STAR重离子碰撞实验集体流的研究进展

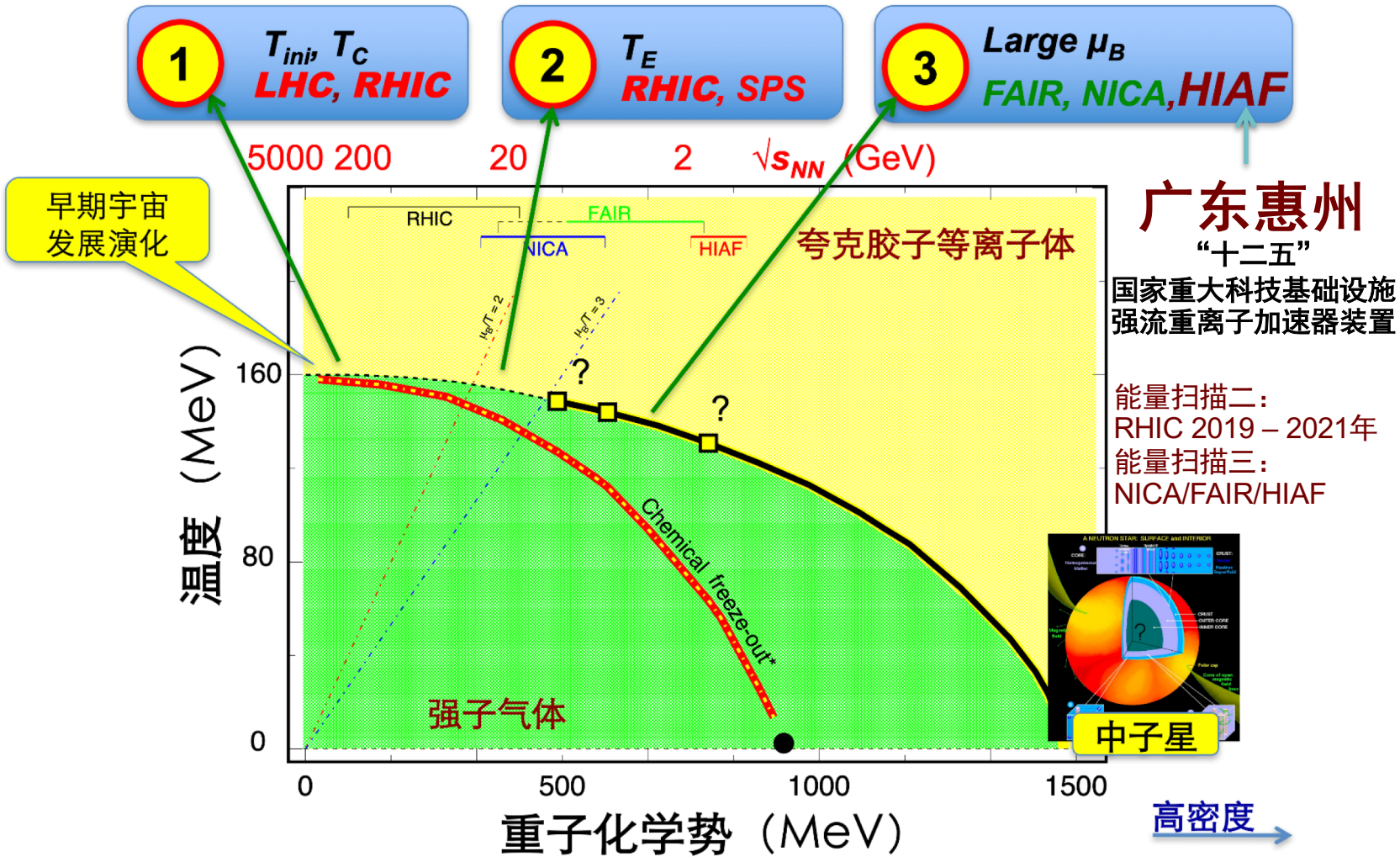
施梳苏

华中师范大学

Outline

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

QCD Phase Diagram



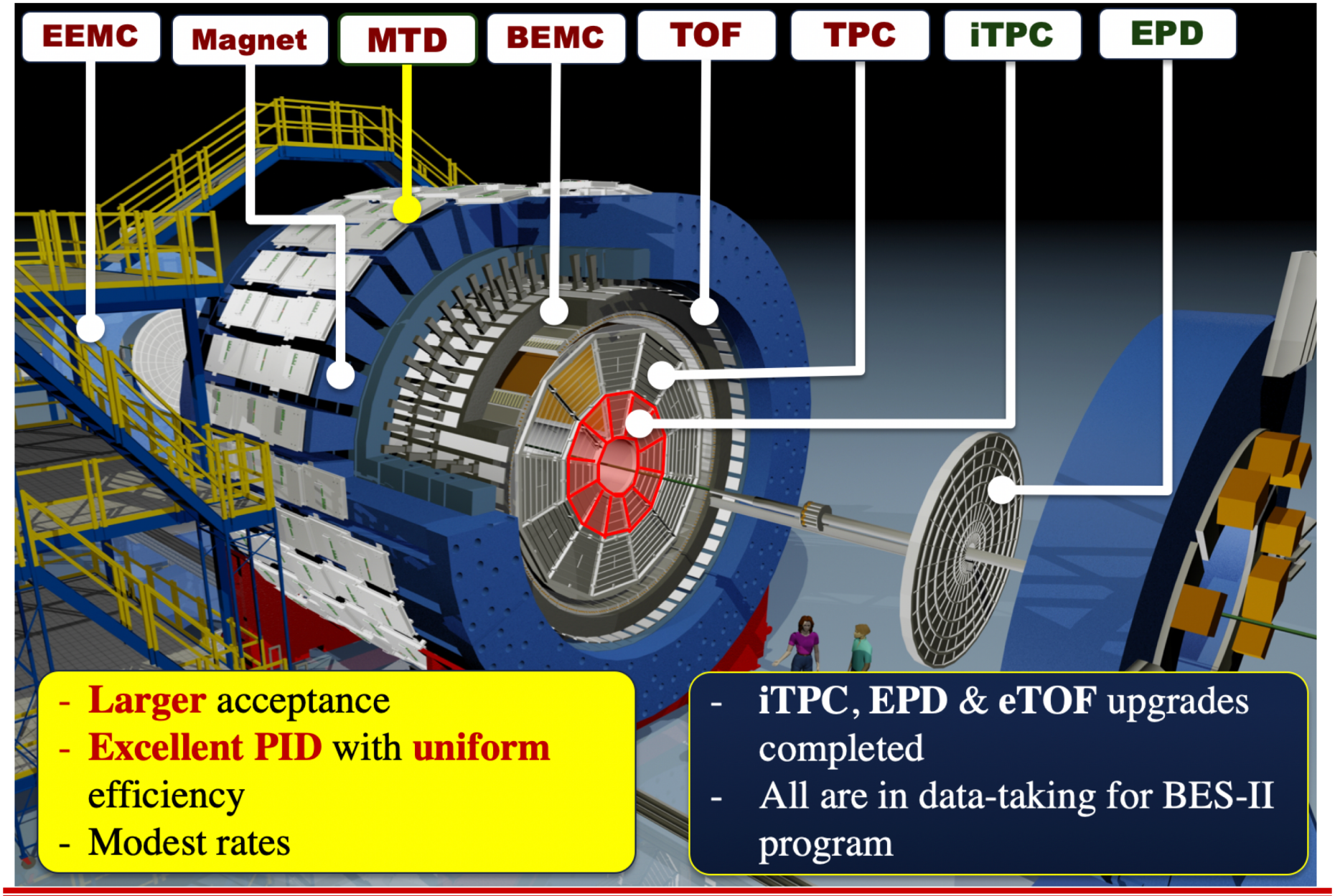
广东惠州
“十二五”
国家重大科技基础设施
强流重离子加速器装置

能量扫描二：
RHIC 2019 – 2021年
能量扫描三：
NICA/FAIR/HIAF

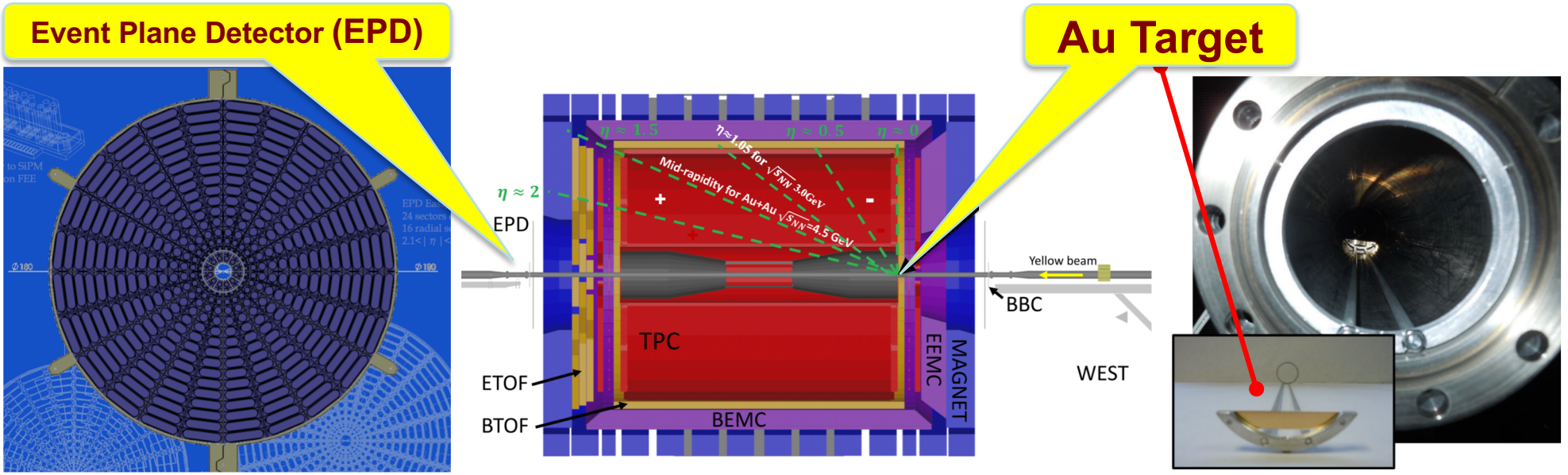
强相互作用相结构的实验研究

- 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



STAR Fixed Target Setup



➢ **Good mid-rapidity coverage for FXT 3 GeV collisions**

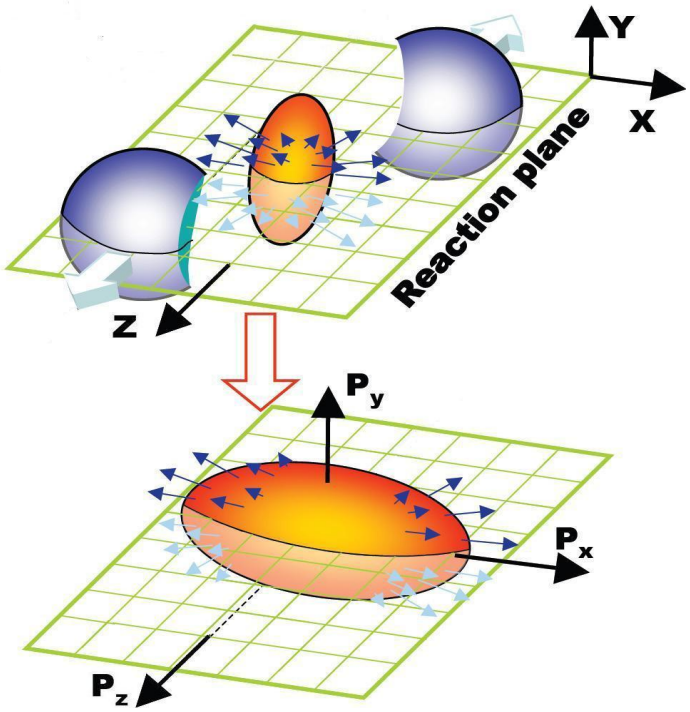
Beam Energy Scan

BES-II data taking has been finished

$\sqrt{s_{NN}}$(GeV)	μ_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

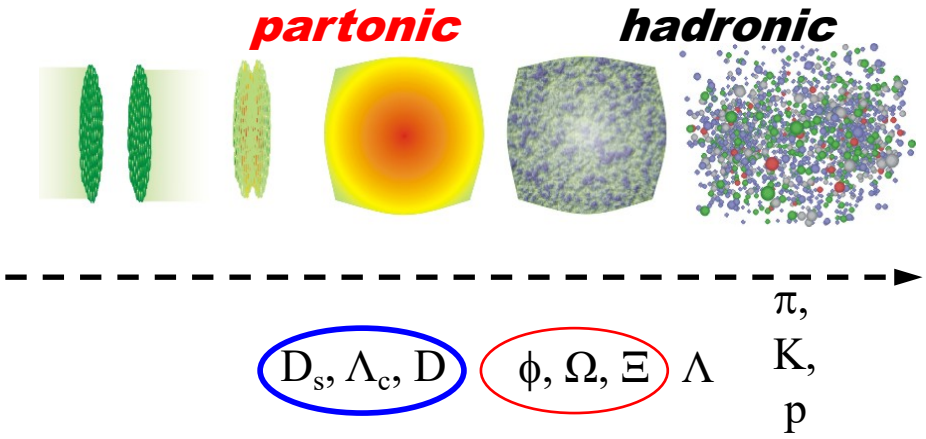
