Anisotropic Flow Measurements from STAR at RHIC BES operation and Fixed Target

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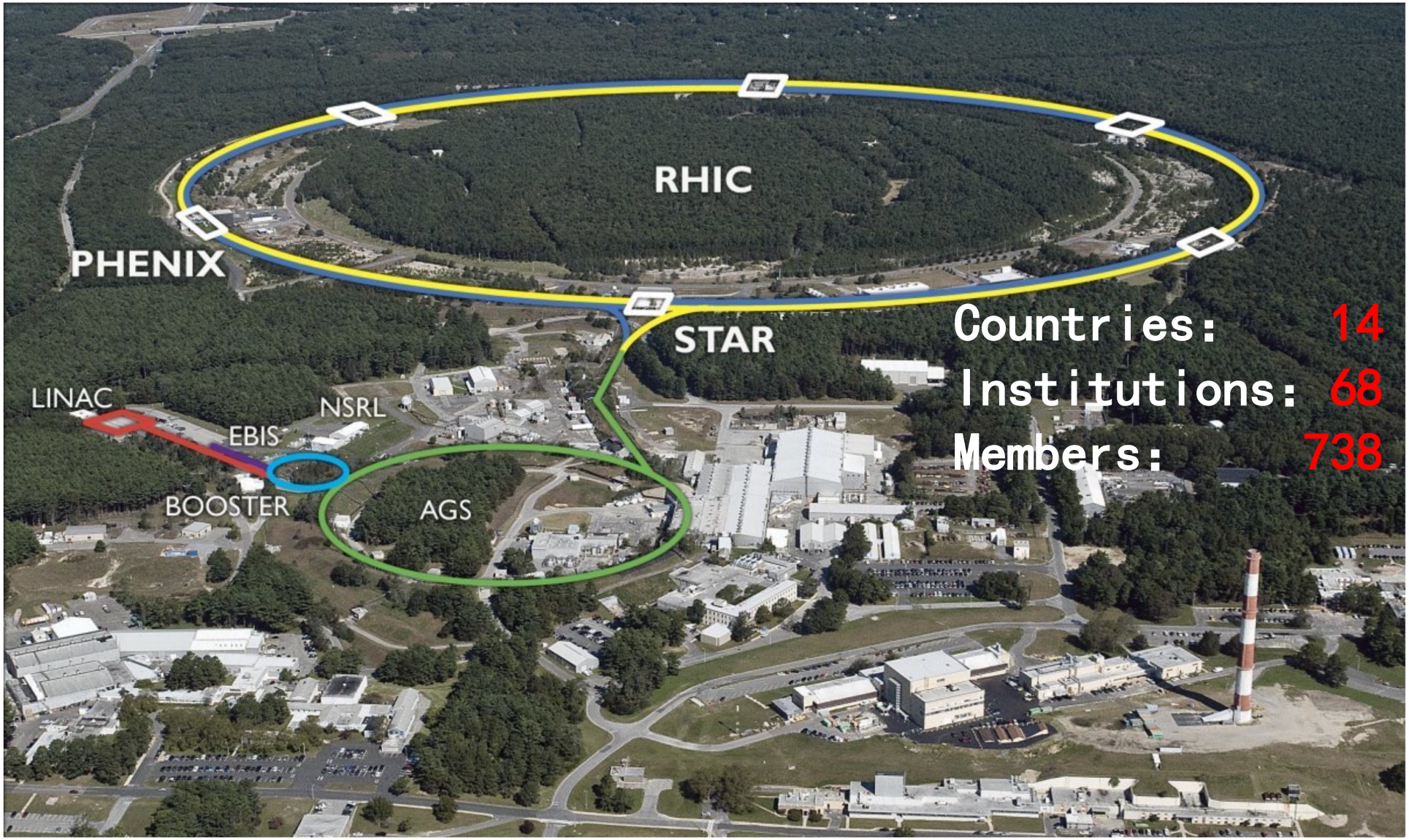
Outline

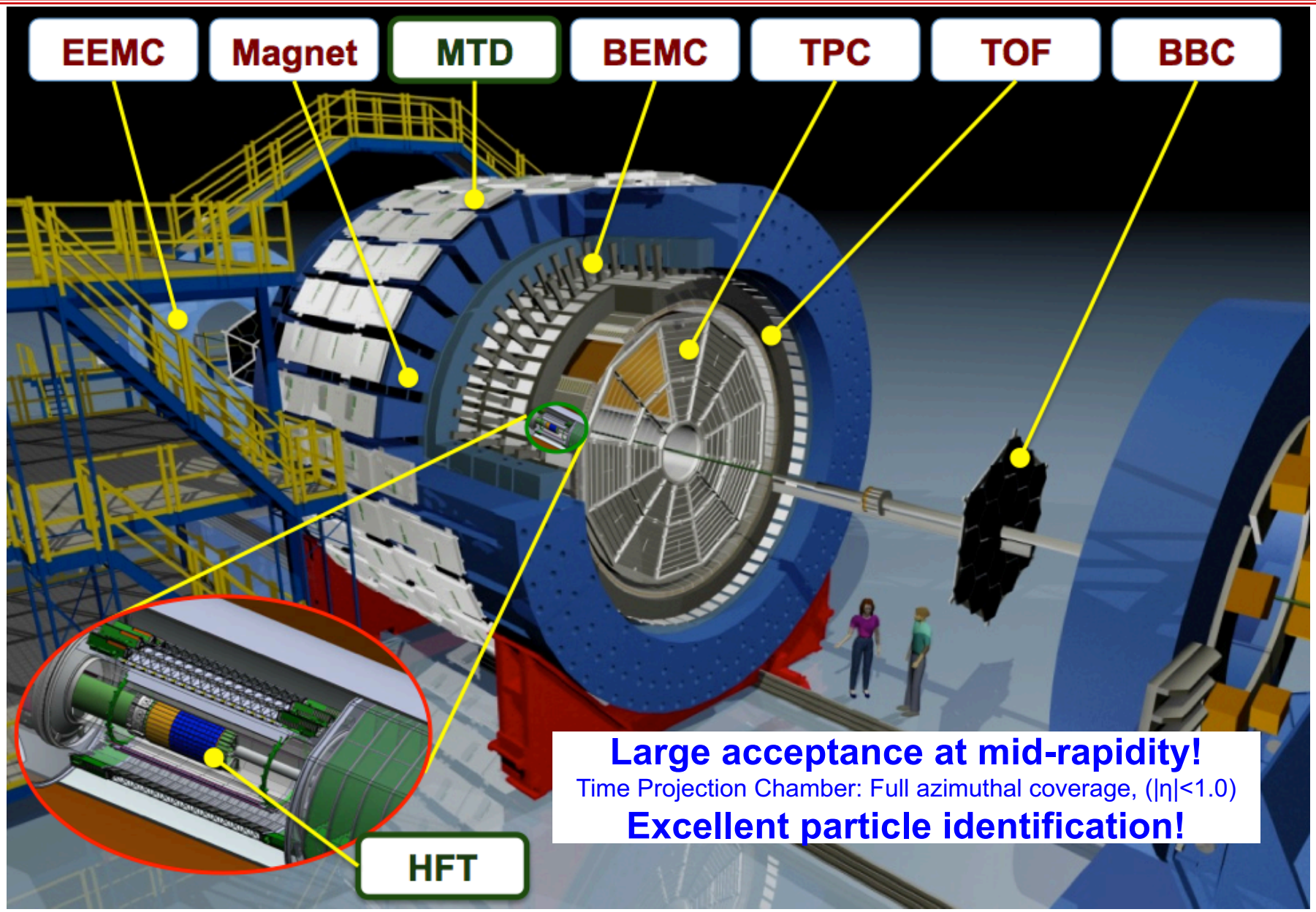
- Introduction
- Anisotropic Flow
- Results and Discussions
- Summary and Outlook

