Production of light and hyper-nuclei in high energy heavy-ion collisions

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Collaborators: Feng-Lan Shao, Jun Song, Yan-Ting Feng, *et al.*

References: Phys. Rev. C **112**, 034908, 2025; Nucl. Sci. Tech. **36**, 185, 2025;
Phys. Rev. C **109**, 034907, 2024; Phys. Rev. C **105**, 054908, 2022;
Phys. Rev. C **103**, 064908, 2021; arXiv: 2603.21164.

Outline

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II. An analytical coalescence model

Formalism of two-body coalescence

General formalism of *N*-body coalescence

III. Applications in heavy-ion collisions at RHIC & LHC

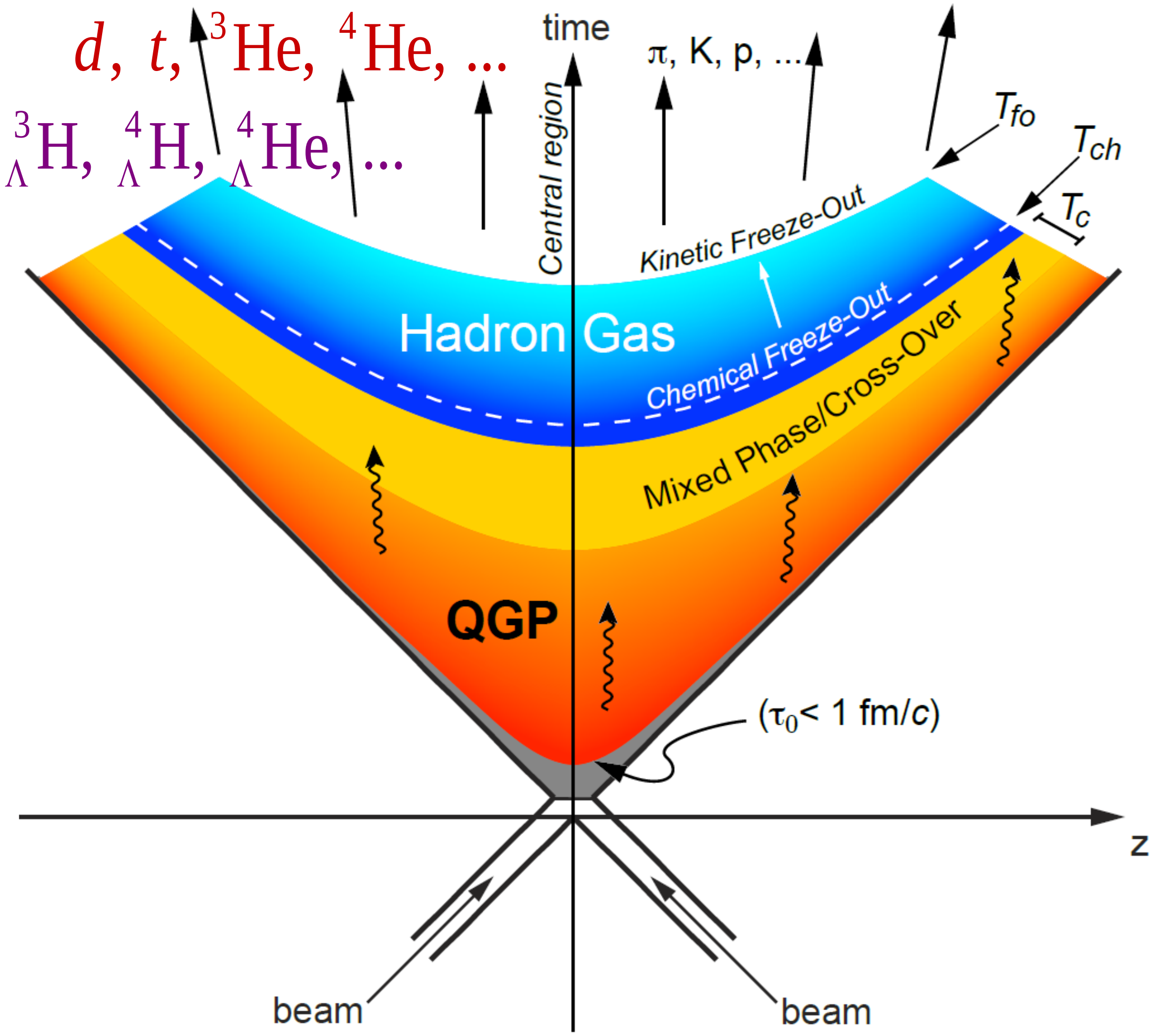
Coalescence factor B_A

p_T spectra

Production correlations of different light (hyper-)nuclei

IV. Summary

What can light and hyper-nuclei in high energy heavy-ion collisions tell us?



- Natural tools for elementary nucleon-nucleon, nucleon-hyperon, and three-body interactions
- Probes of system freeze-out properties
- Production mechanisms of composite particles
- Search for more molecular states
- ……

Thermal models

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

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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;

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Coalescence models

$$f_H \sim f_p^{Z} f_{\Lambda,\Omega}^{N_{\Lambda,\Omega}} f_n^{A-Z-N_{\Lambda,\Omega}} \otimes \mathcal{R}_H$$

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Theoretical studies

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……

Experimental measurements

RHIC: 3~200 GeV

Au+Au, Cu+Cu, Ru+Ru, Zr+Zr, …

LHC: 0.9~13.6 TeV

pp, p+Pb, Xe+Xe, Pb+Pb, …

$d,\ t,\ {}^{3}\mathrm{He},\ {}^{4}\mathrm{He},\ {}^{3}_{\Lambda}\mathrm{H},\ {}^{4}_{\Lambda}\mathrm{H},\ {}^{4}_{\Lambda}\mathrm{He}, \ldots$

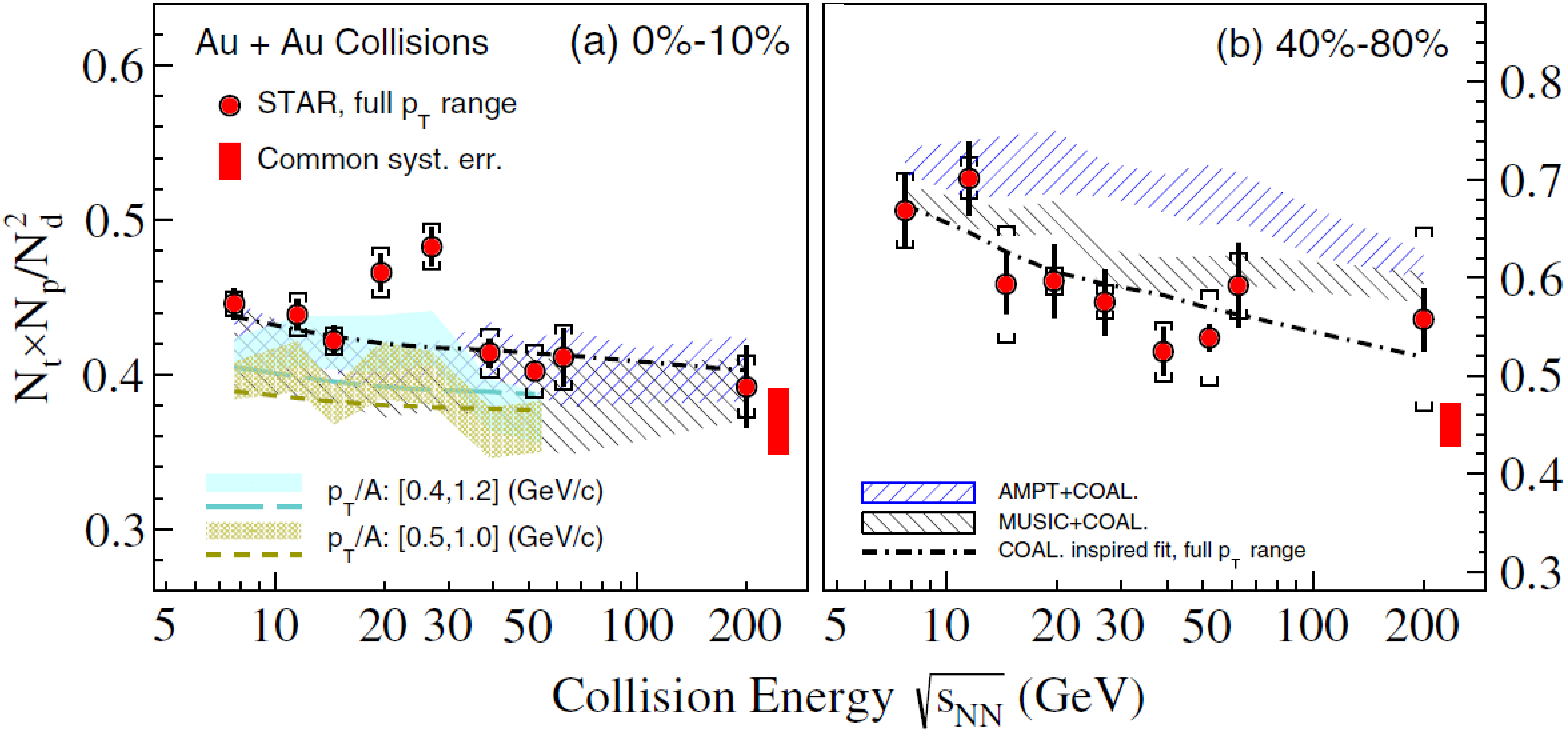
- **coalescence factors B_2 and B_3**
- **p_T spectra**
- **flows v_1, v_2 and v_3**
- **yield ratios**
- ……

