Collective flow in relativistic heavy-ion collisions

mini review of the experimental results

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Outline:

- Quark Gluon Plasma
- Collective flow
- Experimental results from RHIC and LHC
- Summary

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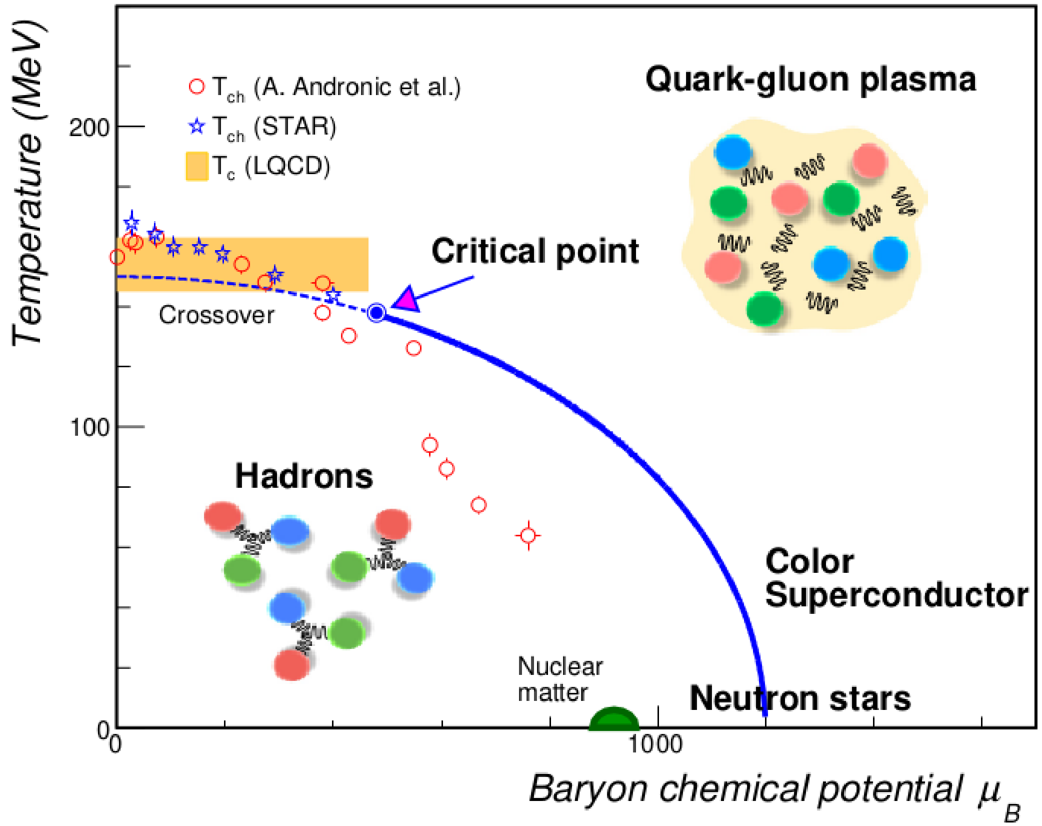
Quark Gluon Plasma (QGP)

- At extreme temperatures 10^{12} K (~200 MeV) and pressure, the hadronic matter transform into a new phase of deconfined quarks and gluons called Quark Gluon Plasma (QGP).
- QGP is a state of matter in which quarks and gluons are no longer confined within hadrons.
- Heavy-ion collisions at relativistic energies are a way to achieve such extreme conditions of temperature and pressure to produce the QGP state of matter.
- Signatures supporting formation of QGP: collective flow, jet quenching, direct photons, and Debye screening effects.

Sketch of QCD phase diagram

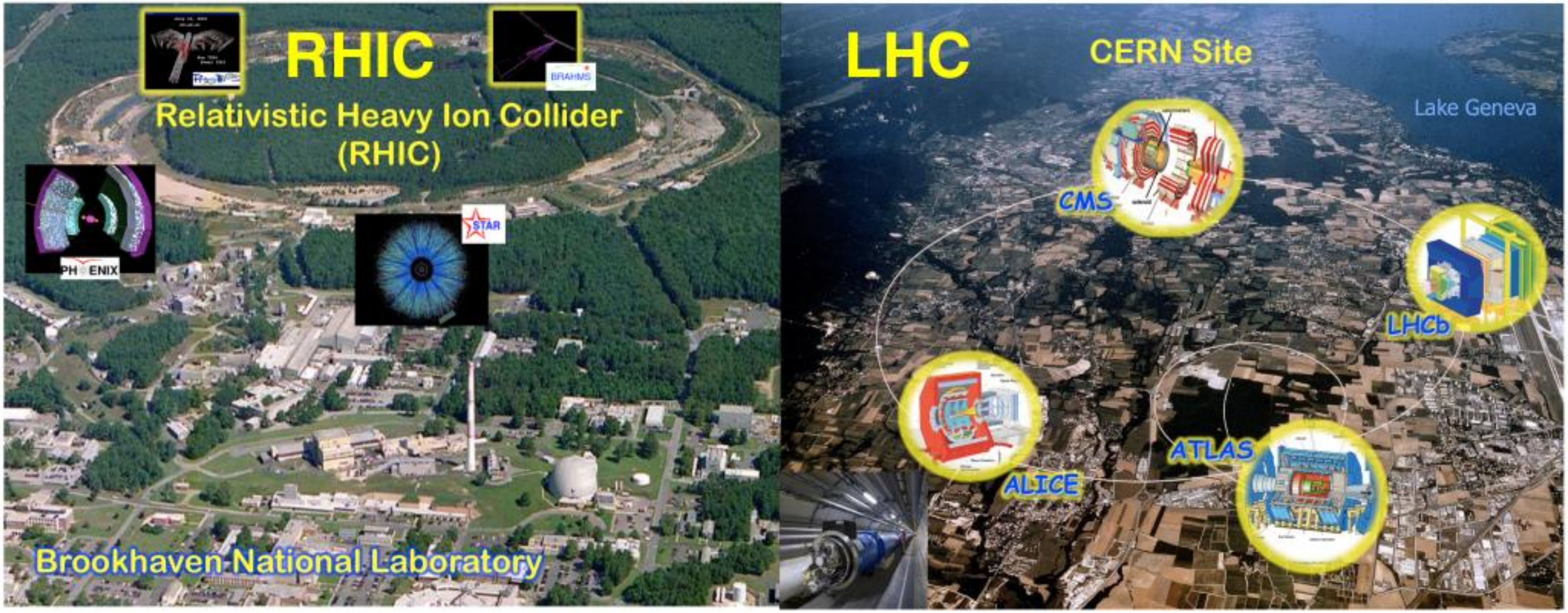


References:

- *J. Schukraft, Nucl. Phys. A 967, 1 (2017).*
- *E. Shuryak, Rev. Mod. Phys. 89, 035001 (2017), arXiv:1412.8393.*
- *P. Braun-Munzinger, V. Koch, T. Schafer, and J. Stachel, Phys.Rept. 621, 76 (2016), arXiv:nucl-th/1510.00442.*
- *B. V. Jacak and B. Müller, Science 337, 310 (2012).*
- *B. Müller and J. L. Nagle, Ann. Rev. Nucl. Part. Sci. 56, 93 (2006), arXiv:nucl-th/0602029.*

Formation of QGP

QGP can be formed by colliding heavy-ions at relativistic energies in Laboratory



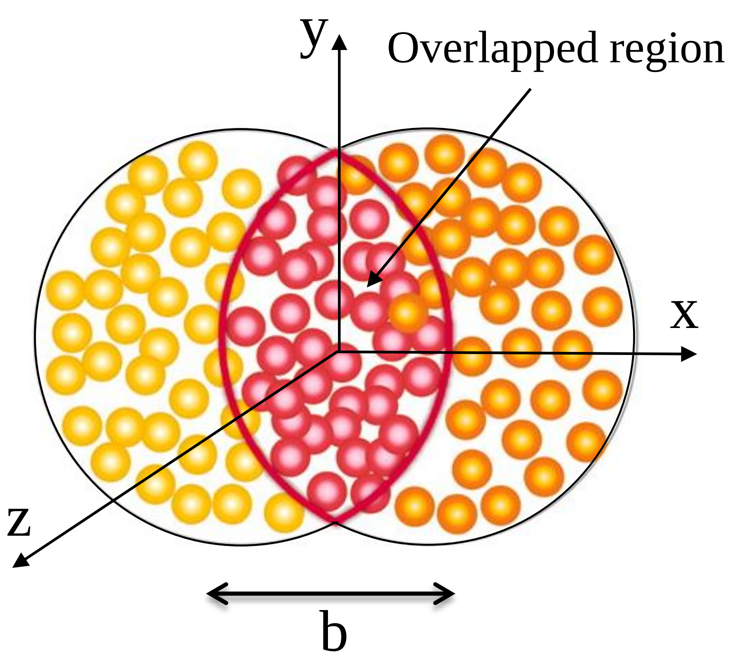
Relativistic Heavy Ion Collider at BNL-AGS

