Strangeness Production at high baryon density region from STAR experiment

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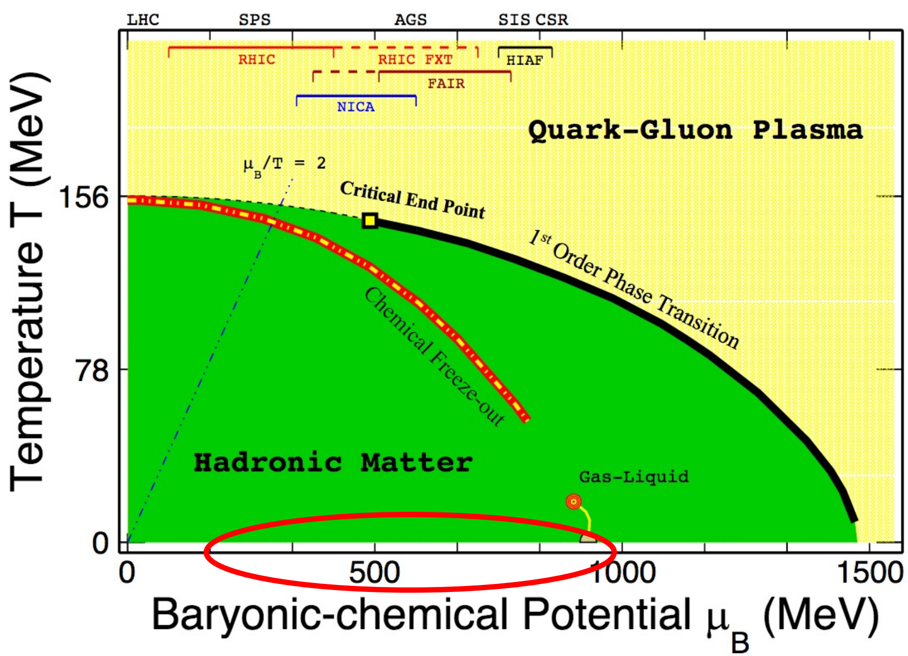
Outline

- Introduction
- STAR Fixed Target Program (FXT)
- Strangeness production in 3 GeV Au+Au collisions from STAR
  - Strangeness spectra
  - Strangeness yields
  - Strangeness yield ratios
  - Kinetic freeze-out properties
- Summary and Outlook

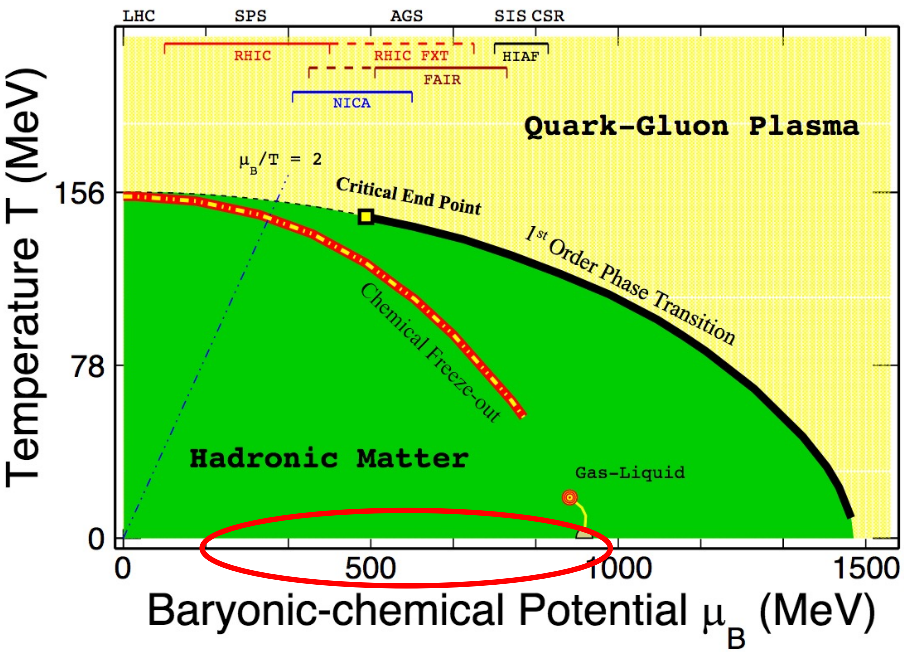
Nuclear collisions at high baryon density



- What is the state of matter in the high μ_B region?
- What is its equation of state?
- What are its temperature and thermodynamic properties?
- Is there a first order phase transition to the QGP phase?
- Do we understand strangeness production in this region?

