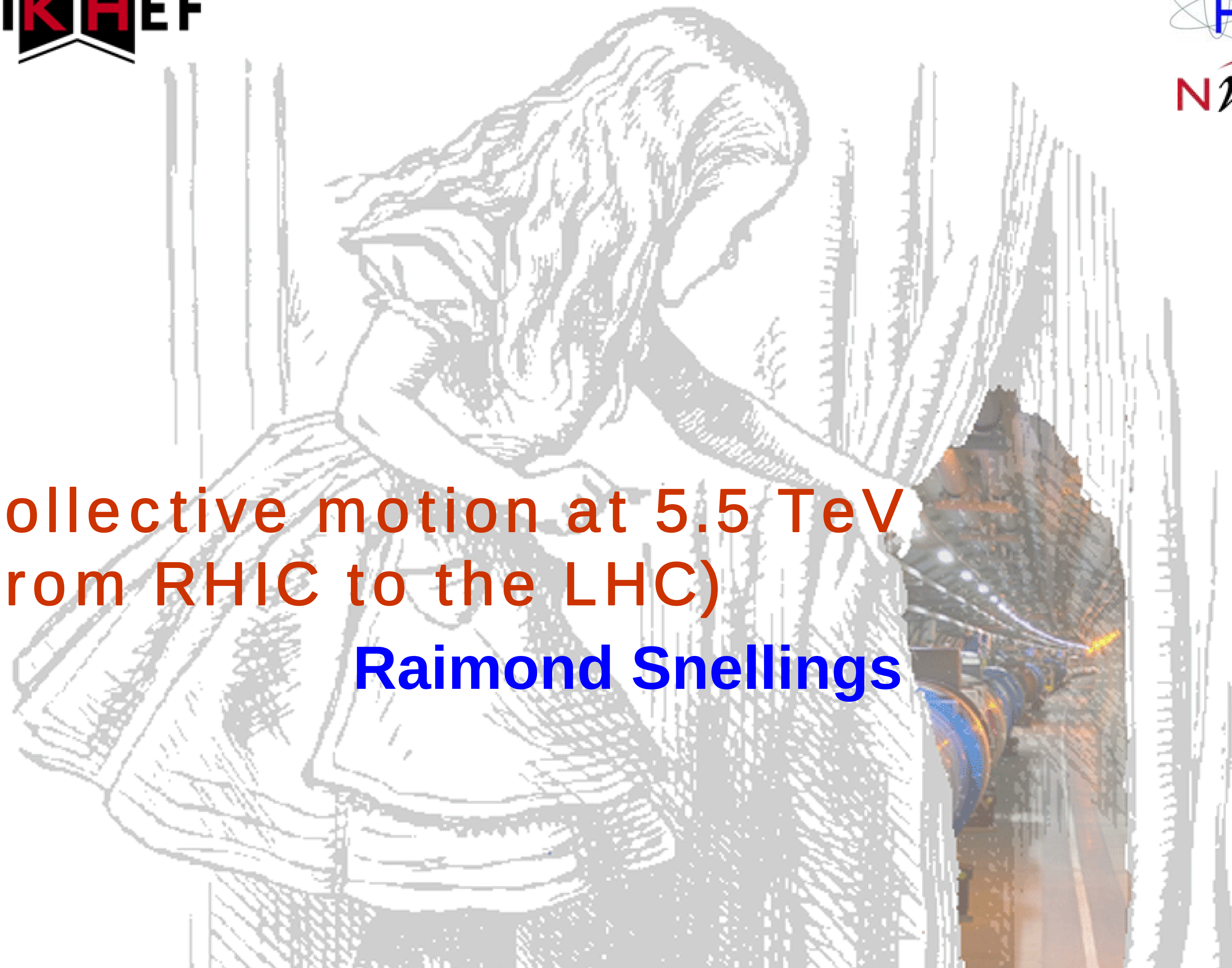


Collective motion at 5.5 TeV (from RHIC to the LHC)

Raimond Snellings

Hunting the Quark Gluon Plasma

BNL -73847-2005
Formal Report

Hunting the Quark Gluon Plasma

Results from the first 3 years at RHIC

Assessments by the experimental collaborations

April 18, 2005

PHOBOS STAR PHENIX BRAHMS

Relativistic Heavy Ion Collider (RHIC) • Brookhaven National Laboratory, Upton, NY 11974-5000

Office of Science U.S. Department of Energy — Brookhaven National Laboratory

Nucl. Phys. A 757 (2005)

- **Strong collective motion (elliptic flow)**
  - **sQGP and nearly perfect liquid**

New State of Matter Is 'Nearly Perfect' Liquid

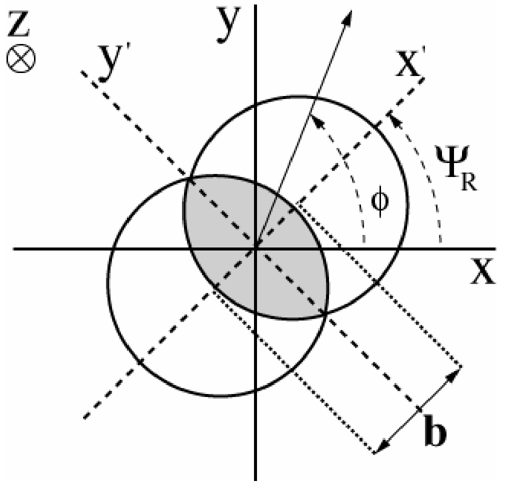
Image: BNL

Physicists working at Brookhaven National Laboratory announced today that they have created what appears to be a new state of matter out of the building blocks of atomic nuclei, quarks and gluons. The researchers unveiled their findings--which could provide new insight into the composition of the universe just moments after the big bang--today in Florida at a meeting of the American Physical Society.

SCIENTIFIC AMERICAN

There are four collaborations, dubbed BRAHMS, PHENIX, PHOBOS and STAR, working at Brookhaven's Relativistic Heavy Ion Collider (RHIC). All of them study what happens when two interacting beams of gold ions smash into one another at great velocities, resulting in thousands of subatomic collisions every second. When the researchers analyzed the patterns of the atoms' trajectories after these collisions, they found that the particles produced in the collisions tended to move collectively, much like a school of fish does. Brookhaven's associate laboratory director for high energy and nuclear physics, Sam Aronson, remarks that "the degree of collective interaction, rapid thermalization and extremely low viscosity of the matter being formed at RHIC make this the most nearly perfect liquid ever observed."

Anisotropic Flow



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

$$v_n = \langle \cos n(\varphi - \Psi_r)\rangle = \langle e^{in(\varphi - \psi_r)}\rangle$$

$$\langle e^{in(\varphi_1 - \varphi_2)}\rangle = \langle e^{in(\varphi_1 - \psi_r)} e^{in(\psi_r - \varphi_2)}\rangle \approx \langle e^{in(\varphi_1 - \psi_r)}\rangle\langle e^{in(\psi_r - \varphi_2)}\rangle = (v_n\{2\})^2$$

Assumption all correlations between particles due to flow, similar to $v_n\{EP_m\}$

Non flow correlation contribute order (1/N), problem if $v_n \approx 1/\sqrt{N}$

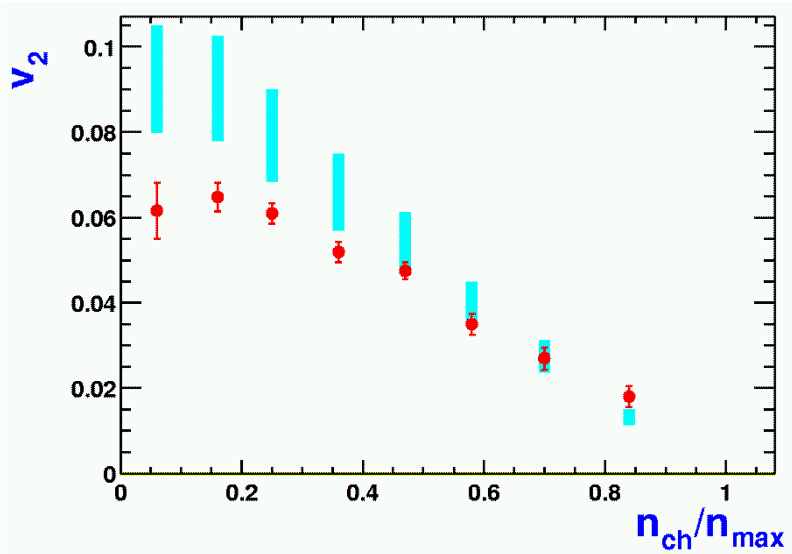
$$\langle e^{in(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)}\rangle - \langle e^{in(\varphi_1 - \varphi_2)}\rangle\langle e^{in(\varphi_3 - \varphi_4)}\rangle - \langle e^{in(\varphi_1 - \varphi_4)}\rangle\langle e^{in(\varphi_3 - \varphi_2)}\rangle \approx -(v_n\{4\})^4$$

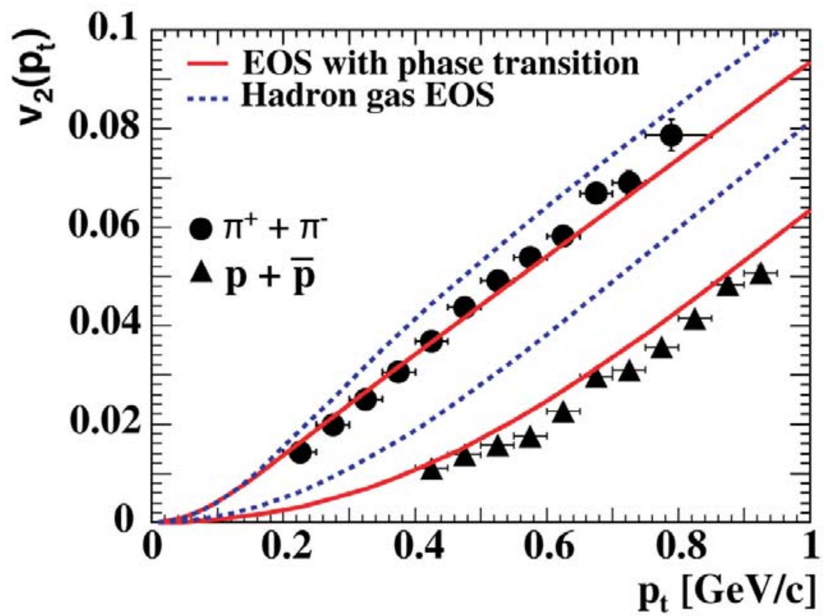
Non flow correlation contribute order ($1/N^3$), problem if $v_n \approx 1/N^{3/4}$

