Recent Studies on *Hypernuclei Lifetimes* from STAR

14th International Conference on Hypernuclear and Strange Particle Physics

Prague, Czech Republic
June 27 – July 1, 2022

- Introduction
- Hypernuclei Lifetimes
    - Measurements from BES-II
    - Anti-Hypernuclei Measurements
- Hypernuclei Branching Ratios
- Summary and Outlook

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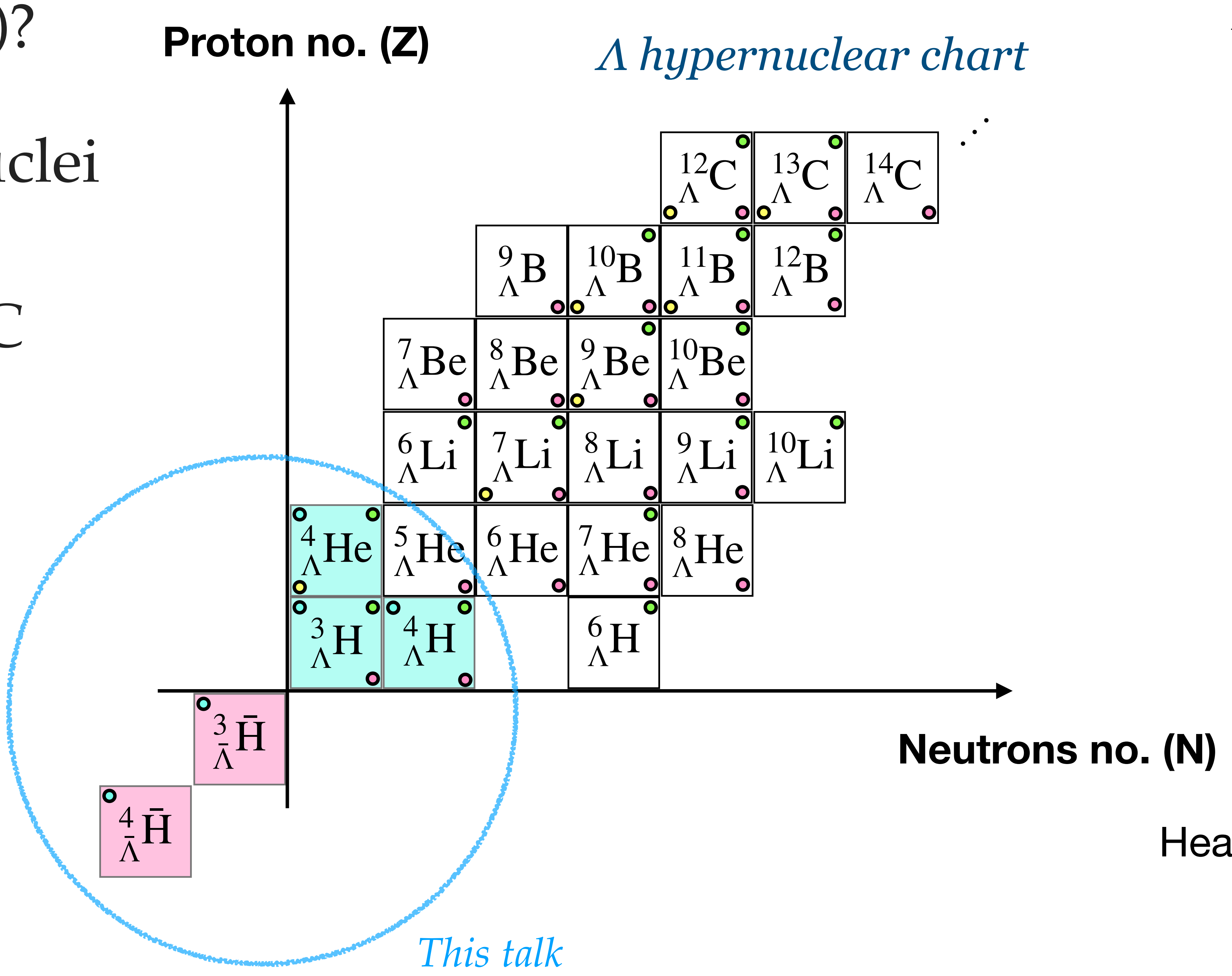
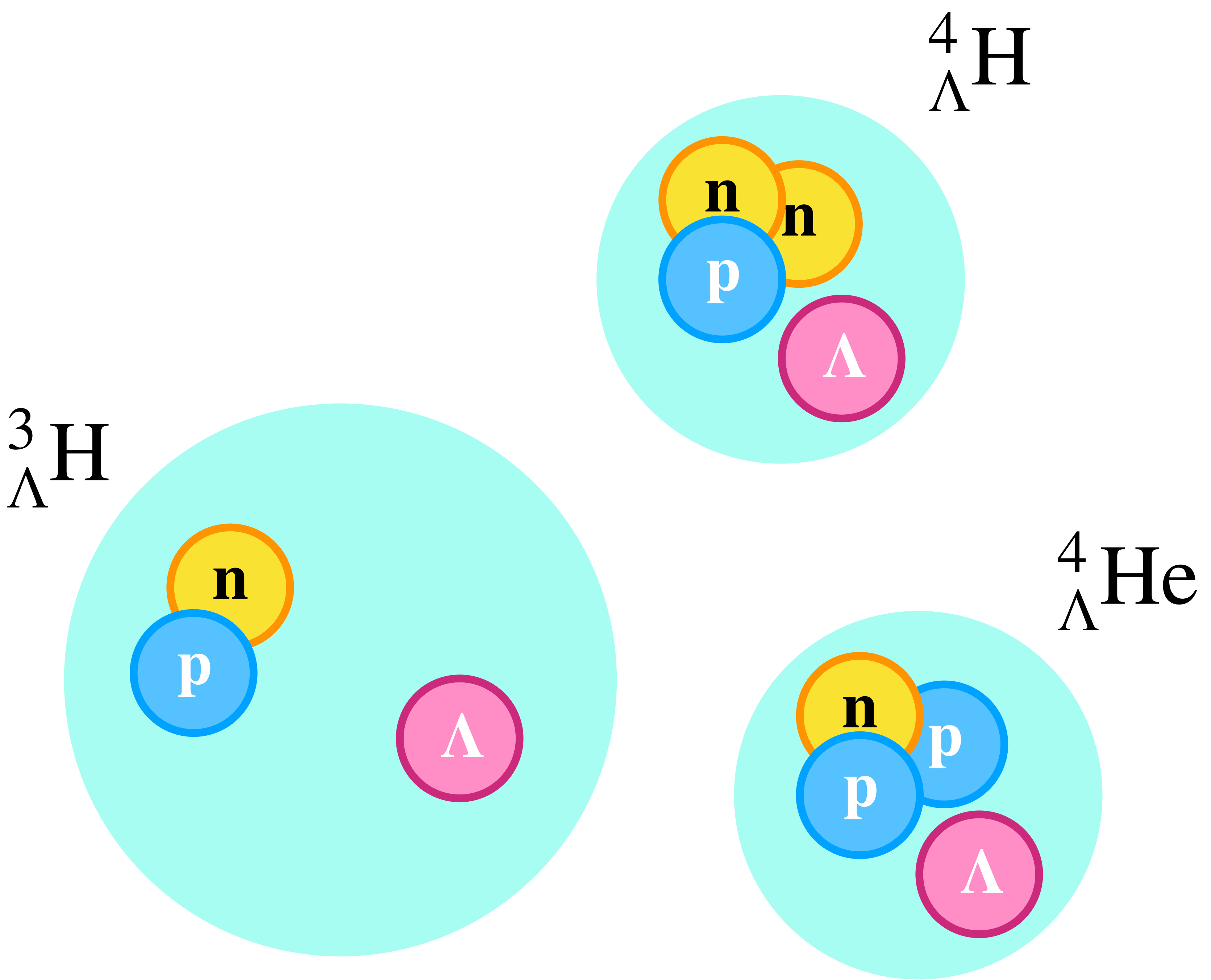
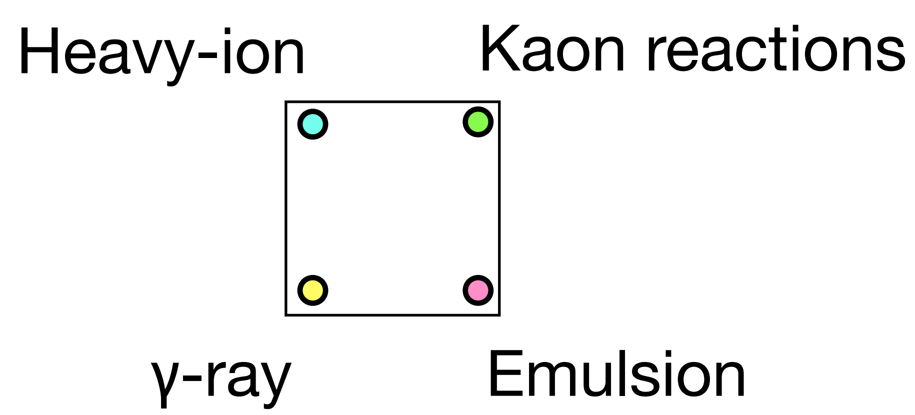
Introduction

- **Hypernuclei** can be used as experimental probes to study the **hyperon–nucleon (Y-N) interaction**
    - EOS of high baryon density objects, e.g. neutron stars
- Why heavy ion collisions (HIC)?
    - Light and anti-hypernuclei may be produced in copious amounts in HIC

→ Potential for high precision measurements







Hypertriton lifetime "puzzle"

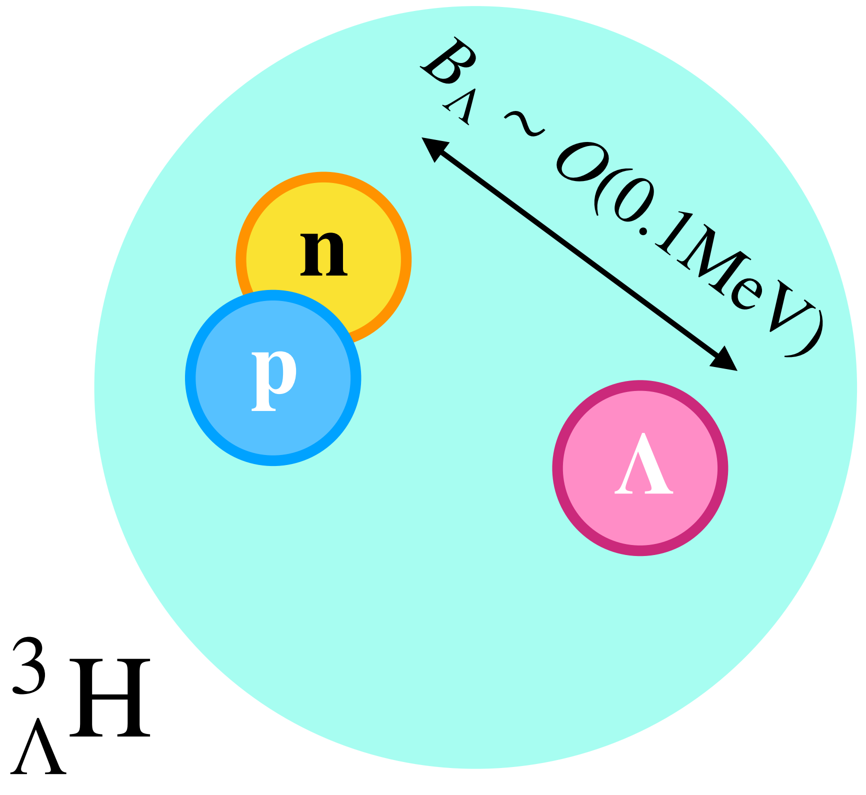
- World average of measured $\tau(^{3}_{\Lambda}\mathrm{H})$ is shorter compared to τ_{Λ} $\sim(30 \pm 10)\,\%$

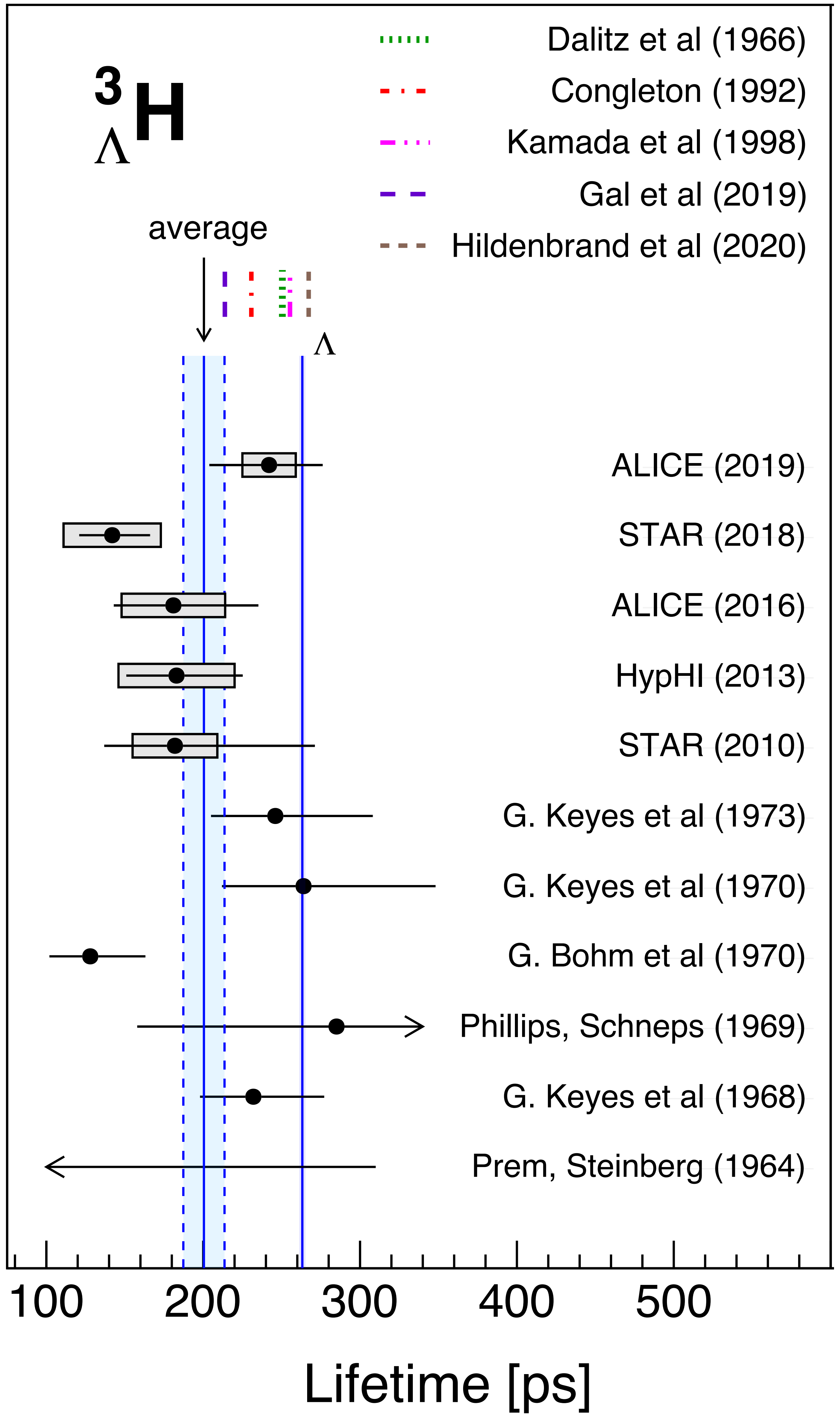
- Tension between recent measurements, albeit with large uncertainties
  - 1.7σ difference between STAR(2018) and ALICE(2019) measurements

ALICE, Phys.Lett. B 797(2019)134905
STAR, Phys. Rev. C 97(2018)54909

- Due to loosely bound nature of $^{3}_{\Lambda}\mathrm{H}$ (B_{Λ}~O(0.1MeV)), theory typically expects $\tau(^{3}_{\Lambda}\mathrm{H})$ to be close to τ_{Λ}

More precise measurements of the hypertriton lifetime is necessary to clarify the situation

