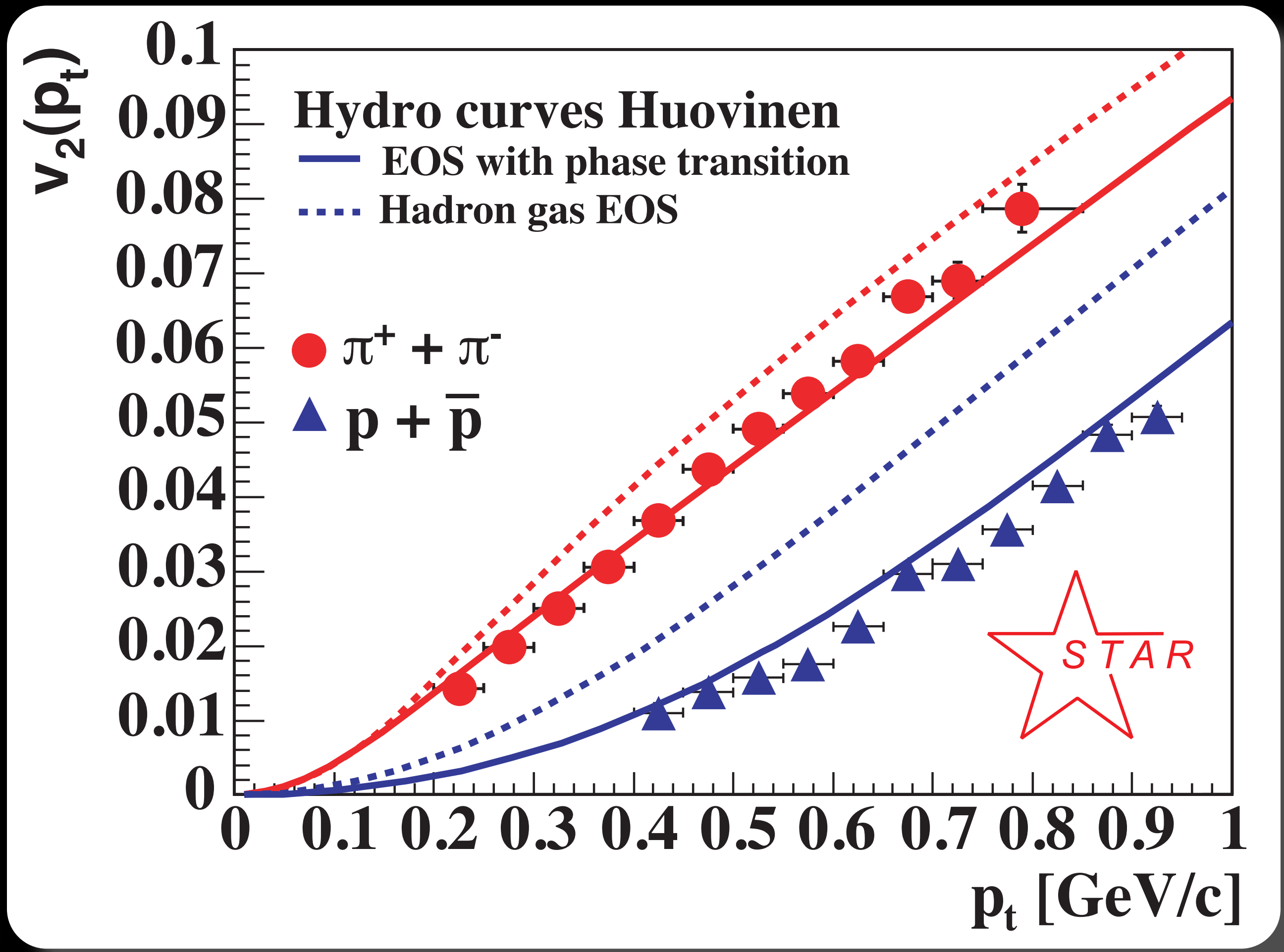
Flow builds up during all phases, probably even contributions from initial conditions: CGC, pQCD, parton cascade, viscous hydro, hadronization, hadron cascade

T. Hirano; arXiv:0808.2684 [nucl-th]
C. Nonaka; arXiv:nucl-th/0702082
talk Yasushi Nara

Ideal hydro does well



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

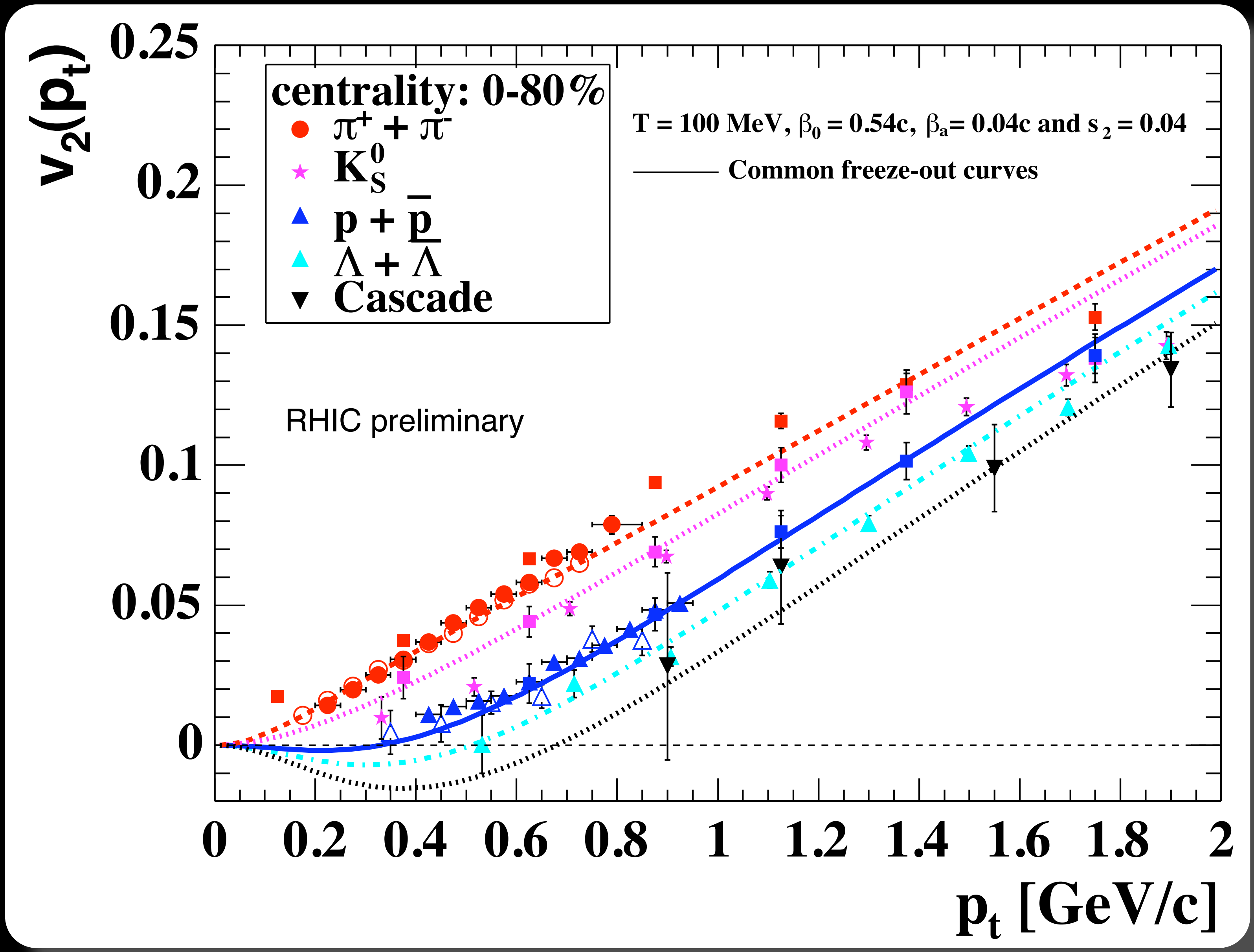


STAR Phys. Rev. Lett. 87, 182301 (2001)

- Ideal hydro gets ~ magnitude and species dependence
- The species dependence is more sensitive to the EoS

The Bulk Matter

- The observed particles can be characterized by a single freeze-out temperature and a common azimuthal dependent boost velocity



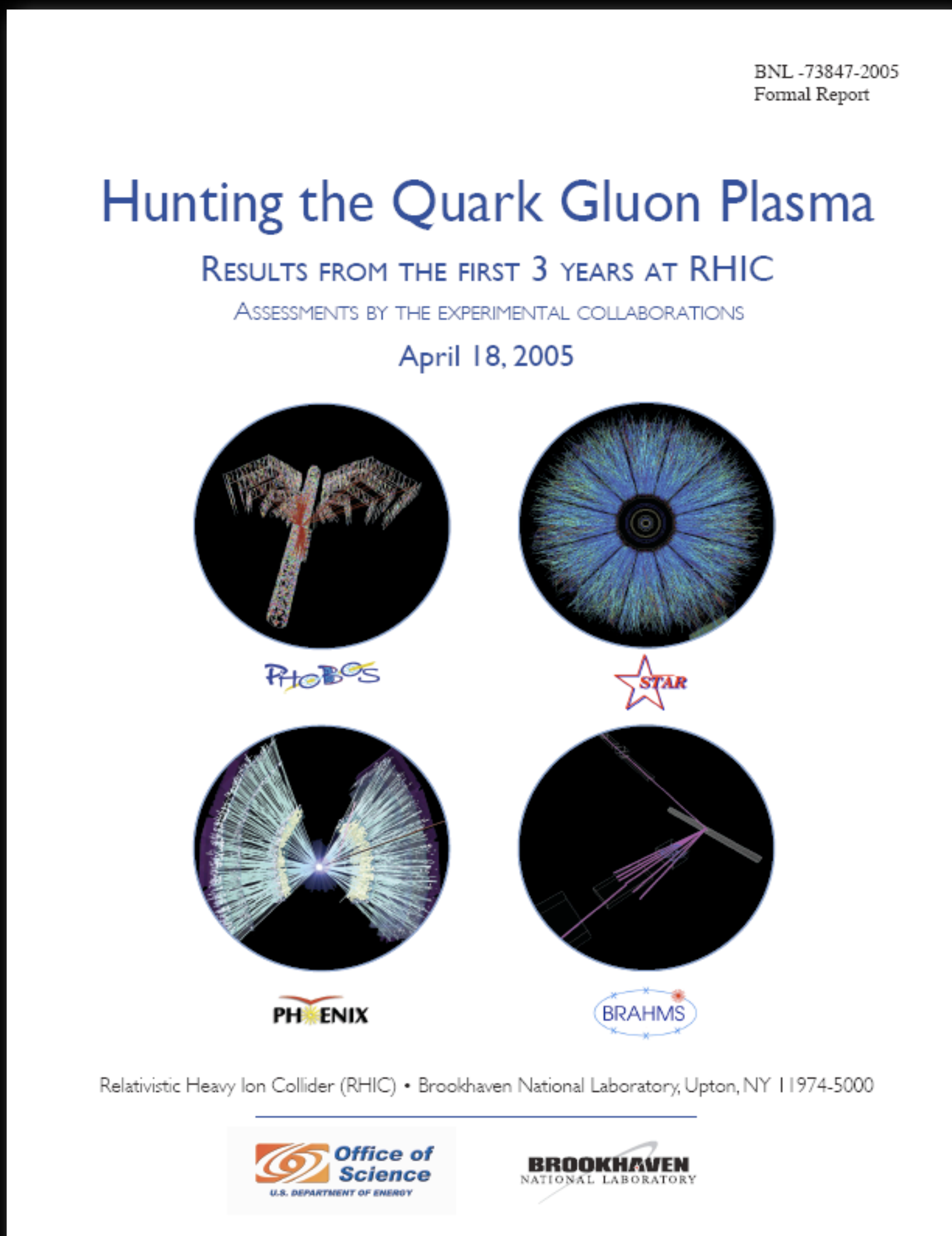
Fits from STAR Phys. Rev. Lett. 87, 182301 (2001)

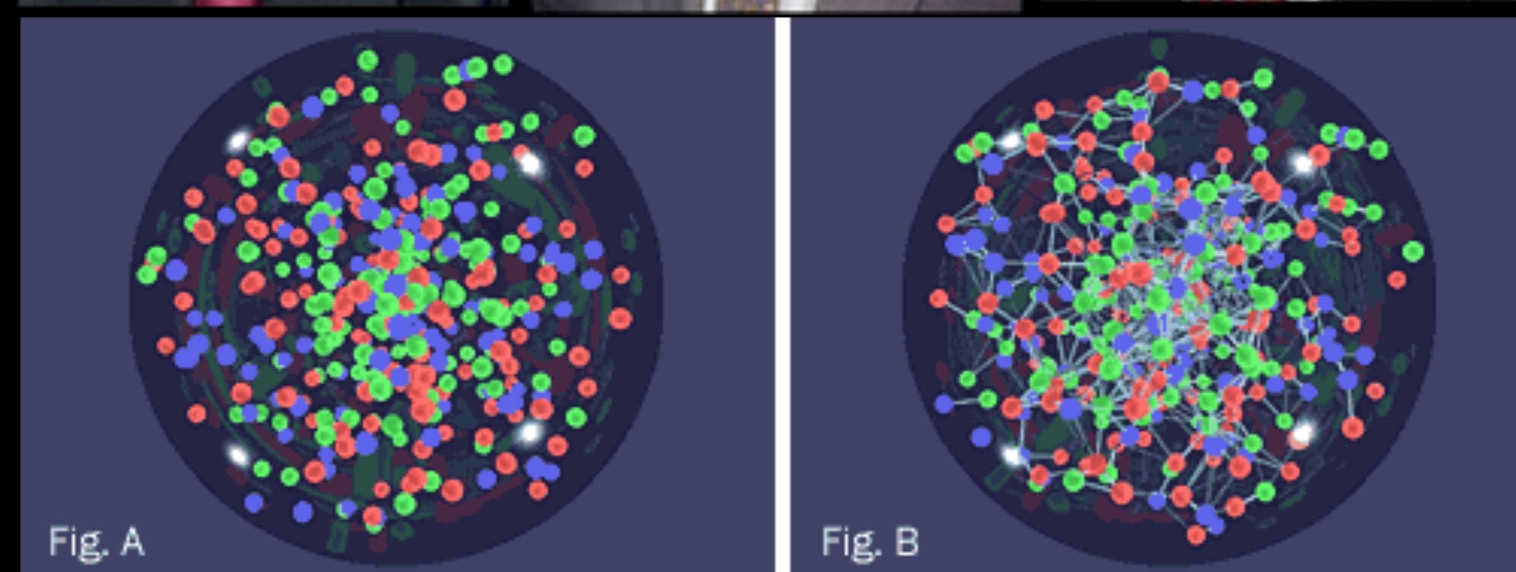
What about early freezout?
What about importance of hadronic phase?

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

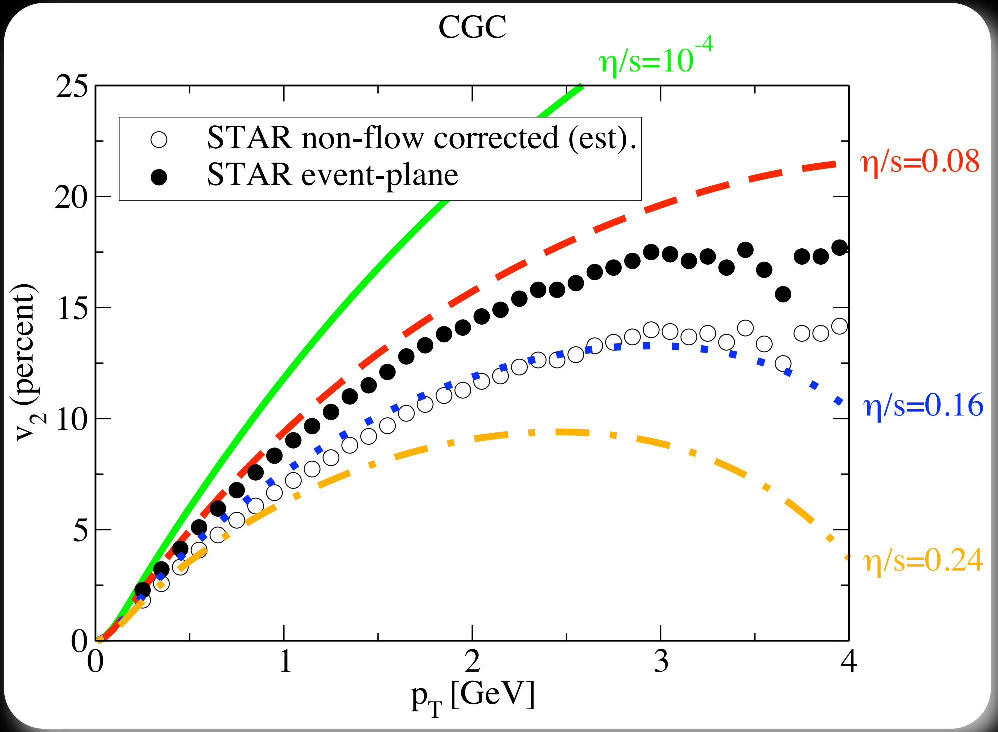
April 18, 2005



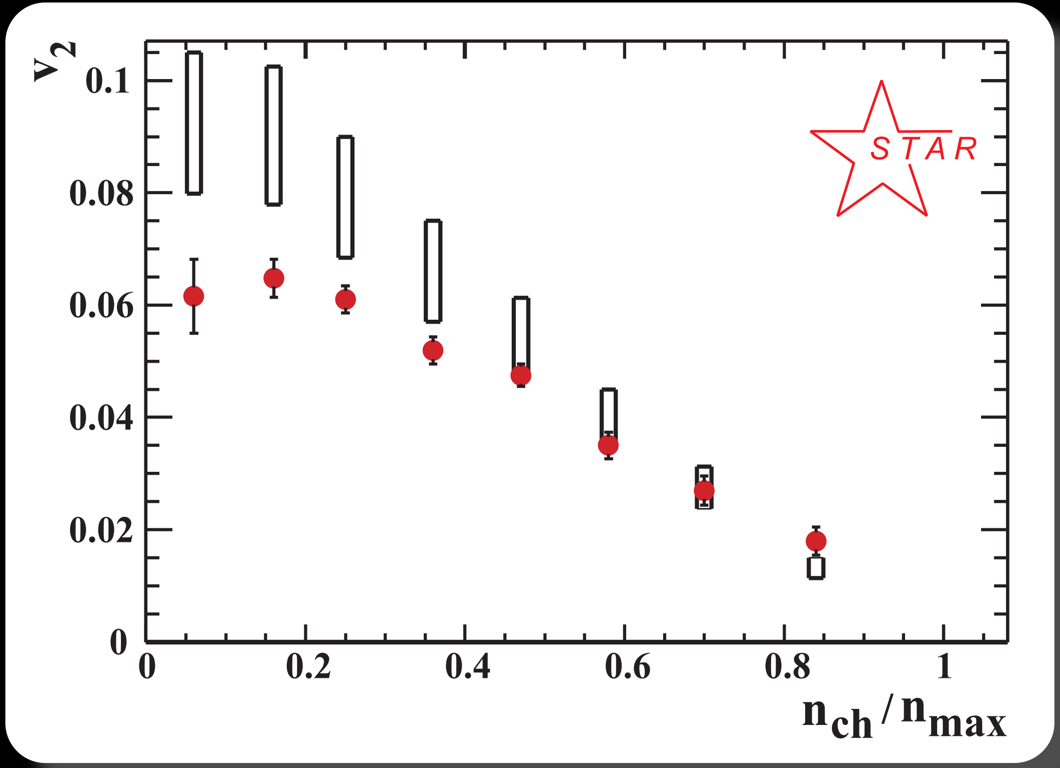


Hydro at RHIC

- significant effects due to shear viscosity
  Derek Teaney
- significant uncertainties due to initial conditions
- ideal hydro agreement somewhat accidental



