Collective Behavior in Heavy Ion Collisions

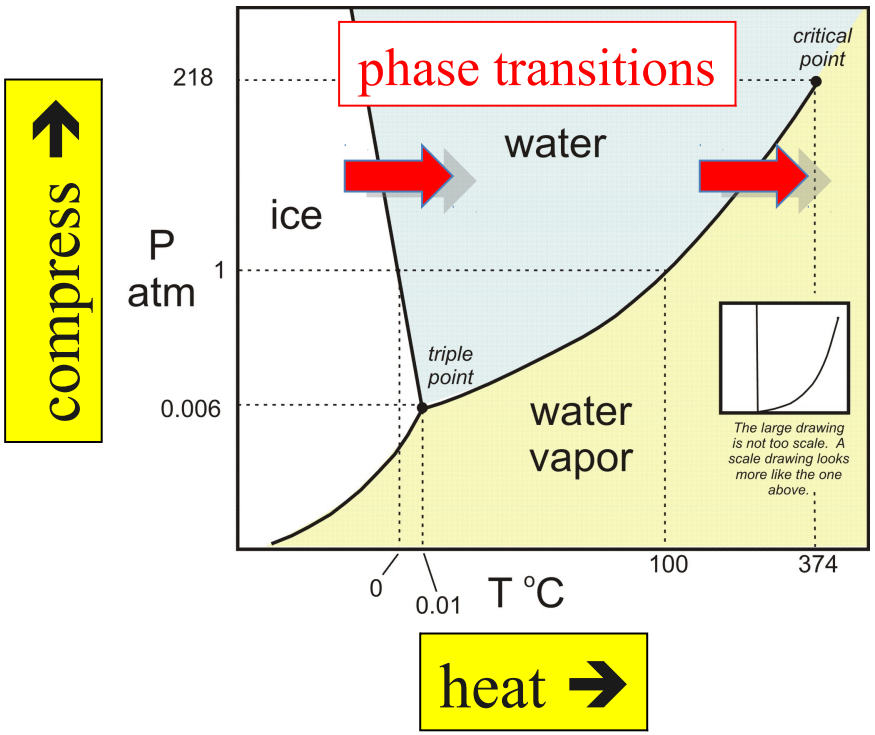
Constantin Loizides
(LBNL/EMMI)

28 July 2011

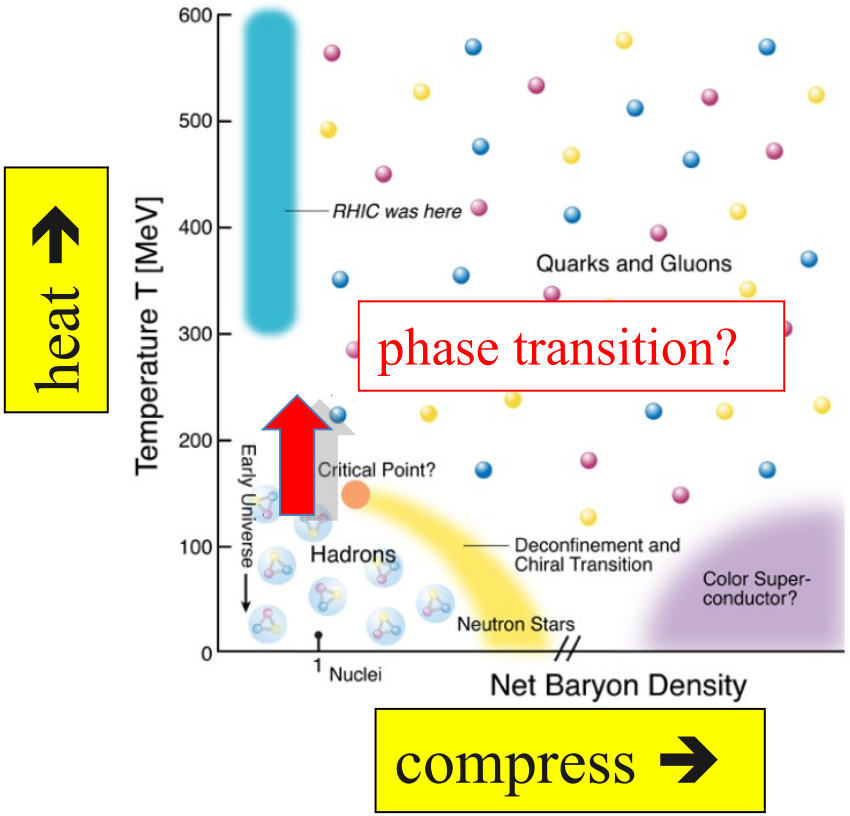
The 19th Particle and Nuclei International Conference, MIT, Cambridge, MA, USA

Study hot QCD matter

Phase diagram of water (simplified)

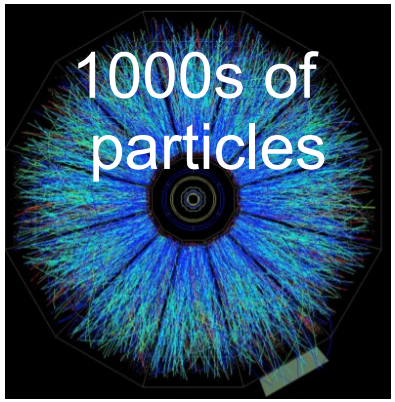


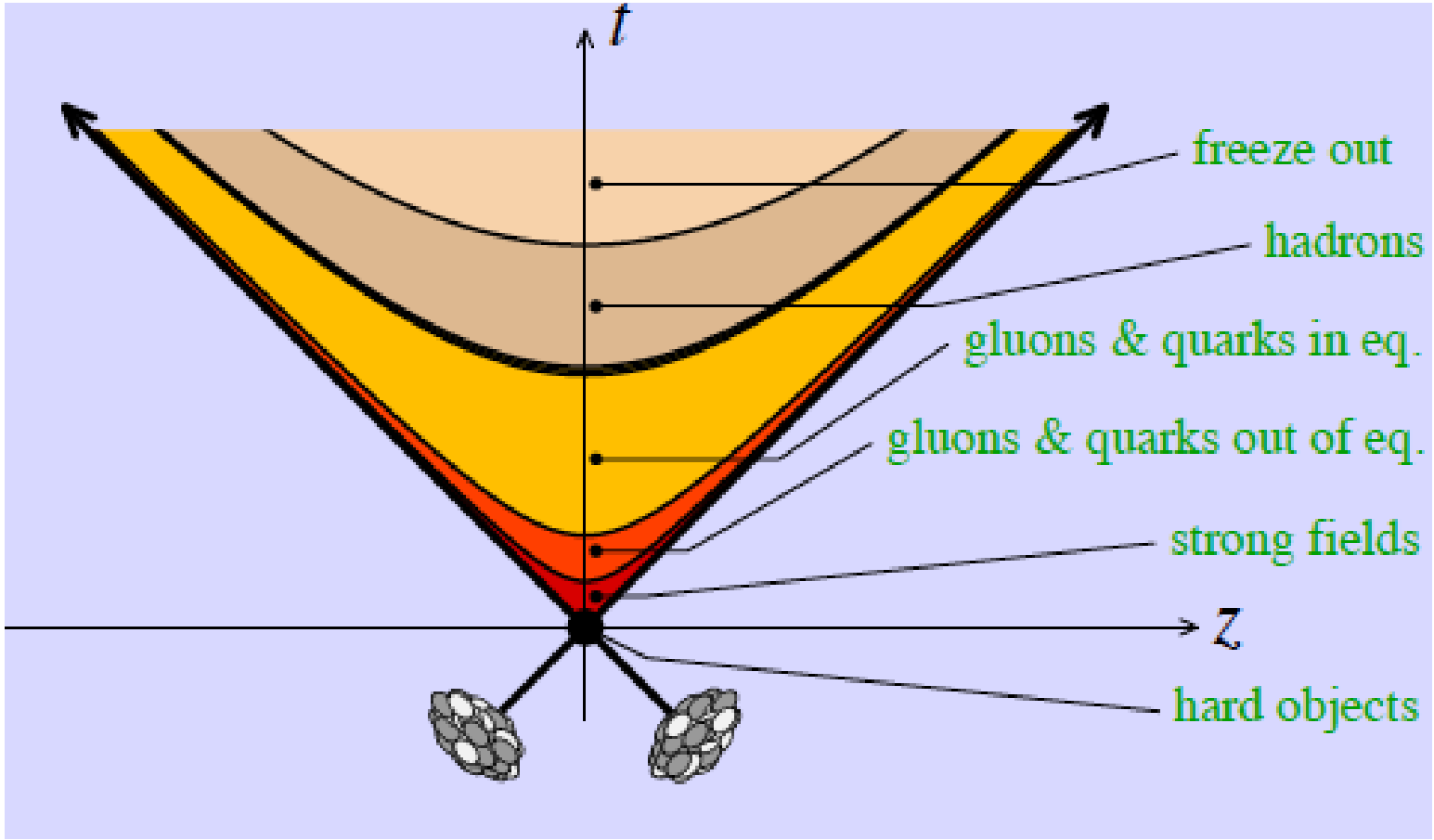
Phase diagram of QCD (simplified)



Experimental study of QCD phase diagram by: colliding nuclei head-on to convert cold nuclear matter into a fireball of partons

Complex collision dynamics



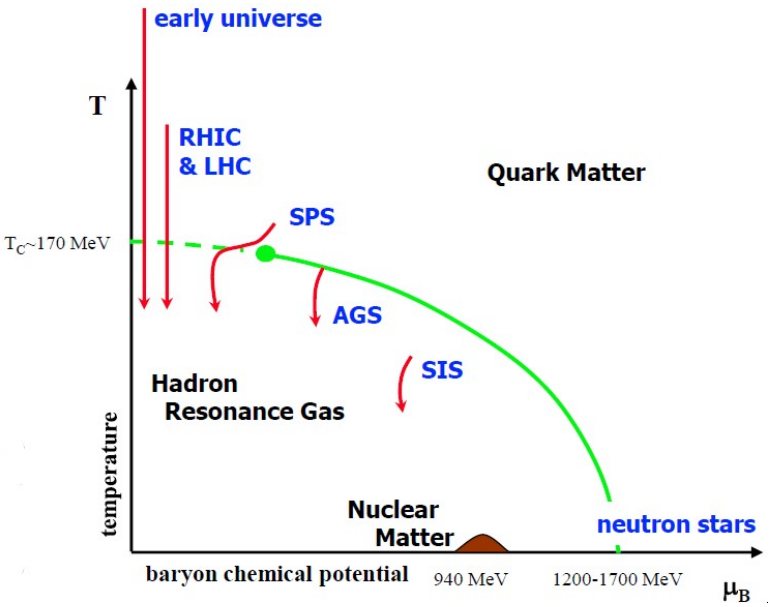


Studying matter in the laboratory

Changing initial conditions:

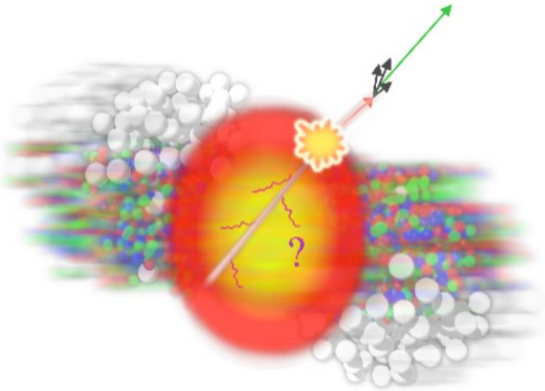
Ideal	Temperature Matter Density
Practical	Species Energy Size Shape

Centrality (#Participants)



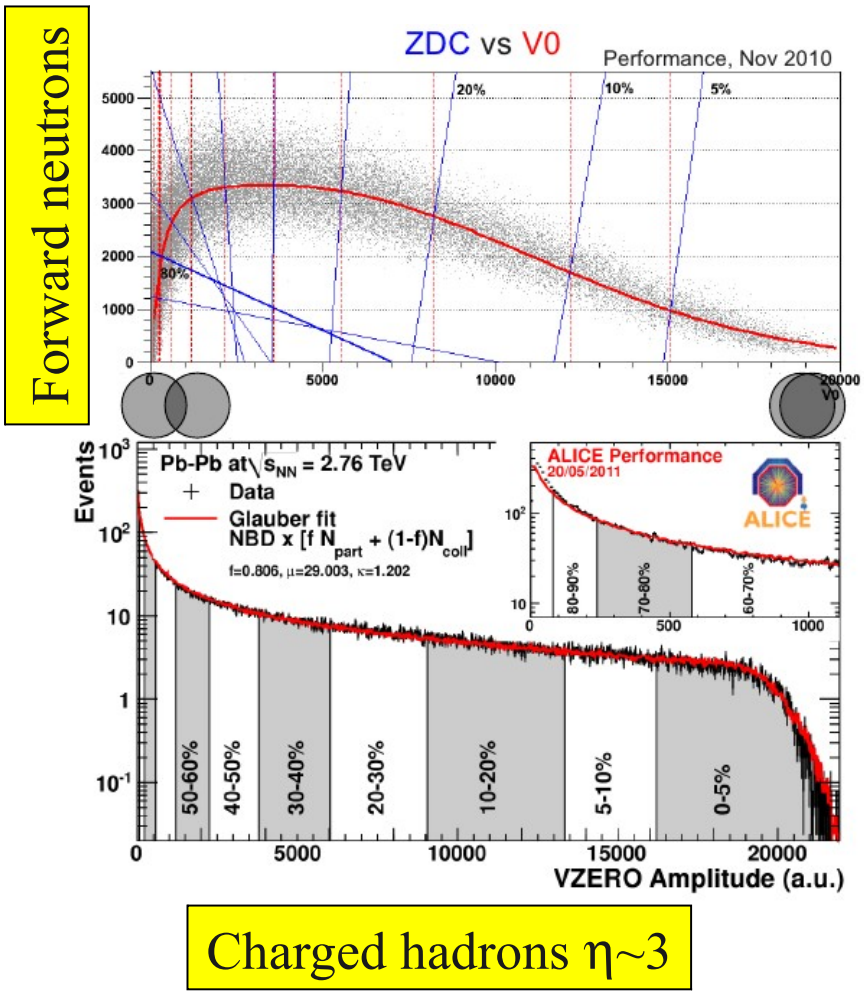
Probing the matter microscopically:
(Hard probes, C.Salgado next)

Ideal	Microscopy Tomography
Practical	Jets Photons Quarkonia

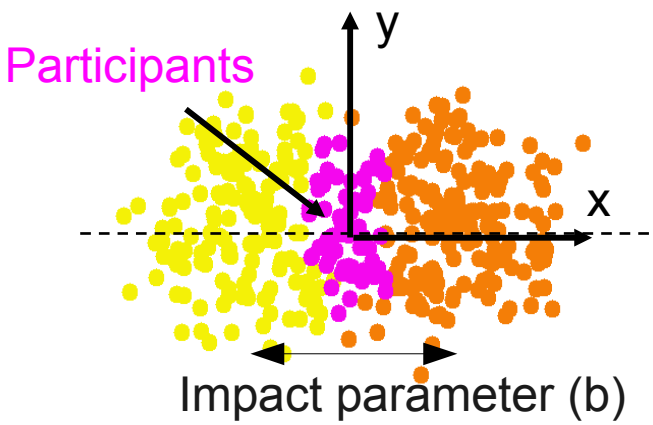


Nuclear geometry and collision centrality

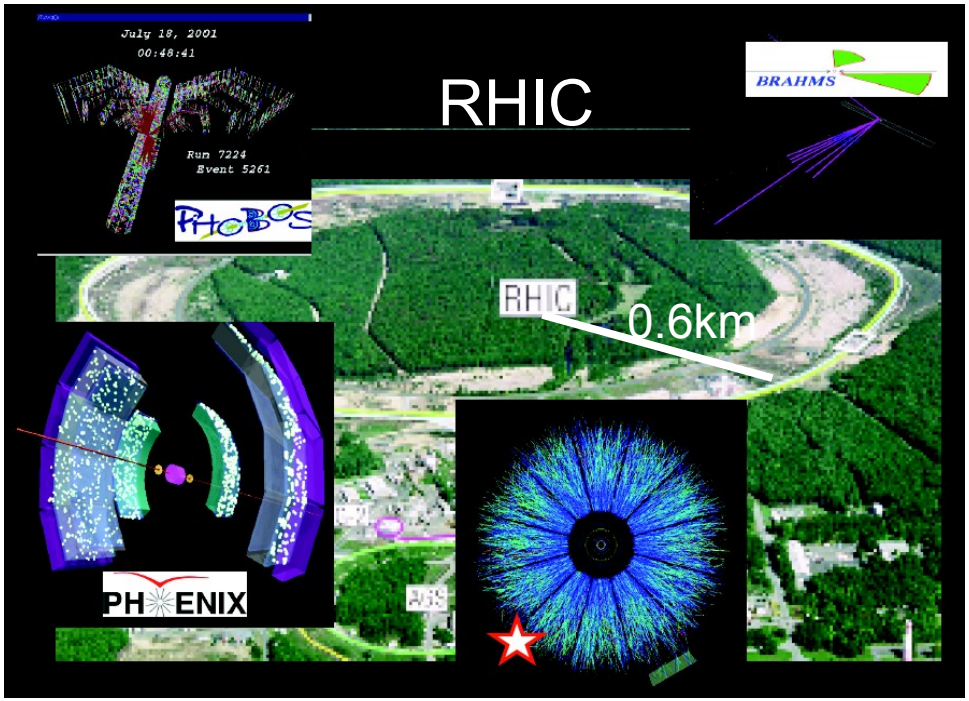
Nuclei are “macroscopic”: Characterize collisions by impact parameter

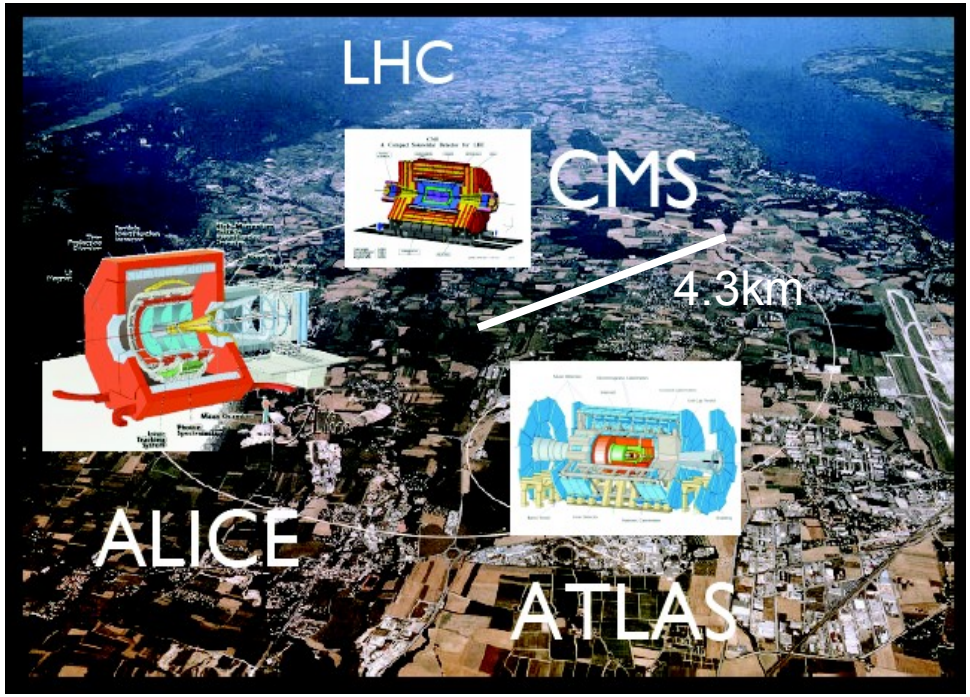


- Correlate yields from disconnected parts of phase space
  - Correlation arises from common dependence on collision impact parameter
- Order events by centrality metric
  - Typically, classify them as “ordered” fraction of total cross section
    - eg. 0-5% most central
  - Number of participants (volume)



Heavy ion experiments at RHIC/LHC

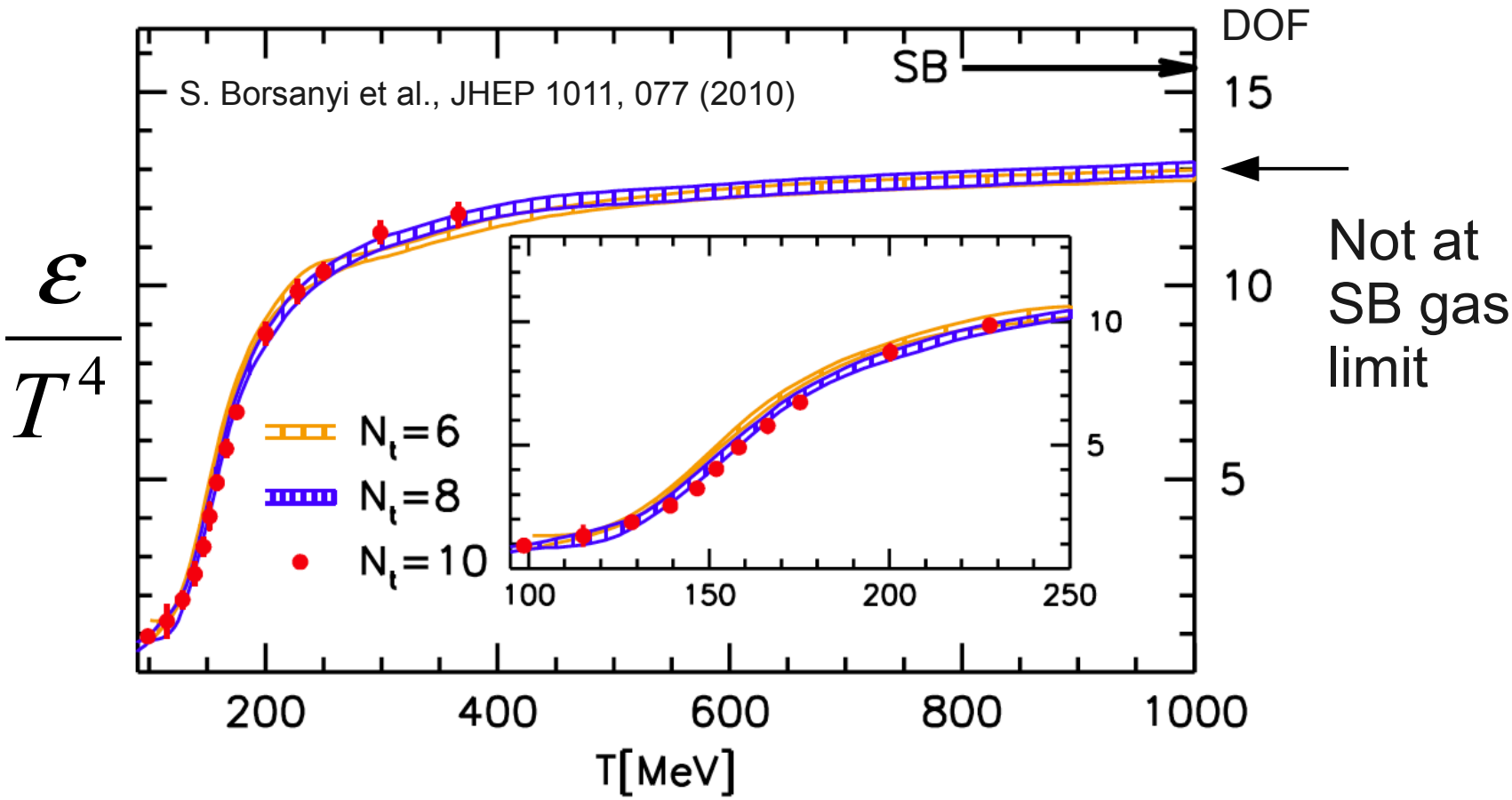




- RHIC: First beams June 2000
  - p+p, d+Au, Cu+Cu, Au+Au (~20, 62.4, 130, 200 AGeV)
- 2 multipurpose (PHENIX, STAR) and 2 specialized (BRAHMS, PHOBOS) experiments
  - >2006, only STAR and PHENIX
- Beam energy scan (2010/11)

