Strangeness and HyperNuclei Production in the High Baryon Density Region

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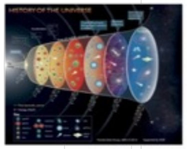
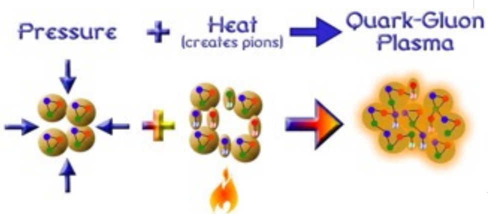
- Introduction
- STAR Experiment & BES-II
- Strangeness Productions @ High μ_B
  - Centrality & rapidity dependence
- HyperNuclei Productions @ High μ_B
  - Properties & energy dependence
- Summary and Outlook

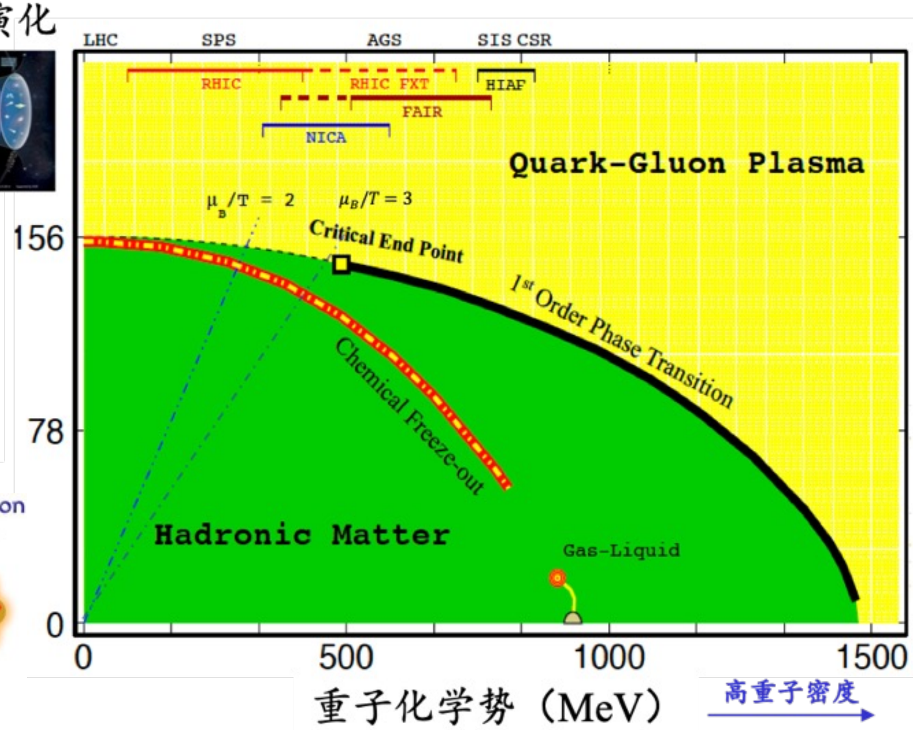
Quark-Gluon Plasma and QCD

宇宙早期演化

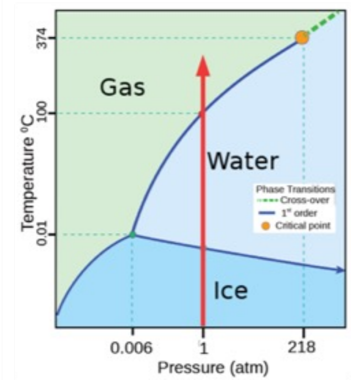


QCD: confinement & asymptotic freedom





类比水的相变图



中子星

Conjectured phase diagram of strong interaction matter

- Lattice QCD predicts a state of deconfined QCD matter at high temperature/density
- QGP expected to exist in early universe($t \sim 10^{-6}$s) and compact object
- Exploring QCD matter properties and phase structure are crucial

Experimental Exploring of QCD Matters

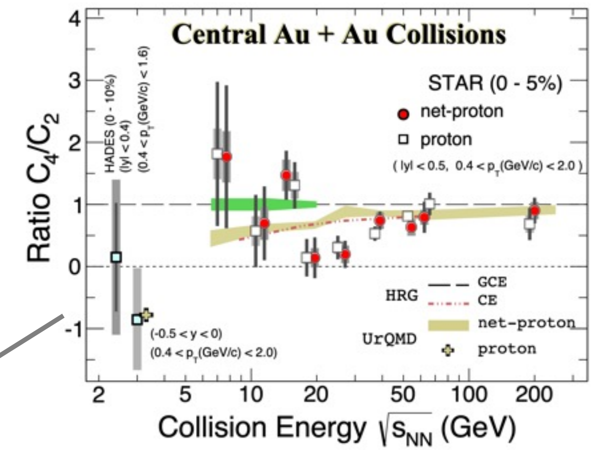
Particle production:
- ➢ Understand medium properties and different particle production mechanisms

Collective flow:
- ➢ Study properties of the produced medium, EoS

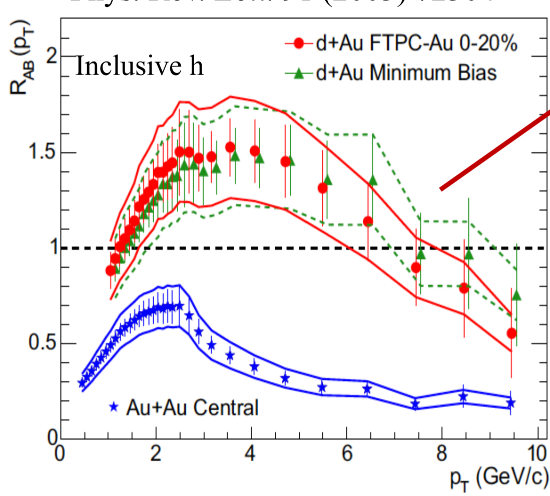
Correlations and Criticality:
- ➢ Critical Point

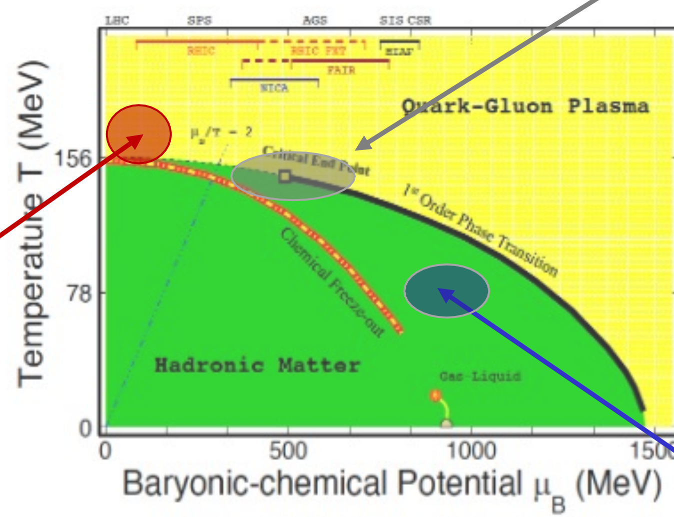
……

Phys. Rev. Lett. 128 (2022) 202303

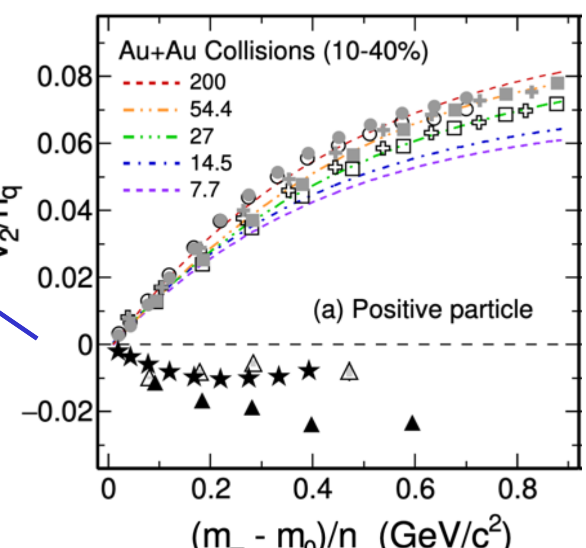


Phys. Rev. Lett. 91 (2003) 72304





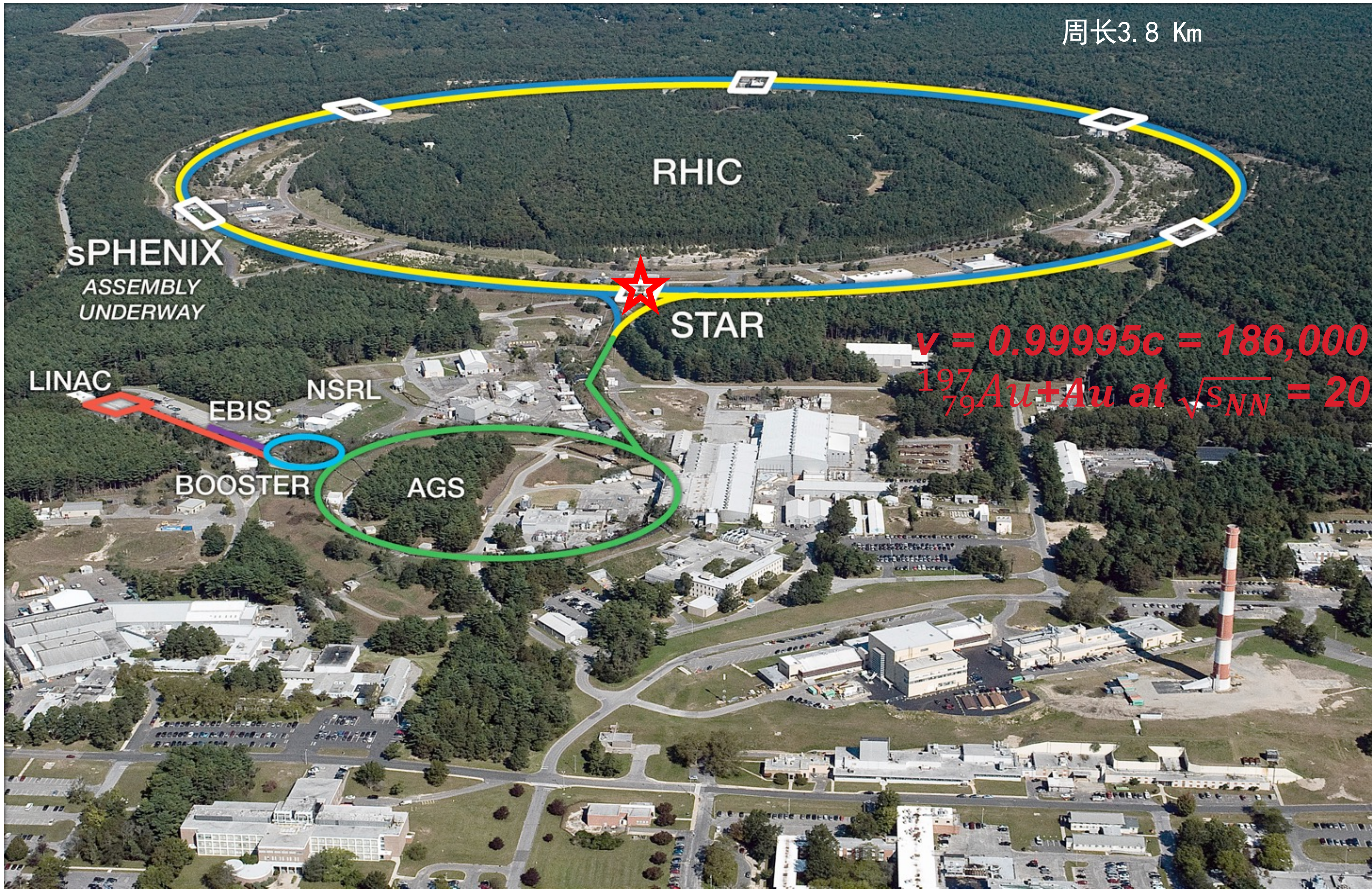
Phys. Lett. B 827 (2022) 137003



- Jet quenching, Strangeness enhancement, flow NCQ scaling, heavy flavor R_{AA}, etc
- High order Cumulants, light nuclei ratios
- NCQ disappearing, strangeness CE

