EXPERIMENTAL ADVANCES IN HYPERNUCLEI RESEARCH: LESSONS FROM RHIC BES-II

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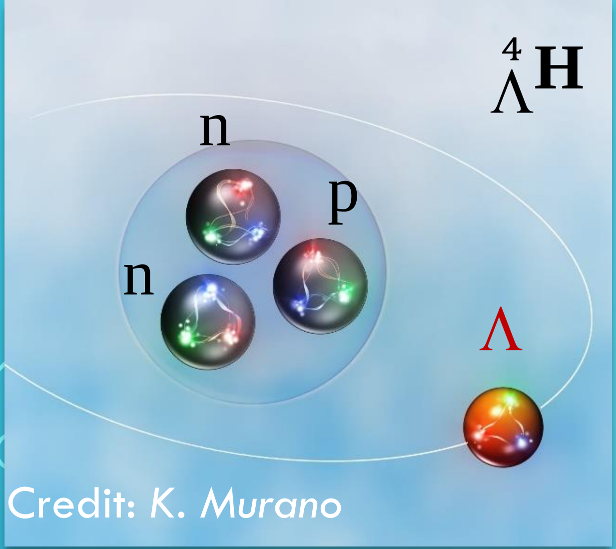
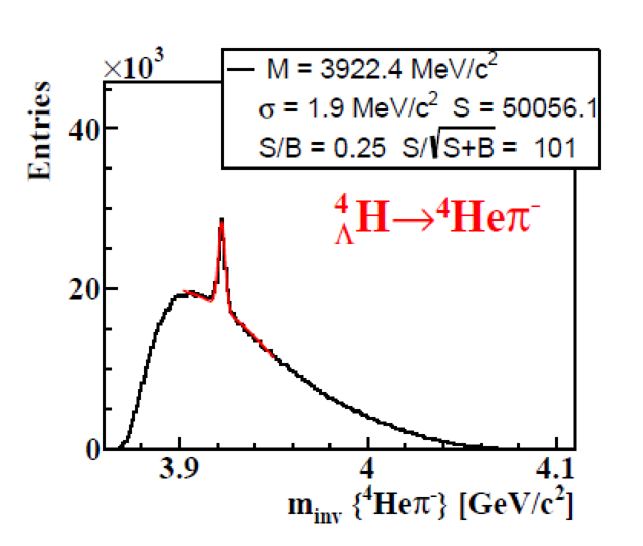
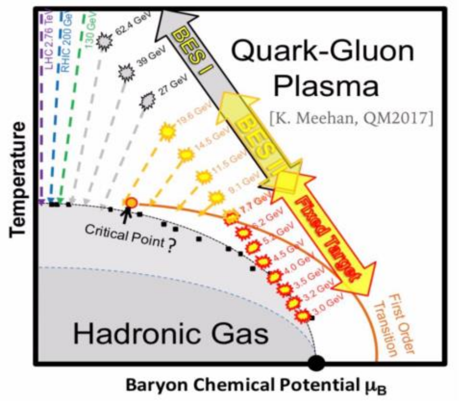
3 – CCNU CENTRAL CHINA NORMAL UNIVERSITY, WUHAN, CHINA



HYPERNUCLEI



- Precise measurements of hypernuclei lifetime (**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 **YN** interaction
- Observation of double lambda hypernuclei can provide an access to the **YY** forces



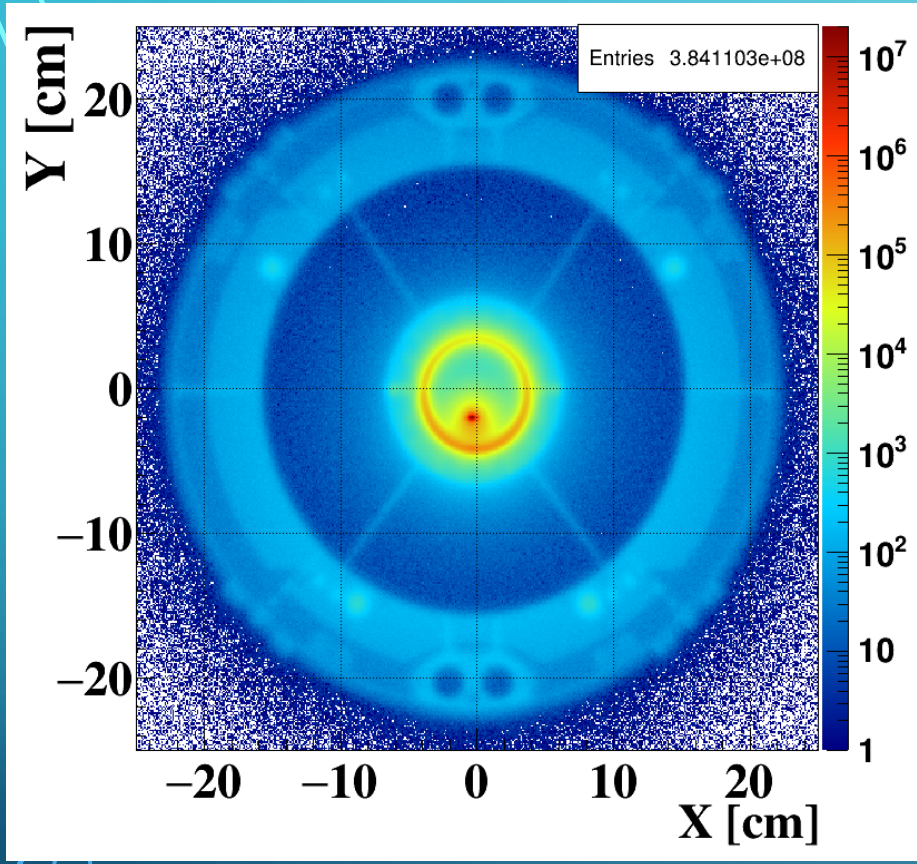
BES - II DATA SETS:

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

STAR DETECTOR TOMOGRAPHY: LESSON 1



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

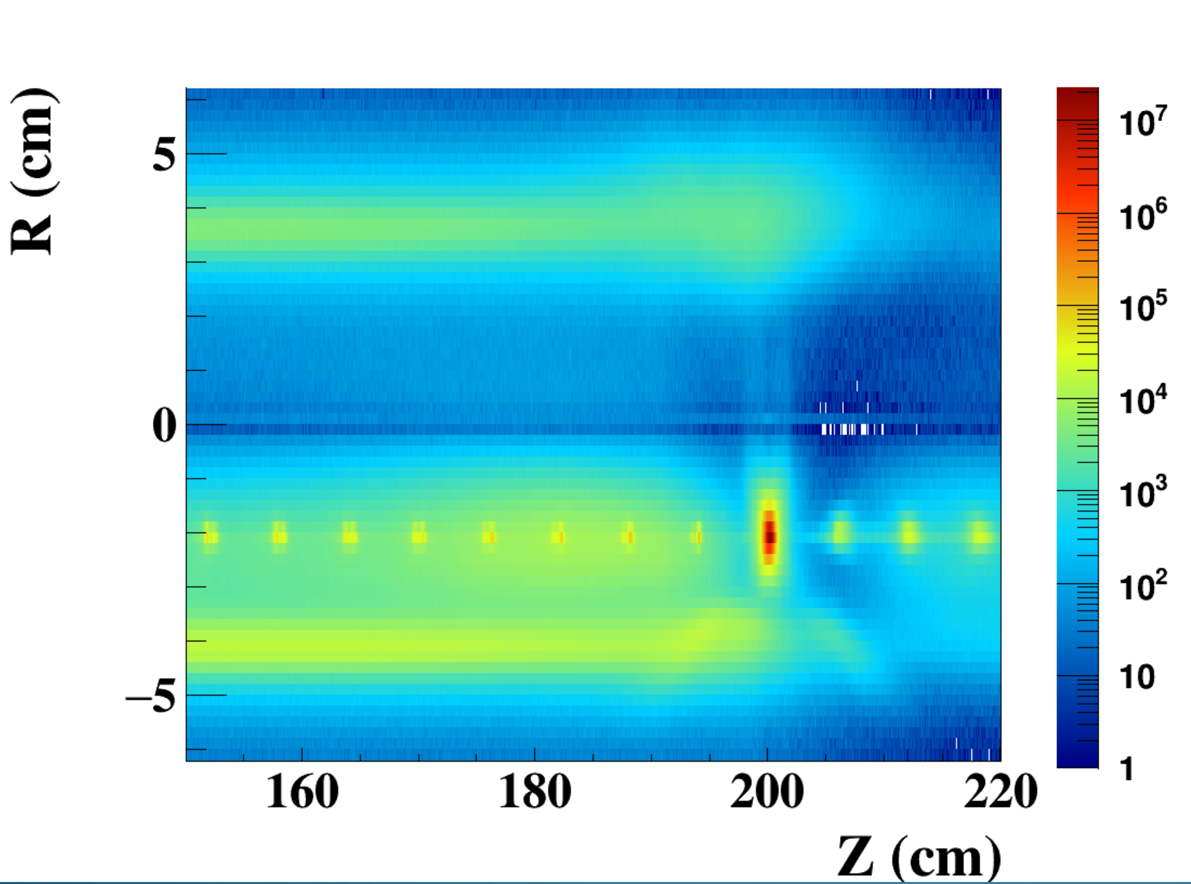
- The structure with R = 2 cm (beam position) is formed by pileup.
- Interactions with the pipe material and support structures are clearly visible.
- Tracks from these vertices lead to higher background, especially in 3-body channels.

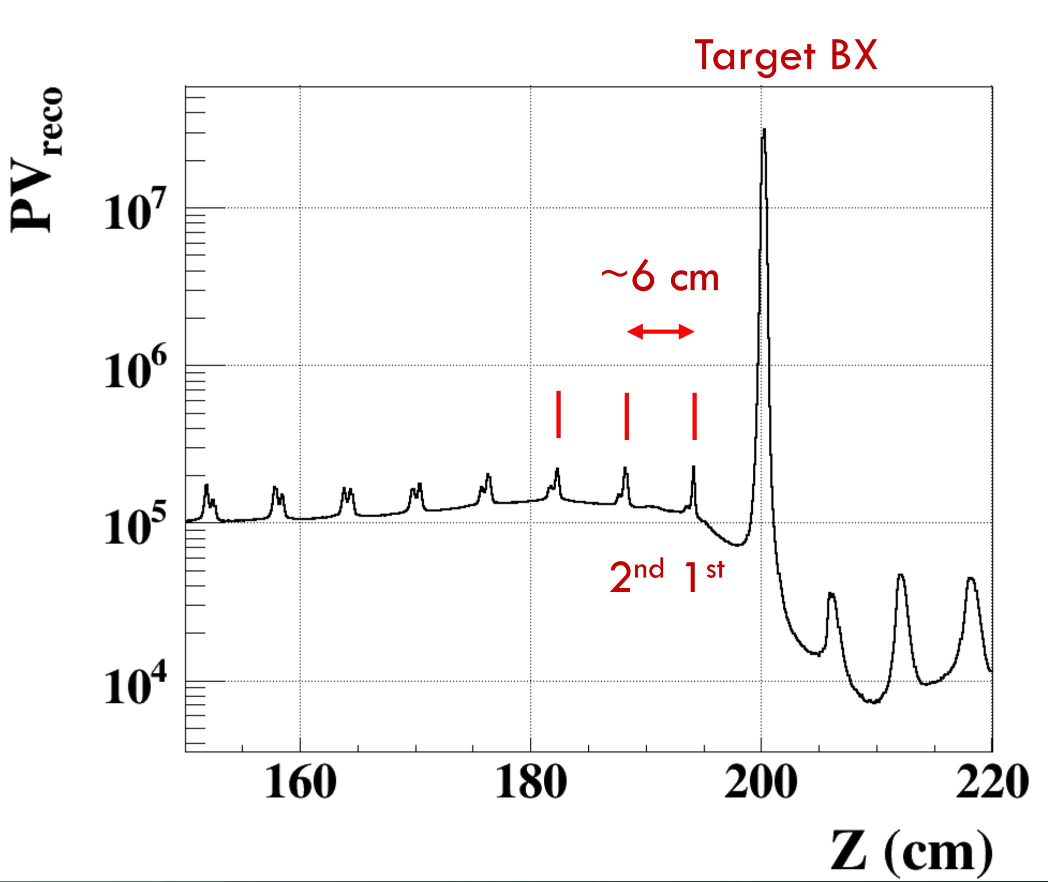
KF Particle package (M. Zyzak)

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.

STAR DETECTOR TOMOGRAPHY: LESSON 1





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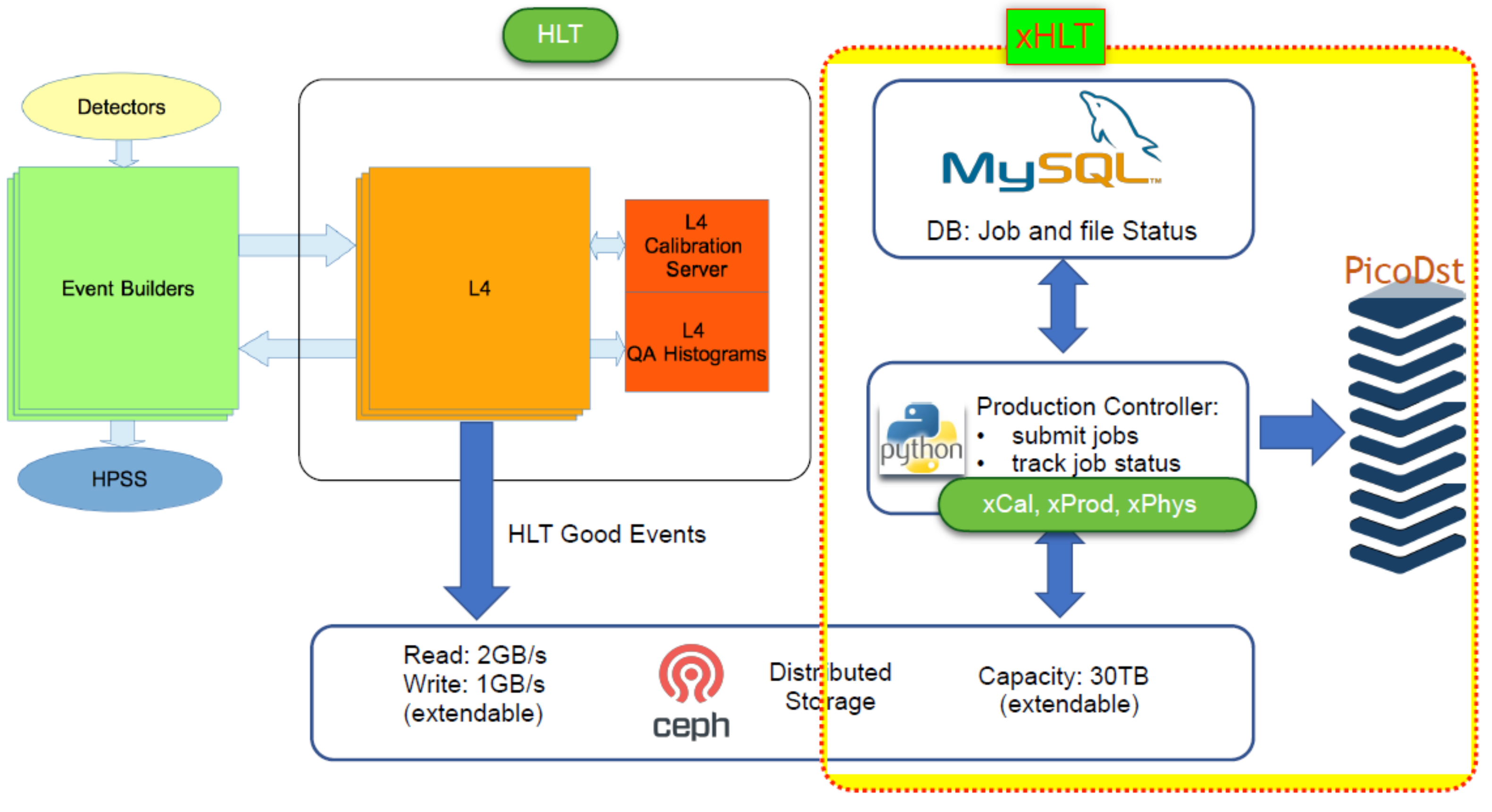
HYPERNUCLEI IN STAR WITH EXPRESS ANALYSIS

