Recent Hypernuclei Measurements from BES Program

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Outline

- Introduction
- Review of hypernuclei study in BES-I
- Recent progress of hypernuclei study
  - Hypernuclei internal structure
    - Hypernuclei branching ratios, lifetimes, Λ binding energies
  - Hypernuclei production in heavy-ion collisions
    - Hypernuclei yields, collectivity
- Summary

Introduction - Hypernuclei

Hypernuclei: bound nuclear systems of non-strange and strange baryons

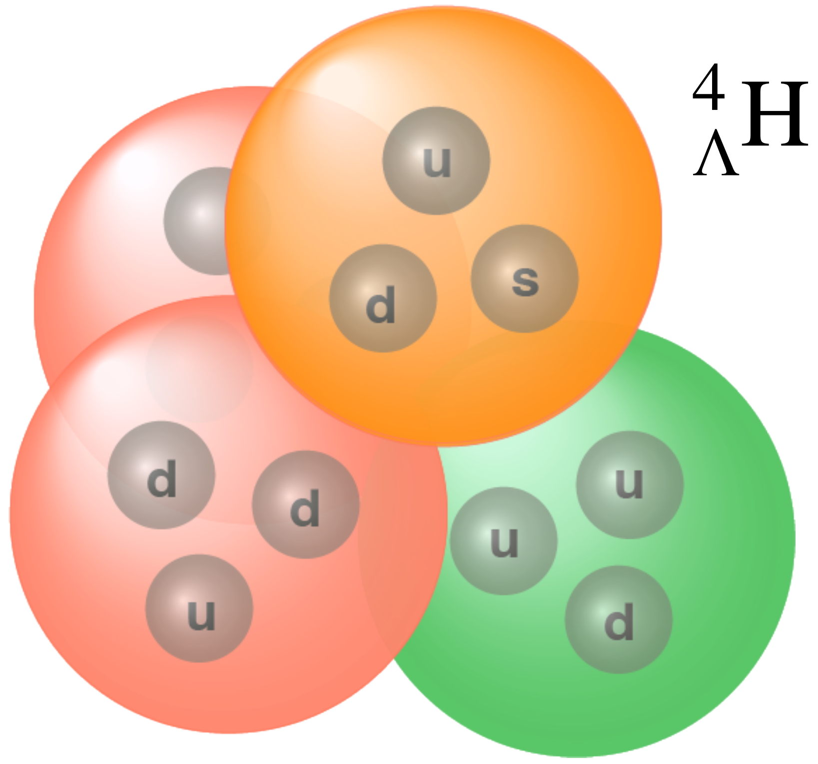
- Probe hyperon-nucleon(Y-N) interaction
  - Strangeness in high density nuclear matter
    - EoS of neutron star
- Experimentally, we can make measurements related to:

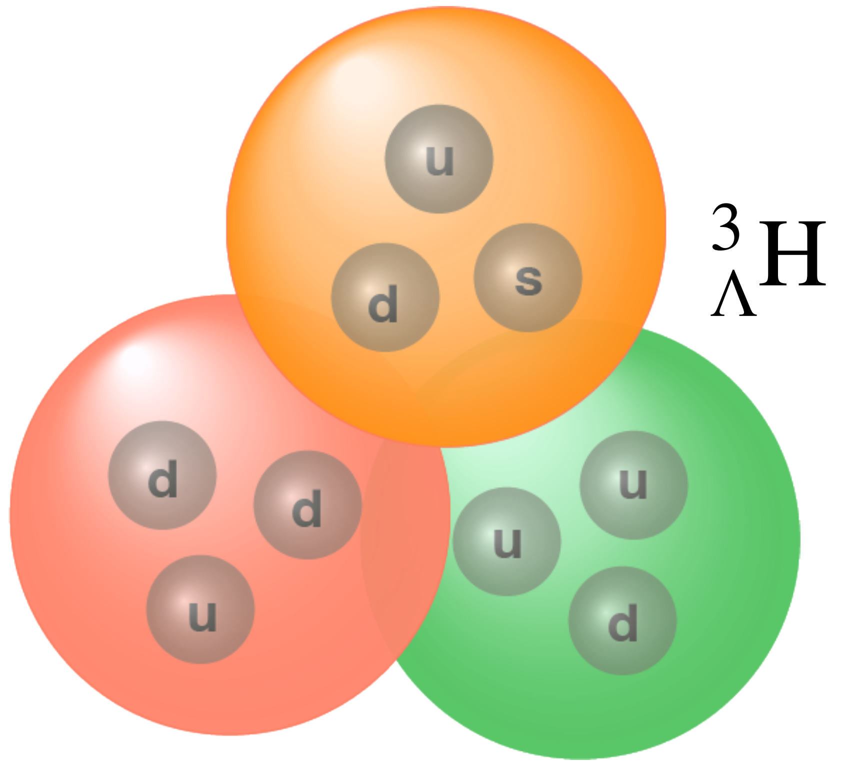
1. Internal structure
   - Lifetime, binding energy, branching ratios etc.

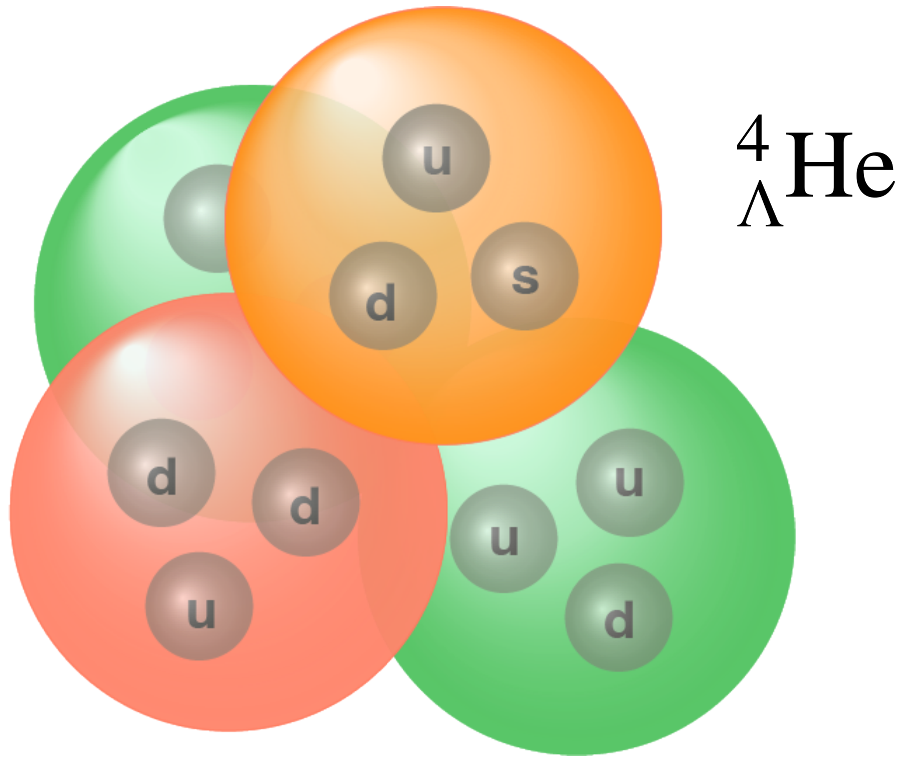
   Understanding hypernuclei structure may give more constraints on the Y-N interaction

2. Production in heavy-ion collisions
   - Spectra, collectivity etc.

   The formation of loosely bound states in violent heavy-ion collisions is not well understood



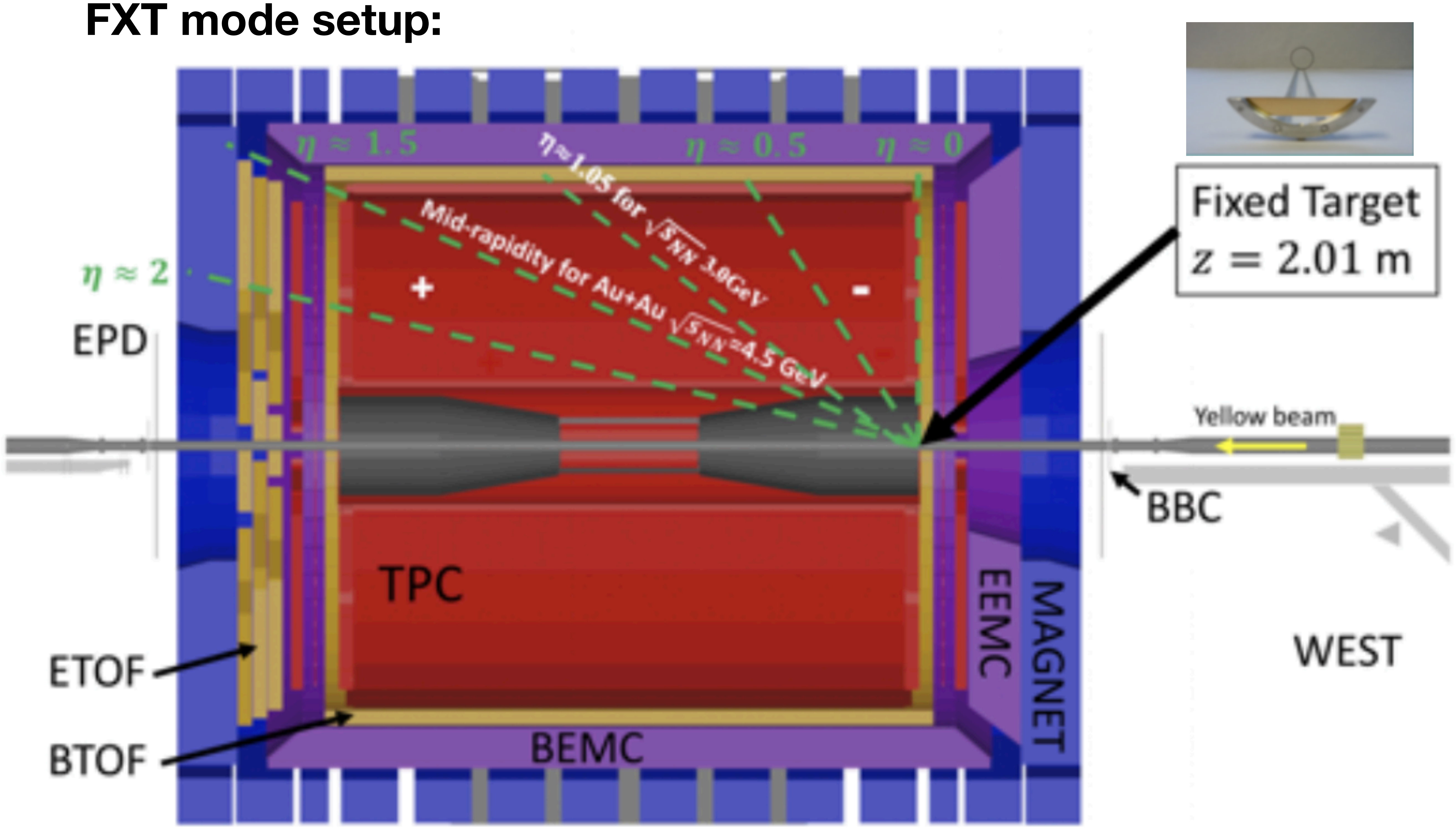


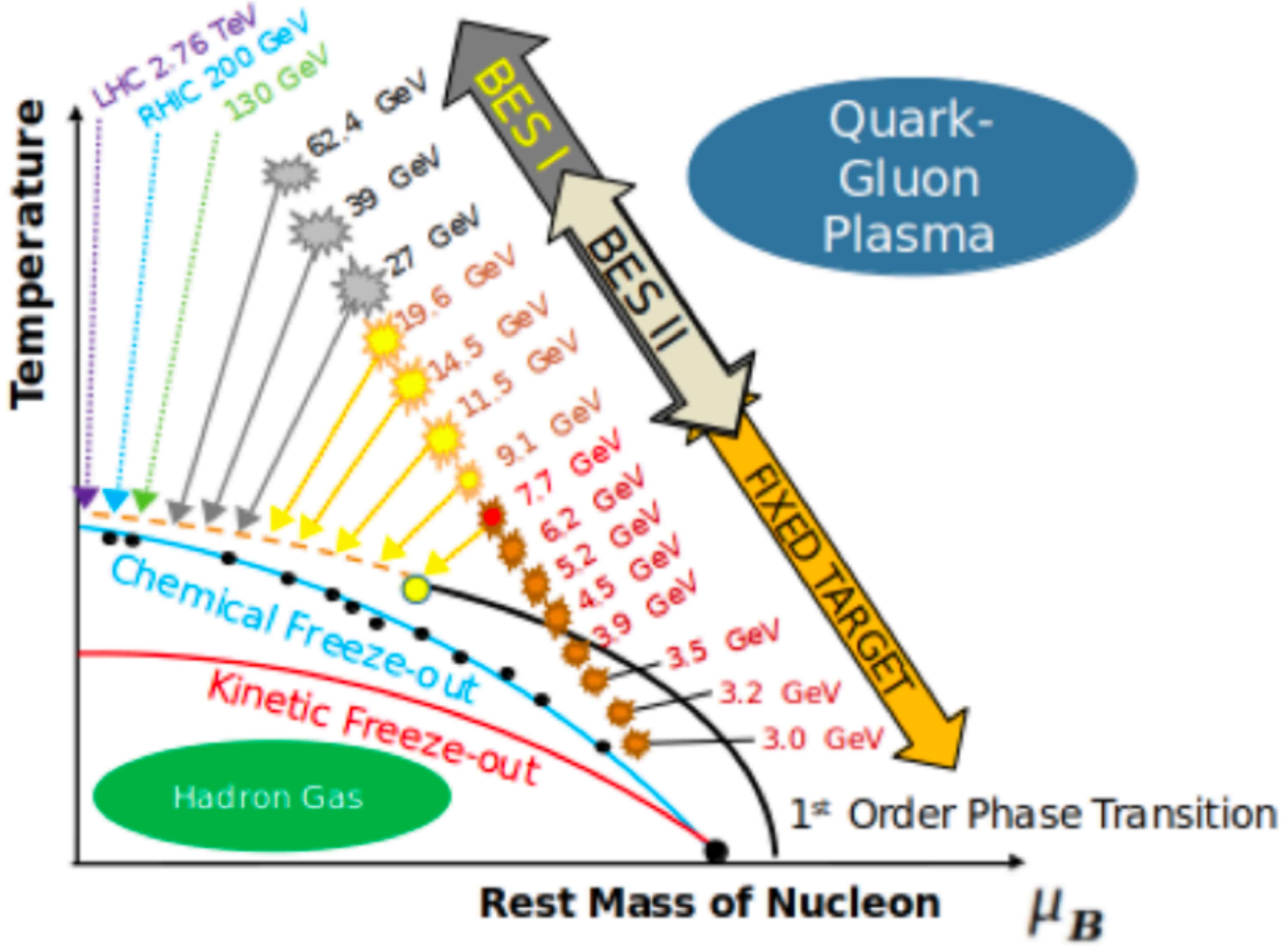


STAR and BES-II

- Collider mode: $\sqrt{s_{NN}}$ = 7.7 - 19.6 GeV
- Fixed Target (FXT) mode: extends collision energy down to $\sqrt{s_{NN}}$ = 3.0 GeV

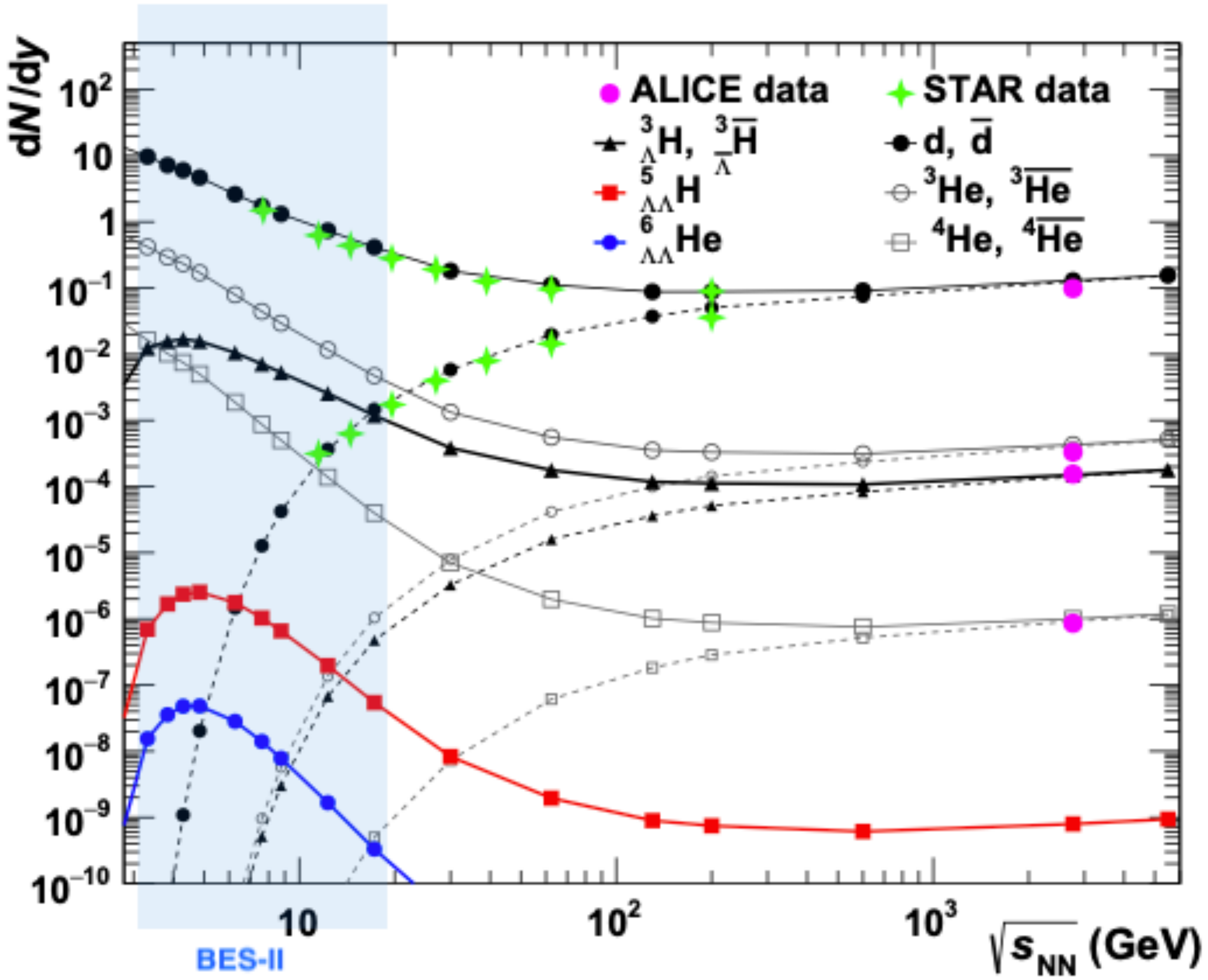
FXT mode setup:





Hypernuclei and STAR BES-II

- **Hypernuclei measurements are scarce in heavy-ion collisions experiments**



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

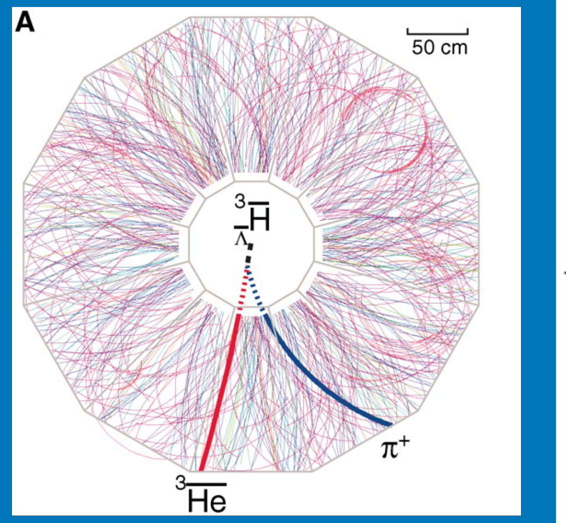
1. At lower beam energies, the hypernuclei production is expected to be enhanced due to high baryon density
2. Datasets of large statistics produced in BES-II

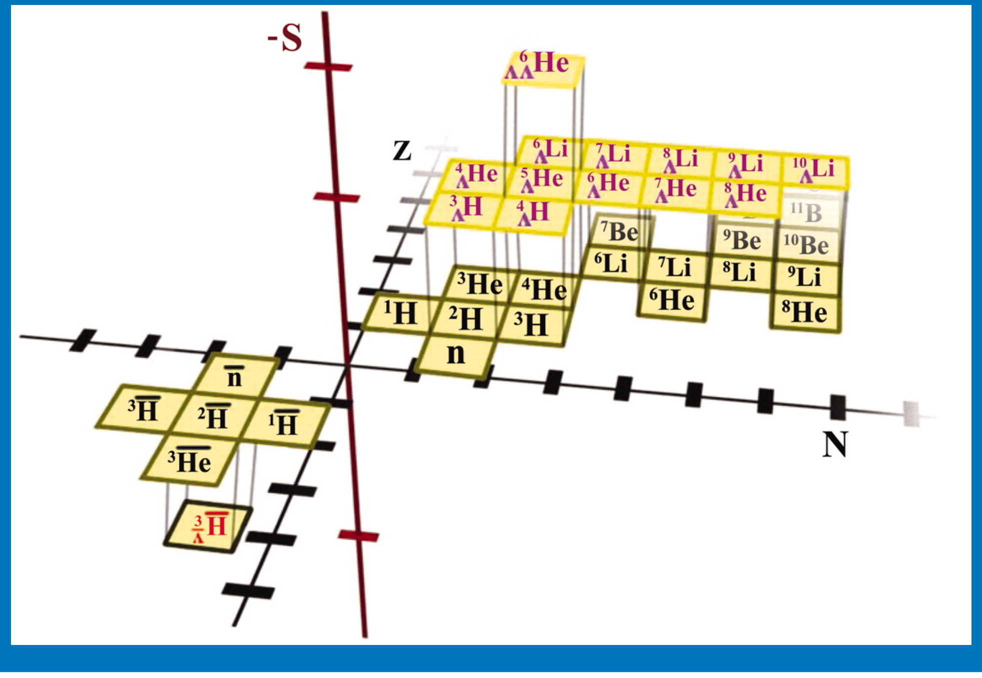
→ STAR BES-II gives a great opportunity to study hypernuclei production

List of BES-II datasets:

Year	$\sqrt{s_{NN}}$ [GeV]	Events
2018	27	555 M
	3.0	258 M
	7.2	155 M
2019	19.6	478 M
	14.6	324 M
	3.9	53 M
	3.2	201 M
	7.7	51 M
2020	11.5	235 M
	7.7	113 M
	4.5	108 M
	6.2	118 M
	5.2	103 M
	3.9	117 M
	3.5	116 M
	9.2	162 M
	7.2	317 M
2021	7.7	101 M
	3.0	2103 M
	9.2	54 M
	11.5	52 M
	13.7	51 M
	17.3	256 M
	7.2	89 M

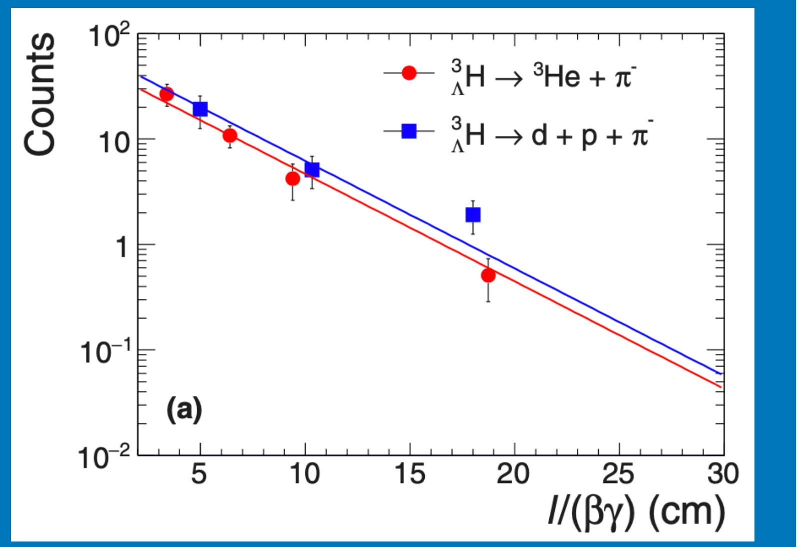
Hypernuclei analysis in STAR BES-I

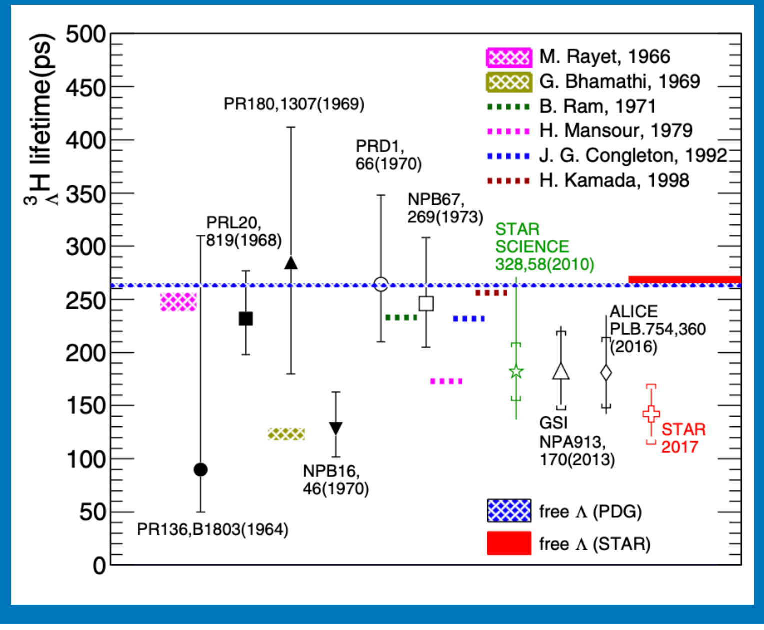




STAR collaboration **found the anti-hyper triton.**

Science 328, 58 (2010) (STAR)

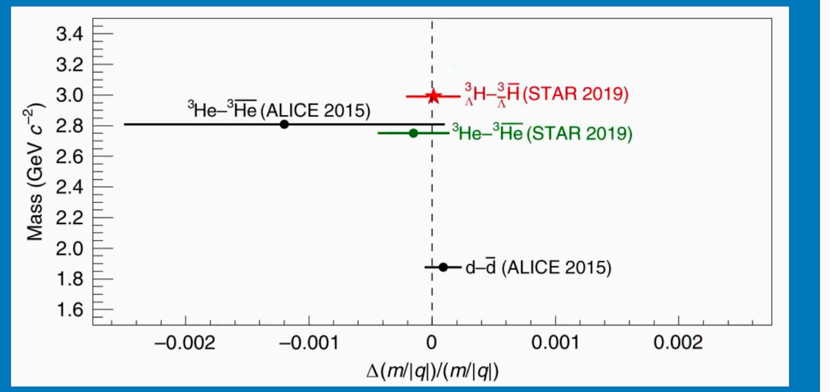


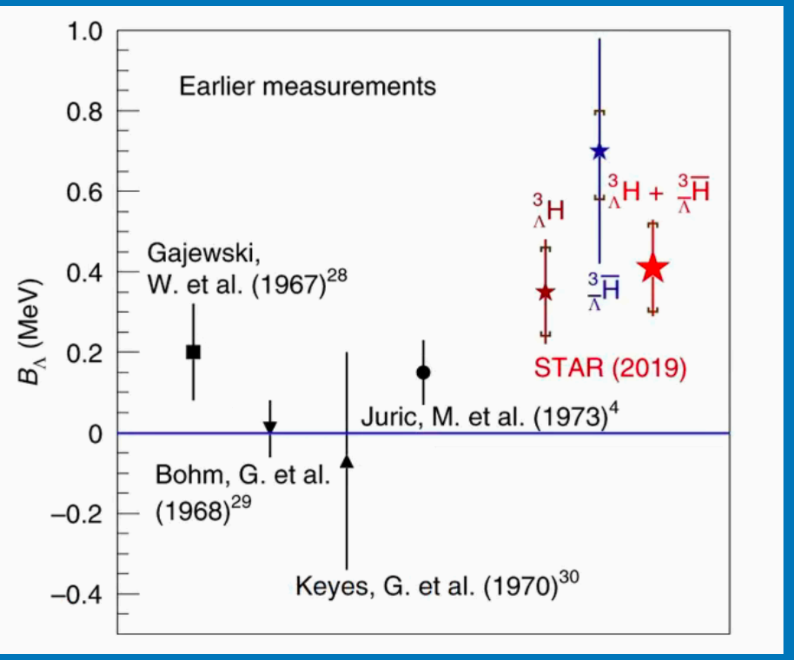


Lifetime measurement of ${}^{3}_{\Lambda}\mathrm{H}$

Science 328, 58 (2010) (STAR)

PRC 97, 054909 (2018) (STAR)

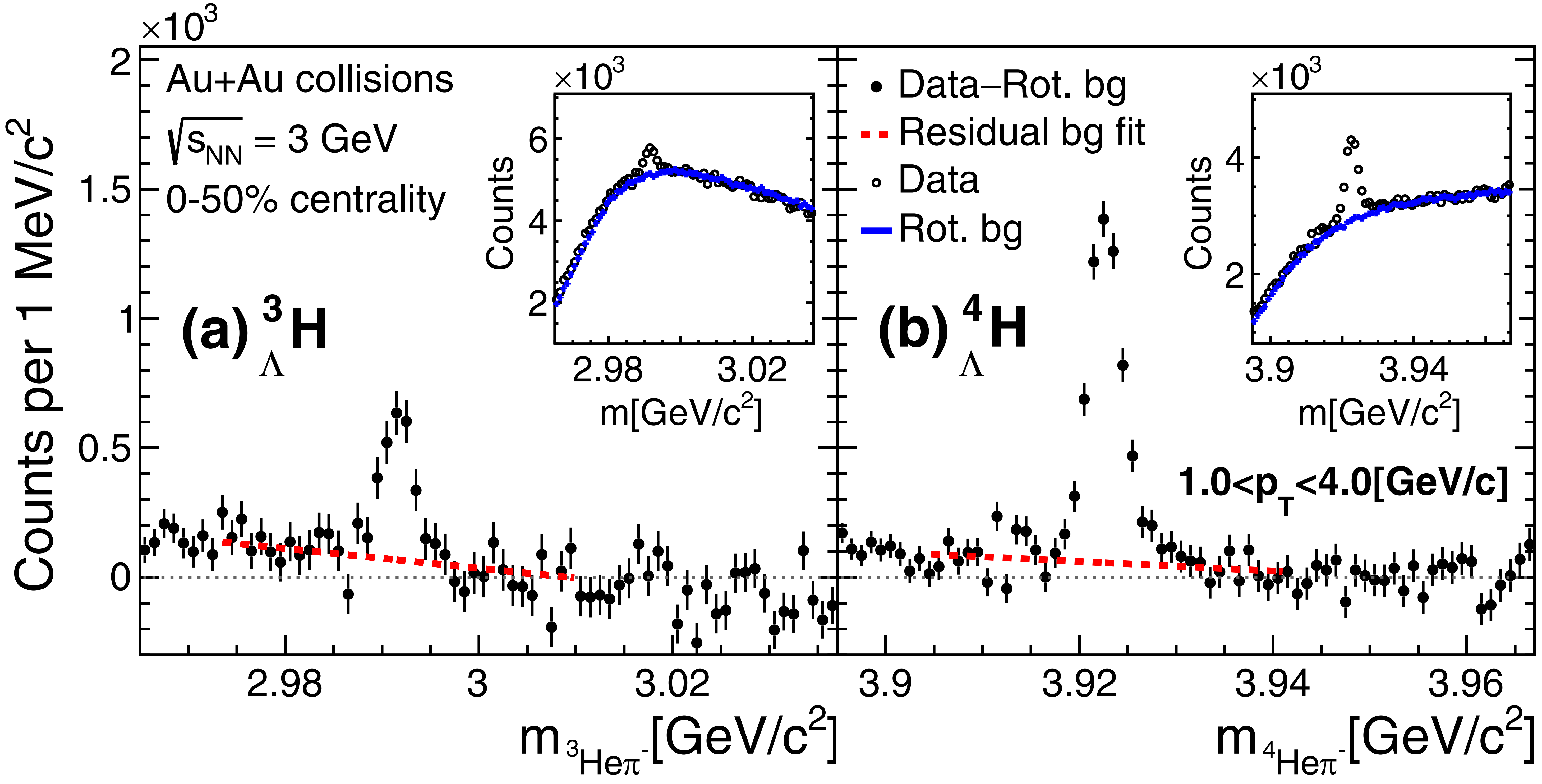


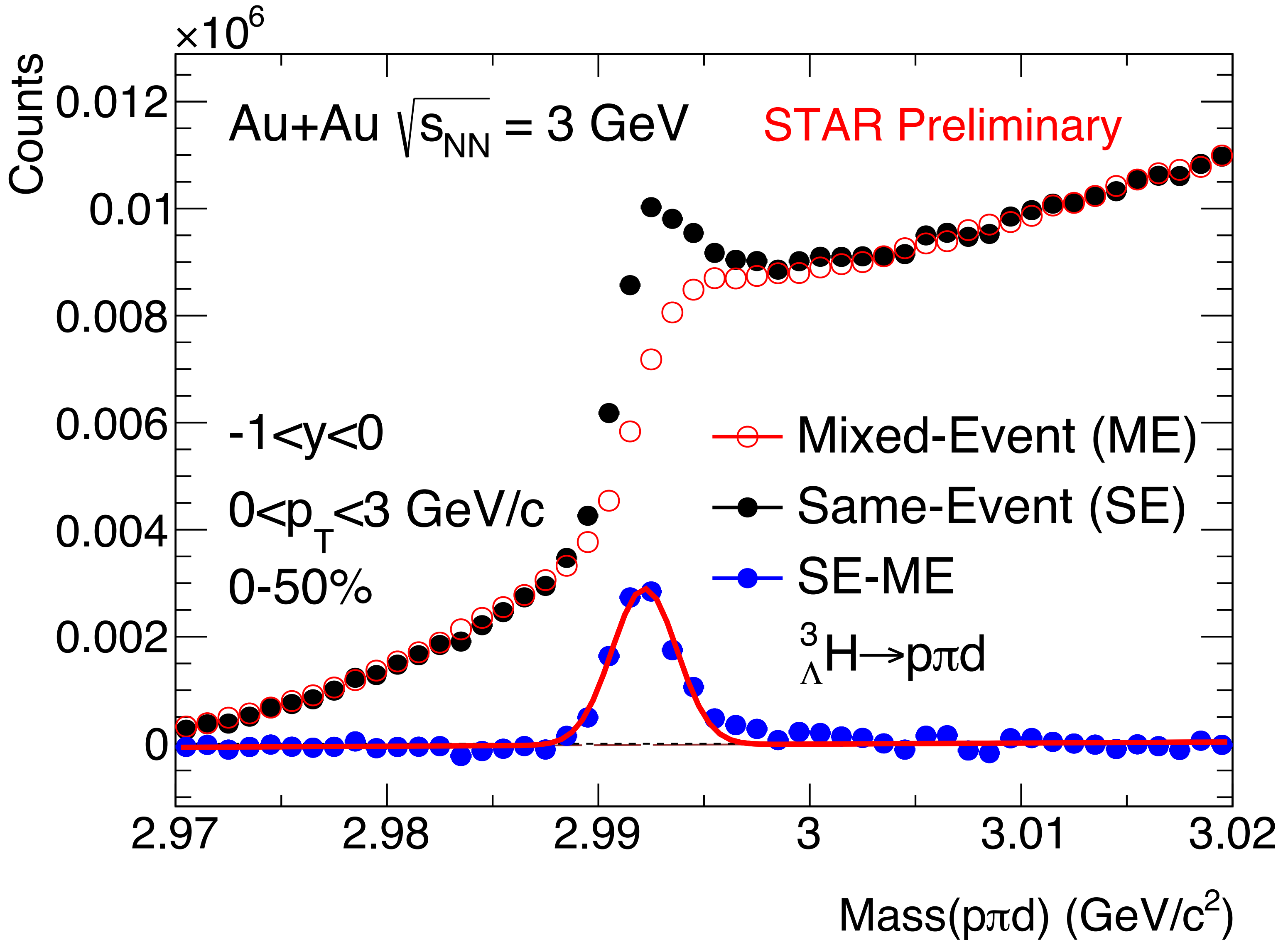


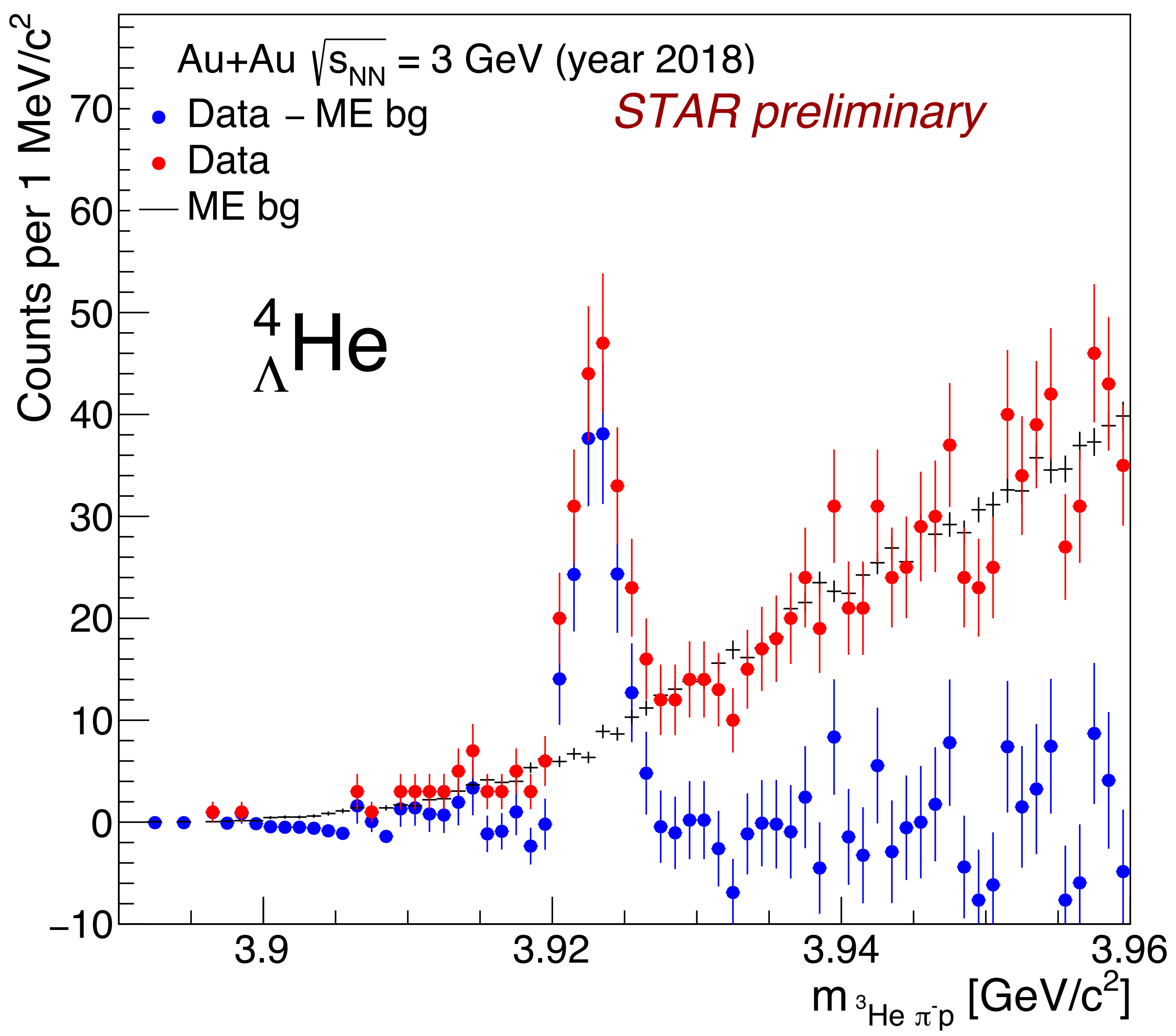
Measurement of mass difference and binding energy of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{3}_{\Lambda}\overline{\mathrm{H}}$

