Recent Hypernuclei Measurements from BES Program

Xiujun Li
University of Science and Technology of China

RHIC & AGS Users' Meeting 2022

Supported in part by the
U.S. DEPARTMENT OF ENERGY | Office of Science

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

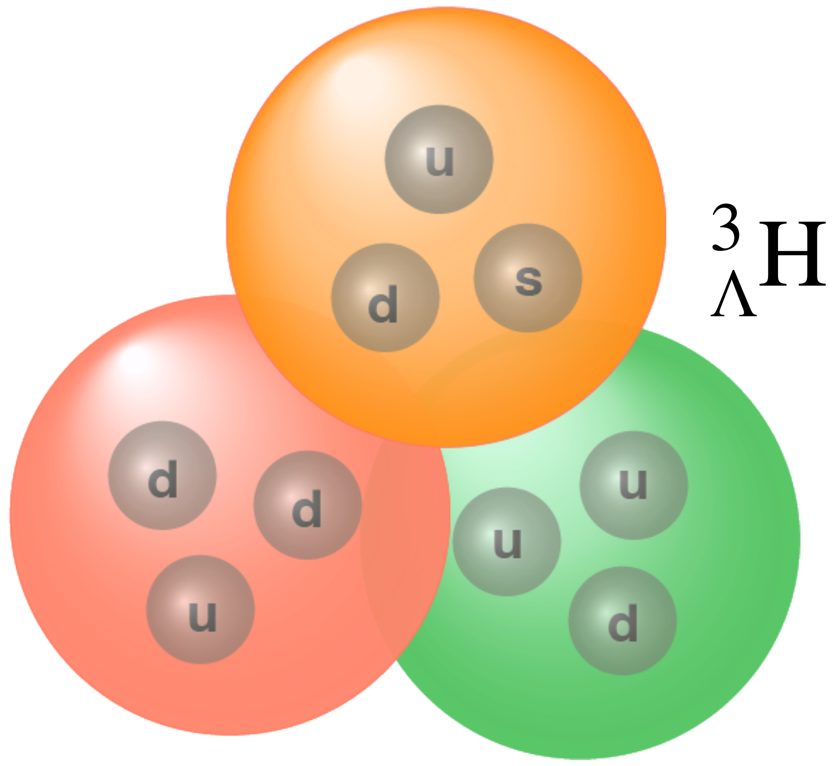
Hypernuclei: bound nuclear systems of non-strange and strange baryons

- 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.

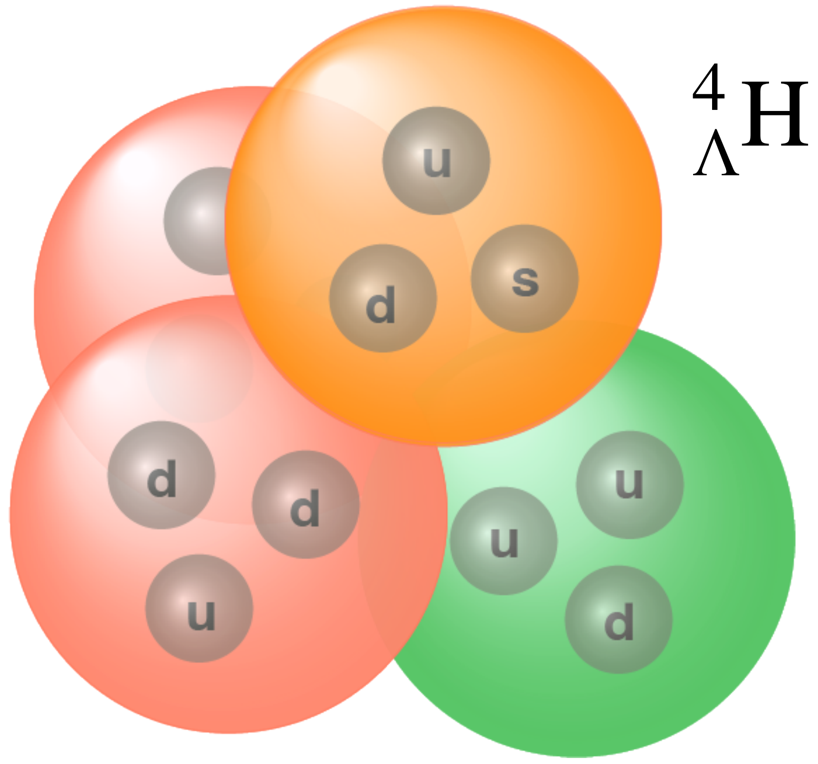
  Understanding hypernuclei structure may give more constraints on the Y-N interaction

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

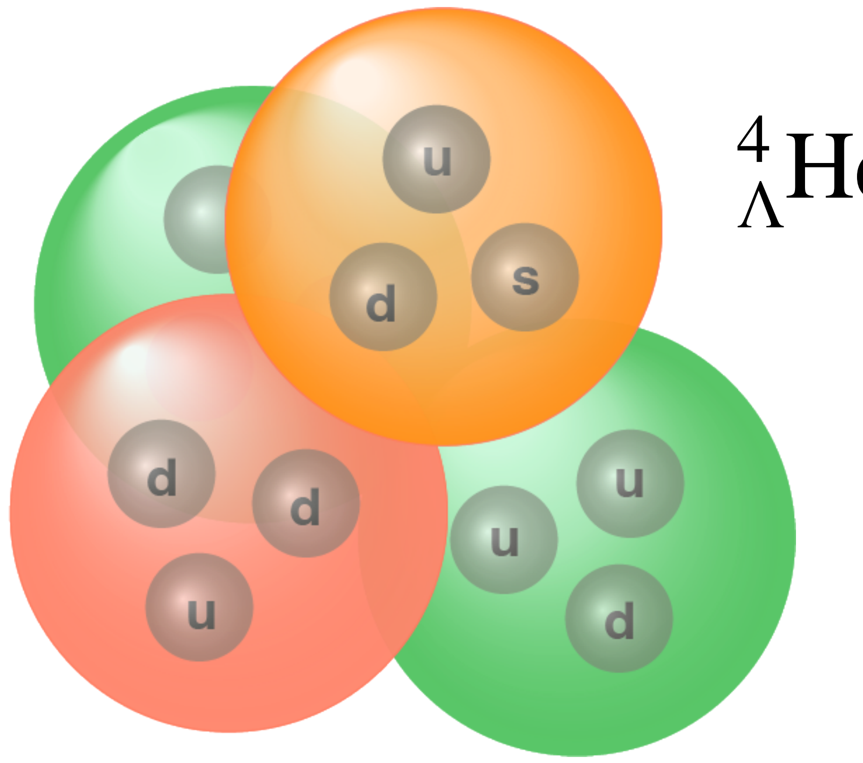
  The formation of loosely bound states in violent heavy-ion collisions is not well understood



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



$^{4}_{\Lambda}\mathrm{H}$

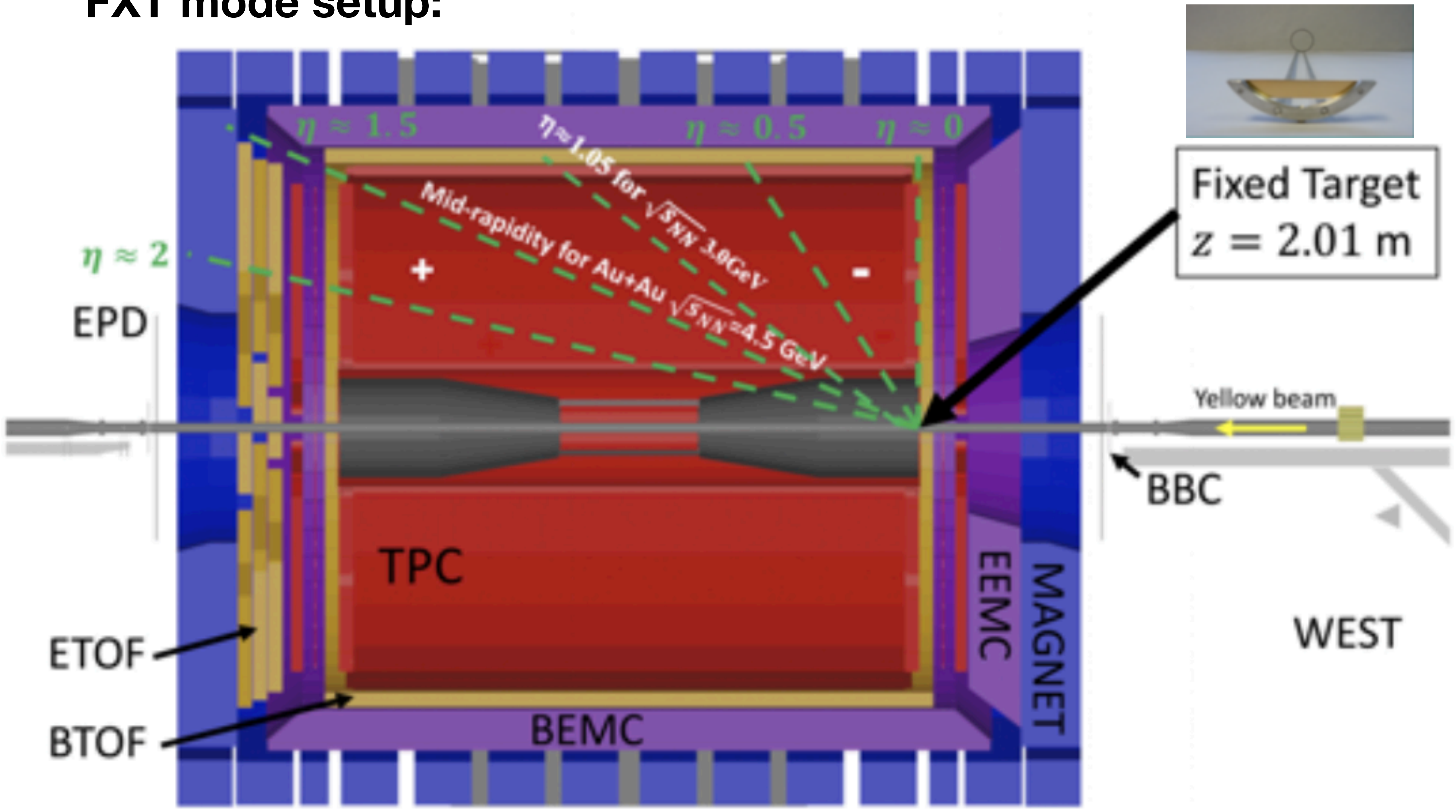


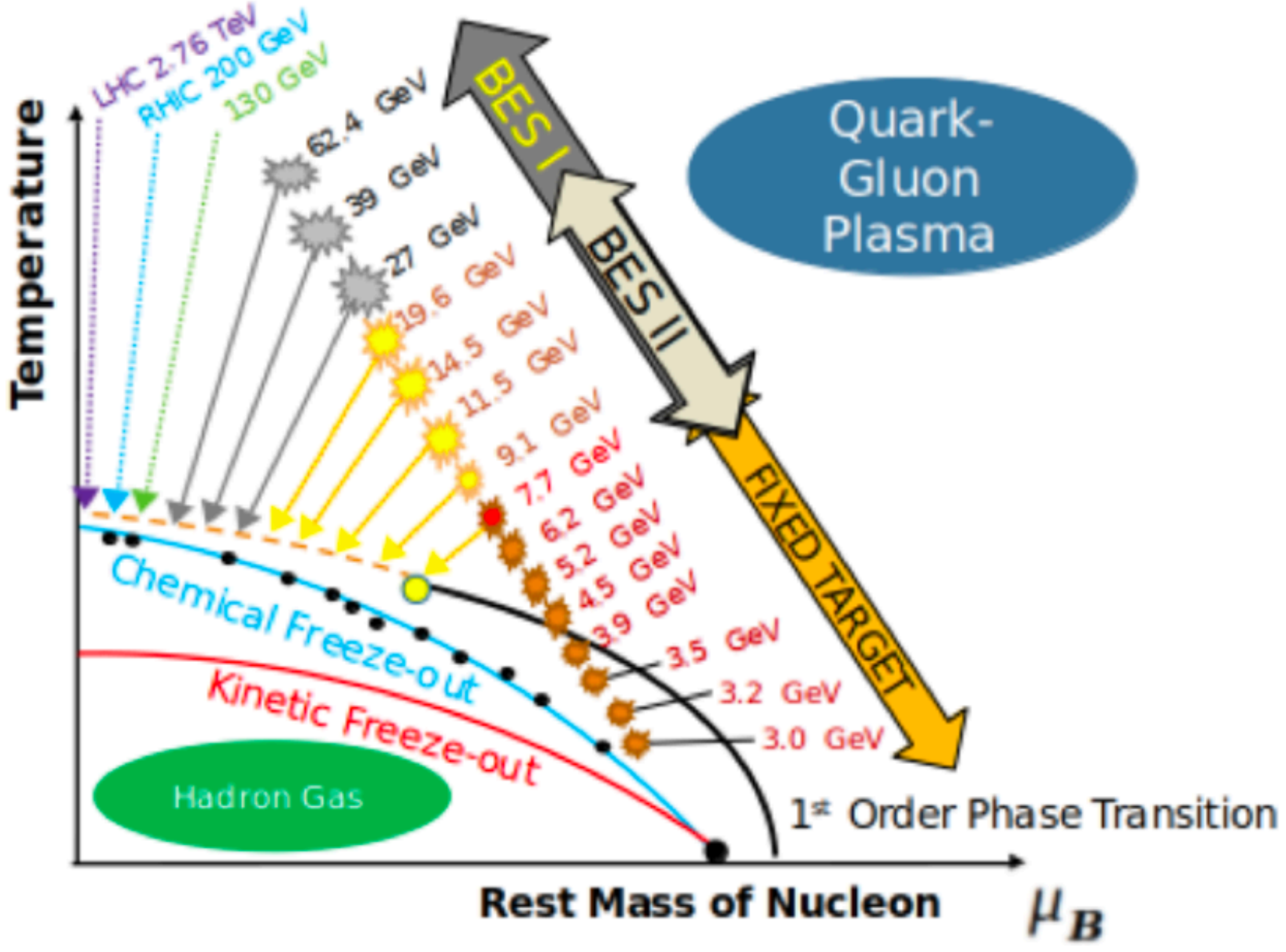
$^{4}_{\Lambda}\mathrm{He}$

STAR and BES-II

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

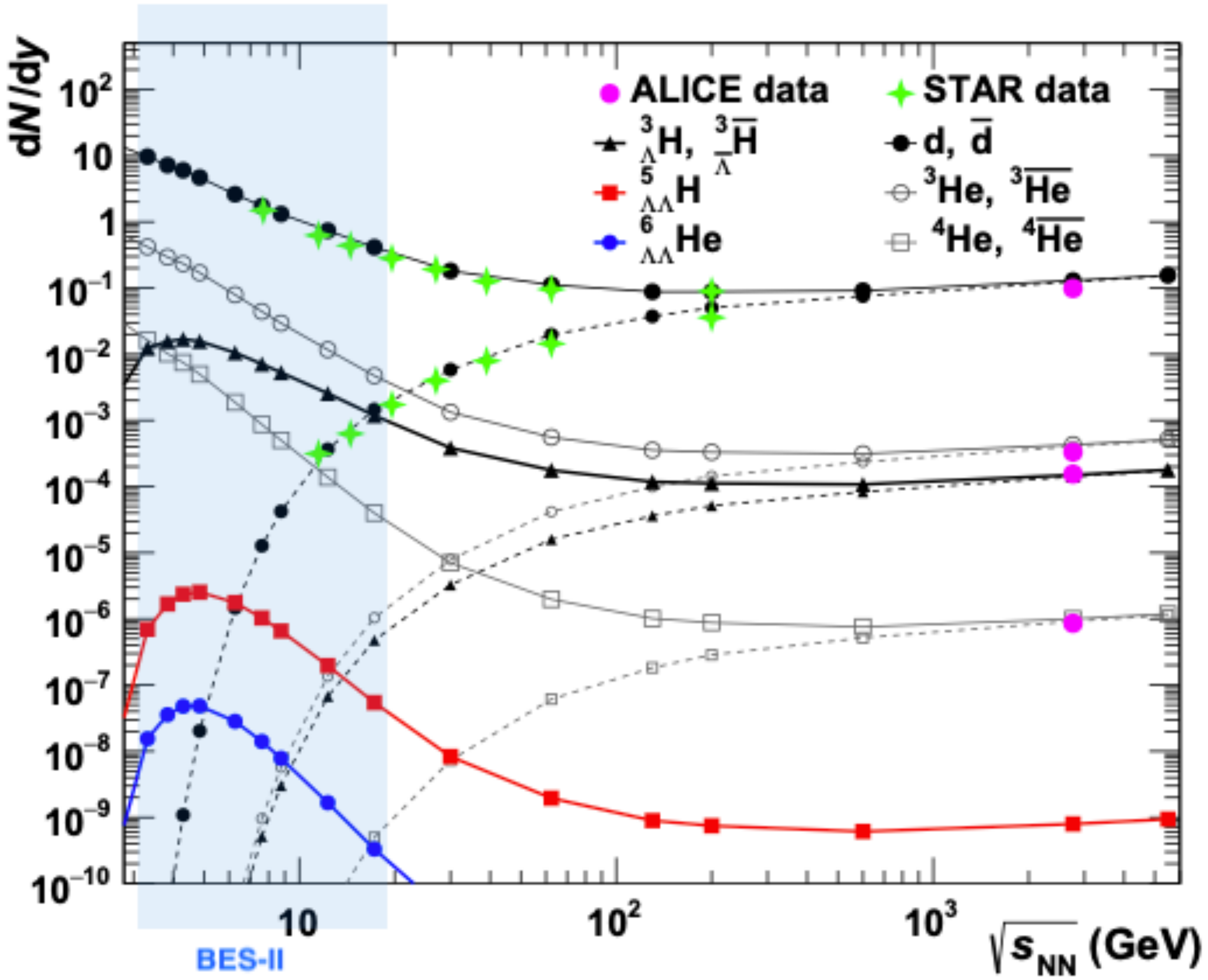
FXT mode setup:





Hypernuclei and STAR BES-II

- **Hyper nuclei measurements are scarce in heavy-ion collisions experiments**

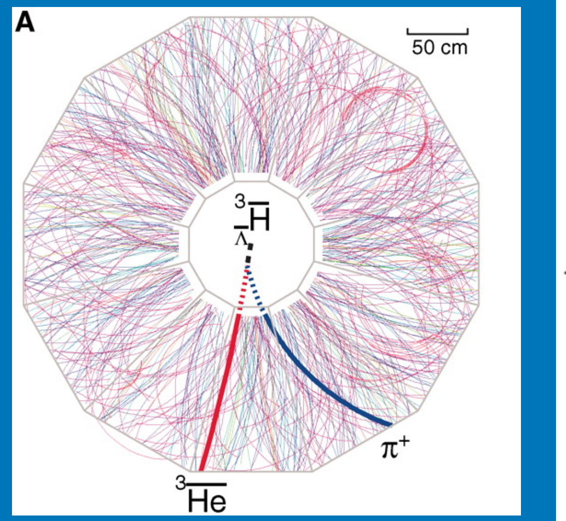


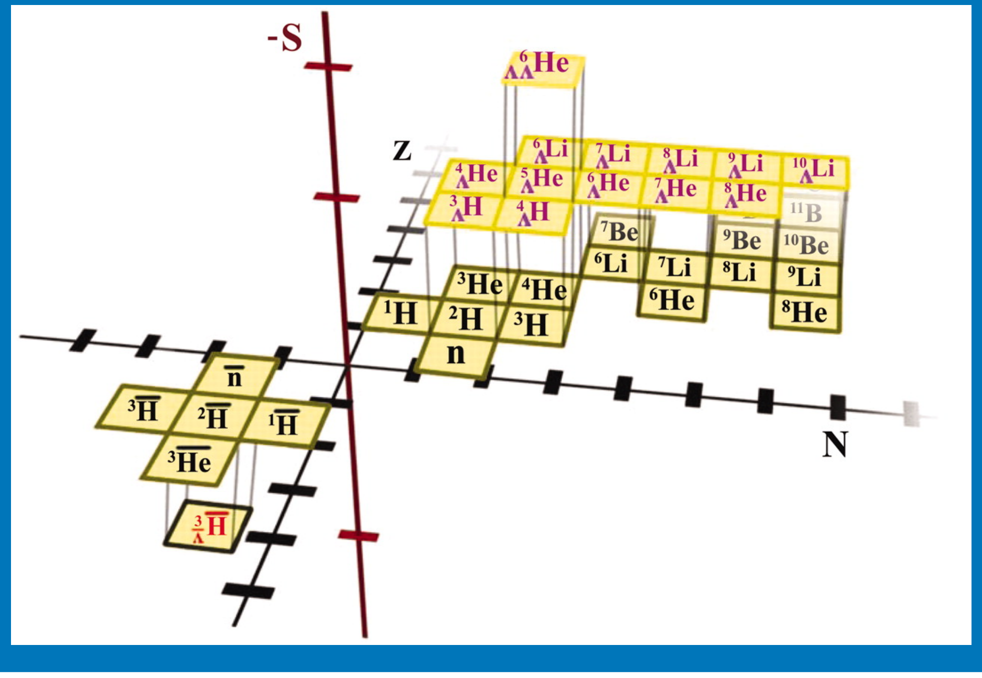
B. Dönigus, Eur. Phys. J. A (2020) 56:280

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

- At lower beam energies, the hypernuclei production is expected to be enhanced due to high baryon density
  - STAR BES-II → great opportunity to study hypernuclei production

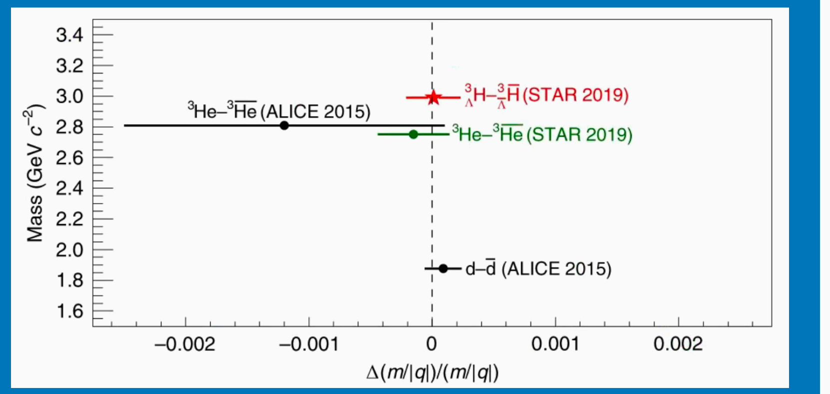
Hypernuclei analysis in STAR BES-I

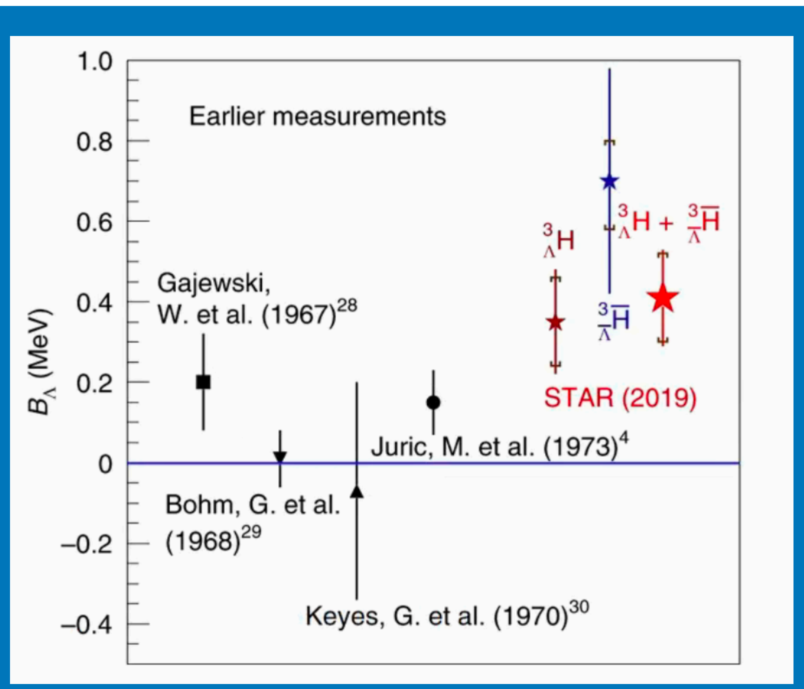




STAR collaboration **found the anti-hyper triton.**

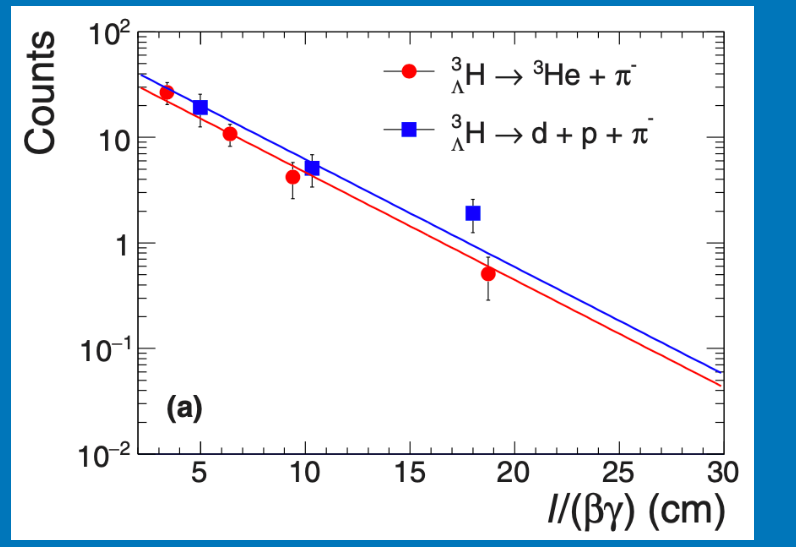
Science 328, 58 (2010) (STAR)

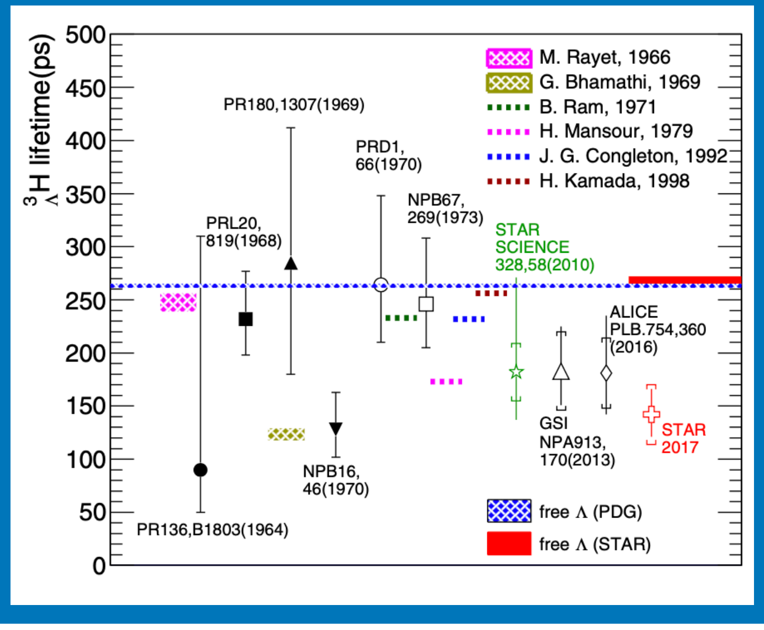




Measurement of mass difference and binding energy of $^{3}_{\Lambda}\mathrm{H}$ and $^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}$

Nature Phys. 16 (2020) 409 (STAR)



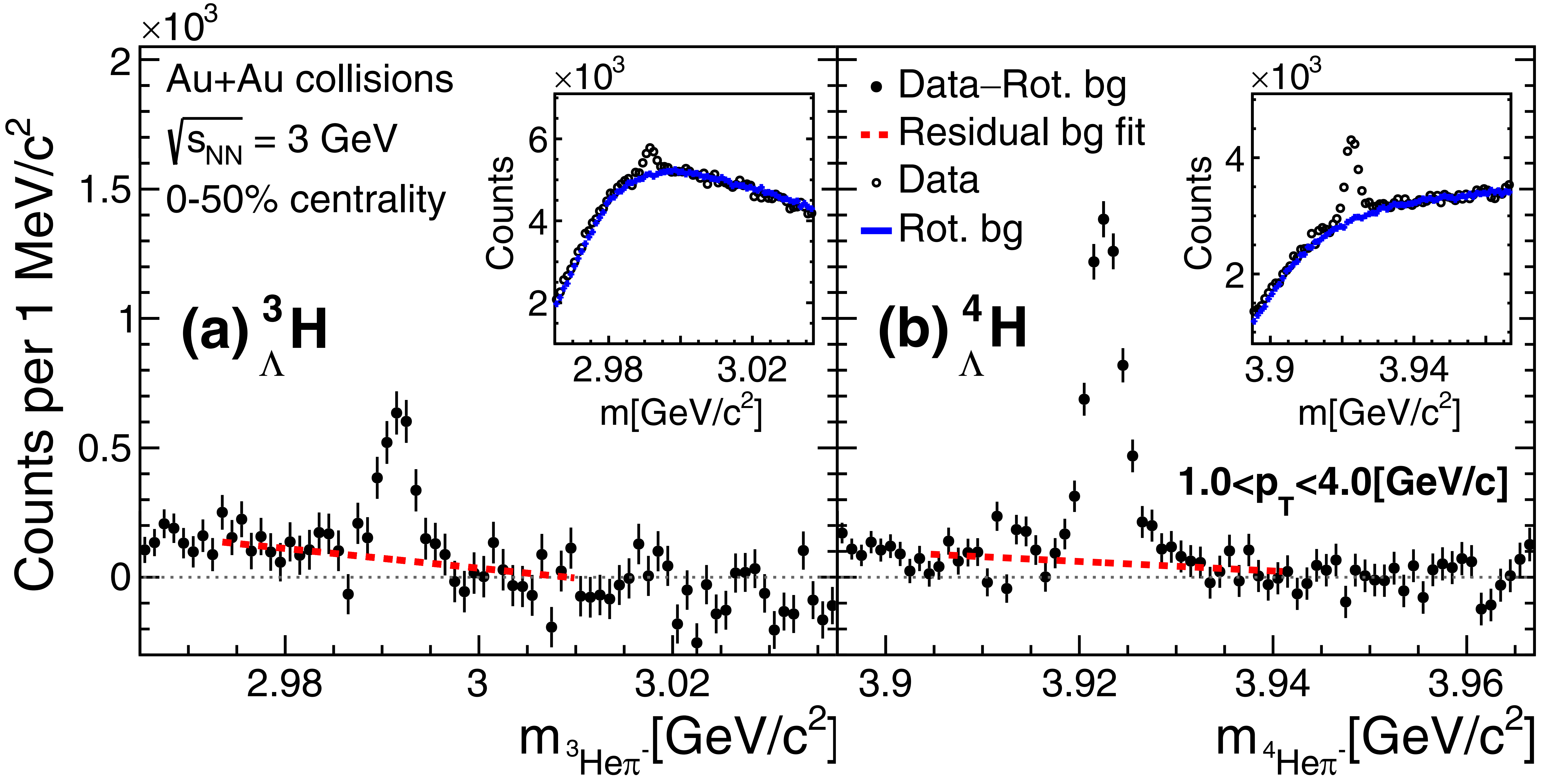


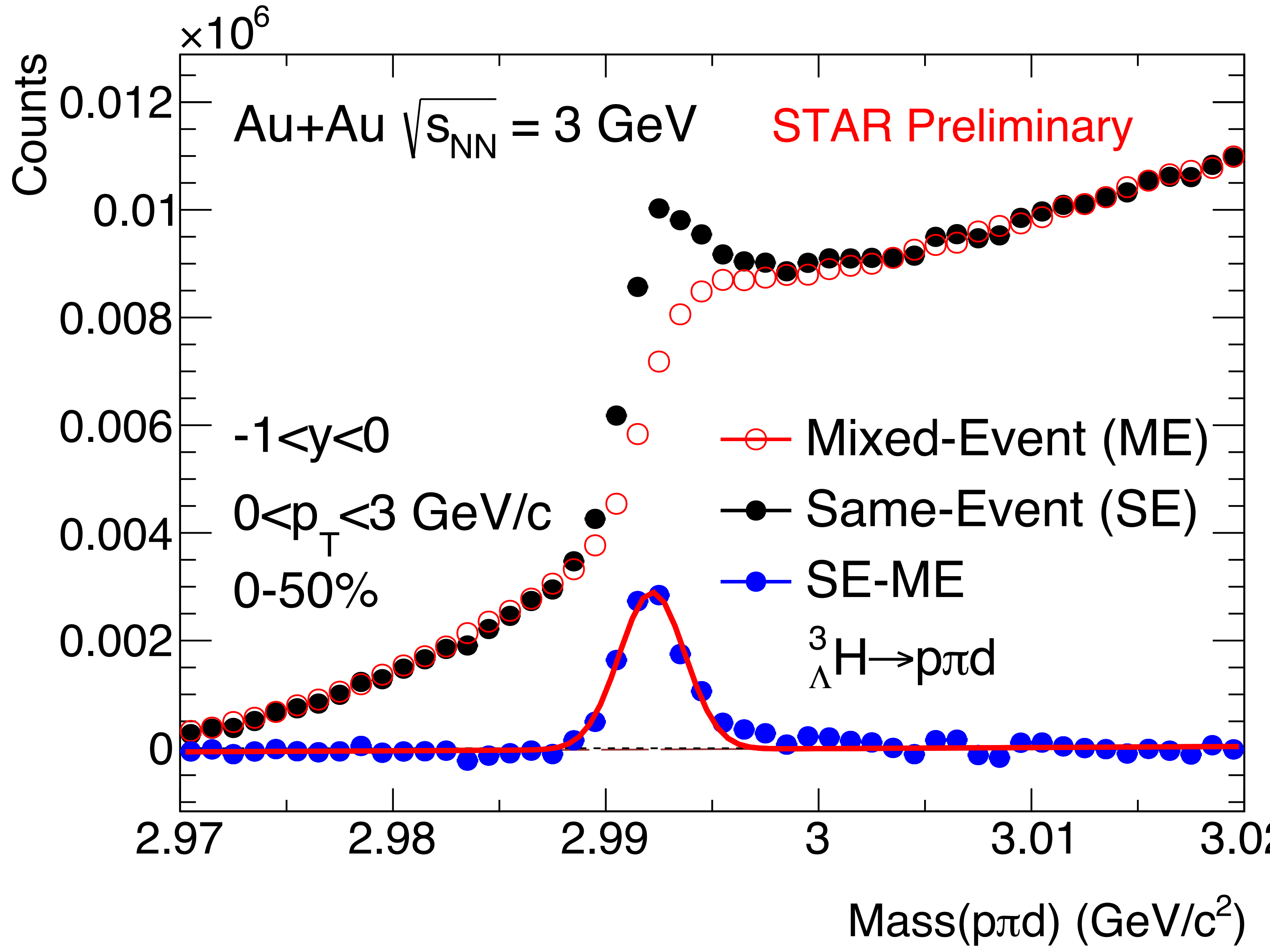
Lifetime measurement of $^{3}_{\Lambda}\mathrm{H}$

