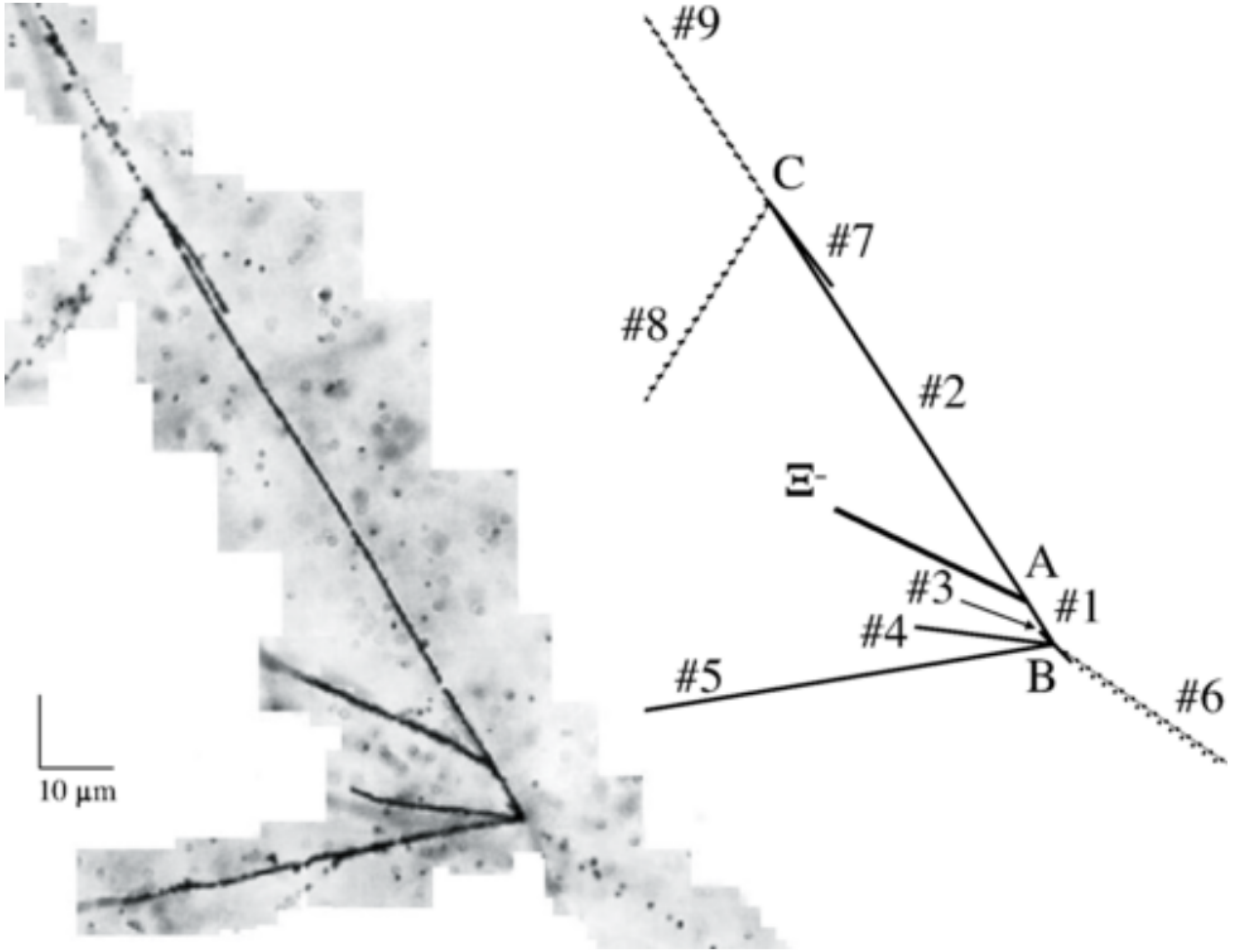
Hypernuclei in low energy Heavy Ion collisions

Maximiliano Puccio (CERN)

Penetrating probes of hot, high-μ_B matter - ECT* Trento - 22nd July 2025

The typical hyper nuclear experiment

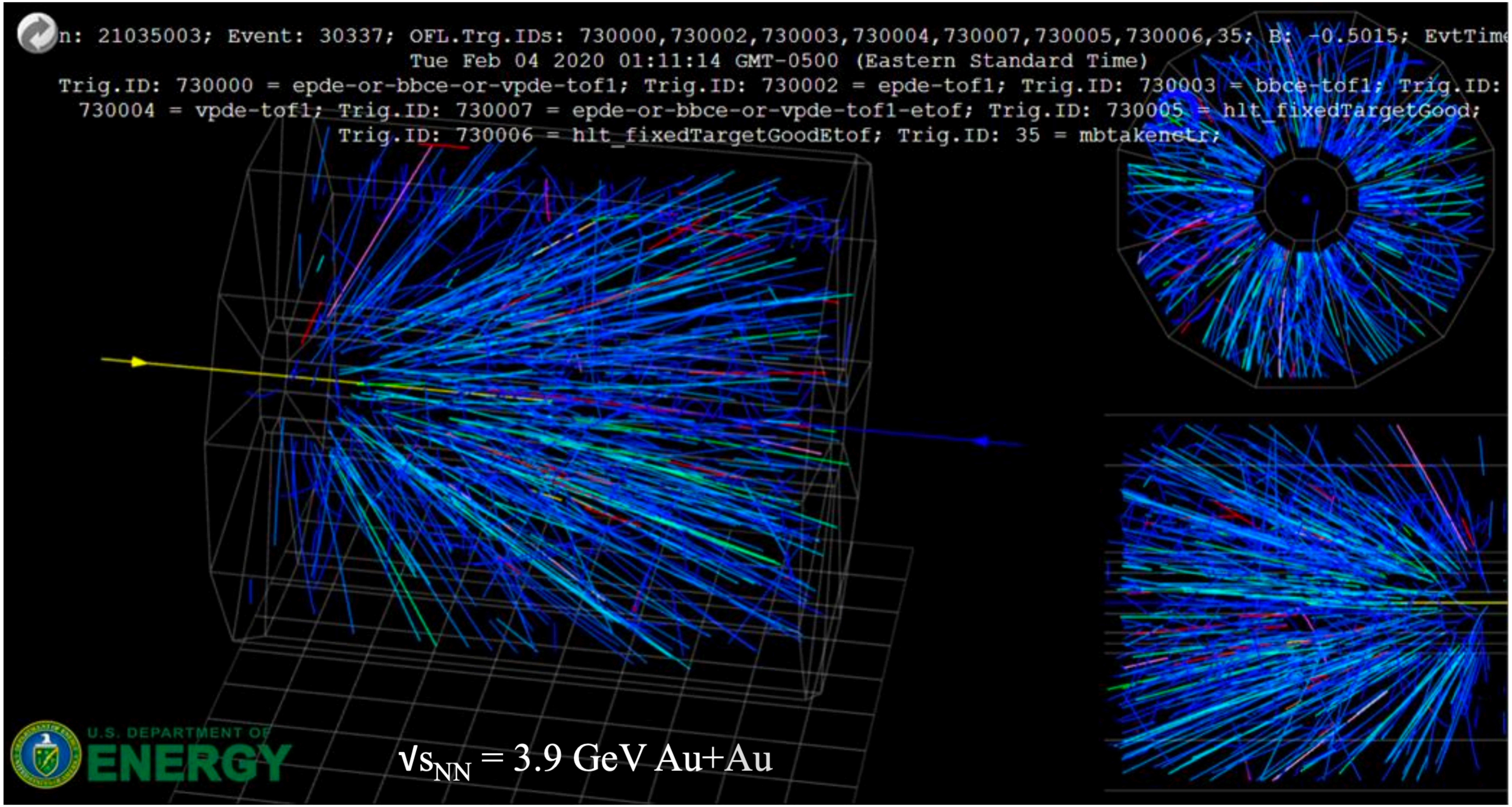
IBUKI event, 10.1103/PhysRevLett.126.062501



Single event discovery physics with cleanly identified production process

The Heavy-Ion environment

Daniel Cebra, APS Virtual Meeting 2021



Statistical identification of hypernuclei created in the aftermath of a heavy-ion collision

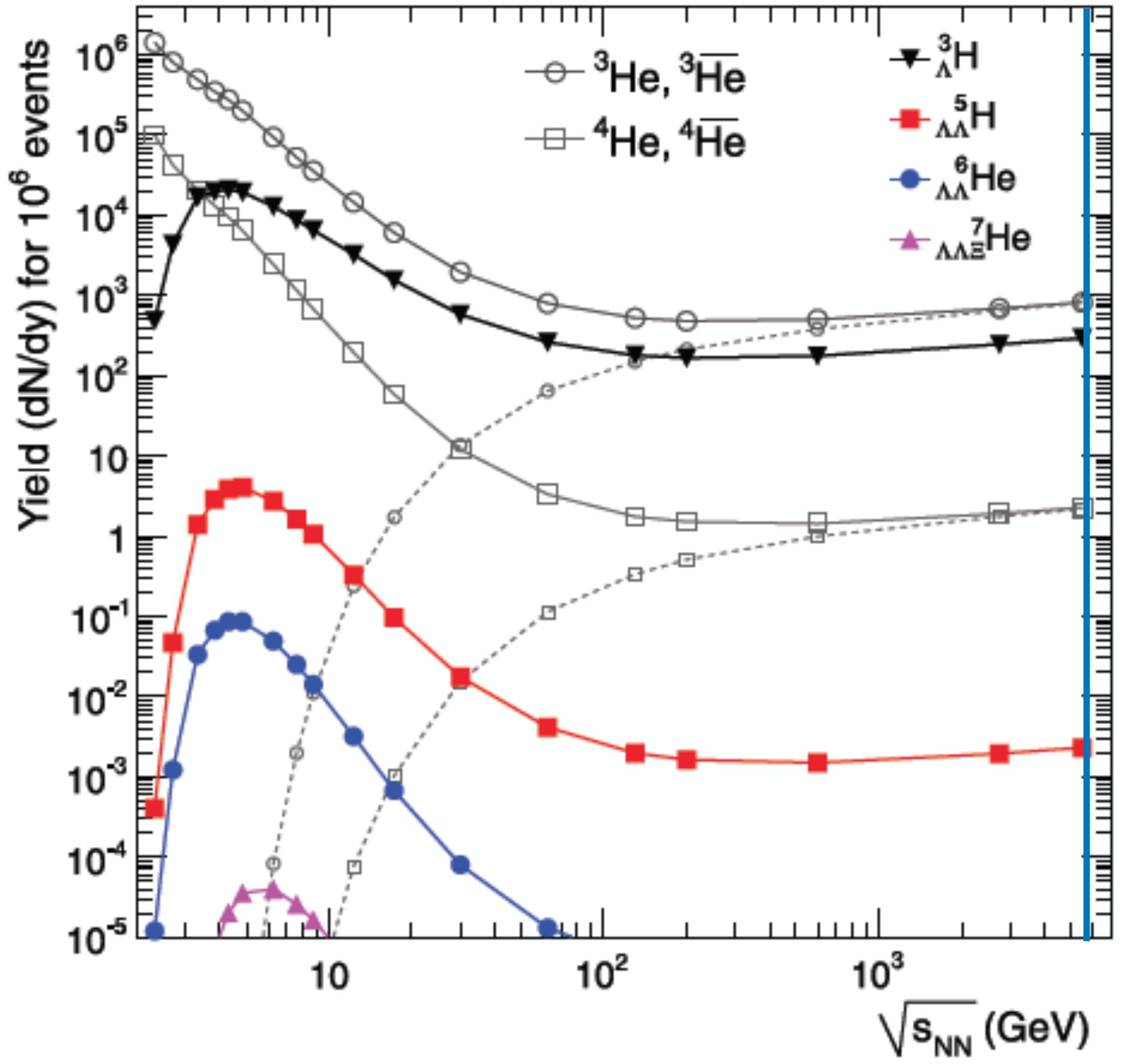
How do we can produce (anti)(hyper)nuclei in pp/AA?

THERMAL MODELS

- ➡Hadrons emitted from the interaction region in statistical equilibrium when the system reaches a limiting temperature
- ➡Freeze-out temperature T_{chem} is a key parameter
- ➡Abundance of a species $\propto \sim \exp(-m/T_{chem})$:
  - ➡For nuclei (large *m*) strong dependence on T_{chem}

Mainly used for Pb-Pb, it can be used in smaller systems by using the canonical ensemble

A. Andronic, P. Braun-Munzinger, J. Stachel and H. Stoecker, Phys. Lett. B607, 203 (2011), 1010.2995



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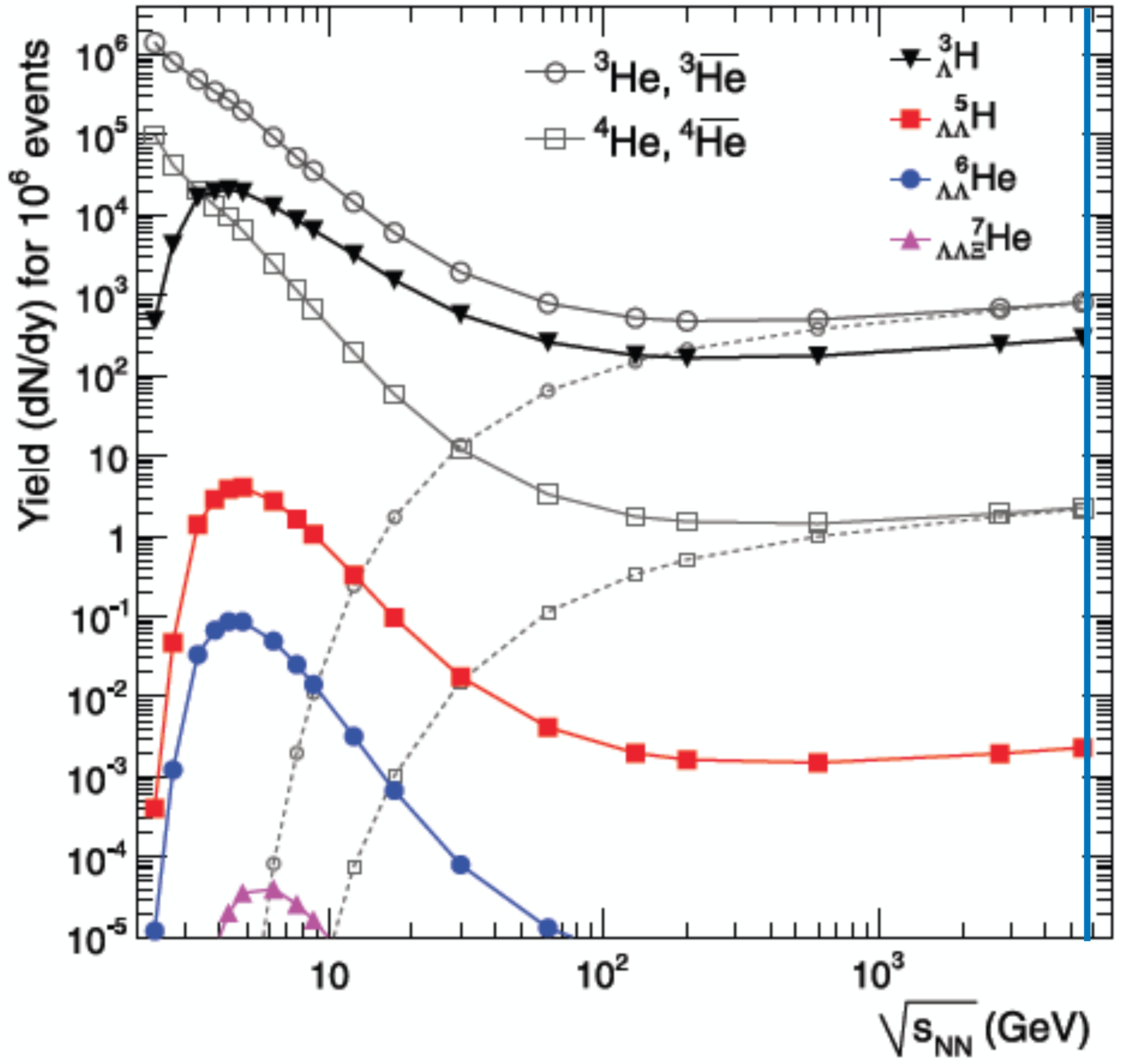
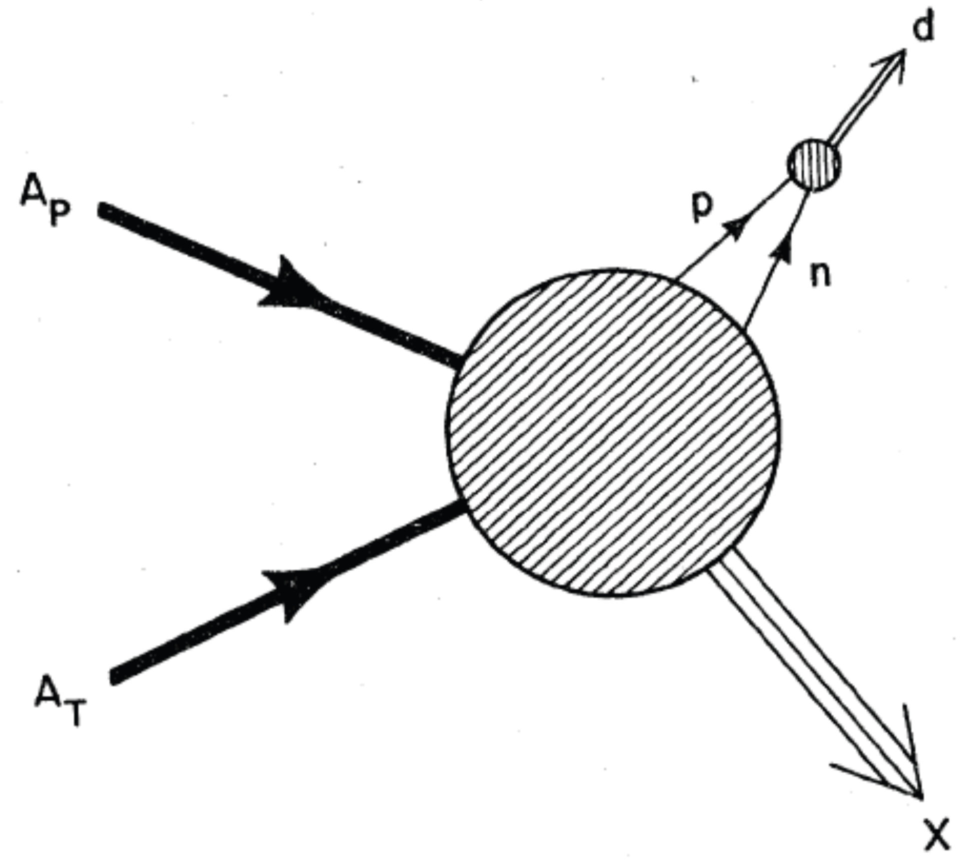




