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# The Recent Results of Collective Flow from Beam Energy Scan II at RHIC-STAR

施梳苏

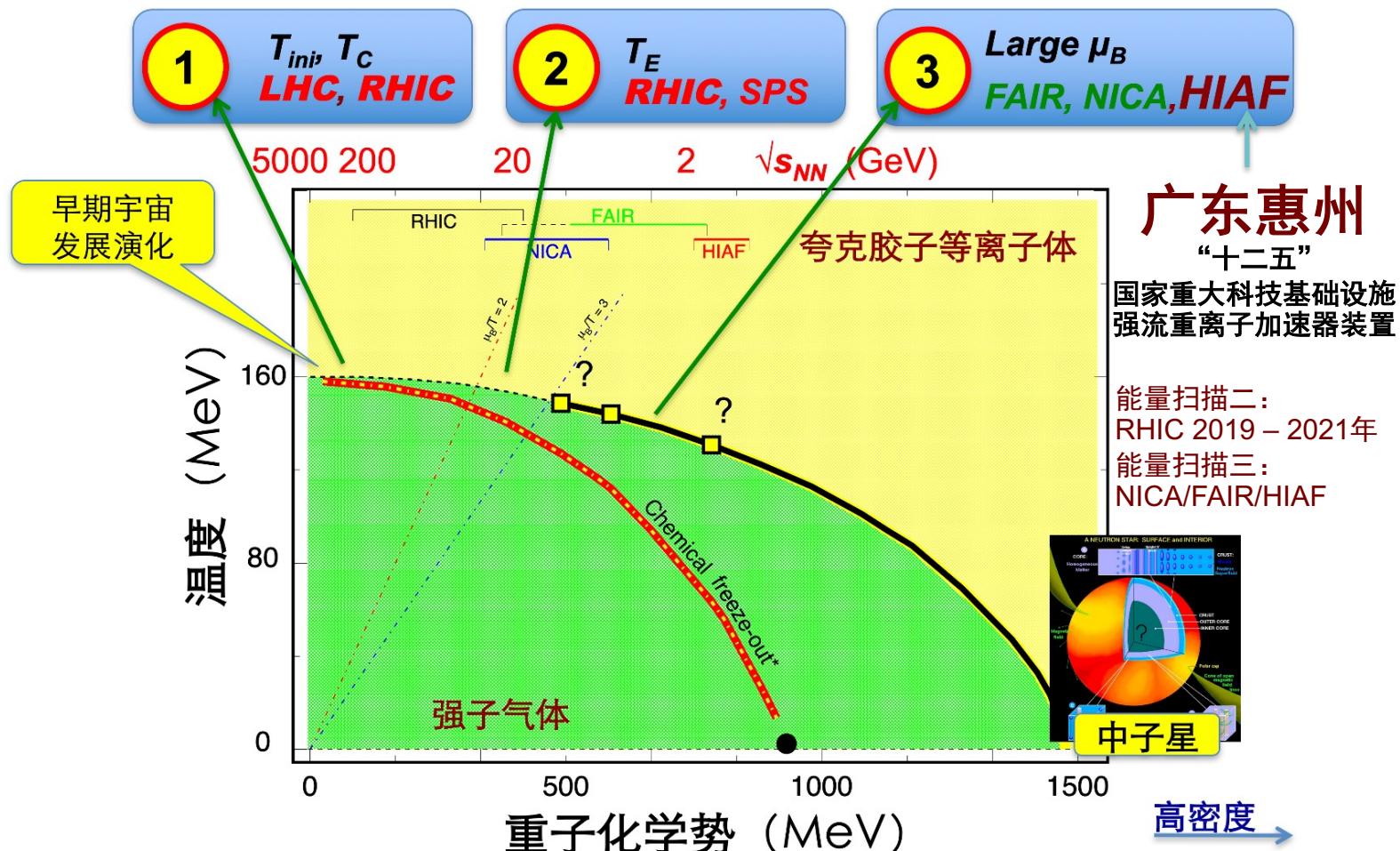
华中师范大学



# Outline

- **Introduction**
- **Beam Energy Scan**
- **Results and Discussions**
- **Summary and Outlook**

