# Heavy Ion Collisions

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Taller Altas Energías Complutense 2012

# Hydrodynamics and flow

# Hydrodynamics

Framework to describe the space-time evolution of matter under local thermal equilibrium

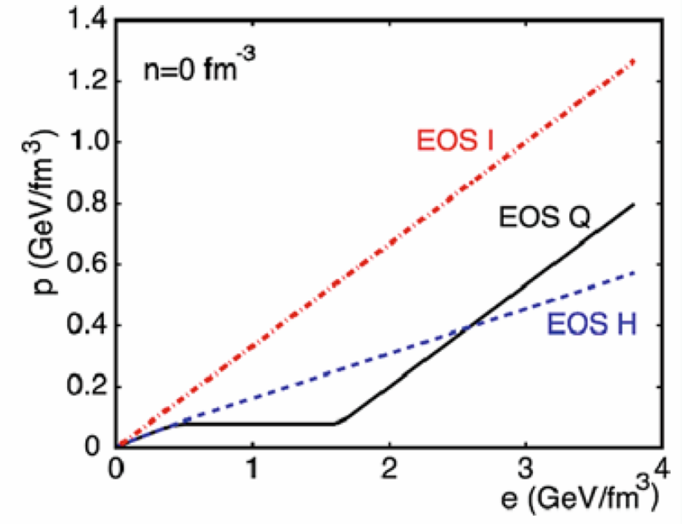
Inputs to hydrodynamical models:

- Equation of state (Ideal hydro):

  P=P(e,n) P: pressure, e: energy density, n: baryon density

  viscous hydro: needs shear viscosity, bulk viscosity, heat conductivity

P.F. Kolb and U.W. Heinz, nucl-th/0305084



EOS I: Ideal gas of relativistic massless particles
EOS Q: Includes hadron masses and phase transition hadronic matter-QGP
EOS H: Hadron resonance gas model

- Energy-momentum conservation and net-baryon current conservation:

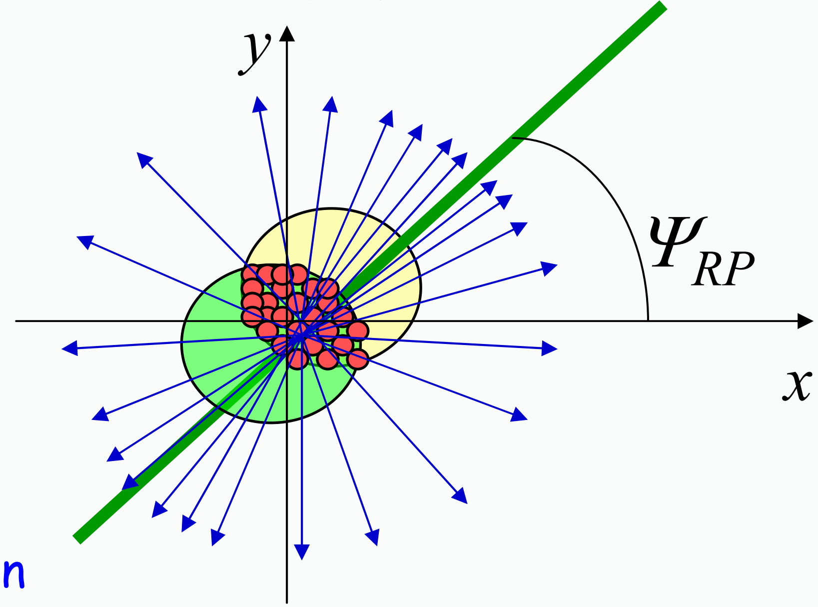
$$\partial_\mu T^{\mu\nu} = 0, \qquad \partial_\mu N_i^\mu = 0,$$

- Initial conditions from Glauber model or Color Glass Condensate model

# Reaction plane and transverse flow

- Anisotropic transverse flow is a **correlation** between the azimuth [=$\tan^{-1}(p_y/p_x)$] of the produced particles and the reaction plane!

⇨ Unambiguous signature of collective behavior

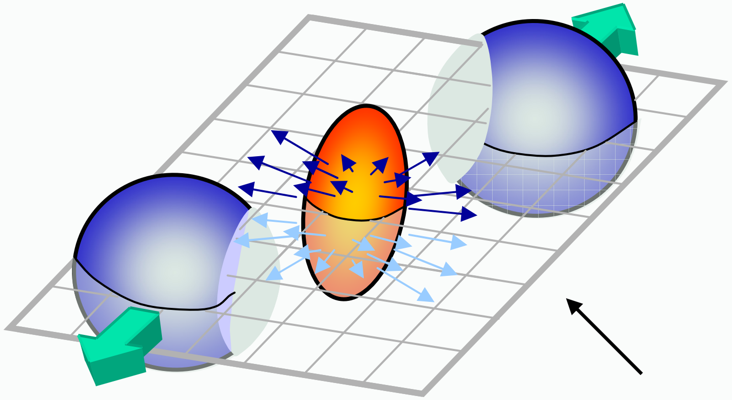


- The reaction plane is the plane defined by the impact parameter and the beam direction

- The orientation of the reaction plane can be estimated from the global event anisotropy

# Reaction plane

- The initial spatial anisotropy is transformed into momentum anisotropy.
  - Created and saturates in first femtometers. The observed $v_2$ is expected to be sensitive to the initial stage of the collision
- Analyze in terms of response of the system to initial pressure
- Deduce (model) thermalizing time, EOS

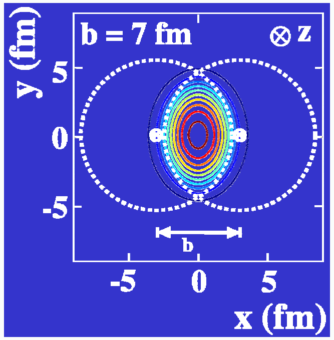


reaction plane

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

$$v_2 = \left\langle\cos 2(\varphi-\Psi_r)\right\rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

The sine terms in the Fourier expansion vanish because of the reflection symmetry with respect to the reaction plane.

