Light Hyper-Nuclei Production in $\sqrt{s_{NN}} = 3$ GeV Au+Au Collisions at RHIC

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Outline

1) Motivation

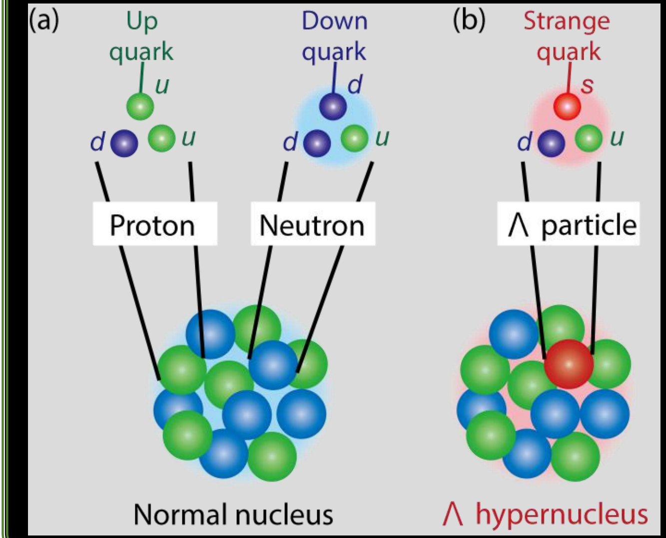
2) STAR Detector System for Fixed-target runs

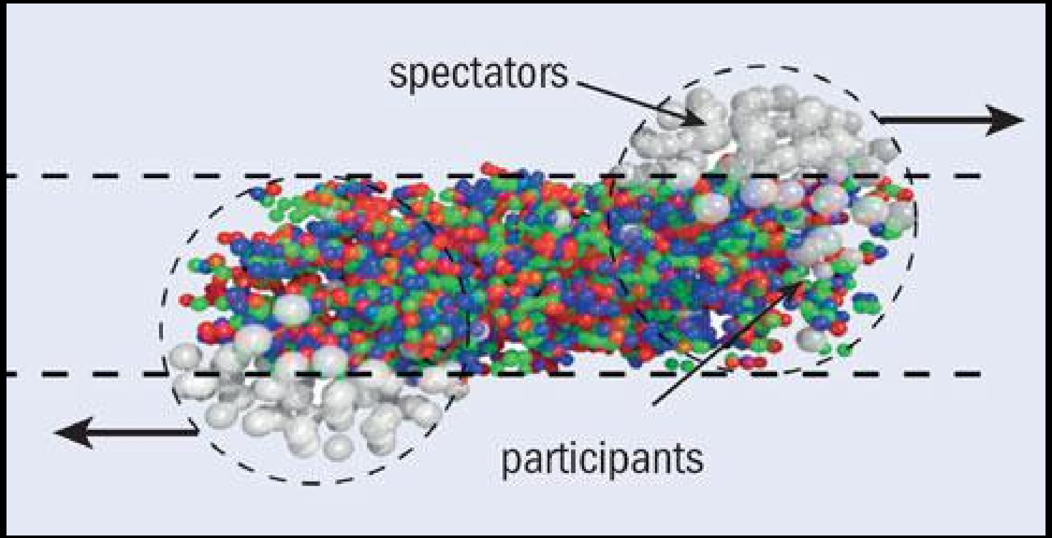
3) Results of Hyper-nuclei ($^{3}_{\Lambda}H$ & $^{4}_{\Lambda}H$) from 3 GeV Au+Au Collisions

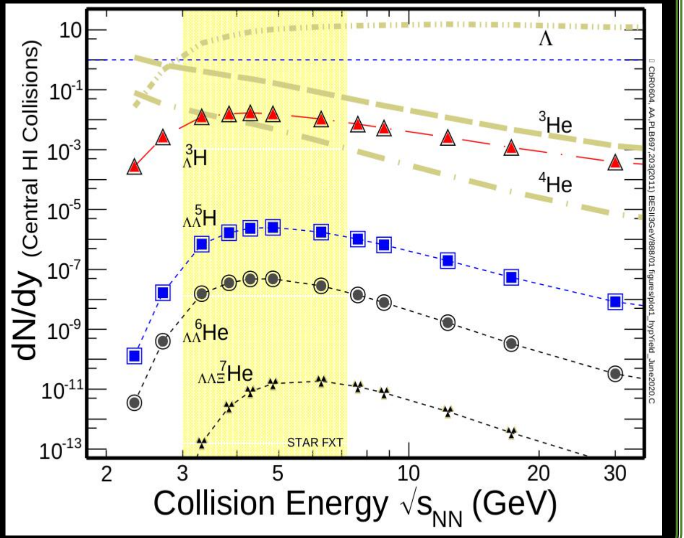
- Precision Lifetime measurements
- Rapidity Density of Hyper-nuclei
- Directed Flow of Hyper-nuclei

4) Summary

Motivation







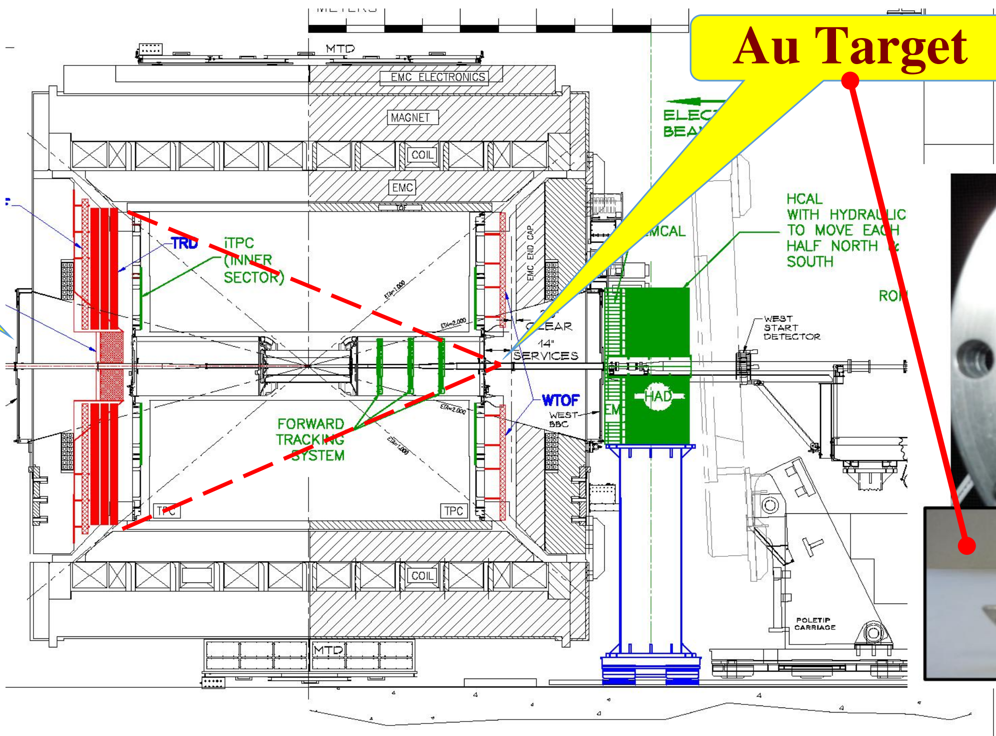
1) Hyper-nucleus provides opportunity for studying hyperon-nucleon (YN) interactions. Important for understanding inner structure of compact stars
2) In high-energy heavy-ion collisions (HICs), hyper-nuclei are abundantly produced in high baryon density region. Ideal environment for studying properties of hyper-nuclei
    - Lifetime
    - Hyper-nuclei production mechanism in HICs
    - Others(decay branching ratio, binding energy, etc)

