RHIC-STAR重离子碰撞实验中集体运动的研究进展

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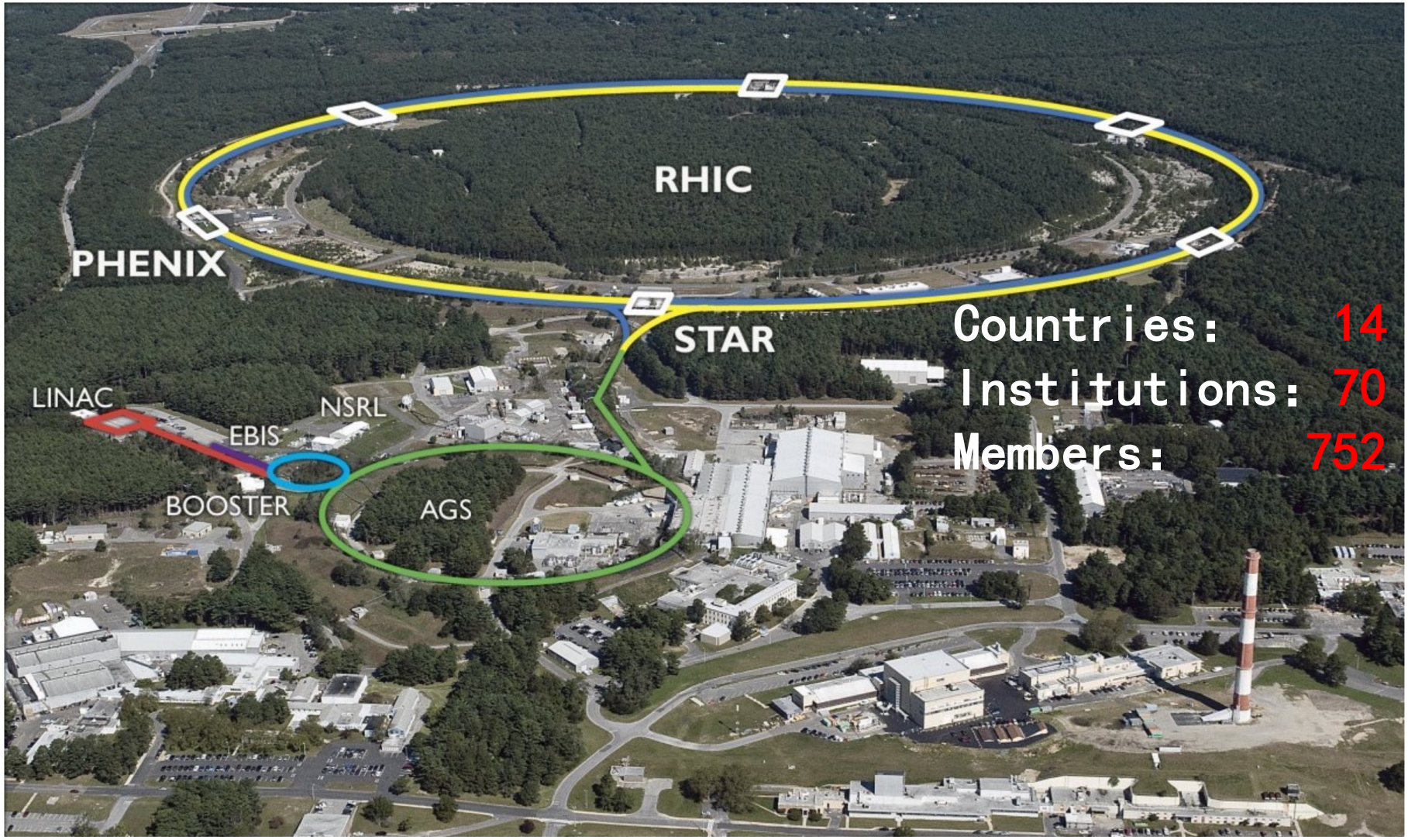
Outline

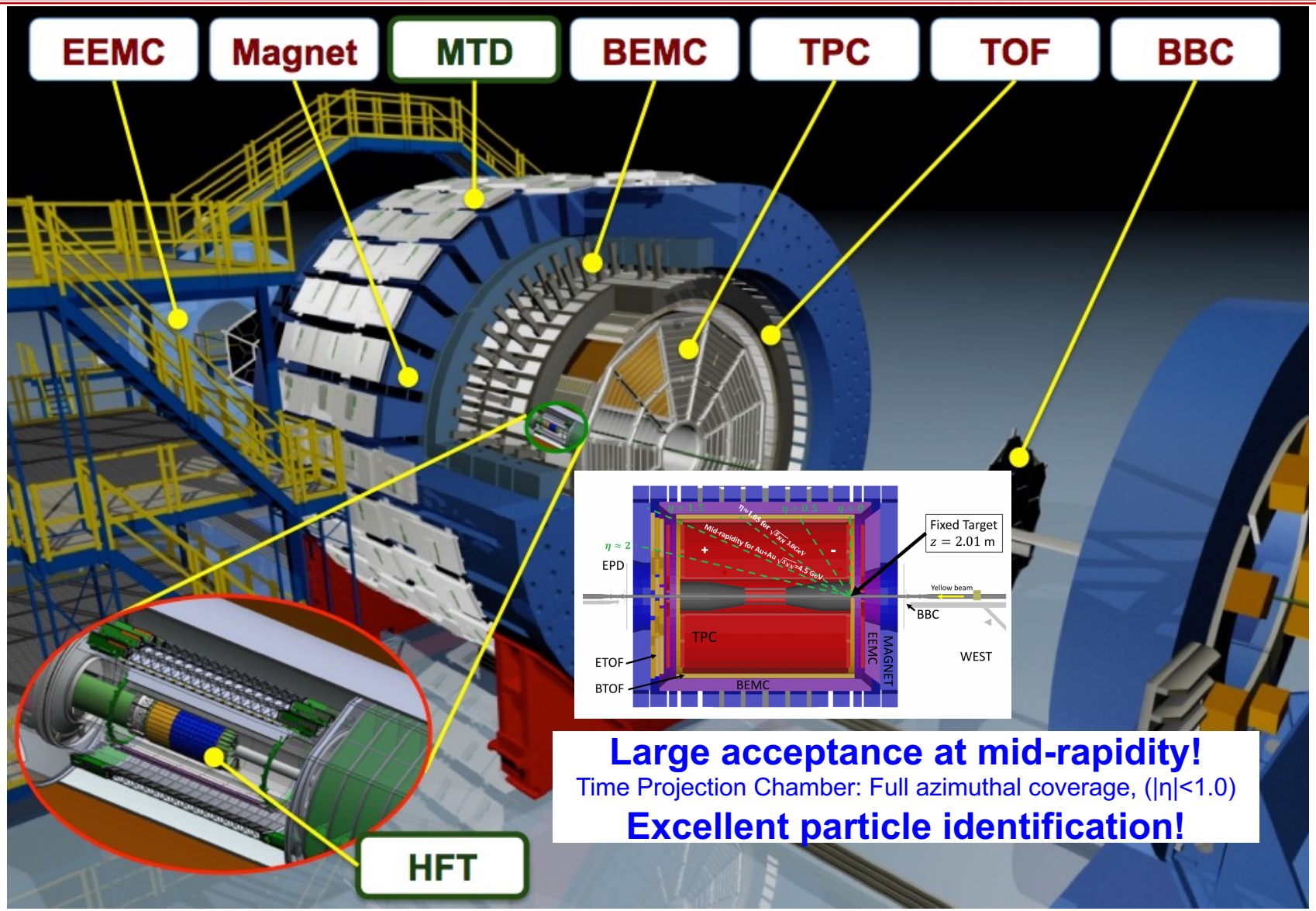
- **STAR experiment**
- **Motivations**
- **Results and Discussions**
- **Summary and Outlook**

