Anisotropic Flow at the LHC as measured by ALICE

«ETTORE MAJORANA» FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE
TO PAY A PERMANENT TRIBUTE TO GALILEO GALILEI, FOUNDER OF MODERN SCIENCE AND TO ENRICO FERMI, THE "ITALIAN NAVIGATOR", FATHER OF THE WEAK FORCES

WORLD FEDERATION OF SCIENTISTS
Founded in Erice
Beijing, Geneva, Moscow, New York

INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS

34th Course: PROBING THE EXTREMES OF MATTER WITH HEAVY IONS

ERICE–SICILY: 16 – 24 SEPTEMBER 2012

Sponsored by the: • Deutsche Forschungsgemeinschaft • European Physical Society • Italian Ministry of University and Research • Sicilian Regional Government

TOPICS AND LECTURERS

Color Glass Condensate and the implications for the LHC
• J. ALBACETE, CEA/Saclay, Gif-sur-Yvette, FR

New results from ALICE I
• P. BRAUN-MUNZINGER, GSI, Damstadt, DE

Penetrating probes for heavy-ion collisions
• T. HEMMICK, SUNY, Stony Brook, NY, US

Hydrodynamic description of ultrarelativistic heavy-ion collisions
• T. HIRANO, University of Tokyo, JP

Gluon saturation, geometric scaling and color glass condensates in heavy-ion collisions
• K. ITAKURA, KEK, Tsukuba, JP

Recent results from PHENIX
• B. JACAK, Stony Brook, NY, US

Dileptons and photons in heavy-ion collisions
• R. RAPP, College Station, Texas AM University, TX, US

Sound propagation in the quark-gluon plasma
• E. SHURYAK, SUNY, Stony Brook, NY, US

The planned NICA facility in Dubna
• A. SORIN, Joint Institute for Nuclear Research, Dubna, RU

Collective flow at the LHC
• R. SNELLINGS, Utrecht University, NL

New results from ALICE II
• J. STACHEL, University of Heidelberg, DE

Recent results from the HADES experiment
• J. STROTH, University of Frankfurt, DE

The equation of state in weak coupling
• A. VUORINEN, University of Bielefeld, DE

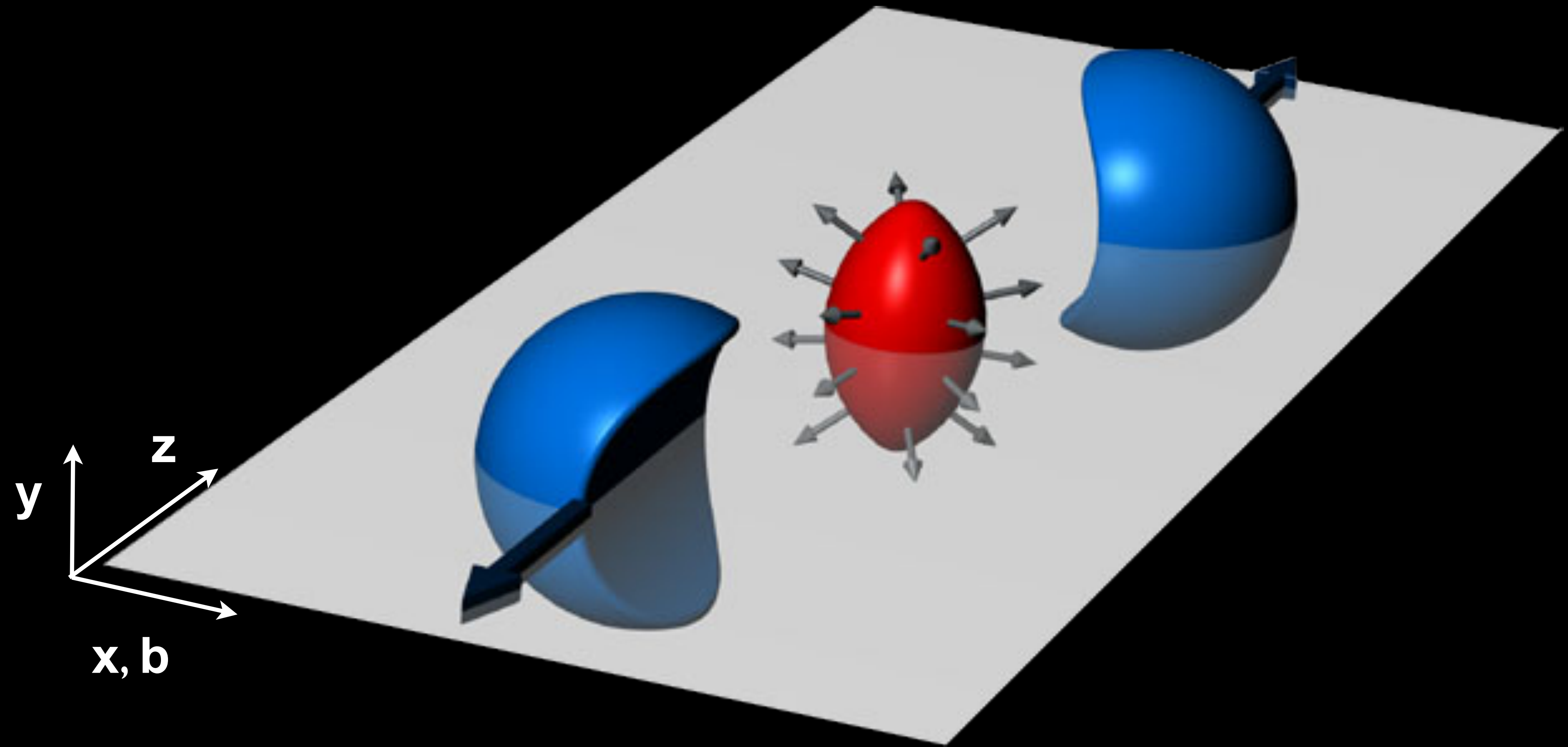
Quarkonia production in heavy-ion collisions
• P. ZHUANG, Tsinghua University, Beijing, CH

Raimond Snellings

Content

1) Elliptic Flow
2) What do we learn from various particle species?
3) Higher harmonics
4) What's next?

In a Heavy Ion Collision

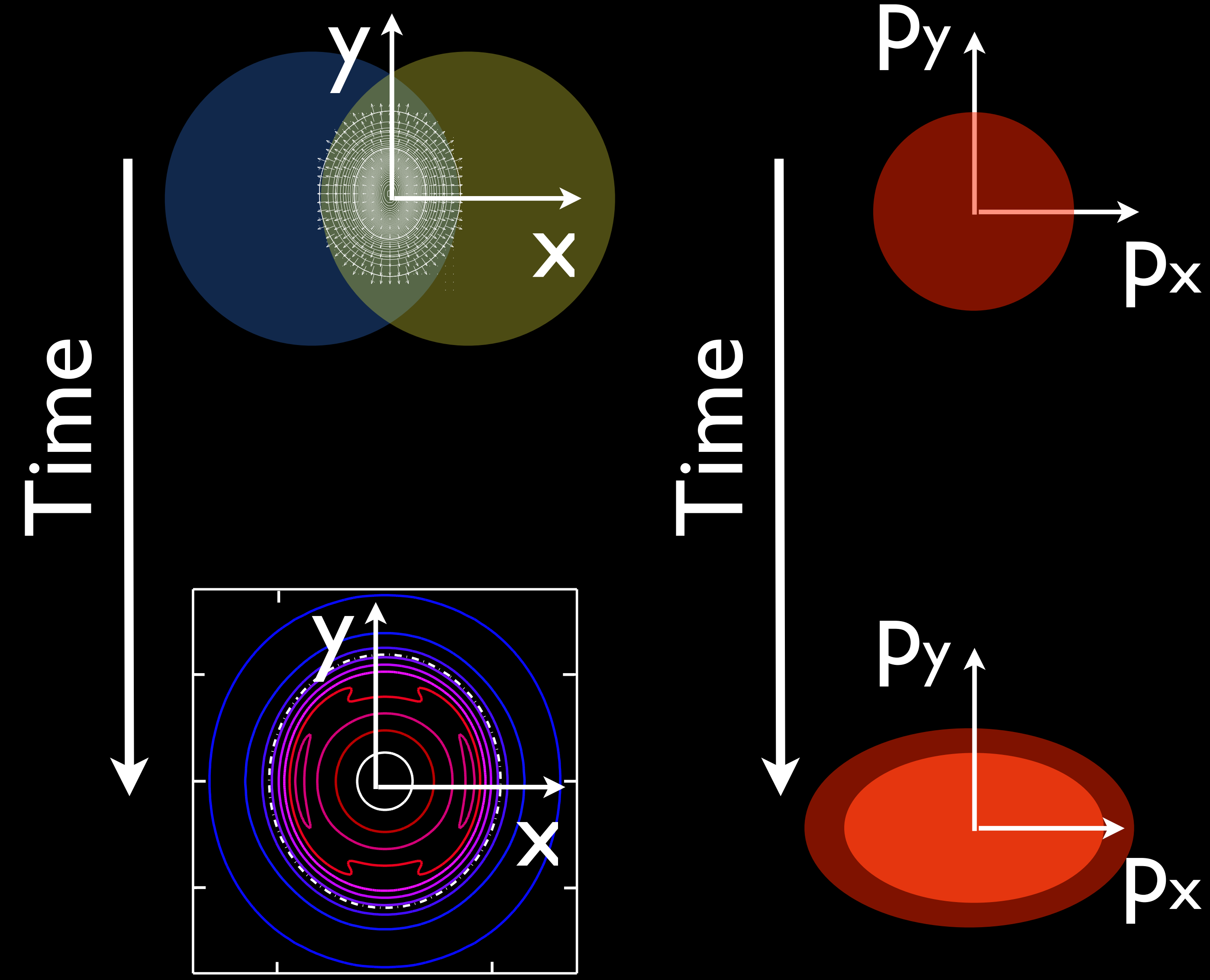


an anisotropic system is created

Elliptic Flow

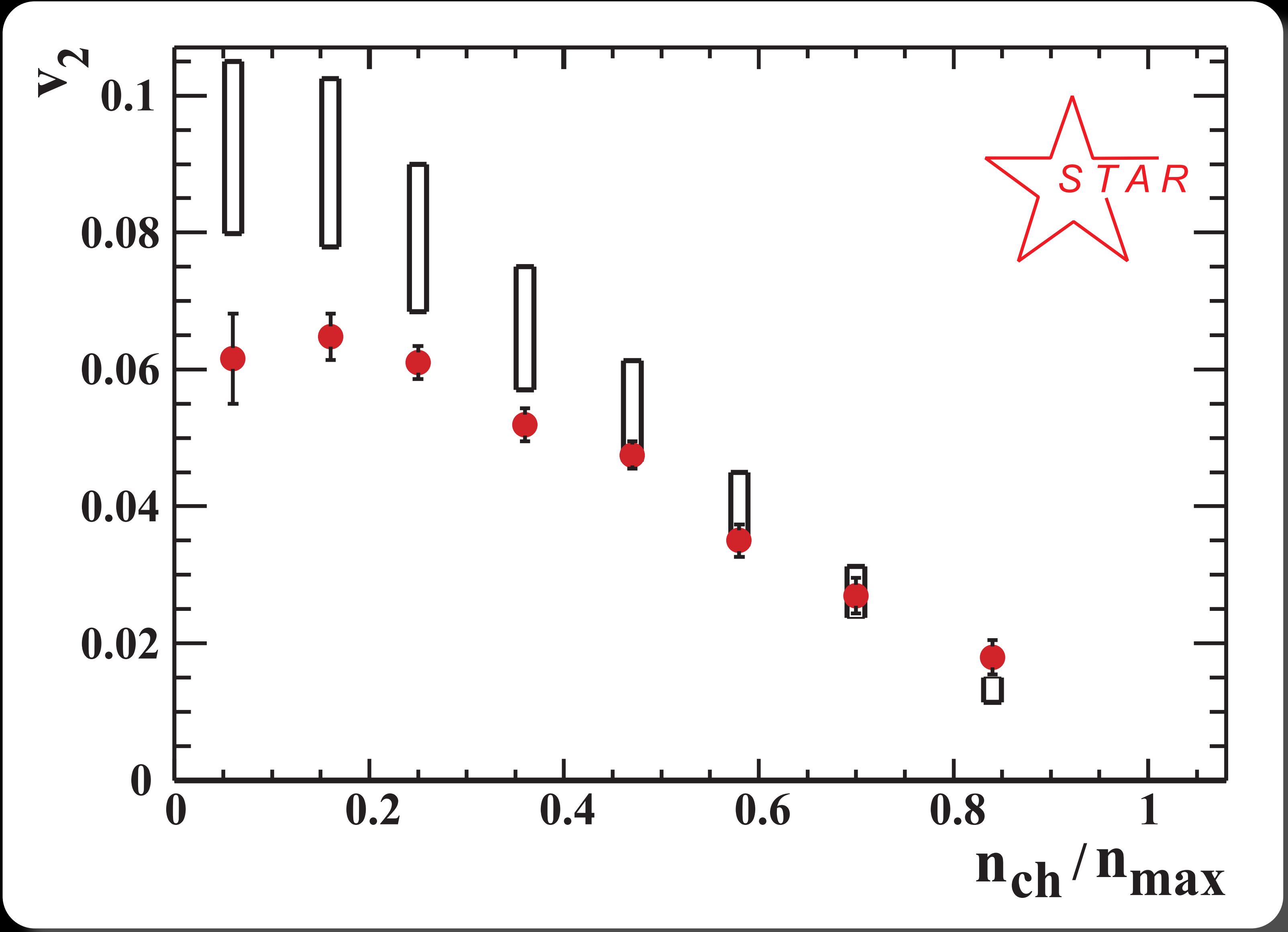
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\phi \rangle$$

- the system in coordinate space configuration is anisotropic (for a non-central collision 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



Flow at RHIC

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



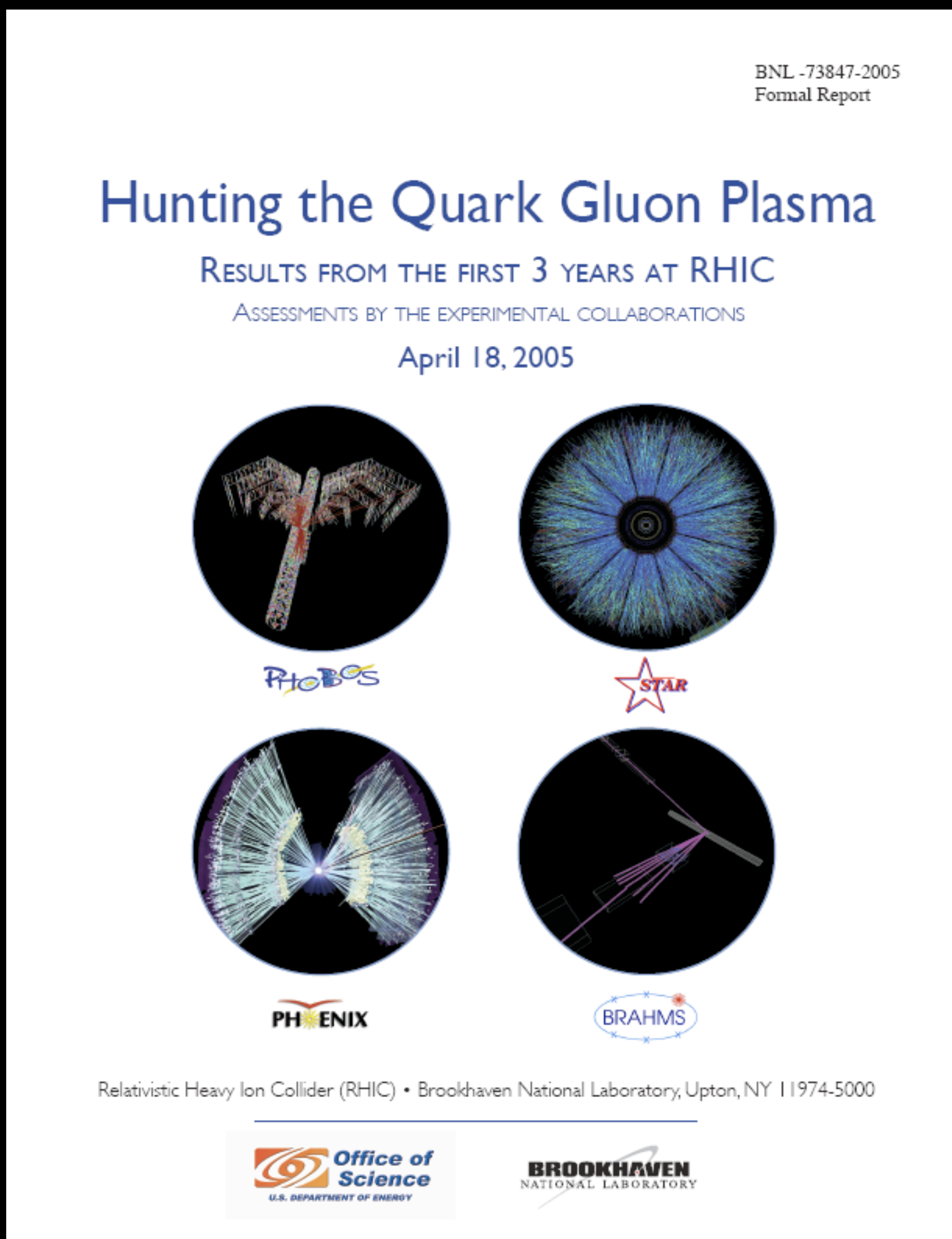
Elliptic flow is large

Ideal hydro gets the magnitude for more central collisions

RHIC Scientists Serve Up "Perfect" Liquid

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

April 18, 2005


BNL -73847-2005
Formal Report

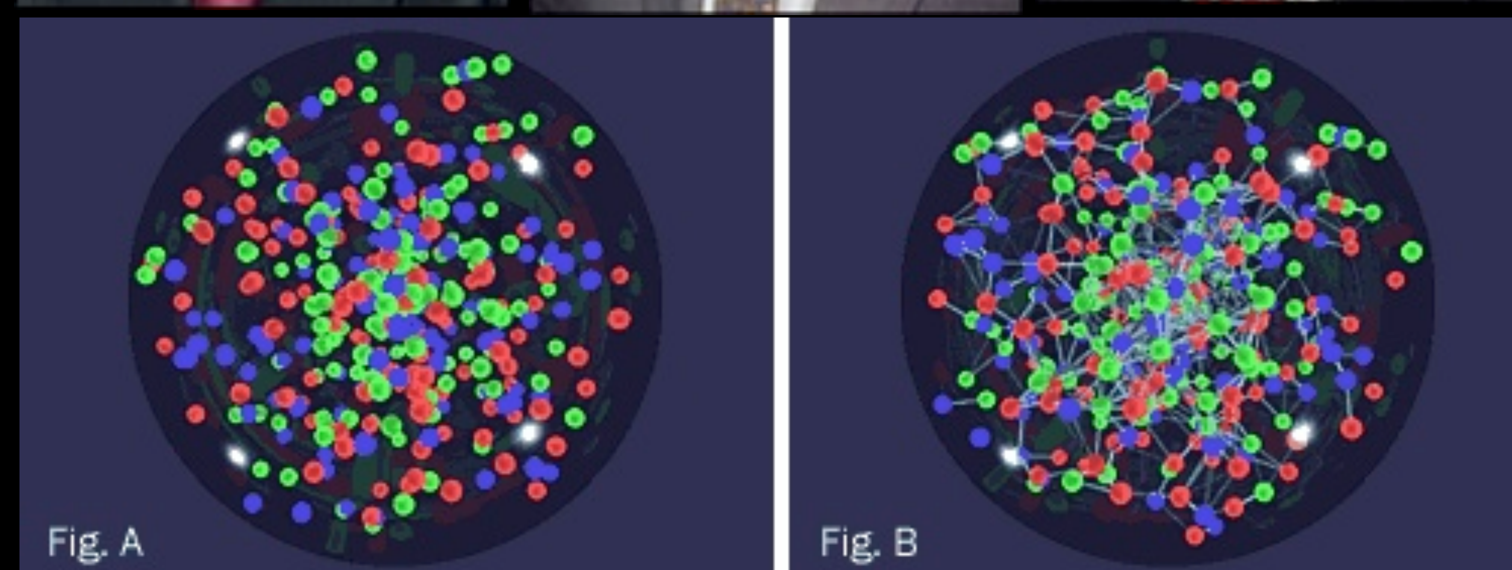
Hunting the Quark Gluon Plasma

RESULTS FROM THE FIRST 3 YEARS AT RHIC

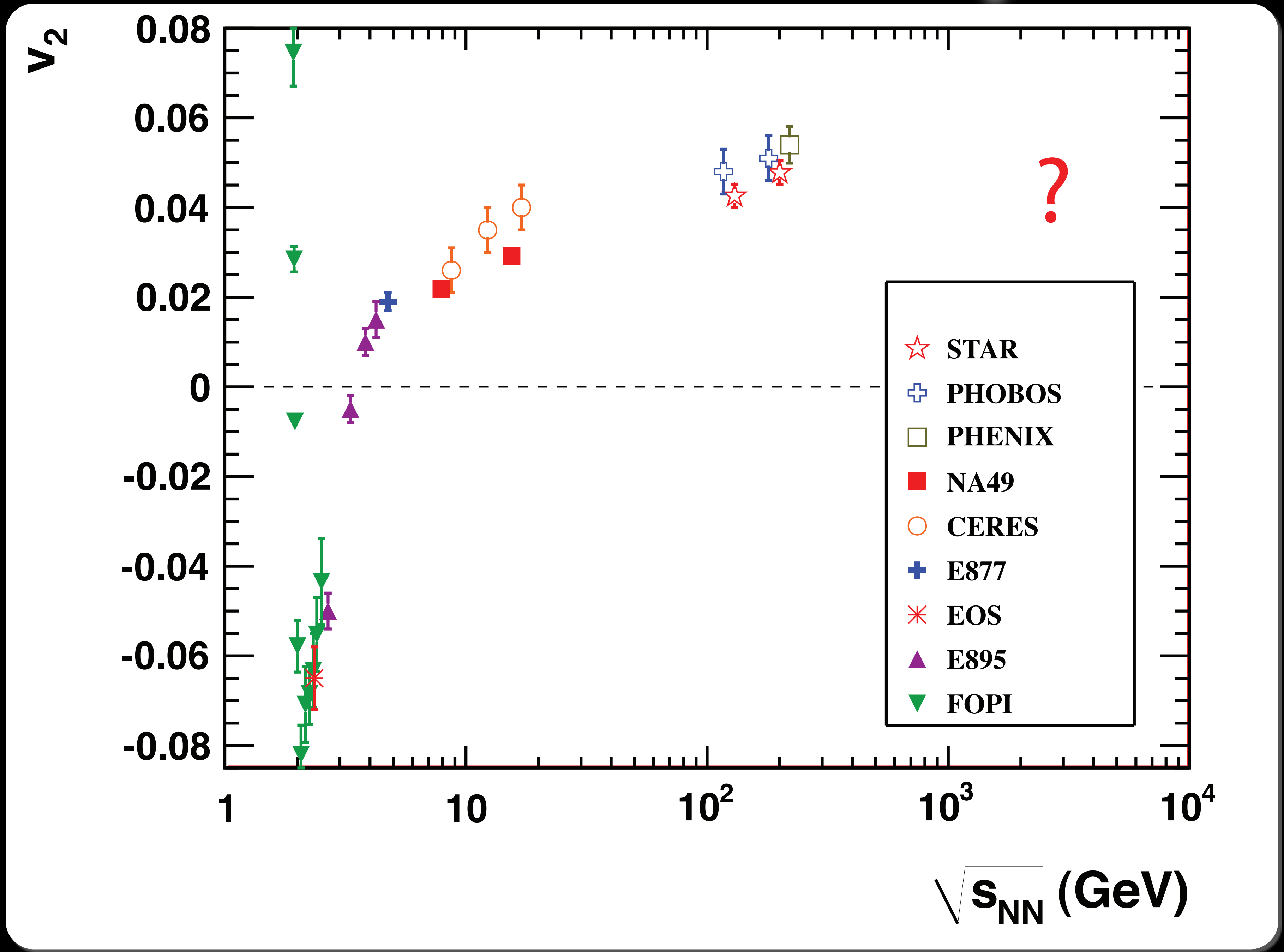
ASSESSMENTS BY THE EXPERIMENTAL COLLABORATIONS