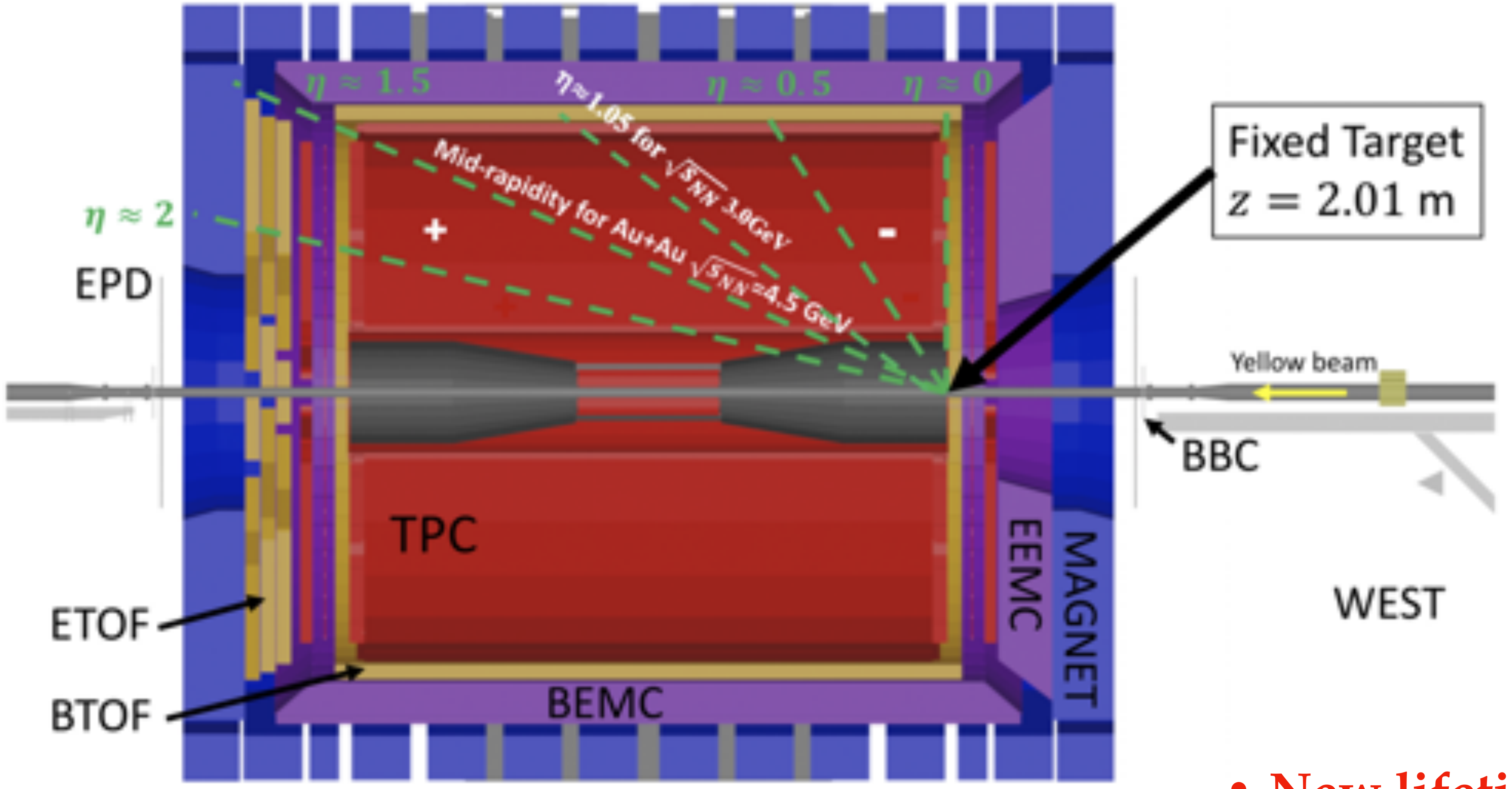




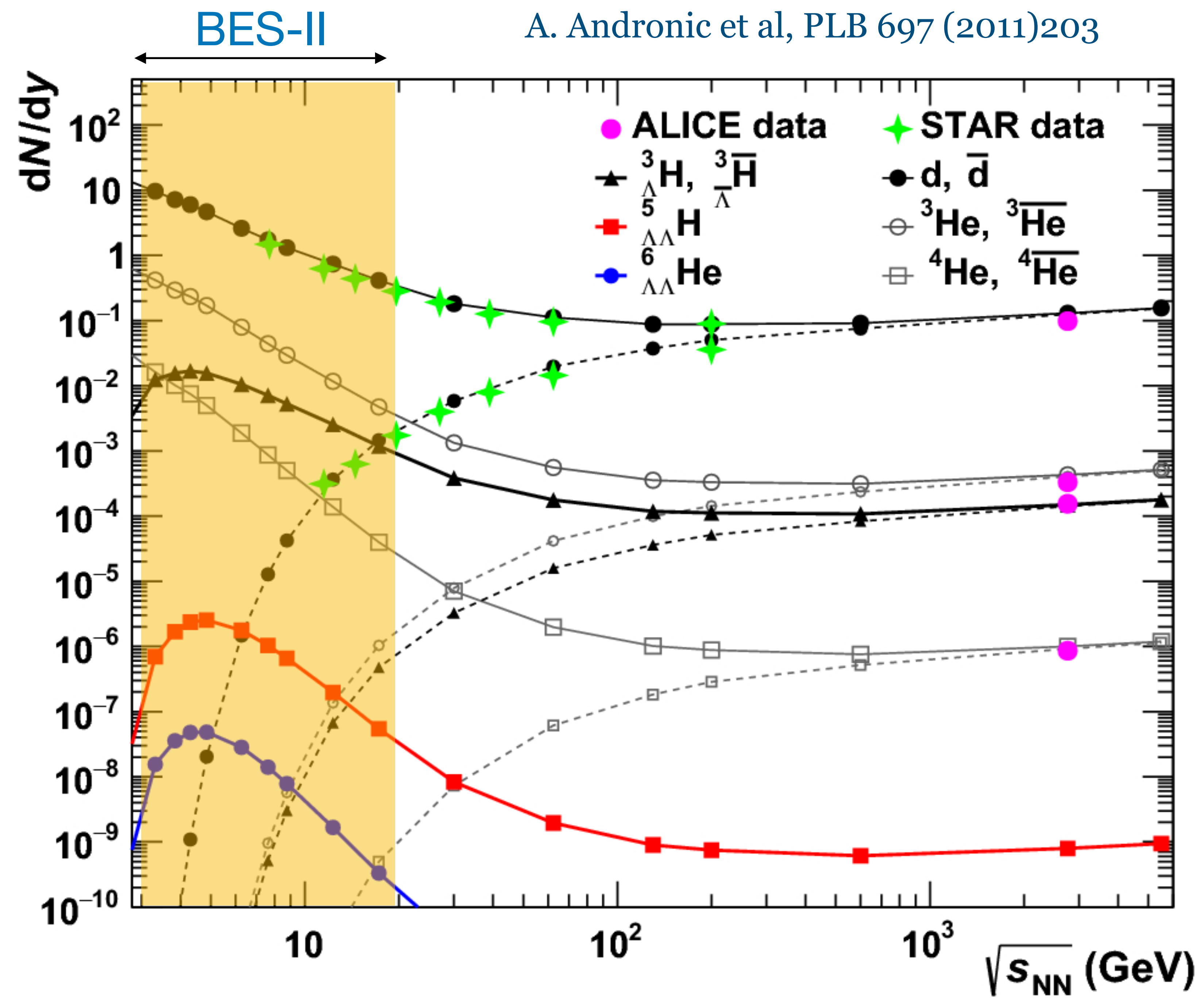
STAR Beam Energy Scan II

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

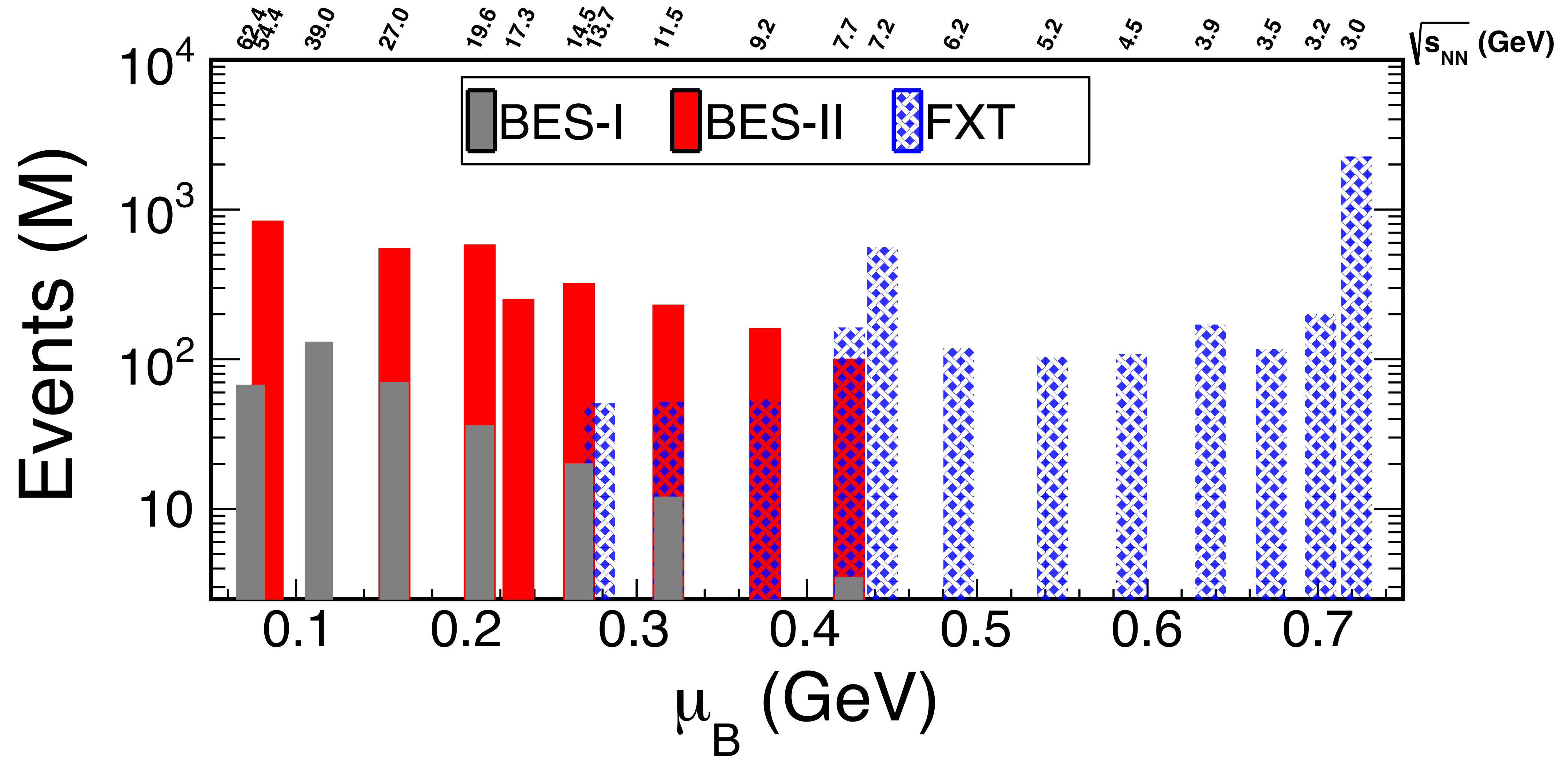
- Hypernuclei measurements are scarce in heavy-ion experiments
- At lower beam energies, hypernuclei yields are expected to be **enhanced due to high baryon density**
  - STAR BES-II -> great opportunity to study hypernuclei production



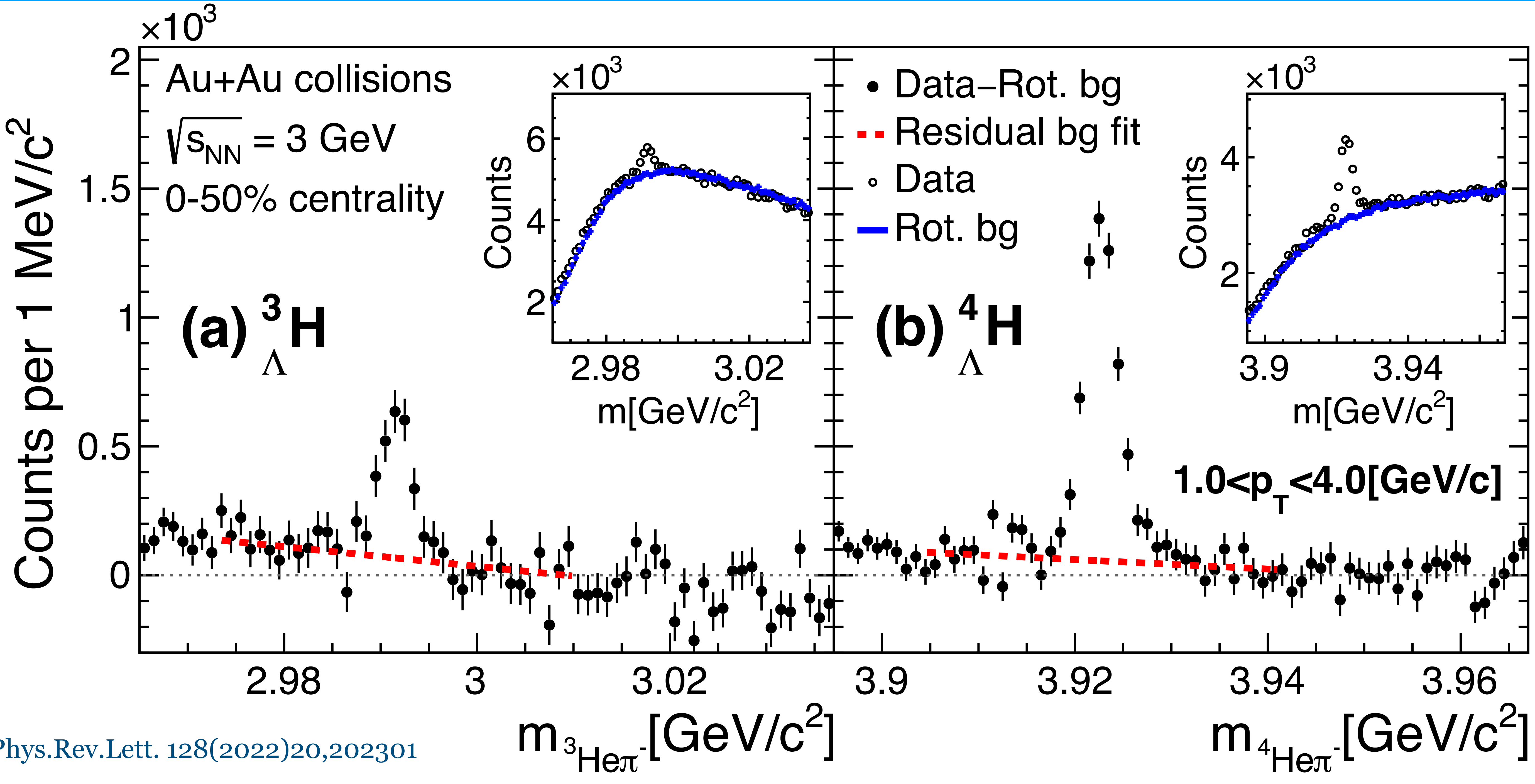
STAR Fixed-target Experiment Setup



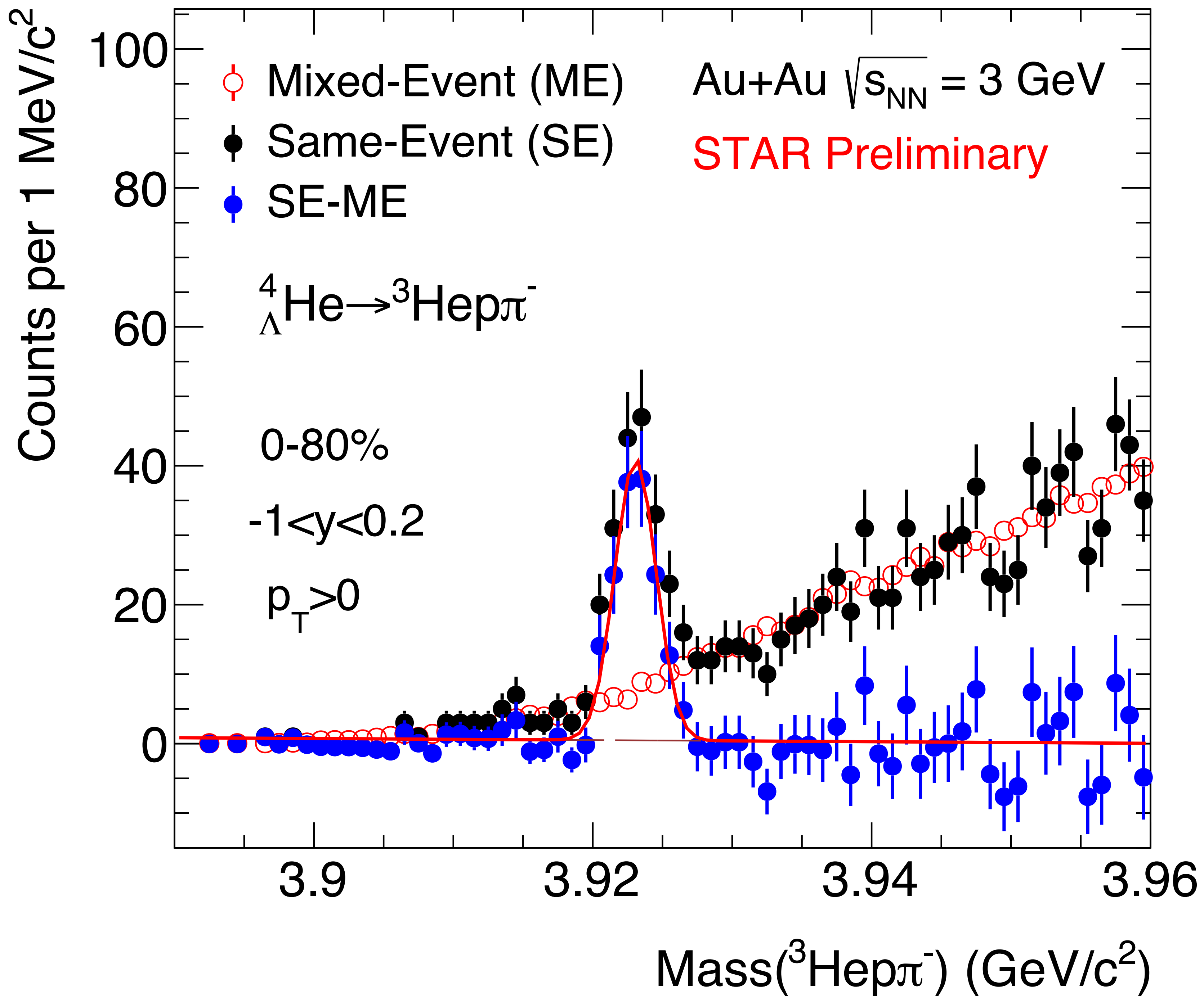
- **New lifetime results from BES-II data**
  - **3.0 GeV, 7.2 GeV**



