

Production properties of Λ -hypernuclei and Ω -hypernuclei in the coalescence mechanism in relativistic heavy-ion collisions

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References: Nucl. Sci. Tech. **36**, 185, 2025; Phys. Rev. C **112**, 034908, 2025.

Outline

I. Introduction

II. An analytical coalescence model

formalism of two-body coalescence

general formalism of N -body coalescence

III. Results in heavy-ion collisions at RHIC and LHC

p_T spectra, dN/dy , $\langle p_T \rangle$ of ${}^3_{\Lambda}\text{H}$, ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$

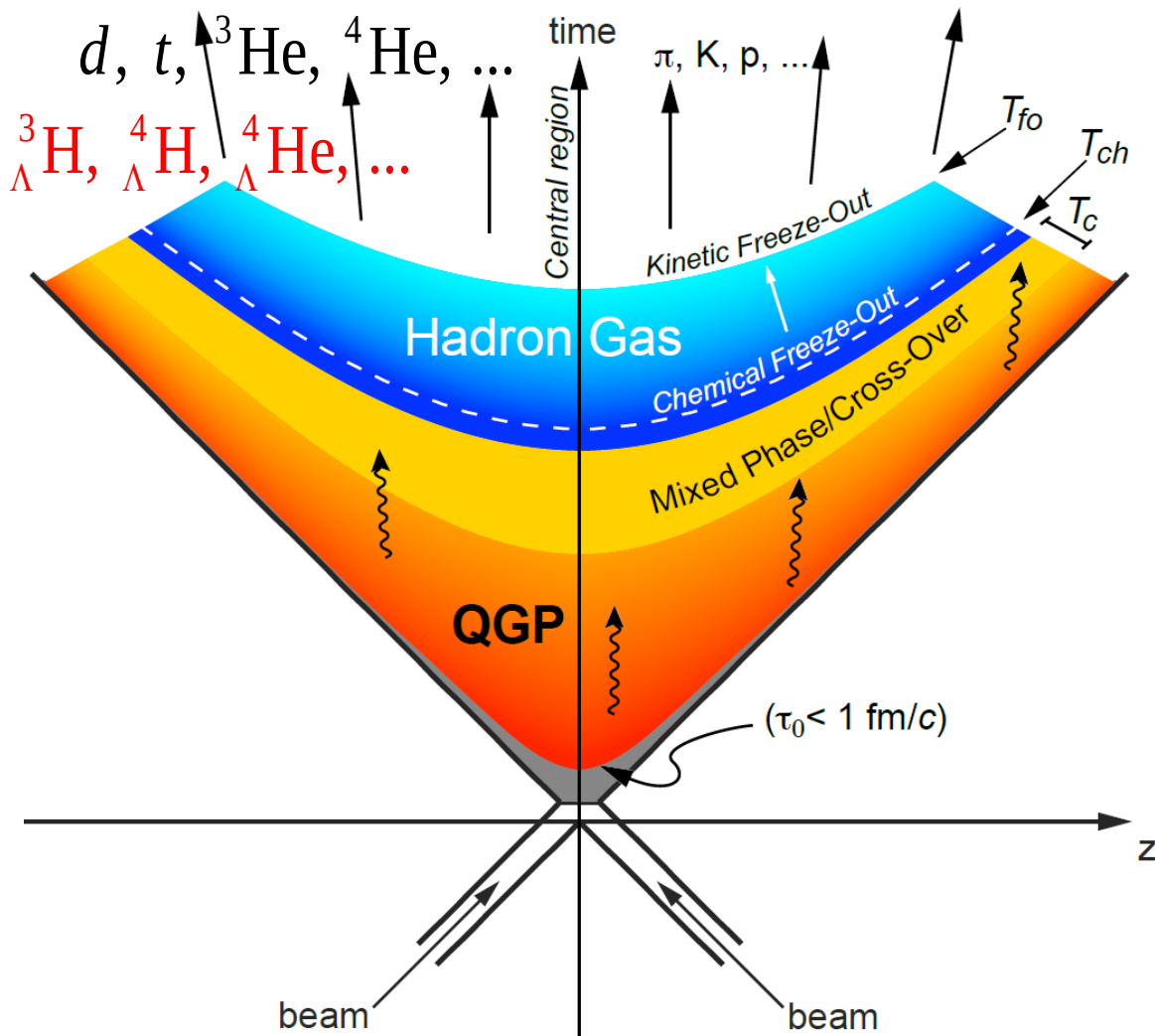
production asymmetry between ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$

predictions for Ω -hypernuclei $\text{H}(p\Omega^-)$, $\text{H}(n\Omega^-)$, and $\text{H}(pn\Omega^-)$

IV. Summary

I. Introduction

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



- Natural tools for elementary hyperon-nucleon and hyperon-hyperon interactions
- Probes of system freeze-out properties
- 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
$$f_H \sim f_p^Z f_{\Lambda, \Omega}^{N_{\Lambda, \Omega}} f_n^{A-Z-N_{\Lambda}} \otimes R_H$$

M. Wakai, Nucl. Phys. A **547**, 89c-94c, 1992;

K.J. Sun and L.W. Chen, Phys. Rev. C **94**, 064908, 2016;

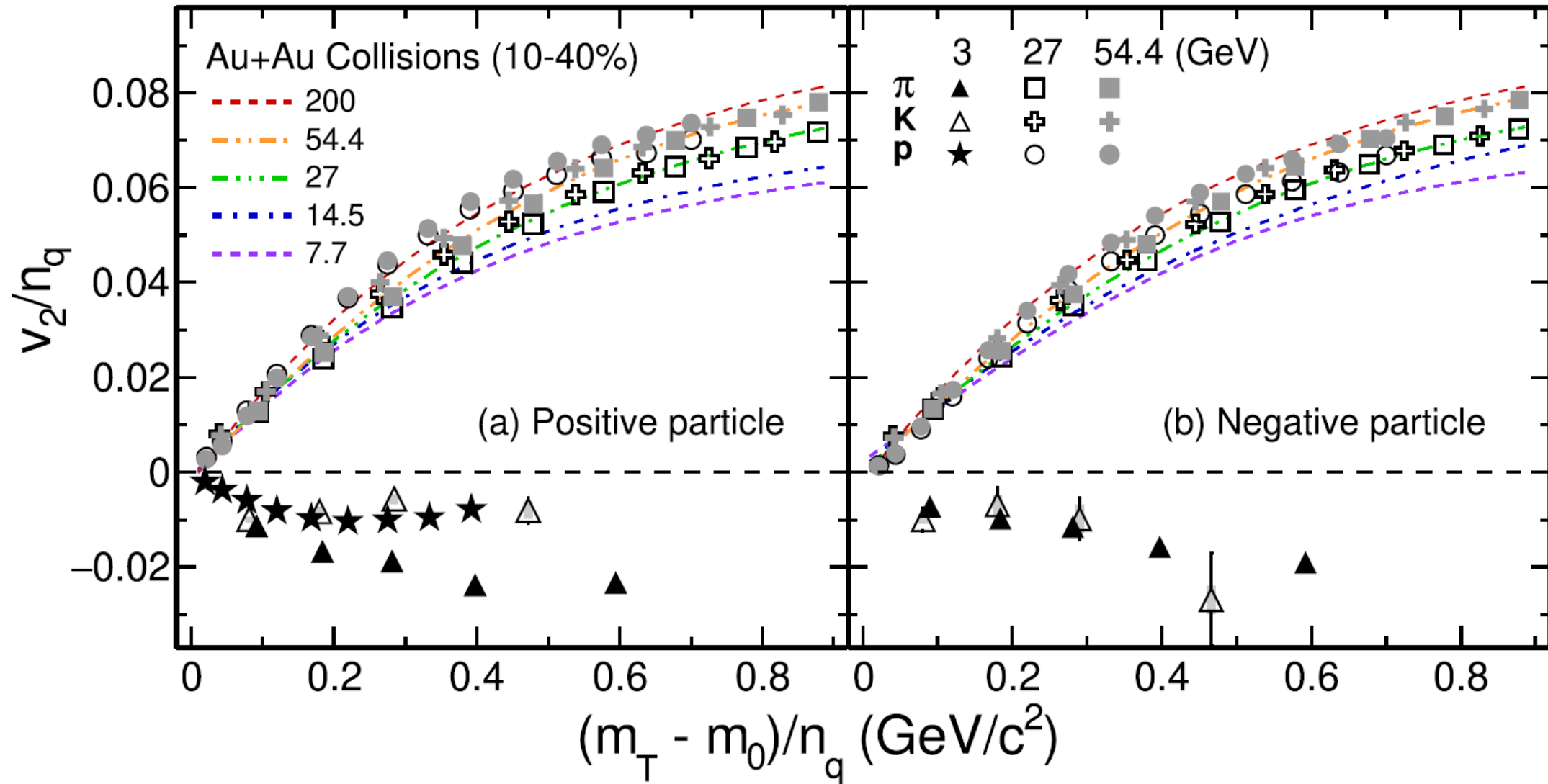
Z. Zhang and C.M. Ko, Phys. Lett. B **780**, 191, 2018;

K.J. Sun, C.M. Ko, and B. Donigus, Phys. Lett. B **792**, 132, 2019;

S. Zhang and Y.G. Ma, Phys. Lett. B **811**, 135867, 2020;

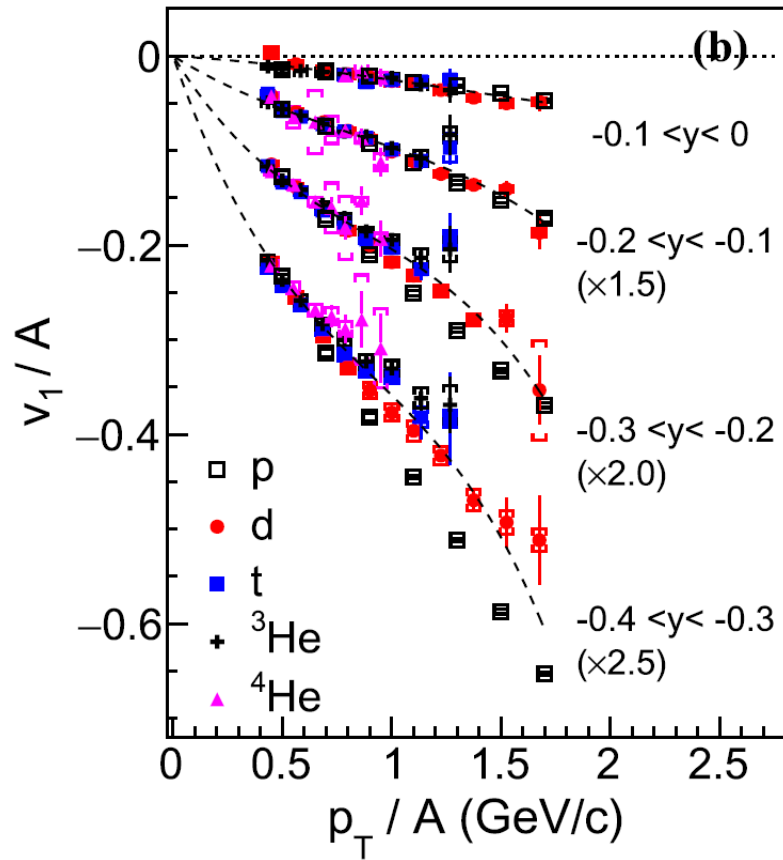
D.N. Liu, C.M. Ko, Y.G. Ma, F. Mazzaschi, M. Puccio, Q.Y. Shou, K.J. Sun, and Y.Z. Wang, Phys. Lett. B **855**, 138855, 2024;

... ..

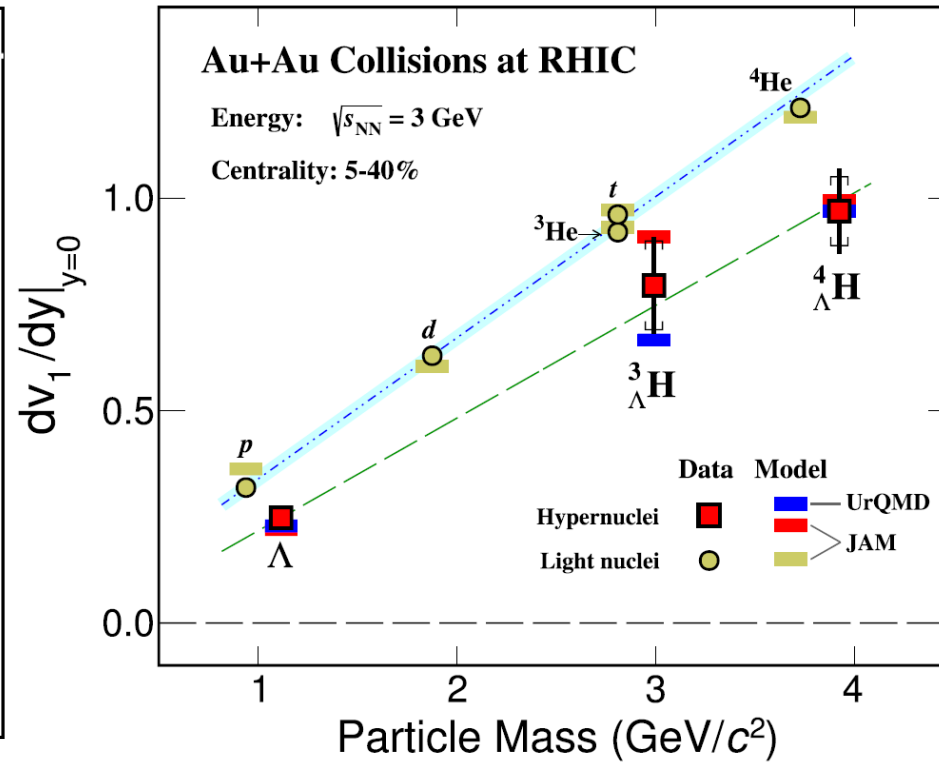


Partonic collectivity disappears and hadronic matter is predominantly created.