J. I. Kapusta, Phys.Rev. C21, 1301 (1980)

COALESCENCE

- ➡If (anti)baryons are close in phase space they can form a (anti)nucleus
- ➡Interplay between the configuration of the phase space of (anti)baryons and the wave function of the (anti)nuclei to be formed
  - the larger the wave function the more we are sensitive to the system size

Thermal model vs coalescence at the LHC

ALICE, Phys. Rev. C 107 (2023) 064904

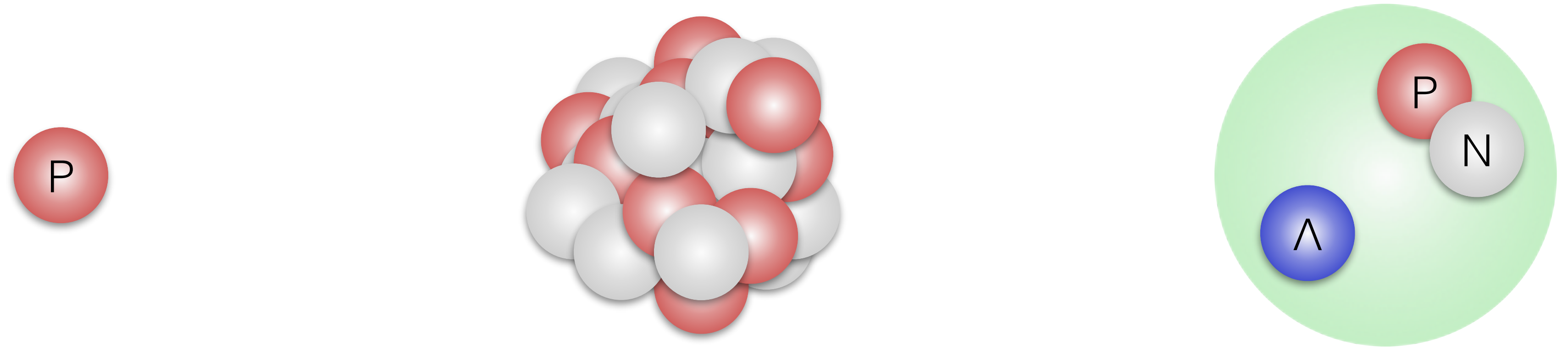
We study the nucleus yield normalised by the proton production as a function of multiplicity

➡ Smooth evolution with multiplicity: same production mechanism in all collision systems?

- Available SHM calculations with canonical ensemble do not describe A=3 nuclei
- Coalescence model provide a good description of the measured ratios

The ultimate test: large bound state in a small system

Proton **Copper** **$^{3}_{\Lambda}H$**



R ~ 0.8 fm **R ~ 5 fm** **$R_{d\Lambda}$ ~ 10 fm**

Halo nucleus: wide dΛ molecule

$^{3}_{\Lambda}H$ / Λ in small systems: large separation between production models

➡SHM: insensitive to size of the hypertriton

➡Coalescence: yield suppressed

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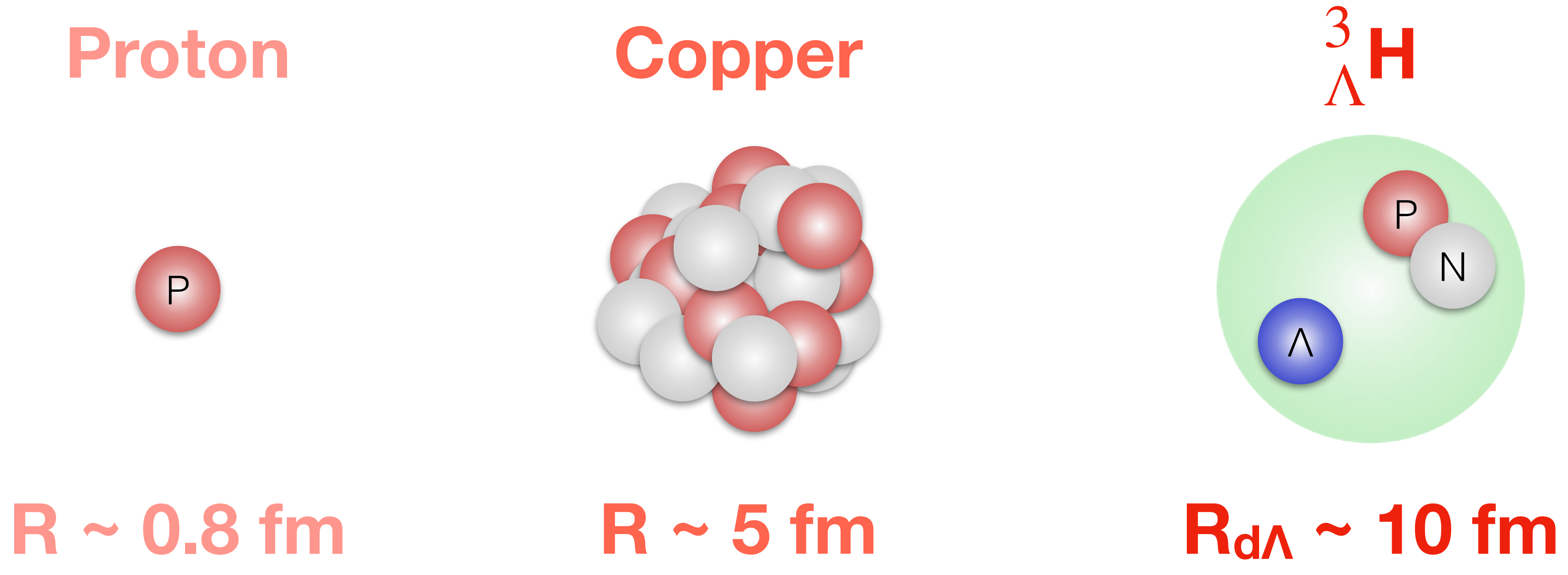

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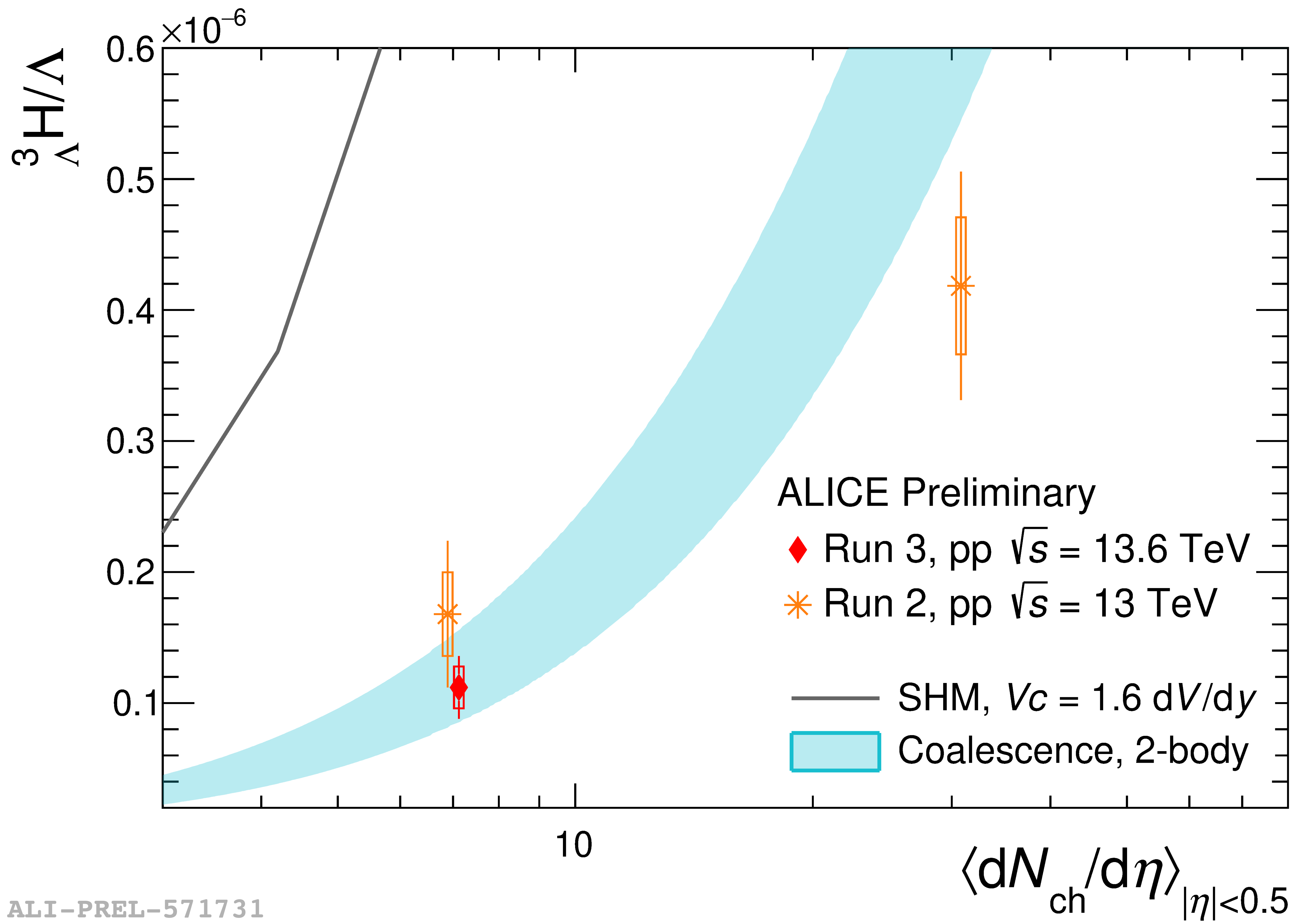

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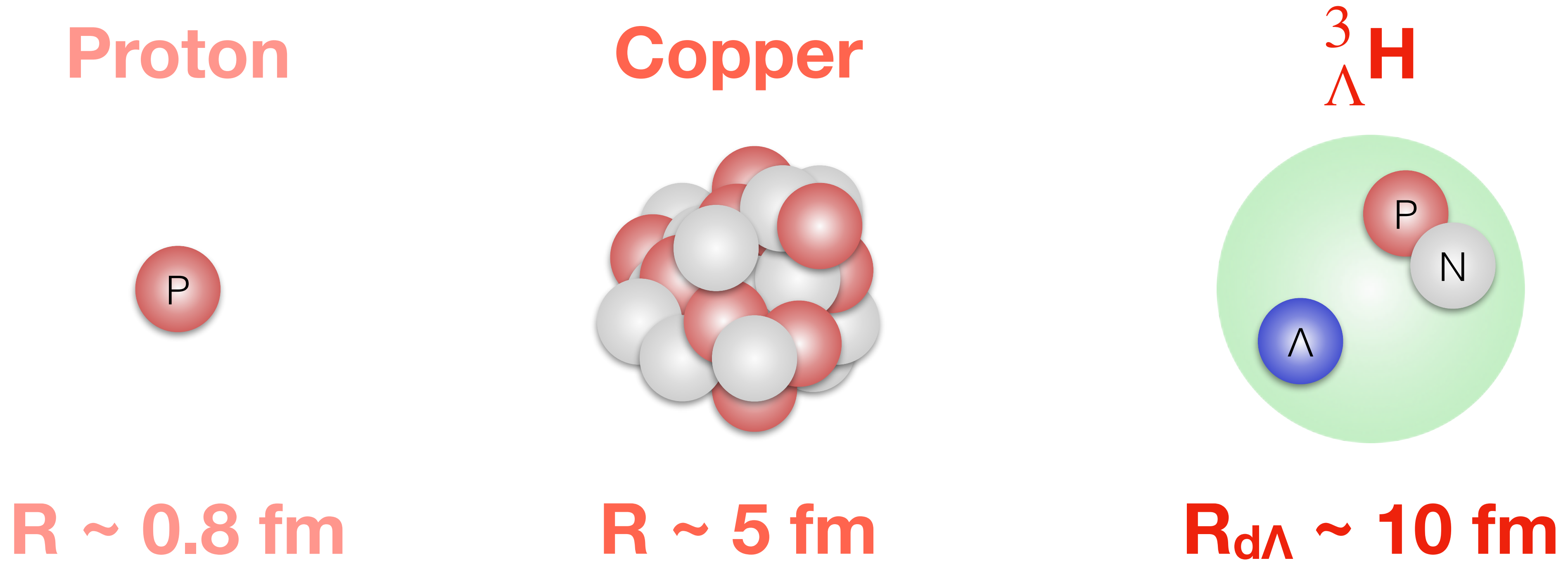

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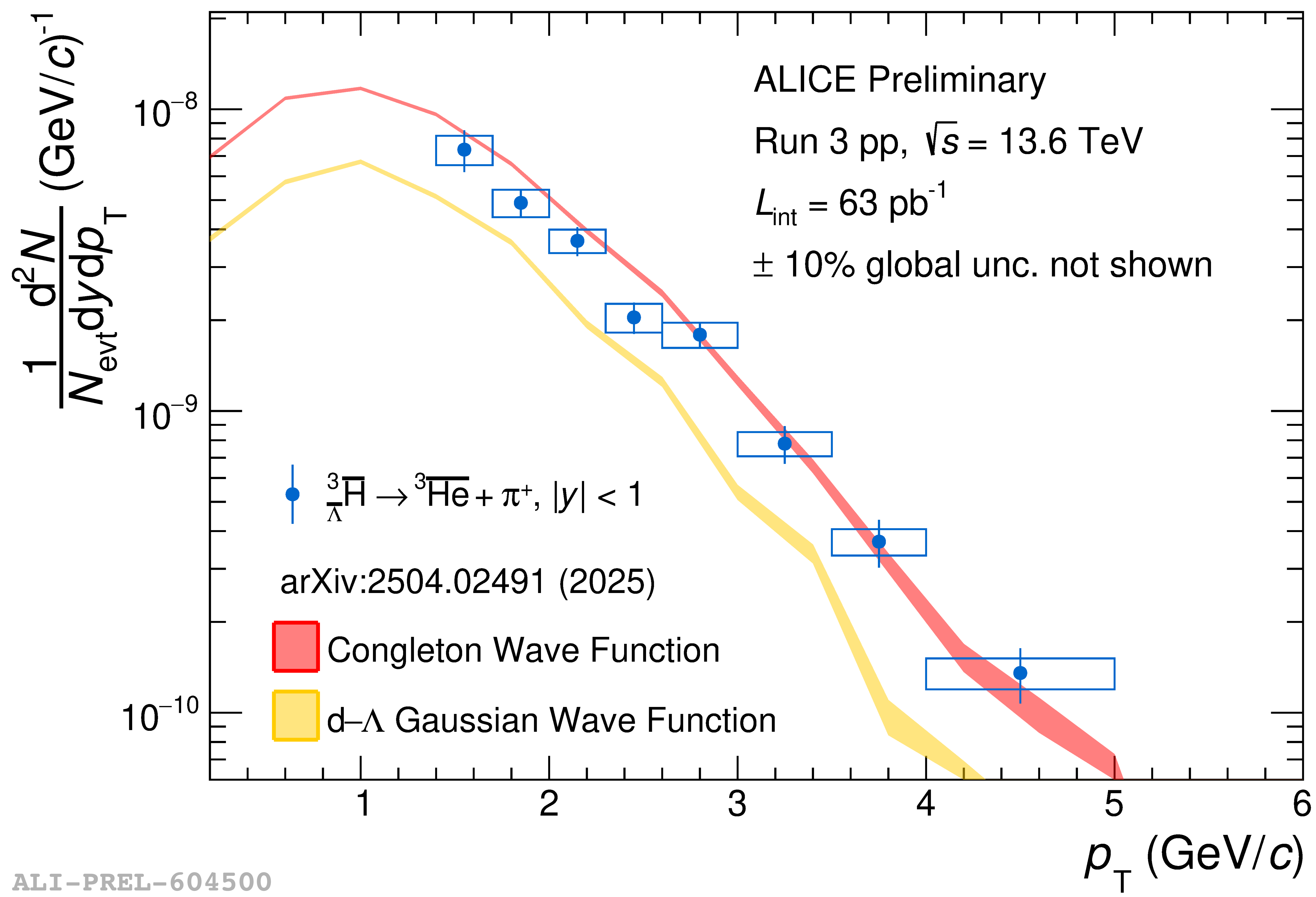
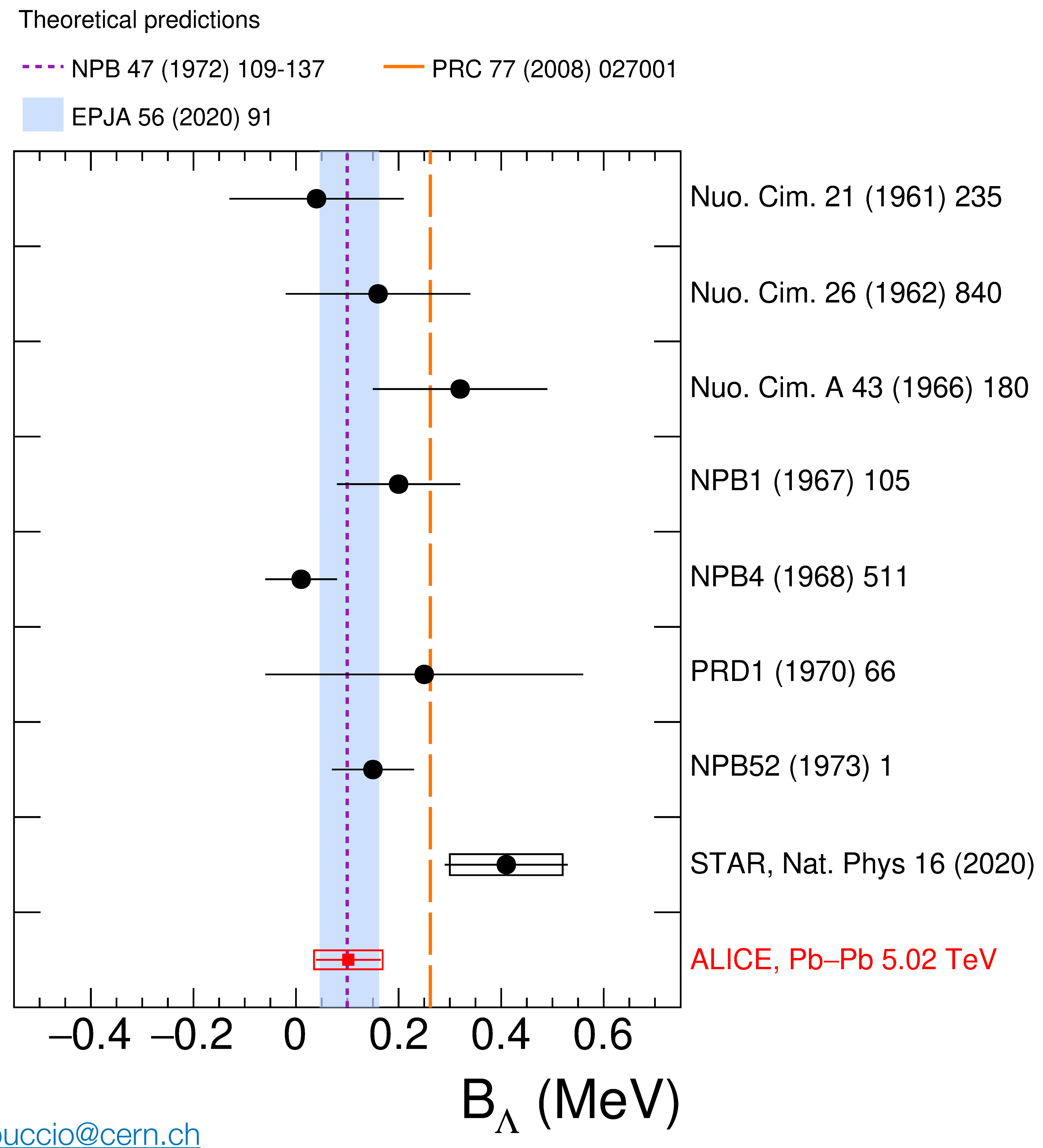


