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Light hypernculei directed flow measurements in $\sqrt{s_{NN}}$ = 3 GeV Au+Au collisions from STAR

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Outline

1) Motivation

2) STAR Detector System for Fixed-target Runs

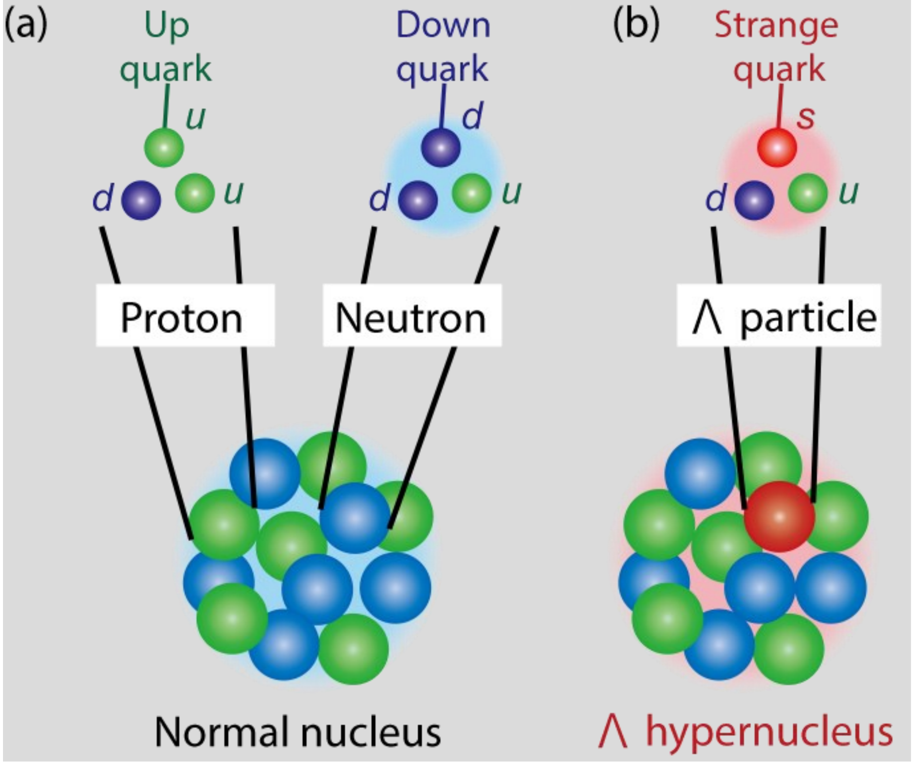
3) ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ Reconstruction

4) Directed flow of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$

5) Summary

1. Hyper-Nuclei and YN interaction

Hyper-nucleus： bound state of the hyperon(s) and nucleons.



Study on hyper-nuclei (i.e. lifetime, binding energy, decay BR.) provides valuable information of hyperon-nucleon (YN) interactions and nuclear force origin.

Binding energy of Λ Hypernuclei:

$$B_\Lambda({}^A_\Lambda Z) = \underbrace{M({}^{A-1}Z)}_{\text{Core mass}} + \underbrace{M(\Lambda)}_{\Lambda\text{ hyperon mass}} - \underbrace{M({}^A_\Lambda Z)}_{\text{Hyper-nuclei mass}}$$