- Operating since year 2000
- Collision systems: p, d, He, Cu, Zr, Ru, Au, U
- Energy range $\sqrt{s_{NN}}$ = 7.7 - 200 GeV

Large Hadron Collider at CERN-SPS

- Operating since year 2009
- Collision systems: p, Pb, Xe
- Energy range $\sqrt{s_{NN}}$ = 0.9 - 13 TeV

Collective Flow



Interactions

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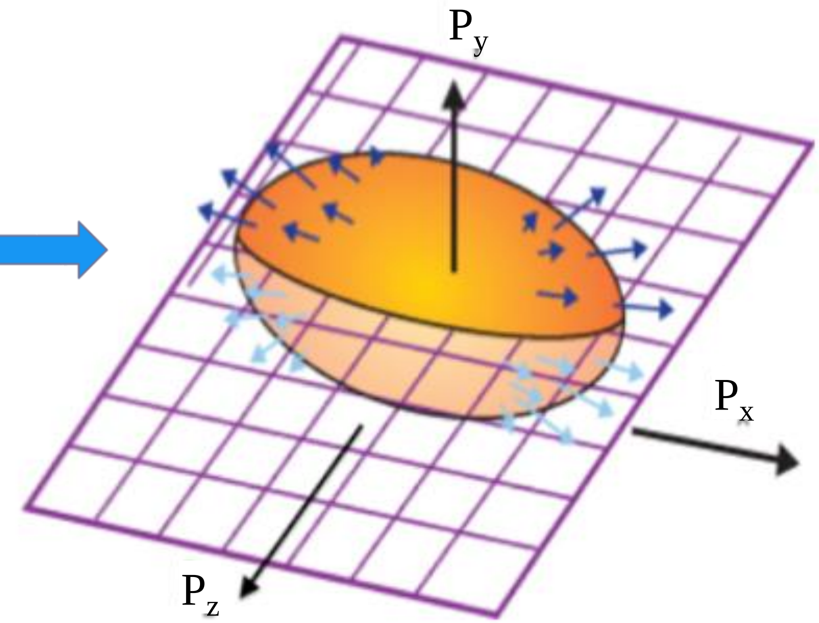
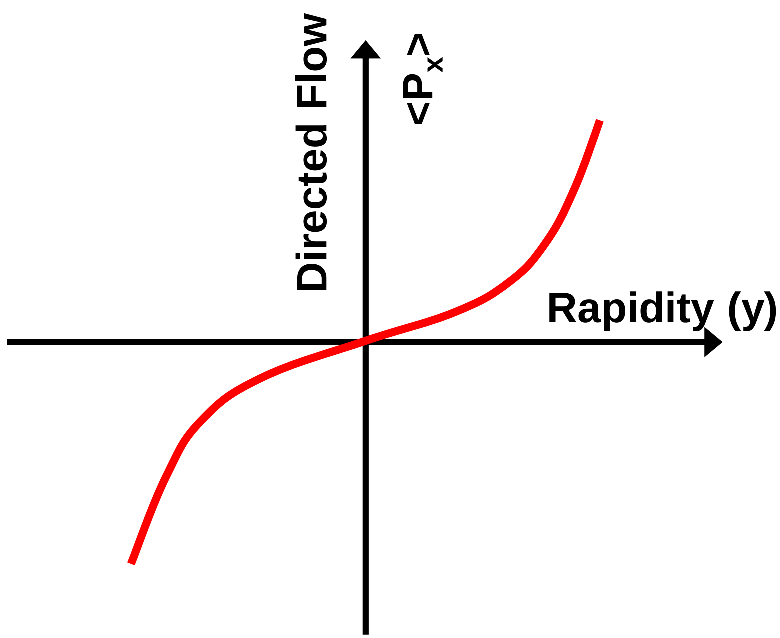
Pressure(P)

$$y > x \rightarrow \frac{\partial P}{\partial x} > \frac{\partial P}{\partial y}$$





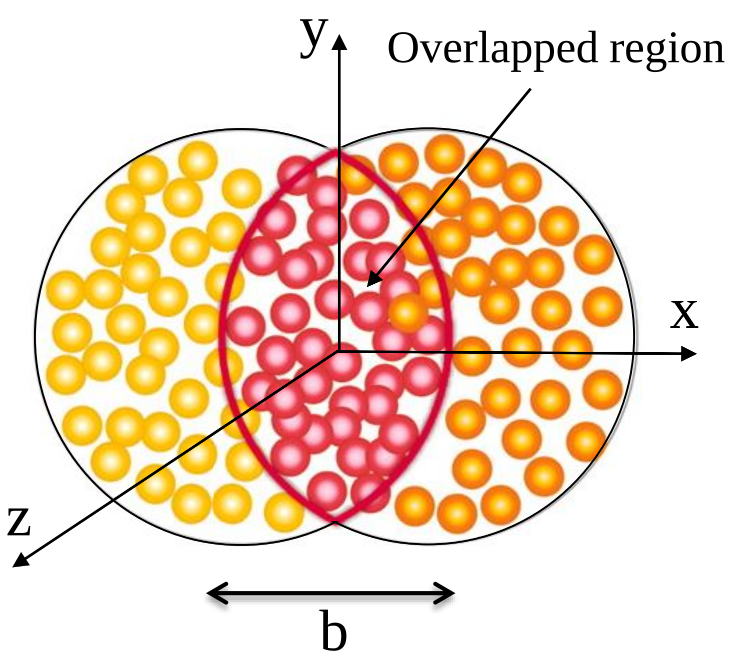
Directed flow (v_1)

Sideward collective motion of produced particles in the reaction plane (x-z plane) and generated during the nuclear passage time (2R/γ) before thermalization.

- **Probe for the early stage of collision dynamics**
- **Signature of the first-order phase transition**
- **Sensitive to equation of state (QGP/Hadronic)**

- *P. Klob, U. W. Heinz, Nucl. Phys. A715, (2003) 653c*

Collective Flow



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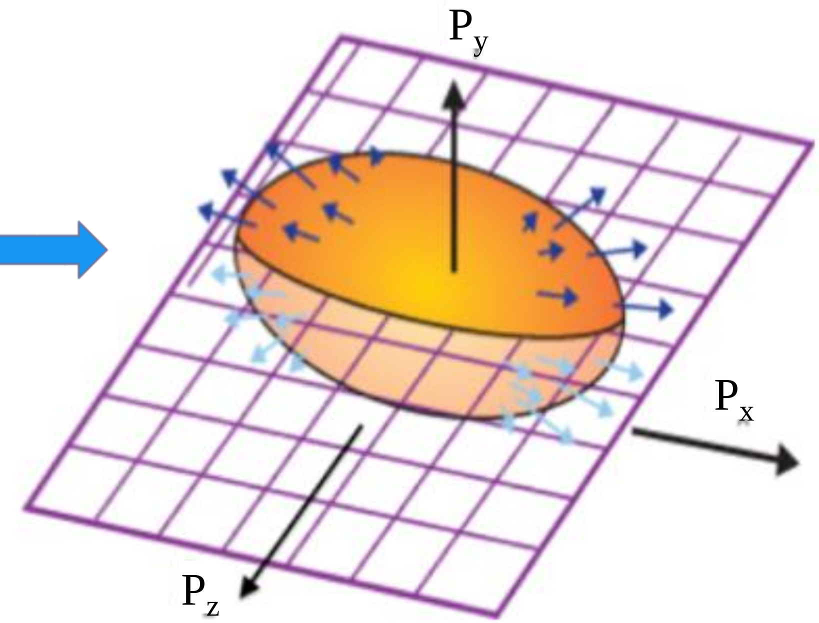
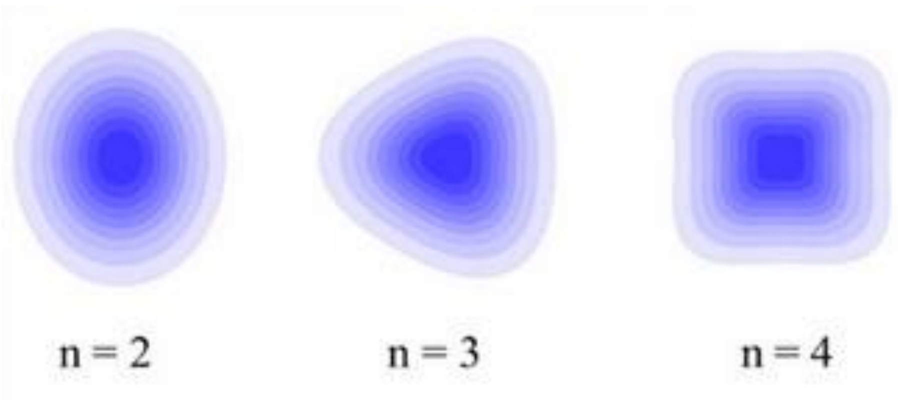


