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# Measurements on the production and properties of light hypernuclei at STAR


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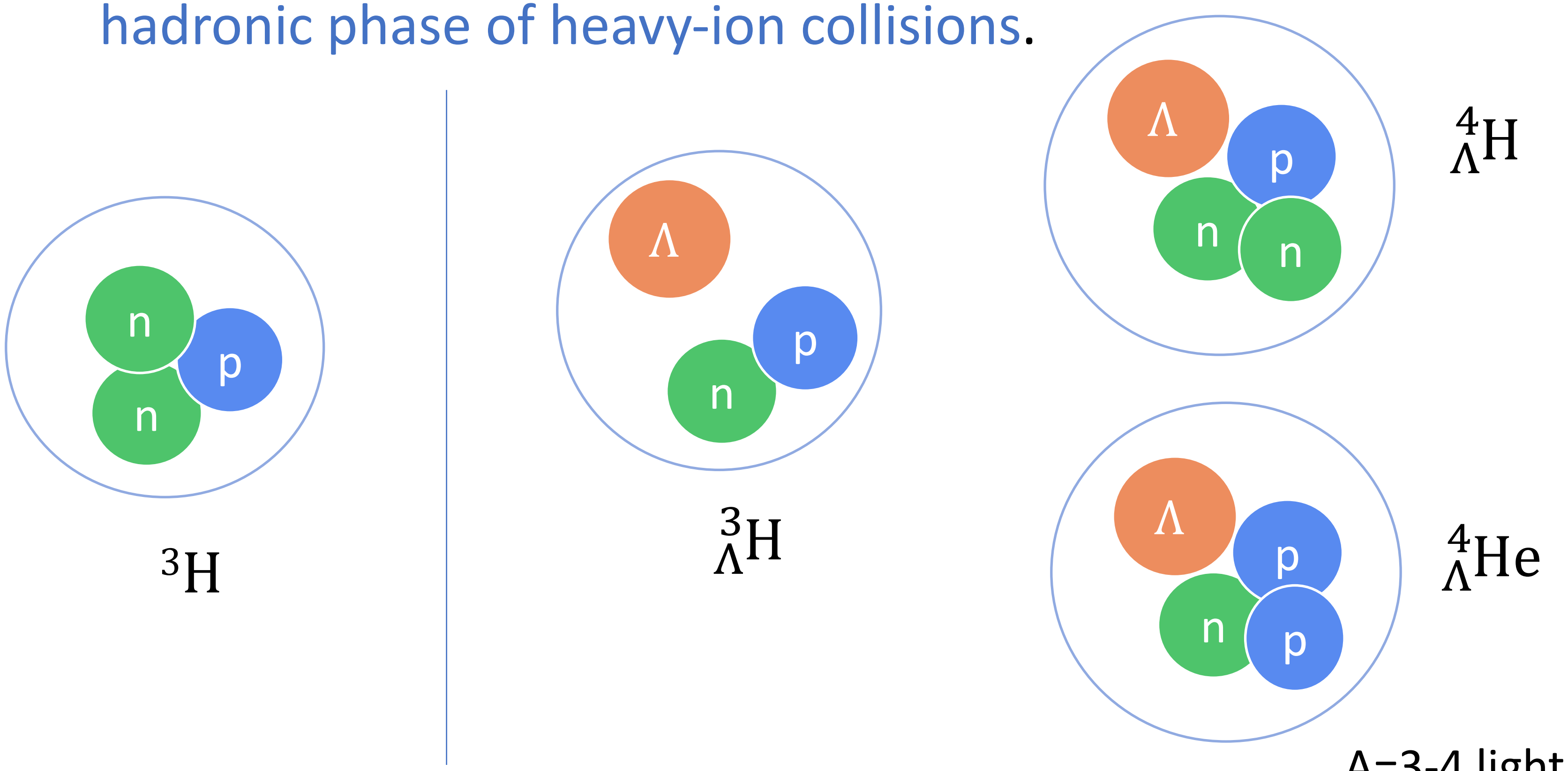
# Why hypernuclei?

Hypernucleus: A bound system of nucleons with ≥ 1 hyperons.

- Introduce additional degree of freedom in baryon interactions: Hyperon-Nucleon (*Y*-*N*) interactions.
  - Important ingredient for understanding the EOS of neutron stars and the hadronic phase of heavy-ion collisions.

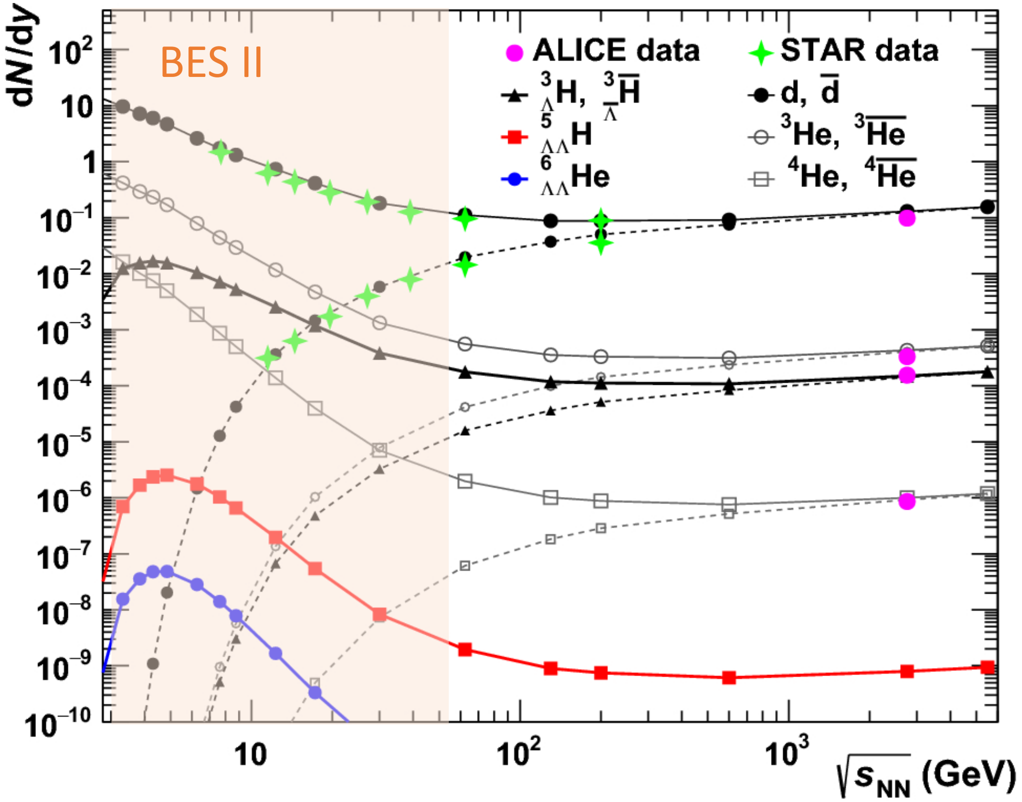



A=3-4 light Λ hypernulei

# STAR BES II program

## Opportunities to hypernuclei physics!

- High statistics data sets from BES II.
- Abundant light hypernuclei produced in high baryon density region!



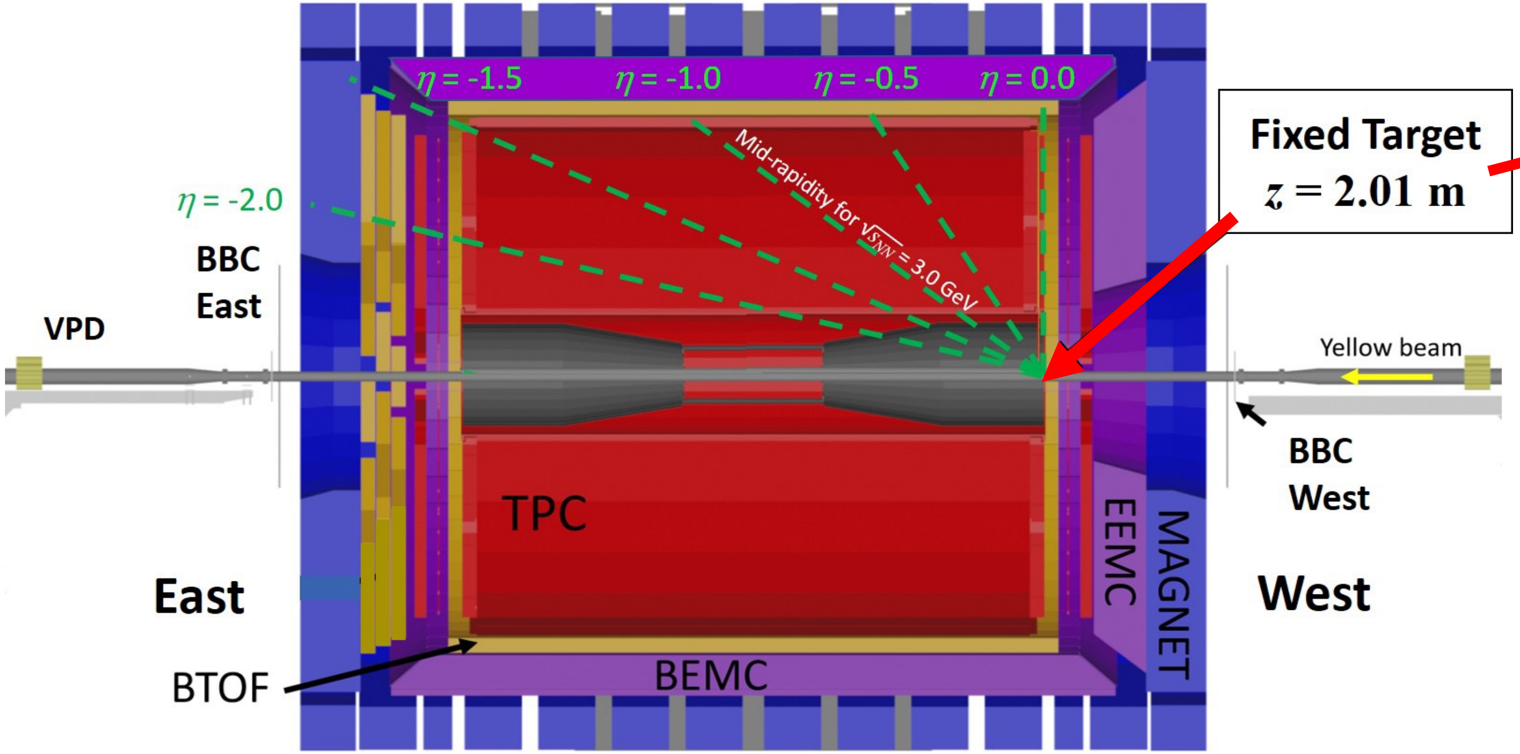

Thermal model: B. Dönigus, Eur. Phys. J. A 56:280 (2020)
A. Andronic et al, PLB 697, 203 (2011)

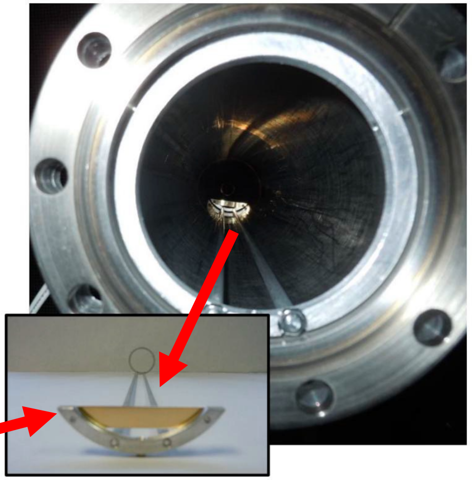
- Collider mode:
  $\sqrt{s_{NN}}$ = 7.7 – 54.4 GeV
- Fixed-Target mode:
  $\sqrt{s_{NN}}$ = 3.0 – 13.7 GeV
  - 3 GeV : 260 M good events collected in 2018.

