Collectivity from RHIC BES-I

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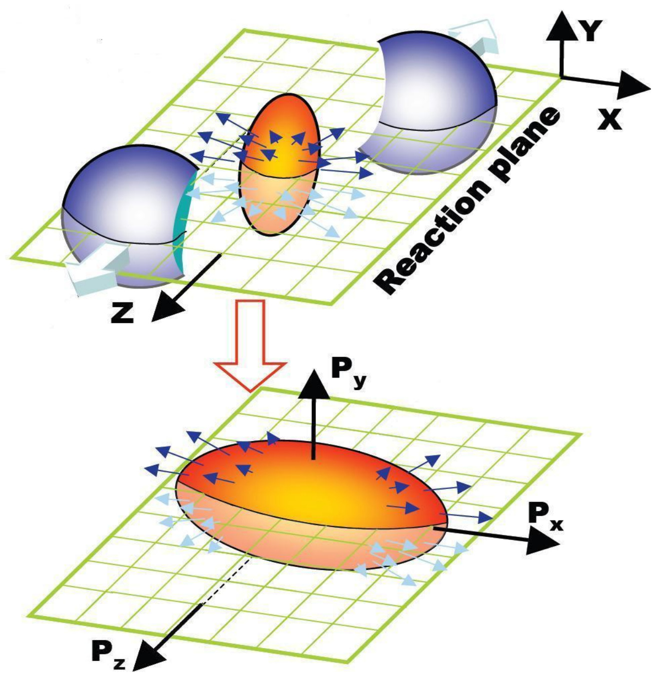
Outline

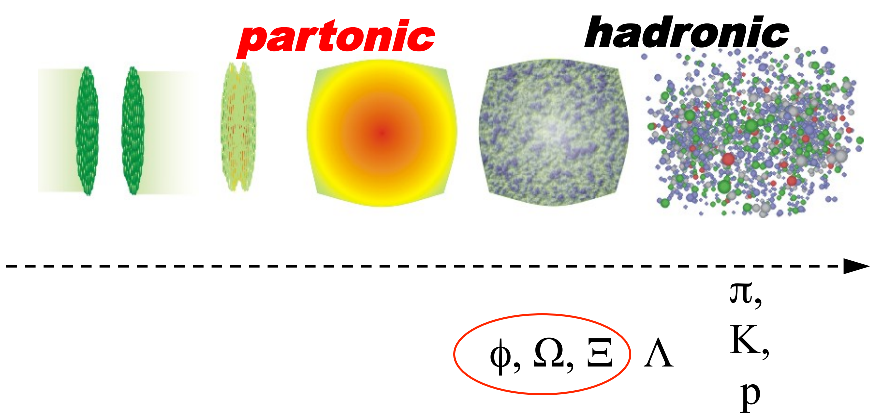
- Introduction
- STAR Detector
- Results and Discussions
- Summary and Outlook

Anisotropic Flow



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

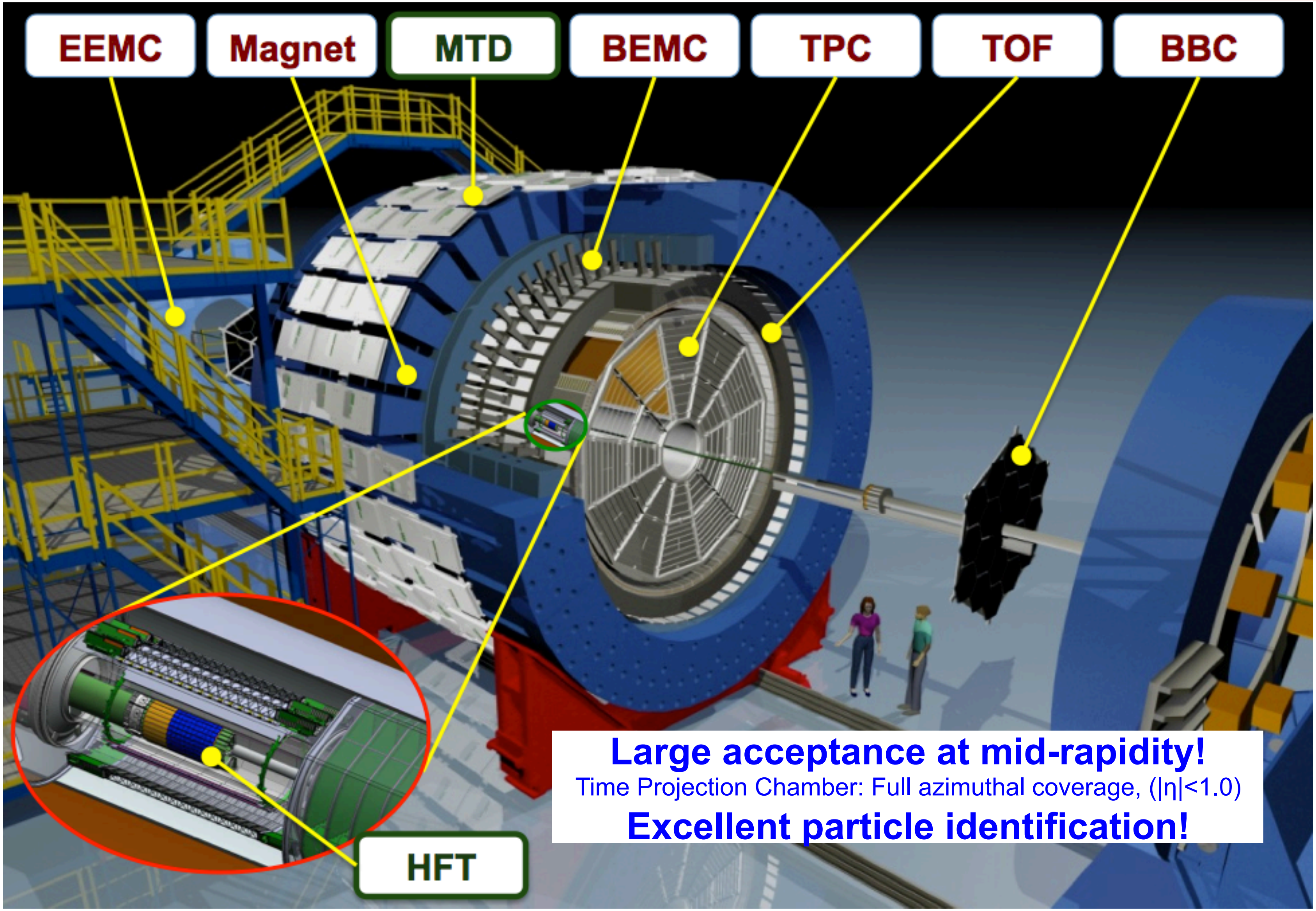
v_1: directed flow; v_2: elliptic flow;
v_3: triangular flow