Core mass

Λ hyperon mass

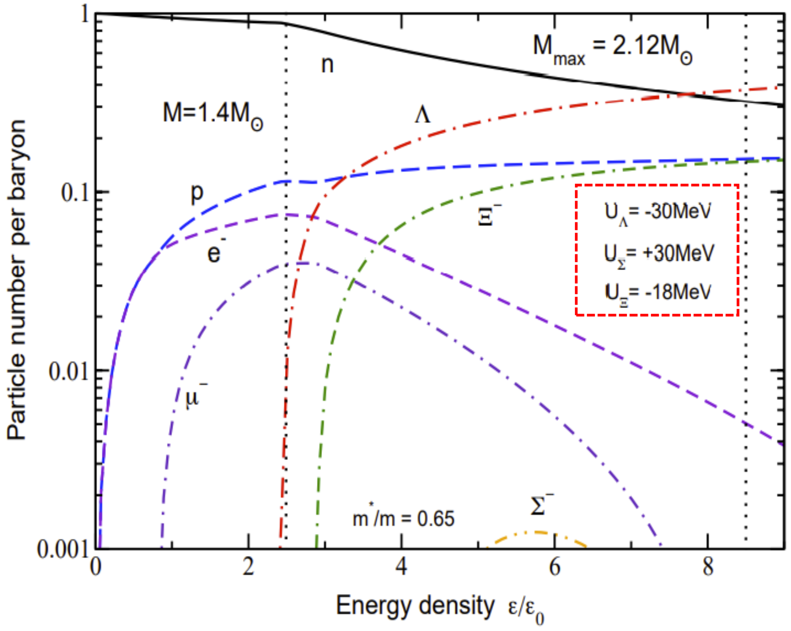
Hyper-nuclei mass

YN-interaction and Neutron Star

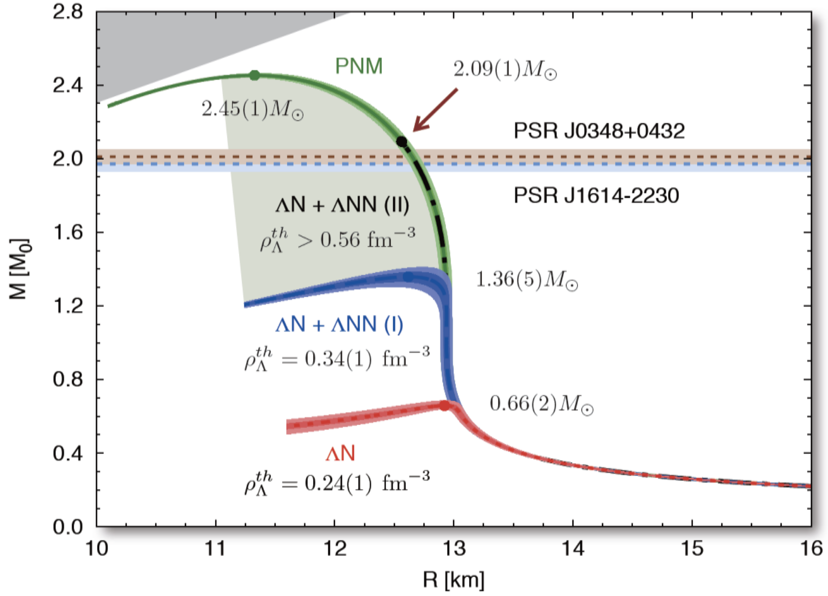
"Hyperon puzzle" : the difficulty to reconcile the measured masses of neutron stars (NSs) with the presence of hyperons in their interiors.

Density-dependent YN and YNN may be important!

[Ignazio Bombaci, JPS Conf. Proc. 17, 101002 (2017)]



Jürgen Schaffner-Bielich, 2021

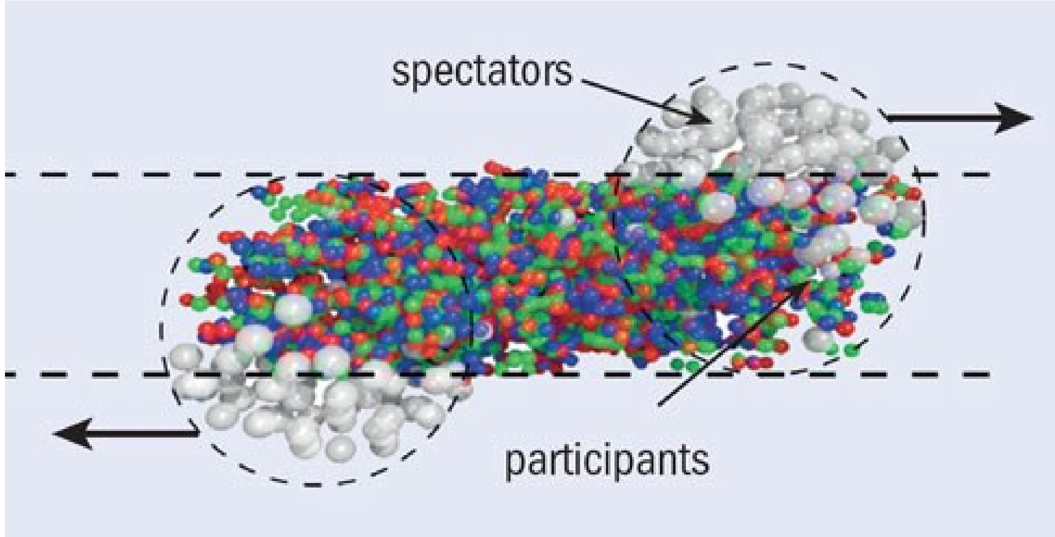


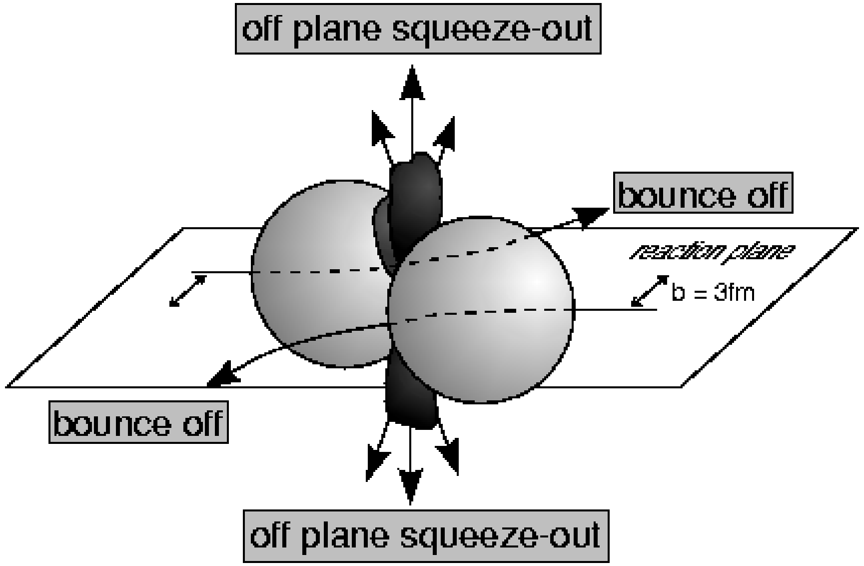
D. Lonardoni et al, PRL 114, 092301 (2015)

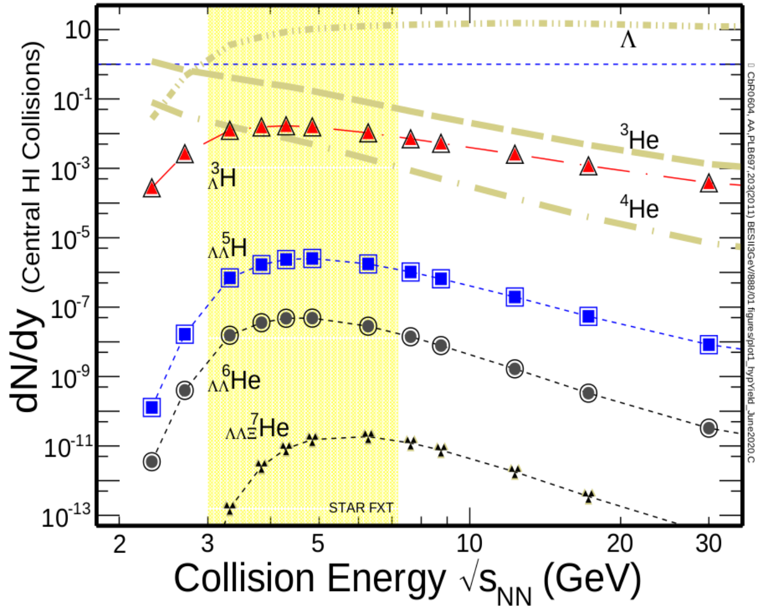
Other "hyperon puzzle" solutions: quark star, hybrid star, dark matter, ...

