Lifetime and Yield Measurements of Light Hypernuclei from STAR Experiment

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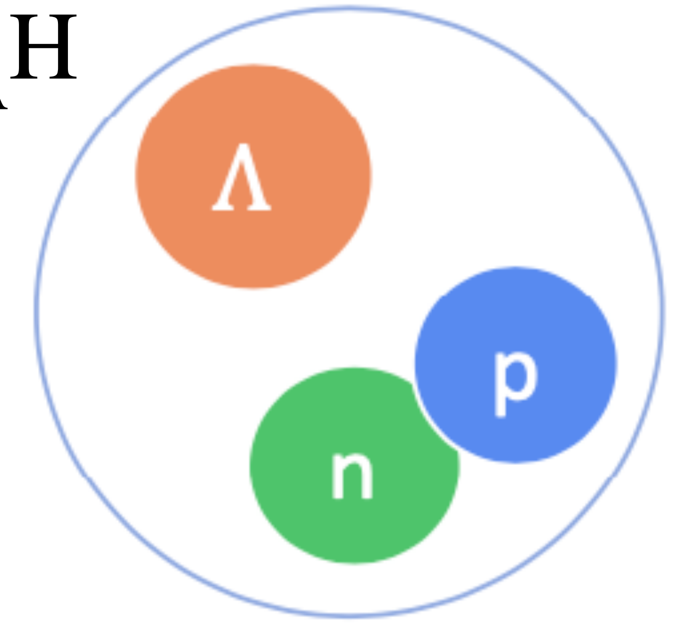
Outline

- Introduction
- Lifetime and yield measurements of hypernuclei from STAR
- Summary
- Outlook

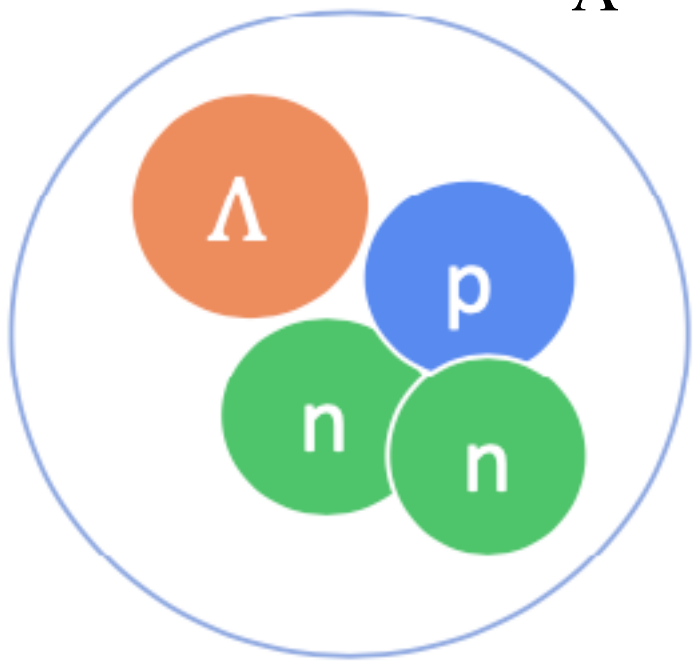
Introduction: what and why

- What are hypernuclei?
  - Bound nuclear systems of non-strange and strange baryons

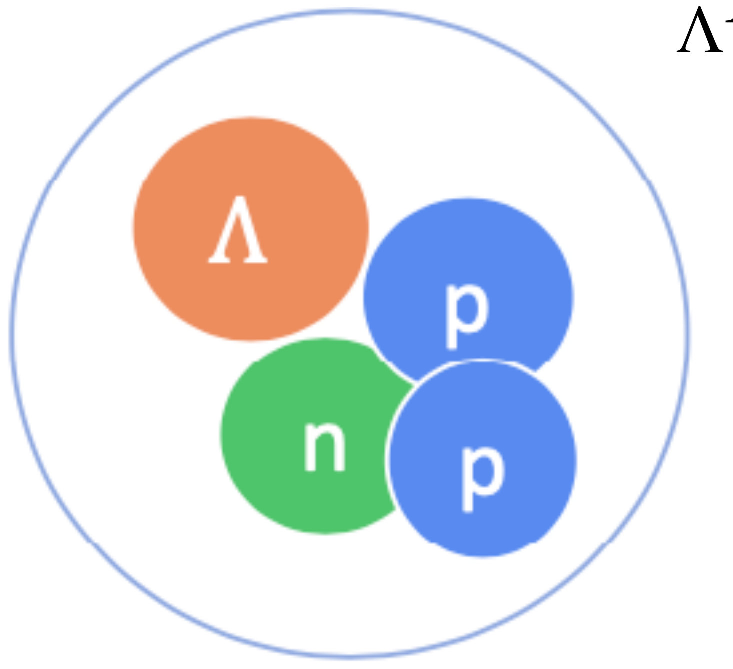
${}^{3}_{\Lambda}\mathrm{H}$



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

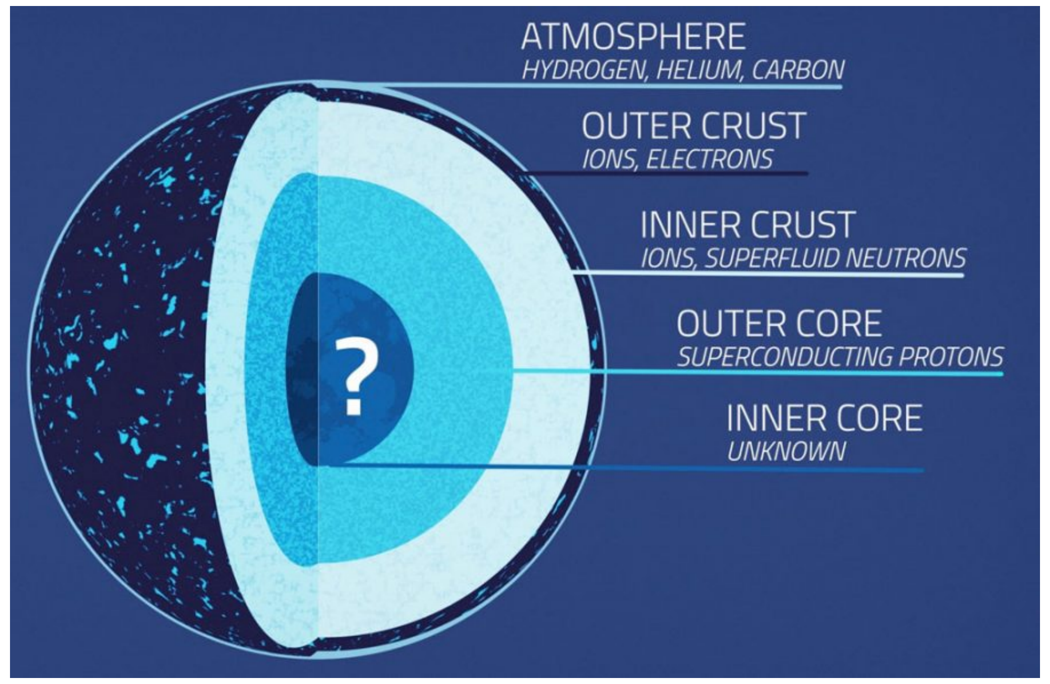


${}^{4}_{\Lambda}\mathrm{He}$

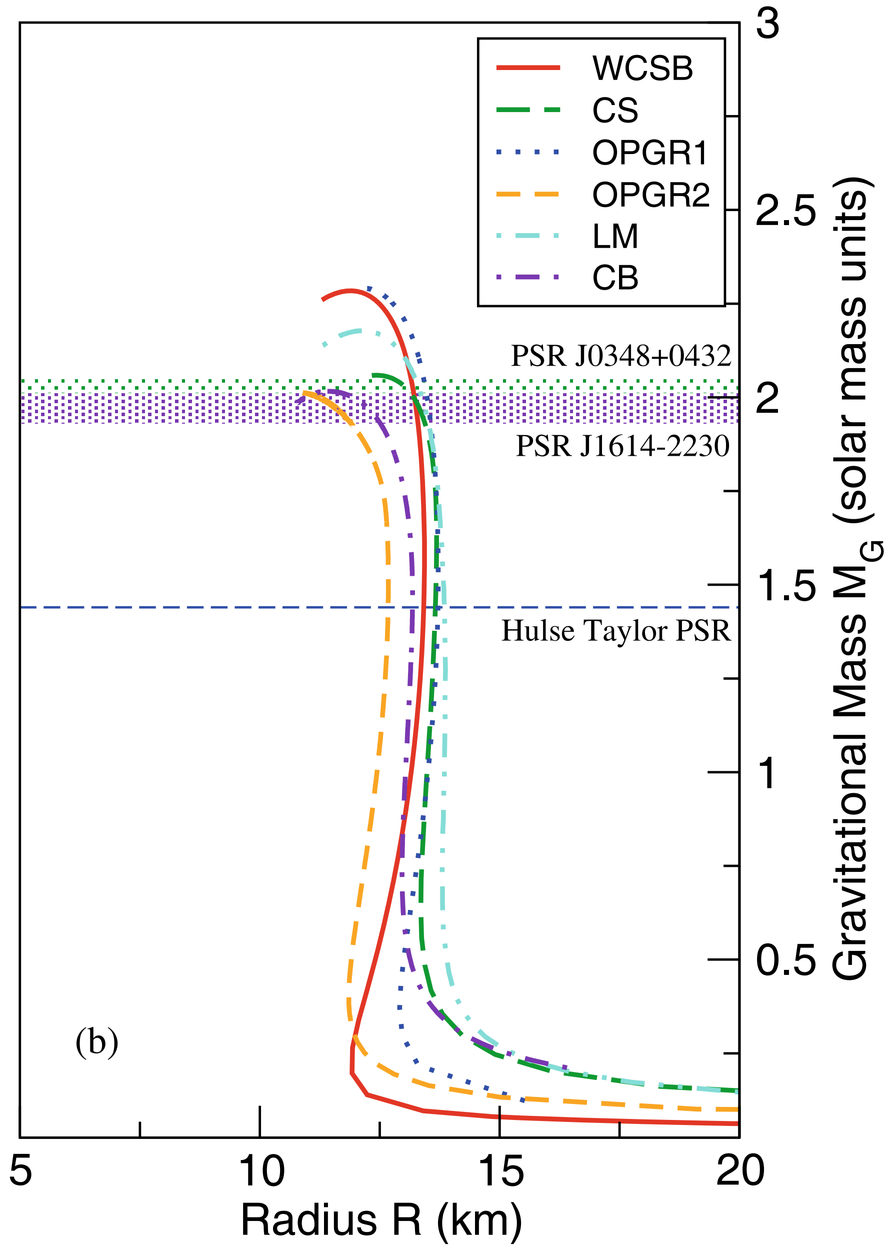


Marian Danysz (right) and Jerzy Pniewski (left) discovered hypernuclei in 1952

- Why hypernuclei?
  - Probe hyperon-nucleon (Y-N) interaction
  - Strangeness in high density nuclear matter
    - Hyperon puzzle in neutron star



