Productions of ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$, and ${}^{4}_{\Lambda}\mathrm{He}$ in different coalescence channels in Au-Au collisions at $\sqrt{s_{NN}} = 3$ GeV

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References: Chin. Phys. C **48** (5), 053112, 2024; arXiv: 2504.13640.

Outline

I. Introduction

II. Analytical coalescence model

formalism of two-body coalescence

formalism of three-body coalescence

general formalism of *N*-body coalescence

III. Results in 3 GeV Au-Au collisions at RHIC

inputs: p_T spectra of nucleons and Λ hyperons

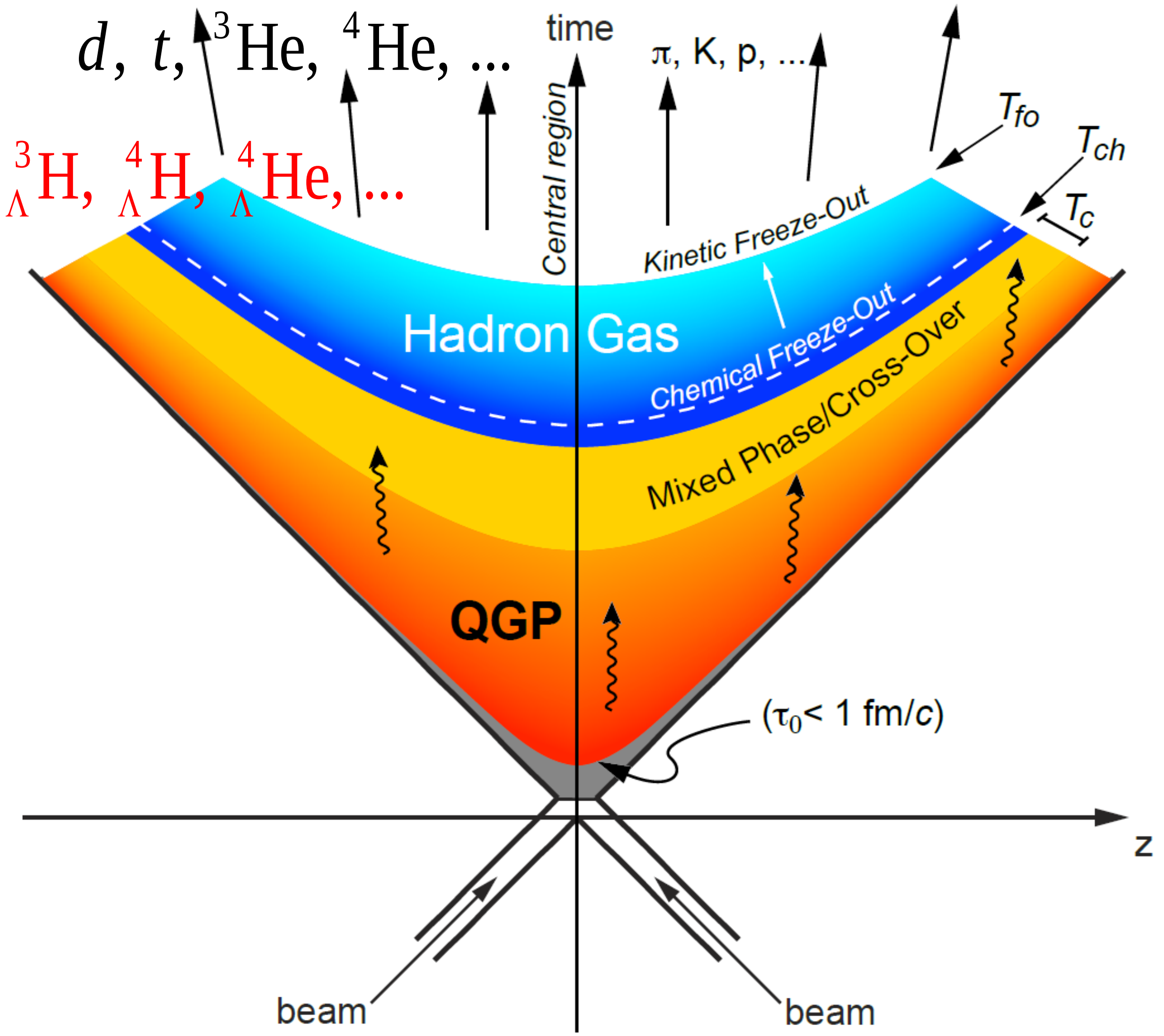
p_T spectra, dN/dy, <p_T> of ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$

production asymmetry between ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$

IV. Summary

I. Introduction

What can hyper-nuclei in relativistic heavy-ion collisions tell us?



- **Natural tools for elementary hyperon-nucleon and hyperon-hyperon interactions**
- **Probes of system freeze-out property**
- **Production mechanisms of composite particles with strangeness flavor quantum number**
- **……**

Theoretical studies

Thermal models

$$N_i = V\int \frac{d^3\vec{p}}{(2\pi)^3} \frac{g_i}{\exp[(\sqrt{\vec{p}^2 + m_i^2} - \mu_i)/T_{ch}] \pm 1}$$

A. Andronic, P. Braun-Munzinger, J. Stachel, and H. Stocker, Phys. Lett. B **697**, 203, 2011;

J. Cleymans, S. Kabana, I. Kraus, H. Oeschler, K. Redlich, and N. Sharma, Phys. Rev. C **84**, 054916, 2011;

V. Vovchenko, B. Donigus, and H. Stoecker, Phys. Lett. B **785**, 171, 2018;

… …

Coalescence models

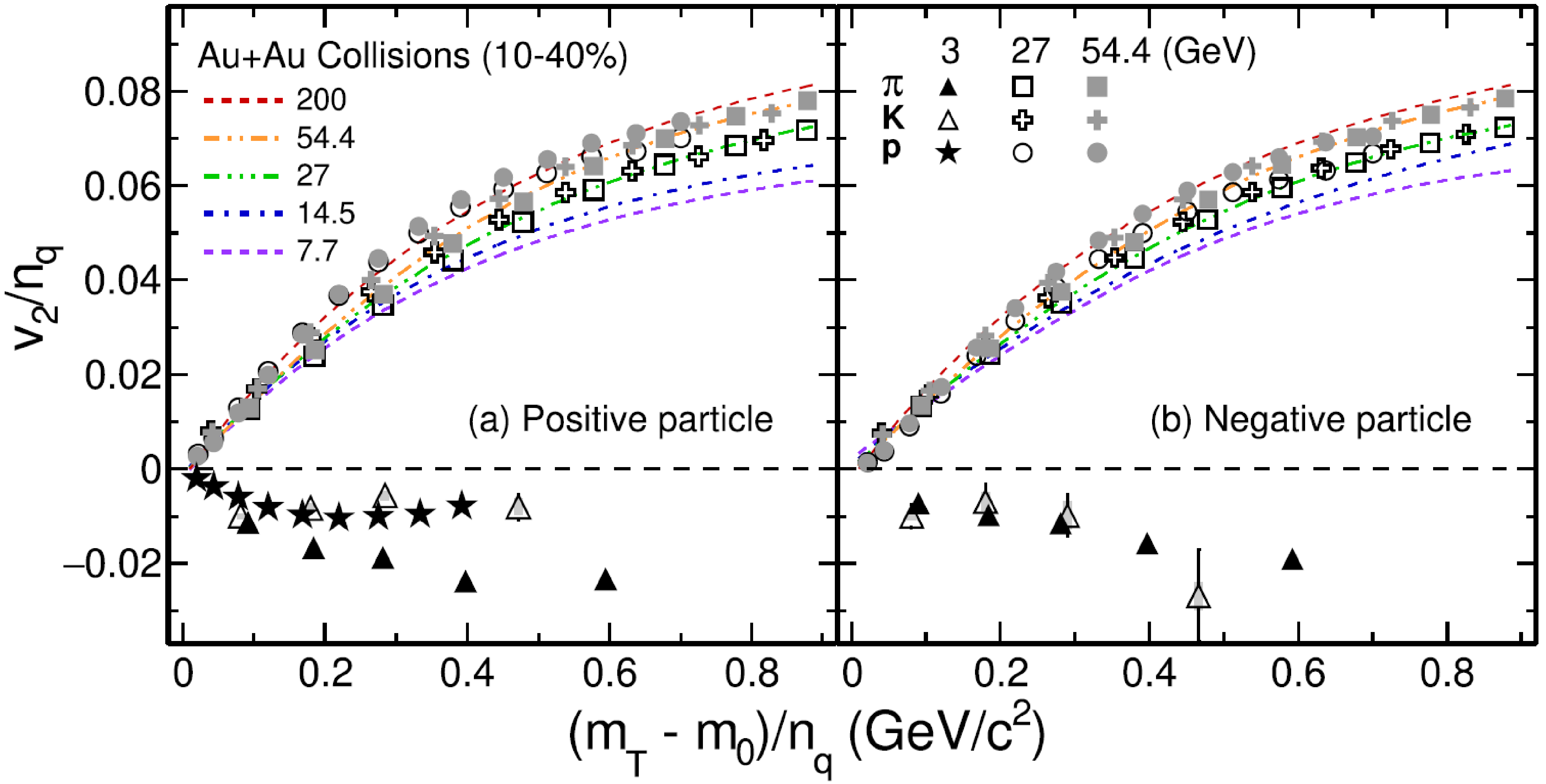
$$f_H \sim f_p^Z f_\Lambda^{N_\Lambda} f_n^{A-Z-N_\Lambda} \otimes R_H$$