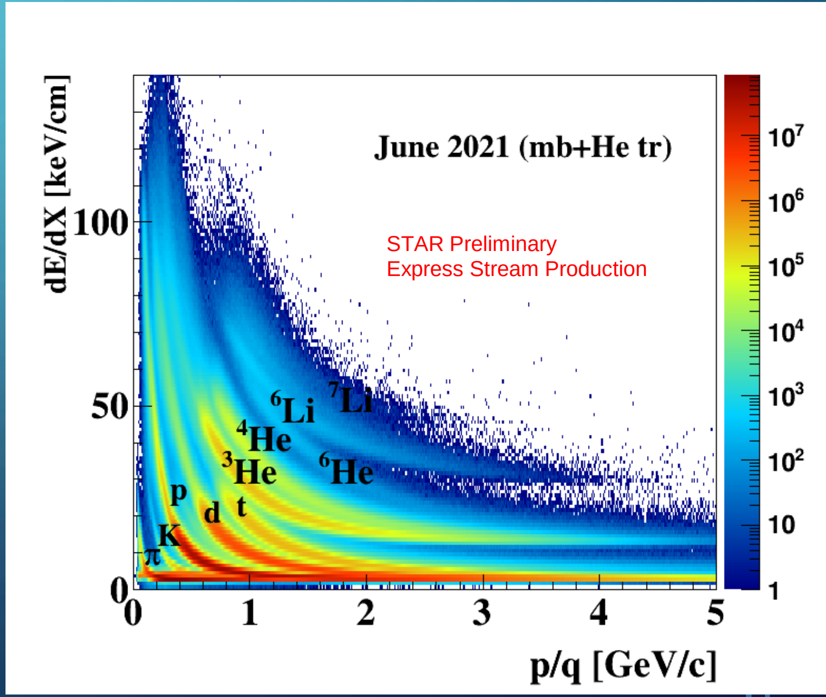


Full chain of express production and analysis has been running since 2019

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

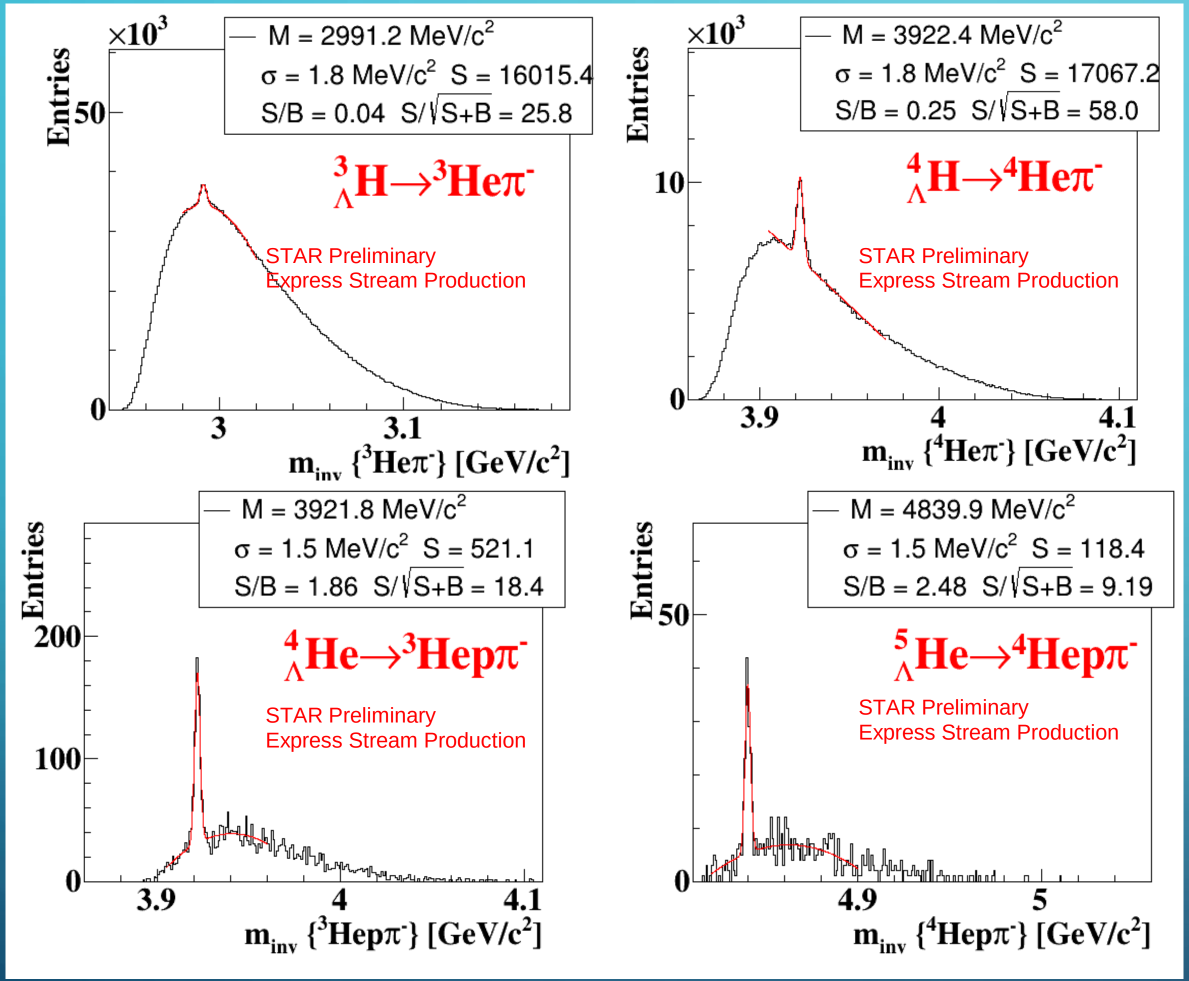


Save HLT good events to a local disk directly

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

HYPERNUCLEI IN STAR WITH ONLINE EXPRESS ANALYSIS

437M AuAu HLT triggered events at 3 GeV



Hypernuclei are reconstructed with KFParticle Finder in following decay channels:

$^{3}_{\Lambda}H \to {}^{3}He + \pi^{-}$
$^{4}_{\Lambda}H \to {}^{4}He + \pi^{-}$
2 body

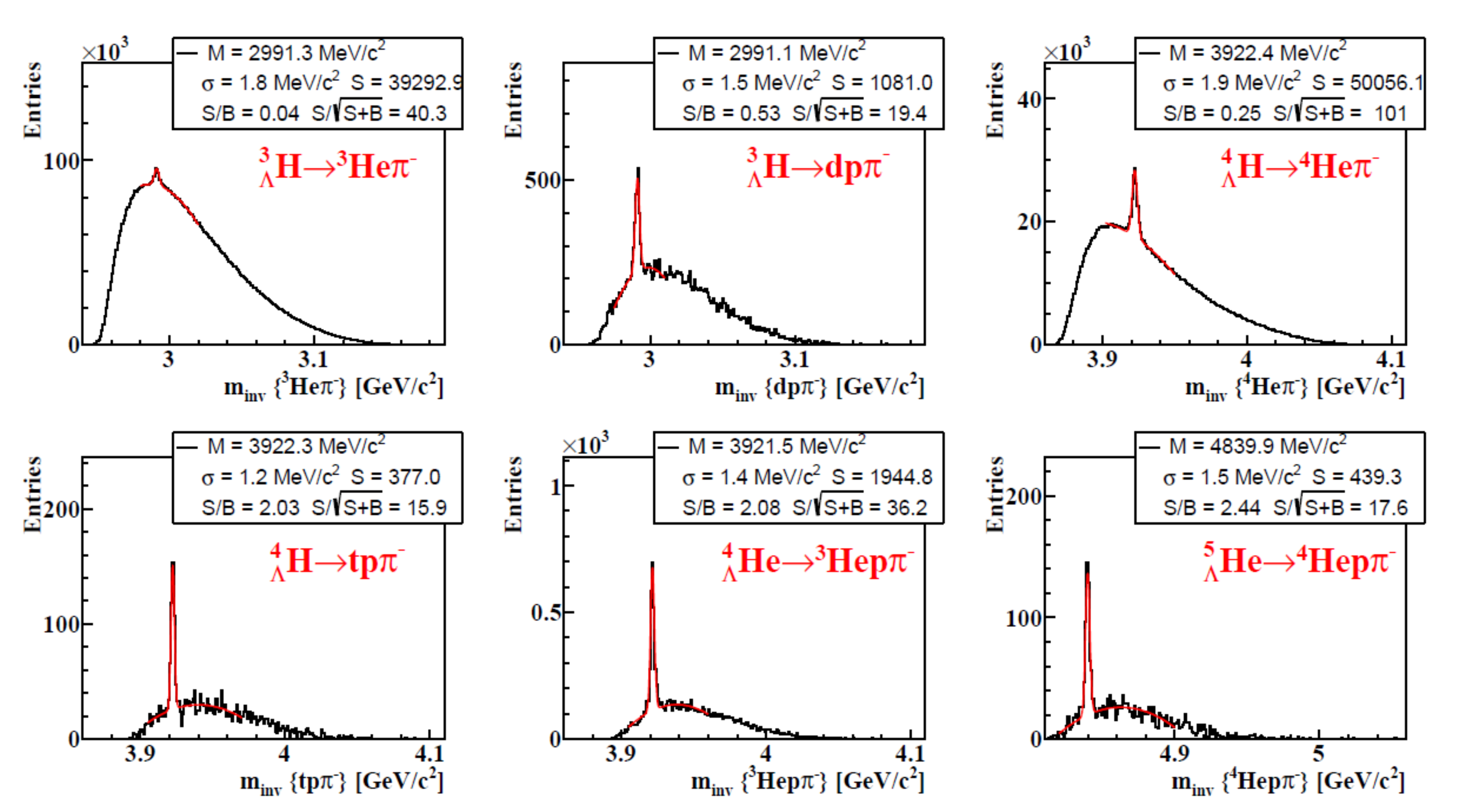
$^{3}_{\Lambda}H \to d + p + \pi^{-}$
$^{4}_{\Lambda}He \to {}^{3}He + p + \pi^{-}$
$^{4}_{\Lambda}H \to t + p + \pi^{-}$
$^{5}_{\Lambda}He \to {}^{4}He + p + \pi^{-}$
3 body

Run by run control
S/Bg ratio, peak positions and mass resolution

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

HYPERNUCLEI IN STAR WITH OFFLINE EXPRESS ANALYSIS

2.11B AuAu events at 3 GeV



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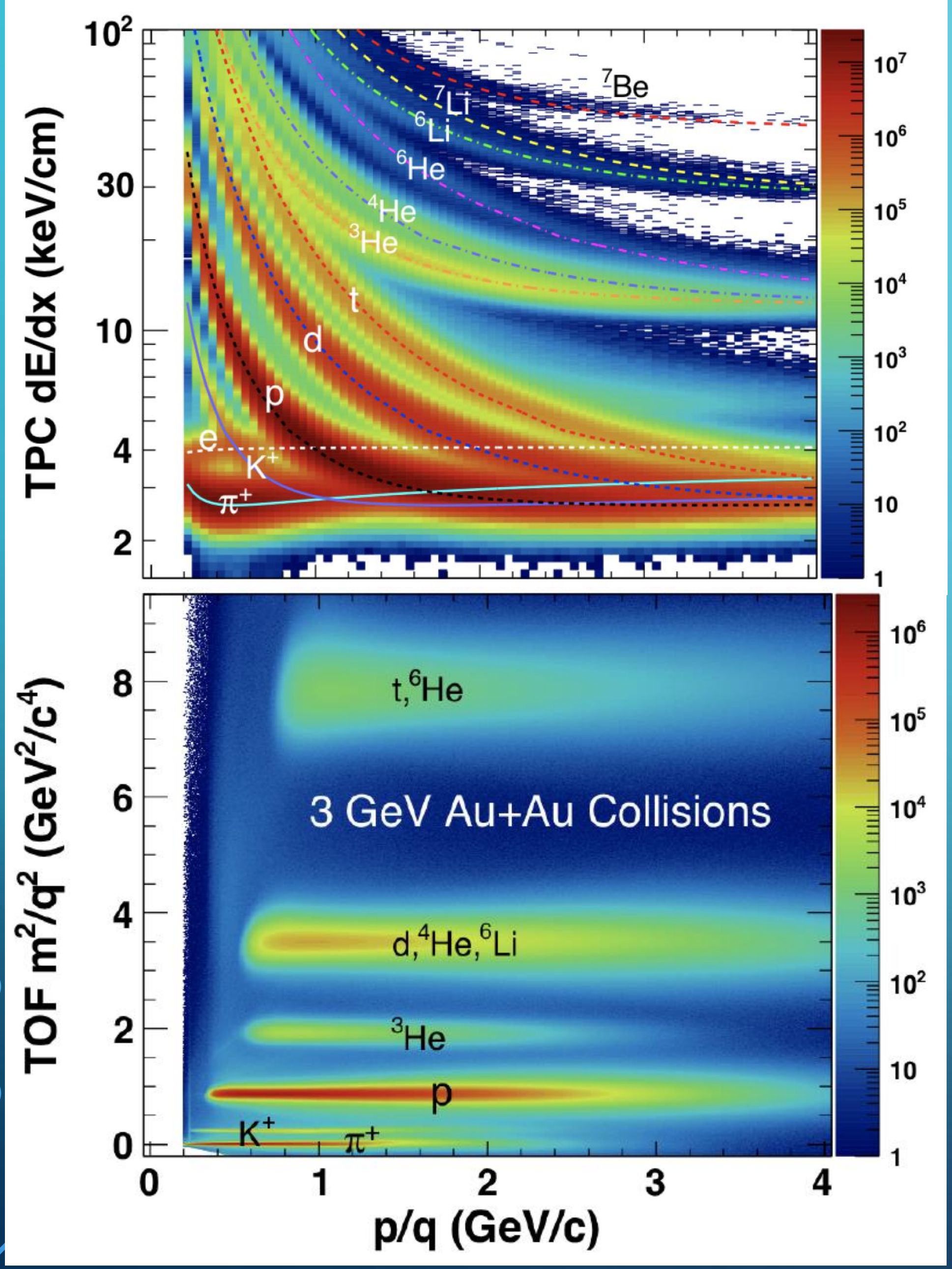
3 body:
- ${}^{3}_{\Lambda}H \rightarrow d + p + \pi^-$
- ${}^{4}_{\Lambda}He \rightarrow {}^{3}He + p + \pi^-$
- ${}^{4}_{\Lambda}H \rightarrow t + p + \pi^-$
- ${}^{5}_{\Lambda}He \rightarrow {}^{4}He + p + \pi^-$