- Higher statistics, better detector performance and more energy points in BES-II
- Explore the QCD phase diagram and constrain the EoS at high baryon density

Anisotropic Flow



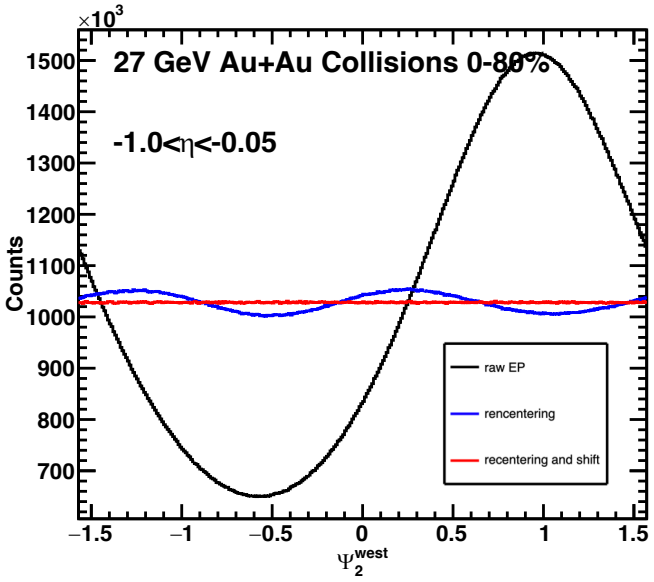
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1} v_n \cos\left[n(\phi - \Psi_n)\right]$$

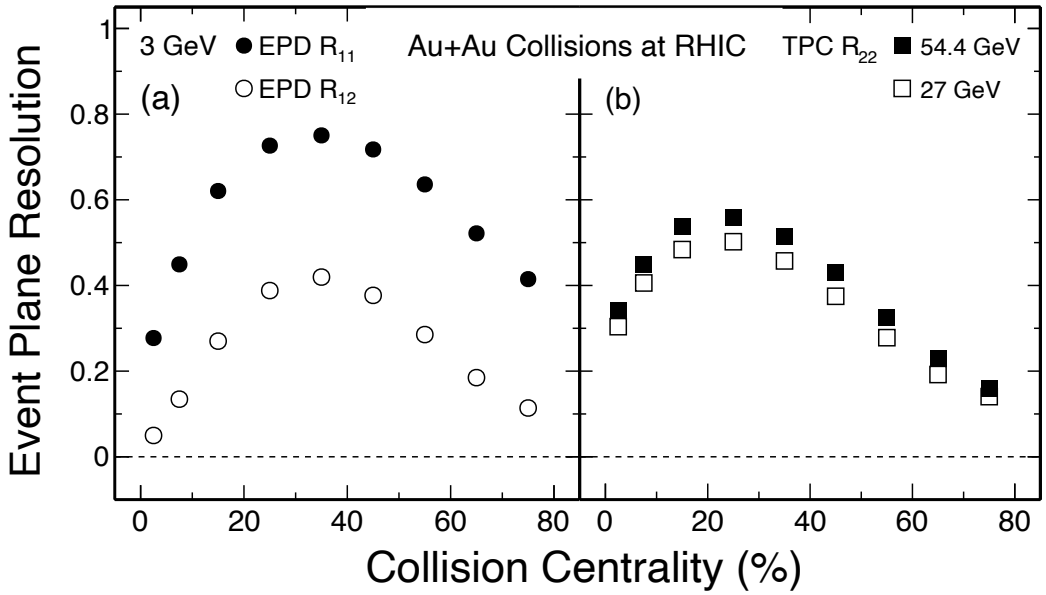
v_1: directed flow; v_2: elliptic flow;
v_3: triangular flow; v_4 .....



- **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 ϕ meson**:
  Less sensitive to late hadronic rescatterings

Event Plane Reconstruction

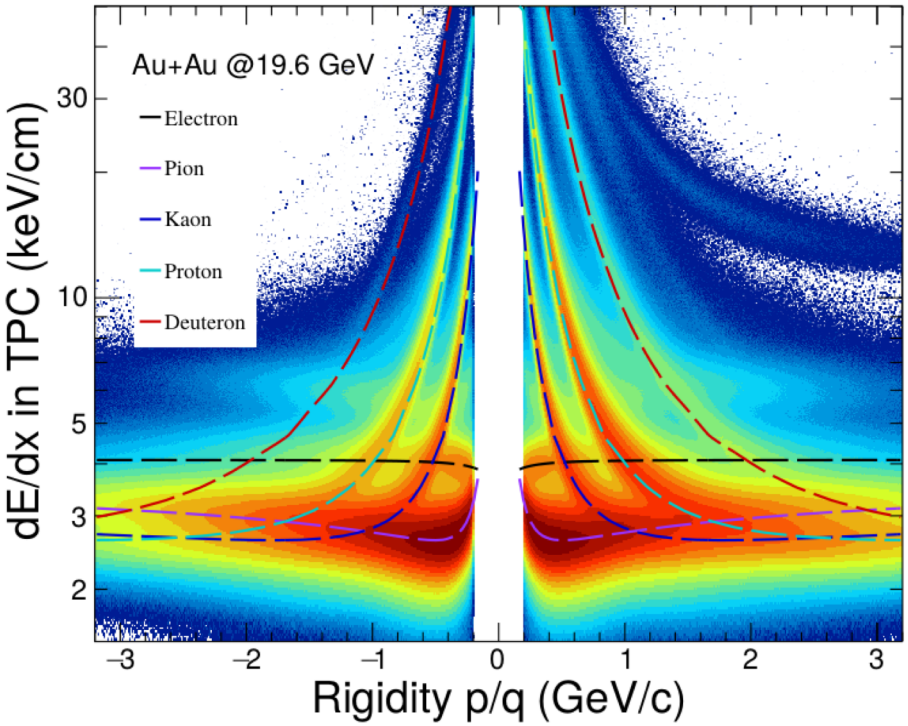


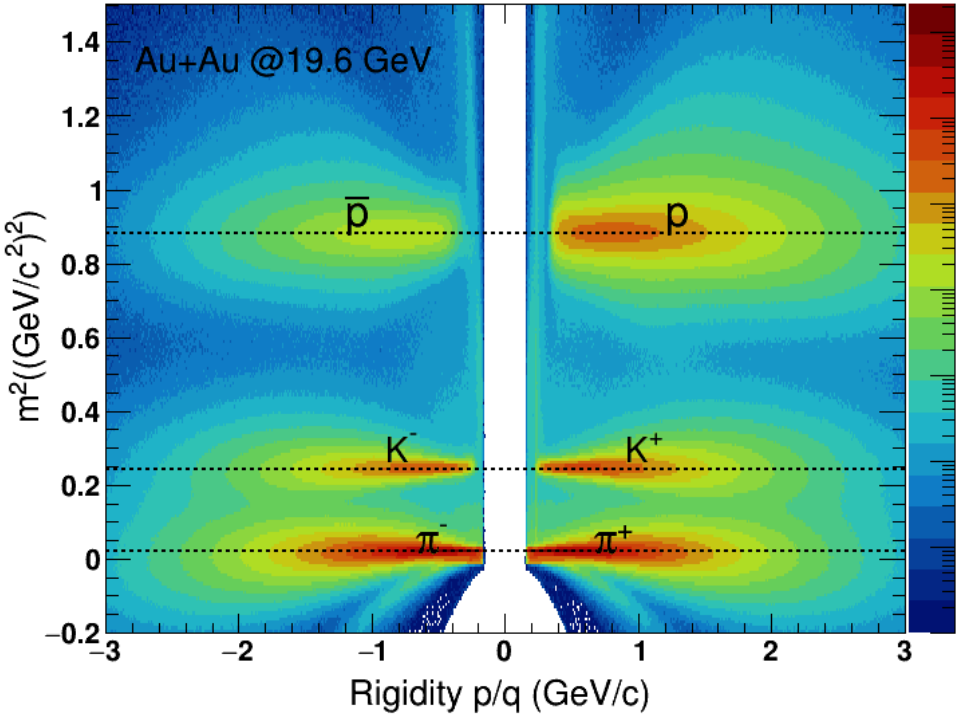


A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C 58, 1671 (1998).