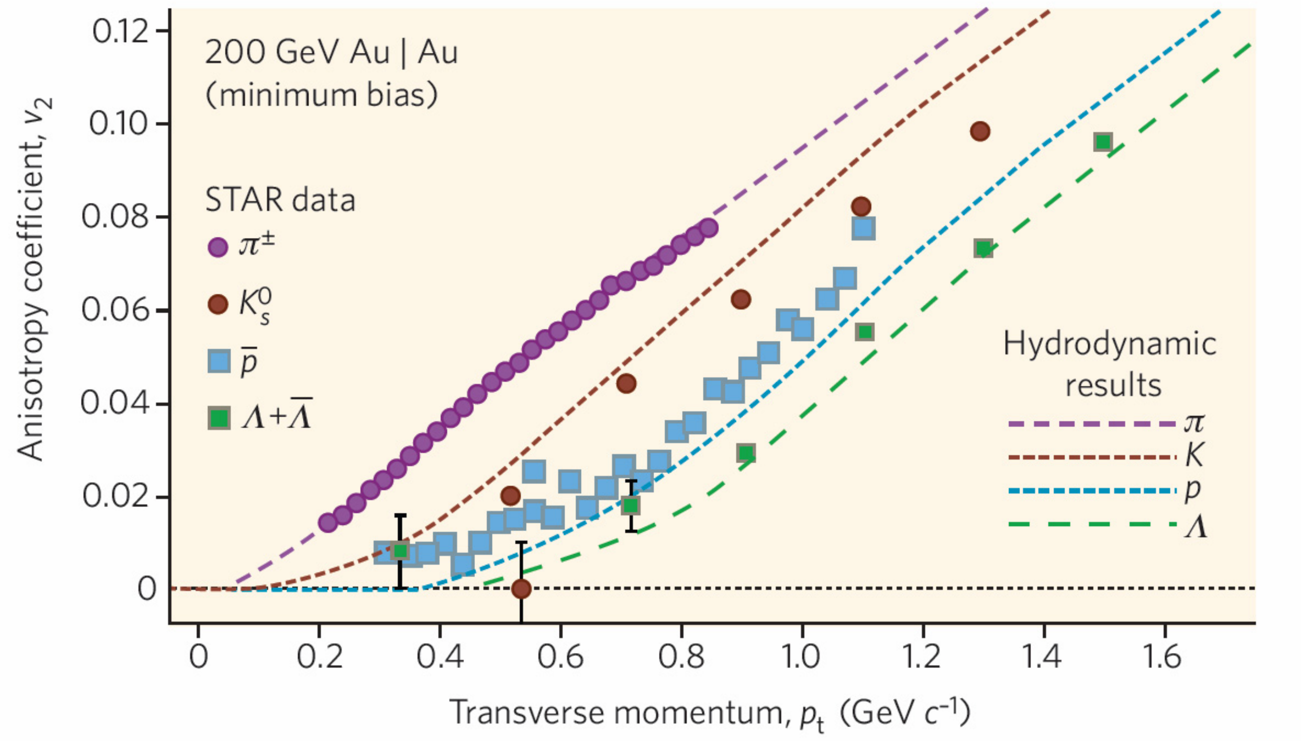


$$\varepsilon \equiv \frac{\left\langle y^2 - x^2\right\rangle}{\left\langle y^2 + x^2\right\rangle}$$

Fourier coefficients: $v_n(p_T\,;\,y) = \langle\cos[n(\phi-\Psi_{RP})]\rangle$
$v_1$ : Strength of the directed flow (small at midrapidity)
$v_2$ : Strength of the elliptic flow

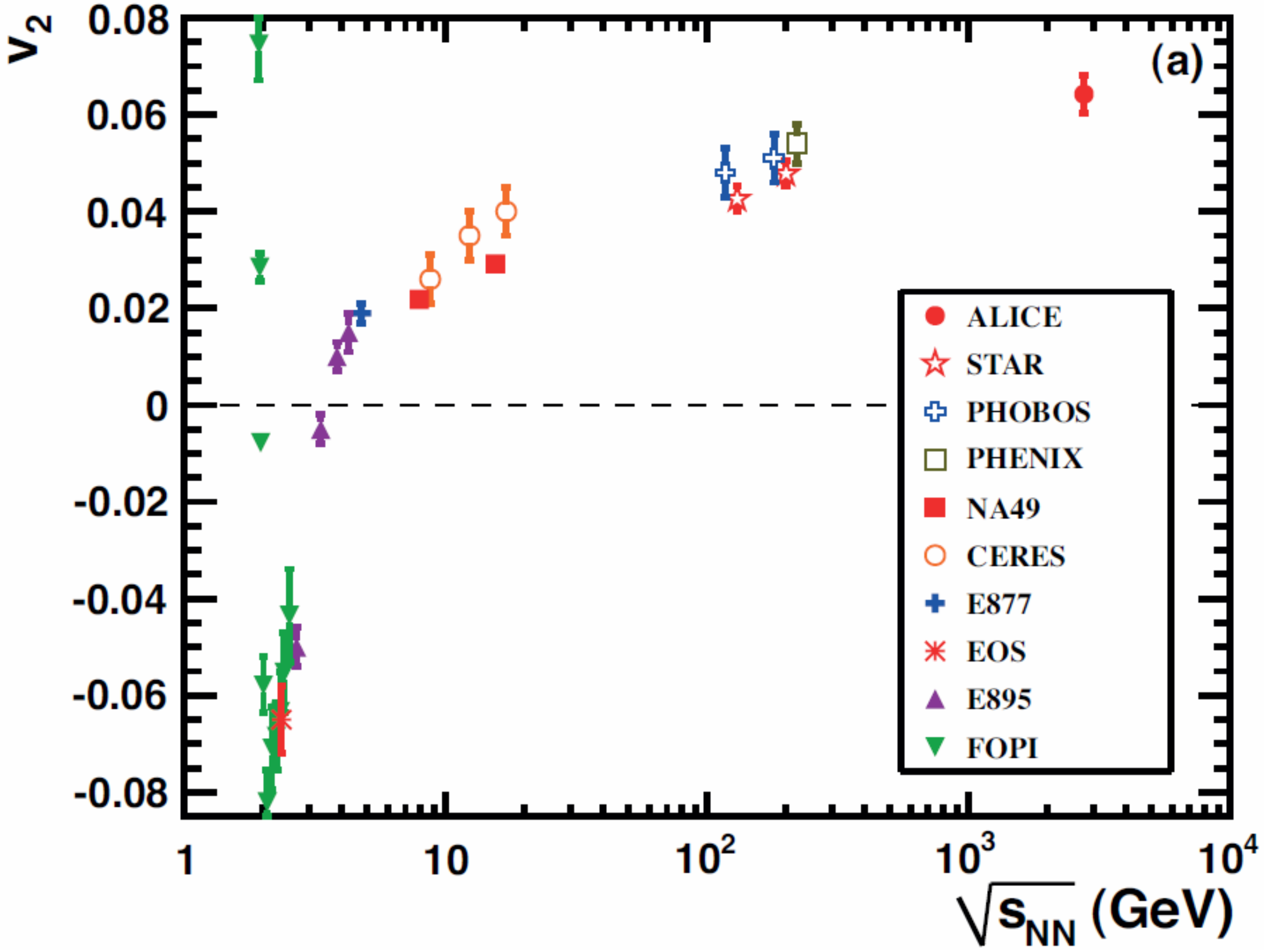
# Elliptic flow at RHIC

Phys. Rev. C72, 014904 (2005), Nature 448 (2007) 302



Mass ordering observed. Agrees with hydro for $p_t$<1.5GeV/c.
It was predicted by ideal hydro.
Perfect liquid created at RHIC.

