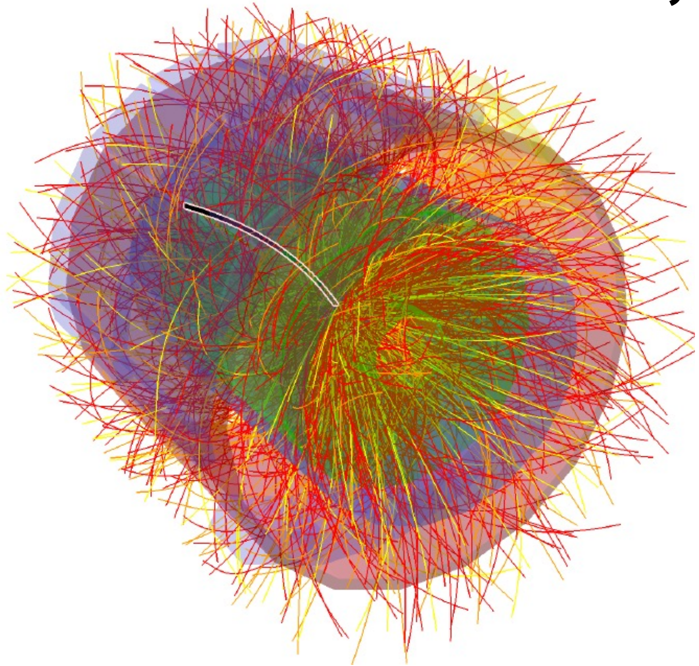
Production of loosely-bound objects in heavy-ion collisions at HADES, RHIC and LHC



April 14, 2025
GSI
Physics of High net-baryon Densities - PHD 2025

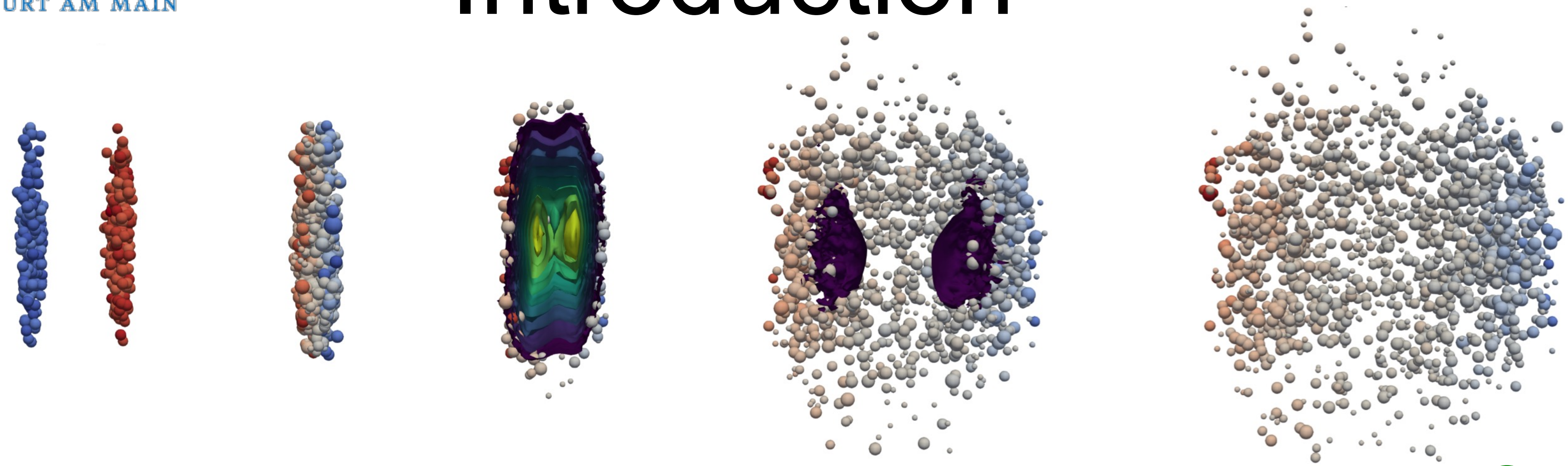
Benjamin Dönigus

Institut für Kernphysik
Goethe Universität Frankfurt

Content

- Introduction
- Nuclei and Exotica
  - (Anti-)nuclei
  - (Anti-)hypernuclei
- Summary & Outlook

Introduction



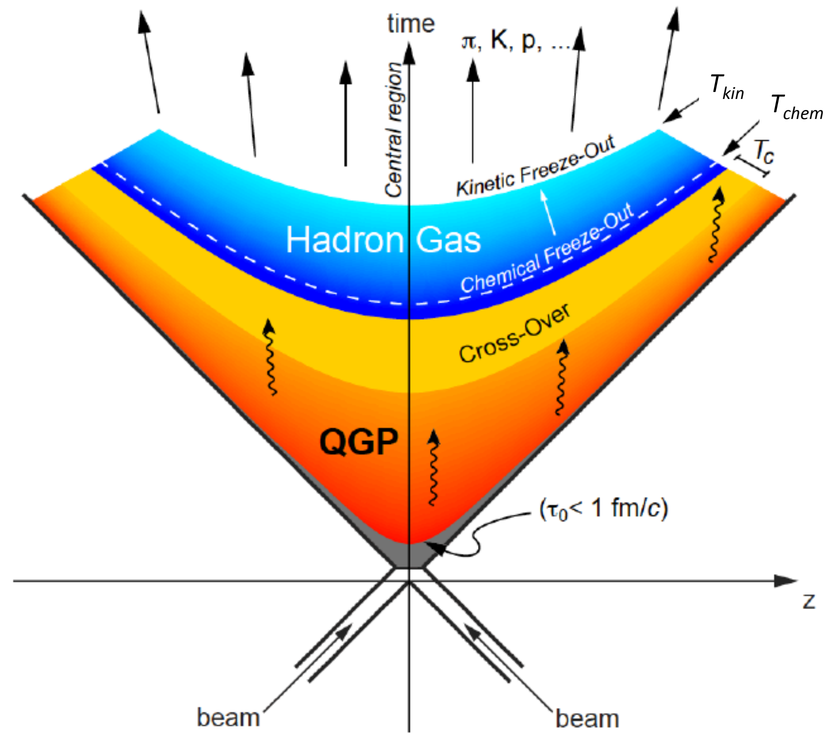
Cartoon of a Ultra-relativistic heavy-ion collision

Left to right:

- the two Lorentz contracted nuclei approach,
- collide,
- form a Quark-Gluon Plasma (QGP),
- the QGP expands and hadronizes,
- finally hadrons rescatter and freeze

SMASH-vHLLE hybrid approach
R. Sattleret al., Poster at QM2025 (#58)
H. Elfner, Theory Summary QM2025

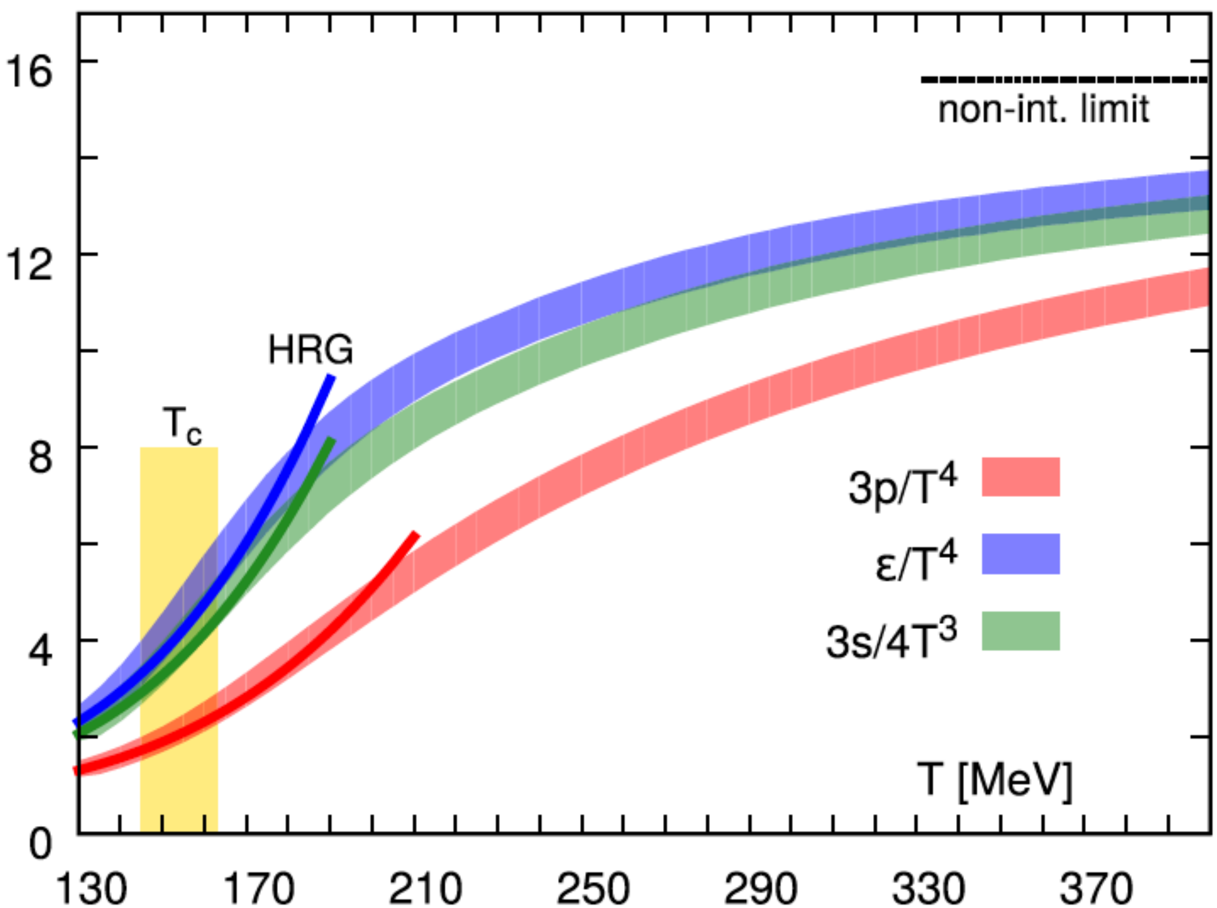
Introduction



The fireball evolution:

- Starts with a “pre-equilibrium state”
- Forms a Quark-Gluon Plasma phase (if T is larger than T_c)
- At *chemical freeze-out*, T_{ch}, *hadrons stop being produced*
- At *kinetic freeze-out*, T_{fo}, *hadrons stop scattering*

Lattice QCD results



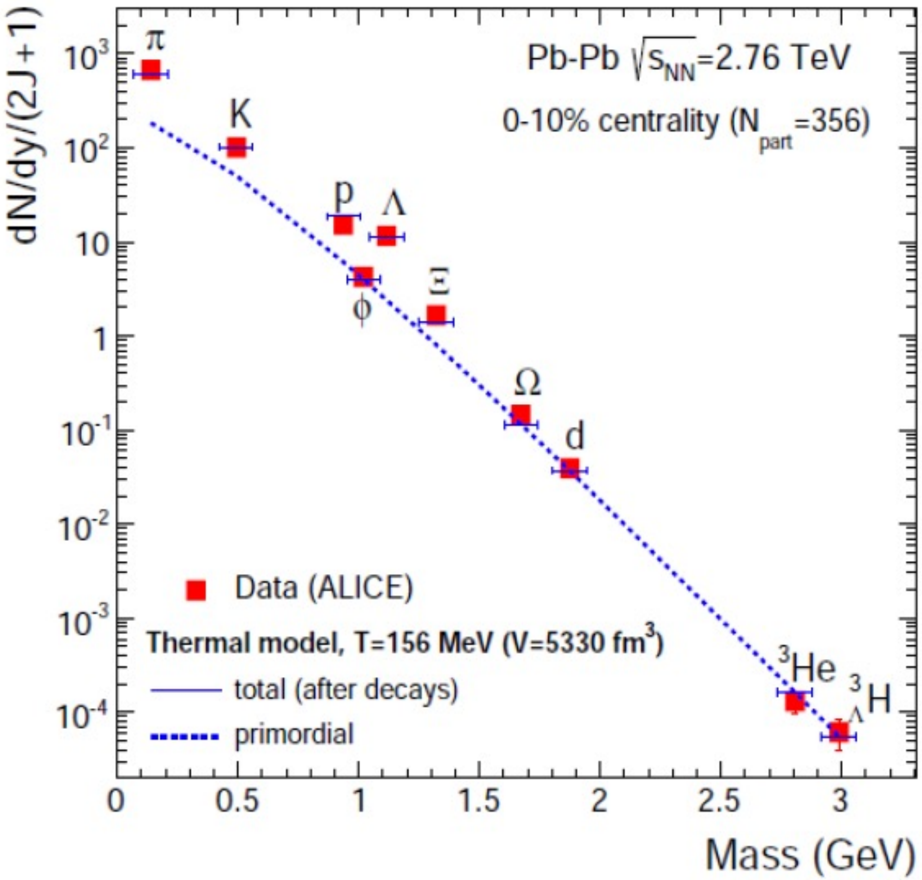
Lattice QCD tells us where to expect the phase transition

Critical energy density:
$\varepsilon_C = 0.34 \pm 0.16$ GeV/fm^3

Critical temperature
$T_C = (157 \pm 2)$ MeV

A. Bazavov et al. (hotQCD) Phys. Rev. D90 (2014) 094503 & PLB 795 (2019) 15
Similar results from Budapest-Wuppertal group: S. Borsányi et al. JHEP 09 (2010) 073 & PRL 125 (2020) 052001

Temperature of the source



Plot by A. Andronic, GSI-Heidelberg group
arXiv:1407.5003 [nucl-ex]

Analogy:

Light source → particle source

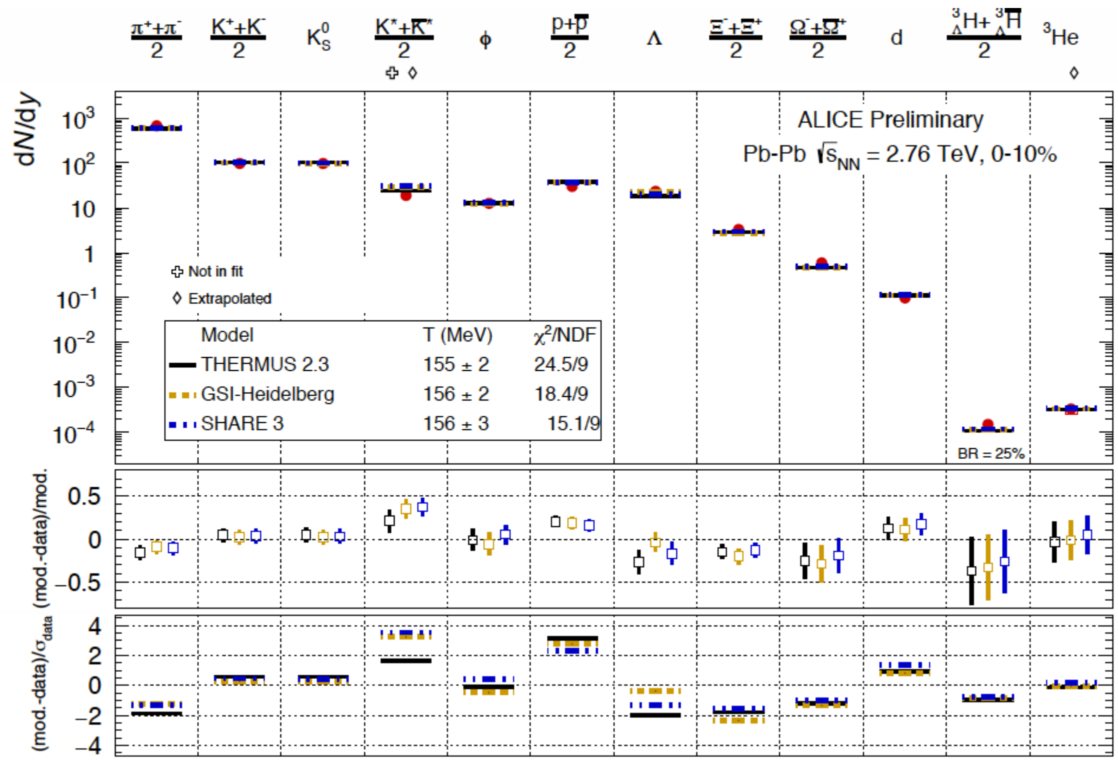
- Multiplicity described best with T = 1 900 000 000 000 °C (1,9 trillion degree centigrade)

→ 100 000 times hotter than in the interior of the sun!

1/40 eV = 20 °C

Thermal model

- Statistical (thermal) model with only three parameters able to describe particle yields (grand chanonical ensemble)

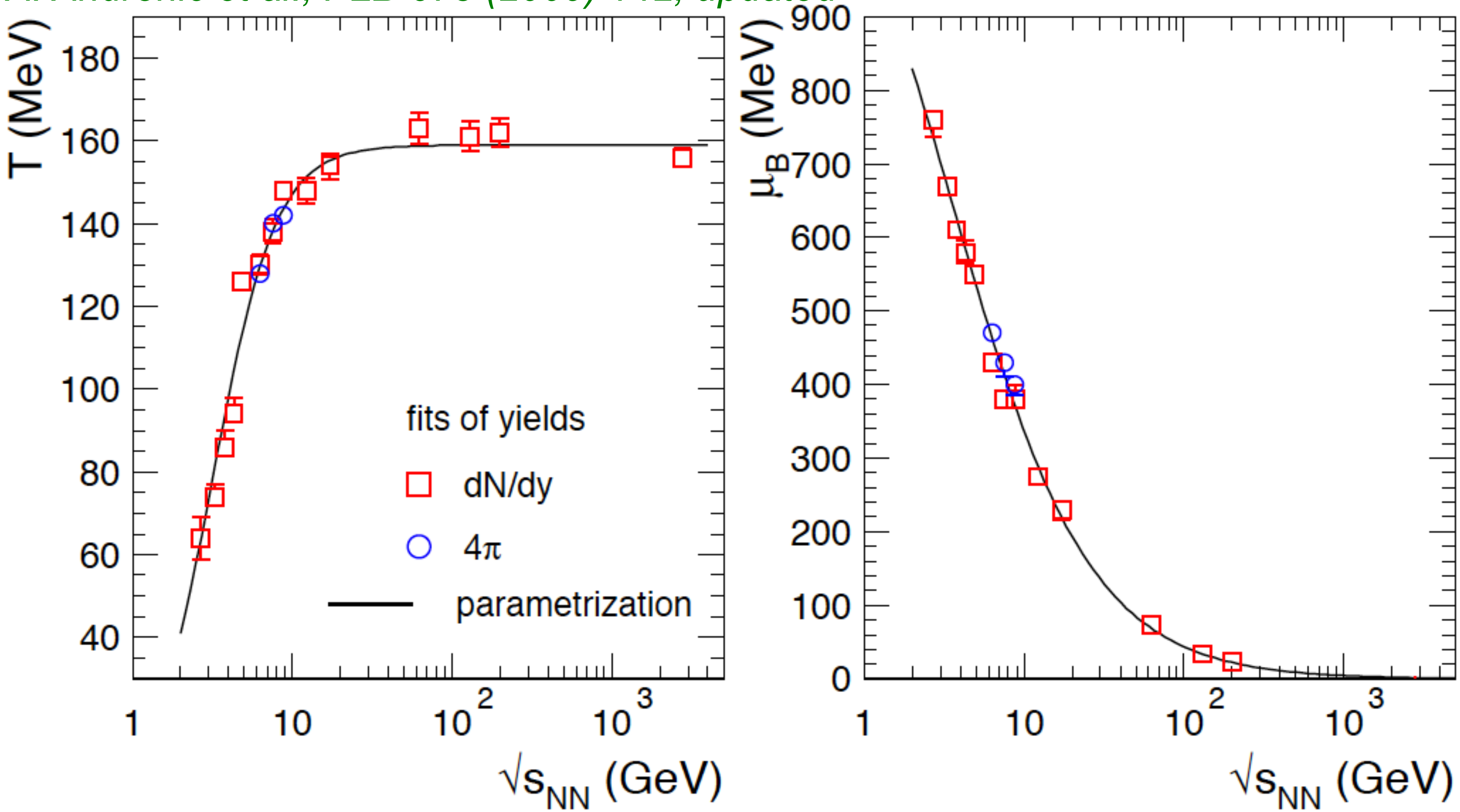


- chemical freeze-out temperature T_{ch}
- baryo-chemical potential μ_B
- Volume V

→ Using particle yields as input to extract parameters

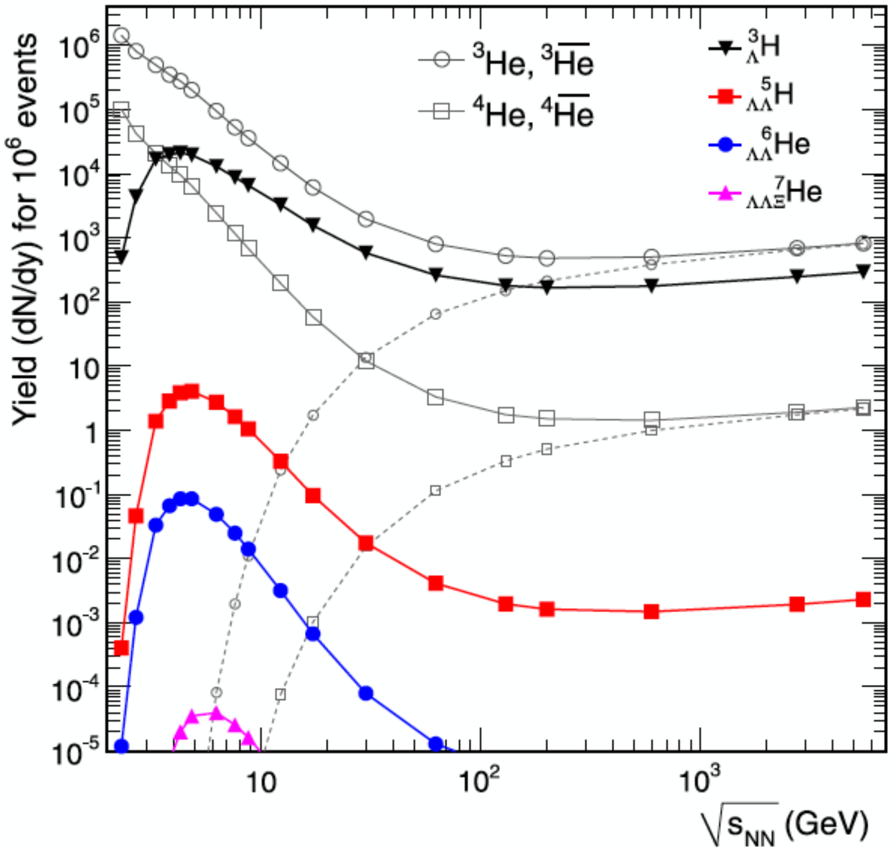
Energy dependence

A. Andronic et al., PLB 673 (2009) 142, updated



Thermal model fits show limiting temperature: T_{lim} = (159 ± 2) MeV

Predicting yields of bound states



A. Andronic et al., PLB 697 (2011) 203

Key parameter at LHC energies:

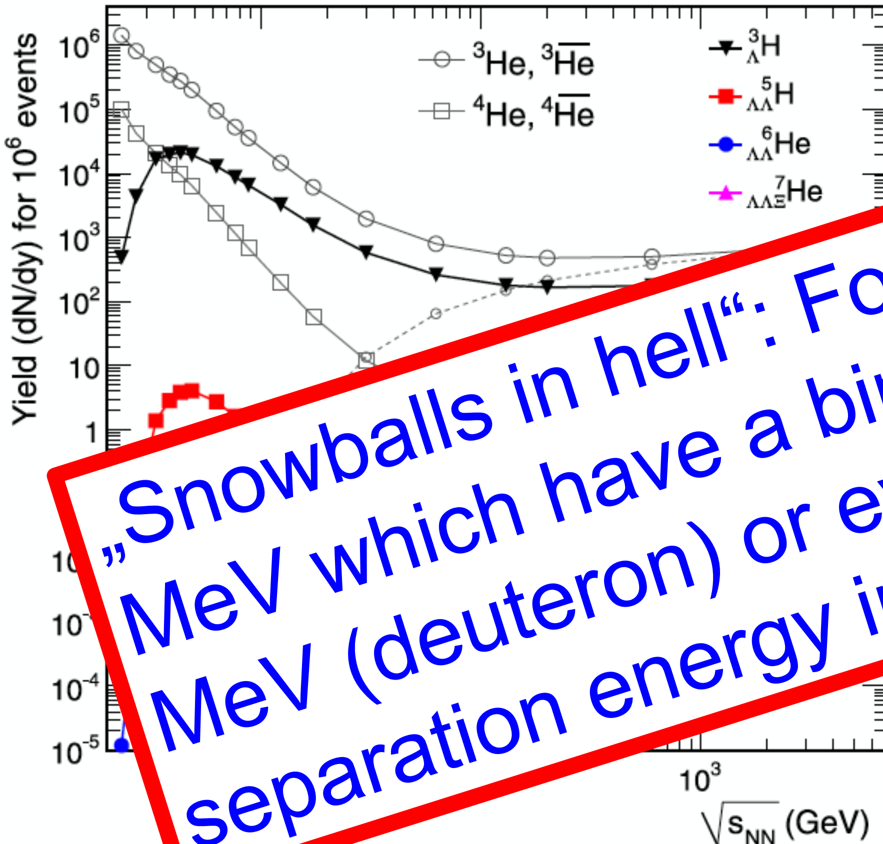
chemical freeze-out temperature T_{ch}

Strong sensitivity of abundance of nuclei to choice of T_{ch} due to:

1. large mass *m*
2. exponential dependence of the yield ~ $\exp(-m/T_{ch})$

→ Binding energies small compared to T_{ch}

Predicting yields of bound states



A. Andronic et al., PLB 697 (2011) 203

„Snowballs in hell": Forming objects at 150 MeV which have a binding energy of only 2.2 MeV (deuteron) or even only 130 keV (Λ separation energy in the hypertriton)

Key parameter at l… energies: …

…el

…e of T_{ch} due to:

1. large mass *m*
2. exponential dependence of the yield ~ exp(-m/T_{ch})

→ Binding energies small compared to T_{ch}

Snowballs in hell

- Already mentioned in S. Weinberg's book: The first three minutes

quantities from the conditions for thermal equilibrium - for instance, we can make the density of water molecules plus hydrogen ions a little greater or less than 3.3 X 10^{22} molecules per cubic centimetre by raising or lowering the pressure - so we need to specify them in order to know what is in our glass.

This example also helps us to understand the shifting meaning of what we call 'conserved' quantities. For instance, if our water is at a temperature of millions of degrees, as inside a star, then it is very easy for molecules or ions to dissociate, and for the constituent atoms to lose their electrons. The conserved quantities are then the numbers of electrons and of oxygen and hydrogen nuclei. The density of water molecules plus hydroxyl atoms under these conditions has to be *calculated* from the rules of statistical mechanics rather than specified in advance; of course, it turns out to be quite small. (Snowballs are rare in hell.) Actually, nuclear reactions do occur under these conditions, so even the numbers of nuclei of each species are not absolutely fixed, but these numbers change so slowly that a star can be regarded as evolving gradually from one equilibrium state to another.

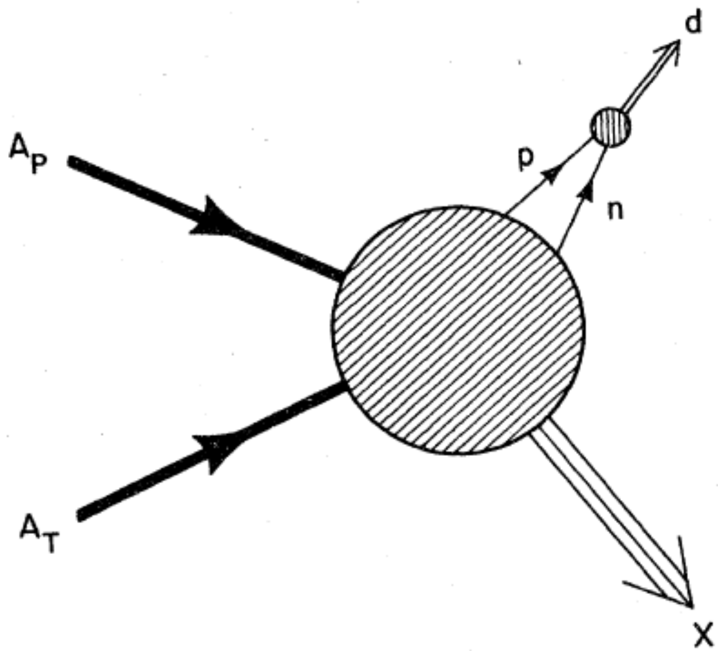
AGS predictions

P. Braun-Munzinger, J. Stachel, J. Phys. G: Nucl. Part. Phys. 21 (1995) L17

- Already at AGS the predictions from thermal model and coalescence were very close
- Looking at production yields alone might not be enough to disentangle models

	Thermal model		
Particles	$T = 0.120$ GeV	$T = 0.140$ GeV	Coalescence model
d	15	19	11.7
$t+{}^3He$	1.5	3.0	0.8
α	0.02	0.067	0.018
H_0	0.09	0.15	0.07
${}^5_{\Lambda\Lambda}H$	3.5×10^{-5}	2.3×10^{-4}	4×10^{-4}
${}^6_{\Lambda\Lambda}He$	7.2×10^{-7}	7.6×10^{-6}	1.6×10^{-5}
${}^7_{\Xi^0\Lambda\Lambda}He$	4.0×10^{-10}	9.6×10^{-9}	4×10^{-8}
${}^{10}_{1}St^{-8}$	1.6×10^{-14}	7.3×10^{-13}	
${}^{12}_{1}St^{-9}$	1.6×10^{-17}	1.7×10^{-15}	
${}^{14}_{1}St^{-11}$	6.2×10^{-21}	1.4×10^{-18}	
${}^{16}_{2}St^{-13}$	2.4×10^{-24}	1.2×10^{-21}	
${}^{20}_{2}St^{-16}$	9.6×10^{-31}	2.3×10^{-27}	

Coalescence



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

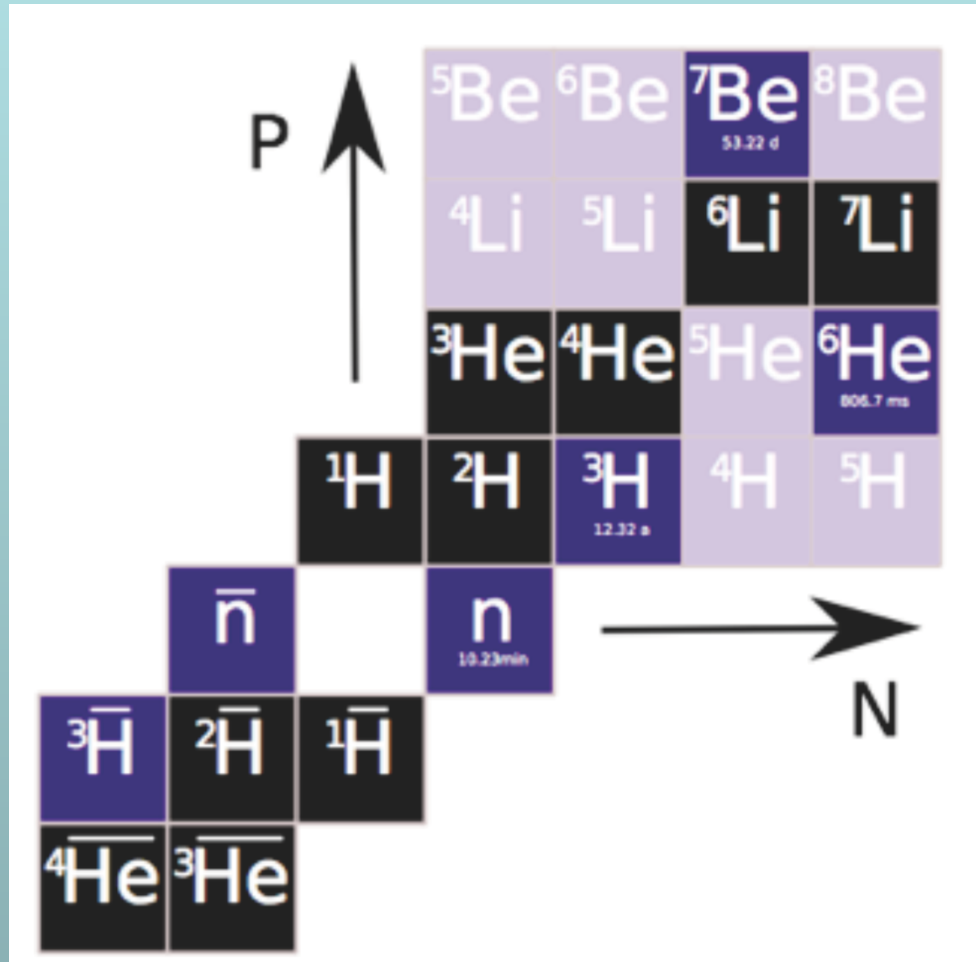
Nuclei are formed by protons and neutrons which are nearby and have similar velocities (after kinetic freeze-out)

Produced nuclei

→ can break apart

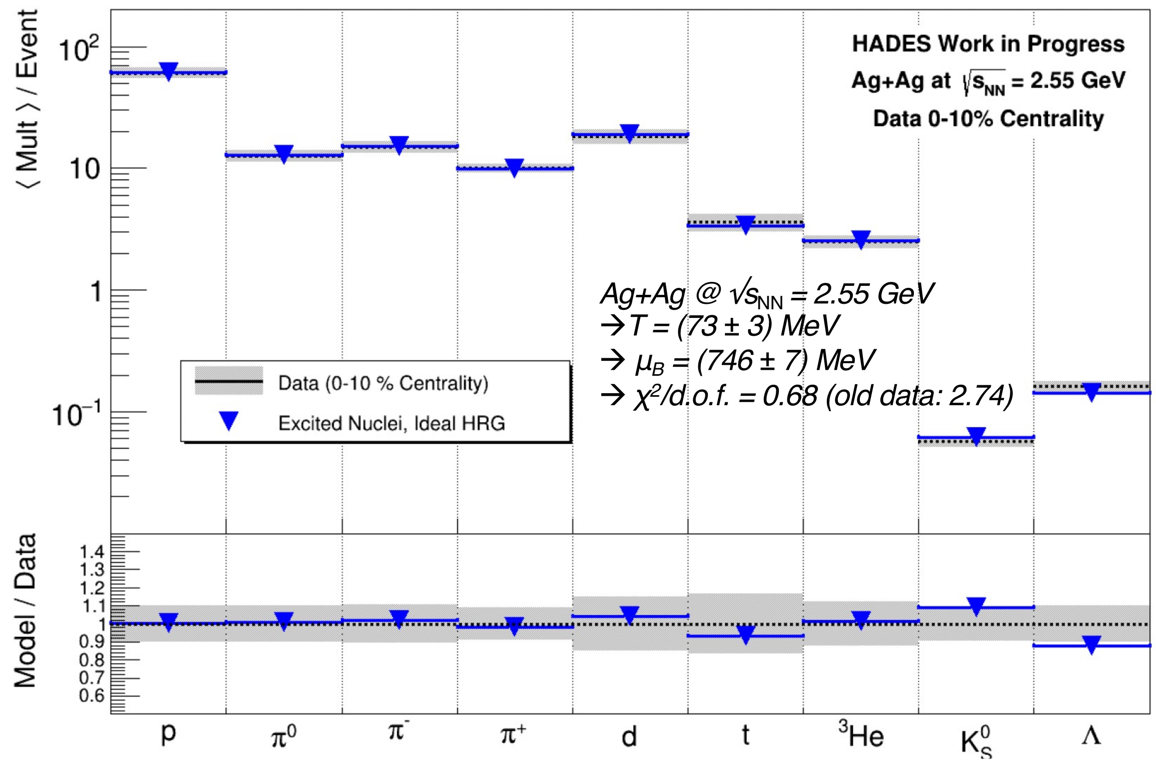
→ created again by final-state coalescence

(Anti-)Nuclei


P
N
^{5}Be
^{6}Be
^{7}Be
53.22 d
^{8}Be
^{4}Li
^{5}Li
^{6}Li
^{7}Li
^{3}He
^{4}He
^{5}He
^{6}He
806.7 ms
^{1}H
^{2}H
^{3}H
12.32 a
^{4}H
^{5}H
$\bar{n}$
n
10.23min
$^3\bar{H}$
$^2\bar{H}$
$^1\bar{H}$
$^4\overline{He}$
$^3\overline{He}$

Thermal model: HADES

- For HADES Ag+Ag data the thermal model fit describes the production of all investigated yields, including nuclei
- Rather good description

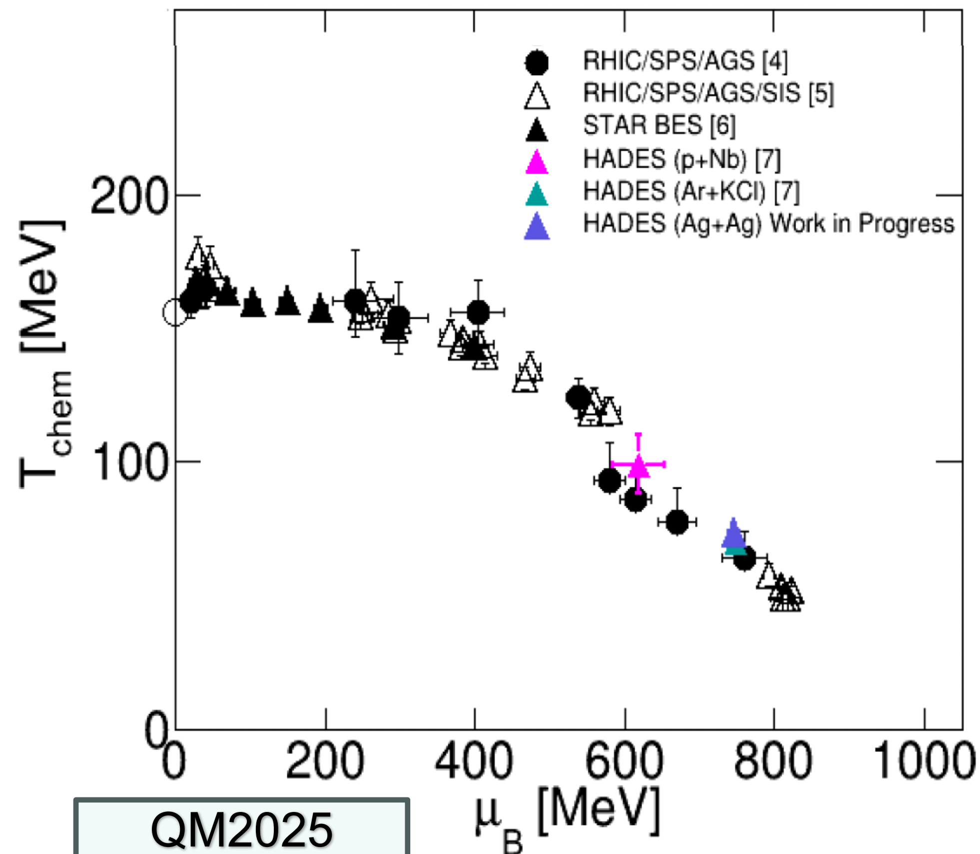


QM2025
Talk #577
S. Spies

QM2025
Poster #576
M. Kohls

Phase diagram

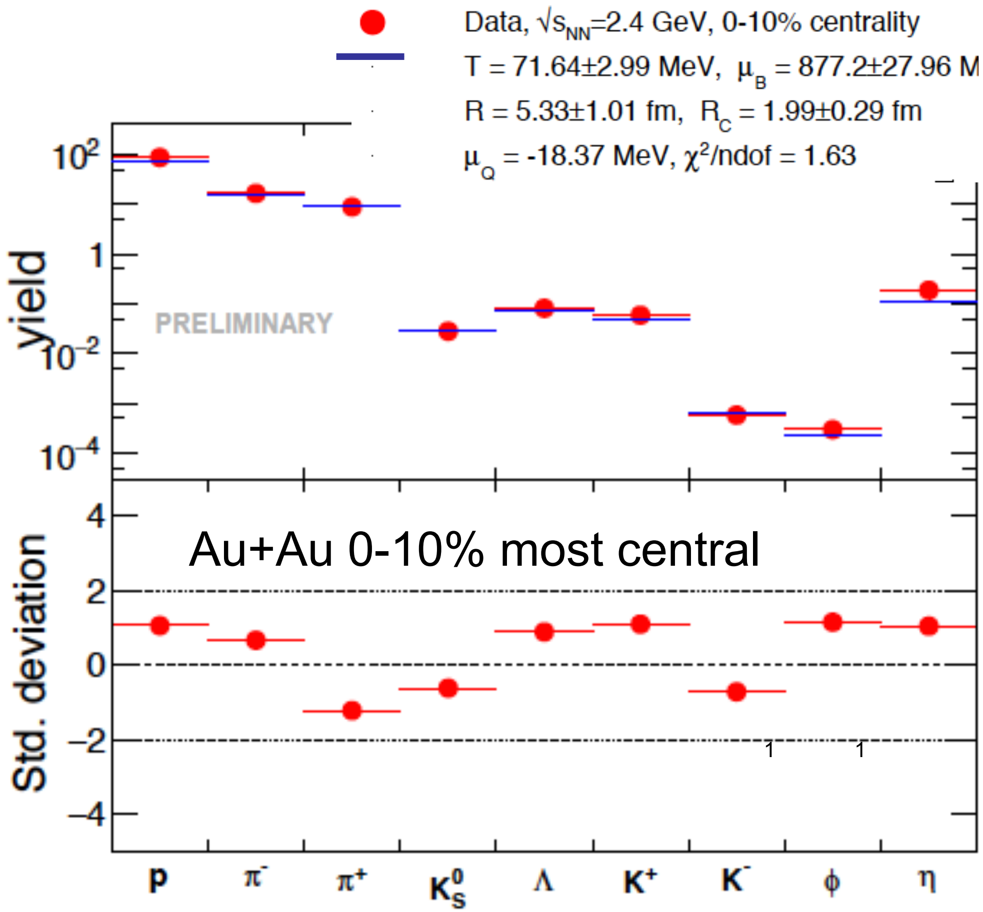
- For HADES Ag+Ag data the thermal model fit describes the production of all investigated yields, including nuclei
- Rather good description
- Including nuclei leads to nice agreements with the trend of the world data