State-of-the-art coalescence as a tool to study the structure of hypernuclei

➡ Unprecedented access to the wave function of the hypernuclei that can't be studied in scattering experiments due to their short lifetime

Hypertriton binding energy in the high precision era



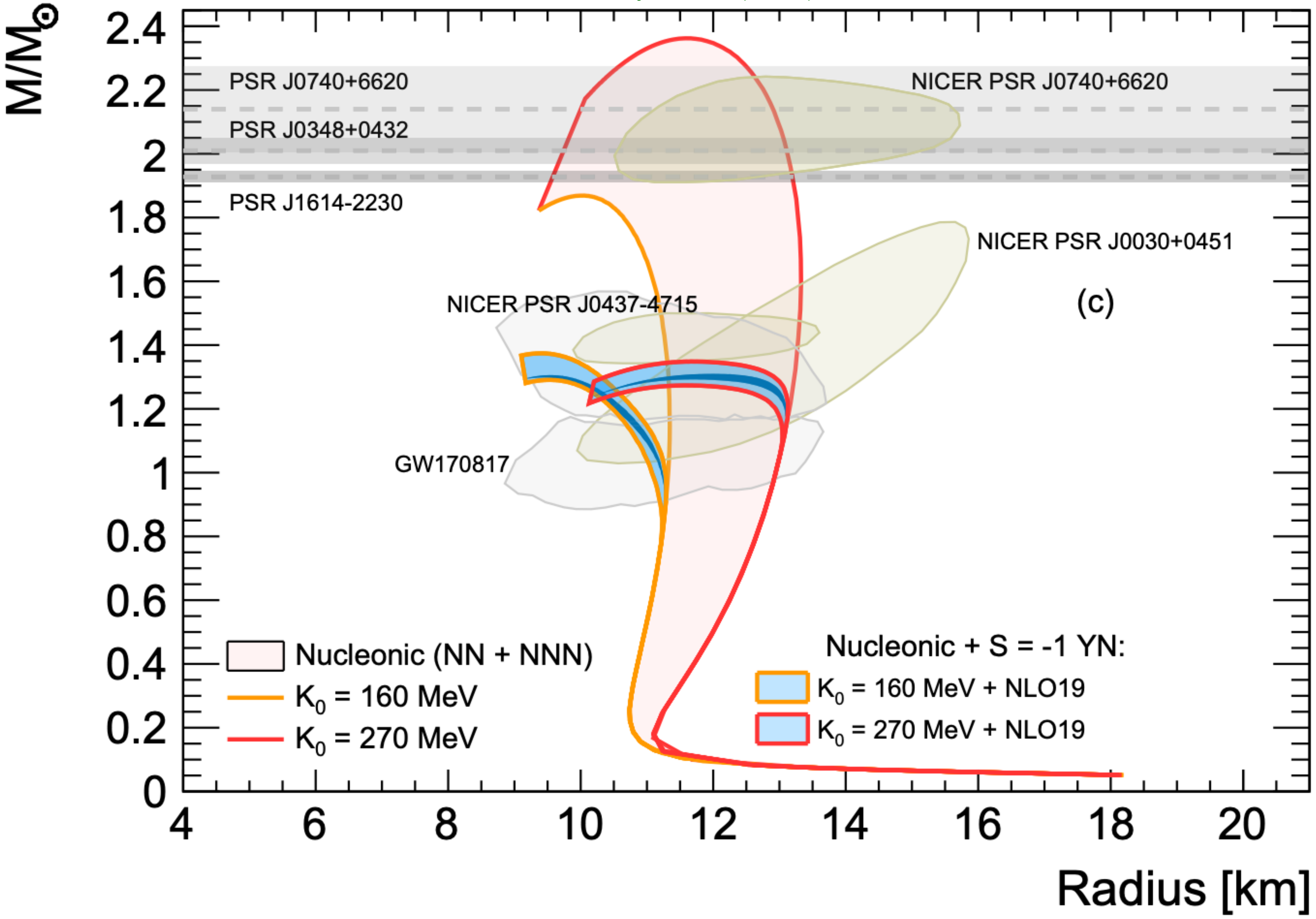
The measured $B_\Lambda(= m_d + m_\Lambda - m_{^3_\Lambda\mathrm{H}})$ is extremely small

➡ Compatible with a loosely bound deuteron-Λ molecule

- Negligible YNN contribution

The hyper nuclear nature of neutron stars

I. Vidana, V. Mantovani Sarti et al. *Eur.Phys.J.A* 61 (2025) 3, 59



High energy density + overpopulation of nucleonic d.o.f. = hyperons likely to appear in neutron star cores

➡ Equation of state becomes soft: how to reconcile with the existence of NS with masses larger than 2 solar masses?

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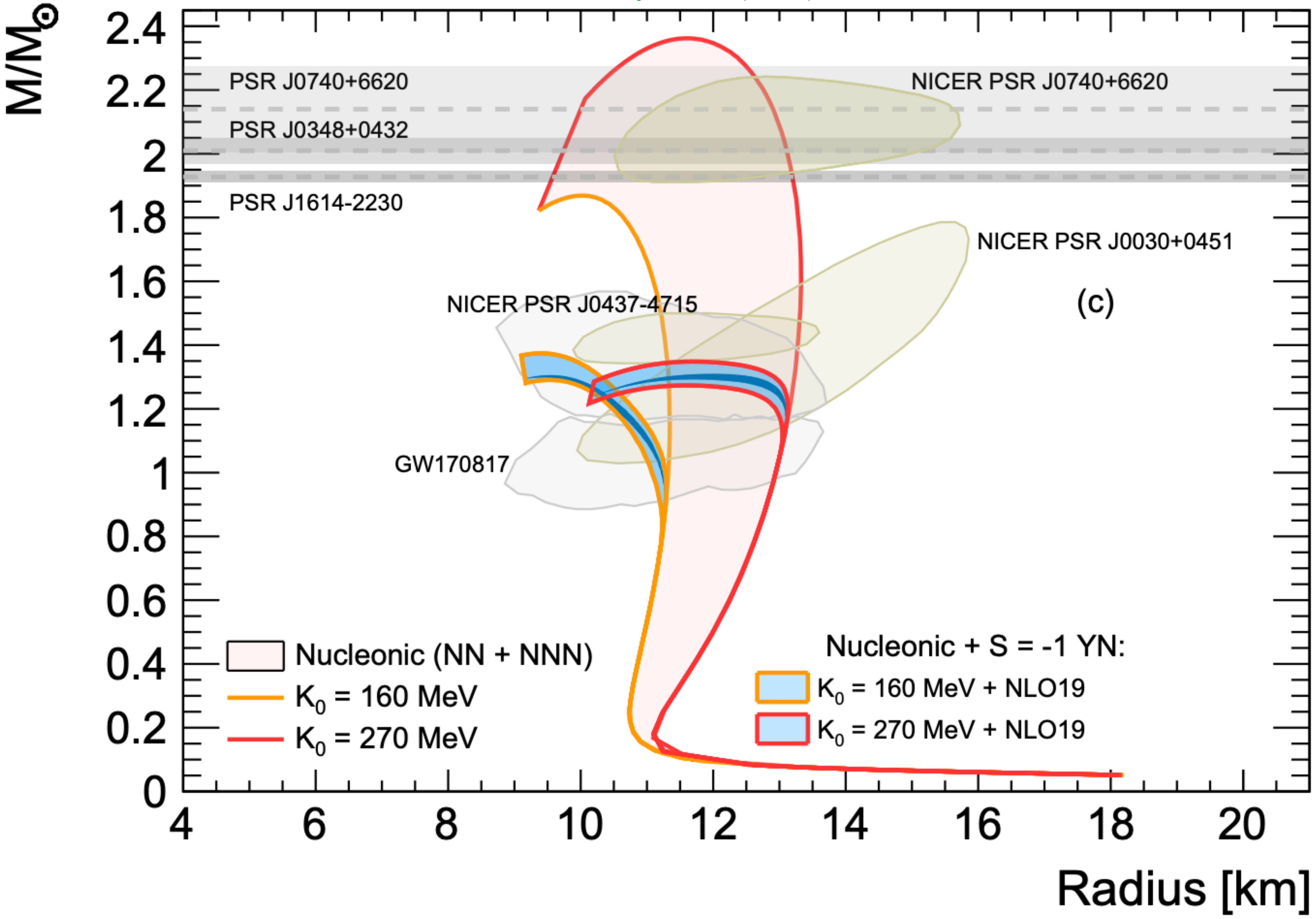

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Multibody forces might be the key to solve this issue

➡ YNN potential largely unknown

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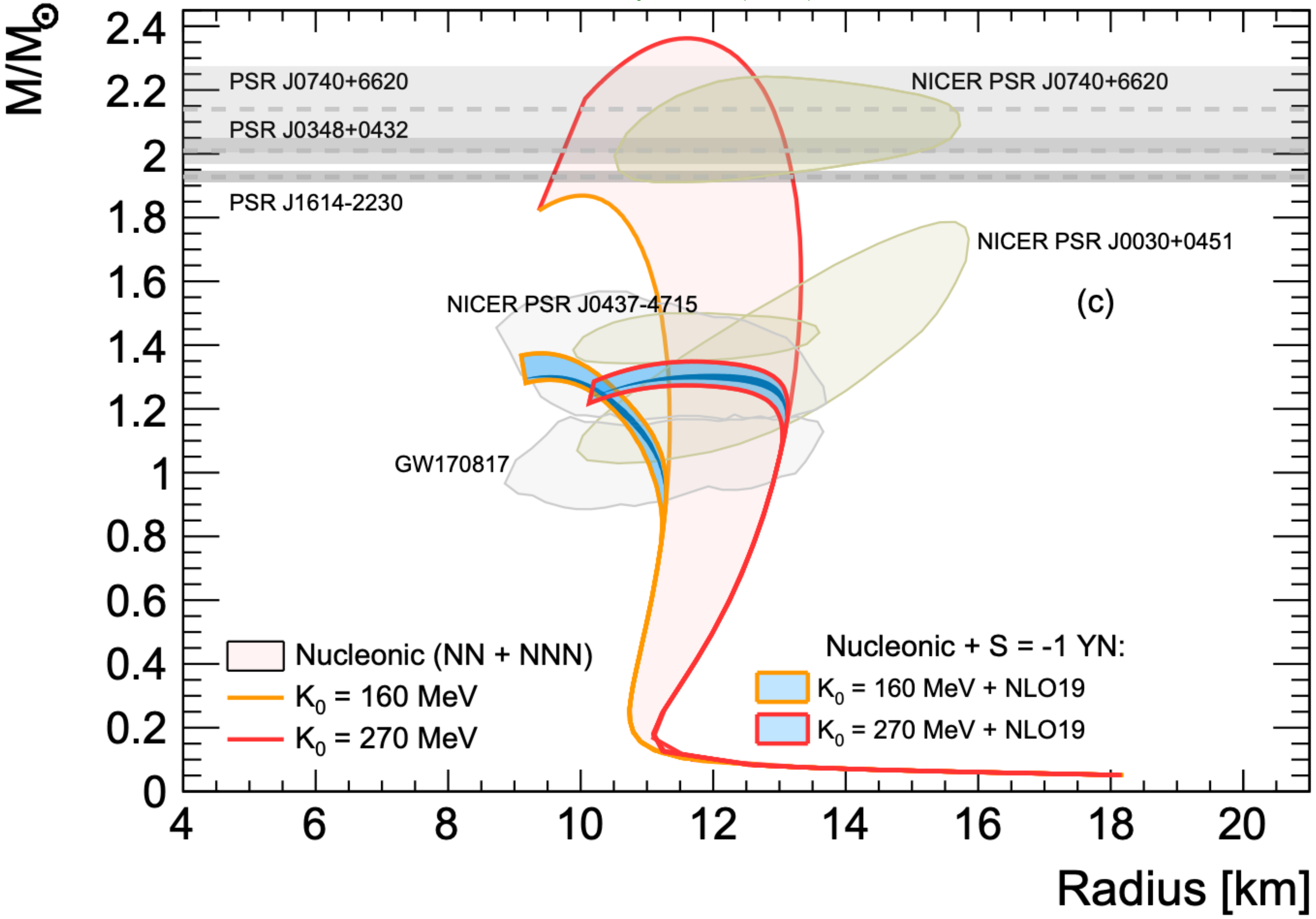


High energy density + overpopulation of nucleonic d.o.f. = hyperons likely to appear in neutron star cores

➡ Equation of state becomes soft: how to reconcile with the existence of NS with masses larger than 2 solar masses?

