Latest Results on *Lifetimes and Binding Energies of A=3, 4 Hypernuclei* from STAR

The 9th International Conference on Quarks and Nuclear Physics (QNP2022)

Online
Sep 5 – 9, 2022

- Introduction
- Hypernuclei Lifetimes
- Hypernuclei Binding Energies
- Hypernuclei Branching Ratios
- Summary and Outlook

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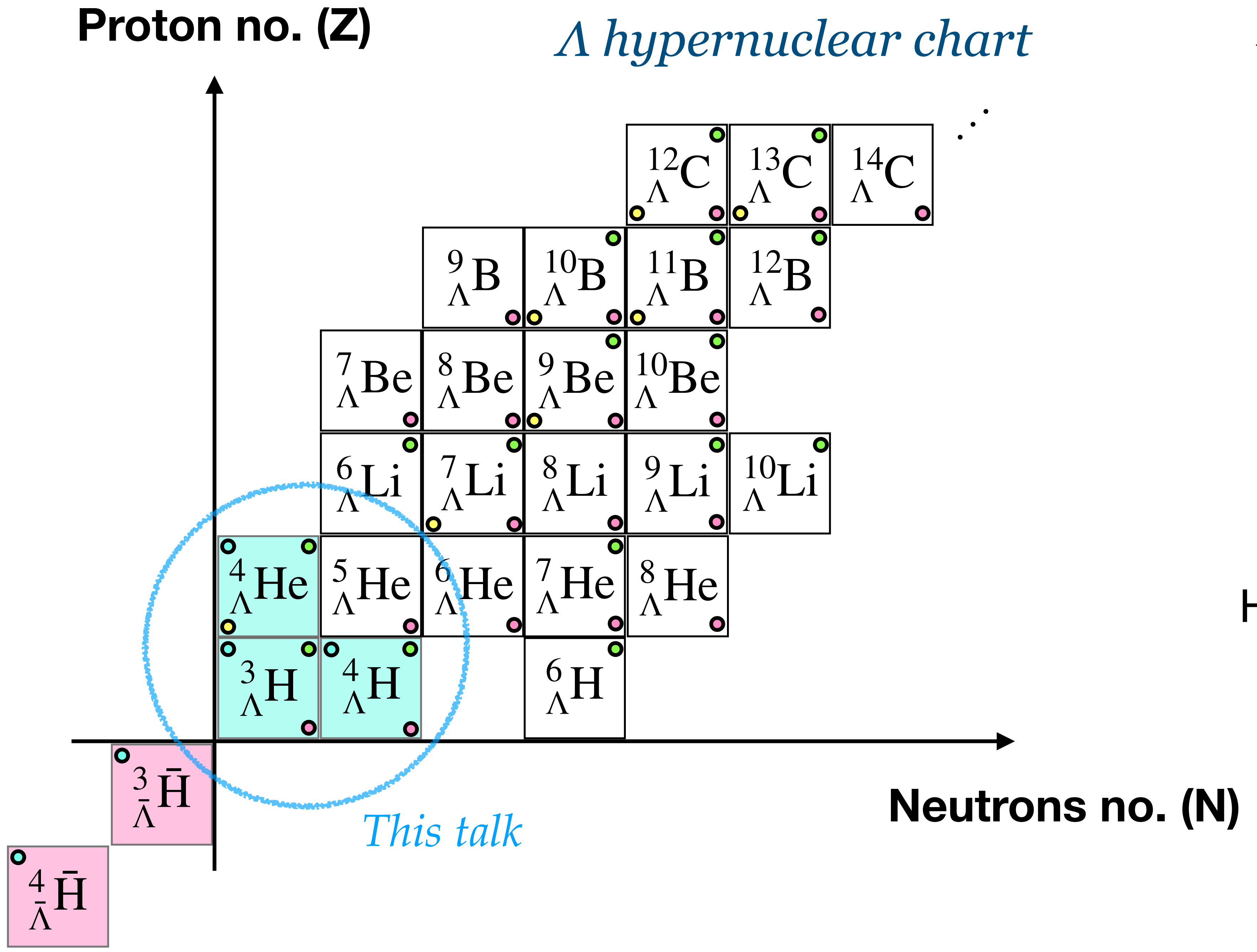
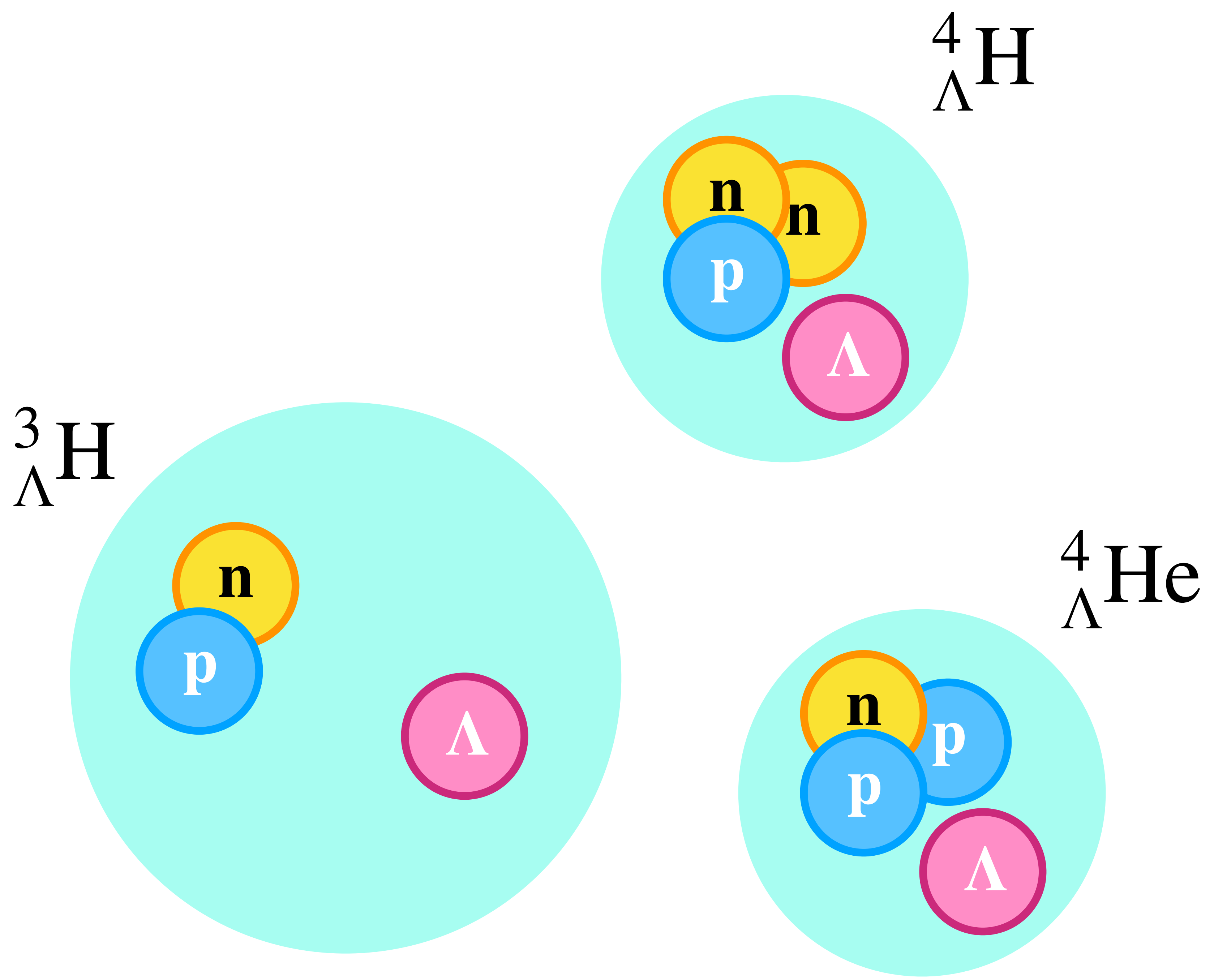
STAR

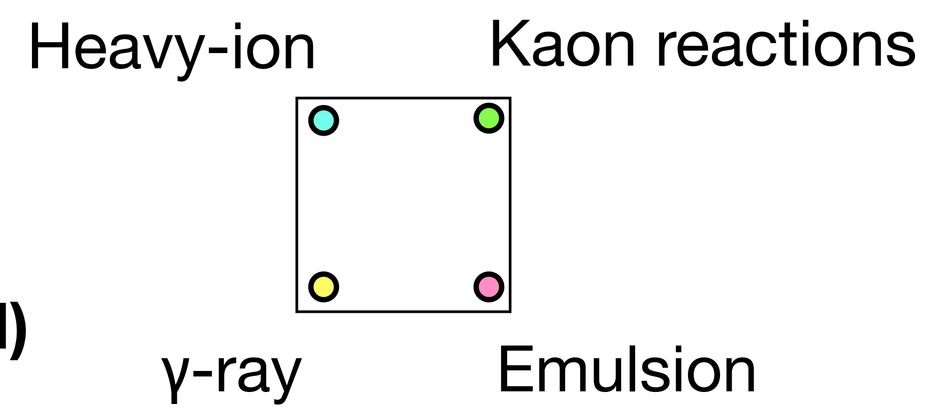
Introduction

- **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 hypernuclei** and their **anti-particles** may be produced in copious amounts in HIC

→ Potential for high precision measurements







Measurements on hypernuclei lifetimes, binding energies, and branching ratios can provide constraints on the Y-N interaction

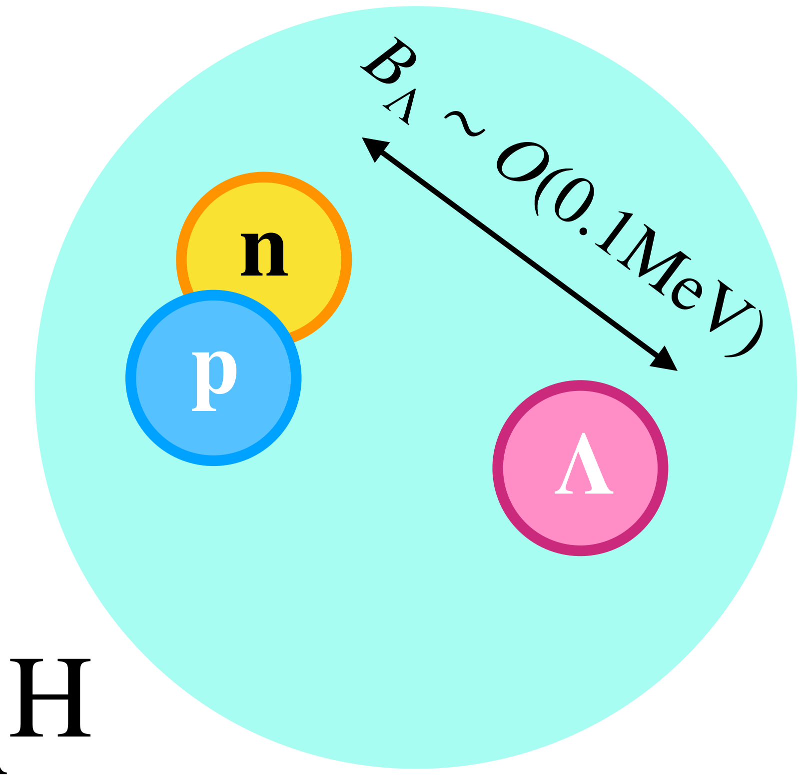
Hypertriton lifetime "puzzle"

- World average of measured $\tau({}^3_\Lambda H)$ is shorter compared to $\tau(\Lambda)$ by $\sim(30 \pm 10)$ %
- Tension between recent measurements, albeit with large uncertainties
  - 1.7σ difference between STAR(2018) and ALICE(2019) measurements

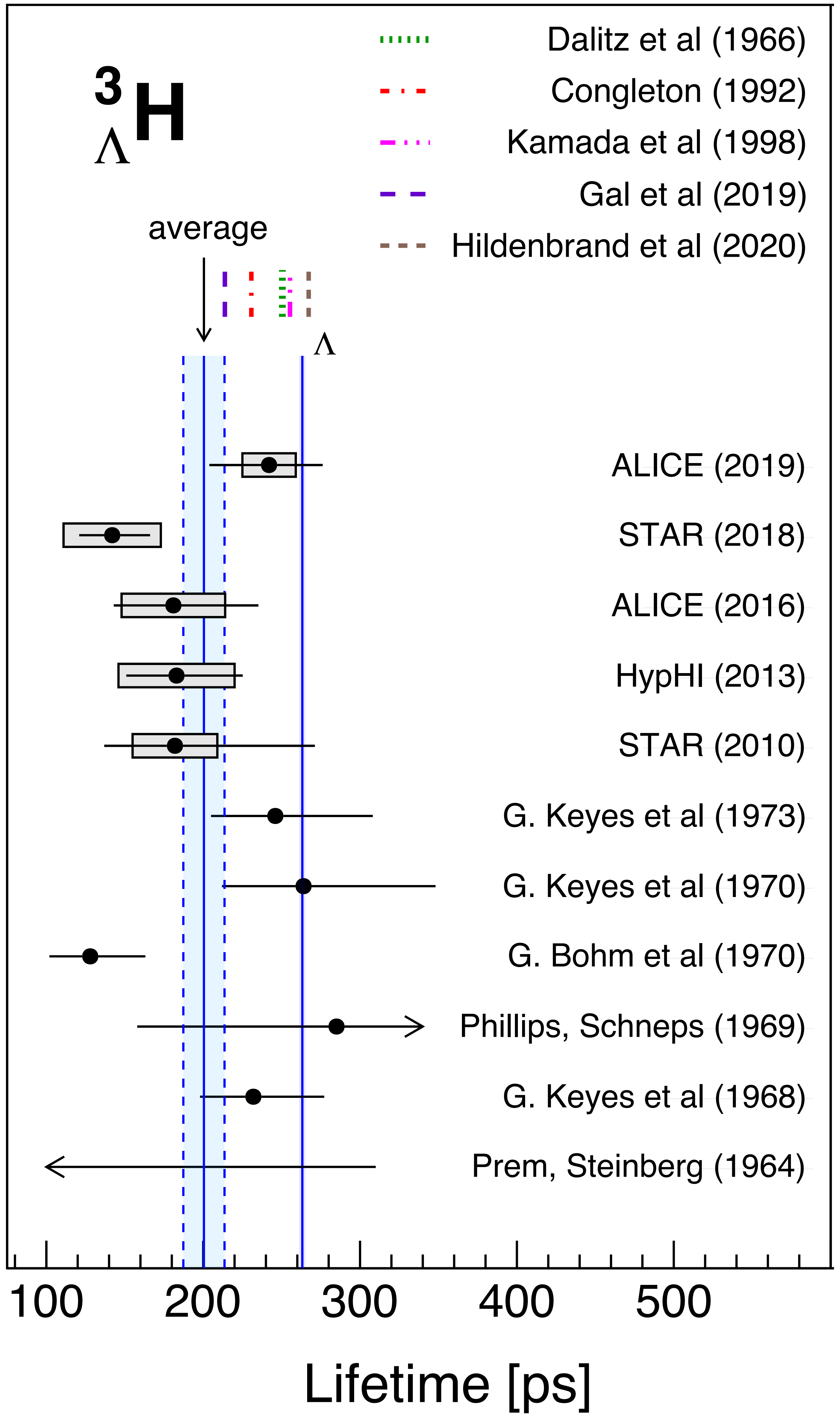
ALICE, Phys.Lett. B 797(2019)134905
STAR, Phys. Rev. C 97(2018)54909

