

Hypernuclei and anti-hypernuclei production in heavy-ion collisions

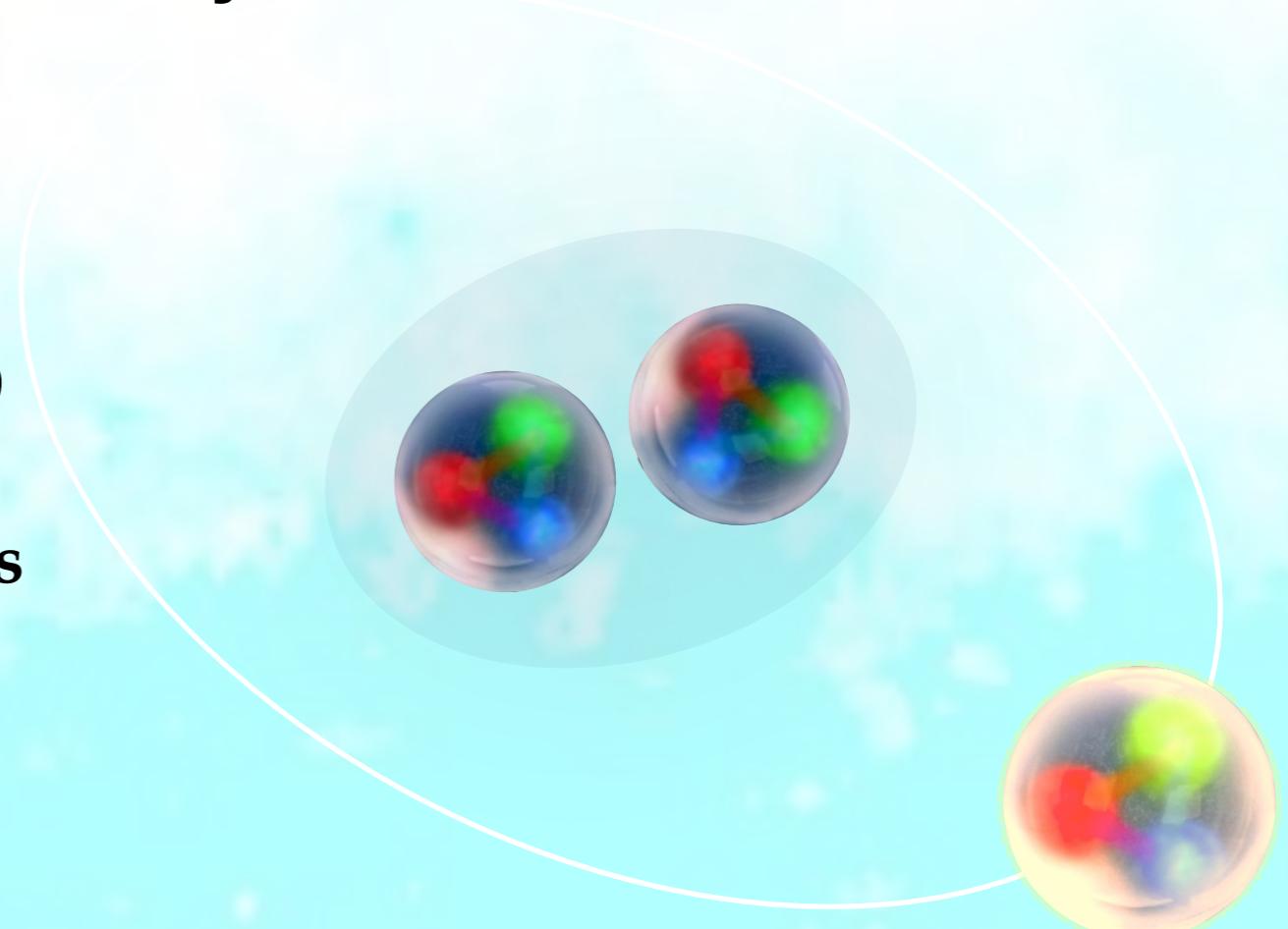
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Lawrence Berkeley National Laboratory

*The 19th International Conference on
Strangeness in Quark Matter*

May 17-21, 2021

- Introduction
- Hypernuclear structure (τ and B_Λ)
- Production in heavy-ion collisions
- Outlook



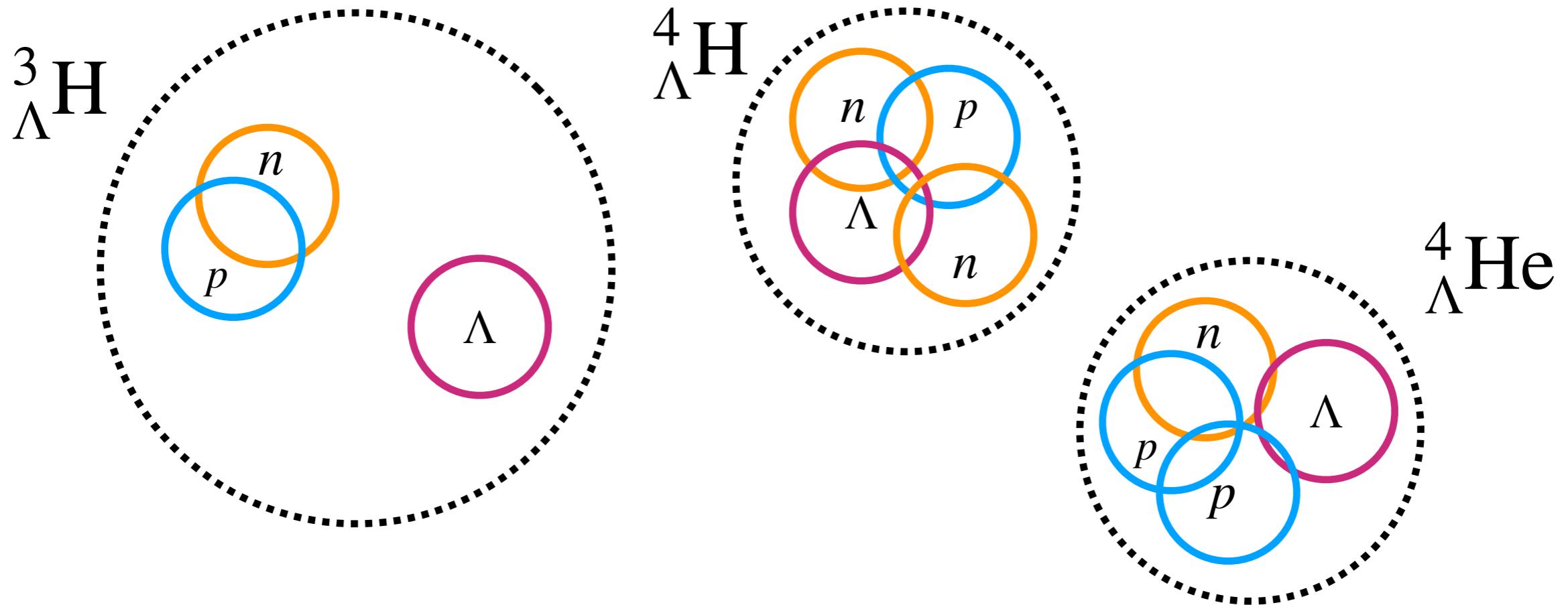
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Hypernuclei



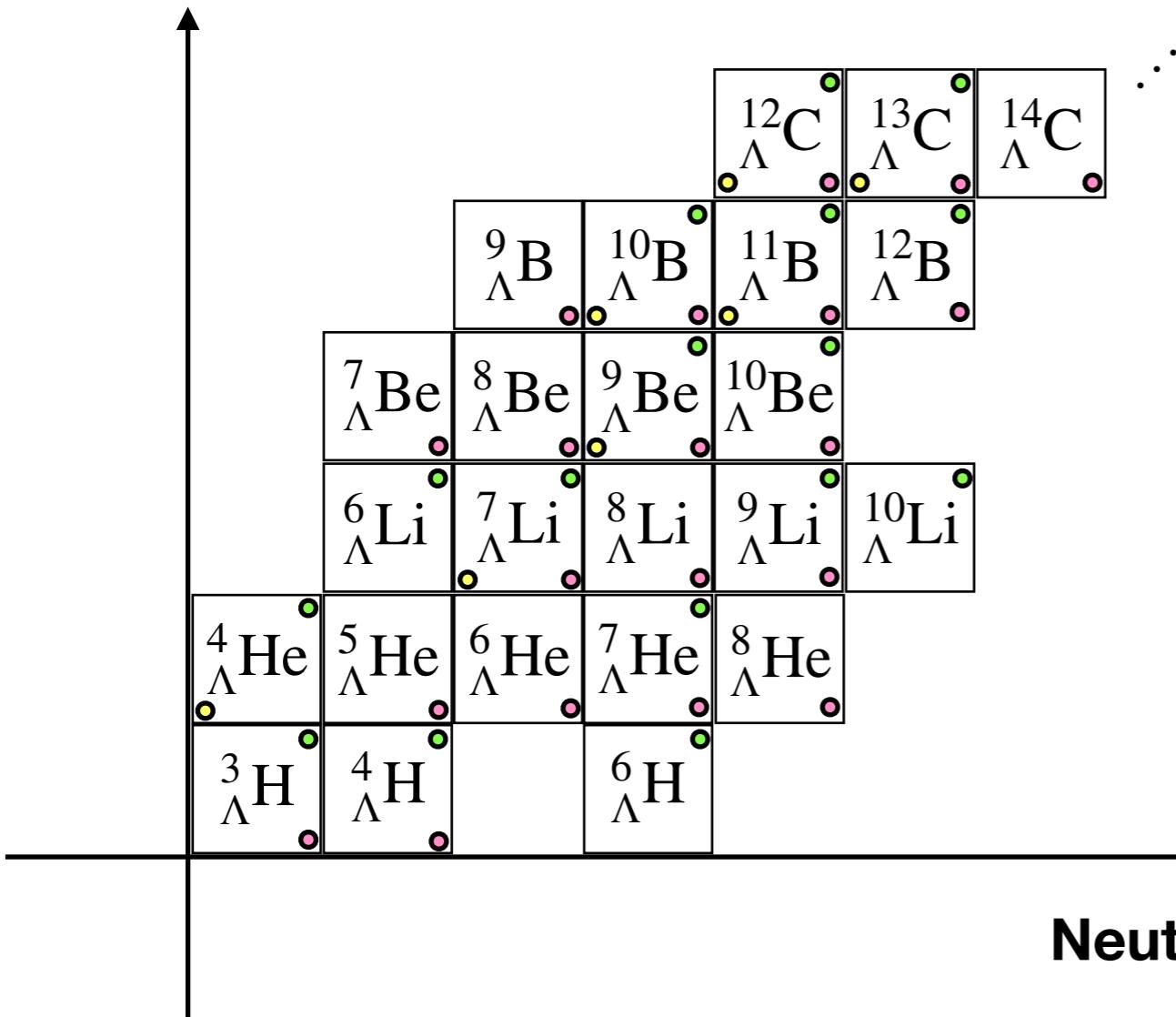
Hypernuclei are nuclei containing at least one hyperon

- provide access to the hyperon–nucleon (Y-N) interaction
 - strangeness in high density nuclear matter
 - EOS of neutron star
 - Hadronic phase of a heavy ion collision

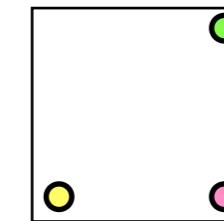
Hypernuclei

Proton no. (Z)

Λ hypernuclear chart



Kaon
reactions



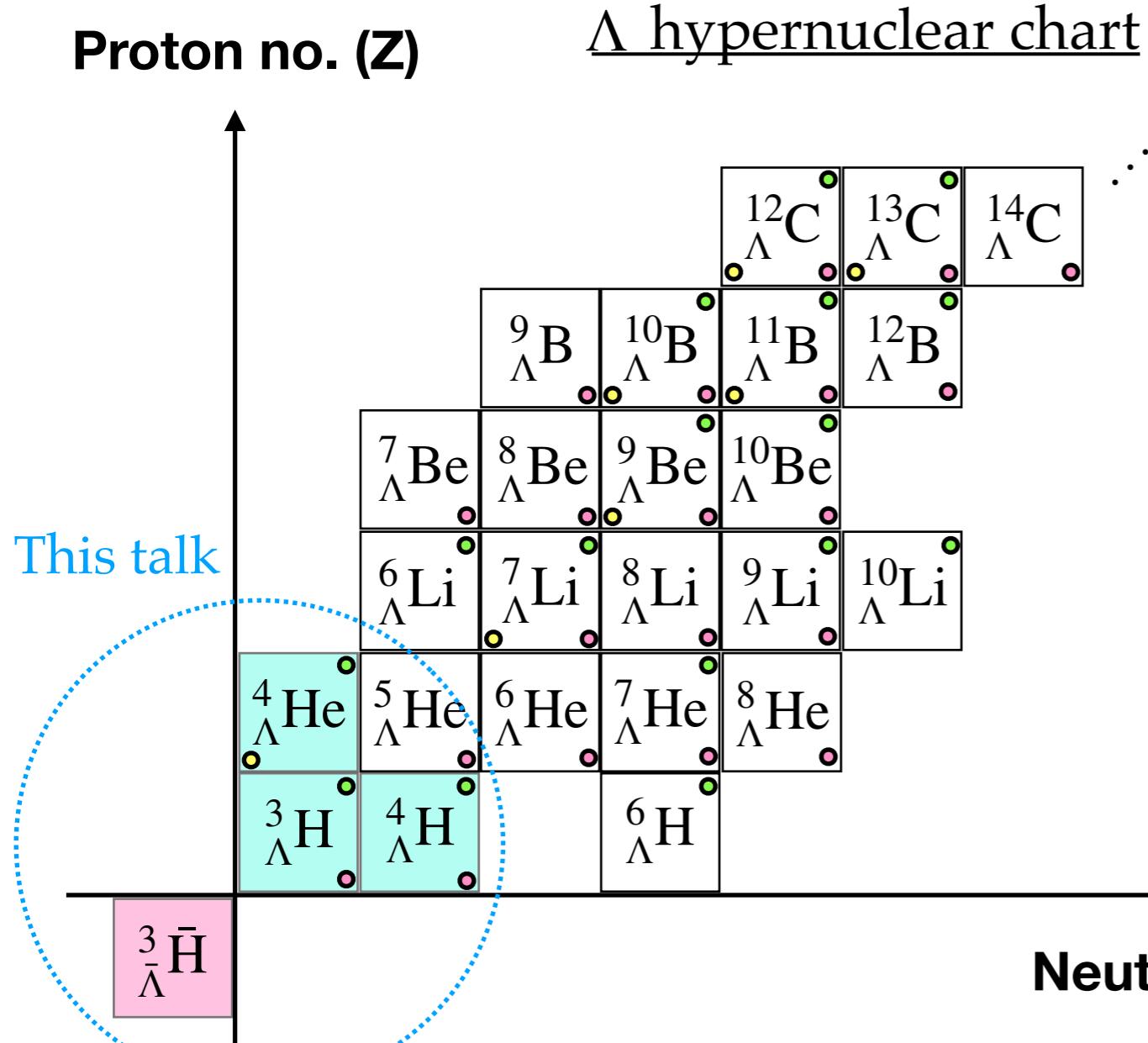
γ -ray Emulsion

[Credits to Isaac Vidaña](#)

Hypernuclei first discovered in 1952 by Marian Danysz and Jerzy Pniewski

- Techniques such as emulsion, γ ray or strangeness exchange reactions used to study properties of hypernuclei

Why heavy ion for hypernuclei?



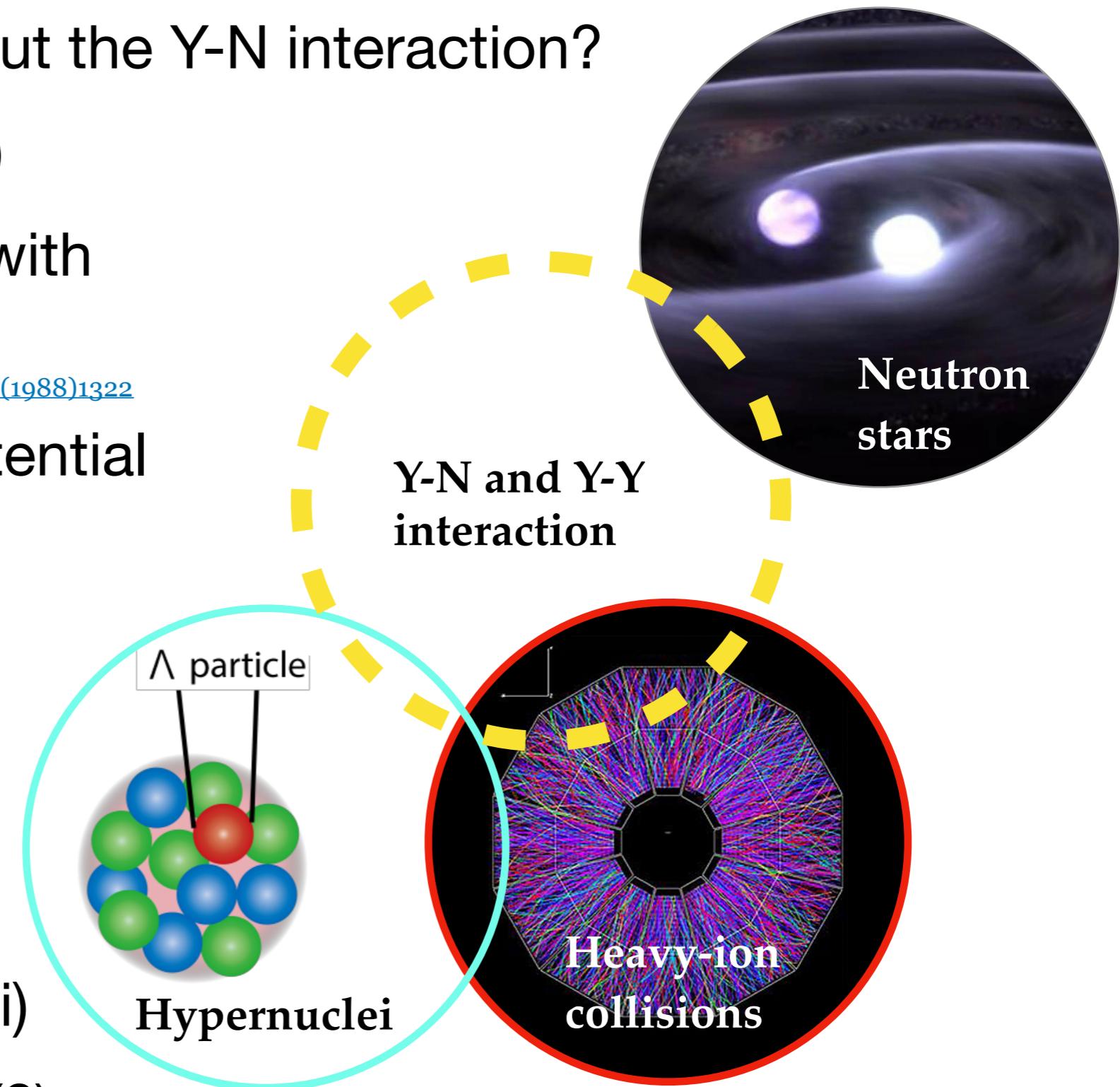
- HIC vs traditional techniques:

- Precise analysis of light/anti hypernuclei structure → Y-N interaction
- Production mechanisms → Y-N interaction + properties of the matter formed
- Search for exotic hypernuclei