RHIC-STAR



Heavy ion collisions: 3 - 200 GeV

STAR Detectors

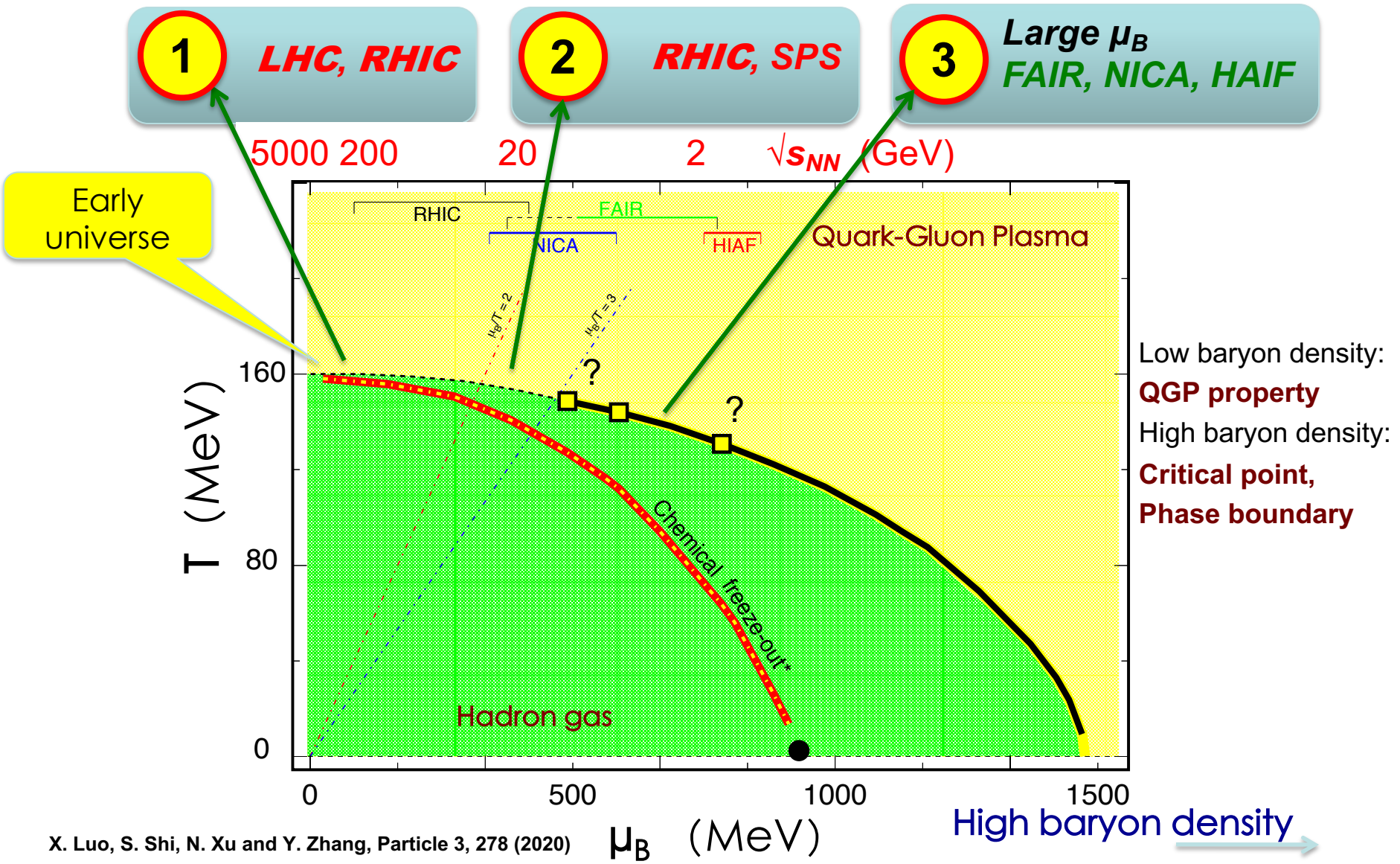


Large acceptance at mid-rapidity!

Time Projection Chamber: Full azimuthal coverage, (|η|<1.0)

Excellent particle identification!