M. Wakai, Nucl. Phys. A **547**, 89c-94c, 1992;
K.J. Sun and L.W. Chen, Phys. Rev. C **94**, 064908, 2016;
Z. Zhang and C.M. Ko, Phys. Lett. B **780**, 191, 2018;
K.J. Sun, C.M. Ko, and B. Donigus, Phys. Lett. B **792**, 132, 2019;
D.N. Liu, C.M. Ko, Y.G. Ma, F. Mazzaschi, M. Puccio, Q.Y. Shou, K.J. Sun, and Y.Z. Wang, Phys. Lett. B **855**, 138855, 2024;

… …

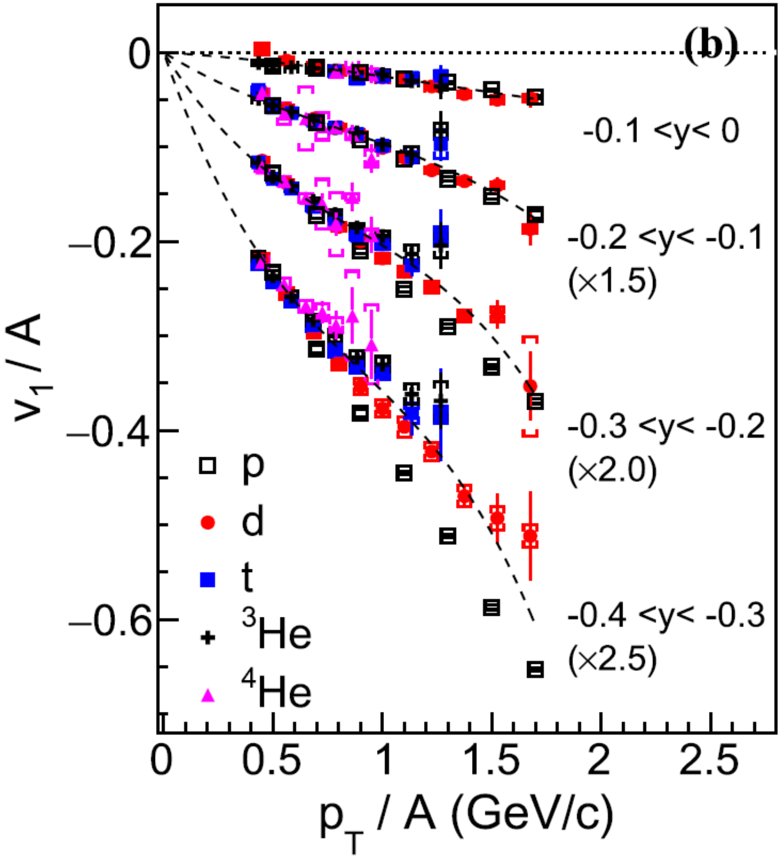
RHIC Experiment: 3 GeV Au-Au

STAR, PLB 827, 137003, 2022

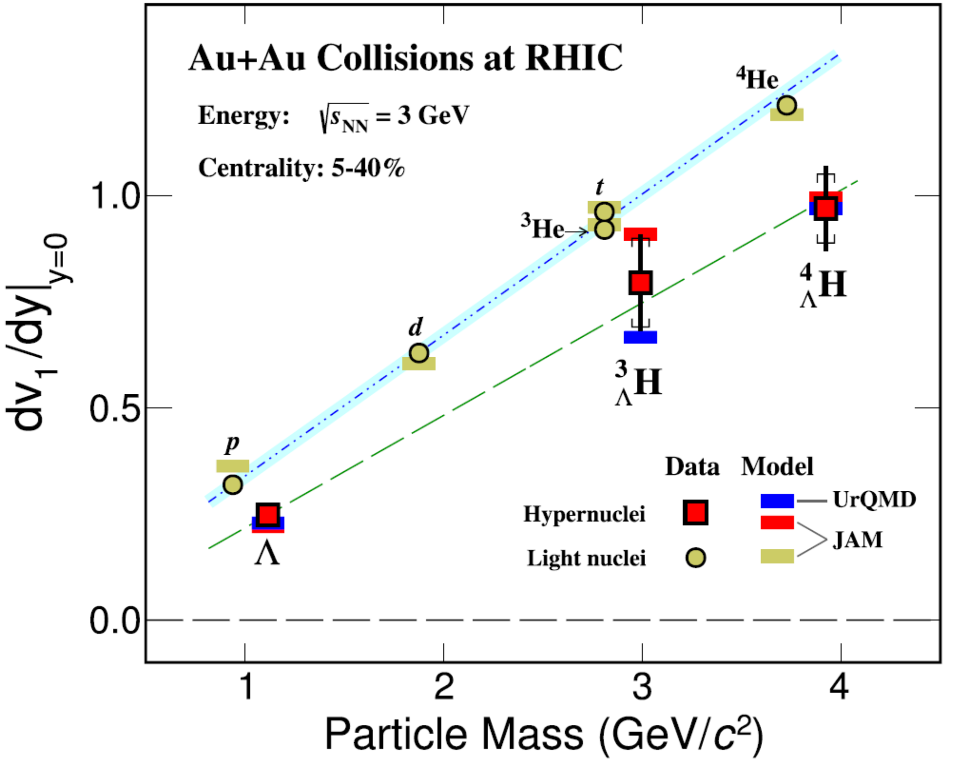


Partonic collectivity disappears and hadronic matter is predominantly created.

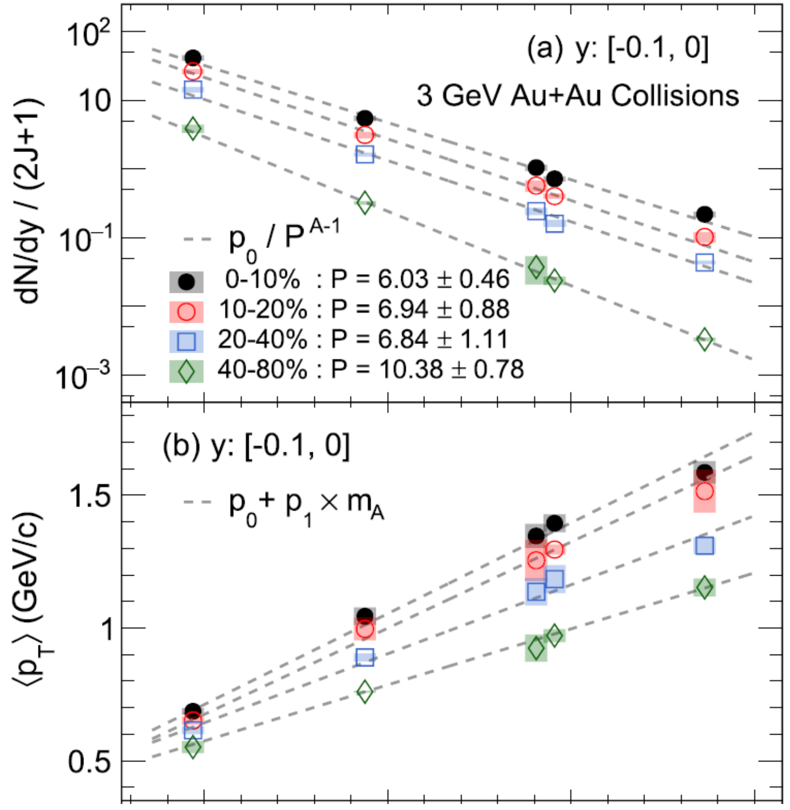
RHIC Experiment: 3 GeV Au-Au



STAR, PLB 827, 136941, 2022



STAR, PRL 130, 212301, 2023



STAR, PRC 110, 054911, 2024

Hadronic collectivity still holds and coalescence production may dominate for nuclei.

We developed an analytical description for the productions of different species of light nuclei in the coalescence picture --- the analytical coalescence model.

