Hypernuclei production in Au+Au collisions at 3 GeV

Yuanjing Ji

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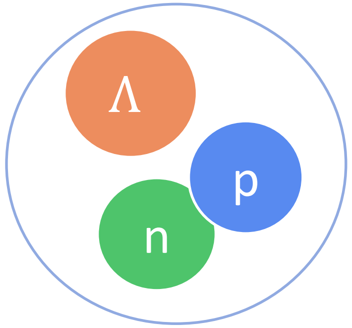
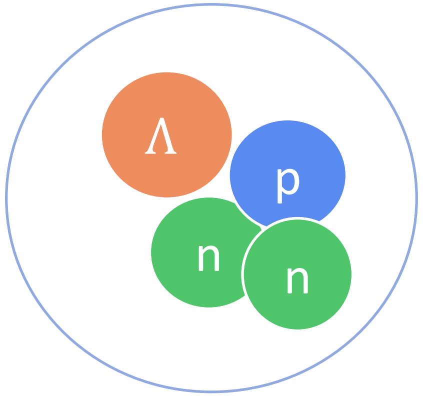
RNC Group Meeting

Motivation

- Hypernuclei introduce hyperon degree of freedom
  - Investigate hyperon-nucleon (*Y-N*) interaction.
    - Important ingredient for the nuclear equation of state.

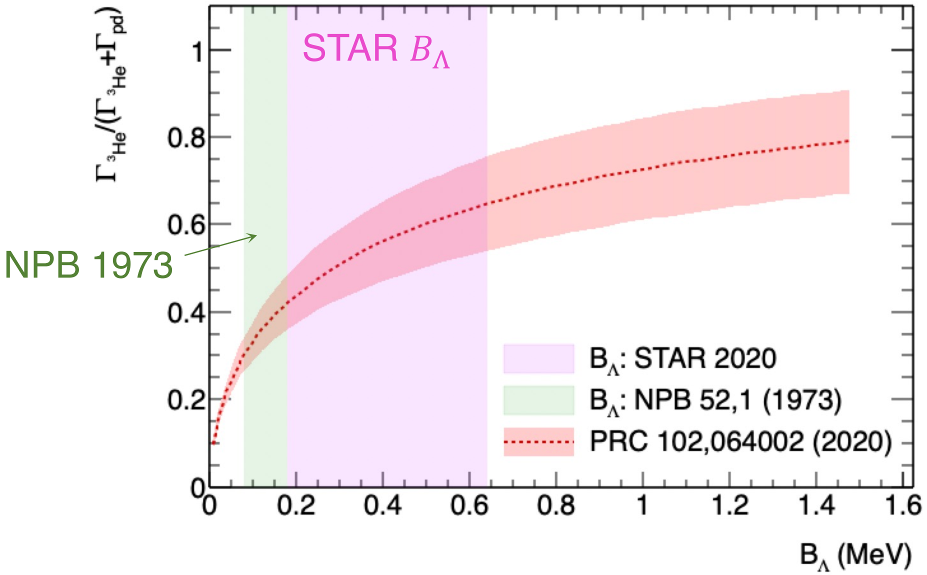


${}^{3}_{\Lambda}\mathrm{H}$



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

- Hypernuclei measurements in Au+Au collisions at 3 GeV
  ${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He}\,\pi^{-}$ ~ B.R. 15-25%, ${}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{p d}\pi^{-}$ ~ B.R. 40-50 %.
  ${}^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He}\,\pi^{-}$ ~ B.R. 50%.
  ${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He}\pi$, ${}^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He}\,\pi^{-}$: STAR, PRL 128, 202301 (2022)
  - ${}^{3}_{\Lambda}\mathrm{H}$ decay branching ratio
    - Recent calculation: R_3 sensitive to B_Λ
    - B_Λ -> directed constraints on Y-N interaction strength
    - An input for model calculation on ${}^{3}_{\Lambda}\mathrm{H}$ lifetime



Strangeness population factor

S. Zhang et al, PLB 684, 224 (2010)

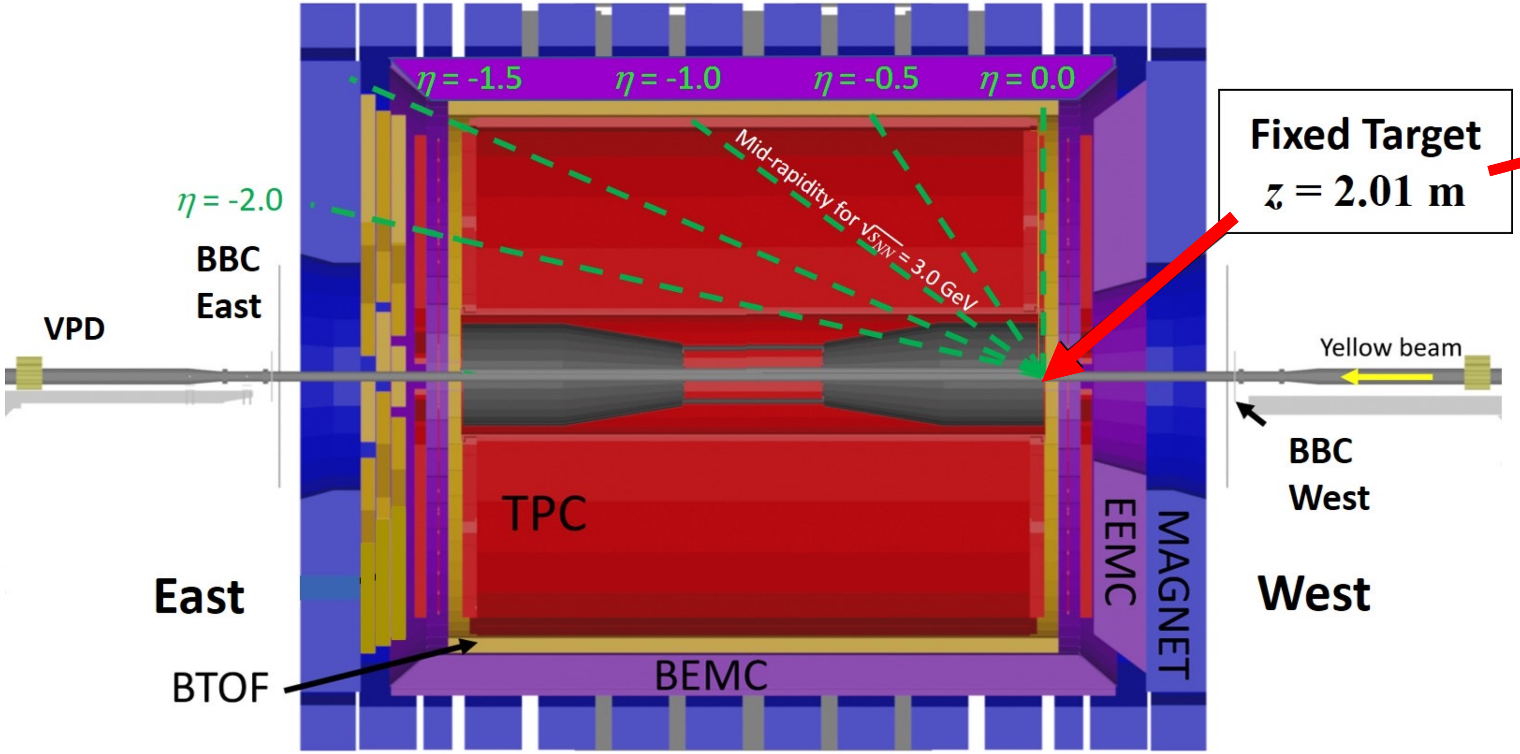
$$S_A = \frac{{}^{A}_{\Lambda}\mathrm{H}}{{}^{A}\mathrm{He} \times \frac{\Lambda}{p}} = \frac{\mathrm{B_A}({}^{A}_{\Lambda}\mathrm{H})(\mathrm{p_T})}{\mathrm{B_A}({}^{A}\mathrm{He})(\mathrm{p_T})}$$