Different flow harmonics



Elliptic flow (v_2) and higher order harmonics

Momentum space anisotropy in the azimuthal angle distribution of produced particles with respect to the reaction plane.

- **Sensitive to initial conditions of collisions**
- **Sensitive to transport properties (η/s) of system**
- **Probe for the particle production mechanism (e.g. quark coalescence)**

- *P. Klob, U. W. Heinz, Nucl. Phys. A715, (2003) 653c*

Flow Measurements

- **Single particle distribution:**

$$E\frac{d^3N}{dp^3} = E\frac{d^2N}{2\pi p_T dp_T d\eta}\left[1 + 2\sum_{n=1}^{\infty} v_n(p_T,\eta)\cos\{n(\phi - \Psi_n)\}\right]$$

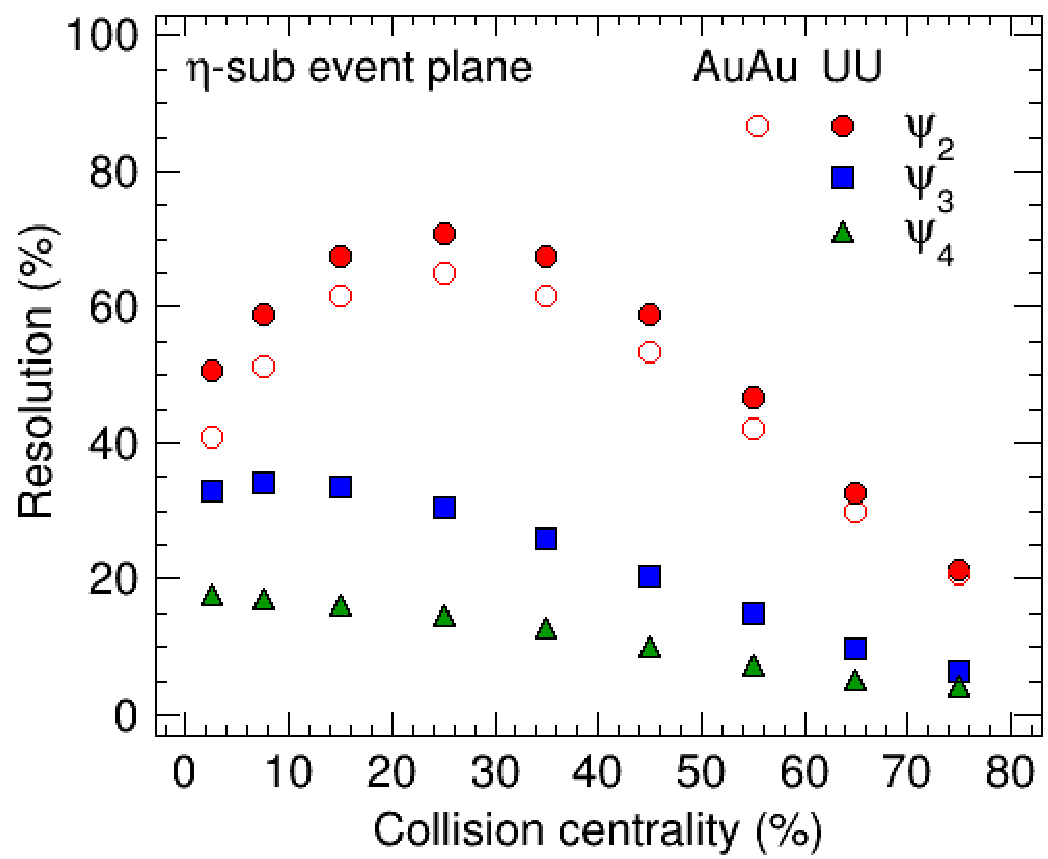
anisotropic flow $v_n = \langle\cos[n(\phi - \Psi_n)]\rangle$, Ψ_n = nth-order reaction plane angle

- **η-sub event plane method**

$$\Psi_n = \frac{1}{n}\tan^{-1}\left(\frac{\sum_{i=1}^{M} w_i \sin(n\phi_i)}{\sum_{i=1}^{M} w_i \cos(n\phi_i)}\right)$$

$$R = \sqrt{\langle\cos[n(\Psi_n^A - \Psi_n^B)]\rangle}$$

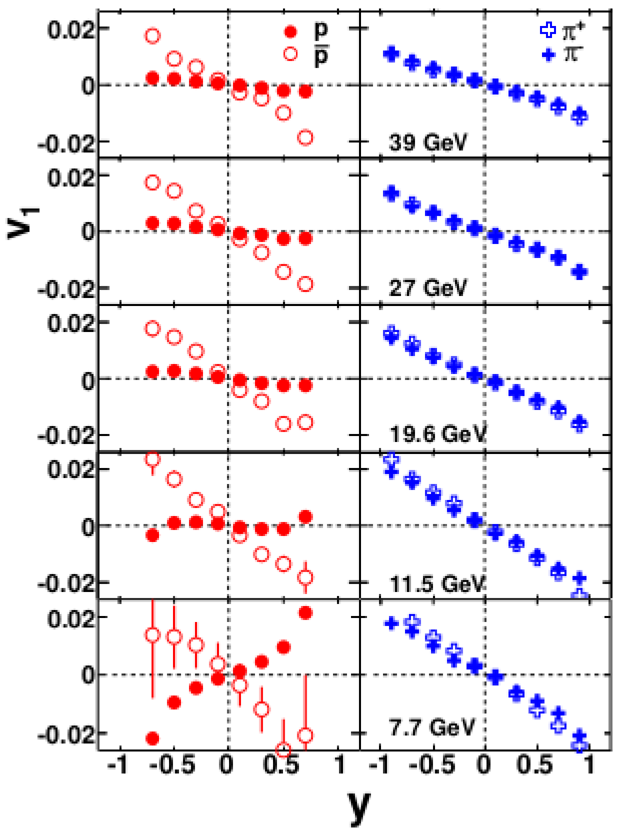
Event plane angle calculated in two sub-events A (0.05 < η < 1.0) and B (-1.0 < η < -0.05).