neutron star

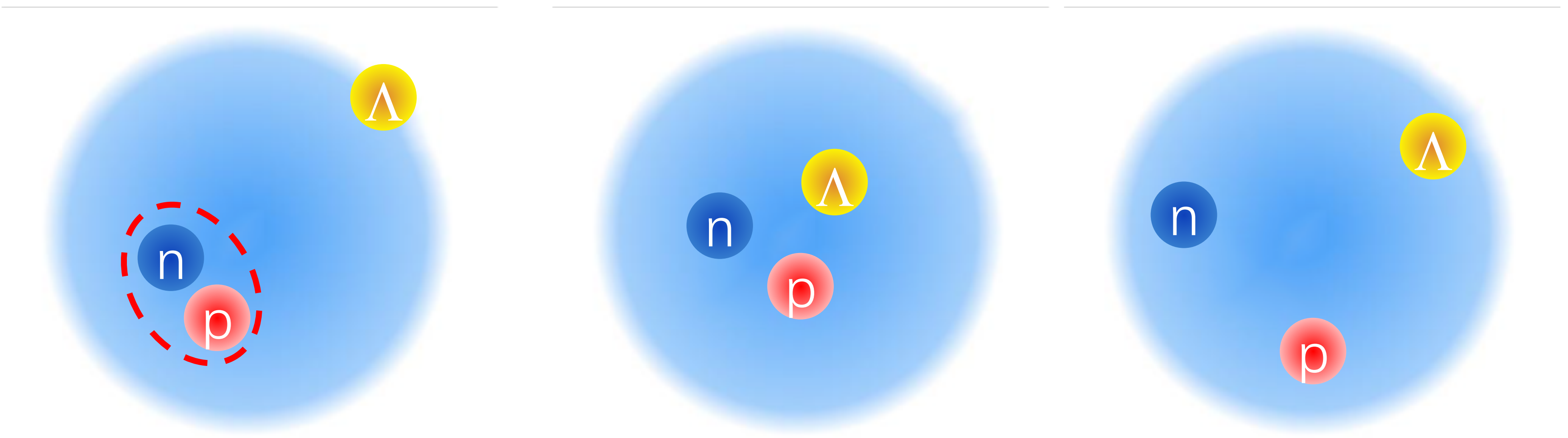


D. Chatterjee, Eur. Phys. J. A (2016) 52: 29

Introduction: how

- Experimentally, we can make measurements related to:

1. Internal structure



   - Lifetime, binding energy, branching ratios etc.

Understanding hypernuclei structure can provide insights to the Y-N interaction

2. Production mechanism

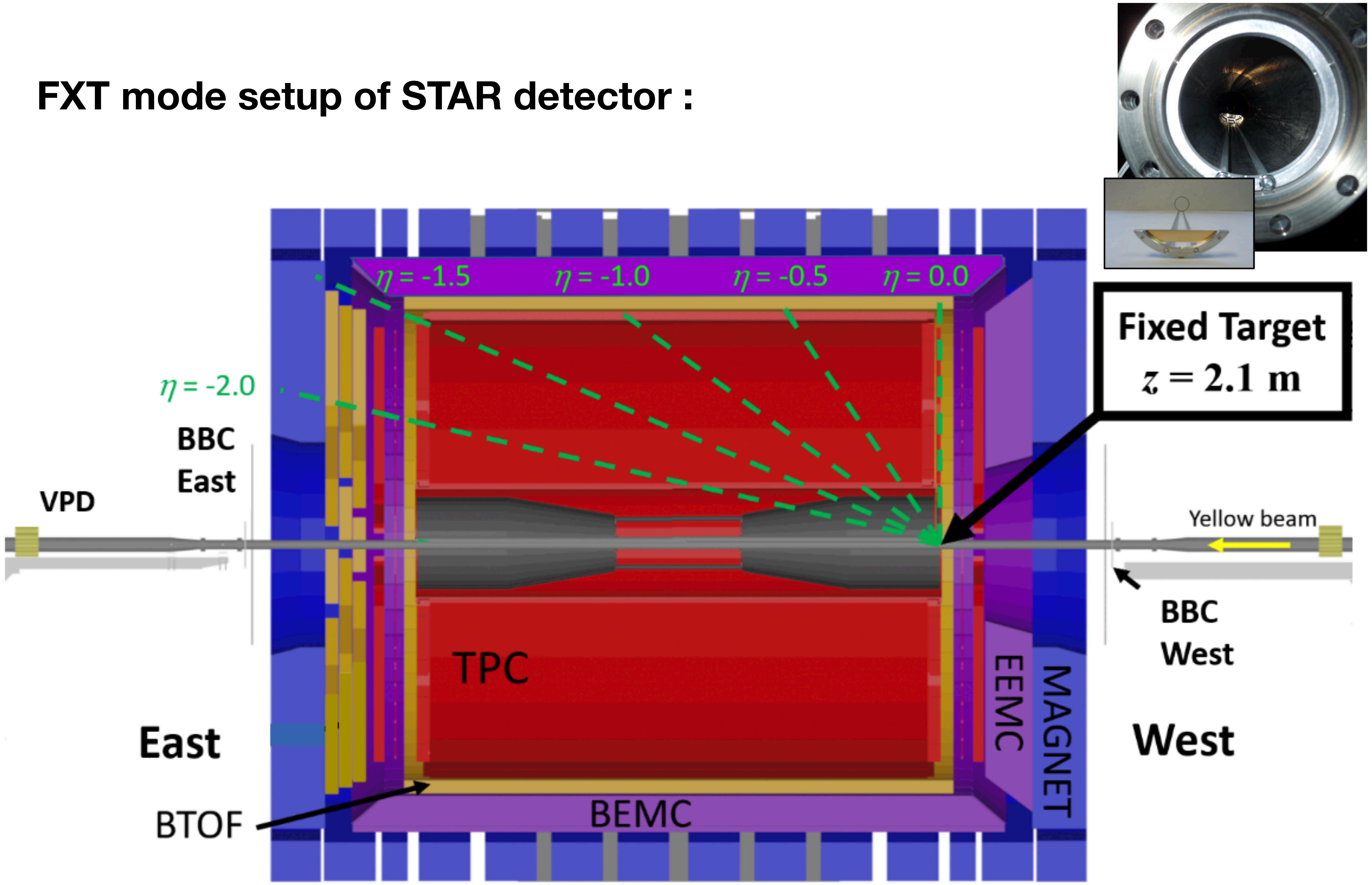
   - Spectra, collectivity etc.

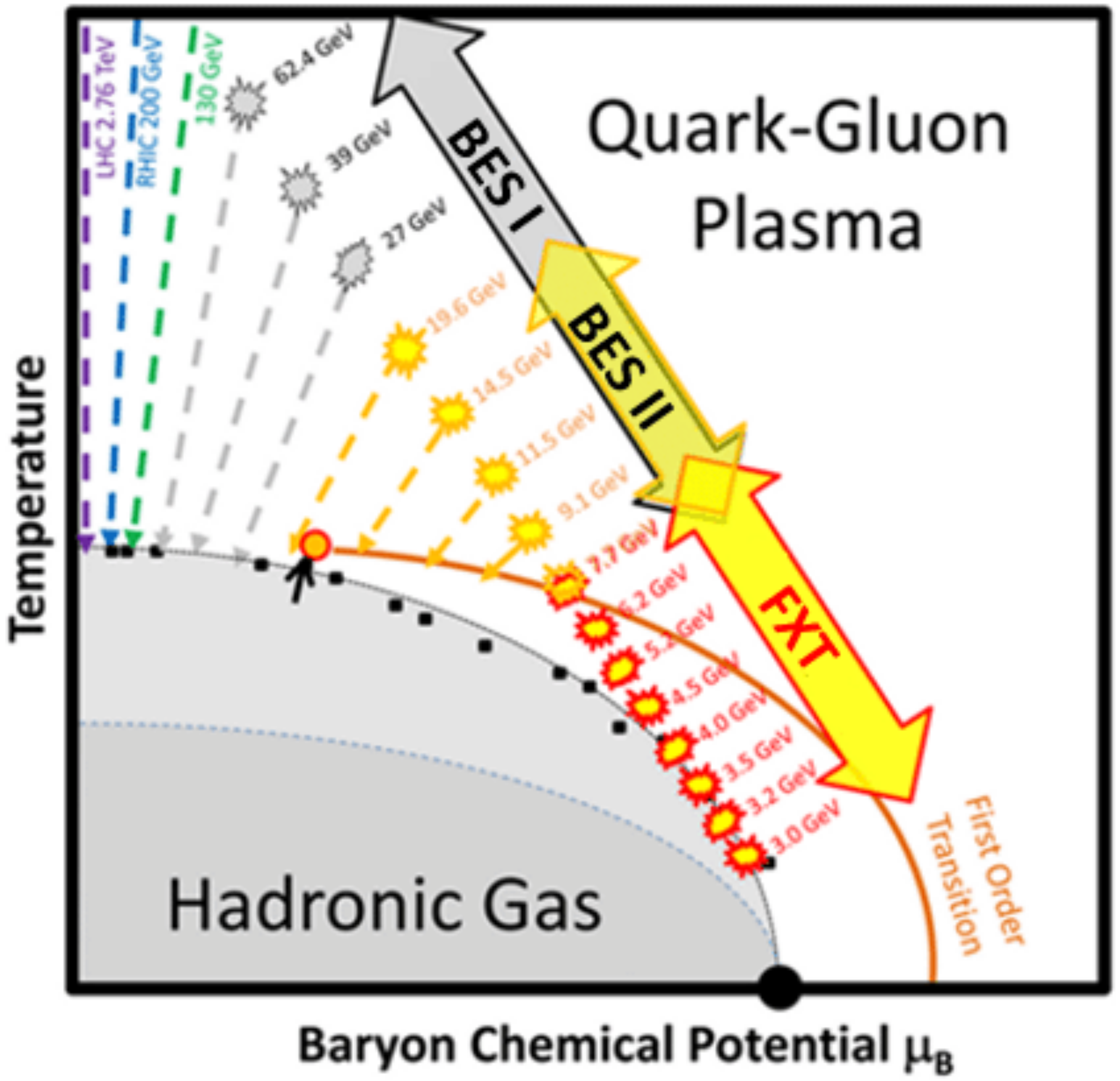
The process of hypernuclei formation in violent heavy-ion collisions is not well understood

RHIC BES-II program

- During the BES-II program, STAR utilized the fixed-target (FXT) setup, which extends the energy reach below $\sqrt{s_{NN}}$ = 7.7 GeV, down to 3.0 GeV