RHIC

Brookhaven National Laboratory (BNL), Upton, NY

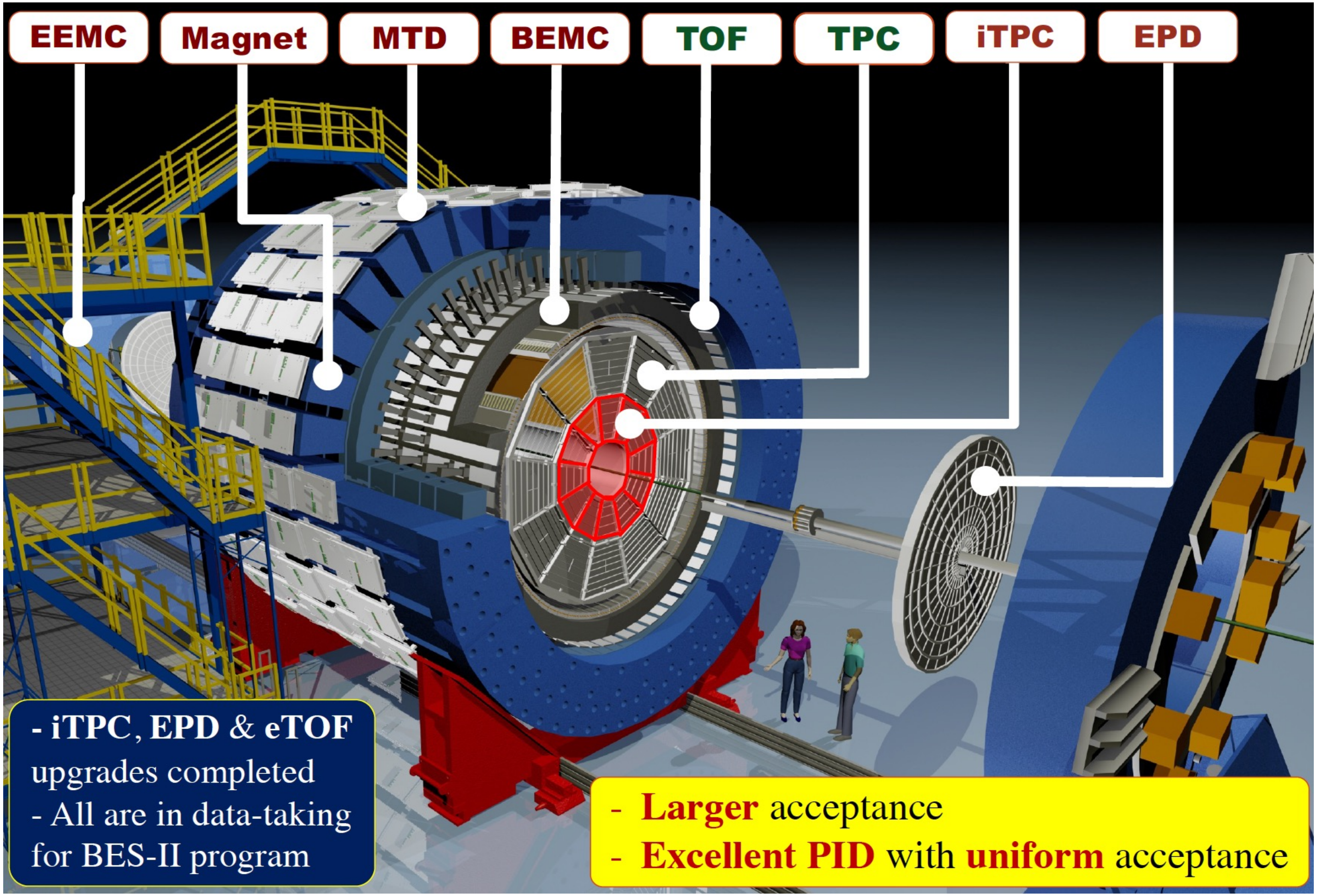


v = 0.99995c = 186,000 miles/sec

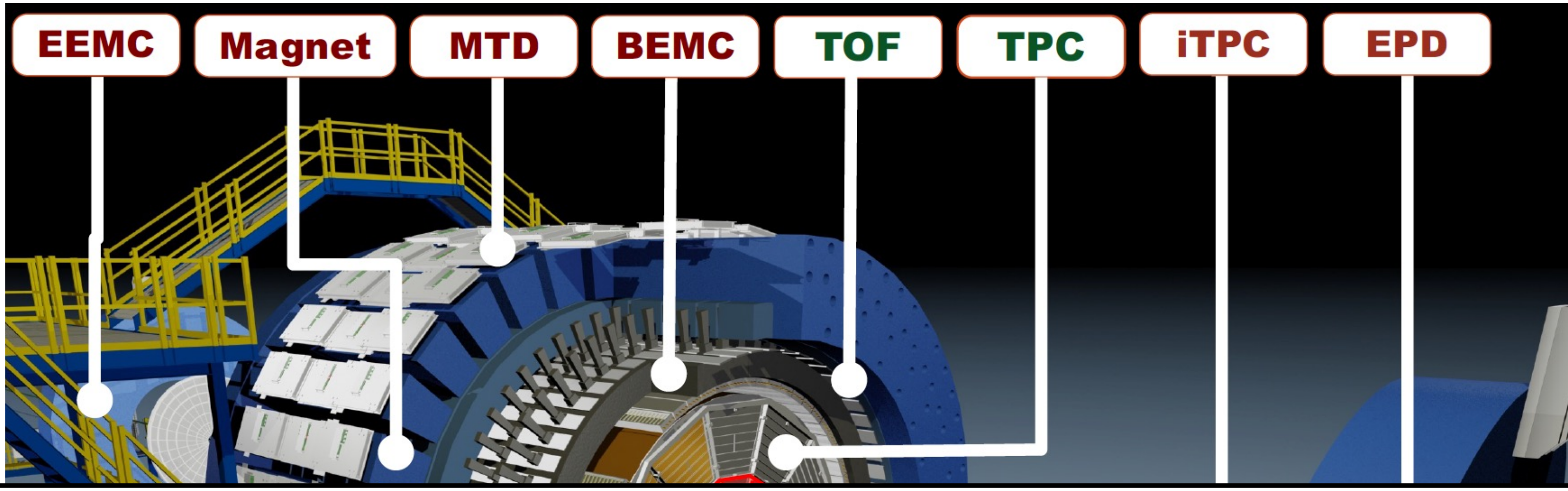
$^{197}_{79}Au$+*Au at* $\sqrt{s_{NN}}$ = *200 GeV*

Relativistic **H**eavy **I**on **C**ollider

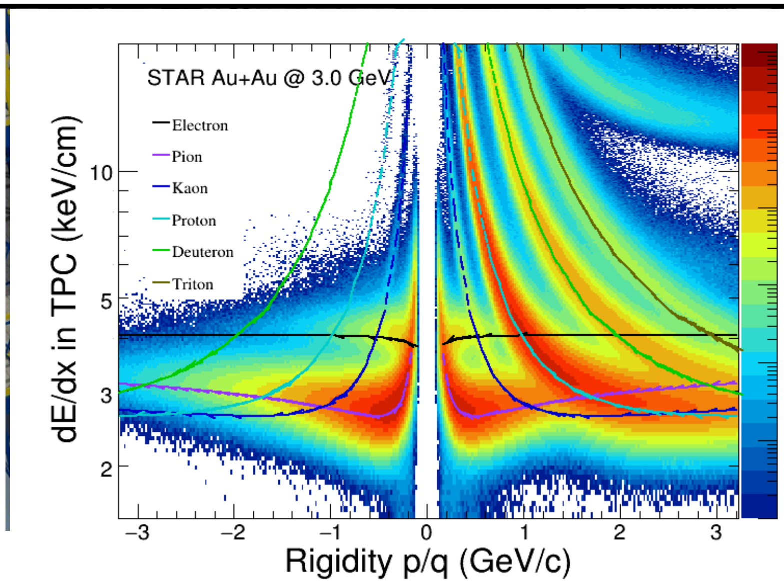
STAR Experimental

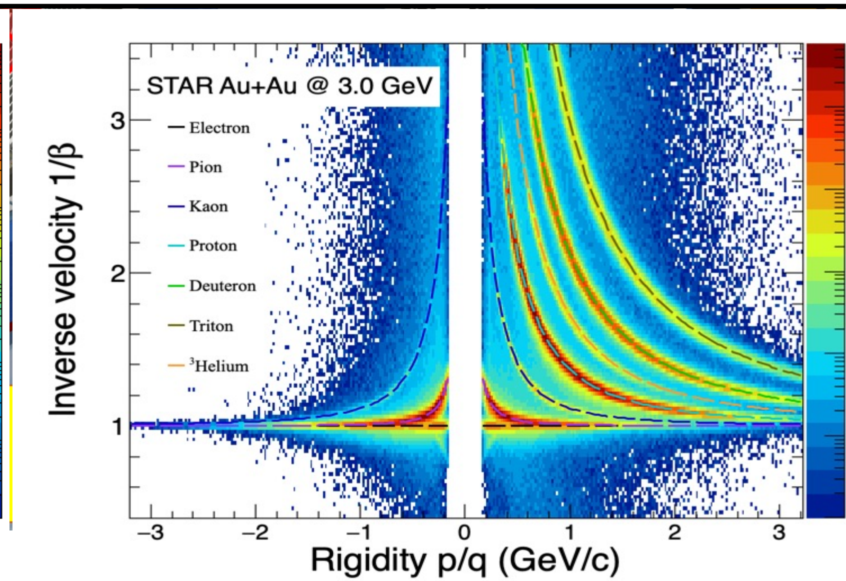


STAR Experimental

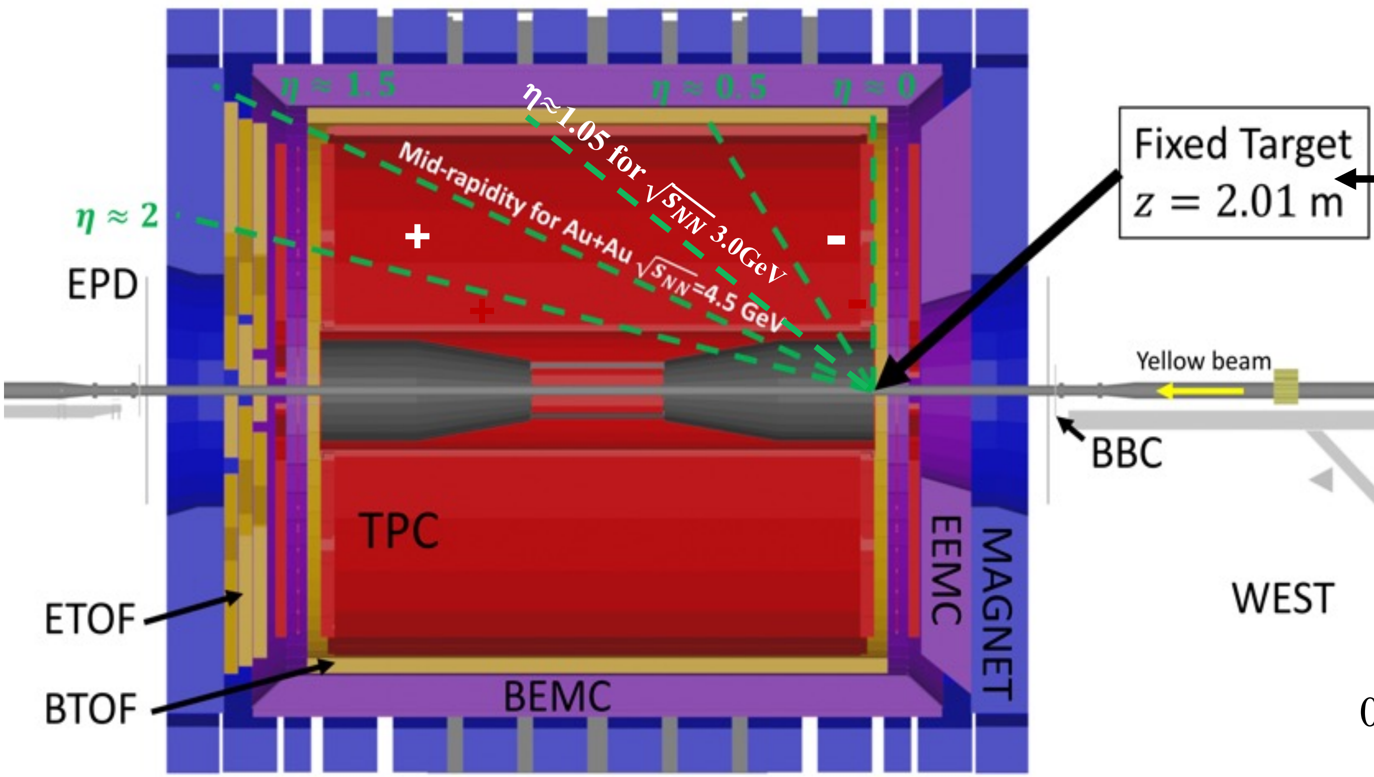


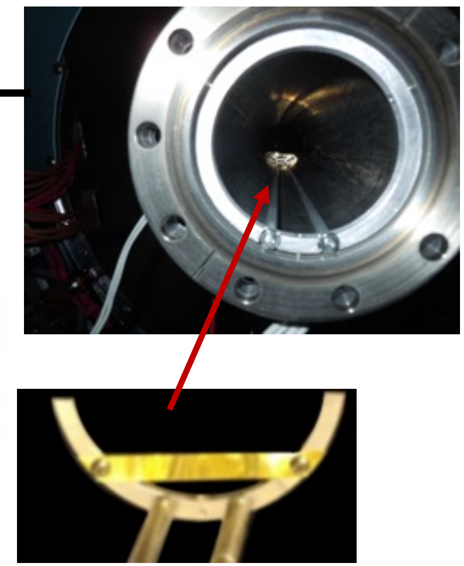
Very good dE/dx and *1/β* resolution for the charged particle identification





FXT Setup @ STAR





0.25 mm thickness Au-Target

Good mid-rapidity coverage for STAR FXT 3 GeV (and up to 4.5GeV)

Conventions: beam-going direction is the positive direction

STAR Beam Energy Scan

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	380M	25MeV	5.3	r10,19	1	13.7(100)	50M	280MeV	-2.69	r21
2	62.4	46M	75MeV		r10	2	11.5(70)	50M	320MeV	-2.51	r21
3	54.4	1200M	85MeV		r17	3	9.2(44.5)	50M	370MeV	-2.28	r21
4	39	86M	112MeV		r10	4	7.7(31.2)	260M	420MeV	-2.1	r18,19,20
5	27	585M	156MeV	3.36	r11,18	5	7.2(26.5)	470M	440MeV	-2.02	r18,20
6	19.6	595M	206MeV	3.1	r11,19	6	6.2(19.5)	120M	490MeV	-1.87	r20
7	17.3	256M	230MeV		r21	7	5.2(13.5)	100M	540MeV	-1.68	r20
8	14.6	340M	262MeV		r14,19	8	4.5(9.8)	110M	590MeV	-1.52	r20
9	11.5	57M	316MeV		r10,20	9	3.9(7.3)	120M	633MeV	-1.37	r20
10	9.2	160M	372MeV		r10,20	10	3.5(5.75)	120M	670MeV	-1.2	r20
11	7.7	104M	420MeV		r21	11	3.2(4.59)	200M	699MeV	-1.13	r19
						12	3.0(3.85)	260+ 2000M	760MeV	-1.05	r18,20

Most Precise data to map the QCD phase diagram, $3 < \sqrt{s_{NN}} < 200\ GeV; 760 > \mu_B > 25\ MeV;$

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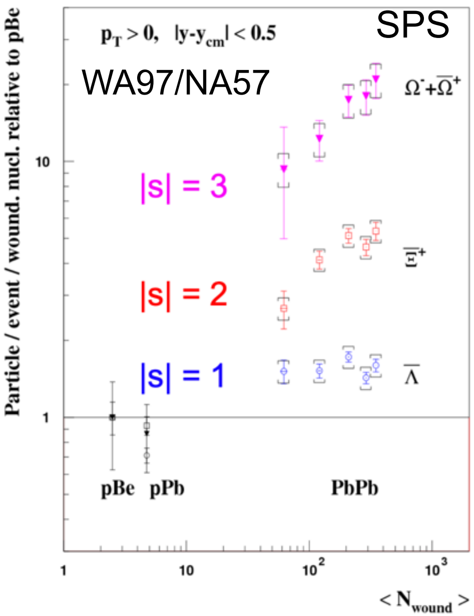
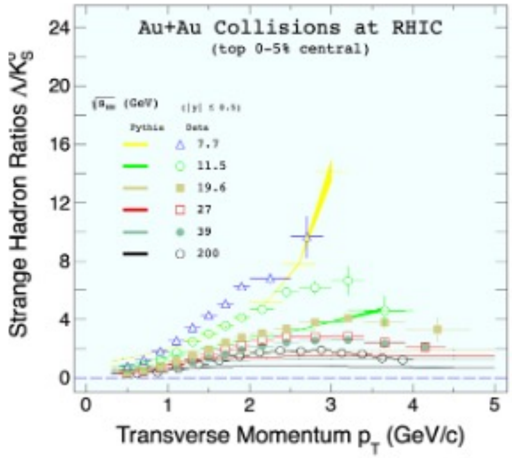
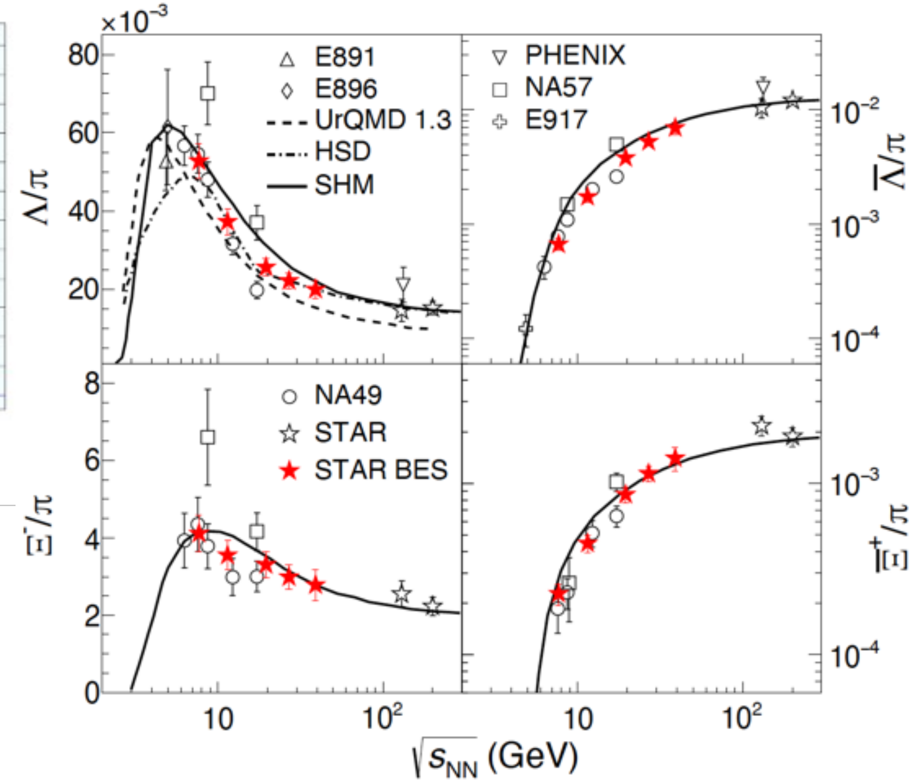
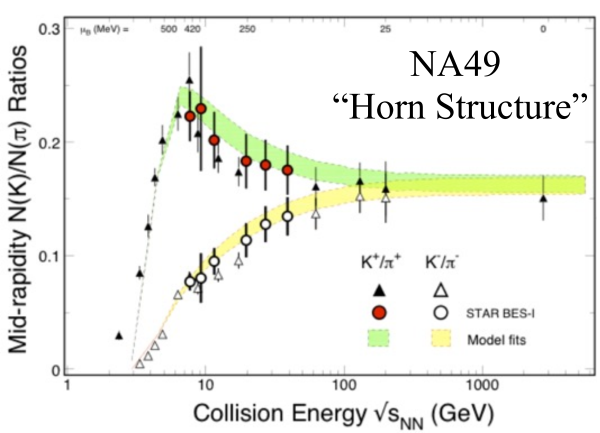
Previous Strange Hadron Measurements