Sooraj R., SQM2022 talk

Nuclear collisions at high baryon density



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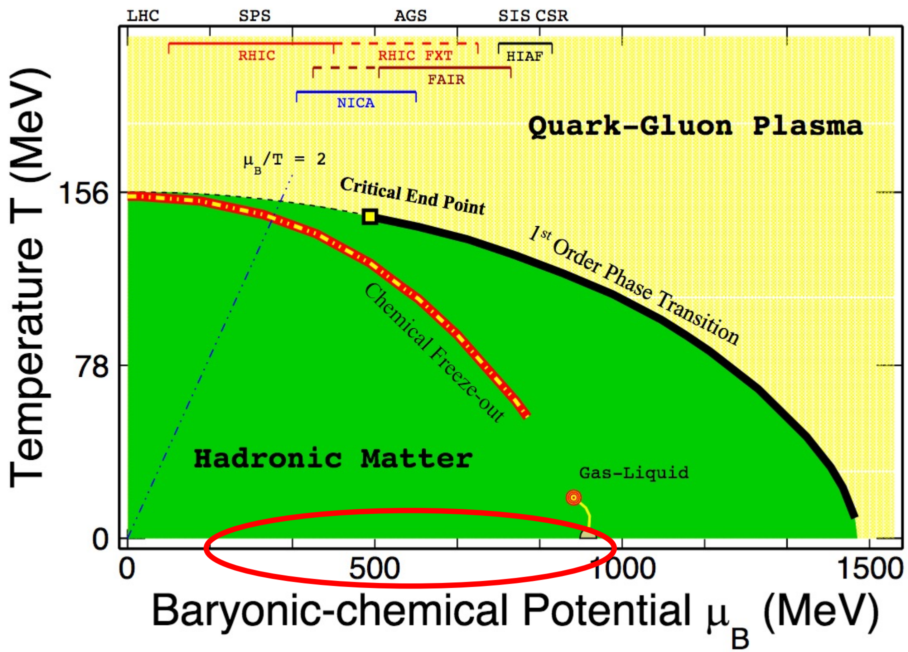

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Sooraj R., SQM2022 talk

- Light and strange hadron production and collectivity measurements are sensitive observables to answer these questions
- Lots of experiments focus in the region!
- STAR Beam Energy Scan-II has completed data taking, with FXT program extending the reach to high baryon density region of μ_B ~ 750 MeV and $\sqrt{s_{NN}}$ down to 3 GeV

STAR BES I and BES II

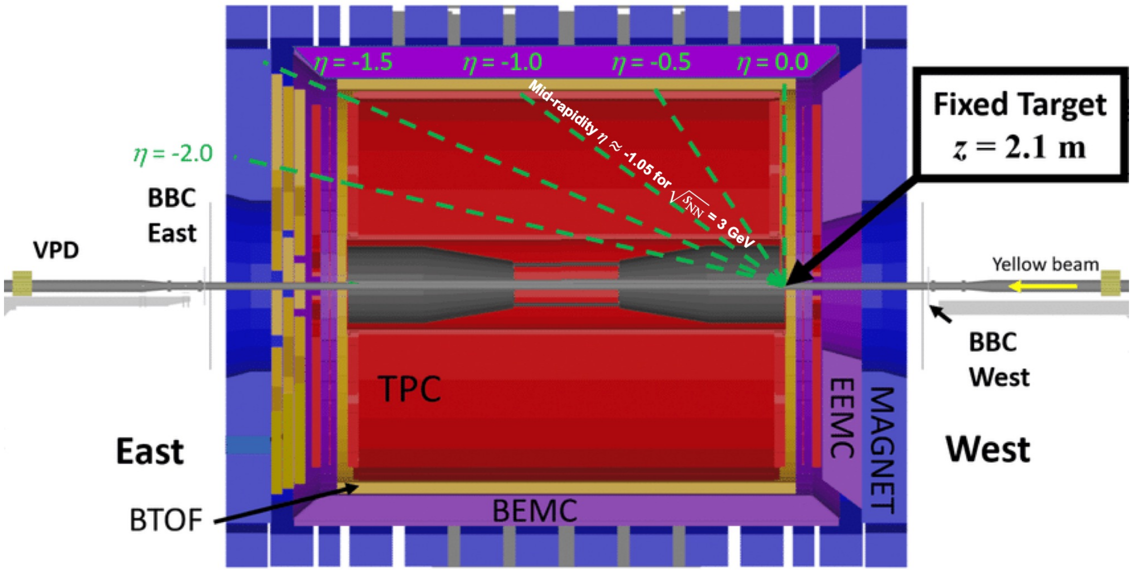
Au+Au Collisions at RHIC												
Collider Runs						Fixed-Target Runs						
	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run		$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	**200**	380 M	**25** MeV	5.3	Run-10, 19	1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	62.4	46 M	75 MeV		Run-10	2	**11.5 (70)**	50 M	320 MeV	-2.51	Run-21
3	54.4	1200 M	85 MeV		Run-17	3	**9.2 (44.5)**	50 M	370 MeV	-2.28	Run-21
4	39	86 M	112 MeV		Run-10	4	**7.7 (31.2)**	260 M	420 MeV	-2.1	Run-18, 19, 20
5	27	585 M	156 MeV	3.36	Run-11, 18	5	7.2 (26.5)	470 M	440 MeV	-2.02	Run-18, 20
6	19.6	595 M	206 MeV	3.1	Run-11, 19	6	6.2 (19.5)	120 M	490 MeV	1.87	Run-20
7	17.3	256 M	230 MeV		Run-21	7	5.2 (13.5)	100 M	540 MeV	-1.68	Run-20
8	14.6	340 M	262 MeV		Run-14, 19	8	4.5 (9.8)	110 M	590 MeV	-1.52	Run-20
9	**11.5**	157 M	316 MeV		Run-10, 20	9	3.9 (7.3)	120 M	633 MeV	-1.37	Run-20
10	**9.2**	160 M	372 MeV		Run-10, 20	10	3.5 (5.75)	120 M	670 MeV	-1.2	Run-20
11	**7.7**	104 M	420 MeV		Run-21	11	3.2 (4.59)	200 M	699 MeV	-1.13	Run-19
						12	**3.0** (3.85)	260 M, 2000 M	**750** MeV	-1.05	Run-18, 21

Nu Xu, SQM2022 talk

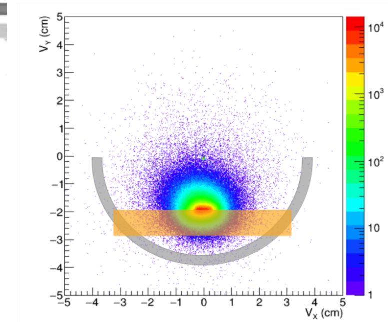
Precision data to map the QCD phase diagram