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

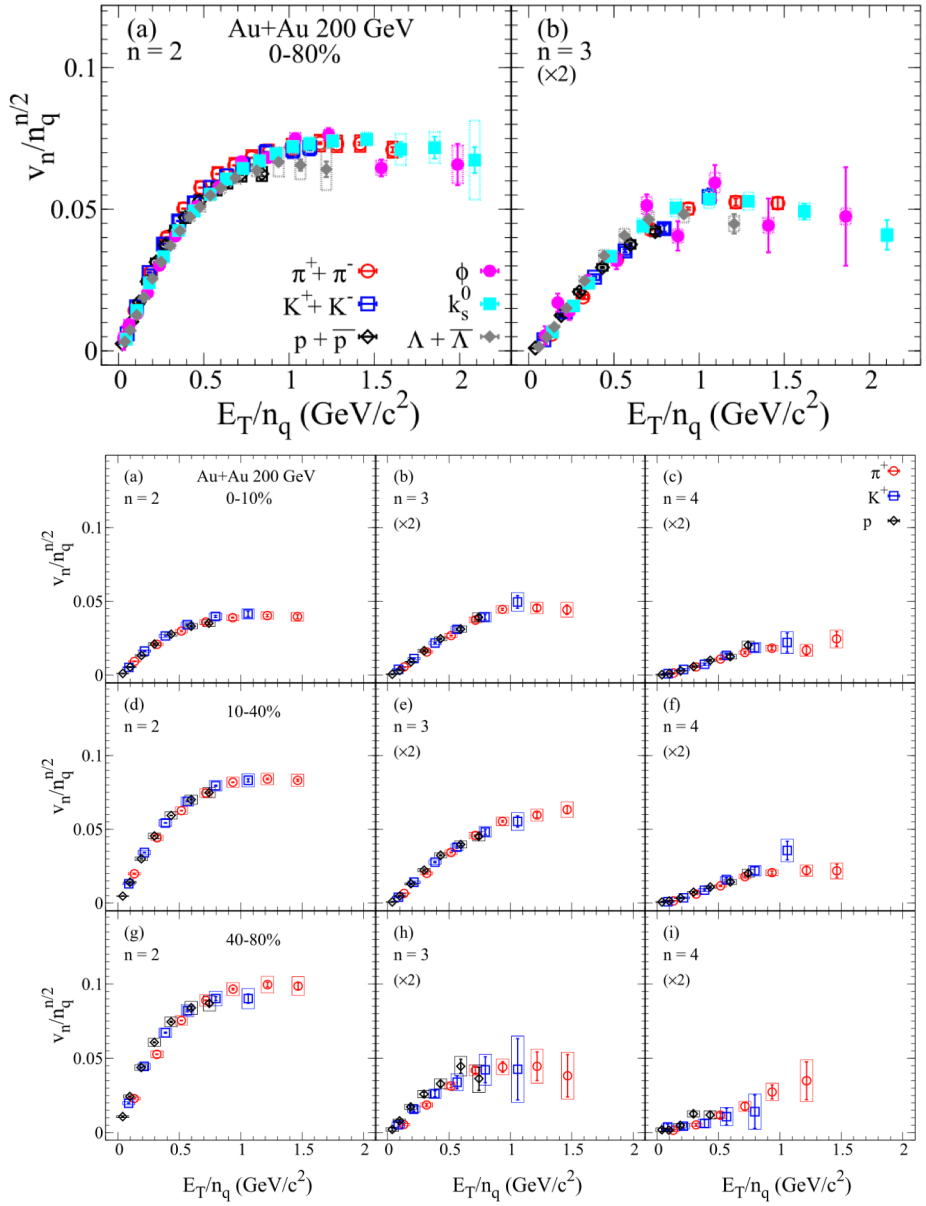
Particle Identification





- Good capability of particle identification based on TPC and TOF

Higher-order Flow in 200 GeV



RHIC top energy

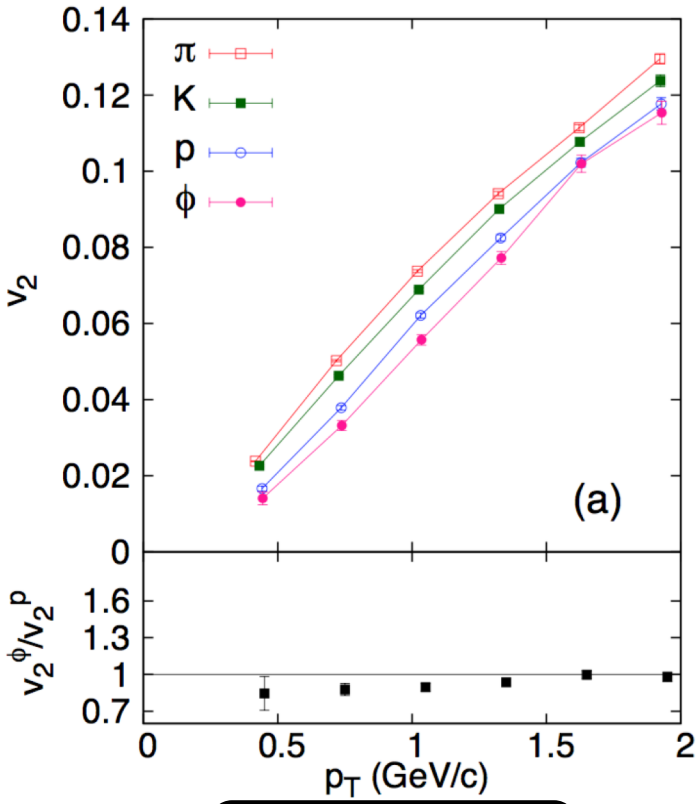
- Light flavor, strange particles and φ mesons
- Follow the NCQ scaling up to v_4

Partonic collectivity

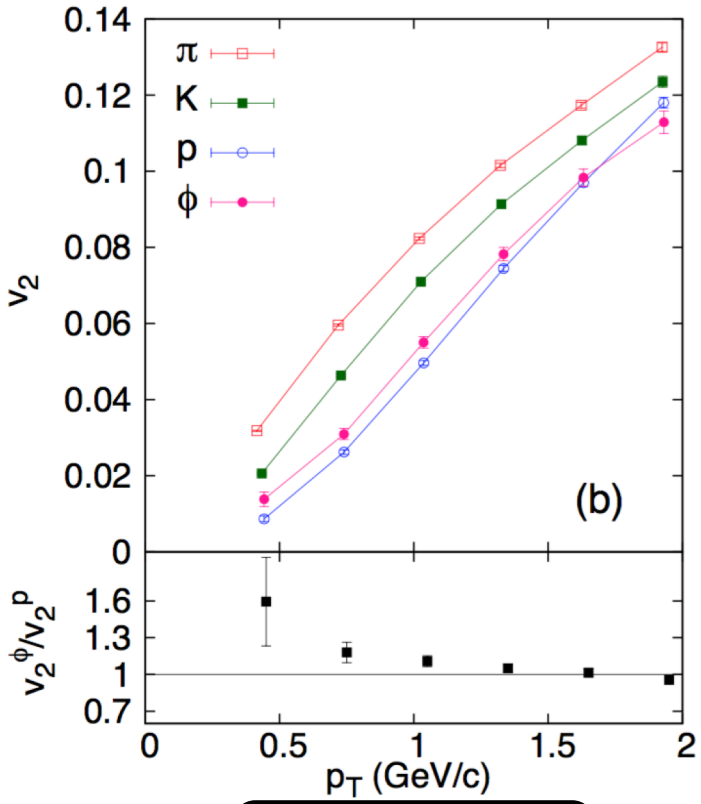
STAR: Phys. Rev. C.105, 064911 (2022)
孙旭，施梳苏等

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

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



Before hadronic re-scattering



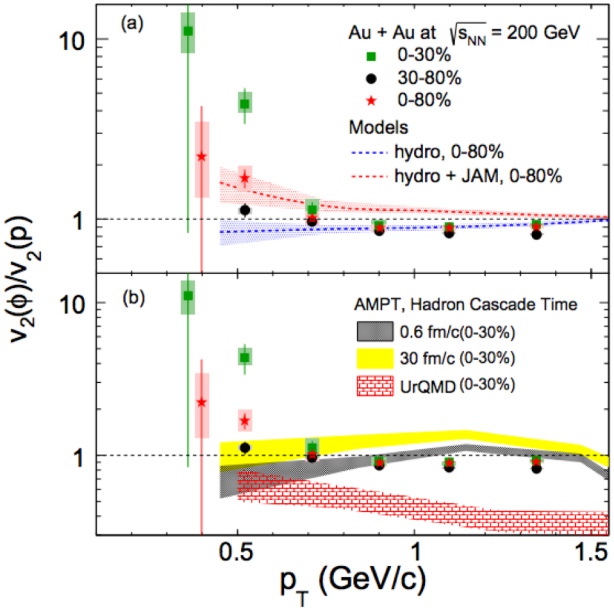
After hadronic re-scattering

- **Ideal hydro + hadron cascade (JAM)**
- **Small hadron cross section + hadronic re-scattering effect on v_2**