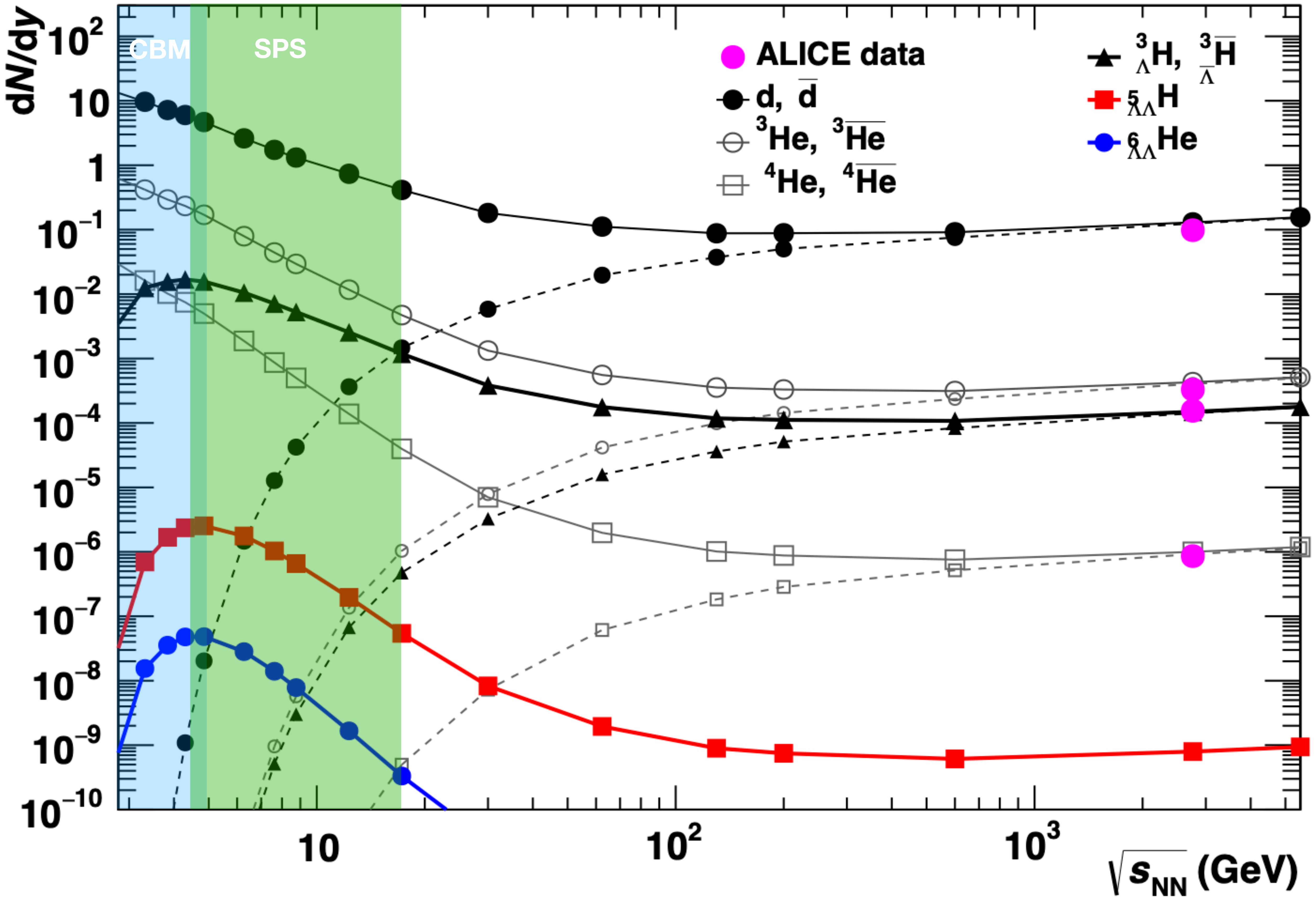
Precision measurements of the properties of hypernuclei with A>3 are the key to understand these interactions

Multibody forces might be the key to solve this issue

➡ YNN potential largely unknown

Low energy heavy-ion as a hyper matter factory

B. Dönigus, P. Braun-Munziger, Nucl.Phys.A 987 (2019) 144-201



In the Statistical Hadronisation Model:

→ hypernuclei yield **peaks at low $\sqrt{s_{NN}}$**

- Gives an order of magnitude sense of the signals we expect

In central HI collisions at $\sqrt{s_{NN}}$=5 GeV

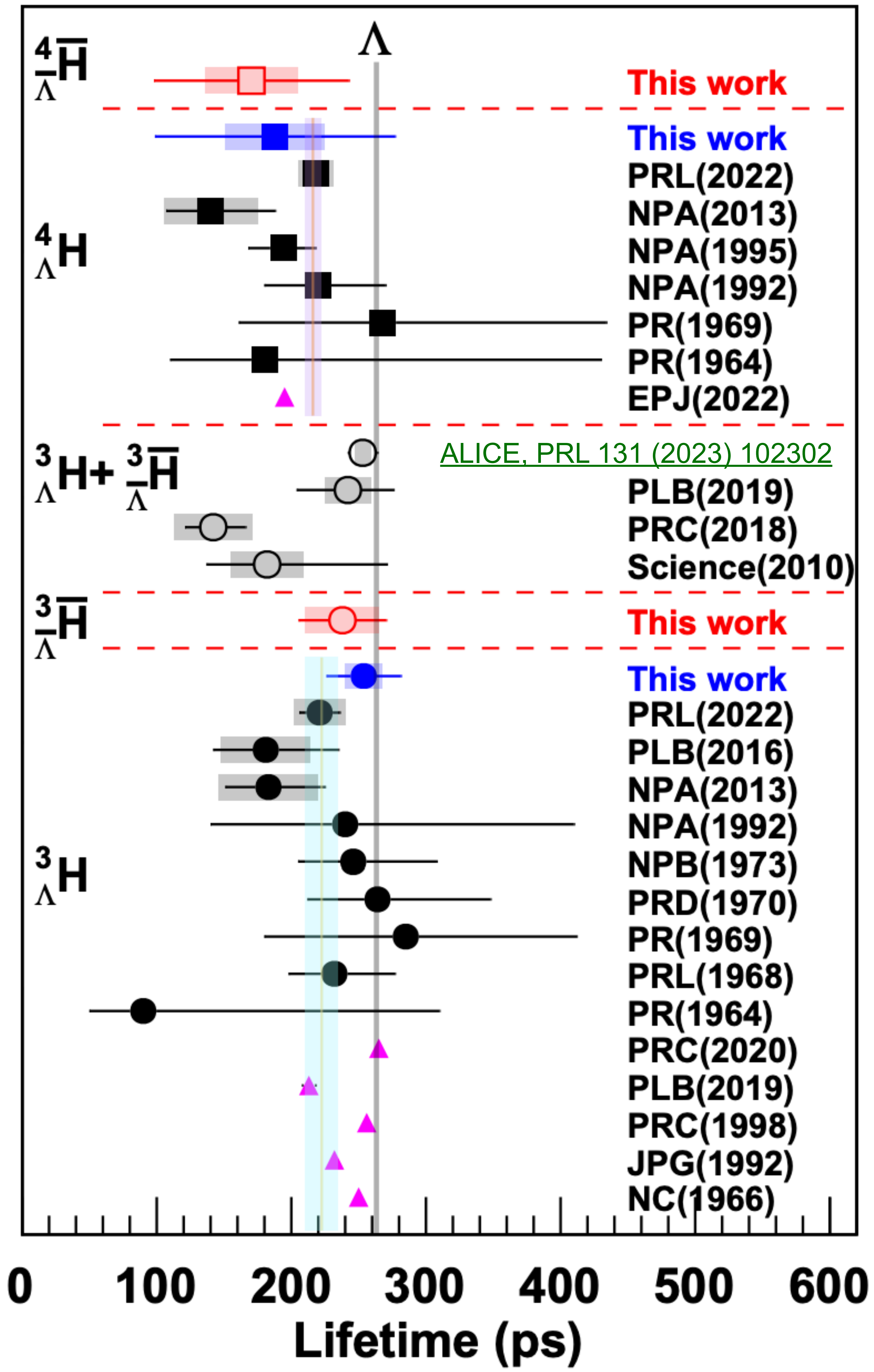
~4 deuterons	~0.02 hypertritons
~2 10^{-4} Helium-4 Λ	~2 10^{-7} Helium-5 Λ Λ

Hypernuclear physics at fixed target:

- Precise study of known states: properties of Λ hypernuclei, charge symmetry breaking
- Discovery and confirmation of poorly known/unknown hypernuclei: A=6, light ΛΛ hypernuclei

A<5 lifetime in the high precision era

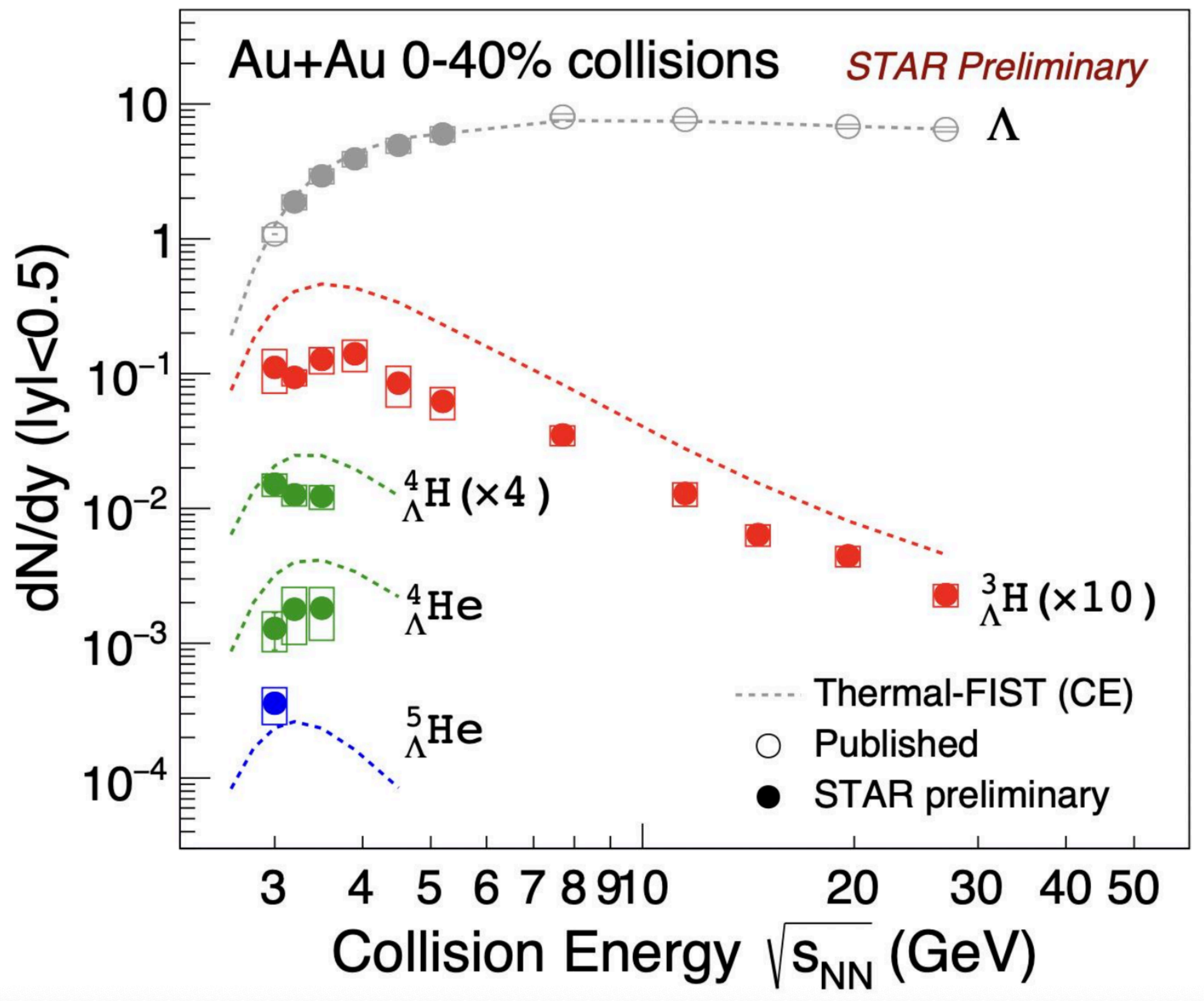
STAR, https://arxiv.org/abs/2310.12674



- ➡ World's leading measurements of the lifetime of hypernuclei with A<5 are from HI experiments
  - A >= 4 mostly at fixed target energies

Production rates in low energy heavy-ion collisions

Lijuan's talk yesterday



SHM trend confirmed

- Quantitative deviations like at the LHC
  - ➡ Missing resonances + coalescence

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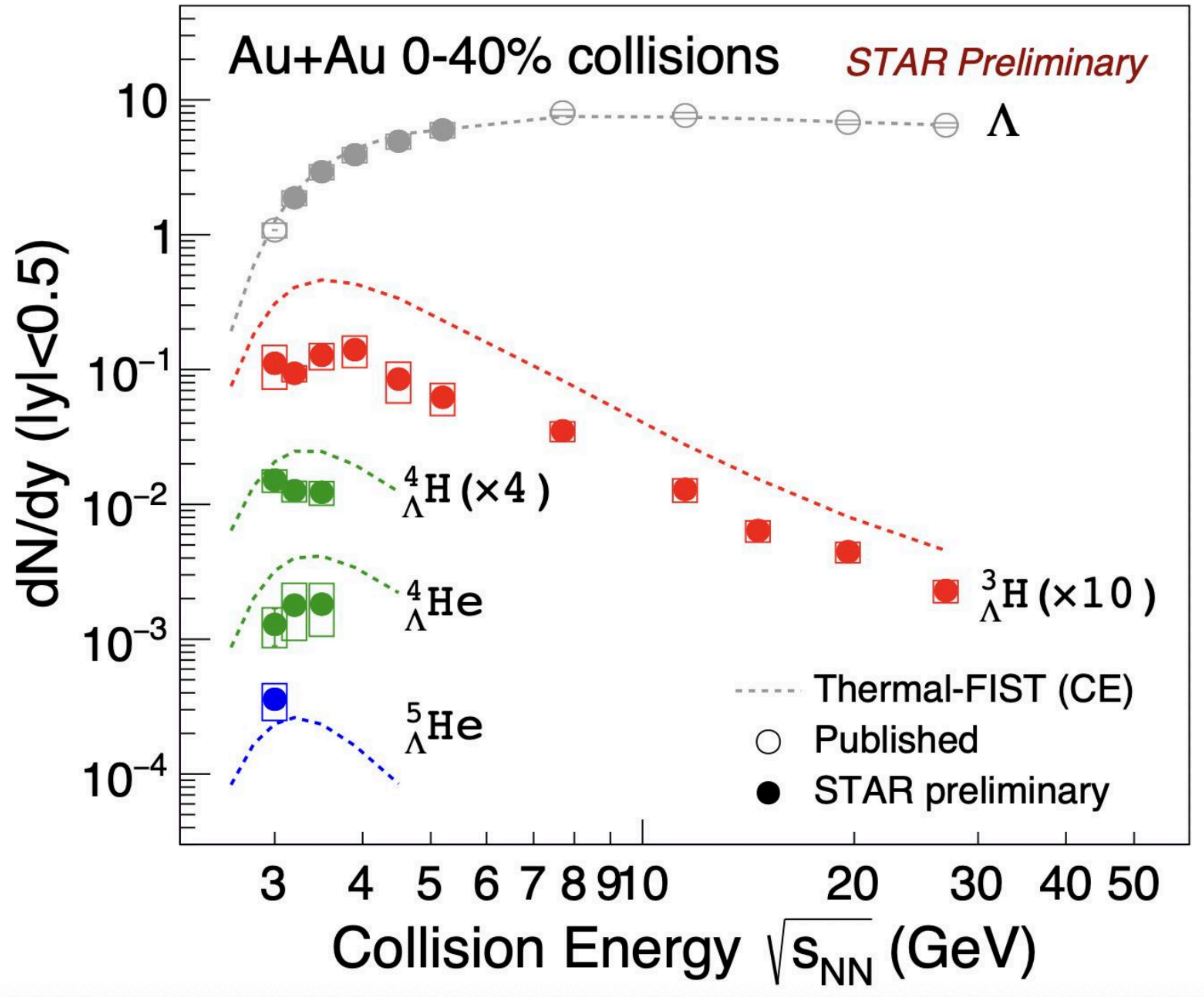
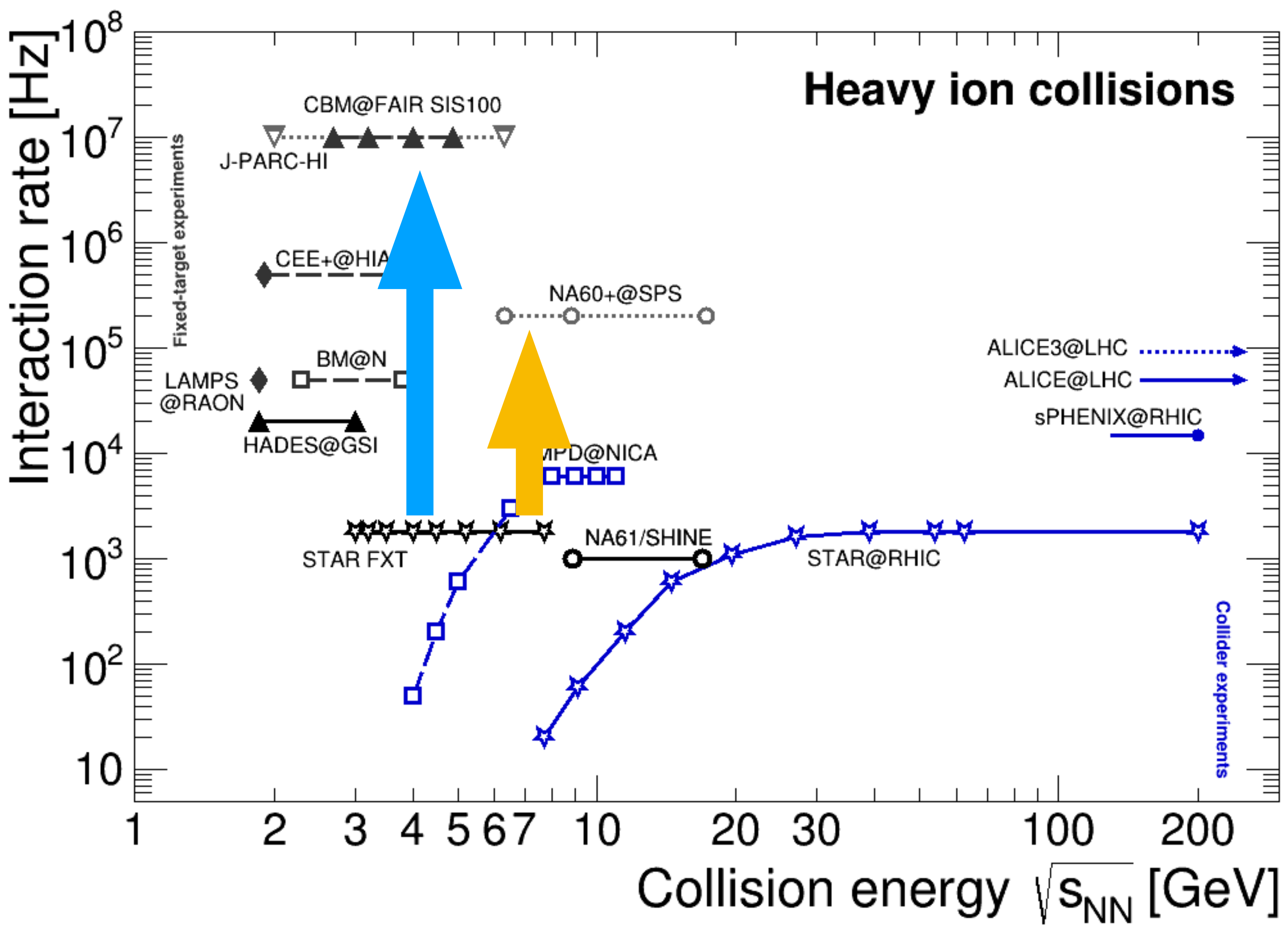


