Nuclei and hypernuclei production in pion induced reactions around threshold energies

Outline:

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

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Based on: Kittiratpattana, A., et al. *Physical Review C* 109.4 (2024): 044913.

Hypernuclei: Equation of State (EoS)

Why are hypernuclei interesting?

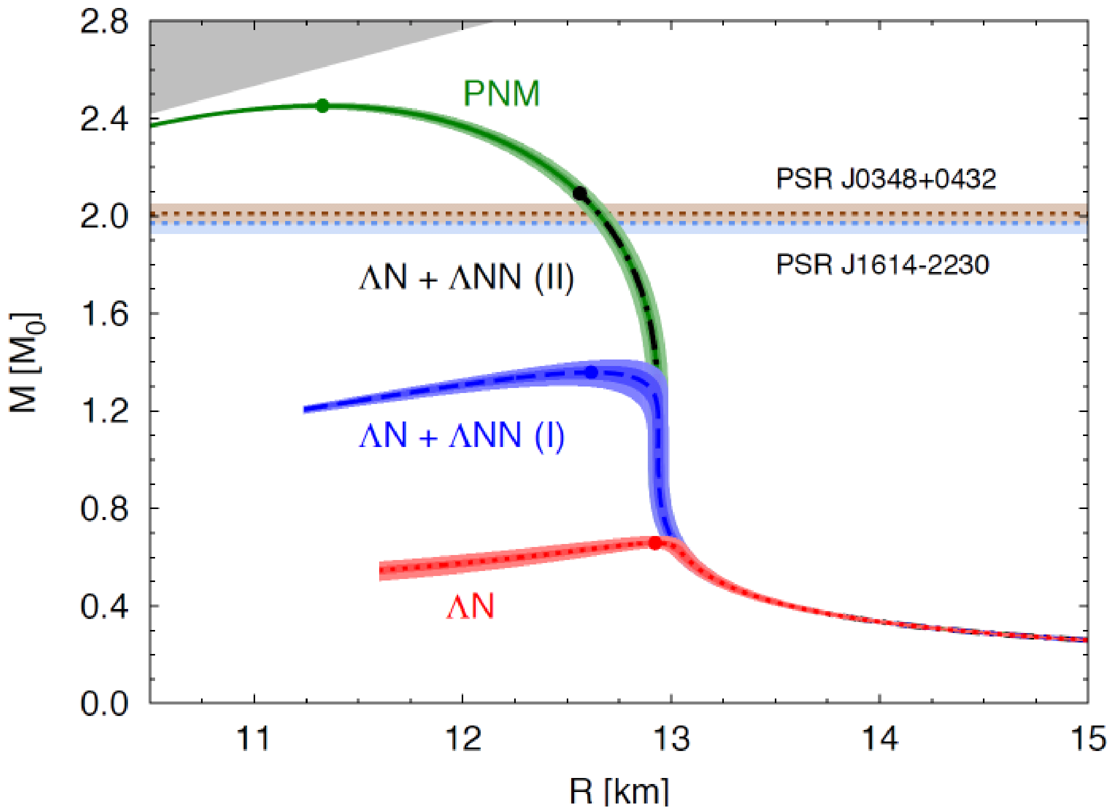
→ Cluster formation (EoS)

→ YN-Interaction (dense matter EoS)

Talks on Monday

EoS for dense matter (neutron stars):

- The presence of hypernuclei softens the EoS
- Stiffer EoS
  - 3-body repulsive potential



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

Hypernuclei: Heavy-ion Collisions

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

- Strongly attractive → Soft EoS (deeply bound)
- More repulsive → Stiff EoS (less bound)

Can coalescence help us study the $\mathbf{\Lambda N}$-interaction?

- Coalescence works (may reflect internal structure)
- Does it work with hypernuclei and different system?

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

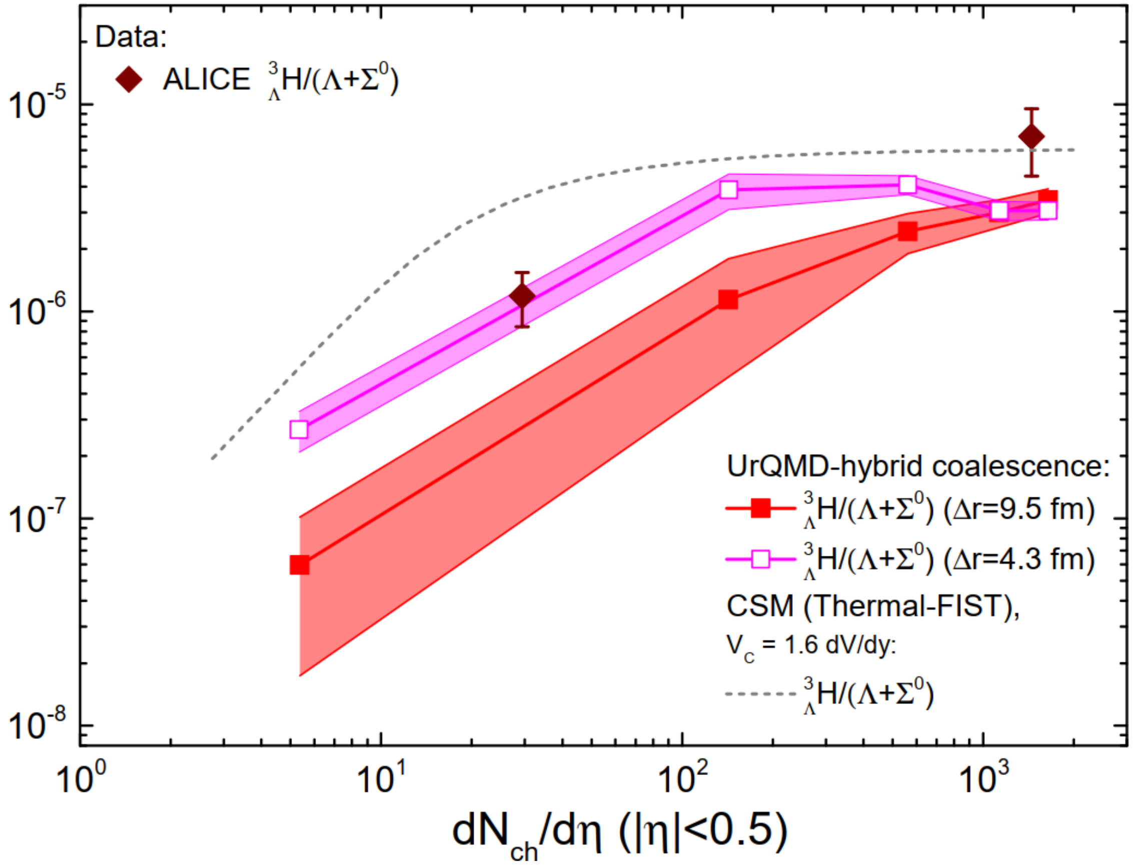
Hypernuclei

What happens when the coalescence size is larger than the system size?

