



中国科学院大学  
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# Measurements of ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$ Production in $\sqrt{s_{\text{NN}}} =$ 3-3.5 GeV Au+Au Collisions at RHIC

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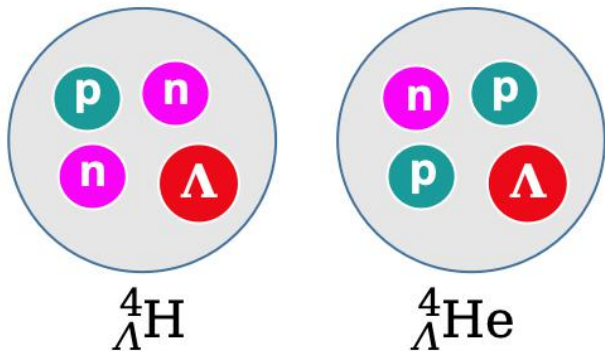
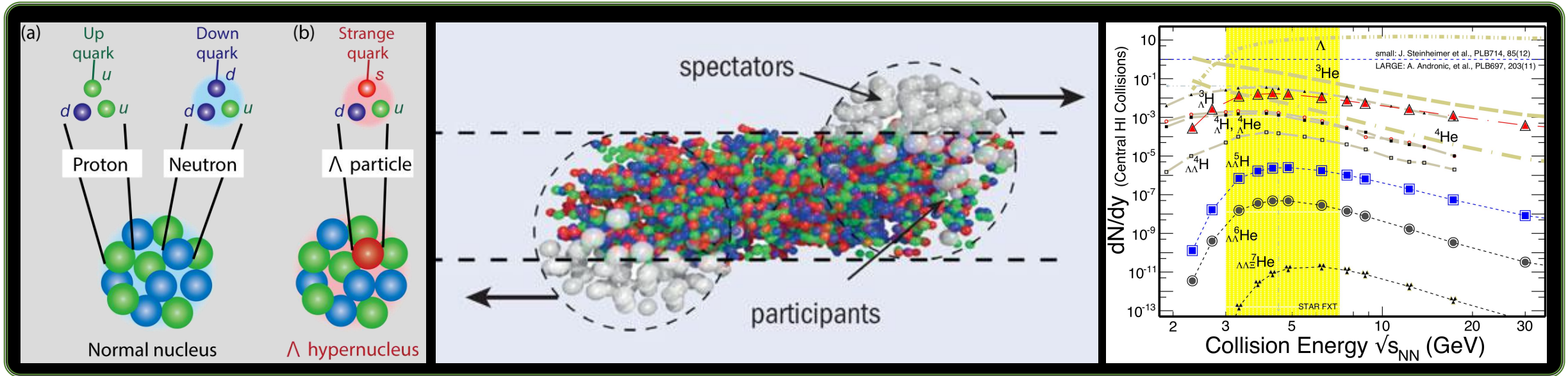


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# Outline

1. Motivation
2. STAR Detector and BES-II
3. Physics Results of Hypernuclei ( ${}^4_{\Lambda}\text{H}$  and  ${}^4_{\Lambda}\text{He}$ ) from 3-3.5 GeV  
Au+Au Collisions
  - 1) Yields
  - 2) Particle Ratio
  - 3) Transverse momentum distribution
4. Summary and Outlook

# Motivation

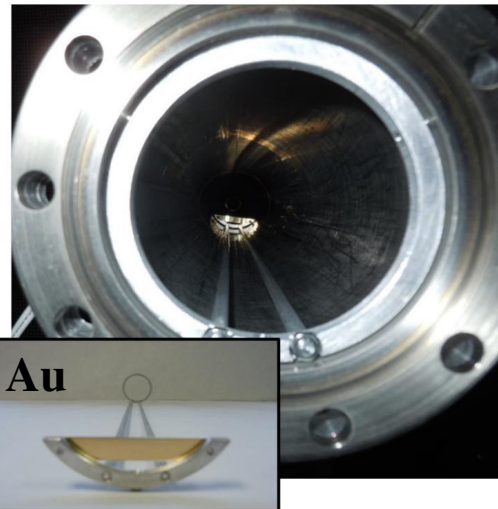
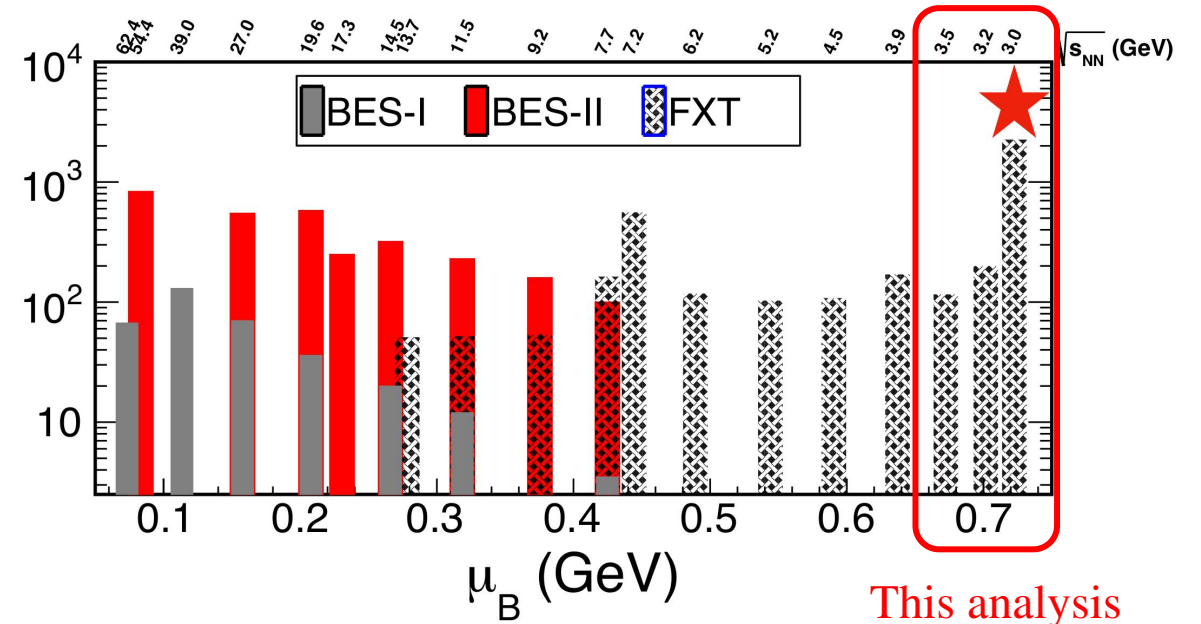
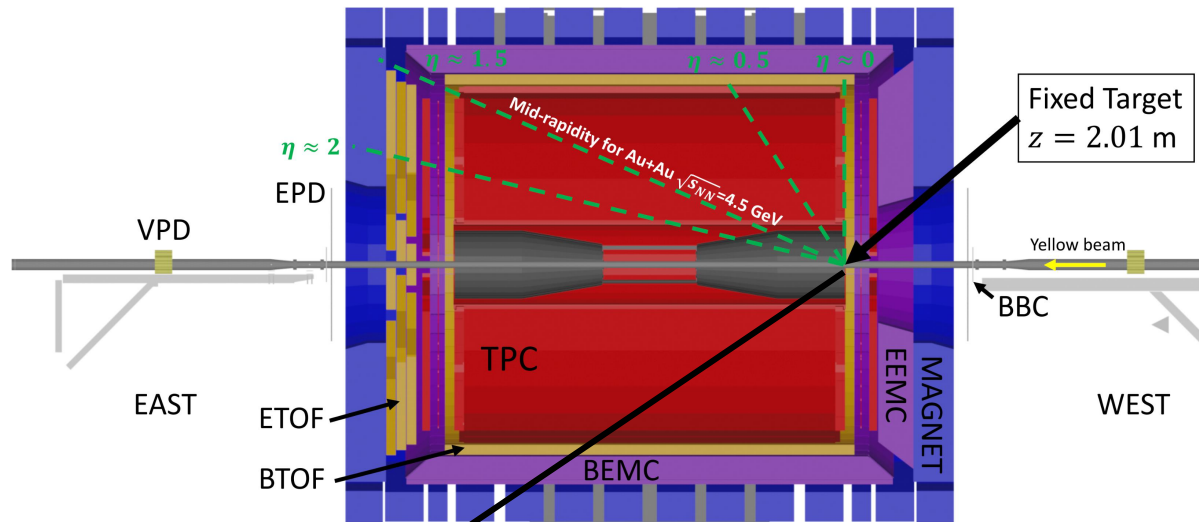