SHM trend confirmed

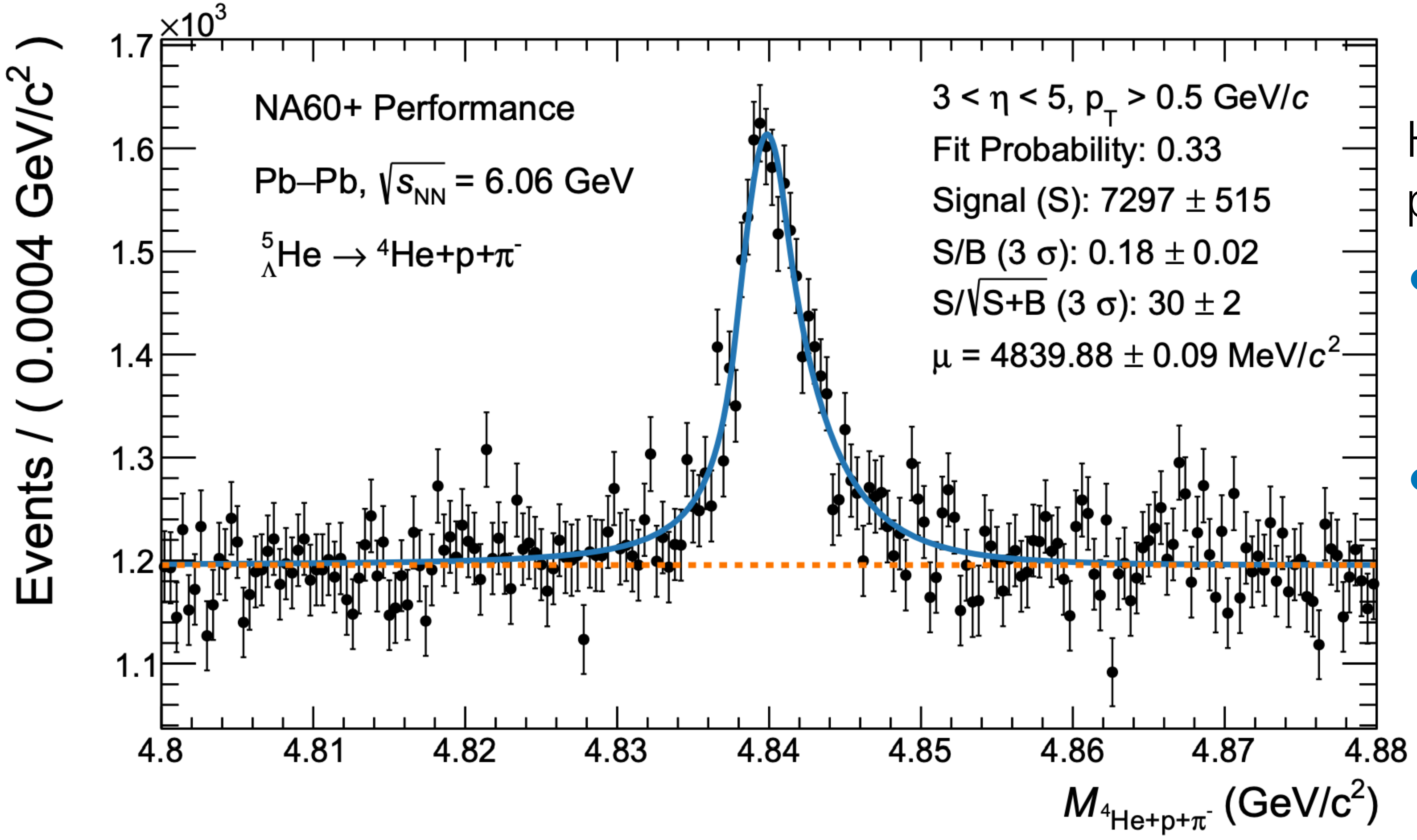
- Quantitative deviations like at the LHC
  - ➡ Missing resonances + coalescence

Statistics limited by the integrated luminosity

➡ Dedicated fixed target experiments will have larger luminosities



Performance at future experiments: NA60+

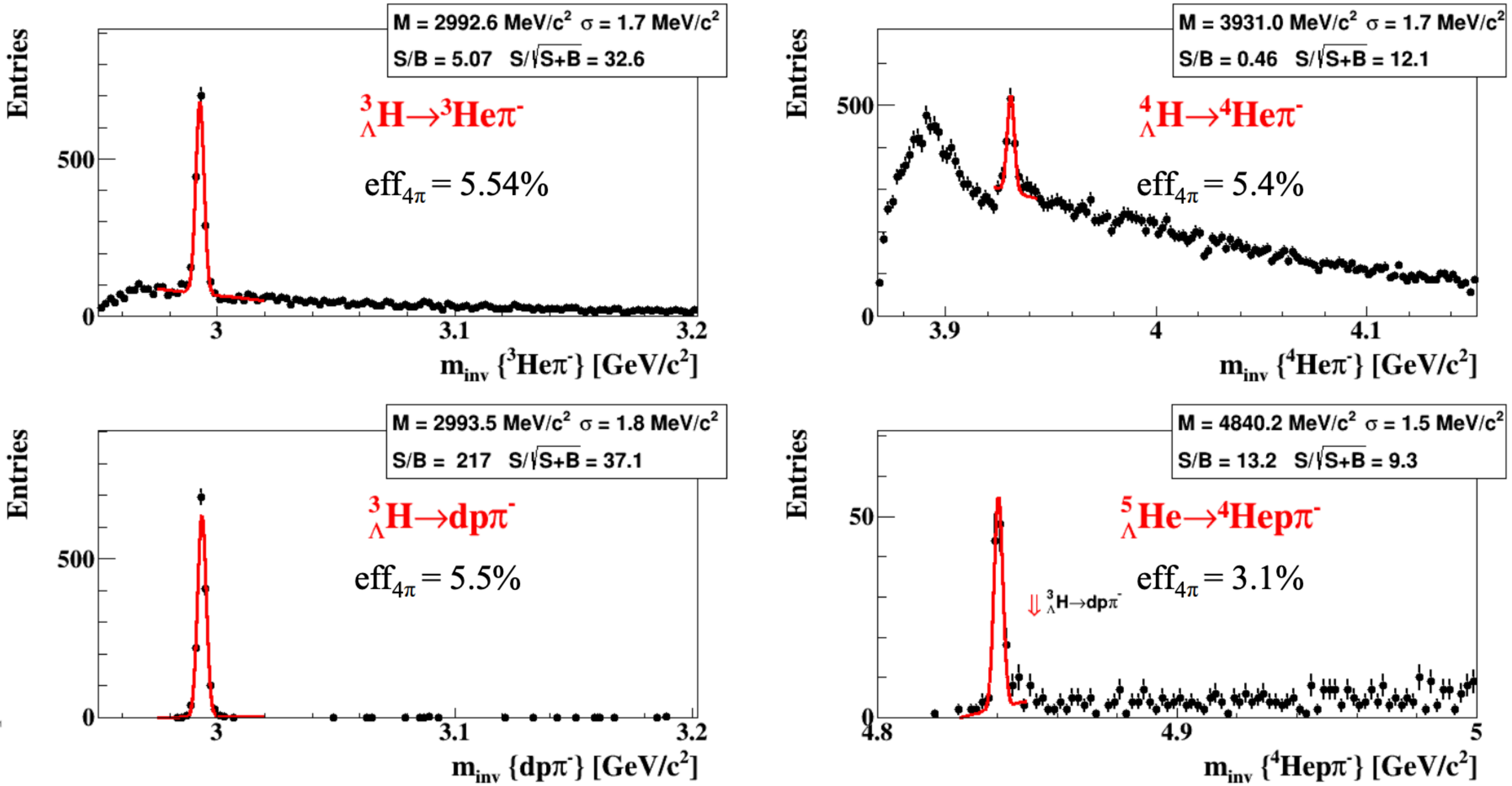


Hadron ID limited in NA60+ to Z=2 particles in the silicon tracker

- Lowest energy point foreseen still not at the peak production energy
- Integrated luminosity enough to comfortably measure the properties of Λ hypernuclei up to A=5

Performance at future experiments: CBM

I. Vassiliev, EMMI Workshop 2023



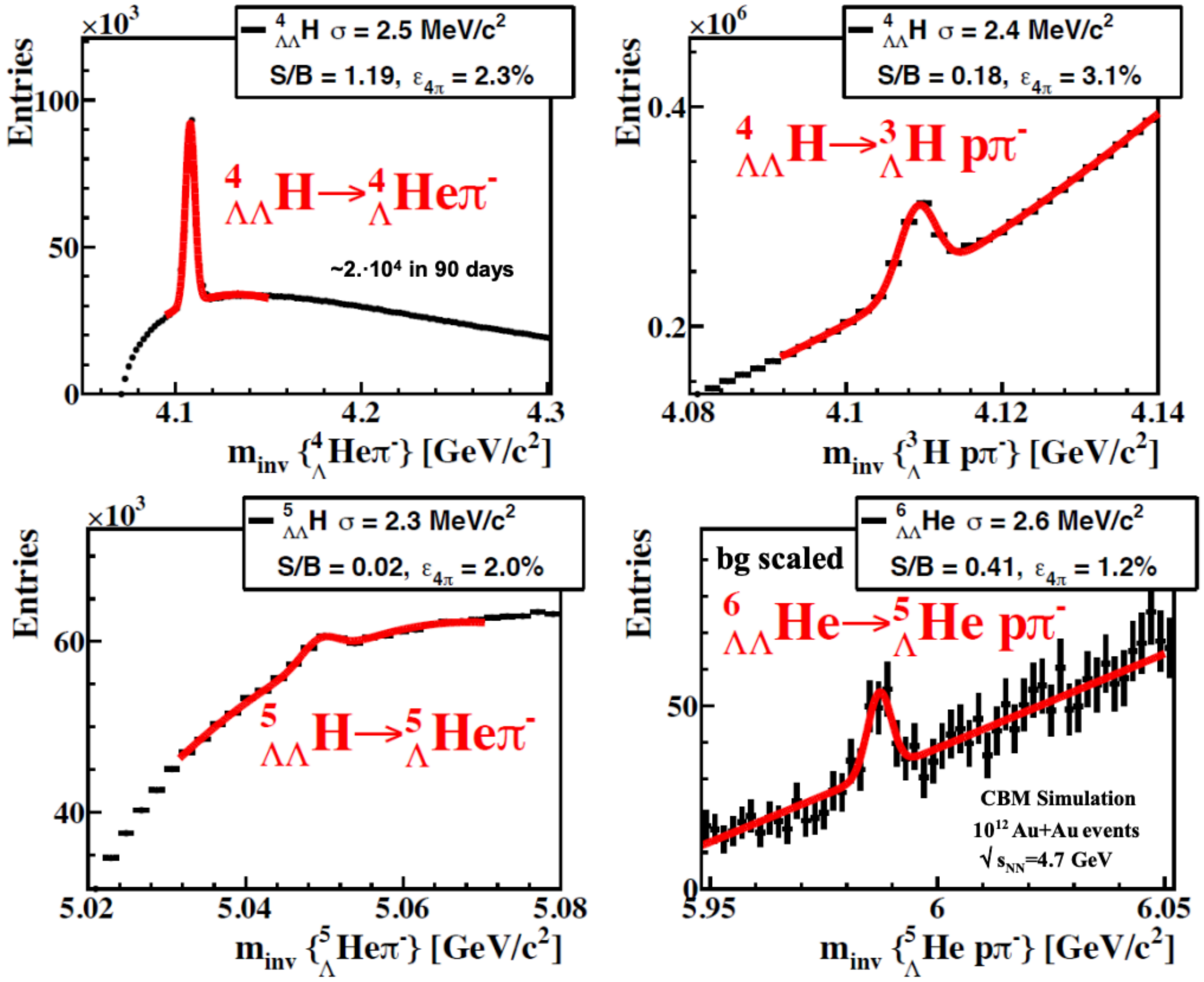
Results from 5 million MB PHQMD s Au +Au @ $\sqrt{s_{NN}}$ = 3 GeV

Excellent hadron PID with CBM

- Possibility to scan in the energy range where the peak production is expected to be

Performance at future experiments: CBM

I. Vassiliev, EMMI Workshop 2023



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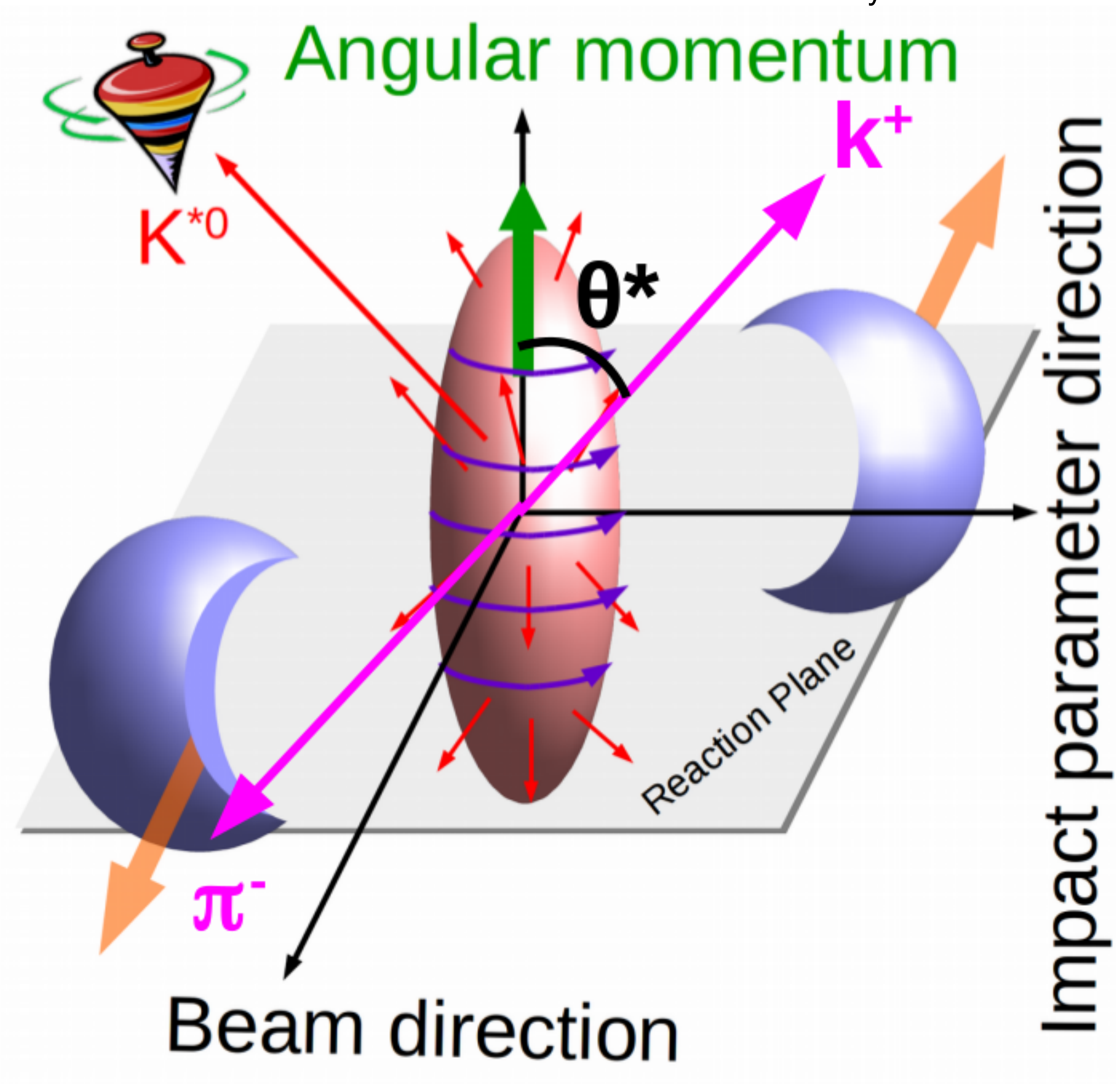
- Possibility to scan in the energy range where the peak production is expected to be

Discovery potential for light ΛΛ hypernuclei

What can we do more?

