Light and hypernuclei production in $\pi^- + \mathrm{C}$ and $\pi^- + \mathrm{W}$ at $p_{\mathrm{lab}} = 1.7\ \mathbf{GeV}$

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Outline:

- Hypernuclei
- $\pi -$ Beam
- UrQMD
- Cluster formation models
- Results

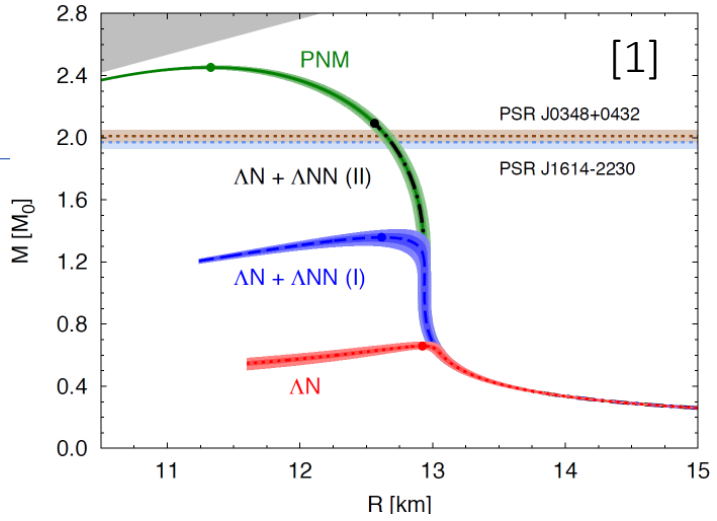
Hypernuclei

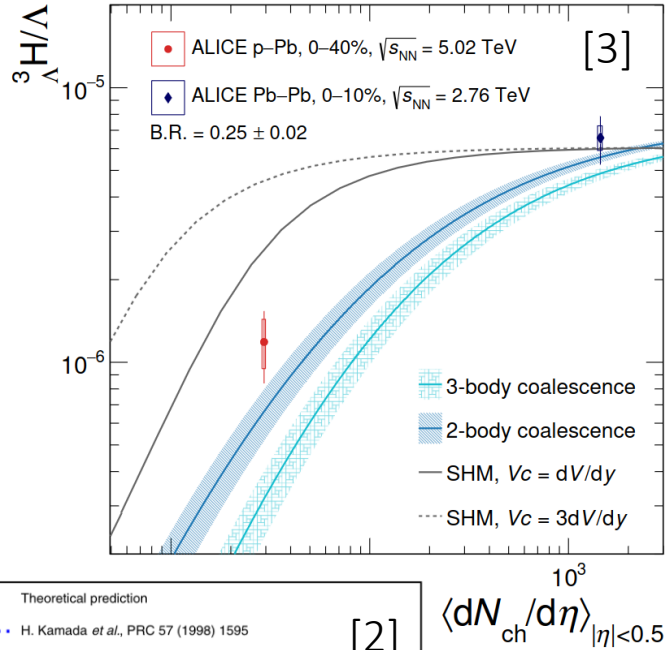
At large/high energy systems:

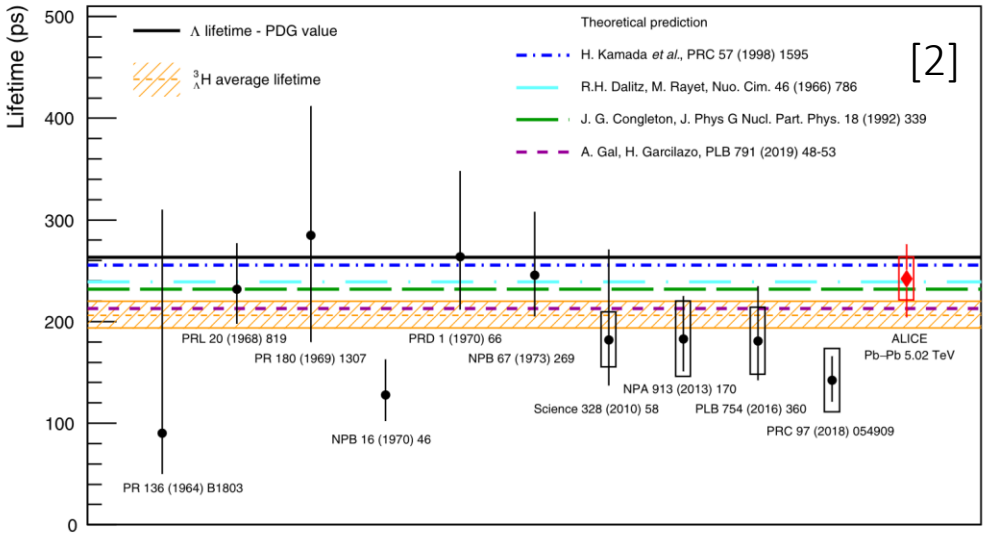
→ YN-Interactions?