Matthew Luzum, Paul Romatschke arXiv:0804.4015



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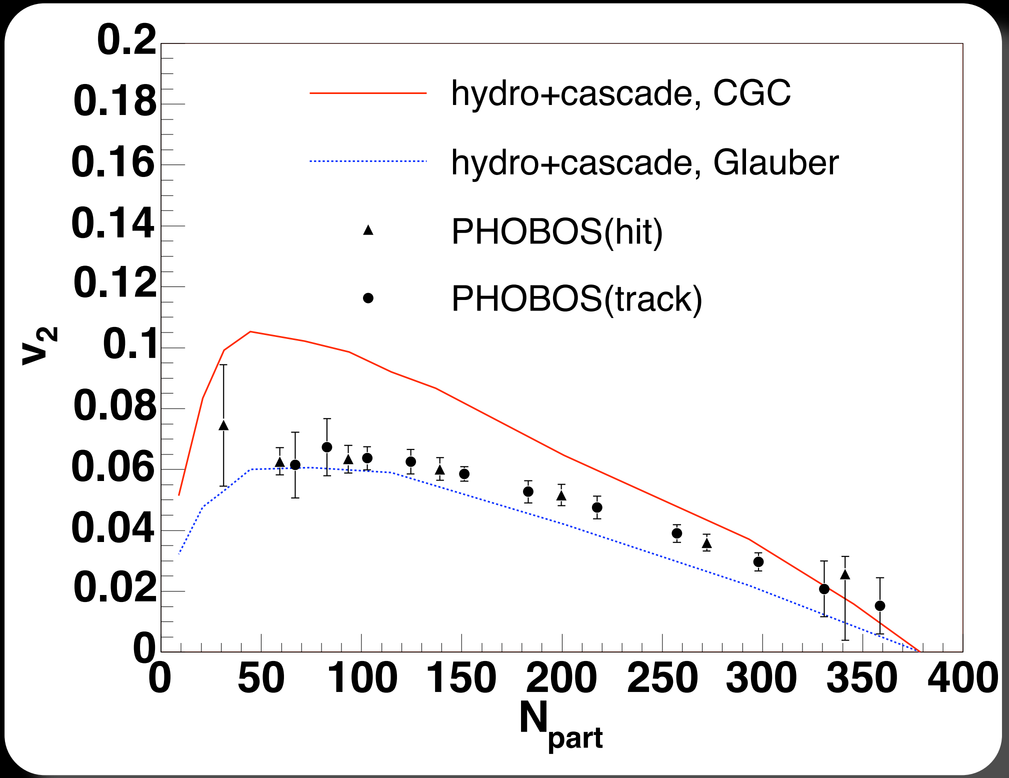


T. Hirano et al., Phys. Lett. B 636 299 (2006)
T. Hirano et al., J.Phys.G34:S879-882,2007

The Perfect Liquid?

In the Low Density Limit (LDL):

$$\frac{v_2}{\epsilon} \propto \sigma \frac{1}{S} \frac{\mathrm{d}N}{\mathrm{d}y}$$

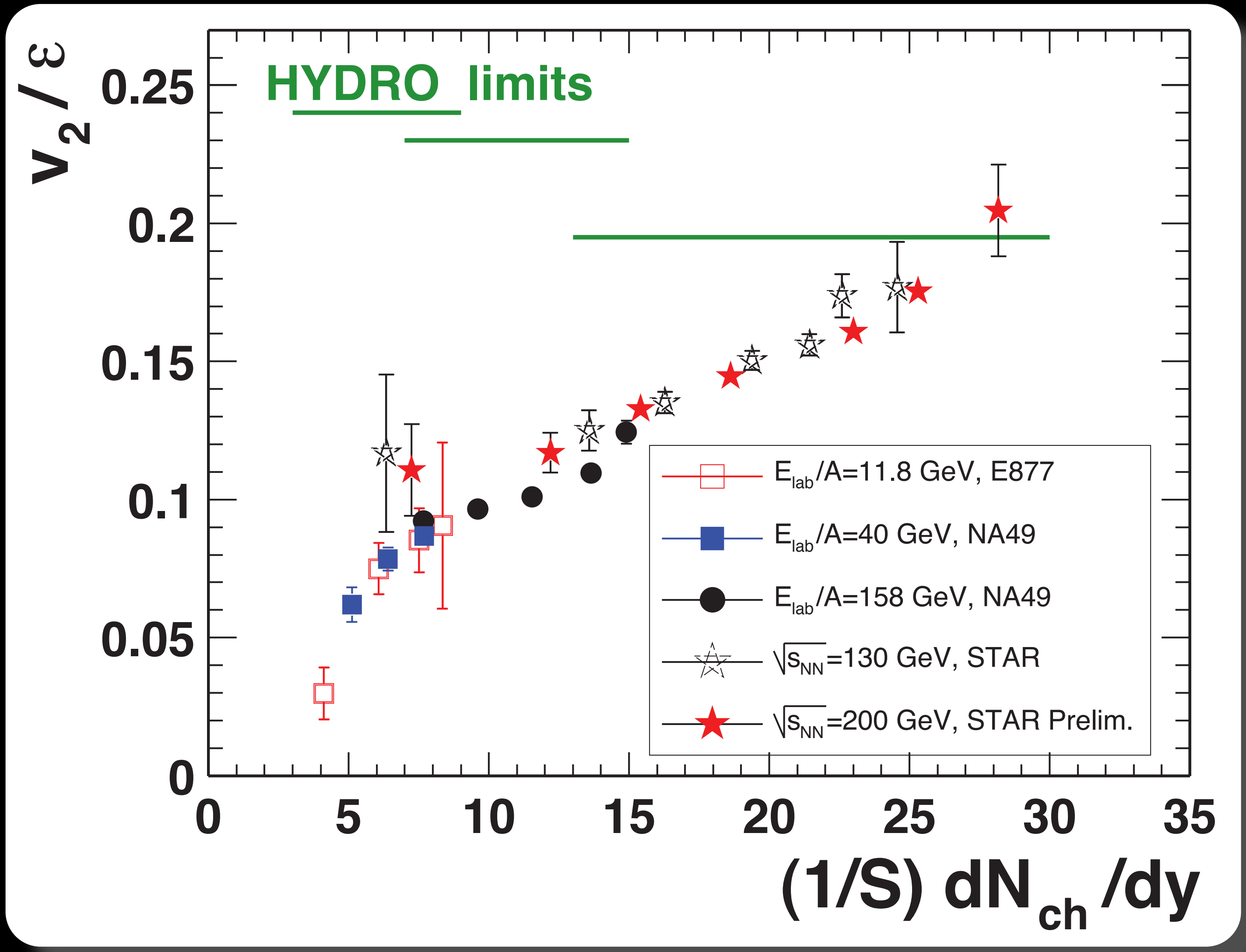
H. Heiselberg and A. M. Levy, Phys. Rev. C 59, 2716 (1999)

S. A. Voloshin and A. M. Poskanzer, Phys. Lett. B 474, 27 (2000)

For ideal hydrodynamics:

$$\frac{v_2}{\epsilon} = h$$

NA49: C. Alt et al., Phys. Rev. C68, 034903 (2003)



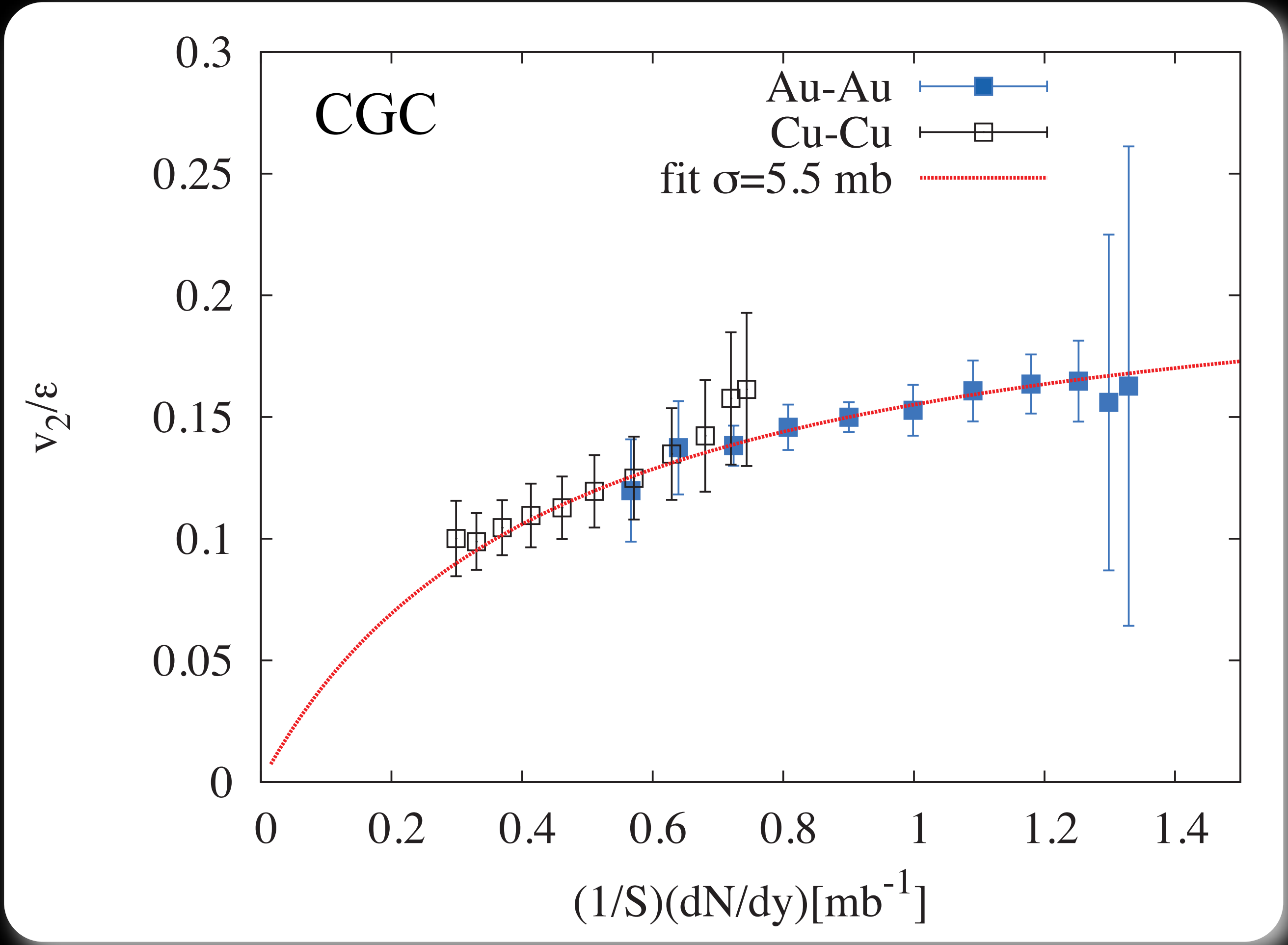
Hydro limits from P.F. Kolb, J. Sollfrank, U.W. Heinz; Phys.Rev.C62:054909,2000.

This figure is <u>not</u> understood in ideal hydrodynamics!

Corrections needed: parton cascade, viscous hydro, hadron cascade ......

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
- Try to use the data to constrain the hydro limit!



$v_2/\varepsilon = h/(1+1.4K)$
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

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

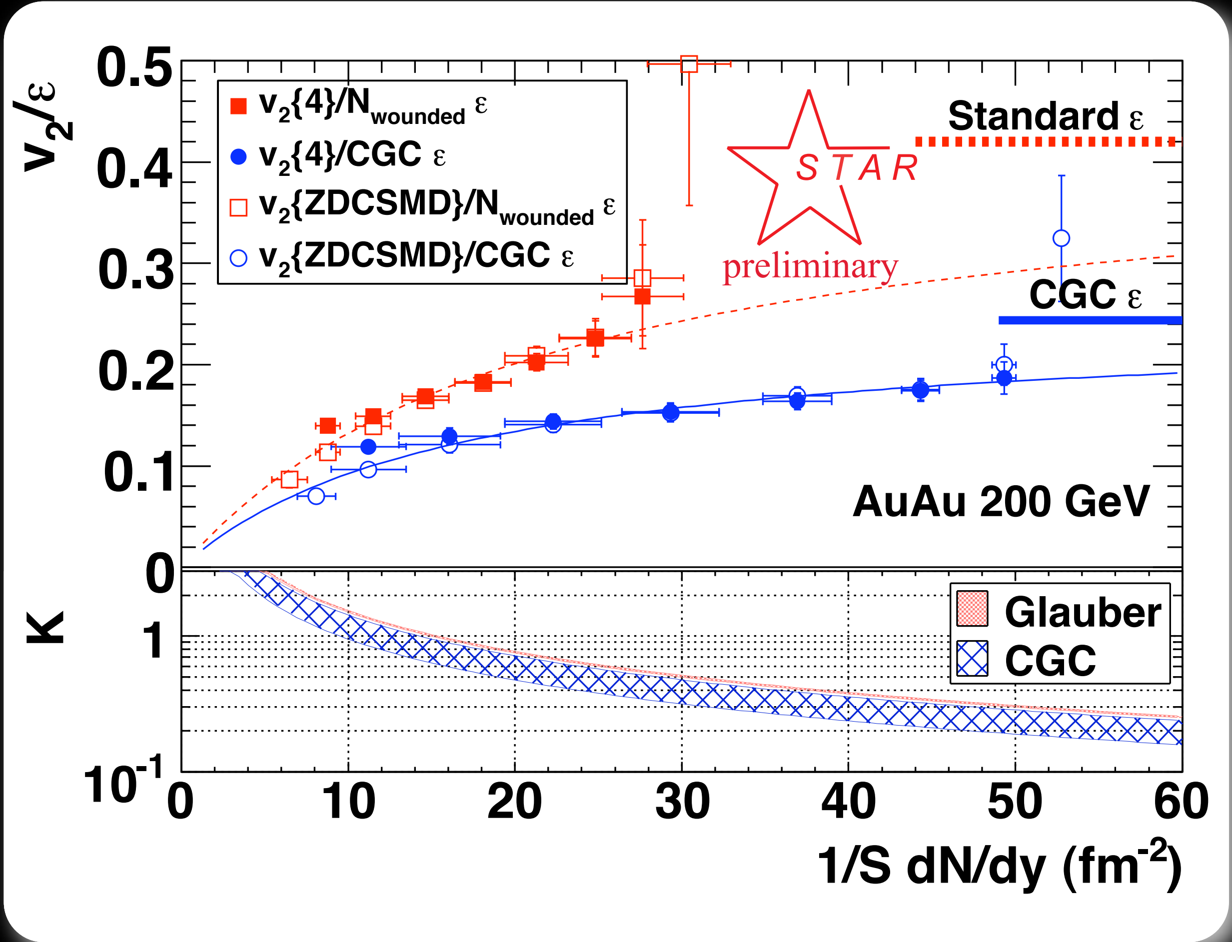
H-J. Drescher, A. Dumitru, C. Gombeaud and J-Y. Ollitrault; Phys.Rev.C76:024905,2007.