April 18, 2005

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



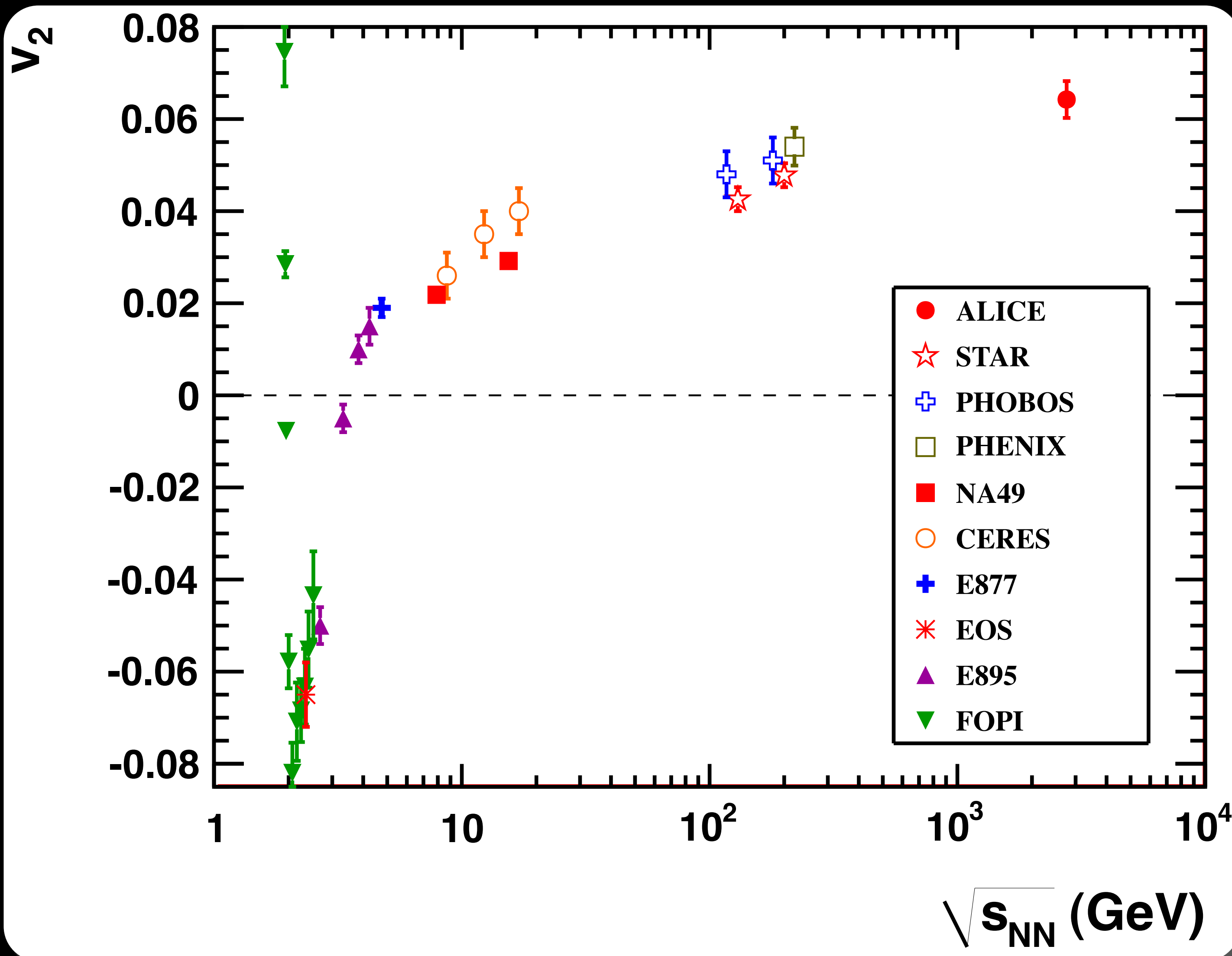
The Perfect Liquid?

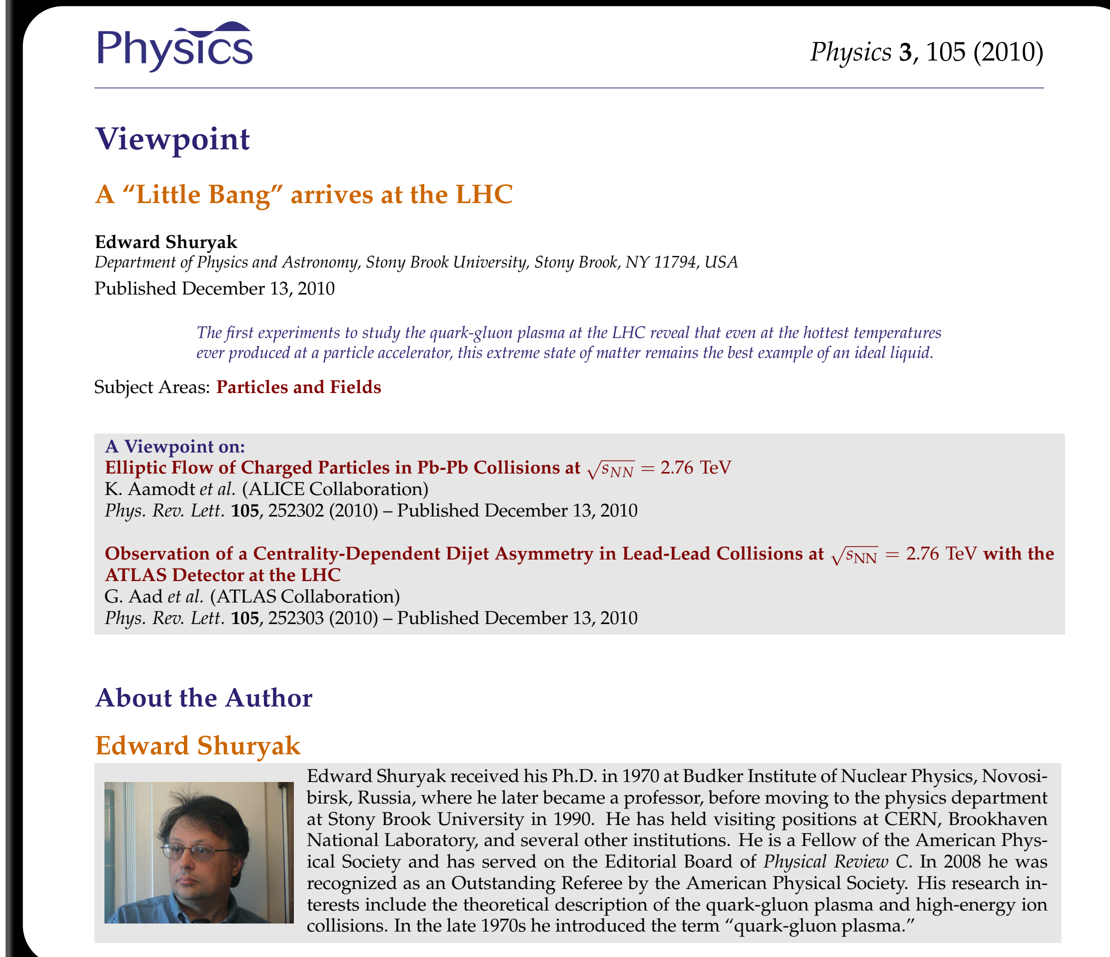


What to expect at the LHC: still the perfect liquid or approaching a viscous ideal gas?

The Perfect Liquid?

K. Aamodt et al. (ALICE Collaboration) PRL 105, 252302 (2010)





Physics | *Physics* **3**, 105 (2010)

Viewpoint

A "Little Bang" arrives at the LHC

Edward Shuryak
Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794, USA
Published December 13, 2010

The first experiments to study the quark-gluon plasma at the LHC reveal that even at the hottest temperatures ever produced at a particle accelerator, this extreme state of matter remains the best example of an ideal liquid.

Subject Areas: **Particles and Fields**

A Viewpoint on:
Elliptic Flow of Charged Particles in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV
K. Aamodt *et al.* (ALICE Collaboration)
Phys. Rev. Lett. **105**, 252302 (2010) – Published December 13, 2010

Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS Detector at the LHC
G. Aad *et al.* (ATLAS Collaboration)
Phys. Rev. Lett. **105**, 252303 (2010) – Published December 13, 2010

About the Author

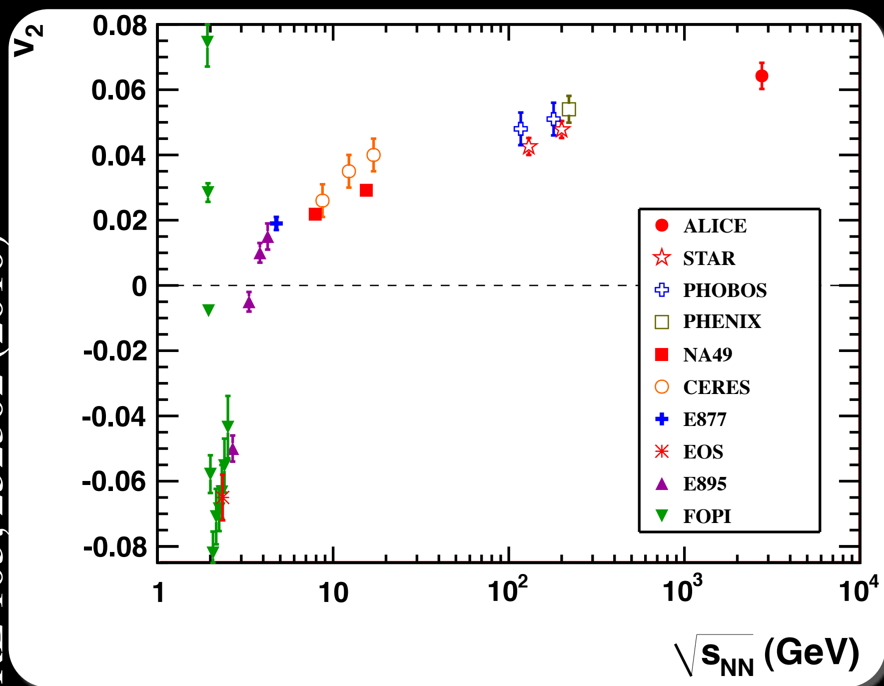
Edward Shuryak

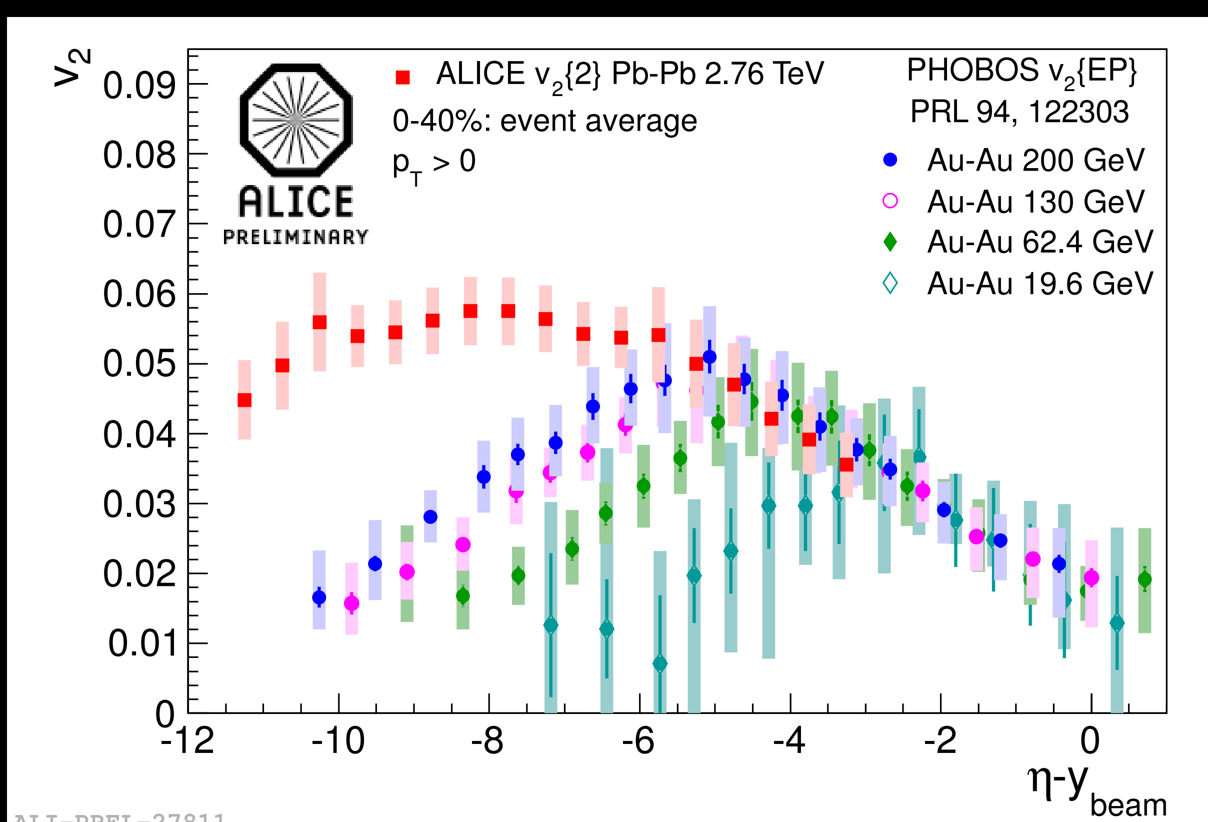
Edward Shuryak received his Ph.D. in 1970 at Budker Institute of Nuclear Physics, Novosibirsk, Russia, where he later became a professor, before moving to the physics department at Stony Brook University in 1990. He has held visiting positions at CERN, Brookhaven National Laboratory, and several other institutions. He is a Fellow of the American Physical Society and has served on the Editorial Board of *Physical Review* C. In 2008 he was recognized as an Outstanding Referee by the American Physical Society. His research interests include the theoretical description of the quark-gluon plasma and high-energy ion collisions. In the late 1970s he introduced the term "quark-gluon plasma."

CERN, November 26, 2010:
'the much hotter plasma produced at the LHC behaves as a very low viscosity liquid (a perfect fluid)..'

First LHC v_2 measurement

K. Aamodt et al. (ALICE Collaboration) PRL 105, 252302 (2010)





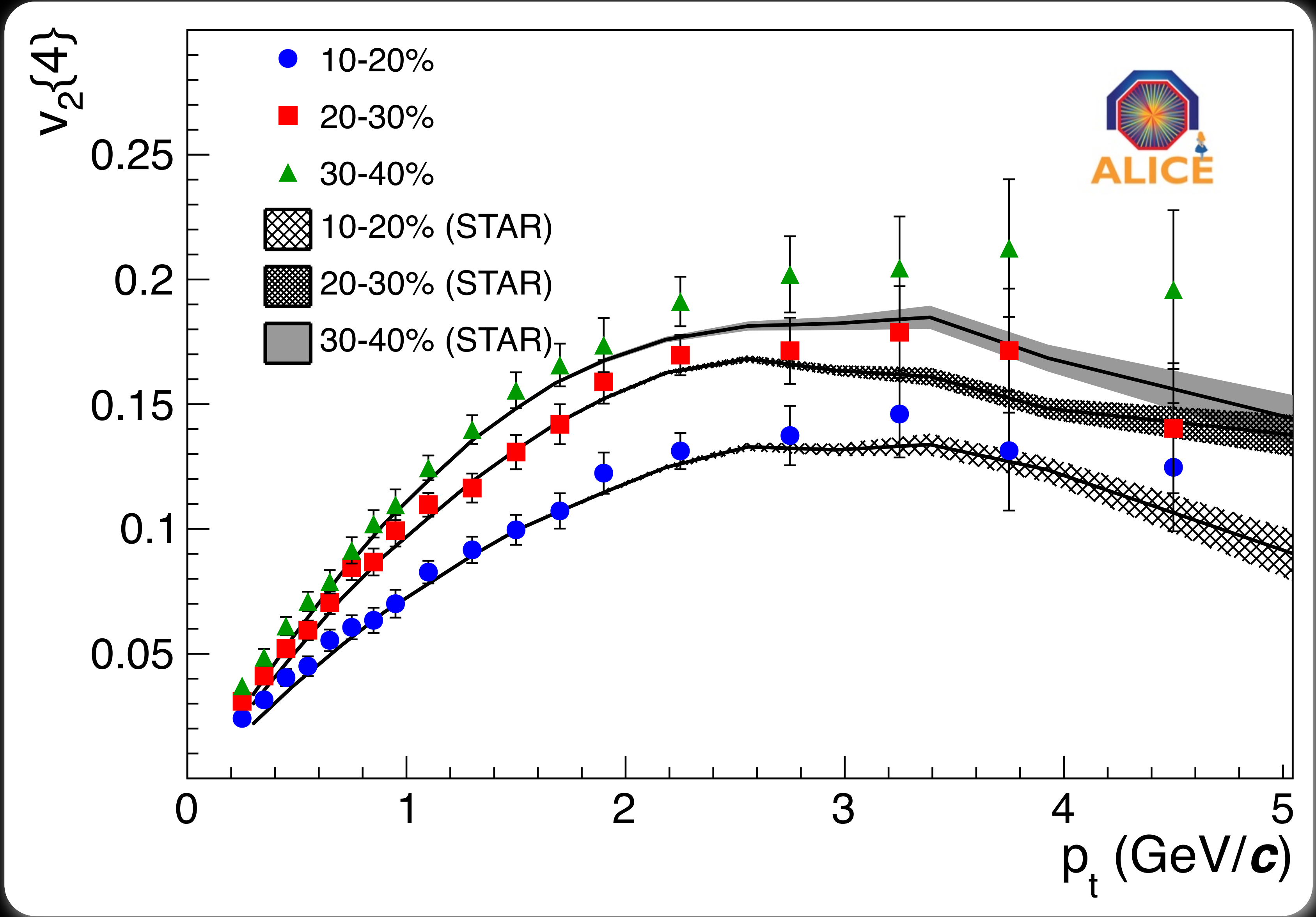
1) not in line with expectations from pure ideal hydro (measured v_2 increased too much)