collision energy, system size, and p_T dependence

mass number scaling

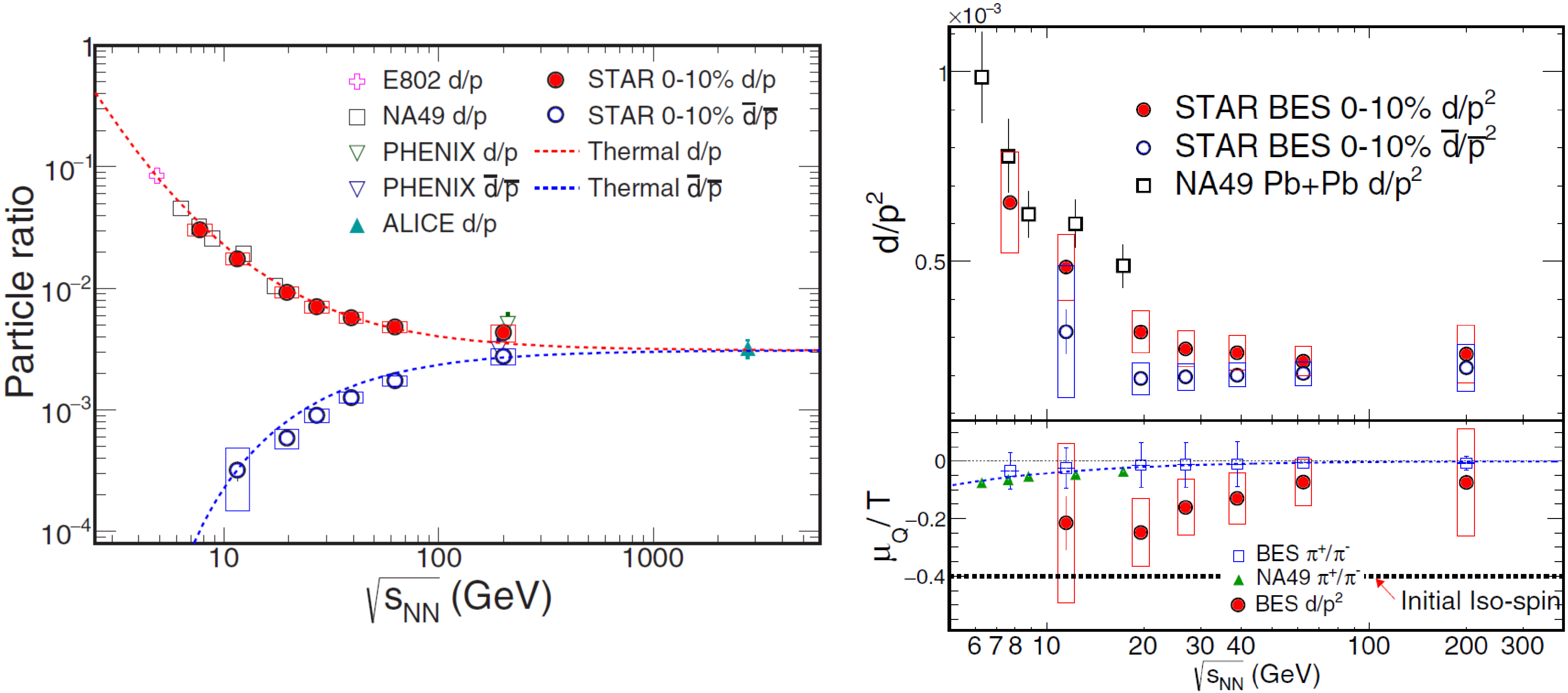
Experiment

STAR, PRL 130, 202301, 2023



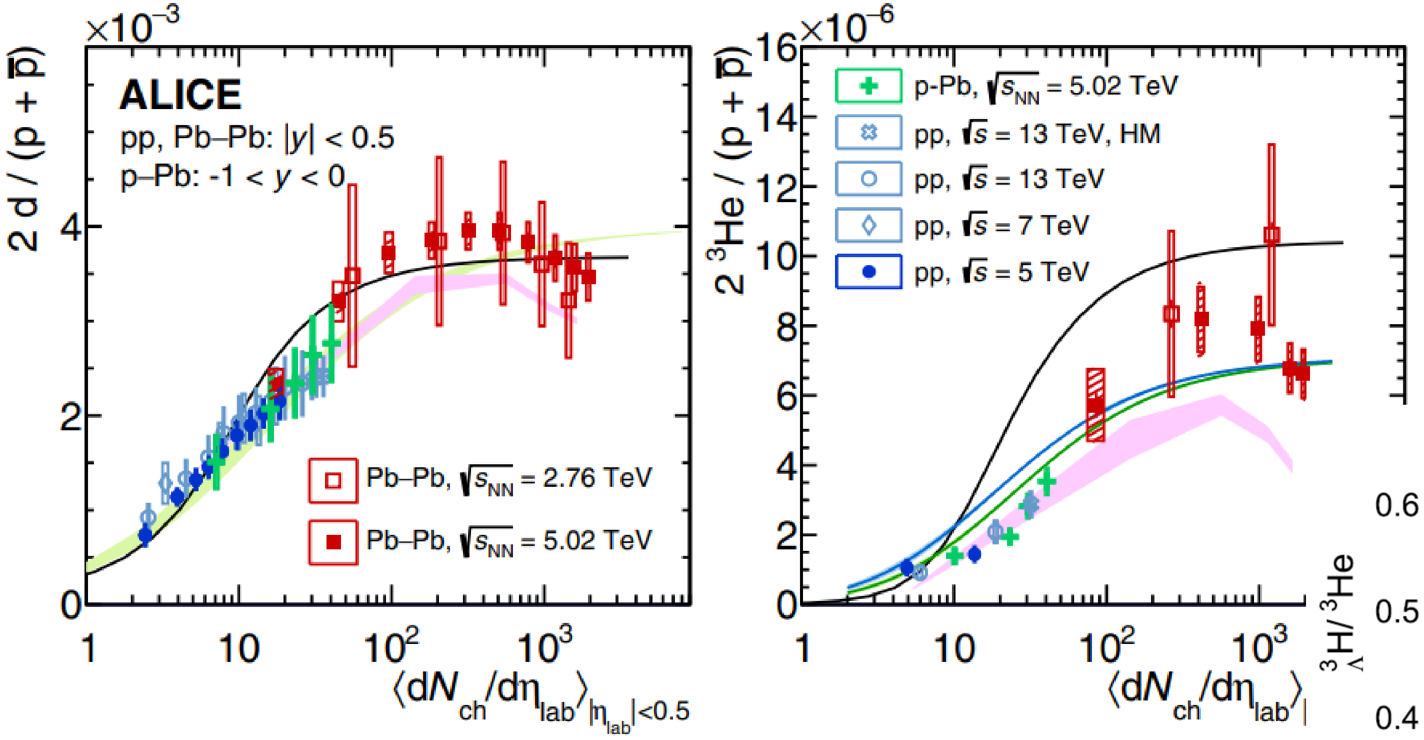
Experiment

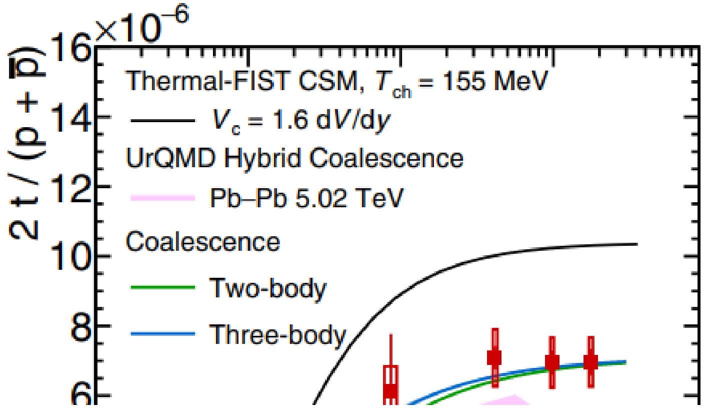
STAR, PRC 99, 064905, 2019

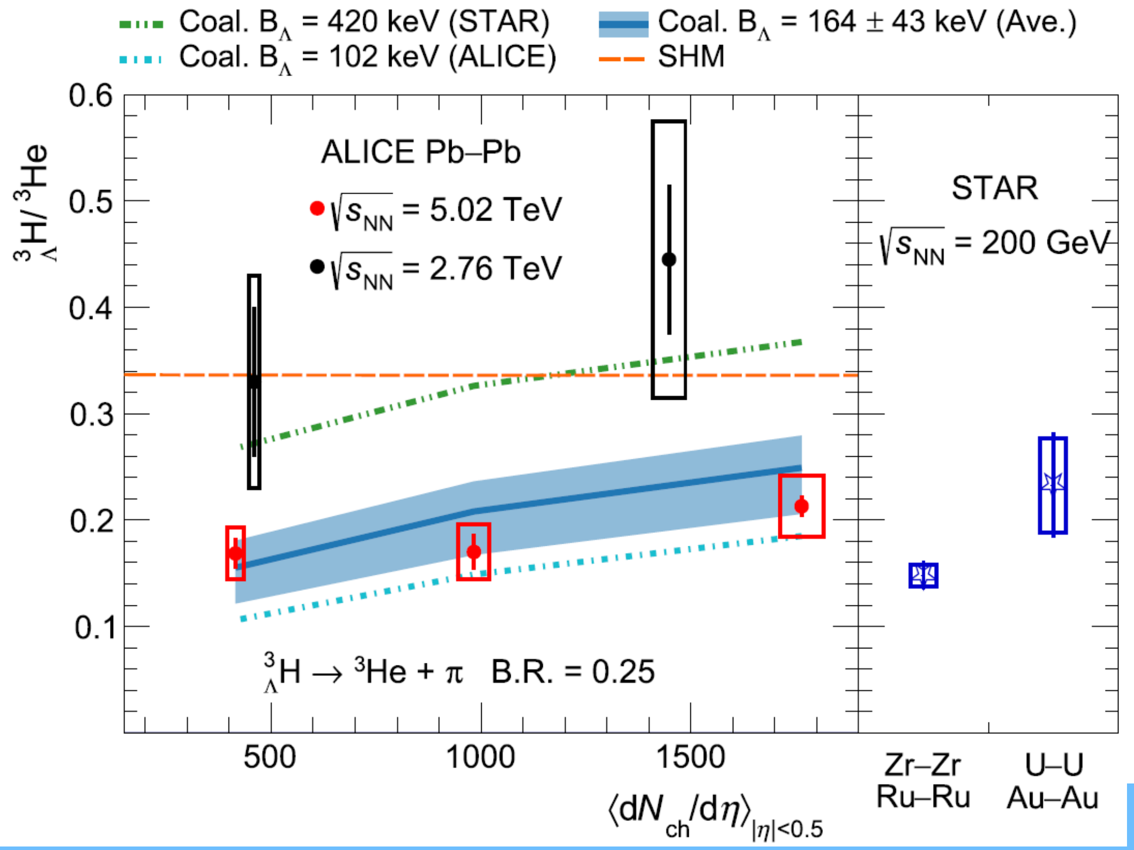


Experiment

ALICE, PRC 107, 064904, 2023







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Experiment

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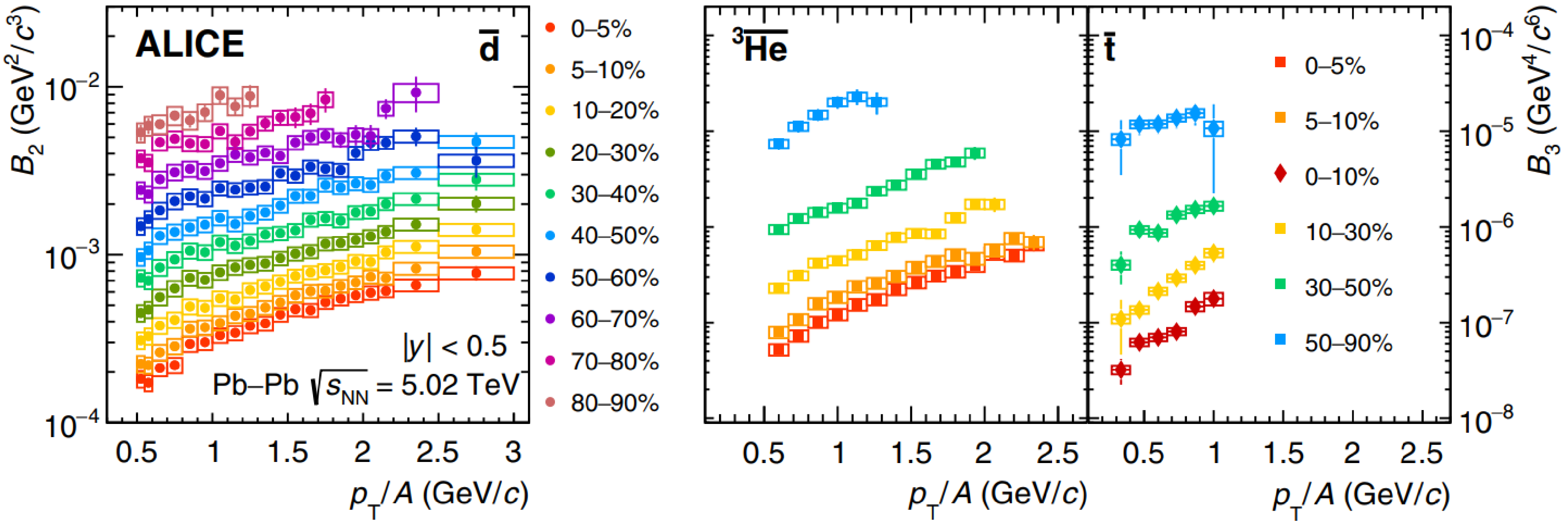