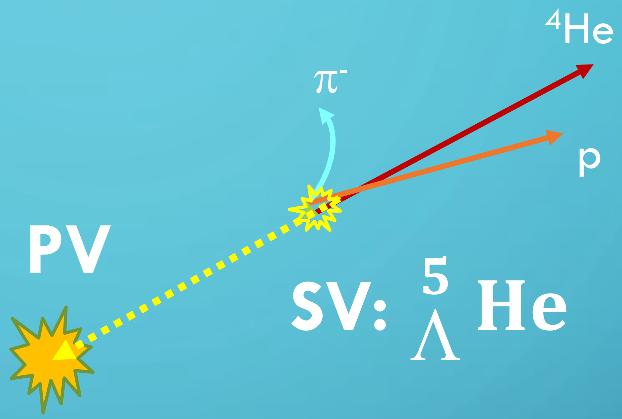
HLT Trigger Efficiency: 0.41 - 0.27
S/Bg On/Off ratio: 0.9 – 1.0
HN Enhansment factor: 1.3 – 1.97

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

HYPERNUCLEI 3-BODY TOPOLOGY: LESSON 2



Signal: $^{5}_{\Lambda}\mathrm{He} \rightarrow {}^4\mathrm{He} + p + \pi^-$



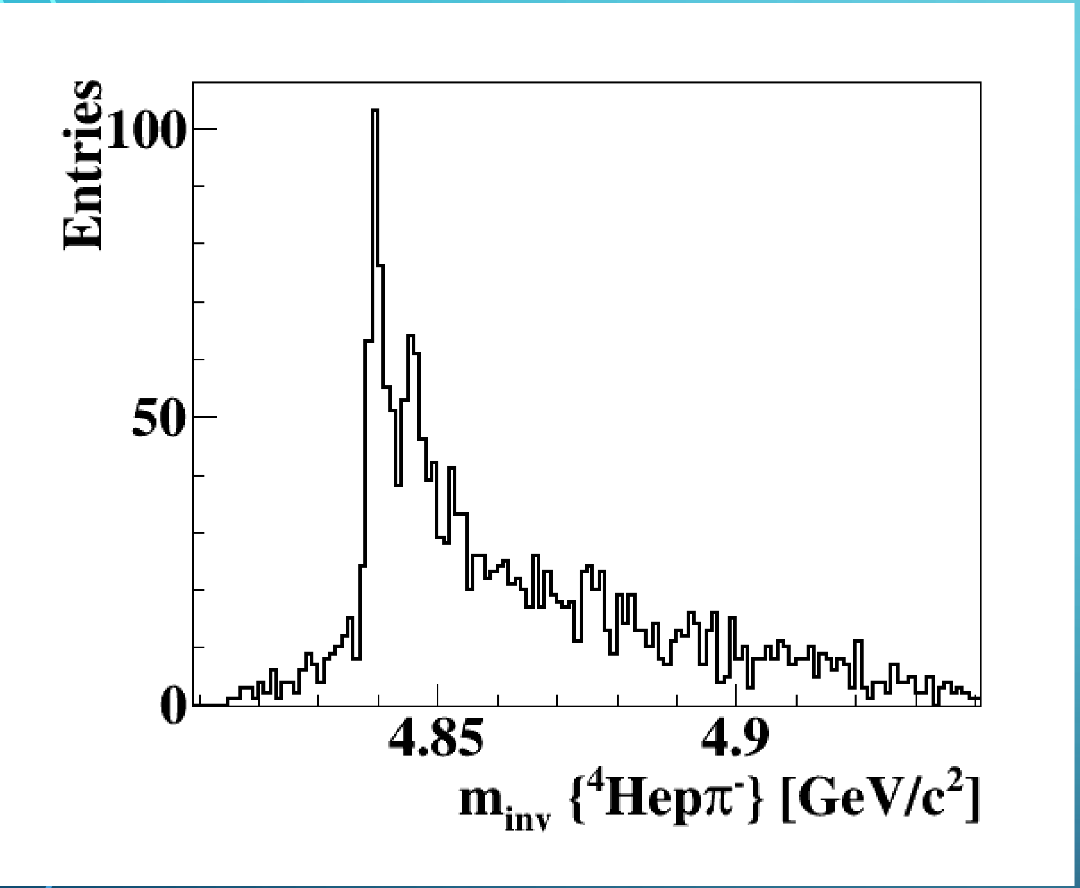
In the analysis, particle identification was performed using the Time Projection Chamber (TPC) and the Time of Flight (TOF) detectors.

Hypernuclei are reconstructed with KFParticle Finder

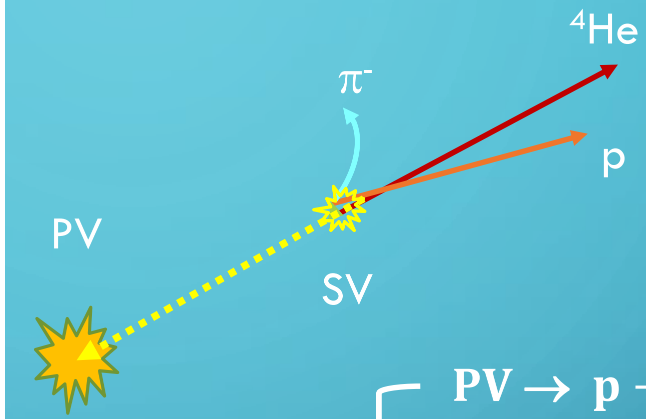
TPC: Nucl. Instrum. Meth. A 499, 659 (2003), nucl-ex/0301015.
TOF: Nucl. Instrum. Meth. A 661, S110 (2012).

HYPERNUCLEI 3-BODY TOPOLOGY: LESSON 2

Hypernuclei are reconstructed with KFParticle Finder



Signal: $^{5}_{\Lambda}He \rightarrow {}^{4}He + p + \pi^{-}$



BG:
- $PV \rightarrow p + {}^{4}_{\Lambda}H \rightarrow p + {}^{4}He + \pi^{-}$ X
- $PV \rightarrow {}^{4}He + \Lambda \rightarrow {}^{4}He + p + \pi^{-}$ √

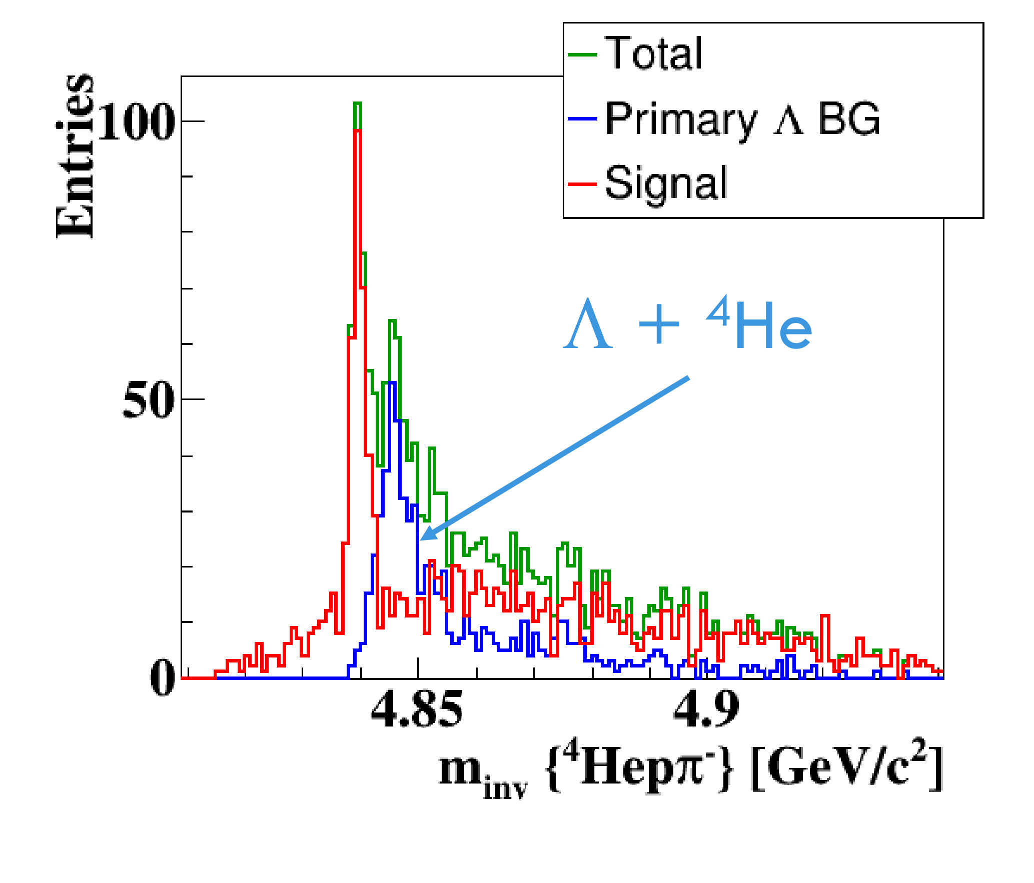
M $^{4}He + p + \pi^{-}$ = 4.8052 (GeV/c²)