A. Li, et al. JHEAp 28, 19 (2020); A. D. Popolo et al, Phys. Dark Universe 28, 100484 (2020);

Hyper-nuclei Productions in Heavy Ion Collisions (HICs)



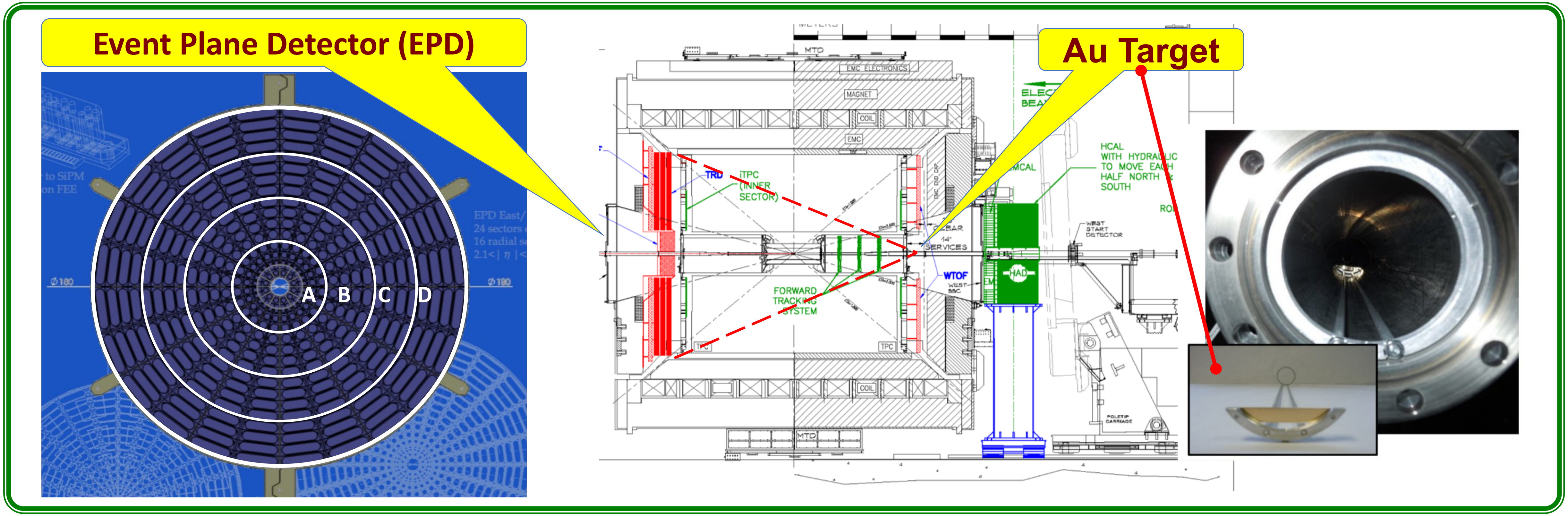




A. Andronic et al., Phys. Lett. **B697**, 203(2011) ; J. Steinheimer et al., Phys. Lett. **B714**, 85(2012)

Collective motion of baryonic matter is driven by the pressure gradient. Flow of hyper-nuclei may shed light on YN-interaction in condensed nuclear matter.

2. Fixed Target Setup at STAR



RHIC Beam Energy BES-II in 2018-2021:

- Fixed Target Run extends collision energy down to : $\sqrt{s_{NN}}$ = 3 - 7.7 GeV corresponding to baryon chemical potential: $750 \geq \mu_B \geq 420$ MeV

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

2018 STAR FXT 3 GeV data set;

260M minimum biased events

1) Hyper-nuclei reconstruction channels:

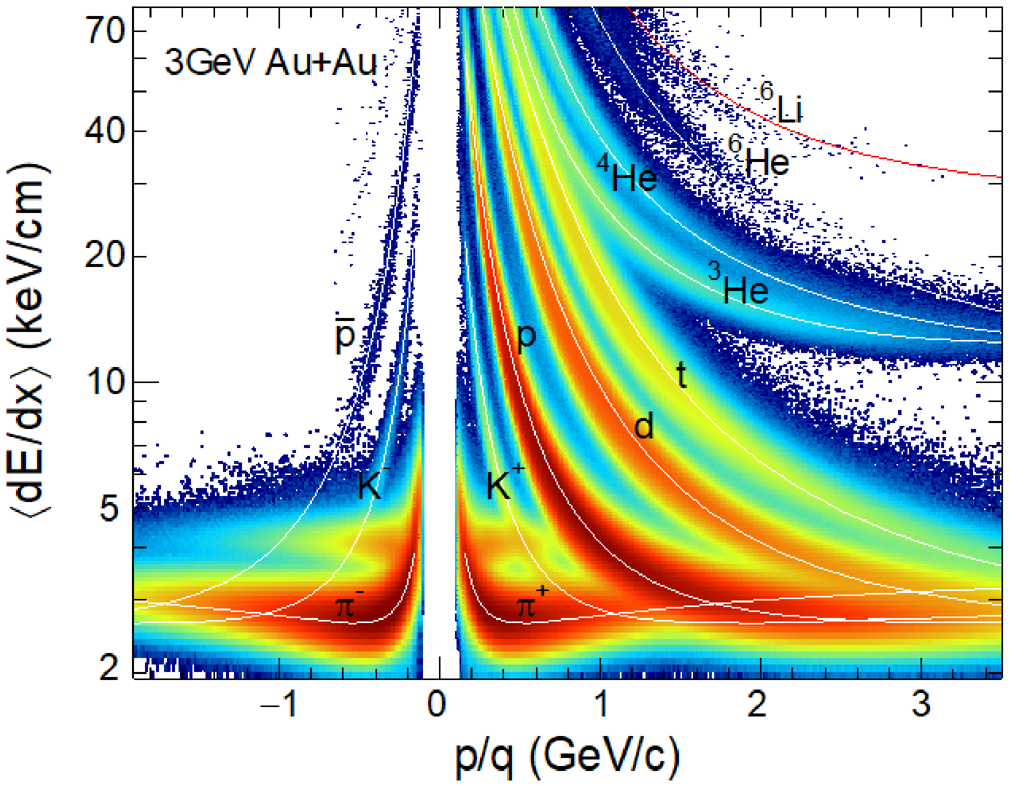
${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$ 2-body