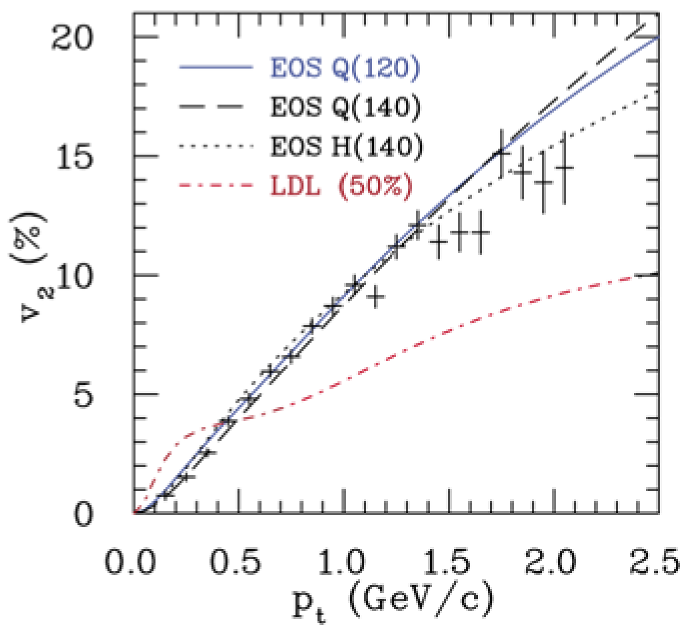
Can be conveniently calculated using generating functions, extended to $v_n\{\infty\}$ using Lee-Yang zeros, reliable $v_n > 1/N$

N. Borghini, P.M. Dinh and J.-Y Ollitrault, Phys. Rev. C63 (2001) 054906

The first RHIC $v_2\{EP\}$ results

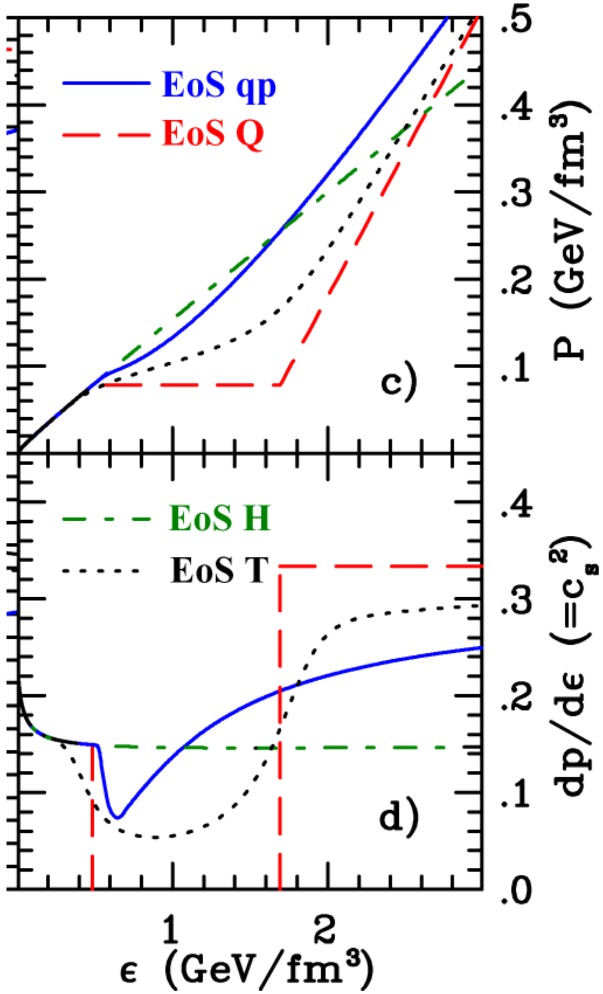




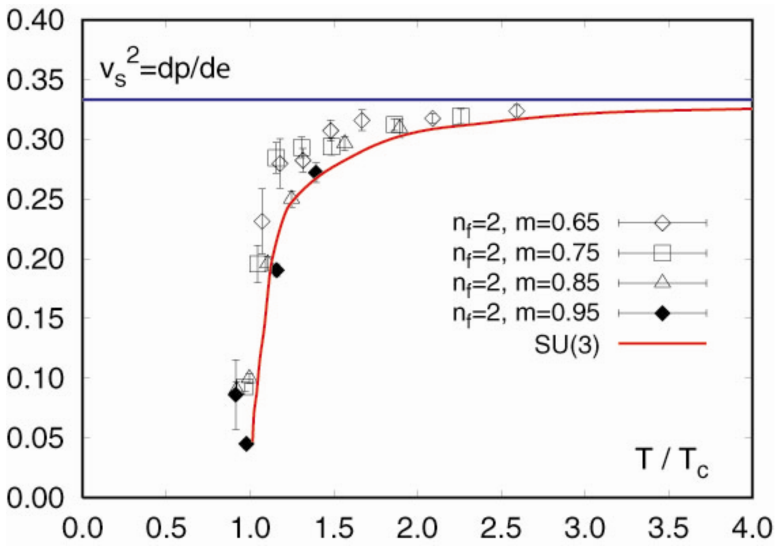


- Magnitude, p_t and mass dependence
- A strongly interacting, more thermalized system which is for more central collisions behaves consistent with ideal fluid behavior!
- Hydro studies show that the system needs to thermalize early (~1 fm/c)
- Best description by QGP EoS!?

Can we test the EoS (the effect of the phase transition)?



Pasi Huovinen, arXiv:nucl-th/0505036

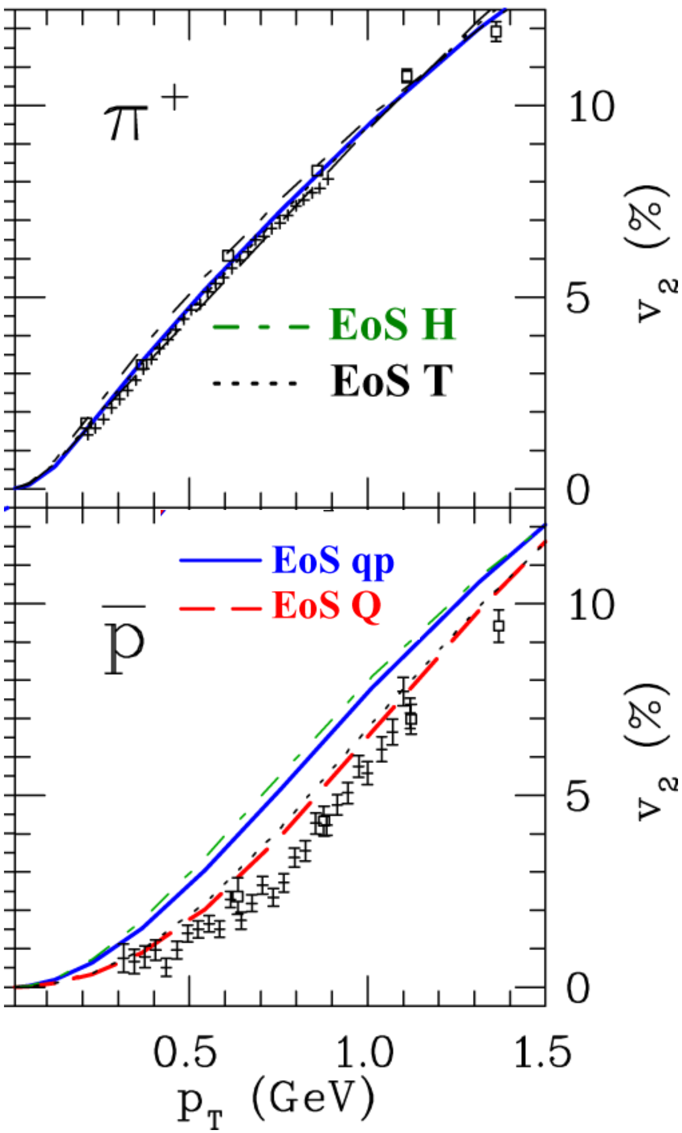


F. Karsch and E. Laermann, arXiv:hep-lat/0305025

- **Test the effect of four different EoS; qp is lattice inspired, Q has first order phase transition, H is hadron gas with no phase transition and T a smooth parameterization between hadron and QGP phase**

Dependence on the EoS!

