STAR ☆

Hypernuclei production at STAR

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for the STAR collaboration

Lawrence Berkeley National Laboratory (LBNL)

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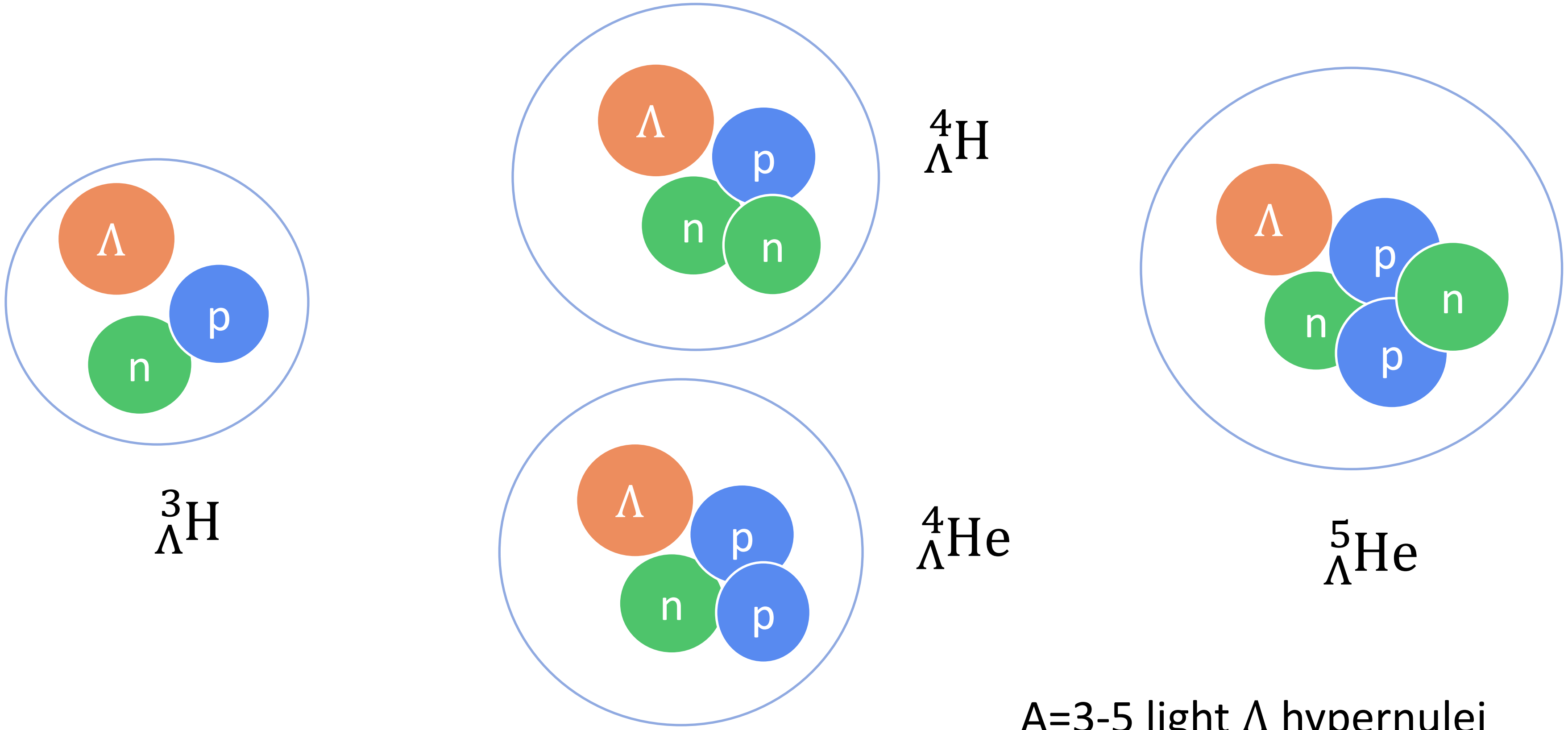
Hypernuclei

Hypernucleus: A bound system of nucleons with ≥ 1 hyperons.

- Investigate the Hyperon-Nucleon (*Y*-*N*) interactions.
  - Important ingredient for the EOS of neutron stars and the hadronic phase of heavy-ion collisions.



A=3-5 light Λ hypernuclei

STAR Beam Energy Scan II program (BES II)

- Map the QCD phase diagram in the region of $200 < \mu_B \leq \sim 750$ MeV
- Search for QCD critical point, 1st order phase transition, signature of QGP turn-off, etc

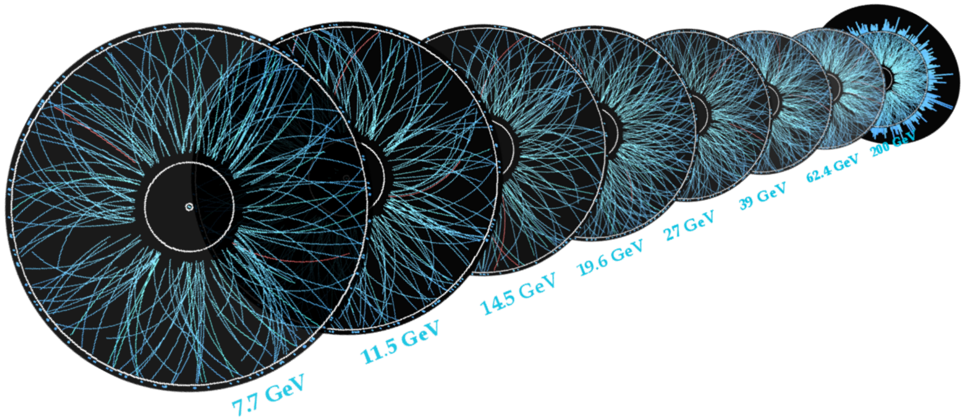
Collider mode:

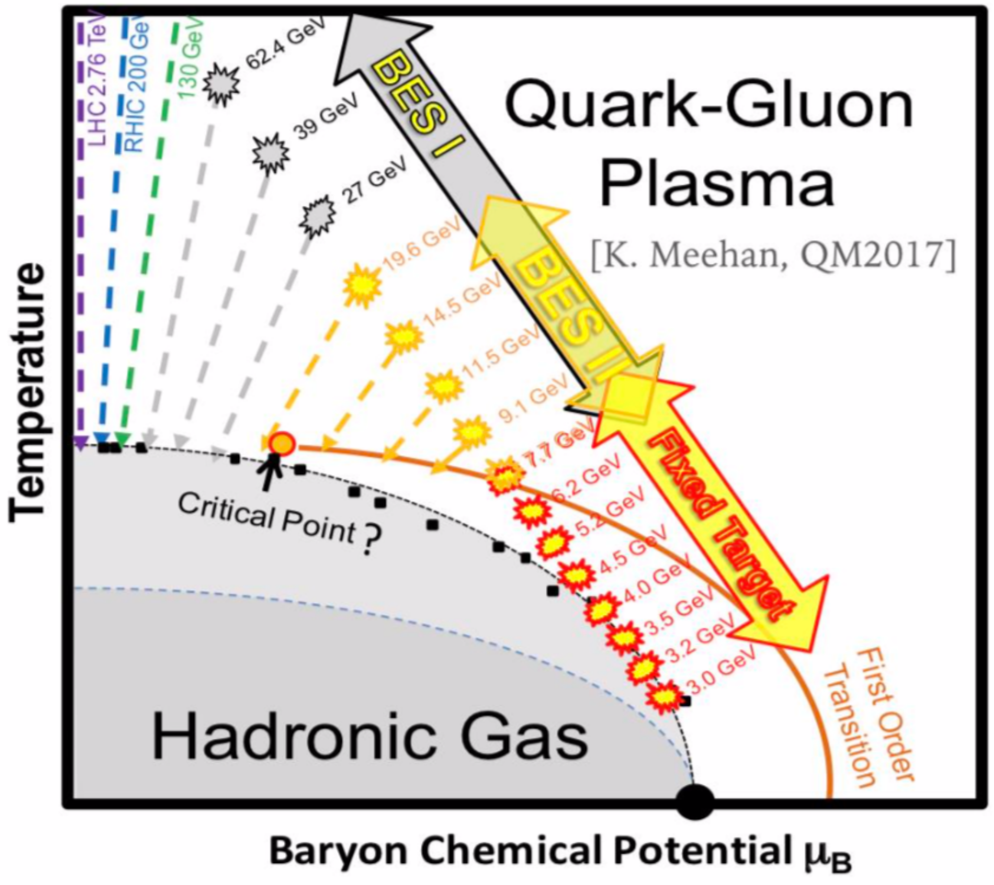
$\sqrt{s_{NN}}$ = 7.7 - 19.6 GeV

Fixed-Target mode:

$\sqrt{s_{NN}}$ = 3.0 – 13.7 GeV

high luminosity



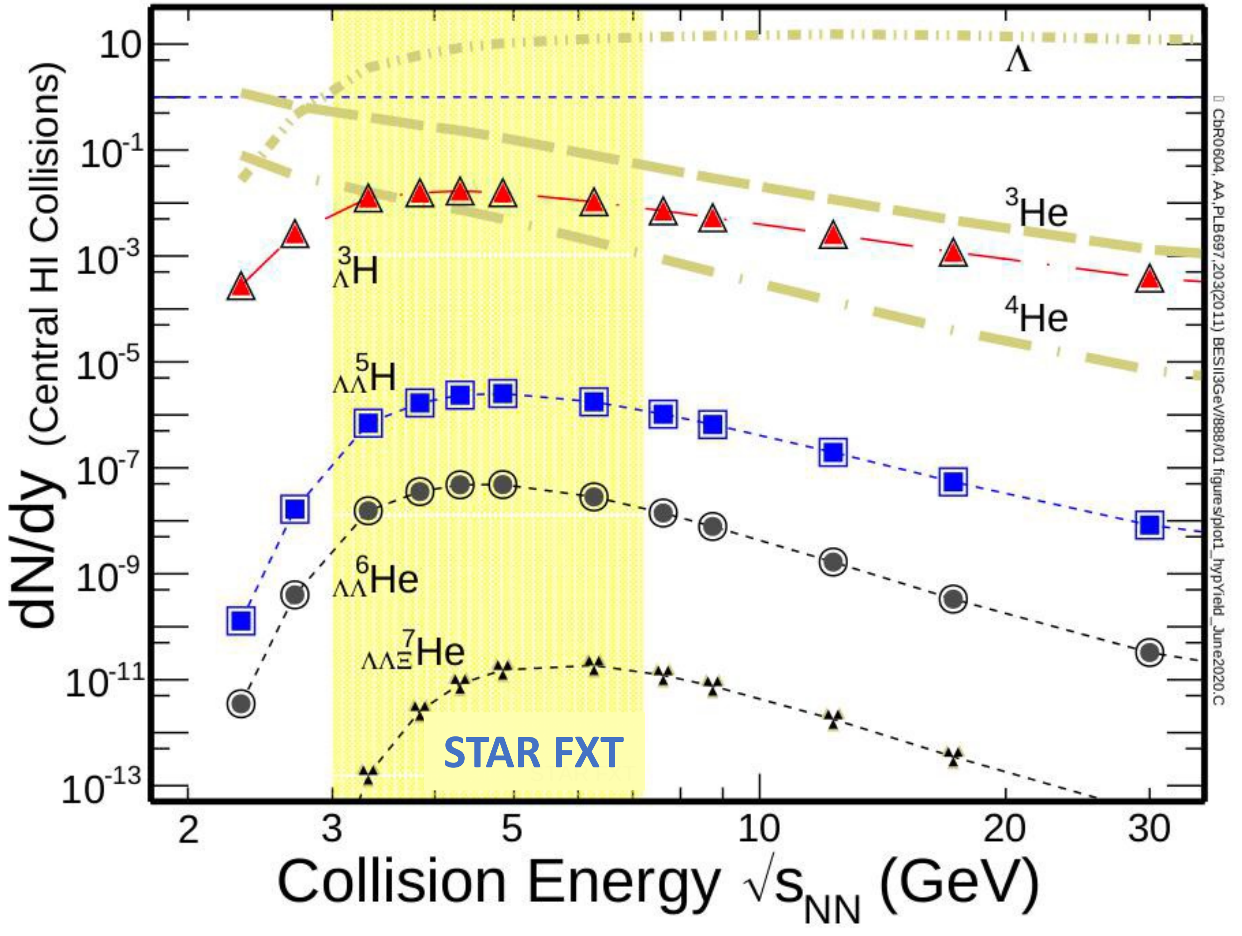


STAR Fixed-Target collisions (FXT)

- Au+Au $\sqrt{s_{NN}}$ = 3–13.7 GeV
  - Fixed-Target collisions
  - 3 GeV: 260M events in 2018

Abundant light hypernuclei produced in high baryon density region!

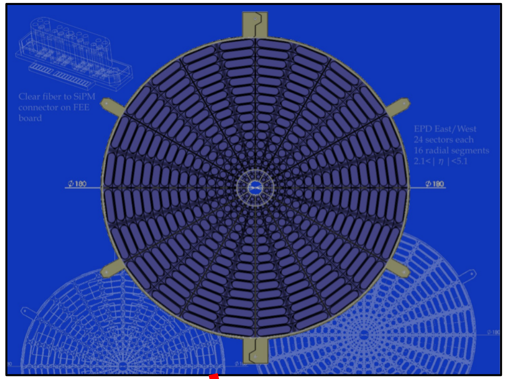
PLB 697, 203 (2011) (Thermal Model)



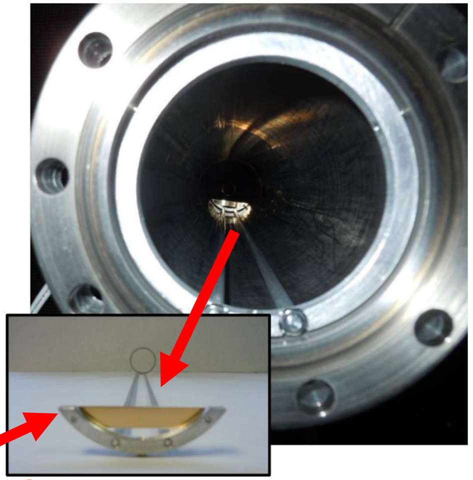
Outline

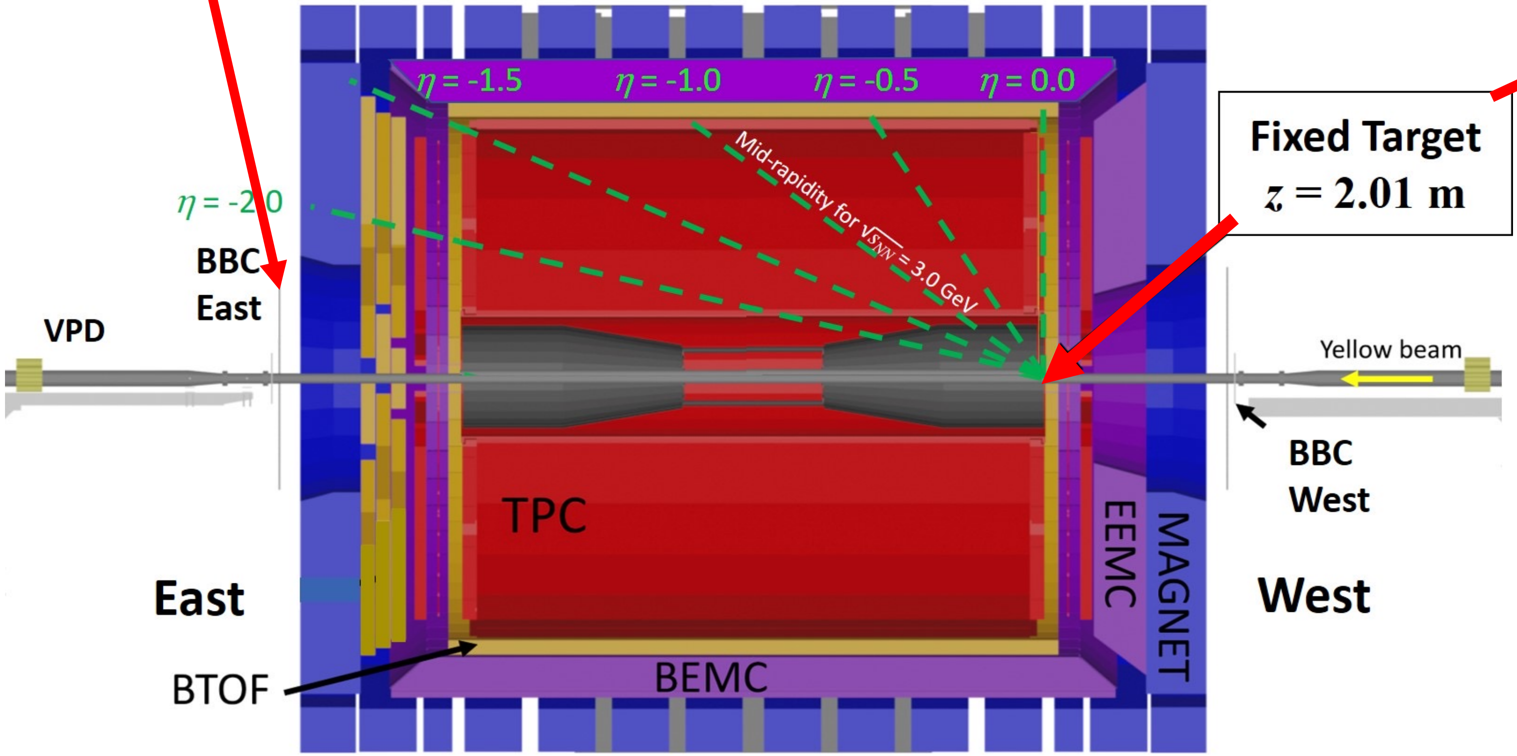
- Intrinsic properties
  - $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H lifetime, $^{3}_{\Lambda}$H decay branching ratio, B_{Λ} of $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He
- Production mechanism
  - dN/dy of $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H
- Collectivity
  - $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H v_1

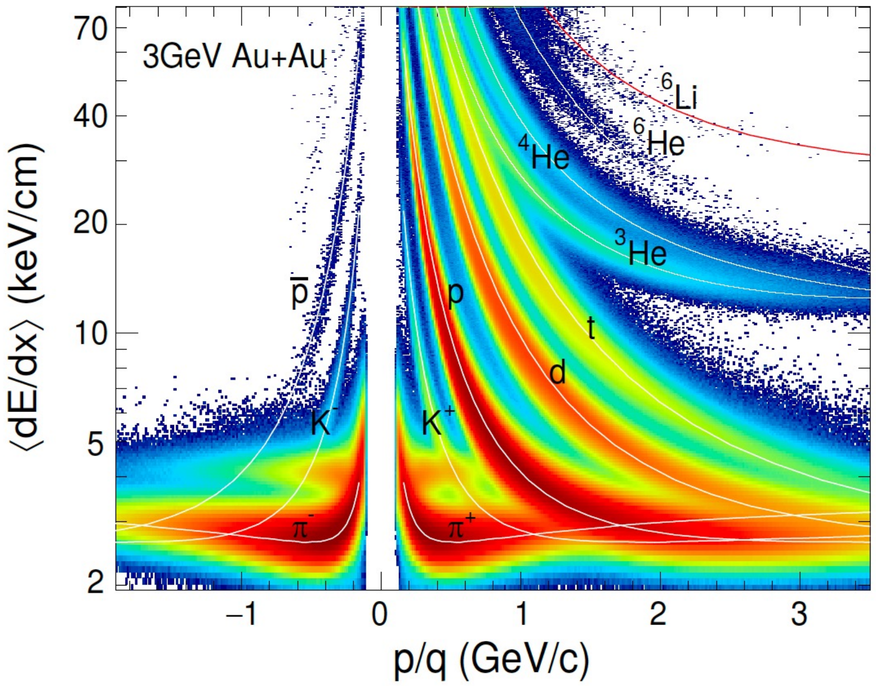
Fixed Target Setup at STAR



Event Plane Detector (EPD)