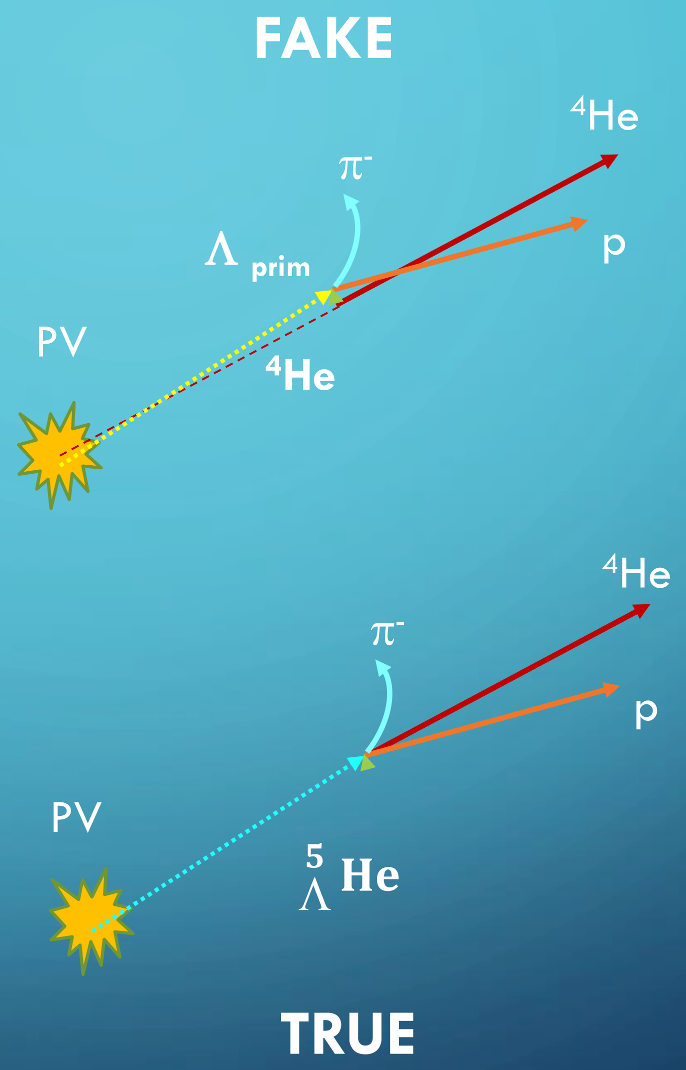
M $^{4}He + \Lambda$ = 4.8431

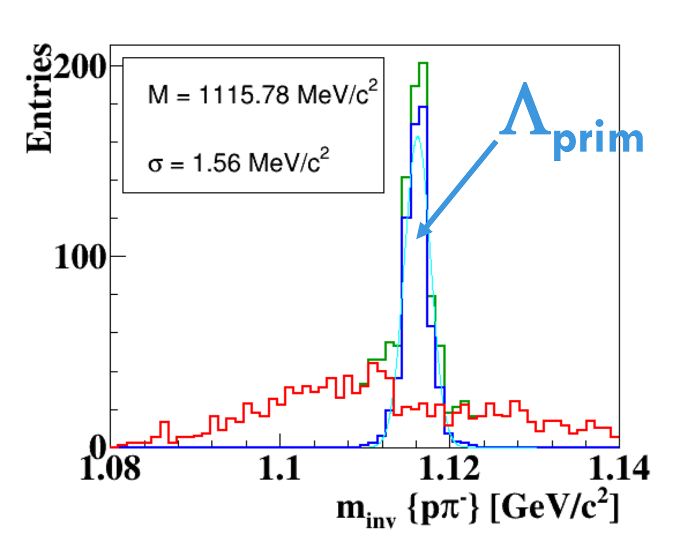
M $^{4}_{\Lambda}H + p$ = 4.8607

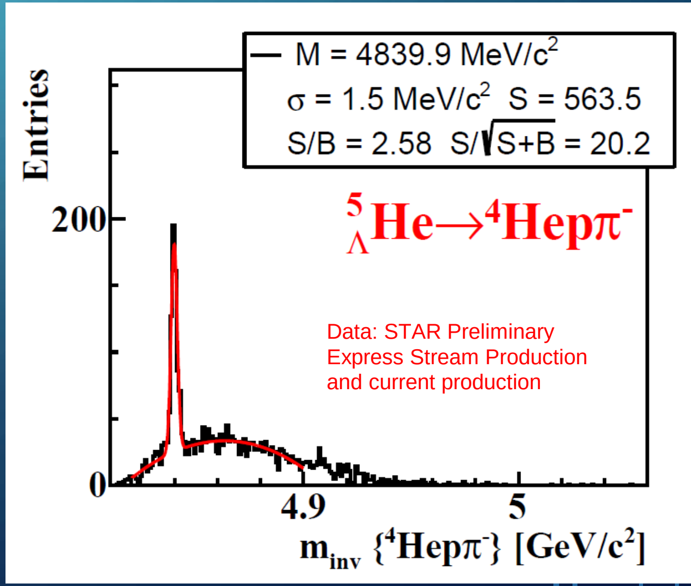
M 1-st peak ~ 4.8398

HYPERNUCLEI 3-BODY TOPOLOGY: LESSON 2

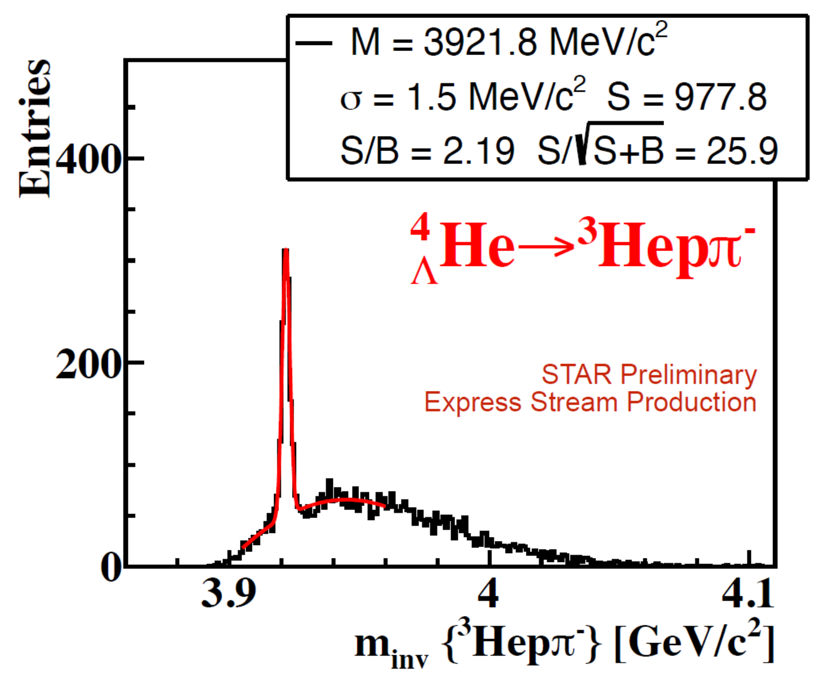


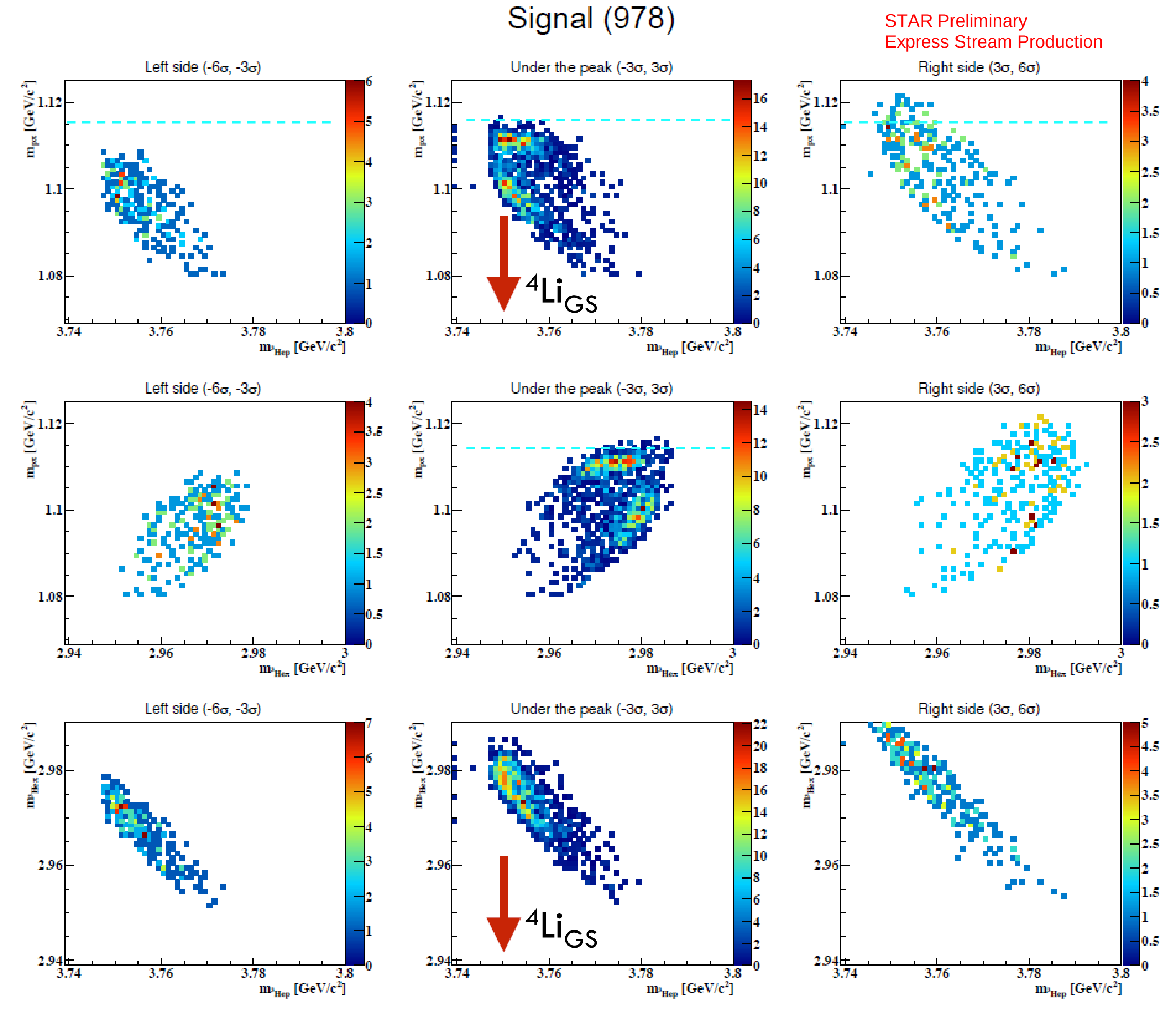






HYPERNUCLEI DALITZ DECAY: LESSON 3





The background was estimated with the side band method and subtracted under the peak.

- The background is smooth and no structures is observed.
- A complex structure in the signal can be explained as a possible spin effect.

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

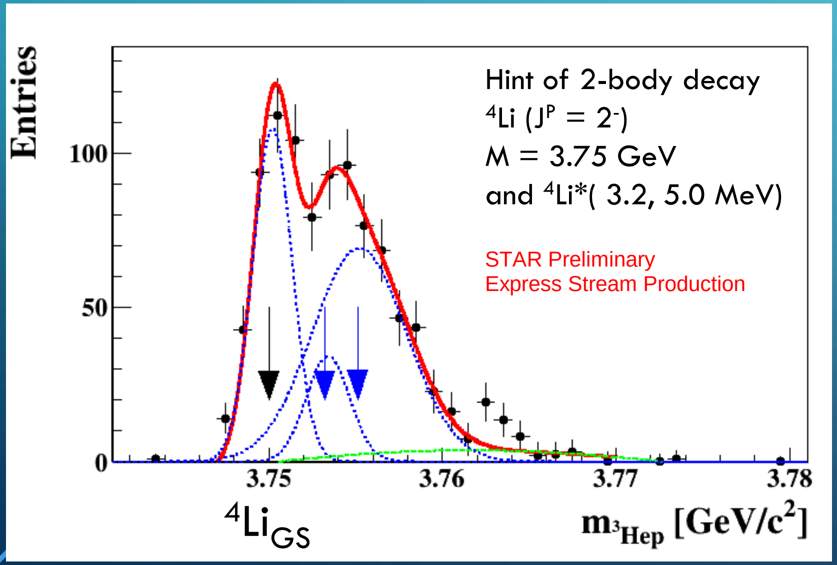
HYPERNUCLEI DALITZ DECAY: LESSON 3

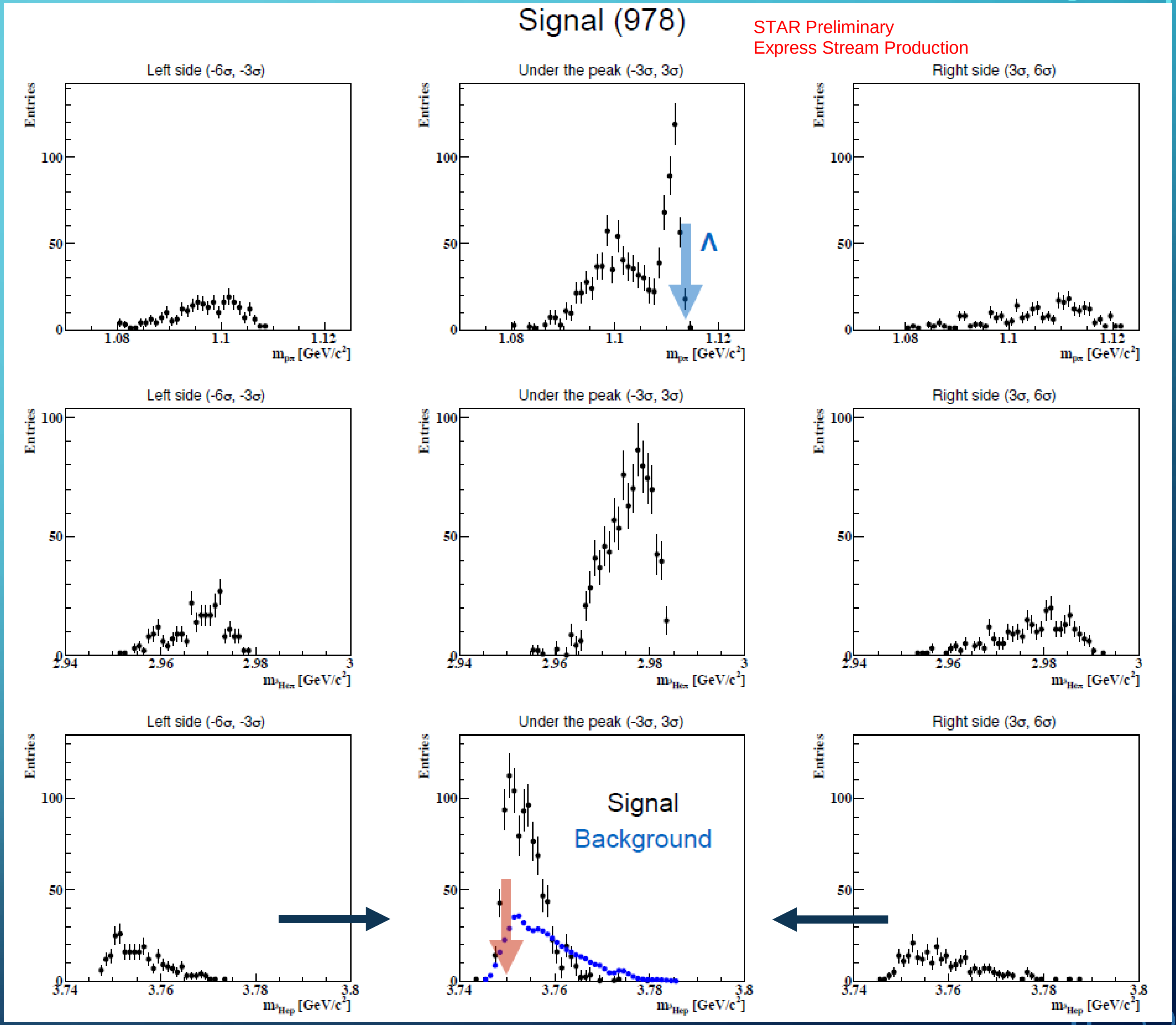
Hypernuclei 3-body decays have complex structures.
• There are hints of kinematic constraint due to spin and parity effects.

• Even with 3 particles in the final state majority of decays could be 2-body with a further cascade decay of a nuclei.

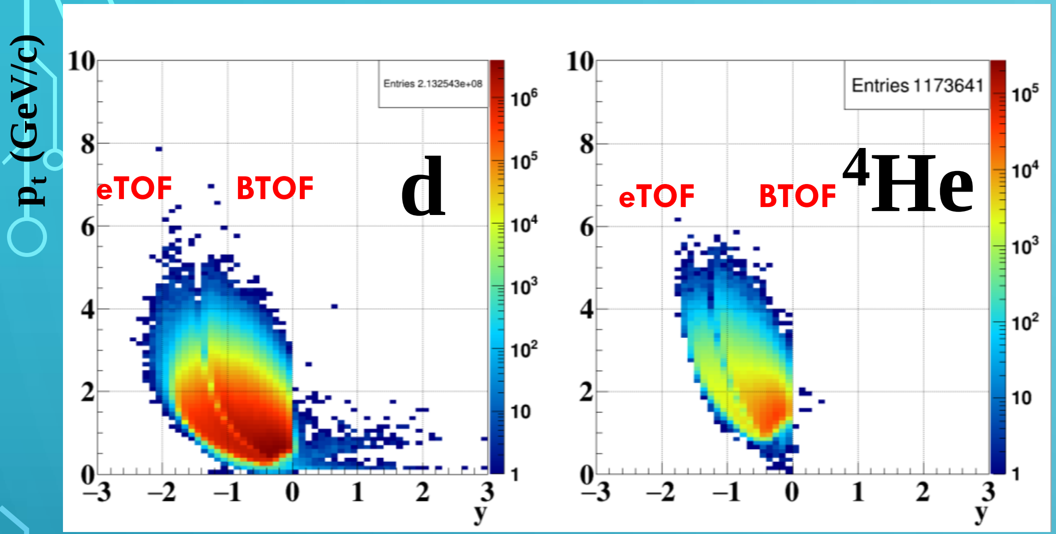
• Efficiencies strongly depend on decay kinematics.

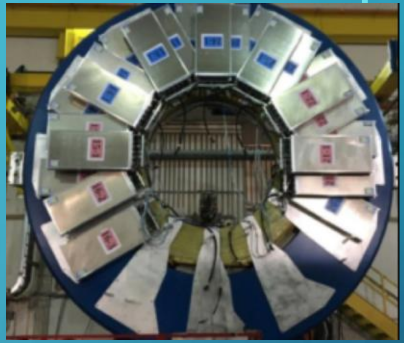
$$^{4}_{\Lambda}\mathrm{He} \rightarrow {}^{4}\mathrm{Li}_{GS}^{*} + \pi^{-} \rightarrow {}^{3}\mathrm{He} + p + \pi^{-}$$





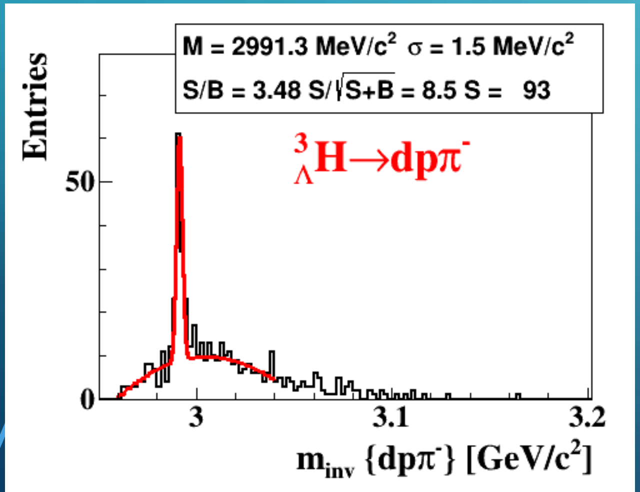
ETOF AT RUN 2020 $\sqrt{S_{NN}}$ = 3.5 GeV

