Collectivity in Heavy Ion Collisions at RHIC-STAR

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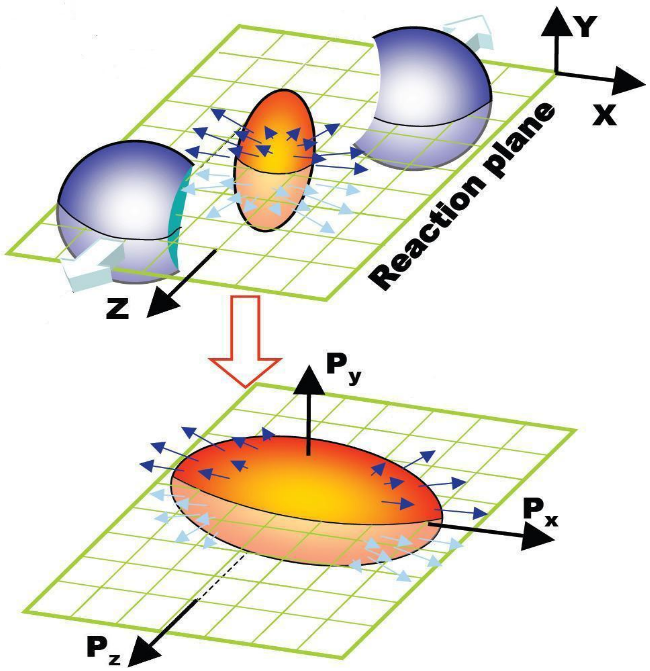
Outline

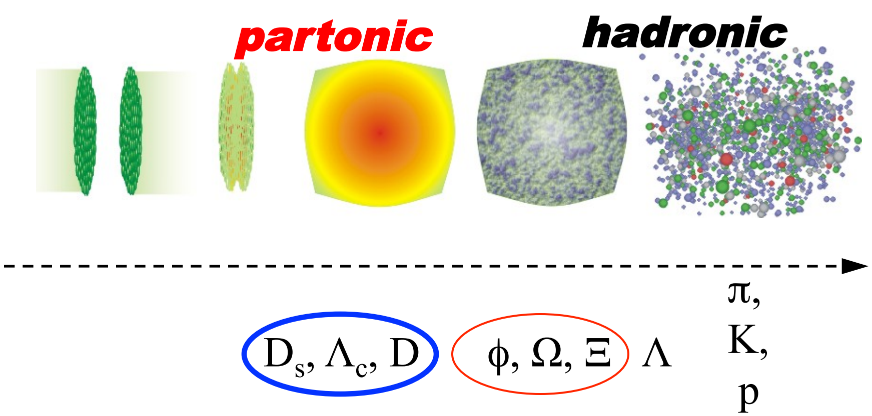
- Introduction
- The STAR Detector
- Results and Discussions
- Summary and Outlook

Anisotropic Flow



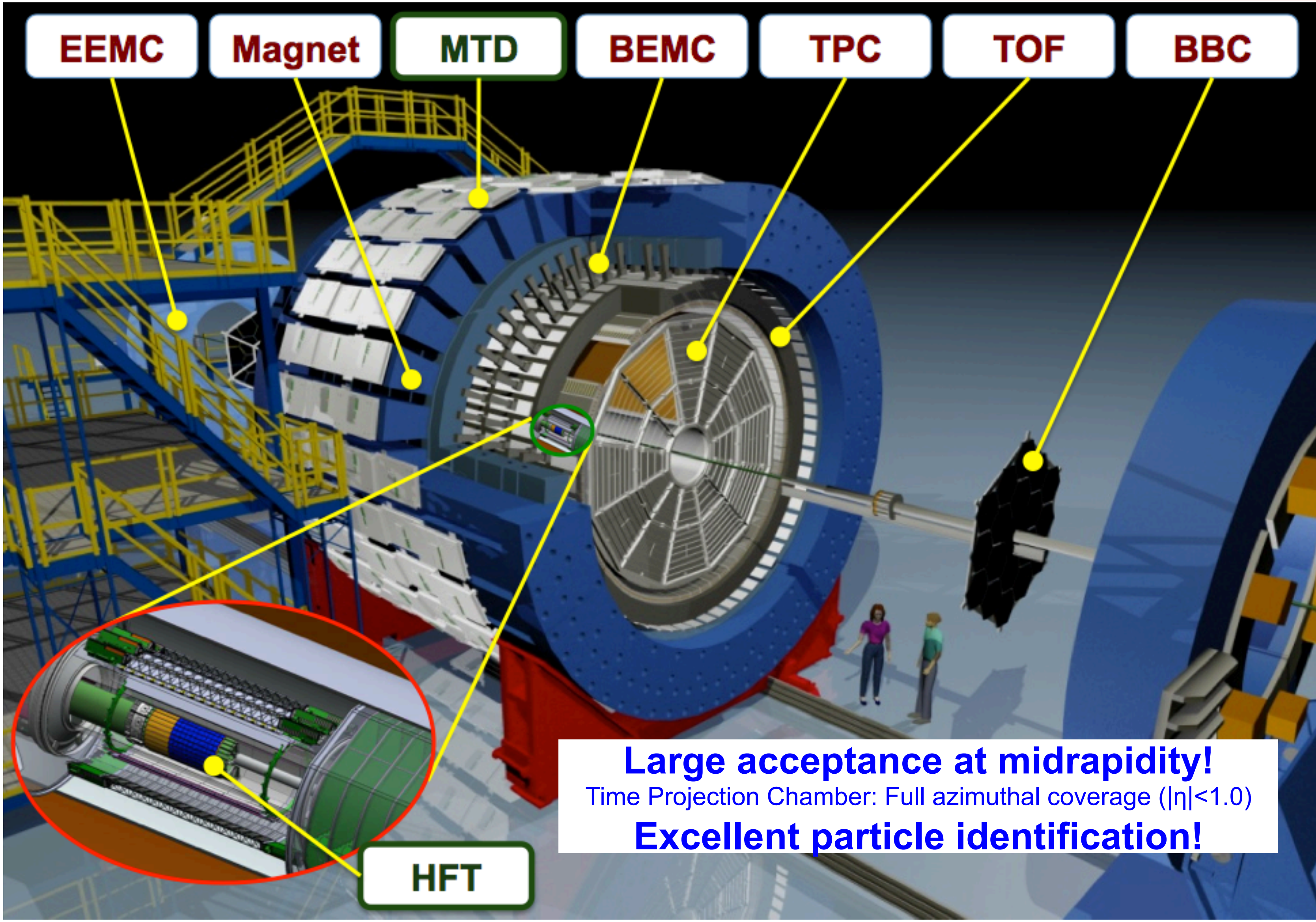
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1} v_n \cos\left[n(\phi - \Psi_n)\right]$$