in 3 GeV Au-Au collisions

besides nucleon coalescence, include other coalescence processes

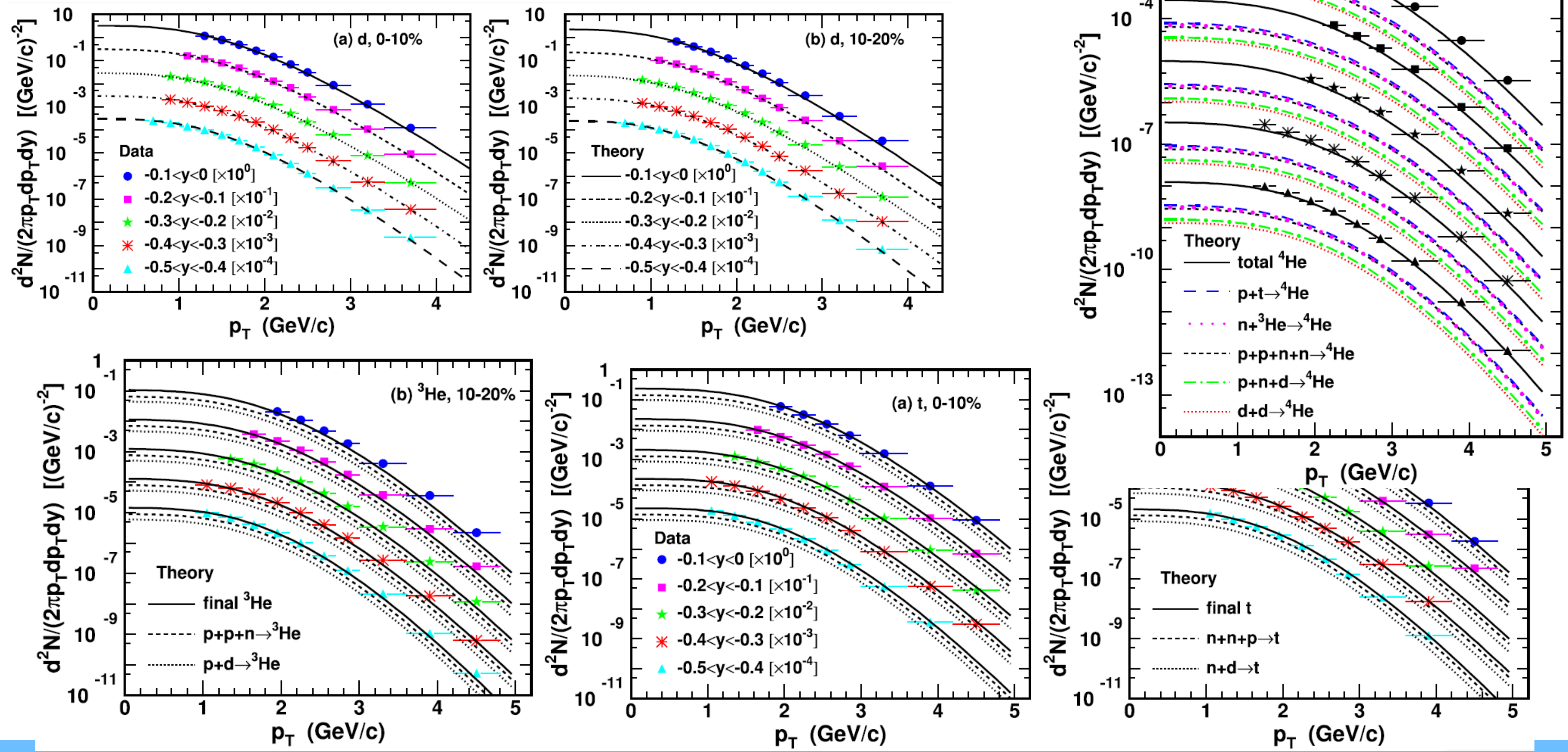
$$p+n\to d;$$

$$p+n+n\to t,\quad n+d\to t;$$

$$p+p+n\to {}^{3}\mathrm{He},\quad p+d\to {}^{3}\mathrm{He};$$

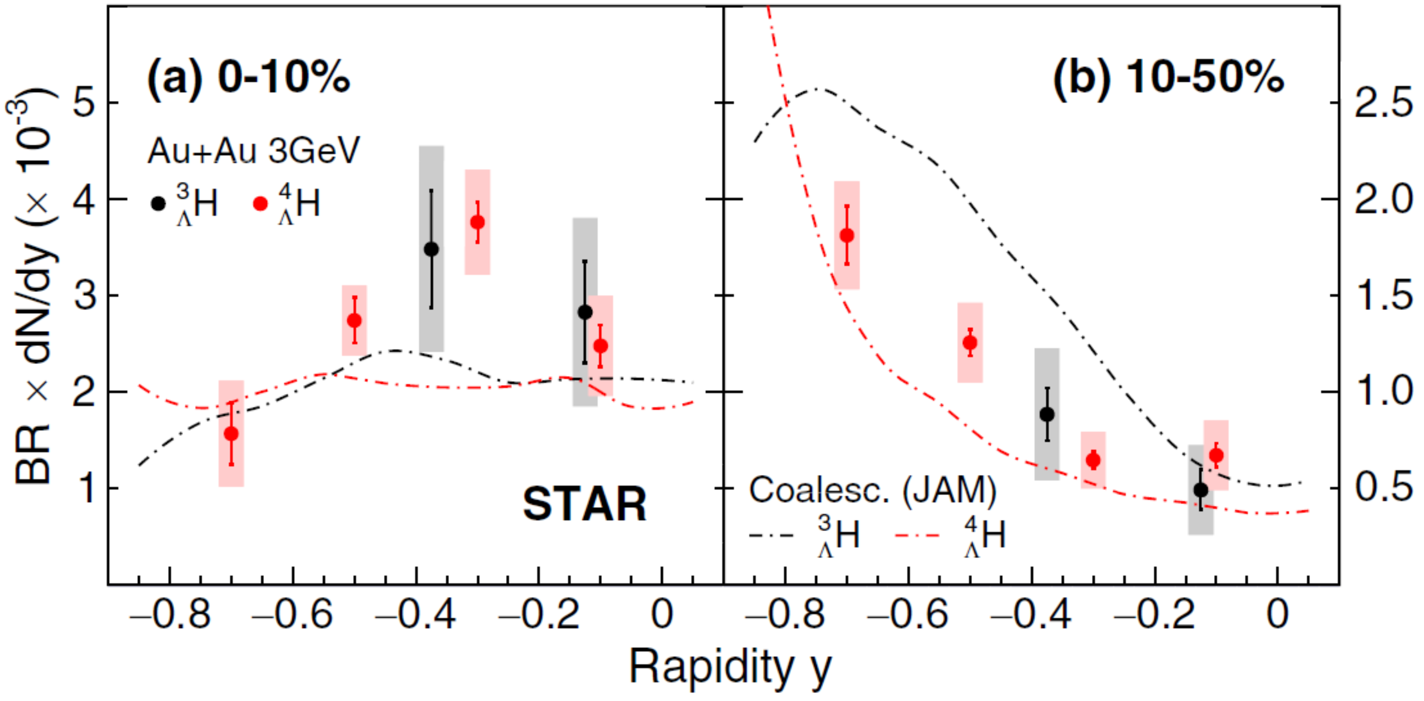
$$p+p+n+n\to {}^{4}\mathrm{He},\ p+n+d\to {}^{4}\mathrm{He},\ p+t\to {}^{4}\mathrm{He},\ n+{}^{3}\mathrm{He}\to {}^{4}\mathrm{He},\ d+d\to {}^{4}\mathrm{He}.$$

RQW, J.P. Lv, Y.H. Li, J. Song, F.L. Shao, Chin. Phys. C 48 (5), 053112, 2024.



Besides nucleon coalescence, nucleus+nucleon coalescence may play a requisite role.

3 GeV Au-Au



- **For hyper-nuclei, besides nucleon+hyperon coalescence, are coalescence processes involving nucleus participation still necessary?**
- **If yes, what new characteristics will they bring?**

We extend the analytical coalescence model to the strange sector to study hyper-nuclei.

Two-body coalescence $h_1 + h_2 \to H_j$

The three-dimensional momentum distribution

$$f_{H_j}(\vec{p}) = \int d\vec{x}_1 d\vec{x}_2 d\vec{p}_1 d\vec{p}_2 \, f_{h_1h_2}(\vec{x}_1, \vec{x}_2; \vec{p}_1, \vec{p}_2) \mathcal{R}_{H_j}(\vec{x}_1, \vec{x}_2; \vec{p}_1, \vec{p}_2, \vec{p})$$

kernel function $\mathcal{R}_{H_j}(\vec{x}_1, \vec{x}_2; \vec{p}_1, \vec{p}_2, \vec{p}) = g_{H_j} \mathcal{R}_{H_j}^{(x,p)}(\vec{x}_1, \vec{x}_2; \vec{p}_1, \vec{p}_2) \delta(\sum_{i=1}^{2} \vec{p}_i - \vec{p})$

$$\mathcal{R}_{H_j}^{(x,p)}(\vec{x}_1, \vec{x}_2; \vec{p}_1, \vec{p}_2) = 8 e^{-\frac{(\vec{x}'_1 - \vec{x}'_2)^2}{2\sigma_{21}^2}} e^{-\frac{2\sigma_{21}^2 (m_2 \vec{p}'_1 - m_1 \vec{p}'_2)^2}{(m_1+m_2)^2}}$$

two-hadron joint coordinate momentum distribution

$$f_{h_1h_2}(\vec{x}_1, \vec{x}_2; \vec{p}_1, \vec{p}_2) = N_{h_1h_2} f_{h_1h_2}^{(n)}(\vec{x}_1, \vec{x}_2; \vec{p}_1, \vec{p}_2) = N_{h_1h_2} f_{h_1h_2}^{(n)}(\vec{x}_1, \vec{x}_2) f_{h_1h_2}^{(n)}(\vec{p}_1, \vec{p}_2)$$

assumption 1: coordinate-momentum factorization

Two-body coalescence $h_1 + h_2 \to H_j$

The three-dimensional momentum distribution

$$f_{H_j}(\vec{p}) = N_{h_1h_2} g_{H_j} A_{H_j} M_{H_j}(\vec{p})$$

$$\vec{X} = \frac{\sqrt{2}(m_1\vec{x}_1 + m_2\vec{x}_2)}{m_1 + m_2}, \ \vec{r} = \frac{\vec{x}_1 - \vec{x}_2}{\sqrt{2}}$$

$$f_{h_1h_2}^{(n)}(\vec{r}) = \frac{1}{(\pi C_1 R_f^2)^{3/2}} e^{-\frac{\vec{r}^2}{C_1 R_f^2}}$$

$$A_{H_j} = 8\int d\vec{x}_1 d\vec{x}_2 f_{h_1h_2}^{(n)}(\vec{x}_1, \vec{x}_2) e^{-\frac{(\vec{x}'_1 - \vec{x}'_2)^2}{2\sigma_{21}^2}} = \frac{8\sigma_{21}^3}{(C_1R_f^2 + \sigma_{21}^2)\sqrt{C_1(R_f/\gamma)^2 + \sigma_{21}^2}}$$

$$M_{H_j}(\vec{p}) = \int d\vec{p}_1 d\vec{p}_2 f_{h_1h_2}^{(n)}(\vec{p}_1, \vec{p}_2) e^{-\frac{2\sigma_{21}^2(m_2\vec{p}'_1 - m_1\vec{p}'_2)^2}{(m_1+m_2)^2}} \delta(\sum_{i=1}^{2}\vec{p}_i - \vec{p}) = (\frac{\sqrt{\pi}}{\sqrt{2}\sigma_{21}})^3 \gamma f_{h_1h_2}(\frac{m_1\vec{p}}{m_1+m_2}, \frac{m_2\vec{p}}{m_1+m_2})$$

assumption 2: delta function approximation

Two-body coalescence $h_1 + h_2 \to H_j$

The three-dimensional momentum distribution

$$f_{H_j}(\vec{p}) = \frac{8\pi^{3/2} g_{H_j} \gamma}{2^{3/2}(C_1 R_f^2 + \sigma_{21}^2)\sqrt{C_1 (R_f/\gamma)^2 + \sigma_{21}^2}} f_{h_1}\left(\frac{m_1 \vec{p}}{m_1 + m_2}\right) f_{h_2}\left(\frac{m_2 \vec{p}}{m_1 + m_2}\right)$$