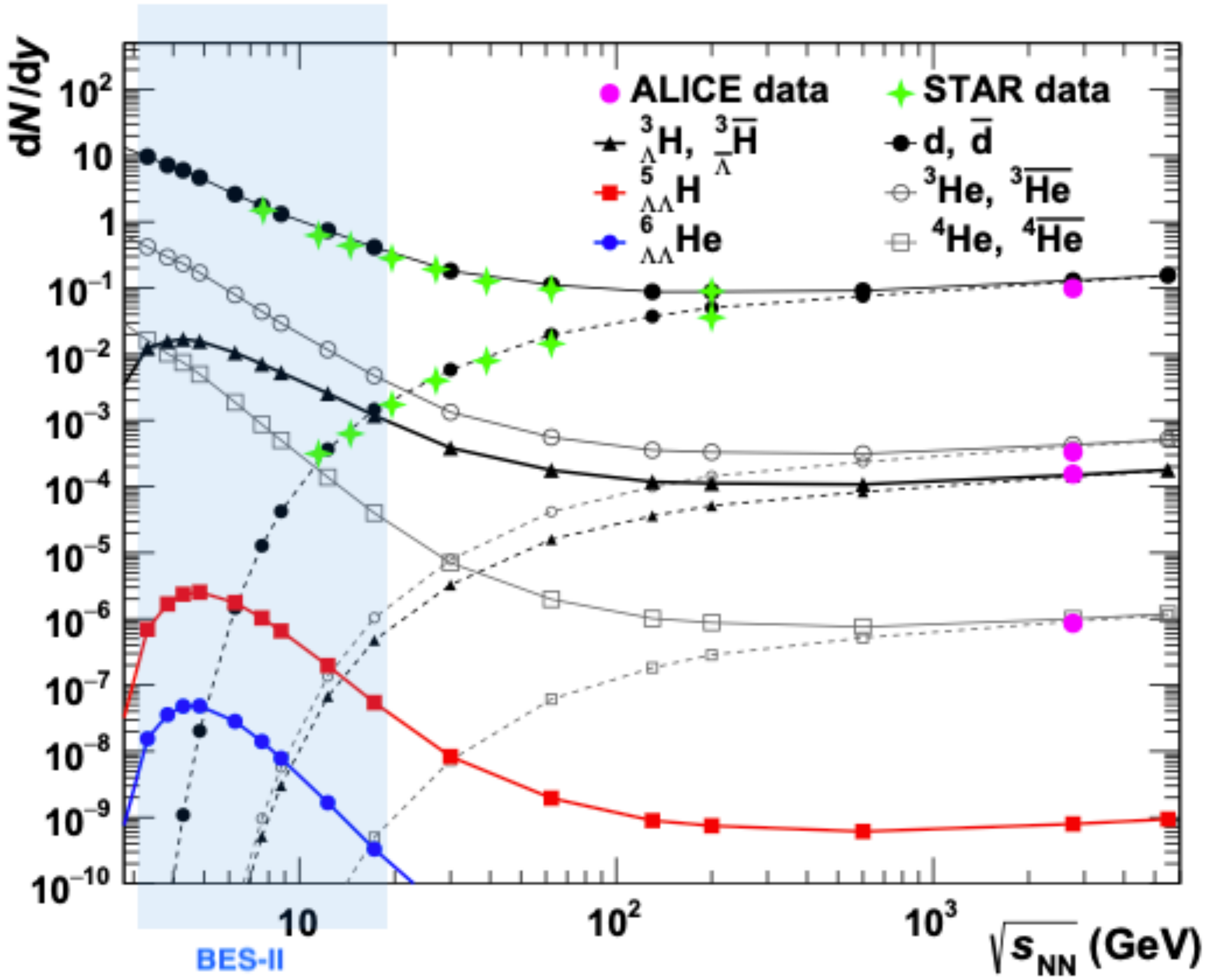
FXT mode setup of STAR detector :





Hypernuclei and STAR BES-II

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



B. Dönigus, Eur. Phys. J. A (2020) 56:280
A. Andronic et al. PLB (2011) 697:203–207

- At low beam energies, hypernuclei production is expected to be enhanced due to high baryon density

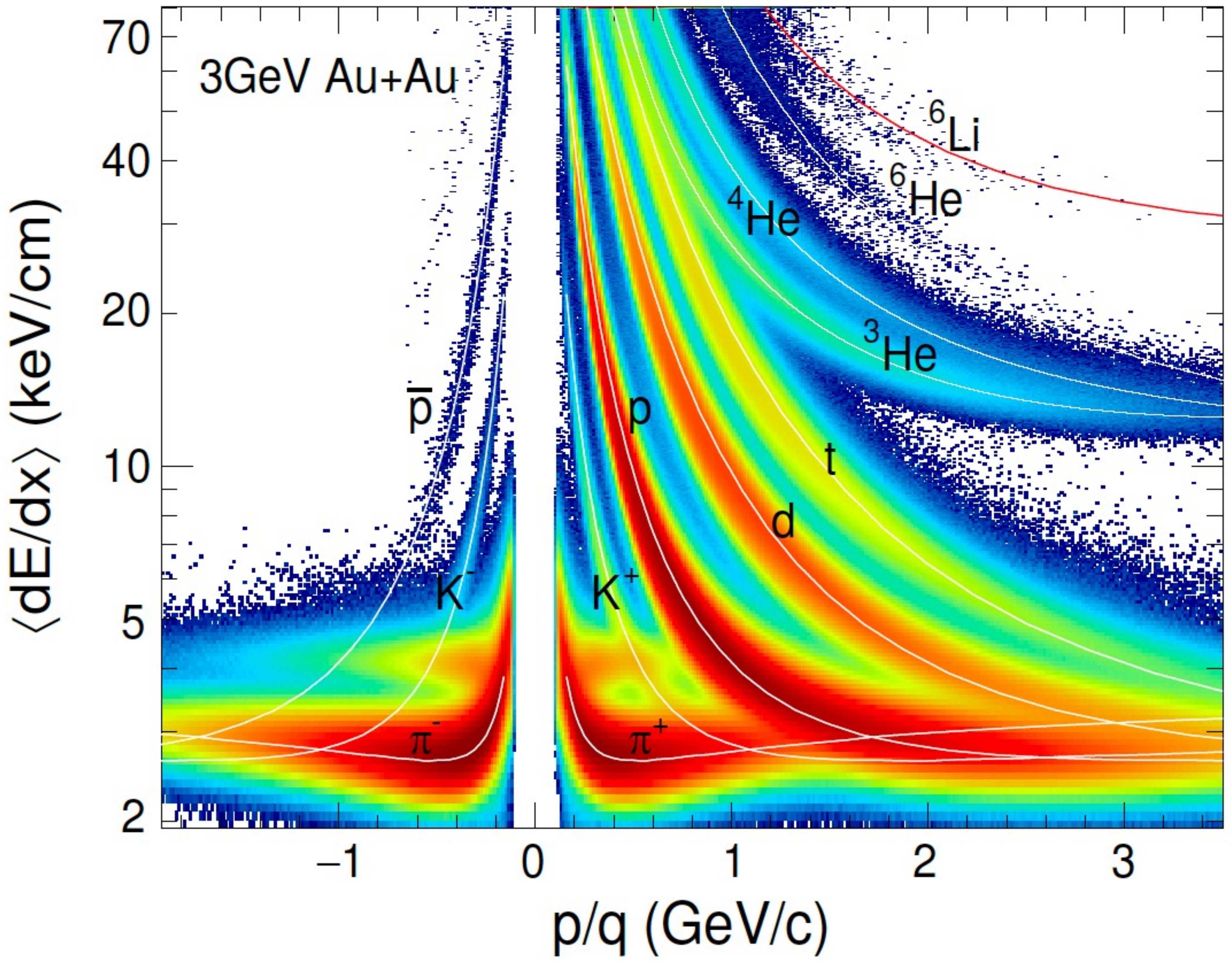
- Datasets with large statistics taken during BES-II

→ A great opportunity to study hypernuclei production

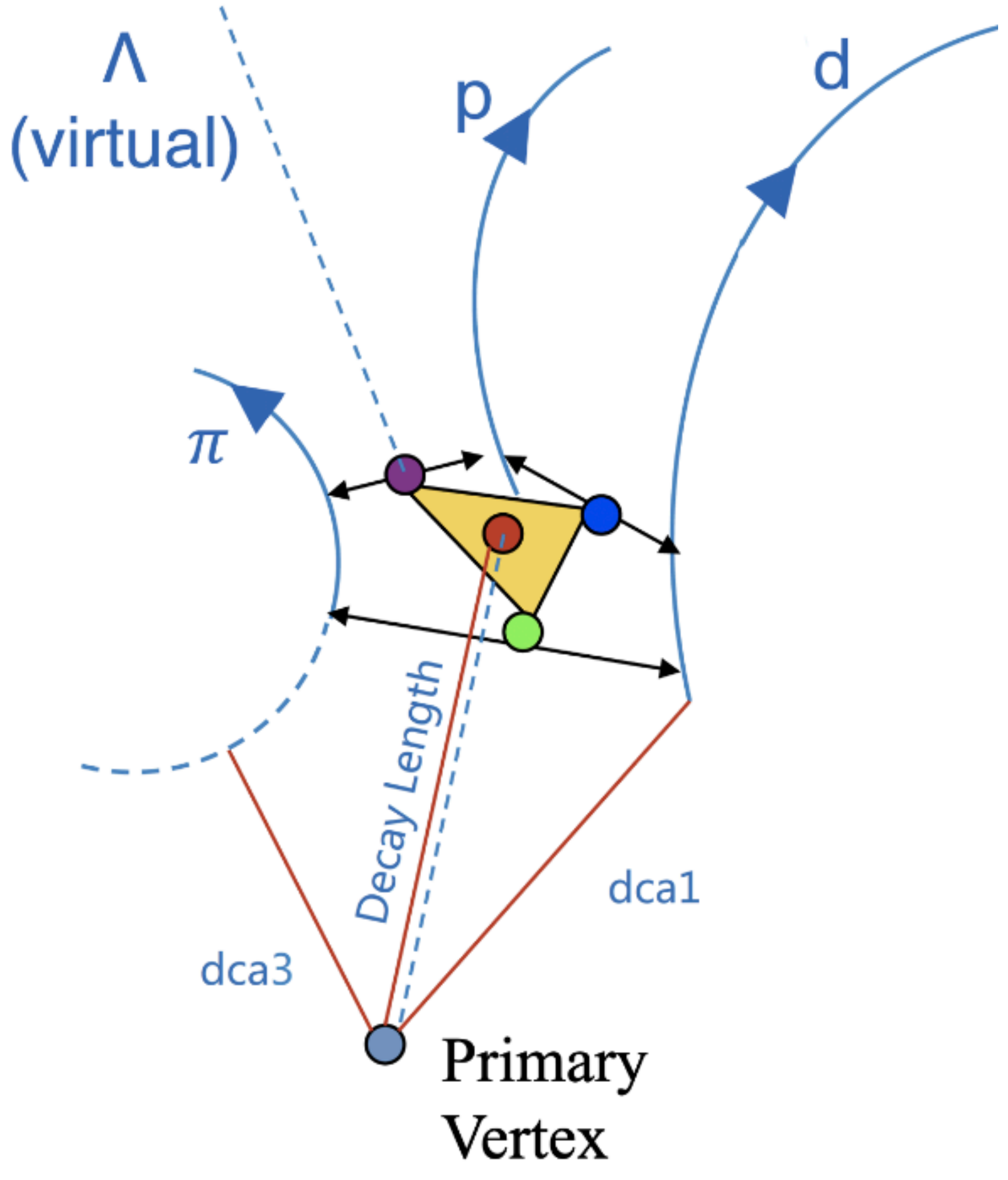
List of BES-II datasets:

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

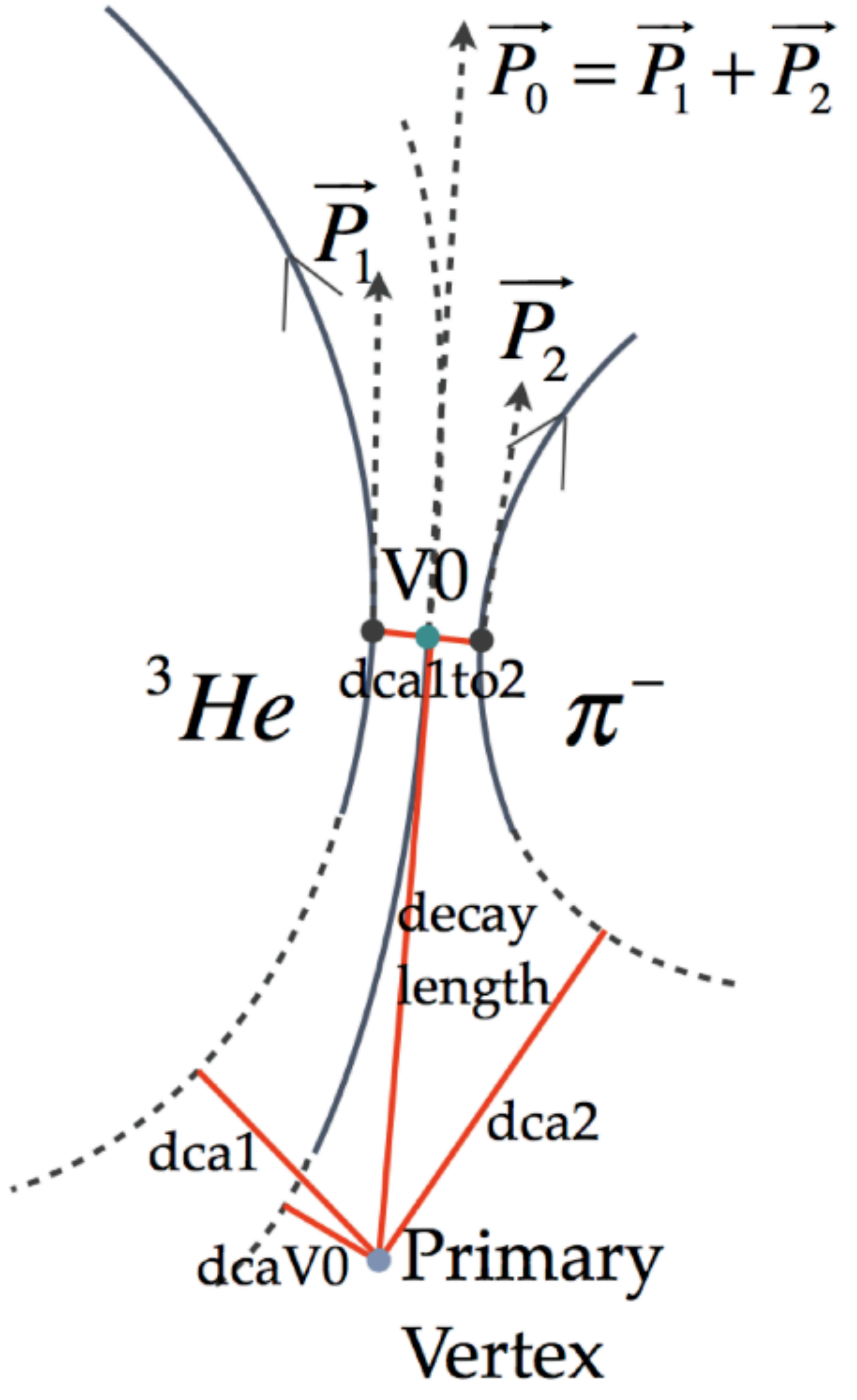
Particle identification and hypernuclei reconstruction@STAR



$^3_\Lambda H \rightarrow d + p + \pi^-$:



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

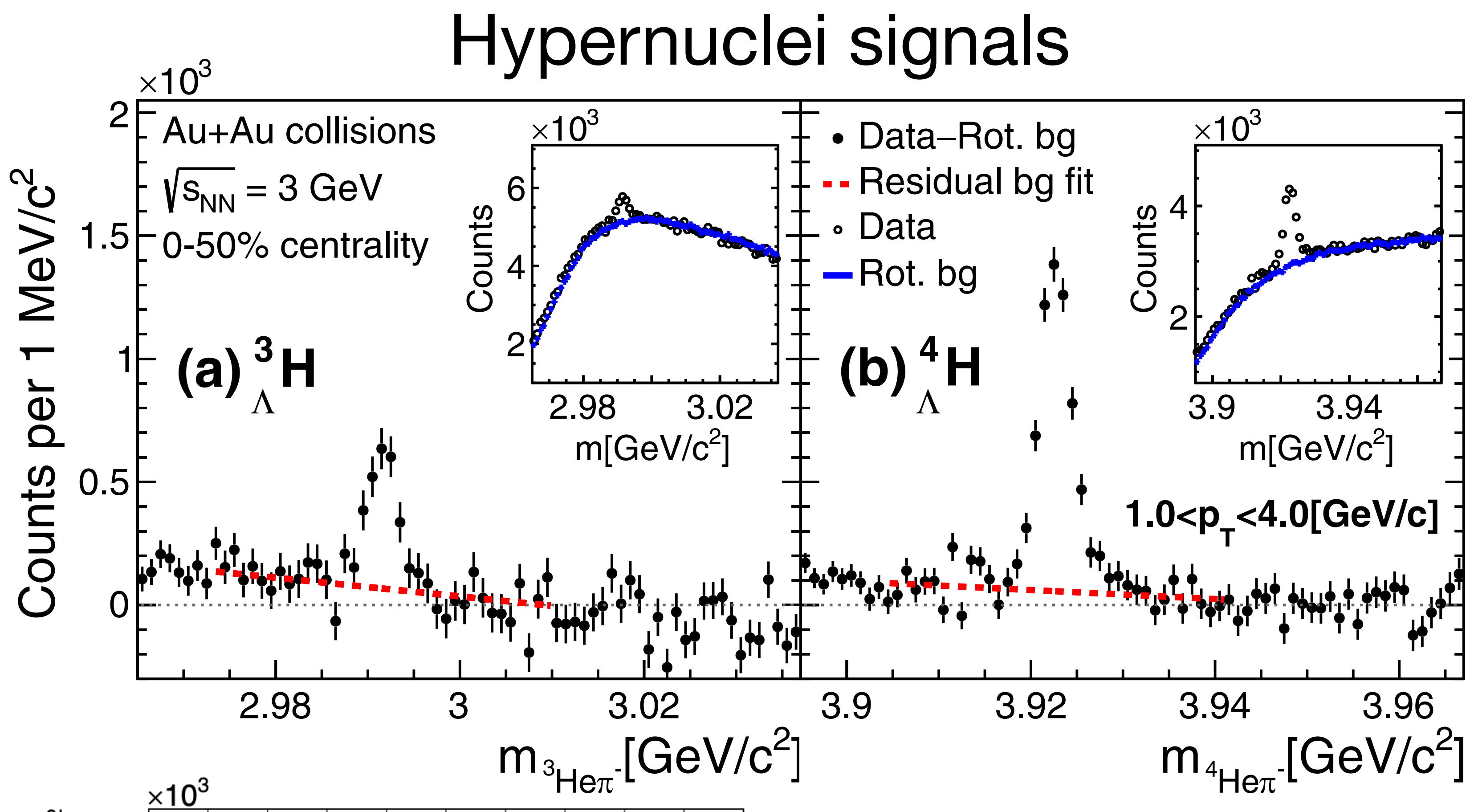


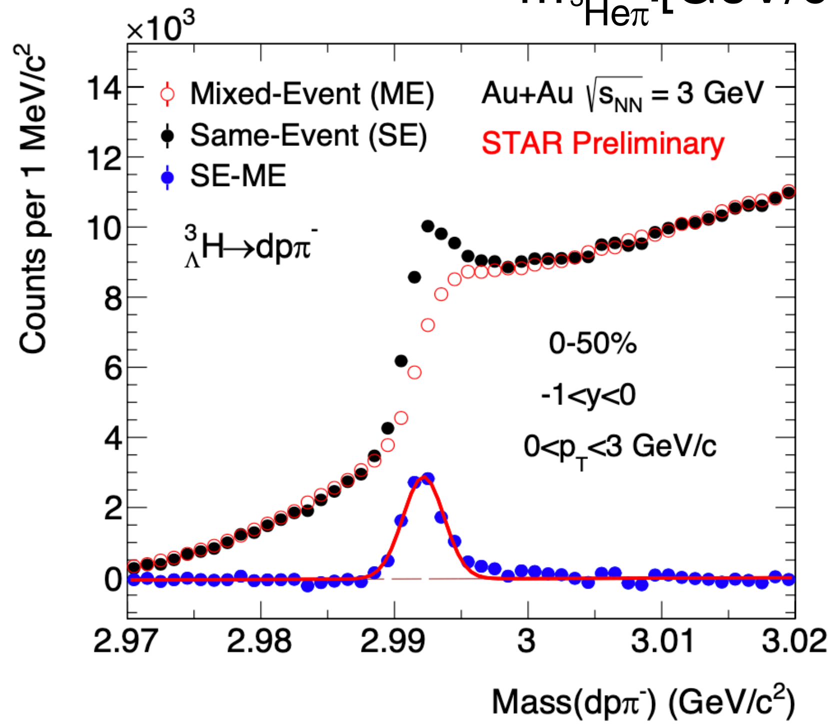
- Particle identification from energy loss measurement provided by TPC
- KF particle package[1] is used for signal reconstruction
- Hypernuclei reconstructed via their weak decay channels:

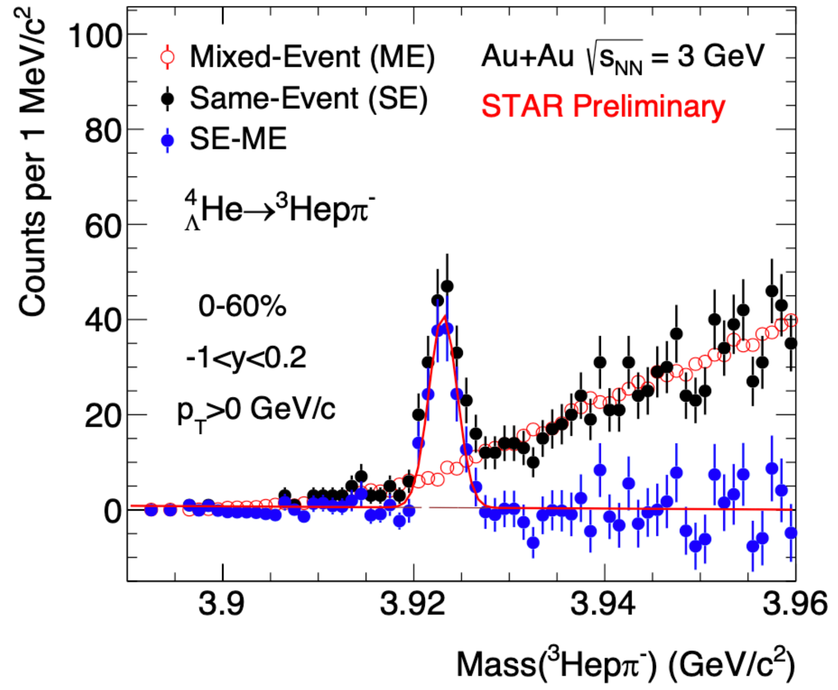
$^3_\Lambda H \rightarrow {}^3He + \pi^-$ $^3_\Lambda H \rightarrow d + p + \pi^-$ $^4_\Lambda H \rightarrow {}^4He + \pi^-$ $^4_\Lambda He \rightarrow {}^3He + p + \pi^-$

[1]Zyzak M, Kisel I, Senger P. Online selection of short-lived particles on many-core computer architectures in the CBM experiment at FAIR[R]. Collaboration FAIR: CBM, 2016.