Pasi Huovinen, arXiv:nucl-th/0505036

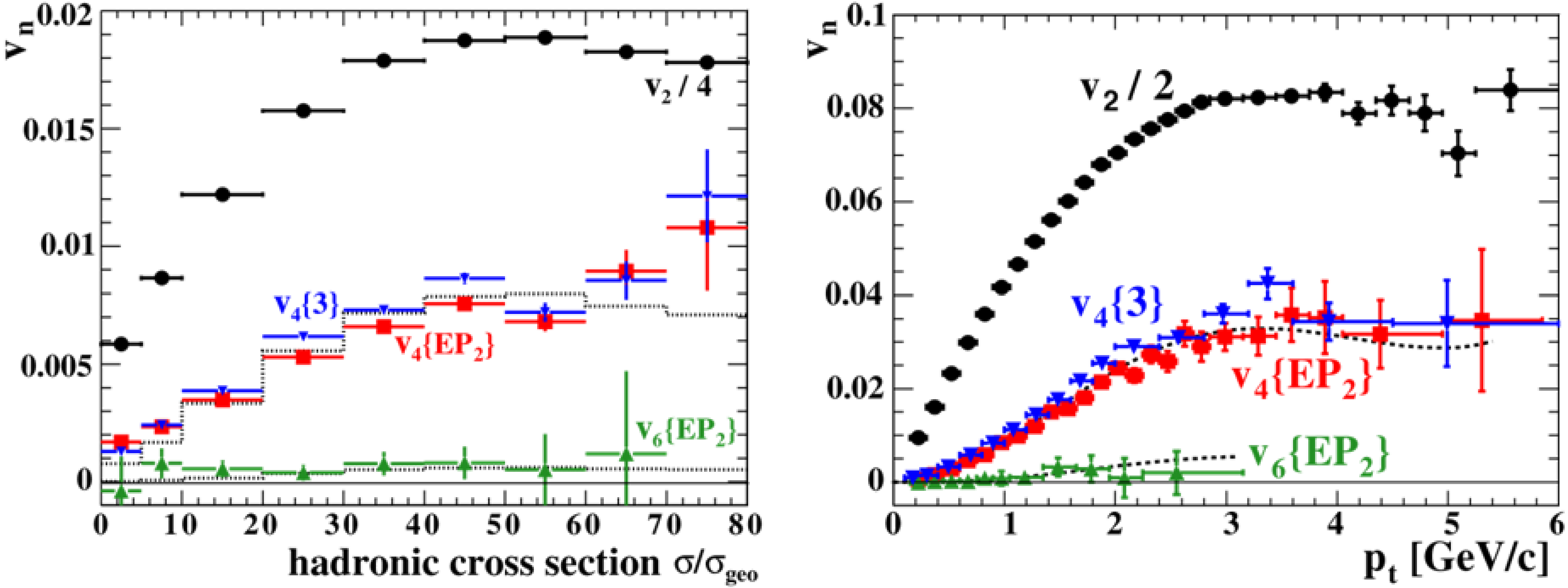


- EoS Q and EoS T (both have significant softening) do provide the best description of the magnitude of the mass scaling in $v_2(p_t)$
- The lattice inspired EoS (EoS qp) in ideal hydro does as poorly as a hadron gas EoS!

Detailed agreement between ideal hydro and measured $v_2(\text{mass},p_t)$ an accident? (Hirano and Gyulassy arXiv:nucl-th/0506049).

Before we can make a connection to the EoS using $v_2(p_t,\text{mass})$ much more work needed in theory (test different EoS, viscosity, hadronic phase)

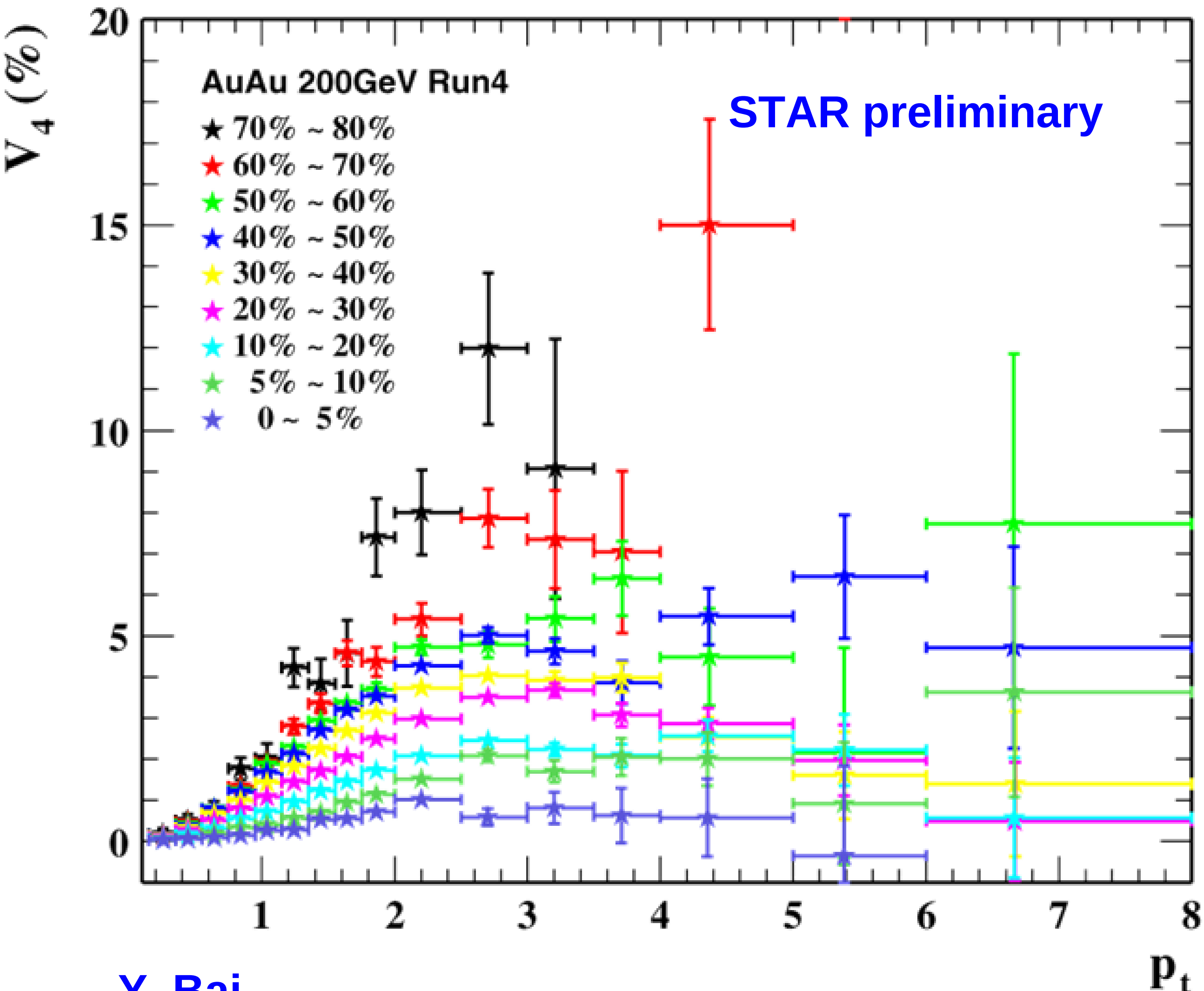
Higher harmonics



STAR, PRL 92 (2004) 062301

- Higher harmonics are expected to be present, for smooth azimuthal distributions the higher harmonics will be small $v_n \sim v_2^{n/2}$
- Data follows the smooth scaling

v_4 as function of centrality



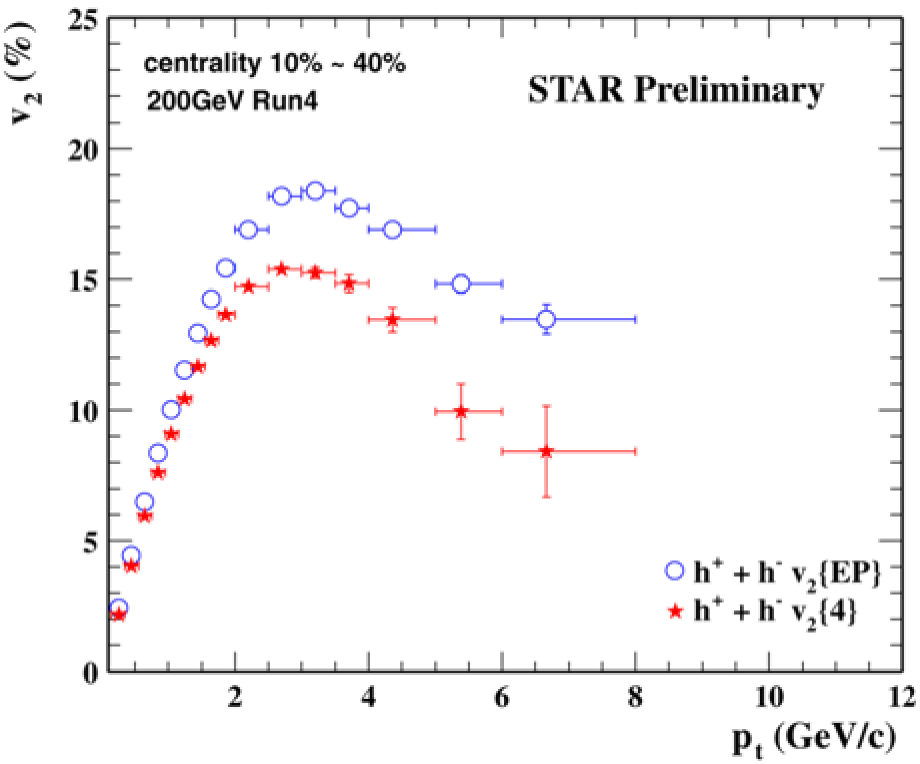
Y. Bai

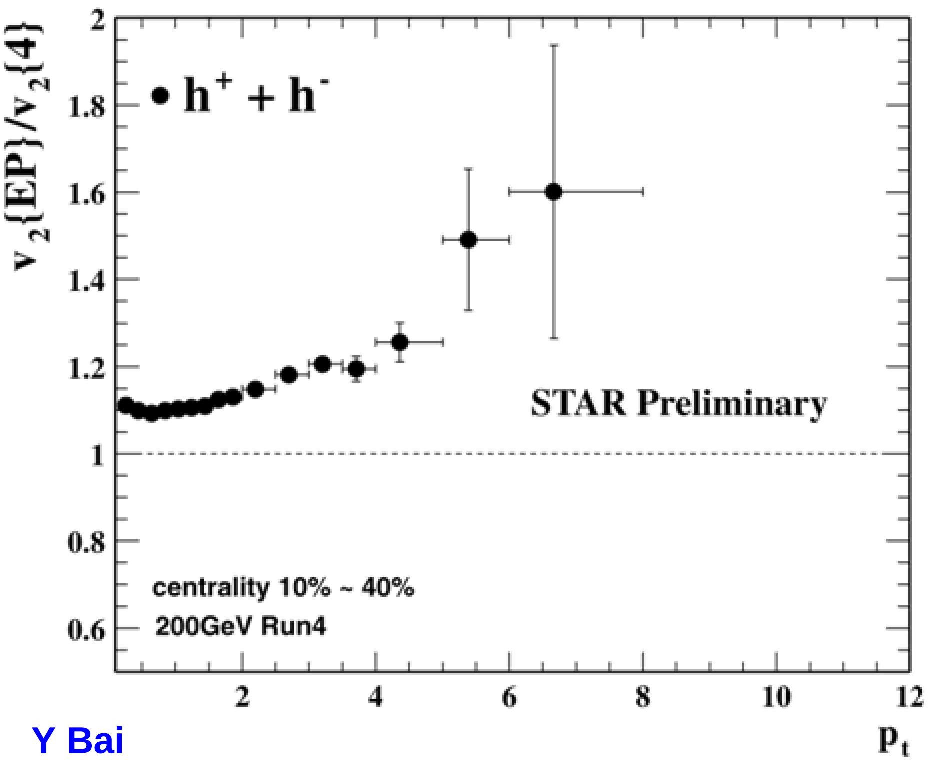
- To first order similar behavior as $v_2(p_t)$, increasing up to 3 GeV/c after which there is a slow decrease

What do we learn from v_4?