The invariant momentum distribution

$$f_{H_j}^{(\mathrm{inv})}(p_T, y) = \frac{8\pi^{3/2} g_{H_j}}{2^{3/2}(C_1 R_f^2 + \sigma_{21}^2)\sqrt{C_1 (R_f/\gamma)^2 + \sigma_{21}^2}} \frac{m_{H_j}}{m_1 m_2} f_{h_1}^{(\mathrm{inv})}\left(\frac{m_1 p_T}{m_1 + m_2}, y\right) f_{h_2}^{(\mathrm{inv})}\left(\frac{m_2 p_T}{m_1 + m_2}, y\right)$$

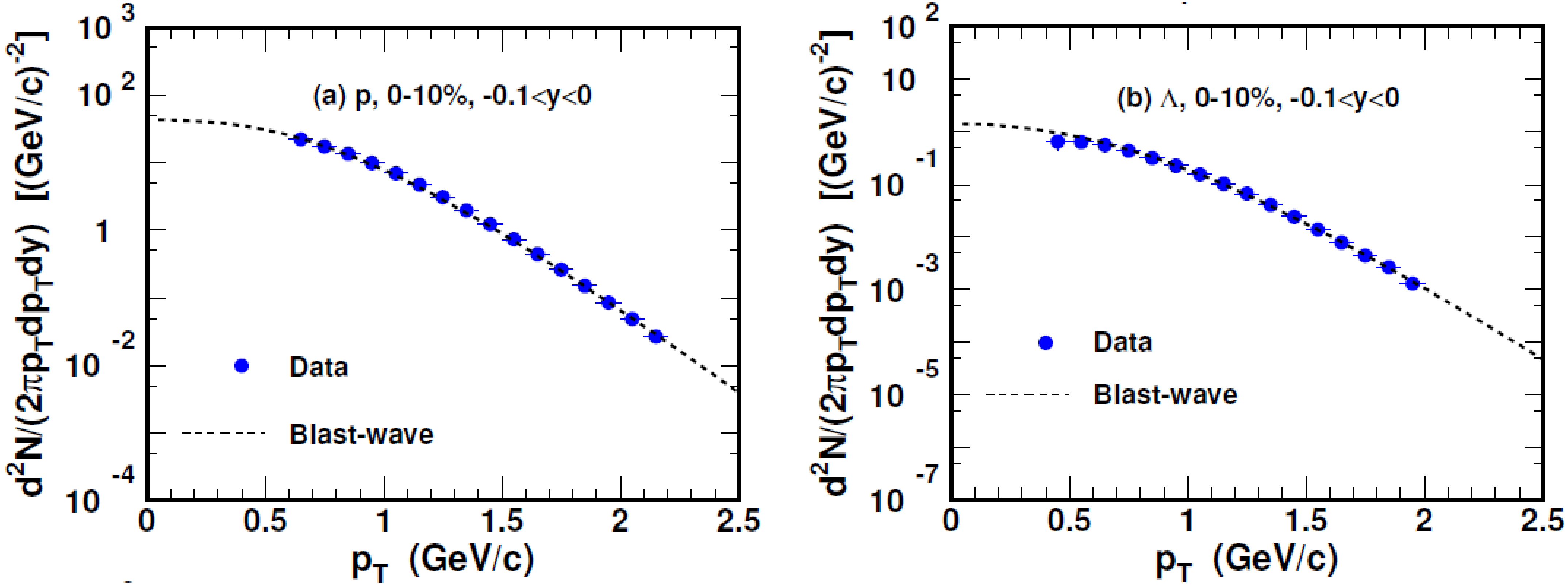
N-body coalescence $h_1 + h_2 + \cdots + h_N \to H_j$

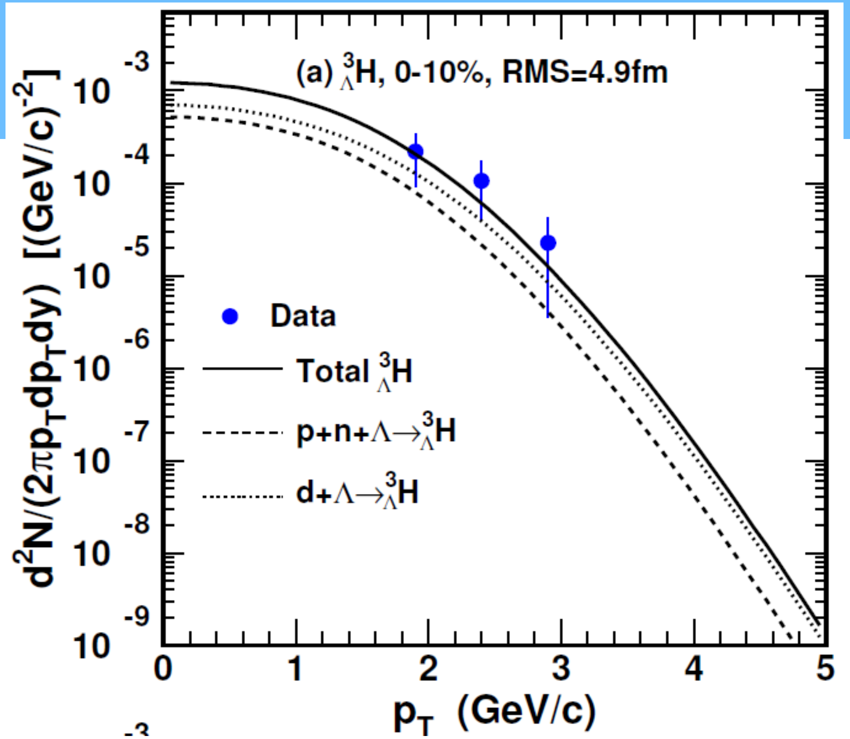
$$f_{H_j}^{(\mathrm{inv})}(p_T, y) = \frac{8^{N-1} \pi^{3(N-1)/2} g_{H_j} m_{H_j}}{N^{3/2} \prod_{k=1}^{N-1} (C_k R_f^2 + \sigma_{Nk}^2)\sqrt{C_k (R_f/\gamma)^2 + \sigma_{Nk}^2}} \prod_{i=1}^{N} \frac{1}{m_i} f_{h_i}^{(\mathrm{inv})}\left(\frac{m_i p_T}{m_1 + m_2 + \cdots + m_N}, y\right)$$

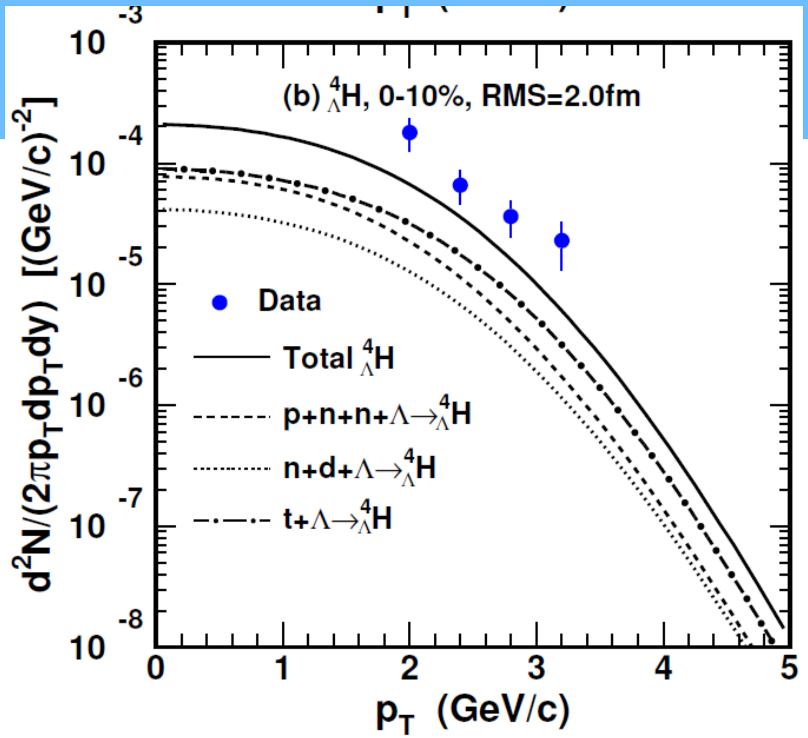
III. Results in Au-Au collisions at 3 GeV

model parameters: $R_f = 3.27$ fm, $Z_{np} = 1.34$ **have been determined via light nuclei.**

model inputs: $p^{\exp} / 80\%$, $\Lambda^{\exp}$







	Coal-channel	dN/dy Data	dN/dy Theory	$\langle p_T \rangle$ Data	$\langle p_T \rangle$ Theory
$^{3}_{\Lambda}H$	$p+n+\Lambda$	– – –	0.323×10^{-2}	– – –	1.191
	$d+\Lambda$	– – –	0.467×10^{-2}	– – –	1.246
	Total	$(1.131 \pm 0.210 \pm 0.384) \times 10^{-2}$	0.790×10^{-2}	$1.254 \pm 0.087 \pm 0.163$	1.224
$^{4}_{\Lambda}H$	$p+n+n+\Lambda$	– – –	0.764×10^{-3}	– – –	1.475
	$n+d+\Lambda$	– – –	0.423×10^{-3}	– – –	1.514
	$t+\Lambda$	– – –	1.001×10^{-3}	– – –	1.566
	Total	$(4.954 \pm 0.434 \pm 1.014) \times 10^{-3}$	2.188×10^{-3}	$1.506 \pm 0.043 \pm 0.122$	1.524

30% lower

56% lower

A possible reason of such underestimations may be omissions of some certain coalescence channels. In these channels some perdue states which have not been affirmed at experiments participate in the coalescence process.

