Anisotropic Flow Measurements of Identified Particles in the STAR Experiment

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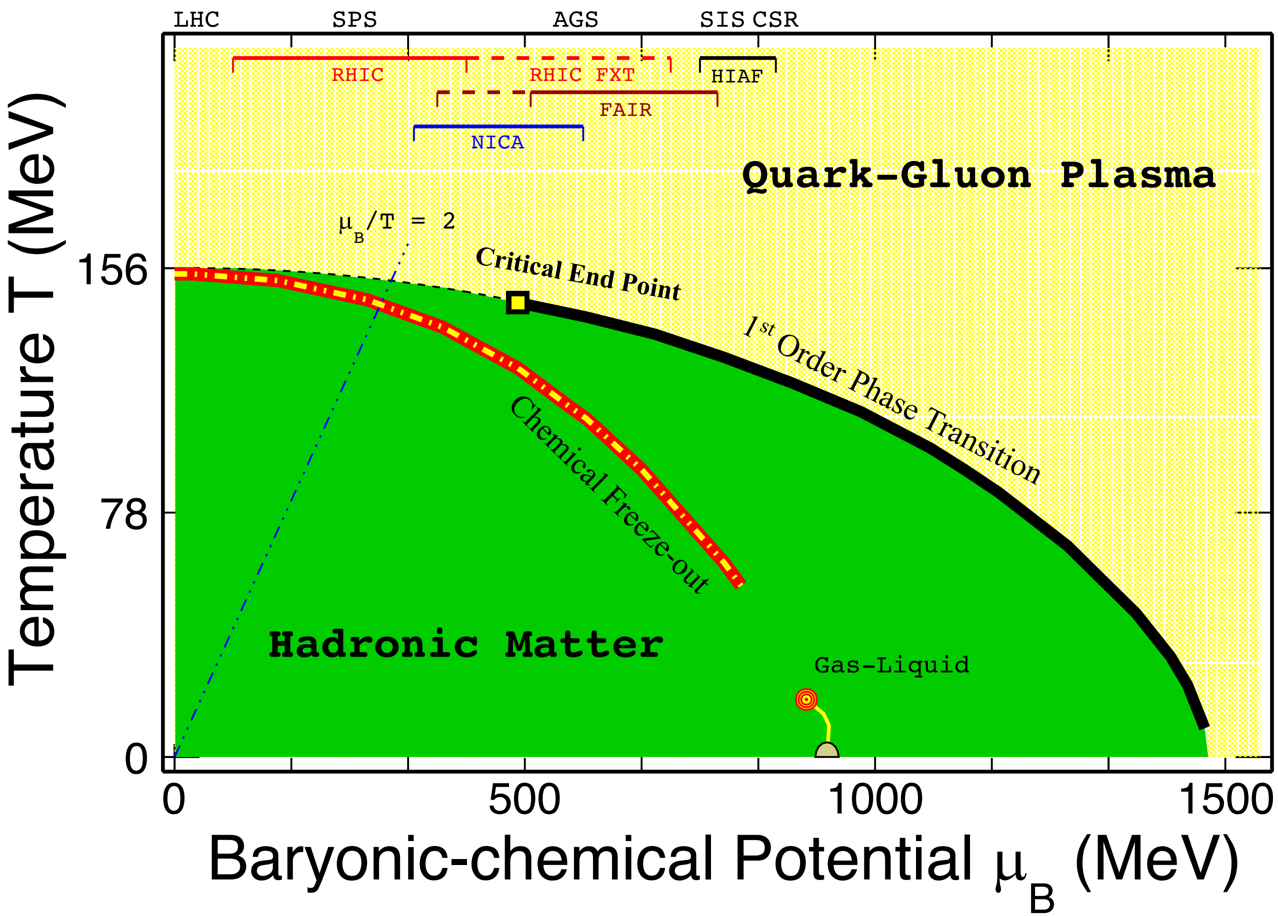
Outline

- Motivation
- Results
  - v_2/v_3 measurements at 200, 54.4, 39 and 27 GeV
  - v_1/v_2 measurements at 3 GeV
- Summary

Motivation

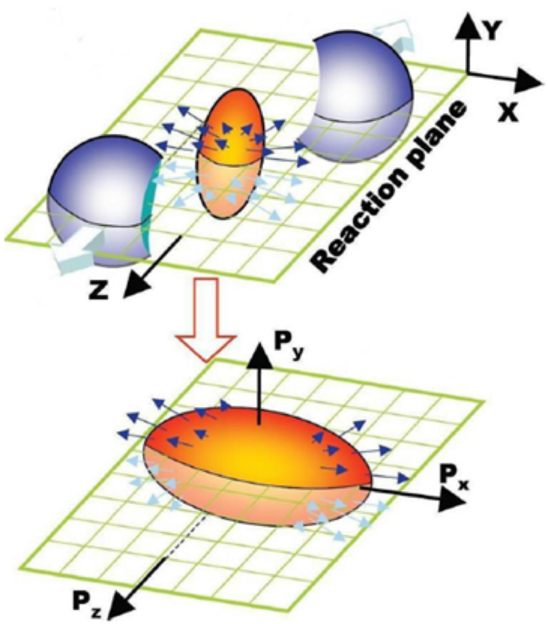


Conjectured phase diagram of strong interactions

- **Study the properties of QCD medium**
- **Search for Critical End Point**
- **Locate the first-order phase boundary**

- **The collective behavior would be different between QGP phase and hadron phase**
  - **They are dominated by different interactions**

Motivation



$$\frac{dN}{d\phi} \sim 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi))$$

Directed flow: $v_1 = \langle \cos(\phi - \Psi) \rangle$

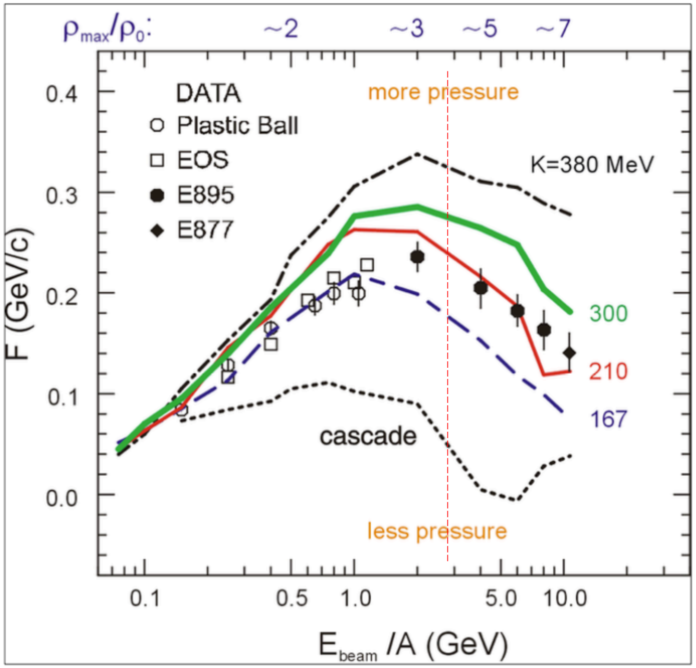
Elliptic flow: $v_2 = \langle \cos(2(\phi - \Psi)) \rangle$