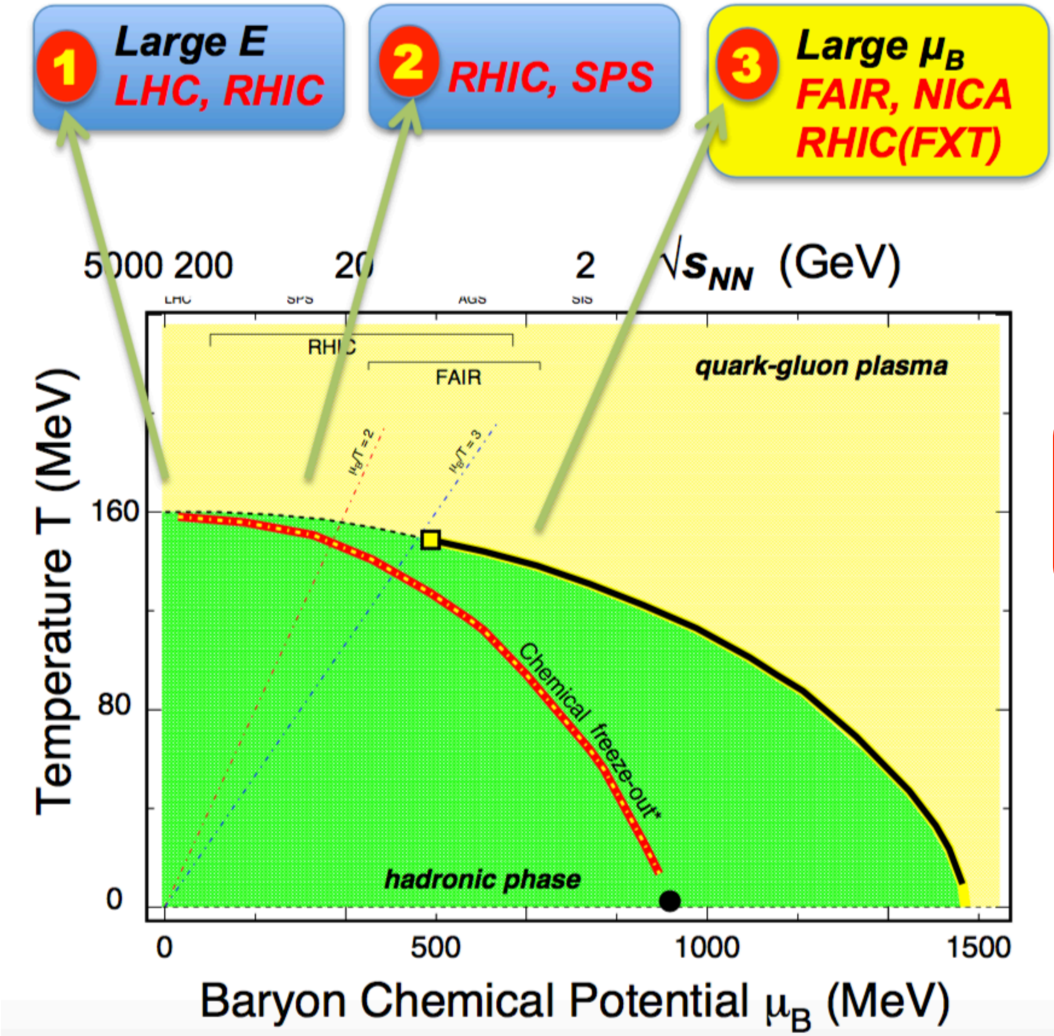
- **Anisotropic flow** :
  Sensitive to the early stage of the collision

- **Multi-strange hadrons and φ meson** :
  Less sensitive to late hadronic rescatterings

STAR Detectors



QCD Phase Diagram and BES



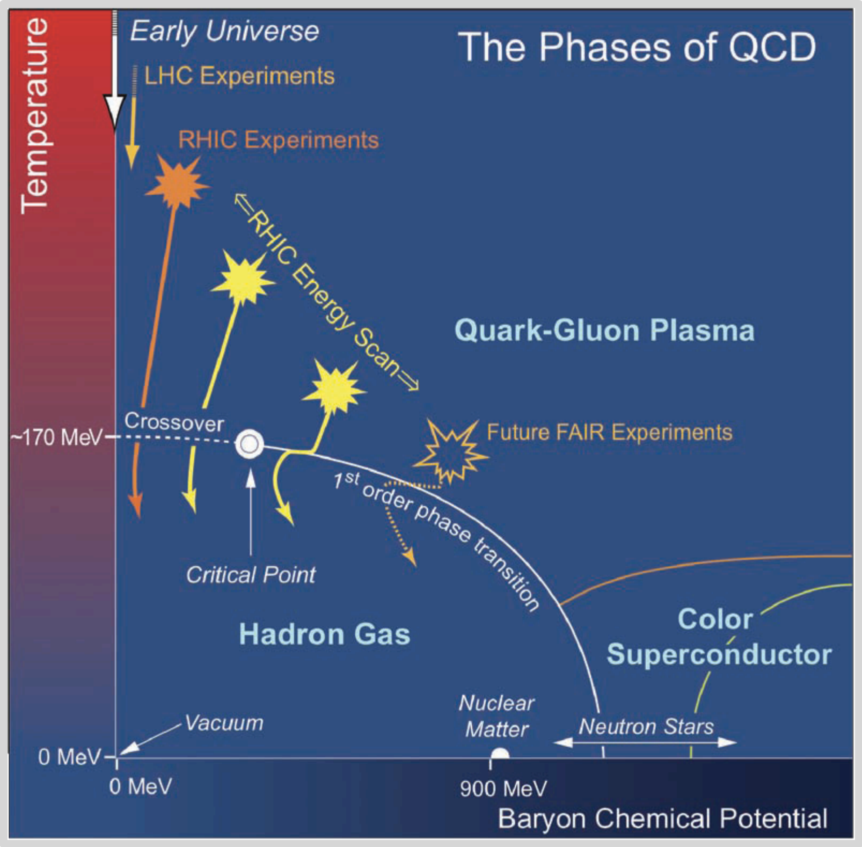
2000 – 2012 RHIC+LHC
Top energy
find QGP

QCD CP and phase transition
2010 – 2017: RHIC BES-I
7.7, 11.5, 14.5, 19.6, 27, 39, 54.4 GeV