- Suppression at small system
  - Δr and ΔP are less correlated
  - (Maybe) reflect soft/stiff EoS?

Study ${}^{3}_{\Lambda}\mathrm{He}$ in diff. system

- (Maybe) help for EoS?
- Pin down the mechanism
- More data is needed!



Note: Coalescence parameter may not directly connect to the wavefunction size

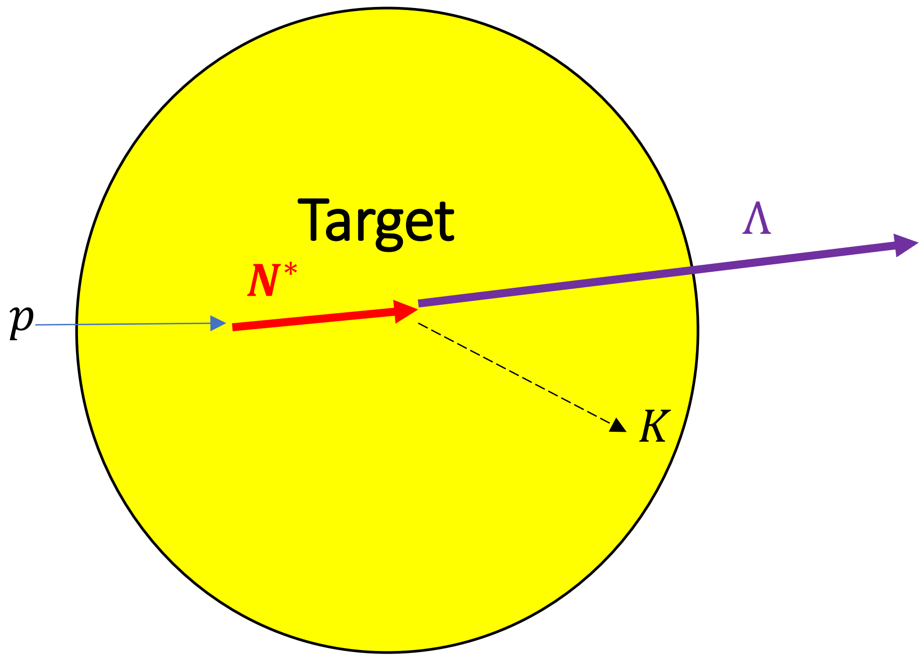
Small system size

New particle production in $p + A$:

Lambda is produced with a large forward momentum

→ Less favorable for hypernuclei production

→ Hypernuclei will be produced outside



Small system size

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

Lambda is produced with a large forward momentum

→ Less favorable for hypernuclei production

→ Hypernuclei will be produced outside

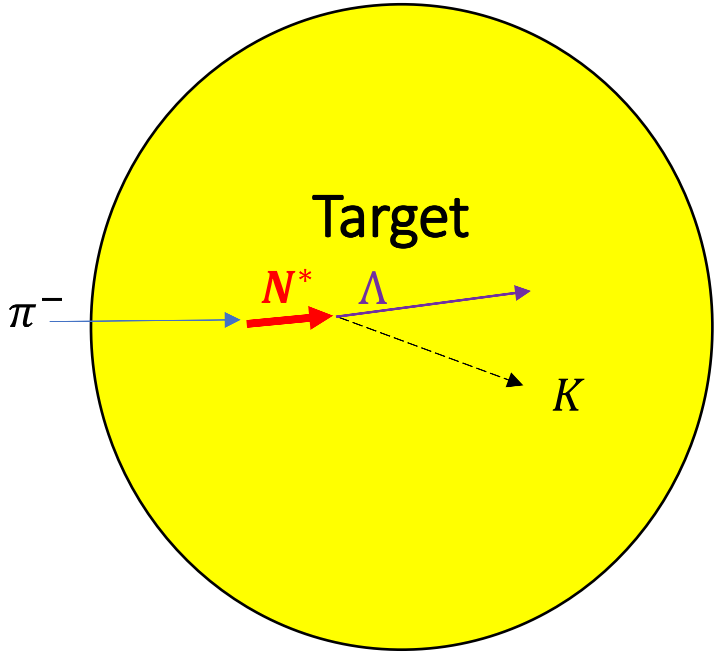
New particle production in $\boldsymbol{\pi}^{-} + \boldsymbol{A}$:

→ Hypernuclei will be formed with the target!

(Allow for large hypernuclei $\mathrm{A} \gg 3$)

Hyperon production

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



Our aim: Study nuclei and hypernuclei formation with pion beam

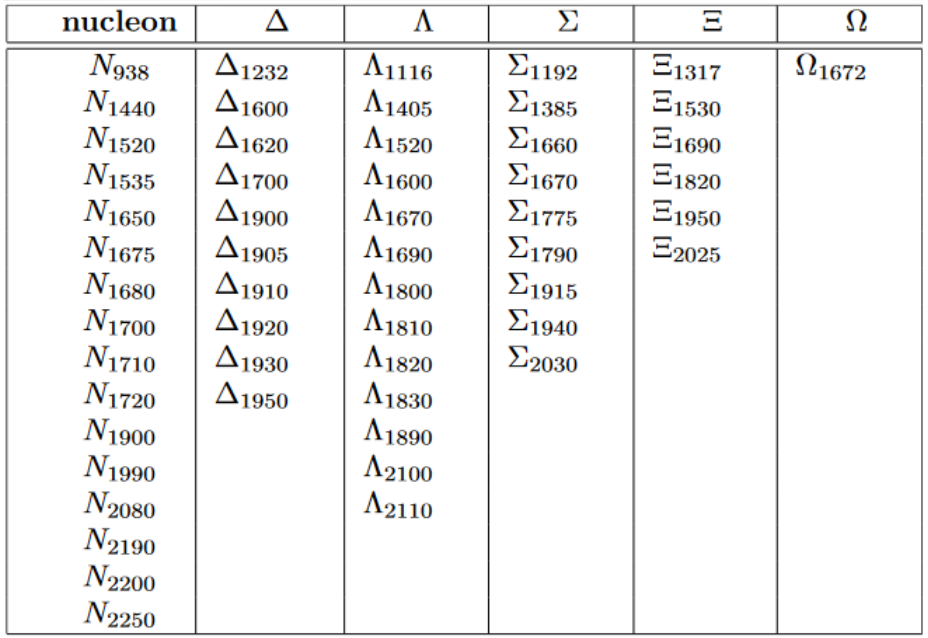
UrQMD

Ultra-relativistic Molecular Dynamics (UrQMD)