# $v_2$ excitation function

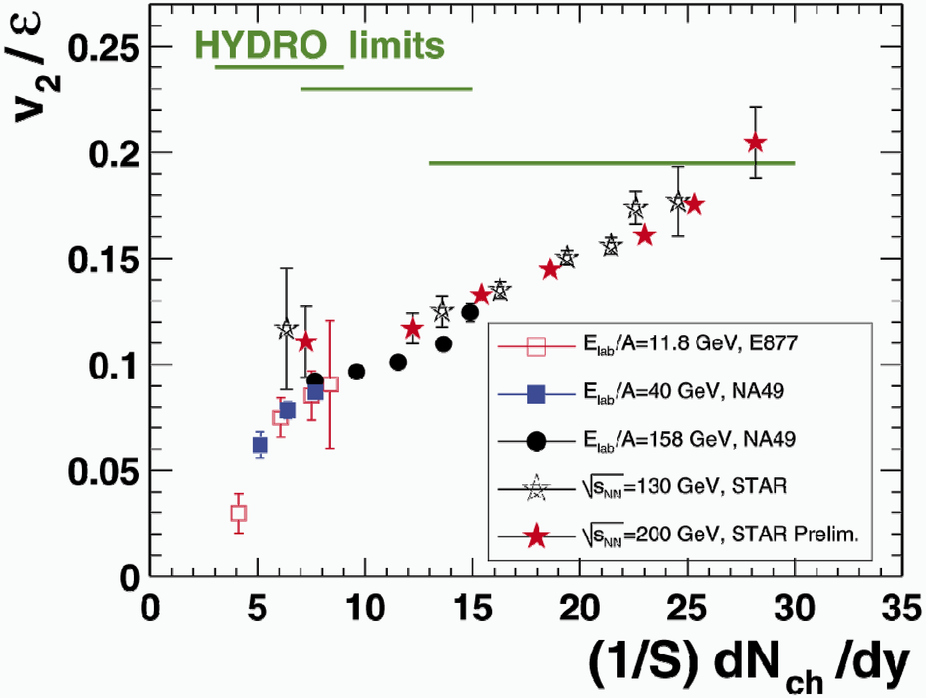


New J.Phys.13:055008,2011, R. Snellings, arXiv:1102.3010,
P. Sorensen, arXiv:0905.0174,
Andronic, Phys. Lett. B612 (2005) 173-180 , nucl-ex/0411024

- $\sqrt{s}_{NN}$ < 2 GeV: In-plane, rotation-like emision
- 2 < $\sqrt{s}_{NN}$ < 4 GeV: Onset of expansion and presence of spectator matter inhibits in plane particle emission ("squeezeout")
- $\sqrt{s}_{NN}$ > ~ 4 GeV: Initial eccentricity leads to pressure gradients that cause positive $v_2$

# Energy dependence of flow

eccentricity vs. particle multiplicity in overlap region



hydrodynamical limit
reached at RHIC
→ 'ideal fluid'

- clear predictions from hydrodynamics
- sensitive to equation-of-state

# $v_2$ quark number scaling

PHENIX, PRL, 98, 162301

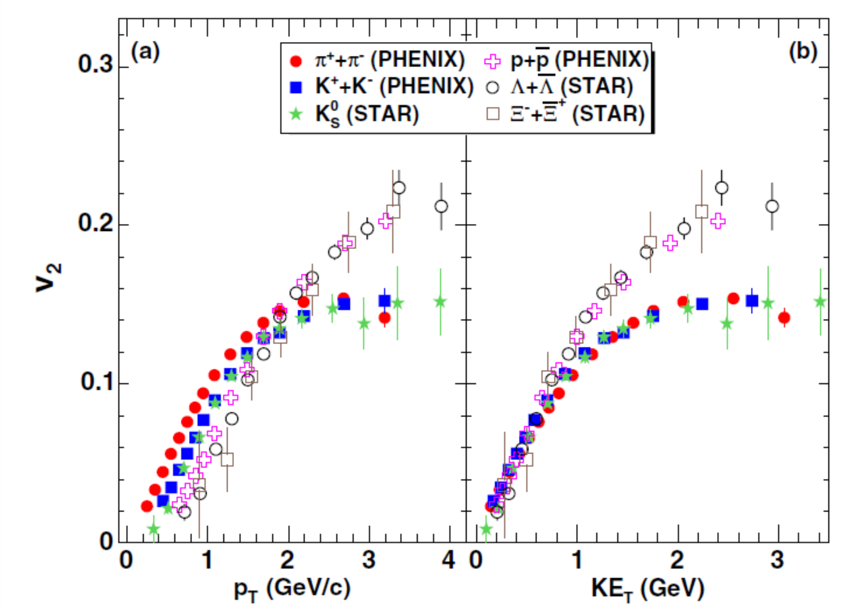


FIG. 2 (color online). (a) $v_2$ vs $p_T$ and (b) $v_2$ vs $\mathrm{KE}_T$ for identified particle species obtained in minimum-bias Au + Au collisions. The STAR data are from Refs. [24,43].