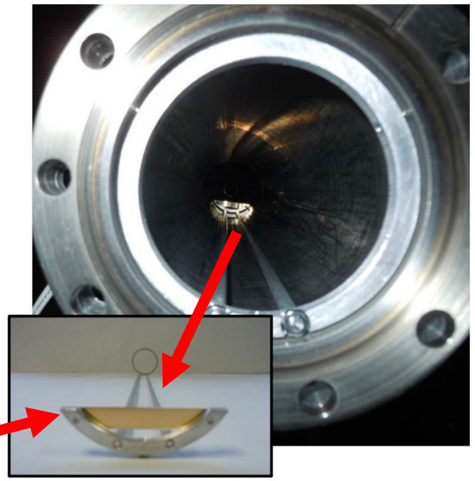
$$E_A \frac{\mathrm{d}^3 N_A}{\mathrm{d}p_A^3} = B_A \left(E_{\mathrm{p,n}} \frac{\mathrm{d}^3 N_{\mathrm{p,n}}}{\mathrm{d}p_{\mathrm{p,n}}^3} \right)^A \Bigg|_{\vec{p}_{\mathrm{p}} = \vec{p}_{\mathrm{n}} = \frac{\vec{p}_A}{A}}$$

Coalescence parameters

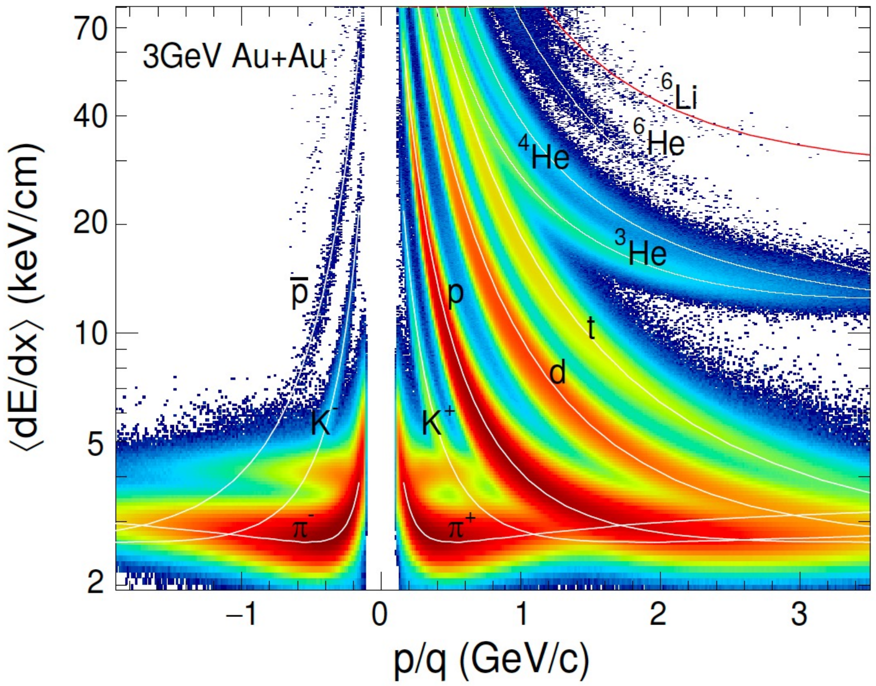
- Understanding *Y-N* interaction and hypernuclei production mechanism in heavy-ion collisions
  - Direct connected to the ratio of the light and hyper nuclei coalescence parameters.
  - In thermal model, S_A does not depend on the chemical potential of the particles and cancel canonical correction factors for strangeness.

Fixed-Target Setup at STAR



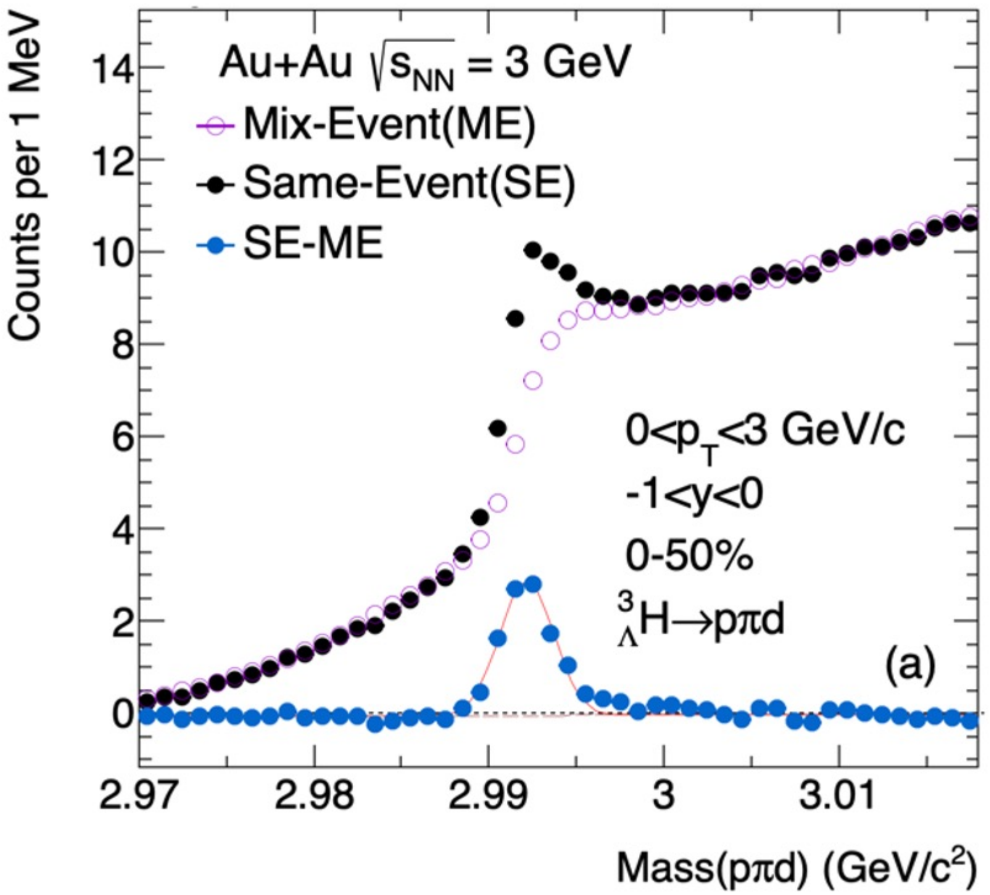


Gold foil, 250 μm thick



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

- ${}^{3}_{\Lambda}H \rightarrow dp\pi^{-}$, B.R. ~ 40-50%
- ${}^{3}_{\Lambda}H$ binding energy
  - $B_{\Lambda} = \left(M_{\Lambda} + M_{d} - M_{{}^{3}_{\Lambda}H}\right) c^{2} \sim 0.2\ \mathrm{MeV}$
  - Weakly bound system
- Combinatorial background
  - Mixed event method.
  - Random combination of $d + p + \pi$ anc uncorrelated $\Lambda + d$.
- Signals contain real ${}^{3}_{\Lambda}H$ signal and kinematically correlated $\Lambda + d$ $(\Lambda \rightarrow p\pi^{-})$.