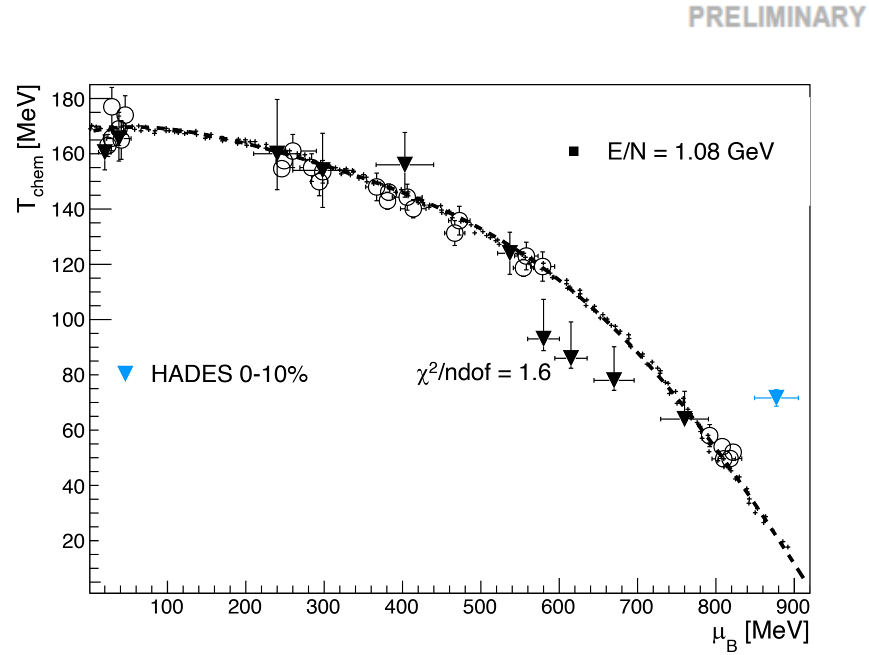


QM2025
Poster #576
M. Kohls

THERMUS V2.3

Phase diagram: HADES



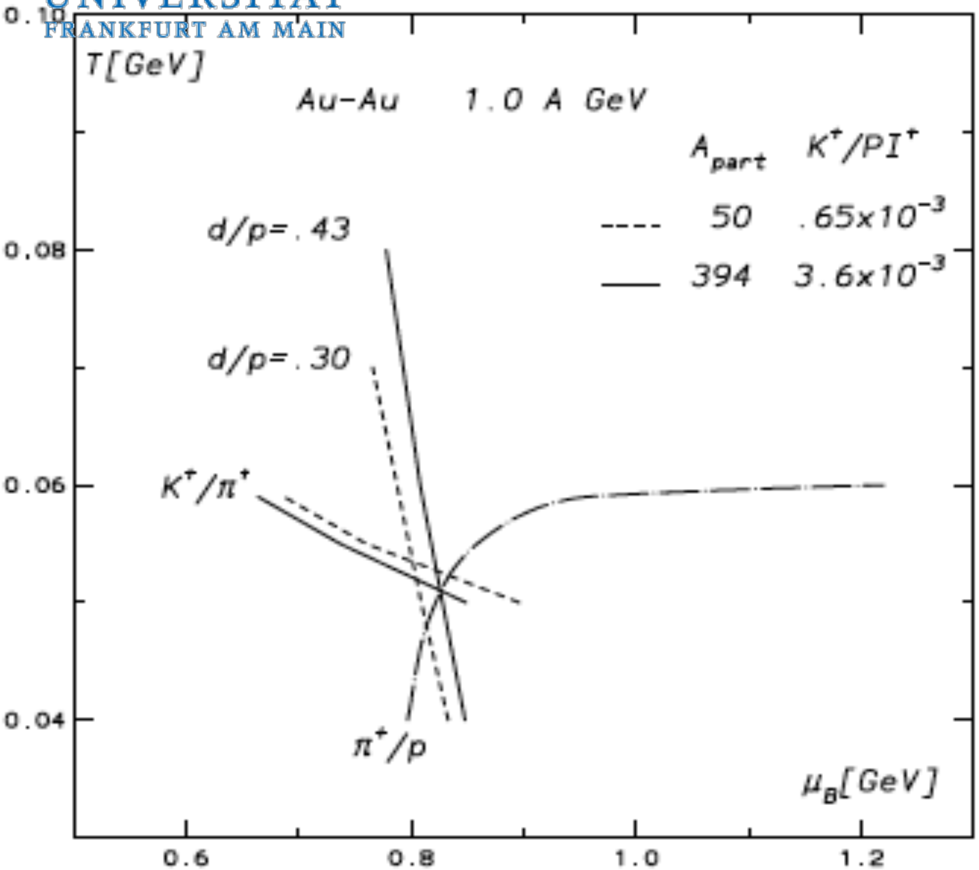


- Freeze-out point stays at higher T and μ_B also for 0-10% most central events

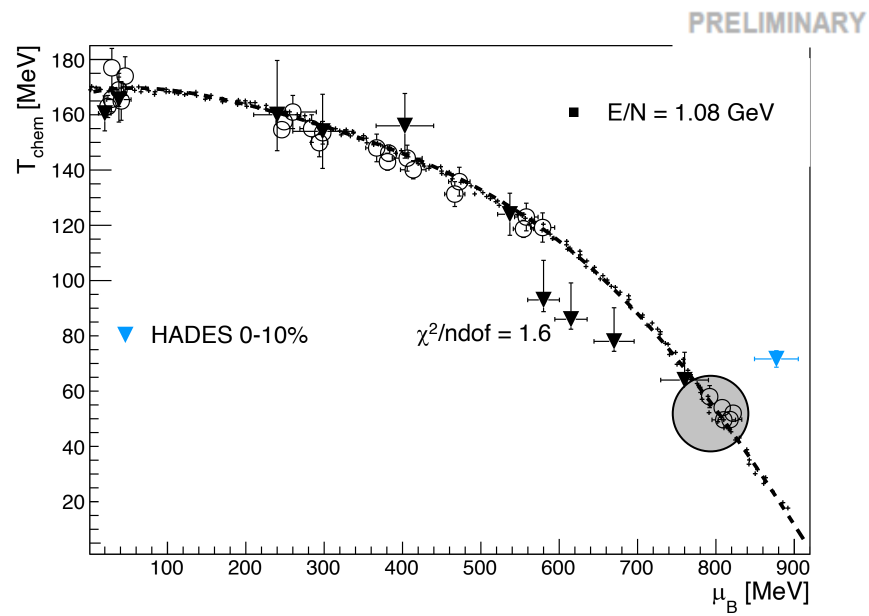
M. Lorenz 2019

[1] scaled from 0-20% most central

Phase diagram: HADES



J. Cleymans, H. Oeschler, K. Redlich, Phys.Rev. C59 (1999))



- Freeze-out points previously estimated based on ratios of p, d, K^+, π^+
- Light nuclei are not included in Thermus V2.3
  Switch to Thermus V3.0 or Thermal-Fist https://github.com/vlvovch/Thermal-FIST

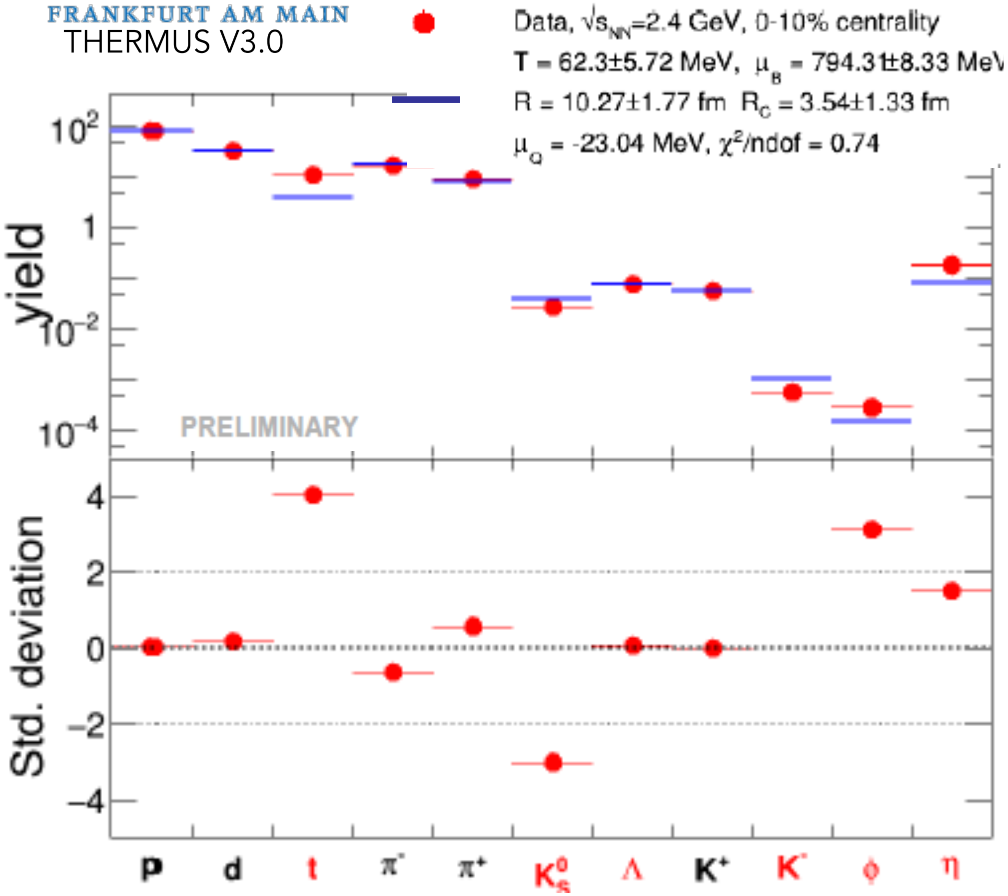
M. Lorenz 2019

-

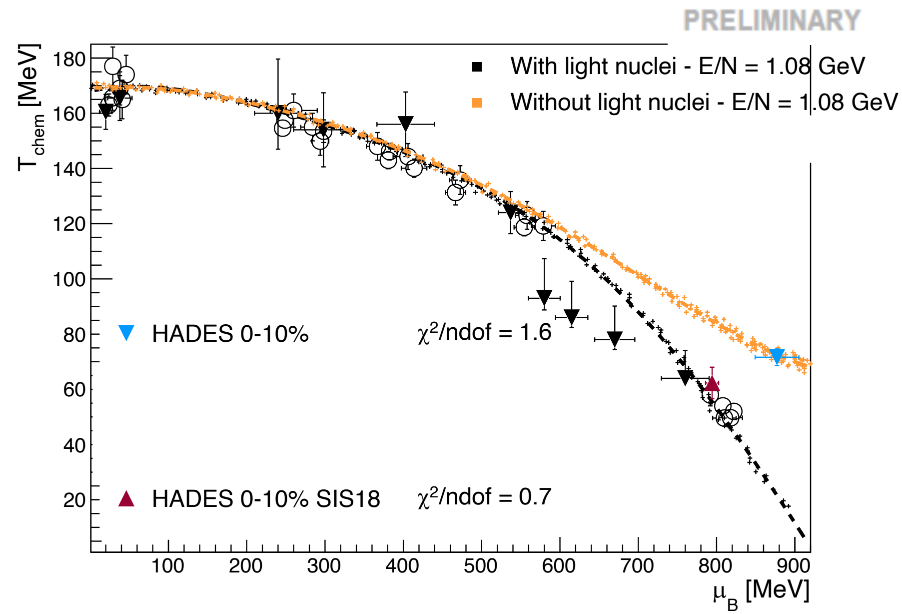
Phase diagram: HADES

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

THERMUS V3.0



J. Cleymans, H. Oeschler, K. Redlich, Phys.Rev. C59 (1999))



- Fit to HADES data consistent with previous works when same hadron yields are used
- E/N=1.08 GeV with or without light nuclei?
- Light nuclei are important to define chemical freeze-out line at high μ_B.

- Freeze-out points previously estimated based on ratios of p, d, K^+, π^+

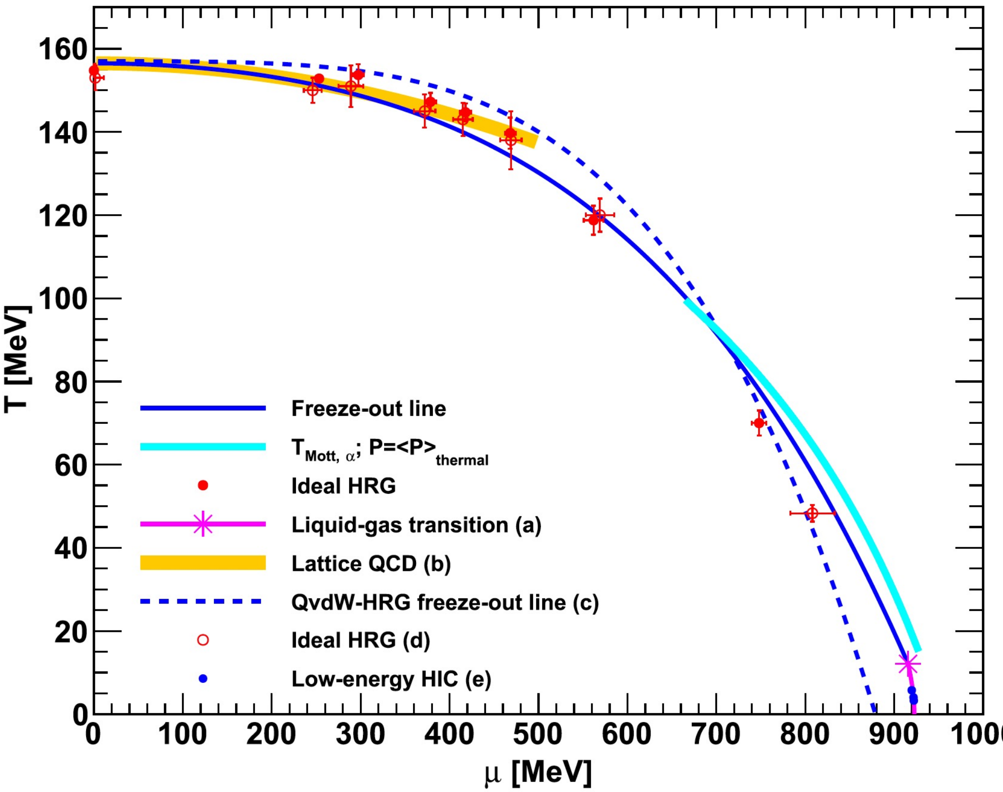
- Light nuclei are not included in Thermus V2.3 Switch to Thermus V3.0 or Thermal-Fist https://github.com/vlvovch/Thermal-FIST

M. Lorenz 2019

-

Phase diagram: Mott α

- If one maps the energy dependence onto a μ_B-T plane one gets experimental access to the QCD phase diagram
- Using parametrizations of the thermal model fits one can get an approximation of the freeze-out curves
- Particular models can even describe their shape, e.g. Mott curves

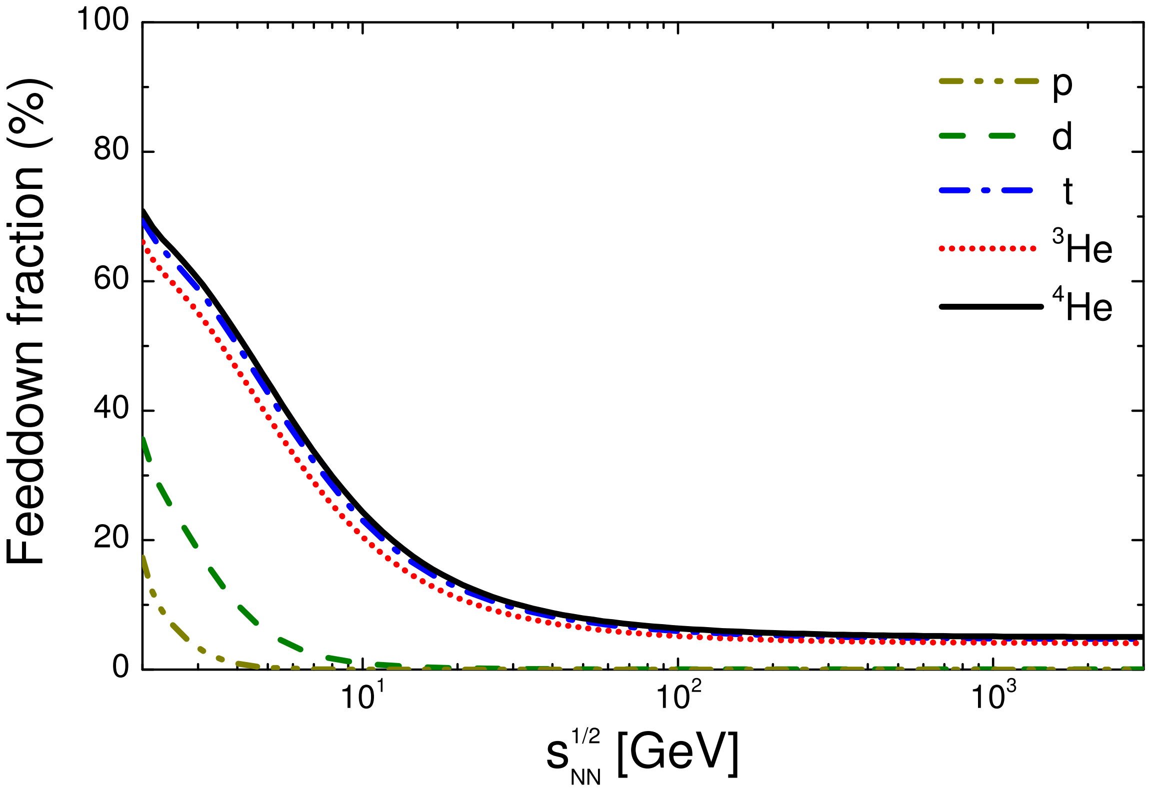


D. Blaschke, S. Liebing, G. Röpke, BD, Phys. Lett. B 860 (2025) 139206

Poster #1096
D. Blaschke et al.

Thermal model

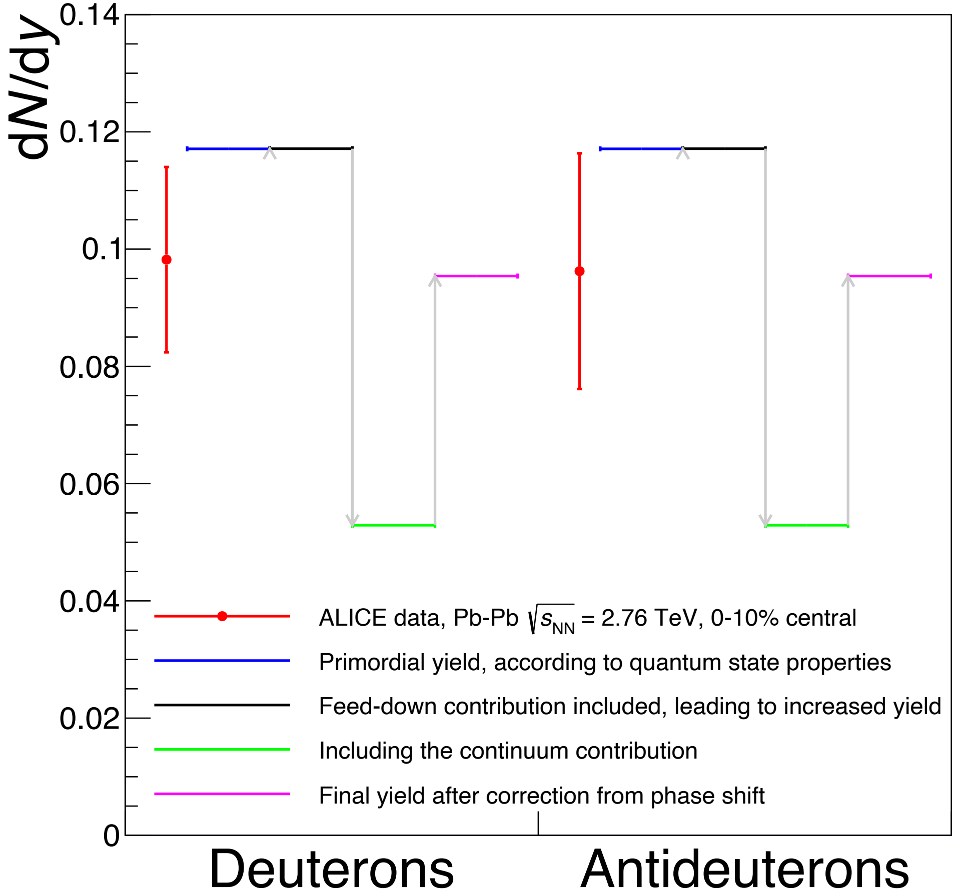
- For the thermal model description of production yields, feed-down is an important ingredient
- All light hadron production yields are populated strongly by resonances
- Seems to not be the case for (hyper-) nuclei at the LHC



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 at the LHC

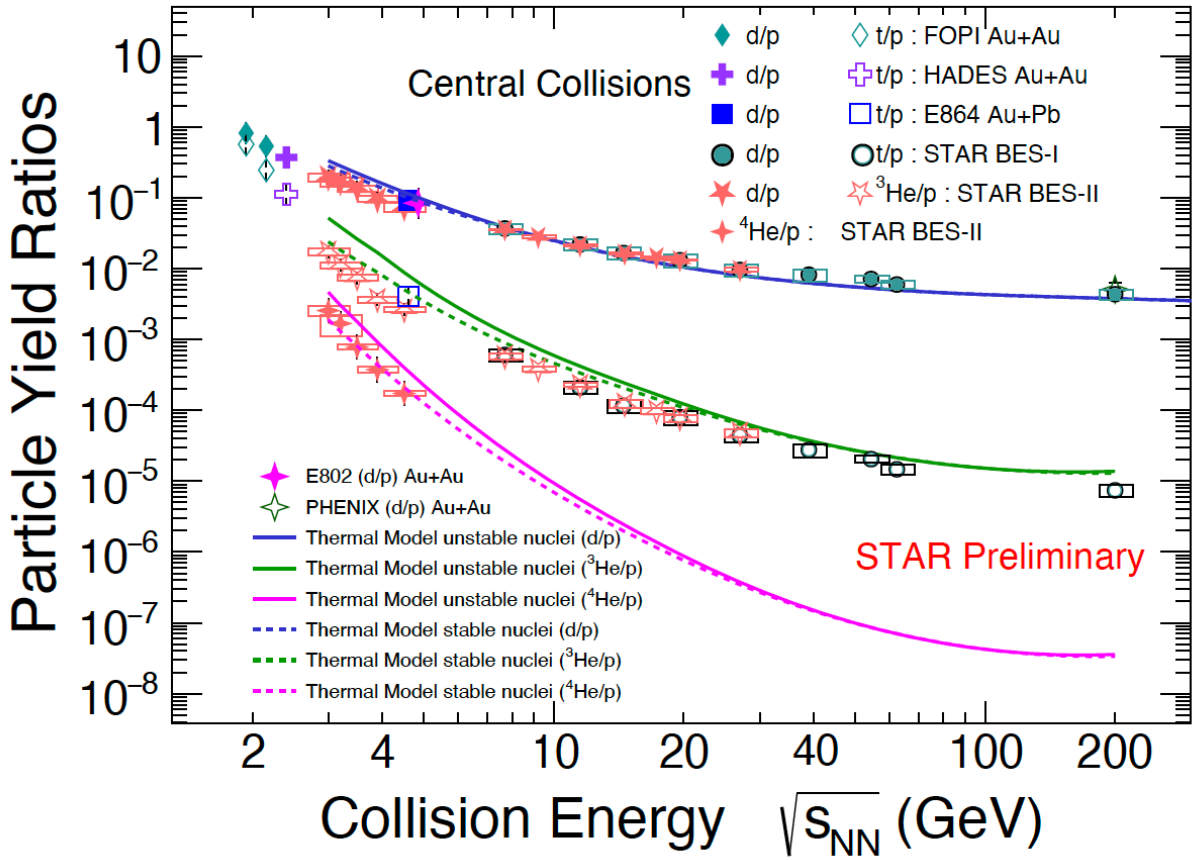


BD, G. Röpke, D. Blaschke, Phys. Rev. C 106 (2022) 044908

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

Light nuclei: yield ratios

- A/p ratio: better described by thermal model with only stable nuclei



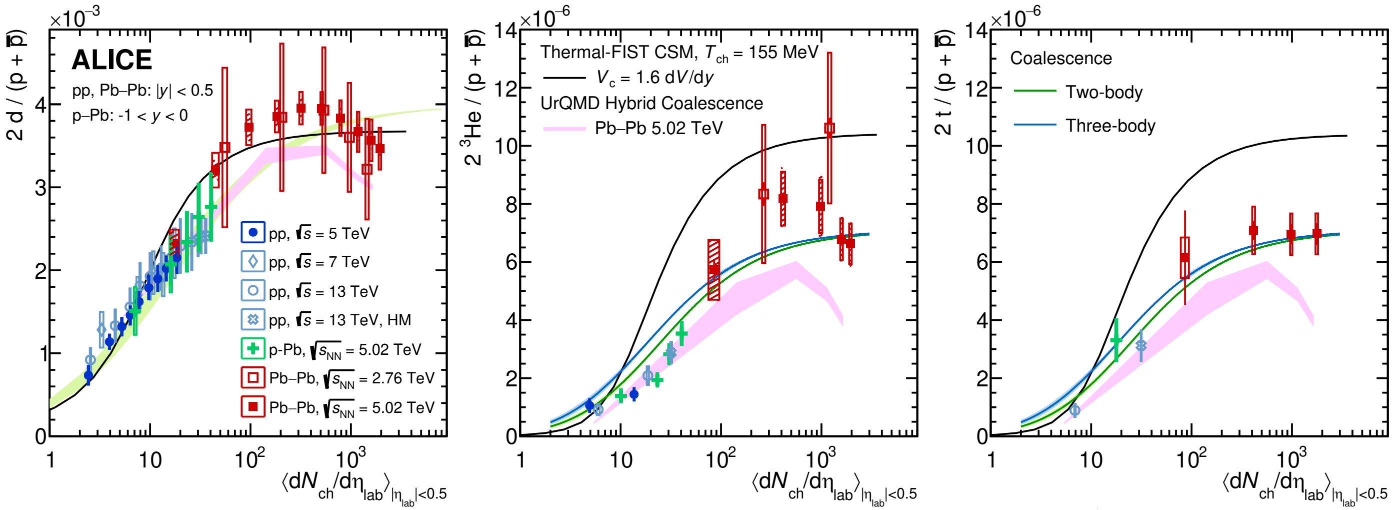
Talk #554
Y. Zhou

Poster #711
L. Chen

Light nuclei: model description

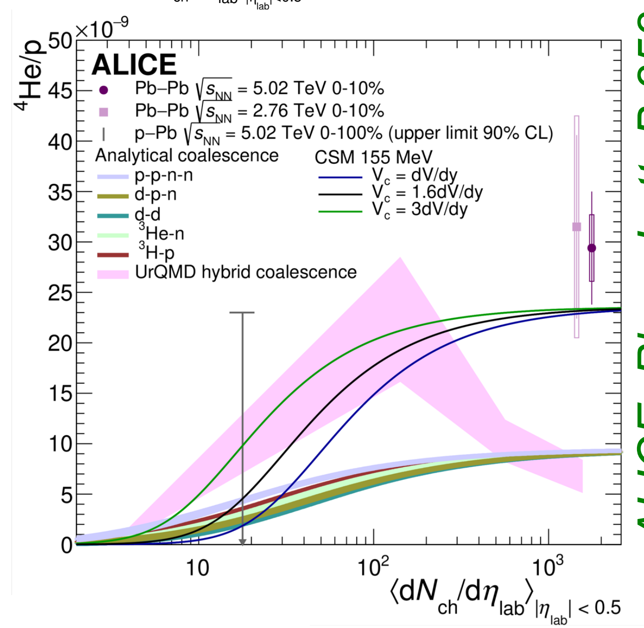
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