v_1: directed flow; v_2: elliptic flow;
v_3: triangular flow

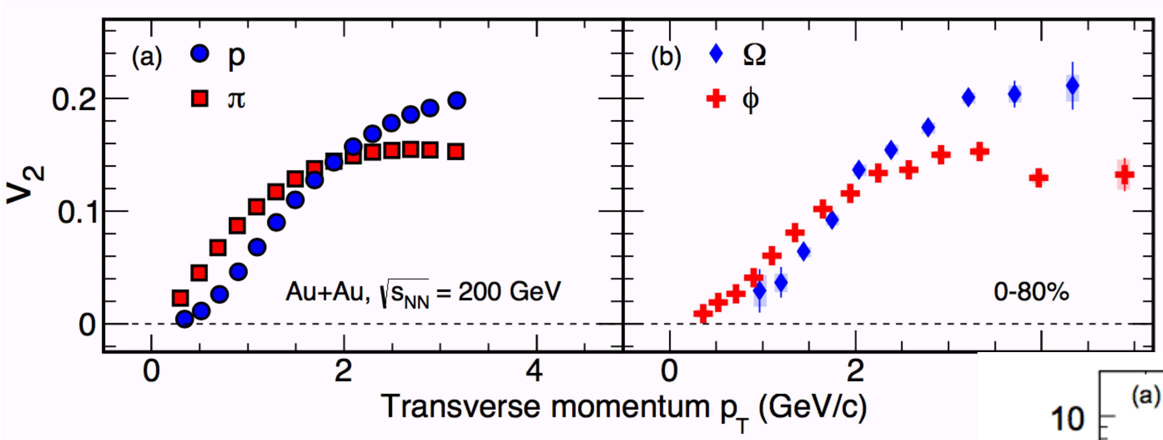


- **Anisotropic flow** *:*
  Sensitive to the early stage of the collision
- **Heavy flavor flow**
  Study medium properties from motion of heavy quarks in medium
- **Multi-strange hadrons and ϕ meson** *:*
  Less sensitive to late hadronic rescatterings

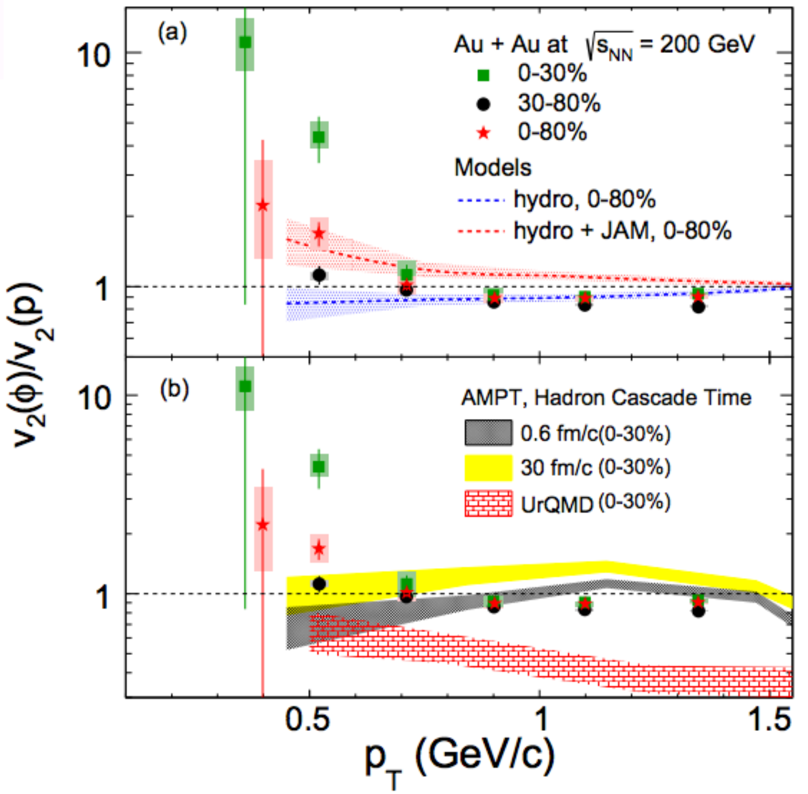
The STAR Detector



Partonic Collectivity

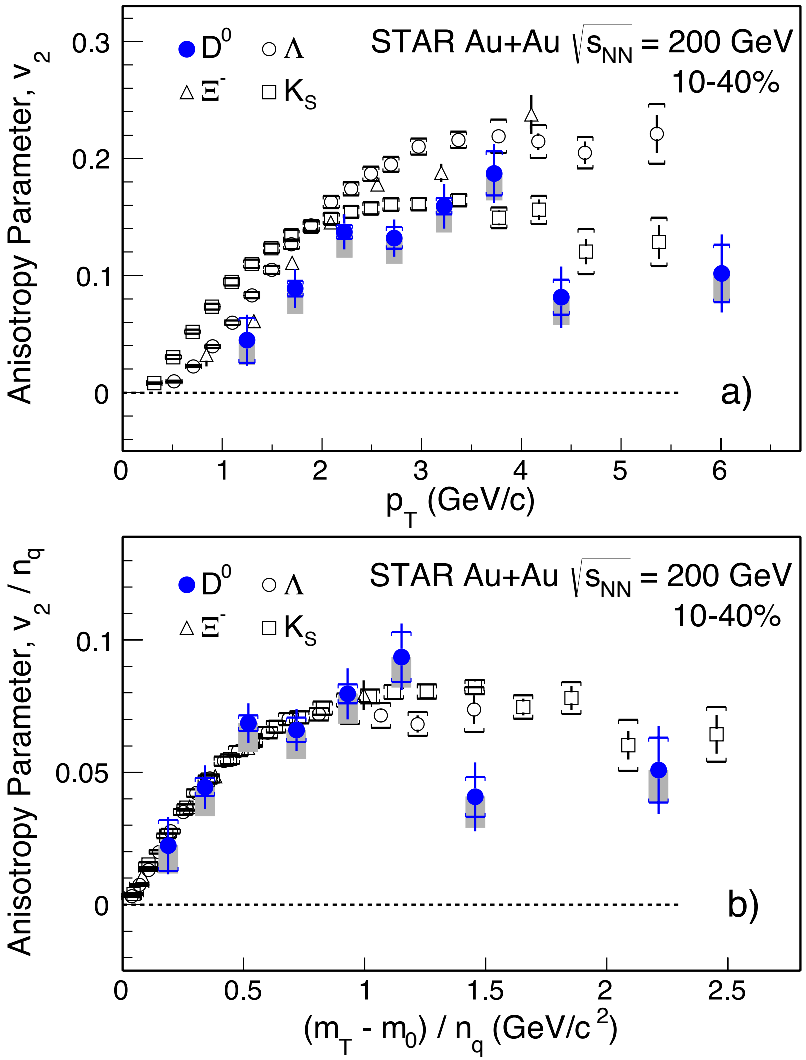


STAR: Phys. Rev. Lett.116, 062301(2016)



- **The baryon-meson v_2 splitting and the similar magnitude of v_2 between Ω and proton: *partonic collectivity***
- **The broken mass ordering for ϕ mesons and protons: *ϕ mesons insensitive to hadronic interactions***