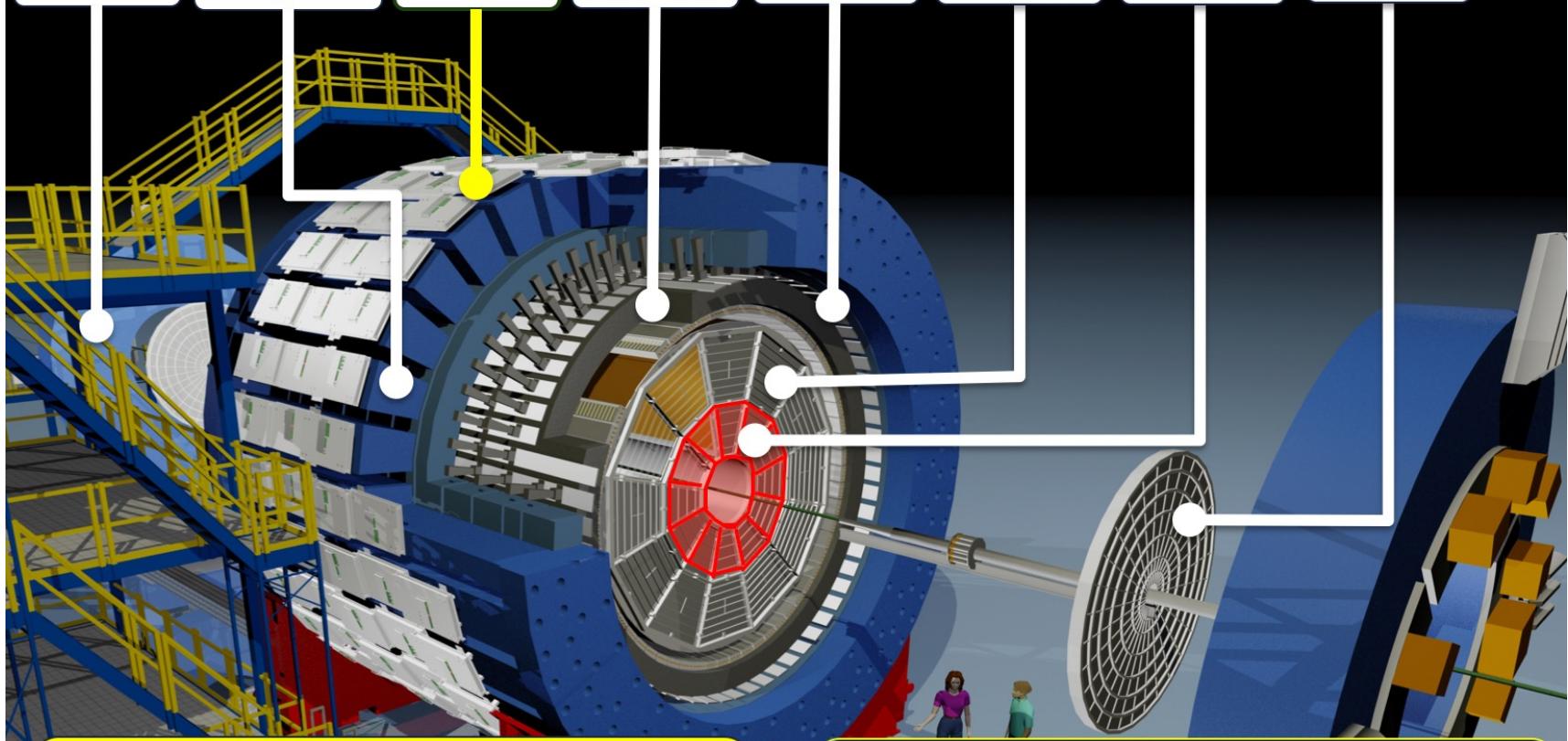
# QCD Phase Diagram



强相互作用相结构的实验研究 ➤ 低重子密度区（高能）：夸克物质的性质  
➤ 高重子密度区（能量扫描）：相边界，临界点

# STAR Detectors

EEMC Magnet MTD BEMC TOF TPC iTPC EPD



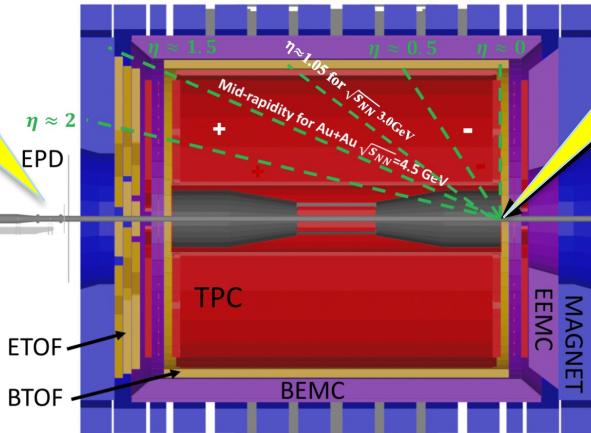
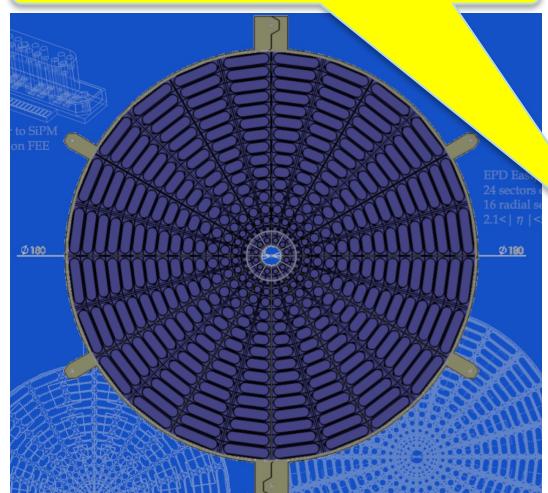
- Larger acceptance
- Excellent PID with uniform efficiency
- Modest rates

- iTPC, EPD & eTOF upgrades completed
- All are in data-taking for BES-II program

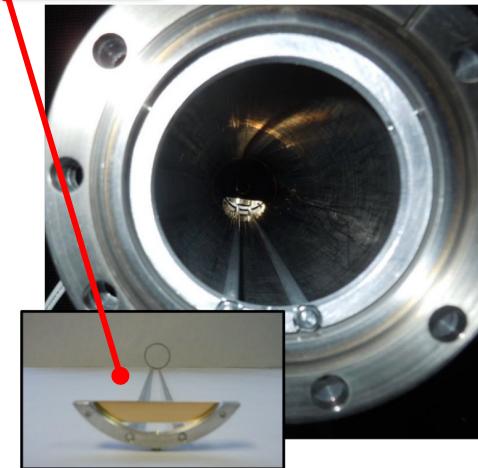
# STAR Fixed Target Setup



Event Plane Detector (EPD)



Au Target



➤ Good mid-rapidity coverage for FXT 3 GeV collisions



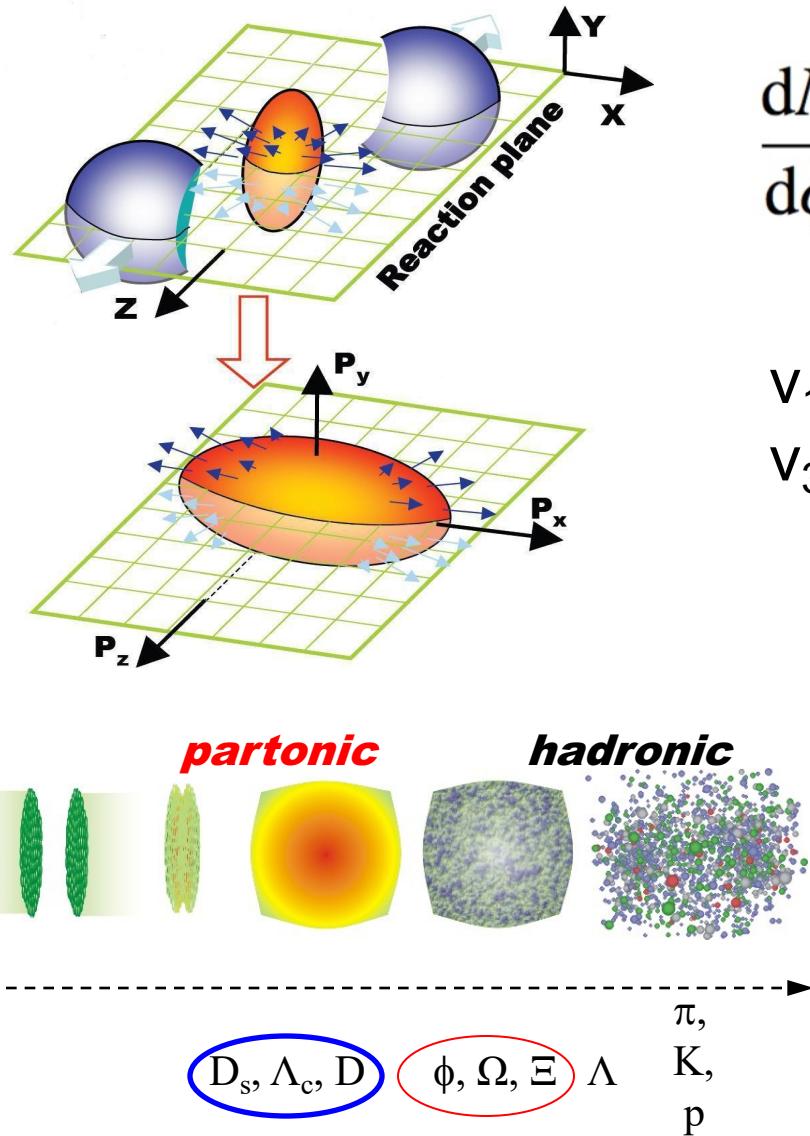
# Beam Energy Scan

BES-II data taking has been finished

$\sqrt{s_{NN}}$ (GeV)	$\mu_B$ (MeV)	Events	Date collected
19.6	206	478 M	2019
14.6	262	324 M	2019
11.5	316	235 M	2020
9.2	373	162 M	2020
7.7	422	101M+163 M	2021
6.2	487	118 M	2020
5.2	541	103 M	2020
4.5	589	108 M	2020
3.9	632	170 M	2020
3.5	666	116 M	2020
3.2	697	201 M	2019
3.0	721	2361 M	2021

- Higher statistics, better detector performance and more energy points in BES-II
- Explore the QCD phase diagram and constrain the EoS at high baryon density