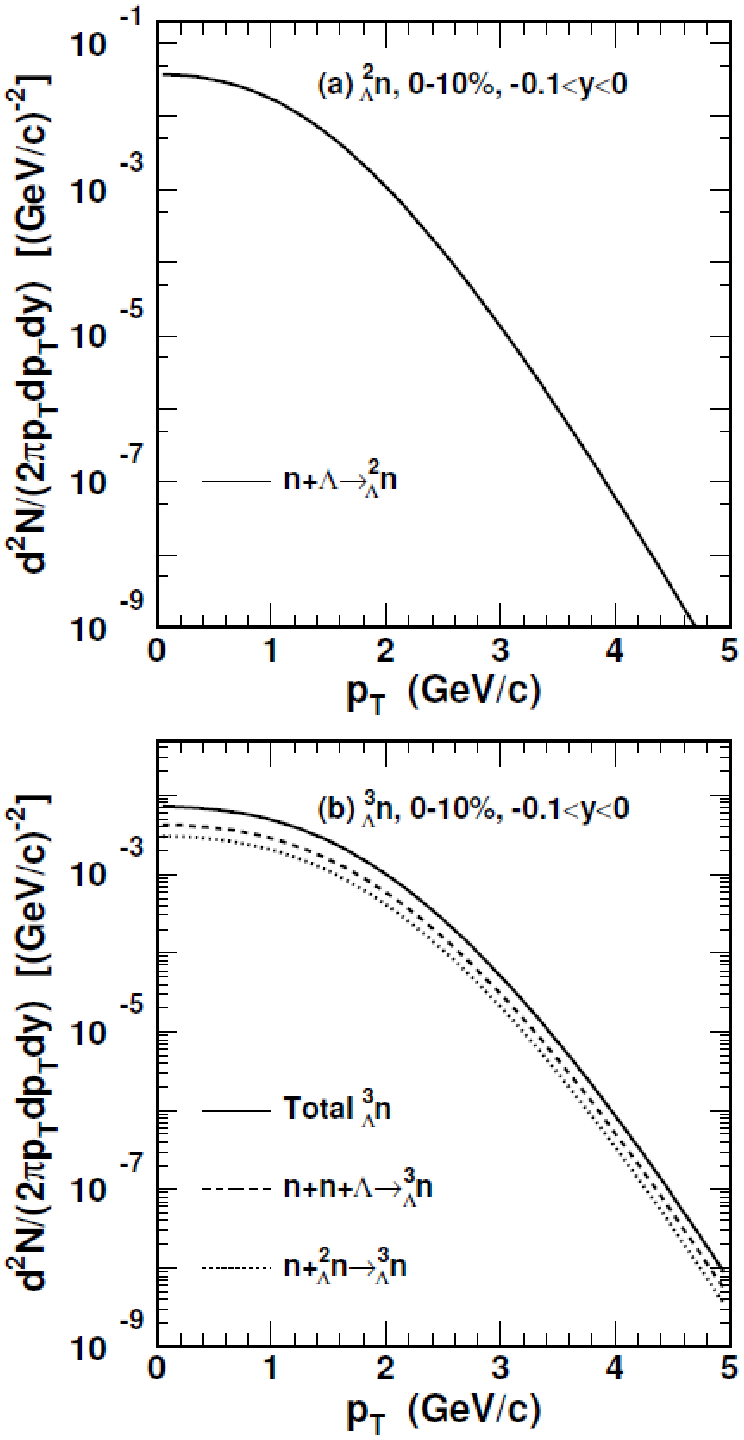
	Coal-channel	dN/dy	$\langle p_T \rangle$
${}^{2}_{\Lambda}n$	$n+\Lambda$	1.438×10^{-1}	0.945
${}^{3}_{\Lambda}n$	$n+n+\Lambda$	2.808×10^{-2}	1.224
	$n+{}^{2}_{\Lambda}n$	1.995×10^{-2}	1.218
	Total	4.803×10^{-2}	1.221

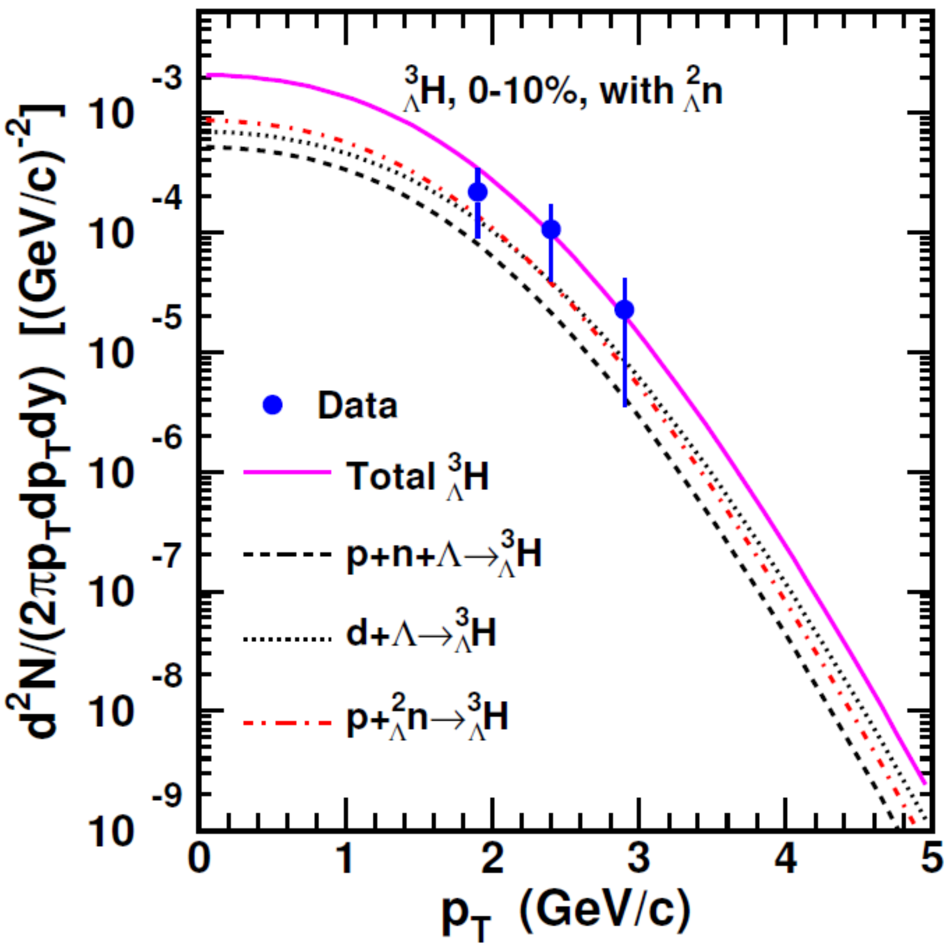
$$p+n+\Lambda \rightarrow {}^{3}_{\Lambda}\mathrm{H},\quad d+\Lambda \rightarrow {}^{3}_{\Lambda}\mathrm{H},$$

$$p+{}^{2}_{\Lambda}n \rightarrow {}^{3}_{\Lambda}\mathrm{H}$$

$$p+n+n+\Lambda \rightarrow {}^{4}_{\Lambda}\mathrm{H},\quad n+d+\Lambda \rightarrow {}^{4}_{\Lambda}\mathrm{H},\quad t+\Lambda \rightarrow {}^{4}_{\Lambda}\mathrm{H}$$

$$p+n+{}^{2}_{\Lambda}n \rightarrow {}^{4}_{\Lambda}\mathrm{H},\quad d+{}^{2}_{\Lambda}n \rightarrow {}^{4}_{\Lambda}\mathrm{H},\quad p+{}^{3}_{\Lambda}n \rightarrow {}^{4}_{\Lambda}\mathrm{H}$$

