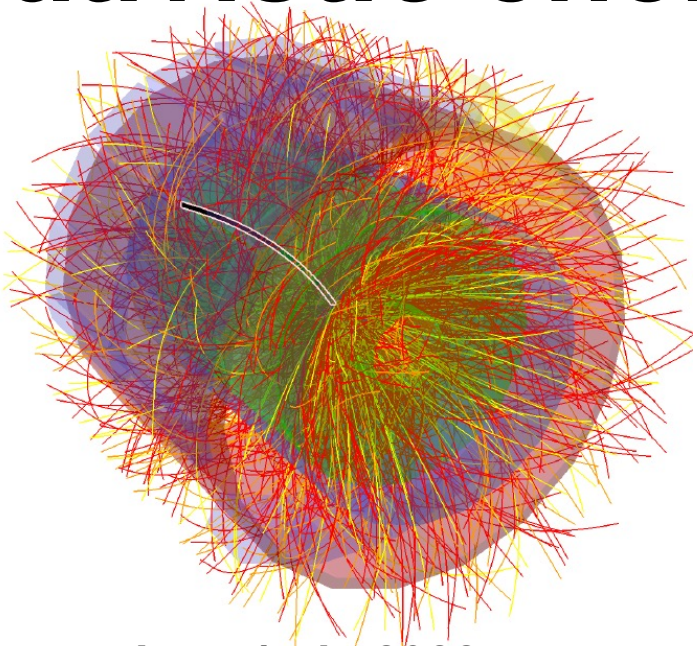
Hypernuclei at relativistic energies



June 17th, 2022

Strangeness in Quark Matter 2022

Benjamin Dönigus

Institut für Kernphysik

Goethe Universität Frankfurt

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

SQM2022

The 20th International Conference on Strangeness in Quark Matter

13-17 June 2022 Busan, Republic of Korea

IKF Institut für Kernphysik Frankfurt

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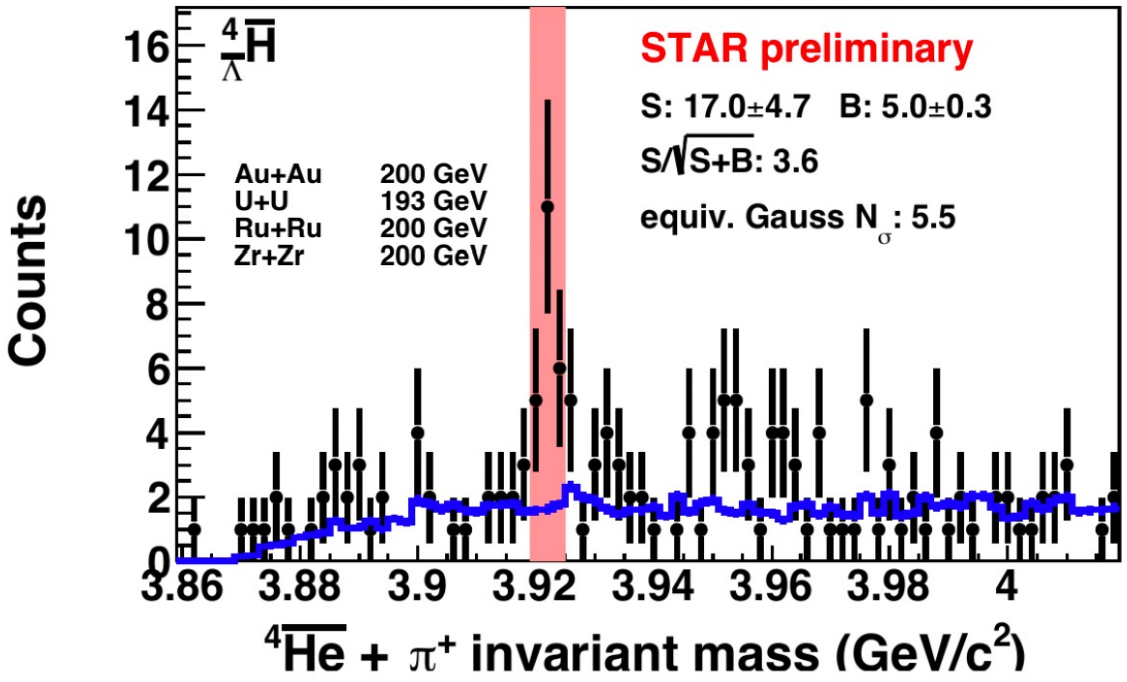
Content

- Highlight
- Introduction
- Hypernuclei
  - Production
  - Lifetime, Branching ratio & Binding energy
- Summary

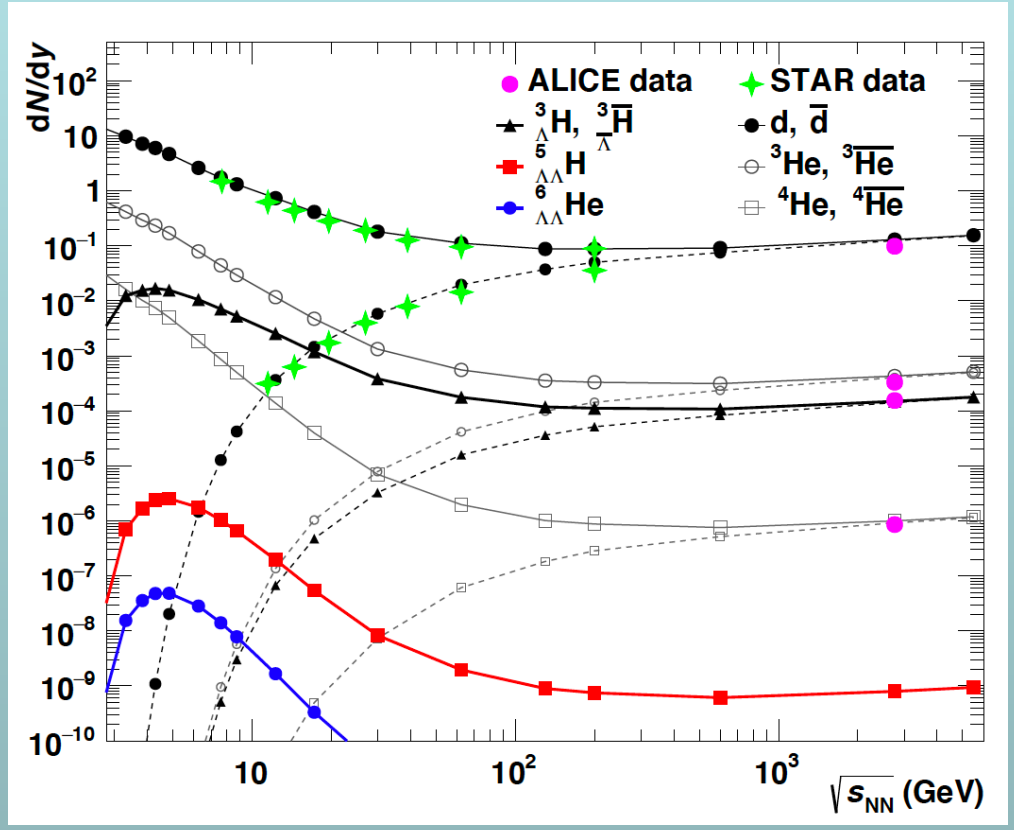
Highlight: Anti-$^{4}_{\Lambda}$H

Plenary by B. Trzeciak, Mon
Parallel by J. Wu, Wed



- First observation of mass 4 anti-hypernucleus
- STAR has discovered the third anti-particle and the second anti-hypernucleus

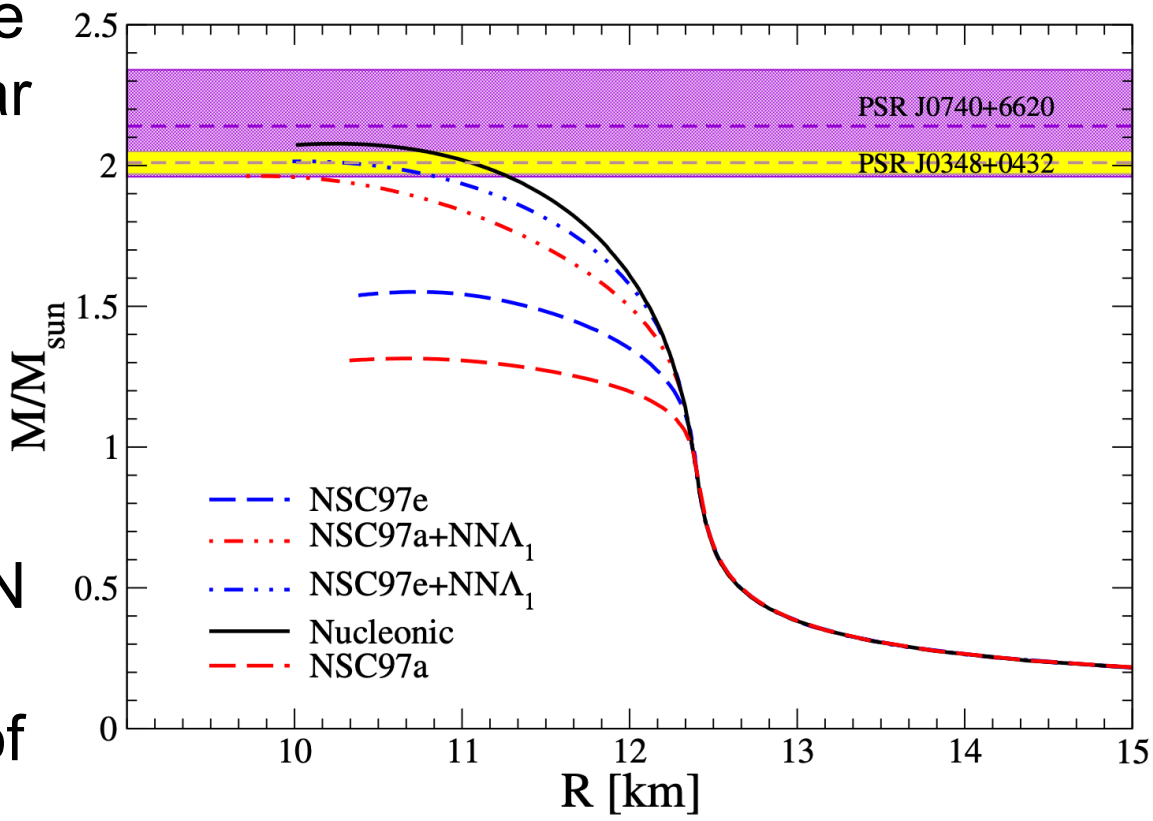
Introduction



BD, Eur. Phys. J A 56 (2020) 258

Hypernuclei

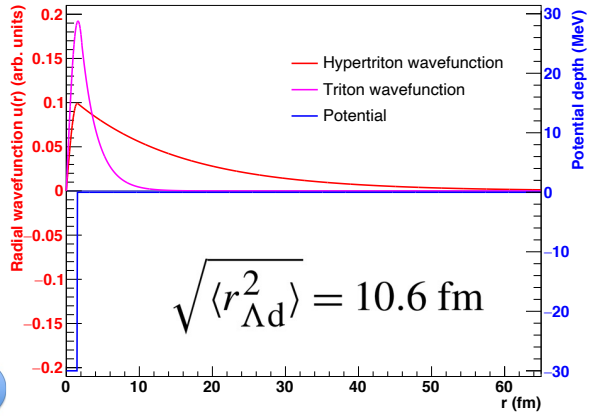
- Hypernuclei are unique probes to study nuclear structure
- Single Λ-hypernuclei are major source of extracting Λ-N interaction
- Correct Λ-N and Λ-N-N interaction needed to understand structure of neutron stars

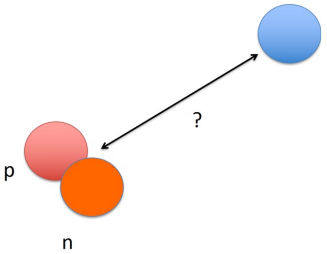


D. Logoteta et al., Astron. Astrophys. 646 (2021) A55

Hypernuclei

- Hypernuclei are decaying weakly (about free Λ lifetime)
- Hypertriton special case: Λ separation energy so low that simple models expect free Λ lifetime: d-Λ system