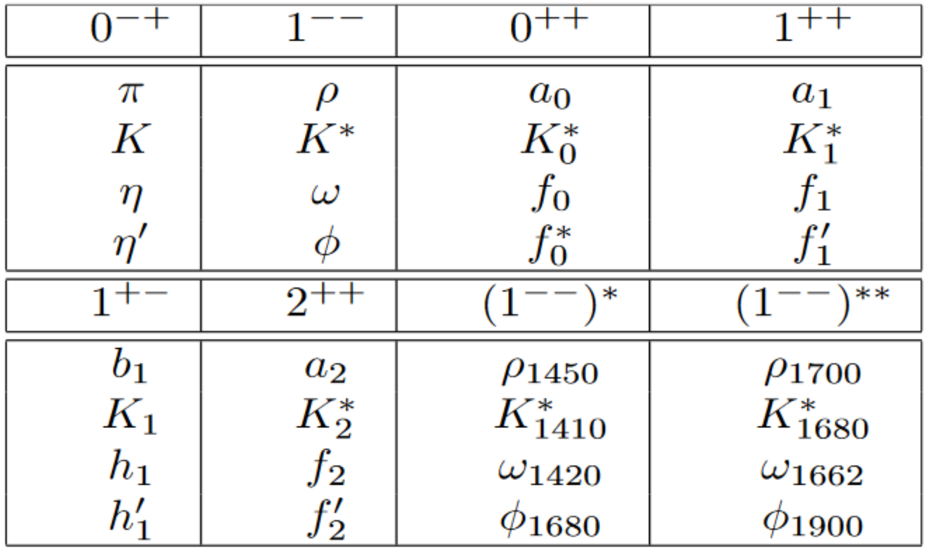
Based on the relativistic Boltzmann transport:

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

- Binary interactions + Re-scattering are treated
- Cross sections are taken from data or models
- Resonances/decays are implemented
- History of all 4-coordinates and 4-momenta



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}

Cluster formation mechanisms

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

J. Staudenmaier et al. Phys.Rev.C 104 (2021) 3, 034908
D. Oliinychenko et al. Phys.Rev.C 99 (2019) 4, 044907
G. Coci et al., Phys.Rev.C 108 (2023) 014902

Potential + MST
- Hamiltonian which binds cluster
- Momentum dependent potential with soft EoS

J. Aichelin et al., PRC 101 (2020) 044905
S. Gläßel et al., PRC 105 (2022) 1

Talk by J. Aichelin on Monday

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

Talk by M. Bleicher on Monday

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

Talk by N. Buyukcizmeci on Thursday

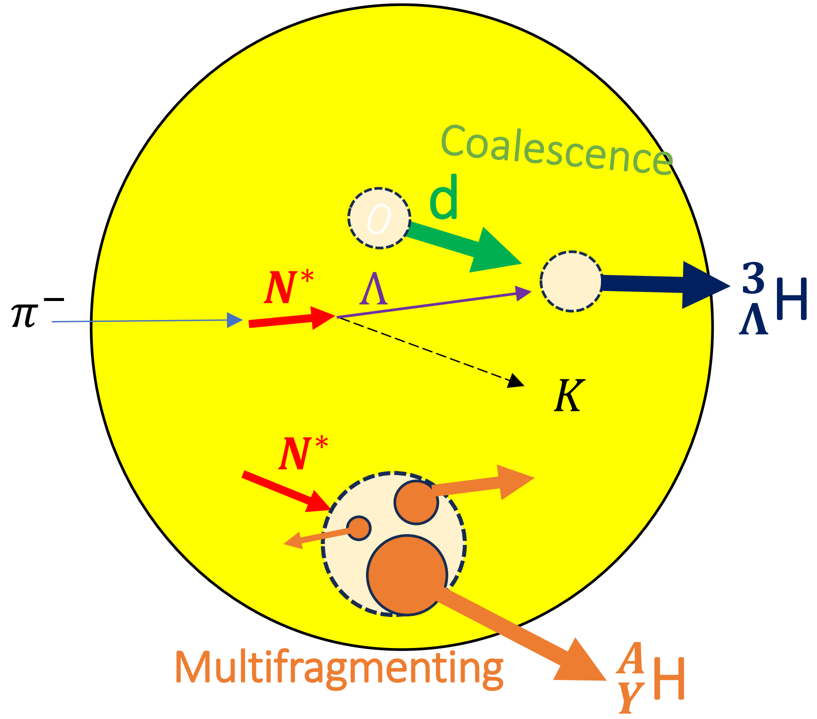
Cluster formation mechanisms

Coalescence Mechanism (UrQMD)

- Phase-space coalescence:

$$dN/d\vec{P} = g \int f_A(\vec{r}_1,\vec{p}_1) f_B(\vec{r}_2,\vec{p}_2) \rho_{AB}(\vec{r}_1,\vec{r}_2,\vec{p}_1,\vec{p}_2) \, \delta(\vec{P} - \vec{p}_1 - \vec{p}_2) d^3r_1 d^3r_2 d^3p_1 d^3p_2$$

- Box coalescence: ρ_{AB}
  - $\Delta\vec{P} \leq \Delta\vec{\mathrm{P}}_{max},\ \Delta\vec{R} \leq \Delta\vec{\mathrm{R}}_{max}$



Statistical Multifragmentation (SMM)

Assume a larger excited nuclear system which subsequently fragments into small clusters

- All participants (and spectators) from UrQMD (at $20\ \mathrm{fm}$) are given to SMM
- Coalesce to heavier nuclei and decays into fragmented nuclei

Results

p_T spectra of protons and Λ hyperons

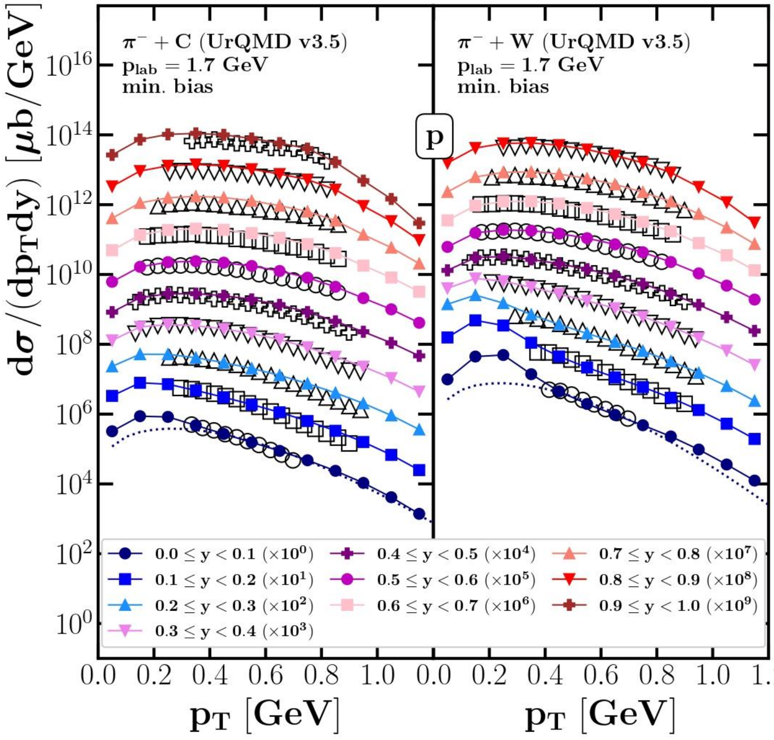
$\boldsymbol{\pi^-} + \mathbf{C}$: $0 < b < 2.5$ fm, $\sigma_{tot}^{\pi^- + \mathrm{C}} = 196.35$ mb
$\boldsymbol{\pi^-} + \mathbf{W}$: $0 < b < 6.5$ fm, $\sigma_{tot}^{\pi^- + \mathrm{W}} = 1327.32$ mb
Kittiratpattana, A., et al. *Physical Review C* 109.4 (2024): 044913.

