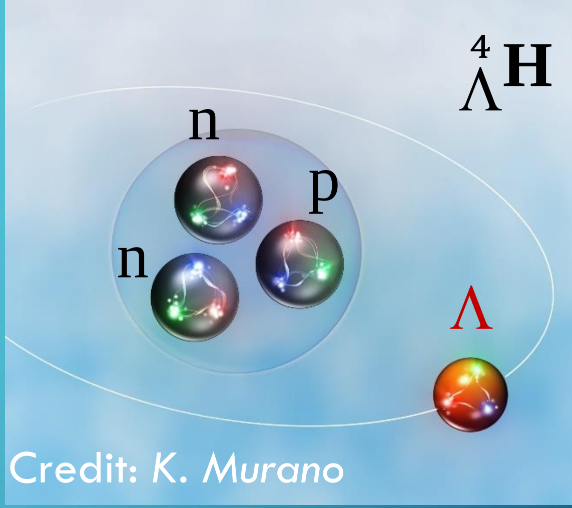
HYPERNUCLEI PRODUCTION AT RHIC

IOURI VASSILIEV

FOR THE STAR COLLABORATION

GSI FAIR

HYPERNUCLEI



Hypernucleus: A bound system of nucleons with one or more hyperon

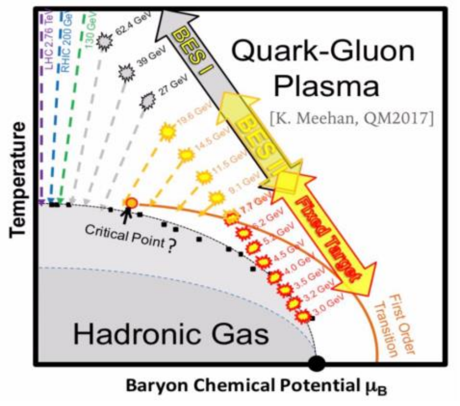
- Precise measurements of hypernuclei lifetime – understanding of **YN** interaction
- Strangeness in high density nuclear matter, EoS for NS, Hadronic phase of HI collisions
- Measurement of branching ratios of hypernuclei decays, Dalitz plots for 3-body decays

  - hypernuclei internal structure
- Measurements of B_Λ in the hypernuclei - direct access to the hyperon-nucleon interaction

BES - II DATA SETS:

Most precise data to map the QCD phase diagram

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

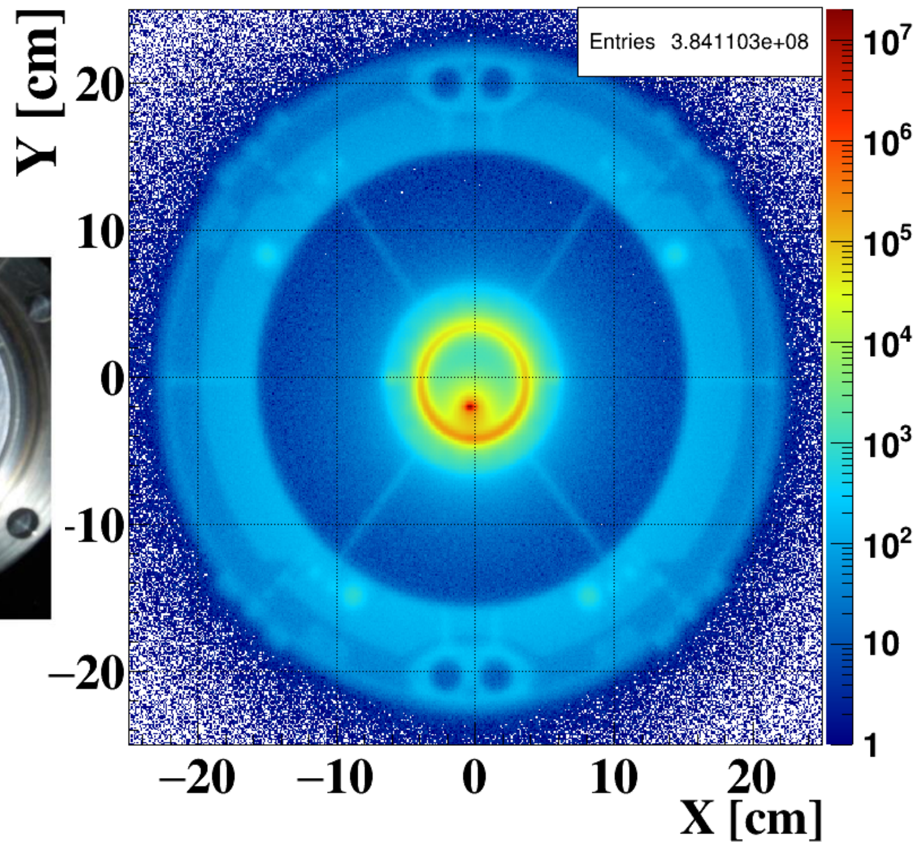


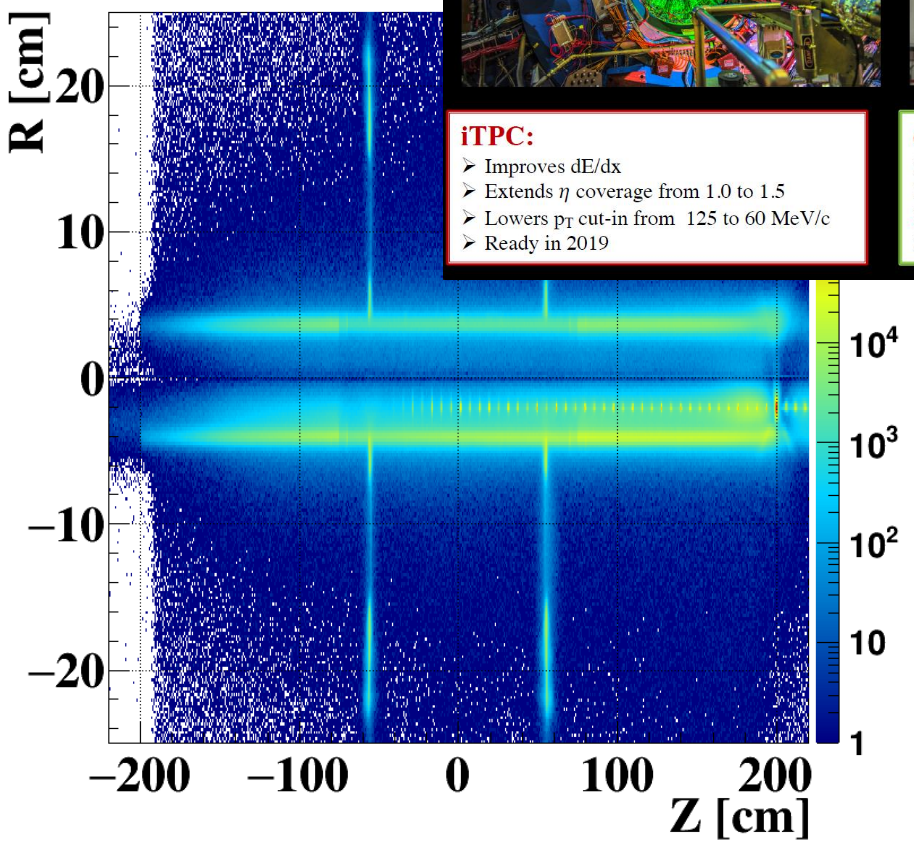
Au+Au Collisions at RHIC

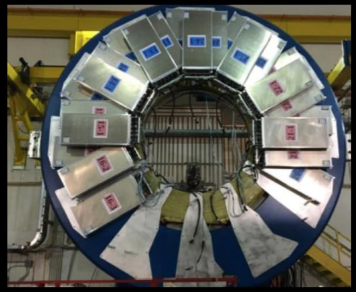
Collider Runs					Fixed-Target Runs				
	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	Run		$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	Run
1	200	380 M	25 MeV	Run 10, 19	1	13.7 (100)	50 M	280 MeV	Run-21
2	62.4	46 M	75 MeV	Run-10	2	11.5 (70)	50 M	320 MeV	Run-21
3	54.4	120 M	85 MeV	Run-17	3	9.2 (44.5)	50 M	370 MeV	Run-21
4	39	86 M	112 MeV	Run-10	4	7.7 (31.2)	260 M	420 MeV	Run-18, 19, 20
5	27	585 M	156 MeV	Run-11, 18	5	7.2 (26.5)	470 M	440 MeV	Run-18, 20
6	19.6	595 M	206 MeV	Run-11, 19	6	6.2 (19.5)	120 M	490 MeV	Run-20
7	17.3	256 M	230 MeV	Run-21	7	5.2 (13.5)	100 M	540 MeV	Run-20
8	14.6	340 M	262 MeV	Run-14, 19	8	4.5 (9.8)	110 M	590 MeV	Run-20
9	**11.5**	57 M	316 MeV	Run-10, 20	9	3.9 (7.3)	120 M	633 MeV	Run-20
10	**9.2**	160 M	372 MeV	Run-10, 20	10	3.5 (5.75)	120 M	670 MeV	Run-20
11	**7.7**	104 M	420 MeV	Run-21	11	3.2 (4.59)	200 M	699 MeV	Run-19
					12	3.0 (3.85)	2300 M	750 MeV	Run-18, 21

PRIMARY VERTEX AT RUN 2020 $\sqrt{S_{NN}} = 3.5$ GeV

STAR DETECTOR TOMOGRAPHY







iTPC:
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut-in from 125 to 60 MeV/c
- Ready in 2019

eTOF:
- Forward rapidity coverage
- PID at $\eta = 0.9$ to 1.5
- **Borrowed from CBM-FAIR**
- Ready in 2019