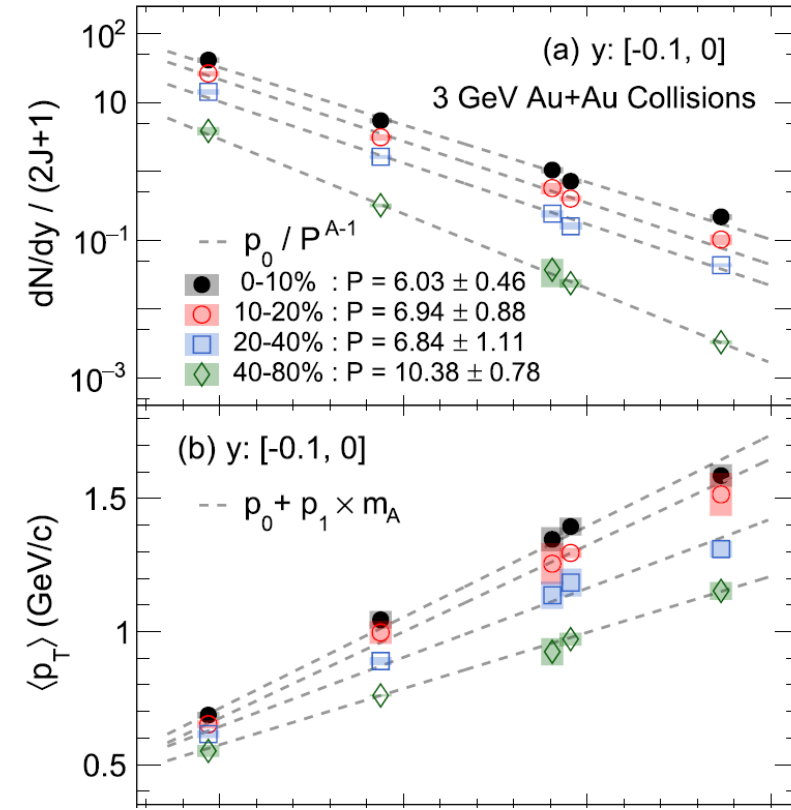
Experiment: RHIC 3 GeV Au-Au



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 --- an analytical coalescence model.

in Au-Au collisions at such low collision energy of 3 GeV

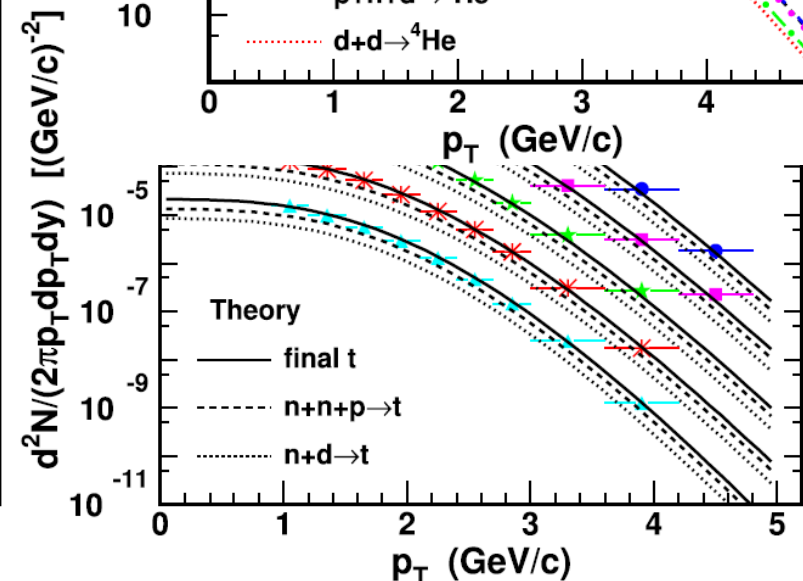
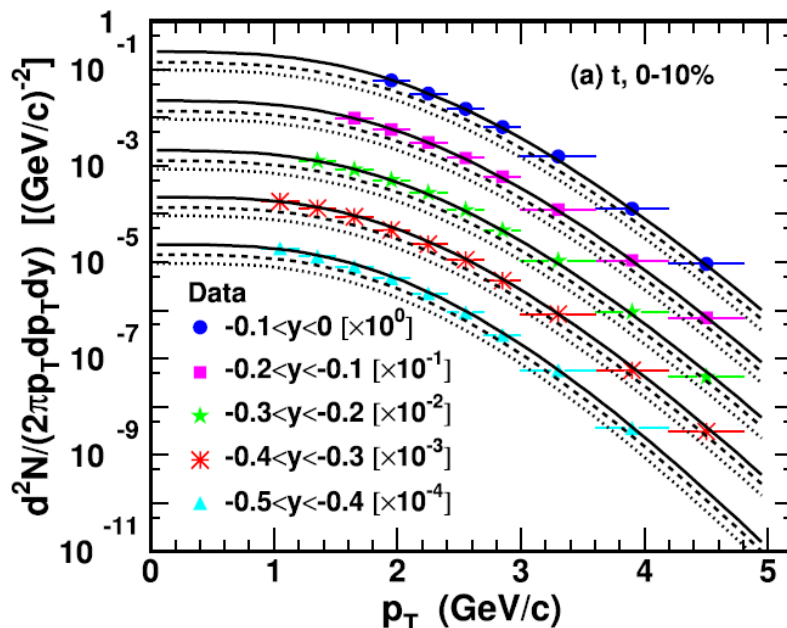
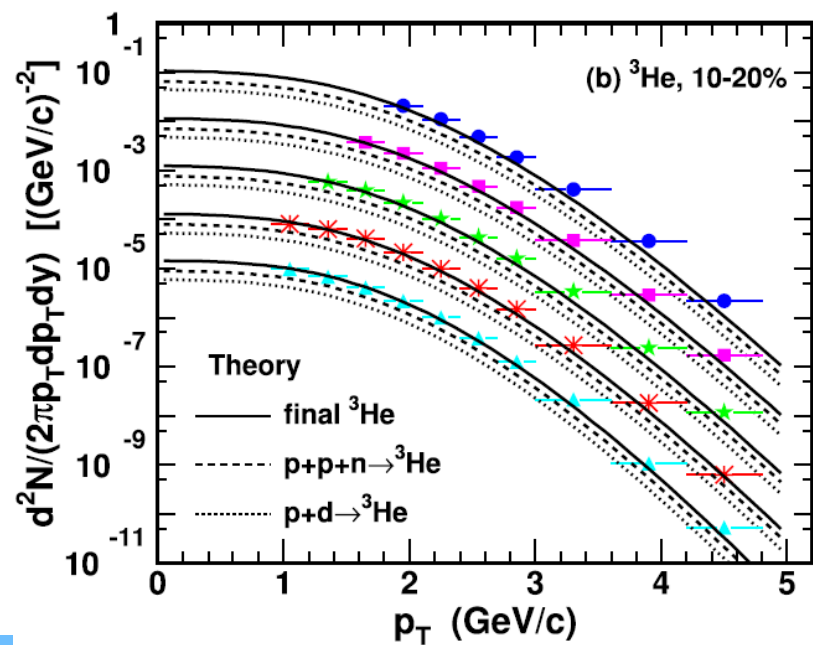
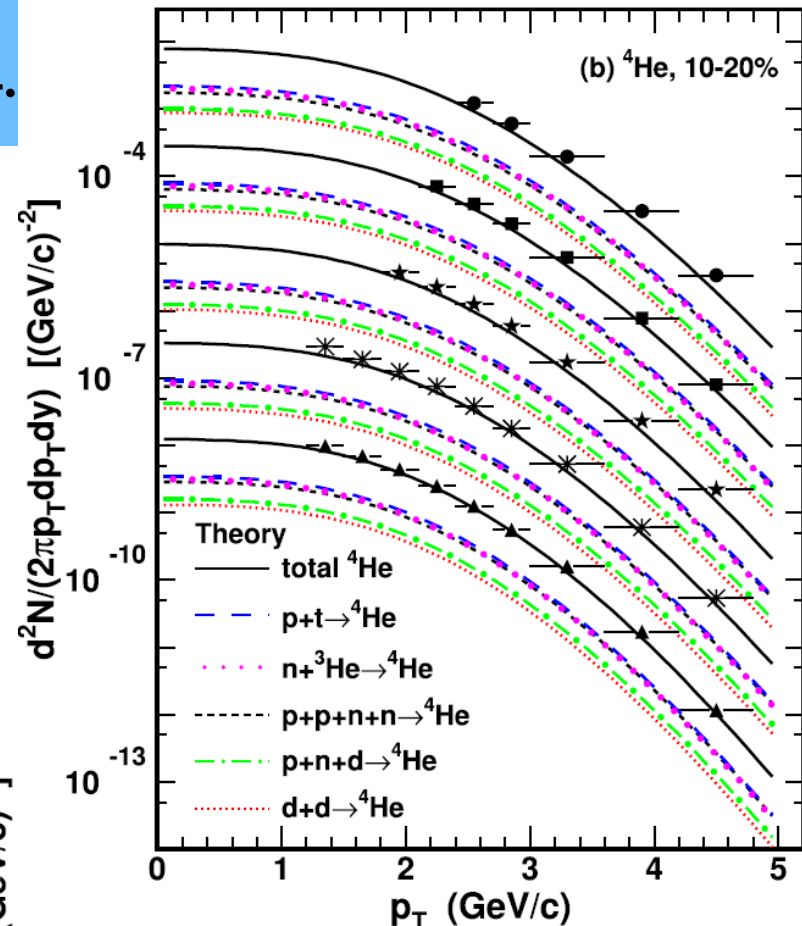
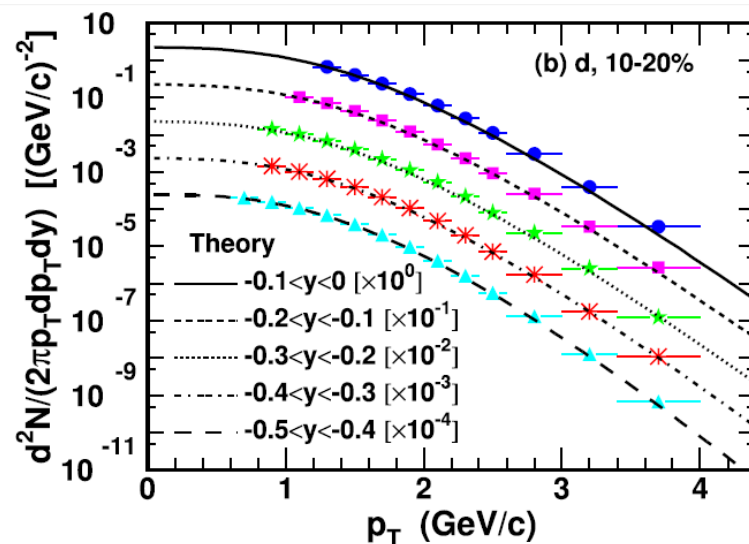
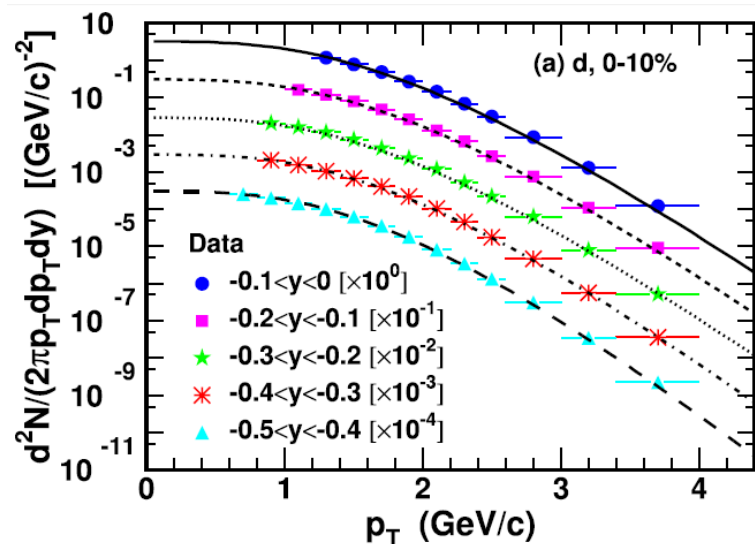
besides nucleon+nucleon coalescence, including other coalescence processes