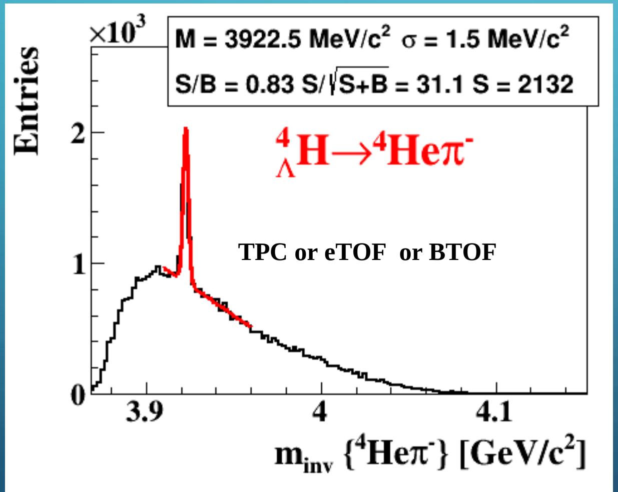


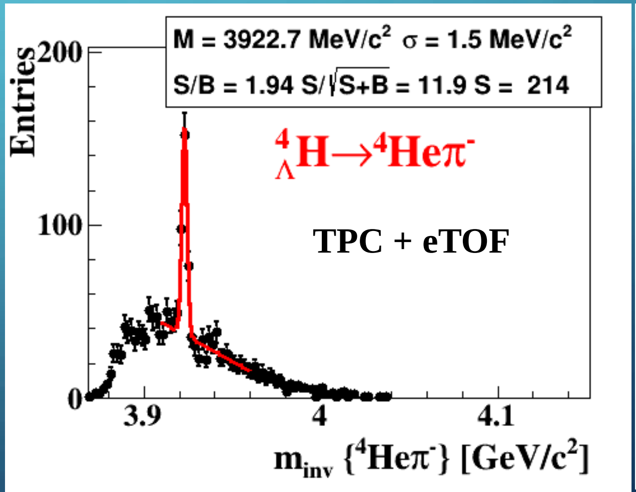


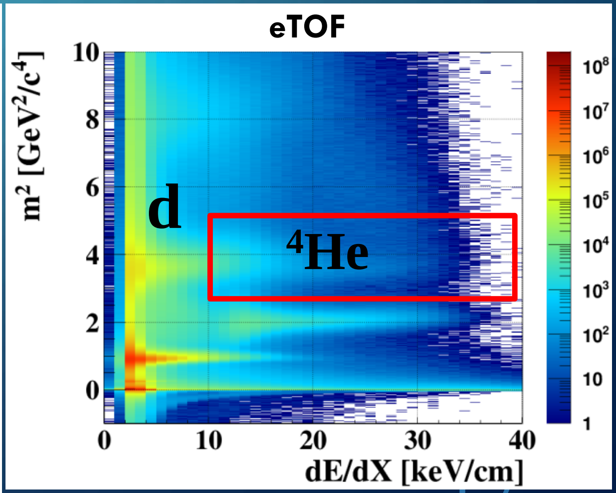
- About 30% more deuterons selected with eTOF
- low rapidity region covered by eTOF

- Signal in 2-body channels remain nearly the same, while background drops about factor of 1.5 and significance increase noticeably.
- Signal and significance increase noticeably in all 3-body channels.





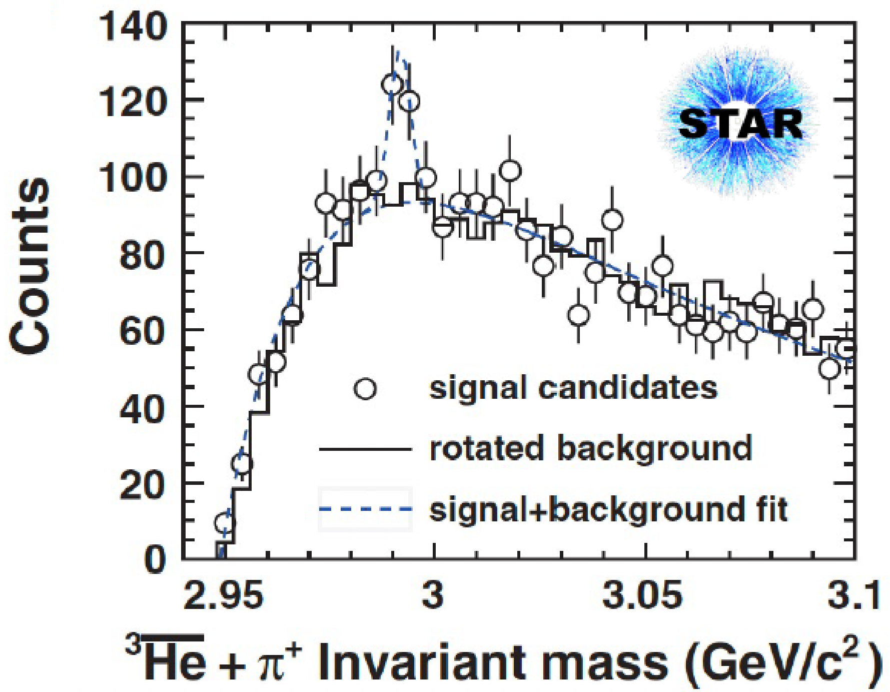




ANTI-MATTER HYPERNUCLEI

Nature 632 (2024) 8027, 1026-1031

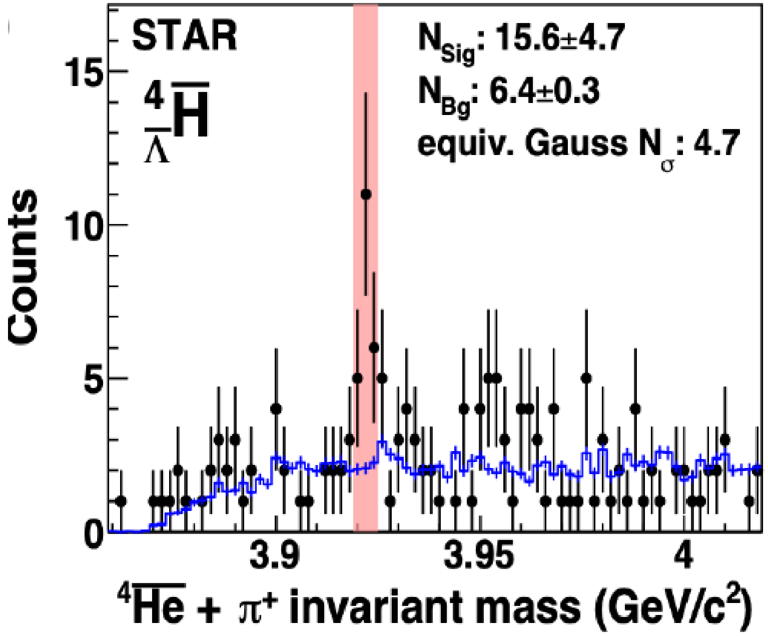
- STAR observed ${}^{4}_{\bar{\Lambda}}\bar{\mathrm{H}}$ in 2023.
  - Benefit from high energy heavy ion collisions ($\mu_B \to 0$).
  - The heaviest observed antimatter nuclear and hypernuclear cluster to date.



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

Science 328 (2010) 58-62

Discovery of A=4 anti-hypernuclei

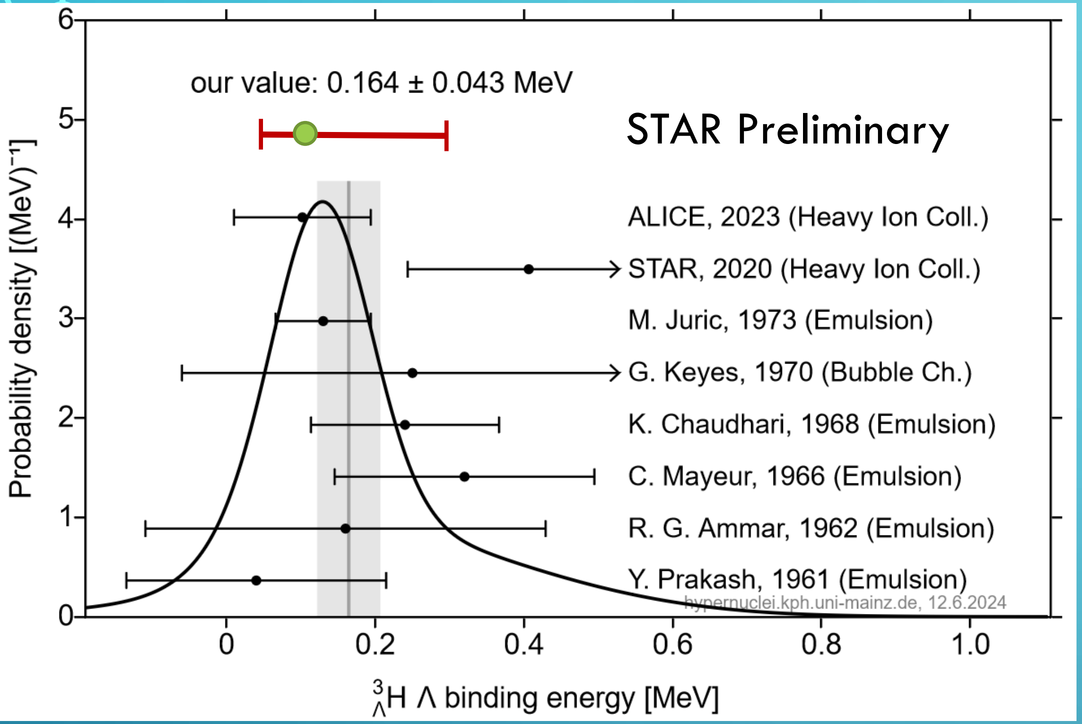


$${}^{4}_{\bar{\Lambda}}\bar{\mathrm{H}} \to {}^{4}\overline{\mathrm{He}} + \pi^{+}$$

arXiv:2310.12674, submitted to Nature

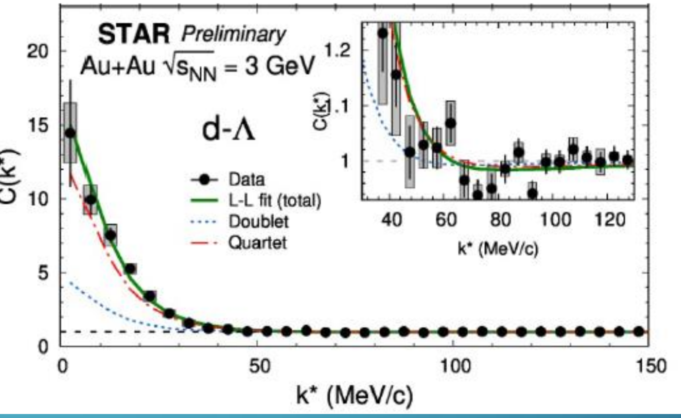
Datasets used:
- 200 GeV collisions
  - Au+Au
  - Zr+Zr/Ru+Ru
- 193 GeV collisions
  - U+U

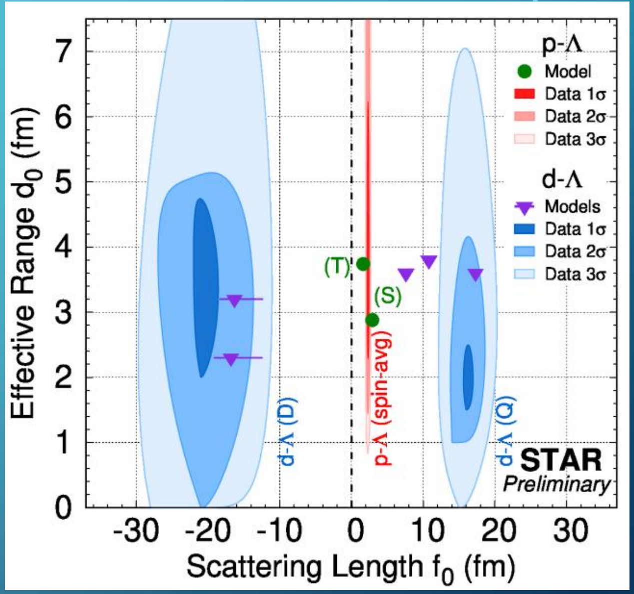
$^3_\Lambda H$ Λ BINDING ENERGY



d - Λ correlation

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





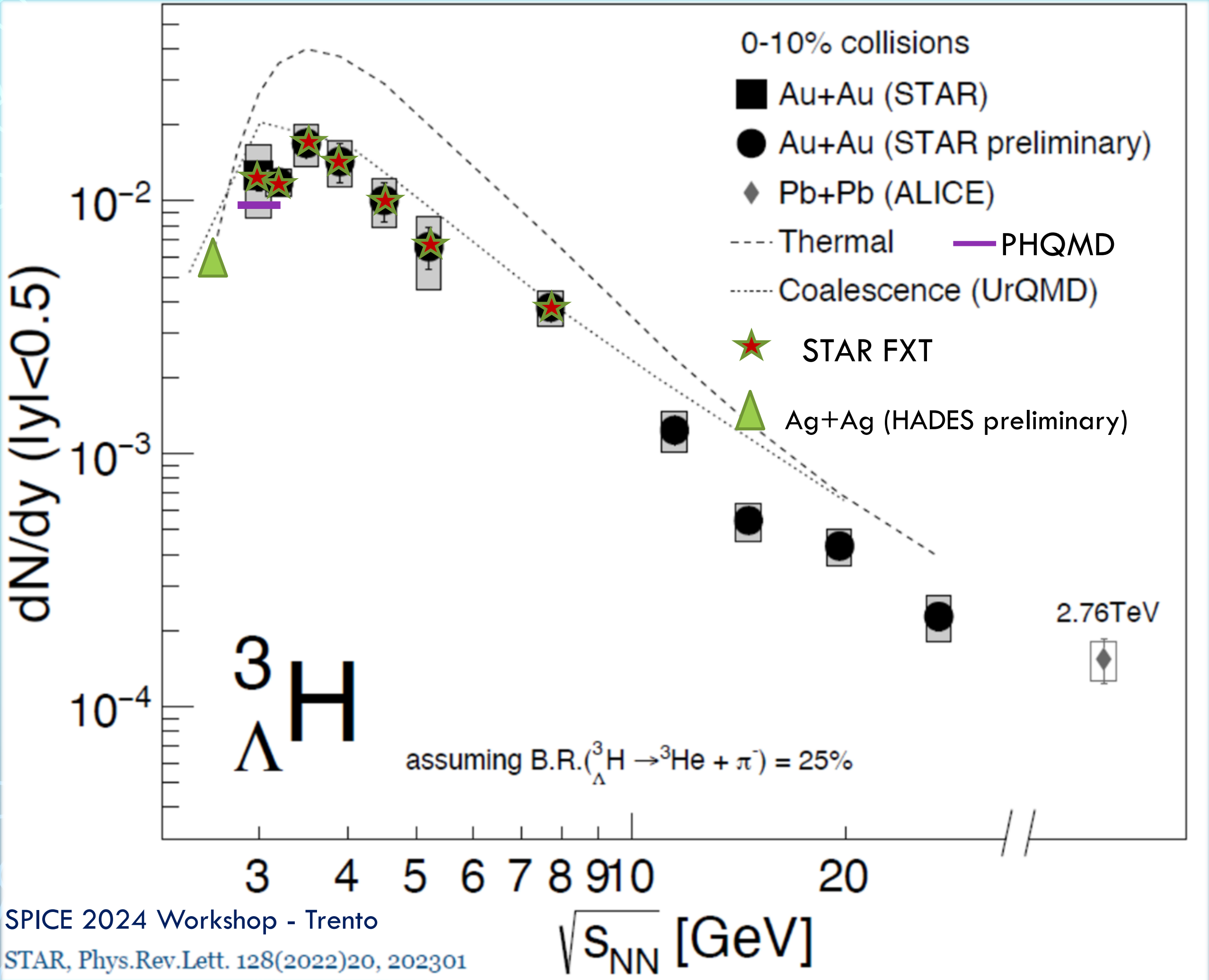
$^3_\Lambda H$ Λ binding energy to be 0.04 to 0.33 MeV at 95% CL