Protons:

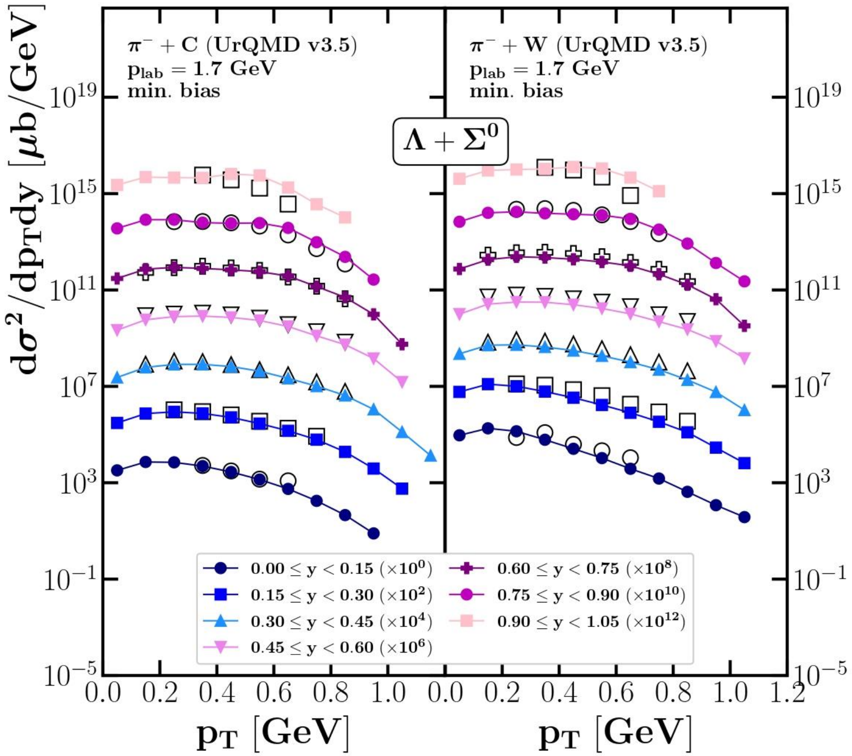
- The slope parameters agree well
- Observe the residue free protons at $p_T \leq 0.4$ GeV ($y \leq 0.1$)
  - More apparent in larger system

Λ hyperons:

- Also agree well



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



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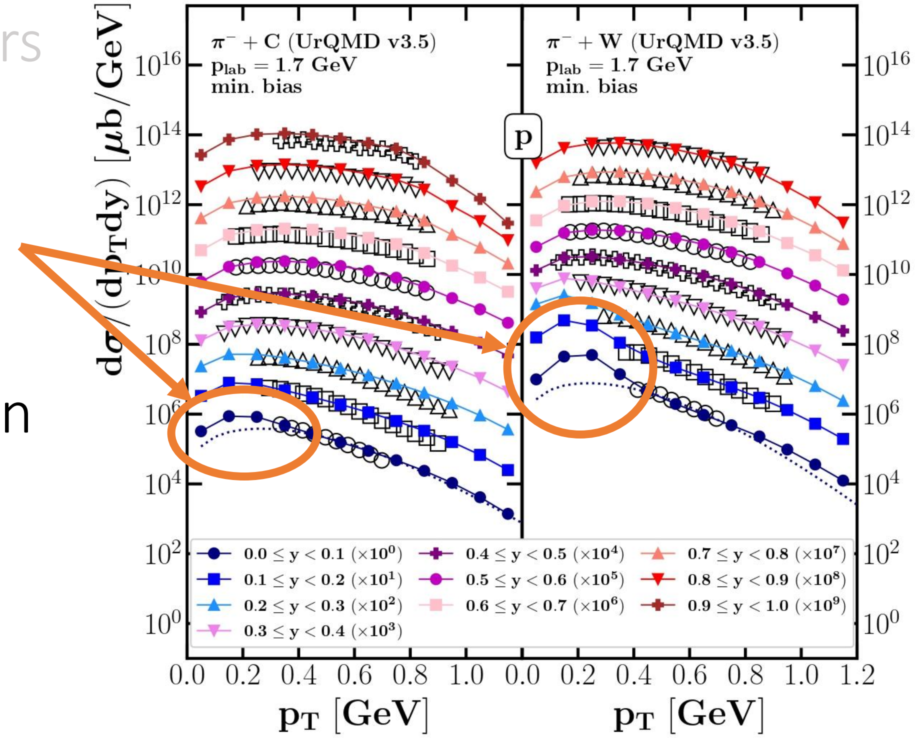
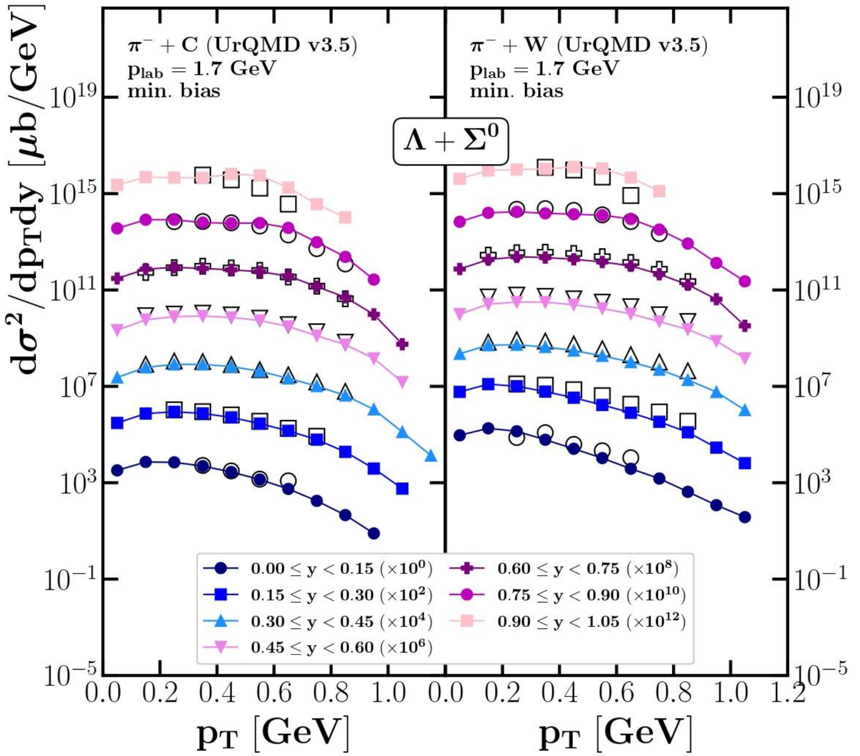
Λ hyperons:

  - Agree well.