- LHC: First beams in Nov 2009
  - p+p (900, 2.36, 2.76, 7 TeV)
  - Pb+Pb at 2.76 ATeV in Nov 2010
- 1 dedicated HI experiment
  - Mid-rapidity, low mass, PID
- 2 large HEP experiments
  - Large acceptance, full calorimetry

QGP cross-over phase transition

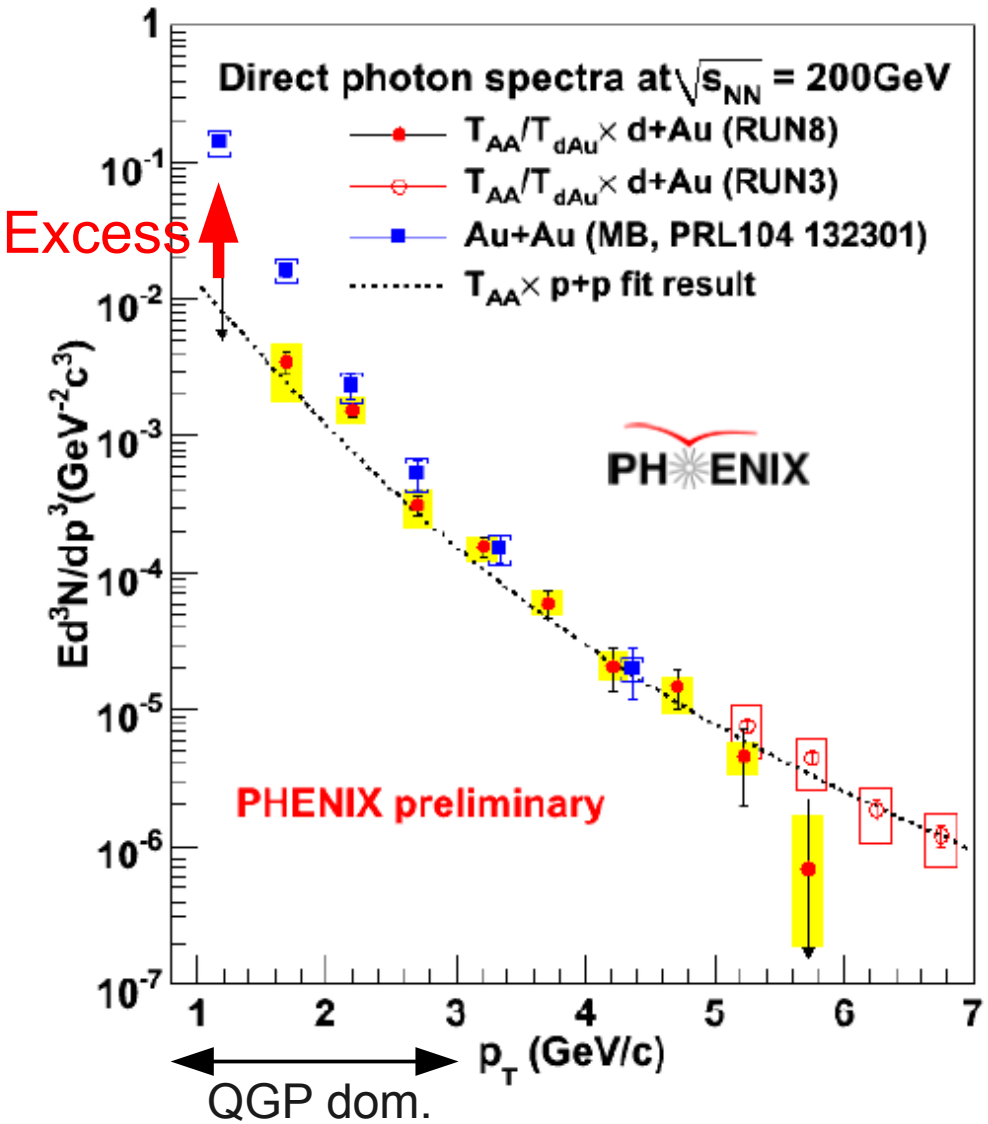


Lattice predicts a cross-over phase transition from hadronic to partonic degrees of freedom

$T_c \approx$ 145-175 MeV
$\varepsilon_c \sim$ 1 GeV/fm3

Initial temperature at RHIC

Direct photons: No charge, no color, ie. they do not interact
Emission over all lifetime convolution of all T



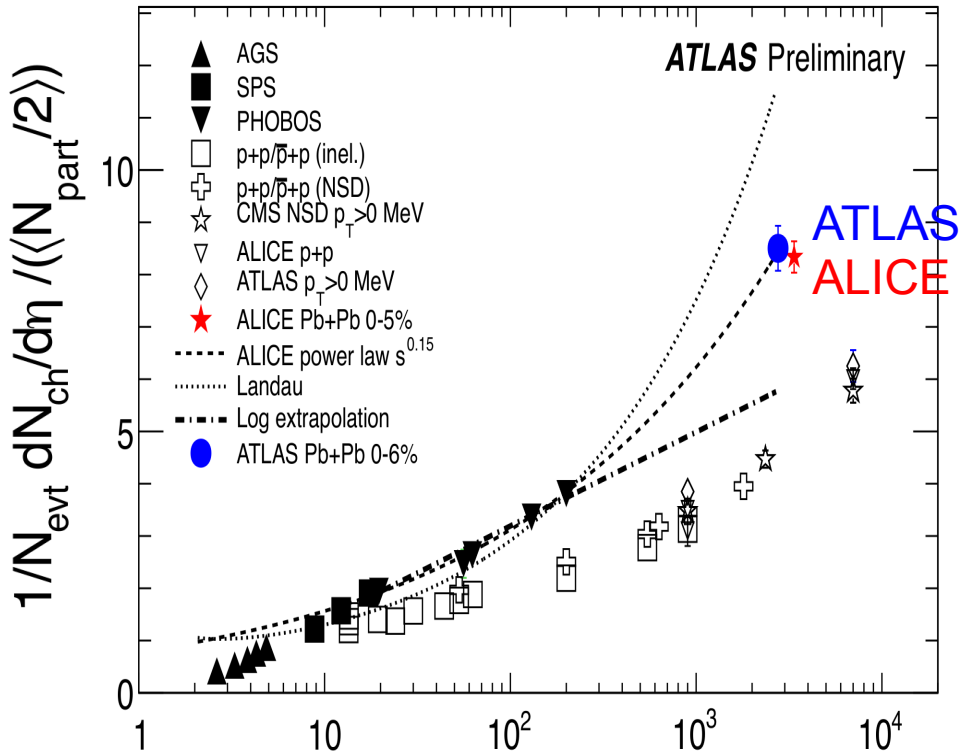
- Exponential (thermal) shape with T~200 MeV
- No excess in d+Au data
- Emission rate and shape consistent with that from equilibrated matter
- T_{hydro} = 300 - 600 MeV (> 2 Tc)

First experimental observation of T>Tc

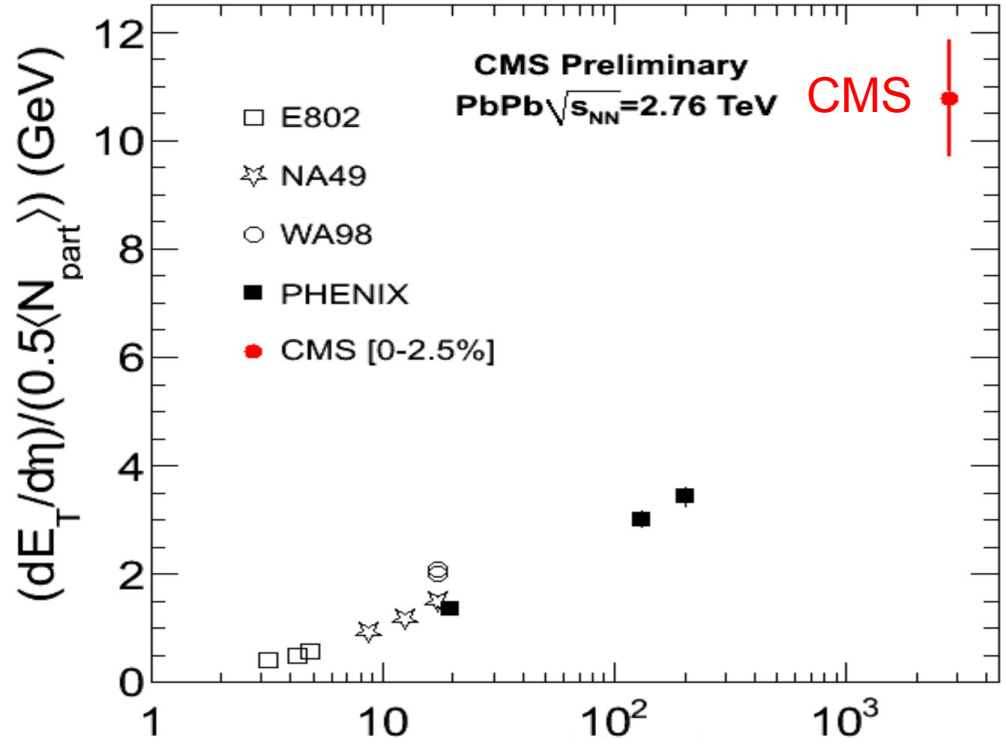
Y.Aramaki, Mon 2L

What do we know already from LHC?

Charged-particle density



Transverse energy density



collision energy, $\sqrt{s_{NN}}$ (GeV)

<u>Compared to top RHIC energy</u>

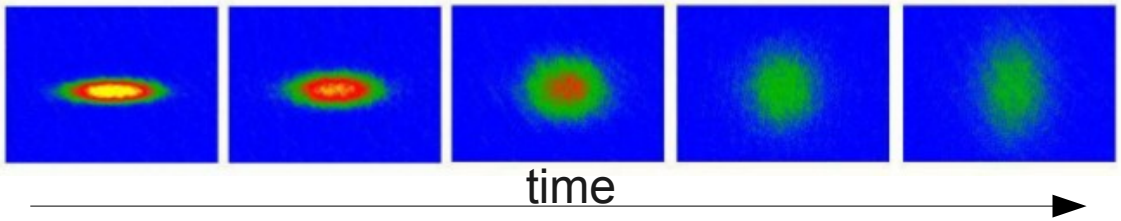
- x2.1 increase in $dN_{ch}/d\eta$ (x1.9 to pp)
- x2.5-3 times larger energy density
  - Midrapidity $dE_T/d\eta$ ~ 2 TeV at LHC

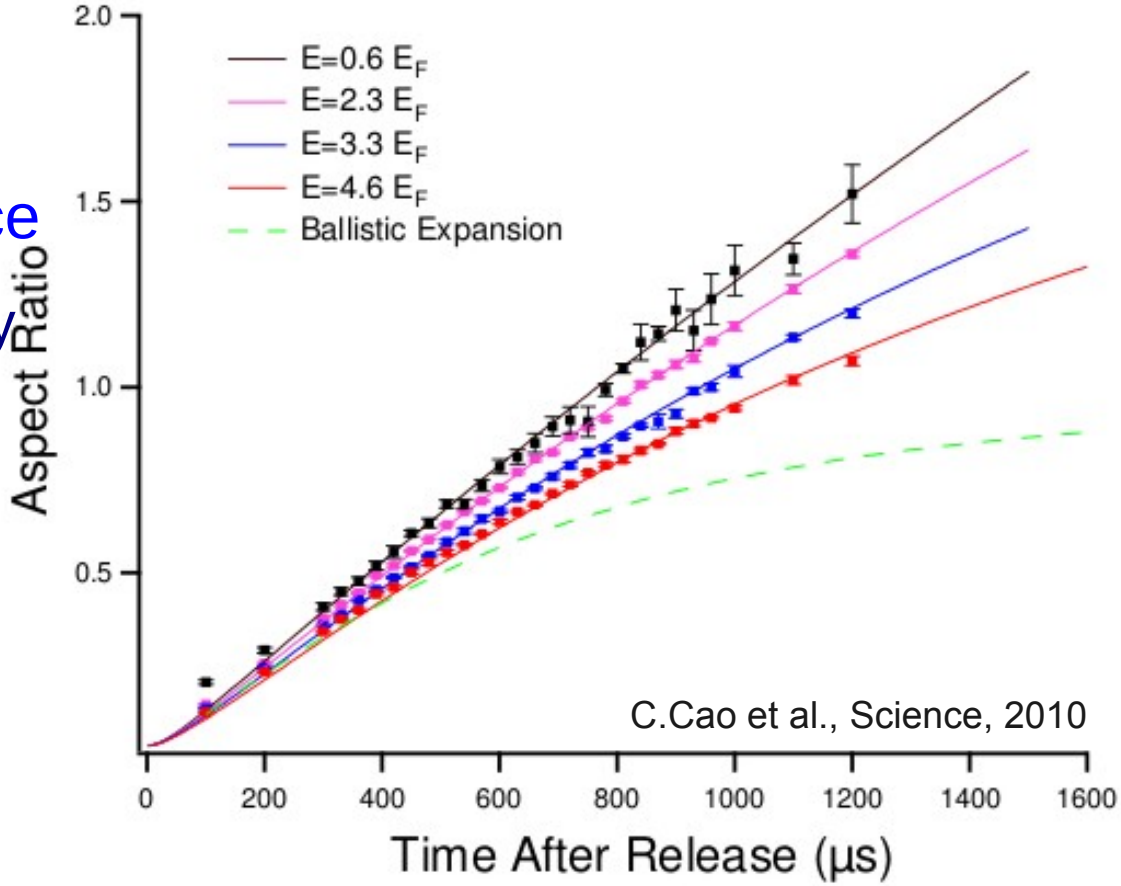
$$\tau\,\epsilon_{LHC} \geq 3 \times \tau\,\epsilon_{RHIC}$$

How can we prove we make matter?

Ultracold Fermionic Atom Fluid (^{6}Li)

- Optically trapped atoms
  - Degenerate Fermi gas
  - NanoKelvin temperature
- Interactions magnetically tuned to Feshbash resonance
  - Unitary limit: Largest 2-body scattering cross section
  - “Strongly-coupled” system
- Prepare system with spatial anisotropy
  - Develops momentum anisotropy
  - Analysis of spatial profile

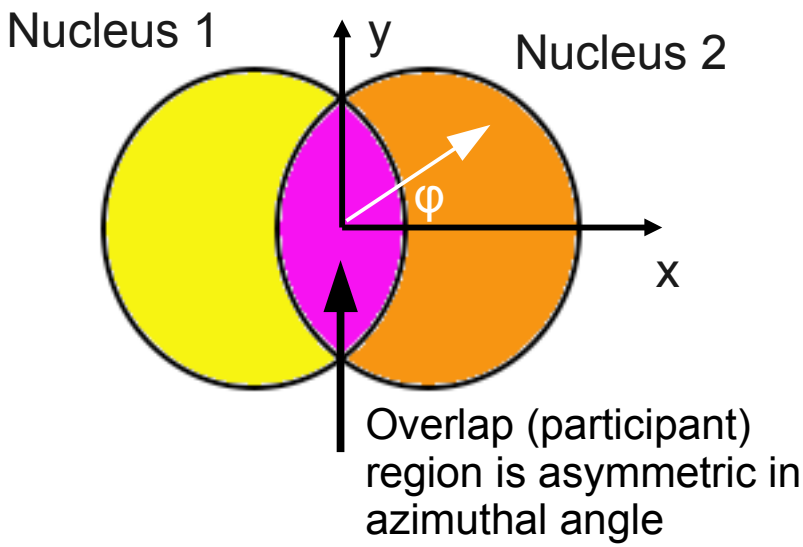




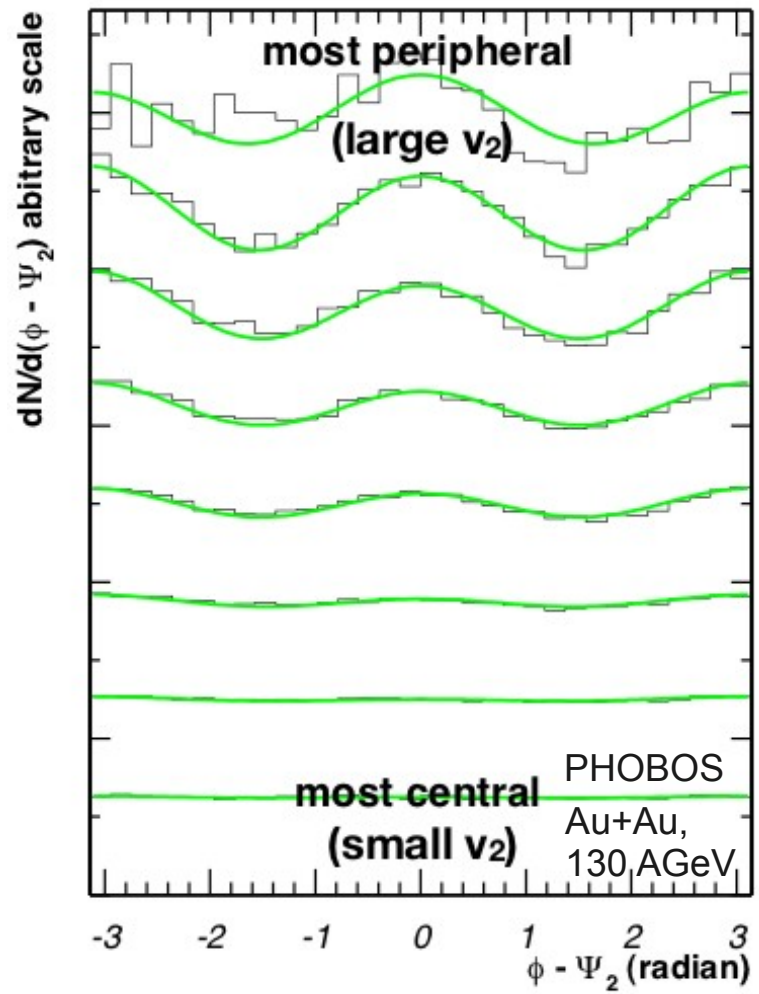
Schaefer/Cao Mon 1K

Initial anisotropy and elliptic flow

Initial spatial anisotropy



Final momentum anisotropy



Eccentricity

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

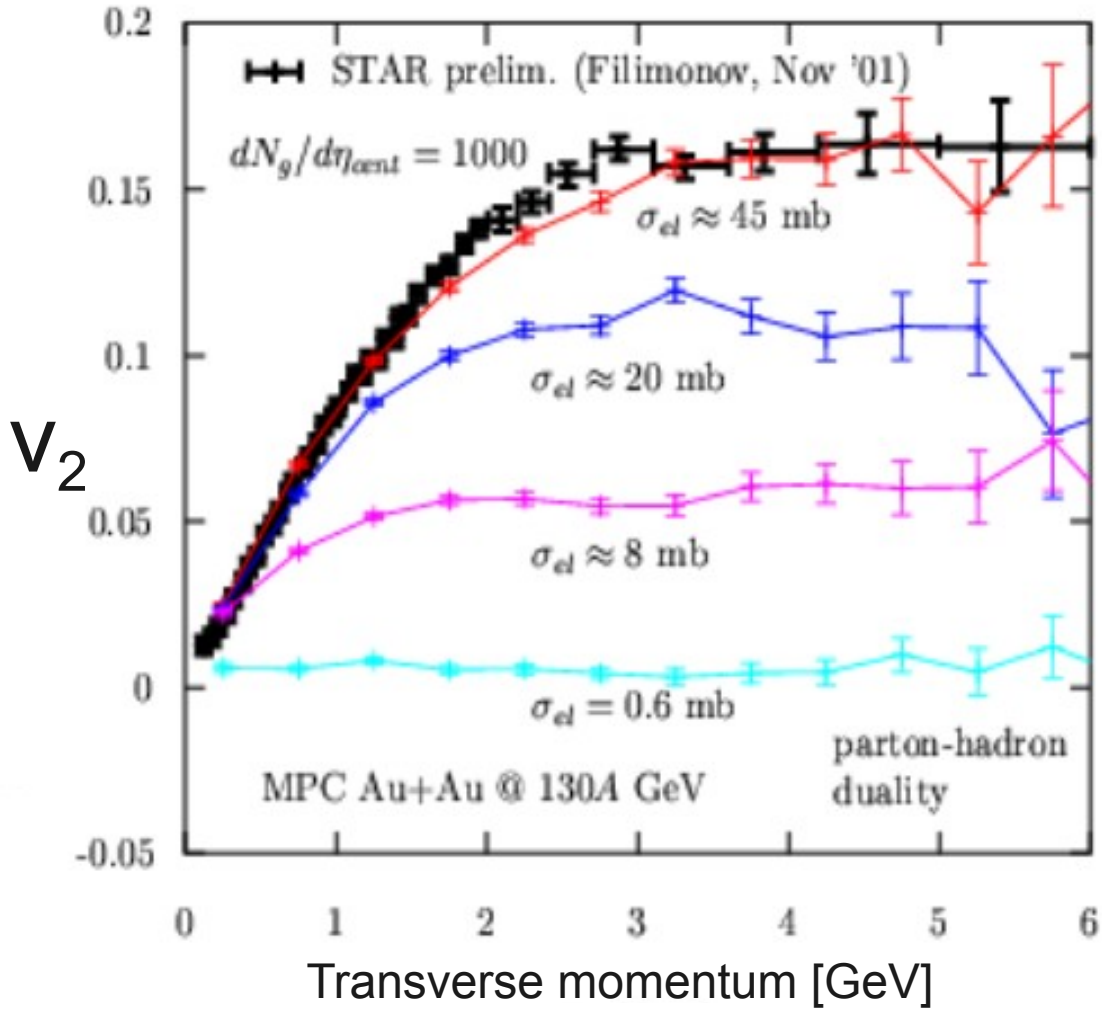
Interactions present early →

Elliptic flow

$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

$$\frac{dN}{d\phi} \sim 1 + 2 v_2 \cos[2(\phi - \psi_R)] + \ldots$$

What's needed partonically to get v_2? 12



Parton transport model: Bolzmann equation with 2-to-2 gluon processes

D.Molnar, M.Gyulassy
NPA 697 (2002)

HUGE cross sections needed to describe v_2

Need large opacity to describe elliptic flow, ie elastic parton cross sections as large as inelastic the proton cross-section.