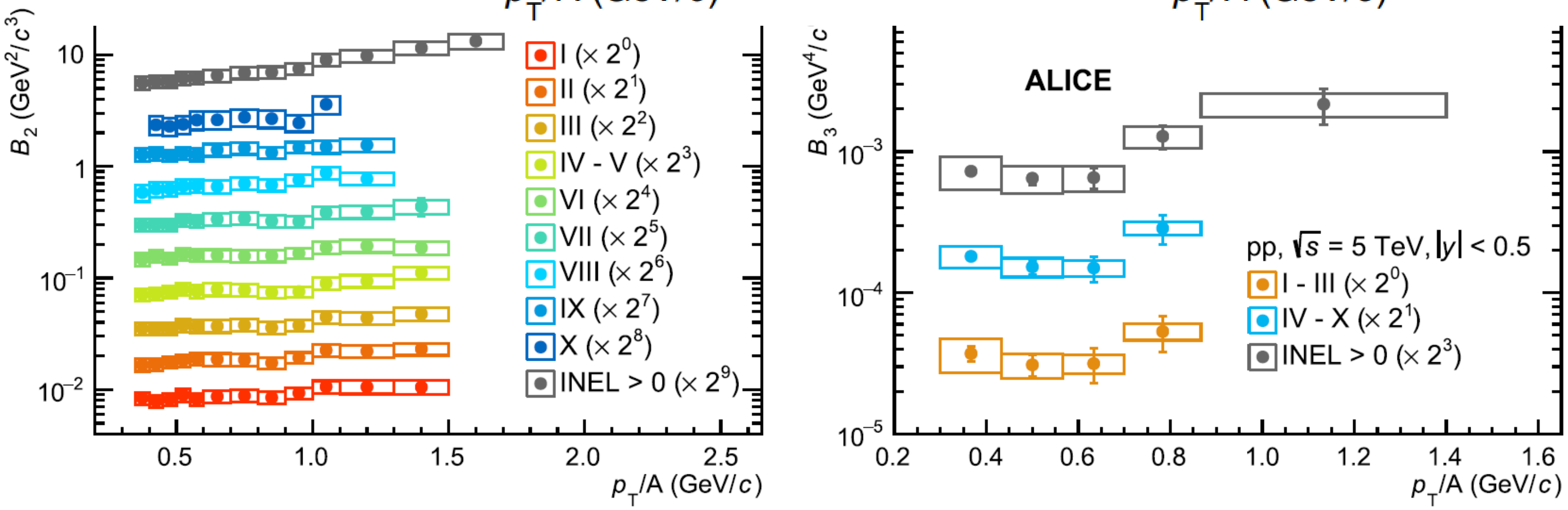

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Experiment

STAR, PRL 130, 212301, 2023

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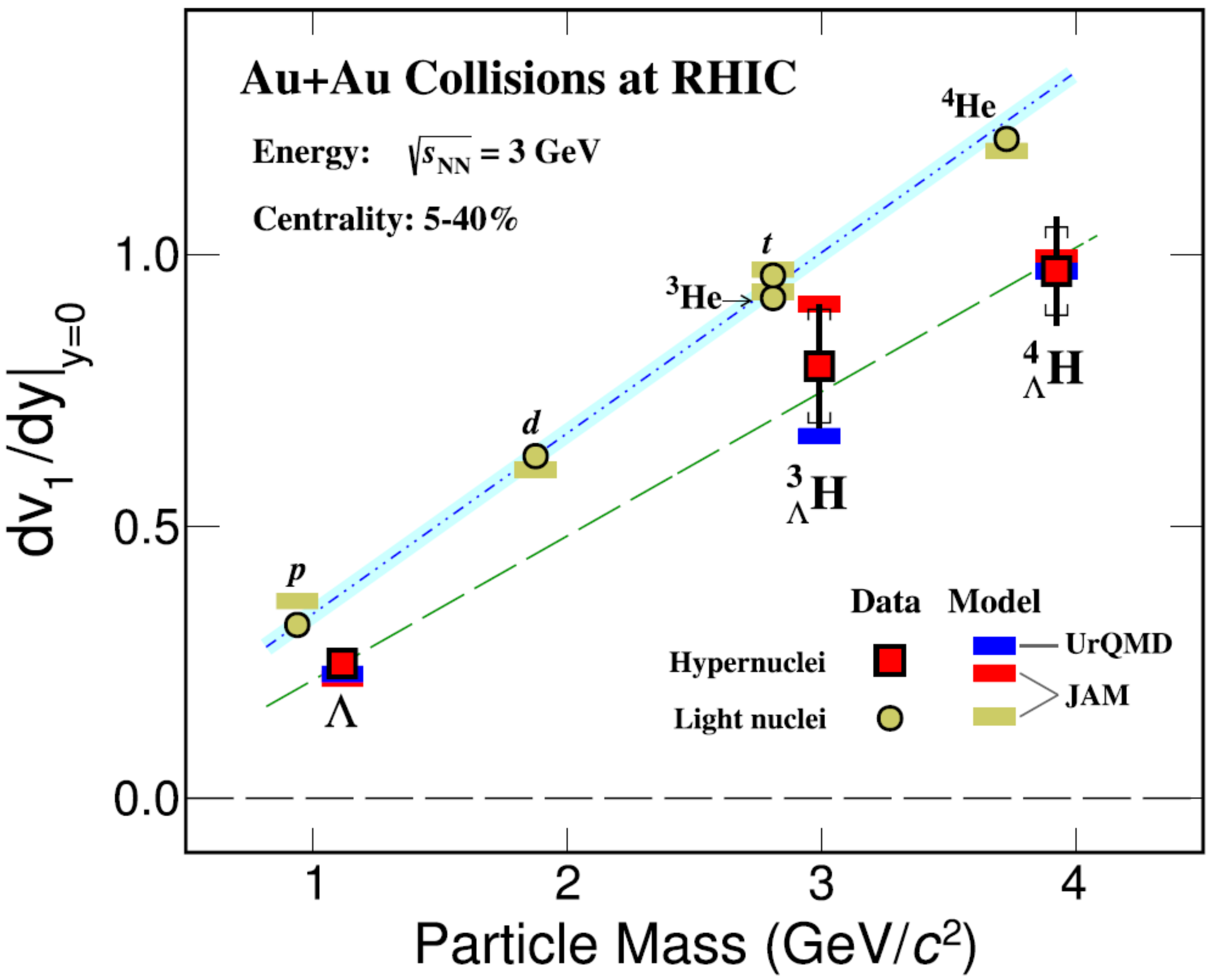
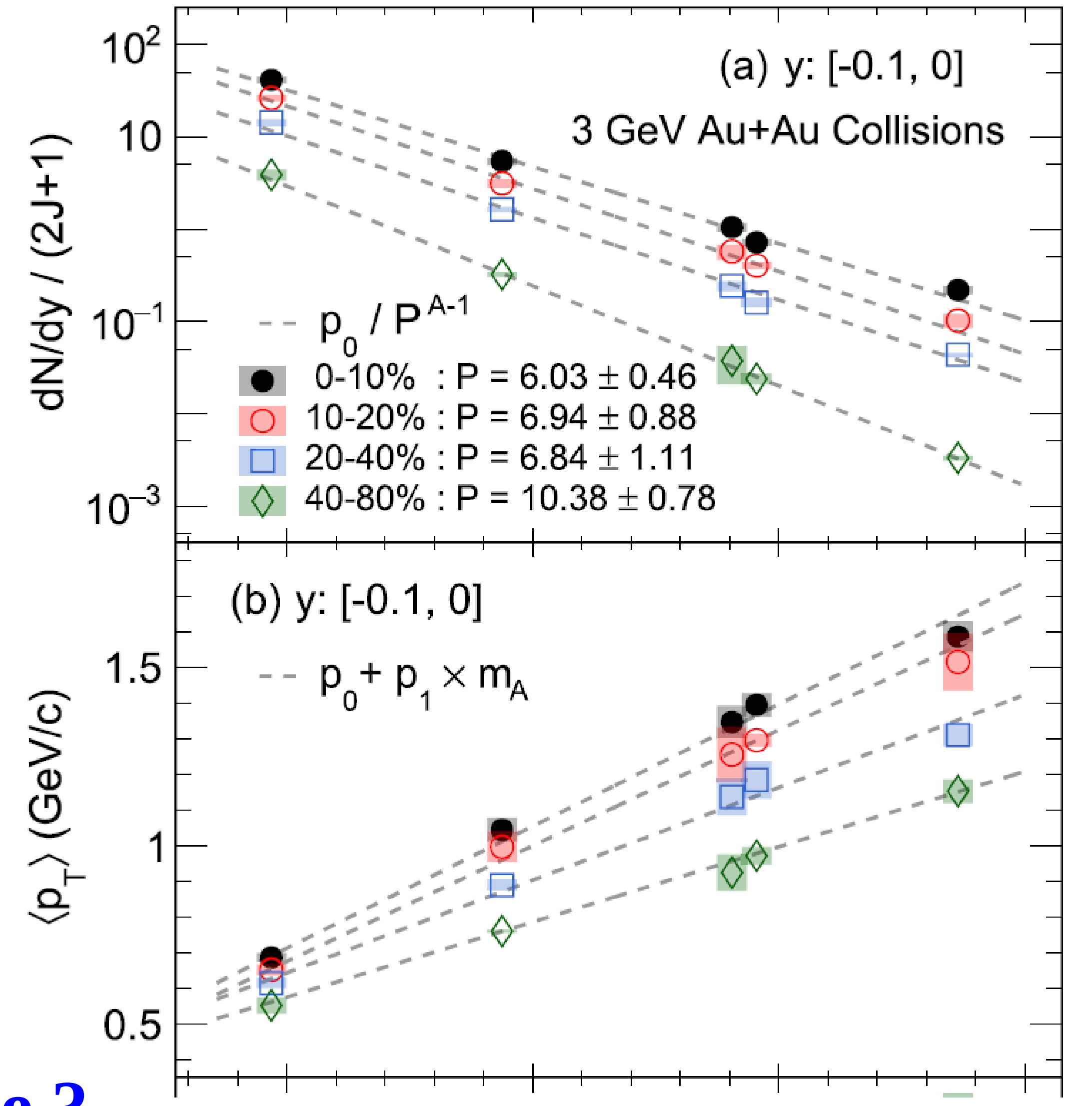


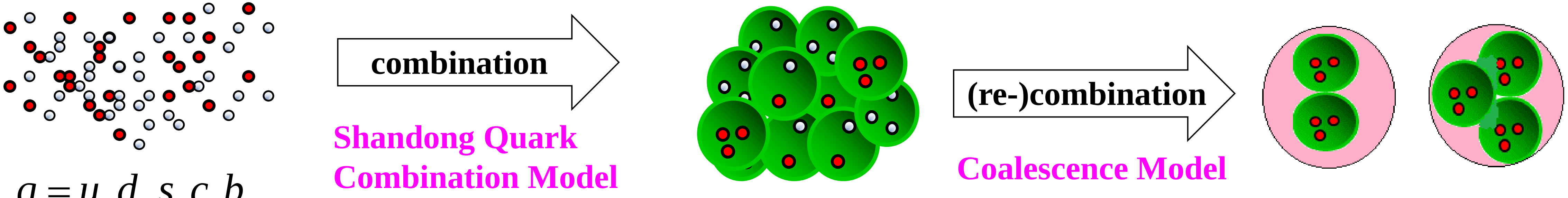


mass number scaling → coalescence ?

How coalescence works for those RHIC & LHC measurements ?

Characteristics originated from coalescence itself ?

quark-antiquark system **hadronic system**



$q = u, d, s, c, b$

$\bar{q} = \bar{u}, \bar{d}, \bar{s}, \bar{c}, \bar{b}$

$M(q\bar{q}), B(qqq)$

$d,\ t,\ ^3\text{He},\ ^3_\Lambda\text{H}, \ldots$

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

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

two-hadron joint coordinate-momentum distribution

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

↑

assumption 1: coordinate-momentum factorization

RQW, Y.H. Li, J. Song, and F.L. Shao, Phy. Rev. C 109, 034907, 2024.

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

The three-dimensional momentum distribution

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

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

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

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

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

equal-velocity combination

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. Applications in heavy-ion collisions at RHIC and LHC

- **Coalescence factor B_A (B_2 & B_3)**

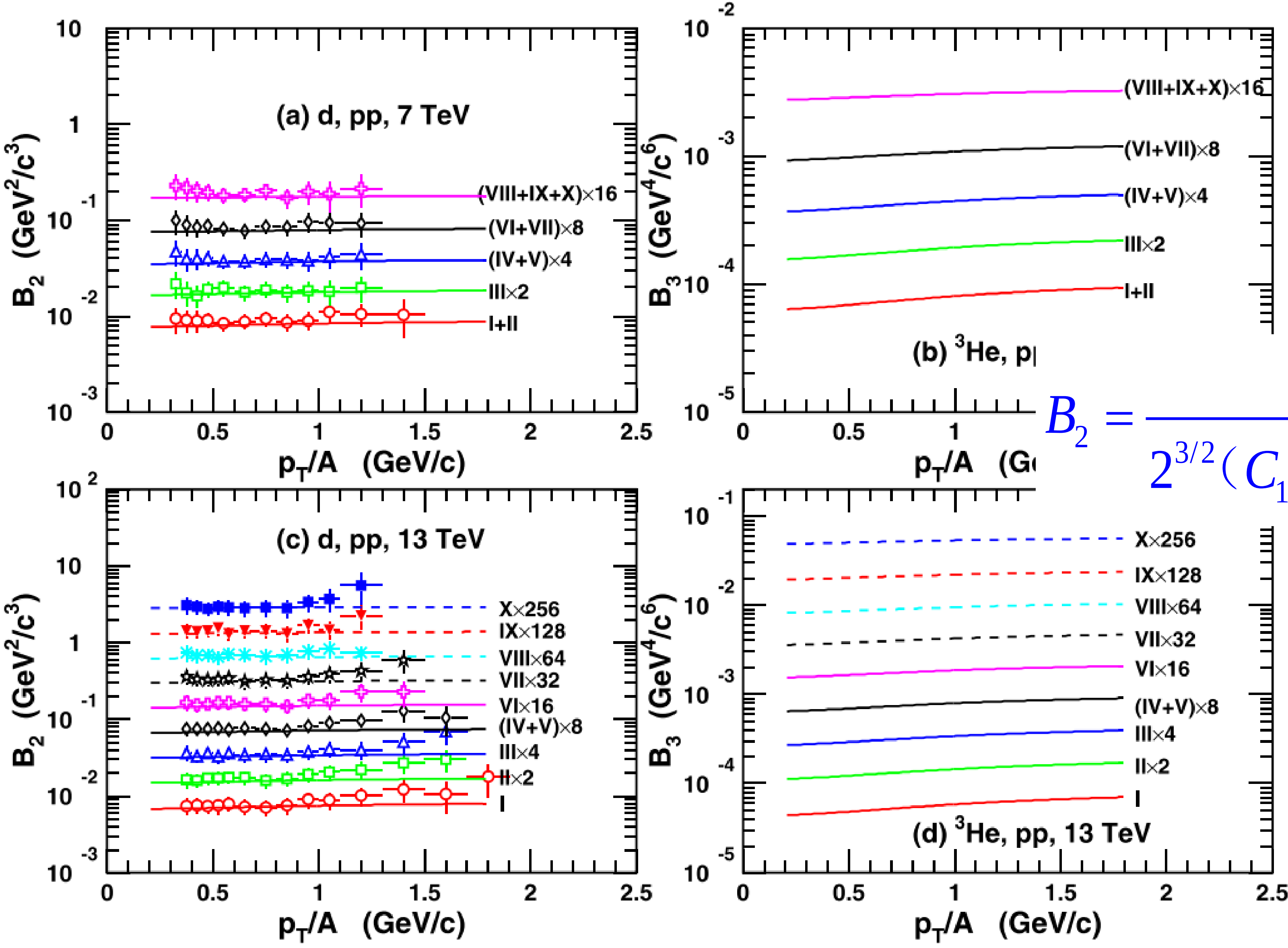
  independent of primordial nucleon/hyperon momentum distributions