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



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

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

Rapidity distribution of protons and $\boldsymbol{\Lambda}$ hyperons

Protons:

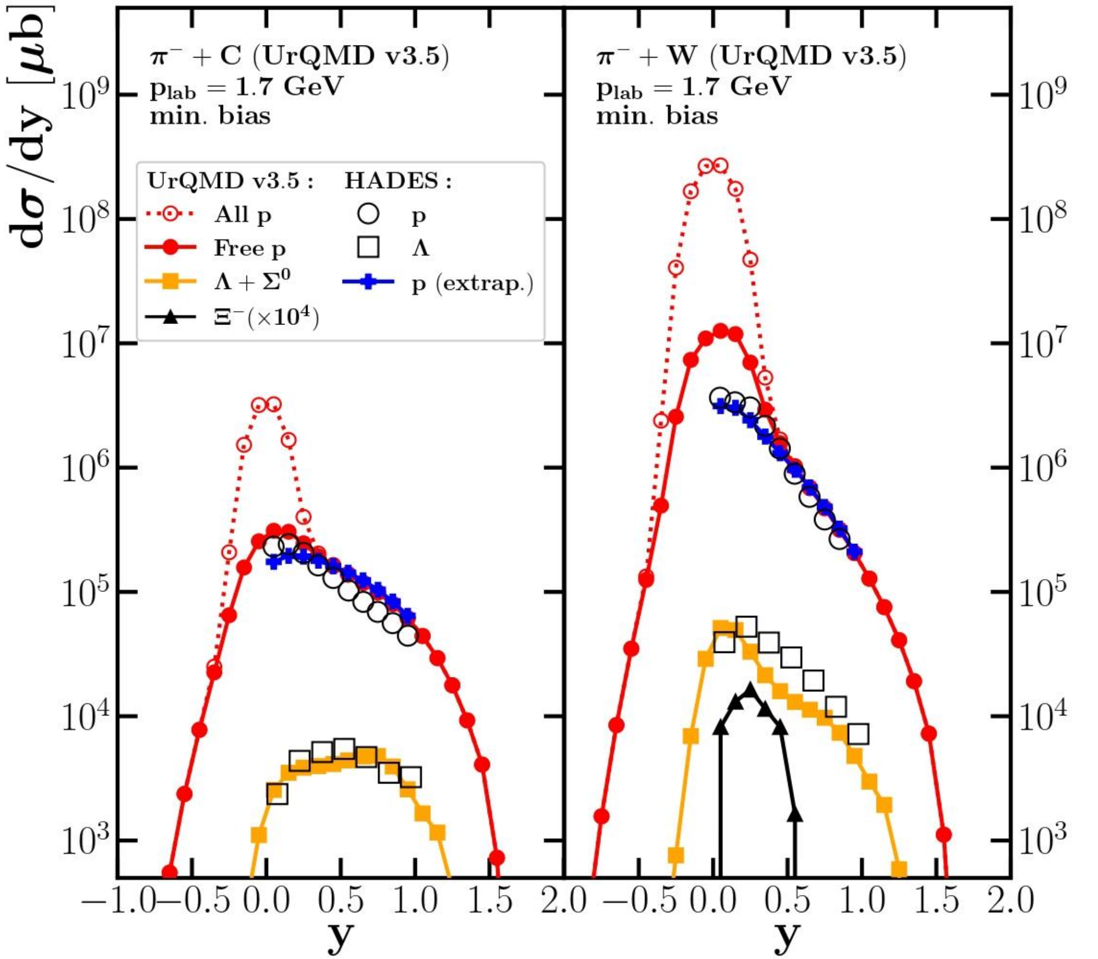
- The extrapolated (UrQMD) and HADES agree well
    - Need adjustment for exponential fit
- All protons are at the target
    - Good for cluster formation

$\boldsymbol{\Lambda}$ hyperons:

- Agree well in general

$\boldsymbol{\Xi^-}$ hyperons:

- Detectable
- $\Xi NN \rightarrow \Lambda\Lambda N$?



Results

p_T distribution of light nuclei

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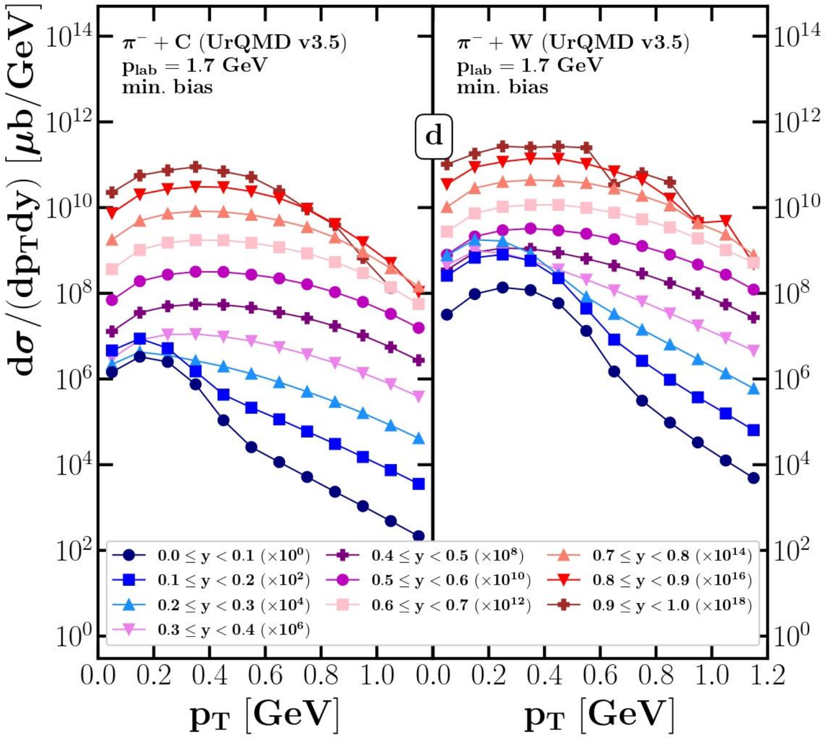