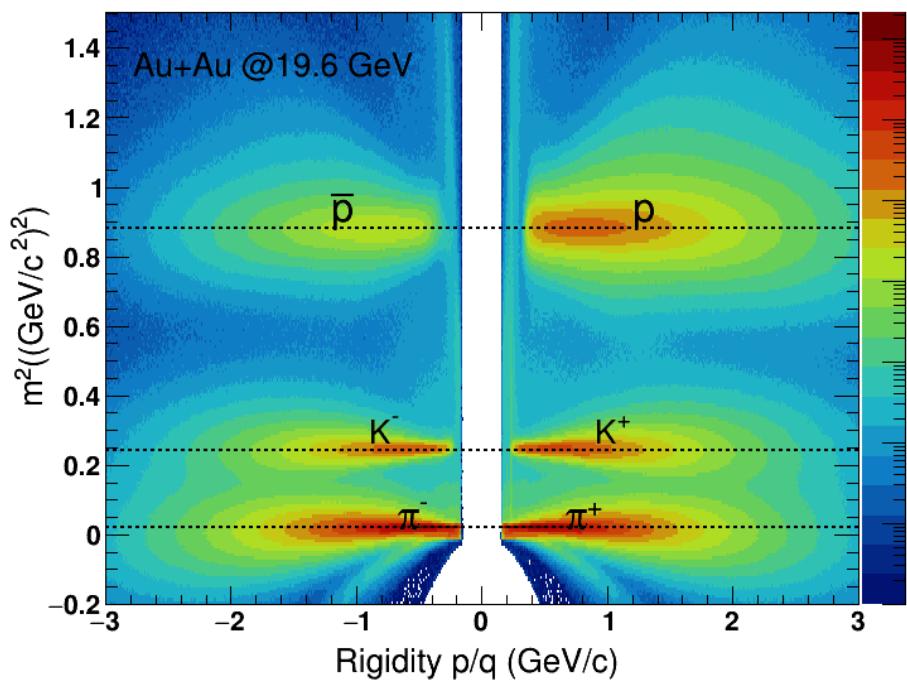
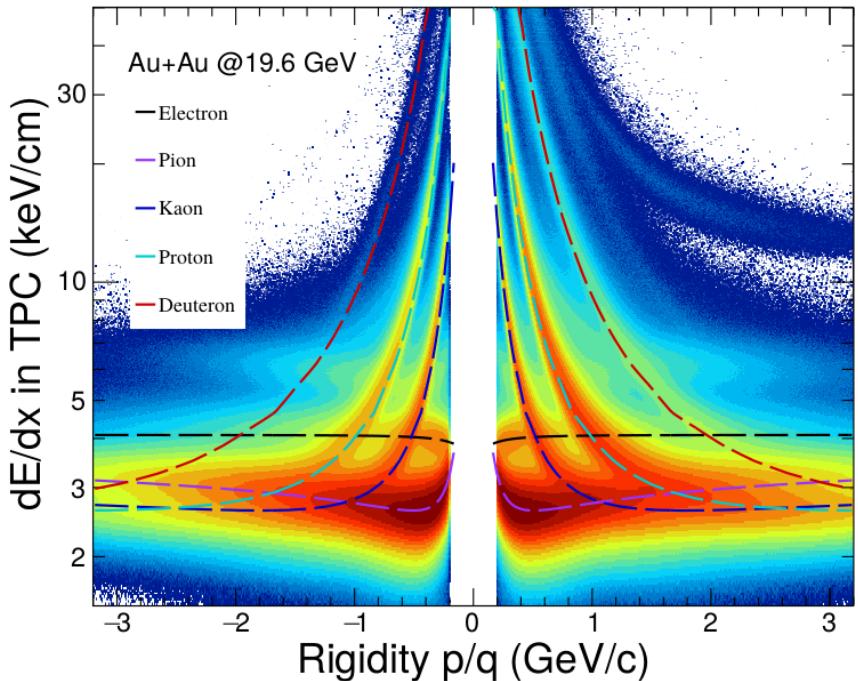
# Anisotropic Flow



$v_1$ : directed flow;  $v_2$ : elliptic flow;  
 $v_3$ : triangular flow;  $v_4$  .....

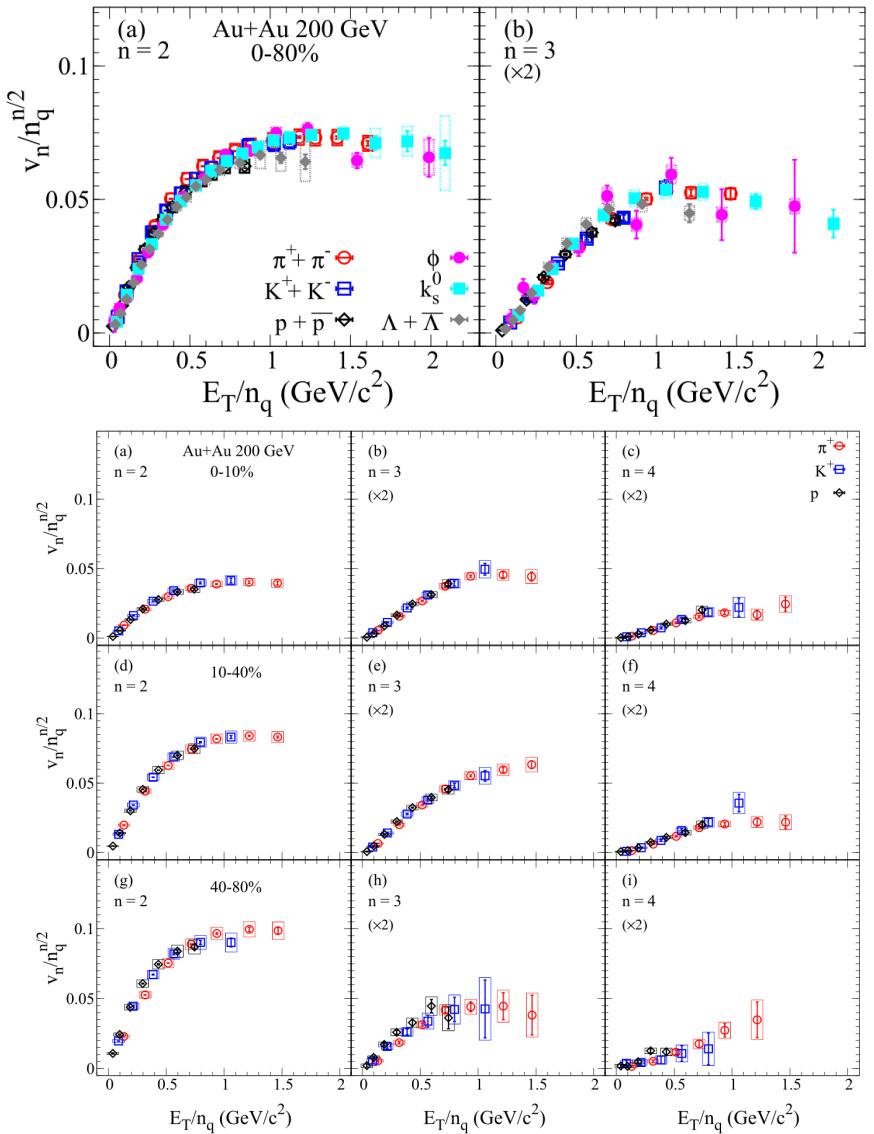
- **Anisotropic flow:**  
*Sensitive to the early stage of the collision*
- **Heavy flavor flow**  
*Study medium properties from motion of heavy quarks in medium*
- **Multi-strange hadrons and  $\phi$  meson:**  
*Less sensitive to late hadronic rescatterings*

# Particle Identification



- Good capability of particle identification based on TPC and TOF

# Higher-order Flow in 200 GeV



RHIC top energy

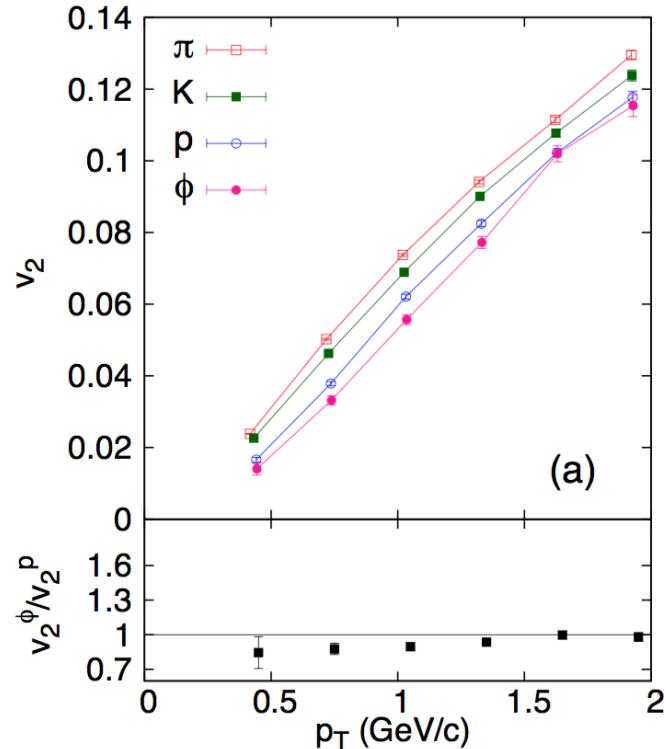
- Light flavor, strange particles and  $\phi$  mesons
- Follow the NCQ scaling up to  $v_4$