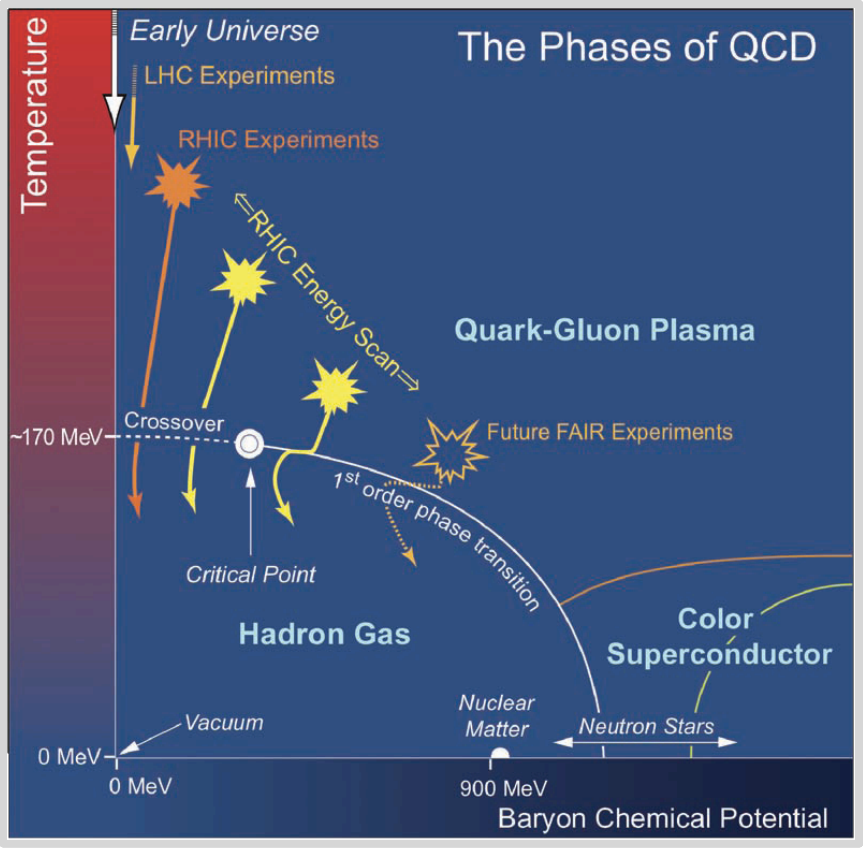
Charm Quark Collectivity



- **Large v_2 values, comparable to light hadrons, is seen for D^0 mesons**
- **Clear mass ordering seen below 2 GeV/c**
- **v_2 values of D^0 scaled with number of constituent quarks (NCQ) follow the same trend as light hadrons**
- **Suggest charm quarks flow with the QGP**

STAR: Phys. Rev. Lett.118, 212301 (2017)

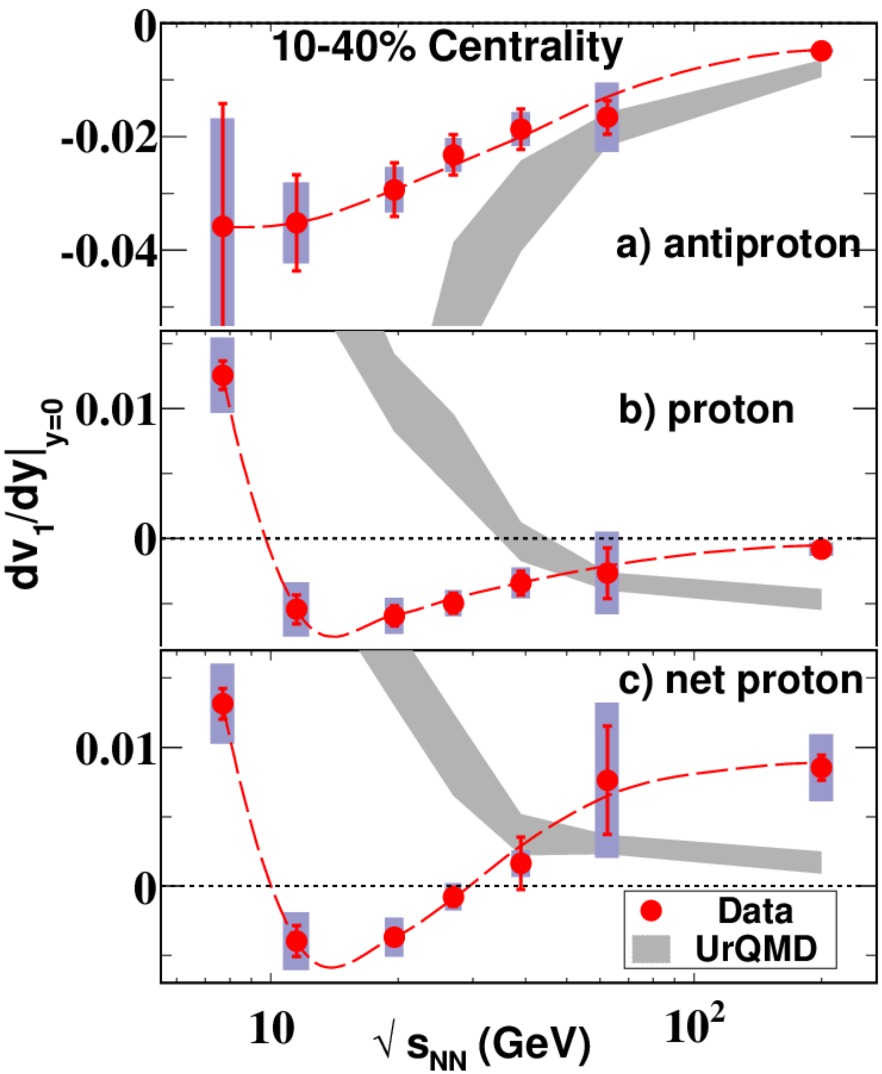
Beam Energy Scan I



$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year
200	350	2010
62.4	67	2010
54.4	**1000**	**2017**
39	39	2010
27	70	2011
19.6	36	2011
14.5	20	2014
11.5	12	2010
7.7	4	2010

Explore the QCD phase structure!

Directed Flow v_1: Softest Point



dv_1/dy: the slope of directed flow versus rapidity near mid-rapidity

- Hydrodynamic calculation with the 1st-order phase transition motivates the study
- Net-proton slope changes sign twice

  EOS softest point?