2) not in line with simple triangular scaling

3) in line with expectations from models incorporating viscous corrections (viscous hydro, parton cascades, hybrid models)

v_2 as function of p_t

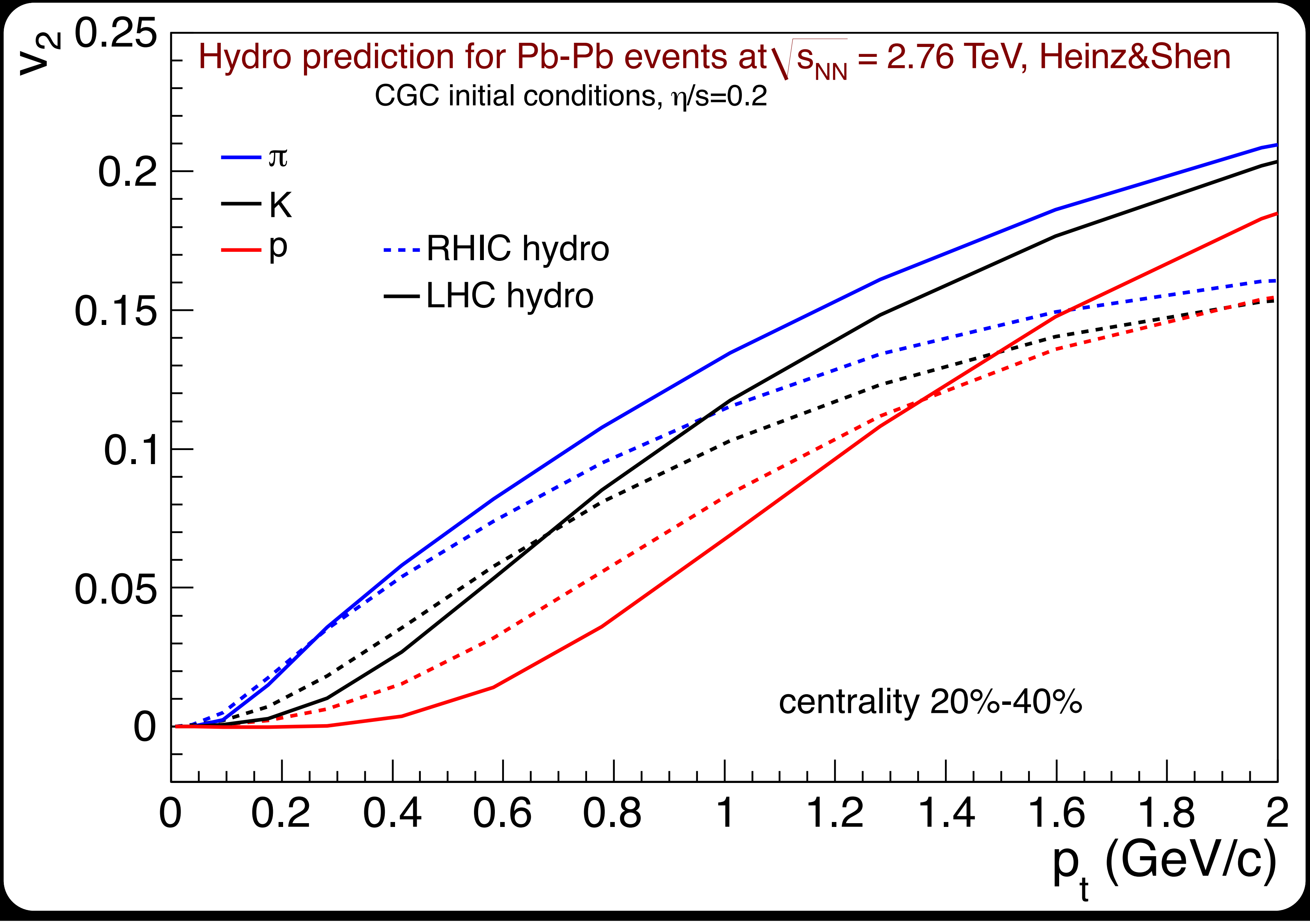
K. Aamodt et al. (ALICE Collaboration)
PRL 105, 252302 (2010)



Elliptic flow as function of transverse momentum does not change much from RHIC to LHC energies, can we understand that?

v_2 as function of p_t

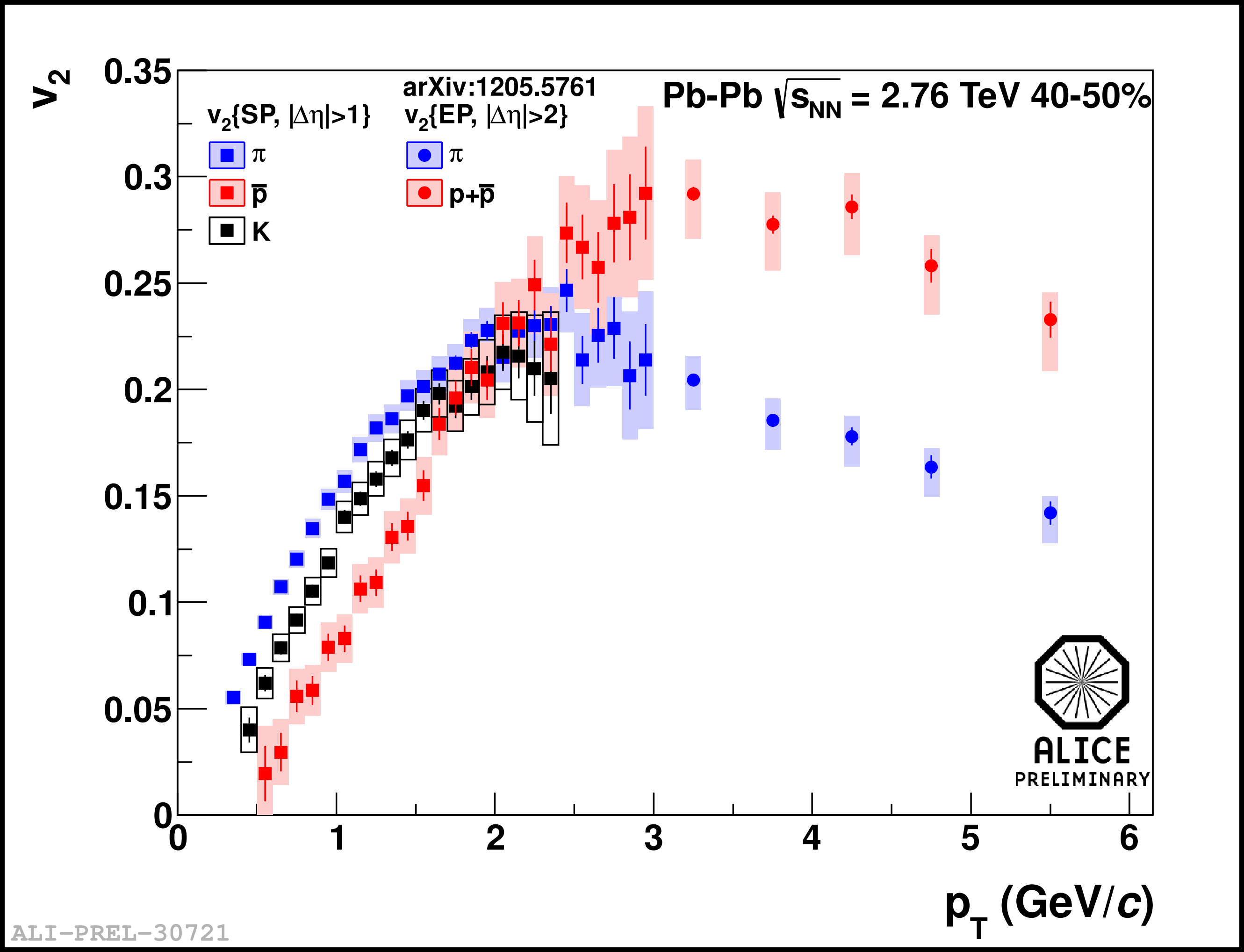
Hydro: Shen, Heinz, Huovinen & Song, arXiv:1105.3226

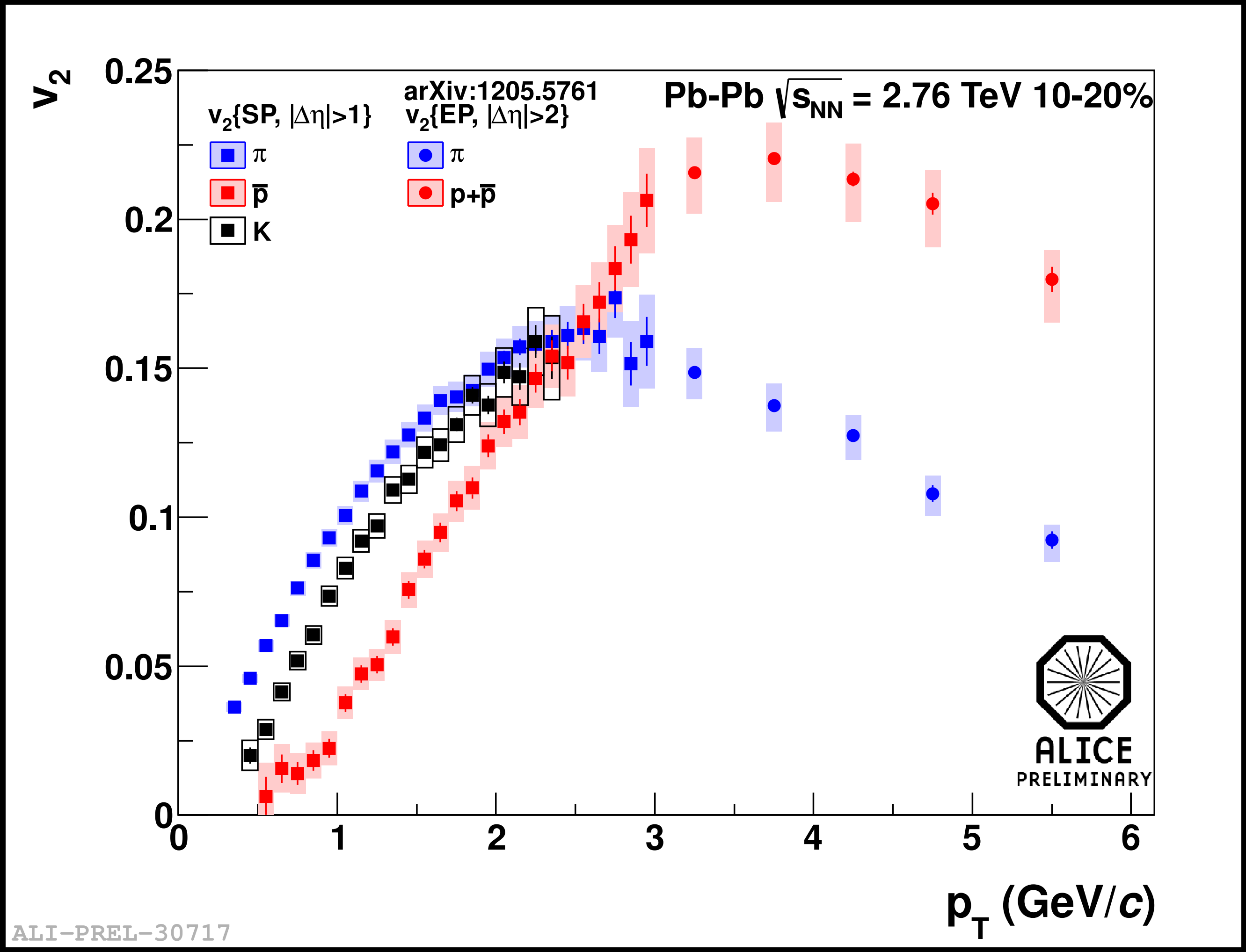


Charged particle flow sums contributions of different mass particles which do individually change significantly as function of beam energy according to hydro

This prediction we can test

Mass dependence of $v_2(p_t)$

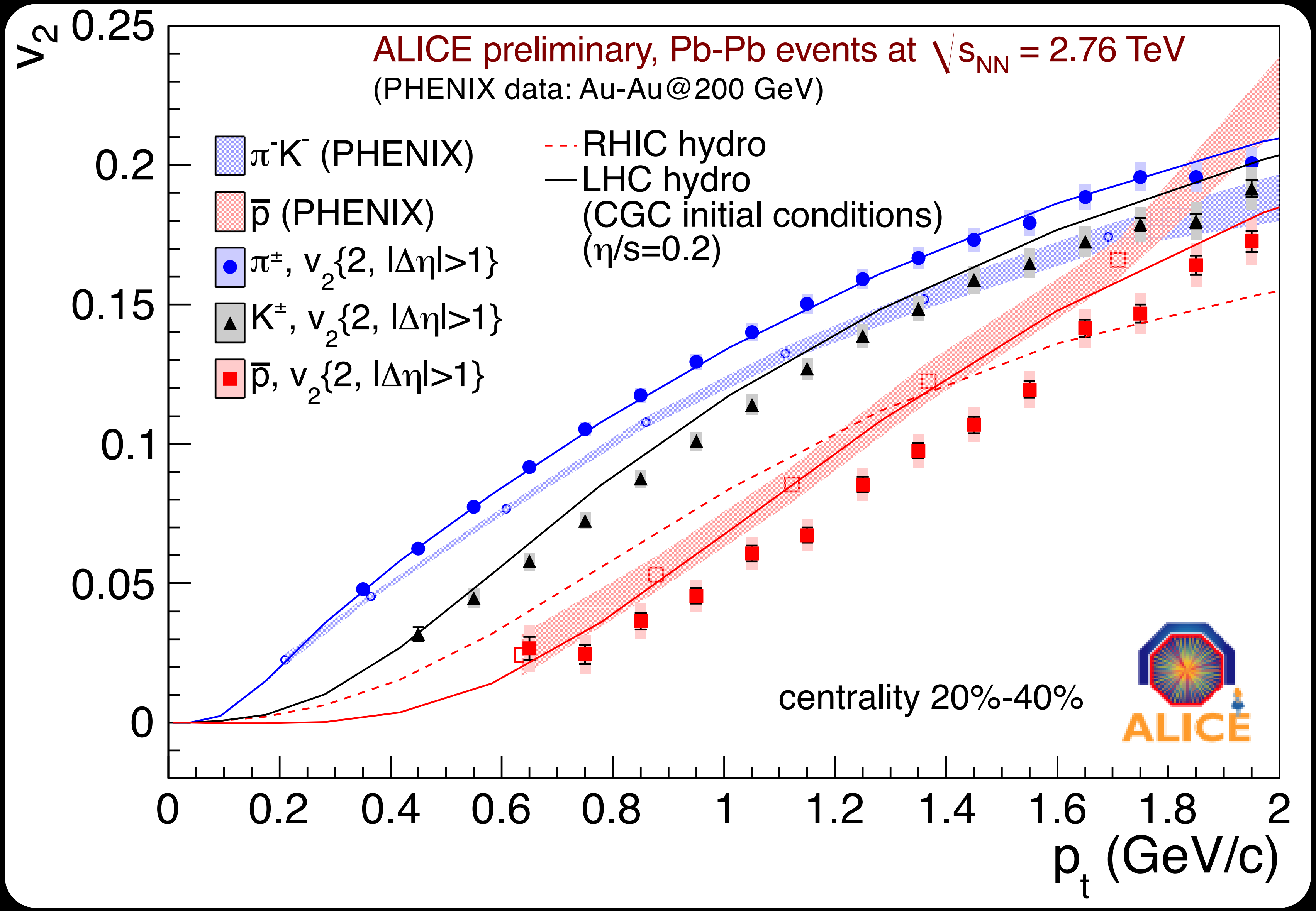




centrality dependence clearly shows the effect of increasing radial flow

Mass dependence of $v_2(p_t)$

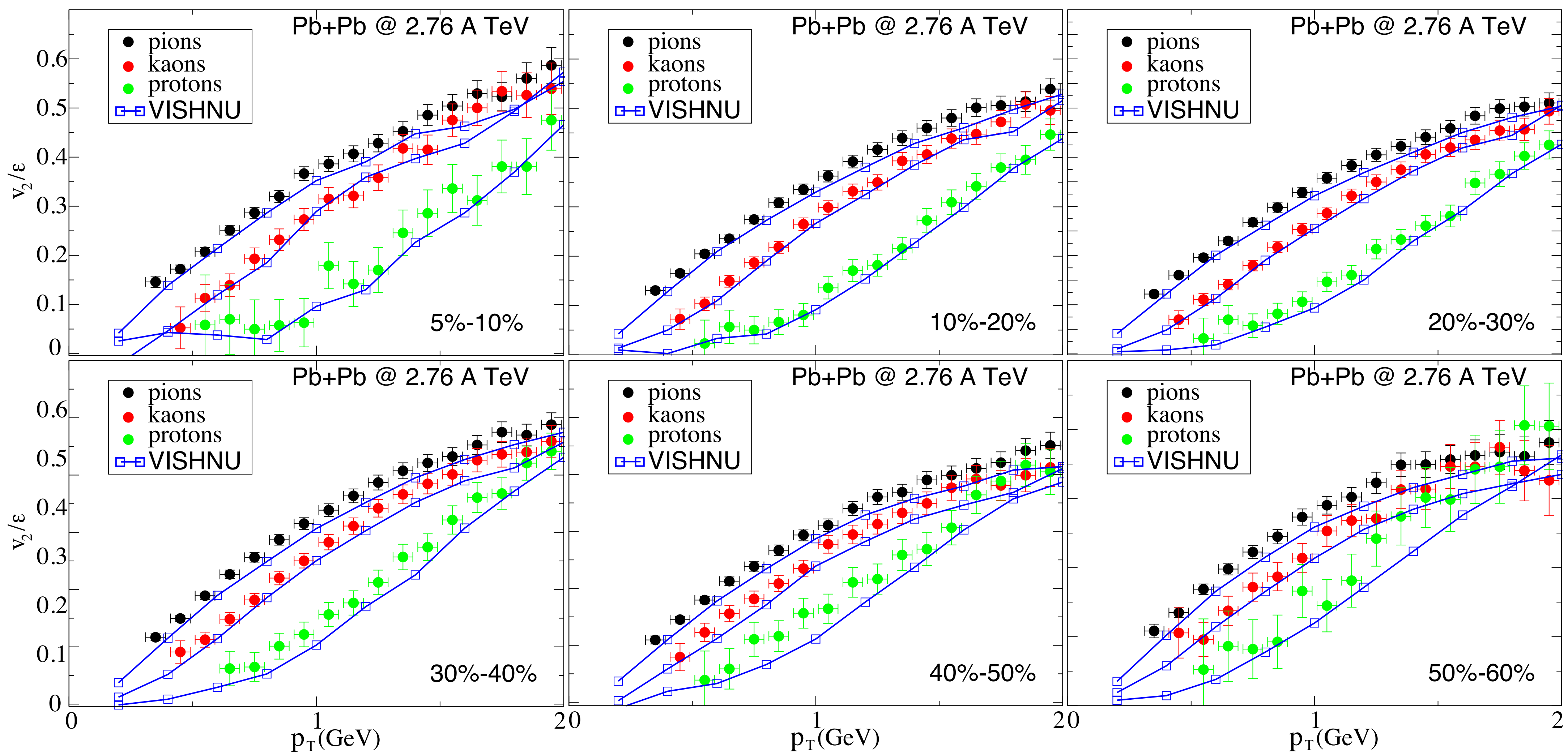
Hydro: Shen, Heinz, Huovinen & Song, arXiv:1105.3226



viscous hydro does capture energy dependence but fails quantitatively for the protons in more central collisions (both for RHIC and the LHC!)