- **p_T spectra**

  need primordial nucleon/hyperon momentum distributions as inputs

- **Production correlation of different light (hyper-)nuclei**

B_A as function of p_T/A in pp collisions at LHC

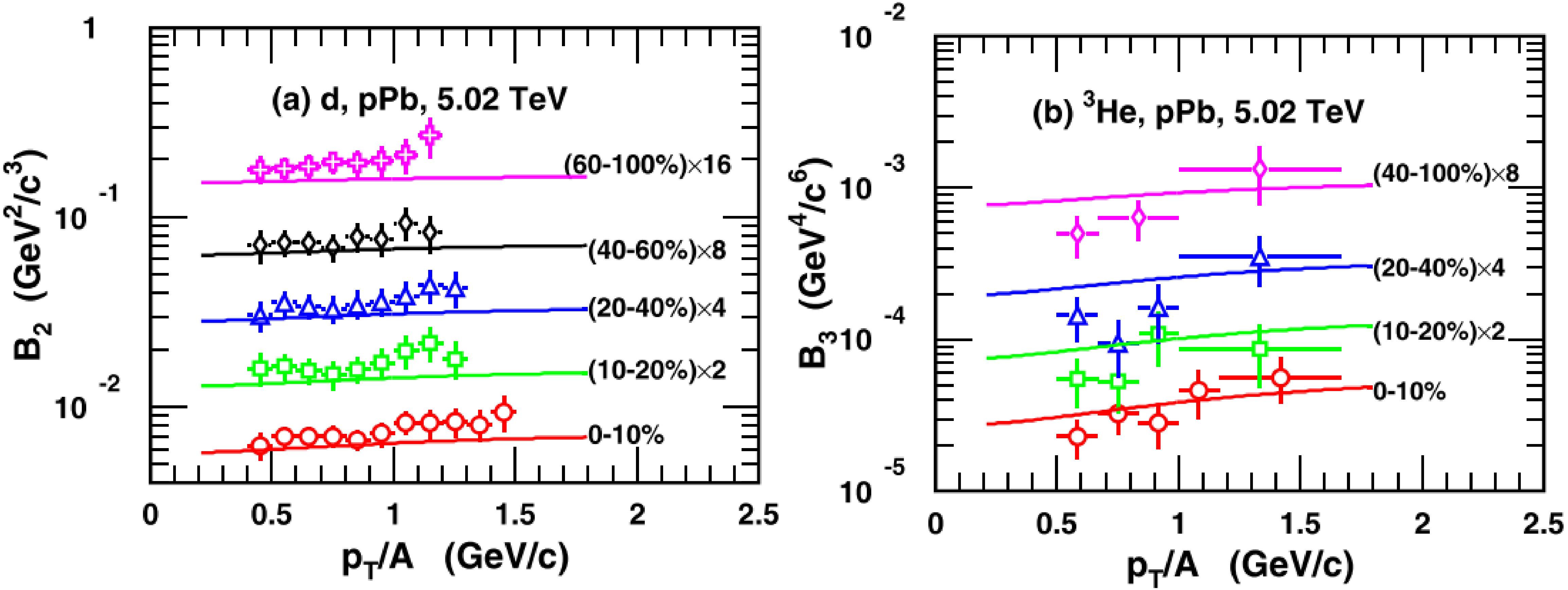


$$B_2 = \frac{8\pi^{3/2} g_d}{2^{3/2}(C_1 R_f^2 + \sigma_d^2)\sqrt{C_1(R_f/\gamma)^2 + \sigma_d^2}} \frac{m_d}{m_p m_n}$$

weak p_T dependence of B_2 and B_3 in pp collisions

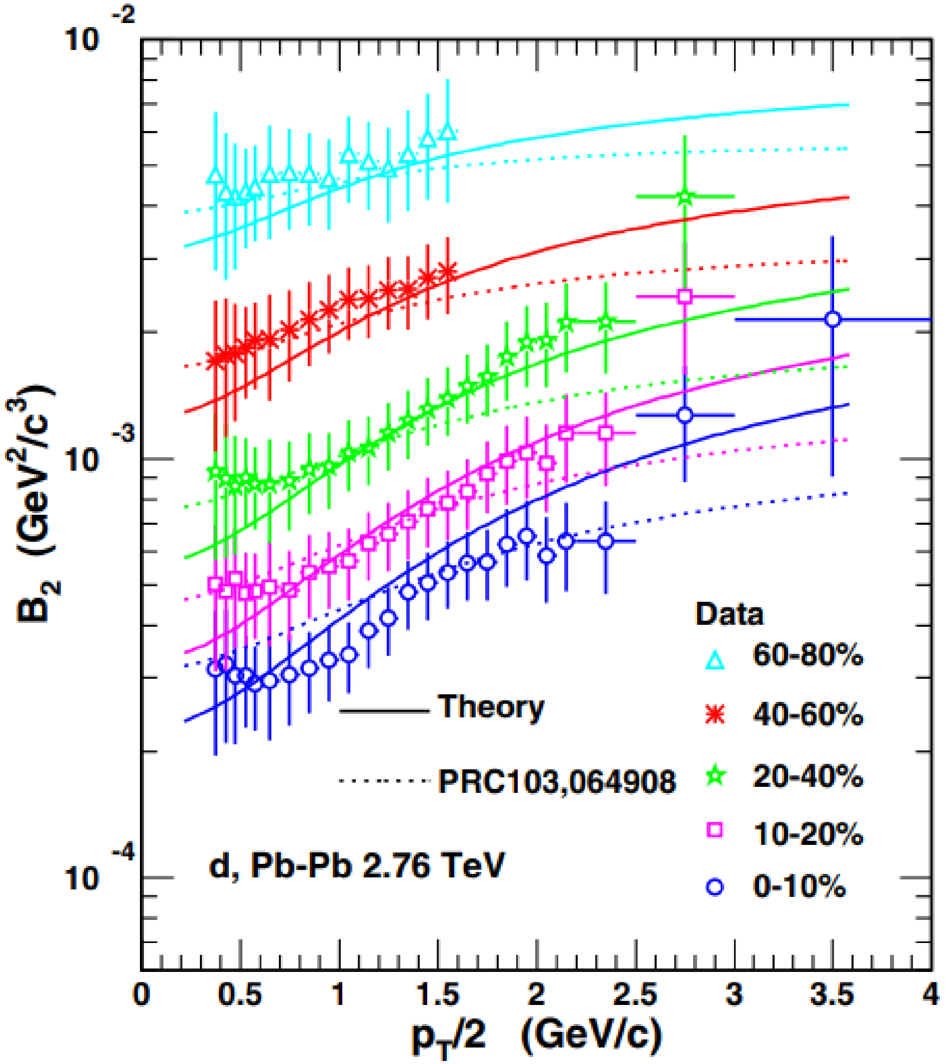
RQW, F.L. Shao, and J. Song, Phy. Rev. C 103, 064908, 2021.

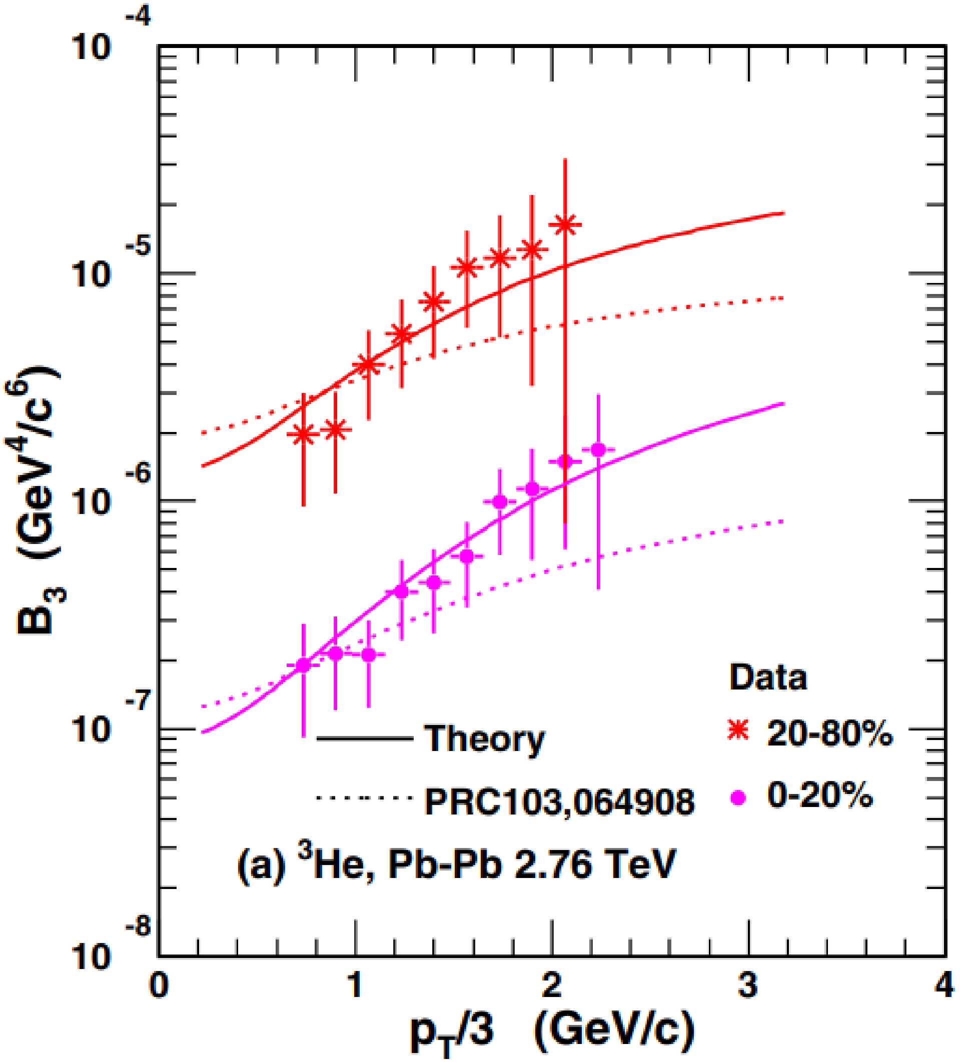
B_A as function of p_T/A in p-Pb collisions at LHC



RQW, F.L. Shao, and J. Song, Phy. Rev. C 103, 064908, 2021.

B_A as function of p_T/A in Pb-Pb collisions at LHC





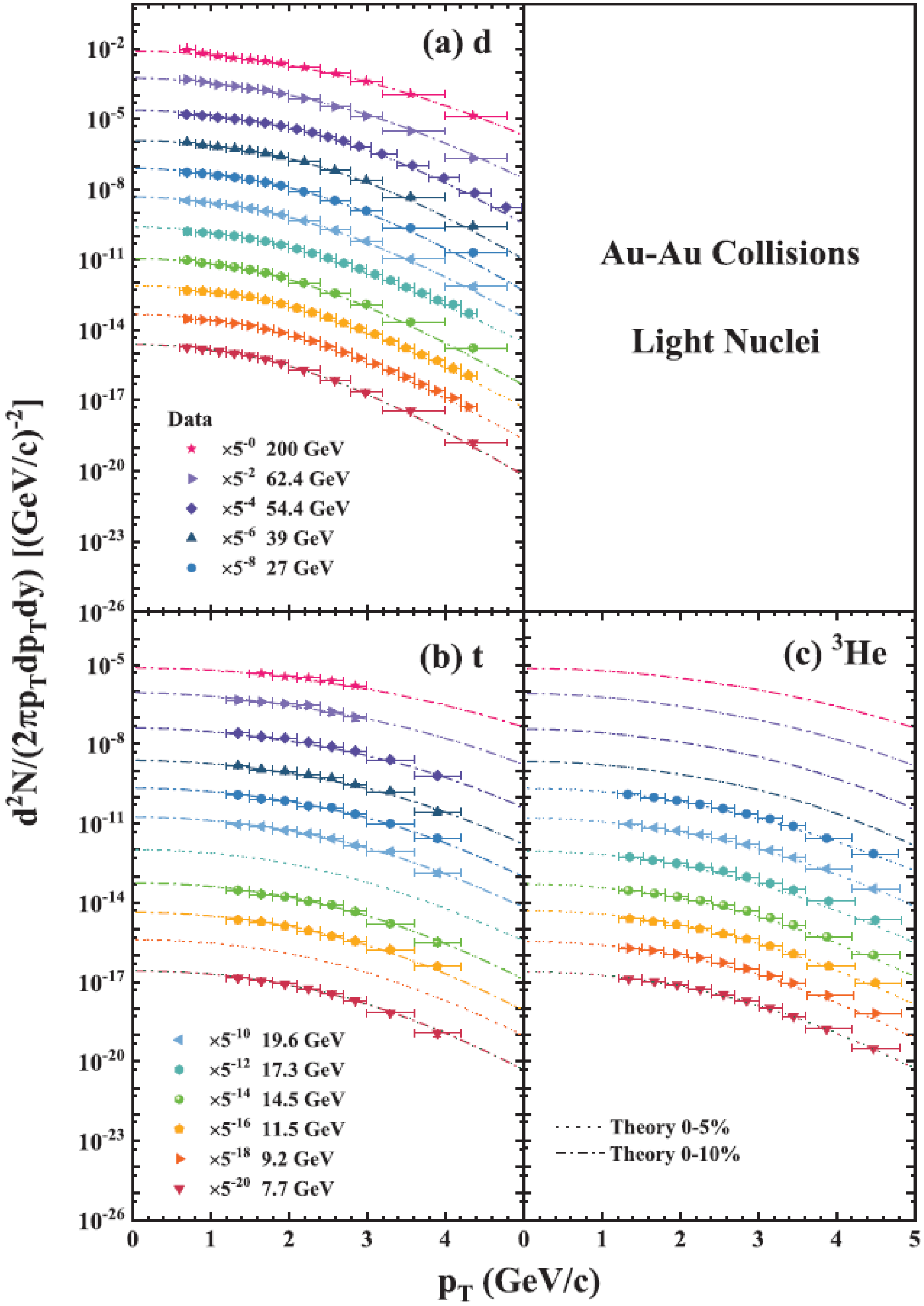
obvious p_T dependence of B_2 and B_3 in large Pb-Pb collision system