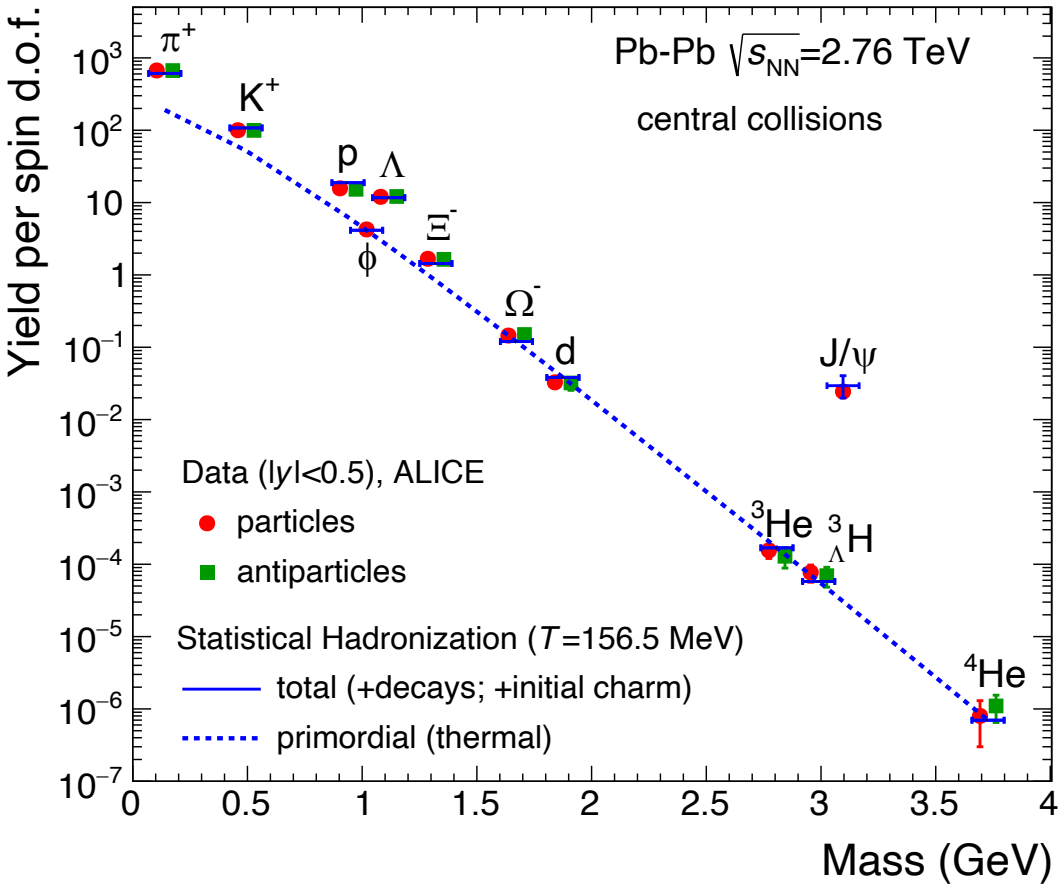


P. Braun-Munzinger, BD, Nucl. Phys. A 987 (2019) 144
F. Hildenbrand, H.-W. Hammer Phys.Rev.C 100 (2019) 3

Symbol	Long Name	Decay Modes	Mass (GeV/c^2)	Λ sep. energy (MeV)
${}^{3}_{\Lambda}\mathrm{H}$	hypertriton	${}^{3}\mathrm{He} + \pi^- + \mathrm{c.c.}$ $\mathrm{d} + \mathrm{p} + \pi^- + \mathrm{c.c.}$	2.991	0.130
${}^{4}_{\Lambda}\mathrm{H}$	hyperhydrogen-4	${}^{4}\mathrm{He} + \pi^- + \mathrm{c.c.}$ ${}^{3}\mathrm{H} + \mathrm{p} + \pi^- + \mathrm{c.c.}$	3.9226	2.169
${}^{4}_{\Lambda}\mathrm{He}$	hyperhelium-4	${}^{3}\mathrm{He} + \mathrm{p} + \pi^- + \mathrm{c.c.}$	3.9217	2.347

Thermal model

- For the thermal model description of production yields, feed-down is an important ingredient
- All light hadron production yields are populated strongly by resonances
- Seems to not be the case for (hyper-)nuclei



A. Andronic et al., Phys.Lett.B 797 (2019) 134836

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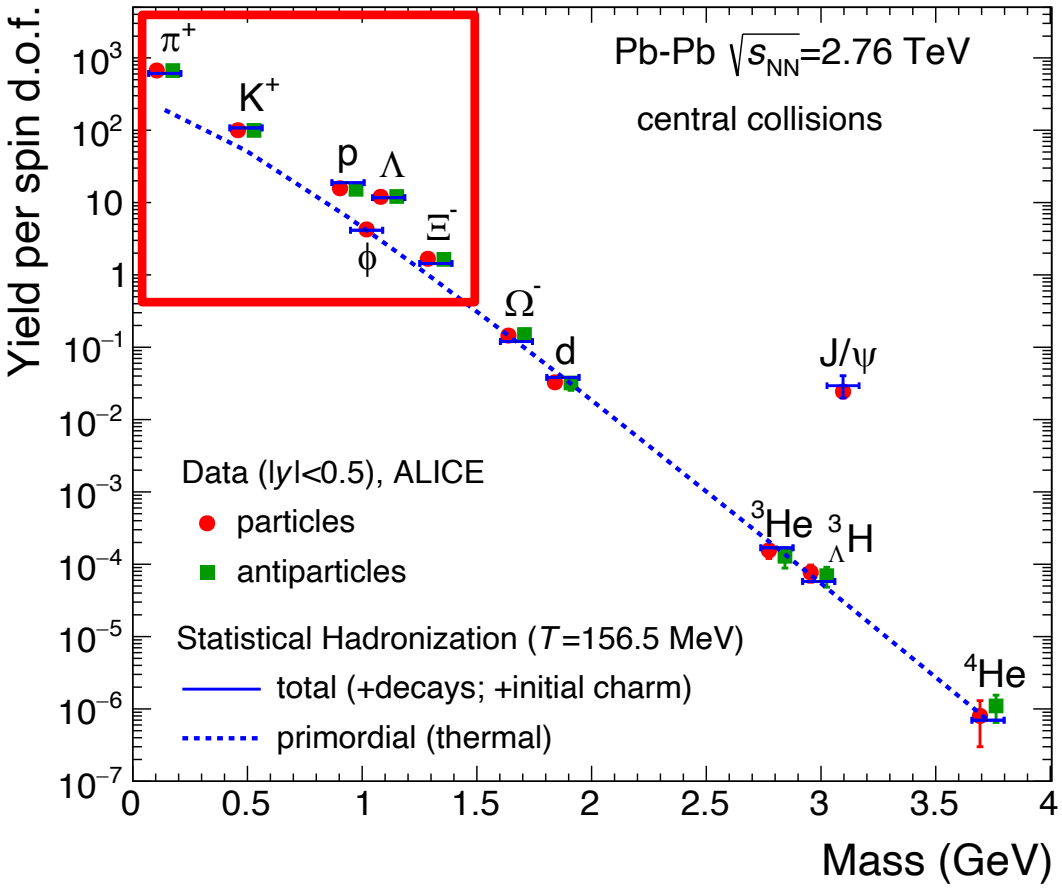

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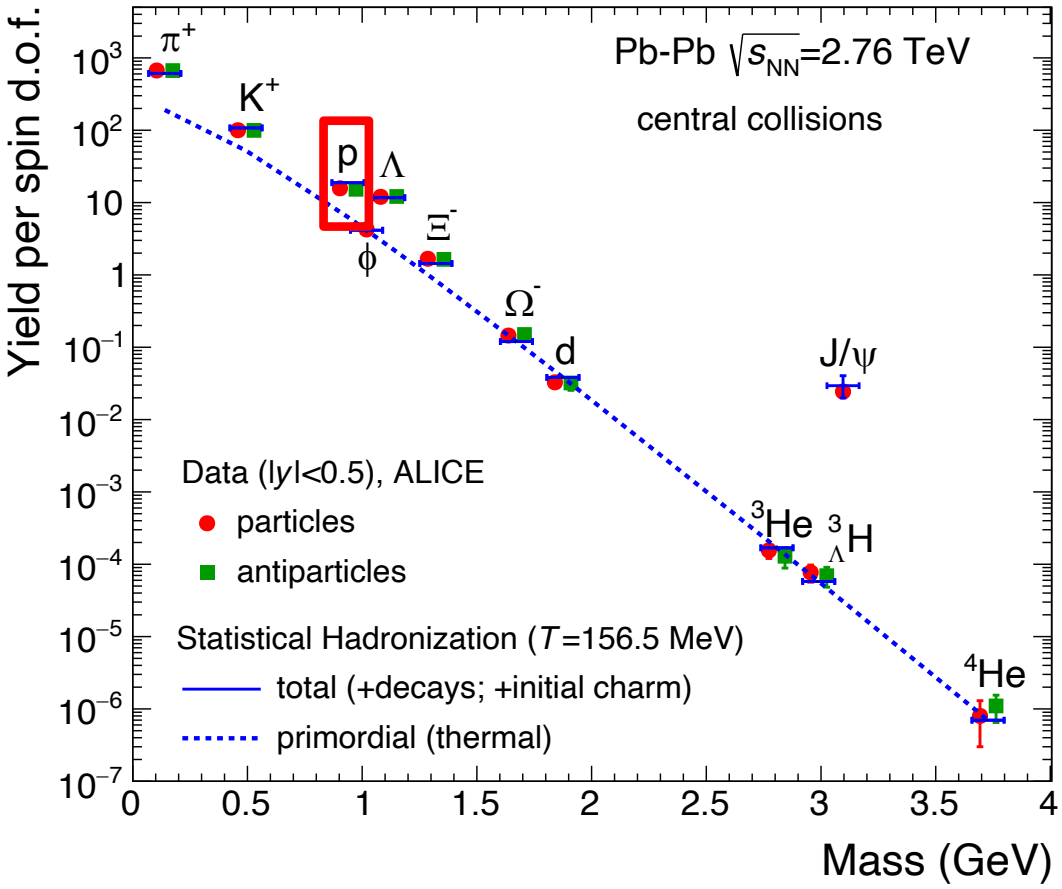

A. Andronic et al., Phys.Lett.B 797 (2019) 134836

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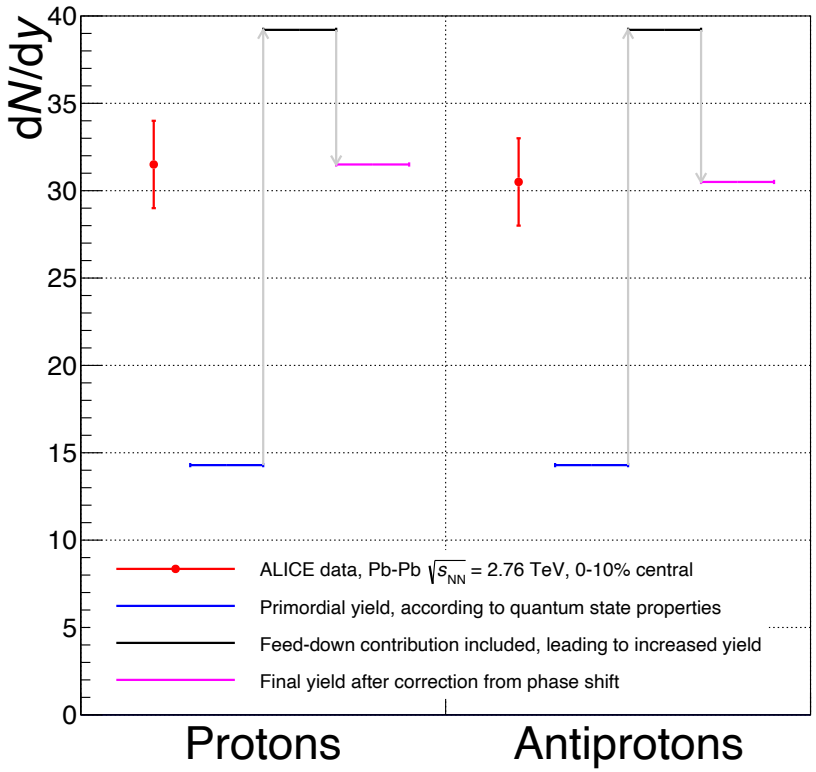
BD, G. Röpke, D. Blaschke, to be submitted



A. Andronic et al., Phys.Lett.B 797 (2019) 134836; Nature 561 (2018) 7723, 321; Phys.Lett.B 697 (2011) 203; Phys.Lett.B 792 (2019) 304