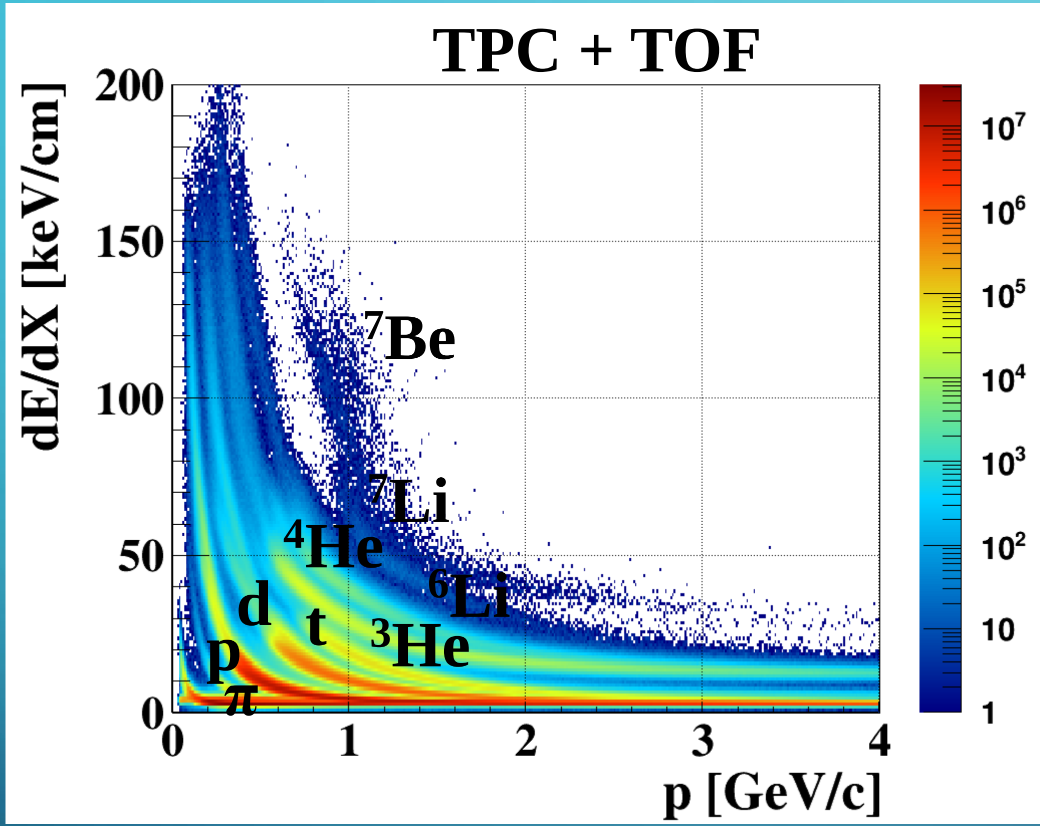
- The structure with R = 2 cm (beam position) is formed by pileup.
- Interactions with the pipe material and support structures are clearly visible.
- Tracks from these vertices lead to higher background, especially in 3-body channels.

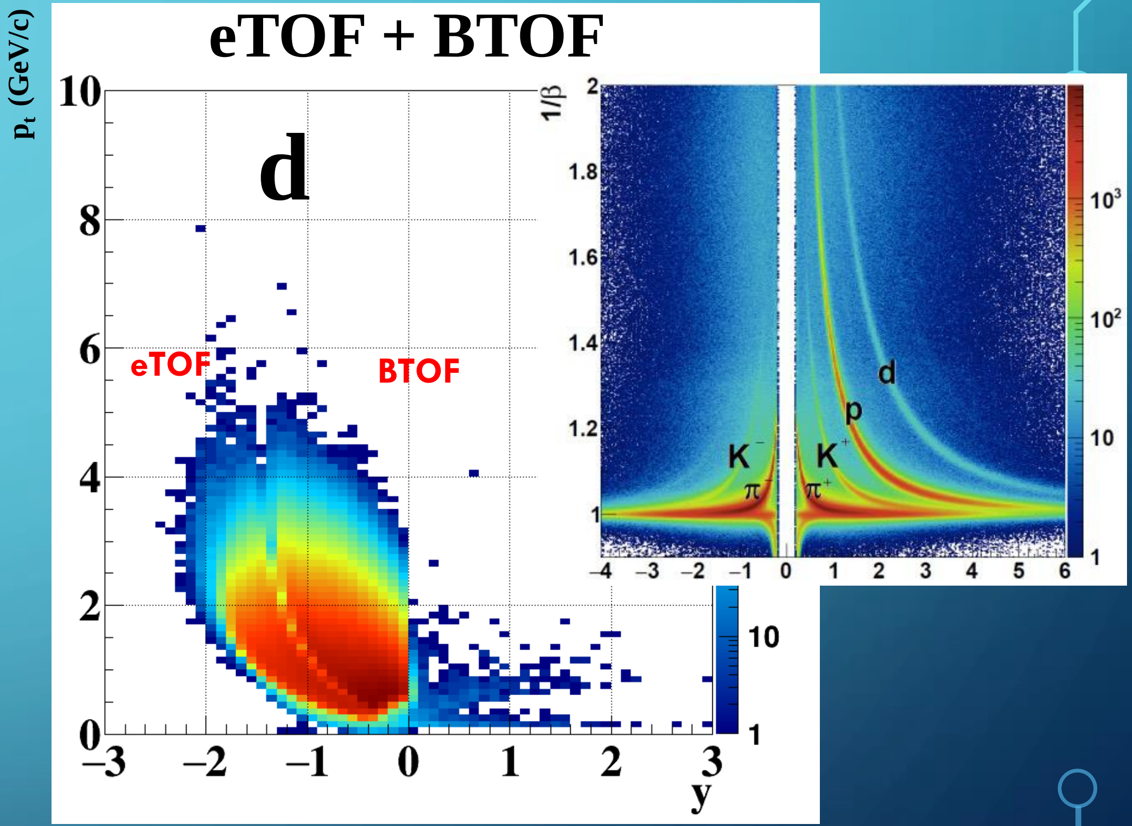
KF Particle package (M. Zyzak)

X. Ju et al. Nucl. Sci. Tech. 34, 10, 158 (2023)

Solution: We reconstruct vertices from **pileup** and interaction with the pipe. Tracks from these vertices are **removed** from further consideration. The procedure allows to noticeably reduce the background in 3-body channels.

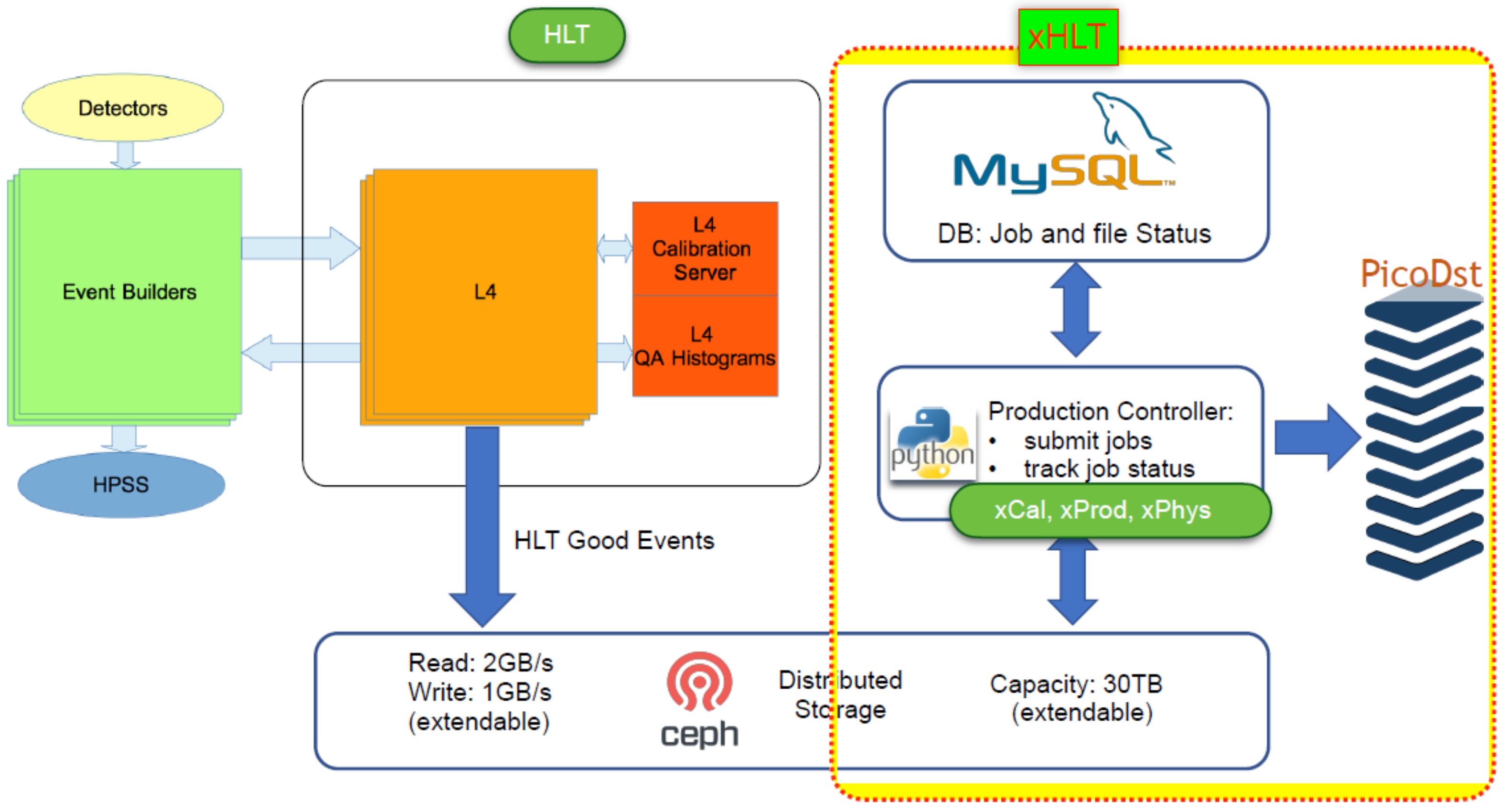
PRODUCTION AT RUN 2020 $\sqrt{S_{NN}}$ = 3.5 GeV