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

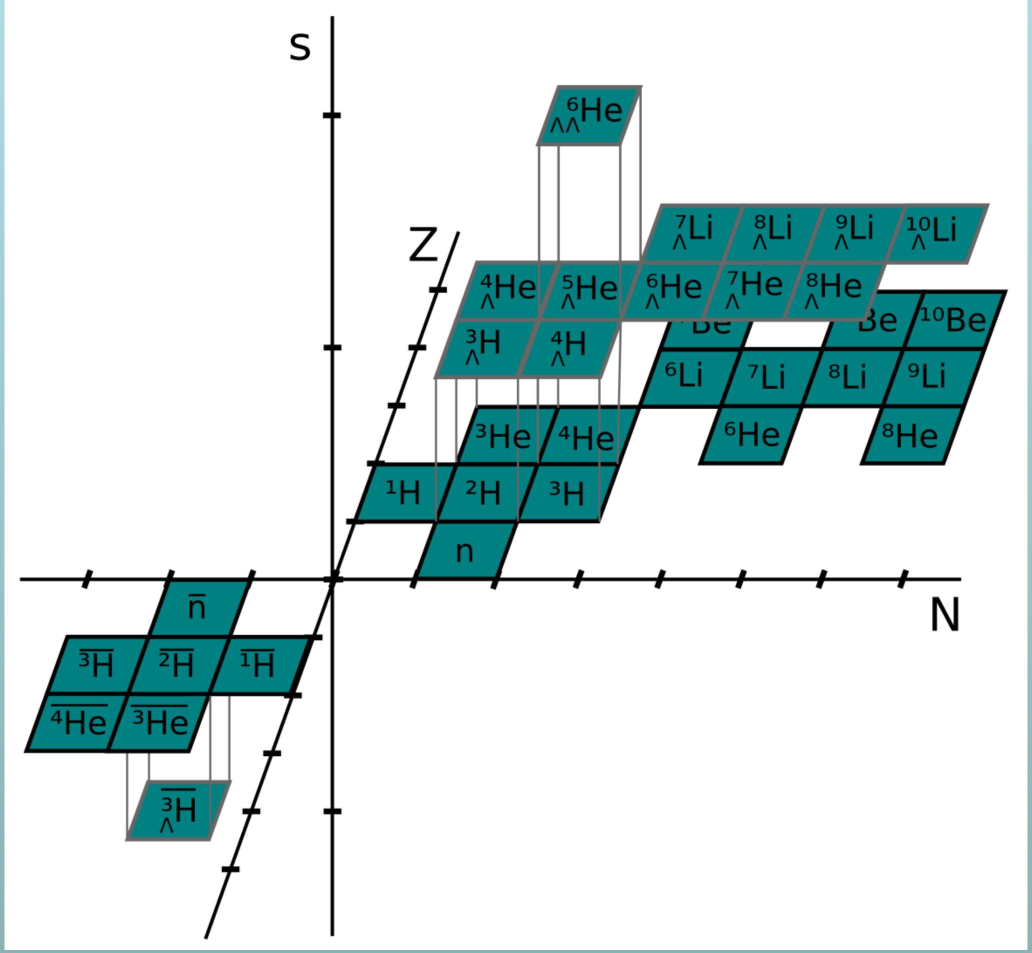


ALICE, Phys. Lett. B 858 (2024) 138943

- Model comparisons in ratios of A/p
- d/p possible to describe by coalescence and thermal models
- ^{3}He seems to prefer coalescence, ^{3}H prefers coalescence
- ^{4}He in contrary clearly prefers themal production

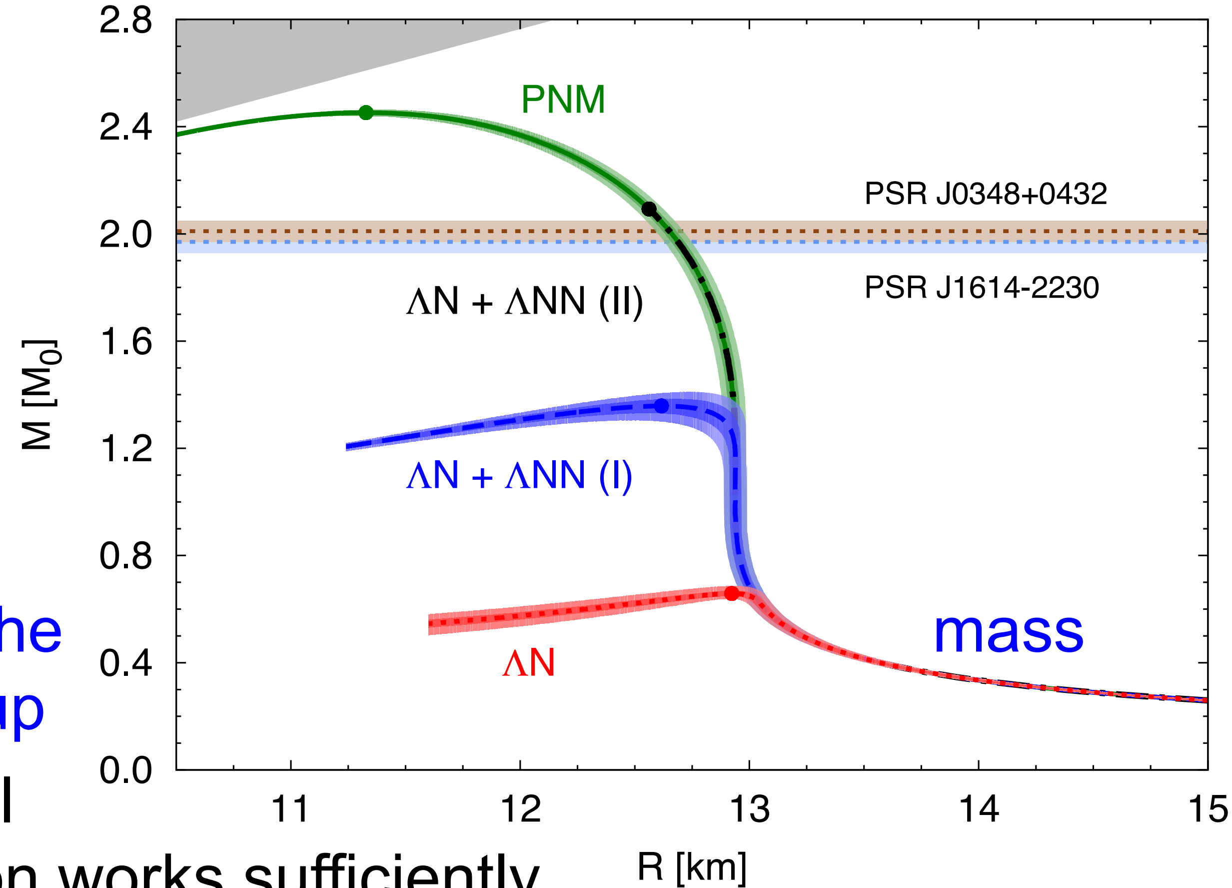


Hypernuclei



Neutron stars and interactions

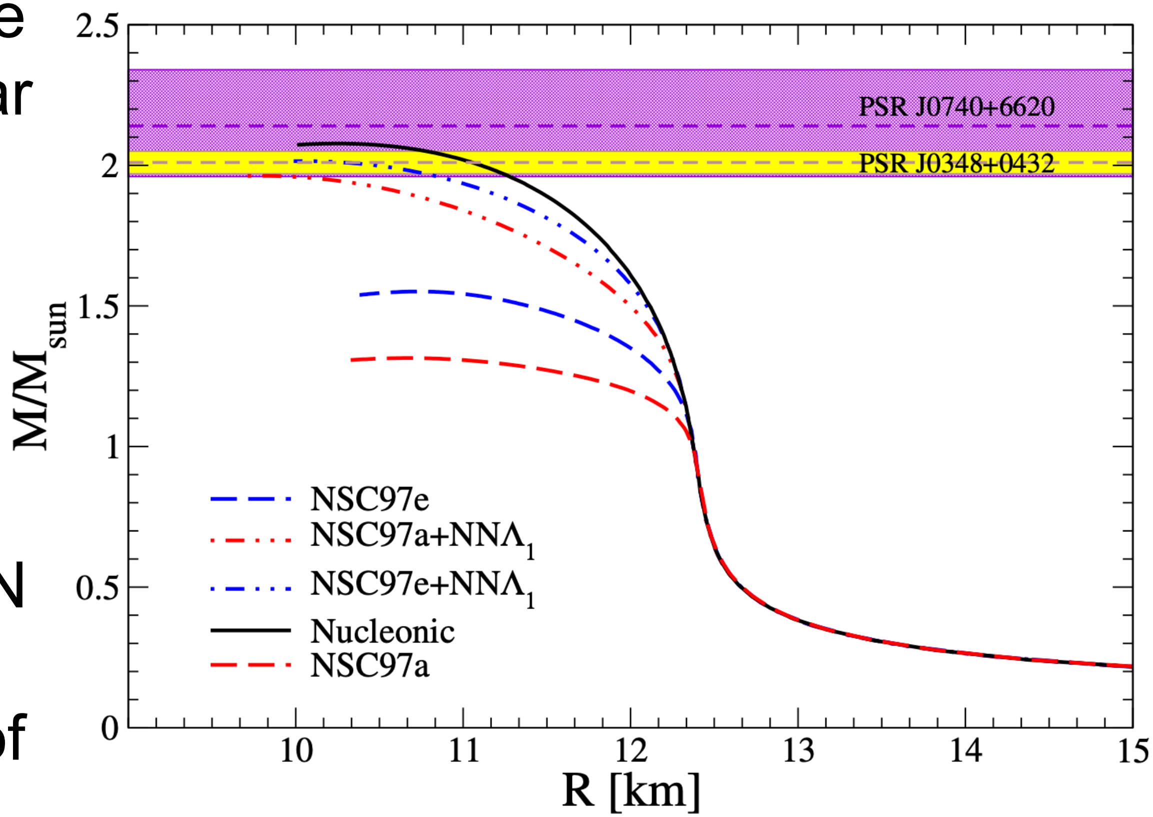
- Hyperon puzzle in neutron stars → hyperons make the EOS softer:
- Pure neutron matter (PNM) works well
- Known ΛN interaction → way to soft
- Including ΛNN forces brings the mass slightly up
- Only additional ΛNN interaction works sufficiently



D.Lonardoni, A Lovato, S.Gandolfi, F Pederiva, PRL 114 (2015) 092301

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

Hypertriton

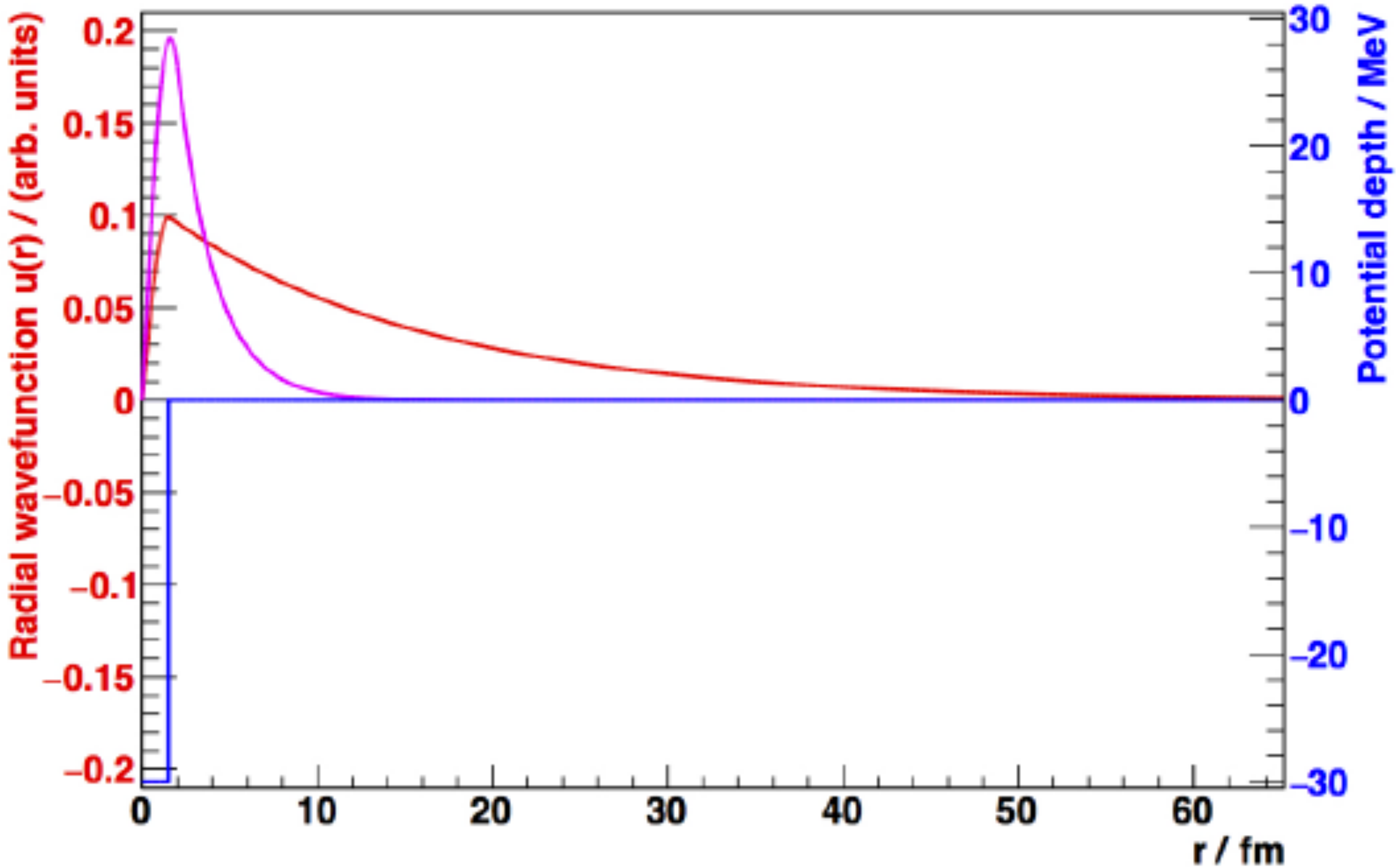
Bound state of Λ, p, n

m = 2.991 GeV/c^2 (B_Λ =130 keV)

Hypertriton

Bound state of Λ, p, n

m = 2.991 GeV/c^2 (B_Λ =130 keV)

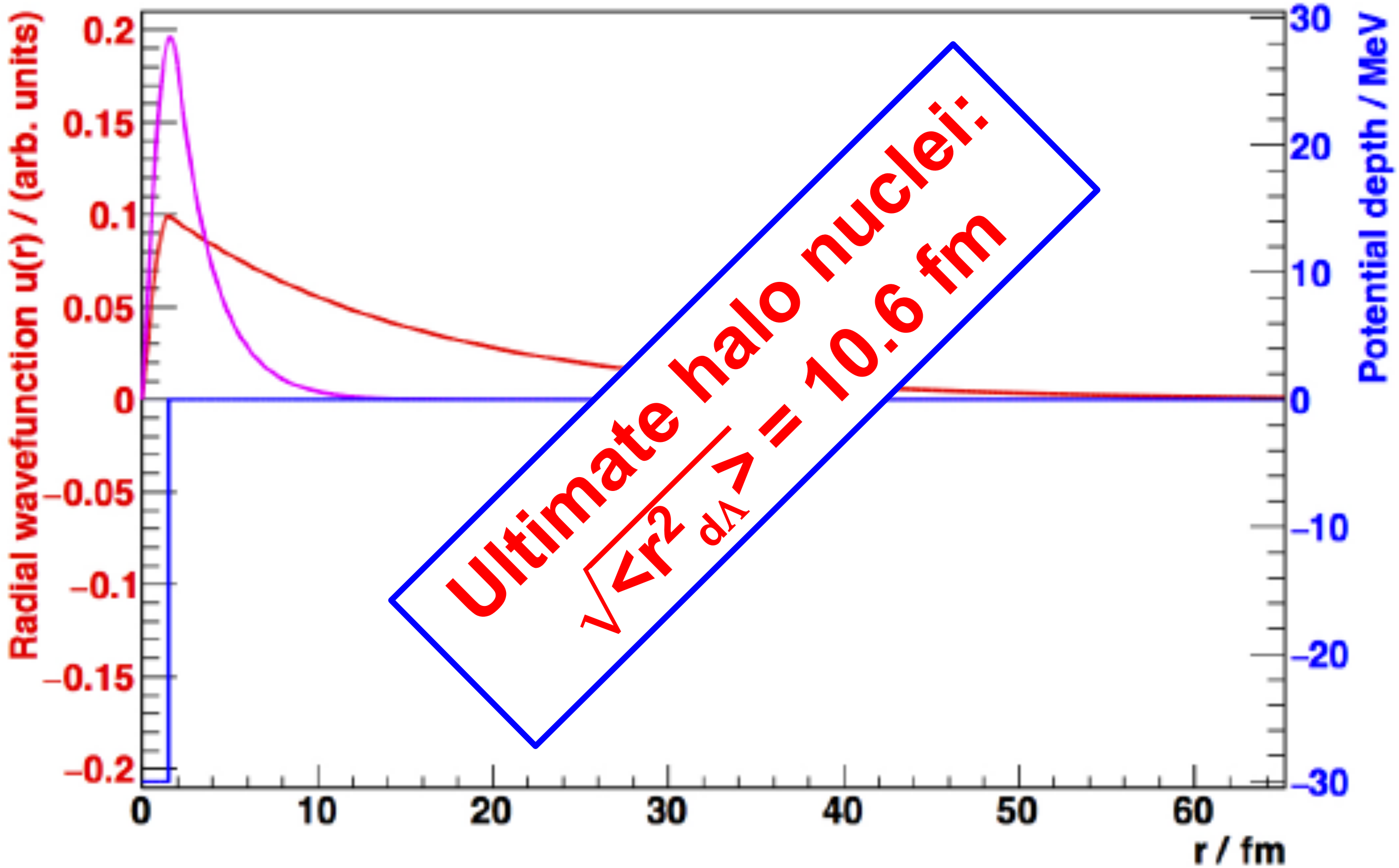


P. Braun-Munzinger, BD, Nucl. Phys. A 987 (2019) 144

Hypertriton

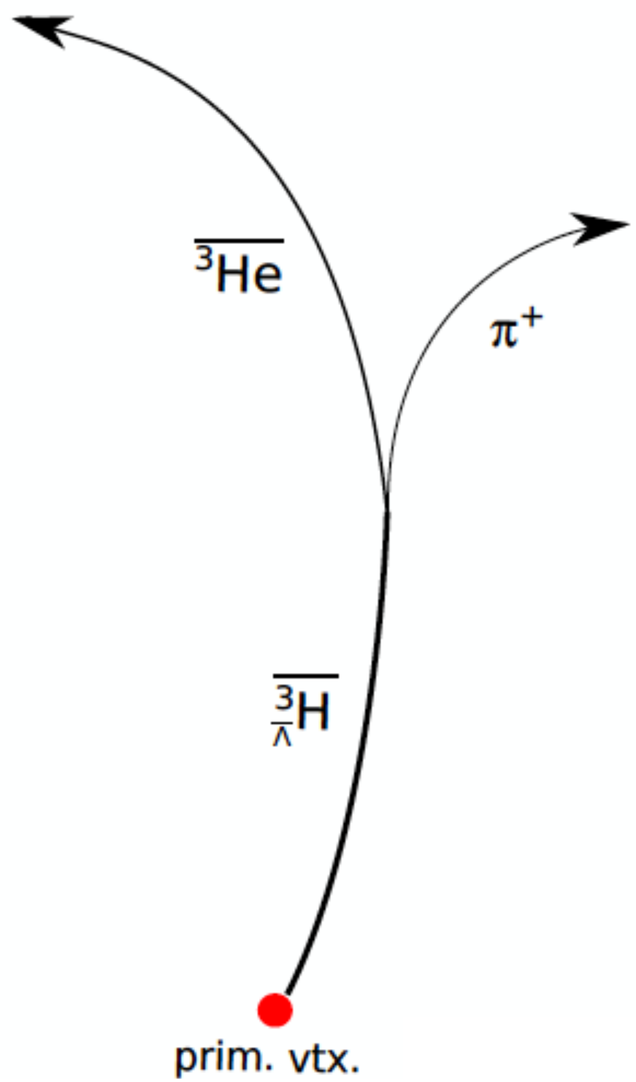
Bound state of Λ, p, n

m = 2.991 GeV/c^2 (B_Λ =130 keV)



P. Braun-Munzinger, BD, Nucl. Phys. A 987 (2019) 144

Hypertriton Identification



Bound state of Λ, p, n

m = 2.991 GeV/c^2 (B_Λ =130 keV)