From LDL to Hydro

$$\frac{v_2}{\epsilon} = \frac{h}{1 + 1.4K}$$

where K is the Knudsen number

$$\frac{1}{K} = \frac{R}{\lambda} = c_s \sigma \frac{1}{S}\frac{\mathrm{d}N}{\mathrm{d}y}$$



From LDL to Hydro:

$K \rightarrow 0 \quad \frac{v_2}{\epsilon} = h - K + K^2 - ..$ hydro

$K \rightarrow \infty \quad \frac{v_2}{\epsilon} = c_s \sigma \frac{1}{S}\frac{\mathrm{d}N}{\mathrm{d}y}$ LDL

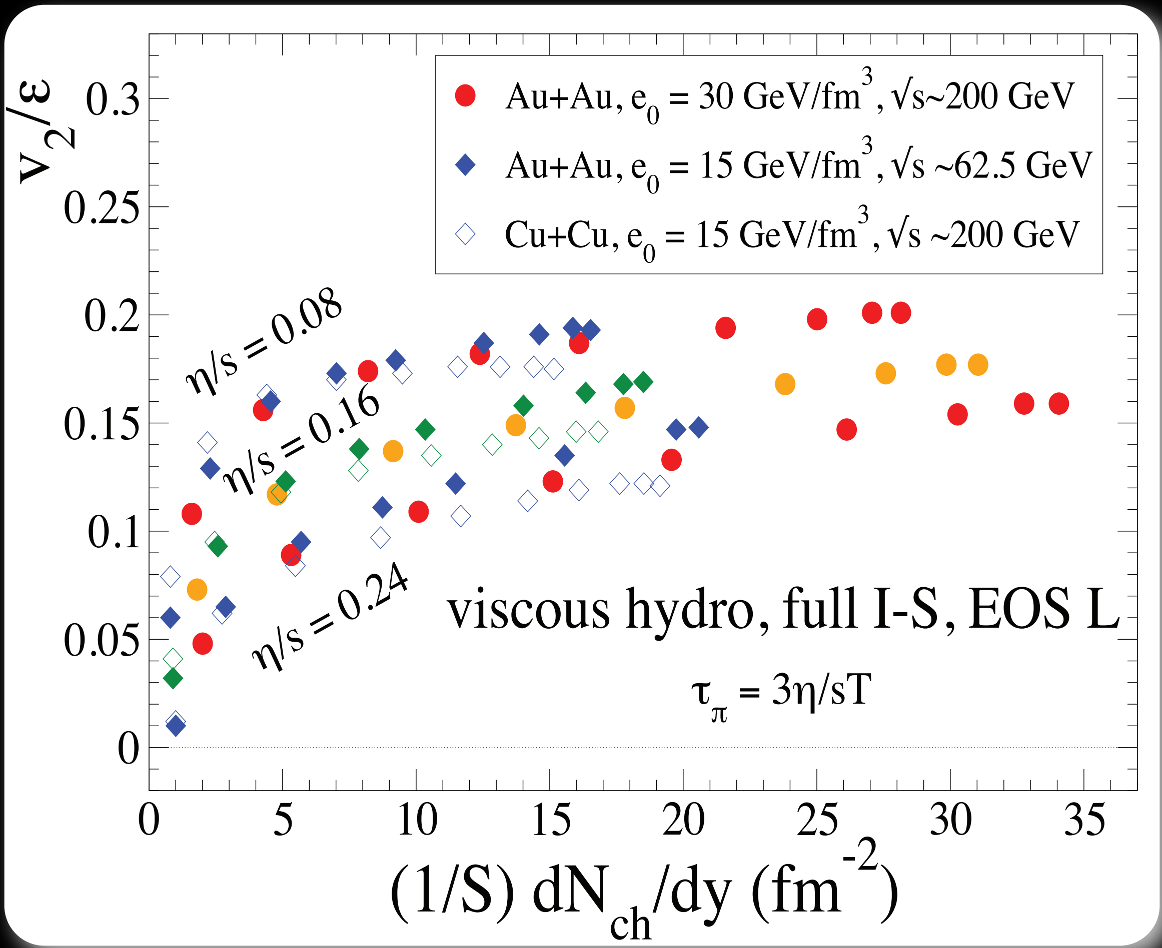
for STAR results see talks Aihong Tang and Hiroshi Masui

reach about 70% of ideal hydro limit!

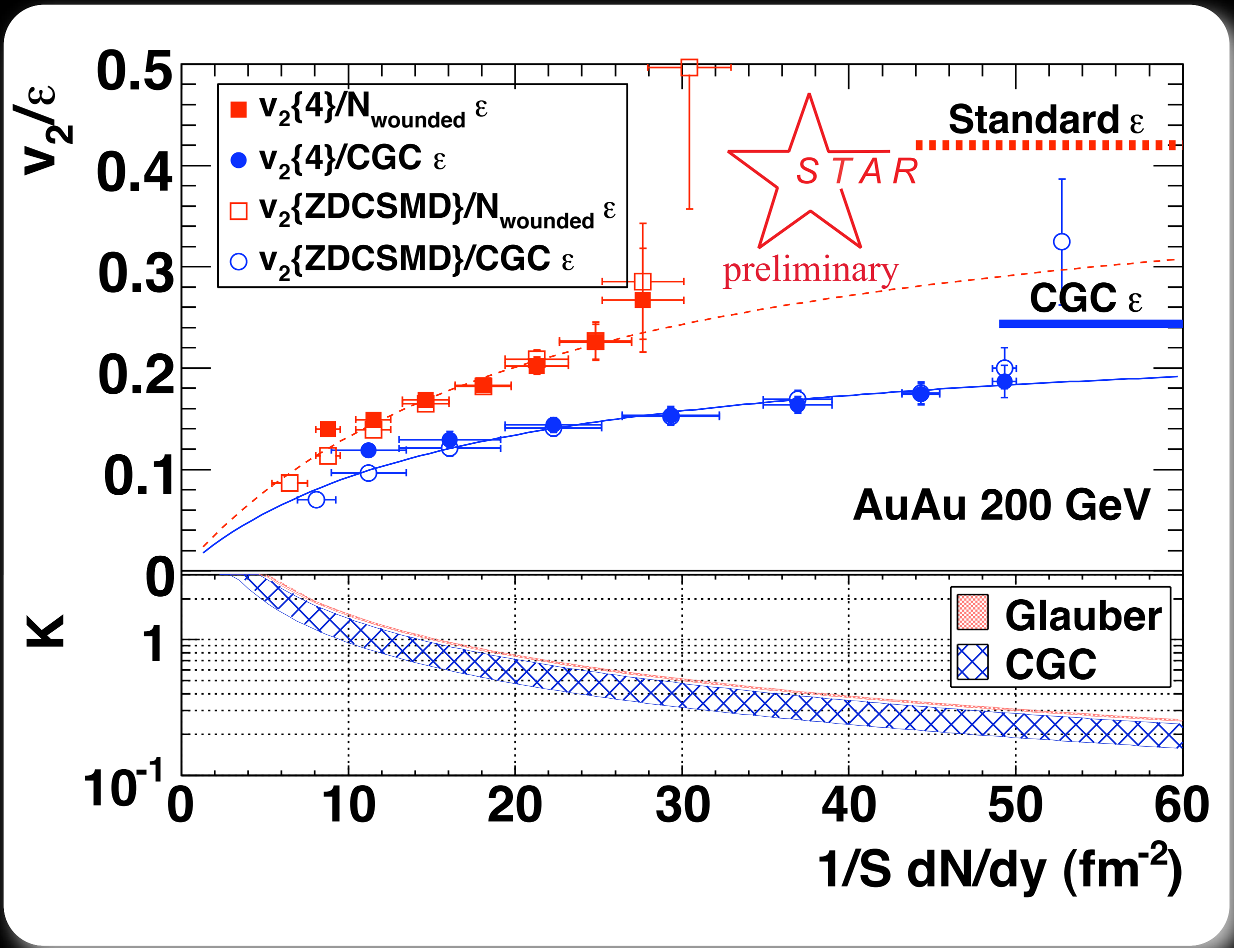
(D. Teaney: Boltzmann η/s = 0.316 T/*cσn*) η/s = 2-3 AdS/CFT limit

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

From LDL to Hydro



H. Song and U. Heinz; arXiv:0805.1756 [nucl-th]



$$K \to 0 \quad \frac{v_2}{\epsilon} = h - K + K^2 - ..$$

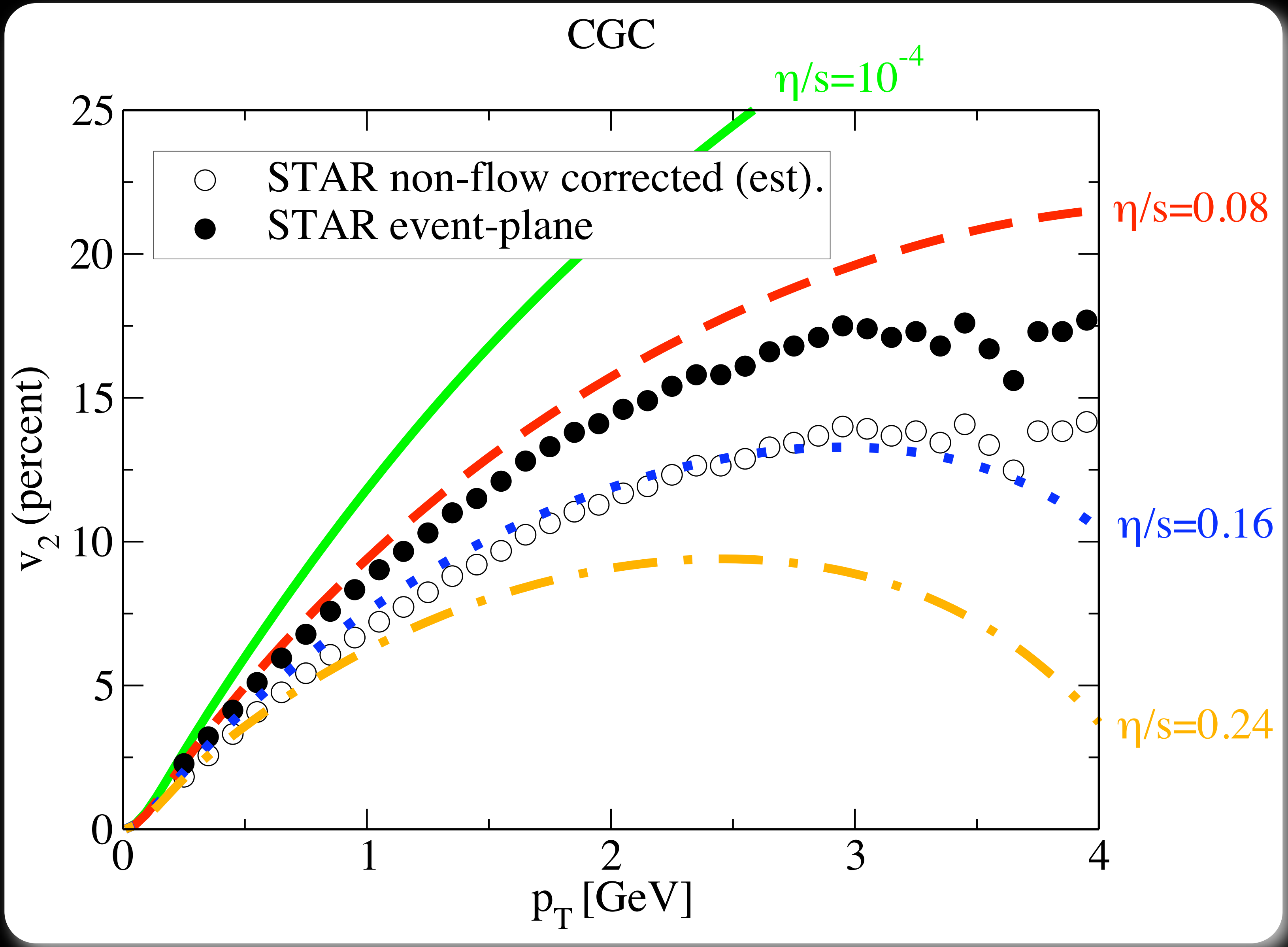
$$K \to \infty \quad \frac{v_2}{\epsilon} = c_s \sigma \frac{1}{S}\frac{\mathrm{d}N}{\mathrm{d}y}$$

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

CGC ε brings centrality dependence measured already rather close to viscous hydro

Viscous hydro

- data described using viscous hydro with η/s between AdS/CFT lower bound 0.08 and 0.16
- need to compare with matching ideal hydro limit (EoS)

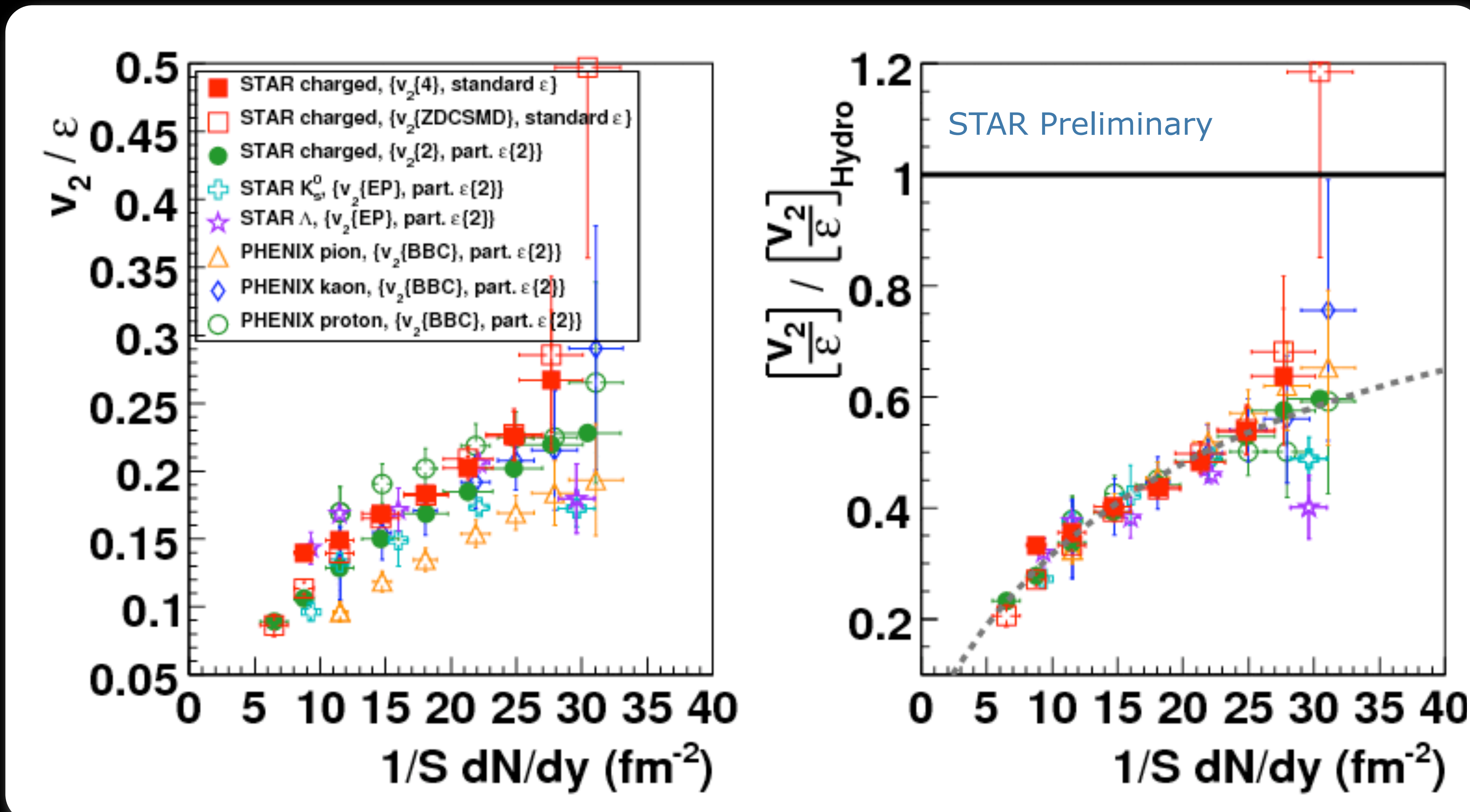


Matthew Luzum, Paul Romatschke arXiv:0804.4015

Compatible estimates of η/s from viscous hydro and Boltzmann cascade!

