Light and strange hadron production and anisotropic flow measurement in Au + Au collisions at $\sqrt{s_{NN}} = 3$ GeV from STAR

Guannan Xie (for the STAR Collaboration)
Lawrence Berkeley National Laboratory

May 17-22, 2021

Online Strangeness in Quark Matter Conference 2021

The 19th International Conference on Strangeness in Quark Matter
May 17-21, 2021, sponsored by Brookhaven National Laboratory, Upton, New York
SQM 2021

Supported in part by
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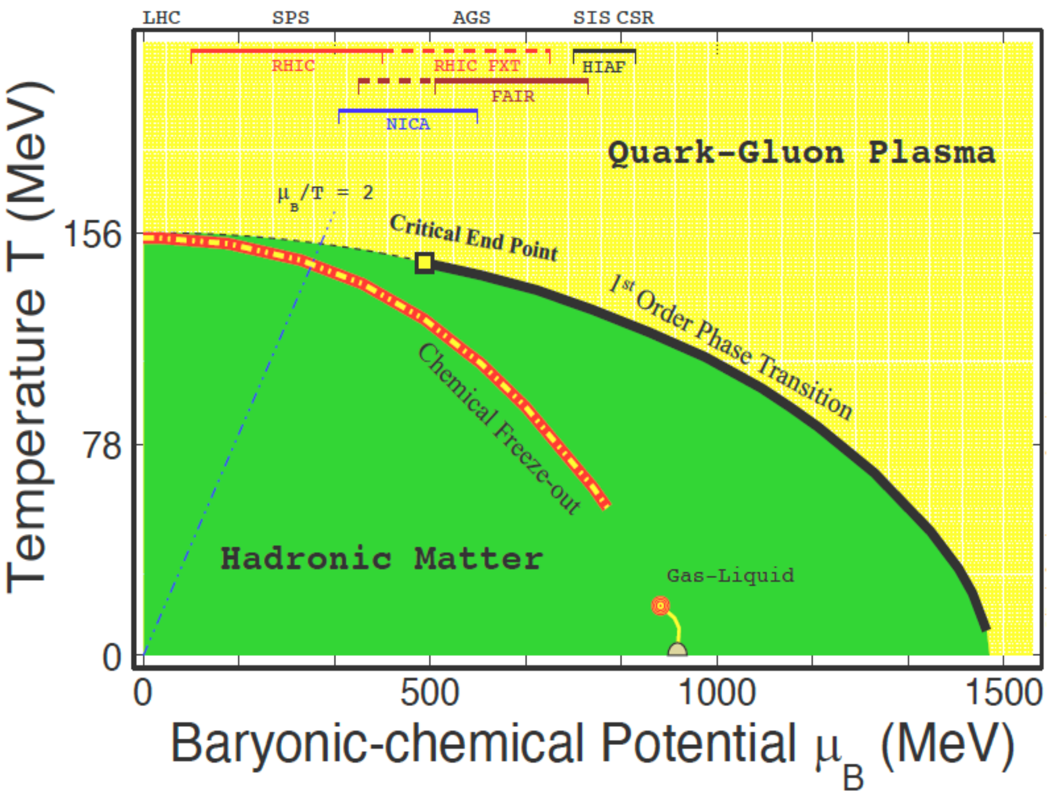
Outline

- Motivation
- STAR Fixed Target (FXT)
- Results of Light and Strange Hadron Production Yields
  - m_T spectra, rapidity distribution, yield ratio
- Results of Light and Strange Hadron Anisotropic Flow
  - v_1, v_2
- Summary and Outlook

Exploring QCD Phase Structure



Conjectured phase diagram of strong interaction matter

- Study properties of the QCD matter
- Locate possible QCD phase boundary

- Where are we? What's the properties? (at 3 GeV)

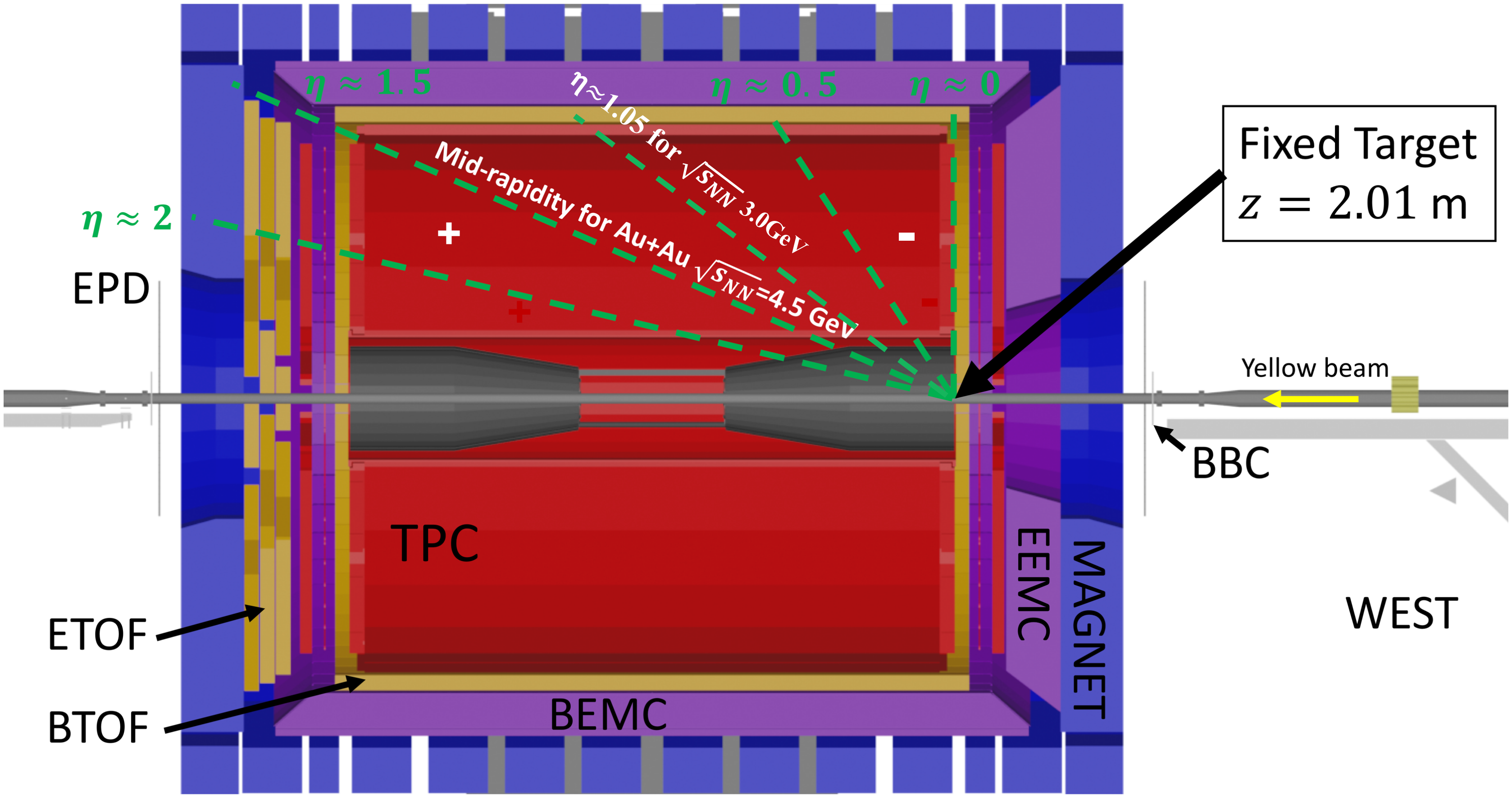
Particle production:

- Understand medium properties and different particle production mechanisms

Collective flow:

- Study properties of the produced medium

FXT Setup @ STAR

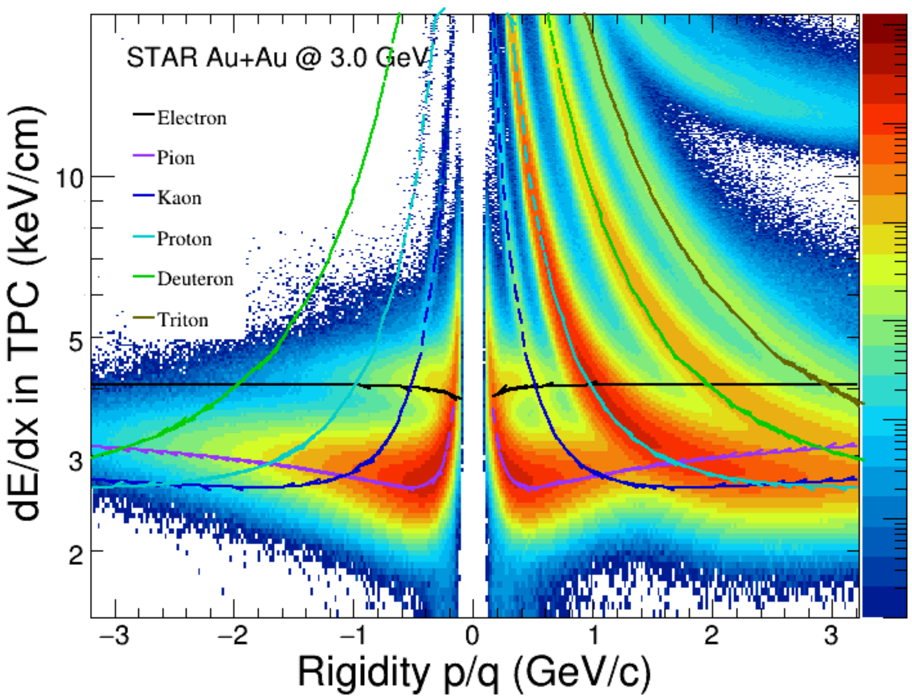


Good mid-rapidity coverage for STAR FXT 3 GeV

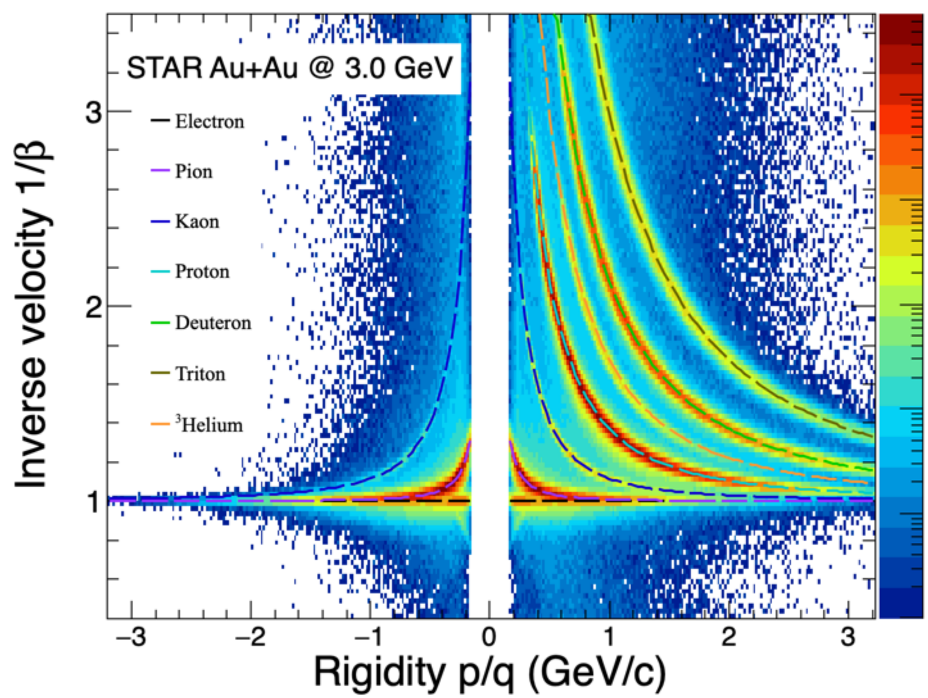
Conventions: beam-going direction is the positive direction

PID @ STAR FXT

TPC



TOF

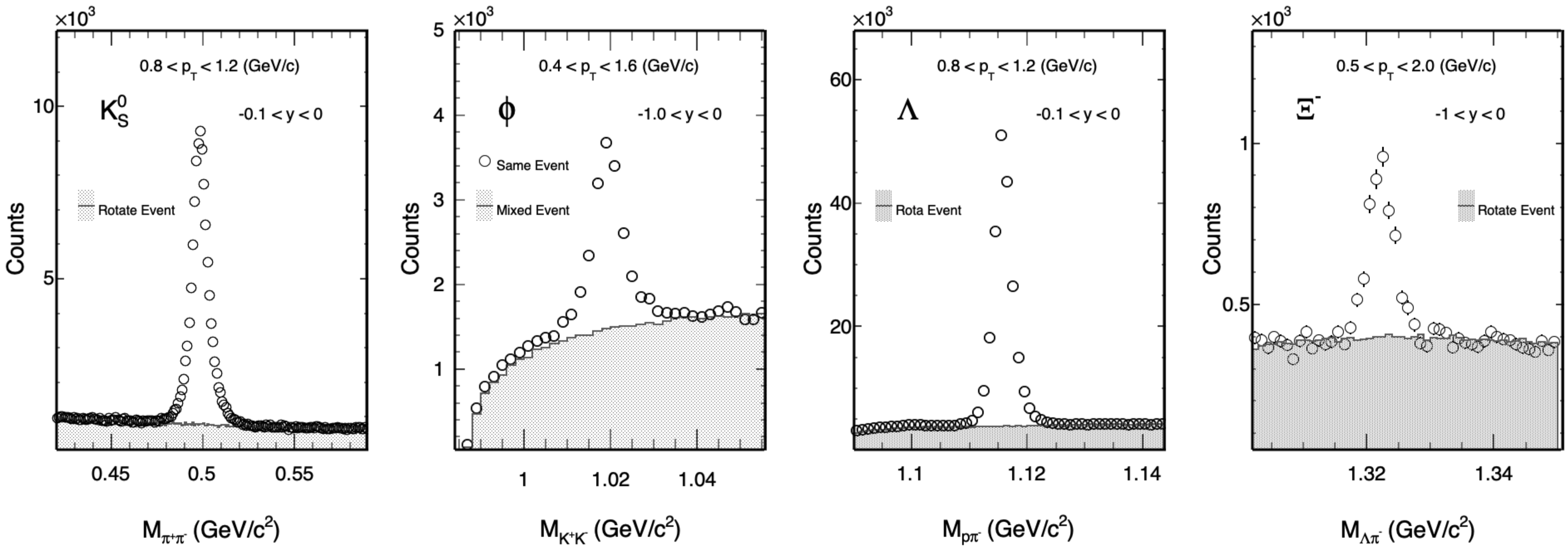


On average, "longer tracks" for FXT events than for collider events, better resolutions for both dE/dx and $1/\beta$ in FXT mode