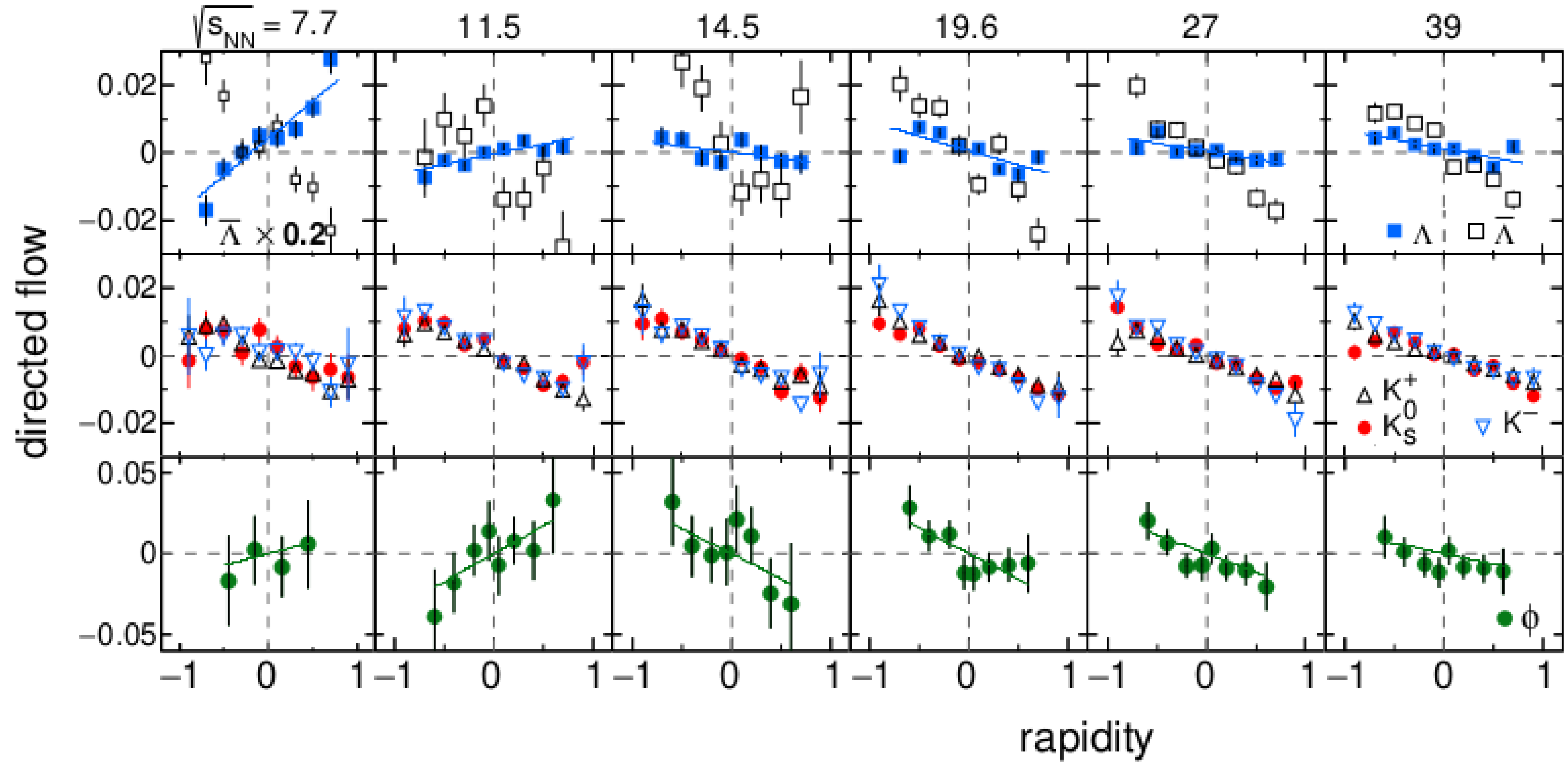


- *A.M. Poskanzer & S.A. Voloshin, Phys.Rev. C 58 (1998)*
- *M. Abdallah et al. (STAR), Phys. Rev. C 103, 064907 (2021)*

Rapidity dependence of directed flow (v_1)

RHIC

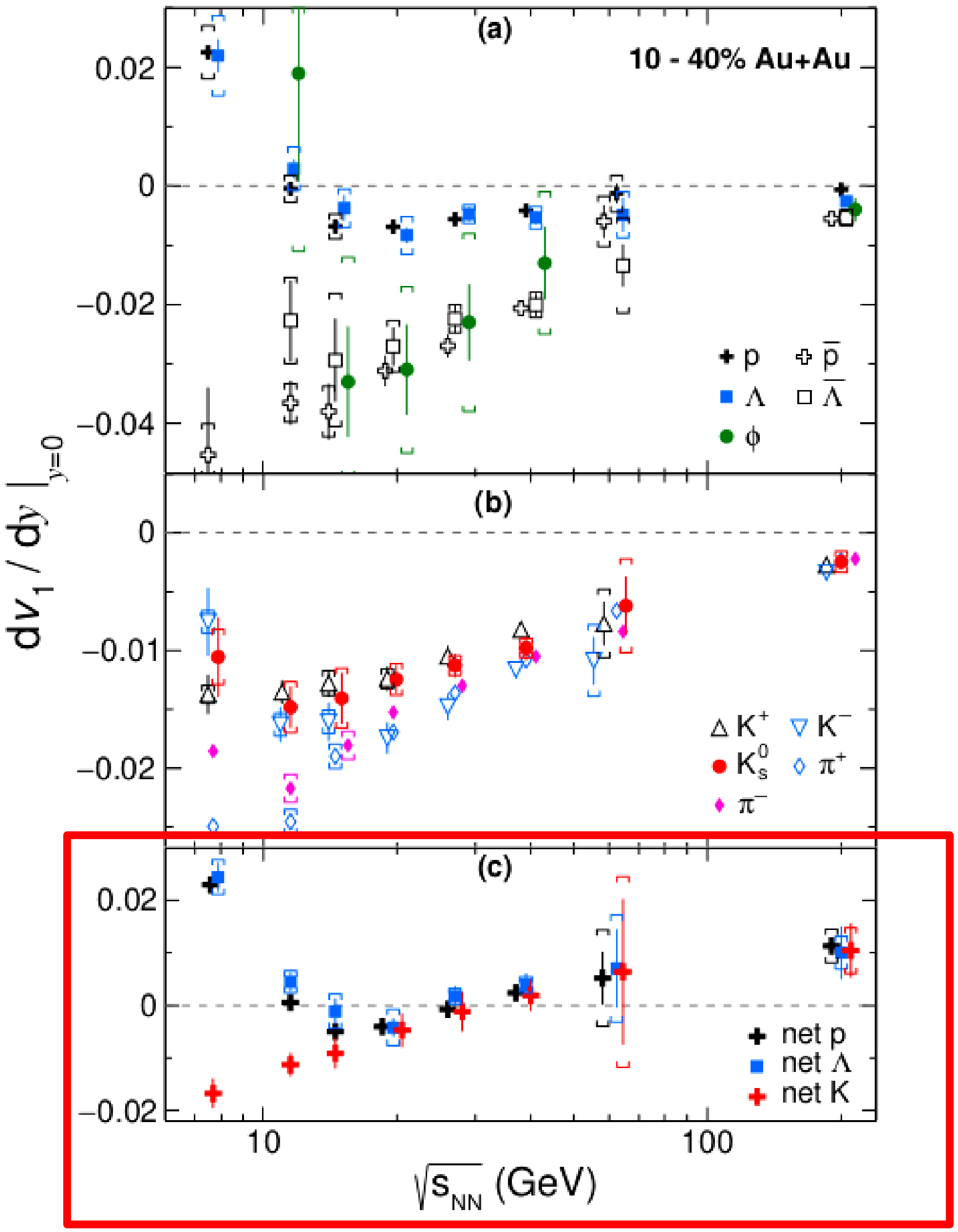




- Rapidity (y) dependence of direct flow (v_1) of identified particles from RHIC at various beam energies.
- Large percentage difference between v_1 of baryons and anti-baryons is observed compare to mesons. The difference increases with decrease in the collision energy.

- *L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. 112, 162301 (2014)*
- *L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. 120, 062301 (2018)*

Slope of directed flow $v_1(y)$



First order phase transition:

- "Net particle" represents the excess yield of a particle species over it's antiparticle which is closely related to the initial transported quarks:

$$[v_1(y)]_{net-p} = \frac{[v_1(y)]_p - r(y)[v_1(y)]_{\bar{p}}}{1 - r(y)}$$

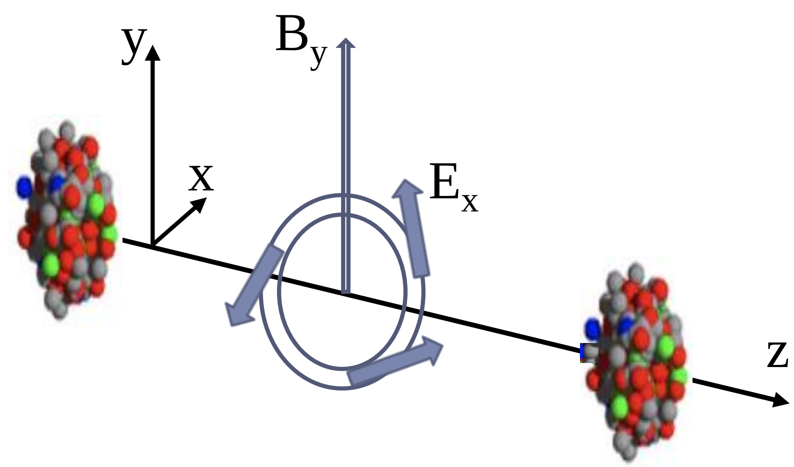
where r(y) is the ratio of observed anti-proton to proton yield at a given collision energy.