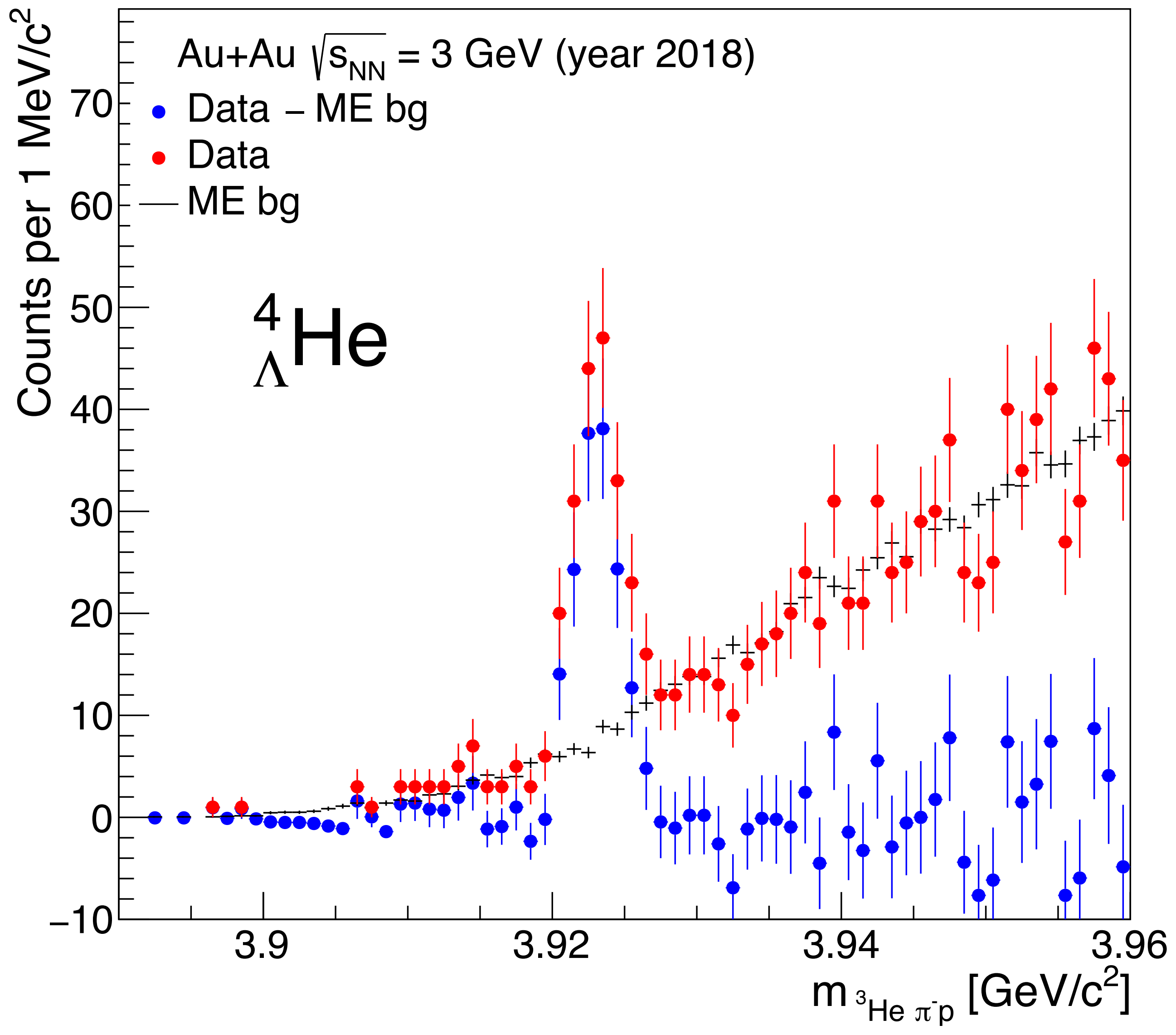
Science 328, 58 (2010) (STAR)

PRC 97, 054909 (2018) (STAR)

Hypernuclei reconstruction







- Decay channels:

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

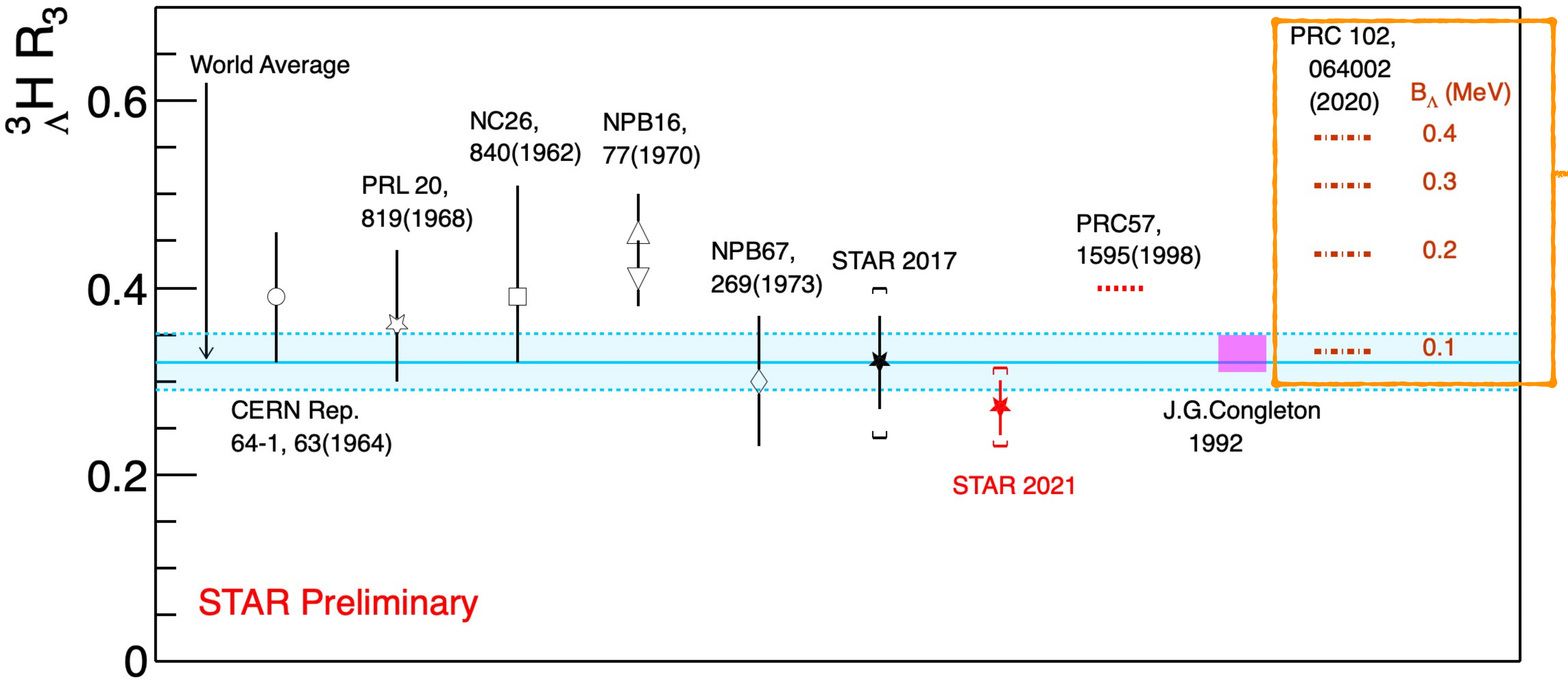
  $^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^{-}$ $\quad$ $^{4}_{\Lambda}\mathrm{He} \rightarrow {}^{3}\mathrm{He} + \mathrm{p} + \pi^{-}$

- Combinatorial background estimated via rotating pion tracks or event mixing

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

QM2022 poster, Yuanjing

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



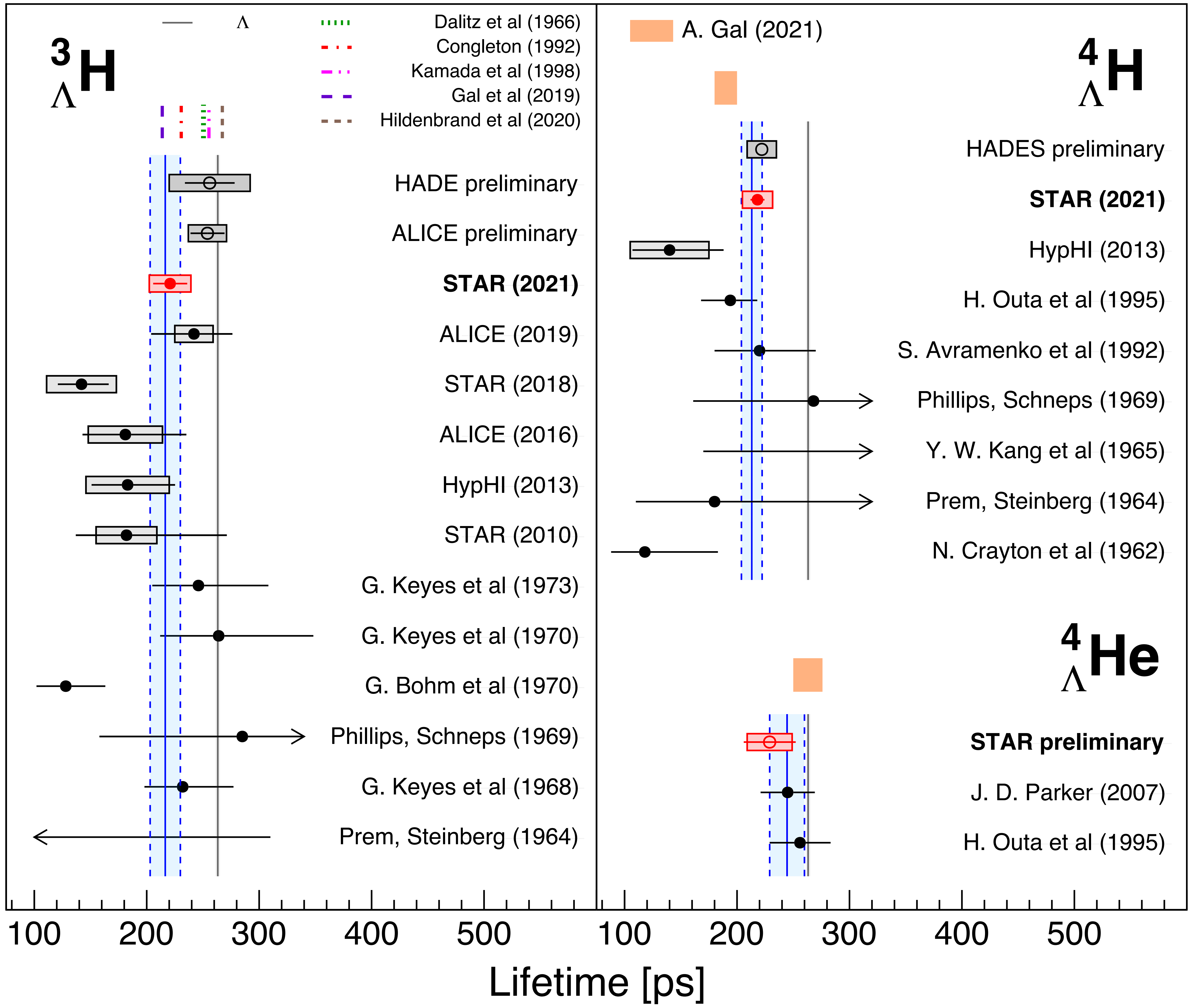
R_3 may be sensitive to the binding energy of ${}^{3}_{\Lambda}\mathrm{H}$

- 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

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

PRL 128, 202301(2022)
QM2022 poster, Xiujun



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

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

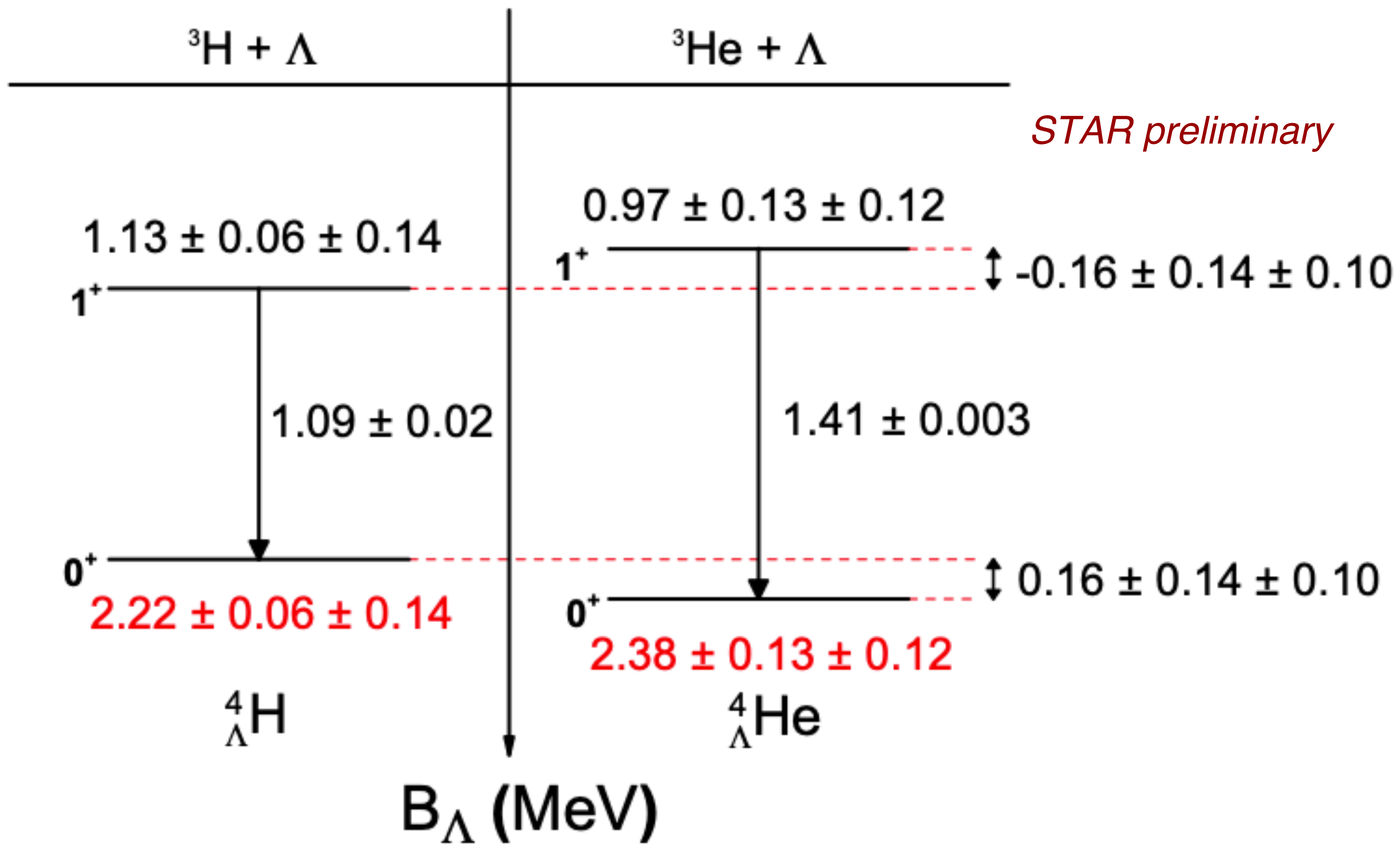
${}^{4}_{\Lambda}$He: $\tau = 229 \pm 23(\text{stat.}) \pm 20(\text{syst.})[\text{ps}]$