1. Hyper-nucleus provides opportunity for studying hyperon-nucleon (YN) interactions. Important for understanding inner structure of compact stars
2. Measurements of  ${}^4_{\Lambda}\text{H}$  and  ${}^4_{\Lambda}\text{He}$  in heavy-ion collisions
  - 1)  $A=4$  mirror hypernuclei ( ${}^4_{\Lambda}\text{H}(0^+)$  and  ${}^4_{\Lambda}\text{He}(0^+)$ )
  - 2) Existence of the spin-1 excited states ( ${}^4_{\Lambda}\text{H}(1^+)$  and  ${}^4_{\Lambda}\text{He}(1^+)$ )
  - 3) Provide new insight on hypernuclei production mechanisms and EoS

[1] A. Andronic et al., Phys. Lett. **B697**, 203(2011)

[2] J. Steinheimer et al., Phys. Lett. **B714**, 85(2012)

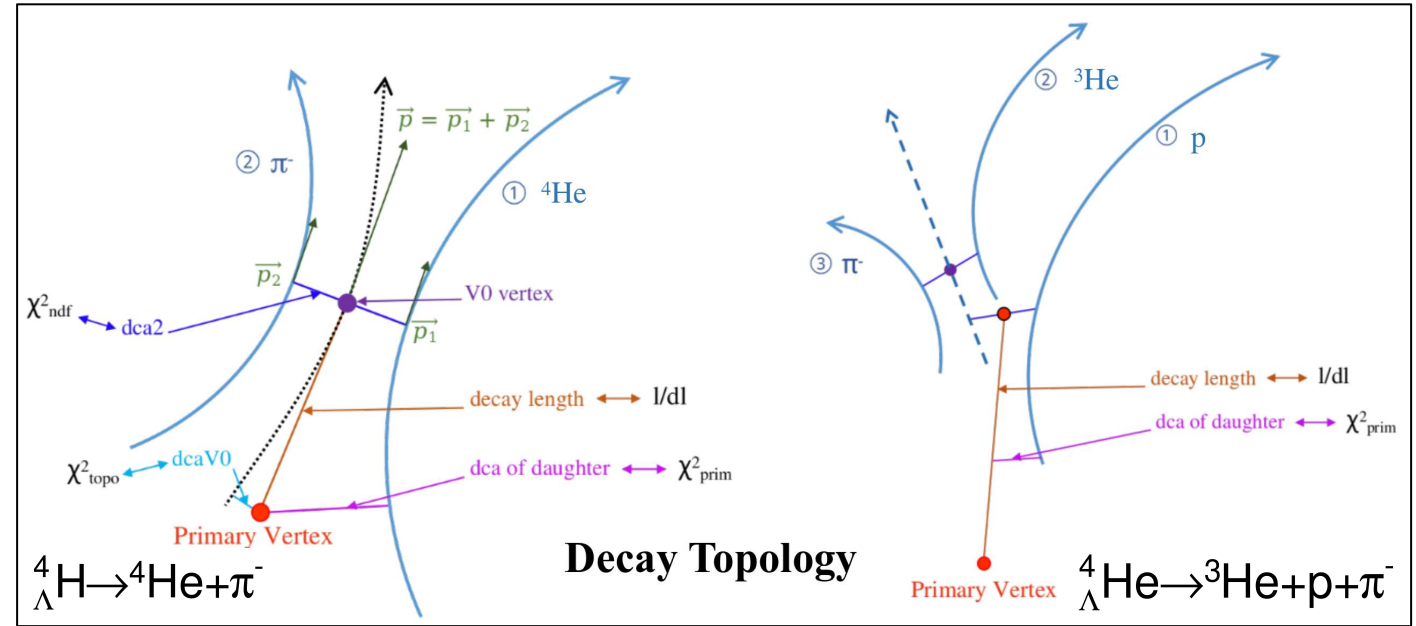
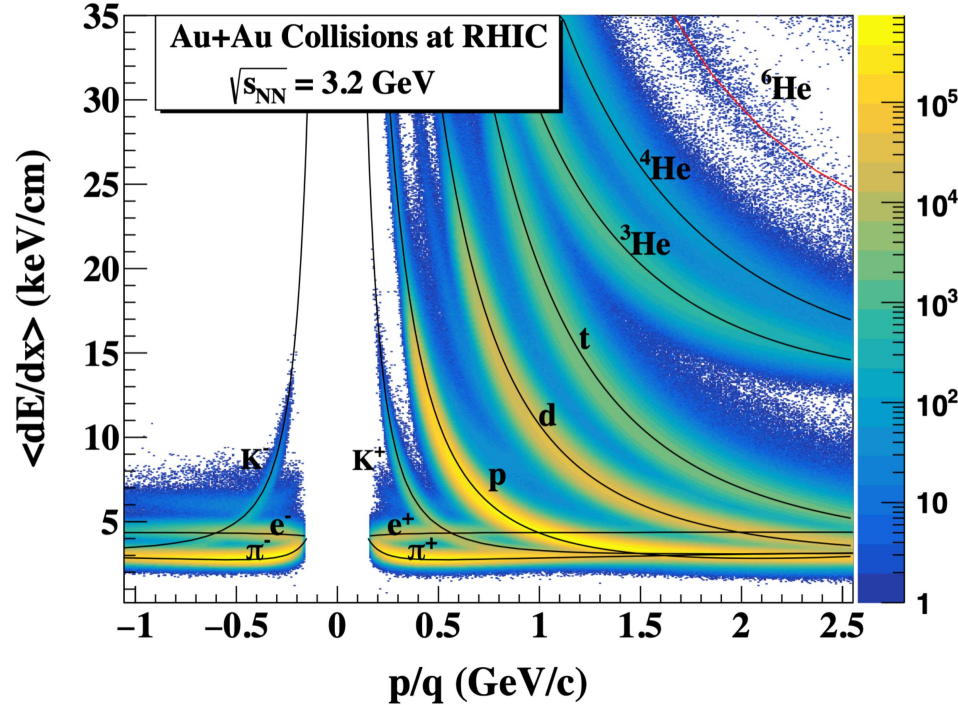
# STAR Detector and BES-II



- BES-II (2018-2021)

- High statistics Au+Au collisions  $\sqrt{s_{NN}} = 3-54.4$  GeV (10  $\times$  statistics compare to BES-I)
- Fixed target (FXT) collisions extend energy reach down to  $\sqrt{s_{NN}} = 3$  GeV
- Detector upgrades: iTPC, eTOF, EPD