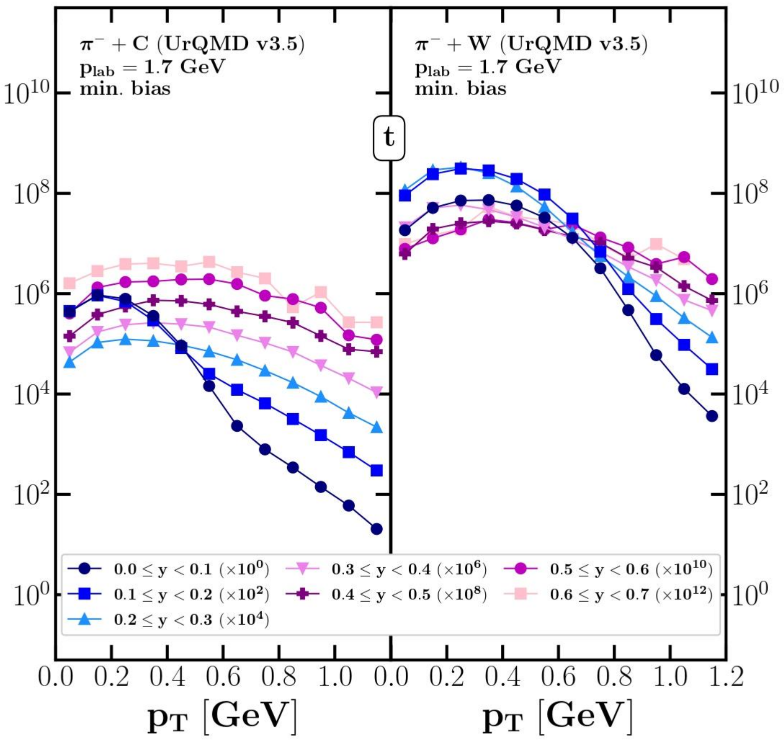

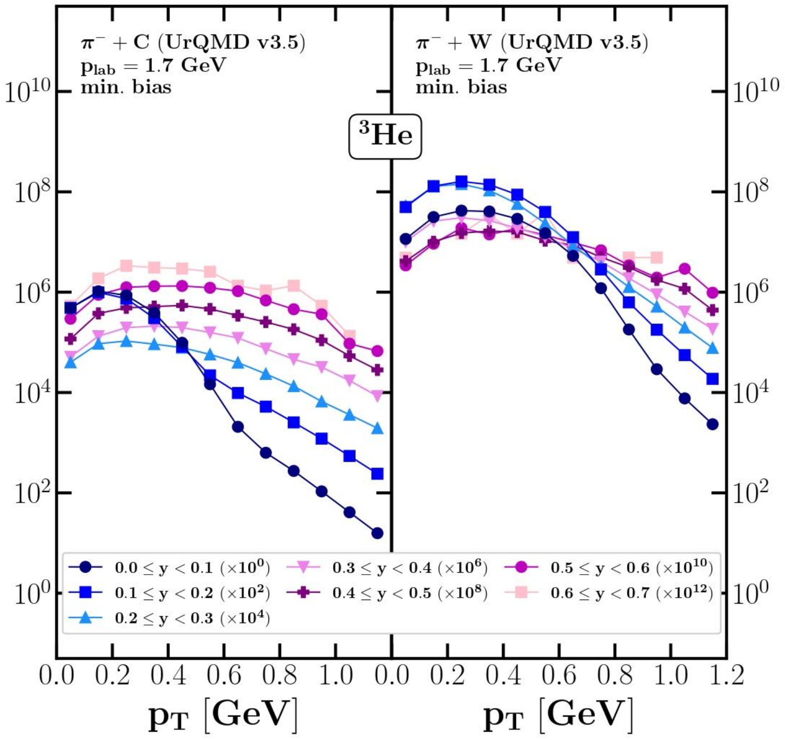

Similar to the residue protons, the light cluster yields also has a bump at $y \approx 0$

Results

Rapidity distribution of light nuclei

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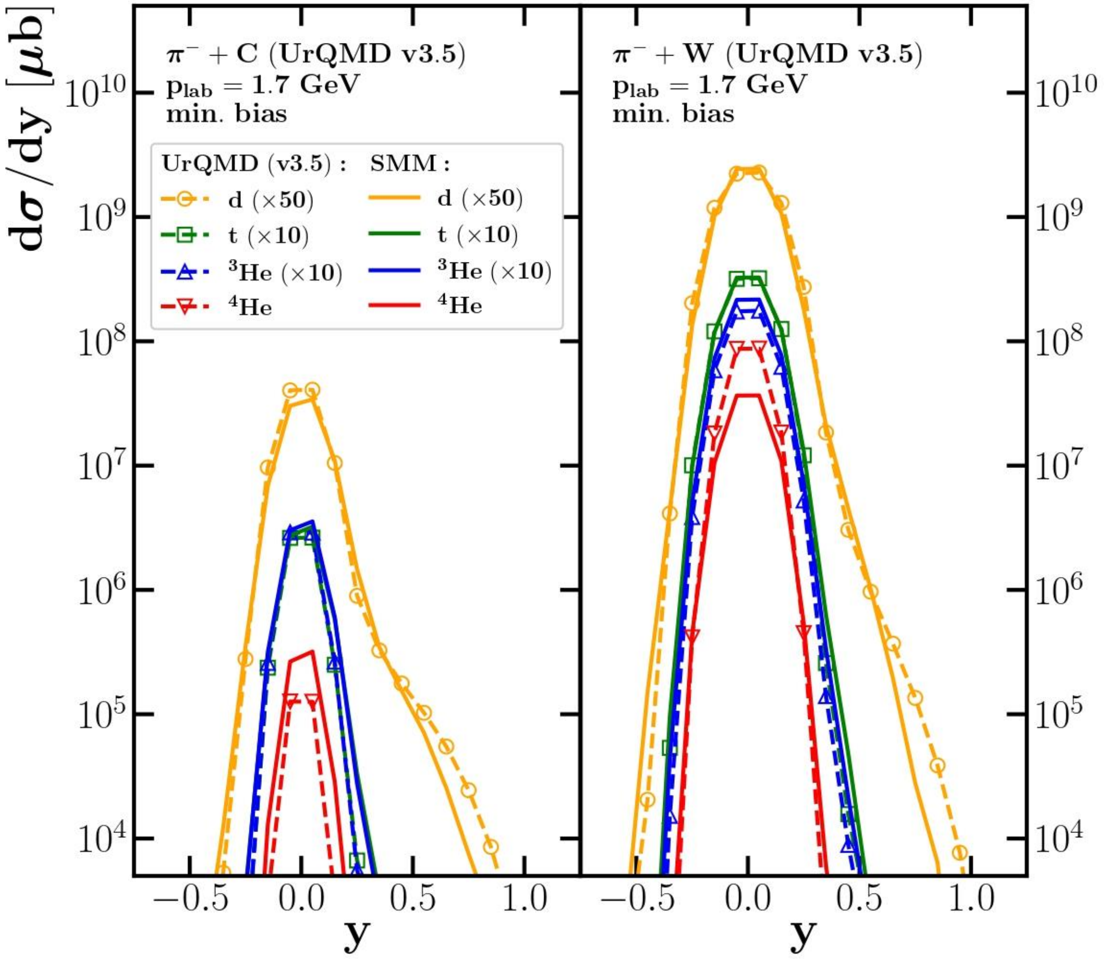
Most cluster are centered around target rapidity where (residue) nucleons are located/fragmented.
→ $A \leq 4 \sim \mathcal{O}(10)$ per event