From LDL to Hydro

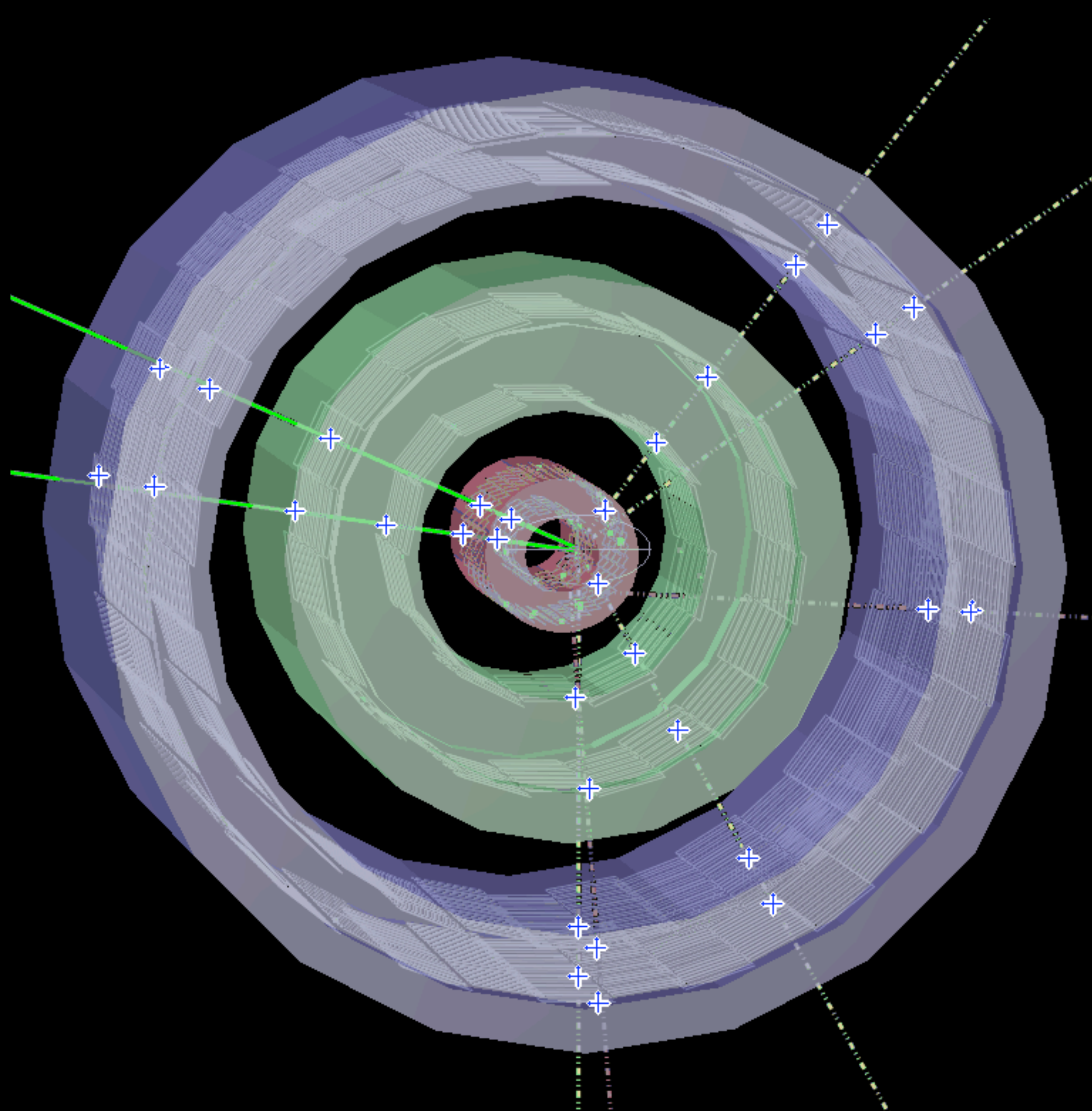
see talks Aihong Tang and Hiroshi Masui

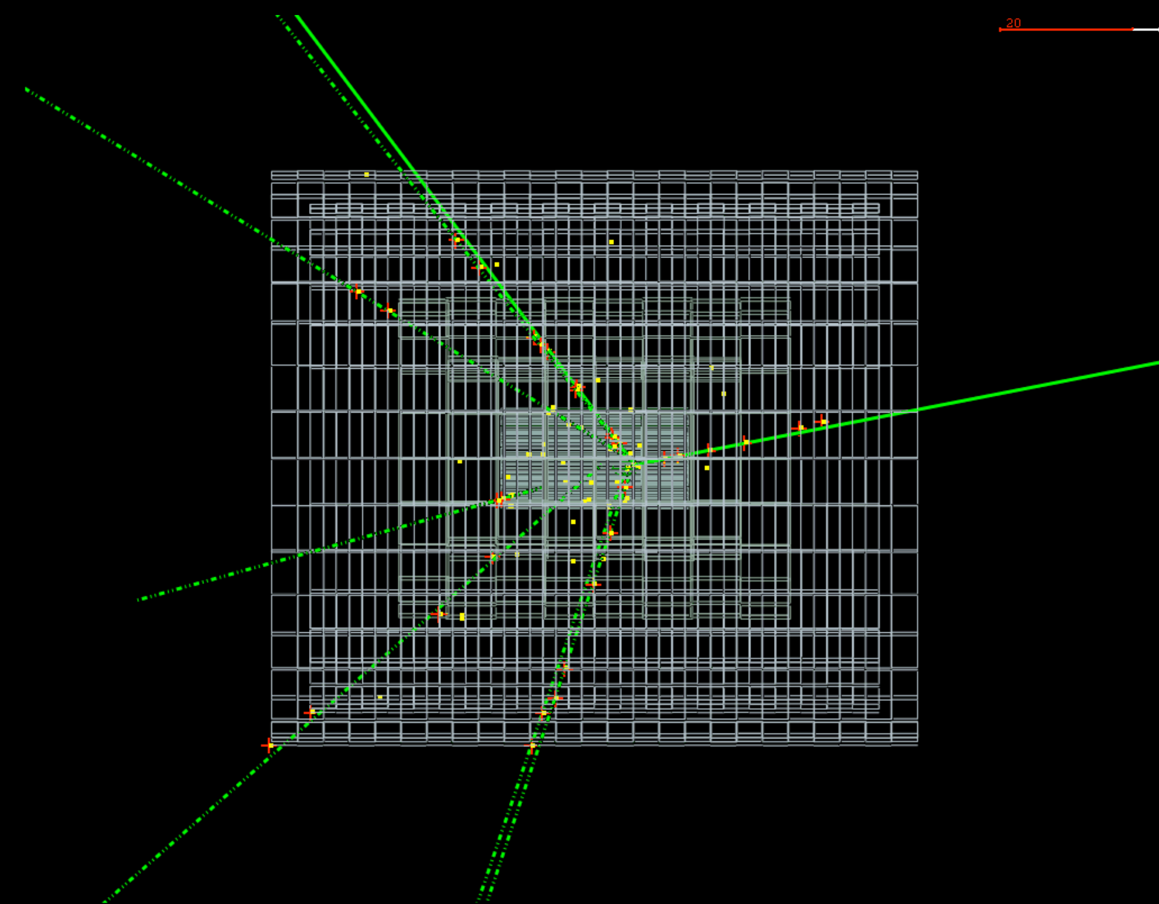


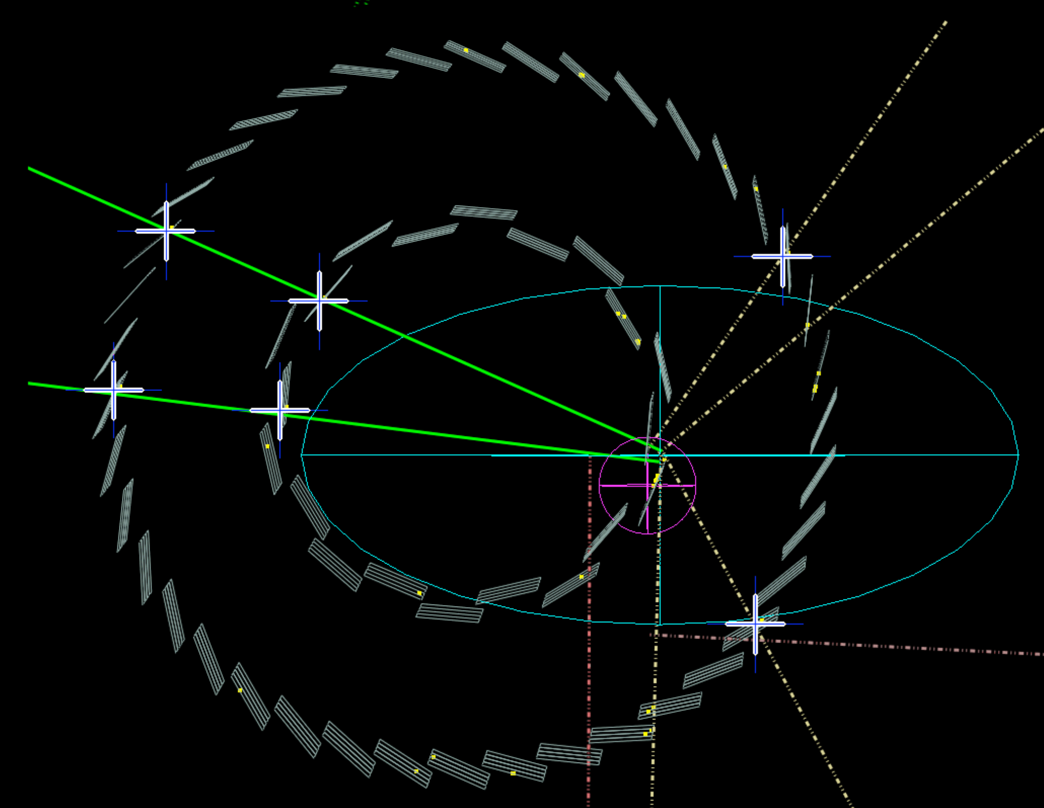
Different species reach same fraction of ideal hydro limit!

different species decouple on average at the same time?