Nature Phys. 16 (2020) 409 (STAR)

Hypernuclei reconstruction







- Decay channels:

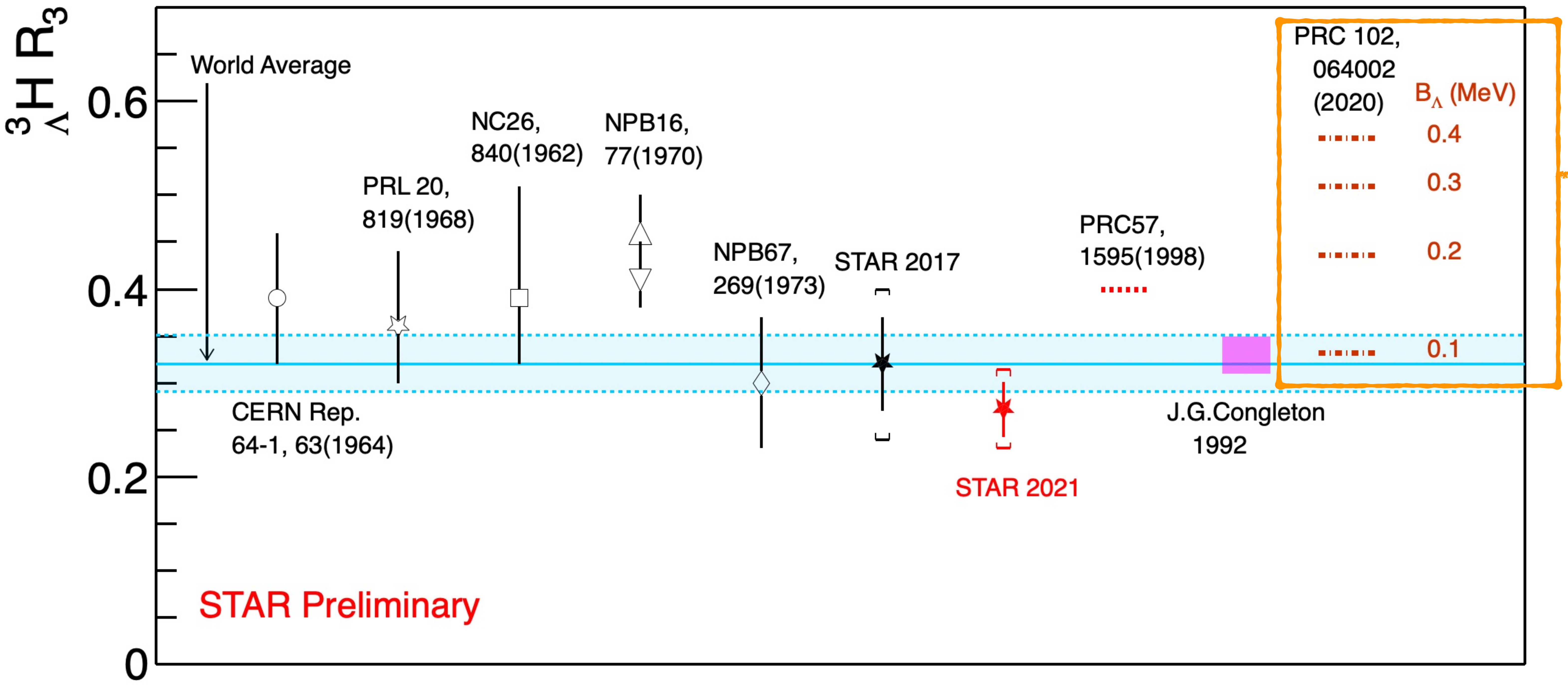
$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^-$ $\quad$ $^{3}_{\Lambda}H \rightarrow d + p + \pi^-$

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

- Combinatorial background estimated via rotating pion tracks or event mixing

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

Relative branching ratio: $\mathrm{R}_3 = \dfrac{\mathrm{B.R.}({}^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{He}\pi^-)}{\mathrm{B.R.}({}^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{He}\pi^-) + \mathrm{B.R.}({}^{3}_{\Lambda}\mathrm{H} \to \mathrm{d}p\pi^-)}$

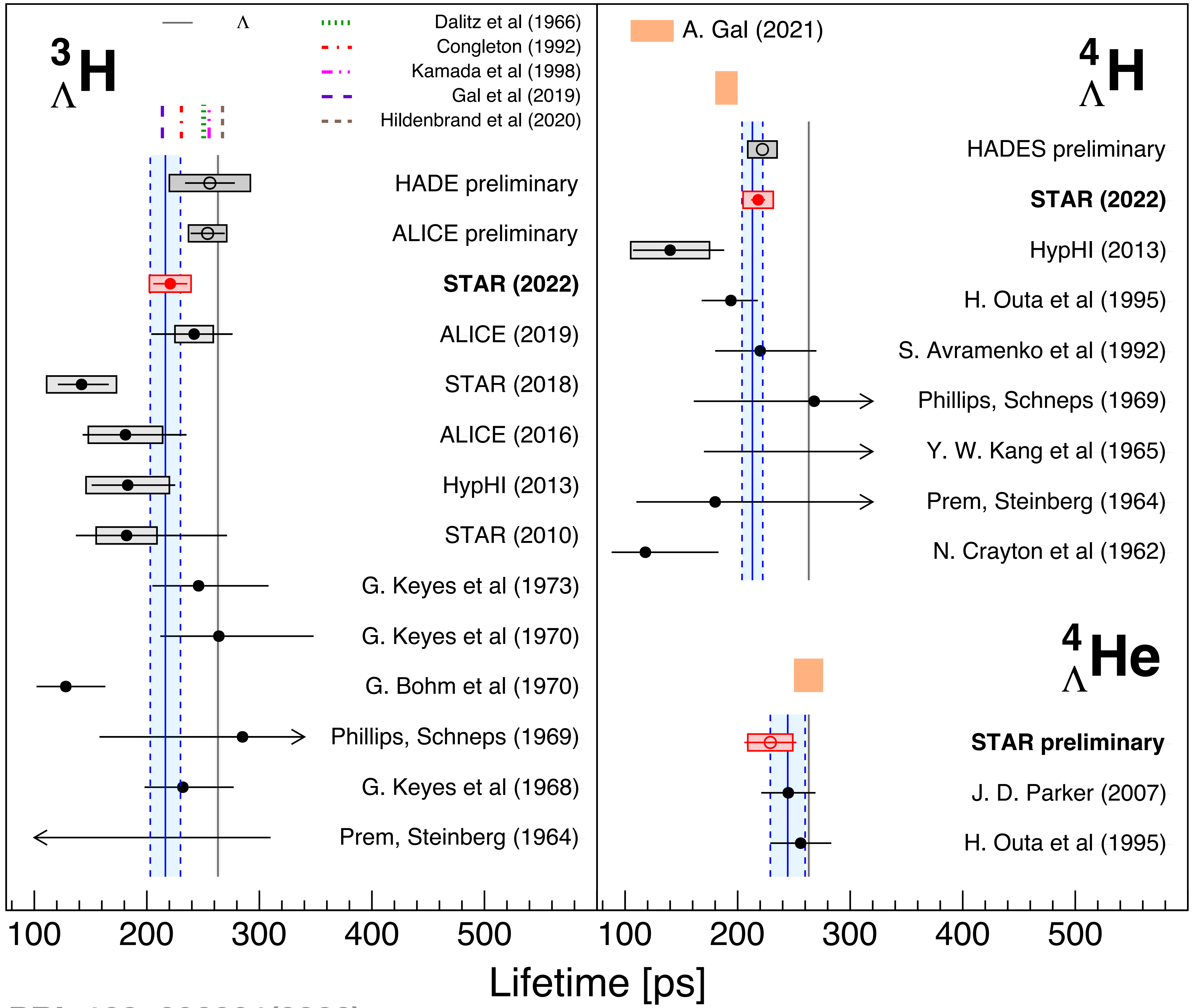


R_3 may be sensitive to the binding energy of ${}^{3}_{\Lambda}\mathrm{H}$

- STAR 2021 (preliminary): $\mathrm{R}_3 = 0.272 \pm 0.030 \pm 0.042$
  - Updated world average R_3 is consistent with theory calculation assuming B_Λ~ 0.1 MeV

- Improved precision on R_3
  - Stronger constraints on hypernuclear interaction models used to describe ${}^{3}_{\Lambda}\mathrm{H}$
  - Stronger constraints on absolute B.R.s

${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$ lifetimes



PRL 128, 202301(2022)

${}^{3}_{\Lambda}\mathrm{H}$: $\tau = 221 \pm 15(\mathrm{stat.}) \pm 19(\mathrm{syst.})[\mathrm{ps}]$

${}^{4}_{\Lambda}\mathrm{H}$: $\tau = 218 \pm 6(\mathrm{stat.}) \pm 13(\mathrm{syst.})[\mathrm{ps}]$

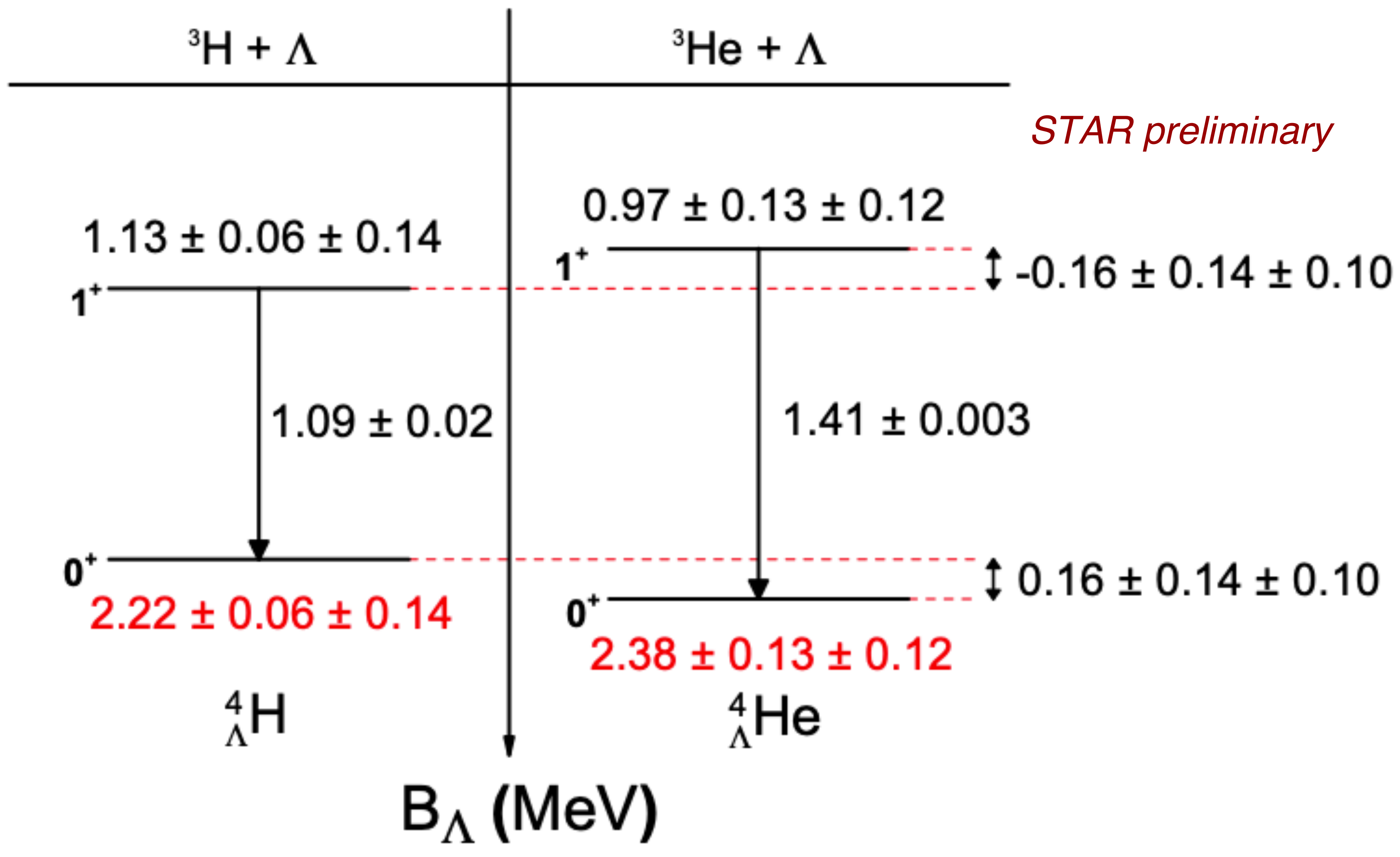
${}^{4}_{\Lambda}\mathrm{He}$: $\tau = 229 \pm 23(\mathrm{stat.}) \pm 20(\mathrm{syst.})[\mathrm{ps}]$

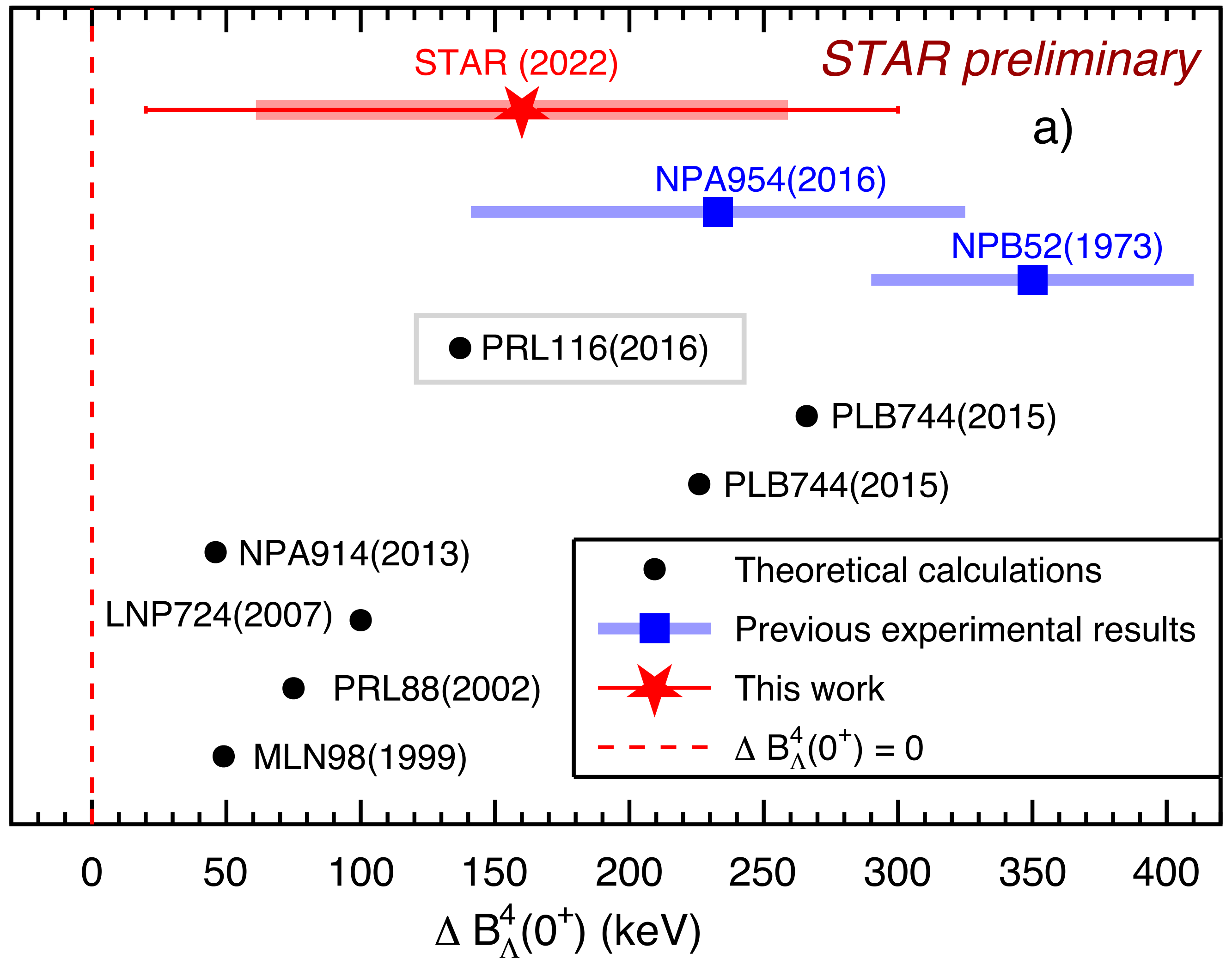
- Lifetime of light hypernuclei ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$ are shorter than that of free Λ (with 1.8σ, 3.0σ, 1.1σ respectively)
- Consistent with former measurements (within 2.5σ for ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$)
- $\tau_{{}^{3}_{\Lambda}\mathrm{H}}$ result consistent with calculation including pion FSI (2019) and calculation under Λd 2-body picture (1992) within 1σ