## Outline

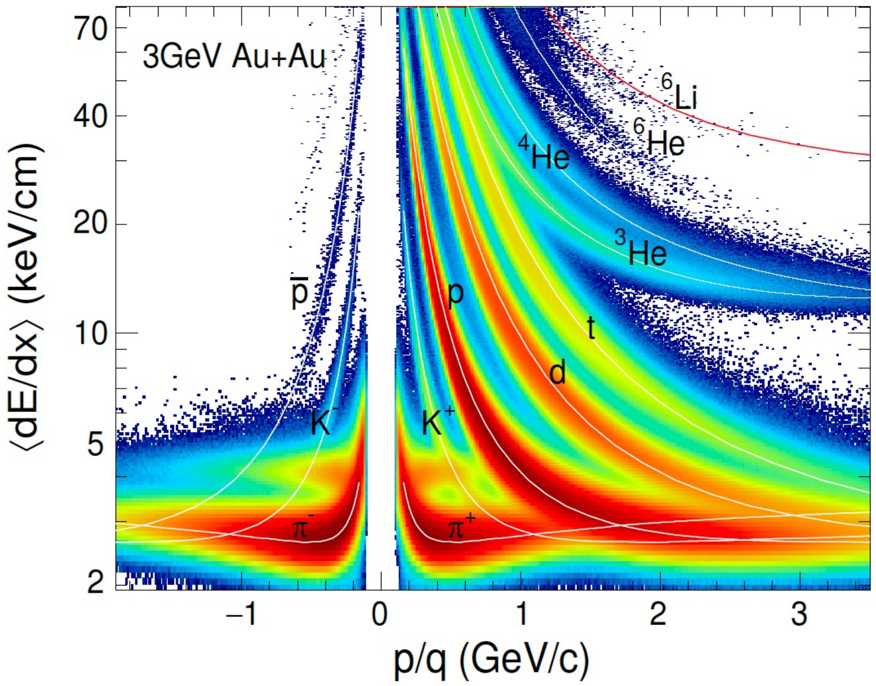
- Intrinsic properties
  - $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He lifetime.
  - $^{3}_{\Lambda}$H decay branching ratio.
- Production mechanism
  - Production yields of $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H in Au+Au collisions.

# Fixed-Target Setup at STAR



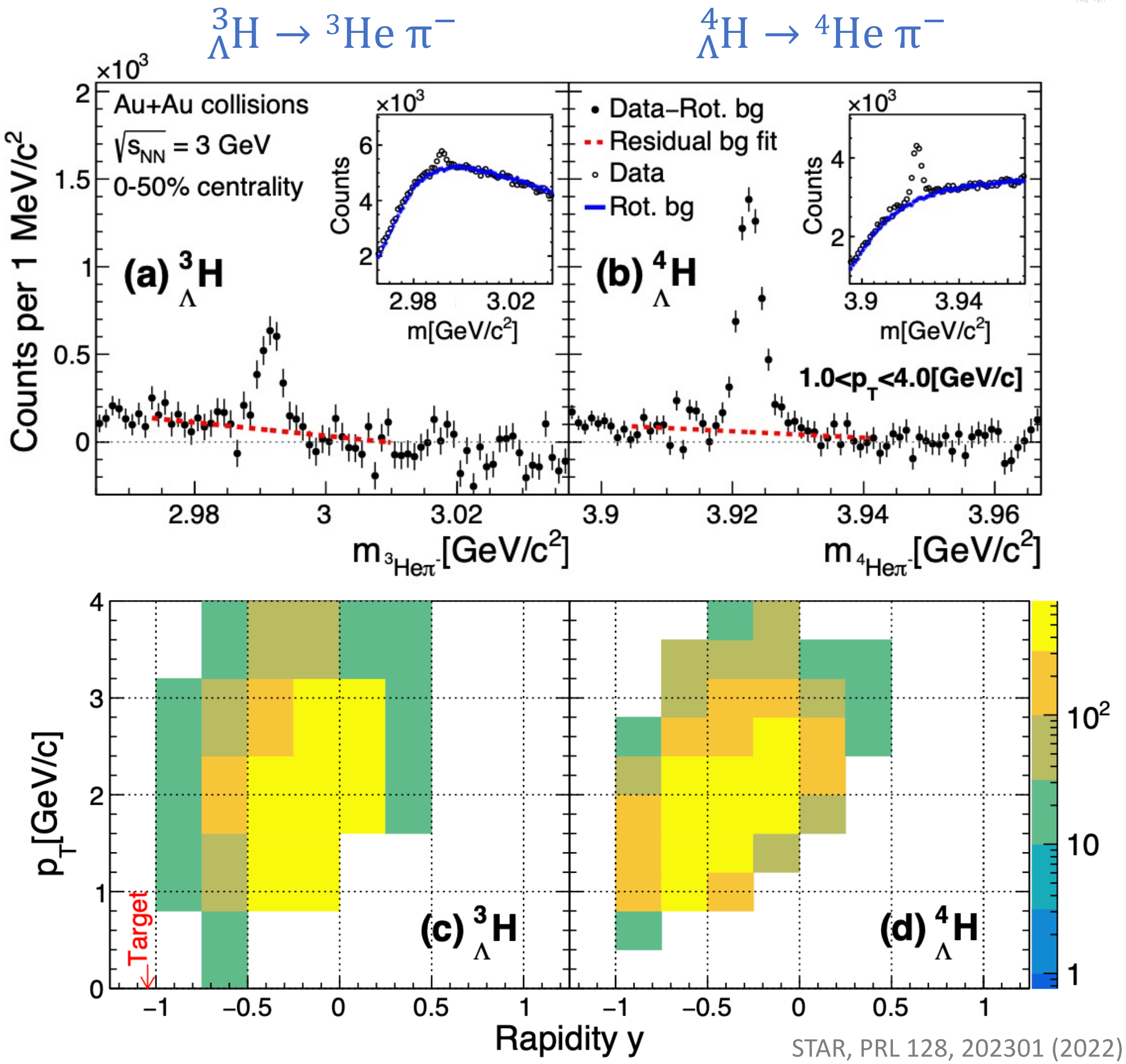



Gold foil, 250 $\mu m$ thick



# $^3_\Lambda$H, $^4_\Lambda$H reconstruction via 2-body channel

- KF particle package is used for signal reconstruction.
- Decay channel:
  $^3_\Lambda H \rightarrow {}^3He\,\pi^-$ ~ B.R. 15-25%,
  $^4_\Lambda H \rightarrow {}^4He\,\pi^-$ ~ B.R. 50%.
- Background reconstructed by rotation of $\pi^-$.




Good kinematic coverage in 3 GeV Au+Au collisions.

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



STAR, PRL 128, 202301 (2022)

# ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$He reconstruction via 3-body channel

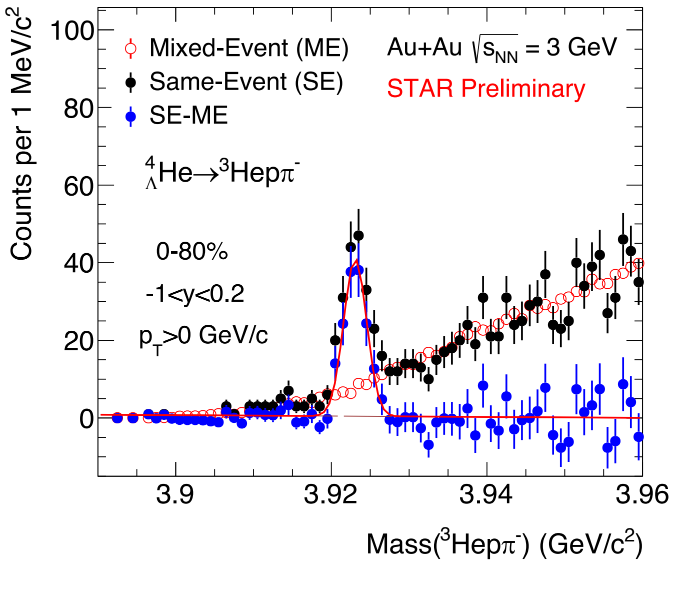
## Signal reconstruction

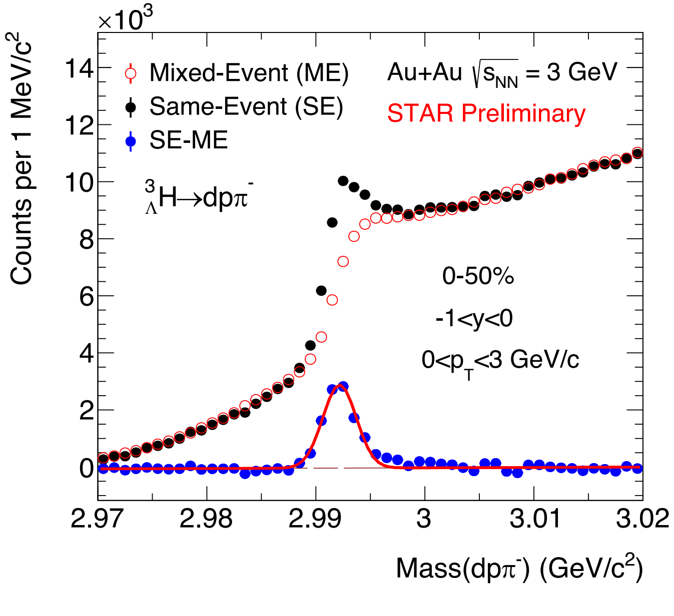
- Combinatorial background is estimated by mixed-event method.
- Correlated Λ+d residual in ${}^{3}_{\Lambda}$H candidates due to weak binding energy $B_{\Lambda}({}^{3}_{\Lambda}\mathrm{H})$~0.2 MeV.