→ Radius of about 10.6 fm

Decay modes:

$$^3_\Lambda\text{H} \rightarrow {}^3\text{He} + \pi^-$$

$$^3_\Lambda\text{H} \rightarrow {}^3\text{H} + \pi^0$$

$$^3_\Lambda\text{H} \rightarrow \text{d} + \text{p} + \pi^-$$

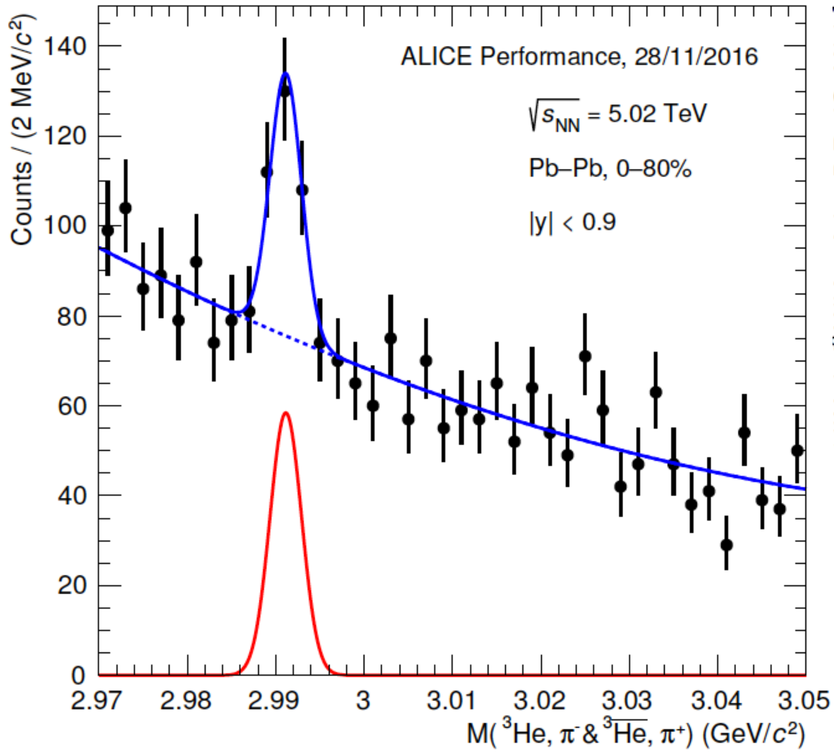
$$^3_\Lambda\text{H} \rightarrow \text{d} + \text{n} + \pi^0$$

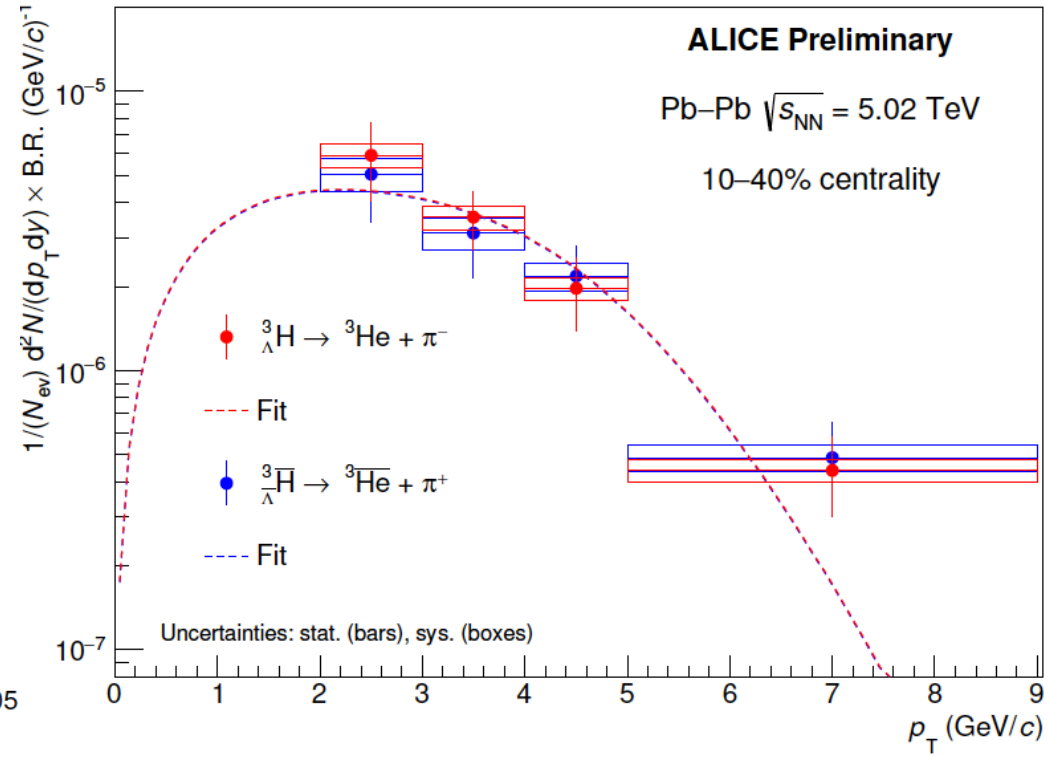
+ anti-particles

→ Anti-Hypertriton first observed by STAR Collaboration:

Science 328,58 (2010)

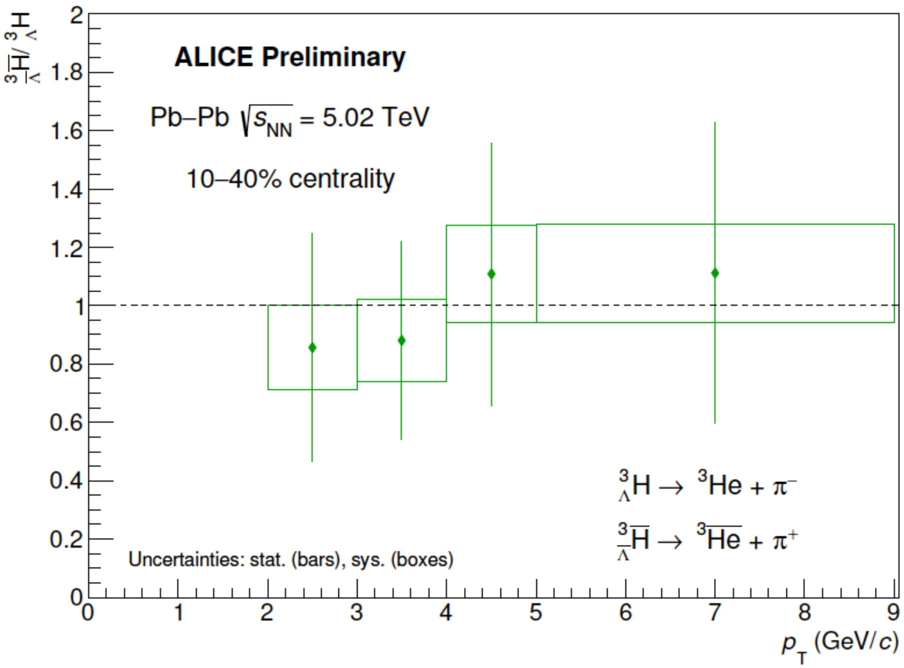
Hypertriton signal

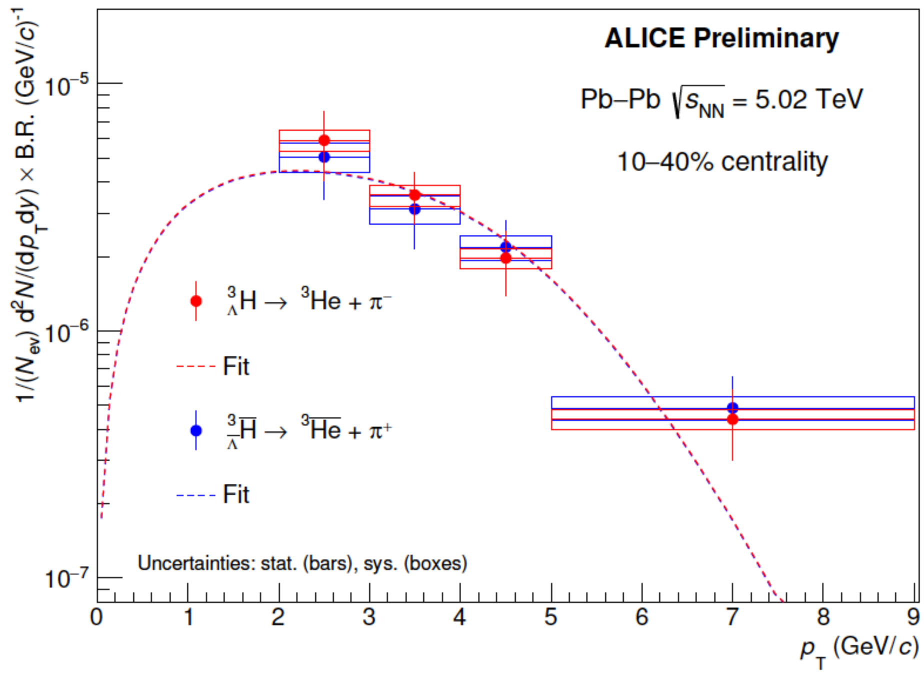




- Clear signal reconstructed by decay products
- Spectra can also be described by Blast-Wave model
  → Hypertriton flows as all other particles

Hypertriton spectra

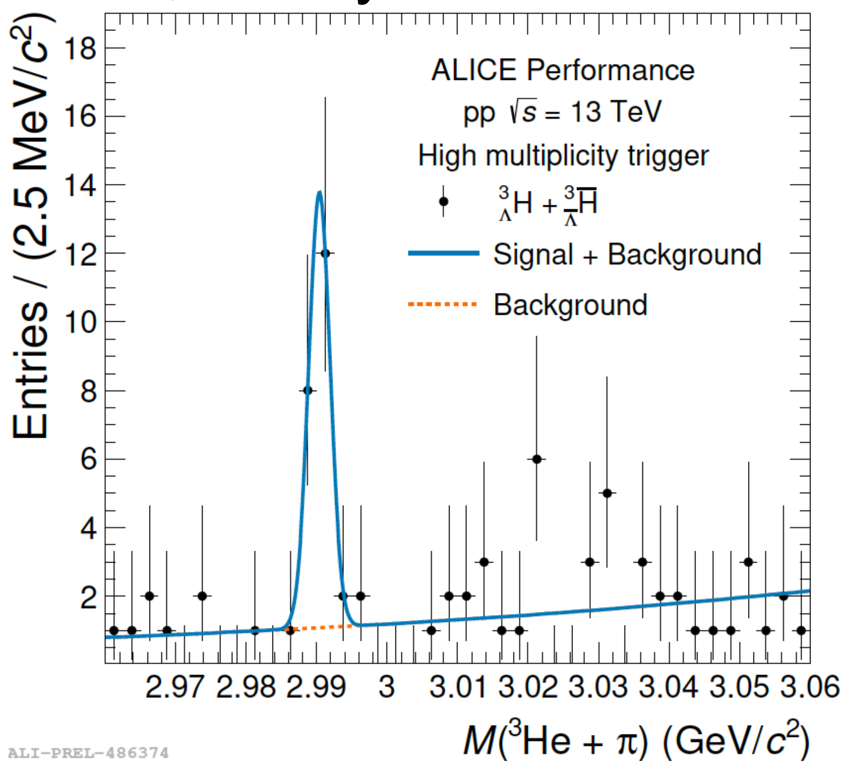


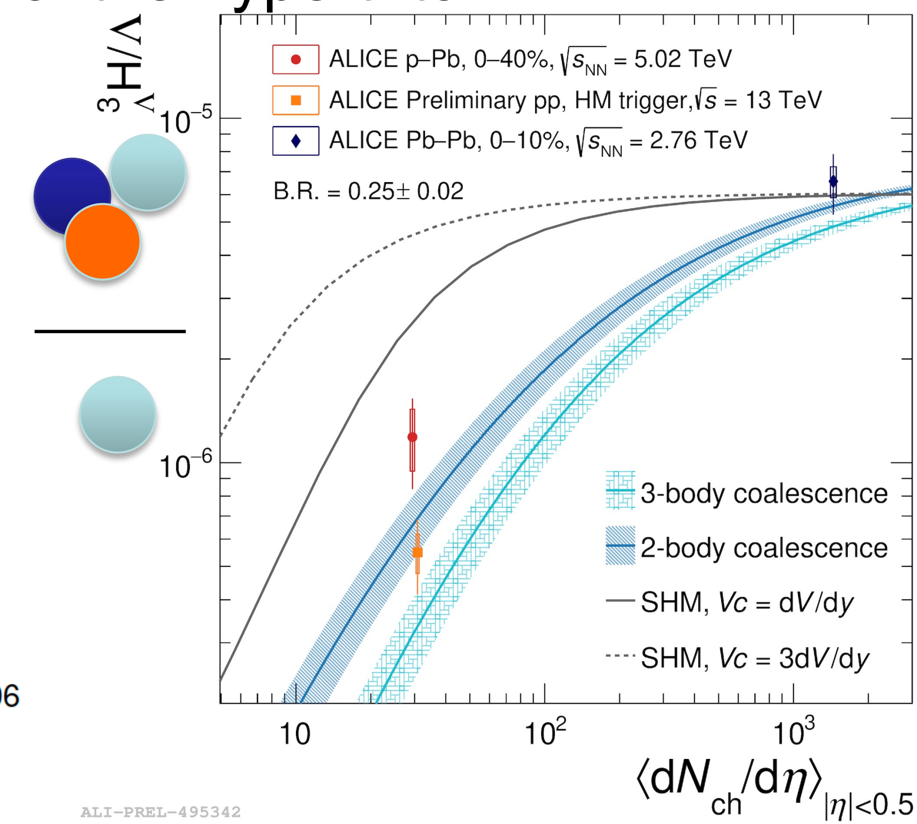


- Anti-hypertriton/Hypertriton ratio consistent with unity vs. p_T

Hypertriton in pp & p-Pb

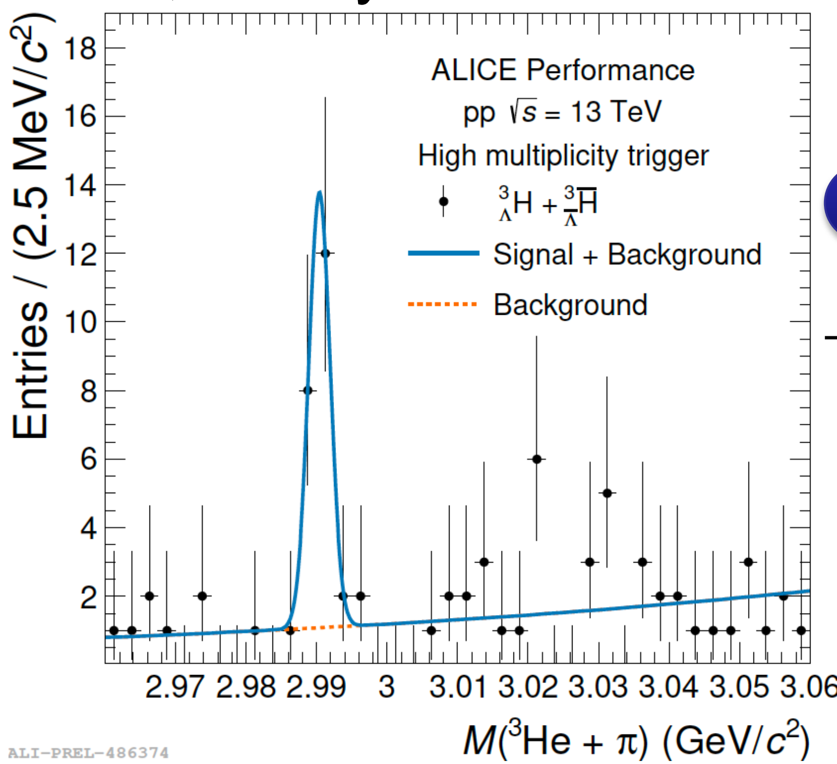
- Hypertriton signal recently also extracted in pp and p-Pb collisions
- Stronger separation between models as for other particle ratios, mainly due to the size of the hypertriton

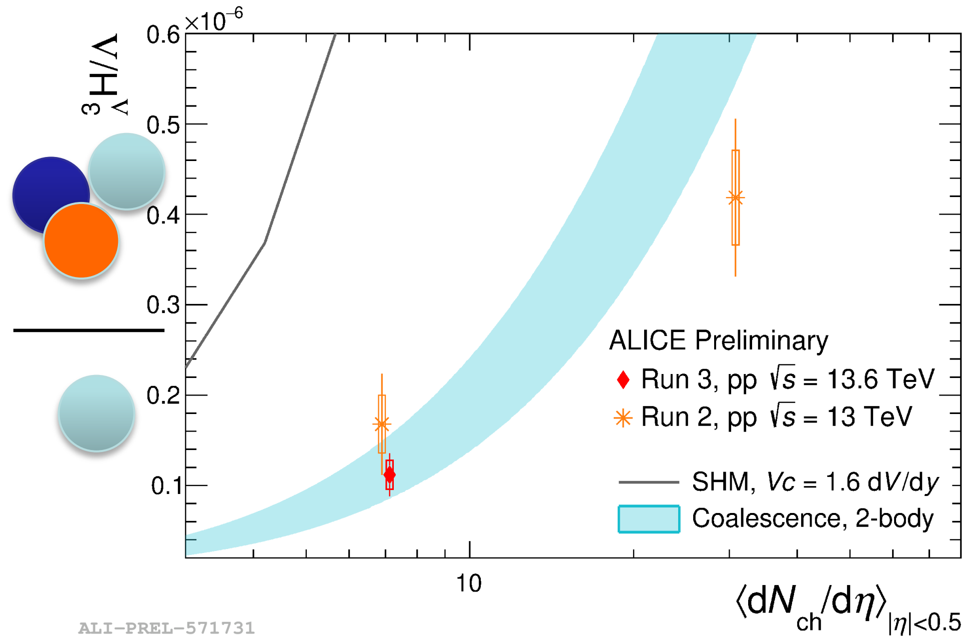




Hypertriton in pp & p-Pb

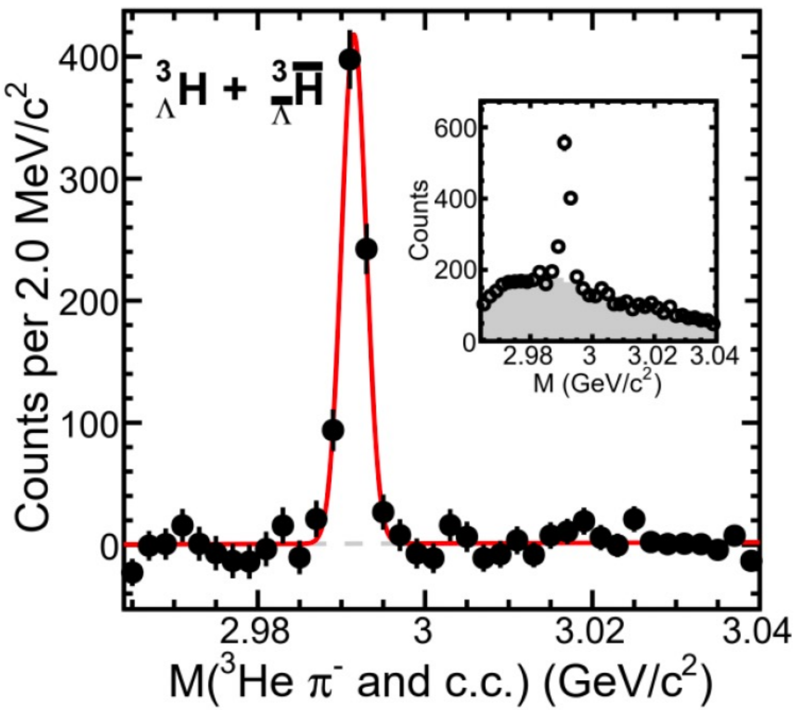
- Hypertriton signal recently also extracted in pp and p-Pb collisions
- Stronger separation between models as for other particle ratios, mainly due to the size of the hypertriton





Hypertriton at RHIC

- Hypertriton signal recently also extracted in isobar collisions



As presented by Dongsheng Li @ SQM2024

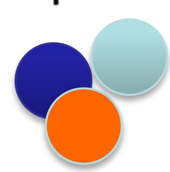
0-80% Zr+Zr & Ru+Ru @ $\sqrt{s_{NN}}$ = 200 GeV

$p_T \leq 5$ (GeV/c)

Same Event (SE)

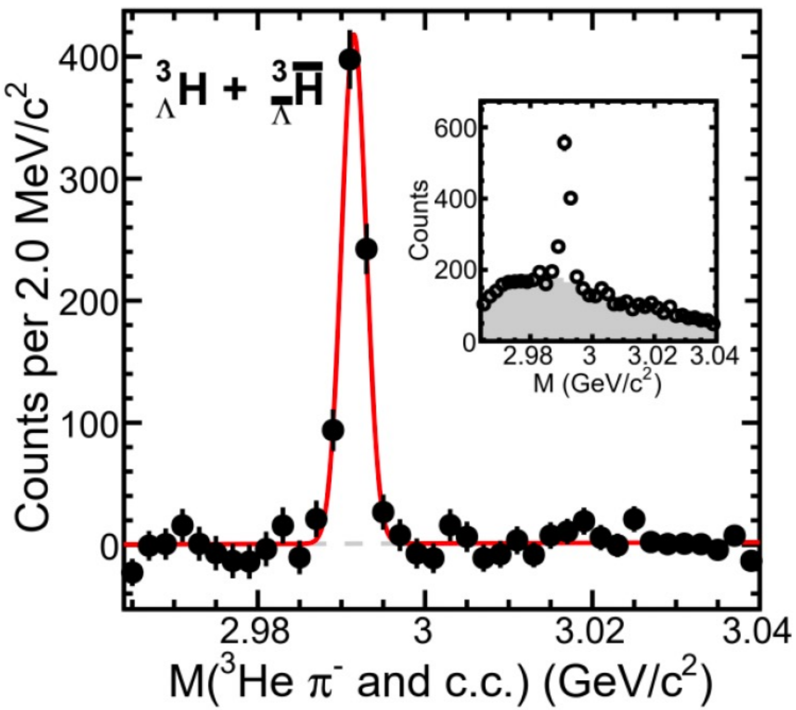
Mixed Event (ME)