Hypernuclei reconstruction



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



- Time Projection Chamber (TPC) is used for particle identification

$\sim 3000\ ^{3}_{\Lambda}\mathrm{H}$ *candidates*

$\sim 7000\ ^{4}_{\Lambda}\mathrm{H}$ *candidates*

- Hypernuclei are reconstructed using the following decay channels:

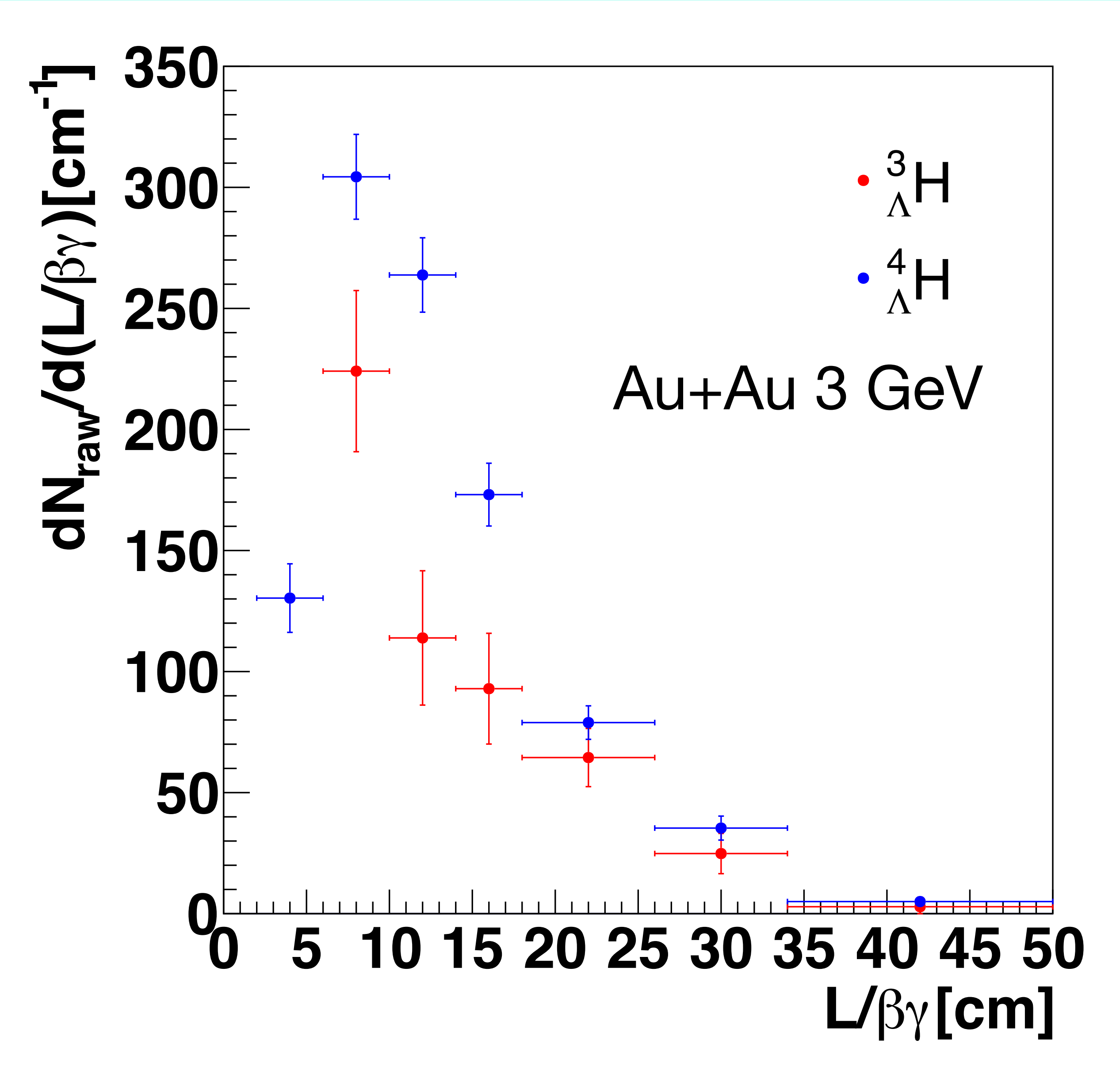
$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$ $\quad$ $^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^{-}$

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

- Combinatorial background estimated via rotating pion tracks or event mixing

Analysis outline

1. Measure the signal counts as a function of L/βγ



L/βγ = ct

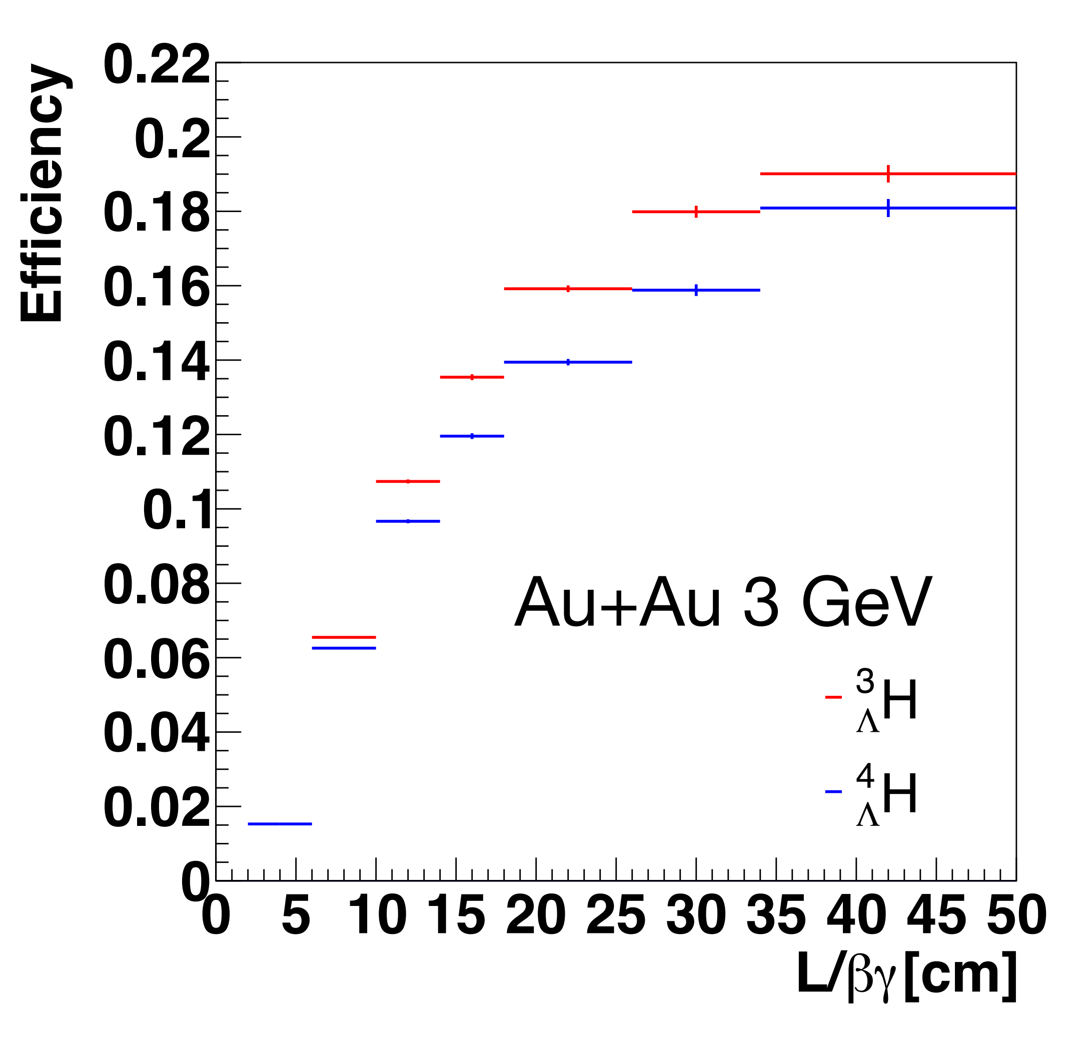
L: decay length
t : proper time

3. Fit with an exponential function to extract the lifetime

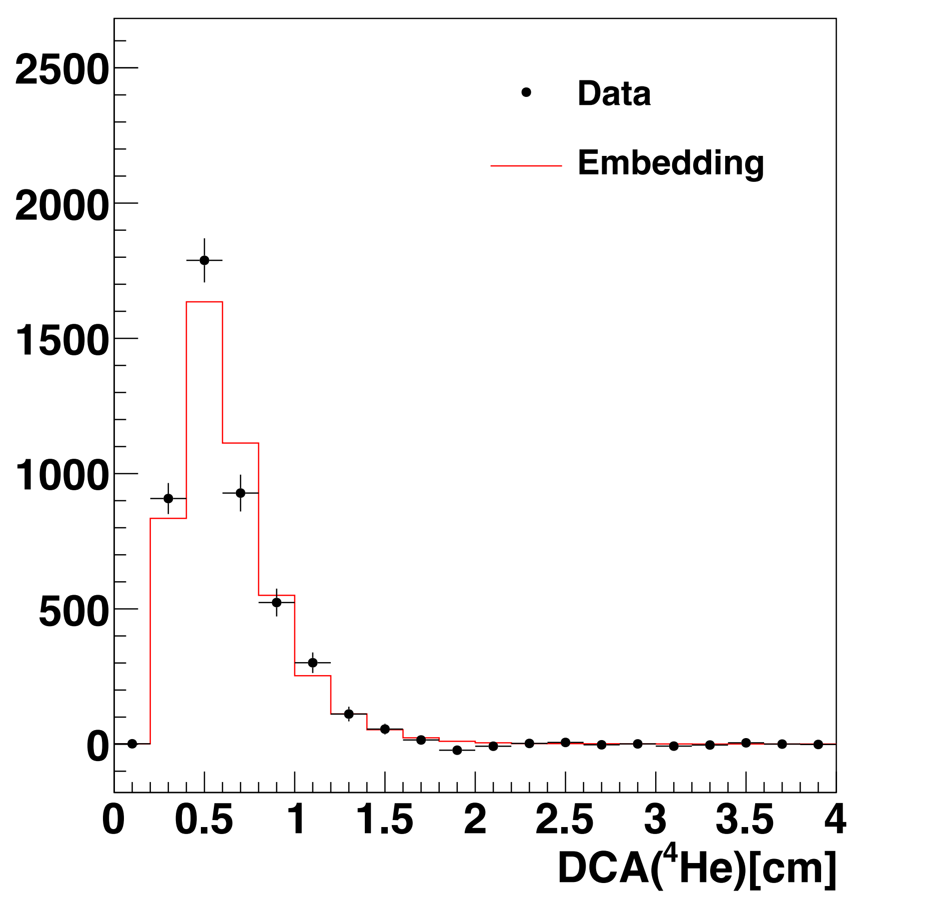
$$N(t) = N_0 e^{-t/\tau} = N_0 e^{-L/\beta\gamma c\tau}$$

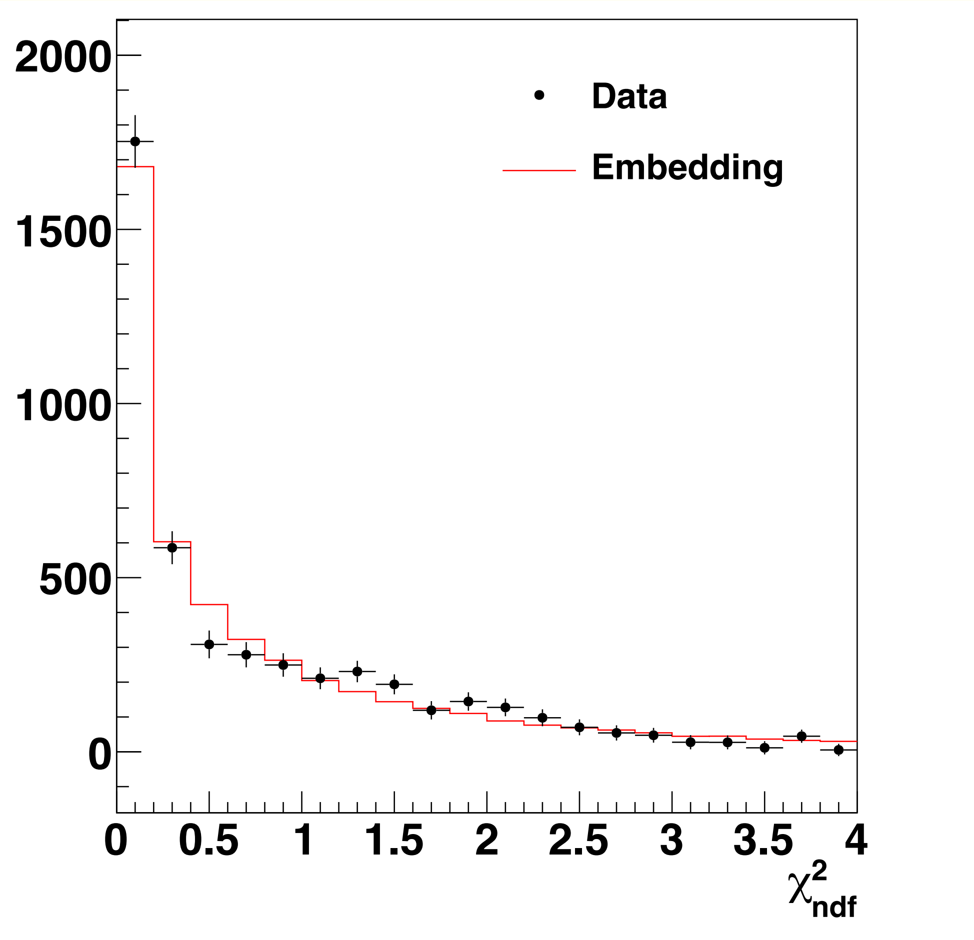
2. Correct for efficiency as a function of L/βγ

- From GEANT3 simulations
  - MC hypernuclei embedded into real data
  - Apply additional weighting to simulations to describe p_T and rapidity distributions in real data