- **Ratio v_4/v_2^2 is sensitive to degree of thermalization (Borghini and Ollitrault nucl-th/0506045)**
  - **$v_4(p_t)/v_2(p_t)^2$ is 1/2 for ideal hydro (more accurate for increasing values of p_t),**
  - **Observed integrated ratio is larger than unity**
    - **incomplete thermalization (but how much)**
- **Do we have intuitive test if the ratio is related to the degree of thermalization?**
  - **ratio v_4/v_2^2 expected to decrease as the collisions become more central**
  - **ratio v_4/v_2^2 expected to increase as function of transverse momenta**

Difference between $v_2\{2\}$ and $v_2\{4\}$



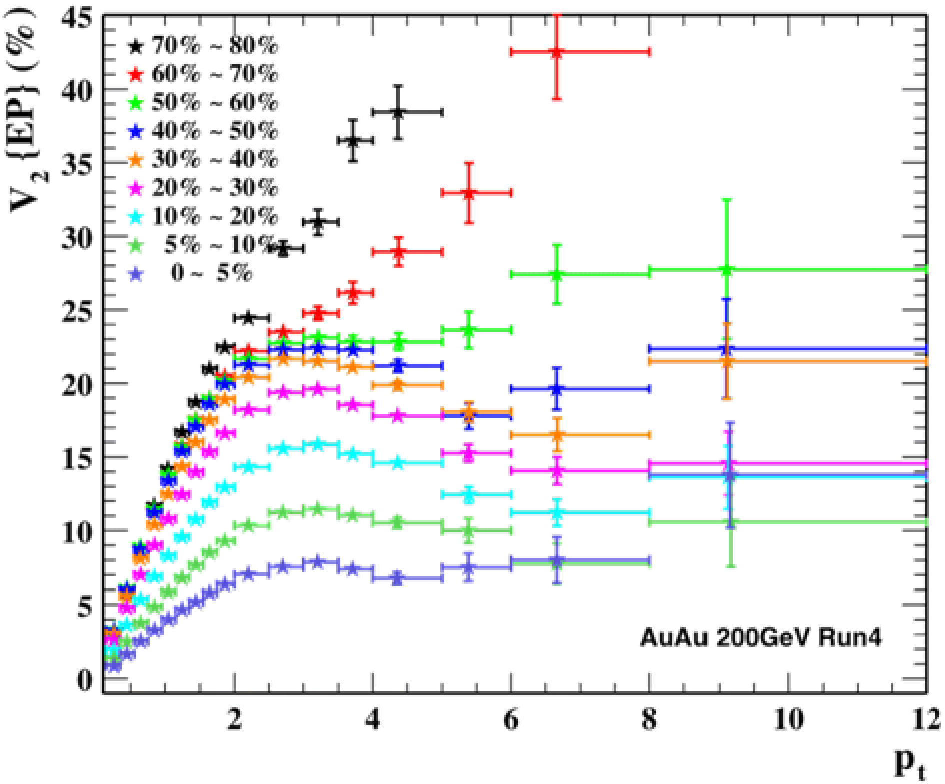


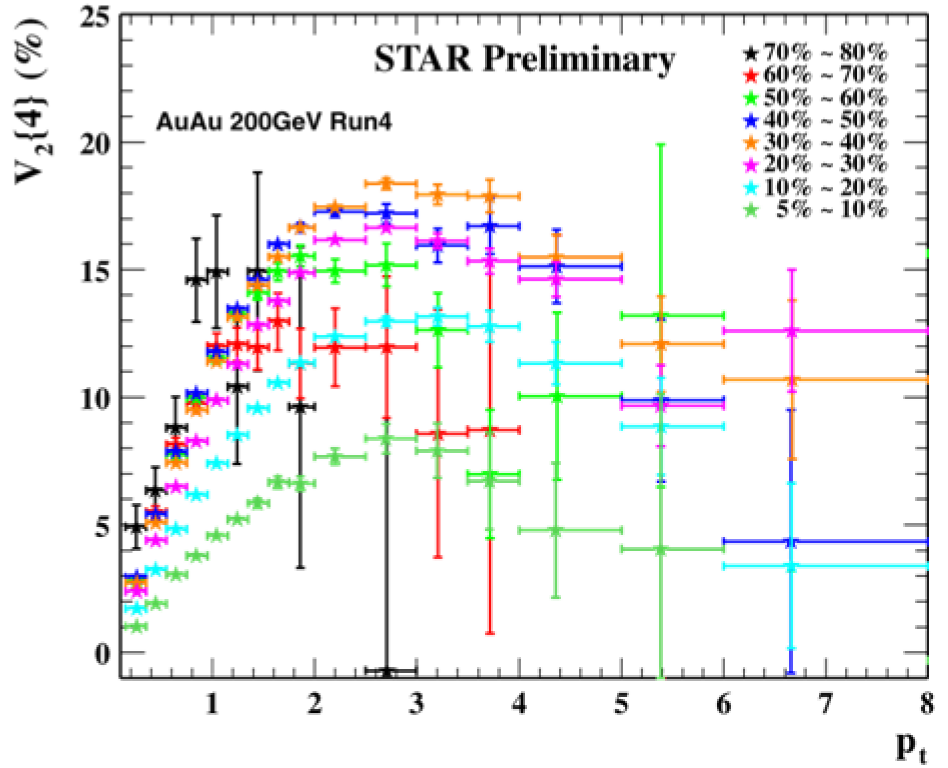
Y Bai

- In more central Au+Au collisions the difference between $v_2\{2\}$ and $v_2\{4\}$ increases from 10% at low-p_t to about 40-50% at intermediate-p_t

Centrality dependence of $v_2\{EP\}$ and $v_2\{4\}$ (year 4 data)