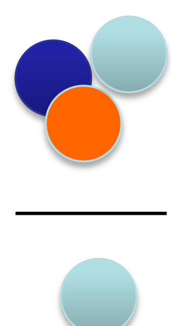
SE - ME

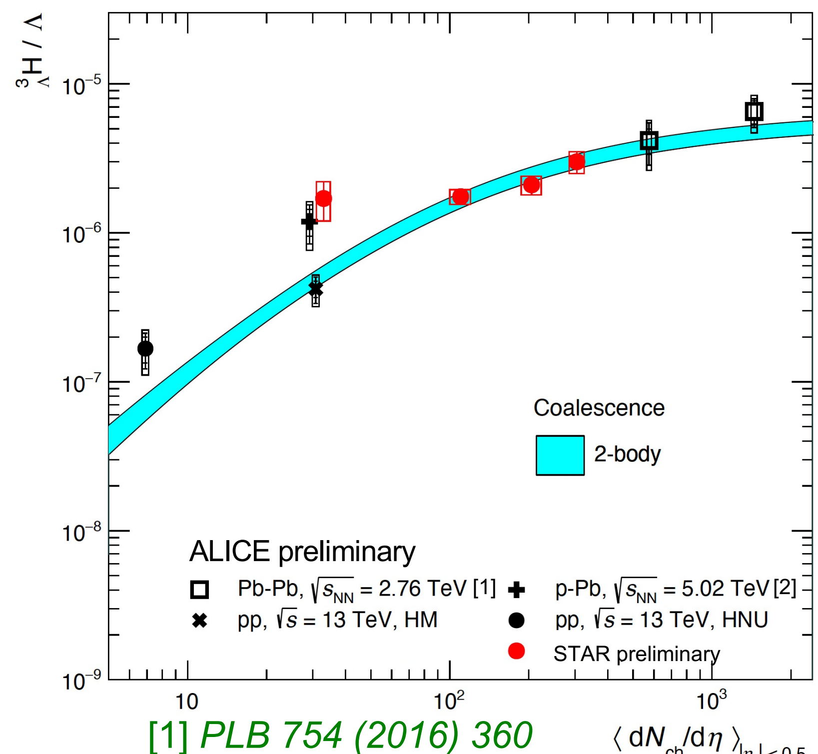


Hypertriton/Λ ratio

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



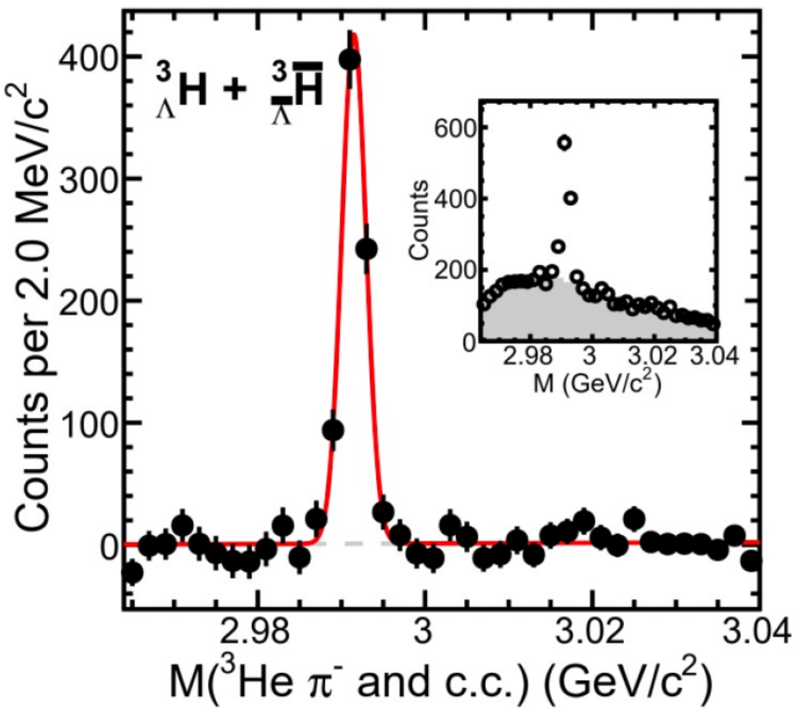


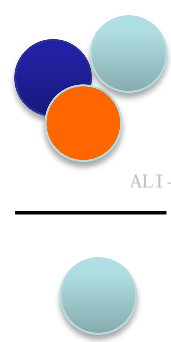


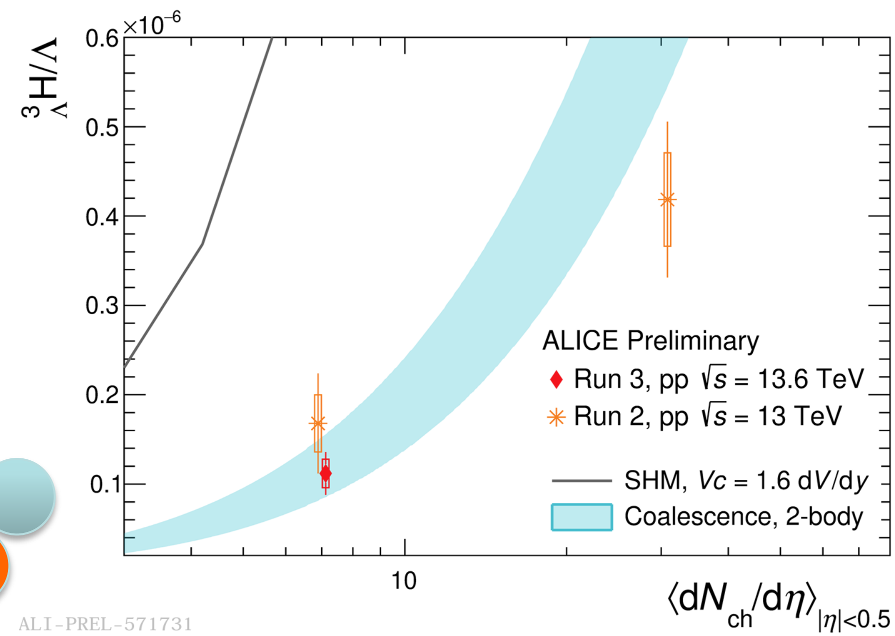
[1] *PLB 754 (2016) 360*
[2] *PRL 128 (2022) 252003*

Hypertriton/Λ ratio

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





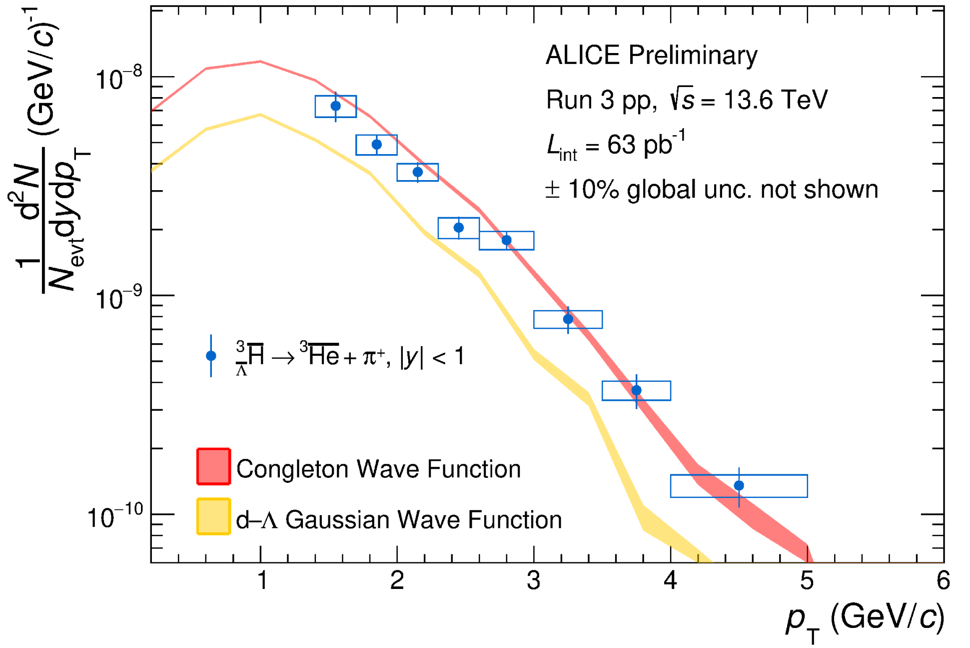


Hypertriton: small systems

- Strong suppression in small systems due to large size of the object compared to the system size
- Coalescence model favoured over canonical statistical model

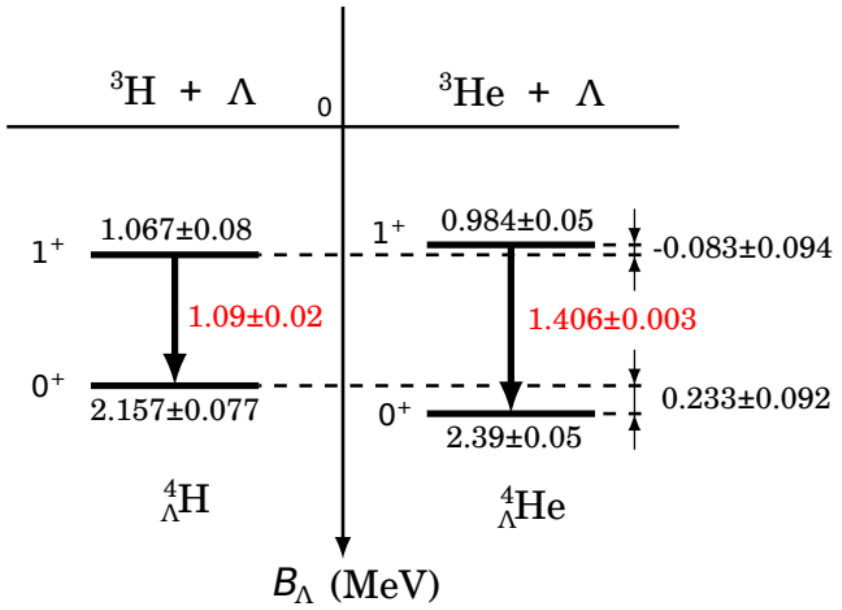
QM2025 Talk #1118 J. Ditzel	QM2025 Poster #493 C. Reetz

M. Mahlein et al. arxiv:2504.02491



A = 4 hypernuclei

- Large suppression expected for A = 4 hypernuclei by the SHM wrt A = 3
- A = 4 hypernuclei are more bound and each has an excited state
  Phys. Rev. Lett. 115, 222501 (2015)
- The yields of these hypernuclei are enhanced with respect to the ground state due to the feed-down from excited states
- Also the yields of the SHM scale with the **spin-degeneracy**
- Resulting in a total enhancement of a factor 4 for both hypernuclei
  BD, EPJ Web Conf. 276 (2023) 04002



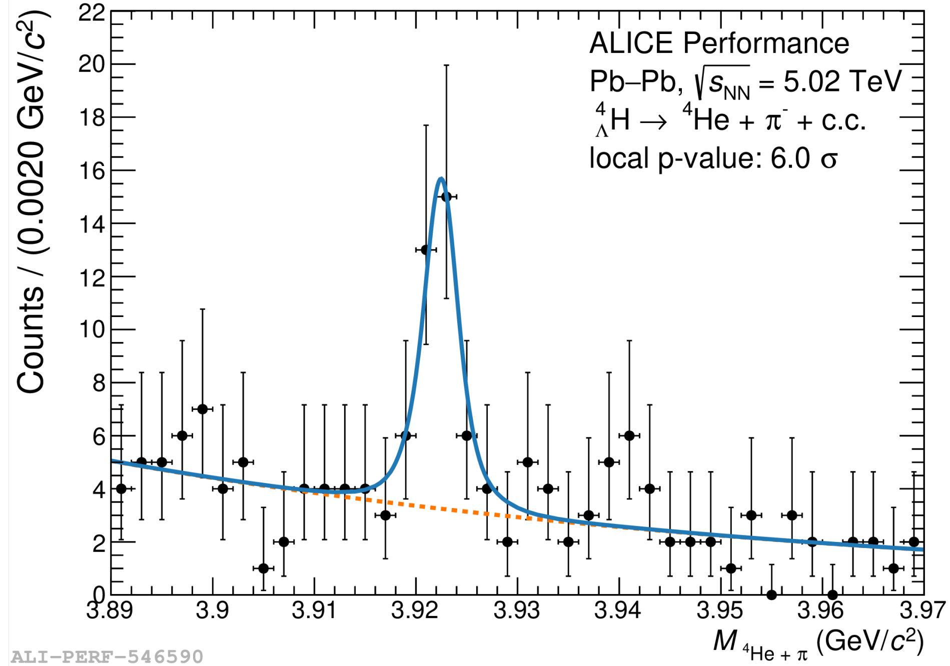
M. Schäfer, N. Barnea, A. Gal, Phys.Rev.C 106, L031001 (2022)

A = 4 hypernuclei

- For the first time, we are able to reconstruct A = 4 (anti)hypernuclei at the LHC and determine their production yield
- **(Anti)hyperhydrogen-4** invariant-mass spectrum in Run 2 Pb-Pb collisions at 5.02 TeV
- Examined in the two-body decay:

  $^{4}_{\Lambda}H \rightarrow \ ^{4}He + \pi^{-} + c.c.$

- Reaching a local p-value of **6σ**



A = 4 hypernuclei

- For the first time, we are able to reconstruct A = 4 (anti)hypernuclei at the LHC and determine their production yield

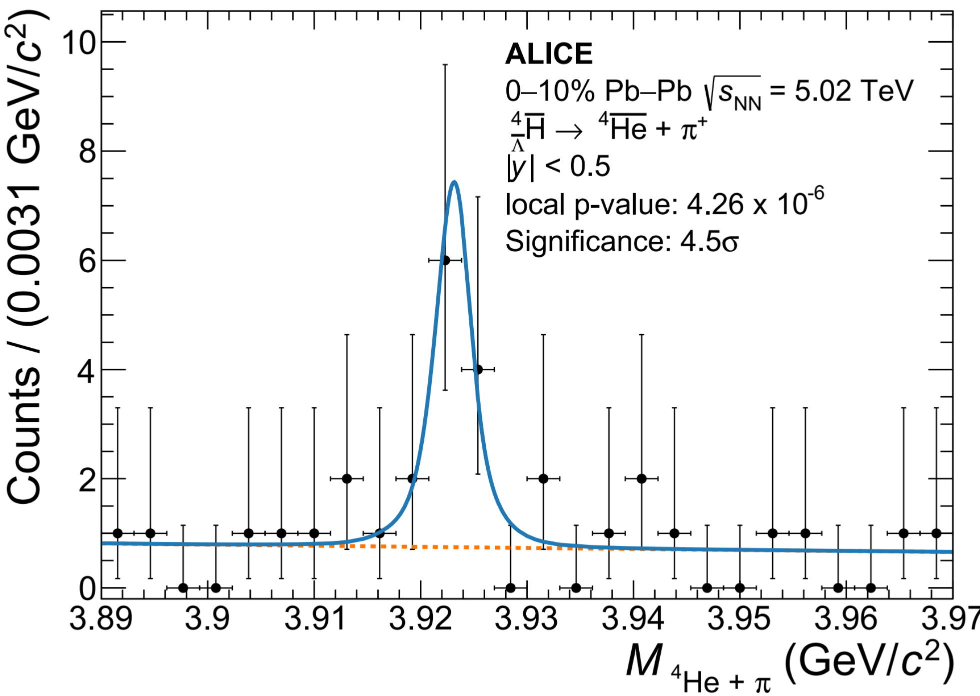
- **(Anti)hyperhelium-4** invariant-mass spectrum in Run 2 Pb-Pb collisions at 5.02 TeV

- Examined in the three-body decay:

  ${}^{4}_{\Lambda}\mathrm{He} \rightarrow {}^{3}\mathrm{He} + p + \pi^{-} + \mathrm{c.c.}$

- Reaching a significance of **4.5σ**

ALICE Collaboration, arXiv:2410.17769



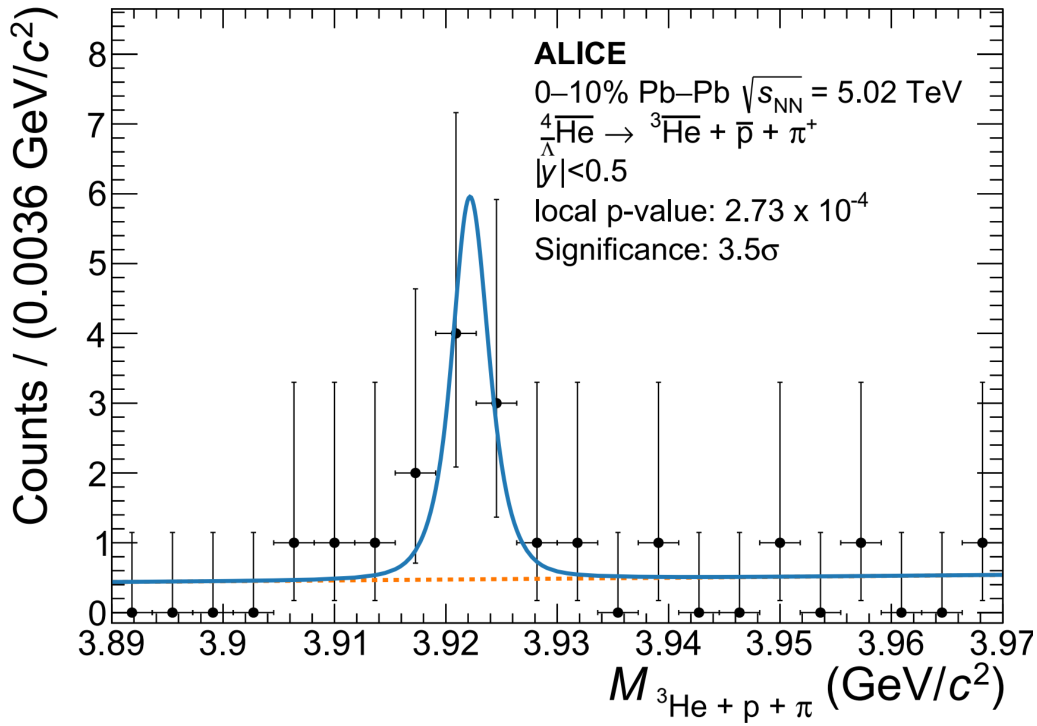
A = 4 hypernuclei

- For the first time, we are able to reconstruct A = 4 (anti)hypernuclei at the LHC and determine their production yield

- **First observation of the antihyperhelium-4** in Run 2 Pb-Pb collisions at 5.02 TeV

- Reaching a significance of **3.5σ**

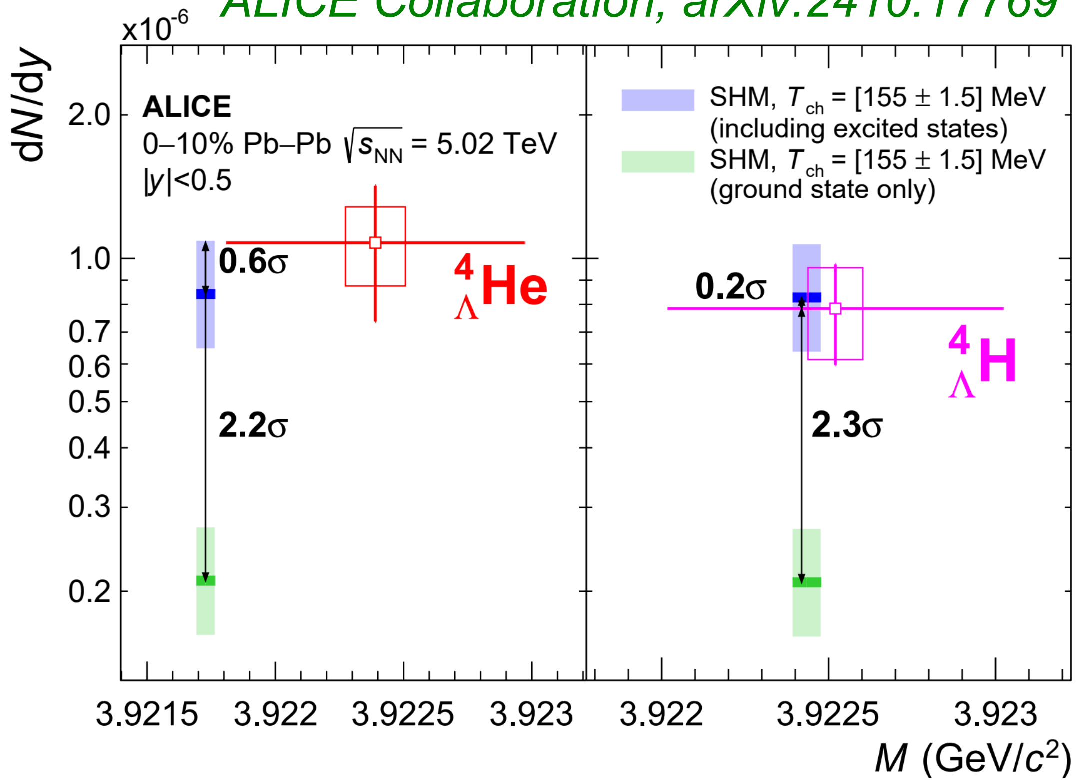
ALICE Collaboration, arXiv:2410.17769



A = 4 hypernuclei

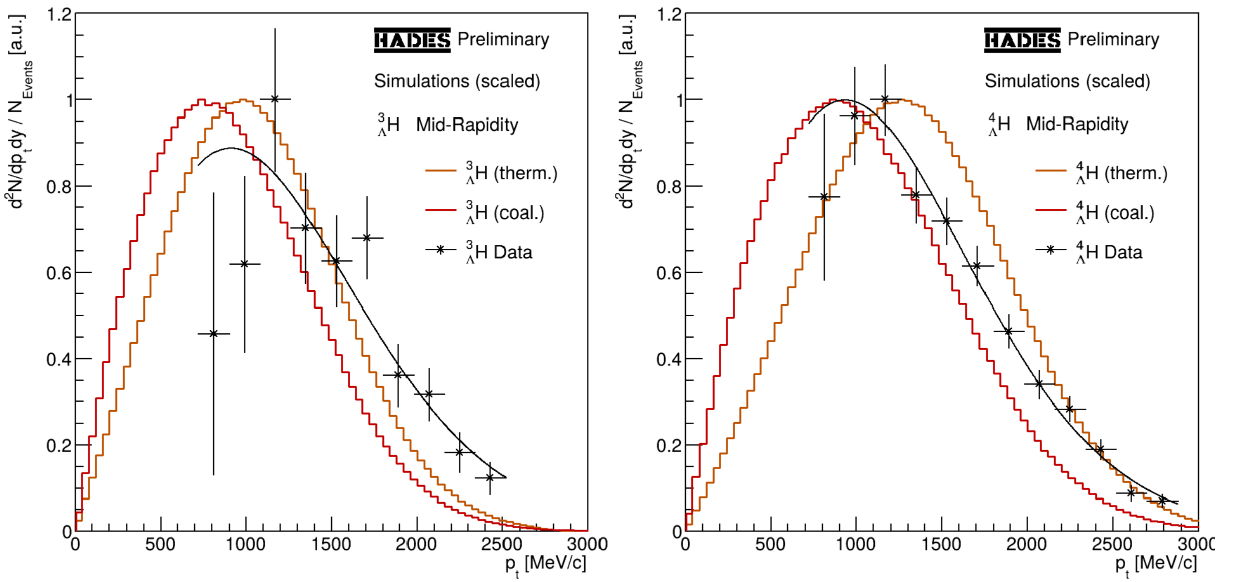
- First measurement of the (anti)hyperhelium-4 production yield
- Testing the dependence of the yields of the SHM with the spin-degeneracy
- Our yields confirm the hypothesis of excited states for both (anti)hypernuclei within 2σ
- currently dominated by statistical uncertainties
- with more data, a high precision measurement will be feasible (like for the Λ hyperon)