RHIC-STAR

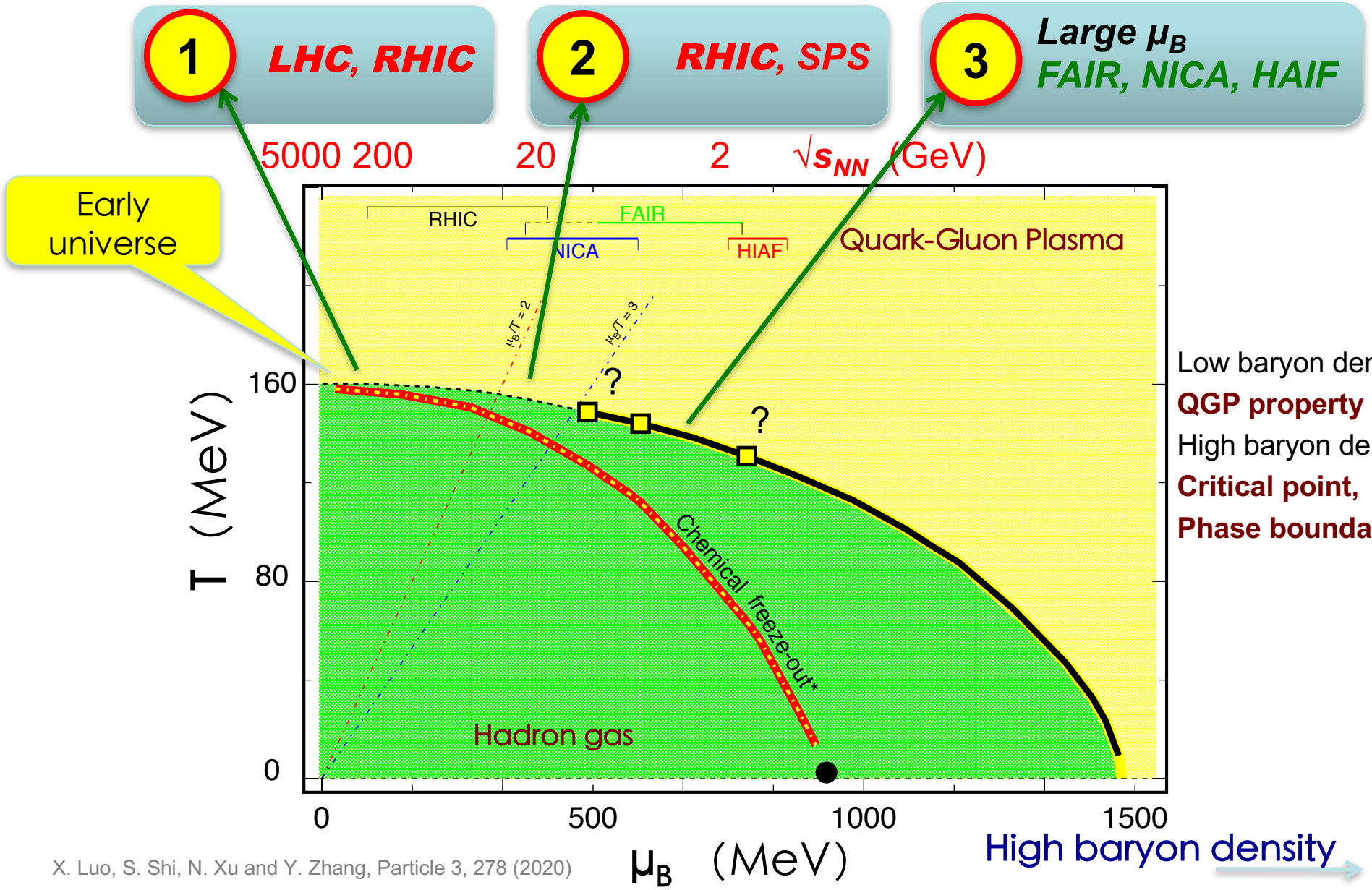


Heavy ion collisions (colliding mode): 7.7-200 GeV

STAR Detectors



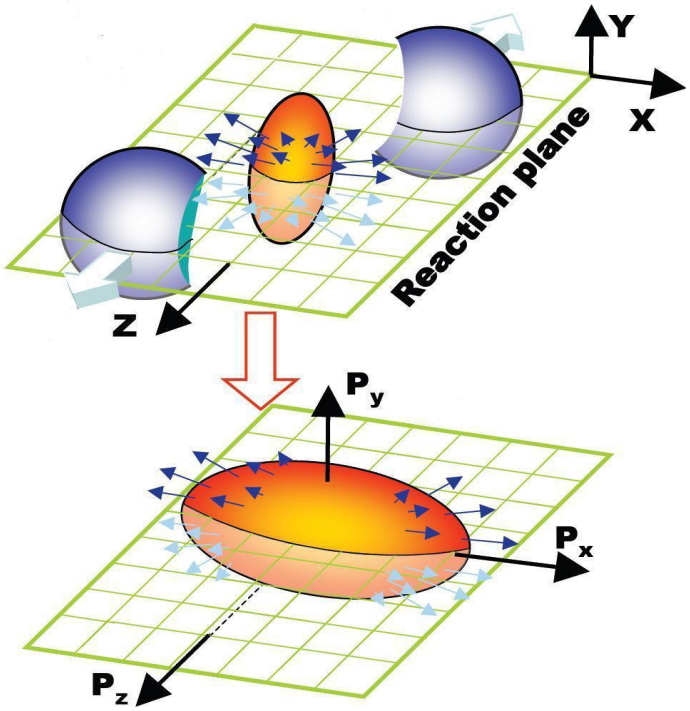
QCD Phase Diagram



Low baryon density:
QGP property
High baryon density:
Critical point,
Phase boundary

X. Luo, S. Shi, N. Xu and Y. Zhang, Particle 3, 278 (2020)

Anisotropic Flow



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

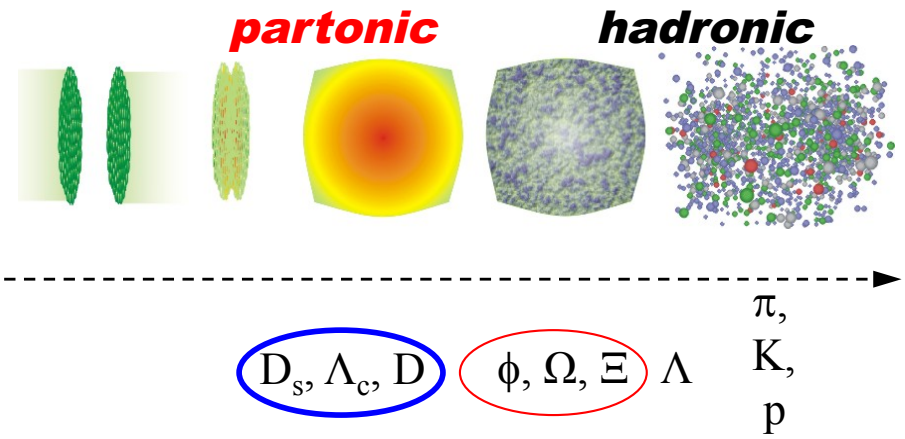
Anisotropic flow

v_1: directed flow;