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

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



${}^3_\Lambda H$



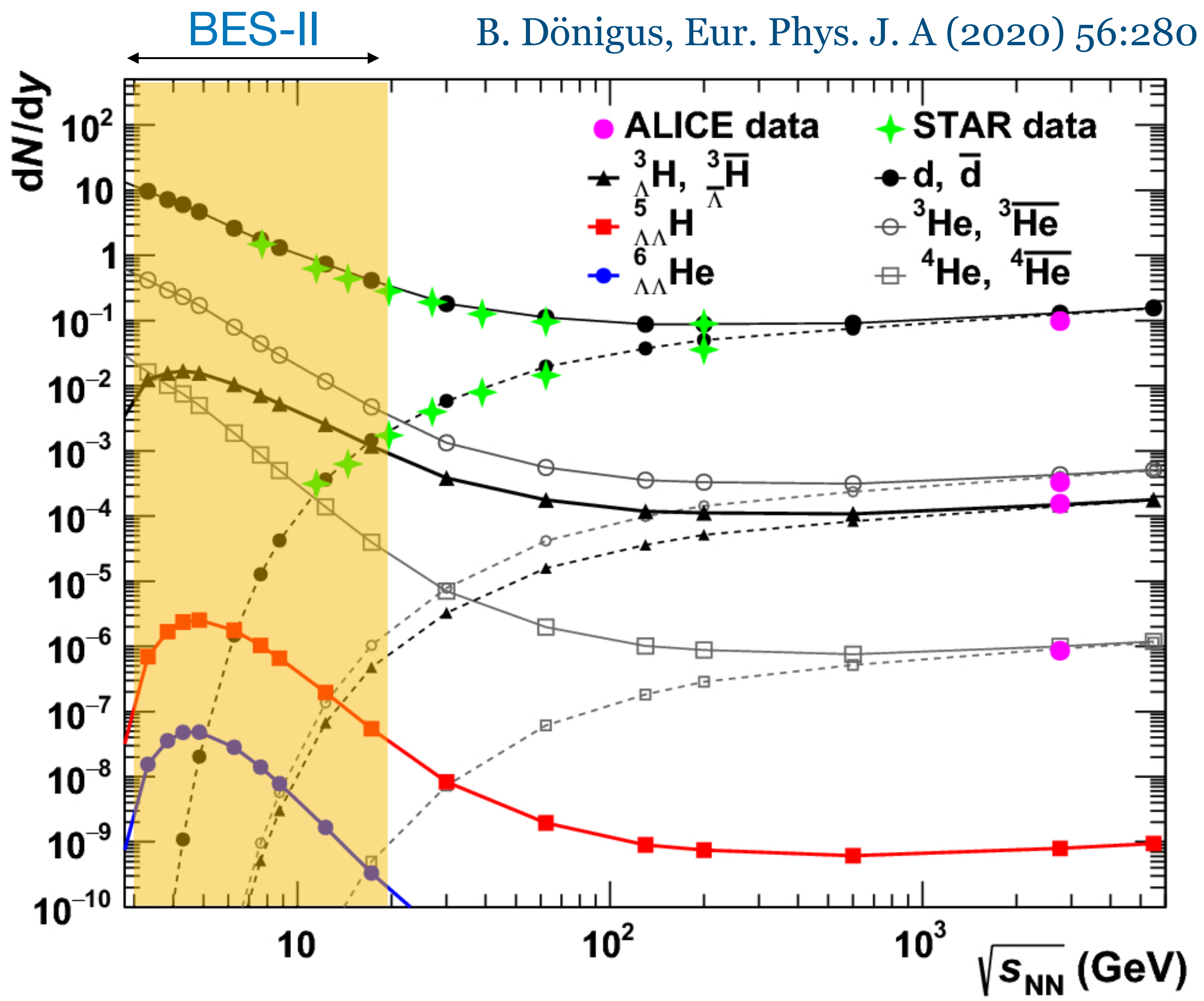
STAR Beam Energy Scan II

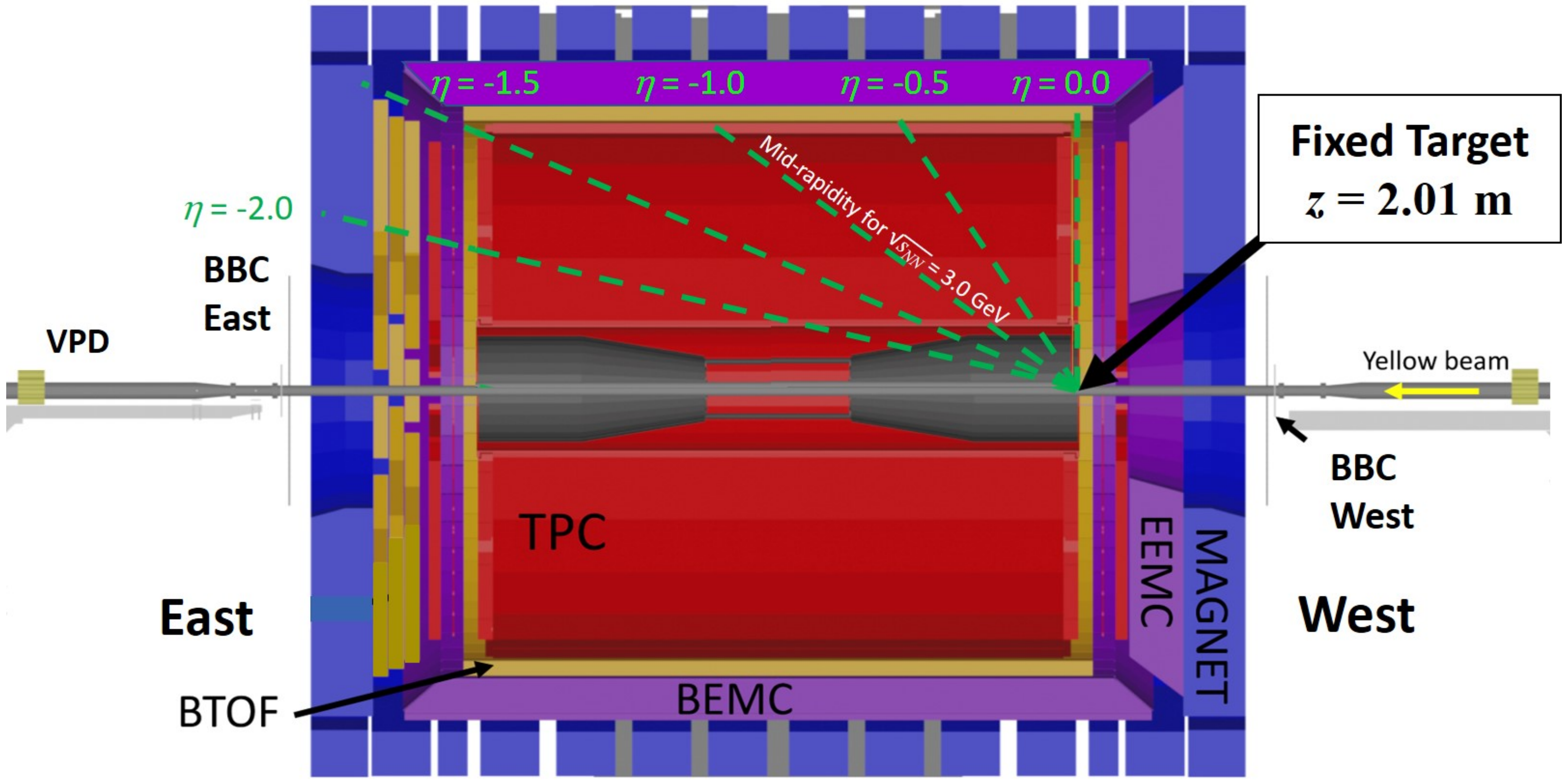
- Hypernuclei measurements are scarce in heavy-ion experiments
- As the beam energy decreases, hypernuclei yields are expected to **increase significantly due to the increased baryon density**

A. Andronic et al, PLB 697 (2011)203

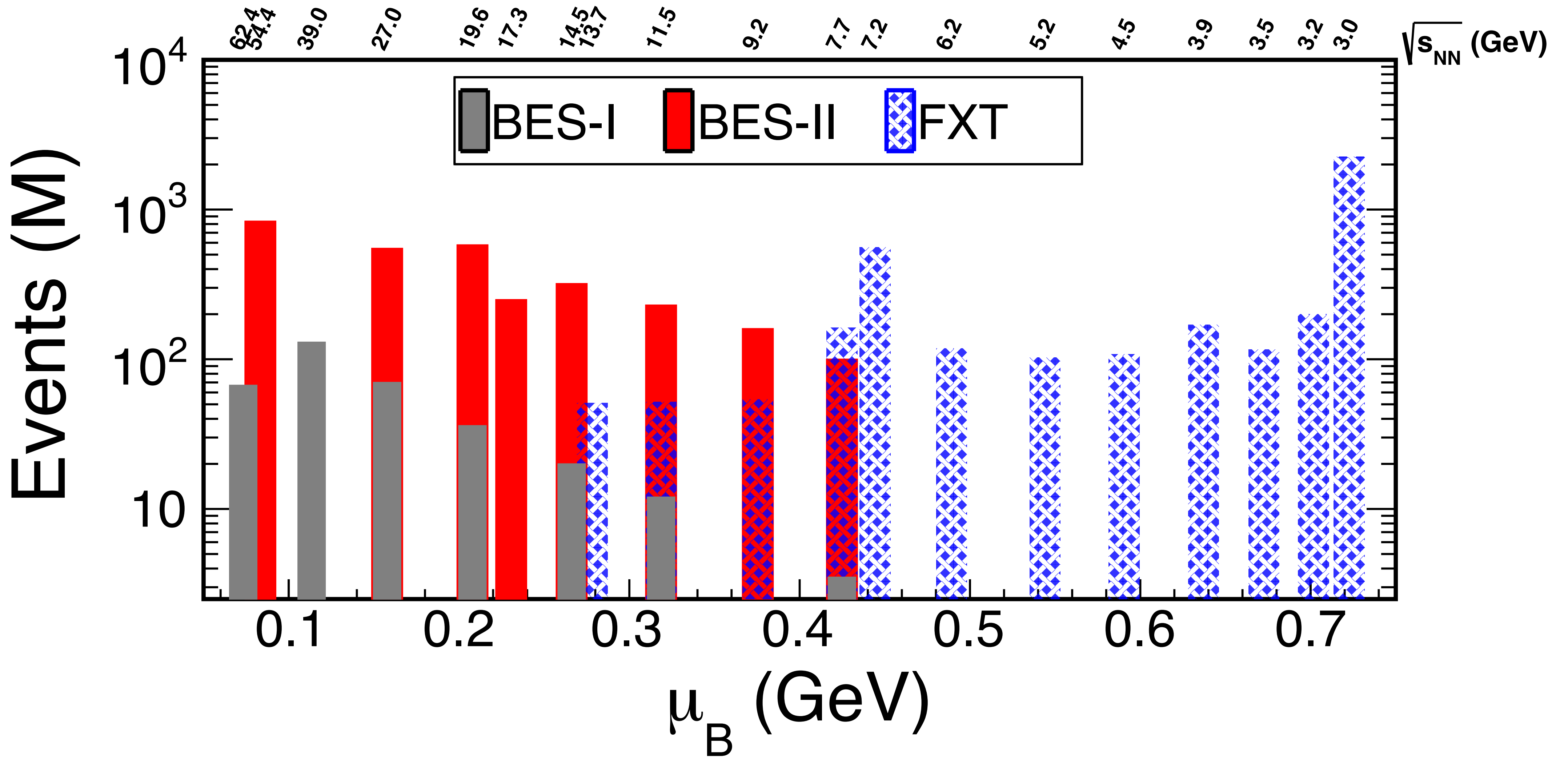
  - STAR BES-II -> great opportunity to study hypernuclei production

B. Dönigus, Eur. Phys. J. A (2020) 56:280

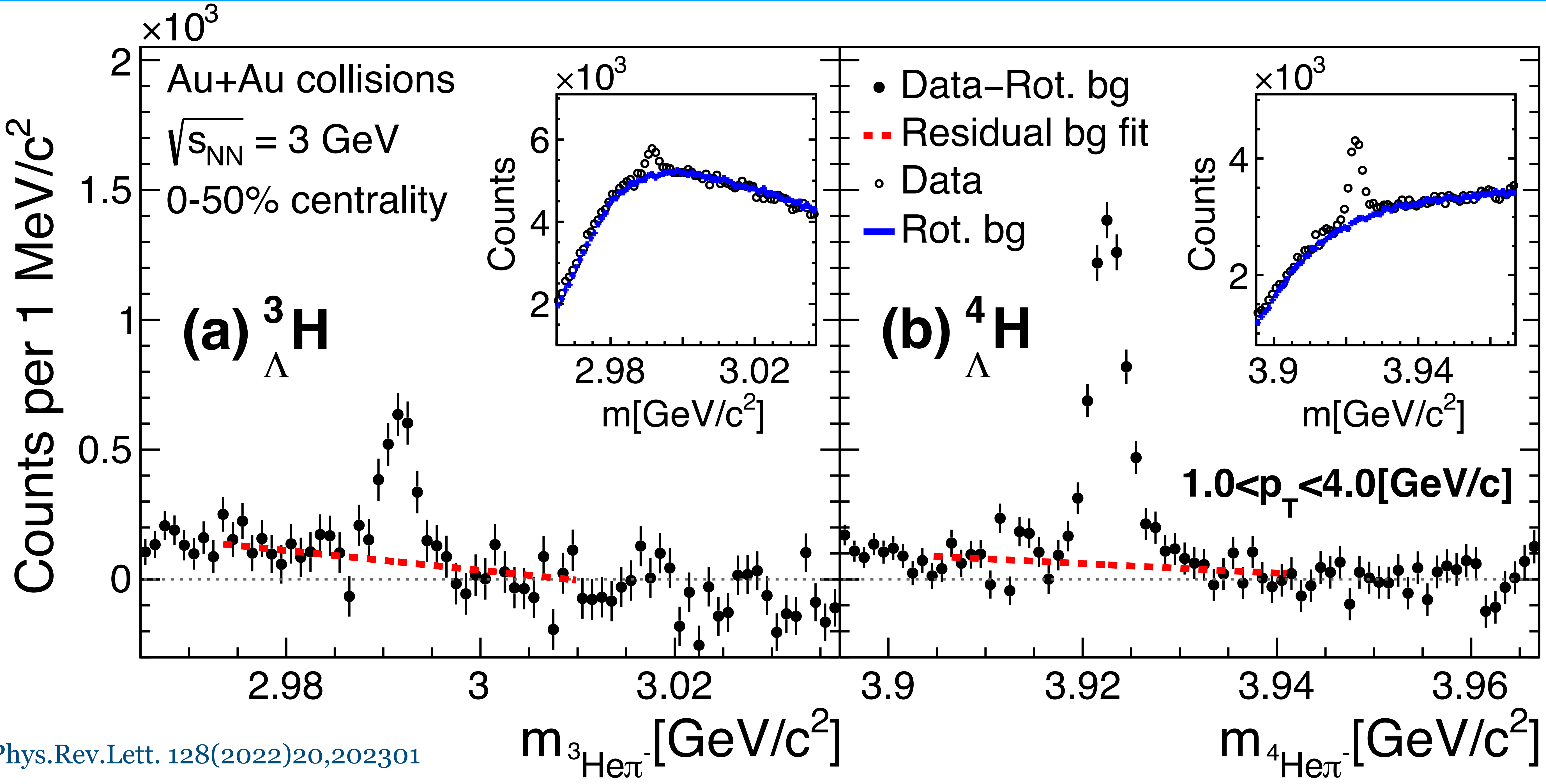




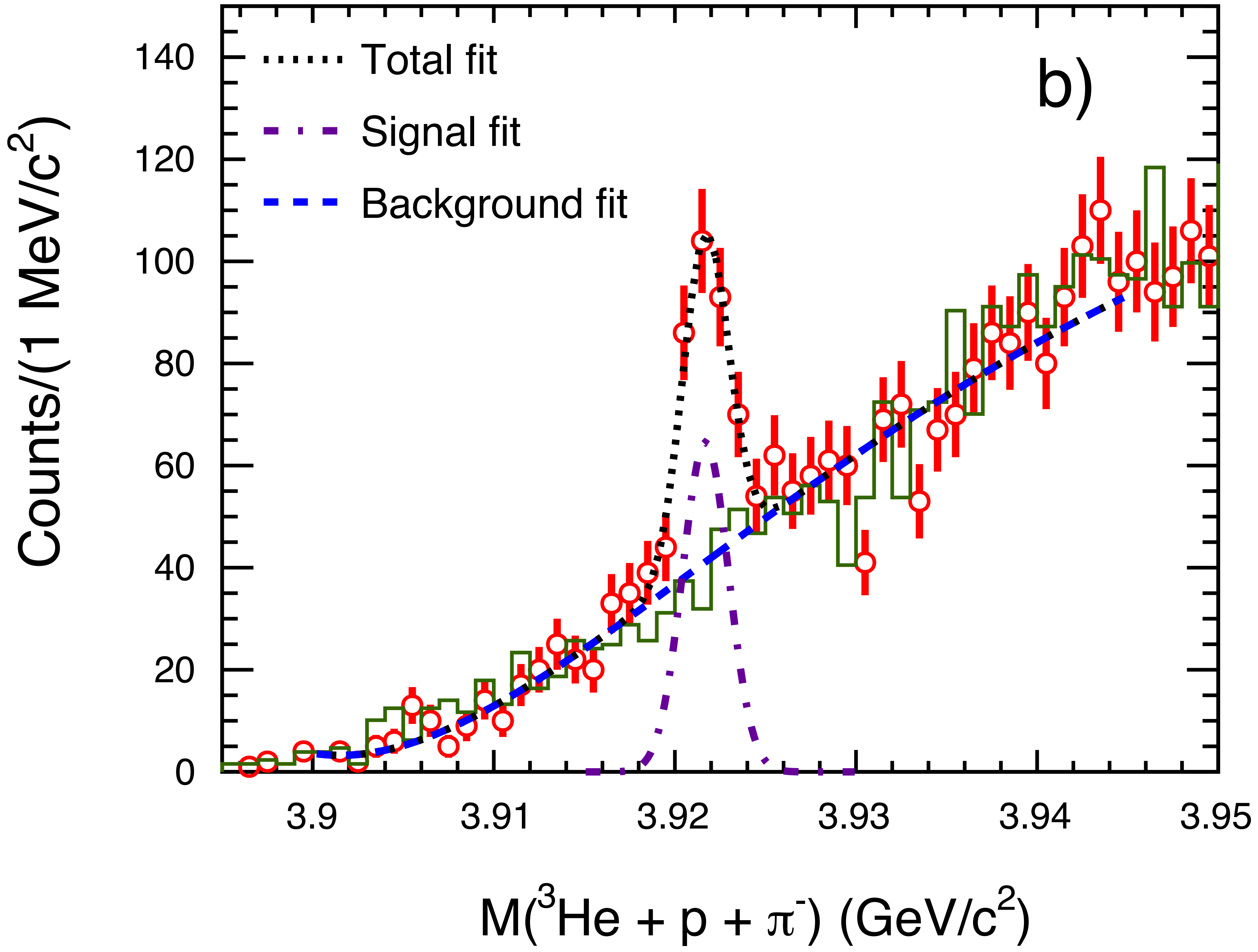
STAR Fixed-target Experiment Setup



Hypernuclei reconstruction



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



STAR, arXiv:2207.00778

- 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:

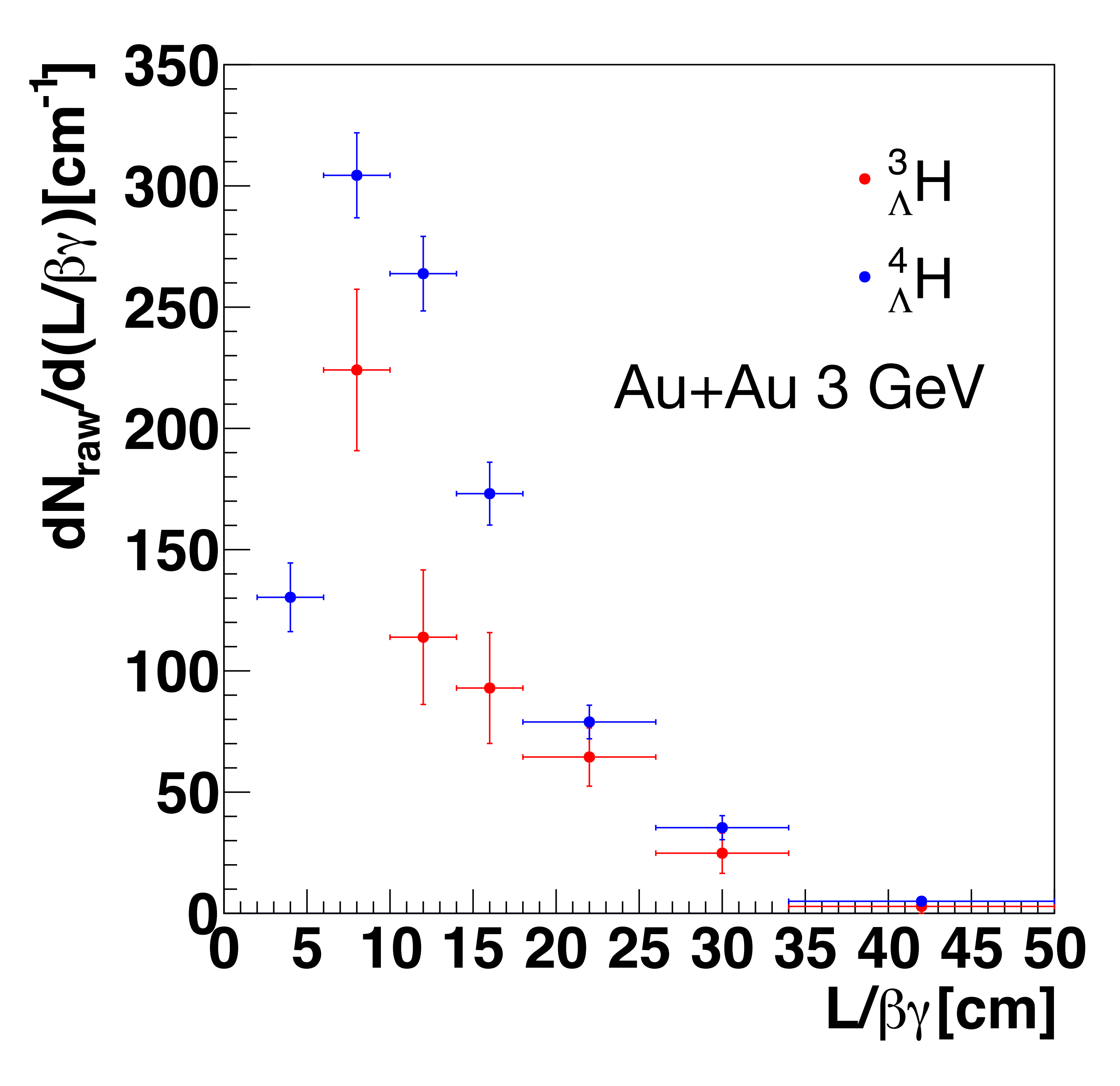
$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^-$ $\quad$ $^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^-$

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

- Combinatorial background estimated via rotating pion tracks or event mixing

Measuring hypernuclei lifetimes

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



$L/\beta\gamma = ct$

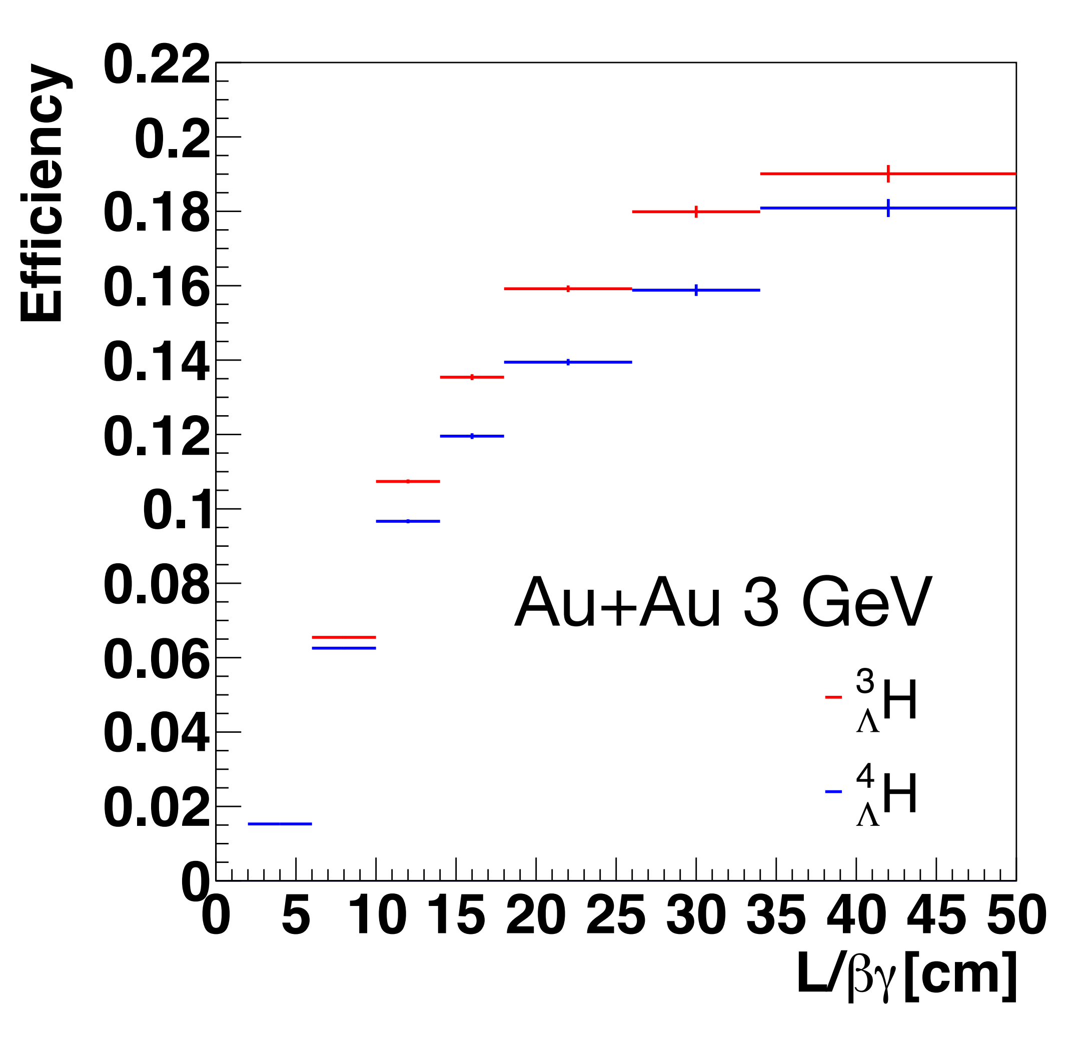
L: decay length
t : proper time

3. Fit with an exponential function to extract the lifetime

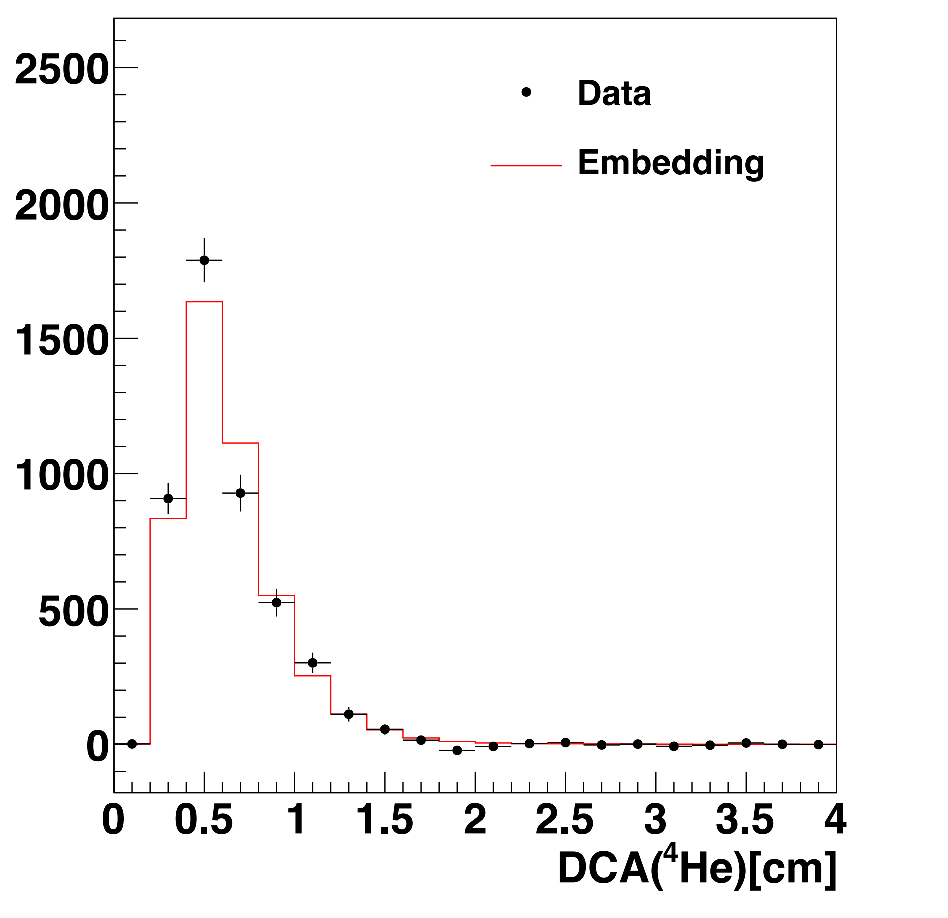
$$N(t) = N_0 e^{-t/\tau} = N_0 e^{-L/\beta\gamma c\tau}$$

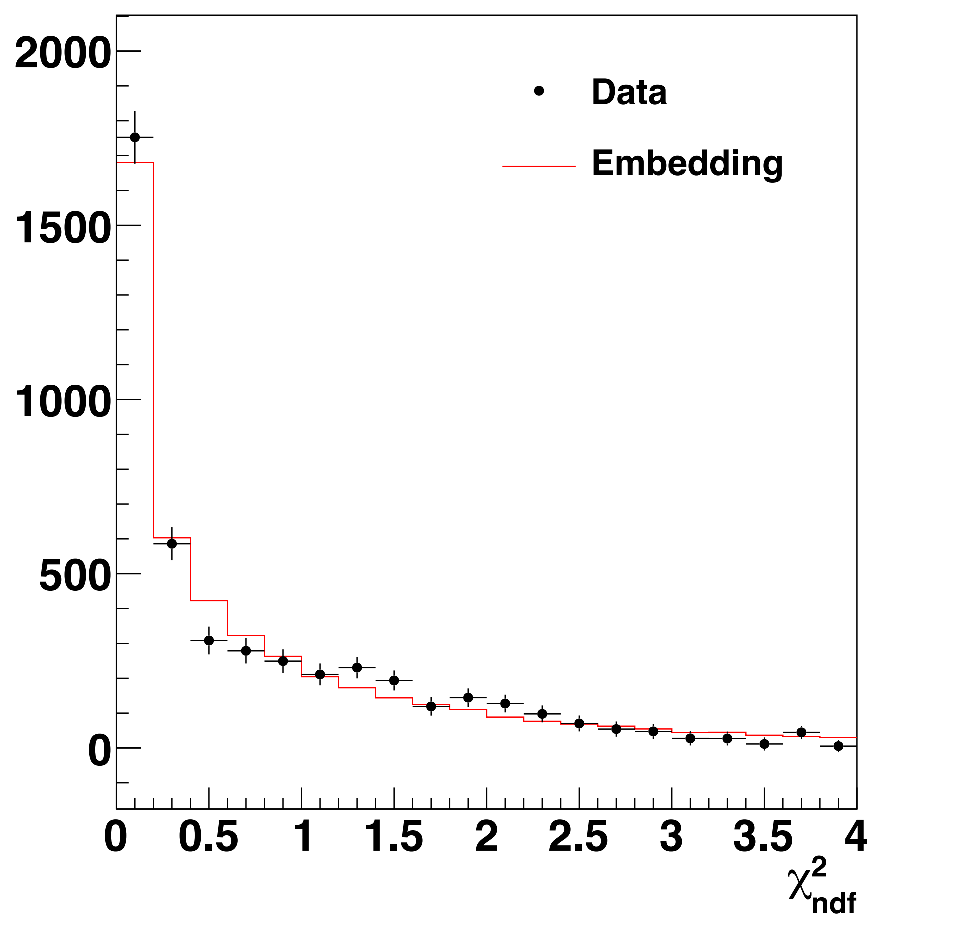
2. Correct for efficiency as a function of L/βγ

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

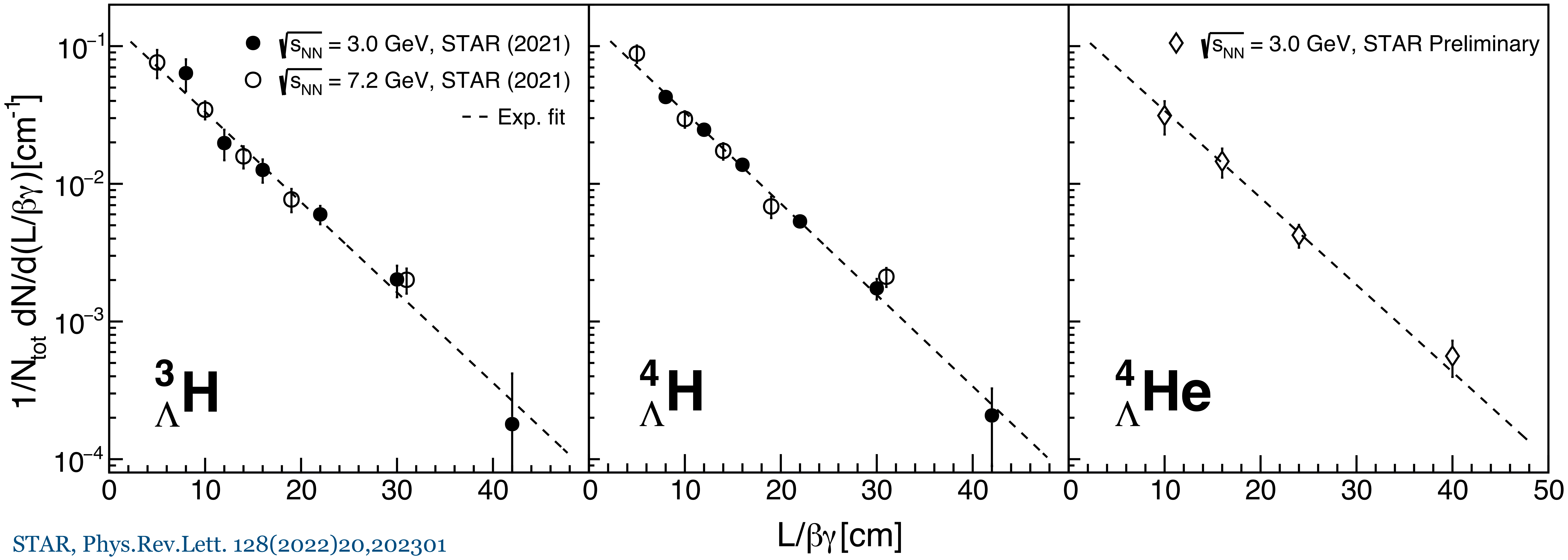


- Simulations provide good description of various topological variable distributions in data

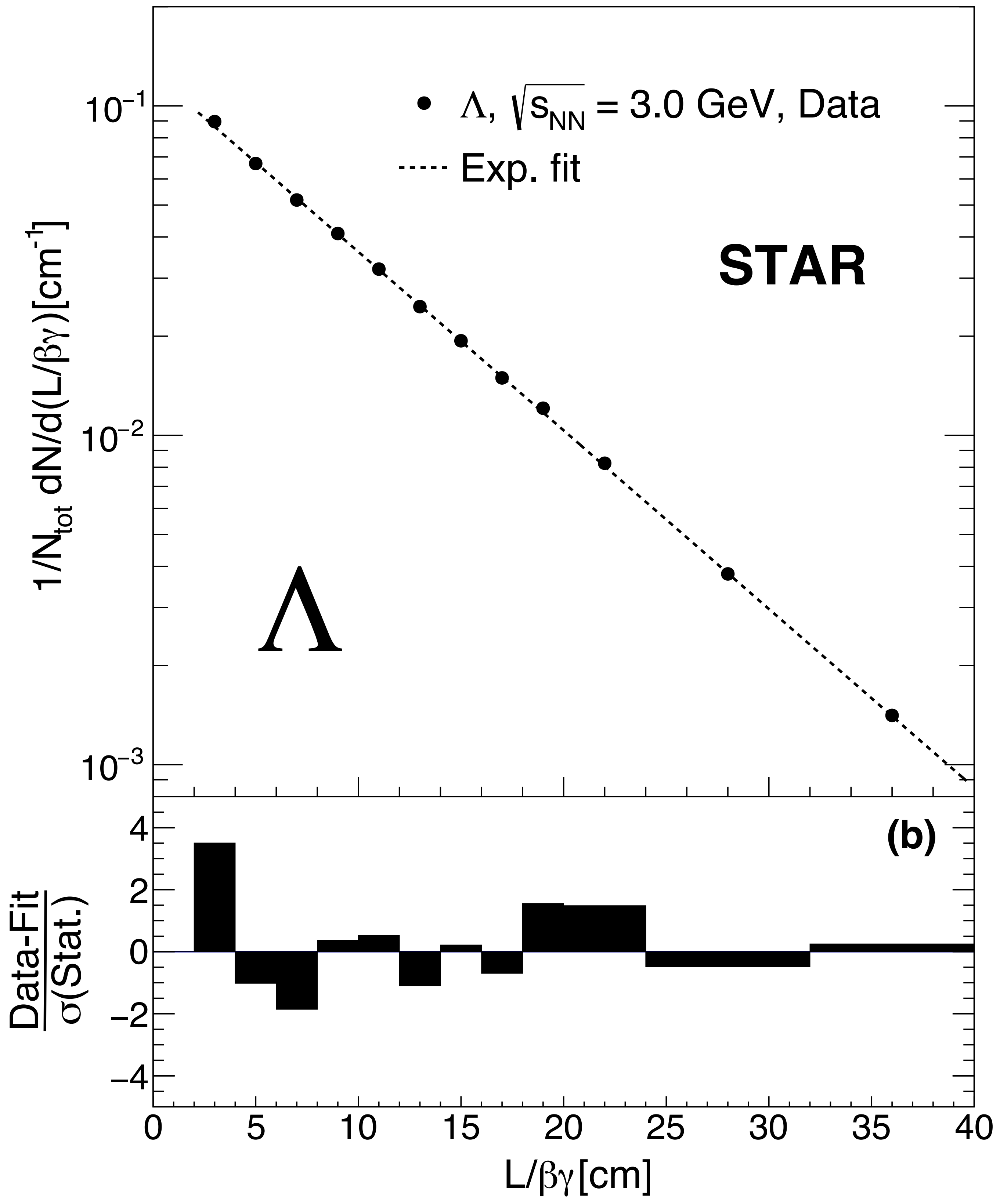




Measuring hypernuclei lifetimes (cont.)