- Neutron stars with $\sim 2M_{\odot}$?
  - Pauli blocking → Soften EoS
  - 3-body interactions [1]
- Hypertriton $^{3}_{\Lambda}\mathrm{H}$ lifetime?
  - Lifetime [2] reflects the internal structure (radius, d-Λ)
  - System size dependence [3]

    → Small system data is needed







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

[2] ALICE Collaboration (2019), Physics Letters B, 797, 134905

[3] Sun, K., Ko, C. M., & Donigus, B. (2019). *Physics Letters B*, *792*, 132–137.

π^- Beam

Low energy + Smaller system
→ Allow more cluster formations

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

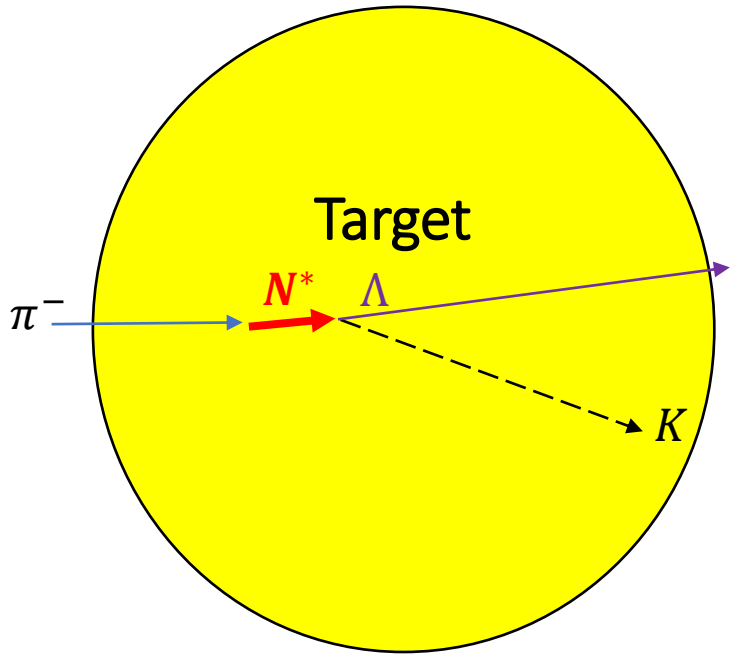


Figure 1: Schematic picture of hypernuclei formation

π^- Beam

Low energy + Smaller system
→ Allow more cluster formations

- Hypernuclei formation
  - $\pi^- + N \rightarrow N^*$ (up to 4 GeV)
  - $N^* \rightarrow \Lambda$K (or even ΞKK)
  - Binding / Multifragmenting
    - $NN, \Lambda N, \Lambda NN, \ldots$