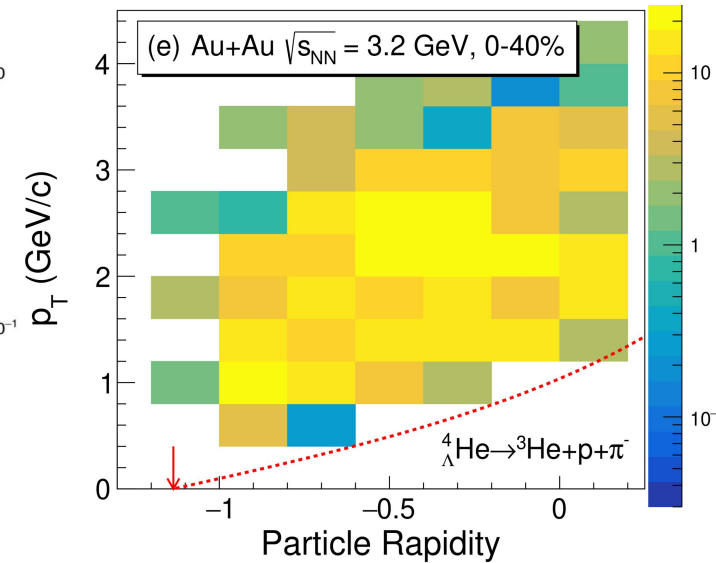
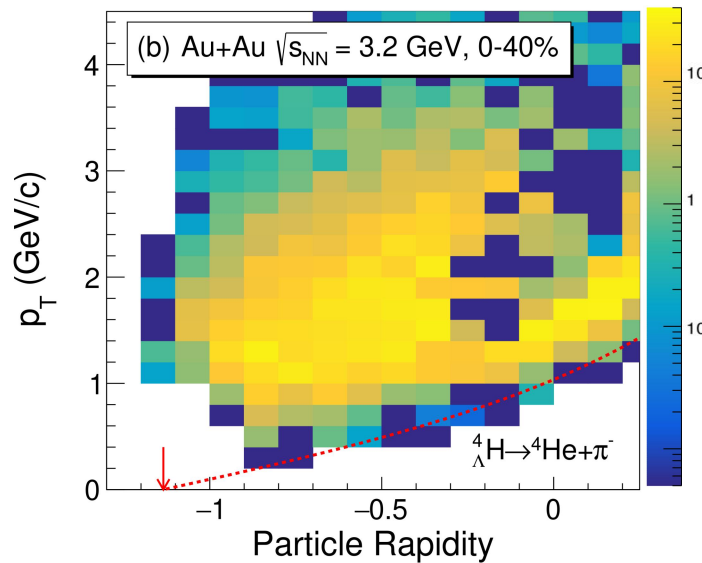
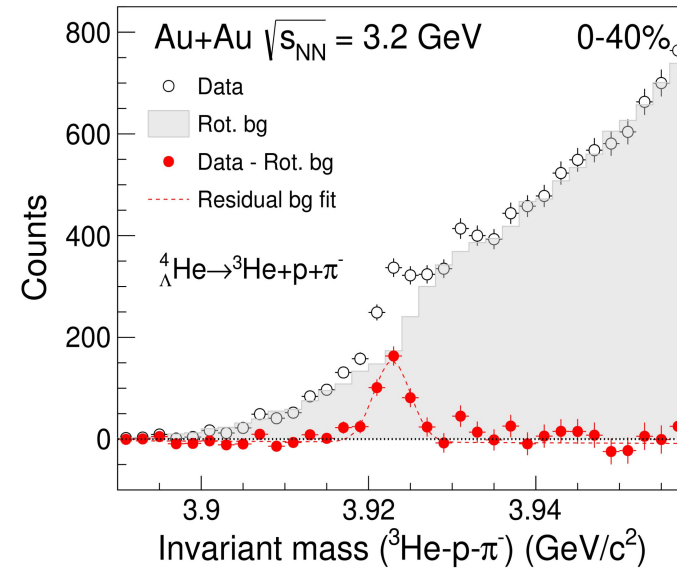
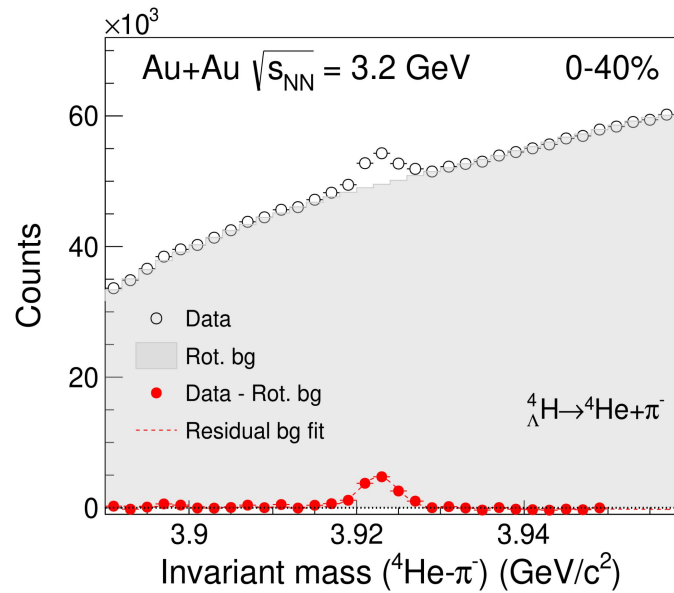
# Particle Identification and Topological Selection



1. Good particle identification capability based on TPC and TOF;
2. The hyper-nuclei reconstruction with KFParticle package based on the Kalman filter method providing a full set of the particle parameters together with their uncertainties;
3. Decay topology tremendously helped on particle identification and background suppression