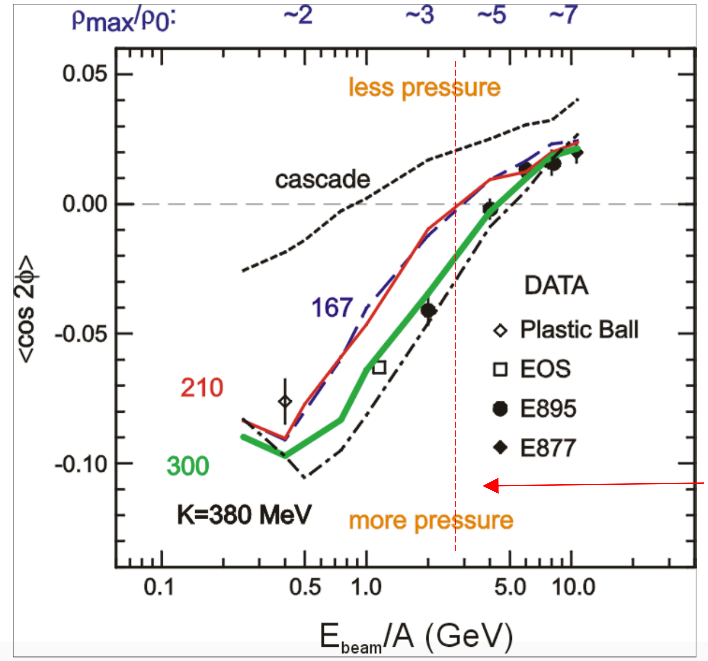
Triangular flow: $v_3 = \langle \cos(3(\phi - \Psi)) \rangle$

- Azimuthal anisotropy parameters (v_1, v_2, v_3) are sensitive to the early stage of the system evolution and Equation-of-State (EoS) of medium
- Elliptic flow (v_2)
  - Positive v_2, preference of in-plane emission
  - Negative v_2, preference of out-of-plane emission ($\sqrt{s_{NN}} \sim< 4$ GeV)

S. A. Voloshin, Phys. Rev. C 58, 1671–1678 (1998)

Motivation: v_1/v_2 Measurements at Low Energy





- Proton $\langle p_x \rangle$ slope (F) ($\langle p_x \rangle$ is similar to v_1) and v_2 results from E895 and E877 ($\sqrt{s_{NN}} \sim$ 2.7 GeV - 5 GeV) show:
  - **Positive slope of $\langle p_x \rangle$ at mid-rapidity**
  - **In-plane v_2 to out-of-plane v_2**

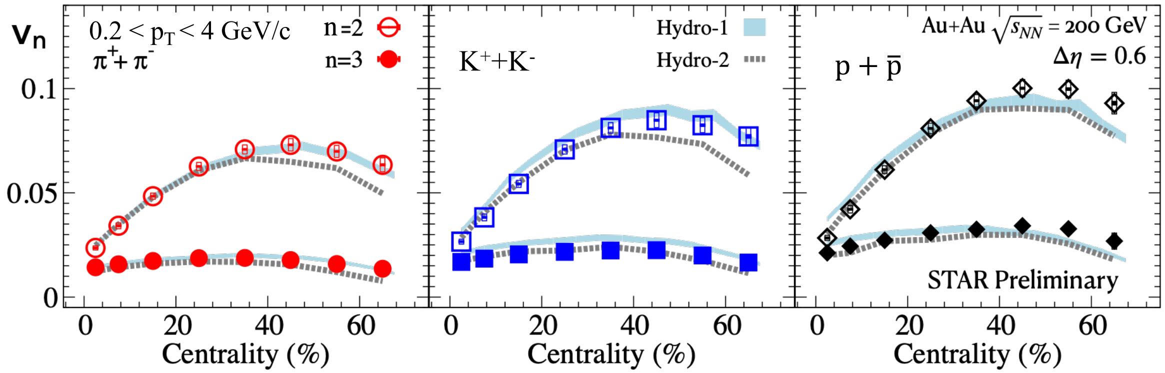
Nuclear incompressibility: $K = 9(\frac{\partial P}{\partial \rho})|_{\rho=\rho_0}$

- v_1 and v_2 are very sensitive to the stiffness of nuclear EoS in the high baryon density region
- K is directly connected to mean-field potential in UrQMD model

P. Danielewicz, R. Lacey, Science **298** (2002) 1592-1596, E877: Phys. Rev. C **56** (1997) 3254-3264, E895: Phys. Rev. Lett. **83** (1999) 1295-1298
E895: Phys. Rev. Lett. **84** (2000) 5488-5492, J. J. Molitoris, Phys. Rev. C **32** (1985) 346, Phys. Rev. Lett. **54** (1985) 289

Results-I

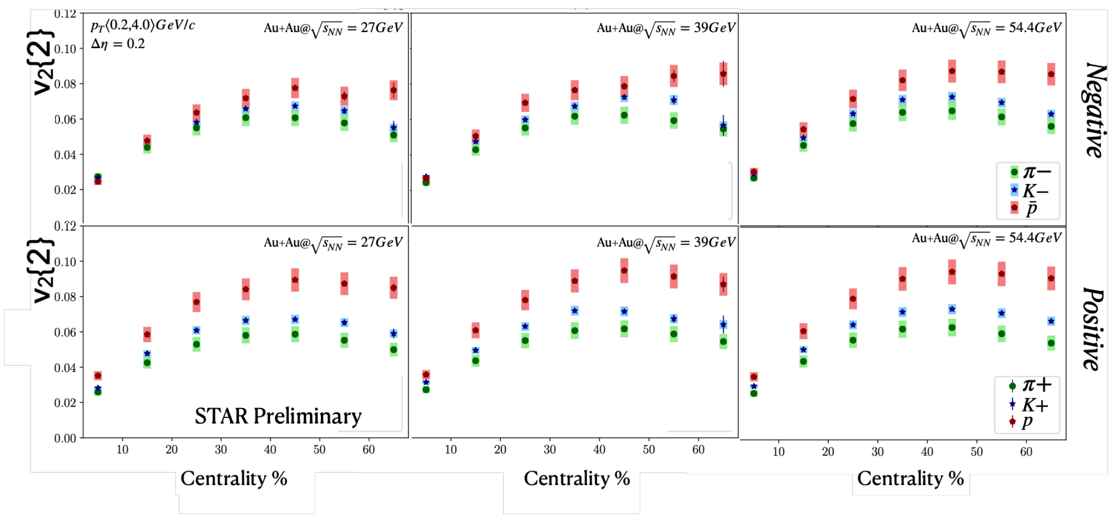
v_2/v_3 Measurements in High Energy Collisions at STAR



	Hydro−1	Hydro−2
η/s	0.05	0.12
Initial conditions	TRENTO	IP-Glasma
Contributions	Hydro + Direct decays	Hydro + Hadronic cascade