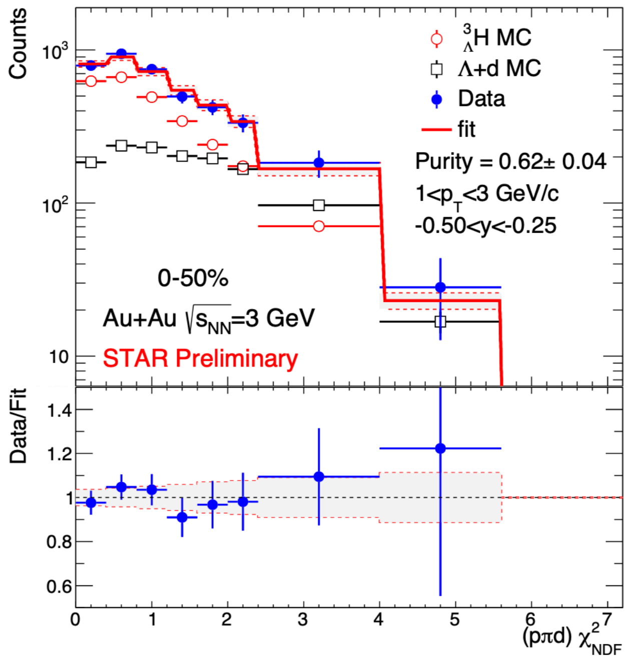
$${}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{dp}\pi^{-}\text{, B.R. ~ 40-50\%}$$
$${}^{4}_{\Lambda}\mathrm{He} \rightarrow {}^{3}\mathrm{He}\mathrm{p}\pi^{-}\text{, B.R. ~ 23\%}$$

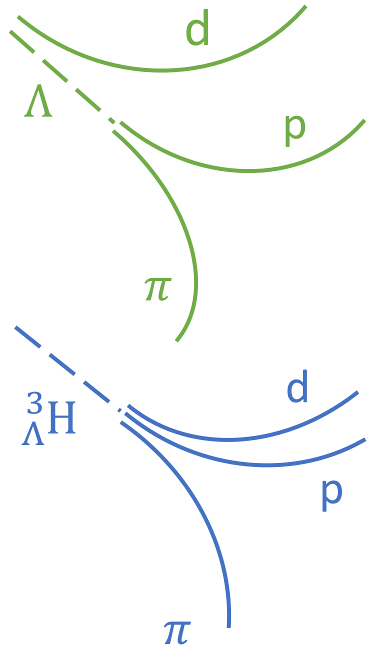
- Template fit method to estimate ${}^{3}_{\Lambda}$H purity statistically.
  - $\chi^2_{NDF\,\Lambda d}, \chi^2_{NDF\,{}^{3}_{\Lambda}\mathrm{H}}$ template estimated from simulations.

$$\chi^2_{NDF\,Data} = p_0 \cdot (\chi^2_{NDF\,\Lambda d} + p_1 \cdot \chi^2_{NDF\,{}^{3}_{\Lambda}\mathrm{H}})$$



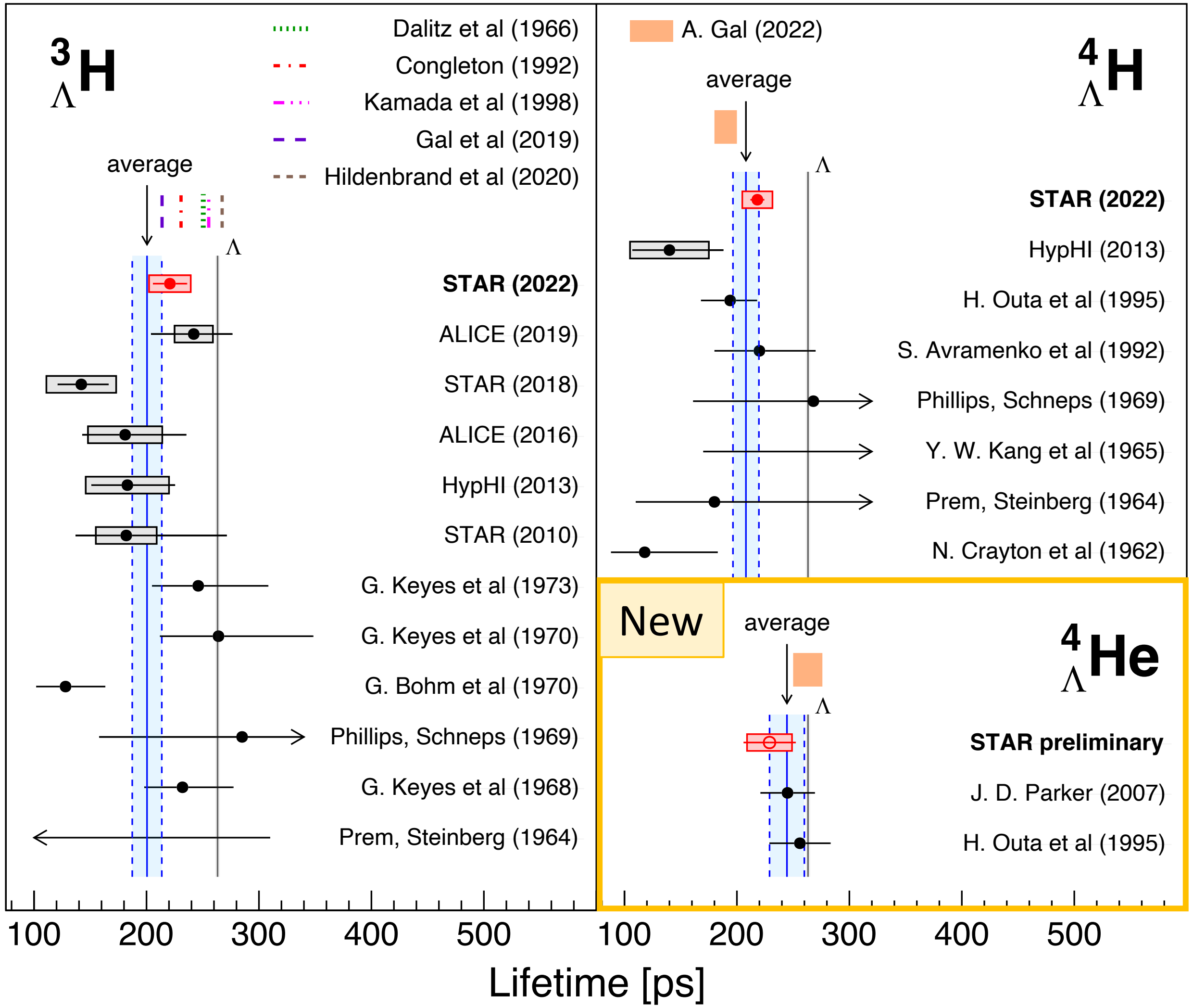
STAR

# Measurements of hypernuclei lifetimes and branching ratio

# Hypernuclei lifetimes

$^{3}_{\Lambda}$H $^{4}_{\Lambda}$H lifetime: STAR, PRL 128, 202301 (2022)

$^{4}_{\Lambda}$He see poster: Xiujun Li RES-02




Shorter lifetimes of $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H than $\tau(\Lambda)$ with 1.8$\sigma$, 3$\sigma$, respectively.

### $^{3}_{\Lambda}$H

A. Gal et al, PLB791, 48 (2019)

- Global avg.=(76±5)%$\tau(\Lambda)$, 4.8$\sigma$< $\tau(\Lambda)$.
- Calculations with pion FSI consistent with data.

### $^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He

A. Gal, arXiv:2108.10179

- $\tau(^{4}_{\Lambda}\mathrm{H})/\ \tau(^{4}_{\Lambda}He)$=0.85±0.07.
- Lifetime ratio consistent with calculation based on isospin rule*(0.74±0.04).

$$* \ \frac{\Gamma(^{4}_{\Lambda}\mathrm{He} \to {}^{4}\mathrm{He} + \pi^{0})}{\Gamma(^{4}_{\Lambda}\mathrm{H} \to {}^{4}\mathrm{He} + \pi^{-})} \approx \frac{1}{2}$$

# ${}^{3}_{\Lambda}H$ branching ratio $R_3$

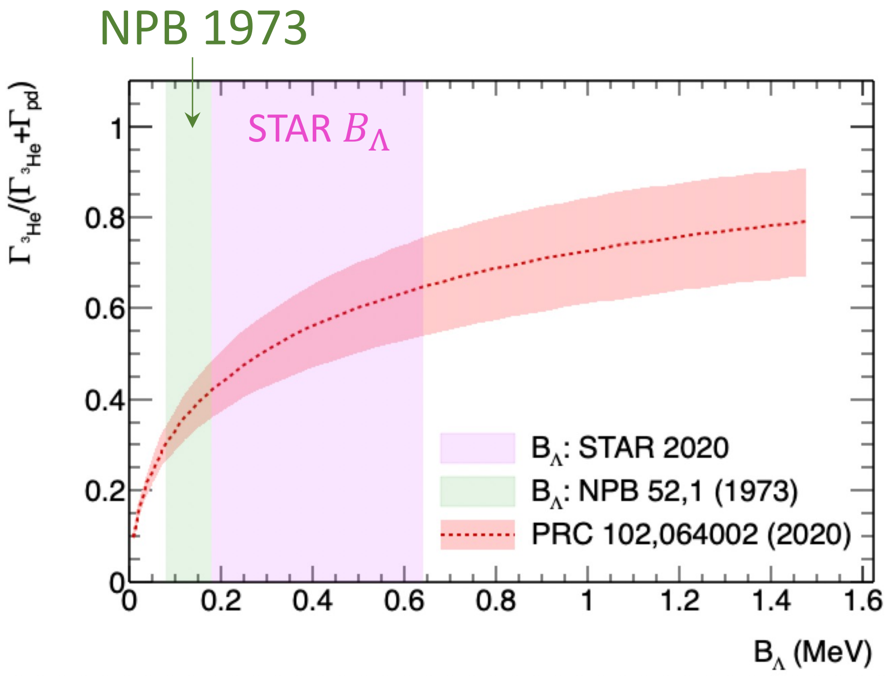
$$R_3 = \frac{B.R.({}^{3}_{\Lambda}H \rightarrow 3He\pi^-)}{B.R.({}^{3}_{\Lambda}H \rightarrow pd\pi^-) + B.R.({}^{3}_{\Lambda}H \rightarrow {}^{3}He\pi^-)}$$