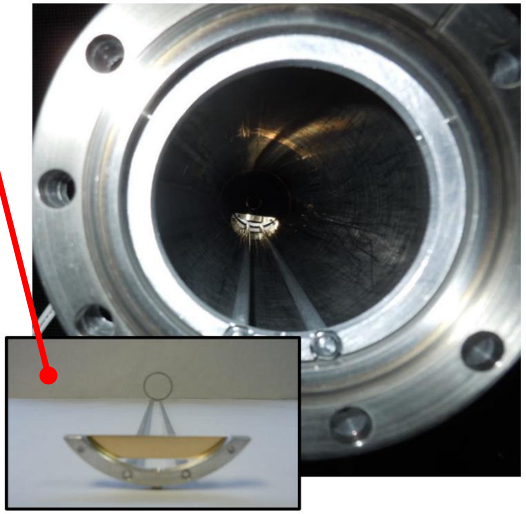
A. Andronic et al., Phys. Lett. **B697**, 203(2011)
J. Steinheimer et al., Phys. Lett. **B714**, 85(2012)

Fixed Target Setup at STAR

Event Plane Detector (EPD)

Au Target



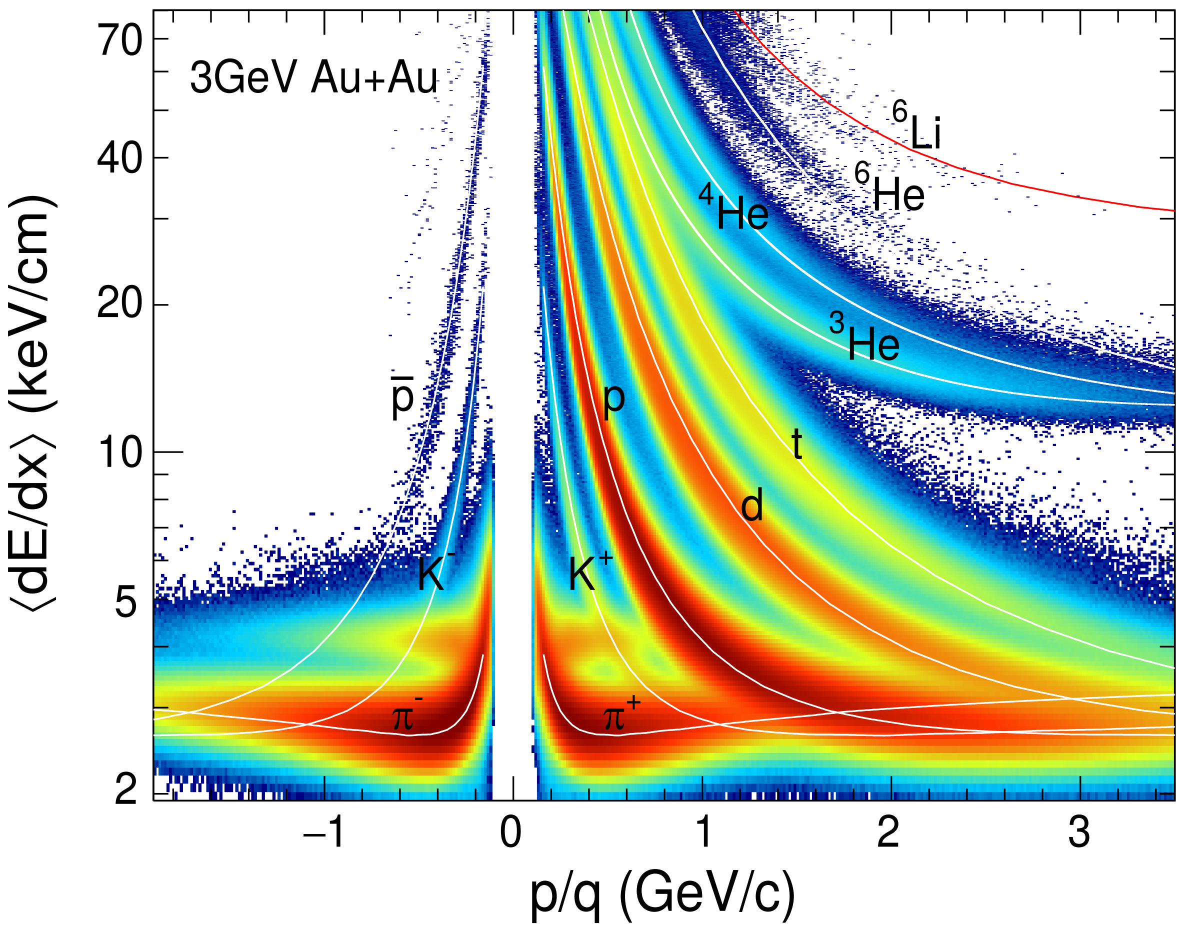


RHIC Beam Energy BES-II in 2019-2021:

- Fixed Target Run extends collision energy down to : $\sqrt{s_{NN}}$ = 3 - 7.2 GeV corresponding to chemical potential: 750 ≥ μ_B ≥ 420 MeV

Charged Hadron PID and ${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$ Reconstruction

STAR TPC Particle Identification



2018 STAR FXT 3 GeV data set;

260M minimum biased events

1) PID functions of p, d, t, ^{3}He, ^{4}He, π^{-} are made based on the dE/dx vs p/q distribution and particles are selected by $|n\sigma|$ method;