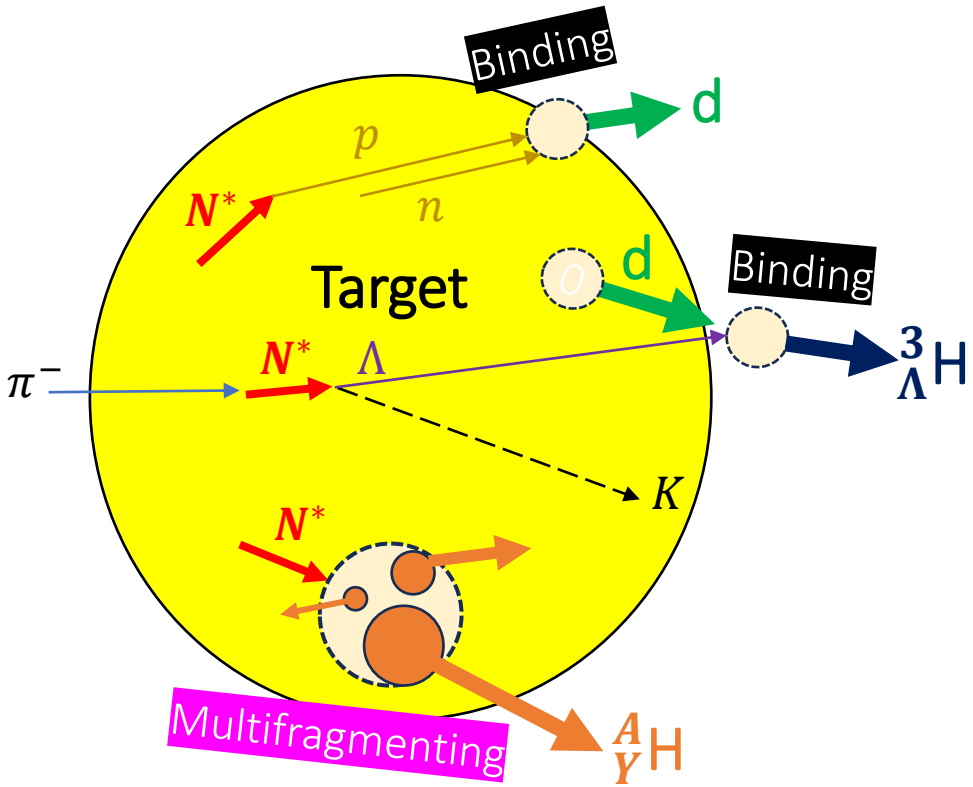


Figure 1: Schematic picture of hypernuclei formation

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

UrQMD

Ultra-relativistic Molecular Dynamics (UrQMD)

Hadron cascade (standard mode)

- 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
- (No in-medium modifications)

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 Models

Coalescence Mechanism

- Phase-space correlations w/ isospins
  - $\Delta\vec{P} \leq \Delta\vec{\mathrm{P}}_{max},\ \Delta\vec{R} \leq \Delta\vec{\mathrm{R}}_{max}$

- Evaluated at respective kinetic freeze-out of the particles.

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 into the SMM

Results

p_T spectra of protons and Λ hyperons

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

Kittiratpattana, Apiwit, et al. *arXiv preprint 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.