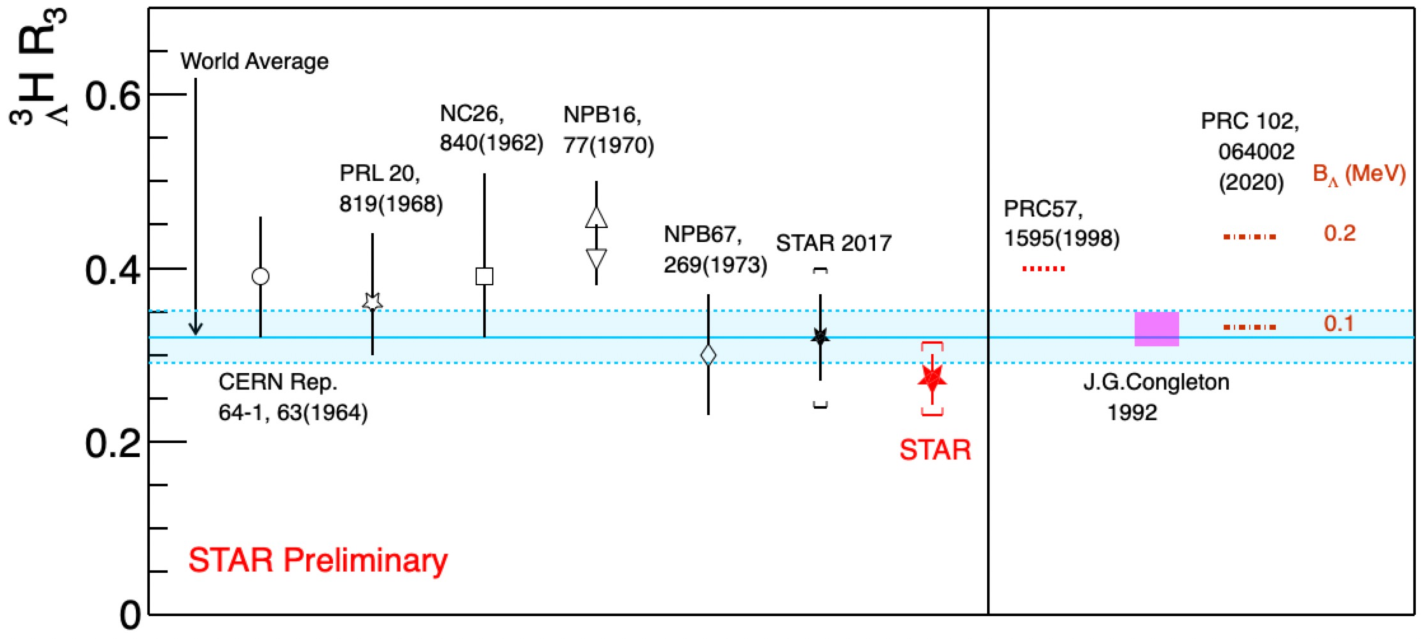
- Recent calculation shows that ${}^{3}_{\Lambda}H$ $R_3$ may be sensitive to $B_\Lambda$. F. Hildenbrand et al. PRC 102, 064002 (2020)
- $B_\Lambda$ -> direct constraints on Y-N interaction.

Old world average: $0.35 \pm 0.04$

Updated world average: $0.32 \pm 0.03$

STAR (new!): $R_3 = 0.272 \pm 0.030 \pm 0.042$



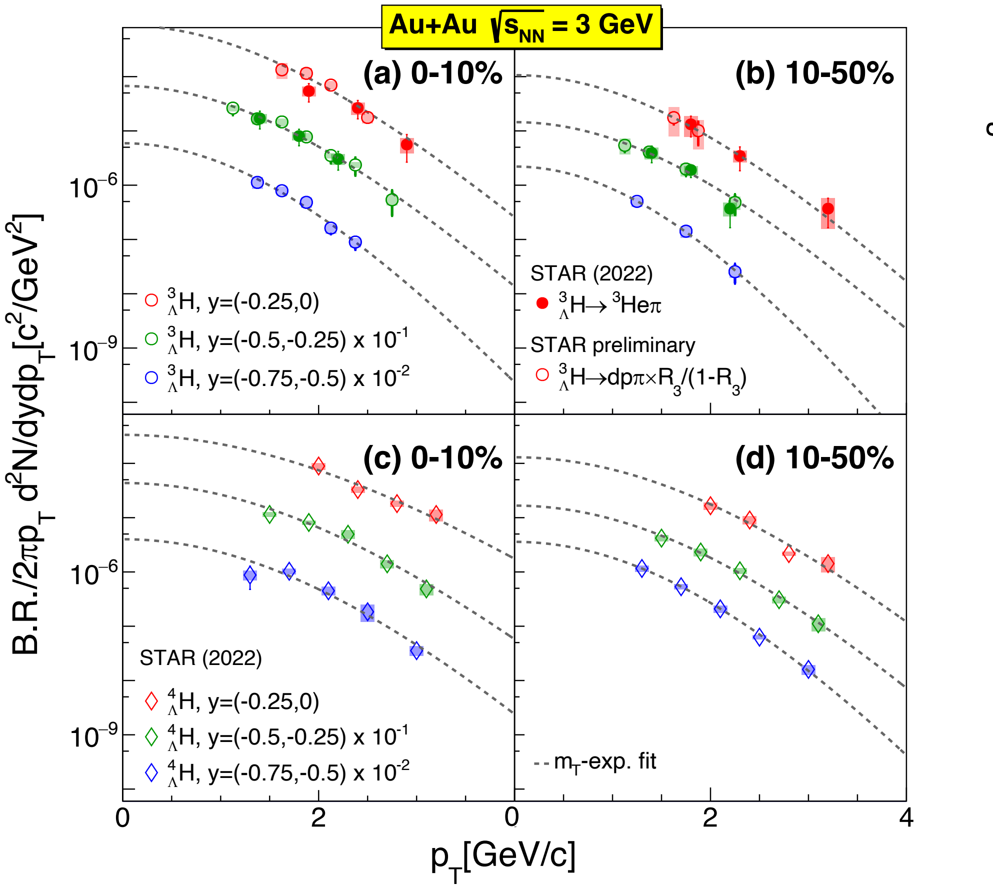




Improved precision on $R_3$.

- Stronger constraints on absolute B.R. and hypertriton internal structure models.

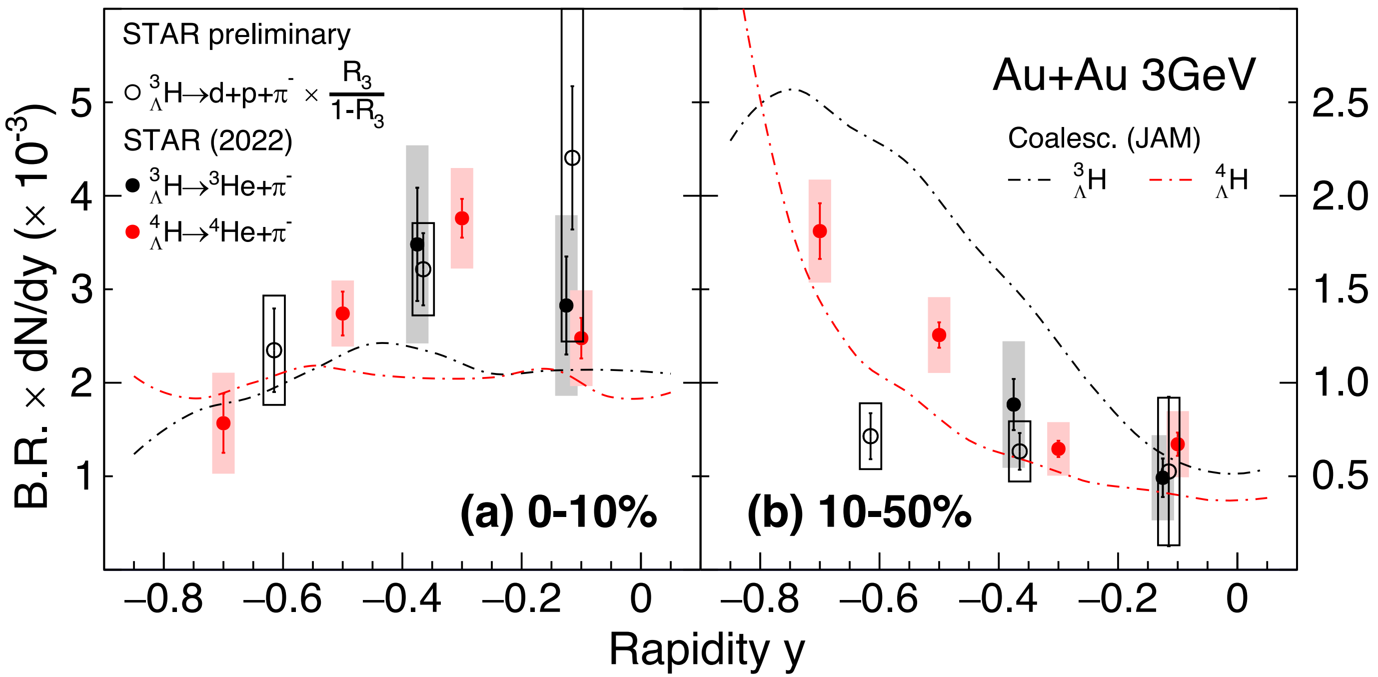
# Measurements of hypernuclei production in Au+Au collisions

# ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H production in Au+Au at 3 GeV




$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He}\pi$, $^{4}_{\Lambda}\mathrm{H}$ data: STAR, PRL 128, 202301 (2022)

Note: Uncertainties (19%) of $^{3}_{\Lambda}\mathrm{H}$ $R_3$ are not shown in the plots.

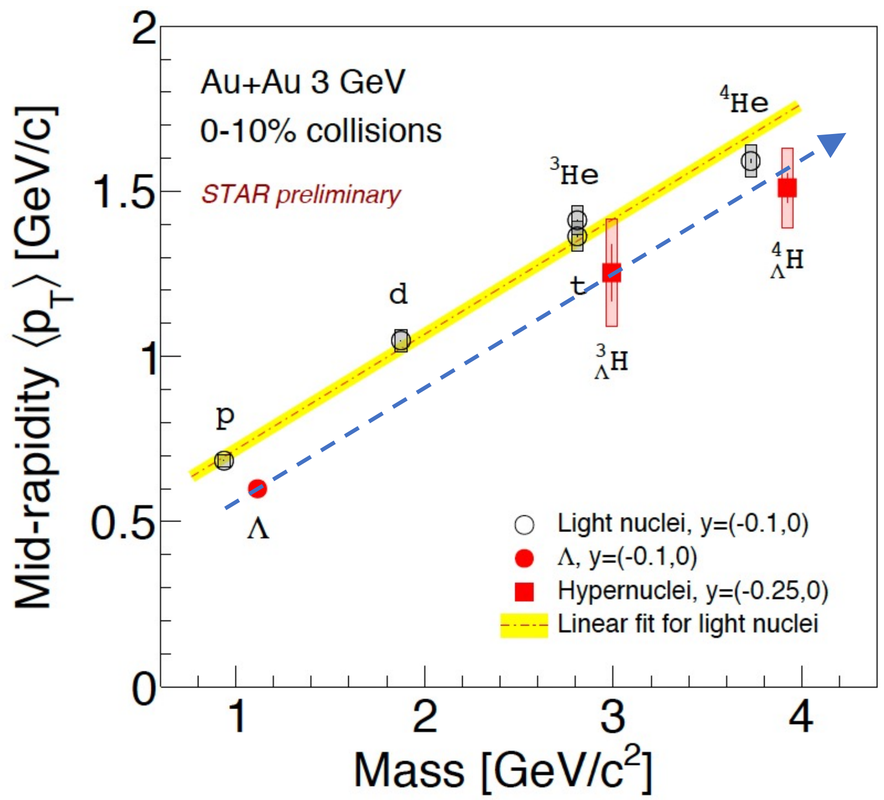



- First measurements on rapidity dependence of hypernuclei yields in heavy ion collisions.
- Different tendency in 0-10% and 10-50% centralities.