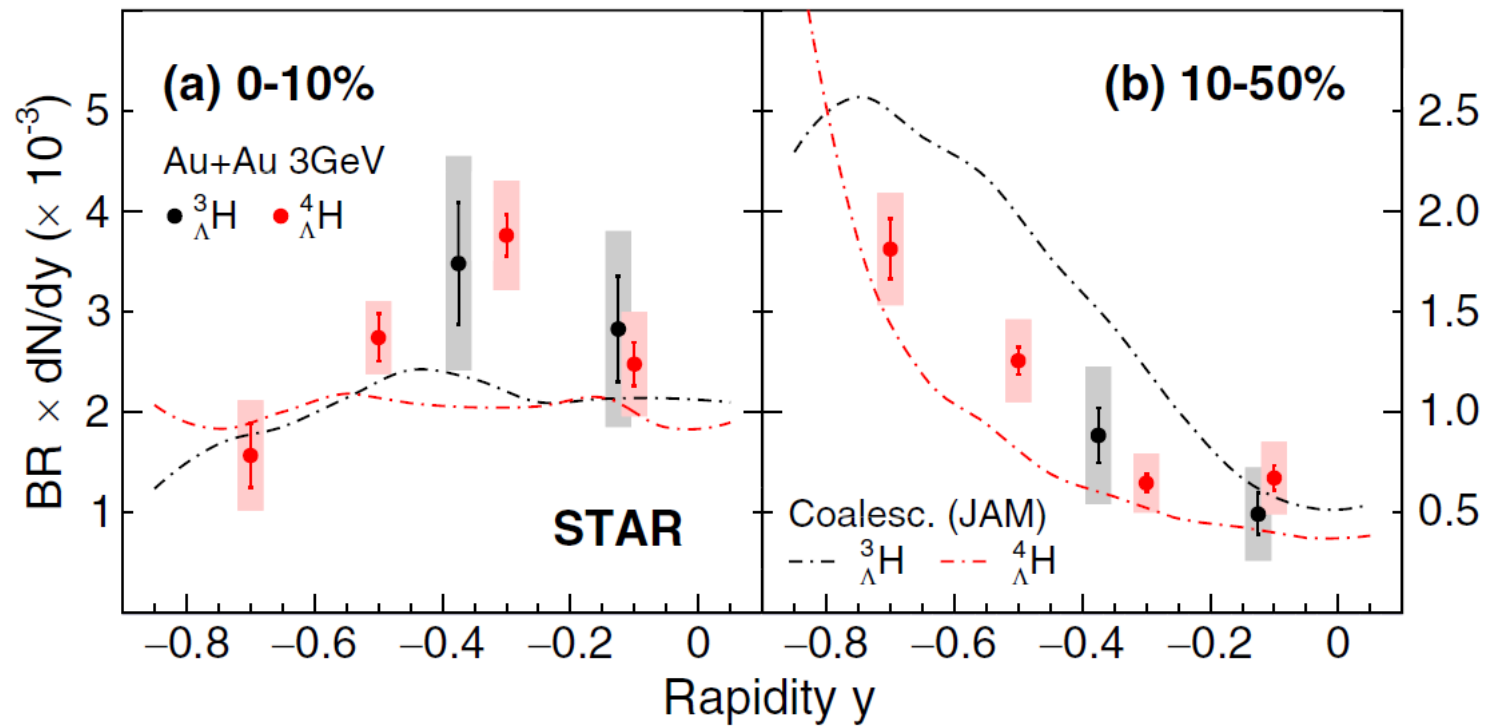
$$p + n \rightarrow d;$$

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

$$p + p + n \rightarrow {}^3\text{He}, \quad p + d \rightarrow {}^3\text{He};$$

$$p + p + n + n \rightarrow {}^4\text{He}, \quad p + n + d \rightarrow {}^4\text{He}, \quad p + t \rightarrow {}^4\text{He}, \quad n + {}^3\text{He} \rightarrow {}^4\text{He}, \quad d + d \rightarrow {}^4\text{He}.$$



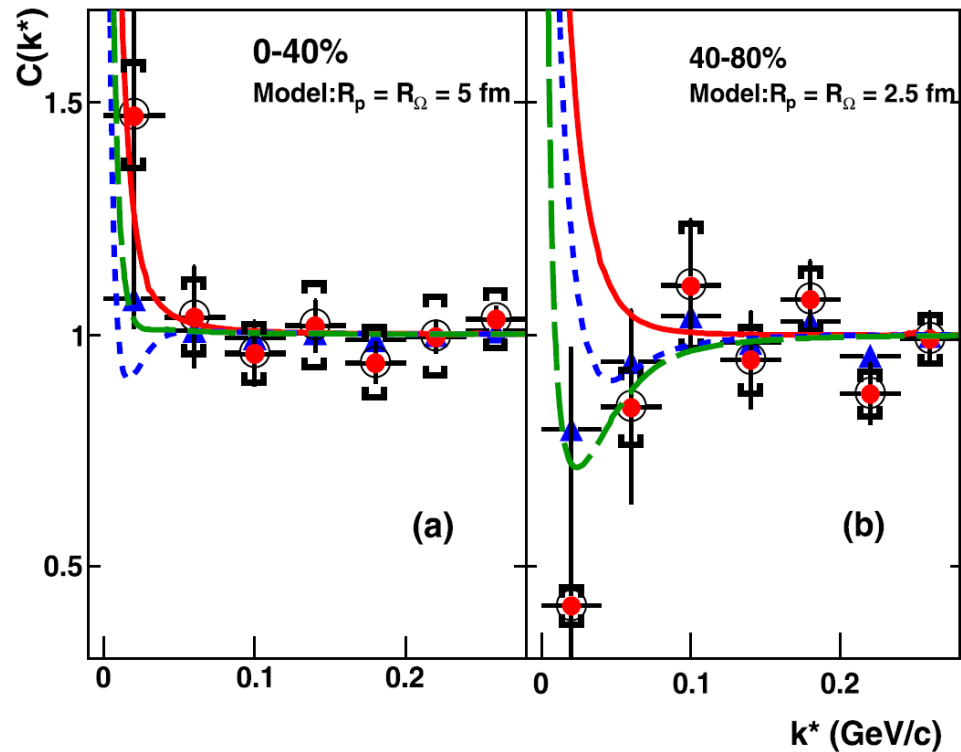


Λ -hypernuclei measurement

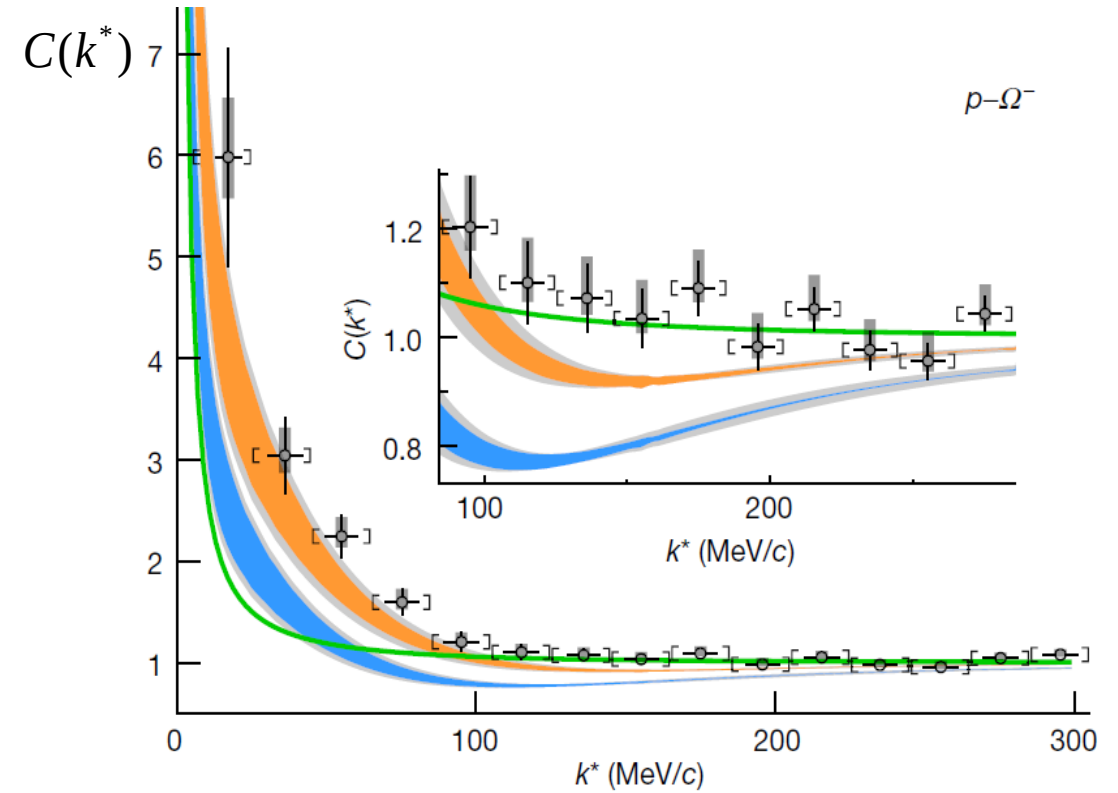
- For such Λ -nuclei, besides nucleon+ Λ coalescence, are coalescence processes involving nucleus participation still necessary?
- If yes, what new characteristics will they bring?

Favor the existence of Ω -hypernuclei

STAR, PLB 790, 490, 2019



ALICE, Nature 588, 232, 2020



We extend the analytical coalescence model to the strange sector to study hypernuclei.

II. An analytical coalescence model

two-body coalescence $h_1 + h_2 \rightarrow H_j$

The three-dimensional momentum distribution

$$f_{H_j}(\vec{p}) = \int d\vec{x}_1 d\vec{x}_2 d\vec{p}_1 d\vec{p}_2 f_{h_1 h_2}(\vec{x}_1, \vec{x}_2; \vec{p}_1, \vec{p}_2) \mathcal{R}_{H_j}(\vec{x}_1, \vec{x}_2; \vec{p}_1, \vec{p}_2, \vec{p})$$

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

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

two-hadron joint coordinate-momentum distribution

$$f_{h_1 h_2}(\vec{x}_1, \vec{x}_2; \vec{p}_1, \vec{p}_2) = N_{h_1 h_2} f_{h_1 h_2}^{(n)}(\vec{x}_1, \vec{x}_2; \vec{p}_1, \vec{p}_2) = N_{h_1 h_2} f_{h_1 h_2}^{(n)}(\vec{x}_1, \vec{x}_2) f_{h_1 h_2}^{(n)}(\vec{p}_1, \vec{p}_2)$$



assumption 1: coordinate-momentum factorization

two-body coalescence $h_1 + h_2 \rightarrow H_j$

The three-dimensional momentum distribution

$$f_{H_j}(\vec{p}) = N_{h_1 h_2} g_{H_j} A_{H_j} M_{H_j}(\vec{p})$$

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

$$f_{h_1 h_2}^{(n)}(\vec{r}) = \frac{1}{(\pi C_1 R_f^2)^{3/2}} e^{-\frac{\vec{r}^2}{C_1 R_f^2}}$$

$$A_{H_j} = 8 \int d\vec{x}_1 d\vec{x}_2 f_{h_1 h_2}^{(n)}(\vec{x}_1, \vec{x}_2) e^{-\frac{(\vec{x}'_1 - \vec{x}'_2)^2}{2\sigma_{21}^2}} = \frac{8\sigma_{21}^3}{(C_1 R_f^2 + \sigma_{21}^2) \sqrt{C_1 (R_f / \gamma)^2 + \sigma_{21}^2}}$$

$$M_{H_j}(\vec{p}) = \int d\vec{p}_1 d\vec{p}_2 f_{h_1 h_2}^{(n)}(\vec{p}_1, \vec{p}_2) e^{-\frac{2\sigma_{21}^2 (m_2 \vec{p}'_1 - m_1 \vec{p}'_2)^2}{(m_1 + m_2)^2}} \delta\left(\sum_{i=1}^2 \vec{p}_i - \vec{p}\right) = \left(\frac{\sqrt{\pi}}{\sqrt{2}\sigma_{21}}\right)^3 \gamma f_{h_1 h_2}\left(\frac{m_1 \vec{p}}{m_1 + m_2}, \frac{m_2 \vec{p}}{m_1 + m_2}\right)$$