Global polarisation measurements

Sketch by S. Kundu



Heavy-ion collisions with non-zero impact parameter

→ Large angular momentum ~ $10^{7}\,\hbar$ transferred to the produced hadrons

Global polarisation measurements

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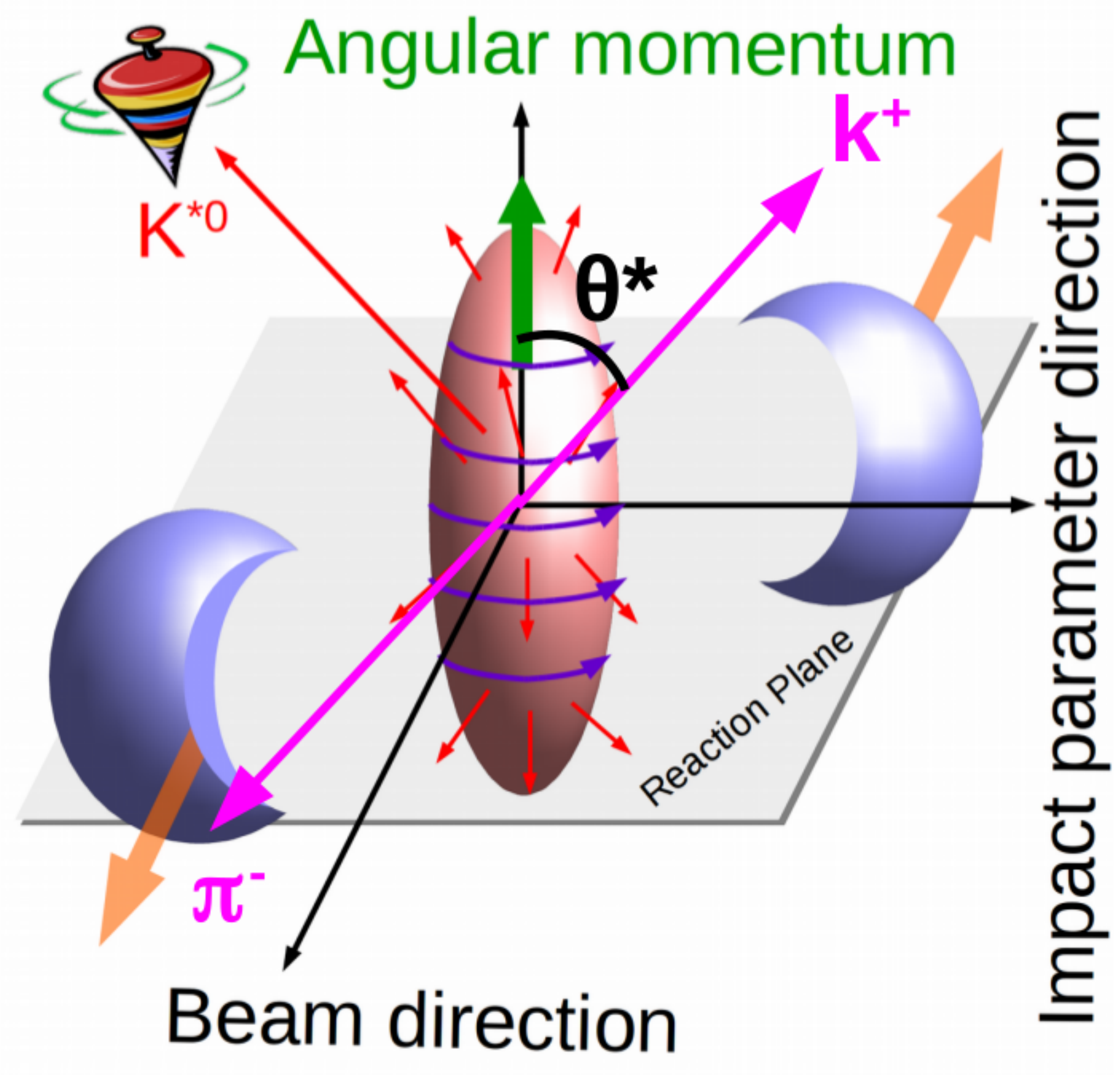
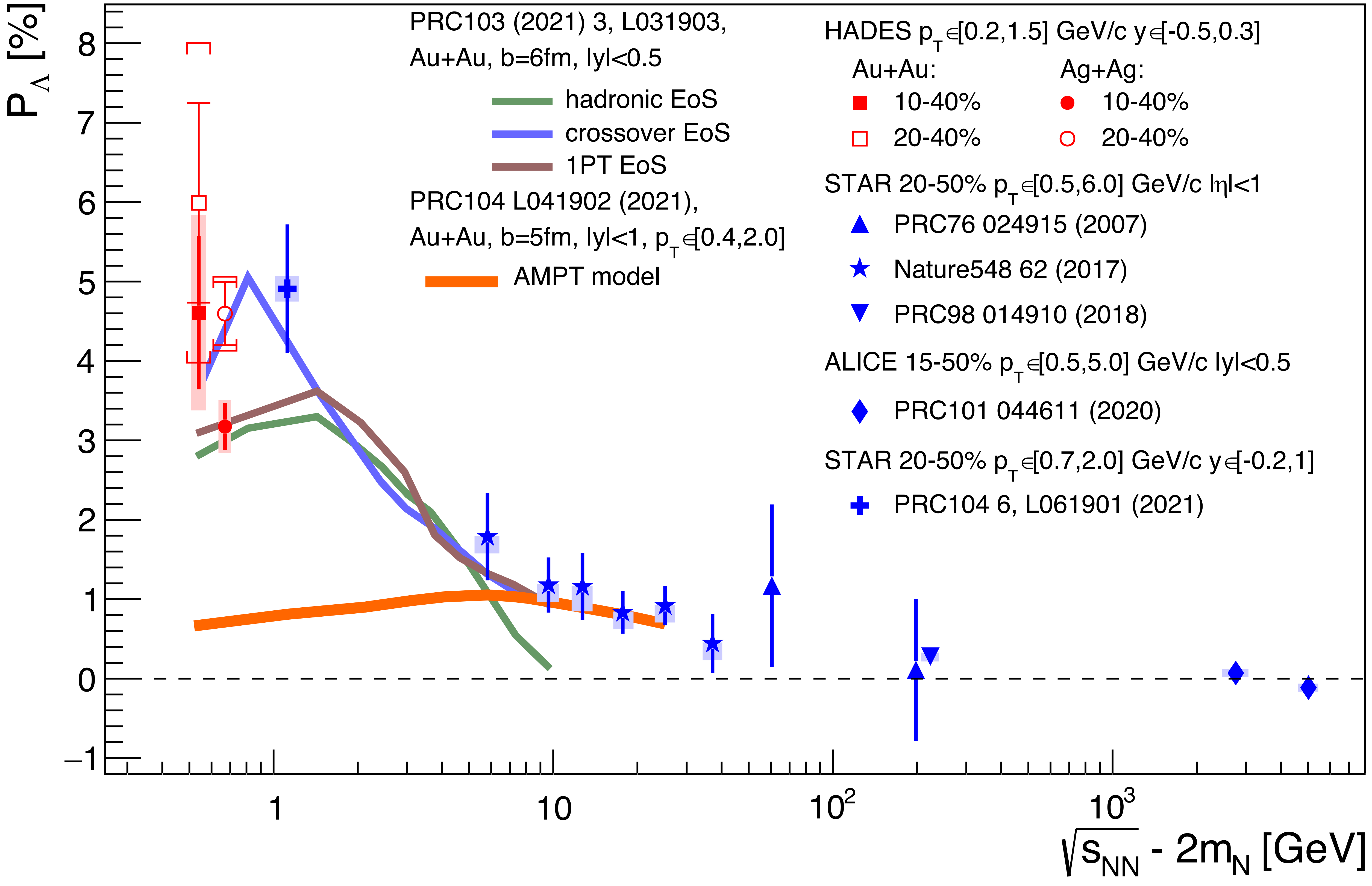


Szymon's talk, yesterday

HADES, Phys. Lett. B **835** (2022) 137506



Heavy-ion collisions with non-zero impact parameter

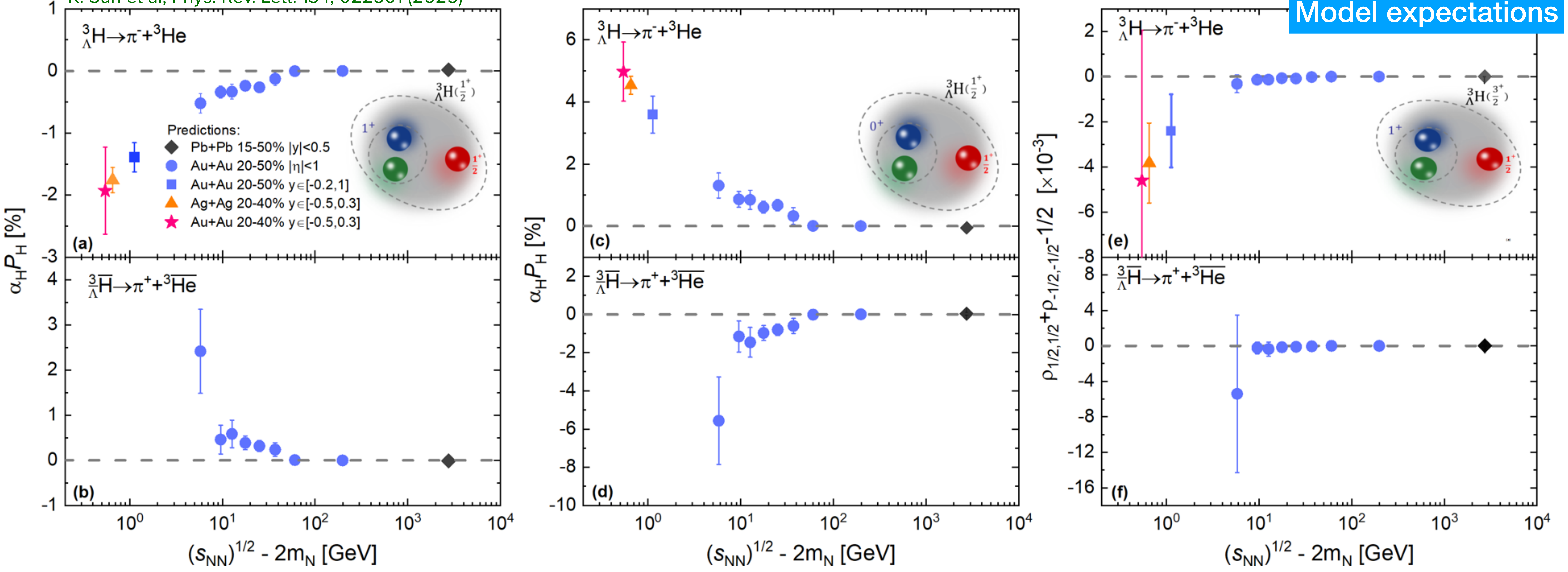
→ Large angular momentum ~ 10 ħ transferred to the produced hadrons

Largest effect in low energy Heavy-Ion collisions

A different *spin* to hyper nuclear physics

K. Sun et al, Phys. Rev. Lett. 134, 022301 (2025)

Model expectations



New directions for low energy heavy ion experiments

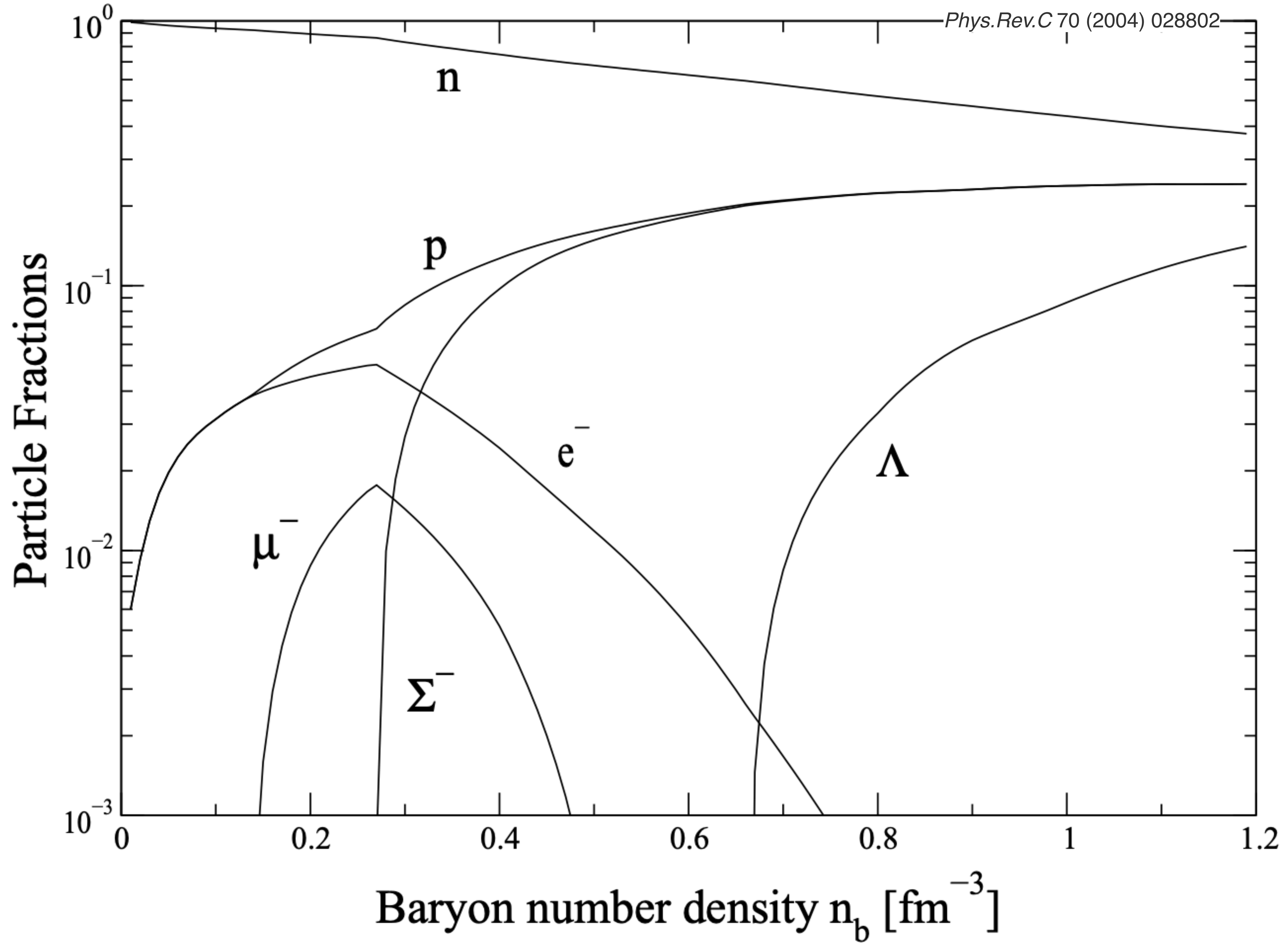
Beyond the properties that can be studied in traditional hyper nuclear experiments

➡ Vorticity in heavy-ion collisions polarizes hypernuclei, allowing for their direct spin determination

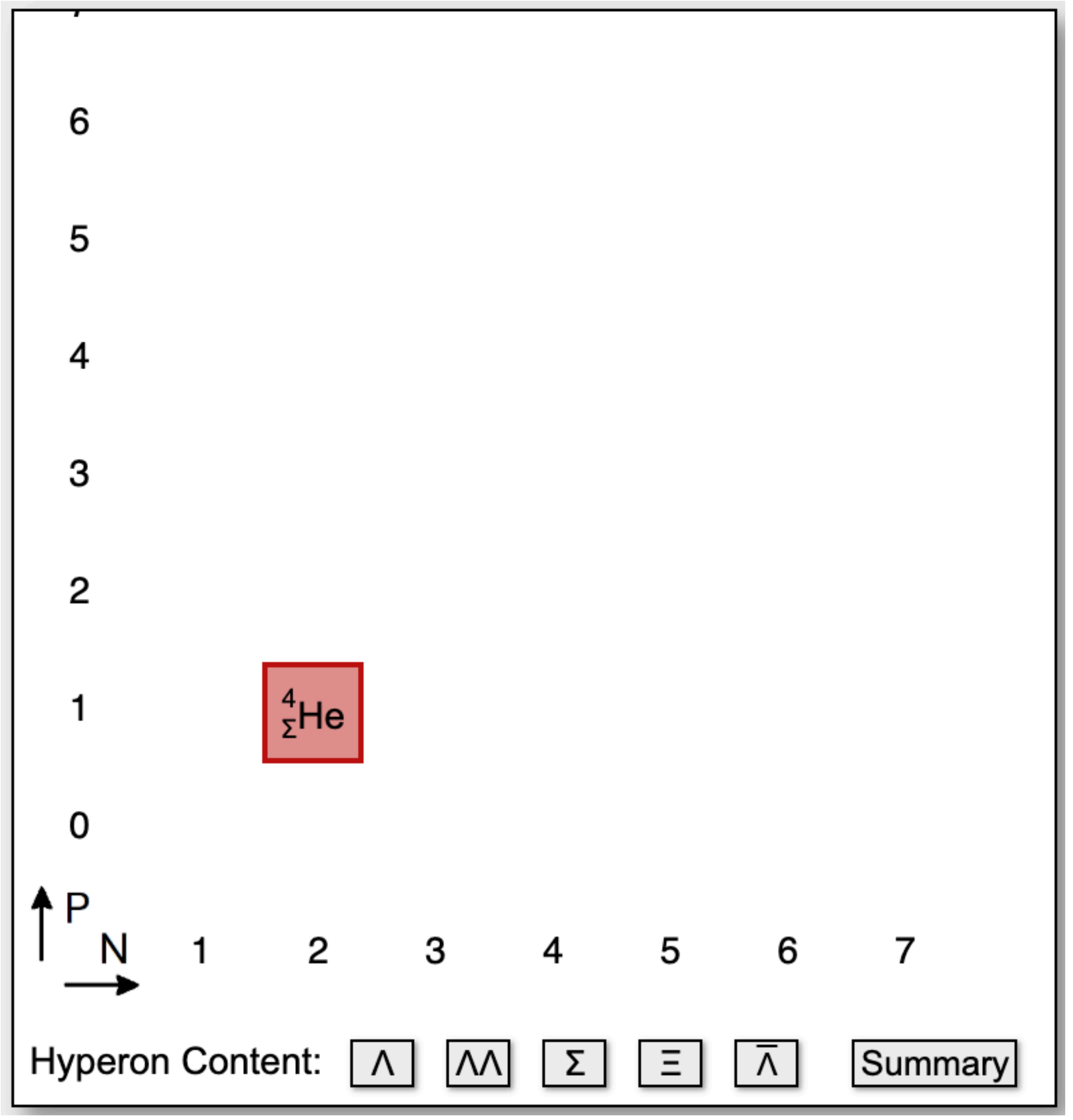
✓ Strongest signal in the fixed target energy range!