Elliptic flow and ideal hydrodynamics

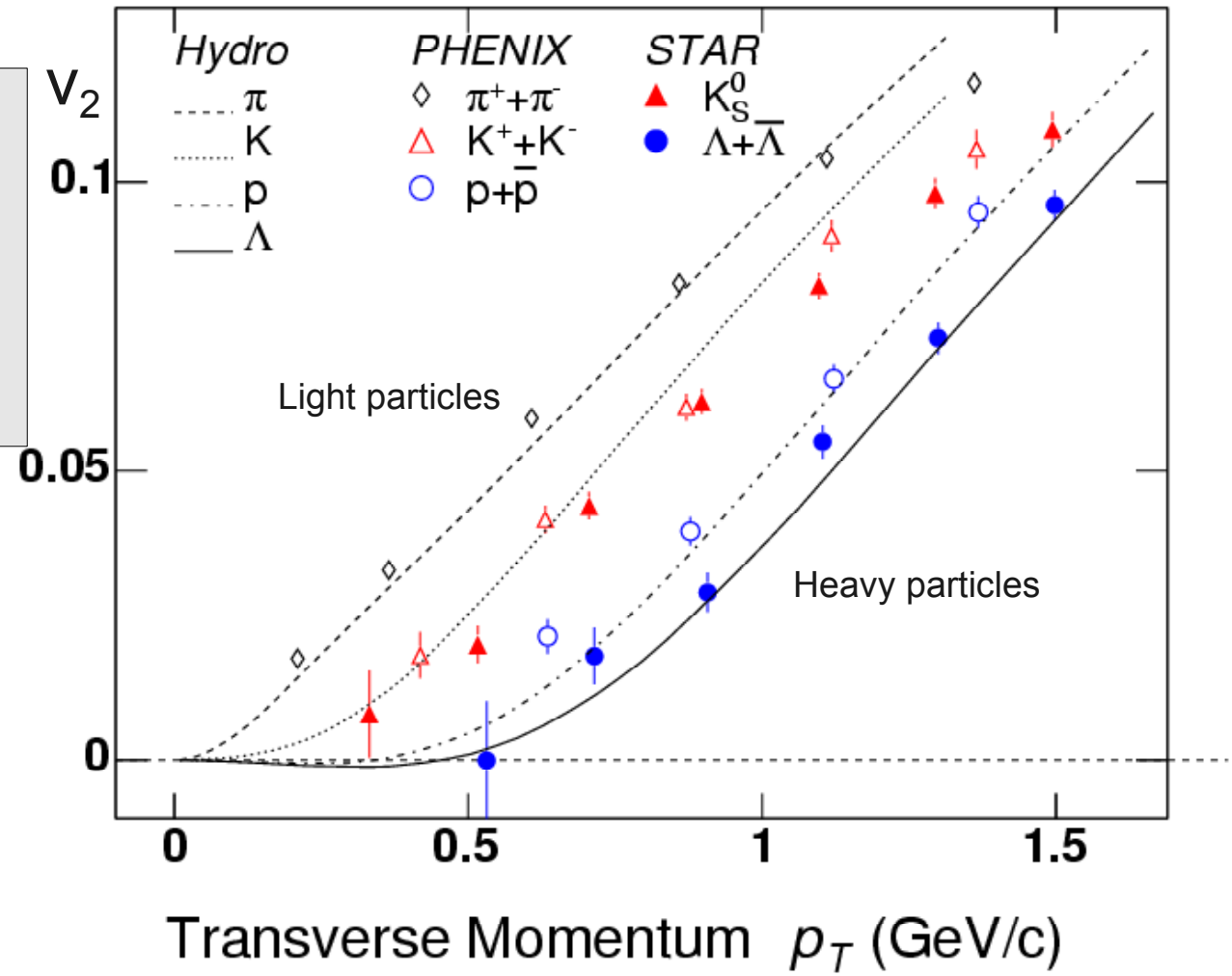
Ideal relativistic hydrodynamics

$$T^{\mu\nu} = (e+p)u^{\mu}u^{\nu} - p\,g^{\mu\nu}$$

$$\delta_{\mu} T^{\mu\nu} = 0$$

$$\delta_{\mu} N_i^{\mu} = 0,\ i = B, S, \ldots$$

$$p = p(e, n)$$ Closure with EoS



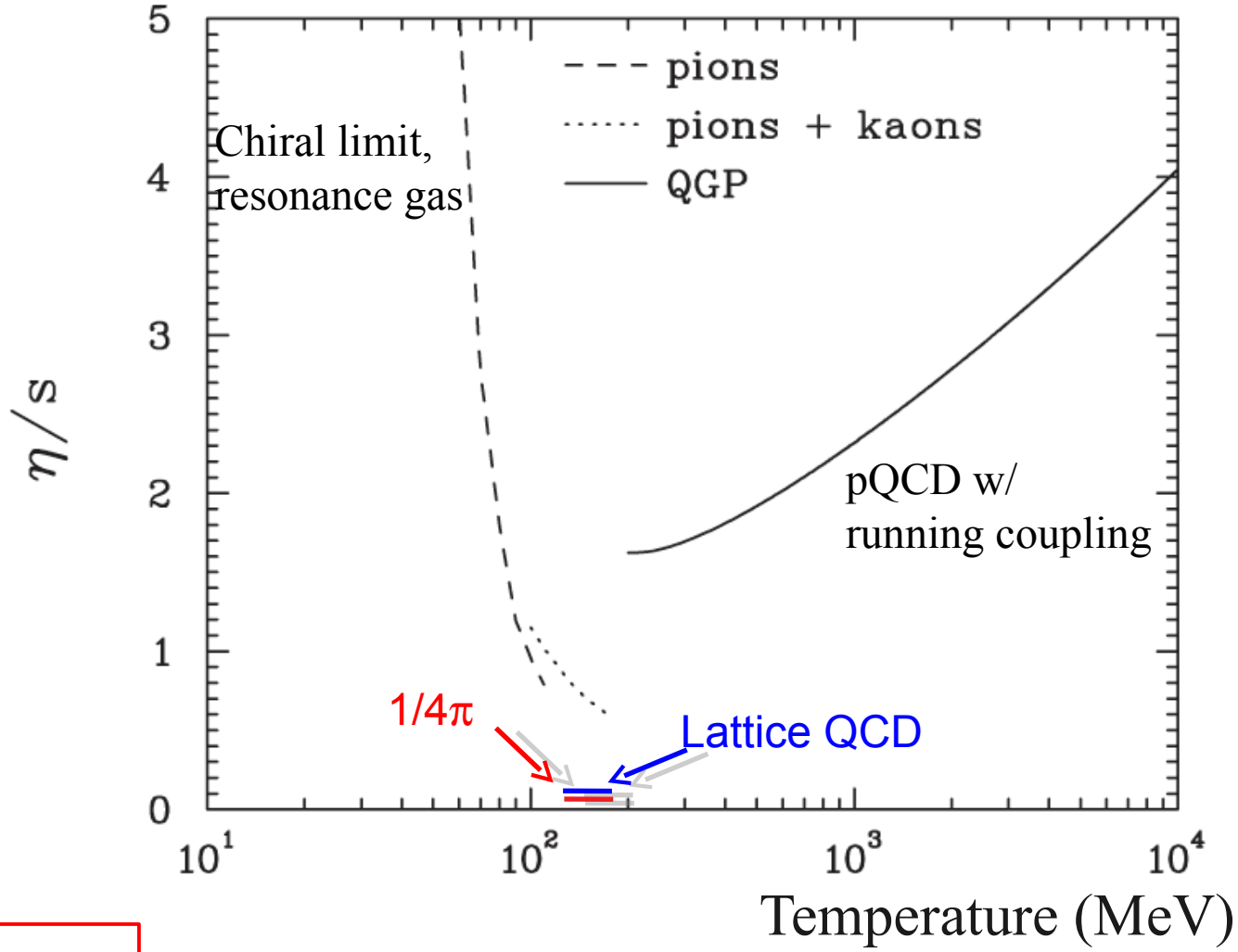
Assumption:
After a thermalization time (≤1fm/c) a system in local equilibrium with zero mean free path and zero viscosity is created

Initial conditions (IC) →
Equation of state (EOS) → **Hydro** → Observables
Freeze-out cond. (FO) →

Perfect fluid?

Shear viscosity in QCD

Analytic: Csernai, Kapusta and McClerran PRL 97, 152303 (2006)
Lattice: H. Meyer, PR D76, 101701R (2007)

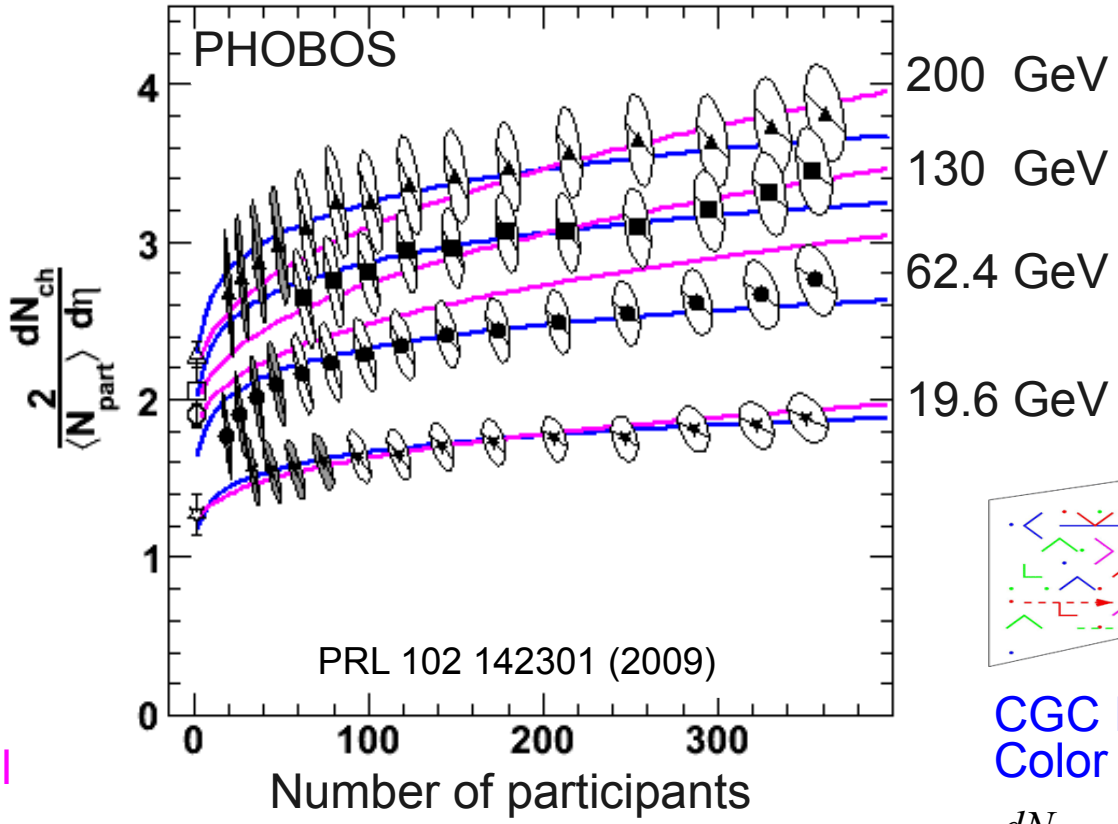


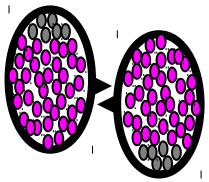
$$\frac{\eta}{s} = \frac{1}{4\pi}$$

For a large class
of holographic duals
(see A.Karch Wed plen.)

Description of initial state?

Mid-rapidity density

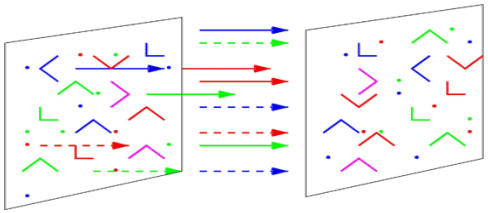




Glauber IC
Two-component model

$$\frac{dN}{d\eta} = \frac{dN}{d\eta^{pp}}\left((1-x)N_{coll} + x\,N_{part}/2\right)$$

PRC 70 021902 (2004)



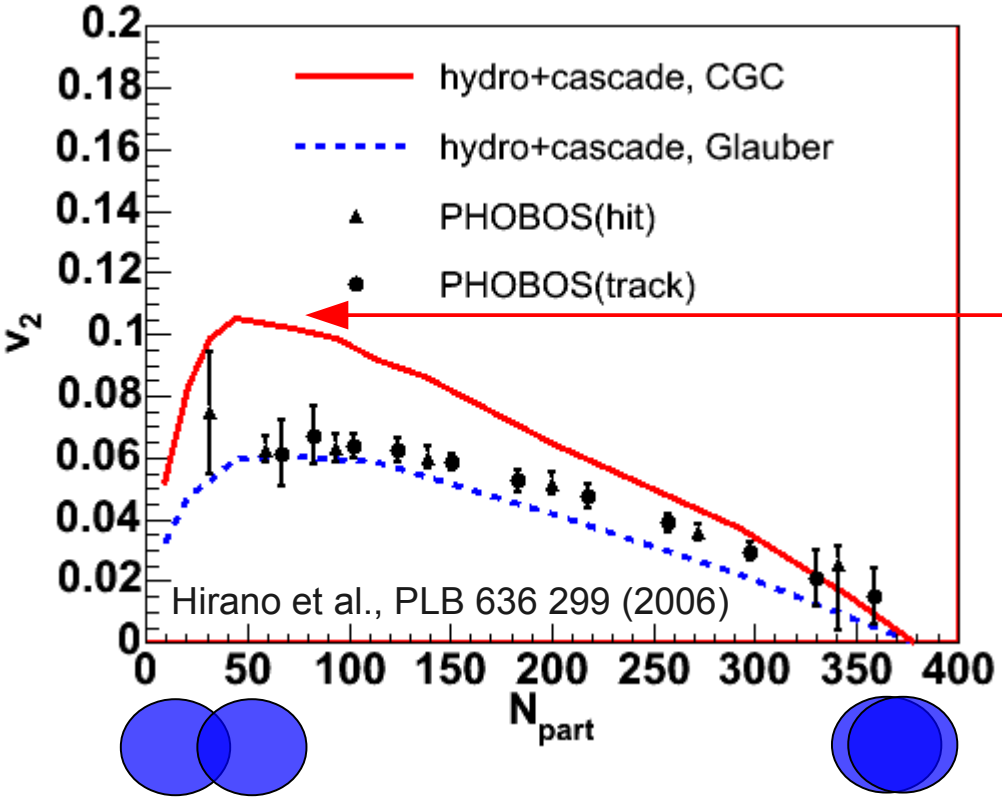
CGC IC
Color glass condensate

$$\frac{dN}{d\eta} \propto N_{part}^{\alpha}\sqrt{s}^{\lambda}$$

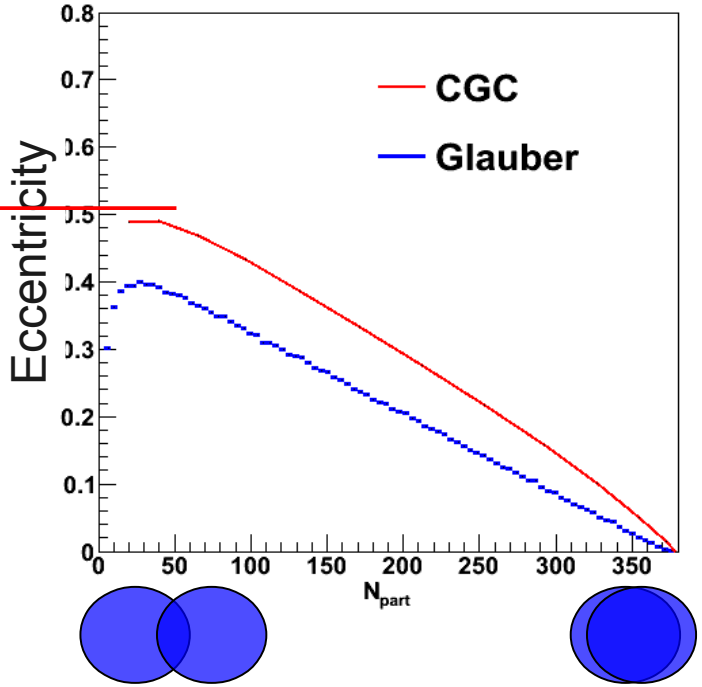
PRL 94 022002 (2005)

Two classes of models describe the multiplicity (believed to be sensitive to initial state) equally well

Ambiguity translates into conclusions

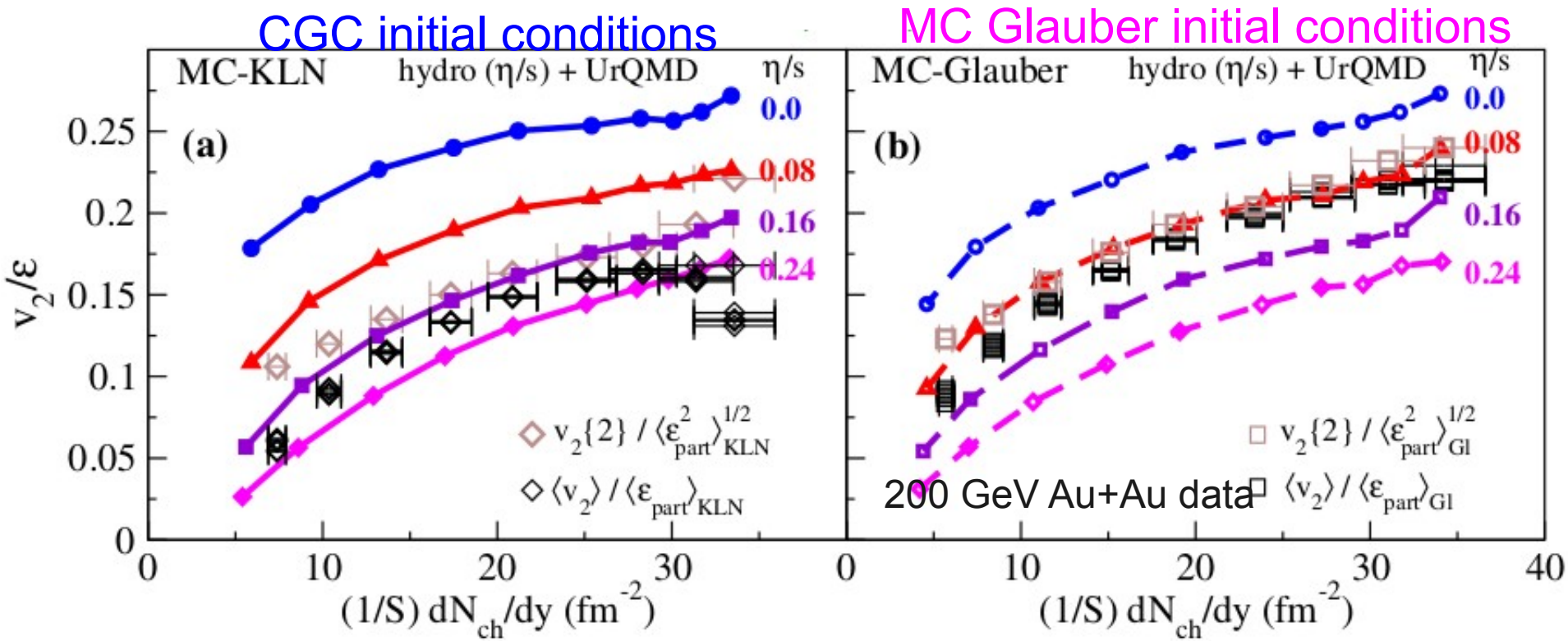


Higher eccentricity leads to higher flow



Ambiguity in description of initial state allows for various models:
Size of viscous corrections and/or soft equation of state?

The hot QGP is a nearly perfect fluid ... 17



Combination of many calculations, including state-of-art results from Israel-Stewart theory for a conformal fluid (2+1D), hint to a low shear viscosity to entropy ratio:

$$\frac{1}{4\pi} < \frac{\eta}{s} < \frac{3}{4\pi}$$

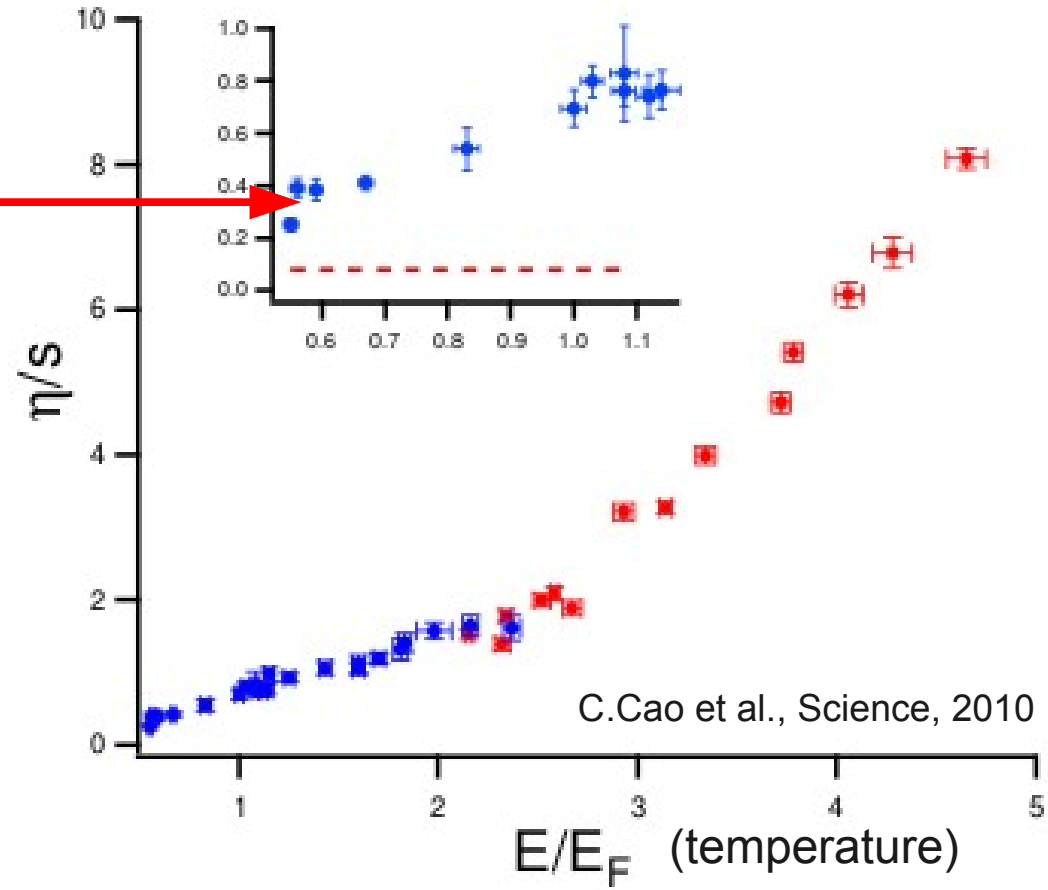
Largest part of uncertainties still from the ambiguity in the description of initial state.