- The dE/dX spectra for $\sqrt{s_{NN}}$ = 3.5 GeV fixed target mode. π, p, d, t, ^{3}He, ^{4}He particles and heavy fragments up to ^{7}Be are clearly seen.
- About 30% more deuterons selected with eTOF, low rapidity region covered by eTOF

HYPERNUCLEI IN STAR WITH EXPRESS ANALYSIS

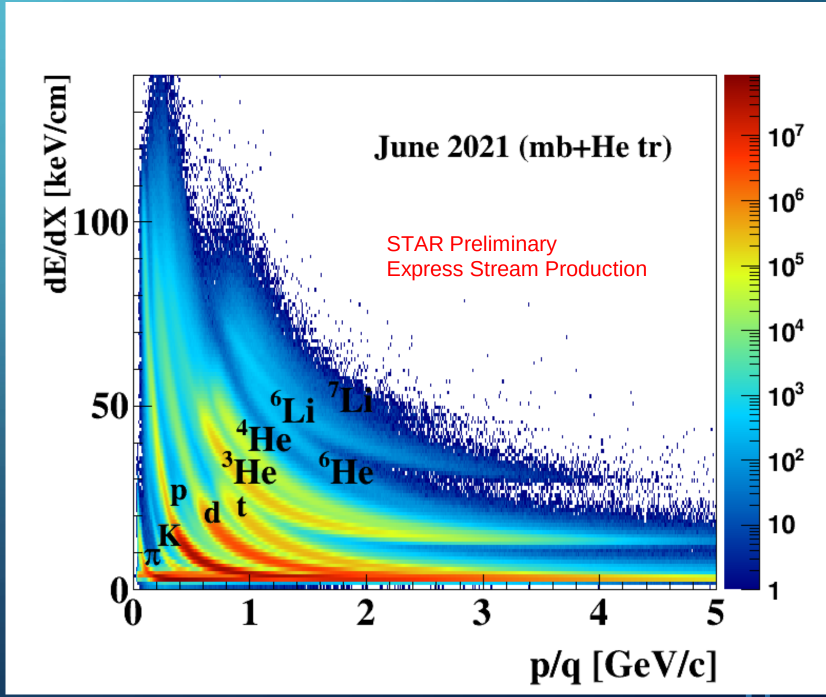


Full chain of express production and analysis has been running since 2019

Express Production (selection) jobs on HLT farm (300-500 job slots)

Trigger on He has been introduced to enhance **hypernuclei.**

437M AuAu HLT triggered events at 3 GeV

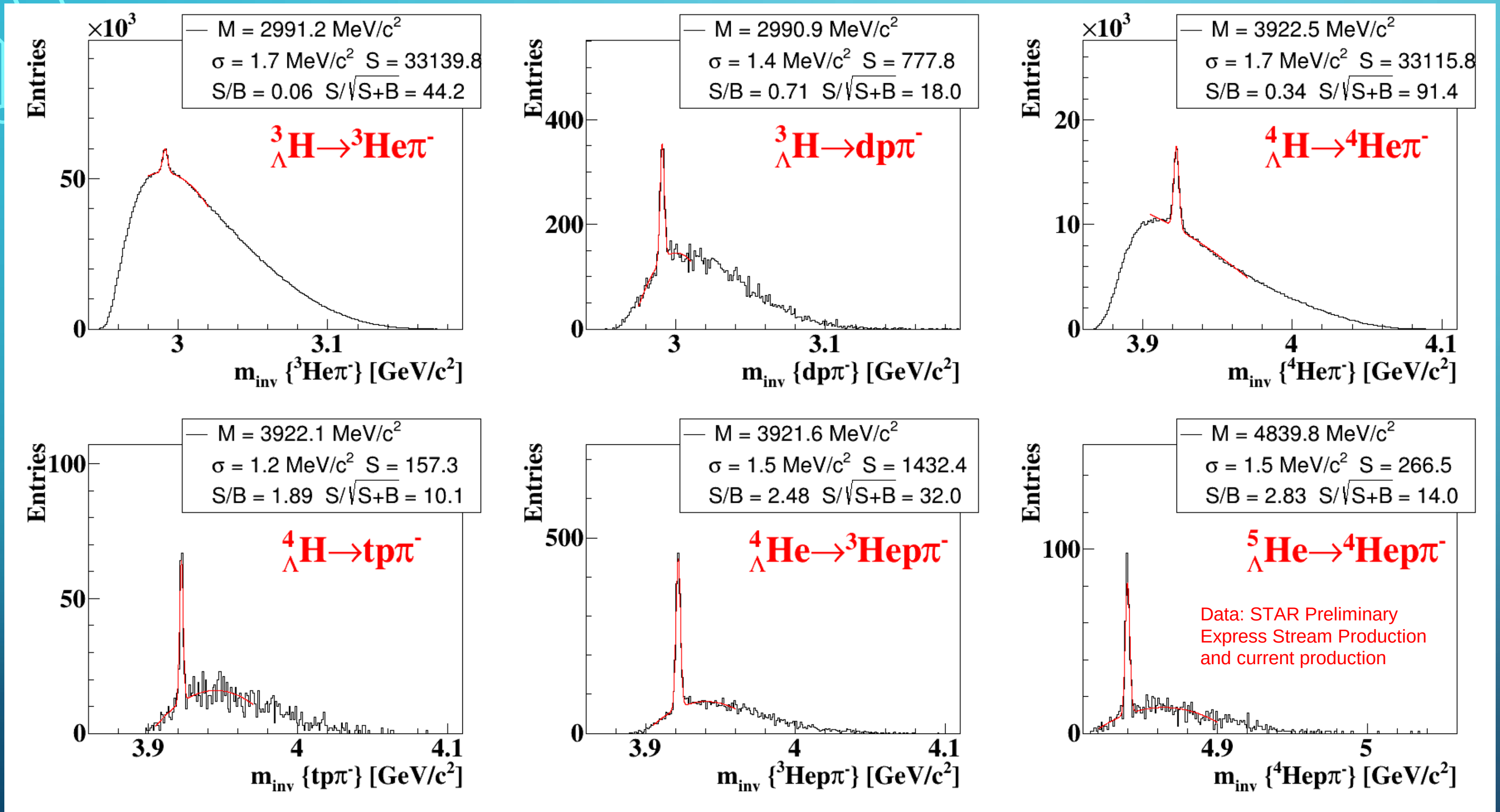


Save HLT good events to a local disk directly

PicoDst files produced in hours (collisions) or days (FXT) after data taking

HYPERNUCLEI COLLECTION

2018-2020, 2021x FXT and 2021x collider at 7.7 GeV



Hypernuclei are reconstructed with KFParticle Finder in following decay channels:

$^{3}_{\Lambda}H \to {}^{3}He + \pi^{-}$

$^{4}_{\Lambda}H \to {}^{4}He + \pi^{-}$

$^{3}_{\Lambda}H \to d + p + \pi^{-}$

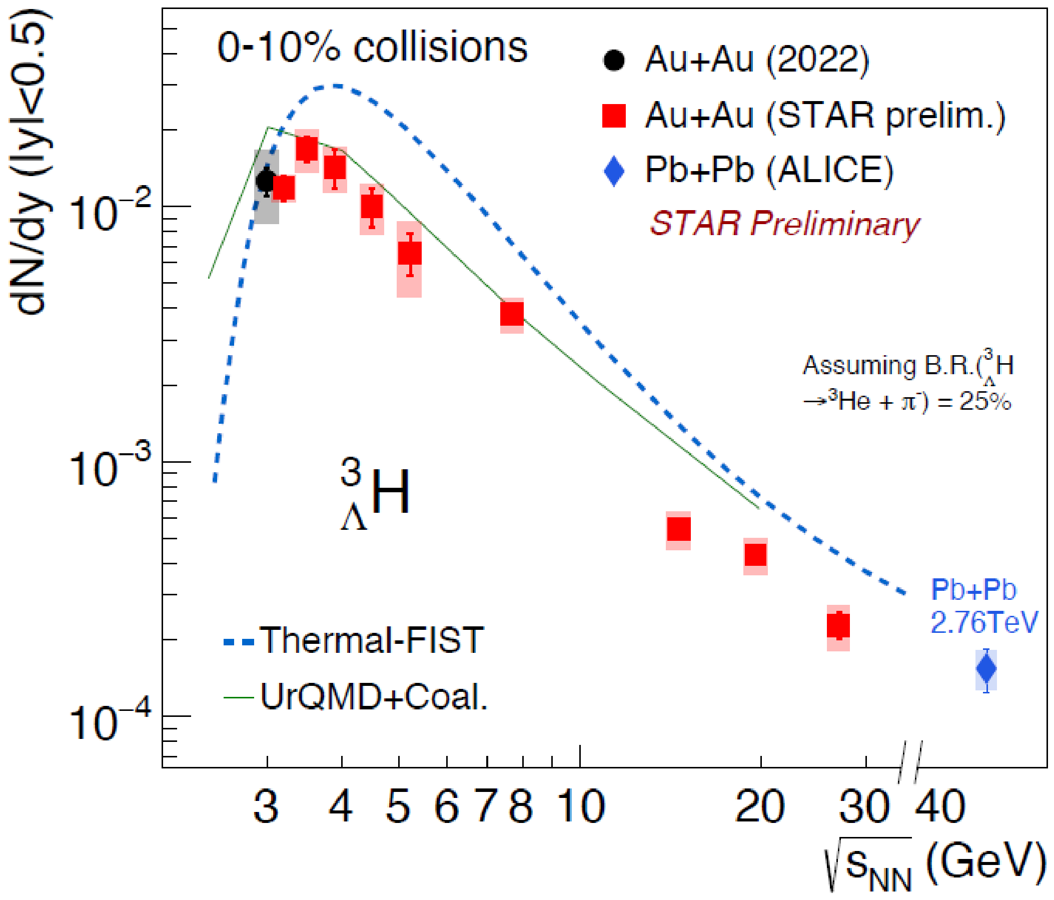
$^{4}_{\Lambda}He \to {}^{3}He + p + \pi^{-}$