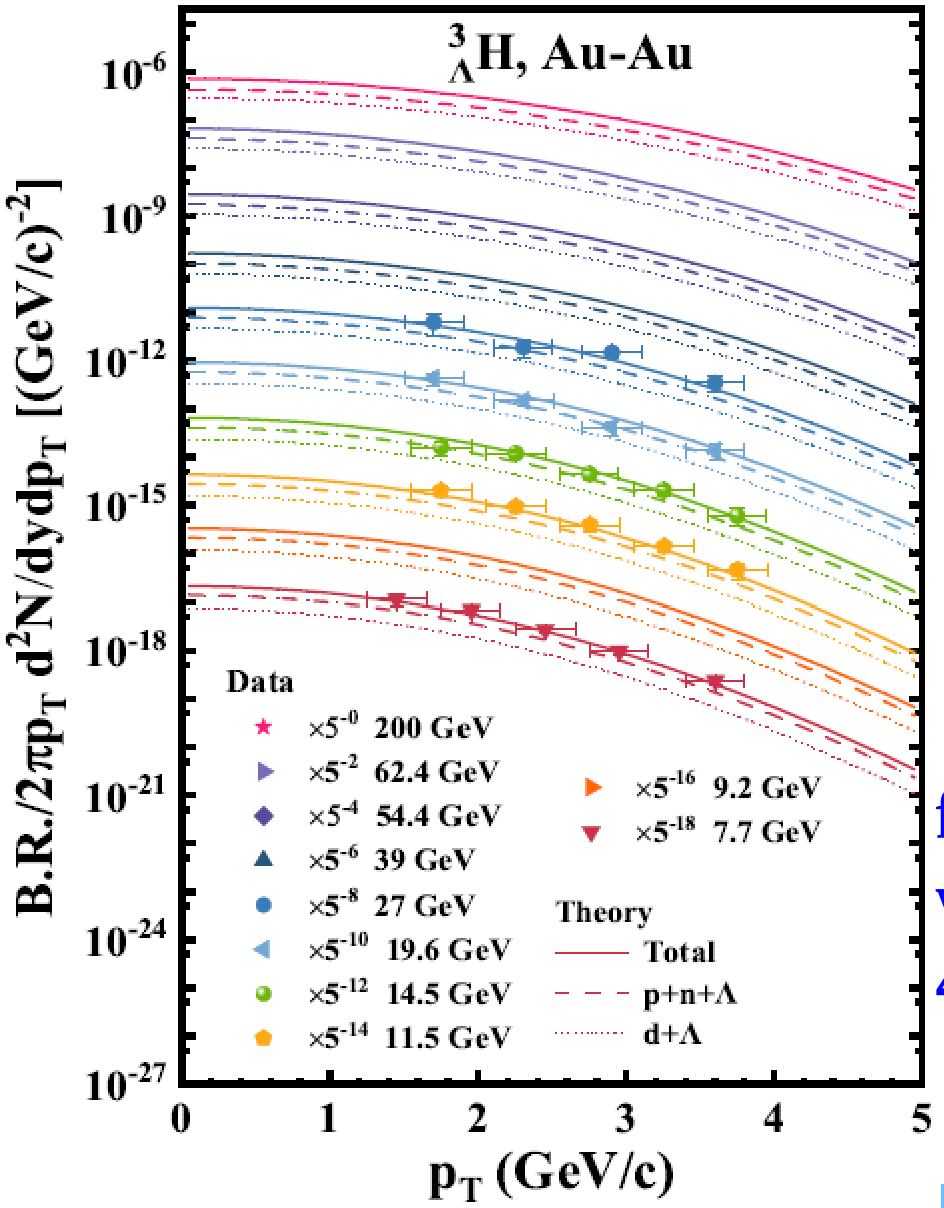
RQW, Y.H. Li, J. Song, F.L. Shao, PRC 109, 034907, 2024.

From results of B_A, we find:

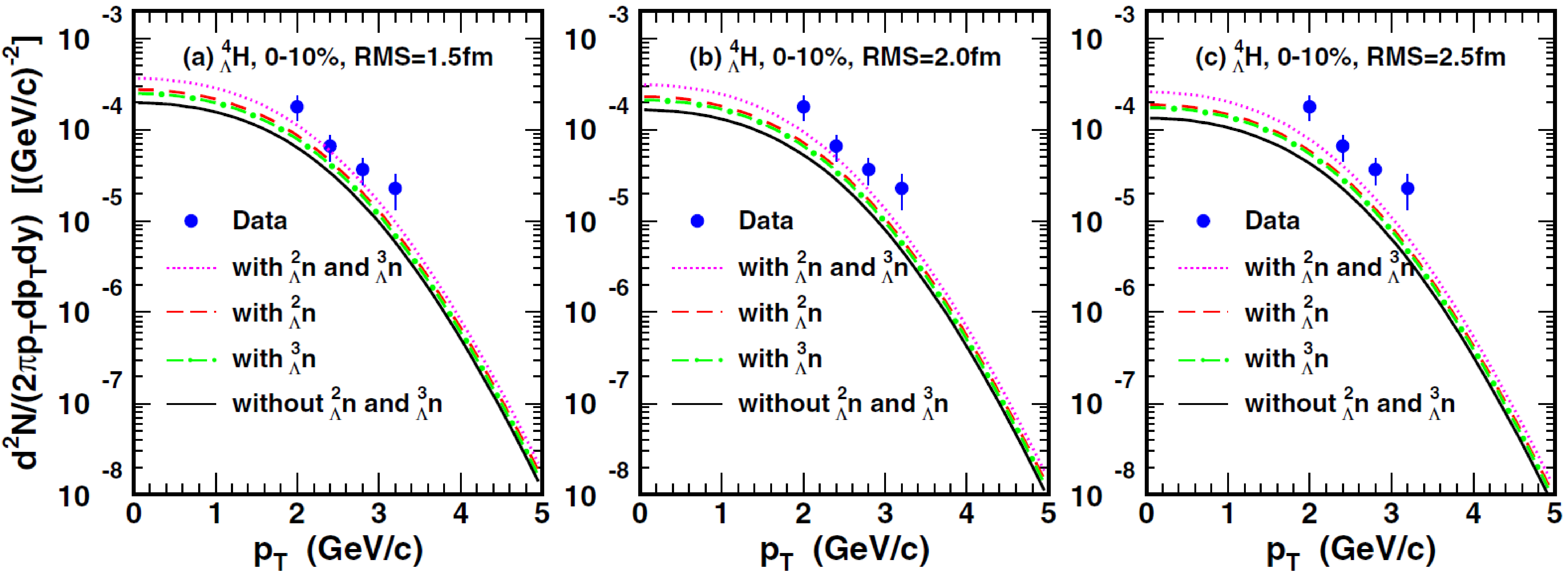
- **Analytical coalescence model can naturally give obvious growth of B_A against p_T in Pb-Pb collisions but relatively weak p_T dependence in pp and p-Pb collisions.**
- **Coordinate-momentum correlation is necessary in large Pb-Pb collisions.**

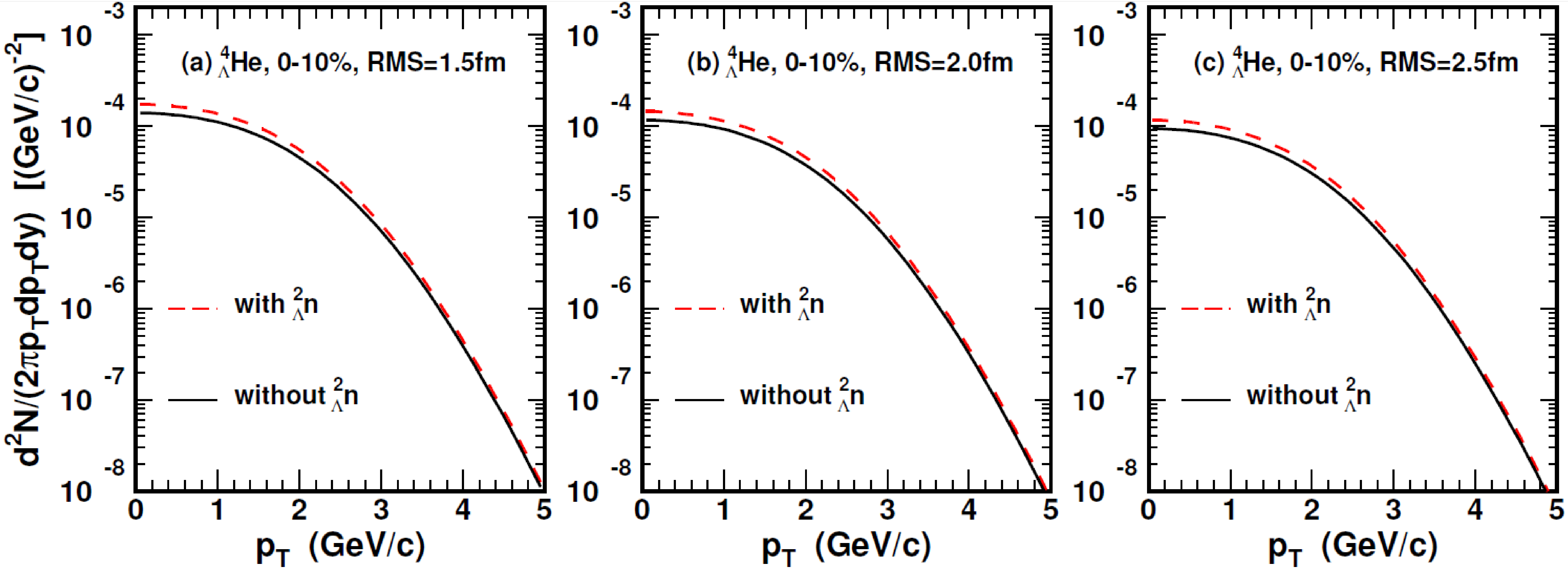
J.H. Qiao, J.Y. Liu, Y.T. Feng, F.L. Shao, RQW, arXiv:2603.21164.

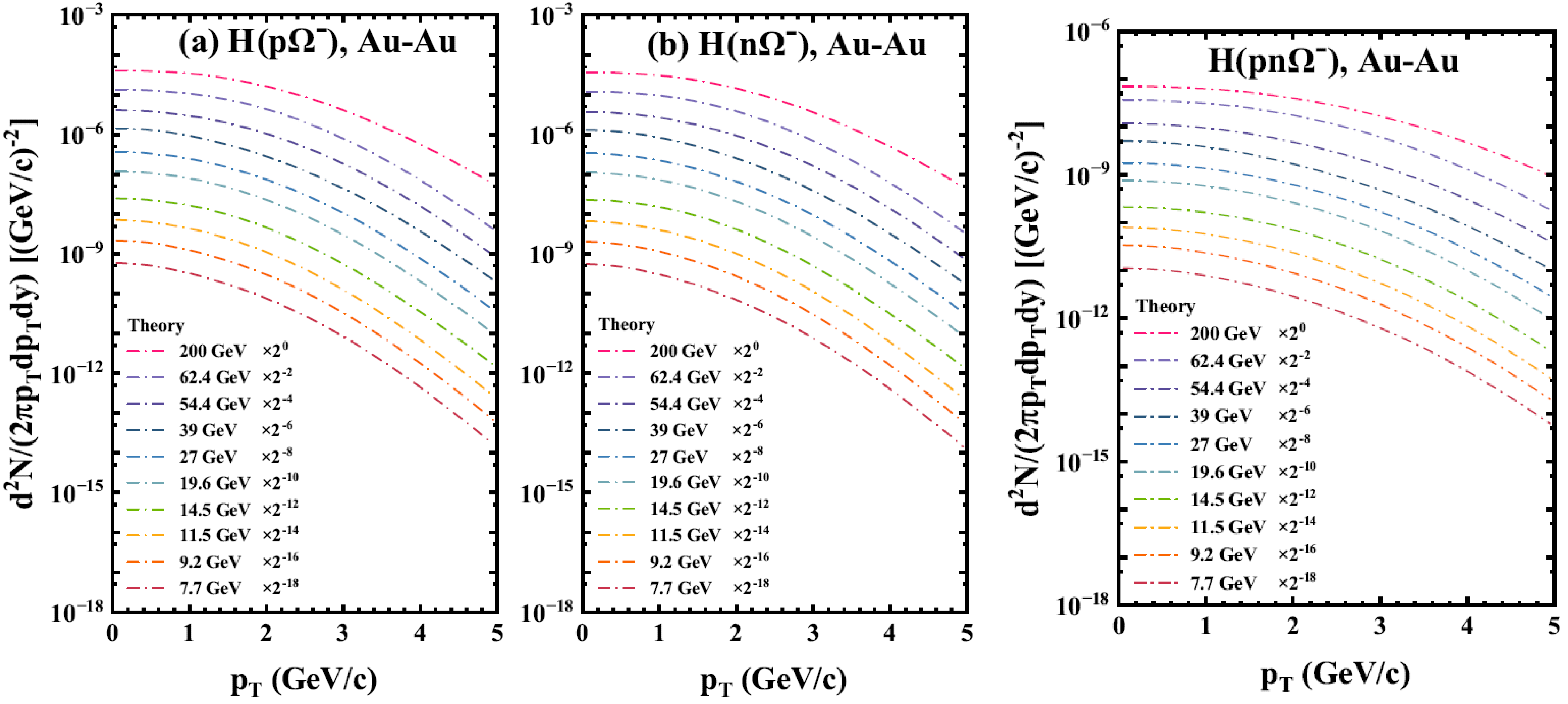




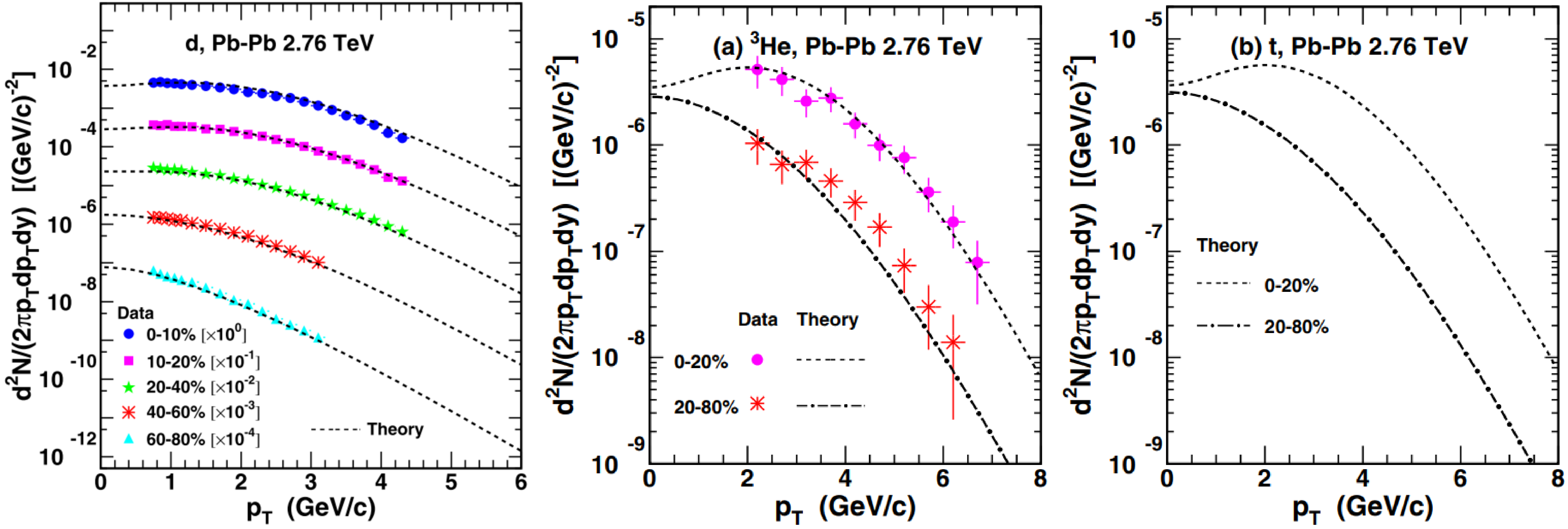
favor halo structure with binding energy 410 keV