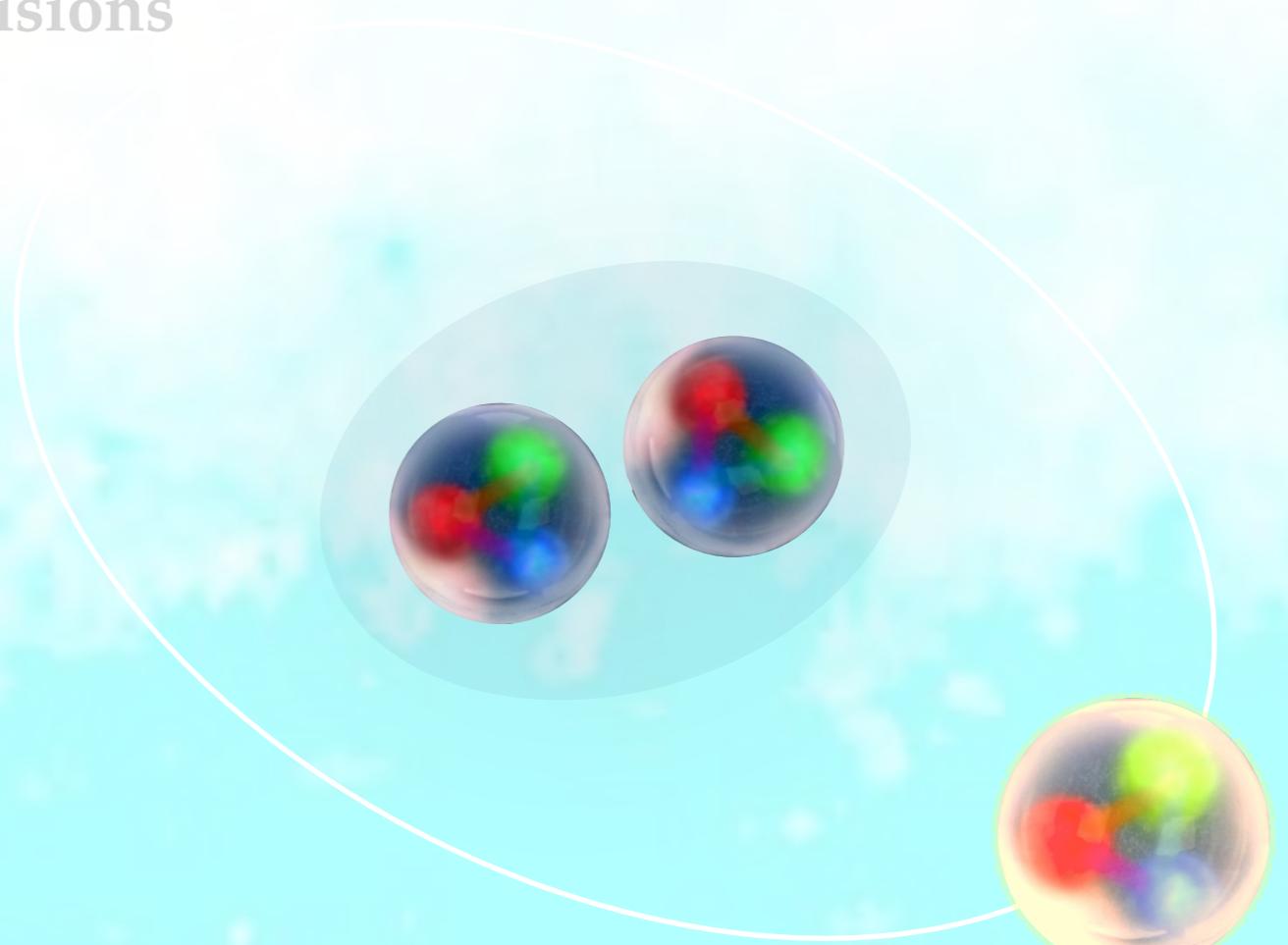
- First hypernuclei production using a beam of heavy ions:
 - Lawrence Berkeley Laboratory Bevatron (1976)
[K.J.Nield et al, PRC13\(1974\)1263](#)
 - First observation of anti-hypernuclei by STAR (2009)
[STAR, Science 328 \(2010\) 58](#)
 - light/anti hypernuclei
 - Identified via weak decays

The hyperon-nucleon (Y-N) interaction

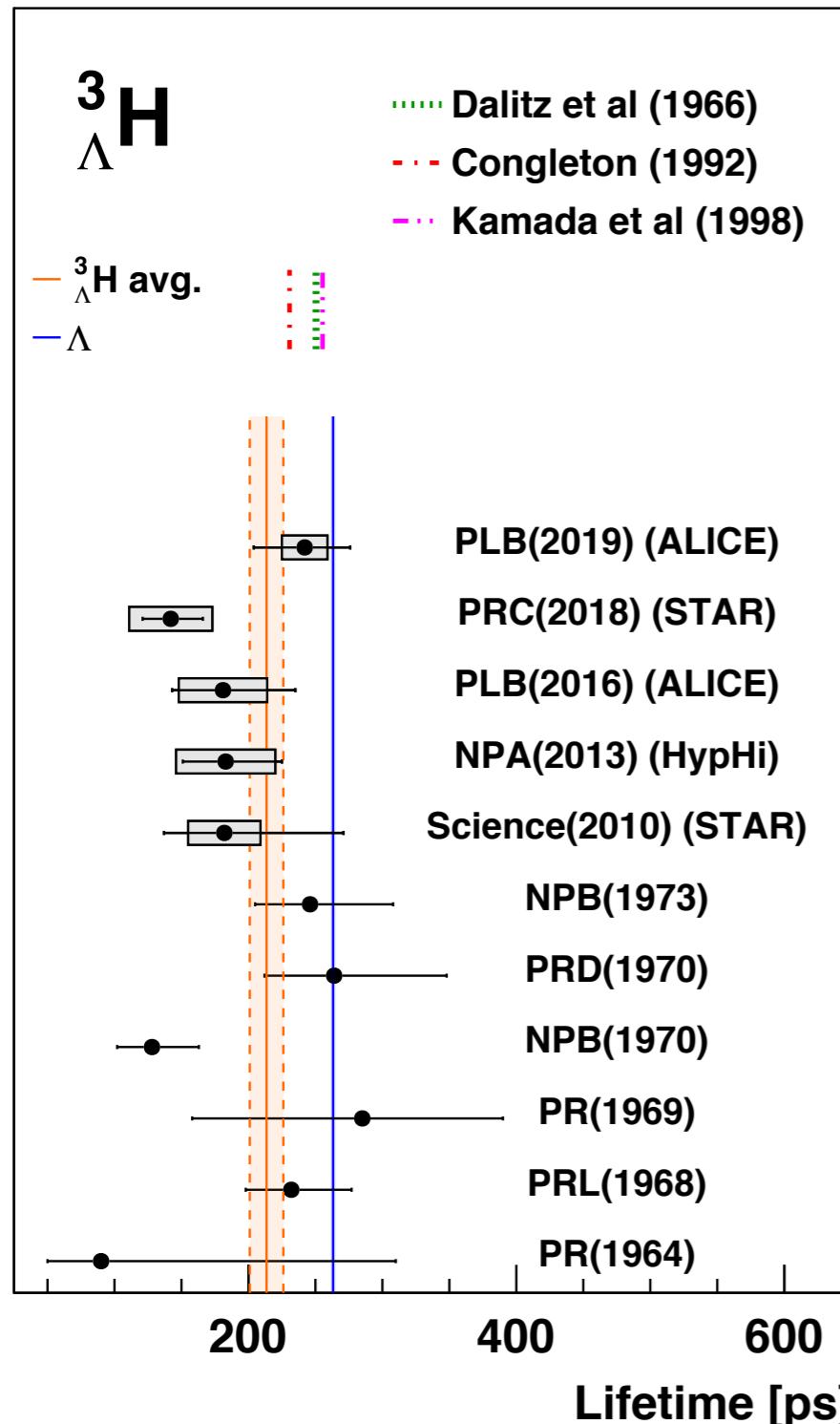
- What have we learnt about the Y-N interaction?
- Λ -N (40+ Λ -hypernuclei)
 - Attractive Λ potential with depth ≈ 30 MeV
[T. Motoba et al, PRC38\(1988\)1322](#)
 - About 2/3 nucleon potential
 - Precise measurements of B_Λ , τ , and decay B.R. can give tighter constraints
- Ξ -N, Σ -N (few Ξ/Σ hypernuclei)
- Λ - Λ , (few Λ - Λ hypernuclei)
 - Λ - Λ weakly attractive (?)



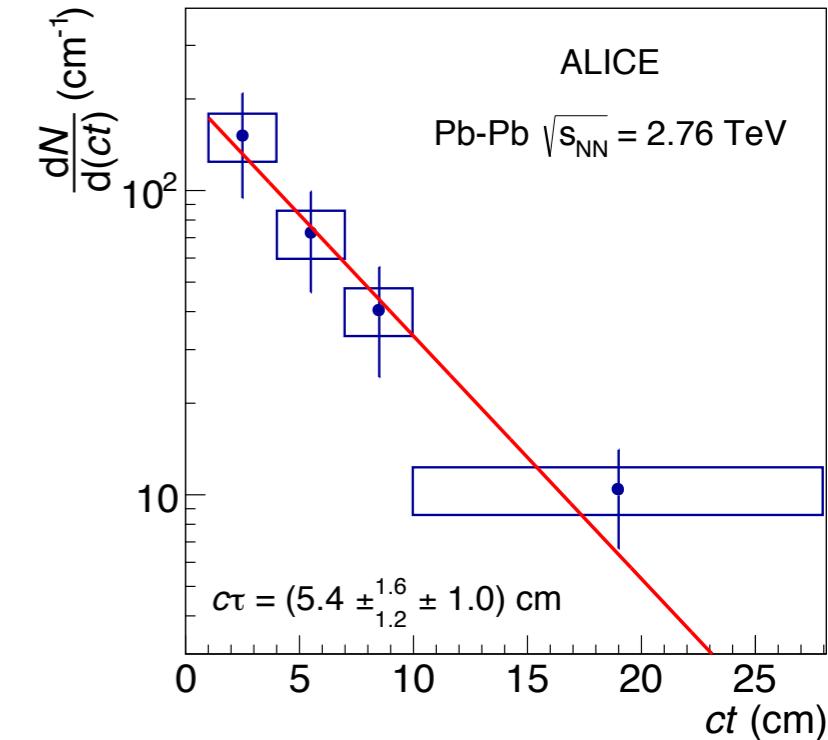
- Introduction
- Internal structure (τ and B_Λ)
- Production yields in heavy-ion collisions
- Outlook



Hypertriton lifetime puzzle



- Lifetime extracted by measuring the yields as a function of the proper decay length

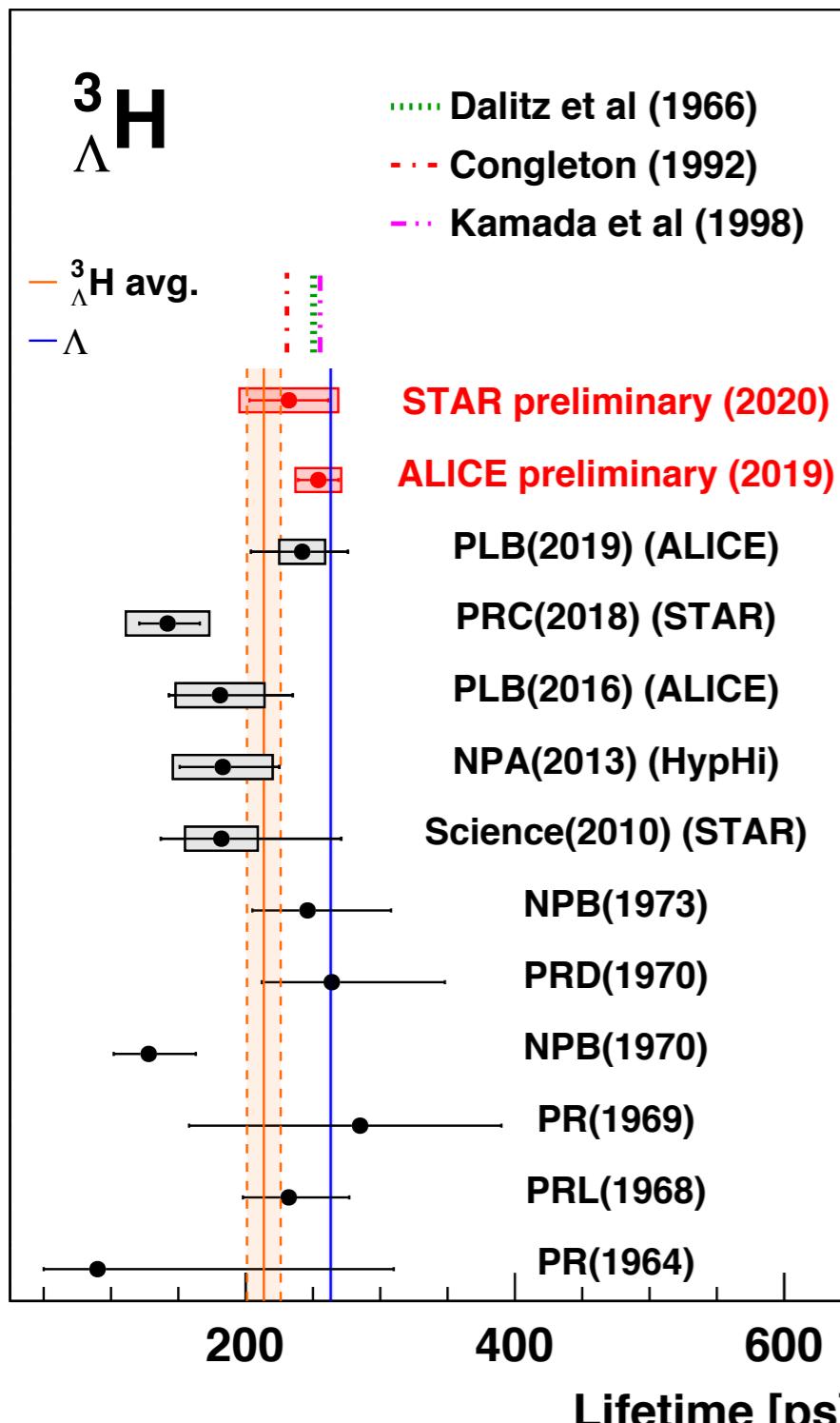


[ALICE, PLB797 \(2019\) 134905](#)

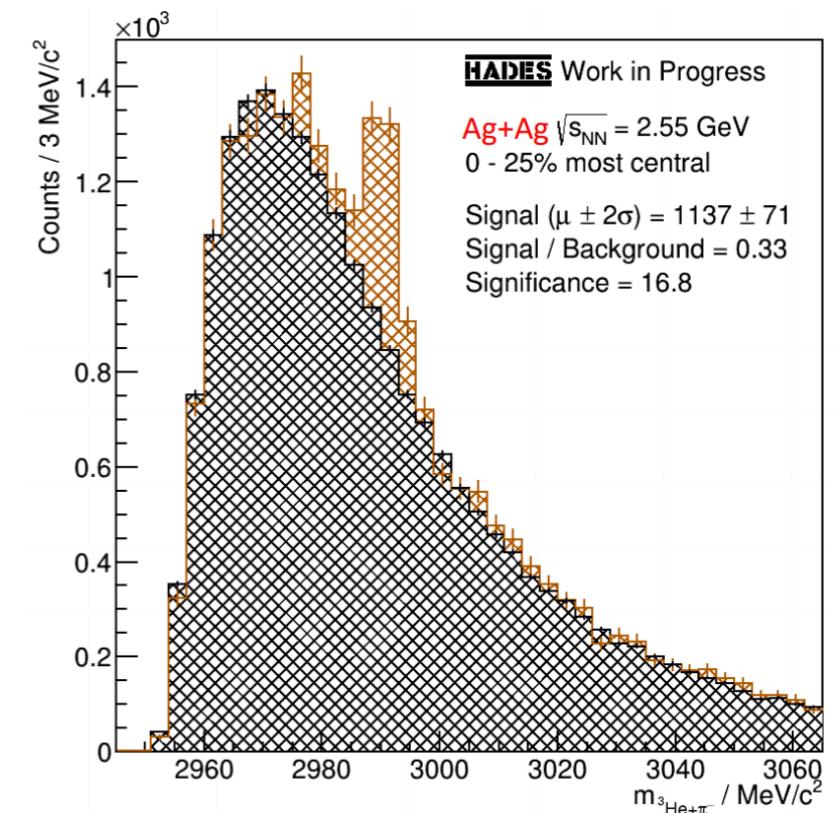
- Theory expects lifetime of hypertriton close to the lambda lifetime (>90% τ_Λ)
- STAR/HypHI reported lifetimes 30-40% shorter than τ_Λ , albeit with large unc.

→ Hypertriton lifetime puzzle

Hypertriton lifetime puzzle

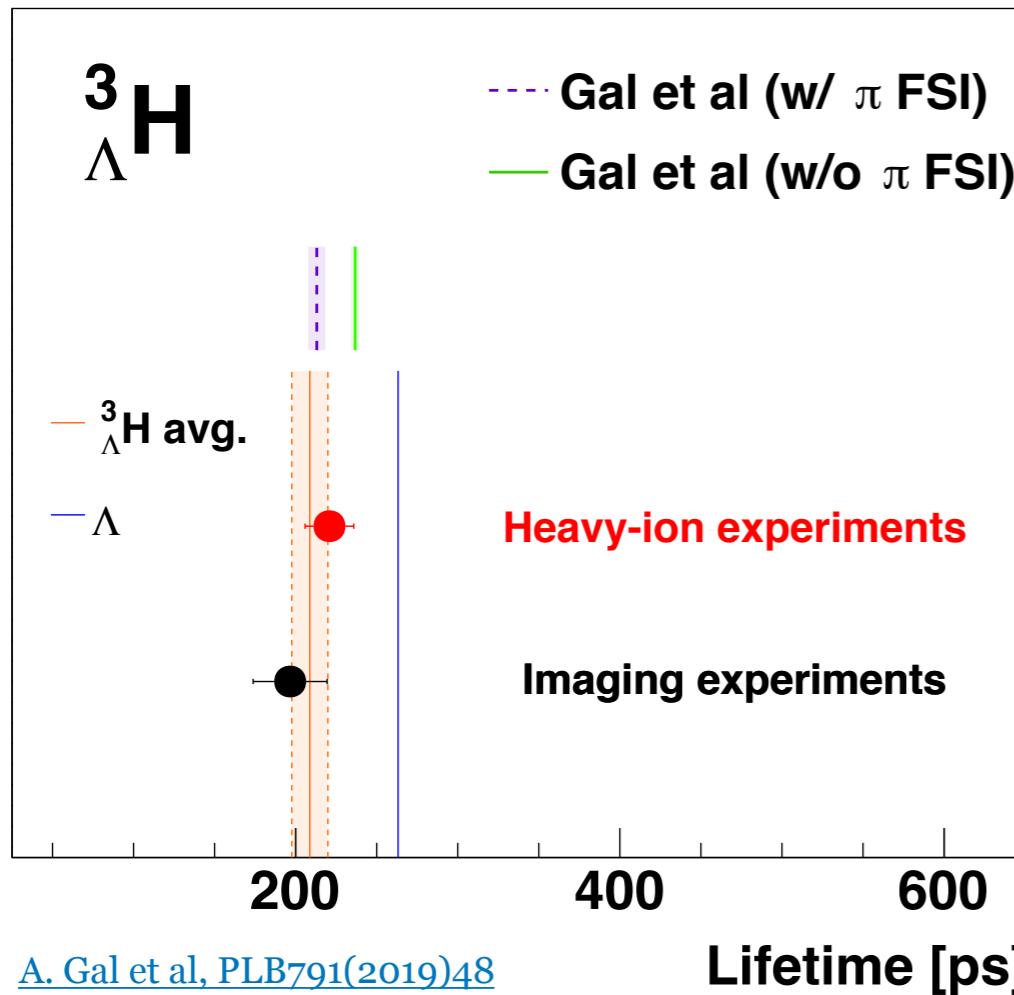


- Recent measurements by STAR / ALICE
- Current Experimental average
 $(81 \pm 5)\% \tau_\Lambda$
- STAR BES-II,
LHC run 3,
HADES expected
to further reduce
the uncertainty