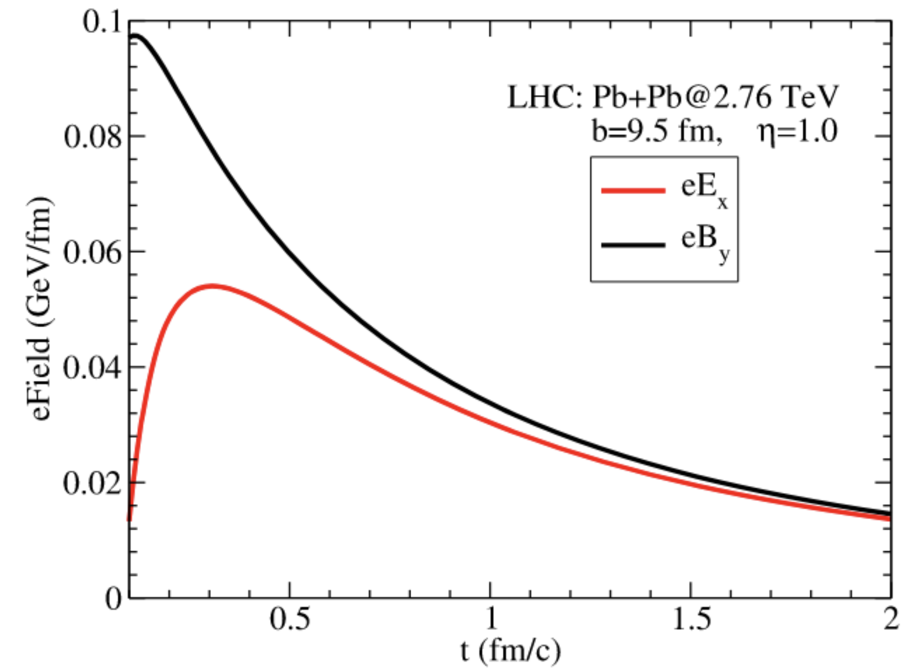
- A dip in dv_1/dy vs $\sqrt{s_{NN}}$ is observed for net-p and net-Λ unlike net-K around $\sqrt{s_{NN}}$ = 10-20 GeV.

Indication of a first order QCD phase transition

- *L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. 112, 162301 (2014)*
- *L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. 120, 062301 (2018)*

Effect of EM field on directed flow of heavy quarks



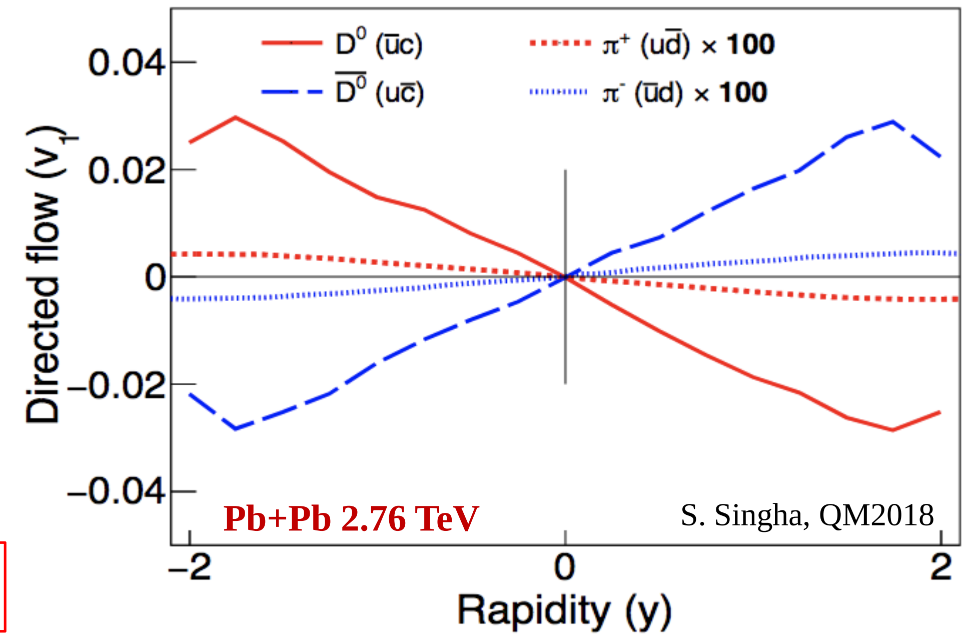


- A large amount of electromagnetic field (eB~10^{18} G) is produced by the outgoing spectator at the highest RHIC energy.

- Heavy quarks (charm) are produced early τ_{CQs} ~ 0.1 fm/c and hence can be affected by the produced EMF.

- Various models predict opposite v_1 for c and $\bar{c}$ induced by the EMF and the magnitude much higher than the light quarks.

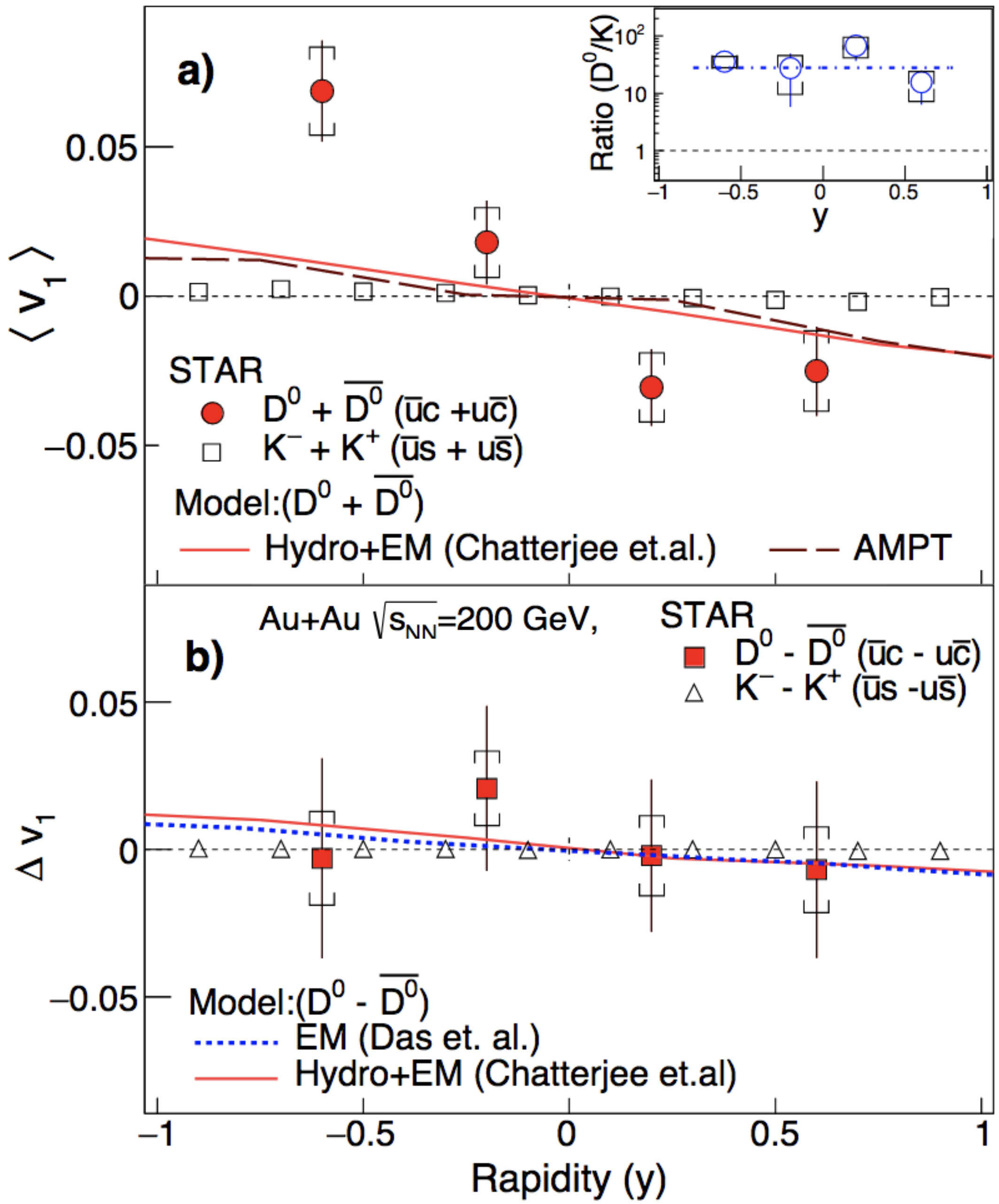
D^0 and $\bar{D}^0$ v_1 can probe the initial produced EMF



- *U. Gürsoy et al., Phys. Rev. C 89, 054905 (2014)*
- *S. K. Das et al, Phys. Lett. B 768, 260-26 (2017)*

Directed flow $v_1(y)$ of D0s

RHIC



- **v_1-slope (dv_1/dy):**

Kaons : $-0.003 \pm 0.0001 \pm 0.0002$,

D^0 : $-0.080 \pm 0.017 \pm 0.016$.