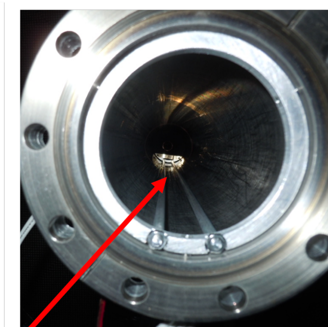
3 < $\sqrt{s_{NN}}$ < 200 GeV; 750 < μ_B < 25 MeV

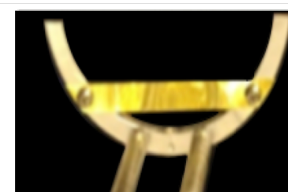
FXT setup at STAR



- Target was installed at the edge of TPC
- 260M events for Au+Au FXT at $\sqrt{s_{NN}}$= 3 GeV (year 2018)
- Good mid-rapidity coverage



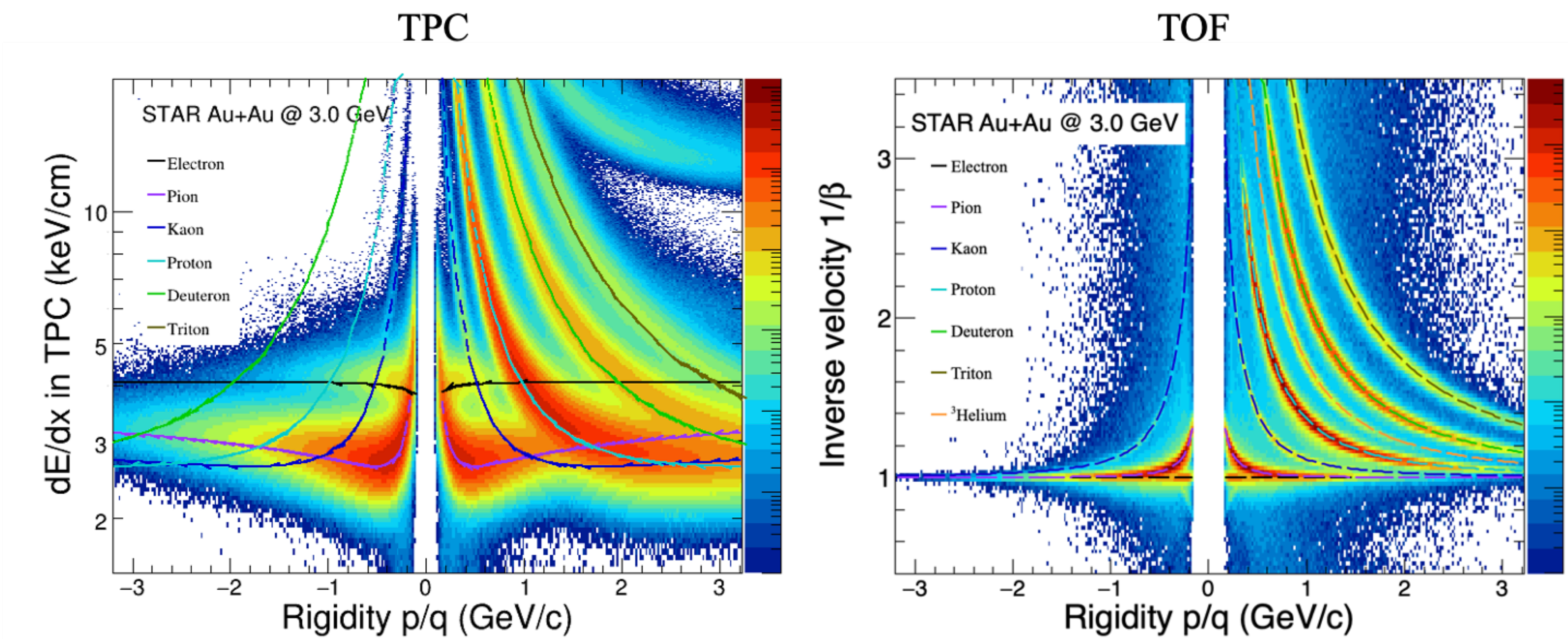




Au-Target = 0.25mm thickness
1% interaction probability

Conventions:
beam-going direction is the positive direction
In C.M. frame, for the 3 GeV collisions