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, $^3_\Lambda H$ production provides unique input for theoretical models (R ~ 5 – 10 Fm) and production mechanism (coalescence)

$^{3}_{\Lambda}H$ EXCITATION FUNCTION: LESSON 4



SPICE 2024 Workshop - Trento

STAR, Phys.Rev.Lett. 128(2022)20, 202301
ALICE, Phys. Lett. B 754(2016)360
T. Reichert et al, Phys.Rev.C 107(2023)014912

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

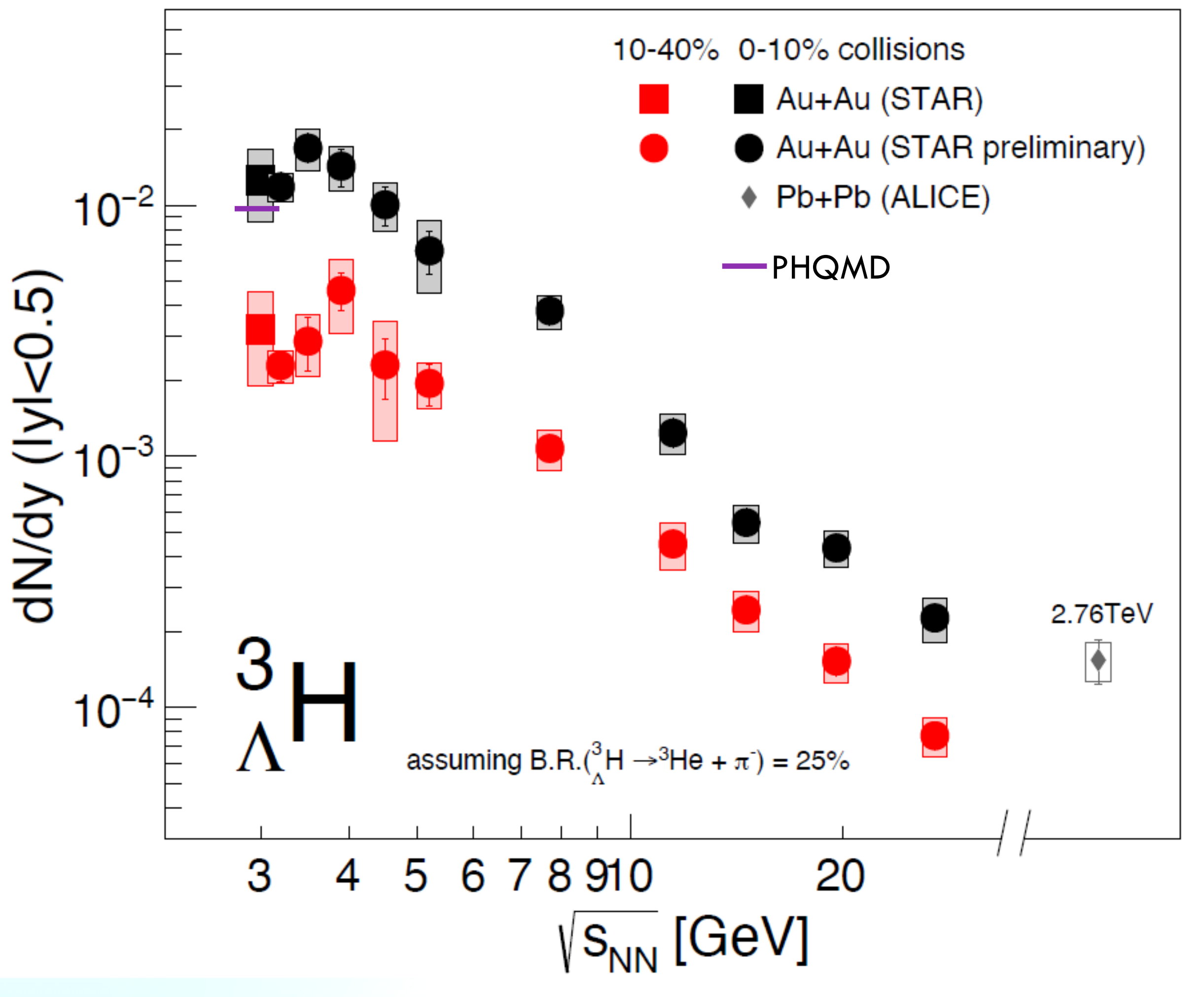
Thermal model reproduces the trend, but does not quantitatively (factor 2) describe the yields of $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$

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

HN yields increase with increasing baryon density
HN yields decrease with strangeness canonical suppression

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

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



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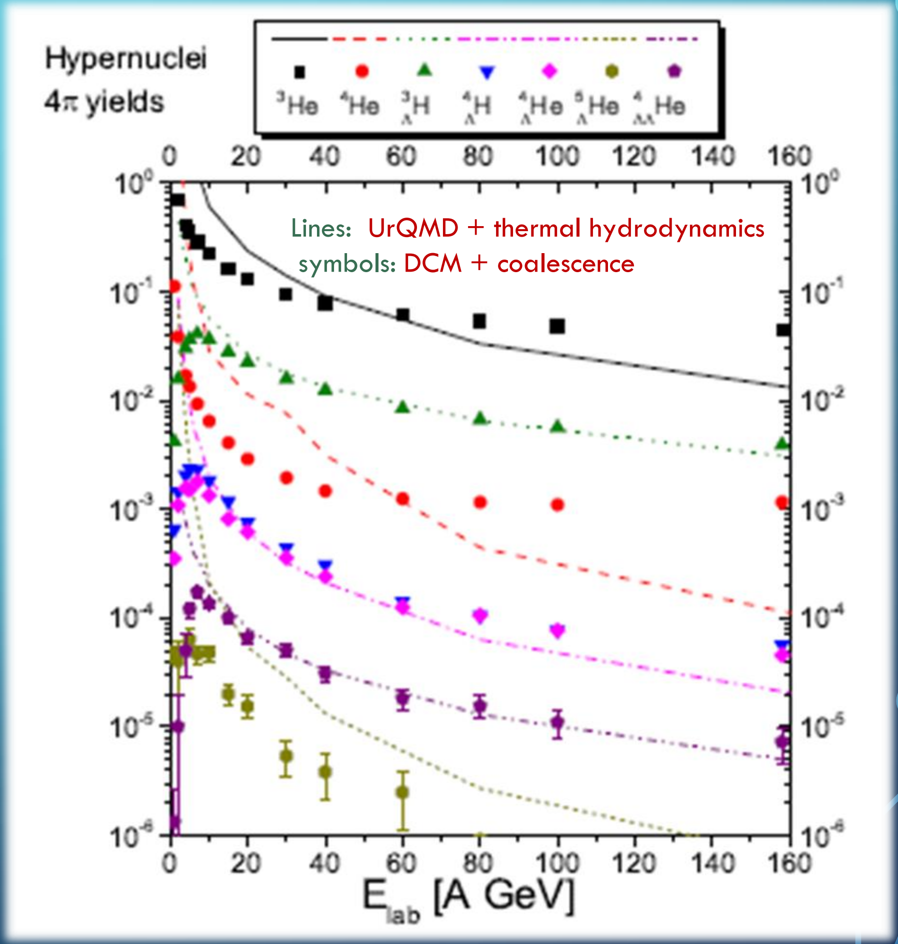
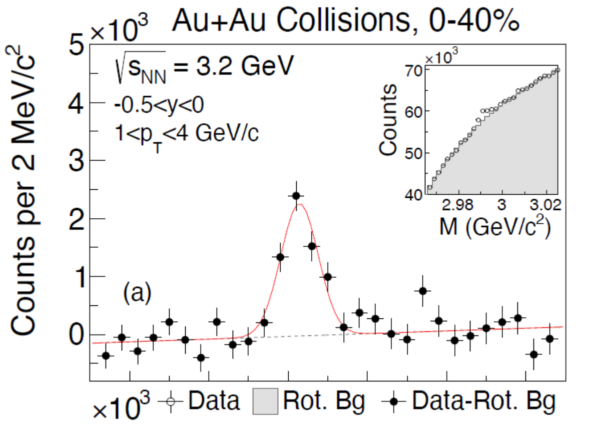


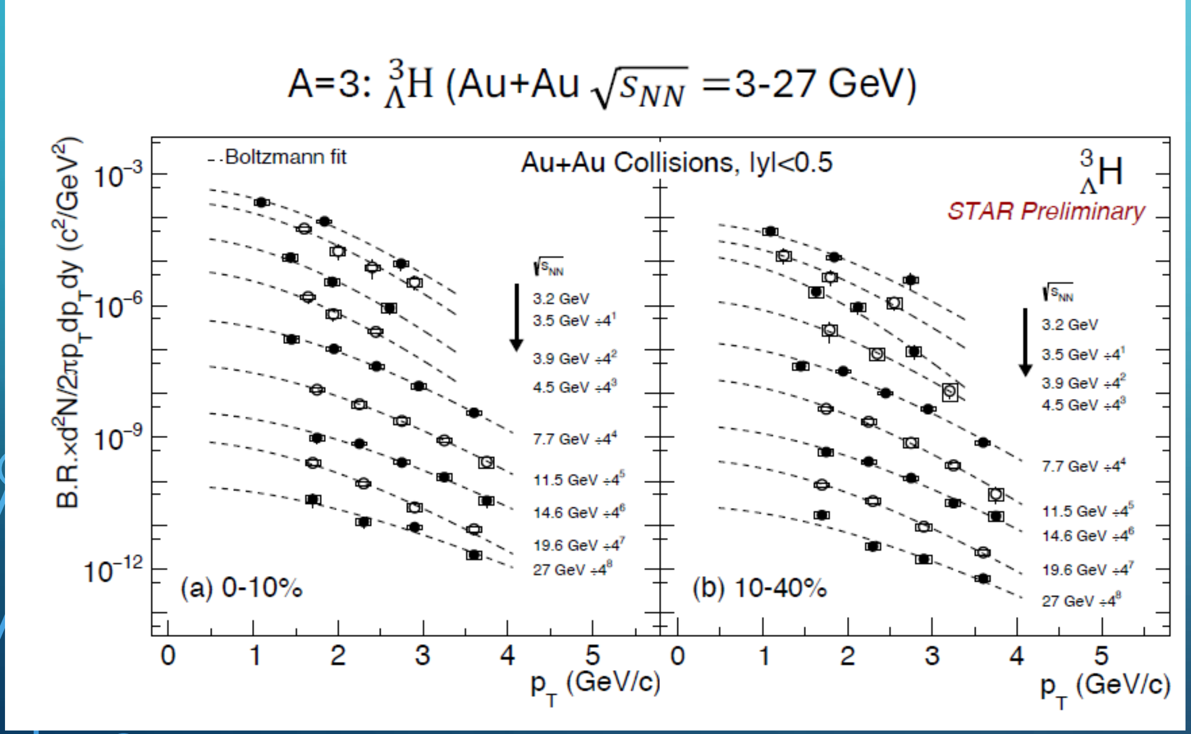
J. Steinheimer, K. Gudima, A. Botvina, I. Mishustin, M. Bleicher, H. Stöcker
Phys. Lett. B**714**, 85, (2012)

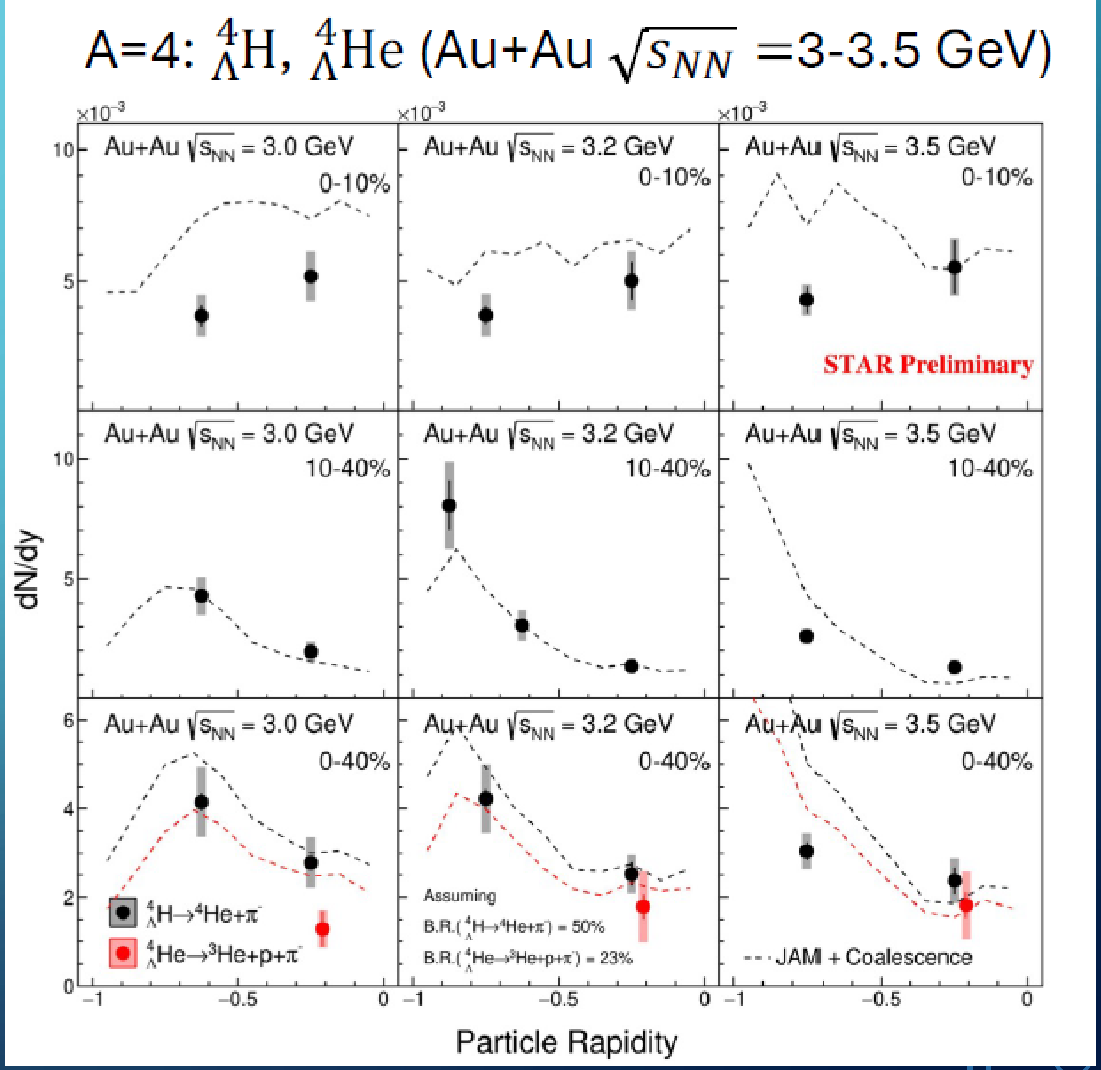
$^{3}_{\Lambda}H$, $^{4}_{\Lambda}H$ & $^{4}_{\Lambda}He$ PRODUCTION