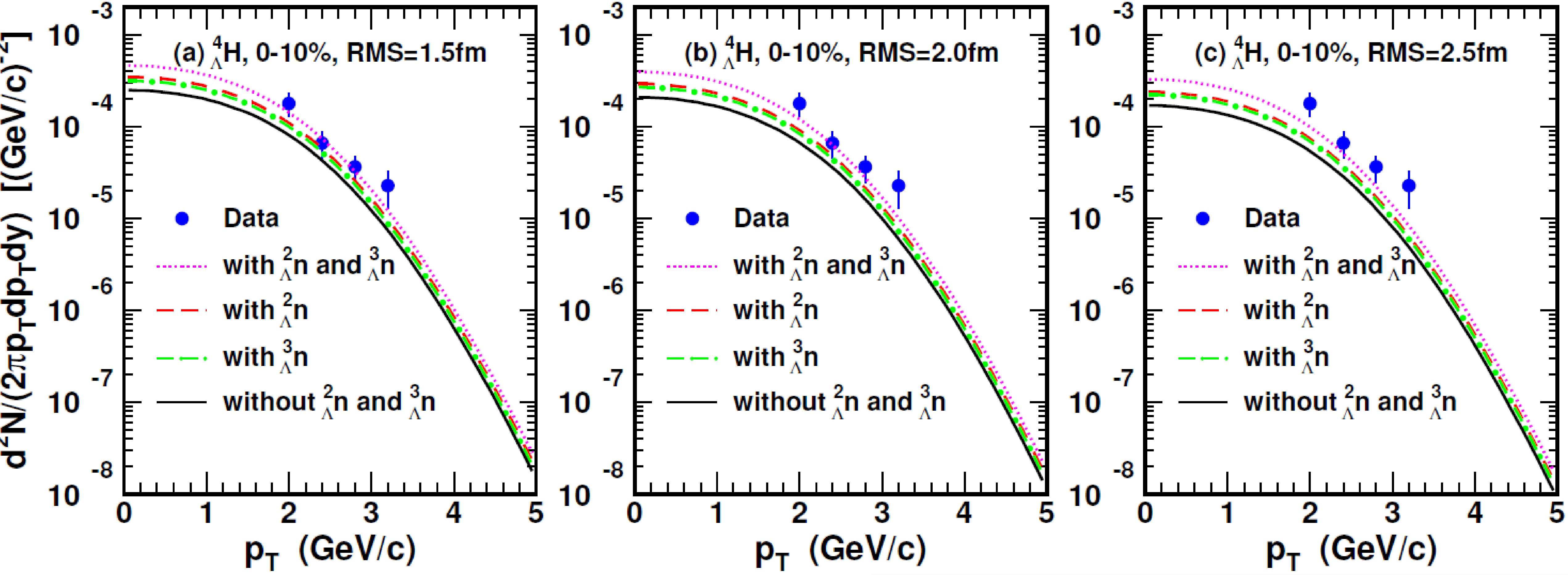




	Coal-channel	dN/dy	$\langle p_T \rangle$
$^{3}_{\Lambda}H$	$p + n + \Lambda$	0.323×10^{-2}	1.191
	$d + \Lambda$	0.467×10^{-2}	1.246
	$p +^{2}_{\Lambda} n$	0.550×10^{-2}	1.200
	Total	1.340×10^{-2}	1.214

18% higher

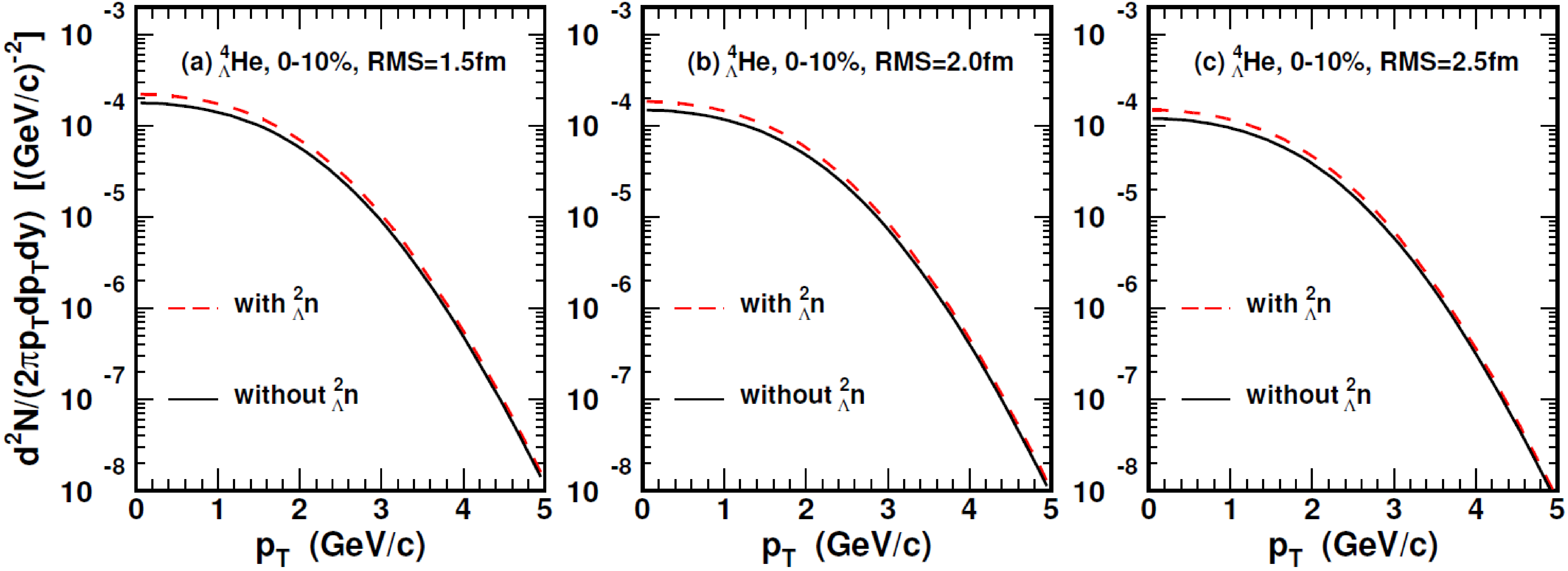
Data $(1.131 \pm 0.210 \pm 0.384) \times 10^{-2}$



(a) $^{4}_{\Lambda}H$, 0-10%, RMS=1.5fm
(b) $^{4}_{\Lambda}H$, 0-10%, RMS=2.0fm
(c) $^{4}_{\Lambda}H$, 0-10%, RMS=2.5fm
Data
with $^{2}_{\Lambda}n$ and $^{3}_{\Lambda}n$
with $^{2}_{\Lambda}n$
with $^{3}_{\Lambda}n$
without $^{2}_{\Lambda}n$ and $^{3}_{\Lambda}n$
$d^2N/(2\pi p_T dp_T dy)$ [(GeV/c)$^{-2}$]
p_T (GeV/c)

$^4_\Lambda H$ Data $(4.954 \pm 0.434 \pm 1.014) \times 10^{-3}$

	Coal-channel	dN/dy			$\langle p_T \rangle$		
		Theory-1.5	Theory-2.0	Theory-2.5	Theory-1.5	Theory-2.0	Theory-2.5
$^4_\Lambda H$	$p+n+n+\Lambda$	0.982×10^{-3}	0.764×10^{-3}	0.565×10^{-3}	1.483	1.475	1.467
	$n+d+\Lambda$	0.511×10^{-3}	0.423×10^{-3}	0.337×10^{-3}	1.520	1.514	1.507
	$t+\Lambda$	1.134×10^{-3}	1.001×10^{-3}	0.864×10^{-3}	1.571	1.566	1.562
	$p+n+^2_\Lambda n$	0.570×10^{-3}	0.471×10^{-3}	0.374×10^{-3}	1.473	1.468	1.462
	$d+^2_\Lambda n$	0.404×10^{-3}	0.350×10^{-3}	0.297×10^{-3}	1.509	1.505	1.501
	$p+^3_\Lambda n$	1.114×10^{-3}	0.991×10^{-3}	0.863×10^{-3}	1.471	1.468	1.464
	Total	4.715×10^{-3}	4.000×10^{-3}	3.300×10^{-3}	1.506	1.502	1.498
$^4_\Lambda He$	$p+p+n+\Lambda$	0.731×10^{-3}	0.569×10^{-3}	0.420×10^{-3}	1.483	1.475	1.467
	$p+d+\Lambda$	0.382×10^{-3}	0.316×10^{-3}	0.252×10^{-3}	1.520	1.514	1.507
	$^3He+\Lambda$	0.766×10^{-3}	0.676×10^{-3}	0.584×10^{-3}	1.590	1.586	1.581
	$p+p+^2_\Lambda n$	0.421×10^{-3}	0.347×10^{-3}	0.276×10^{-3}	1.473	1.468	1.462
	Total	2.300×10^{-3}	1.908×10^{-3}	1.532×10^{-3}	1.523	1.519	1.516



(a) ${}^{4}_{\Lambda}$He, 0-10%, RMS=1.5fm
(b) ${}^{4}_{\Lambda}$He, 0-10%, RMS=2.0fm
(c) ${}^{4}_{\Lambda}$He, 0-10%, RMS=2.5fm
with ${}^{2}_{\Lambda}$n
without ${}^{2}_{\Lambda}$n
$d^2N/(2\pi p_T dp_T dy)$ $[(GeV/c)^{-2}]$
p_T (GeV/c)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0
1
2
3
4
5

Production asymmetry of ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$

*** four-body coalescence and three-body coalescence**

$$\frac{{}^{4}_{\Lambda}\mathrm{He}}{{}^{4}_{\Lambda}\mathrm{H}} = \frac{N_p}{N_n} = \frac{1}{Z_{np}} = 0.746,$$

$$\frac{{}^{4}_{\Lambda}\mathrm{H} - {}^{4}_{\Lambda}\mathrm{He}}{{}^{4}_{\Lambda}\mathrm{H} + {}^{4}_{\Lambda}\mathrm{He}} = \frac{N_n - N_p}{N_n + N_p} = \frac{Z_{np} - 1}{Z_{np} + 1} = 0.145$$

* $t + \Lambda \rightarrow {}^{4}_{\Lambda}\mathrm{H}$ and ${}^{3}\mathrm{He} + \Lambda \rightarrow {}^{4}_{\Lambda}\mathrm{He}$

$$\frac{{}^{4}_{\Lambda}\mathrm{He}}{{}^{4}_{\Lambda}\mathrm{H}} = \frac{N_{^3\mathrm{He}}}{N_t} = 0.687.$$

$$\frac{{}^{4}_{\Lambda}\mathrm{H} - {}^{4}_{\Lambda}\mathrm{He}}{{}^{4}_{\Lambda}\mathrm{H} + {}^{4}_{\Lambda}\mathrm{He}} = \frac{N_t - N_{^3\mathrm{He}}}{N_t + N_{^3\mathrm{He}}} = 0.186$$