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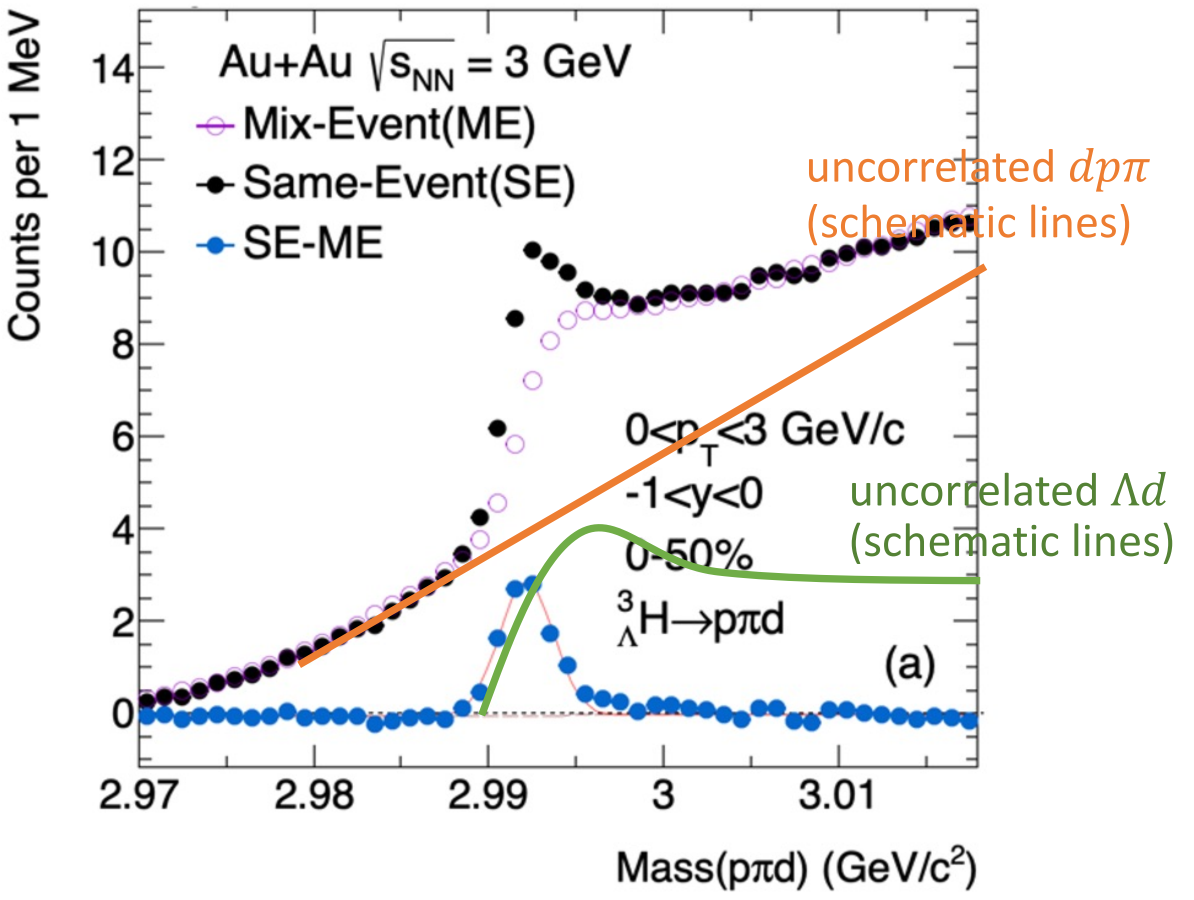

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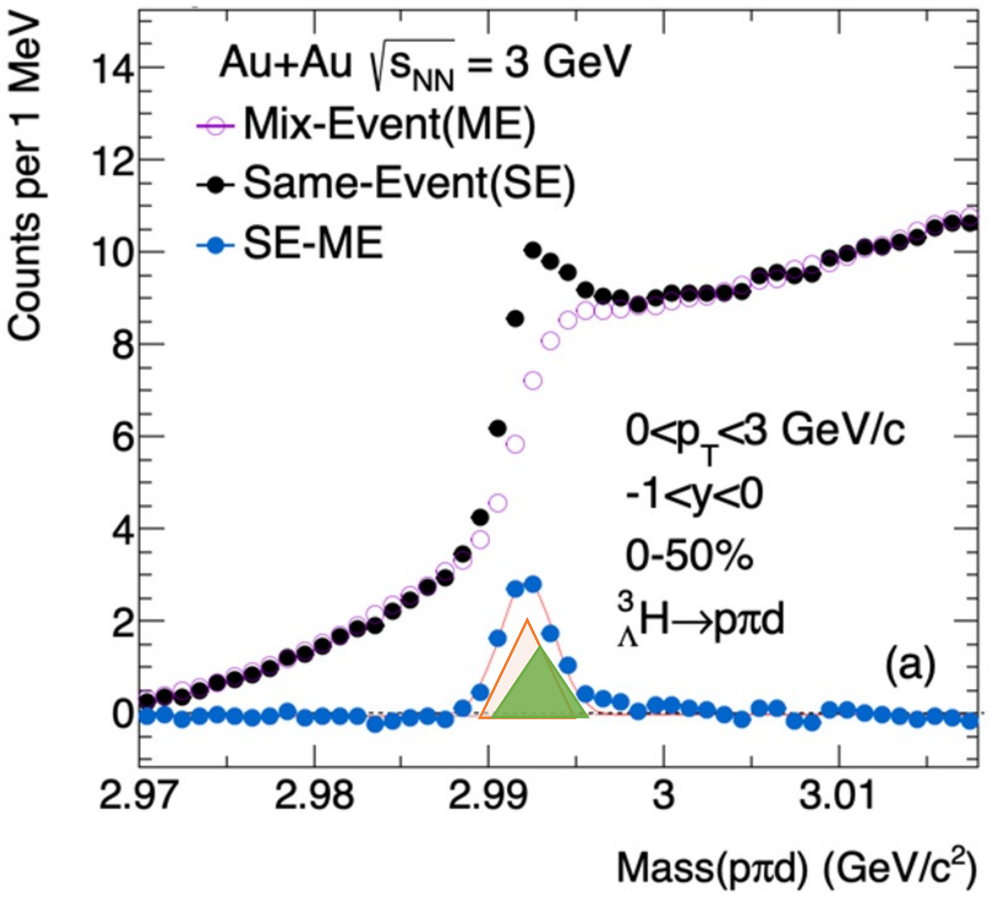
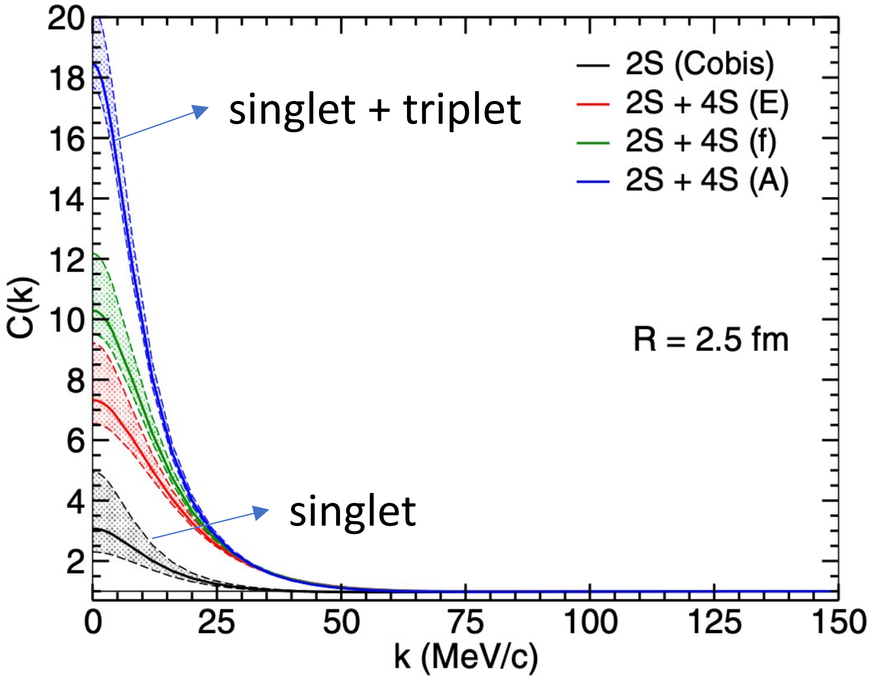


Correlated Λd contamination in ${}^{3}_{\Lambda}\mathrm{H}$ signal

- 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)



When k*=0, in Λ and d pair CMS framework:

$$p_\Lambda = -p_d = 0$$

Λ : (p_Λ, E_Λ) = (0, m_Λ)

