Measurements of ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He Production in $\sqrt{s_{NN}}$ = 3-3.5 GeV Au+Au Collisions at RHIC

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Outline

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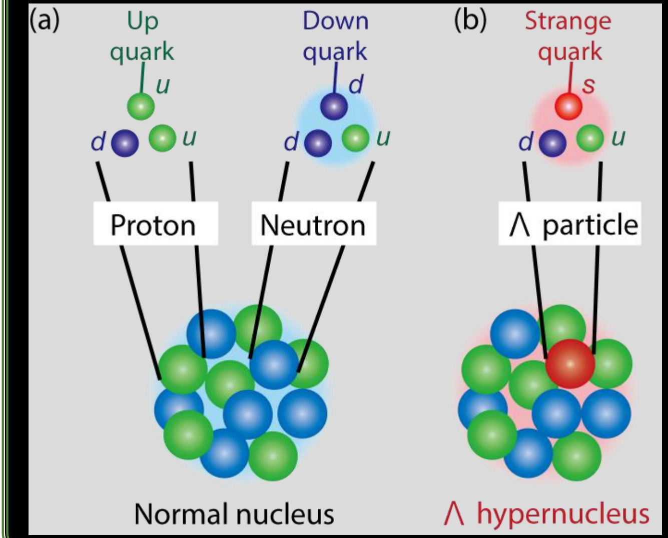
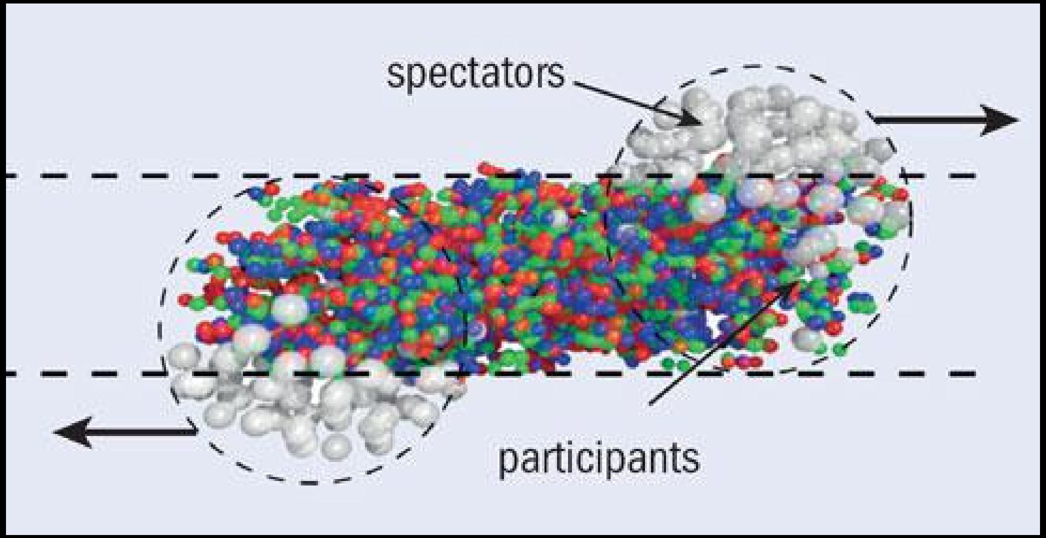
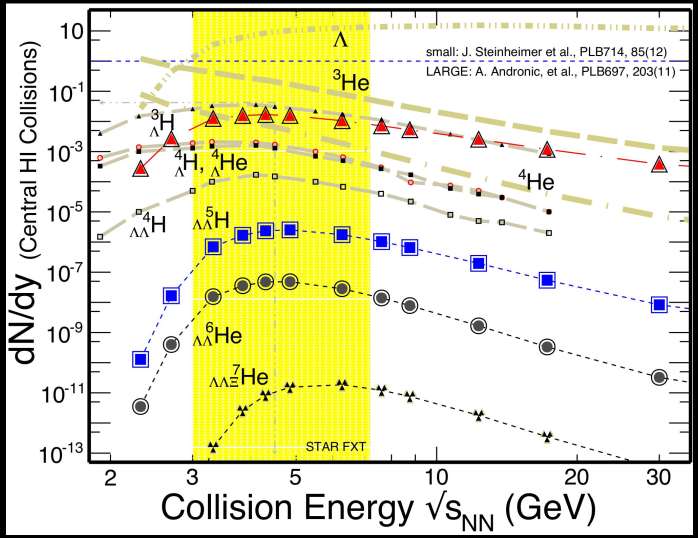
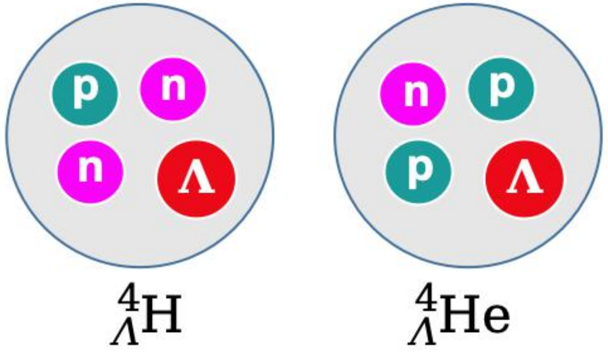
3. Physics Results of Hypernuclei (${}^{4}_{\Lambda}H$ and ${}^{4}_{\Lambda}He$) from 3-3.5 GeV Au+Au Collisions
   1) Yields
   2) Particle Ratio
   3) Transverse momentum distribution
4. Summary and Outlook