- UrQMD fails to reproduce the data

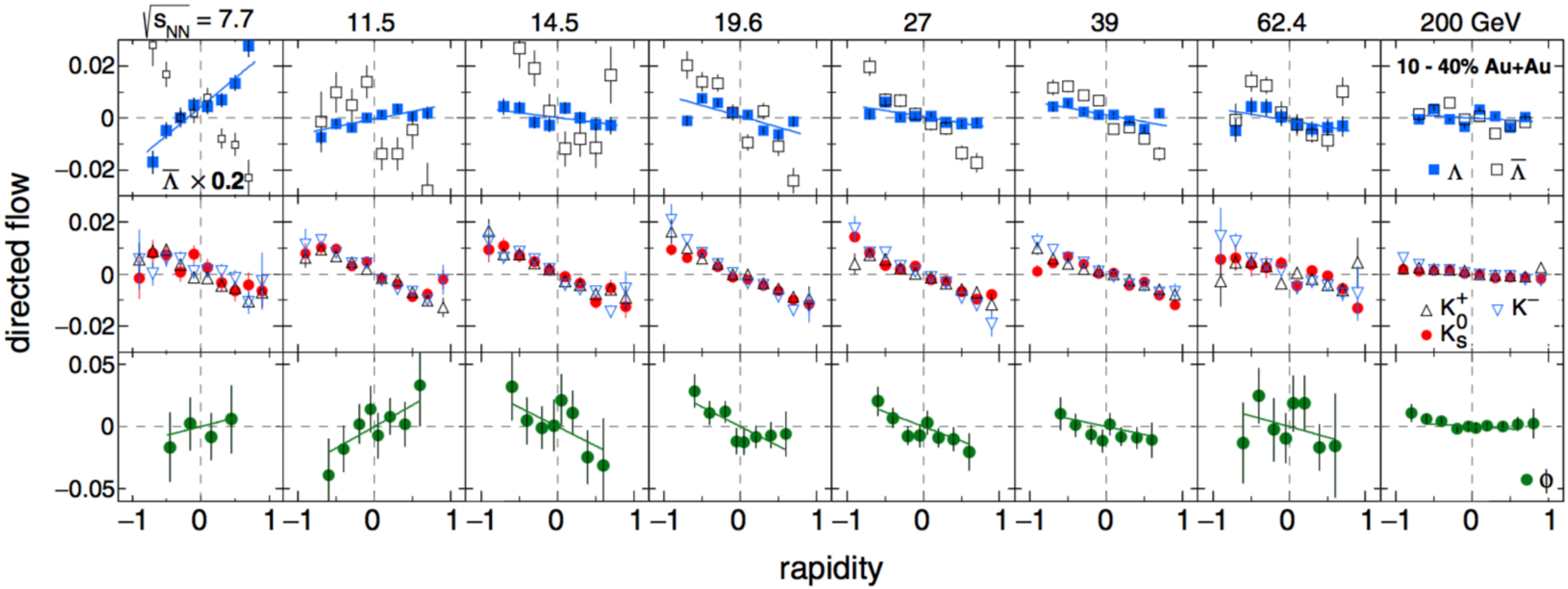
The slope of net-p is based on expressing the y dependence of v1 for all protons as：

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

r： the ratio of anti-p to p.

STAR: Phys. Rev. Lett. 112, 162301(2014)
H. Stoecker, Nucl. Phys. A 750, 121(2005)

Directed Flow v_1: ϕ Mesons

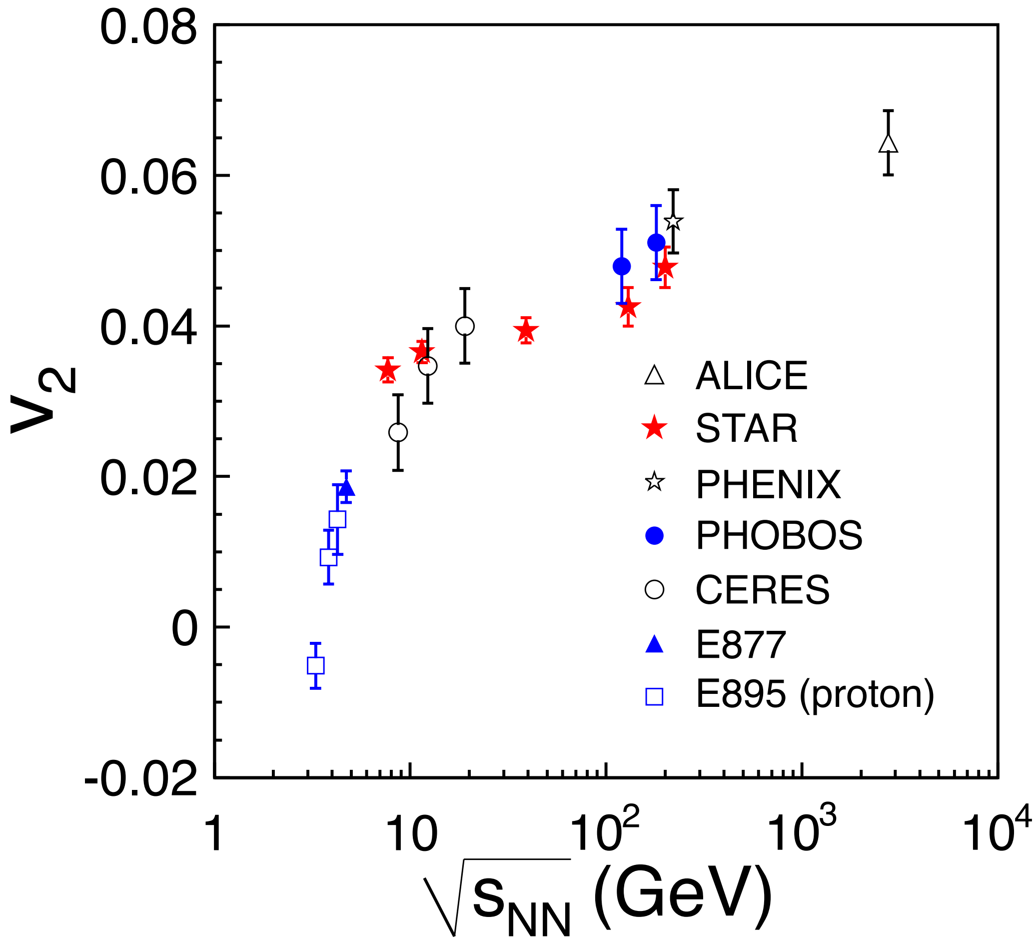


- Mesons and all produced anti-baryons show negative slope except ϕ mesons when collisions energy < 14.5 GeV

Change of medium property? High precision data are needed.

STAR: Phys. Rev. Lett. **120**, 062301(2018)