*Partonic collectivity*

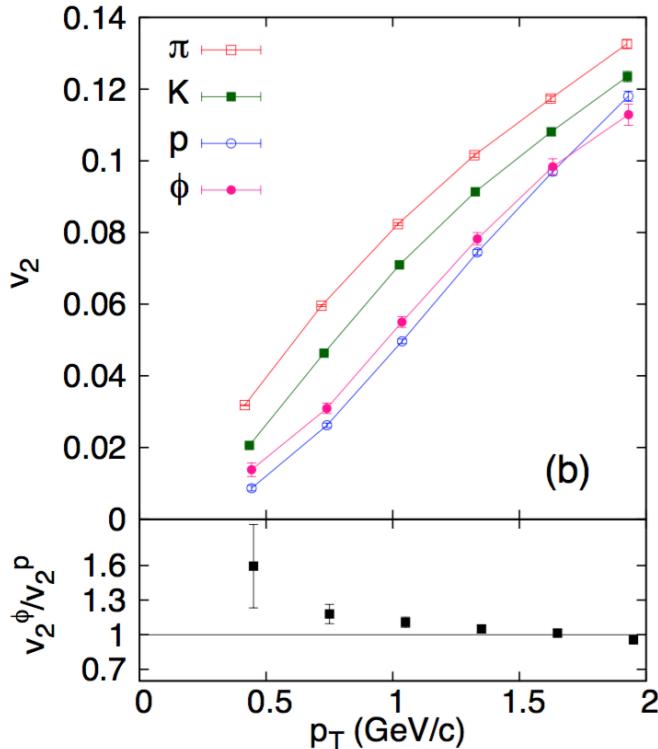
STAR: Phys. Rev. C.105, 064911 (2022)  
孙旭, 施梳苏等

# $v_2(\phi)$ versus $v_2(p)$

Model calculations: T. Hirano et al., ; PRC77, 044909 (2008), PRC92, 044907 (2015)



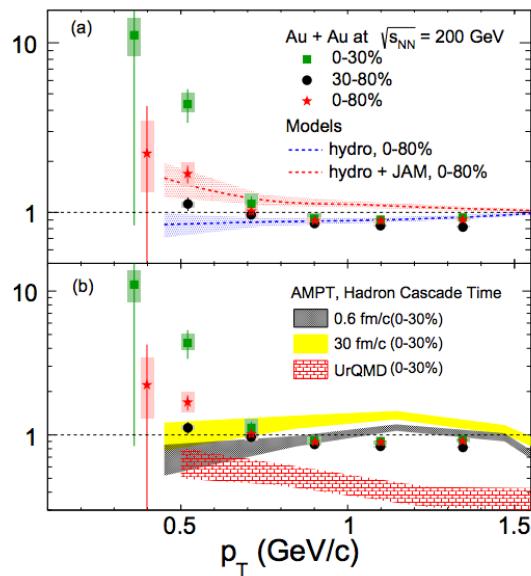
Before hadronic  
re-scattering



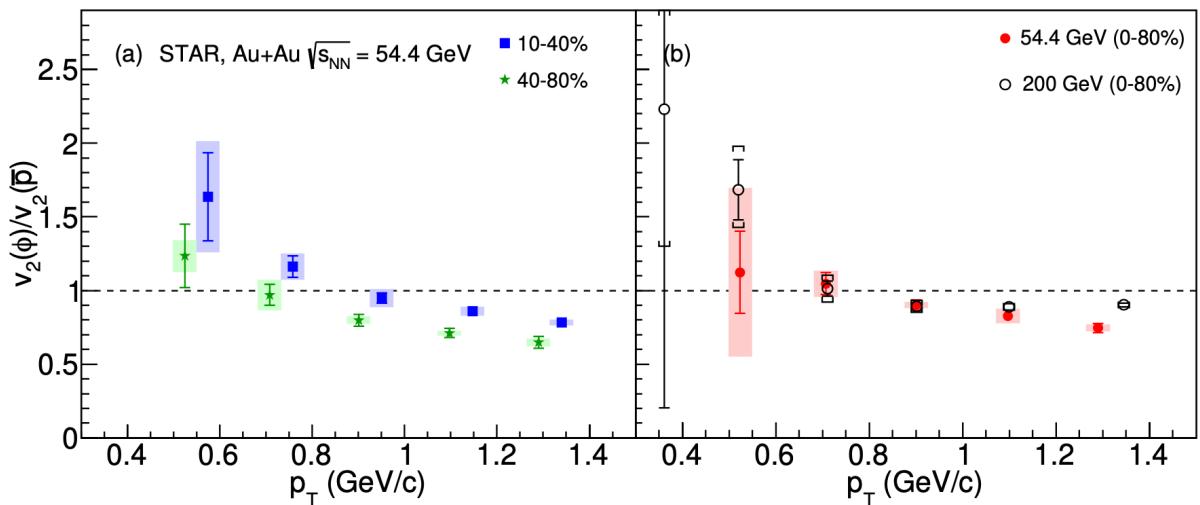
After hadronic  
re-scattering

- Ideal hydro + hadron cascade (JAM)
- Small hadron cross section + hadronic re-scattering effect on  $v_2$   
Mass  $\phi >$  mass  $p \rightarrow v_2(\phi) > v_2(p)$
- ➔ **Break mass ordering for  $\phi$  mesons and protons**