Motivation





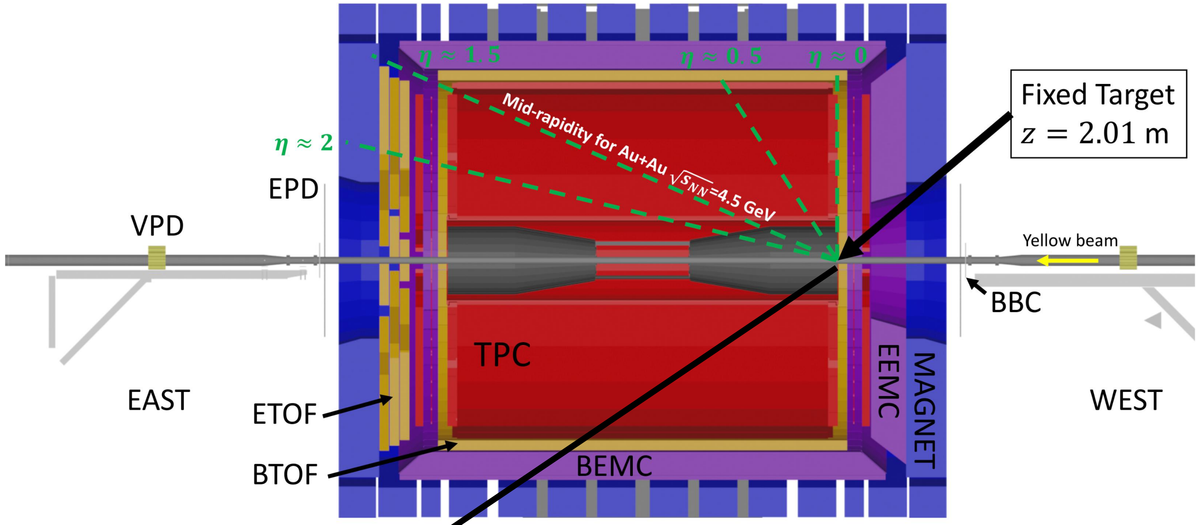


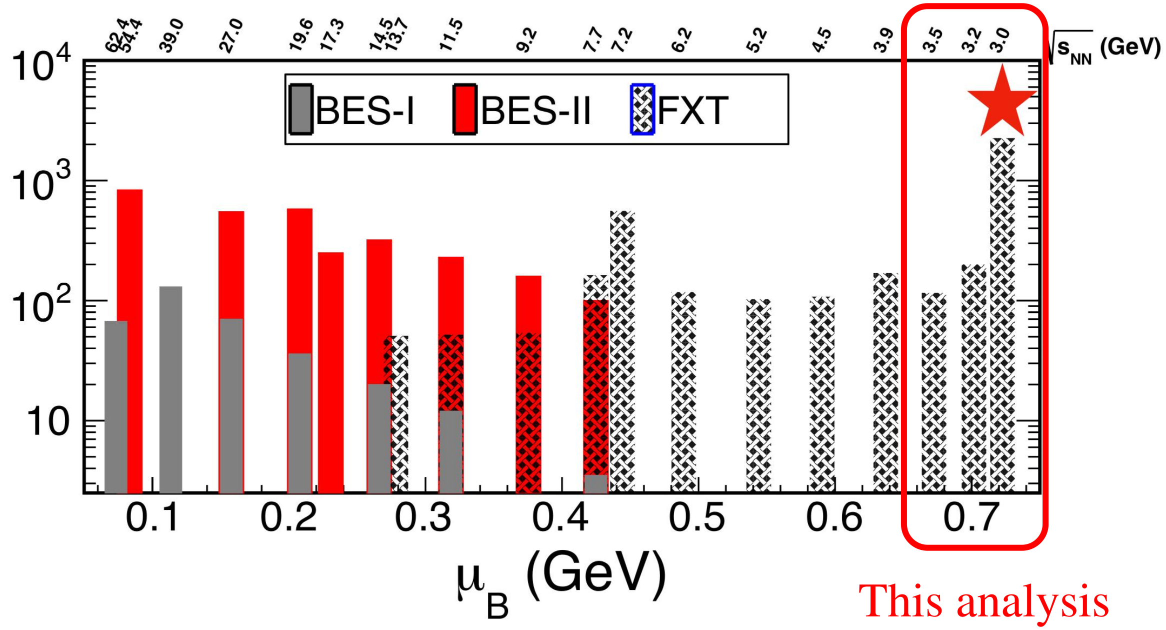


1. Hyper-nucleus provides opportunity for studying hyperon-nucleon (YN) interactions. Important for understanding inner structure of compact stars
2. Measurements of $^4_\Lambda$H and $^4_\Lambda$He in heavy-ion collisions
   1) A=4 mirror hypernuclei ($^4_\Lambda$H(0^+) and $^4_\Lambda$He(0^+))
   2)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

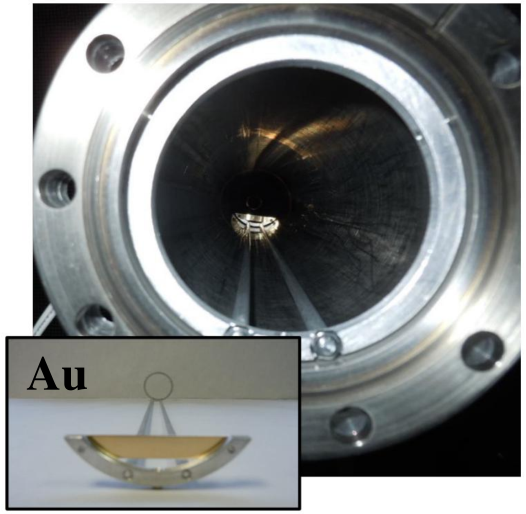
[1] A. Andronic et al., Phys. Lett. **B697**, 203(2011)
[2] J. Steinheimer et al., Phys. Lett. **B714**, 85(2012)