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

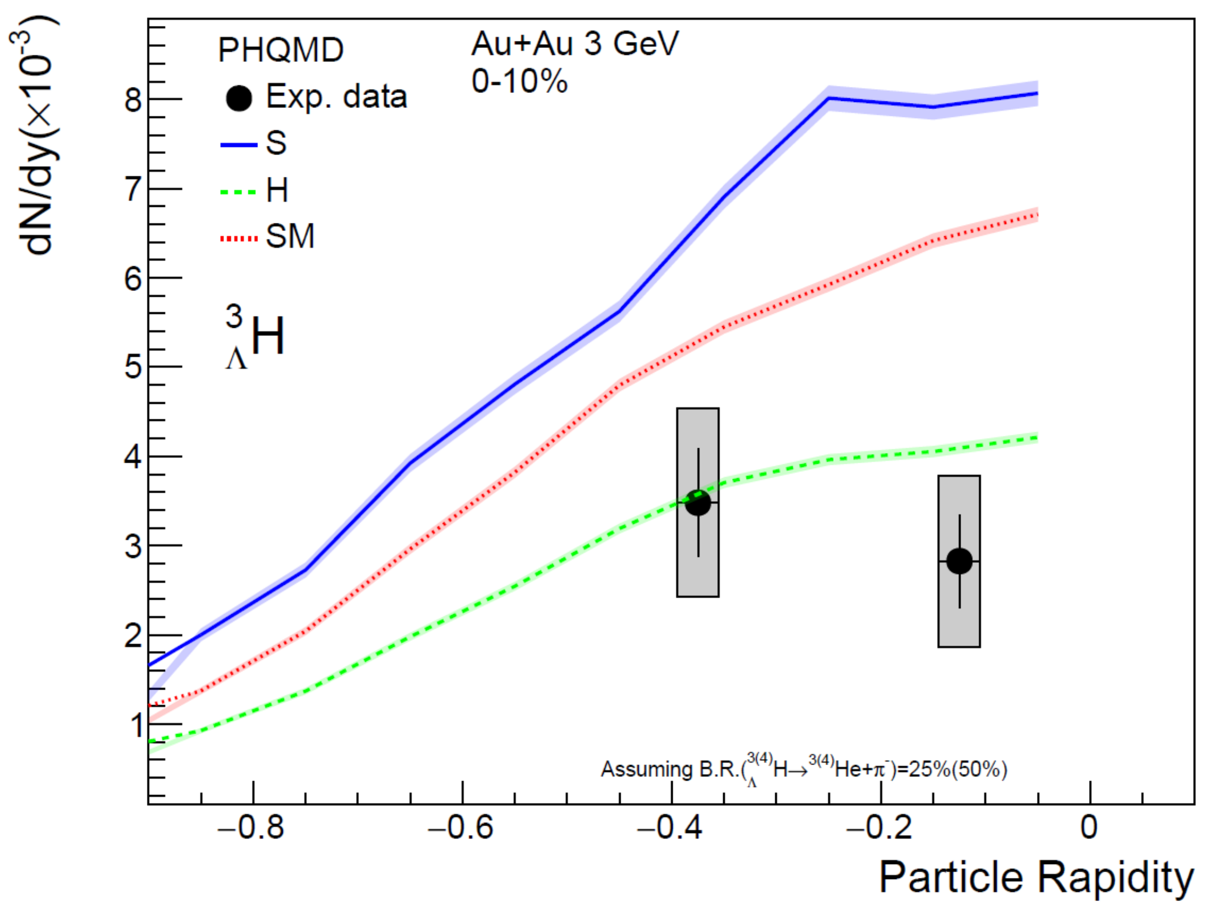
- First measurement of dN/dy vs rapidity of hypernuclei in HI collisions
- New challenges for the models

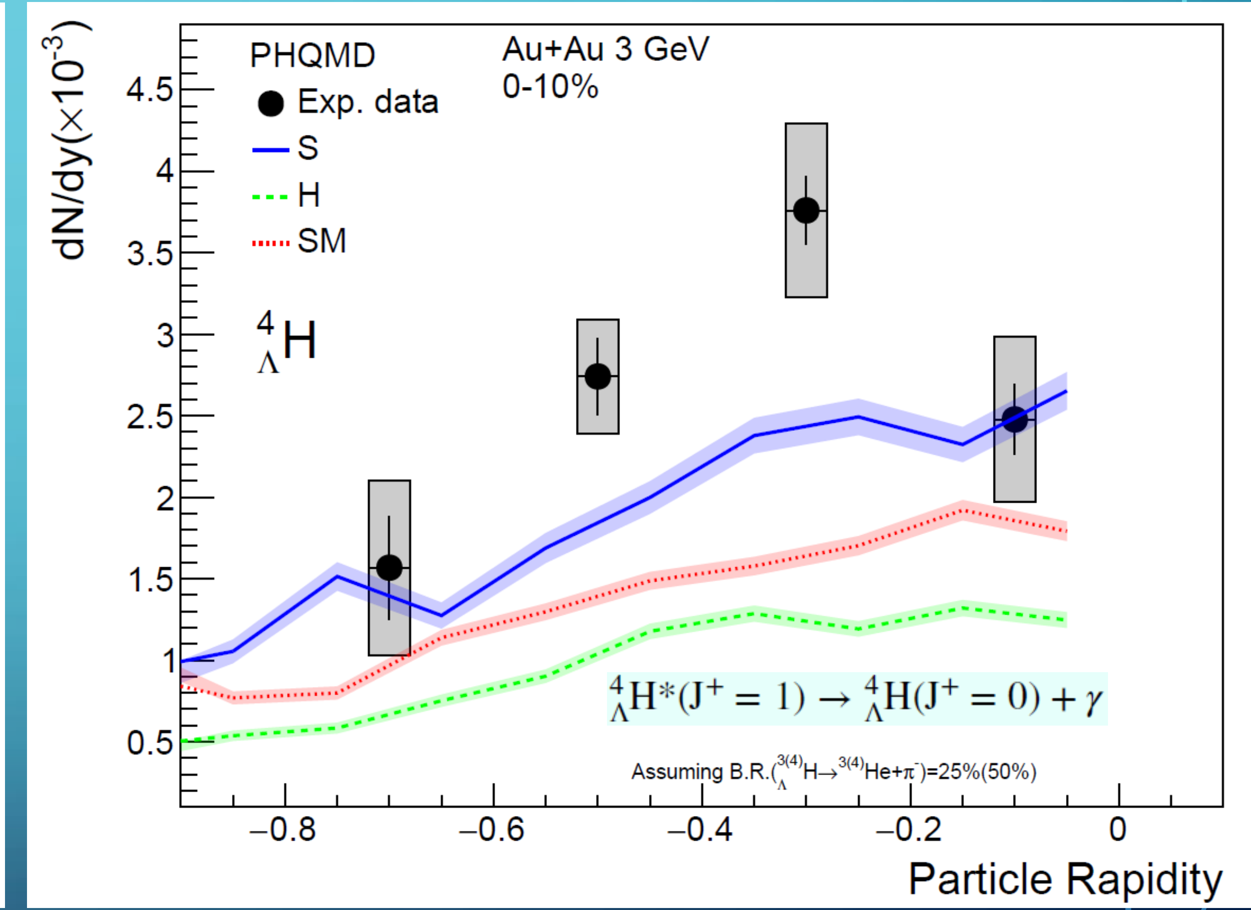




${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$ PRODUCTION VS EOS

➢ **The production of Hypernuclei is sensitive to the choice of the EoS.**

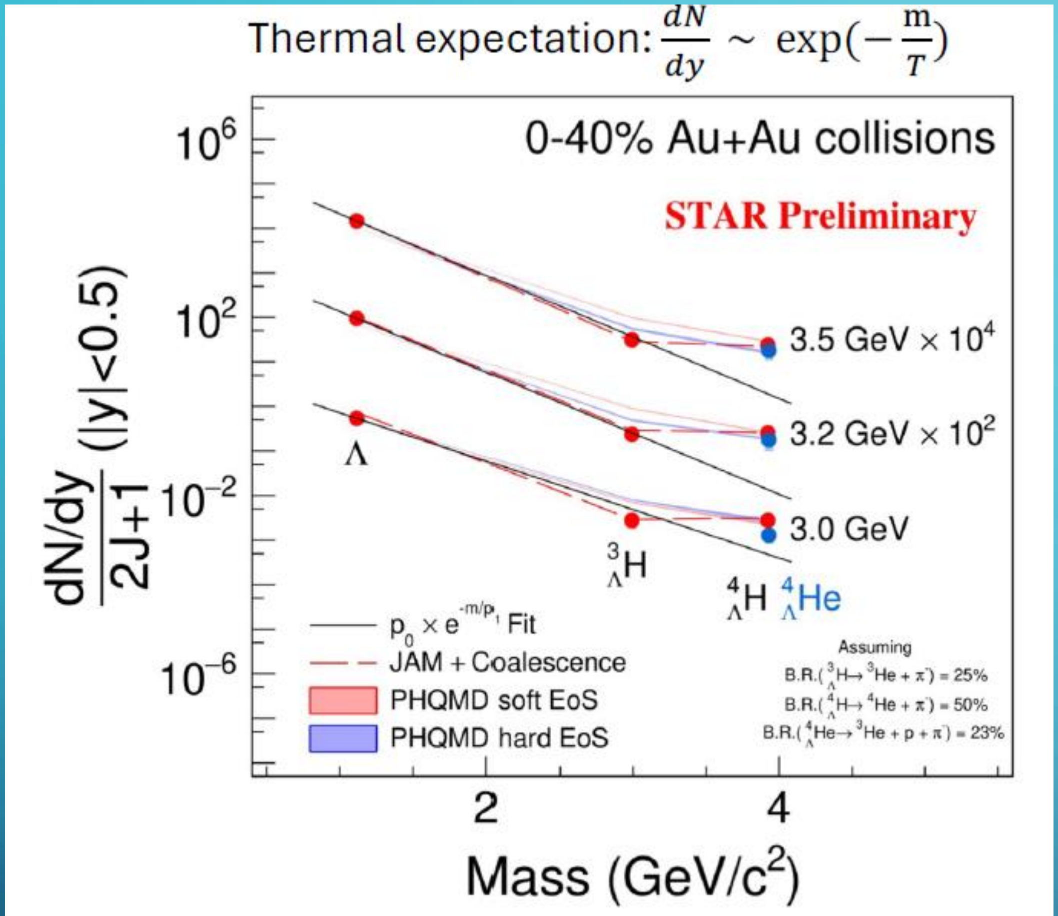


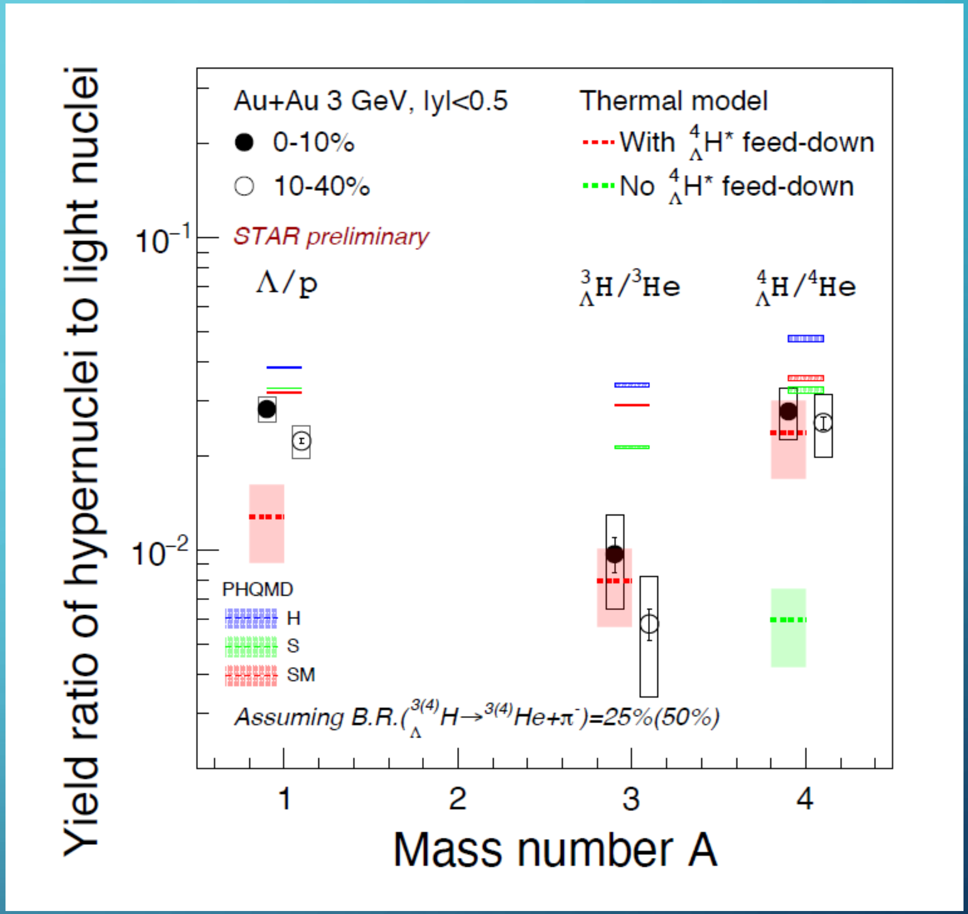


${}^{3}_{\Lambda}\mathbf{H}$ production provides unique input for theoretical models (R ~ 5 – 10 Fm) and production mechanism (coalescence)

Data support creation of excited ${}^{4}_{\Lambda}H^*$ hypernuclei from heavy-ion collisions

HYPERNUCLEI VS LIGHT NUCLEI AT 3 GEV



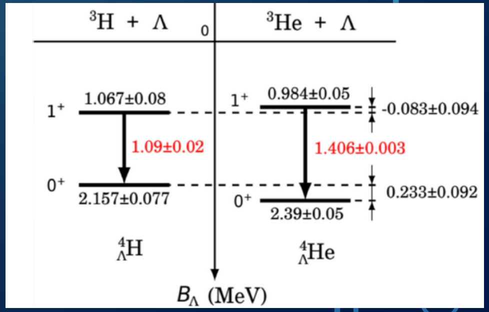


Thermal/coalescence models predict approximately exponential dependence of yields/(2J+1) vs A