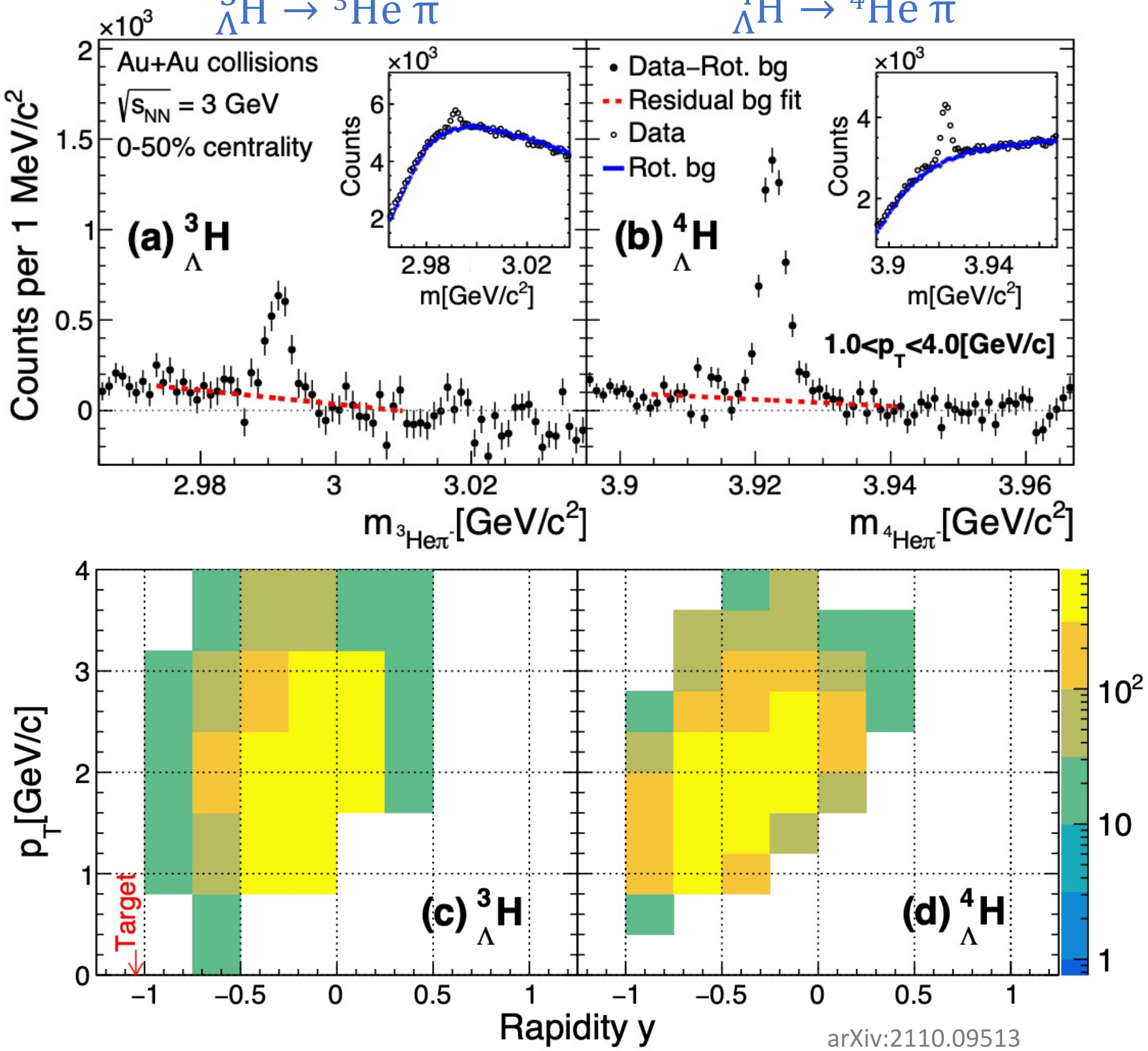


${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H reconstruction via 2 body channel

- KF particle package is used for signal reconstruction.
  - Based on Kalman Filter method.
  - All particles are described by state vectors (e.g. position and four momentum) as well as covariance matrix.
- Decay channel:
  ${}^{3}_{\Lambda}H \rightarrow {}^{3}He\ \pi^{-}$ ~ B.R. 25%,
  ${}^{4}_{\Lambda}H \rightarrow {}^{4}He\ \pi^{-}$ ~ B.R. 50%.
- Background reconstructed by rotation of π^{-}.
- Good kinematic coverage in Au+Au 3 GeV collisions.

KF Particle Finder: M. Zyzak, Dissertation thesis, Goethe University of Frankfurt, 2016

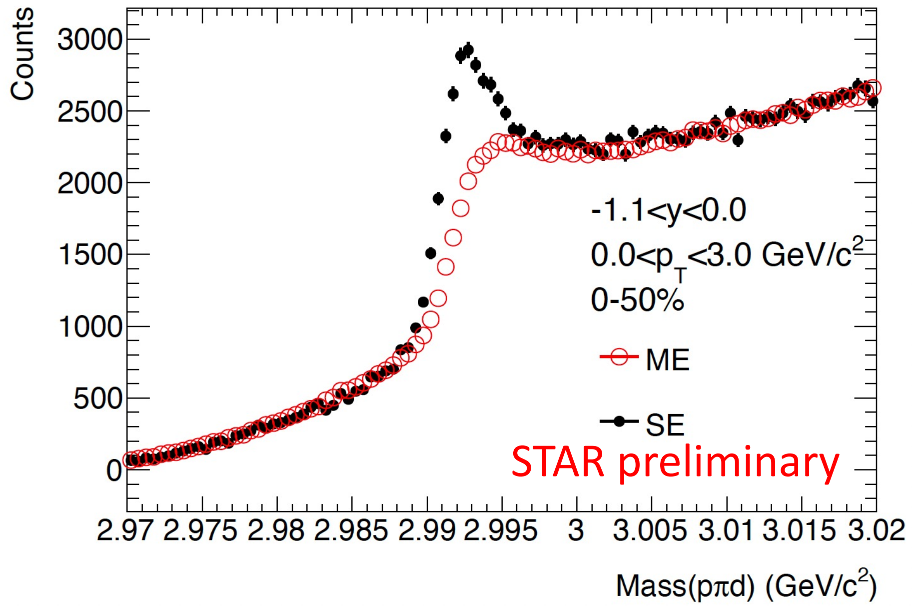
$${}^{3}_{\Lambda}H \rightarrow {}^{3}He\ \pi^{-} \qquad {}^{4}_{\Lambda}H \rightarrow {}^{4}He\ \pi^{-}$$

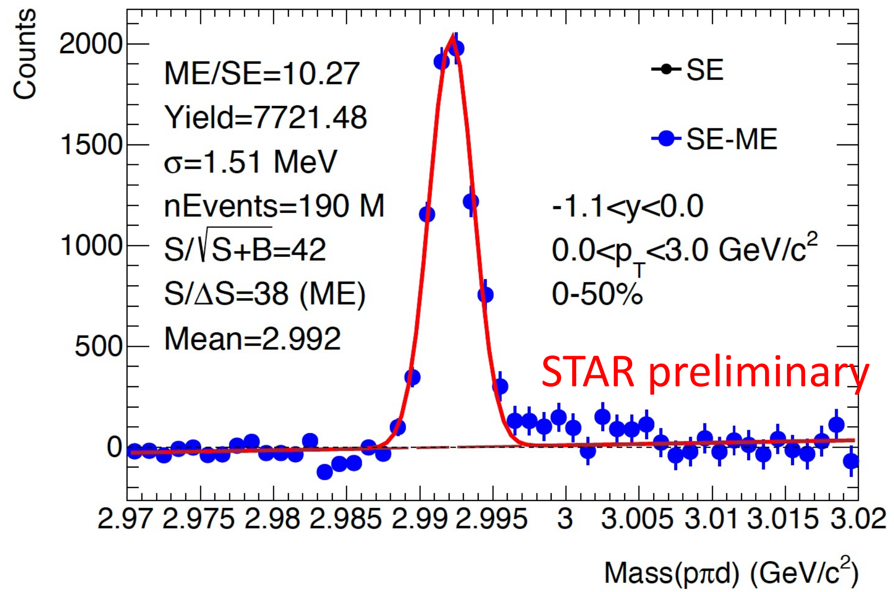


arXiv:2110.09513

${}^{3}_{\Lambda}\mathrm{H}$ reconstruction via ${}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{pd}\pi^{-}$

- Candidates are reconstructed utilizing KF particle package to enhance significance.
- ${}^{3}_{\Lambda}\mathrm{H}$ binding energy: ~0.2 MeV, weakly bound. $\mathrm{B}_{\Lambda} = (\mathrm{M}_{\Lambda} + \mathrm{M}_{\mathrm{core}} - \mathrm{M}_{\mathrm{hypernucleus}})\mathrm{c}^2$
- Combinatorial background is reconstructed by mixed-event method.
  - Random combination of $d + p + \pi$ and uncorrelated $\Lambda + d$.
- Signals contain real ${}^{3}_{\Lambda}\mathrm{H}$ signal and kinematically correlated $\Lambda + d$ $(\Lambda \rightarrow p\pi^{-})$.





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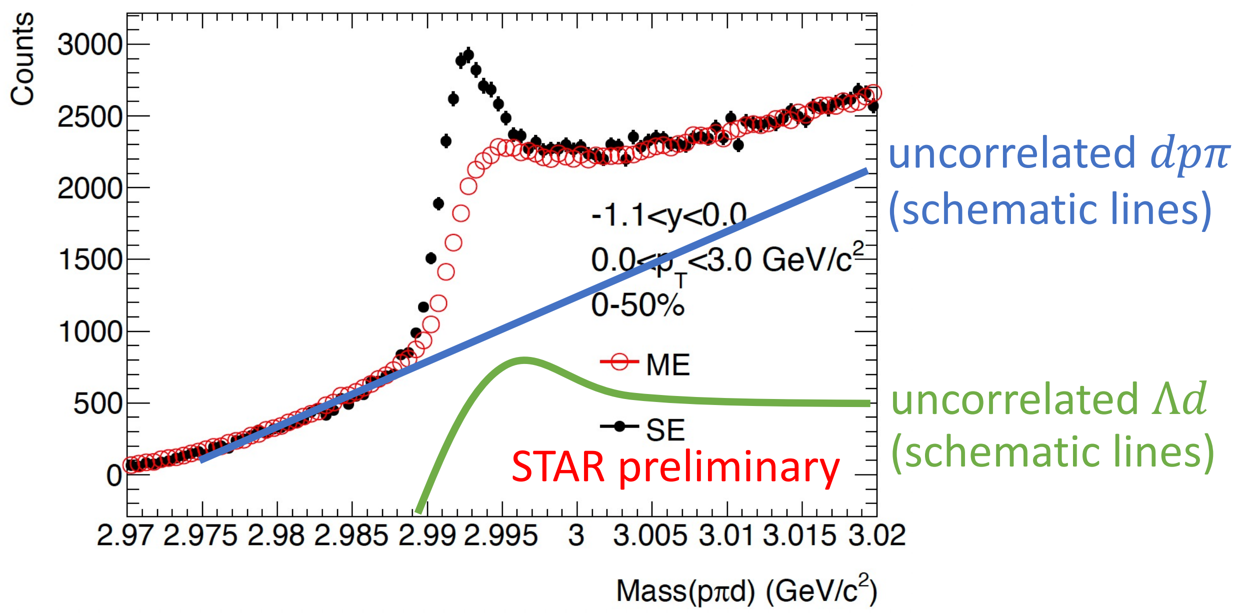