U.Heinz, Mon 1L

... as are the ultracold atoms!

Ultracold Fermionic Atom Fluid (^{6}Li)

$$\frac{\eta}{s} \leqslant \frac{5}{4\pi}$$

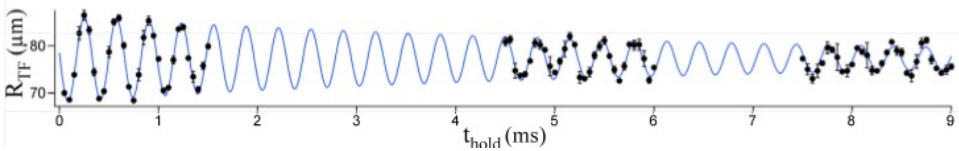


T=0.1neV

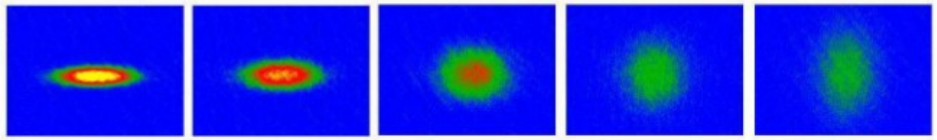
(QGP ~0.3TeV)

Schaefer/
Cao Mon 1K

Low temperature: Breathing mode

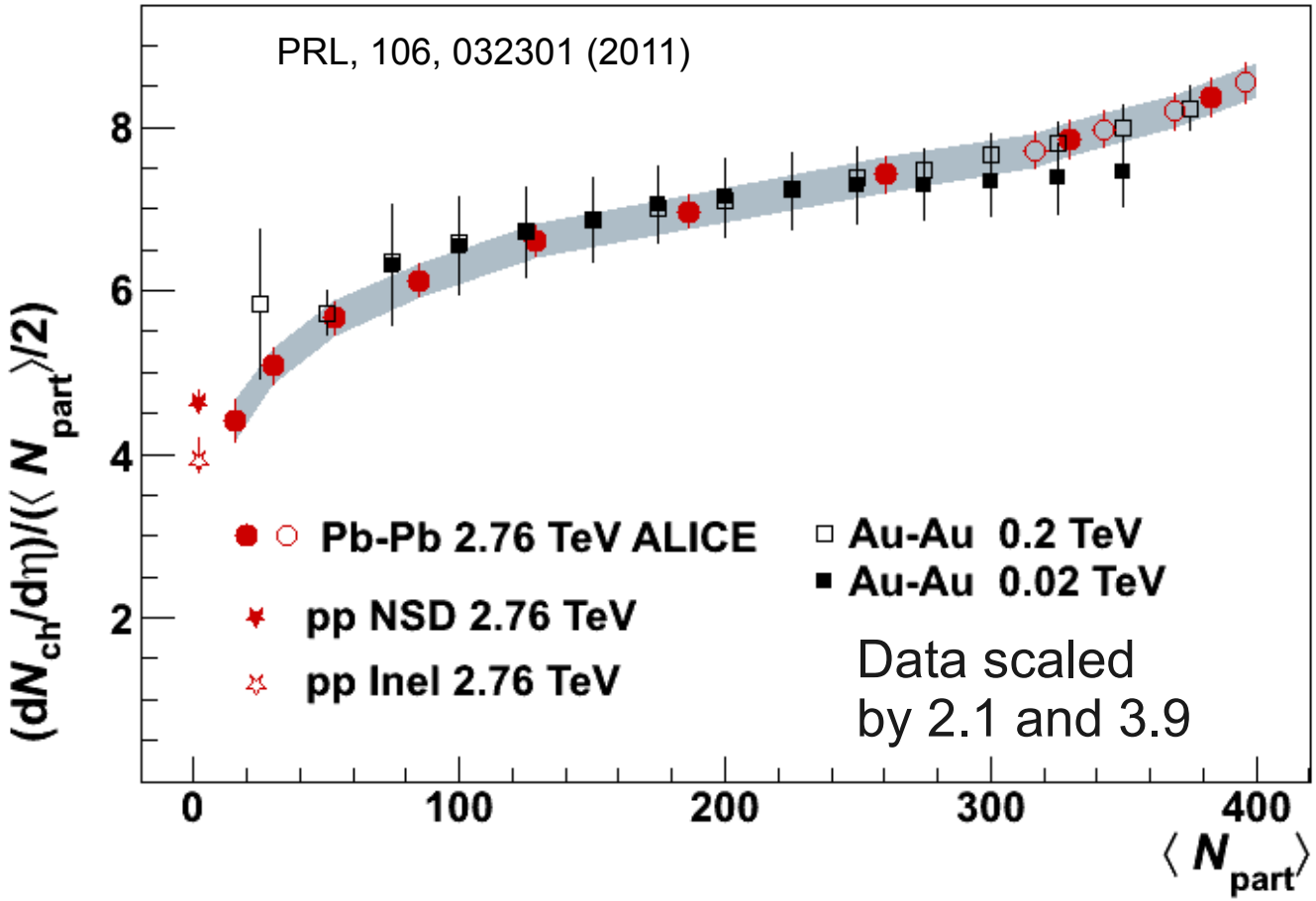


High temperature: Elliptic flow



Does the picture change at the LHC?

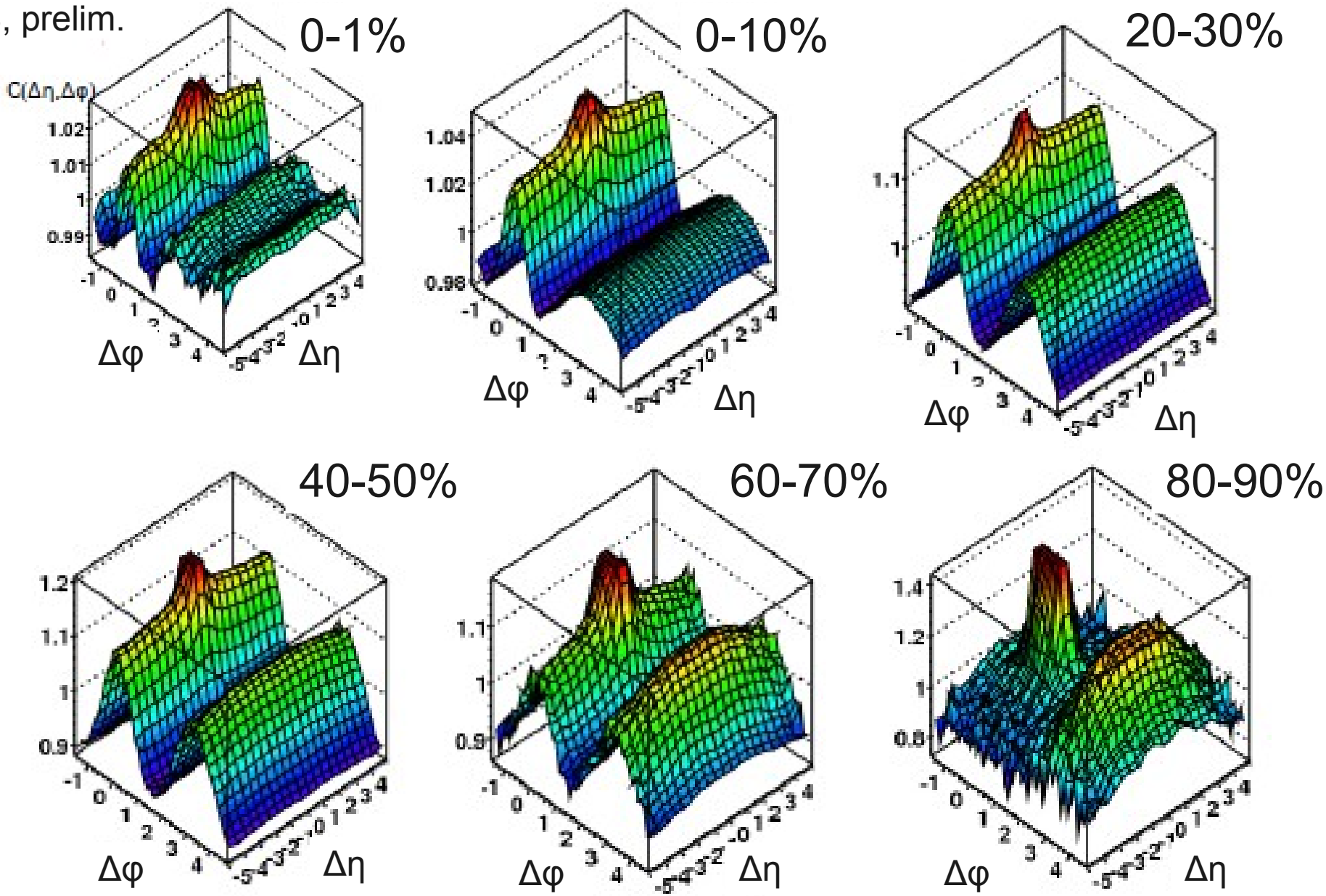
Pseudo-rapidity



Striking similarities between data over about two orders of collision energy. Factorization into energy and centrality.

Two-particle correlation landscape (LHC) 20

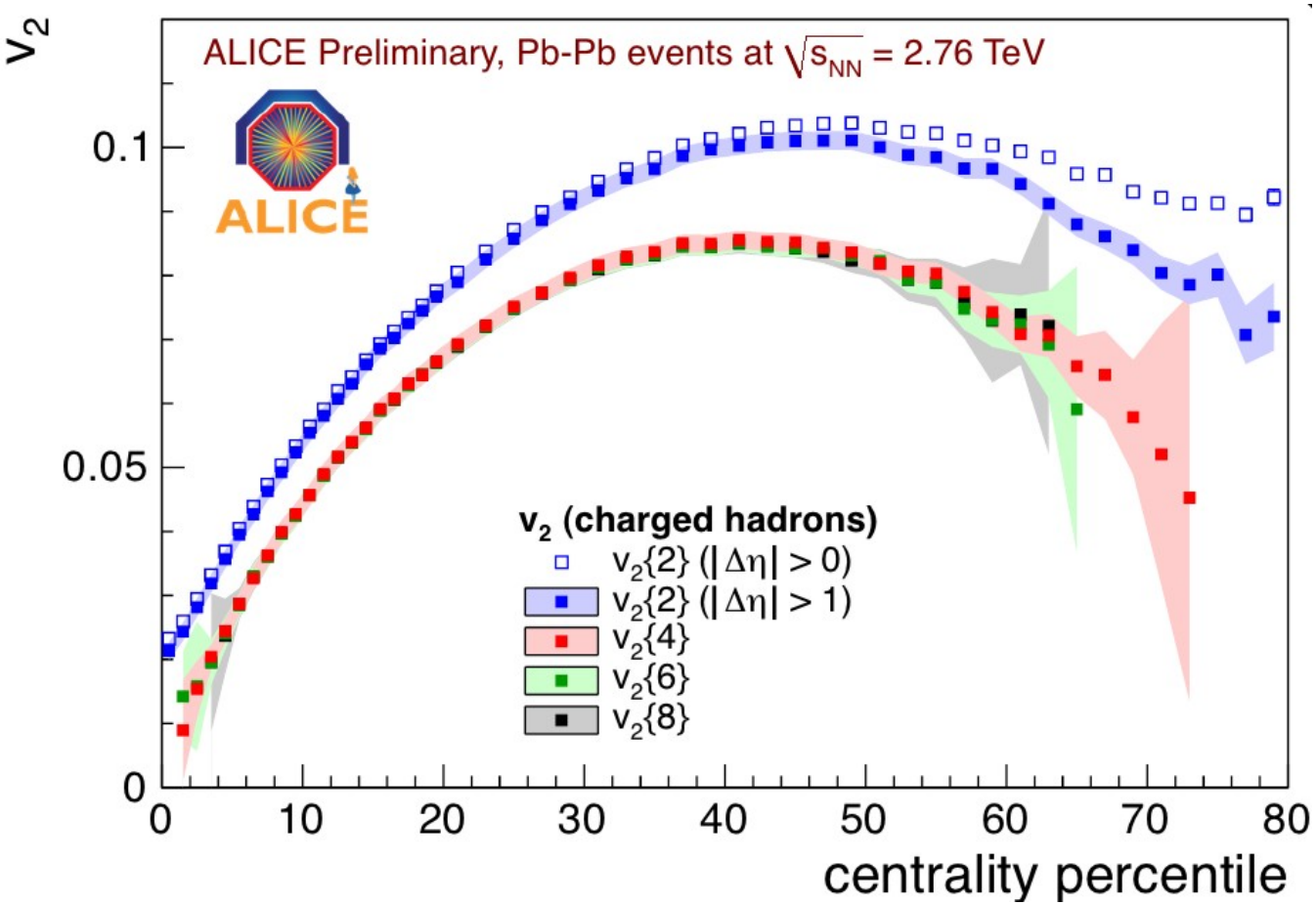
ATLAS, prelim.



$2<pt^{trigger}<pt^{associated}<3$ GeV/c

Multiparticle correlation studies (LHC)

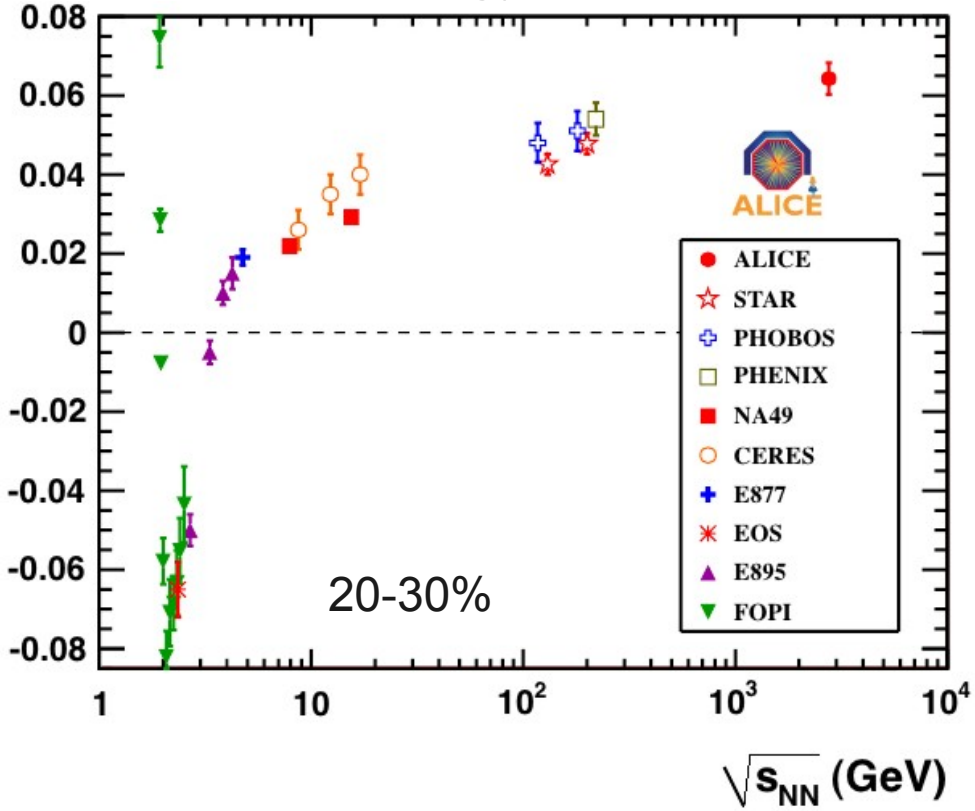
A.Bilandzic for ALICE, QM'11



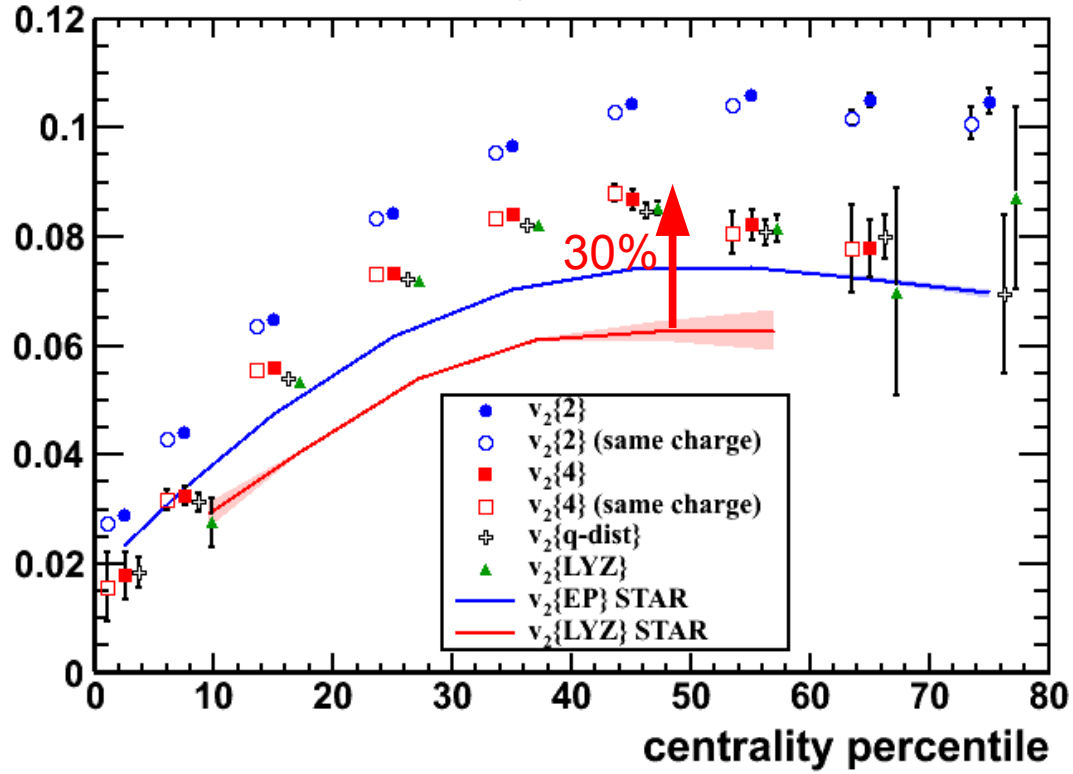
Multi-particle correlations (cumulant) studies extract the genuine multi-particle correlation

LHC “first day”: Elliptic flow

Collision energy dependence



Centrality dependence



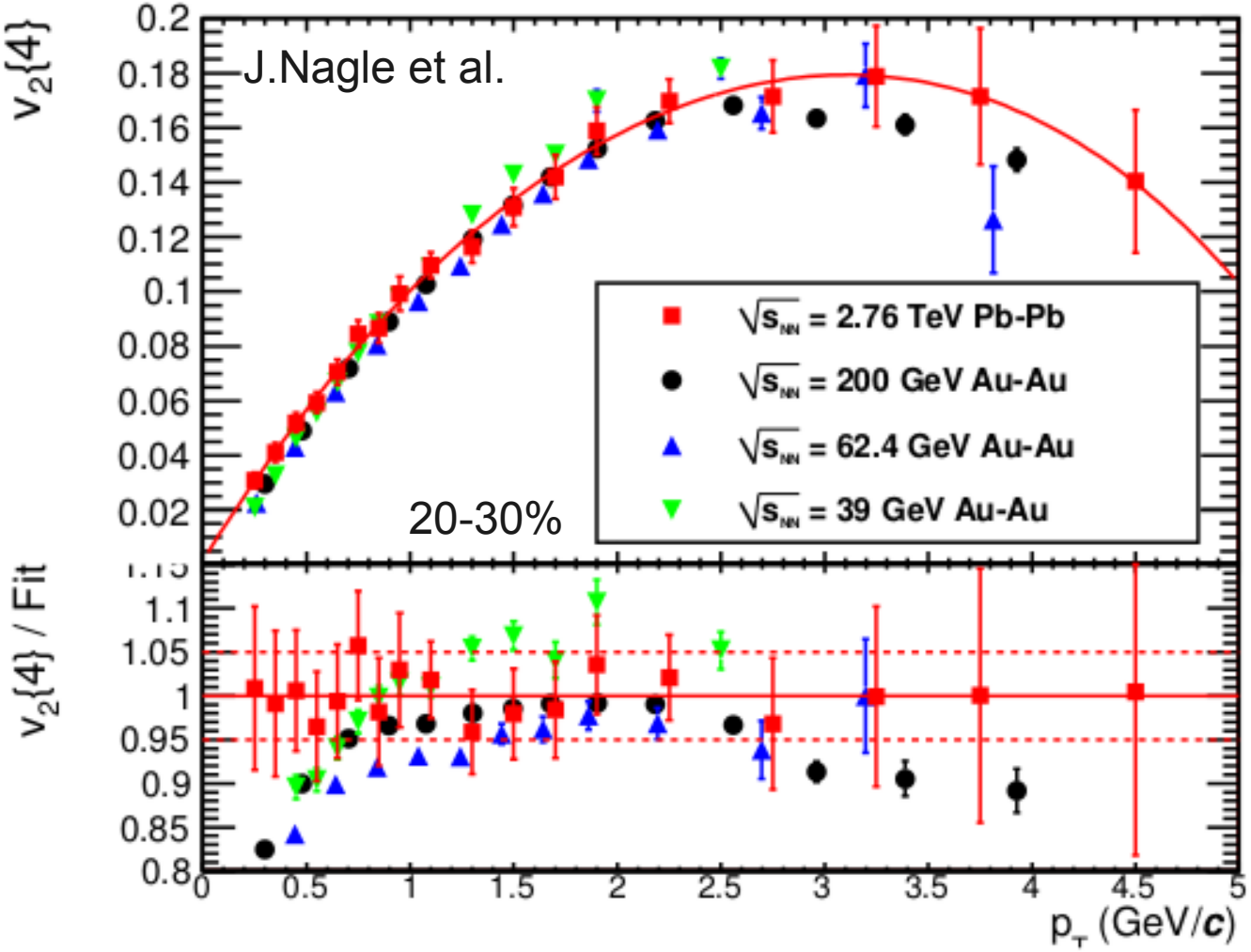
Integrated v_2: 30% increase from 0.2 TeV (STAR) to 2.76 TeV (ALICE)
Over all centrality classes, due to the increase of $\langle p_T \rangle$