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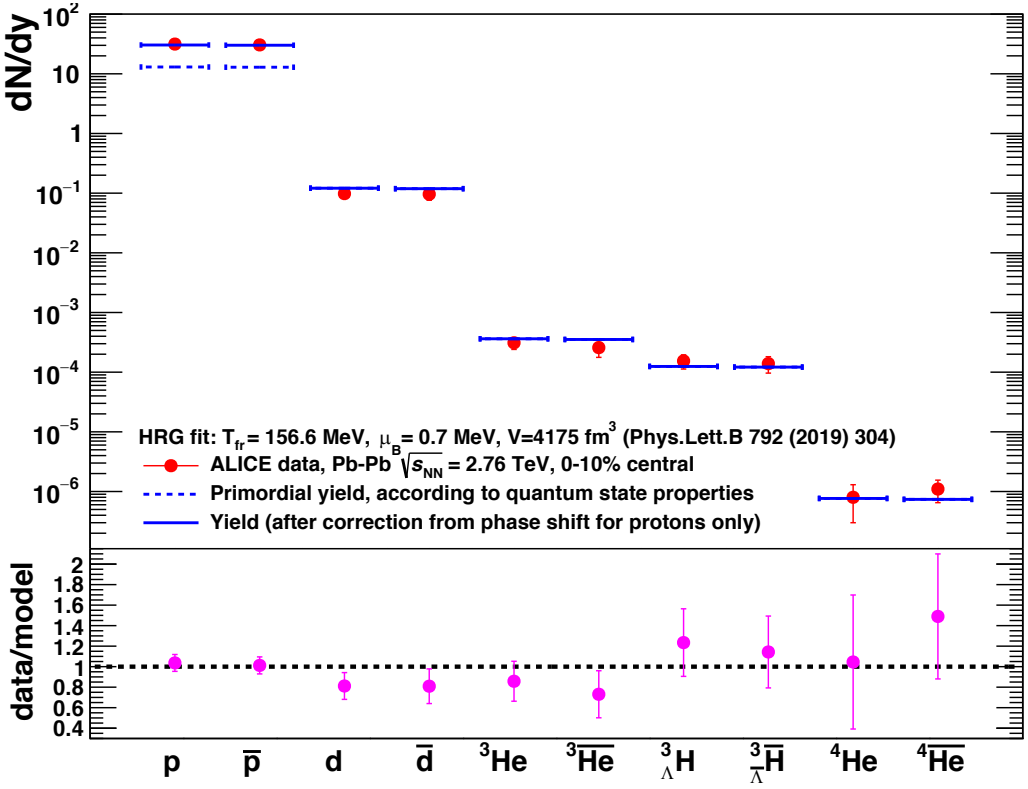

A. Andronic et al., Phys.Lett.B 797 (2019) 134836; Nature 561 (2018) 7723, 321; Phys.Lett.B 697 (2011) 203; Phys.Lett.B 792 (2019) 304

Thermal model

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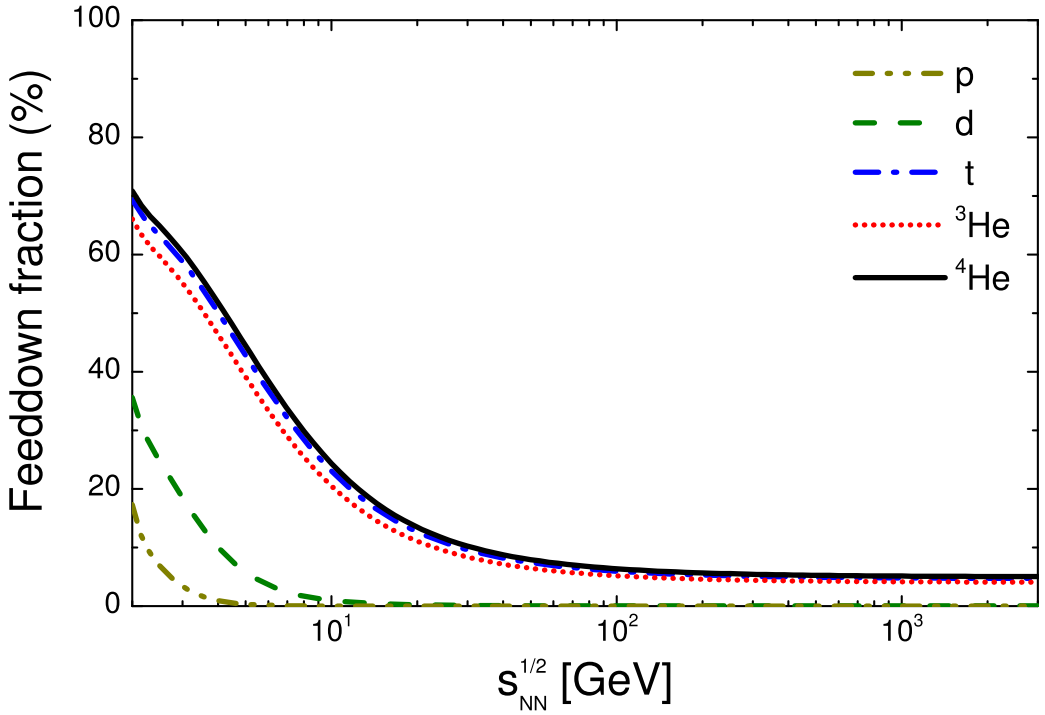
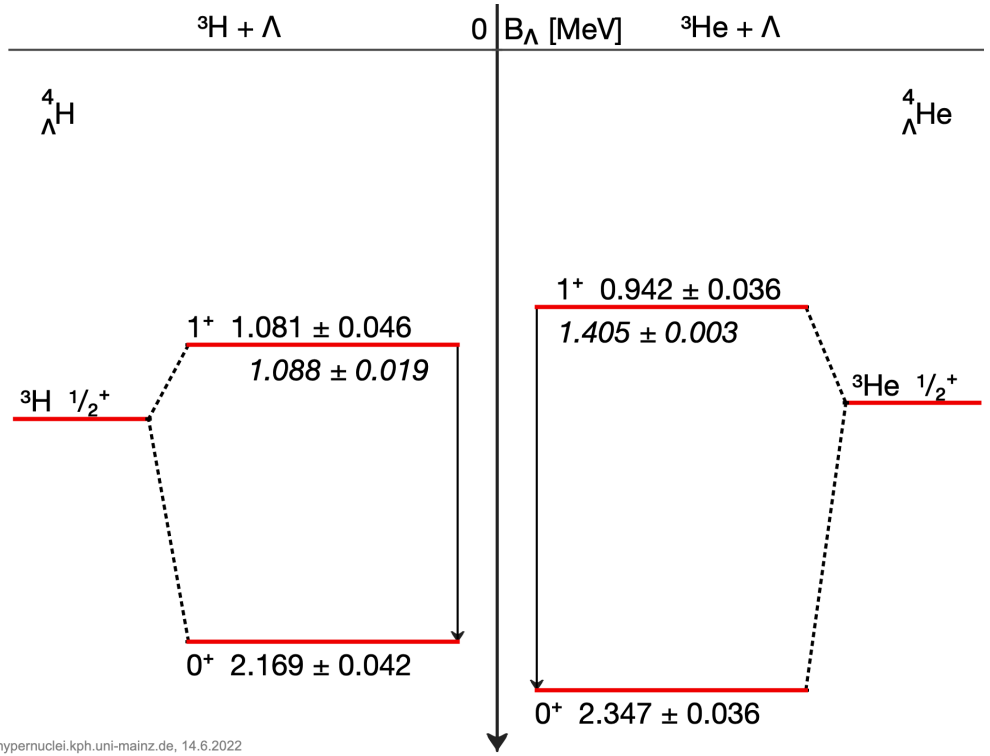
- Seems to not be the case for (hyper-)nuclei at LHC

V. Vovchenko, BD, B. Kardan, M. Lorenz, H. Stoecker, Phys.Lett.B 809 (2020) 135746



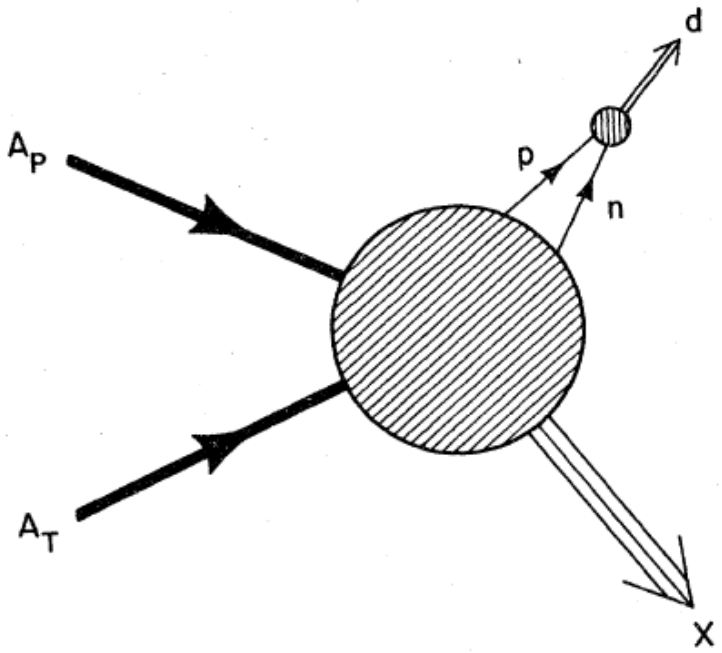
Thermal model

- For the thermal model description of production yields, feed-down is an important ingredient
- All light hadron production yields are populated strongly by resonances
- Seems to not be the case for (hyper-)nuclei
- Important for A=4 hypernuclei !



Exited states have higher population due to degeneracy 2J+1:
Sharing yield in fraction 3 : 1
(mass difference is only 1 MeV to about 4GeV/c^2)

Coalescence



J. I. Kapusta, PRC 21, 1301 (1980)

Nuclei are formed by protons and neutrons which are nearby and have similar velocities (after kinetic freeze-out)