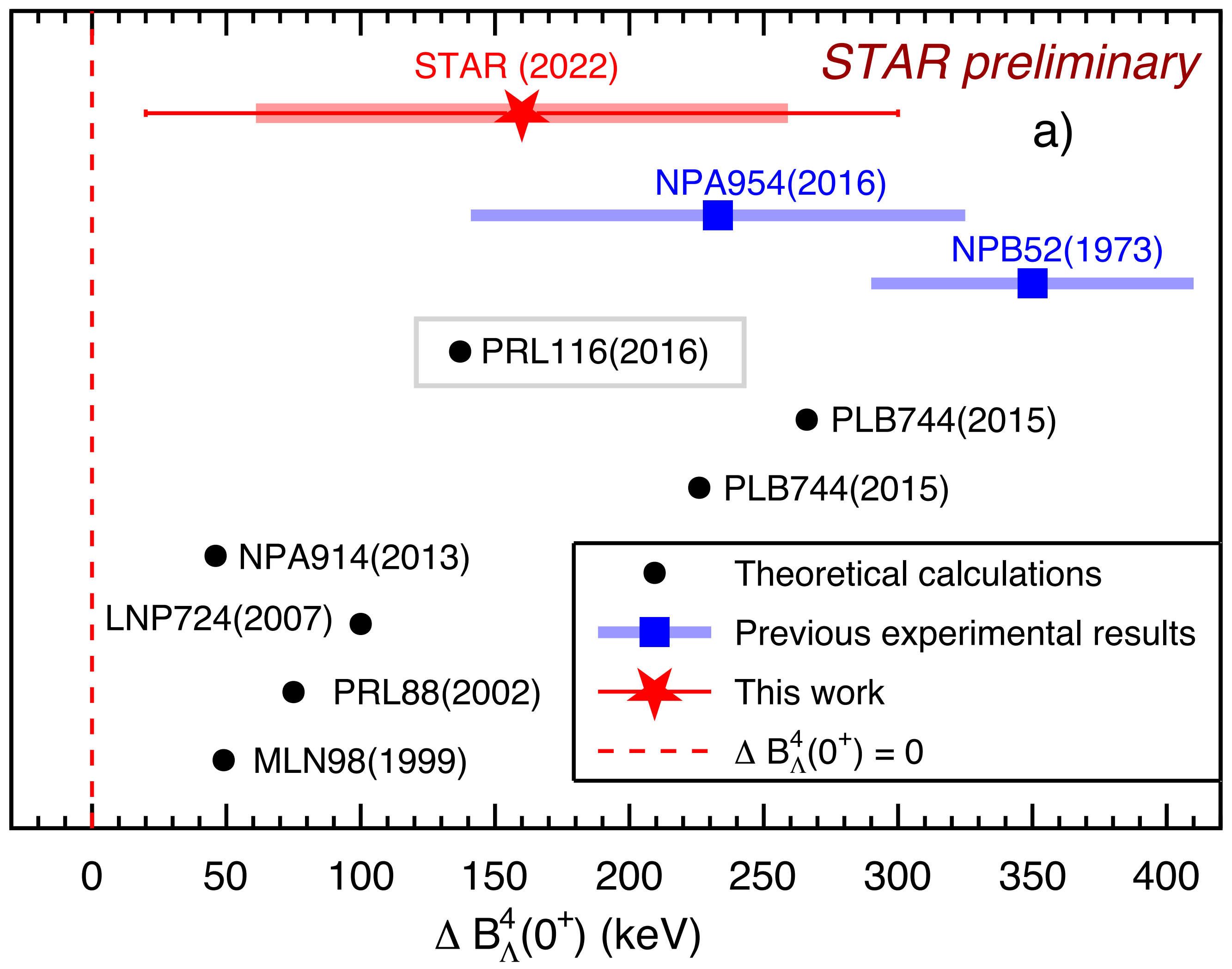
- Lifetime of light hypernuclei ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He are shorter than that of free Λ (with 1.8σ, 3.0σ, 1.1σ respectively)
- Consistent with former measurements (within 2.5σ for ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H)
- $\tau_{{}^{3}_{\Lambda}\text{H}}$ result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

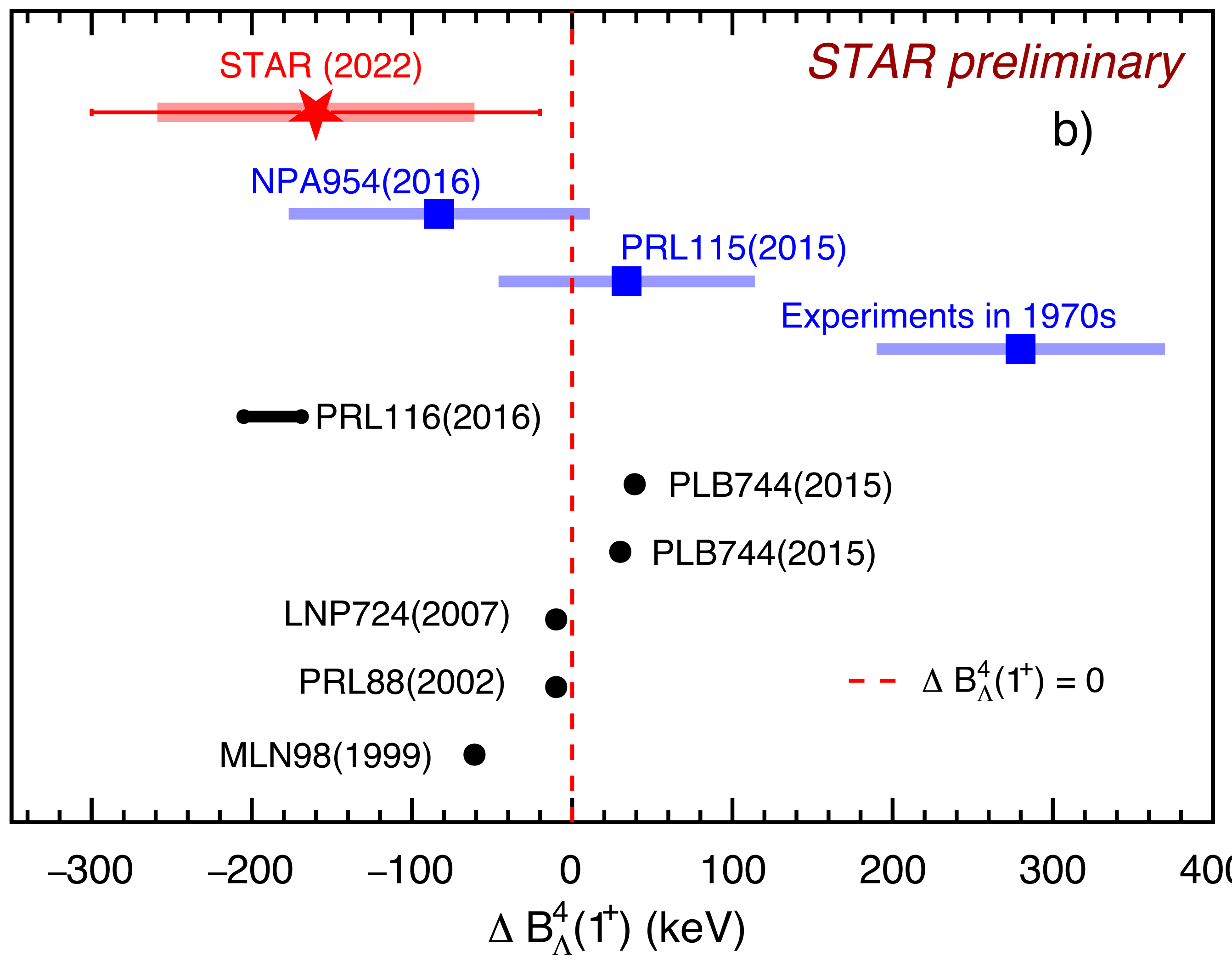
${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H results with improved precision

→ Provide tighter constraints on models.

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







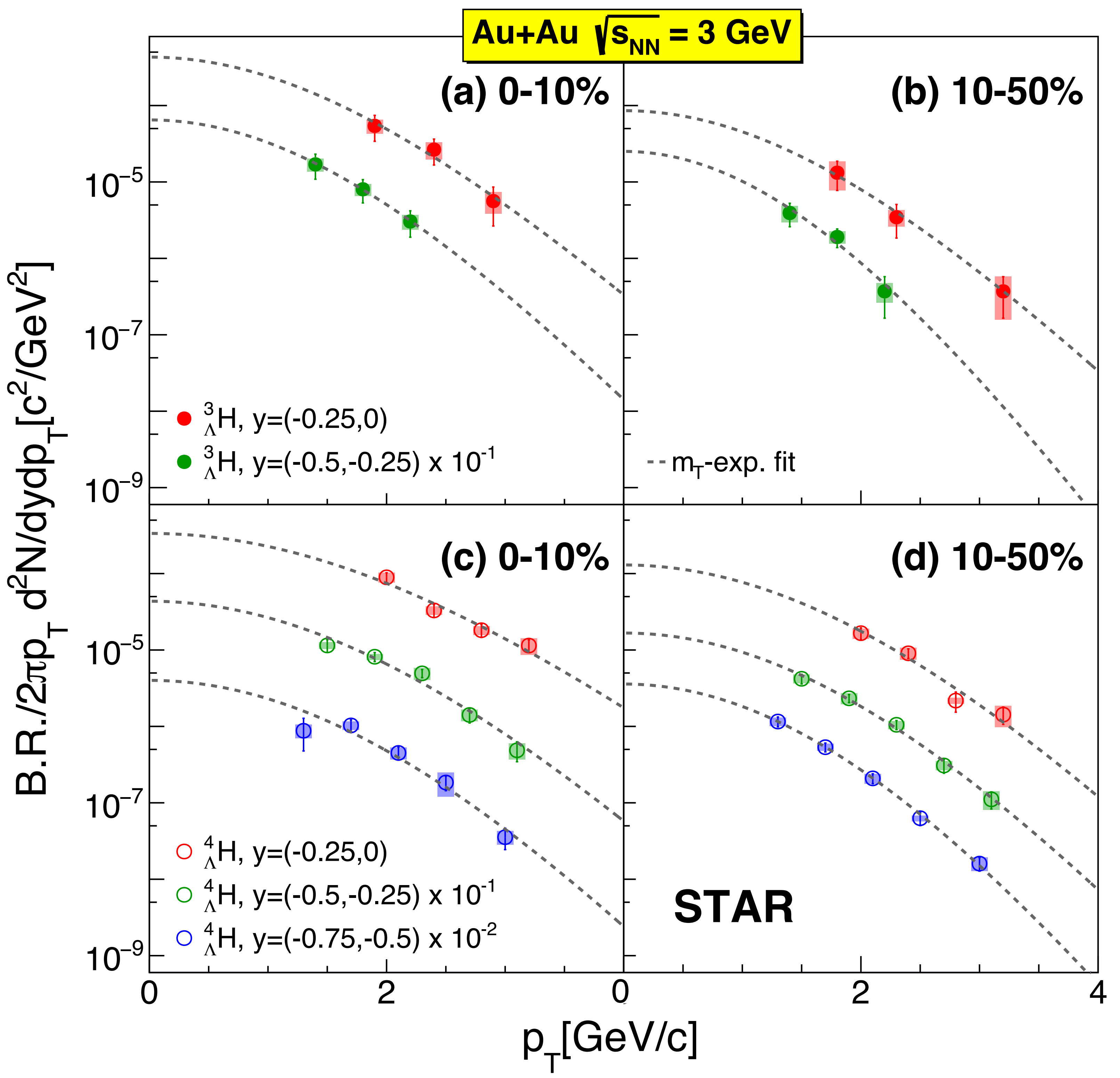
- Λ binding energies and their difference
  - The results for excited states are obtained from the γ-ray transition energies

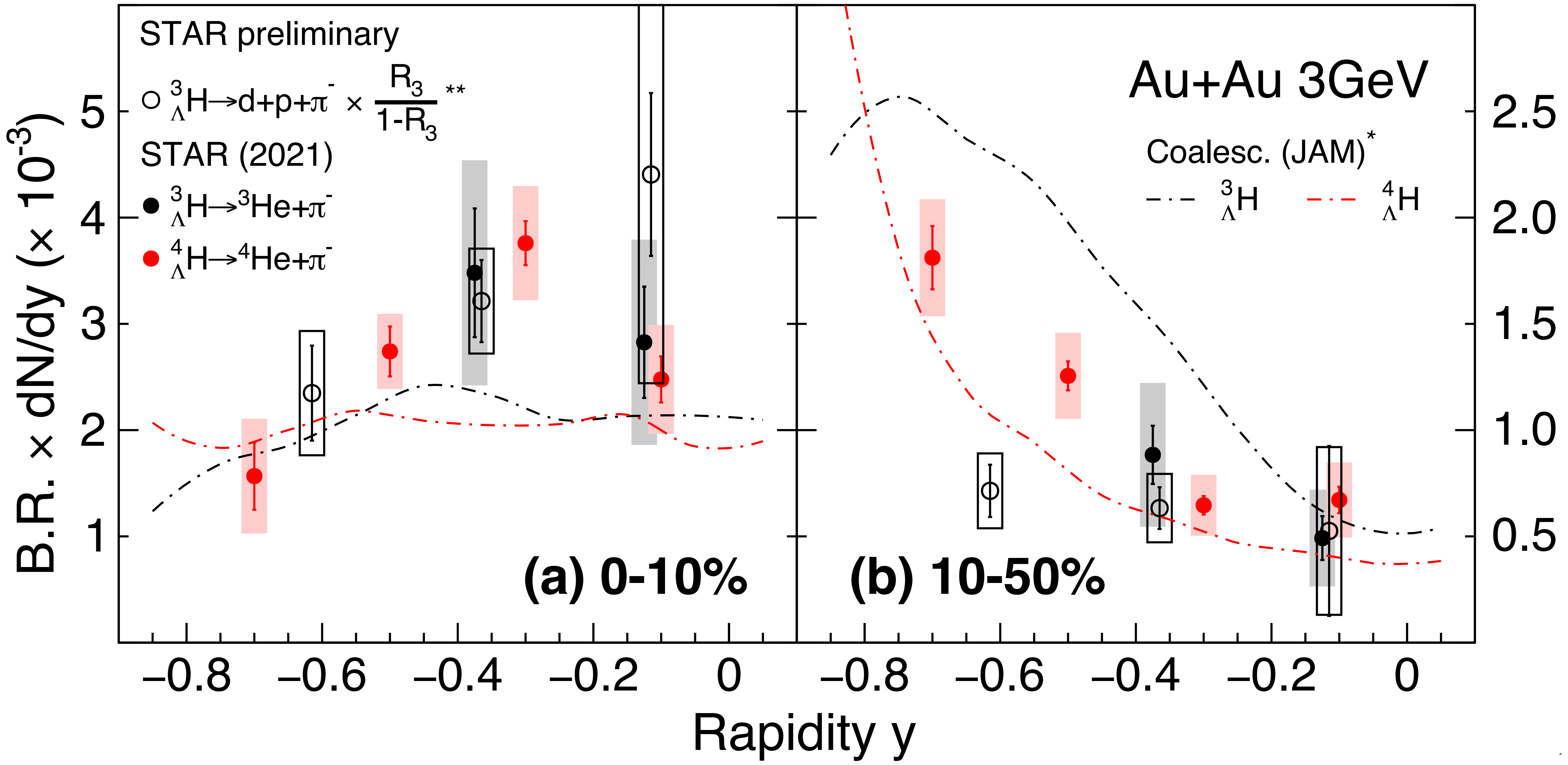
- Λ binding-energy difference

→Study 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.

