Nuclei and hypernuclei production in pion induced reactions around threshold energies

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Outline:

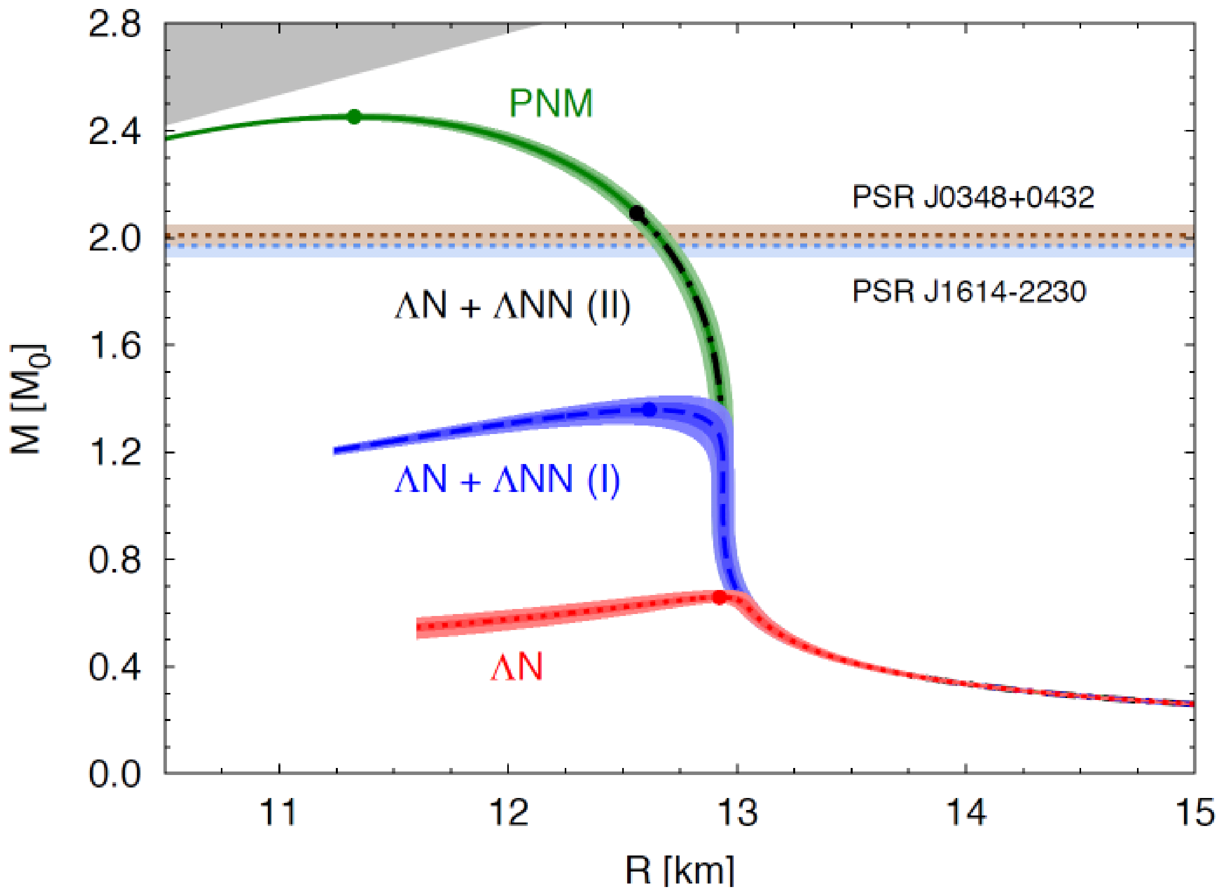
- Hypernuclei
- Small system size
- Cluster formation models
- Results

Hypernuclei

→ YN-Interactions?

- Neutron stars and EoS
  - The presence of hyperon/hypernuclei → Soften the EoS

  - Less attractive → Stiffer EoS
    - 3-body repulsive potential



Lonardoni, D., Lovato, A., Gandolfi, S., & Pederiva, F. (2015). Physical Review Letters, 114(9).

Hypernuclei

Hypertriton $^{3}_{\Lambda}\mathbf{H}$

- Strong attractive → Soft EoS (The hypernuclei are deeply bound)
- More repulsive → Stiffer EoS (The hypernuclei are less bound)

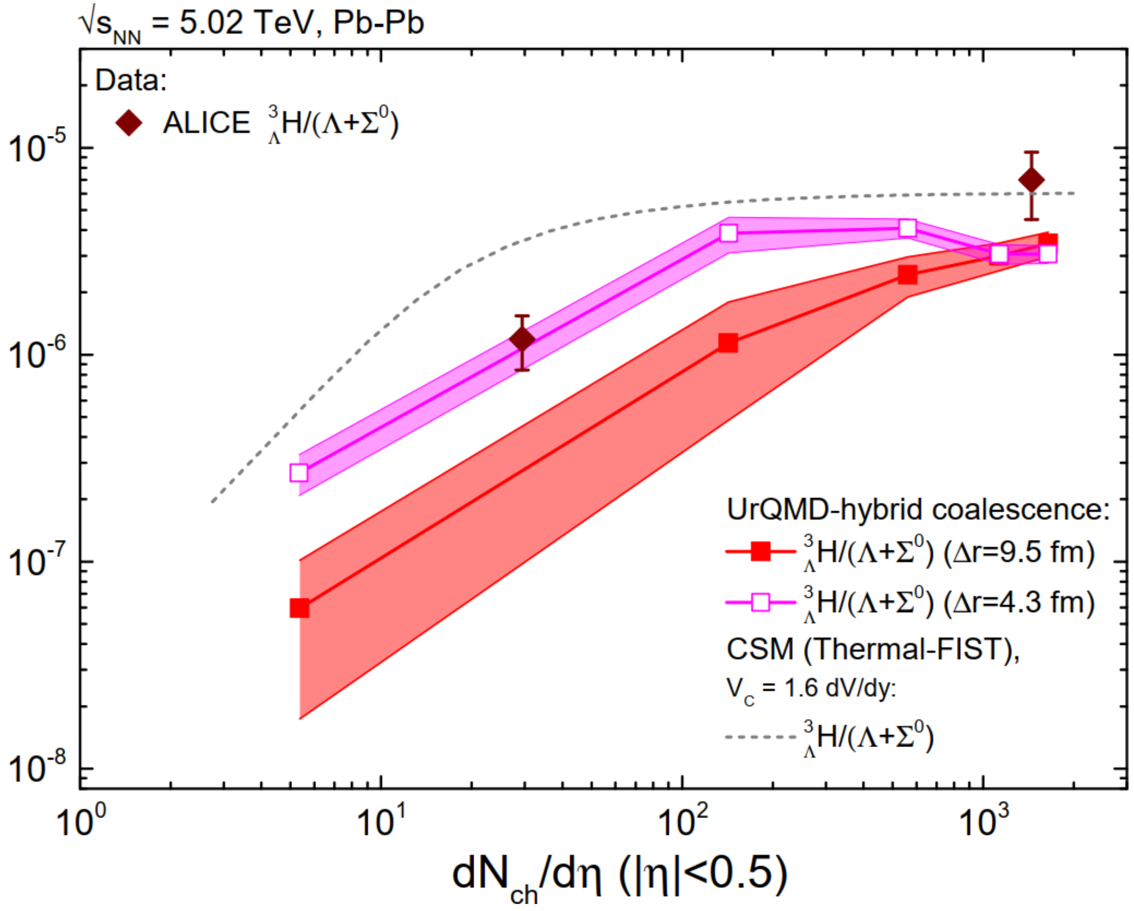
- **Hypernuclei with coalescence from difference phase-space volume?**