2019 – 2020: RHIC BES-II 7.7, 11.5, 14.5, 19.6 GeV
FXT: 4.5, 3.9, 3.6, 3.0 GeV

2025 – : RHIC+FAIR BES-III

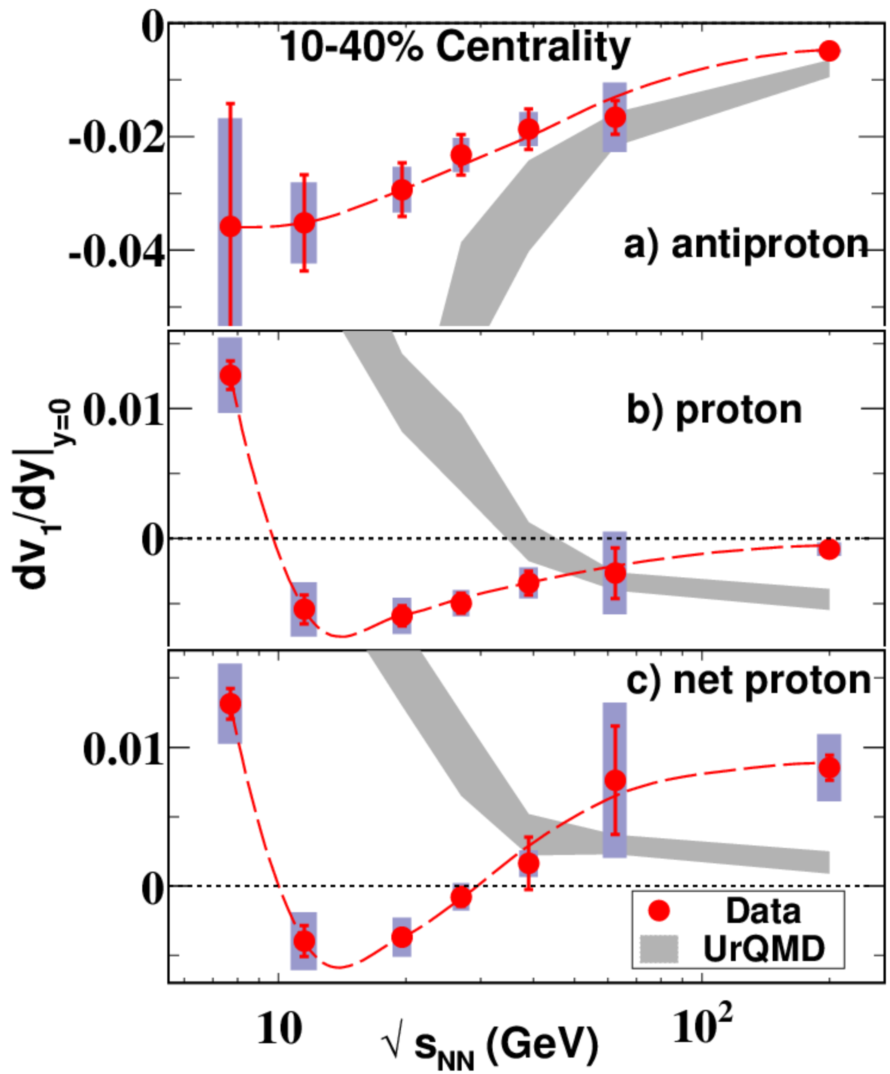
Beam Energy Scan I



$\sqrt{s_{NN}}$ (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

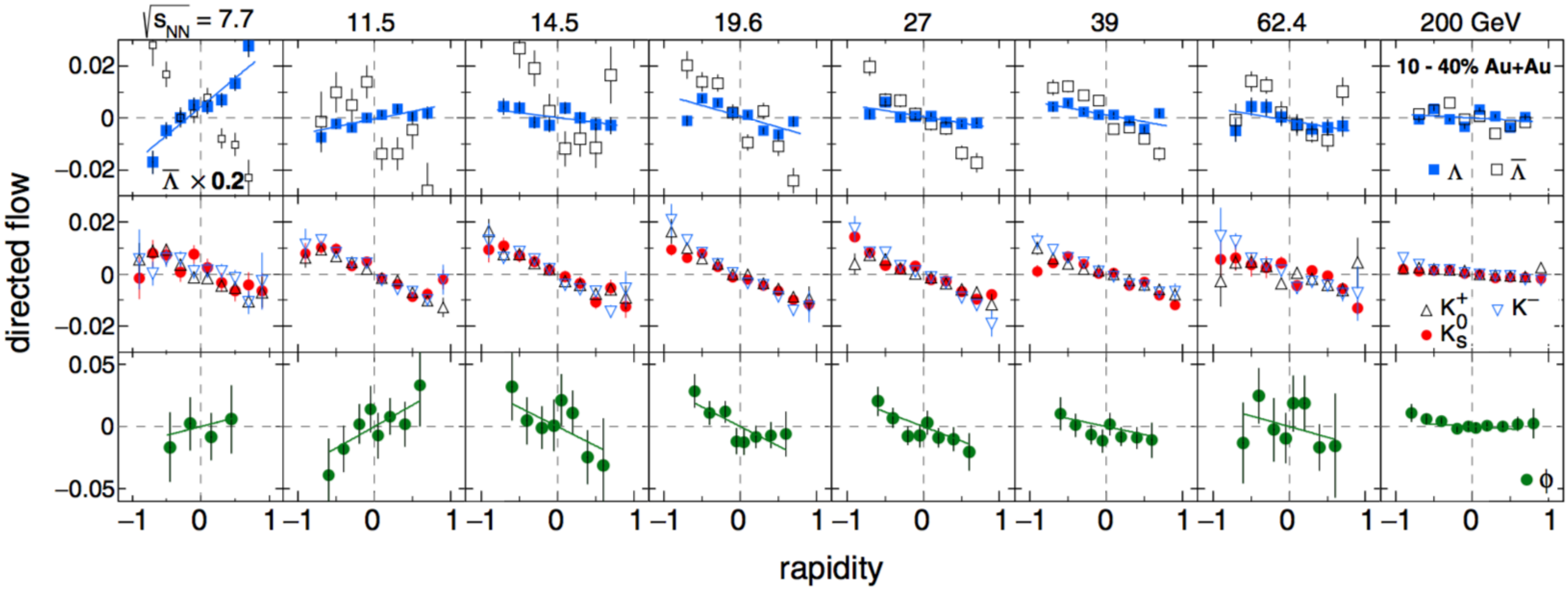
- Hydro calculation with 1st order phase transition motivates the study
- Net-proton slope changes sign twice

  EOS softest point?