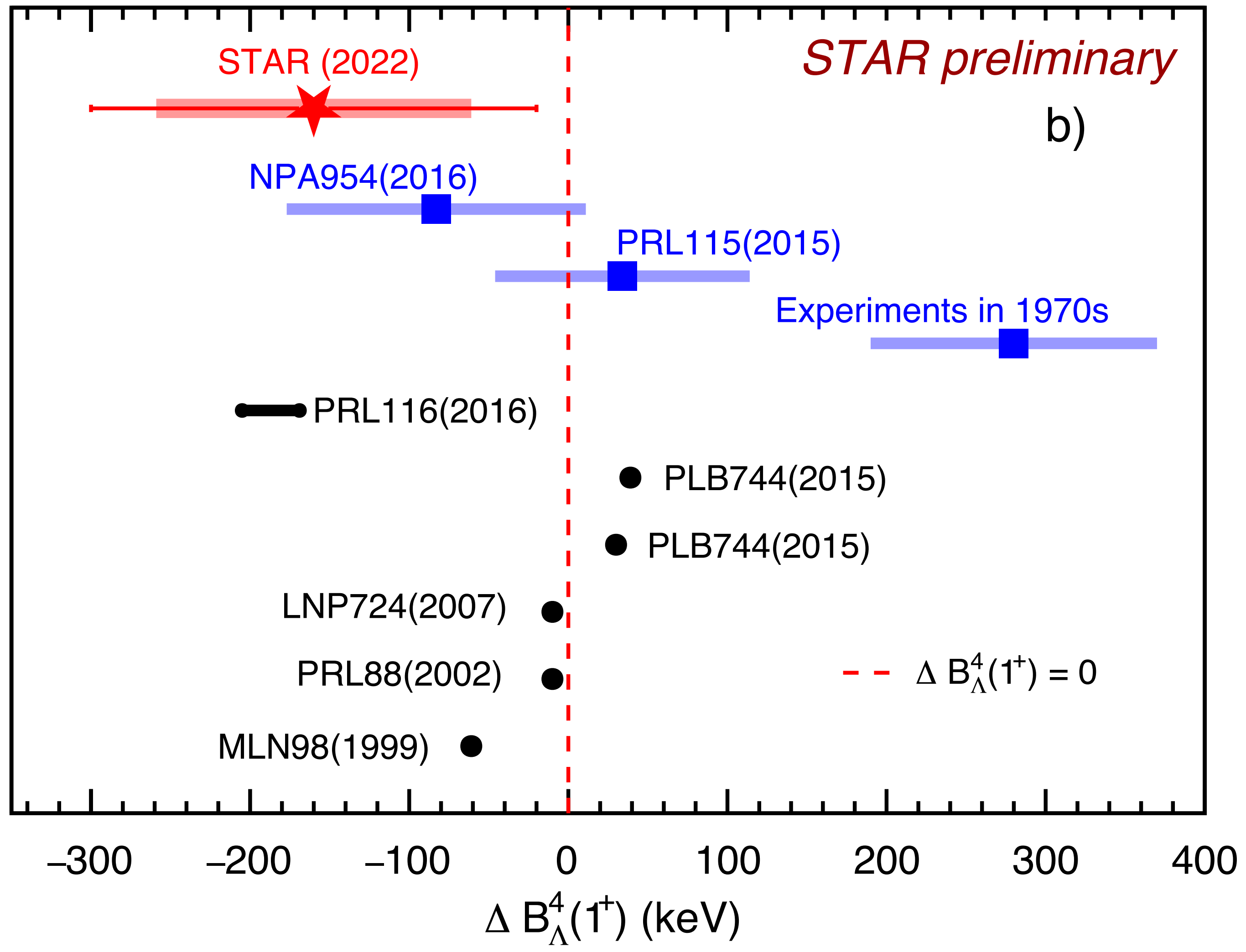
${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$ results with improved precision

→ Provide tighter constraints on models.

B_Λ and ΔB_Λ of ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He







- Λ binding energies(B_Λ) of ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He and their differences ΔB_Λ
  - For ground states, $\Delta B^4_\Lambda(0^+) = B_\Lambda({}^4_\Lambda\mathrm{He},0^+) - B_\Lambda({}^4_\Lambda\mathrm{H},0^+)$
  - For excited states, the results are obtained from the γ-ray transition energies E_γ

$$B^4_\Lambda({}^4_\Lambda\mathrm{He/H},1^+) = B_\Lambda({}^4_\Lambda\mathrm{He/H},0^+) - E_\gamma({}^4_\Lambda\mathrm{He/H})$$

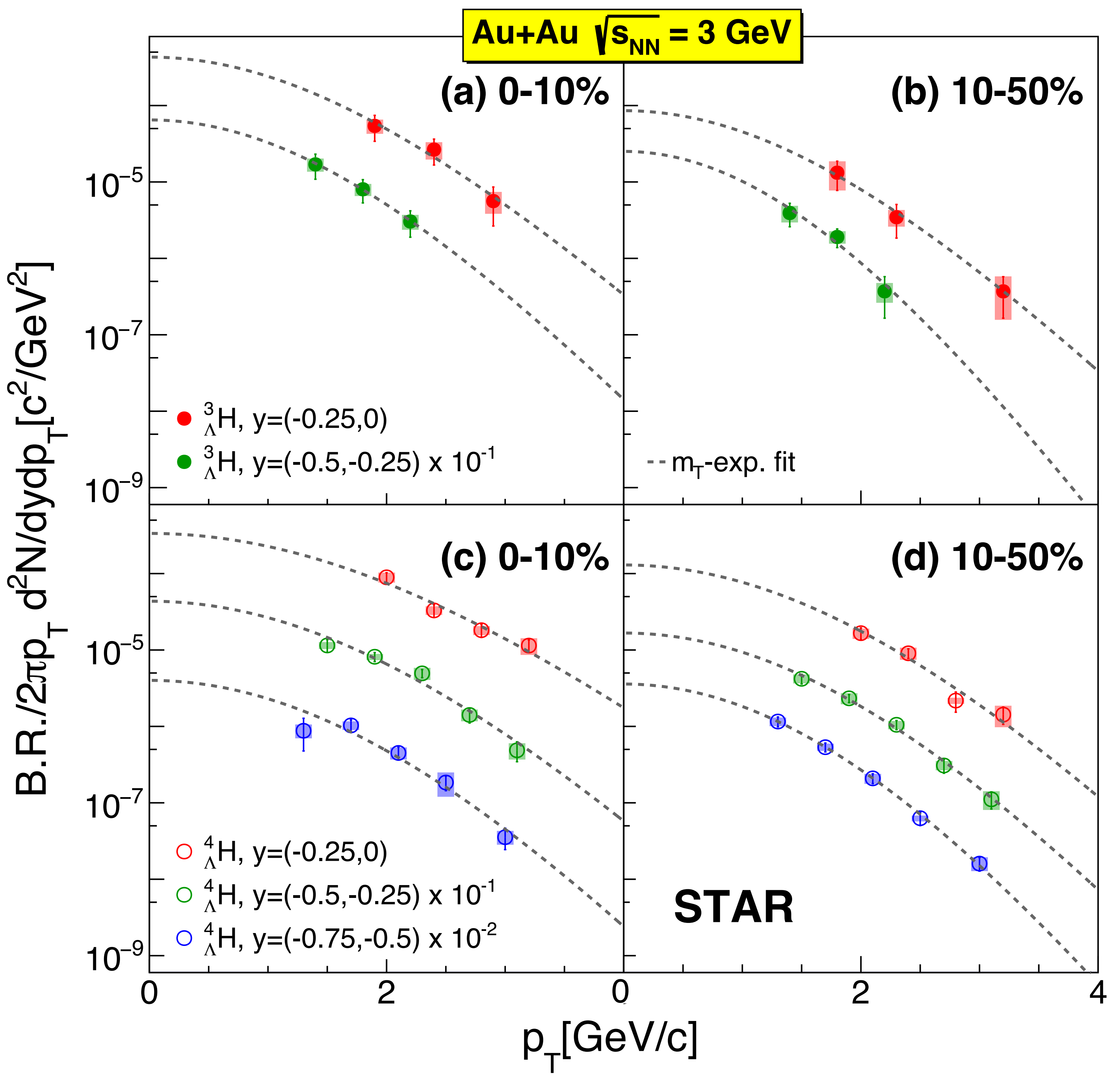
$$\Delta B^4_\Lambda(1^+) = B_\Lambda({}^4_\Lambda\mathrm{He},1^+) - B_\Lambda({}^4_\Lambda\mathrm{H},1^+)$$

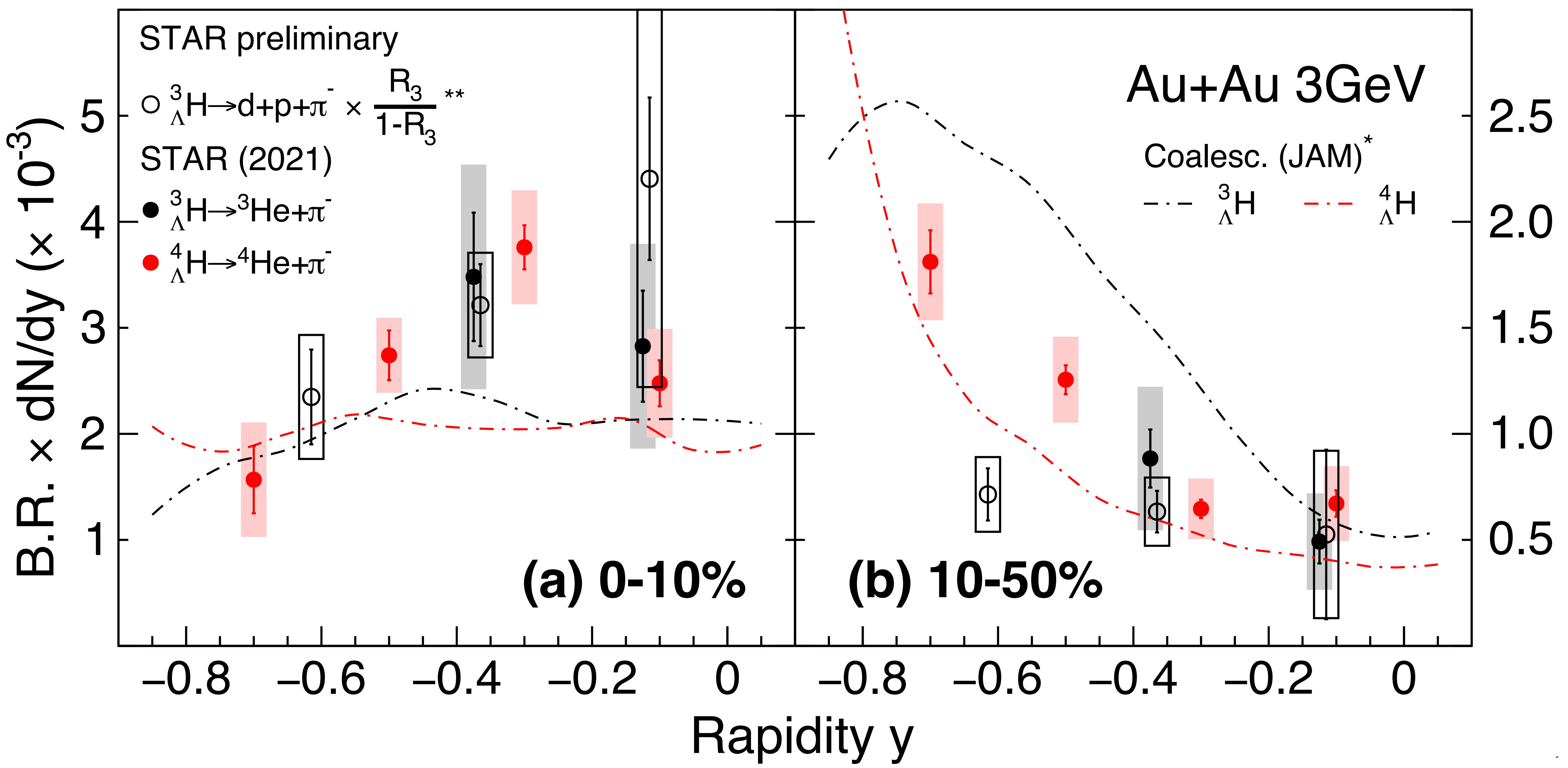
- Λ binding-energy difference

→ Study charge symmetry breaking (CSB) effect in A = 4 hypernuclei

- Differences are comparable large values and have opposite sign in 0^+ and 1^+ states
  - Consistent with the calculation including a CSB effect within uncertainties.

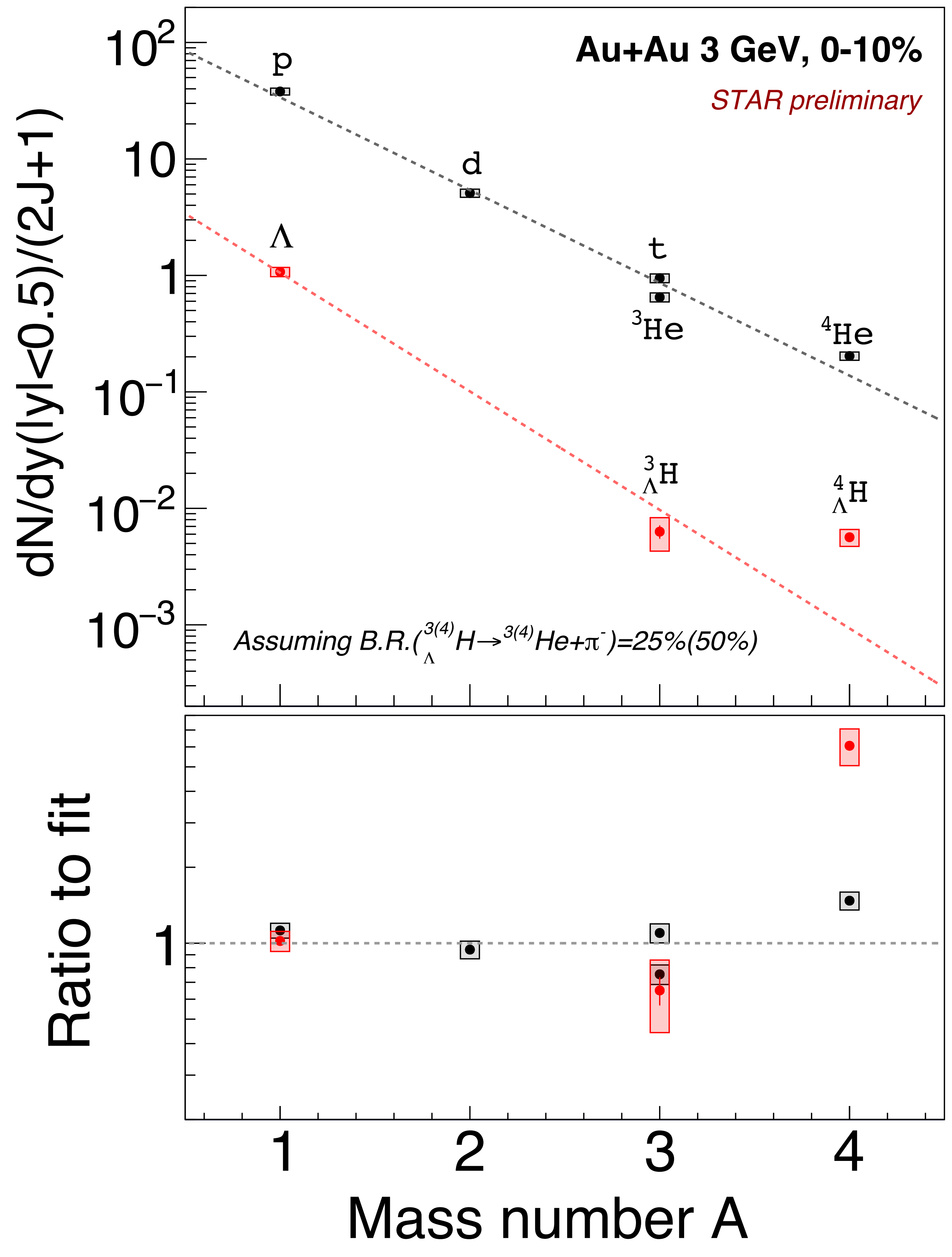
Hypernuclei production at 3 GeV



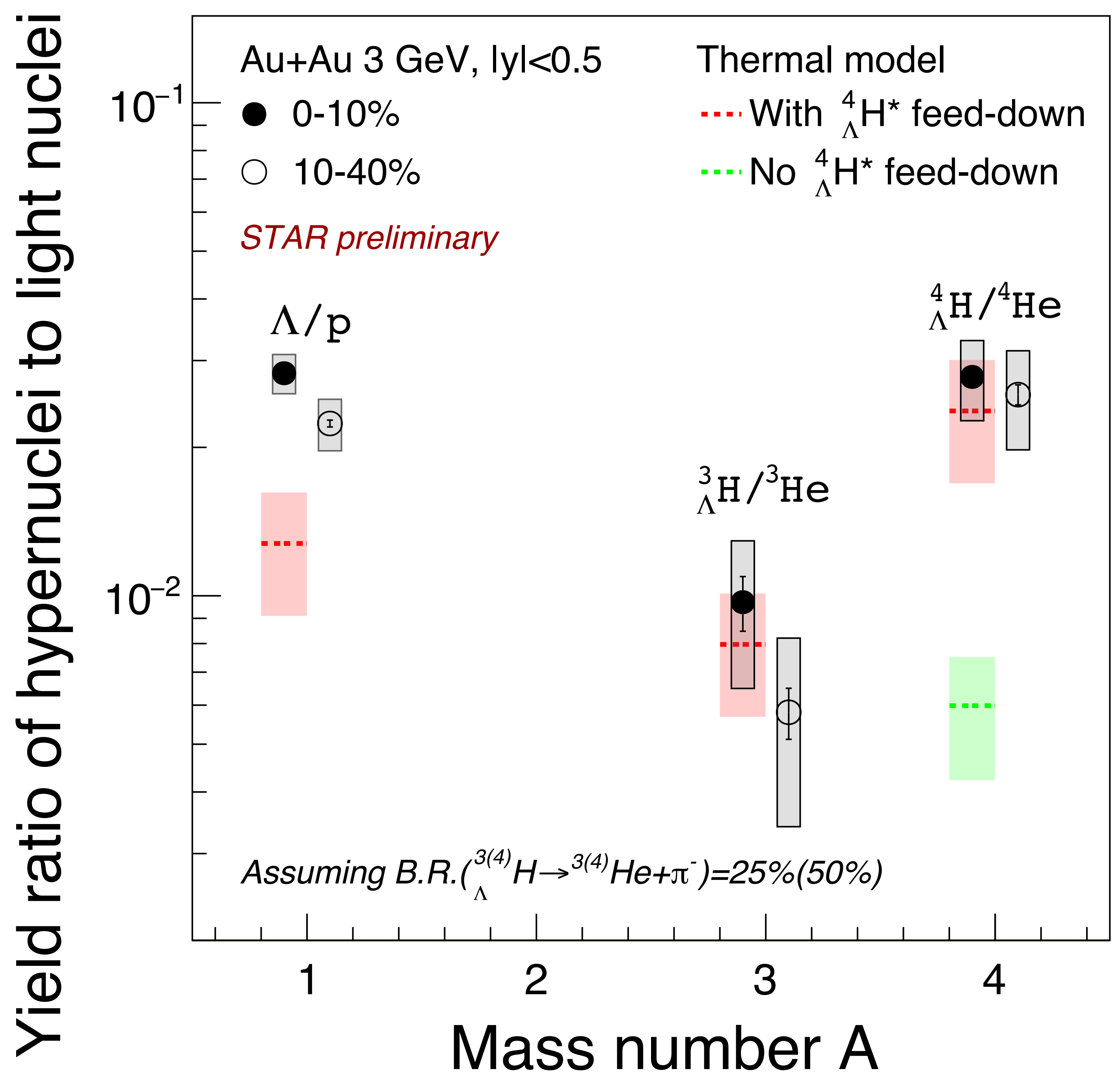


- First measurement of dN/dy of hypernuclei in heavy-ion collisions
- Different trends in the $^4_\Lambda\mathrm{H}$ rapidity distribution in central (0-10%) and mid-central (10-50%) collisions
  - Transport model (JAM) with coalescence reproduces trends of $^4_\Lambda\mathrm{H}$ rapidity distributions seen in data