S. Spies (HADES) SQM2021

Hypertriton lifetime puzzle

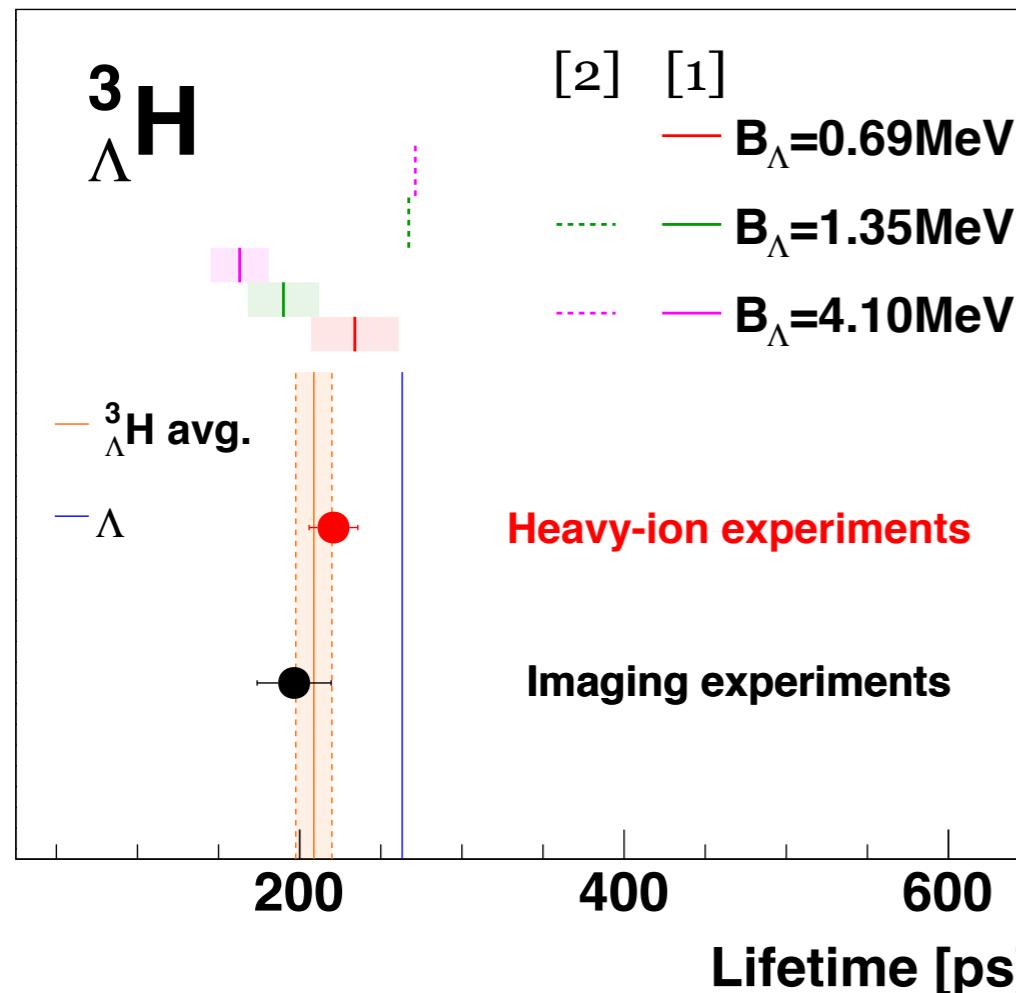


[A. Gal et al, PLB791\(2019\)48](#)

- Recent studies from Gal et. al. indicates that pion FSI may decreases ${}^3_{\Lambda} \text{H}$ lifetime by ~10%

Measurements from HIC experiments significantly improve the precision

Hypertriton lifetime puzzle



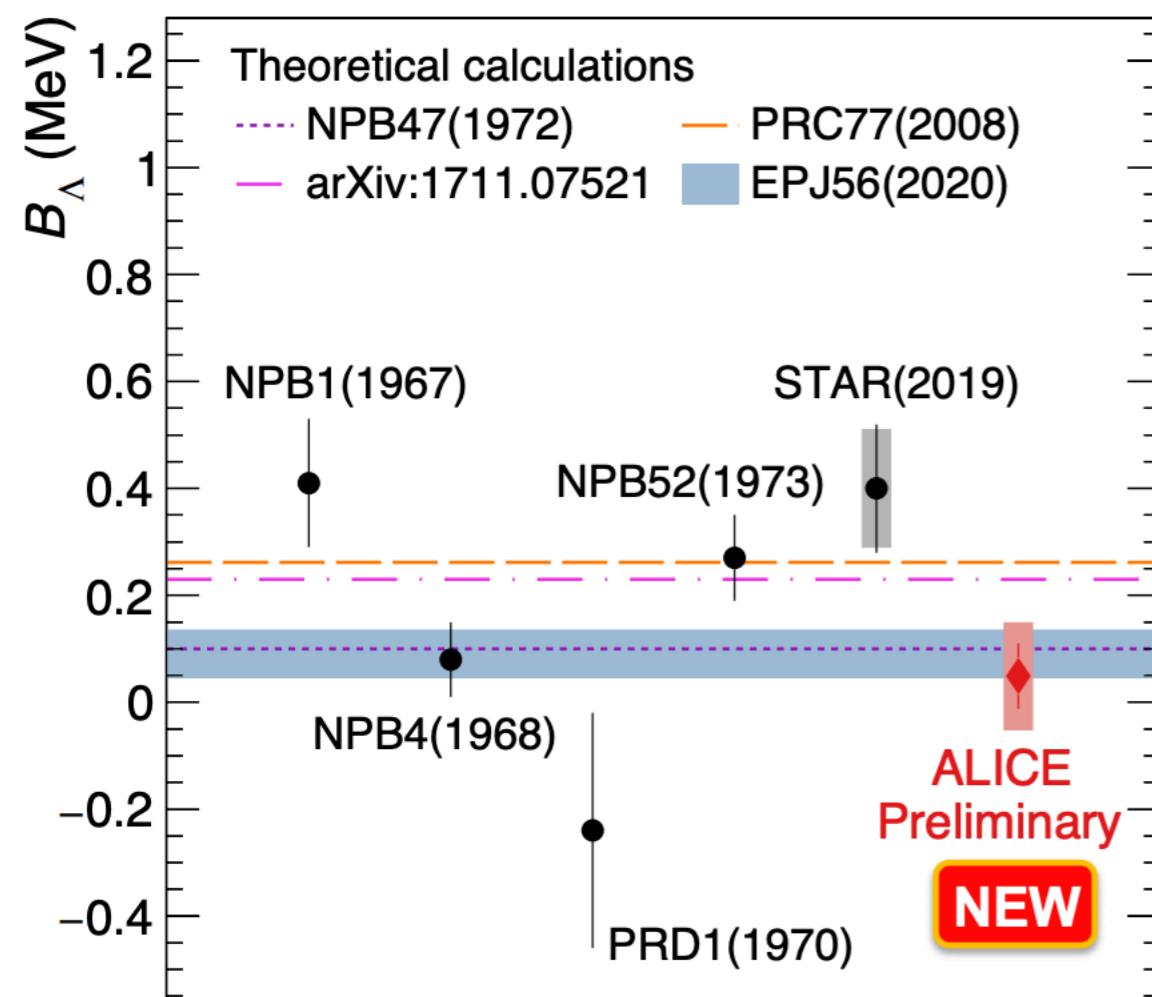
- Recent studies from Gal et. al. indicates that pion FSI may decreases ${}^3_{\Lambda} \text{H}$ lifetime by ~10%
- Off-shell pionic weak decay/ uncertainty in lambda separation energy may affect the ${}^3_{\Lambda} \text{H}$ lifetime ~O(10%)
- Relationship between τ and B_{Λ} suggested

[1] A. Pérez-Obiol et al, PLB811(2020)135916

[2] F. Hildenbrand et al, PRC102(2020)064002

Active progress both experimentally and theoretically
→ working towards a precise understanding of the ${}^3_{\Lambda} \text{H}$ lifetime

Hypertriton Λ separation energy



Pietro Fecchio (ALICE), SQM2021

- STAR (2019) :

$$B_\Lambda(^3\text{H}) = 0.41 \pm 0.12(\text{stat}) \pm 0.11(\text{syst}) [\text{MeV}]$$

- Seemingly in tension with

emulsion experiments $B_\Lambda(^3\text{H}) = 0.13 \pm 0.05$ [MeV]

- Recalibration of emulsion measurements using updated nucleon/hyperon masses gives

$$B_\Lambda(^3\text{H}) = 0.27 \pm 0.08$$
 [MeV]

[Peng Liu et al, Chinese Phys. C 43\(2019\)124001](#)

- ALICE (2021) : **NEW!**

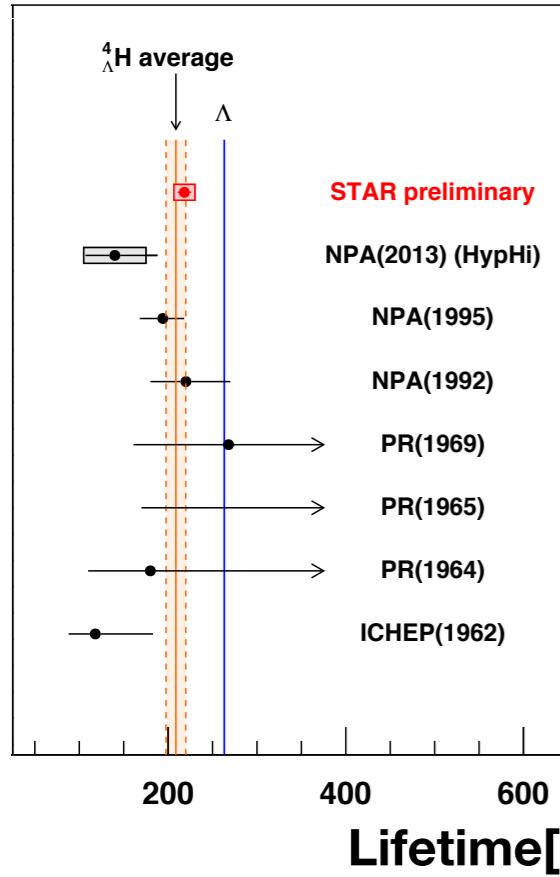
$$B_\Lambda(^3\text{H}) = 0.05 \pm 0.06(\text{stat}) \pm 0.10(\text{syst})$$
 [MeV]

A precise measurement on $B_\Lambda(^3\text{H})$ is important

- Strong influence on production yield
- Potential impact on lifetime

A=4 hypernuclei

${}^4_{\Lambda}\text{H}$ Lifetime

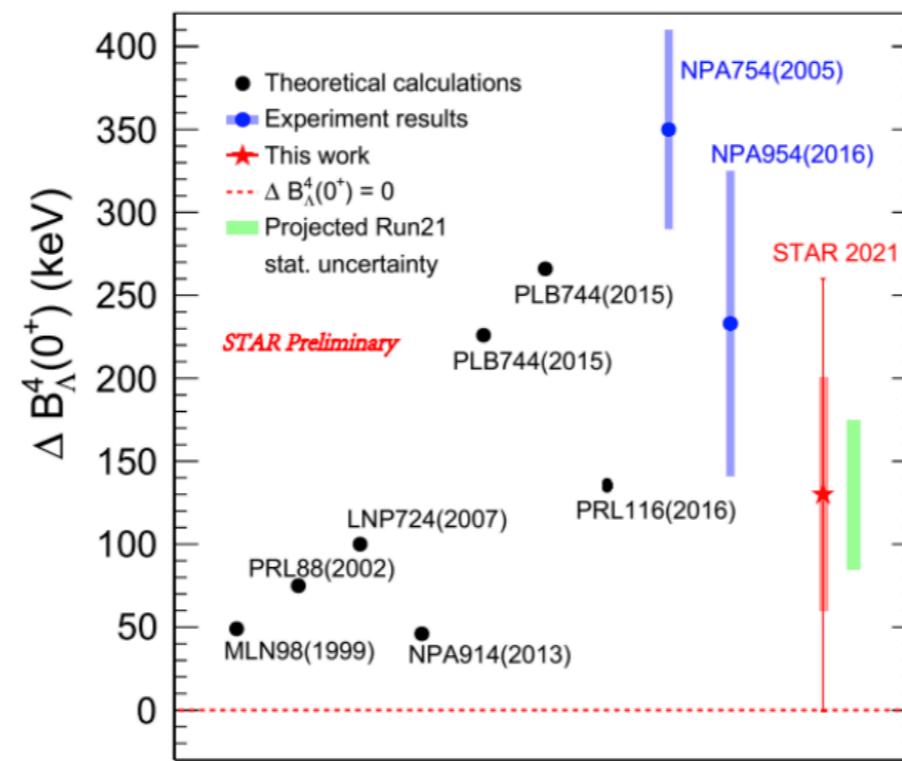


[Chenlu Hu \(STAR\), SQM2021](#)

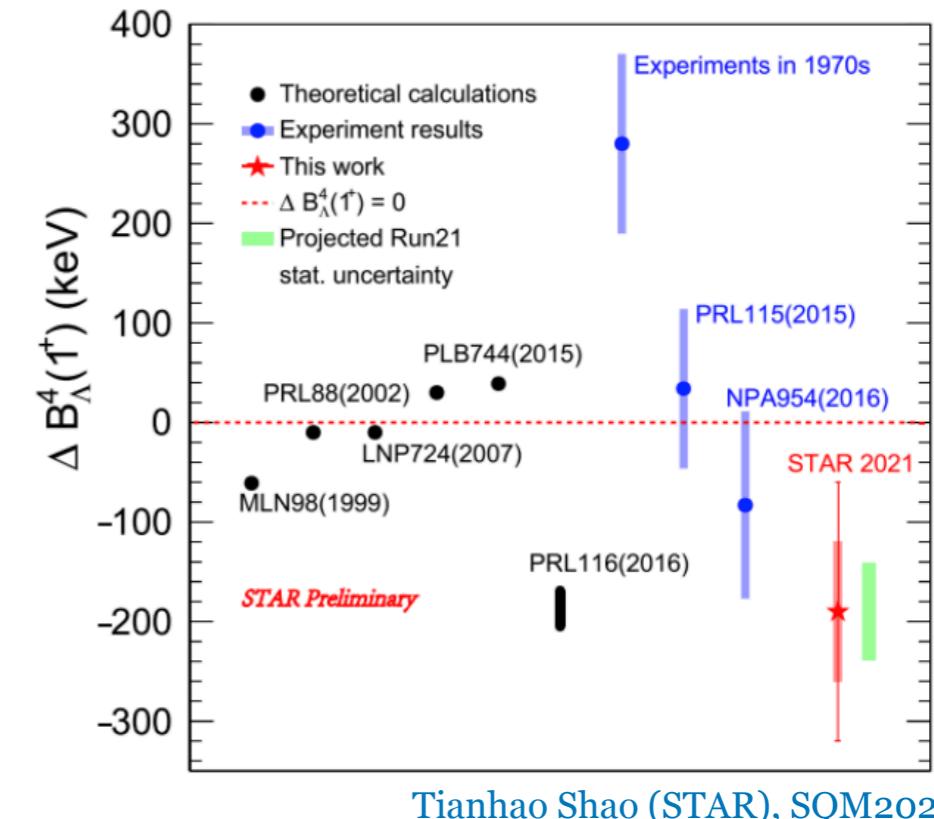
- Lifetime of ${}^4_{\Lambda}\text{H}$ and B_{Λ} of ${}^4_{\Lambda}\text{H}$, ${}^4_{\Lambda}\text{He}$ measured by STAR

- Non-zero $\Delta B_{\Lambda} = B_{\Lambda}({}^4_{\Lambda}\text{He}) - B_{\Lambda}({}^4_{\Lambda}\text{H})$ commonly known as charge symmetry breaking (CSB)
- STAR: $\Delta B_{\Lambda}(0^+) = 130 \pm 130(\text{stat}) \pm 70(\text{syst})[\text{keV}]$ **NEW!**
- Charge symmetry breaking (CSB) effects in ground and excited states are consistent with theoretical calculations

$\Delta B_{\Lambda}(0^+)$, ground state



$\Delta B_{\Lambda}(1^+)$, excited state



[Tianhao Shao \(STAR\), SQM2021](#)

$$\tau({}^4_{\Lambda}\text{H}) = 217 \pm 8(\text{stat}) \pm 12(\text{syst})[\text{ps}]$$

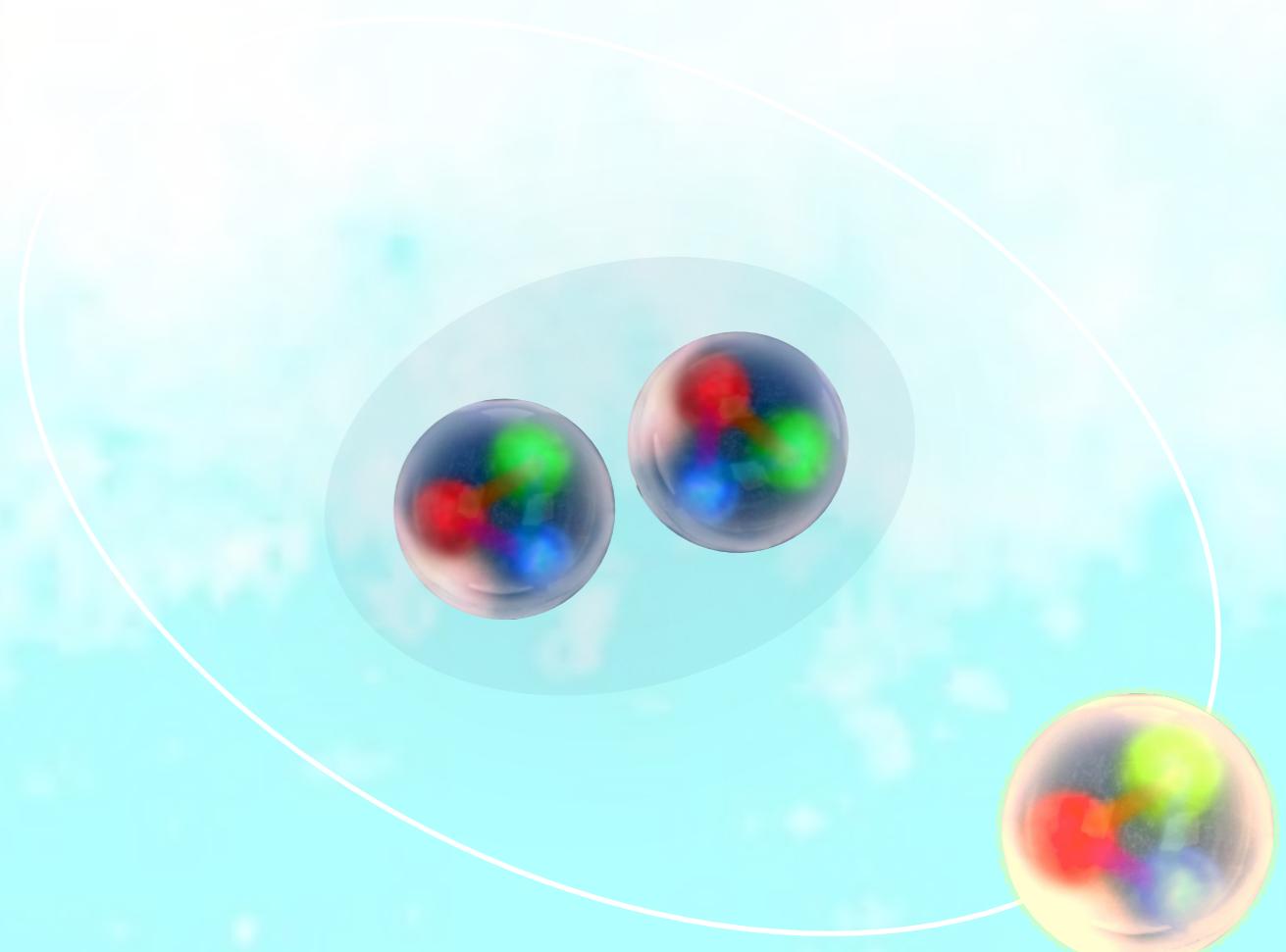
$$B_{\Lambda}({}^4_{\Lambda}\text{H}) = 2.24 \pm 0.06(\text{stat}) \pm 0.18(\text{syst})[\text{MeV}]$$

$$B_{\Lambda}({}^4_{\Lambda}\text{He}) = 2.37 \pm 0.12(\text{stat}) \pm 0.14(\text{syst})[\text{MeV}]$$