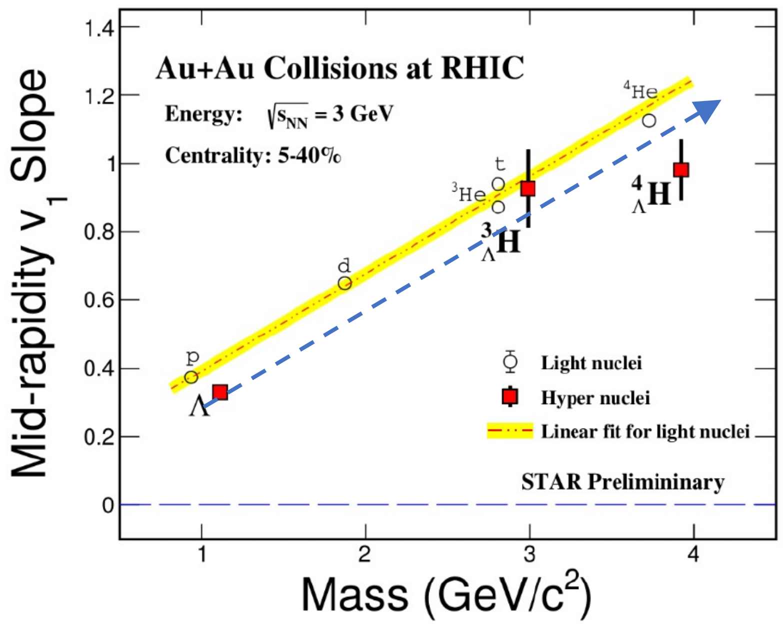
Coalescence models with tuned parameters qualitatively describe the trend of $^{4}_{\Lambda}\mathrm{H}$ yields versus rapidity.

Coales. (JAM): L. Hui et al. PLB 805, 135452 (2020)

# ${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$ $<p_T>$ and $v_1$ in Au+Au at 3 GeV



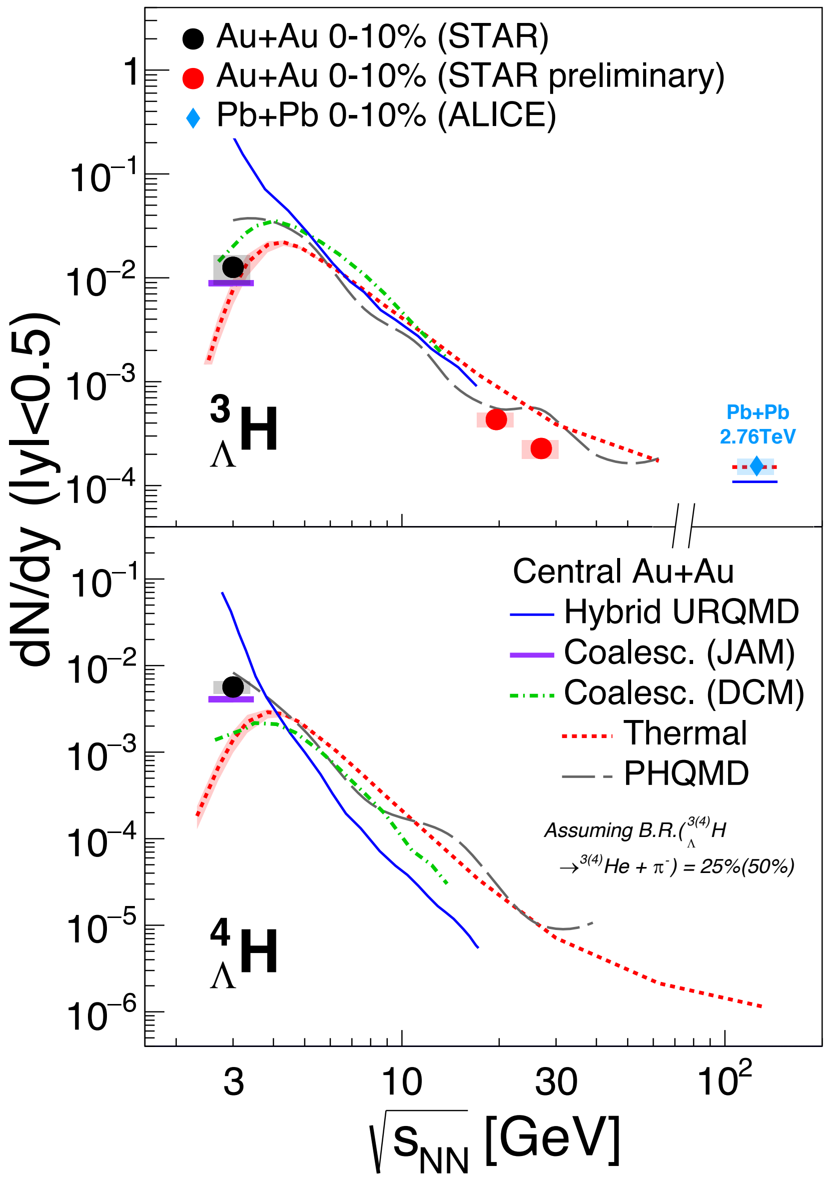

Details of hypernuclei $v_1$ see: Rishabh Sharma, 6.14 12:10 pm




- Linear trend for light- and hyper- nuclei $<p_T>$ reflects dominance of collective radial motion.
- Similar phenomena also seen in $v_1$ slope: follow mass number scaling.

Results qualitatively consistent with hypernuclei production from coalescence of hyperons and nucleons.

# Energy dependence of hypernuclei production




First energy dependence of hypernuclei production yields in high $\mu_B$ region.

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

- Thermal model (GSI-Heidelberg) predicts the trend while not quantitatively describe the yields.

For Au+Au @ 3 GeV

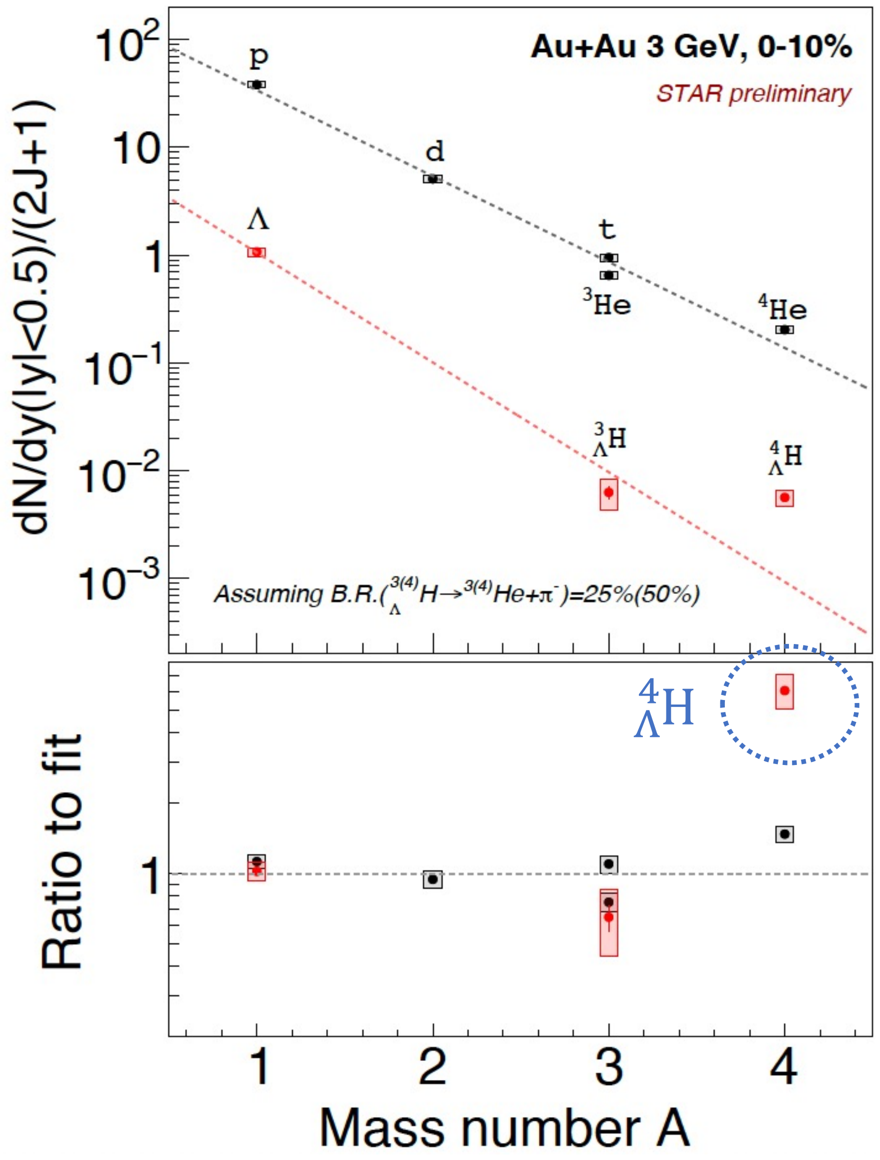
- PHQMD describe $^4_\Lambda$H yields while overestimate $^3_\Lambda$H yields.
- Hybrid URQMD overestimates by an order of magnitude.
- JAM+Coal. : tuned coalescence parameters based on STAR measurments.

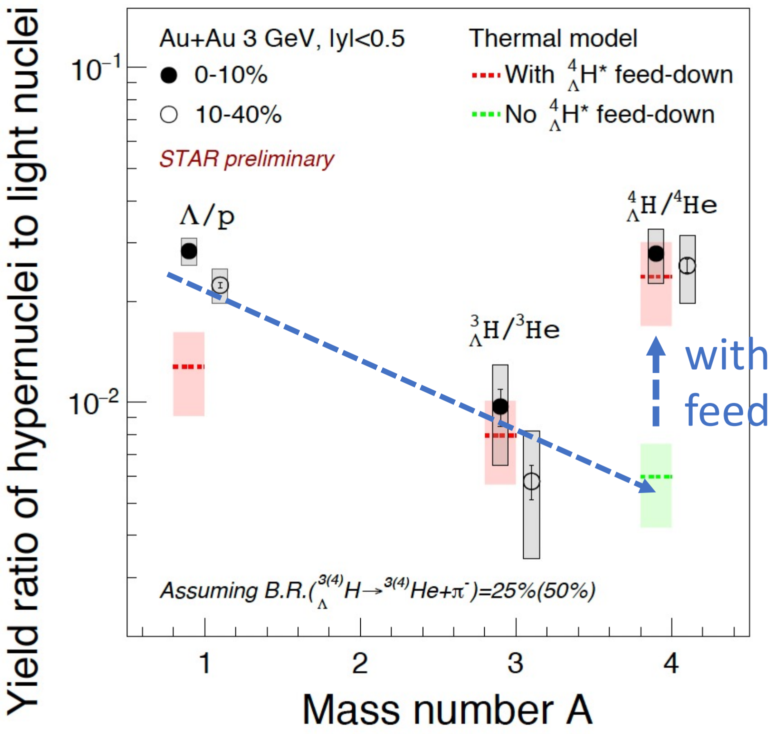

DCM: J. Steinheimer et al. PLB 714, 85-91 (2012)
Thermal: A. Andronic et al. PLB 697,203-207 (2011)
PHQMD: Susanne Gläßel et al. PRC 105, 014908 (2022), V. Kireyeu et al. arXiv:1911.09496
JAM: L. Hui et al. PLB 805, 135452 (2020)
Pb+Pb: ALICE, PLB 754, 360 (2016)
STAR at 3 GeV: PRL 128, 202301 (2022)

# Comparison to Λ and light nuclei at 3 GeV

Data support the creation of excited A=4 hypernuclei in heavy ion collisions.