Hypernuclei

Hypertriton $^{3}_{\Lambda}\mathbf{H}$

- What if the coalescence parameter is larger than the source volume?
- At small system, Δr and ΔP are less correlated
- Strong suppression at small system

- System size dependence
  → Can study the size in diff. system
  → Pin-down the mechanism?
  → Small system data is needed



NOTE: The coalescence parameter may not directly connect to the wavefunction size

Reichert, Tom, et al. Physical Review C 107.1 (2023): 014912.

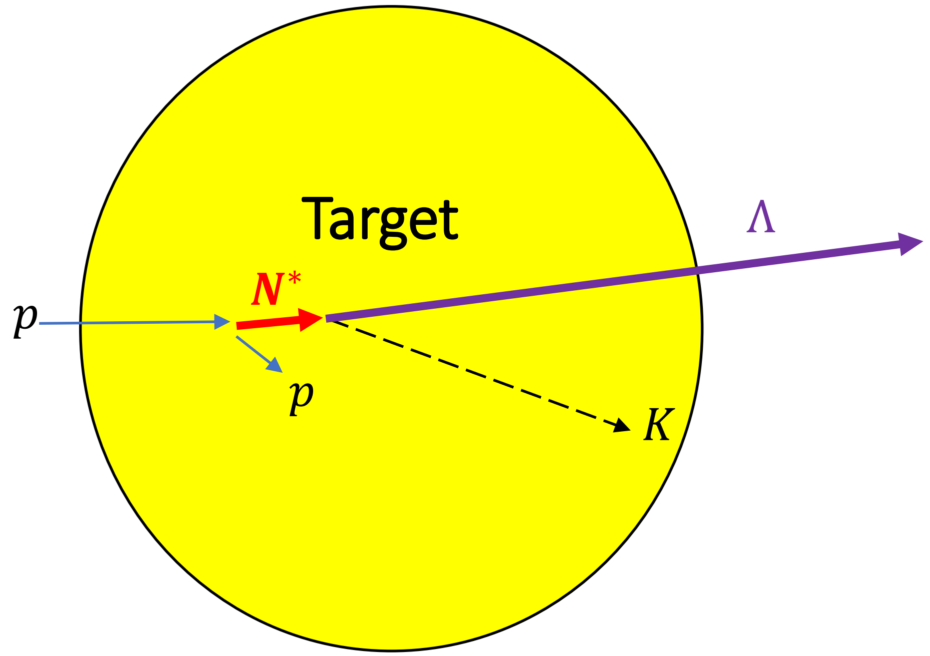
Small system size

New particle production in $\boldsymbol{p+A}$:

Lambda is produced with a large forward momentum

→ Less favorable for hypernuclei production

→ Hypernuclei will be produced outside of the nucleus



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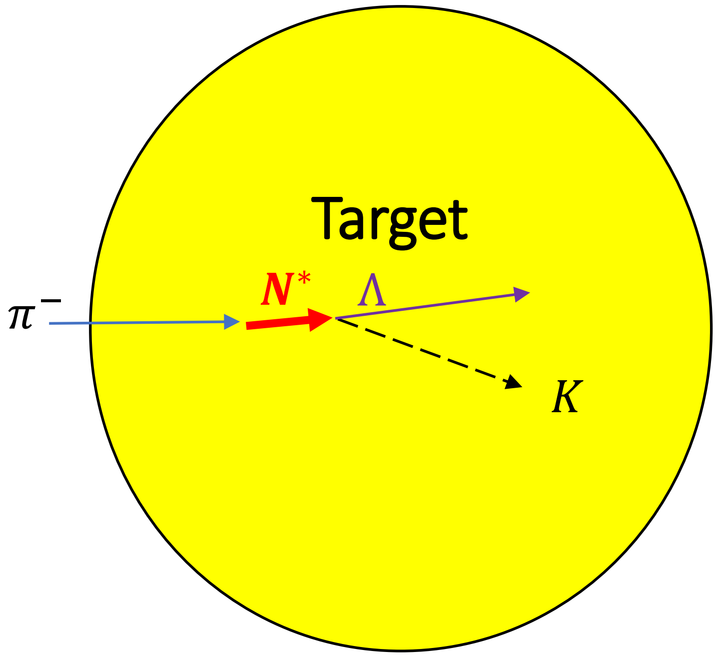
New particle production in $\boldsymbol{\pi^- + A}$:
Larger stopping power
→ Hypernuclei will be formed with the target!
(Allow for large hypernuclei $\mathrm{A} \gg 3$)



Hyperon production

- $\pi^- + N \rightarrow \boldsymbol{N^*}$ (up to 4 GeV)
- $\boldsymbol{N^*} \rightarrow \boldsymbol{\Lambda}\mathrm{K}$ (or even $\Xi K K$)