Phys. Rev. C 102 (2020) 34909







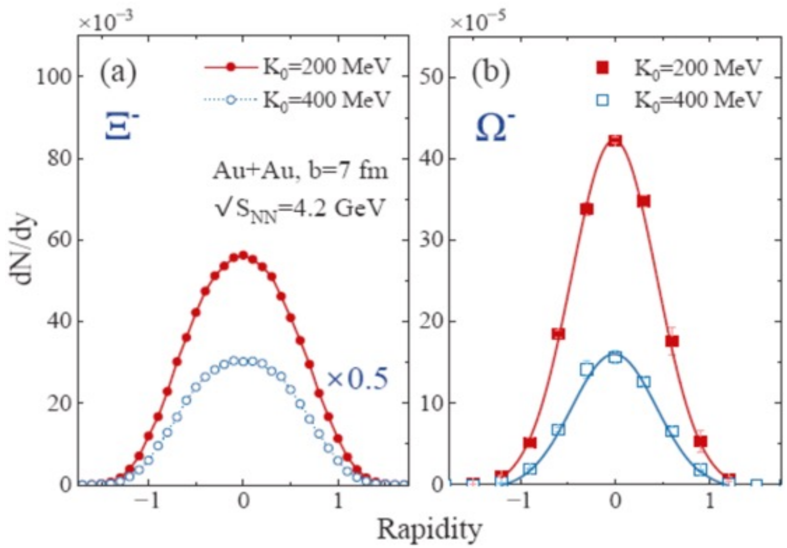


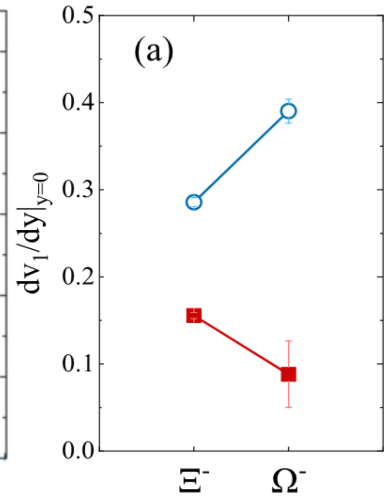
- Historically Strangeness enhancement as a signature of QGP
- Production mechanisms may be very different at high and low baryon density
  - Pair production vs. associate production ($N + N \rightarrow N + Y + K^{+}$)
  - GCE vs. CE (conservation)? Transport approaches?

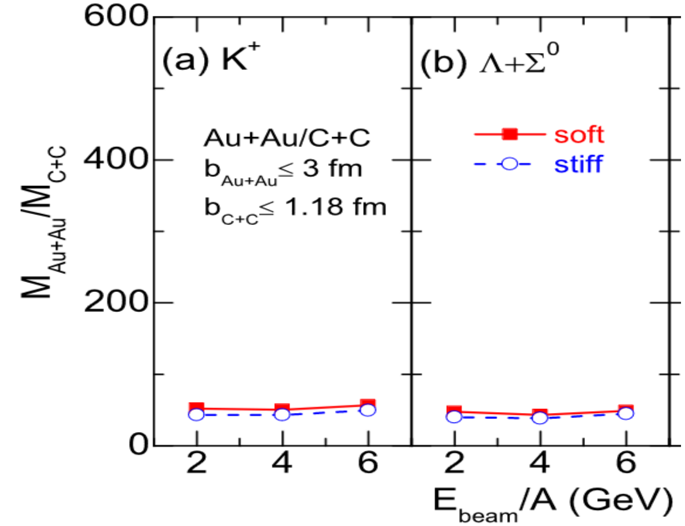
Models: Multi-Strange Hadrons to Probe EoS

Phy. Lett. B 820 (2021) 136521, arXiv:2307.06502
Phys.Rev.C 106 (2022) 2, 024902

$K + \Xi \rightleftharpoons \pi + \Omega$







$\mathrm{NN} \longrightarrow YK^+N, E_{th}(s_{NN}) = 2.55GeV$
$\mathrm{NN} \longrightarrow K^-K^+NN, E_{th} = 2.86GeV$

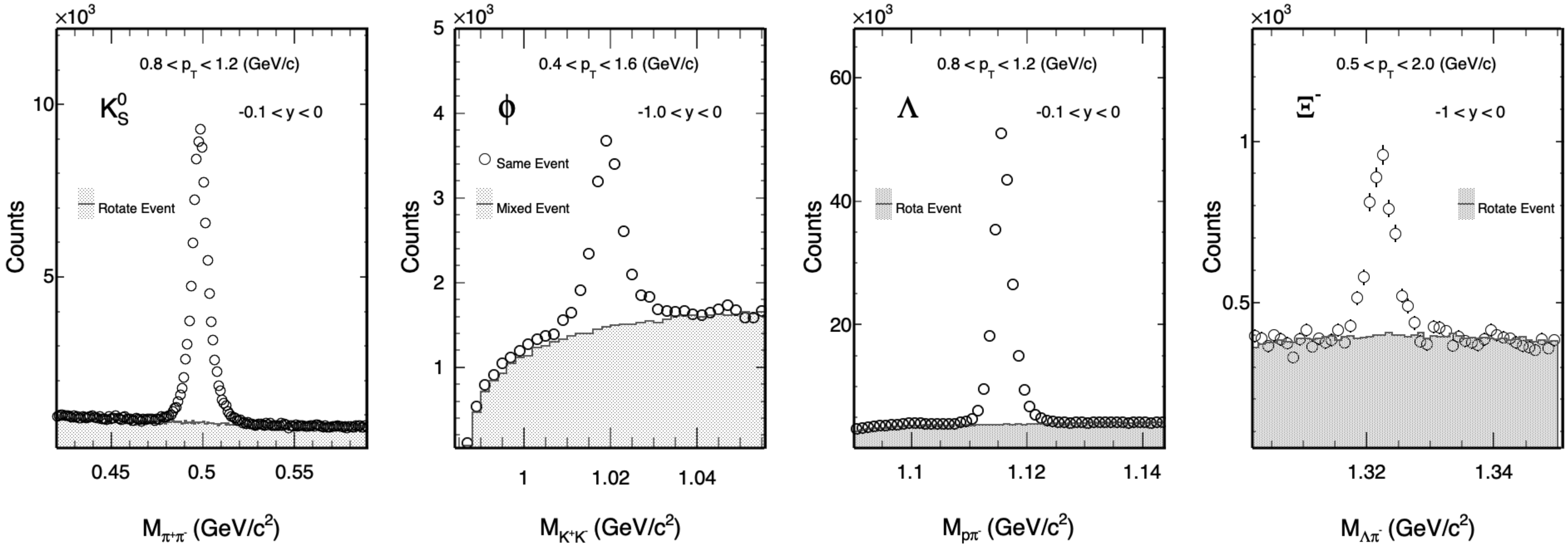
$\mathrm{NN} \longrightarrow \phi NN, E_{th} = 2.89GeV$
$\mathrm{NN} \longrightarrow N\Xi^-K^+K^-, E_{th} = 3.25GeV$
$\mathrm{NN} \longrightarrow N\Omega KKK, E_{th} = 4.1GeV$

- Theory predict that mutli-strange hadrons are sensitive to the Equation of State, **especially near the production threshold**, ϕ, Ξ^- & Ω

Particle Reconstruction

STAR Au+Au @ 3 GeV

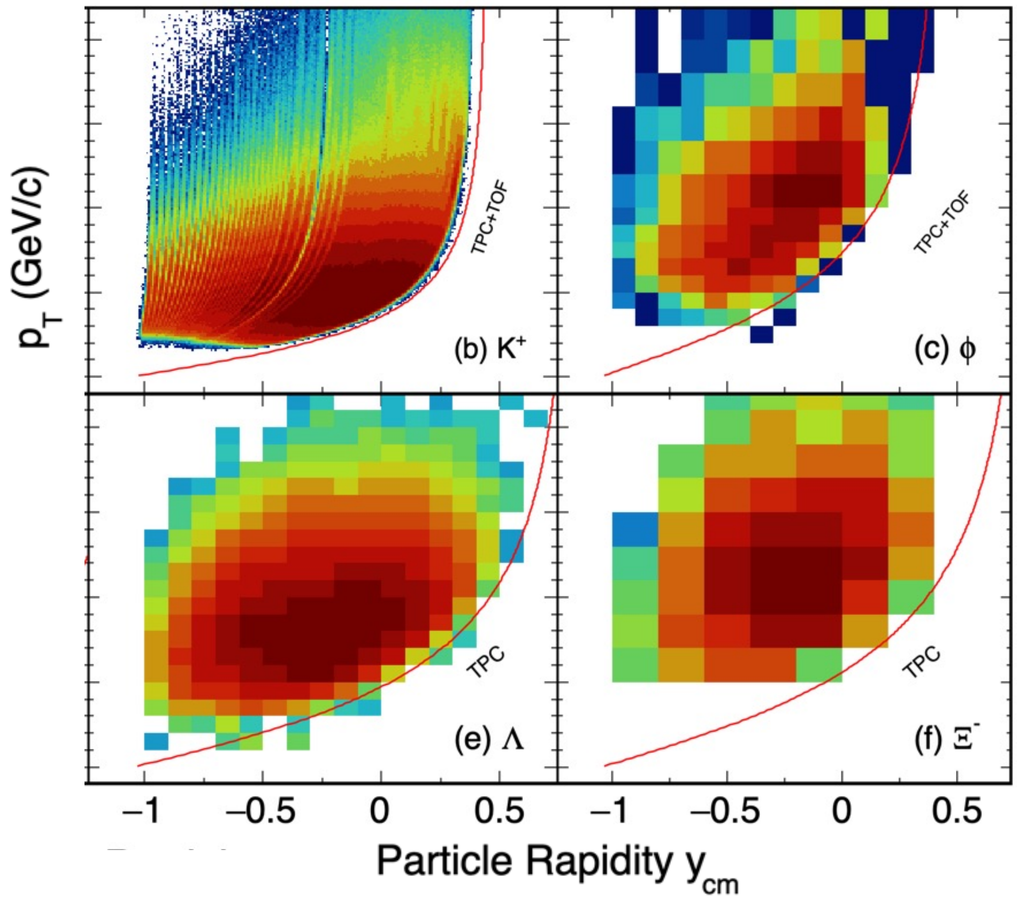
$K_S^0 \rightarrow \pi^+ \pi^-$ $\phi \rightarrow K^+K^-$, $\Lambda \rightarrow p\pi^-$, $\Xi^- \rightarrow \Lambda\pi^-$



- 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

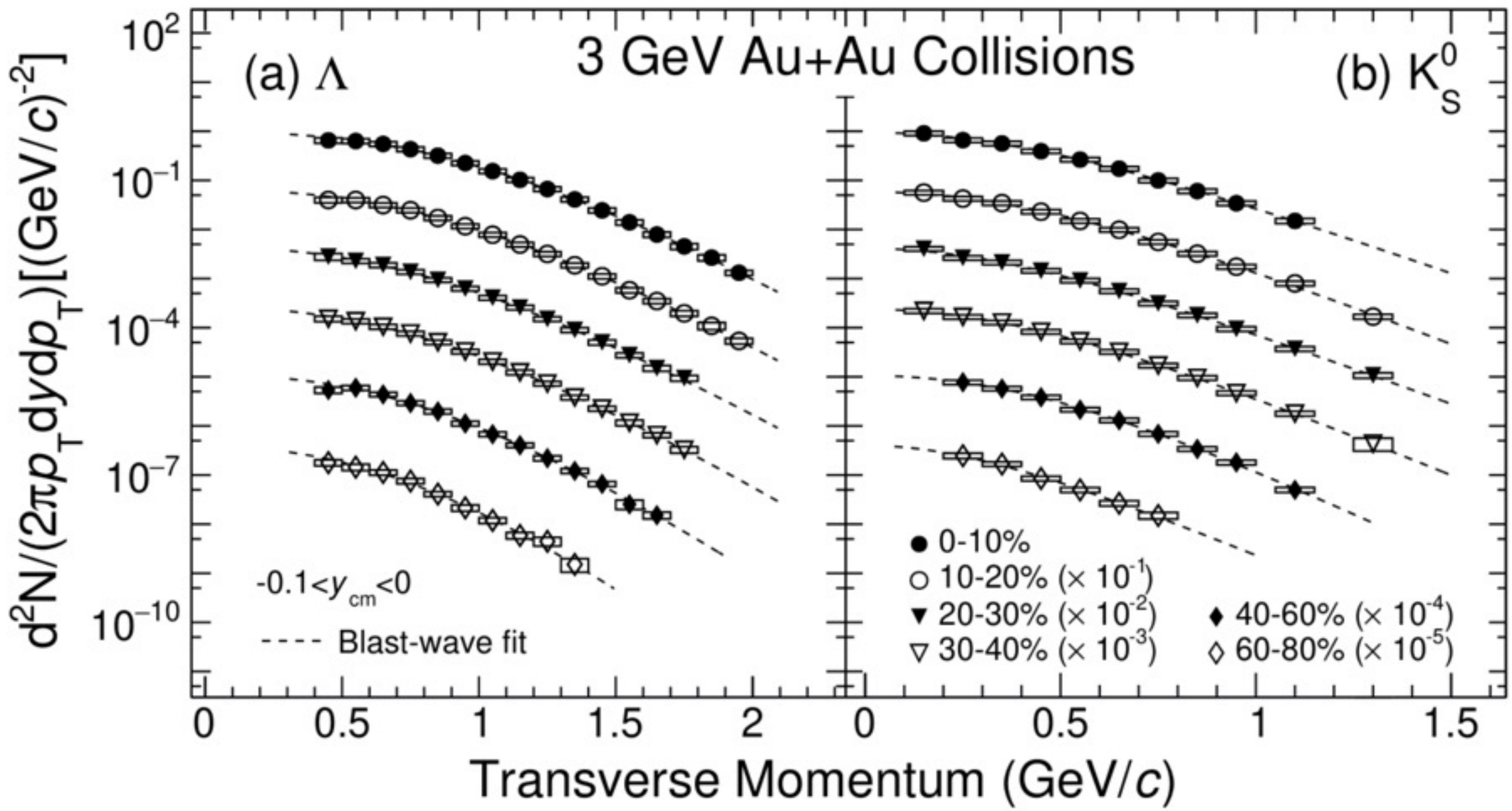
STAR Au+Au @ 3 GeV



- The acceptance plot p_T versus rapidity measured from STAR @ 3 GeV (TPC and TOF) for K, K_S^0, Λ, ϕ and Ξ^-
  - Good mid-rapidity coverage, which is critical