No qualitative change in the observable at the LHC

PRL, 105, 252302 (2010), arXiv:1011.3914

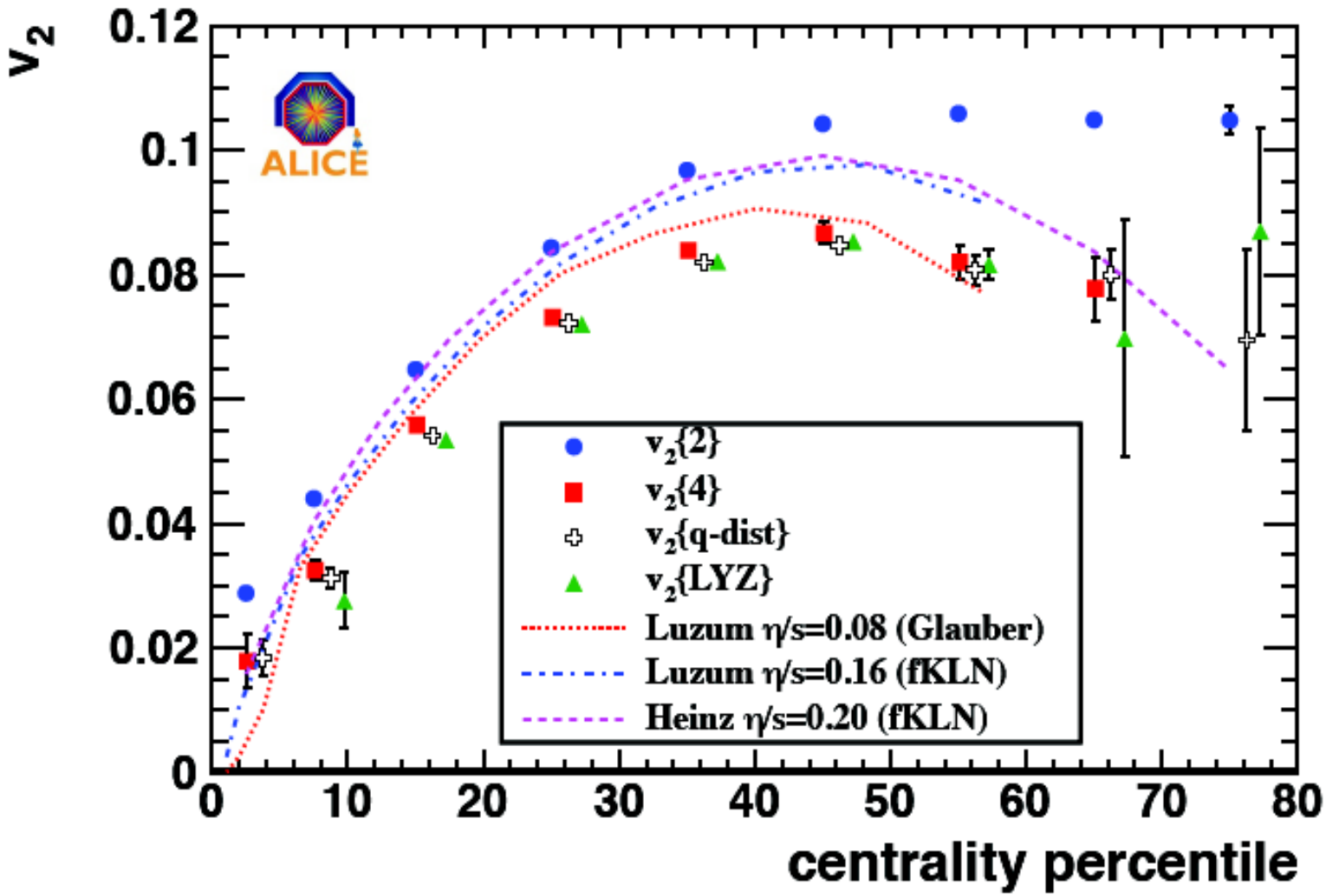
A closer look ...

Elliptic flow v2{4}



Remarkable precision across two systems and experiments.

Low viscosity fluid also at the LHC

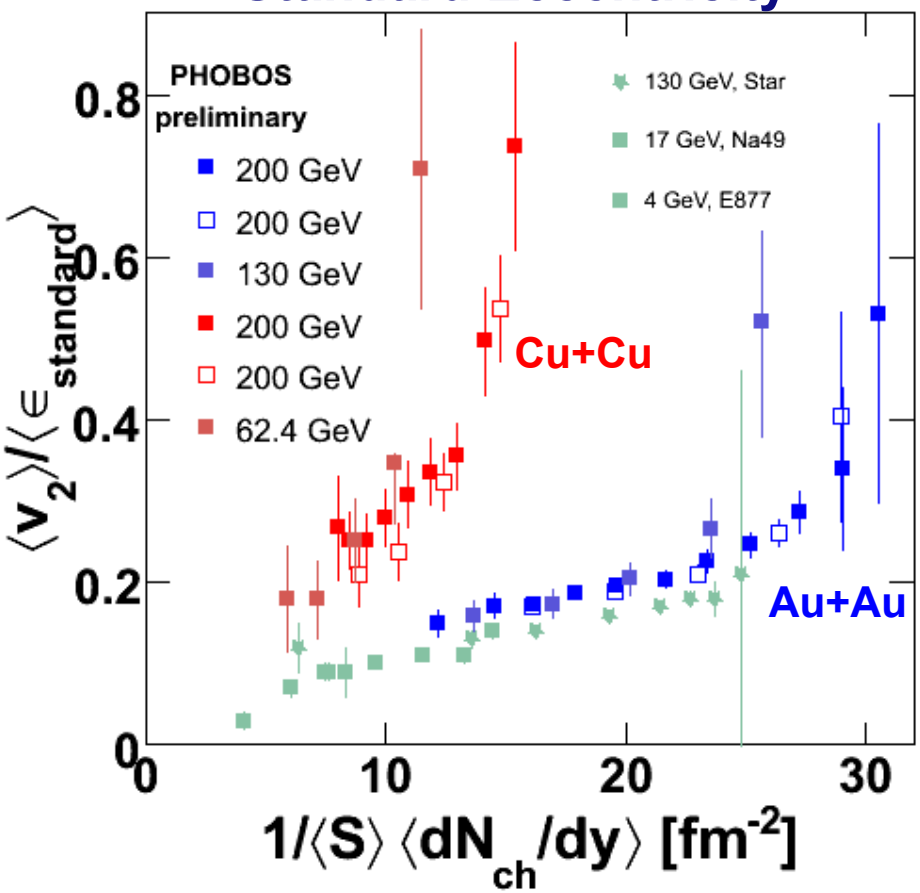


Calculation:
M.Luzum,
arXiv:1011.5173

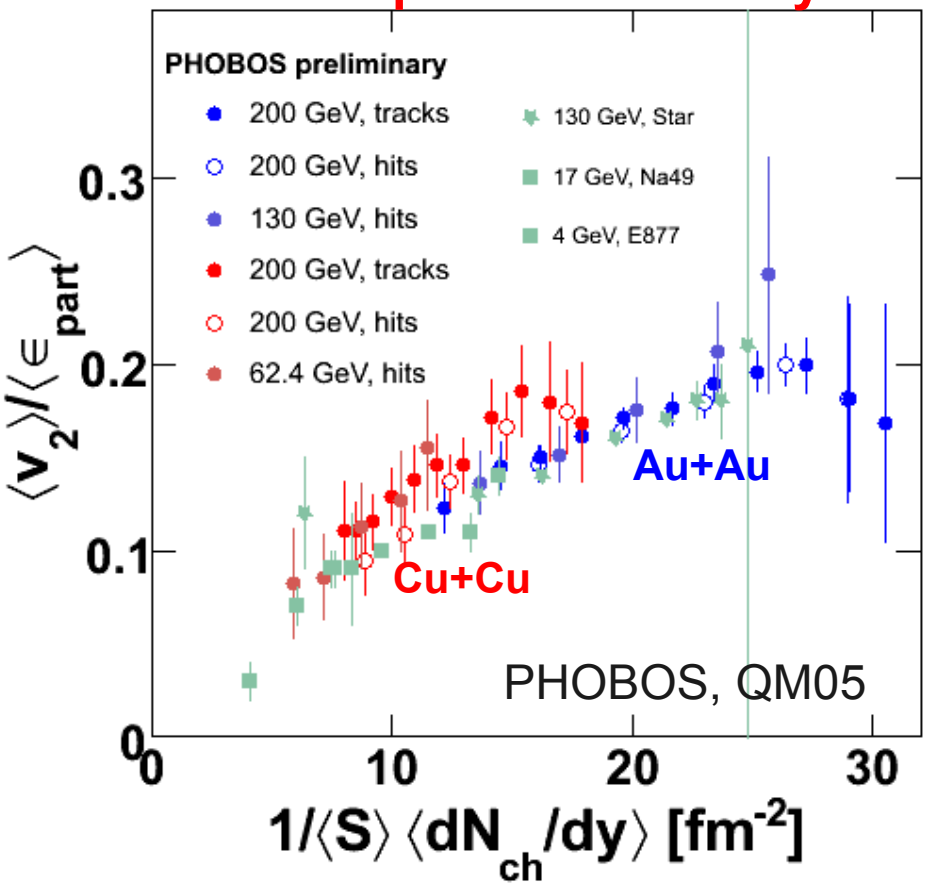
Increase well within the range of viscous hydro predictions

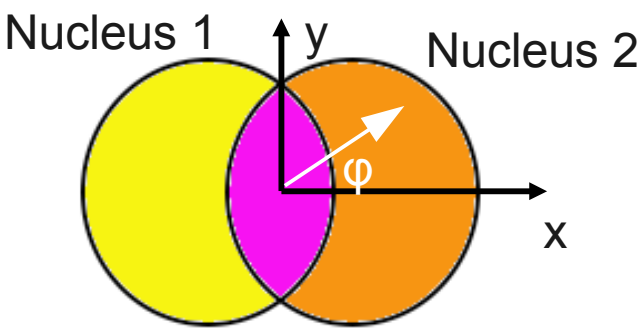
Importance of initial state fluctuations

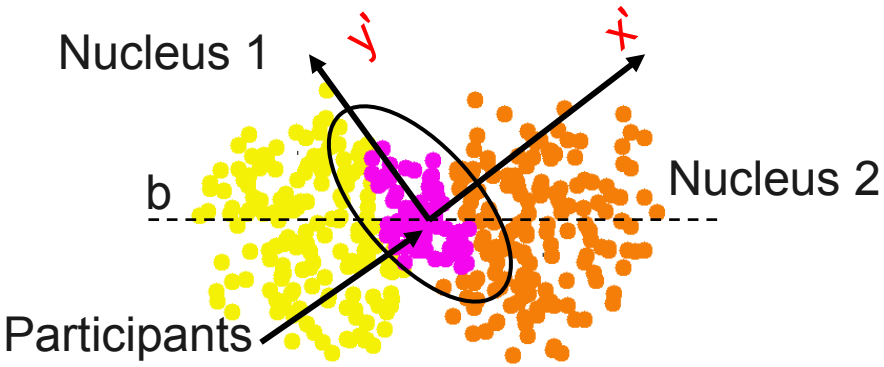
Standard Eccentricity



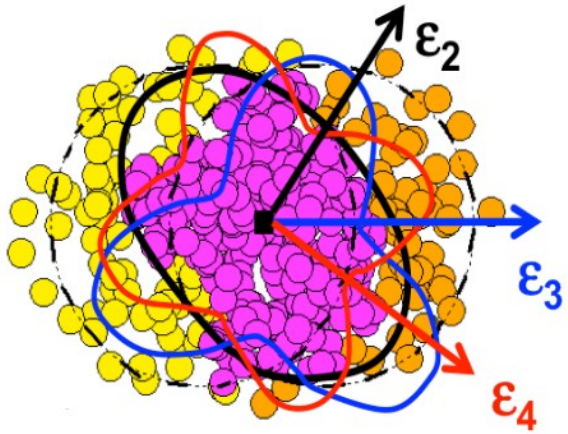
Participant Eccentricity





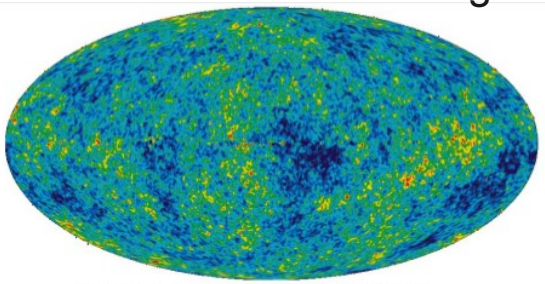


Higher azimuthal harmonics

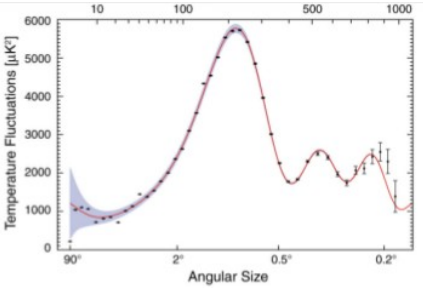


B.Alver, G.Roland
P.Sorenson

Analogous to power spectrum extracted
from cosmic microwave background radiation

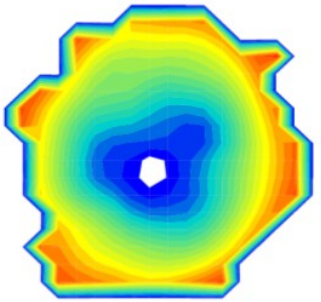


WMAP, Astrophys.J.Suppl.170:288,2007

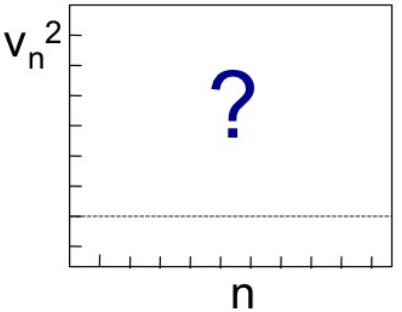


$$N_{pairs} \propto 1 + 2v_1^2 \cos \Delta\varphi + 2v_2^2 \cos 2\Delta\varphi + 2v_3^2 \cos 3\Delta\varphi + 2v_4^2 \cos 4\Delta\varphi + \ldots$$

Kowalski, Lappi and Venugopalan,
Phys.Rev.Lett. 100:022303



K. Werner, Iu. Karpenko, K.
Mikhailov, T. Pierog, arXiv:11043269

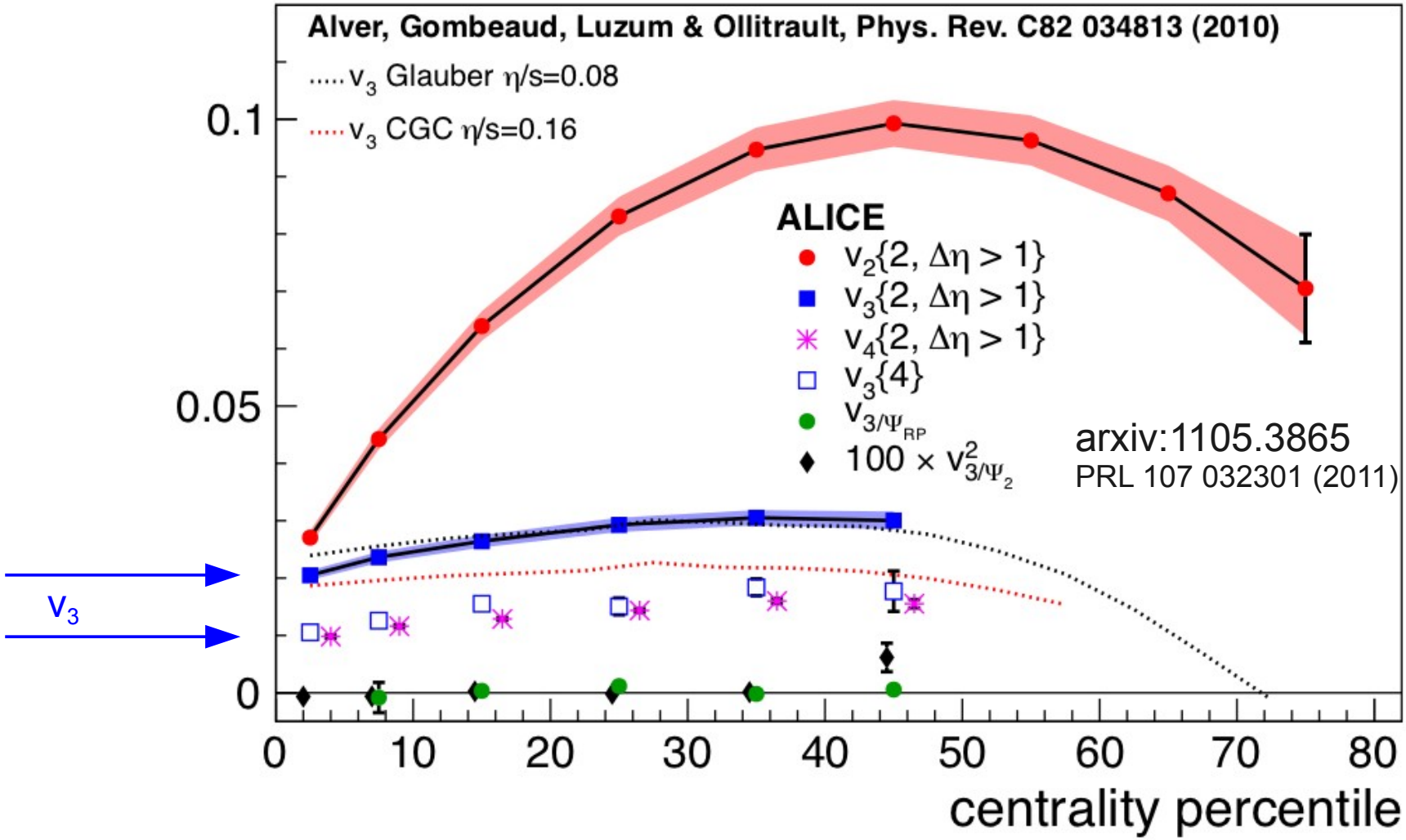


Initial spatial anisotropy not an almond, may lead
to higher harmonic anisotropies in the final state

$$\frac{dN}{d\phi} \sim 1 + 2v_2 \cos[2(\phi - \psi_2)] + 2v_3 \cos[3(\phi - \psi_3)] + 2v_4 \cos[4(\phi - \psi_4)] + 2v_5 \cos[5(\phi - \psi_5)] + \ldots$$

S.Mohapatra/
E.Appelt Mon 2K

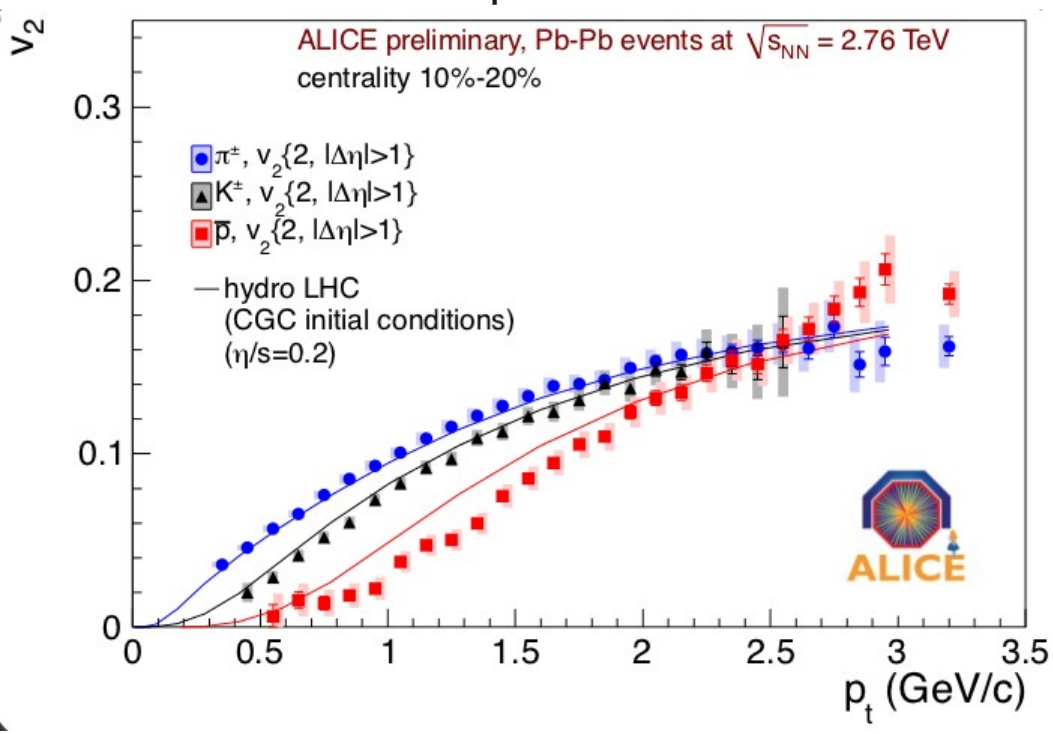
Triangular flow



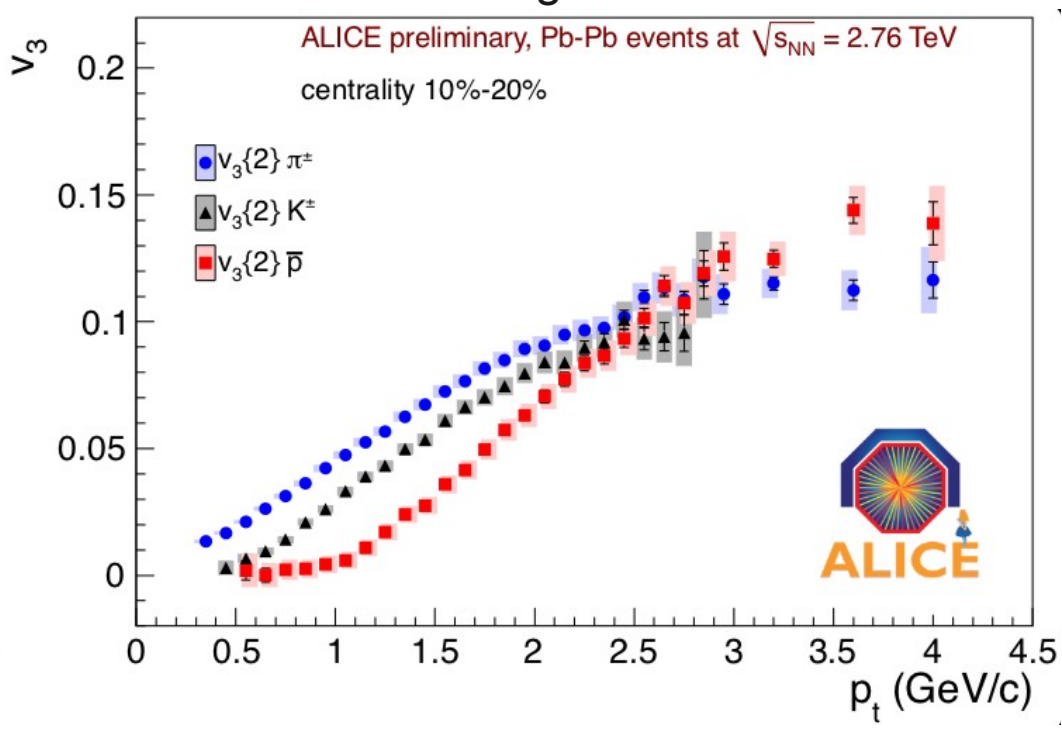
Sizeable triangular flow observed. As expected, centrality dependence is different to that of elliptic flow. Measurements vs reaction planes yield zero as it should if from fluctuations.