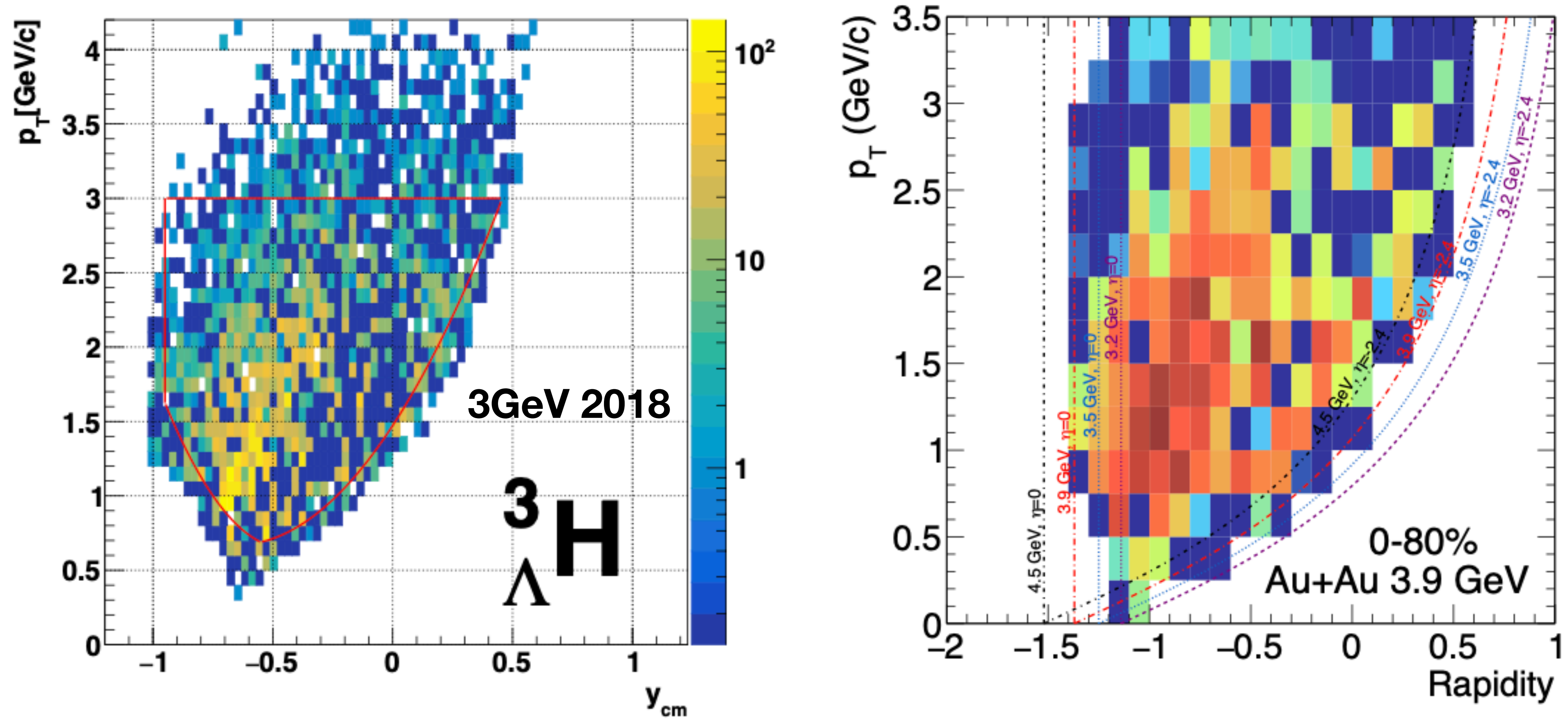
Hypernuclei signal reconstruction @STAR







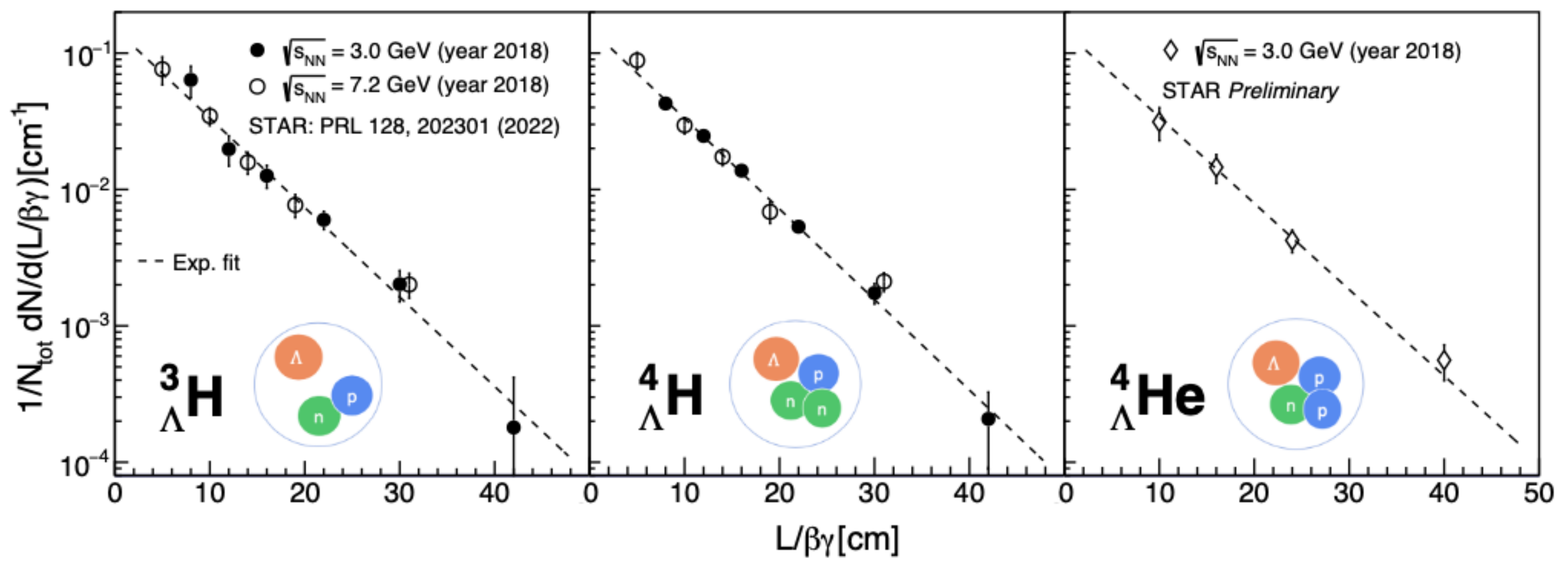
$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$ acceptance at different energies

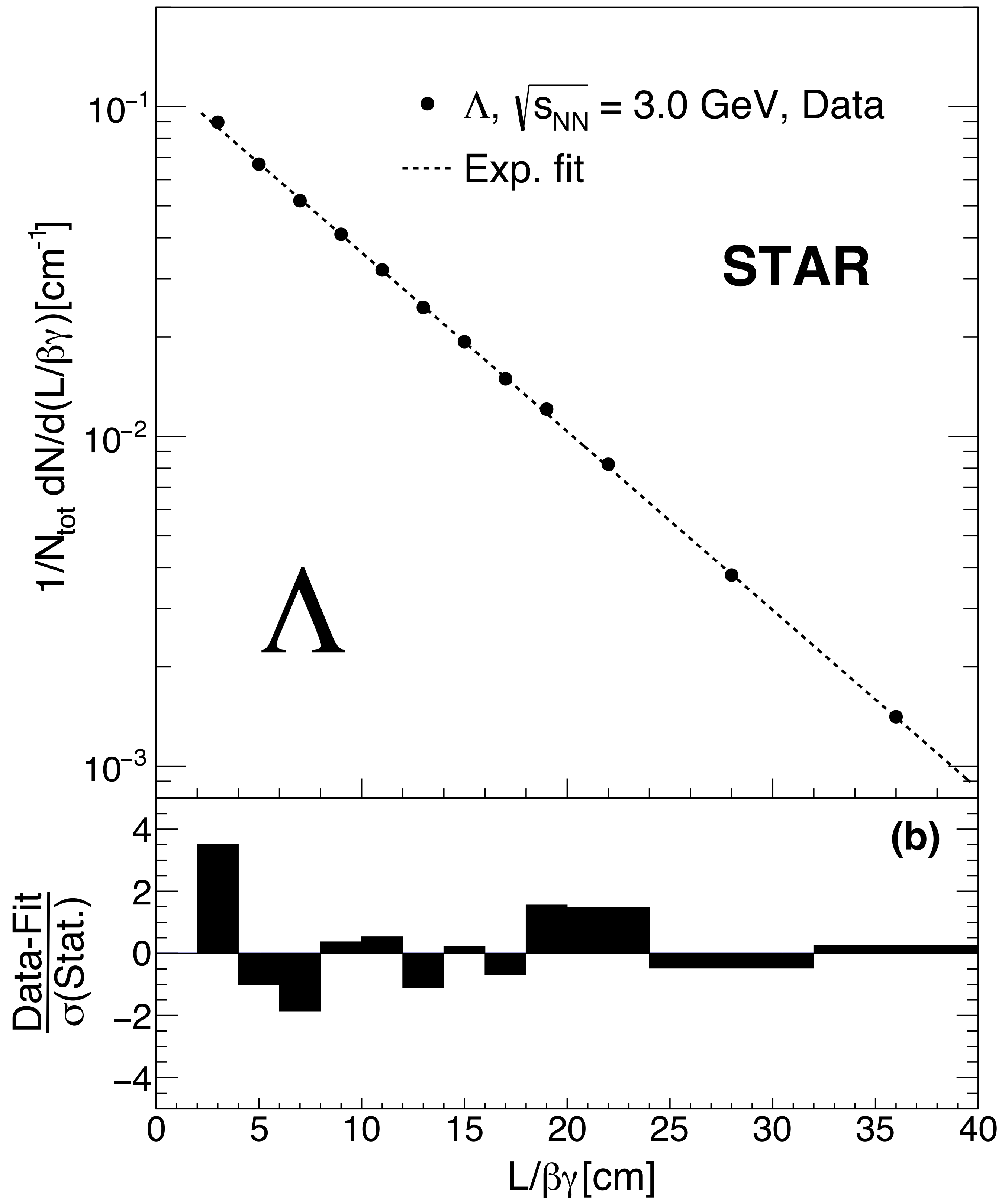


- Combinatorial background estimated via rotational and mix-event background
- Better mid-rapidity coverage for 3.2 GeV(2019) compared with 3 GeV(2018) in CM frame
  - Upgrade on detector in 2019