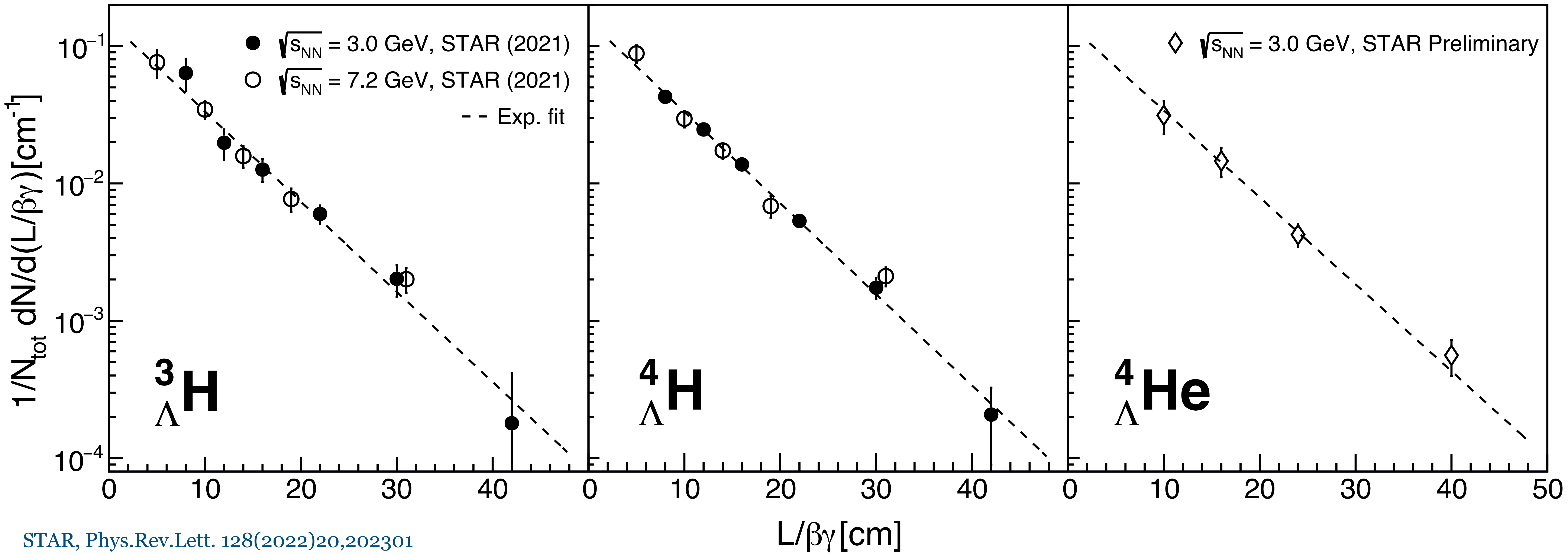


- Simulations provide good description of various topological variable distributions in data

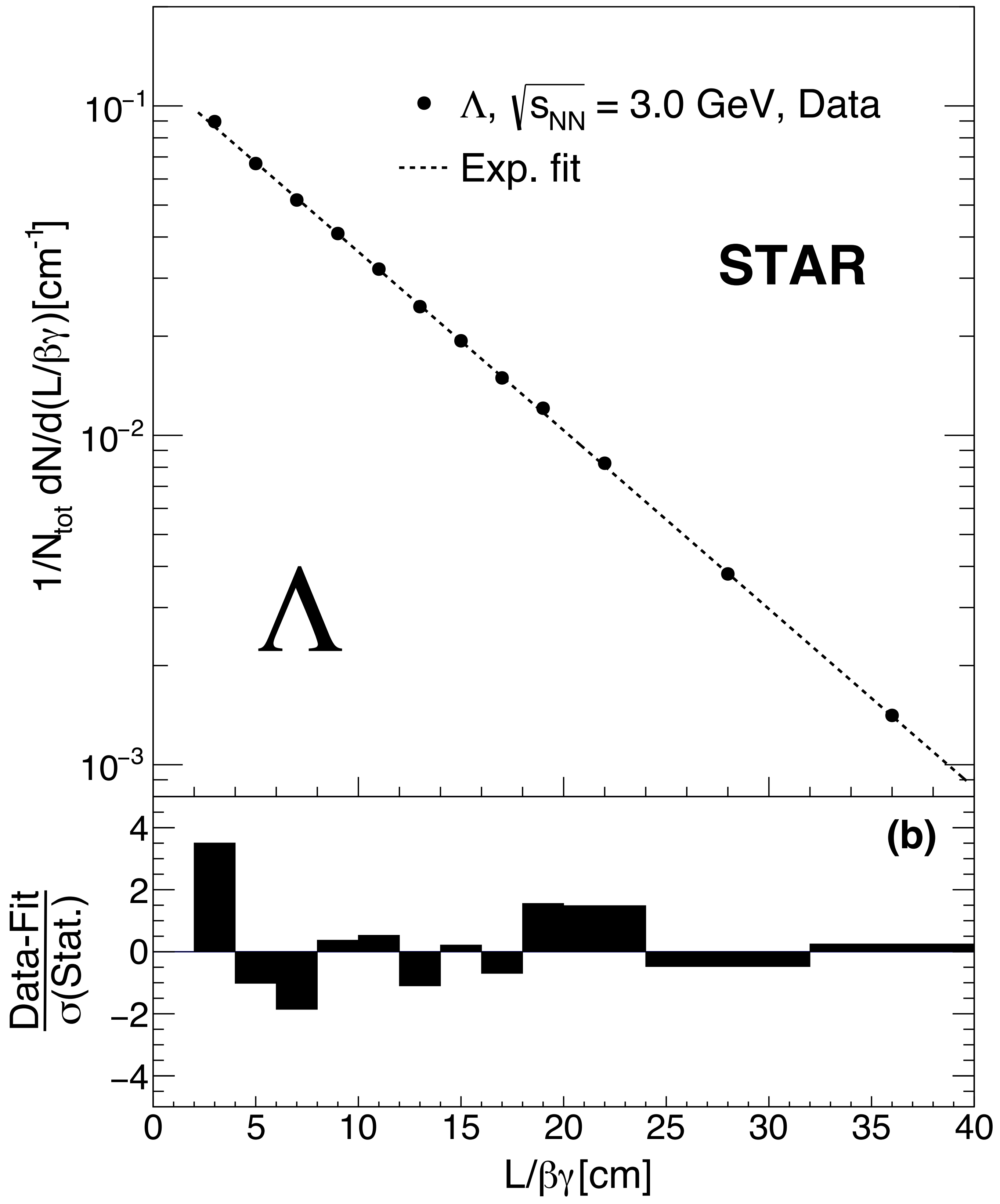




Extracting hypernuclei lifetimes



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



- Lifetimes of $^{3}_{\Lambda}H, ^{4}_{\Lambda}H, ^{4}_{\Lambda}He$ extracted via exponential fit to $\frac{dN}{d(L/\beta\gamma)}$ distributions
- Extracted Λ lifetime 267 ± 4 [ps] consistent with PDG 263 ± 2 [ps]
- $^{3}_{\Lambda}H, ^{4}_{\Lambda}H$ lifetimes from 3.0 GeV consistent with 7.2 GeV analysis

$$\tau(^{3}_{\Lambda}H) = 221 \pm 15(stat) \pm 19(syst)\ [ps]$$
$$\tau(^{4}_{\Lambda}H) = 218 \pm 6(stat) \pm 13(syst)\ [ps]$$
$$\tau(^{4}_{\Lambda}He) = 229 \pm 23(stat) \pm 20(syst)\ [ps]$$

Estimating possible contamination of hypernuclei signal

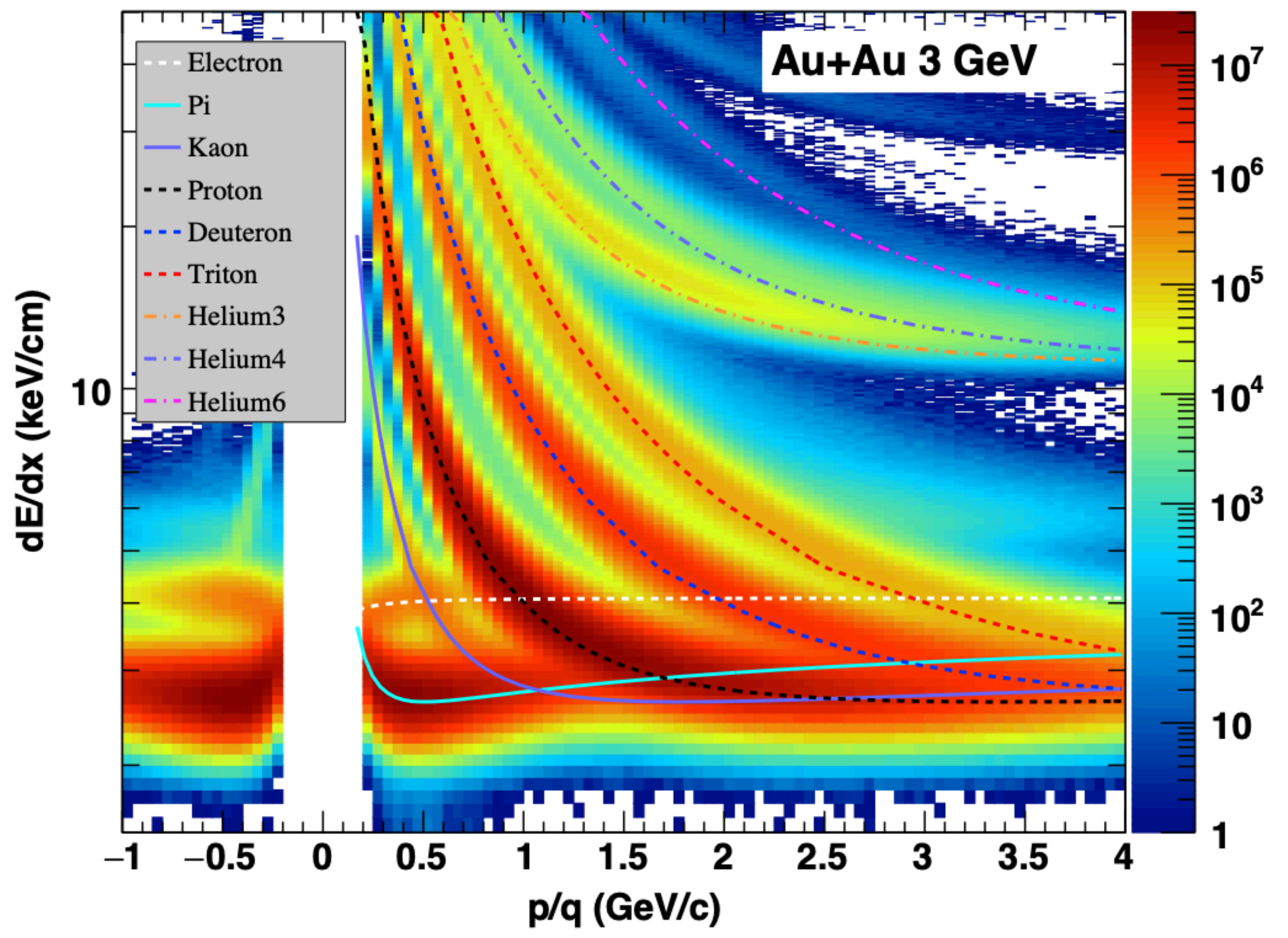
- <u>(a) Contamination from mis-particle-identification</u>
  - TPC energy loss dE/dx is used for particle identification
  - At high momentum, ^{3}He band merges with ^{4}He
    - ${}^{3}_{\Lambda}$H may be mis-identified as ${}^{4}_{\Lambda}$H, and vice versa
  - GEANT simulations used to estimate such contamination (<1%)

e.g.:

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

⋮ mis-PID ↓

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



- <u>(b) Contamination from 3+body decays</u>
  - Hypernuclei 3-body decays may give rise to correlated backgrounds in pair invariant mass distributions
  - GEANT simulations used to estimate the resultant correlated background
    - Situated on the left hand side of the main signal peak
    - <1% effect on lifetime measurements

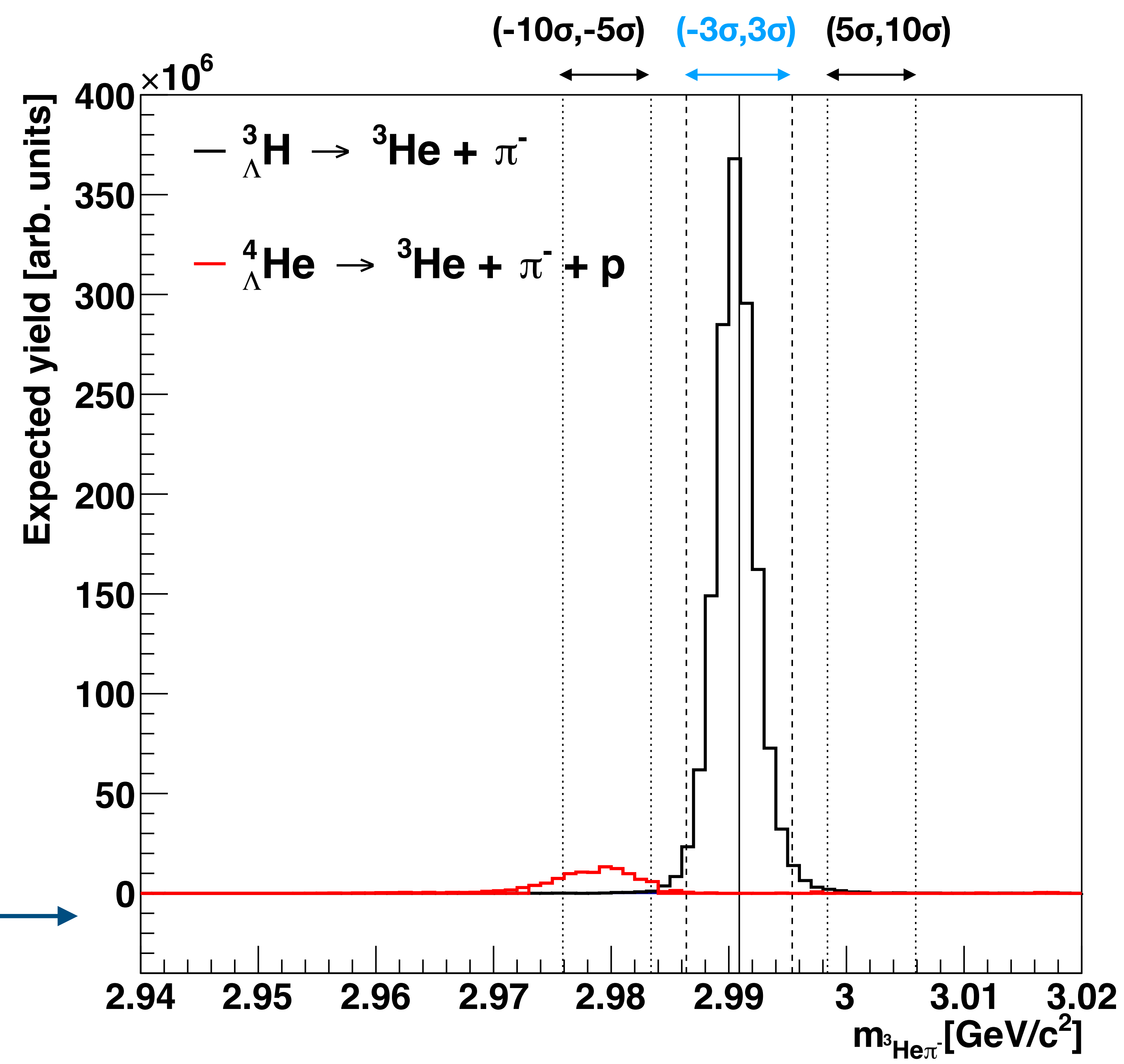
e.g.:

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

⋮ ↓

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

GEANT simulations of correlated backgrounds →



Systematic uncertainties

(1) Analysis cuts

- Imperfect description of topological variables between simulations and real data

(2) Input MC p_T/rapidity

- Imperfect knowledge in the kinematic distributions of the hypernuclei

(3) Single track efficiency

- Mismatch of single track efficiency between simulations and data

(4) Signal extraction

- Uncertainties related to the background subtraction technique

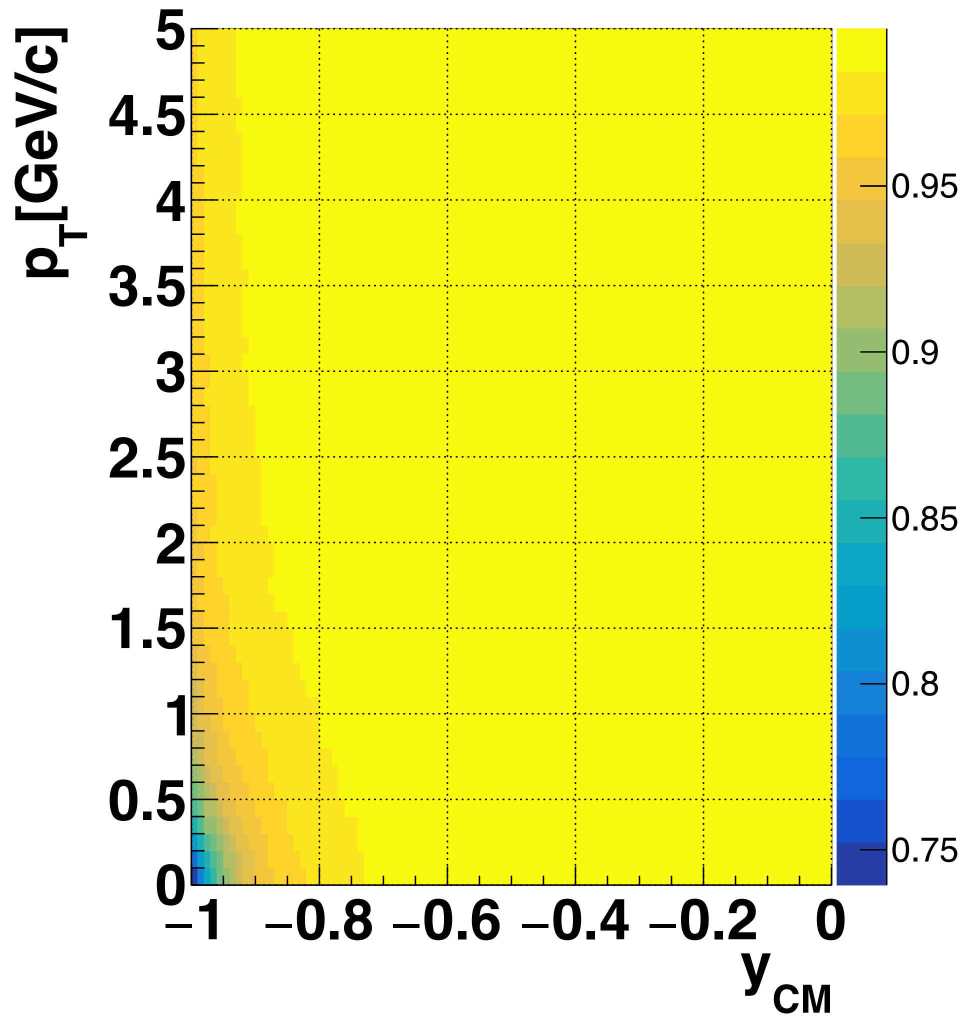
(5) Detector material

- ${}^{3}_{\Lambda}H$ is a loosely bound object (B_{Λ}~O(0.1MeV))
  - Coulomb dissociation as it traverses through material
  - MC study based on analytical dissociation cross section to estimate survival probability