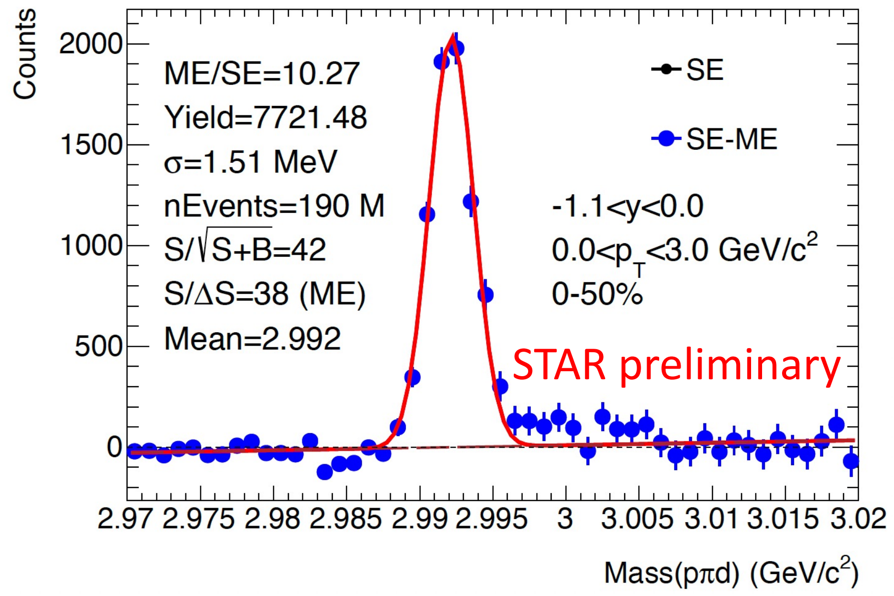

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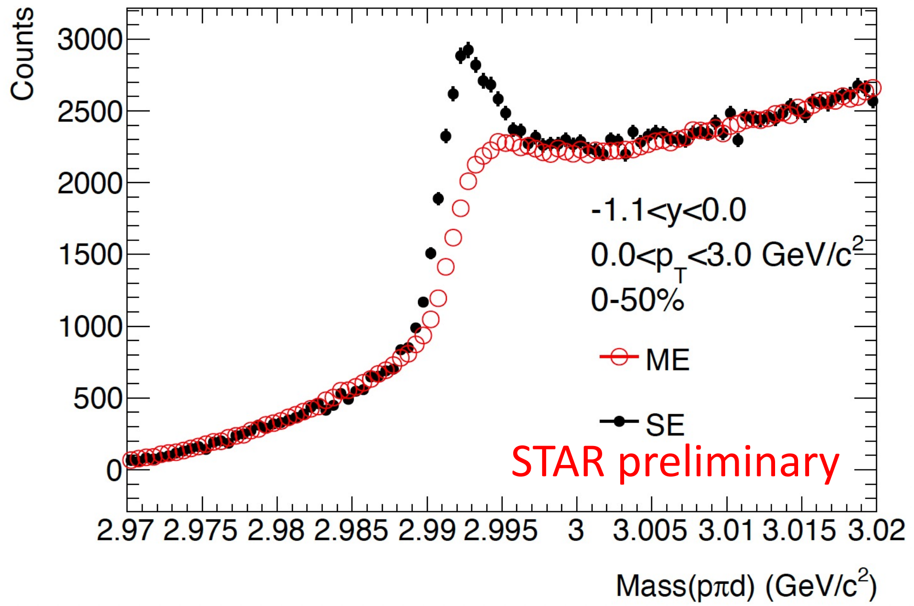
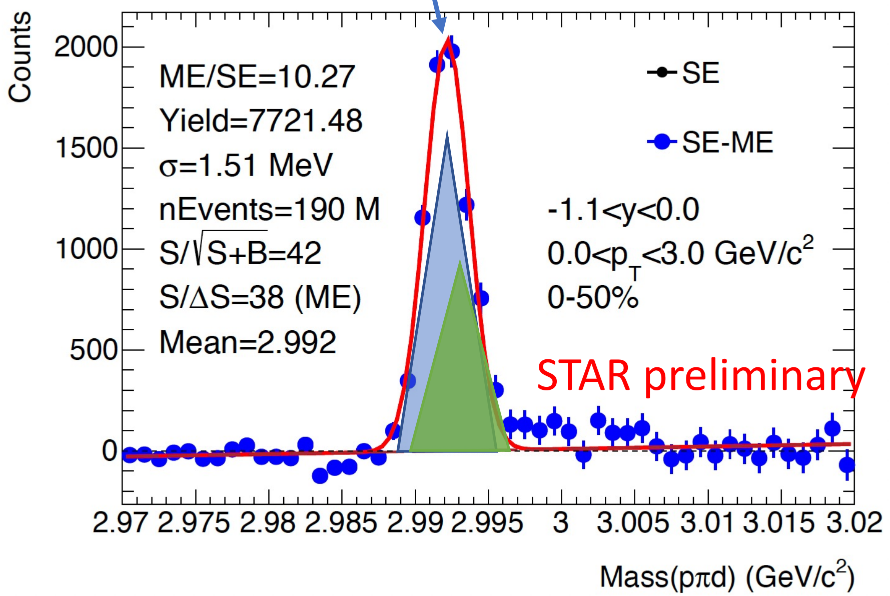


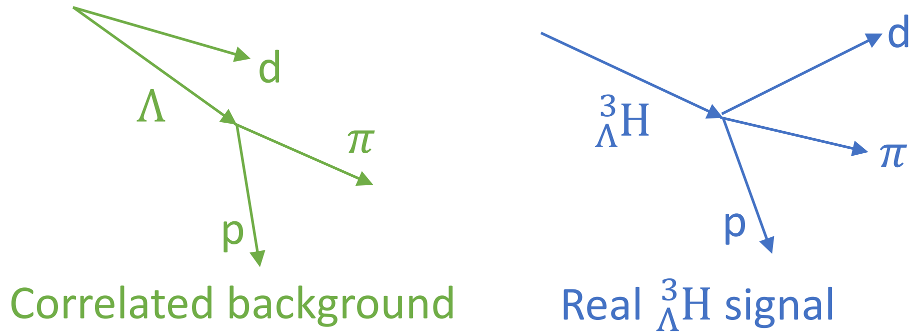
kinematic correlated $\Lambda + d$,
real ${}^{3}_{\Lambda}H$ signal (schematic diagram)

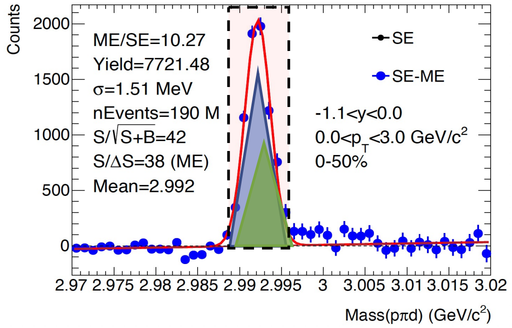


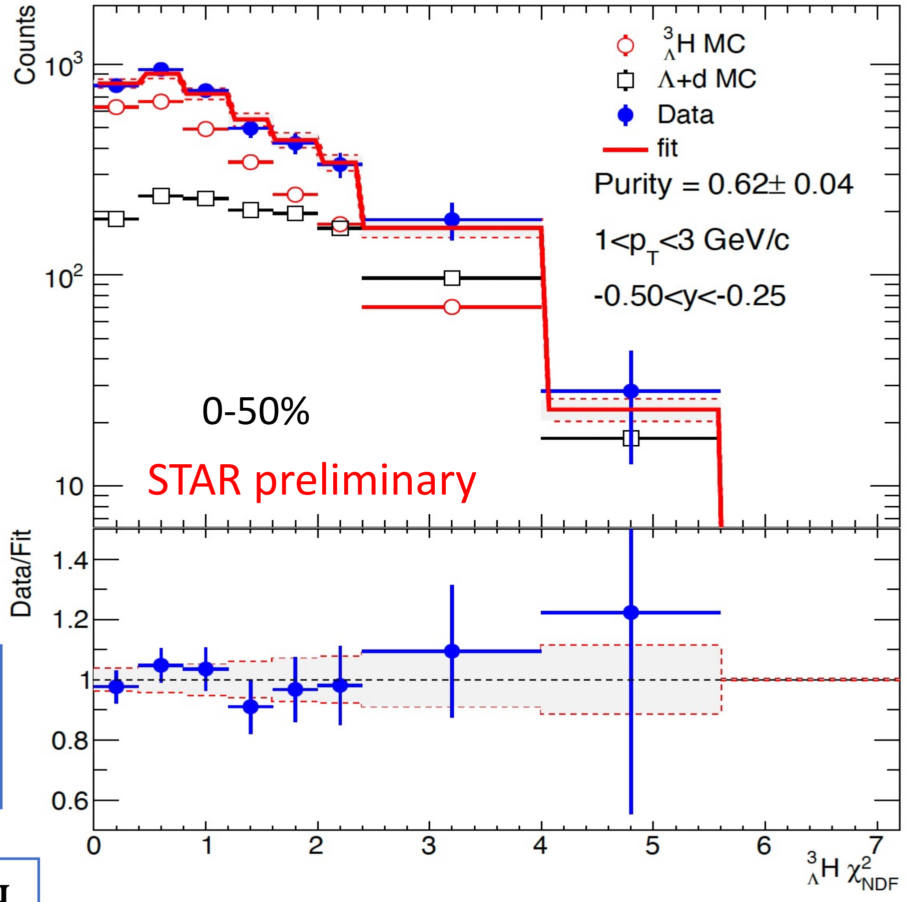
Estimation of real ${}^{3}_{\Lambda}\mathrm{H}$ yield in reconstructed signals

Topological variable: $\chi^2_{NDF} = \chi^2_{fit}/NDF$

- Whether daughters are from the same vertex.