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

STAR, PRL 128, 202301(2022)





- Extract lifetime τ from an exponential fit to the corrected signal counts dN/d(L/βγ) vs. L/βγ
  - $N(t) = N_0 e^{-L/\beta\gamma c\tau}$, L: decay length
- Λ lifetime crosscheck
  - τ_Λ= 267±4 ps, consistent with PDG value(263±2 ps)

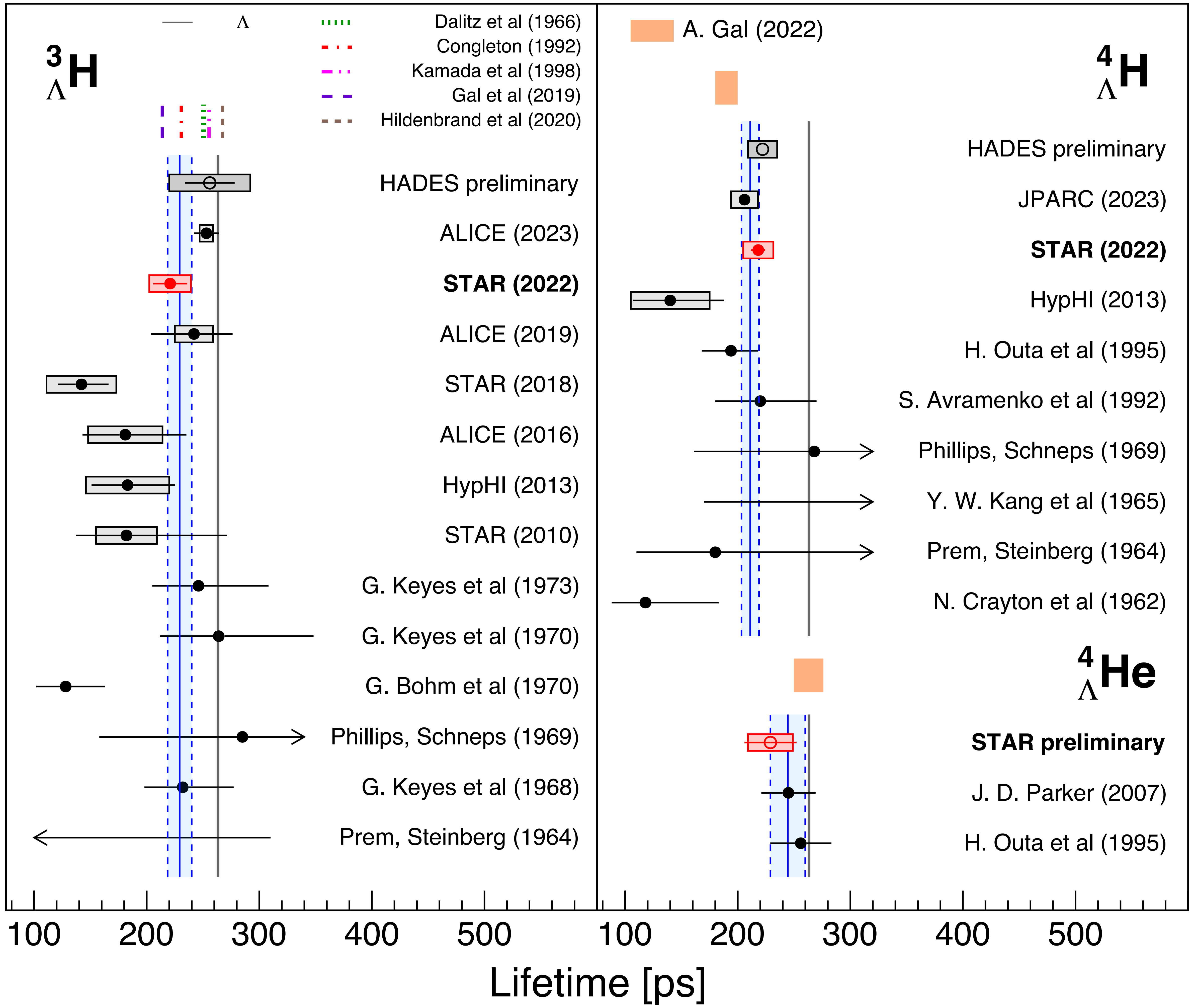
Using $\sqrt{s_{NN}}$ = 3.0 GeV and 7.2 GeV datasets:

$^{3}_{\Lambda}$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: $\tau = 229 \pm 23(\text{stat.}) \pm 20(\text{syst.})[\text{ps}]$

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



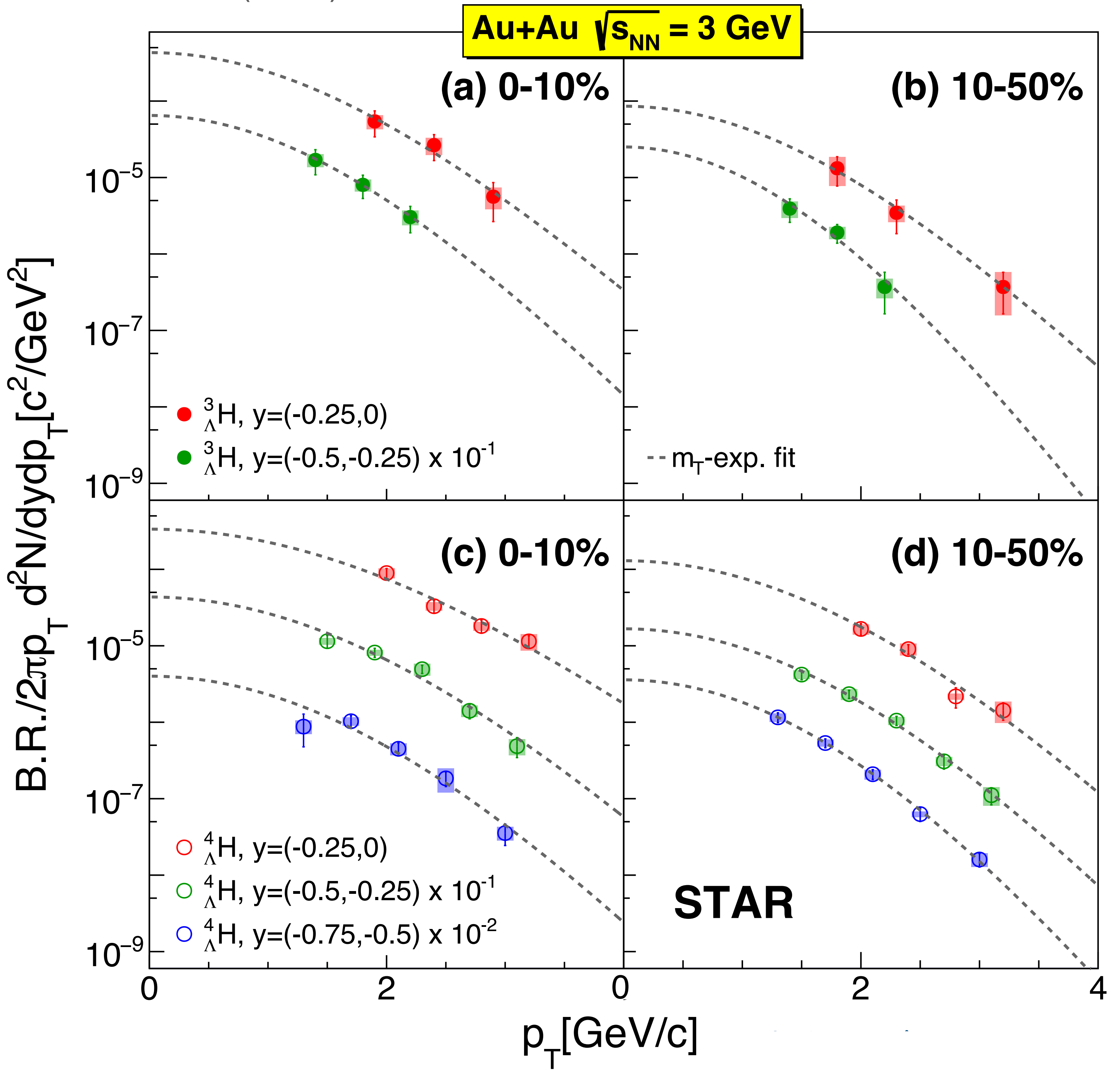
- Indicator of shorter lifetimes for ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He than that of free Λ (with 1.8σ, 3.0σ, 1.1σ respectively)
- Consistent with former measurements (within 2.5σ for ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H)
- STAR provide first ${}^{4}_{\Lambda}$He lifetime measurement in HI

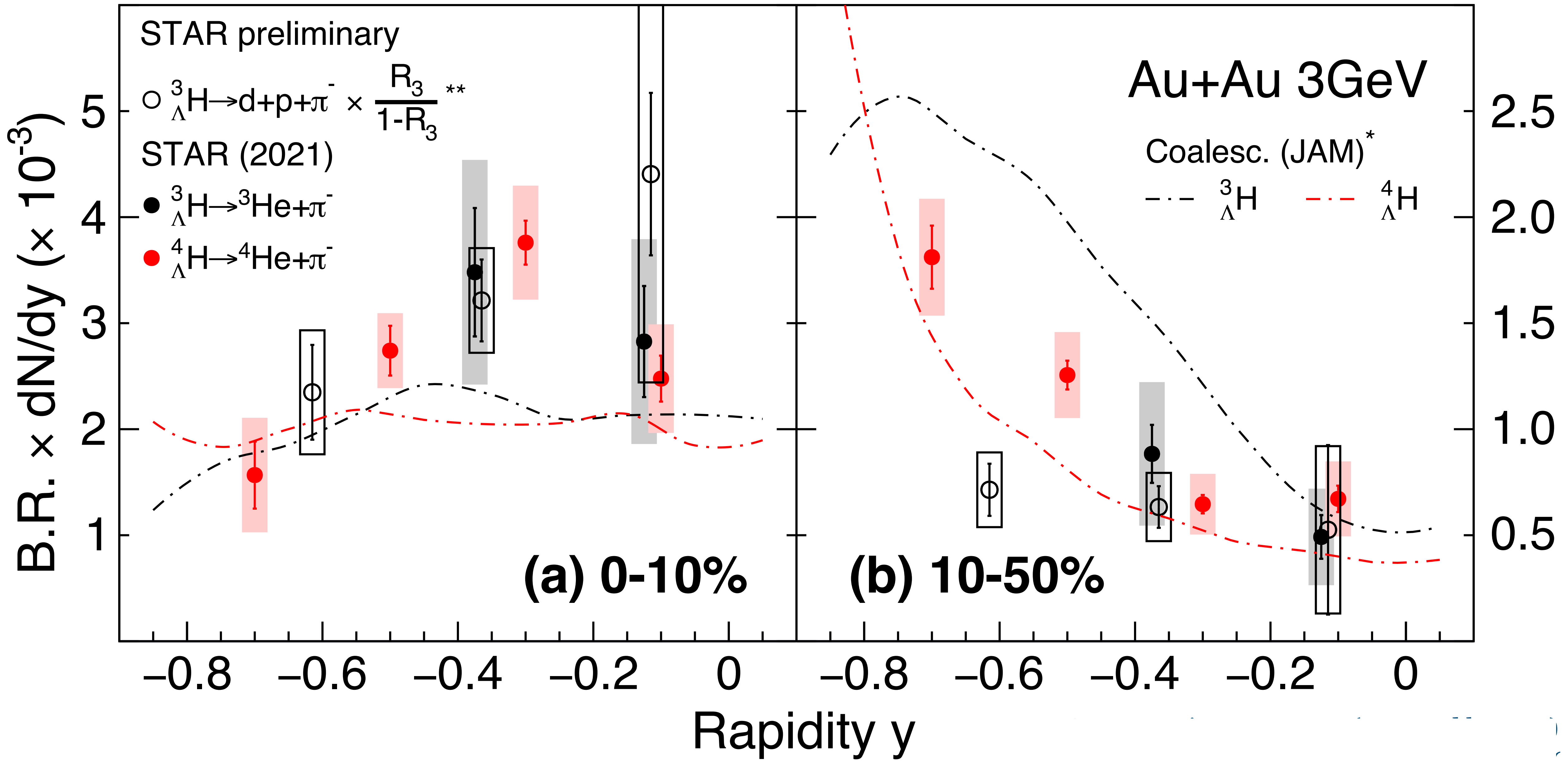
${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H results with improved precision
$\rightarrow$ Provide tighter constraints on models.