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

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

Estimating possible contamination of hypernuclei signal

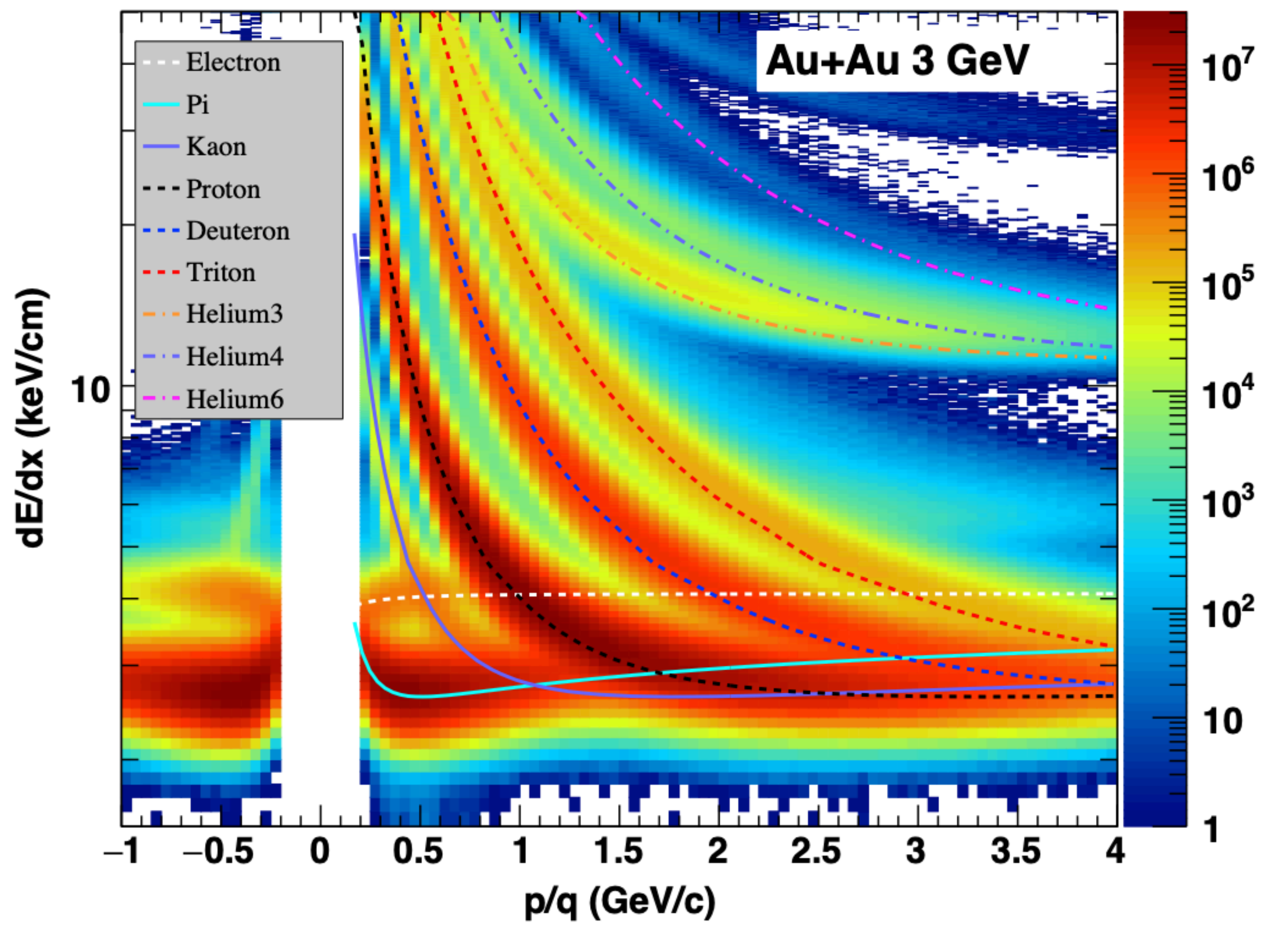
- (a) Contamination from mis-particle-identification
    - Energy loss in TPC (dE/dx) is used for particle identification
    - At high momentum, ^{3}He band merges with ^{4}He
        - ${}^{3}_{\Lambda}H$ may be mis-identified as ${}^{4}_{\Lambda}H$, and vice versa
    - GEANT simulations used to estimate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

e.g.:

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

mis-PID

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



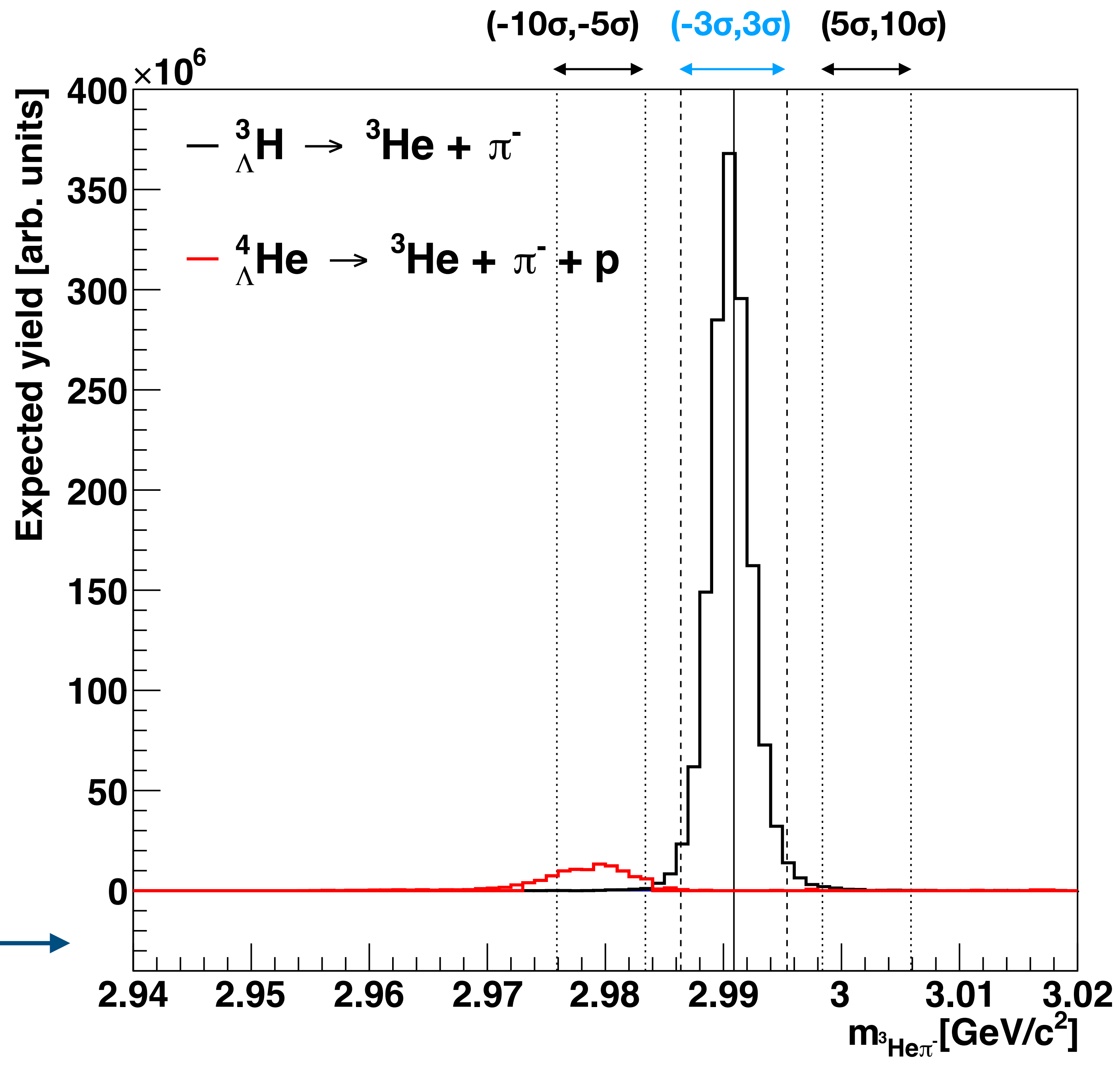
- (b) Contamination from 3+body decays
    - Hypernuclei 3-body decays may give rise to correlated backgrounds in pair invariant mass distributions
    - GEANT simulations used to estimate the resultant correlated background
        - Situated on the left hand side of the main signal peak
        - 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

e.g.:

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

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

GEANT simulations of correlated backgrounds



Systematic uncertainties

(1) Hypernuclei candidate selection

- 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

- Possible mismatch of single track efficiency between simulations and data

(4) Signal extraction

- Uncertainties related to the background subtraction technique

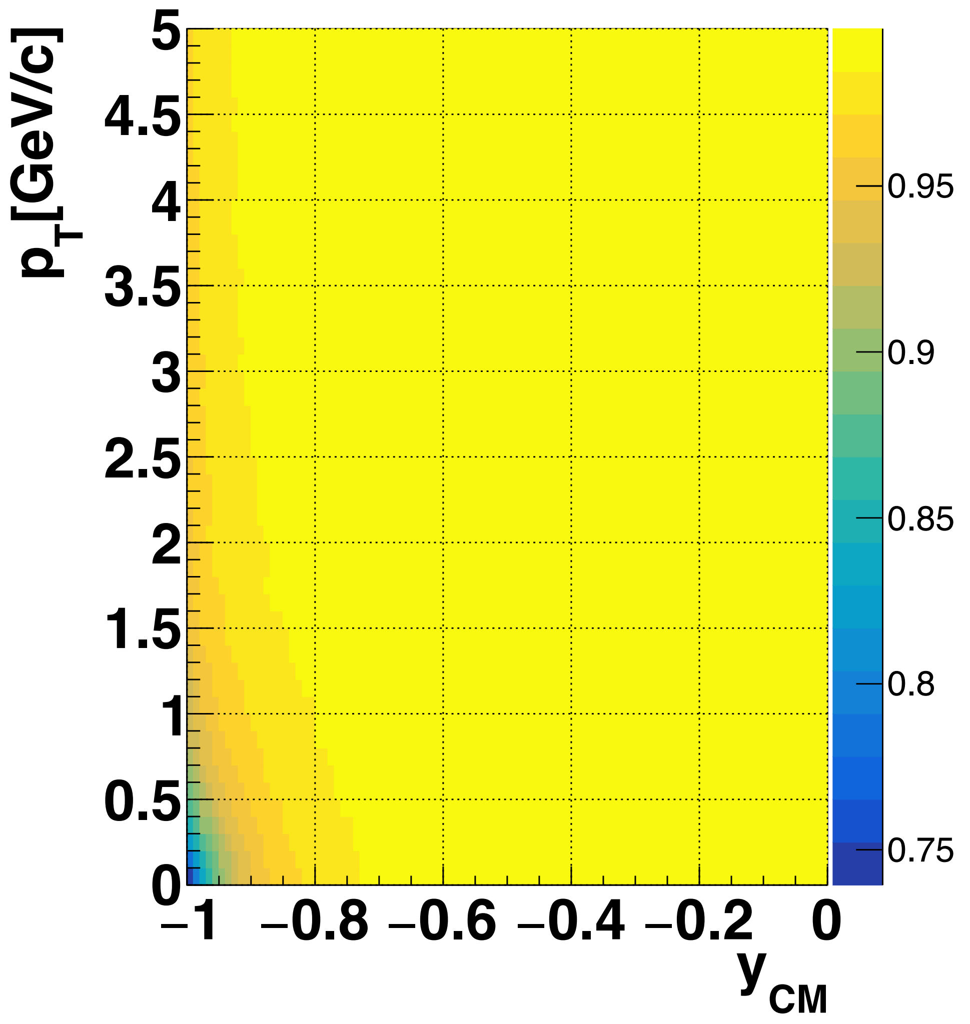
(5) Detector material

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

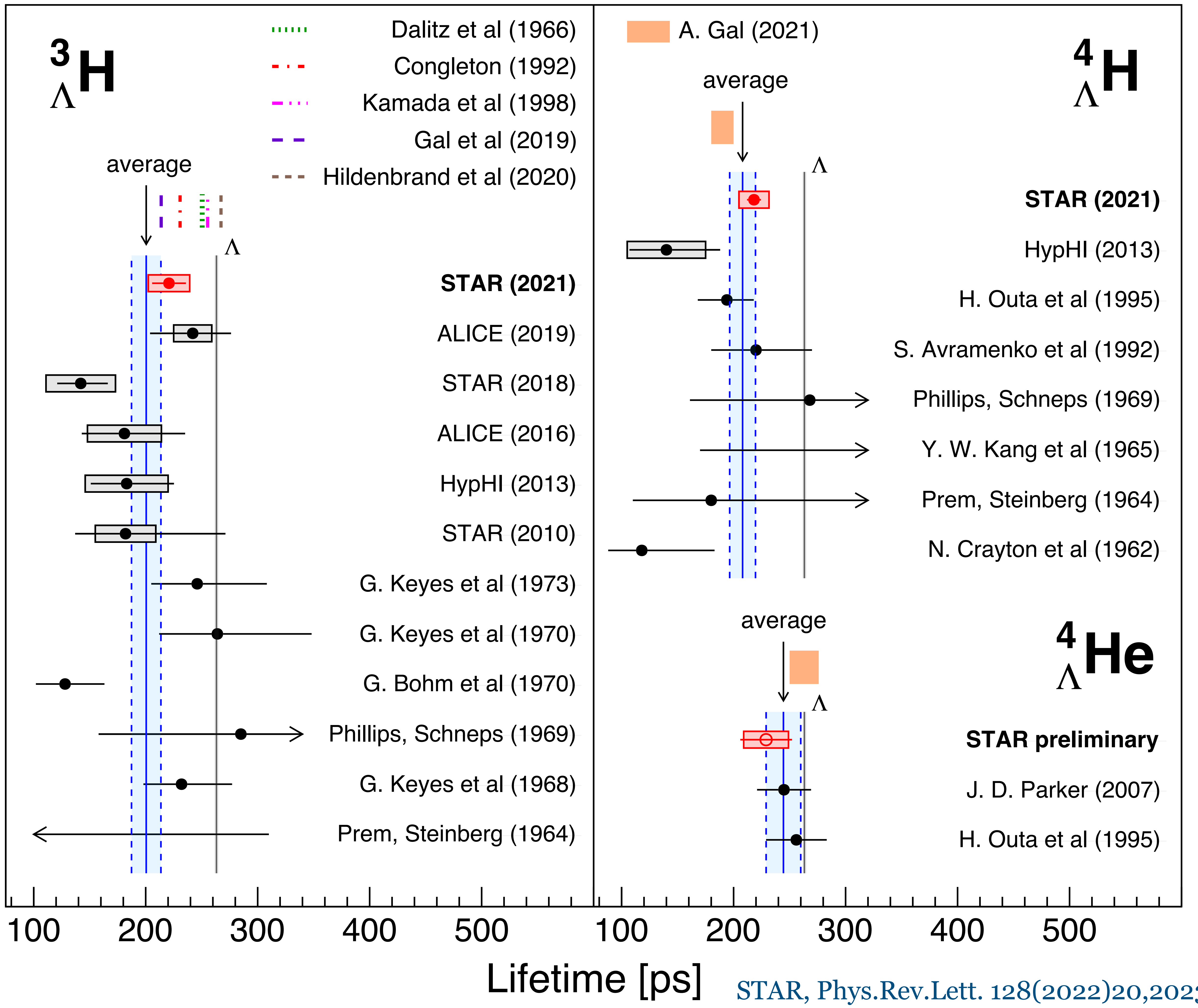
Summary of systematic uncertainties for the lifetime measurements using 3 GeV data

Source	Lifetime ${}^{3}_{\Lambda}H$	Lifetime ${}^{4}_{\Lambda}H$
Hypernuclei candidate selection	5.5%	5.1%
Input MC	3.1%	1.8%
Tracking efficiency	5.0%	2.4%
Signal extraction	1.5%	0.7%
Extrapolation	N/A	N/A
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



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

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 ± 5) % $\tau(\Lambda)$, shorter than τ(Λ) (3.5σ)
- Consistent with theoretical calculations including pion FSI

A. Gal et al, Phys. Lett. B 791(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
- $\dfrac{\tau_{avg}(^4_\Lambda\text{H})}{\tau_{avg}(^4_\Lambda\text{He})} = 0.85 \pm 0.07$, consistent with theoretical estimations: 0.74 ± 0.04