Energy Dependence v_2

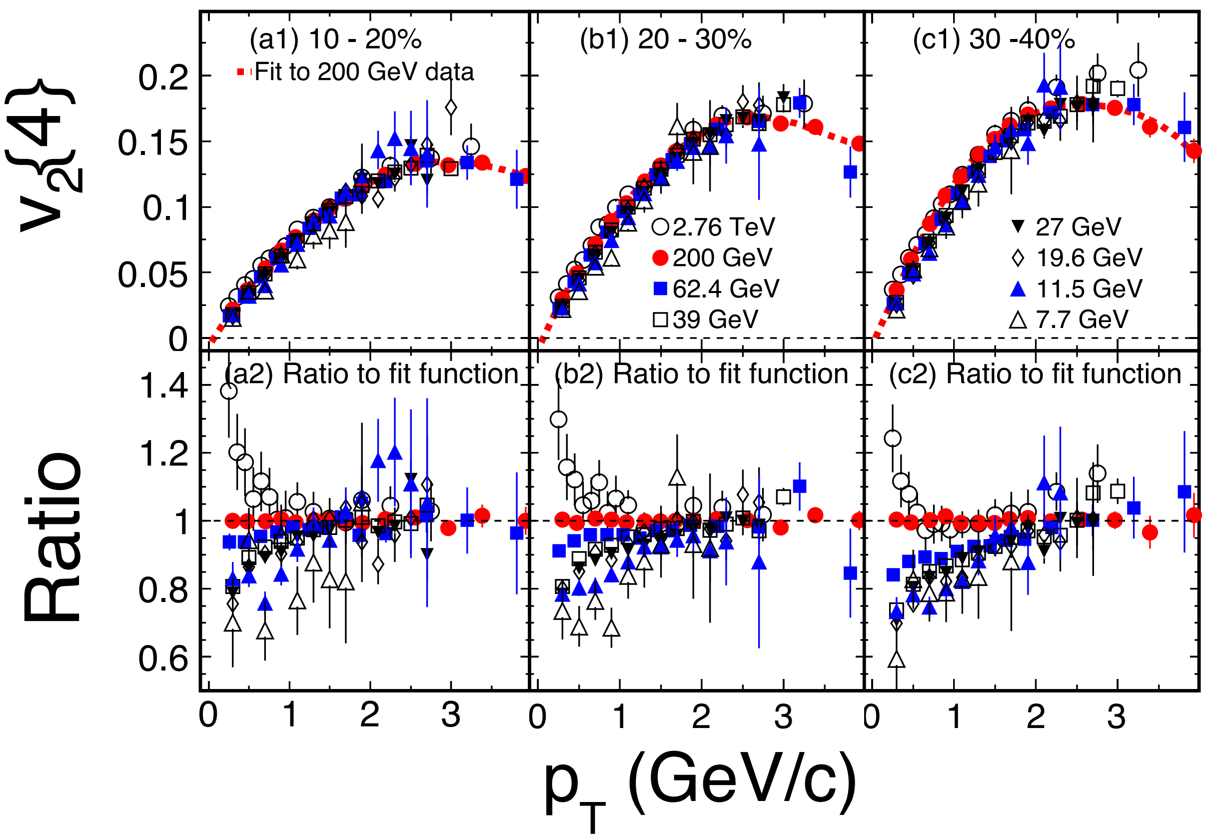


- **STAR, ALICE: $v_2\{4\}$ results**
  - Centrality: 20-30%
- **An increasing trend is observed for p_T integrated v_2 from AGS to LHC**
  - The rate of increase with collision energy is slower from 7.7 to 39 GeV compared to that between 3 to 7.7 GeV

ALICE: Phys. Rev. Lett. 105, 252302 (2010)
PHENIX: Phys. Rev.Lett. 98, 162301 (2007).
PHOBOS: Phys. Rev.Lett. 98, 242302 (2007).
CERES: Nucl. Phys. A 698, 253c (2002).
E877: Nucl. Phys. A 638, 3c(1998).
E895: Phys. Rev. Lett. 83, 1295 (1999).
STAR 130 and 200 GeV: Phys. Rev. C 66,873 034904 (2002); Phys. Rev. C 72,790 014904 (2005)

STAR: Phys. Rev. C 86, 054908(2012)

Energy Dependence v_2

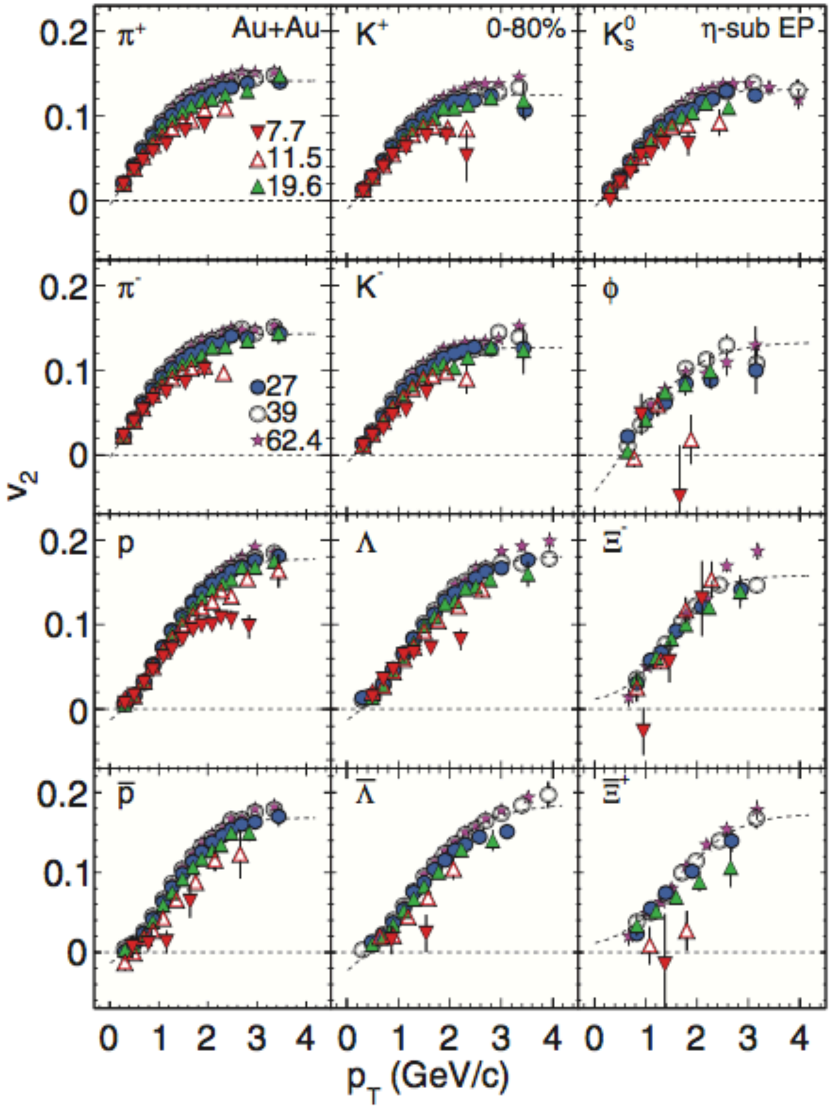


STAR: Phys. Rev. C 86, 054908(2012)

ALICE data: Phys. Rev. Lett. 105, 252302 (2010)

- **$v_2\{4\}$ results**
  - Three centrality bins
- **Consistent $v_2(p_T)$ from 7.7 GeV to 2.76 TeV for p_T > 2 GeV/c**
- **p_T< 2GeV/*c***
  - The v_2 values rise with increasing collision energy
    ->
    Large collectivity? Particle composition?