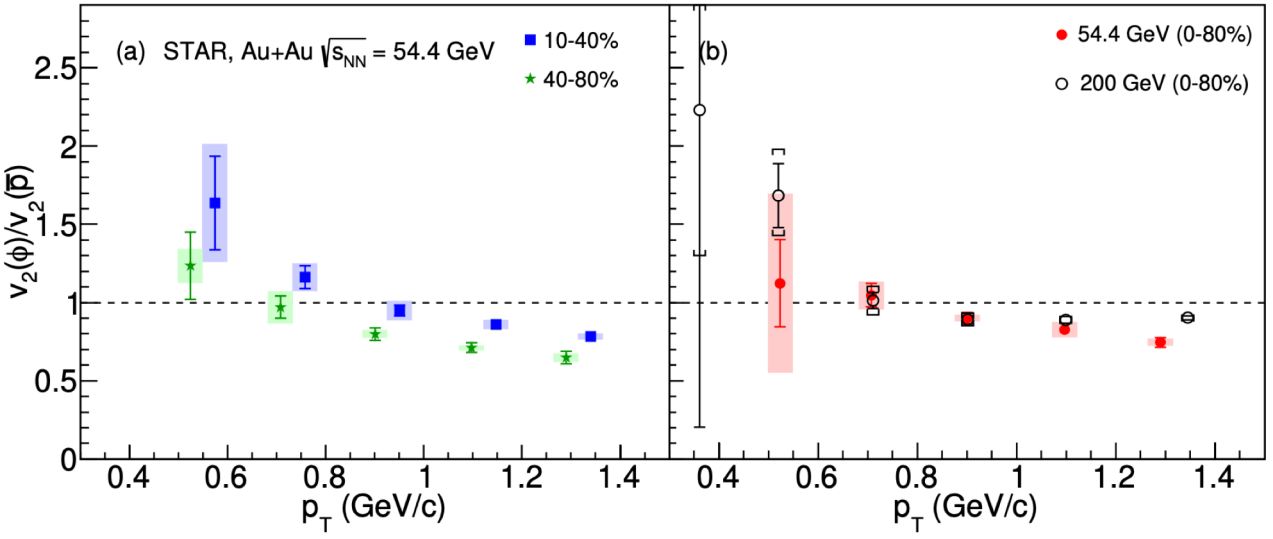
  Mass ϕ > mass p ➔ $v_2(\phi) > v_2(p)$

  ➔ ***Break mass ordering for ϕ mesons and protons***

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



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

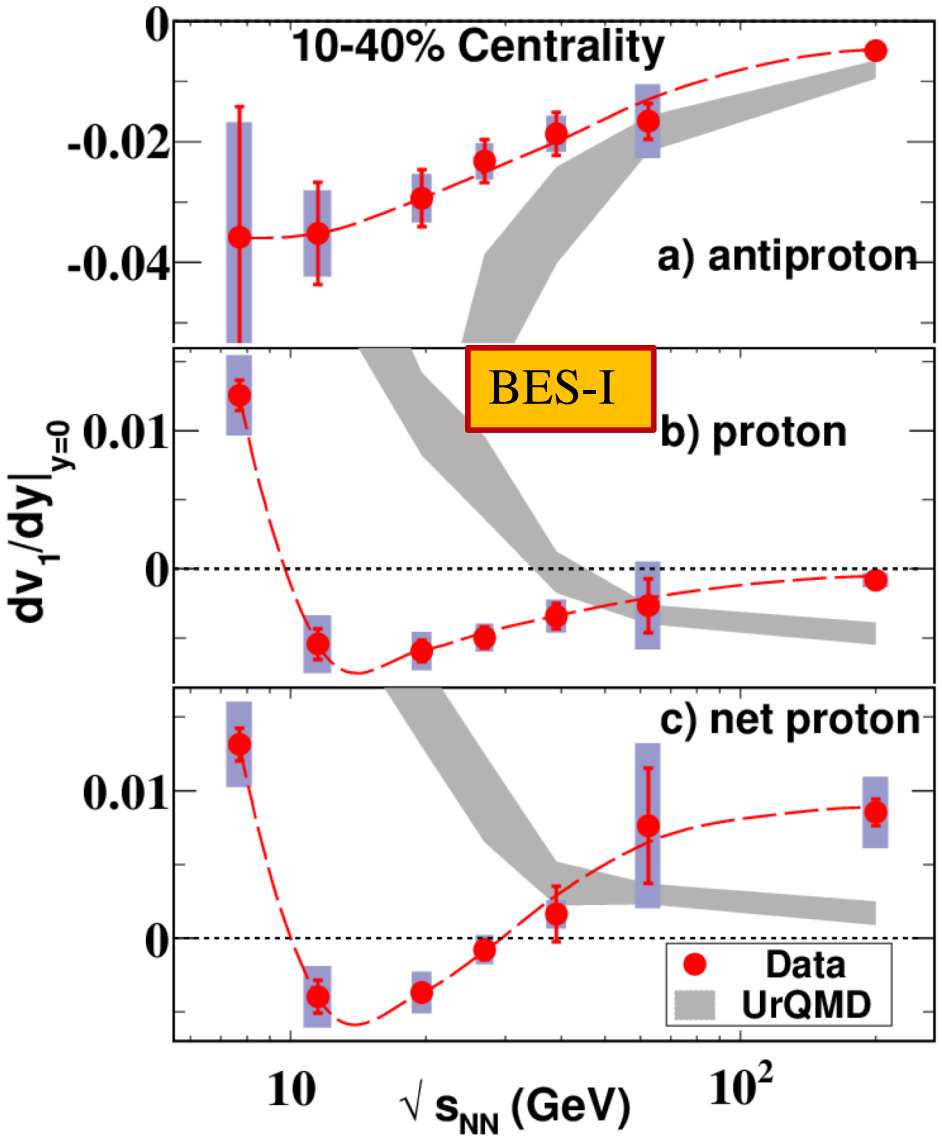


STAR: arXiv: 2205.11073 兰少位，施梳苏等

- 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

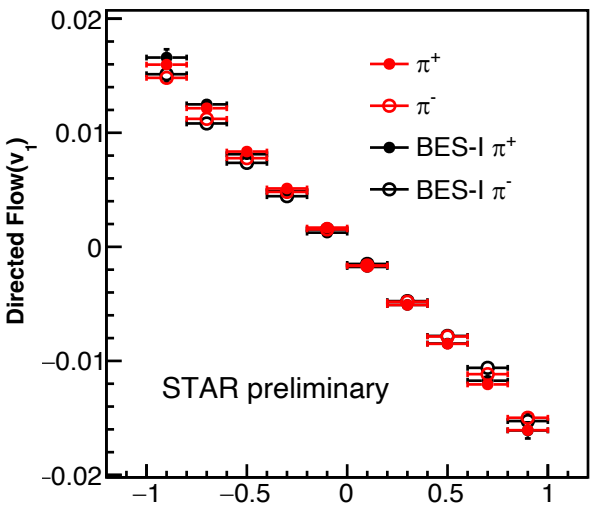
The slope of net-p is based on expressing the y dependence of v1 for all protons as:

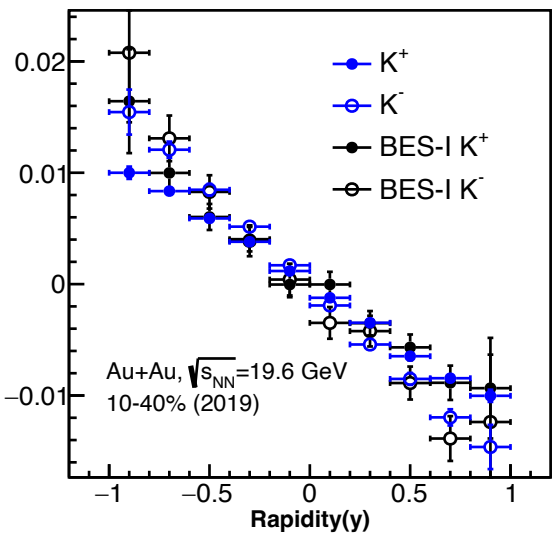
$$[v_1(y)]_p = r(y)[v_1(y)]_{\bar{p}} + [1 - r(y)][v_1(y)]_{\text{net-}p}$$

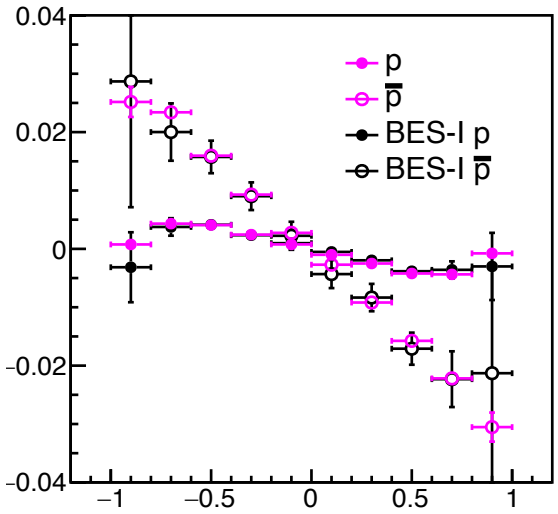
r: the ratio of anti-p to p.