v_2: elliptic flow;

v_3: triangular flow

…



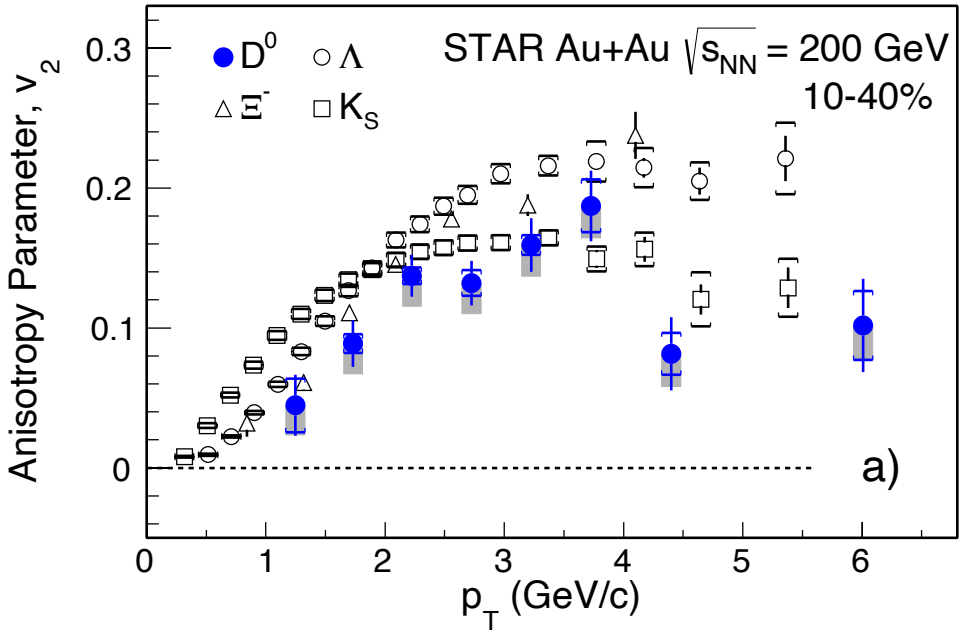
- **Anisotropic flow**:
  Sensitive to the early stage of the collision
- **Multi-strange hadrons and ϕ meson**:
  Less sensitive to late hadronic rescatterings
- **Heavy flavor flow**
  Study medium properties from motion of heavy quarks in medium

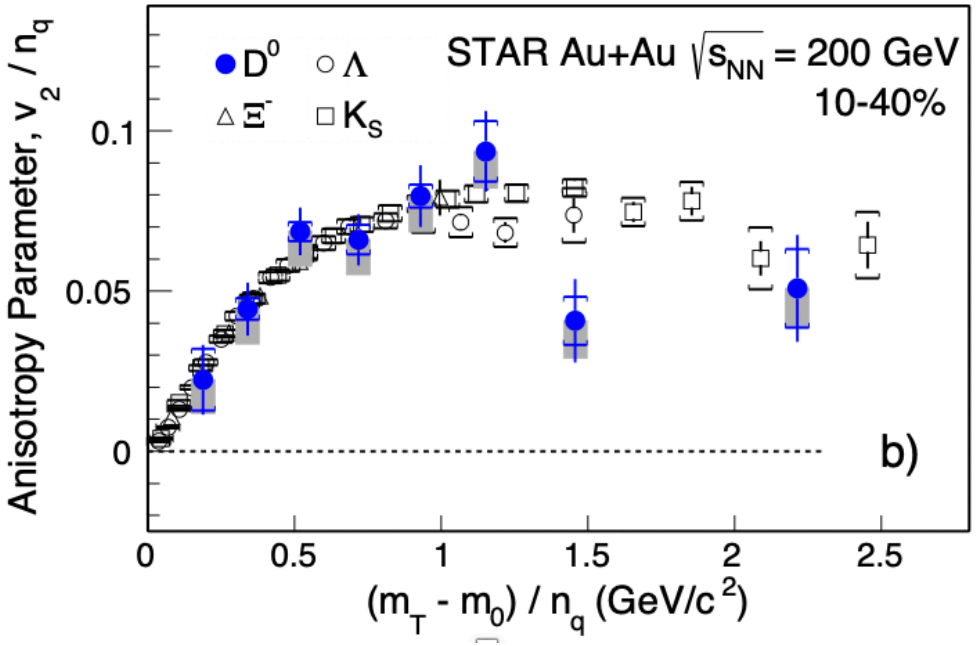
Beam Energy Scan

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II / BES I	Weeks	μ_B (MeV)	T_{CH} (MeV)
200	350	2010		25	166
62.4	67	2010		73	165
54.4	1000	2017			165
39	130	2010		112	164
27	70 (1000)	2011(2018)		156	162
19.6	**580**/ 36	**2019**/ 2011	**3**	206	160
14.5	**325**/ 20	**2019**/ 2014	**2.5**	264	156
11.5	**235** / 12	**2020**/ 2010	**5**	315	152
9.2	**160** / 0.3	**2020**/ 2008	**9.5**	355	140
7.7	**100** / 4	**2021**/ 2010	**14**	420	140

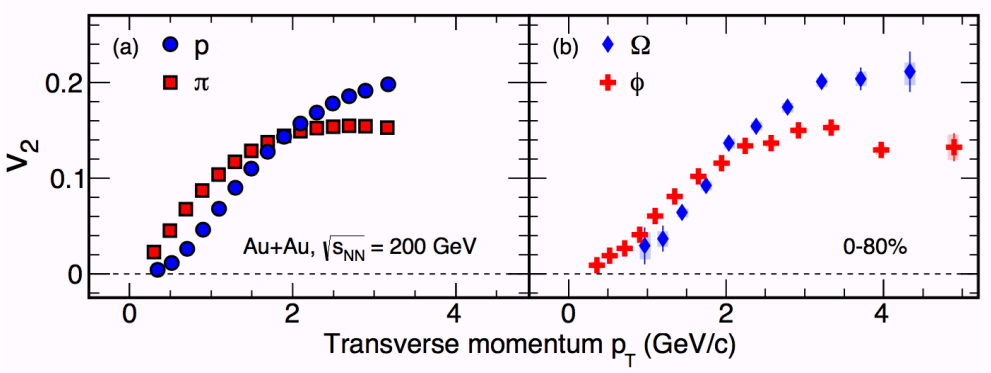
Fixed target program: 4.5, 3.9, 3.6, 3.0 GeV
extends STAR's physics reach to region of compressed baryonic matter