- UrQMD fails to reproduce the data

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

Directed Flow v_1: ϕ Mesons

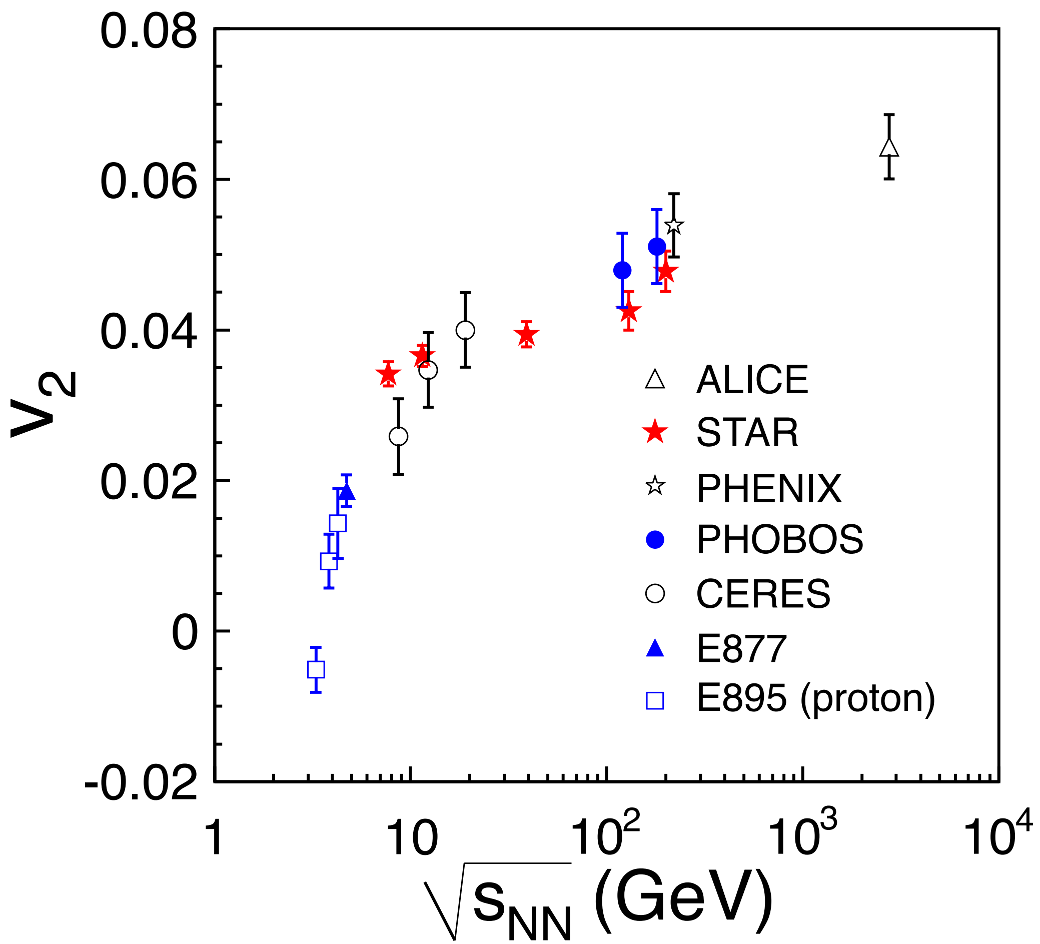


➢ Mesons and all produced baryons show negative slope except ϕ mesons when collisions energy < 14.5 GeV

Change of medium property? High precise data needed.

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

Energy Dependence v_2

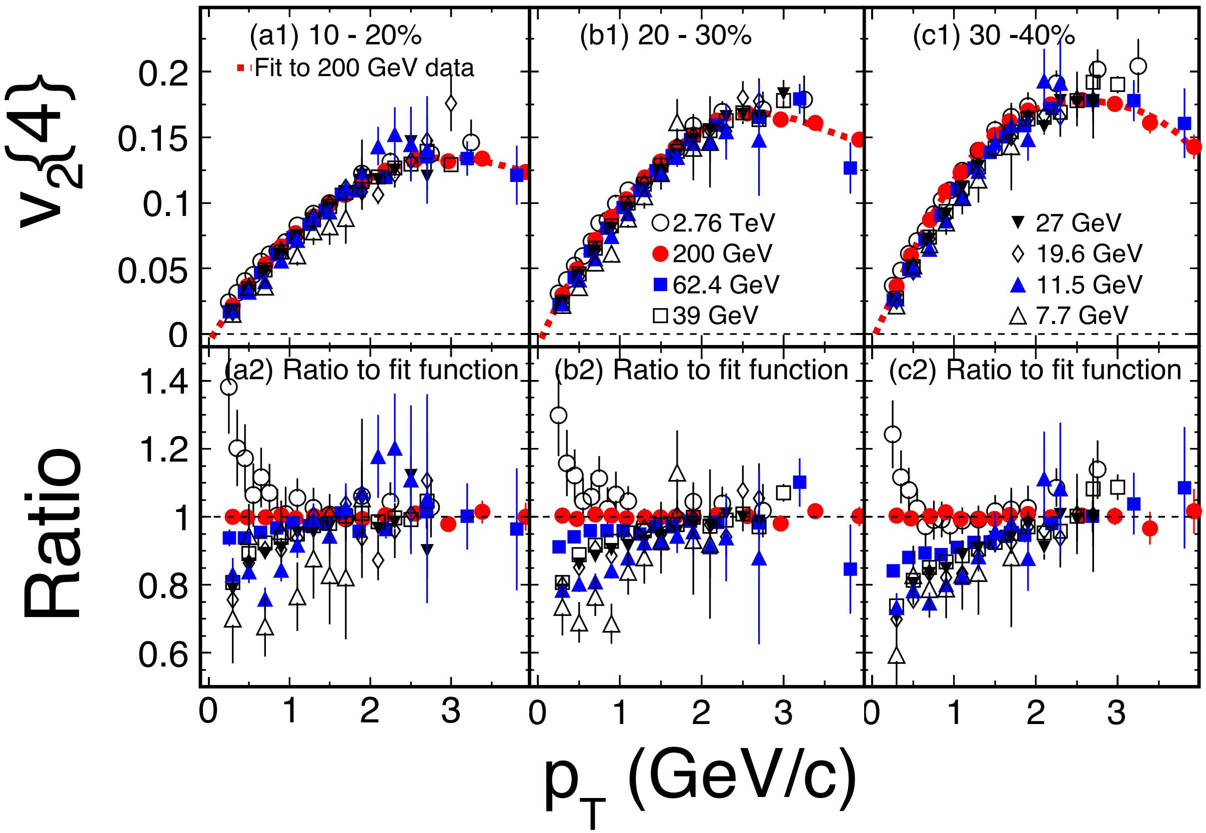


- **STAR, ALICE: $v_2\{4\}$ results**
  - Centrality: 20-30%
- **An increasing trend is observed for p_T integrated v_2 from AGS to LHC**
  - The rate of increase with collision energy is slower from 7.7 to 39 GeV compared to that between 3 to 7.7 GeV