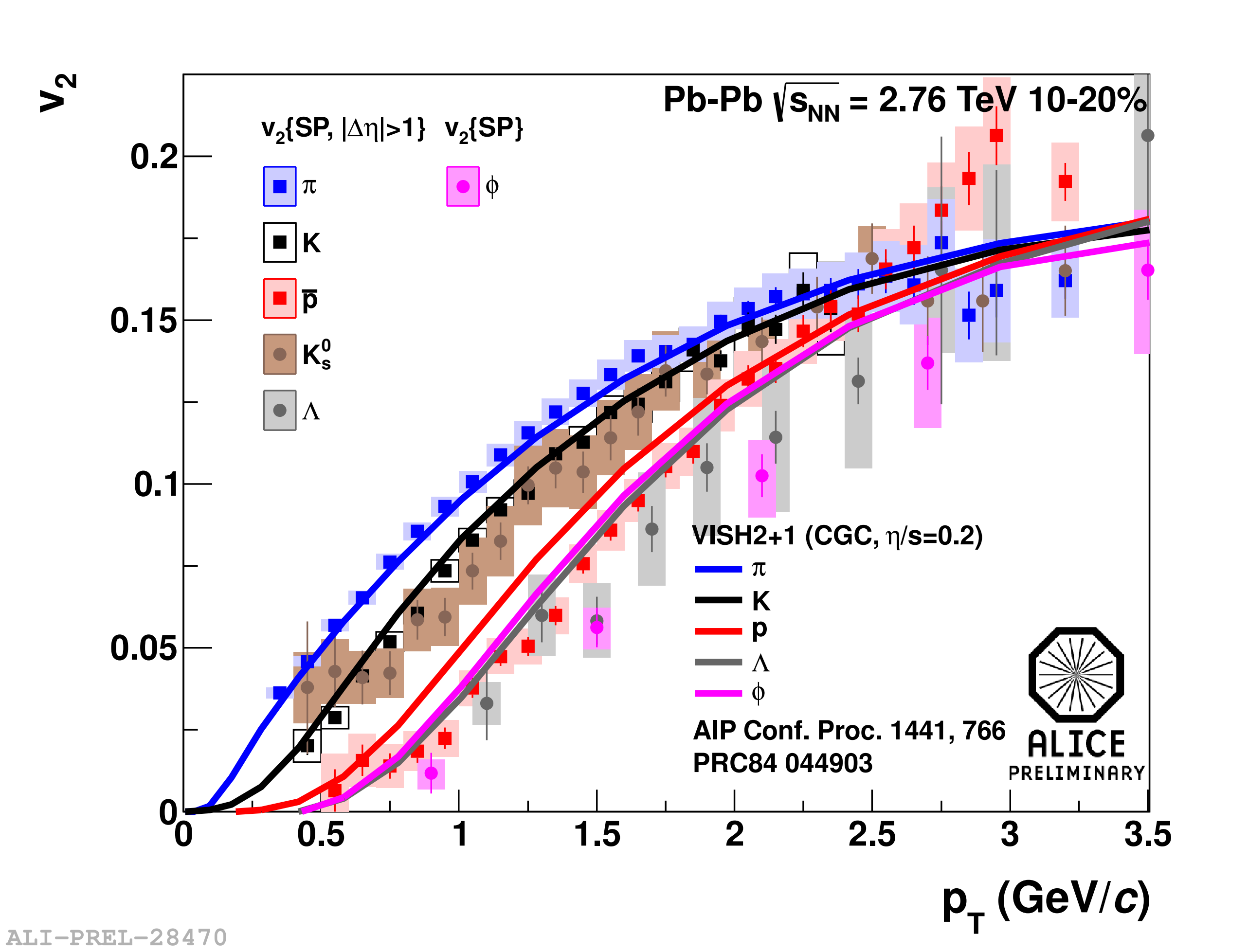
Mass dependence of $v_2(p_t)$

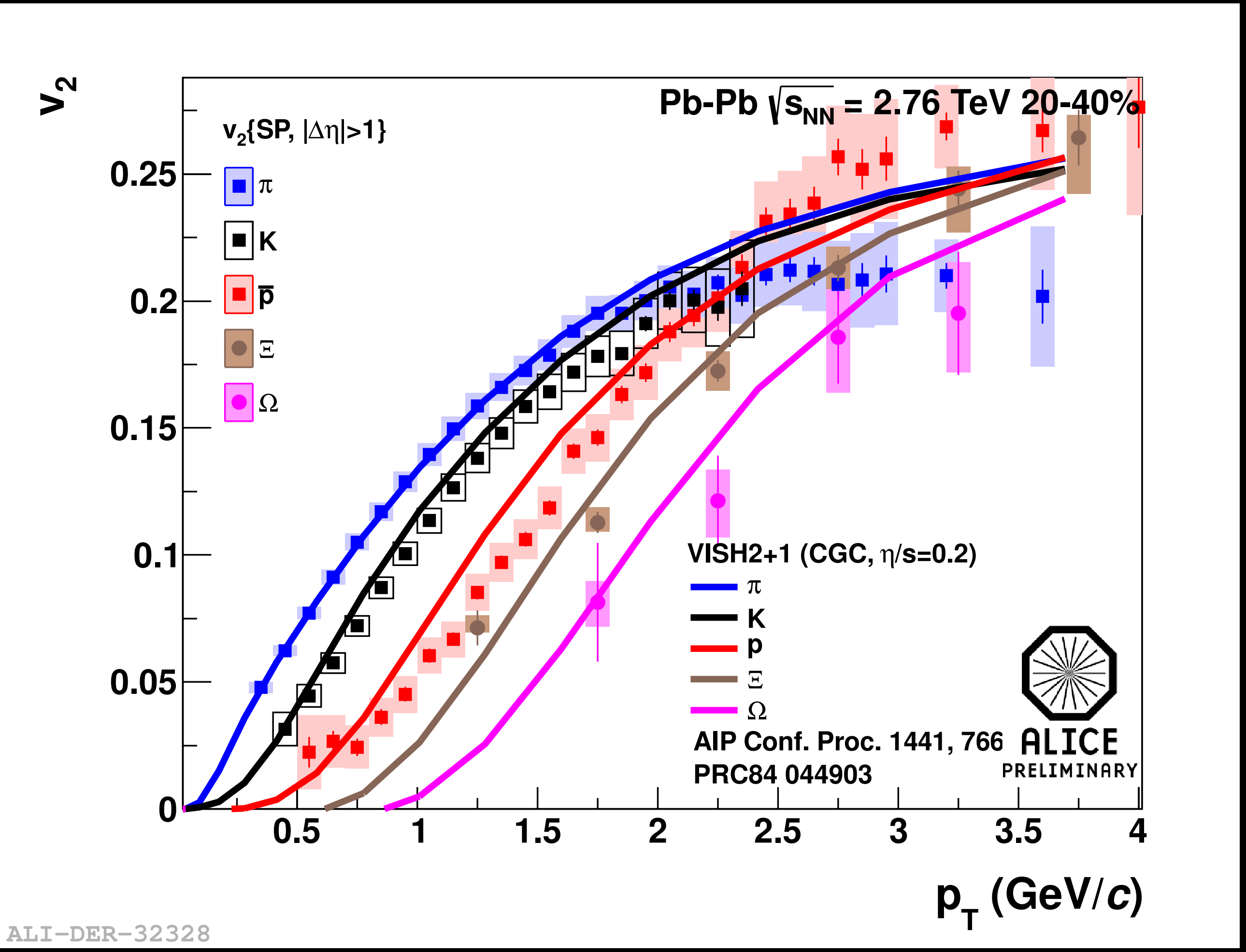
U. Heinz, C. Shen, and H. Song arXiv:1108.5323



Hybrid calculations (VISHNU) fix the more central collisions
Is there a strong contribution from the hadronic phase?

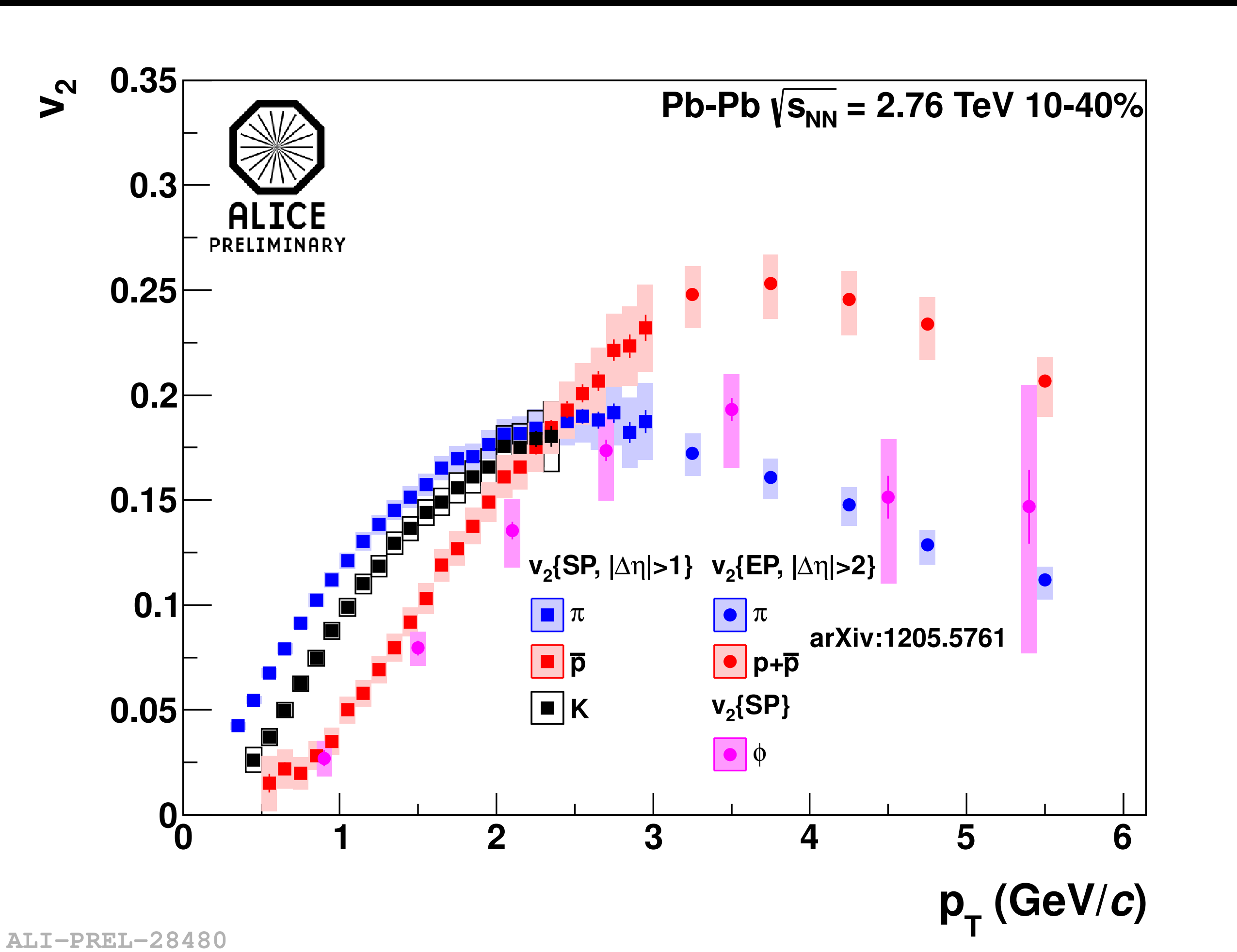
Mass dependence of $v_2(p_t)$

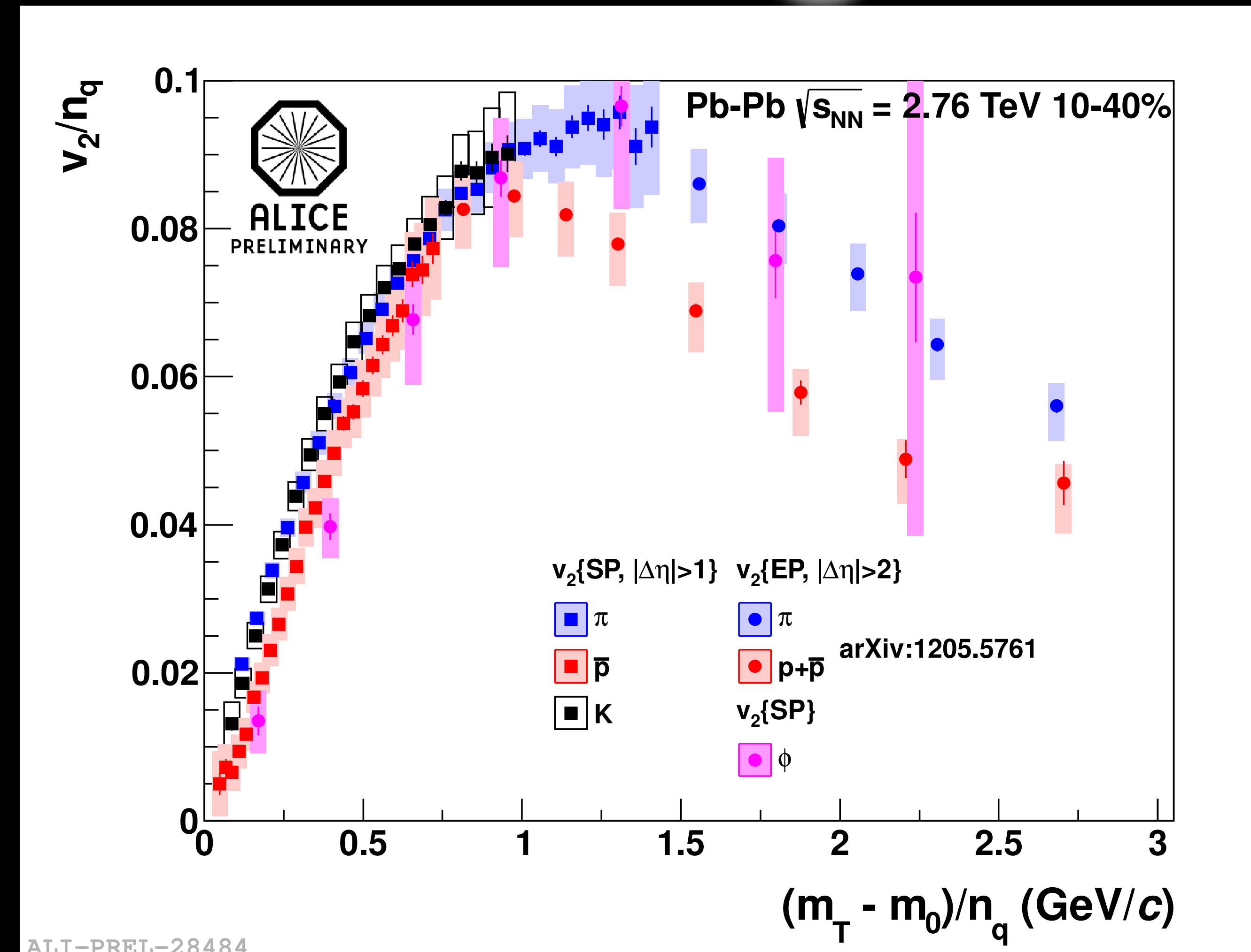


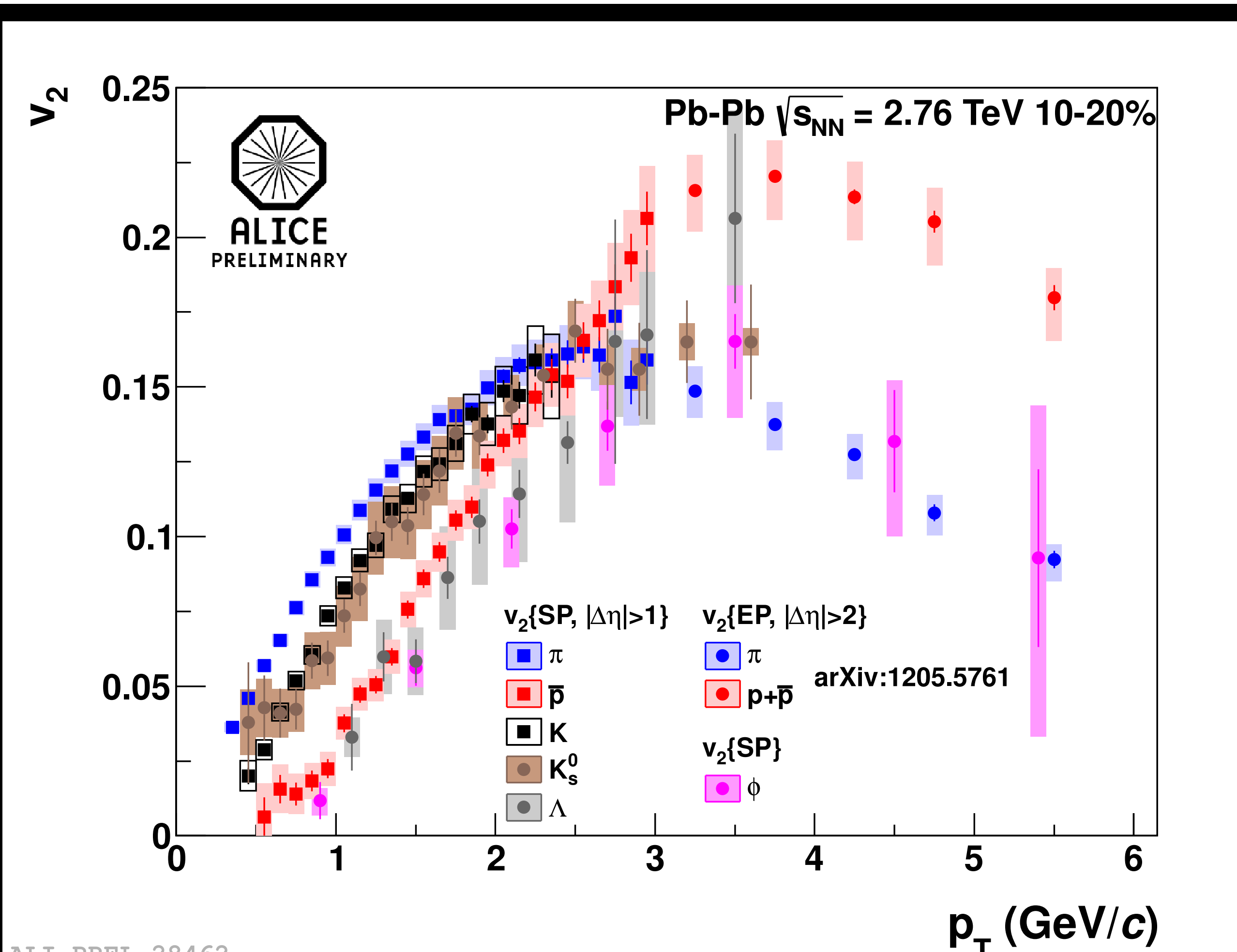


The phi meson is also not described by pure viscous hydro
The multi-strange baryons are closer to viscous hydro
Is this in line with expectations from an hadronic contribution?

Scaling?





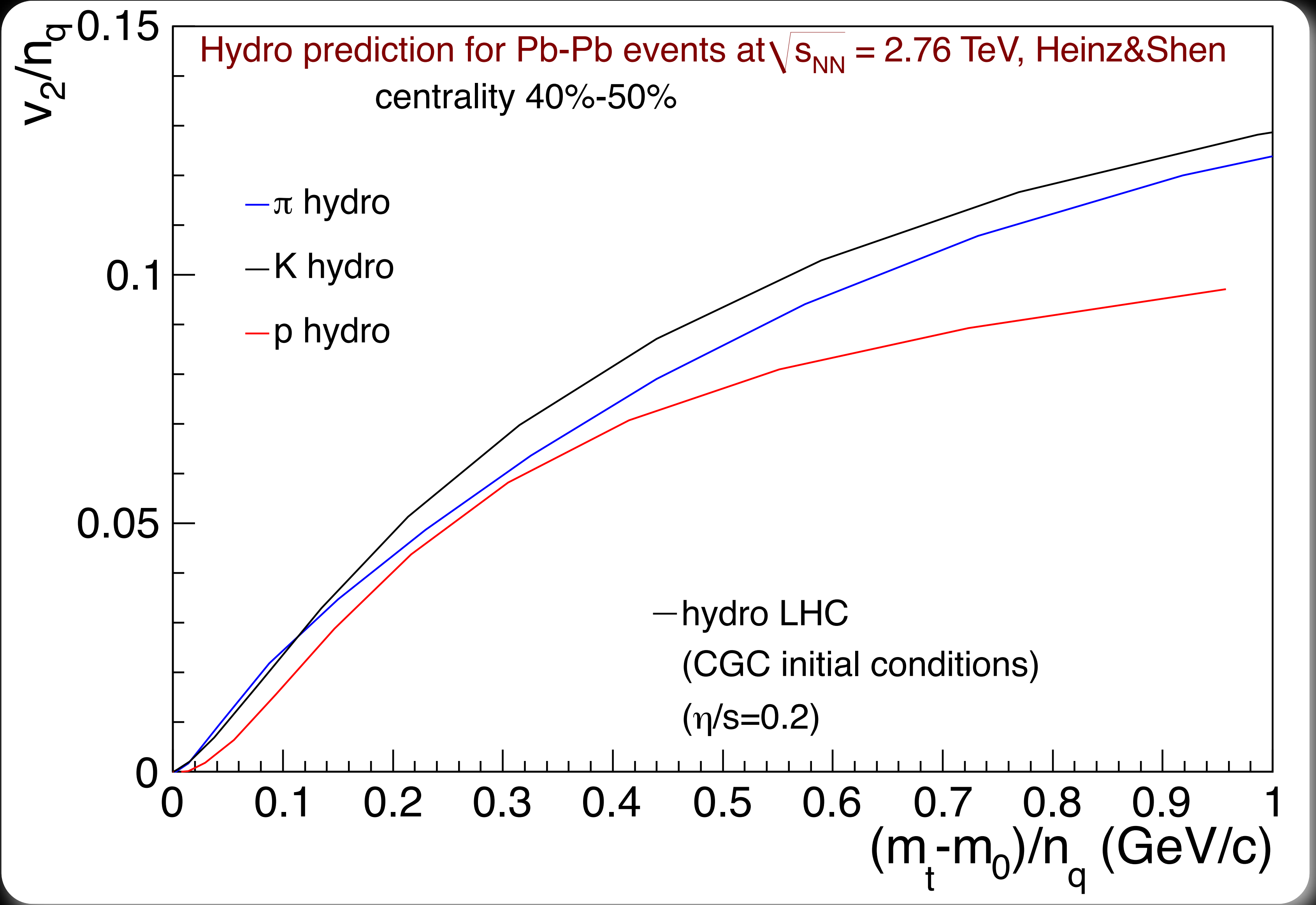


The phi meson follows at low-p_t the mass scaling while at intermediate p_t follows the pions as would be expected in a reco picture

No KET scaling observed

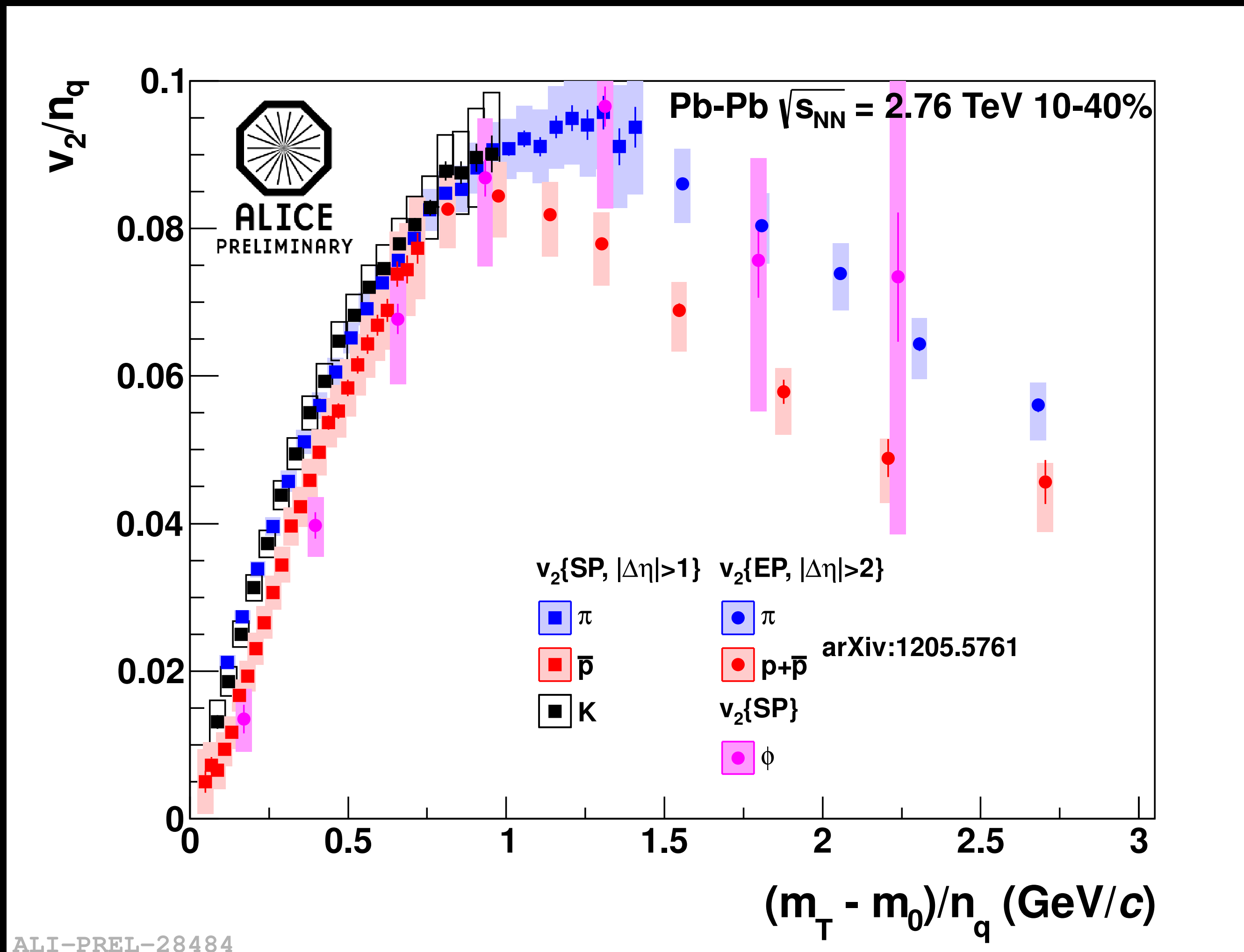
Scaling?