Small system size

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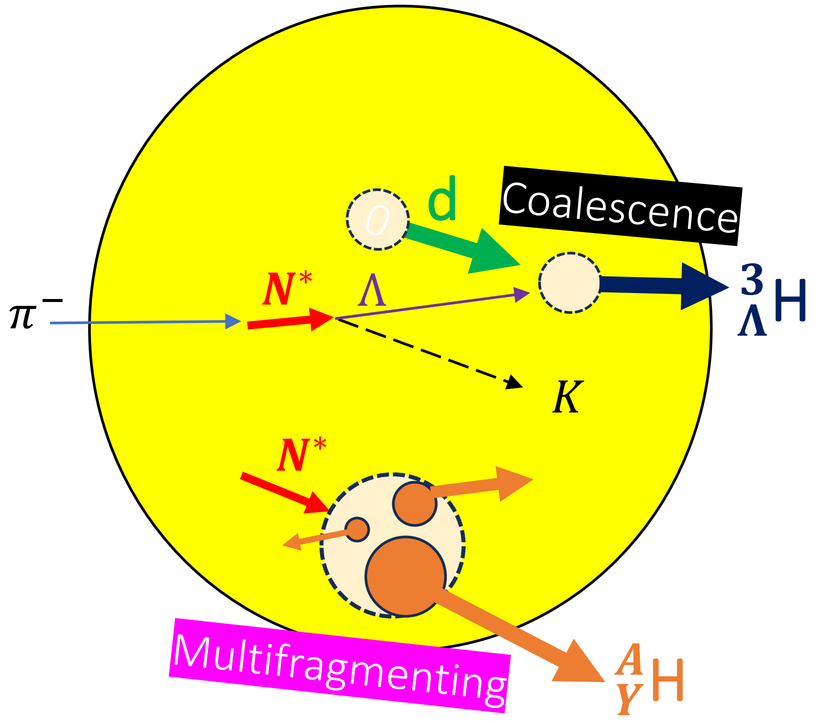


Hyperon production

- $\pi^- + N \rightarrow N^*$ (up to 4 GeV)
- $N^* \rightarrow \Lambda$K (or even ΞKK)

Our aim: Study the yield of cluster formations with coalescence and multifragmentation

UrQMD

Ultra-relativistic Molecular Dynamics (UrQMD)

Based on the relativistic Boltzmann transport:

- $p^{\mu} \cdot \partial_{\mu} f_i(x^{\nu}, p^{\nu}) = C_i$

- Binary interactions + Re-scattering are treated
- Cross sections are taken from data or models
- Resonances/decays are implemented

nucleon	Δ	Λ	Σ	Ξ	Ω
N_{938}	Δ_{1232}	Λ_{1116}	Σ_{1192}	Ξ_{1317}	Ω_{1672}
N_{1440}	Δ_{1600}	Λ_{1405}	Σ_{1385}	Ξ_{1530}	
N_{1520}	Δ_{1620}	Λ_{1520}	Σ_{1660}	Ξ_{1690}	
N_{1535}	Δ_{1700}	Λ_{1600}	Σ_{1670}	Ξ_{1820}	
N_{1650}	Δ_{1900}	Λ_{1670}	Σ_{1775}	Ξ_{1950}	
N_{1675}	Δ_{1905}	Λ_{1690}	Σ_{1790}	Ξ_{2025}	
N_{1680}	Δ_{1910}	Λ_{1800}	Σ_{1915}		
N_{1700}	Δ_{1920}	Λ_{1810}	Σ_{1940}		
N_{1710}	Δ_{1930}	Λ_{1820}	Σ_{2030}		
N_{1720}	Δ_{1950}	Λ_{1830}			
N_{1900}		Λ_{1890}			
N_{1990}		Λ_{2100}			
N_{2080}		Λ_{2110}			
N_{2190}					
N_{2200}					
N_{2250}					

0^{-+}	1^{--}	0^{++}	1^{++}
π	ρ	a_0	a_1
K	K^*	K_0^*	K_1^*
η	ω	f_0	f_1
η'	ϕ	f_0^*	f_1'
1^{+-}	2^{++}	$(1^{--})^*$	$(1^{--})^{**}$
b_1	a_2	ρ_{1450}	ρ_{1700}
K_1	K_2^*	K_{1410}^*	K_{1680}^*
h_1	f_2	ω_{1420}	ω_{1662}
h_1'	f_2'	ϕ_{1680}	ϕ_{1900}

Methods of cluster production

Wigner functions

- Projection on Hulthen wave function
- No free parameters
- No orthogonality of states

M. Kachelriess et al. Eur.Phys.J.A 57 (2021)
M. Gyulassi et al. Nucl.Phys.A 402 (1983)

Kinetic production

- Introduce explicit processes, e.g. $np\pi \rightarrow d\pi$
- Dynamical treatment
- 'Fake' 3-body interactions

J. Staudenmaier et al. Phys.Rev.C 104 (2021) 3, 034908
D. Oliinychenko et al. Phys.Rev.C 99 (2019) 4, 044907

Potential

- Hamiltonian which binds cluster
- Might involve complicated forces
- Difficult for small systems

J. Aichelin, et al. Phys.Rev.C 101 (2020) 4, 044905
S. Gläßel, et al. Phys.Rev.C 105 (2022) 1, 014908

Coalescence

- Employ cut-off parameters
- Event-by-event possible
- 2 free, energy-independent parameters

S. Butler, C. Pearson. Phys.Rev. 129 (1963) 836-842
S. Sombun et al. Phys.Rev.C 99 (2019) 1, 014901

Thermal emission

- Clusters in partition sum
- No free parameter

P. Braun-Munzinger, et al. Phys.Lett.B 344 (1995) 43-48
A. Andronic, et al. Nature 561 (2018) 7723, 321-330
V. Vovchenko, et al. Phys.Lett. B (2020) 135746

Multifragmentation

- Break up of thermal nuclear system
- Microcanonical ensembles
- Deexcitation via Fermi break up

Bondorf et al. Phys.Rept. 257 (1995) 133-221
Steinheimer et al. Phys.Lett.B 714 (2012) 85-91