*** two-body coalescence with ${}^{2}_{\Lambda}\mathrm{n}$ and ${}^{3}_{\Lambda}\mathrm{n}$**

$$\frac{{}^{4}_{\Lambda}\mathrm{He}}{{}^{4}_{\Lambda}\mathrm{H}} = 0,$$

$$\frac{{}^{4}_{\Lambda}\mathrm{H} - {}^{4}_{\Lambda}\mathrm{He}}{{}^{4}_{\Lambda}\mathrm{H} + {}^{4}_{\Lambda}\mathrm{He}} = 1$$

Production asymmetry of ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$

*** Total** ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$

	RMS (fm)	neither ${}^{2}_{\Lambda}n$ nor ${}^{3}_{\Lambda}n$	with ${}^{2}_{\Lambda}n$	with ${}^{3}_{\Lambda}n$	with ${}^{2}_{\Lambda}n$ and ${}^{3}_{\Lambda}n$
$\frac{{}^{4}_{\Lambda}\mathrm{He}}{{}^{4}_{\Lambda}\mathrm{H}}$	1.5	0.715	0.639	0.573	0.488
	2.0	0.713	0.634	0.564	0.477
	2.5	0.711	0.629	0.553	0.464
$\frac{{}^{4}_{\Lambda}\mathrm{H}-{}^{4}_{\Lambda}\mathrm{He}}{{}^{4}_{\Lambda}\mathrm{H}+{}^{4}_{\Lambda}\mathrm{He}}$	1.5	0.166	0.221	0.271	0.344
	2.0	0.167	0.224	0.279	0.354
	2.5	0.169	0.228	0.288	0.366

Comparisons with future measurements can help shed light on the existence constraints of ${}^{2}_{\Lambda}\mathrm{n}$ and ${}^{3}_{\Lambda}\mathrm{n}$.

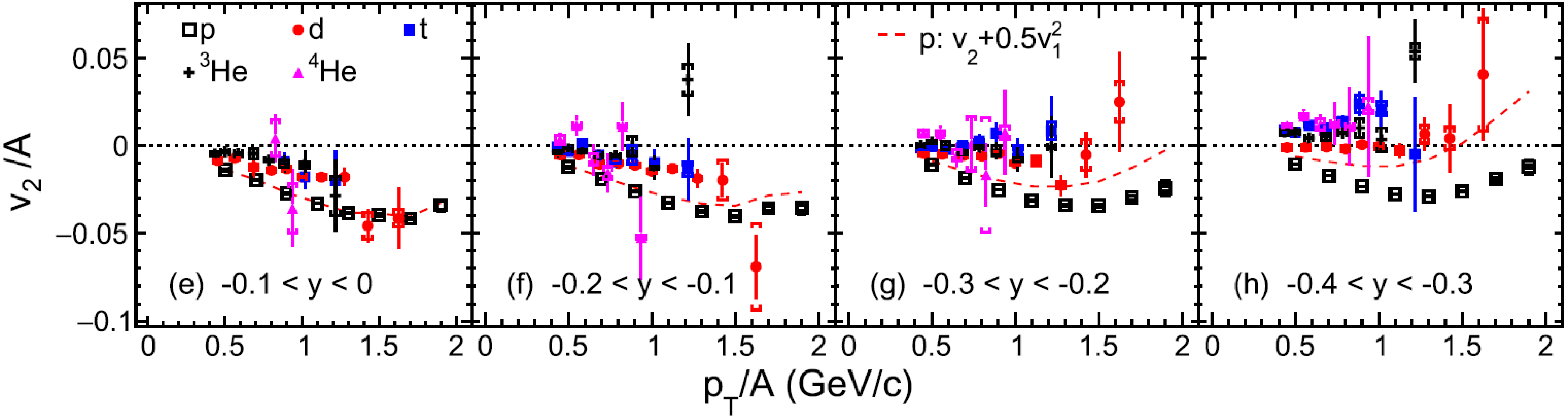
IV. Summary

◆ **We extended an analytical coalescence model to deal with productions of hyper-nuclei besides light nuclei in relativistic heavy-ion collisions. The relationships of hyper-nuclei with primordial nucleons and hyperons were clearly given.**

◆ **We applied the analytical coalescence model to Au-Au@3GeV collisions at RHIC, and gave contributions from different coalescence channels for** ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$ **in their productions.**

◆ **We predicted the production asymmetry between** ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$, **which could shed light on the existence constraints of the possible neutron-Λ bound states.**

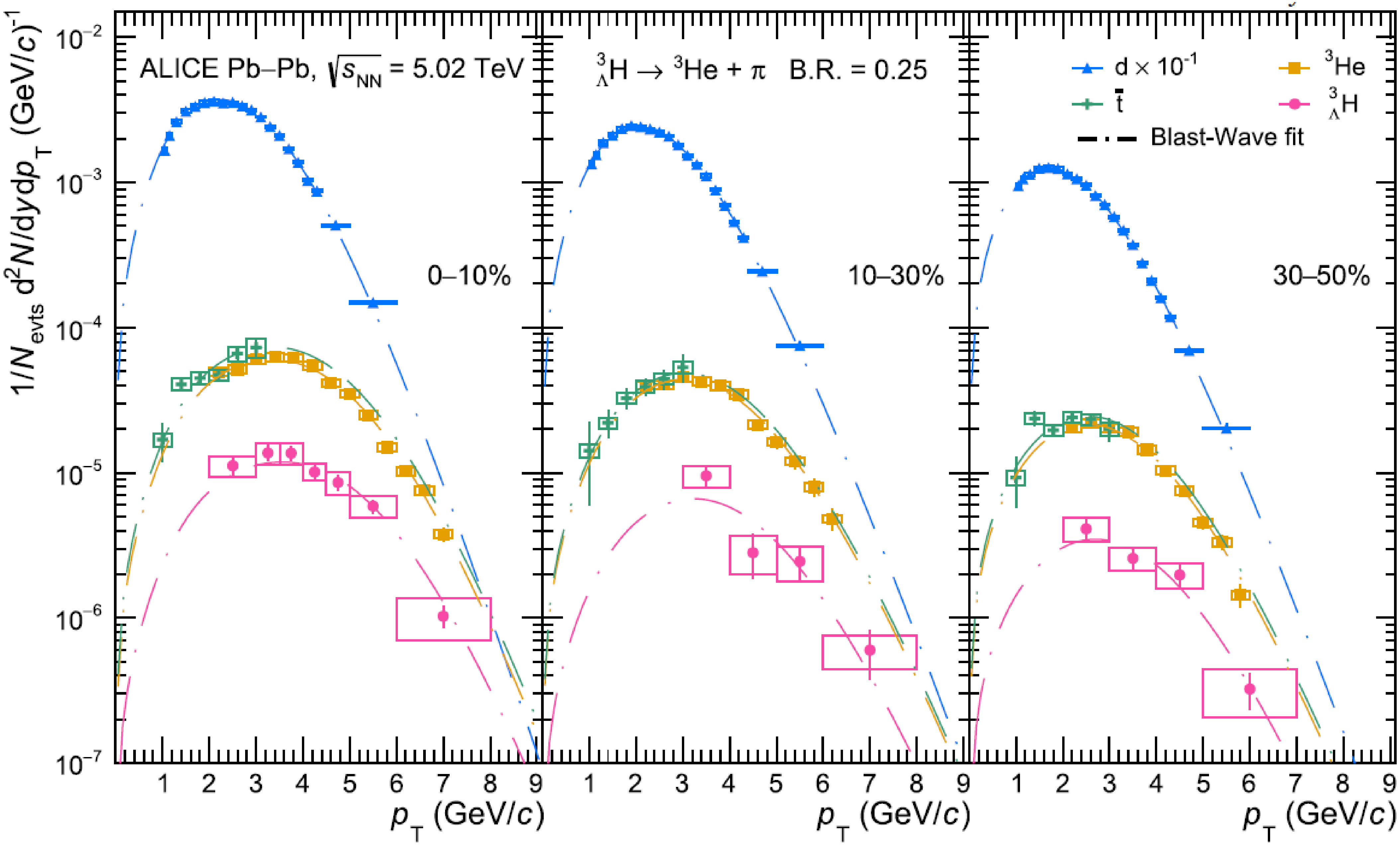
Thank you !