assumption 2: delta function approximation

two-body coalescence $h_1 + h_2 \rightarrow H_j$

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

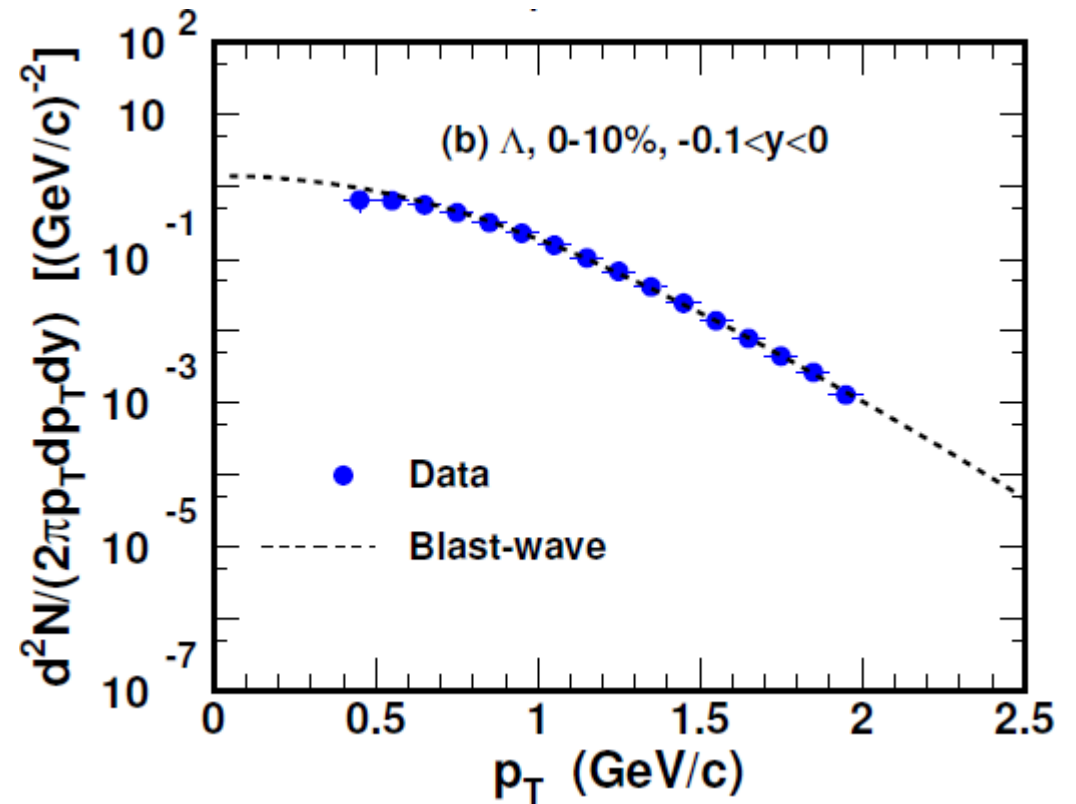
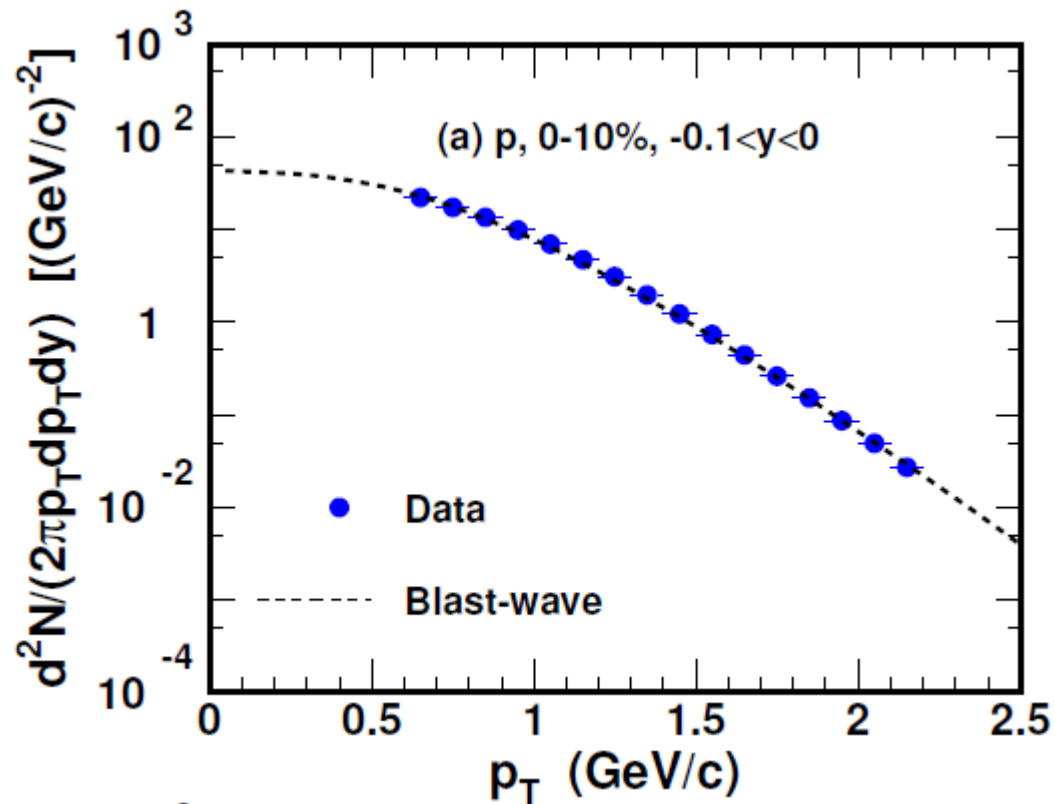
$$f_{H_j}^{(\text{inv})}(p_T, y) = \frac{8\pi^{3/2} g_{H_j}}{2^{3/2} (C_1 R_f^2 + \sigma_{21}^2) \sqrt{C_1 (R_f / \gamma)^2 + \sigma_{21}^2}} \frac{m_{H_j}}{m_1 m_2} f_{h_1}^{(\text{inv})} \left(\frac{m_1 p_T}{m_1 + m_2}, y \right) f_{h_2}^{(\text{inv})} \left(\frac{m_2 p_T}{m_1 + m_2}, y \right)$$

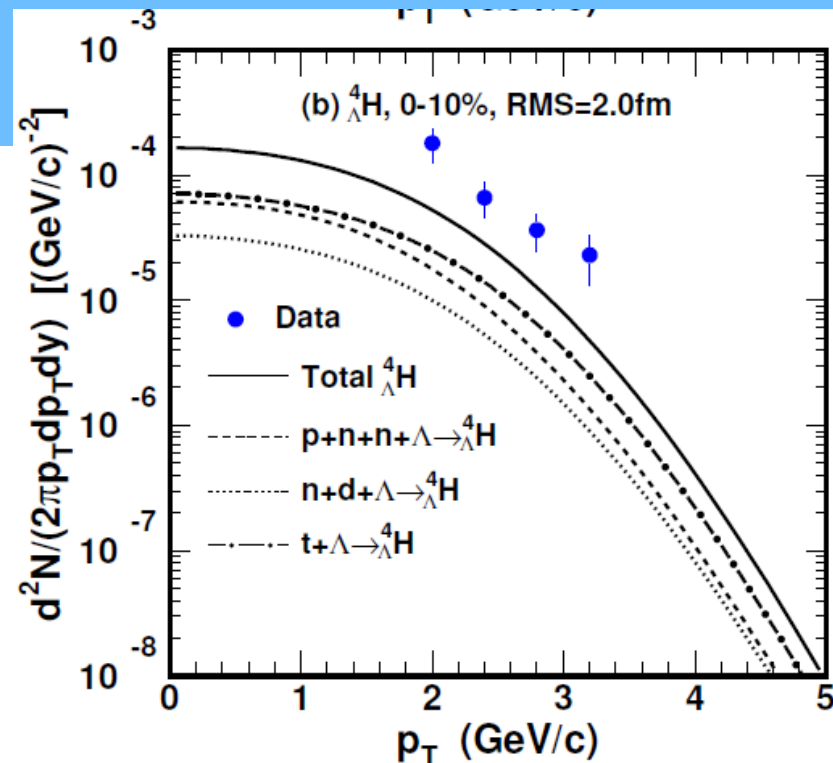
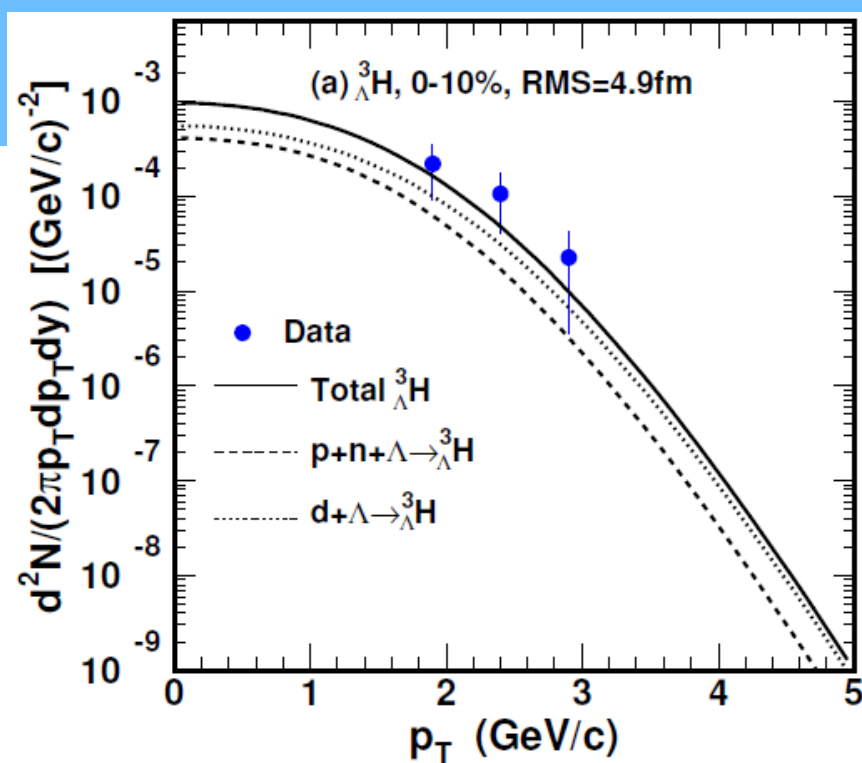
N-body coalescence $h_1 + h_2 + \dots + h_N \rightarrow H_j$