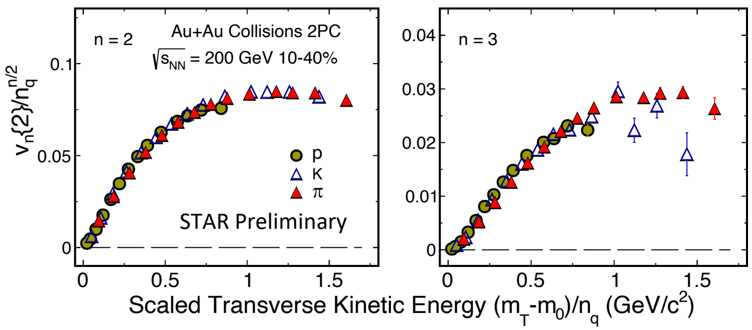
1), P. Alba, et al. PRC **98** (2018) 034909
2), B.Schenke, et al. PRC **99** (2019) 044908

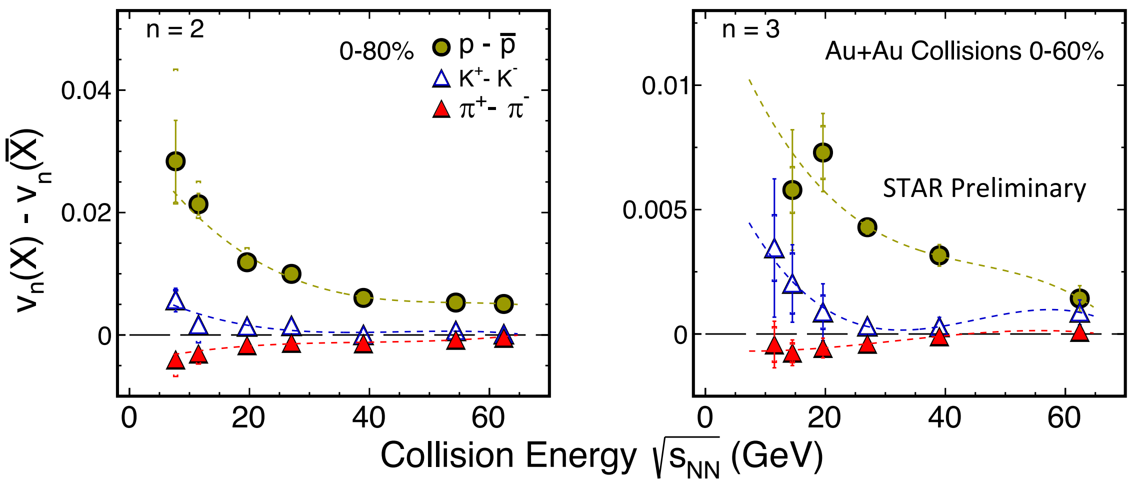
- Both hydro simulations qualitatively reproduce identified particle v_2 and v_3 in 200 GeV Au+Au collisions



- At these three energies (27, 39, and 54.4 GeV), v_2 behaves similarly

Particle-Antiparticle v_n Difference





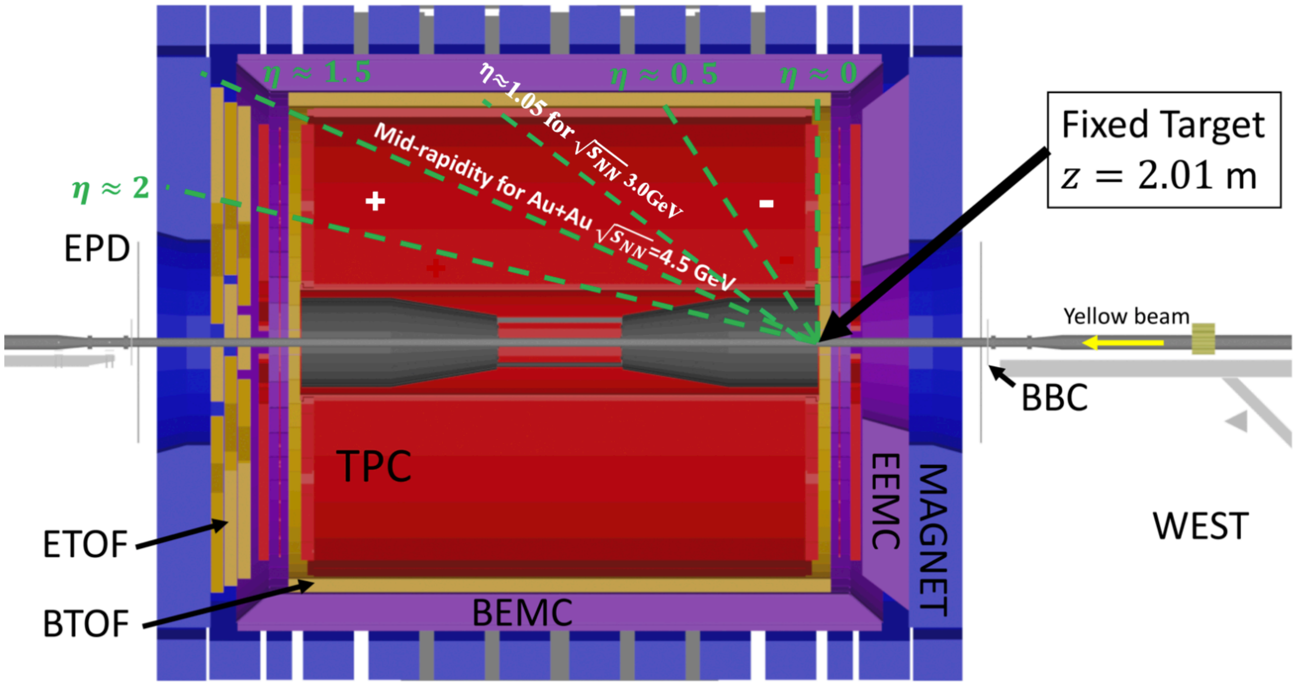
- Number of constituent quark (NCQ) scaling of v_n has been well achieved at 200 GeV
- Difference of v_n between particle and anti-particle increases with decreasing collision energy
- The difference of baryons is larger than mesons

STAR: Phys. Rev. C **88** (2013) 14902, STAR: J. Phys.: Conf. Ser. 1690 012128

J.C. Dunlop, et al. Phys. Rev. C **84** (2011) 044914
Yu. B. Ivanov, Phys. Lett. B **723** (2013) 475-480
Yoshitaka Hatta, et at. Phys. Rev. D **92** (2015) 11, 114010
Jun Xu, et al. Phys. Rev. Lett. **112** (2014) 012301