# $v_2(\phi)$ versus $v_2(p)$



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

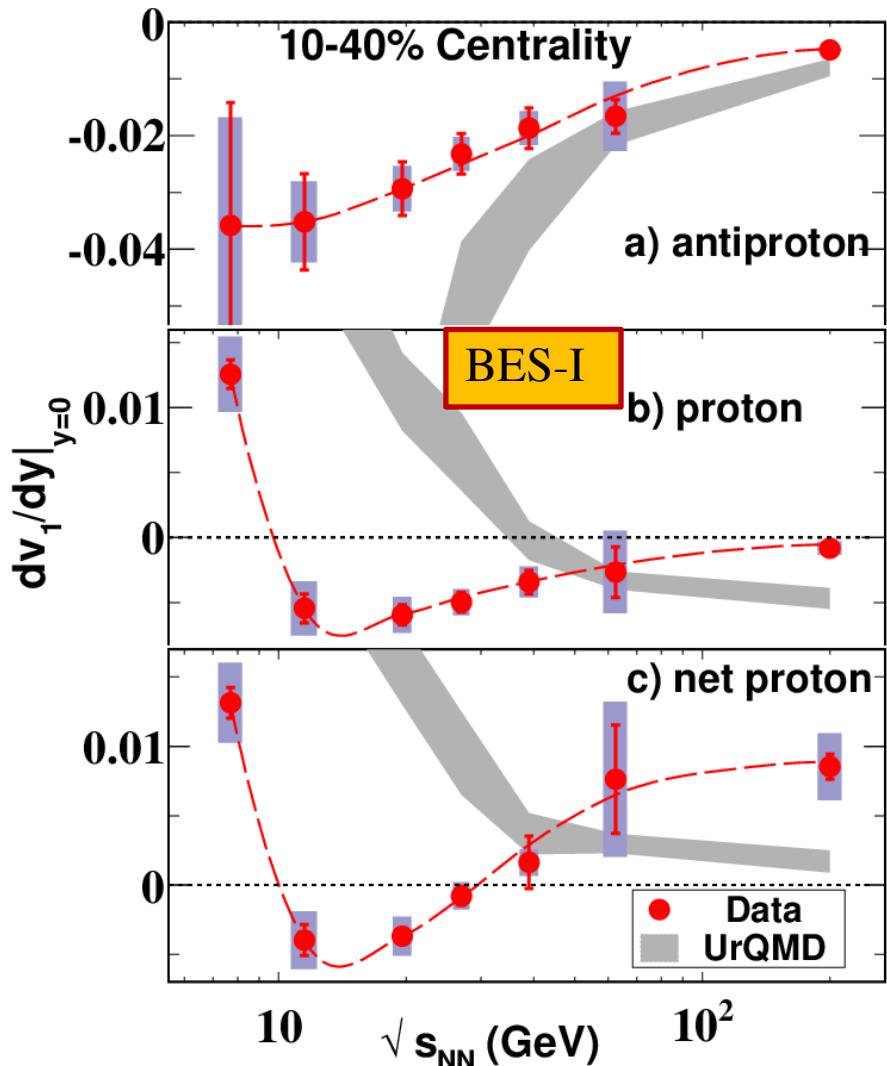


STAR: arXiv: 2205.11073 兰少位, 施梳苏等

- Violation of mass ordering in central collisions at 54.4 and 200 GeV
- Energy and centrality dependence of hadronic rescattering effect

# $v_1$ : Softest Point

BESII : centrality dependence



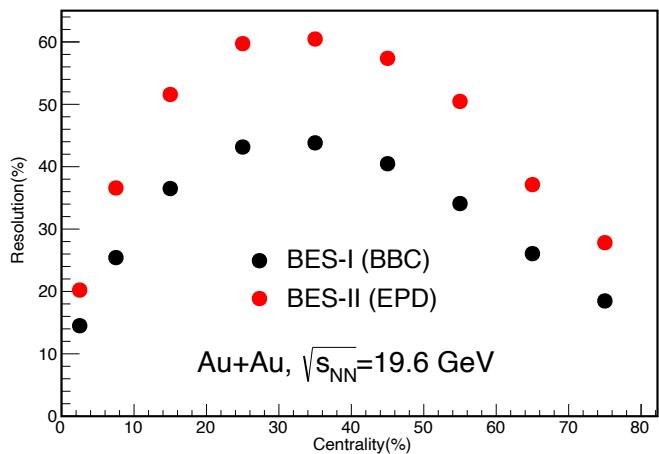
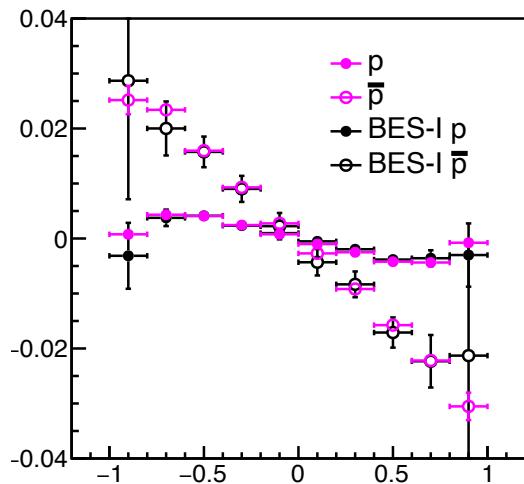
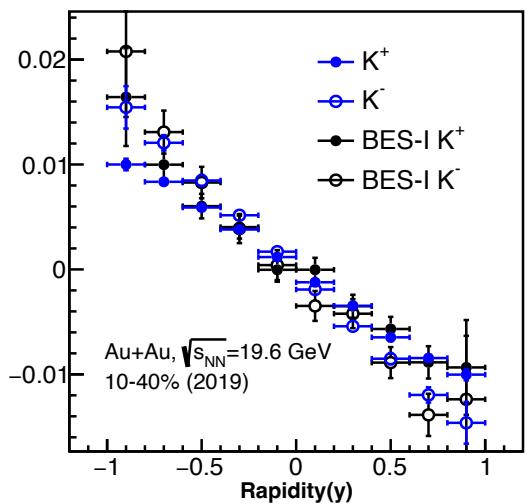
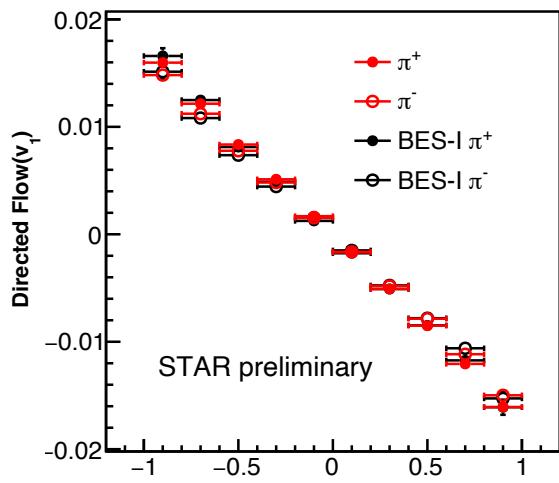
$dv_1/dy$ : the slope of directed flow versus rapidity near mid-rapidity

- 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)

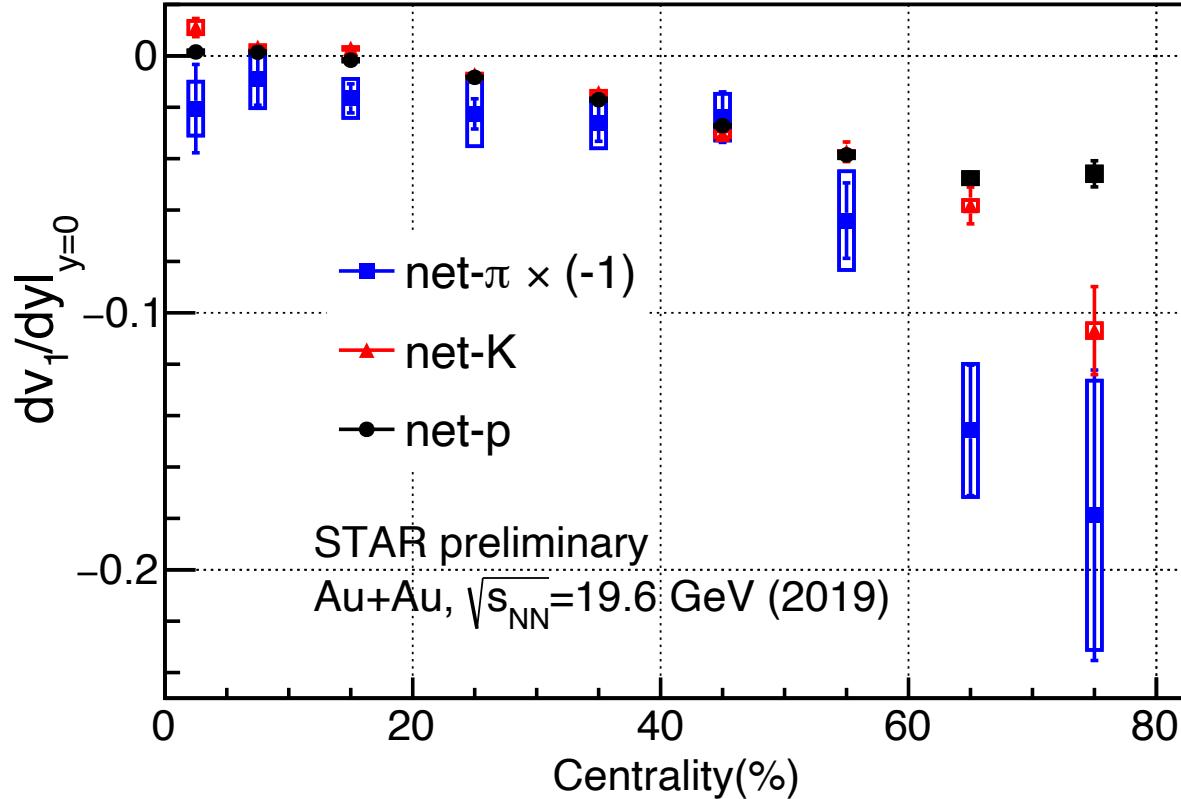
# BESII v<sub>1</sub>: 19.6 GeV



STAR 刘佐文: SQM2022, ISMD2022

- Resolution improved about 50% comparing to BES-I
- The statistical uncertainties reduced by a factor 8 comparing to BES-I results.