- **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



Results

Rapidity distribution of hypernuclei

$\boldsymbol{\pi^-} + \mathbf{C}$: $0 < b < 2.5$ fm, $\sigma_{tot}^{\pi^-+\mathrm{C}} = 196.35$ mb
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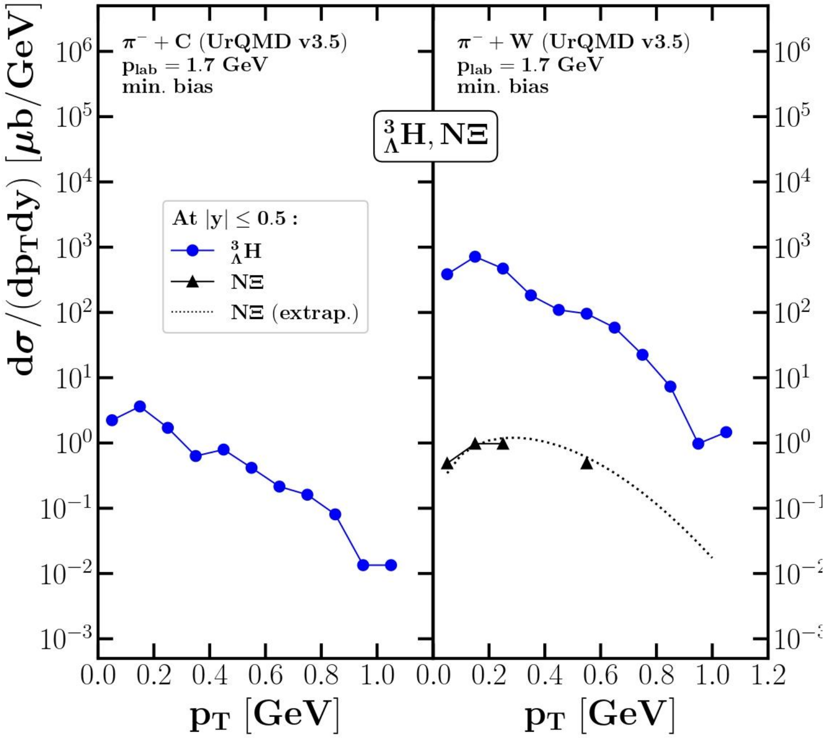
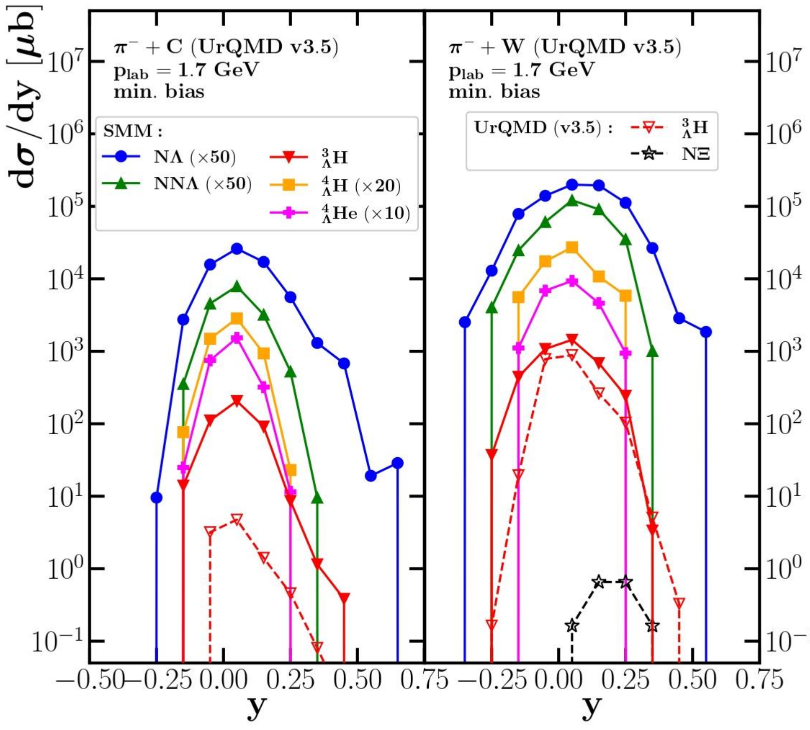
Kittiratpattana, A., et al. *Physical Review C* 109.4 (2024): 044913.

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

- Deceleration: $A < 3$
- In small system (πC), SMM differs from UrQMD by a factor of 10
  - Suppression ${}^{3}_{\Lambda}\mathbf{H}$ in small system