Comparison to Λ and light nuclei at 3 GeV



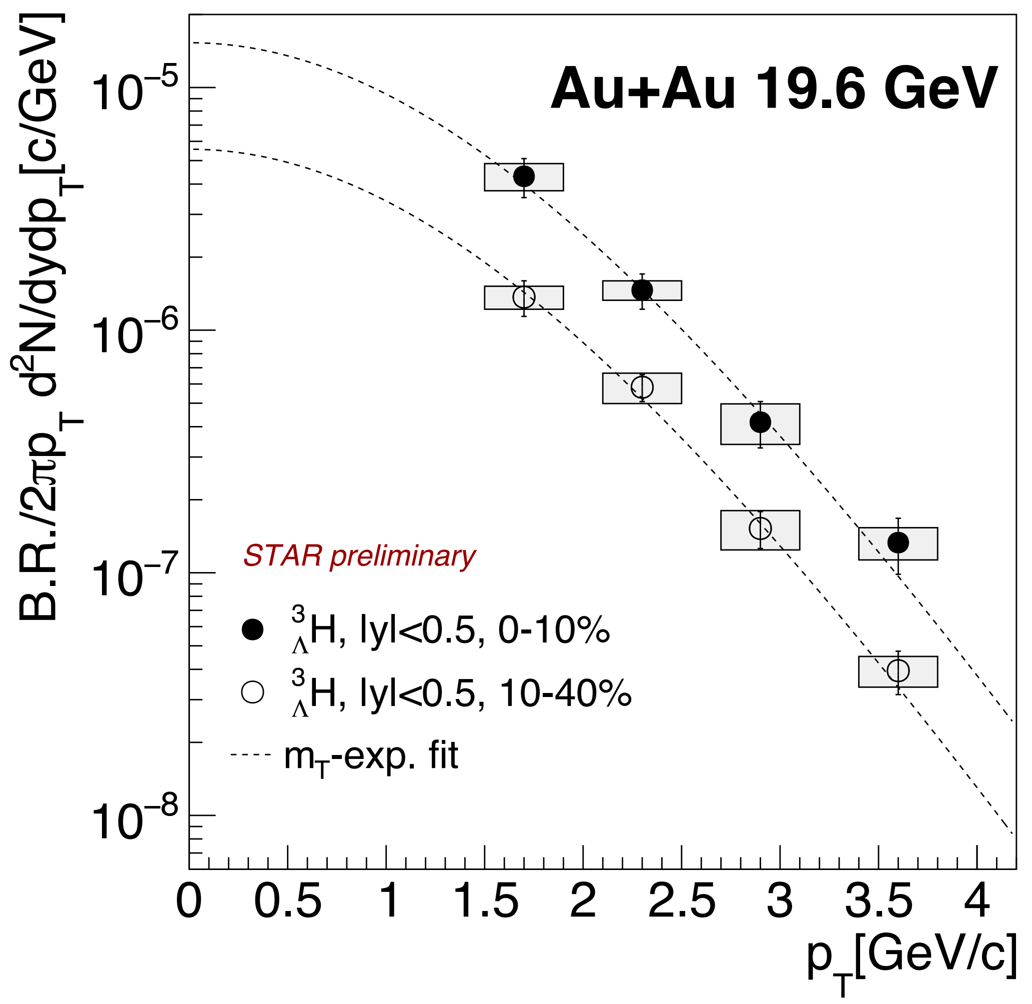
- Thermal/coalescence models predict approx. exponential dependence of yields/(2J+1) vs A
- $^{4}_{\Lambda}\mathrm{H}$ lies a factor of 6 above exponential fit to $(\Lambda, {}^{3}_{\Lambda}\mathrm{H}, {}^{4}_{\Lambda}\mathrm{H})$

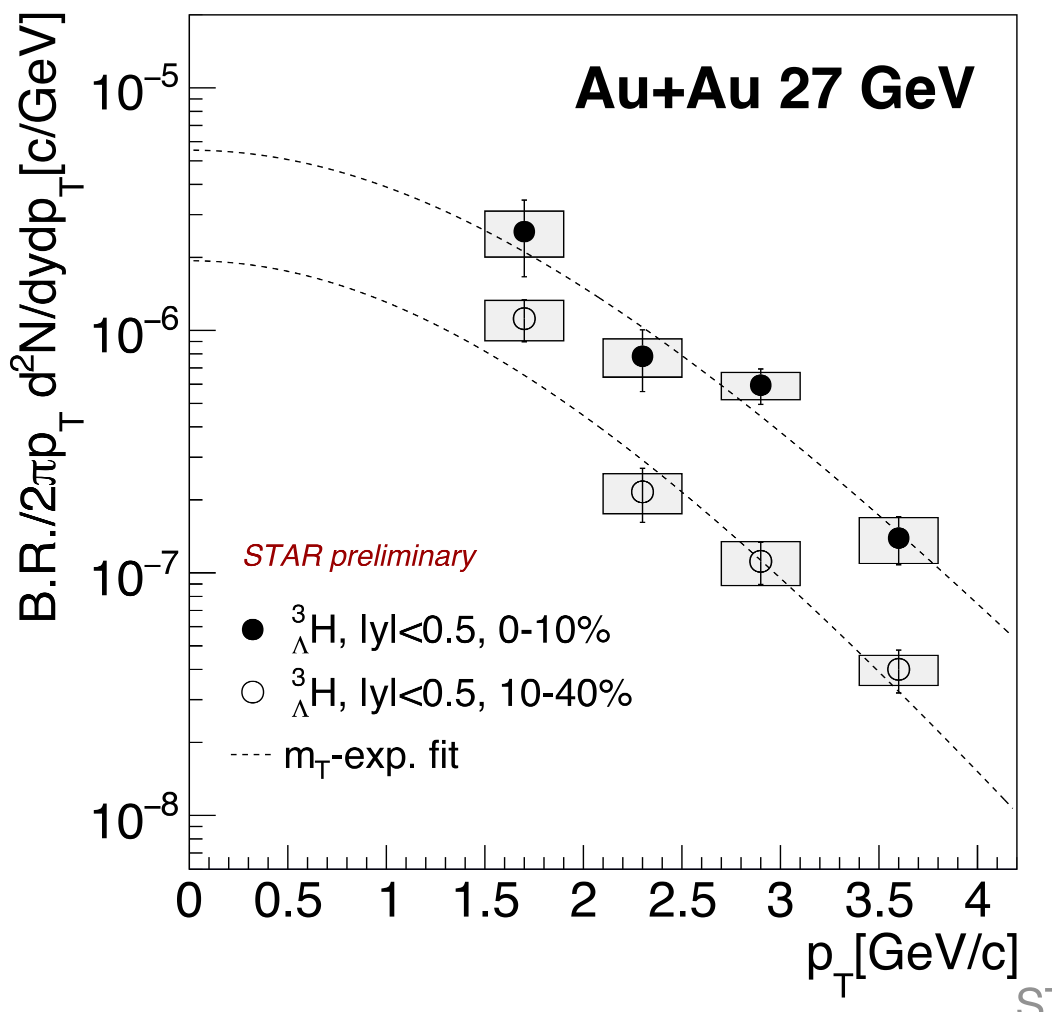


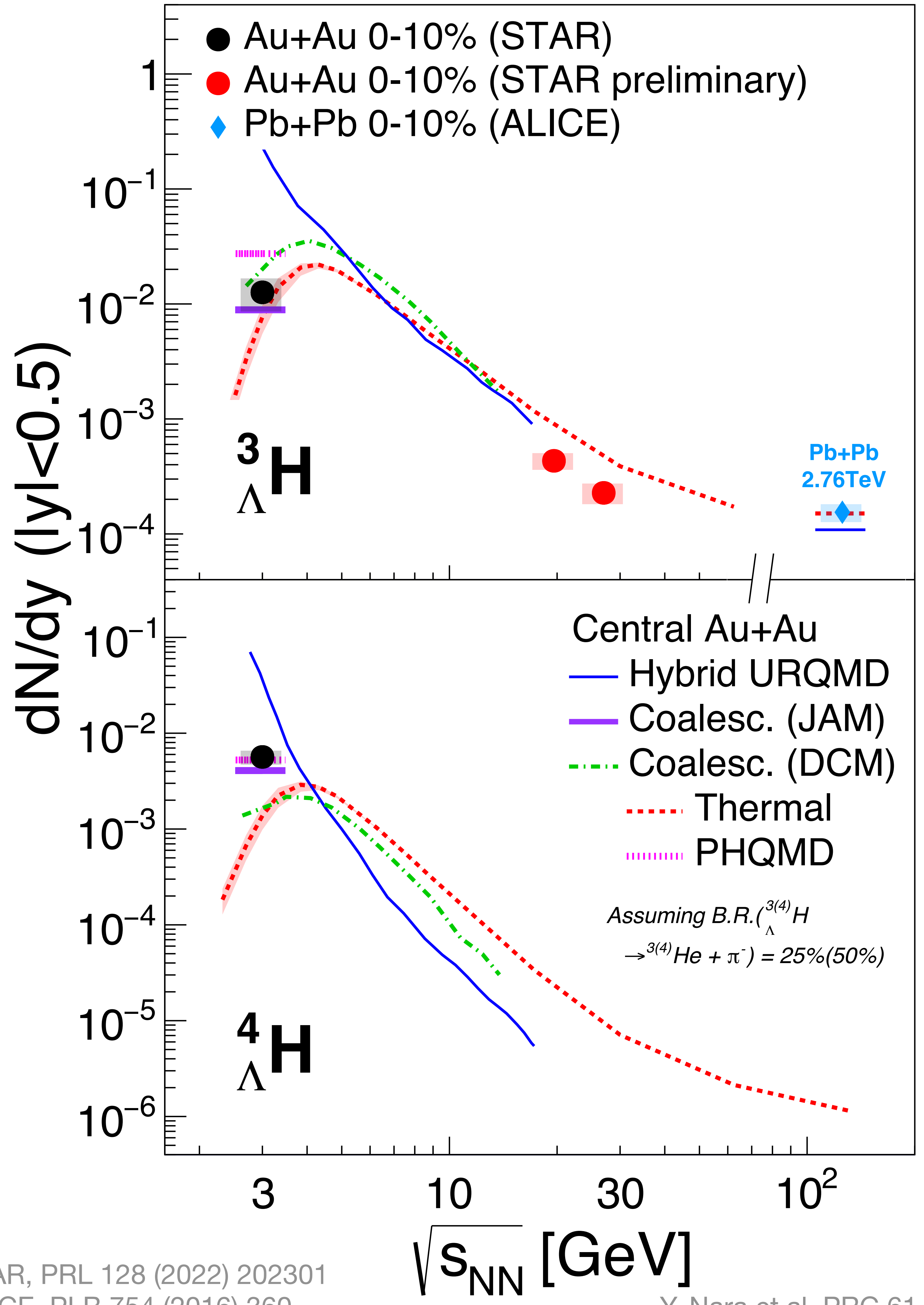
- Non-mononic behavior in light-to-hyper-nuclei ratio vs A observed
  - Thermal model calculations including excited $^{4}_{\Lambda}\mathrm{H}^{*}$ feed-down shows a similar trend

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

Energy dependence of hypernuclei production in heavy-ion collisions







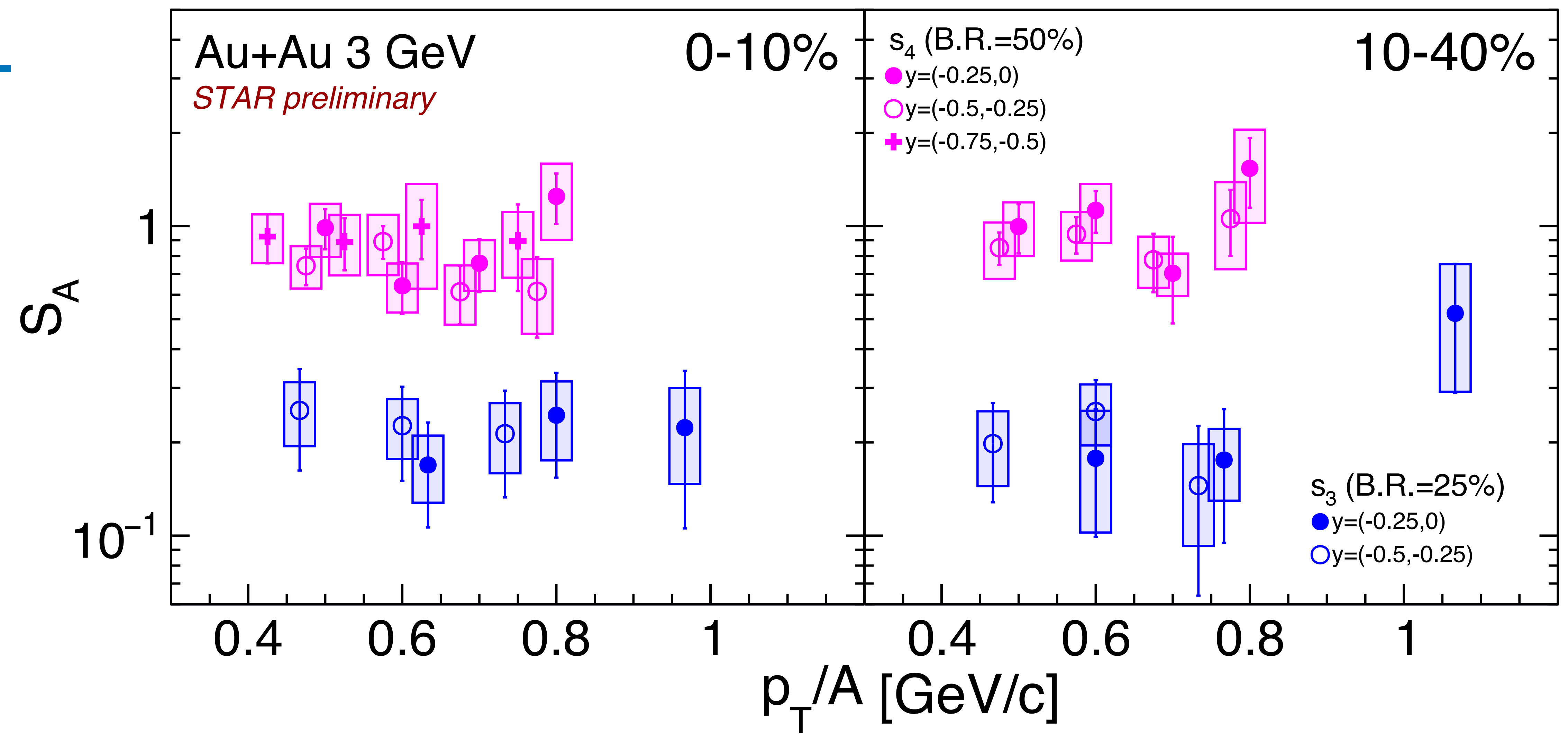
- ${}^{3}_{\Lambda}H$ yield at mid-rapidity increases from 2.76 TeV to 3 GeV
  - Driven by increase in baryon density at low energies
- Thermal model reproduces the trend, but slightly overestimate the yields of ${}^{3}_{\Lambda}H$ at 19.6 and 27 GeV. Meanwhile, ${}^{4}_{\Lambda}H$ is underestimated.
- Coalescence(DCM) cannot describe ${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$ yields using same coalescence parameters, whereas coalescence(JAM) using different parameters approximately can
- PHQMD describes ${}^{4}_{\Lambda}H$ at 3 GeV, but slightly overestimates ${}^{3}_{\Lambda}H$
- Hybrid URQMD overestimates both yields at 3 GeV by an order of magnitude