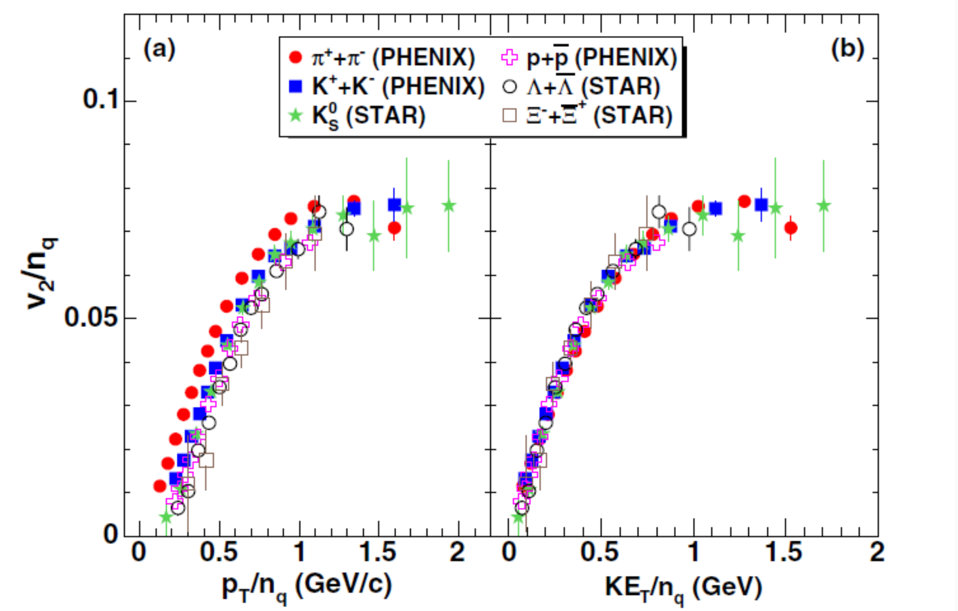
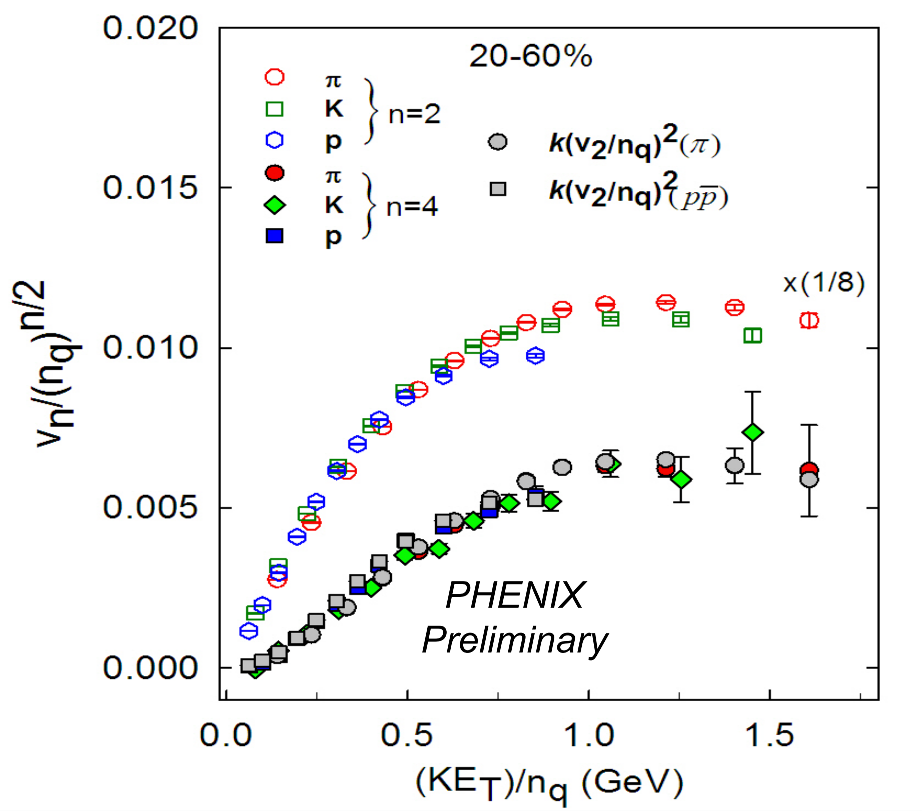


FIG. 3 (color online). (a) $v_2/n_q$ vs $p_T/n_q$ and (b) $v_2/n_q$ vs $\mathrm{KE}_T/n_q$ for identified particle species obtained in minimum-bias Au + Au collisions. The STAR data are from Refs. [24,43].

- Excellent scaling over the full range of $KE_T/n_q$ values. ($KE_T=m_T-m$)
- An indication of the inherent quark like degrees of freedom in the flowing matter.

# Flow universal?

Arkadij Taranenko, QM2009



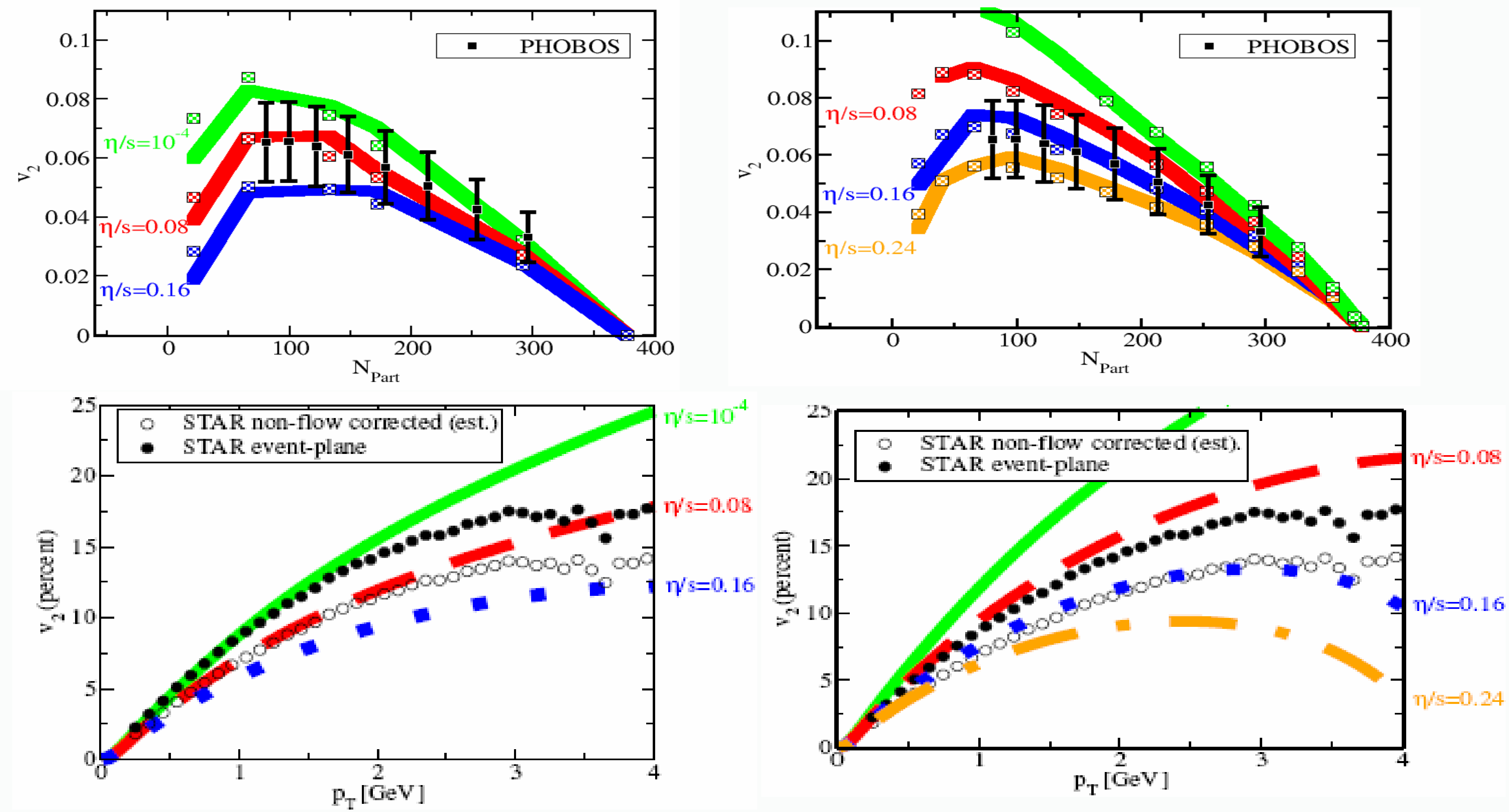
Baryon and meson $V_2$ & $V_4$ scale to a universal curve
as a function of $(KE_T)/n_q$