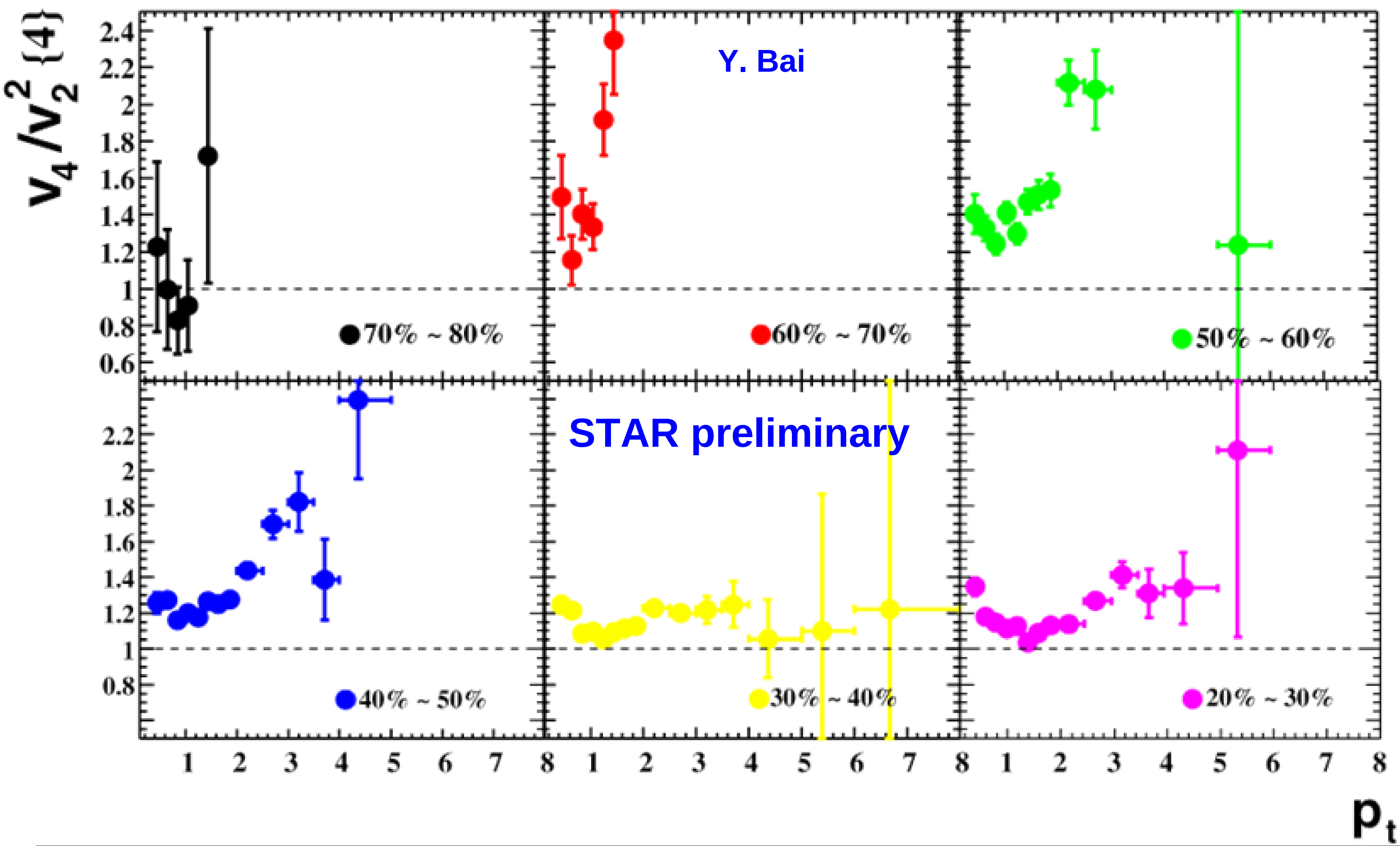
Y Bai





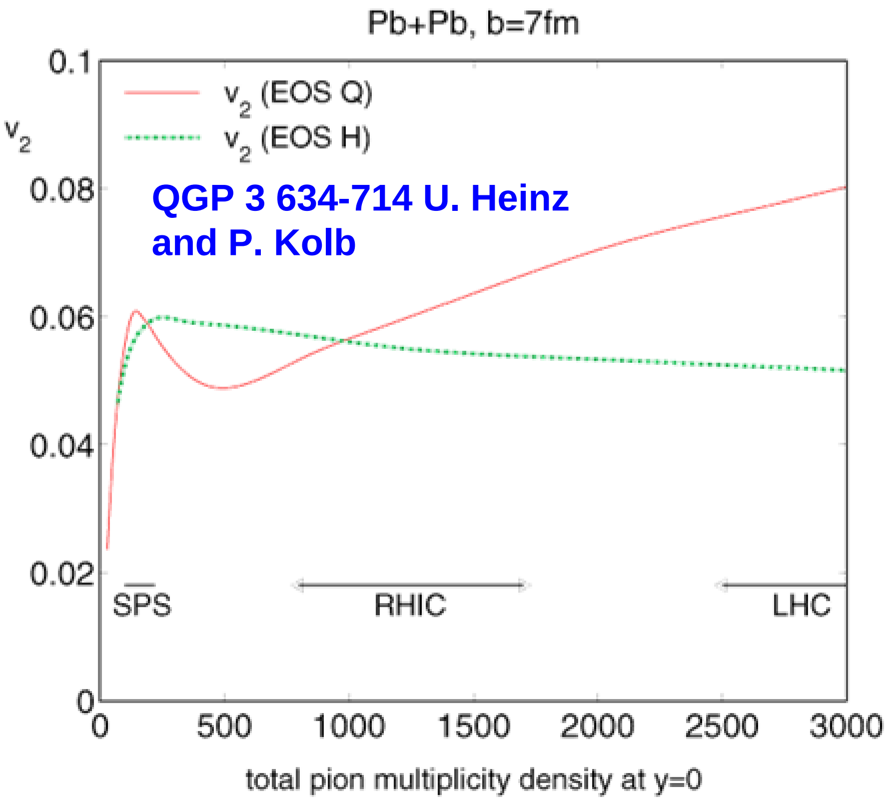
- **At intermediate-p_t the centrality dependence can even change order!**

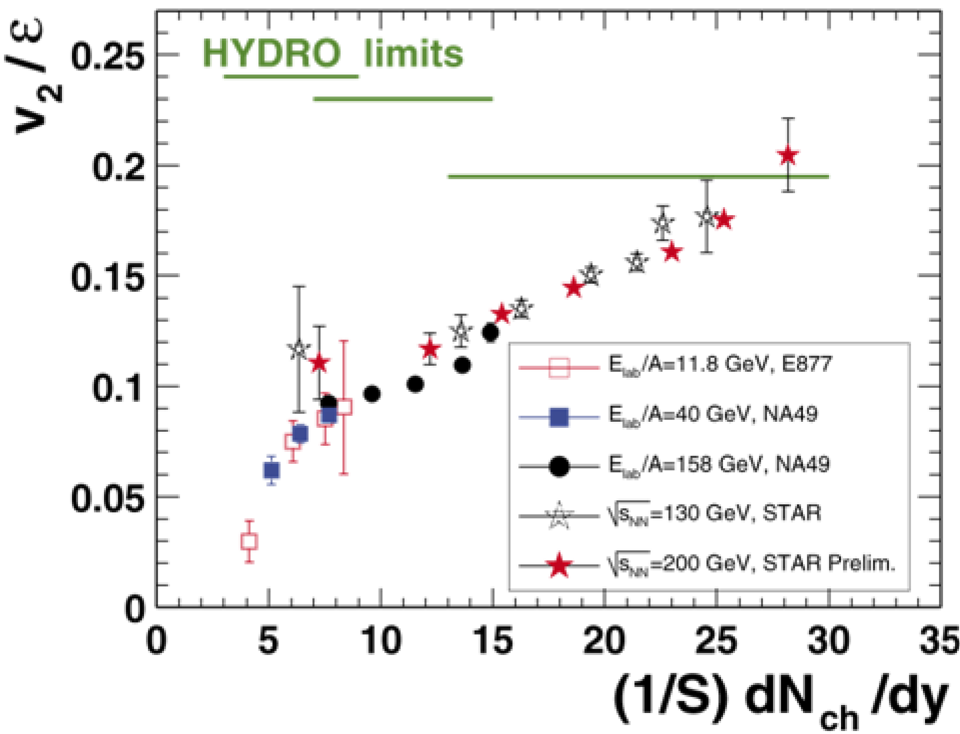
Ratio $v_4/(v_2\{4\})^2$



- Ratio larger than unity and for more peripheral collisions increasing fast as function of transverse momentum
- Need theory input how this would look in microscopic model

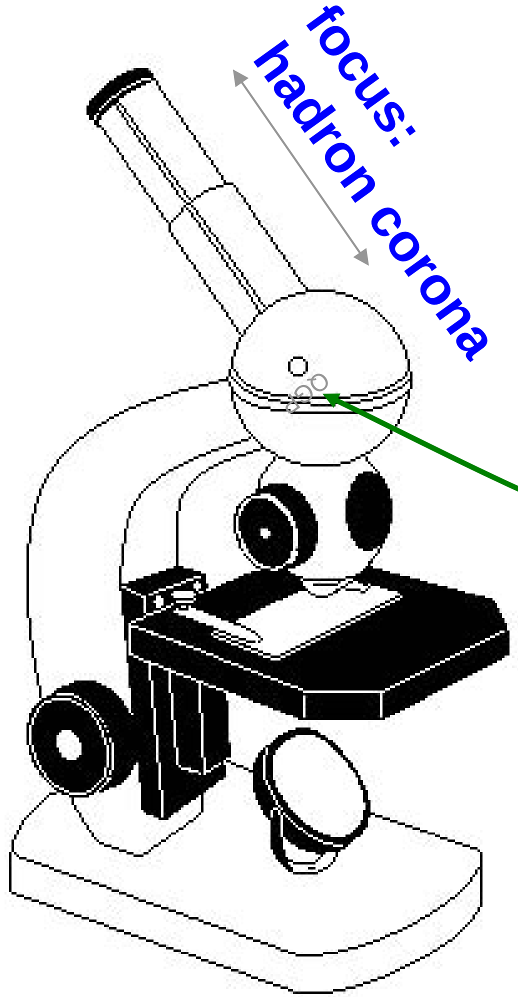
Energy Dependence





- Elliptic flow in hydro sensitive to EoS (C_s)
- Elliptic flow in LDL sensitive to density and transport cross sections of the constituents
  - Data shows rather smooth dependence consistent with LDL

RHIC, the (s)QGP, according to Hirano



QGP

Wanna see this?

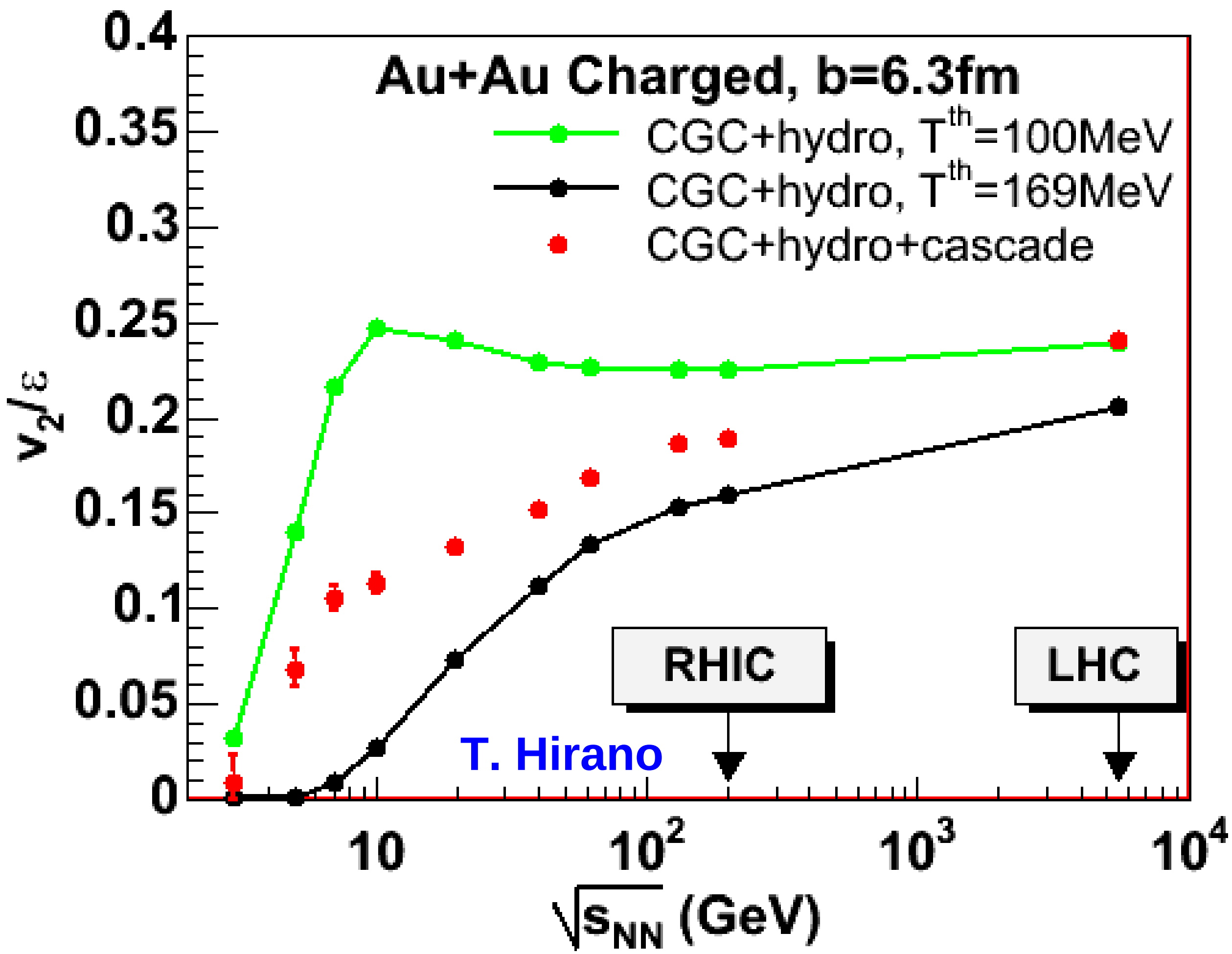
QGP

Fine-tune the “hadronic” focus!