Summary 1

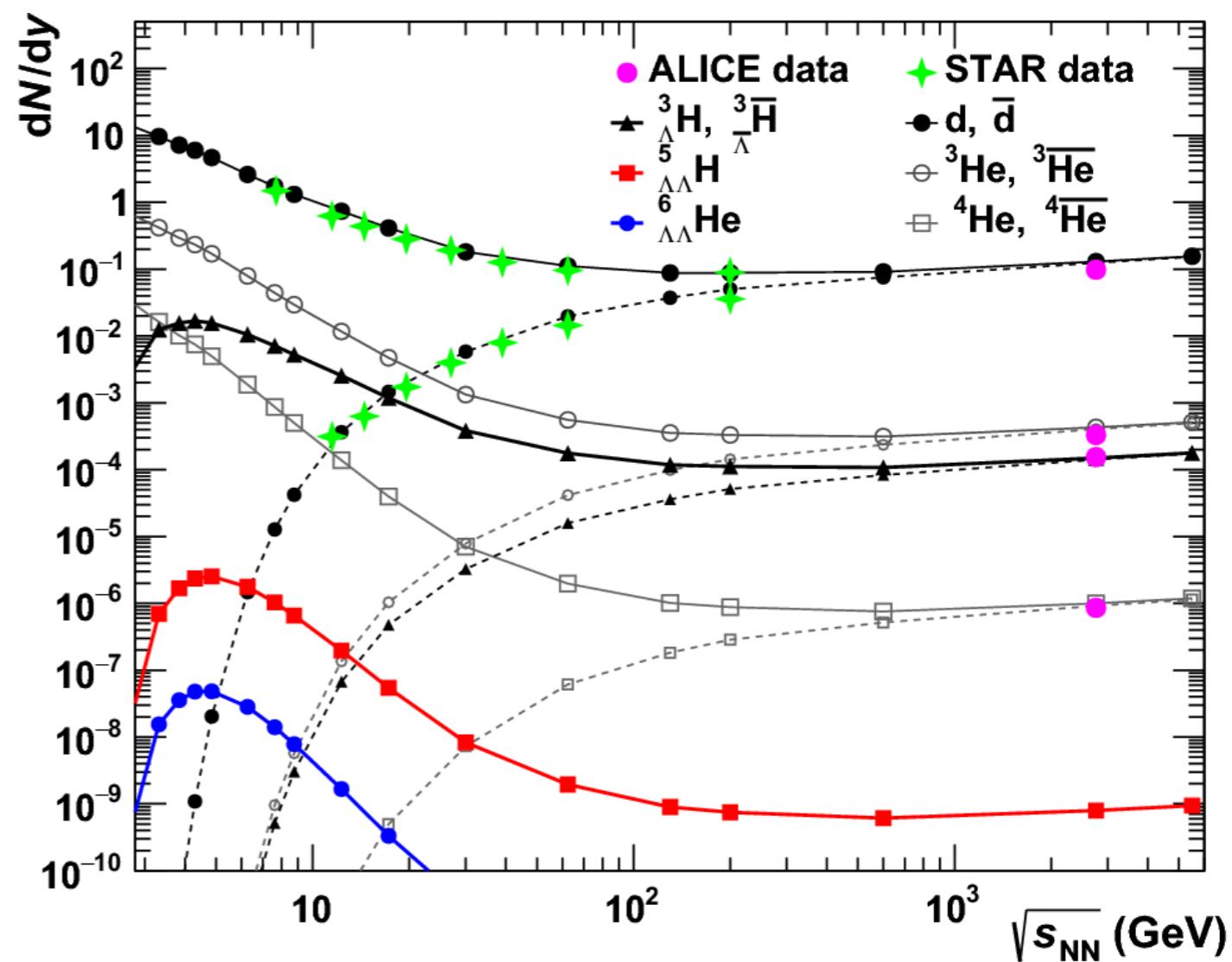
- HIC experiments give **precise** τ and B_Λ of light/anti hypernuclei
 - High statistics data
→ Systematic uncertainties become more important
 - Tighter constraints on the Y-N interaction and hypernuclear structure
 - Important input in understanding the production yield light/anti hypernuclei in HIC

- Introduction
- Internal structure (τ and B_Λ)
- **Production in heavy-ion collisions**
- Outlook



Theoretical models on hypernuclei production in HIC

- Statistical thermal models
 - Hadron yields described within a hadro-chemical equilibrium model
 - chemical freeze-out temp. T
 - baryo-chemical potential μ_b
 - Light nuclei and strange particle yields well described
 - Canonical strangeness suppression in low multiplicity environments
 - **Internal structure of hypernuclei plays no role**

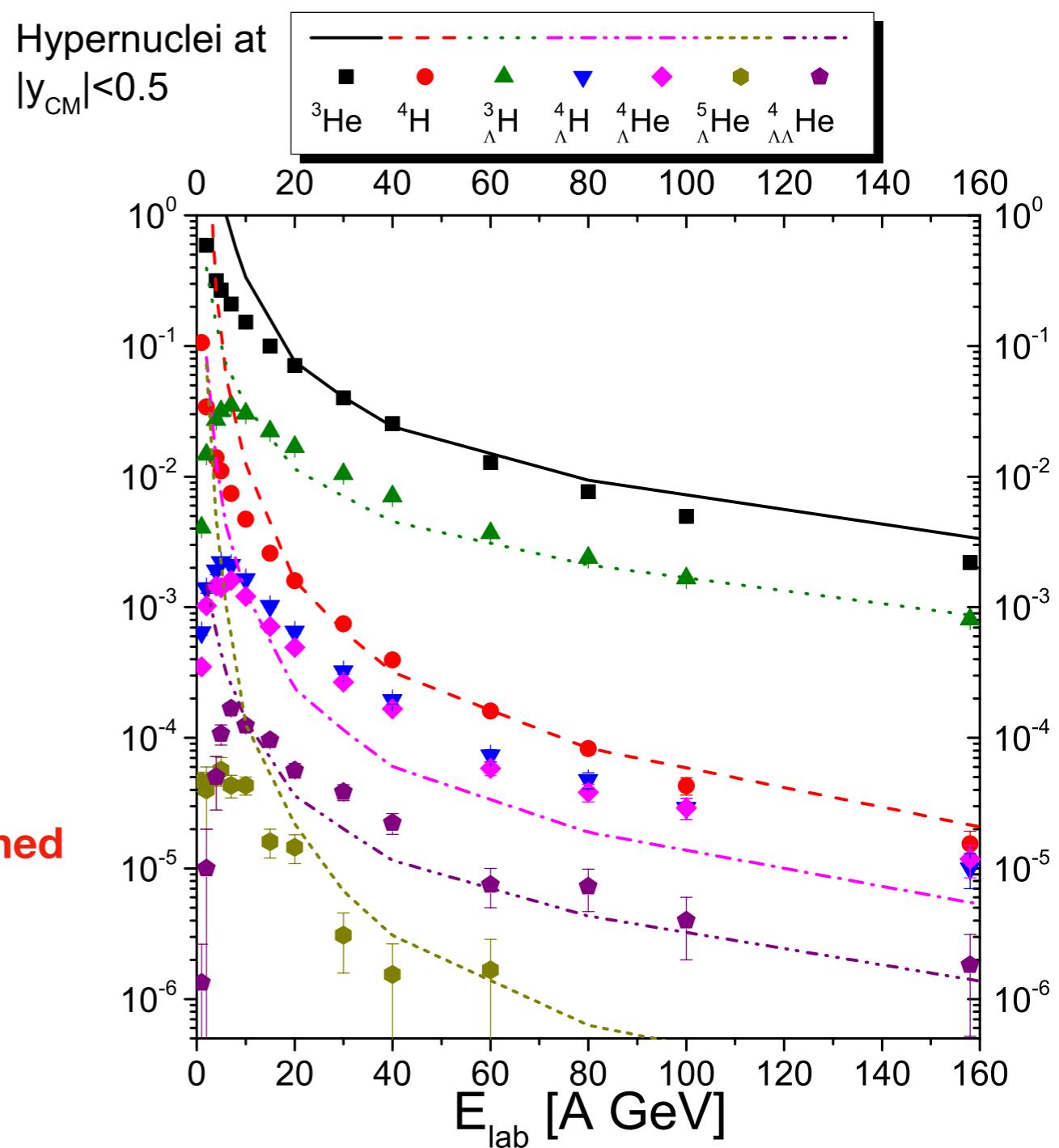


[B. Dönigus, Eur. Phys. J. A \(2020\) 56:280](#)
[A. Andronic et al, PLB 697 \(2011\) 203](#)

• *Can thermal models describe hypernuclei production in the high baryon density region?*

Theoretical models on hypernuclei production in HIC

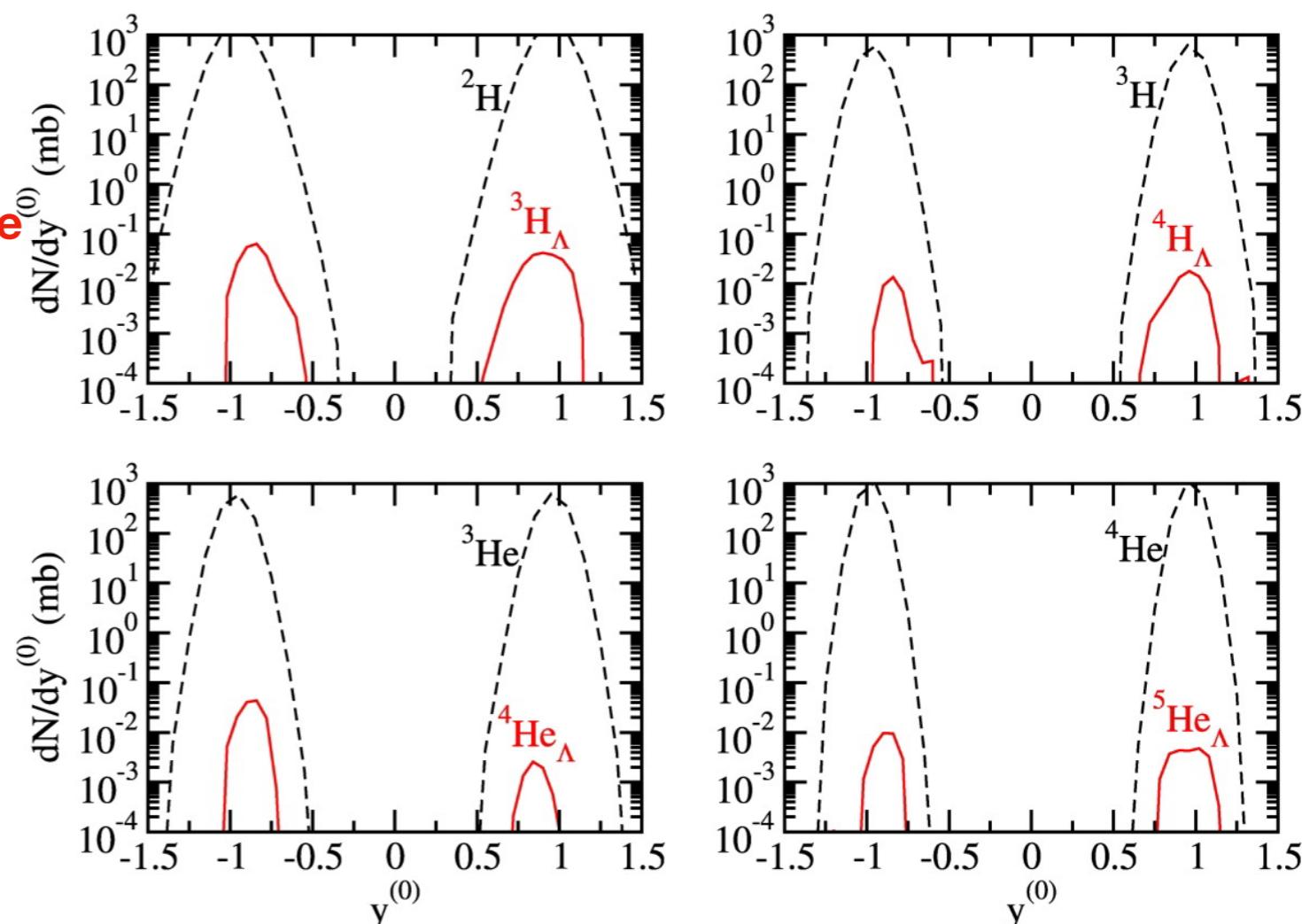
- Statistical thermal models
 - Central HIC
 - Unrelated to hypernuclei internal structure
- Coalescence models
 - Mechanism for composite particles formation from constituents
 - Proximity of nucleons in momentum and(or) coordinate space
 - Hypernuclei data are scarce
 - coalescence parameters not well constrained
 - sensitive to B_Λ
 - Produced hypernuclei can break apart immediately after formation
 - sensitive to the time evolution of produced matter
 - Coalescence and thermal model predictions typically give similar results in HIC



[J. Steinheimer et al, PLB714\(2012\),85](#)

Theoretical models on hypernuclei production in HIC

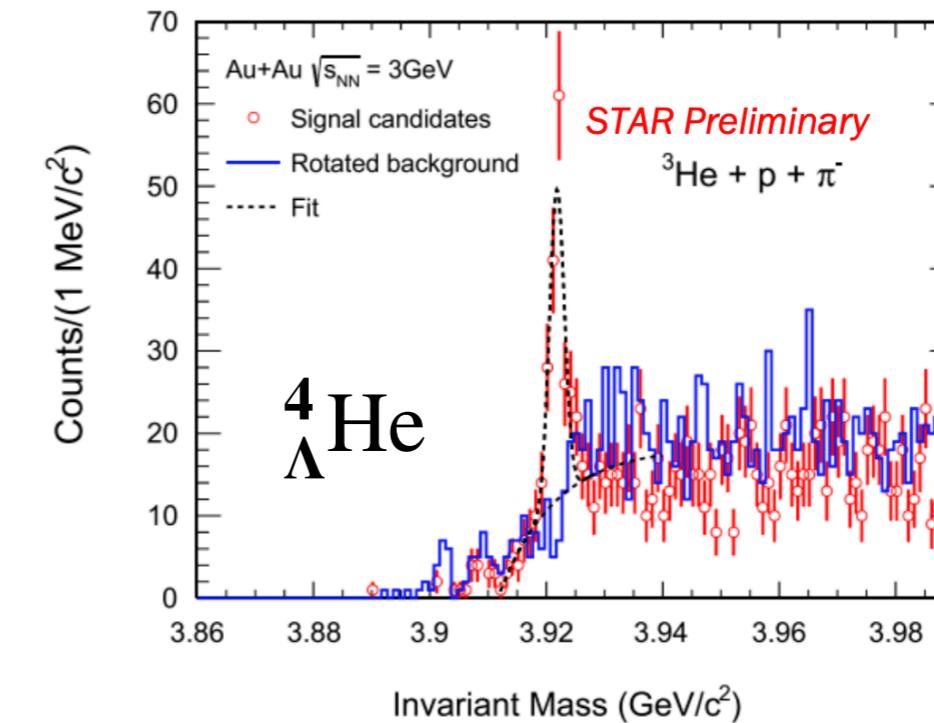
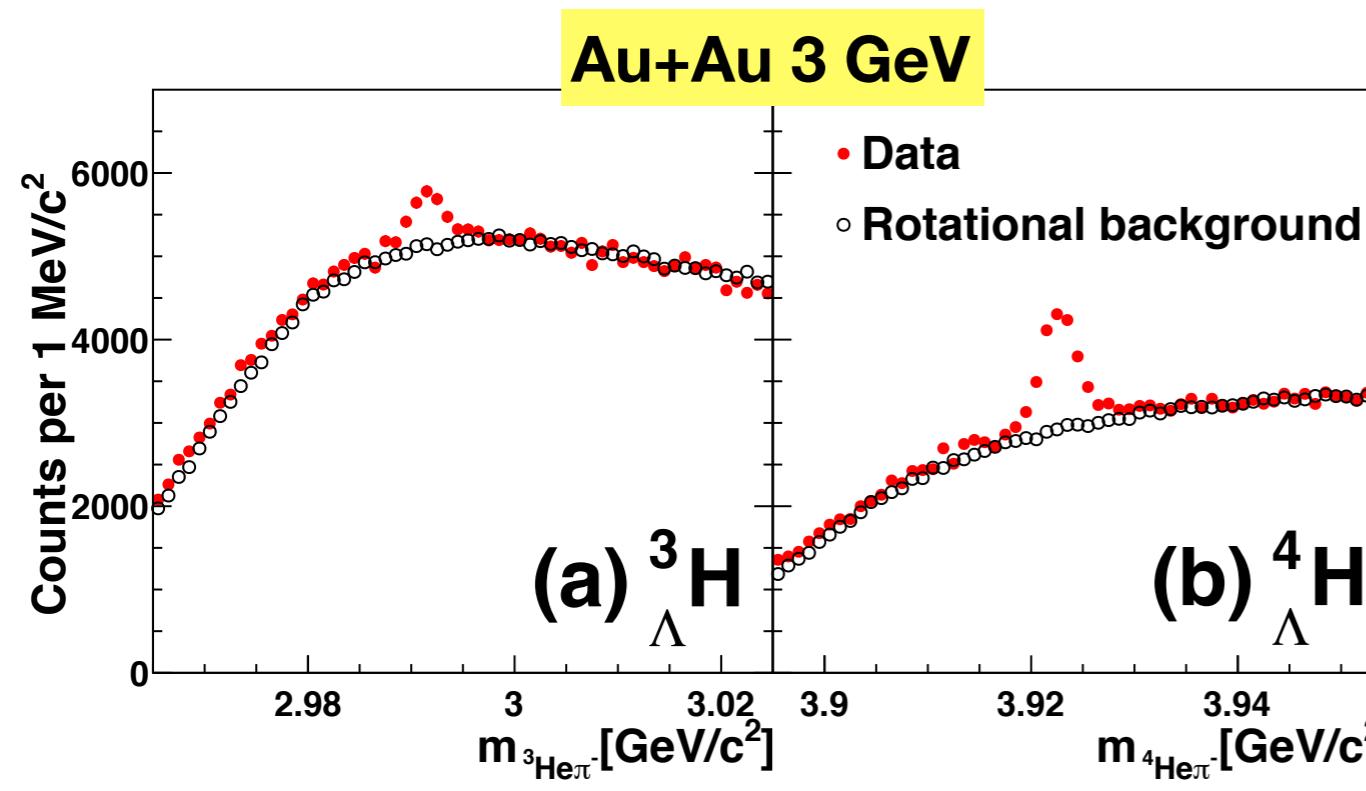
- Statistical thermal models
 - Central HIC
 - Unrelated to hypernuclei internal structure
- Coalescence models
 - Central HIC
 - Sensitive to B_Λ , properties of matter created, etc.
- Spectator hypermatter production
 - Capture of hyperons by spectator matter
→ Formation of excited matter containing a strangeness admixture → Fragmentation
 - Non-central HIC spectator region, LIC
 - Exotic/heavy hypernuclei (?)