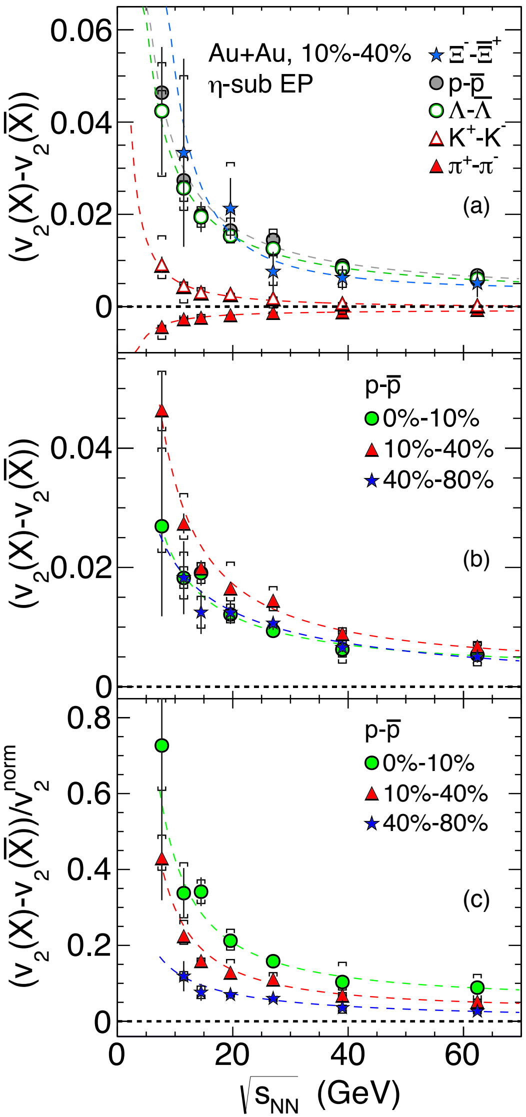
Energy Dependence v_2

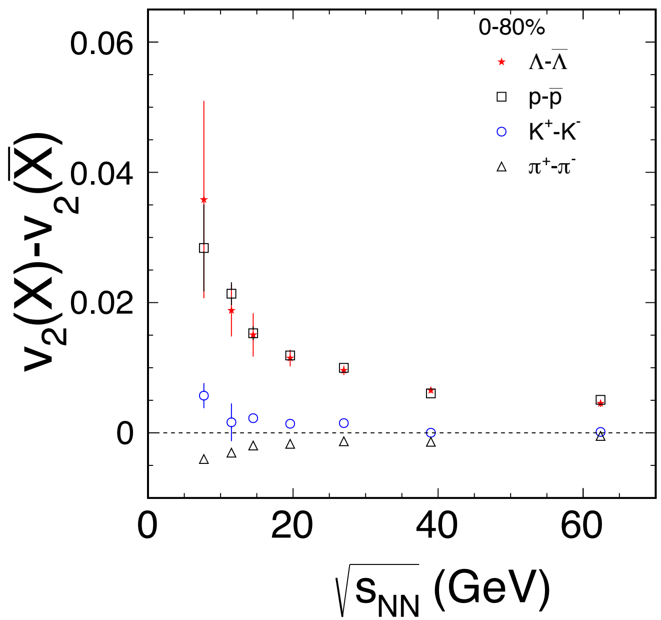


STAR: Phys. Rev. C 88, 014902 (2013)

➢ **Similar shape of $v_2(p_T)$ for different identified particles**

Particle vs. Anti-particle v_2

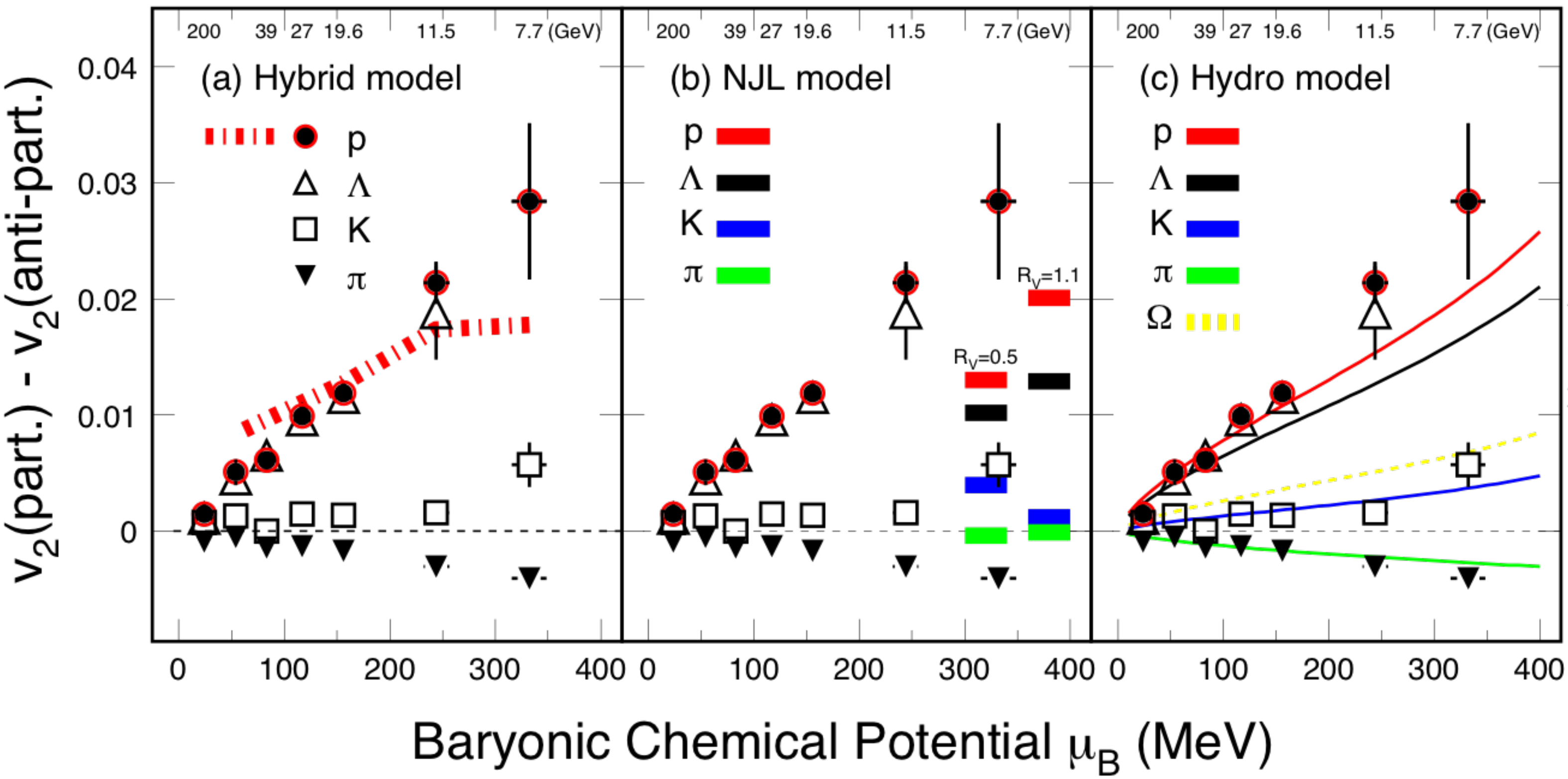




- **Significant difference between baryon and anti-baryon v_2 is observed**
- **The relative difference normalized by v_2^{norm}, the proton elliptic flow at p_T = 1.5 GeV/c, shows a clear centrality dependence with a bigger effect for the more central collisions**

STAR: Phys. Rev. Lett. 110 (2013) 142301
Phys. Rev. C 93, 014907(2016)
S. S. Shi: Adv. High Energy Phys. 2016, 1987432 (2016)