STAR Detector and BES-II



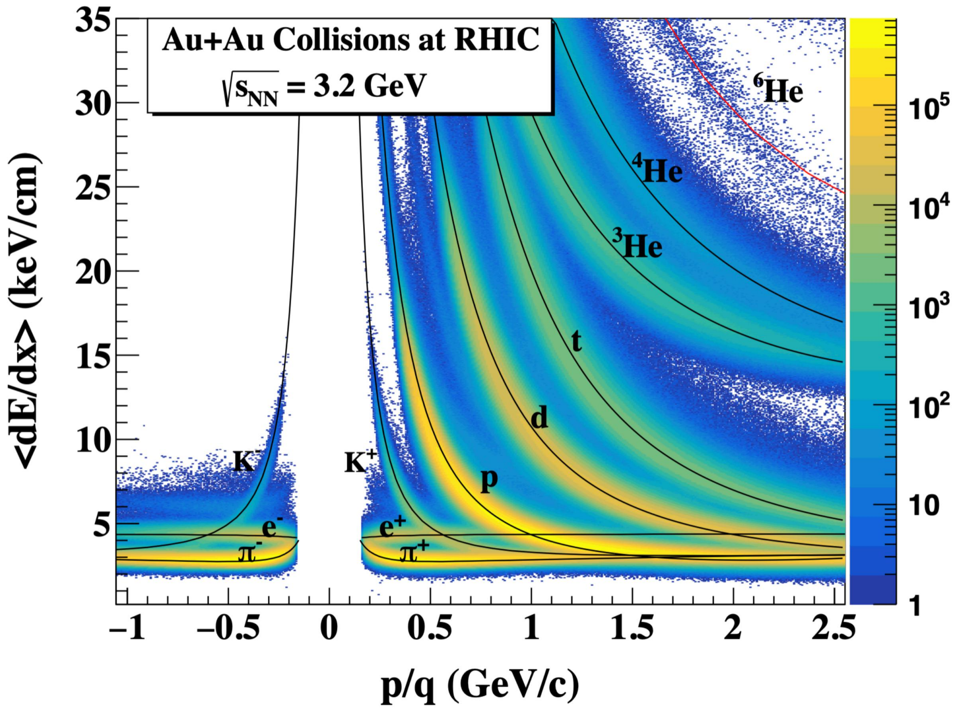


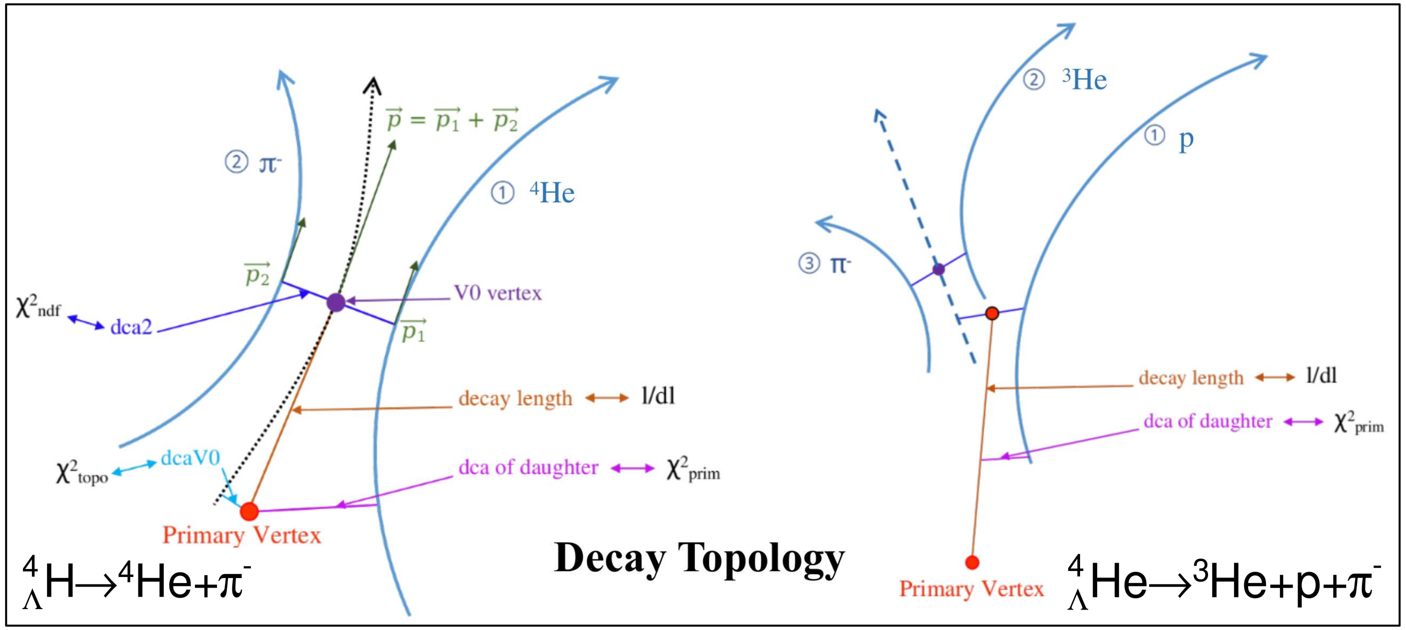
This analysis



- BES-II (2018-2021)
  - High statistics Au+Au collisions $\sqrt{s_{NN}}$ = 3-54.4 GeV (10 × 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

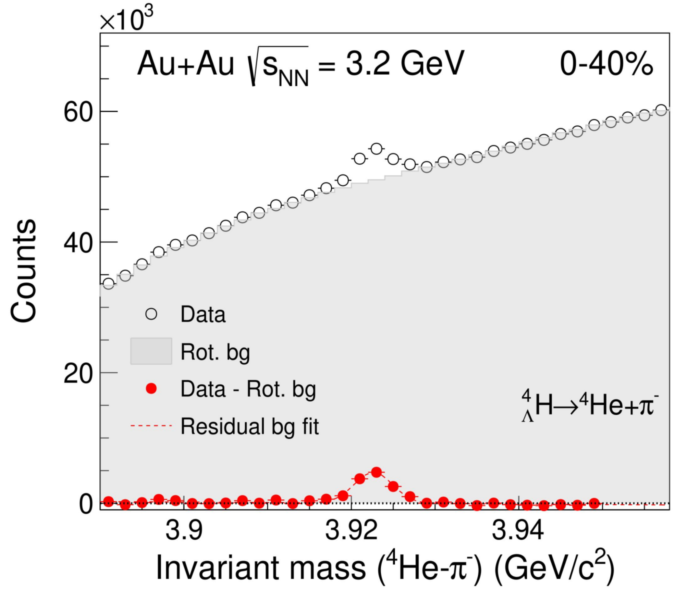


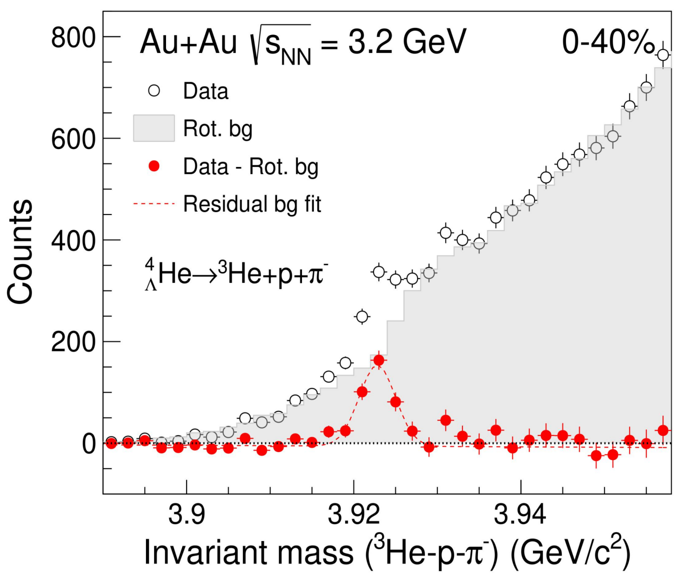


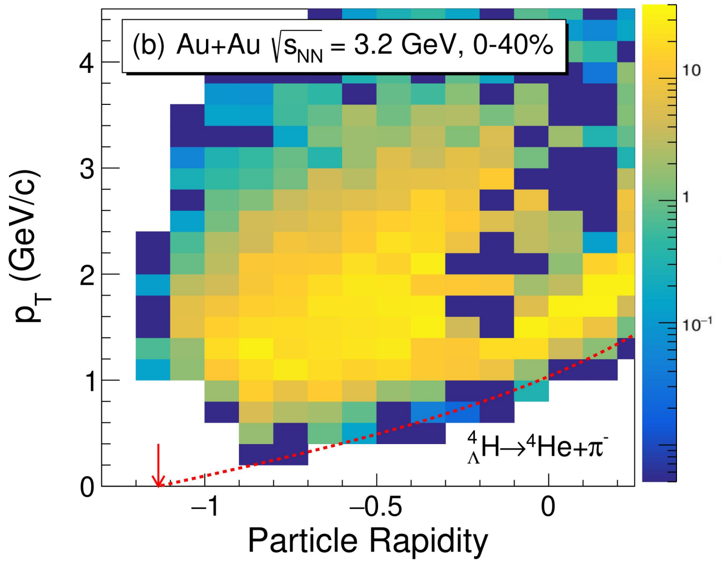
1. Good particle identification capability based on TPC and TOF;
2. The hyper-nuclei reconstruction with KFParticle package based on the Kalman filter method providing a full set of the particle parameters together with their uncertainties;
3. Decay topology tremendously helped on particle identification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

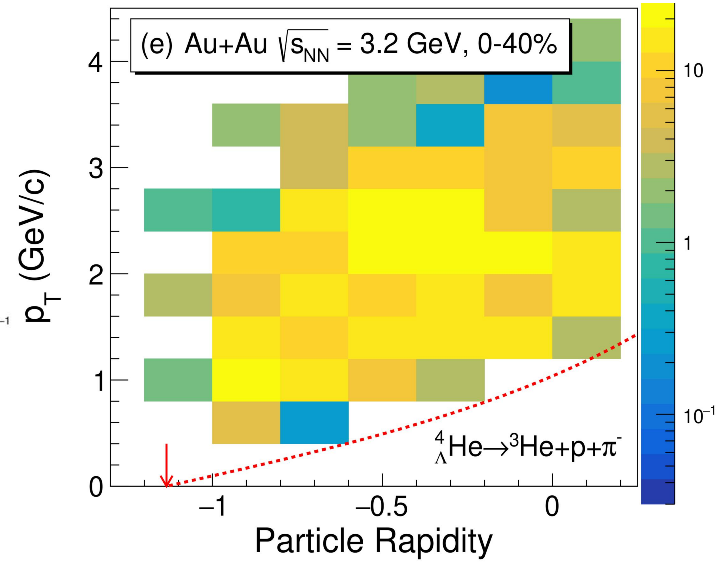
[1] Gorbunov and I. Kisel. CBM-SOFT-note-2007-003, 7 May 2007
[2] Ivan Kisel. J. Phys. Conf. Ser. 1070(1), 012015 (2018)