Particle Reconstruction

STAR Au+Au @ 3 GeV

STAR Preliminary

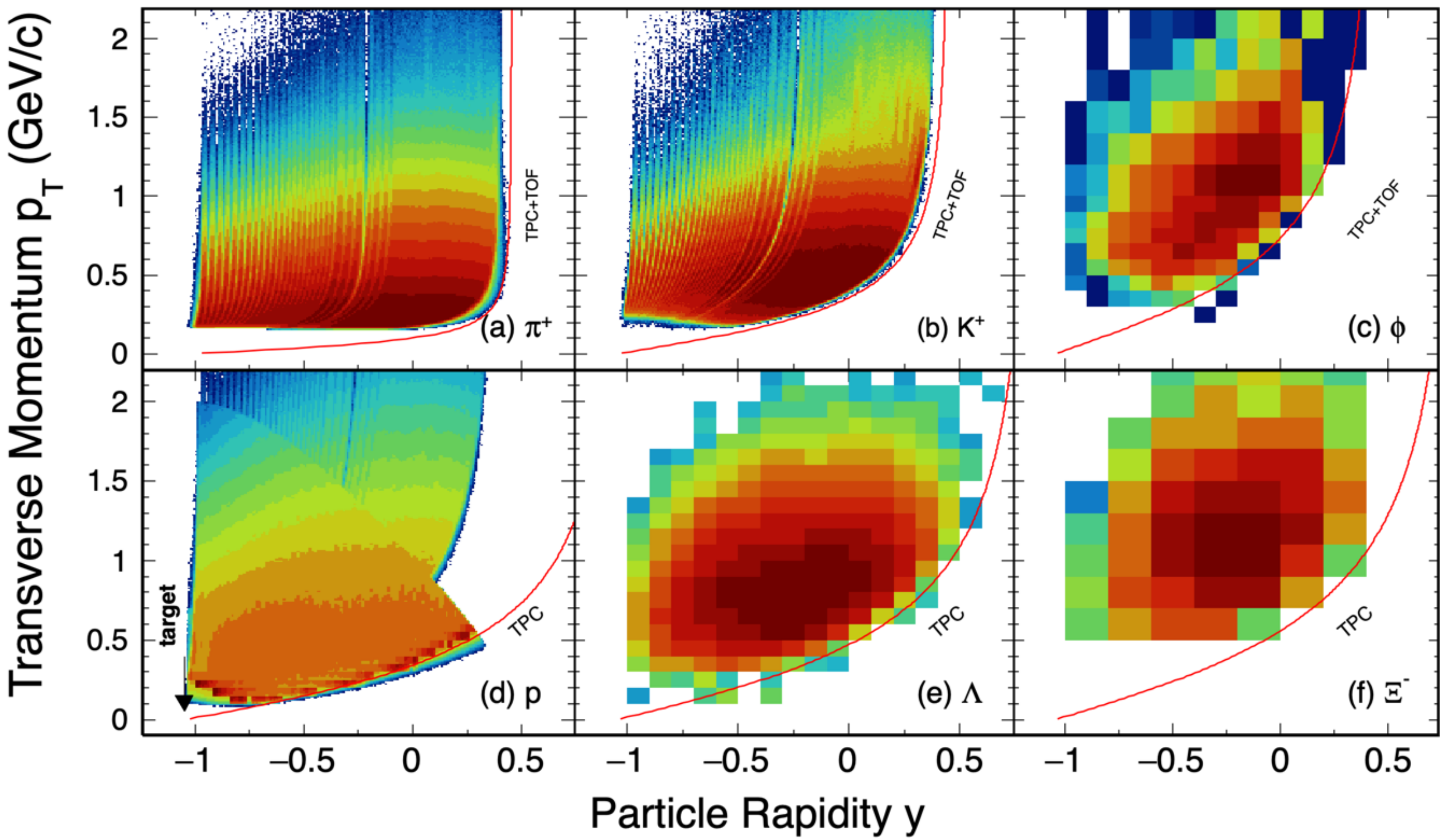


- K_S^0, Λ and $\Xi^-$are reconstructed in $\pi^+\pi^-$, $p\pi^-$and $\Lambda\pi^-$channels respectively using KF particle package, good purity and efficiency is achieved
  - Background is obtained by rotating daughter tracks
- ϕ mesons are reconstructed in K^+K^- channel
  - Background is obtained by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

Particle Acceptance

STAR Au+Au @ 3 GeV

STAR Preliminary



- ➢ The acceptance plot p_T versus rapidity measured from STAR @ 3 GeV (TPC and TOF) for π, $K, p, K_S^0, \Lambda, \phi$ and Ξ^-
  - ➢ Good mid-rapidity coverage