# Sensitivity of $v_2$ to viscosity

**Glauber**

Luzum & Romatschke, PRC 2008

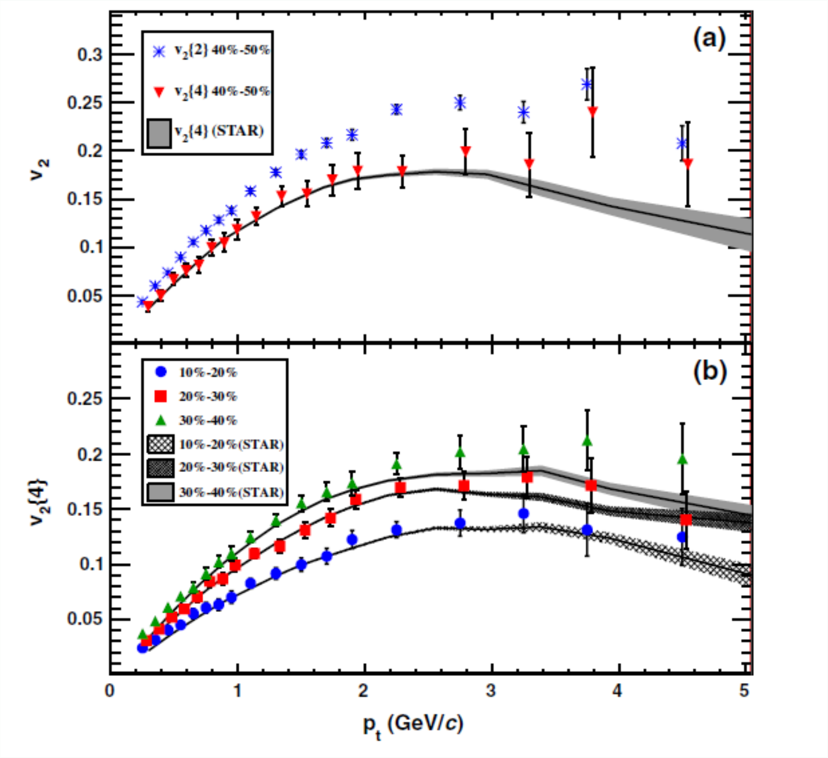
**CGC**

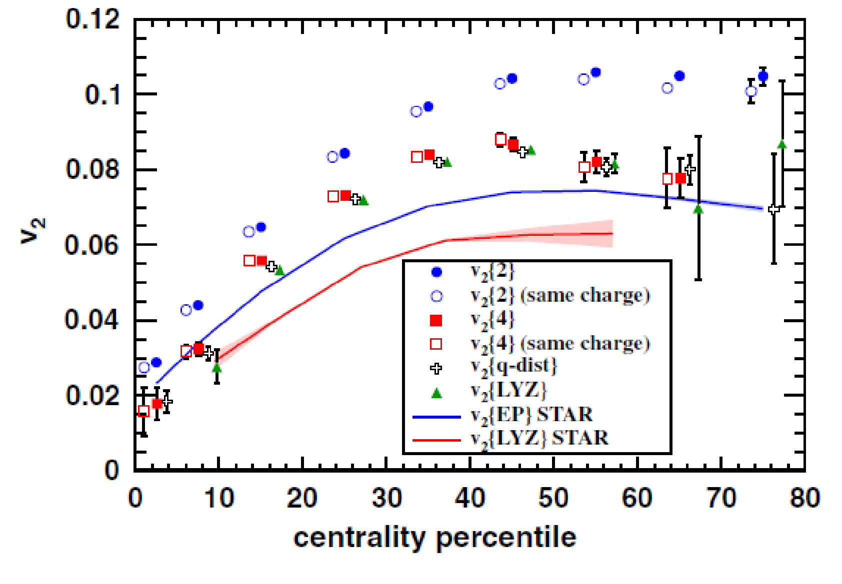


Viscosity reduces $v_2$

Present conservative upper limit: $\eta / s \leq 5 \times (1/4\pi)$

# $v_2$ at LHC: ALICE

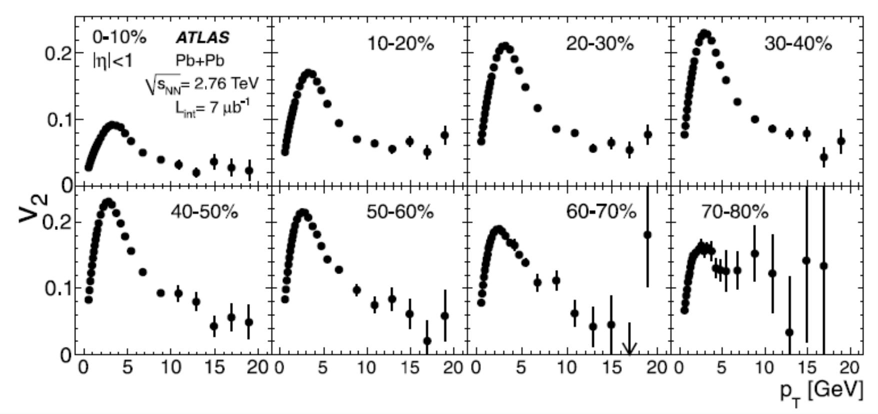


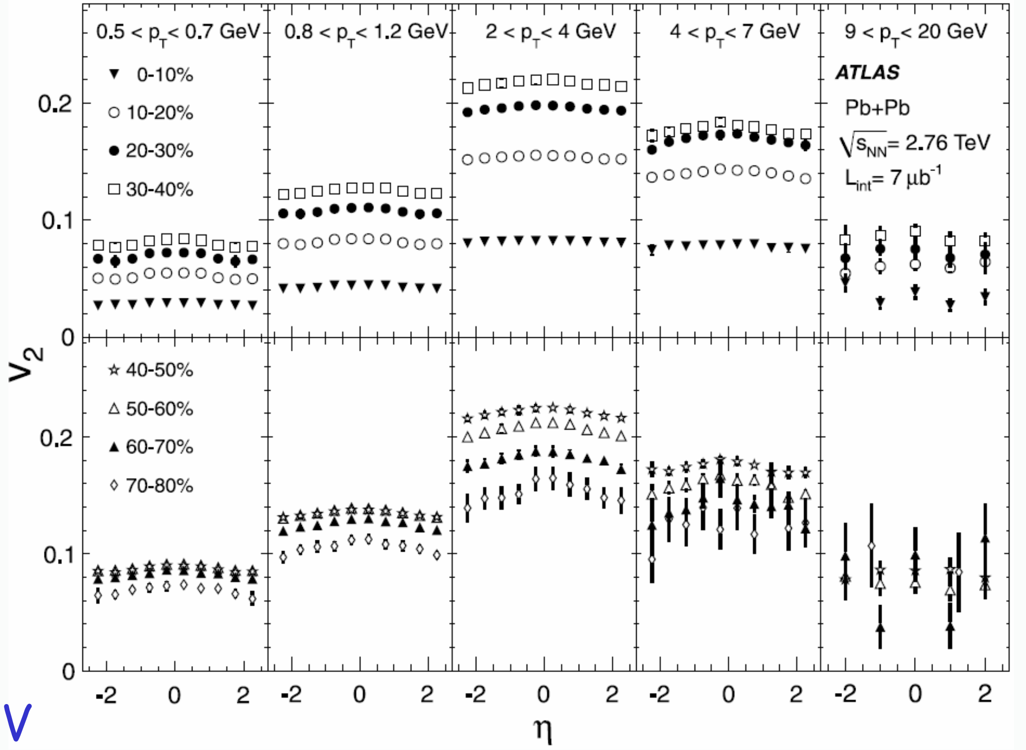


30% increase in the magnitude of integrated $v_2$ at $\sqrt{s_{NN}}$=2.76 TeV compared to RHIC.
Larger $\langle p_t \rangle$ at LHC.

The value of $v_2(p_t)$ does not change within uncertainties from $\sqrt{s_{NN}}$=200 GeV to 2.76 TeV