${}^{3}_{\Lambda}H \rightarrow d + p + \pi^{-}$ 3-body

${}^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$ 2-body

2) PID of p, d, t, ${}^{3}He$, ${}^{4}He$, π^{-} is made based on TPC dE/dx vs p/q distribution;

STAR TPC Particle Identification



KFParticle: Reconstruction of Short-lived Particles

Concept and features:

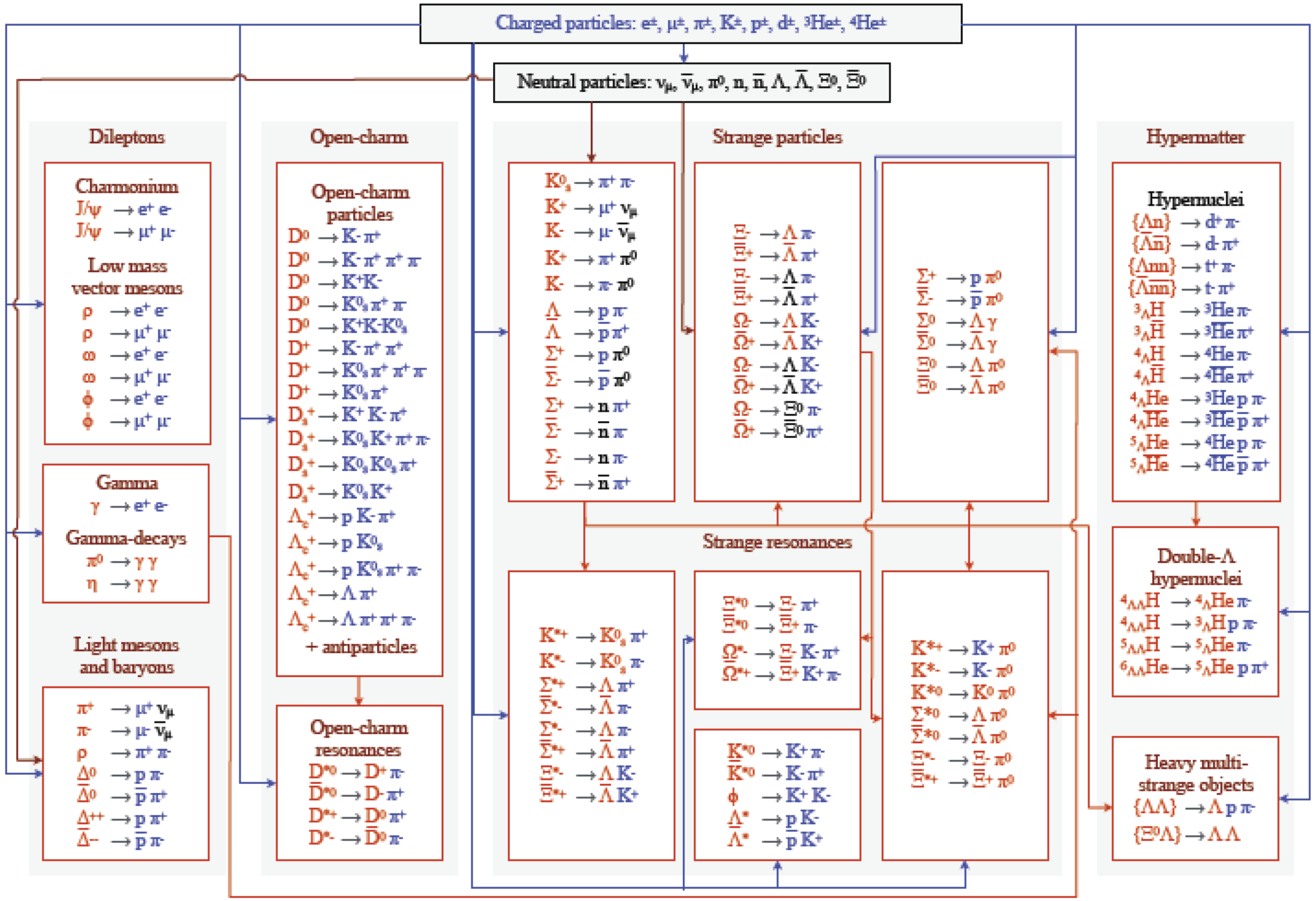
- Based on Kalman Filter (KF)
- Tracking and detector performance contained in Covariance matrix
- Geometry independent and Vectorized
- Natural and simple interface
- Large particle reconstruction database