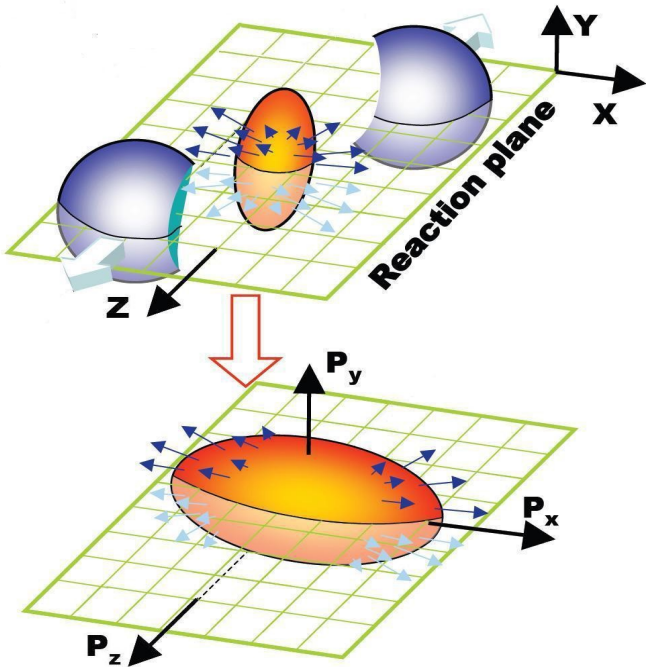
QCD Phase Diagram



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



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

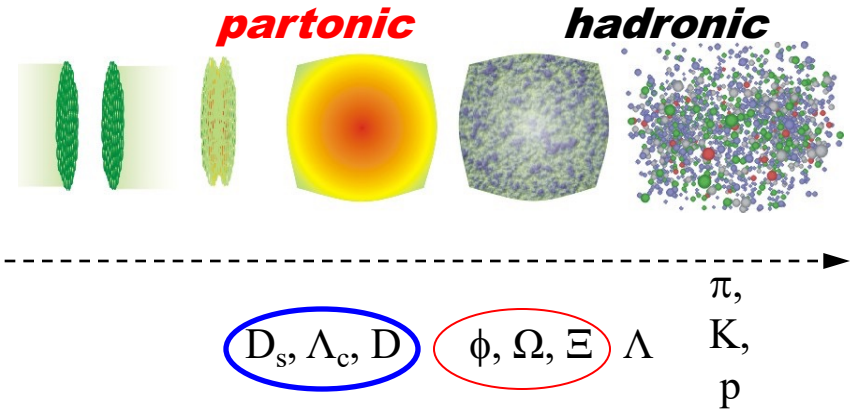
Anisotropic flow

v_1: directed flow;

v_2: elliptic flow;

v_3: triangular flow

…



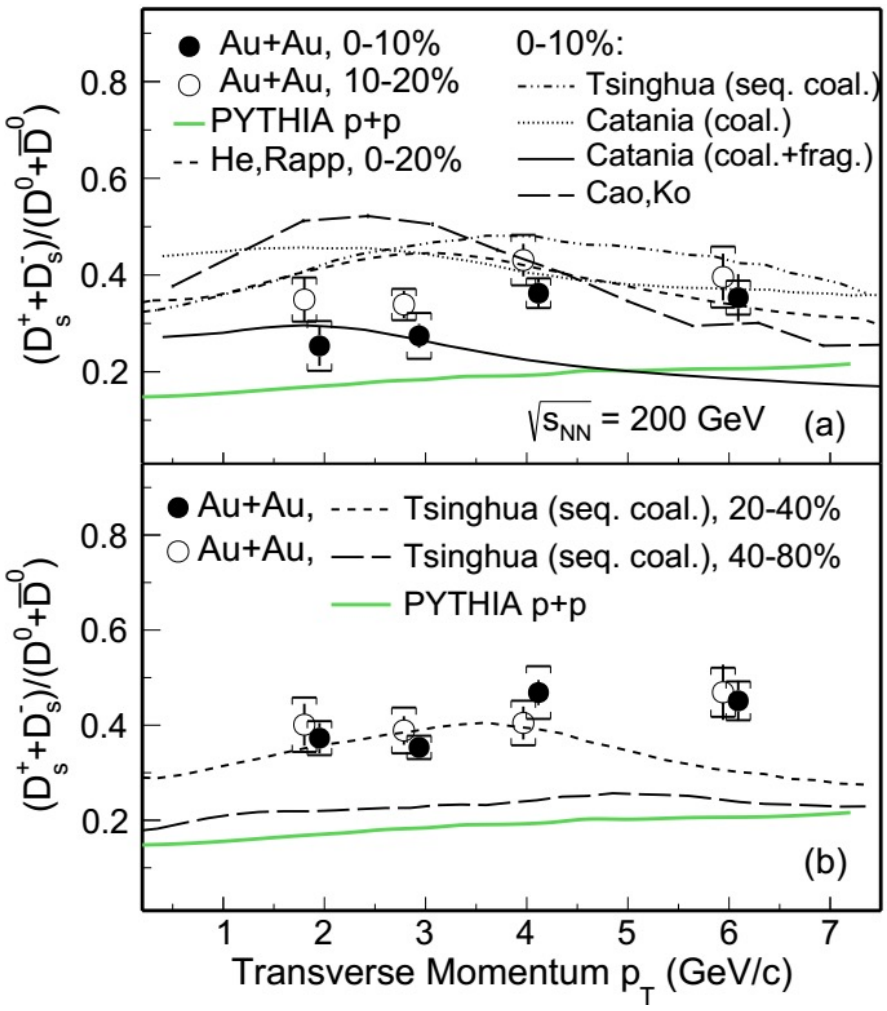
- **Anisotropic flow**:
  Sensitive to the early stage of the collision
- **Multi-strange hadrons and ϕ meson**:
  Less sensitive to late hadronic rescatterings
- **Heavy flavor flow**
  Study medium properties from motion of heavy quarks in medium