STAR, PRL 128, 202301(2022)
ALICE, PRL 131, 102302 (2023)
JPARC, PLB 845, 138128 (2023)

${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ production @3 GeV

STAR, PRL 128, 202301(2022)

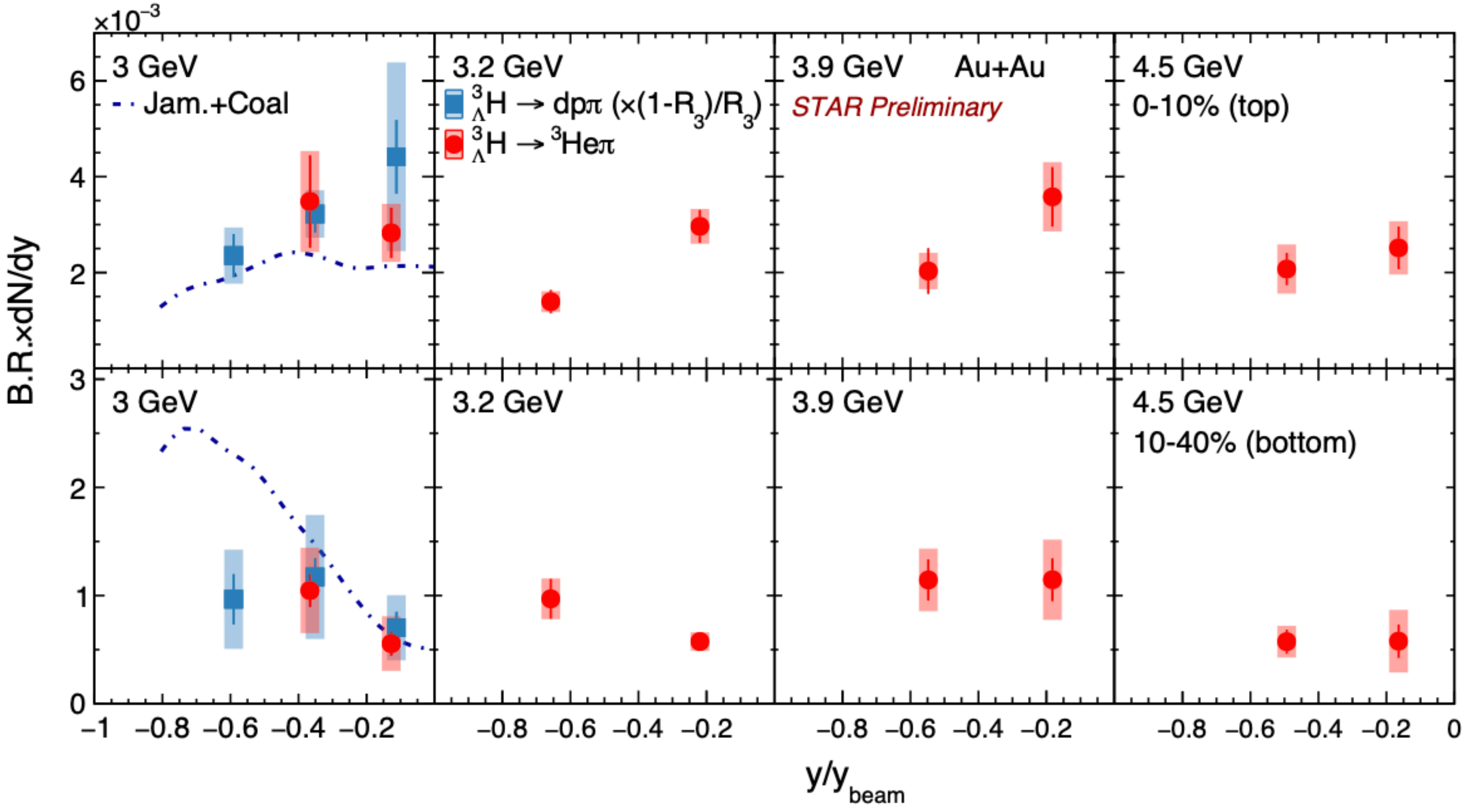


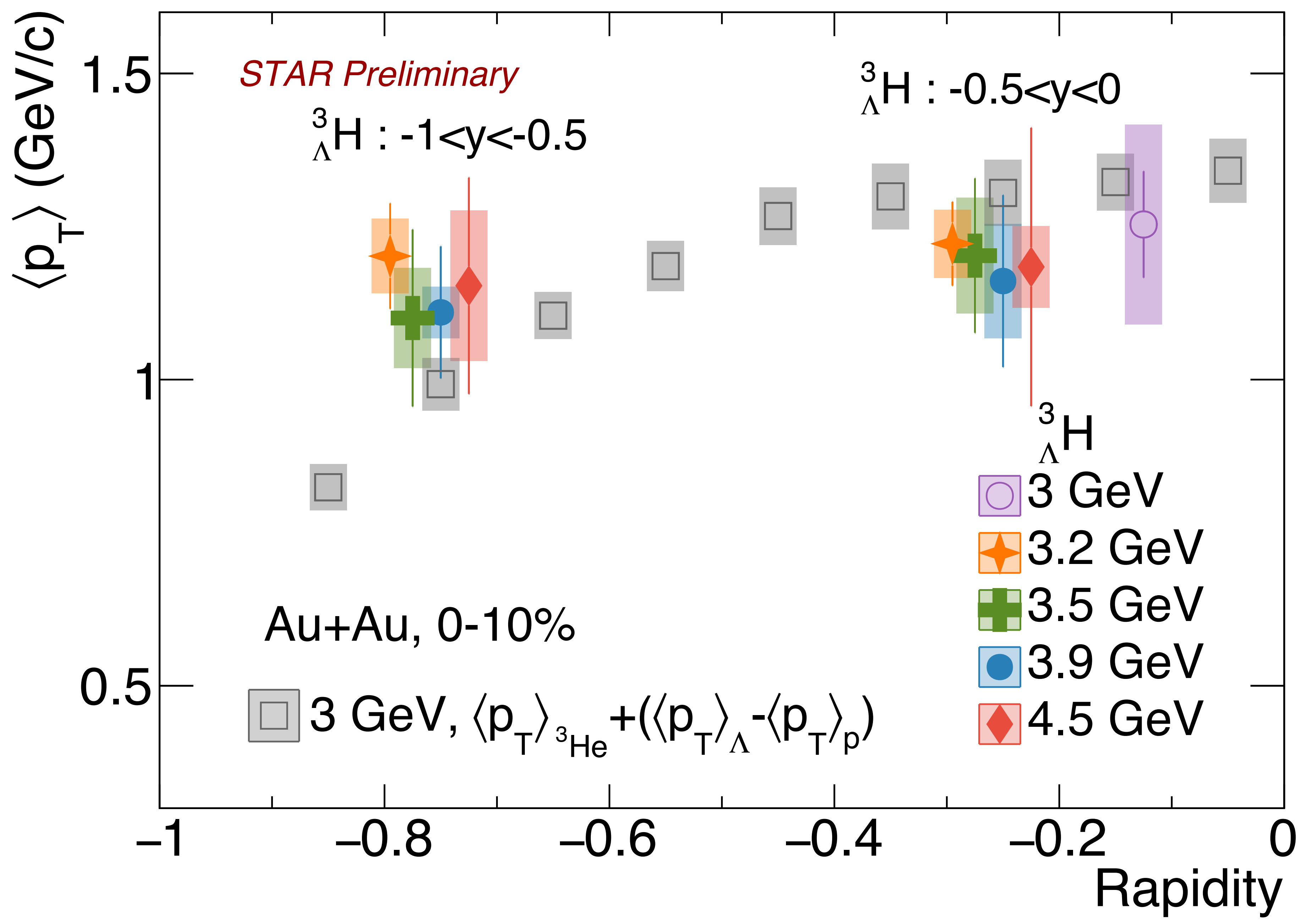


- First measurement of dN/dy vs. y for hypernuclei in heavy-ion collisions
- Different trends in the ${}^{4}_{\Lambda}H$ rapidity distribution in central (0-10%) and mid-central (10-50%) collisions at $\sqrt{s_{NN}}$ = 3.0 GeV

- Transport model (JAM) with coalescence approximately reproduces trends of ${}^{4}_{\Lambda}H$ rapidity distributions seen in data, but fails to reproduce the trend of ${}^{3}_{\Lambda}H$ in 10-50%