Cluster Formation Models

Coalescence Mechanism

- Phase-space correlations
  - $\Delta\vec{P} \le \Delta\vec{\mathrm{P}}_{max},\ \Delta\vec{R} \le \Delta\vec{\mathrm{R}}_{max}$

	ΔP [GeV]	ΔR [fm]
d	0.285	3.575
$t/{}^3$He	0.32	3.5
^{4}He	0.41	3.5
${}^3_\Lambda$H	0.135	9.5
${}^3_\Lambda$H	0.25	4.0

Statistical Multifragmentation (SMM)

- Assume a larger excited nuclear system which subsequently fragments into small clusters
- **All participants (and spectators) from UrQMD (at 20 fm) are given into the SMM**

Results

p_T spectra of protons and Λ hyperons

$\pi^- + \mathbf{C}$: $0 < b < 2.5$ fm, $\sigma_{tot}^{\pi^-+C} = 196.35$ mb
$\pi^- + \mathbf{W}$: $0 < b < 6.5$ fm, $\sigma_{tot}^{\pi^-+W} = 1327.32$ mb

Kittiratpattana, Apiwit, et al. *arXiv:2305.09208* (2023).

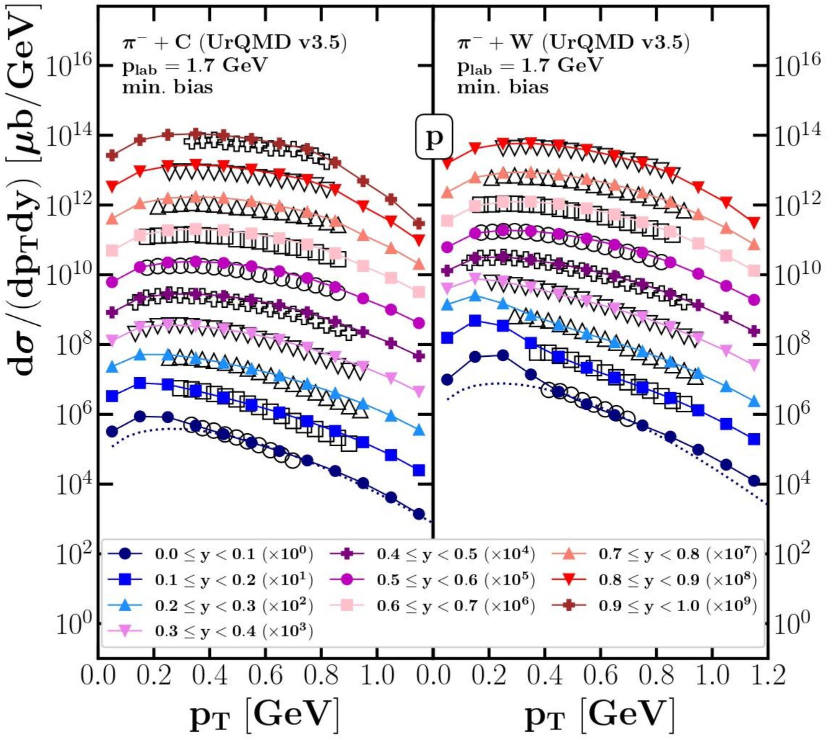
$$\sim C(y) p_T \sqrt{p_T^2 + m_0^2} \exp\left[-\sqrt{p_T^2 + m_0^2}/T(y)\right]$$

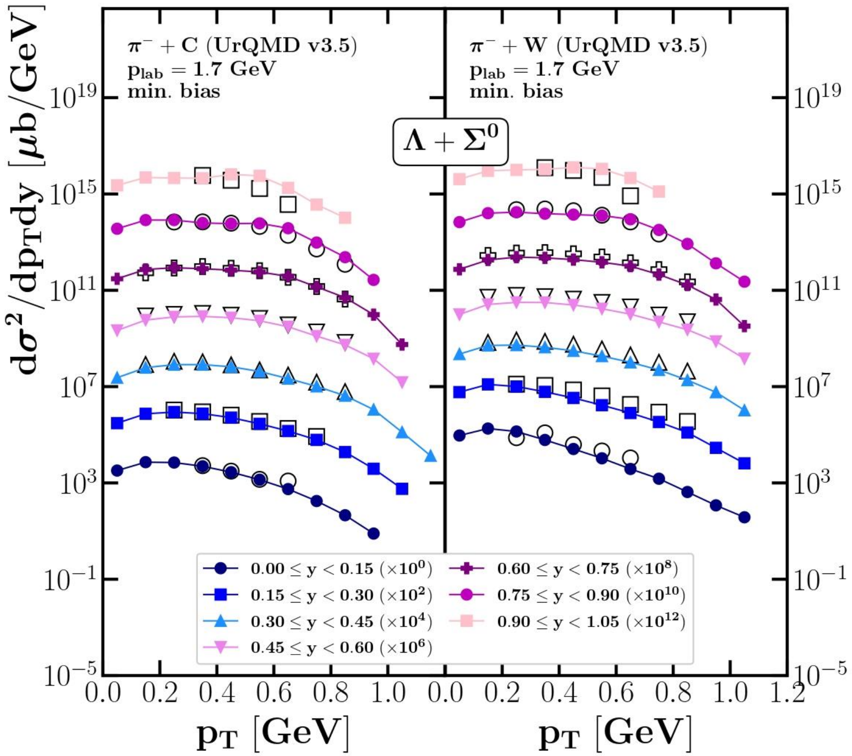
Protons:

- The slope parameters agree well.
- Observe the residue free protons at $p_T \leq 0.4$ GeV $(y \leq 0.1)$
    - More apparent in larger system

Λ hyperons:

- Agree well.