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

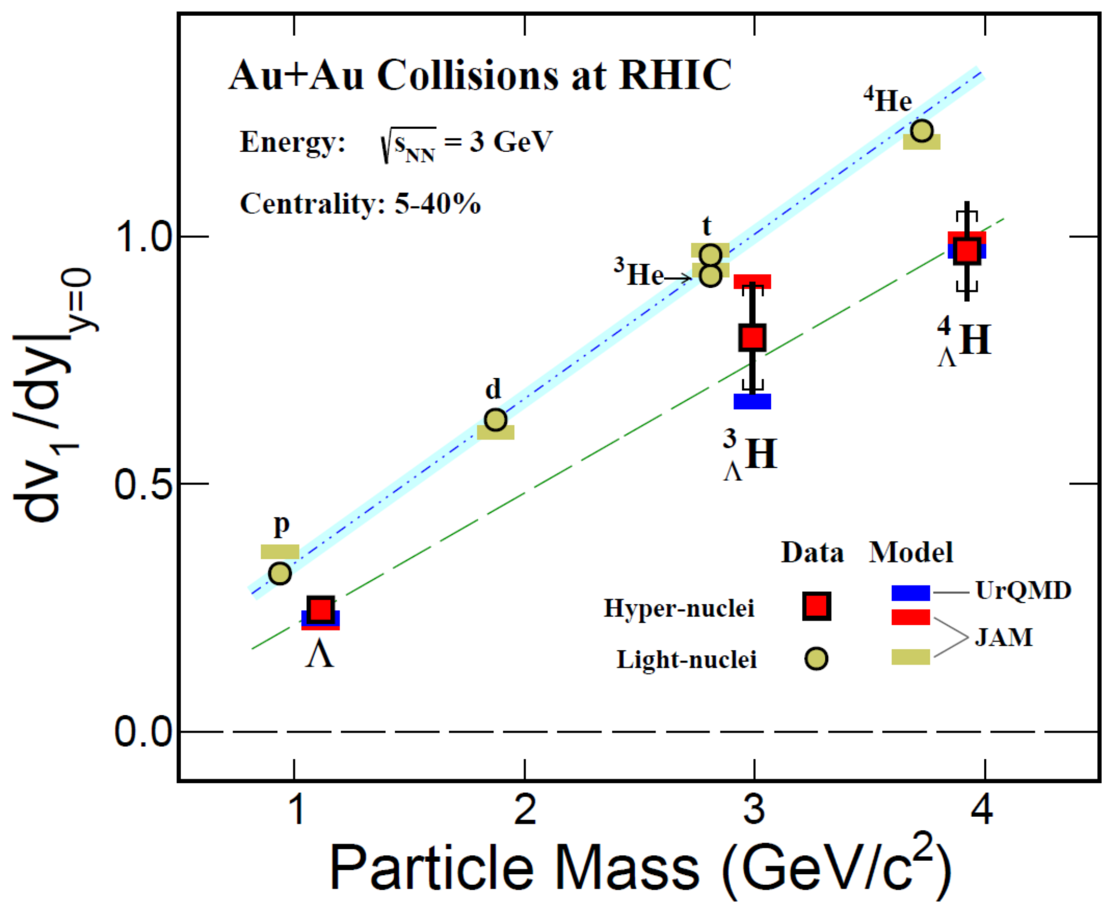
Non-monotonic behavior in light-to hyper-nuclei ratio vs A observed

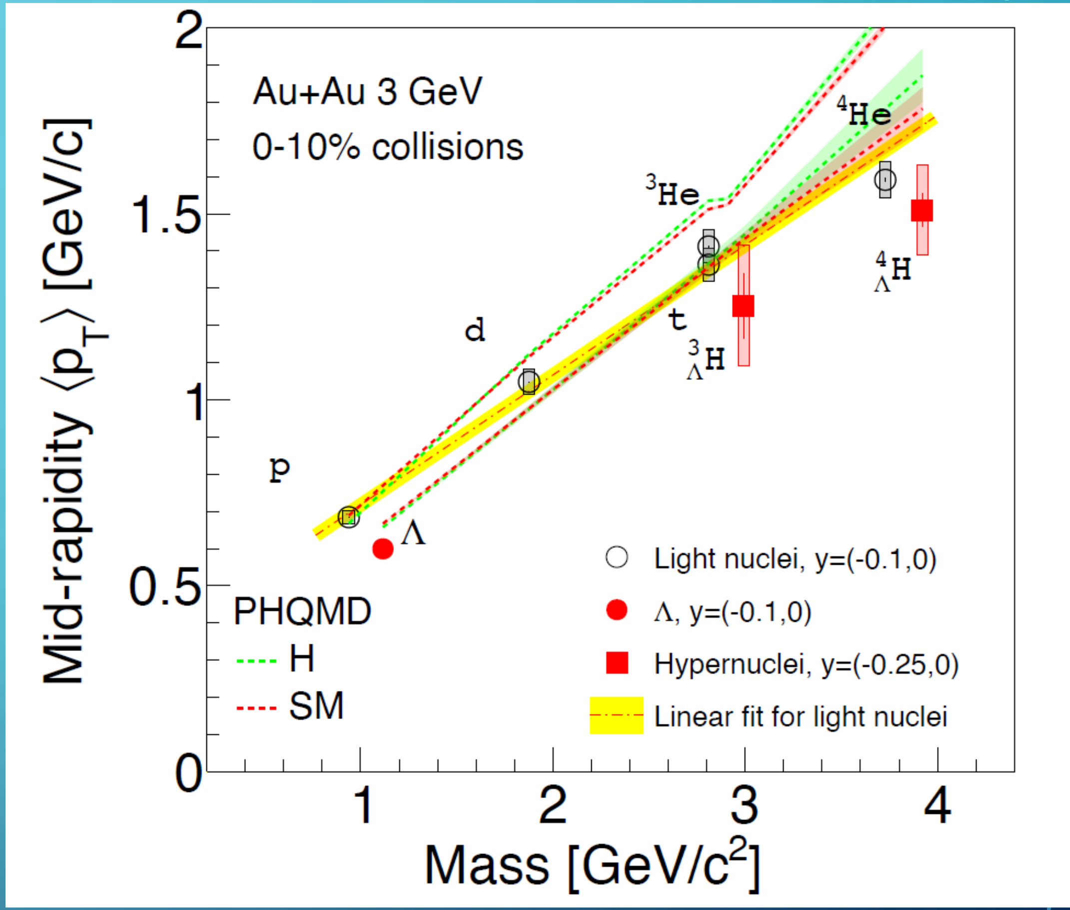
Data support creation of excited A=4 hypernuclei from heavy-ion collisions



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

HYPERNUCLEI COLLECTIVITY AT 3 GEV



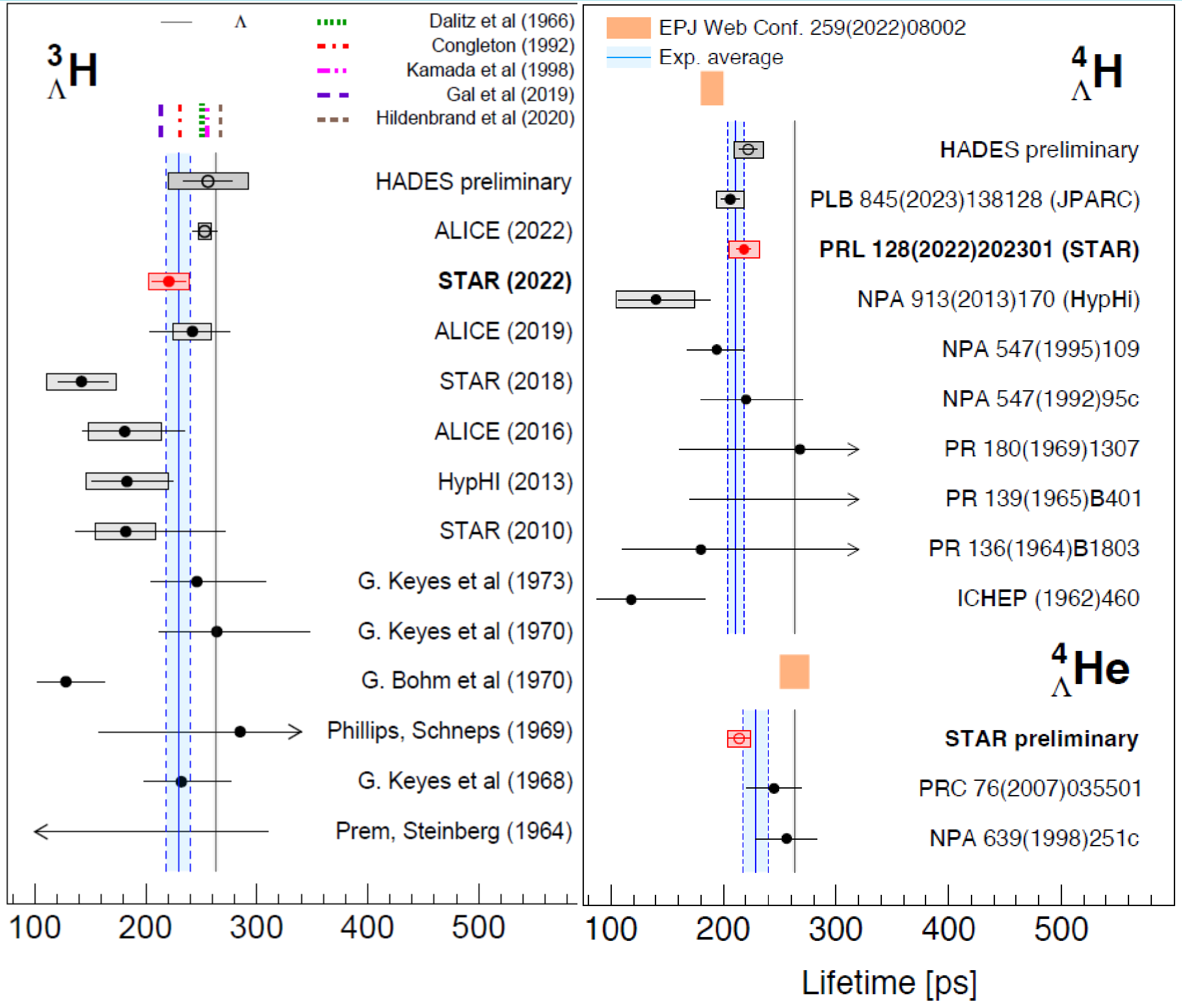


- **First observation of hypernuclei collectivity v_1 in HI collisions**
- v_1 slope follows **mass number scaling** in 5-40% 3 GeV Au+Au collisions, similar to light nuclei
- coalescence is the dominant production mechanism

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

Dominance of collective radial motion

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 (3σ) with the theoretical estimation: 0.74 ± 0.04

A. Gal (2021), arXiv:2108.10179

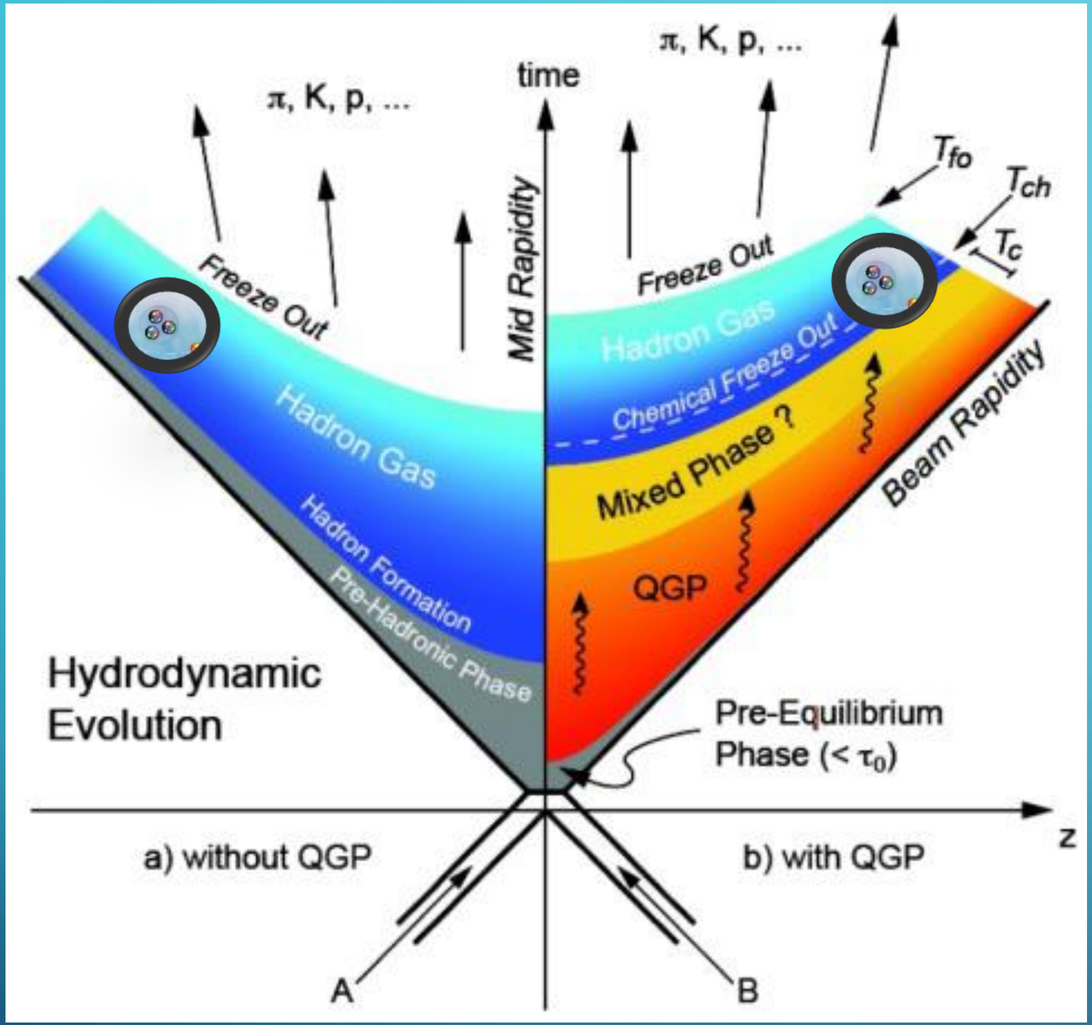
ALICE H3L lifetime (2022) arXiv:2209.07360
HADES H3L, H4L lifetime (preliminary) S. Spies (HADES), QM2022
JPARC H4L lifetime (2022) arXiv:2302.07443

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

STAR Xiujun Li, SQM 2024

SUMMARY

- **Updated set of Hypernuclei measurements in the high baryon density region with high statistical precision at 3.0 - 27 GeV (BES-II).**
- **We observe $^{5}_{\Lambda}He$ with significance of 20 σ.**
- **$^{3}_{\Lambda}H$ yield at mid-rapidity increases about factor of 10^2 from 2.76 TeV to 3 GeV (excitation function).**
- **$^{3}_{\Lambda}H$, $^{4}_{\Lambda}H$ and $^{4}_{\Lambda}He$ lifetimes measured with improved precision.**
- **First observation of Hypernuclei collectivity in v_1 and $\langle p_t \rangle$, similar to light nuclei.**
- **The production of Hypernuclei in the high baryon density region is sensitive to the choice of the EoS.**
- **Coalescence is a dominate mechanism of Hypernuclei formation at mid-rapidity in HI collisions at RHIC.**



Further experimental challenges:

- Further investigation on light Hypernuclei.
  - Production: kinetic freeze-out parameters
  - Collectivity: v1, v2 etc.
  - Intrinsic properties: B_Λ, Dalitz, BR, lifetime etc.

- Search of double Λ Hypernuclei $^{4}_{\Lambda\Lambda}\mathbf{H}$ $^{4}_{\Lambda\Lambda}\mathbf{n}$, $^{6}_{\Lambda\Lambda}\mathbf{He}$ and exotic hyperon states.
  - $Y - Y$ interaction

- Precise measurements on particle correlations.
  - $p - \Lambda$, $d - \Lambda$, $\Lambda - \Lambda$ correlations, etc.

Thank you for your attention!