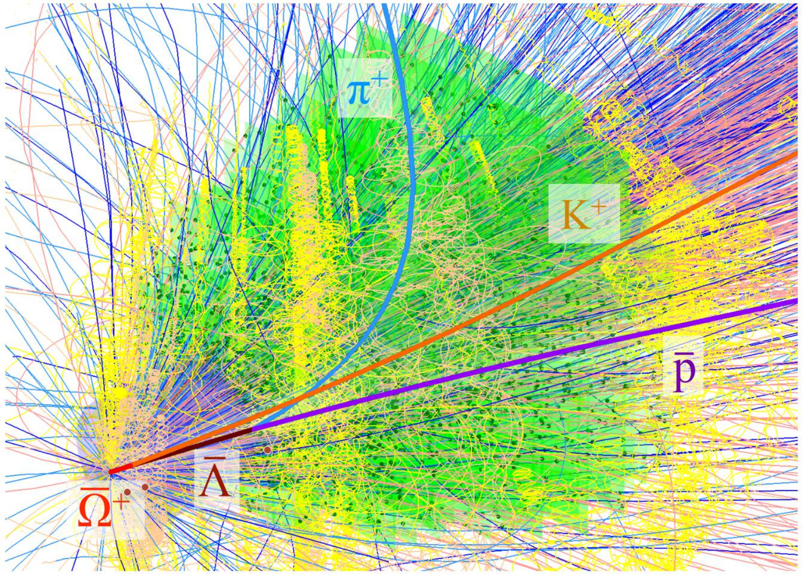
2) Hyper-nuclei reconstruction channels:

${}^{3}_{\Lambda}H \to {}^{3}He + \pi^{-}$	2-body
${}^{3}_{\Lambda}H \to p + d + \pi^{-}$	3-body
${}^{4}_{\Lambda}H \to {}^{4}He + \pi^{-}$	2-body

KF Particle: Reconstruction of Short-lived Particles

Concept:

- Mother and daughter particles have the same state vector and are treated in the same way
- Reconstruction of decay chains
- Kalman Filter (KF) based
- Geometry independent and Vectorized



Simulated AuAu collision at 25 AGeV

$\bar{\Omega}^+ \leftarrow \bar{\Lambda}\, K^+$

$\quad\;\; \uparrow \bar{p}\, \pi^+$

(r,C)

$\mathbf{r} = \{\, x, y, z, p_x, p_y, p_z, E \,\}$

State vector

$$C = \langle \mathbf{r}\mathbf{r}^T \rangle = \begin{bmatrix} \sigma_x^2 & C_{xy} & C_{xz} & C_{xp_x} & C_{xp_y} & C_{xp_z} & C_{xE} \\ C_{xy} & \sigma_y^2 & C_{yz} & C_{yp_x} & C_{yp_y} & C_{yp_z} & C_{yE} \\ C_{xz} & C_{yz} & \sigma_z^2 & C_{zp_x} & C_{zp_y} & C_{zp_z} & C_{zE} \\ C_{xp_x} & C_{yp_x} & C_{zp_x} & \sigma_{p_x}^2 & C_{p_xp_y} & C_{p_xp_z} & C_{p_xE} \\ C_{xp_y} & C_{yp_y} & C_{zp_y} & C_{p_xp_y} & \sigma_{p_y}^2 & C_{p_yp_z} & C_{p_yE} \\ C_{xp_z} & C_{yp_z} & C_{zp_z} & C_{p_xp_z} & C_{p_yp_z} & \sigma_{p_z}^2 & C_{p_zE} \\ C_{xE} & C_{yE} & C_{zE} & C_{p_xE} & C_{p_yE} & C_{p_zE} & \sigma_E^2 \end{bmatrix}$$

Covariance matrix

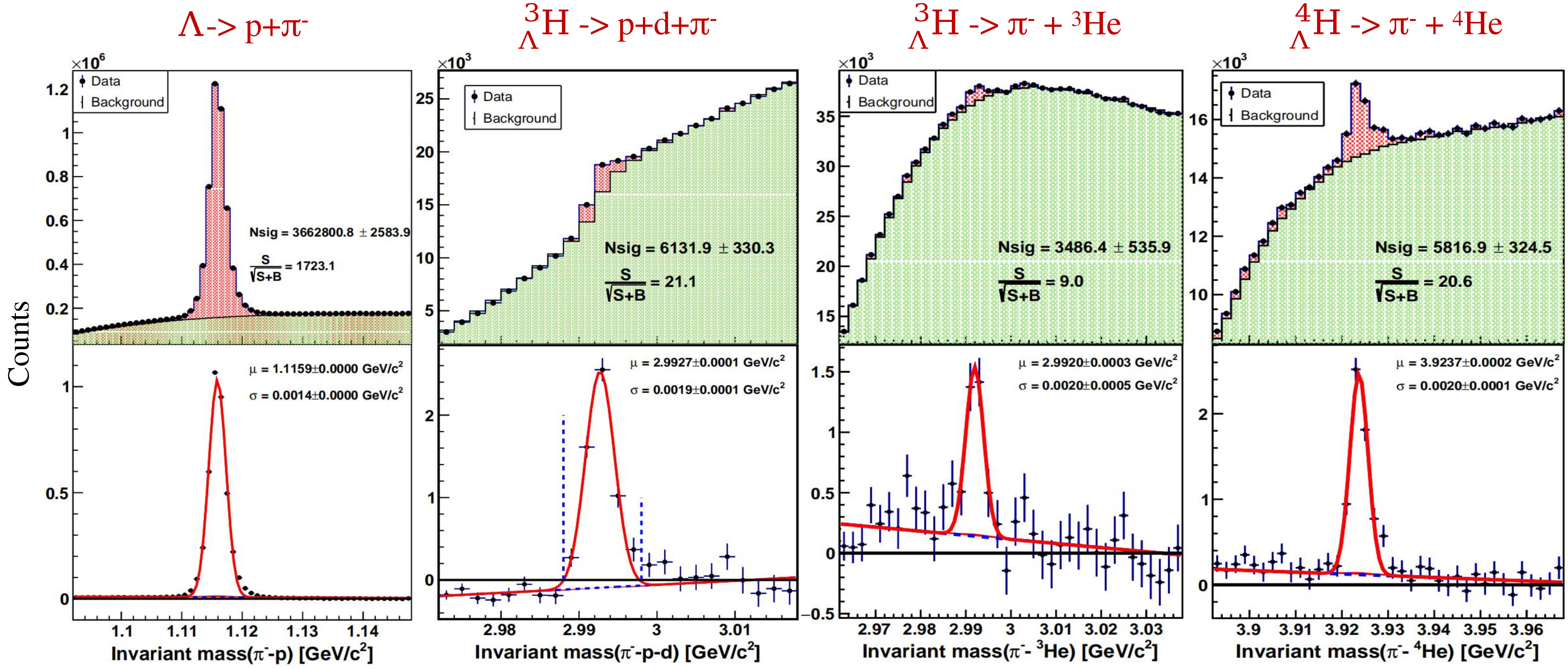
KF Particle package shows a high quality of the reconstructed particles, high effciencies, and high signal to background ratios