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

State vector

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

Covariance matrix

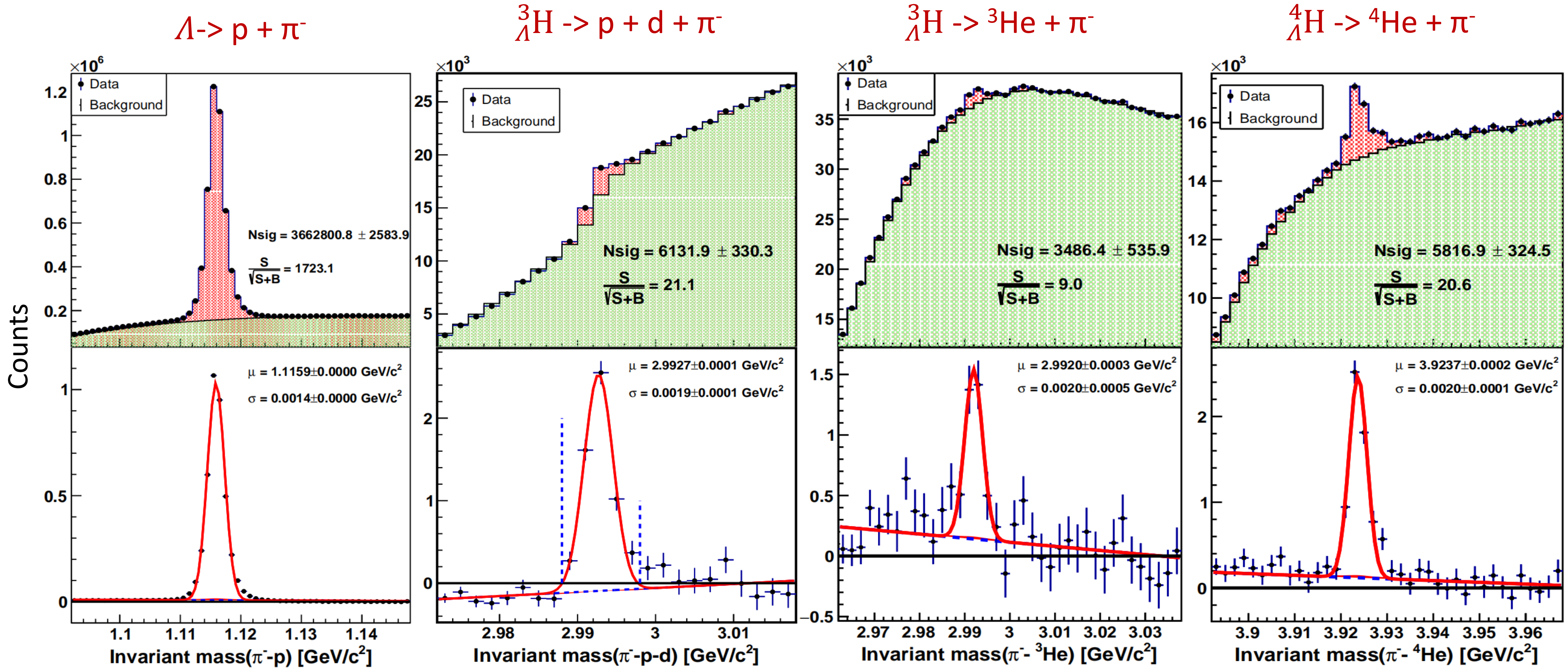


S. Gorbunov and I. Kisel, CBM-SOFT-note-2007-003, 7 May 2007

M. Zyzak, Dissertation thesis, Goethe University of Frankfurt, 2016, http://publikationen.ub.uni-frankfurt.de/frontdoor/index/index/docId/41428

KFParticle package has been adopted by CBM, ALICE, sPHENIX and STAR experiments

3. Λ, ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ Reconstruction

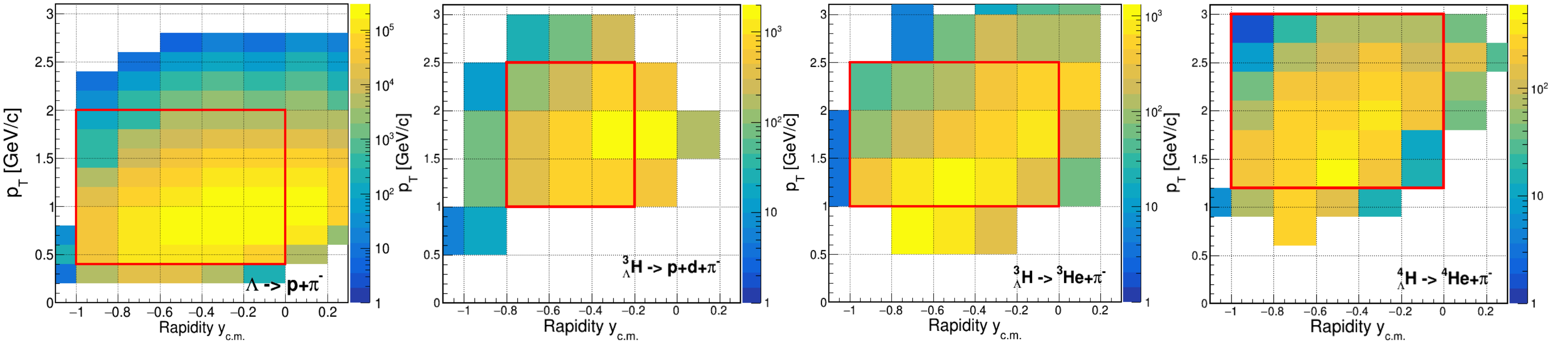


- KFParticle package used for Λ, ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ reconstructions