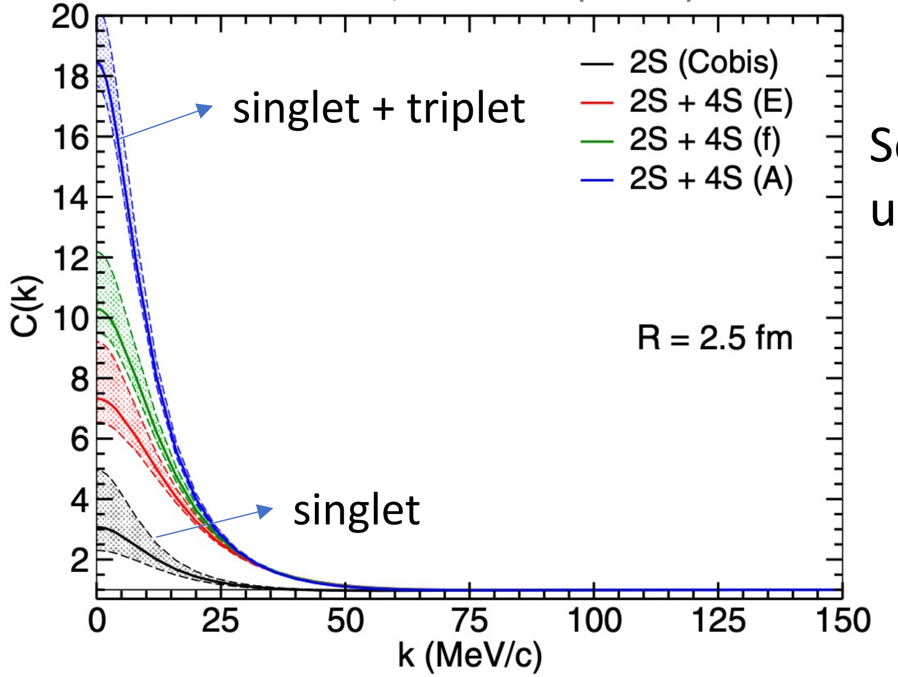
d : (p_d, E_d) = (0, m_d)

-> (Λd) : ($p_\Lambda + p_d$, $E_\Lambda + E_d$) = (0, m_Λ+ m_d)

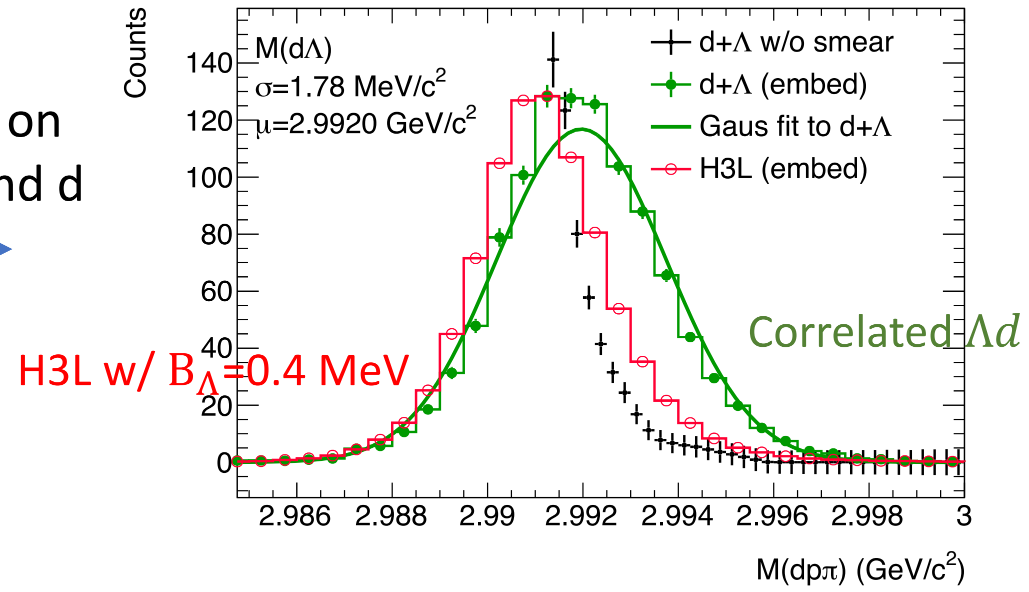
Correlated Λd contamination in ${}^{3}_{\Lambda}\mathrm{H}$ signal

- 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/c², M(${}^{3}_{\Lambda}\mathrm{H}$)~2.991 GeV/c² ($B_{\Lambda} \sim 0.1 - 0.4$ MeV).
  - Mass resolution of H3L in the data ~ 1.5 MeV/c² .
    - Challenge to separate two peaks.

PRC 102, 034001 (2020)



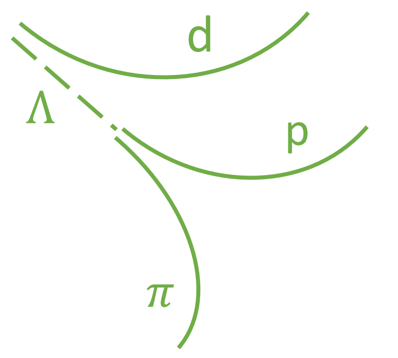
Set C(k*) weight on uncorrected Λ and d



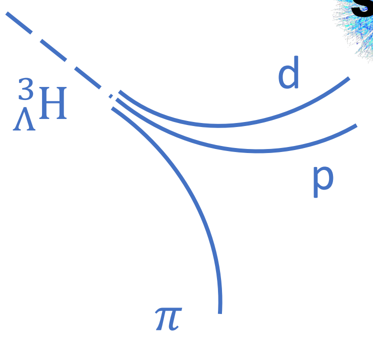
Simulation from embedding samples

${}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{pd}\pi^{-}$ purity estimation

- Challenge to separate Λd and ${}^{3}_{\Lambda}\mathrm{H}$ in invariant mass?
- χ^2_{NDF}: variable to estimate whether tracks intersect
  - Different χ^2_{NDF} distributions for Λd and ${}^{3}_{\Lambda}\mathrm{H}$
- Template fit method to estimate ${}^{3}_{\Lambda}\mathrm{H}$ purity statistically.
  - $\chi^2_{NDF\,Data} = p_0 \cdot (\chi^2_{NDF\,\Lambda d} + p_1 \cdot \chi^2_{NDF\,{}^{3}_{\Lambda}\mathrm{H}})$