Transverse Momentum Spectra

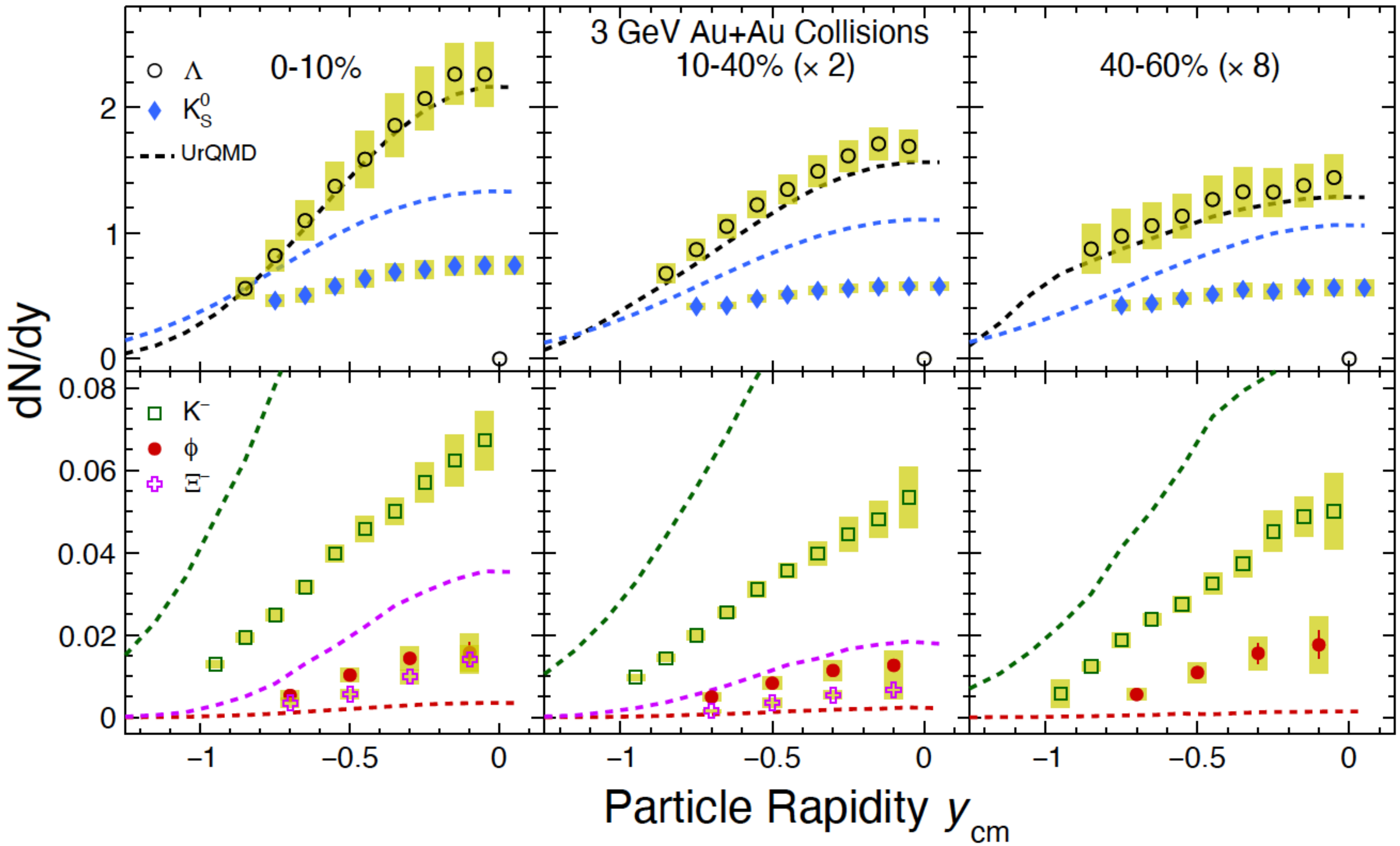
ϕ, Ξ^-: Phys. Lett. B 831 (2022) 137152, K_s^0, Λ: under review



- Tracking efficiency and acceptance effects estimated by GEANT simulations embedded into real events
- Extrapolate to zero p_T to obtain the dN/dy and $\langle p_T \rangle$

Rapidity Density Distributions

ϕ, Ξ^-: Phys. Lett. B 831 (2022) 137152, K_s^0, Λ: under review

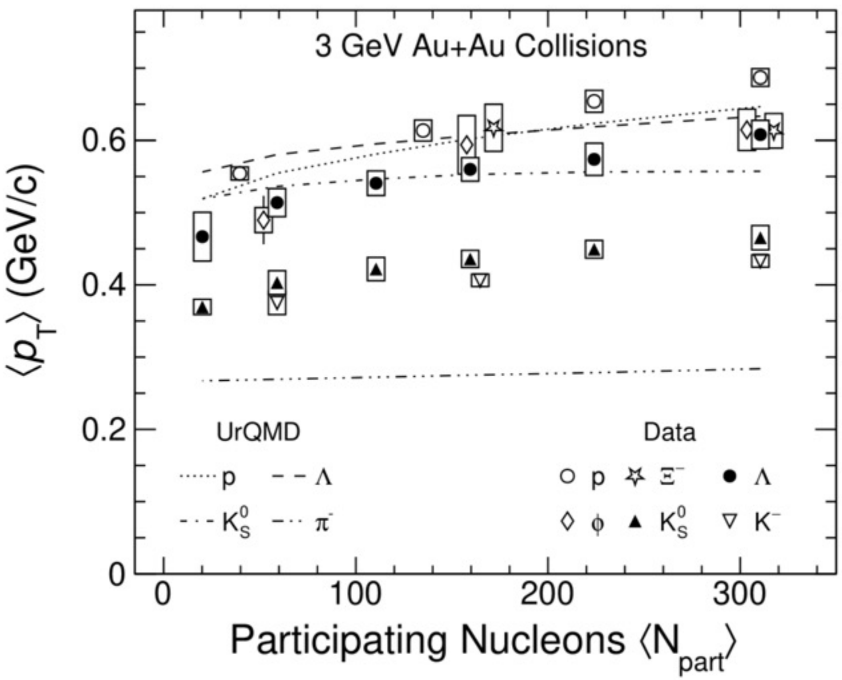


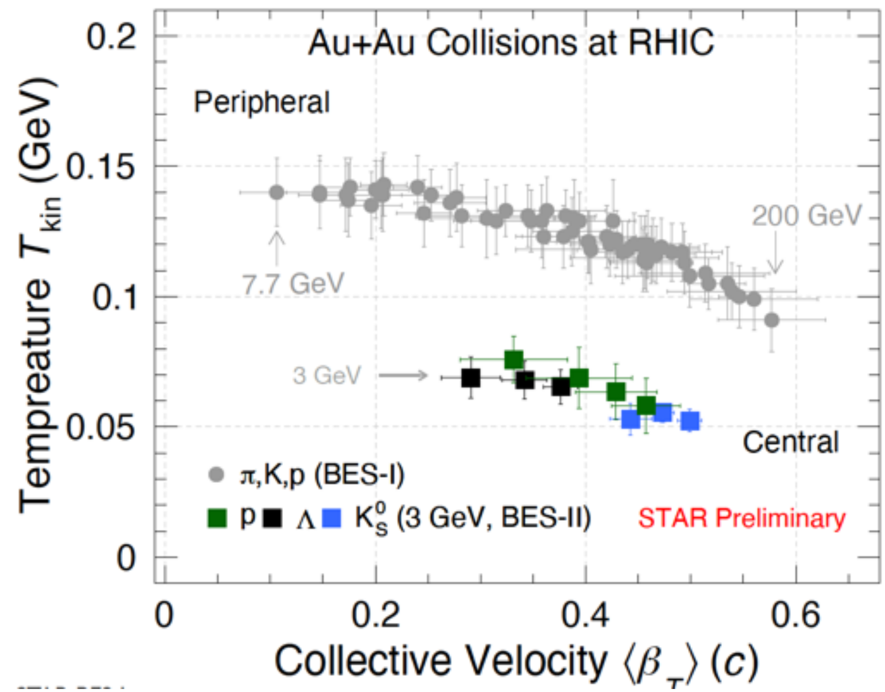
- Rapidity distributions for various strangeness hadrons. Fitted with Gaussian and integrated in the 4π range for total yields.

$\langle p_T \rangle$ and T_{kin}

BW

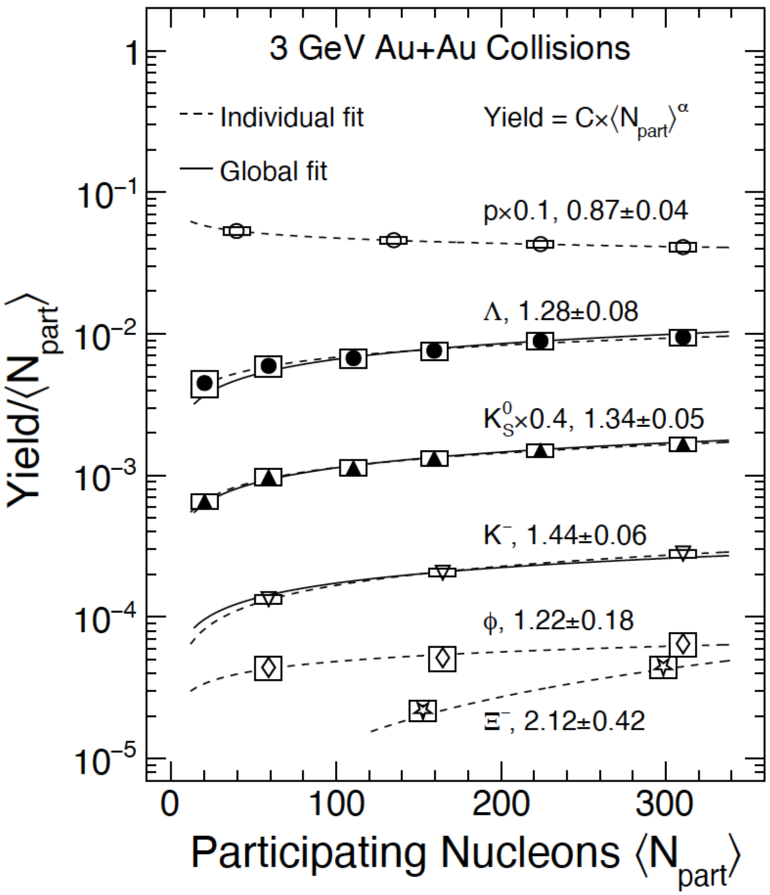
$$\frac{d^2N}{2\pi p_T dp_T dy} = A\int_0^R r dr m_T \times I_0\left(\frac{p_T \sinh\rho(r)}{T_{kin}}\right) K_1\left(\frac{m_T p \cosh\rho(r)}{T_{kin}}\right)$$

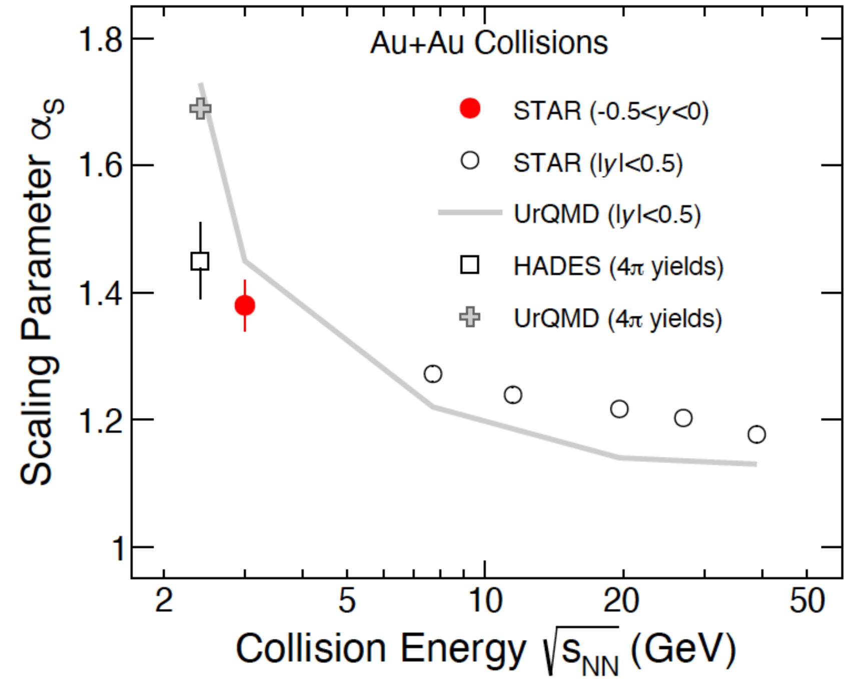




- Mean transverse momentum $\langle p_T \rangle$ for strangeness hadrons at midrapidity as a function of centrality → driven by radial flow
- Stronger collective motion in central compared to peripheral collisions
- Kinetic temperature is systematic lower than the high energies

Yields vs. Npart

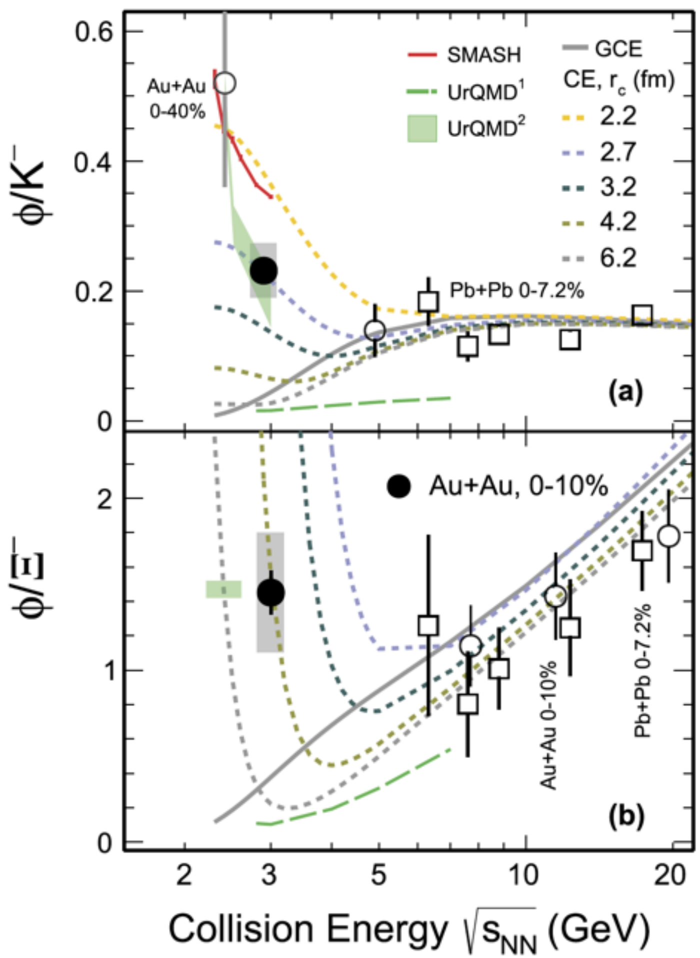




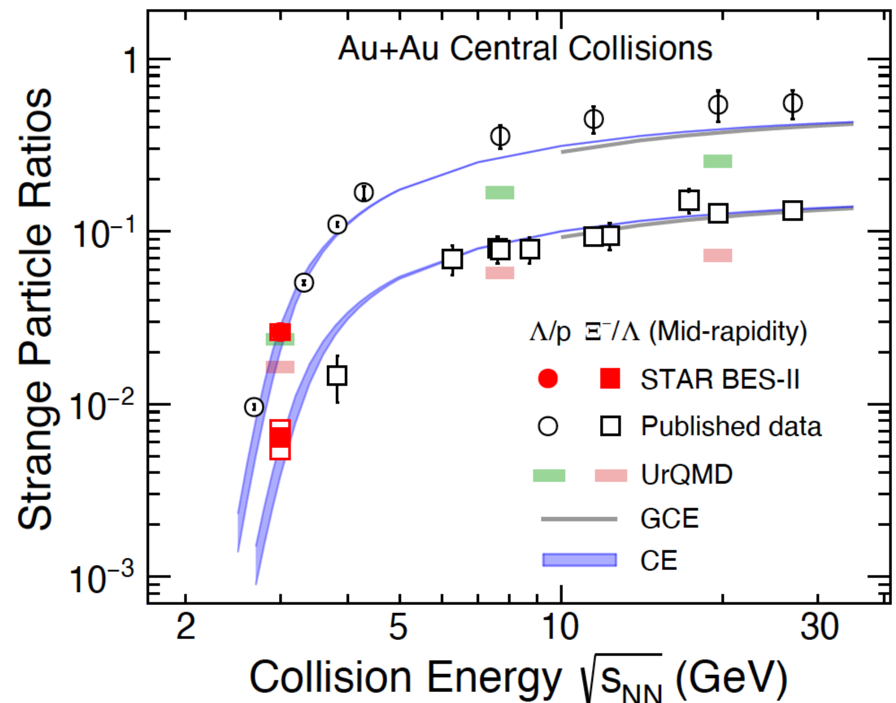
- Strange hadron yields (K, K_s^0, Λ) proportional to $\langle N_{part} \rangle^{\alpha}$,with = 1.37 ± 0.04
- Ξ^- seems to deviate from the scaling trend : subthreshold production
- Proton has a different trend : most protons are not produced and are remnants from the incoming nuclei