$^{4}_{\Lambda}H \to t + p + \pi^{-}$

$^{5}_{\Lambda}He \to {}^{4}He + p + \pi^{-}$

- **Updated set of hypernuclei measurements in the high-baryon-density region with high statistical precision**

$^{3}_{\Lambda}H$ EXCITATION FUNCTION



Thermal-FIST, Coal.+UrQMD: T. Reichert et al, PRC 107, 014912 (2023)
Pb+Pb: ALICE, PLB 754, 360 (2016)
Au+Au: STAR, PRL 128, 202301 (2022)

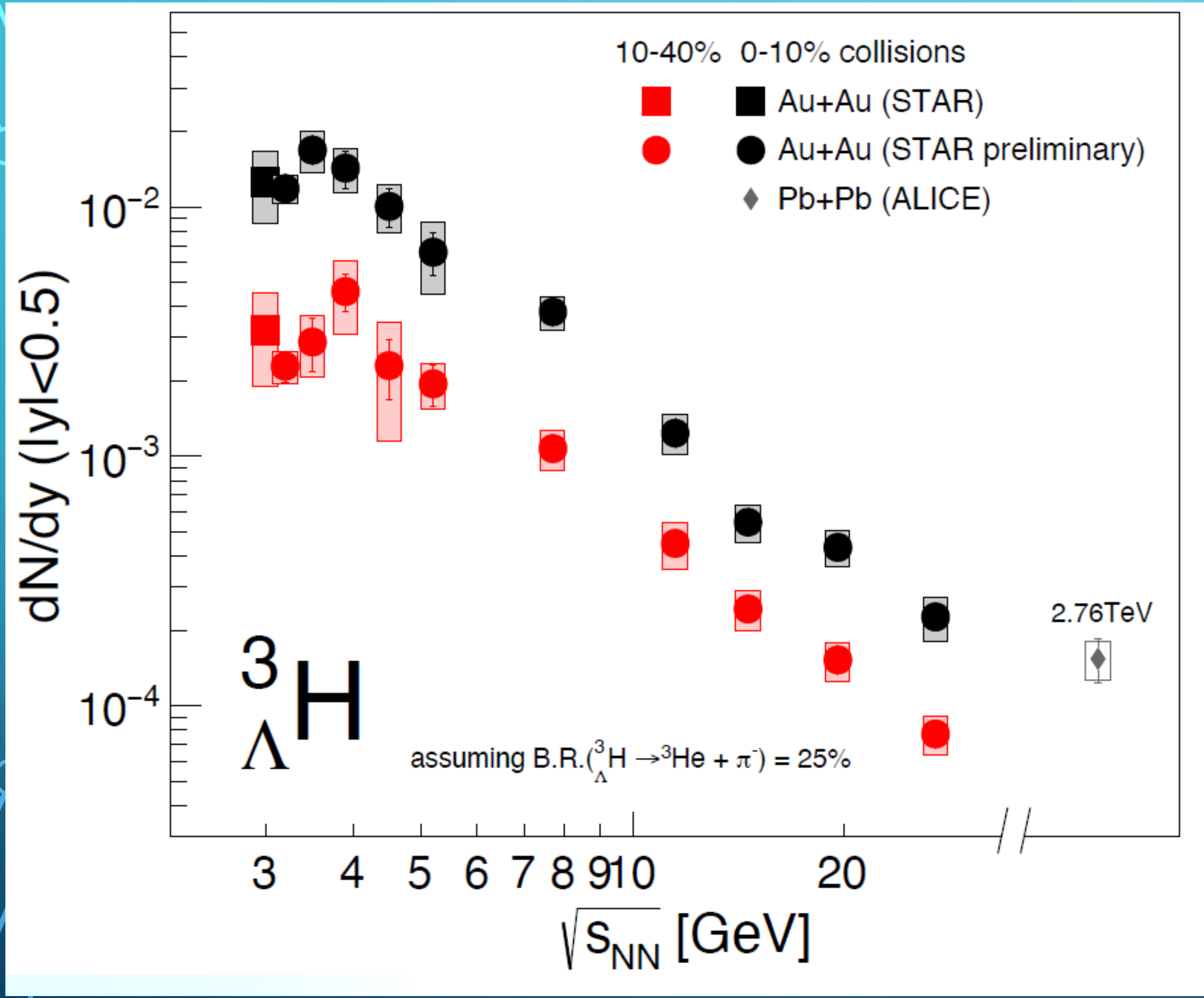
$^{3}_{\Lambda}H$ yield at mid-rapidity increases about factor of 10^2 from 2.76 TeV to 3 GeV

Thermal model reproduces the trend, but does not quantitatively describe the yields of $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$

New data provide first constraints for hypernuclei production models in the high-baryon-density region

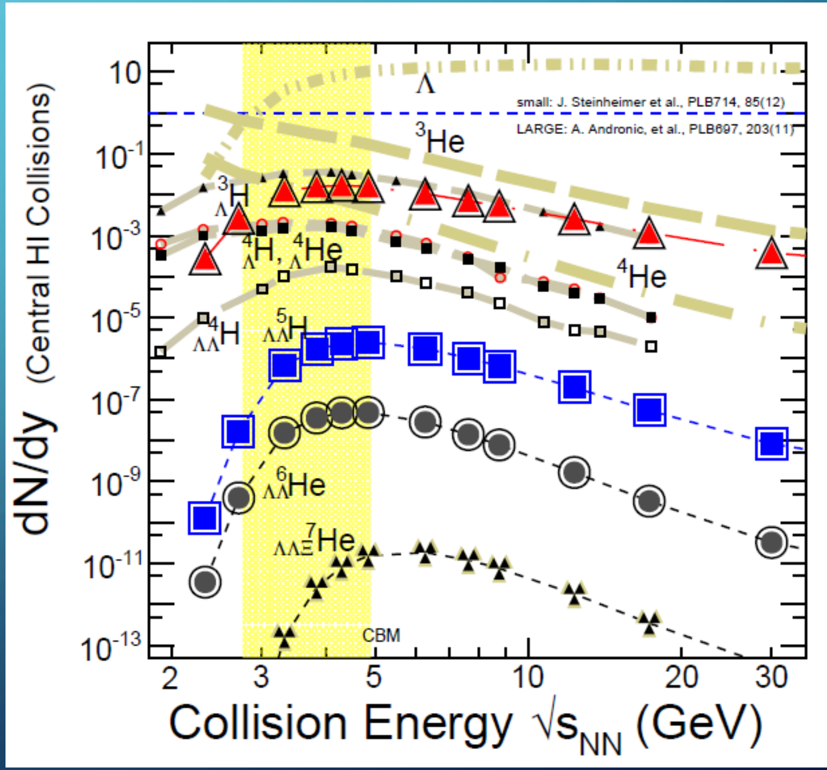
- Interplay between:
  - $\sqrt{s_{NN}}$ ↓, baryon density ↑, yields ↑
  - $\sqrt{s_{NN}}$ ↓, strangeness canonical suppression↑, yields ↓

CENTRALITY DEPENDENCE OF ${}^{3}_{\Lambda}H$ PRODUCTION

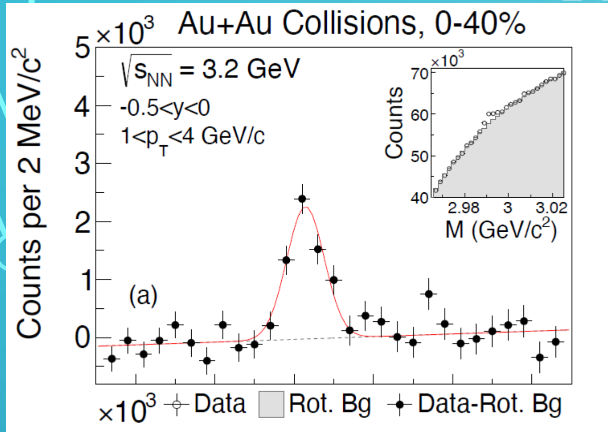


The yield in mid-central (10-40%) collisions follow the same trend as central (0-10%) collisions

New data provide first constraints for hypernuclei production models in the high-baryon-density region