Daughter tracks from different vertex



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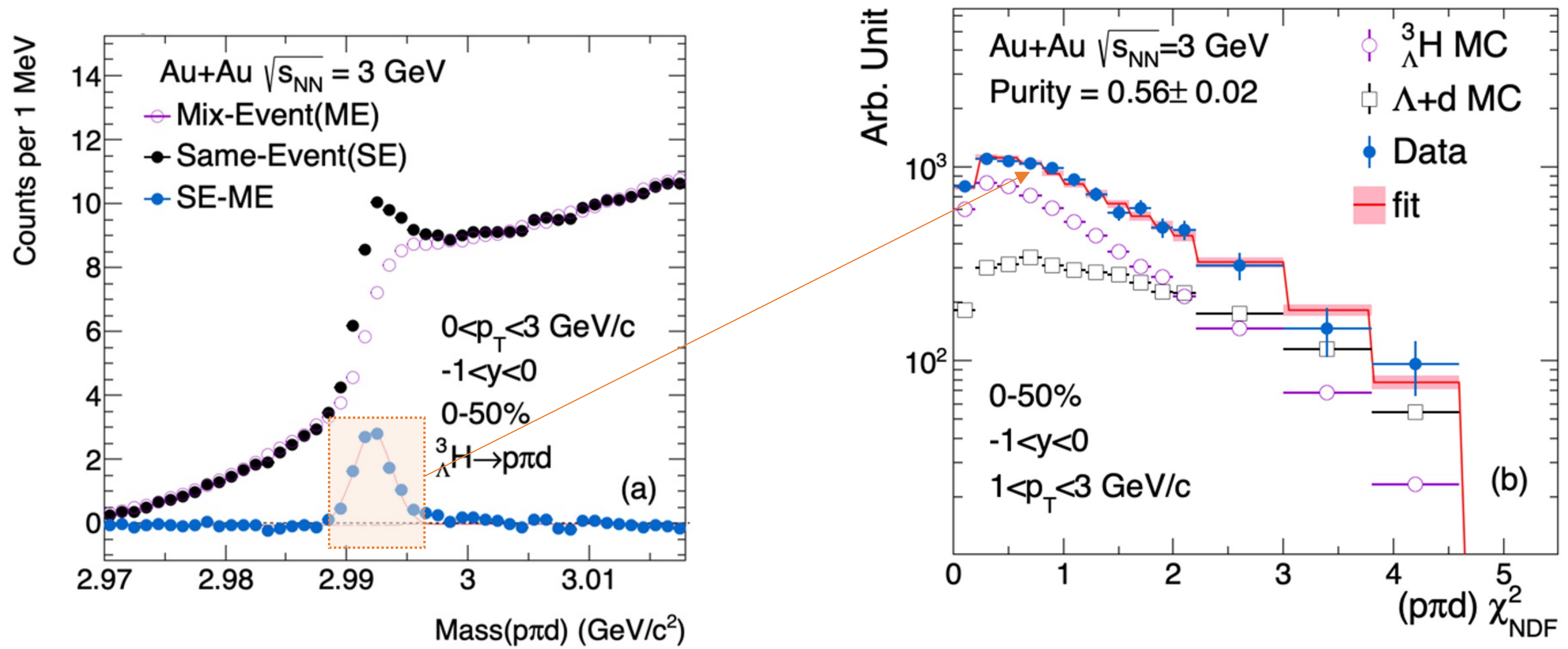


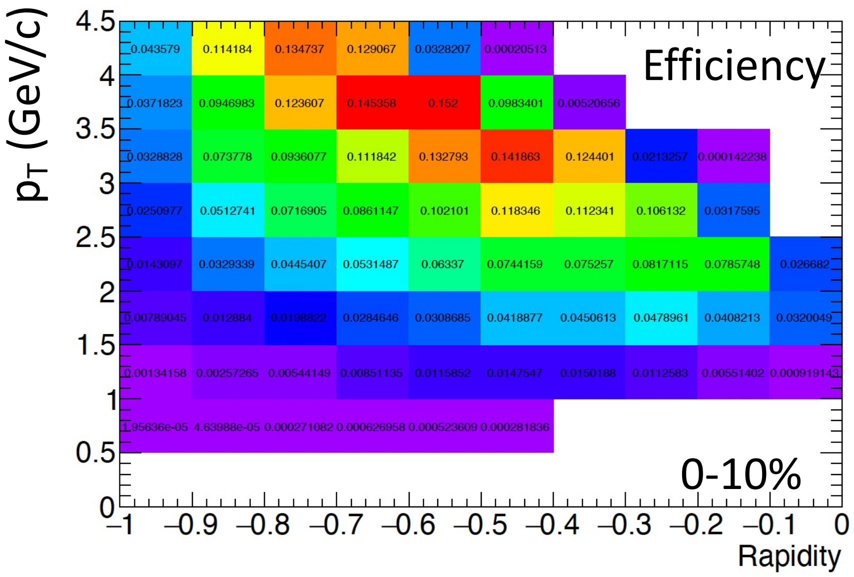
$^{3}_{\Lambda}\mathrm{H} \to \mathrm{pd}\pi^{-}$ efficiency and purity correction

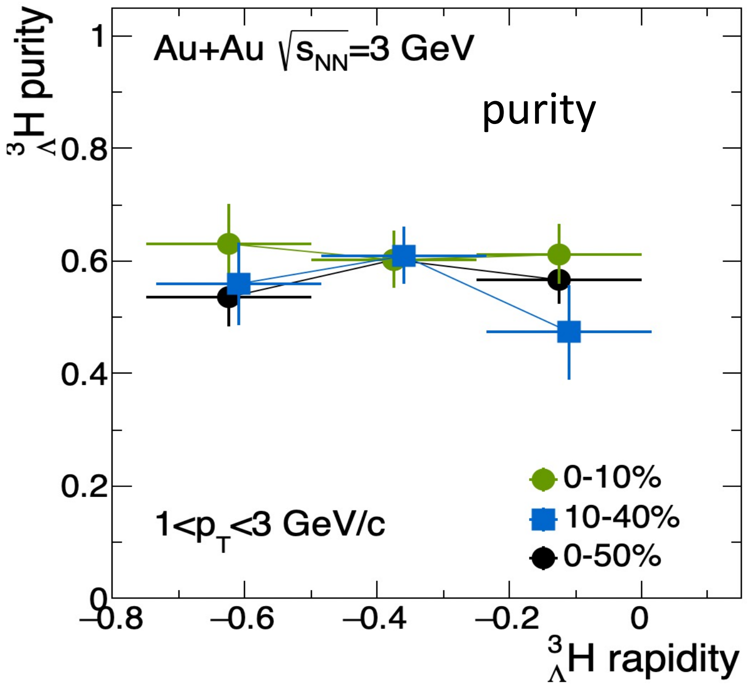
- Reconstruction efficiency
  - Weighted p_T and rapidity, lifetime

$$\epsilon_{\mathrm{reco}} = \frac{\text{Reconstructed H3L after topological cuts}}{\text{MC H3L}}$$

- Corrected yields of $^{3}_{\Lambda}\mathrm{H}$ via 3 body decay

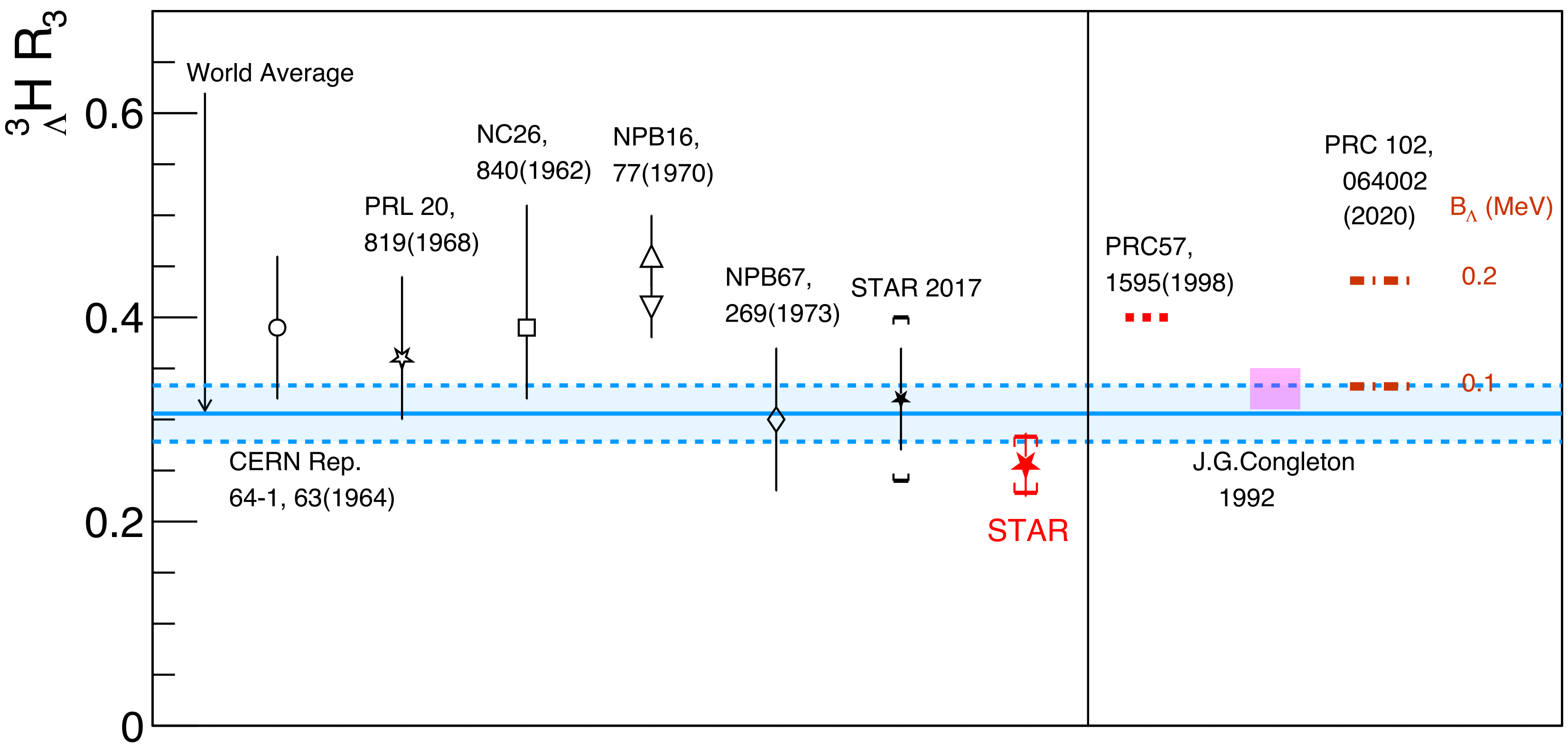
$$= \frac{\text{Raw counts} \times \text{purity}}{\epsilon_{\mathrm{reco}} \times \epsilon_{\mathrm{PID}}}$$