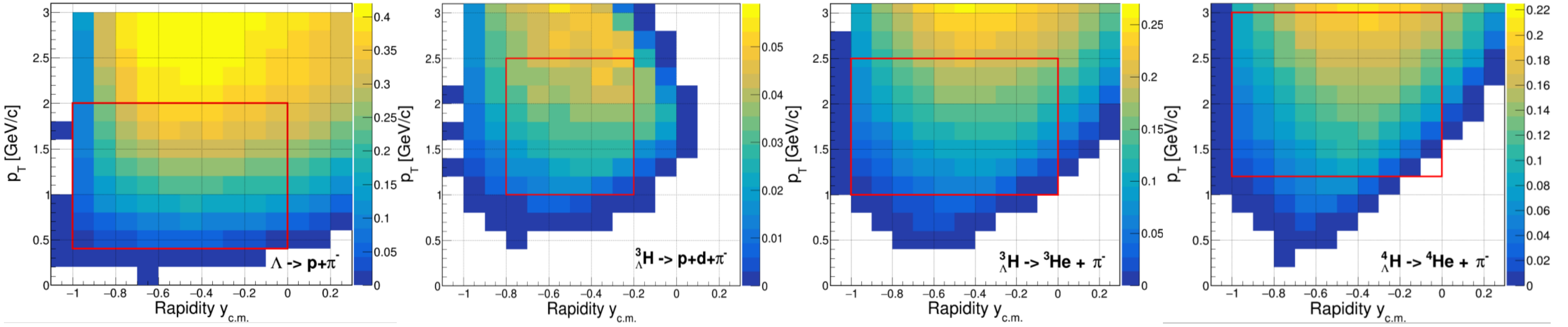
Λ, $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$ Phase Space and Efficiency

Phase space

Red box: phase space region used for flow analysis



Acceptance and Efficiency



4. Collective Flow with Event Plane Method

$$\frac{dN}{d(\varphi-\Psi_R)}=\frac{N_0}{2\pi}\left\{1+\sum_{n=1}^{\infty}2v_n cos[n(\varphi-\Psi_R)]\right\}$$

$-\ v_1$ Directed flow; $-\ v_2$ Elliptic flow …

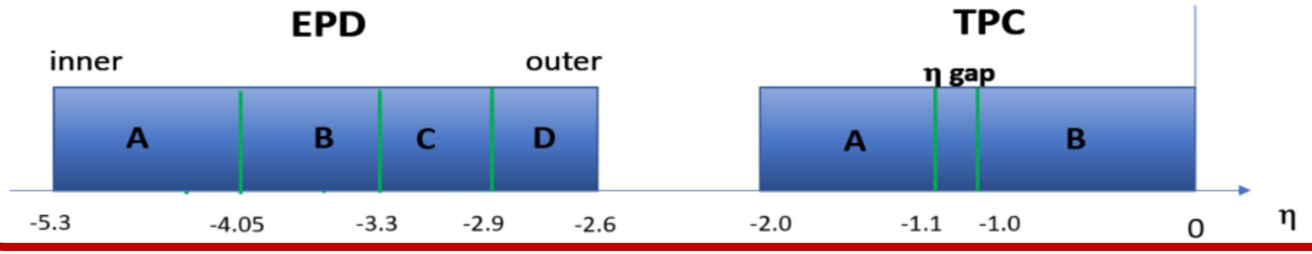
1) Fixed Target $\sqrt{s_{NN}}$ = 3 GeV Au+Au collisions
   $y_{target} \approx -1.045$
2) Charged tracks measured by TPC used for centrality definition

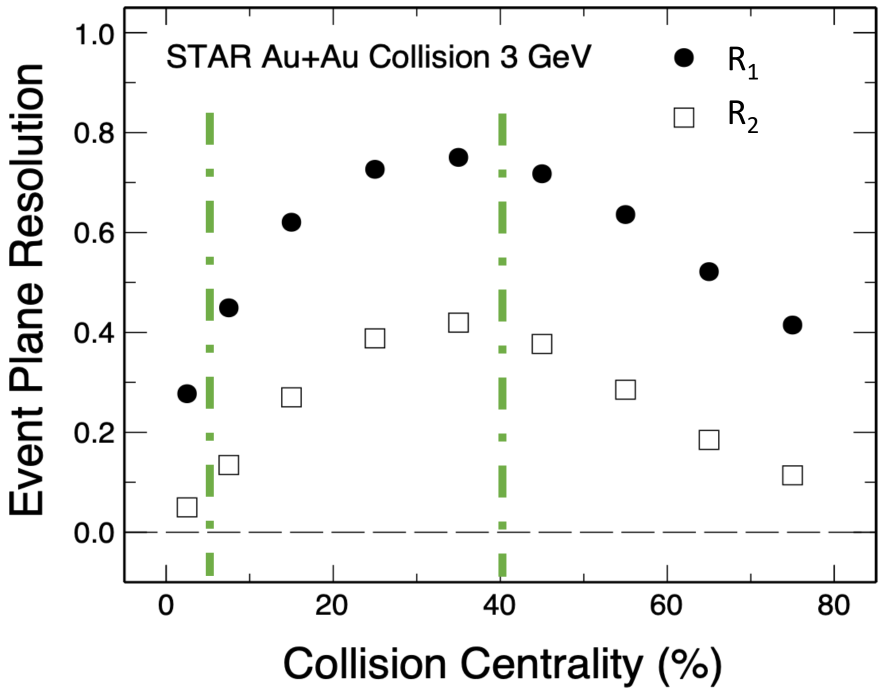
- 1st order event plane angle measured by Event Plane Detector(EPD)
- Event-plane resolution determination:

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

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

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





Directed flow analysis (Event Plane Method)

Fourier expansion of azimuthal distribution:

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}(1+2\sum_{n=1}^{\infty} v_n(p_T,y)\cos[n(\phi - \psi_R)])$$

ϕ : azimuthal angle

ψ_R : the n^th harmonic participant plane

v_n : n-th harmonic coefficient

Directed flow v_1: $v_1 = \langle cos(\phi - \psi_R)\rangle$

Ref. 1: Masui H , Schmah A , Poskanzer A M . Event plane resolution correction for azimuthal anisotropy in wide centrality bins[J]. Nuclear Inst & Methods in Physics Research A, 2016, 833:181-185.