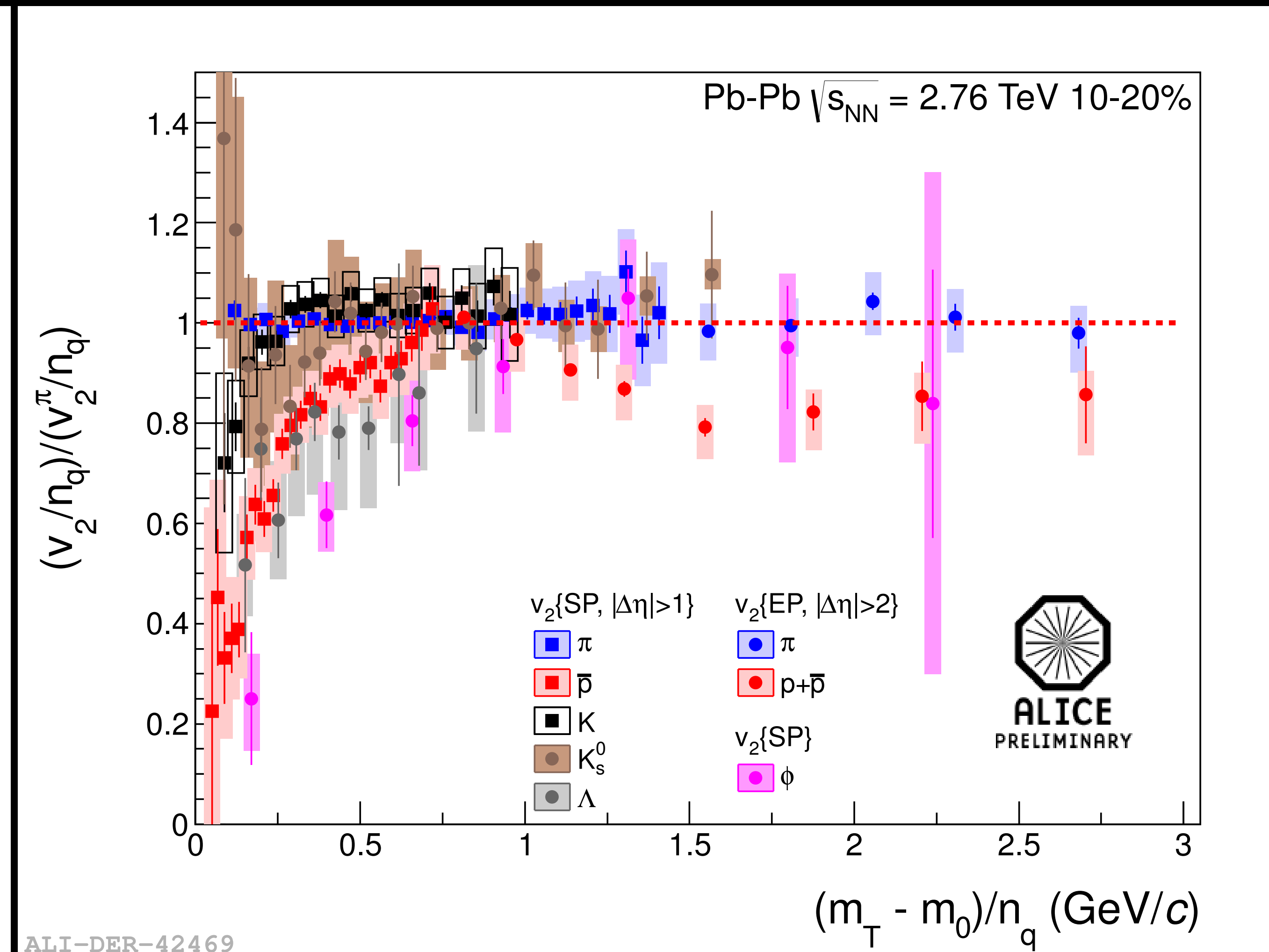
Hydro: Shen, Heinz, Huovinen & Song, arXiv:1105.3226



Viscous hydro and many (most?) models do not show a universal scaling versus KET
In a simple blast-wave model how well the scaling works depends on the magnitude of the transverse flow

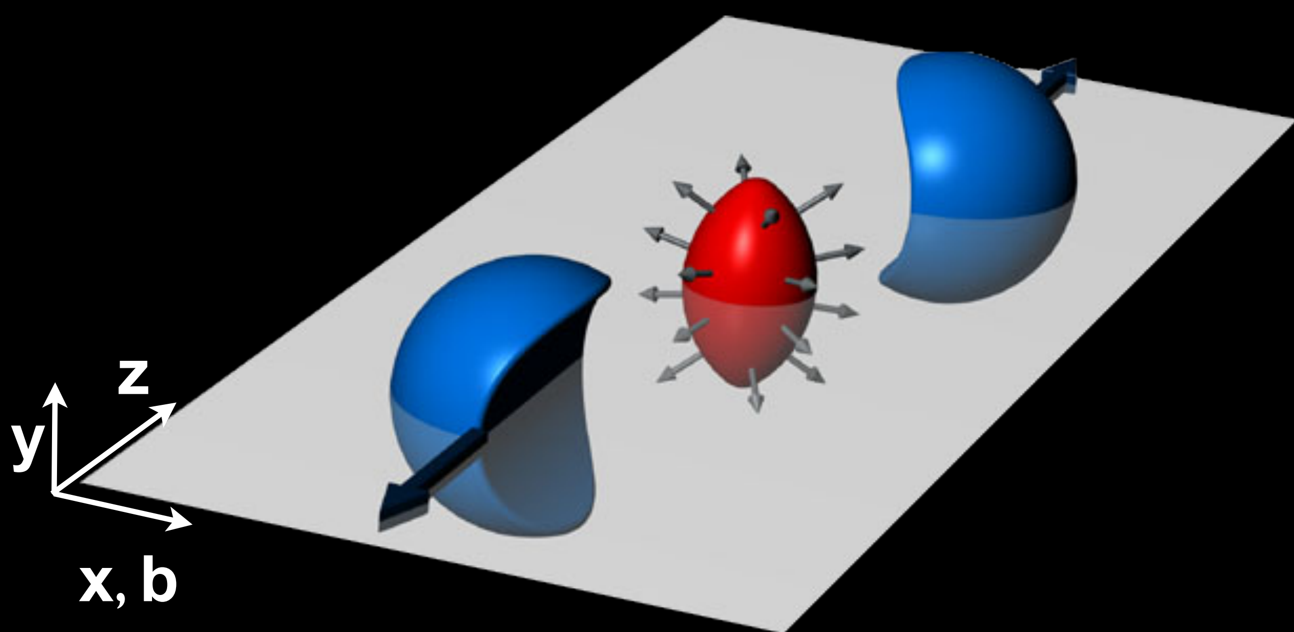
Scaling?





At low p_t the mass ordering of the breaking of the KET scaling in the data is in agreement with that in viscous hydro

Anisotropic Flow



Azimuthal distributions of particles measured with respect to the reaction plane (spanned by impact parameter vector and beam axis) are not isotropic.

$$E\frac{d^3N}{d^3\vec{p}} = \frac{1}{2\pi}\frac{d^2N}{p_T\,dp_T\,dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos\left(n\left(\phi-\Psi_{\mathrm{RP}}\right)\right)\right)$$

$$v_n = \langle \cos n(\phi - \Psi_{\mathrm{RP}})\rangle$$

harmonics v_n quantify anisotropic flow

S. Voloshin and Y. Zhang (1996)

v_n is not an observable

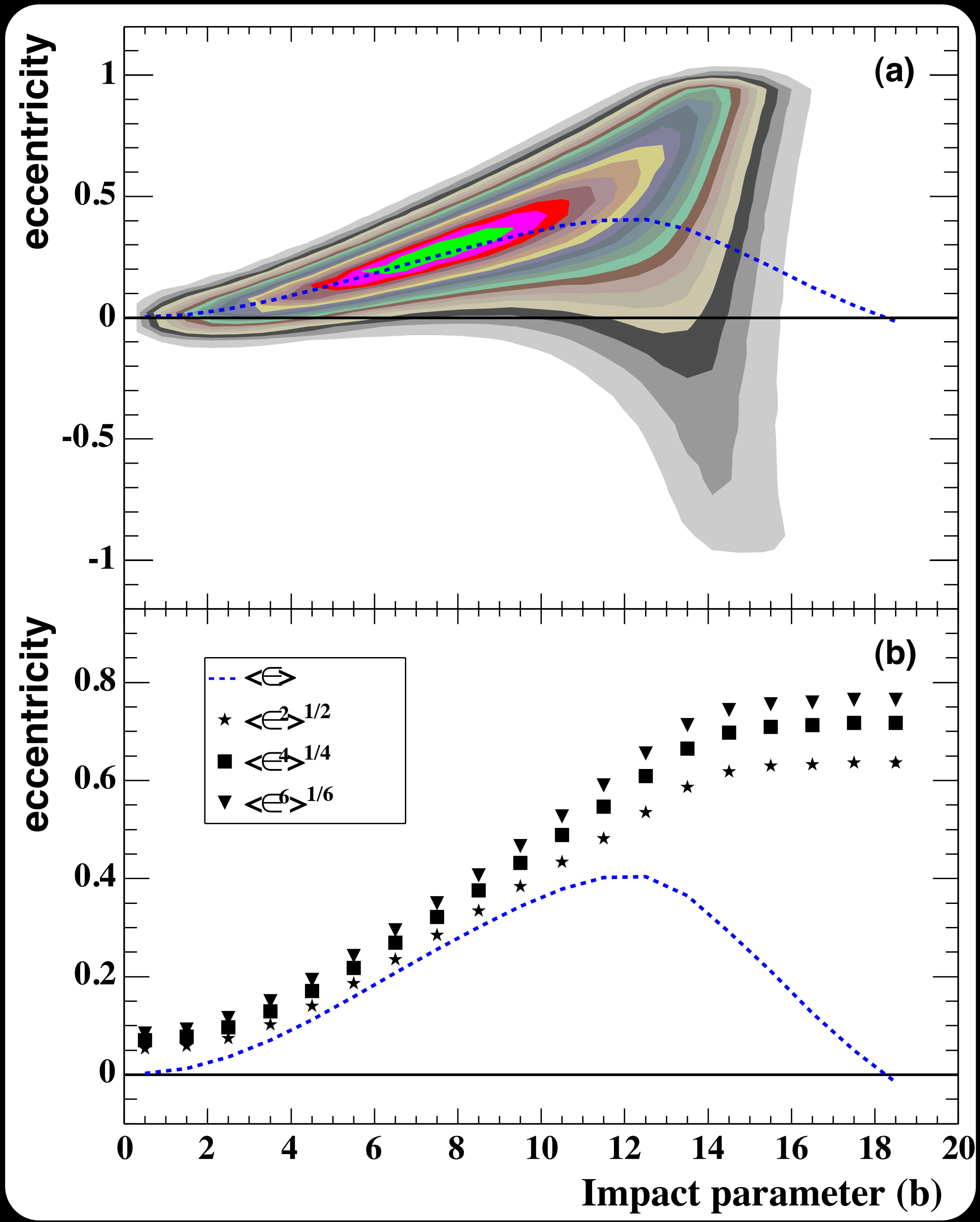
$$\langle v_n \rangle = \langle \langle e^{in(\phi_1 - \Psi_n)} \rangle \rangle$$

- since the common symmetry planes cannot be measured event-by-event, we measure quantities which do not depend on it's orientation: multi-particle azimuthal correlations

$$\begin{aligned}
\langle \langle e^{in(\phi_1 - \phi_2)} \rangle \rangle &= \langle \langle e^{in(\phi_1 - \Psi_n - (\phi_2 - \Psi_n))} \rangle \rangle \\
&= \langle \langle e^{in(\phi_1 - \Psi_n)} \rangle \langle e^{-in(\phi_2 - \Psi_n)} \rangle \rangle \\
&= \langle v_n^2 \rangle
\end{aligned}$$

- assuming that only correlations with the symmetry plane are present - not a very good assumption (jets, resonances, etc)!

v_2 fluctuations



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

- If v_2 fluctuates

$$\langle v_2 \rangle \neq \sqrt{\langle (v_2)^2 \rangle}$$

- If

$$v_2 \propto \varepsilon$$

- -> fluctuations in the initial conditions change our various observables related to v_2

eccentricity fluctuations and its possible effect on v_2 measurements:
M. Miller and RS, arXiv:nucl-ex/0312008 (2003)
participant eccentricity
PHOBOS QM2005: Nucl. Phys. A774: 523 (2006)

Flow Fluctuations

when (2-particle) nonflow is corrected for or negligible!

in limit of "small" (not necessarily Gaussian) fluctuations

$$v_n^2\{2\} = \bar{v}_n^2 + \sigma_v^2$$

$$v_n^2\{4\} = \bar{v}_n^2 - \sigma_v^2$$

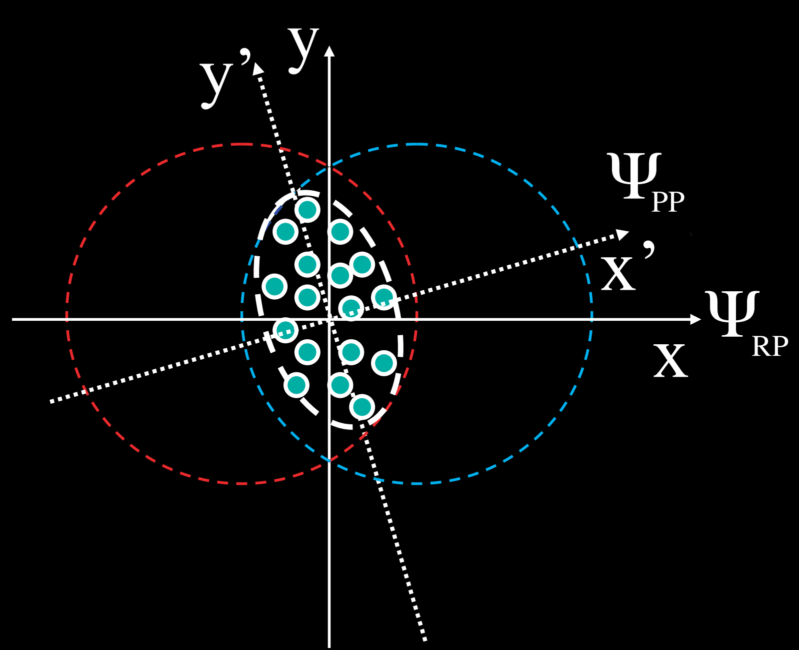
$$v_n^2\{2\} + v_n^2\{4\} = 2\bar{v}_n^2$$

$$v_n^2\{2\} - v_n^2\{4\} = 2\sigma_v^2$$

in limit of only (Gaussian) fluctuations

$$v_n\{4\} = 0$$

$$v_n\{2\} = \frac{2}{\sqrt{\pi}}\bar{v}_n$$



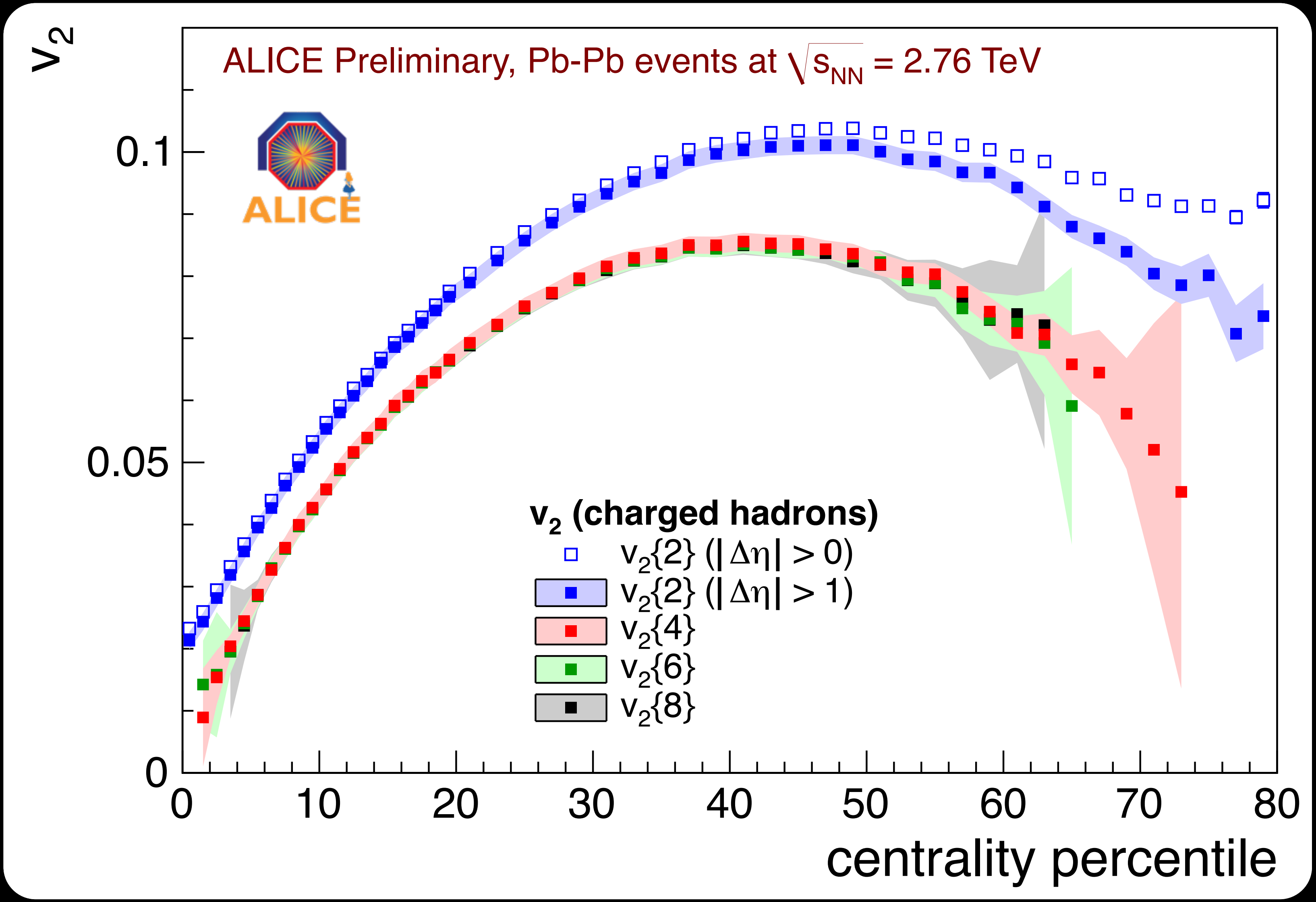
v_2 versus centrality in ALICE

$$v\{2\} = \langle v \rangle + \frac{1}{2}\frac{\sigma_v^2}{\langle v \rangle}$$

$$v\{4\} = \langle v \rangle - \frac{1}{2}\frac{\sigma_v^2}{\langle v \rangle}$$

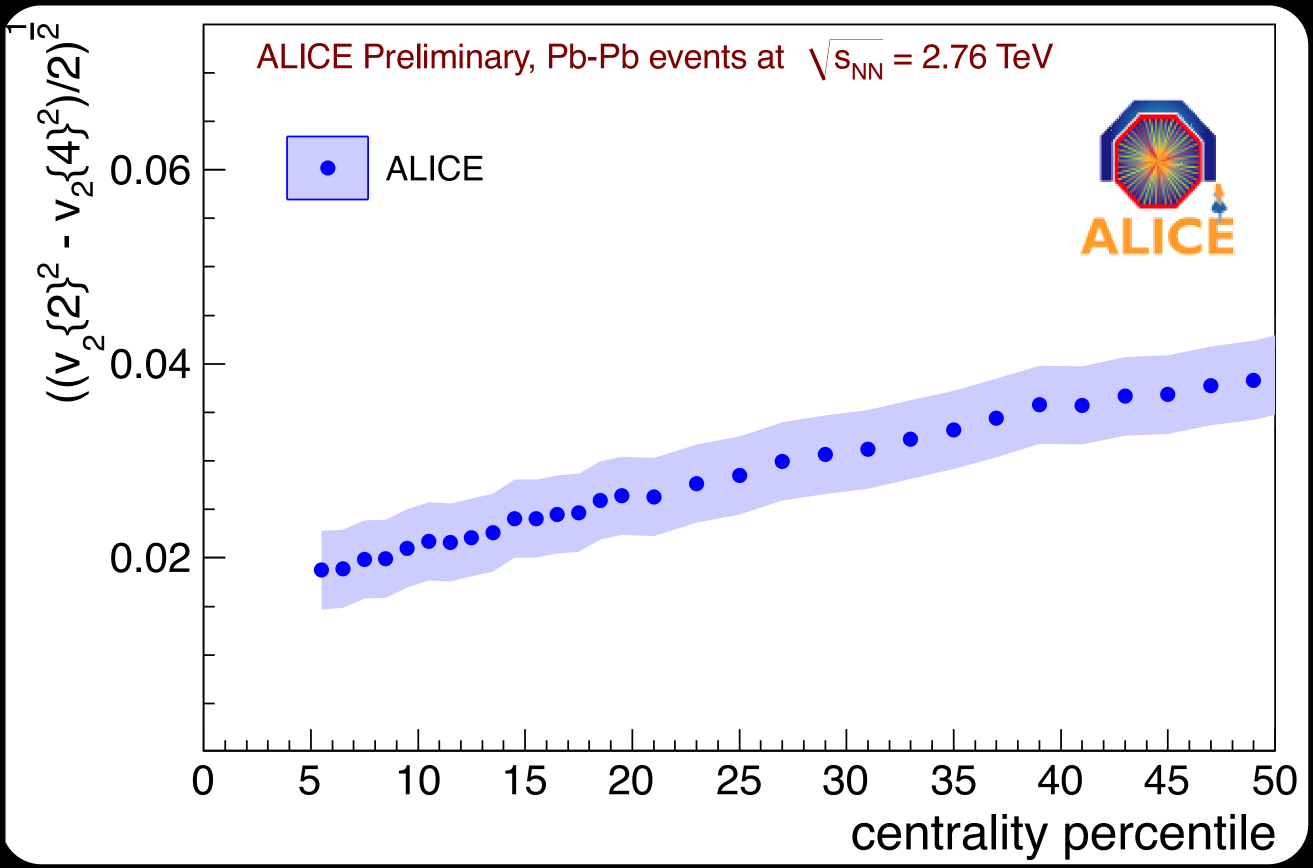
$$v\{6\} = \langle v \rangle - \frac{1}{2}\frac{\sigma_v^2}{\langle v \rangle}$$