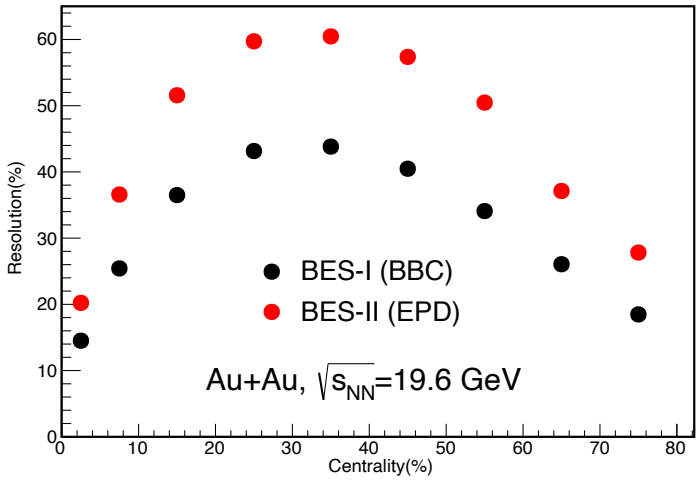
STAR: Phys. Rev. Lett. 112, 162301(2014)
H. Stoecker, Nucl. Phys. A 750, 121(2005)

BESII v_1: 19.6 GeV





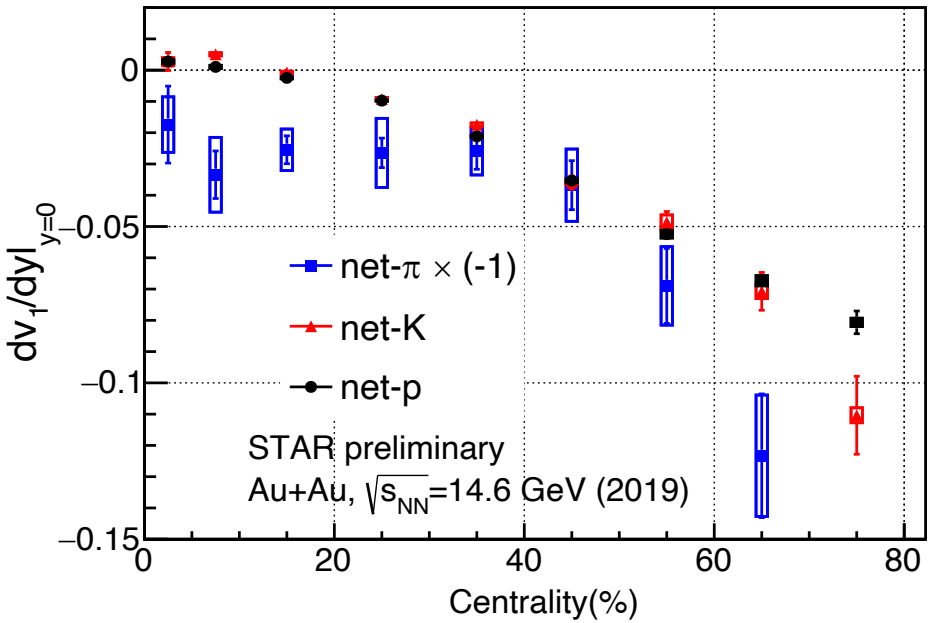


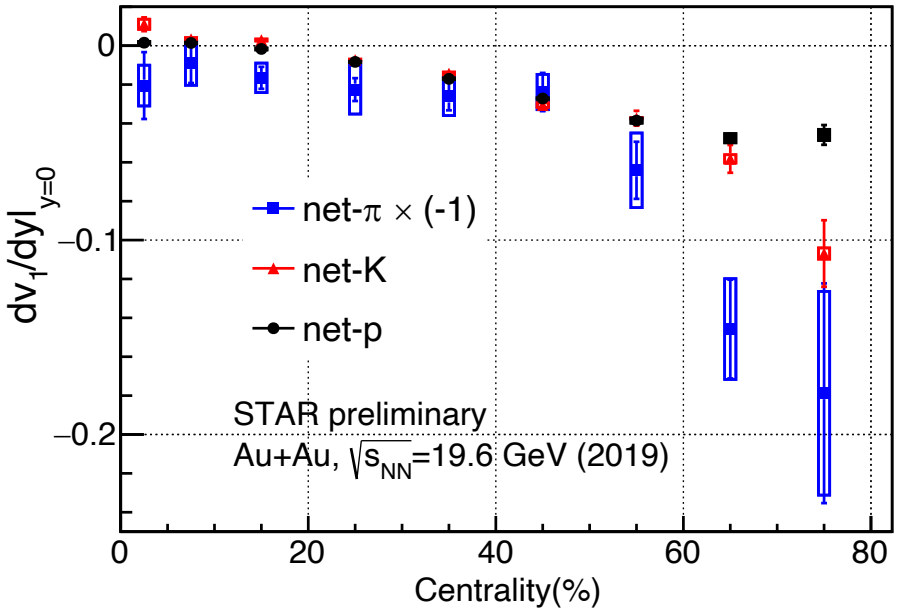


STAR 刘佐文: SQM2022, ISMD2022

- 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

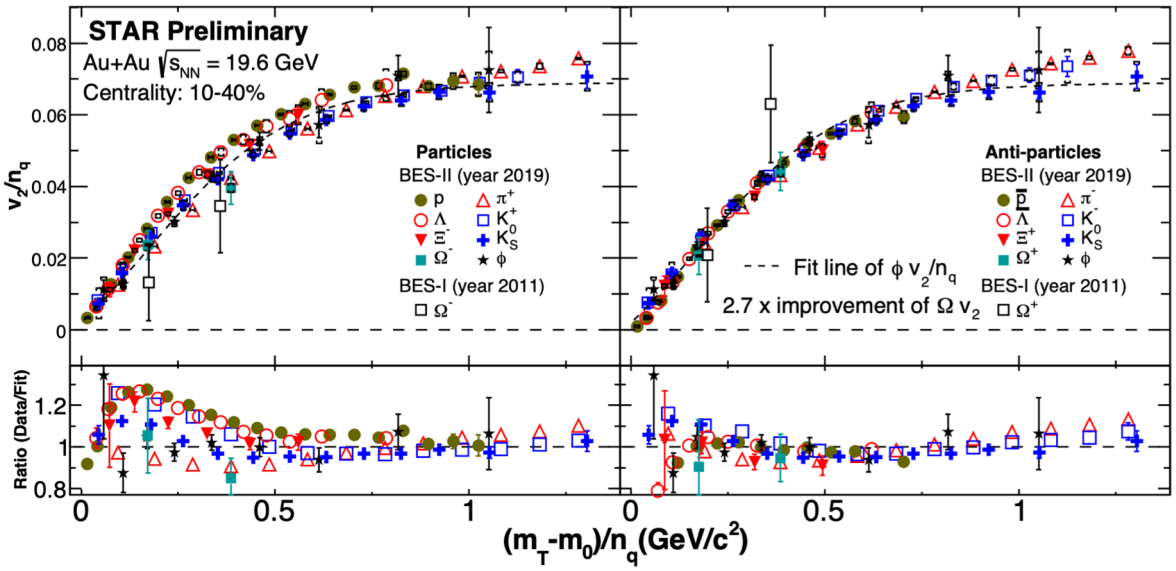




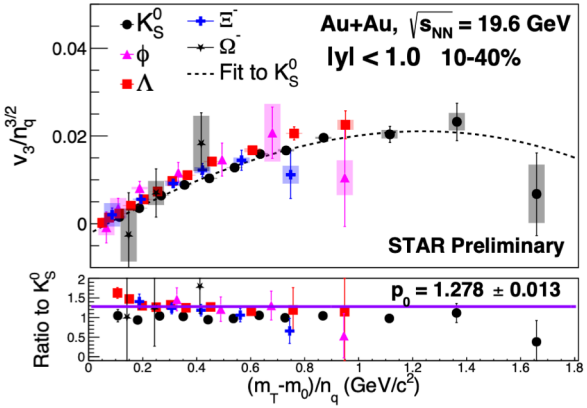
- v_1 slope of net-particle is larger in more peripheral collisions
  More transported quarks in the peripheral collisions
- v_1 slope of net-proton and net-kaon are similar in central and mid-central collisions
- 14.6 GeV: wait for final official centrality definition

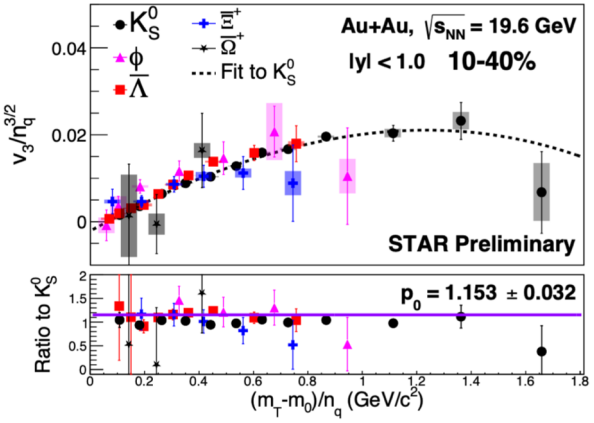
Net-pion dv1/dy is positive at all centralities. To facilitate plotting in the figure opposite, net-pion dv1/dy is shown with reversed sign.