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

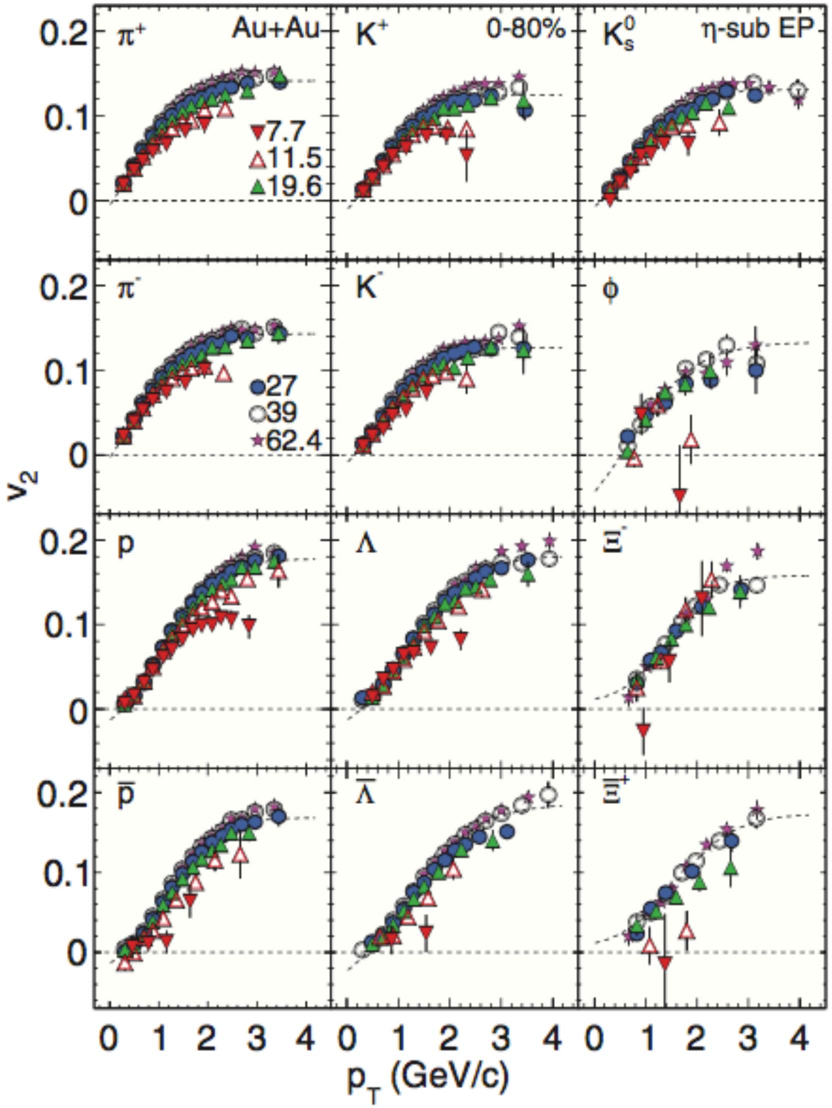


STAR: Phys. Rev. C 86, 054908(2012)

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?