ALICE at the LHC

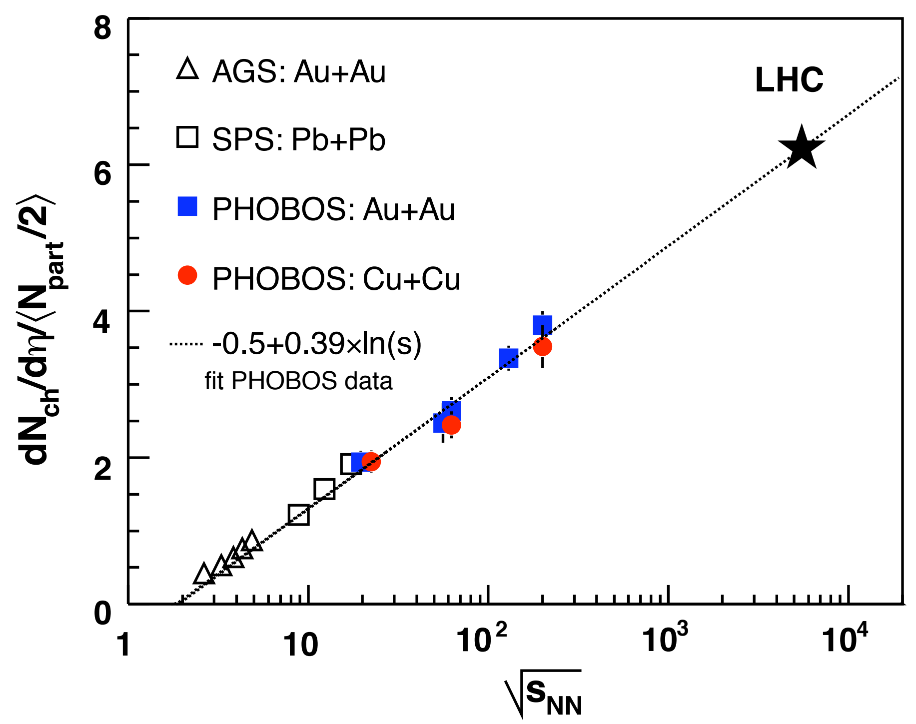


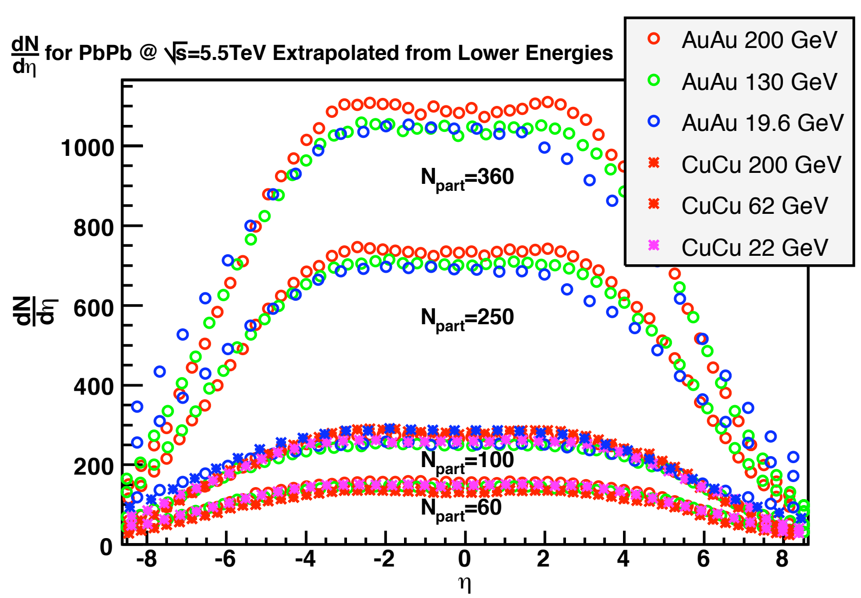




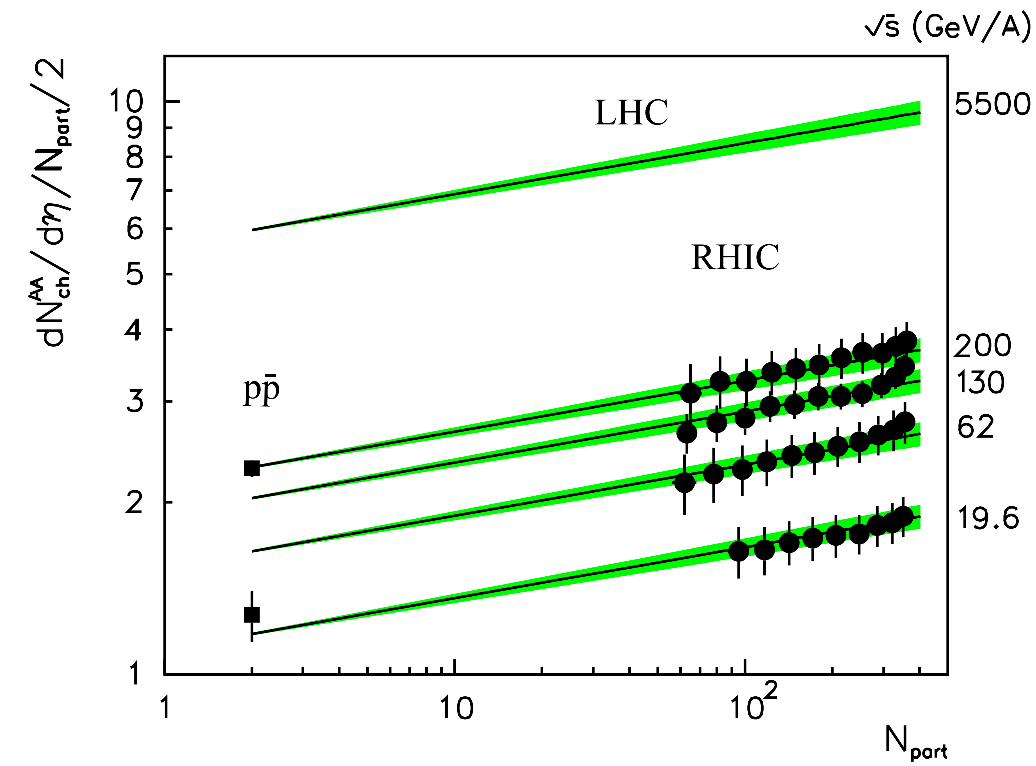
first collision 12/9/2008

LHC: the multiplicity





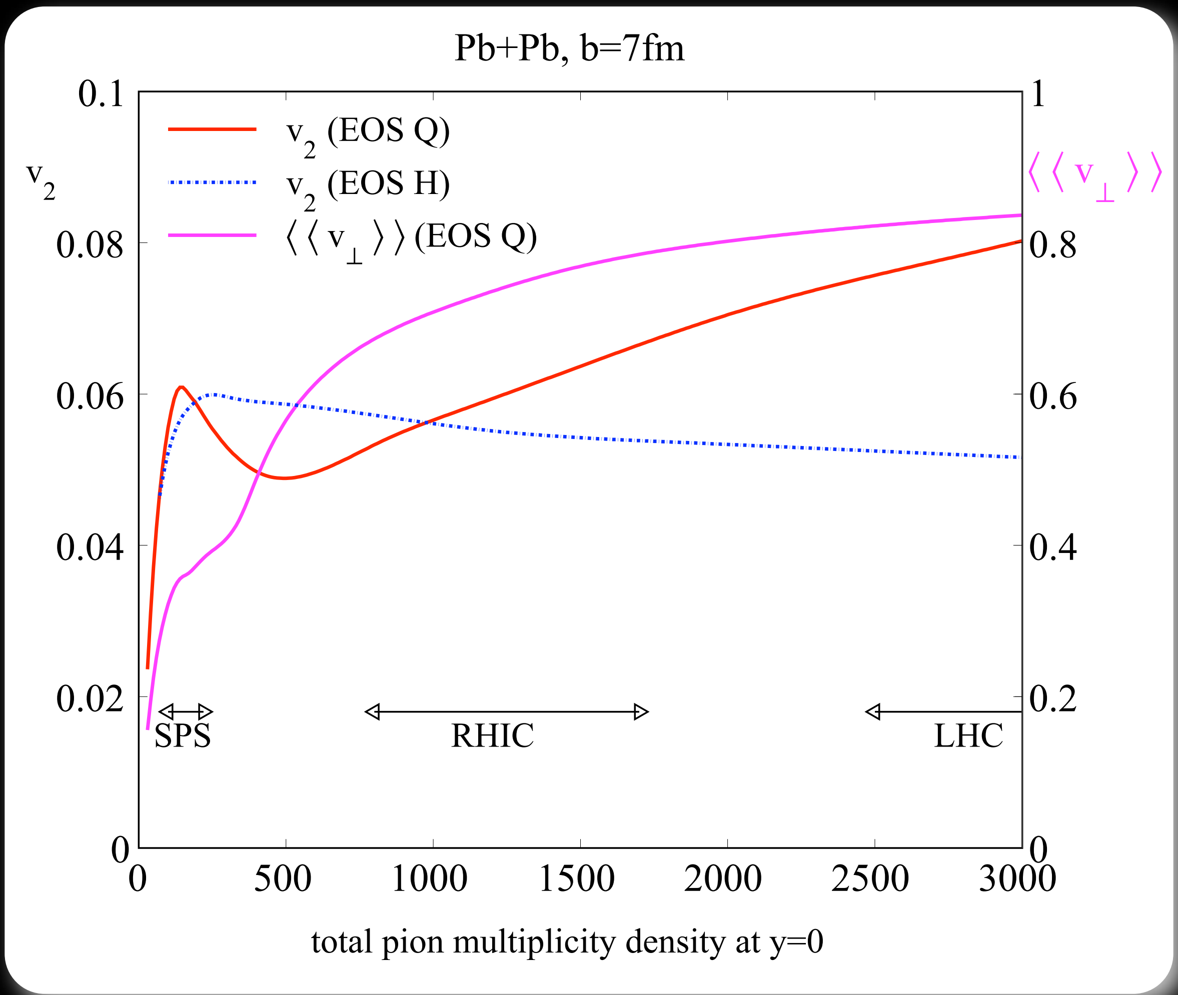
W Busza



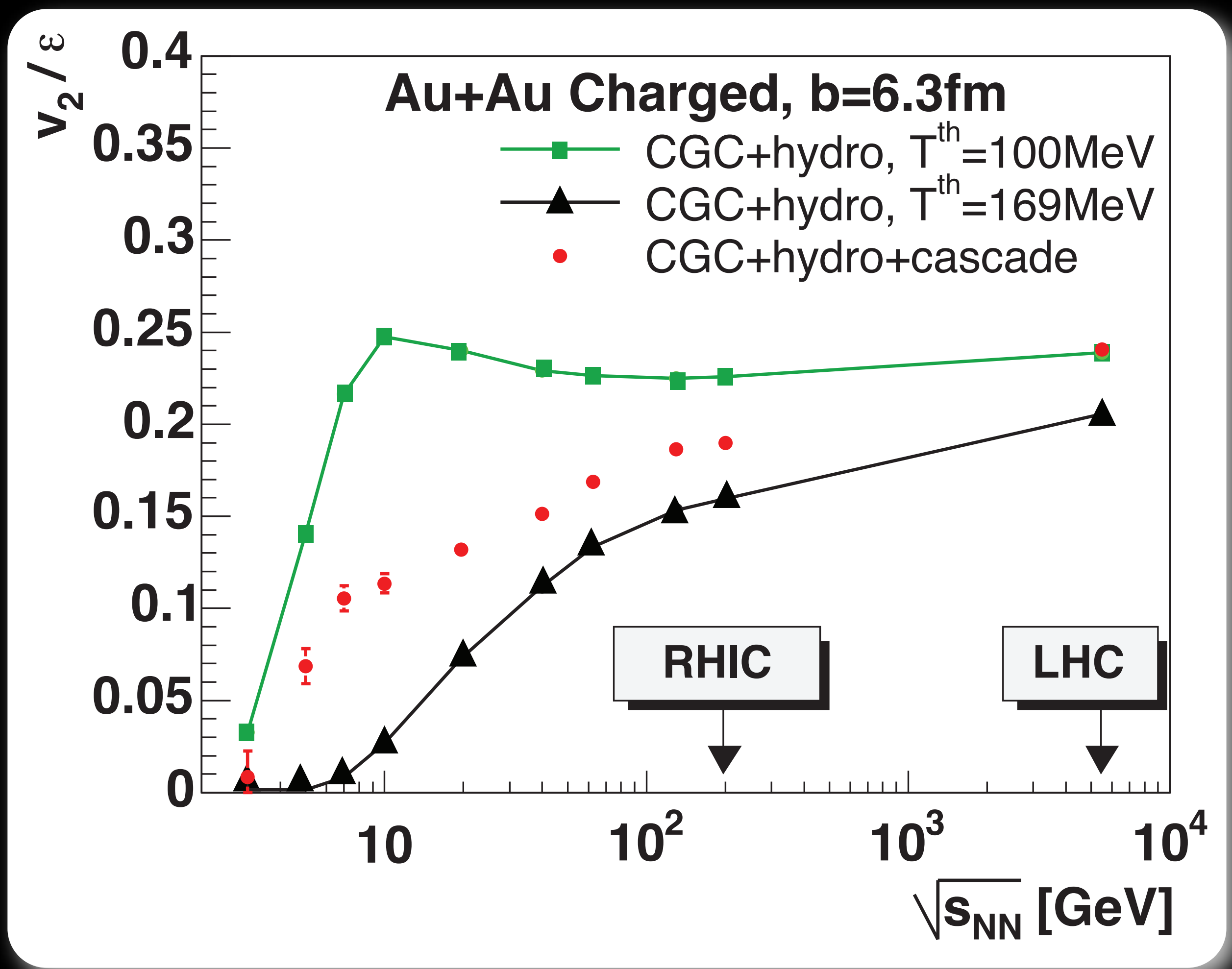
N. Armesto, C.A. Salgado and U.A. Wiedemann

multiplicities:
longitudinal scaling ~ 1200,
saturation ~1500
and HIJING/BB ~ 3500

Ideal hydro at the LHC?



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

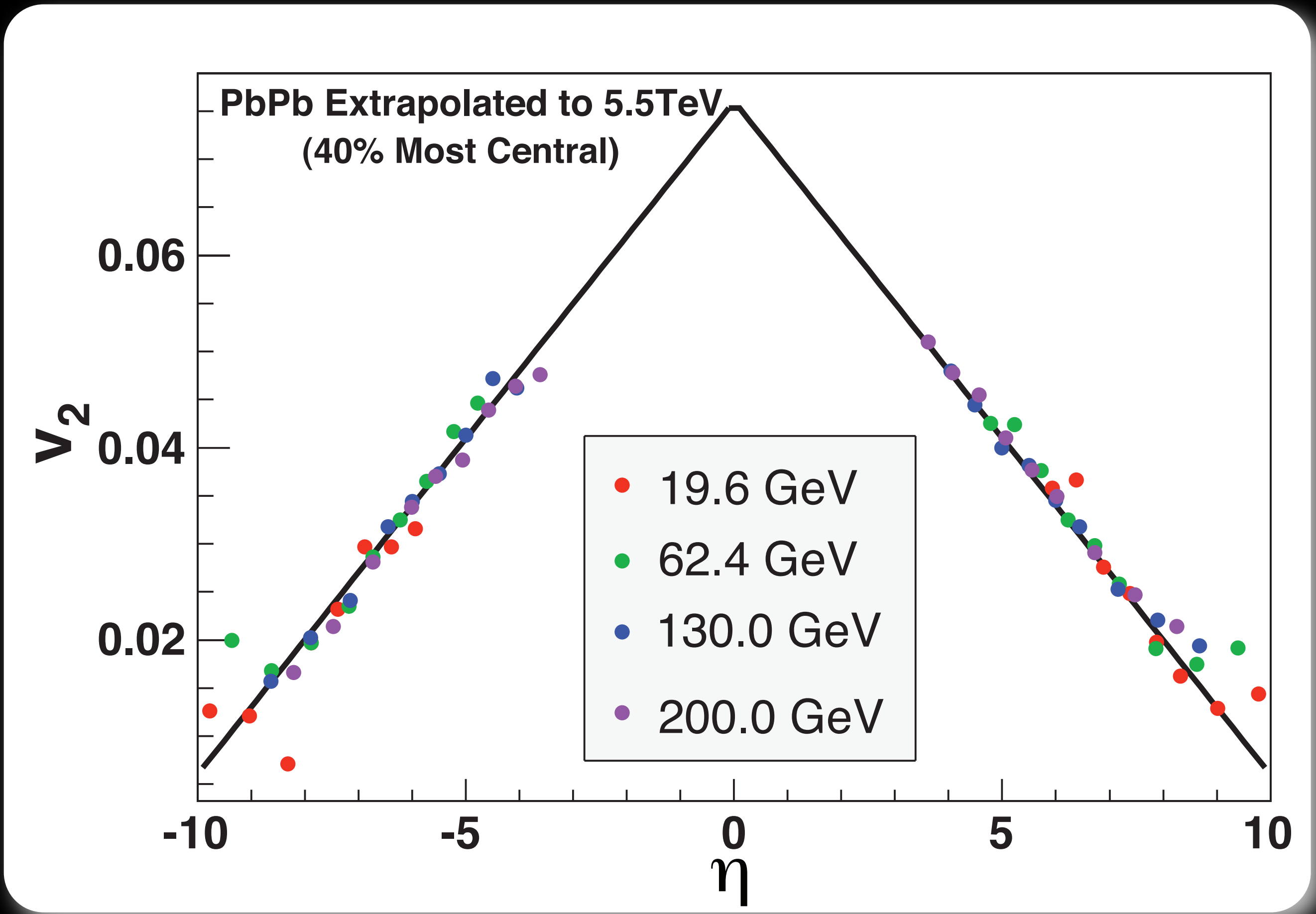


T. Hirano

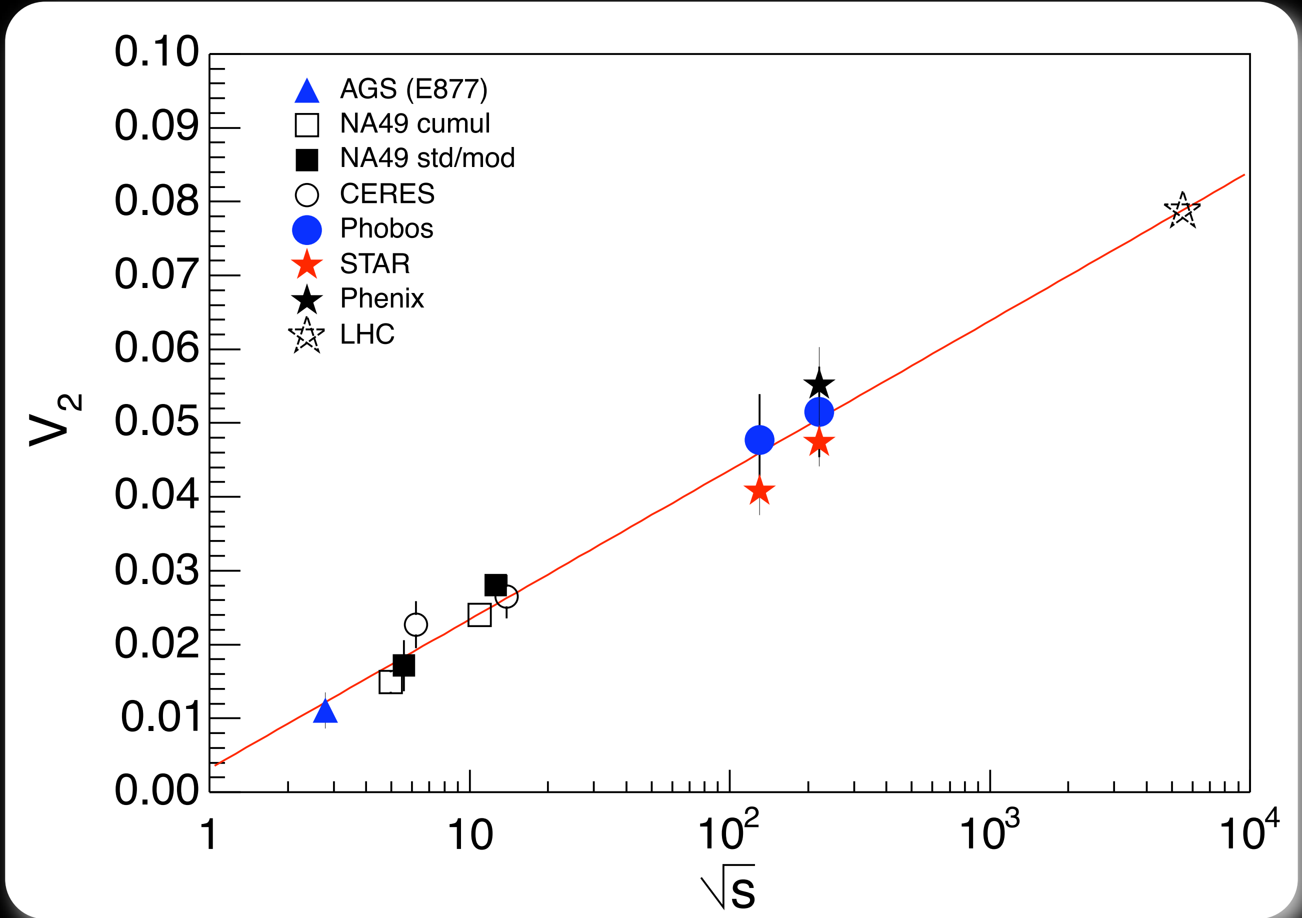
v_2 increase of ~ 0-20%

careful do not connect the multiplicity dependence in the hydro plot to centrality dependence at fixed collision energy!

LDL at the LHC?



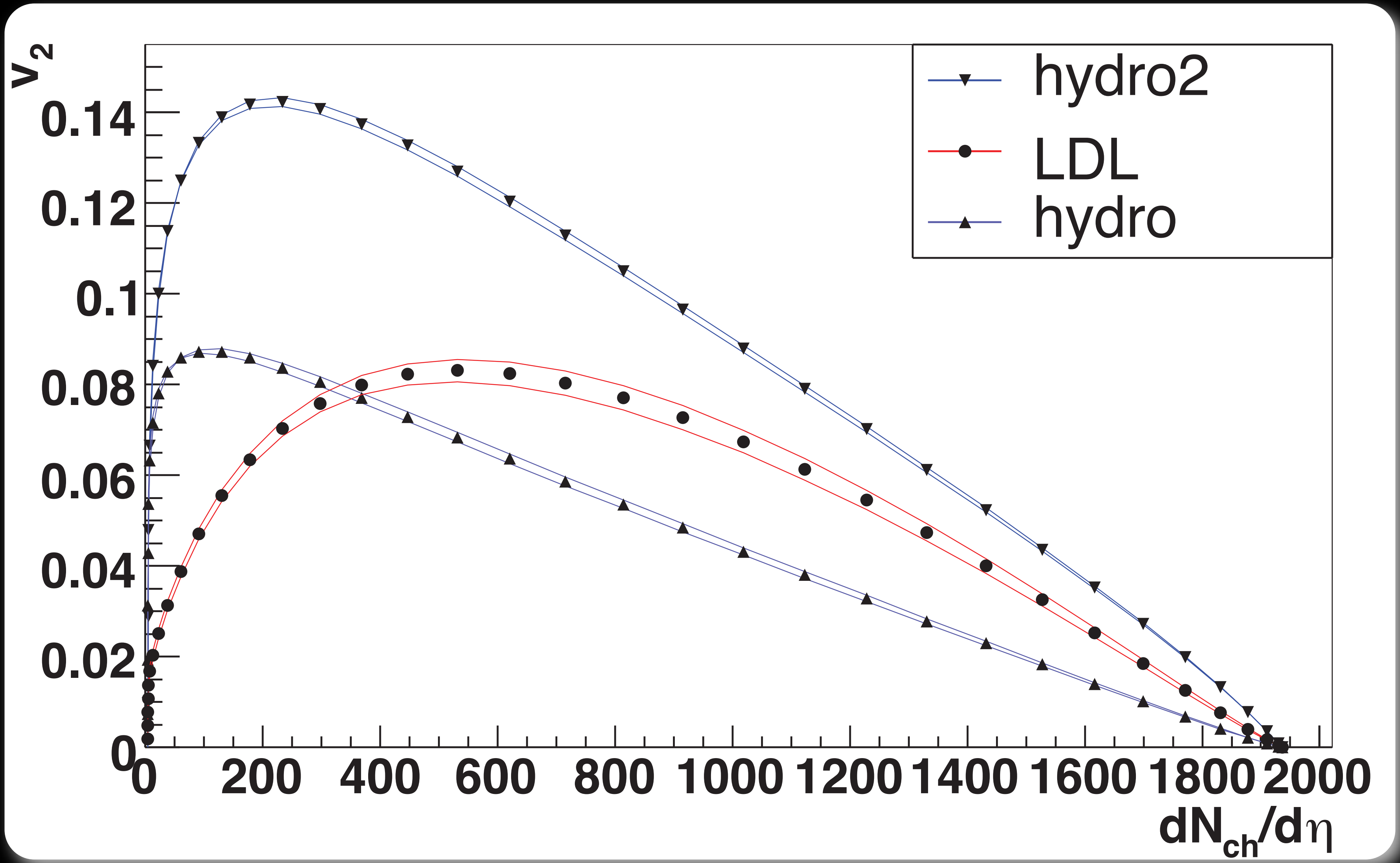
W Busza



v_2 increase of ~ 50%

Centrality dependence!

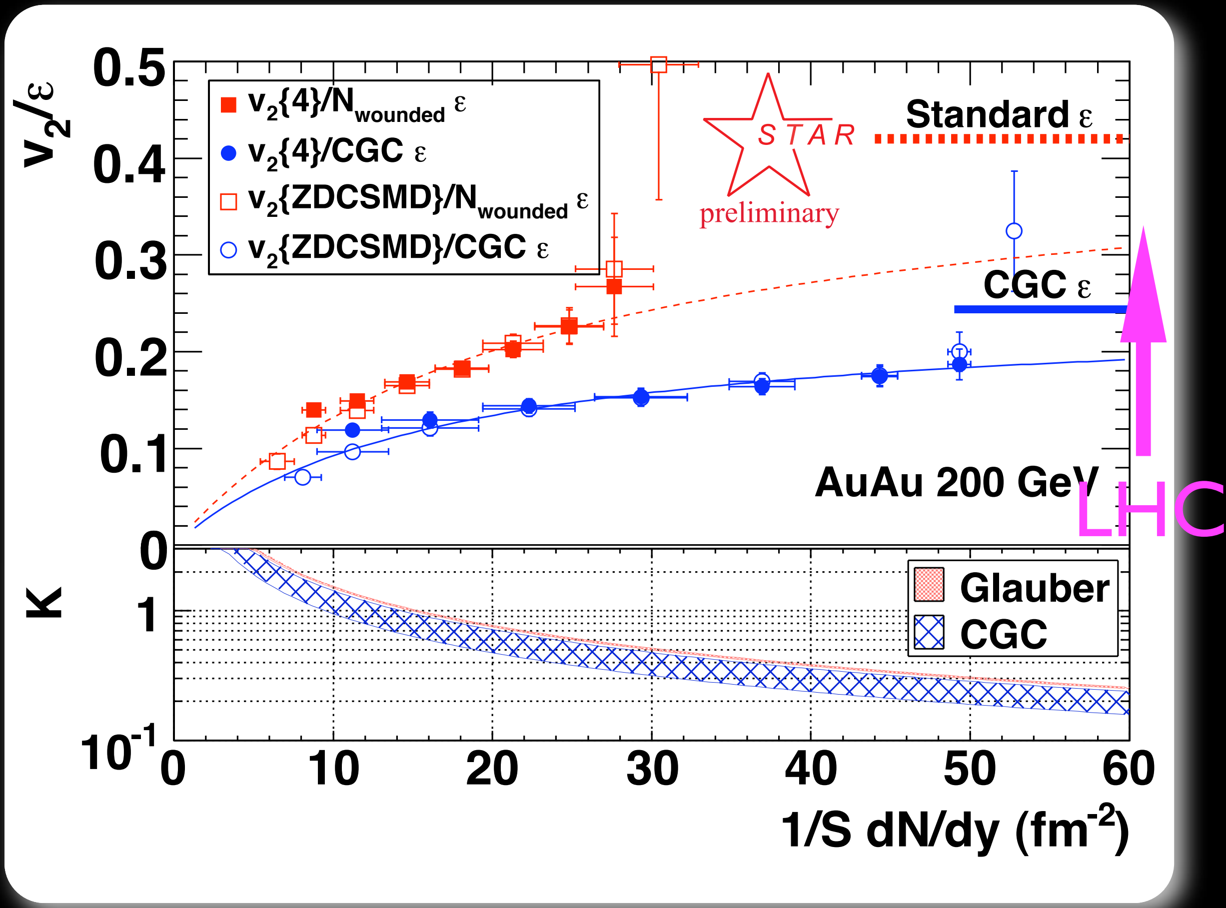
hydro $c_s^2 = 0.22$
hydro2 $c_s^2 = 0.33$