V. L. Lyuboshitz and V. V. Lyuboshitz, Phys. Atom. Nucl. 70, 1617 (2007)

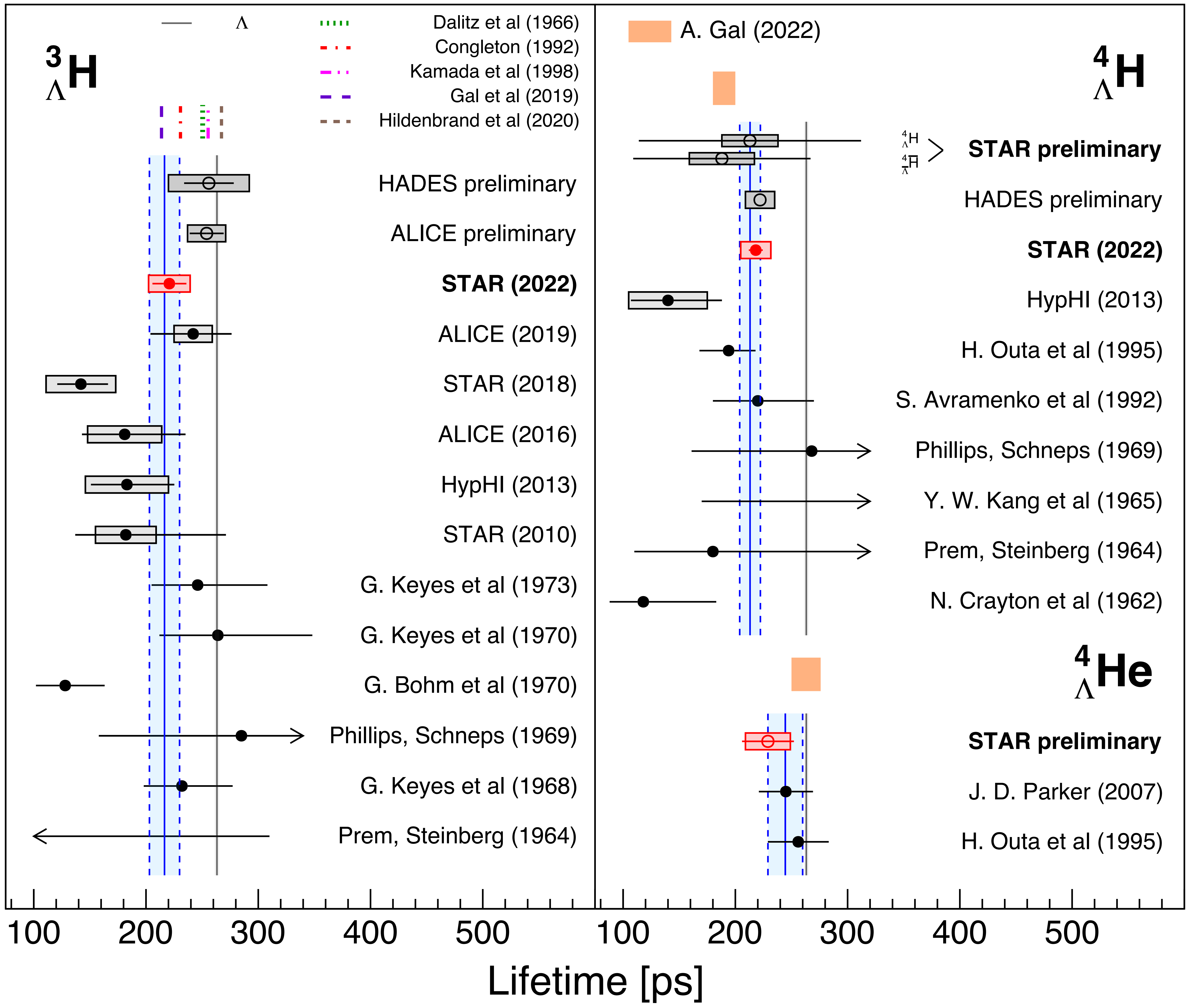
Summary of systematic uncertainties for the lifetime measurements using 3 GeV data

Source	${}^{3}_{\Lambda}H$	${}^{4}_{\Lambda}H$
Analysis cuts	5.5%	5.1%
Input MC	3.1%	1.8%
Tracking efficiency	5.0%	2.4%
Signal extraction	1.5%	0.7%
Detector material	< 1%	< 1%
Total	8.2%	6.0%



Survival prob. for ${}^{3}_{\Lambda}H$ estimated from MC study

A=3 and A=4 hypernuclei lifetimes



New $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H results with improved precision compared to previous measurements

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

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

- Global avg. $= (82 \pm 5)\,\%\,\tau_{\Lambda}$, shorter than τ_{Λ} (3.5σ)
- Consistent with theoretical calculations including pion FSI

A. Gal et al, PLB791(2019)48

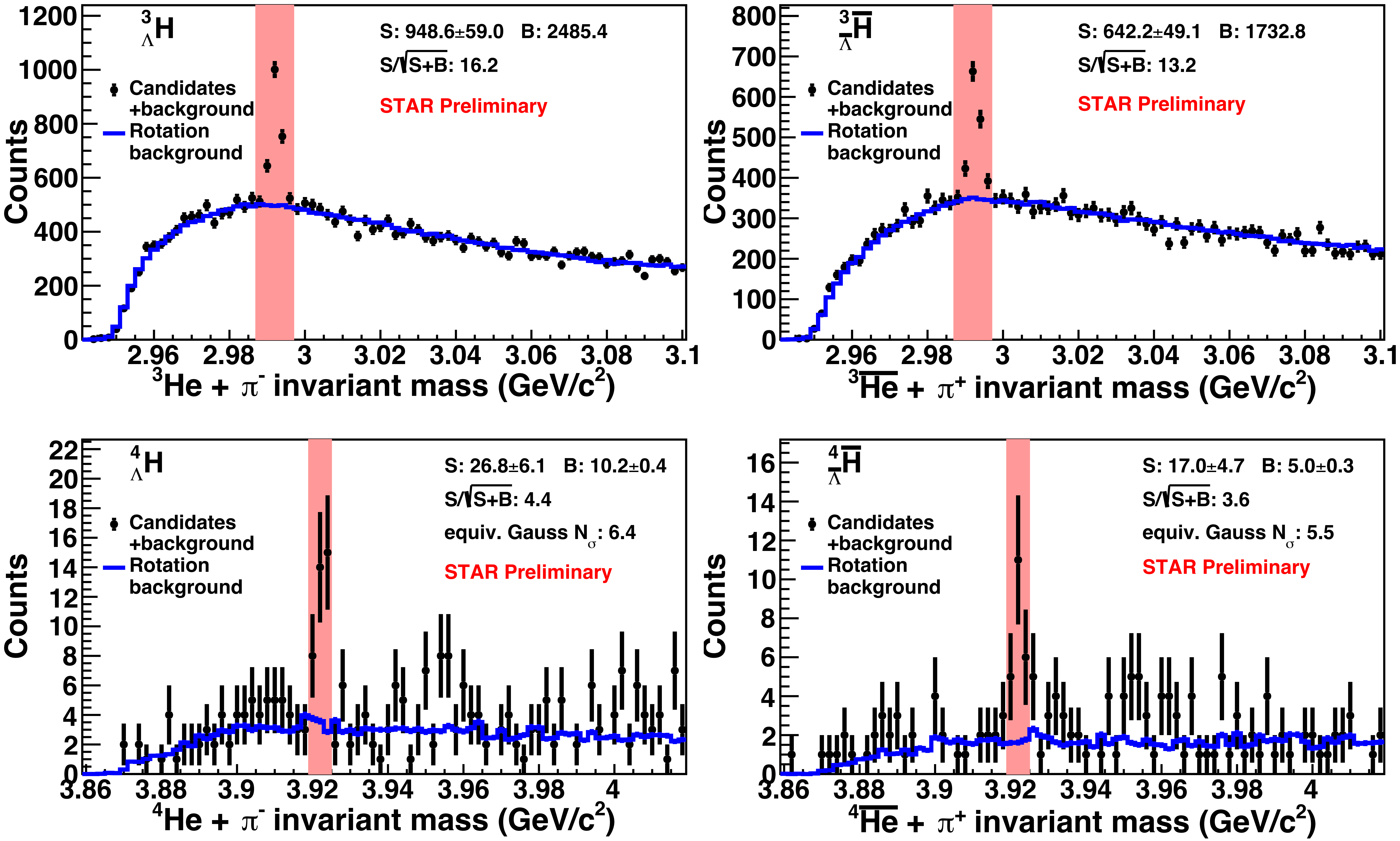
$^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He

- Application of isospin rule* to A=4 hypernuclei suggests lifetime of $^{4}_{\Lambda}$H to be shorter than $^{4}_{\Lambda}$He
- $\dfrac{\tau_{avg}(^{4}_{\Lambda}\mathrm{H})}{\tau_{avg}(^{4}_{\Lambda}\mathrm{He})} = 0.85 \pm 0.07$, consistent with theoretical estimations: 0.74 ± 0.04

A. Gal (2021), arXiv:2108.10179

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

Lifetime measurements of anti-hypernuclei



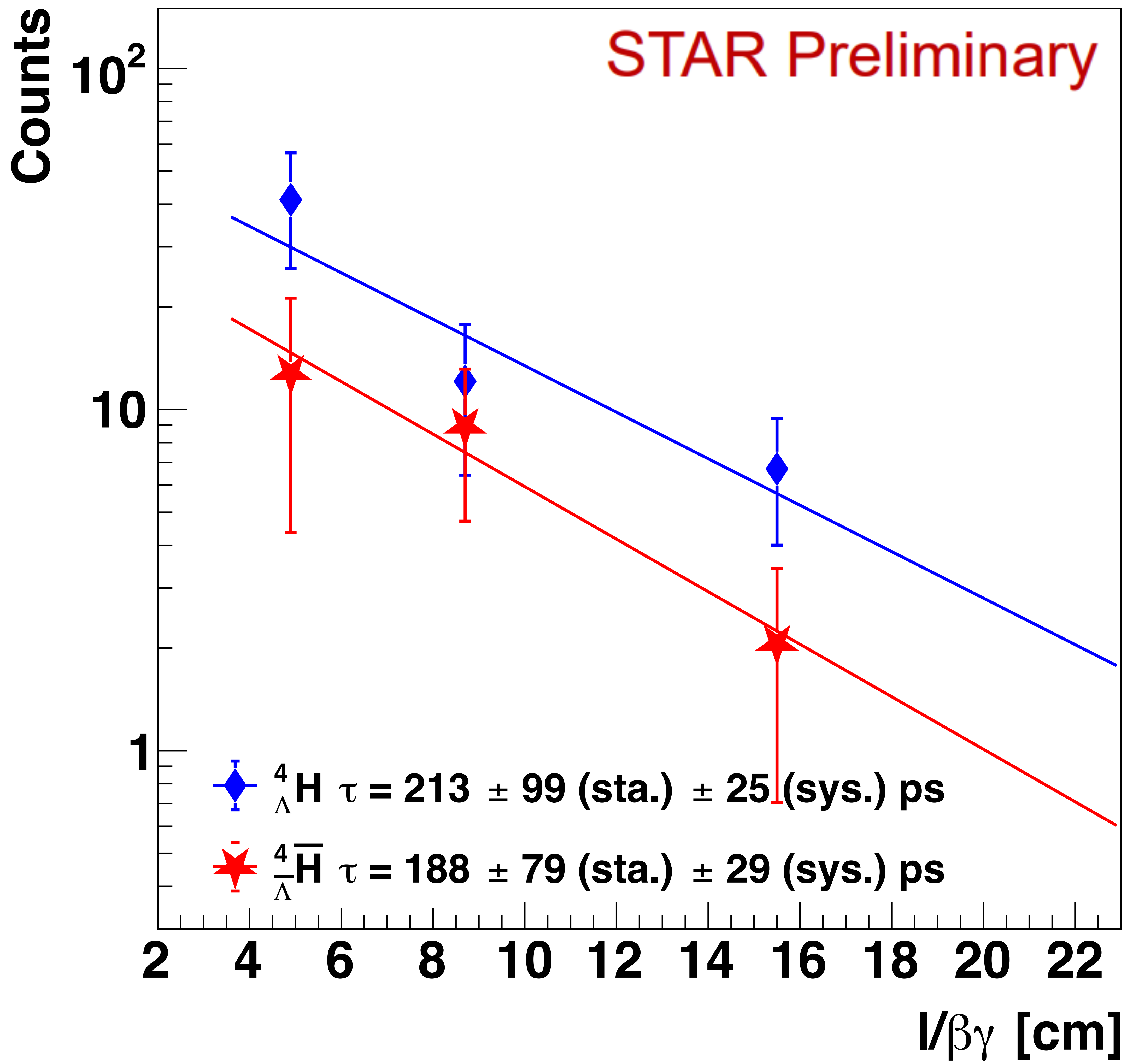
- At higher energies, anti-hypernuclei can be produced and studied

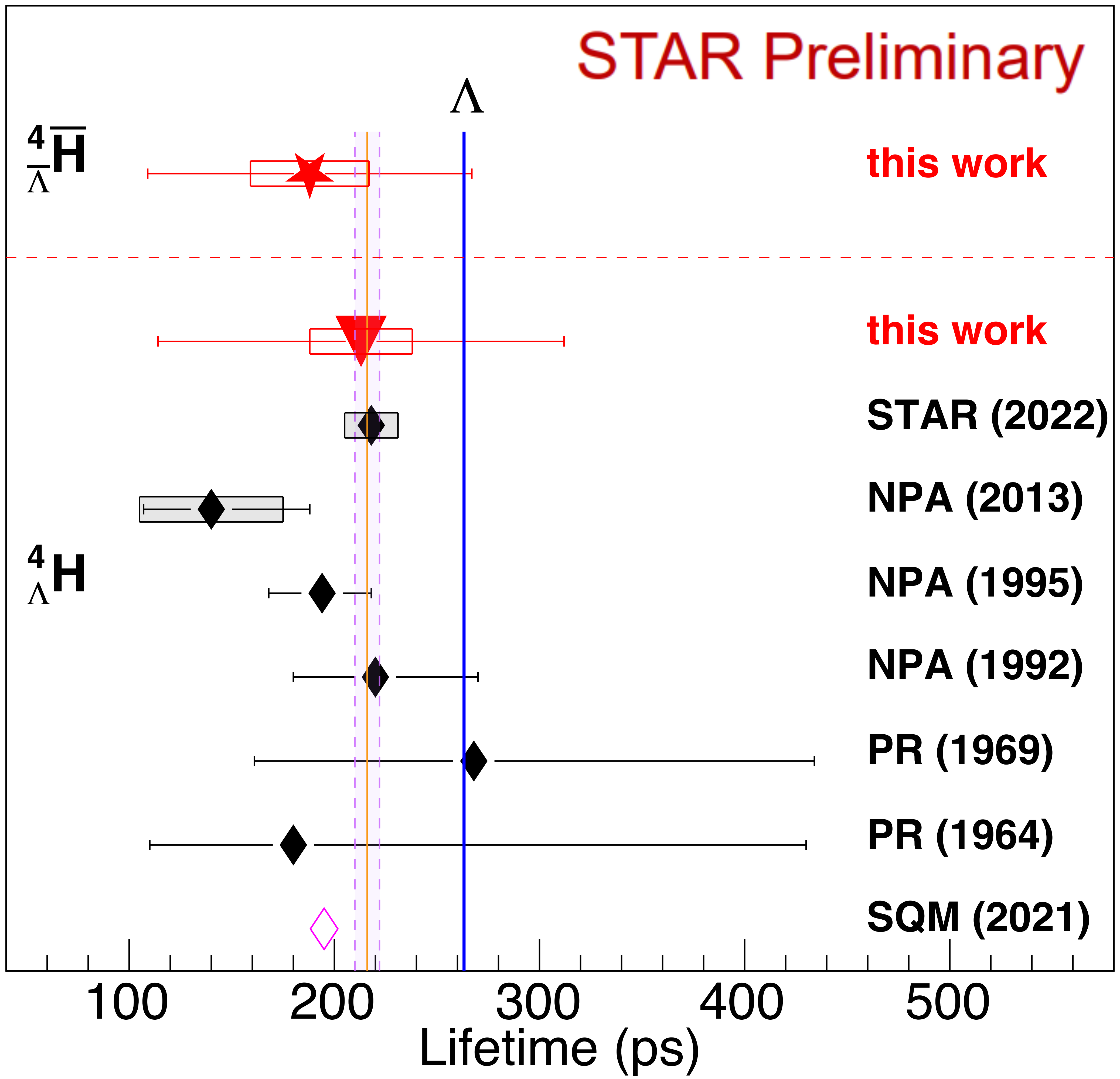
Observation of $^{4}_{\bar{\Lambda}}\bar{H}$ with equivalent Gaussian significance of 5.5 σ