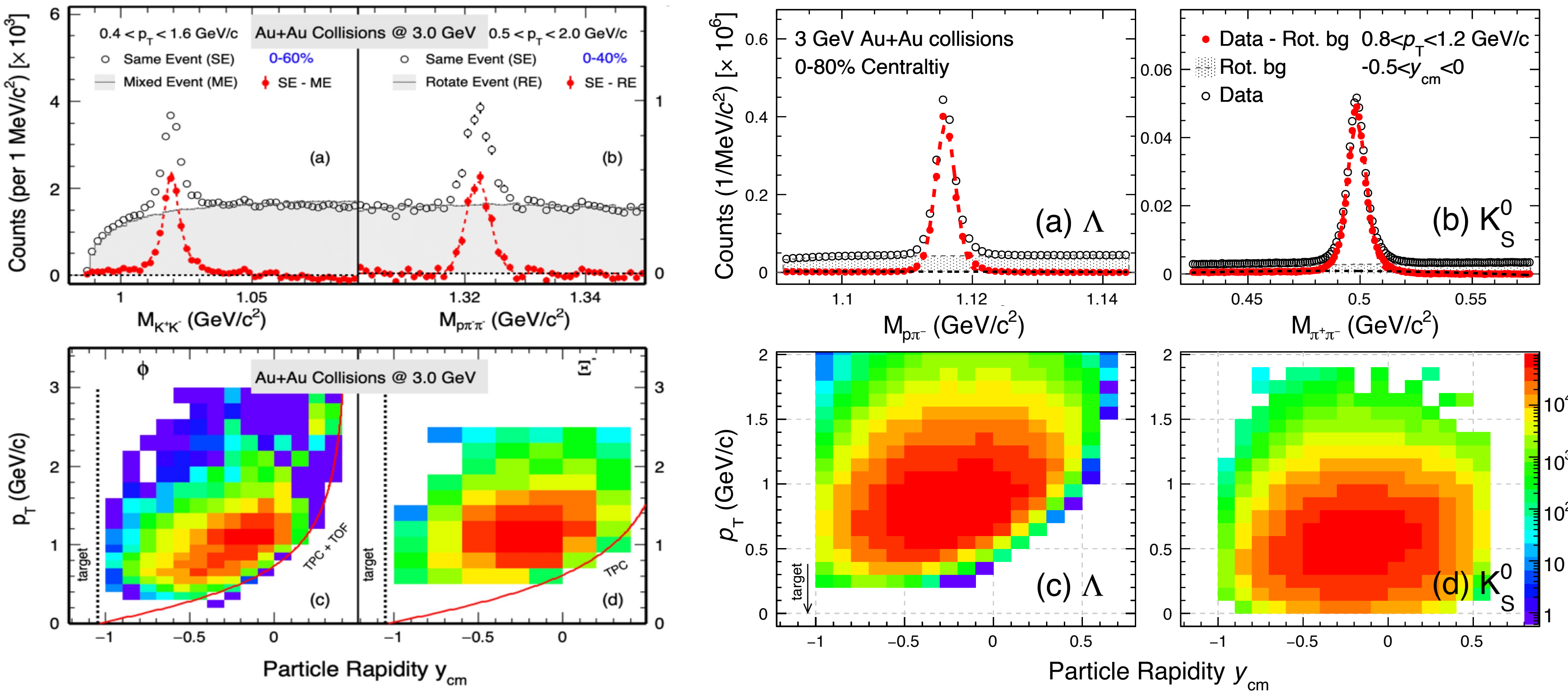
Particle Identification



- TPC (dE/dx) and TOF (β) for pion, kaon and proton particle identification
- K^- PID: TPC+TOF, Hybrid TOF PID for K^+
- Strange hadrons are reconstructed using invariant mass method

$$K_s^0 \rightarrow \pi^+\pi^-, \qquad \phi \rightarrow K^+K^-, \qquad \Xi^- \rightarrow \Lambda(\rightarrow p\pi^-)\pi^-$$

Particle reconstruction

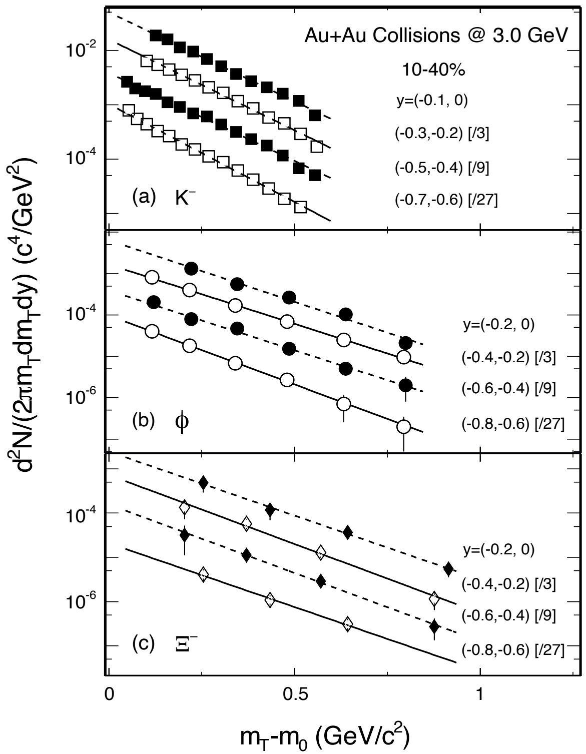


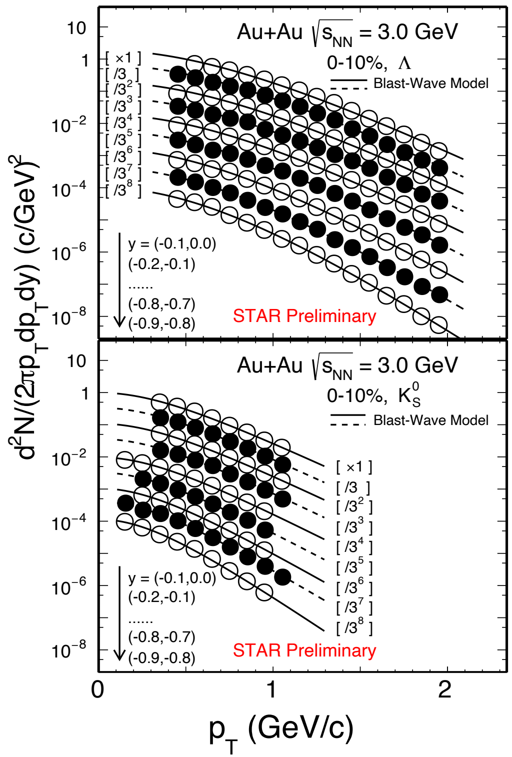
- KF Particle package is used for the strange hadron reconstruction to improve the signal significance