Hyper-Nuclei Reconstruction and Acceptance



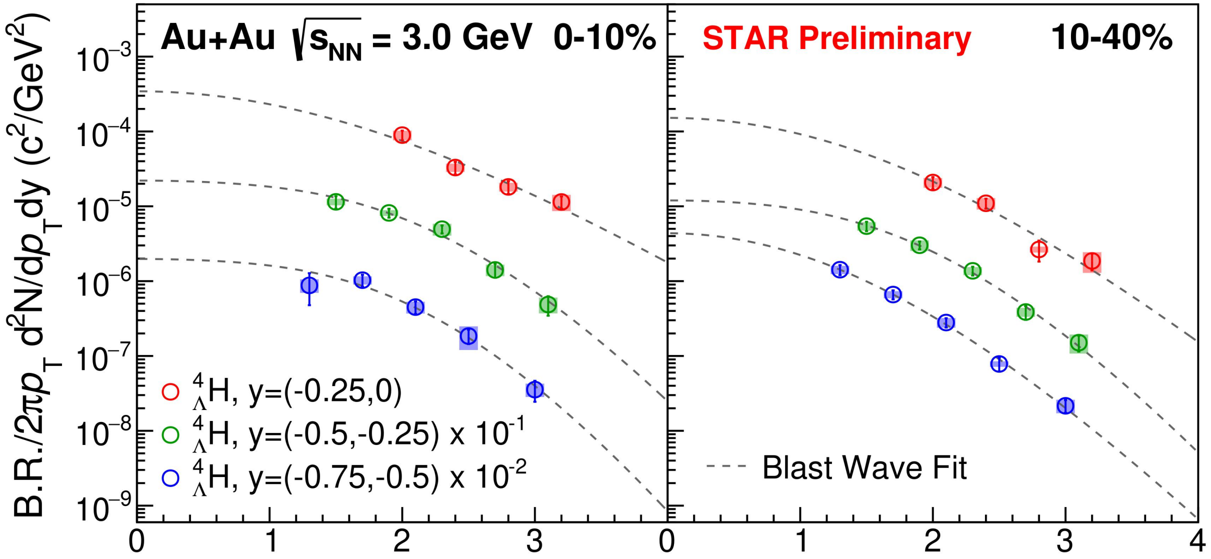


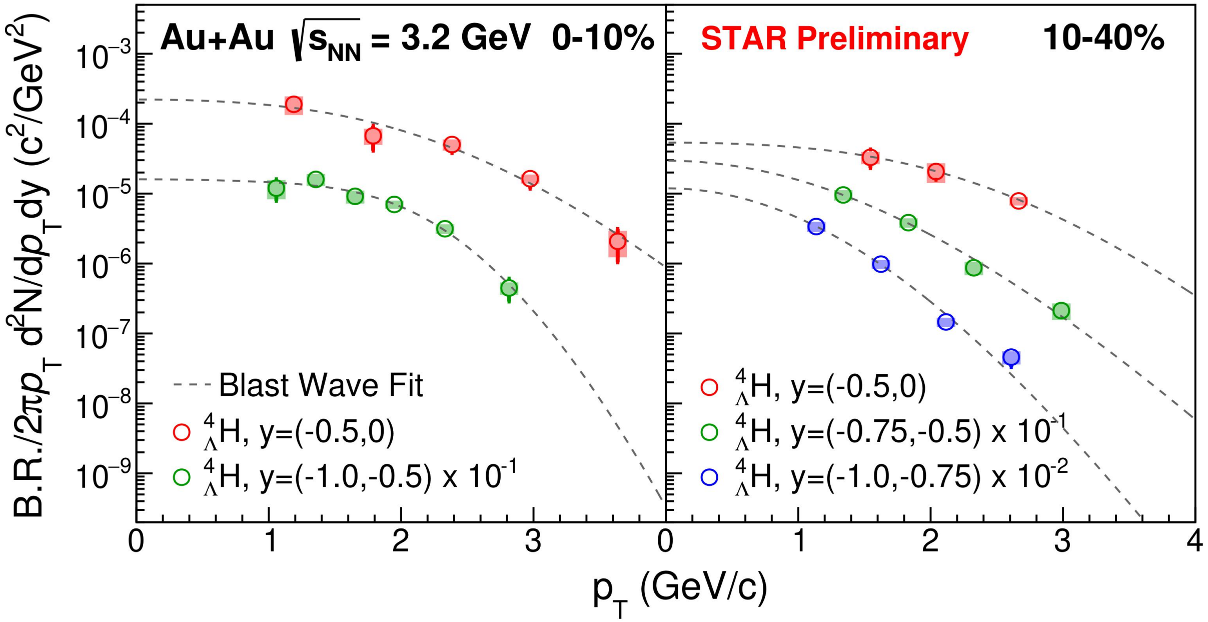


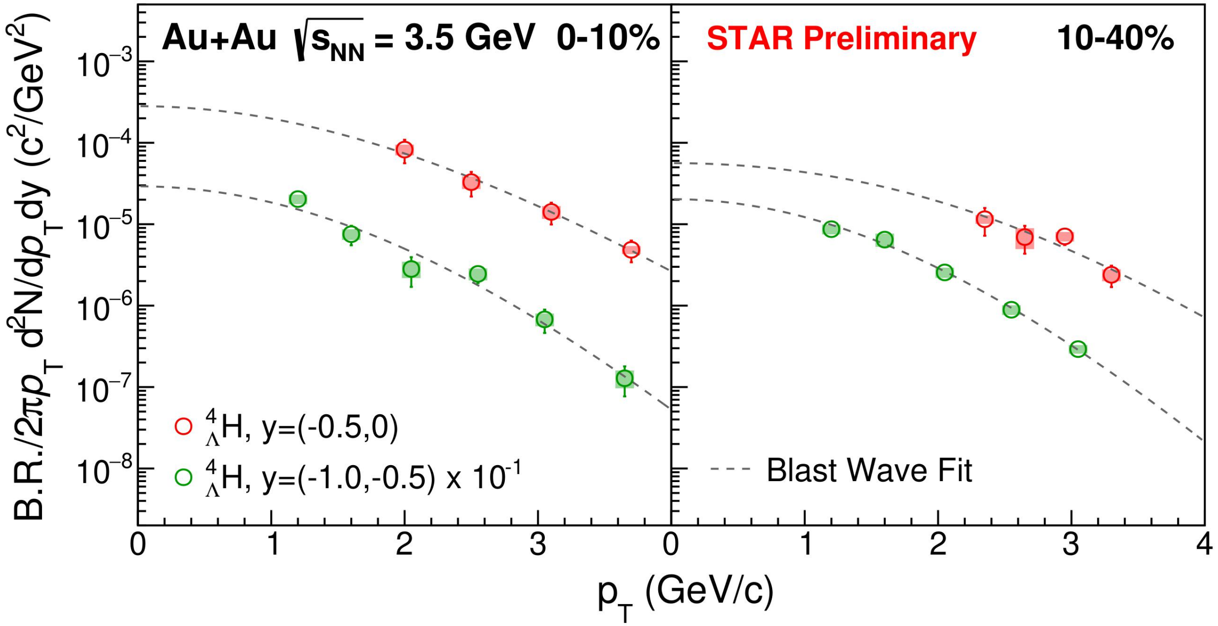


- KFParticle package used for ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He reconstructions;
- Uncorrelated combinatorial backgrounds: Rotation method (rotate ^{4}He for ${}^{4}_{\Lambda}$H and ^{3}He for ${}^{4}_{\Lambda}$He);
- Particle rapidity coverage from beam rapidity to mid-rapidity