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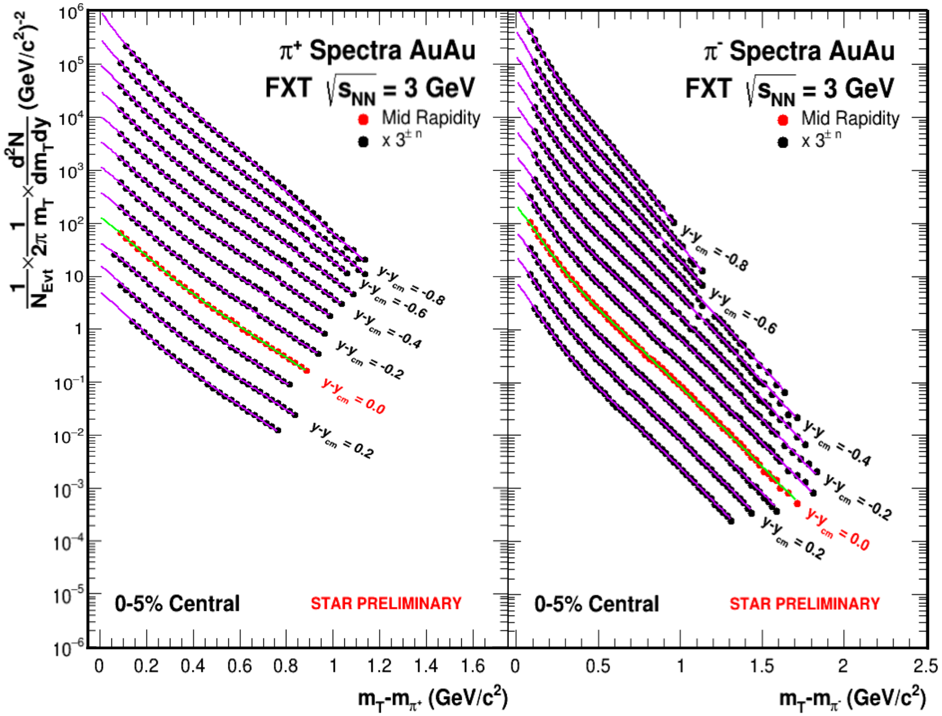
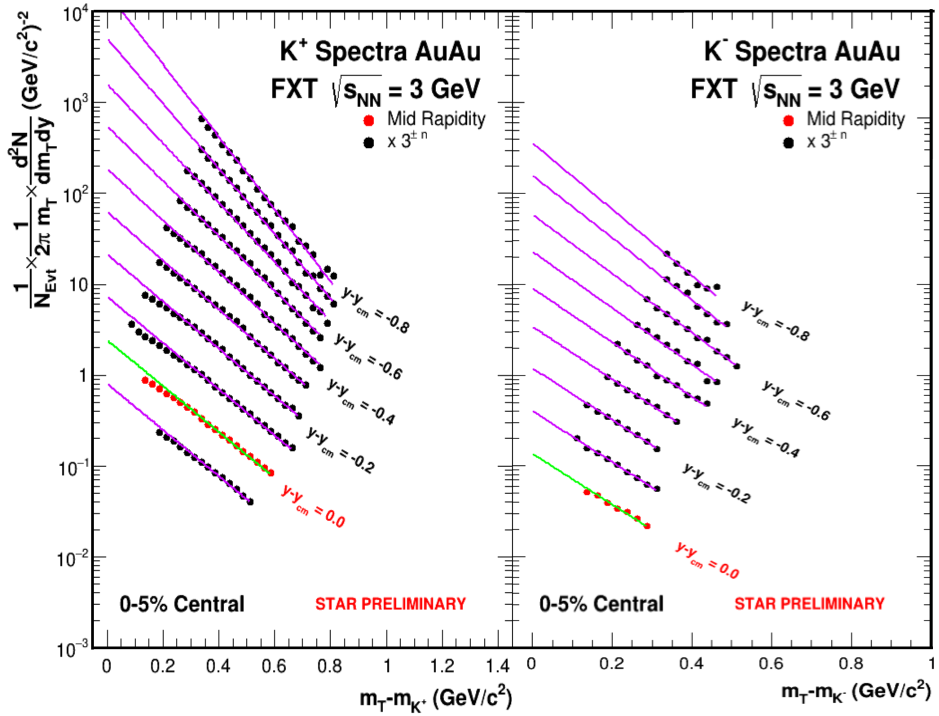
Efficiency Corrected m_T Spectra

π^+ π^- 0-5% central K^+ K^-



$$\frac{1}{2\pi m_T}\frac{d^2N}{dm_T dy} = A m_T e^{-(m_T - m_0)/T}$$



$$\frac{1}{2\pi m_T}\frac{d^2N}{dm_T dy} = A e^{-(m_T - m_0)/T}$$

- Pion spectra described well by double thermal function, which describes thermal production at high m_T-m_0 and production from Δ resonance at low m_T-m_0
- Kaons described well by single thermal function

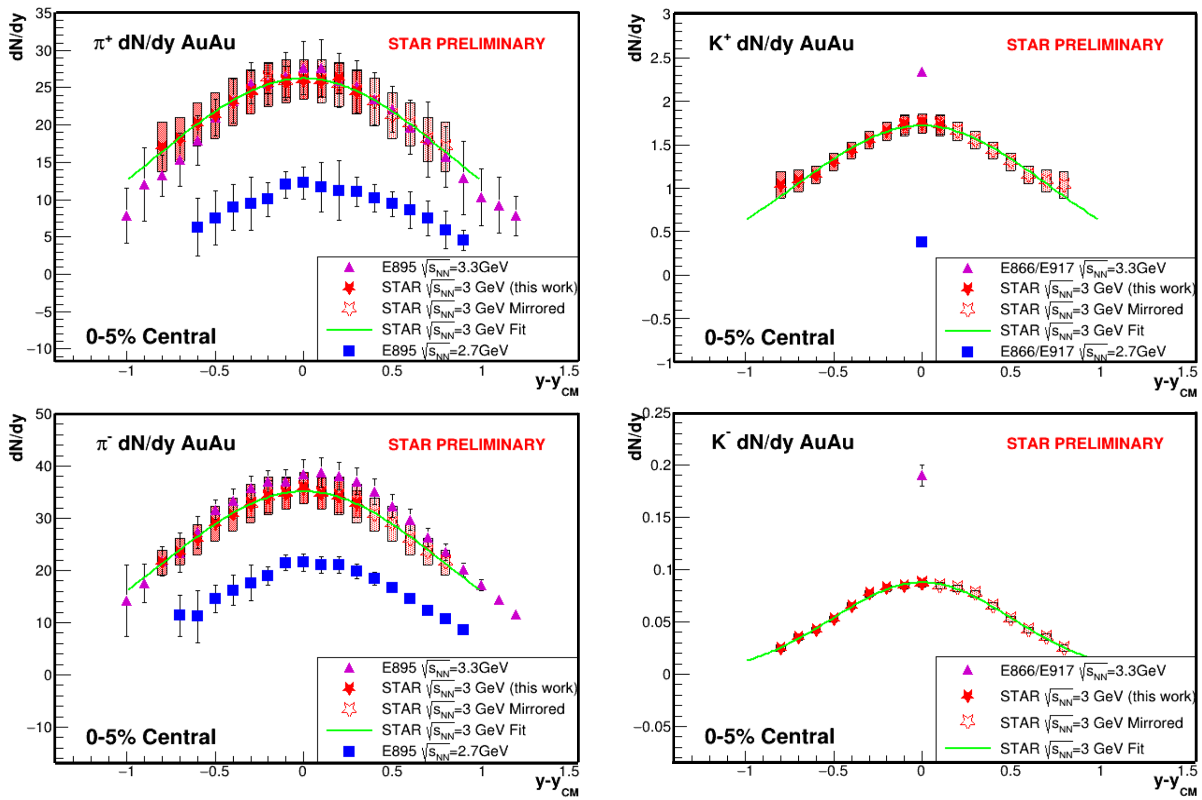
Rapidity Density Distributions

E895, Phys. Rev. C 68, 054905 (2003)
E866 and E917, Phys. Lett. B490, 53 (2000)