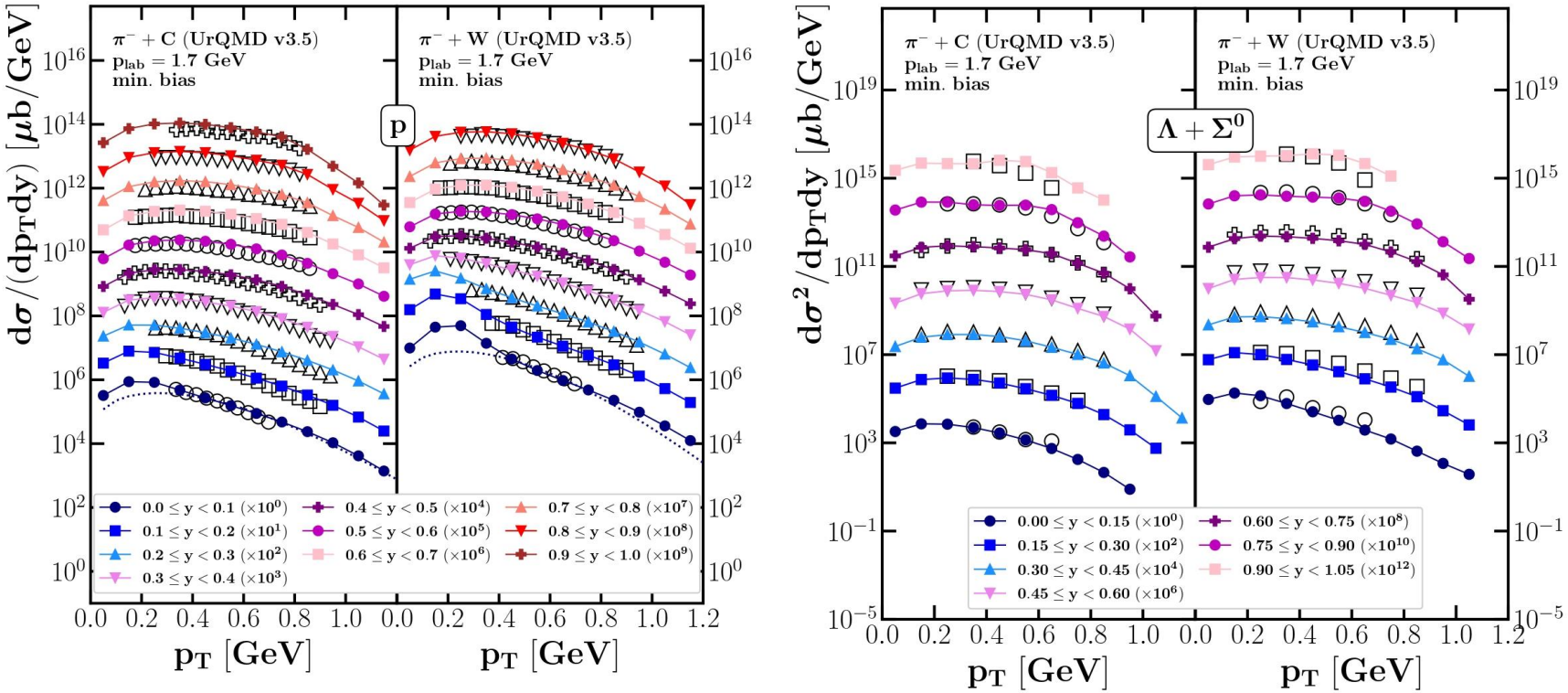


Figure 2: p_T spectra of proton and Λ

Results

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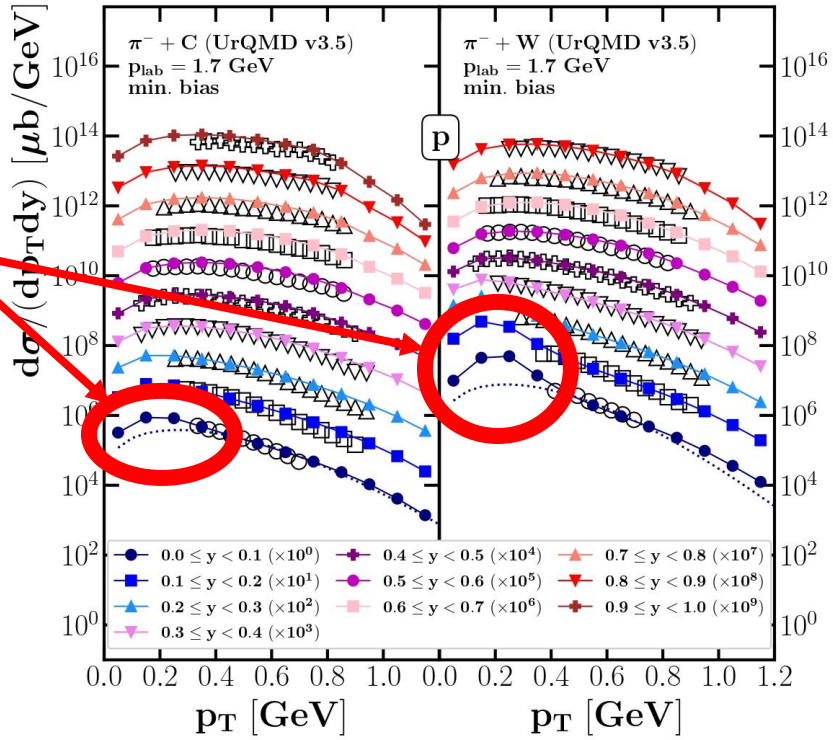

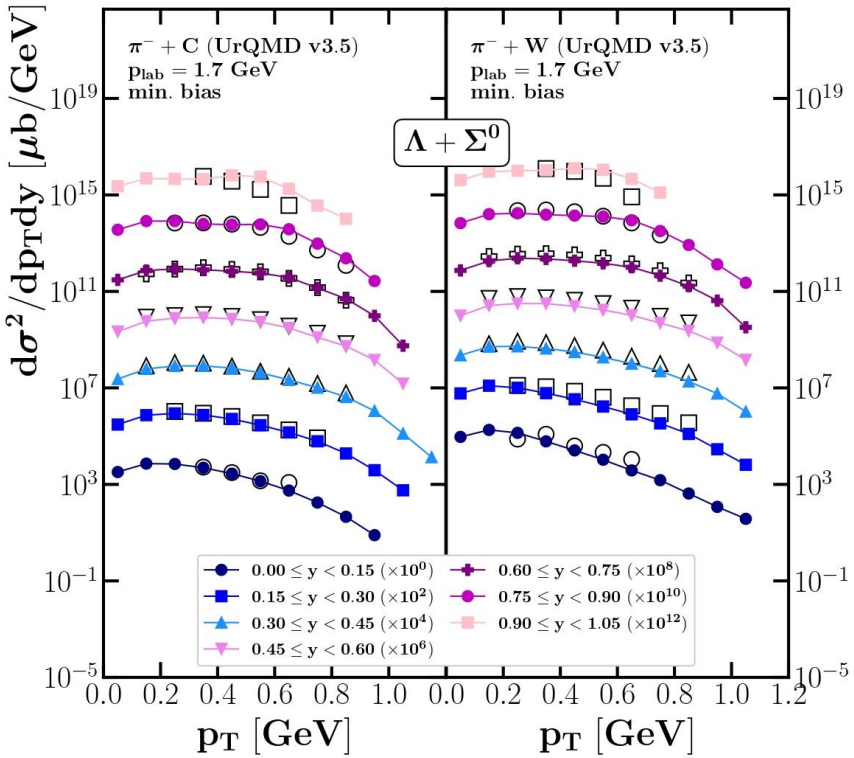

This leads to slightly difference in the extrapolated rapidity densities at $y \approx 0$ (target)

Results

$\pi^- + \mathrm{C}$: $0 < b < 2.5$ fm, $\sigma_{tot}^{\pi^-+\mathrm{C}} = 196.35$ mb
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Rapidity distribution of protons and Λ hyperons

Protons:

- The extrapolated densities and HADES data underestimate the free proton yields 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
- $\Xi NN \rightarrow \Lambda\Lambda N$?