- Charm quark v_1-slope > Light quark v_1-slope
- Negative v_1 for both D^0 and $\overline{D}^0$

- **Δv_1-slope ($d\Delta v_1/dy$):**
  - Negligible Δv_1 splitting of D^0 and $\overline{D}^0$

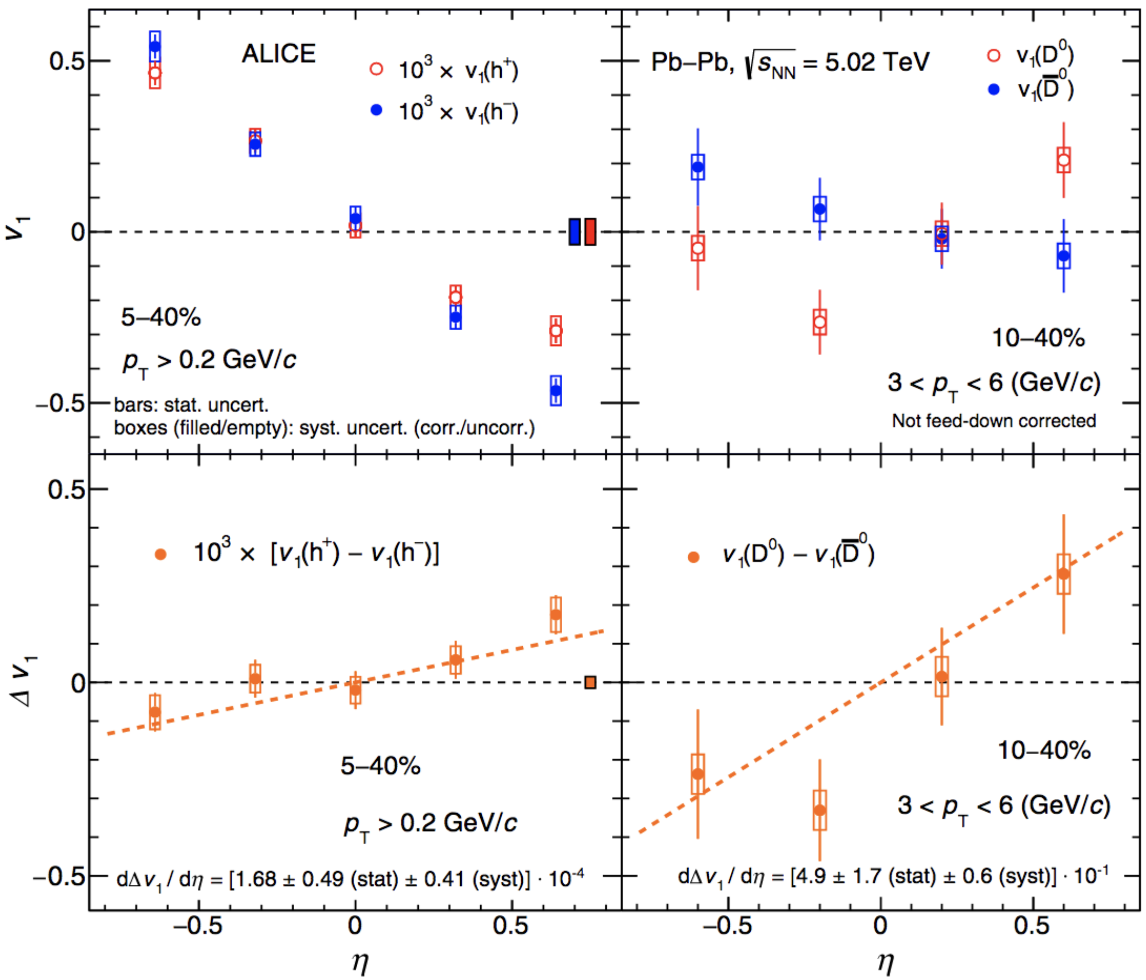
- AMPT and Hydro+EM models predict the v_1 sign of D^0 correctly with magnitude higher than the light-flavor hadrons, but under-predicts the data

- **Hydro+EM:** *S. Chatterjee, P. Bozek: Phys. Rev. Lett 120, 192301 (2018); Phys. Lett. B 798, 134955 (2019)*
- ***AMPT:*** *S. Singha, Md. Nasim, Phys Rev C 97, 064917 (2018)*

- *L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. 120, 062301 (2018)*
- *L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. 123, 162301 (2019)*

Directed flow $v_1(y)$ of D0s

LHC



- **v_1-slope (dv_1/dy):**
  - Charm quark v_1-slope > Light quark v_1-slope
  - Positive slope for D^0 and negative slope for $\overline{D}^0$
- **Δv_1-slope ($d\Delta v_1/dy$):**
  - Positive slope of Δv_1 for charged hadrons and D^0 mesons.

Evidence of magnetic field induced charge separation of heavy quarks

- Δv_1-slope of D^0 meson is significantly higher than corresponding charged hadrons
  - **Tilted source, delay in decay of EMF**

- *S. Acharya et al. (ALICE Collaboration), Phys. Rev. Lett. 125, 022301 (2020)*

Summary: Directed flow

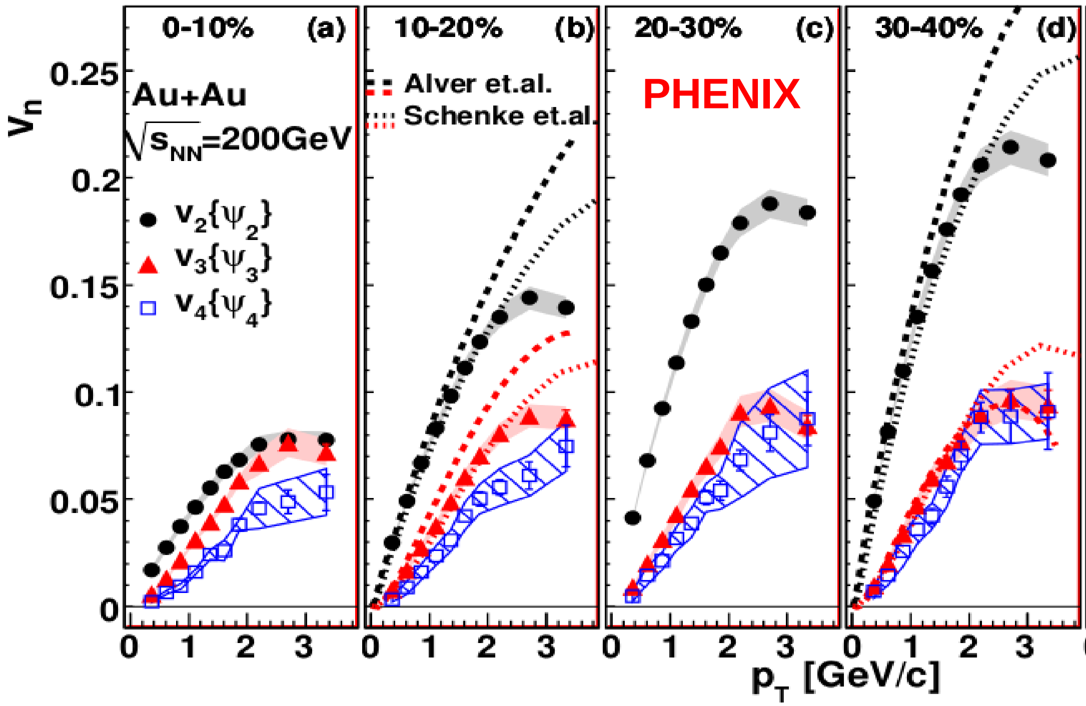
Indication of a first order QCD phase transition