- Thermal/coalescence models predict approximate exponential dependence of yields/(2J+1) vs A.
- ${}^{4}_{\Lambda}\mathrm{H}$ lies a factor of 6 above exponential fit to ($\Lambda$, ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$).



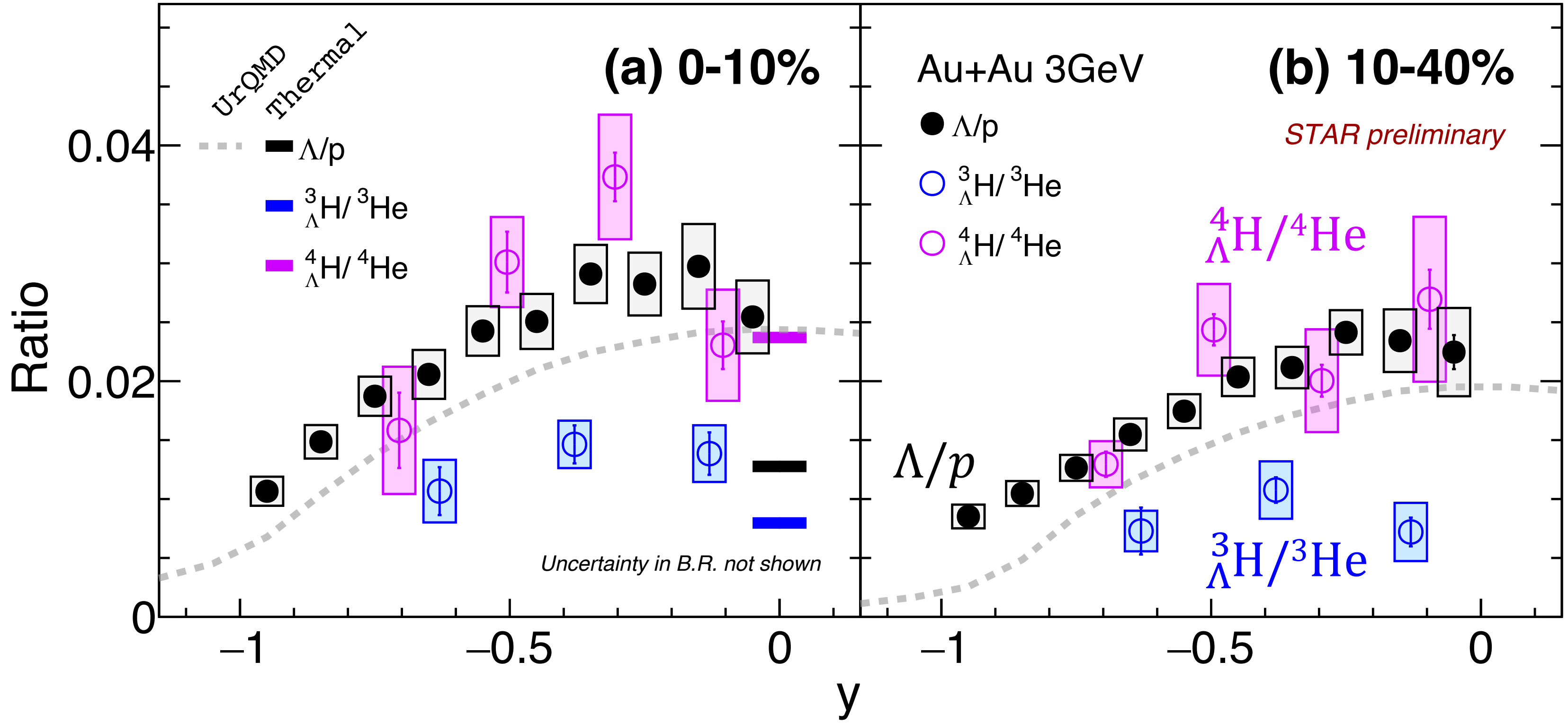

with ${}^{4}_{\Lambda}\mathrm{H}^{*}$ feed down

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

- Thermal model calculation, including excited ${}^{4}_{\Lambda}\mathrm{H}^{*}$ feed down, shows a similar trend.

A. Andronic et al, PLB 697, 203 (2011) (updated, preliminary) (Thermal Model)

# Hyper-to-light nuclei yield ratios at 3 GeV




Note: ${}^{3}_{\Lambda}$H $R_3$=27%, $B.R.\left({}^{4}_{\Lambda}\text{H} \rightarrow {}^{4}\text{He}\,\pi^{-}\right) = 50\%$, uncertainties from B.R. not shown.

- Suppression of ${}^{3}_{\Lambda}\text{H}/{}^{3}\text{He}$ yield ratios compared to that of $\Lambda/p$ at both 0-10% and 10-40% centrality in Au+Au collisions at 3 GeV.
- Comparable ${}^{4}_{\Lambda}\text{H}/{}^{4}\text{He}$ yield ratios to that of $\Lambda/p$.
  - Feed-down from exited state enhances ${}^{4}_{\Lambda}\text{H}$ production.

# $S_3$ and $S_4$ in Au+Au at 3 GeV

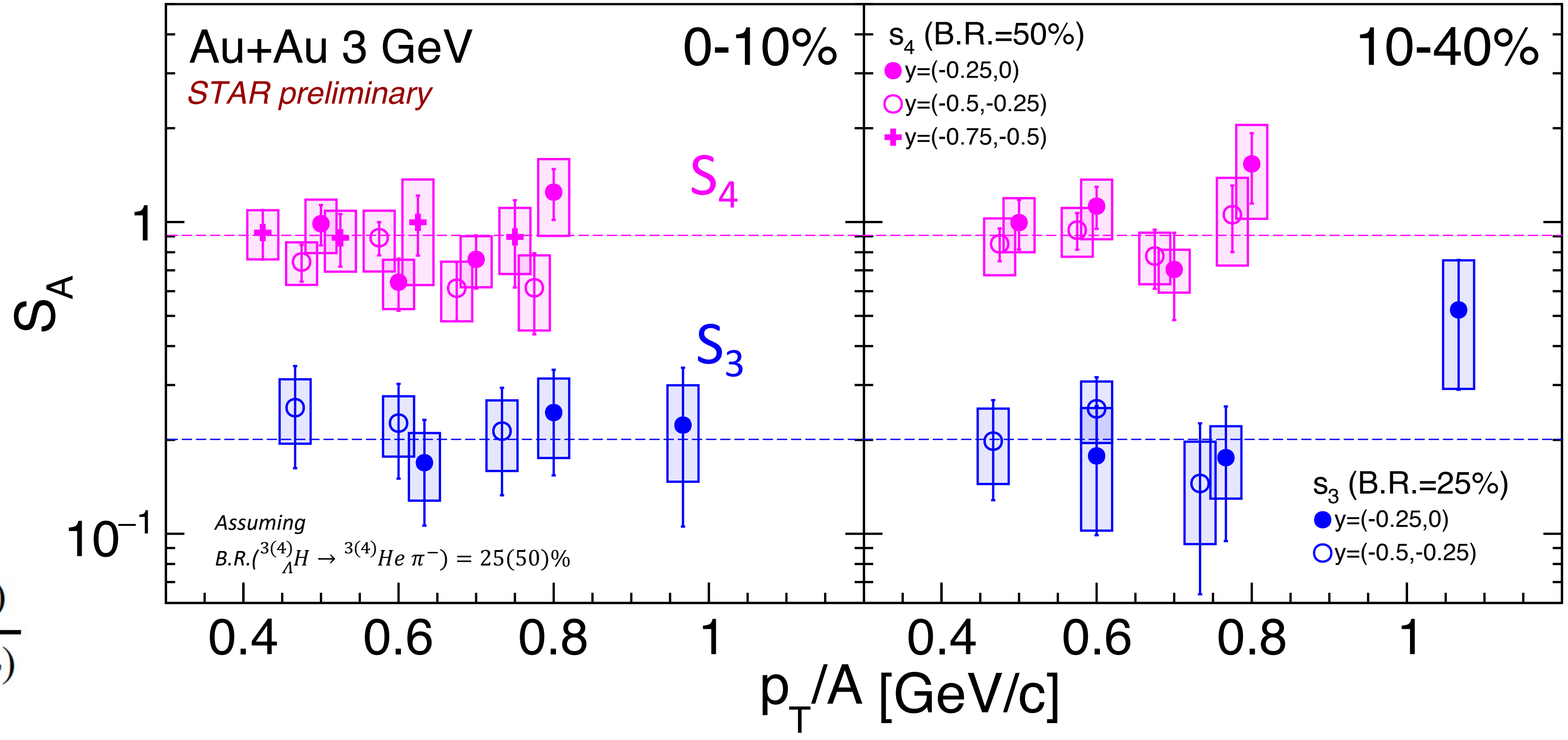
Strangeness population factor:

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

S. Zhang et al, PLB 684, 224 (2010)

- Connection to coalescence parameters:

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




*Dashed lines are only for guidance.

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 versus $p_T$, rapidity and centrality.