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



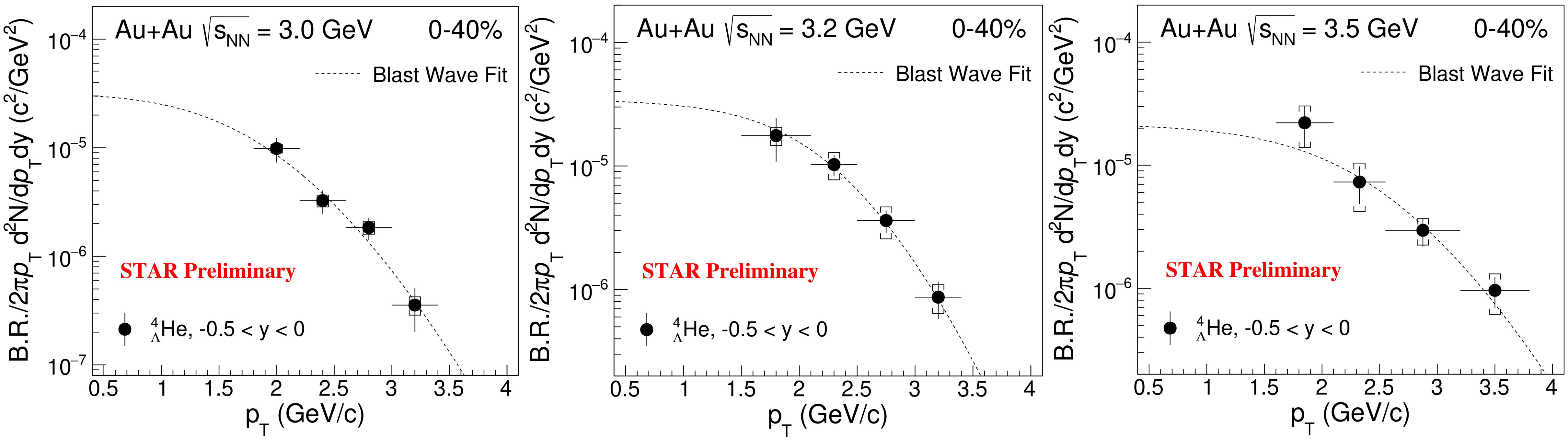




- $^{4}_{\Lambda}$H spectra in 0-10% and 10-40% at 3.0, 3.2 and 3.5 GeV;
- Blast Wave function used for extrapolation to $p_T = 0$ GeV;

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

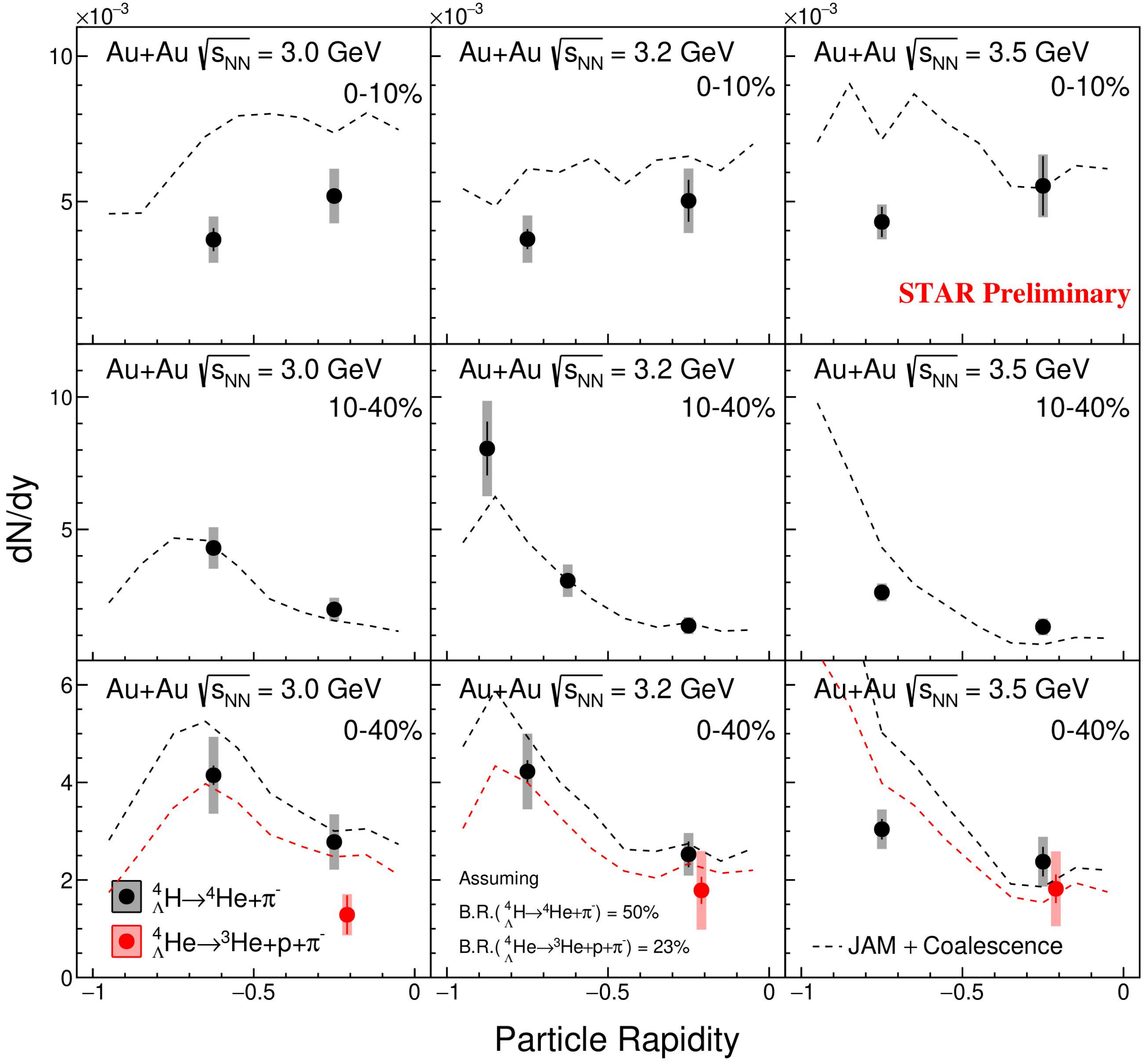
$^4_\Lambda$He p_T Spectra



- $^4_\Lambda$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);

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

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



Data:

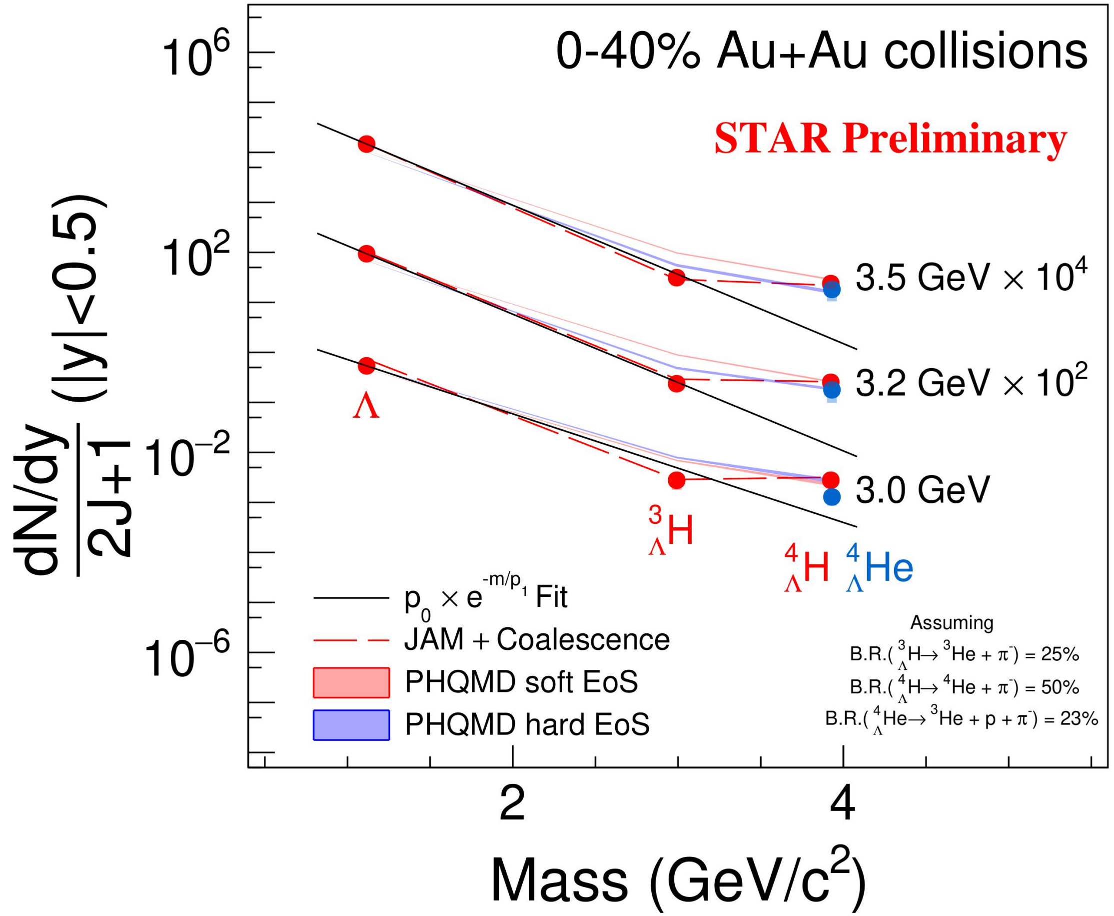
- Different trends in the $^{4}_{\Lambda}$H rapidity distribution in central (0-10%) and mid-central (10-40%) collisions;
  - Likely related to the change in the collision geometry, such as spectators playing a larger role in non-central collisions;
- The $^{4}_{\Lambda}$He yields at the mid-rapidity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

JAM + Coalescence:

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

Yasushi Nara et al, PhysRevC.106.044902 (2022)
J. Steinheimer et al, Phys.Lett.B. 714. 85-91 (2012)

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



Yasushi Nara et al, PhysRevC.106.044902 (2022)
J. Steinheimer et al, Phys.Lett.B. 714. 85-91 (2012)
Susanne Gläßel et al, Phys. Rev. C 105, 014908 (2022)

Data:

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

JAM+Coalescence:

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

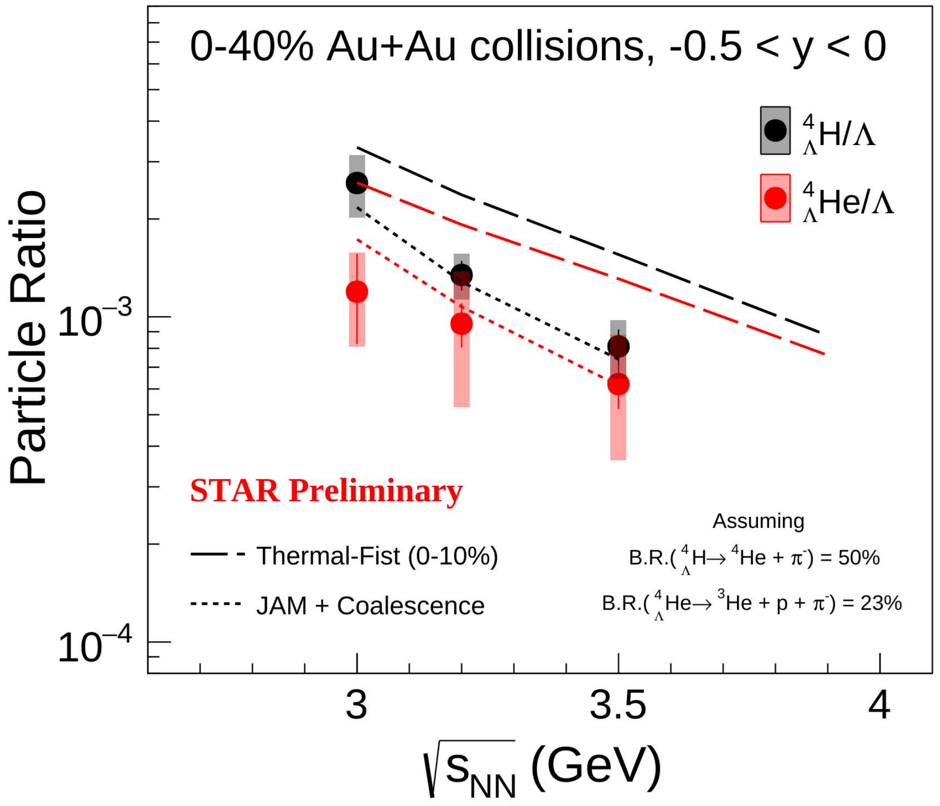
PHQMD:

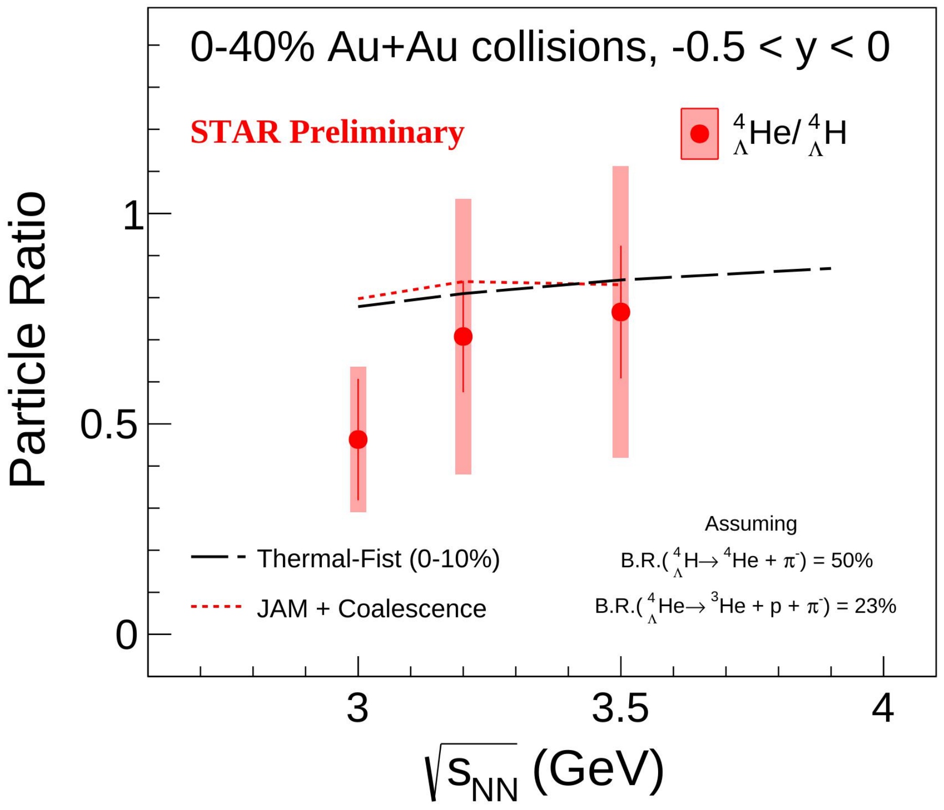
- Describes Λ, ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He, but overestimates ${}^{3}_{\Lambda}$H;