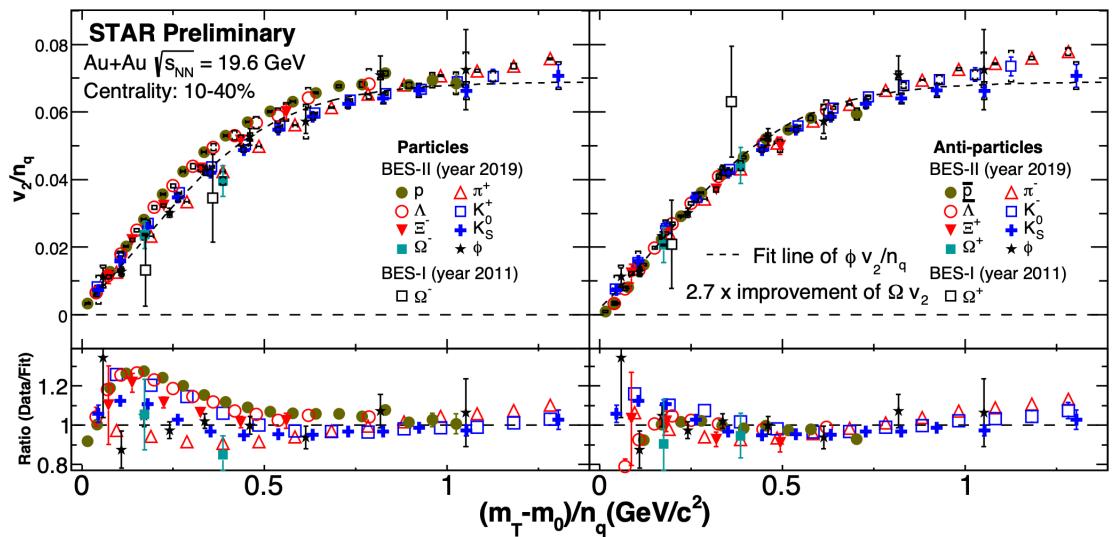
# $dv_1/dy$ vs. Centrality



- $v_1$  slope of net-particle is larger in more peripheral collisions  
 More transported quarks in the peripheral collisions
- $v_1$  slope of net-proton and net-kaon are similar in central and mid-central collisions
- 14.6 GeV: wait for final official centrality definition

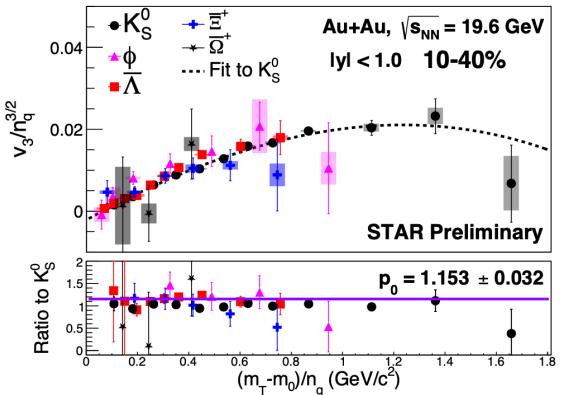
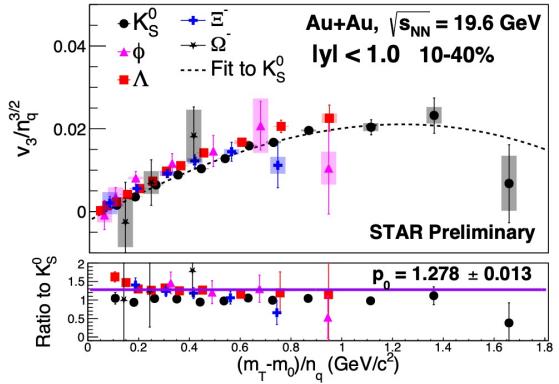
Net-pion  $dv_1/dy$  is positive at all centralities. To facilitate plotting in the figure opposite, net-pion  $dv_1/dy$  is shown with reversed sign.

# BESII v<sub>2</sub>: 19.6 GeV

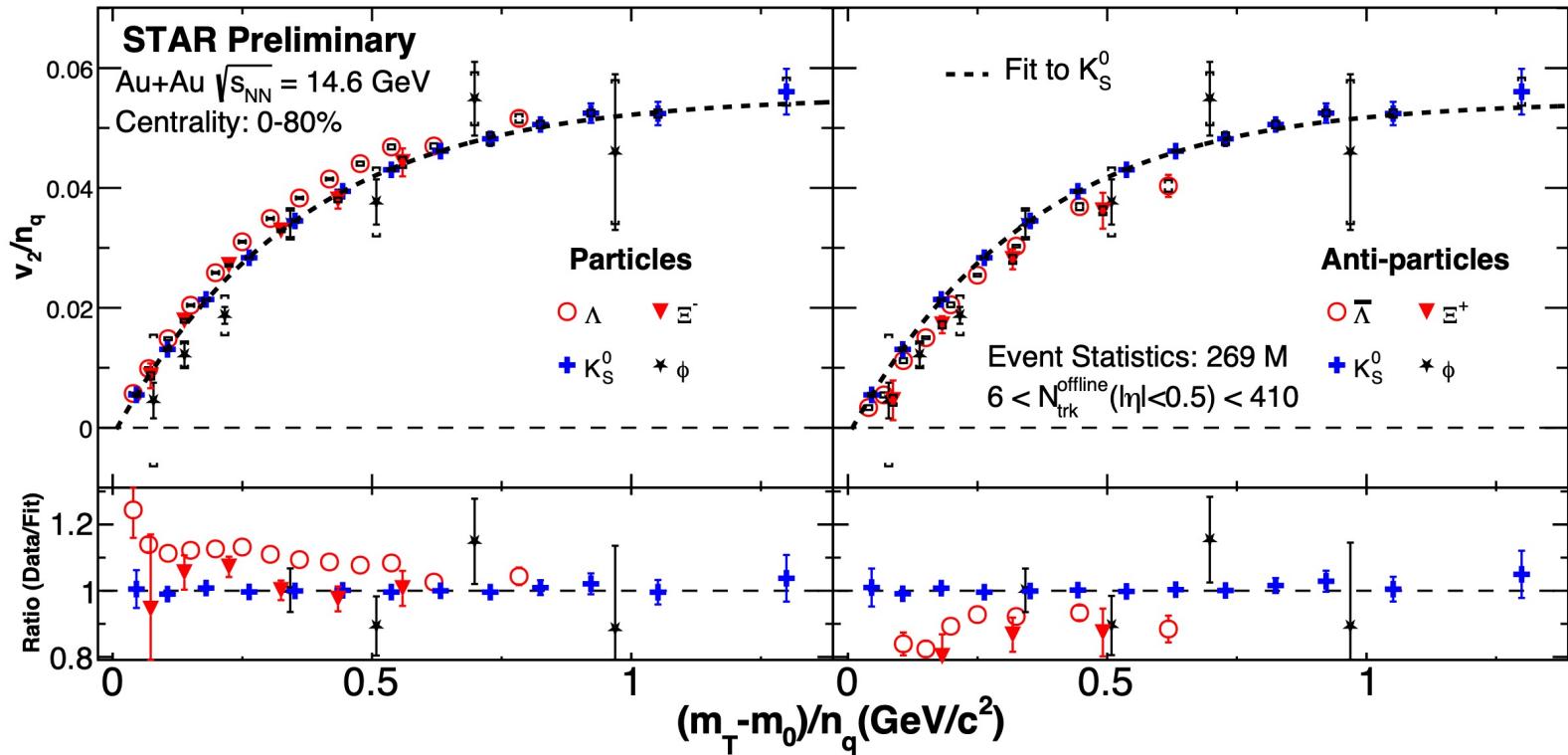


STAR 刘利珂: SQM2022

- The NCQ scaling holds within 20% for particles and within 10% for anti-particles
- The NCQ scaling of anti-particles better than particles: produced vs. transported quarks