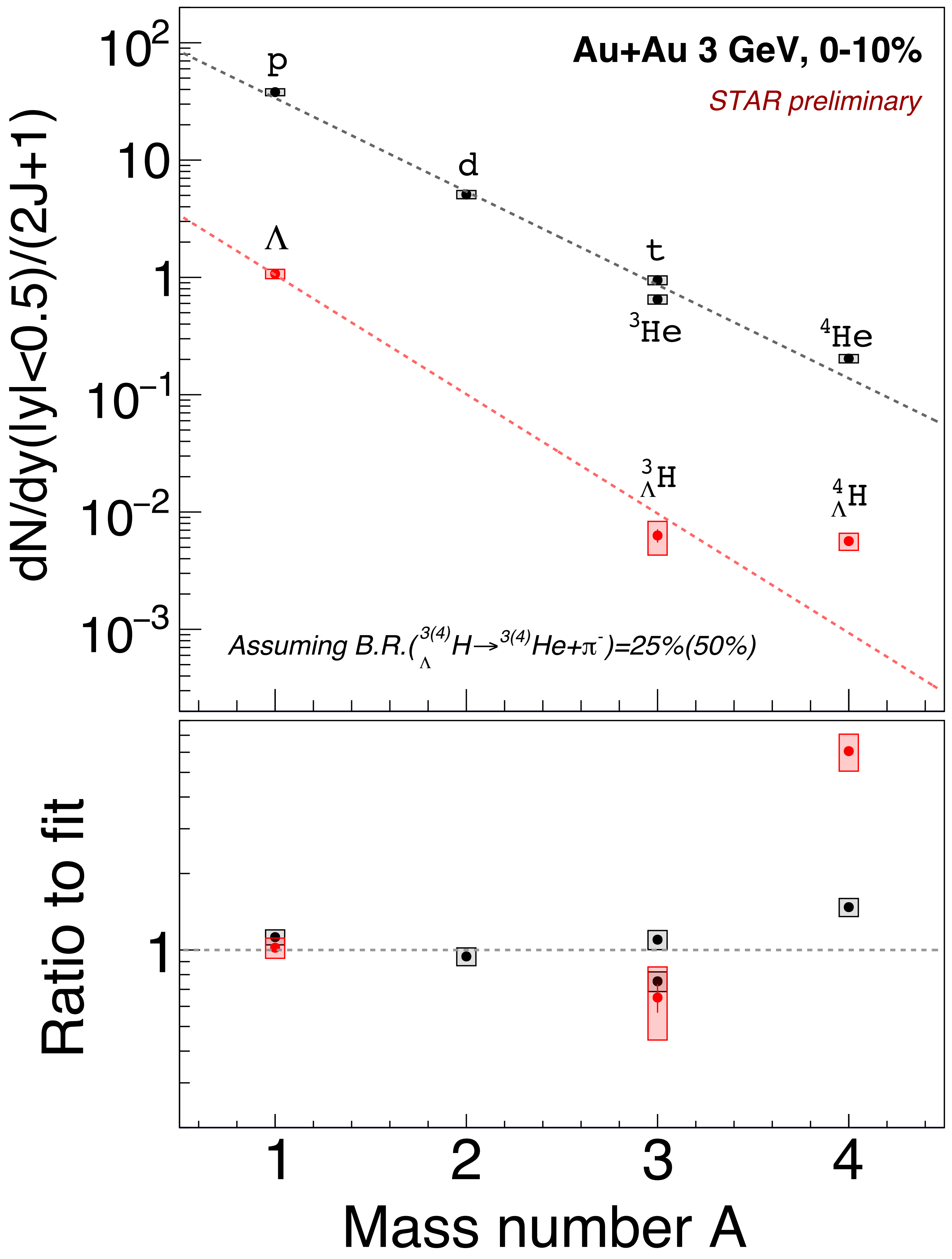
Hypernuclei production at 3 GeV





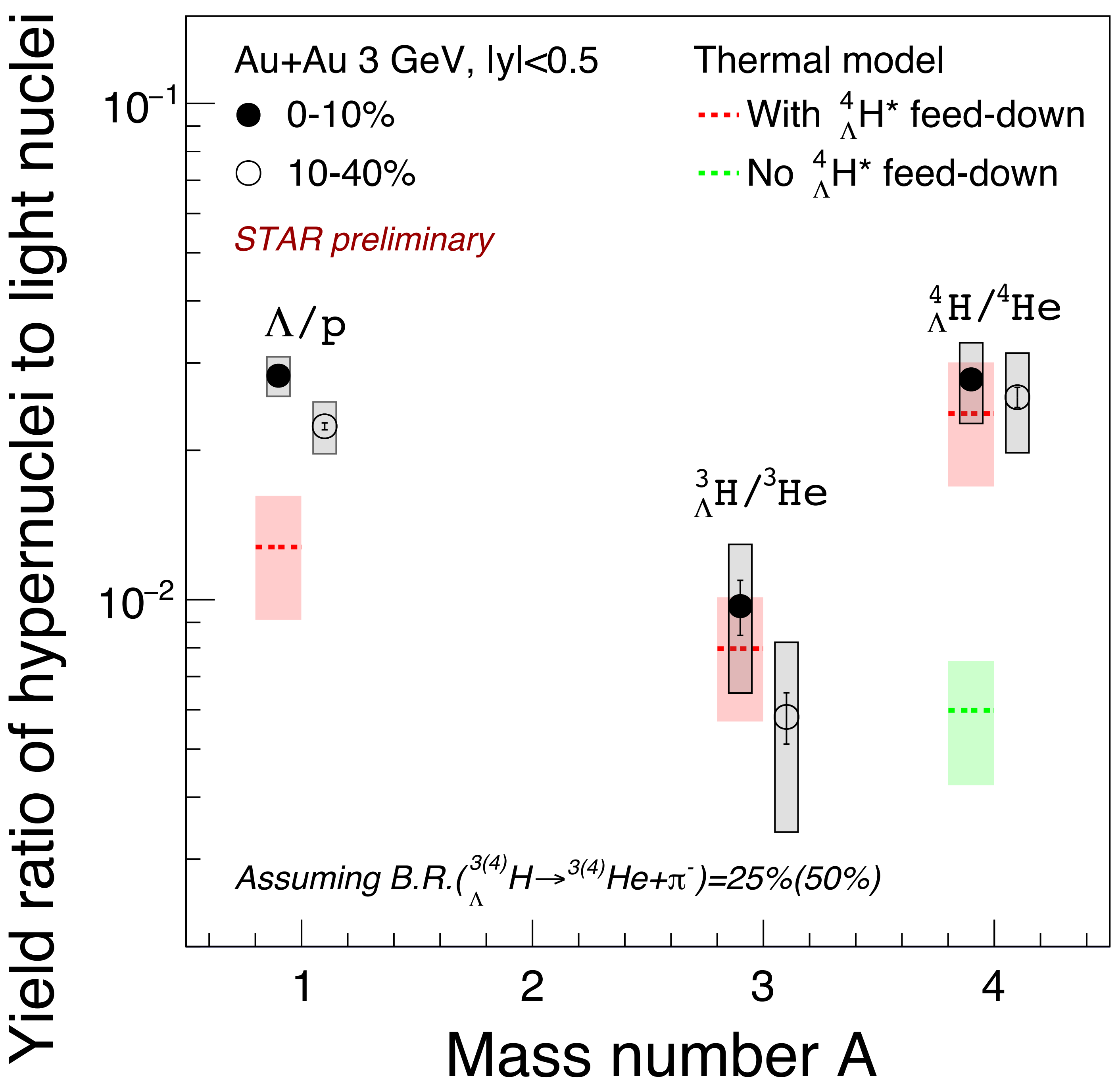
- First measurement of dN/dy of hypernuclei in heavy-ion collisions
- Different trends in the ${}^{4}_{\Lambda}\mathrm{H}$ rapidity distribution in central (0-10%) and mid-central (10-50%) collisions
  - Transport model (JAM) with coalescence reproduce trends of ${}^{4}_{\Lambda}\mathrm{H}$ rapidity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

Comparison to Λ and light nuclei at 3 GeV



QM2022 talk, Yue-hang

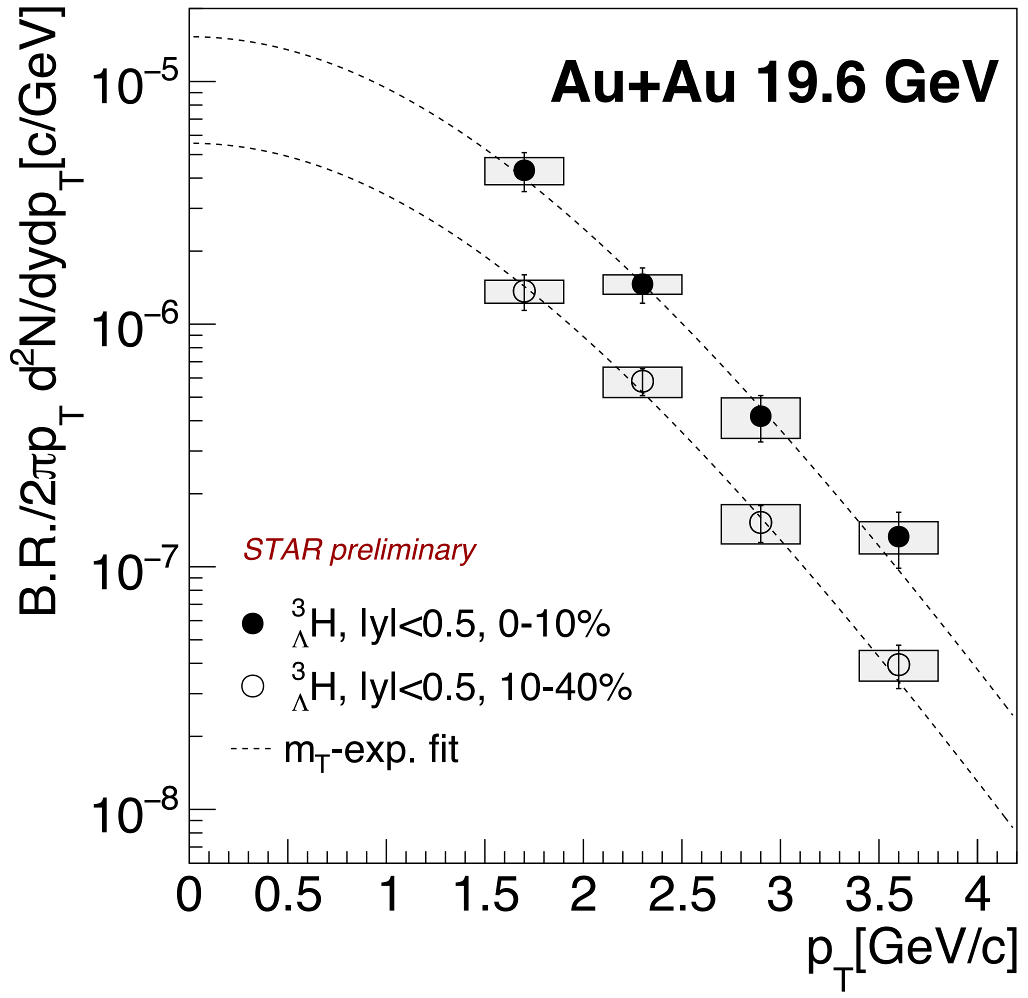
- Thermal/ coalescence models predict approx. exponential dependence of yields/ (2J+1) vs A
- ${}^{4}_{\Lambda}\mathrm{H}$ lies a factor of 6 above exponential fit to $(\Lambda, {}^{3}_{\Lambda}\mathrm{H}, {}^{4}_{\Lambda}\mathrm{H})$

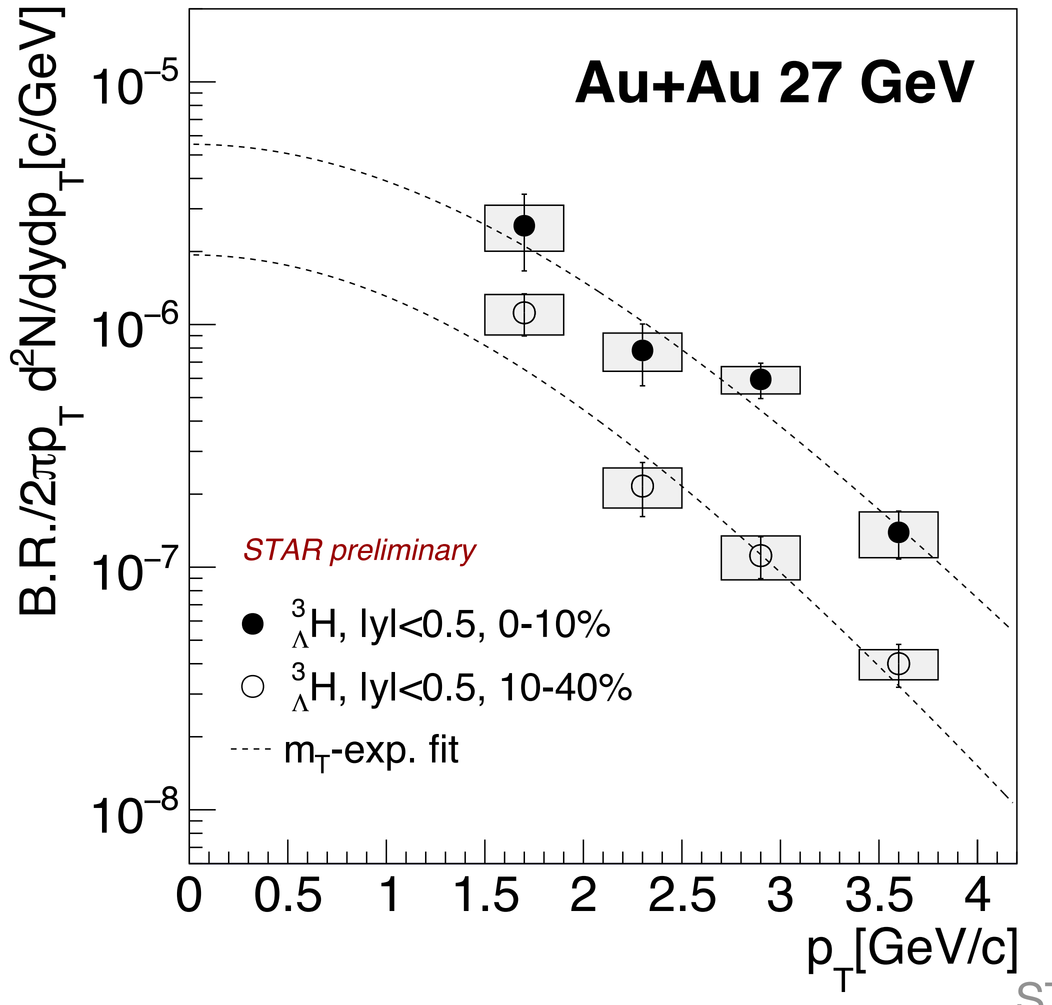


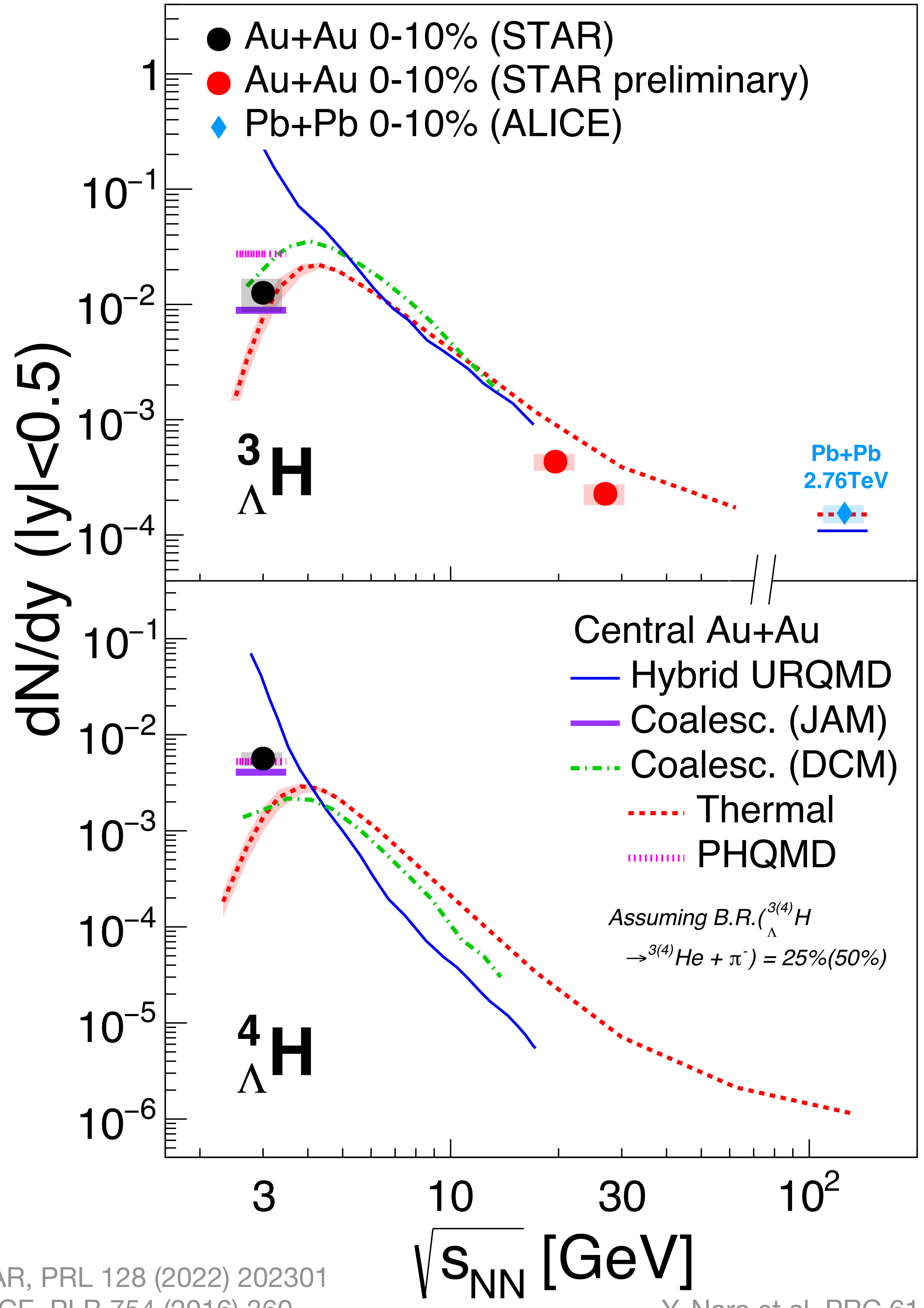
- Non-mononic behavior in light-to-hyper-nuclei ratio vs A observed
  - Thermal model calculations including excited ${}^{4}_{\Lambda}\mathrm{H}^{*}$ feed-down shows a similar trend

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

Energy dependence of hypernuclei production in heavy-ion collisions







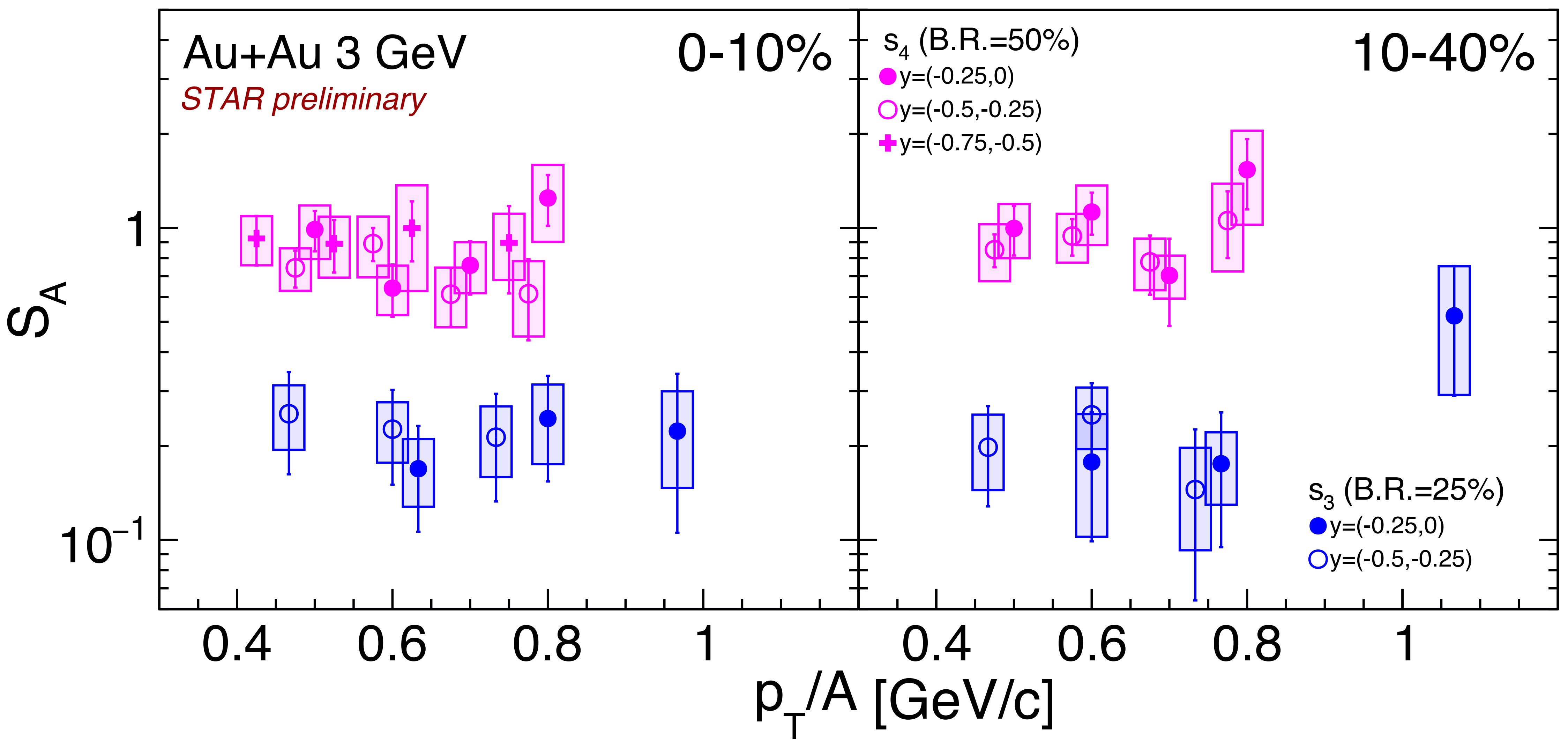
- $^{3}_{\Lambda}H$ yield at mid-rapidity increases from 2.76 TeV to 3 GeV
  - Driven by increase in baryon density at low energies
- Thermal model reproduces the trend, but does not quantitatively describe the yields of $^{3}_{\Lambda}H$. Meanwhile, $^{4}_{\Lambda}H$ is underestimated.
- Coalescence(DCM) 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 3GeV by an order of magnitude