Villasimius

Villasimius

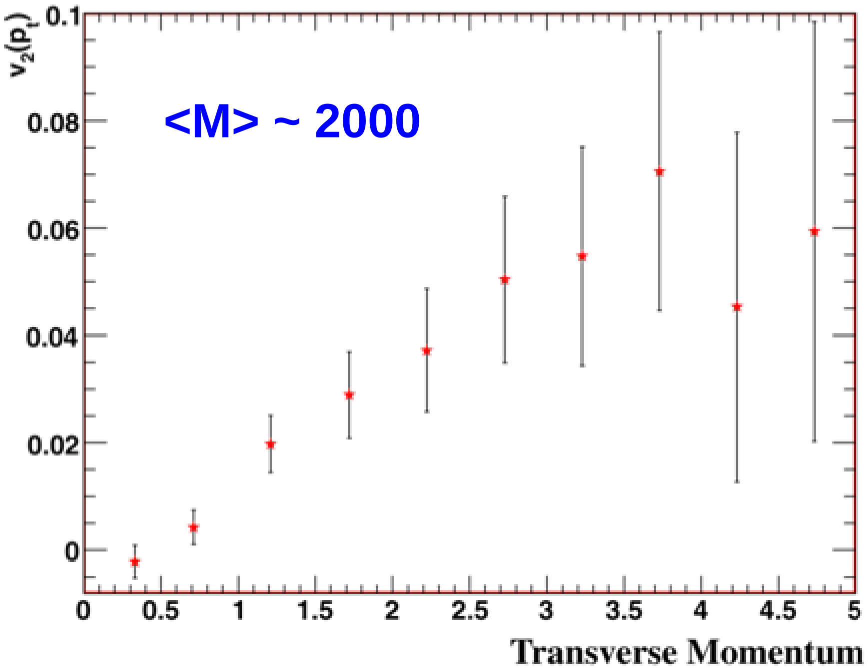
At the LHC the main contribution to v_2 is from the QGP phase!

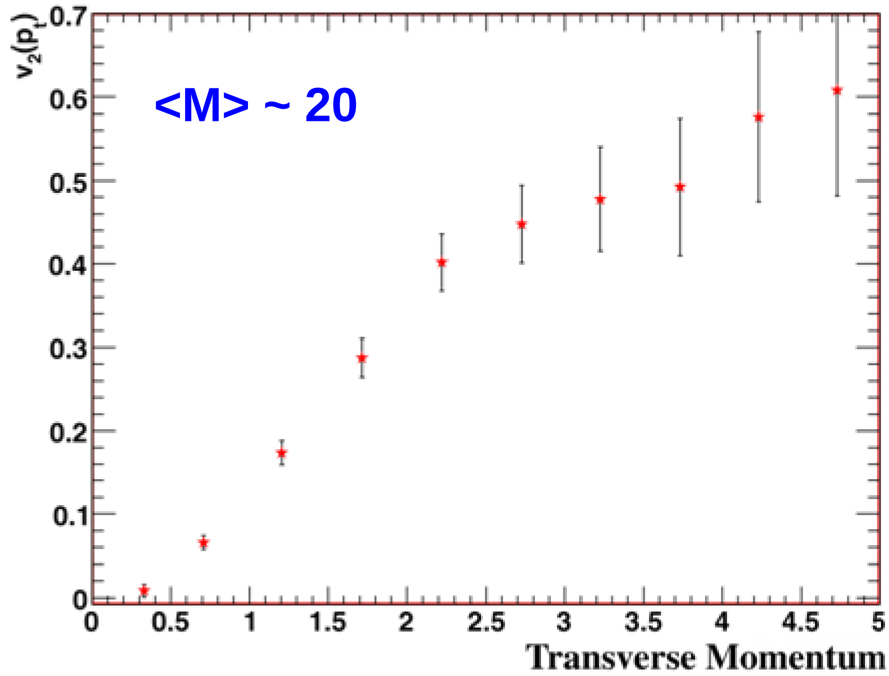


- **(black line) QGP contribution to the v_2, increases with colliding energy**
- **(red dots) total observed signal: QGP + hadron phase**
- **At the LHC about 80% of the integrated flow signal is generated in the QGP phase!**
- **Magnitude is large which makes the measurement easier**

Non-flow at the LHC (HIJING)

E. Simili





- **HIJING events with v_2 =0**
- **For low multiplicity events $v_2\{EP\}$ goes up to 0.6!**

First RHIC non-flow estimates

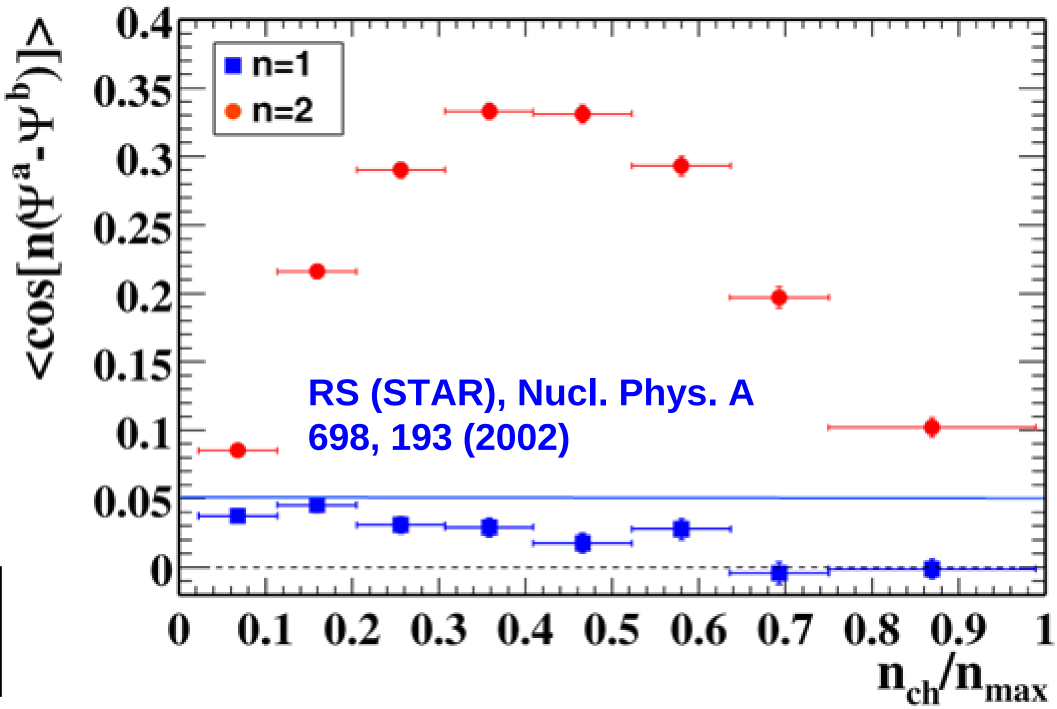
$$\left\langle \cos\left[2\left(\Psi_2^a - \Psi_2^b\right)\right]\right\rangle \approx \left\langle \frac{\sum_{i=1}^{M_{sub}} u_i}{\sqrt{M_{sub}}} \bullet \frac{\sum_{j=1}^{M_{sub}} u_j^*}{\sqrt{M_{sub}}} \right\rangle$$

$$= \frac{M_{sub} M_{sub}}{M_{sub}} \left\langle u_i u_j^* \right\rangle \propto M_{sub}\left(v_2^2 + g\right)$$

$$g = \tilde{g} / M_{sub}$$

$$\left\langle \cos\left[2\left(\Psi_2^a - \Psi_2^b\right)\right]\right\rangle \propto M_{sub} v_2^2 + \tilde{g}$$

K.H. Ackermann et al (STAR), Phys. Rev. Lett 86, 402 (2001)