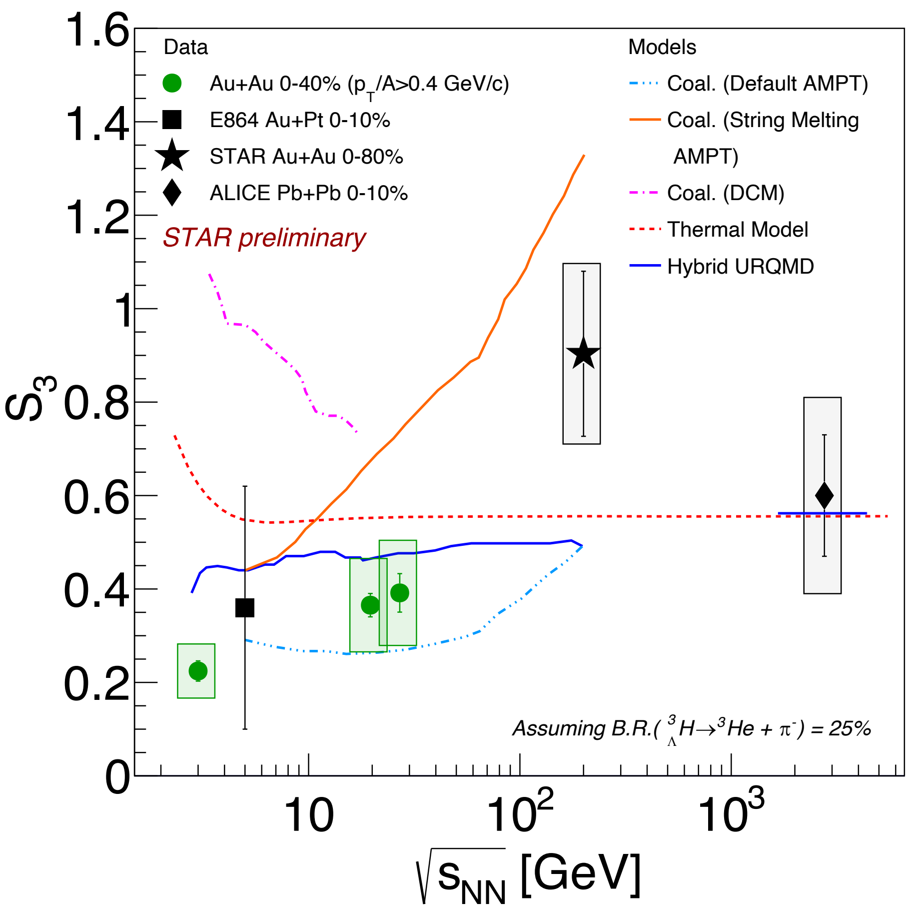
# Energy dependence of $S_3$

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

Why $S_3$ vs energy?

- Removes the absolute difference of $\Lambda/p$ yields versus beam energy.

Au+Au 200GeV: STAR, Science 328, 58 (2010)
Pb+Pb 2.76 TeV: ALICE, PLB 754,360 (2016)
Au+Pt 5 GeV: E864, PRC70, 024902 (2004),
E864, J.Phys.Conf.Ser.110, 032010 (2008)




- Energy dependence: hint of increasing $S_3$ from $\sqrt{s_{NN}} = 3$ GeV to 2.76 TeV.
- None of the shown models describe the $S_3$ data quantitatively.

Note: For 19.6 and 27 GeV, take $^3He/t = 0.93 \pm 0.07$

# Summary

## Intrinsic properties

- Measurements on lifetimes of ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}e$, and ${}^{3}_{\Lambda}\mathrm{H}$ $R_3$ are reported.

  -> Stronger constraints on hypernuclei internal structures.

## Production mechanism

- Kinematic and centrality dependence of ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$ production yields, $S_A$, and flow behavior in Au+Au collisions at 3 GeV are presented.
- Energy dependence of ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$ yields, $S_A$ in the mid-rapdity from 3-27 GeV are also shown.

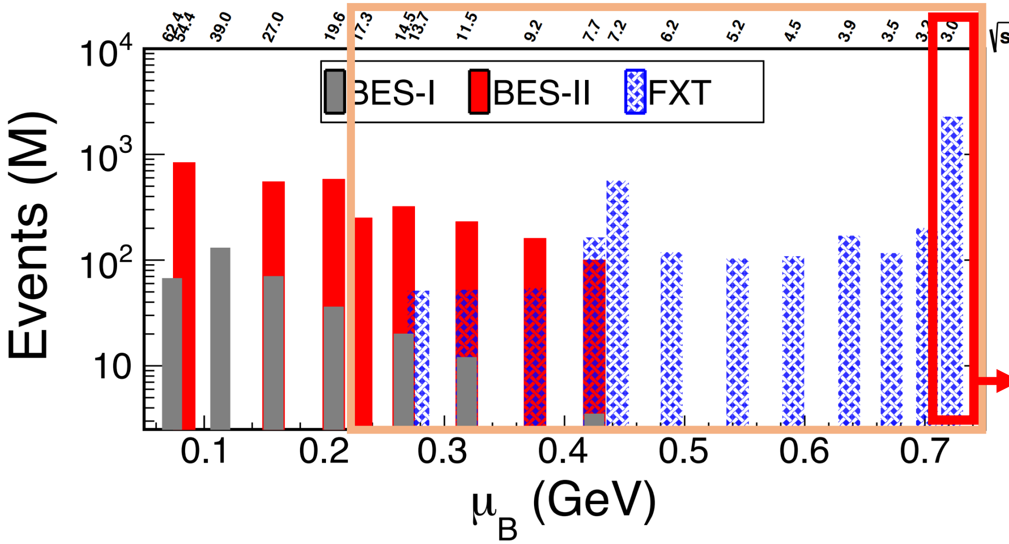
  -> Data support coalescence of hypernuclei production.

  -> No obvious kinematic or centrality dependence of $S_3$ observed in 3 GeV Au+Au collisions.

Provide deeper understanding of the strength of *Y-N* interaction.

# Outlook

High statistical data in STAR BES II $\sqrt{s_{NN}}$ = 3.0 – 54.4 GeV!

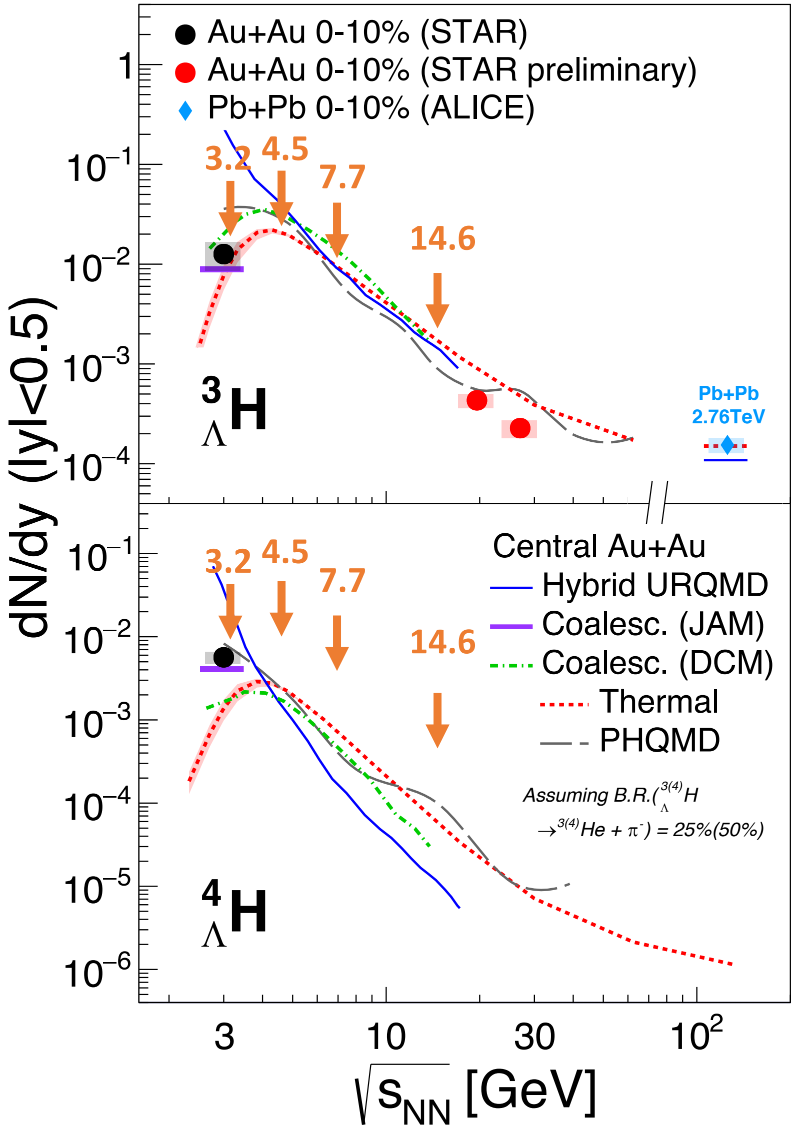



In this report:
3, 27 GeV in 2018,
19.6 GeV in 2019
Future analysis:
3-17 GeV 2019-21
→ 2B@3GeV from 2021

- Energy dependence of hypernuclei yields ($S_A$) and flow.
  - e.g. ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H, ${}^{4}_{\Lambda}$He, ${}^{5}_{\Lambda}$He.
- Precise measurements on hypernuclei intrinsic properties.
  - Branching ratio, lifetime, binding energy, etc .
- Search of double Λ hypernuclei.

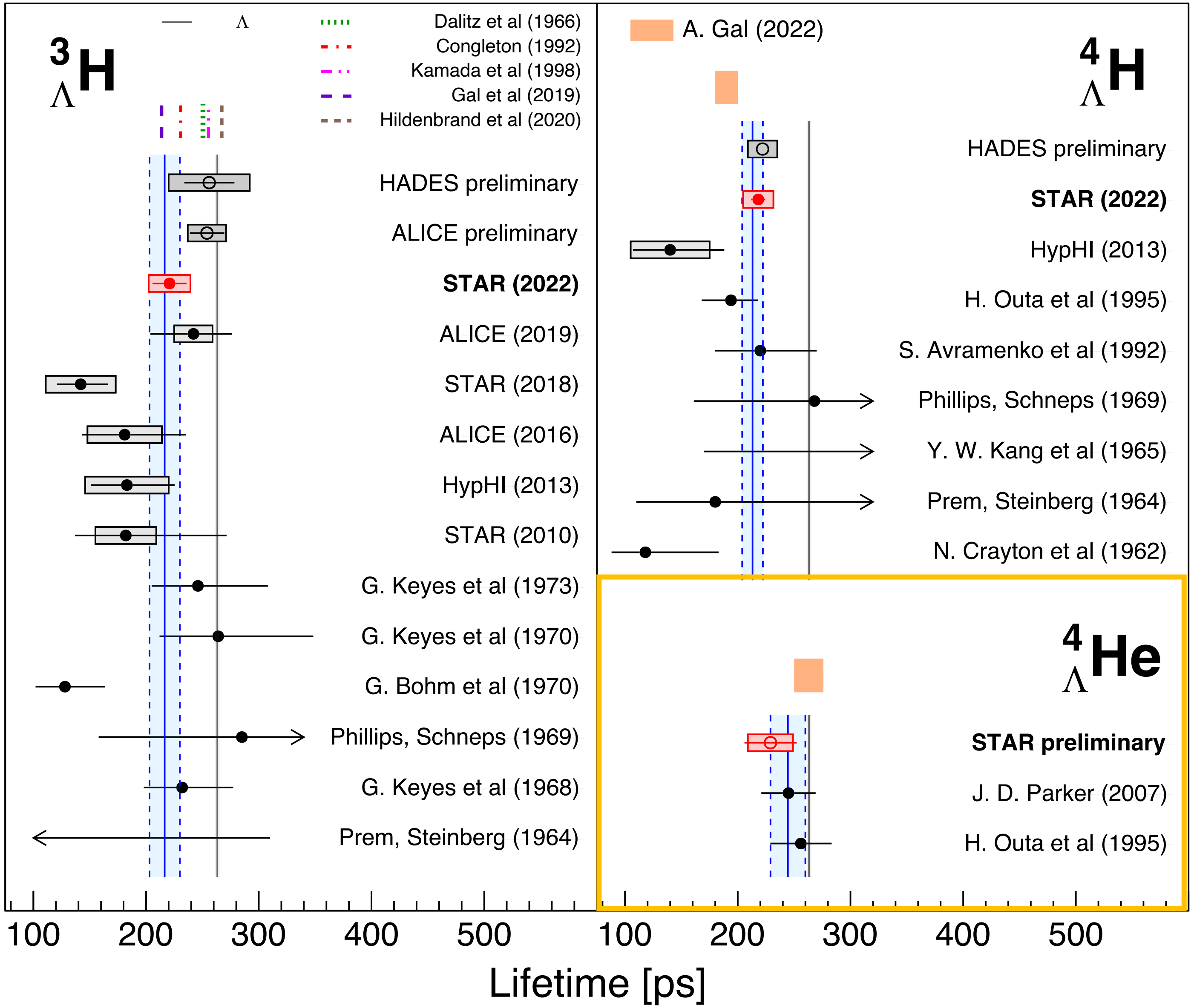
  e.g. ${}^{4}_{\Lambda\Lambda}$He-> ${}^{4}_{\Lambda}$He$\pi$, ${}^{5}_{\Lambda\Lambda}$He -> ${}^{5}_{\Lambda}$He$\pi$

  -> Understanding Y – Y interaction.