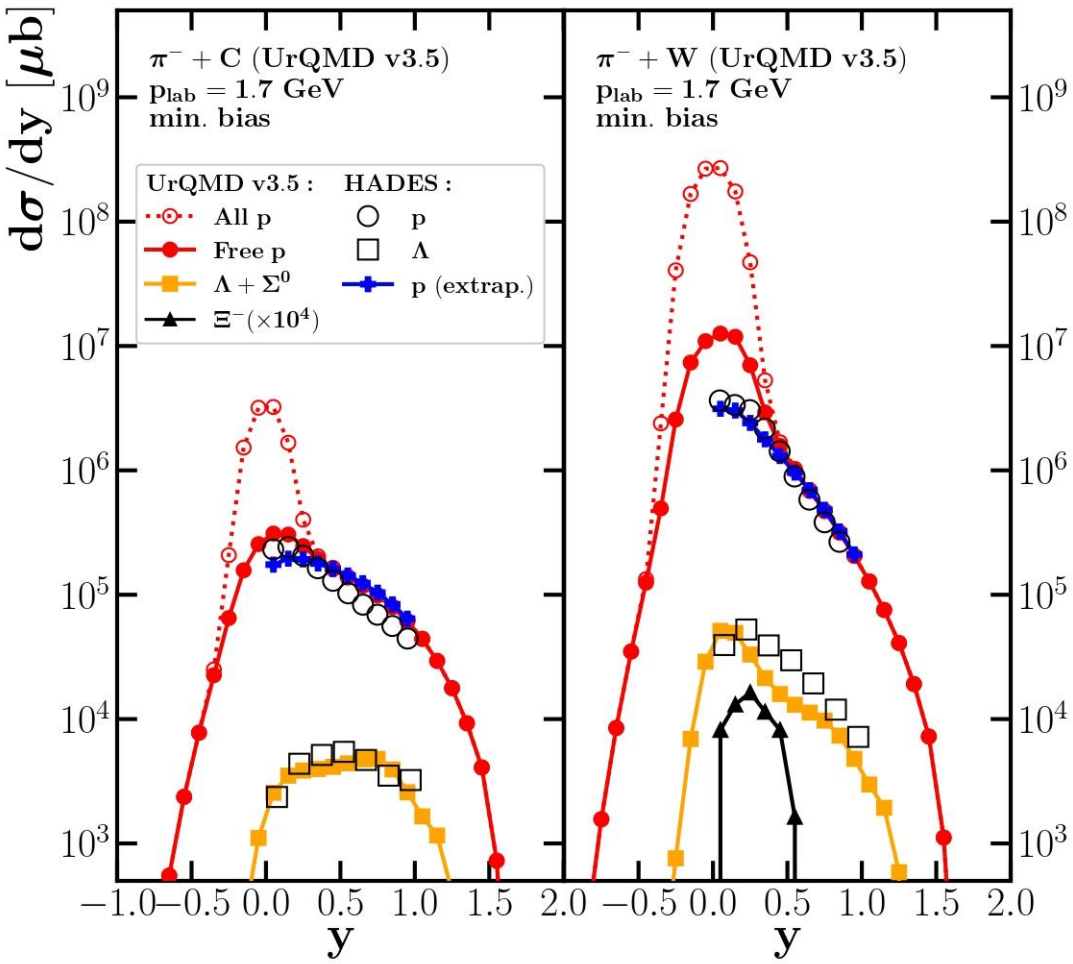

Figure 3: Rapidity distribution of proton and Λ

Results

p_T distribution of light nuclei

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

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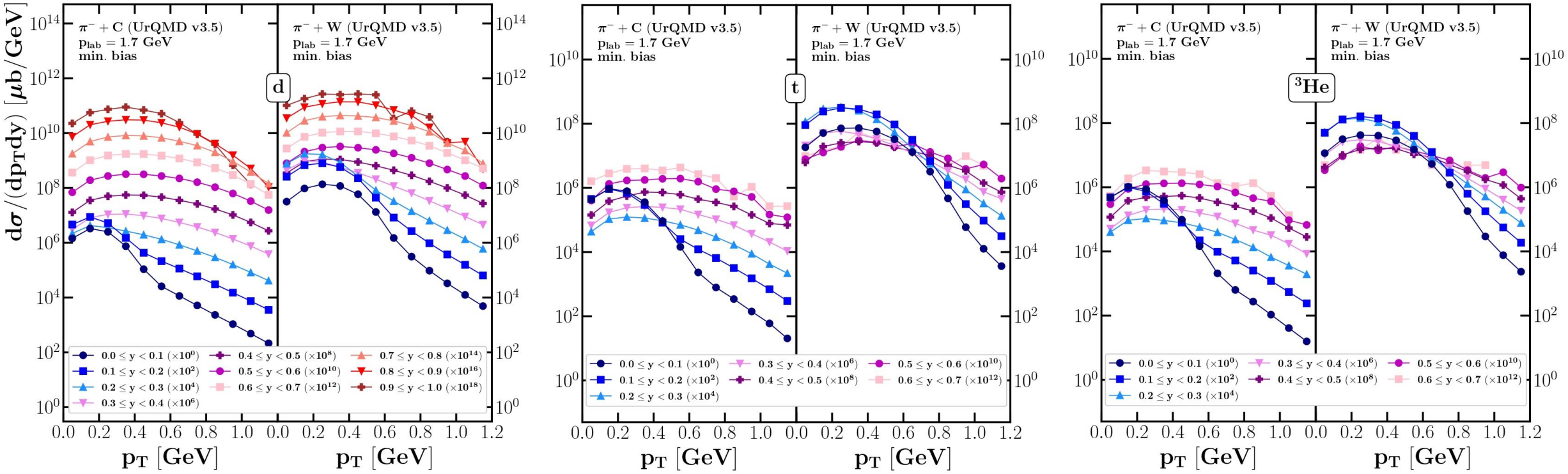

Figure 4: p_T spectra of light clusters

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

Results

Rapidity distribution of light nuclei

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