A. Gal, EPJ Web Conf 259 (2022) 08002

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

Charge symmetry breaking (CSB) in A=4 hypernuclei

- Charge symmetry → expect Λp and Λn interactions to be very similar

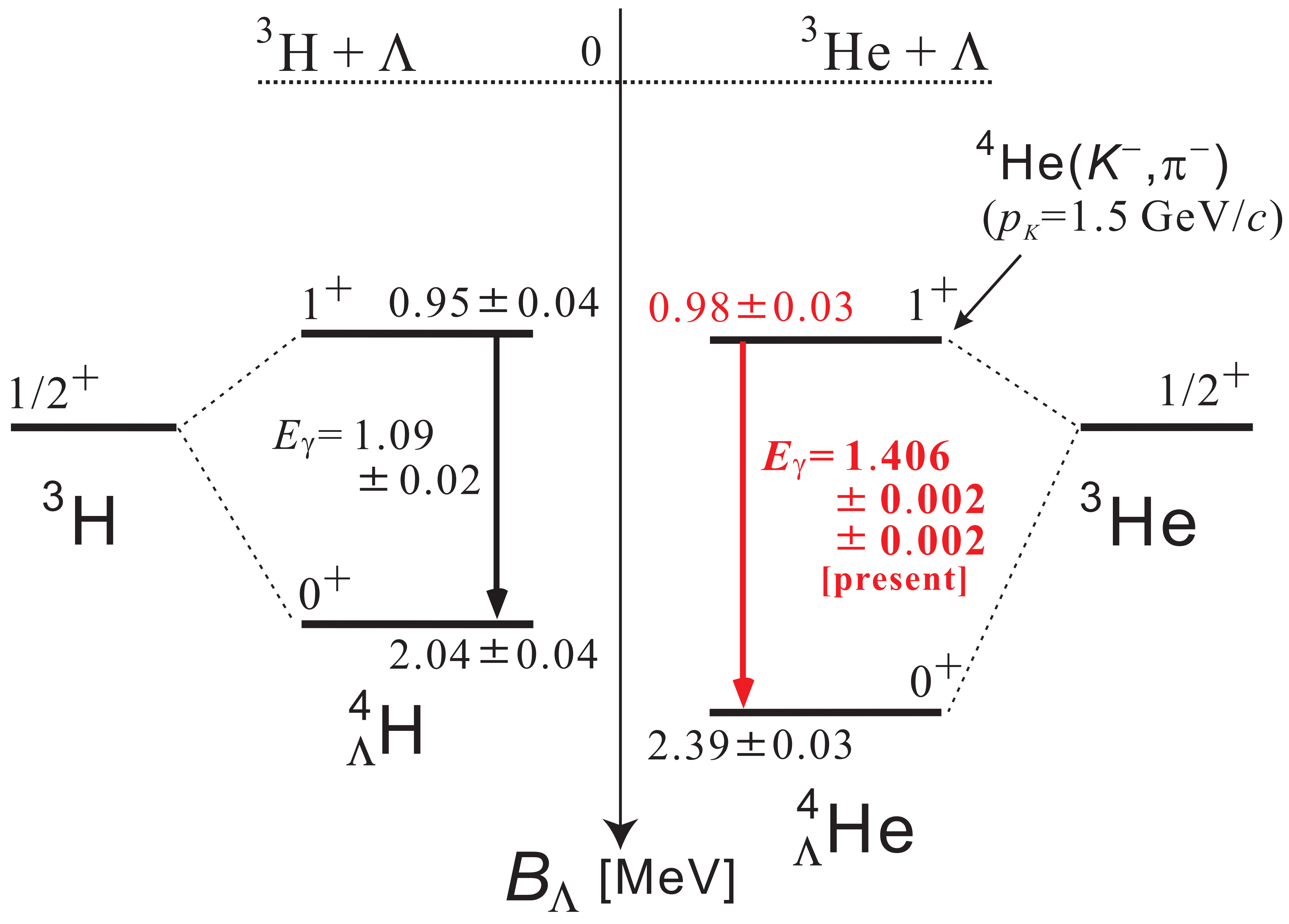
- The Λ binding energy $B_\Lambda = (M_\Lambda + M_{core} - M_{hypernucleus})c^2$ of mirror hypernuclei expected to be similar

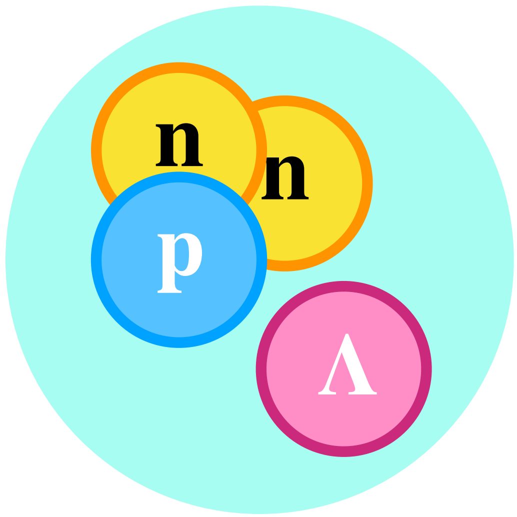
- Previous measurements using imaging techniques reveal large binding energy difference between ${}^4_\Lambda\mathrm{H}$ and ${}^4_\Lambda\mathrm{He}$

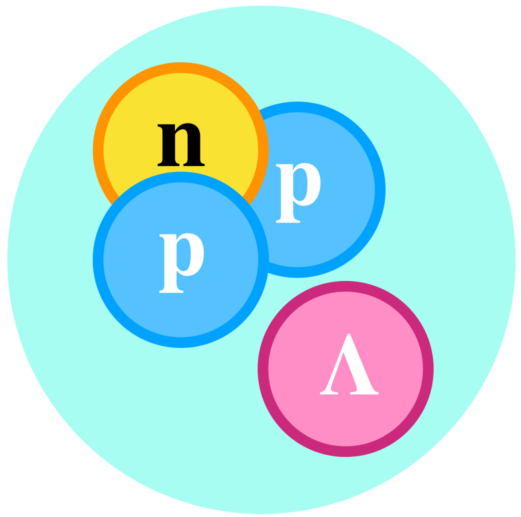
$$\Delta B^4_\Lambda(0^+) = 350 \pm 60[\mathrm{keV}]$$

- The origin of the large charge symmetry breaking is a long-standing puzzle
    - Measurements from independent experiments is needed to confirm this observation

J-PARC E13, Phys. Rev. Lett. 115 (2015) 222501



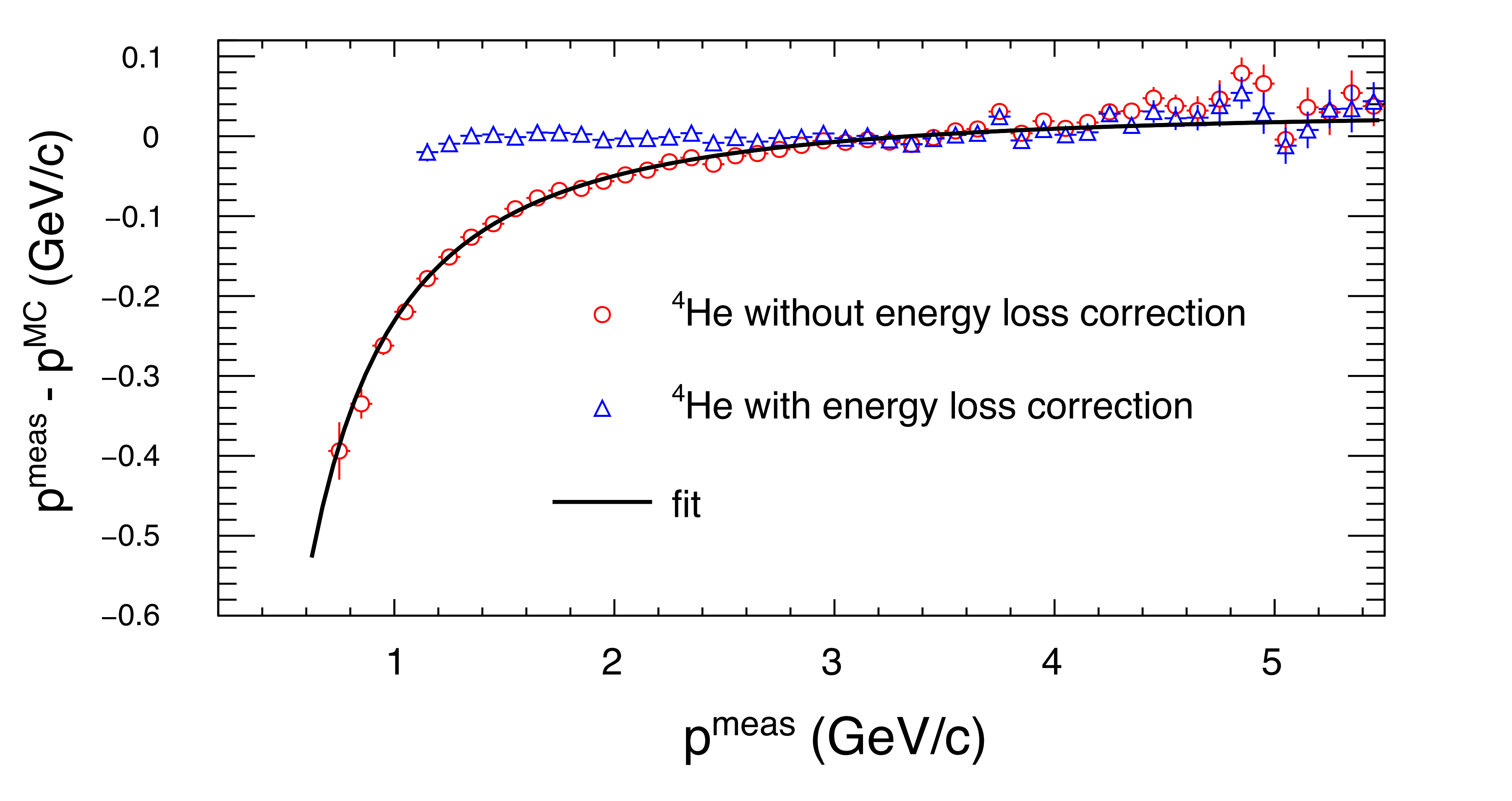




Measuring hypernuclei binding energies

STAR, arXiv:2207.00778

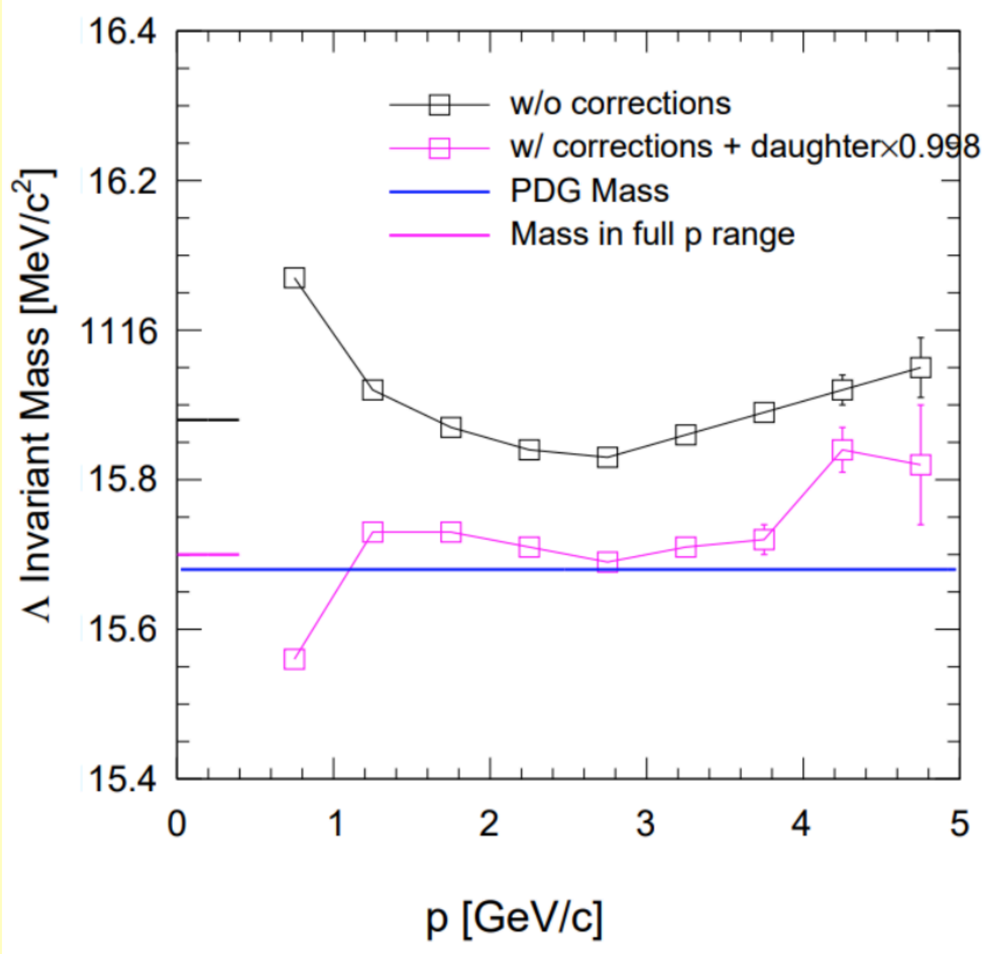
Energy loss correction



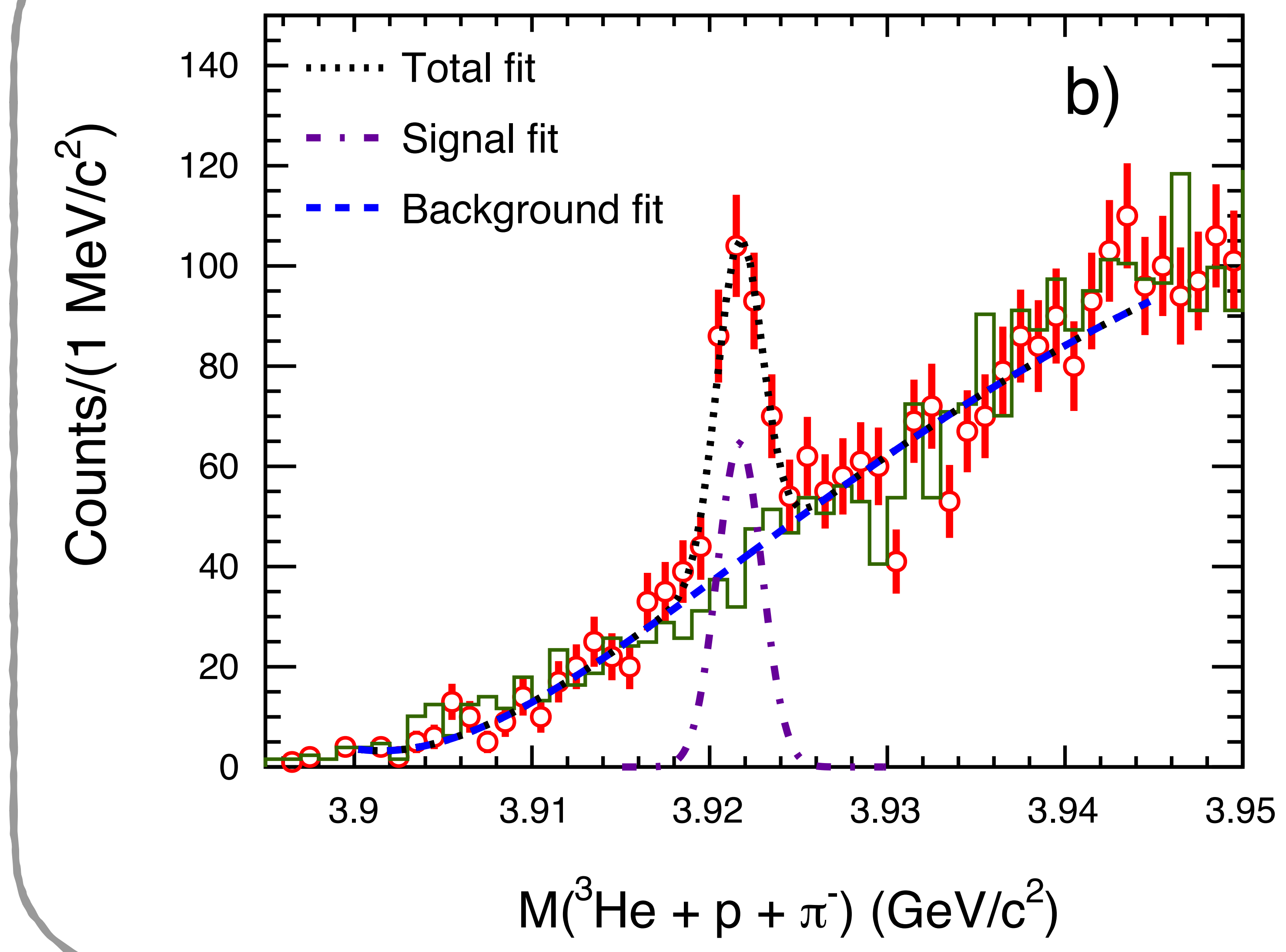
- Energy loss in the material is particle species dependent
  - STAR track reconstruction applies an energy loss correction assuming all particles to be pions
- Additional energy loss correction for p, ^{3}He and ^{4}He estimated via GEANT simulations