S. Gorbunov and I. Kisel, Reconstruction of decayed particles based on the Kalman filter. CBM-SOFT-note-2007-003, 7 May 2007

KF Particle Finder — M. Zyzak, "Online selection of short-lived particles on many-core computer architectures in the CBM experiment at FAIR," Dissertation thesis, Goethe University of Frankfurt, 2016, http://publikationen.ub.uni-frankfurt.de/frontdoor/index/index/docId/41428

KF Particle provides a direct approach to physics analysis: ALICE, CBM, sPHENIX and **STAR**

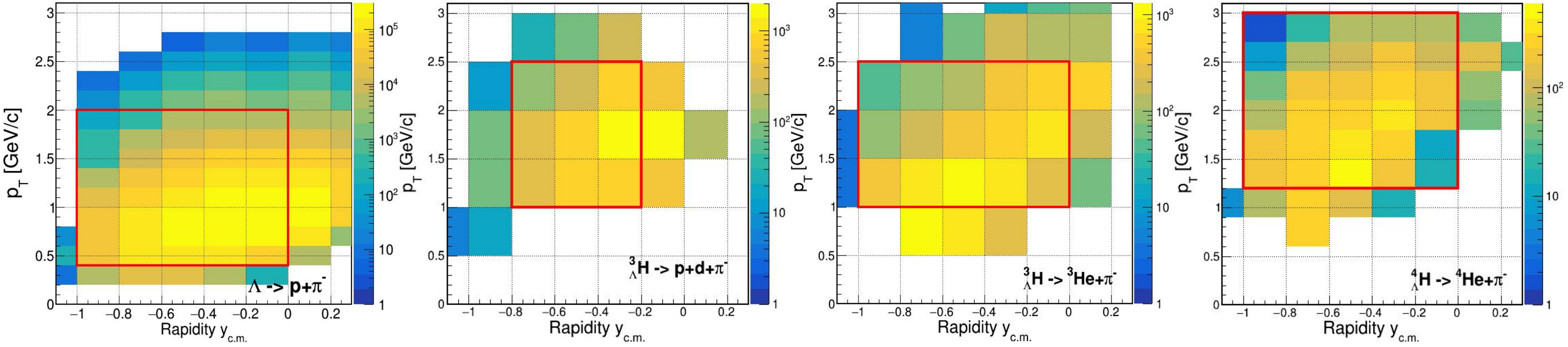
Λ, $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$ Hyper-Nuclei Reconstruction



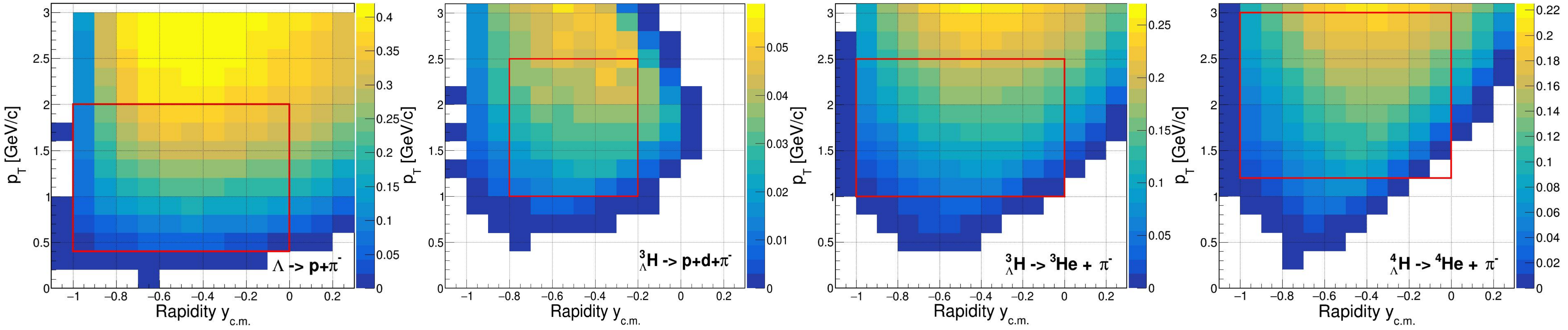
- KFParticle package used for Λ, $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$ reconstructions

Λ, ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H Phase Space and Efficiency