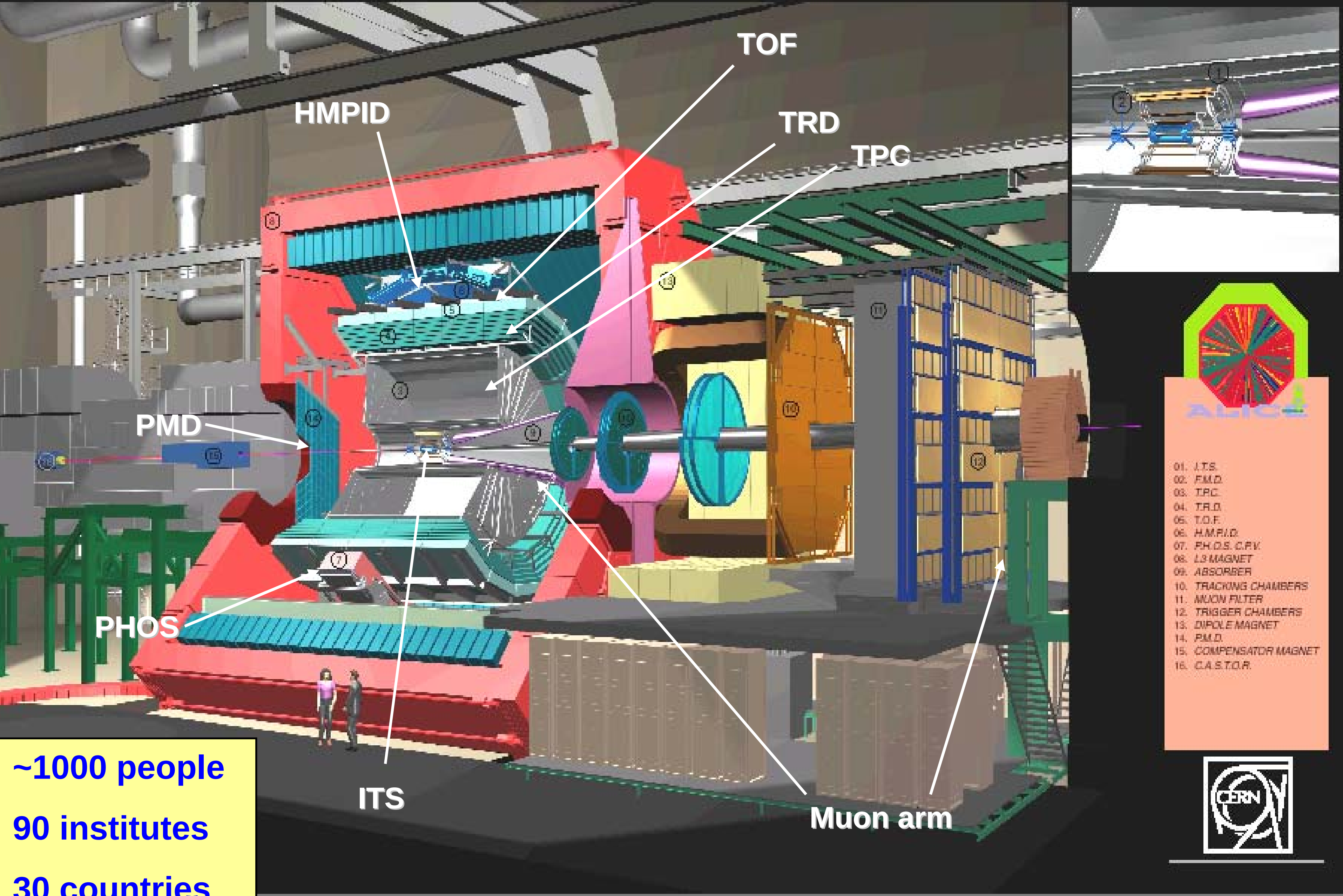


- The non-flow component in HIJING is approximately centrality independent and at LHC energies 0.08 for random subevents, 0.04 for eta subevents, and can be reduced to 0.02 for eta subevents with large rapidity gap (> 1 unit model dependent statement, we know that HIJING does not describe the correlations at RHIC)
- 0.04 is similar to what was observed at RHIC, therefore at midcentral events the true flow correlations is expected to dominate by an order of magnitude (both M and v_2 are expected to be larger)!

Flow from RHIC to the LHC

- **At RHIC**
  - **Strong collective behavior**
    - **Strongly interacting partonic matter**
  - **Theory:**
    - **microscopic picture still missing**
    - **connection to the EoS needs more work**

    } **M. Lisa: the v_2 puzzle**
  - **Experiment: more detailed probes become available**
    - **can v_4 tell us in more detail about the degree of thermalization?**
- **At the LHC**
  - **Current expectations are that we can easily measure anisotropic flow**
  - **The QGP phase is expected to dominate the flow signals**
    - **better access to the EoS above T_c**



~1000 people

90 institutes

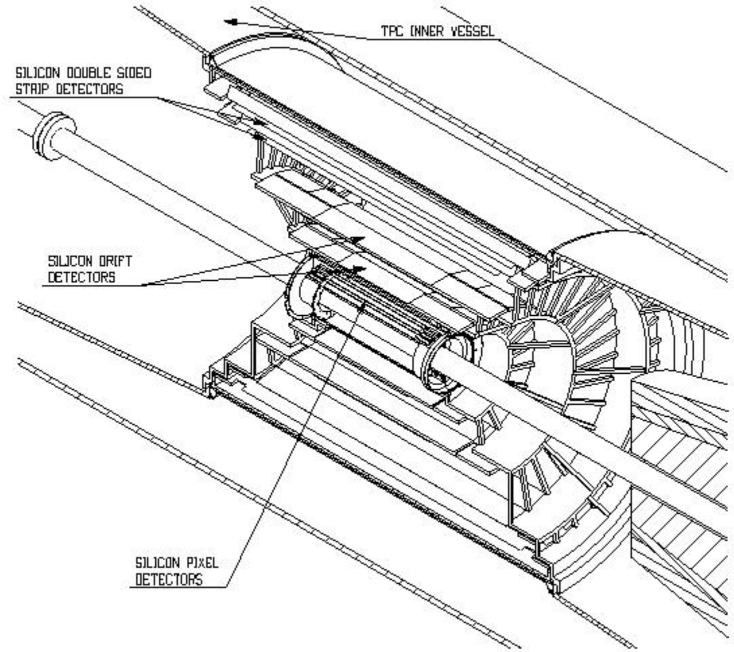
30 countries

ALICE Detector

Inner Tracking System

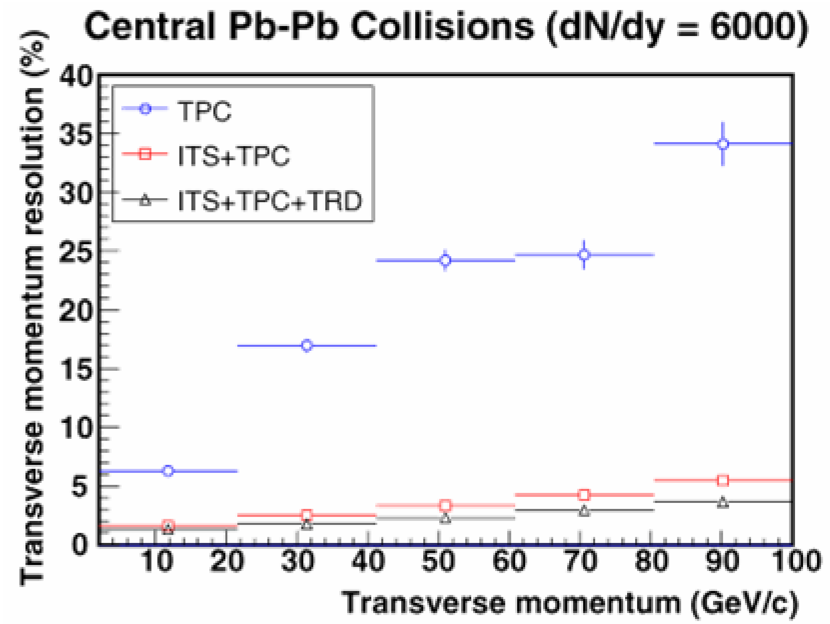
low mass: 7 % X_0

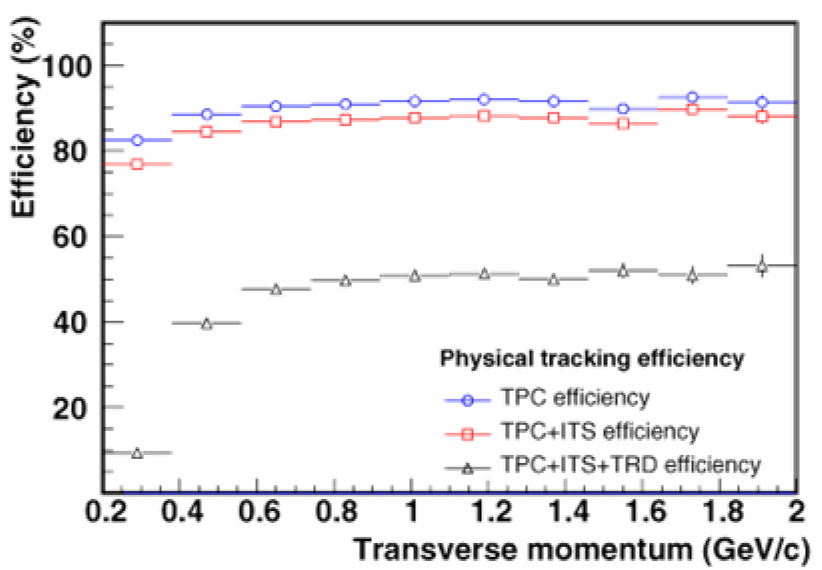
6 layers		R	♦ r⤧	♦ Z
Layer 1	pixels	4 cm	12 ❍m	100 ❍m
Layer 2	pixels	8 cm	12 ❍m	100 ❍m
Layer 3	drift	15 cm	38 ❍m	28 ❍m
Layer 4	drift	24 cm	38 ❍m	28 ❍m
Layer 5	double sided strip	38 cm	17 ❍m	800 ❍m
Layer 6	double sided strip	43 cm	17 ❍m	800 ❍m