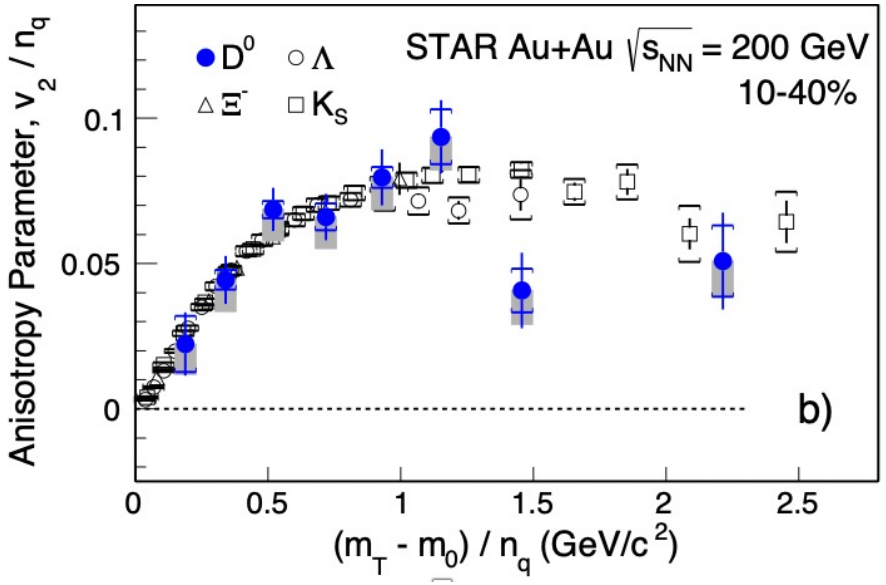
Beam Energy Scan

$\sqrt{s_{NN}}$ (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		92	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	**165** / 0.3	**2020**/ 2008	**9.5**	355	140
7.7	**100** / 4	**2021**/ 2010	**14**	420	139

Fixed target program: 3.0 – 7.7 GeV
extends STAR's physics reach to region of compressed baryonic matter

Collectivity of Heavy Quarks





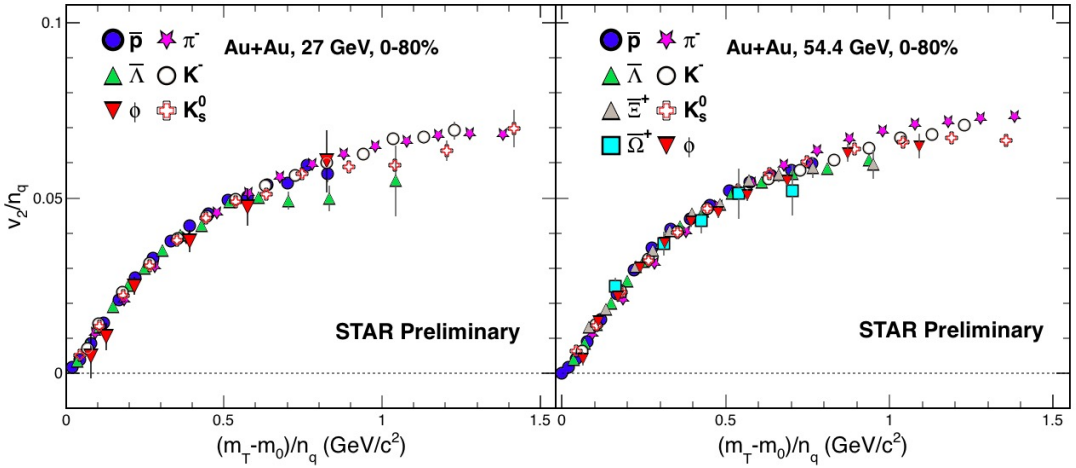
STAR: 傅川, HP2020; arXiv:2101.11793, accepted by PRL
STAR: Phys. Rev. Lett.118, 212301 (2017)