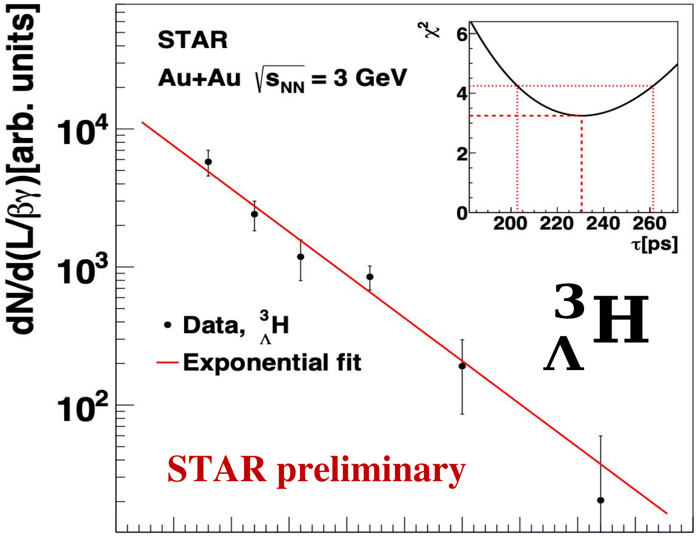
Phase space

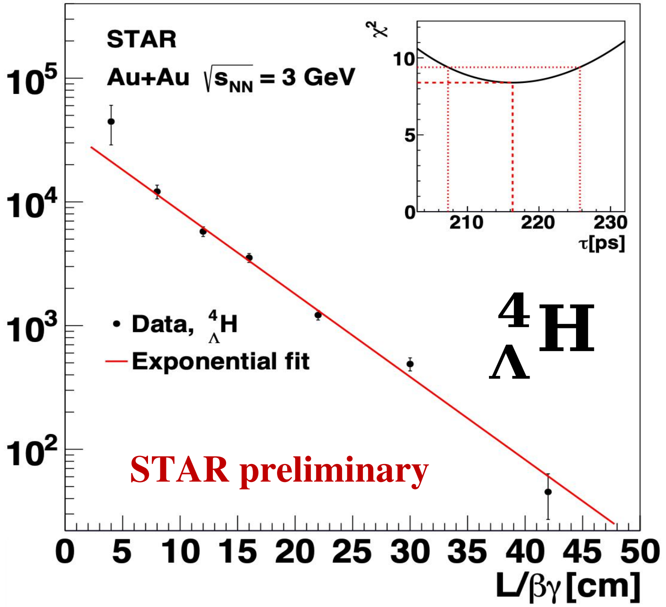


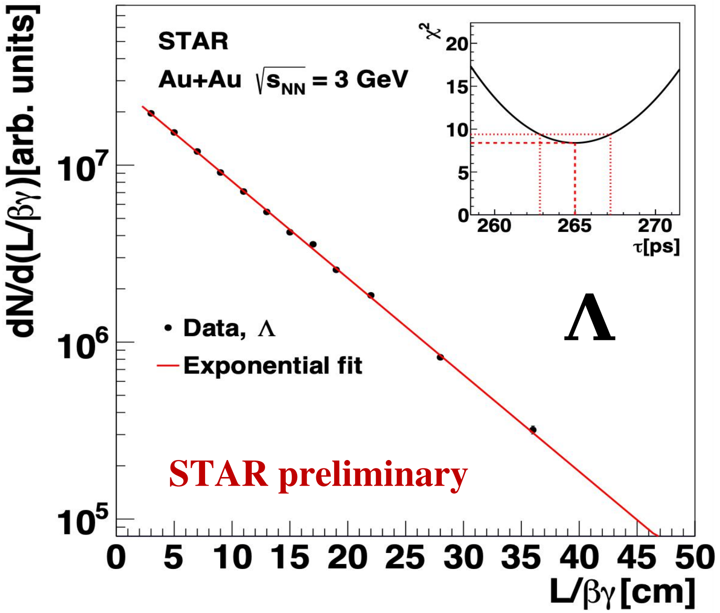
Efficiency



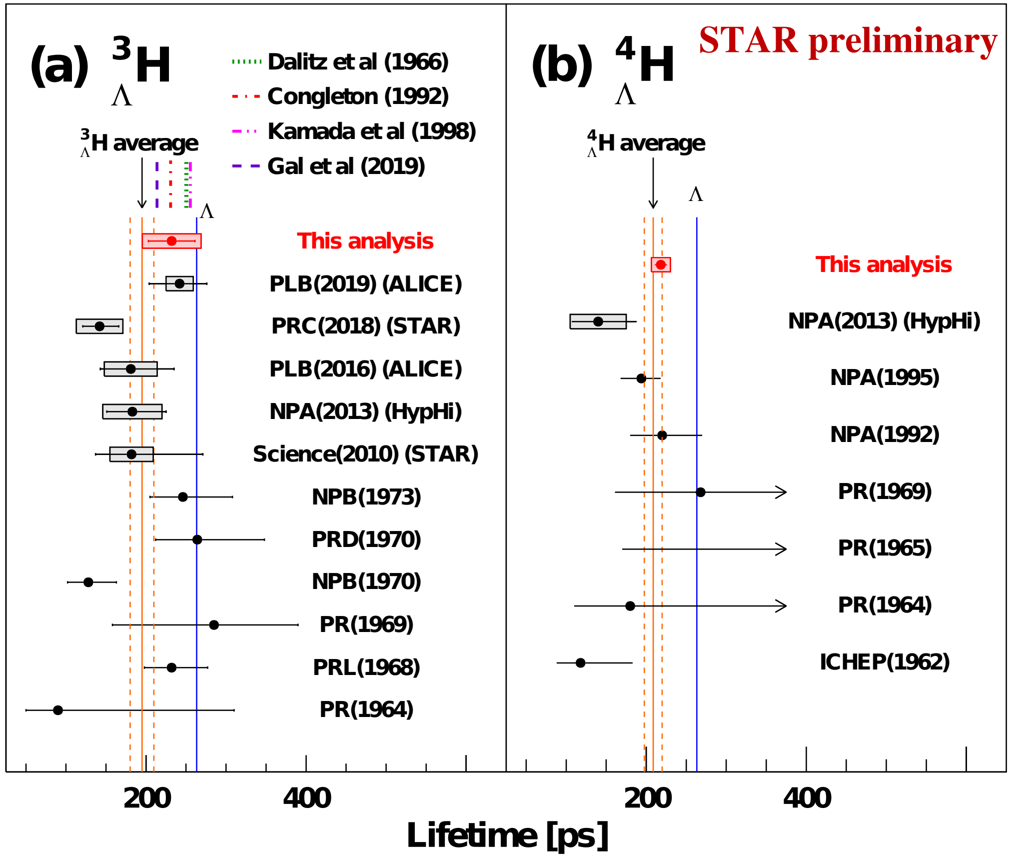
Λ, ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ Lifetime Measurements







- Decay time: t=L/$\beta\gamma$
- Well described by exponential functions: $N(t) = N_0 e^{-L/\beta\gamma c\tau}$
- Lifetime extracted with χ^2 fit
- Extracted Λ lifetime (265.0±2.2)[ps] consistent with PDG value (263.1±2.0)[ps]



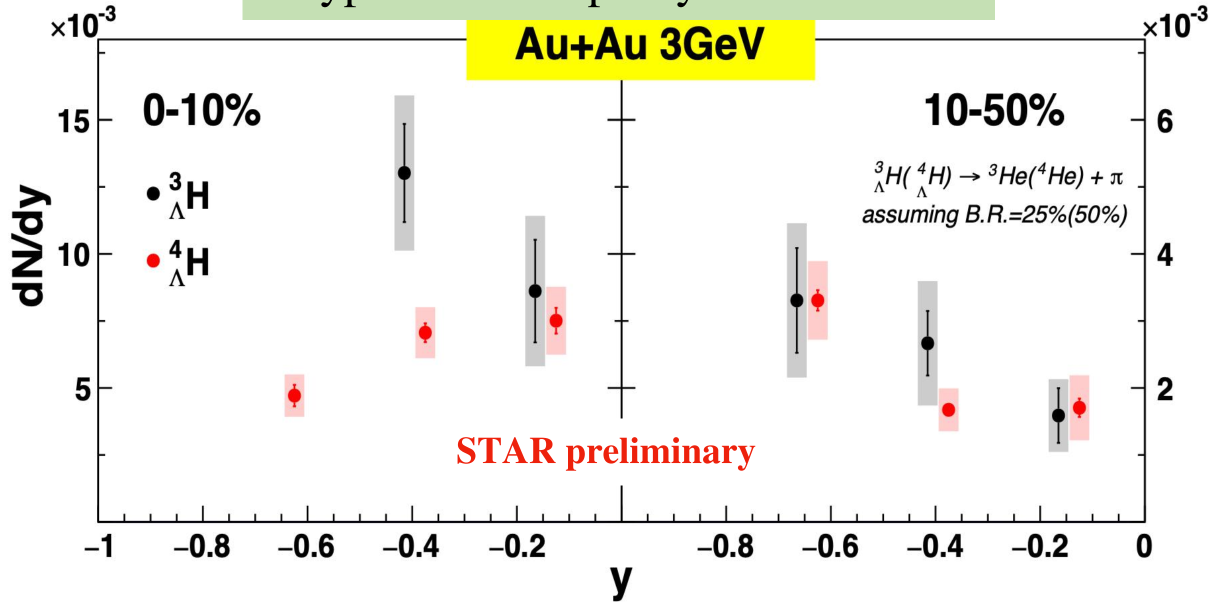
${}^{3}_{\Lambda}H$: τ=231.1±29.2(stat)±36.7(syst) [ps]