- Efficiency also reflecting detector acceptance
  - 3-body channel has best acceptance at y~-0.5 in 3 GeV
- No obvious rapidity of H3L purity

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

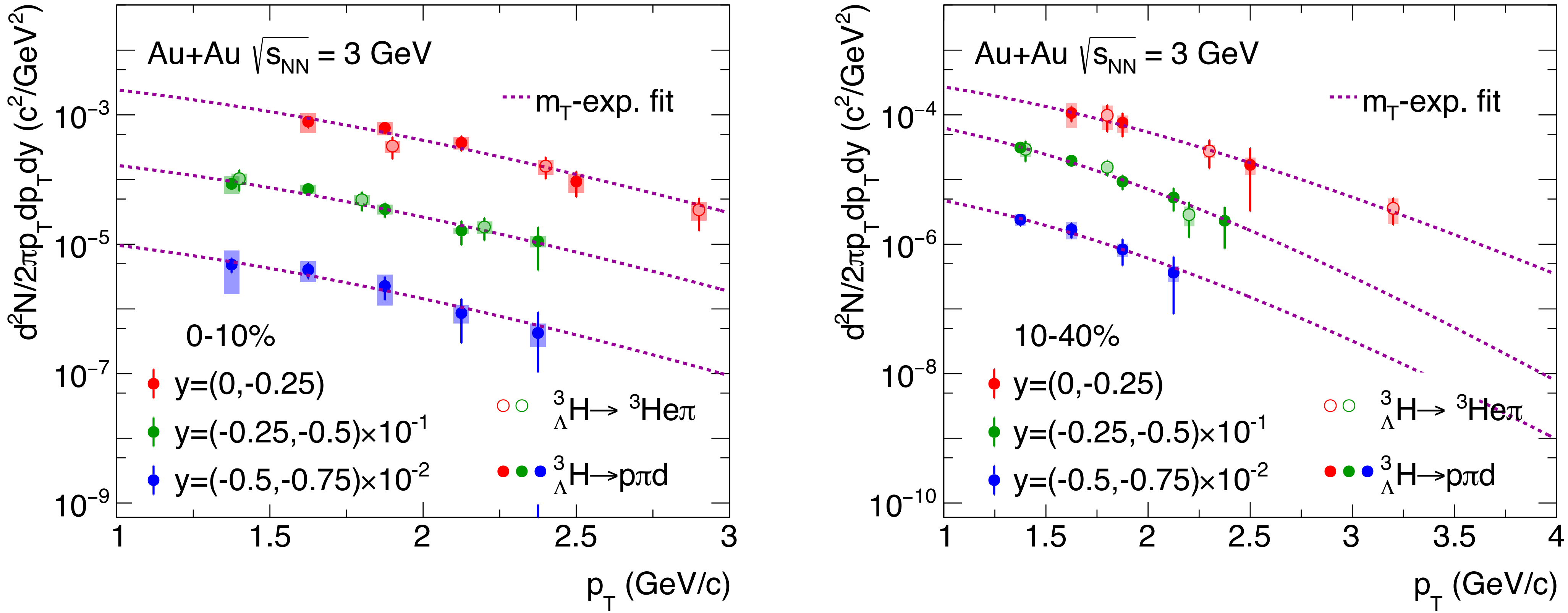


Improved precision on R_3.

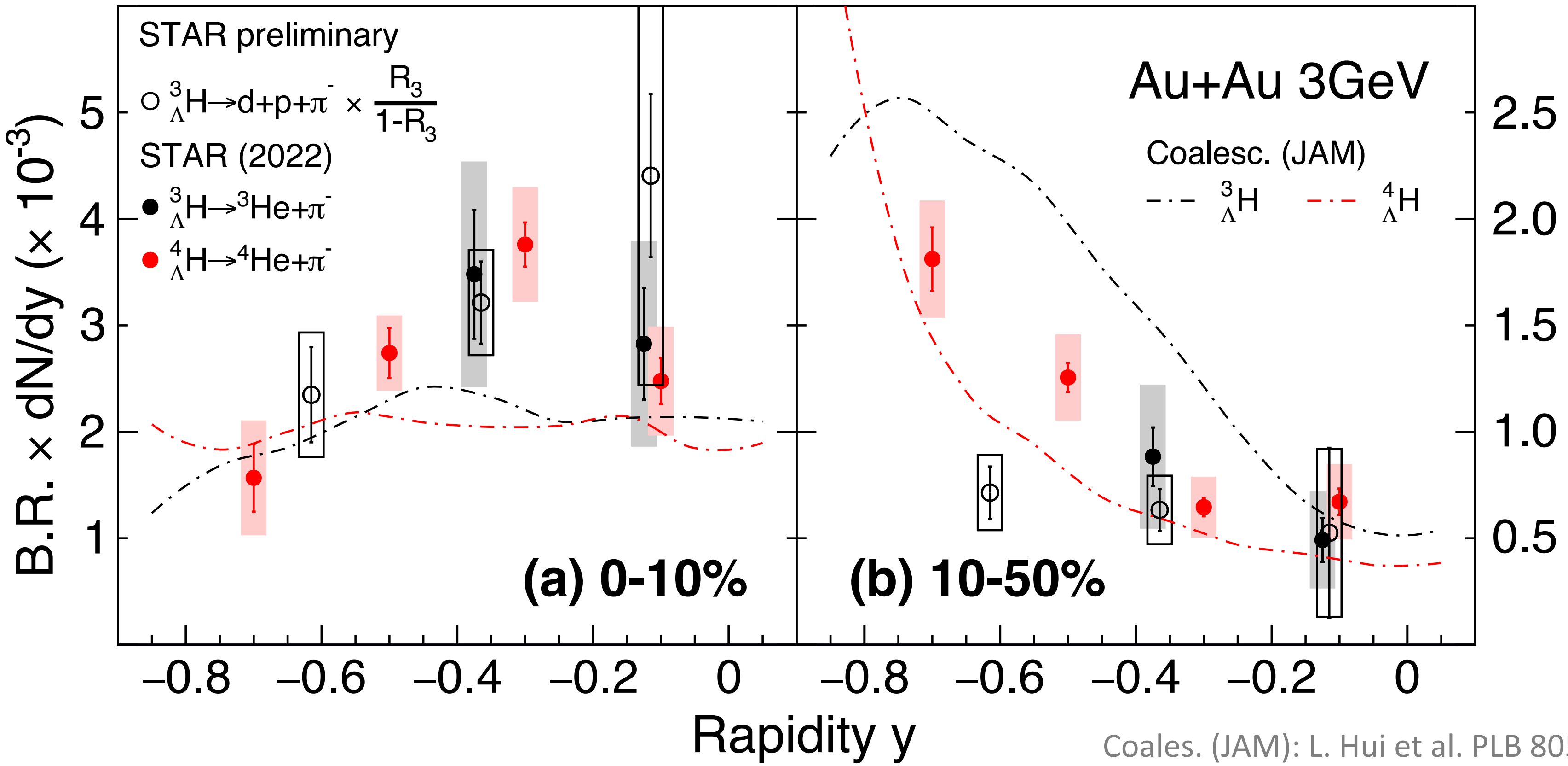
- Stronger constraints on absolute B.R. and hypertriton internal structure.
- Updated world average value favors model calculation with small ${}^{3}_{\Lambda}H$ binding energy.