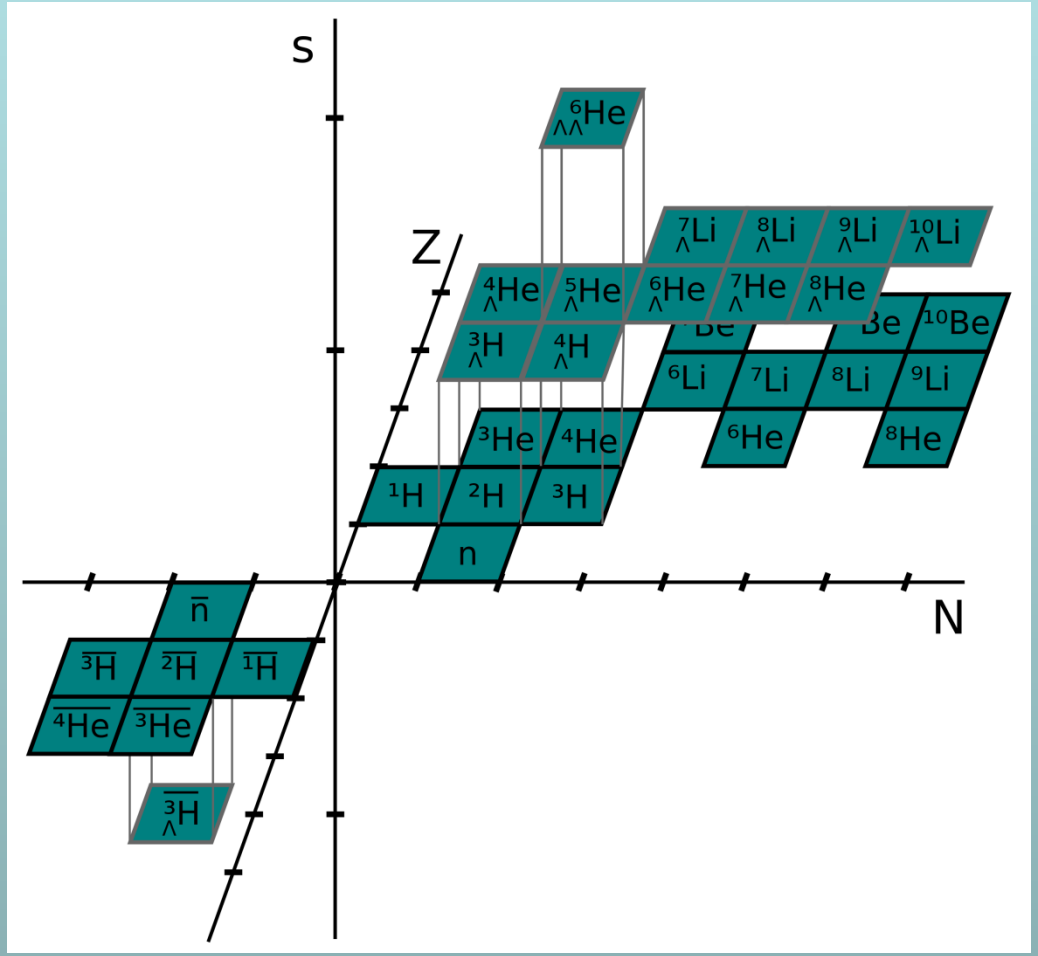
Produced nuclei

➜ can break apart

➜ created again by final-state coalescence

→ Different implementations on the market

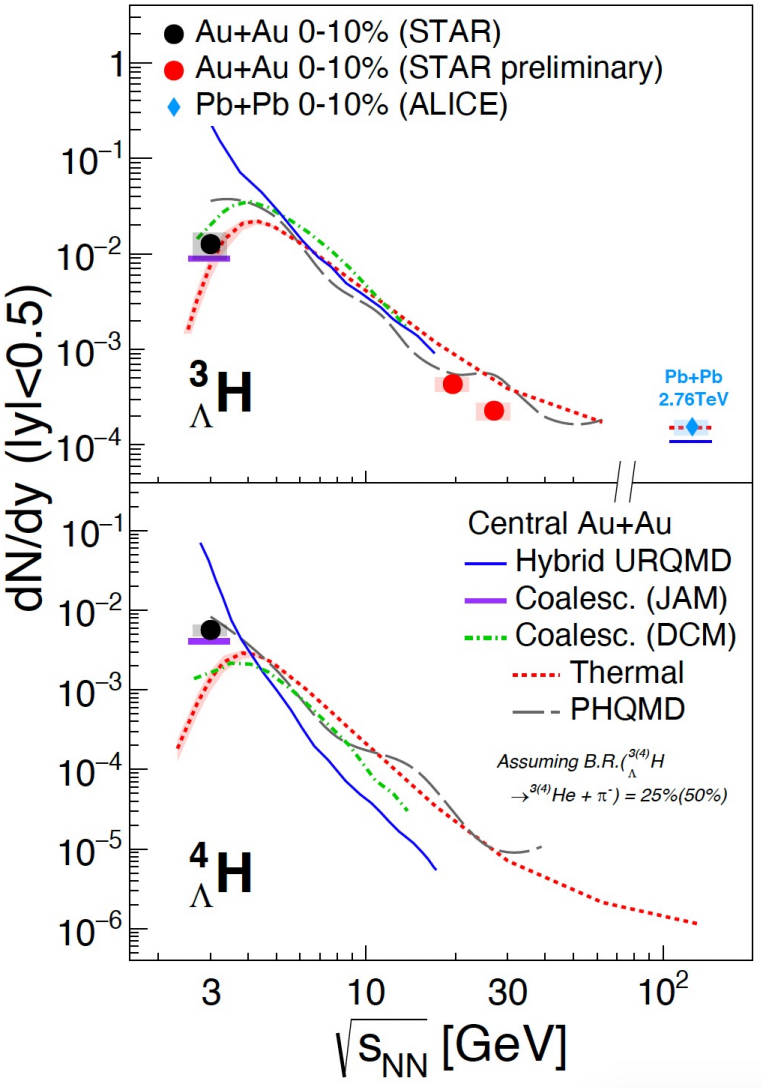
Hypernuclei



Hypernuclei yields

Plenary by B. Trzeciak, Mon
Parallel by Y. Ji, Tue

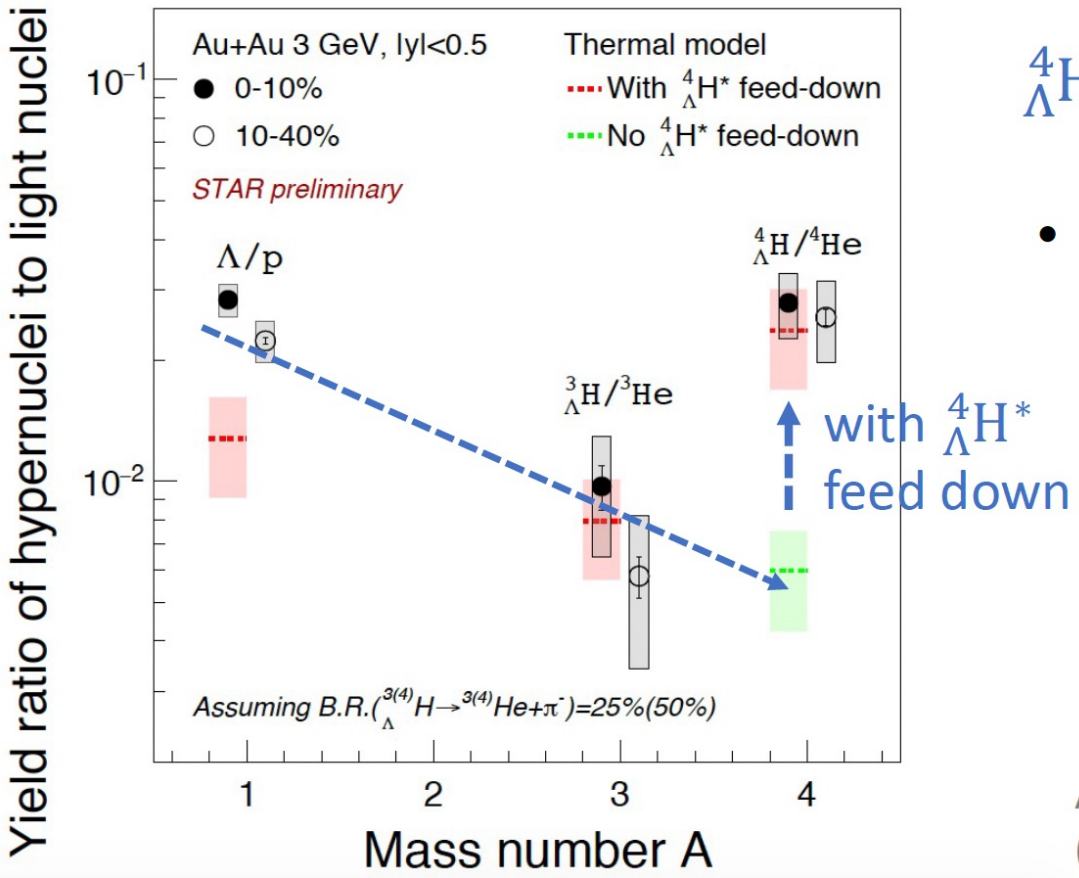
- Recent STAR preliminary results are slightly overestimated by models
- Trend vs. energy described qualitatively by all models



DCM & Hybrid UrQMD: J. Steinheimer et al. PLB 714 (2012) 85
Thermal: A. Andronic et al. PLB 697 (2011) 203
PHQMD: Susanne Gläßel et al. PRC 105 (2022) 014908,
V. Kireyeu et al. arXiv:1911.09496
JAM: L. Hui et al. PLB 805, 135452 (2020)
Pb+Pb: ALICE, PLB 754, 360 (2016)
STAR at 3 GeV: PRL 128, 202301 (2022)

Hypernuclei yields

Parallel by Y. Ji, Tue



$$^{4}_{\Lambda}\mathrm{H}^{*}(\mathrm{J}^{+}=1) \rightarrow {}^{4}_{\Lambda}\mathrm{H}(\mathrm{J}^{+}=0)+\gamma$$

- Thermal model calculation, including excited $^{4}_{\Lambda}\mathrm{H}^{*}$ feed down, shows a similar trend.