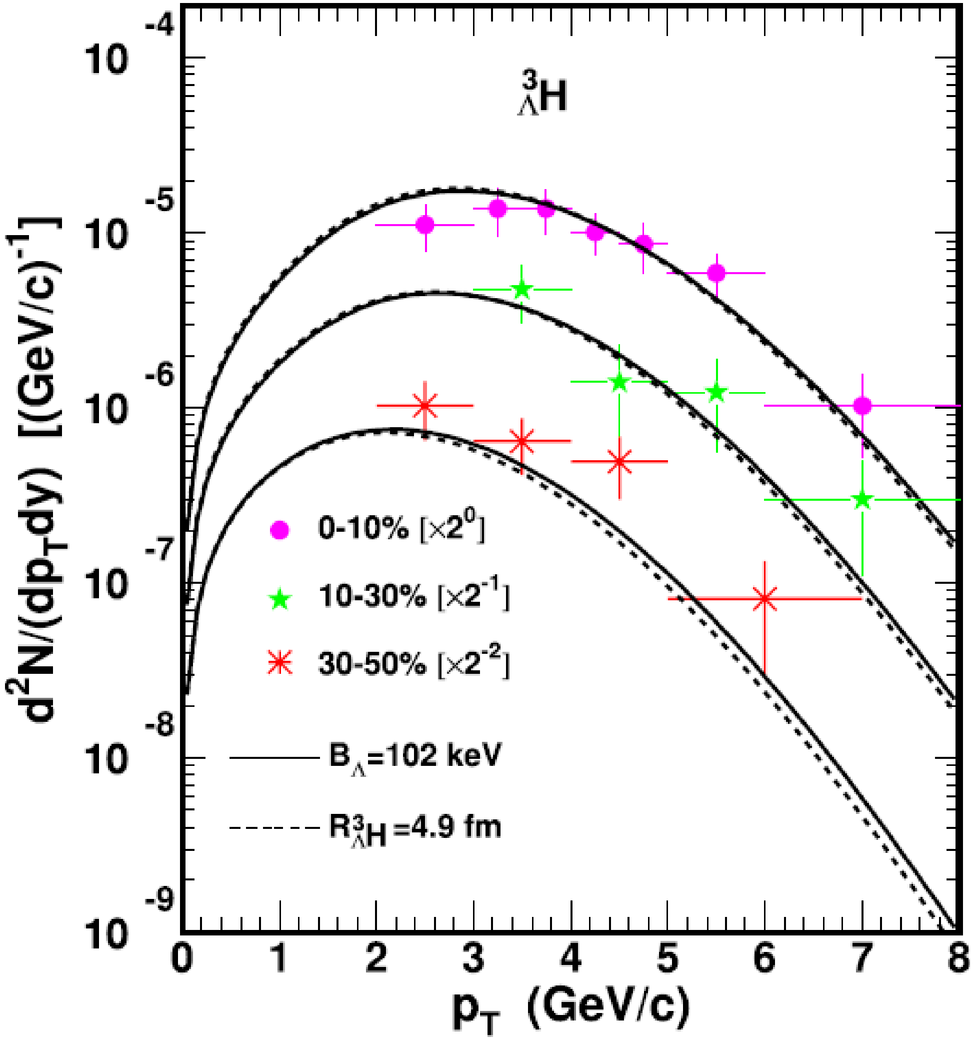

(a) ⁴ΛH, 0-10%, RMS=1.5fm
(b) ⁴ΛH, 0-10%, RMS=2.0fm
(c) ⁴ΛH, 0-10%, RMS=2.5fm
Data
with ²Λn and ³Λn
with ²Λn
with ³Λn
without ²Λn and ³Λn
d²N/(2πpTdpTdy) [(GeV/c)-2]
pT (GeV/c)


(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

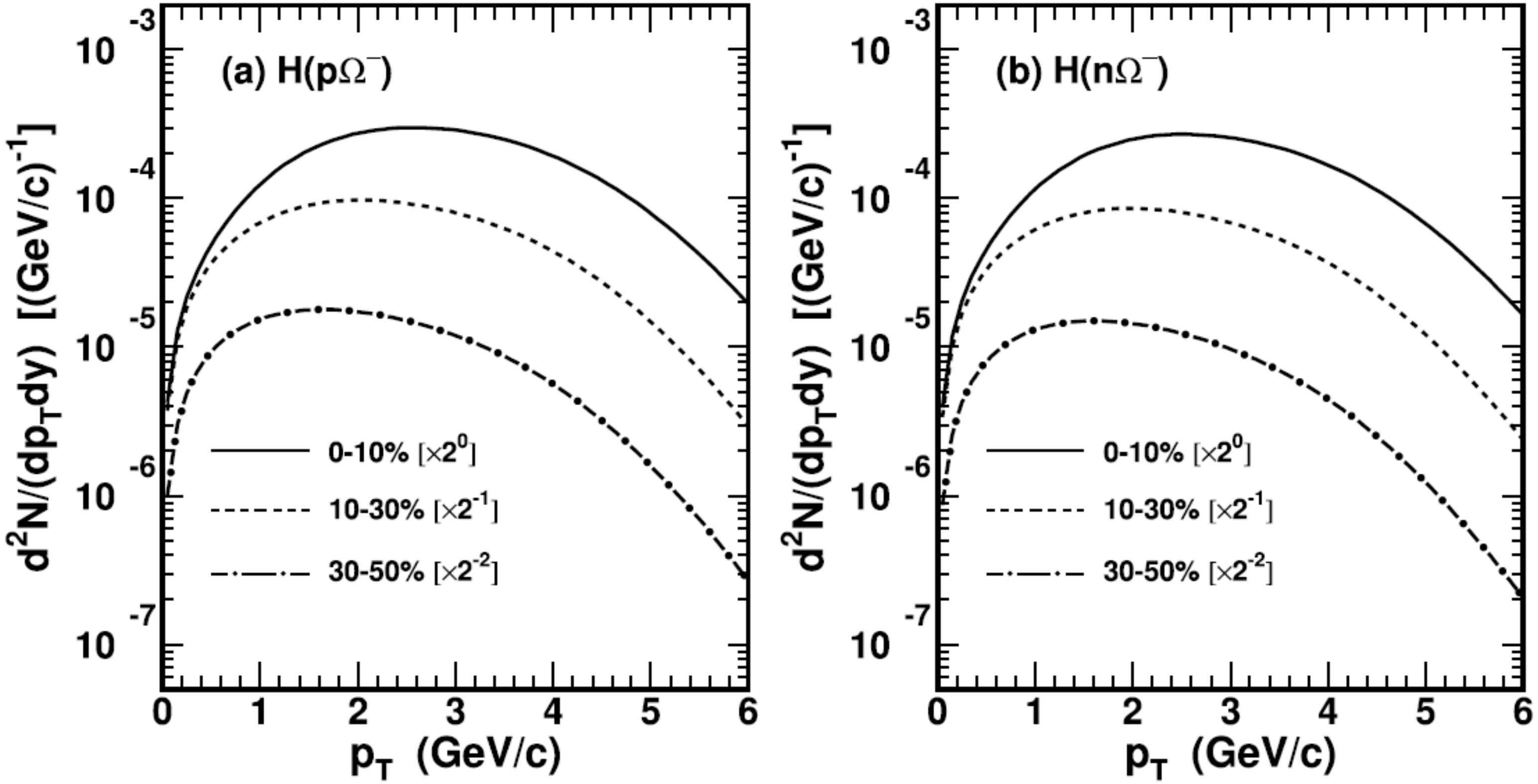

(a) H(pΩ⁻), Au-Au
(b) H(nΩ⁻), Au-Au
H(pnΩ⁻), Au-Au
d²N/(2πp_T dp_T dy) [(GeV/c)⁻²]
p_T (GeV/c)
Theory
200 GeV ×2^0
62.4 GeV ×2^-2
54.4 GeV ×2^-4
39 GeV ×2^-6
27 GeV ×2^-8
19.6 GeV ×2^-10
14.5 GeV ×2^-12
11.5 GeV ×2^-14
9.2 GeV ×2^-16
7.7 GeV ×2^-18

RQW, Y.H. Li, J. Song, F.L. Shao, Phys. Rev. C 109, 034907, 2024.





$^3_\Lambda H$
0-10% [×2^0]
10-30% [×2^-1]
30-50% [×2^-2]
B_Λ=102 keV
R$^3_\Lambda$H =4.9 fm
d²N/(dp_T dy) [(GeV/c)^-1]
p_T (GeV/c)



(a) H(pΩ⁻)
(b) H(nΩ⁻)
0-10% [×2^0]
10-30% [×2^-1]
30-50% [×2^-2]
d²N/(dp_T dy) [(GeV/c)^-1]
p_T (GeV/c)