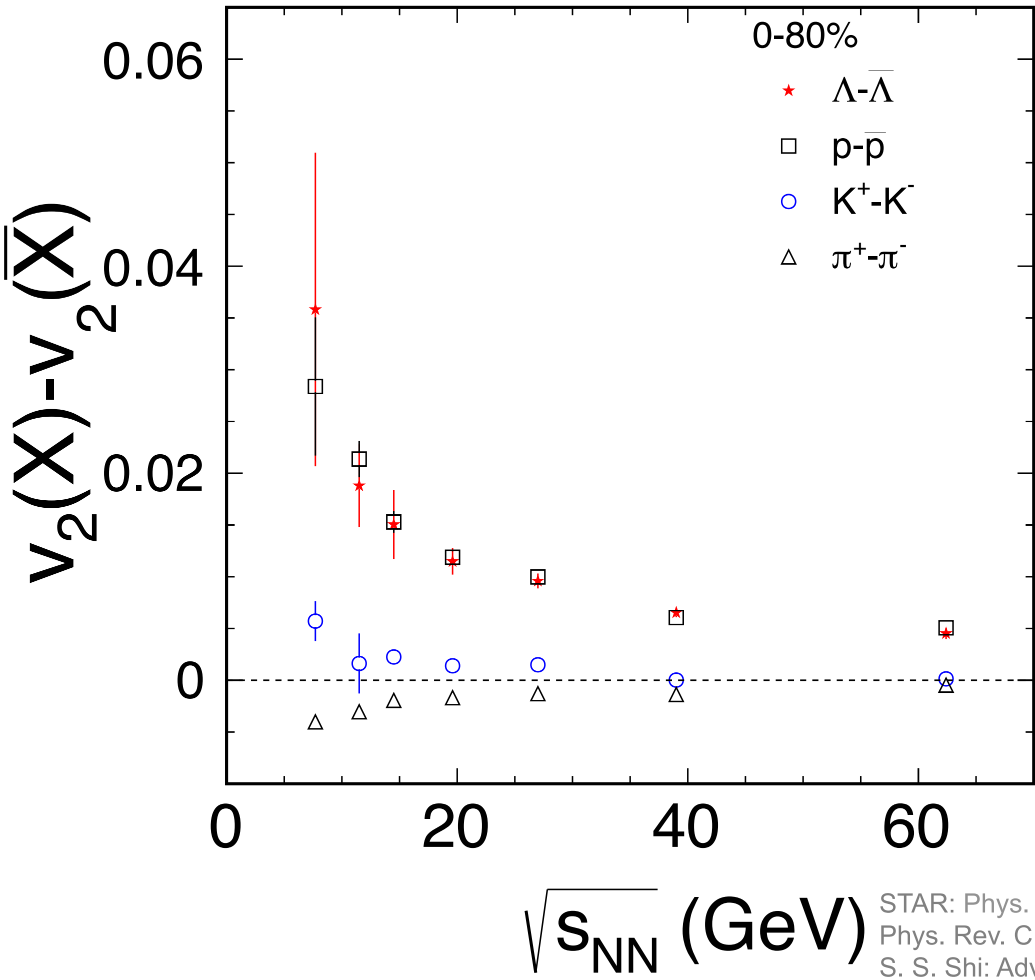
Energy Dependence v_2



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

- **Similar $v_2(p_T)$ shape for PID**

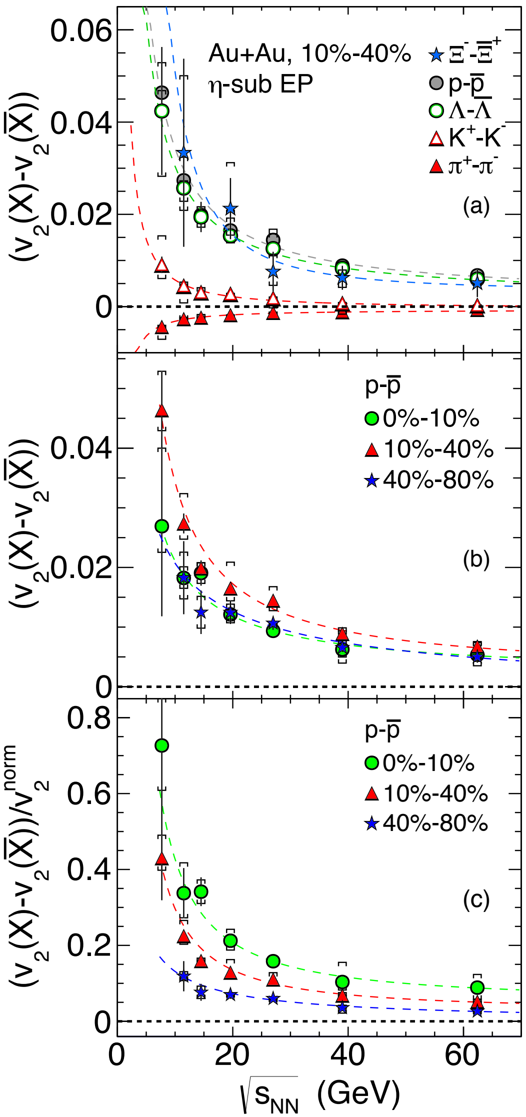
Particle vs. Anti-particle v_2



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

- **Significant difference between baryon and anti-baryon v_2 is observed**

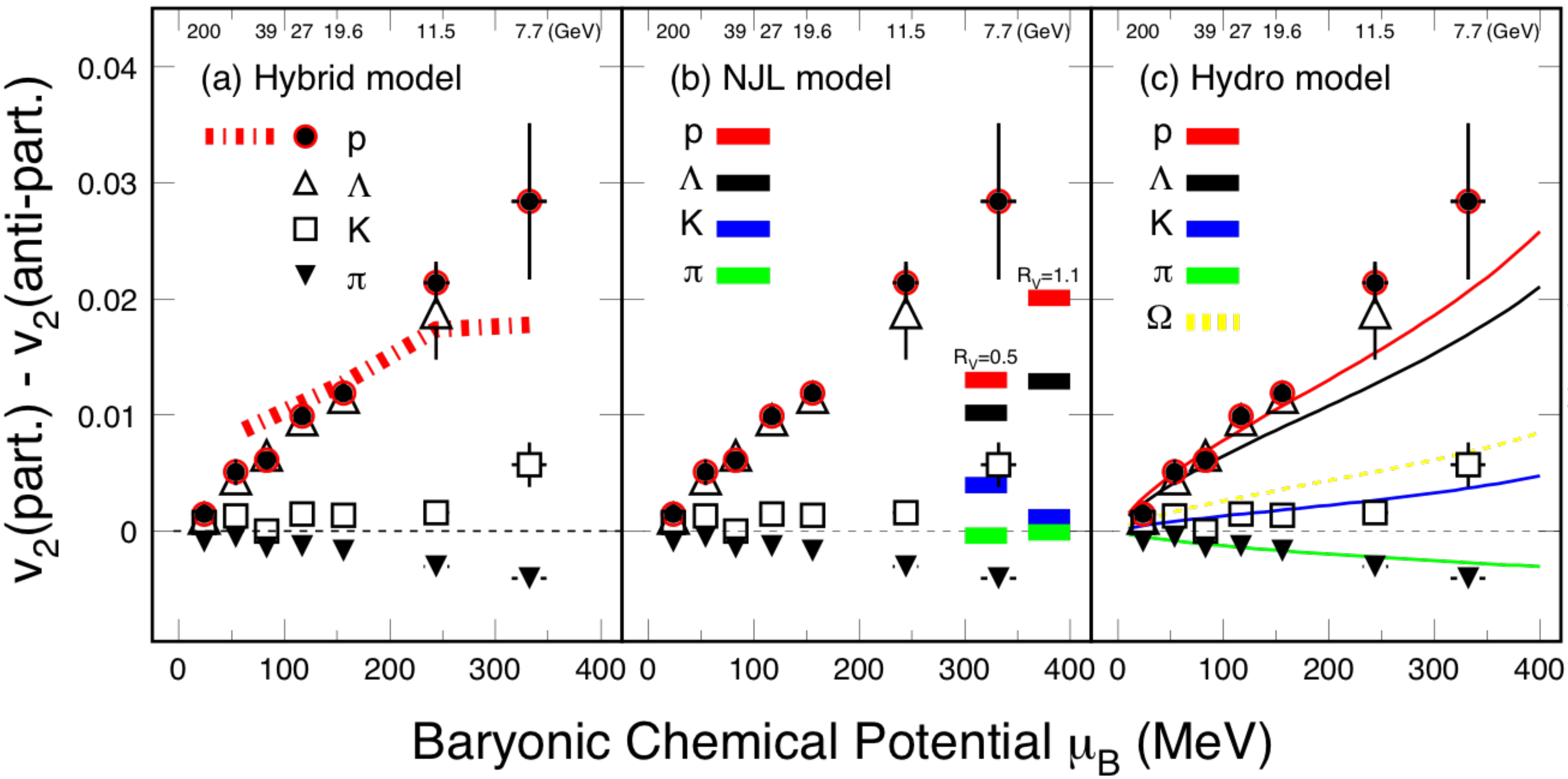
Particle vs. Anti-particle v_2



- **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. C 93, 014907(2016)