Strangeness Yield Ratios : φ/K⁻, φ/Ξ⁻, Ξ⁻/Λ

Phys. Lett. B 831,137152 (2022)



$\phi(s\bar{s}), K^-(s\bar{u}), \Xi^-(ssd), \Lambda(uds)$



$$T_{chem} = \frac{T_{chem}^{lim}}{1 + e^{2.6 - \ln(\sqrt{s_{NN}})/0.45}}, \quad T_{chem}^{lim} = 158.4\,\mathrm{MeV}$$

$$\mu_B = \frac{a}{1 + 0.288\sqrt{s_{NN}}}, \quad a = 1307.5\,\mathrm{MeV}$$

GCE → CE

- Suggest a significant change in the strangeness production compare to high energies.
- Change of Equation-of-State of QCD matter in high baryon density region

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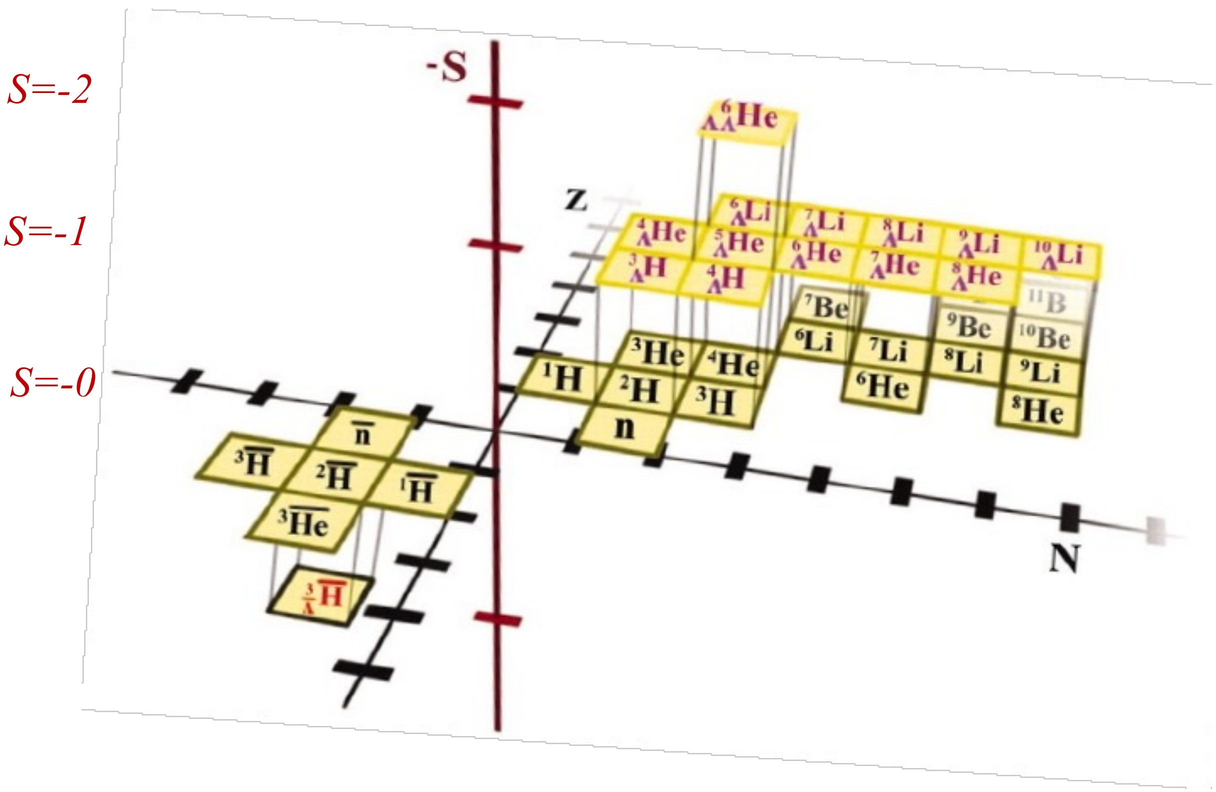
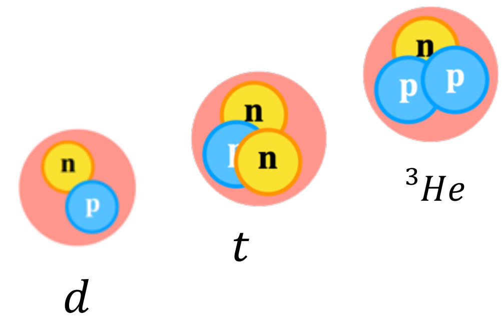
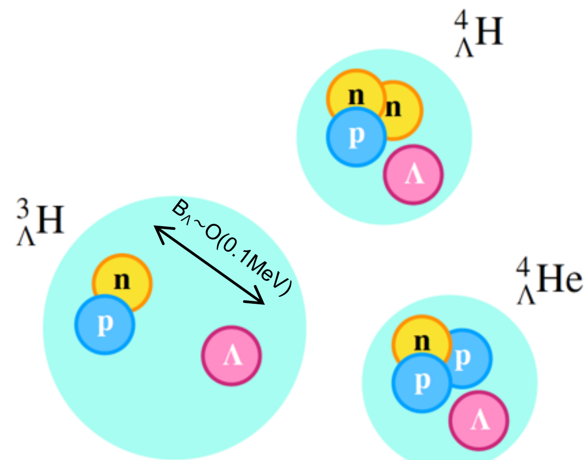
Hypernuclei

Nuclei are loosely bound objects with binding energies of few MeV
Hypernuclei are nuclei containing at least one hyperon
- N/Z + dimension on strangeness







$$B_{\Lambda} = (m_d + m_{\Lambda} - m_{^{3}_{\Lambda}H})c^2$$

Hypernuclei (II)

Phys. Lett. B 684 (2010) 224
Phys. Lett. B 781 (2018) 499
Phys.Rev. Lett. 114, 092301 (2015)

1. What can (hyper)nuclei production in heavy-ion collisions tell us about the QCD phase diagram and the nuclear equation-of-state?

- Sensitive to critical fluctuations and the onset of deconfinement

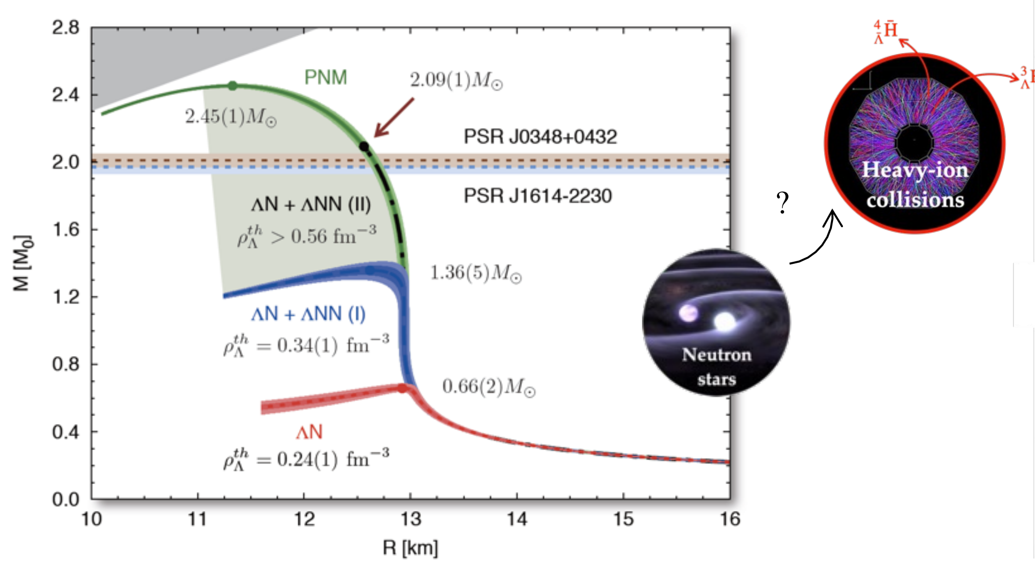
$$\frac{t \times p}{d^2}$$

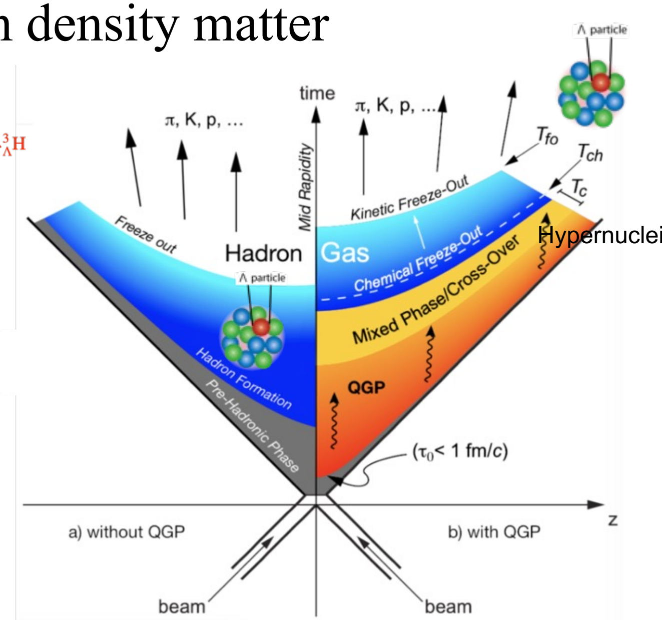
Sensitive to neutron density fluctuations

$$\frac{{}^{3}_{\Lambda}\mathrm{H}}{{}^{3}\mathrm{He} \times \frac{\Lambda}{p}}$$

Sensitive to baryon-strangeness correlations

2. What is the role of hyperon-nucleon (YN) and hyperon-hyperon (YY) interaction in the equation-of-state of high baryon density matter





- Hyperon Puzzle: difficulty to reconcile the measured masses of neutron stars with the presence of hyperons in their interiors

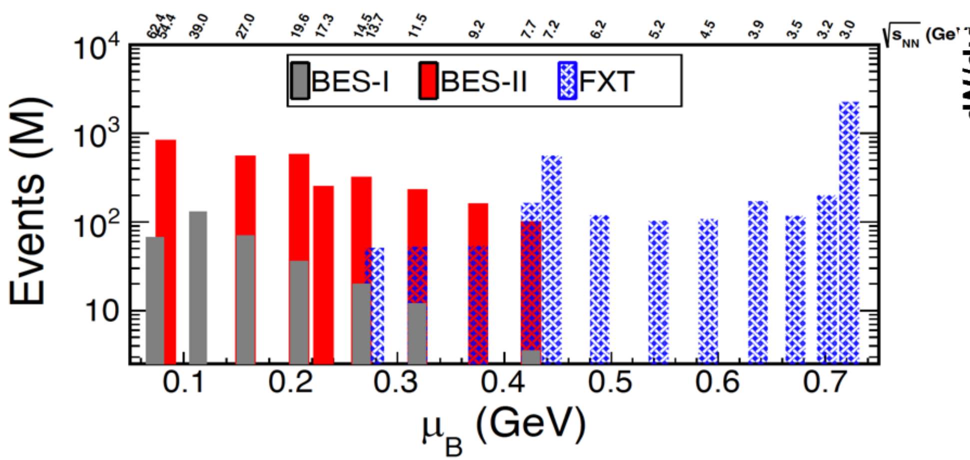
When are hypernuclei formed? At freezeout? Or in medium?

(Hyper)Nuclei in HIC at High Baryon Density

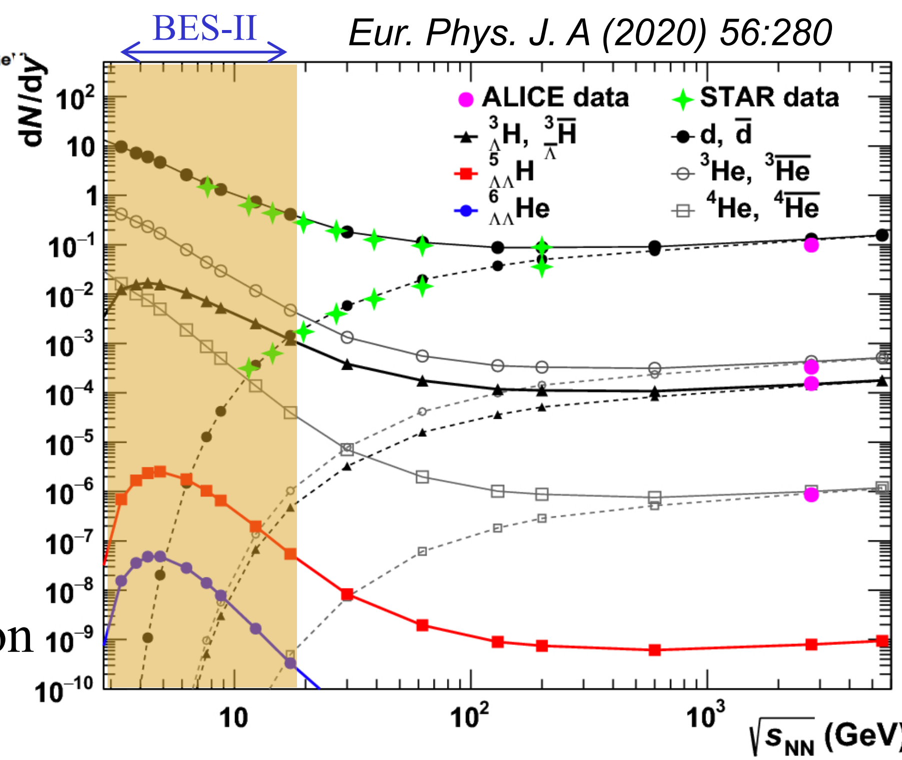
Why heavy-ion collisions (HIC)?

- produced in copious amounts in HIC
- Potential for high precision measurements

- Collider mode: $\sqrt{s_{NN}}$ = 7.7 - 54GeV
- Fixed-Target mode: $\sqrt{s_{NN}}$ = 3.0 - 13.7GeV



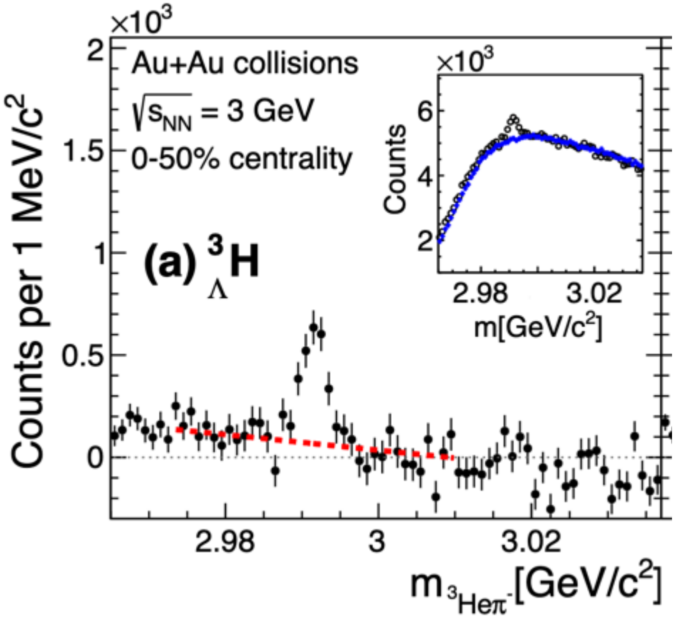
Eur. Phys. J. A (2020) 56:280

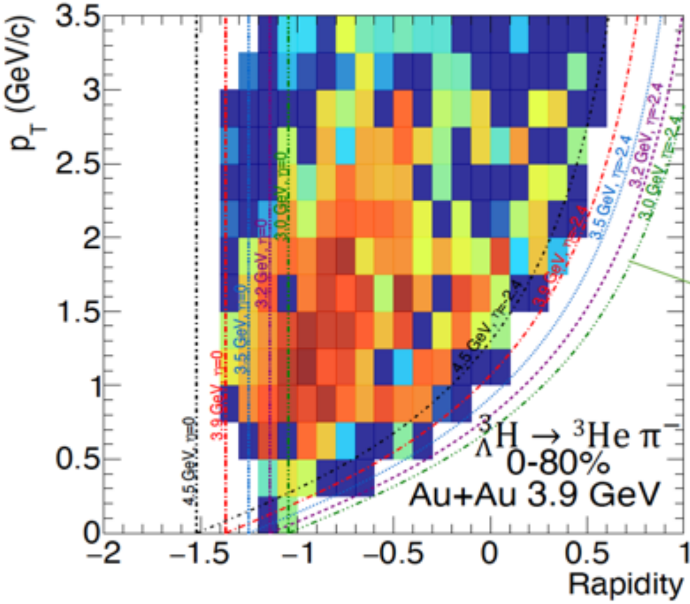


- Productions mechanism
  - thermal, coalescence, fragmentation
- Intrinsic properties
  - cτ, B_Λ, *BR*.