KF Particle Finder: M. Zyzak, Dissertation thesis, Goethe University of Frankfurt, 2016

- Combinatorial backgrounds are reconstructed by the rotation/mixing method

Strange hadron spectra





STAR K⁻, φ, Ξ⁻: Phys. Lett. B 831 (2022),137152

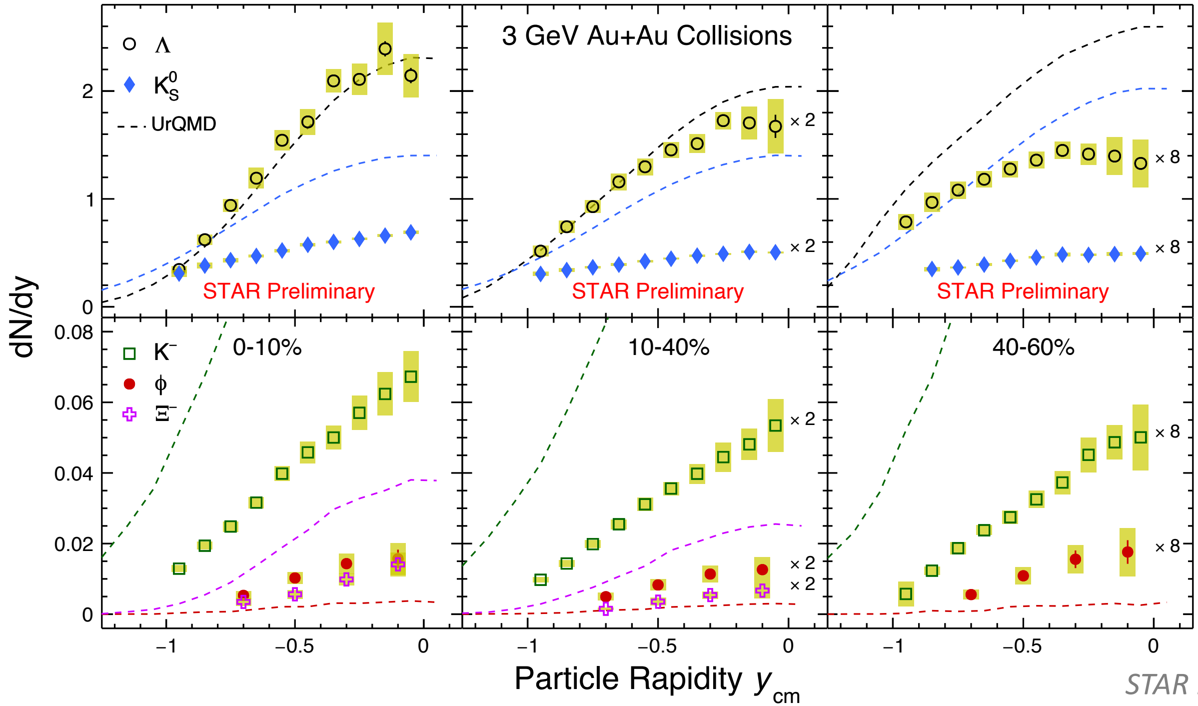
- High statistics dataset and mid-rapidity acceptance
- p_T spectra well described by Blast Wave fits

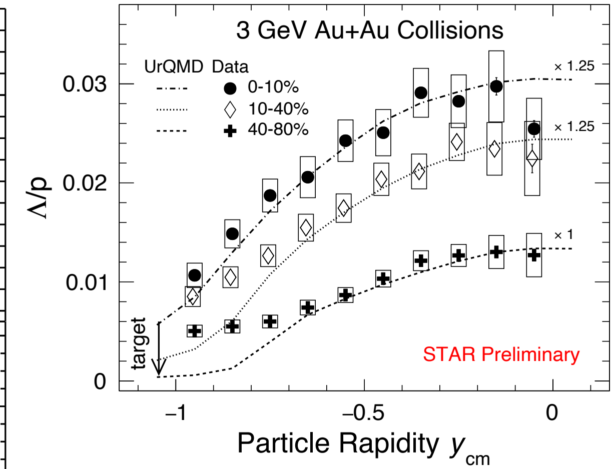
$$\frac{d^2N}{2\pi p_T dp_T dy} = A\int_0^R r dr m_T \times I_0\left(\frac{p_T \sinh\rho(r)}{T_{kin}}\right) K_1\left(\frac{m_T p \cosh\rho(r)}{T_{kin}}\right)$$

T_{kin}: the kinetic freeze-out temperature
$\langle\beta_T\rangle$: average transverse radial flow velocity
n: the exponent of flow velocity profile, n=1
I_0 and K_1 are from Bjorken Hydrodynamic assumption

- Tracking efficiency and detector acceptance are estimated with GEANT simulations embedded into real events
- Alternative fit functions are used to estimate the systematic uncertainty in dN/dy