Results-II

STAR Fixed Target Setup

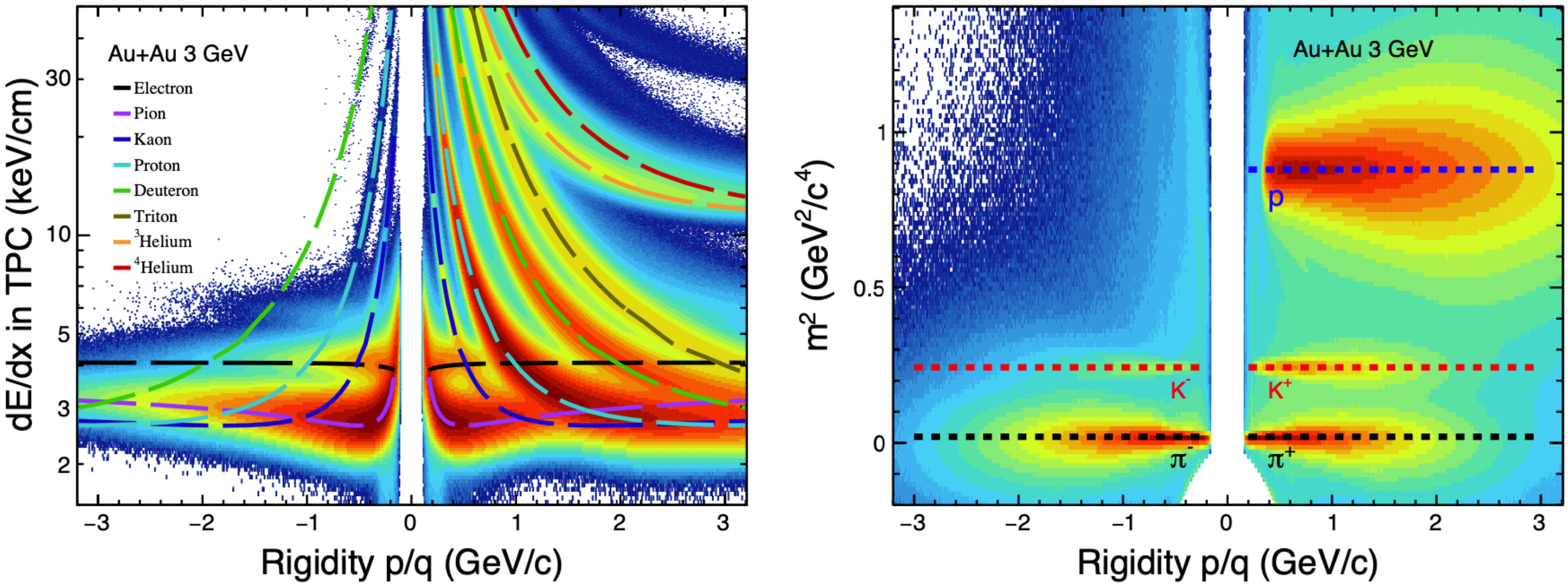


Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	Events (M)	Year	μ_B (MeV)
3.85	3.0	250	2018	721

Conventions: beam-going direction is the positive direction (Yellow beam)

J. Cleymans et al. Phys. Rev. C **73** (2006) 034905

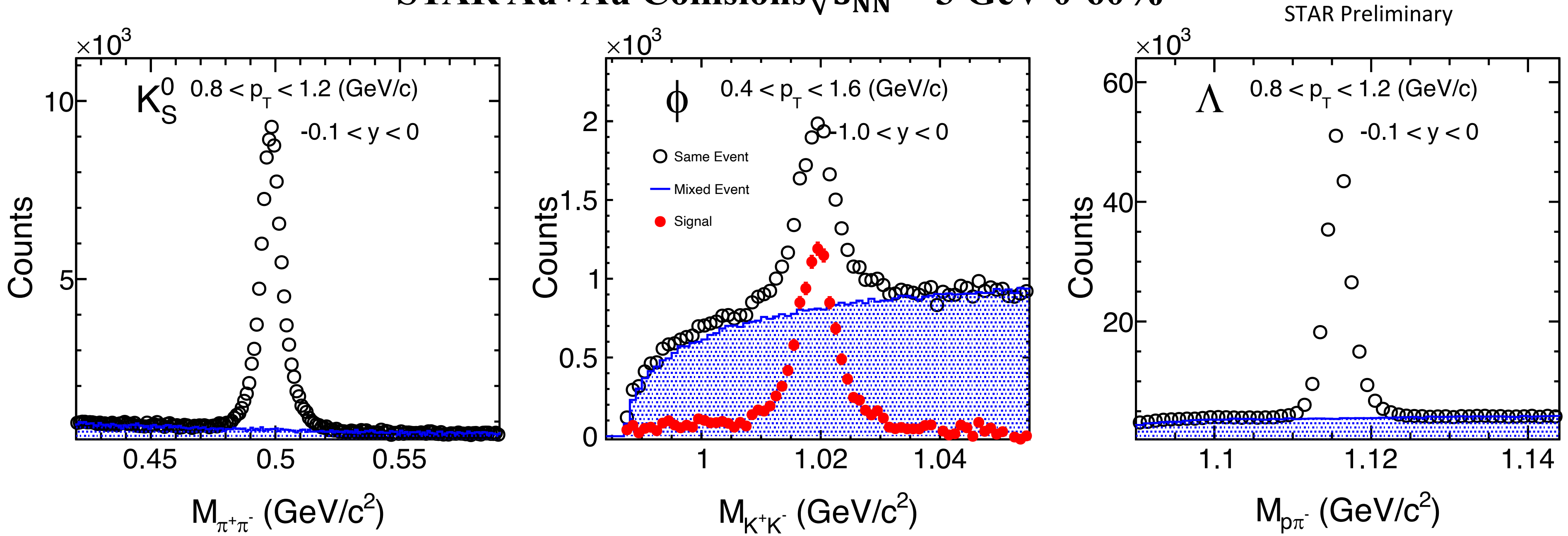
Particle Identification



➢ Good capability of particle identification by using Time Projection Chamber (TPC) and Time of Flight (TOF) at STAR