# $v_2$ at LHC: ATLAS

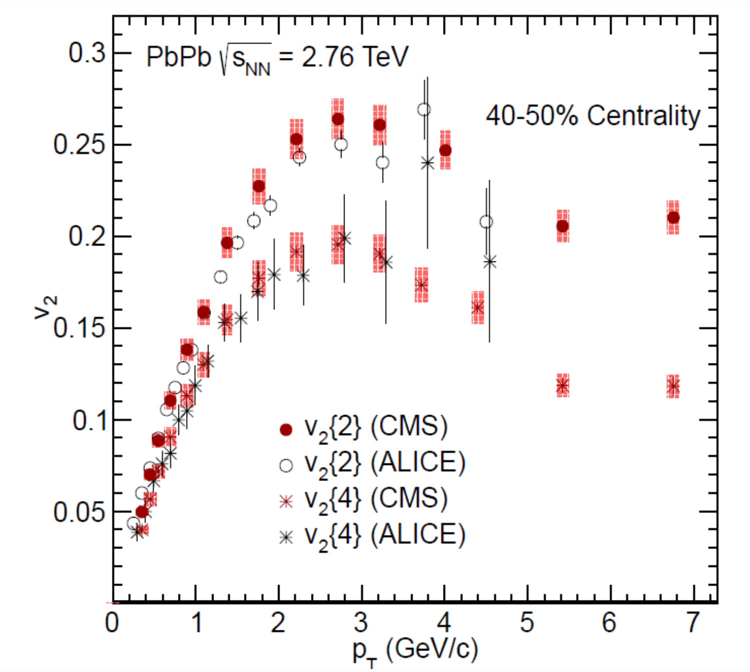


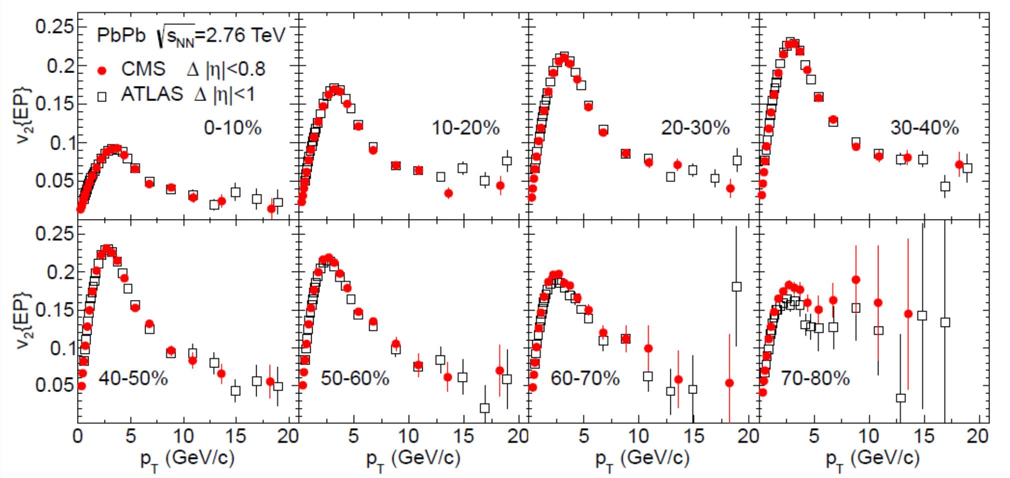


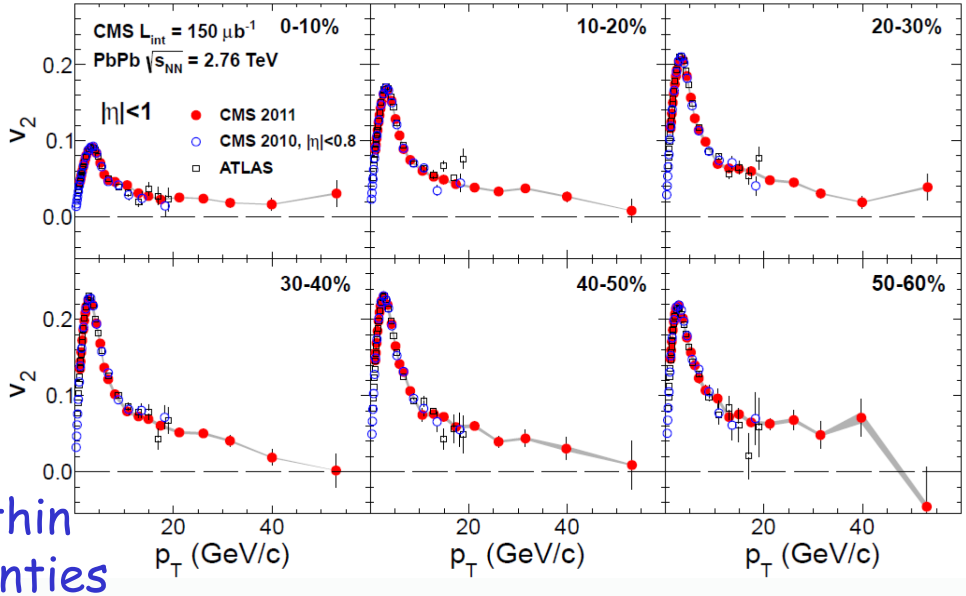
Rapid rise in $v_2(p_T)$ up to $p_T$ = 3 GeV,
A decrease out to 7–8 GeV
A weak $p_T$ dependence beyond 9–10 GeV