Common origin interpreted by hydro

Elliptic flow



Triangular flow

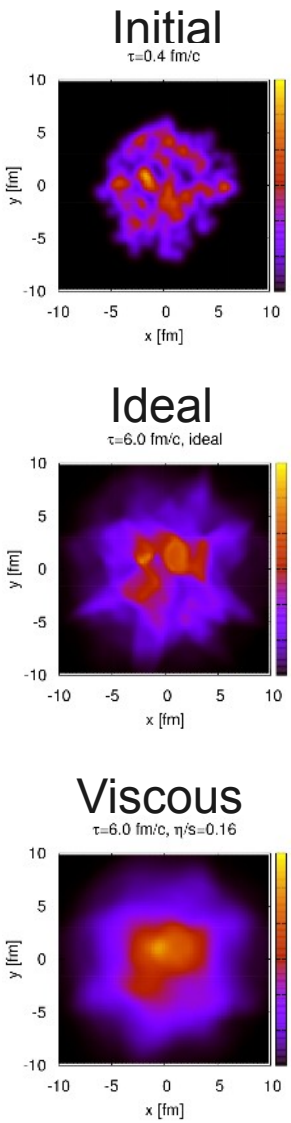


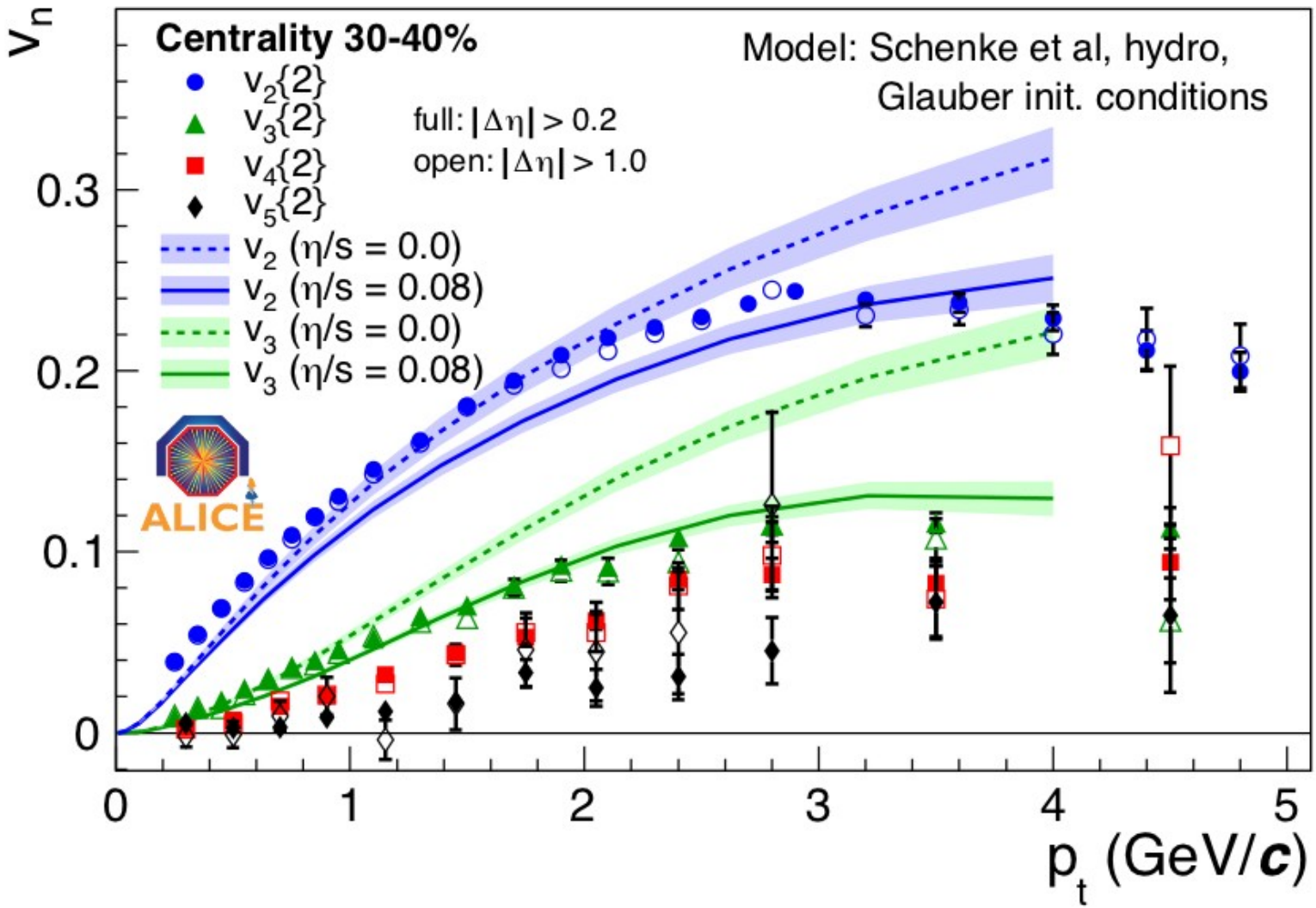
Same mass splitting for v_3 as predicted for v_2 by hydro.

(Note also that the crossing between (anti-) protons and pions happens at the same p_T which for v2 was considered a sign of recombination.)

Hydro: Shen et al., arxiv:1105.3226 (no afterburner)

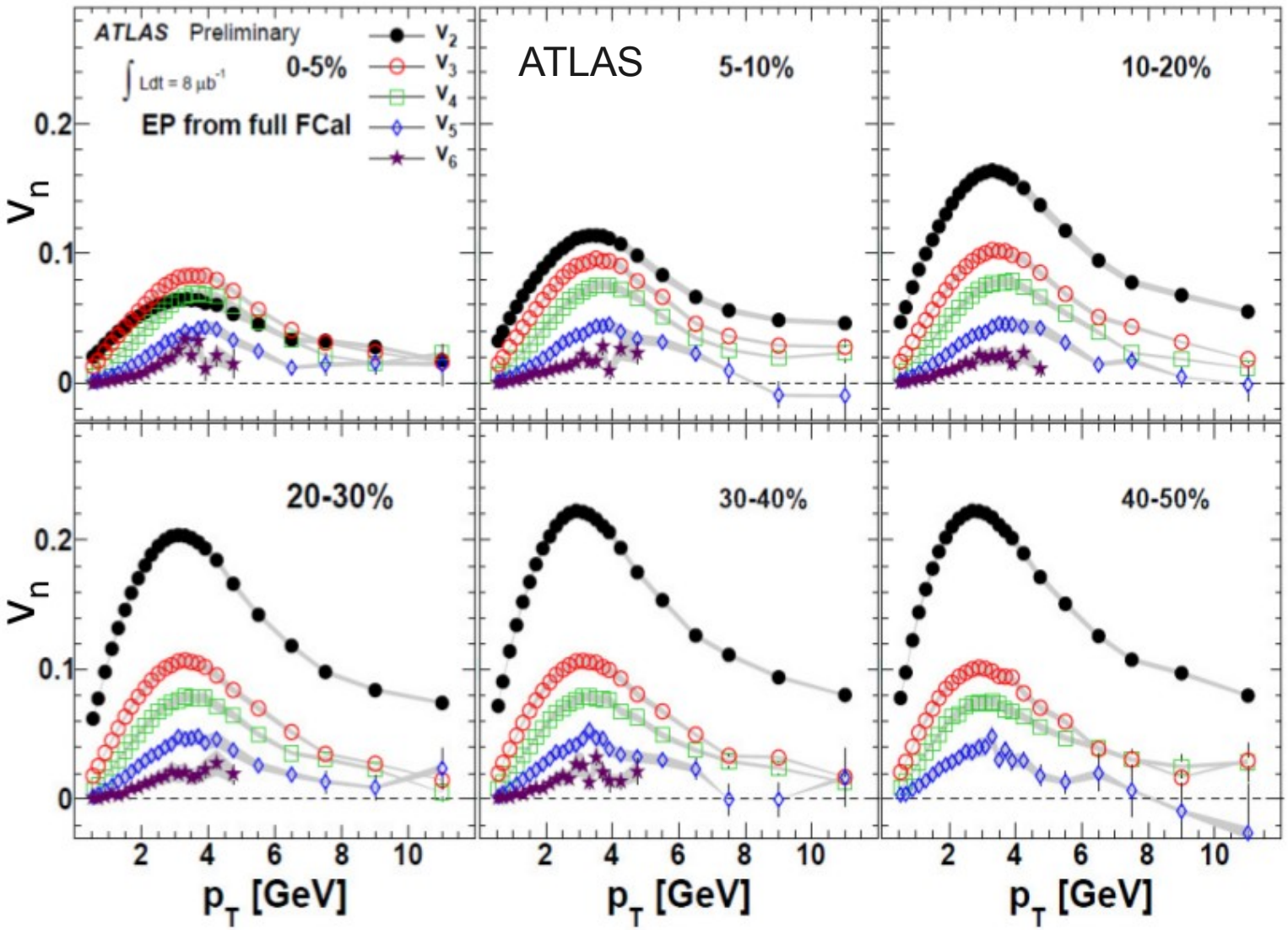
Fluctuations, viscosity and e-by-e hydro





The overall dependence of v_2 and v_3 is described. However, not yet for a single η/s value. More constraints on initial conditions provided by v_3 and higher harmonics.

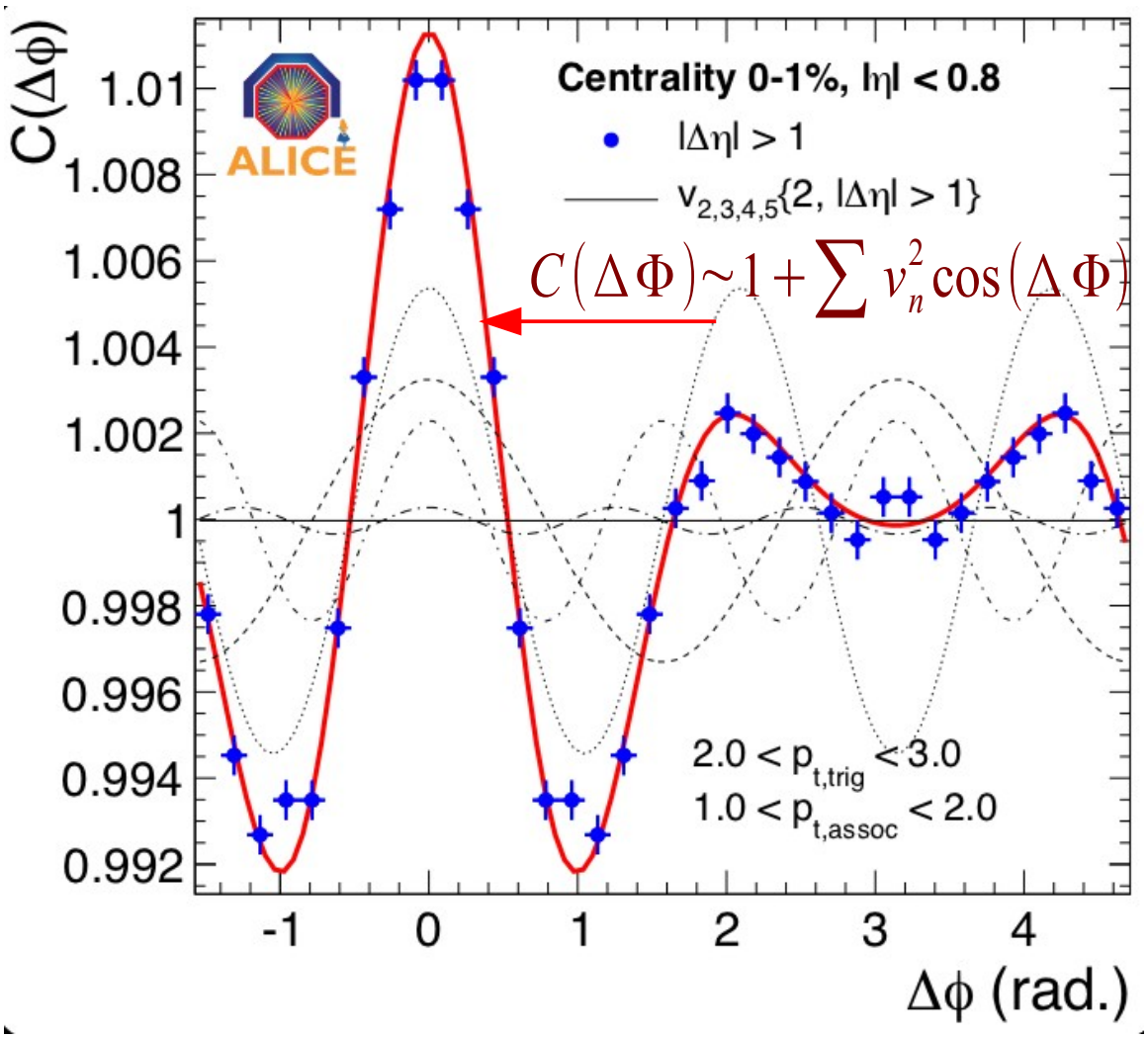
Many higher moments measured



Higher moments are measured up to v_6. Power spectrum of QGP. (Results by all collaborations at RHIC/LHC.)

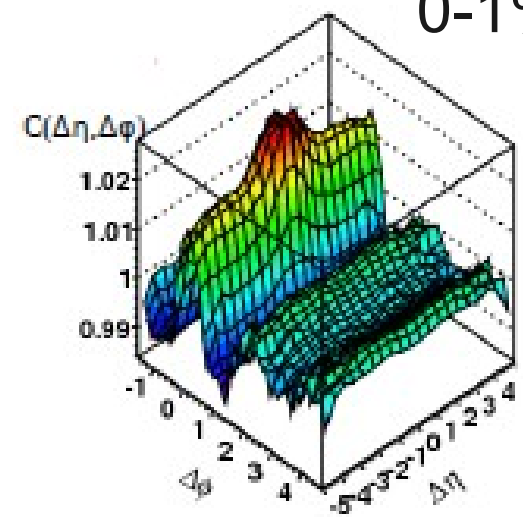
Two particle angular correlations

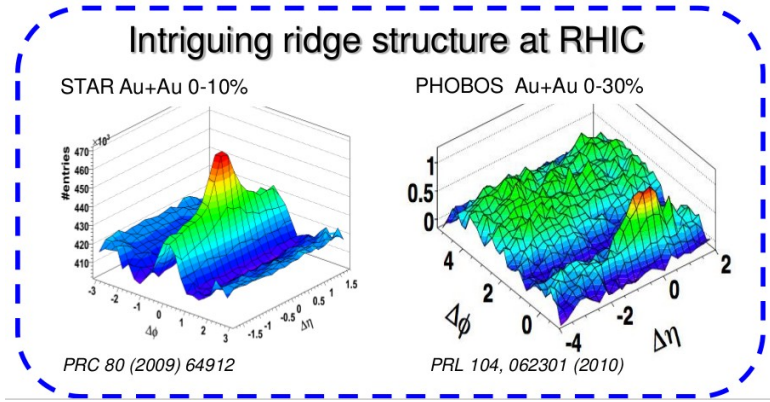
arxiv:1105.3865, PRL 107 032301 (2011)



$$C(\Delta\Phi) \sim 1 + \sum v_n^2 \cos(\Delta\Phi)$$

0-1%





Structures seen in two particle correlations (reported mainly at RHIC) are naturally explained by measured anisotropic flow coefficients.

Where does the decomposition break? 32

$$\frac{dN^{pairs}}{d\Delta\phi} \propto 1 + \sum_n 2V_{n\Delta}(p_T^t, p_T^a)\cos(n\Delta\phi)$$

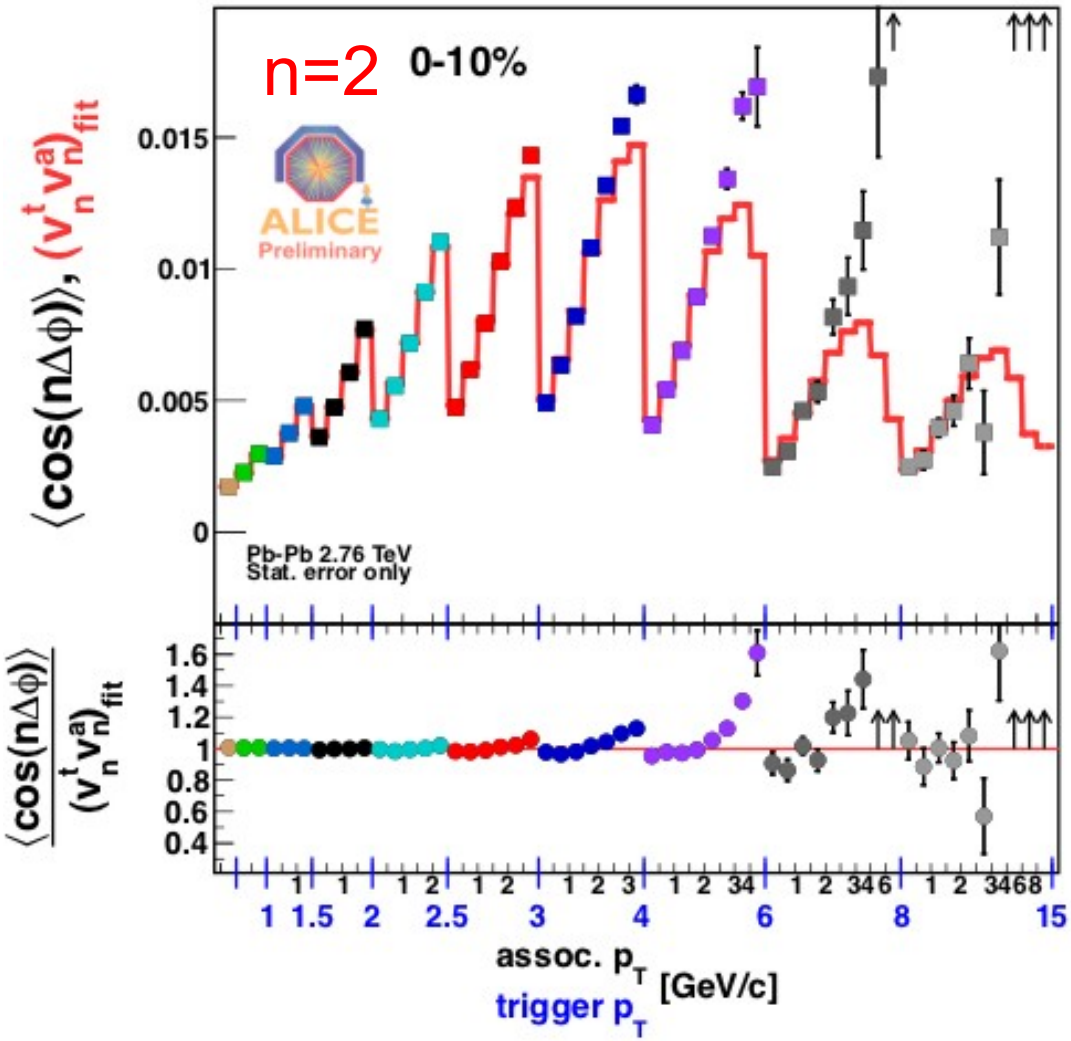
$$\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n(p_T)\cos(n(\phi - \Psi_n))$$

If bulk flow then:

$$V_{n\Delta}(p_T^t, p_T^a) = v_n(p_T^t)\, v_n(p_T^a)$$

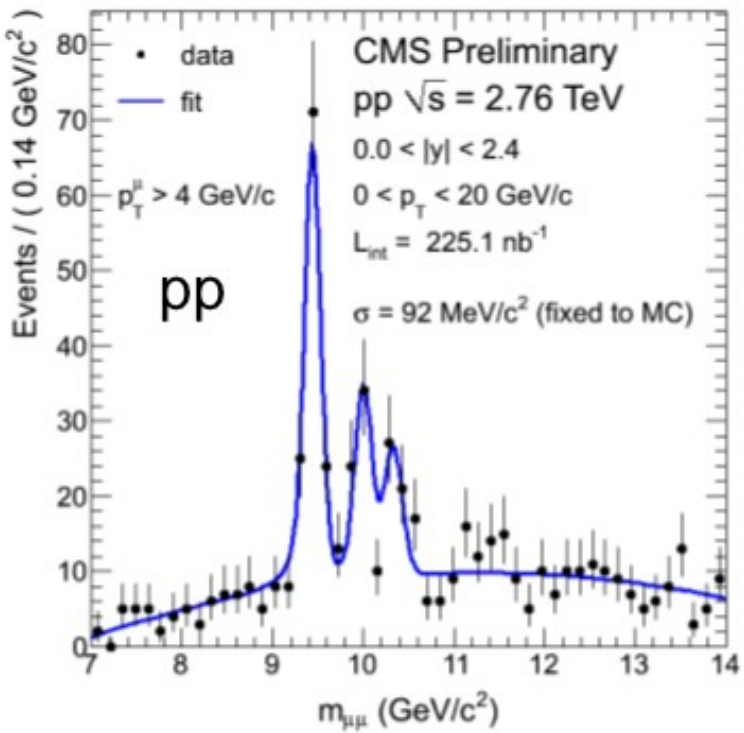
Perform global fit for each harmonics

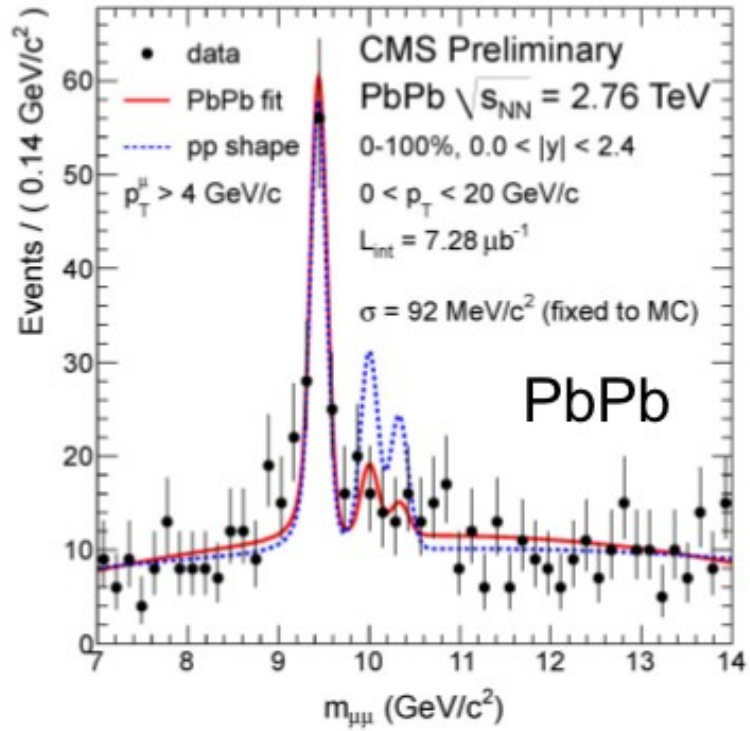
A.Adare for ALICE, QM'11



Two particle correlations are well described via bulk flow decomposition up to about 4 GeV. Similar for other harmonics (except v_1). Challenge the jet heating picture (next talk)?