Embedding MC Λ+d → Normalized χ^2_{NDF} distribution $f_{\Lambda d}$

Embedding MC ${}^{3}_{\Lambda}\mathrm{H}$ → Normalized χ^2_{NDF} distribution $f_{{}^{3}_{\Lambda}\mathrm{H}}$

χ^2_{NDF} distribution from reconstructed signals $(M({}^{3}_{\Lambda}\mathrm{H}) \pm 2\sigma)$: f_{Data}

Template fitting:
$$f_{Data} = p_0 \cdot (f_{\Lambda d} + p_1 \cdot f_{{}^{3}_{\Lambda}\mathrm{H}})$$

${}^{3}_{\Lambda}\mathrm{H}$ purity: the fraction of real ${}^{3}_{\Lambda}\mathrm{H}$ $f_{{}^{3}_{\Lambda}\mathrm{H}}$ in signals f_{Data} (χ^2_{NDF}<3)

Measurements of hypernuclei intrinsic properties

${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H lifetime

Precise measurements of ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H lifetime.

- $\tau({}^{3}_{\Lambda}\mathrm{H})$ and $\tau({}^{4}_{\Lambda}\mathrm{H})$ are ~20% lower than $\tau(\Lambda)$.

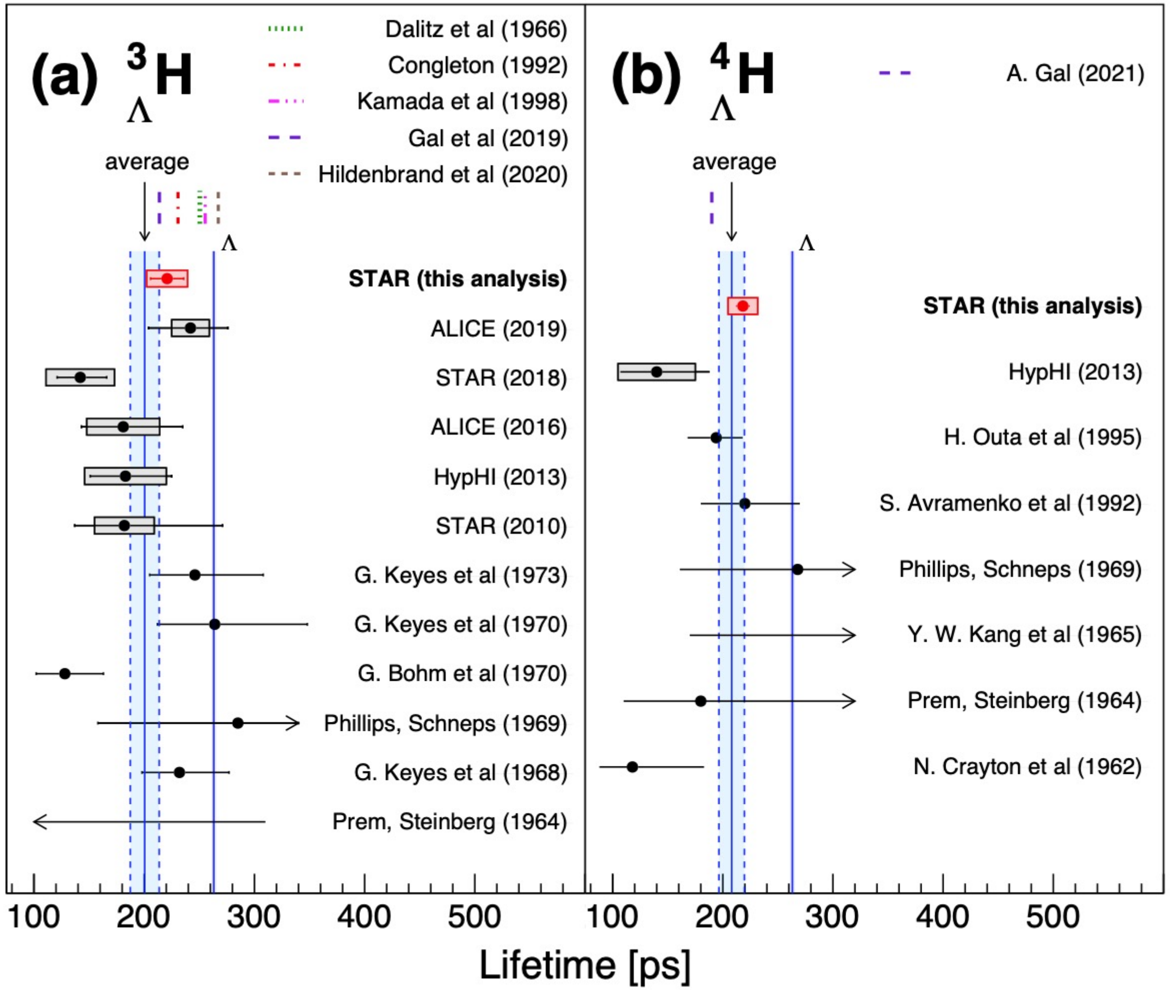
$\tau({}^{3}_{\Lambda}\mathrm{H})$

- Early calculations assuming weakly bound Λ: $\tau({}^{3}_{\Lambda}\mathrm{H}) \sim \tau(\Lambda)$.
- Consistent with data after incorporating attractive pion final state interactions in recent calculation.

$\tau({}^{4}_{\Lambda}\mathrm{H})$

- Calculation based on empirical isospin rule agrees with data within 1σ.

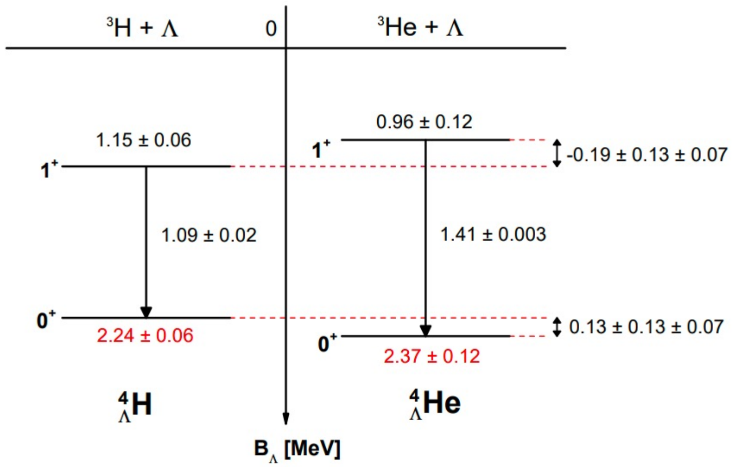
A. Gal, arXiv:2108.10179



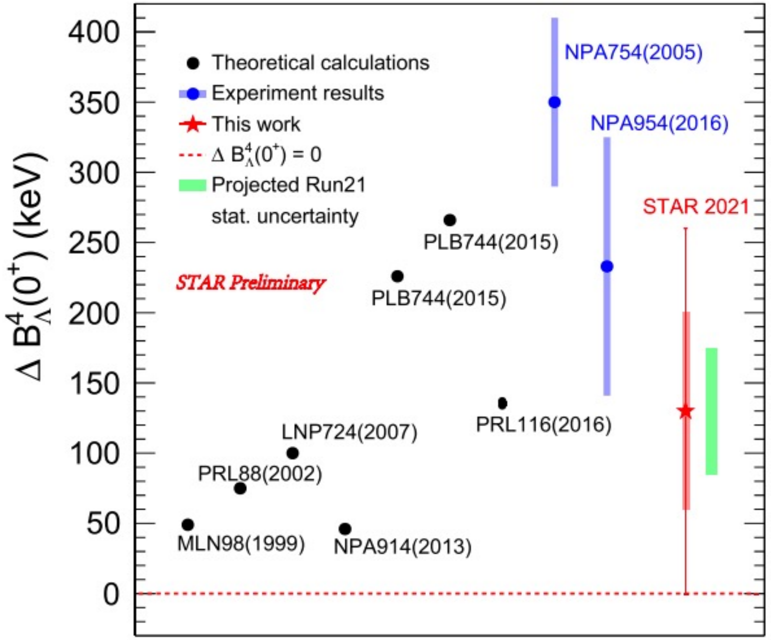
STAR: arXiv:2110.09513

Provide tighter constrains on models and deeper understanding in hypernuclei structure and *Y-N* interaction.

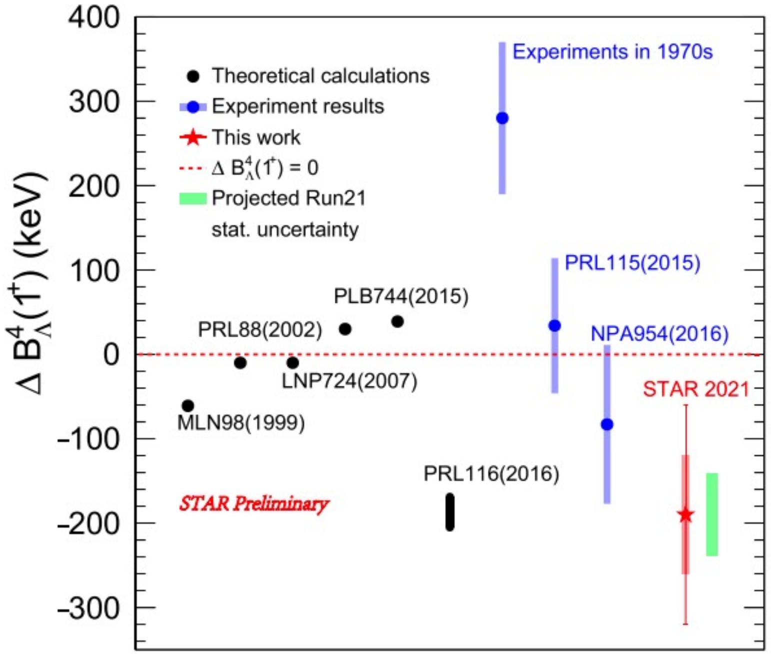
B_Λ and charge symmetry breaking



$B_\Lambda(^4_\Lambda\mathrm{H}) = 2.24 \pm 0.06(stat) \pm 0.18(sys)$ MeV
$B_\Lambda(^4_\Lambda\mathrm{He}) = 2.37 \pm 0.12(stat) \pm 0.14(sys)$ MeV



$\Delta B^4_\Lambda(0^+)$ ground state



$\Delta B^4_\Lambda(1^+)$ excited state

- Λ binding energy $B_\Lambda = (M_\Lambda + M_{core} - M_{hypernucleus})c^2$.
- Non-zero $B(\Lambda)$ difference between $^4_\Lambda$H and $^4_\Lambda$He: $\Delta B^4_\Lambda = B(\Lambda)_{^4_\Lambda He} - B(\Lambda)_{^4_\Lambda H}$ due to charge symmetry breaking (CSB).
- The result indicates that CSB effect in ground and excited states may be comparable and opposite in sign.