Strange hadron yields





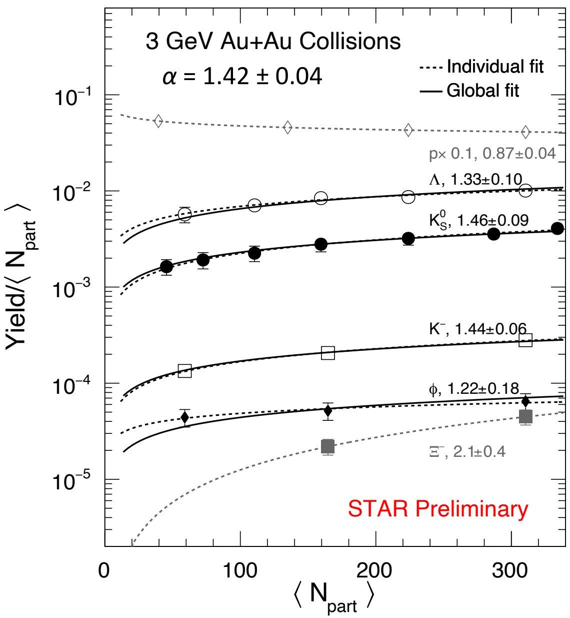
UrQMD: 0-10% and 10-40% centrality are scaled up by 25%

STAR K⁻, φ, Ξ⁻: Phys. Lett. B 831 (2022),137152

- Rapidity dependent yields obtained from integrating data and Blast-wave function (or m_T exponential function) fits of spectra for the unmeasured p_T region
- UrQMD reproduces the yields of Λ except in the 40-60% centrality bin, but overestimates K_S^0, K^-, Ξ^- and underestimates ϕ mesons
- Λ/p ratio larger at mid-rapidity: constraints for strangeness and hypernuclei production at high μ_B

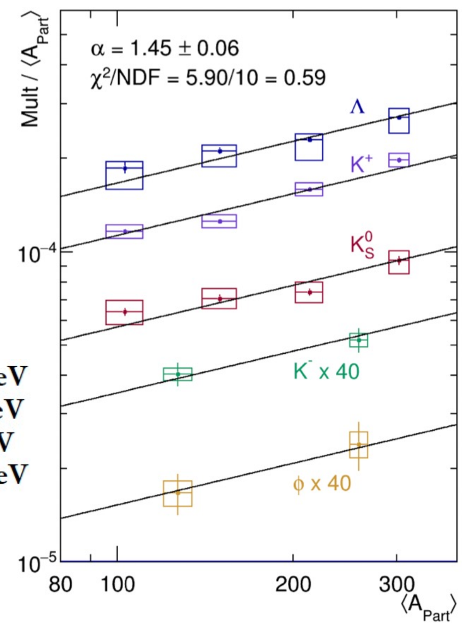
Strange hadron yields vs N_{part}

STAR: Au+Au 3.0 GeV

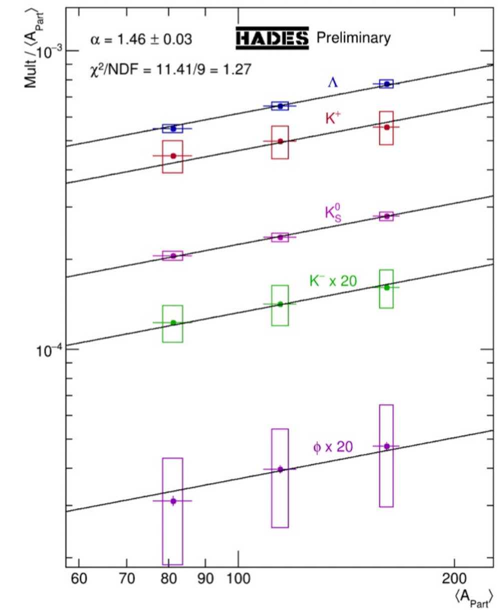


$K^0_S\ \sqrt{s_{thr}} \sim 2.55$ GeV
$\Lambda\ \sqrt{s_{thr}} \sim 2.55$ GeV
$\phi\ \sqrt{s_{thr}} \sim 2.89$ GeV
$\Xi^-\ \sqrt{s_{thr}} \sim 3.25$ GeV