Partonic Collectivity



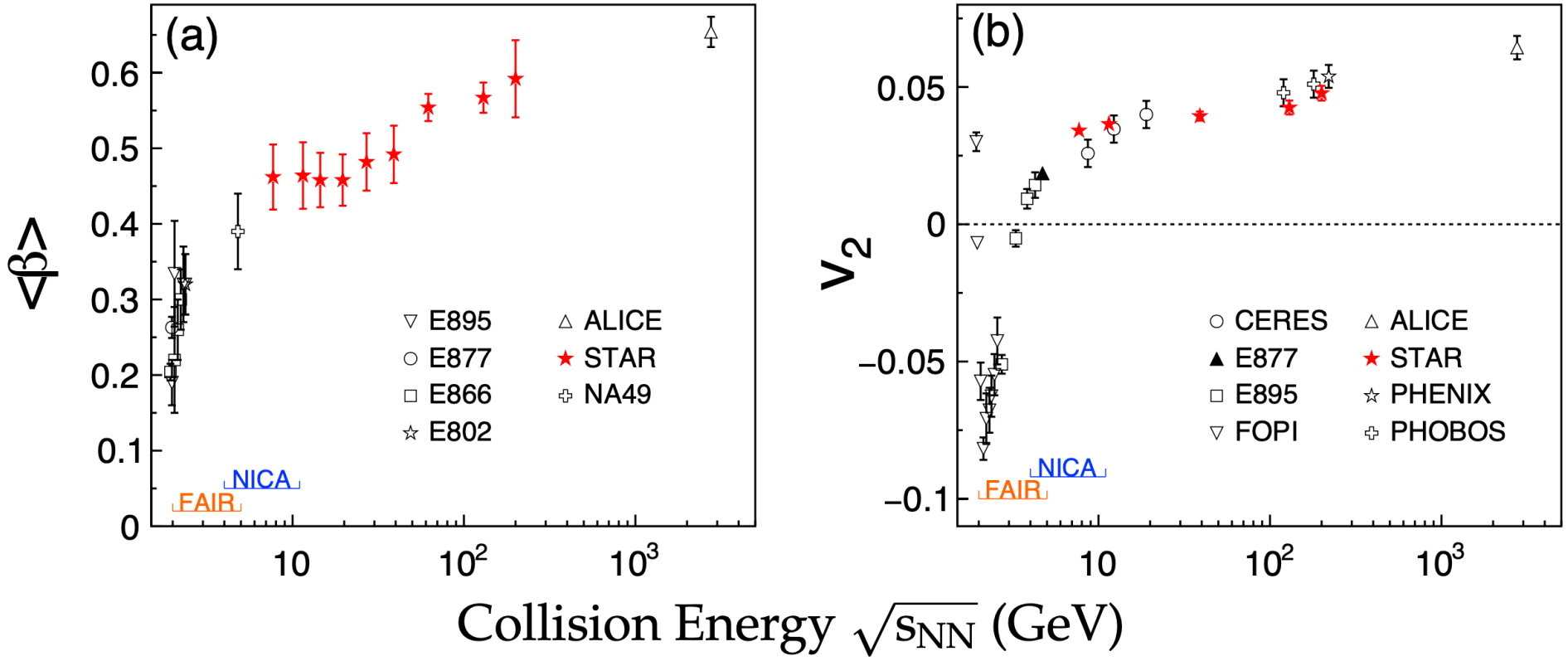


STAR: Phys. Rev. Lett.118, 212301 (2017)
STAR: Phys. Rev. Lett.116, 062301 (2016)



Partonic collectivity
light (u, d and s) quarks to charm quarks

Radial Flow and v_2: Softest Point

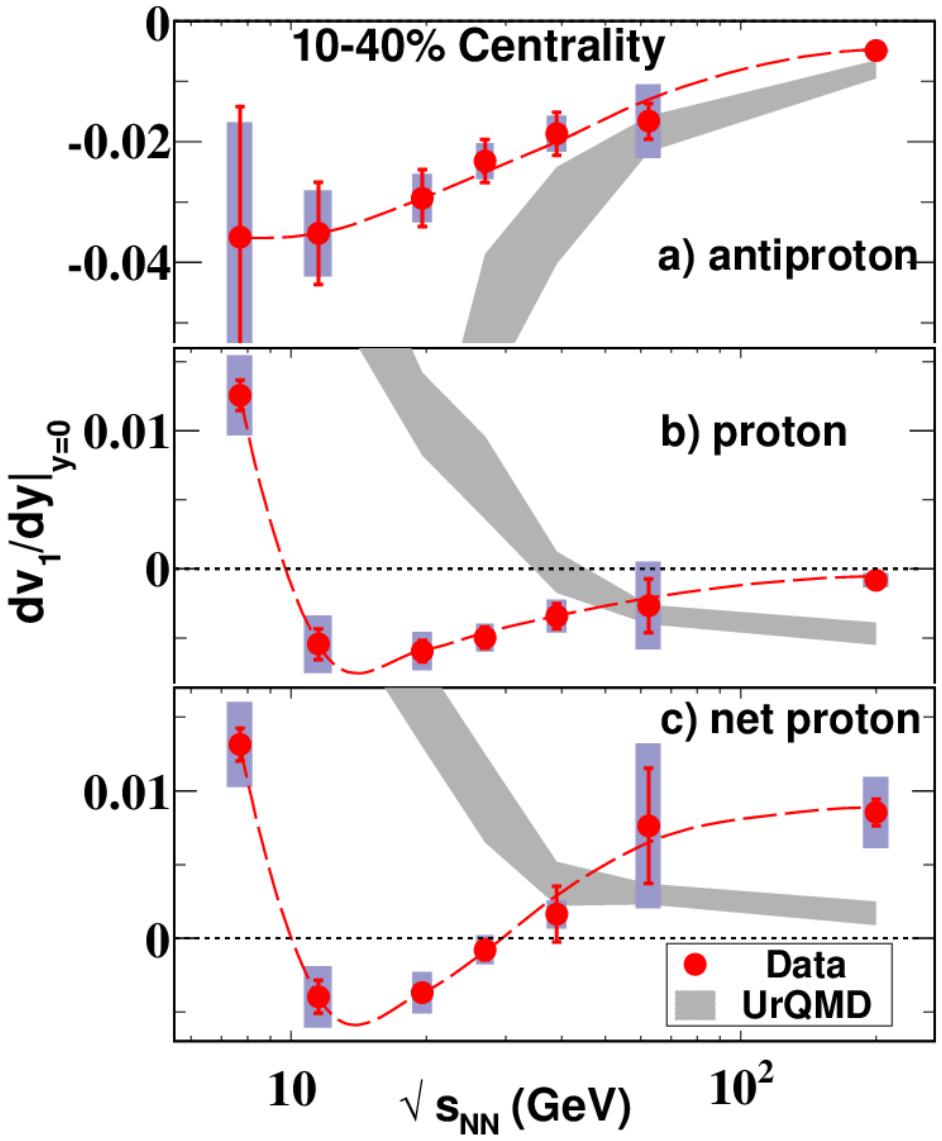


- A non-monotonic variation could be observed around the so-called "softest point of EOS"