➡ Particle identification and direct tracking enable the study of rare decay channels

The case of Σ hypernuclei



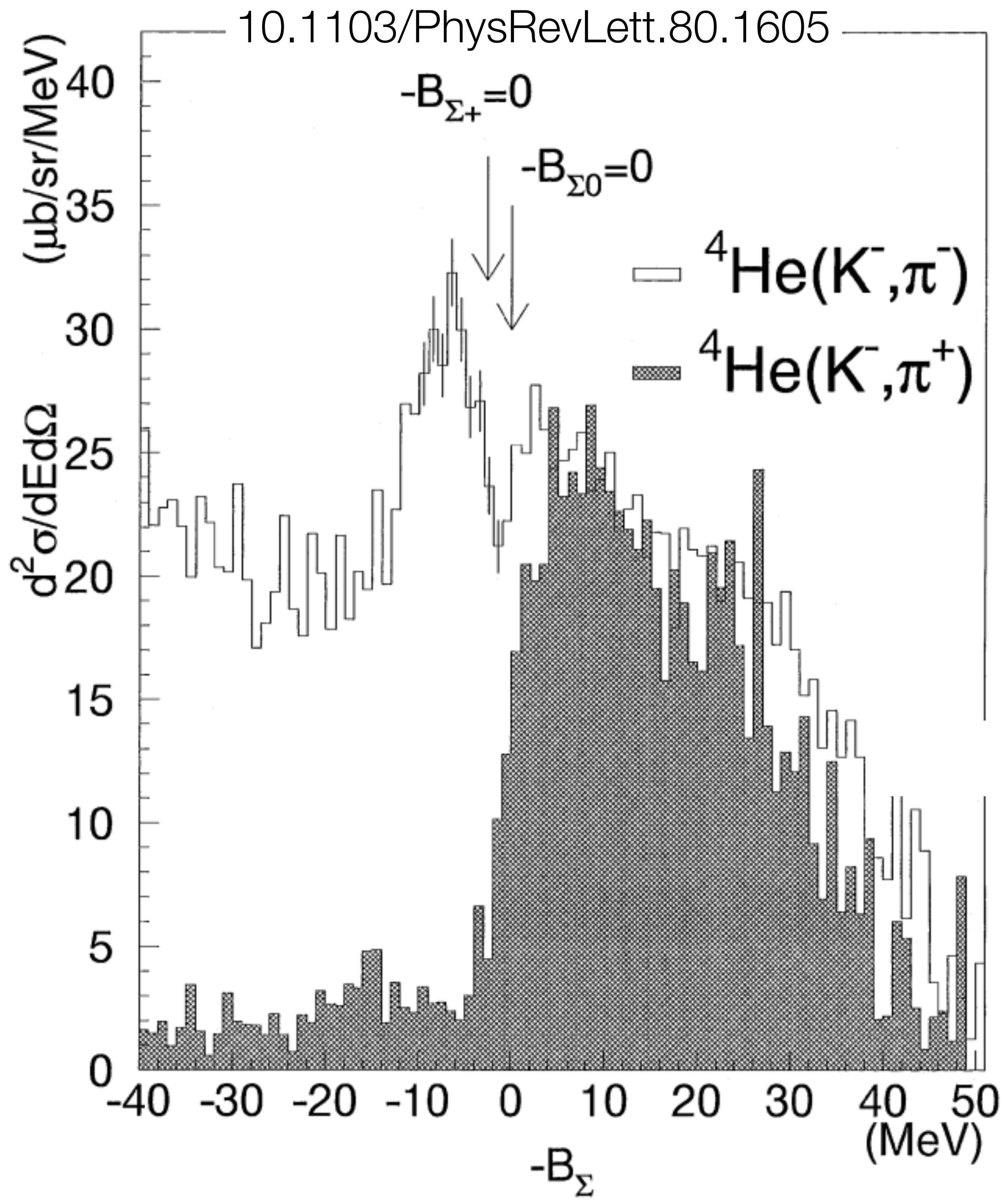
Hypernuclear database:



Σ hyperons can contribute significantly to the EOS of NS

- Little experimental evidence for Σ hypernuclei: only one Σ^+ hyper nucleus claimed

Experimental detection of Σ and Ξ hypernuclei



Due to coupled channel dynamics (ΣN→NΛ) Σ hypernuclei will be detected as strong resonances

- ^{3}He or ^{3}H + Λ decay: larger experimental backgrounds, excellent PID is a requirement

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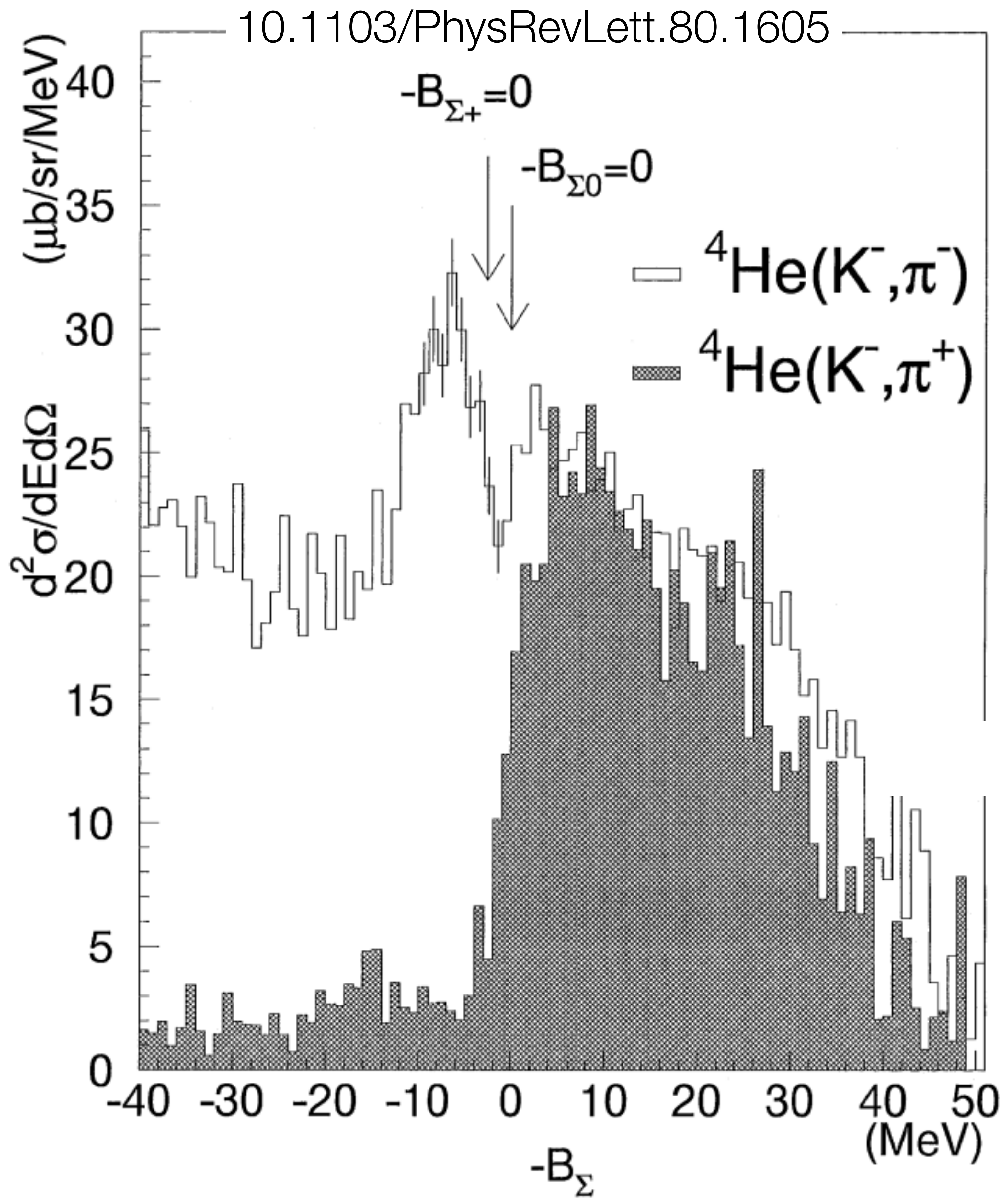
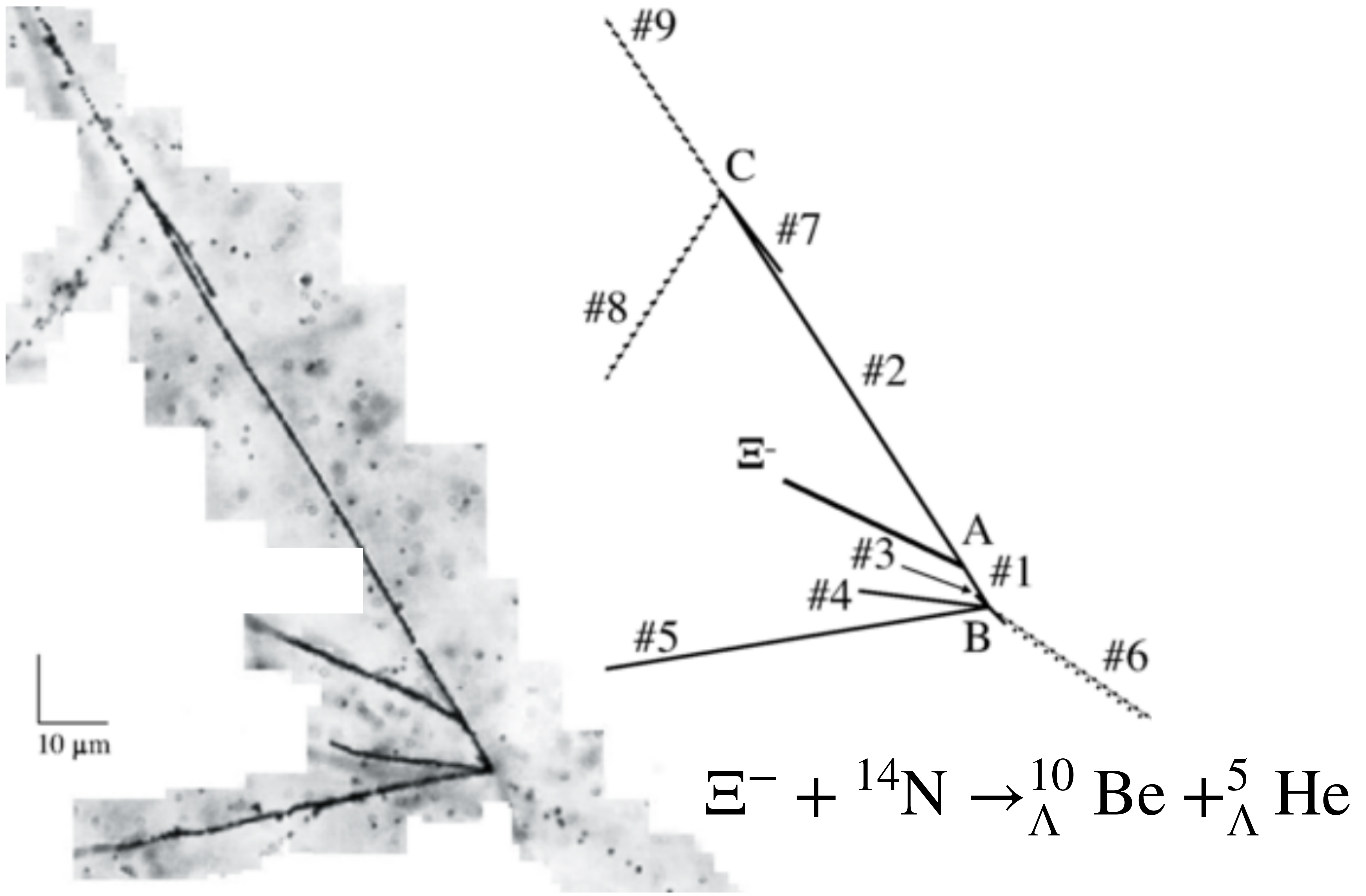


IBUKI event, 10.1103/PhysRevLett.126.062501

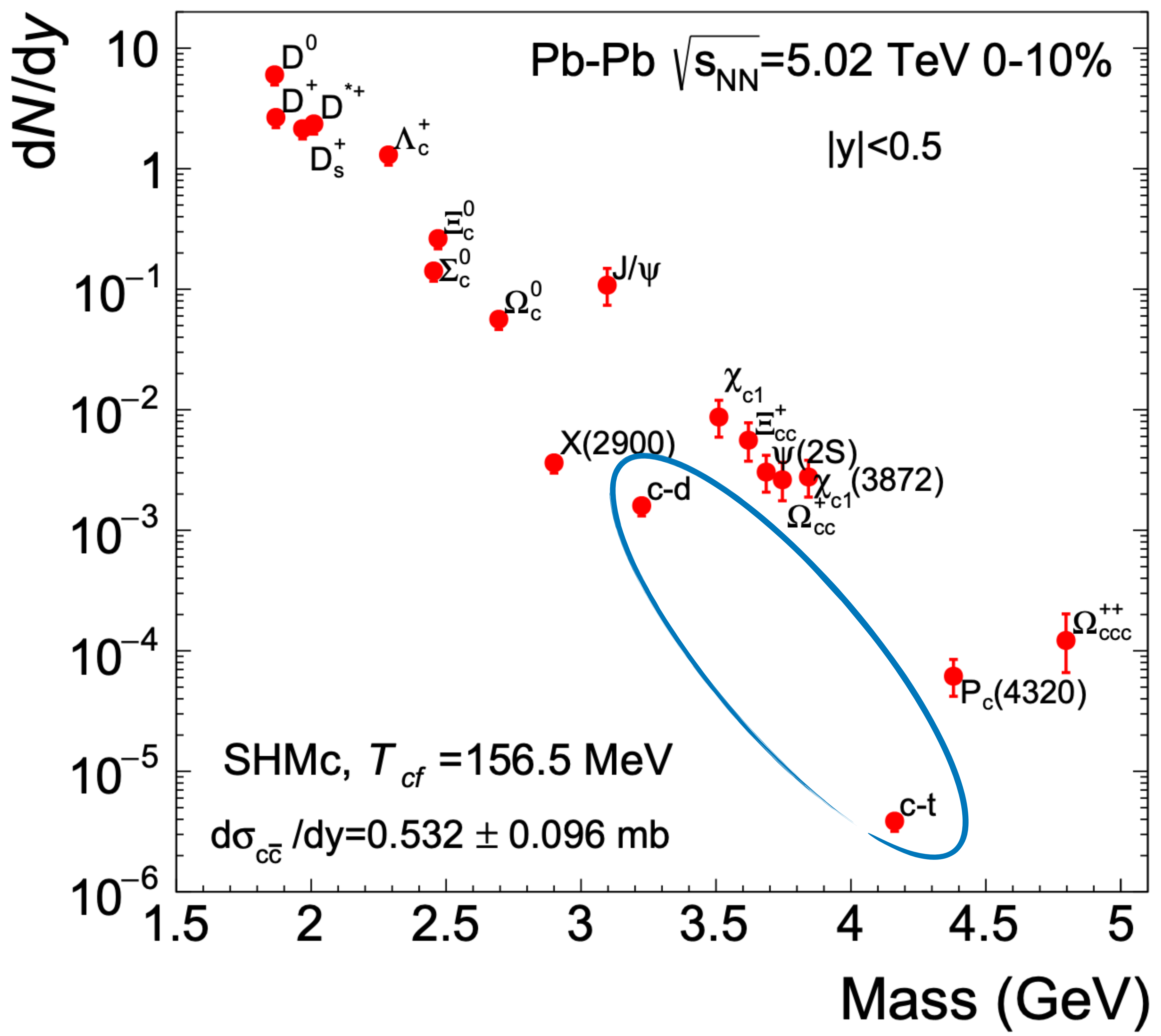


Due to coupled channel dynamics (ΣN→NΛ) Σ hypernuclei will be detected as strong resonances

- ^{3}He or ^{3}H + Λ decay: larger experimental backgrounds, excellent PID is a requirement
- Same issue for Ξ hypernuclei: Ξ convert to pairs of single strangeness hyperons

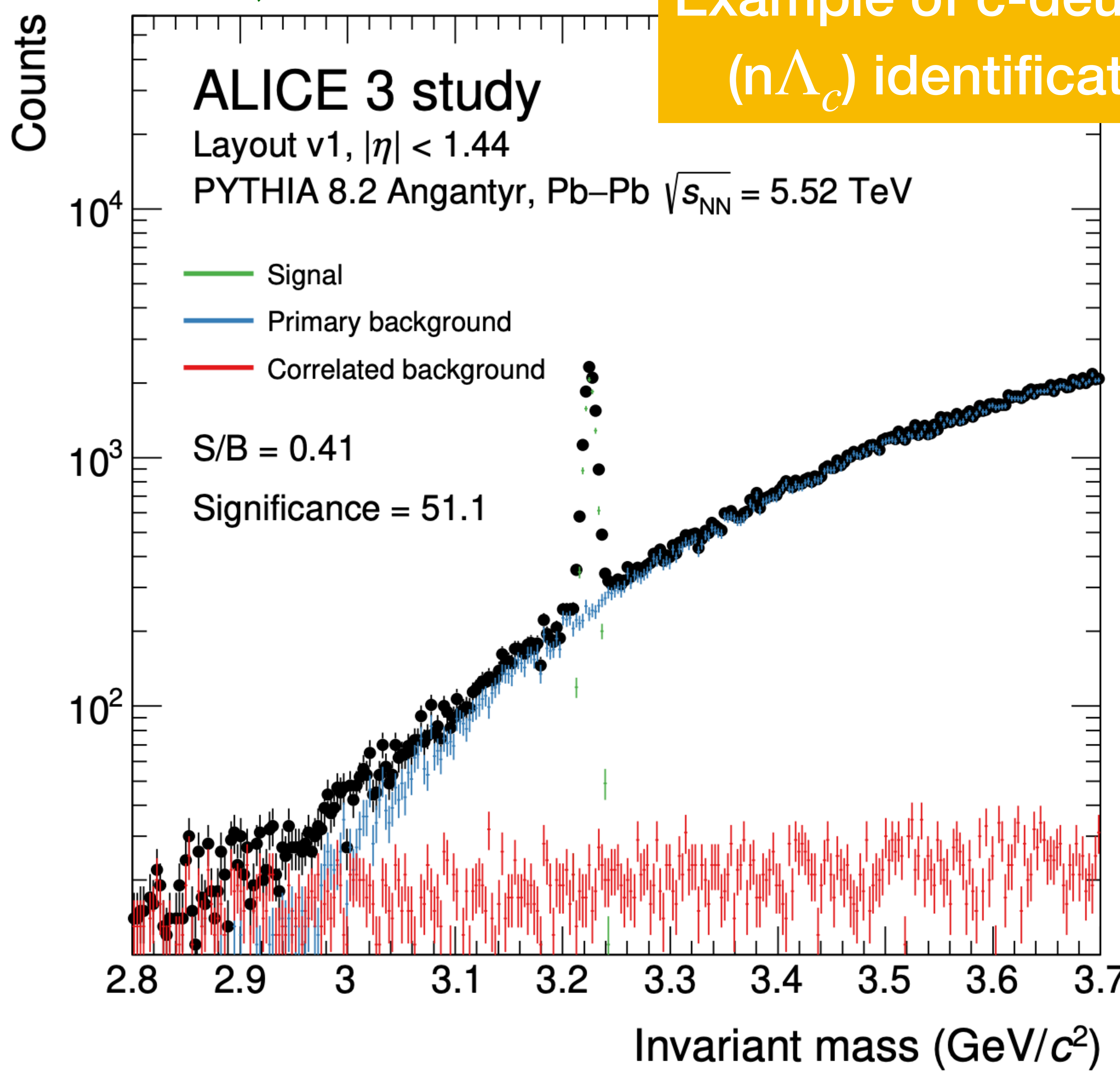
A possible discovery: charm nuclei at the LHC with ALICE3

A. Andronic et al., *JHEP* 07 (2021) 035



ALICE, arxiv:2211.02491

Example of c-deuteron ($n\Lambda_c$) identification



One of the physics highlights for future HI at LHC

Look for the existence of charmed nuclei

- Verify Lattice QCD predictions for A=2 and 3 charm nuclei

} Is high energy the best place to hunt for these objects?