0-5% central

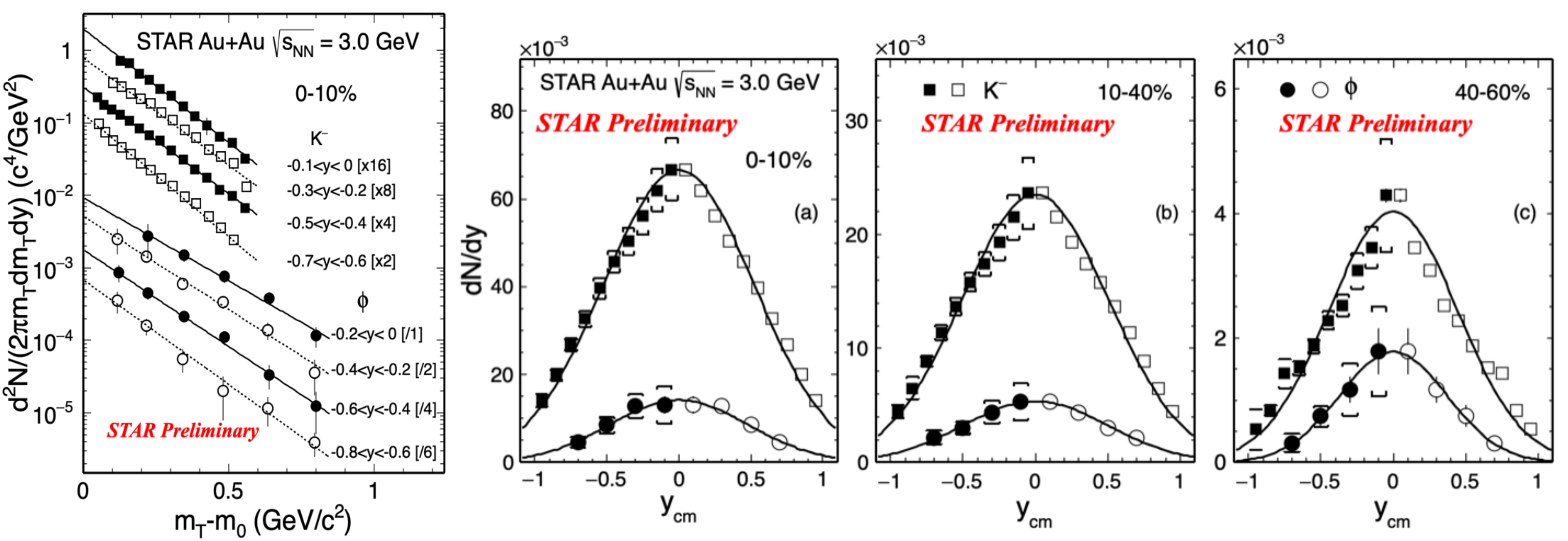
π^+ K^+

π^- K^-



- Yields obtained from integrating fits of spectra and are then fit with a Gaussian
- Yields as expected by interpolating between E895 and E866 results from the AGS

ϕ−meson m_T Spectra & dN/dy Distribution

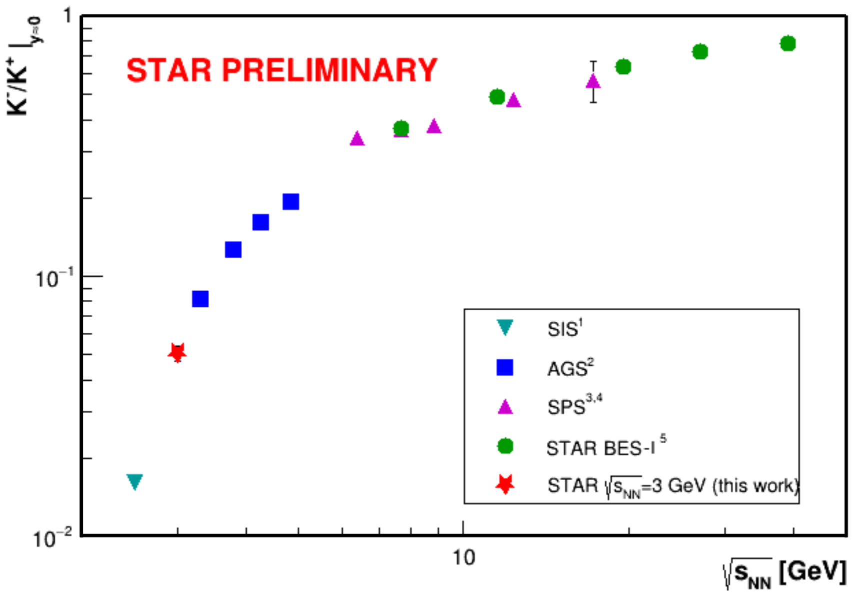


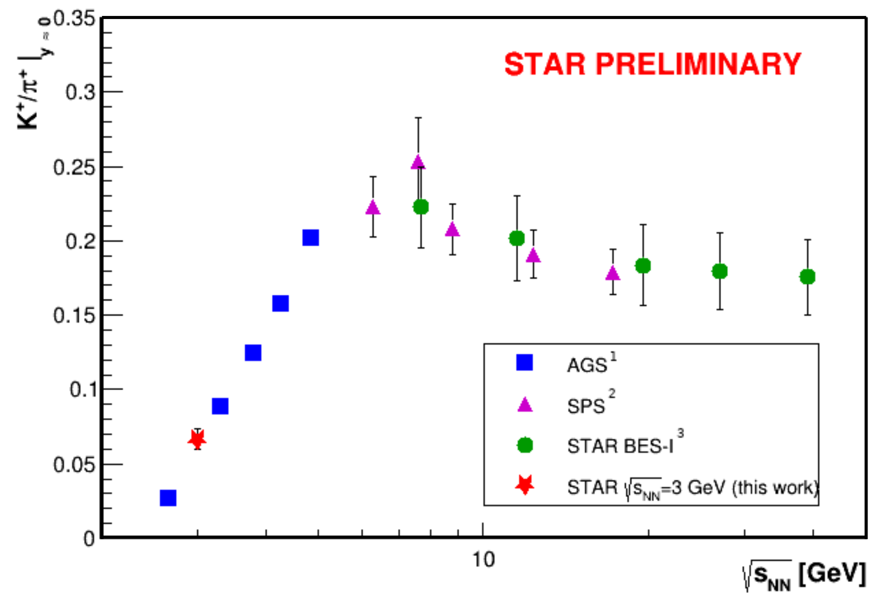
- ϕ-meson invariant yields in 0-10% for various rapidity regions. Yields are integrated from exponential fits
- Rapidity distributions of $K^-$and ϕ-meson for various centrality regions. Fitting with Gaussian. Solid symbols are measured data, open ones are reflection

K^-/K^+ & K^+/π^+ Ratio

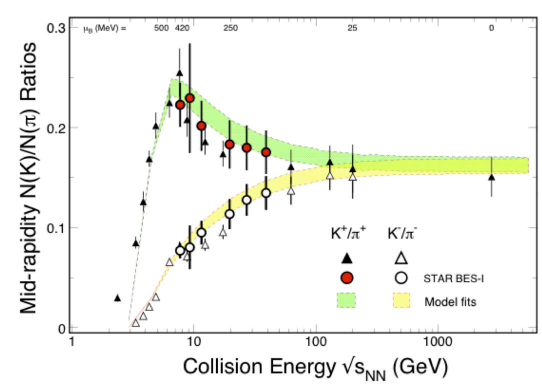
Beam energy dependence of strangeness production