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

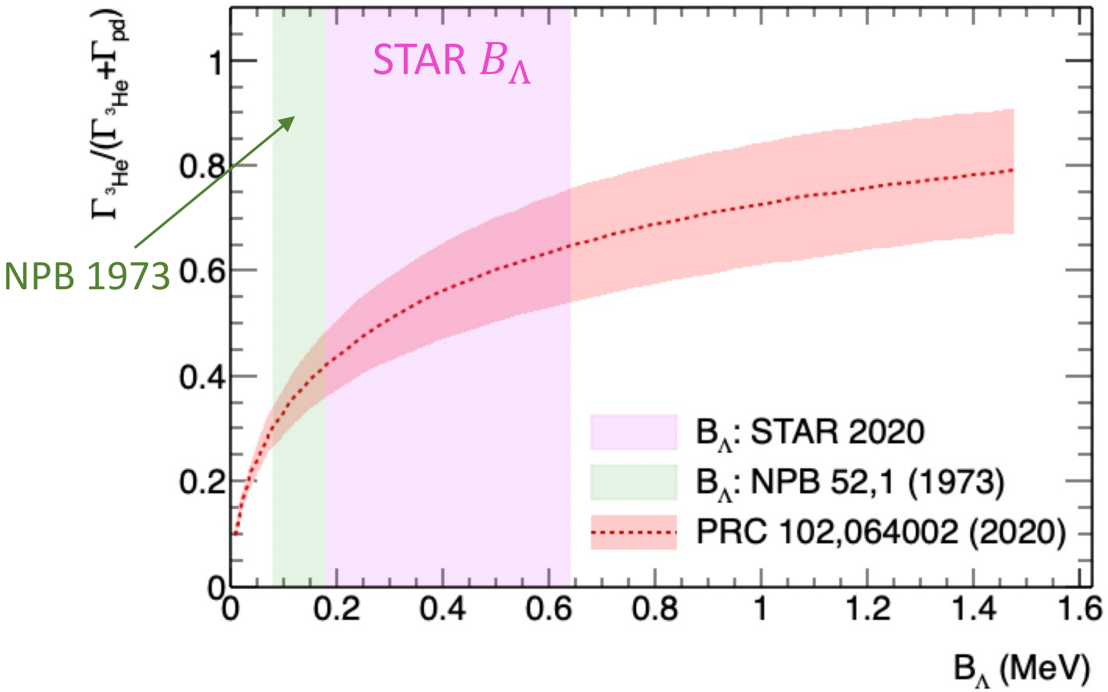
>99% of ${}^{3}_{\Lambda}\mathrm{H} \rightarrow \pi\mathrm{N}$: ${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He}\pi^{-}({}^{3}\mathrm{H}\pi^{0})$ ~ 33%, ${}^{3}_{\Lambda}\mathrm{H} \rightarrow \pi^{-}\,\mathrm{pd}(\pi^{0}nd)$ ~67%.

- Sensitive to B_Λ from recent theory calculation.
- B_Λ: direct constrain on *Y-N* interaction strength.

F. Hildenbrand and H.-W. Hammer, PRC 102, 064002 (2020)

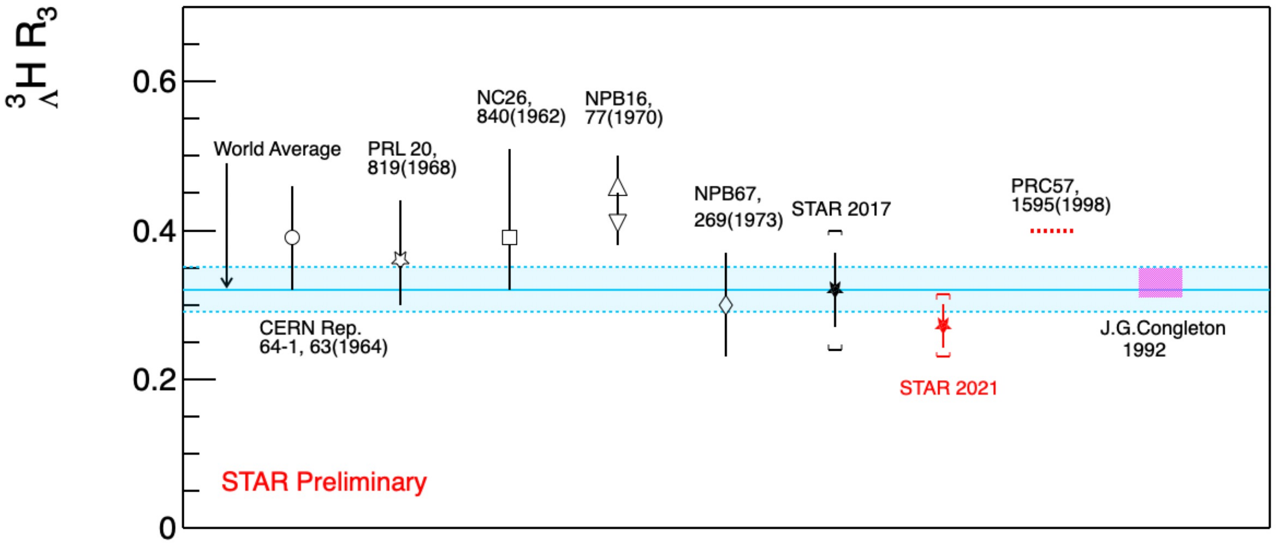
Improved uncertainty compared to previous measurements

STAR: Nature Phys. 16, 409–412 (2020)



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

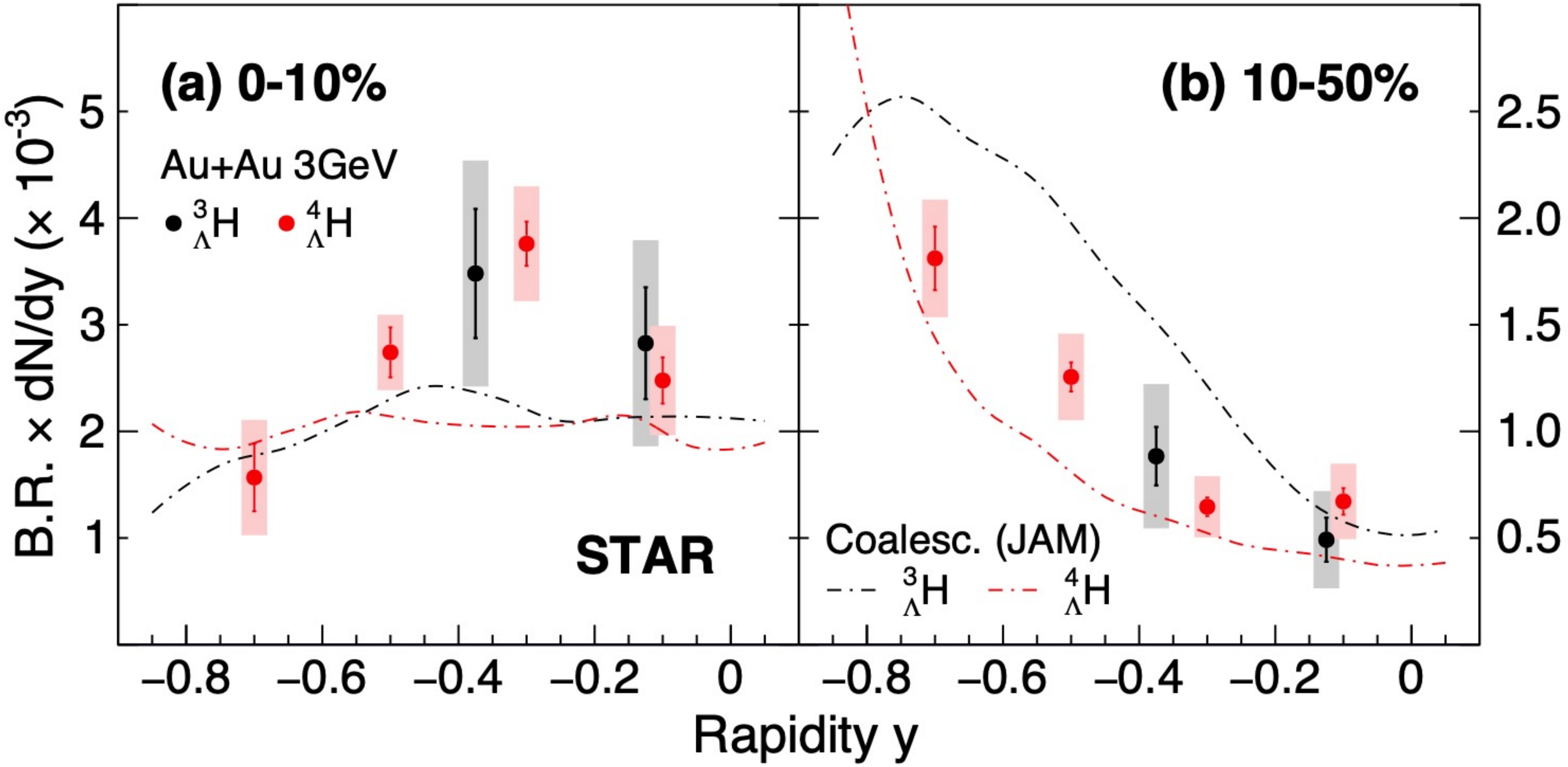
$R_3 = 0.2725 \pm 0.0295 \pm 0.0424$



STAR

Measurements of hypernuclei production yields in Au+Au 3 GeV

Production of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ in Au+Au 3 GeV