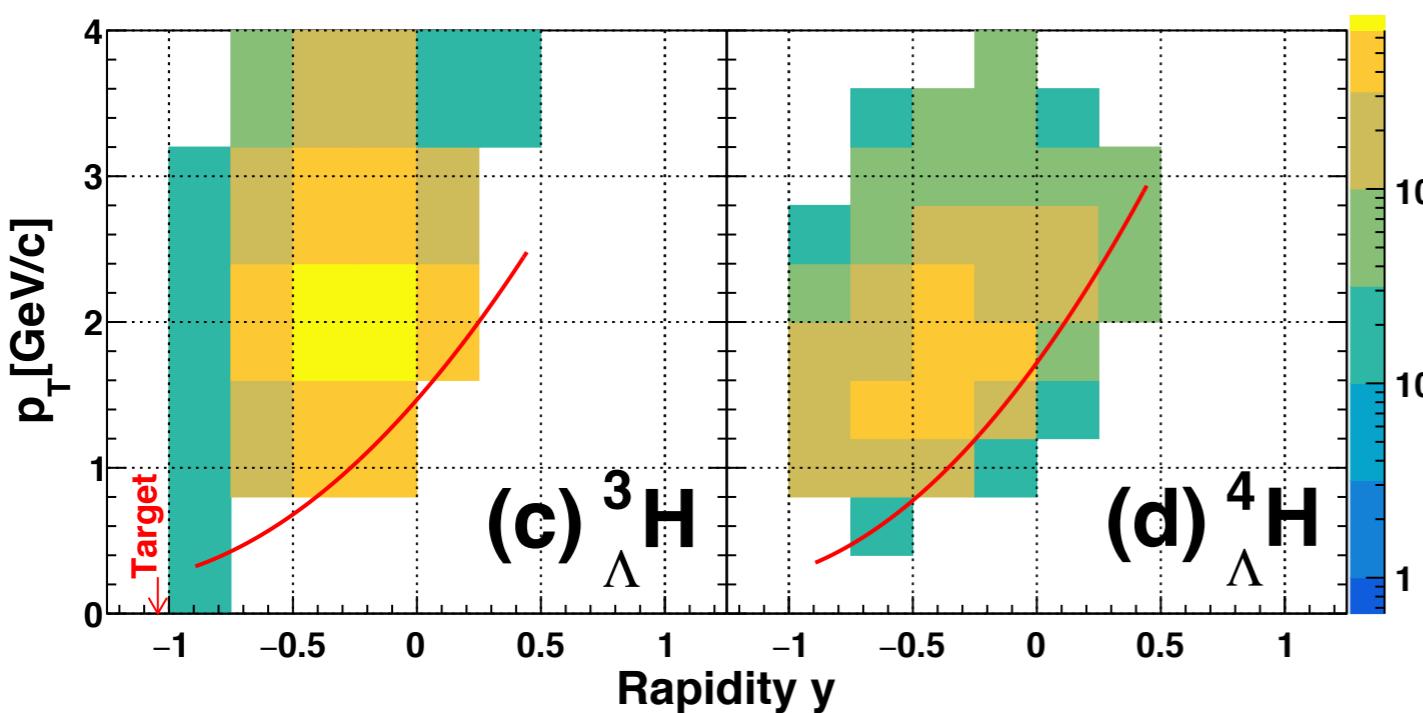
Spectator fragmentation calculation in C+C@2A GeV

[T.Gaitanos et al PLB 675\(2009\)297](#)

Hypernuclei in 3 GeV Au+Au collisions



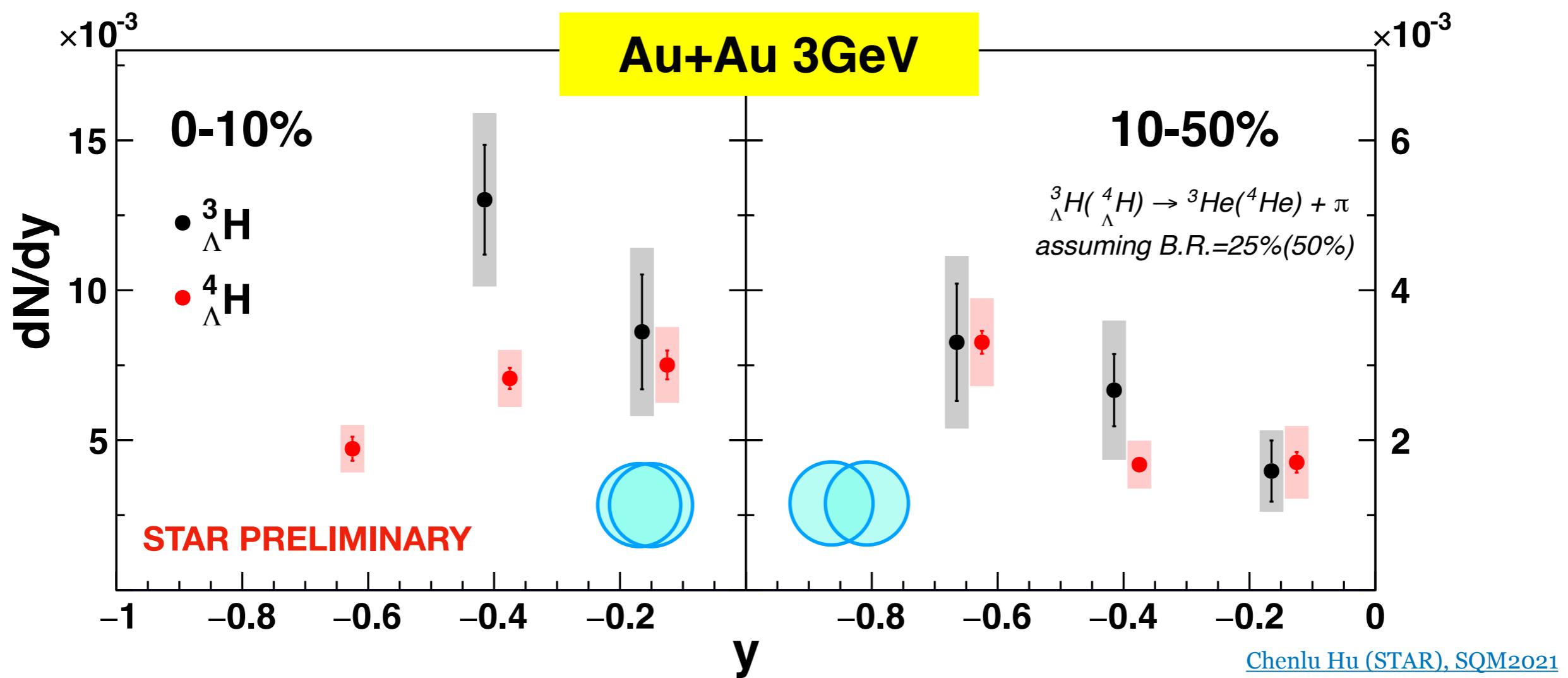
[Tianhao Shao \(STAR\), SQM2021](#)



[Yue-Hang Leung \(STAR\), CPOD2021](#)

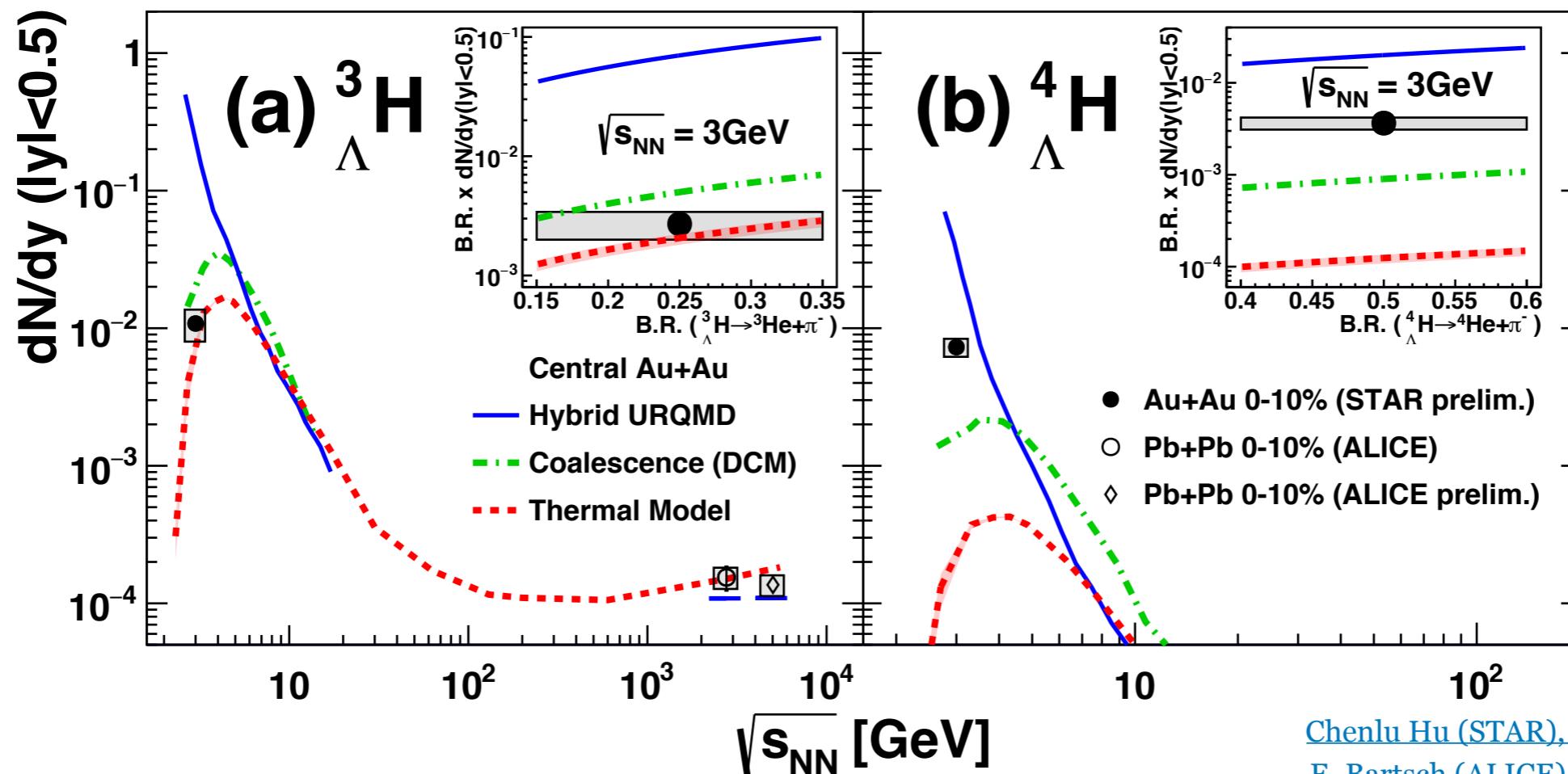
- STAR: Au+Au @ $\sqrt{s_{\text{NN}}} = 3 \text{ GeV}$ **NEW!**
 - ${}^3_{\Lambda}\text{H}$: significance ~ 10
 - ${}^4_{\Lambda}\text{H}$: significance ~ 30
 - ${}^4_{\Lambda}\text{He}$: significance ~ 10
- Mid-rapidity coverage

Rapidity dependence at $\sqrt{s_{\text{NN}}} = 3 \text{ GeV}$



- First measurement of rapidity distributions of hypernuclei in HIC
 - Different trends in rapidity distribution in central (0-10%) and mid-central (10-50%) collisions for ${}^4_{\Lambda}H$
 - Possible due to spectator reactions in non-central

Hypernuclei yields vs $\sqrt{s_{\text{NN}}}$ in central HIC



- ALICE ${}^3\Lambda\text{H} + {}^3\bar{\Lambda}\text{H}$: Pb+Pb @ $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}, 5.02 \text{ TeV}$
- STAR ${}^3\Lambda\text{H}, {}^4\Lambda\text{H}$: Au+Au @ $\sqrt{s_{\text{NN}}} = 3 \text{ GeV}$ **NEW!**

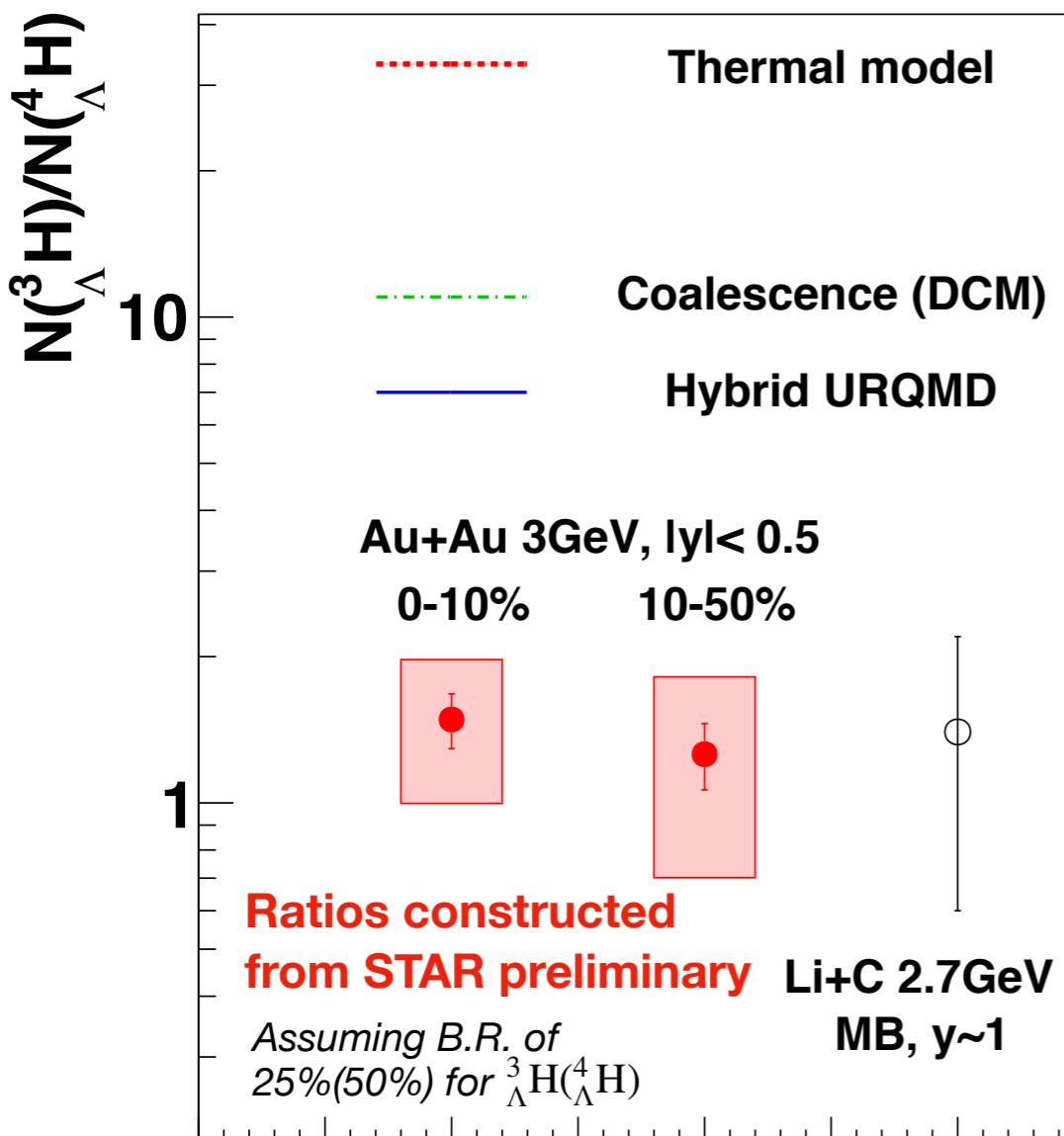
[Chenlu Hu \(STAR\), SQM2021](#)
[E. Bartsch \(ALICE\), NPA1005\(2021\)121791](#)
[ALICE, PLB 754 \(2016\)360](#)

- Thermal model (GSI-Heidelberg) which adopts the canonical ensemble and coalescence (DCM) model describes ${}^3\Lambda\text{H}$ yield at 3 GeV
- Yield of ${}^4\Lambda\text{H}$ not described by any model

[J. Steinheimer et al, PLB714\(2012\),85](#)
[\(Hybrid URQMD, Coalescence\(DCM\)\)](#)

[PLB 697 \(2011\)203 \(updated, preliminary\) \(Thermal Model\)](#)

Hypernuclei ratio at $\sqrt{s_{\text{NN}}} = 3 \text{ GeV}$



[J. Steinheimer et al, PLB714\(2012\),85
\(Hybrid URQMD, Coalescence\(DCM\)\)](#)

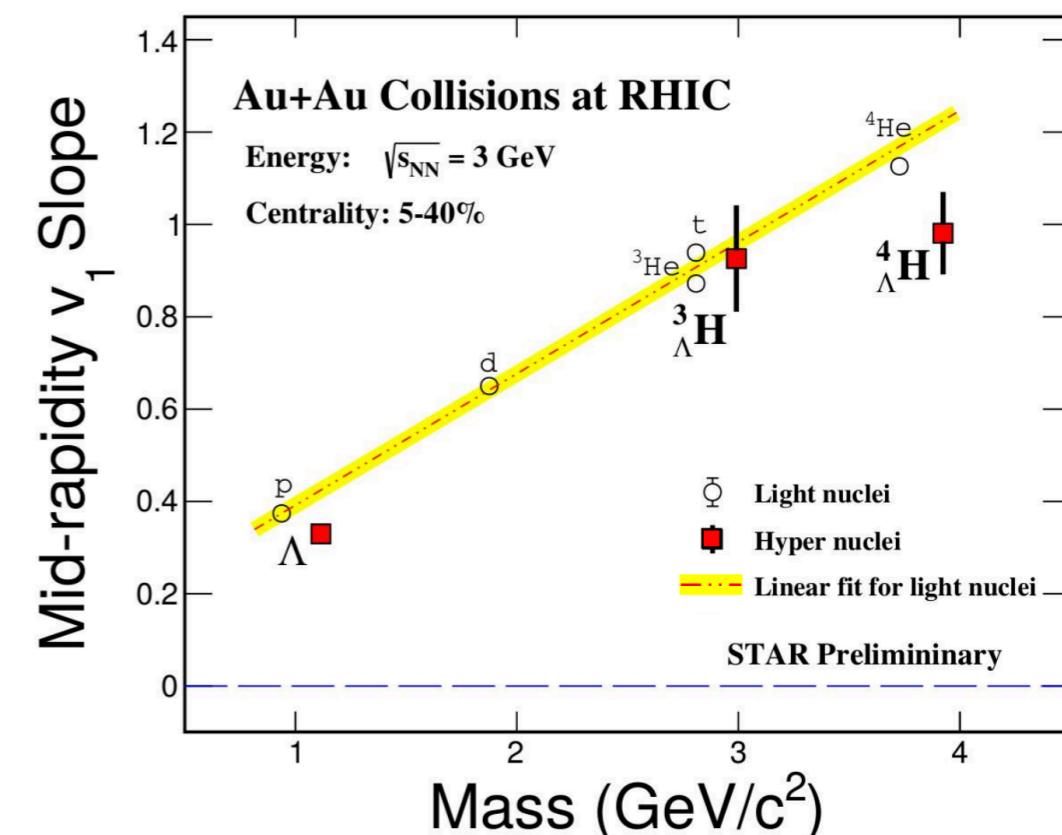
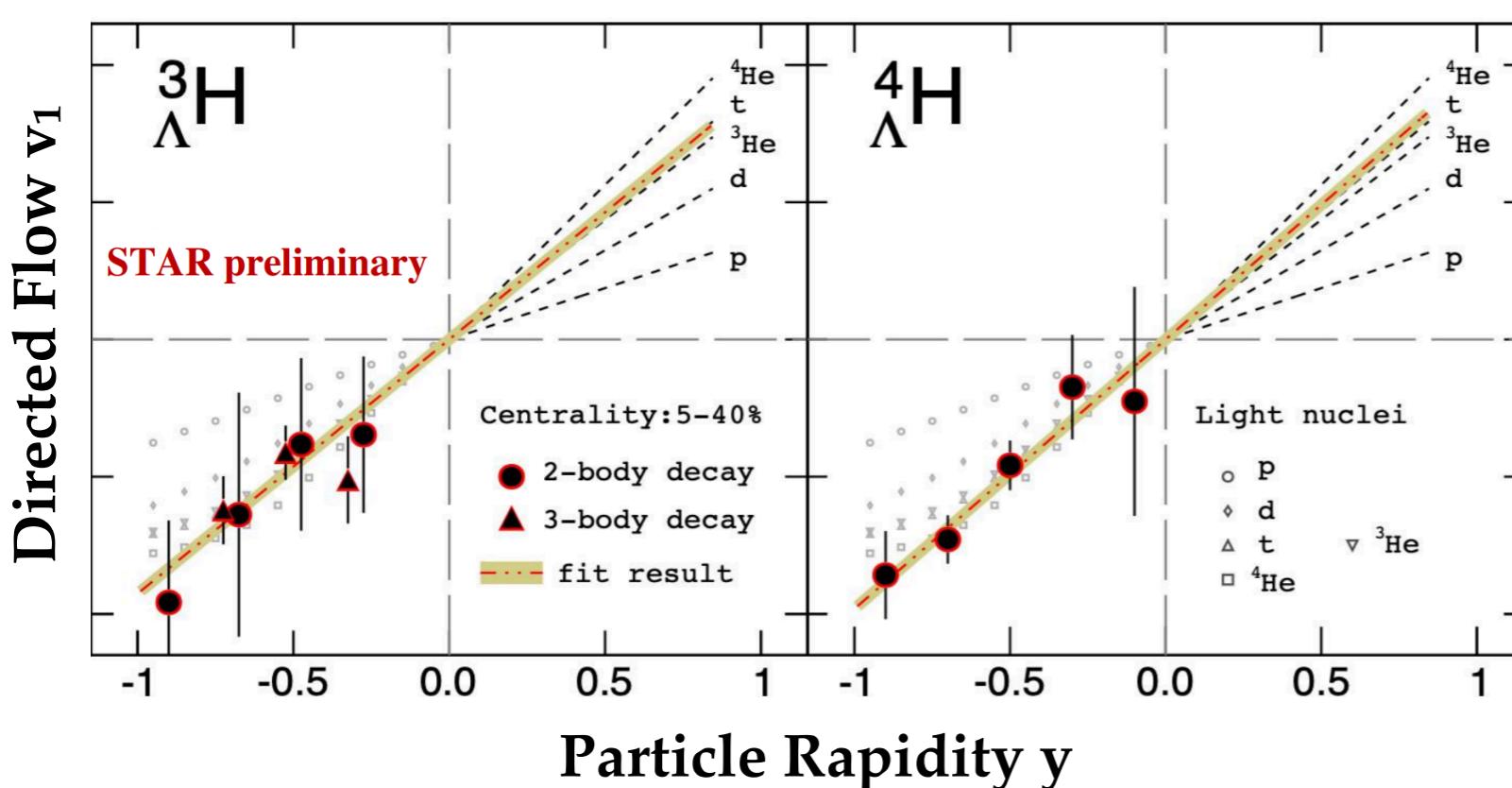
[PLB 697 \(2011\)203 \(updated,
preliminary\) \(Thermal Model\)](#)