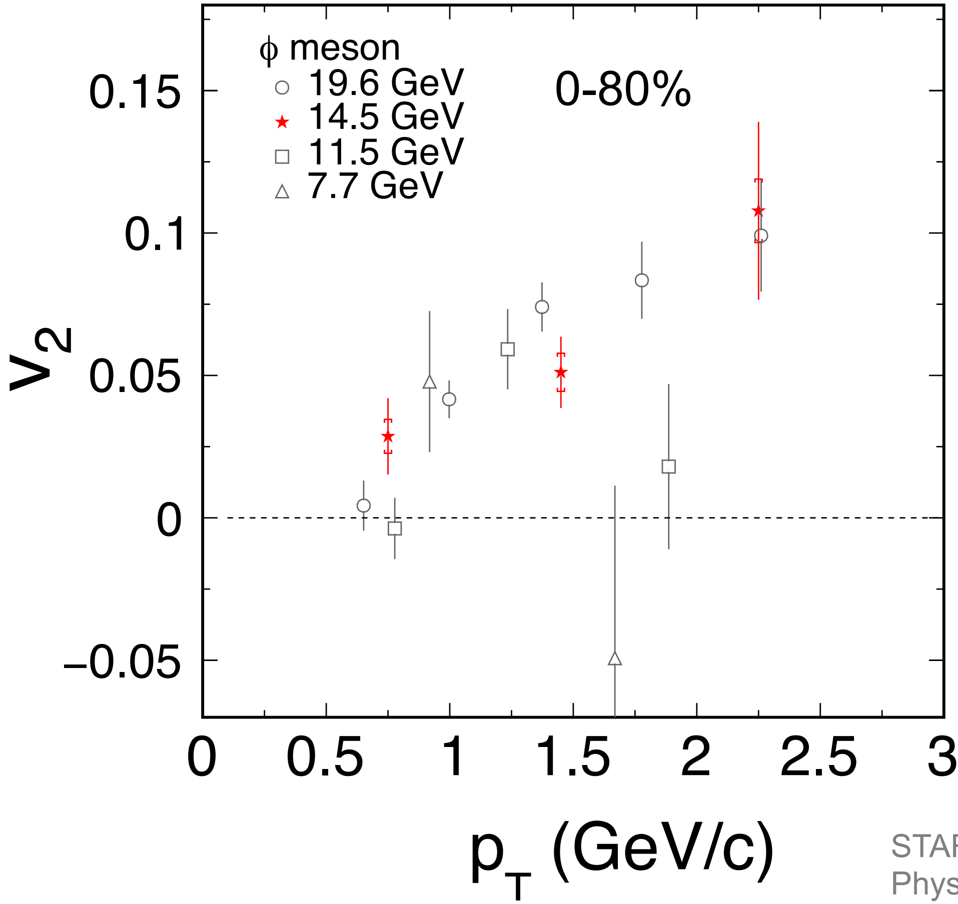
Particle vs. Anti-particle v_2



- **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: $\Delta v_2^{\bar{p}} > \Delta v_2^{\Lambda} > \Delta v_2^{\Xi} > \Delta v_2^{\Omega}$

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



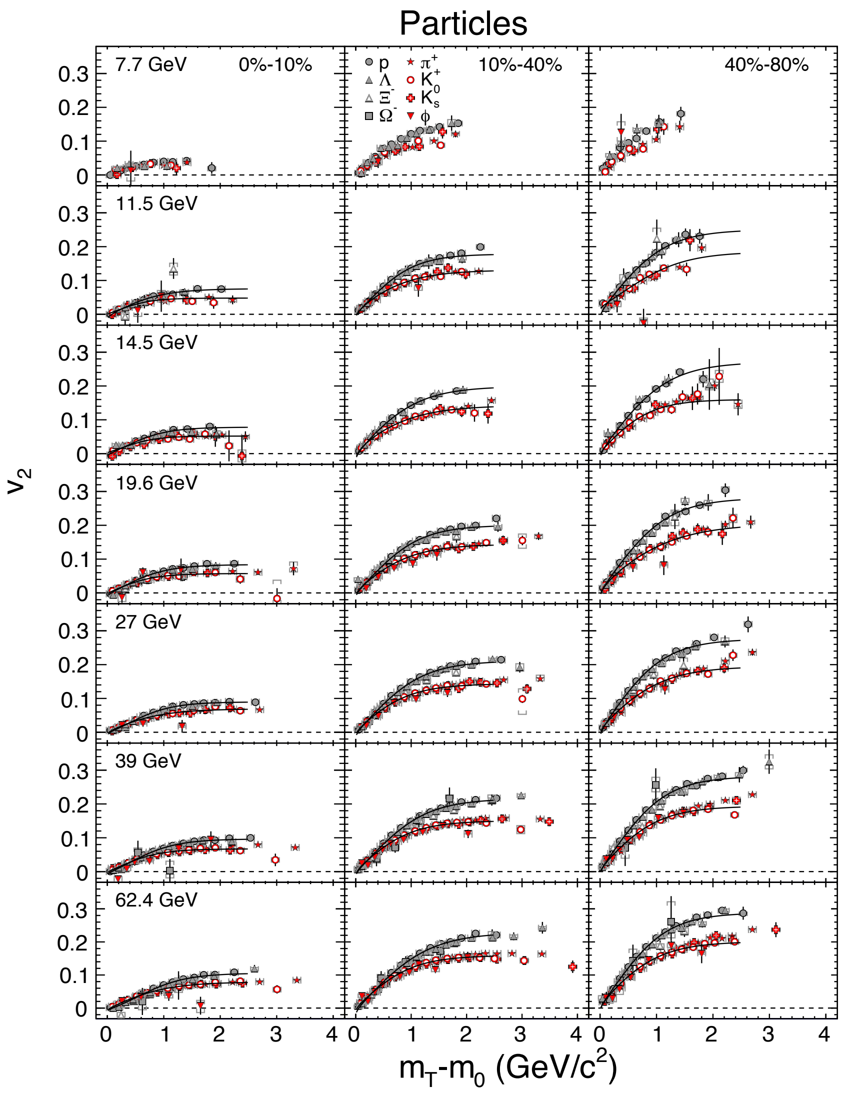
ϕ meson is less sensitive to late hadronic interactions[1]

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

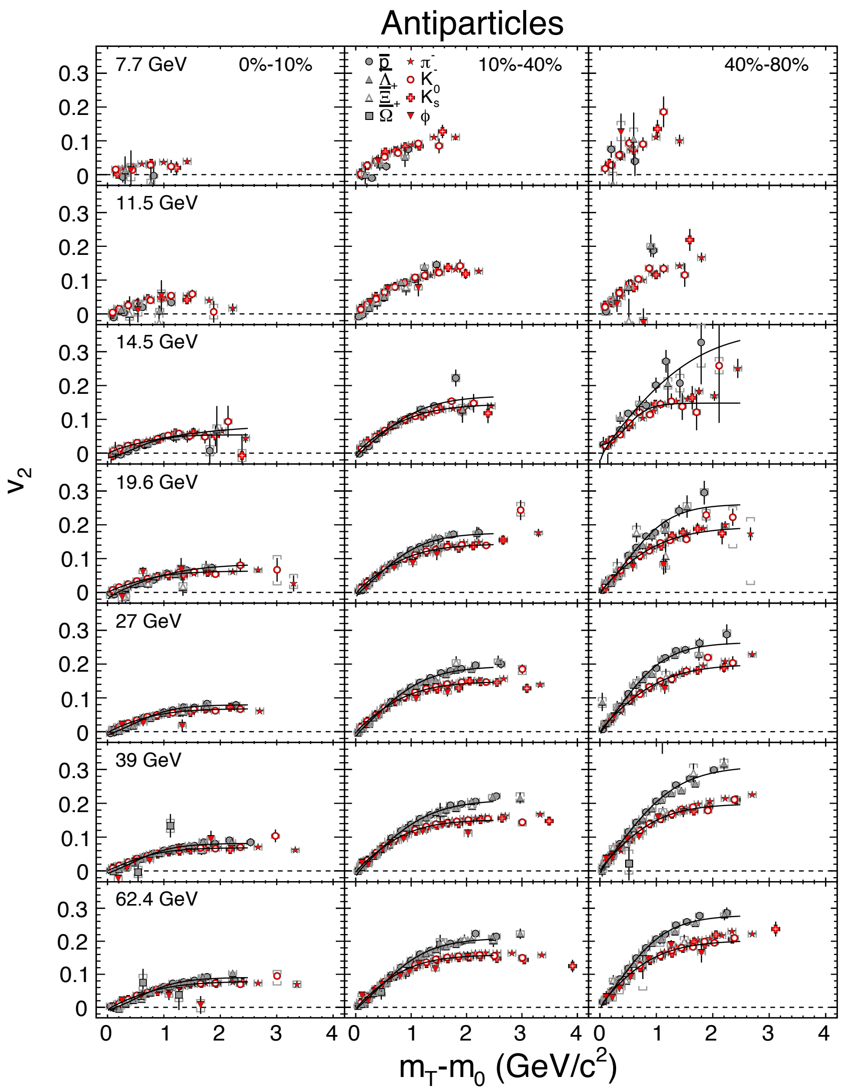


A splitting between baryons and mesons is observed at all energies except 7.7 GeV and all centralities.