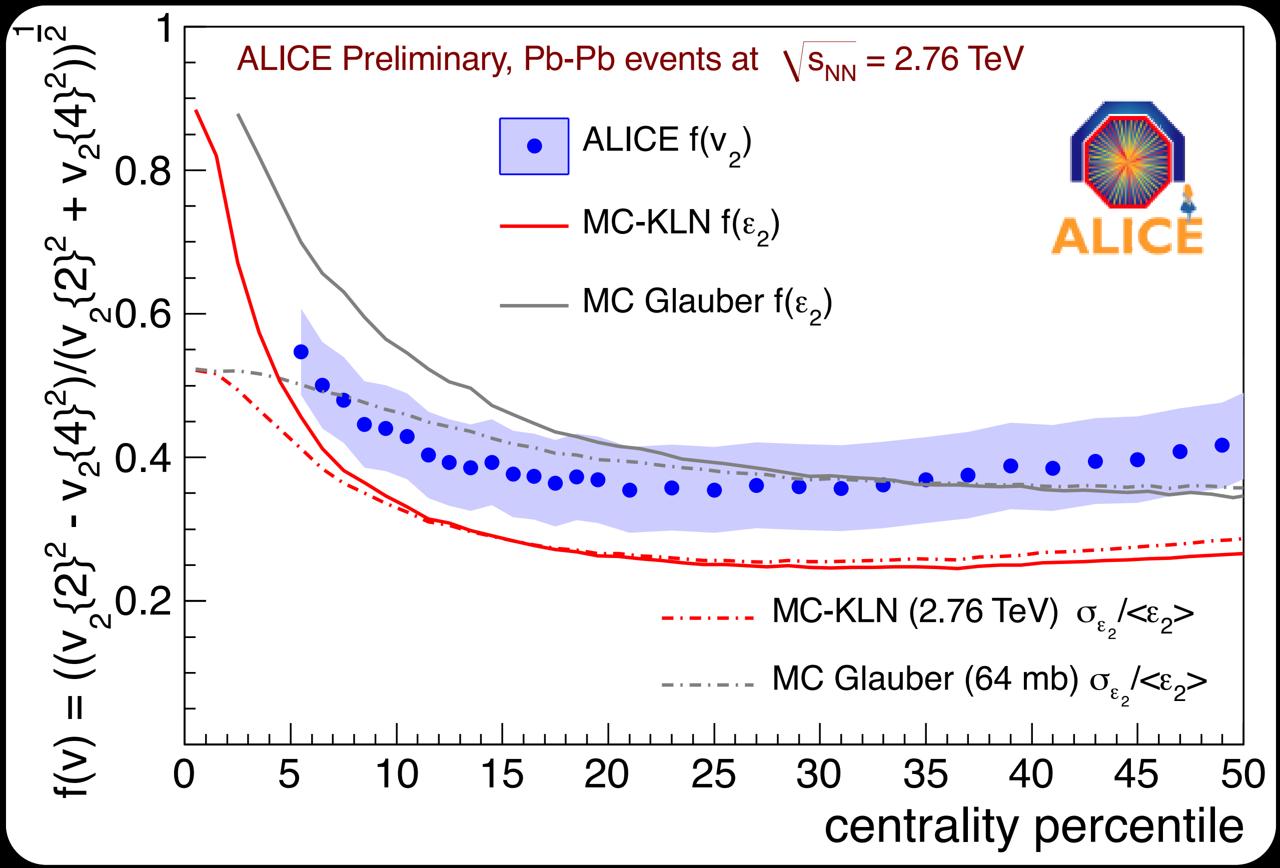
$$v\{8\} = \langle v \rangle - \frac{1}{2}\frac{\sigma_v^2}{\langle v \rangle}$$



Clear separation between $v_2\{2\}$ and higher order cumulants
Higher order cumulant v_2 estimates are consistent within uncertainties

v_2 fluctuations



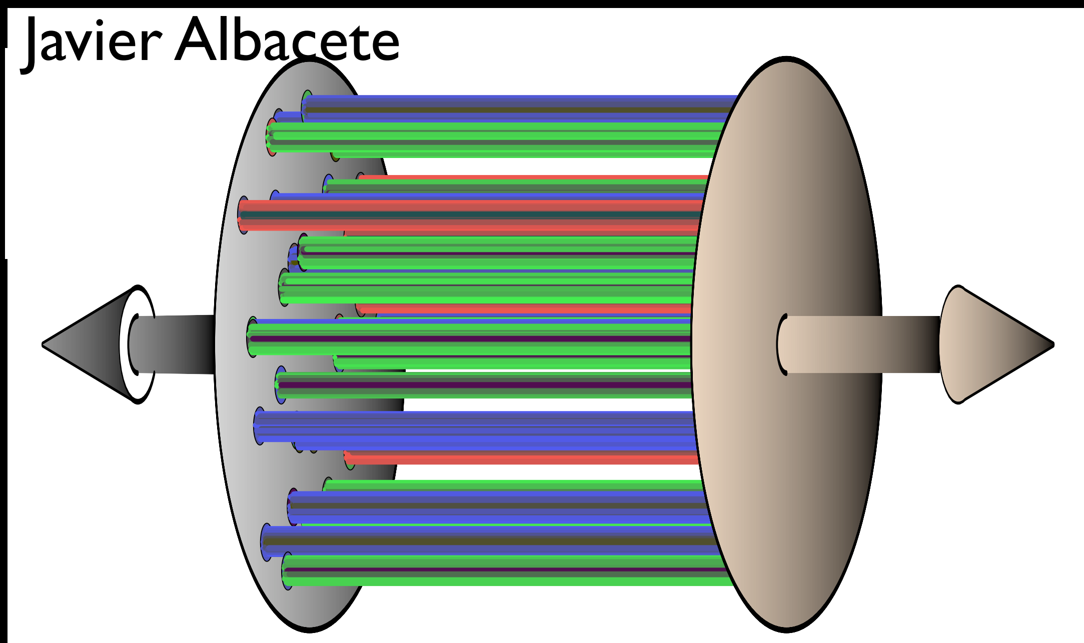


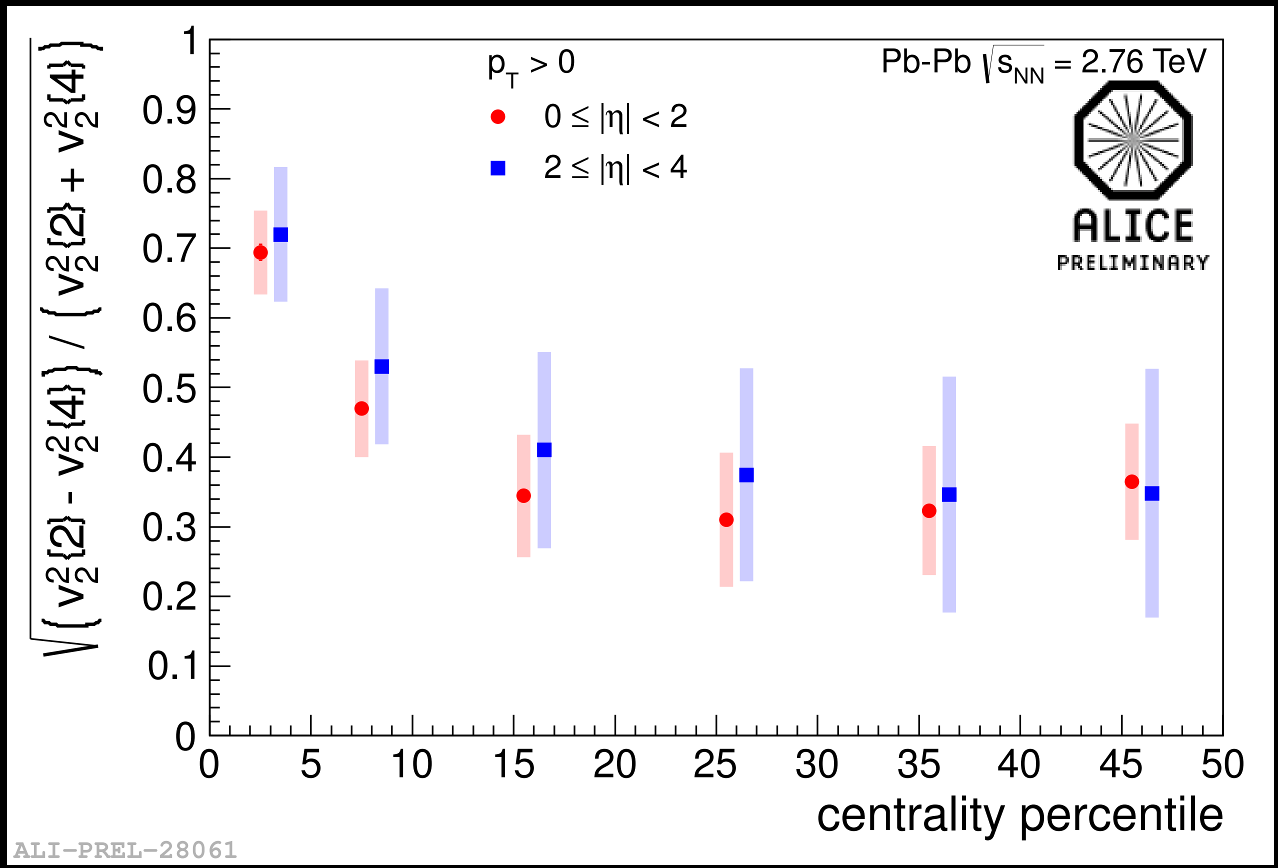
$$\sigma_{v_n} \simeq [\frac{1}{2}\left(v_n^2\{2\} - v_n^2\{4\}\right)]^{\frac{1}{2}}$$

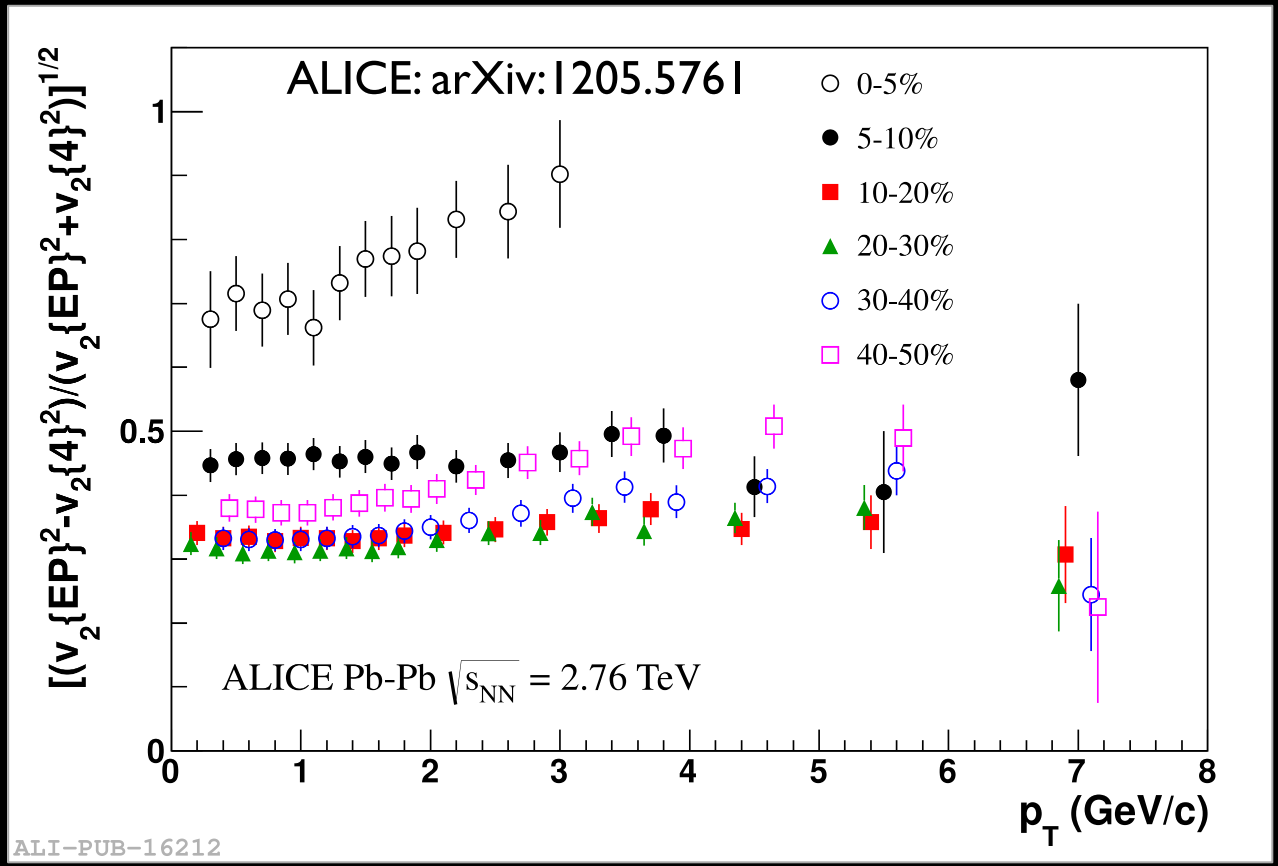
$$\frac{\sigma_{v_n}}{v_n} \simeq \left(\frac{v_n^2\{2\} - v_n^2\{4\}}{v_n^2\{2\} + v_n^2\{4\}}\right)^{\frac{1}{2}}$$

For more central collisions the data is between MC Glauber and MC-KLN CGC

v_2 fluctuations

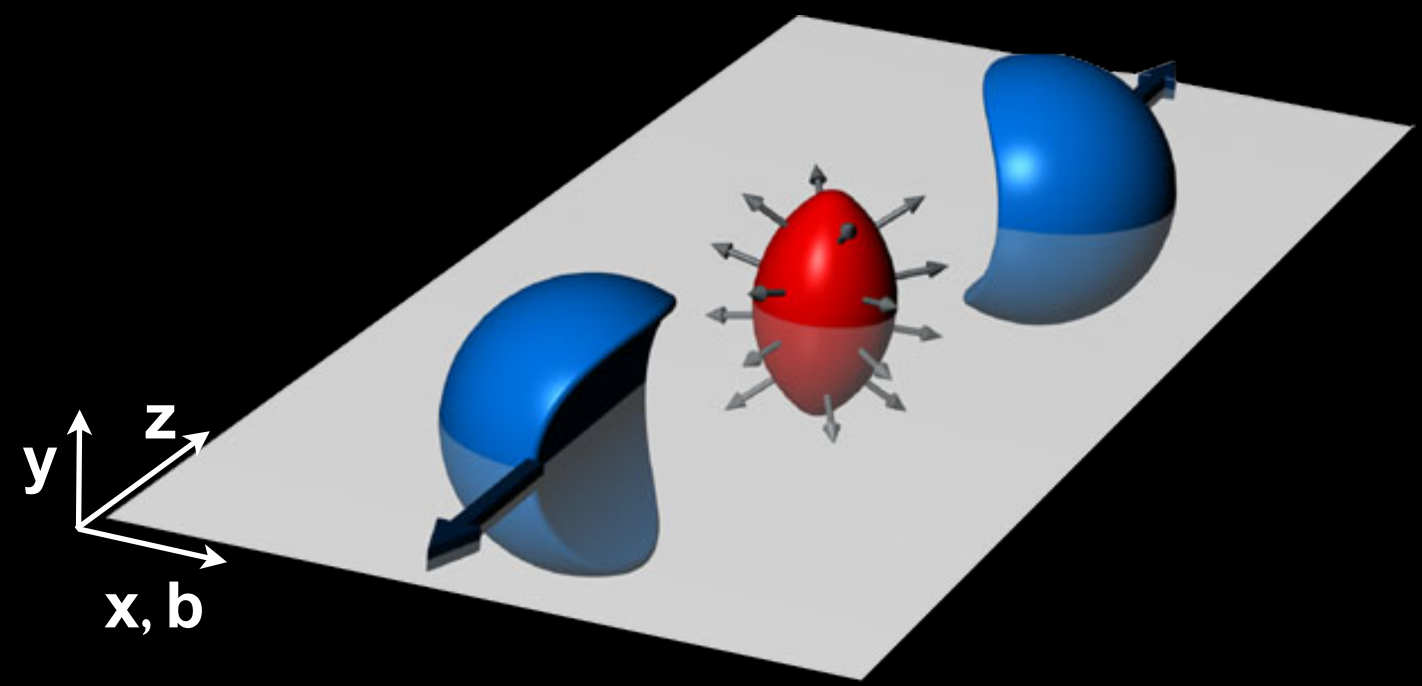




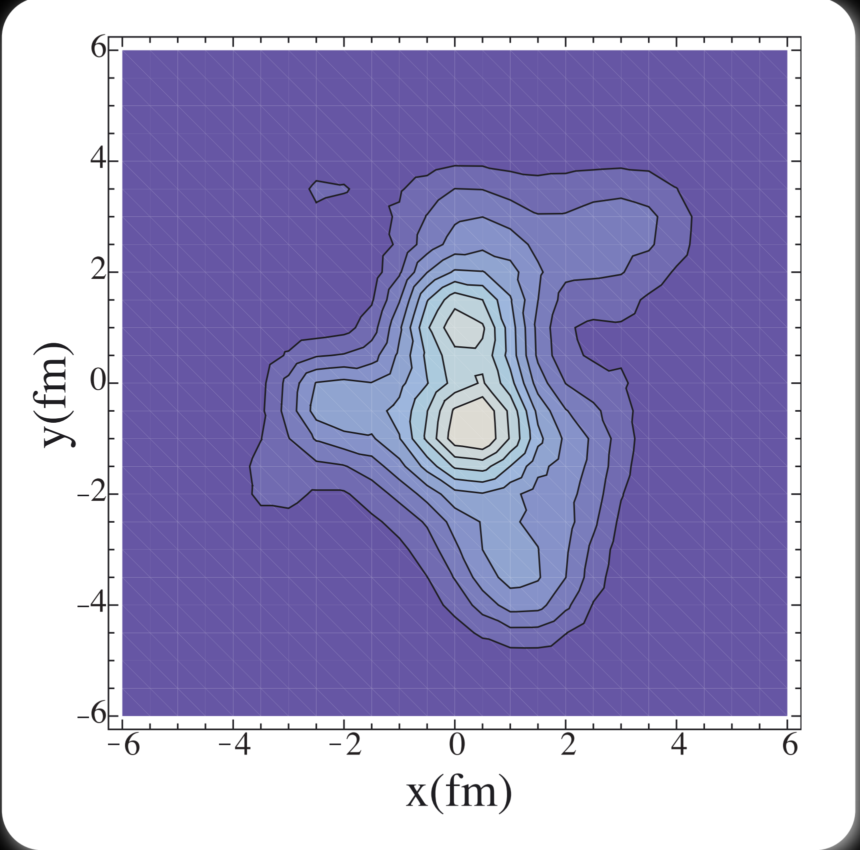


The v_2 fluctuations are very similar as function of η and p_t

Initial conditions and v_n



G. Qin, H. Petersen, S. Bass, and B. Muller



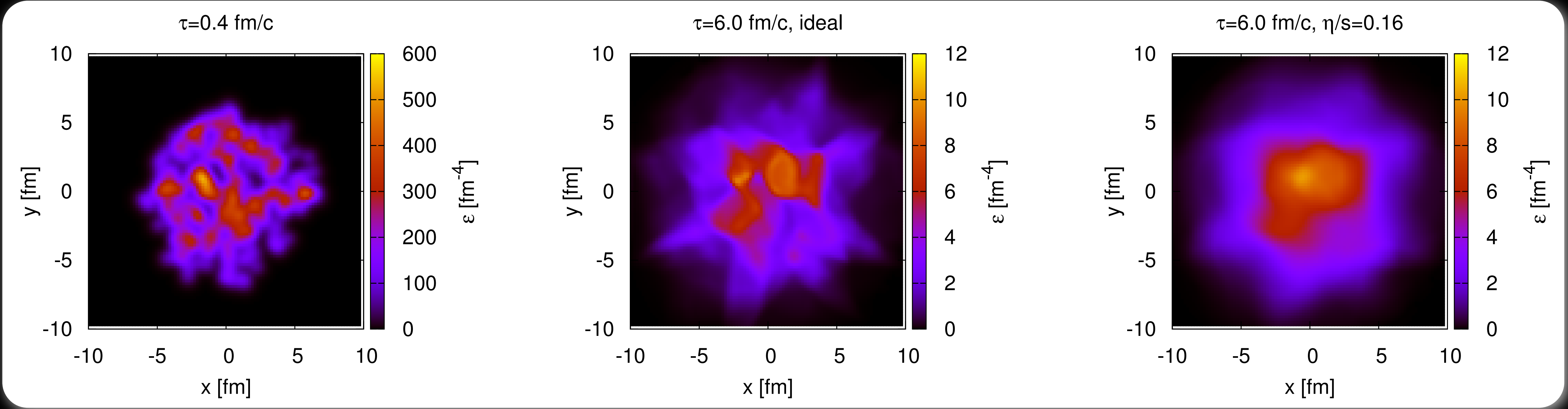
$$\frac{2\pi}{N}\frac{dN}{d\phi} = 1 + \sum_{n=2,4,6,\ldots}^{\infty} 2v_n \cos n(\phi - \Psi_R)$$

$$\frac{2\pi}{N}\frac{dN}{d\phi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos n(\phi - \Psi_n)$$