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

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

model inputs: $p^{\text{exp}} / 80\%$, $\Lambda^{\text{exp}} \times 78.8\%$





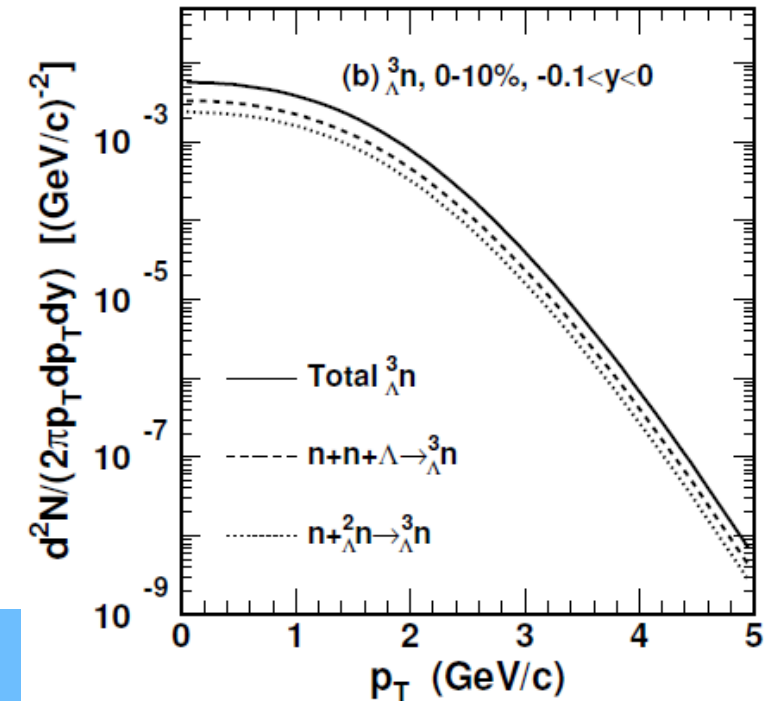
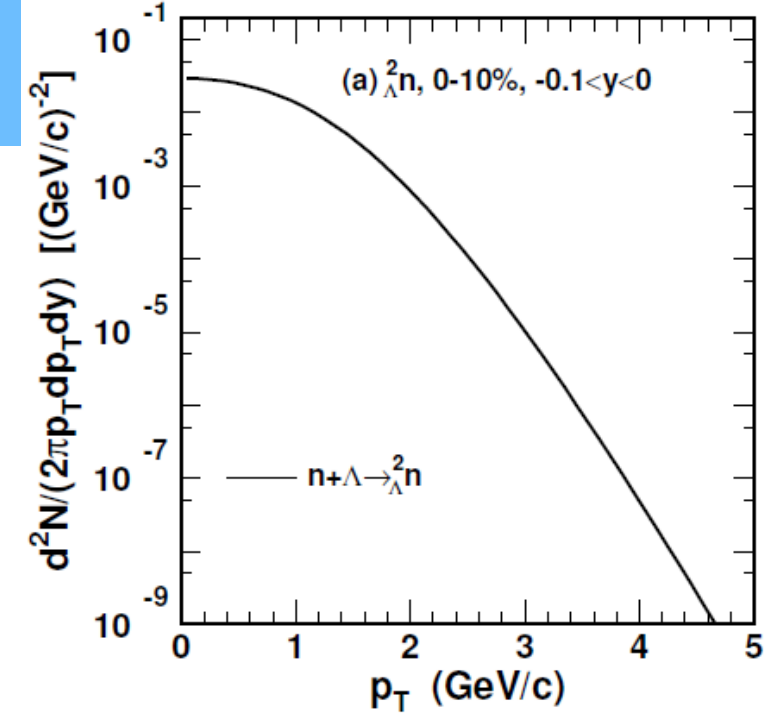
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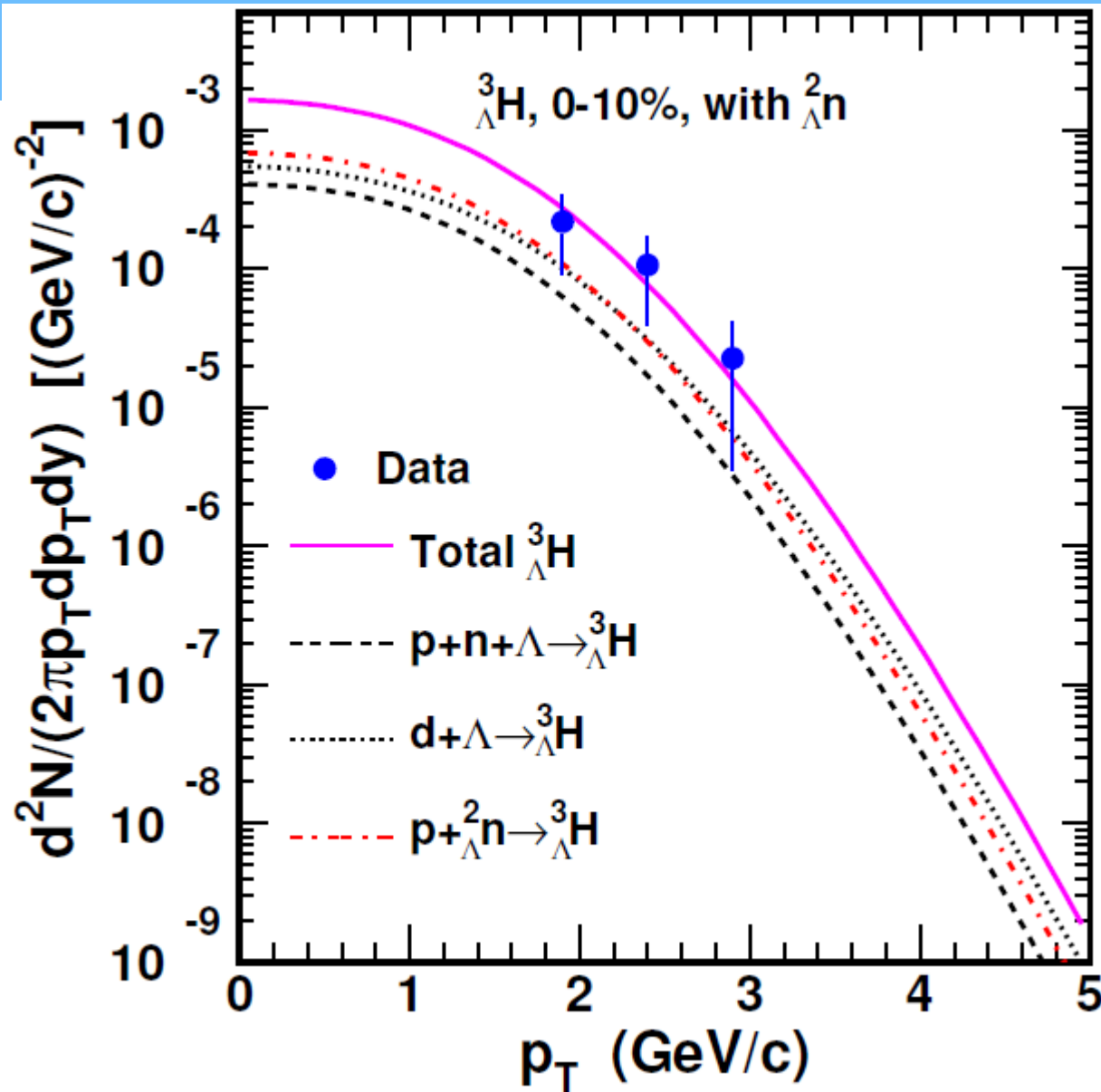
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Coal-channel		dN/dy		$\langle p_T \rangle$	
		Data	Theory	Data	Theory
${}^3_\Lambda\text{H}$	$p + n + \Lambda$	— — —	0.254×10^{-2}	— — —	1.191
	$d + \Lambda$	— — —	0.368×10^{-2}	— — —	1.246
	Total	$(1.131 \pm 0.210 \pm 0.384) \times 10^{-2}$		$1.254 \pm 0.087 \pm 0.163$	1.224
${}^4_\Lambda\text{H}$	$p + n + n + \Lambda$	— — —	0.602×10^{-3}	— — —	1.475
	$n + d + \Lambda$	— — —	0.333×10^{-3}	— — —	1.514
	$t + \Lambda$	— — —	0.789×10^{-3}	— — —	1.566
	Total	$(4.954 \pm 0.434 \pm 1.014) \times 10^{-3}$		$1.506 \pm 0.043 \pm 0.122$	1.524

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.

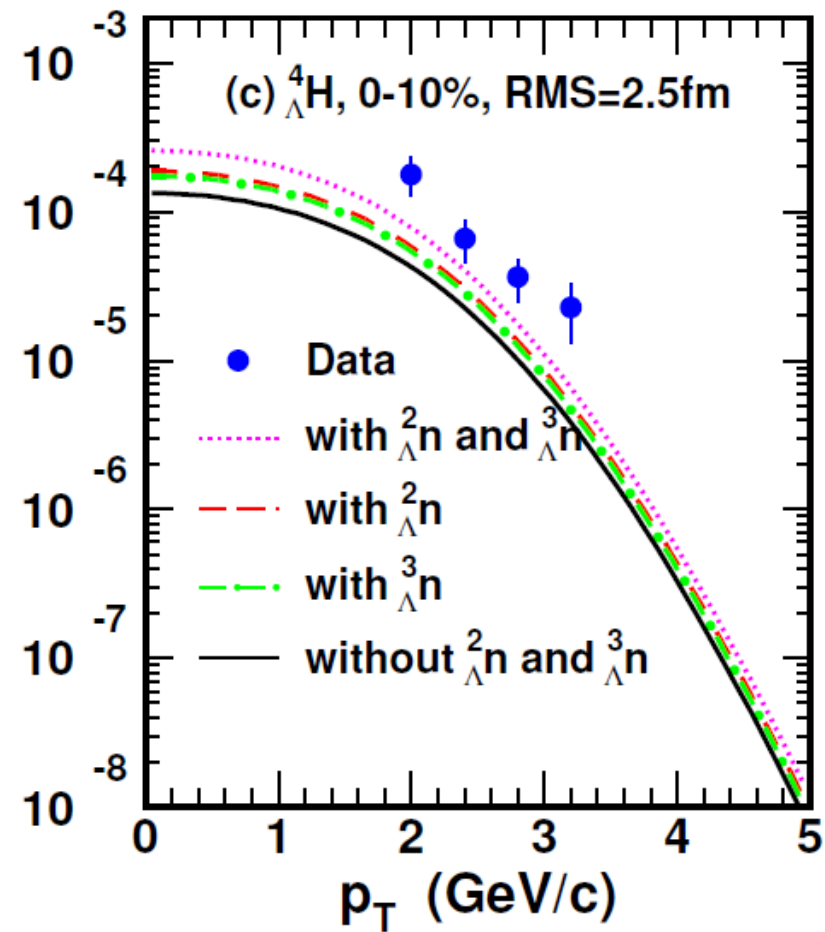
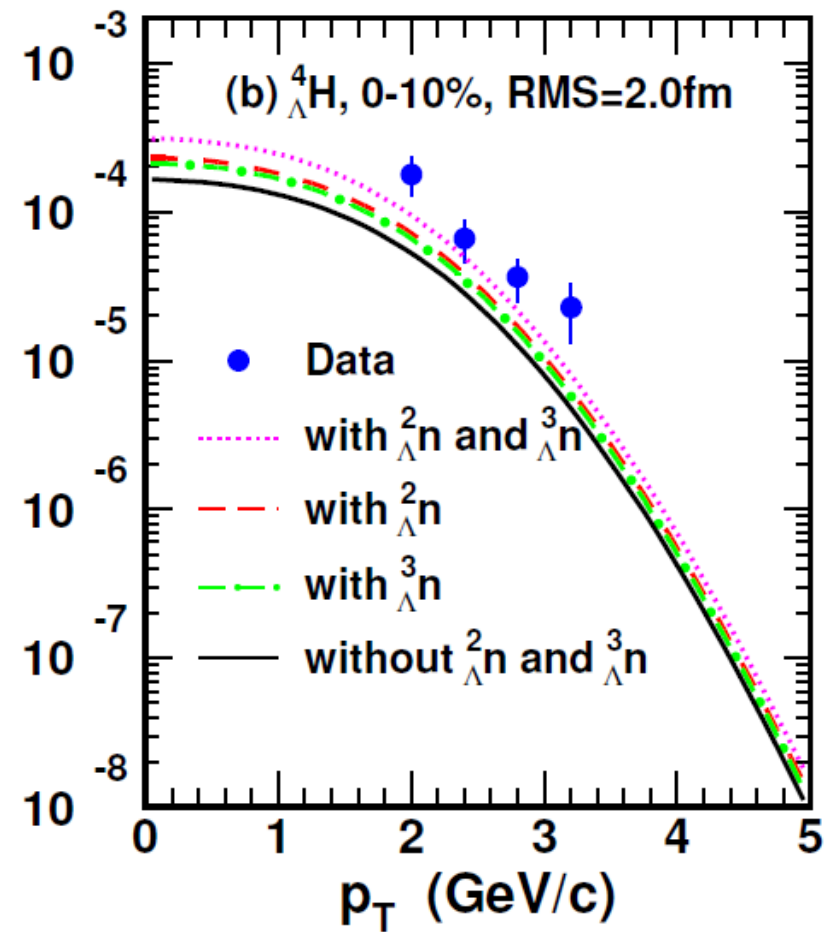
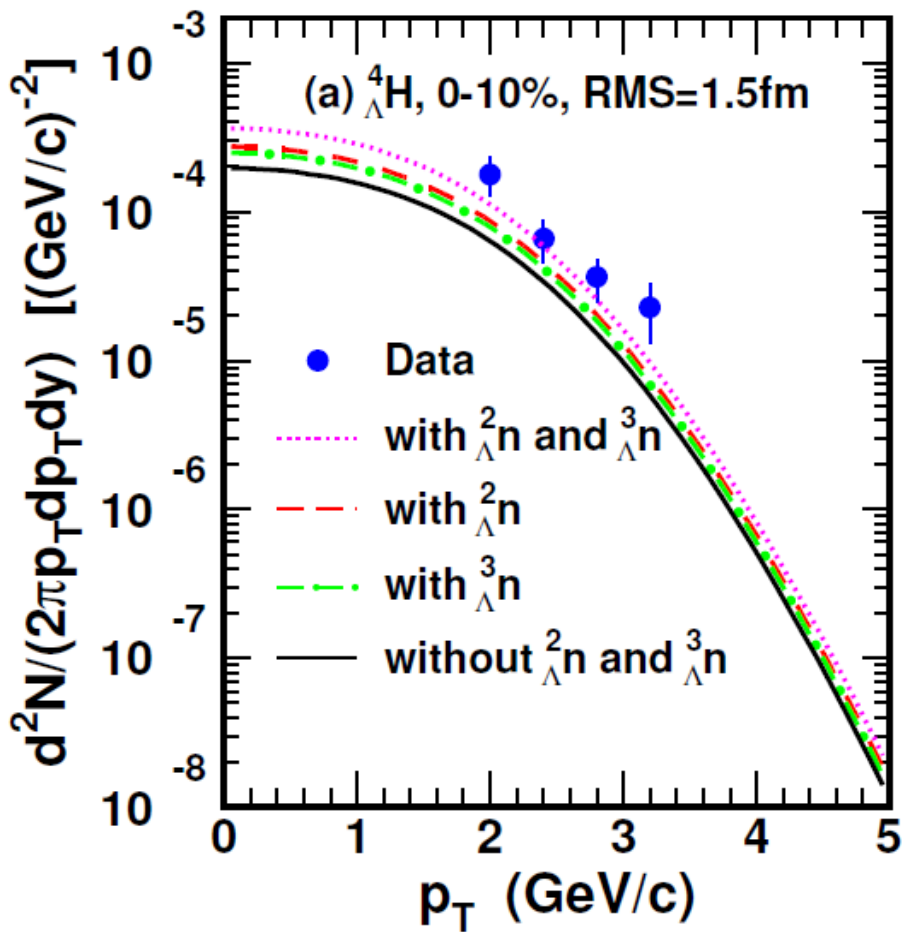
	Coal-channel	dN/dy	$\langle p_T \rangle$
${}^2_{\Lambda}n$	$n + \Lambda$	1.133×10^{-1}	0.945
	$n + n + \Lambda$	2.212×10^{-2}	1.224
${}^3_{\Lambda}n$	$n + {}^2_{\Lambda}n$	1.572×10^{-2}	1.218
	Total	3.784×10^{-2}	1.221