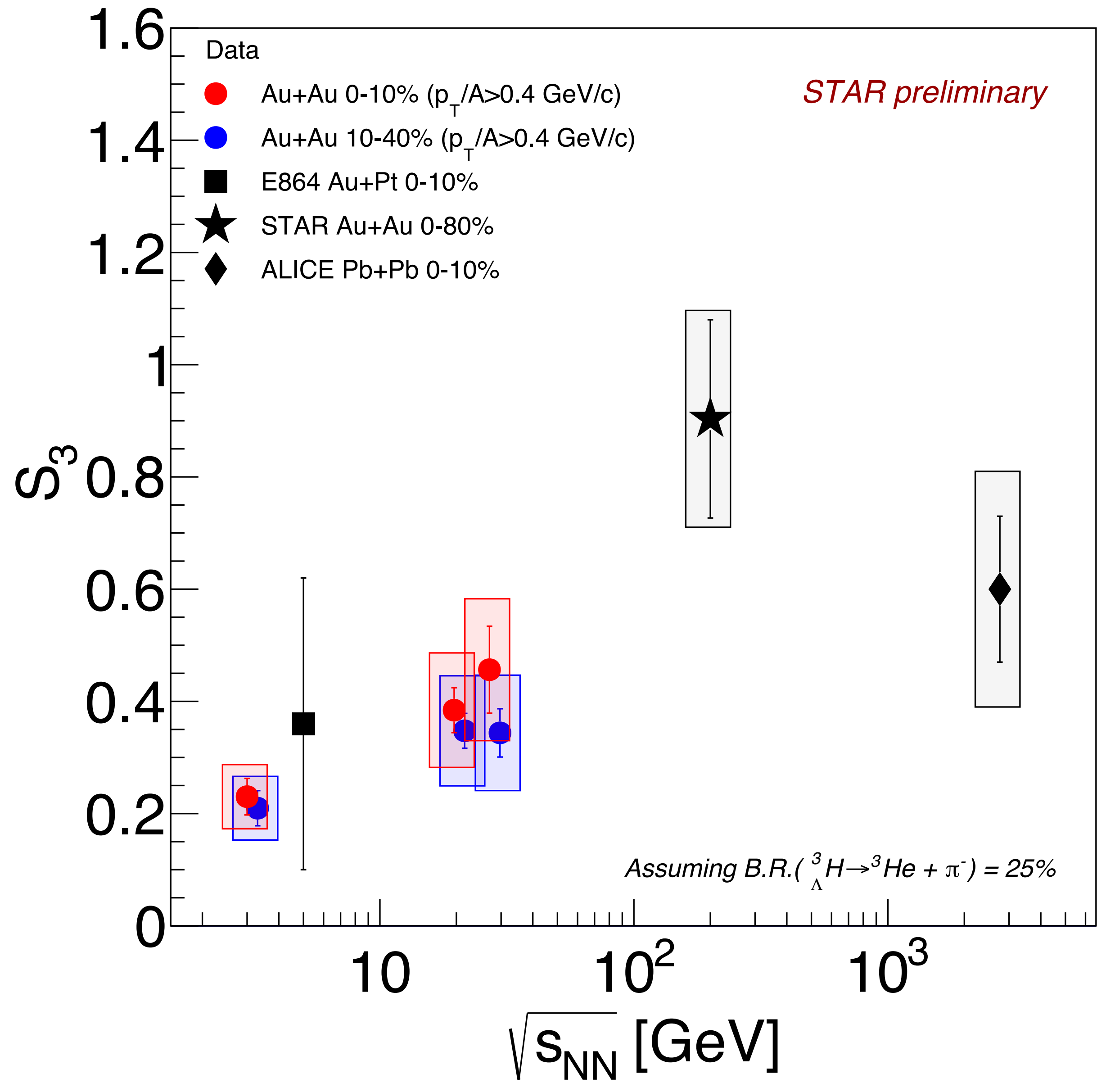
Provide first constrains for hypernuclei production models in the high-baryon-density region

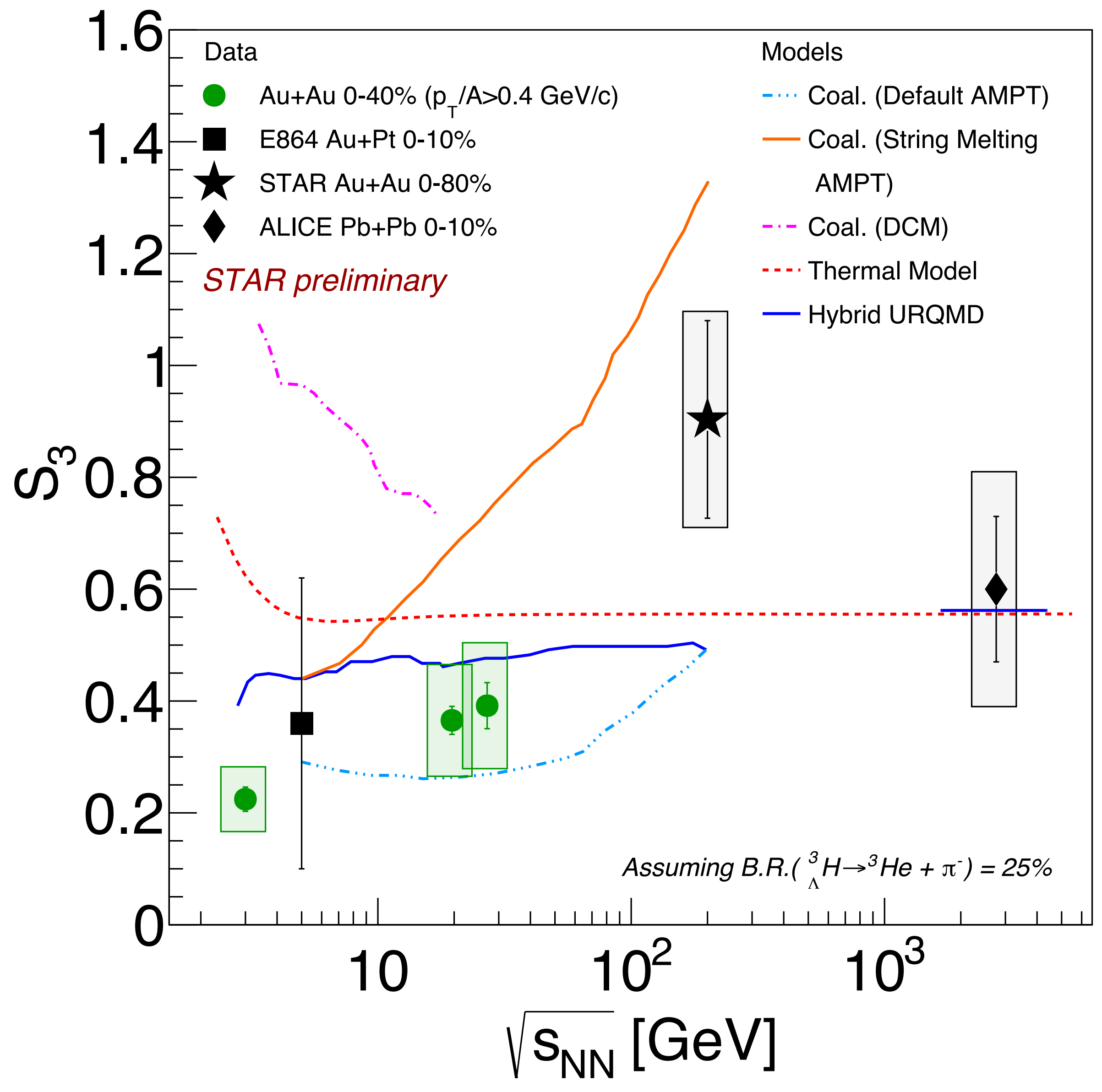
STAR, PRL 128 (2022) 202301
ALICE, PLB 754 (2016) 360
A. Andronic et al, PLB 697 (2011) 203 (Thermal model)
J. Steinheimer et al, PLB 714 (2021) (H. URQMD, DCM)
Y. Nara et al, PRC 61 (1999) 024901 (JAM)
S. Gläßel et al, arXiv: 2106,14839 (PHQMD)

S_3 and S_4

- S_A: relative suppression of hypernuclei production compared to light nuclei production
  $$S_A = \frac{{}^{A}_{\Lambda}H}{{}^{A}He \times \frac{\Lambda}{p}}$$
  - Expect ~1 if no suppression naively
    - $S_3 < 1$ → relative suppression of ${}^{3}_{\Lambda}H$ to ${}^{3}He$
    - $S_4 > S_3$ → enhanced ${}^{4}_{\Lambda}H$ production due to feed-down from excited state



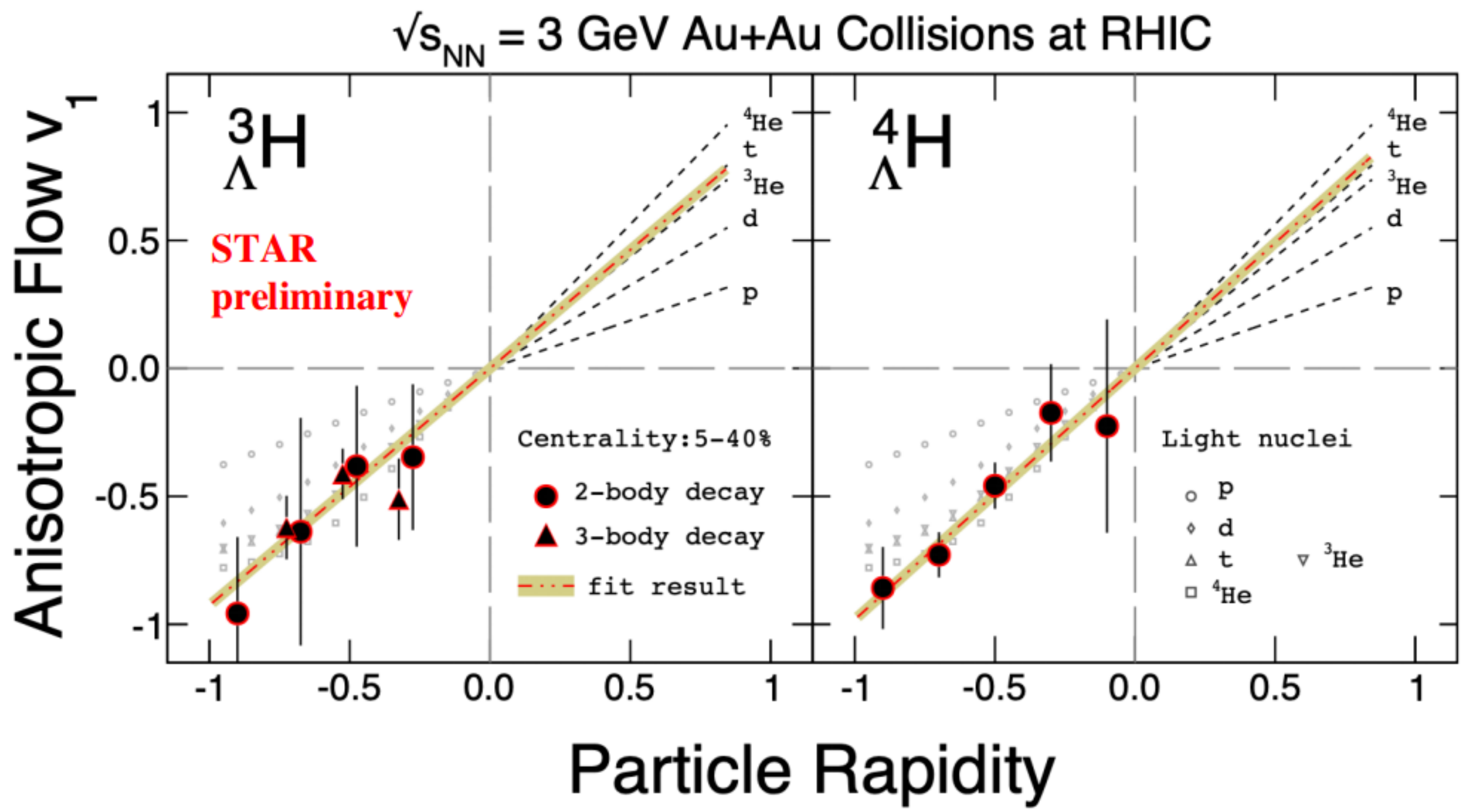


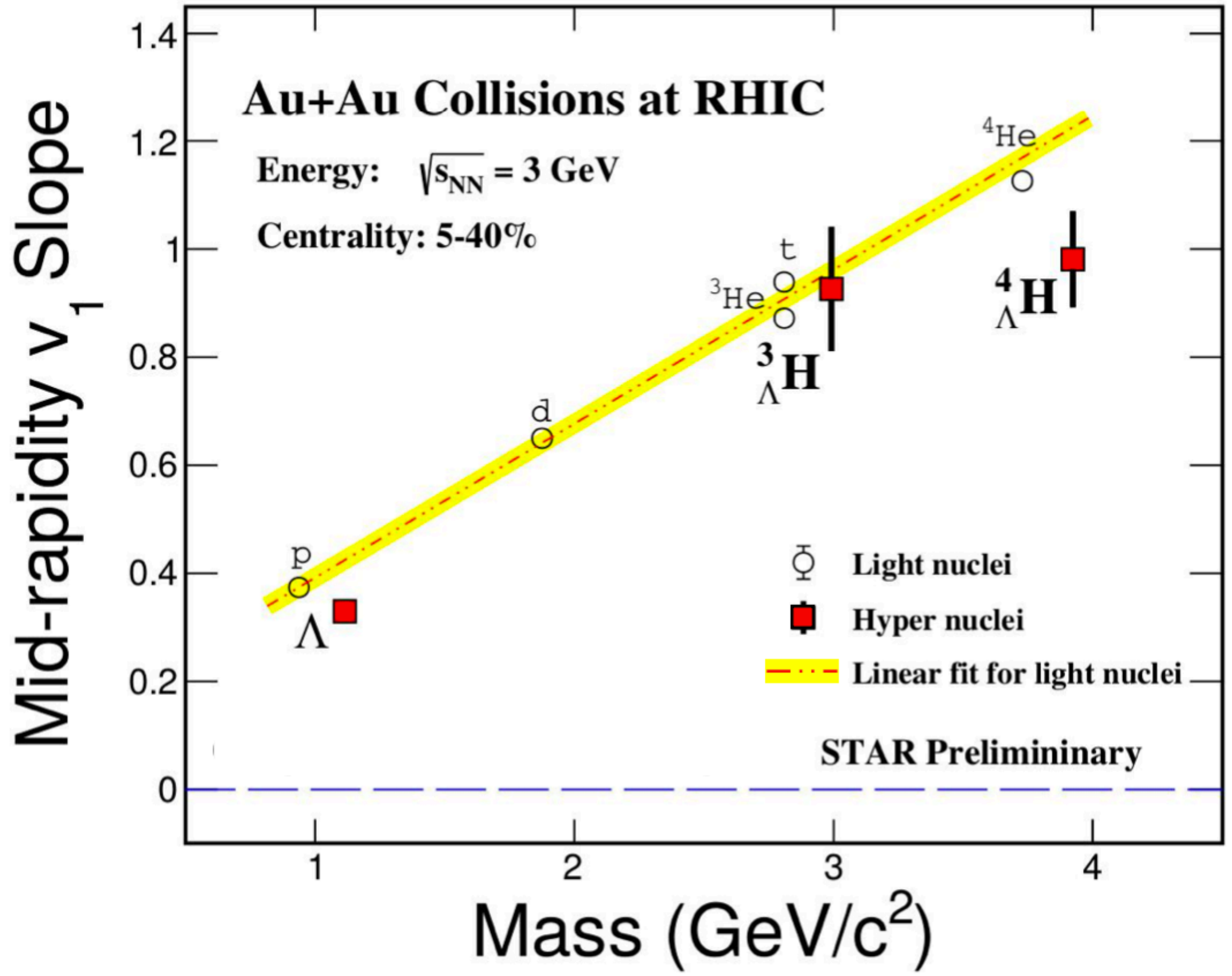


- No clear centrality dependence
- Hint of an increasing trend from $\sqrt{s_{NN}} = 3.0$ GeV to 2.76 TeV
- None of the models describe the S_3 data quantitatively

STAR, Science 328 (2010) 58
ALICE, PLB 754 (2016) 360
E864, PRC 70 (2004) 024902
NA49, J.Phys.Conf.Ser.110(2008)032010
A. Andronic et al, PLB 697 (2011) 203 (Thermal model)
J. Steinheimer et al, PLB 714 (2021) (H. URQMD, Coal.(DCM))
S. Zhang PLB 684(2010)224 (Coal.+AMPT)

${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ directed flow at 3 GeV





- First measurements of ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ directed flow (v_1) from 5 - 40% centrality
- v_1 slopes of ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ seem to follow a mass number scaling.

→ **Imply coalescence is a dominant process for hypernuclei formation in heavy-ion collisions**