KaoS, *J. Phys. G 28, 2011 (2002)*
E866/E917, *Phys. Lett. B490, 53 (2000)*
NA49, *Phys. Rev. C 77, 024903 (2008)*
NA49, *Phys. Rev. C 66, 054902 (2002)*
STAR, *Phys. Rev. C 96, 044904 (2017)*
E866/E917, *Phys. Lett. B476, 1 (2000)*
Thermal, *Phys. Lett. B, 673, 142 (2009)*



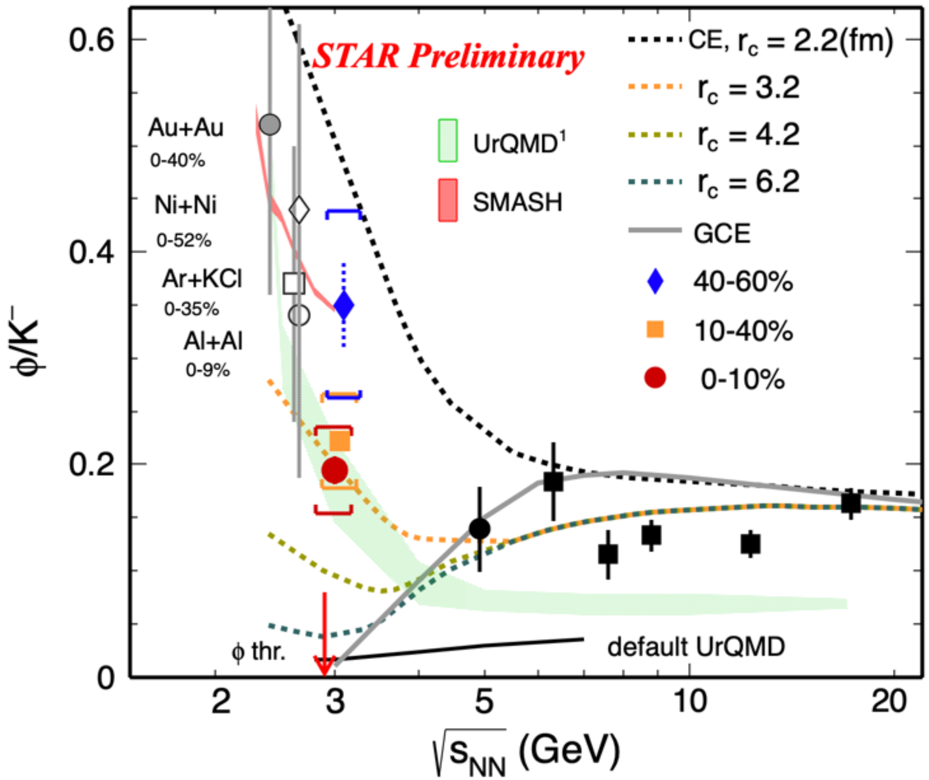


- K^-/K^+ ratio shows importance of K^+ production in association with the Λ ($N + N \rightarrow N + \Lambda + K$)
- K^+/π^+ ratio proposed by NA49 as a possible signal of onset of deconfinement. Statistical model describes the data
- Results at $\sqrt{s_{NN}} = 3.0$ GeV follow the world trend



ϕ/K^- Ratio

Beam energy dependence of strangeness production



HADES: Phys. Lett. B 778, 2018.403-407, Phys. Rev. C. 80.025209. (2009);
E917: Phys. Rev. C. 69.054901 (2004);
NA49 : Phys. Rev. C 78, 044907 (2008), Phys. Rev. C 77, 024903 (2008), Phys. Rev. C 66, 054902 (2002)

CE,GCE, K. Redlich: Phys. Lett. B 603, 146 (2004); Private Communication;
UrQMD[1]: J. Phys. G: Nucl. Part. Phys. 43 (2016) 015104 (14pp);
UrQMD (public version): Prog. Part. Nucl. Phys. 41 (1998) 225-370
SMASH : Phys. Rev, C 99, 064908 (2019)

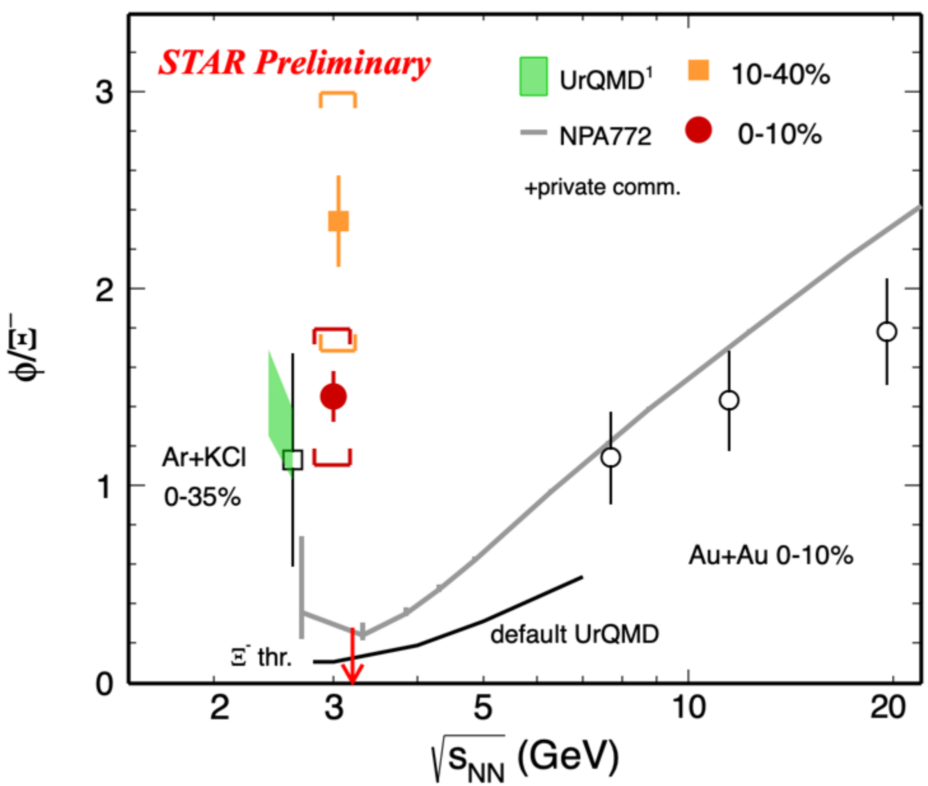
$\phi(s\bar{s}), K^-(s\bar{u})$

r_c : correlation length, radius of the volume inside which the production of particles with open strangeness is canonically conserved.