P. F. Kolb, J. Sollfrank and U. Heinz, Phys. Rev. C 62, 054909 (2000).
H. Sorge, Phys. Rev. Lett. 82, 2048 (1999).

v_1: Softest Point

BESII : centrality dependence



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

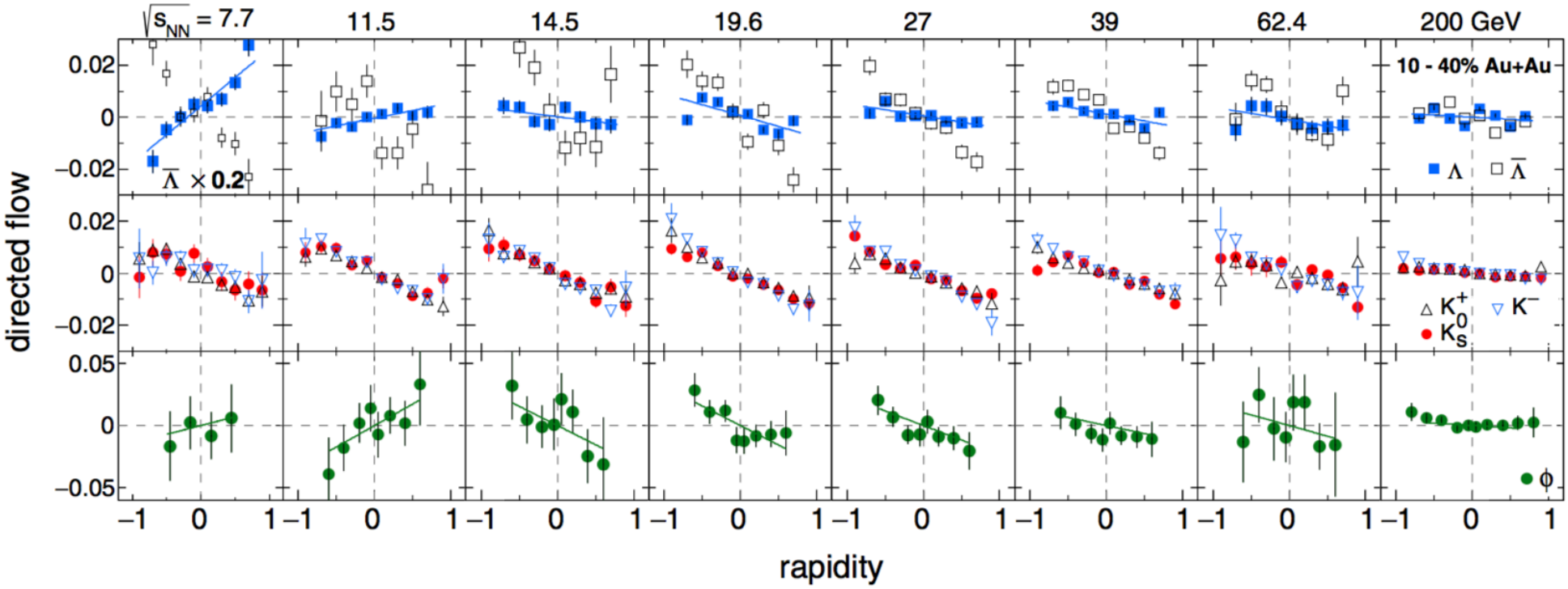
The slope of net-p is based on expressing the y dependence of v_1 for all protons as:

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

r: the ratio of anti-p to p.

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

v_1: ϕ Mesons

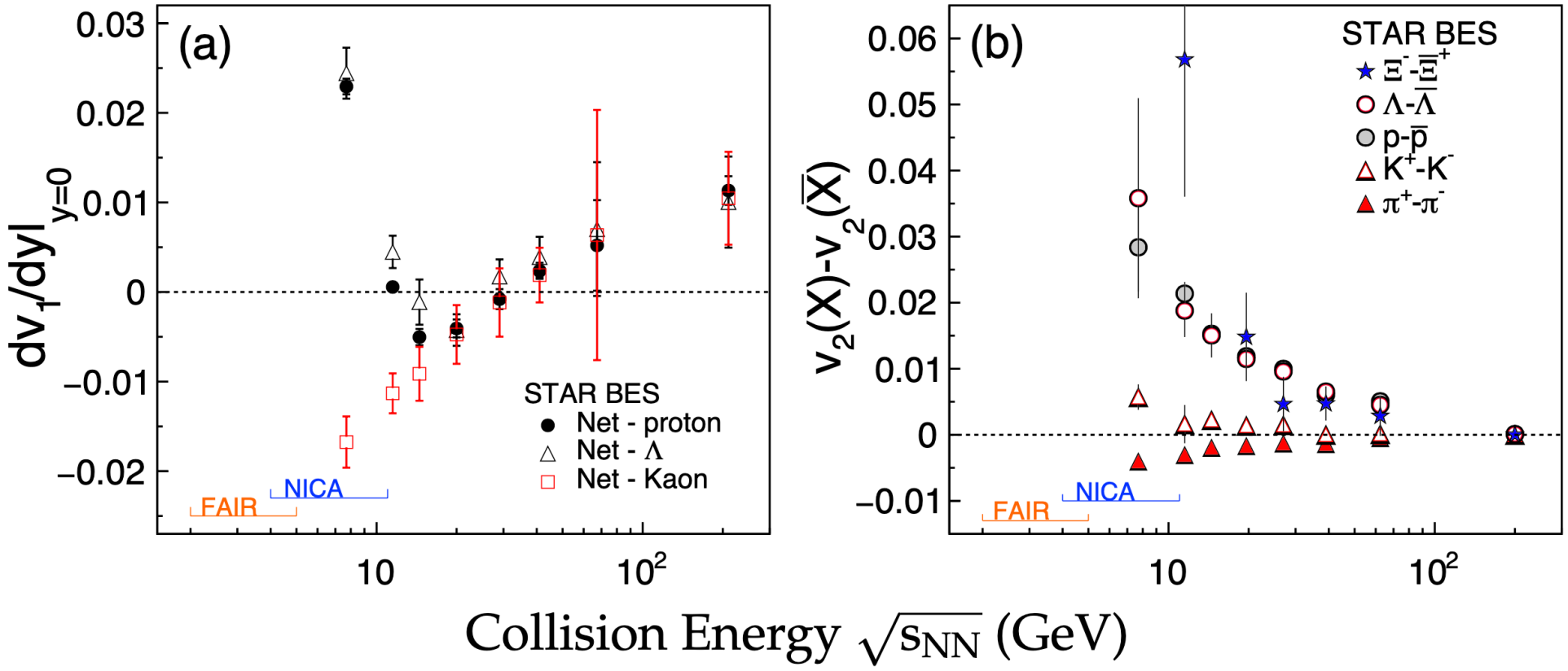


- Mesons and all anti-baryons show negative slope except ϕ mesons when collisions energy < 14.5 GeV