BESII v_2: 19.6 GeV



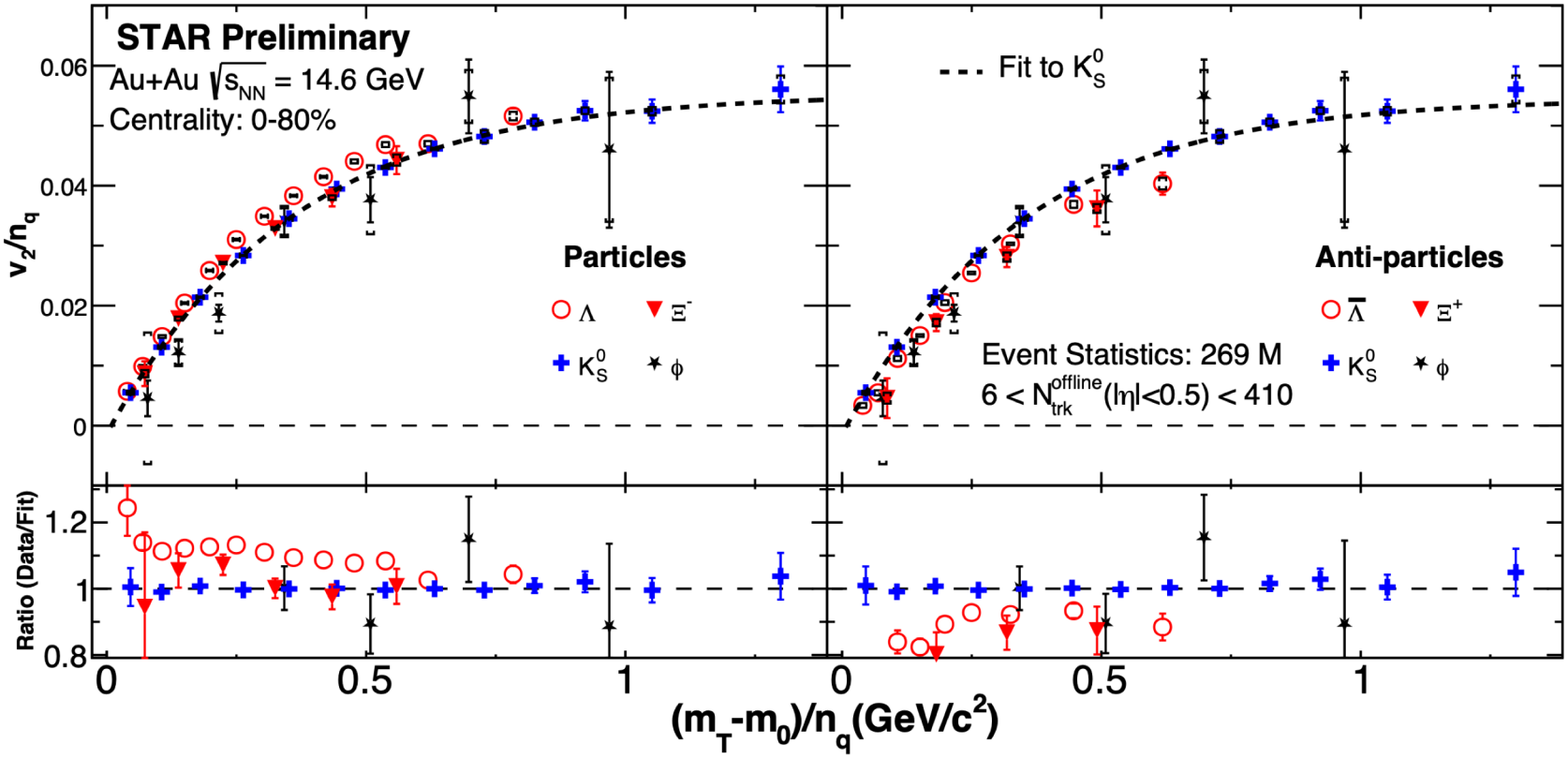
STAR 刘利珂: SQM2022





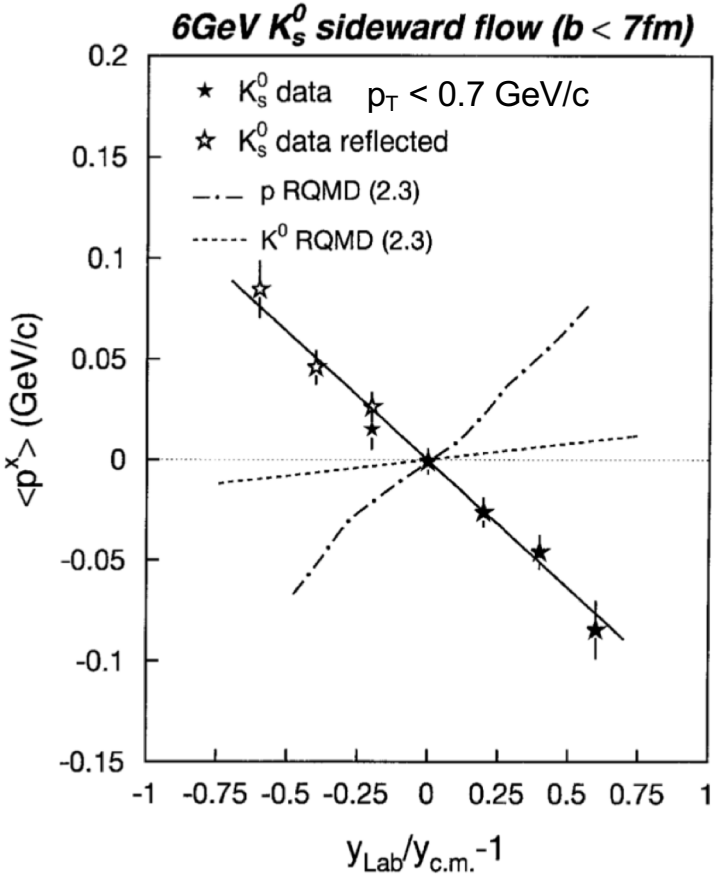
- The NCQ scaling holds within 20% for particles and within 10% for anti-particles
- The NCQ scaling of anti-particles better than particles: produced vs. transported quarks

BESII v_2: 14.6 GeV

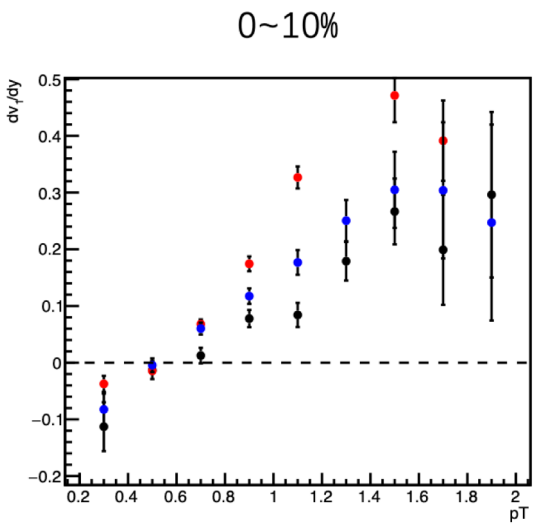


- The NCQ scaling holds within at 20% level

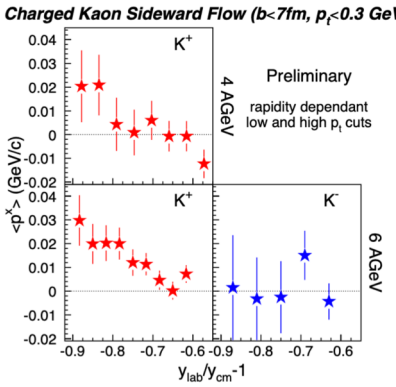
FXT 3-3.9 GeV: Kaon Anti-flow?

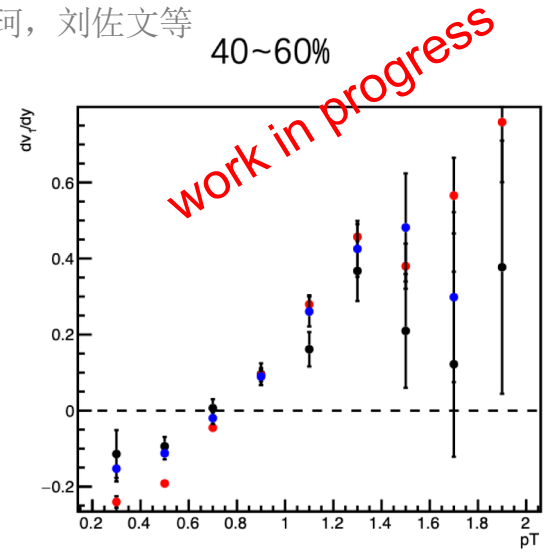


P. Chung et al [E895], Phys. Rev. Lett.85.940 (2000)
C. Pinkenburg et al [E895], Nucl. Phys. A 698 (2002)



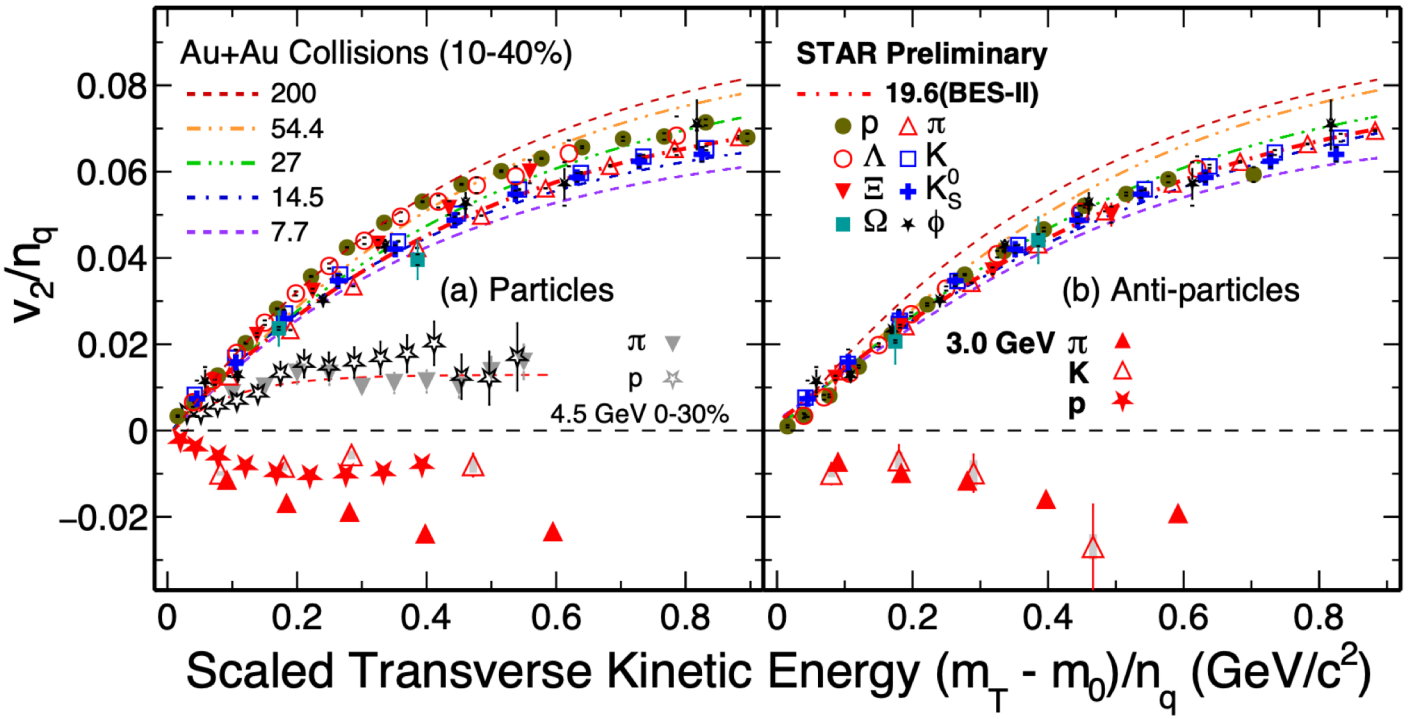
STAR 刘利珂，刘佐文等





Anti-flow of K_S^0 and $K^{\pm}$ at 6A ($\sqrt{s_{NN}}$ = 3.61) GeV ?