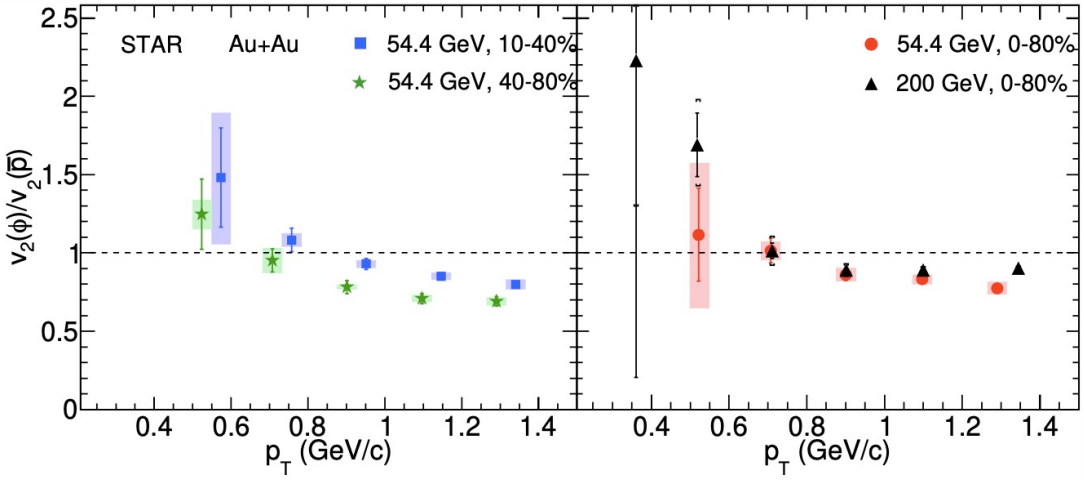
Partonic collectivity

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

D_s/D_0: strangeness enhancement + charm quark coalescence

New results: 54.4 and 27 GeV



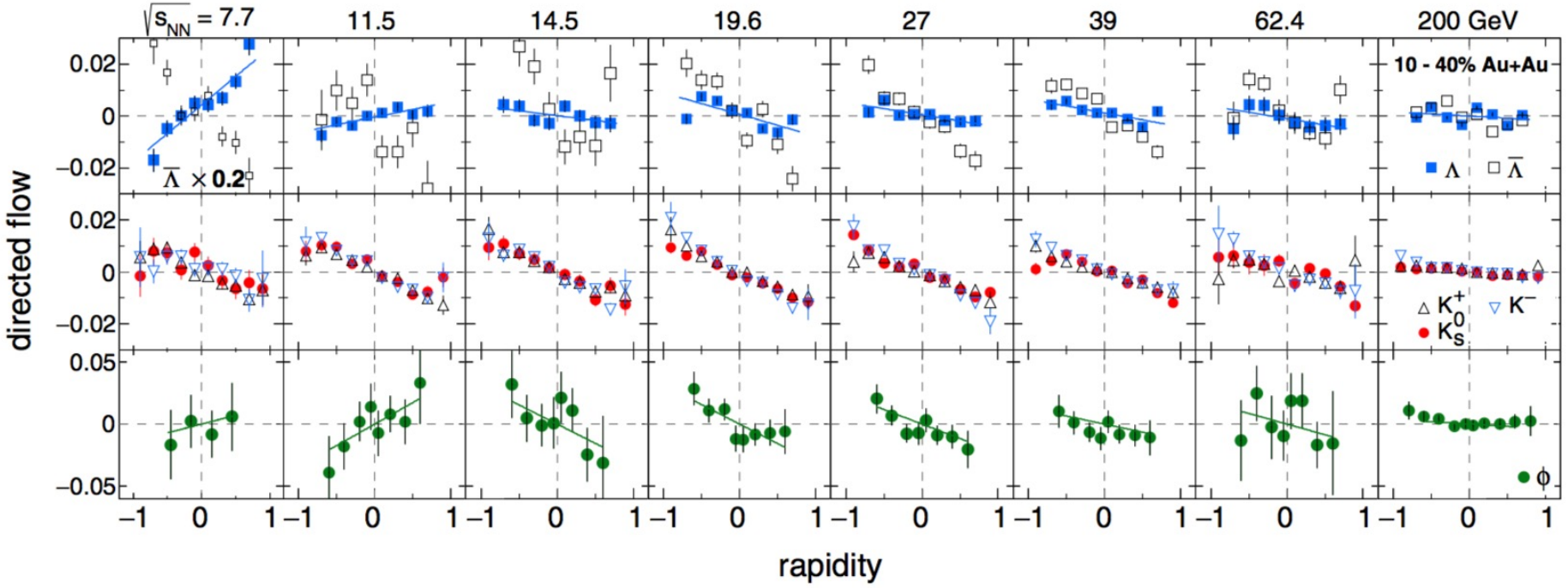


- NCQ scaling holds: Partonic collectivity in the initial stage

- Violation of mass ordering for $\bar{p}$ and ϕ
  Effect of hadronic interaction on $\bar{p}$ v2

STAR: Phys. Rev. Lett 116, 062301(2016)
SQM2021

v_1: ϕ Mesons

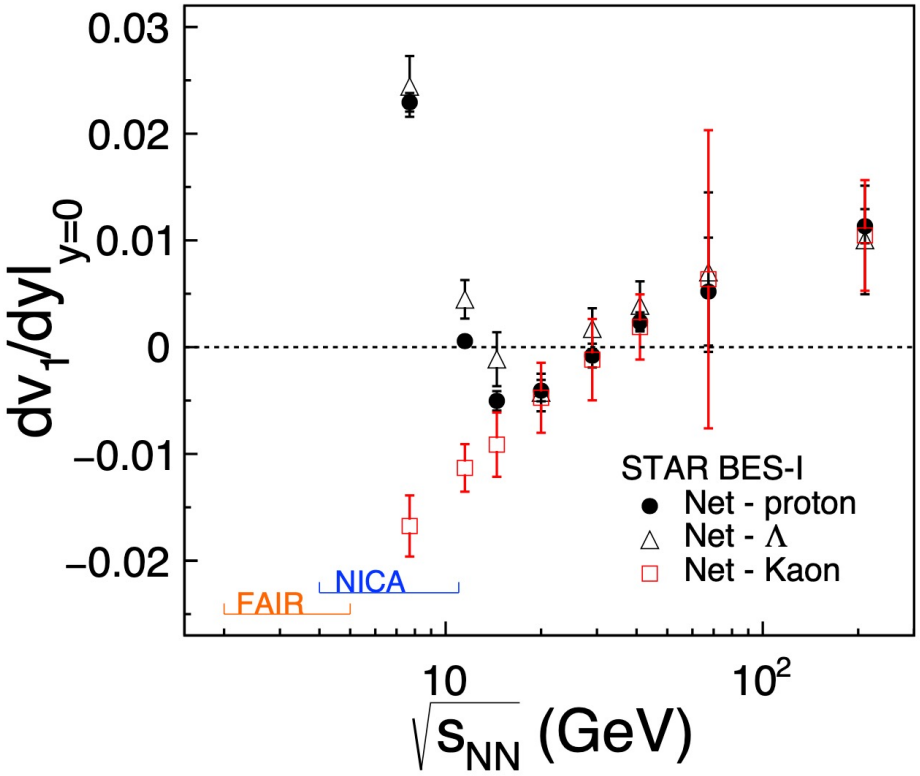


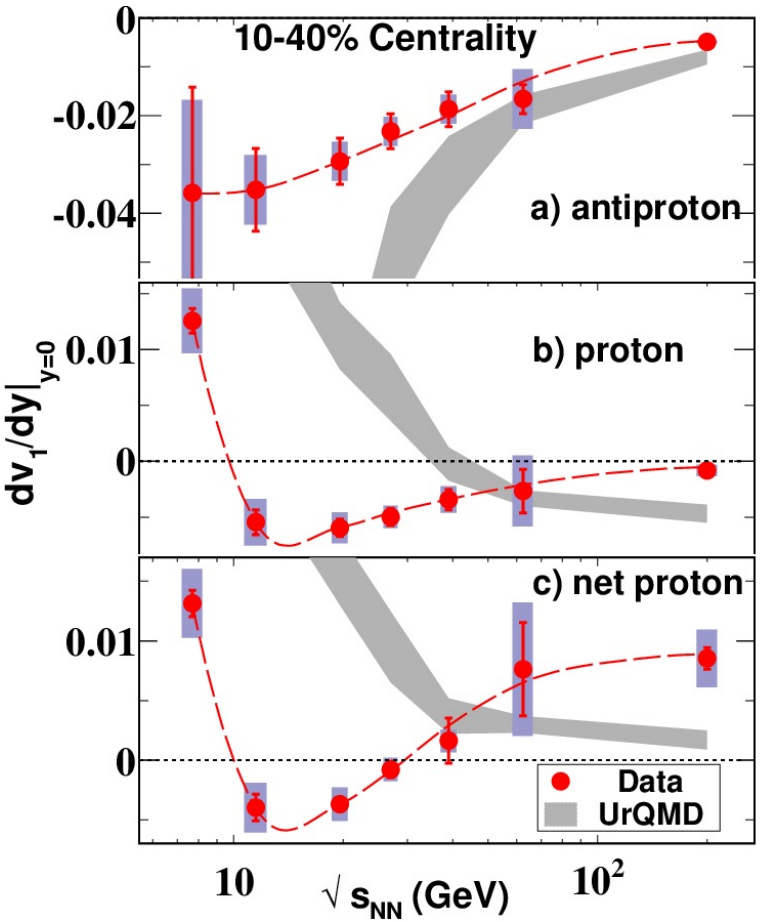
- Mesons and all anti-baryons show negative slope except ϕ mesons when collisions energy < 14.5 GeV