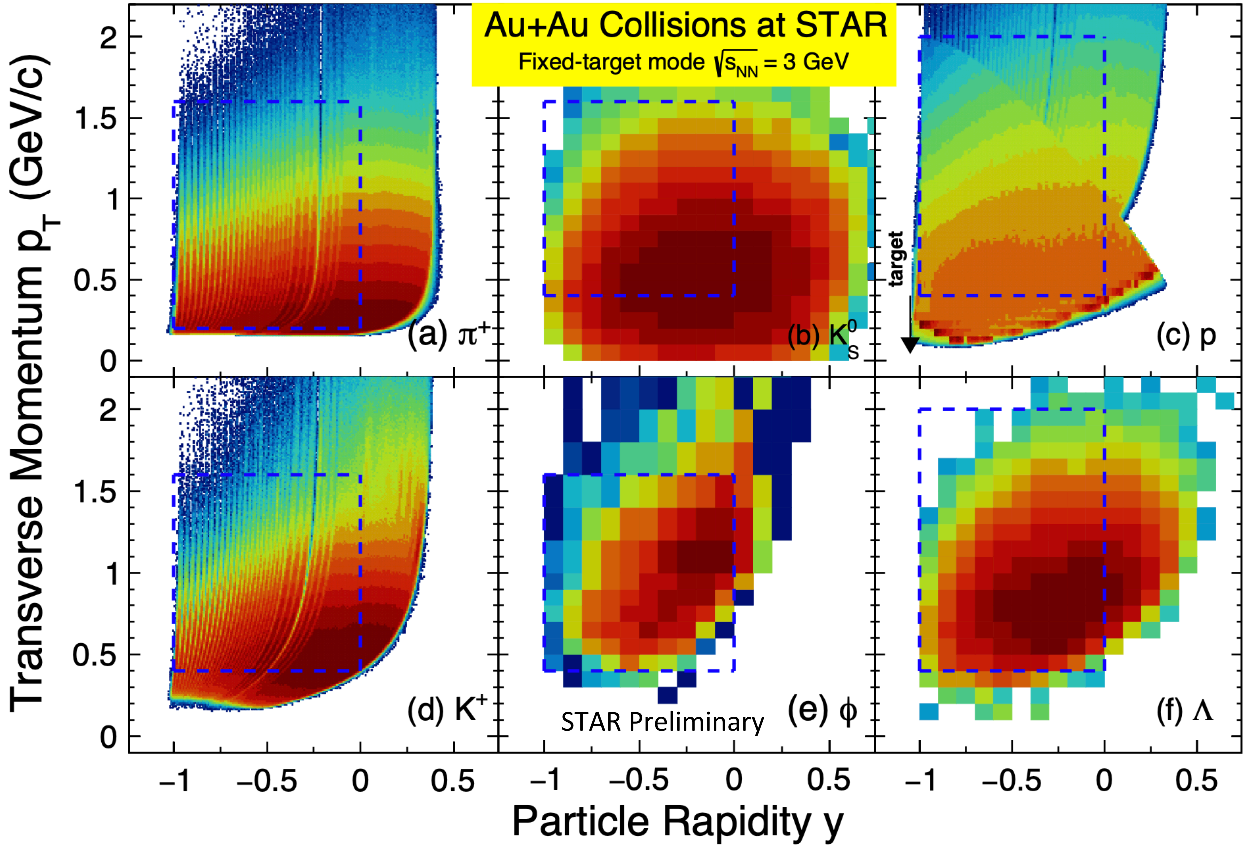
Particle Identification

STAR Au+Au Collisions $\sqrt{s_{NN}}$ = 3 GeV 0-60%



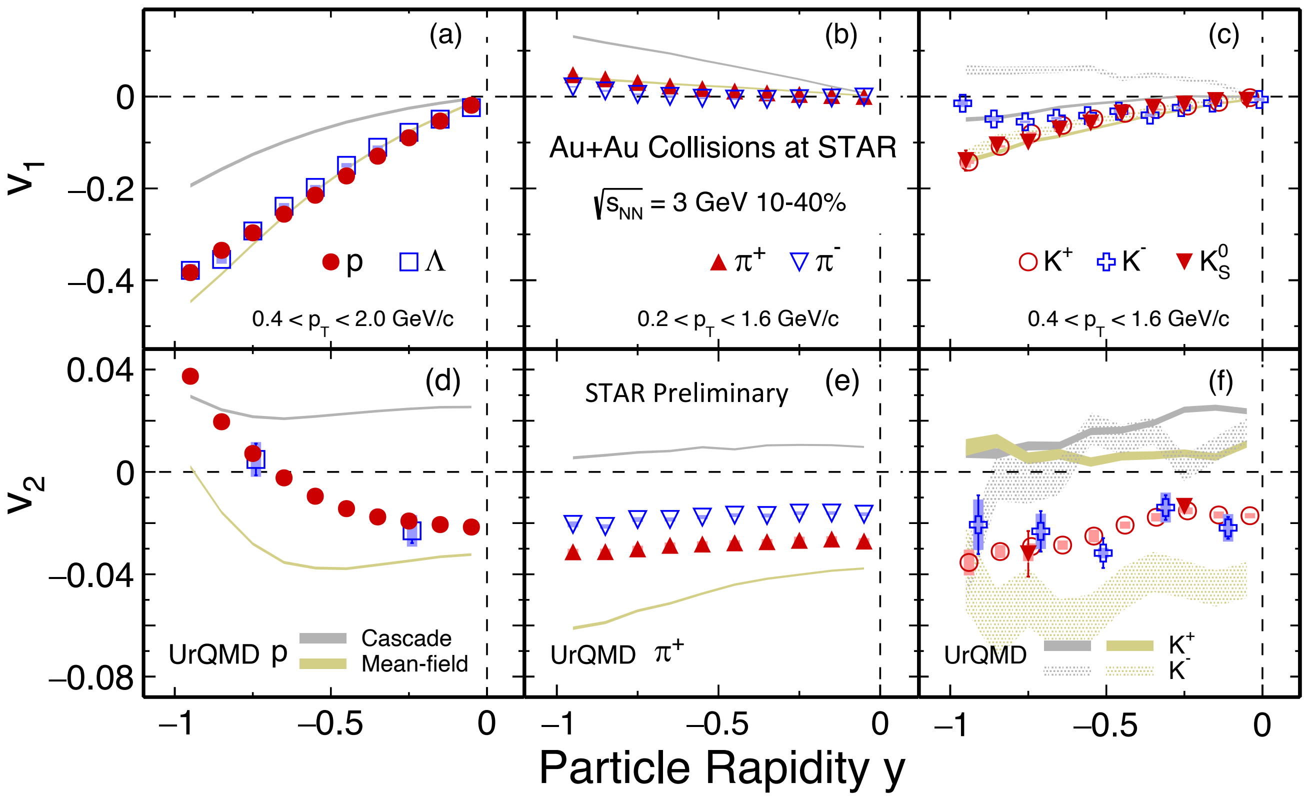
- K^0_S and Λ are reconstructed in $\pi^+\pi^-$ and $p\pi^-$ channel respectively using KF particle package, good purity is achieved
  - Background is obtained by rotating daughter π^- tracks
- ϕ mesons are reconstructed in K^+K^- channel
  - Background is obtained by using mixed event

Particle Acceptance



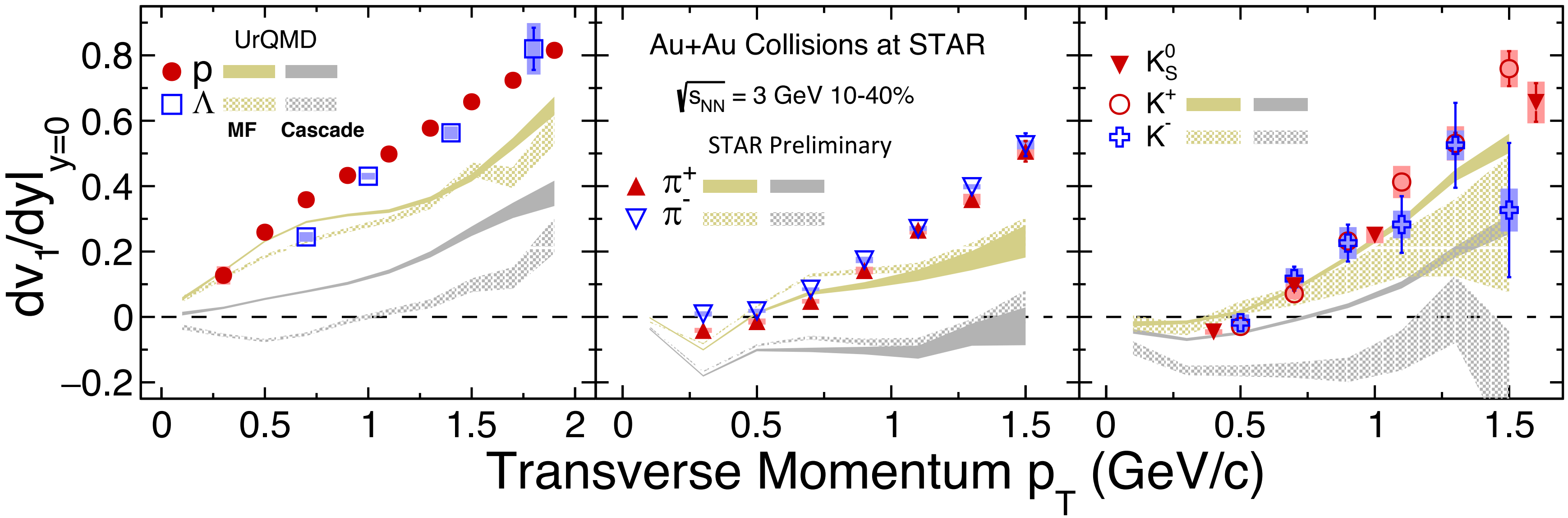
- ➢ The acceptance plot p_T versus rapidity measured by using STAR detector (TPC and TOF) for π^+, K^+, K^0_S, p, ϕ and Λ
- ➢ The acceptance of all particles covers from mid-rapidity to target rapidity region