NCQ Scaling at 3 GeV

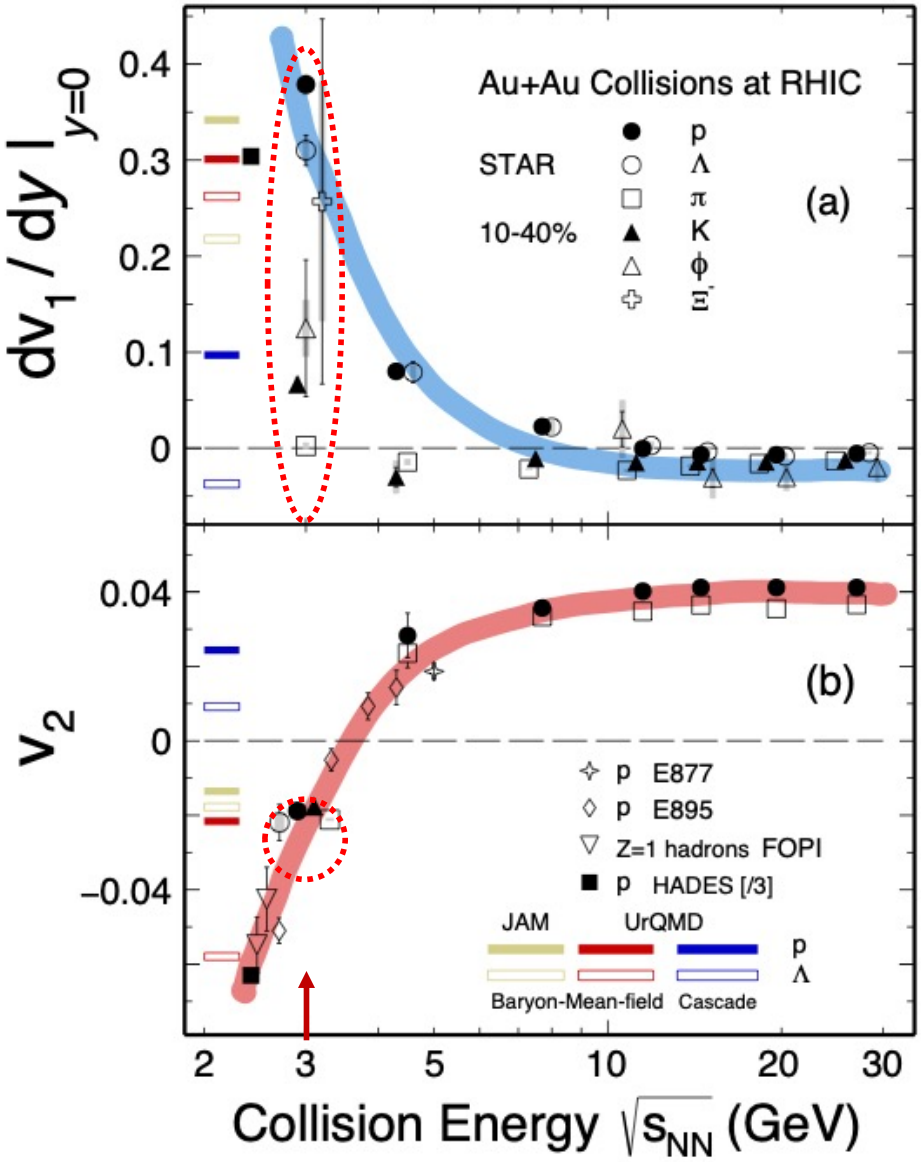


STAR: Phys. Lett. B 827 (2022) 137003 兰少位，施梳苏等

- 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 ϕ 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

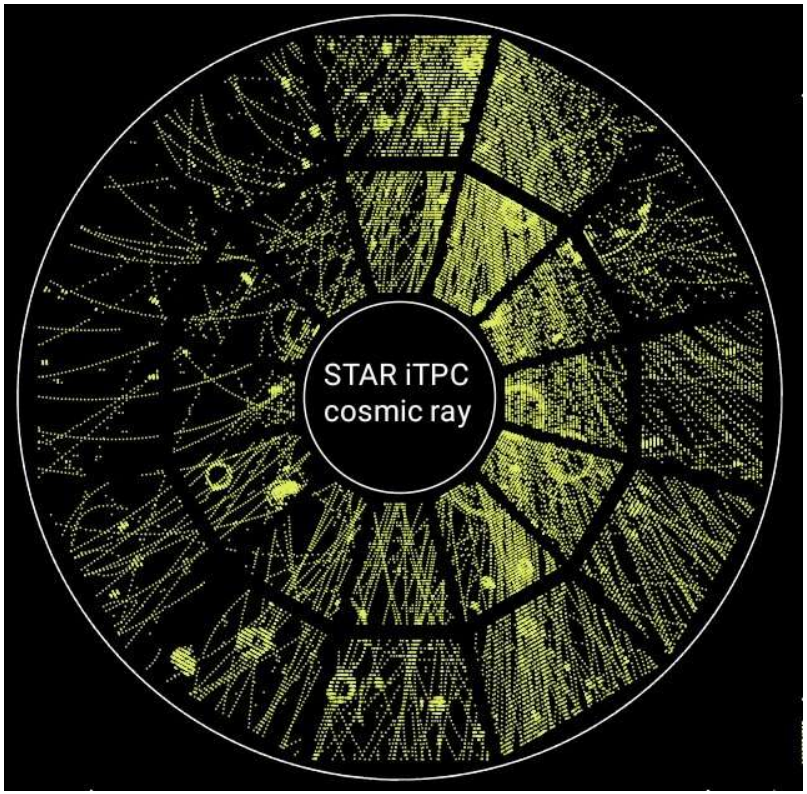
19.6, 17.1, 14.5, 11.5, 9.2 and 7.7 GeV
FXT: 3-7.7 GeV
Focus on $\sqrt{s_{NN}} \leq 20$ GeV region

Detector upgrade

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

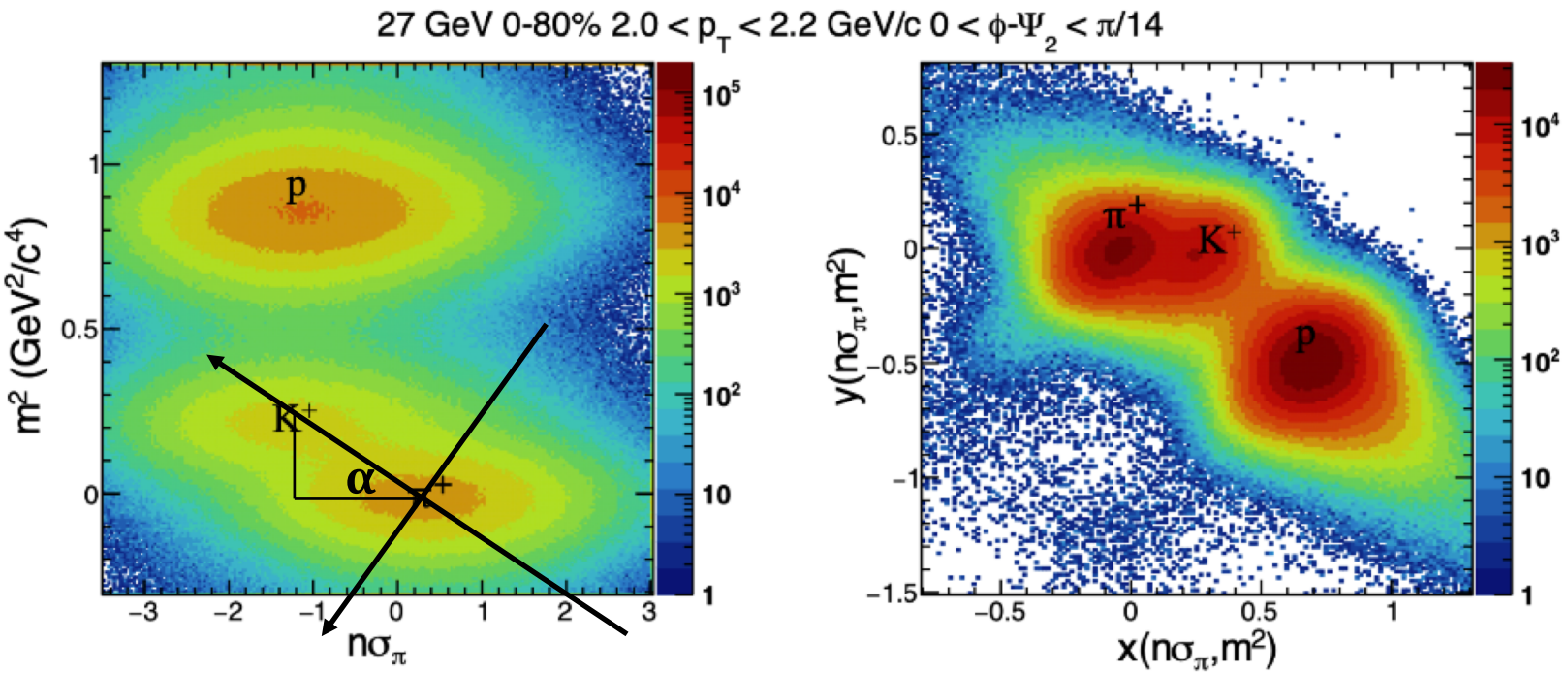
Fixed target program

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



Backup

π, K Particle Identification



- Transformation consists of a shift and rotation
- Aim to have a maximal separation between pions and kaons