Change of medium property? High precision data needed: BESII

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

v_1 Slope

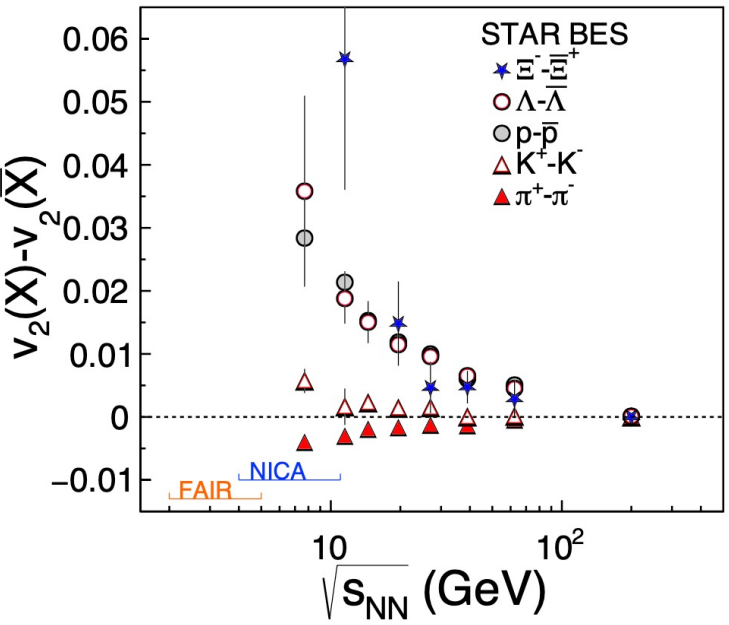


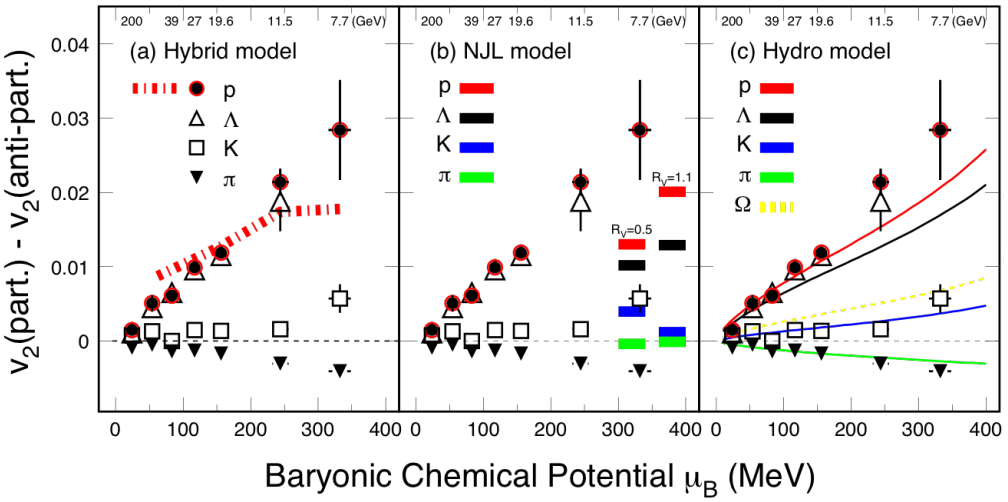


- dv_1/dy shows large divergence between net-kaon and net-proton (net-Λ) below $\sqrt{s_{NN}}$ < 20 GeV: Hydro calculation + 1st-order phase transition consistent with net-proton results

STAR: Phys. Rev. Lett. **120**, 062301(2018) ; Phys. Rev. Lett. **112**, 162301(2014)
H. Stoecker, Nucl. Phys. A 750, 121(2005)