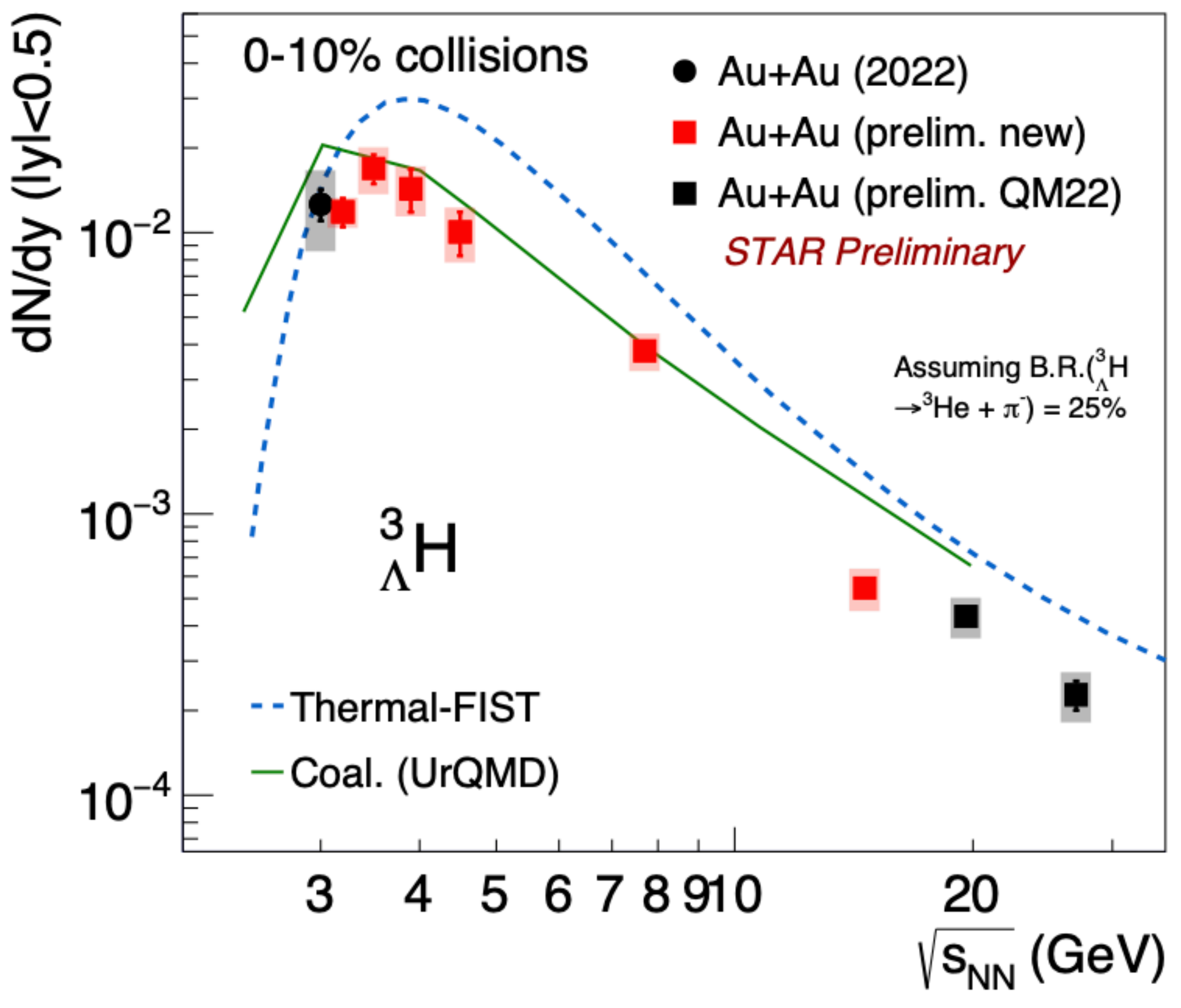
Rapidity dependence of ${}^{3}_{\Lambda}H$ yields and <p_T>

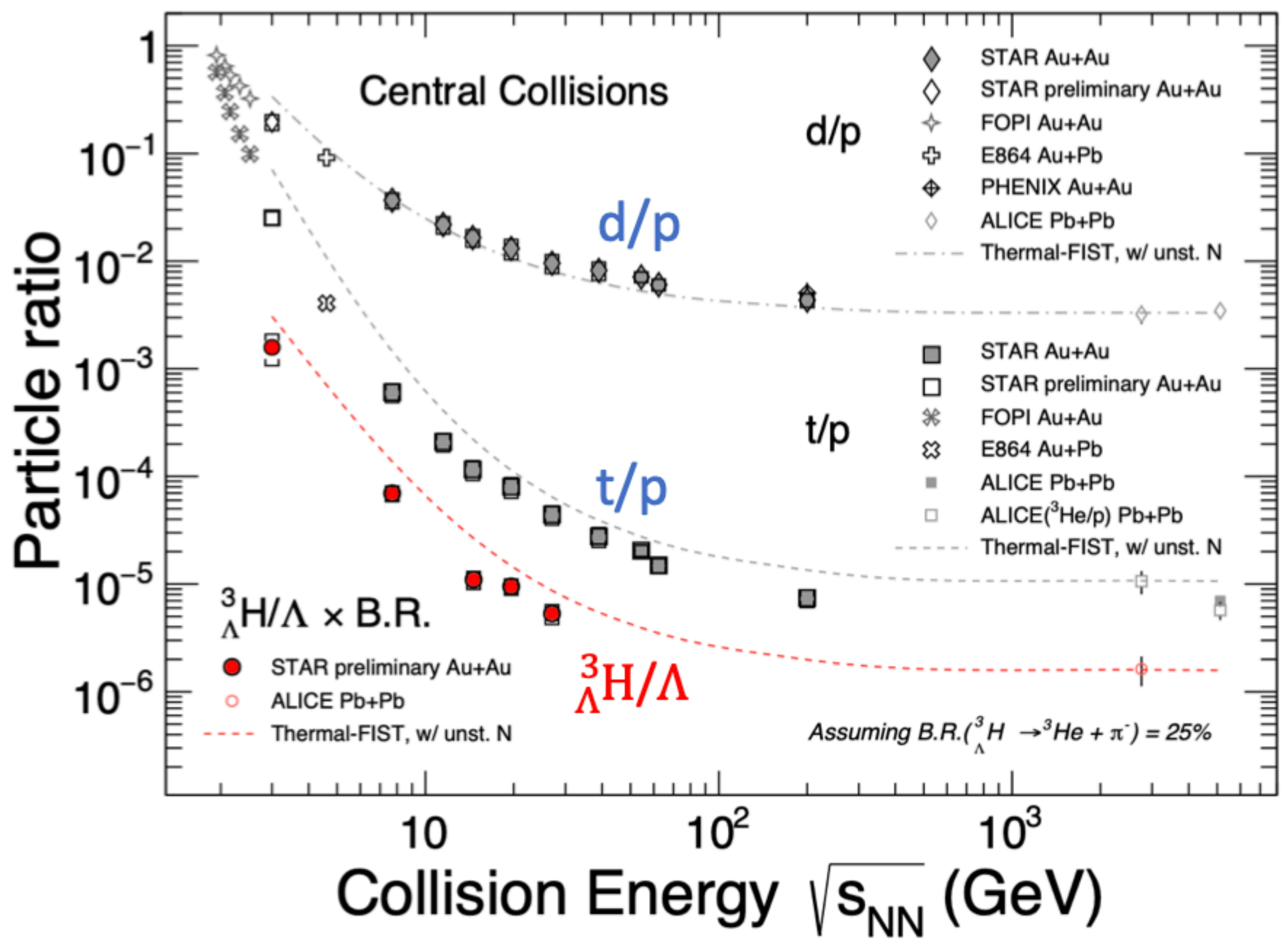




- 0-10% 3-4.5 GeV mid-rapidity yields and <p_T> are close
- Radial flow (v_0, <p_T> corresponds to v_0) behavior of hypernuclei is similar as light nuclei

Energy dependence of ${}^{3}_{\Lambda}\mathrm{H}$ yields in heavy-ion collisions





STAR, PRL 128 (2022) 202301
ALICE, PLB 754 (2016) 360

Thermal-FIST, UrQMD: Phys.Rev.C 107 (2023) , 014912

First energy dependence of hypernuclei production yields in the high-baryon-density region

- High production yields of ${}^{3}_{\Lambda}\mathrm{H}$ around 3-4 GeV and decrease towards higher energies
  - Hadronic transport + coalescence models qualitatively describe the data
  - Thermal model calculation ~2 times higher than data in BES-II energies

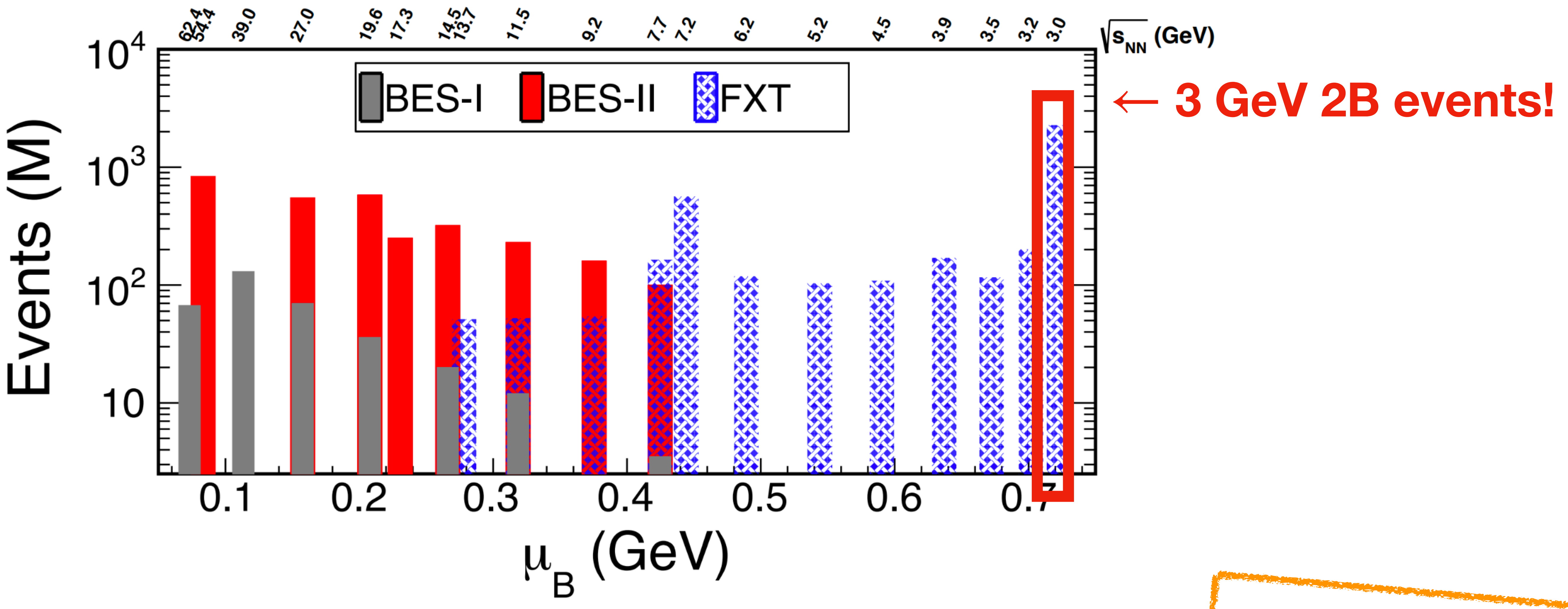
Summary

- STAR BES-II provides a unique opportunity to study hypernuclei at high-baryon-density region
  - Precision ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$ lifetimes measured
  - First ${}^{4}_{\Lambda}\mathrm{He}$ lifetime measurement in HI experiment
  - Light hypernuclei production yields from Au+Au collisions at BES-II
    - First measurement of dN/dy vs. y for hypernuclei
    - First energy dependence of hypernuclei dN/dy
    - Provide constraints to hypernuclei production models @ high μ_{B}

Outlook

Huge datasets form BES-II:

- Precision measurements on hypernuclei properties and yields



- Expected significance from BES-II:

$^4_\Lambda$H : 60σ

$^4_\Lambda$He: 40σ

$^5_\Lambda$He: 10σ

Chance for A>=4 hypernuclei

Thank you!