HADES: Au+Au 2.42 GeV



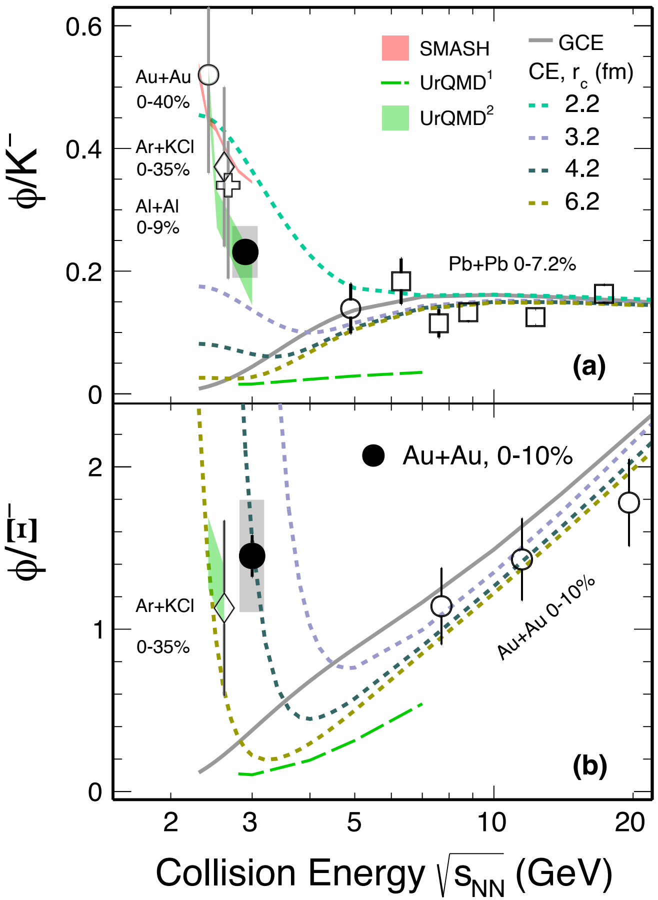
HADES: Ag+Ag 2.55 GeV



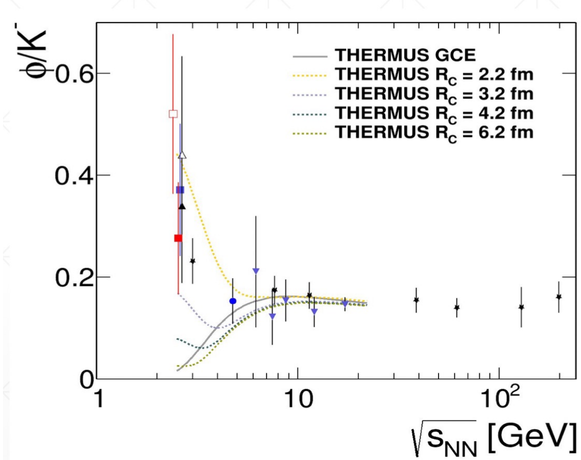
HADES, Phys. Lett. B 793 (2019) 457

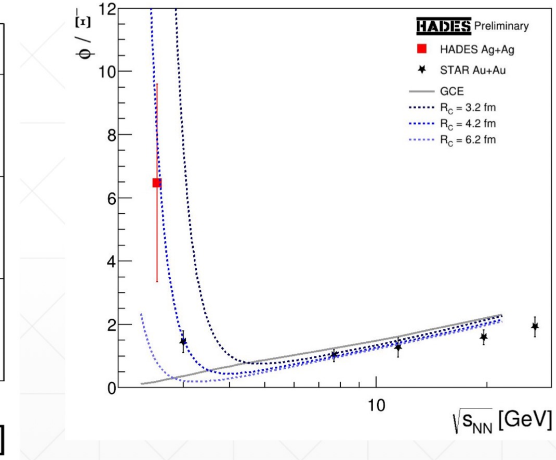
- Strange hadron yields proportional to $<N_{part}>^{\alpha}$, with α ~ 1.4, despite different production thresholds
- Ξ^- seems to deviate from the scaling trend
- Yields scale with total strangeness production: Percolation of meson cloud? Soft deconfinement? *K. Fukushima, et al, Phys. Rev. D 102, 096017 (2020)*

Strange hadron yield ratio



STAR K-, φ, Ξ-: Phys. Lett. B 831 (2022),137152



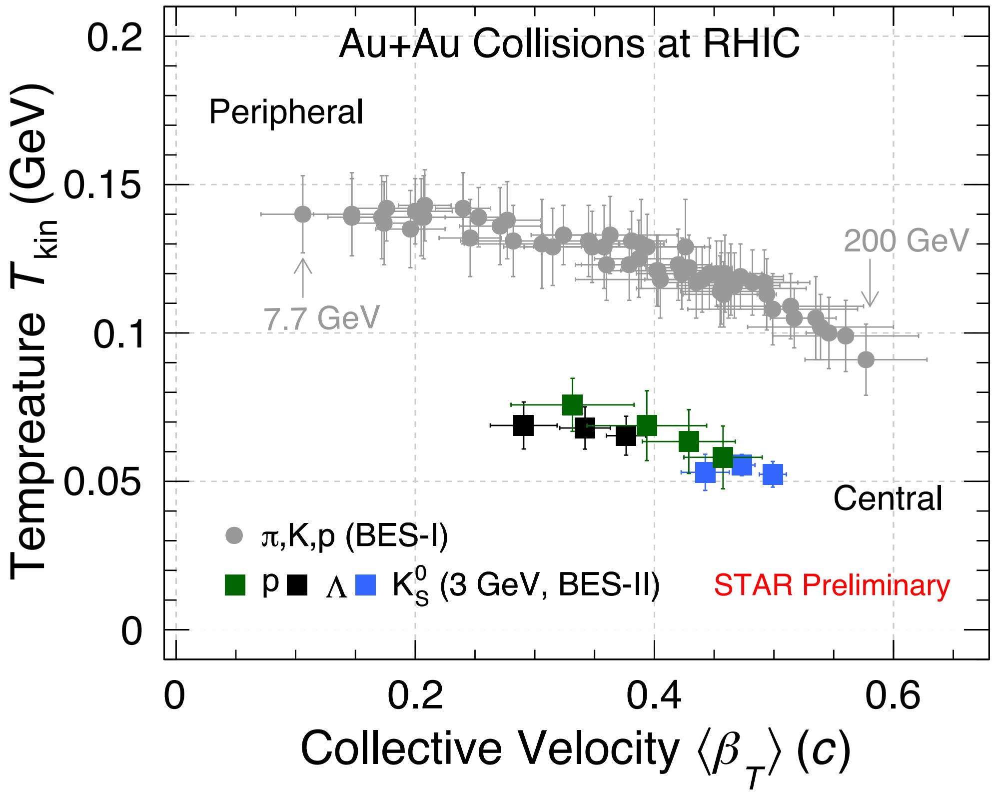


- Local strangeness conservation is required!
  → GCE to CE transition!
- Can help to constrain strangeness correlation length in the medium
- Default UrQMD failed to describe the data
- Transport models with high-mass resonance decay to ϕ and Ξ^- can describe the data

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

UrQMD[1]: Prog. Part. Nucl. Phys. 41 (1998) 225-370
UrQMD[2]: J. Phys. G: Nucl. Part. Phys. 43 015104
Thermal CE: Phys. Lett. B 603, 146 (2004)