Correction applied to all daughter tracks

Correction to magnetic field strength

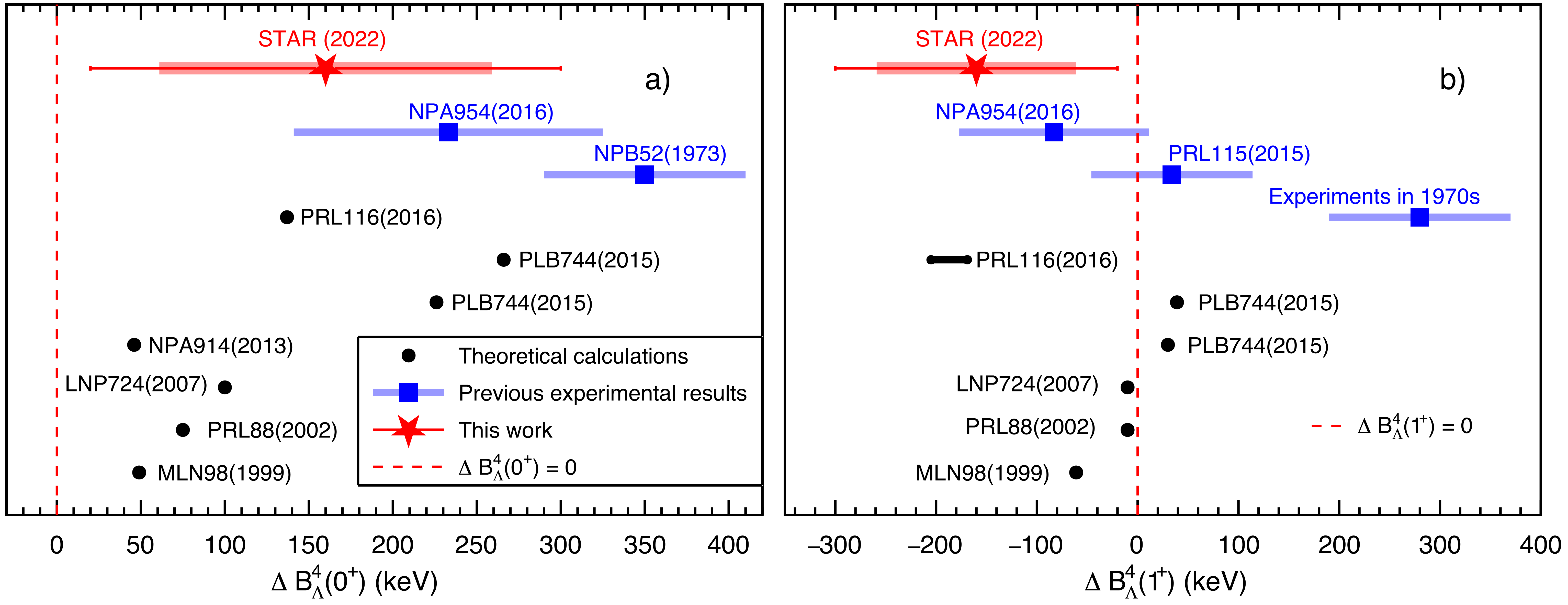


- Discrepancy between true and nominal magnetic field strength
  - Estimated to be 0.2% from Λ mass

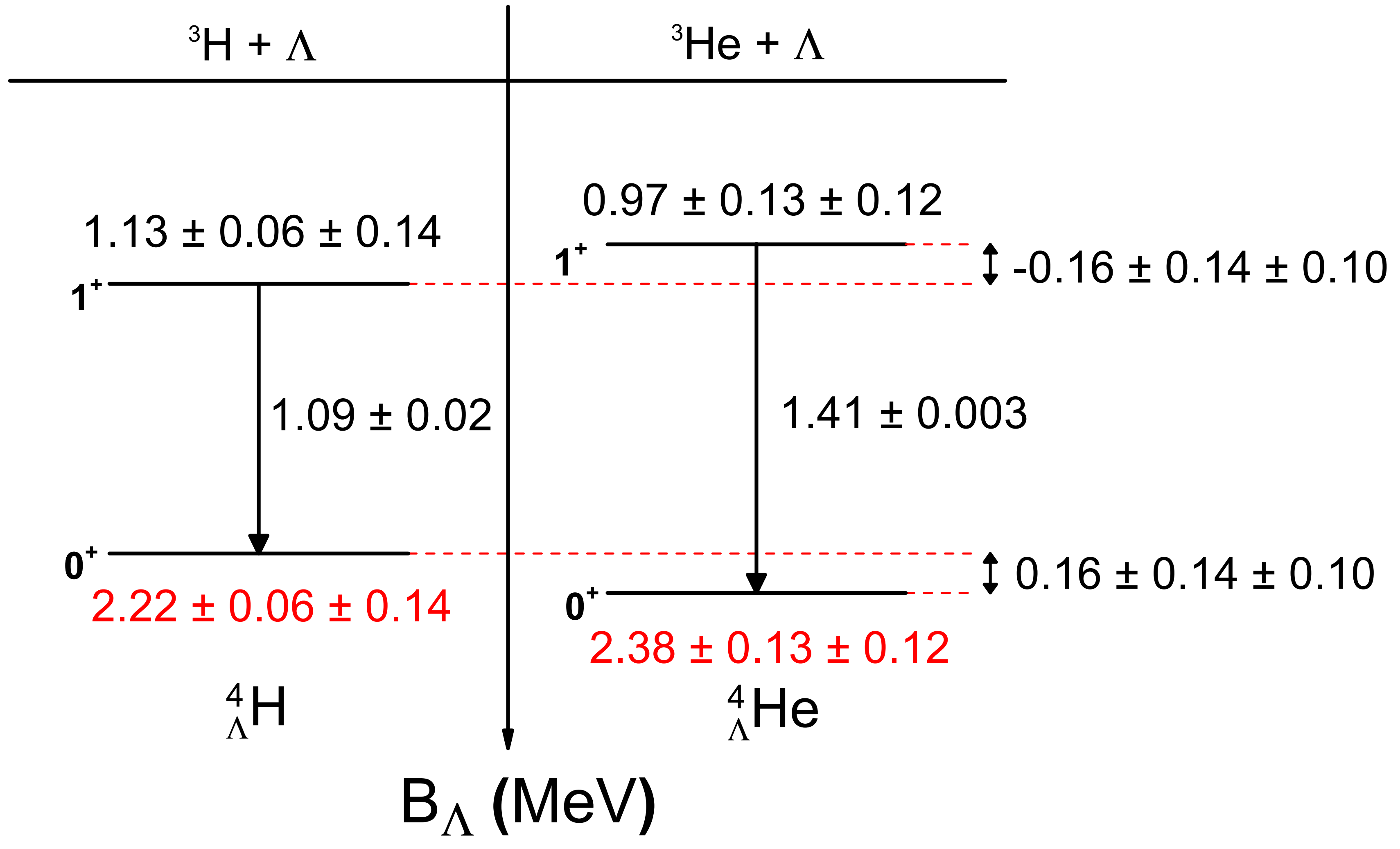


- Peak position obtained via fitting
  - Gaussian shape assumed for signal

A=4 hypernuclei binding energies



STAR, arXiv:2207.00778



$B_\Lambda(^4_\Lambda\mathrm{H}) = 2.24 \pm 0.06(\mathrm{stat}) \pm 0.14(\mathrm{syst})[\mathrm{MeV}]$

$B_\Lambda(^4_\Lambda\mathrm{He}) = 2.38 \pm 0.13(\mathrm{stat}) \pm 0.12(\mathrm{syst})[\mathrm{MeV}]$

- Charge symmetry breaking recently proposed to originate from CSB Λ-Σ^0 mixing vertex   Gazda and Gal, Phys. Rev. Lett. 116(2016)122501
    - Predicts $\Delta B^4_\Lambda(1^+) \approx -\Delta B^4_\Lambda(0^+)$
- Binding energies for 1^+ obtained from γ-ray transition energy measurements   M. Bedjidian et al., Phys. Lett. B 62, 467-470 (1980)
J-PARC E13, Phys. Rev. Lett. 115, 222501 (2015)

$\Delta B^4_\Lambda(0^+) = 160 \pm 140(stat) \pm 100(syst)[\mathrm{keV}]$

$\Delta B^4_\Lambda(1^+) = -160 \pm 140(stat) \pm 100(syst)[\mathrm{keV}]$

CSB in ground and excited states comparable, consistent with theoretical calculations

→ Look forward to Run 21 data (2B Au+Au events at 3 GeV)

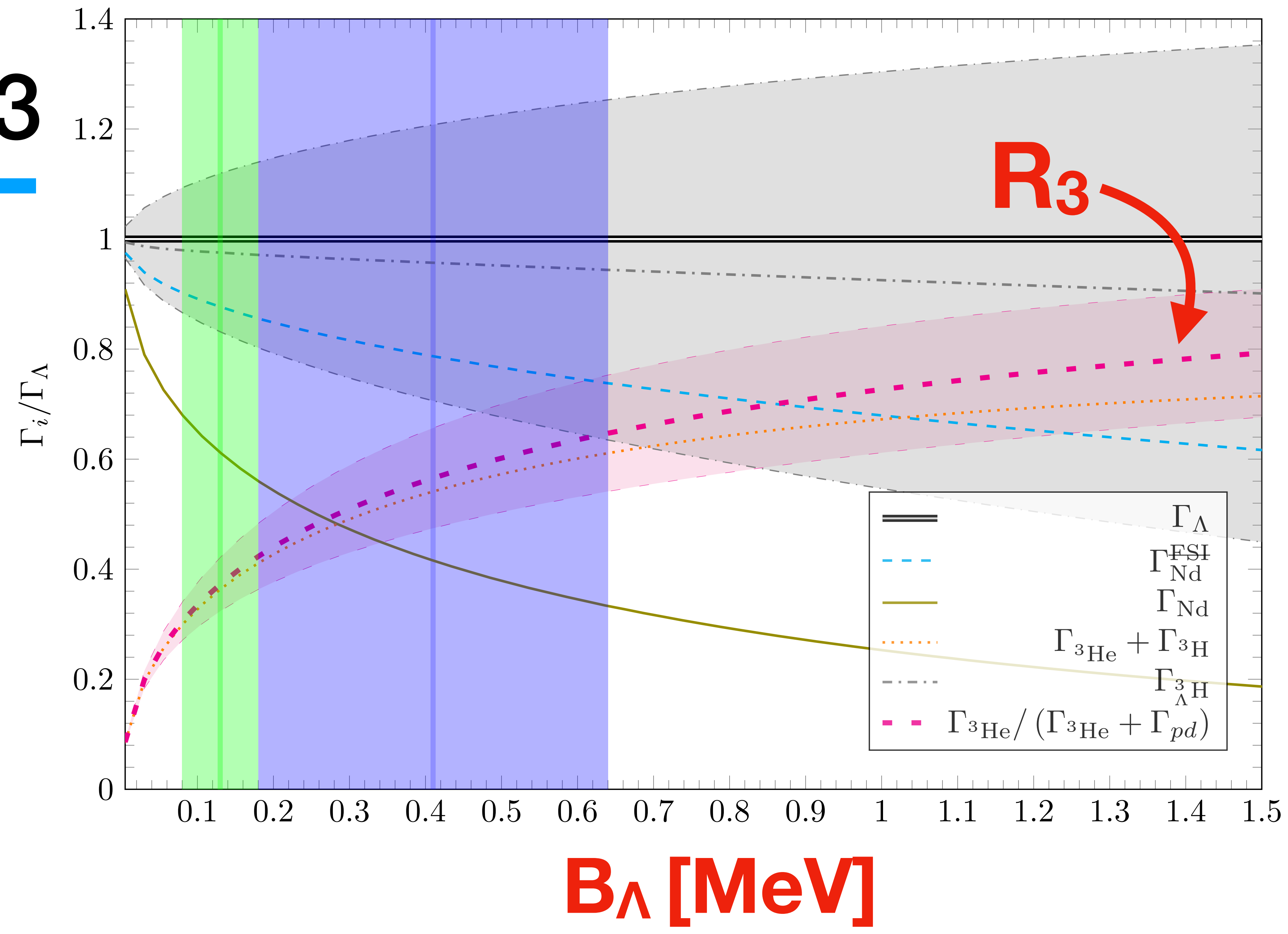
Hypertriton relative branching ratio R_3

- The ${}^{3}_{\Lambda}\mathrm{H}$ relative branching ratio, R_3, is defined as:

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

- Recent calculations predict a strong dependence of R_3 on the binding energy

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

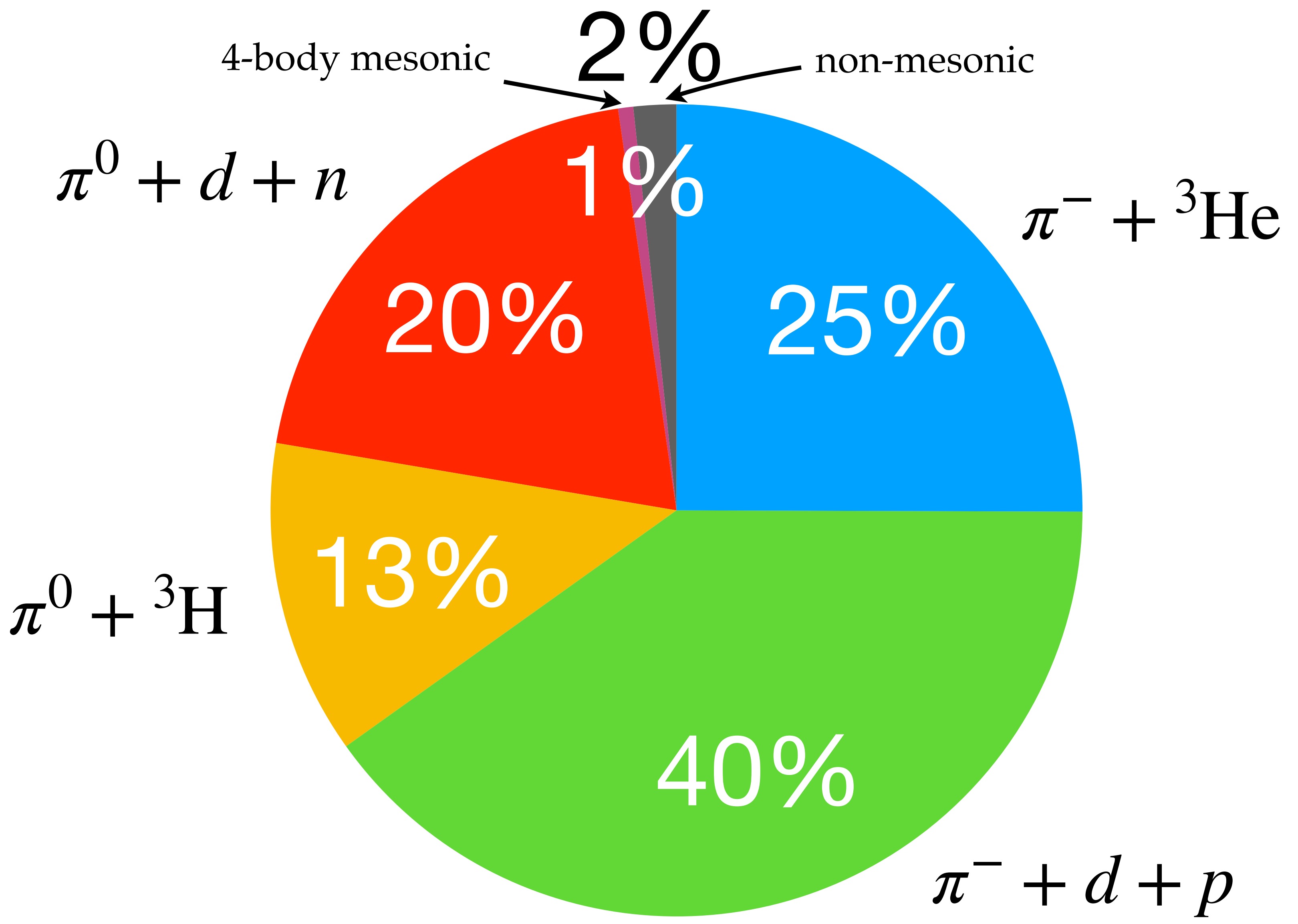


Calculated decay rates vs B_Λ from Hildenbrand et al.

- 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)



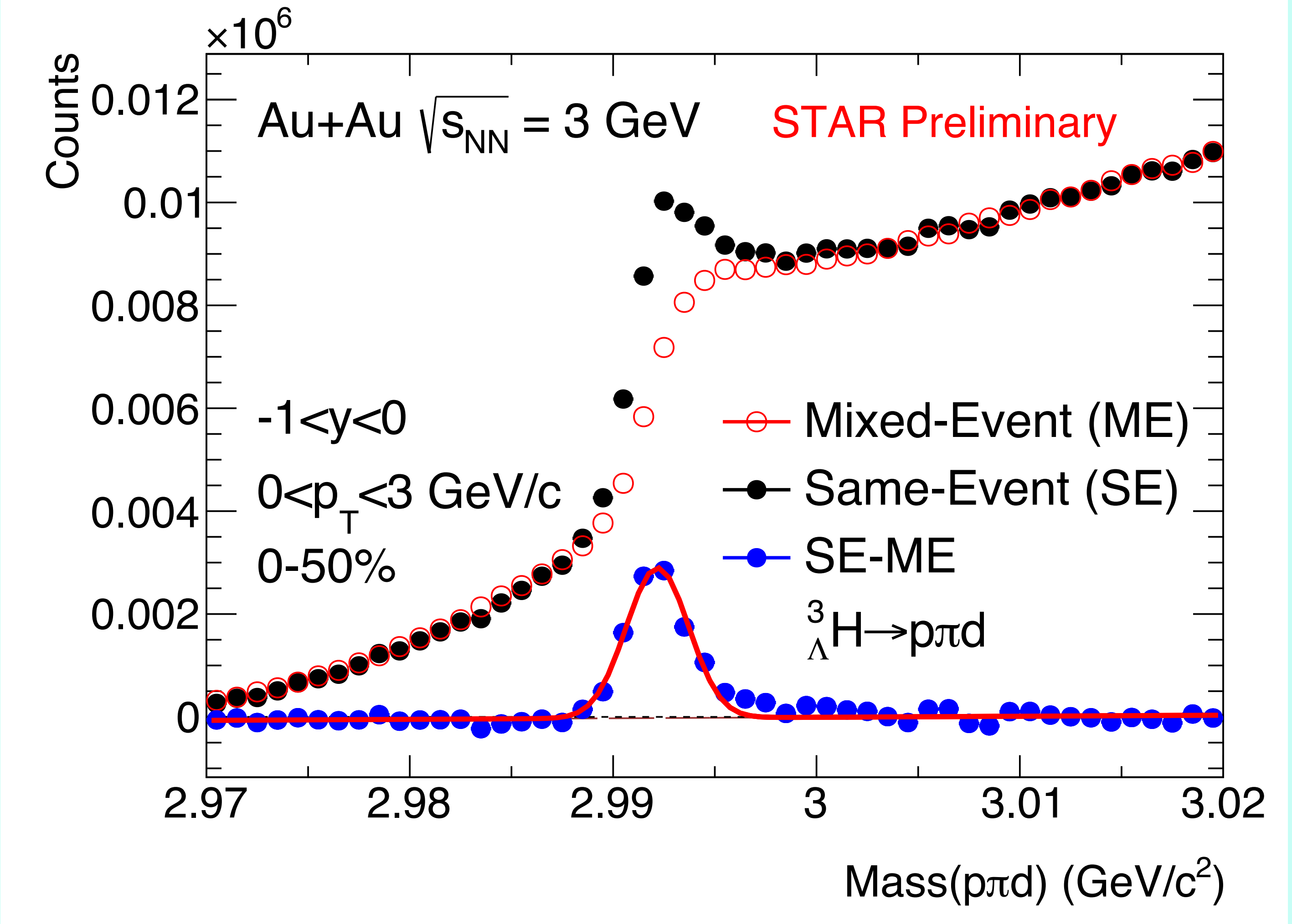
Calculated decay B.R. from Kamada et al.