v_2 Difference

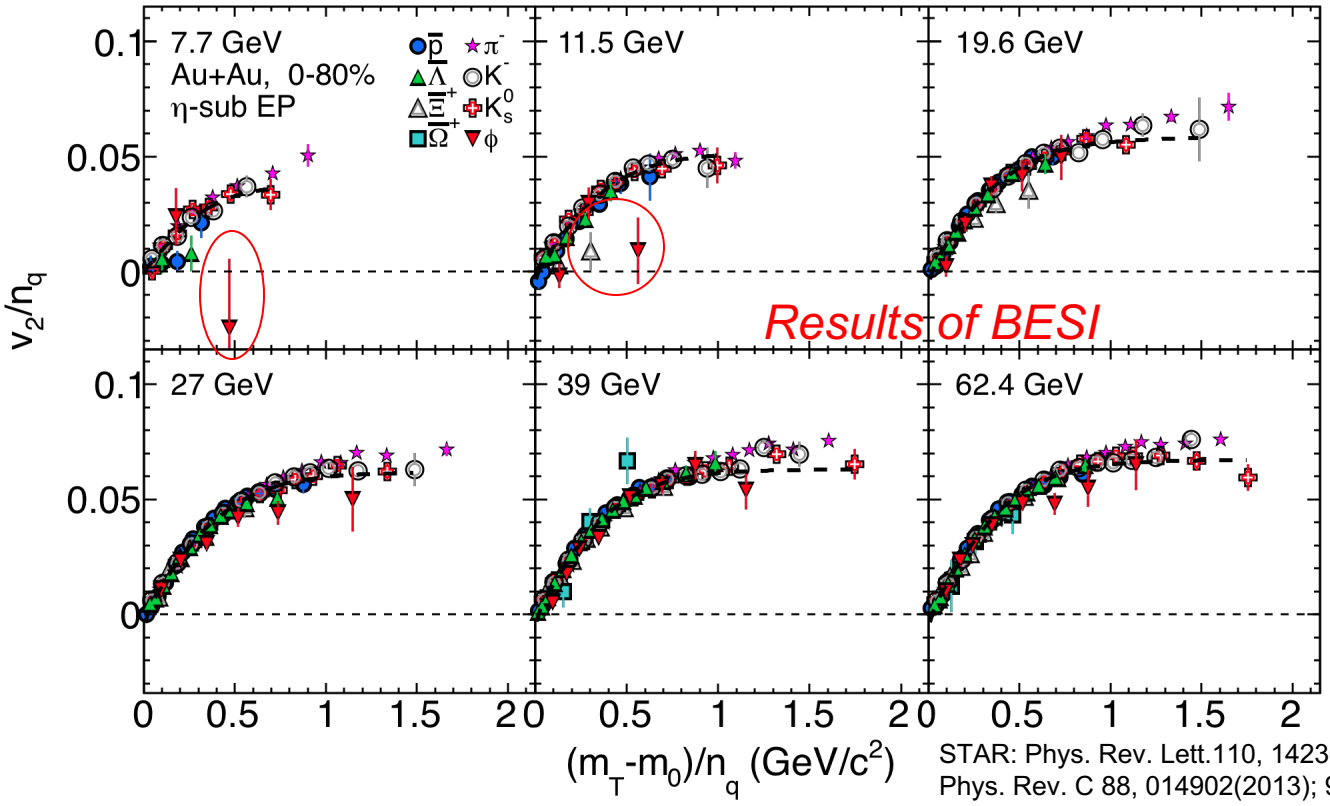




- Particle and anti-particle v_2 differences increase dramatically below $\sqrt{s_{NN}}$ < 20 GeV
- Model comparison
  - Hydro + Transport (UrQMD): consistent with baryon data
  - Nambu-Jona-Lasino (NJL) model (partonic + hadronic potential): hadron splitting consistent
  - Analytical hydrodynamic solution：

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

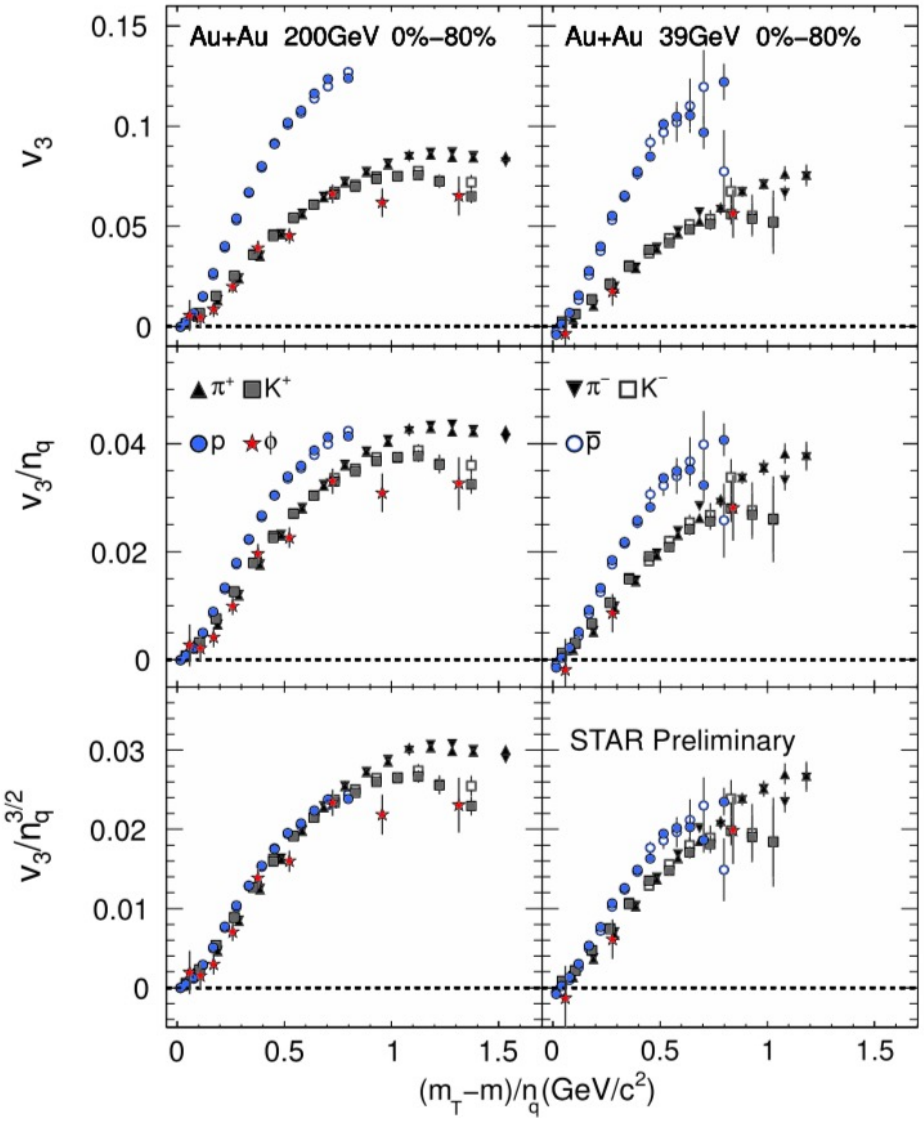


STAR: Phys. Rev. Lett.110, 142301(2013)
Phys. Rev. C 88, 014902(2013); 93, 014907(2016)