Event Plane Method

procedure：

1. Signal extraction for a given ϕ - Ψ_m bin[ref.1];

$$N^R(\phi - \Psi_m) = \int_R dM \frac{1}{R_n}\frac{dN}{d(\phi - \Psi_m)}$$

$N^R(\phi - \Psi_m)$: number of particles for a given ϕ - Ψ_m bin

$\frac{1}{R_n}$: event plane resolution for each centrality bin

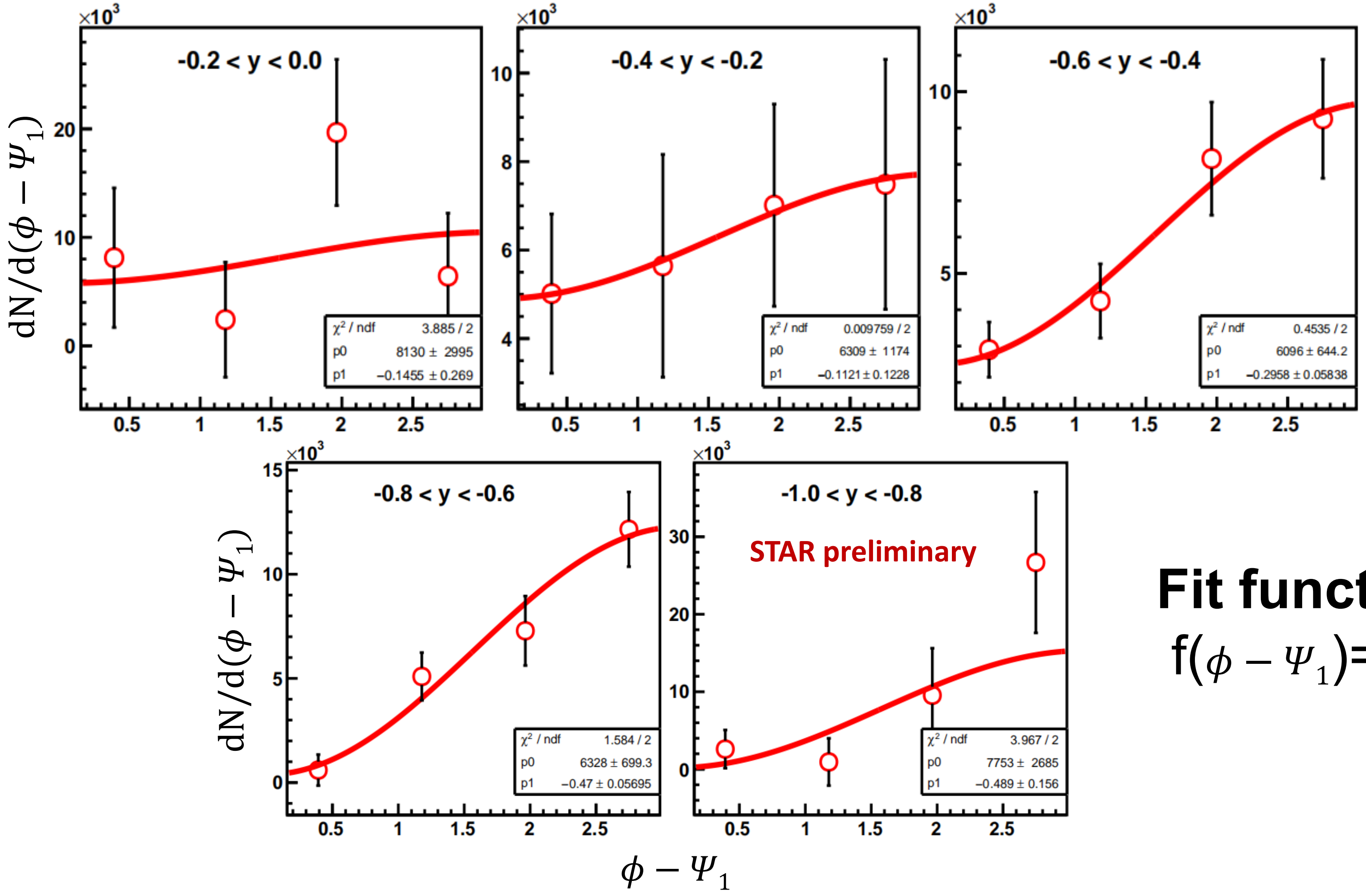
2. Fit dN/d$(\phi - \psi_1)$ distribution in rapidity bins to extract observed flow coefficients v_1^R;

3. Correct v_n^R with signal number weighted EP resolution;

$$\langle v_n\rangle = \langle v_n^R\rangle \langle\frac{1}{R_n}\rangle, \quad \langle\frac{1}{R_n}\rangle = \frac{\sum_i N_i * \langle\frac{1}{R_i}\rangle}{\sum_i N_i}$$