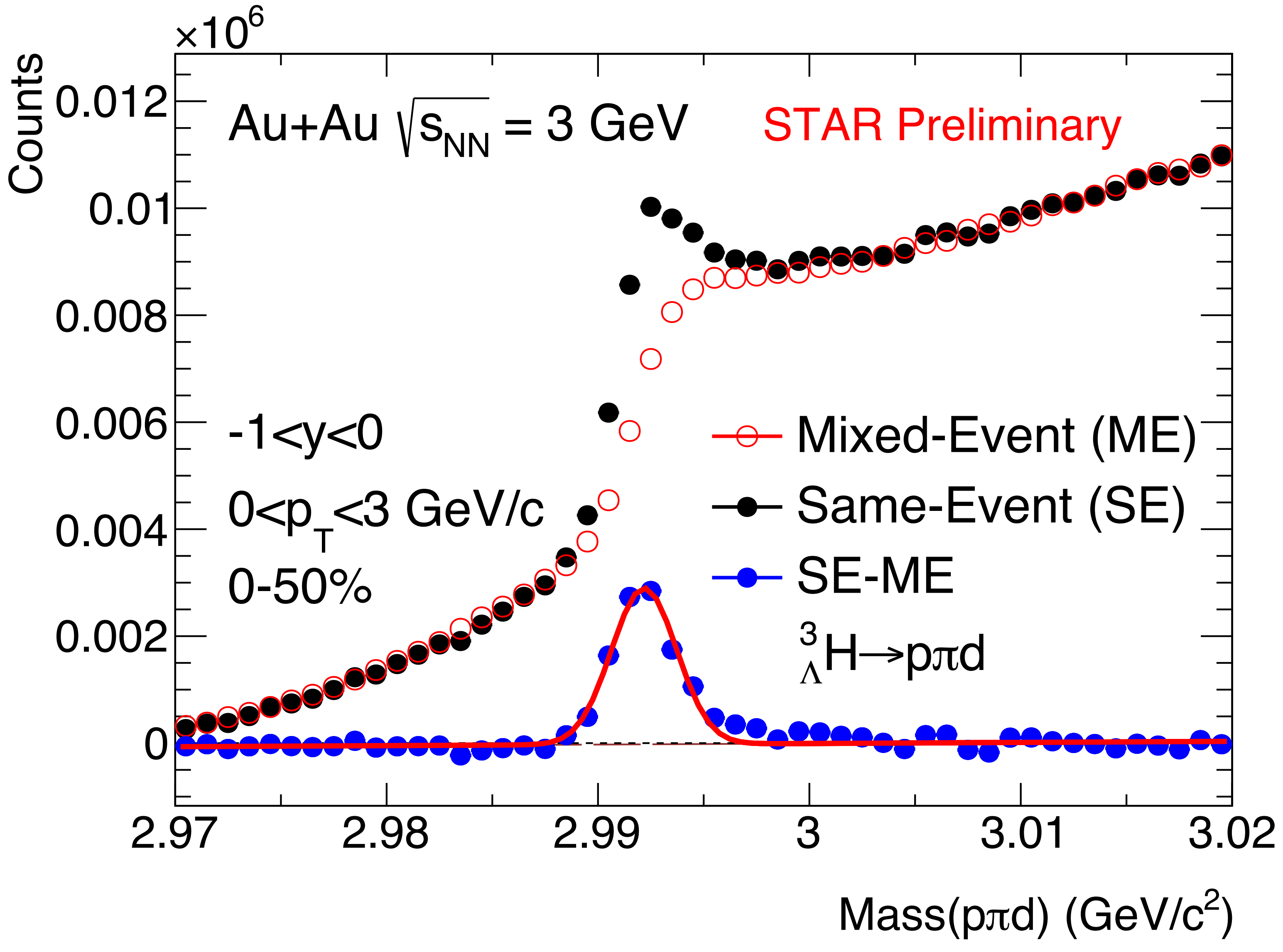
Summary

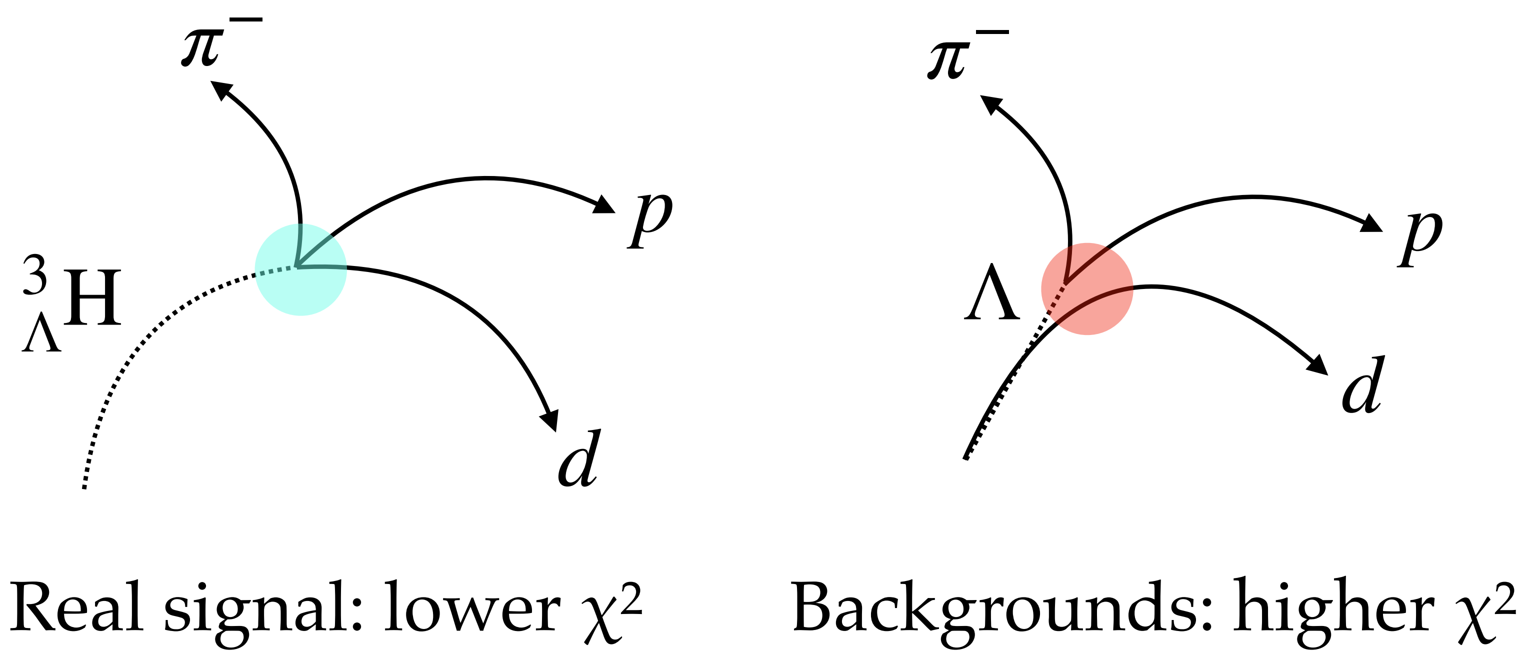
- STAR BES-II provides a unique opportunity to study hypernuclei, especially at high-baryon-density region
  - ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$ lifetimes measured with improved precision
  - Relative branching ratio R_3 of ${}^{3}_{\Lambda}\mathrm{H}$ with improved precision
    - Precision lifetime and R_3 provide stronger constraints on hyper nuclear interaction models
  - Λ binding-energy difference between ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$
    - Hint of CSB effect at A=4
  - First measurement of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ collectivity v_1
    - Mass number scaling is observed for the light hypernuclei → qualitatively consistent with coalescence
  - First measurement of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ dN/dy vs y in heavy-ion collisions.
    - Provide first constraints to hypernuclei production models @ high μ_{B}
  - Outlook: 1. iTPC and eToF fully installed in 2019 → improve η acceptance and PID at large η

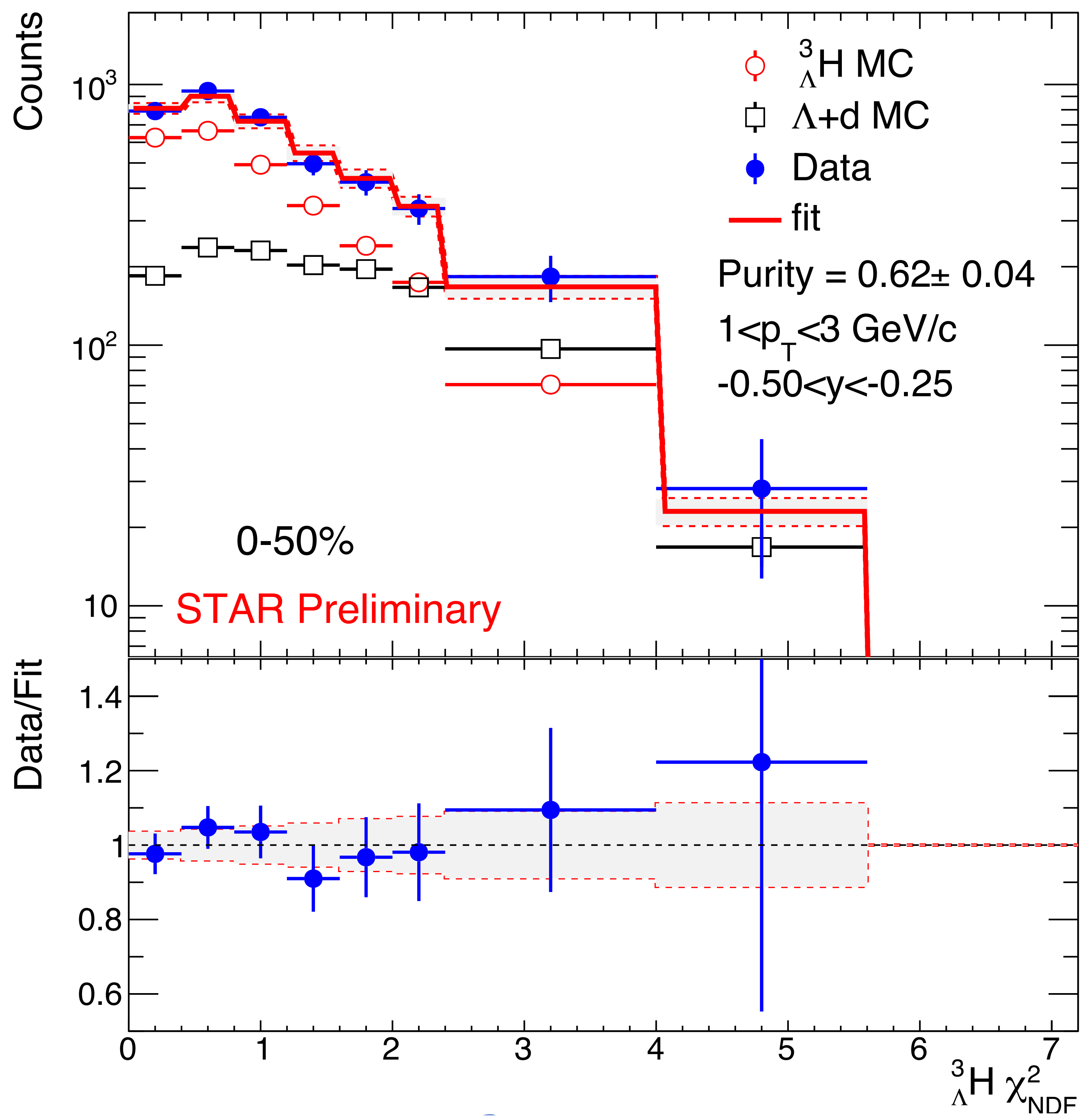
    2. 2 billion events collected at 3 GeV in 2021 → larger statistics, higher precision
    - Expect precision measurements and more information of hypernuclei production with wider η range

Back up

${}^{3}_{\Lambda}$H 3-body signal



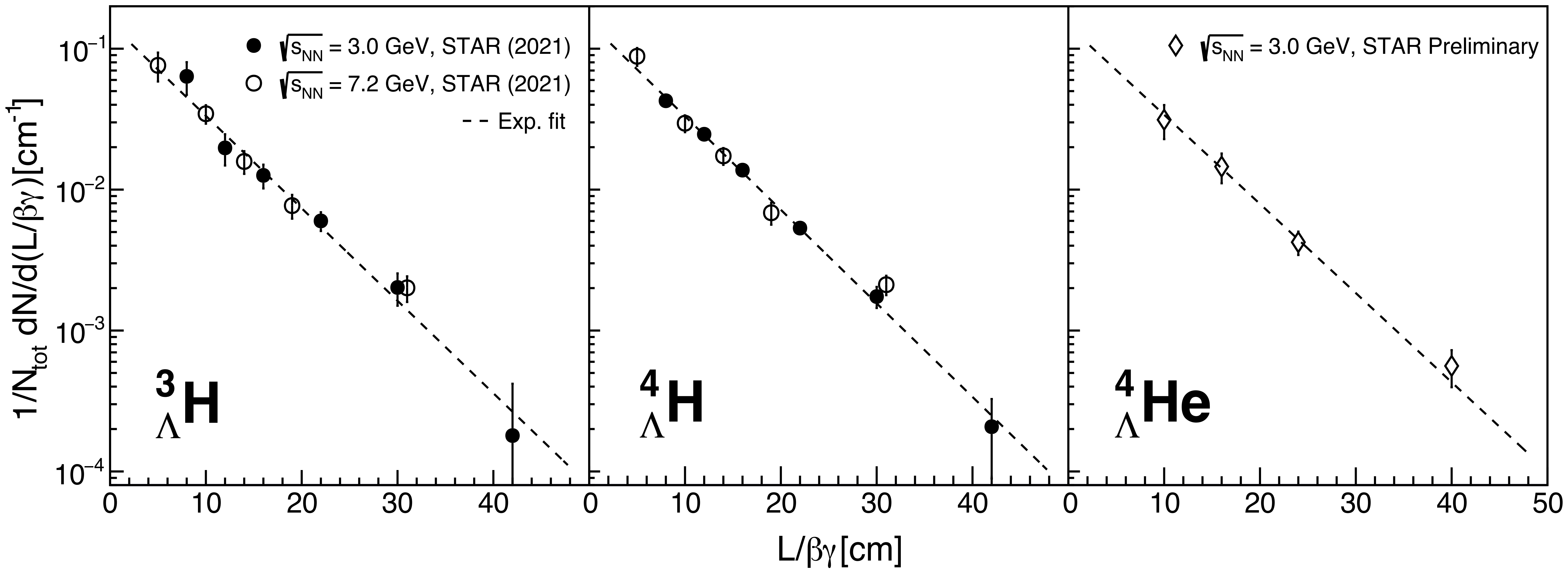


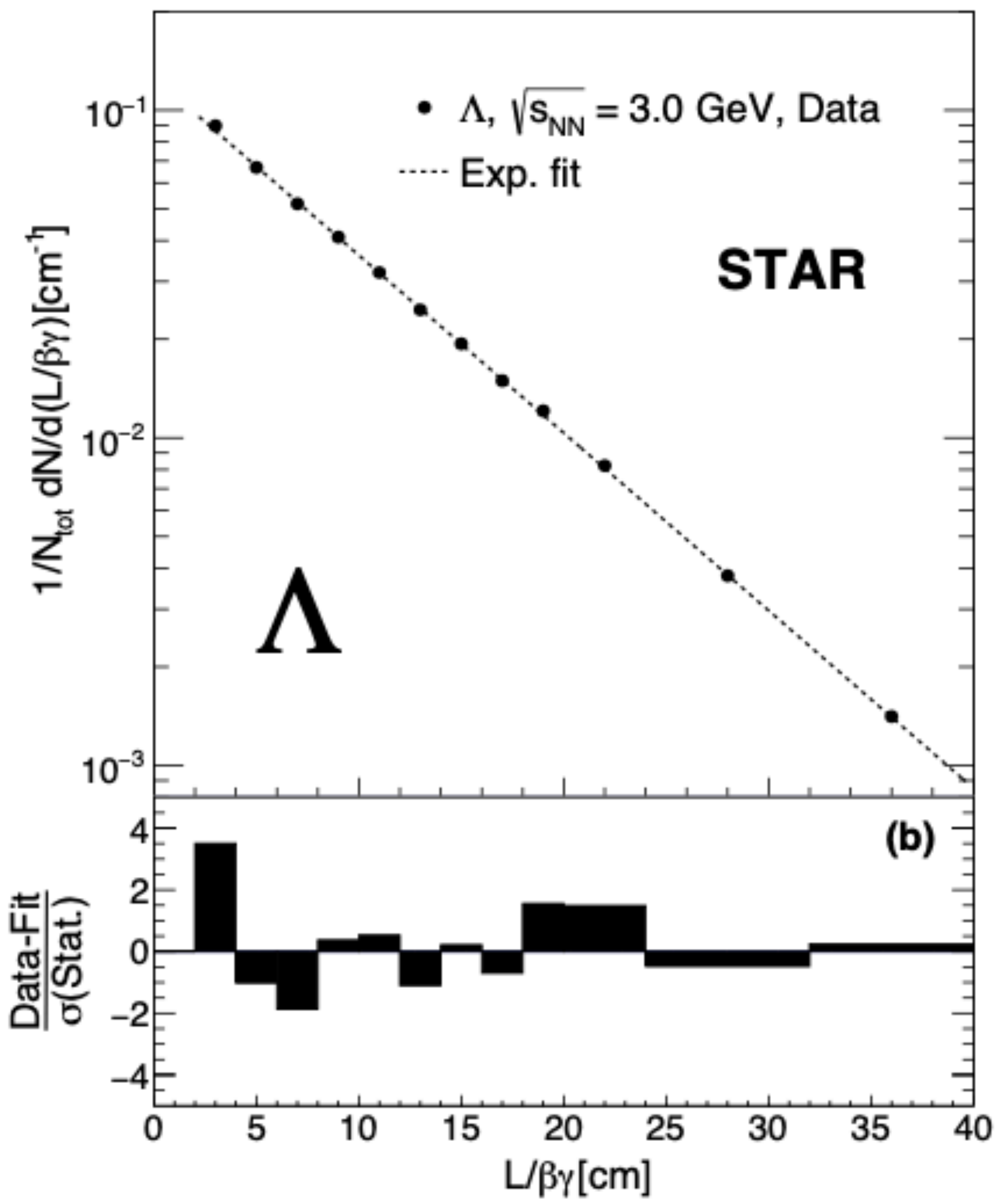


- SE-ME signals contains real signal and kinematically correlated $\Lambda + \mathrm{d}(\Lambda \rightarrow \mathrm{p}\pi^{-})$

- Estimation of ${}^{3}_{\Lambda}\mathrm{H}$ purity in signals
  - Normalized χ^2_{NDF} distribution of $\Lambda + \mathrm{d}$ and ${}^{3}_{\Lambda}\mathrm{H}$ template from MC ($f_{\Lambda d}$ and $f_{{}^{3}_{\Lambda}\mathrm{H}}$), and reconstructed signal f_{Data}
  - Purity: the fraction of real ${}^{3}_{\Lambda}\mathrm{H}$ signals $f_{{}^{3}_{\Lambda}\mathrm{H}}$ in signals f_{Data} from fitting $f_{Data} = p_0 \cdot (f_{\Lambda d} + p_1 \cdot f_{{}^{3}_{\Lambda}\mathrm{H}})$

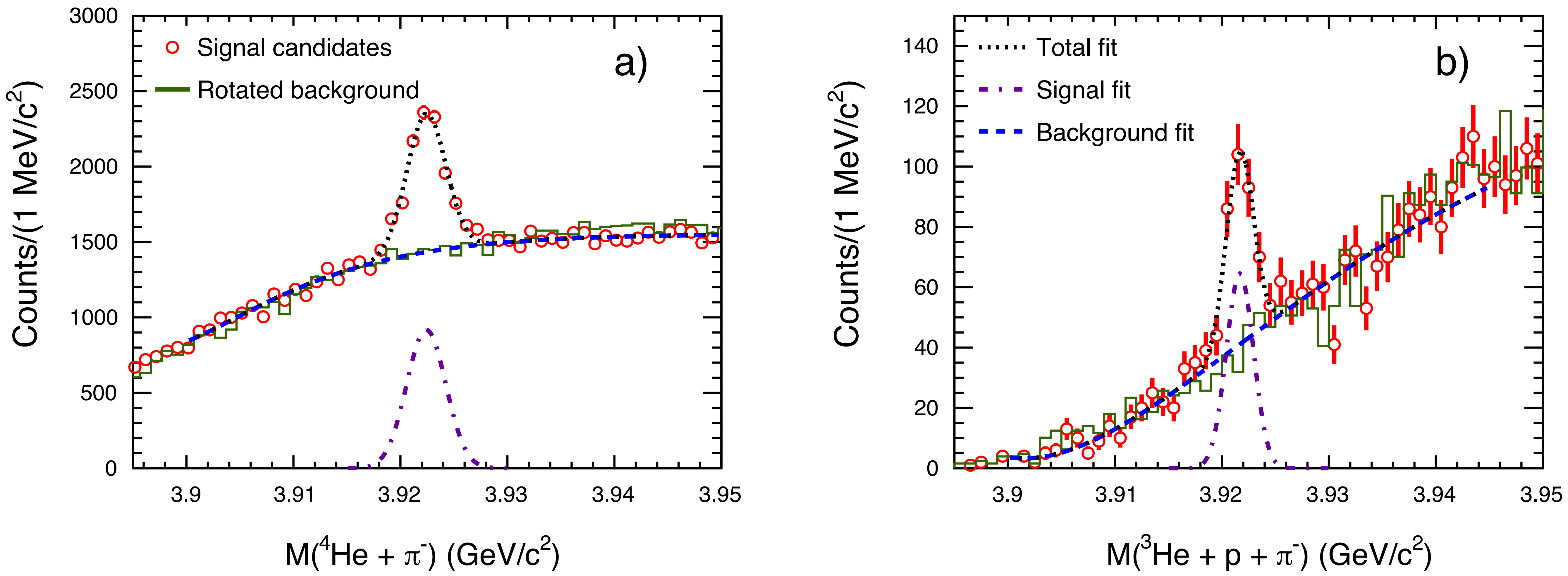
Lifetime





- Lifetime τ extracted via $\mathrm{N(t) = N_0 e^{-L/\beta\gamma c\tau}}$
- Λ lifetime cross check : 267±4 ps, consistent with PDG value (263±2 ps)
- $^{3}_{\Lambda}\mathrm{H}$ and $^{4}_{\Lambda}\mathrm{H}$ lifetimes from 3.0 GeV consistent with 7.2 GeV results