Rapidity Dependence



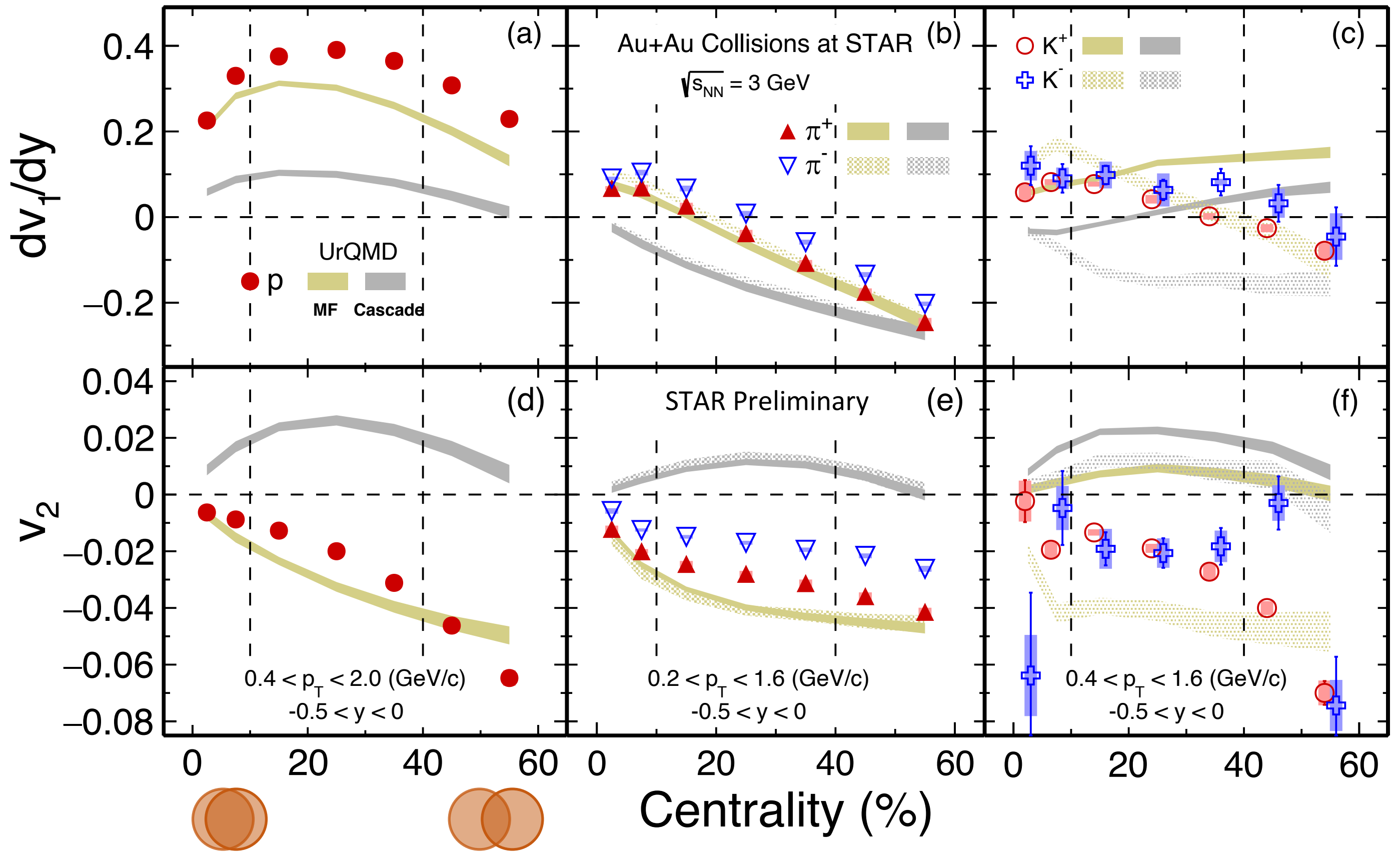
- Rapidity dependence of v_1 and v_2 for identified particles ($\pi^\pm, K^\pm, K^0_S$, p, Λ)
- The negative elliptic flow observed at mid-rapidity region for all hadrons
- The results from UrQMD with baryonic mean-field potential qualitatively describe the data

p_T Dependence of dv_1/dy



- Strong p_T dependence of the slope of directed flow (dv_1/dy) for identified particles ($\pi^{\pm}, K^{\pm}, K^0_S, p, \Lambda$)
- Small charge dependence for pions and kaons
- The UrQMD calculations with baryonic mean-field (MF) potential qualitatively describe the data

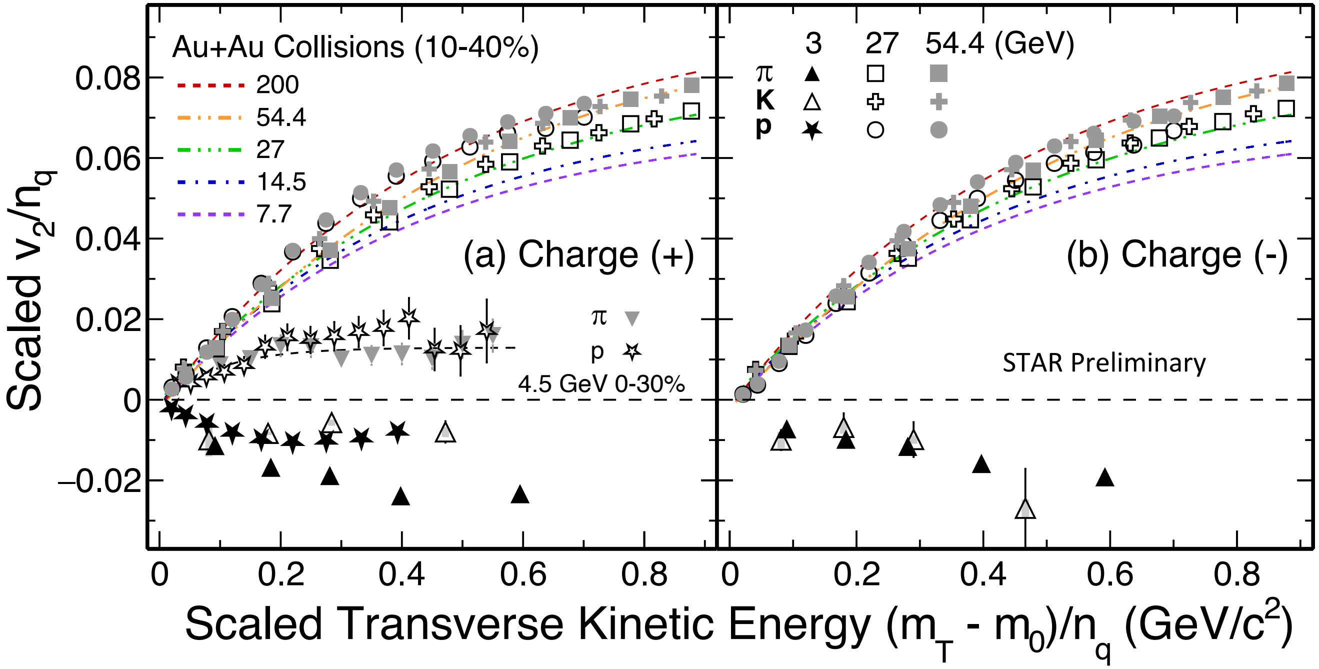
Centrality Dependence of dv_1/dy and v_2