Change of medium property? High precision data needed: BESII

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

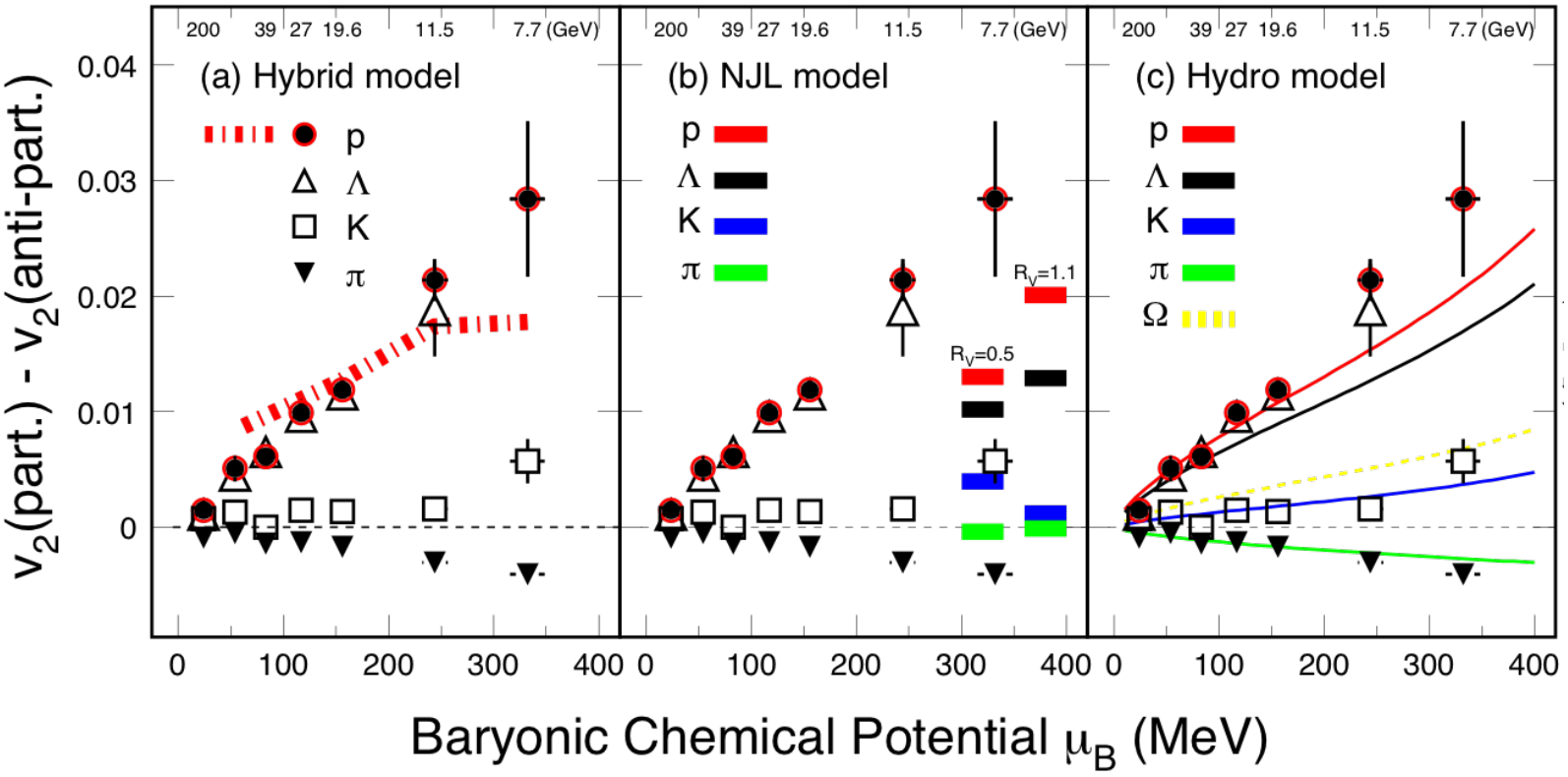
v_1 Slope and v_2 Difference



- dv_1/dy shows large divergence between net-kaon and net-proton (net-Λ) below $\sqrt{s_{NN}} < 20$ GeV
- Particle and anti-particle v_2 differences increase dramatically below $\sqrt{s_{NN}} < 20$ GeV

STAR: Phys. Rev. Lett. **120**, 062301(2018)
Phys. Rev. Lett. **110**, 142301(2013)

Particle vs. Anti-particle v_2

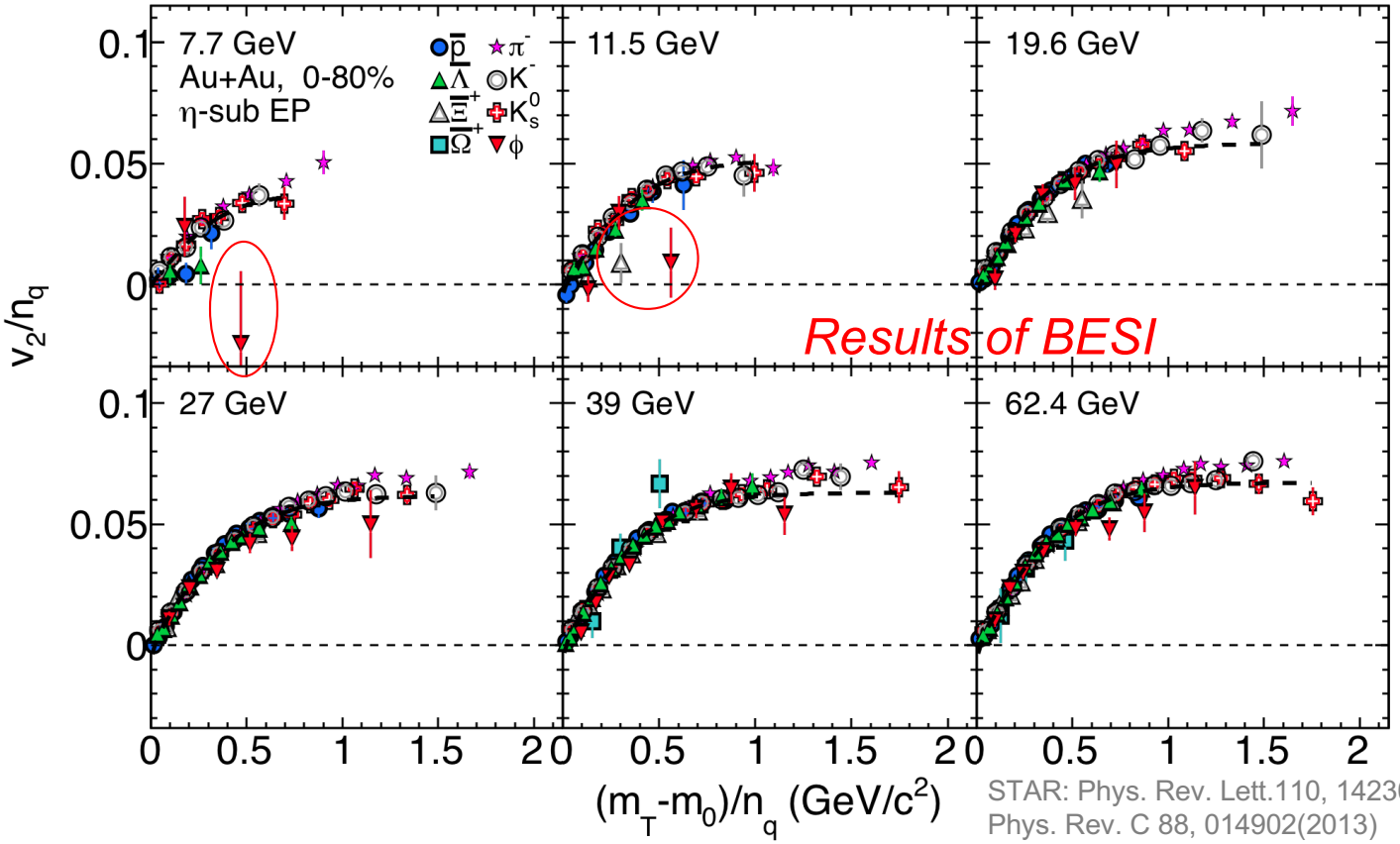


BESII : multi-strange hadrons

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

J. Steinheimer et al., PRC86, 44903(2012); J. Xu et al., PRL112, 012301(2014), H. Liu et al., PLB798, 135002(2019).; Y. Hatta et al., PRD92, 114010(2015)