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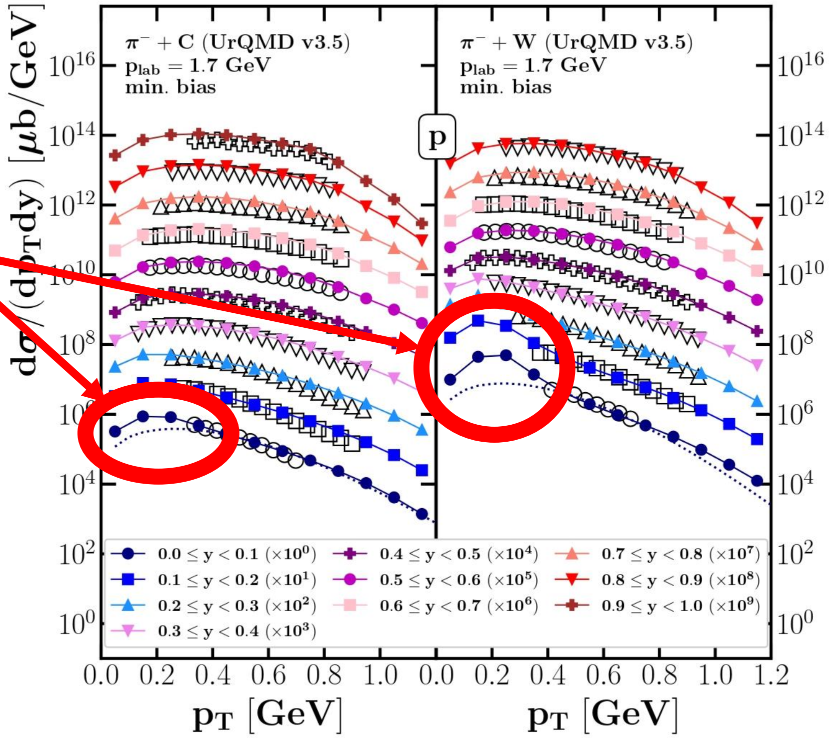

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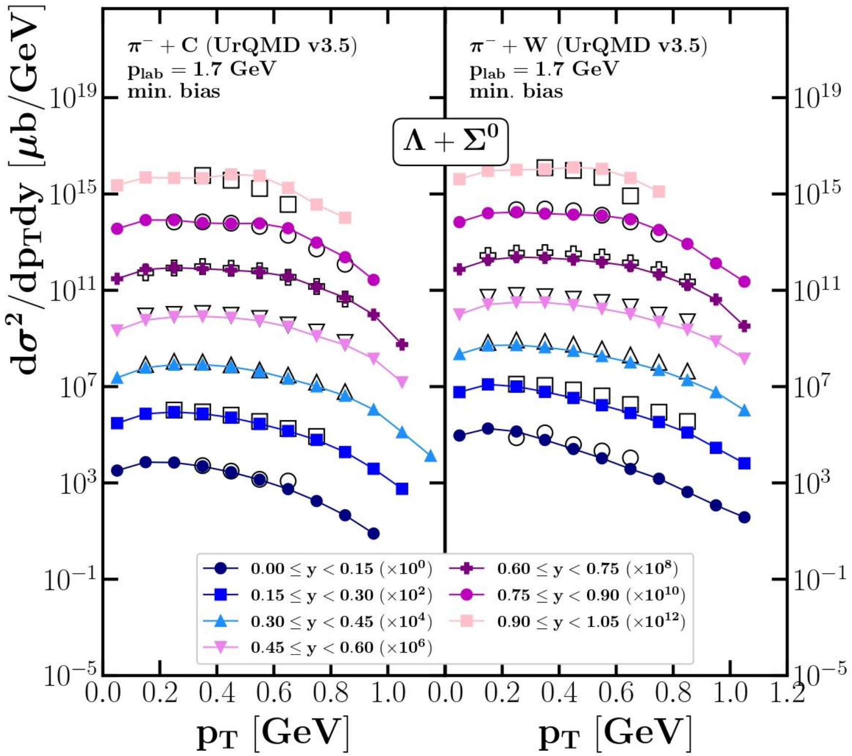

This leads to slightly difference in the extrapolated rapidity densities at $y \approx 0$ (target)

$\pi^- + \mathbf{C}$: $0 < b < 2.5$ fm, $\sigma_{tot}^{\pi^-+C} = 196.35$ mb
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Kittiratpattana, Apiwit, et al. *arXiv:2305.09208* (2023).

Results

Rapidity distribution of protons and Λ hyperons

Protons:

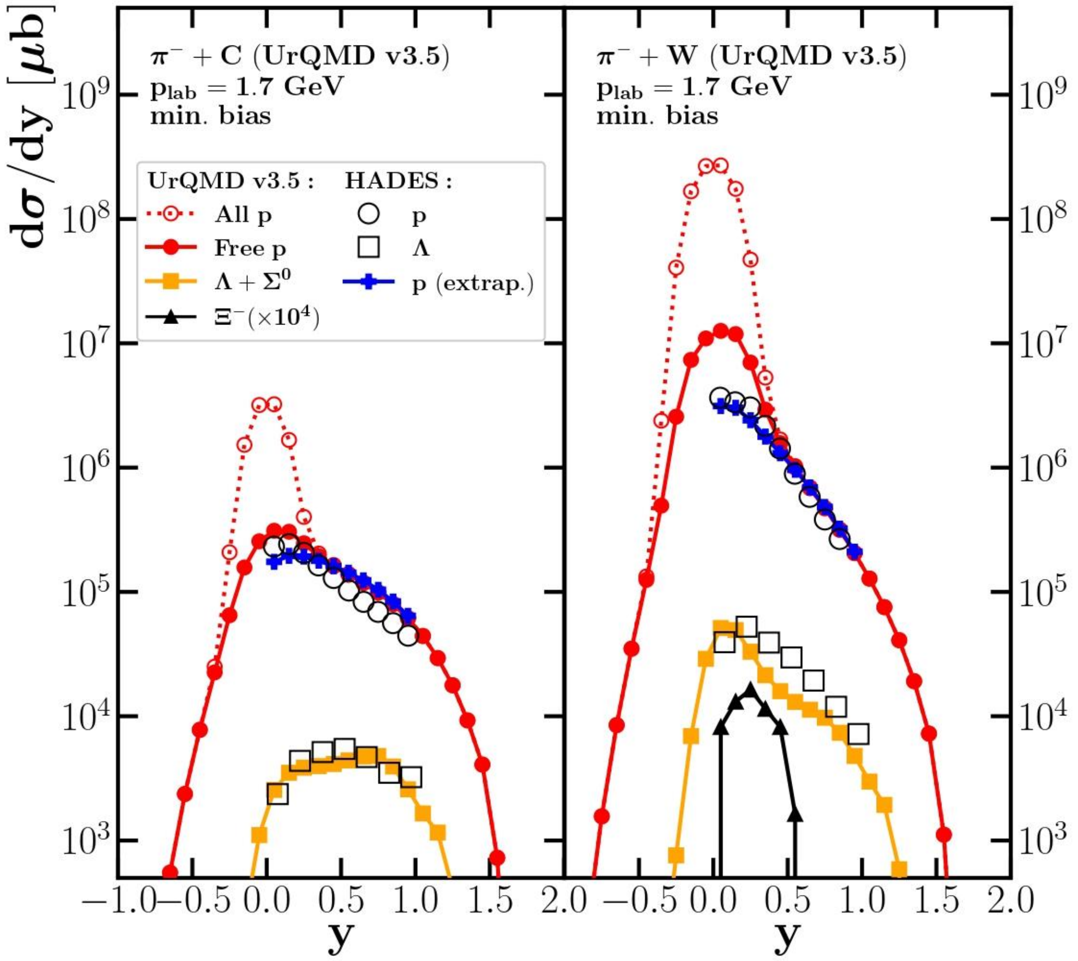
- The extrapolated densities and HADES data does not see the free proton at $y \approx 0$ (Acceptance $p_T < 0.4$ GeV)
- Larger effects in W system