H3L->dpπ spectra

- Combine two decay channel to extend kinematic coverage.
  - In FXT mode, H3L->dpπ has better coverage in backward rapidity while ${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He}\pi^{-}$ performaces better in mid rapidity.



dN/dy as a function of rapidity

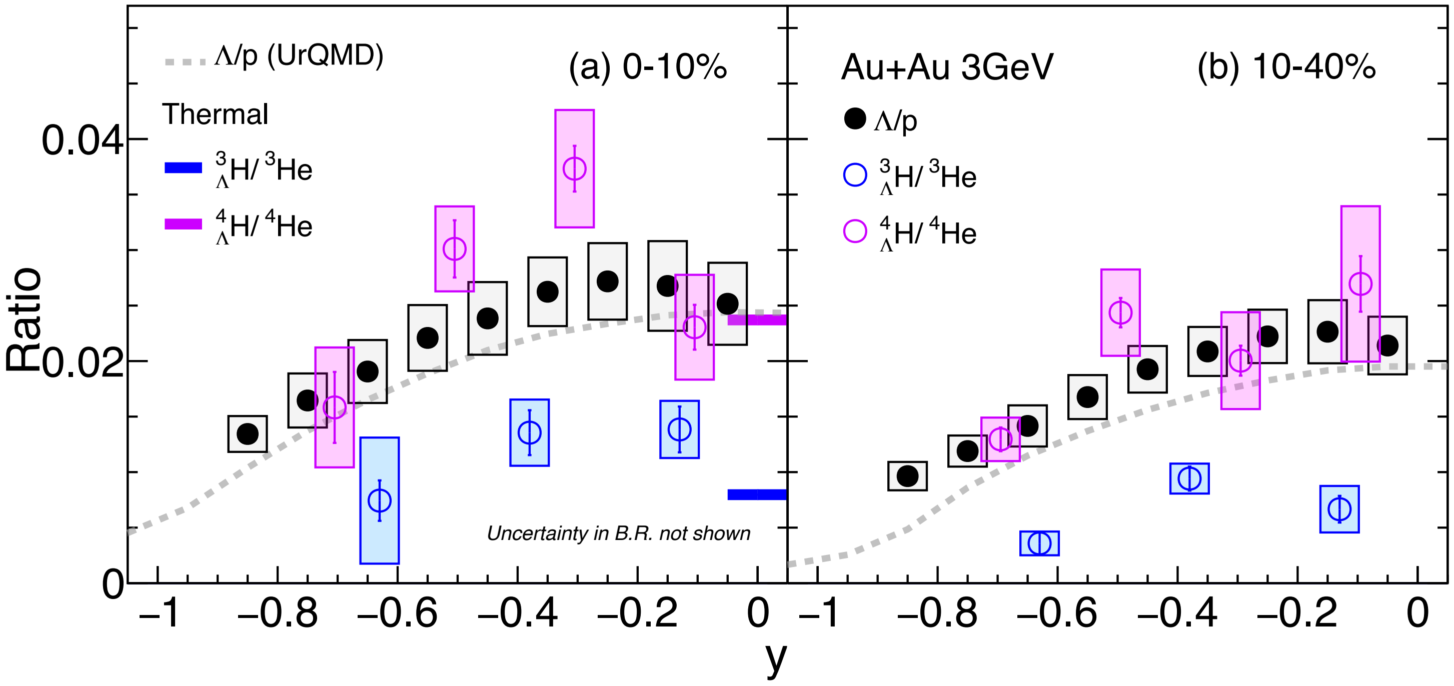


Coales. (JAM): L. Hui et al. PLB 805, 135452 (2020)

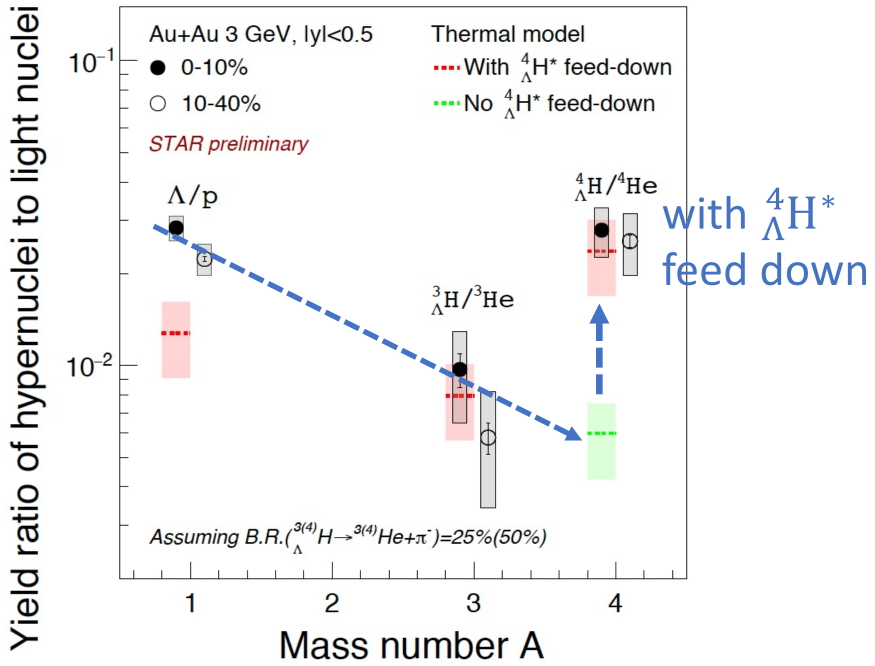
$^{3}_{\Lambda}H \rightarrow {}^{3}He\pi$, $^{4}_{\Lambda}H$ data: STAR, PRL 128, 202301 (2022)

- Coalescence calculation with tuned parameters are able to describe the trend of $^{4}_{\Lambda}H$ yields versus rapidity but fail for $^{3}_{\Lambda}H$ at 10-50% centrality.