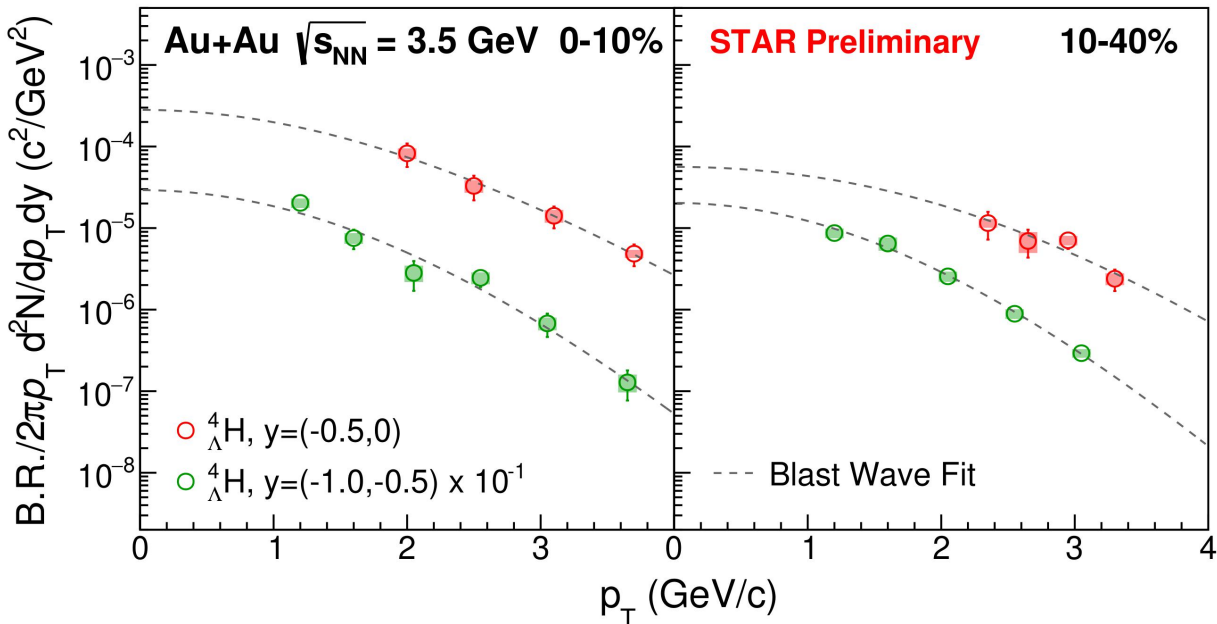
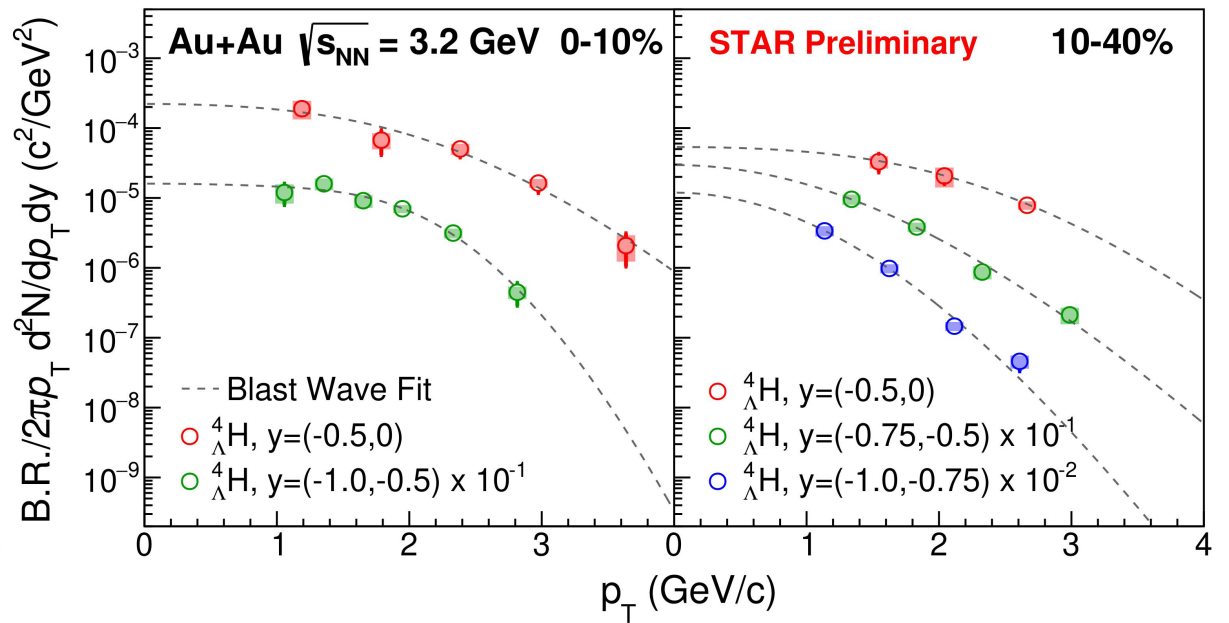
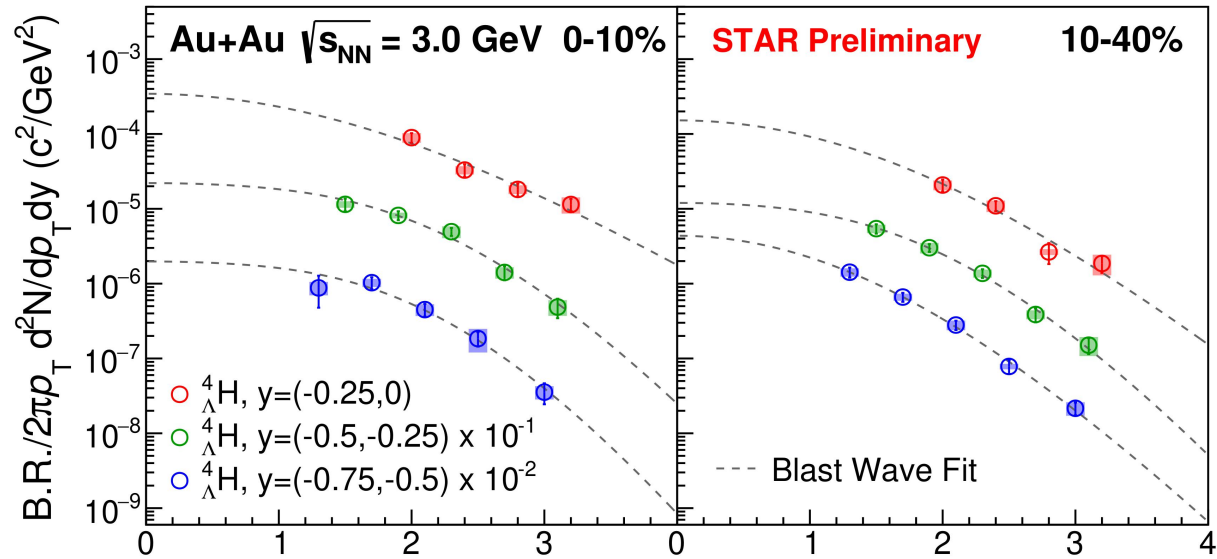
XY. Ju et al. Nucl.Sci.Tech. 34 (2023) 10, 158

# Hyper-Nuclei Reconstruction and Acceptance



- KFParticle package used for  ${}^4_{\Lambda}\text{H}$  and  ${}^4_{\Lambda}\text{He}$  reconstructions;
- Uncorrelated combinatorial backgrounds: Rotation method (rotate  ${}^4\text{He}$  for  ${}^4_{\Lambda}\text{H}$  and  ${}^3\text{He}$  for  ${}^4_{\Lambda}\text{He}$ );
- Particle rapidity coverage from beam rapidity to mid-rapidity

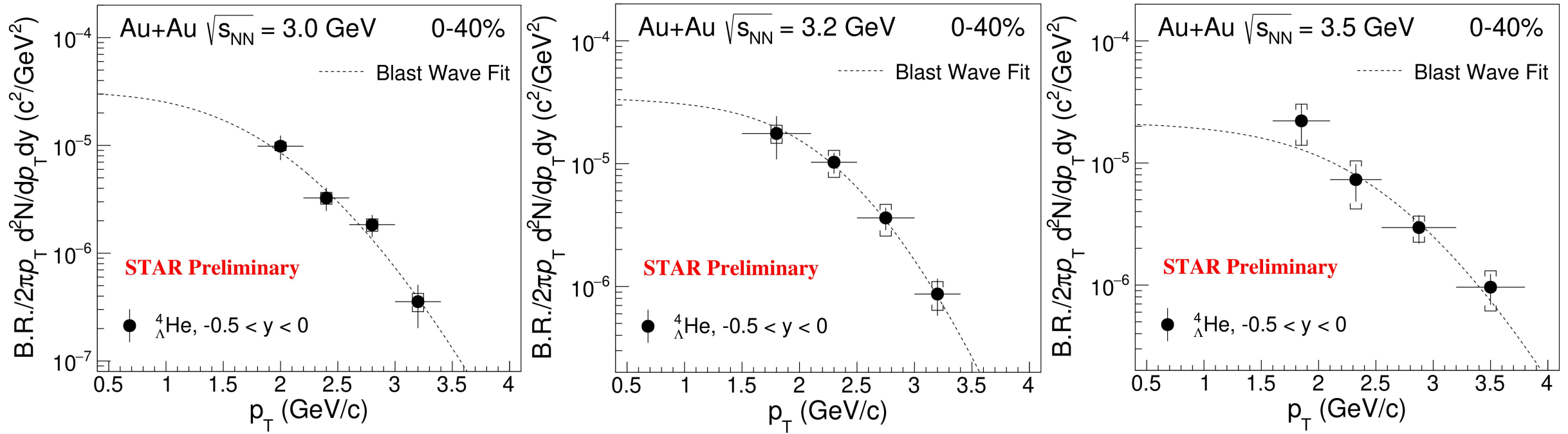
# ${}^4_{\Lambda}\text{H}$ $p_T$ Spectra



- ${}^4_{\Lambda}\text{H}$  spectra in 0-10% and 10-40% at 3.0, 3.2 and 3.5 GeV;
- Blast Wave function used for extrapolation to  $p_T = 0$  GeV;

$$\frac{1}{2\pi p_T} \frac{d^2N}{dp_T dy} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh \rho}{T}\right) K_1\left(\frac{m_T \cosh \rho}{T}\right)$$