Λ hyperons:

- Agree well in general

Ξ^- hyperons:

- Might be able to measure
- $\Xi NN \rightarrow \Lambda\Lambda N$?

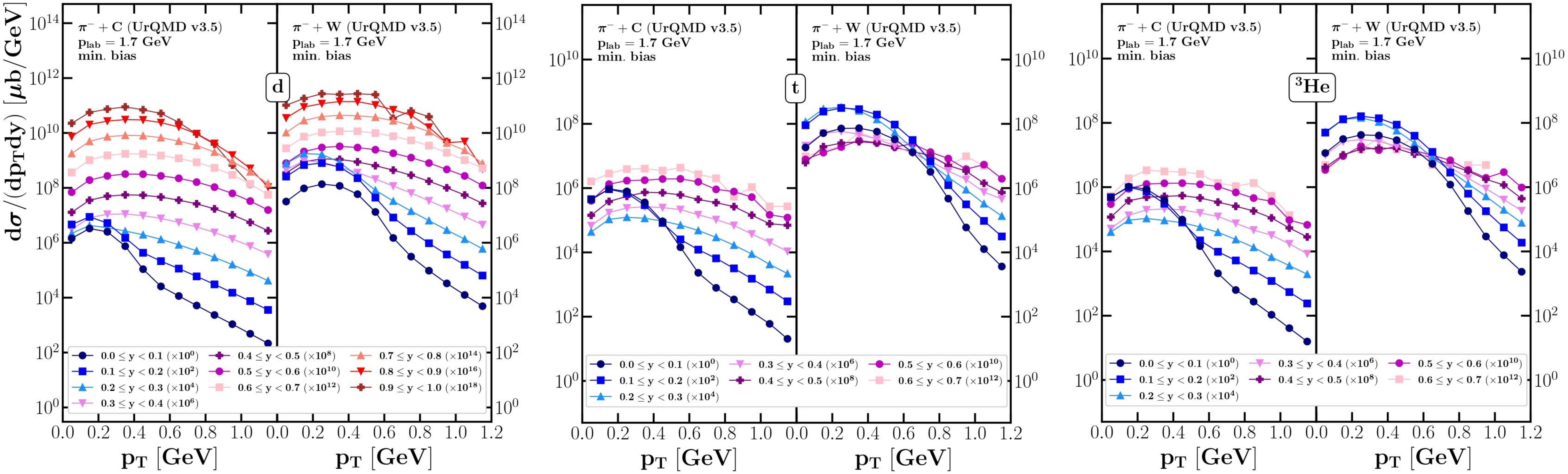


Results

p_T distribution of light nuclei

$\boldsymbol{\pi^-} + \mathbf{C}$: $0 < b < 2.5$ fm, $\sigma_{tot}^{\pi^- + C} = 196.35$ mb
$\boldsymbol{\pi^-} + \mathbf{W}$: $0 < b < 6.5$ fm, $\sigma_{tot}^{\pi^- + W} = 1327.32$ mb

Kittiratpattana, Apiwit, et al. *arXiv:2305.09208* (2023).



Similar to the residue protons, the light cluster yields also has a bump at $y \approx 0$