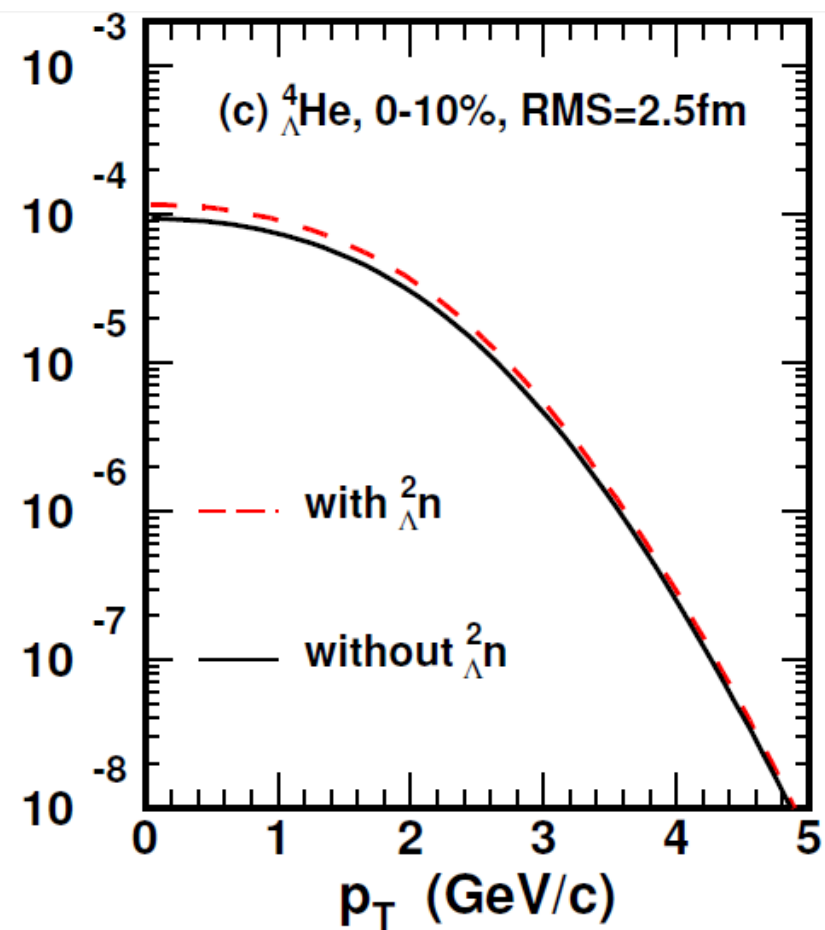
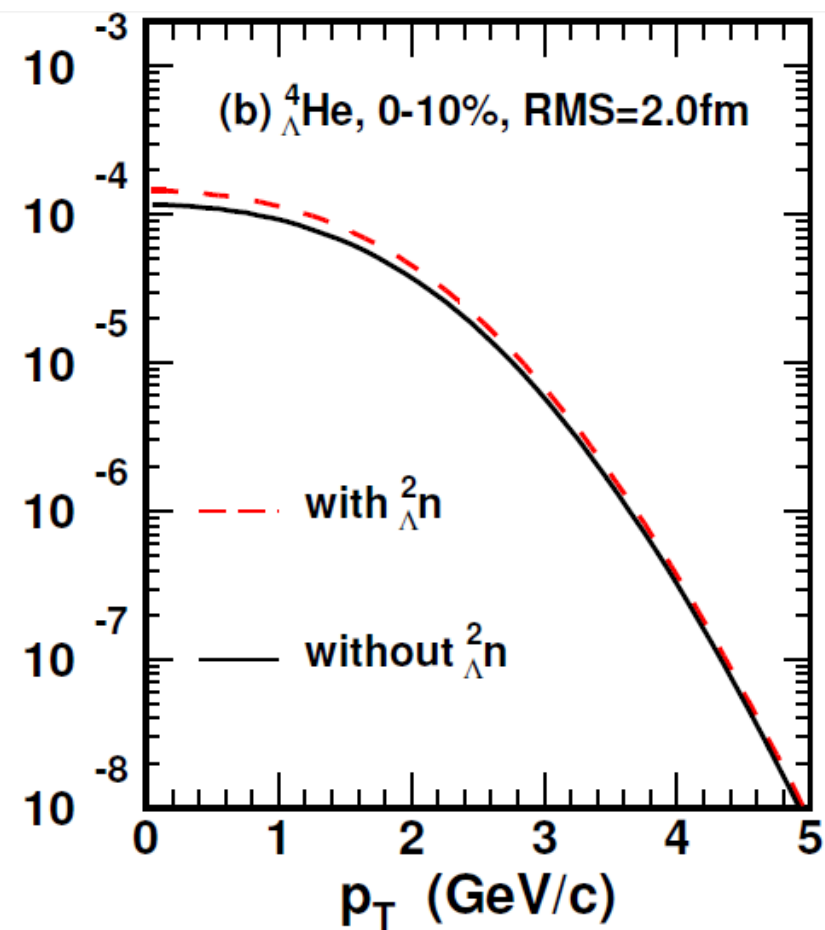
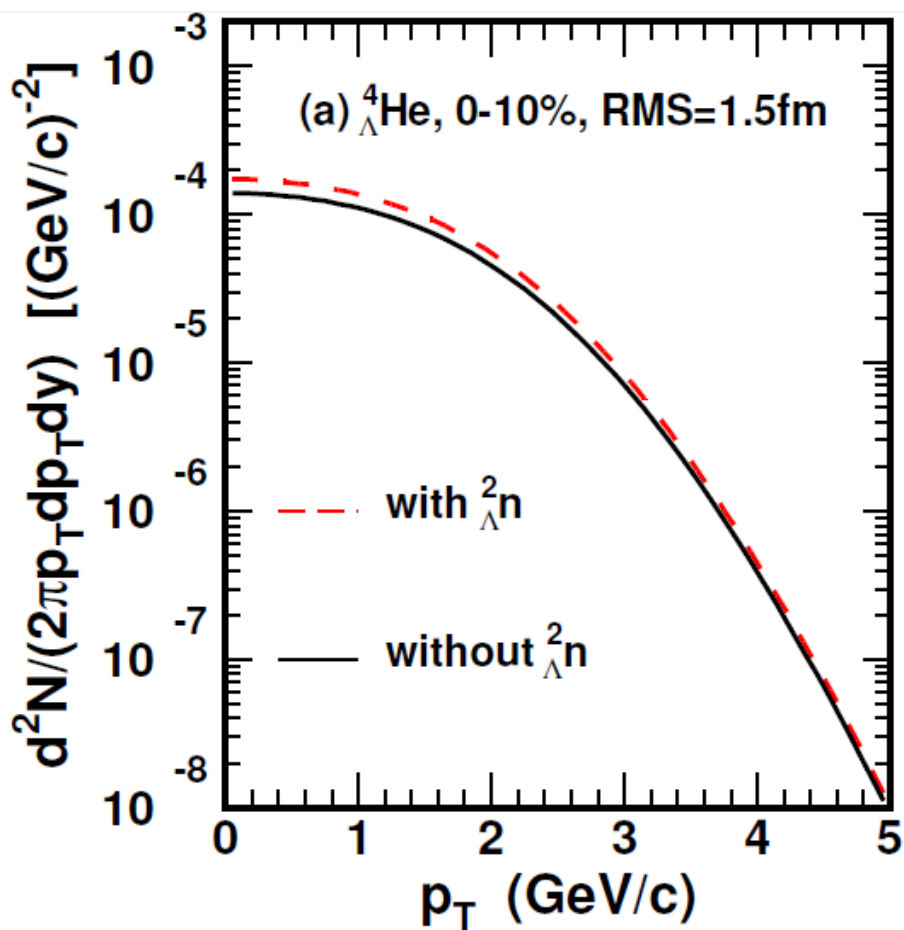
	Coal-channel	dN/dy	$\langle p_T \rangle$
$^3_{\Lambda}\text{H}$	$p + n + \Lambda$	0.254×10^{-2}	1.191
	$d + \Lambda$	0.368×10^{-2}	1.246
	$p + ^2_{\Lambda}n$	0.434×10^{-2}	1.200
	Total	1.056×10^{-2}	1.214
Data $(1.131 \pm 0.210 \pm 0.384) \times 10^{-2}$			

Including $^2_{\Lambda}\text{n}$ contribution, the theoretical results agree with the data well.



$${}^4_{\Lambda}\text{H } dN / dy \text{ data } (4.954 \pm 0.434 \pm 1.014) \times 10^{-3}$$

	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
${}^4_{\Lambda}\text{H}$	$p + n + n + \Lambda$	0.774×10^{-3}	0.602×10^{-3}	0.445×10^{-3}	1.483	1.475	1.467
	$n + d + \Lambda$	0.403×10^{-3}	0.333×10^{-3}	0.266×10^{-3}	1.520	1.514	1.507
	$t + \Lambda$	0.894×10^{-3}	0.789×10^{-3}	0.681×10^{-3}	1.571	1.566	1.562
	$p + n + {}^2_{\Lambda}n$	0.449×10^{-3}	0.371×10^{-3}	0.295×10^{-3}	1.473	1.468	1.462
	$d + {}^2_{\Lambda}n$	0.319×10^{-3}	0.276×10^{-3}	0.234×10^{-3}	1.509	1.505	1.501
	$p + {}^3_{\Lambda}n$	0.878×10^{-3}	0.781×10^{-3}	0.680×10^{-3}	1.471	1.468	1.464
	Total	3.717×10^{-3}	3.152×10^{-3}	2.601×10^{-3}	1.506	1.502	1.498
${}^4_{\Lambda}\text{He}$	$p + p + n + \Lambda$	0.576×10^{-3}	0.448×10^{-3}	0.331×10^{-3}	1.483	1.475	1.467
	$p + d + \Lambda$	0.301×10^{-3}	0.249×10^{-3}	0.198×10^{-3}	1.520	1.514	1.507
	${}^3\text{He} + \Lambda$	0.603×10^{-3}	0.533×10^{-3}	0.460×10^{-3}	1.590	1.586	1.581
	$p + p + {}^2_{\Lambda}n$	0.332×10^{-3}	0.274×10^{-3}	0.218×10^{-3}	1.473	1.468	1.462
	Total	1.812×10^{-3}	1.504×10^{-3}	1.207×10^{-3}	1.523	1.519	1.516



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

* four-body coalescence or three-body coalescence

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

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

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

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

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

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

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

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

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

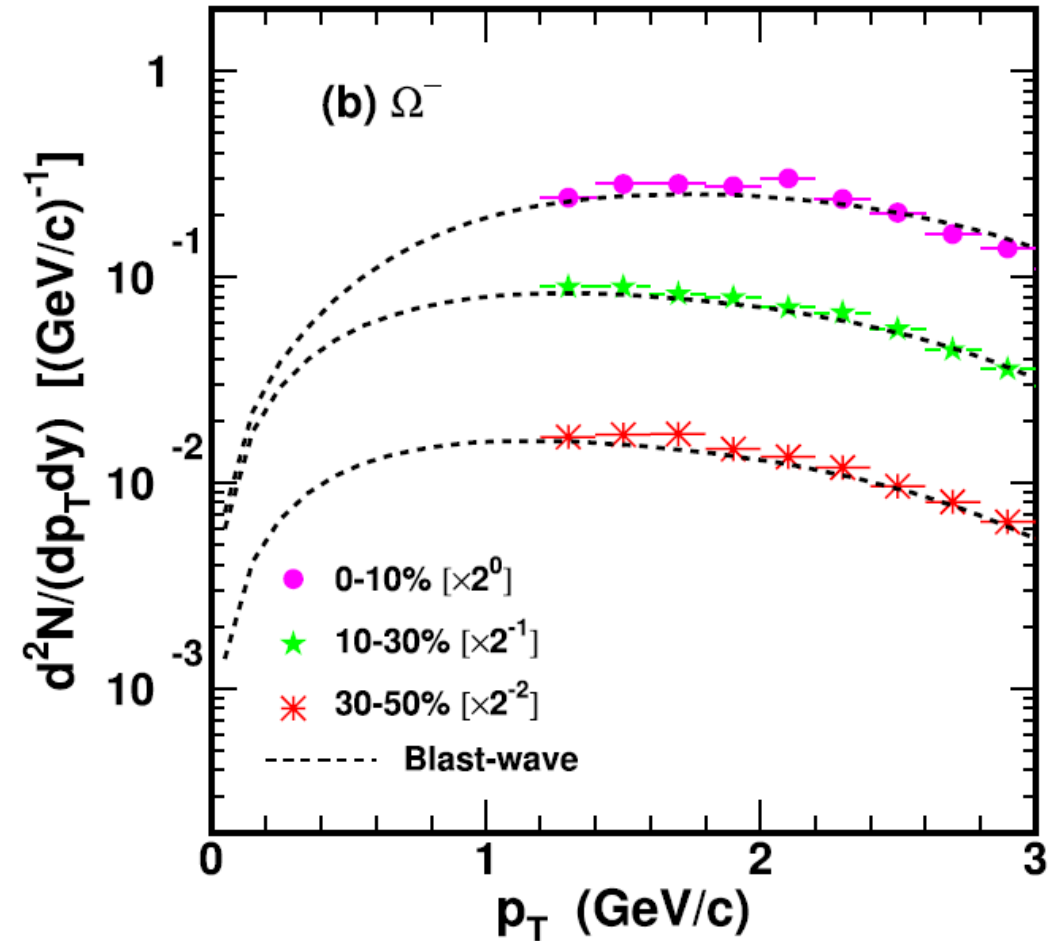
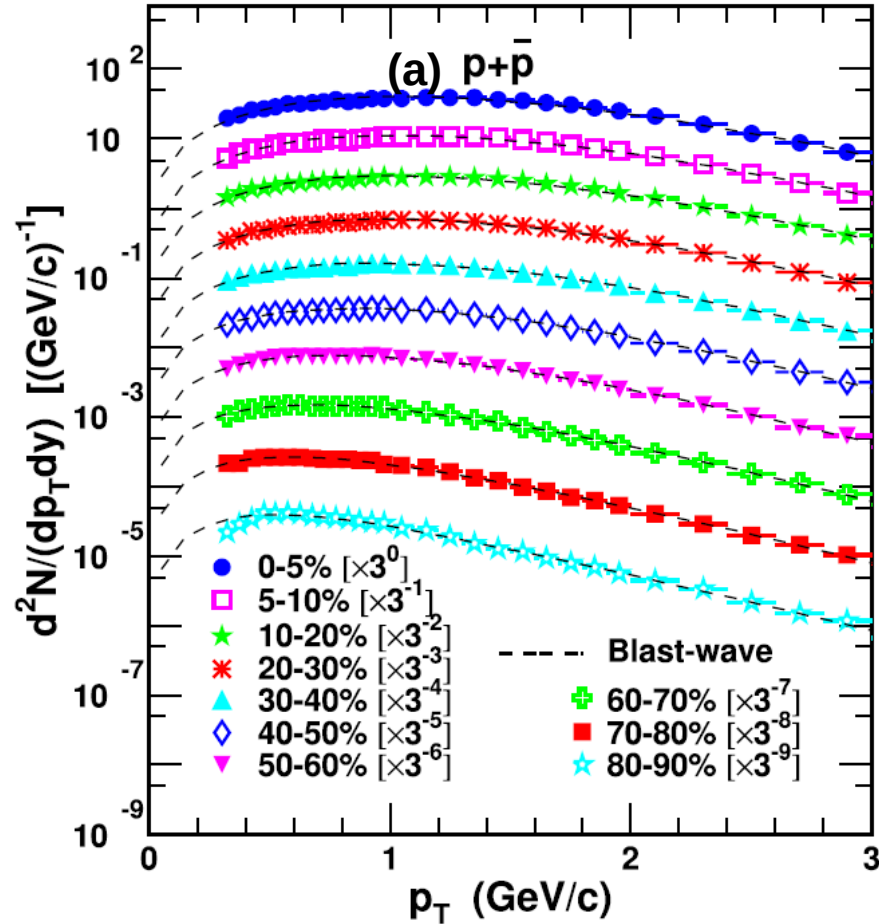
* **Total** ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$