A. Andronic et al, PLB 697, 203 (2011) (updated, preliminary) (Thermal Model)

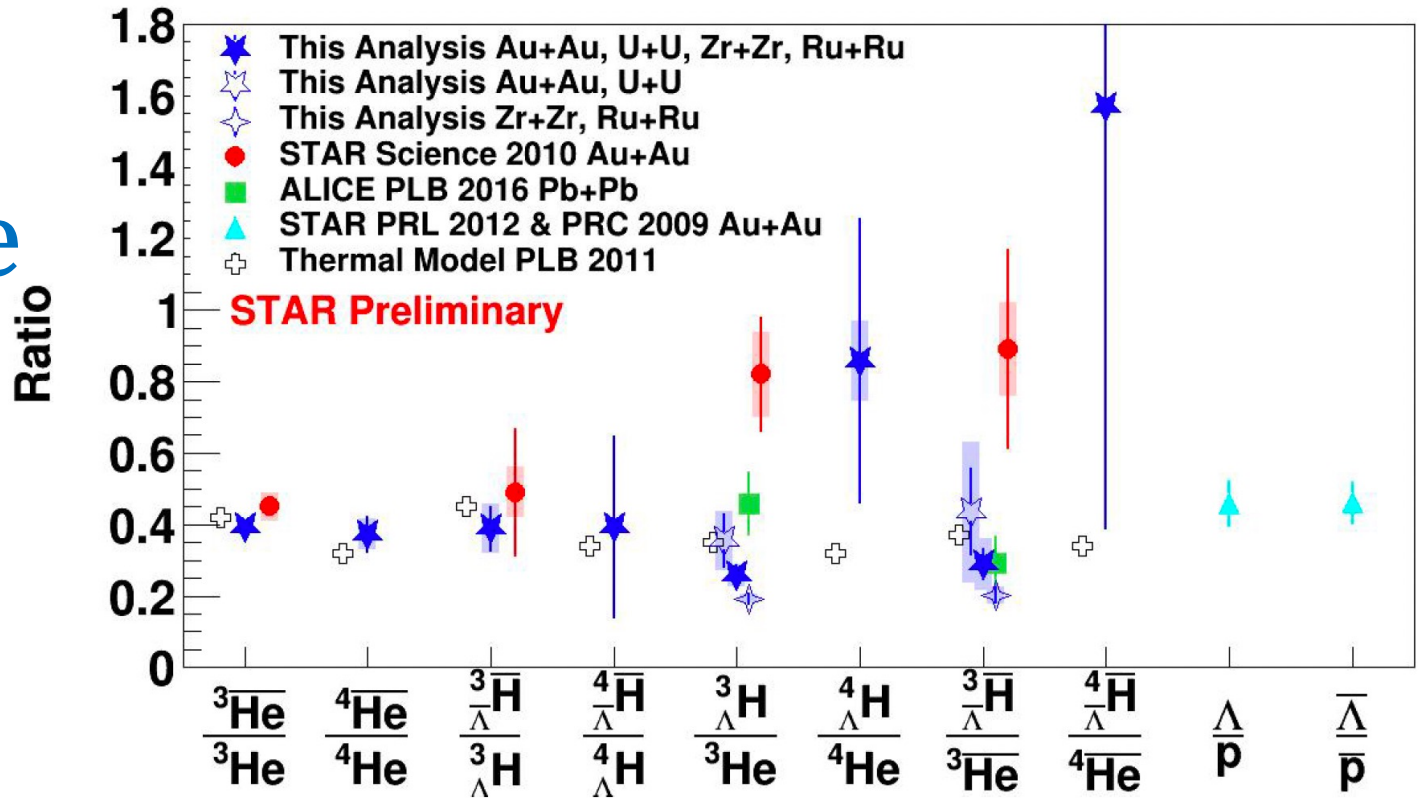
Yield ratios

Parallel by J. Wu, Wed

- Yield ratios of new mixed data set(s) follow expectation from thermal model

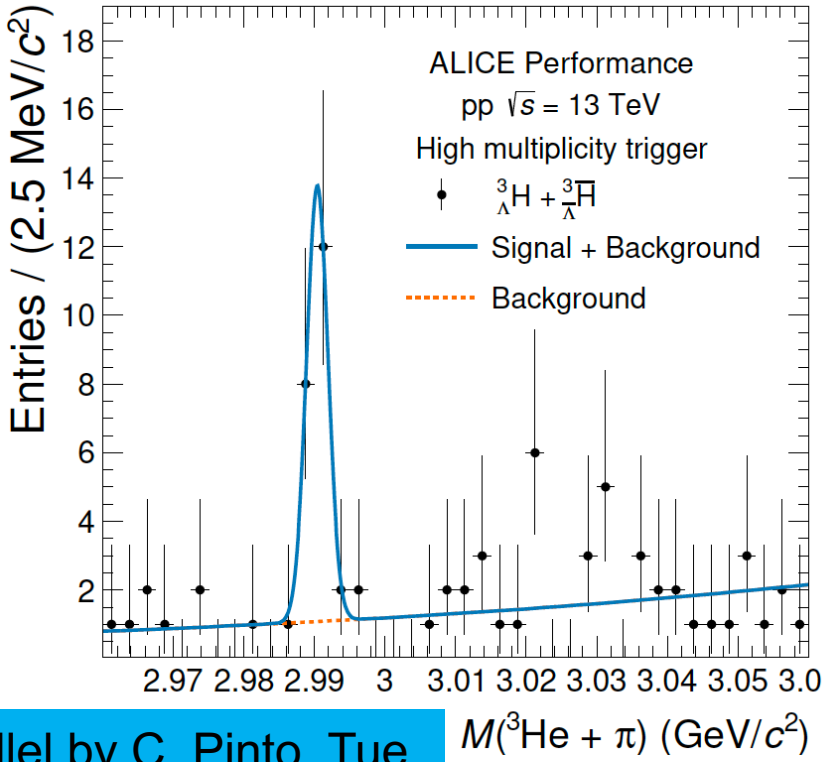
→ Only exception

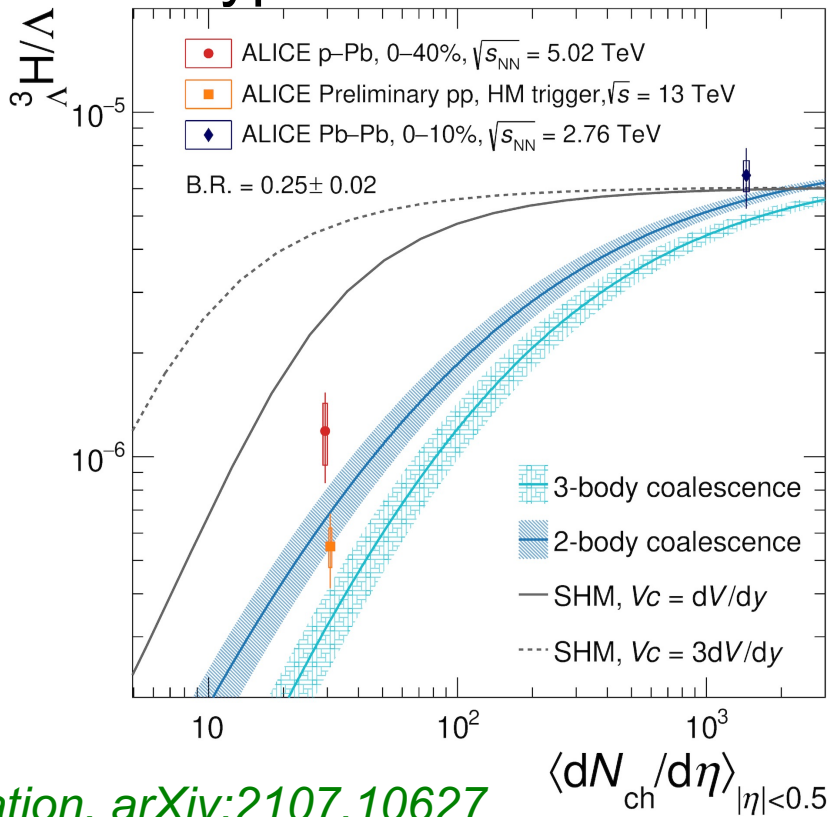
$^{4}_{\Lambda}\mathrm{H} / {}^{4}\mathrm{He}$



Hypertriton in pp & p-Pb

- Hypertriton signal recently also extracted in pp and p-Pb collisions
- Stronger separation between models as for other particle ratios, mainly due to the size of the hypertriton





V. Vovchenko, BD, H. Stoecker, PLB 785 (2018) 171
K.-J. Sun, C.-M. Ko, BD, PLB 792 (2019) 132

Parallel by C. Pinto, Tue

ALICE Collaboration, arXiv:2107.10627

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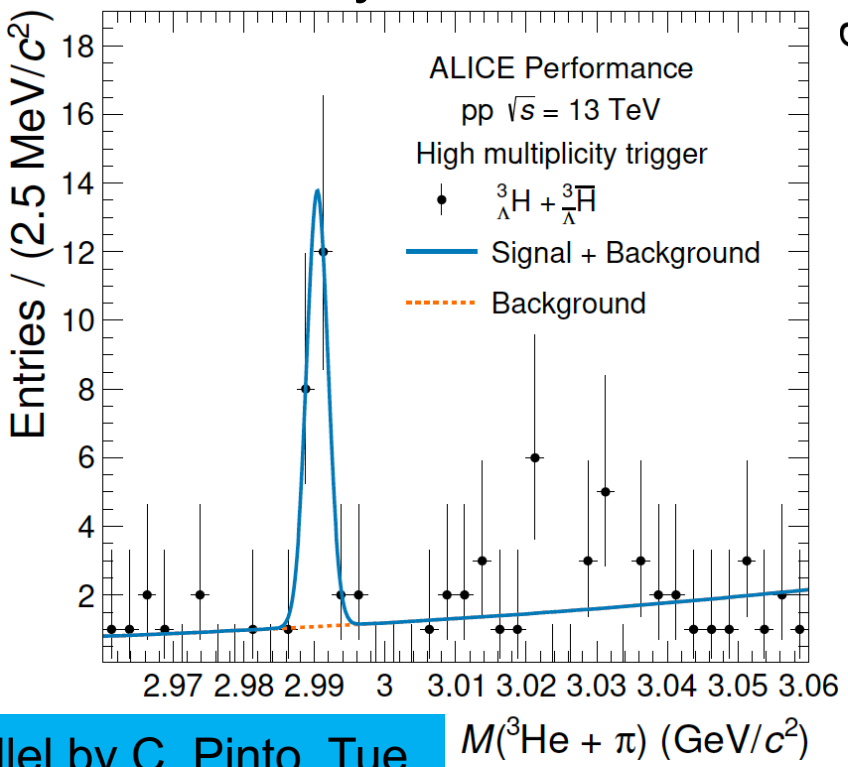

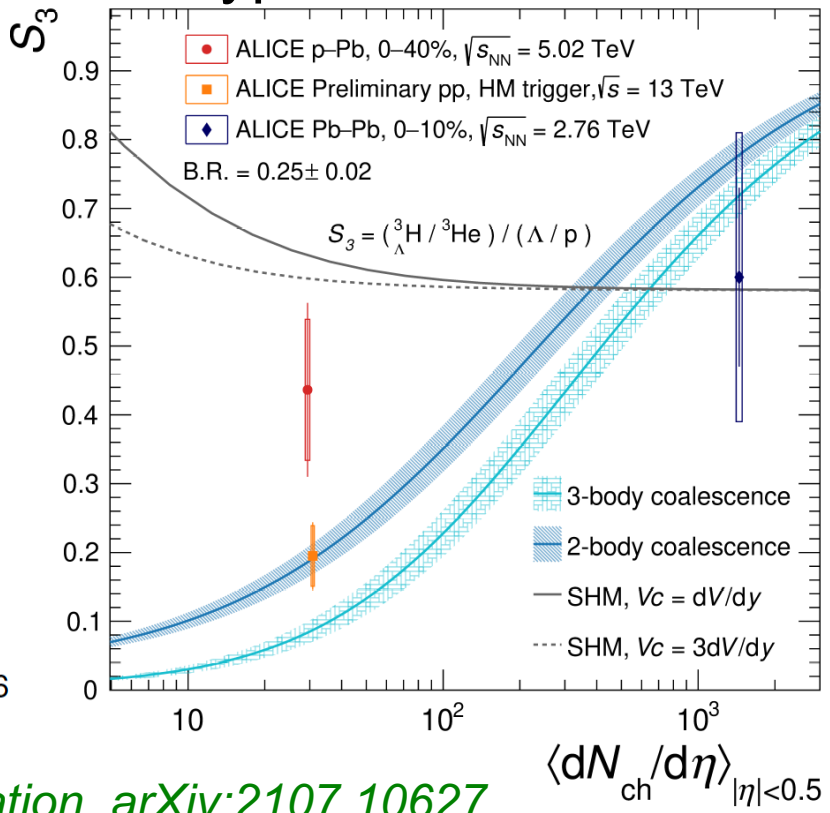

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K.-J. Sun, C.-M. Ko, BD, PLB 792 (2019) 132

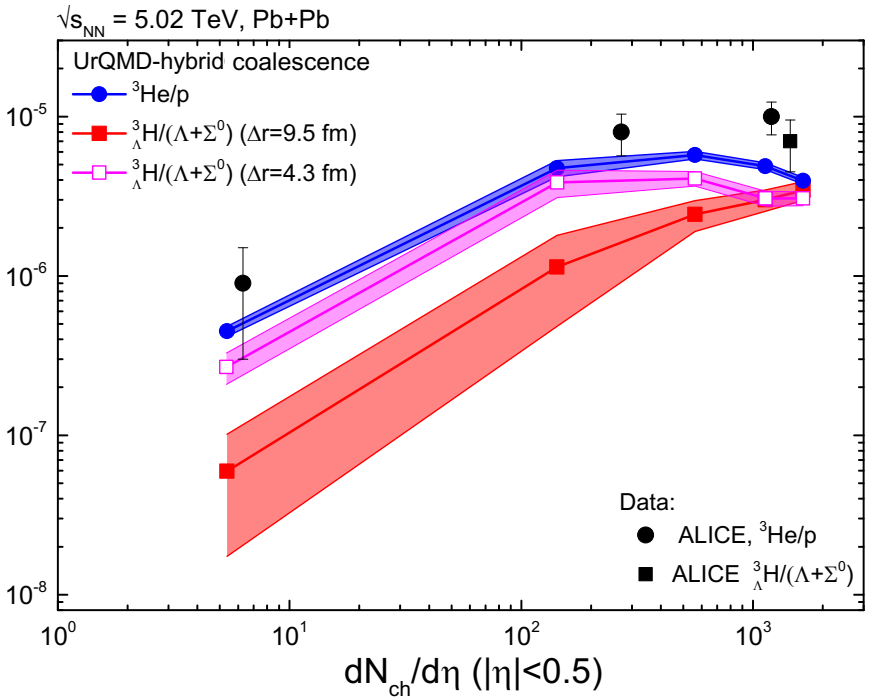
Parallel by C. Pinto, Tue

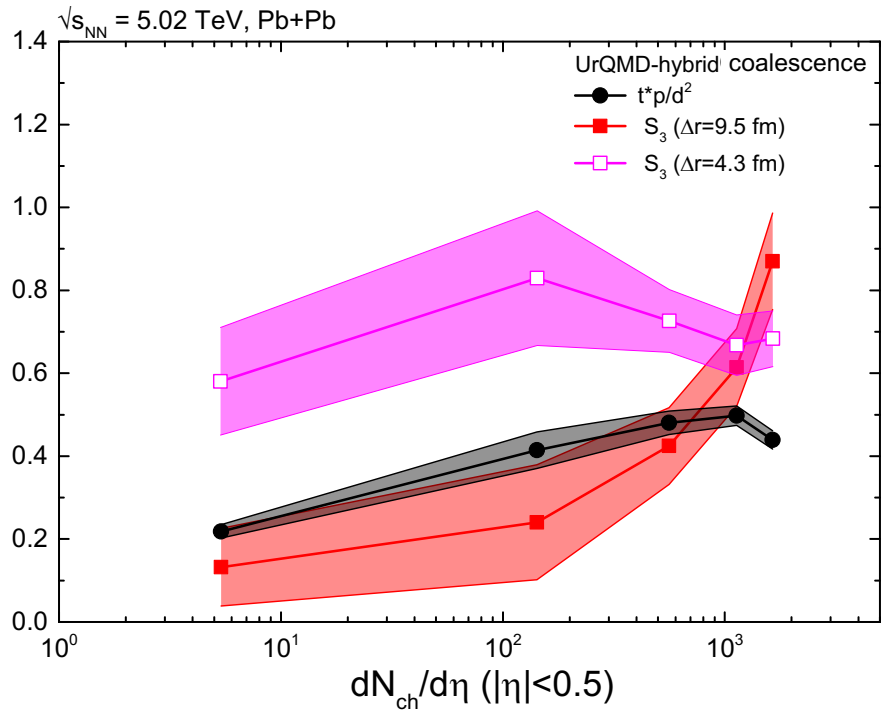
ALICE Collaboration, arXiv:2107.10627

Ratios

- Same trend also in „box“ coalescence model, restricting candidates in momentum and spatial phase space
- Playing with the size parameter gives different multiplicity dependence