Datasets used:

Collision	Energy	Year	#events
Au+Au	200GeV	2010	660M
Au+Au	200GeV	2011	680M
U+U	193GeV	2012	660M
Zr+Zr, Ru+Ru	200GeV	2018	4.6B

${}^{4}_{\Lambda}H$ and ${}^{4}_{\bar{\Lambda}}\bar{H}$ lifetimes





Lifetime of anti-${}^{4}_{\Lambda}H$ consistent with ${}^{4}_{\Lambda}H$ within uncertainties

Hypertriton relative branching ratio R_3

- Relative branching ratio:

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

- The 2-body and 3-body mesonic decay channels are expected to contribute ~97% of the total decay rate

Kamada et al, Phys. Rev. C 57 (1998) 1595

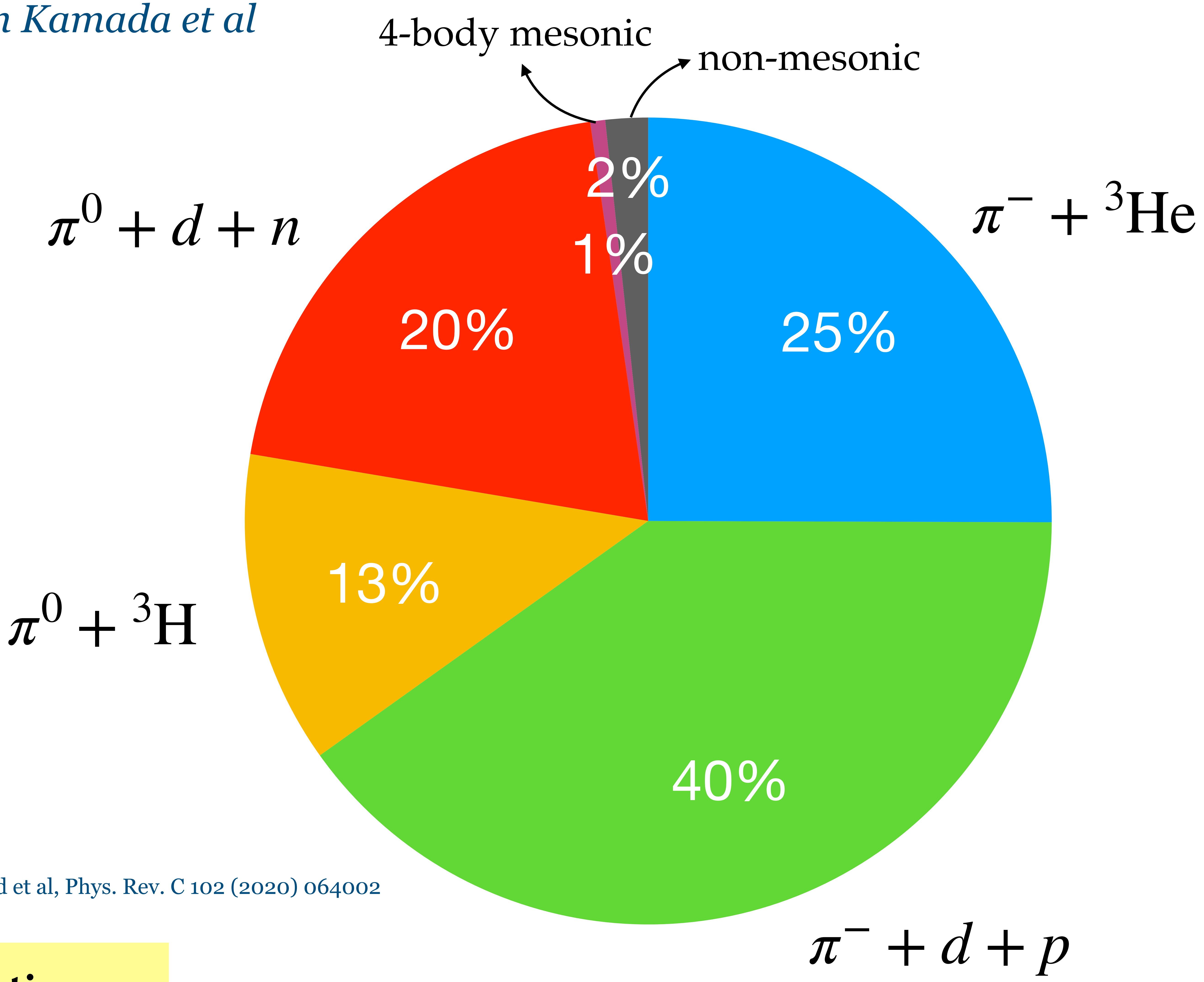
- $\pi^- : \pi^0$ decay rates expected to follow isospin rule (2:1)

- The lifetime can also be estimated by computing the $\pi^- + {}^3He$ decay rate, combined with the experimentally determined R_3 value

Hildenbrand et al, Phys. Rev. C 102 (2020) 064002

R_3: Important input to hypertriton lifetime calculations

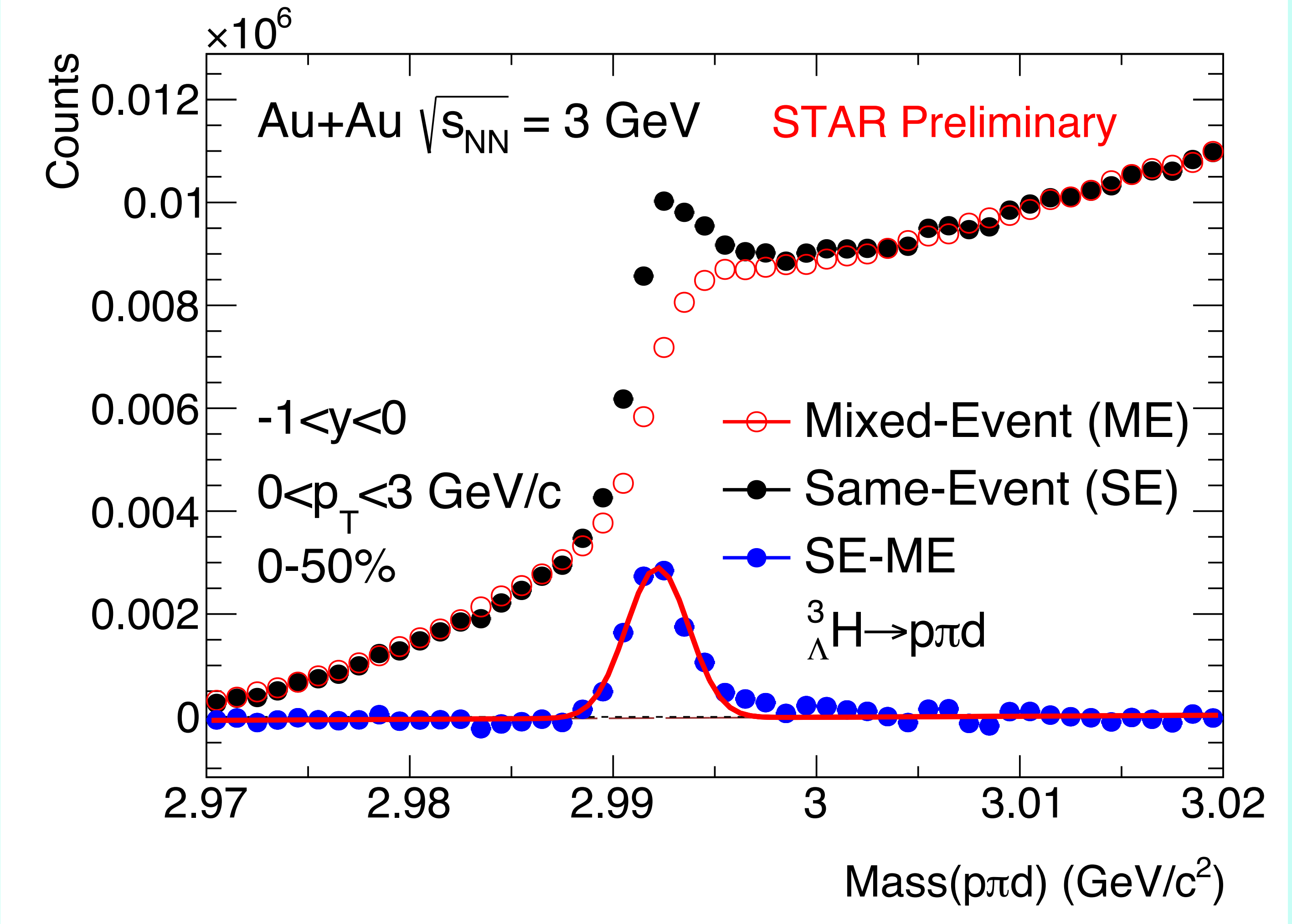
Calculated decay B.R. from Kamada et al



${}^{3}_{\Lambda}H$ reconstruction via 3-body decay

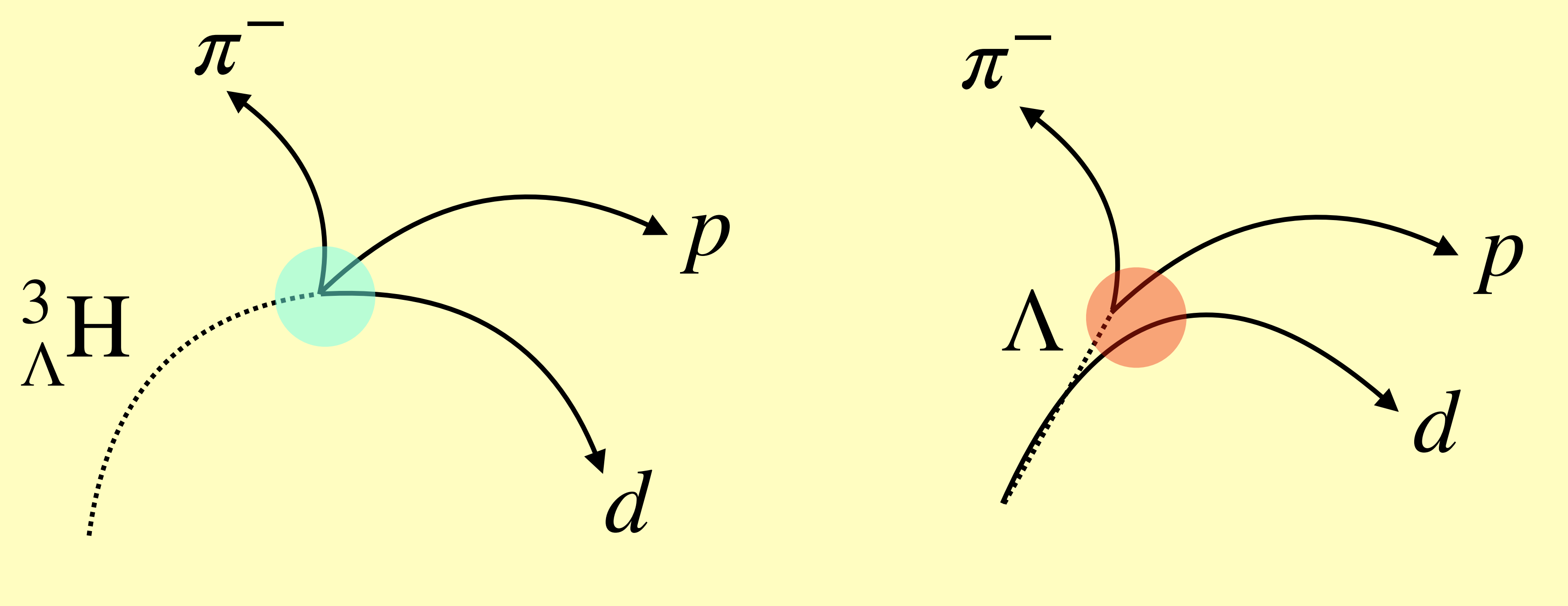
- To obtain corrected yields from hypertriton 3-body decay ${}^{3}_{\Lambda}H \rightarrow d + p + \pi^{-}$:

1. Subtract uncorrelated background, estimated via event-mixing

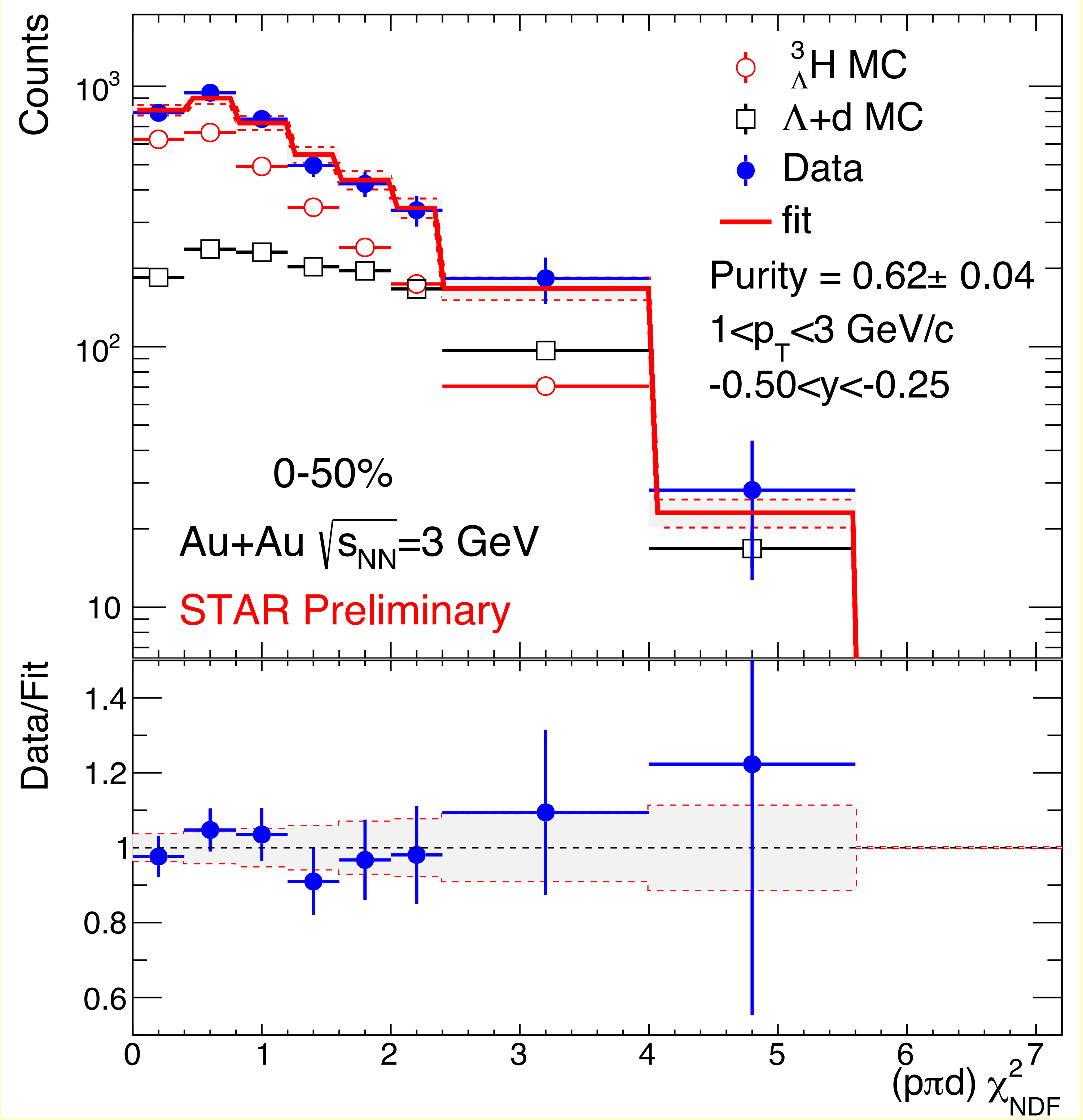


2. Excess around hypertriton peak contains correlated background

- Purity estimated via template fit to χ^2 of secondary vertex fit

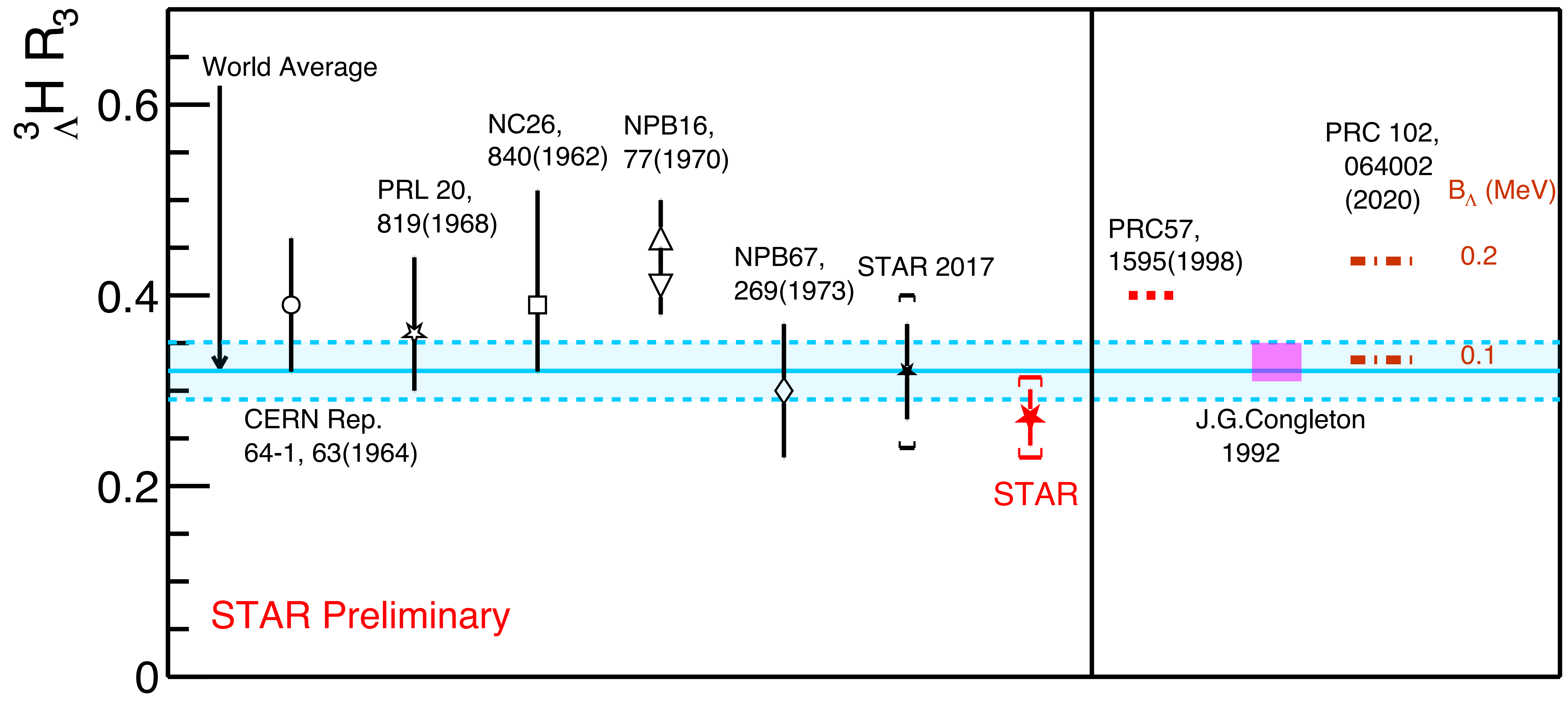


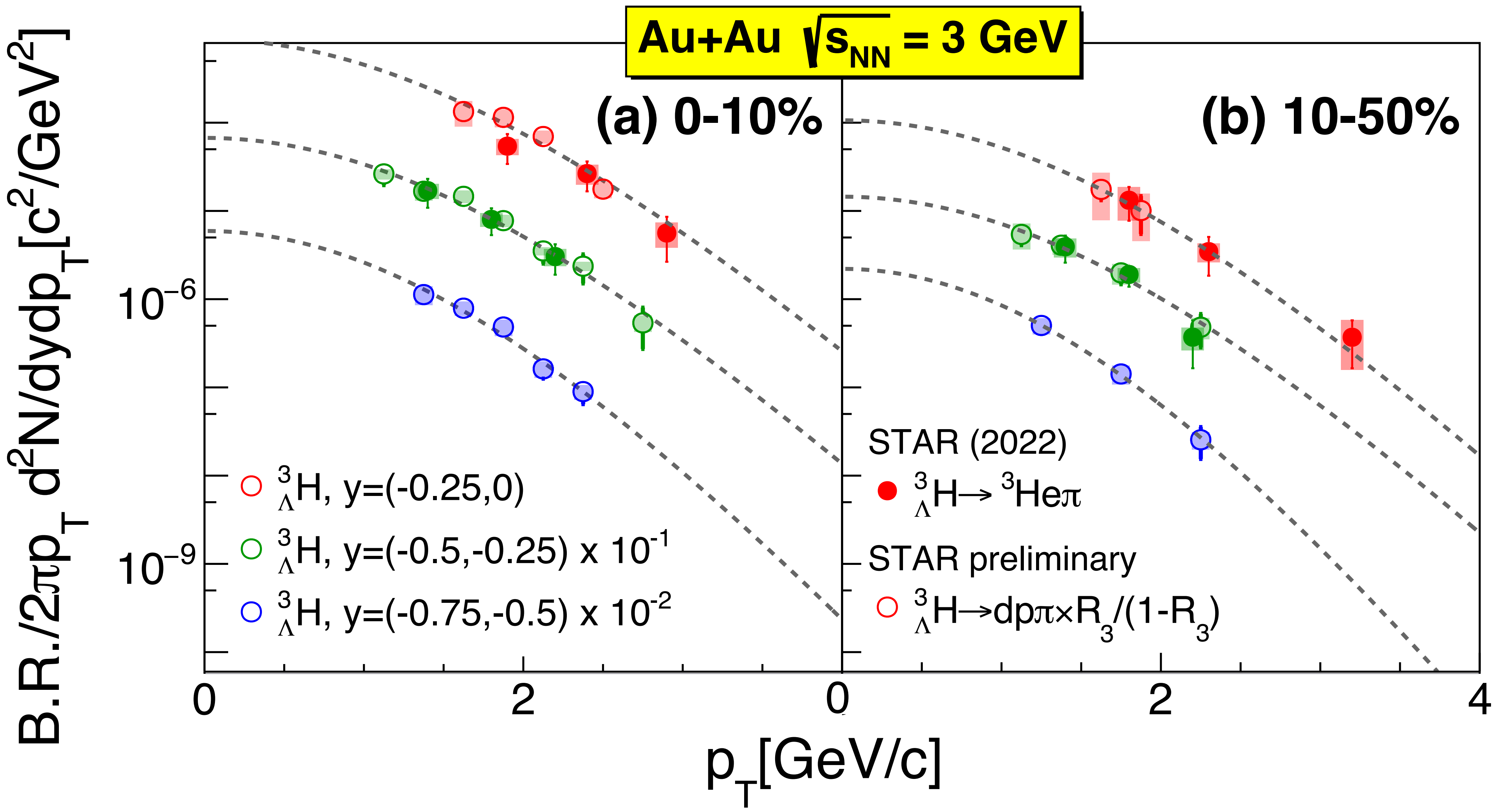
Real signal: lower χ^2 Background: higher χ^2



3. Correct for efficiency of real signal

Relative branching ratio R_3 measurement





- Differential yield from 3-body and 2-body measurements agree with each other

- R_3 measurement is obtained by comparing the efficiency corrected yield from 3-body and 2-body decays

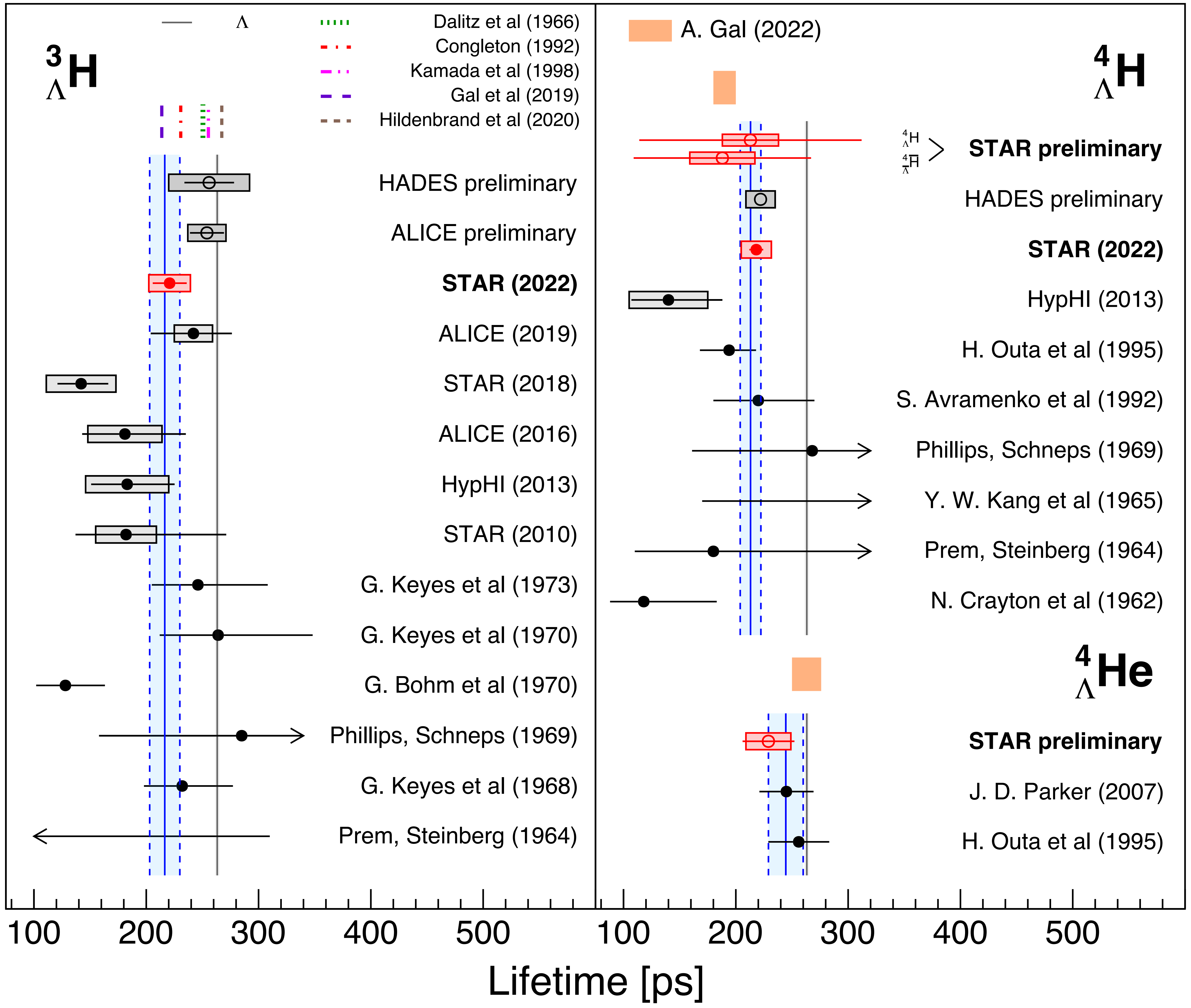
- Improved precision on R_3

  → Stronger constraints on hypernuclear interaction models used to describe $^3_\Lambda H$

  → Improve our understanding of hypertriton lifetime and binding energy

Summary

- **New ${}^{3}_{\Lambda}\mathrm{H}, {}^{4}_{\Lambda}\mathrm{H}, {}^{4}_{\Lambda}\mathrm{He}$ lifetime measurements from STAR BES-II data**
  - Improved precision on ${}^{3}_{\Lambda}\mathrm{H}, {}^{4}_{\Lambda}\mathrm{H}$ lifetimes compared to previous measurements
  - Average ${}^{3}_{\Lambda}\mathrm{H}$ lifetime = $(82 \pm 5)\,\%\,\tau_{\Lambda}$, consistent with theoretical calculations including pion FSI



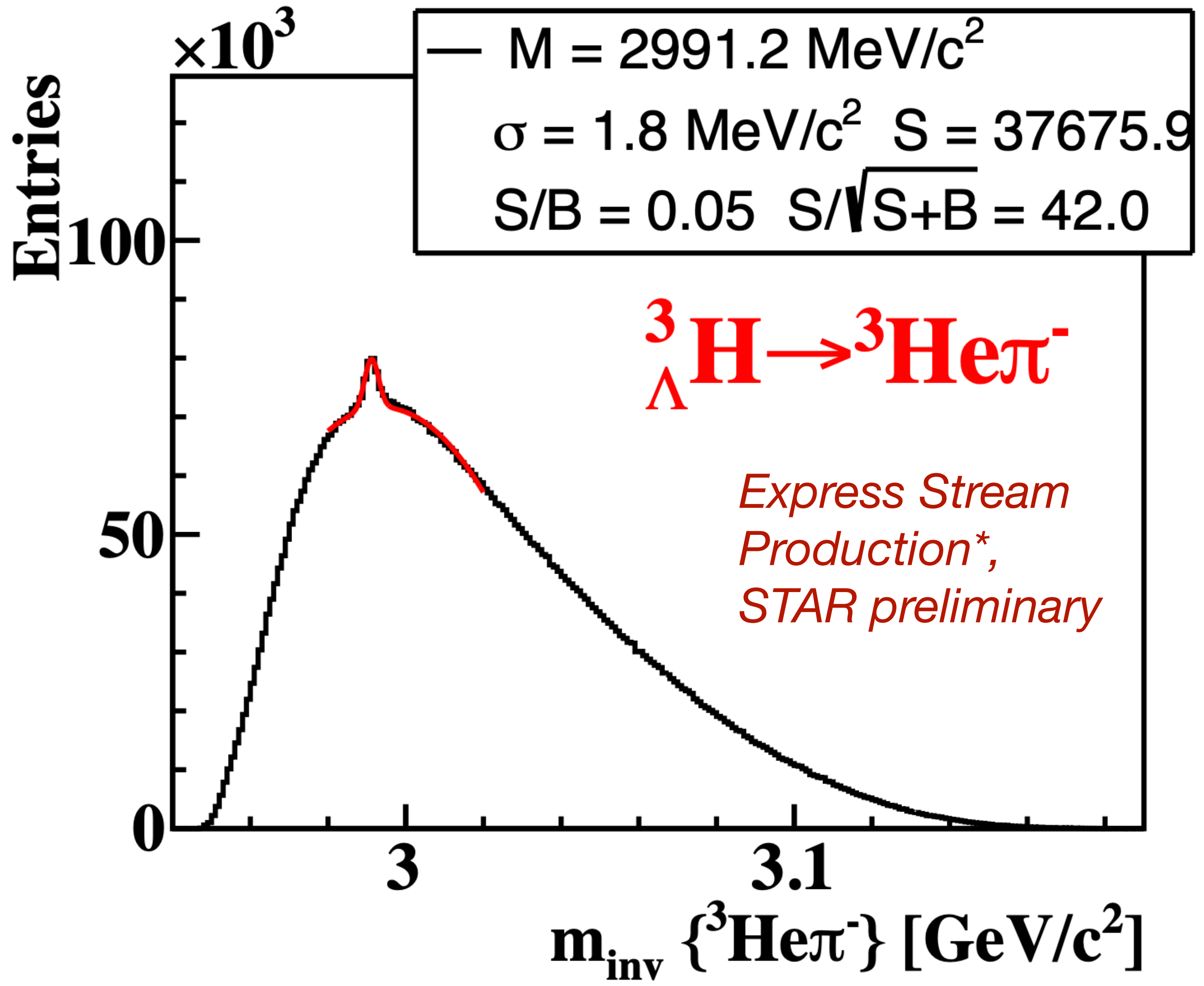
- **New measurements of anti-hypernuclei from STAR 200 GeV data**
  - First observation of anti-${}^{4}_{\Lambda}\mathrm{H}$
  - First extraction of anti-${}^{4}_{\Lambda}\mathrm{H}$ lifetime, consistent with ${}^{4}_{\Lambda}\mathrm{H}$

- **New R_3 measurement from STAR BES-II data**
  - New method to extract 3-body yields via template fitting
  - Important input to ${}^{3}_{\Lambda}\mathrm{H}$ lifetime calculations