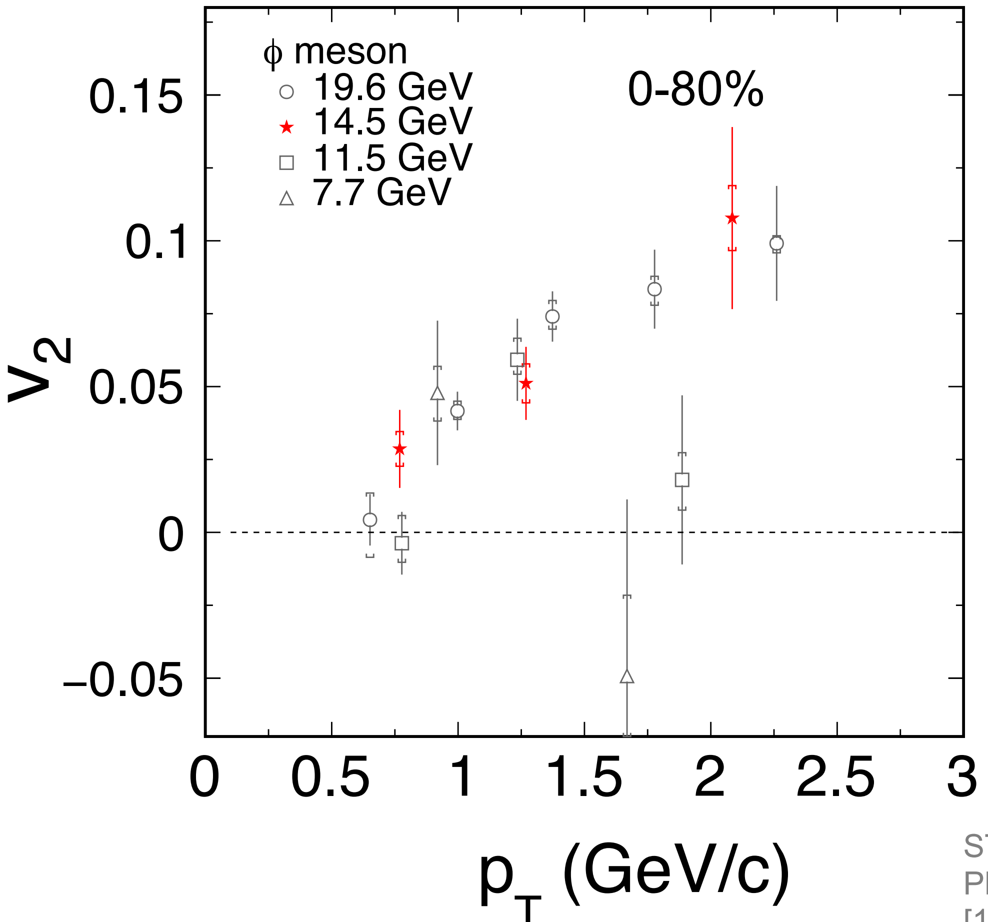
Particle vs. Anti-particle v_2



- **The difference between particles and anti-particles increases with decreasing beam energy – NCQ scaling breaks**
- **Model comparison** STAR: Phys. Rev. Lett. **110** (2013) 142301
  - Hydro + Transport (UrQMD): consistent with baryon data
  - Nambu-Jona-Lasino (NJL) model (partonic + hadronic potential): hadron splitting consistent
  - Analytical hydrodynamic solution： $\Delta v_2^p > \Delta v_2^\Lambda > \Delta v_2^\Xi > \Delta v_2^\Omega$

J. Steinheimer et al., PRC86, 44903(2012); J. Xu et al., PRL112, 012301(2014); Y. Hatta et al., PRD92, 114010(2015)

φ Meson v_2



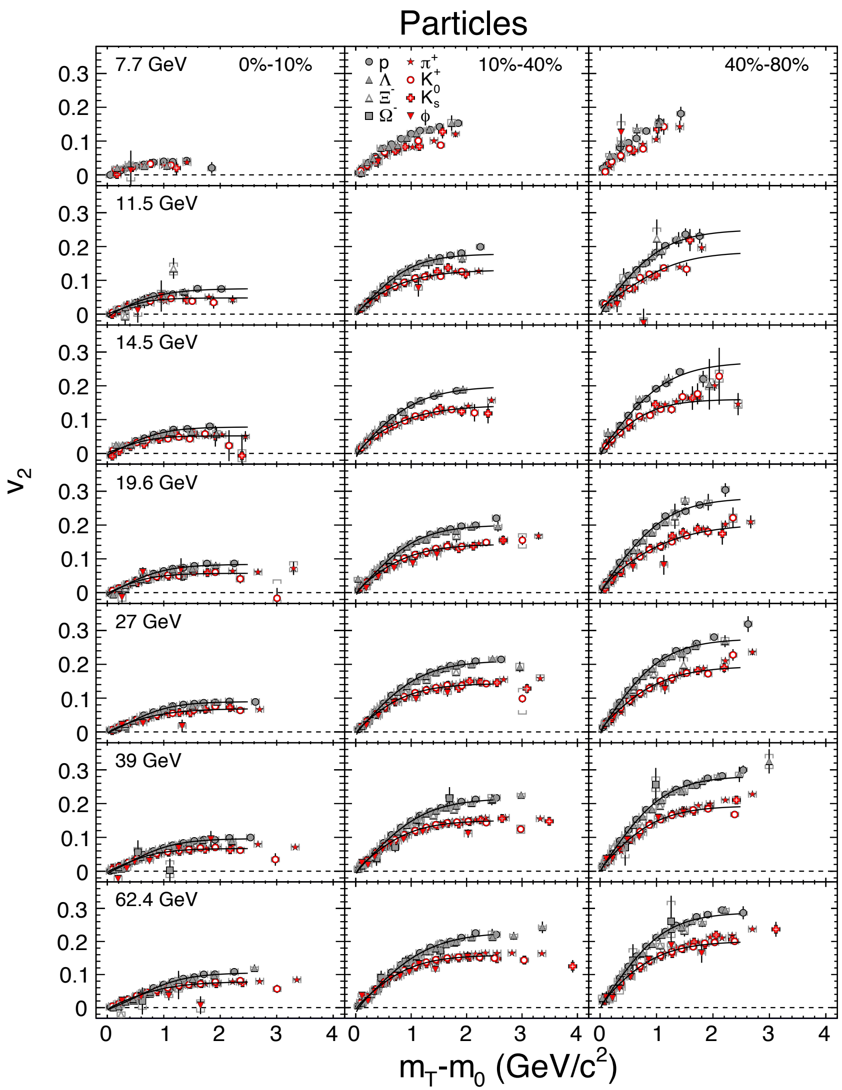
φ meson is less sensitive to late hadronic interactions[1]

Sizable φ meson v_2: comparable to 19.6 GeV

High statistics and more energies below 20 GeV needed!

STAR: Phys. Rev. C 88, 014902(2013)
Phys. Rev. C 93, 014907(2016)
[1] STAR: Phys. Rev. Lett. 116, 062301(2016)