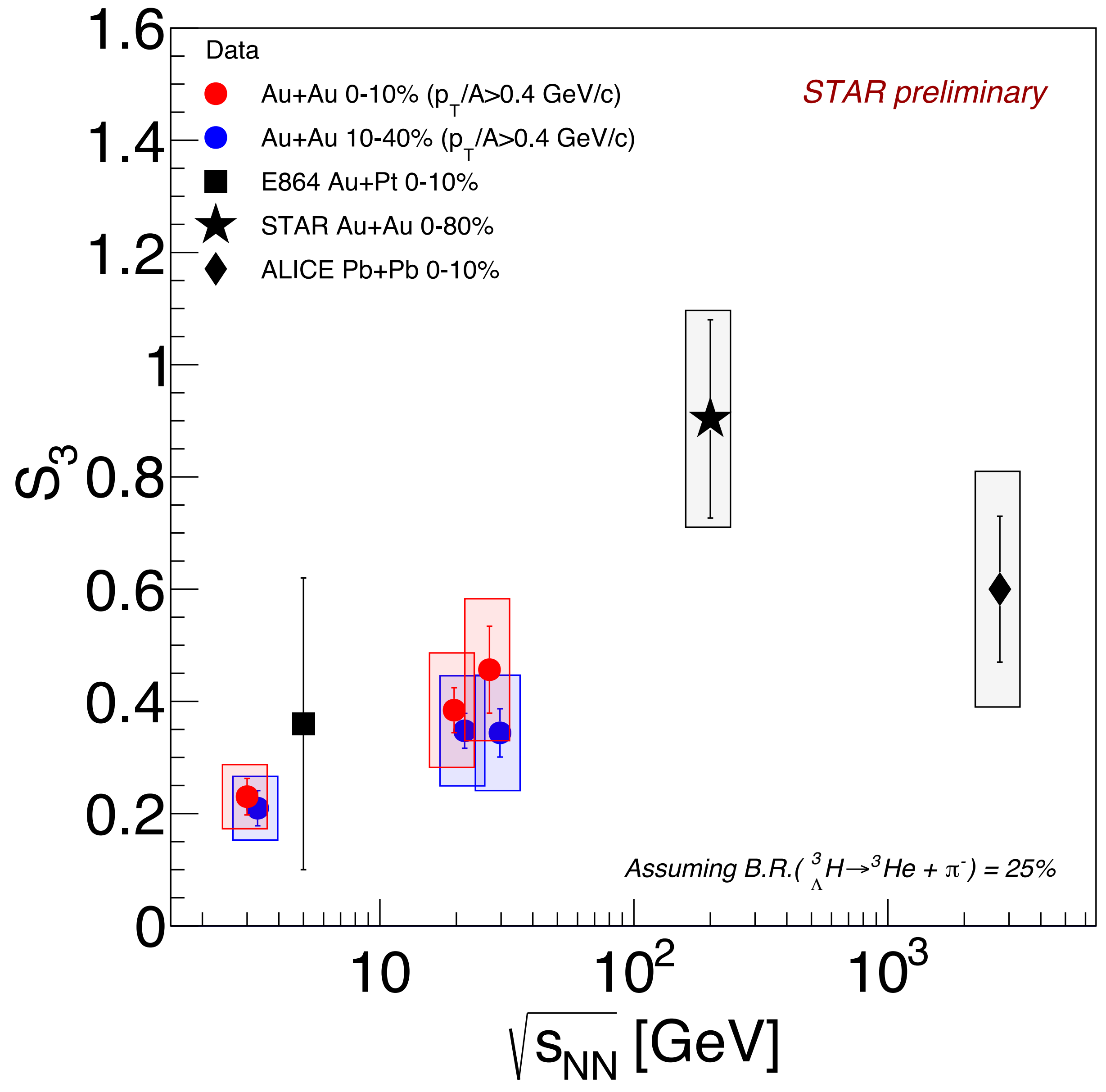
Provide first constrains for hypernuclei production models in the high-baryon-density region

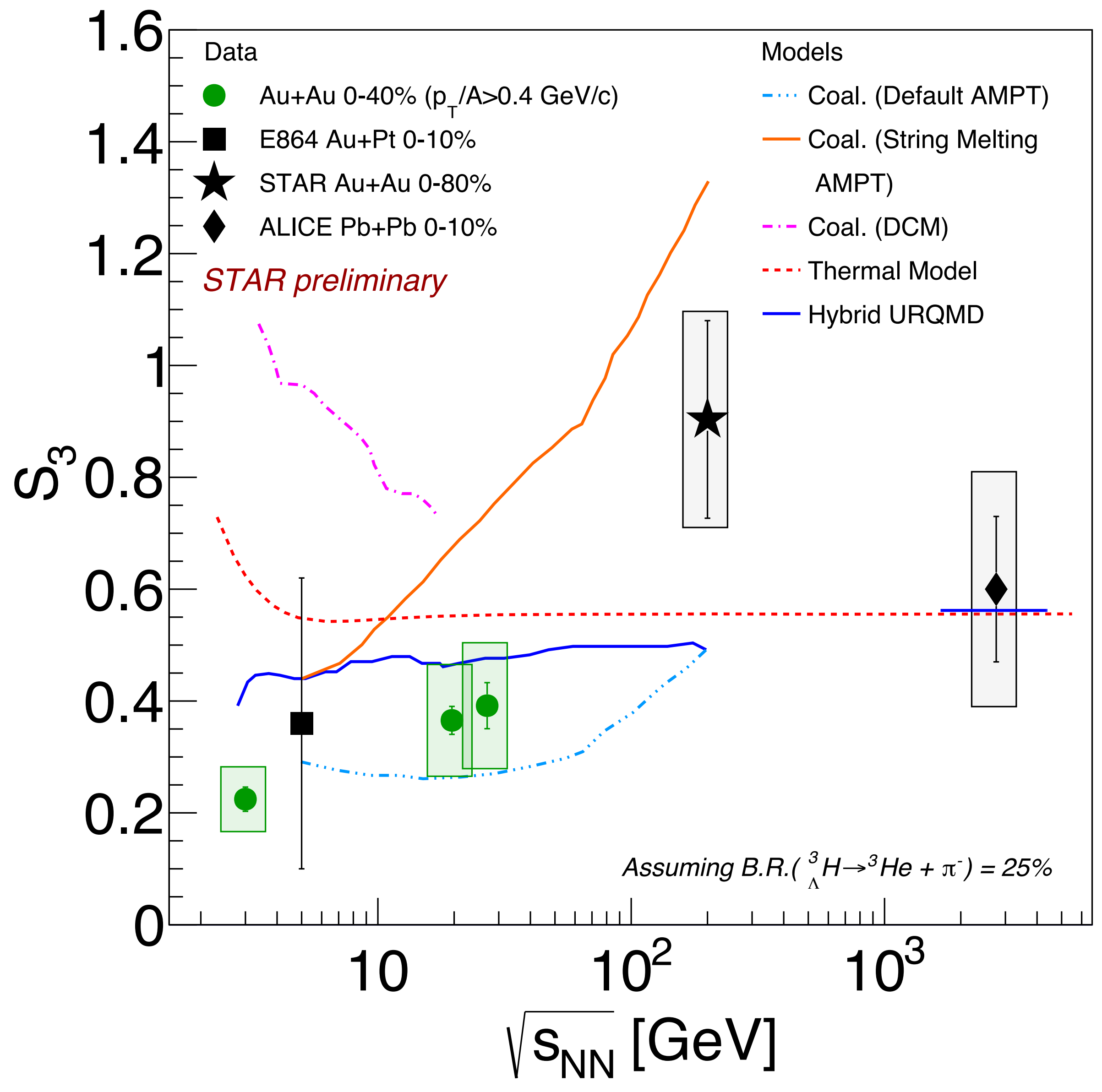
STAR, PRL 128 (2022) 202301
ALICE, PLB 754 (2016) 360
A. Andronic et al, PLB 697 (2011) 203 (Thermal model)
J. Steinheimer et al, PLB 714 (2021) (H. URQMD, DCM)
Y. Nara et al, PRC 61 (1999) 024901 (JAM)
S. Gläßel et al, arXiv: 2106,14839 (PHQMD)

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
    - $S_3 < 1 \rightarrow$ relative suppression of ${}^{3}_{\Lambda}H$ to ${}^{3}He$
    - $S_4 > S_3 \rightarrow$ enhanced ${}^{4}_{\Lambda}H$ production due to feed-down from excited state





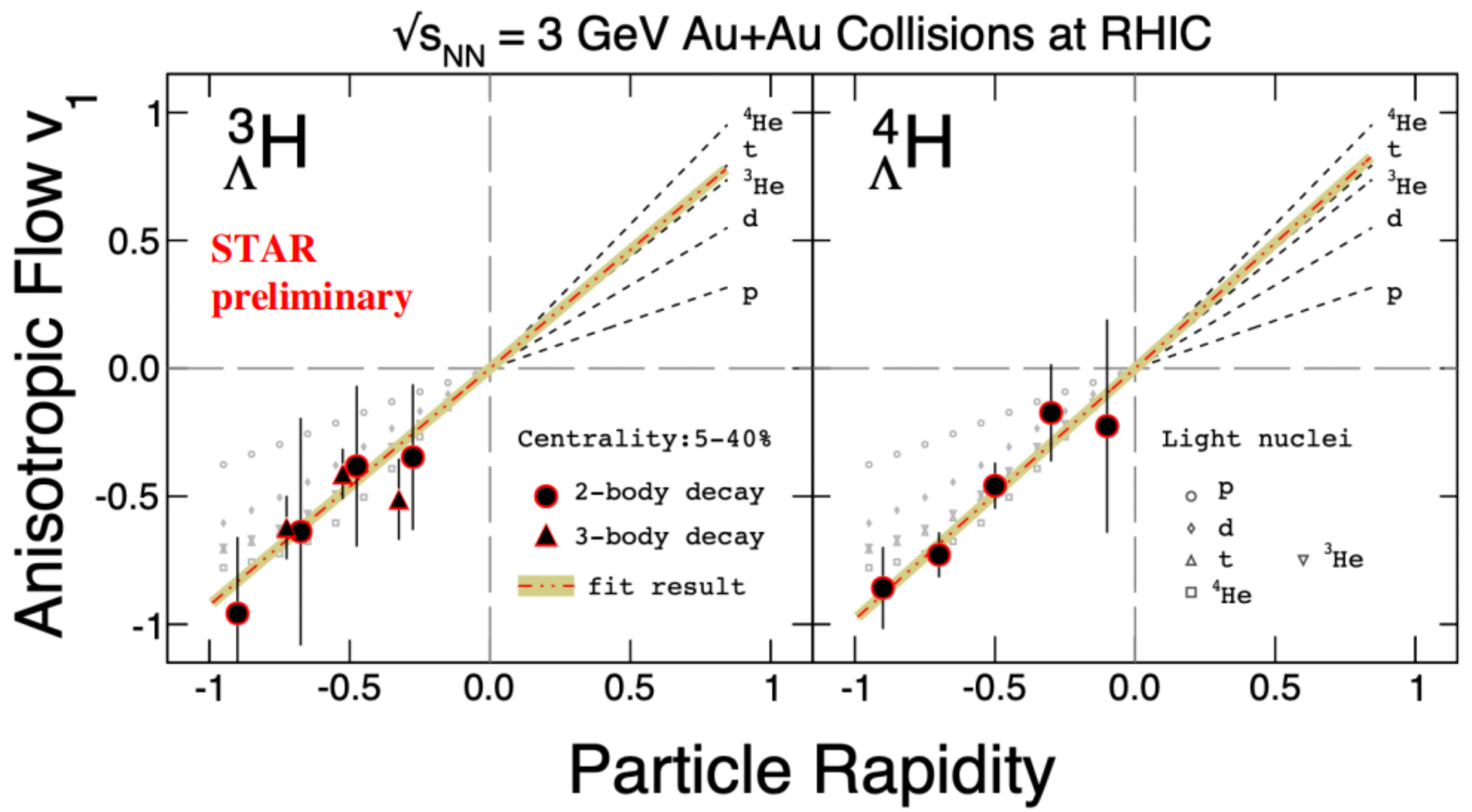


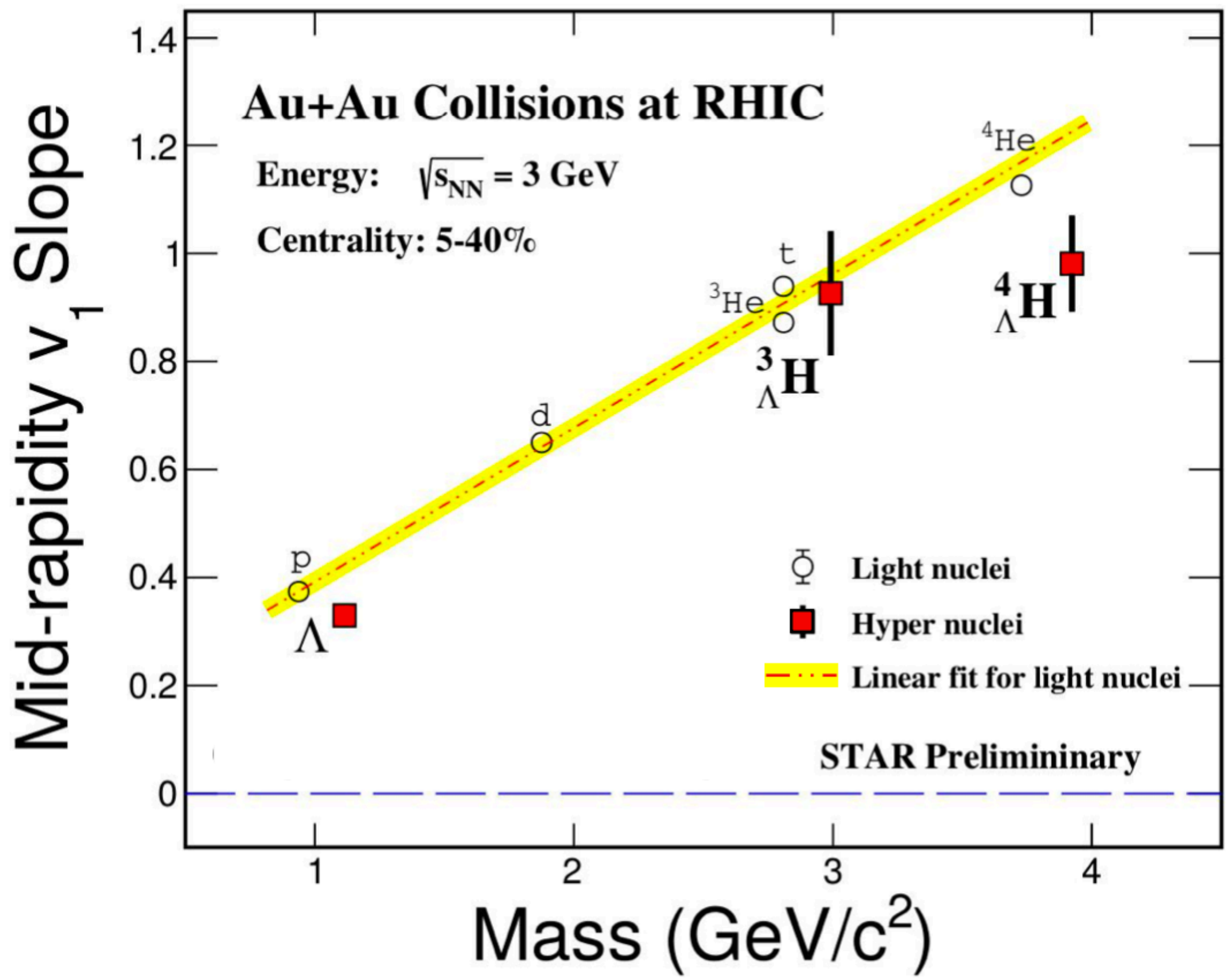
- No clear centrality dependence
- Hint of an increasing trend from $\sqrt{s_{NN}} = 3.0$ GeV to 2.76 TeV
- None of the models describe the S_3 data quantitatively

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

Chenlu





- First measurements of ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ directed flow (v_1) from 5 - 40% centrality
- dv_1/dy slopes of ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ seem to flow a mass number scaling.