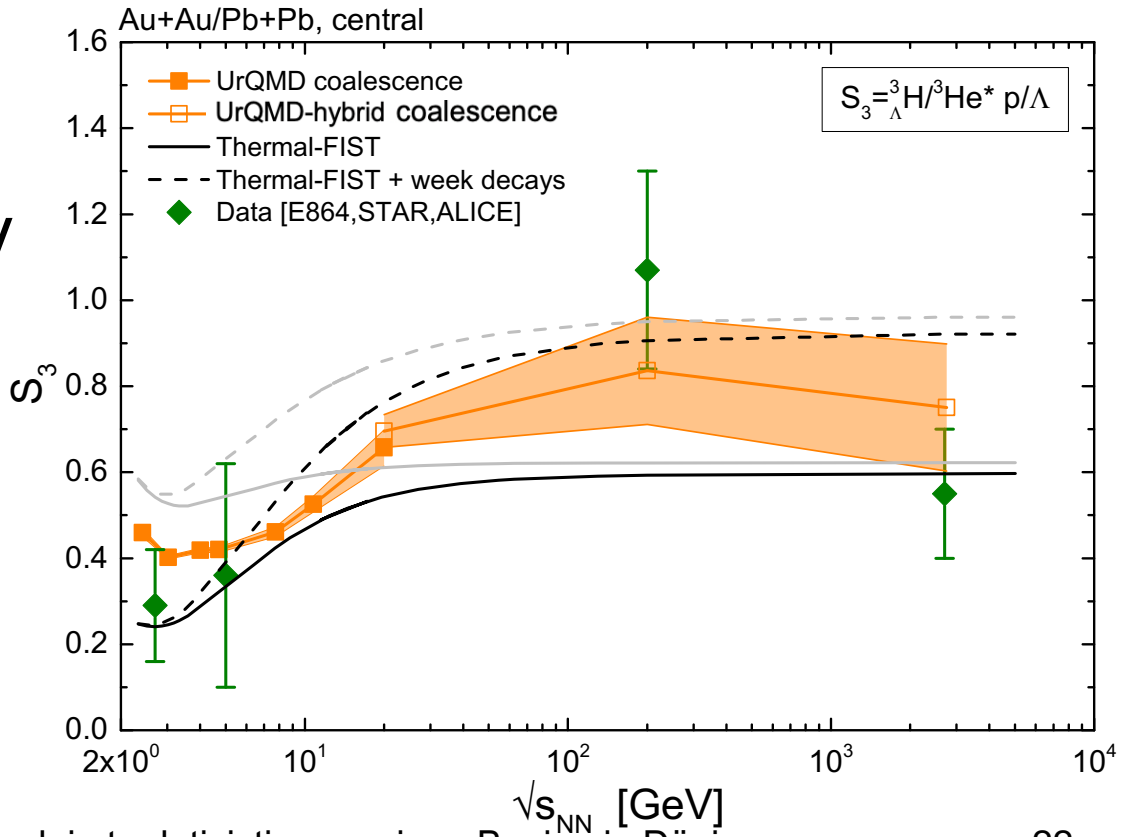
Parallel by T. Reichert, Tue





S_3 vs energy

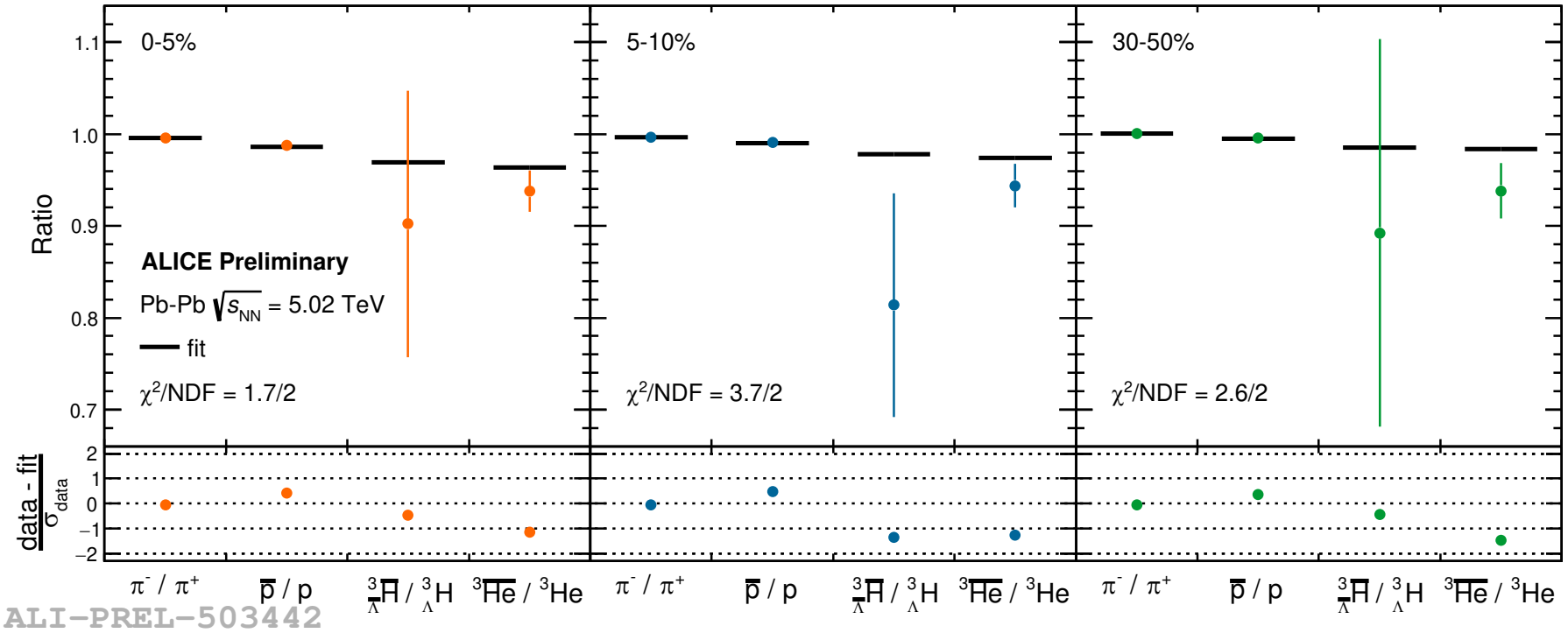
- Trend of the data reproduced by UrQMD/UrQMD-hybrid model using a large space parameter for the hypertriton
- Thermal model can only catch top RHIC energy data point by taking weak decays into account



Parallel by T. Reichert, Tue

Hypertriton Pb-Pb

- Hypertriton antiparticle-to-particle ratio part of data used to constrain μ_B at LHC heavy-ion collisions

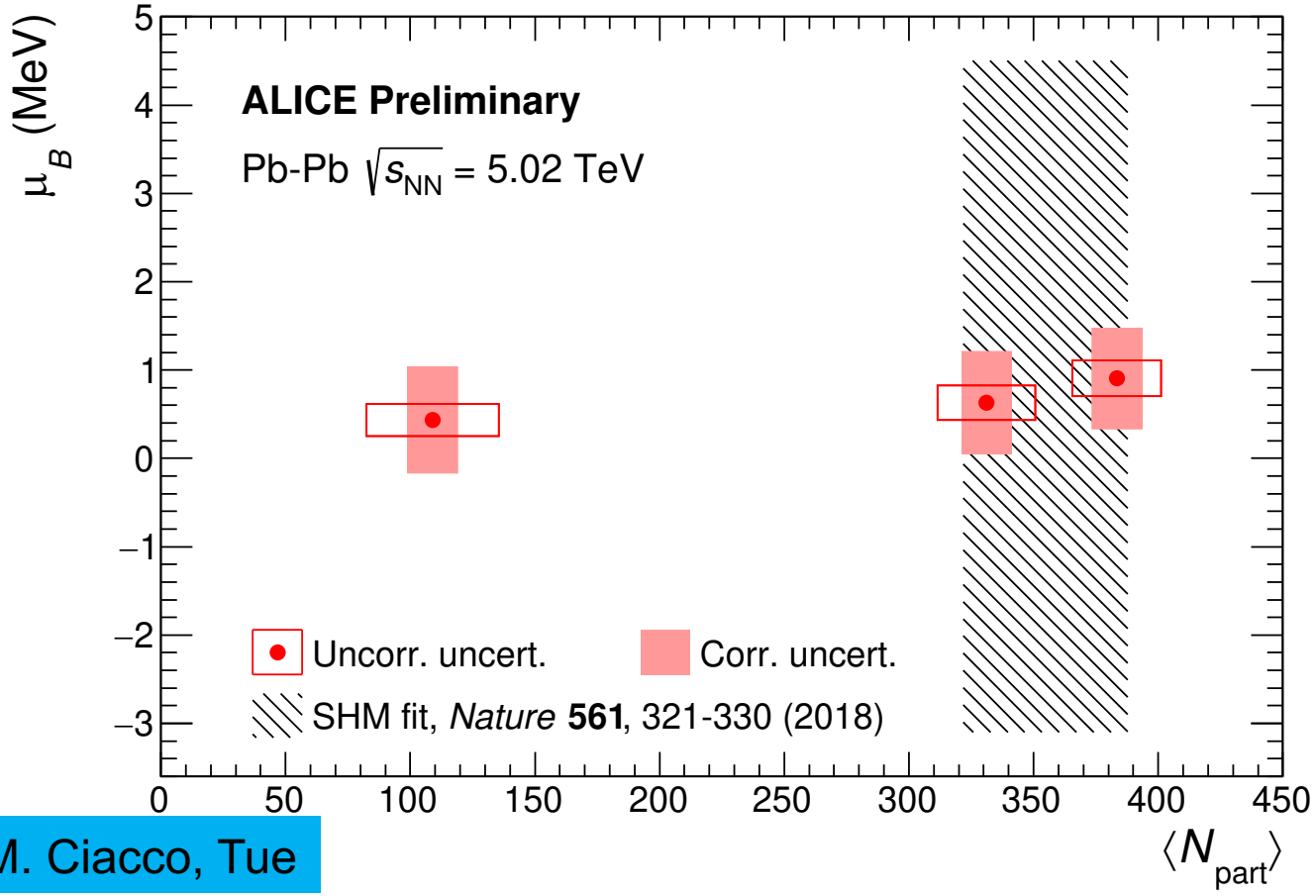


Parallel by M. Ciacco, Tue

$$\overline{h}/h \propto \exp\left[-2\left(B+\frac{S}{3}\right)\frac{\mu_B}{T} - 2I_3\frac{\mu_{I_3}}{T}\right]$$

Hypertriton Pb-Pb

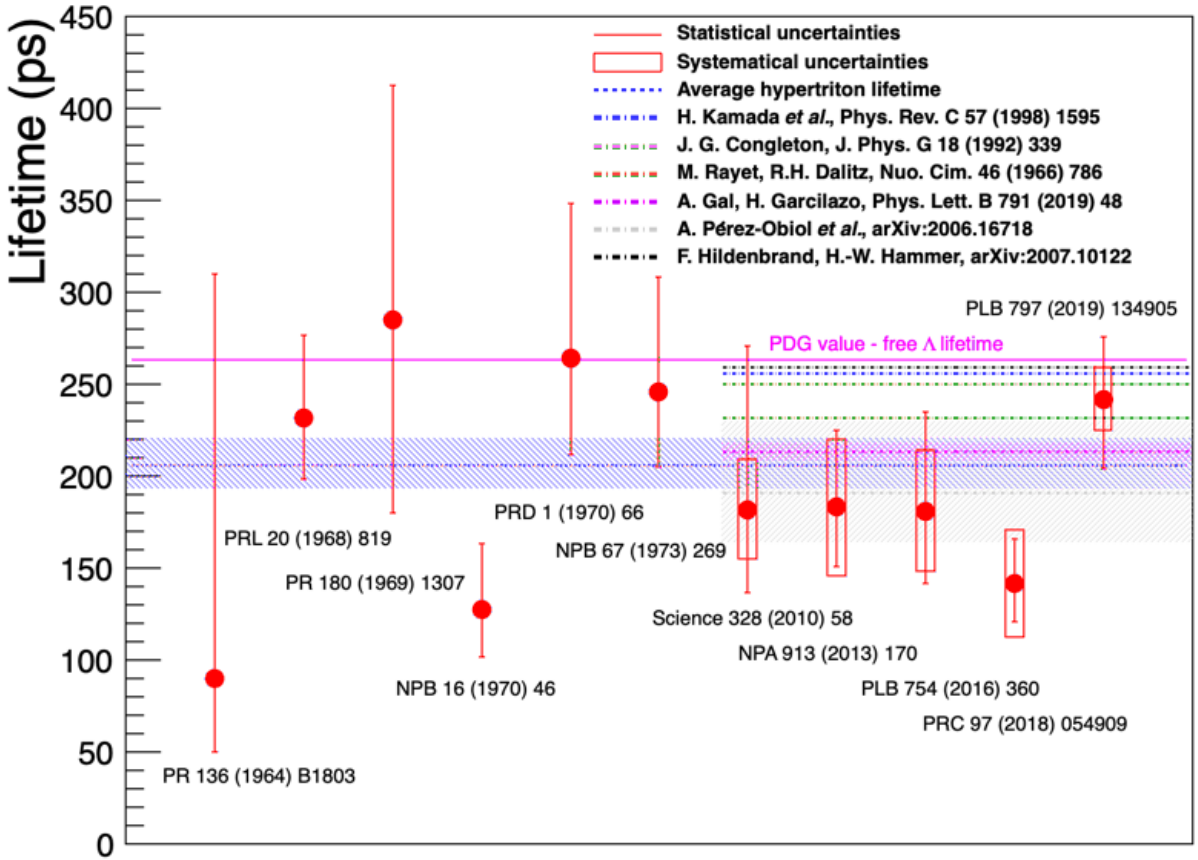
- Hypertriton antiparticle-to-particle ratio part of data used to constrain μ_B at LHC heavy-ion collisions



Parallel by M. Ciacco, Tue

Hypertriton „Puzzle“

- Recently measured lifetimes are significantly below the lifetime of the free Λ → new results agree with the world average of all known measurements and with the free Λ lifetime
- Most recent calculations include „final-state“ interaction and agree well with the data