- Recently released hypertriton results from 3.2, 3.5, 3.9, 4.5,7.7,14.6 GeV

Hypernuclei in Heavy ion Collisions



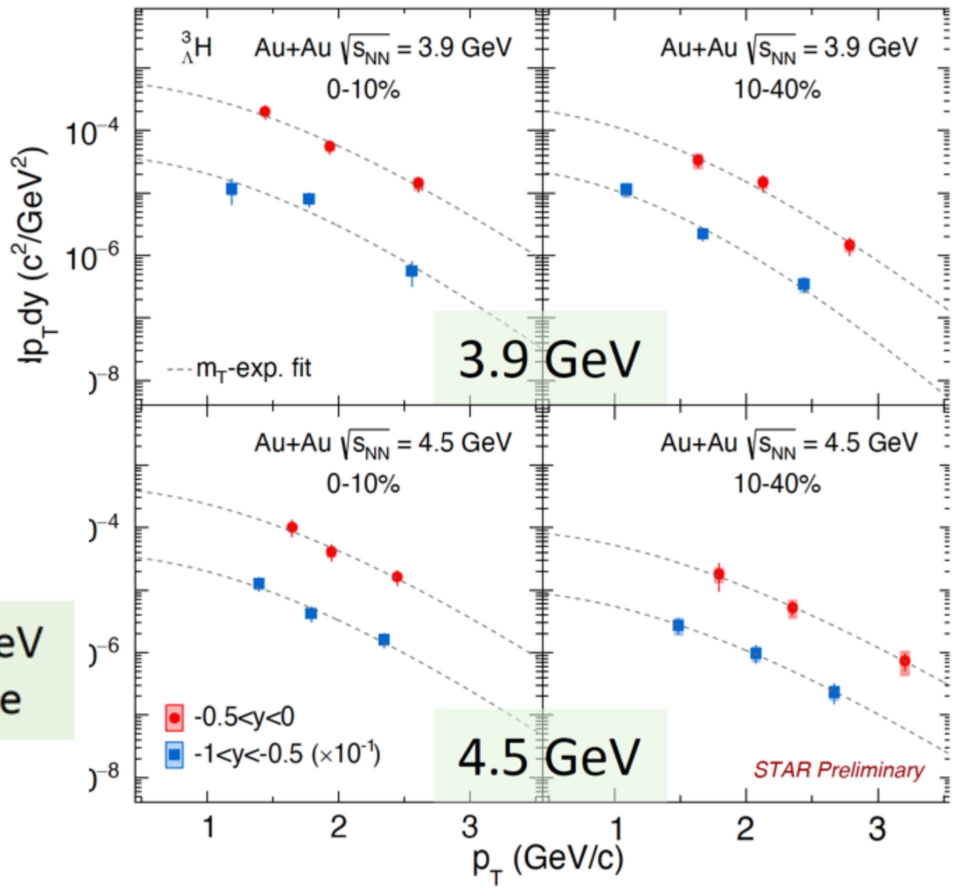


3 GeV edge

Phys. Rev. Lett. *128 (2022) 20, 202301*
Y. Ji. STAR, QM 2023

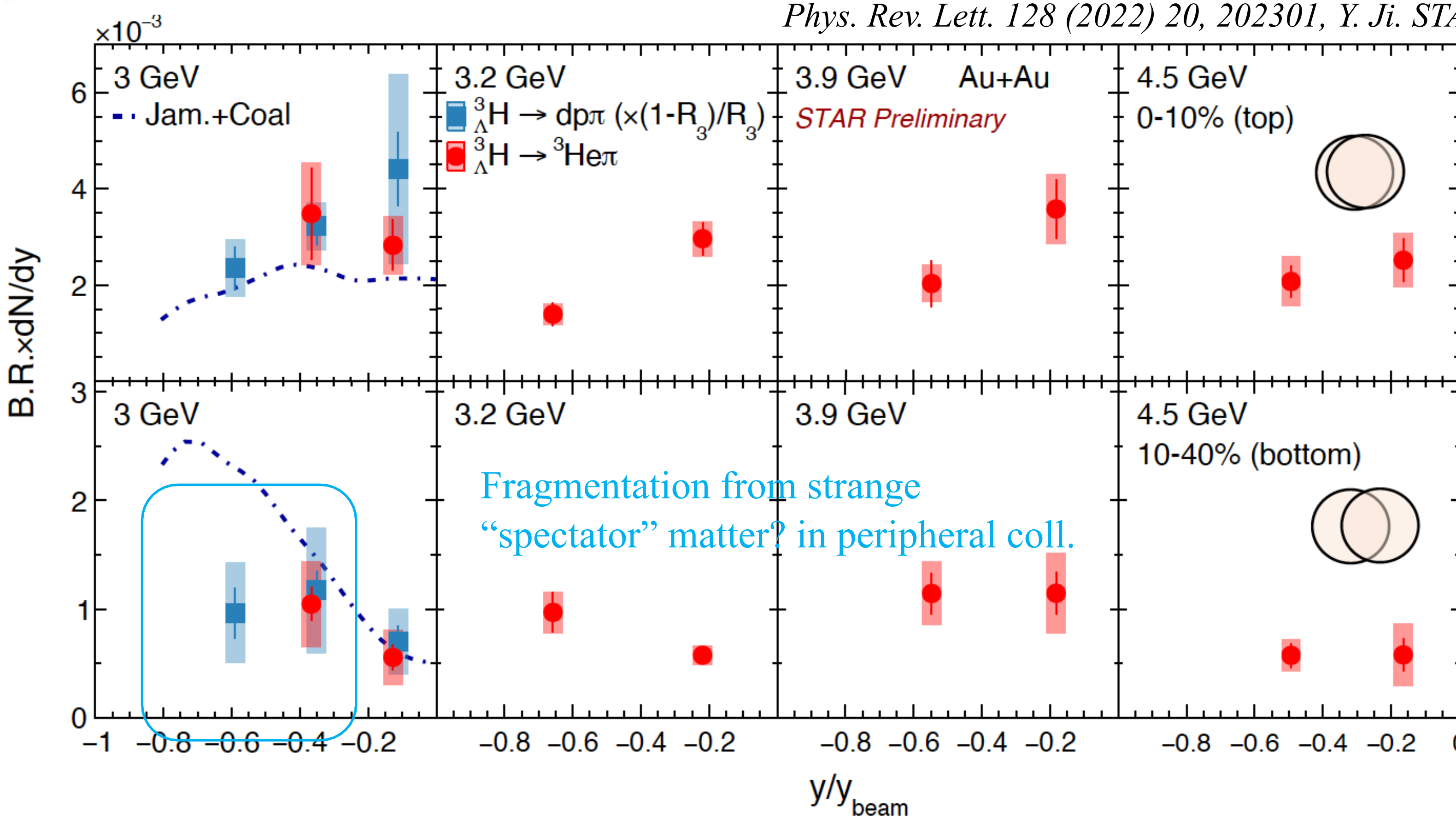
$^{3}_{\Lambda}H \rightarrow {}^{3}He\,\pi^+$

New hypertriton results from 3.2, 3.5, 3.9, 4.5, + 7.7,14.6 GeV



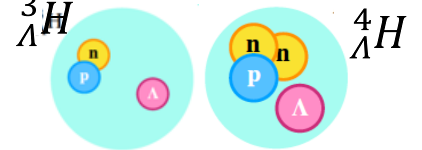
Hypernuclei Rapidity Distribution

Phys. Rev. Lett. 128 (2022) 20, 202301, Y. Ji. STAR, QM 2023

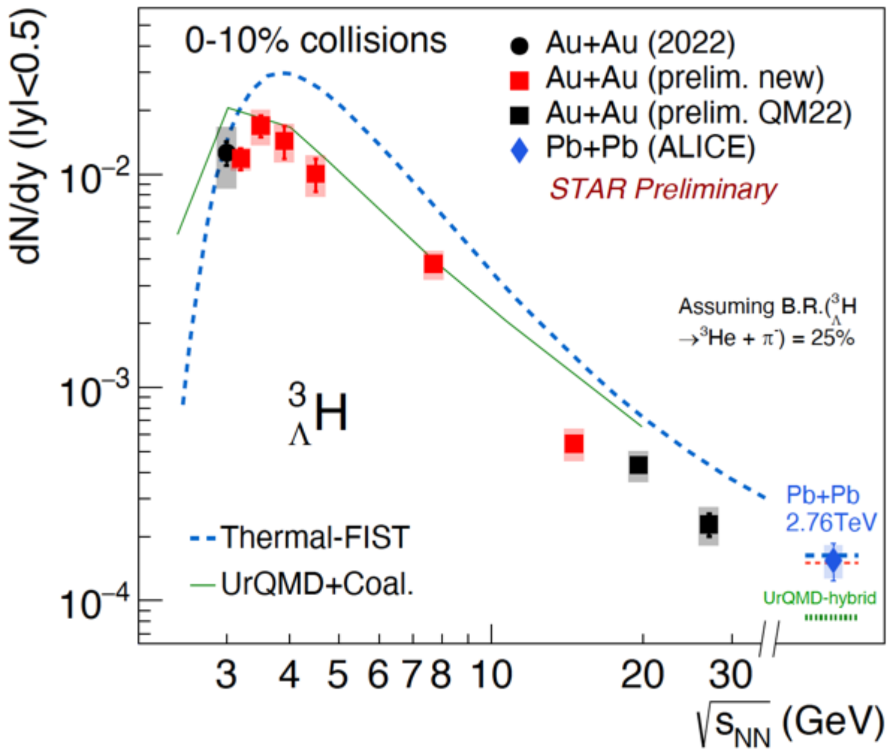


First measurements on rapidity dependence of hypernuclei yields in heavy ion collisions.
Different trends in rapidity in 10-40% centrality regions.
Consistent results between two body and three body decay channels.
Transport model (JAM) with coalescence afterburner qualitatively reproduce trends of the rapidity distributions seen in the data

Hypernuclei Yield vs. $\sqrt{s_{NN}}$



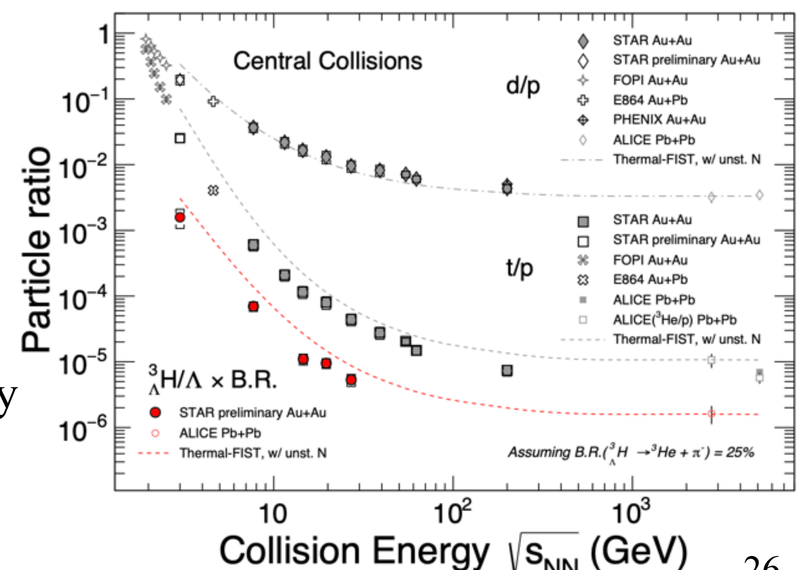
Phys. Rev. Lett. 128 (2022) 20, 202301



First energy dependence of hypernuclei production yields in high baryon region

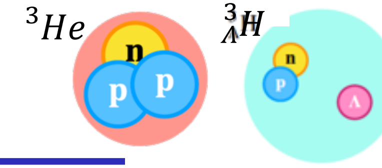
Enhanced hypernuclei production at RHIC BES II w.r.t LHC due to increased baryon density at low energies.

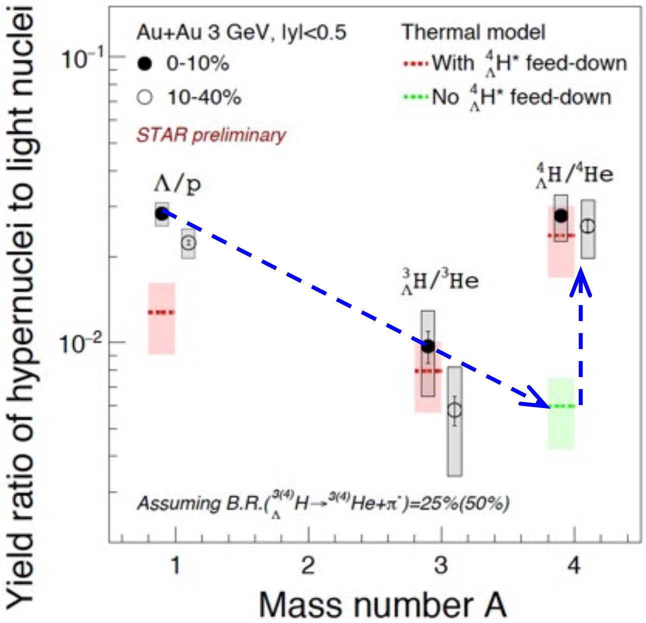
Hadronic transport + coalescence models qualitatively describe the data.

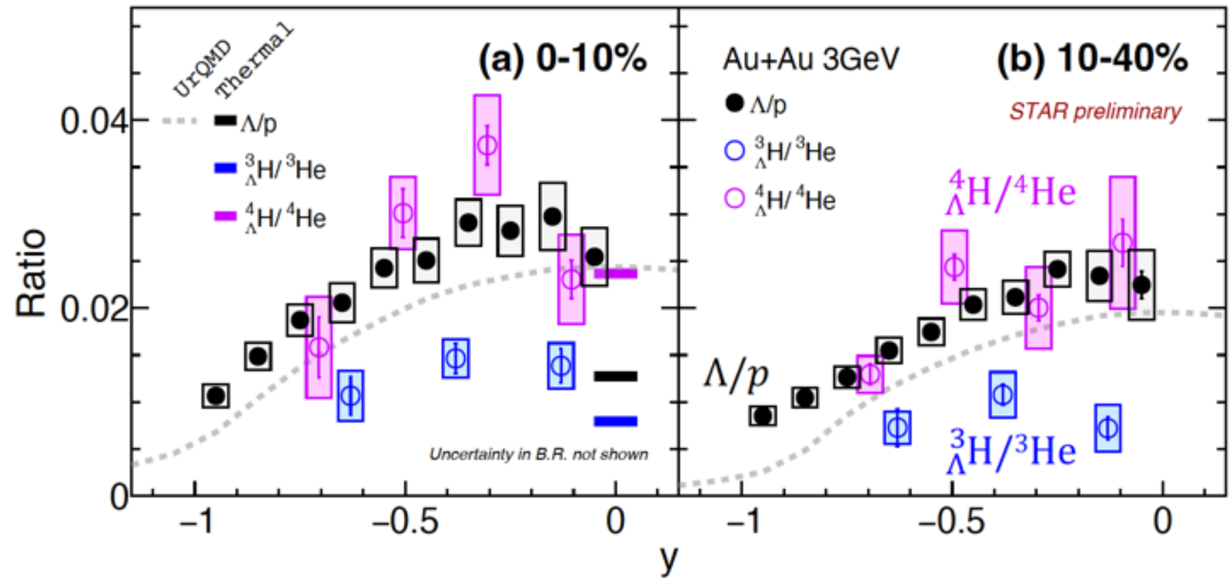


Both hypertriton and triton yields are not fixed at chemical freeze-out (disfavor thermal), likely fixed at a later stage (coal.)