$v_2$ depends very weakly on $\eta$ over the measured pseudorapidity region

# $v_2$ at LHC





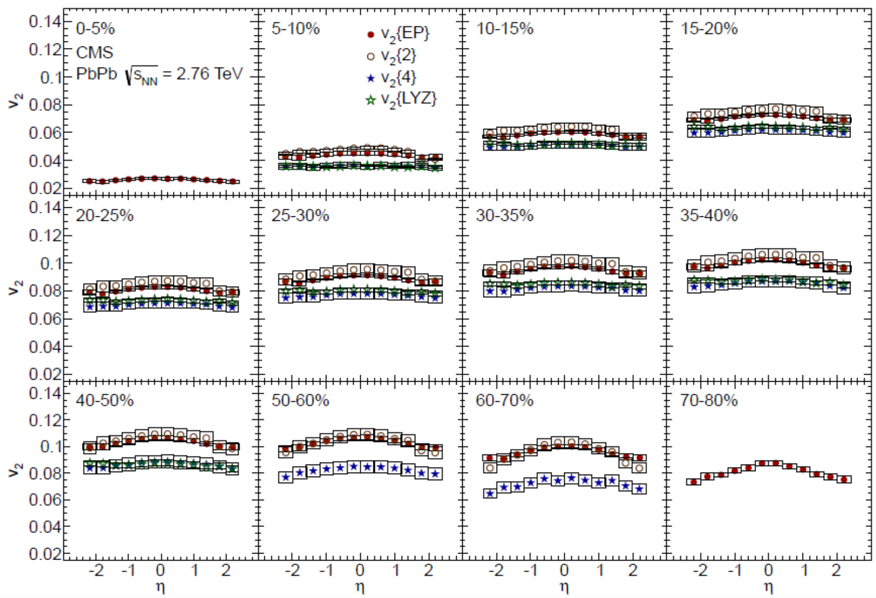


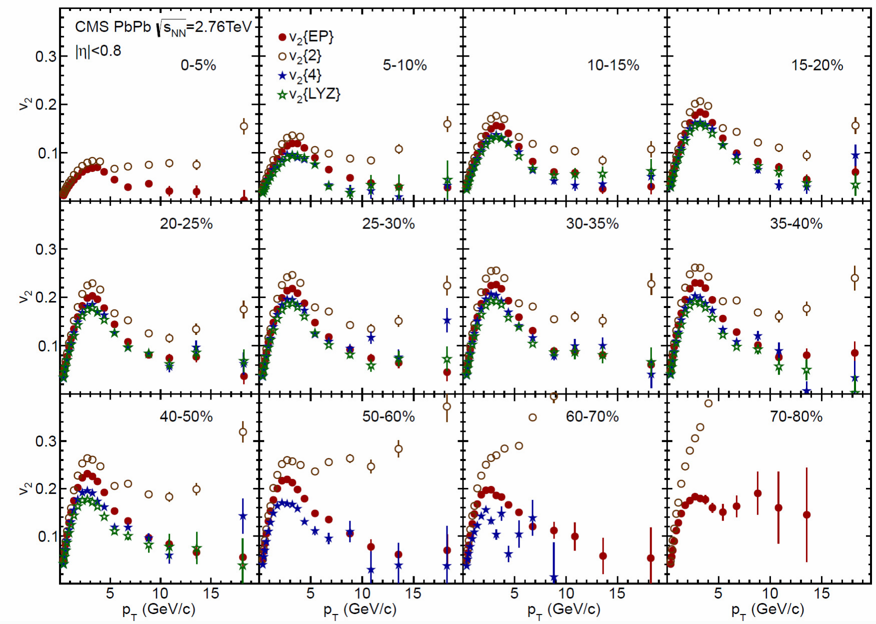
Phys. Rev. Lett. **105** (2010) 252302,
Phys. Lett. B **707** (2012) 330,
arXiv:1204.1409, arXiv:1204.1850