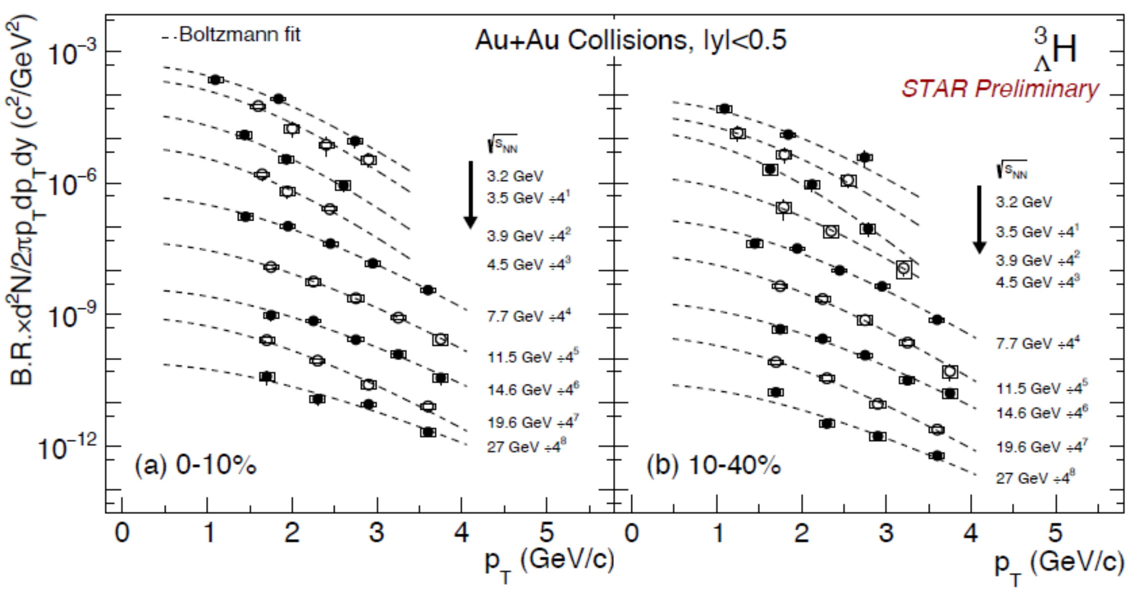
${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H & ${}^{4}_{\Lambda}$He PRODUCTION



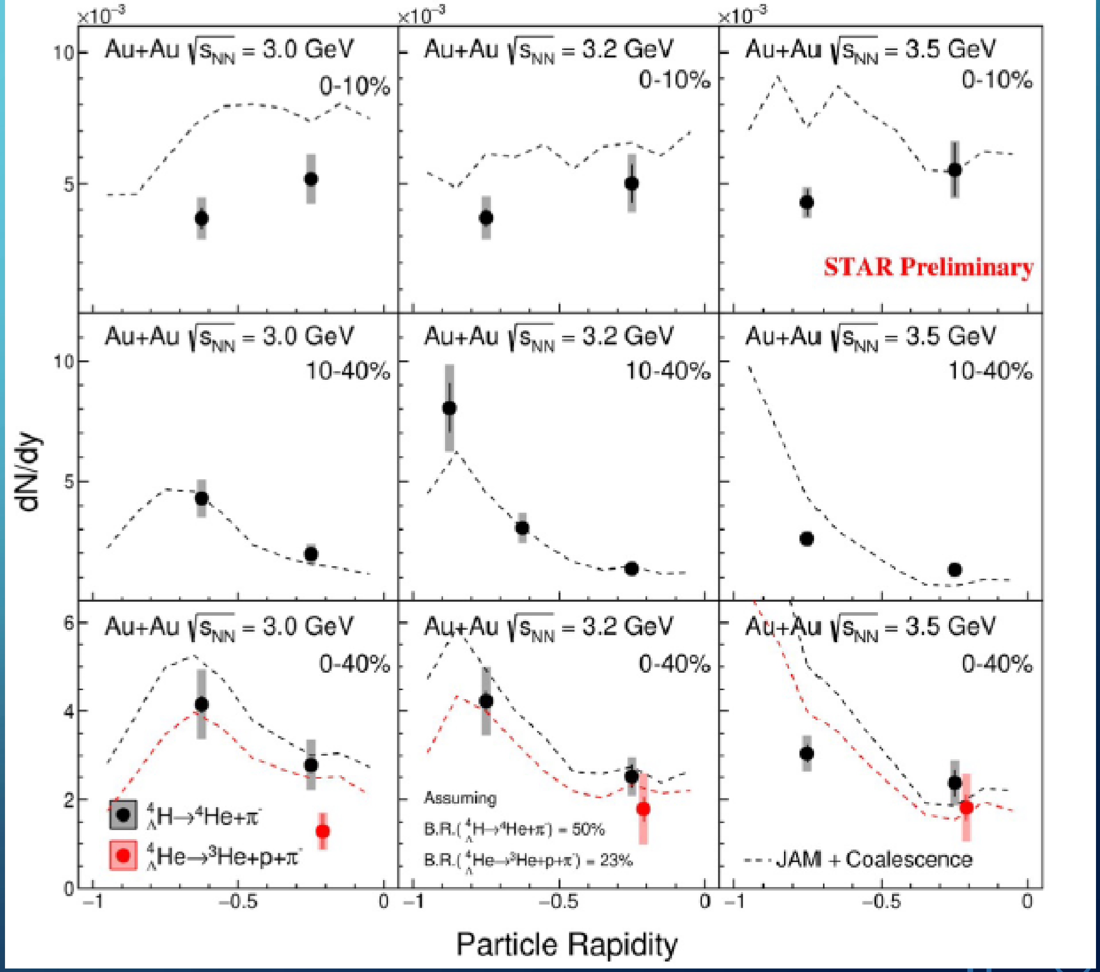
${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H yields obtained **multi-differentially** as a function of p_T, rapidity and centrality

- ➢ **First measurement of dN/dy of hypernuclei in HI collisions**
- ➢ New challenges for the models

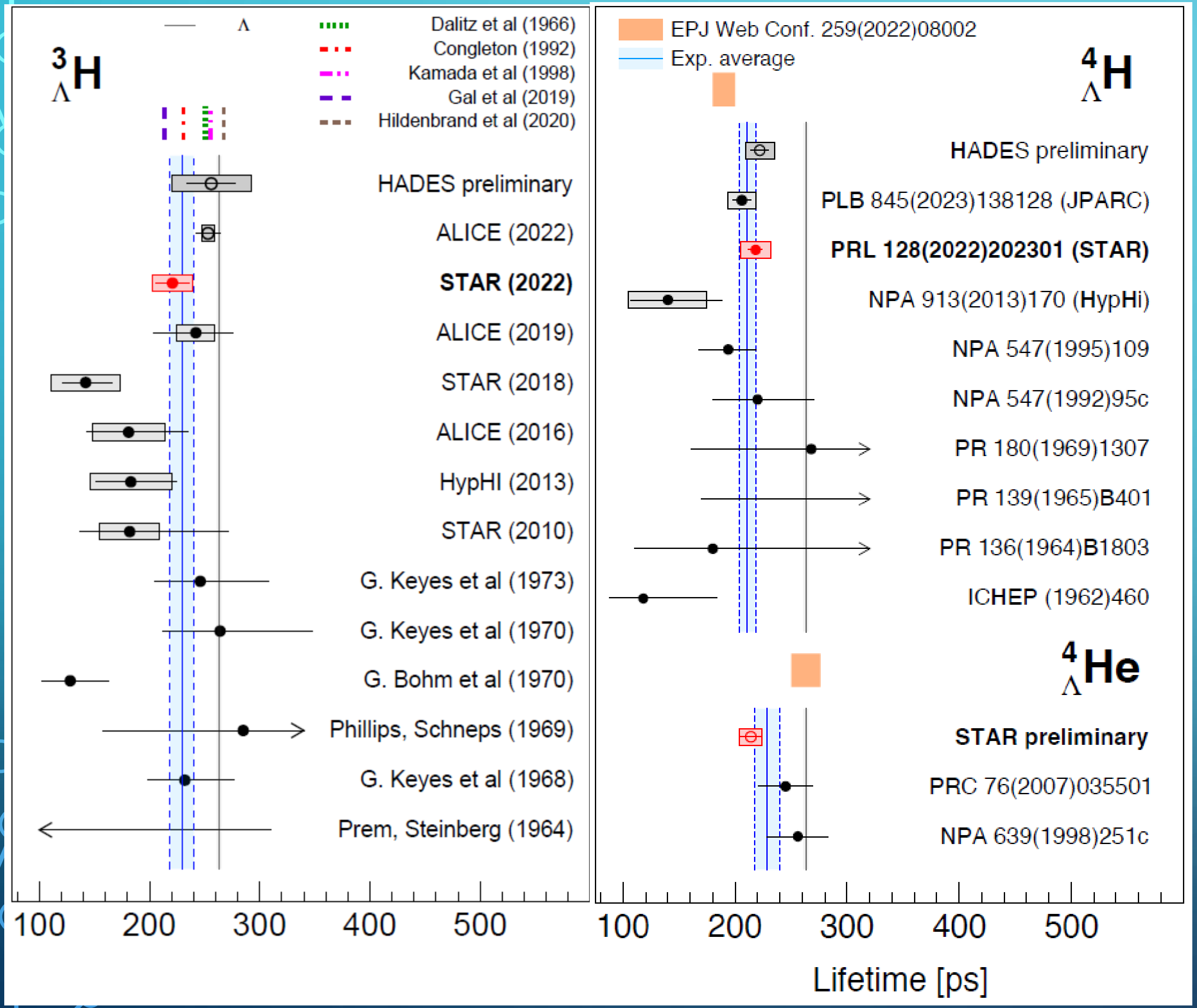
A=3: ${}^{3}_{\Lambda}$H (Au+Au $\sqrt{s_{NN}}$ =3-27 GeV)