- 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

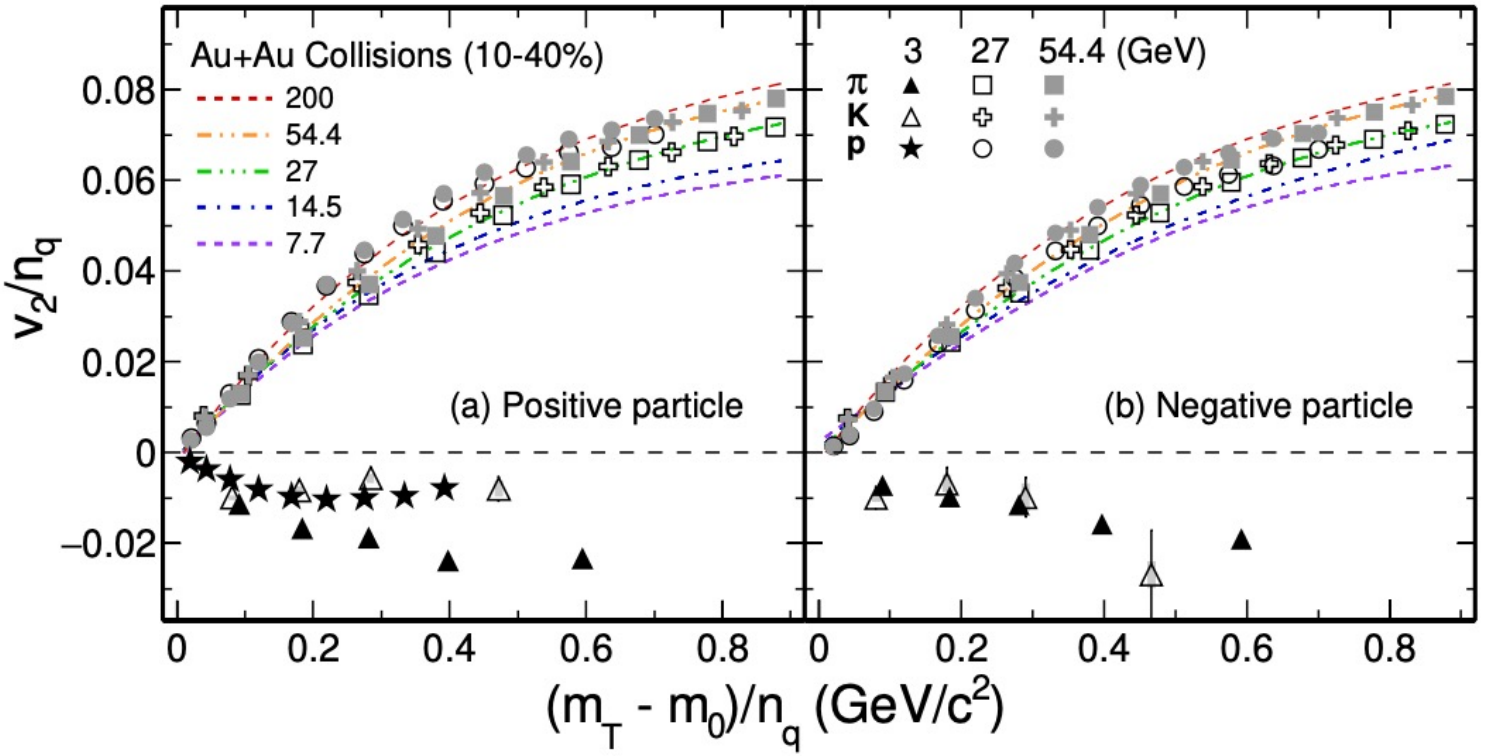
v_3



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 $n_q^{3/2}$

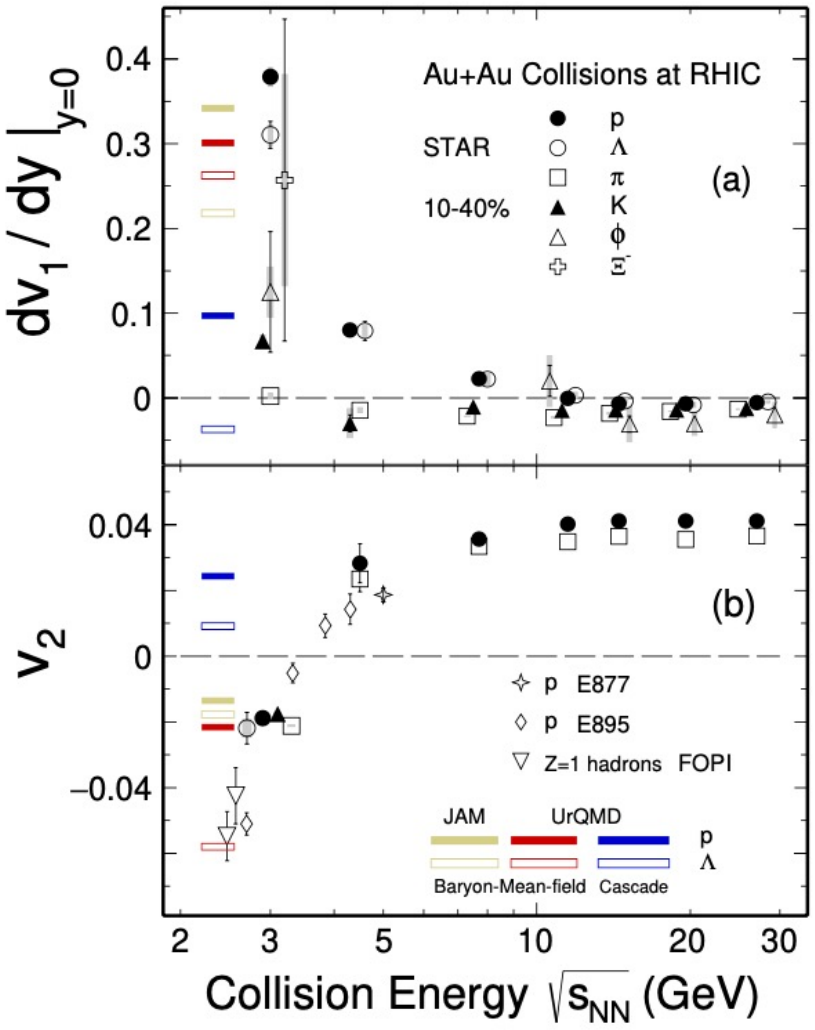
FXT: 3 GeV



- NCQ scaling at high energy(200, 54.4, 39 and 27 GeV) -> Partonic collectivity
- NCQ scaling breaks at 3 GeV: new medium properties and an EoS dominated by baryonic interactions

STAR: arXiv:2108.00908; 兰少位, CPOD2021

FXT: 3 GeV



- The data are qualitatively consistent with hadronic transport models (JAM and UrQMD) with baryonic mean-field

  →

  The dominant degrees of freedom at 3 GeV are hadrons

STAR: arXiv:2108.00908; 兰少位, CPOD2021

Summary

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

- **Beam Energy Scan**
  - **v_1 slope of net-baryon:** *non-monotonic as energy*
  - **ϕ meson and multi-strange v_n:** *partonic vs. hadronic*
  - **3 GeV:** *EoS dominated by hadronic interactions*

BESII: RHIC 2019 – 2021

BESIII: RHIC FAIR/NICA/HIAF 2022 –

Explore QCD phase structure!

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**
  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

RHIC BES-II: 2019-2021

19.6 GeV (580 M),
14.5 GeV (325 M),
11.5 GeV (235 M),
9.2 GeV (165 M)
7.7 GeV (100 M)
FXT 3 GeV (1.8 B)

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