Λ binding energy analysis

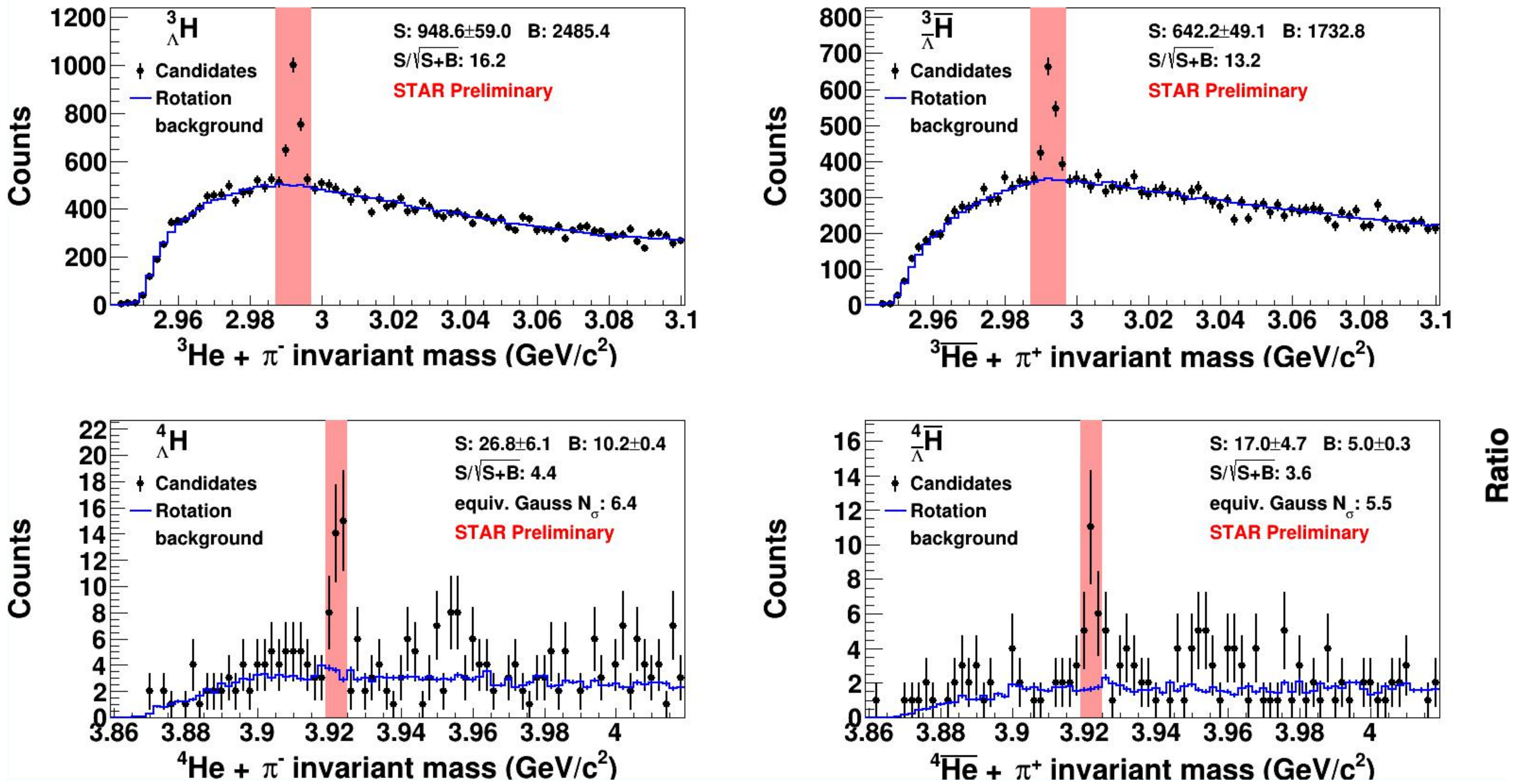


- The background are obtained by rotating $^4\mathrm{He}$ or $^3\mathrm{He}$ track by 180 degrees
- The signal and the background are fitted by a Gaussian distribution and a double-exponential function, respectively.

$m(^4_\Lambda\mathrm{H}) = 3922.38 \pm 0.06(\mathrm{stat.}) \pm 0.14(\mathrm{syst.})\ \mathrm{MeV}/c^2$ $\quad m(^4_\Lambda\mathrm{He}) = 3921.69 \pm 0.13(\mathrm{stat.}) \pm 0.12(\mathrm{syst.})\ \mathrm{MeV}/c^2$

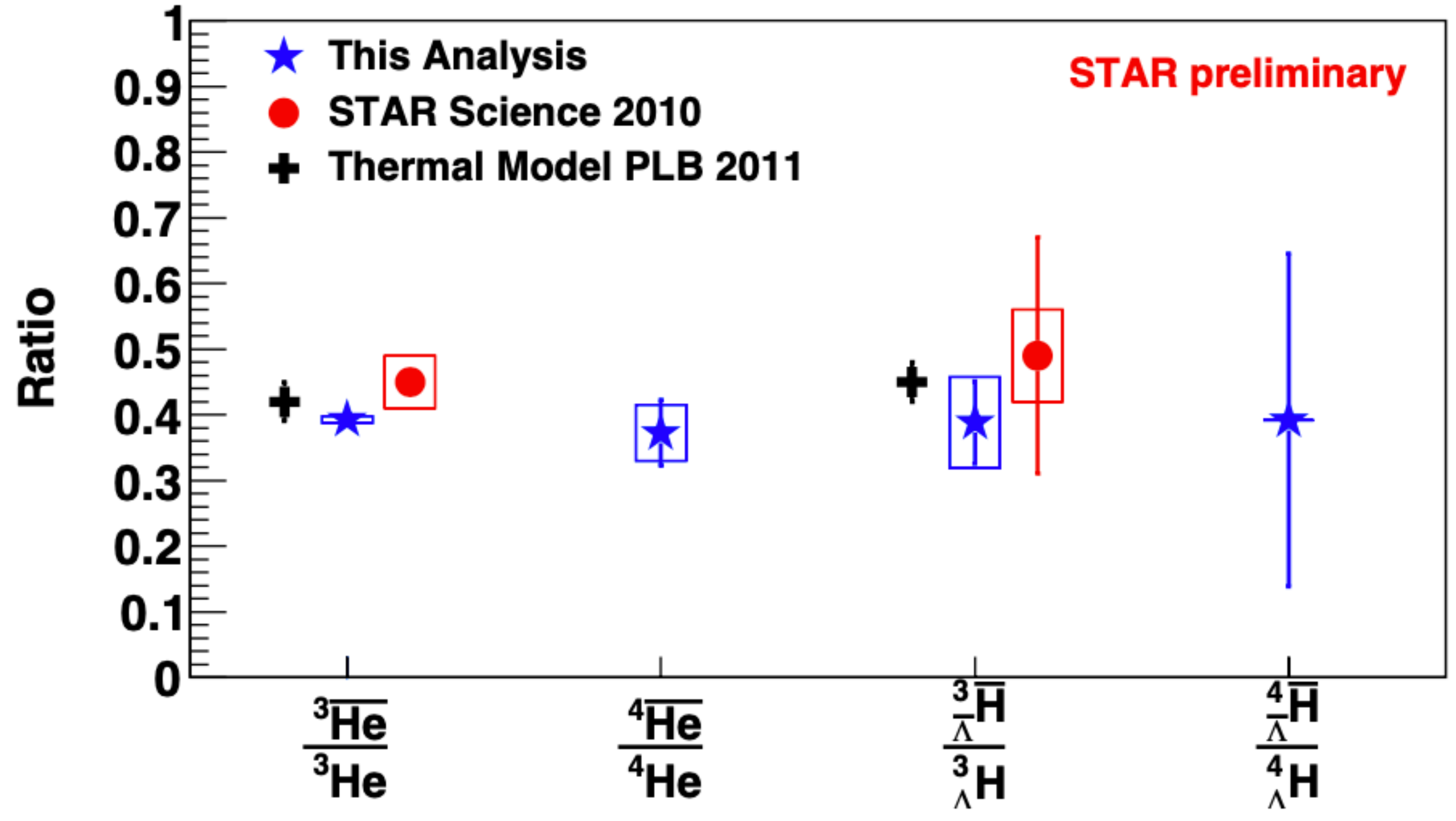
- Λ binding energy : $B_\Lambda = (M_\Lambda + M_{\mathrm{core}} - M_{\mathrm{hypernucleus}})c^2$

Observation of ${}^{4}_{\Lambda}\overline{\mathrm{H}}$



- Datasets from STAR at RHIC facility

Year	$\sqrt{s_{NN}}$ GeV	System	Events
2010	200	Au+Au	0.67B
2011	200	Au+Au	0.68B
2012	193	U+U	0.67B
2018	200	Ru+Ru, Zr+Zr	4.61B



Antimatter/matter yield ratios are consistent with previous results and models.

- **First observation of ${}^{4}_{\Lambda}\overline{\mathrm{H}}$** with ~5$\sigma$ significance
  - First observation of heaviest anti-hyper nucleus in experiment
  - New opportunity for the study of matter-antimatter asymmetry

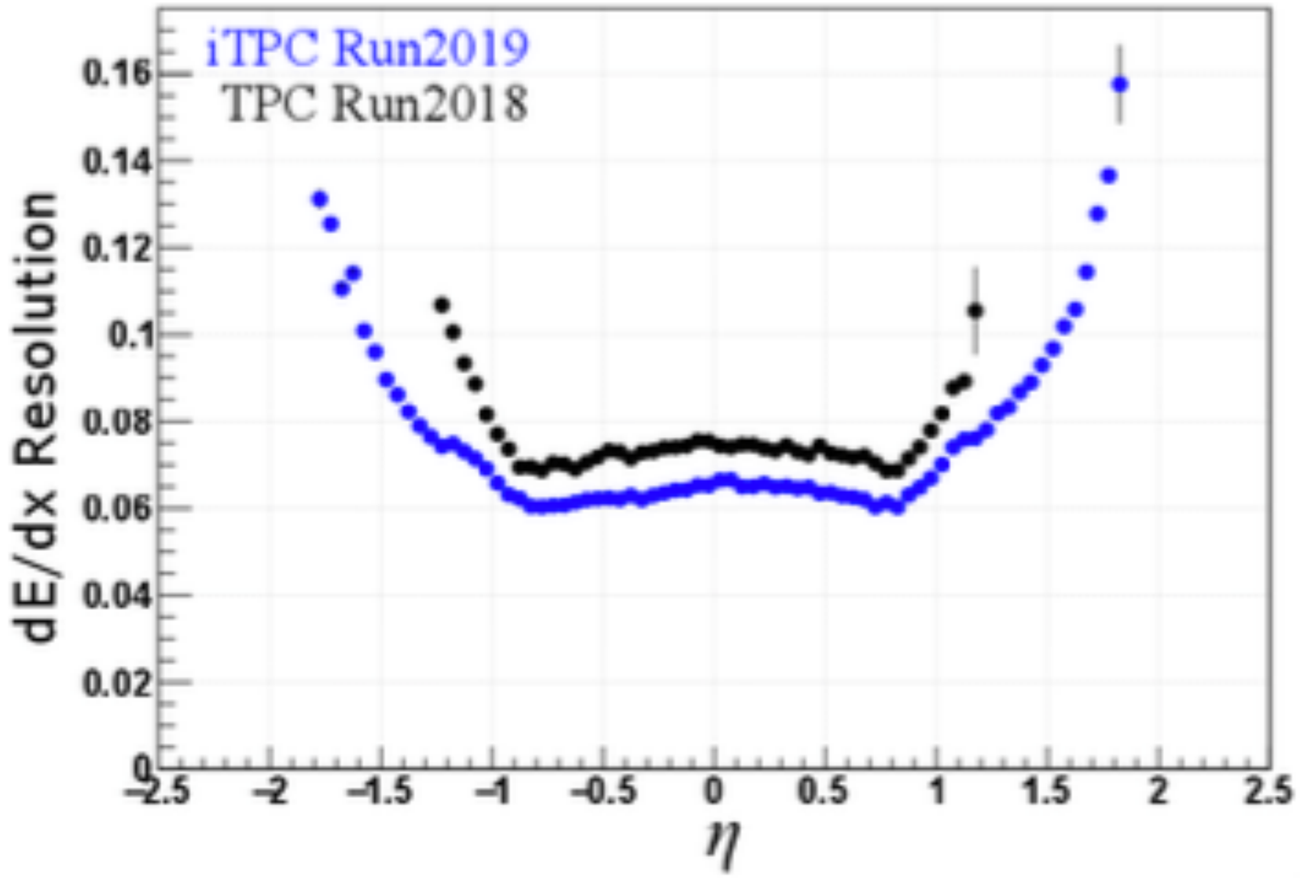
Detector upgrade

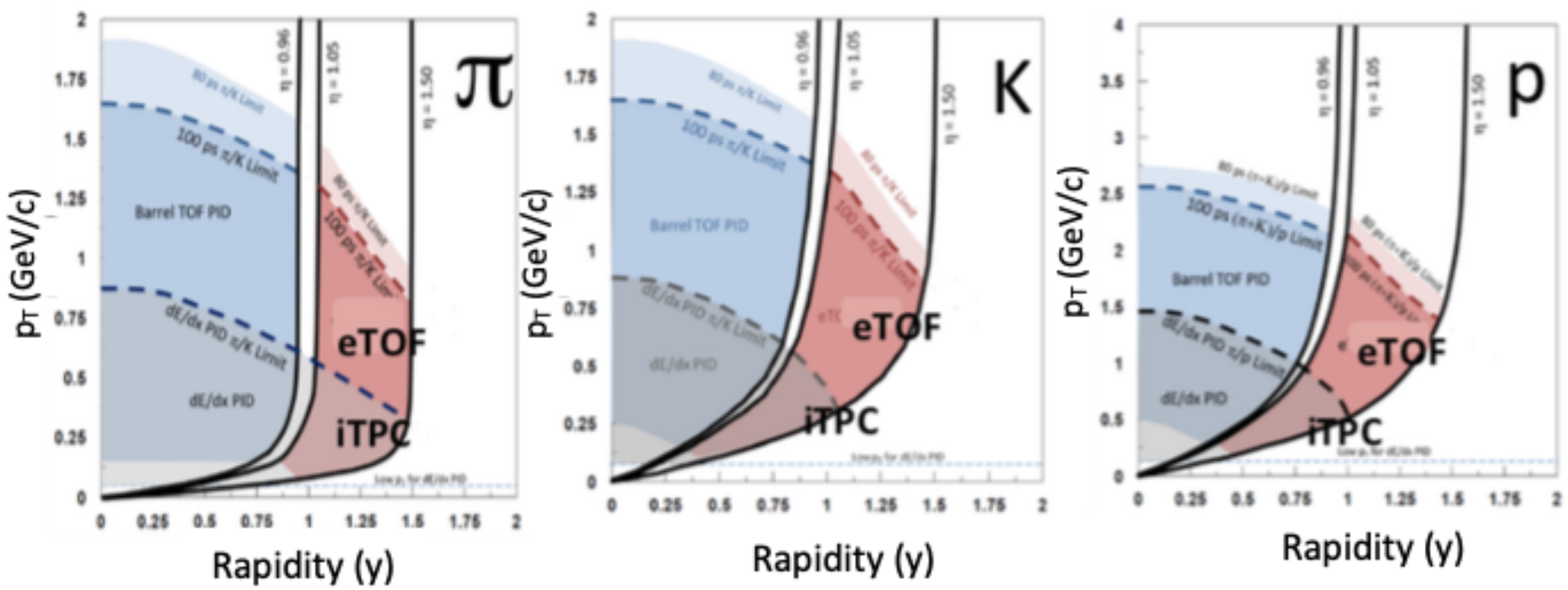
In year 2019:

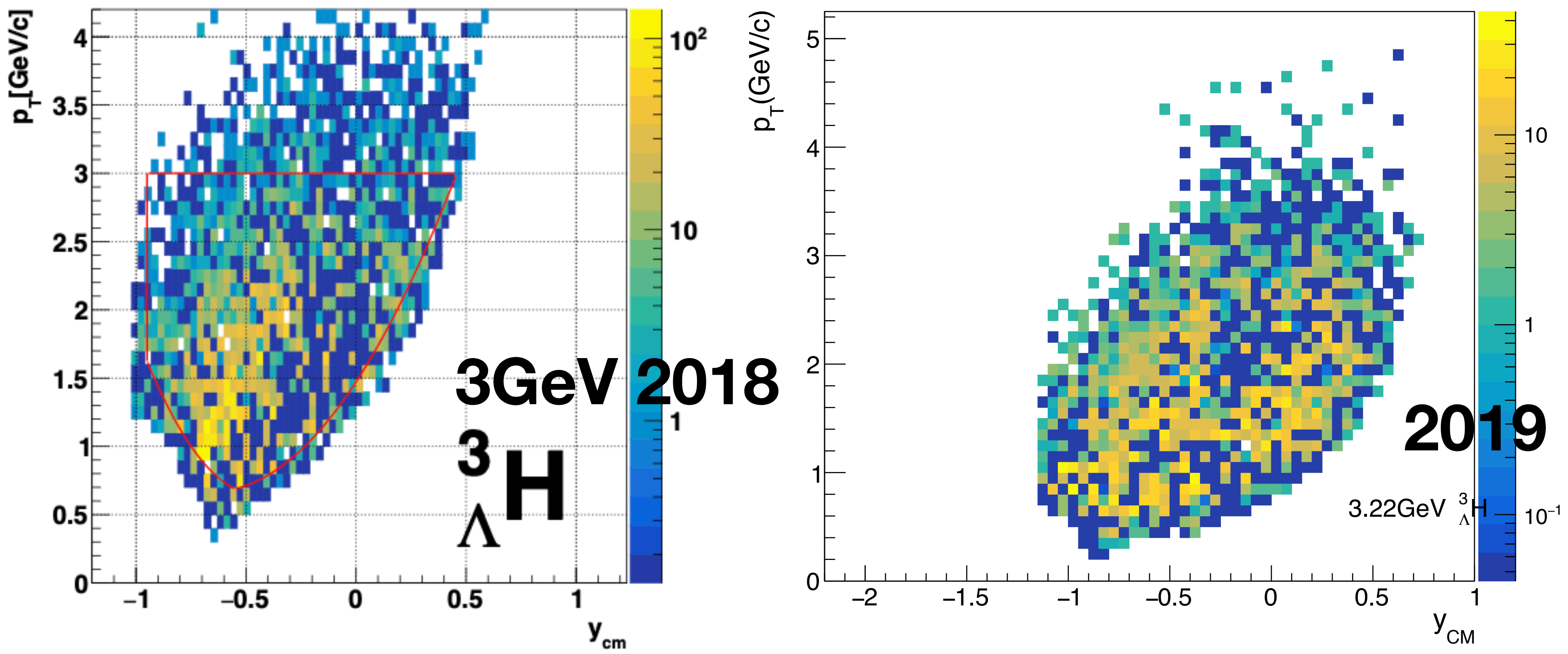
QM2019 talk, Yi Yang

1. iTPC fully operational
2. eTof fully installed

They both improve η acceptance and PID at large η.







High statistics in BES-II + wider ηcoverage than in year 2018

→ Expect precision measurements and more information at large η