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

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

Baryon/Meson Separation

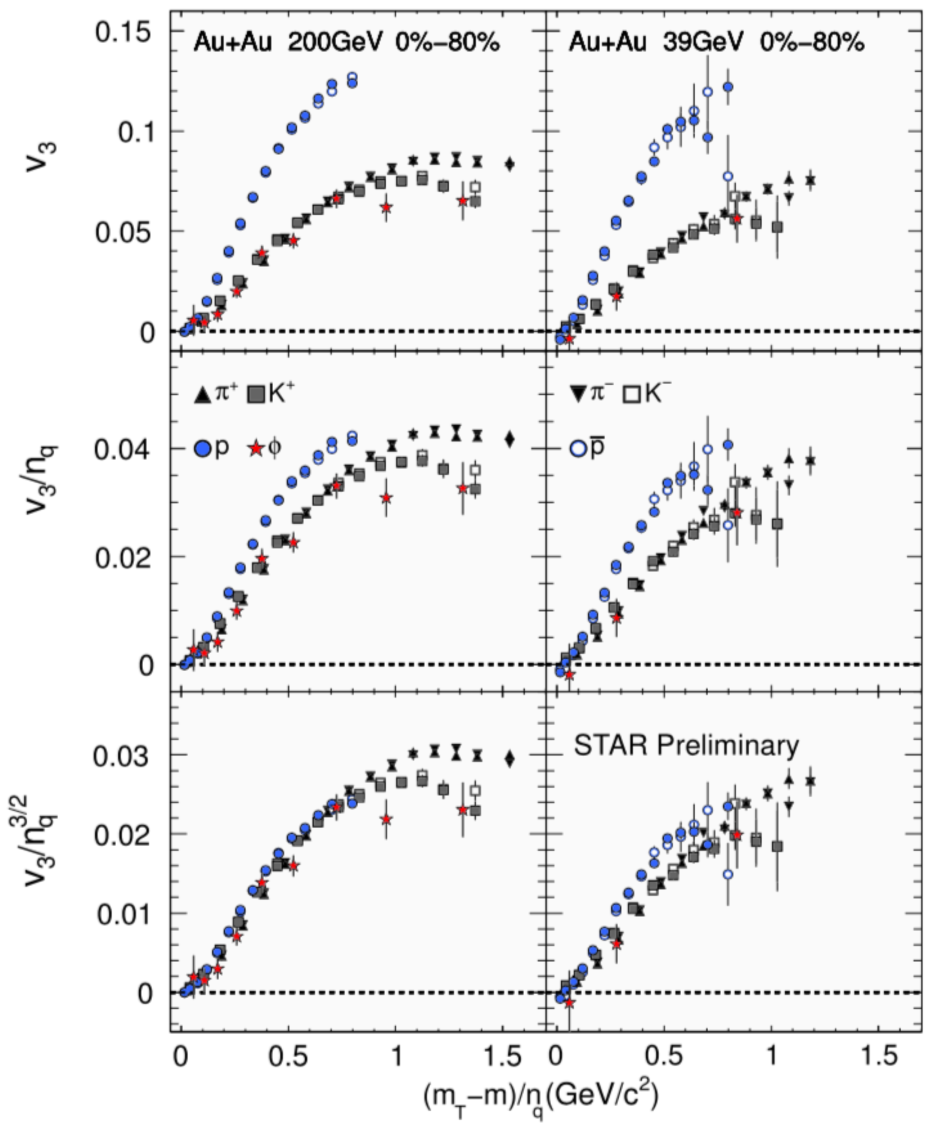


The splitting between baryons and mesons is observed significant for all energies above 14.5 GeV and also at 14.5 GeV for 40%–80%.

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

- **v_1: slope of net-proton**

  consistent with 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

- **v_3: $n_q^{3/2}$ scaling holds at 39 and 200 GeV**

RHIC BES-II:

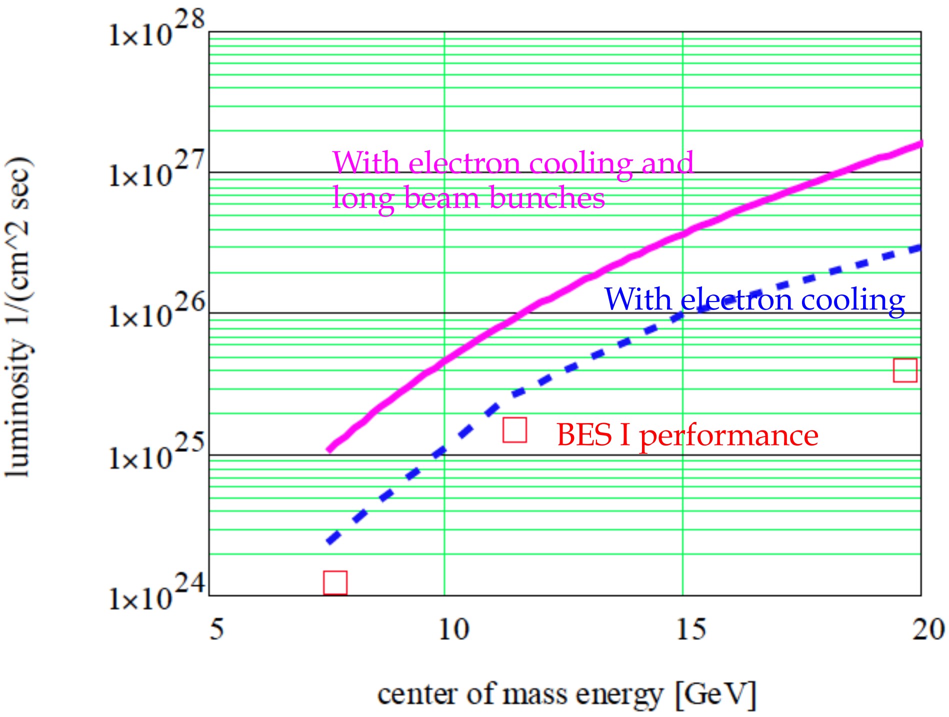
Focus on $\sqrt{s_{NN}} \leq 20$ GeV region

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