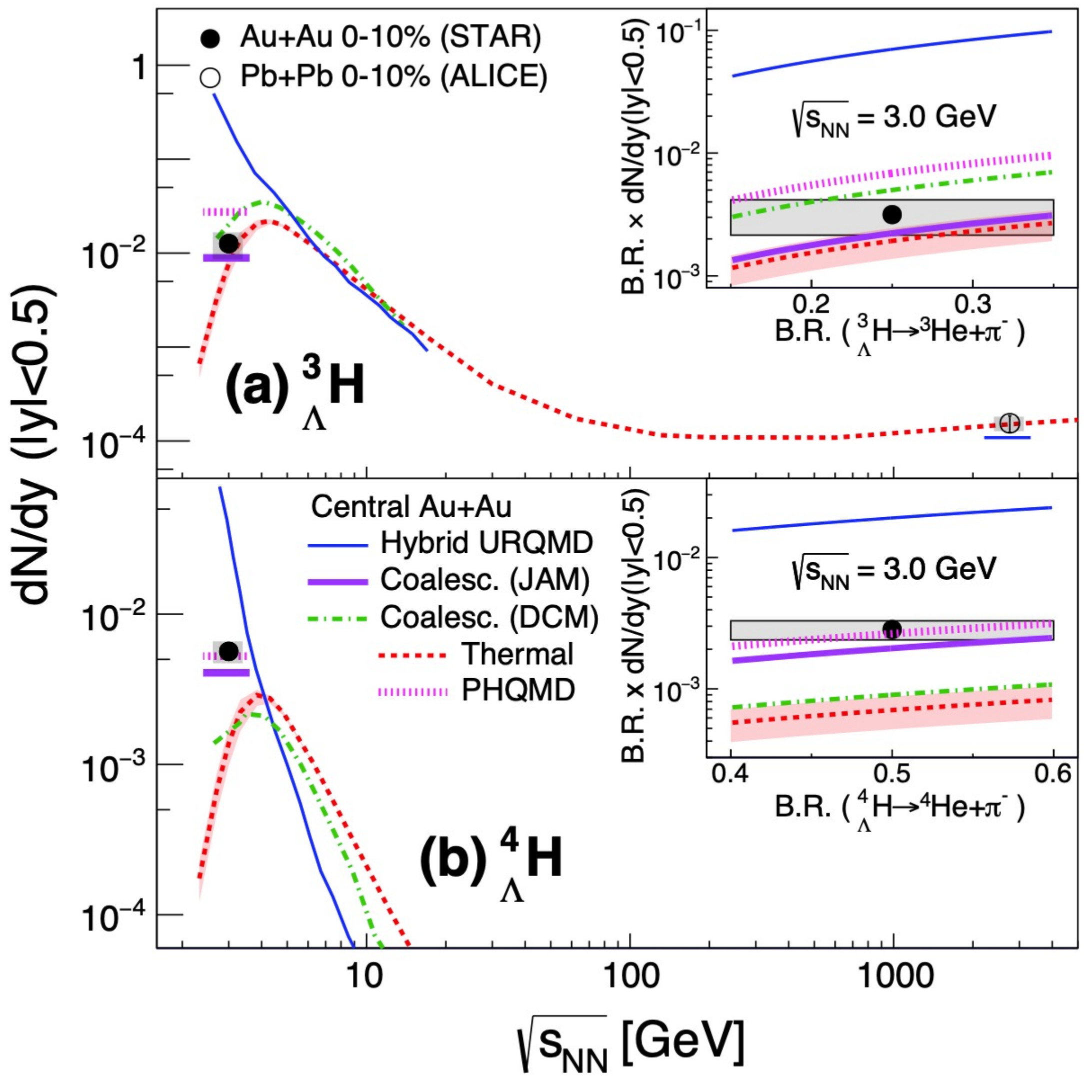
- First measurements on rapidity dependence of hypernuclei yields in heavy ion collisions.
- Coalescence models with tuned parameters qualitatively describe data.
  - Transport model (JAM) with coalescence of all hadrons as afterburner.

STAR data: arXiv:2110.09513 Coalesc.(JAM): PLB 805, 135452 (2020)

Energy dependence of hypernuclei production

- Thermal model describes yields of ${}^{3}_{\Lambda}\mathrm{H}$ at both RHIC and LHC energy, while underestimates that of ${}^{4}_{\Lambda}\mathrm{H}$ at 3 GeV.
- Hadronic transport models JAM and PHQMD calculations reasonably reproduce both ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ yields.
  - JAM: baryonic mean-field approach.
  - PHQMD: modelled by density dependent 2-body baryonic potentials.
- DCM consists with ${}^{3}_{\Lambda}\mathrm{H}$ yields while underestimates ${}^{4}_{\Lambda}\mathrm{H}$ yields, possibly due to the choice of coalescence parameters.

DCM: PLB 714, 85-91 (2012)
Thermal model: PLB 697,203-207 (2011)
PHQMD: arXiv:2106.14839, arXiv:1911.09496
JAM: PLB 805, 135452 (2020)

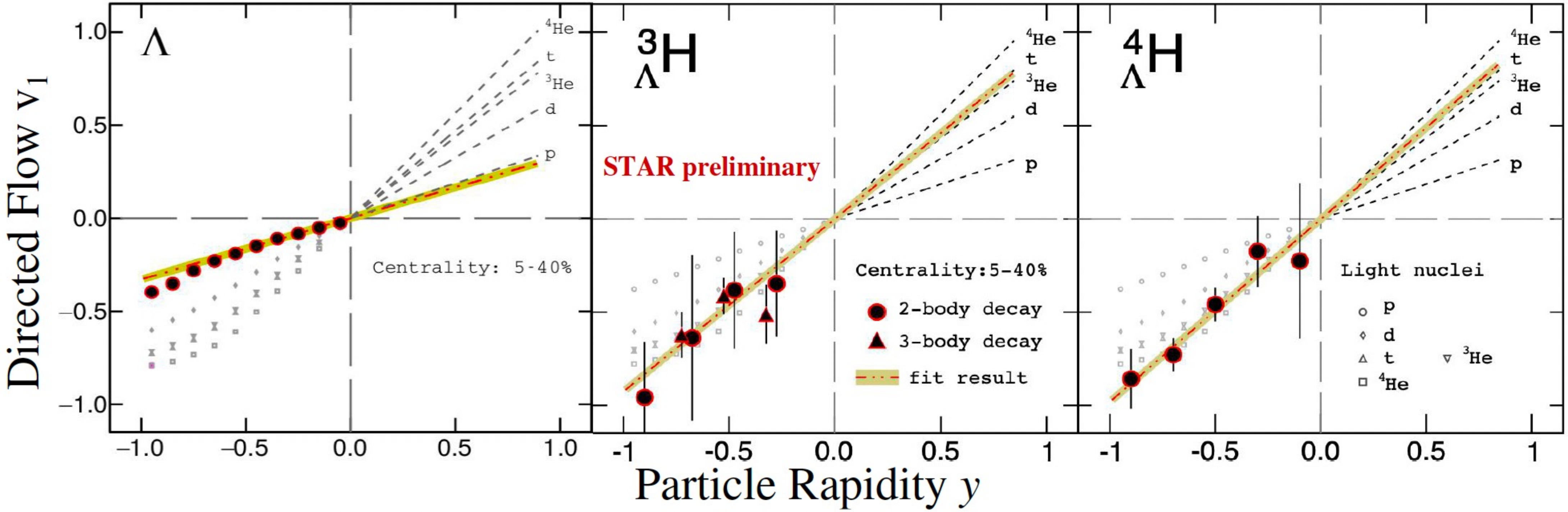


arXiv:2110.09513

Measurements of hypernuclei collectivity in Au+Au 3 GeV

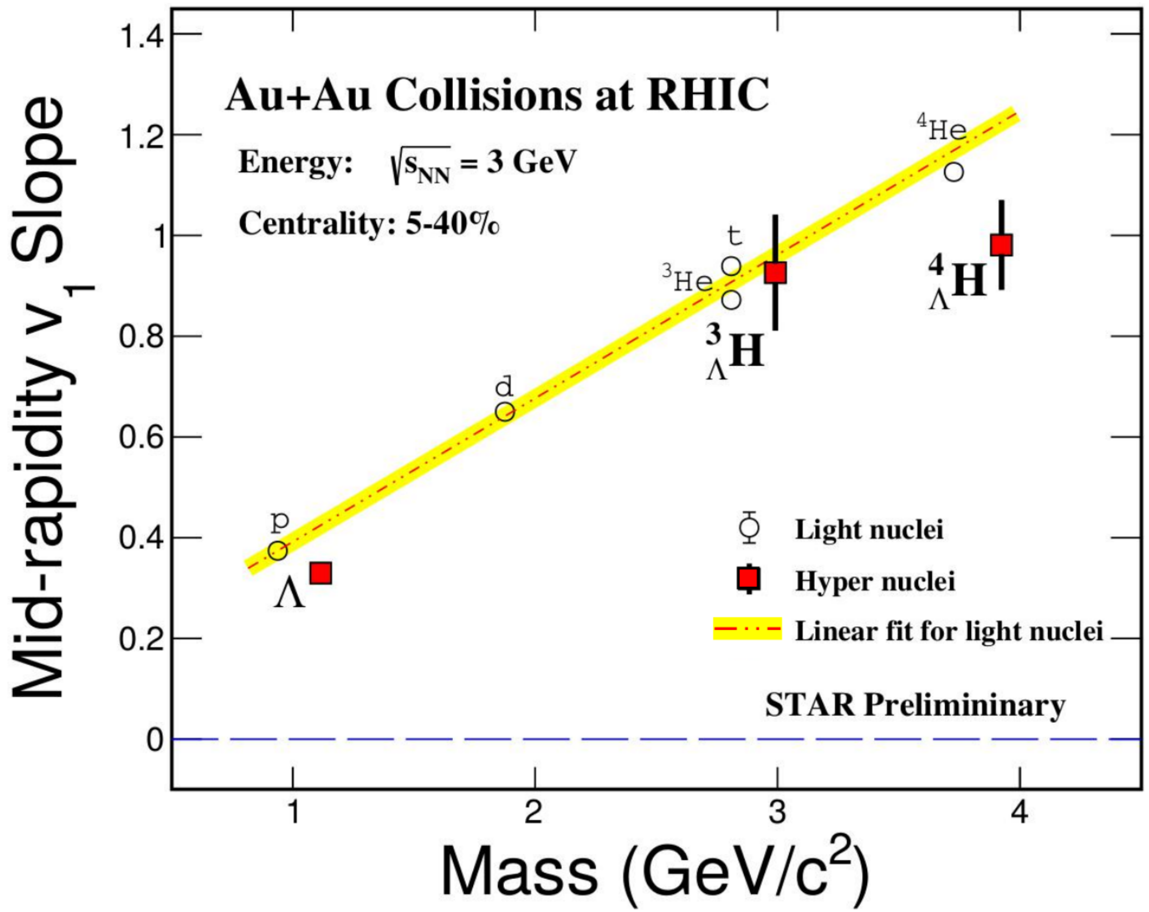
Directed flow of light hypernuclei vs rapidity

Au+Au $\sqrt{s_{NN}}$= 3 GeV



- First observation of hyper-nuclei collectivity v_1 in heavy-ion collisions.
- Hyper-nuclei v_1 follows baryon number scaling within uncertainties similar as light nuclei v_1 in Au+Au 3 GeV collision at 5-40% centrality.