BD, Eur. Phys. J 56 (2020) 258

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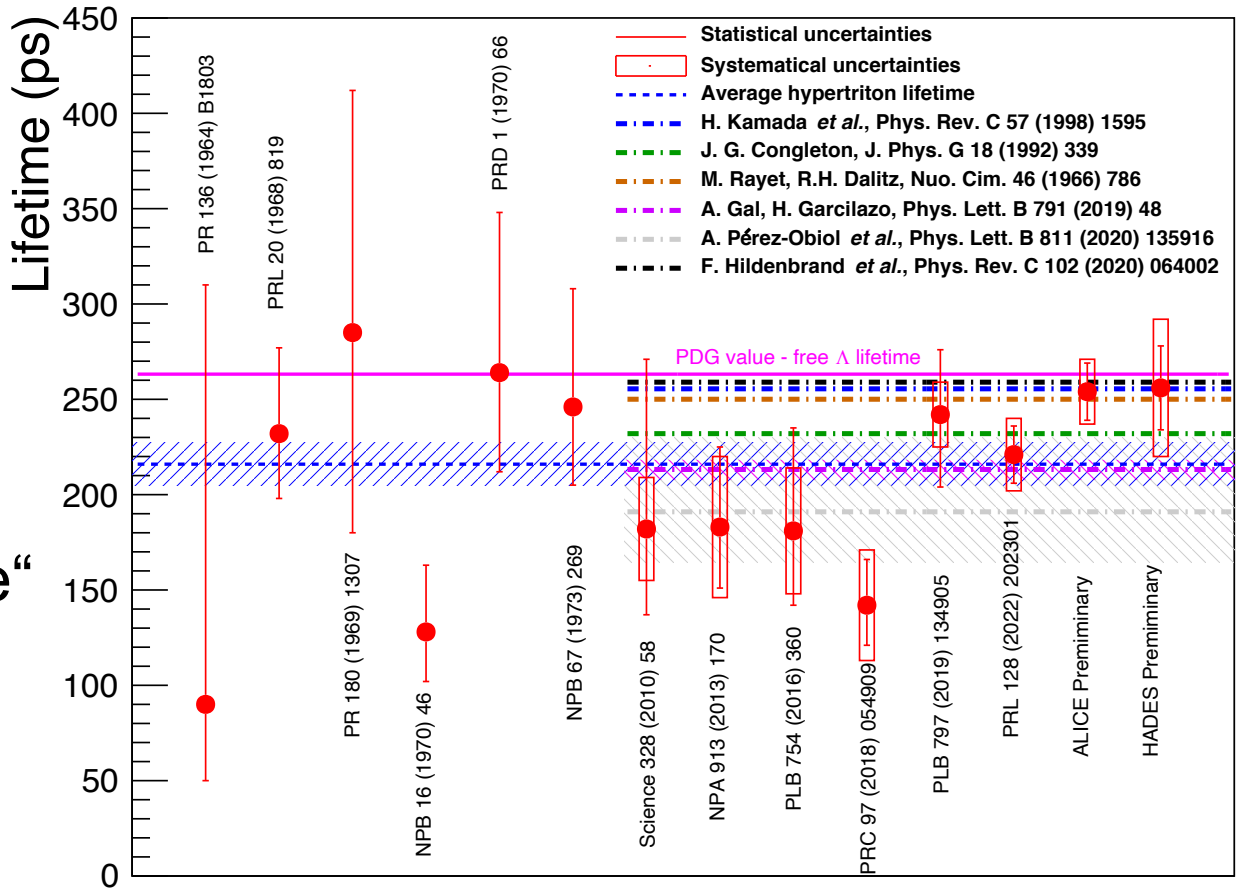
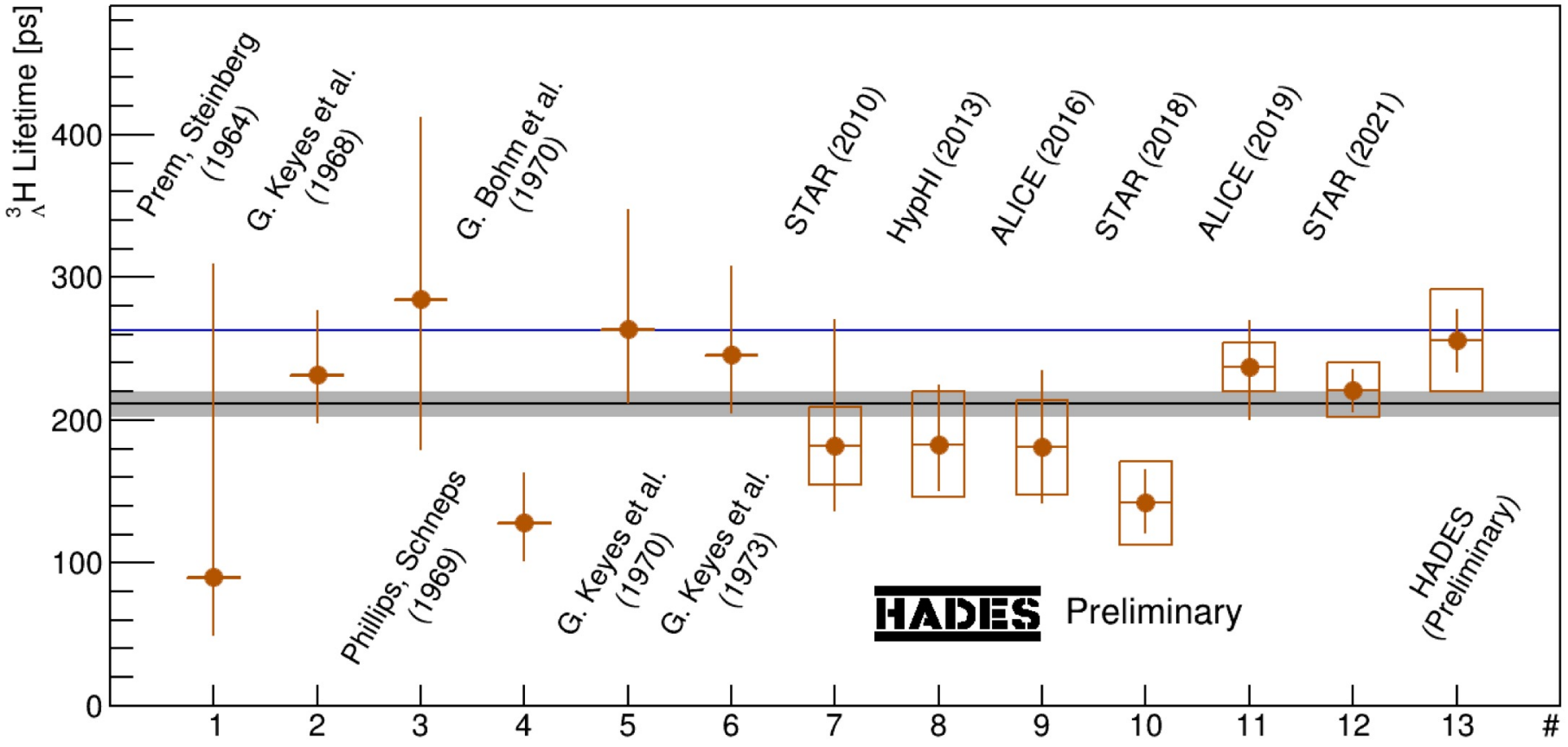


Lifetime: HADES

- HADES has first lifetime results for hypernuclei from Ag+Ag

Plenary by L. Chlad, Mon



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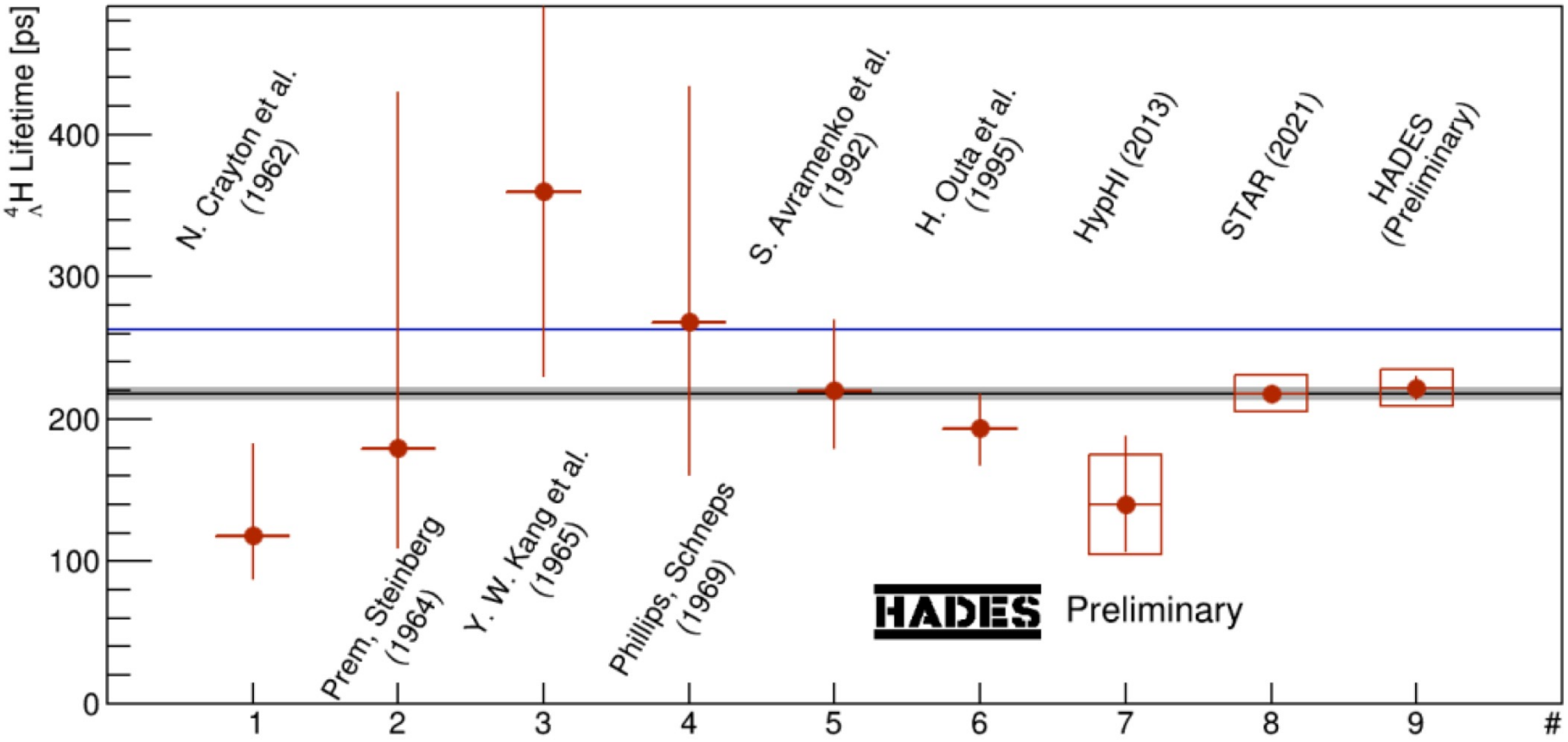
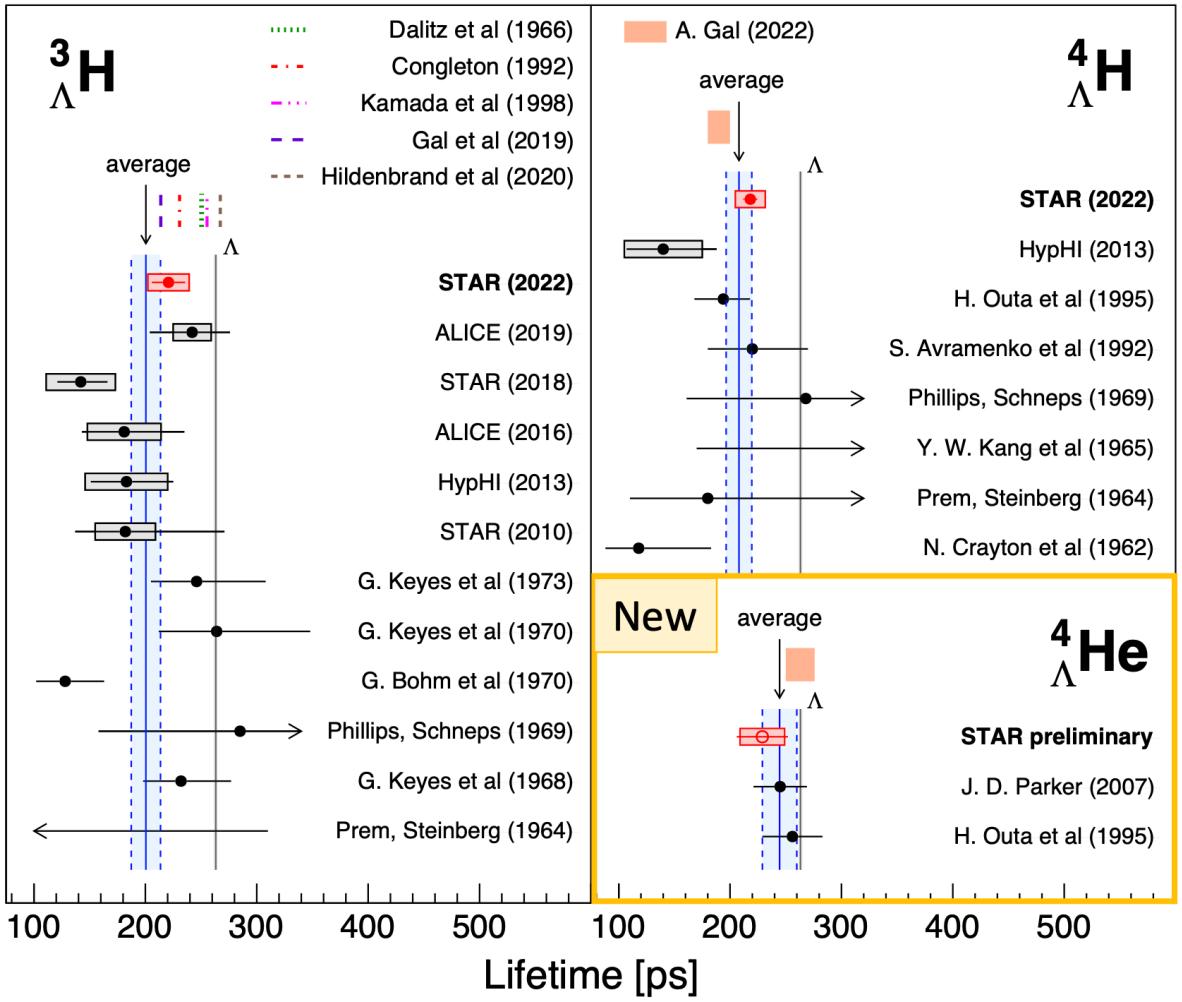