Results

Total abundance for larger (hyper)nuclei

$\boldsymbol{\pi^- + \mathrm{C}}$: $0 < b < 2.5$ fm, $\sigma_{tot}^{\pi^-+\mathrm{C}} = 196.35$ mb
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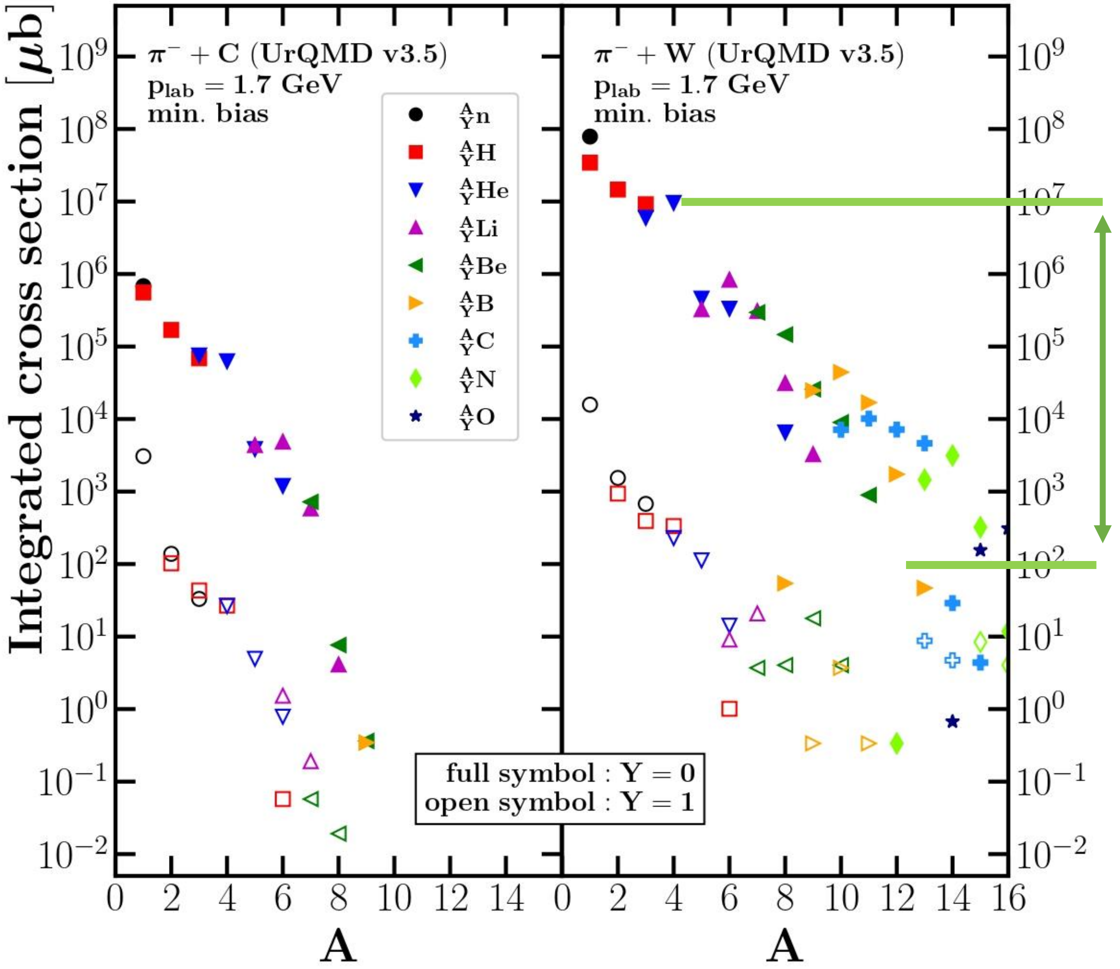
Signal extractions by HADES ($\sim 10^9$ events)

- **Nuclei $A > 3$** → $10^{-4} - 10$ / event
- **Hypernuclei $A \geq 3$** → $10^{-6} - 10^{-3}$ / event

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

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



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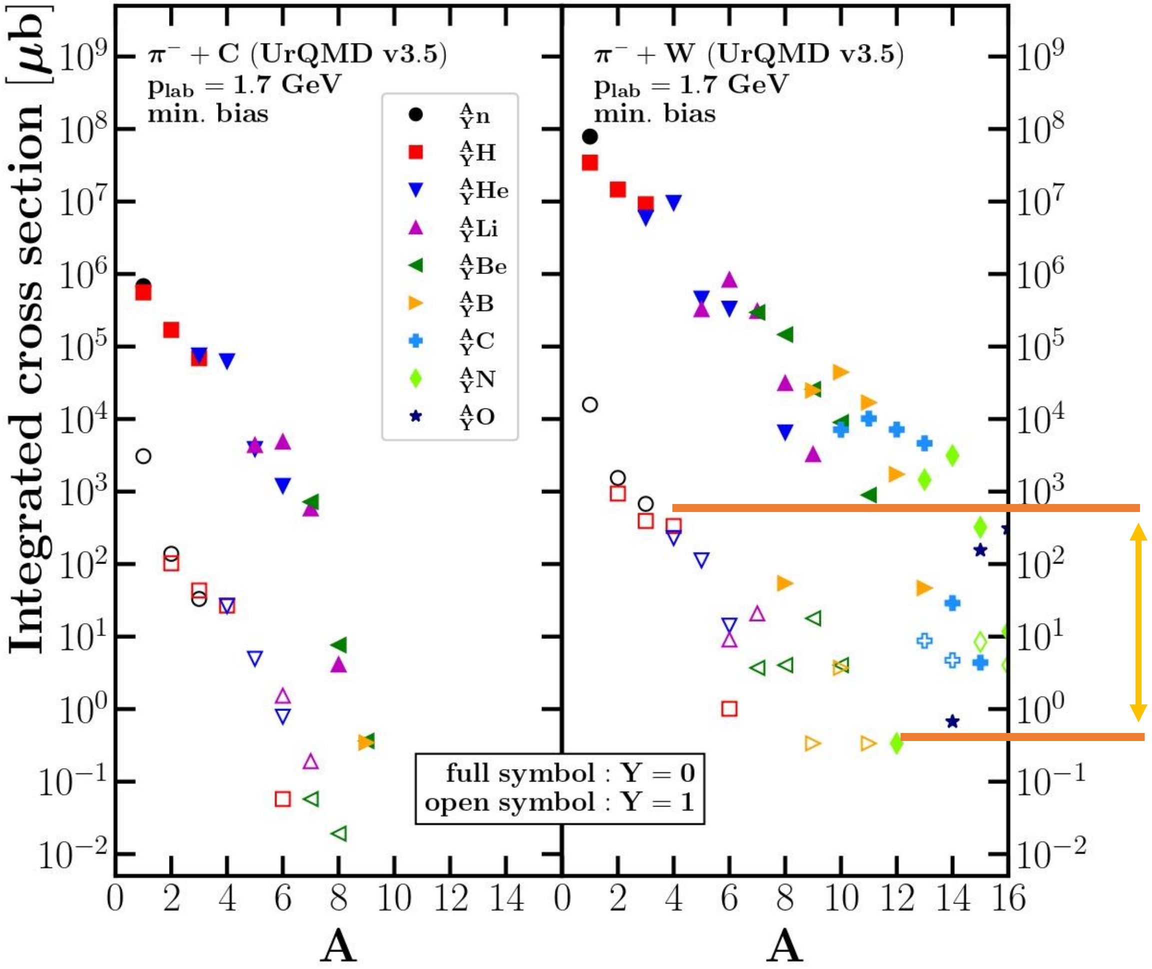

Summary

UrQMD is employed to simulate $\pi^- + \mathrm{C}$ and $\pi^- + \mathrm{W}$ at $p_{\mathrm{lab}} = 1.7\ \mathrm{GeV}$

We predict clusters with coalescence and SMM

- Nuclei $A > 3 \rightarrow 10^{-4} - 10$ / event
- Hypernuclei $A \geq 3 \rightarrow 10^{-6} - 10^{-3}$ / event
- $\mathcal{O}(10^{-3})$ of ${}^{3}_{\Lambda}\mathrm{H}$ per event
- Large targets are favorable (more stopping)
- Strong suppression supports coalescence

Ξ and double-Λ at higher beam momenta?