# ${}^4_{\Lambda}\text{He}$ $p_T$ Spectra

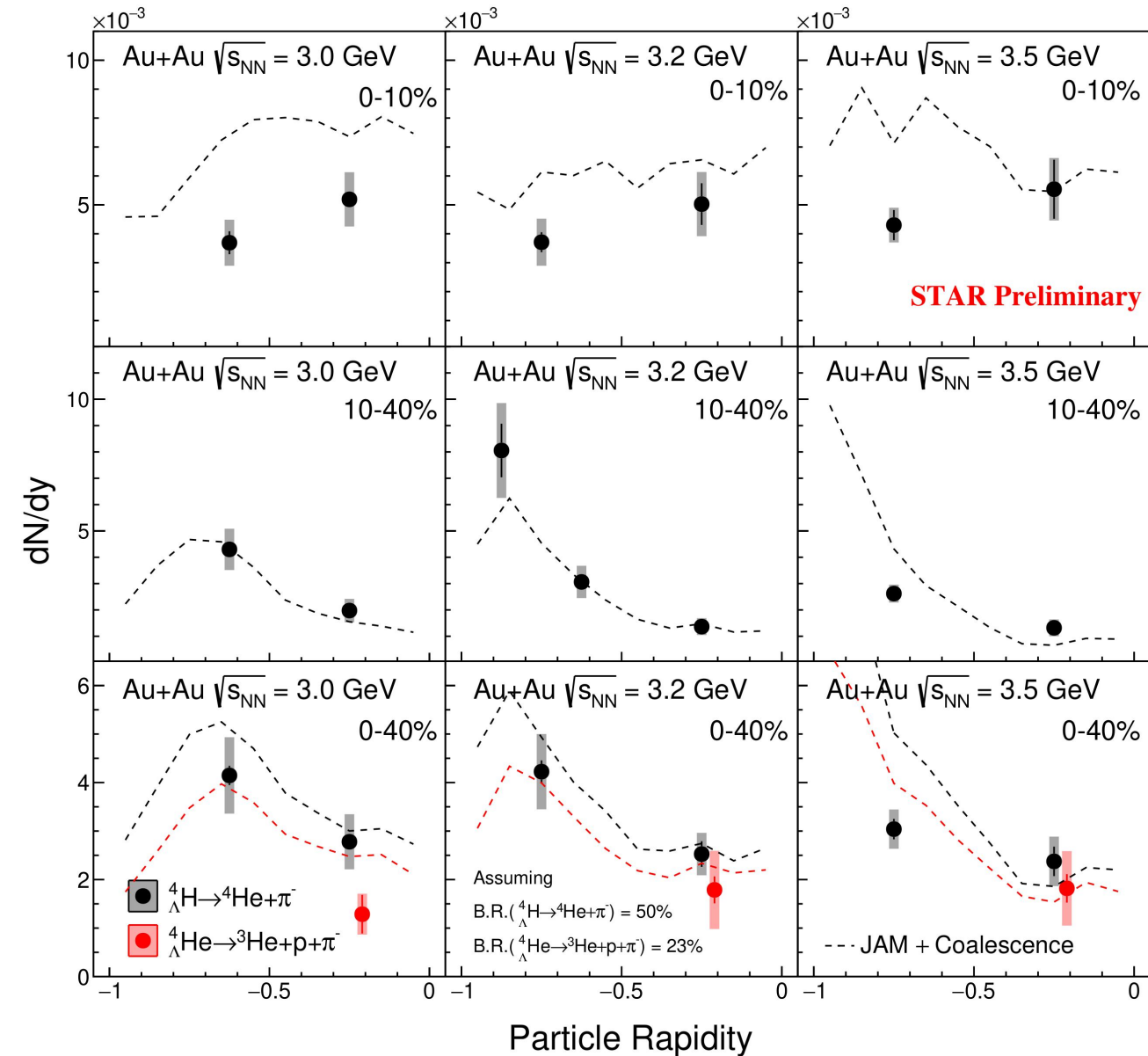


- ${}^4_{\Lambda}\text{He}$  spectra in 0-40% centrality at 3.0, 3.2 and 3.5 GeV;
- Extrapolate to  $p_T = 0$  GeV to obtain  $dN/dy$  (Blast Wave function);

$$\frac{1}{2\pi p_T} \frac{d^2N}{dp_T dy} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh \rho}{T}\right) K_1\left(\frac{m_T \cosh \rho}{T}\right)$$



# ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$ $dN/dy$



## Data:

- Different trends in the  ${}^4_{\Lambda}\text{H}$  rapidity distribution in central (0-10%) and mid-central (10-40%) collisions;
  - Likely related to the change in the collision geometry, such as spectators playing a larger role in non-central collisions;
- The  ${}^4_{\Lambda}\text{He}$  yields at the mid-rapidity are comparable to that of  ${}^4_{\Lambda}\text{H}$  in 0-40%;

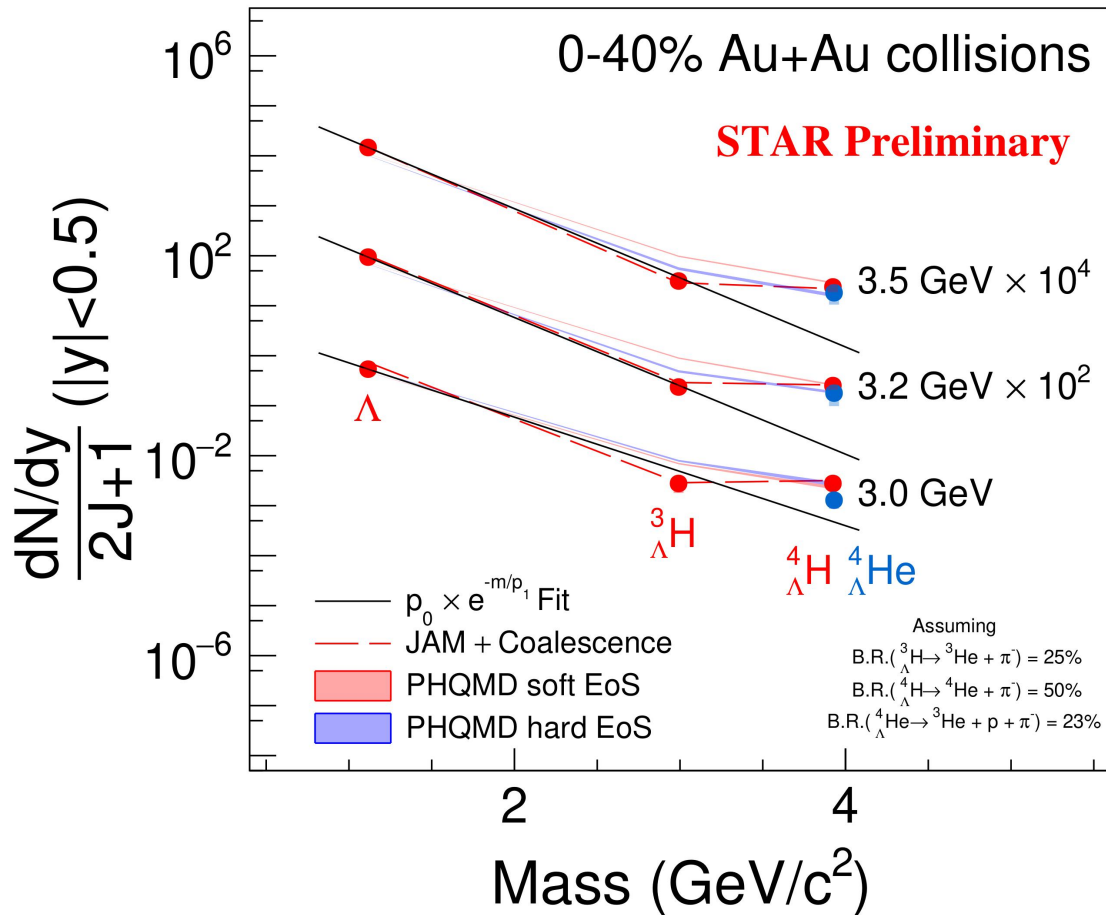
## JAM + Coalescence:

- Reproduce the rapidity dependence of  $dN/dy$  for  ${}^4_{\Lambda}\text{H}$  qualitatively;

Yasushi Nara et al, PhysRevC.106.044902 (2022)

J. Steinheimer et al, Phys.Lett.B. 714. 85-91 (2012)

# ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$ $|y| < 0.5$ Yields/( $2J+1$ ) vs Energy



## Data:

- Yields of  ${}^4_{\Lambda}\text{H}$  and  ${}^4_{\Lambda}\text{He}$  are comparable at  $\sqrt{s_{\text{NN}}} = 3\text{-}3.5$  GeV within uncertainties;
- Systematic deviation from exponential dependence of yields/( $2J+1$ ) vs mass;
  - Possible explanation: feed-down from excited  ${}^4_{\Lambda}\text{H}^*(1^+)$  and  ${}^4_{\Lambda}\text{He}^*(1^+)$ ;

## JAM+Coalescence:

- $\Lambda$  is weighted to the data;
- Different coalescence parameters for  ${}^3_{\Lambda}\text{H}$  and  ${}^4_{\Lambda}\text{H}({}^4_{\Lambda}\text{He})$  are needed to describe the data ( $(\Delta R, \Delta P)$ ): (4.8 fm, 0.24 GeV/c) for  ${}^3_{\Lambda}\text{H}$  and (4.8 fm, 0.38 GeV/c) for  ${}^4_{\Lambda}\text{H}({}^4_{\Lambda}\text{He})$ ;
  - Could be reflective of the tighter binding of  ${}^4_{\Lambda}\text{H}$  and  ${}^4_{\Lambda}\text{He}$ ;

## PHQMD:

- Describes  $\Lambda$ ,  ${}^4_{\Lambda}\text{H}$  and  ${}^4_{\Lambda}\text{He}$ , but overestimates  ${}^3_{\Lambda}\text{H}$ ;

Yasushi Nara et al, PhysRevC.106.044902 (2022)

J. Steinheimer et al, Phys.Lett.B. 714. 85-91 (2012)

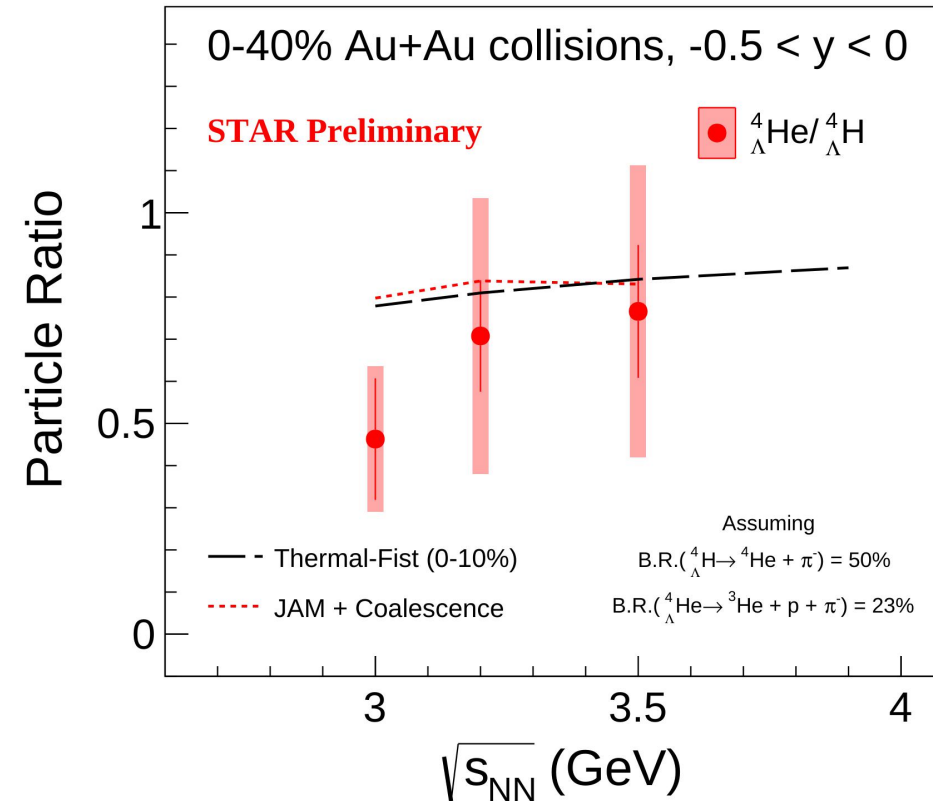
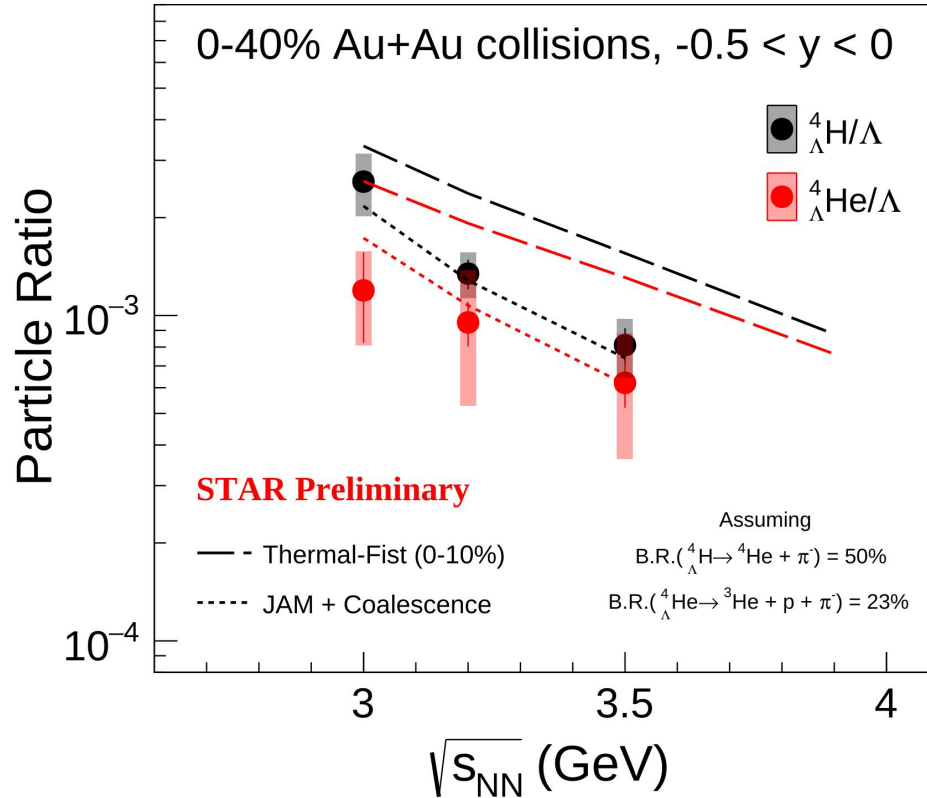
Susanne Gläsel et al, Phys. Rev. C 105, 014908 (2022)

# ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$ Yield Ratio

Yasushi Nara et al, PhysRevC.106.044902 (2022)