A=4: ${}^{4}_{\Lambda}$H, ${}^{4}_{\Lambda}$He (Au+Au $\sqrt{s_{NN}}$ =3-3.5 GeV)



HYPERNUCLEI LIFETIMES



$^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H lifetimes shorter than τ_{Λ} (with 1.8σ, 3.0σ respectively)

Consistent with theoretical calculations including pion FSI

A. Gal et al, PLB791(2019)48

$$\frac{\tau_{avg}\ {}^{4}_{\Lambda}H}{\tau_{avg}\ {}^{4}_{\Lambda}He} = 0.92 \pm 0.06,$$

consistent (3.0σ) with the theoretical estimation: 0.74 ± 0.04

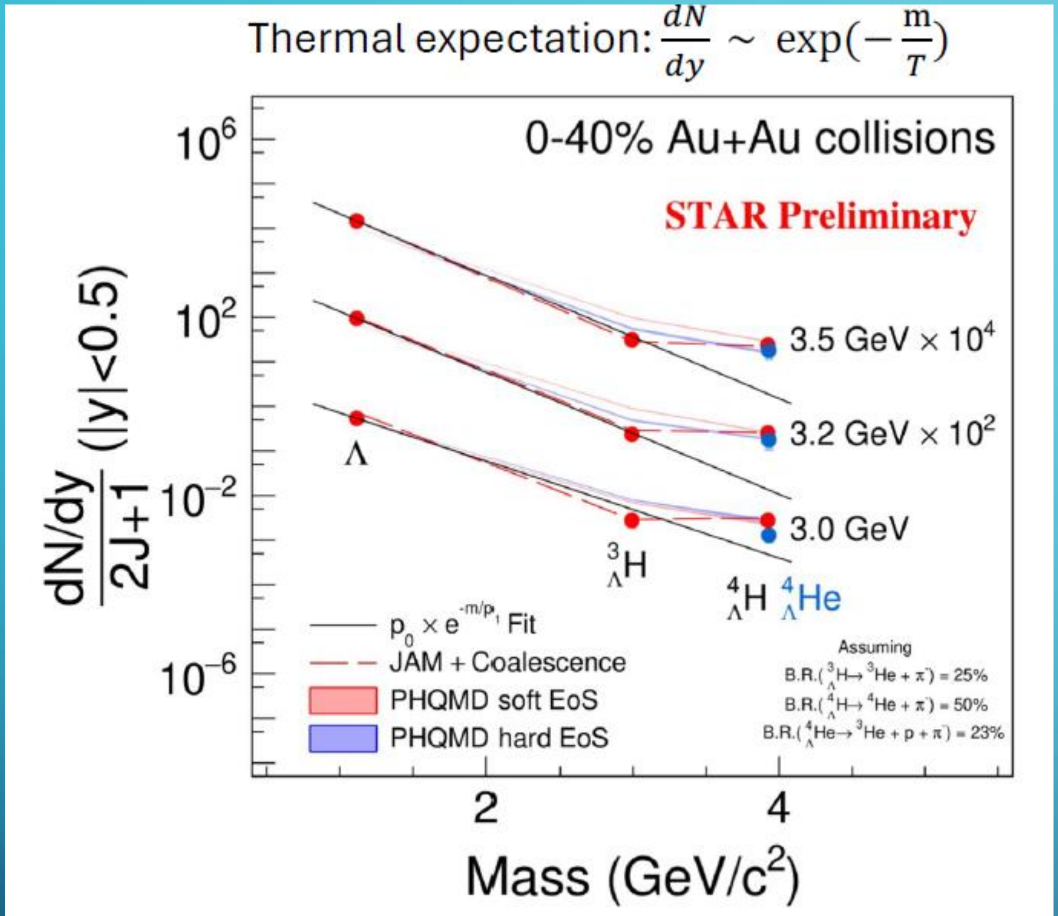
A. Gal (2021), arXiv:2108.10179

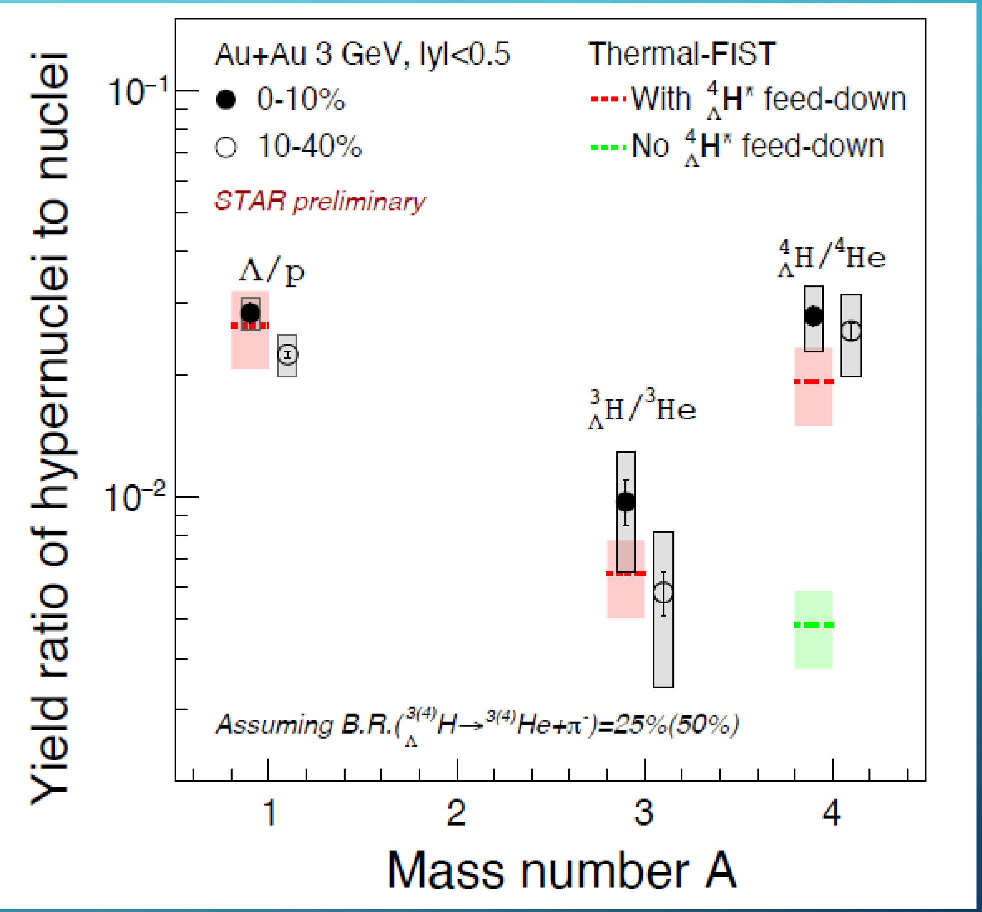
ALICE H3L lifetime (2022) arXiv:2209.07360
HADES H3L, H4L lifetime (preliminary) S. Spies (HADES), QM2022
JPARC H4L lifetime (2022) arXiv:2302.07443

$$\tau({}^{3}_{\Lambda}H) = 221 \pm 15(stat) \pm 19(syst)\ [ps]$$
$$\tau({}^{4}_{\Lambda}H) = 218 \pm 6(stat) \pm 13(syst)\ [ps]$$
$$\tau({}^{4}_{\Lambda}He) = 214 \pm 10(stat) \pm 10(syst)\ [ps]$$

STAR Xiujun Li, SQM 2024

HYPERNUCLEI VS LIGHT NUCLEI AT 3 GEV





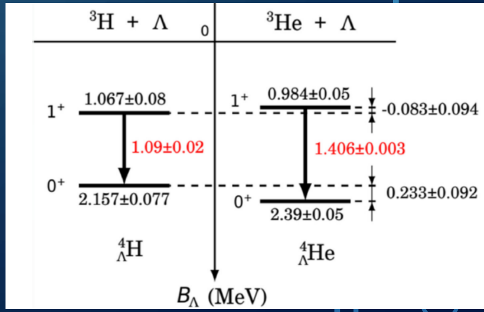
Thermal/coalescence models predict approximately exponential dependence of yields/(2J+1) vs A