Melting of Upsilon (2S,3S)





$$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$$

$$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

Direct access to the deconfined matter state? Stay tuned
Melting temperatures from the lattice are about 1.2 and 1.6 Tc.

M.Calderon, Mon 1L

Summary

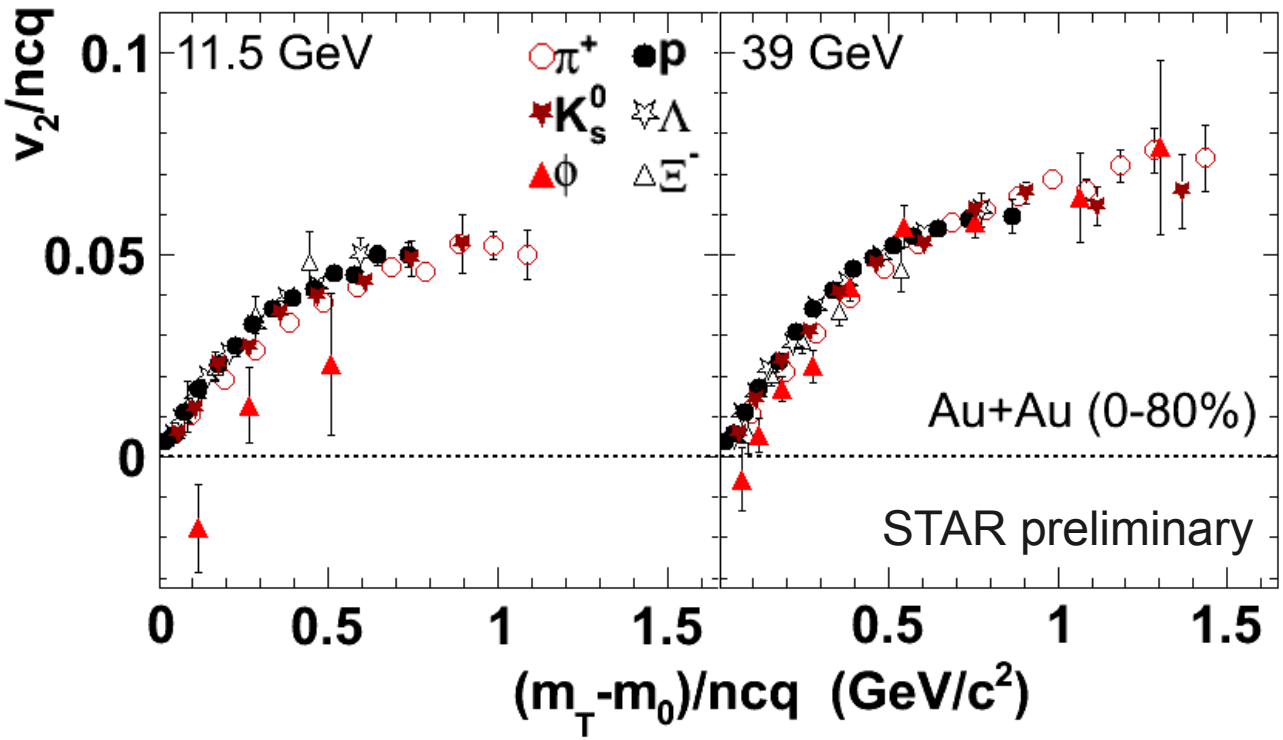
- Exciting and stimulating time in our field with fruitful interplay of heavy-ion experiments at RHIC and LHC.
  - Characterization of LHC bulk properties well underway
    - No big picture changes (unlike the transition from SPS to RHIC)
  - Also first results from beam-energy scan (not discussed)
- Tremendous progress in the measurement of the QGP viscosity
  - The most perfect known fluids are the coldest and the hottest
  - QGP power spectrum (Vn) from fluctuations extracted
    - Expected to provide further constraints on η/s
  - Too early to conclude about precise value of η/s at the LHC

Special thanks to ALICE, ATLAS, CMD, STAR+PHENIX collaborations for their exiting new results and apologies to what I could have not shown for space-time restrictions.

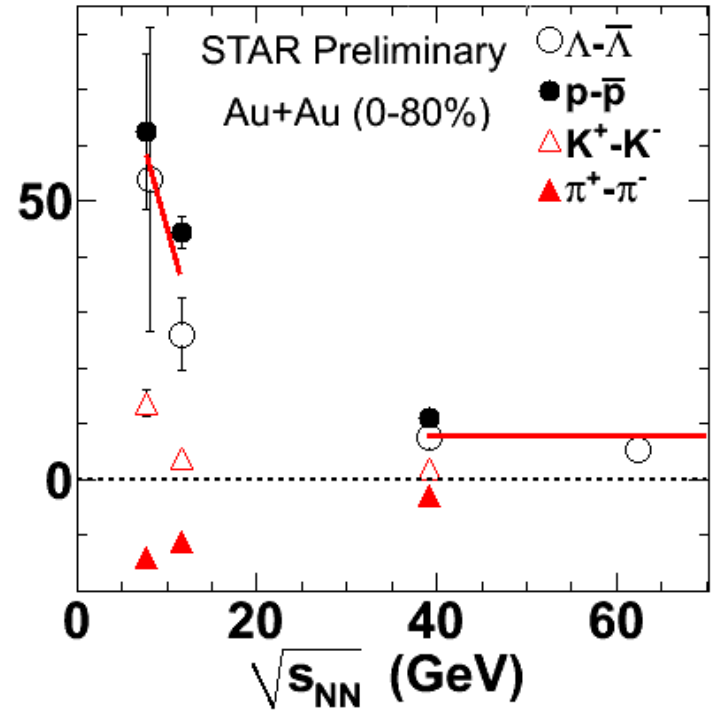
Extra

Number of quark scaling (Beam-Scan)

v_2 scaled with number of quark

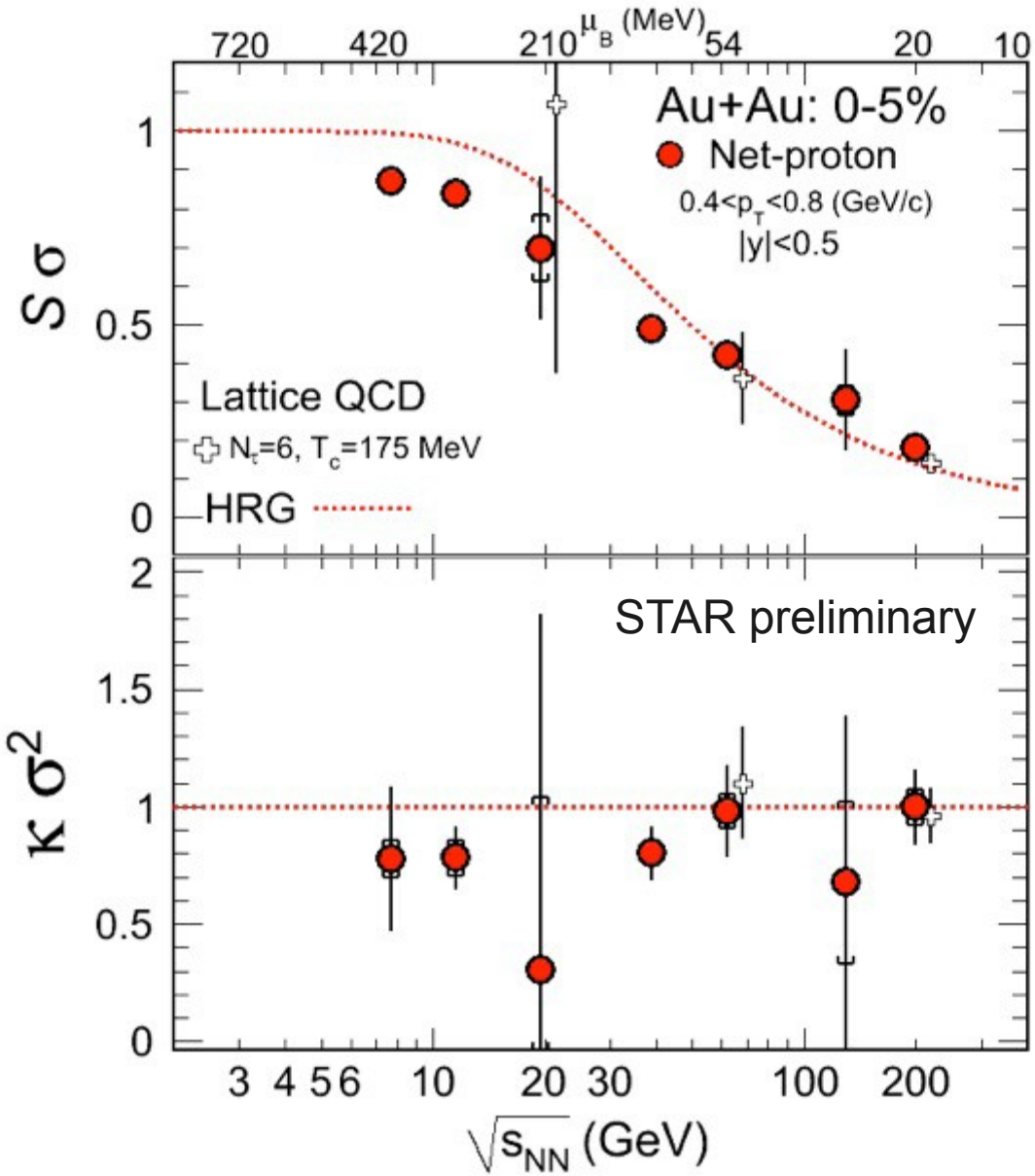


$[v_2^p - v_2^{\bar{p}}]/v_2^p$,%



- v_2 of ϕ meson does not follow the trend for other hadrons at 11.5 GeV
- Significant difference between baryon/anti-baryon v_2 @ 7.7&11.5 GeV
  No scaling between particles and anti-particles

Higher moments (Beam Scan)



Moments of net proton distribution (χ):

1st - mean, 2nd - variance (σ^2)

3rd - skewness (S), 4th - kurtosis (k)

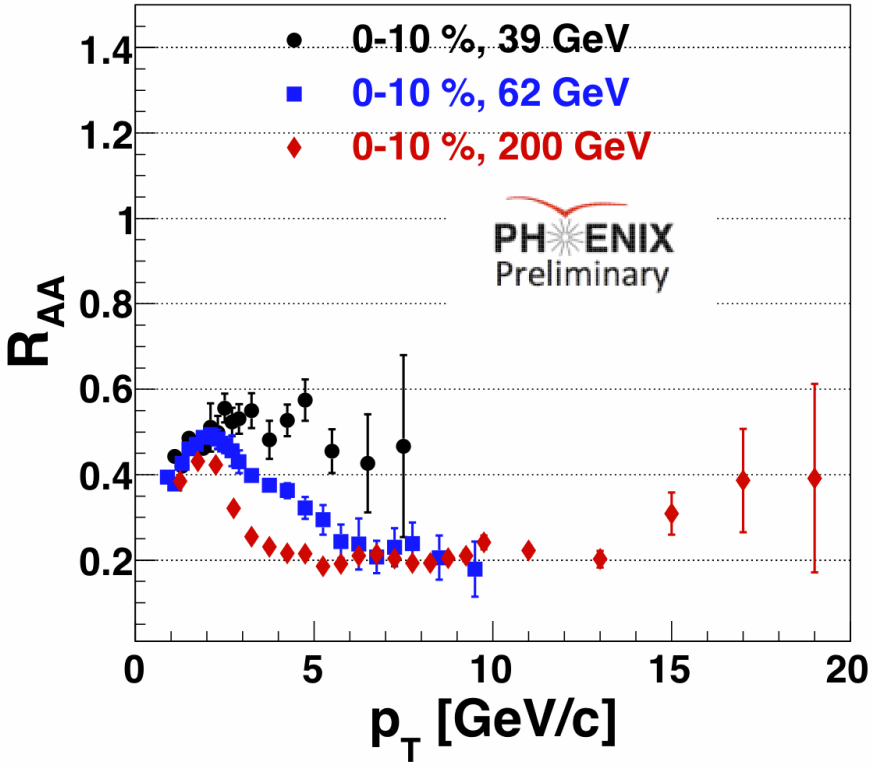
- Connected to hydrodynamic susceptibilities
- Sensitive to the correlation length of the system

$$S\sigma = \chi^{(3)}/\chi^{(2)} \qquad k\sigma^2 = \chi^{(4)}/\chi^{(2)}$$

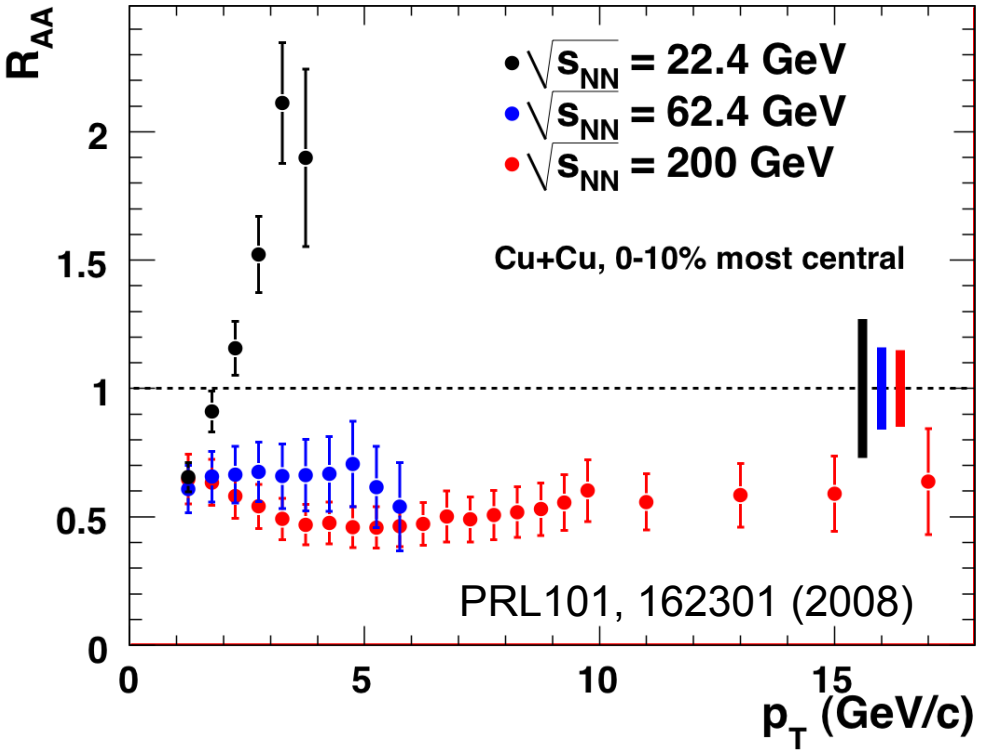
- Consistent with Lattice QCD and Hadron Resonance Gas (HRG) model at higher energies
- Deviates from HRG below 39 GeV

Change in R_{AA} between 22.4 and 39 GeV

Neutral pion R_{AA}

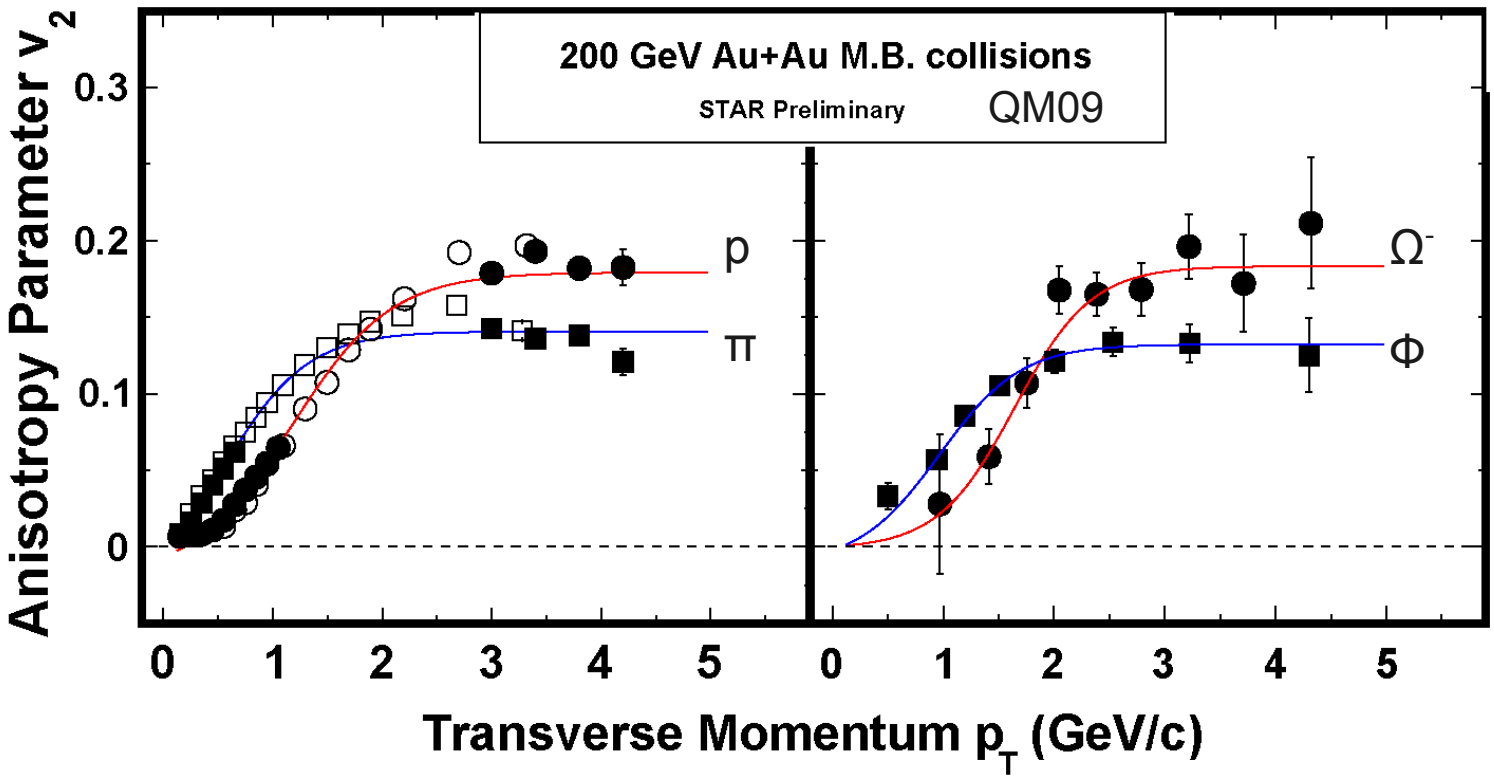


PHENIX Collaboration



- Suppression p_t > 3 GeV/c consistent with parton energy loss at 62.4, 200 GeV:
- No suppression at 22.4 GeV
  Enhancement consistent with Cronin enhancement
- Some hints from Beam Energy Scan program at RHIC on critical points between 7 and 20 GeV - **stay tuned!**

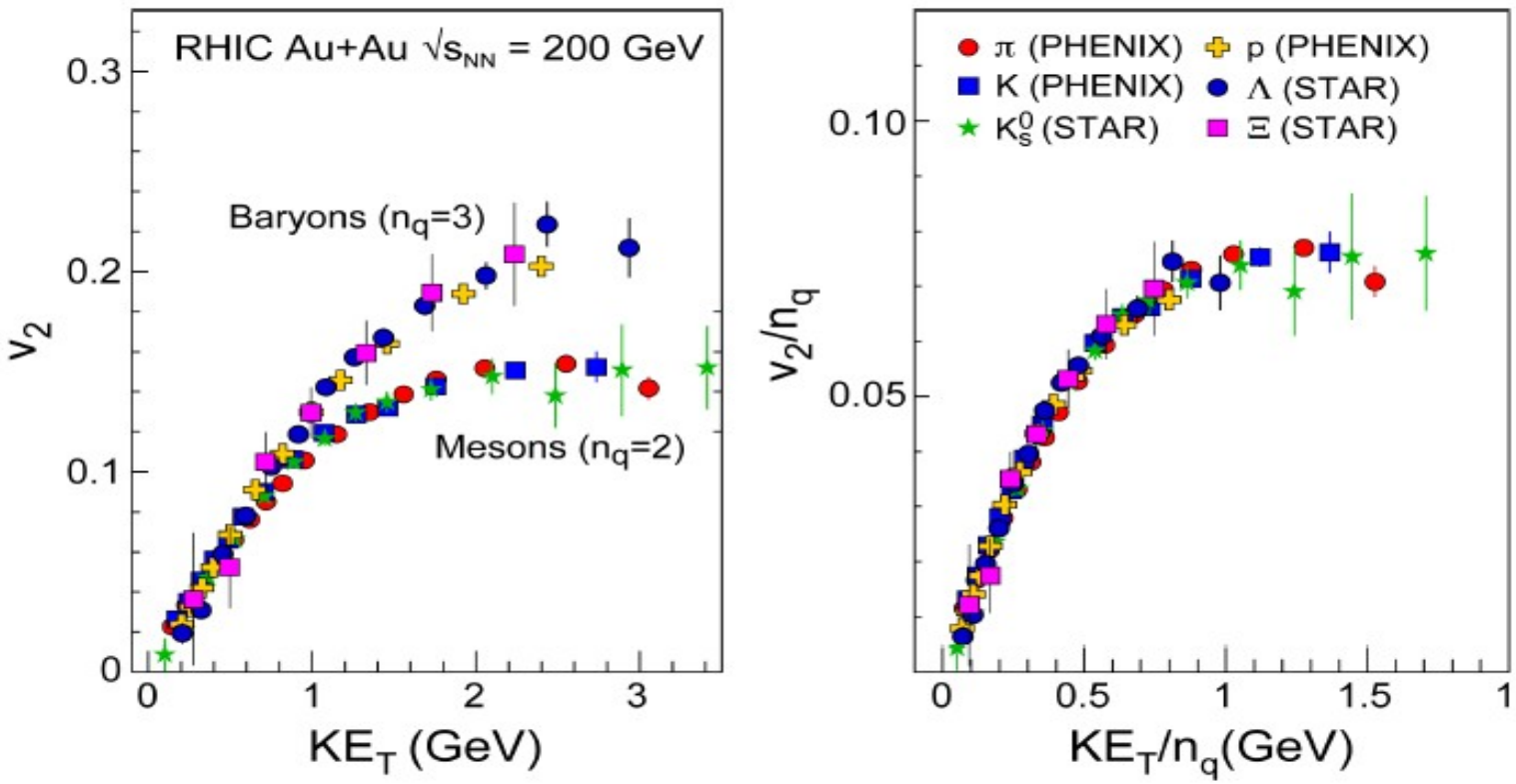
Even heaviest particles flow



Partonic collectivity at RHIC:
Heavy multi-strange particles flow as protons and pions

PHENIX π and p: nucl-ex/0604011v1
NQ inspired fit: X. Dong et al. PLB 597 328 (2004)

Constituent quark scaling



All particles flow as if frozen out from a flowing soup of constituent quarks.