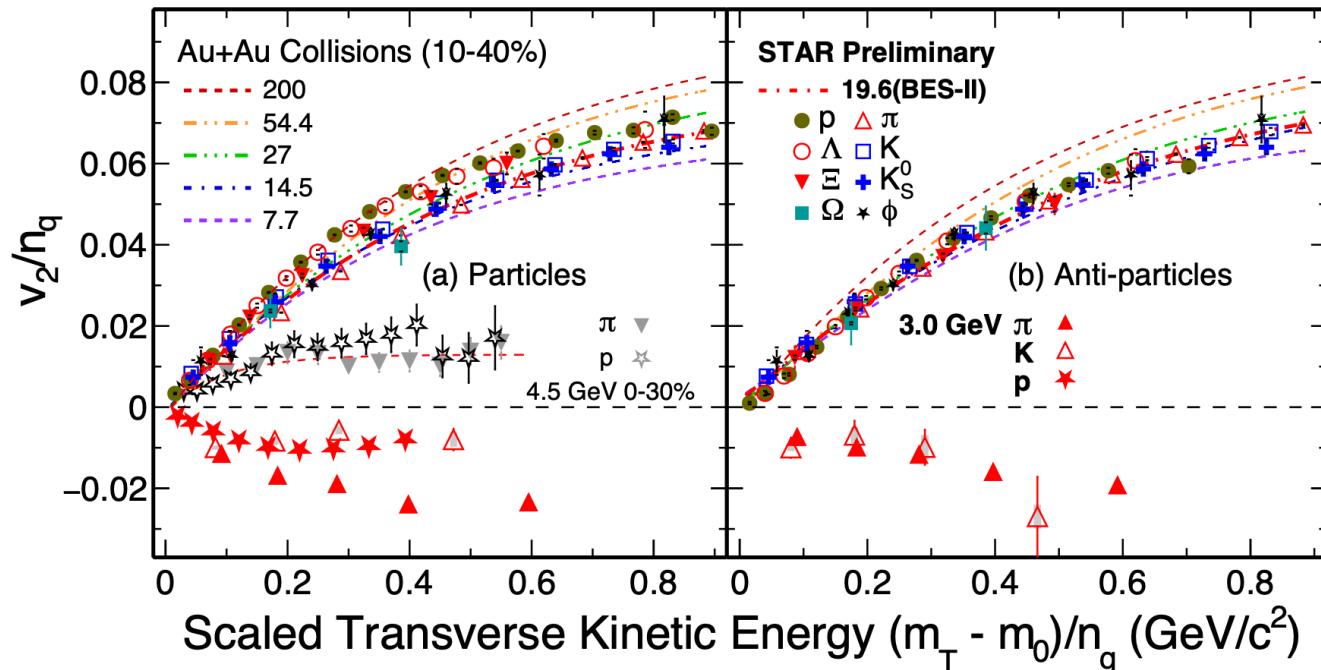


# BESII v<sub>2</sub>: 14.6 GeV



➤ The NCQ scaling holds within at 20% level

# NCQ Scaling at 3 GeV



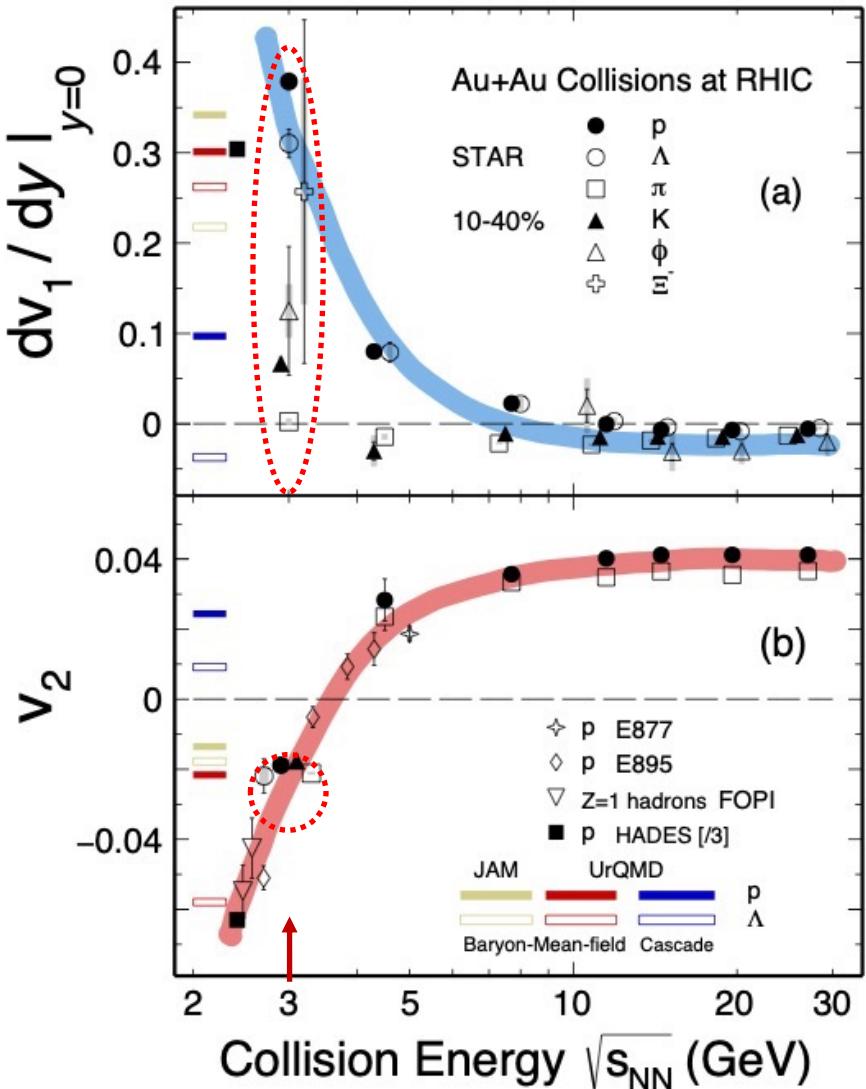
STAR: Phys. Lett. B 827 (2022) 137003 兰少位, 施梳苏等

- The number of constituent quark (NCQ) scaling for  $v_2$  holds down to 4.5 GeV, consistent with the nature of partonic collectivity
- At 3 GeV, the measured  $v_2$  for all particles are negative and NCQ scaling is absent, especially for positive charged particles

STAR: Phys. Rev. C 88 (2013) 14902; Phys. Lett. B 827 (2022) 137003

X. Dong et al. Phys. Lett. B 597 (2004) 328-332

# $v_1$ Slope and $v_2$ vs. Energy



- The  $v_1$  slopes ( $dv_1/dy|_{y=0}$ ) of baryons at 3 GeV are positive and larger than those of mesons
- For the first time, kaon and  $\phi$   $v_1$  slopes are found to be positive at 3 GeV
- Opposite collective behavior to high energy results
- The results from UrQMD with baryonic mean-field potential qualitatively describe data at 3 GeV