- Clear centrality dependence of dv_1/dy and v_2 for identified particles
- Shadowing effect of spectators in the peripheral collisions
  - More negative v_2
- The UrQMD calculations with baryonic mean-field (MF) potential qualitatively describe the data except kaons

Prog. Part. Nucl. Phys. **41** (1998) 225-370. J. Phys. G: Nucl. Part. Phys. **25** (1999) 1859-1896. G. Hartnack, et al. Eur. Phys. J. A **1** (1998) 151-169

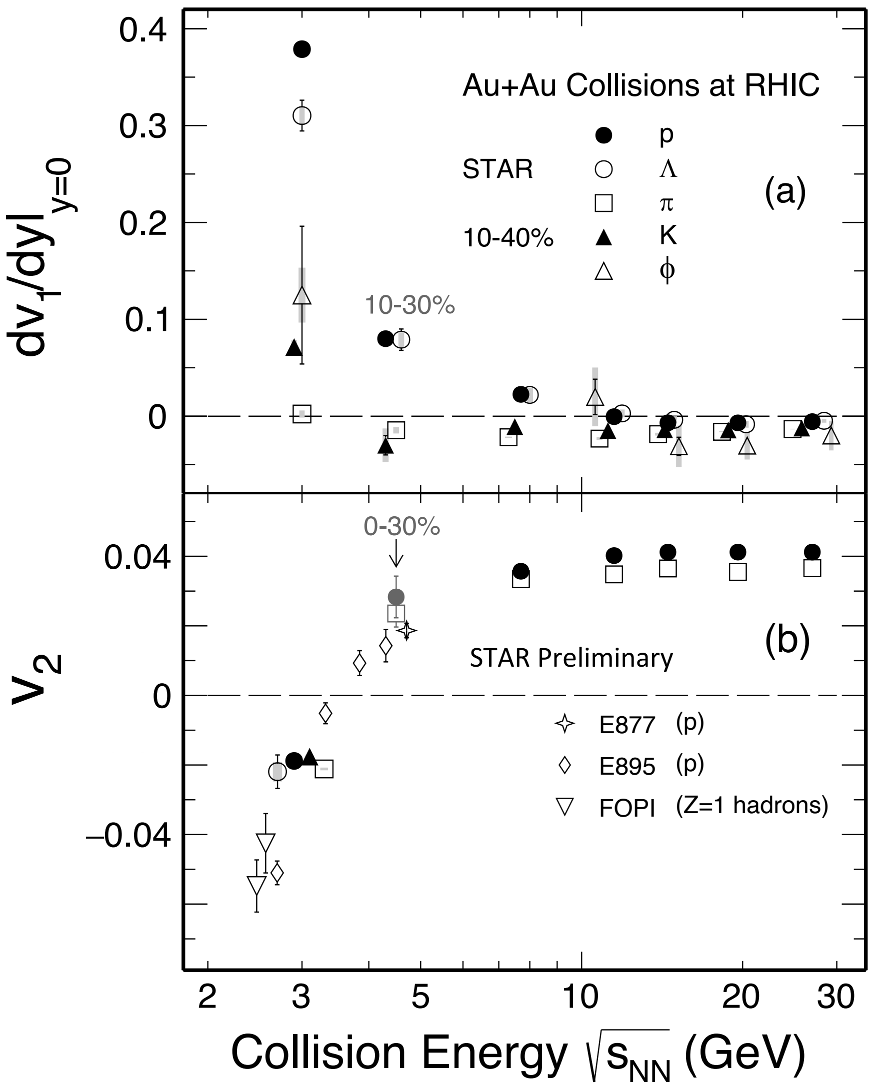
Scaling Properties



- The number of constituent quark (NCQ) scaling for v_2 holds down to 4.5 GeV, consistent with the nature of partonic collectivity
- Different color dash lines represent the fit to data from 200 GeV – 4.5 GeV
- At 3 GeV, the measured v_2 for all particles are negative and NCQ scaling is absent, especially for positive charged particles

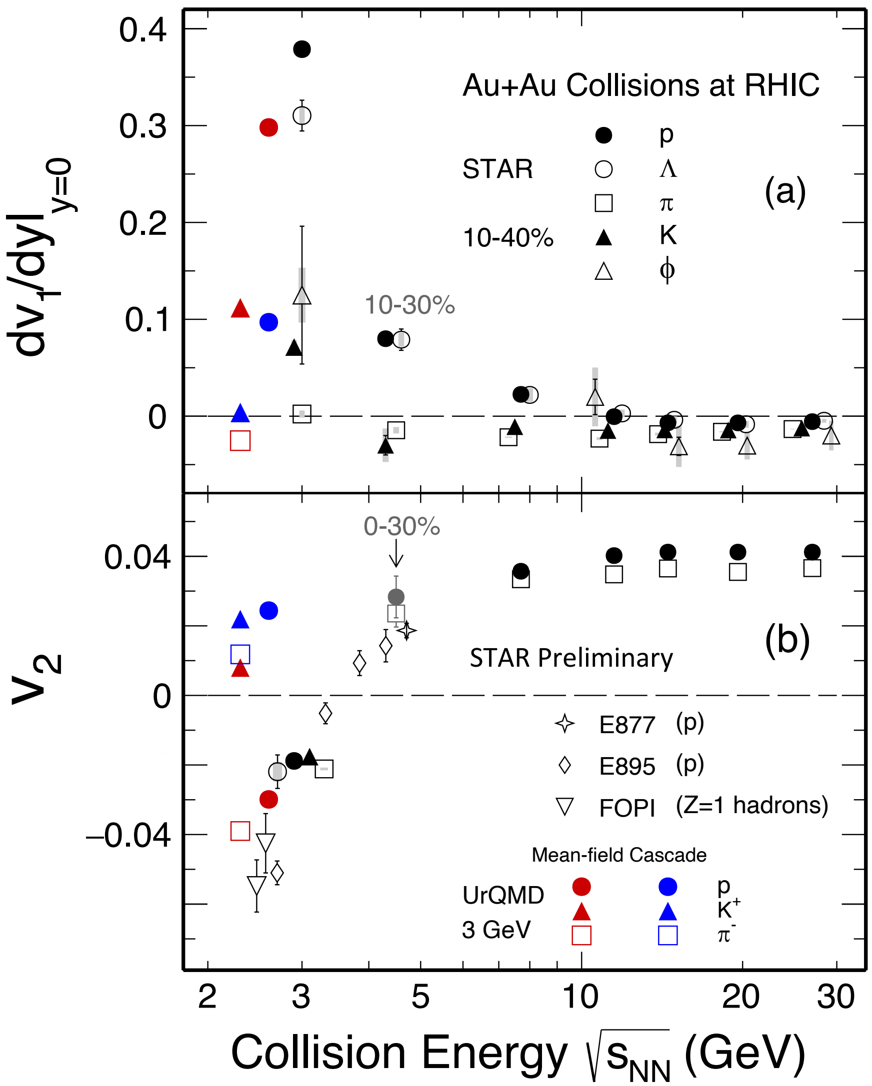
STAR: Phys. Rev. C **88** (2013) 14902 , STAR: arXiv:2007.14005, X. Dong et al. Phys. Lett. B **597** (2004) 328-332