Kinetic freeze-out properties



STAR BES-I:
Phys. Rev. C. 96. (2017) 044904,
Phys. Rev. C 102 (2020) 34909

- Λ and K_s^0: Similar value for freeze-out velocity but much lower temperatures at 3 GeV
- Freeze-out T_{kin} and $<\beta_T>$ for proton also show similar trend as Λ and K_s^0 at 3 GeV
- Implying different EOS at freeze-out at 3 GeV: **hadronic interaction dominant!**

Summary

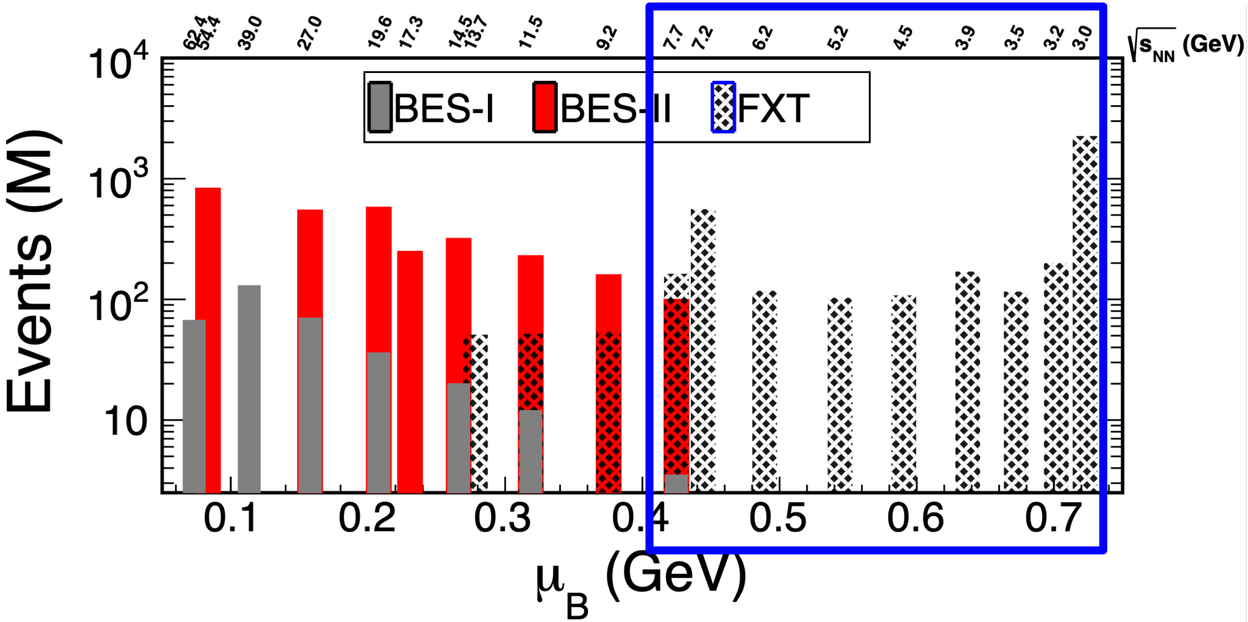
- Presented measurements on strangeness production in 3 GeV Au+Au collisions
  - ✓ Precise centrality & rapidity dependence of yields
  - ✓ ϕ/K^- and ϕ/Ξ^- show canonical suppression of strangeness *Phys. Lett. B 831 (2022),137152*
  - ✓ Λ and K_s^0 spectra indicate lower kinetic freeze-out temperature than pion, Kaon, proton at higher energy collisions *SQM2022 talk*

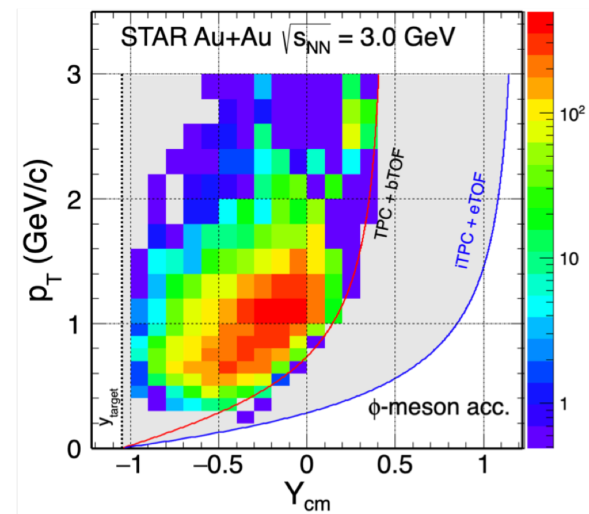
- At 3 GeV, the measured v_2 for all particles are negative and the NCQ scaling breaks, especially for positive charged particles *Phys. Lett. B 827 (2022),137003*
- The suppression of C_4/C_2 is consistent with fluctuations driven by baryon number conservation which indicates a hadronic interaction dominated region in the top 5% central Au+Au collisions at 3 GeV *Phys. Rev. Lett. 128 (2022), 202303*
- The freeze-out parameter (T_{kin}) of deuteron is systematically higher than that of proton at 3 GeV, which is different from higher energies *QM2022 talk*

→ All results from 3 GeV Au+Au collisions: particle production mechanism dominated by hadronic interactions

Outlook

- 2B Au+Au events at $\sqrt{s_{NN}}$ = 3 GeV collected in 2021
- High statistics data at high μ_B region from STAR BES II $\sqrt{s_{NN}}$ = 3 – 7.7 GeV, iTPC + eTOF
- Measurements of strangeness production at several different FXT energies ongoing, expect many more exciting results soon





Thanks for your attention!
Many thanks to Organizers!