Results

Rapidity distribution of light nuclei

$\boldsymbol{\pi^- + \mathrm{C}}$: $0 < b < 2.5$ fm, $\sigma_{tot}^{\pi^-+\mathrm{C}} = 196.35$ mb
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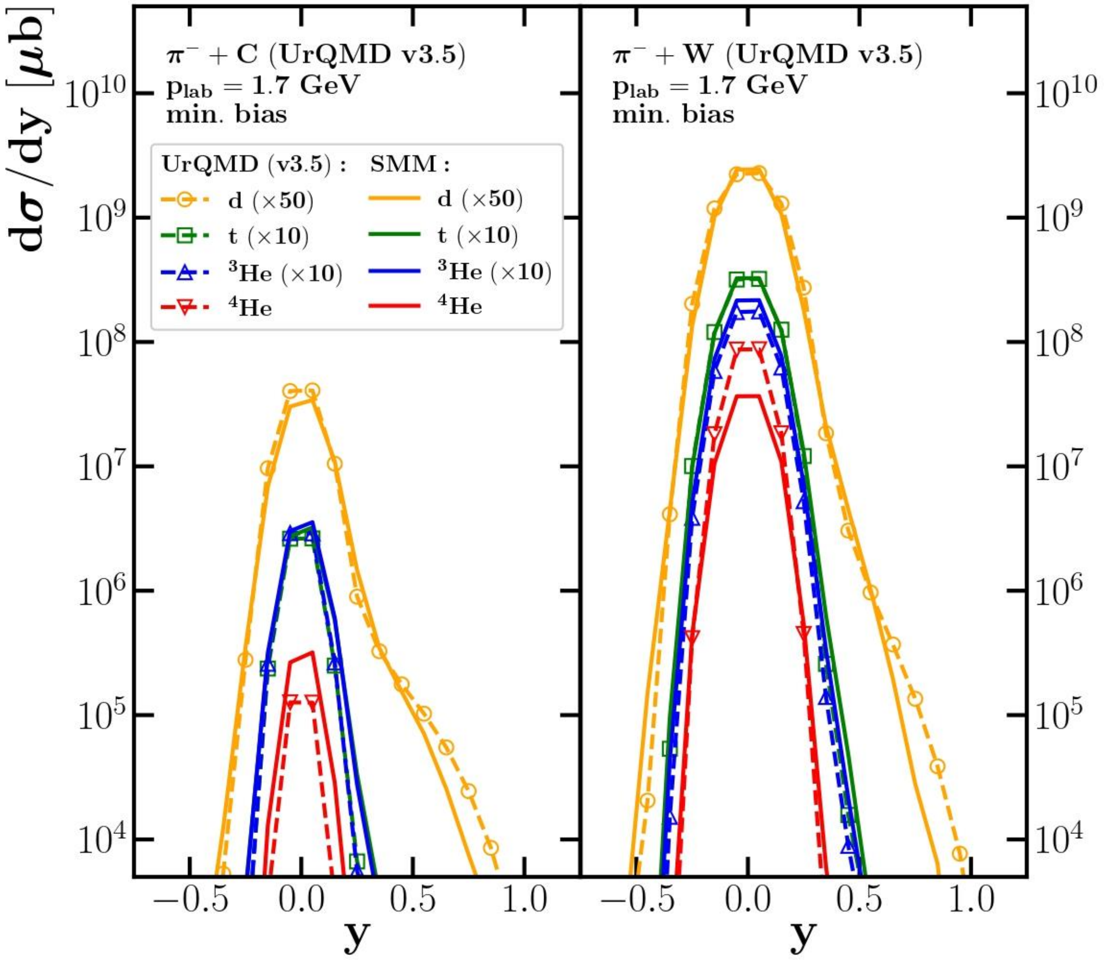
Kittiratpattana, Apiwit, et al. *arXiv:2305.09208* (2023).

Most cluster are centered around target rapidity where (residue) nucleons are located/fragmented.

$\rightarrow A \leq 4 \sim \mathcal{O}(10)$ per event

- **Deceleration:**
  - Deuterons are much more pronounce at forward rapidity
  - π^- is more likely to knock $1-2$ nucleons from the target
  - Larger nucleus decelerates stronger



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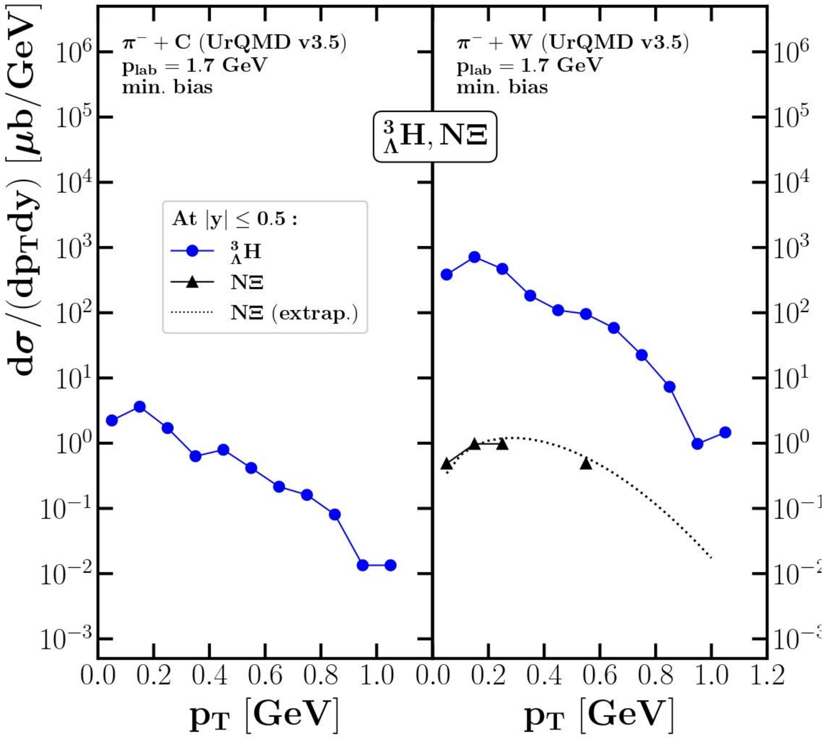
Results

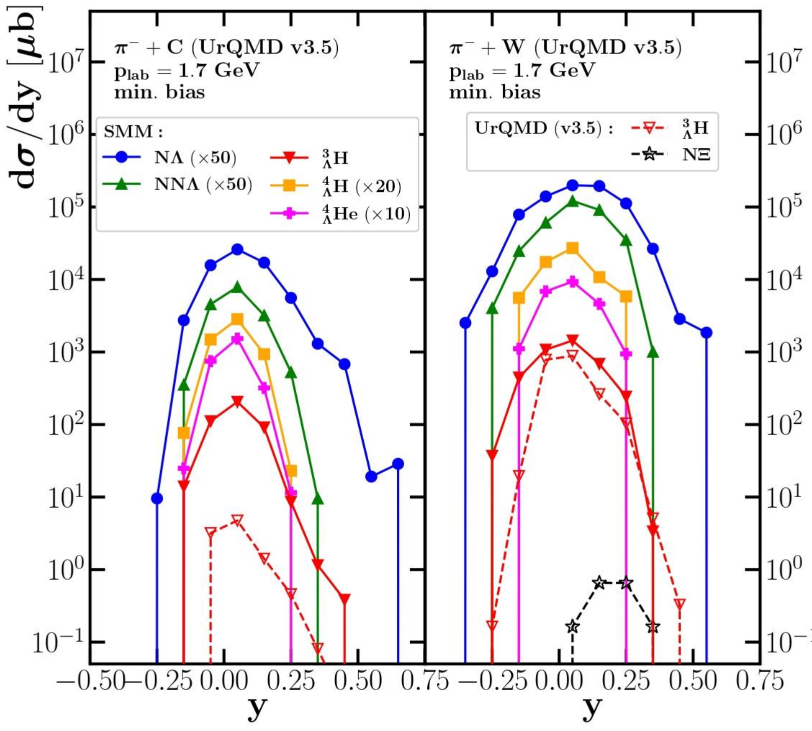
Rapidity distribution of hypernuclei

- More clusters formation at $y \approx 0$
- $\mathcal{O}(10^{-3})$ of ${}^{3}_{\Lambda}$**H** per events.
- $N\Xi$ signal?