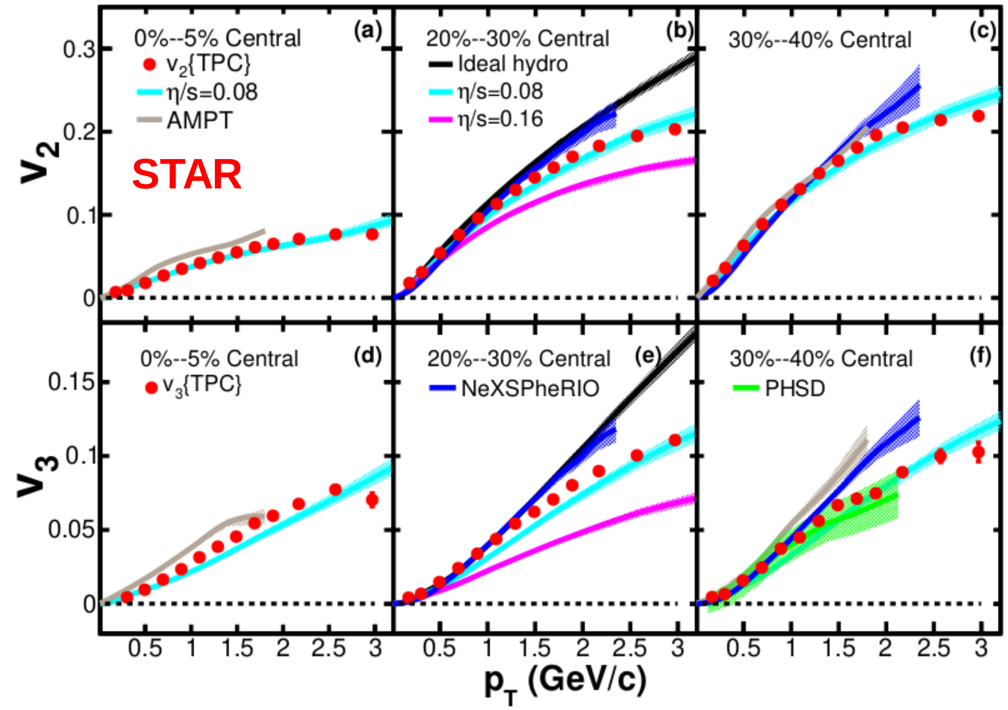
- A dip in the net-p and net-Λ around collision energies 10-20 GeV shows the softening of EoS as predicted by various hydrodynamic and transport models.

Evidence of magnetic field induced charge separation of heavy quarks

- v_1 of charm quark is larger than the corresponding light flavor quarks.
- Δv_1 splitting between D^0 and $\overline{D}^0$ might be an evidence of magnetic field induced charge separation of heavy quarks
- The measurements are important for constraining the theoretical models which could not predicts the correct sign of Δv_1-slope between the D^0 and $\overline{D}^0$

p_T evolution of flow harmonics





Effect of initial conditions (collision geometry/eccentricity):

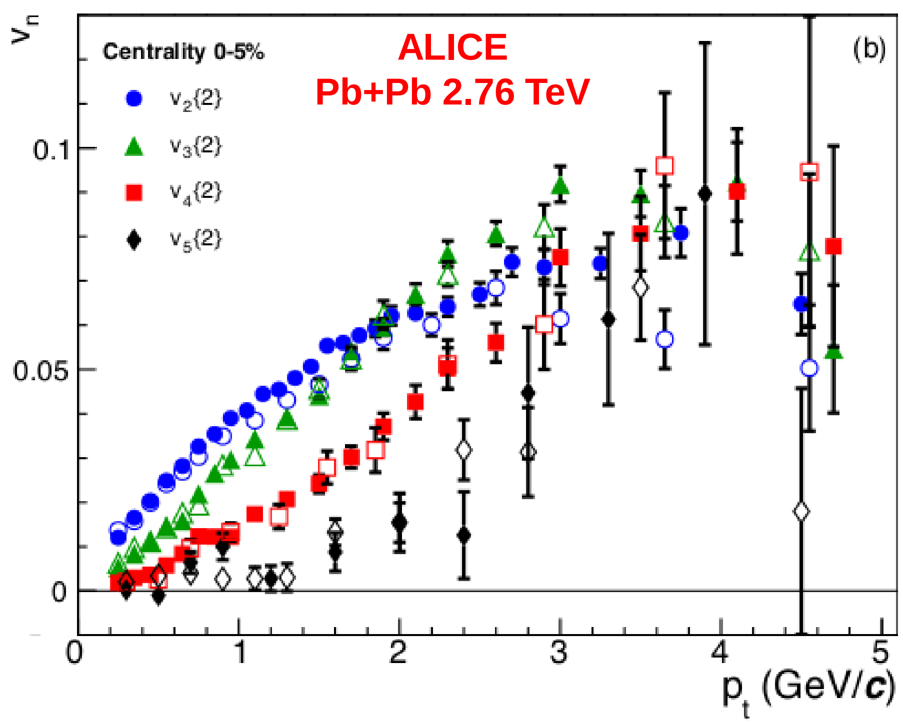
- Flow harmonics increase with p_T then start saturating around $p_T \approx 2.0\text{-}3.0$ GeV/c.
- Elliptic flow v_2 strongly depends on the centrality while higher order harmonics have weak centrality dependence.

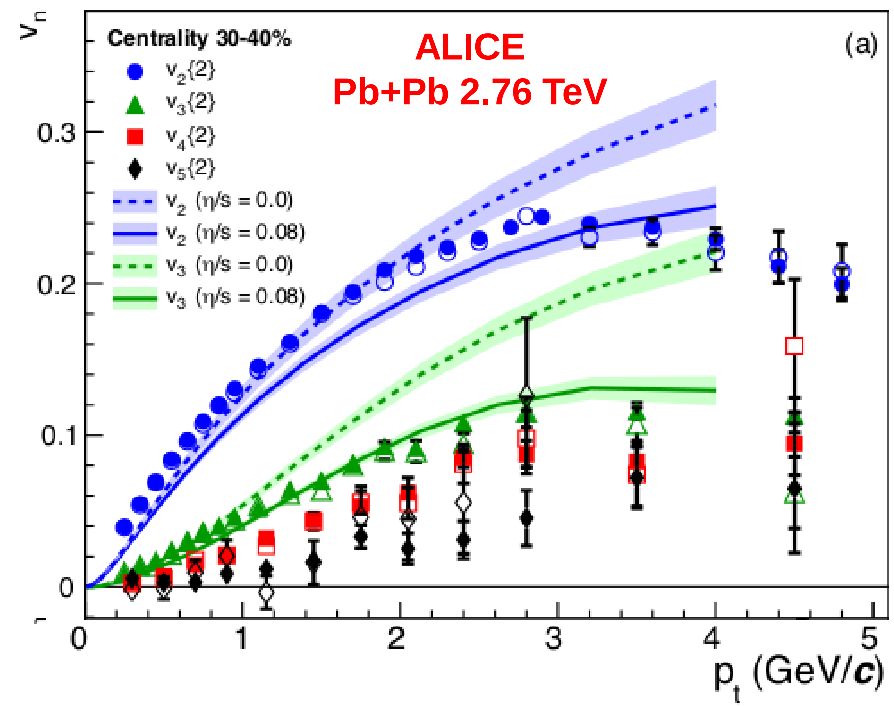
Sensitivity to the transport properties (shear viscosity to entropy density η/s):

- Higher order flow harmonics provide better constrains for the extraction of transport properties.
- 3+1D viscous hydro model with Glauber-MC initial conditions with $\eta/s = 0.08$ ($\approx 1/4\pi$) agrees better with the experimental results.