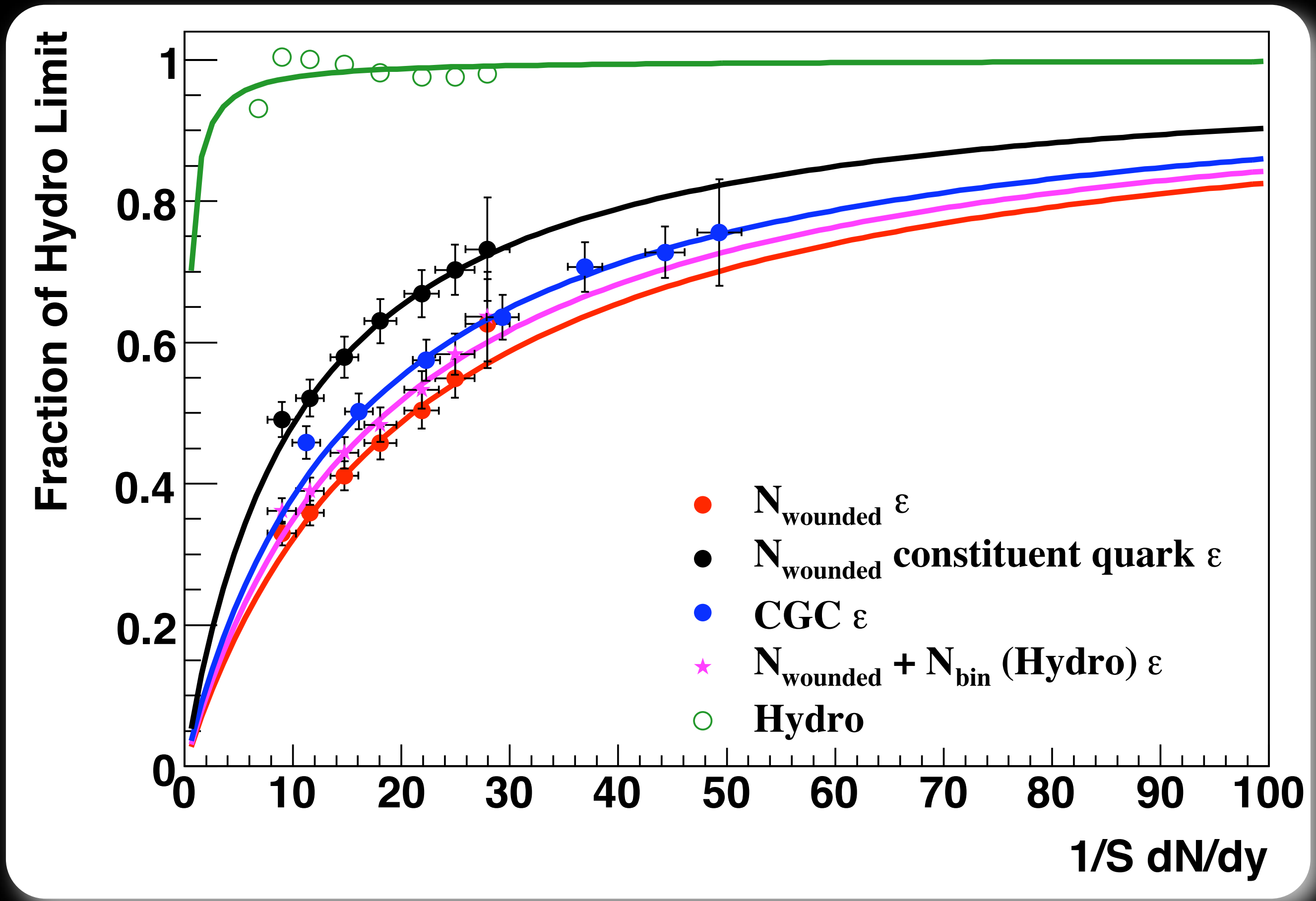


E. Simili, PhD thesis

Only centrality dependence can determine which picture is more correct!

The LHC hydro limit?





only centrality dependence is predicted (knowing ε) not the absolute magnitude (magnitude depends on effective c_s)

Measurement of the centrality dependence will allow us to discriminate between this, ideal hydro and LDL

NIKHEF

Fluctuations and nonflow

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

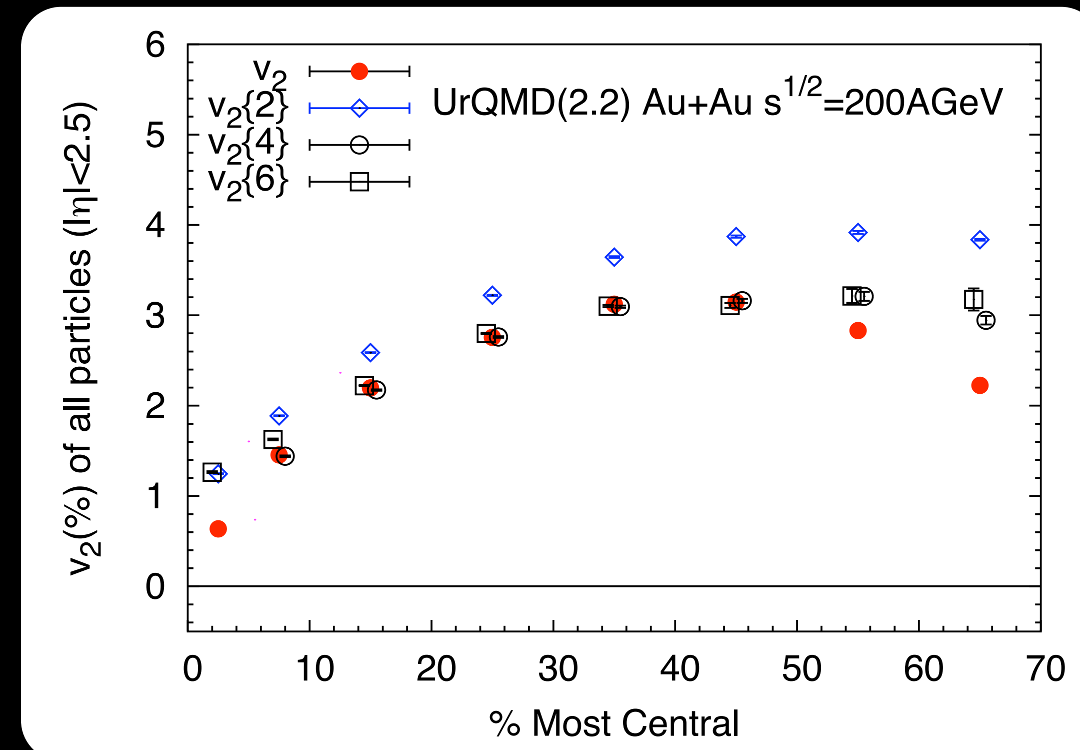
$$v_2\{2\} = \sqrt{(\langle v_2\rangle^2 + \sigma_v^2 + \delta)}$$

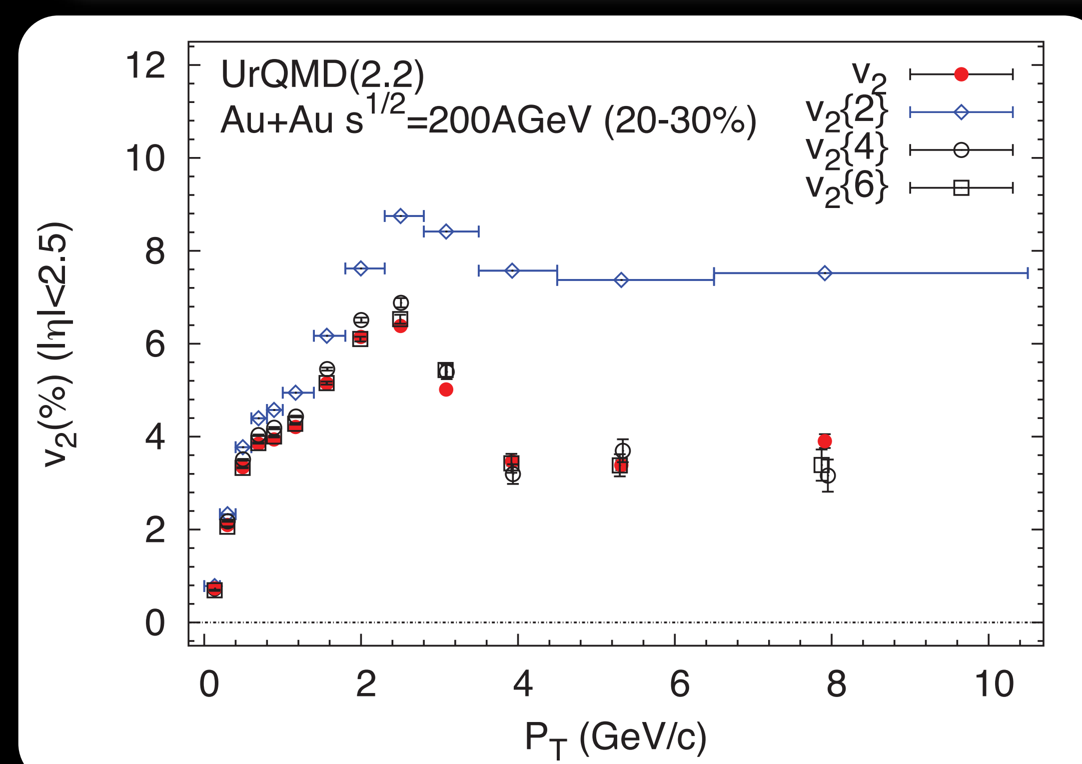
- two-particle correlation methods (v_2\{EP\}, v_2\{2\}) measure flow in participant plane (+ nonflow)

PHOBOS QM2005: Nucl. Phys. A774: 523 (2006)

- multi-particle methods (v_2\{4\} and higher, v_2\{LYZ\}) and methods using the spectators measure flow in the reaction plane and in addition remove the nonflow

R.S. Bhalerao , J-Y. Ollitrault Phys.Lett.B641:260-264,2006
S.A. Voloshin, A.M. Poskanzer, A. Tang, G. Wang Phys.Lett.B659:537-541,2008

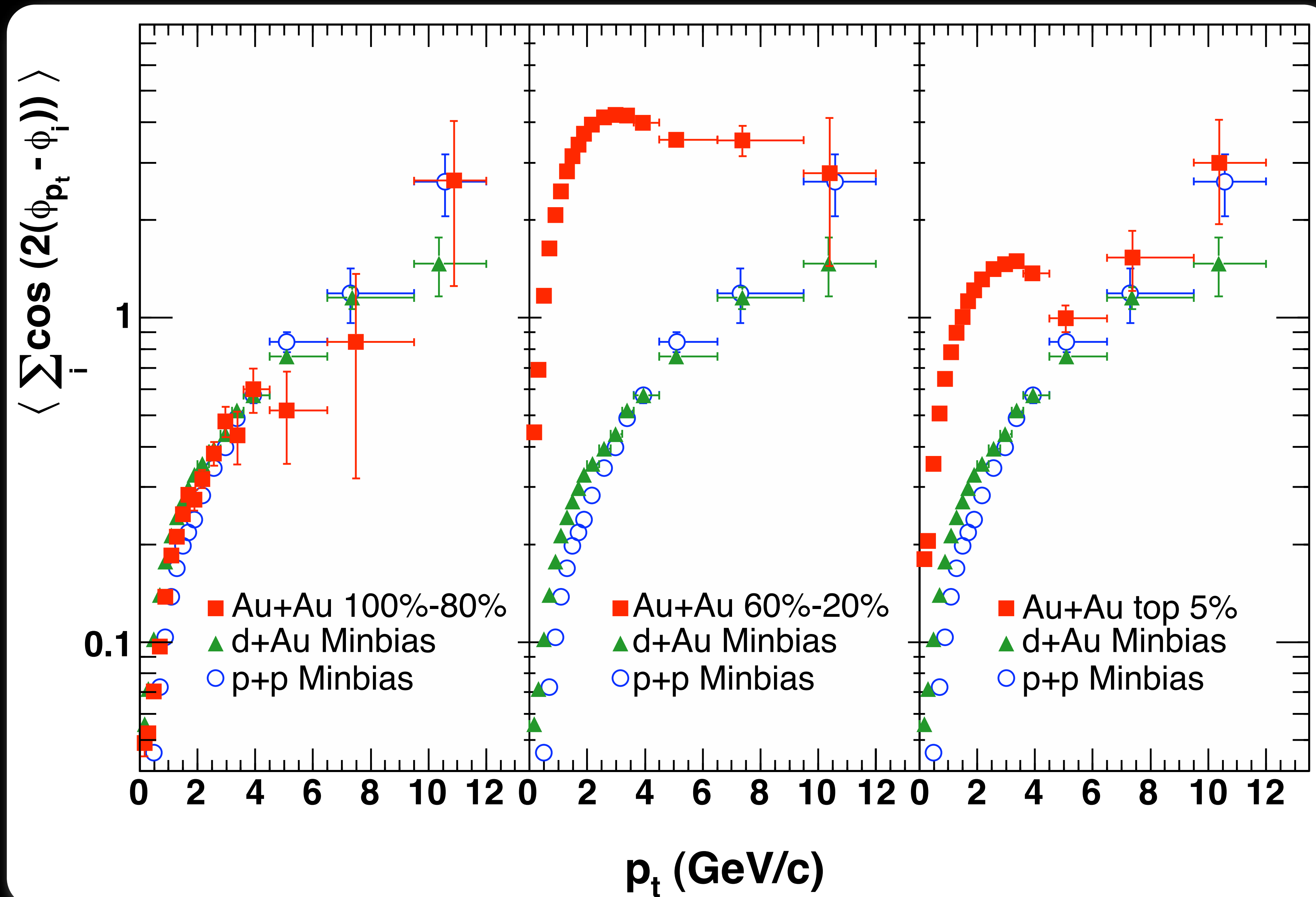




X Zhu, M. Bleicher, H. Stoeker, Phys.Rev.C72:064911(2005)

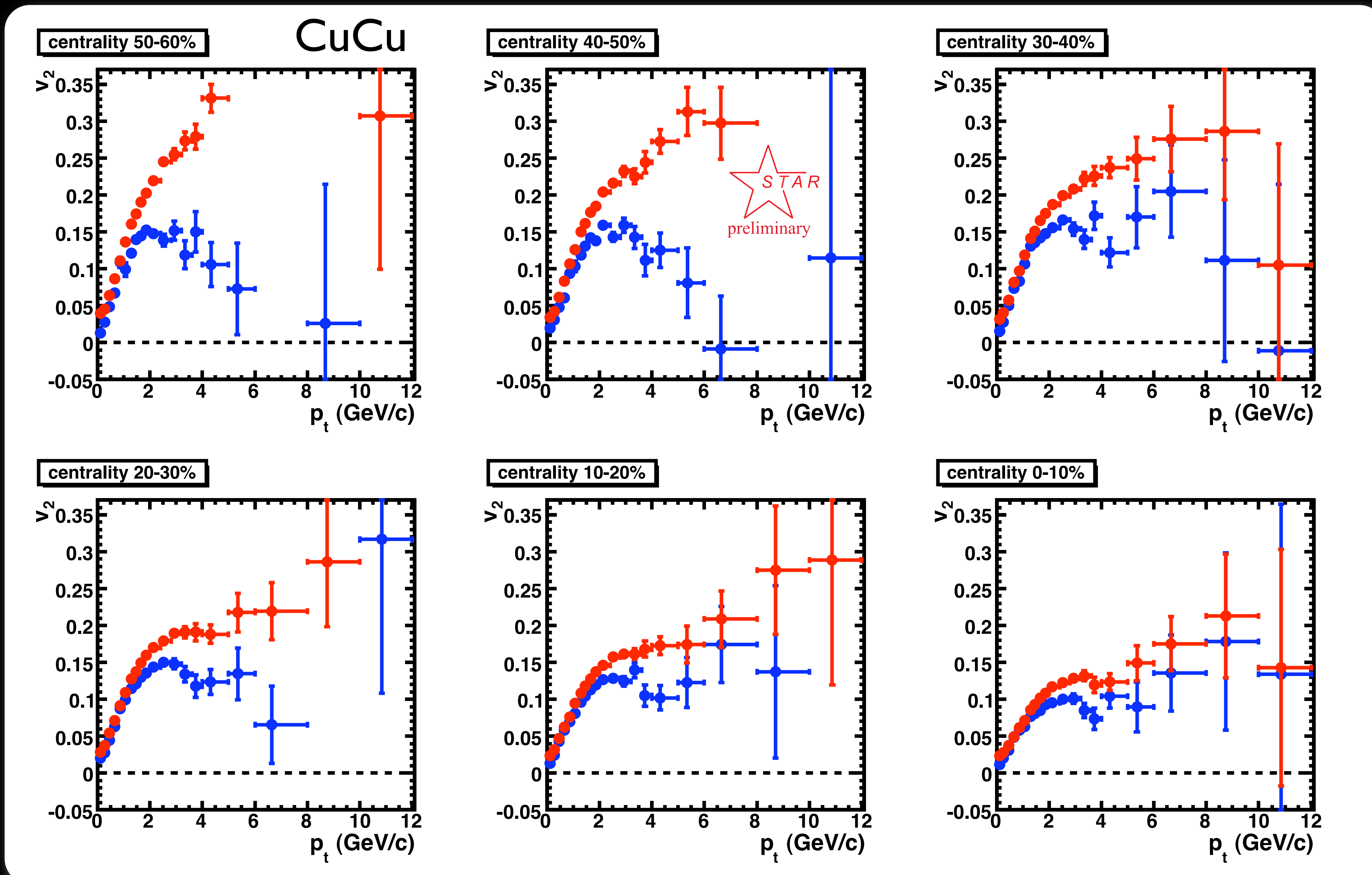
Flow and nonflow

- compare two-particle azimuthal correlations in pp, dA and AA
- in most peripheral and most central collisions and at high-p_t the correlation is very similar in the three systems