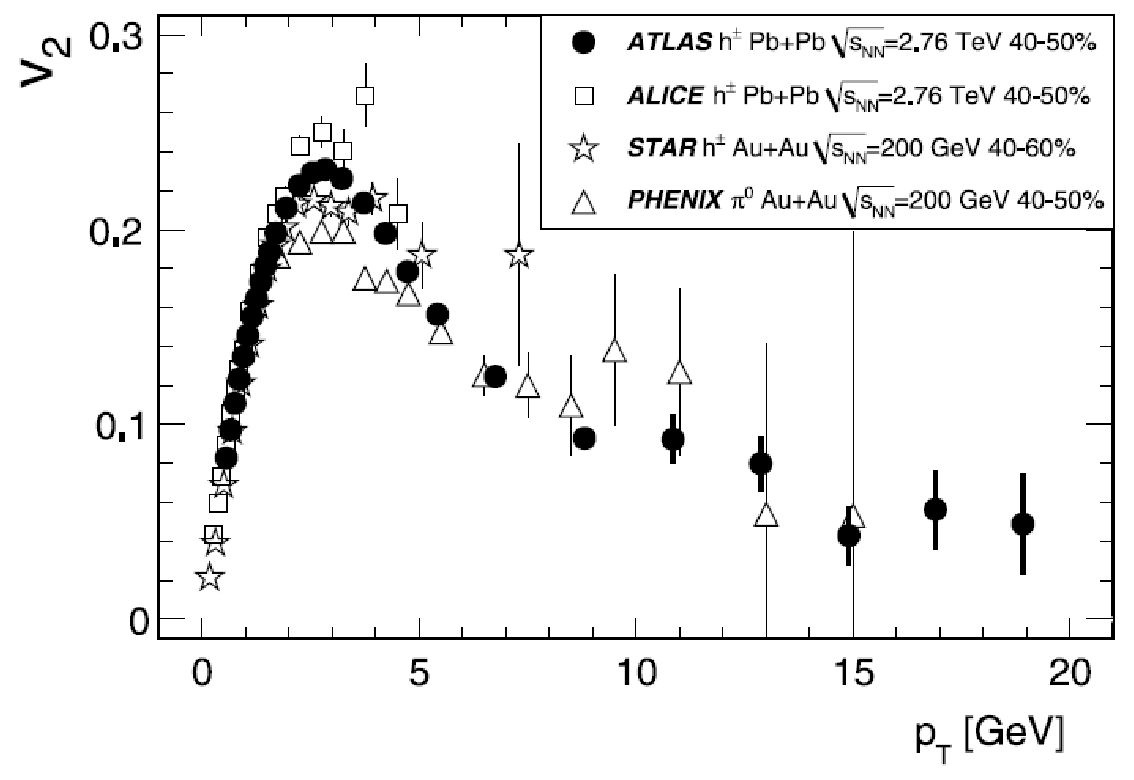
The results are in good agreement within the statistical and systematic uncertainties

# Backup

# $v_2$ at LHC:CMS

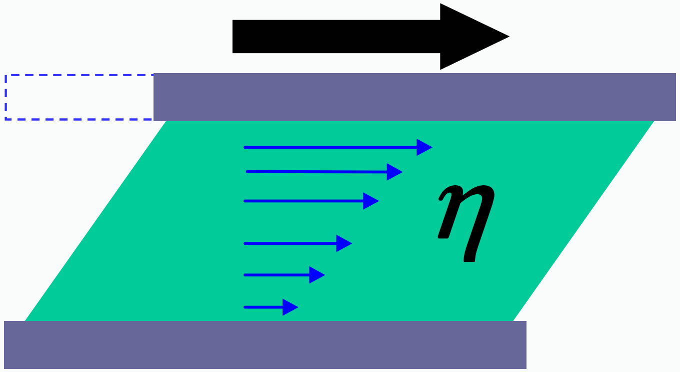

0-5%
CMS
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
5-10%
10-15%
15-20%
20-25%
25-30%
30-35%
35-40%
40-50%
50-60%
60-70%
70-80%
● $v_2\{EP\}$
○ $v_2\{2\}$
★ $v_2\{4\}$
☆ $v_2\{LYZ\}$
$v_2$
0.02
0.04
0.06
0.08
0.1
0.12
0.14
-2
-1
0
1
2
η


CMS PbPb $\sqrt{s_{NN}}$=2.76TeV
|η|<0.8
0-5%
5-10%
10-15%
15-20%
20-25%
25-30%
30-35%
35-40%
40-50%
50-60%
60-70%
70-80%
● $v_2\{EP\}$
○ $v_2\{2\}$
★ $v_2\{4\}$
☆ $v_2\{LYZ\}$
$v_2$
0.1
0.2
0.3
5
10
15
$p_T$ (GeV/c)

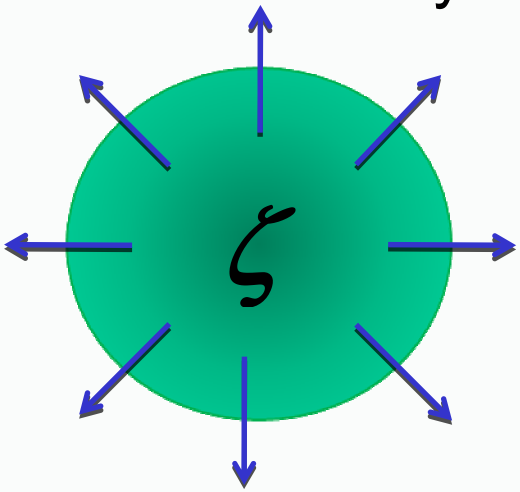

$v_2$
0.3
0.2
0.1
0
0
5
10
15
20
$p_T$ [GeV]
ATLAS $h^{\pm}$ Pb+Pb $\sqrt{s_{NN}}$=2.76 TeV 40-50%
ALICE $h^{\pm}$ Pb+Pb $\sqrt{s_{NN}}$=2.76 TeV 40-50%
STAR $h^{\pm}$ Au+Au $\sqrt{s_{NN}}$=200 GeV 40-60%
PHENIX $\pi^0$ Au+Au $\sqrt{s_{NN}}$=200 GeV 40-50%

# Viscous hydro with shear & bulk viscosity

shear viscosity



bulk viscosity



Conservation laws: $\partial_\mu T^{\mu\nu}(x) = 0$

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

Evolution equations for shear pressure tensor $\pi^{\mu\nu}$ and bulk presurre:

$$\tau_\pi \Delta^{\alpha\mu}\Delta^{\beta\nu}\dot{\pi}_{\alpha\beta} + \boxed{\pi^{\mu\nu} = 2\eta\sigma^{\mu\nu}} - \frac{1}{2}\pi^{\mu\nu}\frac{\eta T}{\tau_\pi}\partial_\lambda\left(\frac{\tau_\pi}{\eta T}u^\lambda\right)$$

$$\tau_\Pi \dot{\Pi} + \boxed{\Pi = -\zeta(\partial \cdot u)} - \frac{1}{2}\Pi\frac{\zeta T}{\tau_\Pi}\partial_\lambda\left(\frac{\tau_\Pi}{\zeta T}u^\lambda\right)$$

(2nd order shear-bulk -mixing term (Muronga, Rischke) not included.)