[HypHI, Phys. Lett. B747, 129 \(2015\)](#)

- Coalescence parameters cancel when taking ratio of hypernuclei
- $\frac{N(\Lambda^3H)}{N(\Lambda^4H)} = 1.5 \pm 0.5$, models overpredict this ratio

Indicates the production of loosely bound objects in high baryon density region not fully understood

Hypernuclei directed flow v_1 , Au+Au 3 GeV



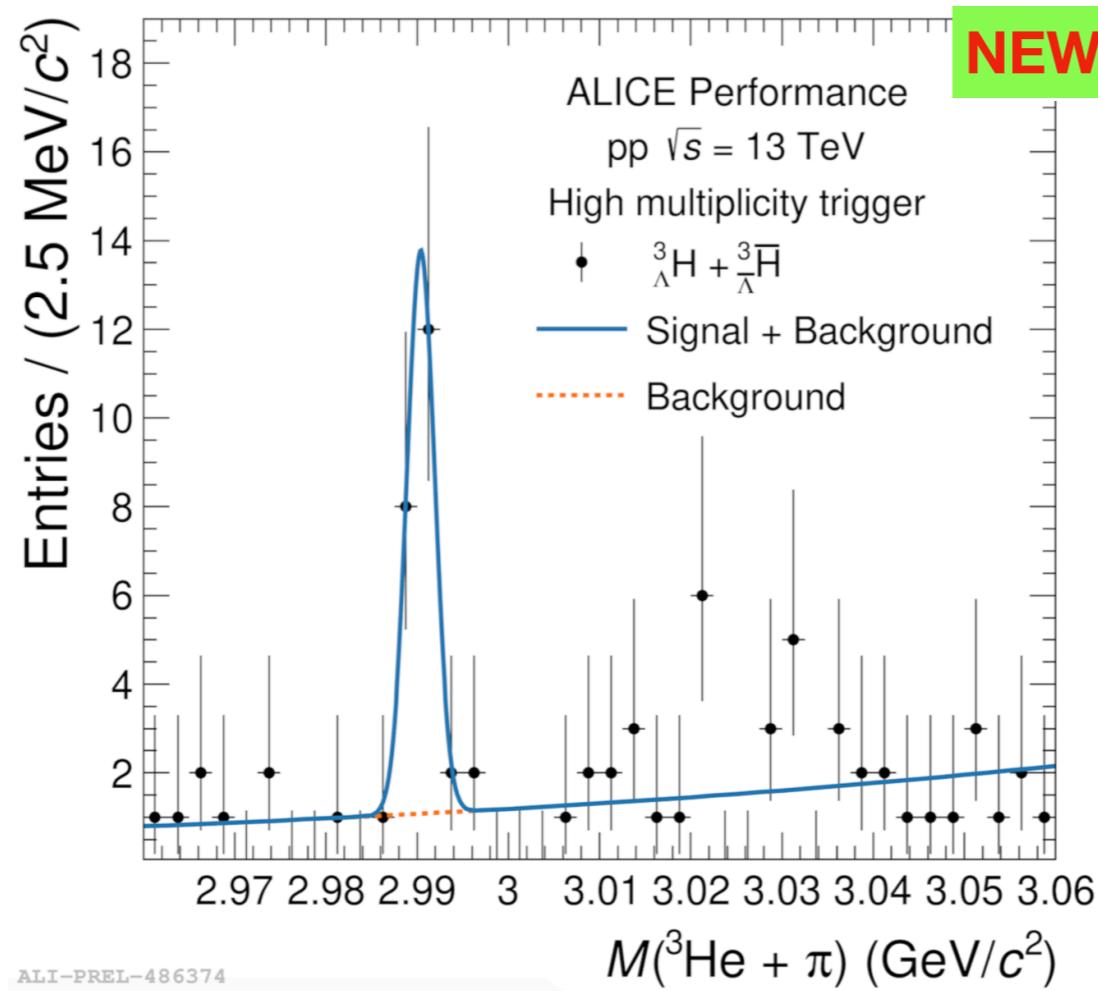
[Chenlu Hu \(STAR\), SQM2021](#)

- First observation of hypernuclei collectivity v_1 in HI collisions
- v_1 slope follow baryon number scaling in 5-40% 3 GeV Au+Au collisions

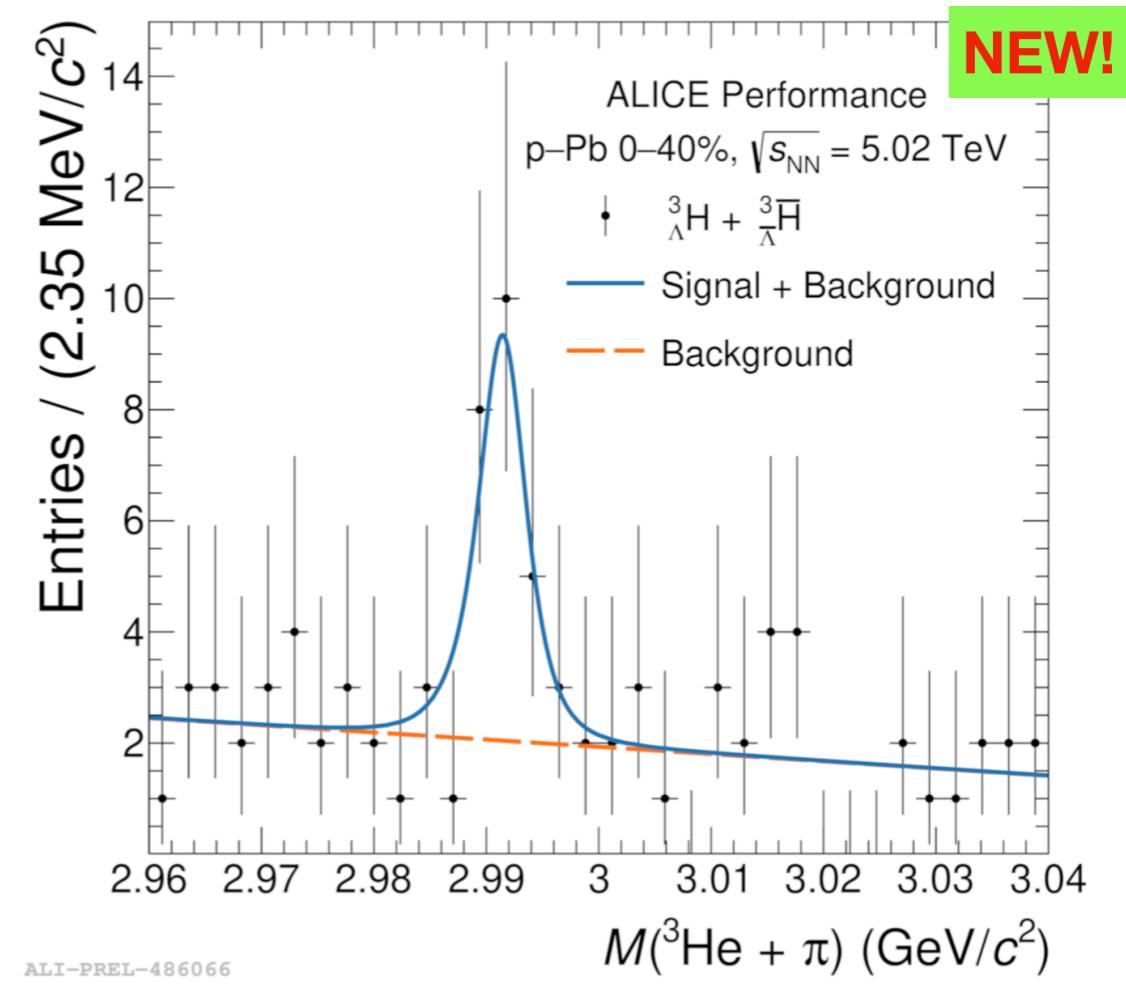
Results consistent with hypernuclei production from coalescence of hyperons and nucleons at mid-rapidity

Hypernuclei in small systems

p+p @ $\sqrt{s} = 13$ TeV, high multiplicity



p+Pb @ $\sqrt{s_{\text{NN}}} = 5.02$ TeV, 0-40%



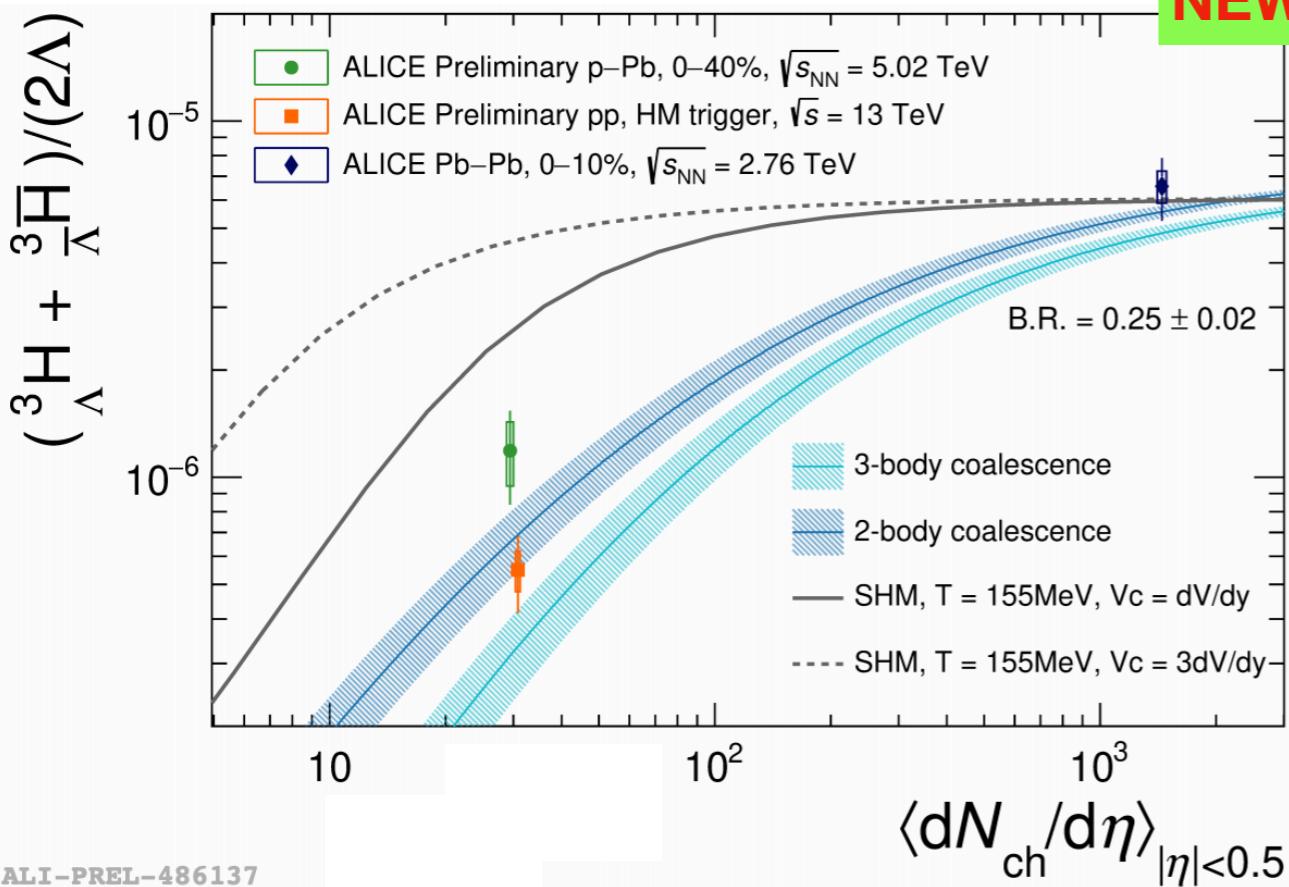
[Pietro Fecchio \(ALICE\), SQM2021](#)

- ALICE: p+p @ $\sqrt{s} = 13$ TeV, high multiplicity
- ALICE: p+Pb @ $\sqrt{s_{\text{NN}}} = 5.02$ TeV, 0-40%
- ${}^3_{\Lambda}\text{H} + {}^3_{\bar{\Lambda}}\bar{\text{H}}$ signal observed with $\sim 5\sigma$ significance

Hypernuclei in small systems

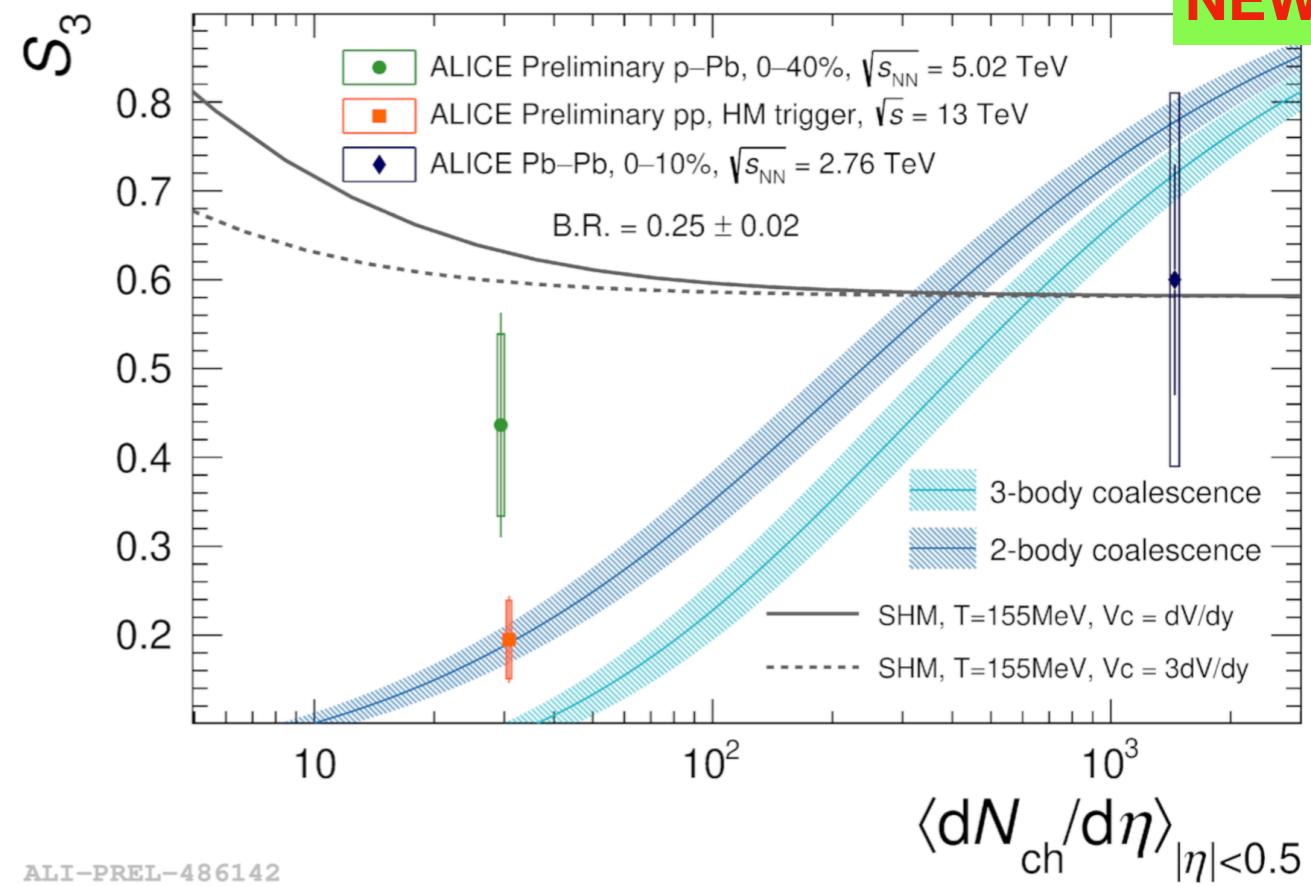
$$\frac{\Lambda^3 H + \bar{\Lambda}^3 \bar{H}}{2\Lambda}$$

NEW!



$$S_3 = \frac{\Lambda^3 H}{^3 He} \times \frac{p}{\Lambda}$$

NEW!