J. Adams et al. [STAR Collaboration], Phys. Rev. Lett. 93, 252301 (2004)

Flow and nonflow

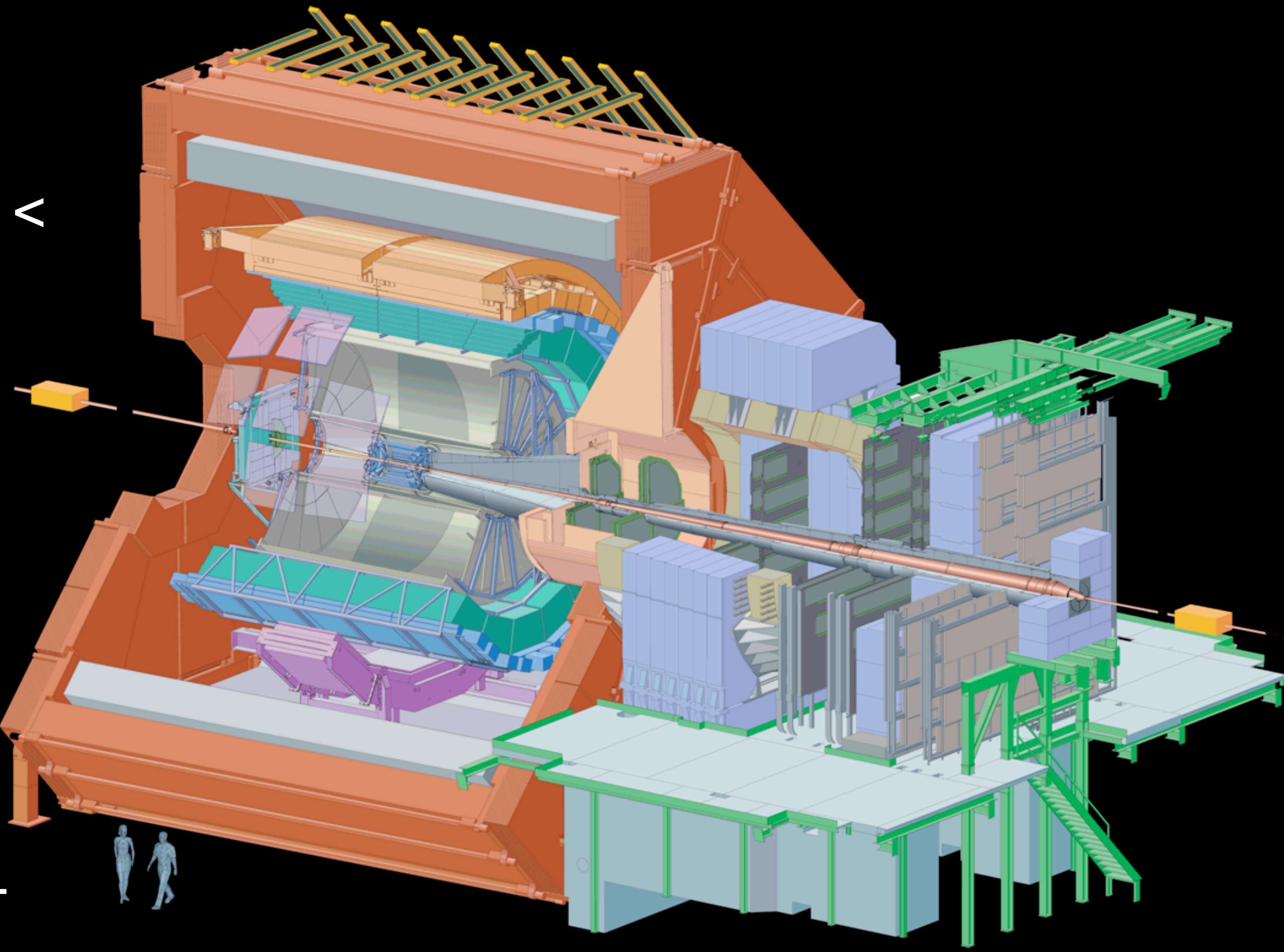


S.Voloshin QM2006

A rapidity gap (Δη=2-3) is also not always sufficient!

ALICE

- detectors at forward rapidity
  - PMD, FMD ($2 < \eta < 5$, $-1.7 < \eta < -3.4$) ZDCs
- multiplicity large enough for multi-particle correlations
  - cumulants
  - Lee Yang Zeroes
  - Lee Yang Zeroes + event plane



RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions
April 18, 2005

- now better quantitative understanding
  - viscous correction are important!
    - in early "hydro" phase or hadronic phase
  - initial conditions (e.g. ε, initial flow fields) not sufficiently constrained!
  - current estimates of η/s are ~ 2x the conjectured lower bound from AdS/CFT
- at the LHC elliptic flow will again be one of the first results coming from heavy-ions
  - centrality dependence of elliptic flow at the LHC can easily kill or confirm the perfect fluid picture discovered at RHIC
  - the answer to the question how much of the viscosity comes from the hadronic or partonic phase can come from identified particles v_2 like the Φ

ありがとうございます。

Arigatou gozaimasu

Thank you

Initial Conditions?

initial flow fields

radial flow

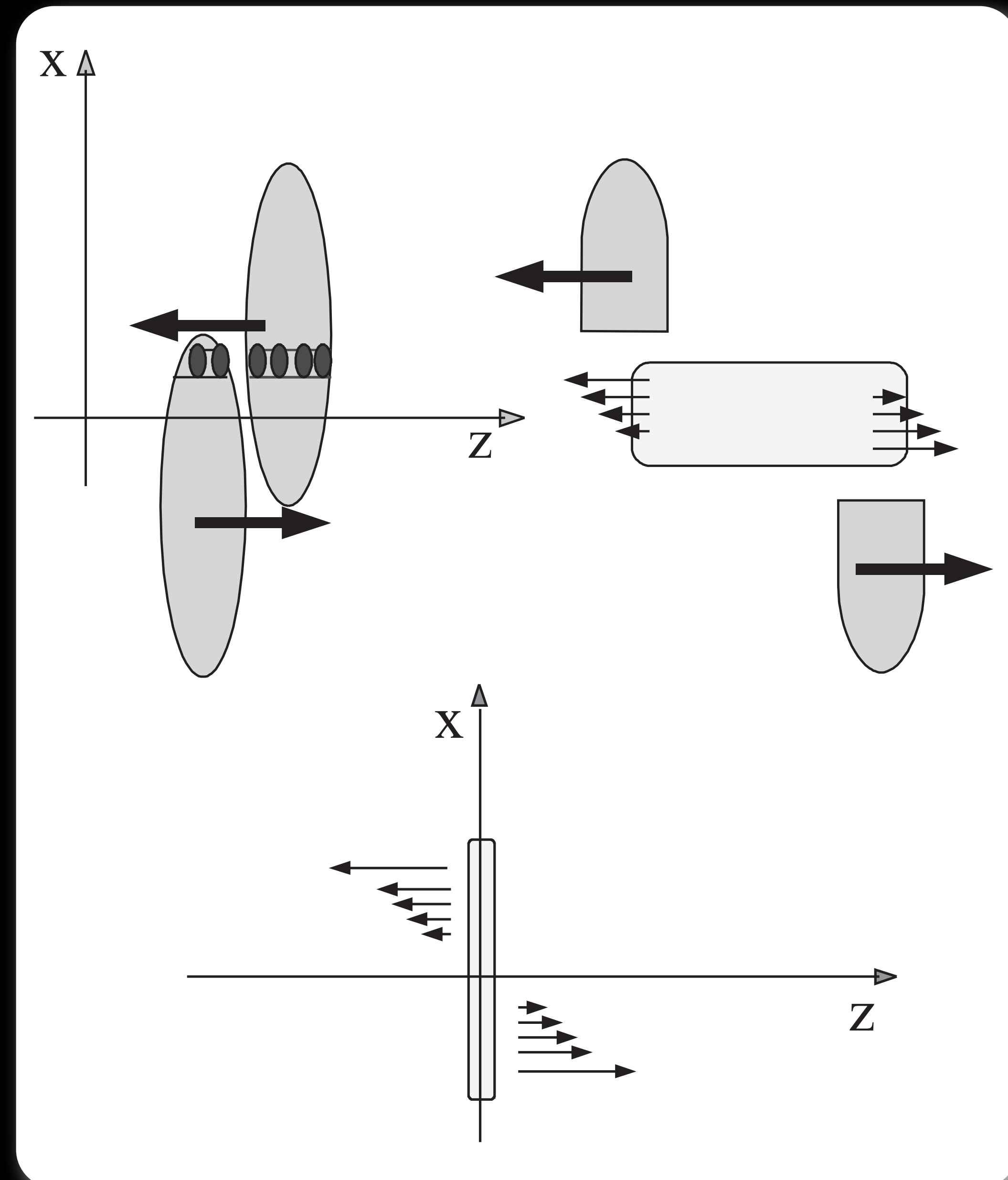
Peter F. Kolb, Ralf Rapp

Phys.Rev. C67 (2003) 044903

faster initial expansion

hydrodynamics + statistical hadronization

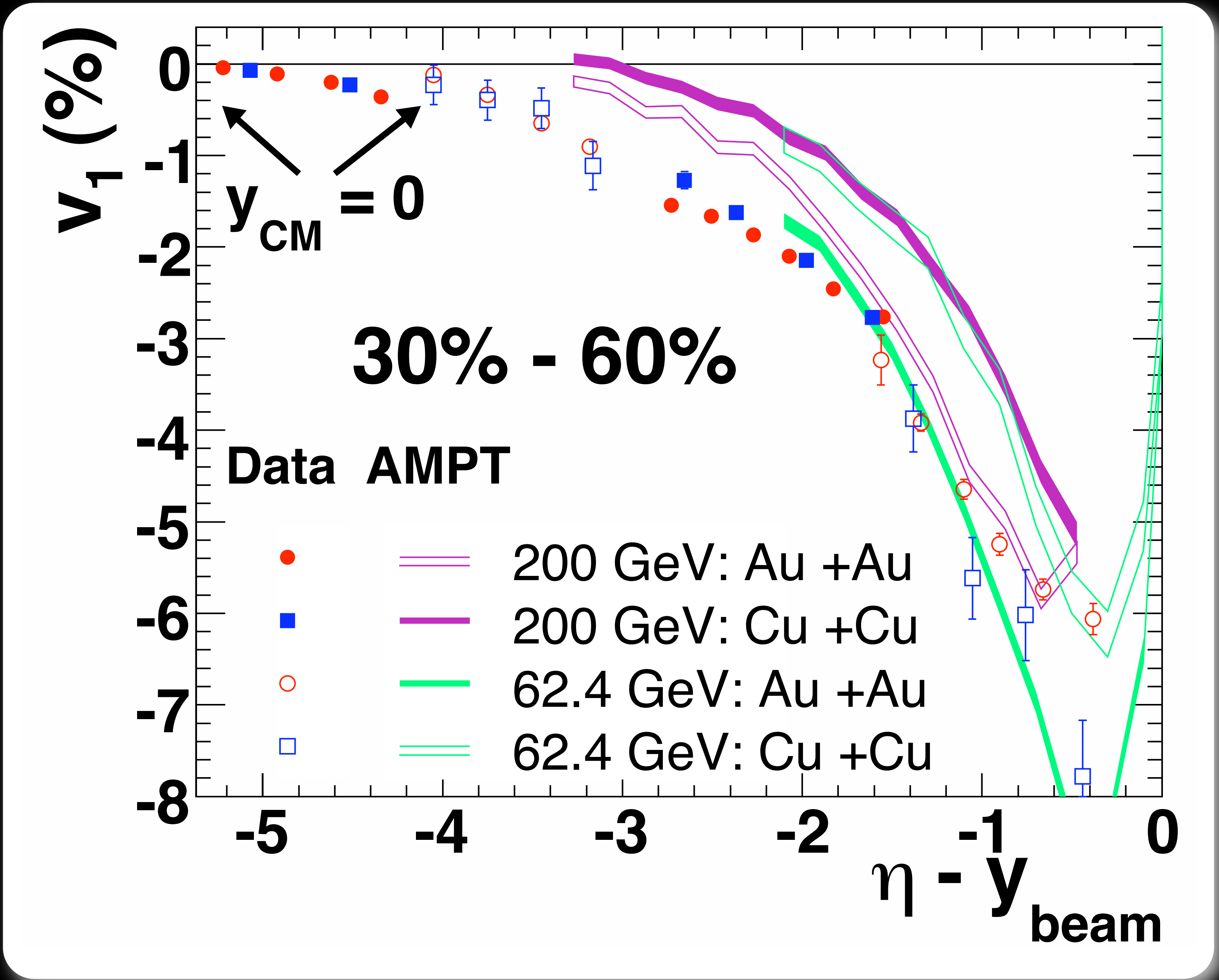
Mikolaj Chojnacki, Wojciech Florkowski, Wojciech Broniowski, Adam Kisiel

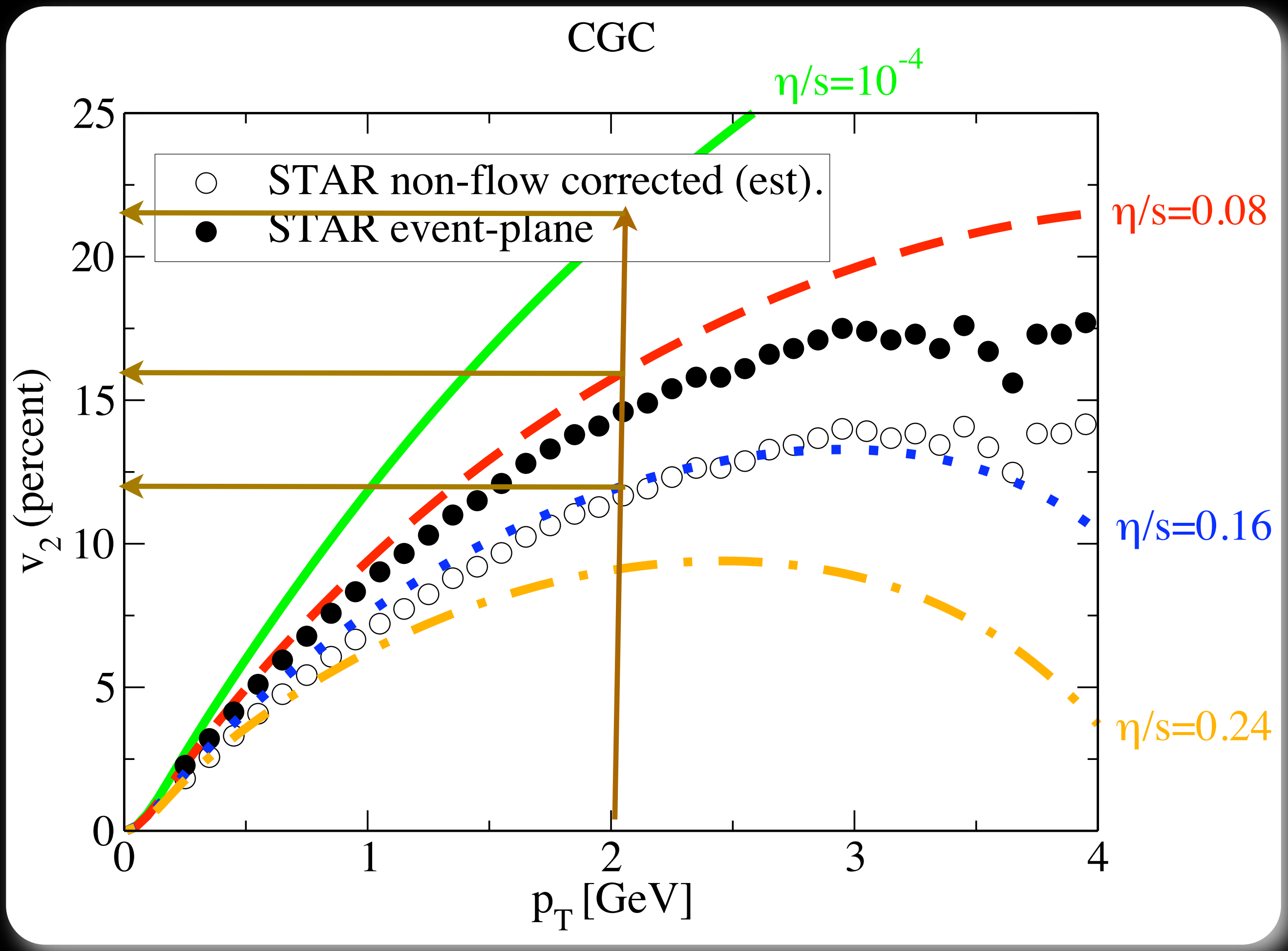


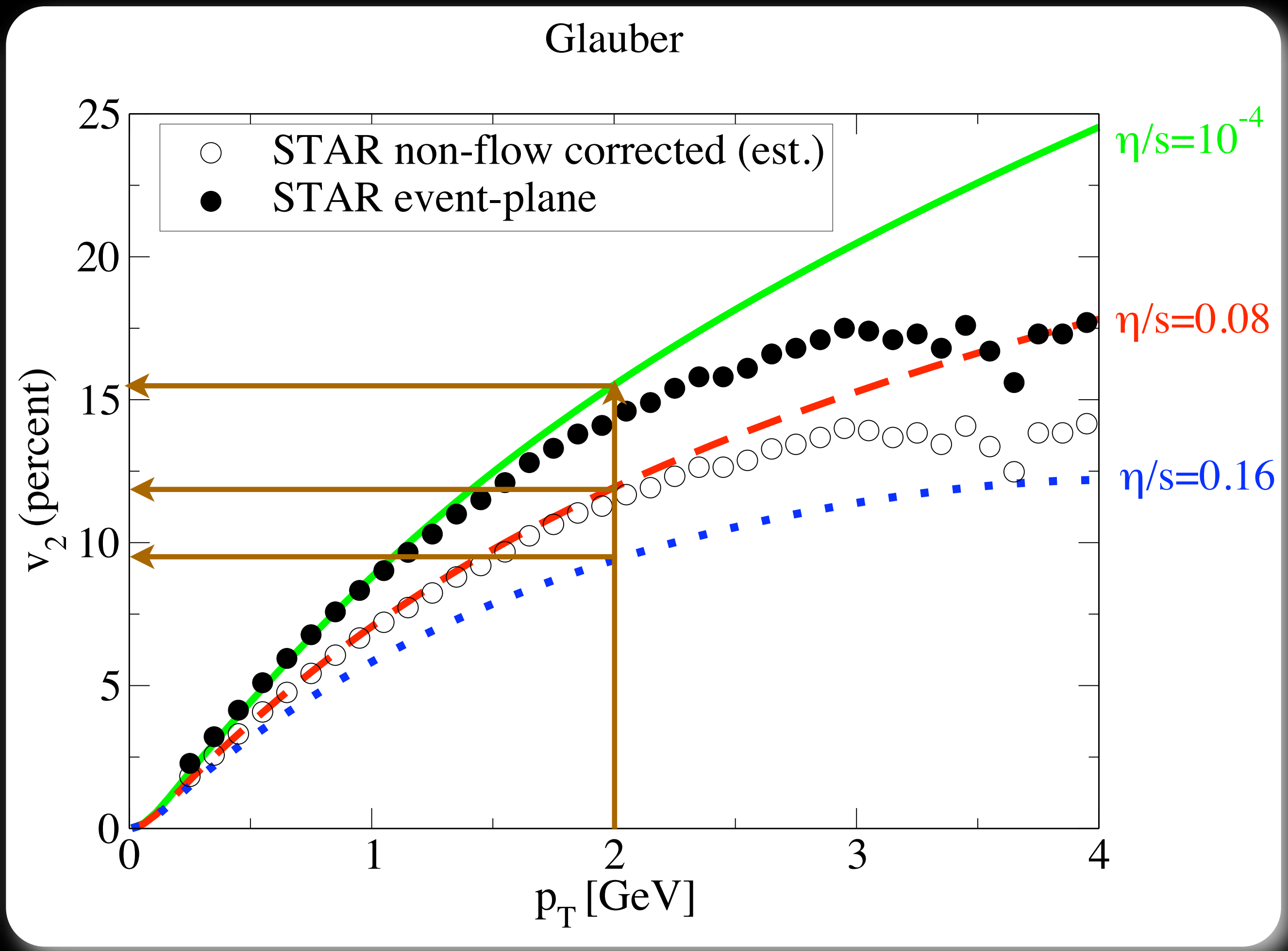
F. Becattini, F. Piccinini, J. Rizzo
arXiv:0711.1253

Initial Conditions?