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

Yasushi Nara et al, PhysRevC.106.044902 (2022)
J. Steinheimer et al, Phys.Lett.B. 714. 85-91 (2012)

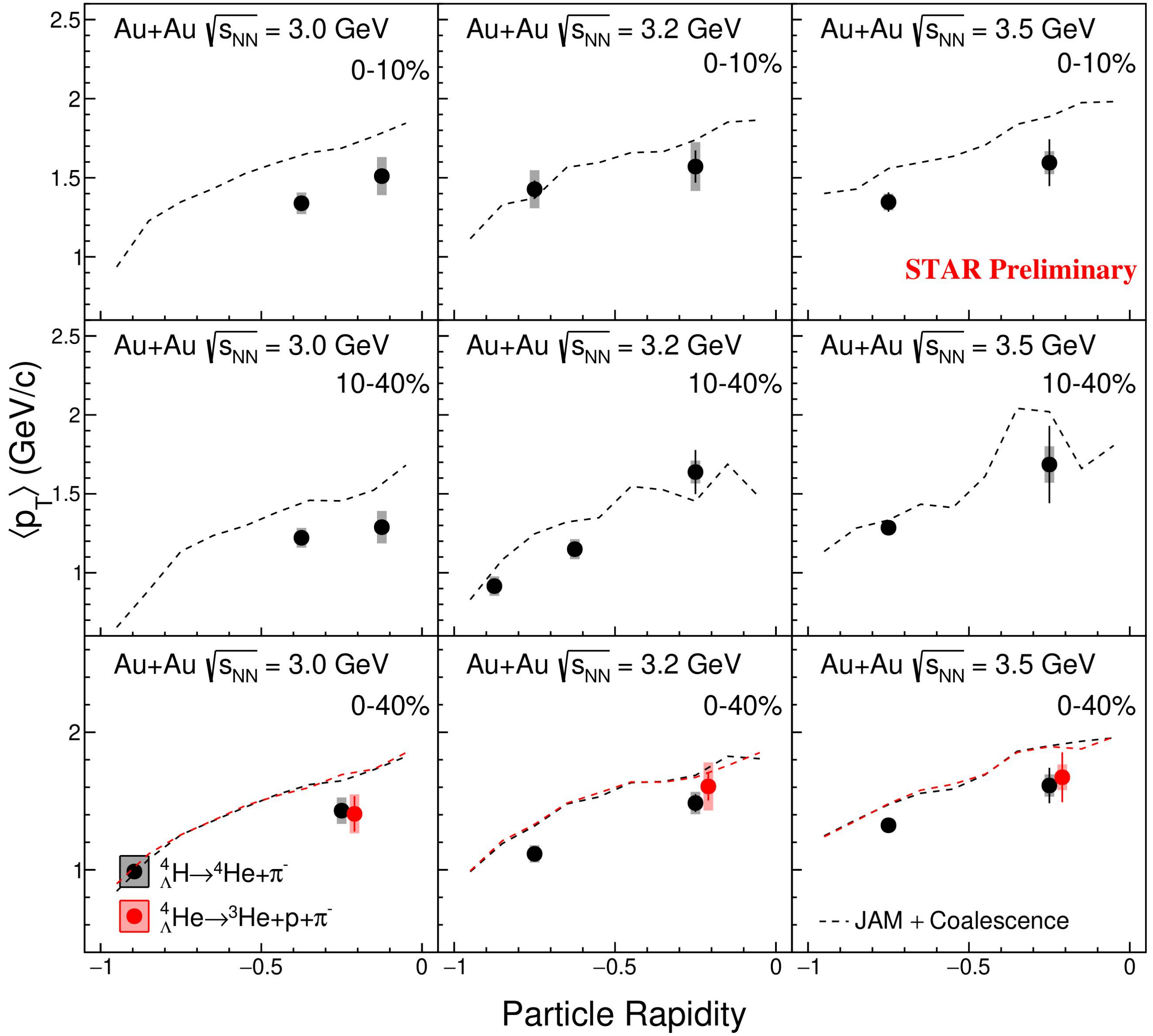
Thermal-Fist: T. Reichert et al, PRC 107 , 014912 (2023)





- The ratio of $^{4}_{\Lambda}\mathrm{H}/\Lambda$ and $^{4}_{\Lambda}\mathrm{He}/\Lambda$ 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 $^{4}_{\Lambda}\mathrm{He}/^{4}_{\Lambda}\mathrm{H}$ is consistent with thermal predictions, and JAM+coalescence calculations;

Mean Transverse Momentum $\langle p_T \rangle$



Data:

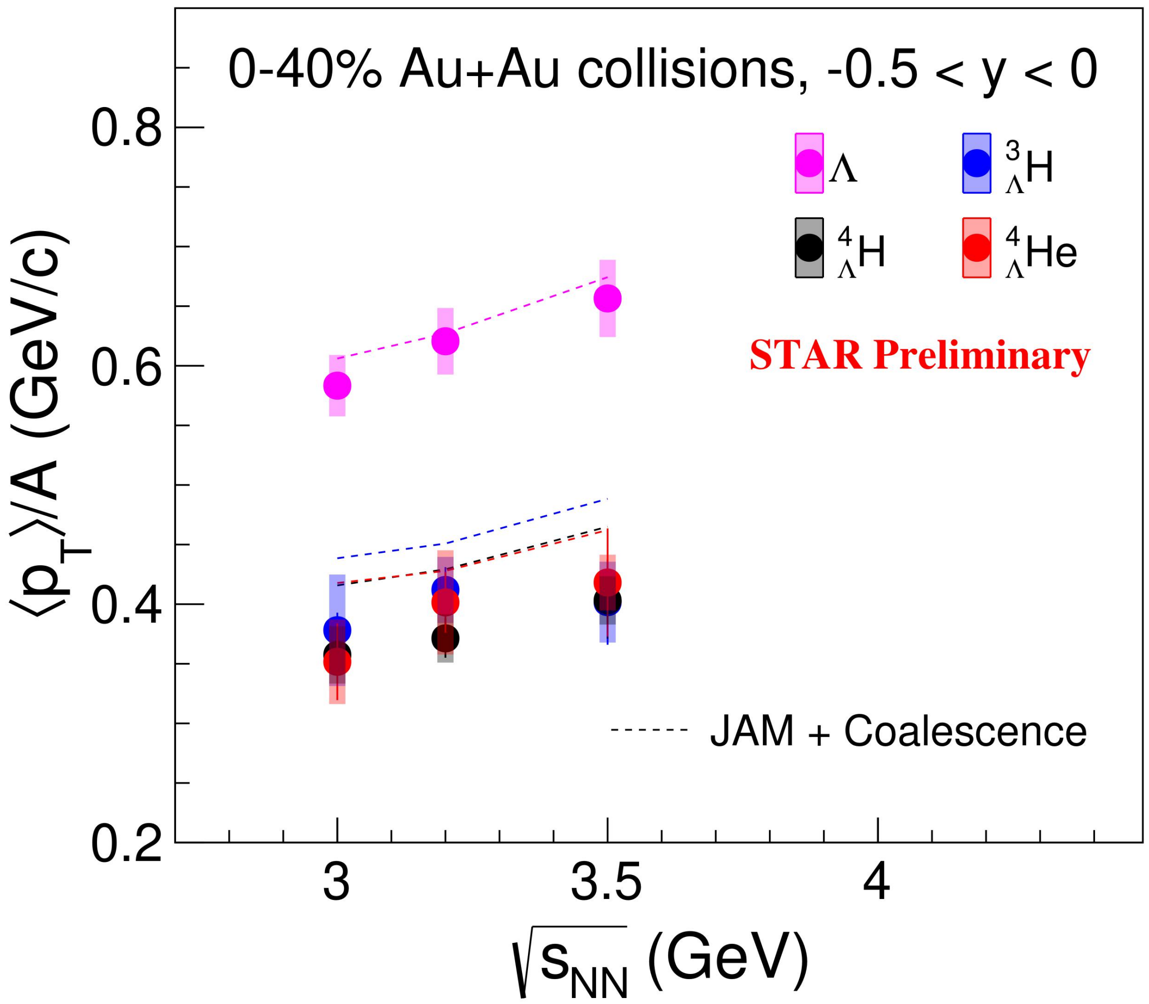
- The $\langle p_T \rangle$ of $^{4}_{\Lambda}H$ shows a monotonically decreasing trend from middle to target rapidity;
- The $\langle p_T \rangle$ of $^{4}_{\Lambda}He$ is similar to $^{4}_{\Lambda}H$;

JAM+Coalescence:

- Could describe the rapidity dependence of $\langle p_T \rangle$ for $^{4}_{\Lambda}H$ and $^{4}_{\Lambda}He$ 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 Λ;
- The $\langle p_T \rangle$/A of $^{4}_{\Lambda}$He, $^{4}_{\Lambda}$H and $^{3}_{\Lambda}$H are similar;
  - Follow the mass hierarchy;

JAM+Coalescence:

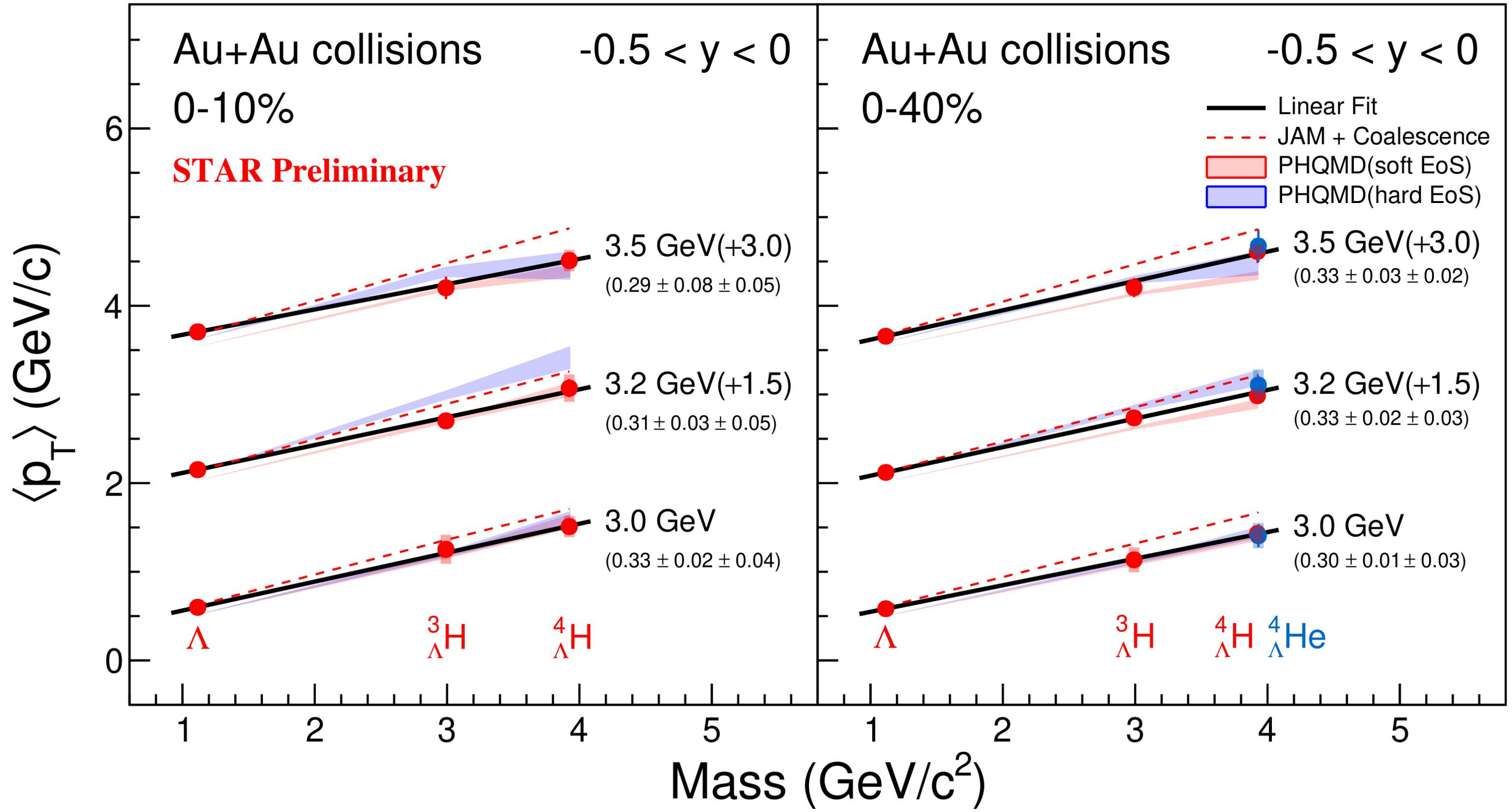
- Qualitatively reproduces the energy dependence;
- Overestimates $\langle p_T \rangle$ of $^{3}_{\Lambda}$H;

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 Gläßel 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 ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$ dN/dy in Au+Au collisions at $\sqrt{s_{NN}}$ = 3-3.5 GeV
   1) Rapidity and centrality dependences of ${}^{4}_{\Lambda}\mathrm{H}$ production are qualitatively reproduced by JAM+Coalescence;
   2) The yields of (Λ, ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{He}$) 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 ${}^{4}_{\Lambda}\mathrm{H}/\Lambda$ and ${}^{4}_{\Lambda}\mathrm{He}/\Lambda$ are well described with JAM + Coalescence calculations, overestimated by Thermal-Fist;

2. Measurement of ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$ mean transverse momentum $\langle p_T \rangle$
   1) A trend of monotonically decreasing $\langle p_T \rangle$ of ${}^{4}_{\Lambda}\mathrm{H}$ 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. ${}^{5}_{\Lambda}\mathrm{He}$, ${}^{6}_{\Lambda}\mathrm{H}$) 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