${}^{4}_{\Lambda}H$: τ=218.3±7.5(stat)±11.8(syst) [ps]

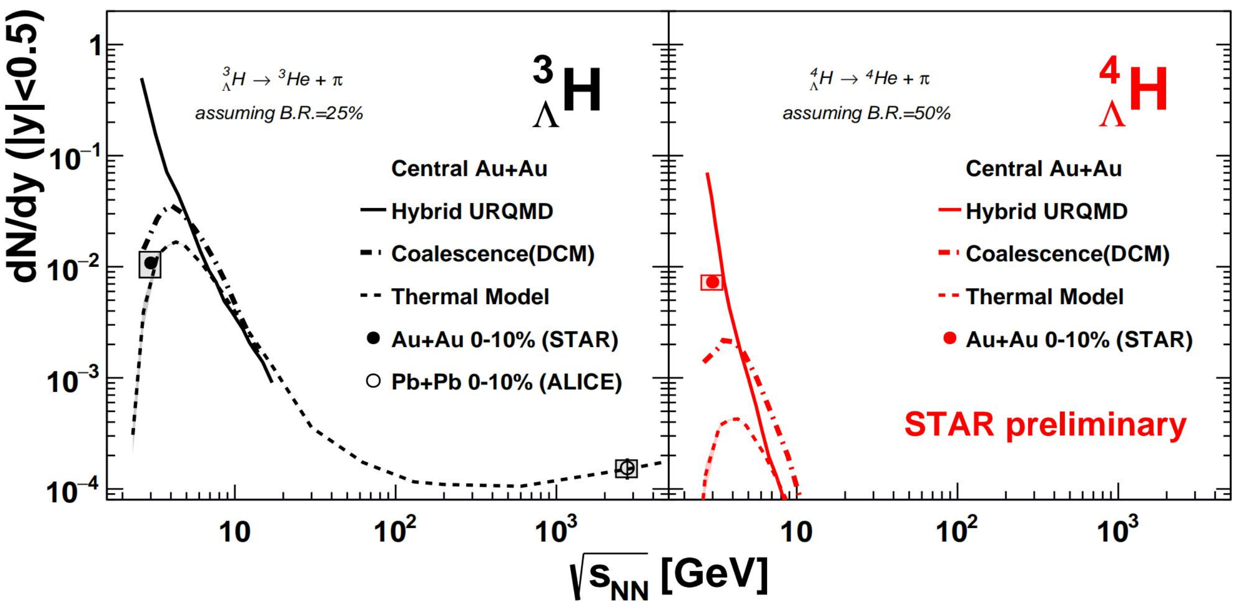
Lifetimes of light hyper-nuclei ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ are close to that of **Λ**
→ Precise measurements provide tighter constraints on models.

$^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$ Rapidity Density

Hyper-nuclei rapidity distributions



Mid-rapidity yields comparing with models



1) **First measurement** of hyper-nuclei rapidity distribution from high-energy nuclear collisions;
2) Mid-rapidity yield of $^{3}_{\Lambda}H$ described by thermal and coalescence model calculations while calculations from the thermal and coalescence model underpredict the yield of $^{4}_{\Lambda}H$

PLB714(2012),85 (Hybrid URQMD, Coalescence(DCM))
PLB 754 (2016)360 (ALICE)
PLB 697 (2011)203 (updated, preliminary) (Thermal Model)

${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ Collective Flow v_1

$$\frac{d^2N}{p_T dp_T d\varphi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T}\left\{1 + \sum_{n=1}^{\infty} 2v_n(p_T)\cos[n(\varphi - \Psi_R)]\right\}$$

– v_1 Directed flow; – v_2 Elliptic flow …

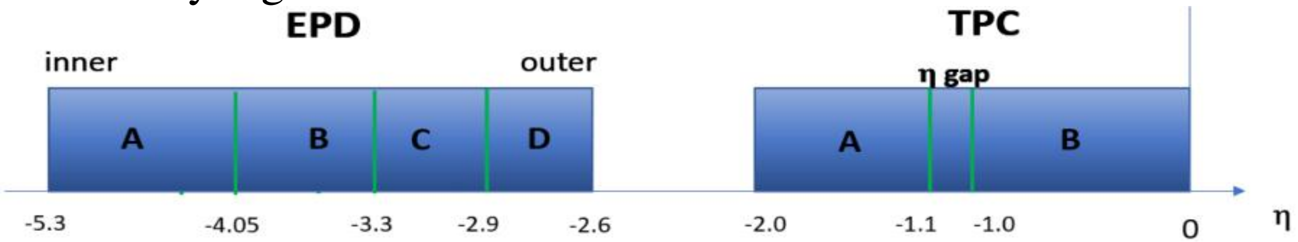
1) Fixed Target $\sqrt{s_{NN}}$ = 3 GeV Au+Au collision; $y_{target} \approx -1.045$
2) Charged tracks measured by TPC used for centrality defination;

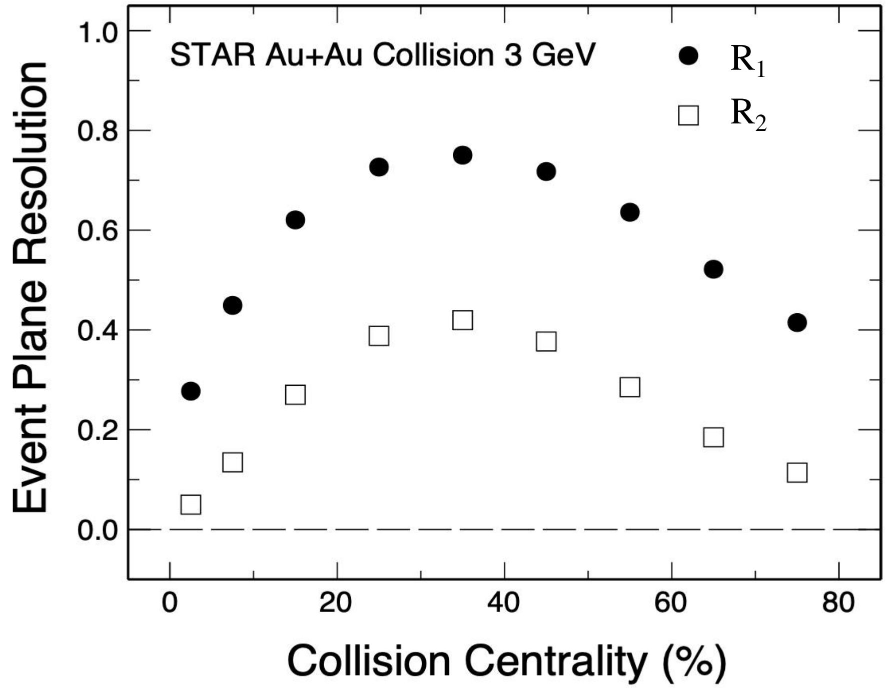
- 1st order event plane angle measured by Event Plane Detector(EPD)
- Event-plane resolution determination:

$$R_1 = \langle\cos(\Psi_1 - \Psi_r)\rangle = \frac{\sqrt{\pi}}{2\sqrt{2}}\chi_1 \exp(-\frac{\chi_1^2}{4})[I_0(\frac{\chi_1^2}{4}) + I_1(\frac{\chi_1^2}{4})]$$

$$R_2 = \langle\cos(2(\Psi_1 - \Psi_r))\rangle = \frac{\sqrt{\pi}}{2\sqrt{2}}\chi_1 \exp(-\frac{\chi_1^2}{4})[I_{\frac{1}{2}}(\frac{\chi_1^2}{4}) + I_{\frac{3}{2}}(\frac{\chi_1^2}{4})]$$

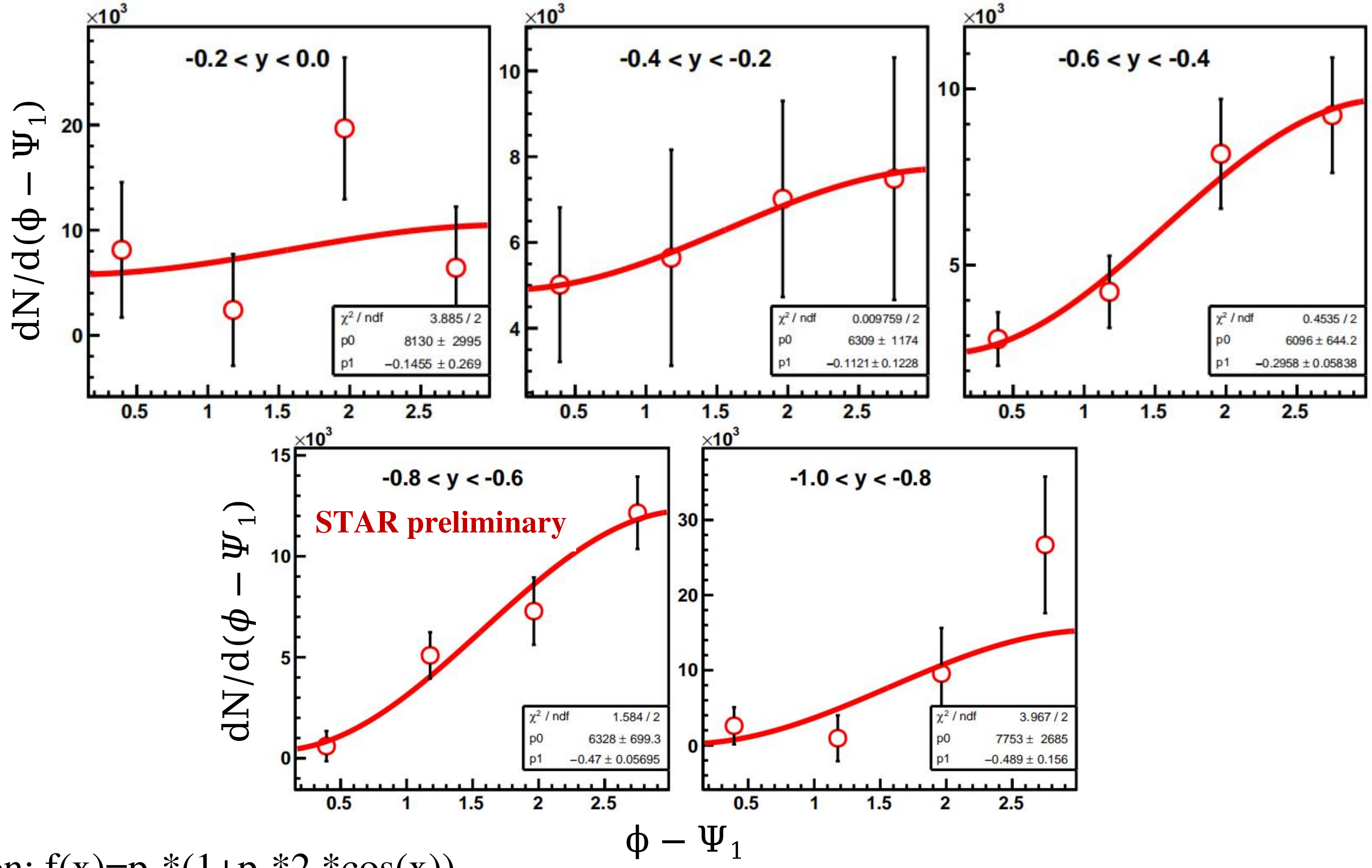
- The event plane resolution is in the range of 40 – 75% for the mid-centrality region 5-40% 3 GeV Au+Au collisions