factor 6 above fit for $^4_\Lambda\mathrm{H}, ^4_\Lambda\mathrm{He}$

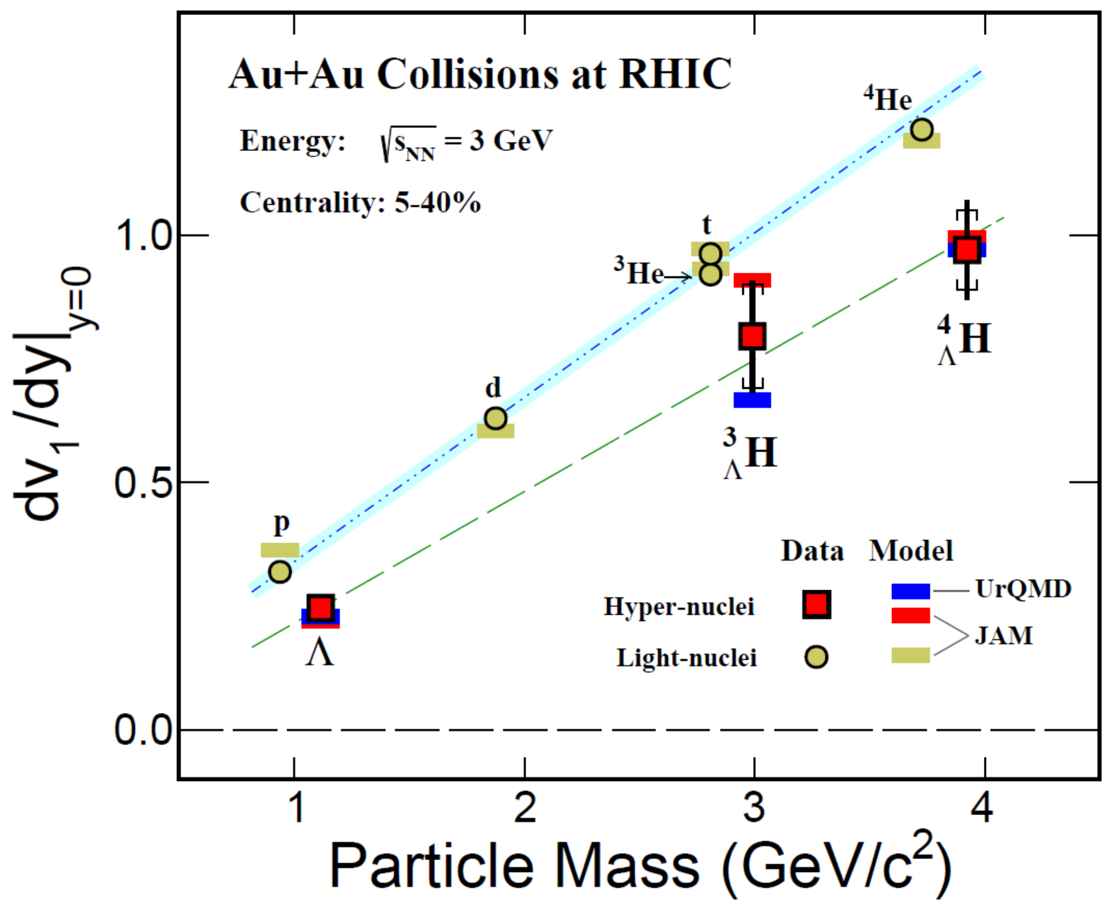
Non-monotonic behavior in light-to hyper-nuclei ratio vs A observed

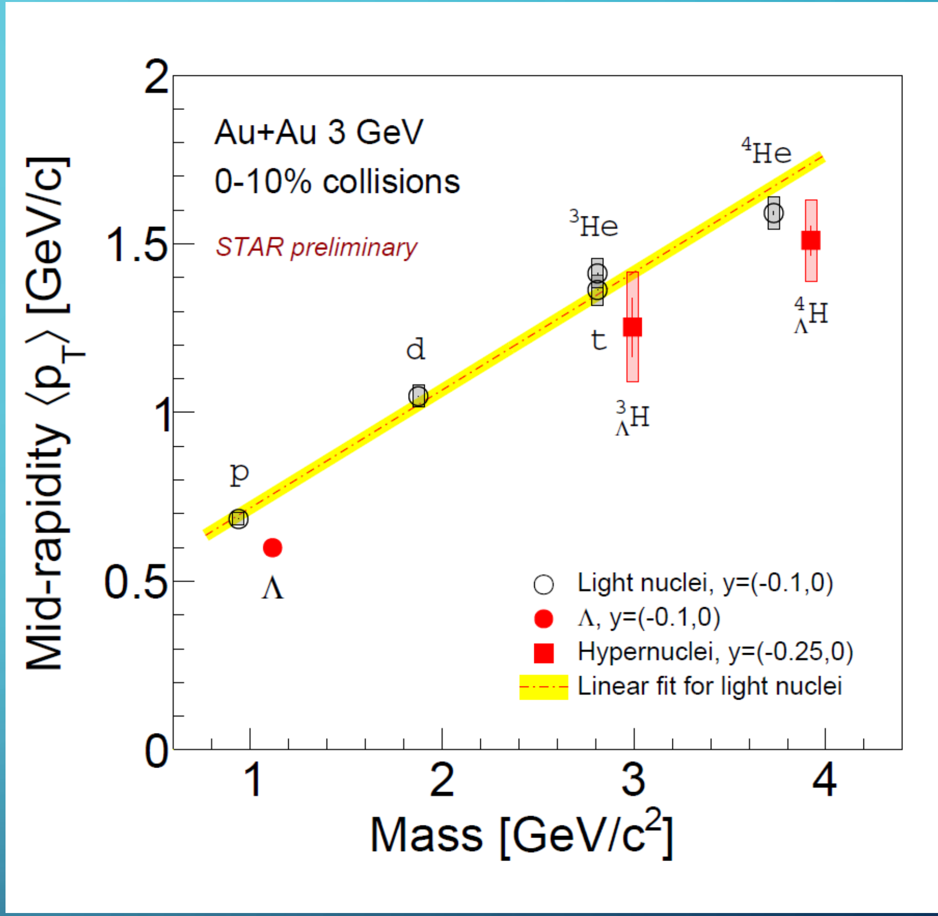
Data support creation of excited A=4 hypernuclei from heavy-ion collisions

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



HYPERNUCLEI COLLECTIVITY AT 3 GEV





- **First observation of hypernuclei collectivity v_1 in HI collisions**
- v_1 slope follows **mass number scaling** in 5-40% 3 GeV Au+Au collisions, similar to light nuclei
- coalescence is the dominant production mechanism

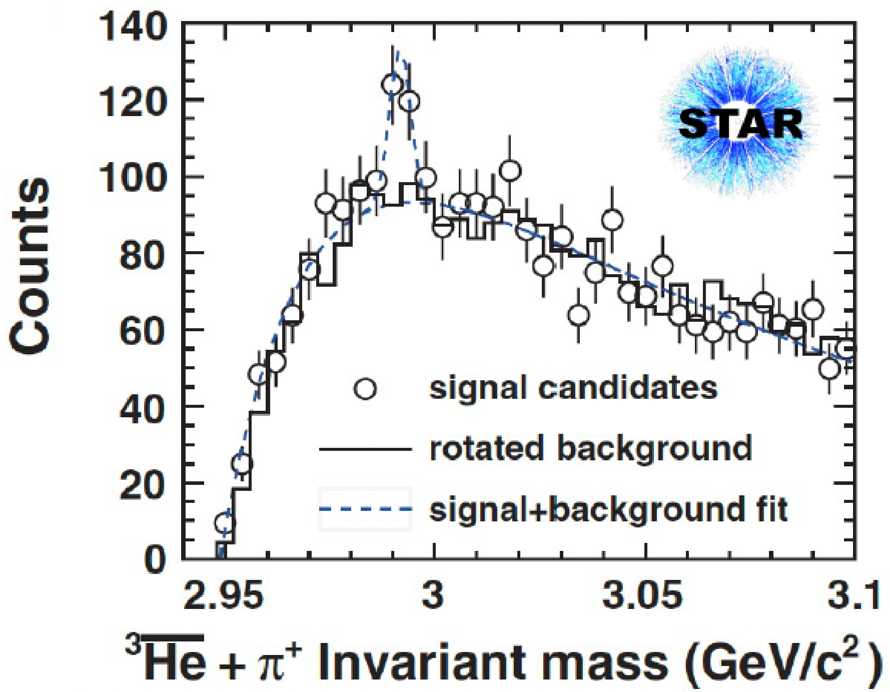
Phys. Rev. Lett. **130**, 212301 (2023)

Dominance of collective radial motion

ANTI-MATTER HYPERNUCLEI

- STAR observed ${}^{4}_{\bar{\Lambda}}\overline{\mathrm{H}}$ in 2023.
  - Benefit from high energy heavy ion collisions ($\mu_B \to 0$).
  - The heaviest observed antimatter nuclear and hypernuclear cluster to date.

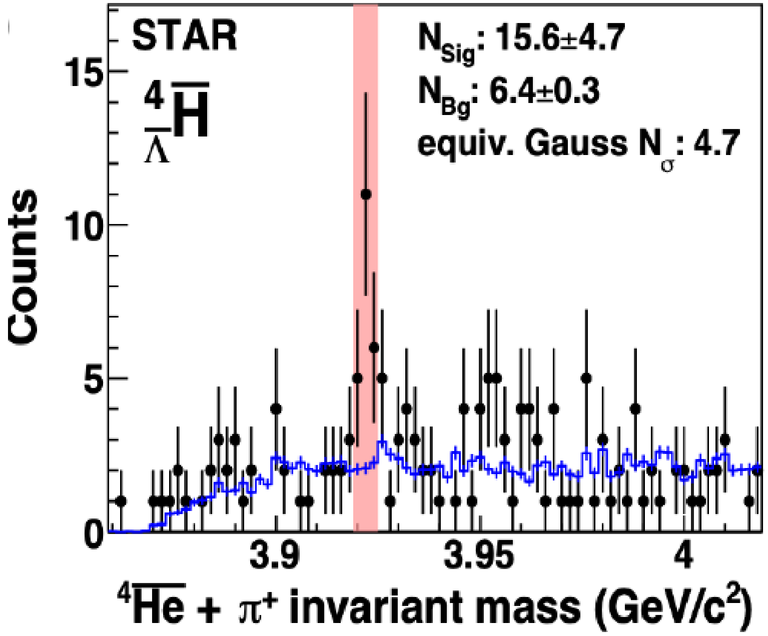
STAR Yuanjing Ji, SQM 2024



$${}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}} \to {}^{3}\overline{\mathrm{He}} + \pi^{+}$$