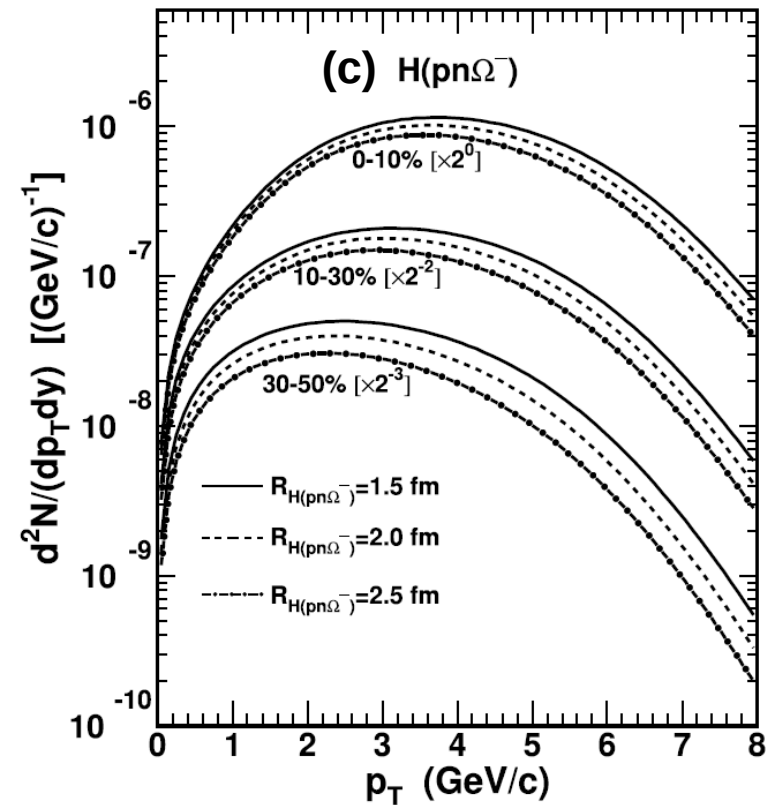
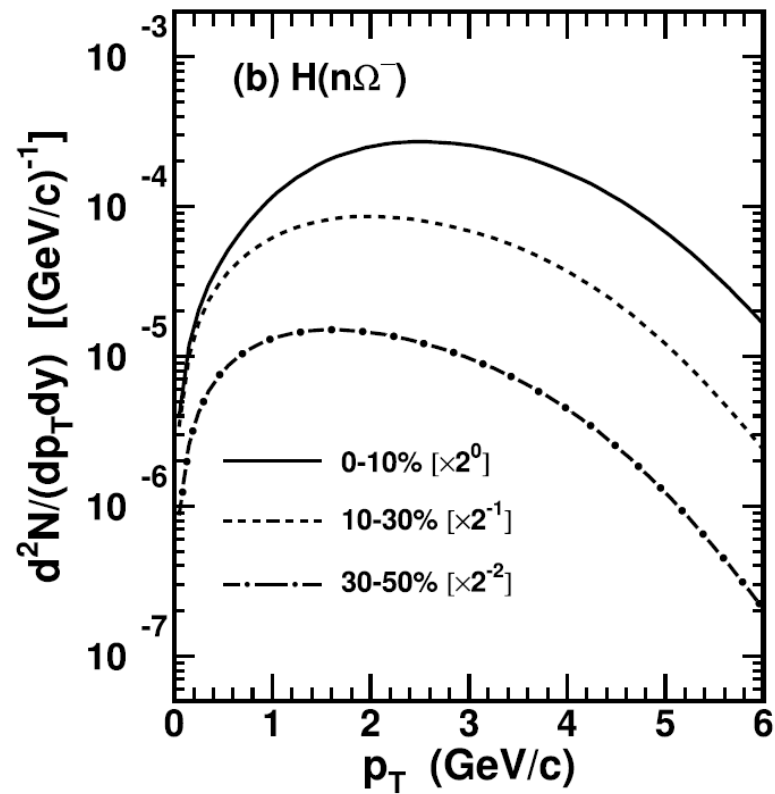
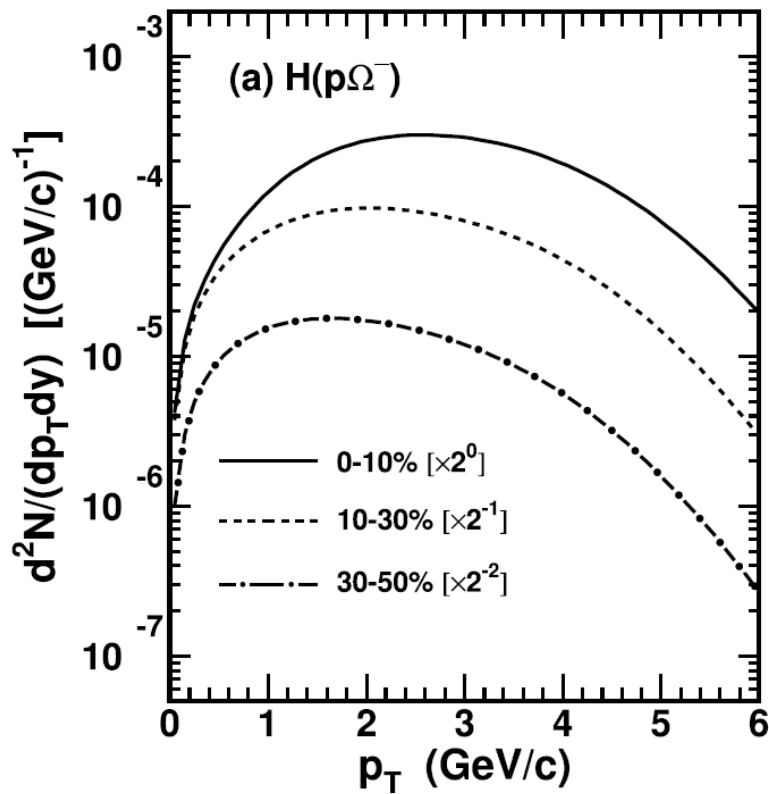
	RMS (fm)	neither ${}^2_{\Lambda}n$ nor ${}^3_{\Lambda}n$	with ${}^2_{\Lambda}n$	with ${}^3_{\Lambda}n$	with ${}^2_{\Lambda}n$ and ${}^3_{\Lambda}n$
$\frac{{}^4_{\Lambda}\text{He}}{{}^4_{\Lambda}\text{H}}$	1.5	0.715	0.639	0.573	0.488
	2.0	0.713	0.634	0.564	0.477
	2.5	0.711	0.629	0.553	0.464
$\frac{{}^4_{\Lambda}\text{H}-{}^4_{\Lambda}\text{He}}{{}^4_{\Lambda}\text{H}+{}^4_{\Lambda}\text{He}}$	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

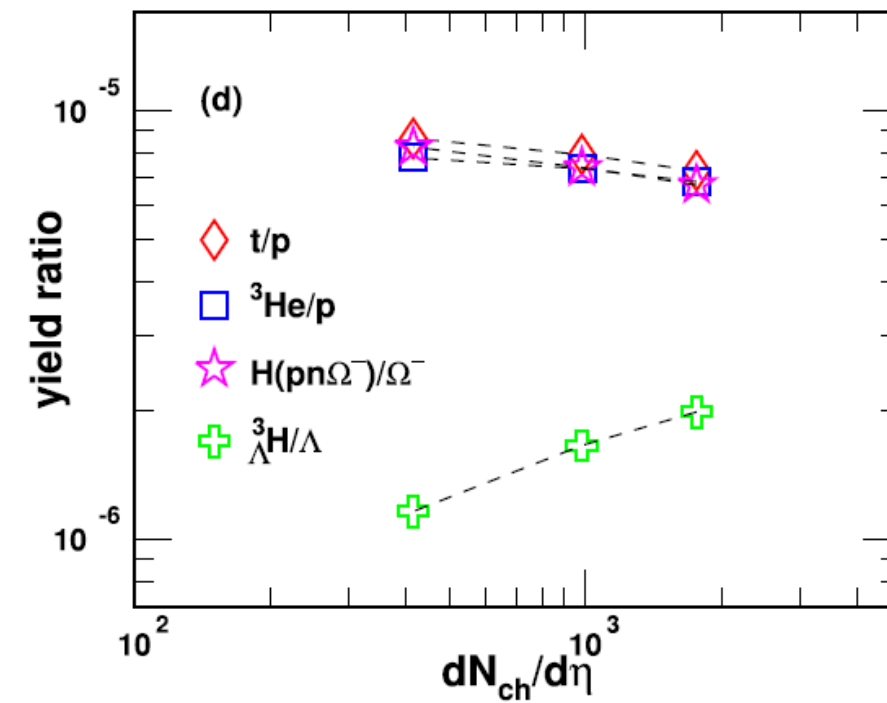
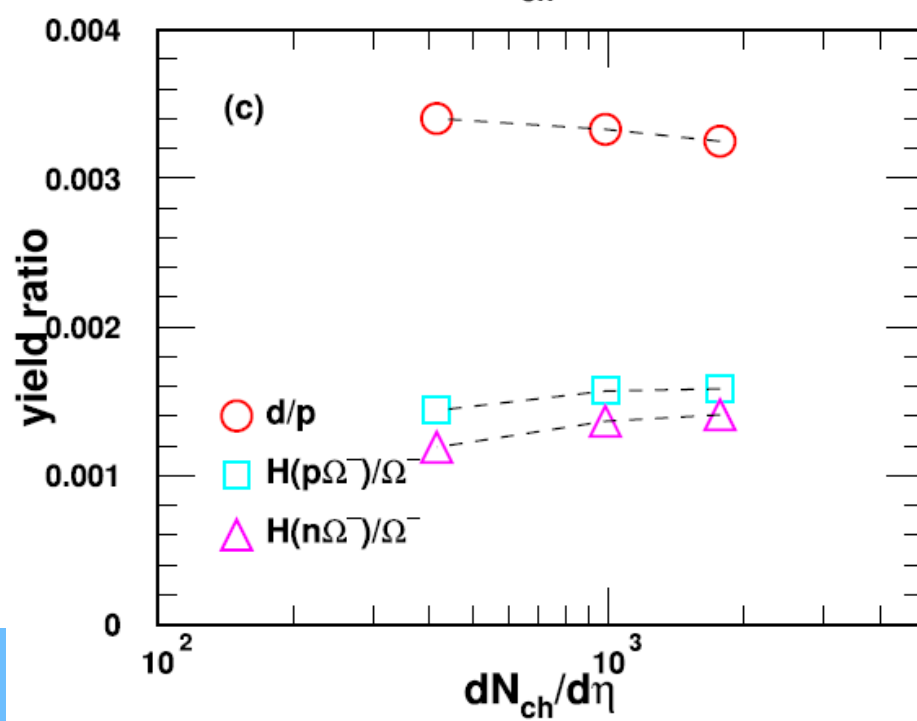
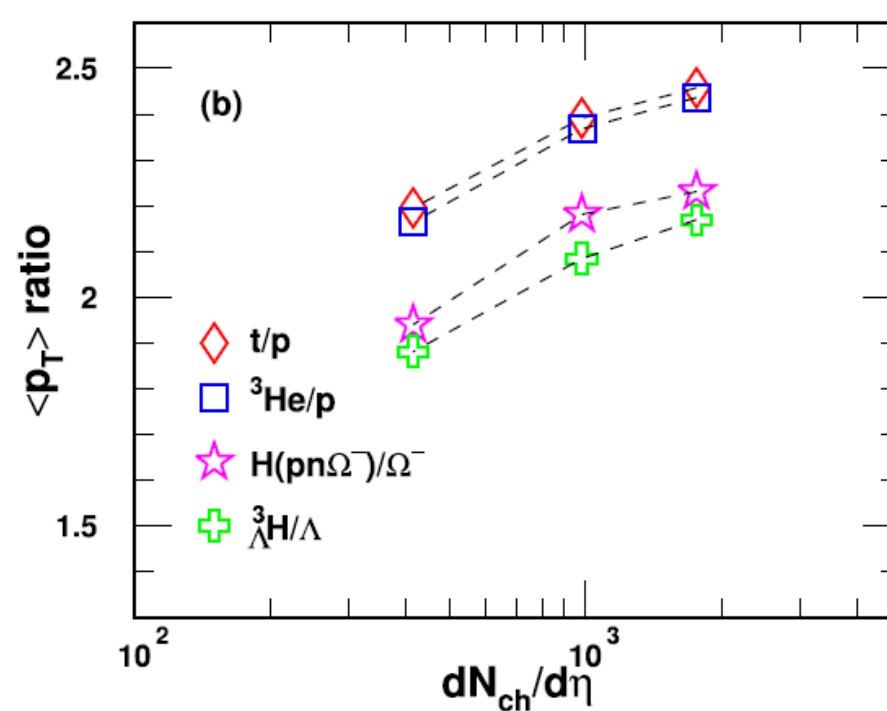
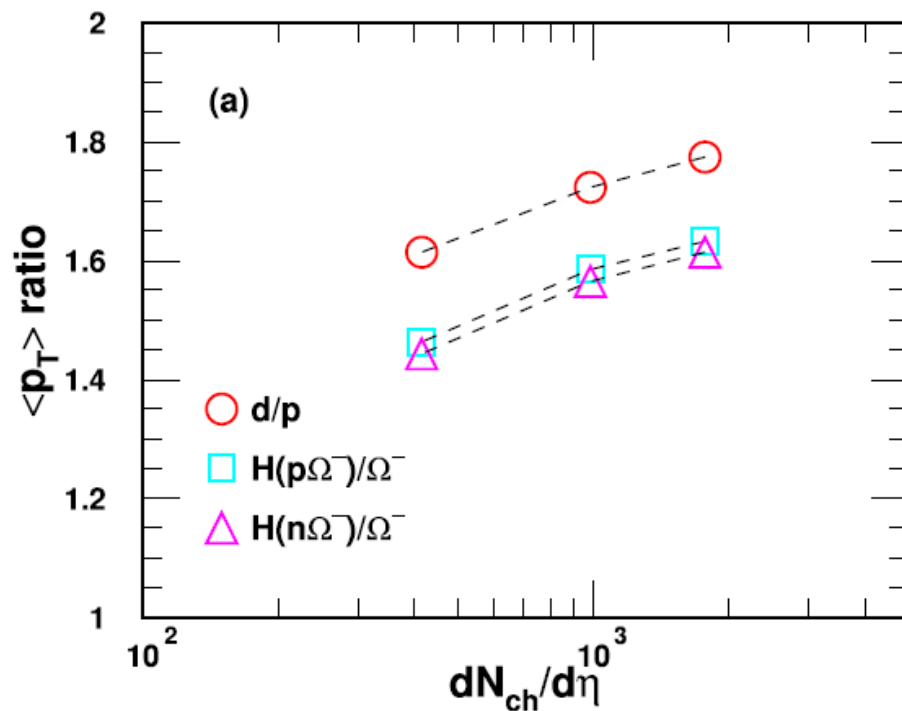
Comparisons with future measurements can help shed light on the existence constraints of ${}^2_{\Lambda}n$ and ${}^3_{\Lambda}n$.