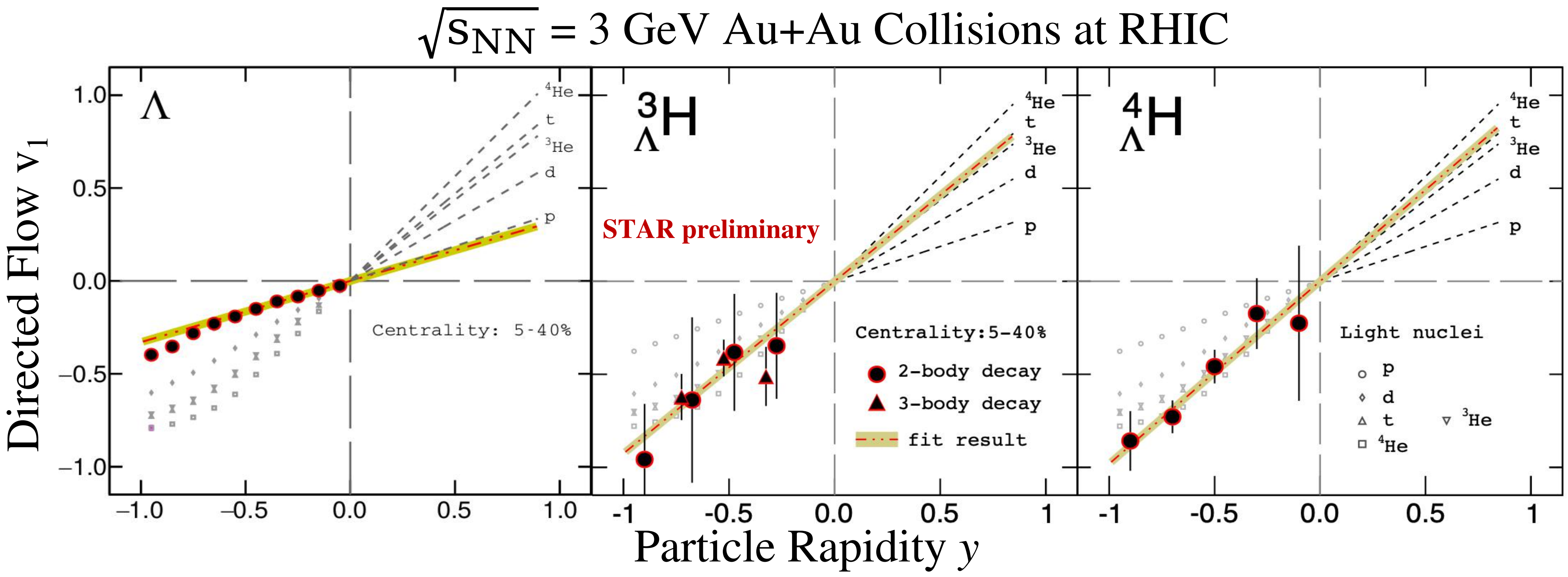
$^{4}_{\Lambda}H$ Angular Distributions

$^{4}_{\Lambda}H$ p_T: (1.2, 3.0) GeV/c; y: (-1.0, 0.0); Centrality: 5-40%



Fit function: $f(x)=p_0*(1+p_1*2.*\cos(x))$

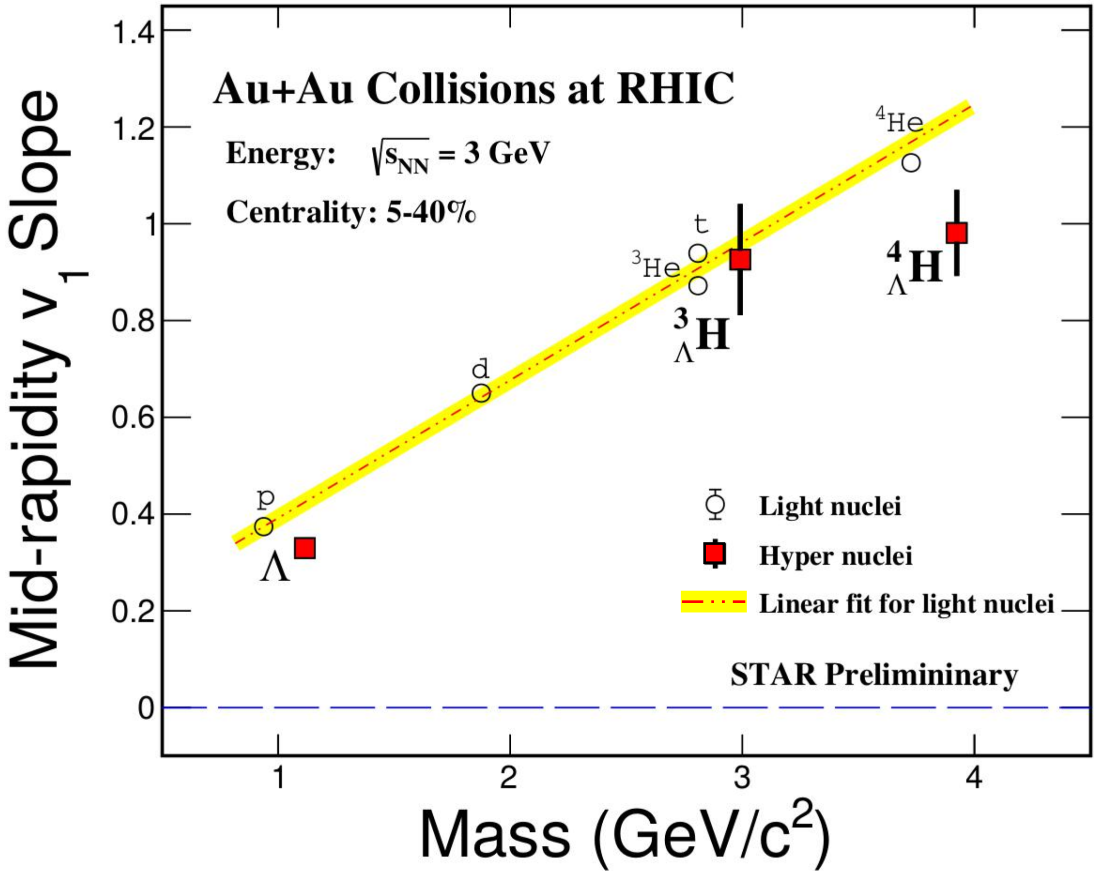
Λ, ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ Directed Flow v_1 vs. Rapidity



1) **First observation** of hyper-nuclei collectivity v_1 in high-energy nuclear collisions, EP resolution and efficiency corrections applied;
2) Like the cases for light nuclei, hyper-nuclei v_1 seems to follow the mass number scaling within uncertainties →

Coalescence is a dominant process for mid-rapidity hyper-nuclei formation in the collisions

Λ, ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ v_1-Slope vs. Particle Mass



1) Within statistical uncertainties, the slopes of v_1 for hyper-nuclei ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ seem following the mass number scaling in the 5-40% 3 GeV Au+Au collisions;
2) Analysis of systematic uncertainties under way;

→ Coalescence is a dominant process for hyper-nuclei formation in the collisions

Summary

1) Light hyper-nuclei ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ are reconstructed from 3 GeV Au+Au collisions at RHIC;

2) Three main results are in order:

   - Precision measurements of lifetime for both hyper-nuclei;

     ${}^{3}_{\Lambda}H$: 232.1±29.2(stat) ±36.7(sys) ps; **${}^{4}_{\Lambda}H$:** 218.3±7.5(stat) ±11.8(sys) ps

   - First measurement of ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ rapidity density from two centrality events;

   - First measurement of ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ collectivity v_1 from 5 – 40% centrality bin. Mass number scaling is observed for the light hyper-nuclei.

→ Light hyper-nuclei ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ are loosely bounded resulting in their lifetime close to that of Λ and v_1 slopes seem to follow the mass number scaling

Thank you very much for your attention!

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