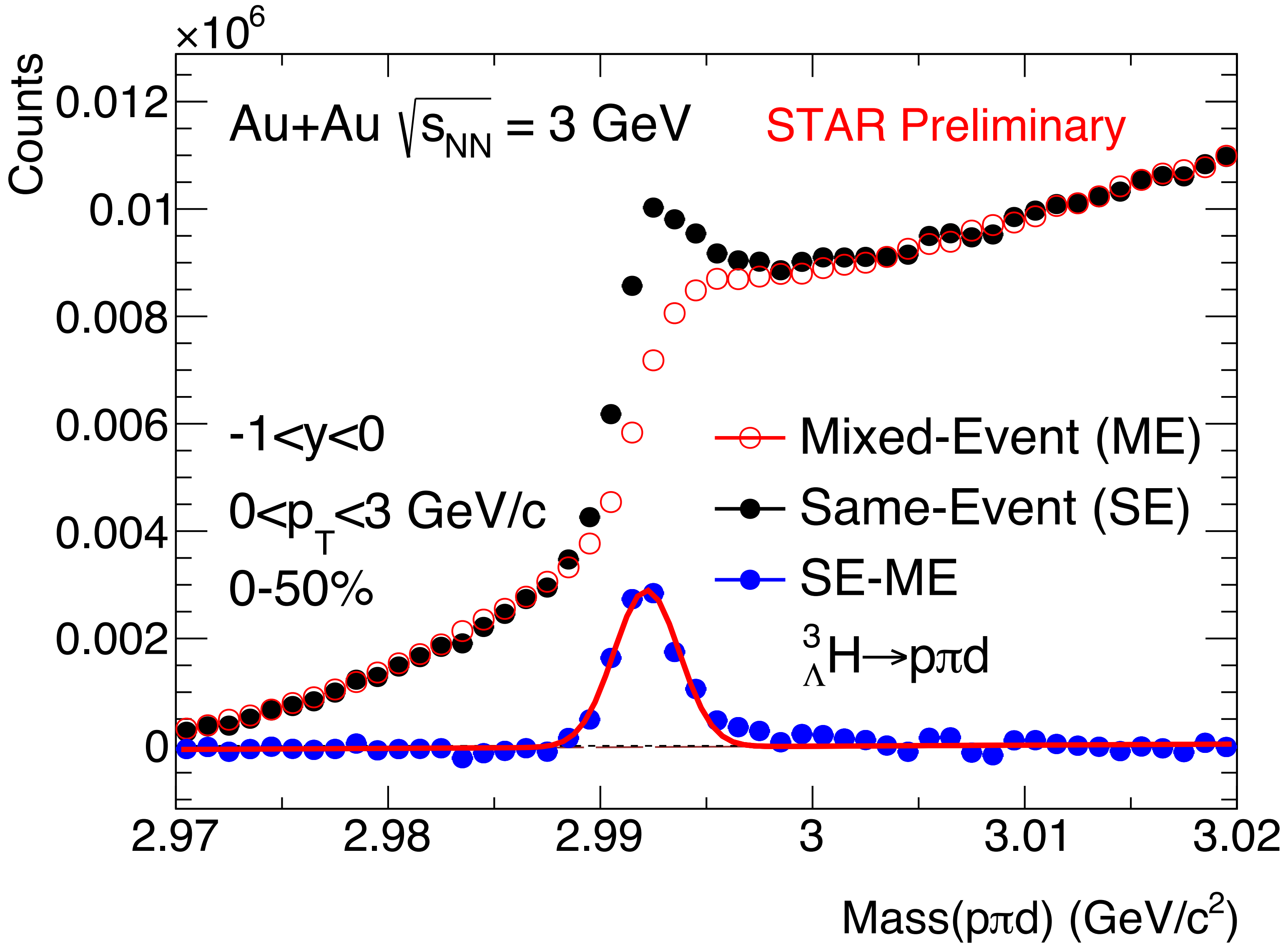
→ **Imply coalescence is a dominant process for hypernuclei formation in heavy-ion collisions**

Summary

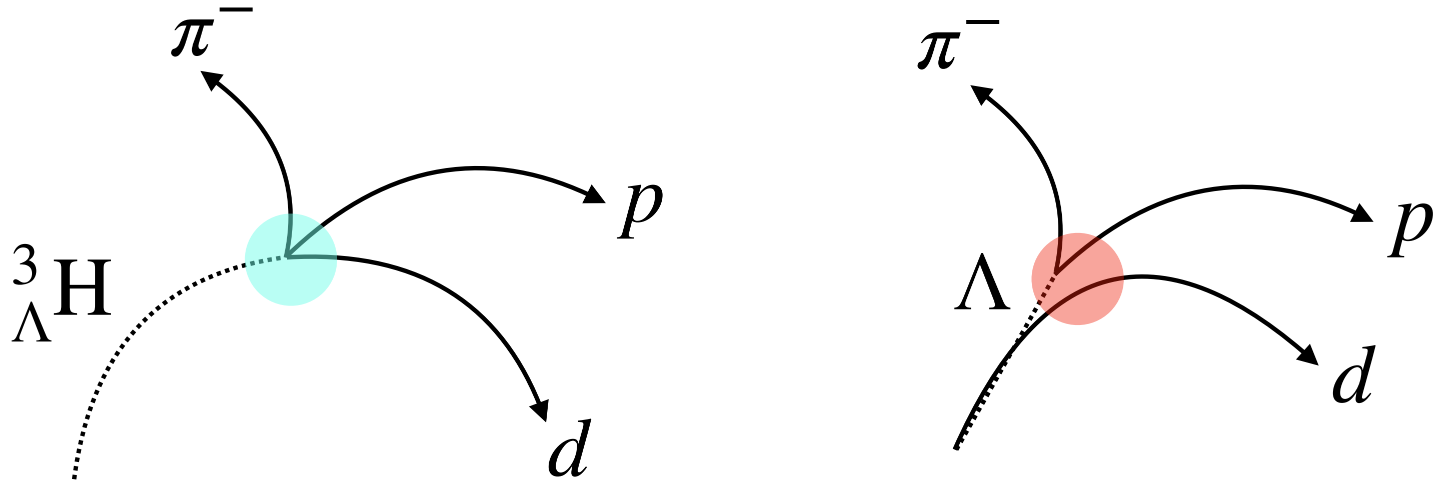
- STAR BES-II provides a unique opportunity to study hypernuclei, especially at high-baryon-density region
  - ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$ lifetimes measured with improved precision
  - Relative branching ratio R_3 of ${}^{3}_{\Lambda}\mathrm{H}$ with improved precision
    - 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: iTPC and eToF fully installed in 2019 → improve η acceptance and PID at large η
    - Expect precision measurements and more information of hypernuclei production with wider η range

Back up

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

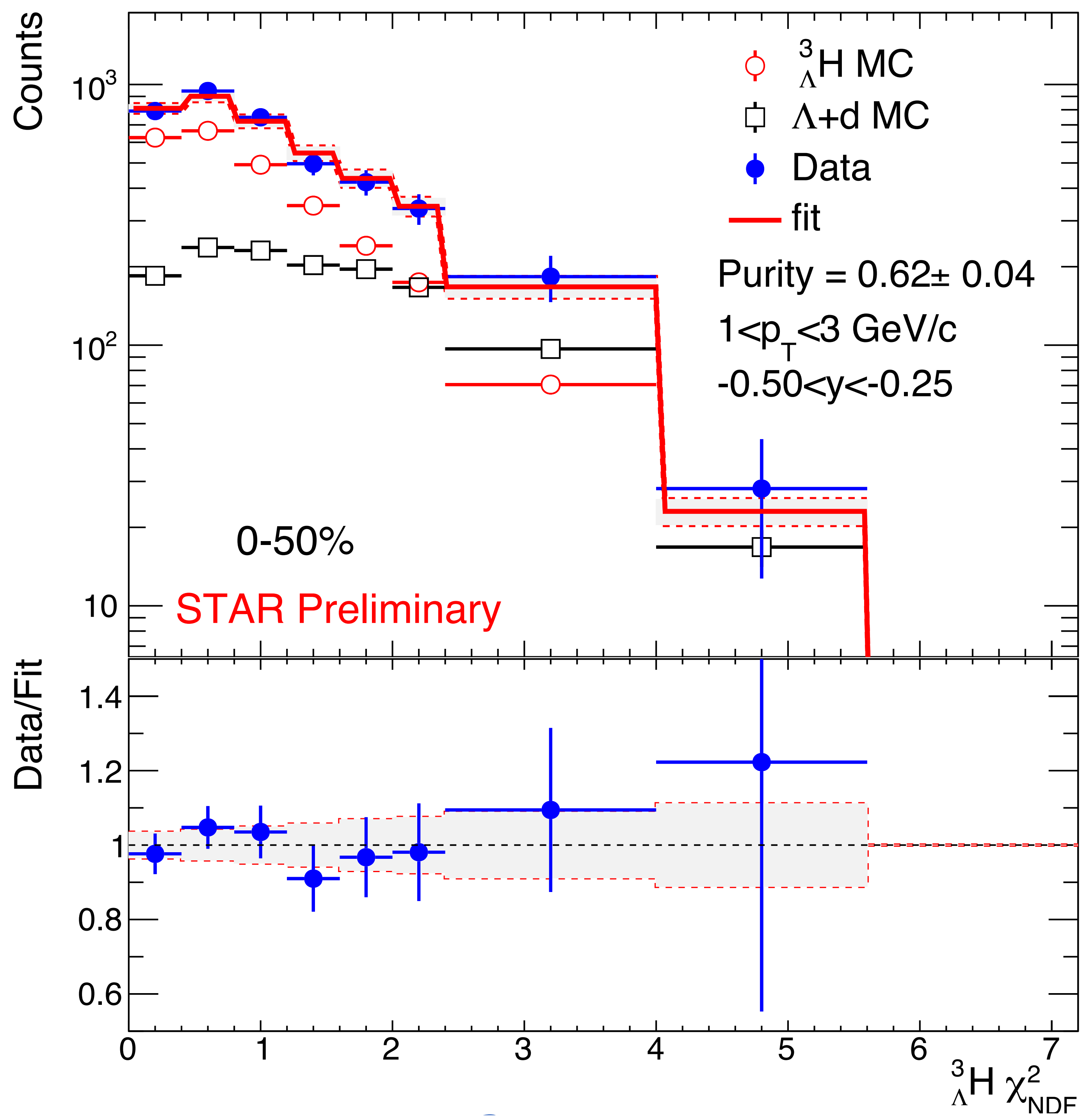


- SE-ME signals contains real signal and kinematically correlated $\Lambda + \mathrm{d}(\Lambda \rightarrow p\pi^{-})$