PHENIX, PRL 98 162301 (2007)

Flow methods

Two-particle cumulant

$$v\{2\}=\sqrt{\langle\cos(\phi_1-\phi_2)\rangle}$$

Measures:

$$v\{2\}^2=\langle v\rangle^2+\sigma_{v_2}^2+\delta$$

$$v\gg 1/\sqrt{M}$$

Four-particle cumulant

$$v\{4\}=\left(2\langle\cos(\phi_1-\phi_2)\rangle^2-\langle\cos(\phi_1+\phi_2-\phi_3-\phi_4)\rangle\right)^{1/4}$$

Measures:

$$v\{4\}^2=\langle v\rangle^2-\sigma_{v_2}^2$$

$$v\gg 1/M^{3/4}$$

$$v\{\mathrm{subEP}\}=\frac{\langle\cos(\phi-\psi_A)\rangle}{R}$$

$$R=\sqrt{\langle\cos(\psi_A-\psi_B)\rangle}$$

Measures:

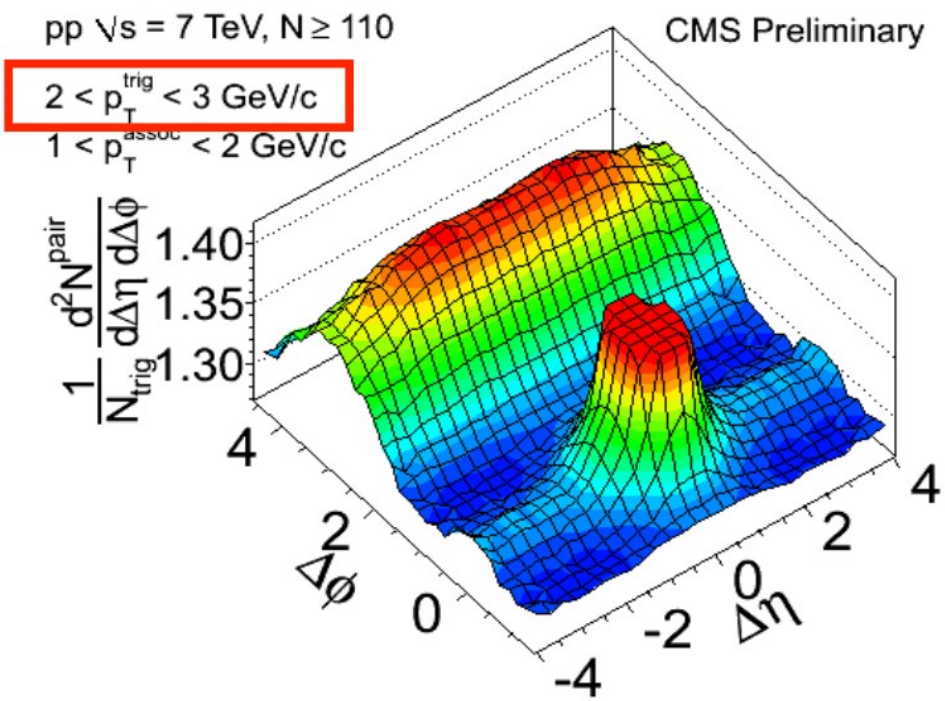
$$v\{\mathrm{subEP}\}^2=\langle v\rangle^2+\left(1-f(R)\right)\sigma_{v_2}^2+\left(1-2f(R)\right)\delta$$

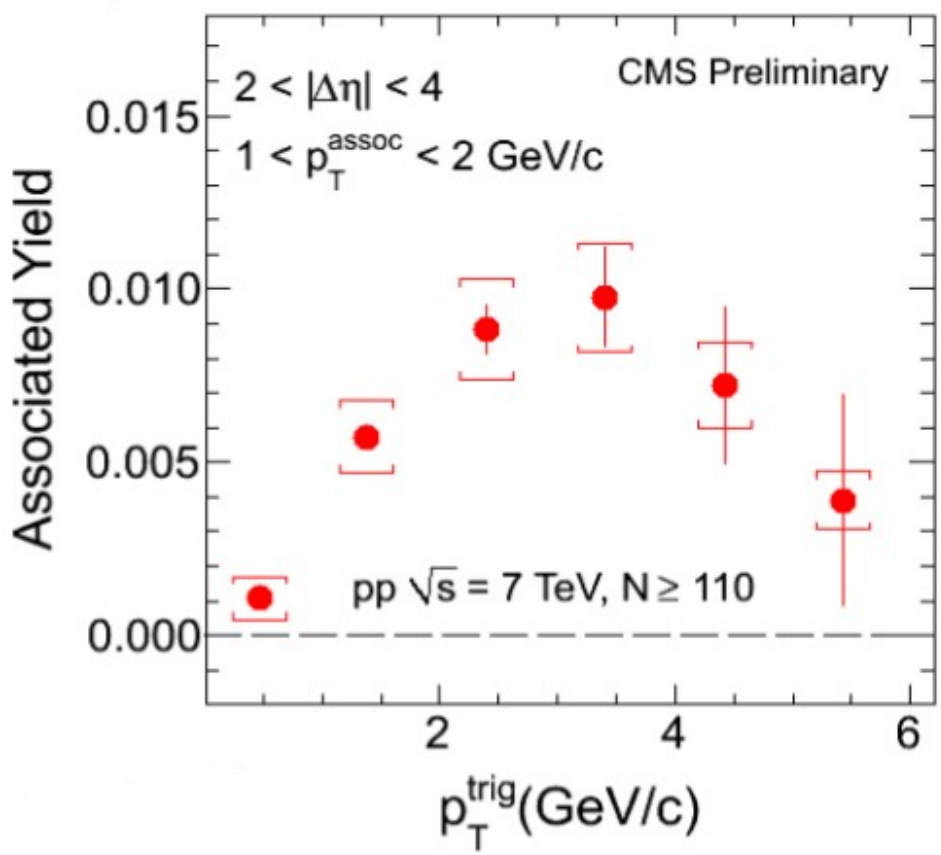
NB: For simplicity, n (as index and in cos terms) dropped

Ollitrault, Poskanzer, Voloshin
PRC 80 80 014904 (2009)

Ridge in high-multiplicity p+p at LHC

Zero-Yield-At-Minimum in ridge region

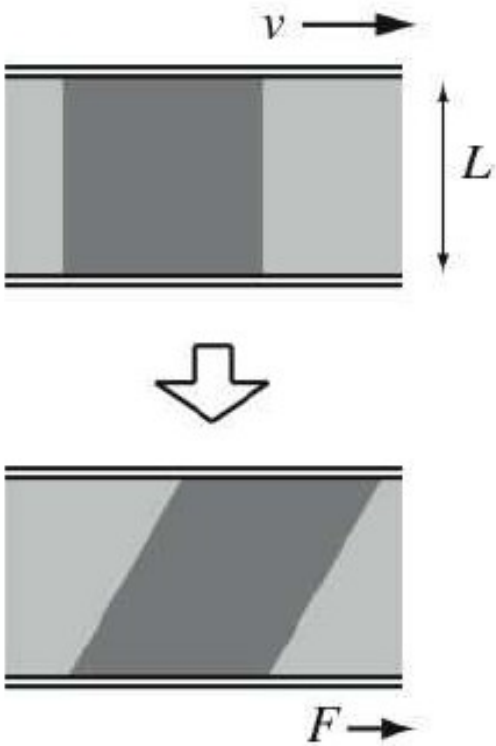


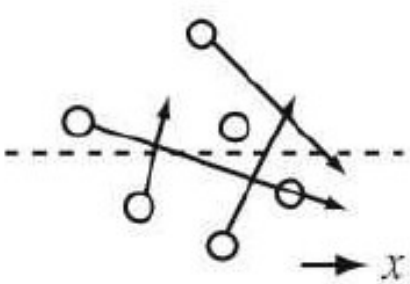


Observation of ridge in high density proton-proton collisions

W.Li, Session 1L

Shear viscosity in fluids





Shear viscosity characterizes the efficiency of momentum transport

$$\frac{F}{A} = \eta \frac{v}{L}$$

$$\eta = \rho \langle v \rangle \lambda_{mfp} \sim \frac{1}{\sigma}$$

quasi-particle interaction cross section

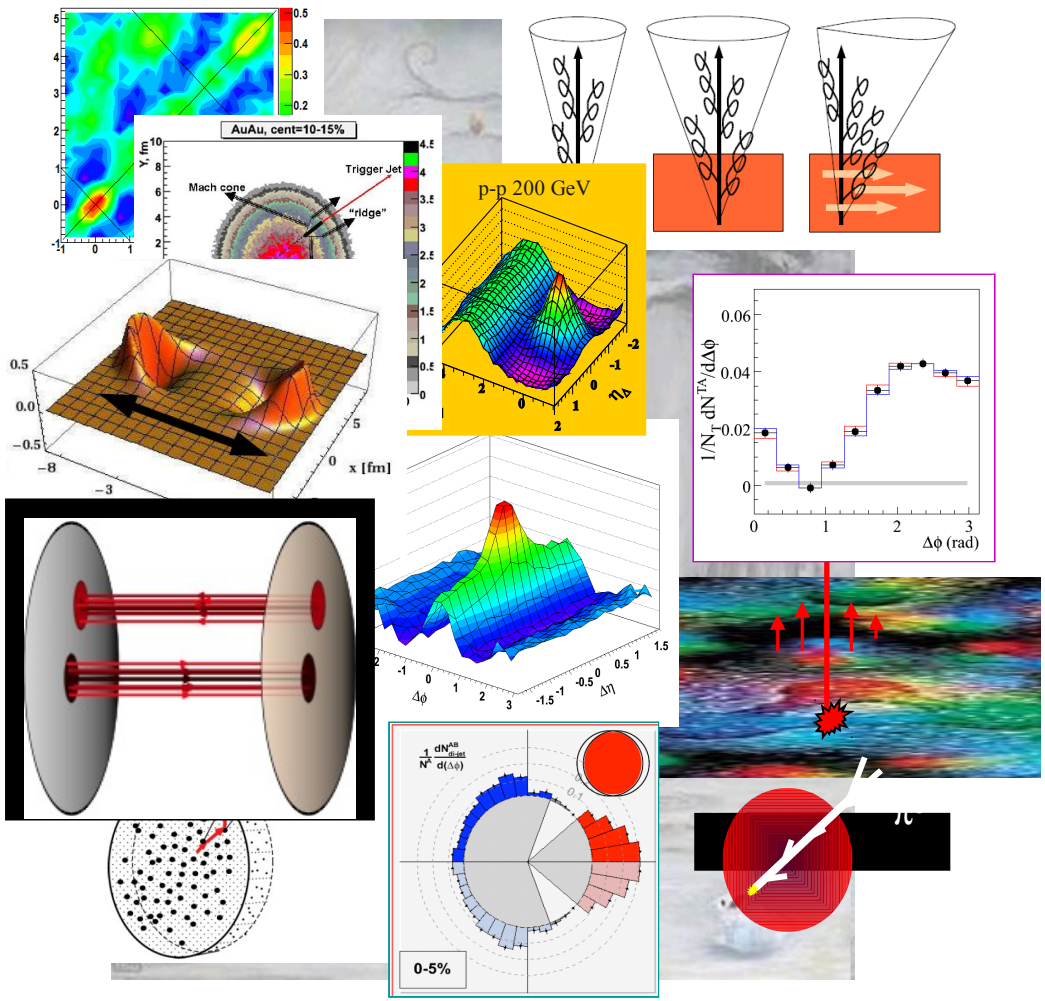
Comparing relativistic fluids: η/s

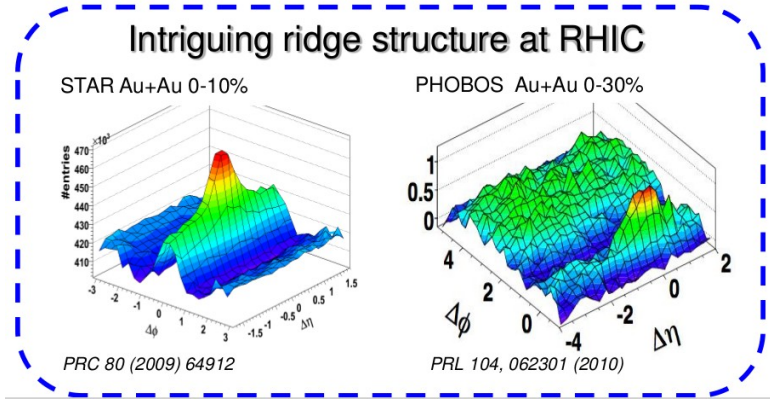
- s = entropy density
- scaling param. η/s emerges from relativistic hydro eqns.
- generalization for non-rel. fluids: η/w (w=enthalpy) (Liao and Koch, Phys.Rev. C81 (2010) 014902)

Large σ ➔small η/s
➔Strongly-coupled matter
➔"perfect liquid"

“Death of the Mach cone and the ridge” 44

Dozen's of models

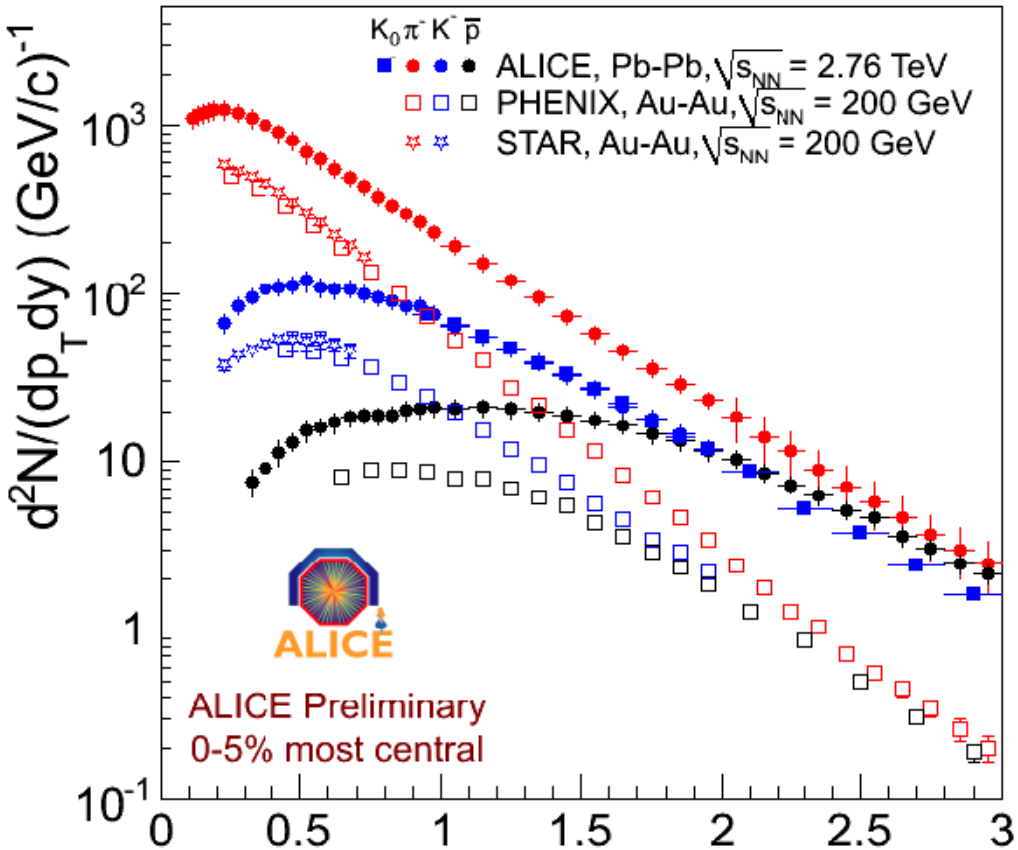




Structures seen in two particle correlations (reported mainly at RHIC) are naturally explained by measured anisotropic flow coefficients.

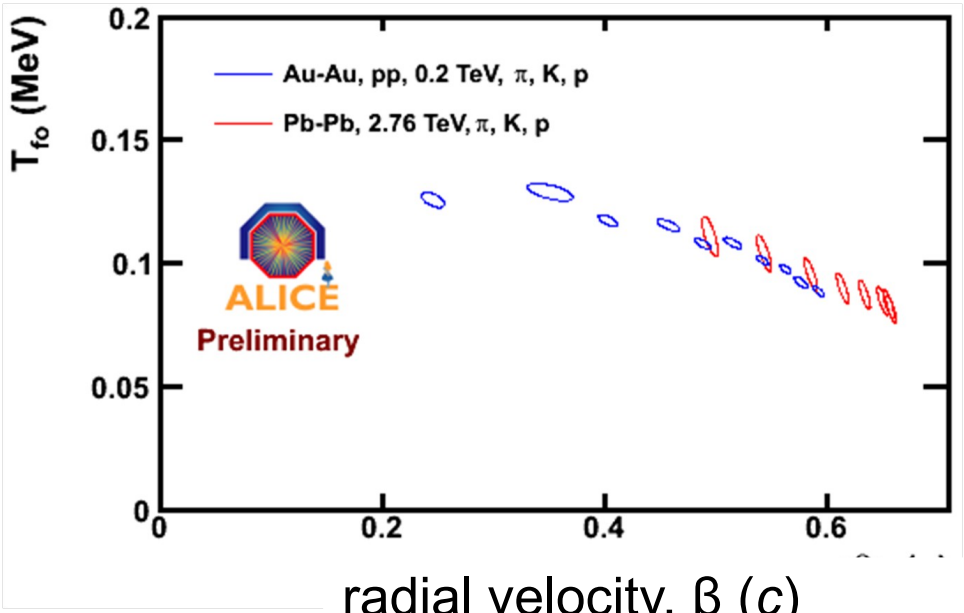
From Jamie Nagle's talk at QM'09

Final state: Kinetic equilibrium



transverse momentum, pt (GeV/c)

Freeze-out temperature & radial velocity from blast-wave fit

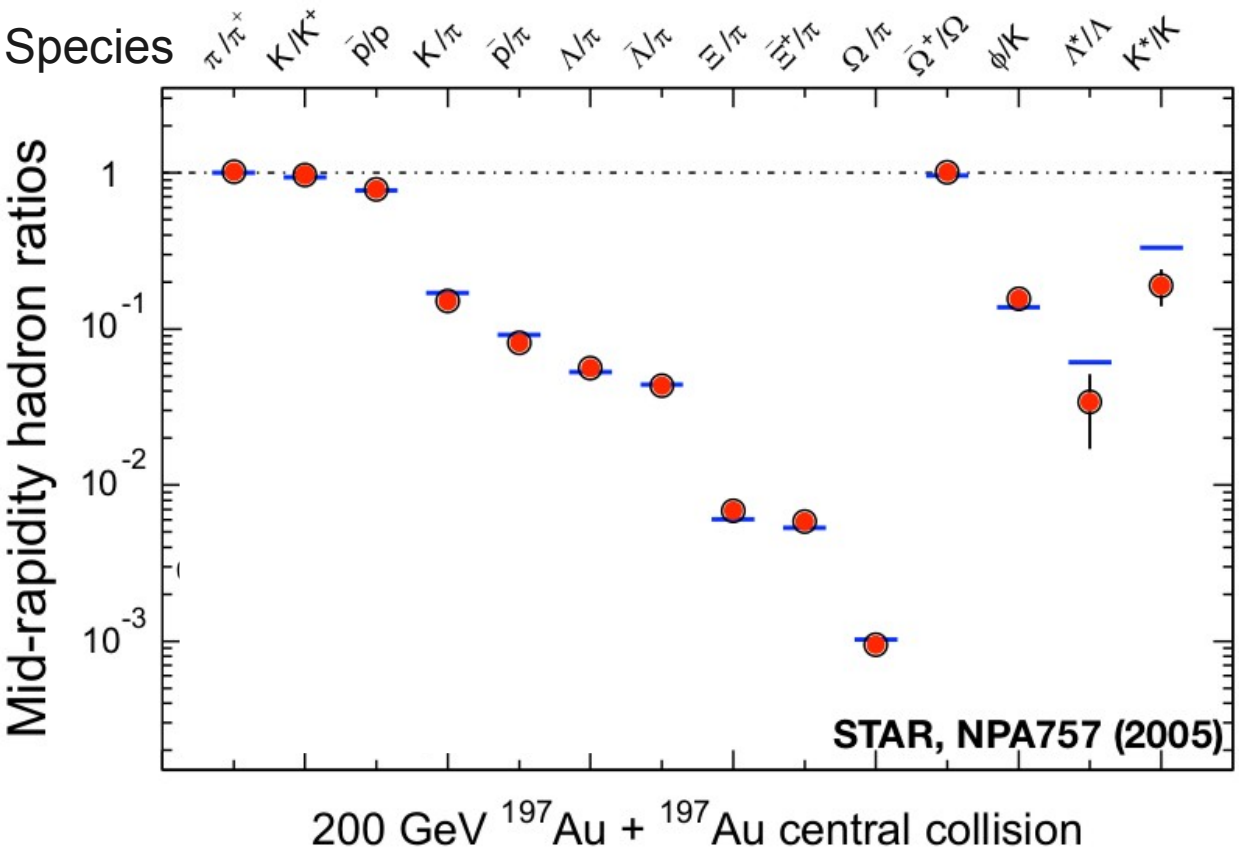


radial velocity, β (*c*)

Blast-wave model: Thermal Boltzmann source boosted with linear velocity profile

Spectra consistent with common temperature plus radial flow velocity. 20% stronger radial flow at LHC.

Final state: Chemical equilibrium



Grand-canonical ensemble analysis

$$N_i \propto V \int \frac{d^3 p}{2\pi^3} \frac{1}{e^{(E_i - \mu_B B_i)/Tch} \pm 1}$$

T_{ch} Chemical freeze-out temperature

μ_B Baryochemical potential

All hadron species emitted from a thermal source: Tch = 163 ± 4 MeV, μ_B = 24 ± 4 MeV

System decouples at $T_{ch} \sim T_c$