- *A. Adare et al. (PHENIX Collaboration), Phys. Rev. Lett. 107, 252301 (2011)*
- *L. Adamczyk et al. (STAR Collaboration), Phys. Rev. C 88, 014904 (2013)*

p_T evolution of flow harmonics





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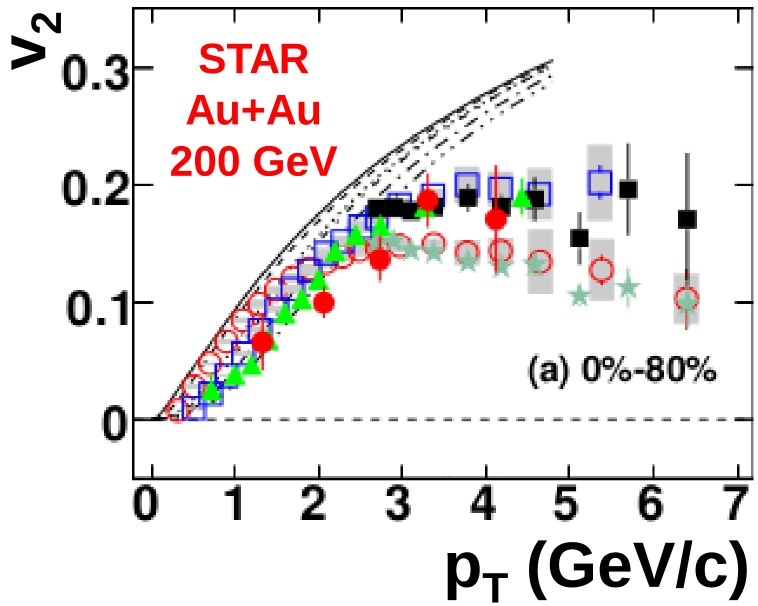
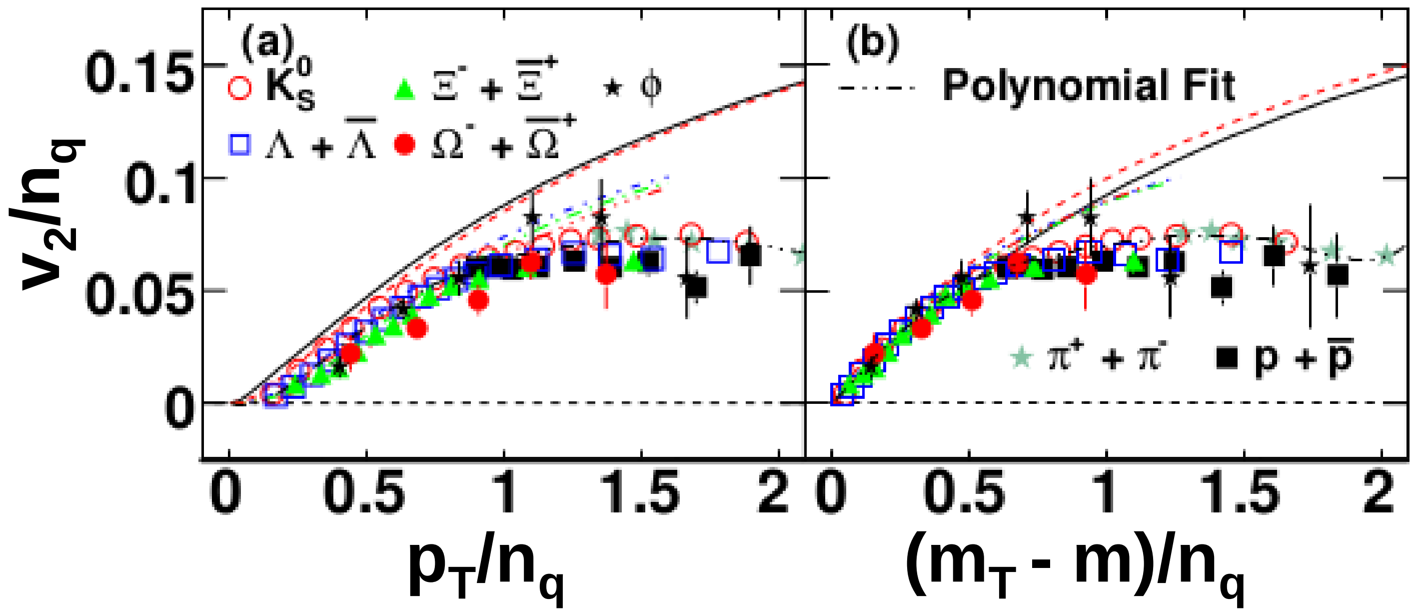
- *J. Adam et al. (The ALICE Collaboration), Phys. Rev. Lett. 116, 132302 (2016)*

p_T evolution of flow harmonics





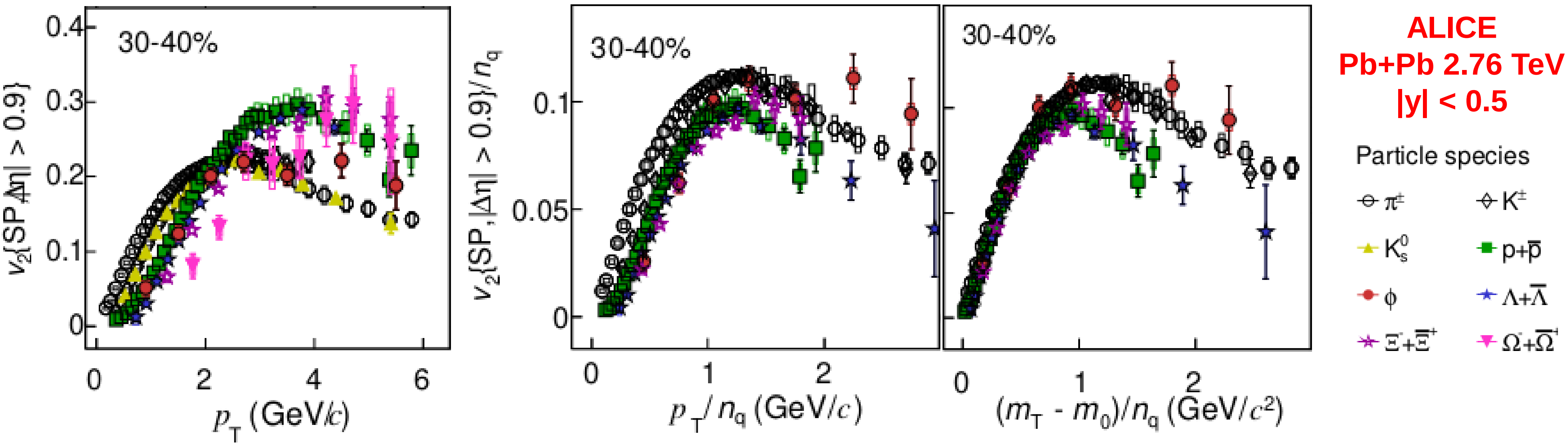
- **Hydrodynamics flow:**
  - ► large v_2 for lighter mass particles compare to the heavier mass particles consistent with the hydrodynamics flow.
  - ► Mass ordering of v_2 below p_T < 2-3 GeV/c indicates effect of radial flow.
- **Hadronisation via quark coalescence:**
  - ► Elliptic flow v_2 of baryons > mesons above intermediate $p_T \approx$ 2-3 GeV/c. v_2 scaled by number of constituent quarks (n_q) follows a single curve.
  - ► The NCQ scaling of v_2 suggests quark coalescence as dominate particle production mechanism.

• *B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C 77, 054901 (2008)*

Identified hadrons

p_T evolution of flow harmonics

LHC



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- *B. Abelev et. al (ALICE Collaboration), JHEP 06, 190 (2015)*

Summary: Elliptic flow & higher harmonics

Sensitive to initial conditions and transport properties of the system

- Strong centrality dependence of elliptic flow v_2 compare to higher order harmonics.
- Weak/no centrality dependence of higher harmonics reflects E-by-E fluctuations as the origin of higher order flow harmonics.
- Agreement with 3+1D viscous hydrodynamics ($\eta/s = 0.08$) with Gluaber-MC fluctuating initial conditions suggests formation of strongly coupled quark gluon plasma.

Hydrodynamic flow and partonic collectivity

- Mass ordering of v_2 at low $p_T < 2\text{-}3$ GeV/c suggest hydrodynamic flow of identified hadrons.
- NCQ scaling of v_2 at intermediate p_T indicates parton coalescence as dominate particle production mechanism.

Thank you!