Super nuclei for the Super Proton Synchrotron

Vincenzo, this morning

REAL DISCLAIMER: HF is a probe not yet really explored at 5-20 AGeV even theoretically &
I have never worked at all on HIC in this energy range
I likely may miss some relevant aspect

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The following is pure speculation and calculations are required!

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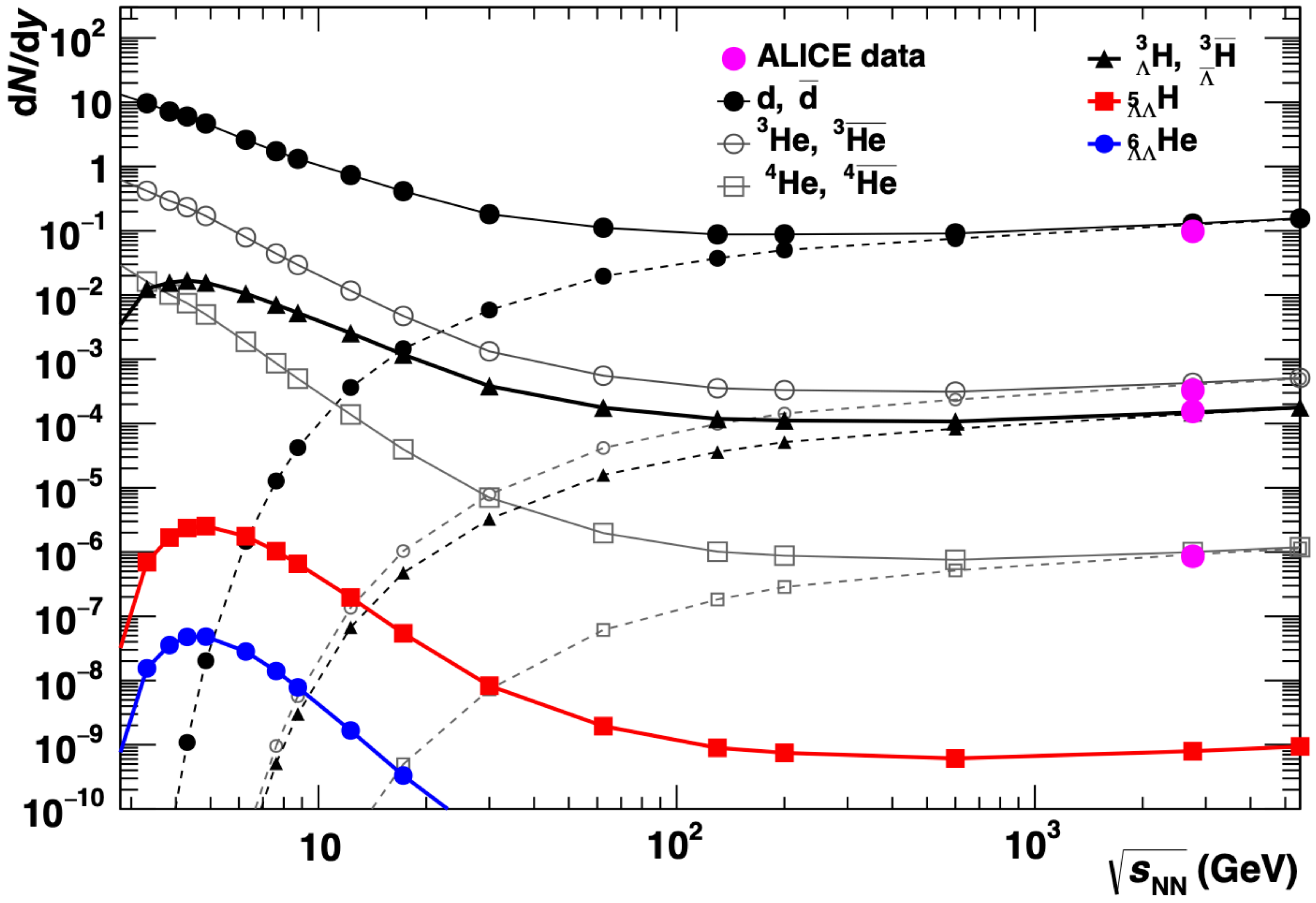
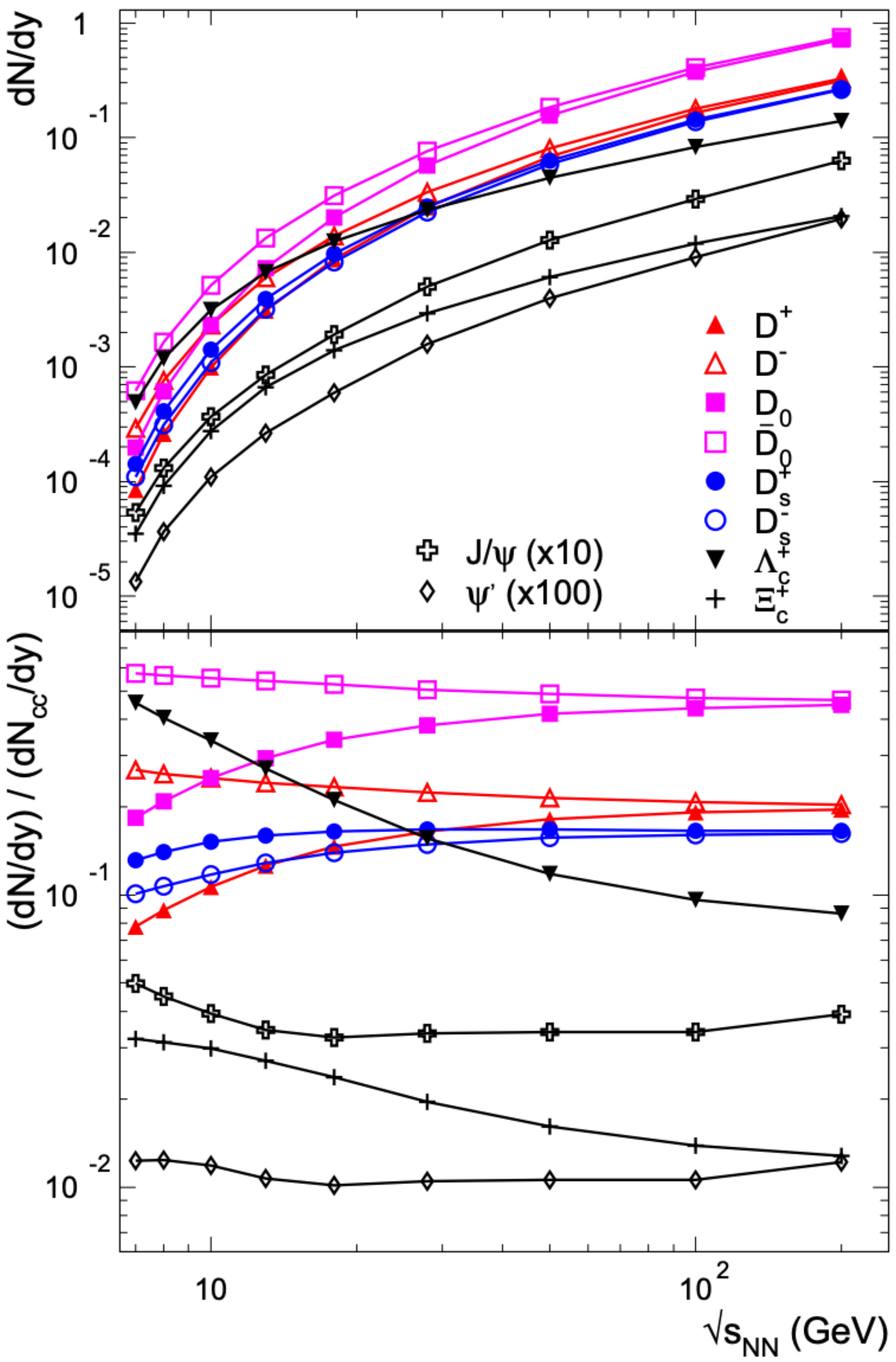




AA et al, PLB 659 (2008) 149

Cluster formation is greatly suppressed above 20 GeV

- Charm baryon production instead keeps monotonously increase
- Does the super nuclei production peak at top SPS energy?
  - Call for predictions!

Summary

Penetrating probes of **cold**, high-μ_B matter

Hypernuclei give unique information on the YN interactions

- Understanding the structure/properties of hypernuclei is a stepping stone to understanding NS EOS

➡In a way, they are penetrating probes of **cold**, high-μ_B matter

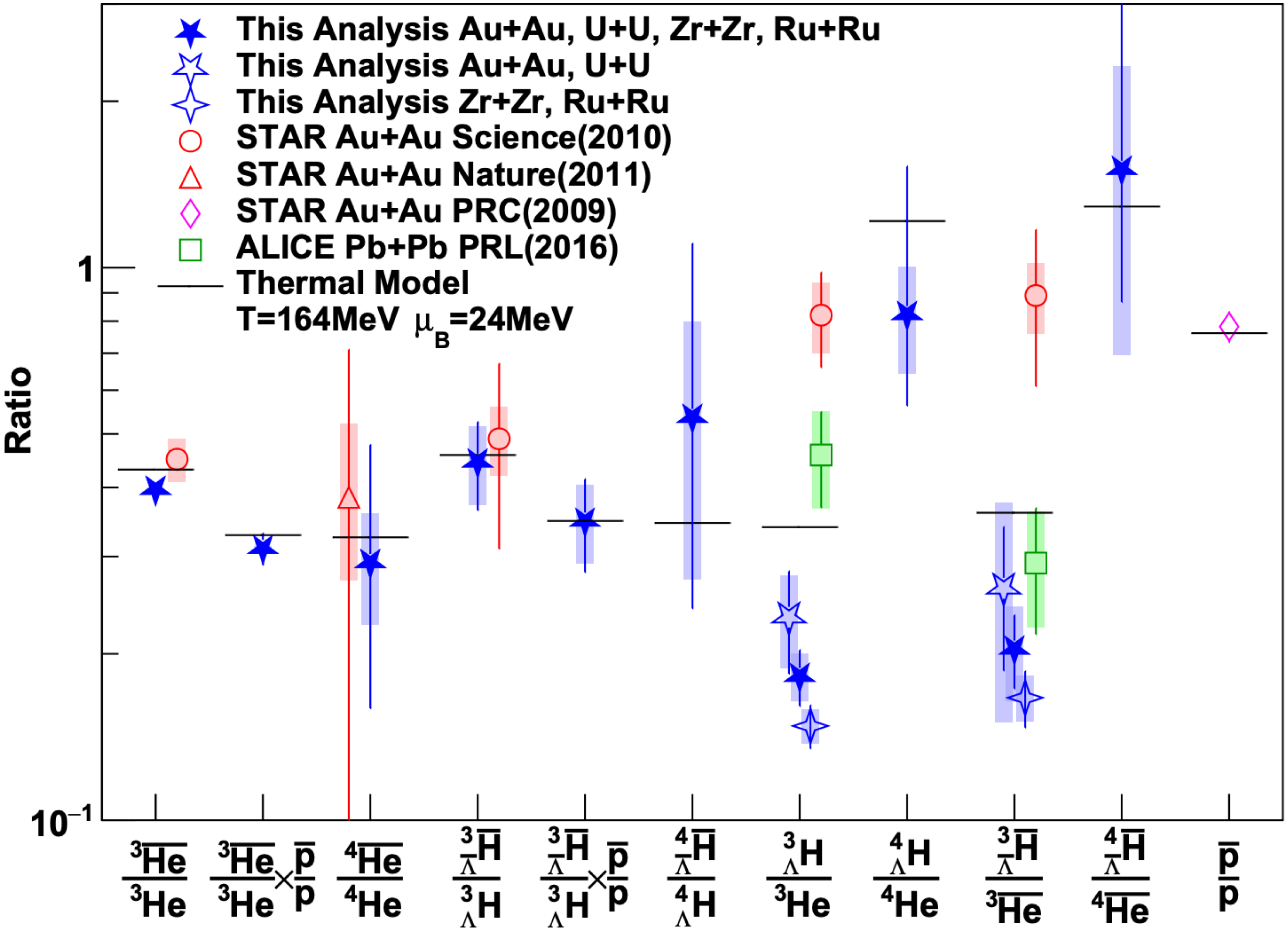
Heavy-ion experiments are unique tools to study them

- Most of the physics we can squeeze out of these apparata is not worked out
  - Light multi-strange, Σ^- and charm hypernuclei would be true discoveries for our experiments

Backup

Hypertriton production suppression at RHIC?

STAR, https://arxiv.org/abs/2310.12674



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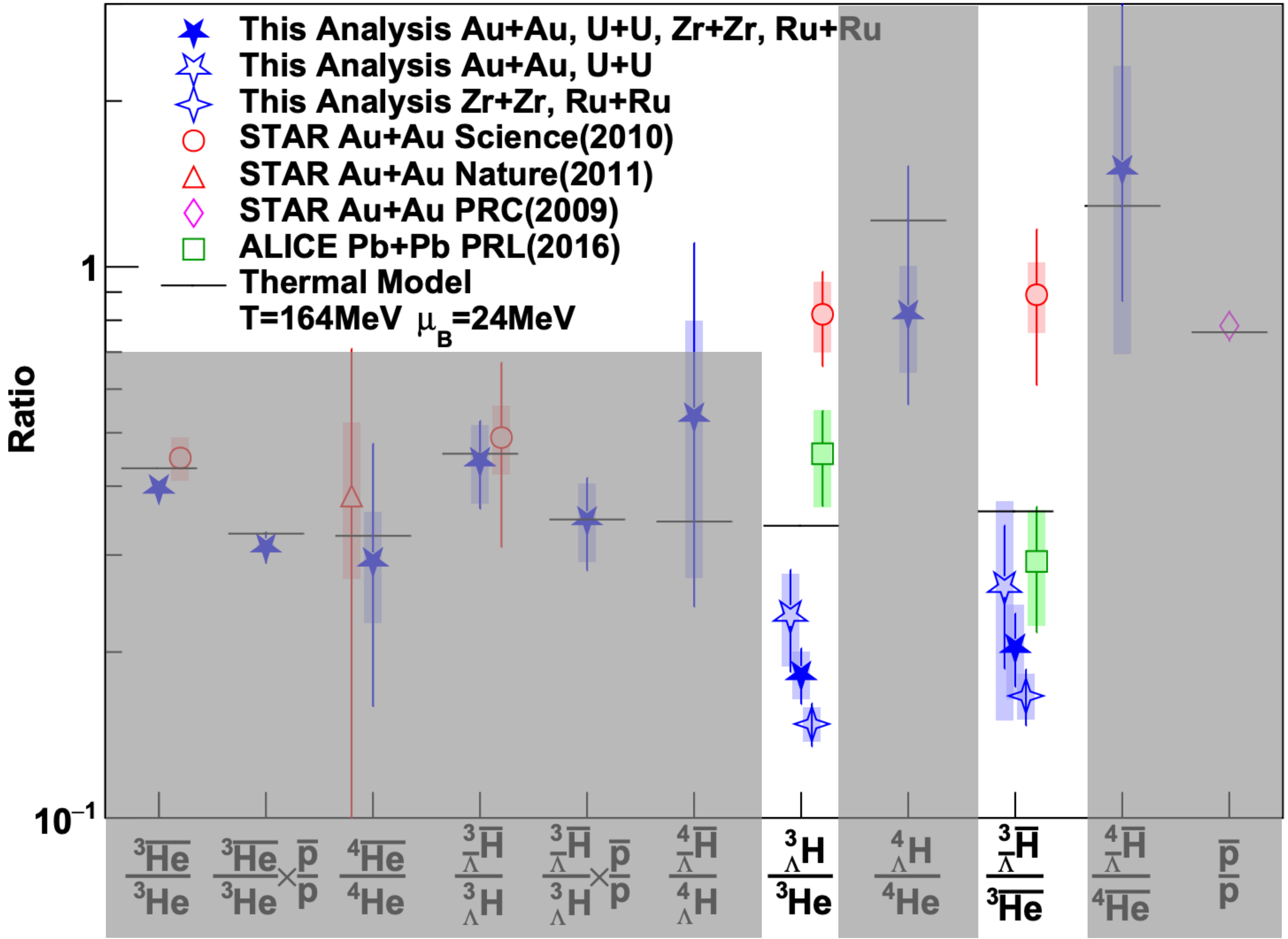

Indication of larger deviation from the SHM prediction in the collision among “small” ions

- Same effect as going to p-Pb or pp collisions at the LHC!