- R_3 connects the ${}^{3}_{\Lambda}\mathrm{H}$ lifetime to its two-body $\pi^{-} + {}^{3}\mathrm{He}$ decay rate
  - Used as a constraint to model calculations of the lifetime

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

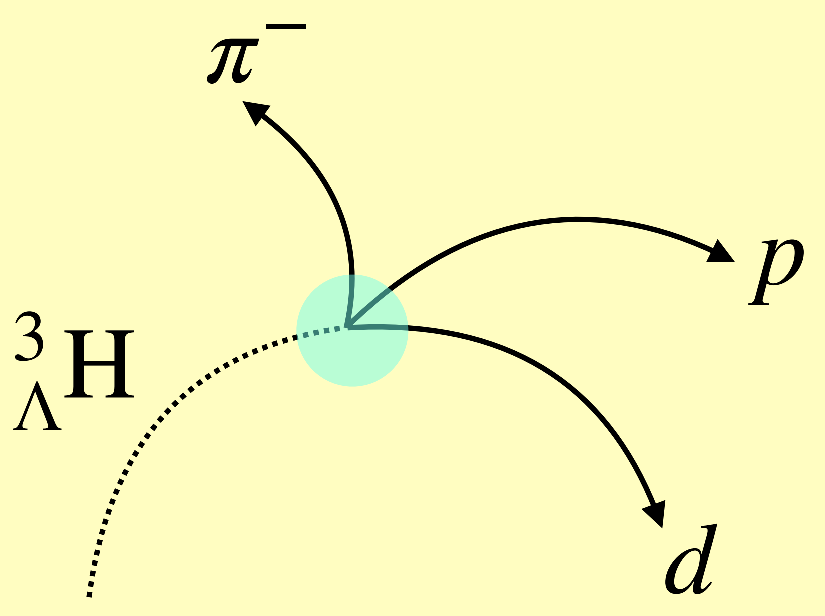
- To obtain corrected yields from hypertriton 3-body decay ${}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^{-}$:

1. Subtract uncorrelated background, estimated via event-mixing

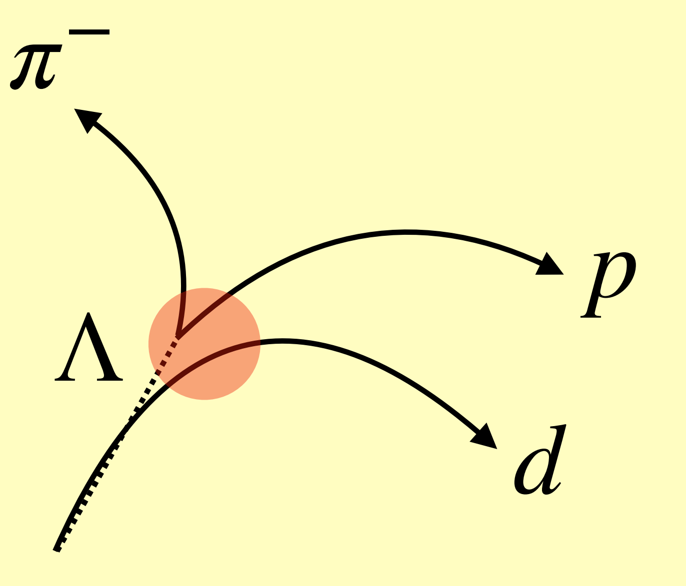


2. Excess around hypertriton peak contains correlated background

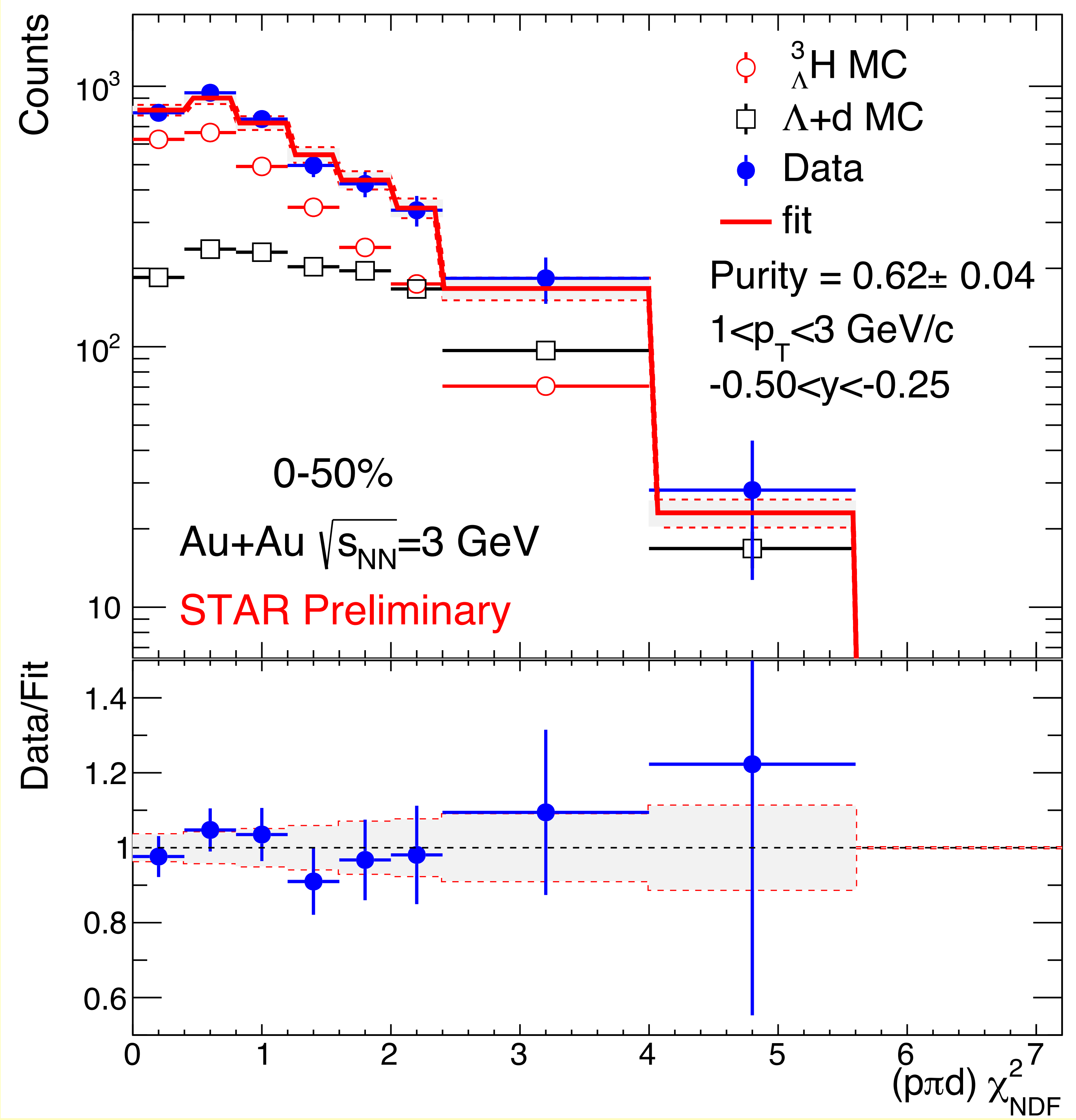
- Purity estimated via template fit to χ^2 of secondary vertex fit



Real signal: lower χ^2

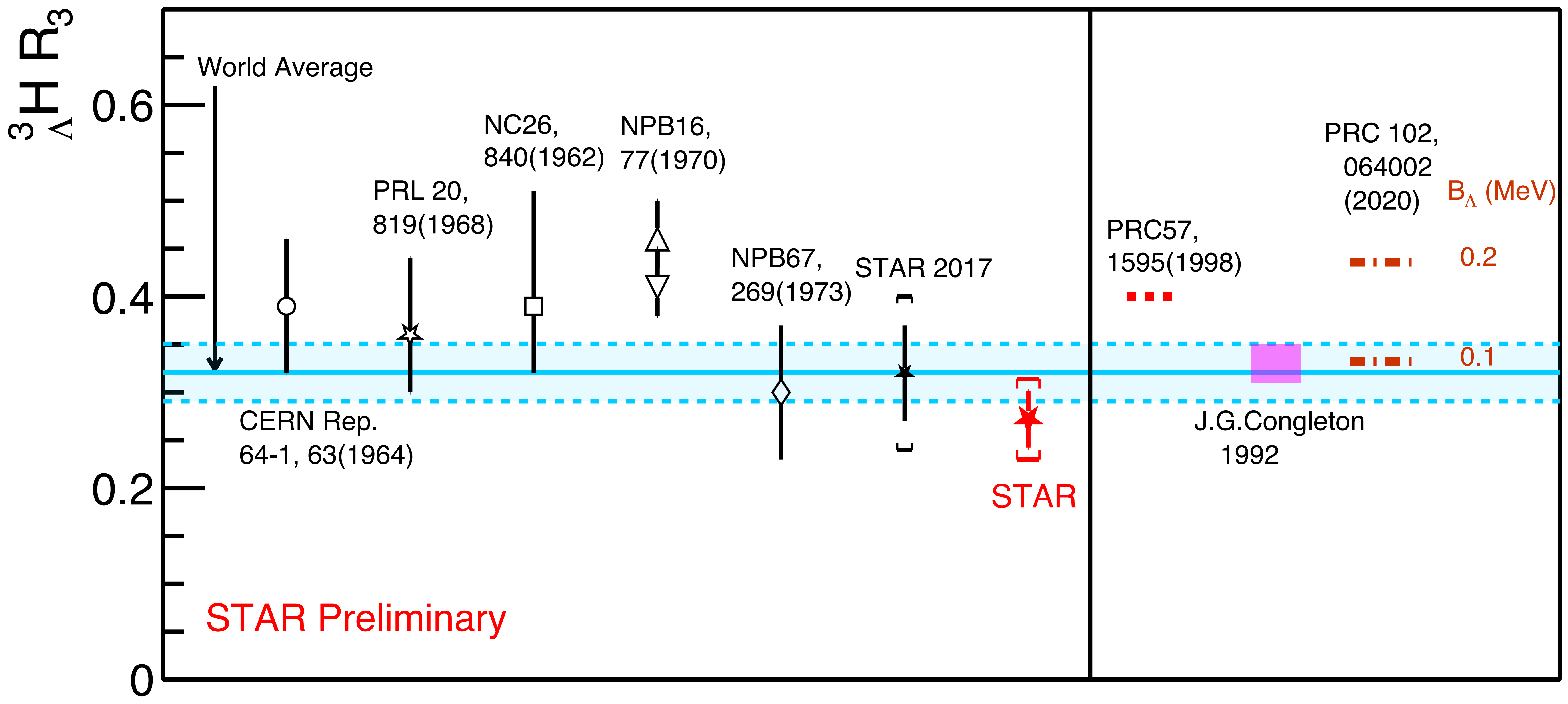


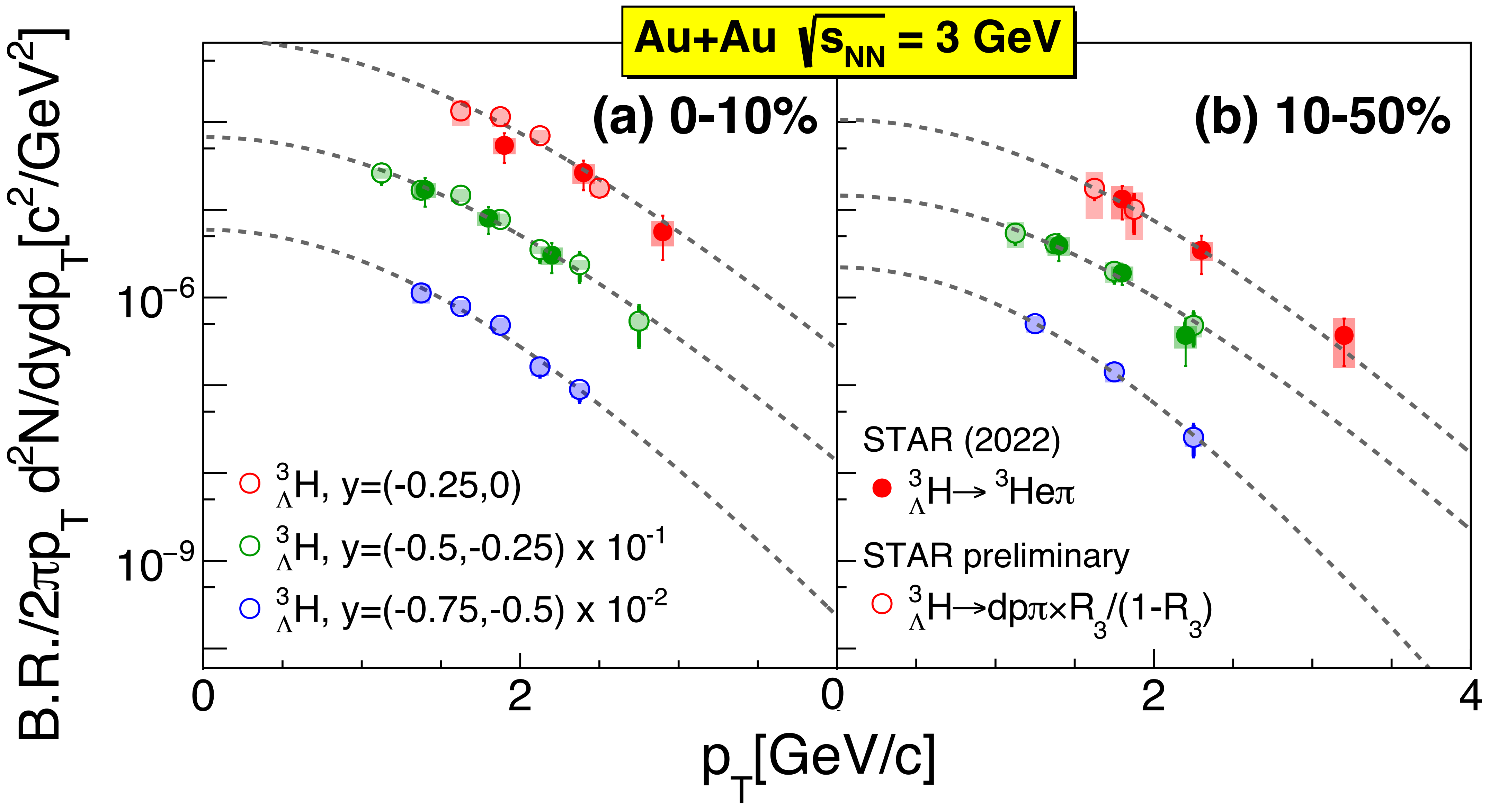
Background: higher χ^2



3. Correct for efficiency of real signal

Relative branching ratio R_3 measurement





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

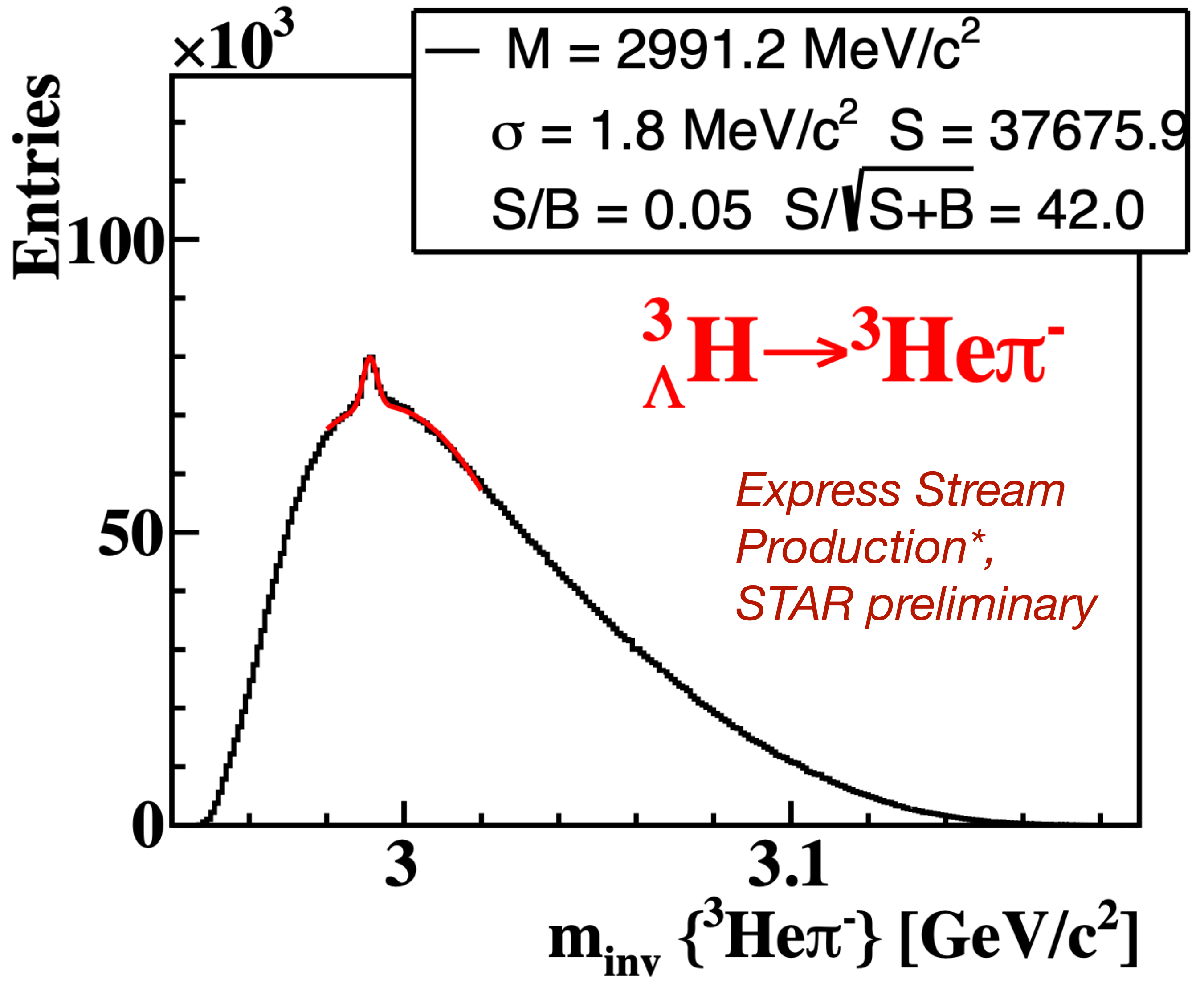
- R_3 measurement is obtained by comparing the efficiency corrected yields from 3-body and 2-body decays

- New measurement on R_3 :
  - → Provides input for connecting theoretically computed two-body mesonic rates and $^3_\Lambda$H lifetime
  - → Favors a small binding energy according to calculations from Hildenbrand et al.