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

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

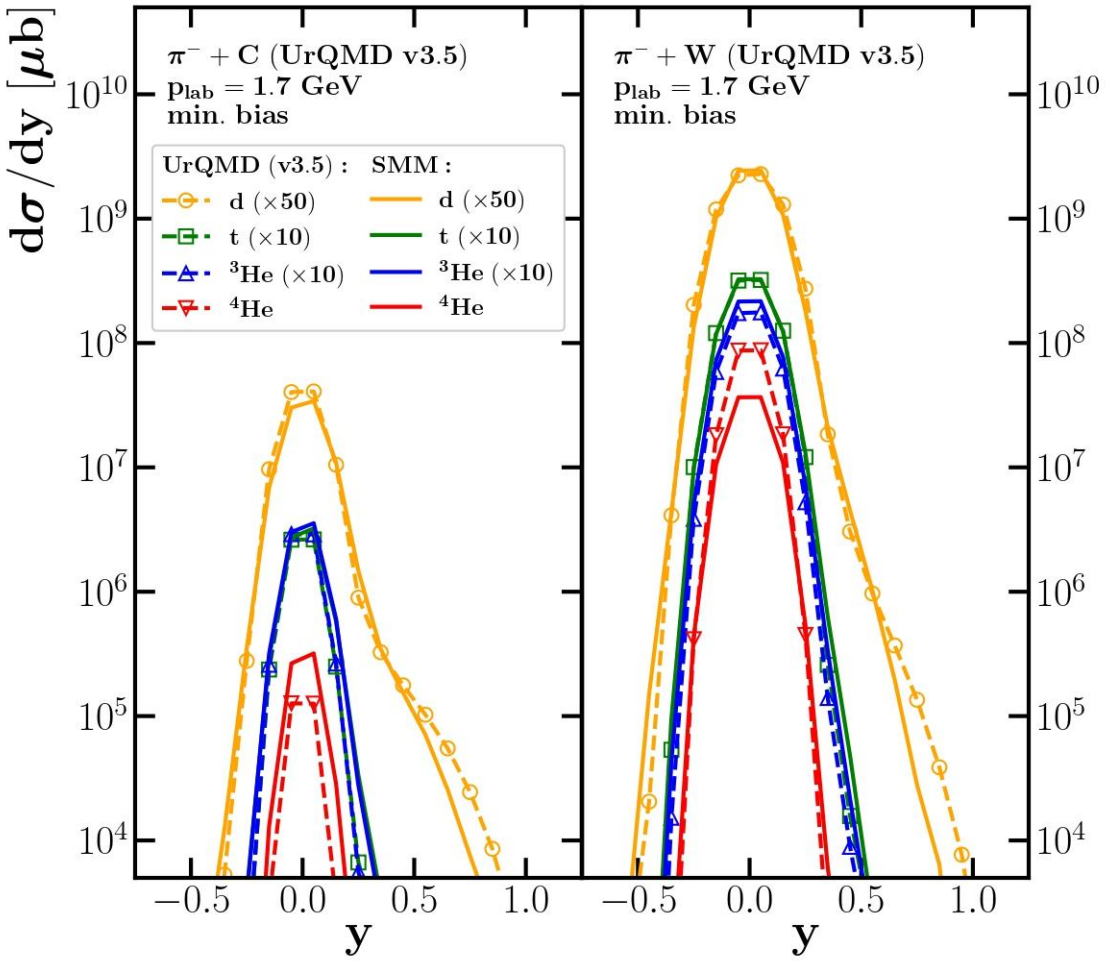

Figure 5: Rapidity distribution of light clusters

Results

Rapidity distribution of hypernuclei

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

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- $\mathcal{O}(10^{-3})$ of ${}^{3}_{\Lambda}\mathbf{H}$ per events.
- $N\Xi$ signal?