III. Results in heavy-ion collisions at RHIC and LHC **Pb-Pb at 5.02 TeV**

model inputs:







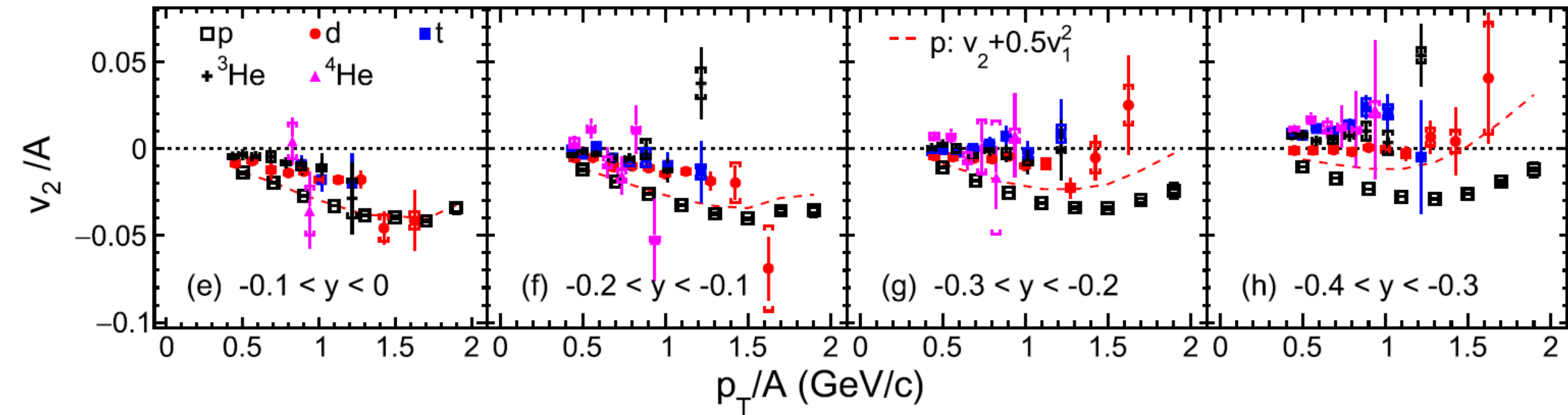
Correlation is more interesting!

RQW, X.L. Hou, Y.H. Li, J. Song, and F.L. Shao, Nucl. Sci. Tech. 36, 185, 2025.

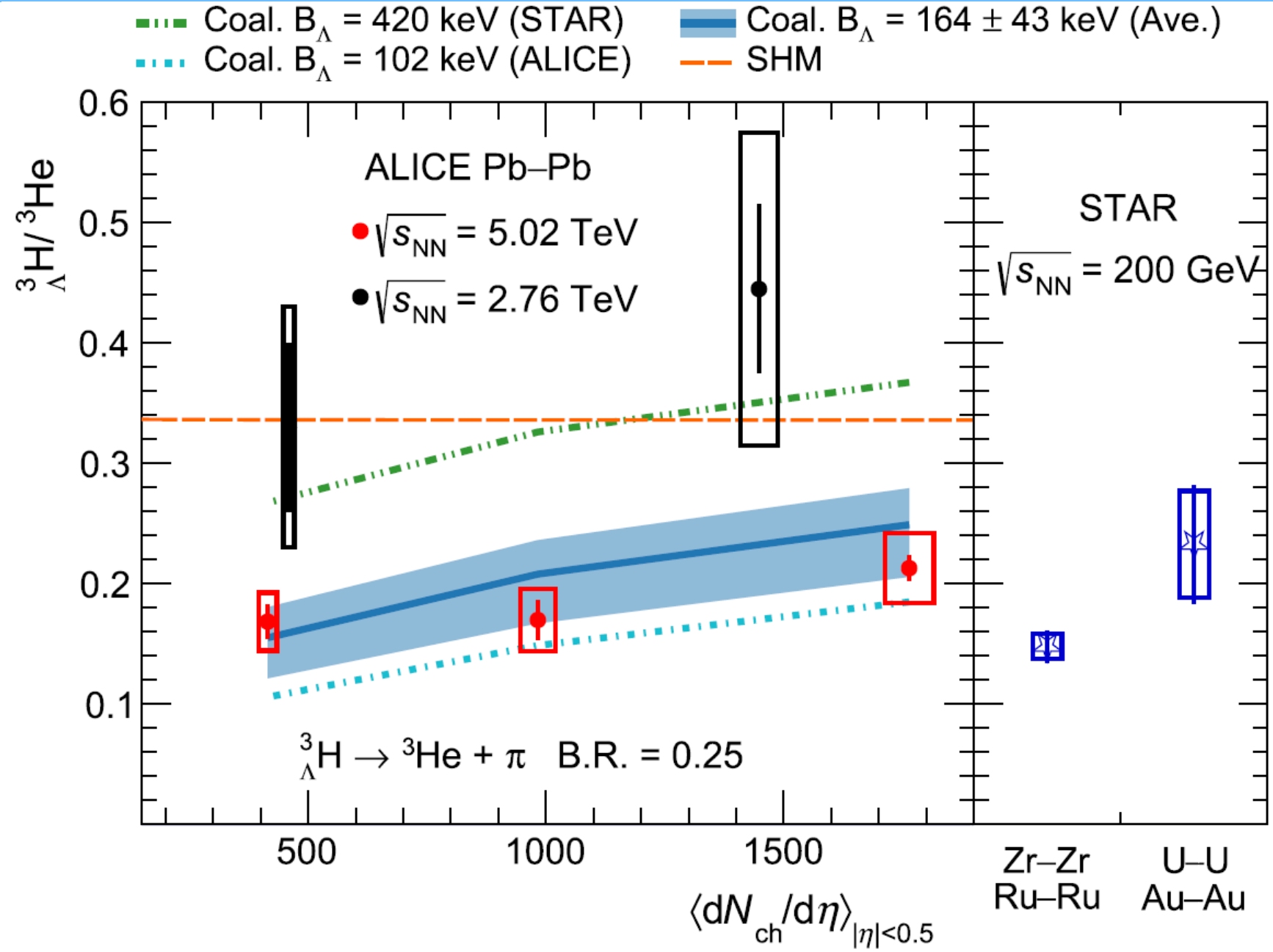
IV. Summary

- ◆ We extended an analytical coalescence model to deal with productions of hypernuclei besides light nuclei in relativistic heavy-ion collisions. The relationships of hypernuclei with primordial nucleons and hyperons were clearly given.
- ◆ We applied the extended coalescence model to Au-Au@3GeV collisions at RHIC, and gave contributions from different coalescence channels for ${}^3_{\Lambda}\text{H}$, ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$ in their productions.
- ◆ We predicted the production asymmetry between ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$, which could shed light on the existence constraints of the possible neutron- Λ bound states.
- ◆ We predicted the production of different Ω -hypernuclei at LHC.

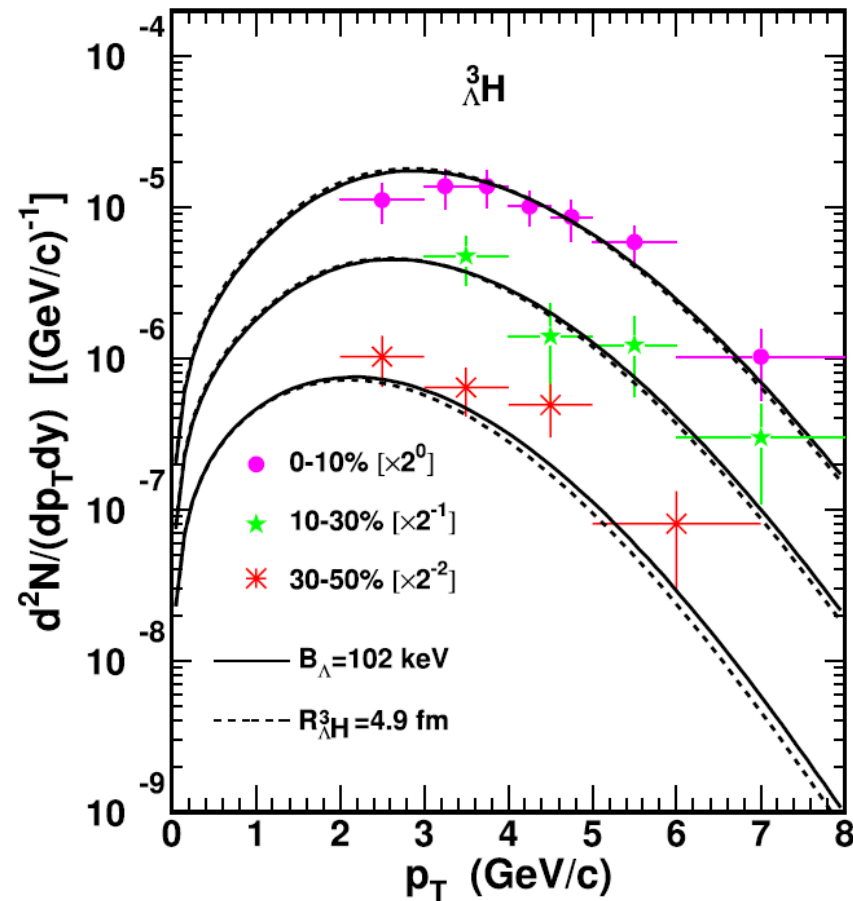
Thank you!



no v_2/A scaling



Our results at LHC



$H(p\Omega^-)$ is about 3.24 fm

$H(n\Omega^-)$ is 3.77 fm

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Nucl. Sci. Tech. 36, 185, 2025.