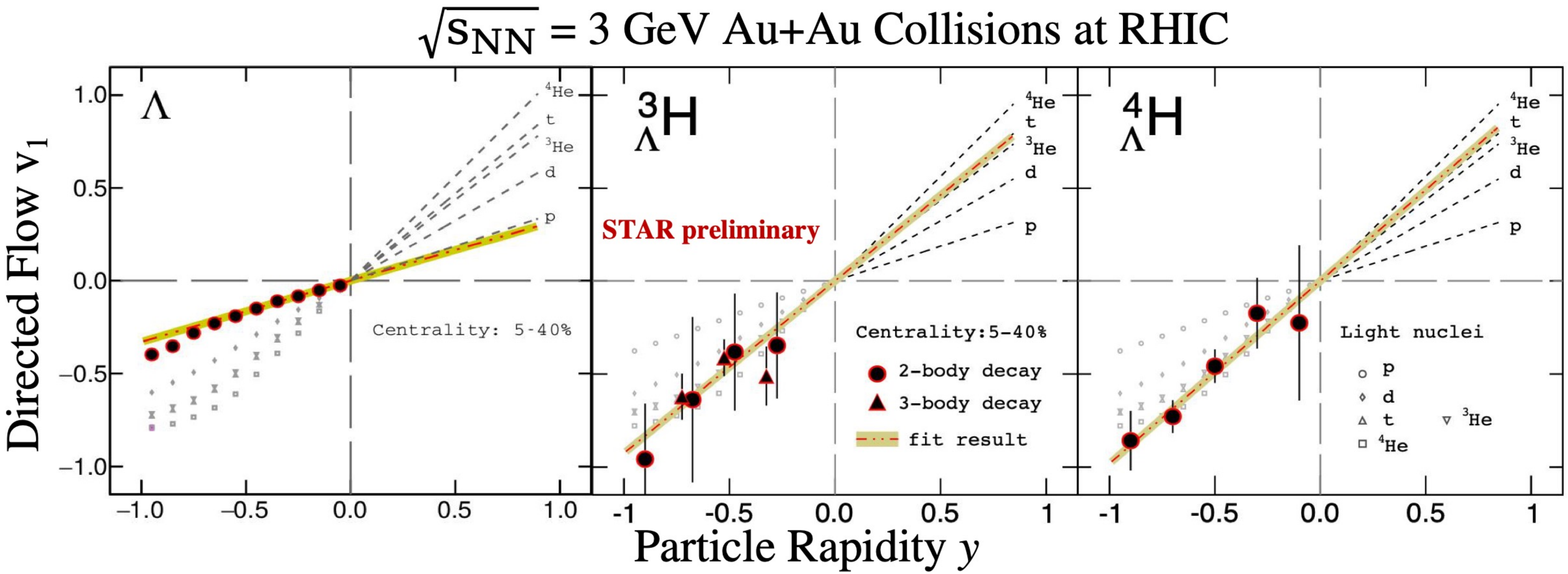
- Back up

# Hyper nuclei lifetime



# Directed flow vs rapidity

Details of hypernuclei $v_1$ see:
Rishabh Sharma, 6.14 12:10 pm



# Calculate ${}^{3}_{\Lambda}\mathrm{H}$ *B.R.* from $R_3$

- *B.R.*$({}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{3He}\pi^{-})$ = 0.178±0.034
- *B.R.*$({}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{pd}\pi^{-})$ = 0.475±0.090

Assumption:

- Isospin rule:

$$\frac{\Gamma({}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{3He}\pi^{-})}{\Gamma({}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{3H}\pi^{0})} = \frac{\Gamma({}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{pd}\pi^{-})}{\Gamma({}^{3}_{\Lambda}\mathrm{H} \rightarrow nd\pi^{0})} = 2$$

PRC 57, 1595-1603 (1998)

- 2% contribution from non-pion decay channels and other pion decay channel.

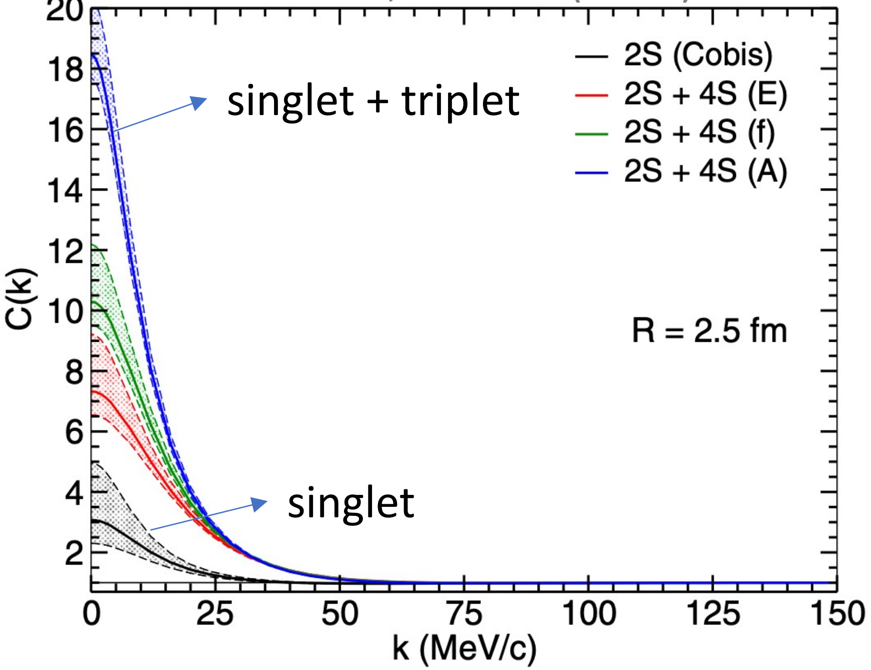
-> *B.R.*$({}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{3He}\pi^{-})$ = $R_3 \times 0.98 \times \frac{2}{3}$

# Correlated $\Lambda d$ contamination in ${}^{3}_{\Lambda}\mathrm{H}$ signal

- $\Lambda d$ may have kinematic correlations according to theory calculation.

C(k*)=$\frac{P(\Lambda d)}{P(\Lambda)P(d)}$ , p is the possibility of finding particle
No correlation -> C(k*)=1
k* -> relative momentum between $\Lambda$ and $d$

PRC 102, 034001 (2020)




When k*=0, in $\Lambda$ and $d$ pair CMS framework:

$$p_\Lambda = -p_d = 0$$

$$\Lambda : ( p_\Lambda, E_\Lambda ) = (0, m_\Lambda)$$

$$d : ( p_d, E_d ) = (0, m_d)$$

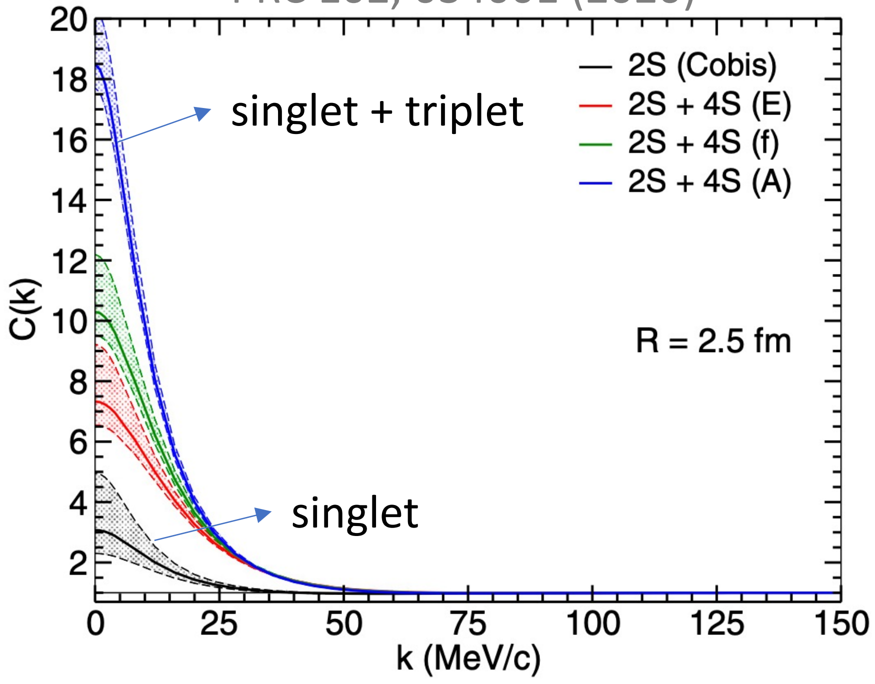
-> $(\Lambda d) : ( p_\Lambda + p_d, E_\Lambda + E_d)$ = $(0, m_\Lambda + m_d)$

# Correlated $\Lambda d$ contamination in ${}^{3}_{\Lambda}\mathrm{H}$ signal

- $\Lambda d$ may have kinematic correlations according to theory calculation.
- When $\Lambda d$ C(k*) >1 at k*-> 0, peak structure is formed near $M(\Lambda) + M(d)$ threshold.
  - $M(\Lambda) + M(d)$ ~2.9913 GeV/$c^2$, M(${}^{3}_{\Lambda}\mathrm{H}$)~2.991 GeV/$c^2$ .

-> Correlated $\Lambda d$ could result in real signal even after subtracting combinatorial background.

PRC 102, 034001 (2020)




Set C(k*) weight on uncorrected Λ and d

From Λ(MC)+d(data) embedding