Science 328 (2010) 58-62

Discovery of A=4 anti-hypernuclei



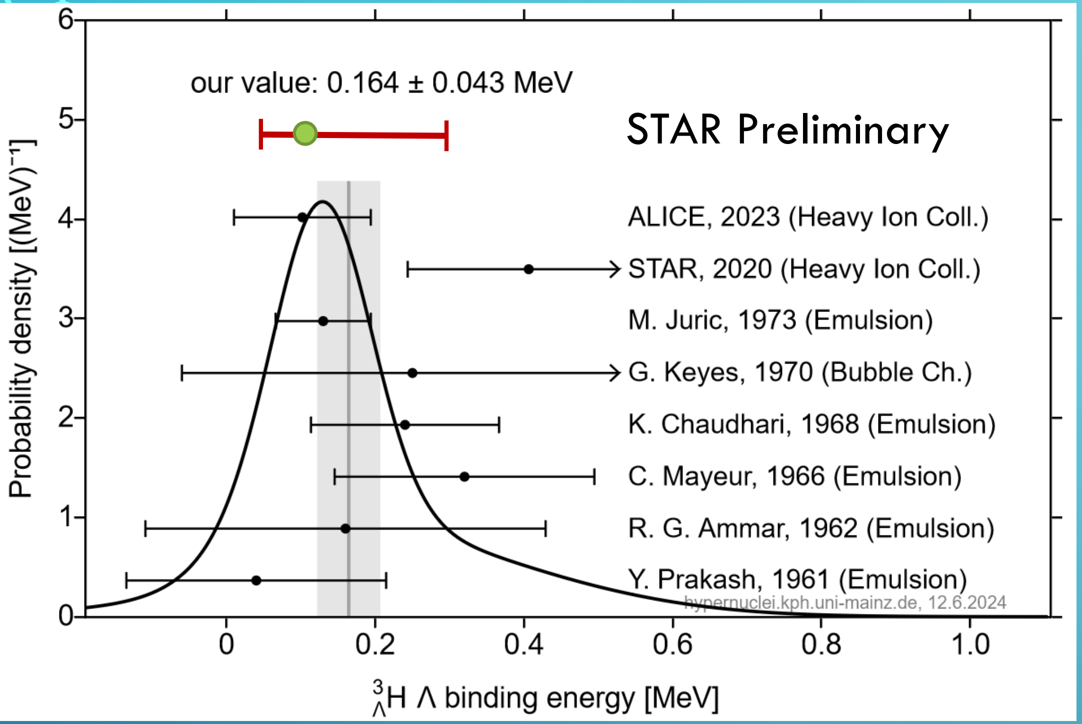
$${}^{4}_{\bar{\Lambda}}\overline{\mathrm{H}} \to {}^{4}\overline{\mathrm{He}} + \pi^{+}$$

arXiv:2310.12674, submitted to Nature

Datasets used:

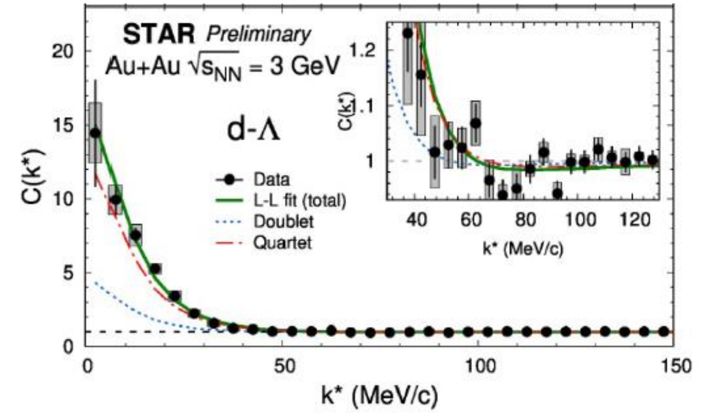
- 200 GeV collisions
  - Au+Au
  - Zr+Zr/Ru+Ru
- 193 GeV collisions
  - U+U

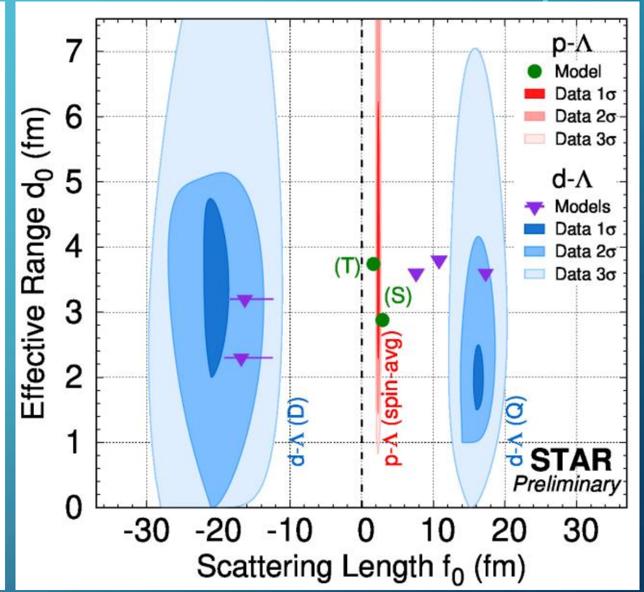
$^{3}_{\Lambda}\mathrm{H}$ Λ BINDING ENERGY



d - Λ correlation

- Femtoscopy method
  - $\frac{1}{-f_0} = \gamma - \frac{1}{2} d_0 \gamma^2, B_\Lambda = \frac{\gamma^2}{2\mu_{d\Lambda}}$





$^{3}_{\Lambda}\mathrm{H}$ Λ binding energy to be 0.04 to 0.33 MeV at 95% CL

Provides a new method to study the hypernuclei structure in the HI collision experiment

arXiv:2401.00319v1 [nucl-ex] 30 Dec 2023

Due to its very small binding energy, $^{3}_{\Lambda}\mathrm{H}$ production provides unique input for theoretical models (R ~ 5 – 10 Fm) and production mechanism (coalescence)

SUMMARY

- Updated set of hypernuclei measurements in the high-baryon-density region with high statistical precision

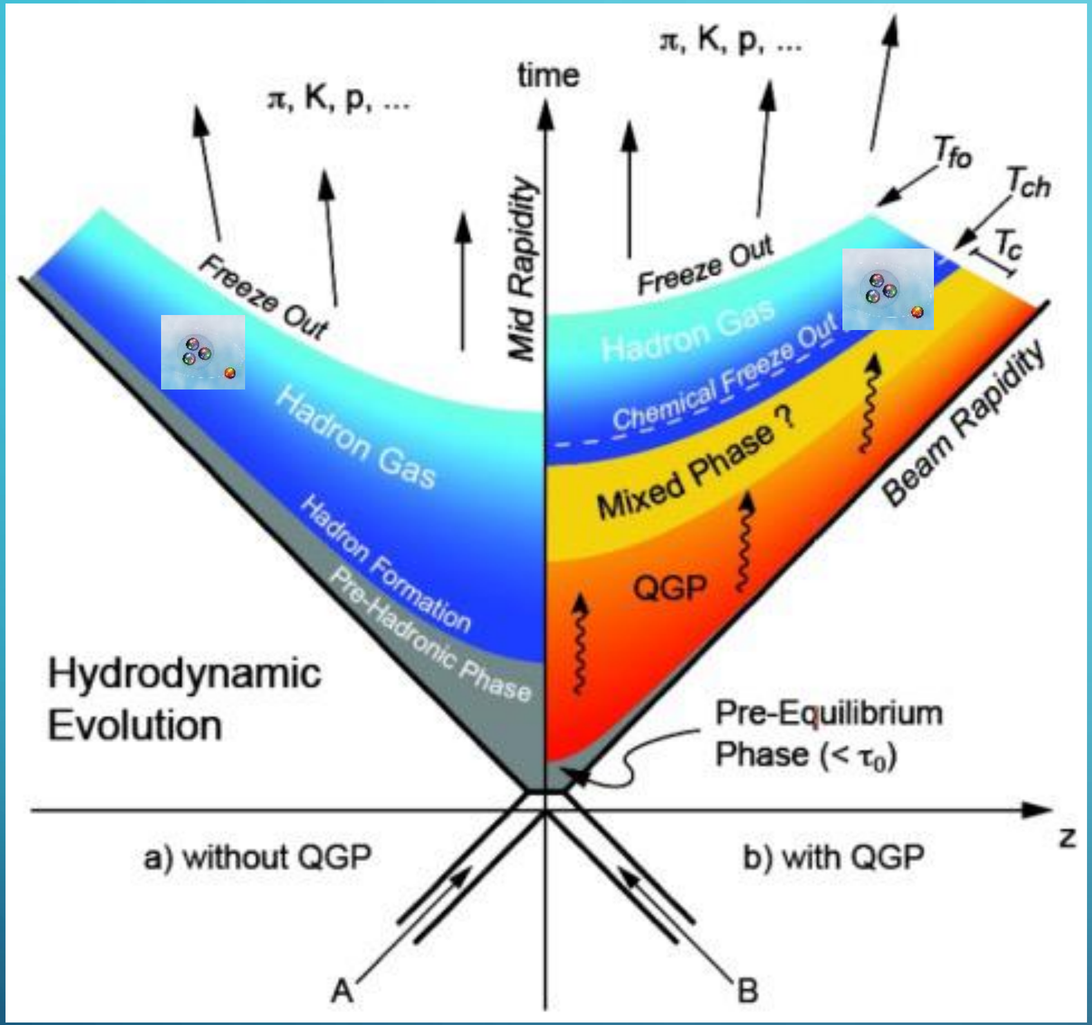
- ${}^{3}_{\Lambda}\mathrm{H}$ yields in central collisions overestimated by thermal model by a factor of 2

- ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$ lifetimes measured with improved precision

- New measurements of ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$ differential yields at 3.0 - 27 GeV

- First observation of hypernuclei collectivity v_1

- We observe ${}^{5}_{\Lambda}\mathrm{He}$ with significance of 14.0 σ



Thank you for your attention!