ALICE Collaboration, arXiv:2410.17769



Hypernuclei: HADES

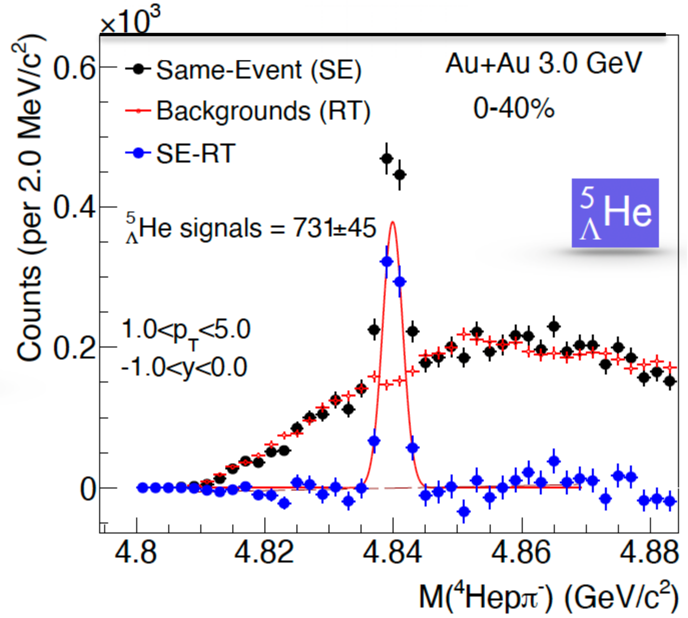
- Lifetimes of investigated hypernuclei consistent with world data
- p_T and y distributions hint to (thermal) production



QM2025
Talk #577
S. Spies

Hypernucleus: ${}^{5}_{\Lambda}\mathrm{He}$

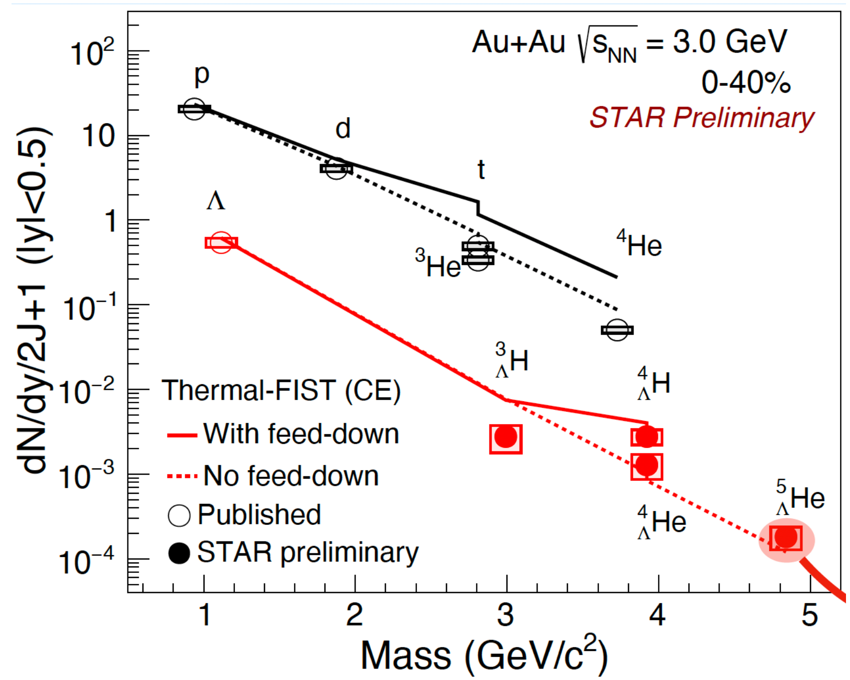
- Highlight: clear signal of hyperhelium-5 in Au+Au at 3.0 GeV



QM2025
Talk #554
Y. Zhou

Hypernucleus: ${}^{5}_{\Lambda}\mathrm{He}$

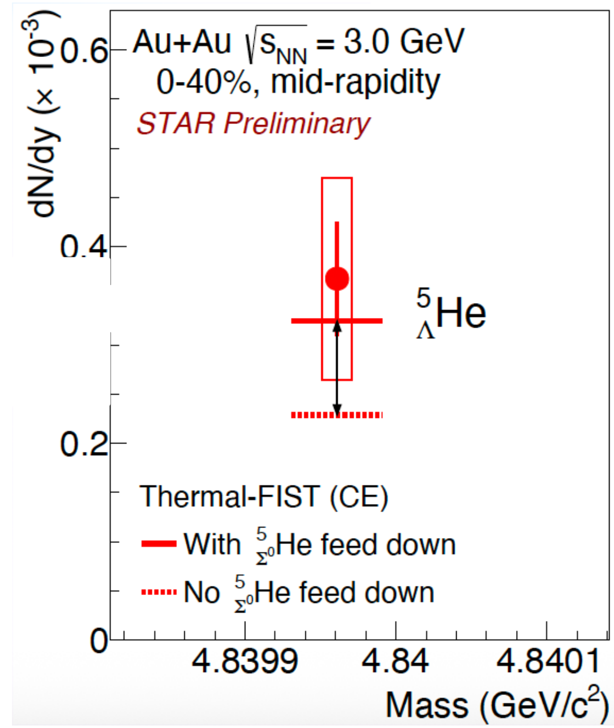
- Highlight: clear signal of hyperhelium-5 in Au+Au at 3.0 GeV
- Comparison to thermal model seems to work only up to A=2, even when excited states are considered



QM2025
Talk #554
Y. Zhou

Hypernucleus: $^{5}_{\Lambda}\mathrm{He}$

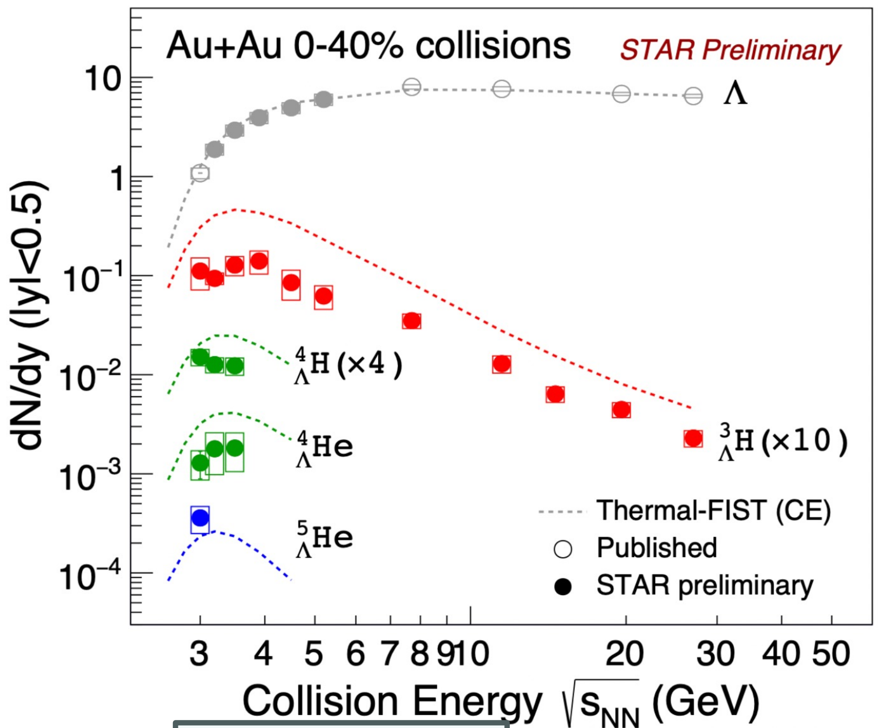
- Highlight: clear signal of hyperhelium-5 in Au+Au at 3.0 GeV
- Comparison to thermal model seems to work only up to A=2, even when excited states are considered
- Hypothesis of A=5 Σ-hypernucleus would help explaining the data



QM2025
Talk #554
Y. Zhou

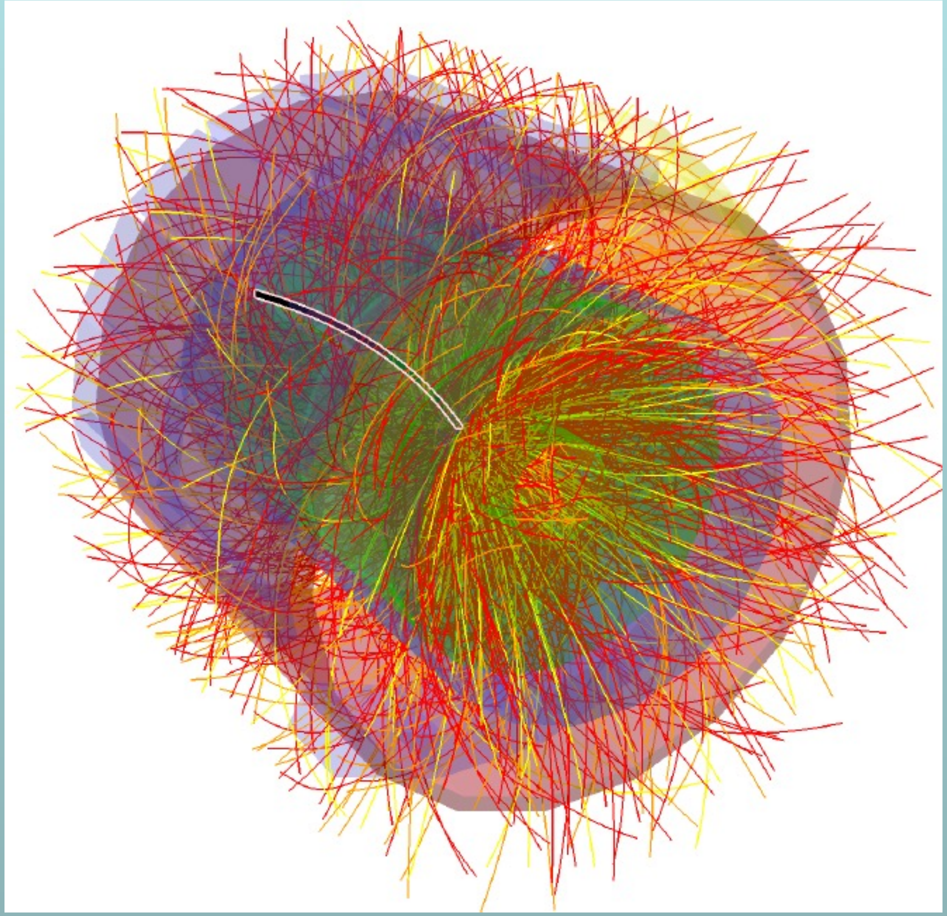
Hypernucleus: ${}^{5}_{\Lambda}\mathrm{He}$

- Highlight: clear signal of hyperhelium-5 in Au+Au at 3.0 GeV
- Comparison to thermal model seems to work only up to A=2, even when excited states are considered
- Hypothesis of A=5 Σ-hypernucleus would help explaining the data
- Energy dep. shows slight offset for all hypernuclei

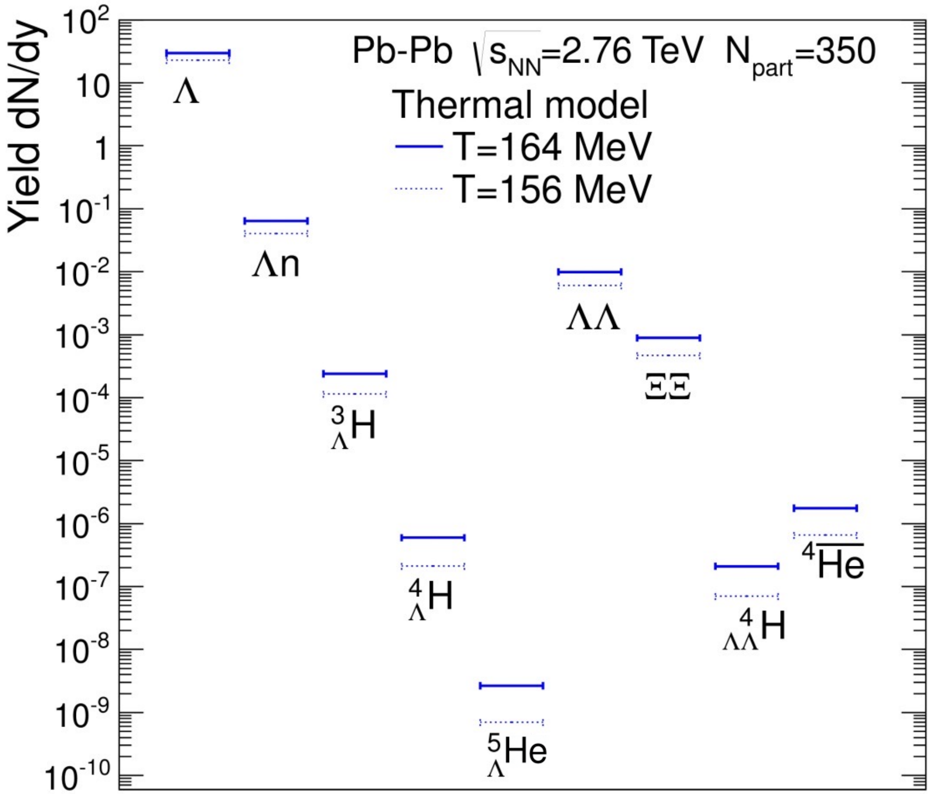


QM2025
Talk #554
Y. Zhou

Outlook & Summary



Outlook

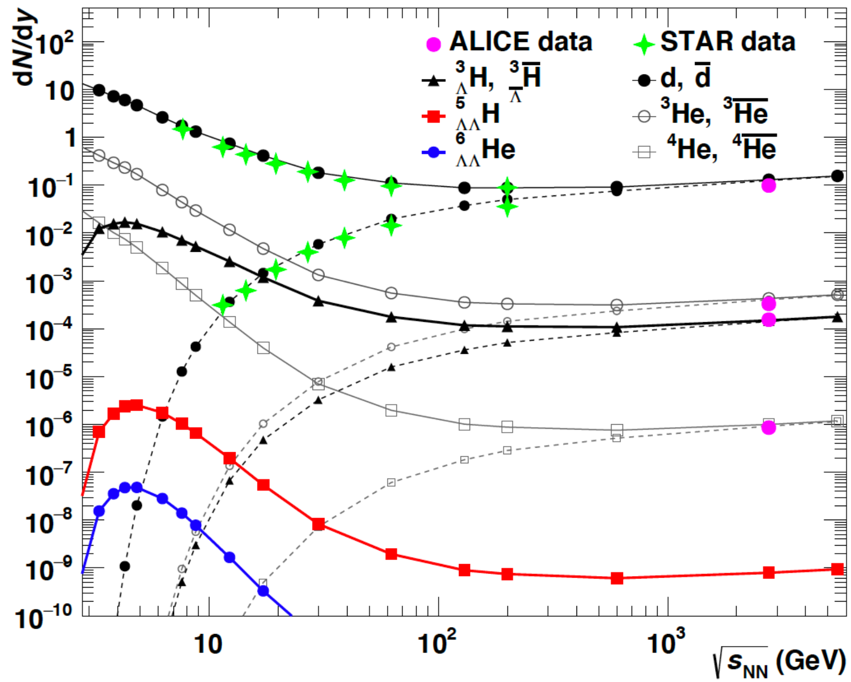


A. Andronic, private communication, model described in A. Andronic et al., PLB 697, 203 (2011) and references therein

- Explore QCD and QCD inspired model predictions for (unusual) multi-baryon states
- Search for rarely produced anti- and hyper-matter
- Test model predictions, e.g. thermal and coalescence

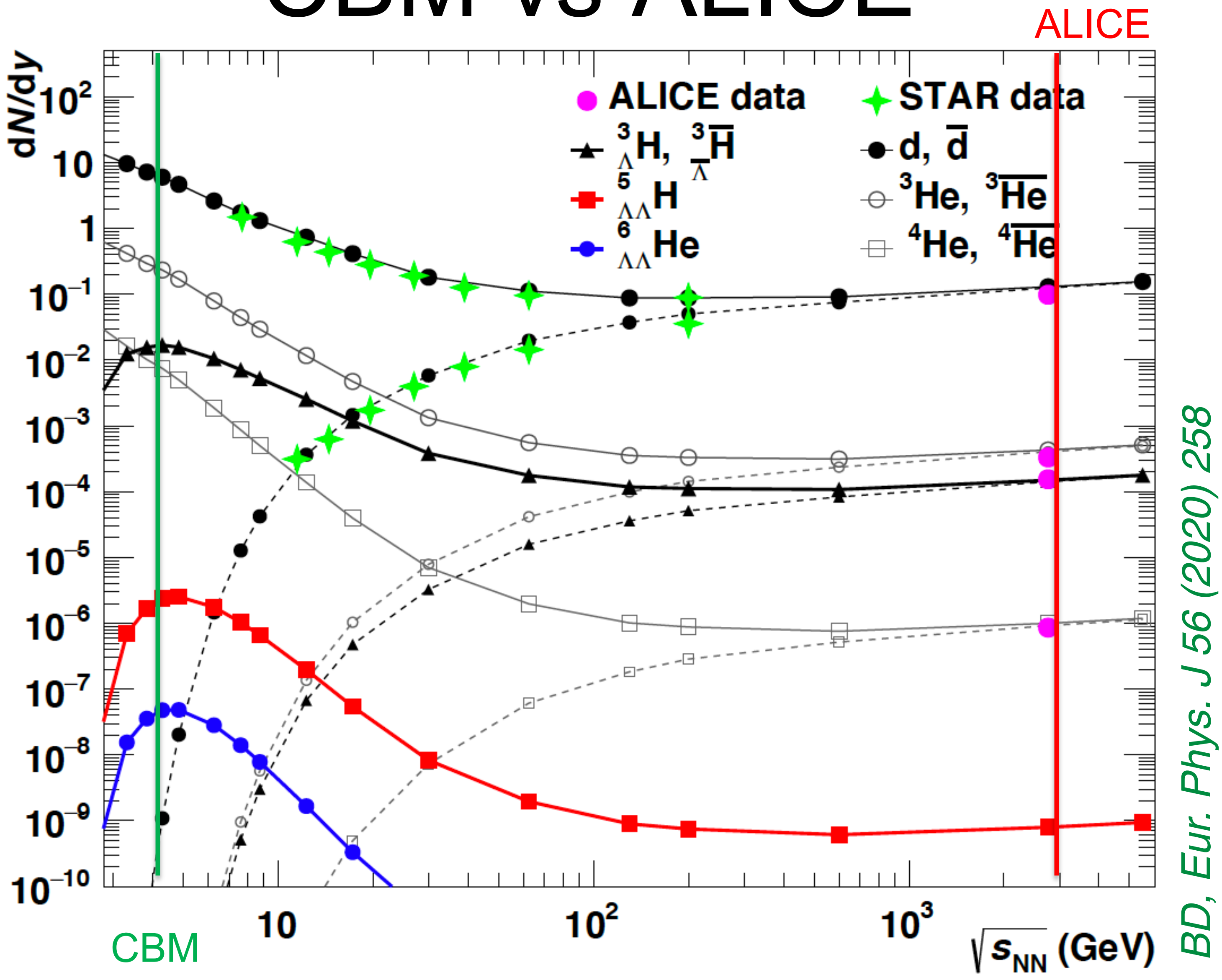
Conclusion

- ALICE@LHC, HADES@GSI and STAR@RHIC are well suited to study light (anti-)(hyper-) nuclei and perform searches for exotic bound states (A<5)
- Copious production of loosely bound objects measured by ALICE, HADES and STAR as predicted by the thermal model
- Models describe the data rather well
- Ratios vs. multiplicity trend described by both models
  - only tension: Alpha vs. ${}^{3}_{\Lambda}H$
- New and more precise data can be expected in the next years



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

CBM vs ALICE

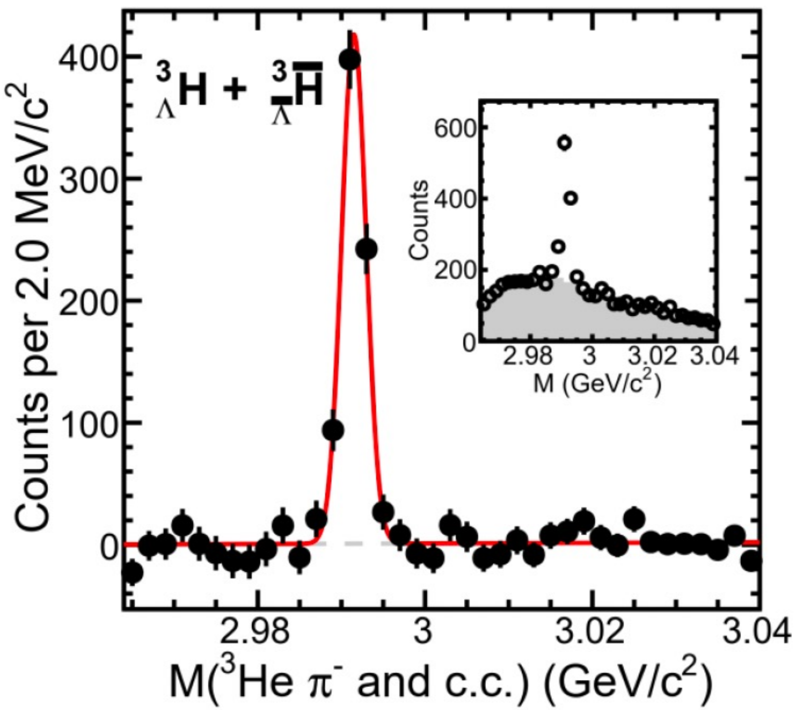


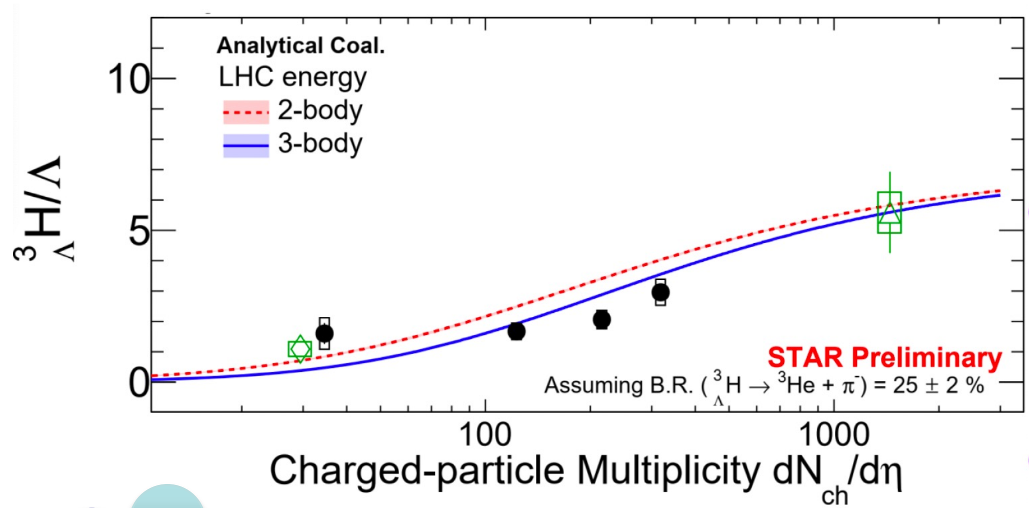
ALICE
dN/dy
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
ALICE data
STAR data
${}^{3}_{\Lambda}H$, ${}^{3}_{\bar{\Lambda}}\bar{H}$
d, $\bar{d}$
${}^{5}_{\Lambda\Lambda}H$
${}^{3}He$, ${}^{3}\overline{He}$
${}^{6}_{\Lambda\Lambda}He$
${}^{4}He$, ${}^{4}\overline{He}$
10
10^2
10^3
$\sqrt{s_{NN}}$ (GeV)
CBM
BD, Eur. Phys. J 56 (2020) 258