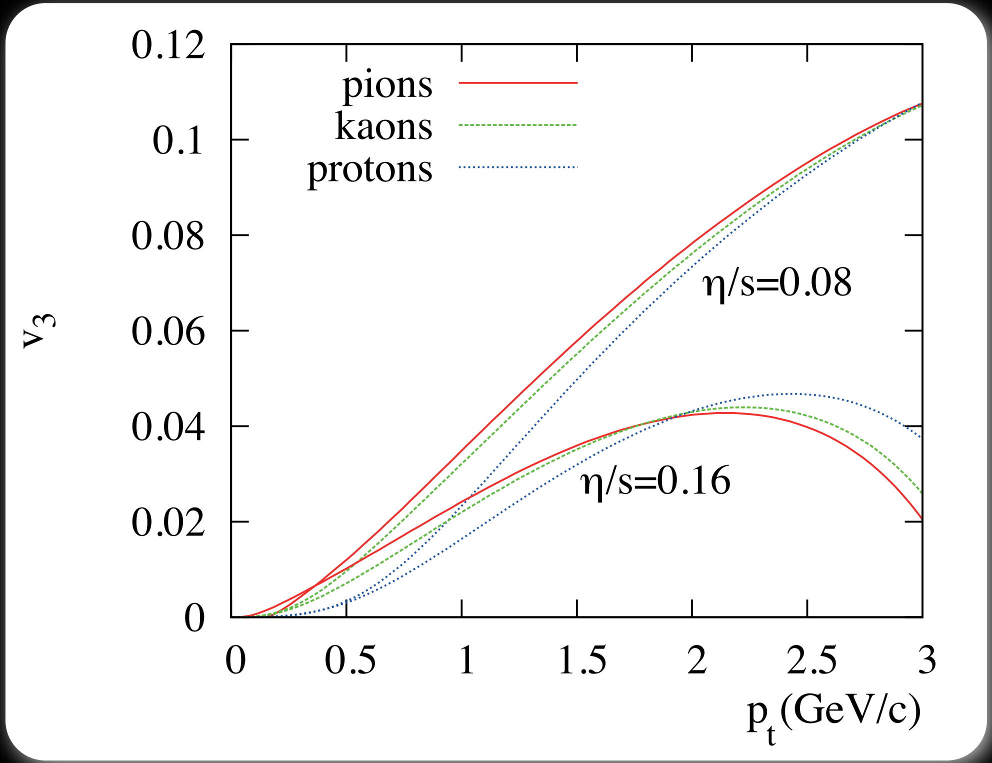
initial spatial geometry not a smooth almond (for which all odd harmonics are zero due to reflection symmetry) may give rise to higher odd harmonics versus their planes of symmetry

Shear Viscosity

Music, Sangyong Jeon



initial conditions | ideal hydro $\eta/s=0$ | viscous hydro $\eta/s=0.16$



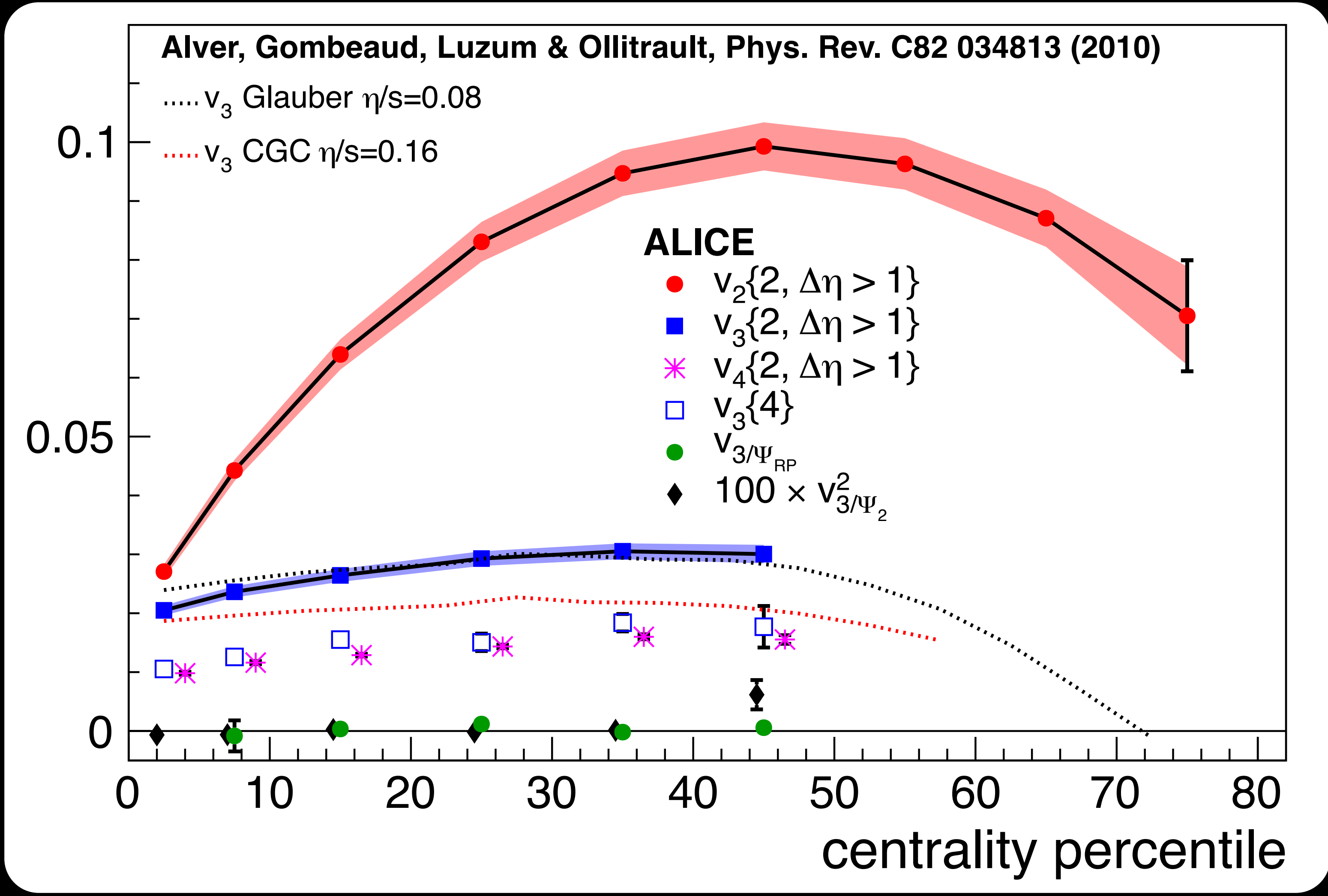
Larger η/s clearly smoothes the distributions and suppresses the higher harmonics (e.g. v_3)

Hydro: Alver, Gombeaud, Luzum & Ollitrault, Phys. Rev. C82 (2010)

the v_n's

The v_3 with respect to the reaction plane determined in the ZDC and with the v_2 participant plane is consistent with zero as expected if v_3 is due to fluctuations of the initial eccentricity

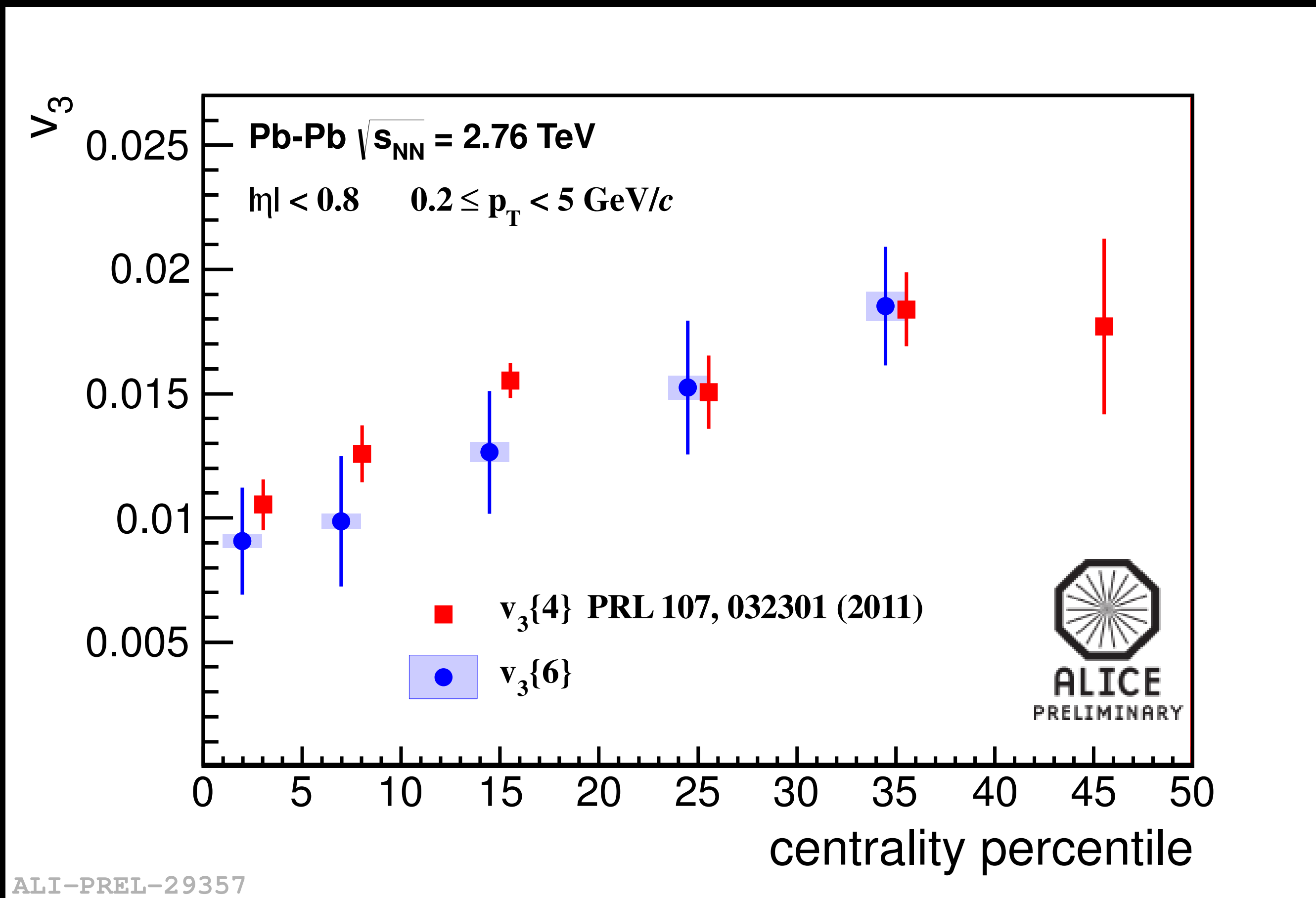
The $v_3\{2\}$ is about two times larger than $v_3\{4\}$ which is also consistent with expectations based on initial eccentricity fluctuations

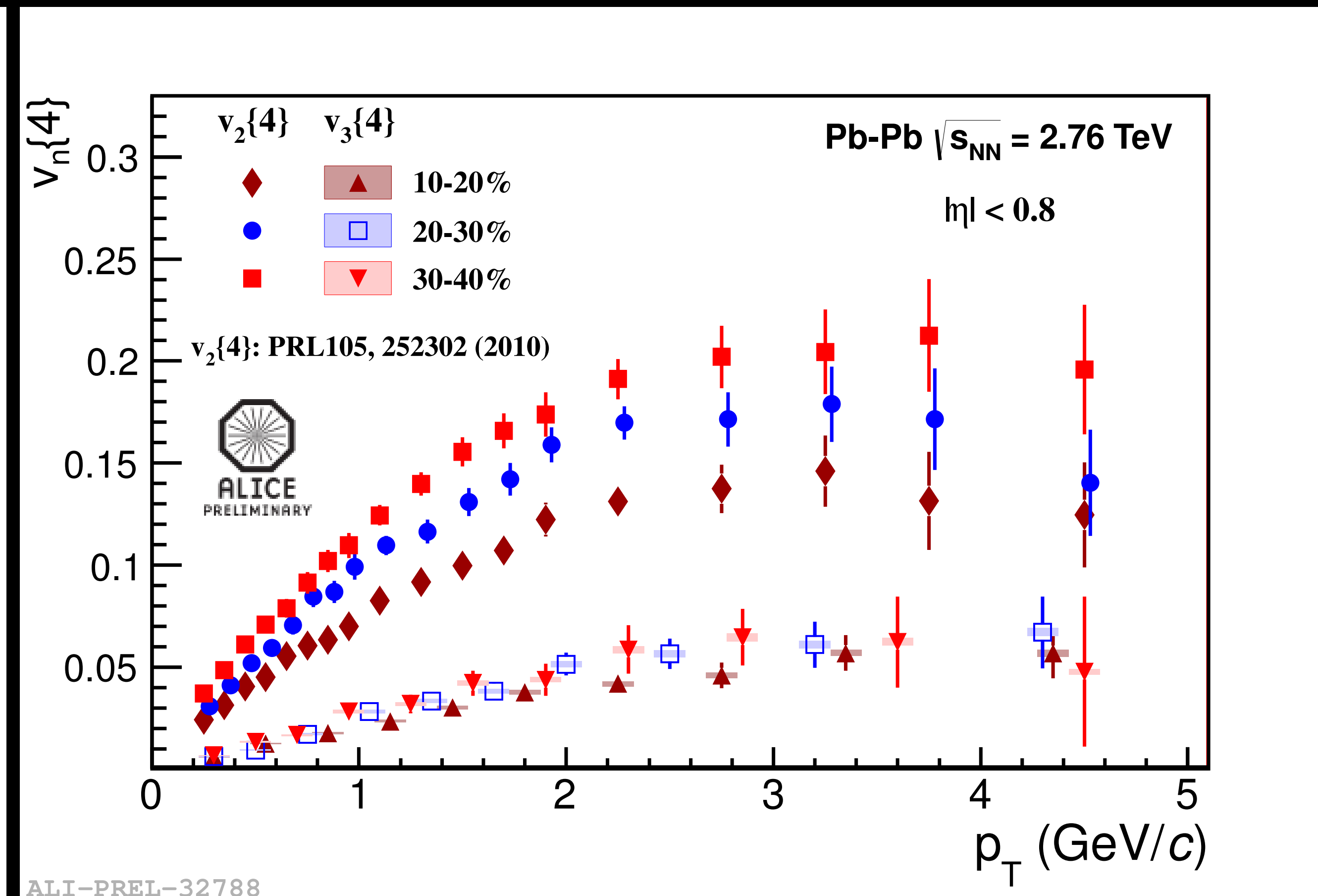


ALICE Collaboration, arXiv:1105.3865
PRL 107 (2011) 032301

We observe significant v_3 and v_4 which compared to v_2 has a different centrality dependence (strong constrain for η/s)

v_3

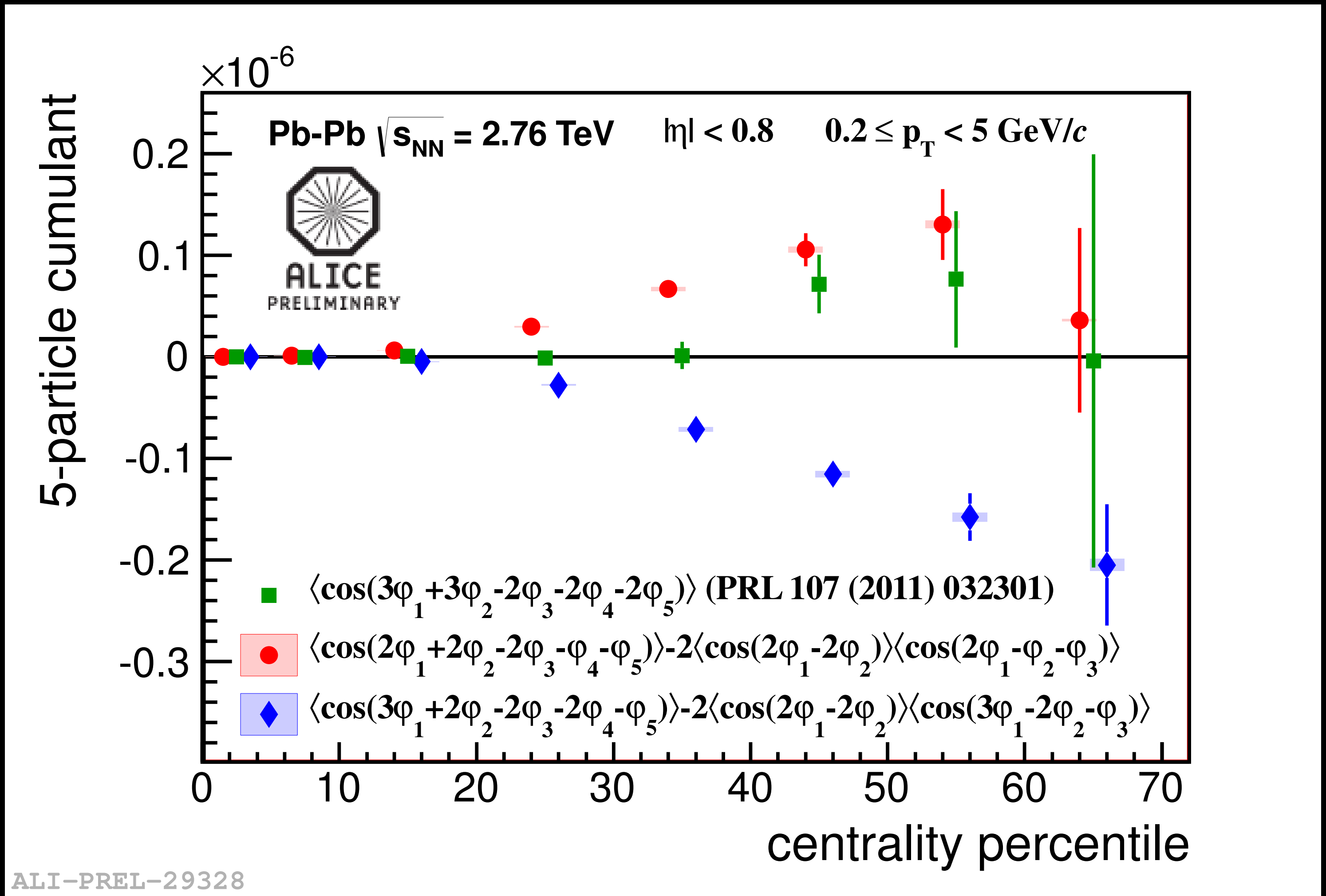




We observe as for v_2 that $v_3\{4\}$ and $v_3\{6\}$ agree within errors and the difference of about a factor 2 between $v_3\{2\}$ and $v_3\{4\}$ and $v_3\{6\}$ matches that observed in Glauber calculations (indication of the number of sources?)