Angular Distributions of Hyper-nuclei

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

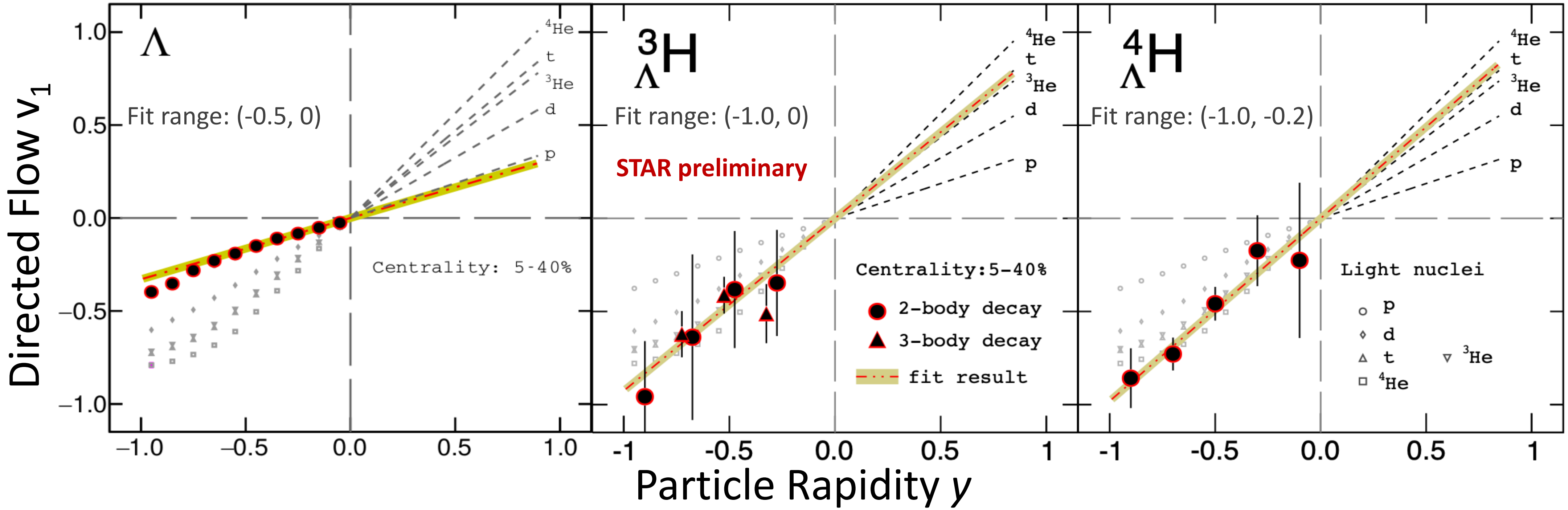


Fit function:

$$f(\phi - \Psi_1) = p_0 * (1 + v_1 * 2. * \cos(\phi - \Psi_1))$$

Directed Flow v_1 vs. Rapidity

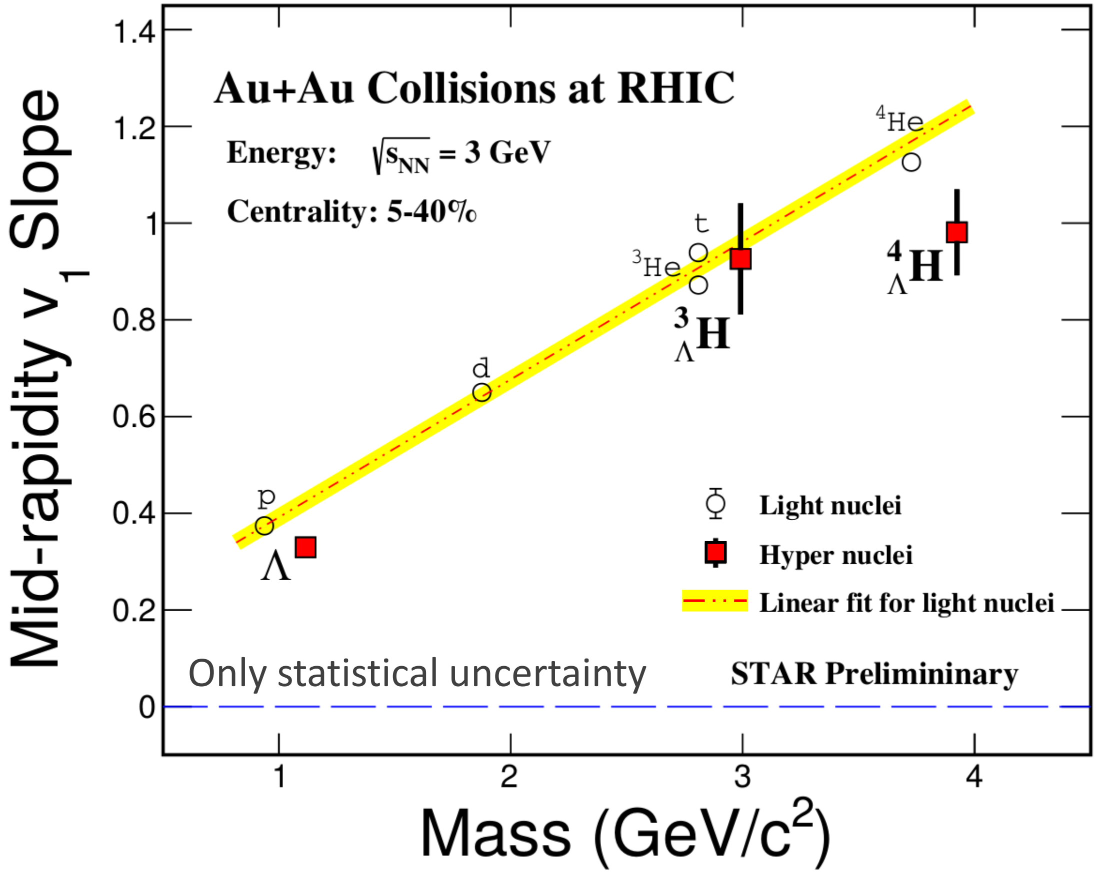
$\sqrt{s_{NN}}$ = 3 GeV Au+Au Collisions at RHIC



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 a mass number scaling in the 5-40% 3 GeV Au+Au collisions.

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

→ **Theoritical inputs for collective flow of hyper-nuclei are needed**

5. Summary

1) Light hyper-nuclei ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ are reconstructed from 3 GeV Au+Au collisions at RHIC; Largest ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ data samples collected.
2) First measurements of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ directed flow (v_1) from 5 – 40% centrality. Analysis of the systematic uncertainties is underway.
3) dv_1/dy slopes of hyper-nuclei ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ seem to follow a mass number scaling. This result implies that *coalescence* is a dominant process for hyper-nuclei formation in such collisions.
4) Theoretical inputs for collective flow of hyper-nuclei in HICs are needed.

Thank you very much for your attention!

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