Lifetime

Plenary by B. Trzeciak, Mon
Parallel by Y. Ji, Tue

- Latest lifetime results from STAR Collaboration nicely agree with the world averages for the different hypernuclei



Lifetime

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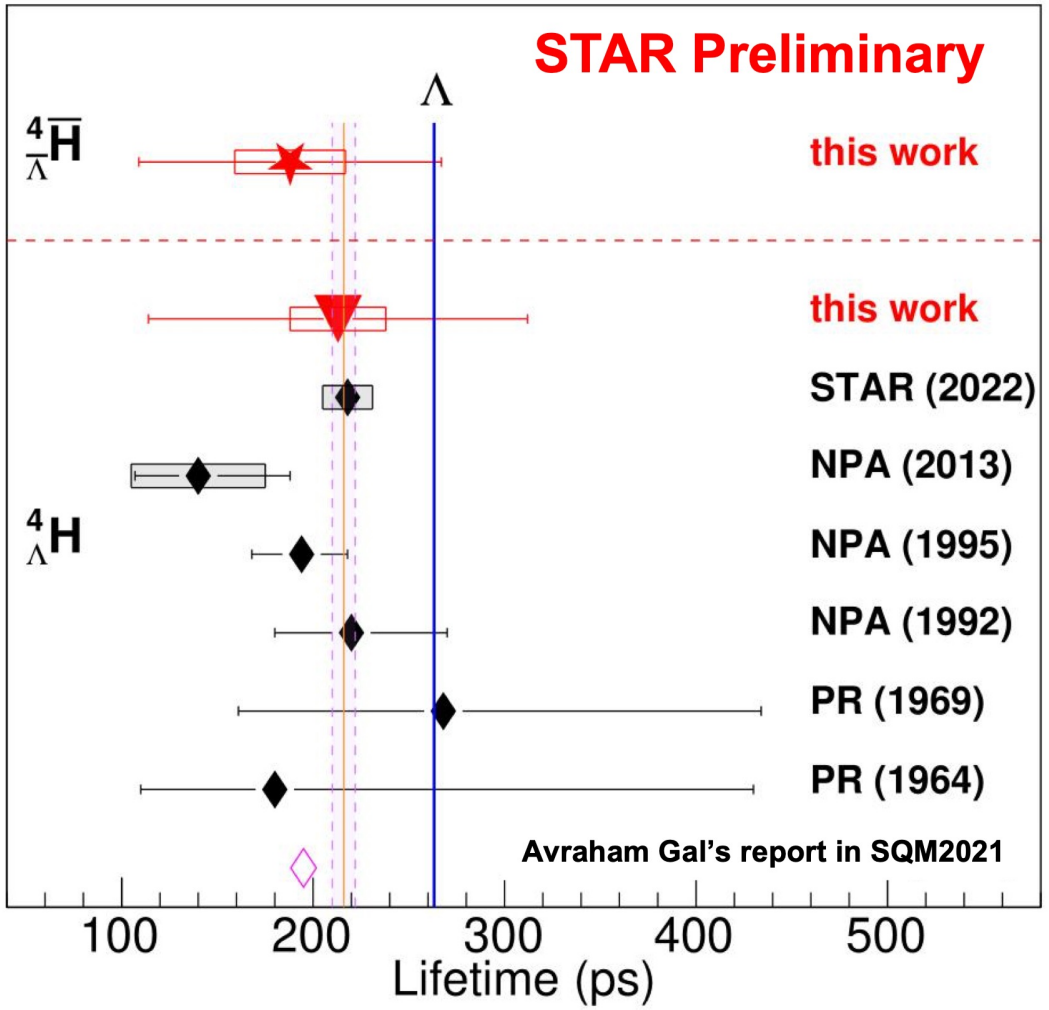
Parallel by J. Wu, Wed

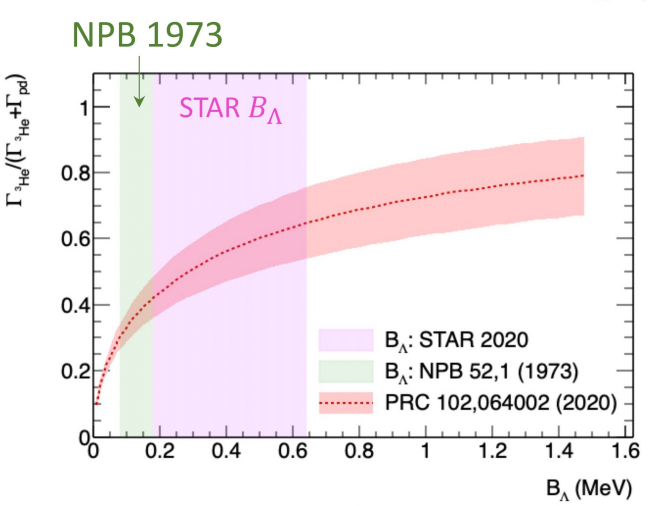
- Latest lifetime results from STAR Collaboration nicely agree with the world averages for the different hypernuclei
  → also newly observed $^{4}_{\Lambda}\overline{\mathrm{H}}$

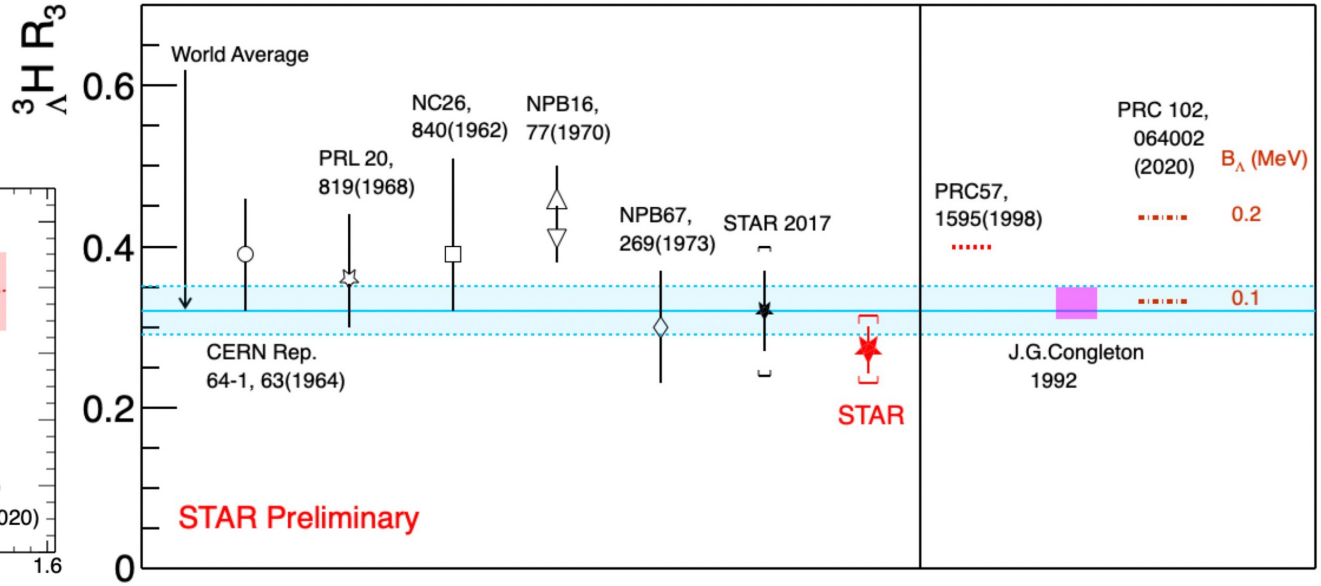


Branching ratio

Parallel by Y. Ji, Tue

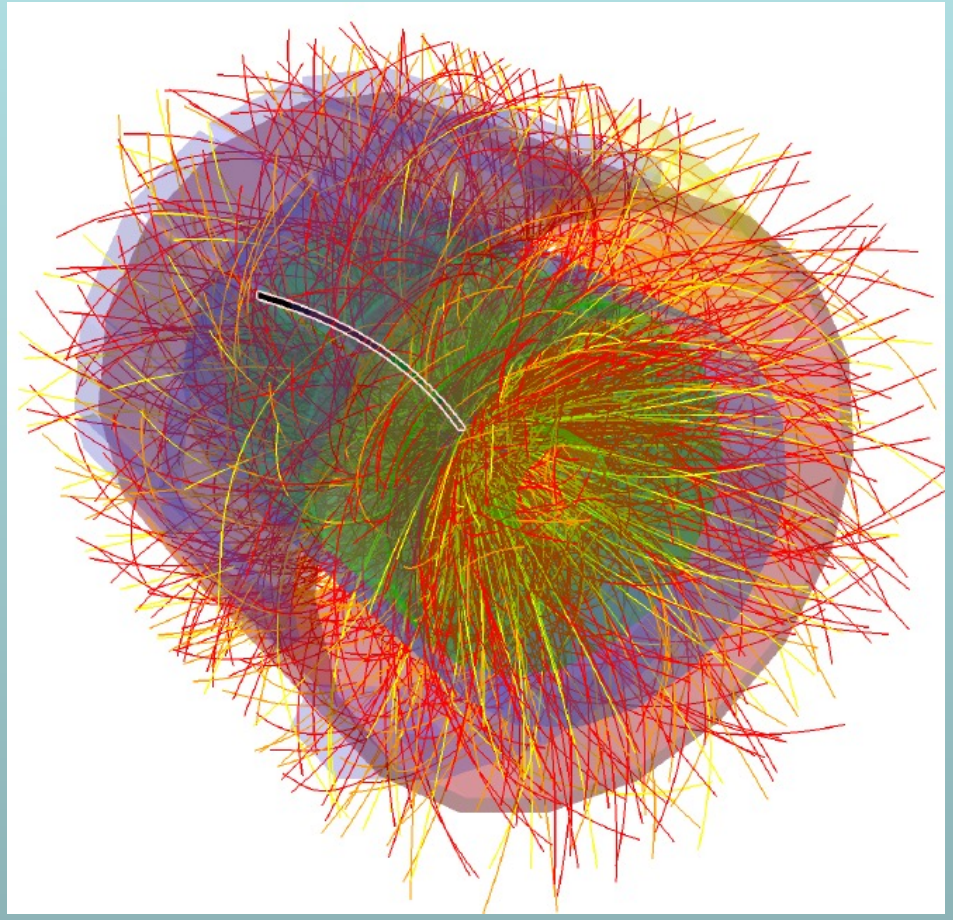
- Strong correlation between R_3 ratio and binding energy





$$R_3 = \frac{\Gamma\left({}^3_\Lambda\mathrm{H} \to {}^3\mathrm{He} + \pi^-\right)}{\Gamma\left({}^3_\Lambda\mathrm{H} \to \text{all } \pi^- \text{channels}\right)}$$

Summary



Conclusions

- Many new interesting results on (anti-)(hyper)nuclei
  - First observation of anti-hyperhydrogen-4 by STAR
- Production models (thermal & coalescence) are giving differently good description at different energies
  - Results at small systems seem to slightly prefer coalescence
- (Average) lifetimes of all hypernuclei are significantly below the free Λ lifetime
- New and more precise data can be expected in the next years by all experiments