[Pietro Fecchio \(ALICE\), SQM2021](#)

- **p+p** data tension with SHM, consistent with **2-body coalescence**
- **p+Pb** data excludes some SHM configs., consistent with **2-body coalescence**, **3-body coalescence** slightly disfavored

[V. Vovchenko et al., PLB 785 \(2018\)171, PRC 100 \(2019\) 054906 \(SHM\)](#)
[K.-J. Sun et al., PLB 792\(\(2019\)132\(Coalescence Model\)](#)

Summary 2

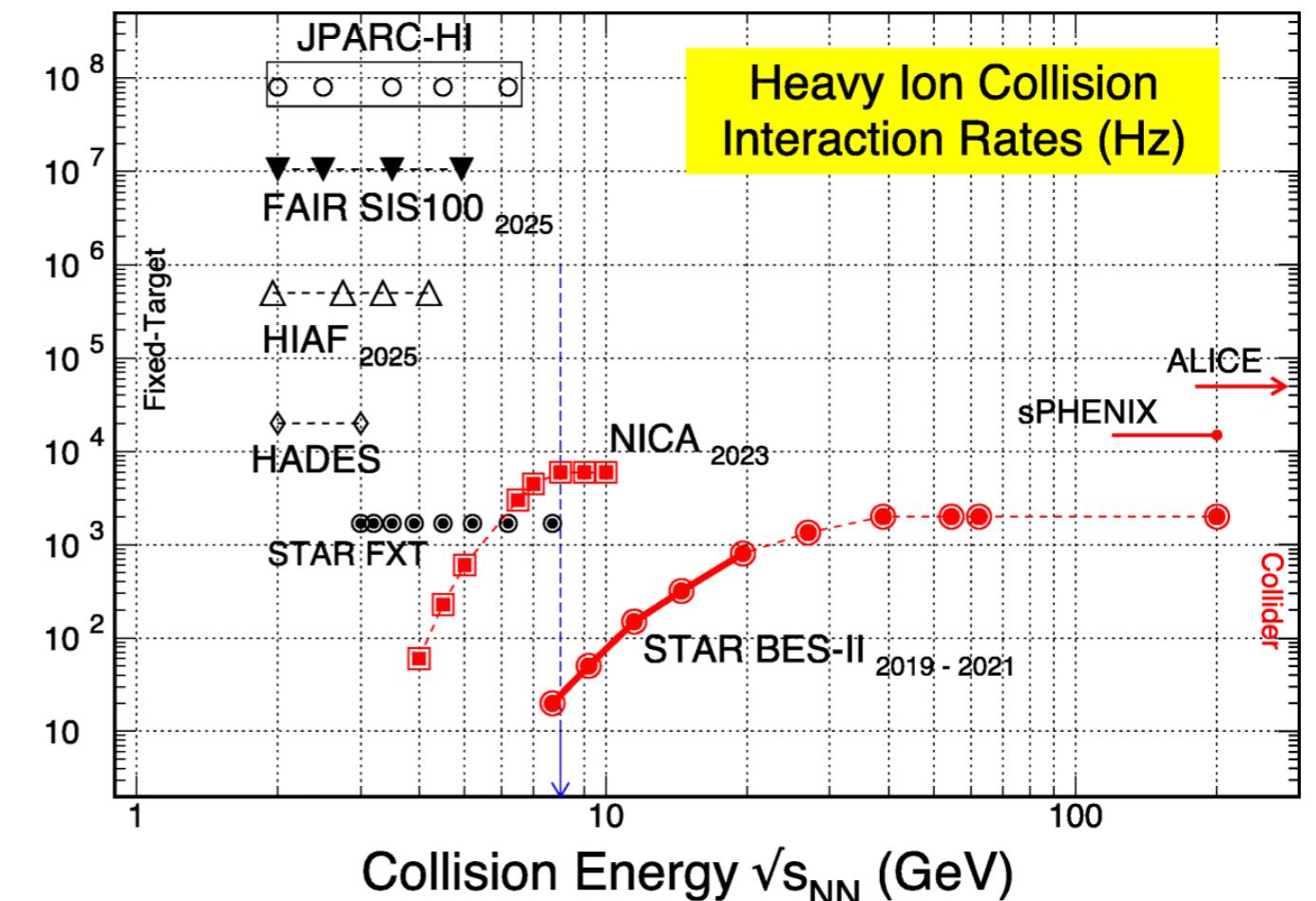
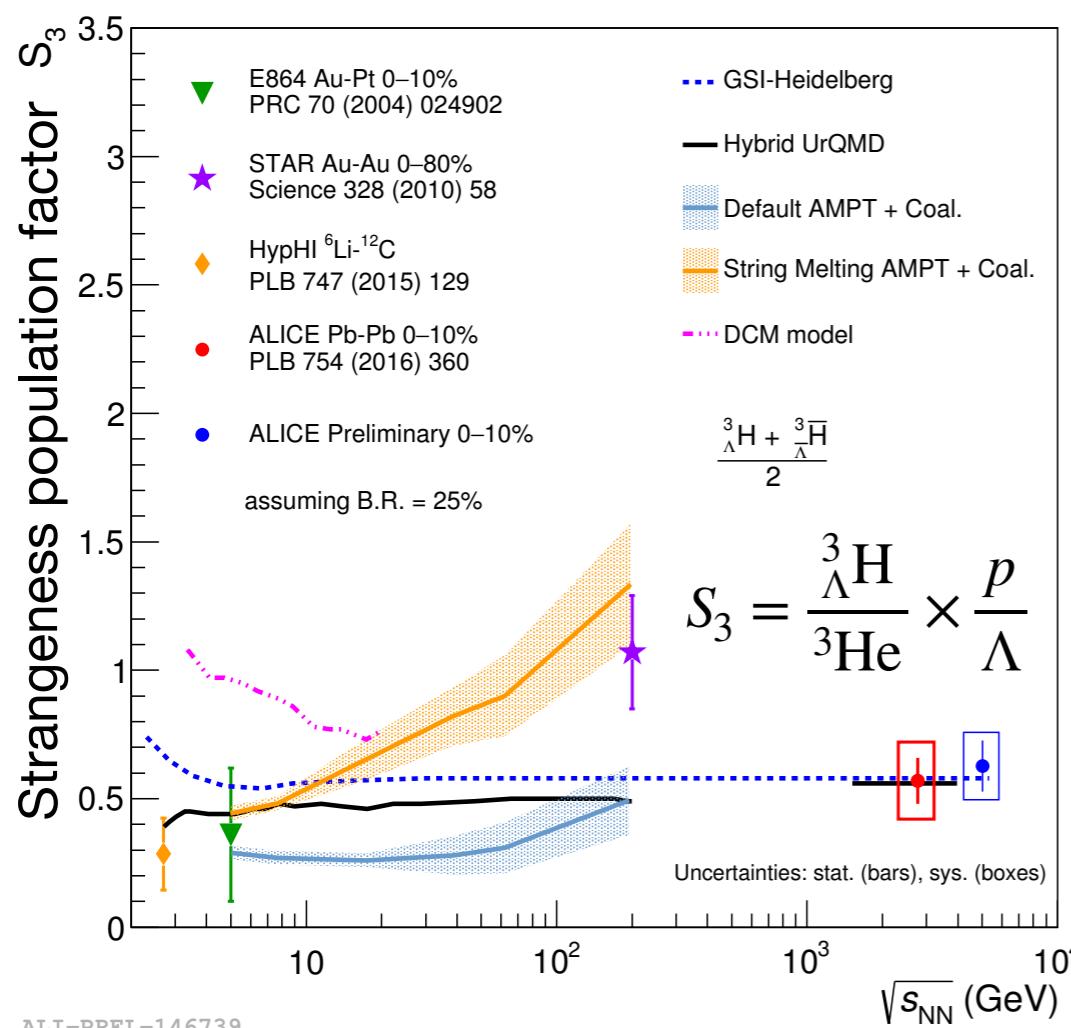
- HIC collisions
 - Thermal model describes the mid-rapidity yield of ${}^3_{\Lambda}\text{H}$ over few orders of magnitude of $\sqrt{s_{\text{NN}}}$
 - Momentum spectra and directed flow consistent with coalescence prescription
 - but the ${}^4_{\Lambda}\text{H}$ mid-rapidity yields are not well described
- p+p/LI collisions
 - Data favor 2-body coalescence, tension with thermal model
- To achieve a qualitative understanding hypernuclei production in HIC, we need a better understanding in
 - the matter created in HIC (high baryon density region)
 - the production mechanism(s)
 - the structure of the hypernuclei (B_{Λ} , etc)
- **Hopefully these new data will spark theoretical developments**

- Introduction
- Internal structure (τ and B_Λ)
- Production in heavy-ion collisions
- **Experimental Outlook**

Future prospects in hypernuclei production in HIC

Production mechanisms

- Energy dependence
 - Present: STAR, ALICE, HADES
 - Future: CBM, NICA, BM&N, JPARC-HI
 - Particle ratios vs energy
→ *production mechanisms vs energy?*



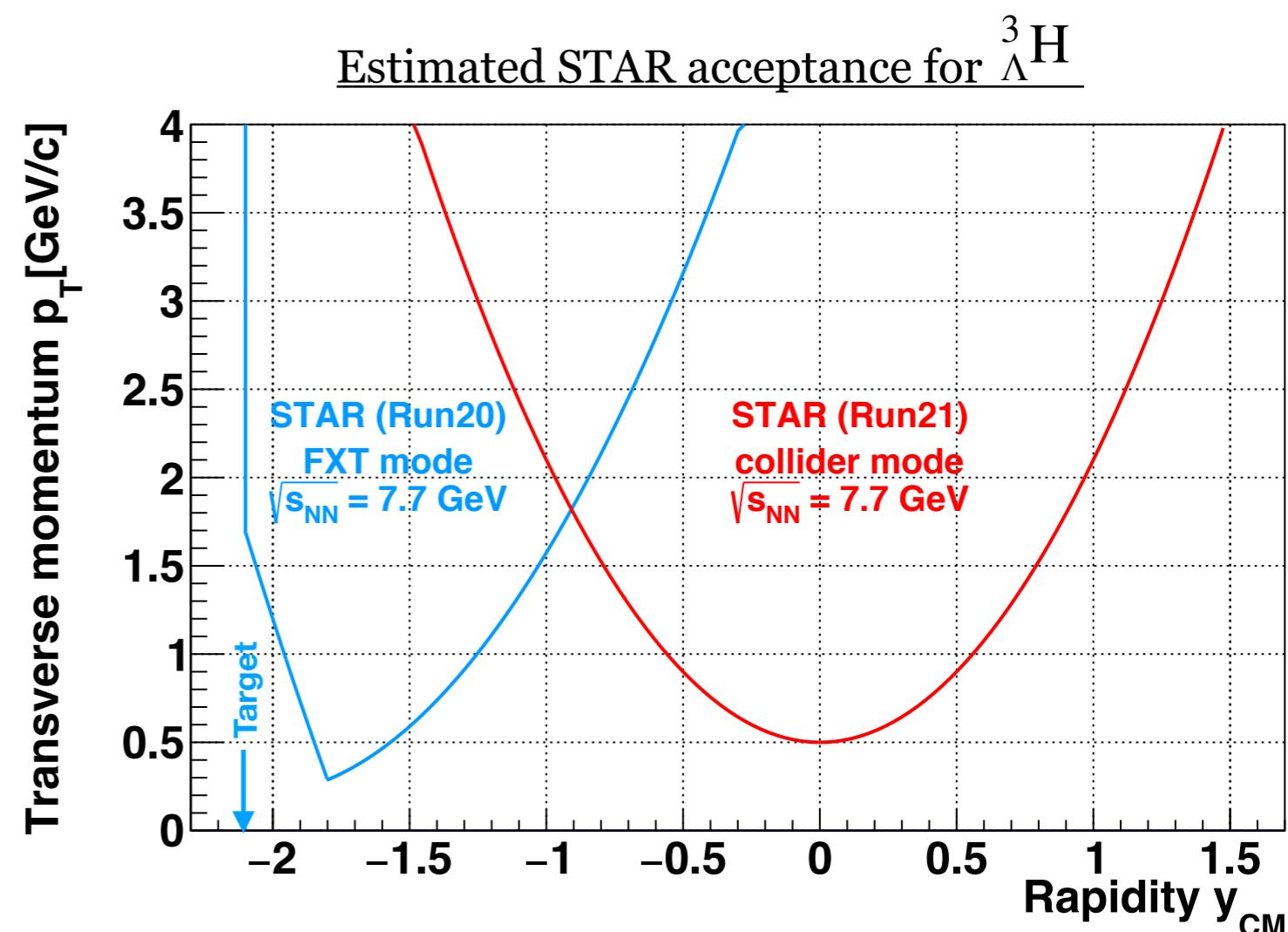
R. Lea (ALICE) WWND2020

Yue Hang Leung - Lawrence Berkeley National Laboratory

Future prospects in hypernuclei production in HIC

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 - Particle ratios vs energy
→ *production mechanisms vs energy?*
- p_T , rapidity dependence
 - Fixed target experiments may help us access the spectator rapidity region
→ *Different mechanisms dominate different kinematic regions?*



Future prospects in hypernuclei production in HIC

Production mechanisms

- Energy dependence
 - Present: STAR, ALICE, HADES
 - Future: CBM, NICA, BM&N, JPARC-HI
 - Particle ratios vs energy
 - *production mechanisms vs energy?*

→ production mechanisms vs energy?

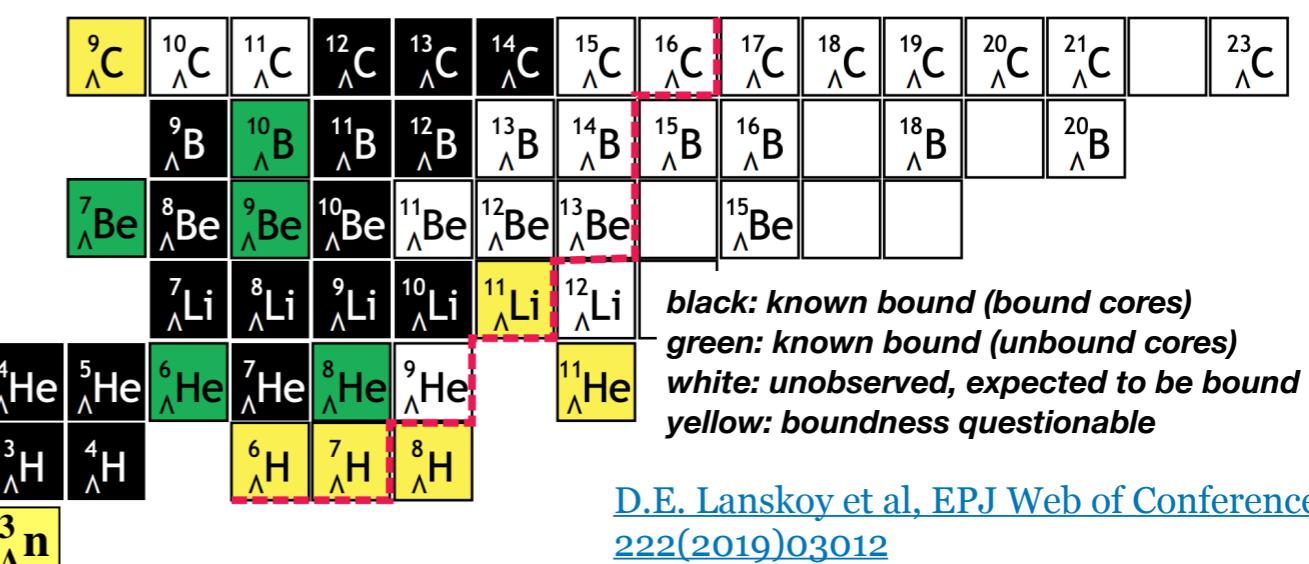
- p_T , rapidity dependence
 - Fixed target experiments may help us access the spectator rapidity region

→ Different mechanisms dominate different kinematic regions?

- Small systems
 - *How are hypernuclei produced in small systems?*

Y-N interaction, hypernuclear structure

- 3+ body decay phase space
 - *Is the weak decay phase space well understood theoretically?*
 - Exotic hypernuclei
 - Neutron rich hypernuclei
 - *Which neutron-rich isotopes of hyperhydrogen are bound?*



D.E. Lanskoy et al, EPJ Web of Conferences
222(2019)03012

- Double-Λ hypernuclei

Relations to astrophysics

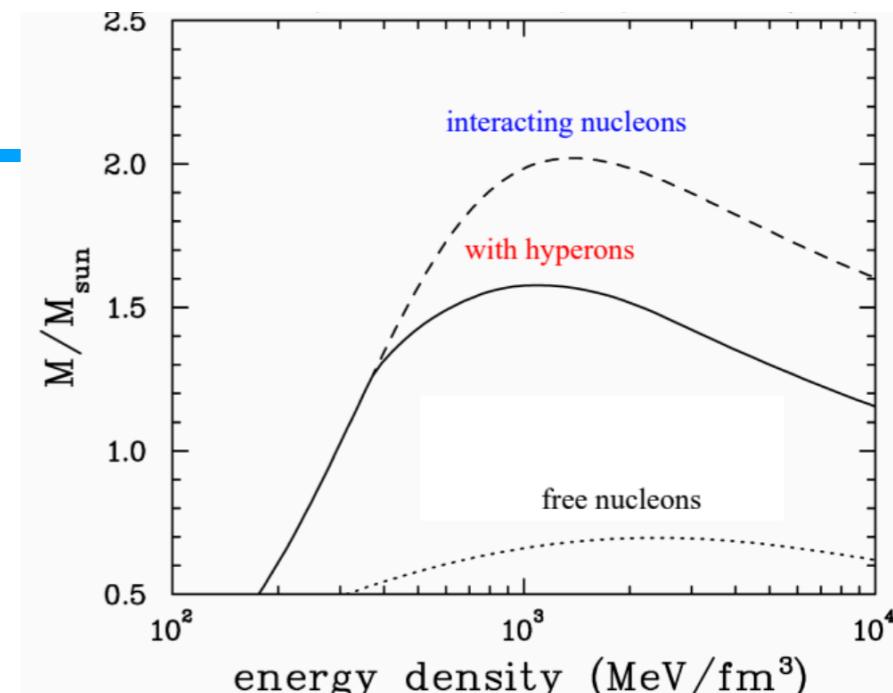
- Hyperons believed to be present in neutrons stars
 - Added degree of freedom -> Softening of the EOS
- Neutron stars with mass = $2 \times M_{\text{sun}}$ have been observed → **The hyperon puzzle**

A full understanding of the EOS requires knowledge in Λ -N and Λ - Λ interactions

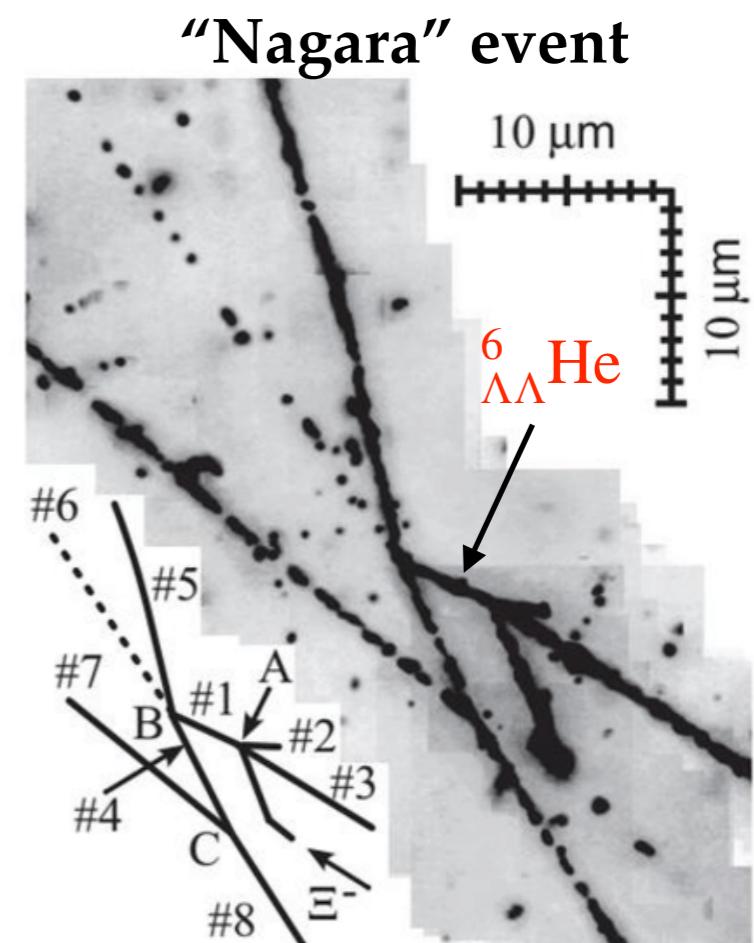
- Single- Λ hypernuclei → Λ -N potential
 - Attractive Λ potential with depth ~ 30 MeV
- Double- Λ hypernuclei → Λ - Λ potential
 - Not well understood

$^6_{\Lambda\Lambda}\text{He}$, $^{10}_{\Lambda\Lambda}\text{Be}$, $^{11}_{\Lambda\Lambda}\text{Be}$