Energy Dependence of dv_1/dy and v_2



- 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, consistent with a change of EoS
- Negative elliptic flow at mid-rapidity for all hadrons at 3 GeV

Energy Dependence of dv_1/dy and v_2



- ➢ 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, consistent with a change of EoS
- ➢ Negative elliptic flow at mid-rapidity for all hadrons at 3 GeV
- ➢ The results from UrQMD with baryonic mean-field potential qualitatively describe data at 3 GeV
- ➢ **EoS dominated by the baryonic interactions at 3 GeV**

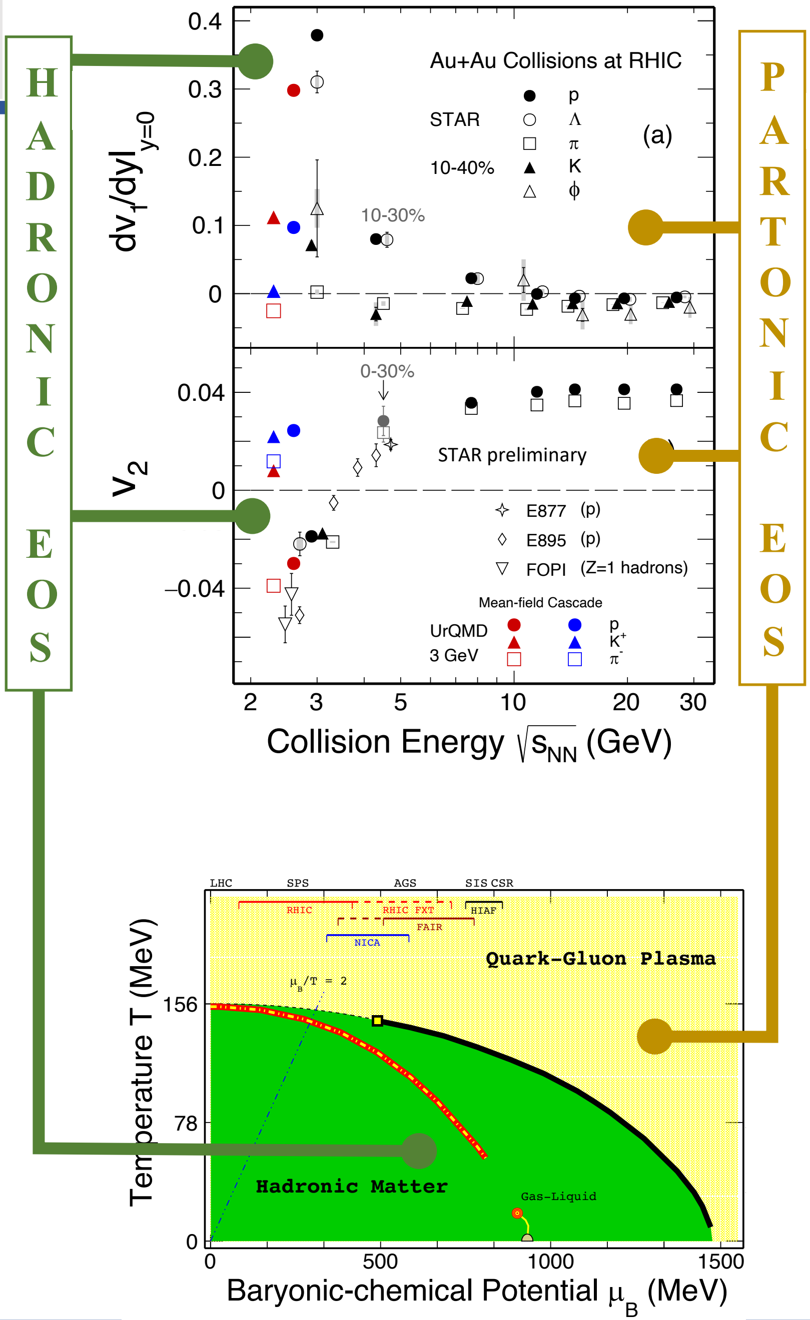
Summary

- Flow measurements in high energy collisions at 200, 54.4, 39 and 27 GeV
  → **Partonic collectivity**

- At 3 GeV, negative elliptic flow and positive slope of directed flow at mid-rapidity for all hadrons are observed

- Hadronic transport model (UrQMD) with baryonic mean-field potential qualitatively describe the data at 3 GeV

  → **New medium properties and an EoS dominated by baryonic interactions, produced in 3 GeV Au+Au collisions**



Thank you for your attention!

Backup

Flow Method

- **2-particle Correlation Method (2PC)**

$$c_n\{2\} = \langle\langle 2 \rangle\rangle_{a|b} = \langle\langle e^{in\left(\phi_1^a - \phi_2^b\right)} \rangle\rangle = \frac{\langle\langle Q_{n,a} Q_{n,b}^* \rangle\rangle}{\langle\langle M_a M_b \rangle\rangle}$$

  - The non-flow contribution is reduced with $\Delta\eta$ gap

Integrated **p_T (PID) – differential flow harmonics**

$$v_n\{2\} = \sqrt{c_n\{2\}} \qquad v_n(p_T) = v_n(p_T, p_T^{ref}) / \sqrt{v_n^2(p_T^{ref}, p_T^{ref})}$$

- **Event Plane Method (EP)**

$$\Psi_n = \left(\tan^{-1} \frac{\sum_i w_i \sin(n\phi_i)}{\sum_i w_i \cos(n\phi_i)} \right) / n \qquad v_n = \frac{\langle cos(n(\phi - \Psi_n)) \rangle}{\langle cos(n(\Psi_n - \Psi_{RP})) \rangle} = \frac{v_n^{obs}}{R_n}$$

  - The detector acceptance effect has been corrected by applying re-centering and shift calibration

$$\langle cos(km(\Psi_m - \Psi_r)) \rangle = \frac{\sqrt{\pi}}{2\sqrt{2}} \chi_m exp(-\chi_m^2/4) \left[I_{(k-1)}(\chi_m^2/4) + I_{(k+1)/2}(\chi_m^2/4) \right]$$

  - Modified Bessel function is used for resolution calculation

NCQ scaling for v_2