Multi-strange Hadron and ϕ Meson v_2

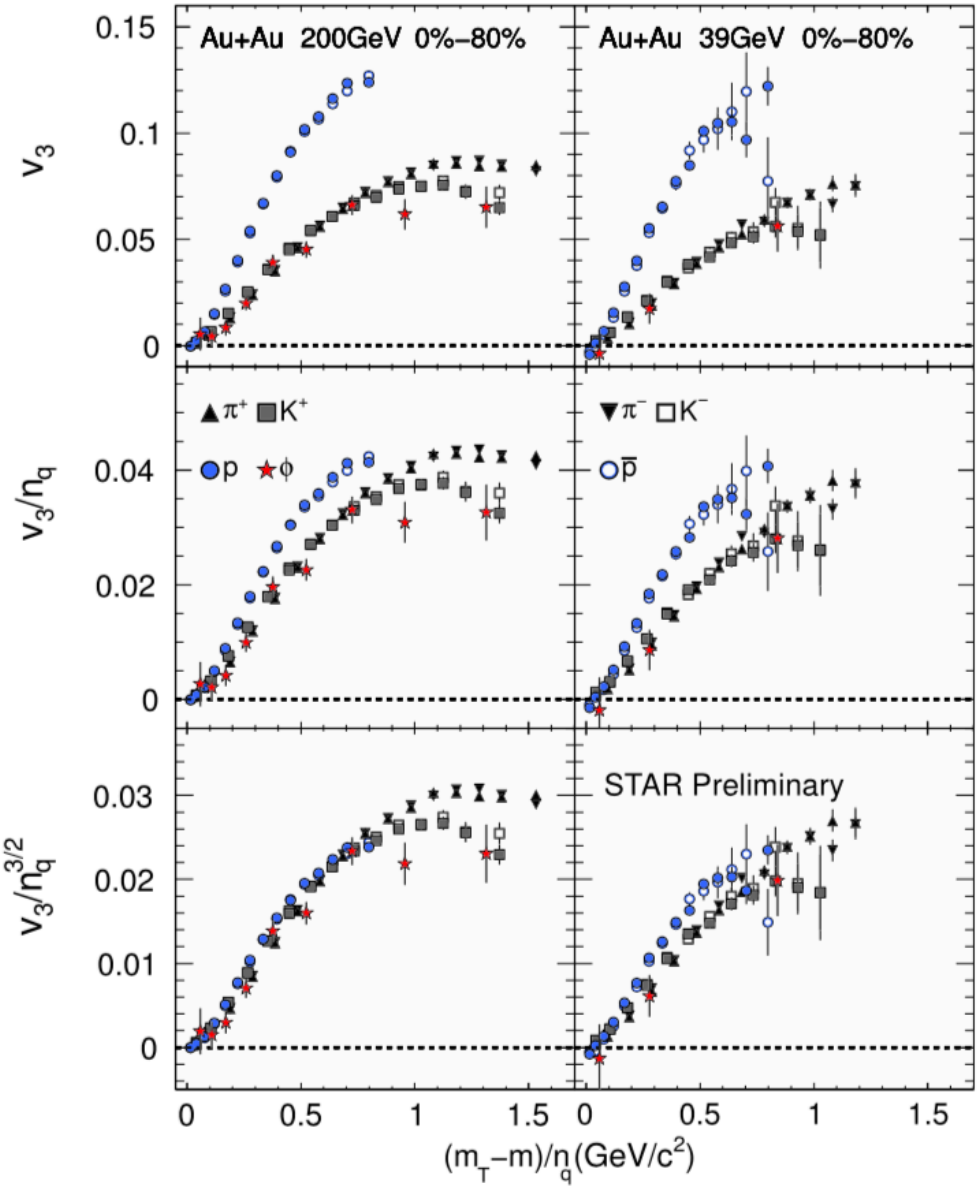


STAR: Phys. Rev. Lett.110, 142301(2013)
Phys. Rev. C 88, 014902(2013)
Phys. Rev. C 93, 014907(2016)

- **BESI: v_2 of multi-strange hadrons and ϕ mesons seems dropping when collision energy < 20 GeV**
- **BESII: precise measurements will offer information on partonic vs. hadronic degree of freedom: *QCD phase structure***