Hypernuclei to Nuclei Ratios

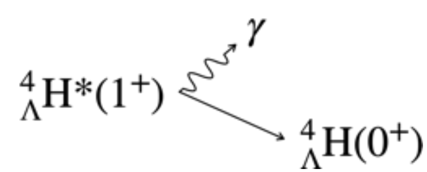






- ${}^{4}_{\Lambda}H/He^{3}$ yield ratios is lower than to that of Λ/p at both 0-10% and 10-40% centrality in Au+Au collisions at 3 GeV.
- ${}^{4}_{\Lambda}H/He^{4}$ yield ratios are comparable to that of Λ/p
- Enhanced ${}^{4}_{\Lambda}H$ production indicates a significant excited state feed-down contributions.

$$ {}^{4}_{\Lambda}He^{*}(J^{+}=1) \rightarrow {}^{4}_{\Lambda}He^{*}(J^{+}=0) + \gamma $$



Strangeness Population Factor @ 3GeV

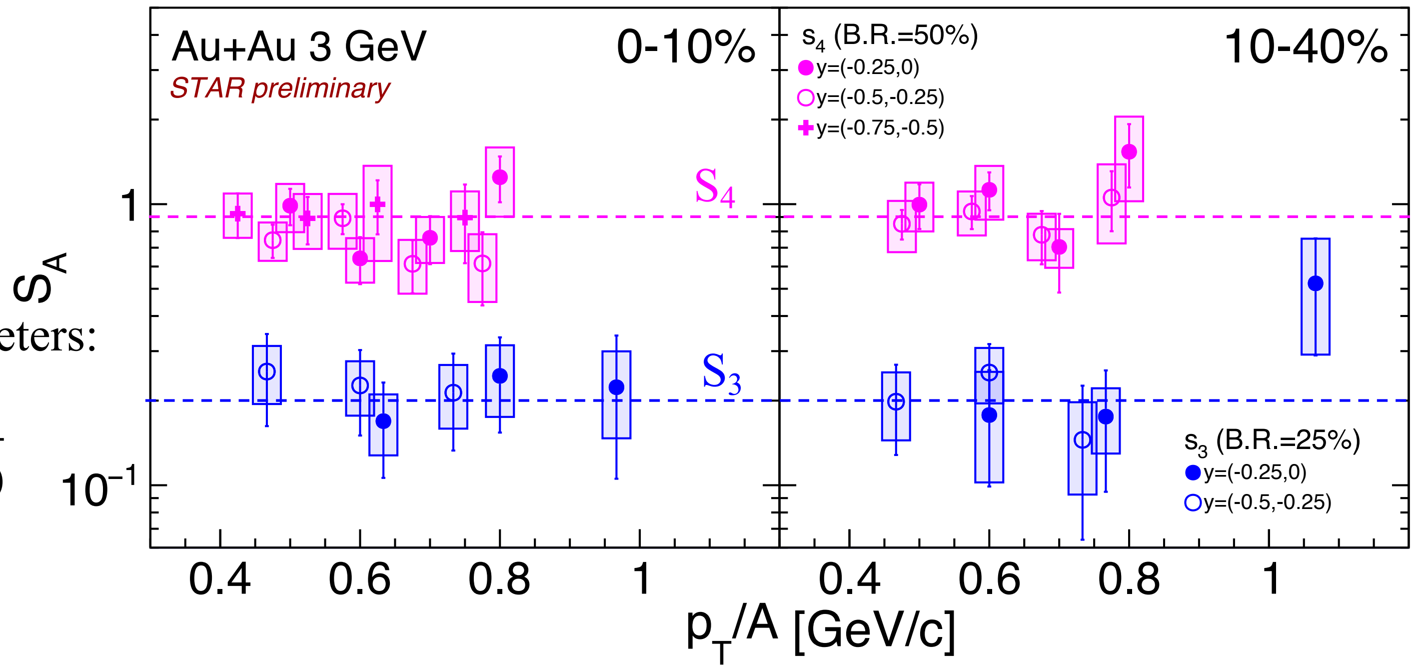
Phys. Lett. B 684 (2010) 224

$$S_A = \frac{{}^{A}_{\Lambda}H}{{}^{A}He \times \frac{\Lambda}{p}}$$

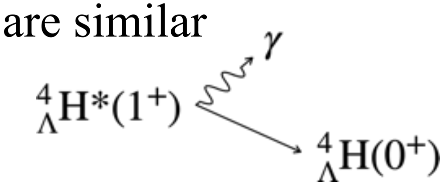
- Connection to coalescence parameters:

$$= \frac{{}^{A}_{\Lambda}H(p_T)}{{}^{A}He(p_T) \times \frac{\Lambda}{p}(p_T/A)}$$

$$= \frac{B_A({}^{A}_{\Lambda}H)(p_T)}{B_A({}^{A}He)(p_T)}$$

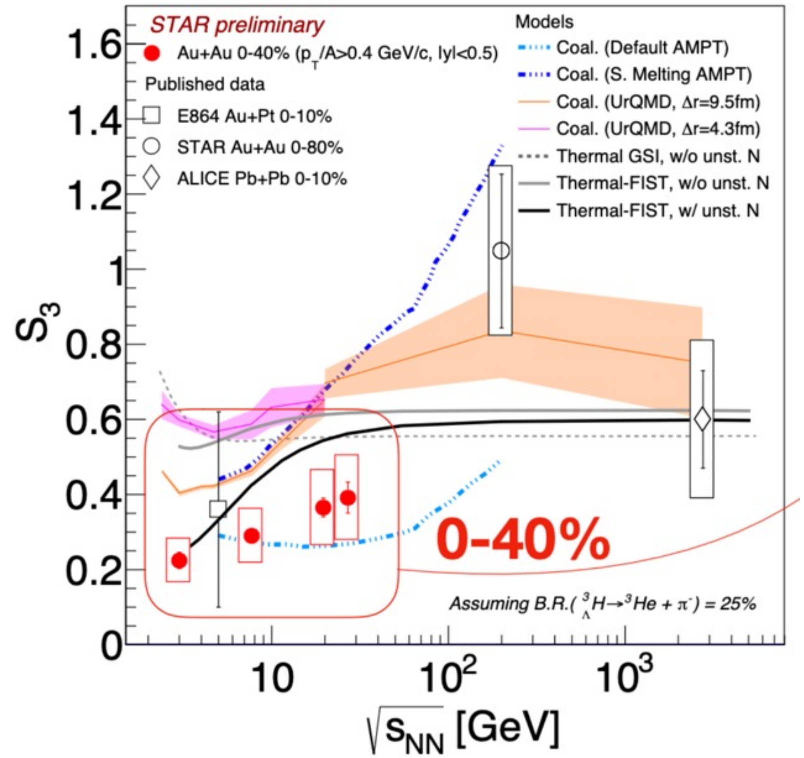


- No obvious p_T, rapidity and centrality dependence of S_A observed at 3 GeV.
- Evidence that B_A of light and hyper nuclei follow similar tendency, mechanics behind formation for hypernuclei and nuclei are similar
- $S_4 \approx 3S_3$, Feed-down from exited state ${}^{4}_{\Lambda}H$ production



Strangeness Population Factor vs. $\sqrt{s_{NN}}$

Phys. Lett. B 684 (2010) 224



Increasing trend of S_3 originally proposed as a signature of onset of deconfinement

$$S_3 = \frac{{}^{3}_{\Lambda}H}{{}^{3}He \times \frac{\Lambda}{p}}$$

: removes the absolute difference of Λ/B yields versus beam energy.

- Data shows a hint of an increasing trend
- Coalescence + transport also suggest increasing trend – ${}^{3}_{\Lambda}H$ suppression due to large size

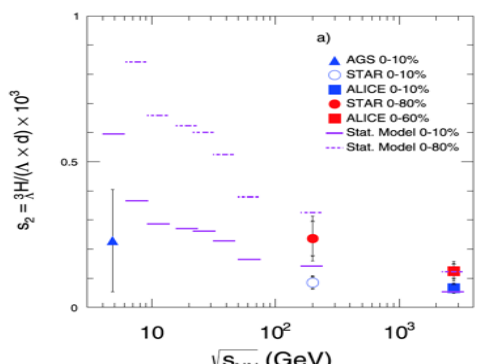
  Phys. Rev. C 107 (2023) 1, 014912
  Phys. Let. B 809 (2020) 135746

- Thermal-FIST also suggest increasing trend : unstable nuclei breakup ${}^{4}Li \rightarrow {}^{3}He\ p$

$$S_2 = \frac{{}^{3}_{\Lambda}H}{\Lambda \times d}$$

: recently s_2 also proposed as a sensitive probe

Chin. Phys. C 44, 11 (2020) 114001

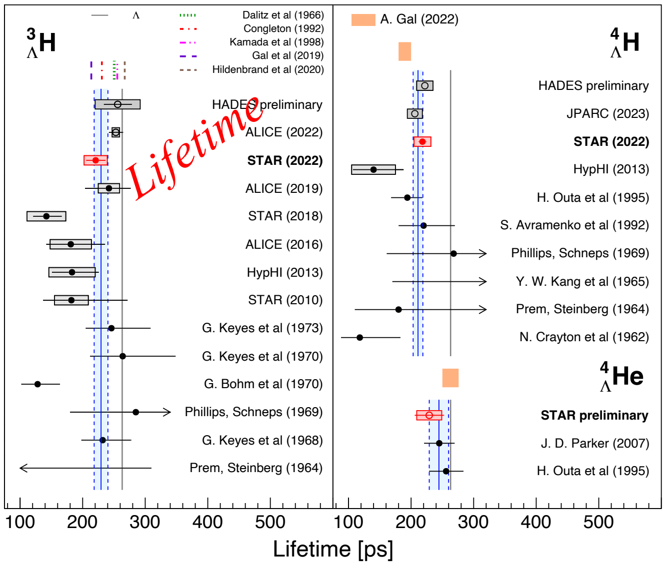


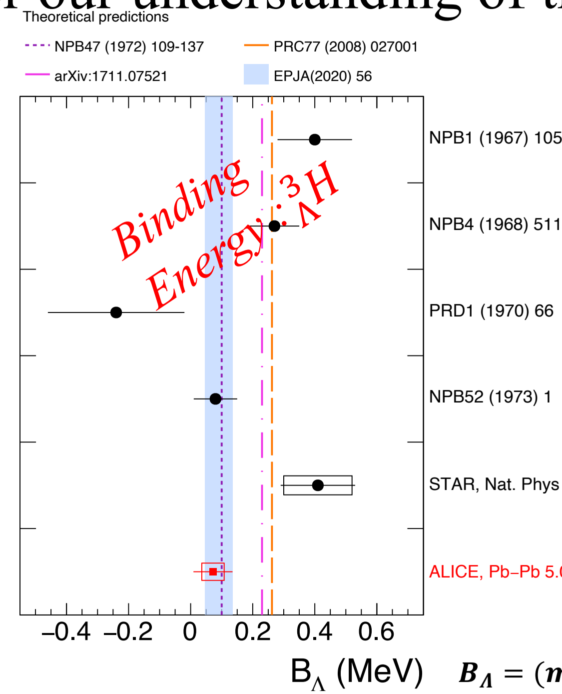
Note: For 19.6 and 27 GeV, take ³He/t = 0.93±0.07

intrinsic properties: Lifetime, B_Λ and BR.

- Light hypernuclei serves for our understanding of the YN interaction

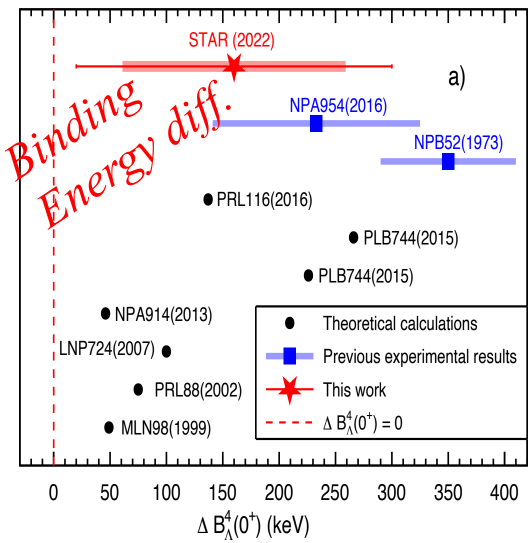
Phys. Rev. Lett. 128 (2022) 20, 202301

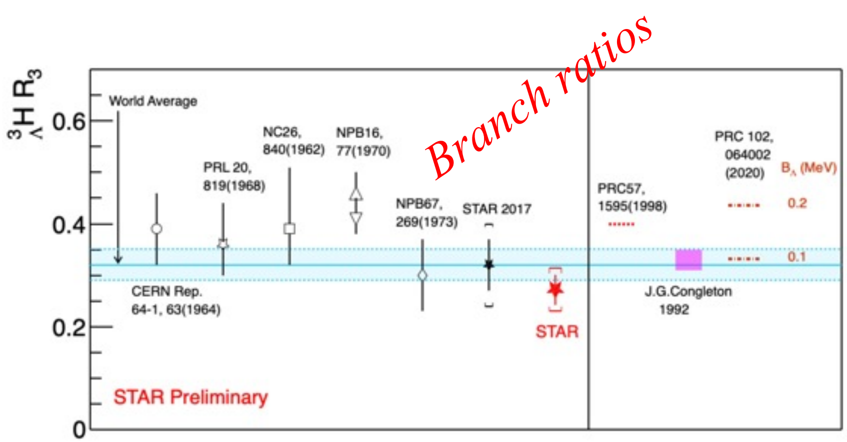


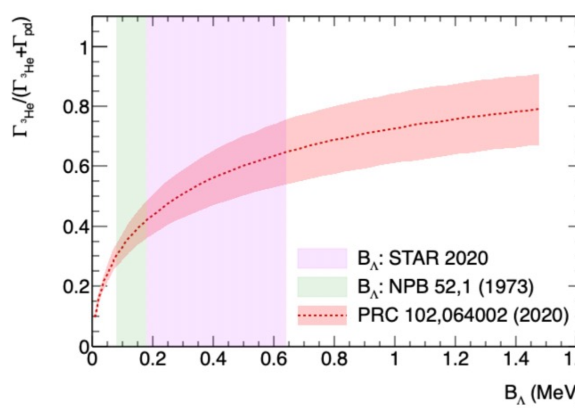


$B_\Lambda = (m_d + m_\Lambda - m_{^3_\Lambda H})$

Phys. Lett. B 834 (2022) 137449





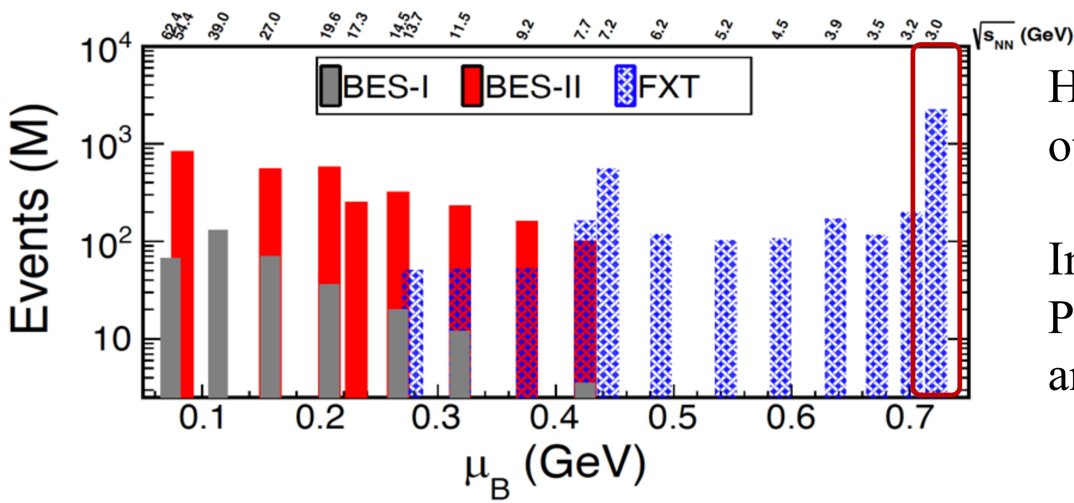


$$R_3 = \frac{B.R.(^3_\Lambda H \rightarrow {}^3He\,\pi^-)}{B.R.(^3_\Lambda H \rightarrow p\,d\,\pi^-) + B.R.(^3_\Lambda H \rightarrow {}^3He\,\pi^-)}$$

Summary

- Systematic studies on the (multi)strangeness production in the high baryon density region near the production threshold.
- First measurement of the ${}^{3}_{\Lambda}H$ excited functions (along with energy).
- The strangeness production mechanism may be different at high baryon density compared to high energies collisions.
- The properties of the created medium in the high baryon density region behavior differently compare to the high energies.