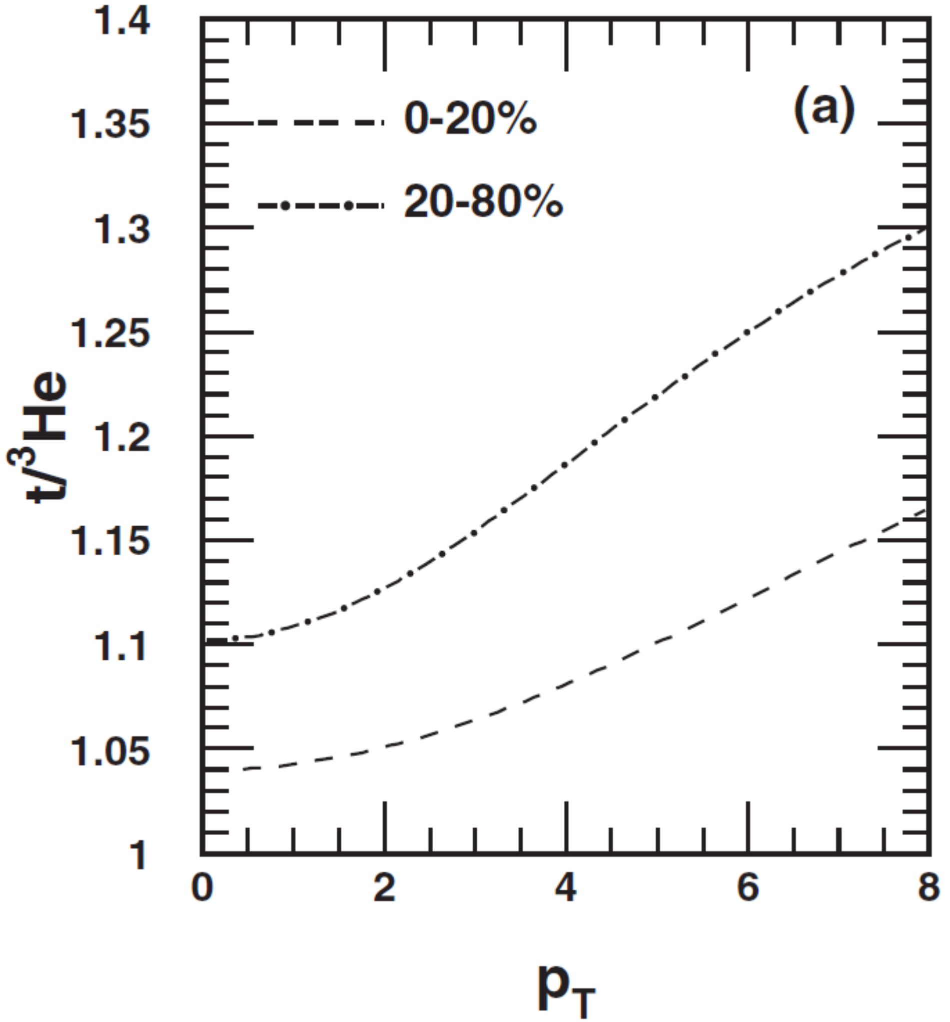
From results of p_T spectra,

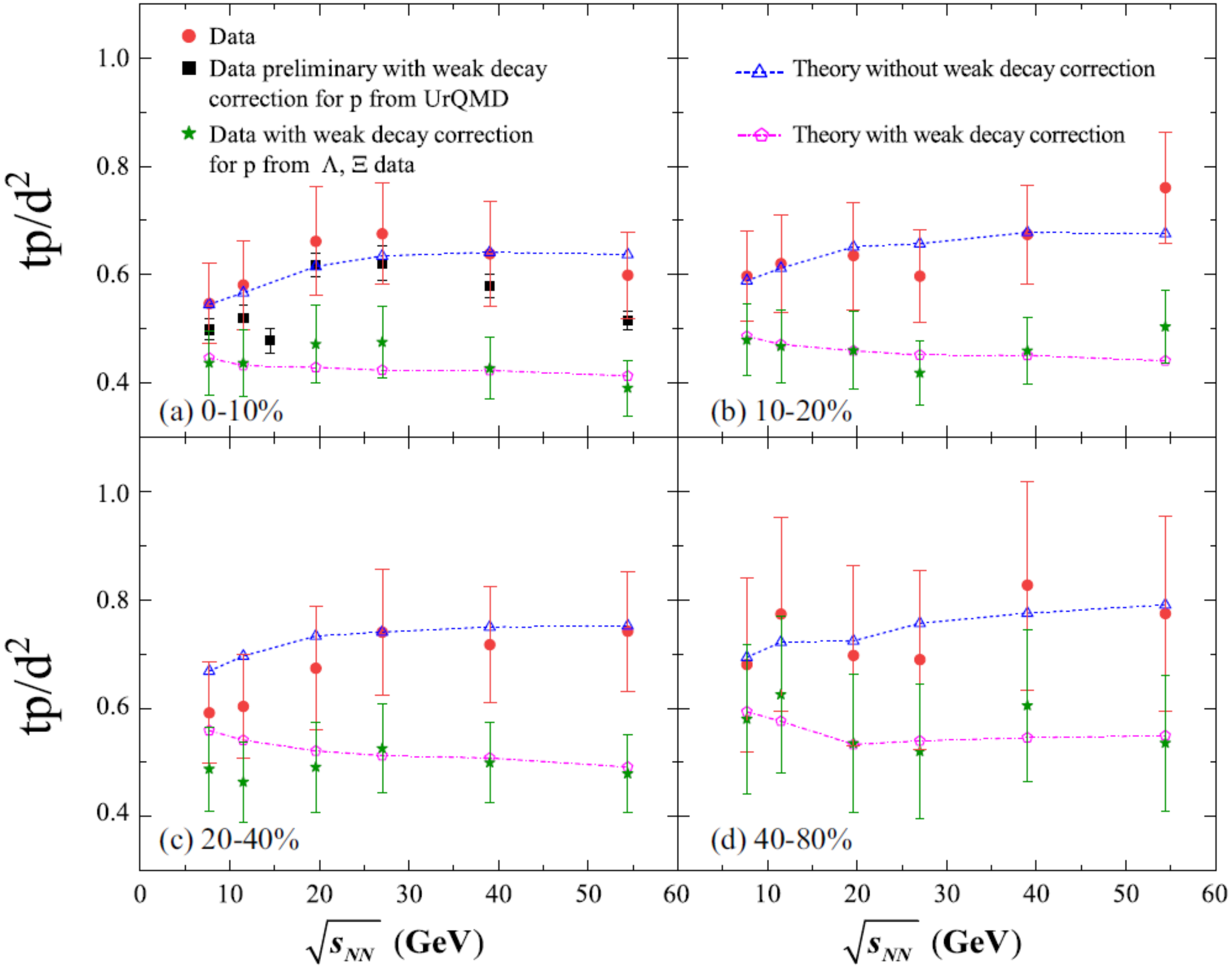
- **Analytical coalescence model can reproduce the available data of p_T spectra of d, t, He, ${}^{3}_{\Lambda}\mathrm{H}$ from 3 GeV to 5.02 TeV.**

- **We give corresponding predictions of ${}^{4}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{He}$ and Ω–hypernuclei.**

RQW, Y.H. Li, J. Song, F.L. Shao, Phys. Rev. C 109, 034907, 2024.

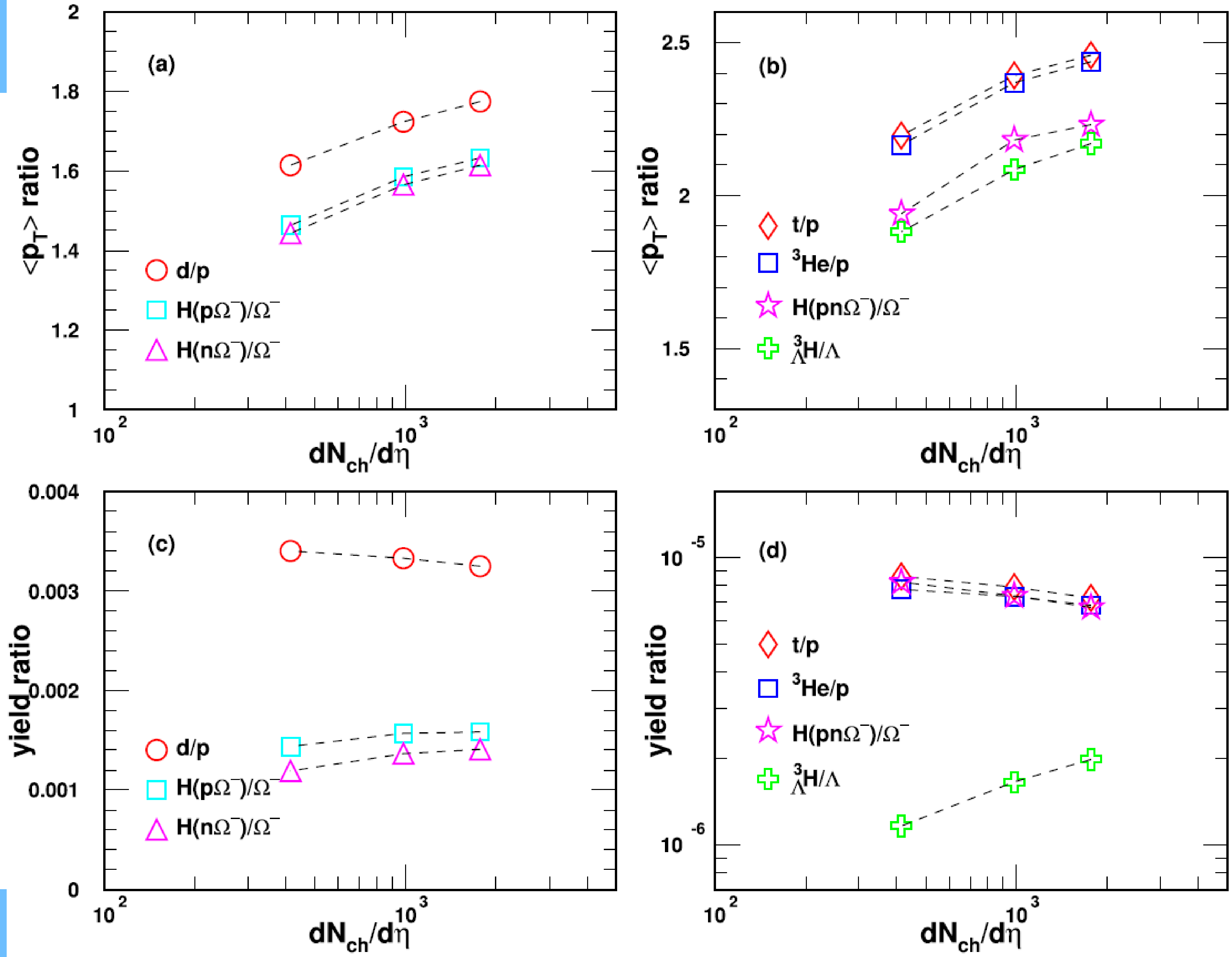
X.Y. Zhao, Y.T. Feng, F.L. Shao, RQW, J. Song, Phys. Rev. C 105, 054908, 2022.





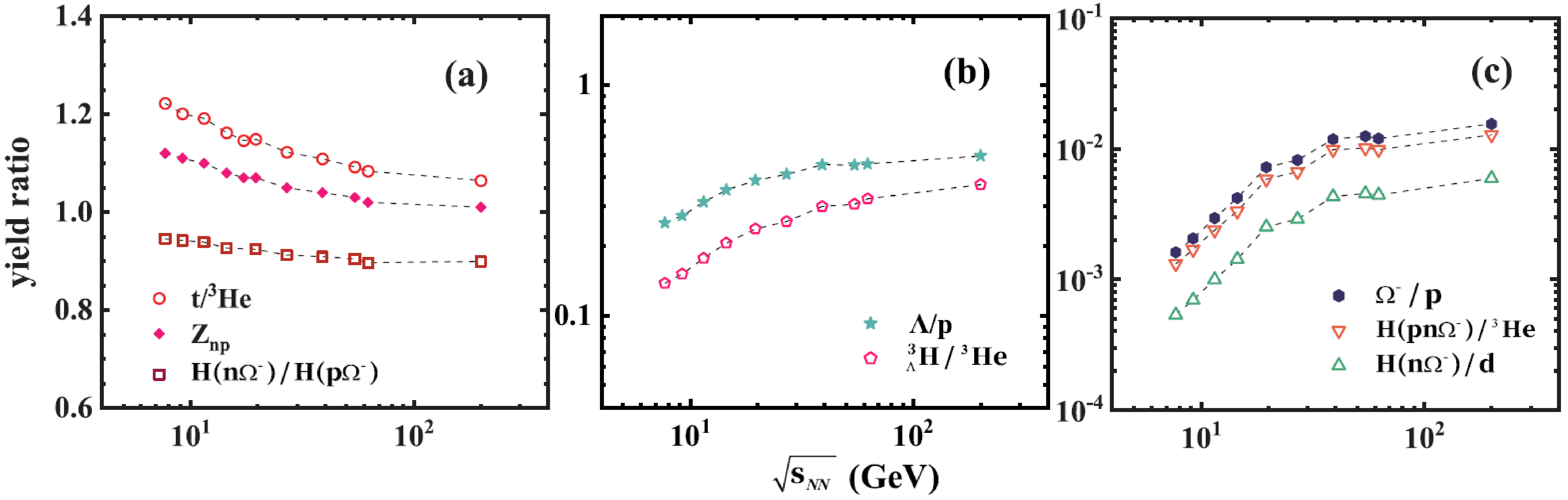
t/^{3}He can reveal production mechanisms of light nuclei.

no peak without phase transition



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

sensitive observables to production mechanism



characteristics from coalescence itself

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

*** four-body coalescence or three-body coalescence**

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

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

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

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

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

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

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

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

sensitive to different coalescence channels

RQW, J. Song, M.Y. Wu, H.T. Xue, and F.L. Shao, Phy. Rev. C 112, 034908, 2025.

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

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

IV. Summary

◆ We developed an analytical coalescence model to deal with productions of light and hyper-nuclei in high energy heavy-ion collisions. The relationships of light (hyper-)nuclei with primordial nucleons and hyperons were clearly given.

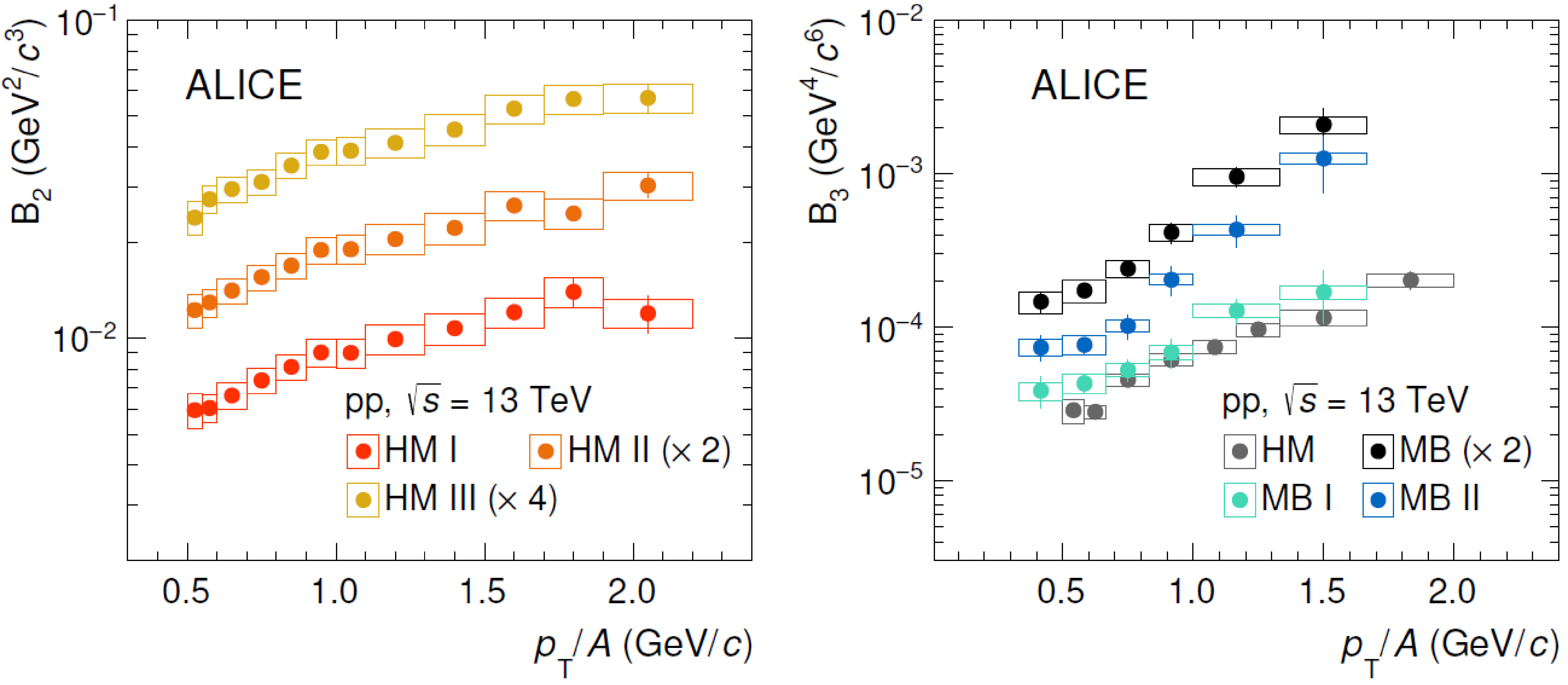
◆ We applied the coalescence model to heavy-ion collisions at RHIC and LHC, and gave explanations for different experimental observables.