BESII : multi-strange hadrons and ϕ meson

v_3

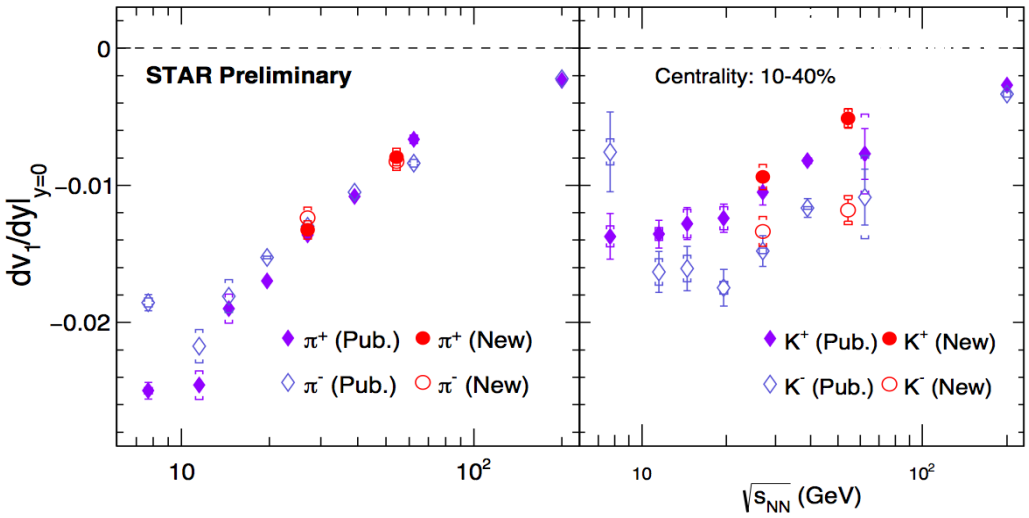


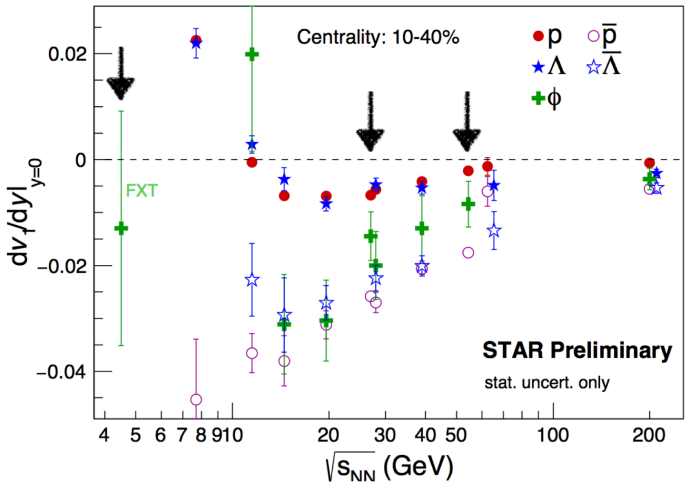
BESII : v_3 of low energies

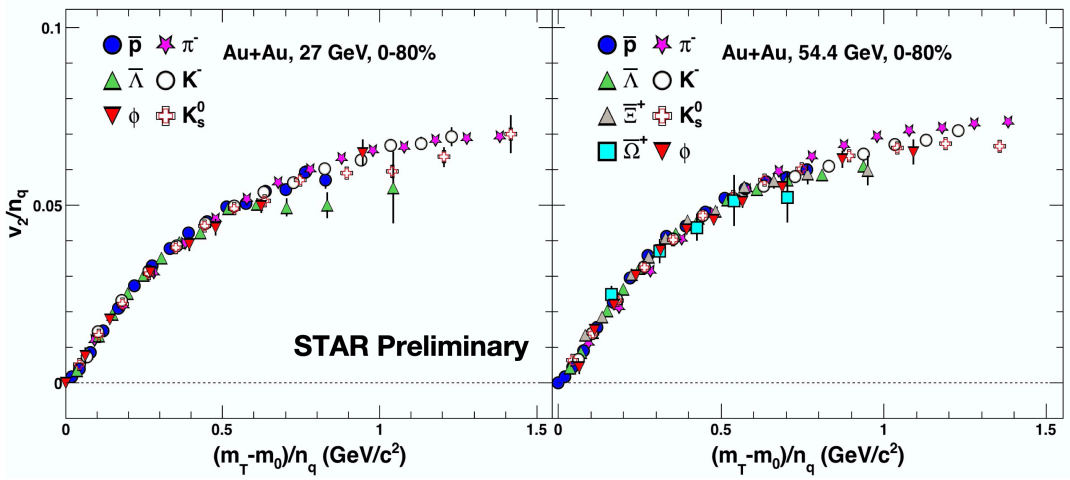
Better NCQ scaling achieved at 39 GeV (up to 0.8 GeV/c^2) and 200 GeV (up to 0.8 GeV/c^2) by using scaling factor $n_q^{3/2}$

STAR: QM2014
R. Lacey, J. Phys. G 38 (2011) 124048

New Results from 54.4 and 27 GeV



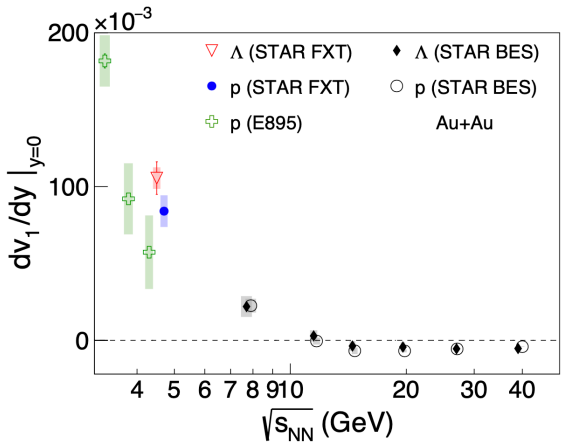


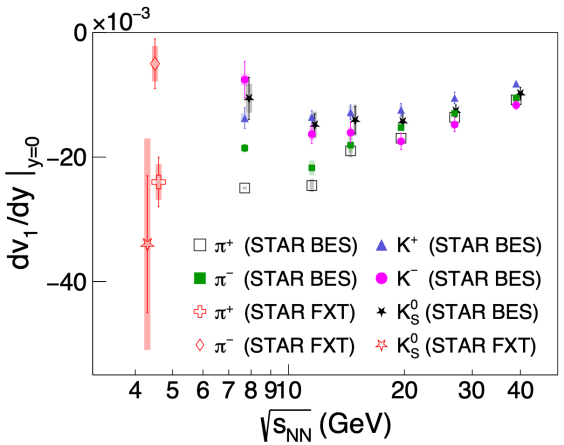


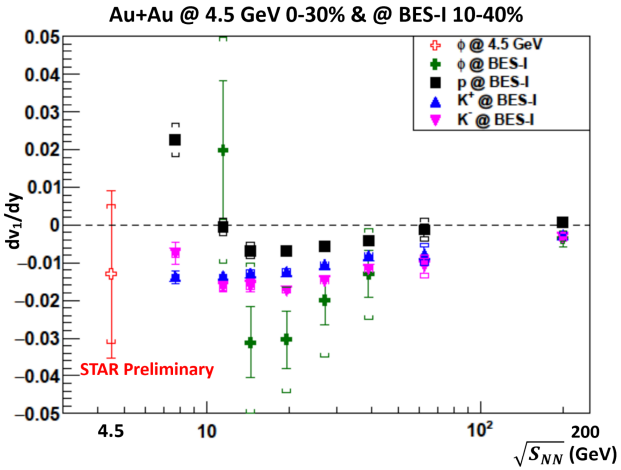
- **Consistent with energy trend**

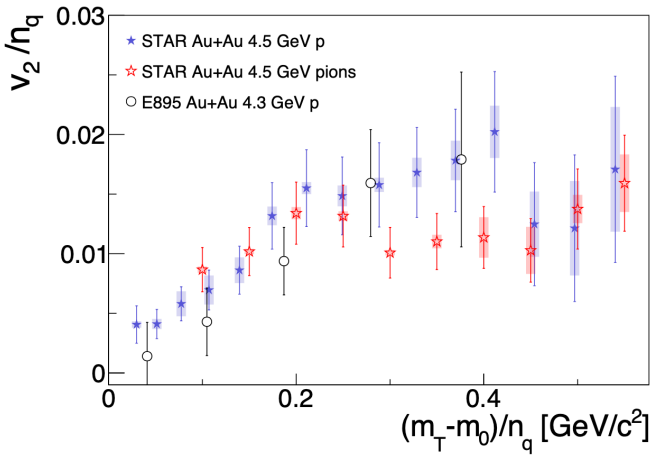
S. Lan and K. Nayak for STAR: QM2019

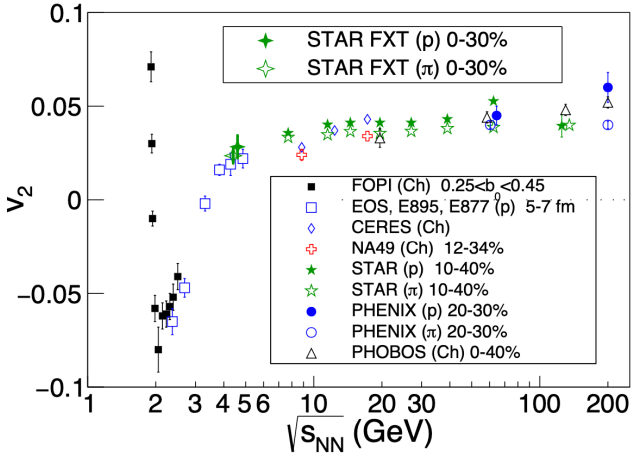
FXT: Au+Au at $\sqrt{s_{NN}}$ = 4.5 GeV











Follows energy trend

The Λ v_1 results fit into the trend of STAR

D. Chen for STAR: QM2019
STAR: arXiv:2007.14005

Summary

- **Top Energy Collisions**
  - **Partonic collectivity:** *light flavor to charm*

- **Beam Energy Scan II**
  - **v_1 slope of net-baryon:** *non-monotonic as energy*
  - **ϕ meson and multi-strange v_n:** *partonic vs. hadronic*

BESII: RHIC 2019 – 2021

BESIII: RHIC FAIR/NICA/HIAF 2022 –

Explore QCD phase structure!

BES-II is Ongoing

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

Detector upgrade

- **Event Plane Detector**
  forward EP and centrality definition: 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
4.5, 3.9, 3.6, 3.0 GeV

RHIC BES-II: 2019-2021

19.6 (580 M), 14.5 (325 M), 11.5 (235 M), 9.2 (135M ongoing) and 7.7 GeV
Focus on $\sqrt{s_{NN}} \leq 20$ GeV region