- Low energies, strangeness production is rare, local strangeness conservation may be required
- ~5σ deviation from zero (GCE) for 0-10% central collisions. Data favors the CE with $r_c \sim 3.2\ fm$
- Transport models with high mass resonance can reasonably describe data at low energies

ϕ/Ξ^- Ratio

Beam energy dependence of strangeness production



HADES: Eur. Phys. J. A (2016) 52: 178
STAR: Phys. Rev. C 102 (2020) 34909

NPA772: A. Andronic et al. Nucl. Phys. A 772, 167 (2006); +private communication
UrQMD[1]: J. Phys. G: Nucl. Part. Phys. 43 (2016) 015104 (14pp);
UrQMD (public version): Prog. Part. Nucl. Phys. 41 (1998) 225-370

NPA772: GCE+I_0/I_S + V_C=1500±500 fm^3

$\phi(s\bar{s})$, $\Xi^-(dss)$

- Transport models with high mass resonance decay to ϕ and Ξ^- can reasonably describe previous measurement from SIS energies
- NPA772: GCE + I_0/I_S+V_C=1500 fm^3 describes data well at > 5 GeV, but underestimate our measurement at 3 GeV. Canonical suppression is important at low energies

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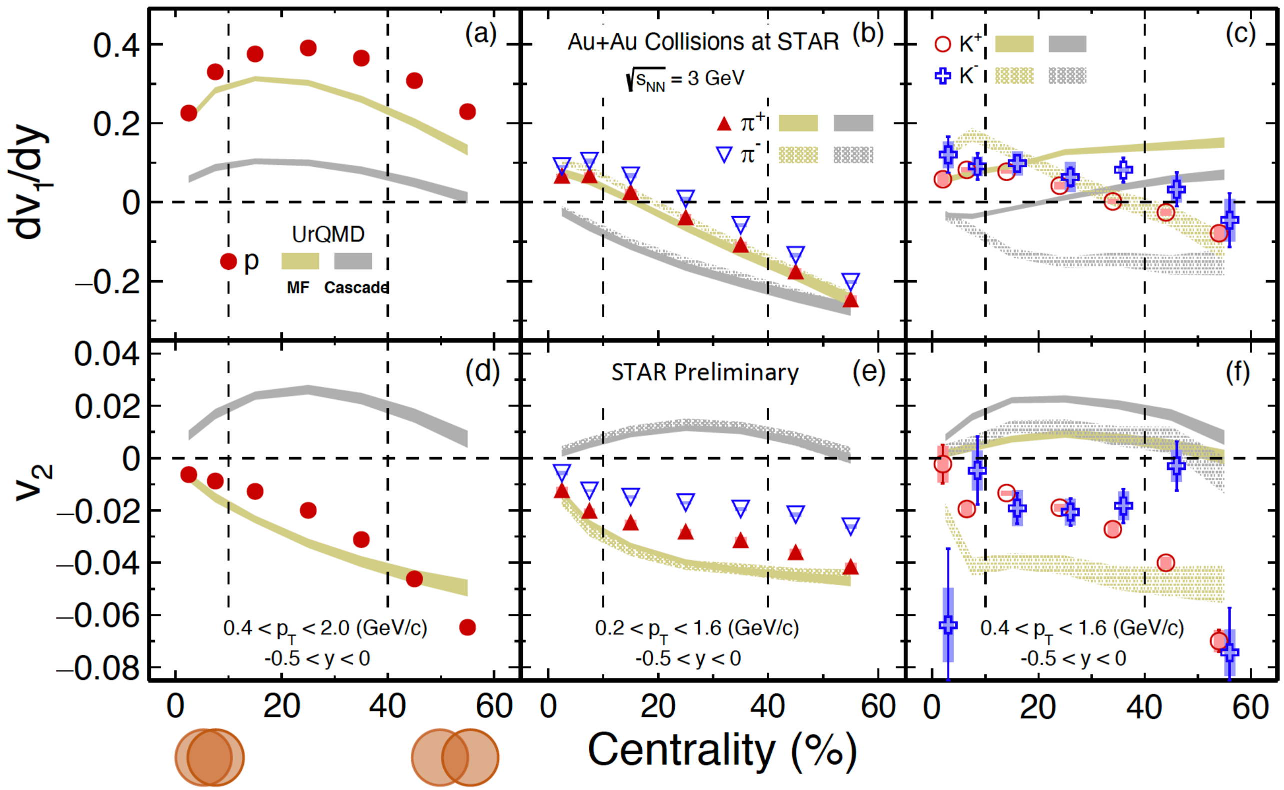
Centrality Dependence of dv_1/dy and v_2

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



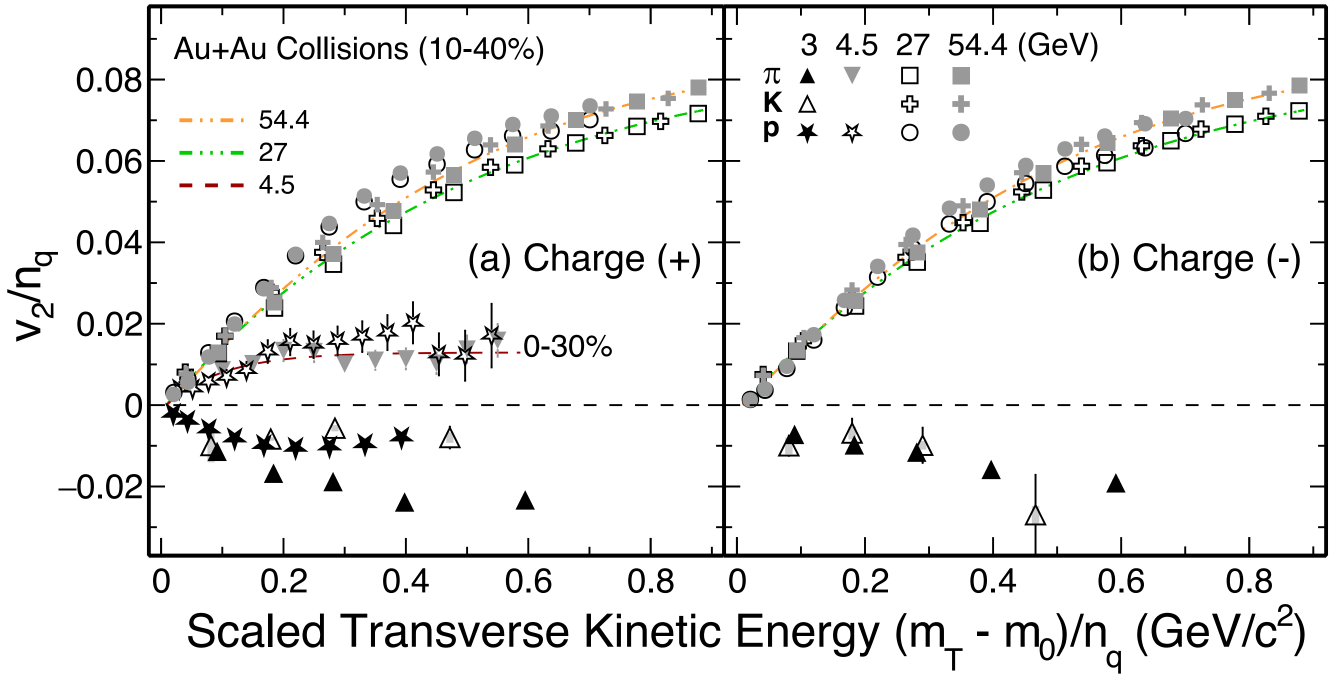
Peripheral: spectator shadowing effect

Positive v_2, in-plane
Negative v_2, out-of-plane

- v_1, v_2 are sensitive to the stiffness of nuclear EoS at high baryon density region
- Clear centrality dependence of dv_1/dy and v_2 for identified particles
  - central collisions: positive v_1 slope
  - peripheral collisions: more negative v_2
- The UrQMD calculations with baryonic mean-field (MF) potential qualitatively describe the data