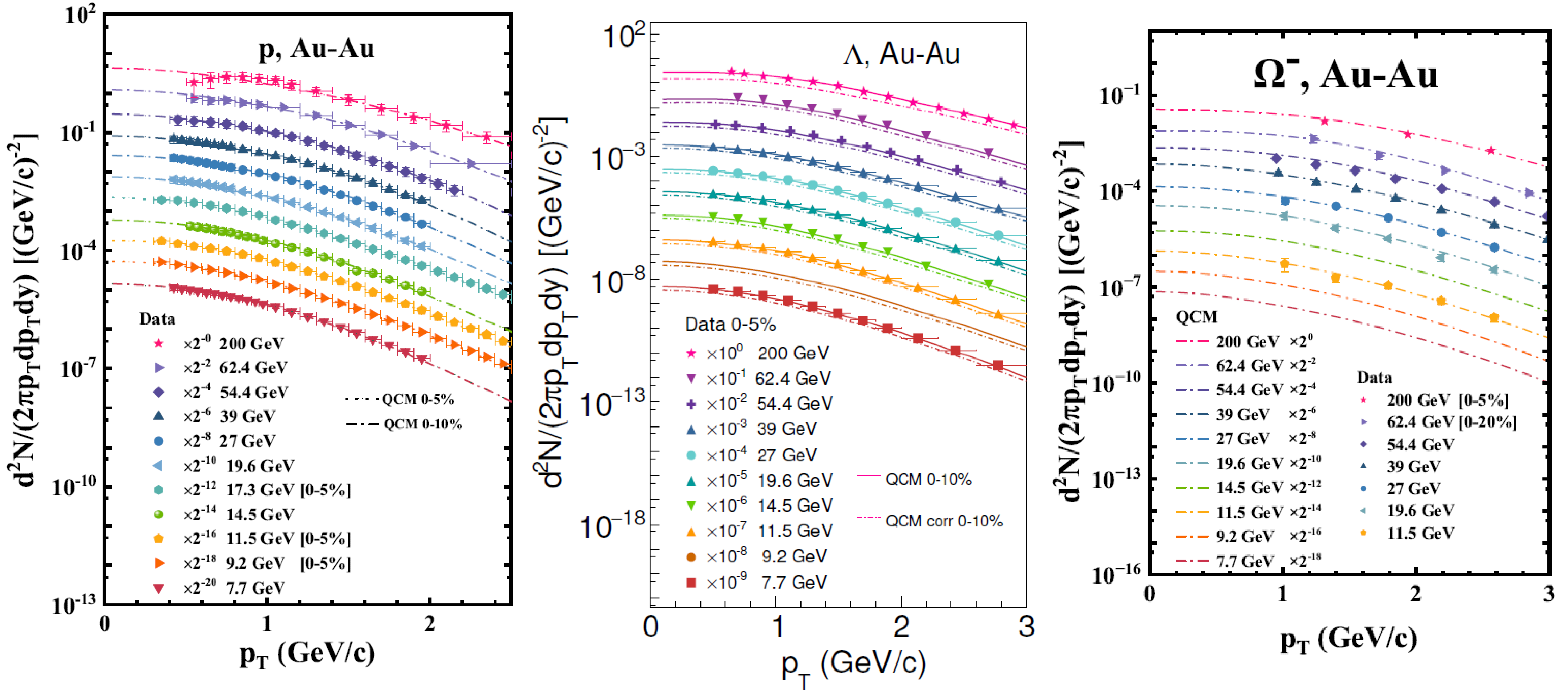
◆ We presented production correlations of different species of light (hyper-)nuclei from coalescence itself.

◆ The analytical coalescence model can be further applied to other molecular states.

Thank you !

ALICE, JHEP 01, 106, 2022



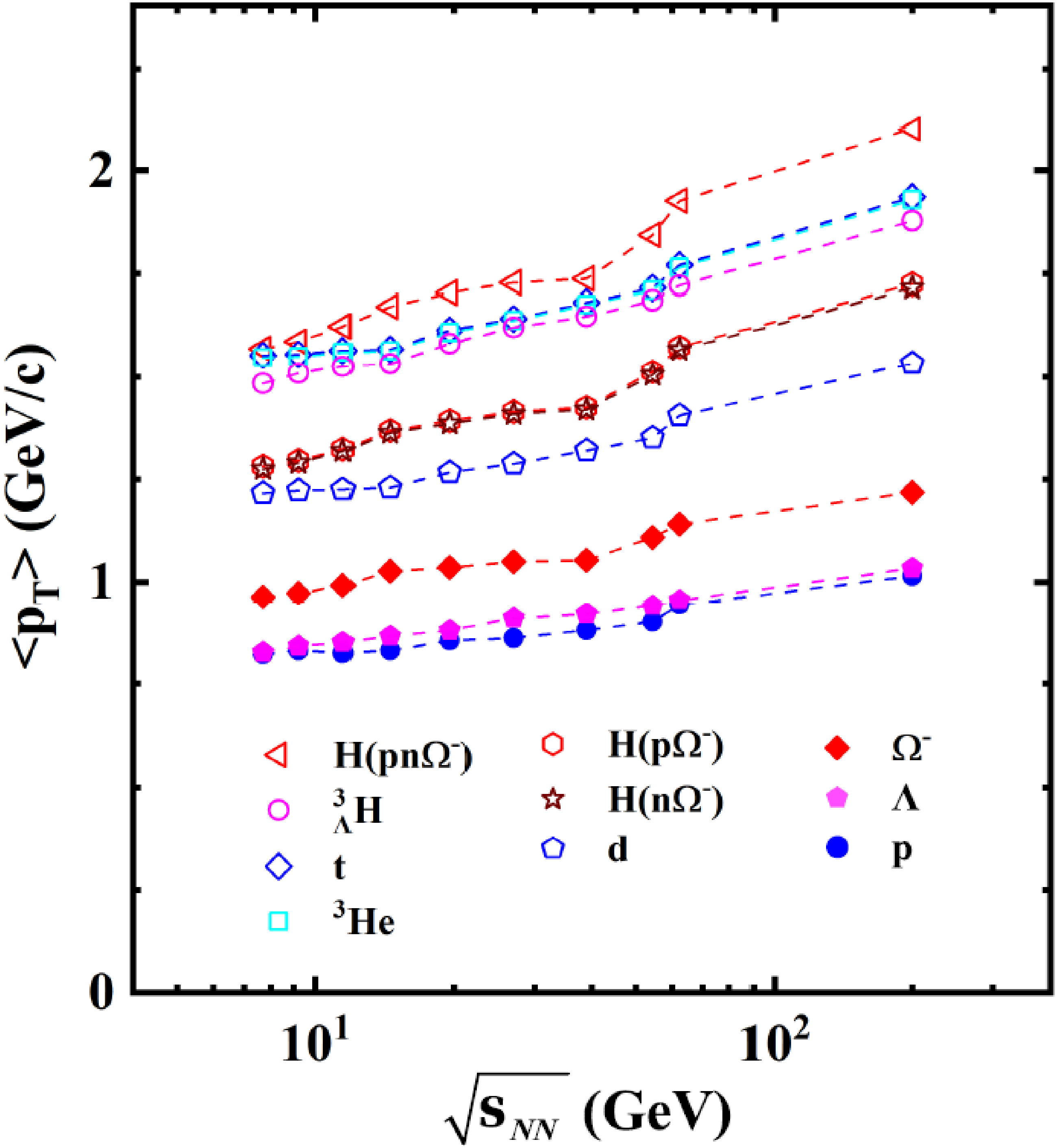


p, Au-Au
d²N/(2πp_T dp_T dy) [(GeV/c)⁻²]
p_T (GeV/c)
Data
×2⁻⁰ 200 GeV
×2⁻² 62.4 GeV
×2⁻⁴ 54.4 GeV
×2⁻⁶ 39 GeV
×2⁻⁸ 27 GeV
×2⁻¹⁰ 19.6 GeV
×2⁻¹² 17.3 GeV [0-5%]
×2⁻¹⁴ 14.5 GeV
×2⁻¹⁶ 11.5 GeV [0-5%]
×2⁻¹⁸ 9.2 GeV [0-5%]
×2⁻²⁰ 7.7 GeV
QCM 0-5%
QCM 0-10%
Λ, Au-Au
d²N/(2πp_T dp_T dy) [(GeV/c)⁻²]
p_T (GeV/c)
Data 0-5%
×10⁰ 200 GeV
×10⁻¹ 62.4 GeV
×10⁻² 54.4 GeV
×10⁻³ 39 GeV
×10⁻⁴ 27 GeV
×10⁻⁵ 19.6 GeV
×10⁻⁶ 14.5 GeV
×10⁻⁷ 11.5 GeV
×10⁻⁸ 9.2 GeV
×10⁻⁹ 7.7 GeV
QCM 0-10%
QCM corr 0-10%
Ω⁻, Au-Au
d²N/(2πp_T dp_T dy) [(GeV/c)⁻²]
p_T (GeV/c)
QCM
200 GeV ×2⁰
62.4 GeV ×2⁻²
54.4 GeV ×2⁻⁴
39 GeV ×2⁻⁶
27 GeV ×2⁻⁸
19.6 GeV ×2⁻¹⁰
14.5 GeV ×2⁻¹²
11.5 GeV ×2⁻¹⁴
9.2 GeV ×2⁻¹⁶
7.7 GeV ×2⁻¹⁸
Data
200 GeV [0-5%]
62.4 GeV [0-20%]
54.4 GeV
39 GeV
27 GeV
19.6 GeV
11.5 GeV

$\sqrt{s_{NN}}$ (GeV)	dN/dy ($\times 10^{-4}$)						
	Theory						Data
	I	II halo			III	Total	
	spherical	102 keV	148 keV	410 keV	d+Λ		
7.7	7.274	7.282	10.071	18.899	9.895	28.794	37.9±5.1±5.8
9.2	4.860	4.839	6.647	12.253	6.534	18.786	– – –
11.5	2.664	2.636	3.592	6.486	3.533	10.018	12.4±1.8±2.1
14.5	1.670	1.643	2.222	3.933	2.186	6.120	5.42±0.73±0.95
19.6	1.039	1.017	1.363	2.362	1.342	3.704	4.31±0.59±0.69
27	0.602	0.587	0.780	1.324	0.768	2.092	2.26±0.30±0.31
39	0.340	0.330	0.435	0.722	0.428	1.150	– – –
54.4	0.240	0.232	0.303	0.495	0.299	0.794	– – –
62.4	0.233	0.226	0.294	0.478	0.290	0.768	– – –
200	0.130	0.125	0.159	0.247	0.157	0.404	– – –

$$R_f = k \times \left(\frac{dN_{\rm ch}}{dy}\right)^{1/3} \times \left(\sqrt{p_T^2 + m_{H_j}^2}\right)^a + b,$$

$\sqrt{s_{NN}}$ (GeV)	$H(p\Omega^-)$		$H(n\Omega^-)$		$H(pn\Omega^-)$	
	dN/dy ($\times 10^{-4}$)	$\langle p_T \rangle$ (GeV/c)	dN/dy ($\times 10^{-4}$)	$\langle p_T \rangle$ (GeV/c)	dN/dy ($\times 10^{-5}$)	$\langle p_T \rangle$
7.7	7.829	1.281	7.402	1.275	2.735	1.569
9.2	7.496	1.295	7.061	1.289	2.091	1.586
11.5	6.641	1.323	6.236	1.318	1.342	1.623
14.5	6.465	1.368	5.992	1.362	0.984	1.671
19.6	7.942	1.392	7.340	1.386	0.909	1.704
27	6.306	1.414	5.754	1.408	0.542	1.729
39	6.046	1.425	5.498	1.419	0.380	1.738
54.4	5.152	1.512	4.660	1.505	0.263	1.843
62.4	4.945	1.574	4.435	1.567	0.235	1.926
200	4.545	1.725	4.087	1.716	0.139	2.102



2
1
0
$\langle p_T \rangle$ (GeV/c)
10^1
10^2
$\sqrt{s_{NN}}$ (GeV)
H(pnΩ⁻)
H(pΩ⁻)
Ω⁻
$^3_\Lambda$H
H(nΩ⁻)
Λ
t
d
p
^{3}He