Double- Λ hypernuclei discovered



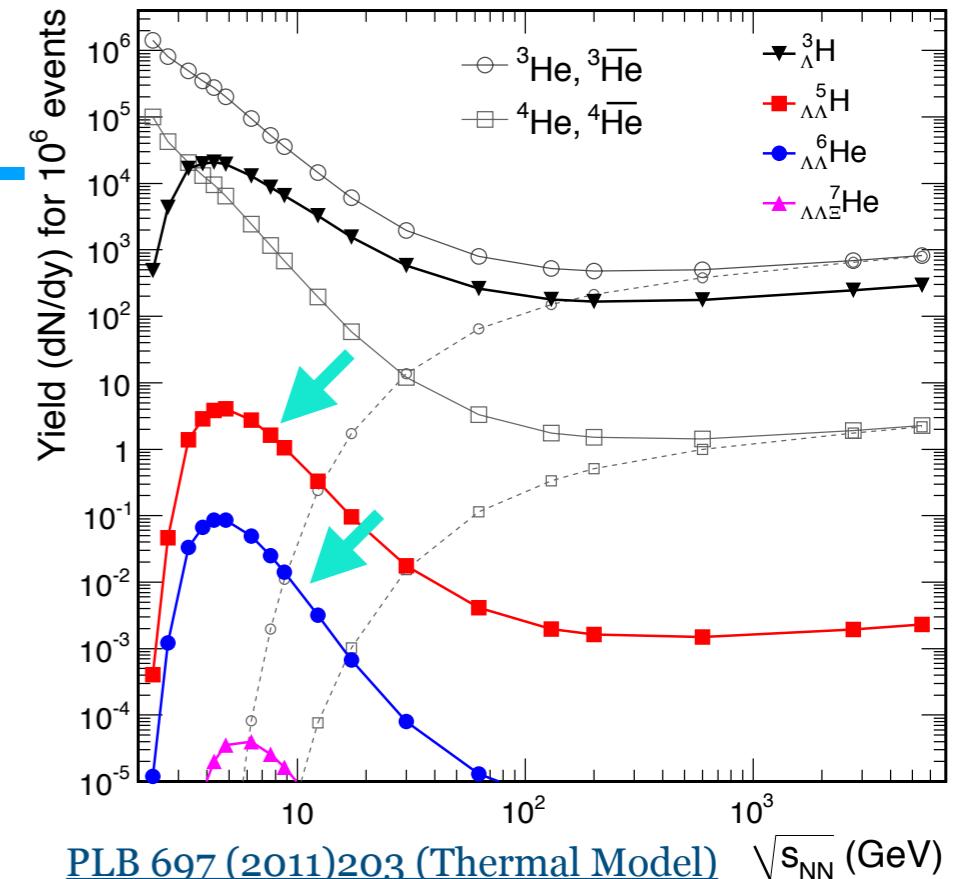
[Kapusta and Gale, Finite Temperature Field Theory](#)



[H. Takahashi et al., Phys. Rev. Lett. 87, 212502 \(2001\)](#)
[J.K. Ahn et al., Phys. Rev. C 88, 014003 \(2013\)](#)

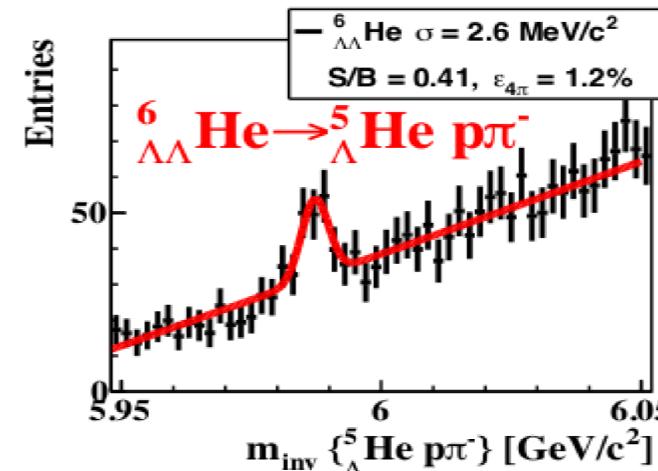
Relations to astrophysics

- Modest production rate according to thermal model predictions
- CBM, STAR etc. search for double- Λ hypernuclei



Double- Λ hypernuclei

${}^4_{\Lambda\Lambda}\text{H}$	Existence under debate due to low binding energy
${}^5_{\Lambda\Lambda}\text{H}, {}^5_{\Lambda\Lambda}\text{He}$	The lightest double- Λ hypernuclei (?)
${}^6_{\Lambda\Lambda}\text{He}, {}^{10}_{\Lambda\Lambda}\text{Be}, {}^{11}_{\Lambda\Lambda}\text{Be}$	Double- Λ hypernuclei discovered



CBM SIS100:
 $146 {}^6_{\Lambda\Lambda}\text{He}$ in 10 weeks

Partha Pratim Bhaduri, CPOD2021

A discovery of these bound states will have a high impact on understanding of YY interactions

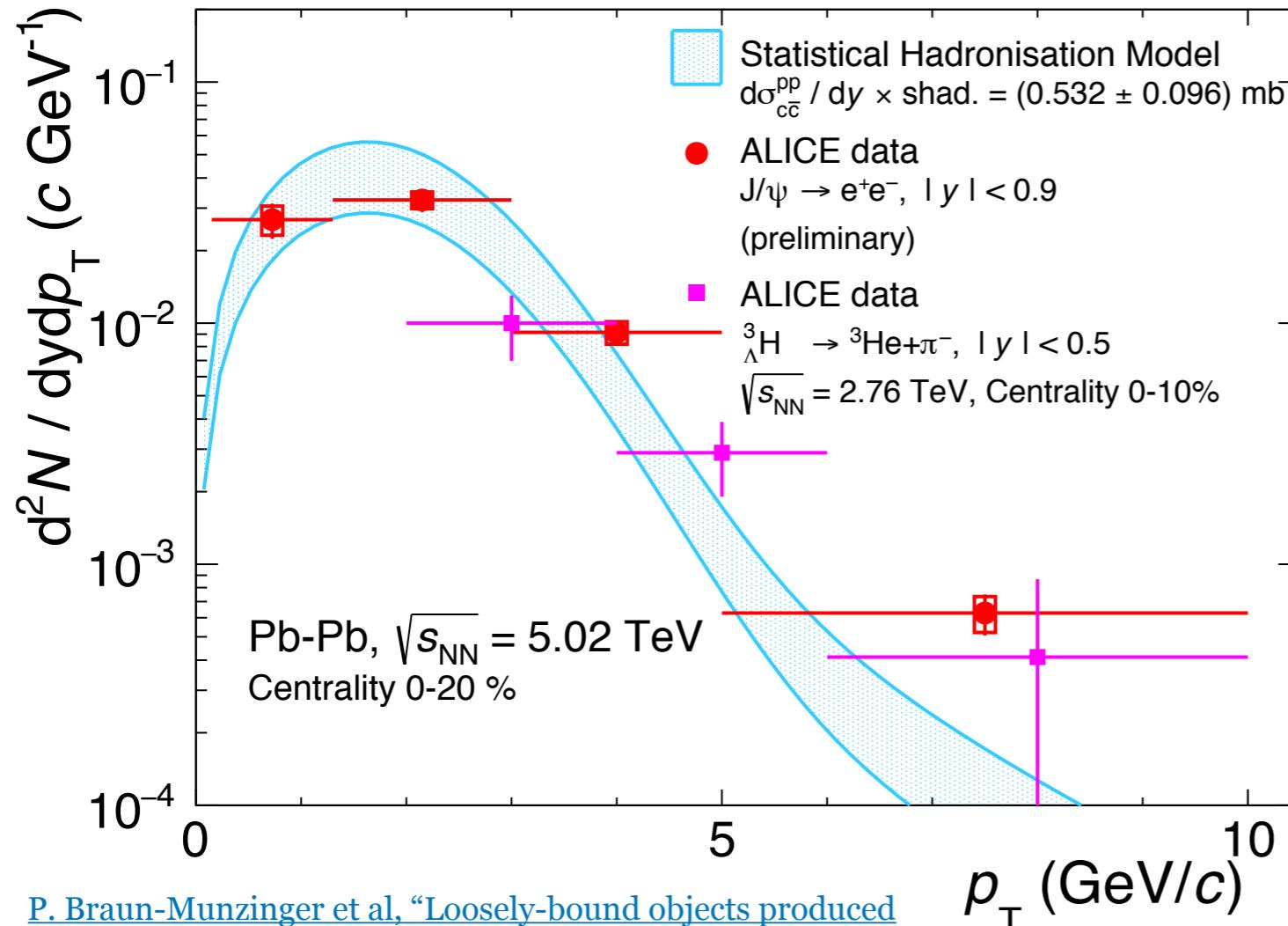
Summary

- Measurements on light hypernuclei present (STAR, ALICE, HADES) and near future (CBM, NICA, BM&N, JPARC-HI etc.) from HIC
 - Will contribute to a precise understanding of light hypernuclear structure and production mechanisms in HIC
- Open questions remain → high impact on nuclear physics and astrophysics
 - **Exciting times ahead of us!**

Thank you for your attention!

Backup slides follow

Hypernuclei p_T spectra in Pb+Pb 5.02 TeV



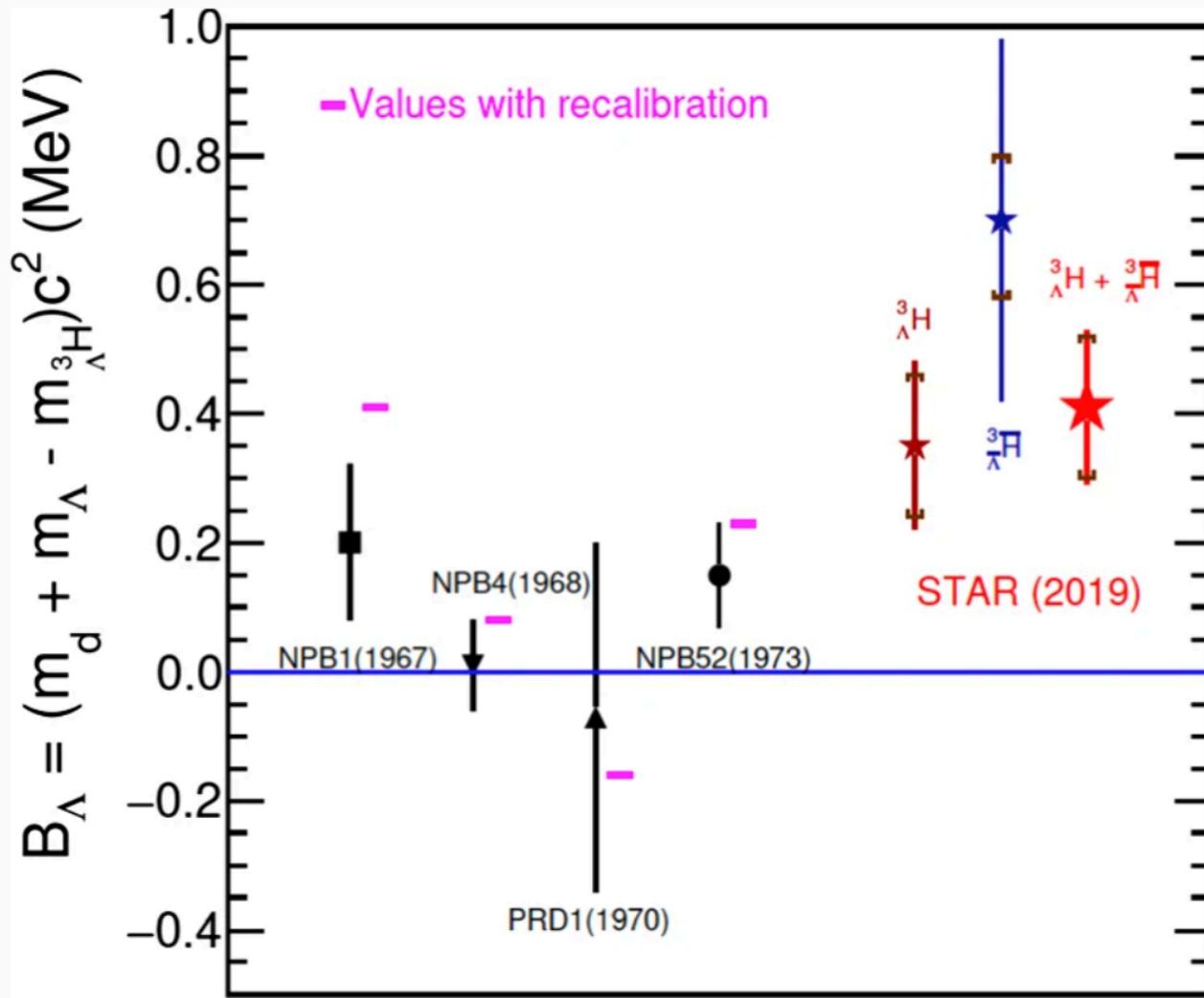
[P. Braun-Munzinger et al, "Loosely-bound objects produced in nuclear collisions at the LHC", NPA 987\(2019\)144-201](#)

- Shape of transverse momentum spectra of $^3\Lambda H$ ($m = 2.99[\text{GeV}/c]$) comparable to ^3He ($m = 2.81[\text{GeV}/c]$) J/ψ ($m = 3.10[\text{GeV}/c]$)
- $\langle p_T \rangle$ related to radial flow
→ driven by collectivity

Hydrodynamic flow of hypernuclei very comparable to light nuclei/heavy flavor with similar mass

- Consistent with coalescence picture

Hypertriton Λ separation energy



Peng Liu et al, Chinese Phys. C 43(2019)124001

- STAR: $B_\Lambda(^3\text{H}) = 0.41 \pm 0.16$ [MeV]
- Seemingly in tension with emulsion experiments
 $B_\Lambda(^3\text{H}) = 0.13 \pm 0.05$ [MeV]
- Recalibration of older measurements using updated nucleon/hyperon masses gives
 $B_\Lambda(^3\text{H}) = 0.27 \pm 0.08$ [MeV]

- Strong influence on production yield
- Potential impact on lifetime

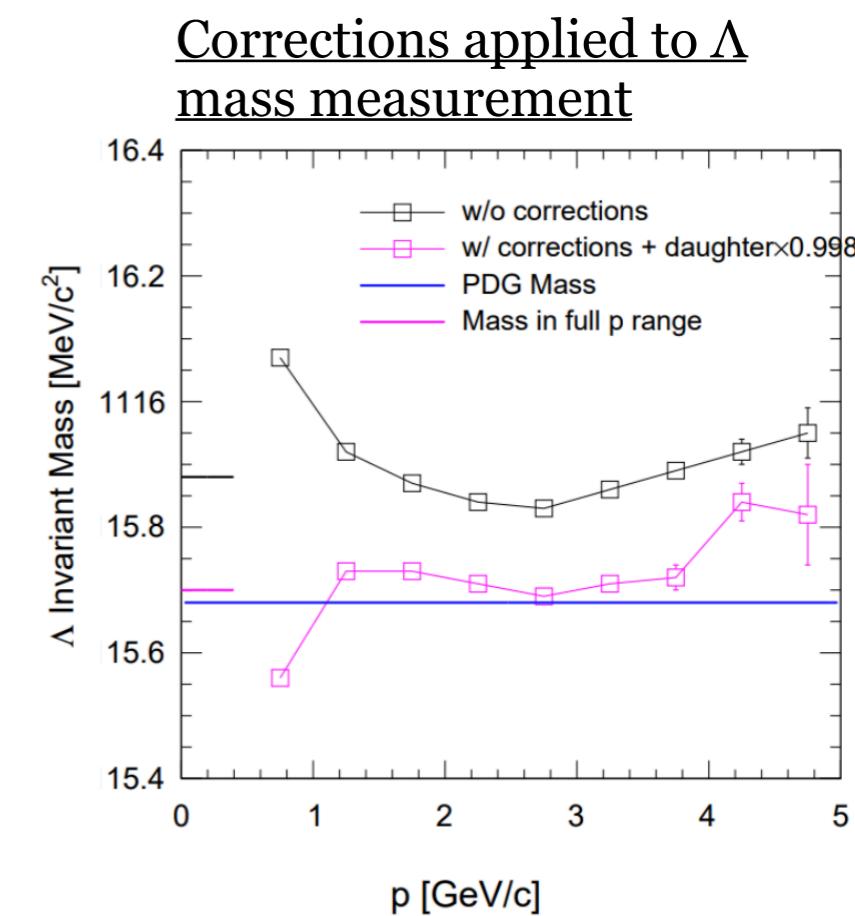
More on experimental systematic uncertainties

- More data sets from LHC and RHIC incoming
-> Entering the era of precision measurements
 - *What about systematic uncertainties?*
- Main systematic uncertainties on B_Λ from STAR
 - Energy loss corrections
 - Field distortion corrections
- Corrections can approx. recover the Λ mass ,
 - *O(0.1 MeV) systematic unc. , can this be improved?*

A thorough understanding of the energy loss/field corrections in experimental data is essential

Systematic uncertainties for hypernuclei B_Λ

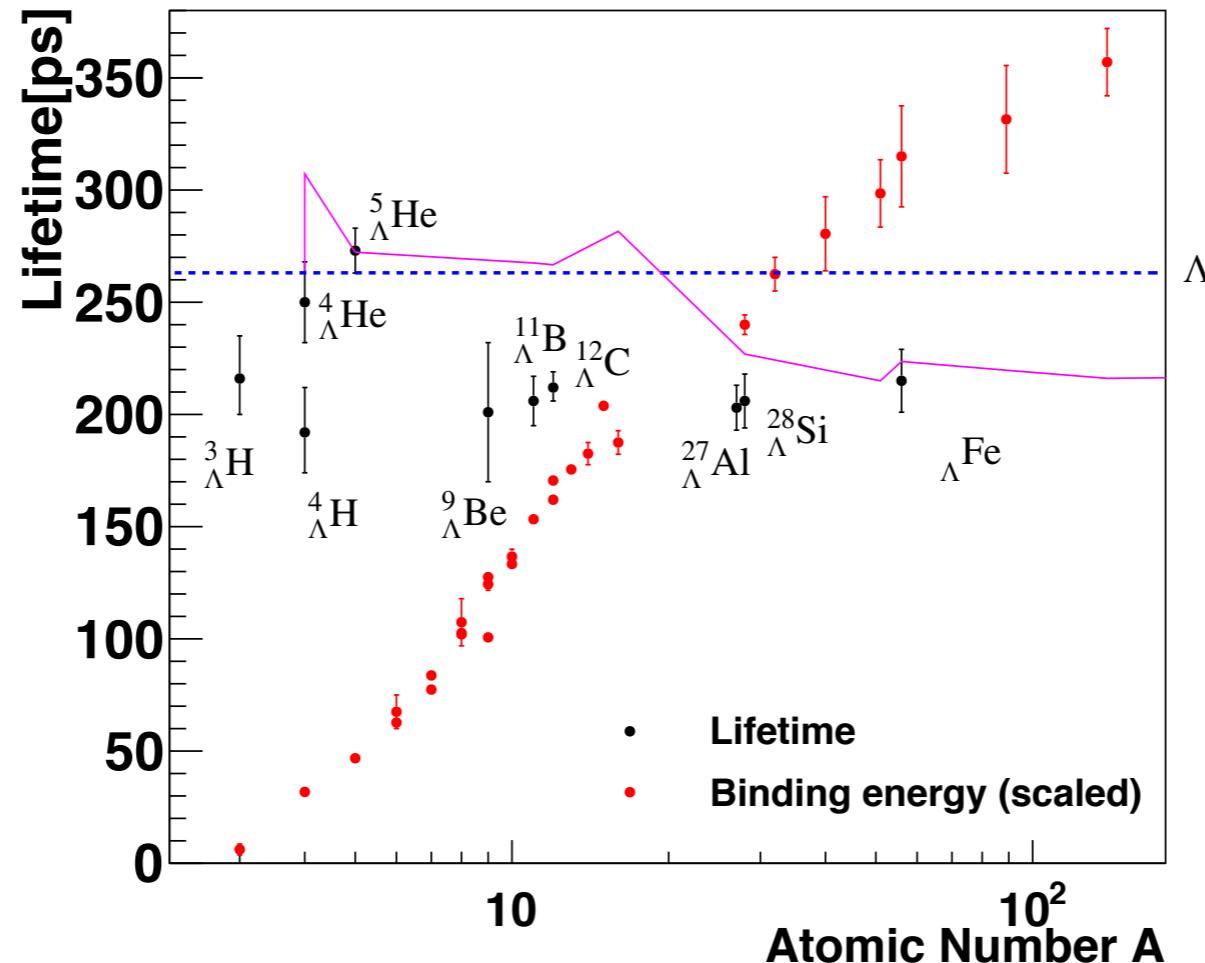
Error source	${}^4_\Lambda H$ Systematic error (MeV)	${}^4_\Lambda He$ Systematic error (MeV)
Magnet field distortion	0.16	0.11
Energy loss correction	0.06	0.07
BDT cut	0.01	0.05
Fit method	0.04	0.02
Total	0.18	0.14



[Tianhao Shao \(STAR\), SQM2021](#)

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Hypernuclei lifetime and binding energy



[Riv.Nuovo Cim. 38 \(2015\) 9, 387-448](https://doi.org/10.1007/s11048-015-0387-4)

- Hypernuclei lifetime is quite stable from light– to medium–A hypernuclei
- Almost constant above A = 20, at ~210 ps, which corresponds to ~80% of the free Λ lifetime.