v_2 Scaling Properties

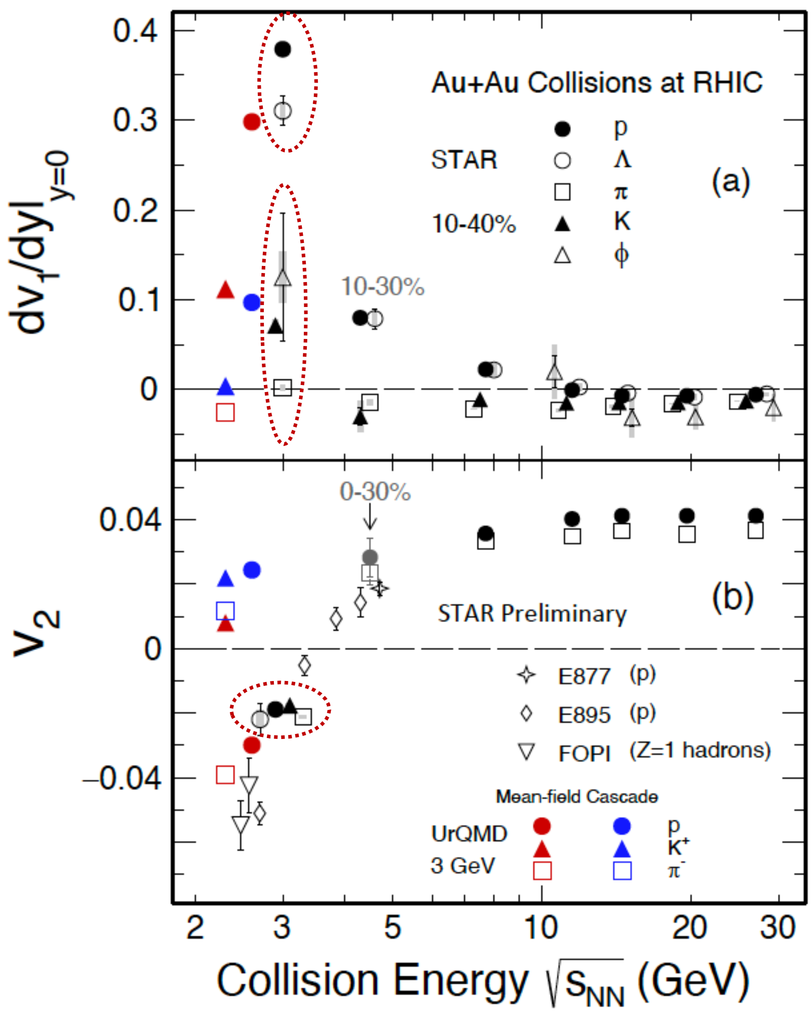
STAR: Phys. Rev. C 88 (2013) 14902 ,
STAR: Phys. Rev. C 103, 034908 (2021),
X.Dong et al Phys. Lett. B 597 (2004) 328-332



- 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 the NCQ scaling breaks, especially for positive charged particles

Energy Dependence of v_1 and v_2

E877: Phys. Rev. C 56, 3254-3264
E895: Phys. Rev. Lett.85, 940
FOPI: Phys. Lett. B612, 173



- Positive v_1 slope and negative v_2 for all measured particles in 3 GeV collisions. Opposite behaviors with that in high energy collisions
- Positive v_1 slope observed for kaons and ϕ-meson for the first time
- Results from UrQMD with baryonic mean-field potential qualitatively describe the measurement at 3GeV
- EoS dominated by the baryonic interactions at 3 GeV

Summary and Outlook

- Light and strangeness production in Au+Au 3 GeV collisions
  - Particle production mechanism may differ from that at high energy
  - ϕ/K^- and ϕ/Ξ^- show strong effect of canonical suppression, indicating a change of EoS

- Collectivity measurements in Au+Au 3 GeV collisions
  - The EoS dominated by baryonic interactions

Outlook

- Global thermal fit together with all other particles at 3 GeV on the way (T_{ch}, T_{kin}, μ_B)
- More data from STAR BES-II with upgraded detectors (iTPC+eTOF+EPD)
  - ~8-10 times more data @ 3 GeV from BES-II

backup

backup

170 A. Andronic et al. / Nuclear Physics A 772 (2006) 167–199

The basic quantity required to compute the thermal composition of hadron yields measured in heavy ion collisions is the partition function $Z(T, V)$. In the grand canonical (GC) ensemble, the partition function for species i is ($\hbar = c = 1$):

$$\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 \, dp \ln\left[1 \pm \exp\left(-(E_i - \mu_i)/T\right)\right], \quad (1)$$

172 A. Andronic et al. / Nuclear Physics A 772 (2006) 167–199

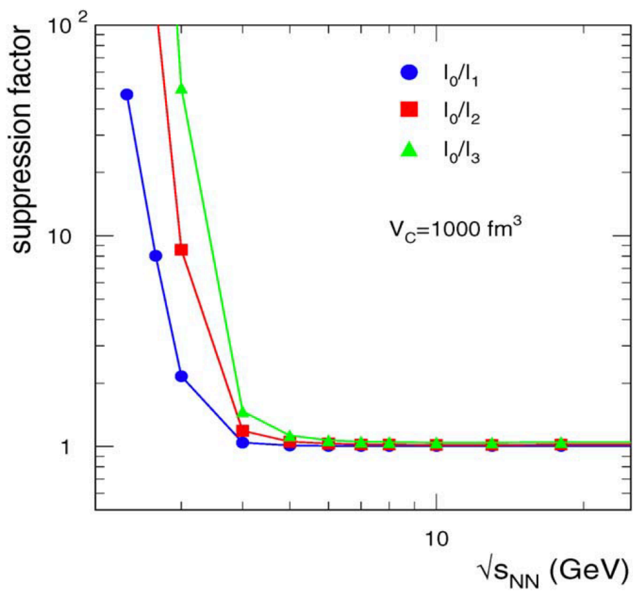


Fig. 2. The energy dependence of the canonical suppression factor for strangeness, calculated for the canonical volume $V_C = 1000$ fm^3.

NPA772: Nucl. Phys. A 772, 167 (2006);

NPA772: GCE+I_0/I_s + V_C=1000 fm^3

- Strangeness suppression start from < 5 GeV, a details dependent on the implement