- directed flow as function of collision energy and system size reduces to a single distribution when plotted versus η-y_{beam}
- none of the available models so far provides a description for this
- connection to the initial conditions?





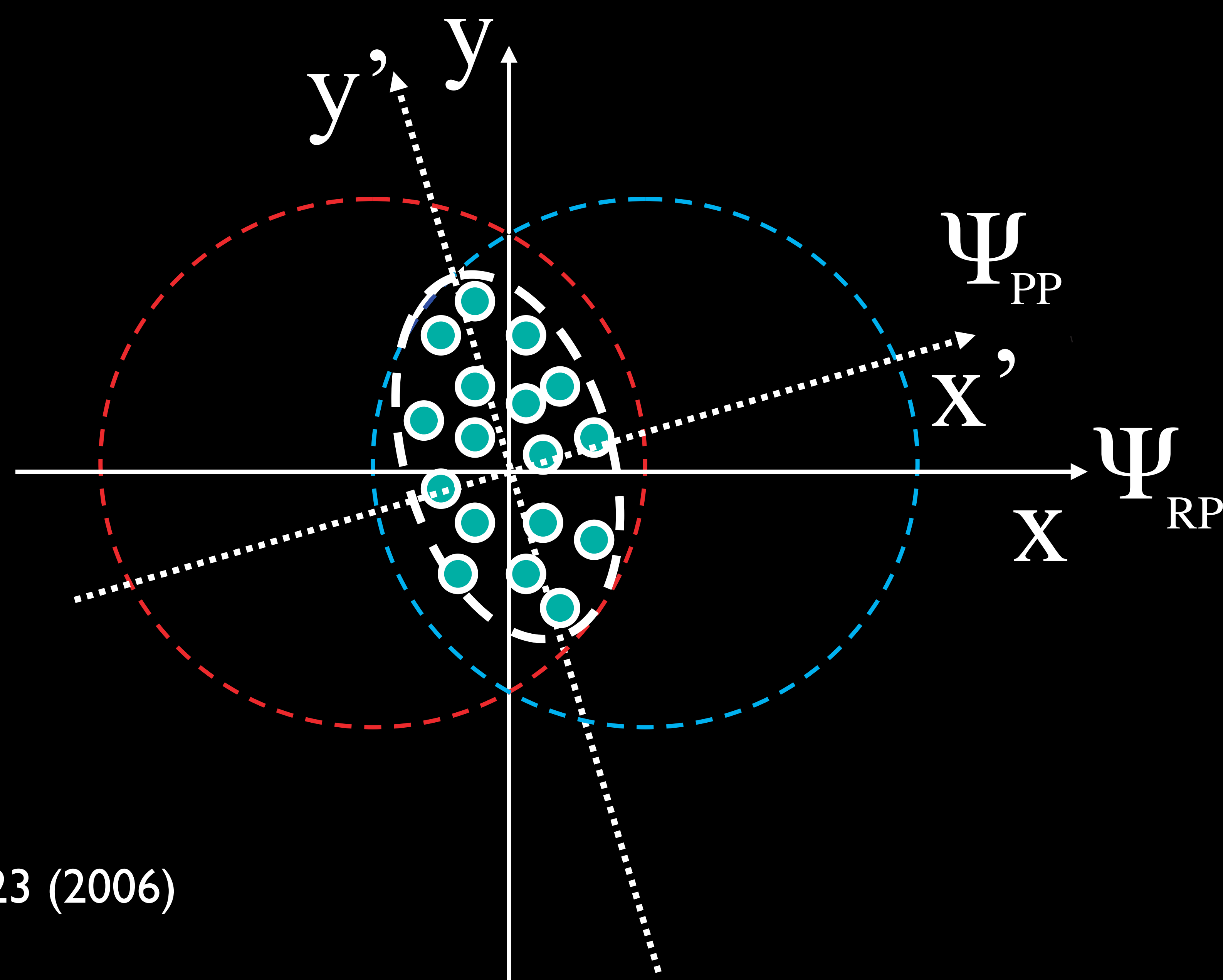


ideal (22), 1/4π ~ 30% reduction (16), 2/4π ~ 45% reduction (12)

ideal (15.5), 1/4π ~ 25% reduction (12), 2/4π ~ 40% reduction (9.5)

Fluctuations and Planes

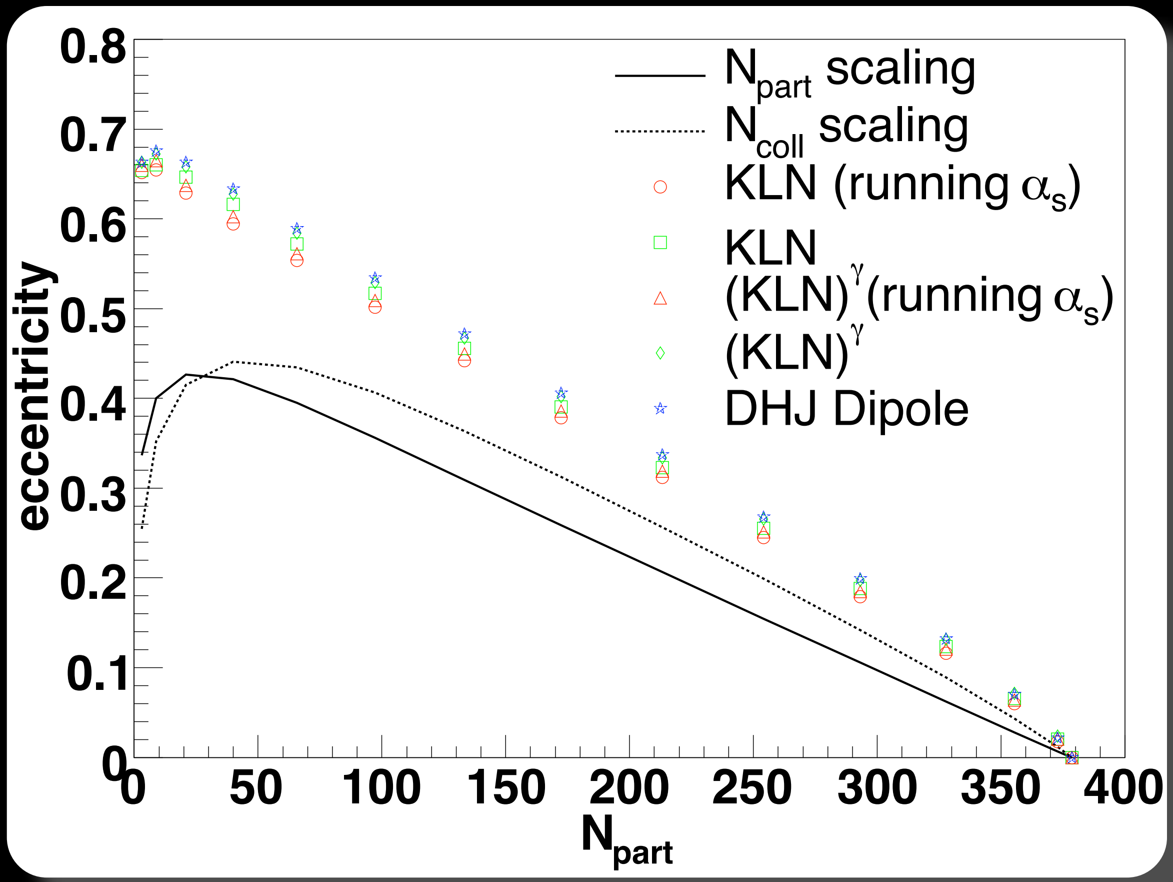
- RP the reaction plane, defined by the impact parameter
- PP the participant plane, defined by the major axis of the created system



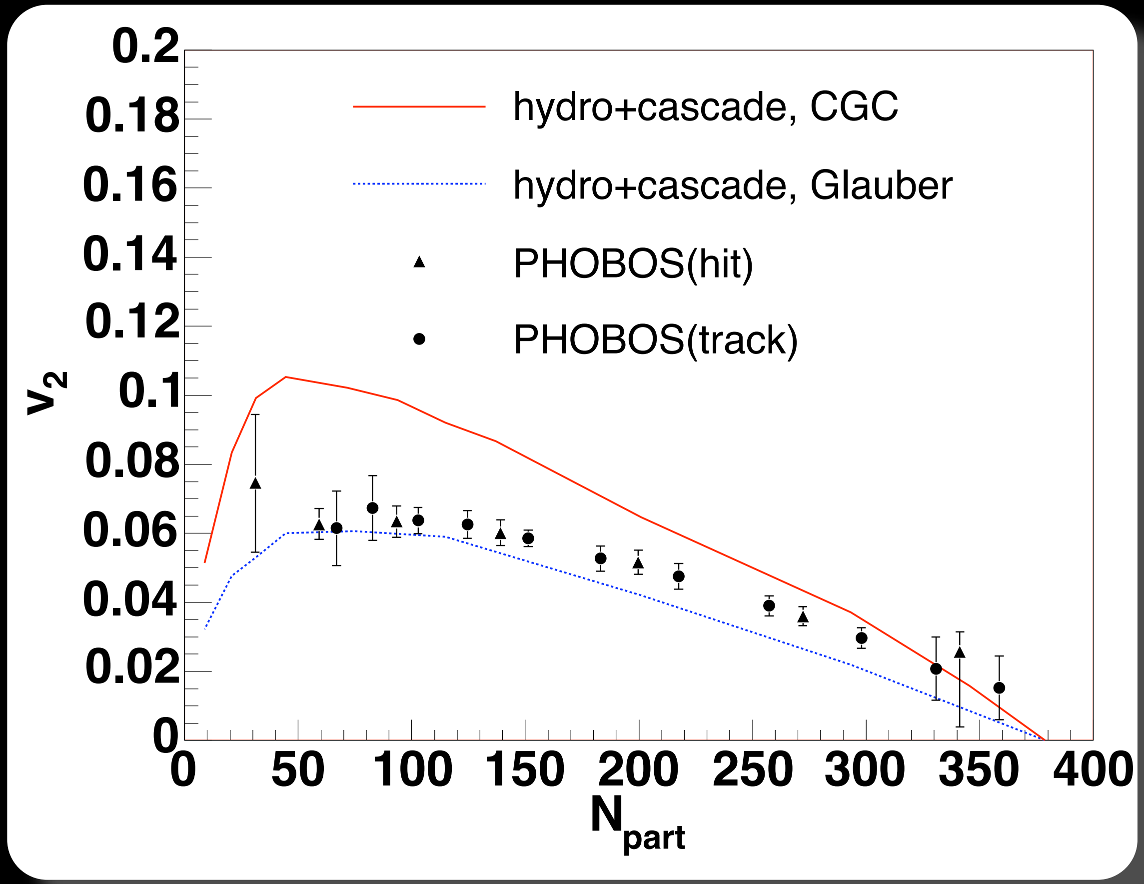
PHOBOS QM2005: Nucl. Phys. A774: 523 (2006)

- Fluctuations change the angle of the symmetry plane

Initial Eccentricity?



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

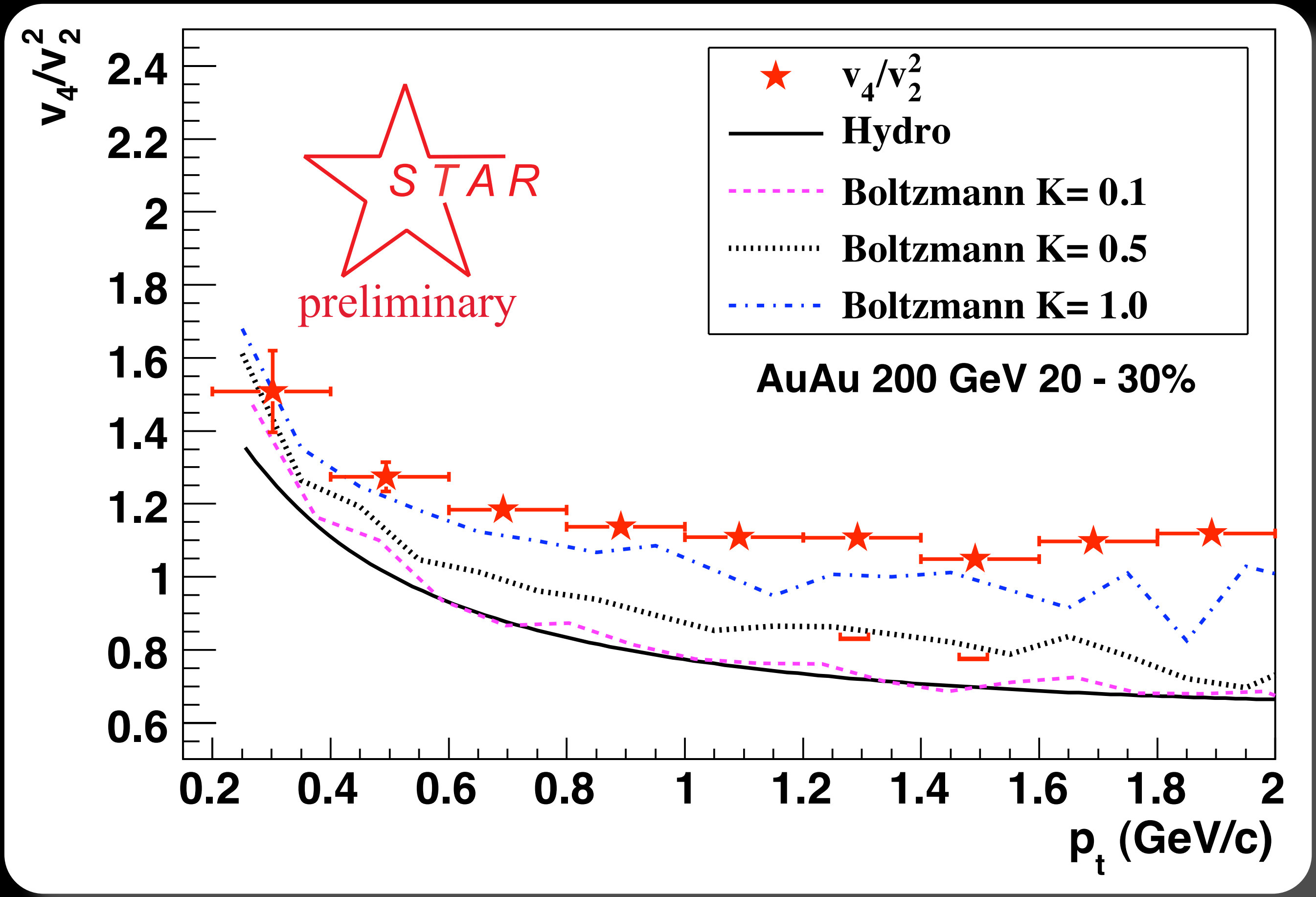


T. Hirano et al., Phys. Lett. B 636 299 (2006)
T. Hirano et al., J.Phys.G34:S879-882,2007

- CGC initial conditions give a much (up to 50%) larger ε
  - reduces v_2/ε below the ideal hydro limit
- The perfect liquid conclusion depends on the choice of ε!

Higher Harmonics

- Ratio v_4/v_2^2 is sensitive to the degree of thermalization
- Updated analysis from QM06 with smaller systematic uncertainties
- The Boltzmann curves are from the same calculation as used for v_2/ε, which for most central collisions reached K~ 0.5
- Also these measured ratios indicate that ideal hydro limit is not yet reached



Yuting Bai PhD thesis, Jocelyn Mlynarz

Boltzmann curves J-Y. Ollitrault

Elliptic Flow at RHIC

- strong elliptic flow
- constituent quark degrees of freedom
- large energy loss