- Deceleration: More $\boldsymbol{A = 2}$ in forward region
- In small system, SMM differs from UrQMD by a factor of 10
  → Uncertainty…

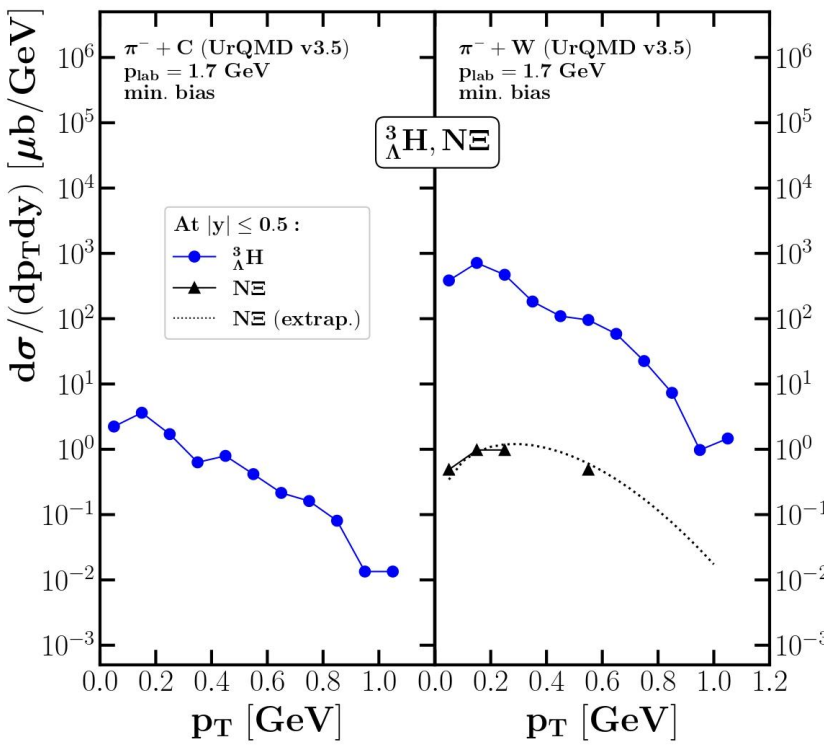

Figure 6: p_T spectra of hypernuclei

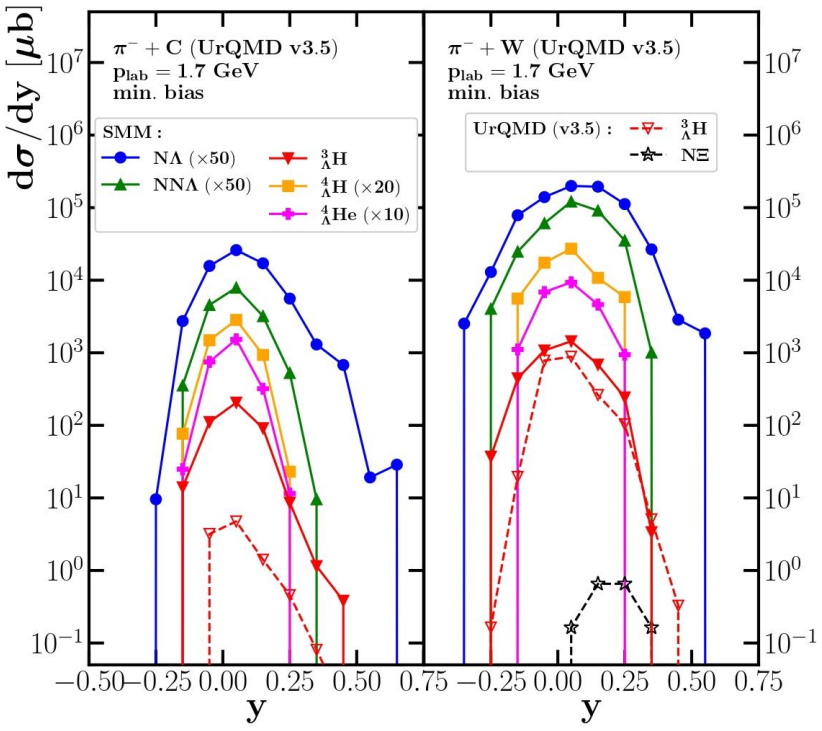

Figure 7: Rapidity distribution of hypernuclei

Results

Total abundance for larger (hyper)nuclei

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

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Signal extractions by HADES

- 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? ($\Xi + N + N \rightarrow \Lambda + \Lambda + N$)