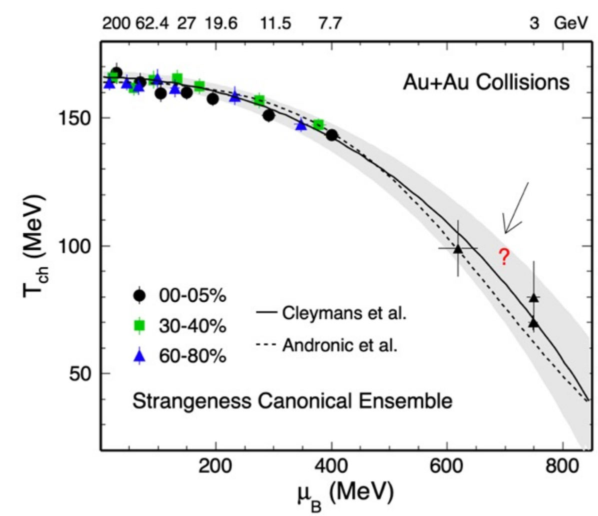
Outlook



High statistical data from BES-II and other facilities and experiments

In this report:
Part of the STAR BES-II dataset are analyzed and reported, stay tune

- Systematic measurements of the multi-strangeness production near the threshold (ϕ, Ξ^- & $\Omega^-, \overline{\Lambda}$) vs $\sqrt{s_{NN}}$: production mechanism and EoS, etc
- Systematic measurements of the hypernuclei production and the properties, $^{3}_{\Lambda}H$, $^{4}_{\Lambda}H$, $^{4}_{\Lambda}He$, $^{5}_{\Lambda}He$, $^{6}_{\Lambda\Lambda}He$: Y-N, EoS
- Mapping the phase diagram and explore EoS at high μ_B



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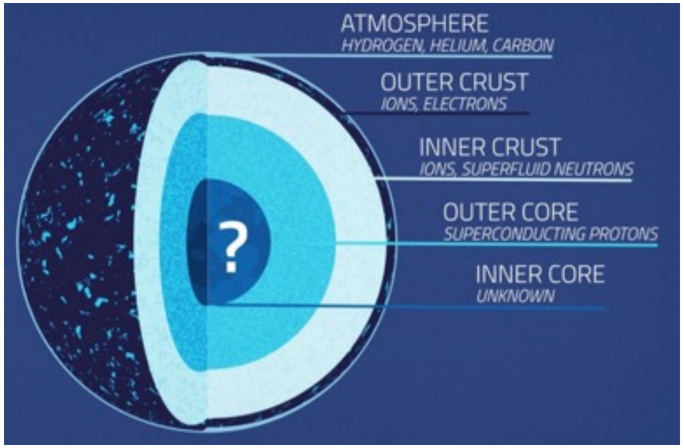
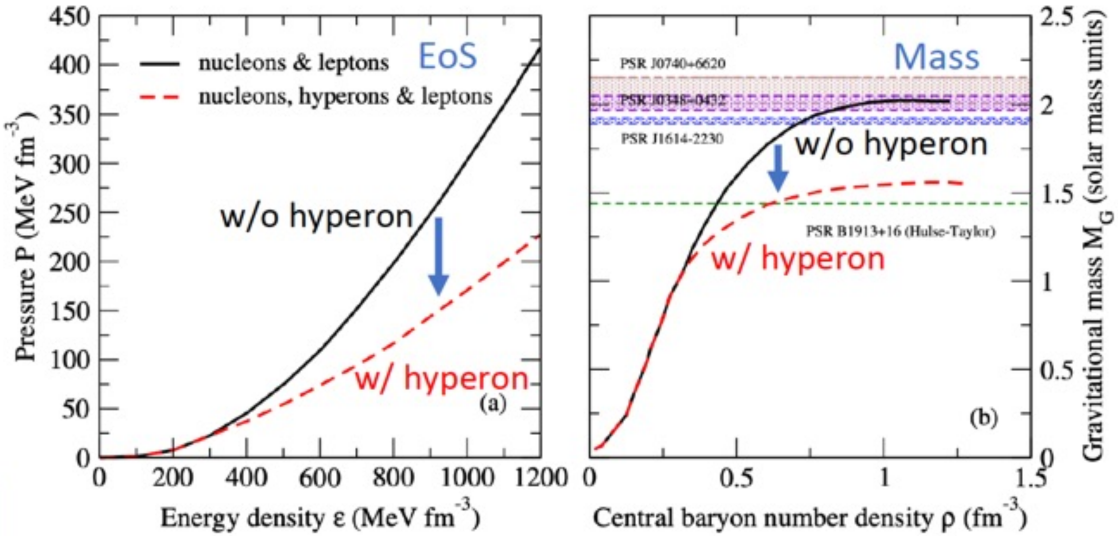
Thanks for Listening!

Hypernuclei

PSR J1614-2230: Nature 467,1081 (2010)
PSR J0348+0432: Science 340, 1233232 (2013)
PSR J0740+6620: Nature Astronomy 10,1038 (2019

Hypernucleus: Introduce additional degree of freedom in baryon interactions.
- Investigate Hyperon-Nucleon (Y-N) interactions in the nuclear experiments.
• Constrain the strangeness degree of freedom of Equation of State (EoS).
• e.g. EoS of neutron stars and hadronic phase of heavy ion collisions.



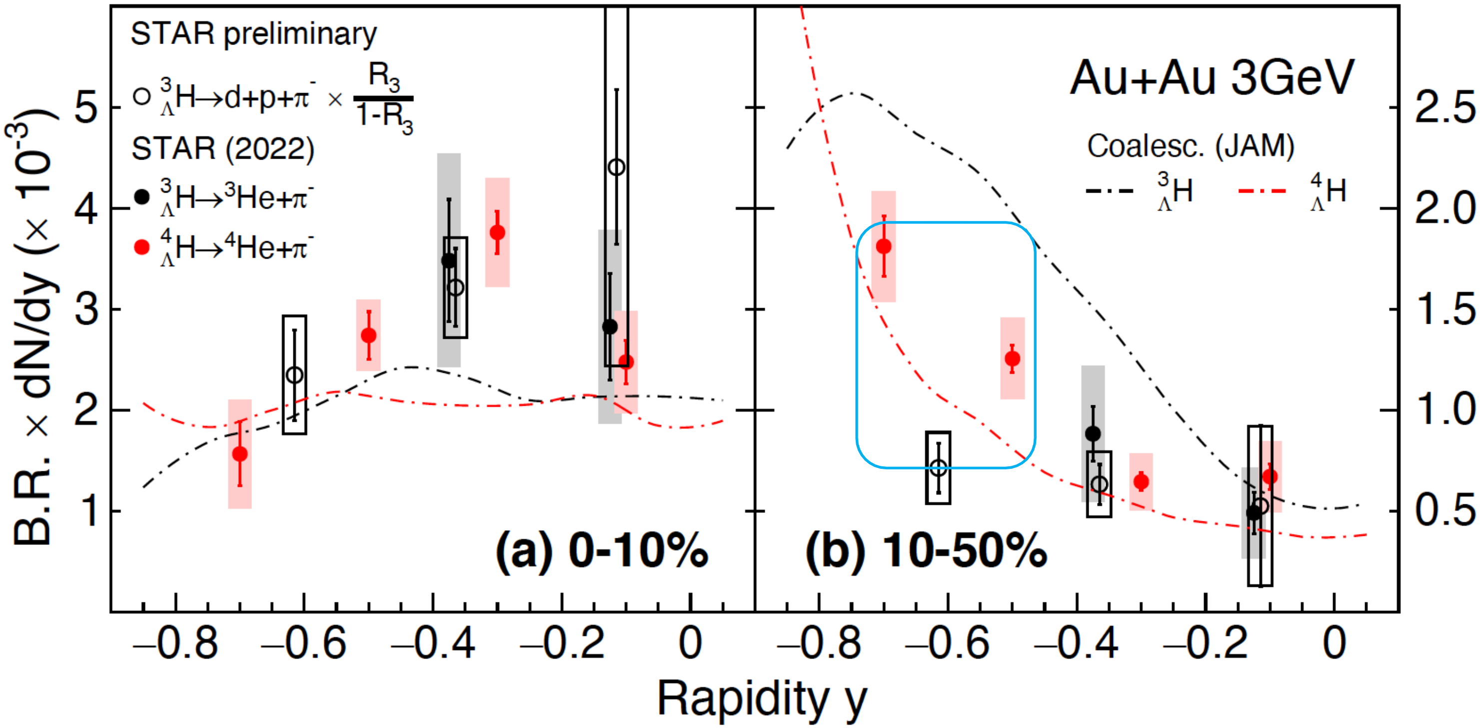


EoS governs the structure of neutron stars.

Hypernuclei Rapidity Distribution @ 3GeV

Phys. Rev. Lett. 128 (2022) 20, 202301

Fragmentation from strange "spectator" matter?

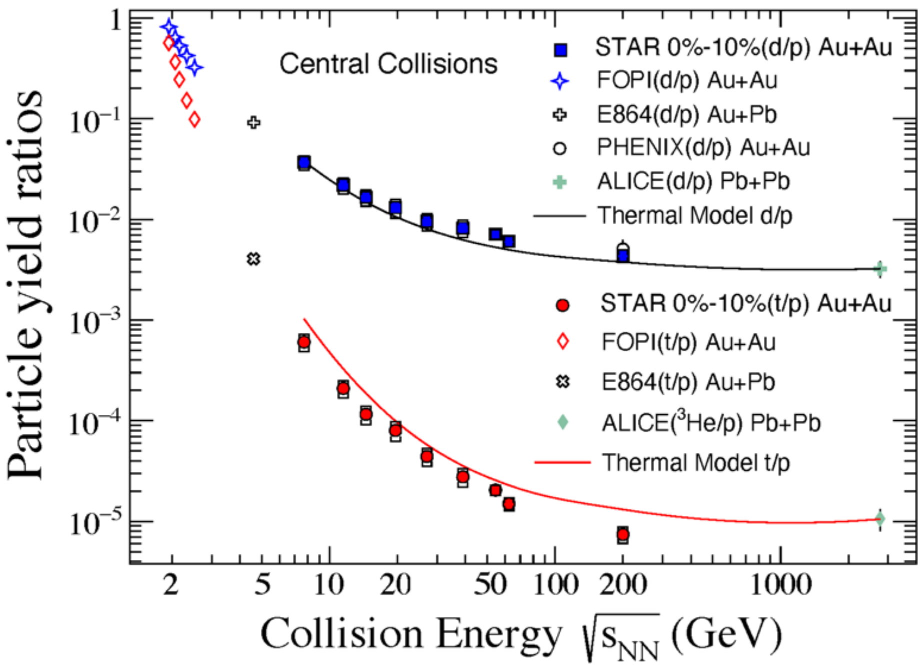


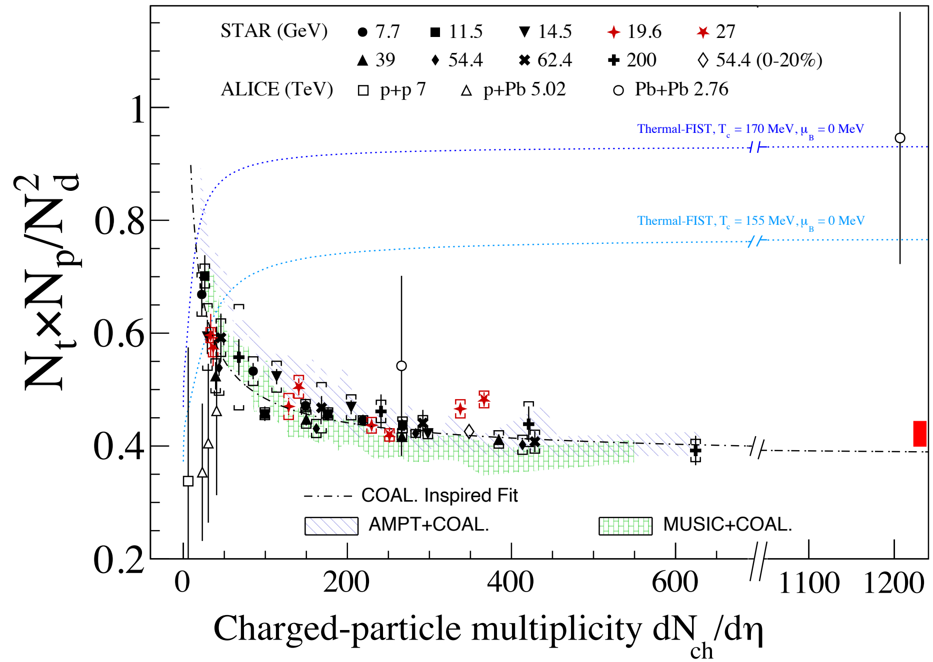
First measurements on rapidity dependence of hypernuclei yields in heavy ion collisions.
Different trends in rapidity in 10-50% centrality regions for ${}^{4}_{\Lambda}H$.
Consistent results between two body and three body decay channels.
Transport model (JAM) with coalescence afterburner qualitatively reproduce trends of the rapidity distributions seen in the data

Light Nuclei Ratios from BES-I

THERMAL-fist: Comput. Phys. Commun. 244, 295 (2019)

Phys. Rev. Lett. 130 (2023) 202301.





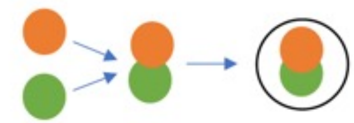
- d/p fairly well described by thermal model, but t/p is overestimated
- Effects from hadronic re-scattering?

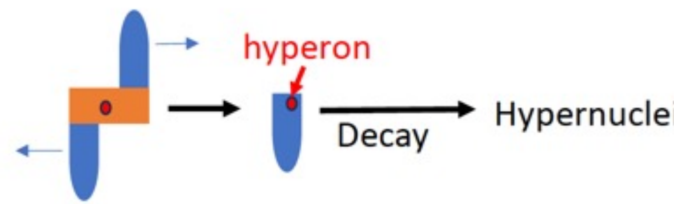
Dynamic, $\pi\, t \leftrightarrow \pi\, n\, n\, p$, *arXiv:2207.12532*

- Light nuclei yield ratio deviates strongly from thermal model from $\sqrt{s_{NN}}$ = 7.7-200 GeV
- Yield ratio exhibits approx. scaling behavior with $dN_{ch}/d\eta$

HyperNuclei Production

- **When and how loosely bound hypernuclei are formed in HIC?** ${}^{3}_{\Lambda}\mathrm{H}$ B_{Λ}~0.07-0.4 MeV, T_{ch}>>B_{Λ}
- **Formation mechanism can be classified as:**
  - Coalescence formation
    - Dominates at mid-rapidity.
      - Baryons / nuclei very close in phase space ($\vec{p}, \vec{r}$).
  - Nuclear fragmentation of hypercluster
    - Dominates at beam rapidity.
      - Dominate for heavy hypernuclei formation.





- **Production models**

Thermal model

- Hadron chemical freeze out T_{ch} and μ_B.

Coalescence approach

- Coalescence via final state interactions among nucleons.

Dynamical cluster formation

- Reaction-based; clusters can be formed before kinetic freeze-out.