Hyper to light nuclei yields ratio

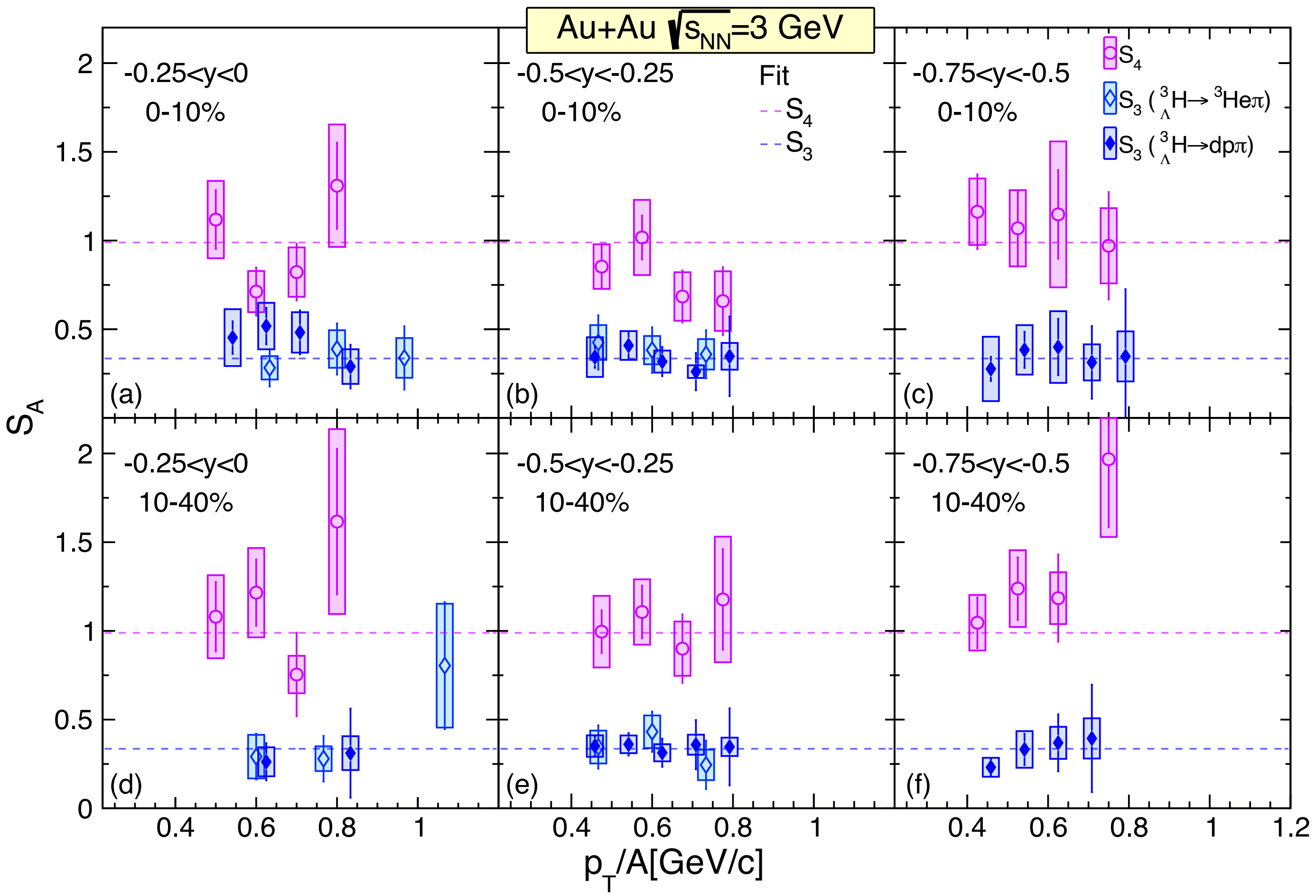


$^4_\Lambda H^*(J^+ = 1) \rightarrow {}^4_\Lambda H(J^+ = 0) + \gamma$



- Suppression of ${}^3_\Lambda H/{}^3He$ yield ratios compared to that of Λ/p is observed at both 0-10% and 10-40% centrality in Au+Au collisions at 3 GeV.
- The ${}^4_\Lambda H/{}^4He$ yield ratios are comparable to that of Λ/p, which is possibly due to feed-down from exited state enhances ${}^4_\Lambda H$ production.

$S_{3,4}$ as a function of p_T

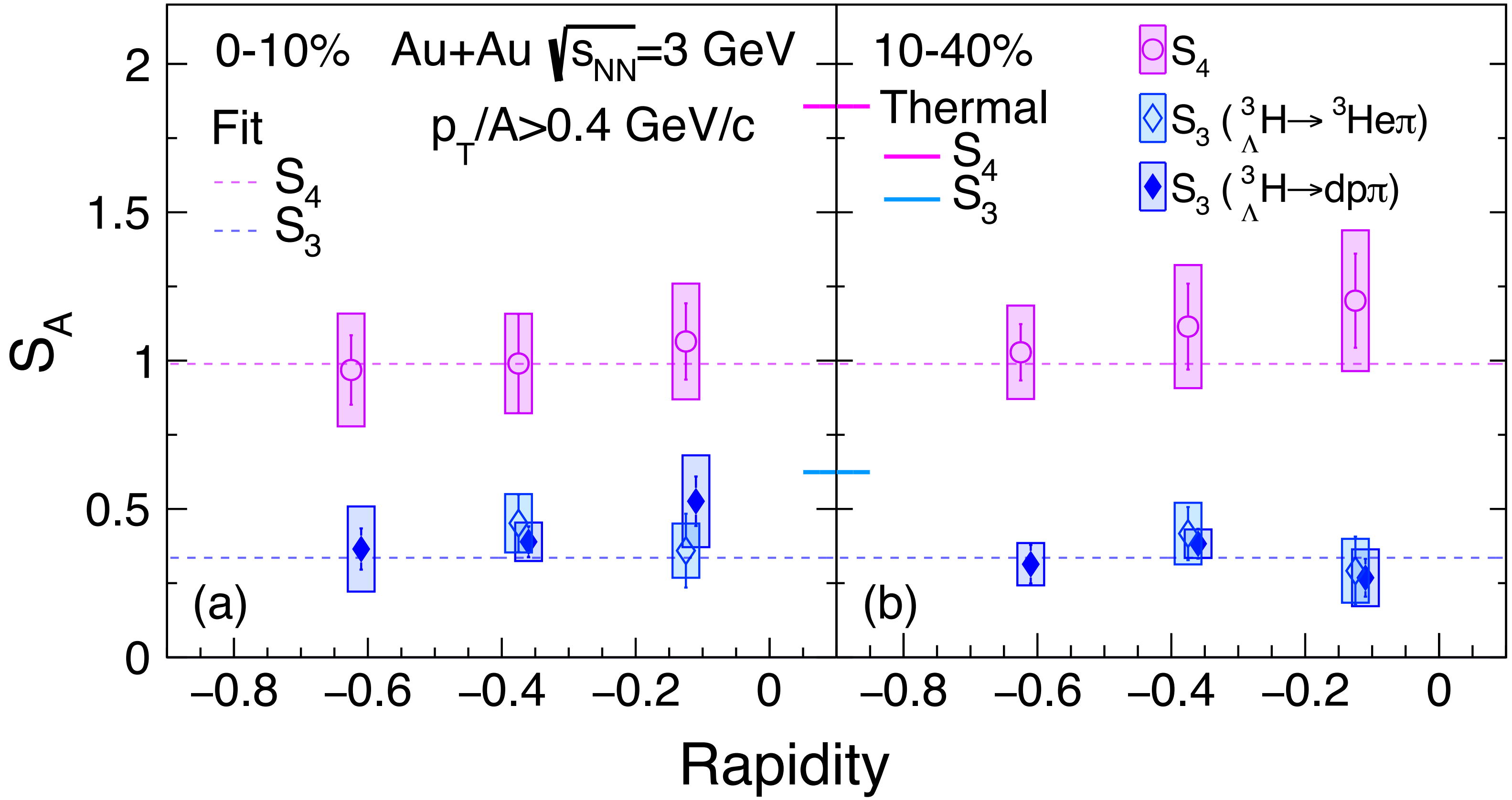


Strangeness population factor

$$S_A = \frac{{}^{A}_{\Lambda}\mathrm{H}}{{}^{A}\mathrm{He}\times\frac{\Lambda}{p}}$$

- No obvious kinematic and centrality dependence of S_A is observed at 3 GeV.
- Evidence that coalescence parameter B_A of light and hyper nuclei follow similar tendency versus p_T, rapidity and centrality.

$S_{3,4}$ versus rapidity at $p_T/A>0.4$ GeV/c



- No obvious rapidity and centrality dependence of S_A ($p_T/A>0.4$ GeV/c) is observed at 3 GeV.

Conclusion

- Production of hypertriton are measured via (both) 3-body decay (and 2-body) channel, and branching ratio R_3 are reported.

- Suppression of ${}^{3}_{\Lambda}\mathrm{H}/{}^{3}\mathrm{He}$ yield ratios compared to that of Λ/p is observed at both 0-10% and 10-40% centrality in Au+Au collisions at 3 GeV.

- The ${}^{4}_{\Lambda}\mathrm{H}/{}^{4}\mathrm{He}$ yield ratios are comparable to that of Λ/p, which is possibly due to feed-down from exited state enhances ${}^{4}_{\Lambda}\mathrm{H}$ production.

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