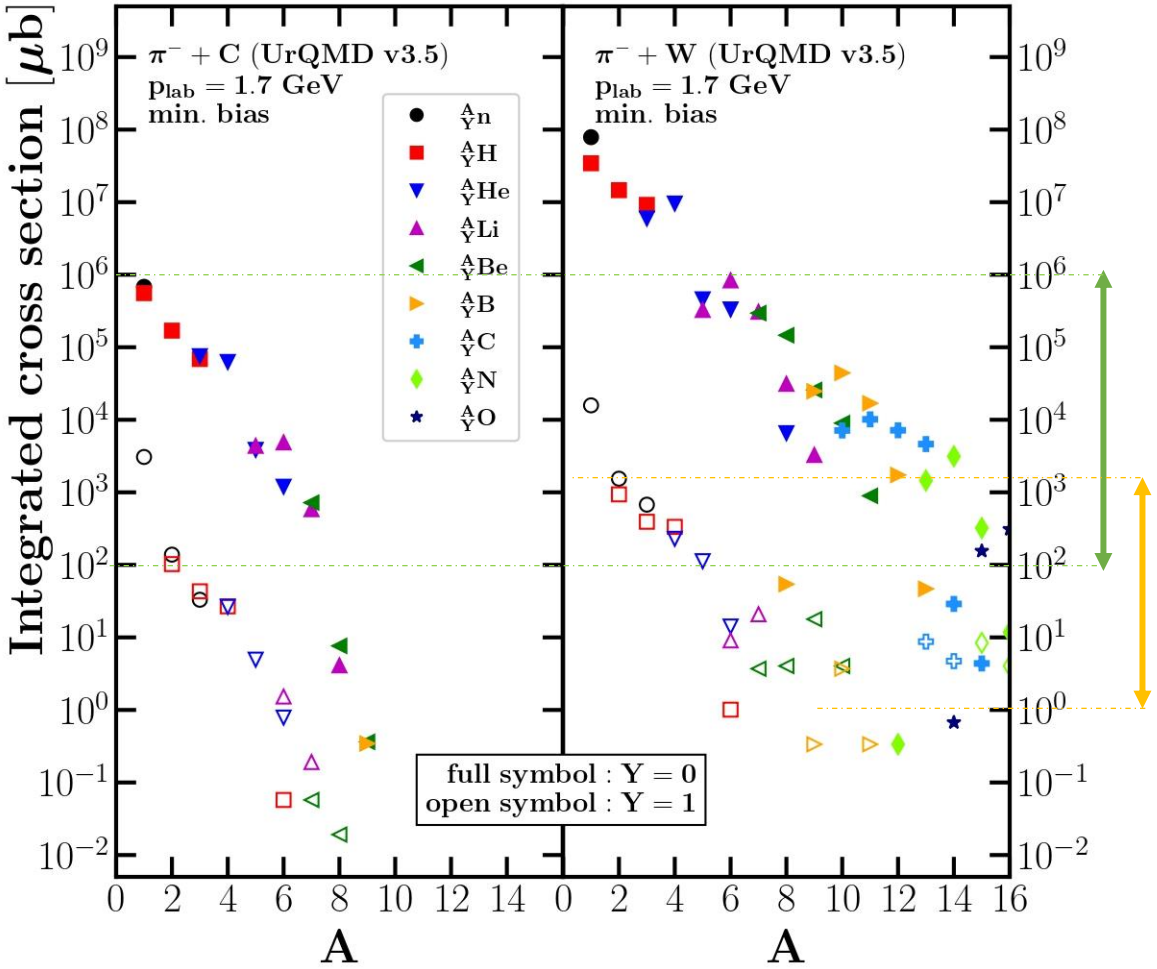

Figure 8: Integrated cross section

Summary

- UrQMD is employed to simulate $\pi^- + \mathrm{C}$ and $\pi^- + \mathrm{W}$ at $p_{\mathrm{lab}} = 1.7\ \mathrm{GeV}$
- Residue protons and clusters at low p_T $(y \leq 0.2)$
  - Extrapolated func. needs to be adjusted.
- We contrast our <u>coalescence</u> results with <u>SMM</u> for light nuclei and hypernuclei
  - Smaller system less decelerates $A = 2$
  - $\mathcal{O}(10^{-3})$ of ${}^{3}_{\Lambda}\mathrm{H}$ per event
- Light nuclei $A > 3 \rightarrow 10^{-4} - 1$ / event
- Hypernuclei $A > 3 \rightarrow 10^{-6} - 10^{-3}$ / event
- Ξ and double-Λ might be seen at higher beam momenta?