Future hypernuclei studies from STAR

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

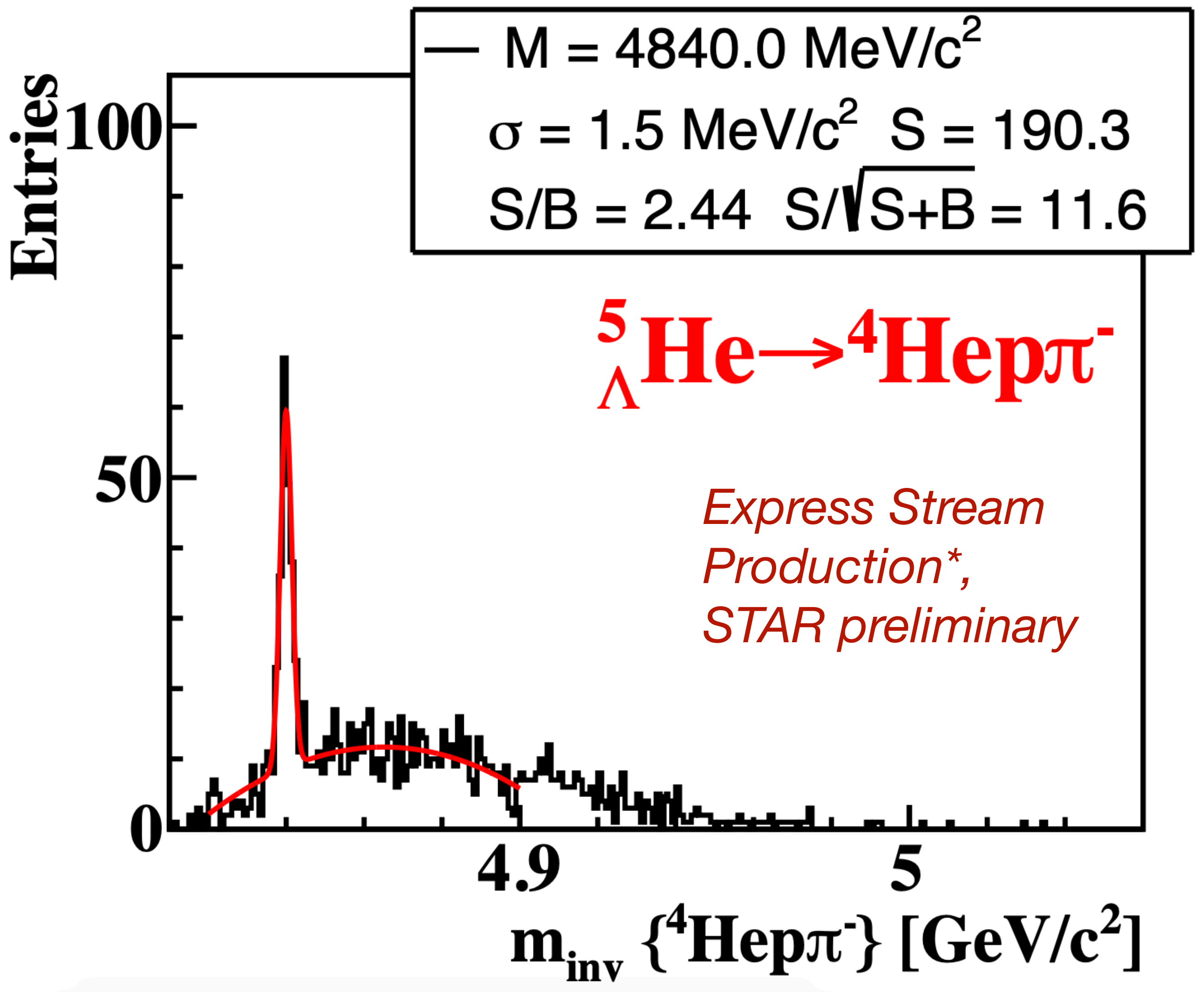
- ~42σ ${}^{3}_{\Lambda}H$ signal observed using BES-II data
- Entering the precision era



*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

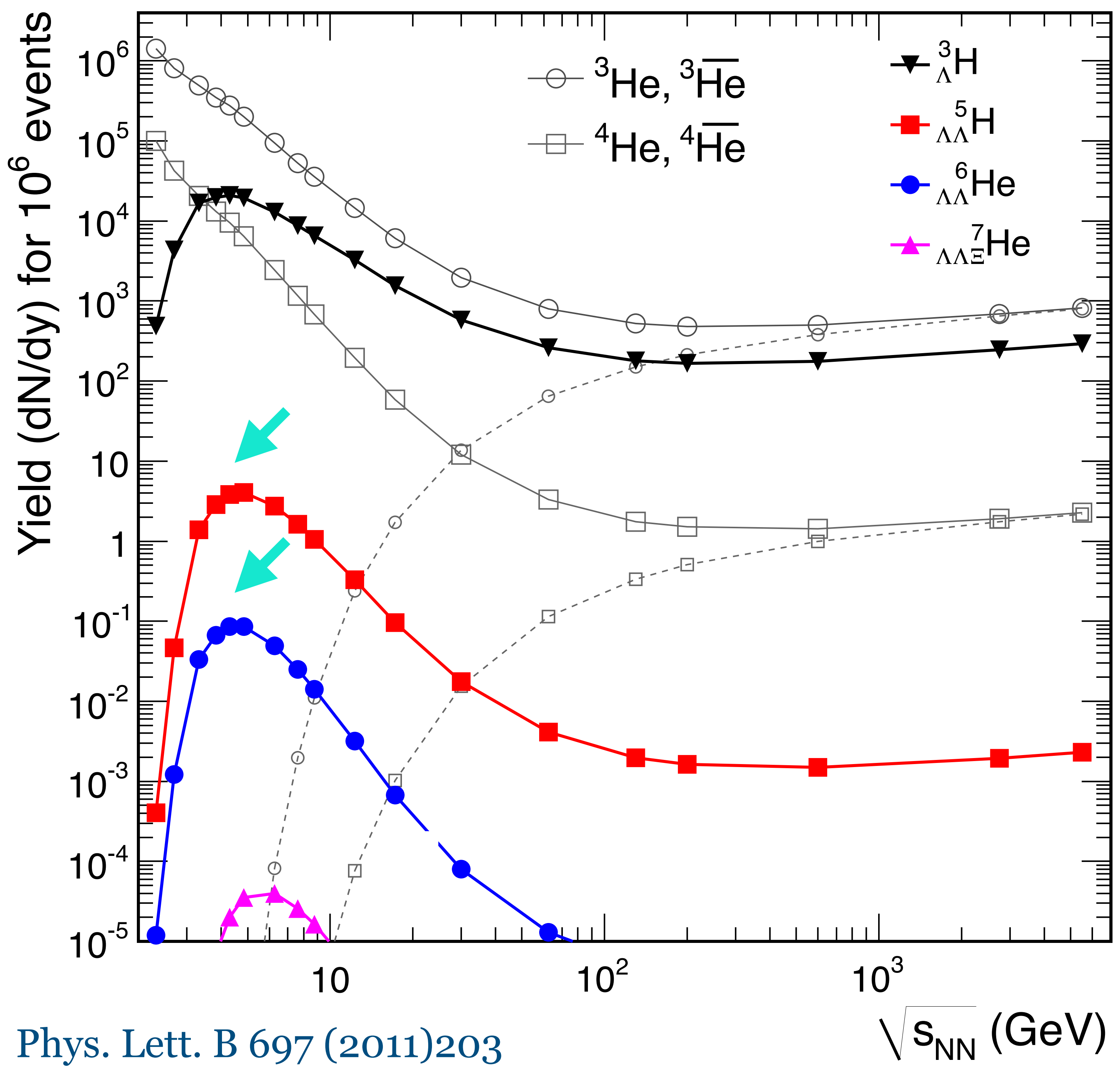
✤**Studies on heavier hypernuclei**

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



✤**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

Summary

- **STAR BES-II** presents new opportunities for investigating the internal structure of hypernuclei

✤ $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He **lifetime measurements**

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

✤ $^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He **binding energy measurements**

- Comparable binding energy differences in ground and excited states, with opposite sign
- Consistent with theoretical calculations with Λ-Σ^0 mixing

✤ $^{3}_{\Lambda}$H **R_3 measurement**

- New method to extract 3-body yields via template fitting
- Intimately connected to $^{3}_{\Lambda}$H lifetime and binding energy

- Backup slides follow

Systematic uncertainties on binding energy measurement

(1) Momentum scaling factor

- Imperfect knowledge in magnetic field strength
- Estimated from discrepancy between Λ mass and PDG value

(2) Energy loss correction

- Imperfect knowledge in material budget

(3) BDT response cut

- Assess possible effects of topological cuts on measured mass

Summary of systematic uncertainties for the binding energy measurements using 3 GeV data

Source	${}^{4}_{\Lambda}\mathrm{H}$ [MeV]	${}^{4}_{\Lambda}\mathrm{He}$ [MeV]
Momentum scaling factor	0.11	0.11
Energy loss correction	0.08	0.05
BDT response cut	0.03	0.01
Total	0.14	0.12

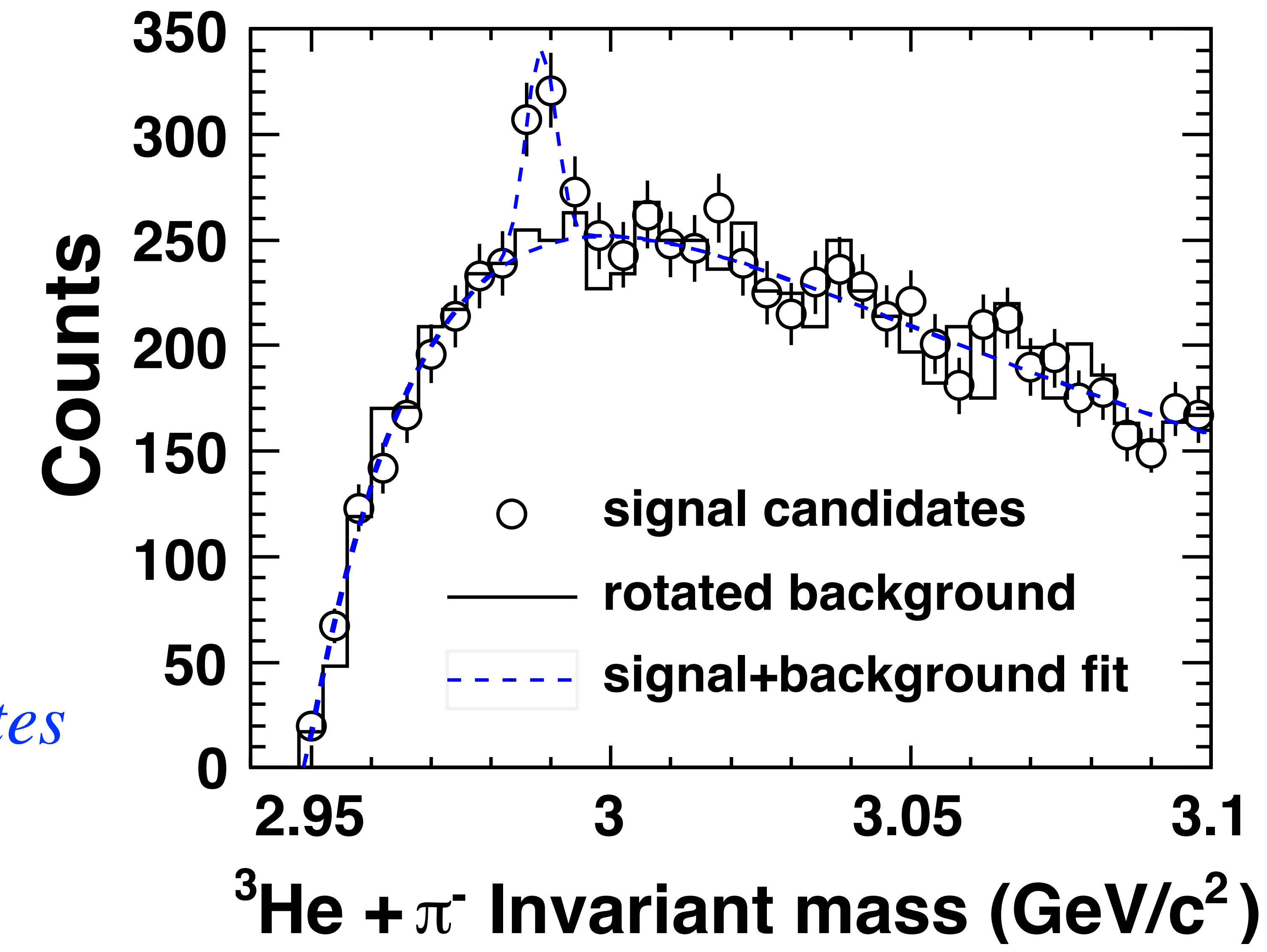
Past studies of hypernuclei lifetime at STAR

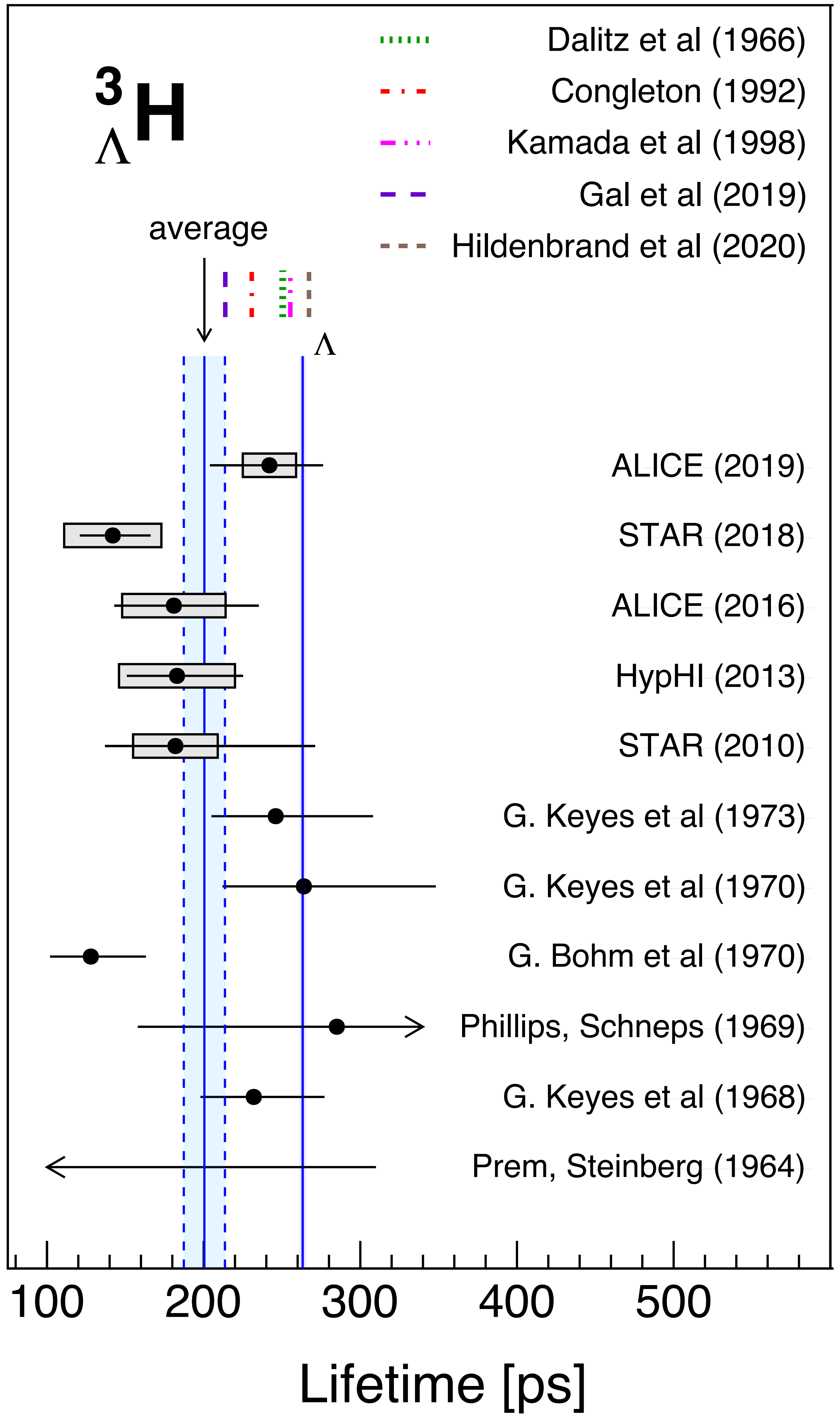
- In 2010, STAR observed the anti-hypertriton
  - First measurement of hypertriton lifetime from heavy ion collisions

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

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

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