**EoS dominated by the baryonic interactions at 3 GeV**

# Summary

- **High Energy Collisions**
  - Higher-order flow: *partonic collectivity*
  - $v_2(\phi)/v_2(p)$ : *hadronic contribution on partonic flow*
- **Beam Energy Scan (II)**
  - $v_1$ : *centrality dependence done for 19.6 and 14.6 GeV*
  - $v_2$  and  $v_3$ : *multi-strange hadrons done for 19.6 and 14.6 GeV*
  - **3 GeV**: *indication of new medium properties and an EoS dominated by baryonic interactions*

**Mapping the QCD phase diagram with more collision energies from BES-II**

# BES-II

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

**RHIC BES-II: 2019-2021**

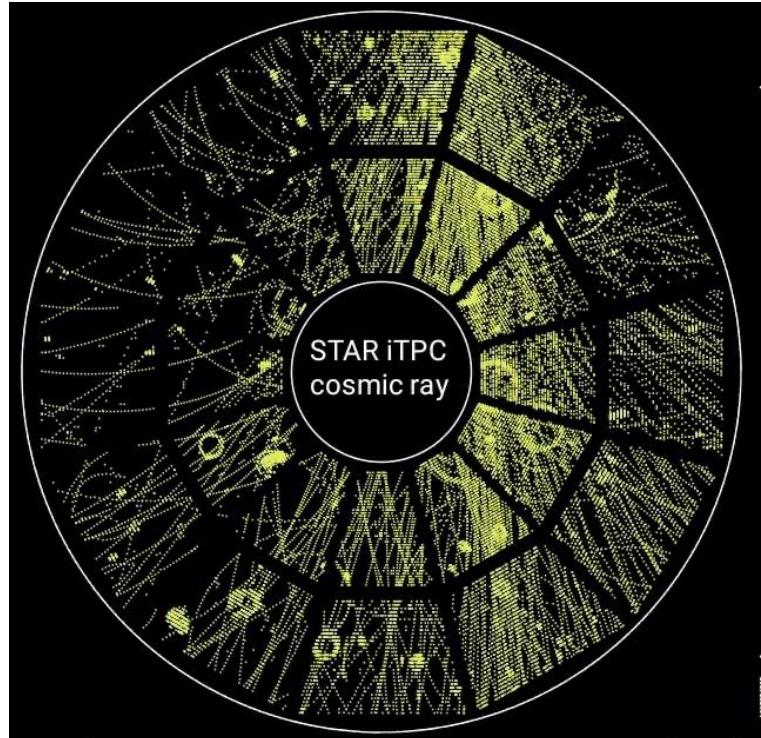
**19.6, 17.1, 14.5, 11.5, 9.2 and 7.7 GeV  
FXT: 3-7.7 GeV  
Focus on  $\sqrt{s_{NN}} \leq 20$  GeV region**

## Detector upgrade

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

## Fixed target program

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





# Backup



# Beam Energy Scan

## Collider mode    Au+Au Collisions    FXT mode

$\sqrt{s}_{NN}$ (GeV)	Events ( $10^6$ )	BES II / BES I	$\mu_B$ (MeV)	$T_{CH}$ (MeV)
200	238	2010	25	166
62.4	46	2010	73	165
54.4	1200	2017	83	165
39	86	2010	112	164
27	30 (560)	2011/2018	156	162
19.6	538 / 15	2019/2011	206	160
14.5	325 / 13	2019/2014	264	156
11.5	230 / 7	2020/2010	315	152
9.2	160 / 0.3	2020/2008	355	140
7.7	100 / 3	2021/2010	420	140
17.3	250	2021	230	158

BES-II data taking has been finished

$\sqrt{s}_{NN}$ (GeV)	Events ( $10^6$ )	BES II / BES I	$\mu_B$ (MeV)	$T_{CH}$ (MeV)
7.7	50+112	2019+2020	420	140
6.2	118	2020	487	130
5.2	103	2020	541	121
4.5	108	2020	589	112
3.9	117	2020	633	102
3.5	116	2020	666	93
3.2	200	2019	699	86
3.0	259	2018	750	80
3.0	2000	2021	750	80

$(\mu_B, T_{CH})$  : J. Cleymans et al., PRC73, 034905 (2006)

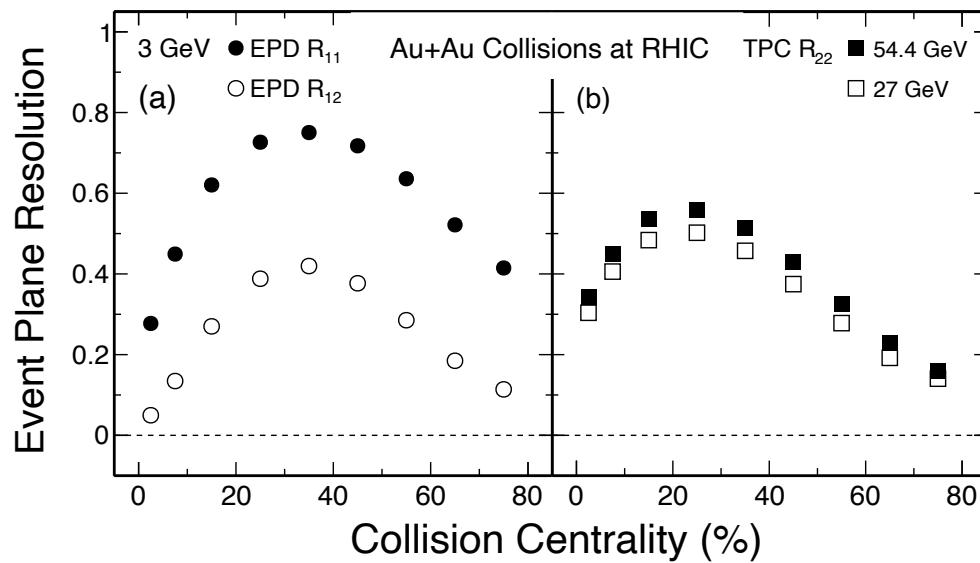
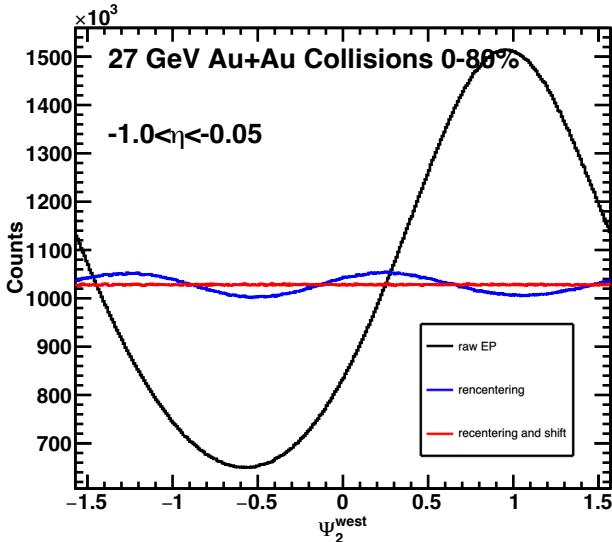
STAR, arXiv:1007.2613

<https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493>

<https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598>

- Higher statistics, better detector performance and more energy points in BES-II
- Explore the QCD phase diagram and constrain the EoS at high baryon density

# Event Plane Reconstruction



A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C 58, 1671 (1998).

- TPC 2<sup>nd</sup> order event plane
  - EP resolution ( $R_{22}$ ) is calculated by two sub-event method
  
- The 1<sup>st</sup> order event plane from east side EPD at 3 GeV
  - The 1<sup>st</sup> order EP resolution ( $R_{11}$ ) is calculated by three sub-event method
  - $R_{12}$  is for  $v_2$  measurement