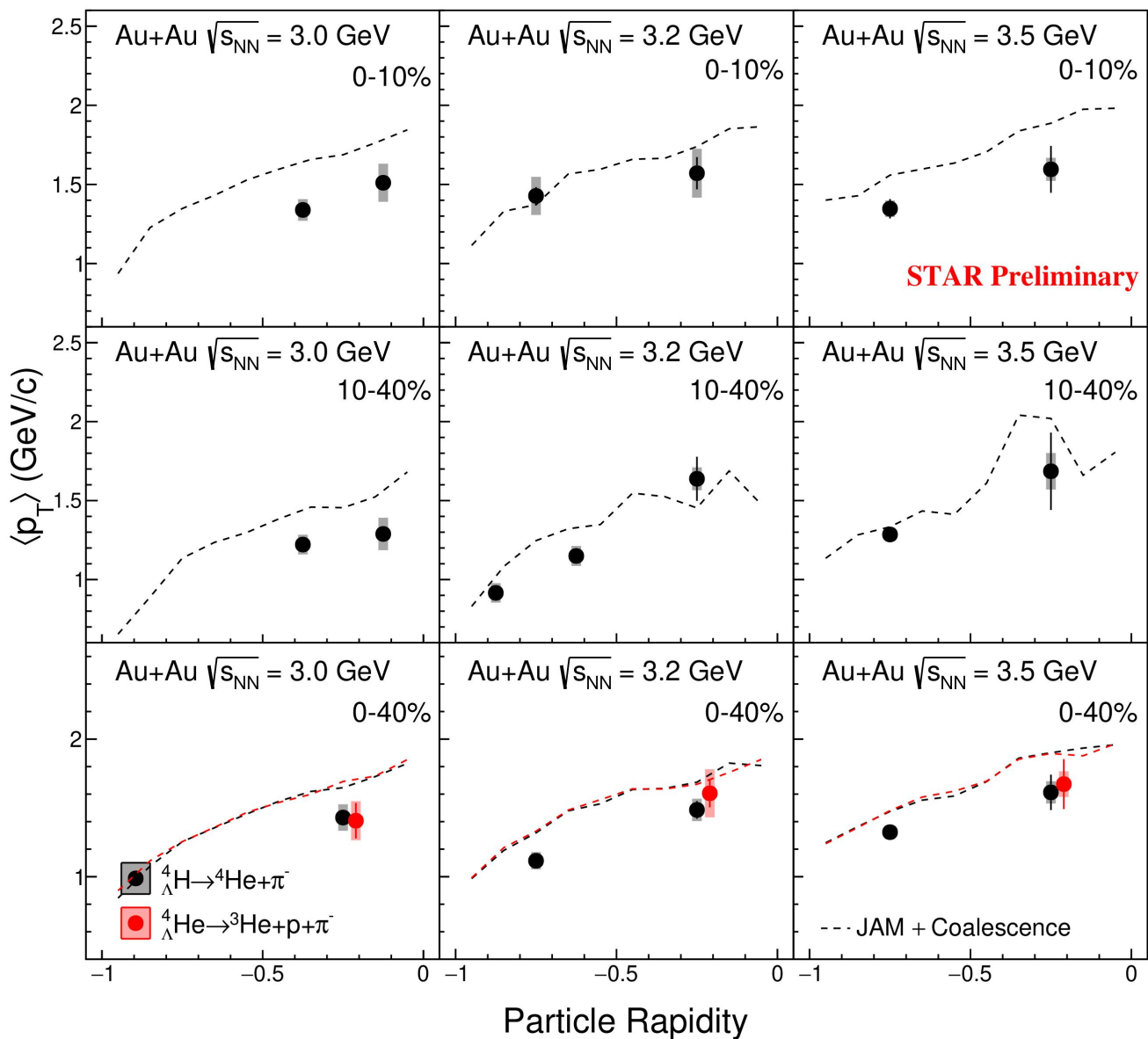
J. Steinheimer et al, Phys.Lett.B. 714. 85-91 (2012)

Thermal-Fist: T. Reichert et al, PRC 107 , 014912 (2023)



- The ratio of  ${}^4_{\Lambda}\text{H}/\Lambda$  and  ${}^4_{\Lambda}\text{He}/\Lambda$  vs energy have similar trend from 3.0 GeV to 3.5 GeV
  - Well described with JAM + Coalescence calculations, overestimated by Thermal-Fist;
- The ratio of  ${}^4_{\Lambda}\text{He}/{}^4_{\Lambda}\text{H}$  is consistent with thermal predictions, and JAM+coalescence calculations;

# Mean Transverse Momentum $\langle p_T \rangle$



## Data:

- The  $\langle p_T \rangle$  of  ${}^4_{\Lambda}\text{H}$  shows a monotonically decreasing trend from middle to target rapidity;
- The  $\langle p_T \rangle$  of  ${}^4_{\Lambda}\text{He}$  is similar to  ${}^4_{\Lambda}\text{H}$ ;

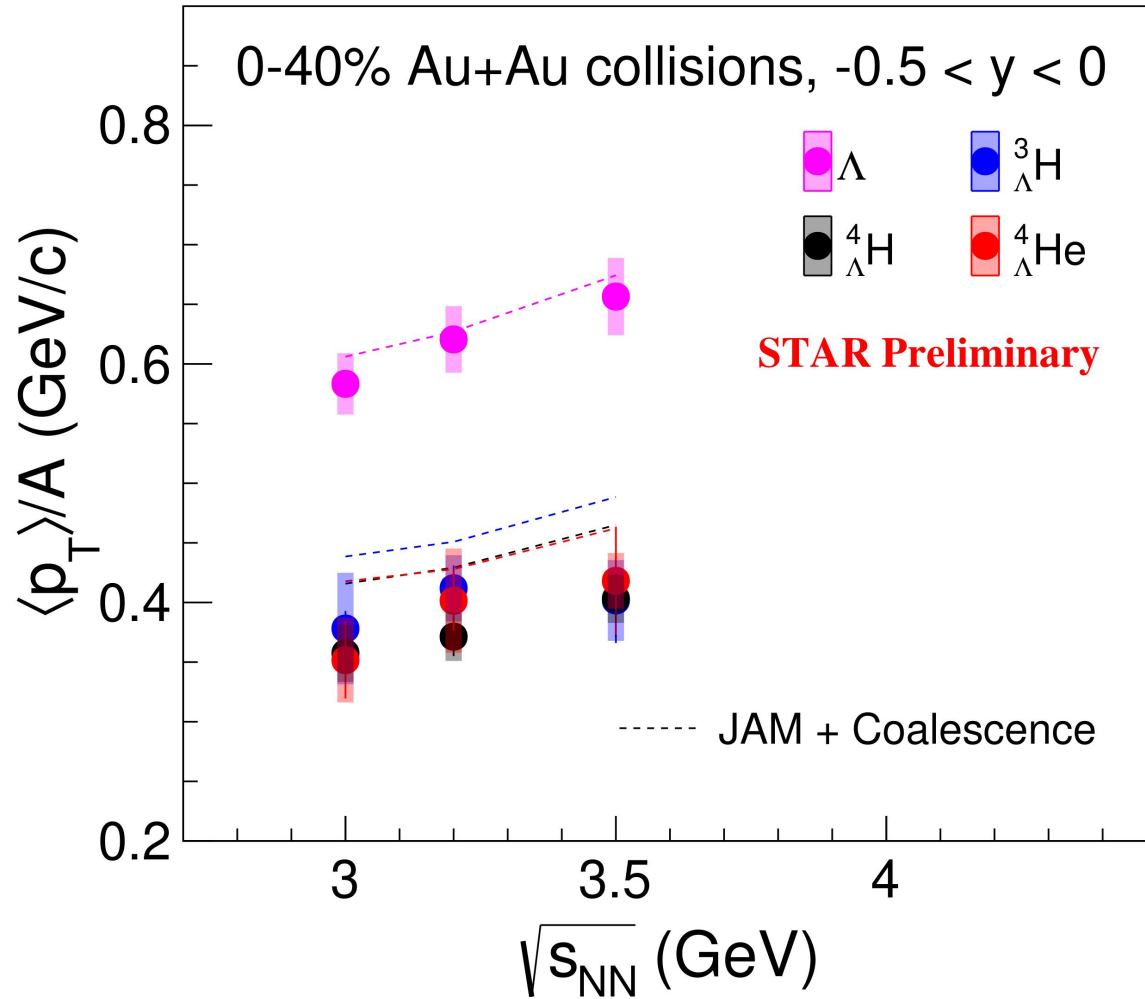
## JAM+Coalescence:

- Could describe the rapidity dependence of  $\langle p_T \rangle$  for  ${}^4_{\Lambda}\text{H}$  and  ${}^4_{\Lambda}\text{He}$  qualitatively;

Yasushi Nara et al, PhysRevC.106.044902 (2022)

J. Steinheimer et al, Phys.Lett.B. 714. 85-91 (2012)

# $\langle p_T \rangle / A$ vs Energy



## Data:

- From 3.0 GeV to 3.5 GeV, hint of increasing trend in  $\langle p_T \rangle / A$  vs energy for  $\Lambda$ ;
- The  $\langle p_T \rangle / A$  of  ${}^4_{\Lambda}\text{He}$ ,  ${}^4_{\Lambda}\text{H}$  and  ${}^3_{\Lambda}\text{H}$  are similar;
  - Follow the mass hierarchy;

## JAM+Coalescence:

- Qualitatively reproduces the energy dependence;
- Overestimates  $\langle p_T \rangle$  of  ${}^3_{\Lambda}\text{H}$ ;

10.1103/PhysRevC.105.014911 (2022)

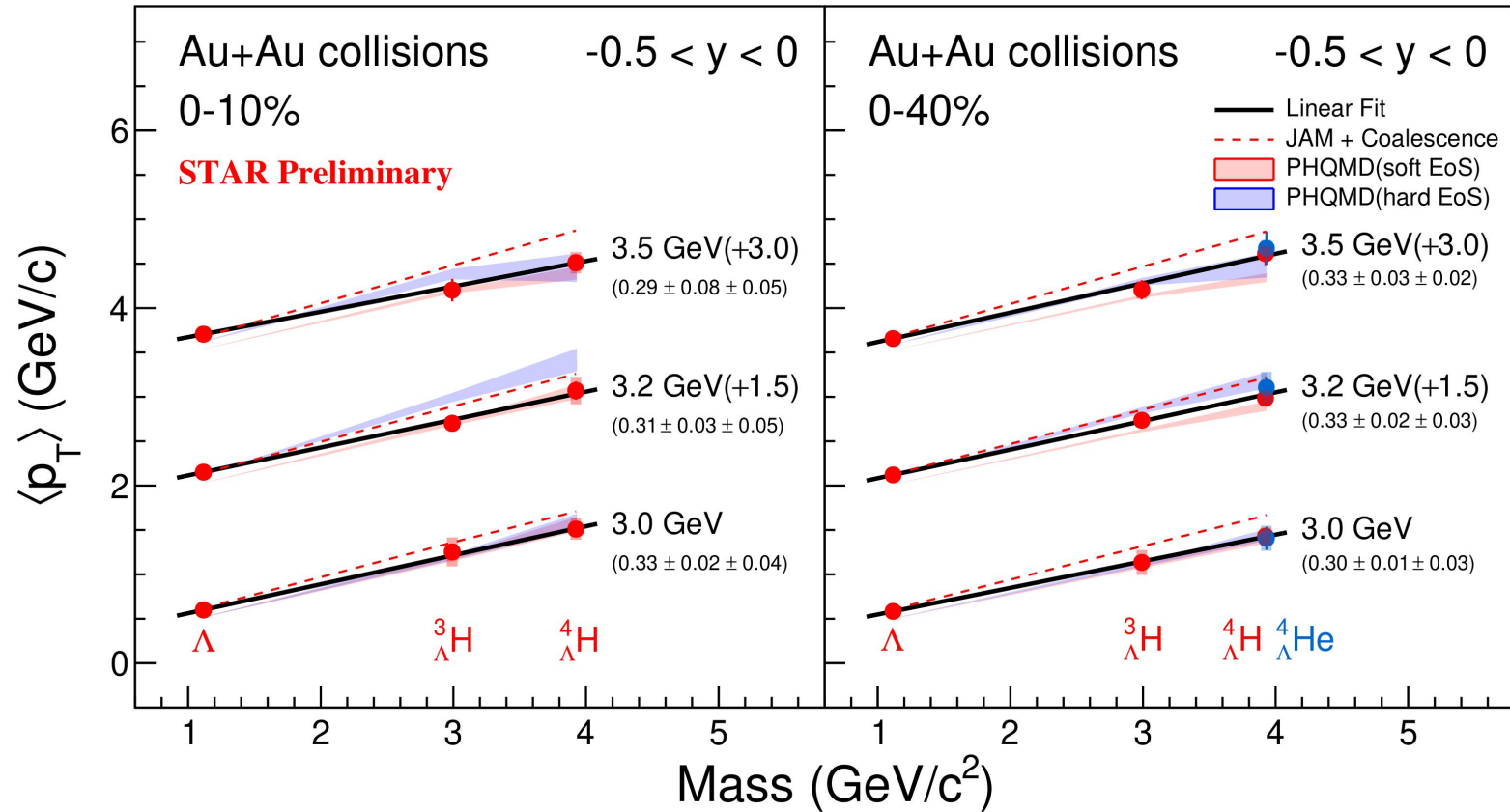
10.1016/j.physletb.2012.06.069 (2012)

# Mean $p_T$ Slope vs Energy

Yasushi Nara et al, PhysRevC.106.044902 (2022)

J. Steinheimer et al, Phys.Lett.B. 714. 85-91 (2012)

Susanne Gläsel et al, Phys. Rev. C 105, 014908 (2022)



- Data:  $\langle p_T \rangle$  vs mass follow the linear mass scaling up to 3.5 GeV:
  - Consistent with coalescence as the dominant process for hypernuclei production at mid-rapidity;
- JAM + Coalescence and PHQMD: reproduce the mass dependence of  $\langle p_T \rangle$  qualitatively;

# Summary and Outlook

## Summary:

1. Measurement of  ${}^4_{\Lambda}\text{H}$  and  ${}^4_{\Lambda}\text{He}$   $dN/dy$  in Au+Au collisions at  $\sqrt{s_{\text{NN}}} = 3\text{-}3.5$  GeV
  - 1) Rapidity and centrality dependences of  ${}^4_{\Lambda}\text{H}$  production are qualitatively reproduced by JAM+Coalescence;
  - 2) The yields of ( $\Lambda$ ,  ${}^3_{\Lambda}\text{H}$ ,  ${}^4_{\Lambda}\text{H}$ ,  ${}^4_{\Lambda}\text{He}$ ) do not follow an exponential scaling with mass when divided by spin degeneracy, suggesting significant contributions from feed-down of excited  $A=4$  hypernuclei;
  - 3) The ratio of  ${}^4_{\Lambda}\text{H}/\Lambda$  and  ${}^4_{\Lambda}\text{He}/\Lambda$  are well described with JAM + Coalescence calculations, overestimated by Thermal-Fist;
2. Measurement of  ${}^4_{\Lambda}\text{H}$  and  ${}^4_{\Lambda}\text{He}$  mean transverse momentum  $\langle p_T \rangle$ 
  - 1) A trend of monotonically decreasing  $\langle p_T \rangle$  of  ${}^4_{\Lambda}\text{H}$  observed from middle to target rapidity in 0-10%, 10-40% and 0-40%;
  - 2) Linear mass scaling observed in  $\langle p_T \rangle$  vs mass up to 3.5 GeV, well described by JAM + Coalescence afterburner and PHQMD calculations qualitatively;
    - Consistent with coalescence as the dominant process for hypernuclei production at mid-rapidity;

## Outlook:

1. Heavier hypernuclei (e.g.  ${}^5_{\Lambda}\text{He}$ ,  ${}^6_{\Lambda}\text{H}$ ) may be accessible using Run 21 3 GeV data which allows a comprehensive study of the mass dependence of hypernuclei production;

**Thank you very much for your  
attention!**



# Particle Acceptance

Particle rapidity coverage from beam rapidity to mid-rapidity