Baryon/Meson Separation

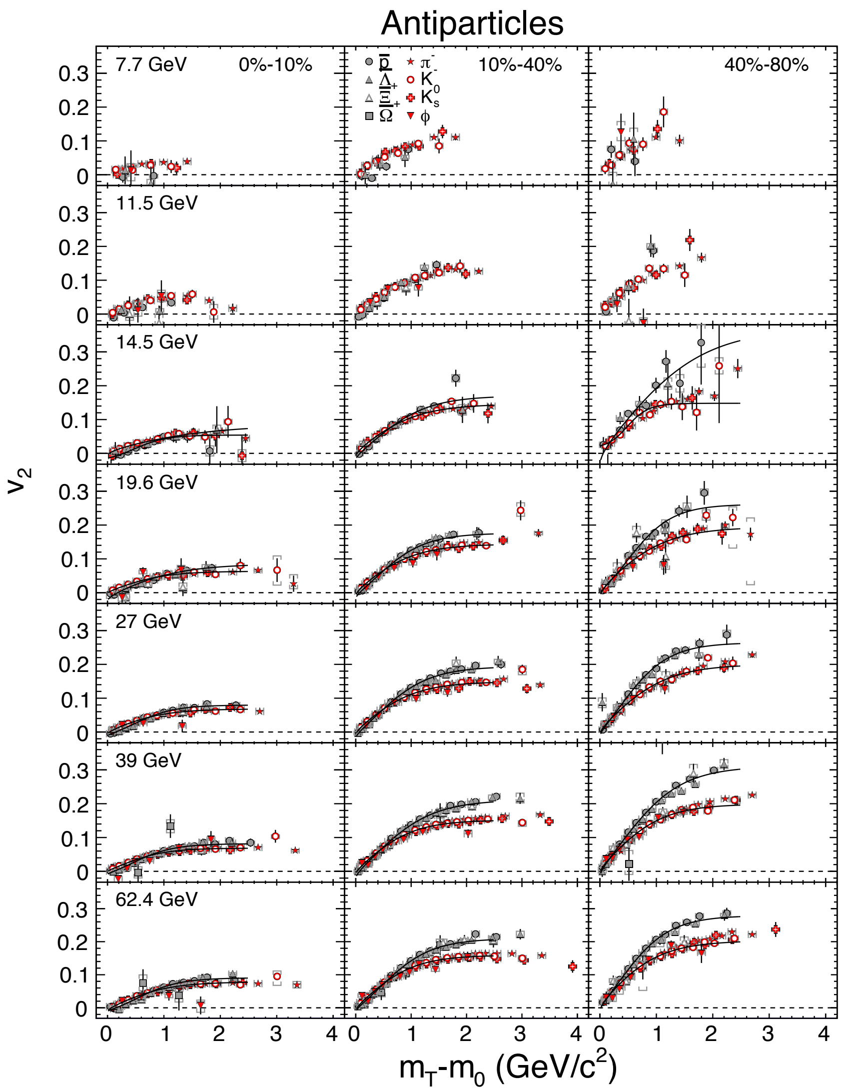


A splitting between baryons and mesons is observed at all energies except 7.7 GeV and all centralities.

At 7.7 GeV we are limited by the number of events.

STAR: Phys. Rev. C 93, 014907(2016)

Baryon/Meson Separation

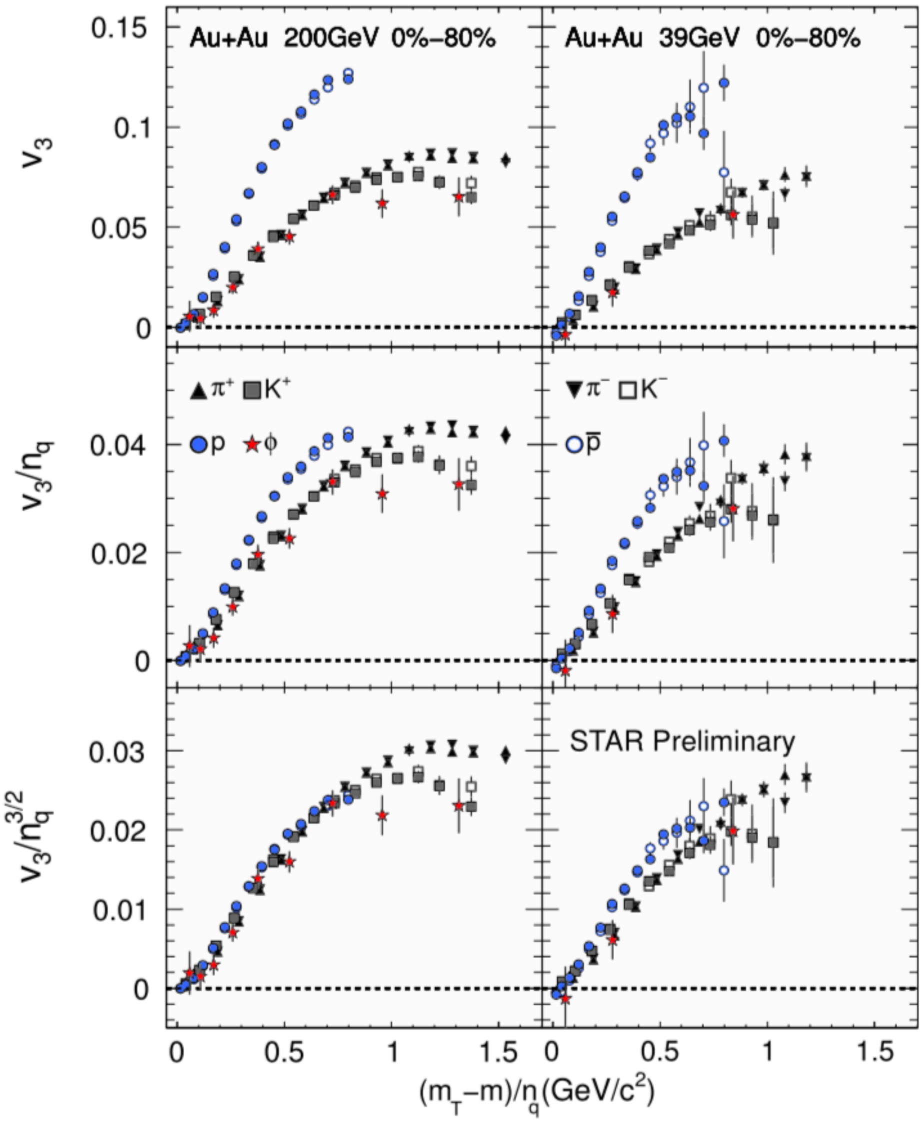


The splitting between baryons and mesons is observed significant for all energies above 14.5 GeV and also at 14.5 GeV for 40%–80%.

For these energies below 11.5 GeV, we are limited by the number of events.

STAR: Phys. Rev. C 93, 014907(2016)

Triangular Flow



Better NCQ scaling achieved at 39 GeV (up to 0.8 GeV/c²) and 200 GeV (up to 0.8 GeV/c²) by using scaling factor $n_q^{3/2}$

STAR: QM2014

R. Lacey, J. Phys. G 38 (2011) 124048

Summary

- **Study the QGP properties**
  - ***D*^{0} meson v_2:** *charm quarks flow*
  - **Mass ordering break for ϕ and proton v_2:**

    Hadronic effect on partonic flow
- **Explore the QCD phase structure**
  - **v_1: slope of net-proton**

    Possible signature of the 1st-order phase transition

    Further progress in models needed
  - **Particle vs. anti-particle v_2**

    The difference increases with decreasing beam energy
  - **ϕ meson v_1/v_2 and baryon/meson separation**

    Limited by statistics when beam energy < 14.5 GeV

BES-II

Electron cooling + longer beam bunches for BES-II
factor 4-15 improvement in luminosity compared with BES-I

Detector upgrade

- **Event Plane Detector**
  important for flow and fluctuation analyses
- **iTPC upgrade**
  increases TPC acceptance to ~1.7 in η; improves dE/dx resolution
- **ETOF upgrade**
  New charged hadron PID capabilities for 1.1<|η|<1.6

Fixed target program

extends STAR's physics reach to region of compressed baryonic matter

RHIC BES-II：2019-2010

19.6, 14.5, 11.5, 9.2 and 7.7 GeV

Focus on $\sqrt{s_{NN}} \leq 20$ GeV region