Future lifetime studies from STAR

✤**More precise measurements of the hypertriton and anti-hypertriton**

- ~42σ $^{3}_{\Lambda}$H signal observed using BES-II data
- ~13σ $^{3}_{\bar{\Lambda}}\bar{\text{H}}$ signal observed using $\sqrt{s_{NN}}$ = 200 GeV data
- Entering the precision era

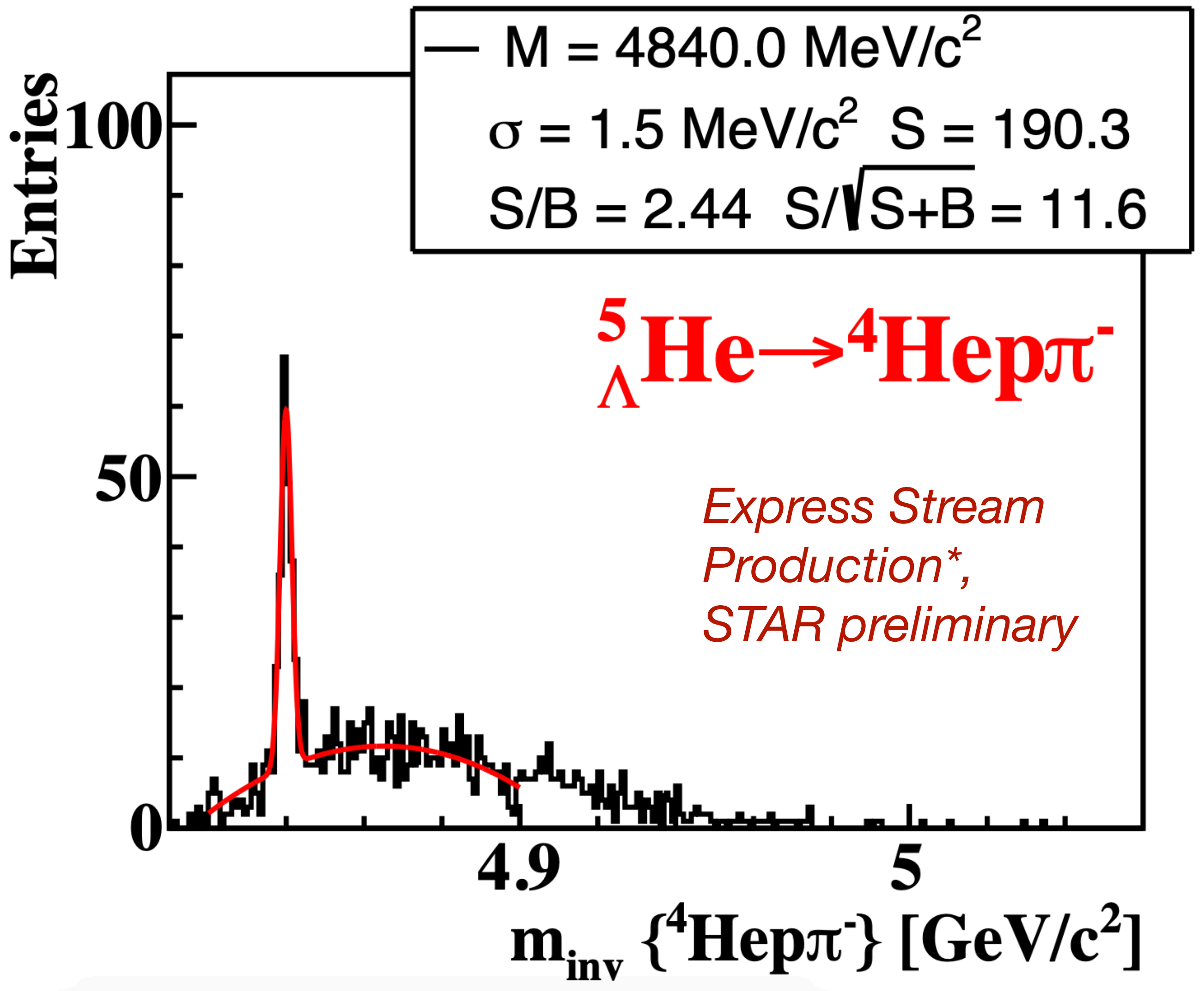


*Data from express stream (Au+Au $\sqrt{s_{NN}}$=3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.7 GeV) are not with the final calibrations

✤**Studies on heavier hypernuclei**

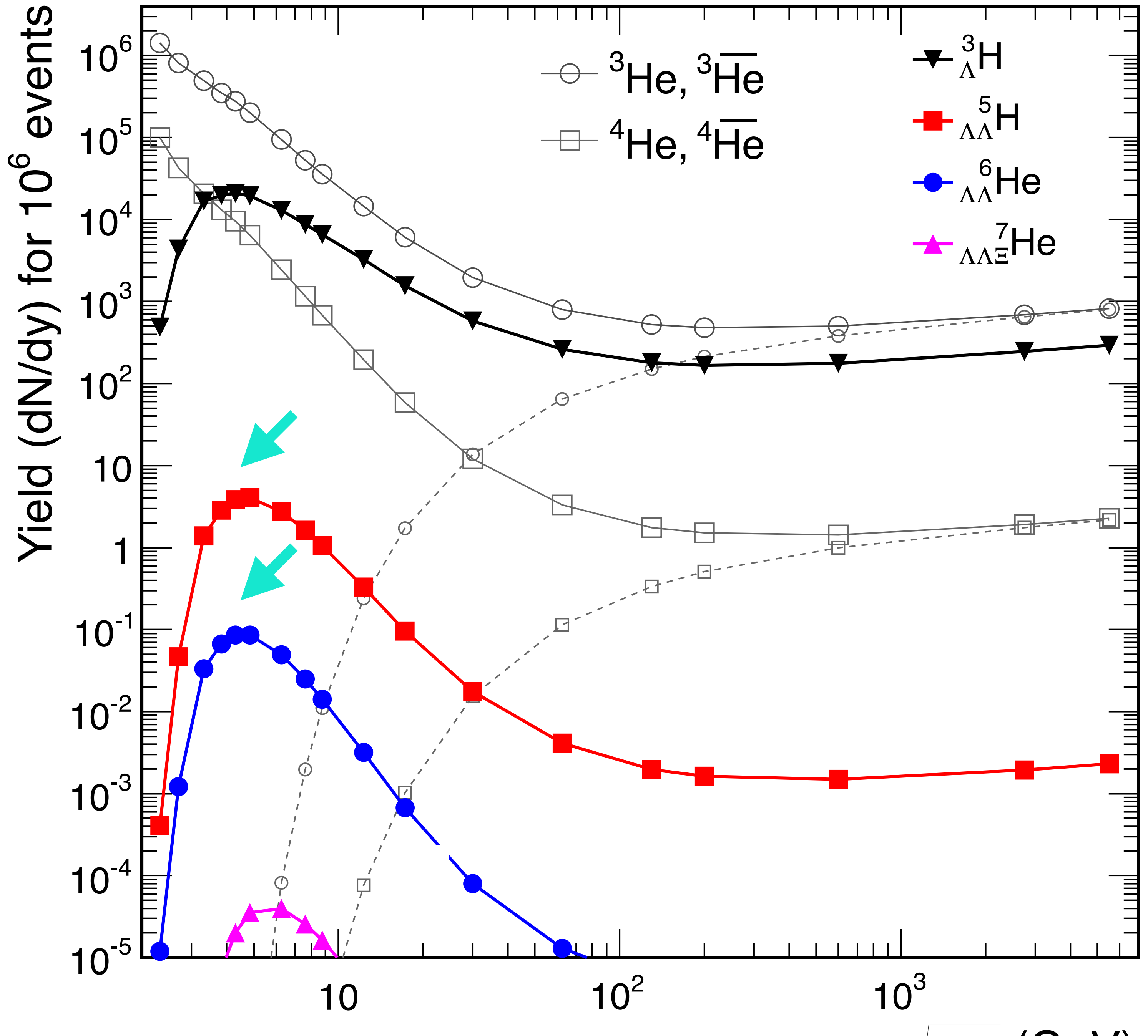
- >20σ $^{4}_{\Lambda}$He , >10σ $^{5}_{\Lambda}$He signal observed using BES-II data

See talk by Ivan Kisel



✤**Search for double-Λ hypernuclei?**

- Modest production rate at $\sqrt{s_{NN}}$ ~ 3-8 GeV according to thermal model
  - STAR BES-II brings possibility of discovery



Phys. Lett. B 697 (2011)203

- Backup slides follow

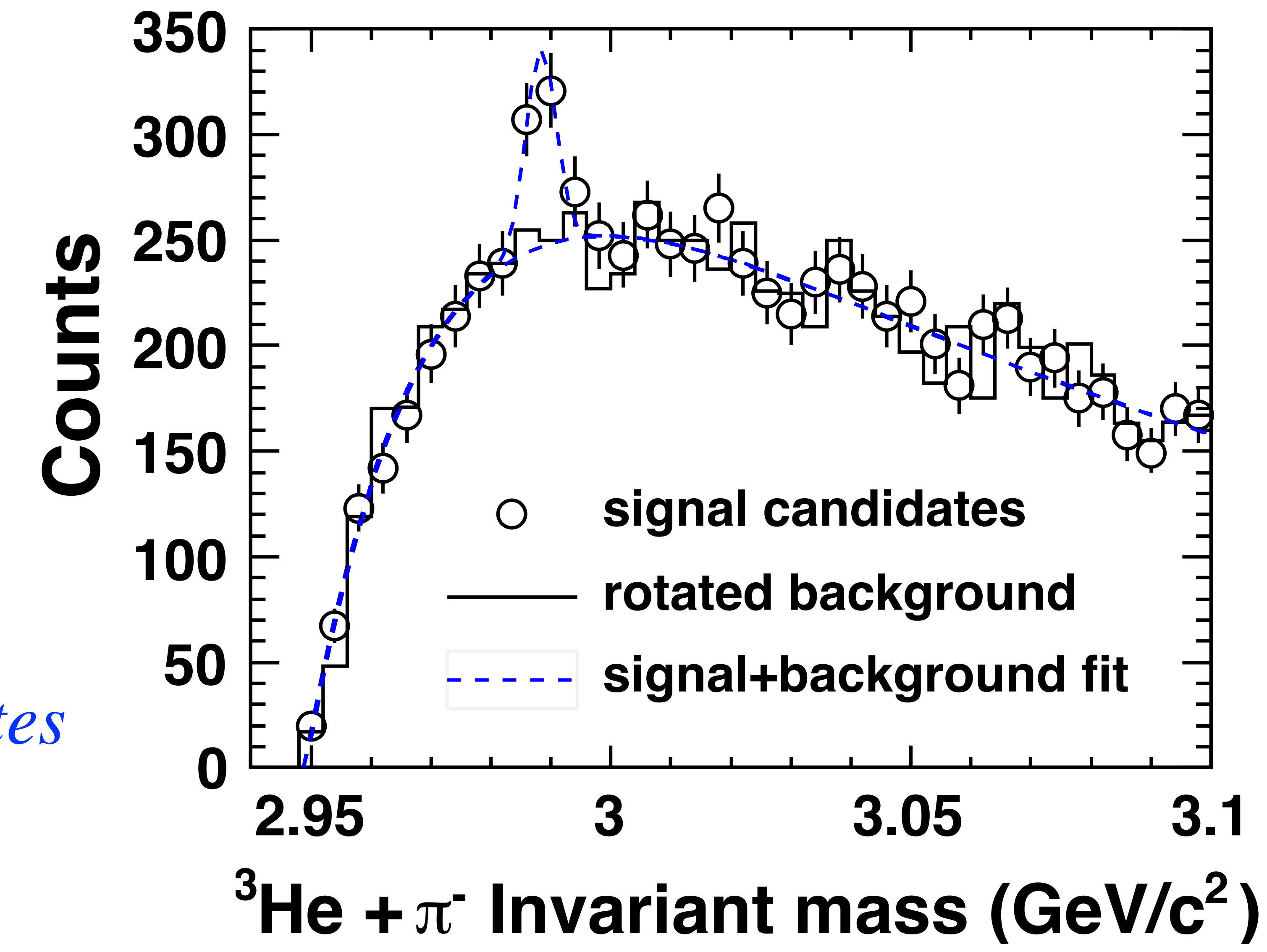
Past studies of hypernuclei lifetime at STAR

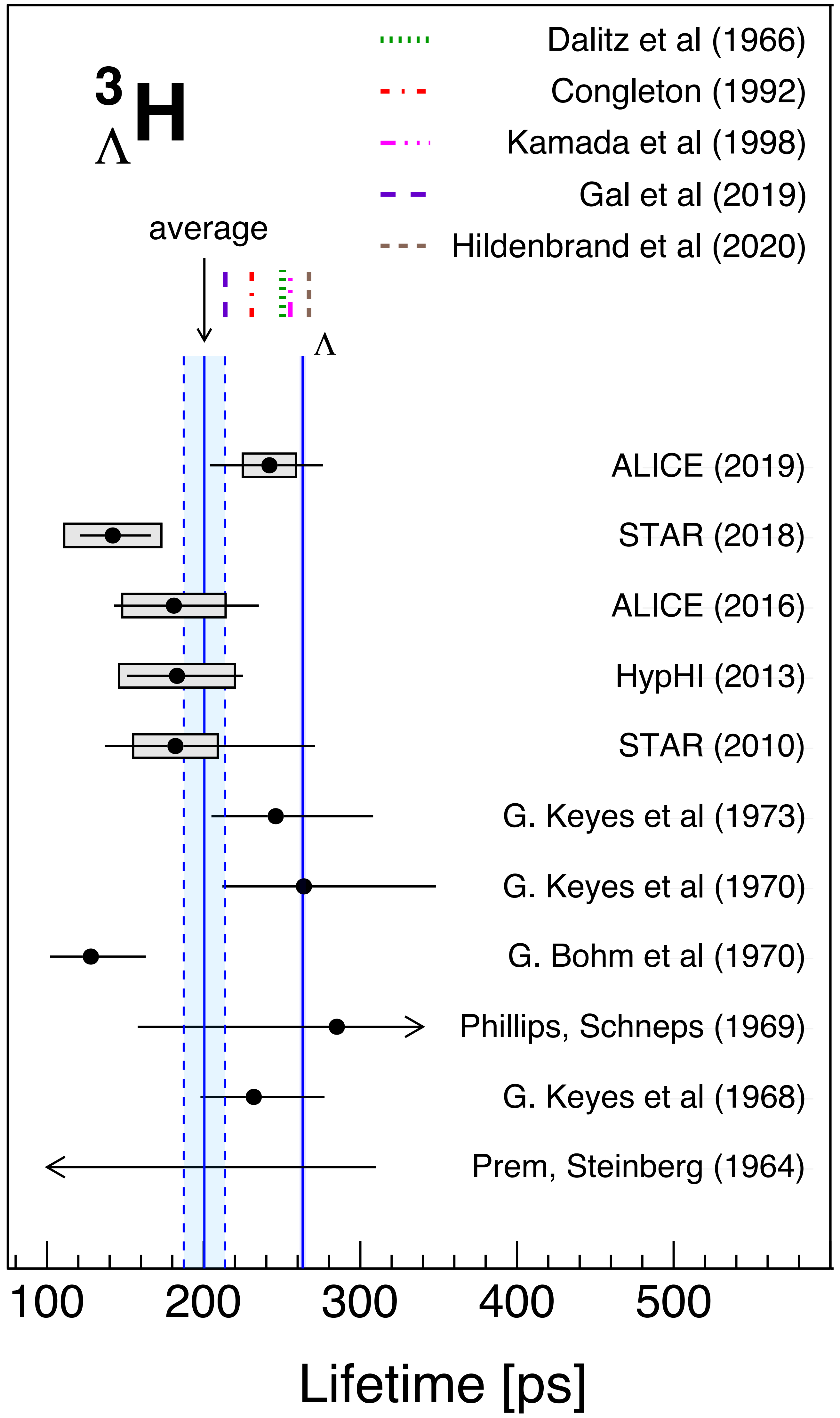
- In 2010, STAR observed the anti-hypertriton
    - First measurement of hypertriton lifetime from heavy ion collisions

Science 328 (2010) 58

$$\tau({}^{3}_{\Lambda}\mathrm{H}) = 182 \pm^{89}_{45} (stat.) + 27(syst.)$$

$227 \pm 34 \ \ ({}^{3}_{\Lambda}\mathrm{H} + {}^{3}_{\bar{\Lambda}}\bar{\mathrm{H}}) \ candidates$





- In 2019, STAR published hypertriton lifetime, obtained using Beam Energy Scan I data

Phys. Rev. C 97 (2018) 54909

$$\tau({}^{3}_{\Lambda}\mathrm{H}) = 142 \pm^{24}_{21} (stat.) + 31(syst.)$$

$354 \pm 43 \ \ ({}^{3}_{\Lambda}\mathrm{H} + {}^{3}_{\bar{\Lambda}}\bar{\mathrm{H}}) \ candidates$