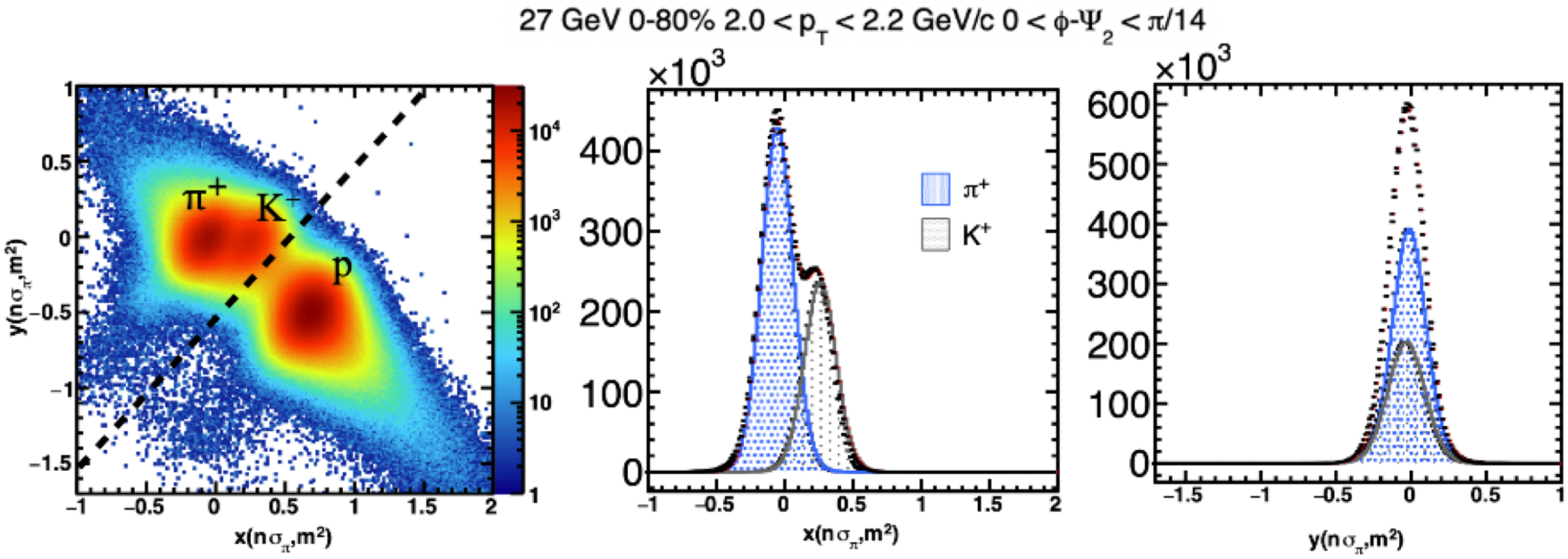
Shift:

$$f_{scale} = \sigma(n\sigma_\pi)/\sigma(m^2(\pi))$$
$$x' = (n\sigma_\pi - \mu(n\sigma_\pi))/f_{scale}$$
$$y' = m^2 - \mu(m^2(\pi))$$

Rotation:

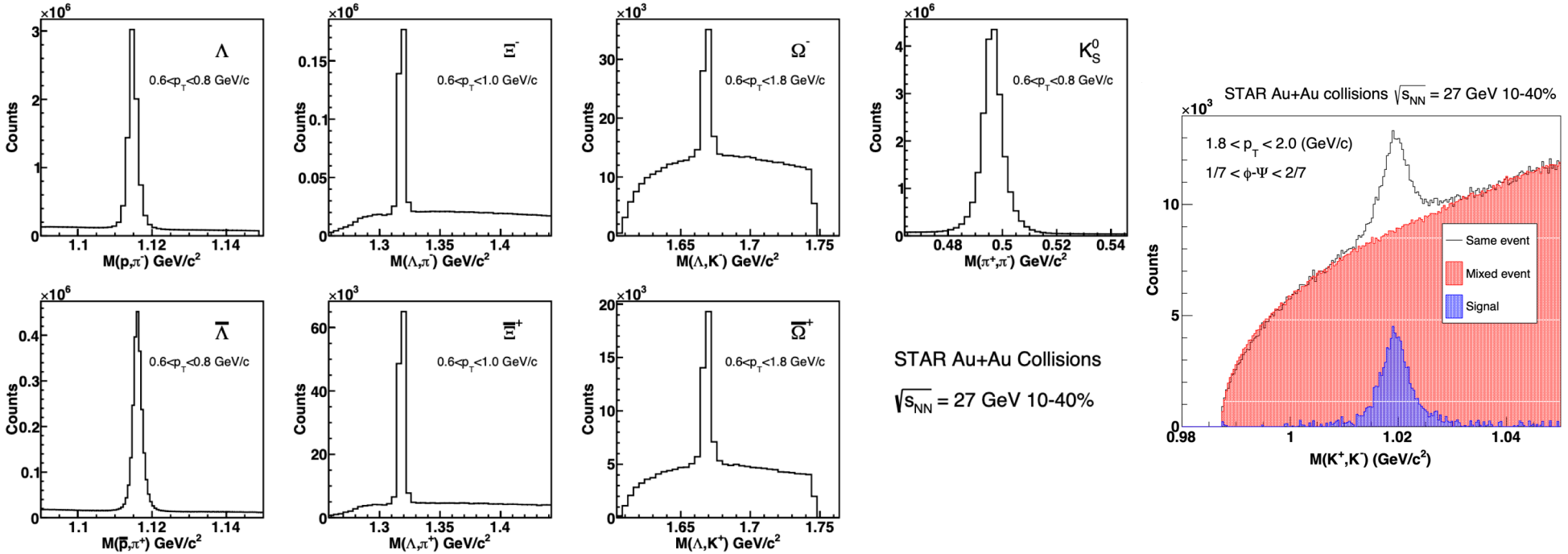
$$\alpha = tan^{-1}\left[\frac{\mu(m^2(K)) - \mu(m^2(\pi))}{\mu(n\sigma_K) - \mu(n\sigma_\pi)}\right]$$
$$\begin{pmatrix} x(n\sigma_\pi, m^2) \\ y(n\sigma_\pi, m^2) \end{pmatrix} = \begin{pmatrix} cos(\alpha) & -sin(\alpha) \\ sin(\alpha) & cos(\alpha) \end{pmatrix} \begin{pmatrix} x' \\ y' \end{pmatrix}$$

π, K Particle Identification



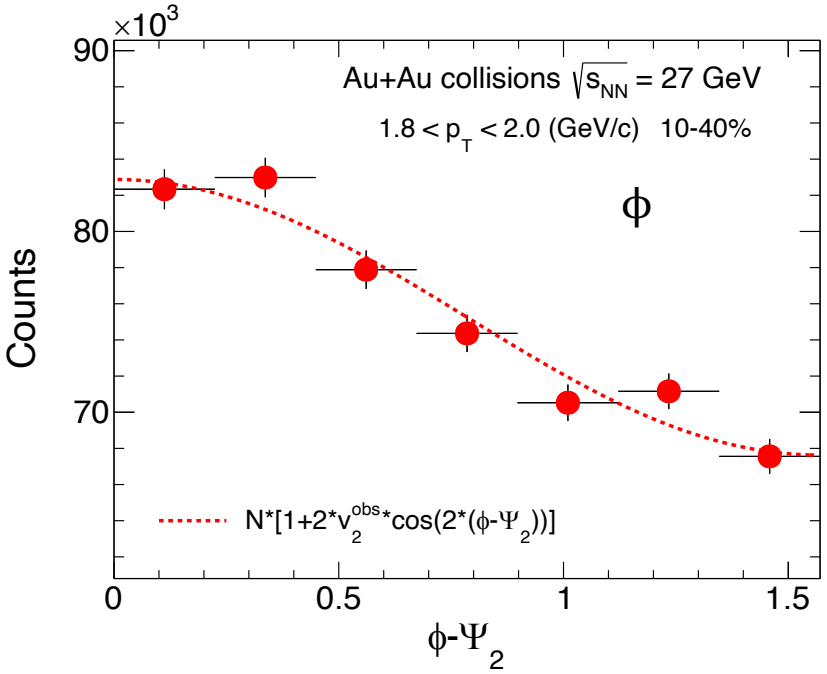
- Using 2D student-t function to describe the combined m^2 and $n\sigma_\pi$ distribution
- Subtract proton yields to reduce the degree of freedom of fitting function
- Multi-fit to get the best signal of pions and kaons
- Have a maximal separation between pions and kaons

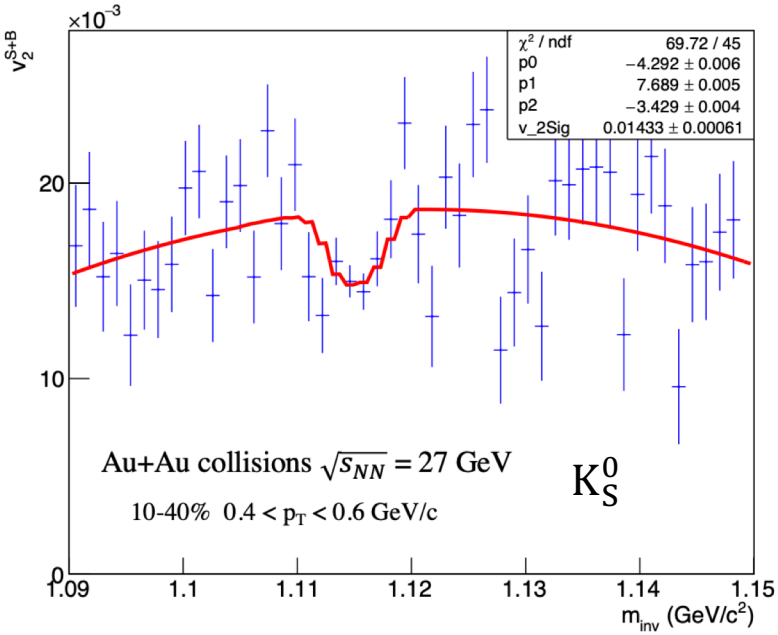
Short Lived Particle PID



- The weak decay particles ($K^0_S, \Lambda, \Xi, \Omega$) are through their hadronic decay channel
  - The additional optimized decay topology cuts can effectively suppress the background
- ϕ-mesons are reconstructed in K^+K^- channel with primary tracks
  - Background is obtained by using mixed event

Method for v_2 Calculation





- π, K, p, ϕ v_2 calculation:
  - Event plane method: Fit ϕ-Ψ_2 distribution with:

$$\frac{1}{R}\frac{dN}{d(\phi-\Psi_2)} \propto 1 + 2v_2\cos[2(\phi-\Psi_2)]$$

- $K^0_S, \Lambda, \Xi, \Omega$ v_2 calculation:
  - Invariant mass method: Fit v_2^{Sig+Bg} vs. m_{inv} with:

$$v_2^{\mathrm{Sig+Bg}}(m_{\mathrm{inv}}) = v_2^{\mathrm{Sig}}(m_{\mathrm{inv}})\frac{\mathrm{Sig}}{\mathrm{Sig}+\mathrm{Bg}}(m_{\mathrm{inv}}) + v_2^{\mathrm{Bg}}(m_{\mathrm{inv}})\frac{\mathrm{Bg}}{\mathrm{Sig}+\mathrm{Bg}}(m_{\mathrm{inv}})$$

Beam Energy Scan

Collider mode Au+Au Collisions **FXT mode**

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II / BES I	μ_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	μ_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

(μ_B, T_{CH}) : J. Cleymans et al., PR**C73**, 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