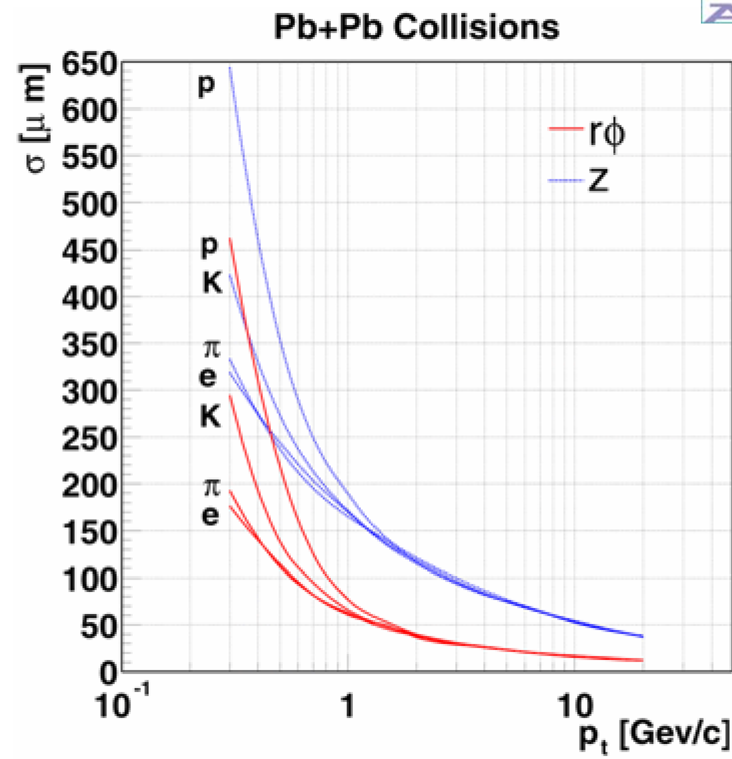


- **The ITS is the center of the ALICE tracking system**
  - –needed to get reasonable momentum resolution at higher p_t
  - –needed to reconstruct secondary vertices
  - –needed to track low momentum particles

ITS + TPC





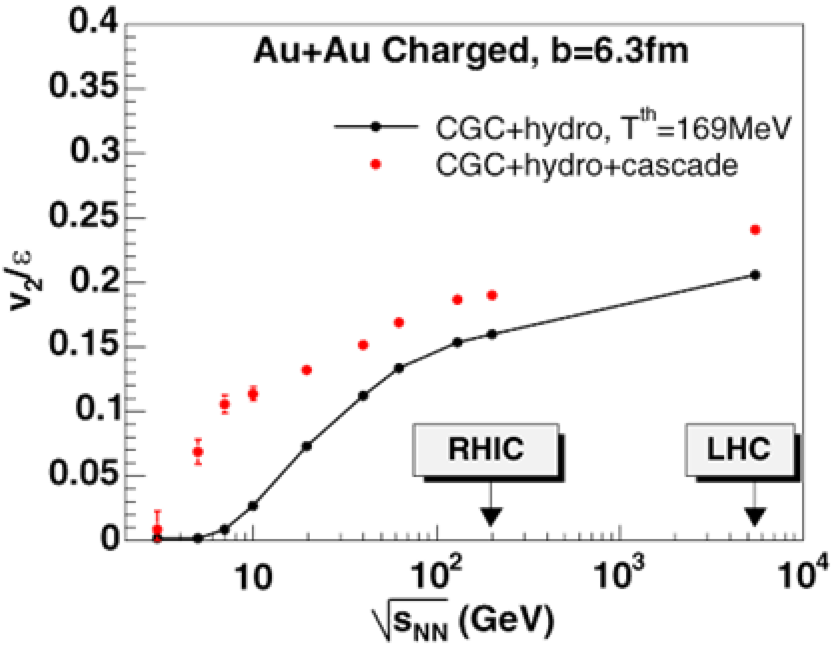


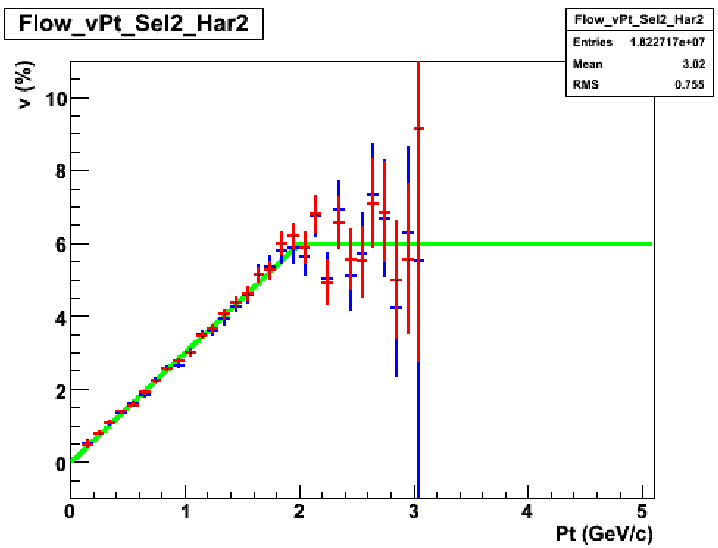
Impact parameter resolution is crucial for the detection of short-lived particles
- charm and beauty mesons and baryons

At least one component has to be better than 100 ❍m (c♦ for D^0 meson is 123 ❍m)

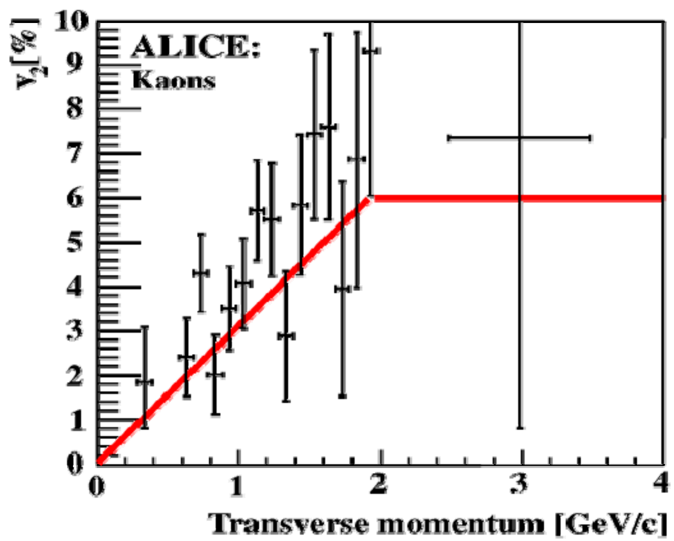
Completed SSD Ladder

ALICE Flow preparations



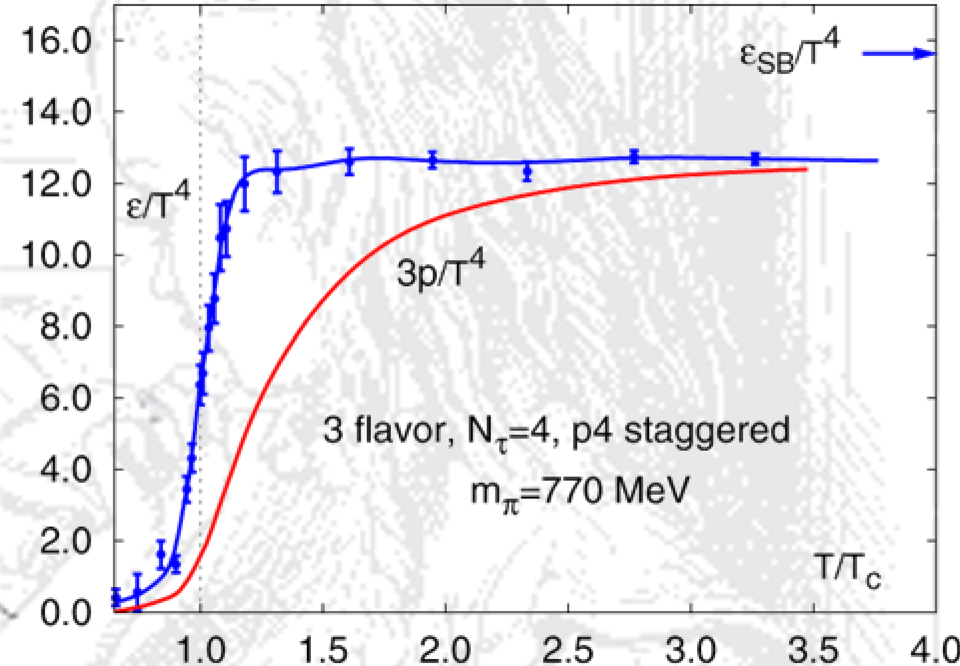


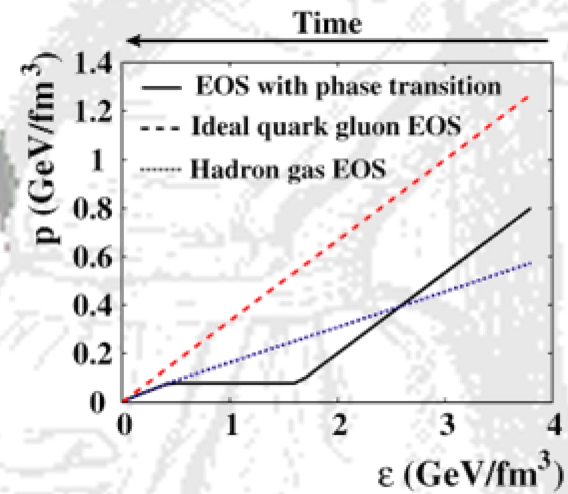
- ALICE various detectors enable reaction plane determination (ITS + TPC, PMD,FMD, ZDC)
- First theory prediction of charged particle flow (and the QGP EoS) can be tested with just one day of data taking
- More stringent tests will come from measuring jet correlation versus the reaction plane and the flow of heavy quarks (dead cone in radiative energy loss, more sensitive to collisional energy loss)



How ideal is nearly perfect?

- **How well is the system created in heavy-ion collisions at RHIC described as an ideal fluid? What can we say about the EoS (theorist claimed perfect fluid behavior with QGP EoS)?**
  - **Elliptic flow (v_2)**
    - **Centrality dependence**
    - **Mass and p_t dependence (T and β_0)**
    - **Energy dependence**
  - **v_4**
    - **v_4 / v_2^2**





P.F. Kolb and U. Heinz, in Quark Gluon Plasma, nucl-th/0305084