- **Deceleration: $A > 2$**
- In small system (πC), SMM differs from UrQMD by a factor of 10
  - Suppression in small system

Kittiratpattana, Apiwit, et al. *arXiv:2305.09208* (2023).





Results

Total abundance for larger (hyper)nuclei

$\boldsymbol{\pi^-} + \mathbf{C}$: $0 < b < 2.5$ fm, $\sigma_{tot}^{\pi^-+C} = 196.35$ mb
$\boldsymbol{\pi^-} + \mathbf{W}$: $0 < b < 6.5$ fm, $\sigma_{tot}^{\pi^-+W} = 1327.32$ mb

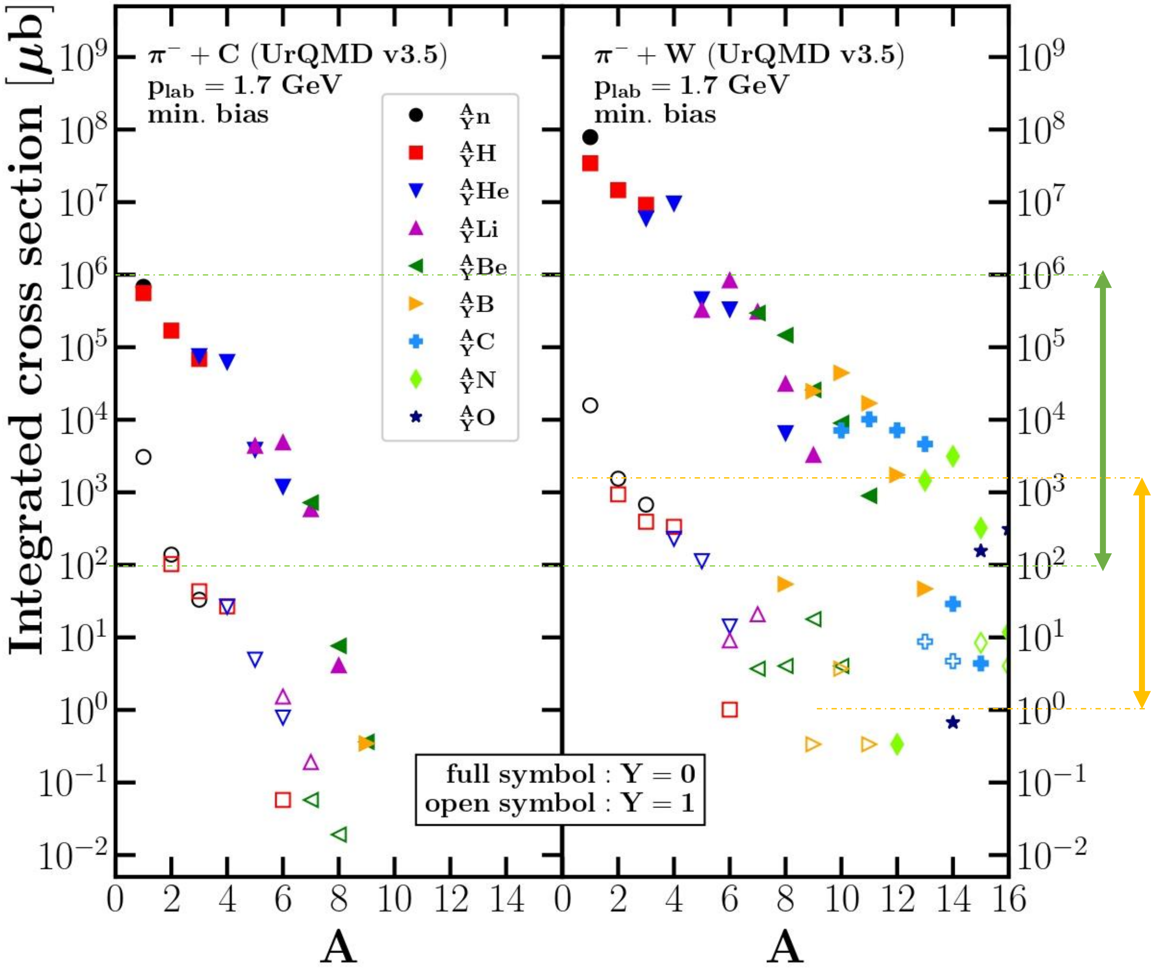
Kittiratpattana, Apiwit, et al. *arXiv:2305.09208* (2023).

Signal extractions by HADES (~10^9 events)

- Light nuclei $A > 3 \rightarrow 10^{-4} - 1$ / event
- Hypernuclei $A > 3 \rightarrow 10^{-6} - 10^{-3}$ / event

HADES with $\boldsymbol{p_{\mathrm{lab}} = 2.5}$ GeV?

- Ξ-hypernuclei might be seen ($N^* \rightarrow \Xi + K + K$)
- Double-Λ ($\Xi + N + N \rightarrow \Lambda + \Lambda + N$)



Summary

- UrQMD is employed to simulate $\pi^- + \mathrm{C}$ and $\pi^- + \mathrm{W}$ at $p_{\mathrm{lab}} = 1.7$ GeV
- We predict clusters with <u>coalescence</u> and <u>SMM</u> for light nuclei and hypernuclei
  - Light nuclei $A > 3 \rightarrow 10^{-4} - 1$ / event
  - Hypernuclei $A > 3 \rightarrow 10^{-6} - 10^{-3}$ / event
  - $\mathcal{O}(10^{-3})$ of ${}^{3}_{\Lambda}$H per event
  - Large targets are favorable (more stopping)
- Suppression in small system is similar to LHC
- **Ξ** and **double-Λ** might be seen at higher beam momenta?