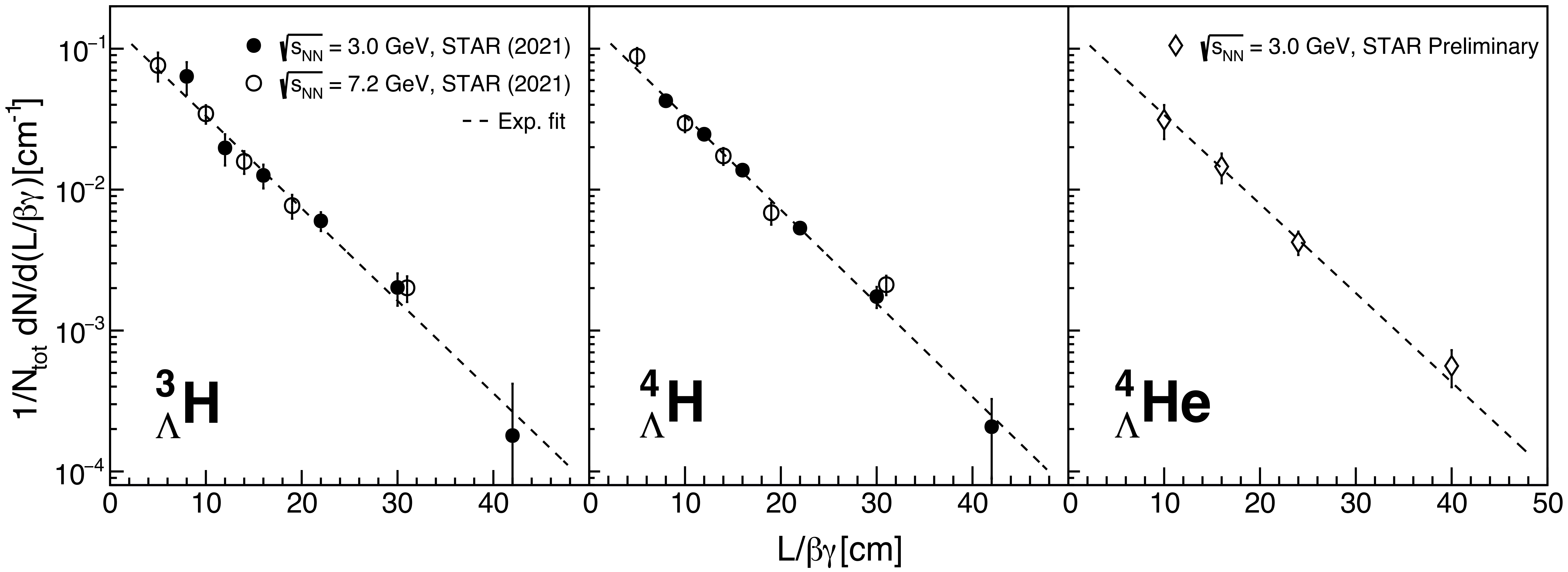
Real signal: lower χ^2

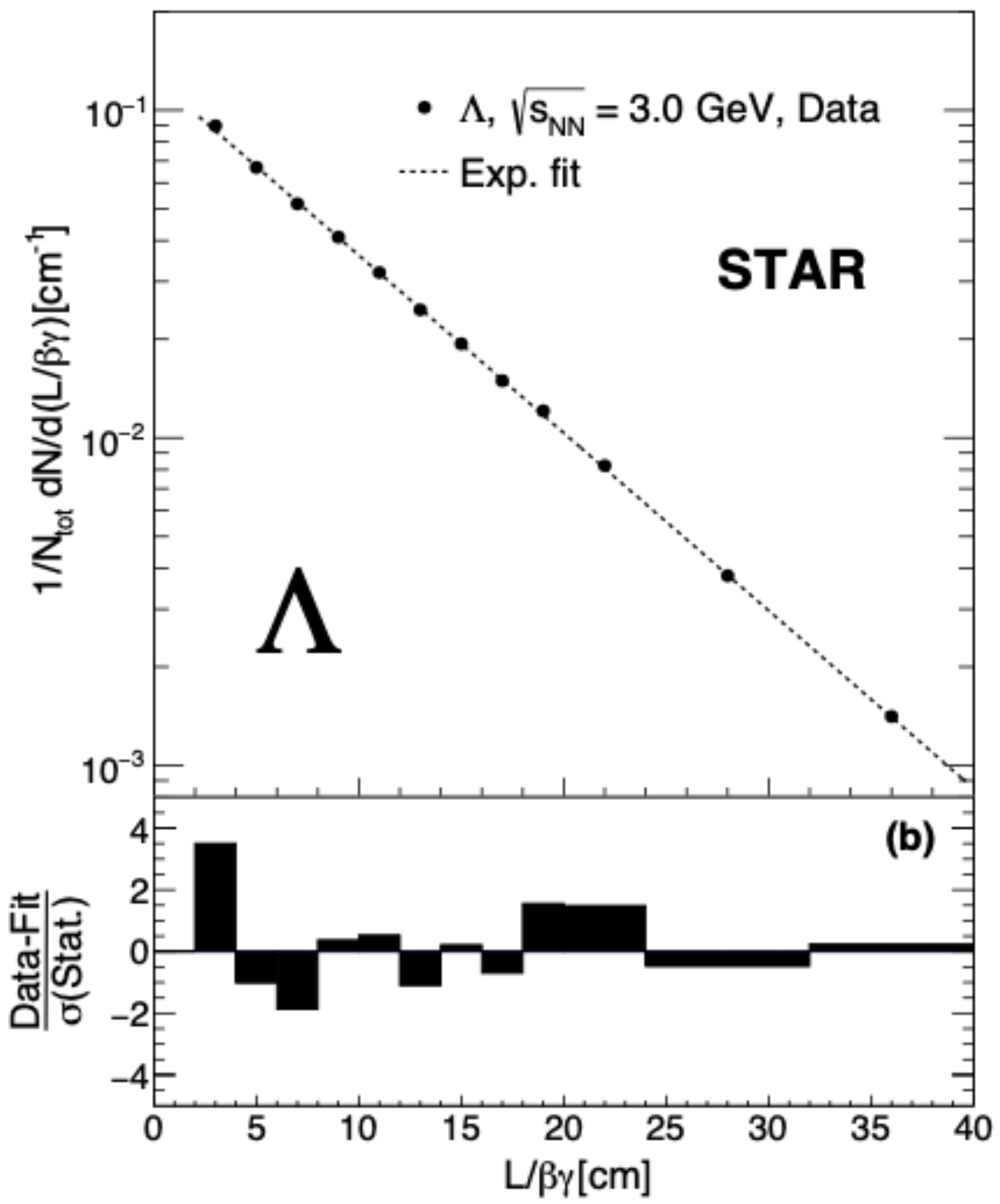
Backgrounds: higher χ^2



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

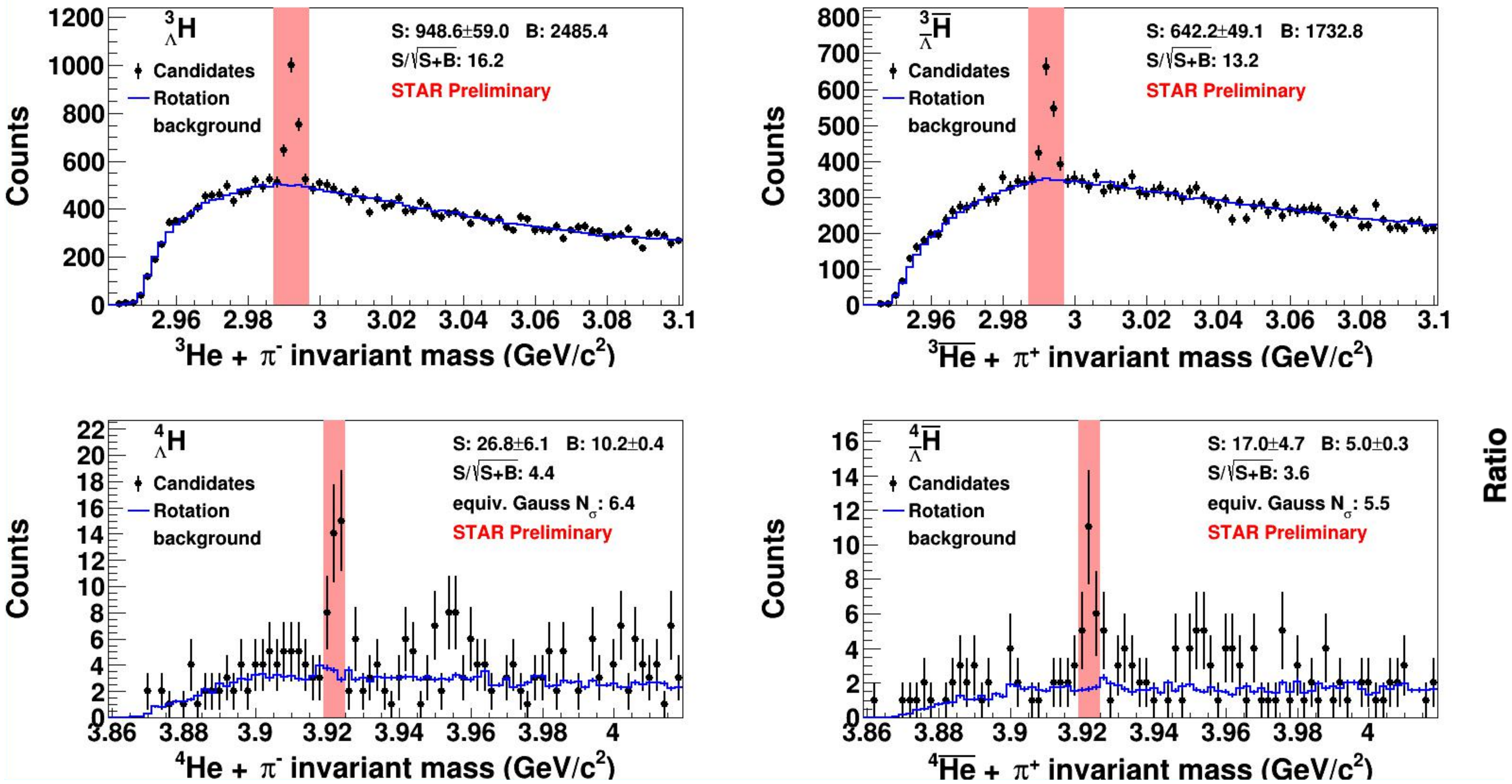
Lifetime





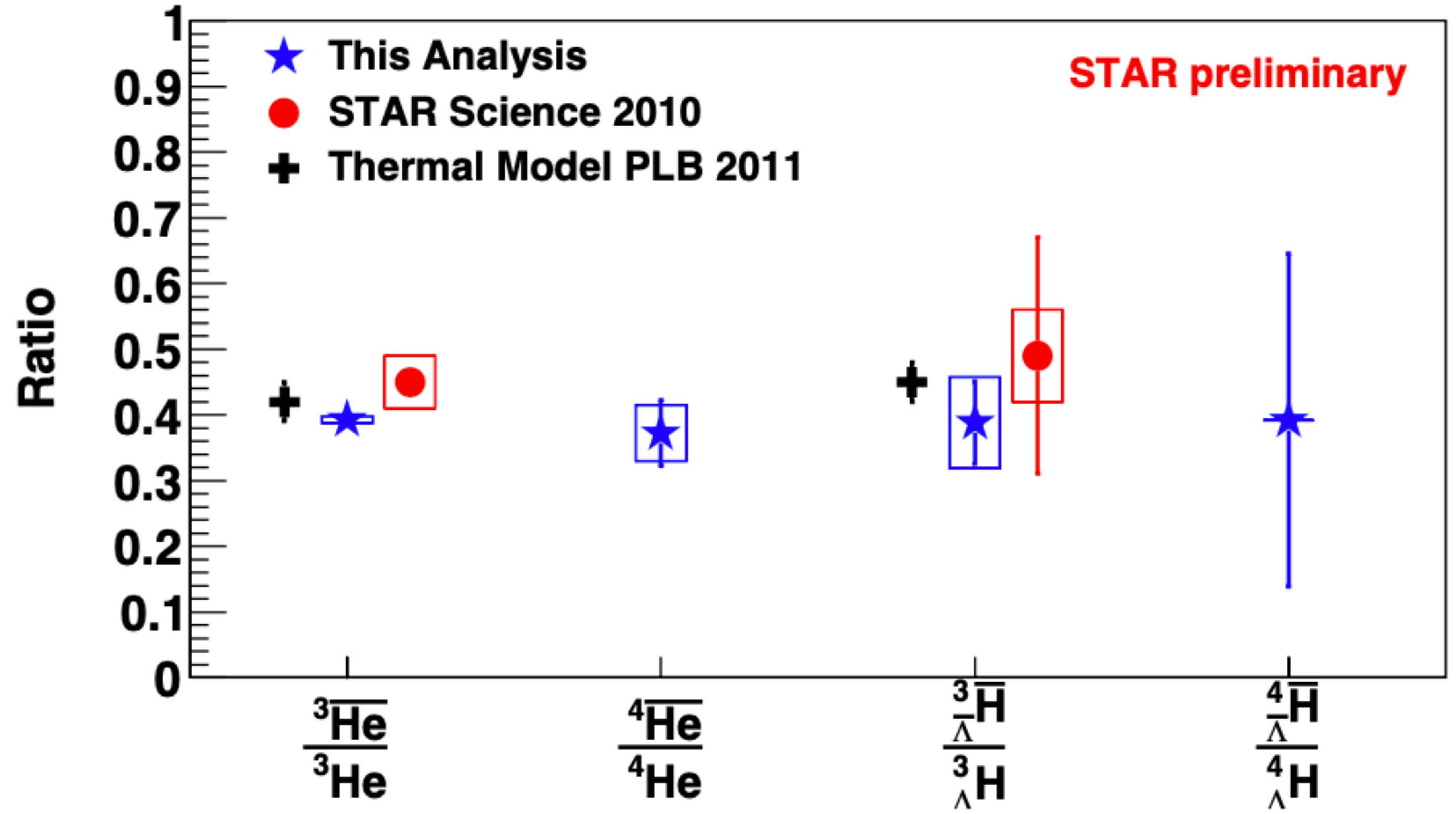
- Lifetime τ extracted via $N(t) = N_0 e^{-L/\beta\gamma c\tau}$
- Λ lifetime cross check : 267±4 ps, consistent with PDG value (263±2 ps)
- $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$ lifetimes from 3.0 GeV consistent with 7.2 GeV results

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

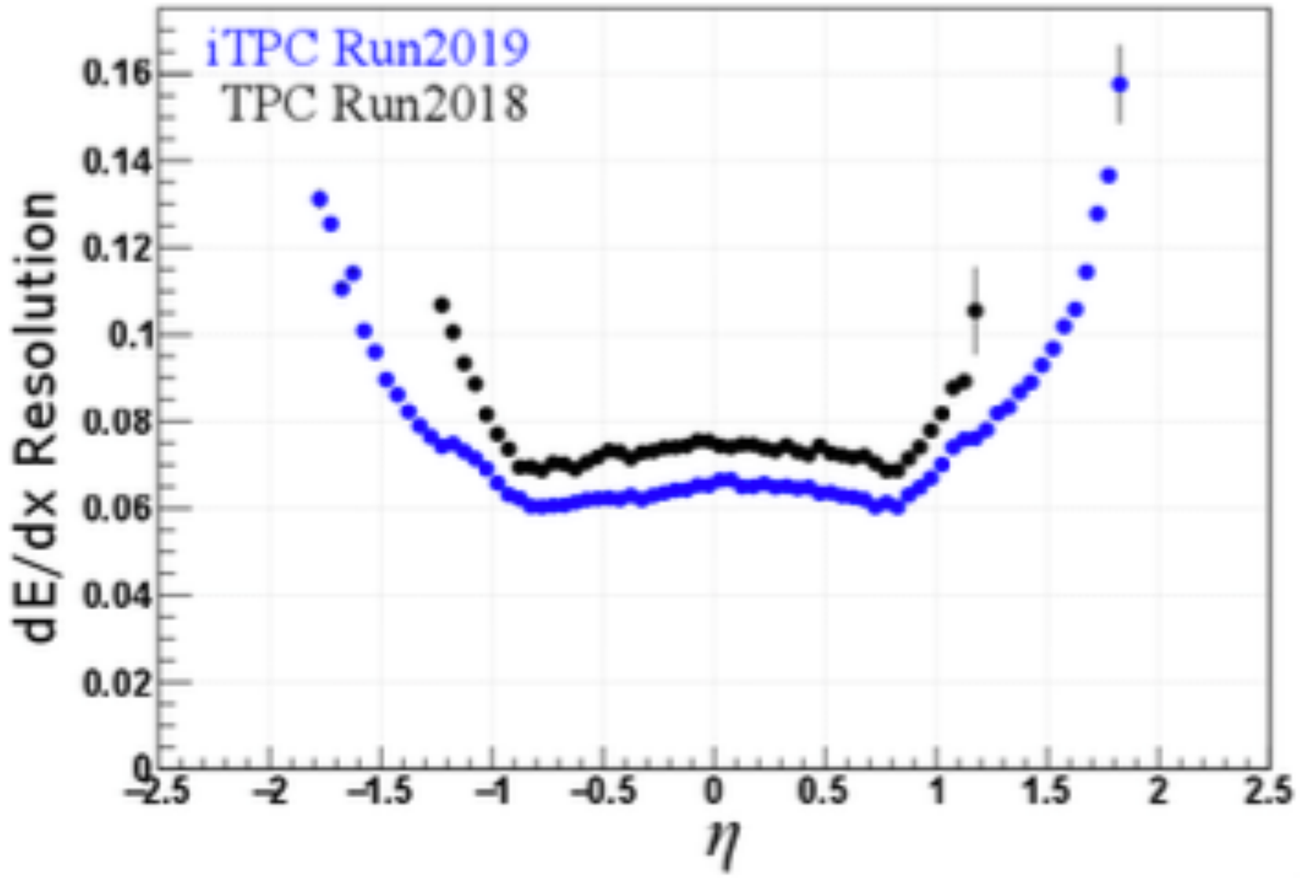
Detector upgrade

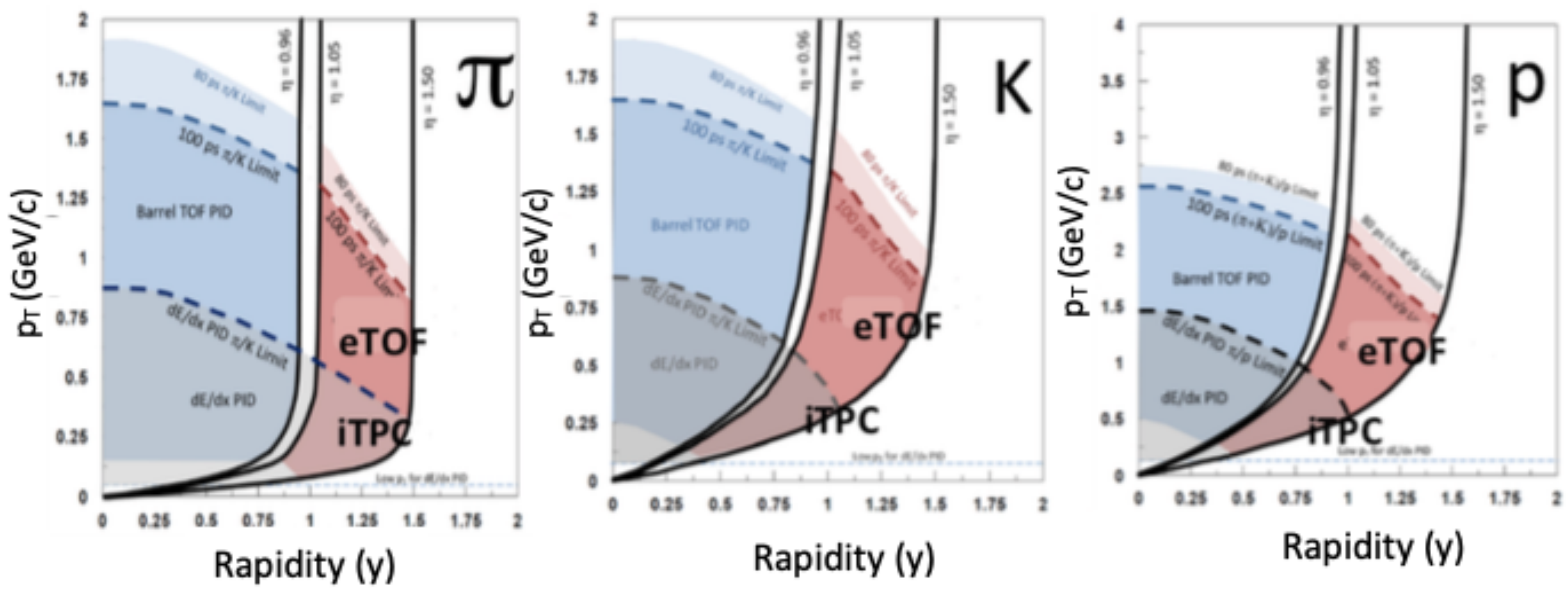
In year 2019:

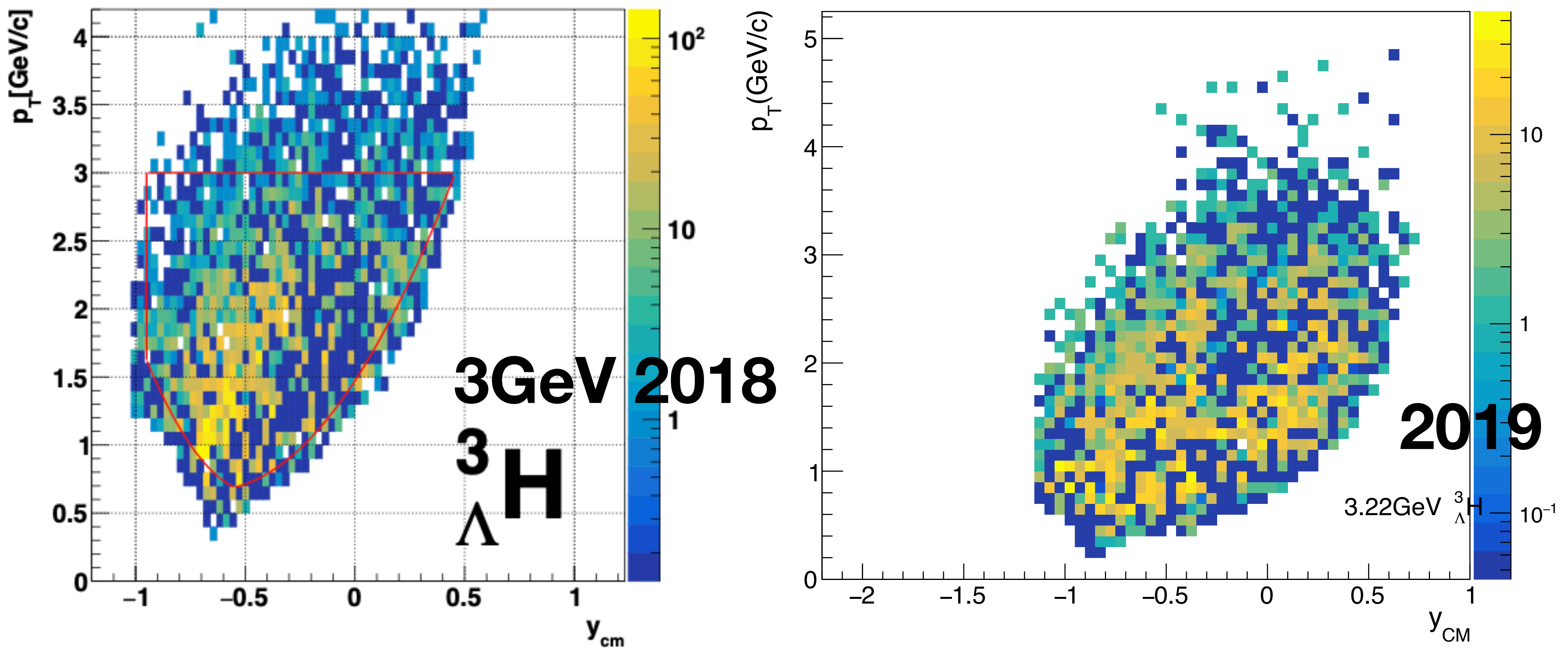
QM2019 talk, Yi Yang

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