No v_2 /A scaling

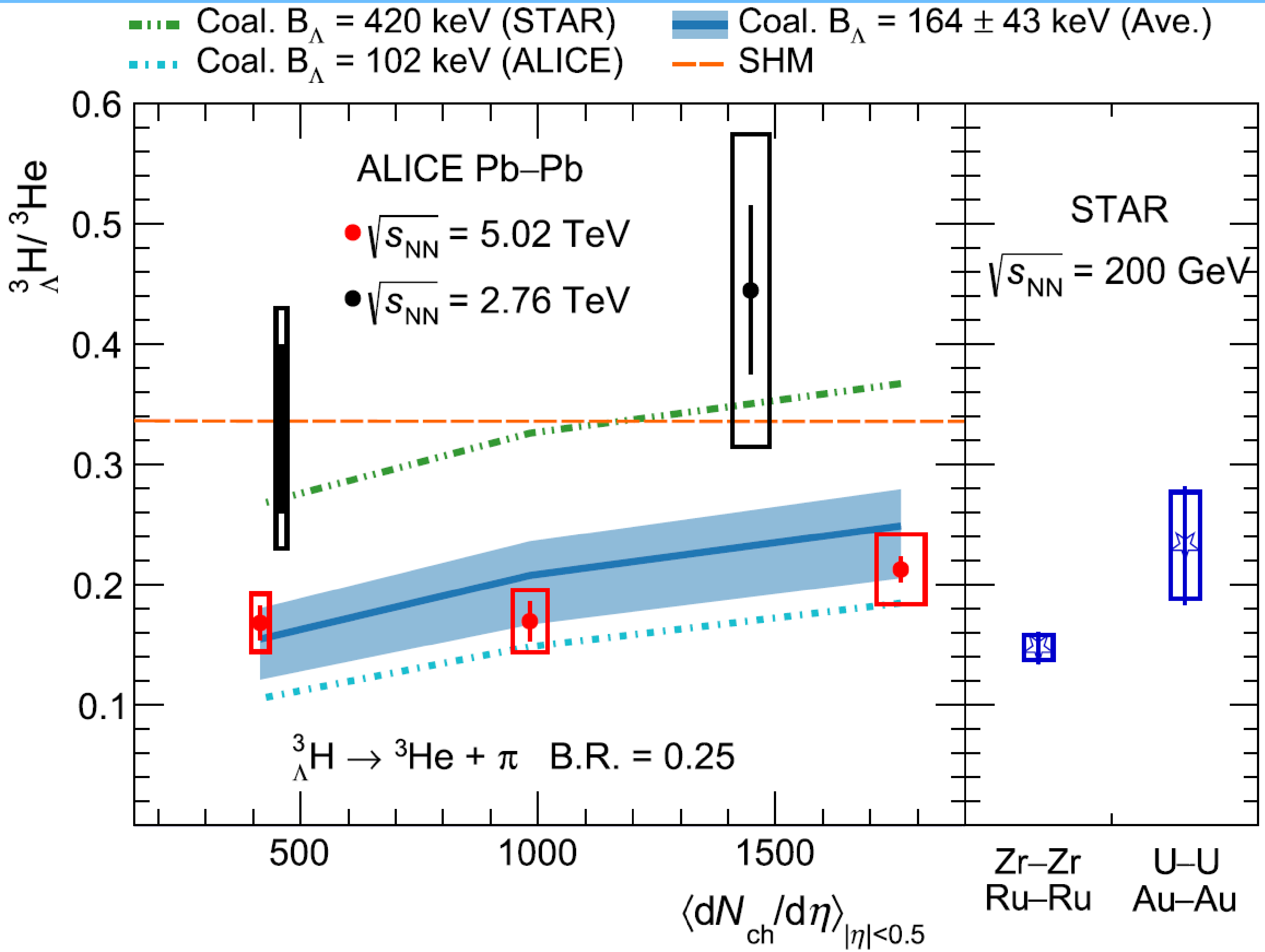
LHC Experiment:

ALICE, PLB 860, 139066, 2025

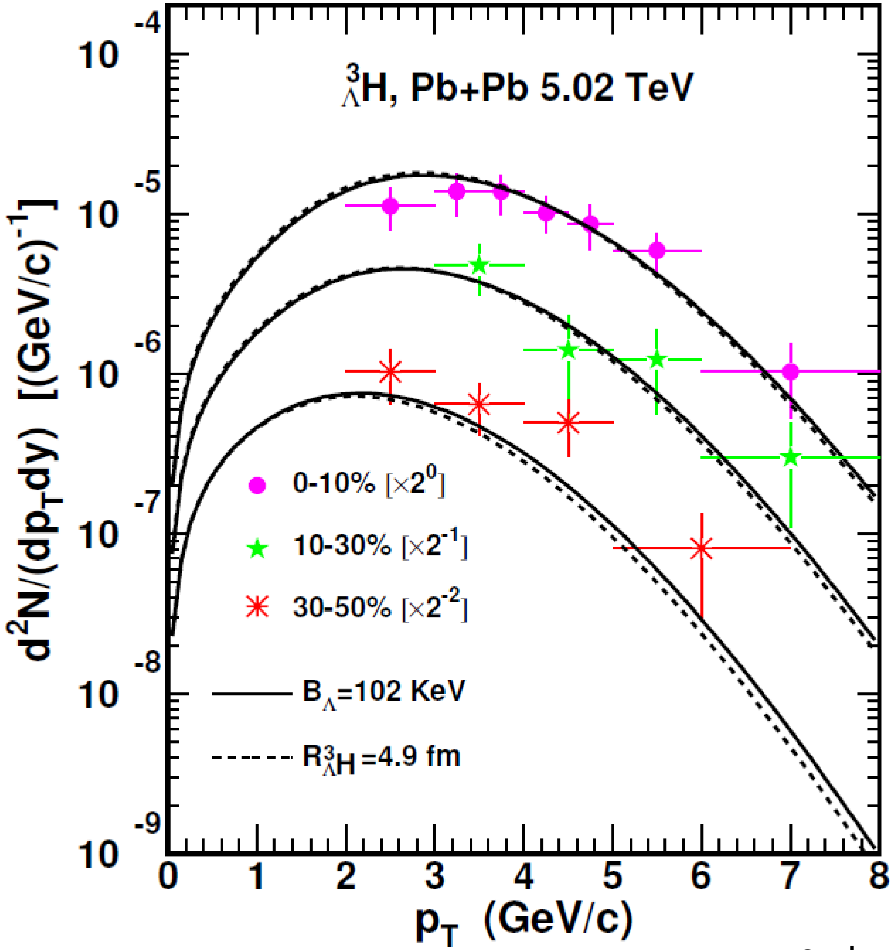


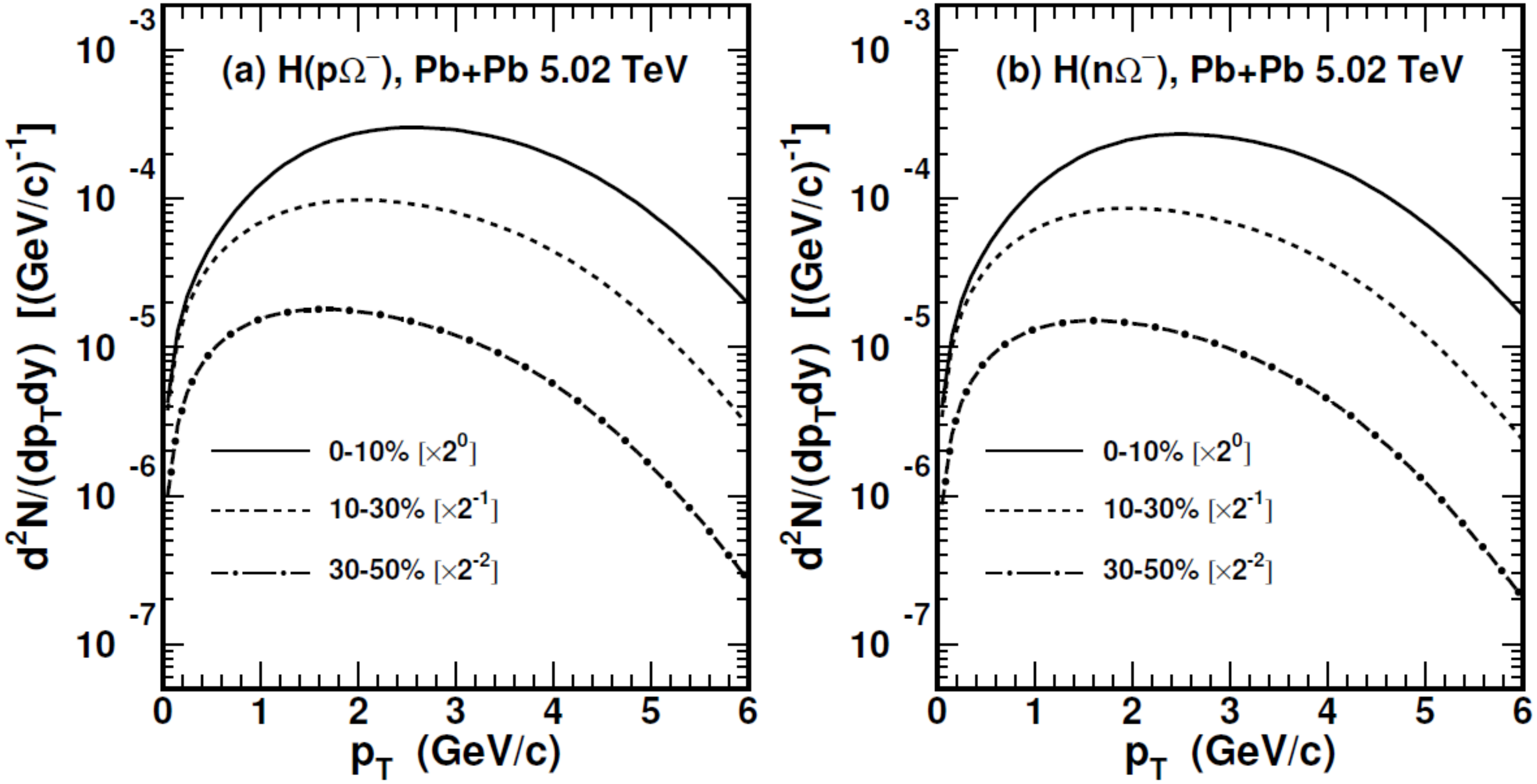
LHC Experiment:

ALICE, PLB 860, 139066, 2025



Our results at LHC   2408.06384





$$p+p+n+\Lambda \to {}^{4}_{\Lambda}\mathrm{H},\quad p+d+\Lambda \to {}^{4}_{\Lambda}\mathrm{H},\quad {}^{3}\mathrm{He}+\Lambda \to {}^{4}_{\Lambda}\mathrm{H}$$

$$p+p+{}^{2}_{\Lambda}n \to {}^{4}_{\Lambda}\mathrm{He}$$