Directed flow slope of light hypernuclei



- The slopes of v_1 for hyper-nuclei follow the baryon number scaling in the 5-40% 3 GeV Au+Au collisions.

- Coalescence of hyperons and nucleons is a dominant process for hypernuclei formation at mid rapidity.

Summary

- Abundant light hypernuclei (${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$) produced in Au+Au 3 GeV collisions.

- Provide stronger model constraints and deeper understanding of the *Y-N* interaction strength.
  - Precise lifetime measurements of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$.
    - $\tau({}^{3}_{\Lambda}\mathrm{H})$ and $\tau({}^{4}_{\Lambda}\mathrm{H})$ are ~20% lower than $\tau(\Lambda)$.
  - Precise branching ratio R_3 measurements on ${}^{3}_{\Lambda}\mathrm{H}$.
  - Measurements on $\Delta B^{4}_{\Lambda}= B(\Lambda)_{{}^{4}_{\Lambda}\mathrm{He}} - B(\Lambda)_{{}^{4}_{\Lambda}\mathrm{H}}$ indicate that charge symmetry effect in ground and excited states may be comparable and opposite in sign.

- First rapidity dependence of dN/dy and directed flow v_1 measurements of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ in heavy-ion collisions.
  - Qualitatively consistent with coalescence prescription.
  - Give insights into hypernuclei production mechanism.

Outlook

- High statistical data in STAR BES II

  $\sqrt{s_{NN}}$ = 3.0 - 27 GeV
  - Expected ~ 8 times statistics of Au+Au 3 GeV collisions in Run 2021

- Energy dependence of production yield and flow behavior of light hypernuclei

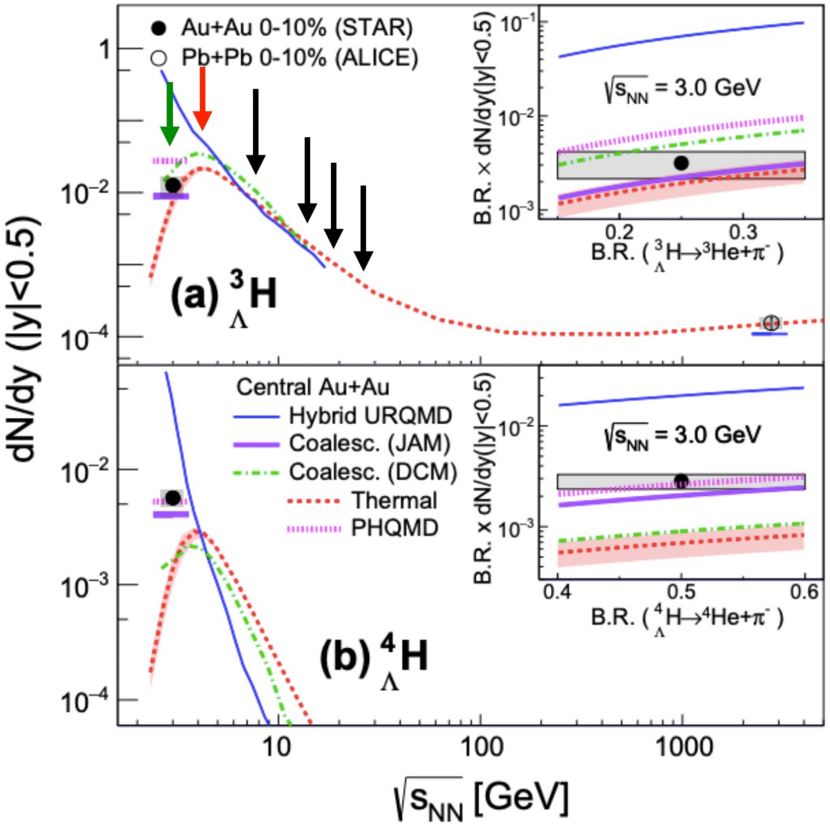
  ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{He}$, ${}^{5}_{\Lambda}\mathrm{He}$

- Precise Hypernuclei property measurements
  - e.g. ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$ branching ratio, binding energy

- Search of double Λ hypernuclei

  e.g. ${}^{4}_{\Lambda\Lambda}\mathrm{He}$-> ${}^{4}_{\Lambda}\mathrm{He}\pi$, ${}^{5}_{\Lambda\Lambda}\mathrm{He}$ -> ${}^{5}_{\Lambda}\mathrm{He}\pi$

arXiv:2110.09513



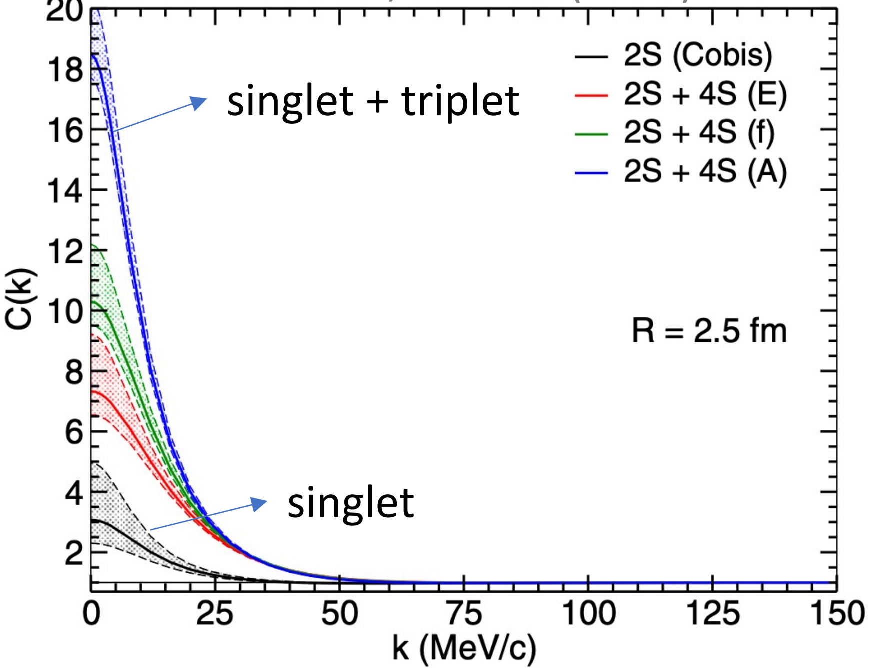
- back ups

Correlated Λd contamination in ${}^{3}_{\Lambda}\mathrm{H}$ signal

- Λd may have kinematic correlations according to theory calculation.

C(k*)=$\frac{P(\Lambda d)}{P(\Lambda)P(d)}$, p is the possibility of finding particle
No correlation -> C(k*)=1
k* -> relative momentum between Λ and d

PRC 102, 034001 (2020)

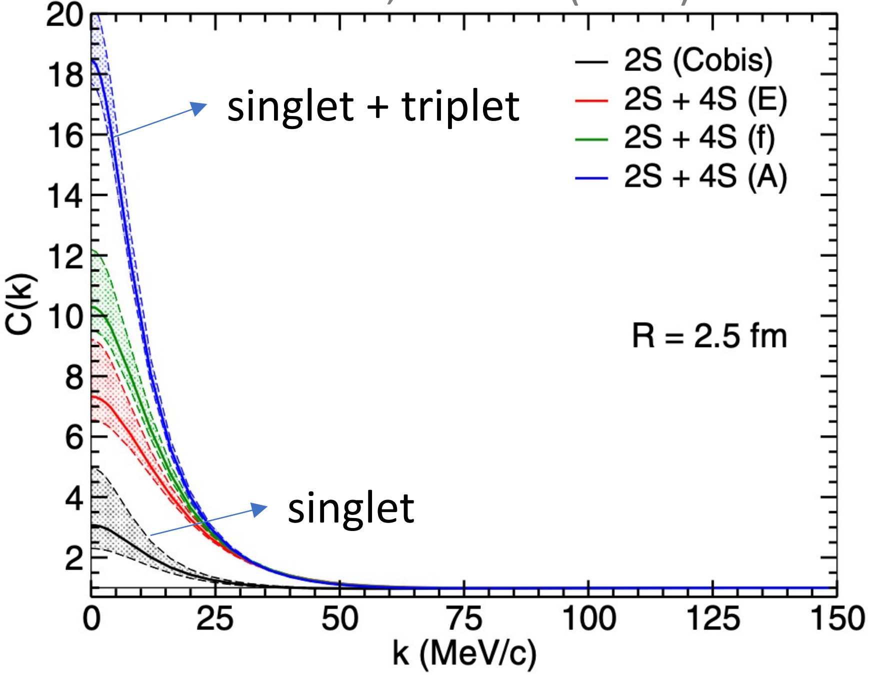


Correlated Λd contamination in ${}^{3}_{\Lambda}\mathrm{H}$ signal

- Λd may have kinematic correlations according to theory calculation.
- When Λd C(k*) >1 at k*-> 0, peak structure is formed near $M(\Lambda) + M(d)$ threshold.
  - $M(\Lambda) + M(d)$ ~2.9913 GeV/c^2, M(${}^{3}_{\Lambda}\mathrm{H}$)~2.991 GeV/$c^2$.

-> Correlated Λd could residual in real signal even after subtracting combinatorial background.

PRC 102, 034001 (2020)



Set C(k*) weight on uncorrected Λ and d

From Λ(MC)+d(data) embedding