We can now even measure the p_t dependence of v_3 using higher order cumulants

Correlations between v_n



$$\langle\cos(3\phi_1+3\phi_2-2\phi_3-2\phi_4-2\phi_5)\rangle = v_3^2 v_2^3\cos[6(\Psi_3-\Psi_2)]$$

$$\langle\cos(2\phi_1+2\phi_2-2\phi_3-\phi_4-\phi_5)\rangle - 2\langle\cos(2\phi_1-\phi_2-\phi_3)\rangle\langle\cos(2\phi_1-2\phi_2)\rangle = -v_2^3 v_1^2\cos[2(\Psi_2-\Psi_1)]$$

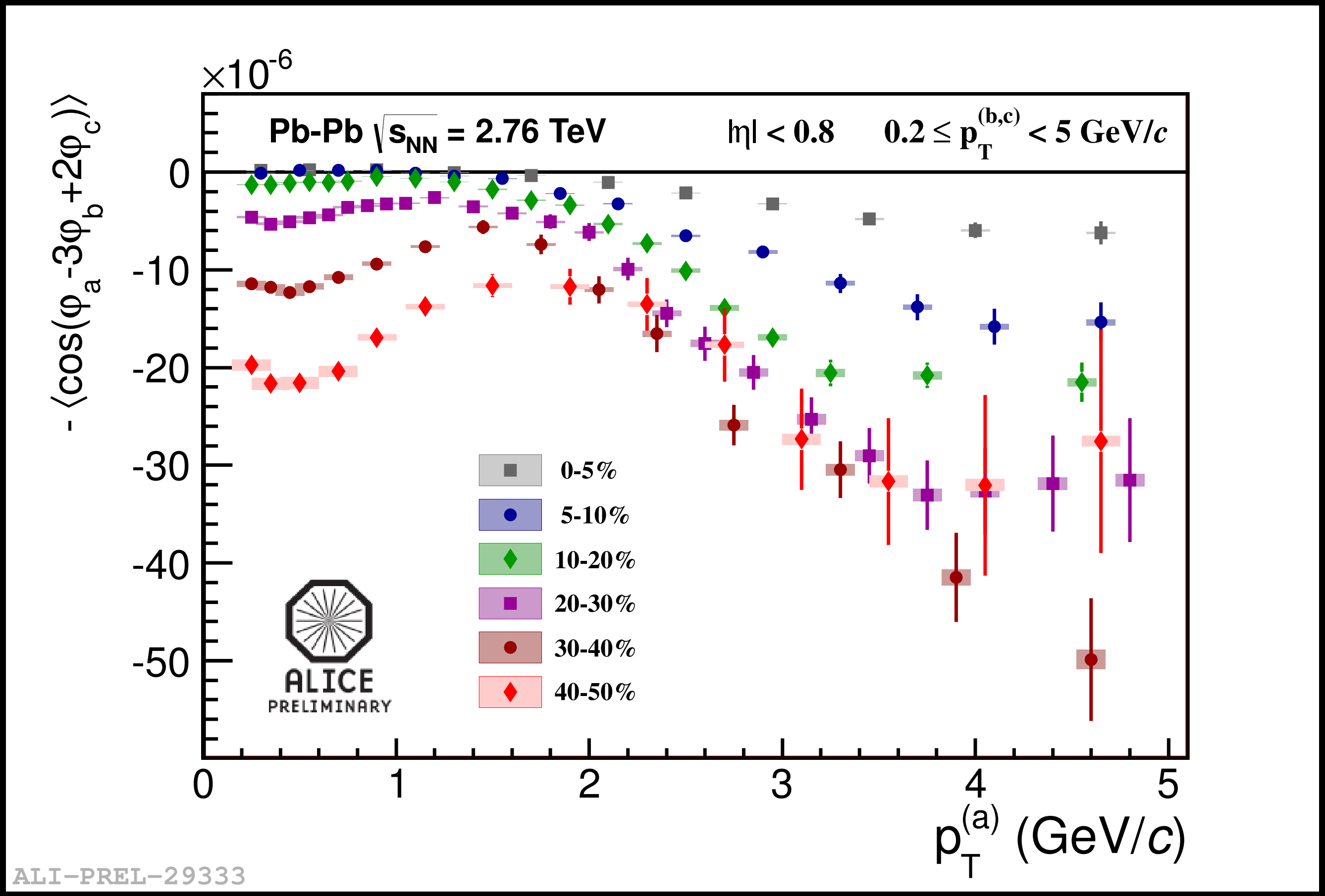
$$\langle\cos(3\phi_1+2\phi_2-2\phi_3-2\phi_4-\phi_5)\rangle - 2\langle\cos(3\phi_1-2\phi_2-\phi_3)\rangle\langle\cos(2\phi_1-2\phi_2)\rangle = -v_3 v_2^3 v_1\cos[3\Psi_3-2\Psi_2-\Psi_1]$$

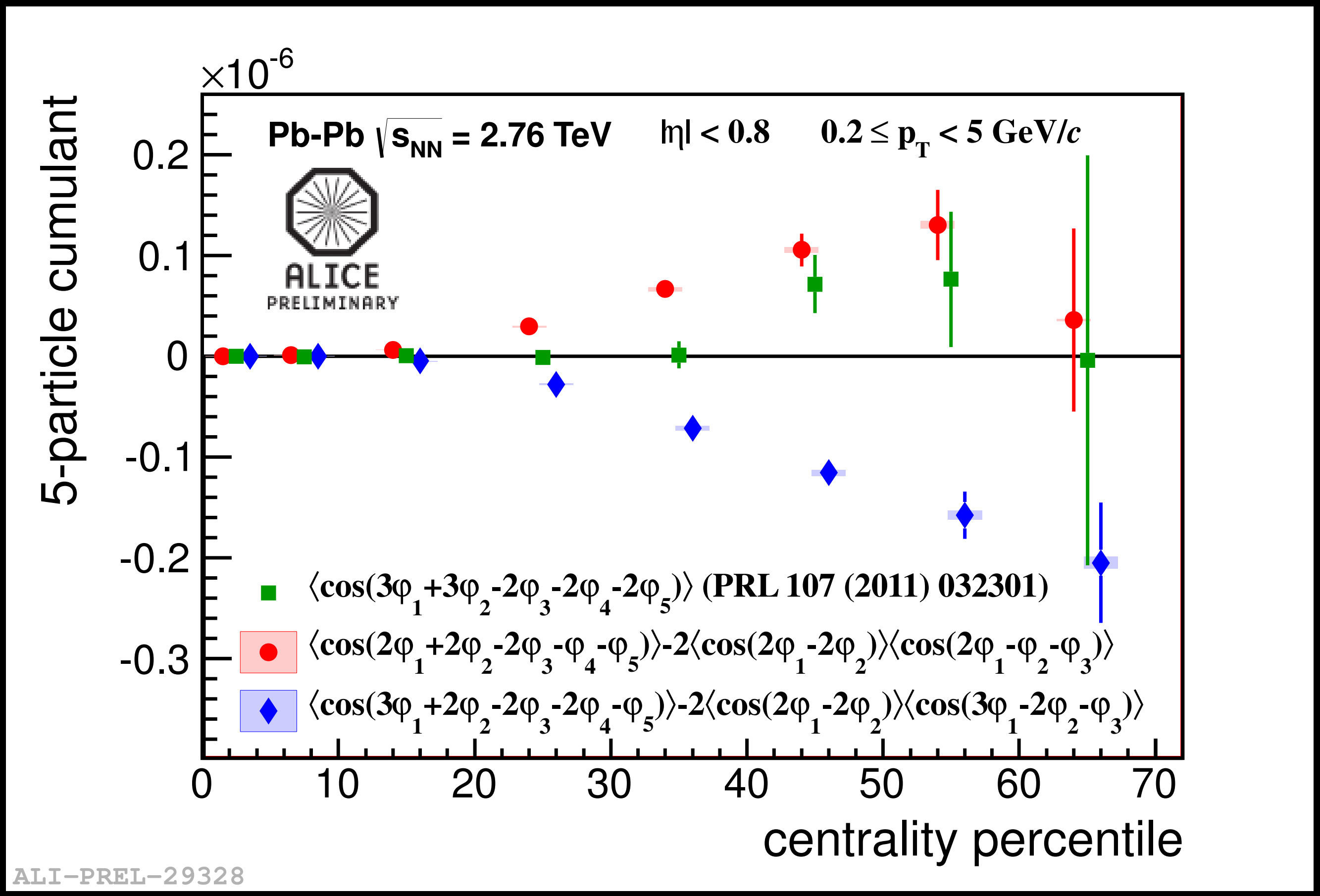
The 5 particle cumulants allow us to cleanly measure if there is a correlations between the various planes

Conclusions

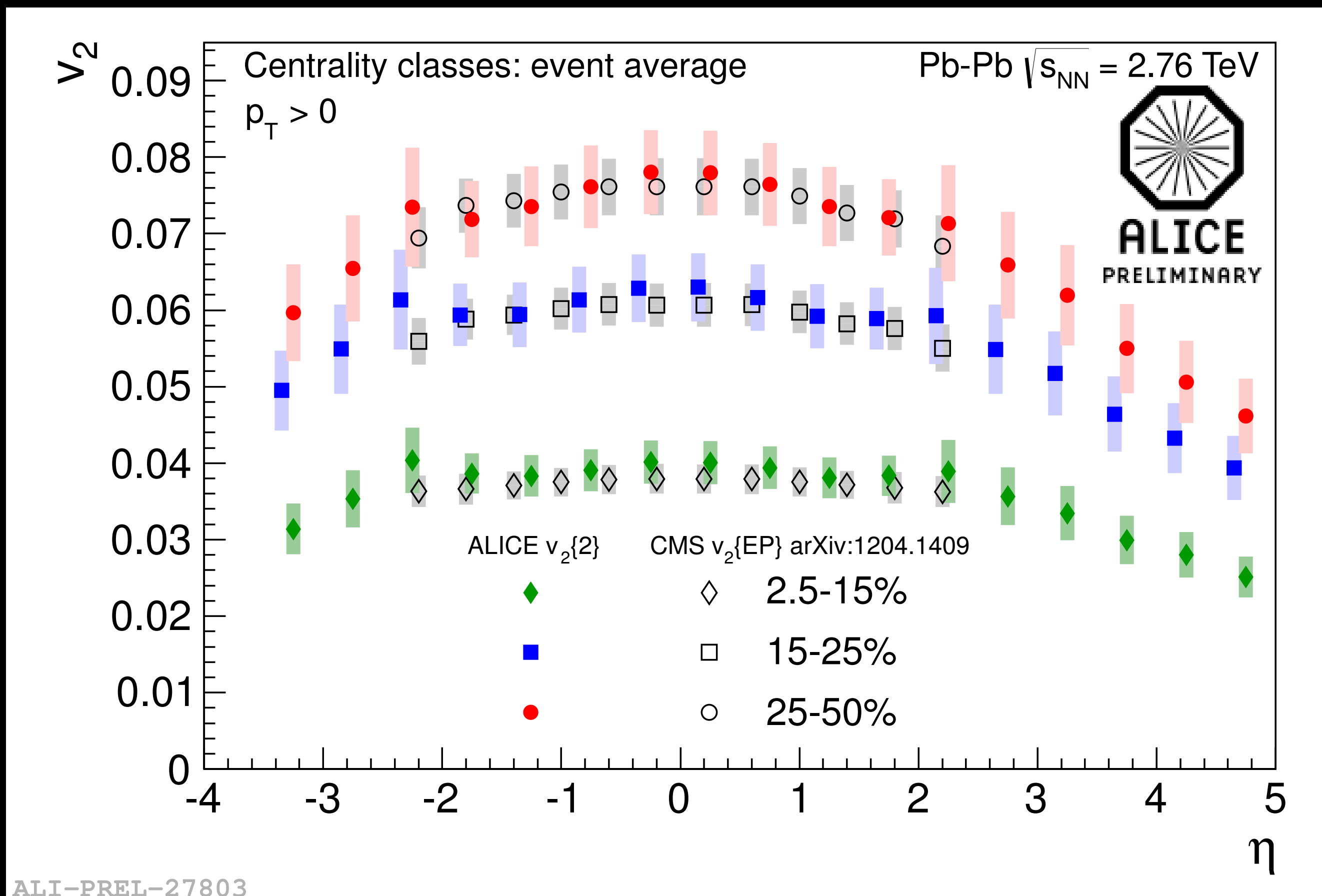
- Elliptic flow measurements provided strong constraints on the bulk properties of hot and dense matter produced at RHIC and LHC energies and have led to the new paradigm of the QGP as the so called perfect liquid
  - At the LHC we observe even stronger flow than at RHIC which is expected for almost perfect fluid behavior
- viscous hydro calculations fail to describe proton v_2 while hybrid models do a much better job
  - does this hadronic contribution also explain the v_2 of the phi meson and multi-strange baryons?
- At the LHC KET scaling is broken (but was it ever a well founded scaling?)
- v_2 fluctuations are in qualitative agreement with expectations from Glauber models and rather independent of η and p_t
- The measurements of v_3 and higher v_n's at RHIC and at the LHC indicate that these flow coefficients behave as expected from a created system which has a small η/s
- The fluctuations can be used to do "event shape engineering" which provides new ways to compare to models

multi-particles

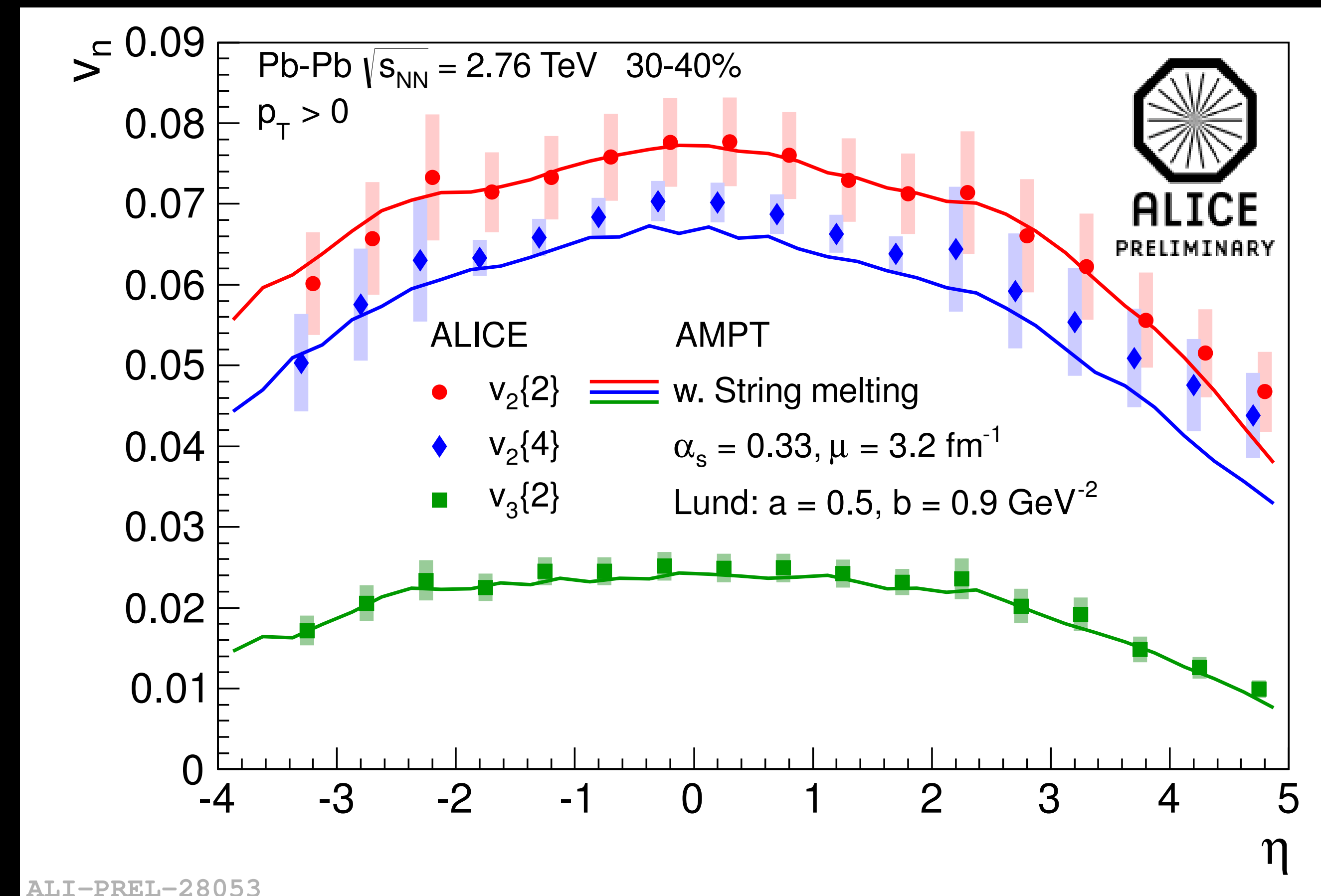




v_2 and v_3

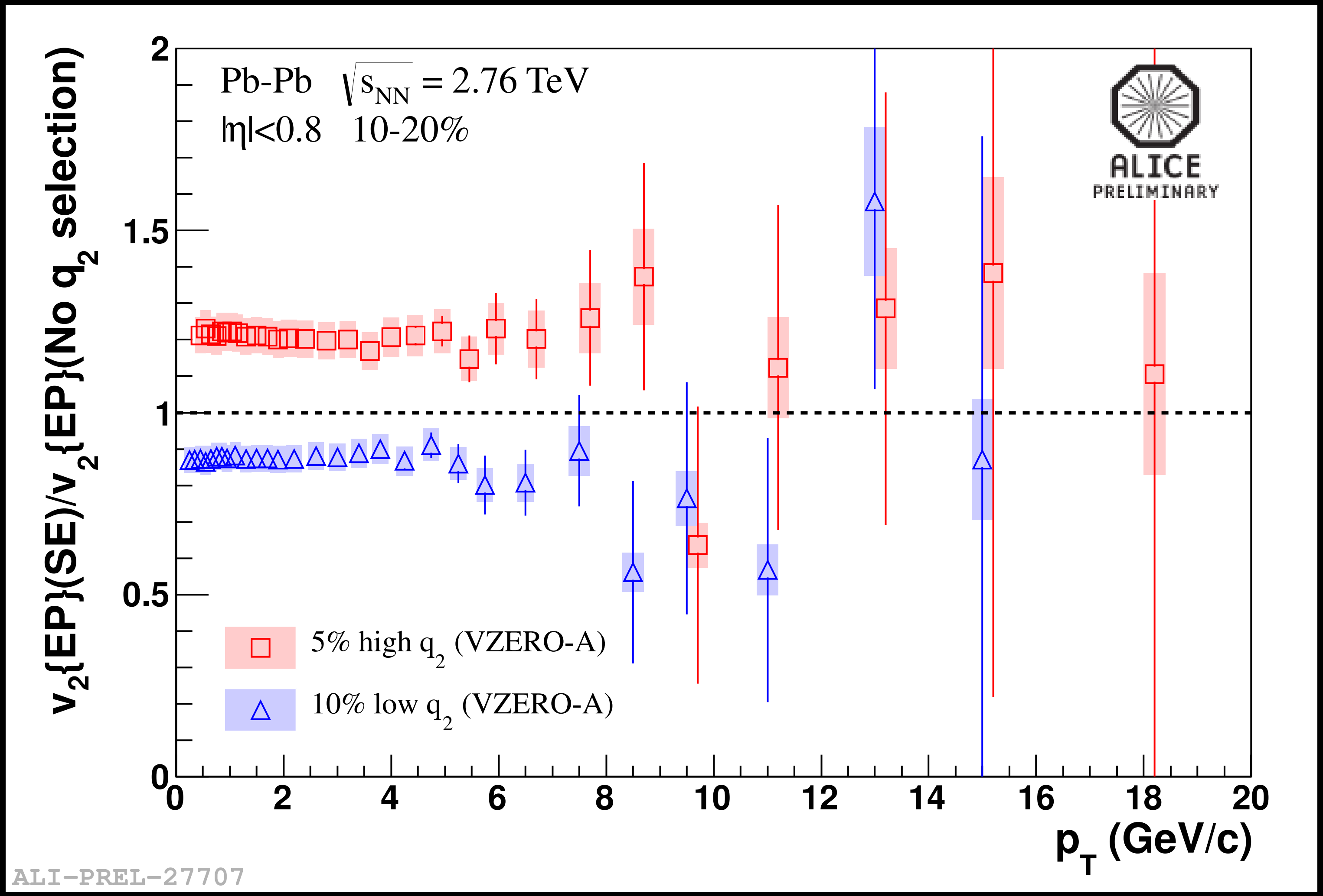


Centrality classes: event average
Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
$p_T > 0$
ALICE
PRELIMINARY
ALICE $v_2\{2\}$
CMS $v_2\{EP\}$ arXiv:1204.1409
2.5-15%
15-25%
25-50%
v_2
η
ALI-PREL-27803



Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV 30-40%
$p_T > 0$
ALICE
PRELIMINARY
ALICE
AMPT
$v_2\{2\}$
$v_2\{4\}$
$v_3\{2\}$
w. String melting
$\alpha_s = 0.33, \mu = 3.2\ fm^{-1}$
Lund: a = 0.5, b = 0.9 GeV^{-2}
v_n
η
ALI-PREL-28053

Event shape engineering



Flow Fluctuations

$$
\begin{aligned}
v\{2\} &= \langle v\rangle + \frac{1}{2}\frac{\sigma_v^2}{\langle v\rangle} \\
v\{4\} &= \langle v\rangle - \frac{1}{2}\frac{\sigma_v^2}{\langle v\rangle} \\
v\{6\} &= \langle v\rangle - \frac{1}{2}\frac{\sigma_v^2}{\langle v\rangle} \\
v\{8\} &= \langle v\rangle - \frac{1}{2}\frac{\sigma_v^2}{\langle v\rangle}
\end{aligned}
$$

- for $\sigma_v << <v>$ this is a general result to order σ^2