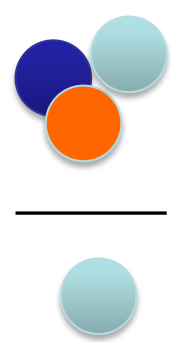
Backup

Hypertriton/Λ ratio

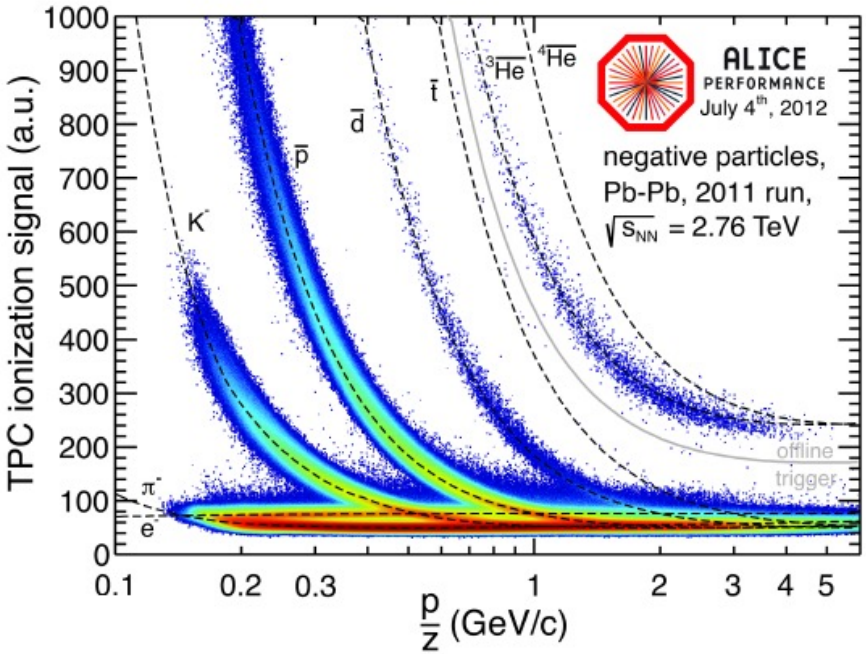
- Hypertriton signal recently also extracted in isobar collisions
- Stronger separation between models as for other particle ratios, mainly due to the size of the hypertriton

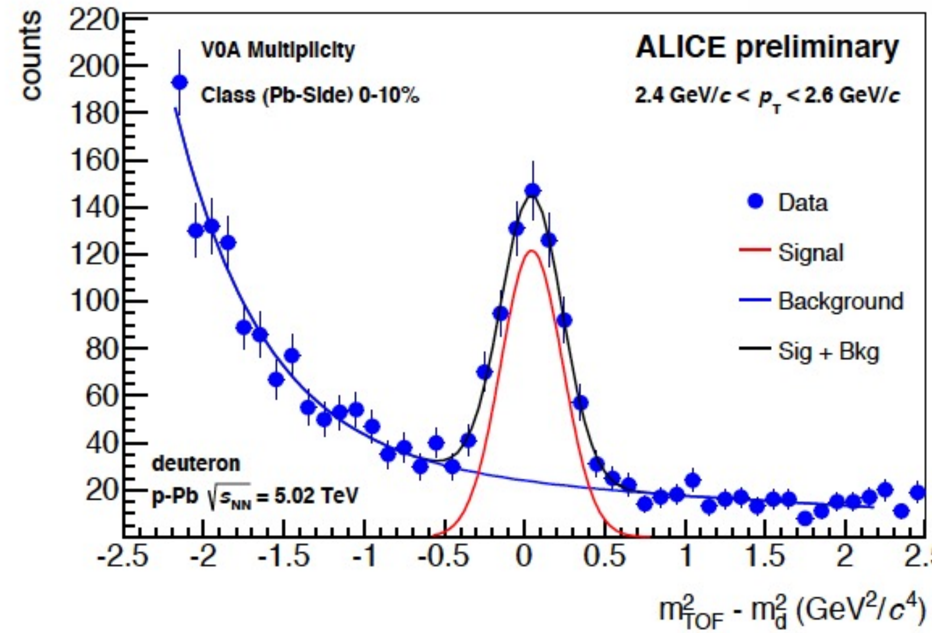






Particle Identification



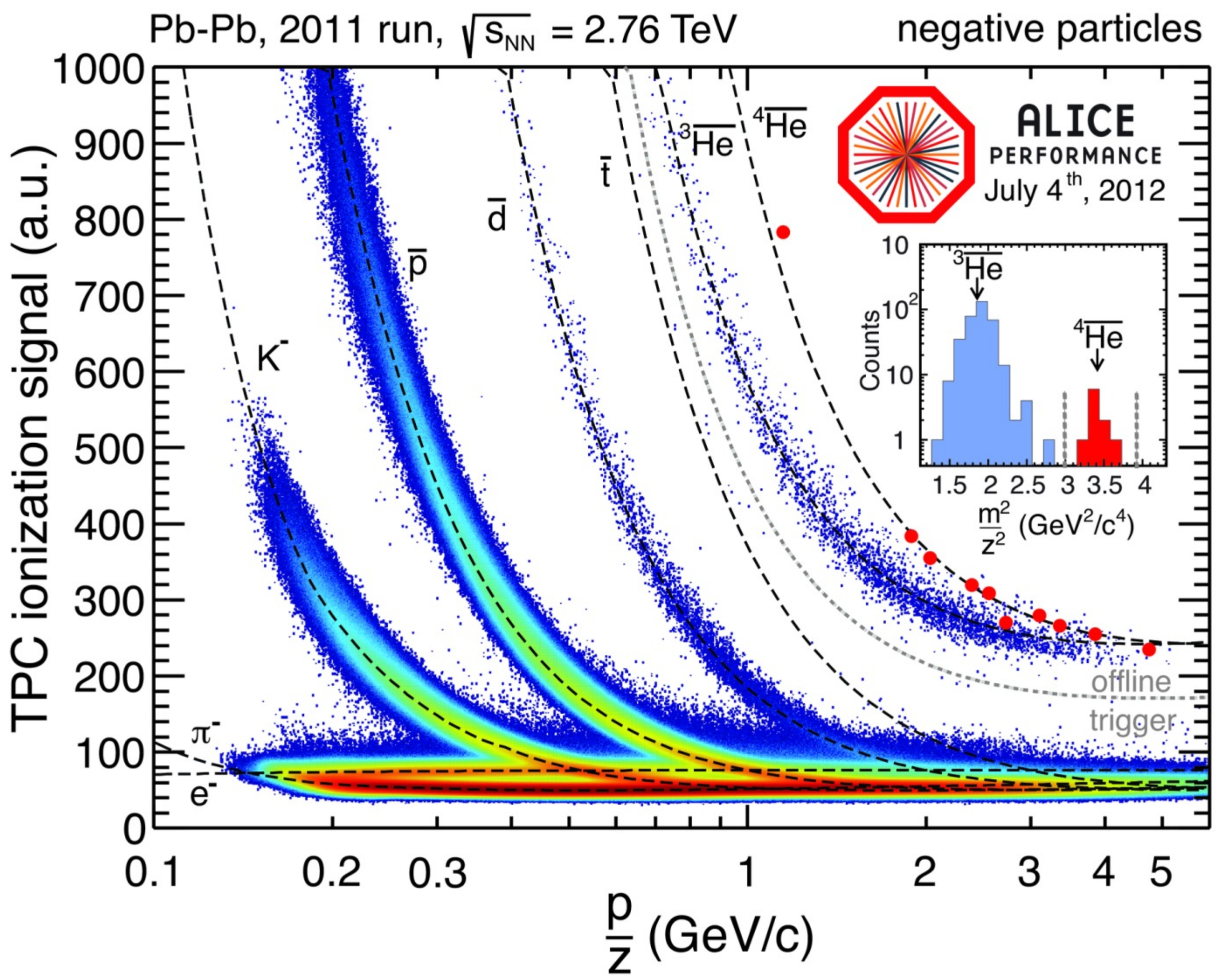


Low momenta:
Nuclei are identified using the d*E*/d*x* measurement in the Time Projection Chamber (TPC)

Higher momenta:
Velocity measurement with the Time-of-Flight (TOF) detector is used to calculate the m^2 distribution

Anti-Alpha

For the full statistics of 2011 ALICE identified 10 Anti-Alphas using TPC and TOF

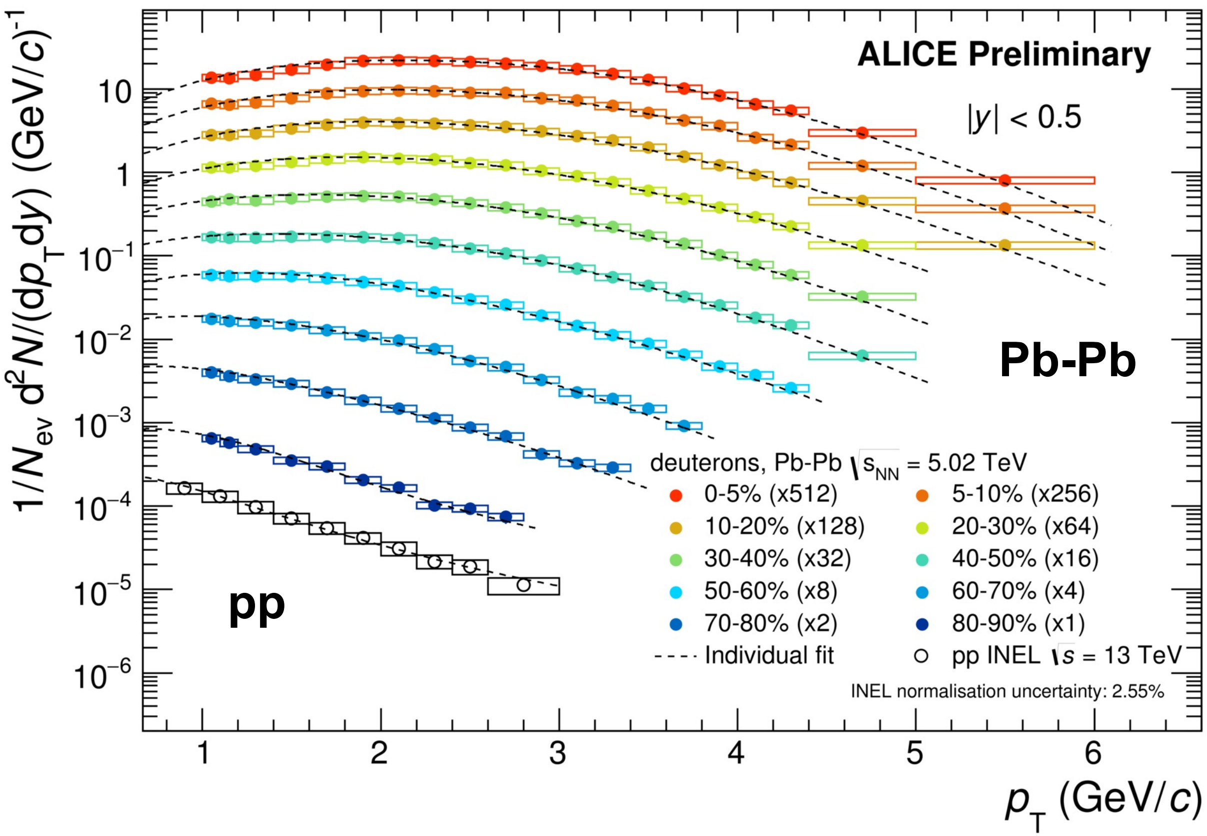


STAR observed the Anti-Alpha in 2010:

Nature 473, 353 (2011)

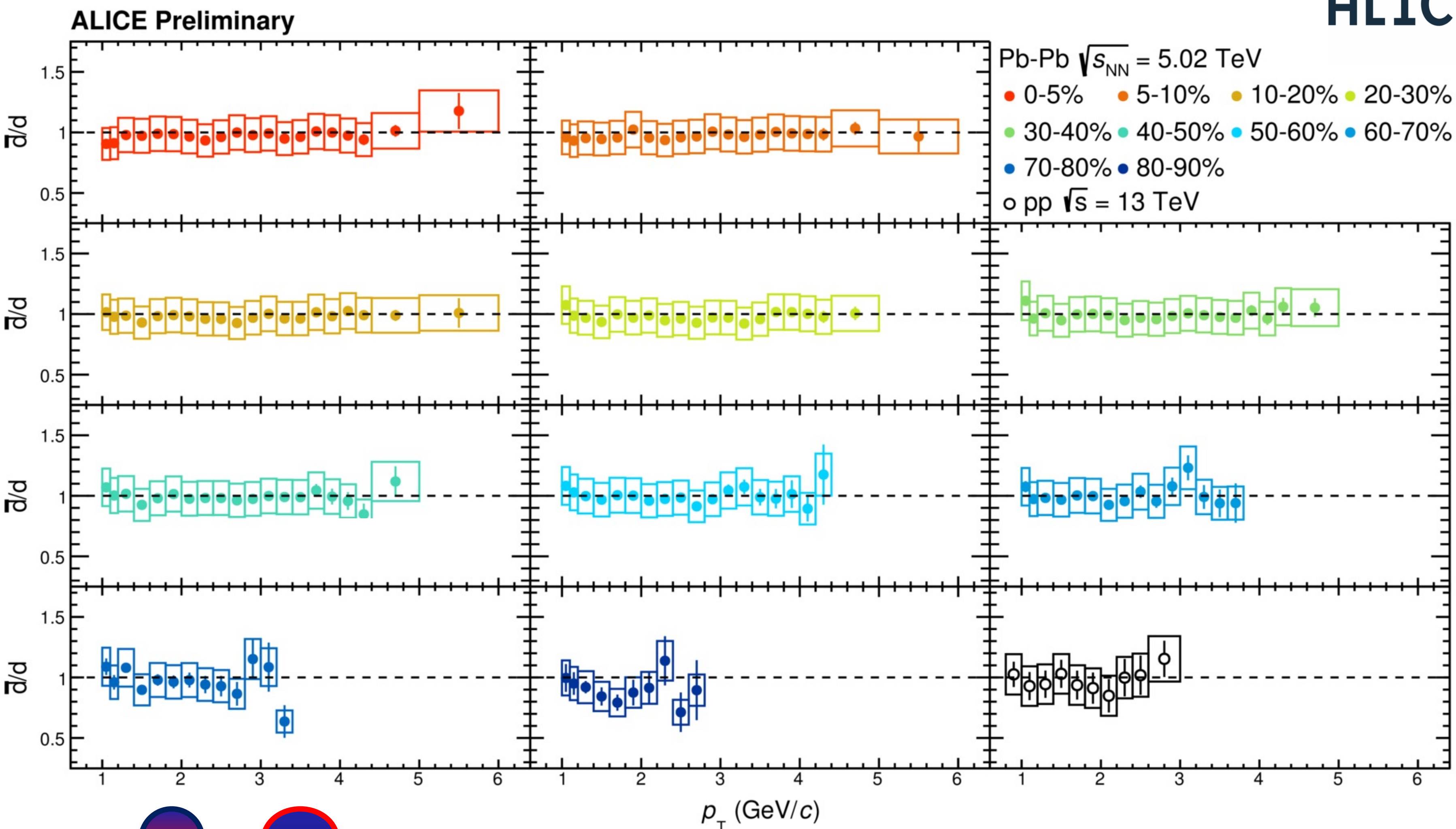
Deuterons

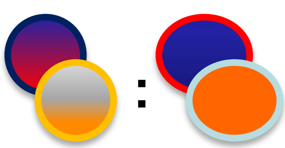
ALICE-PUBLIC-2017-006



- p_T spectra getting harder for more central collisions (from pp to Pb-Pb) → showing clear radial flow
- Blast-Wave fits describe the data in Pb-Pb very well
- No hint for radial flow in pp

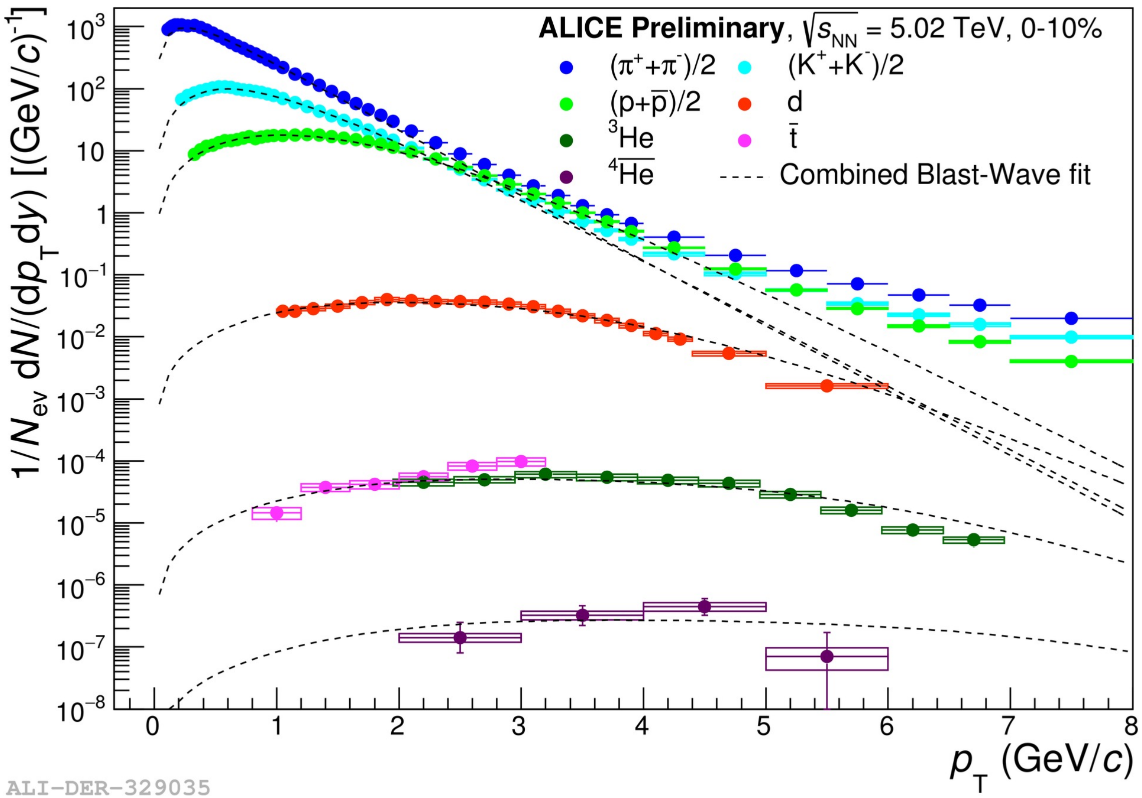
(Anti-)Deuteron ratio



 -ratios consistent with unity, as expected

Combined Blast-Wave fit

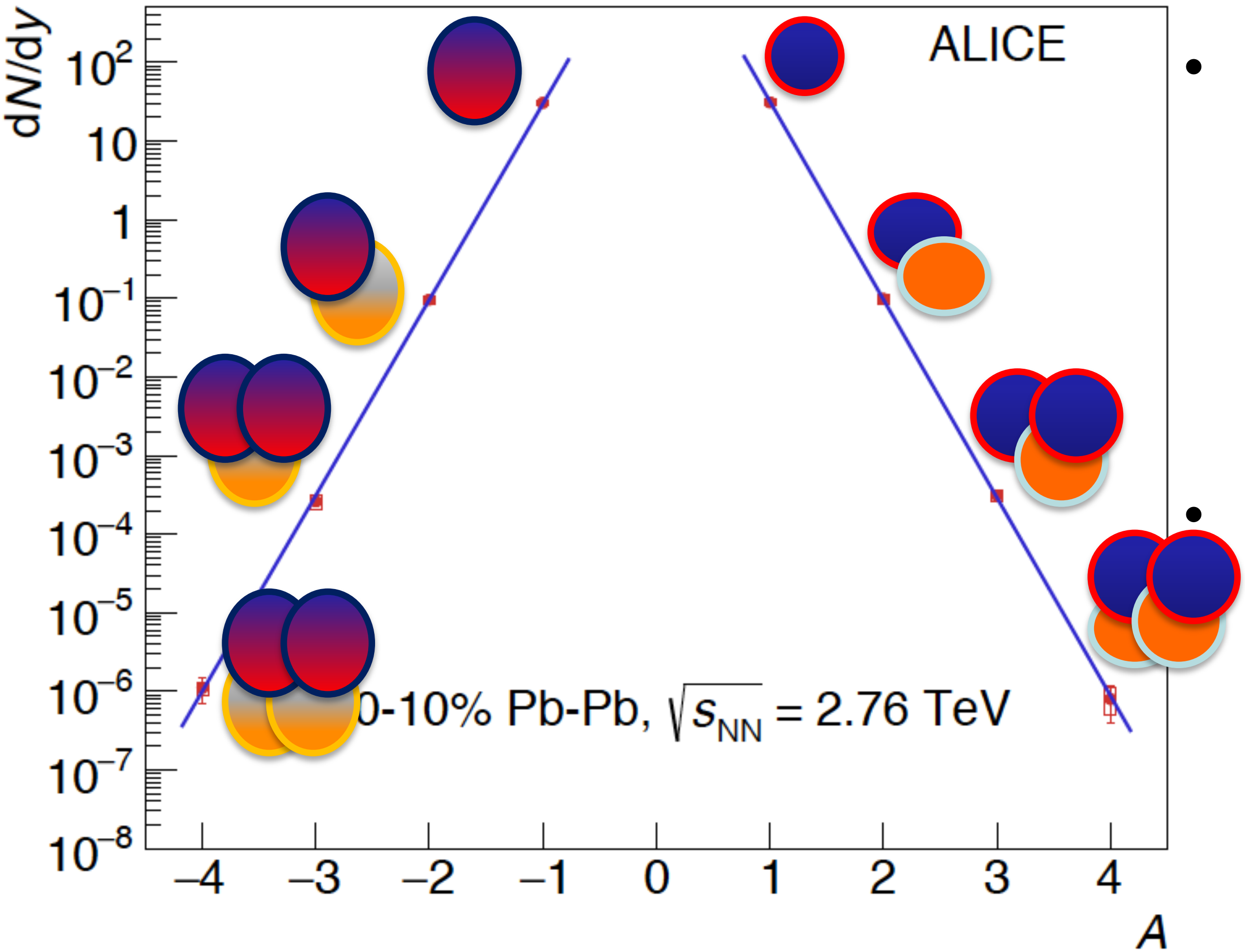
ALICE Collaboration, arXiv:1910.07678, see also arXiv:2311.11758



- Simultaneous Blast-Wave fit of π^+, K^+, p, d, t, ^{3}He and ^{4}He spectra for central Pb-Pb collisions leads to values for $\langle\beta\rangle$ and T_{kin} close to those obtained when only π,K,p are used

- All particles are described rather well with this simultaneous fit

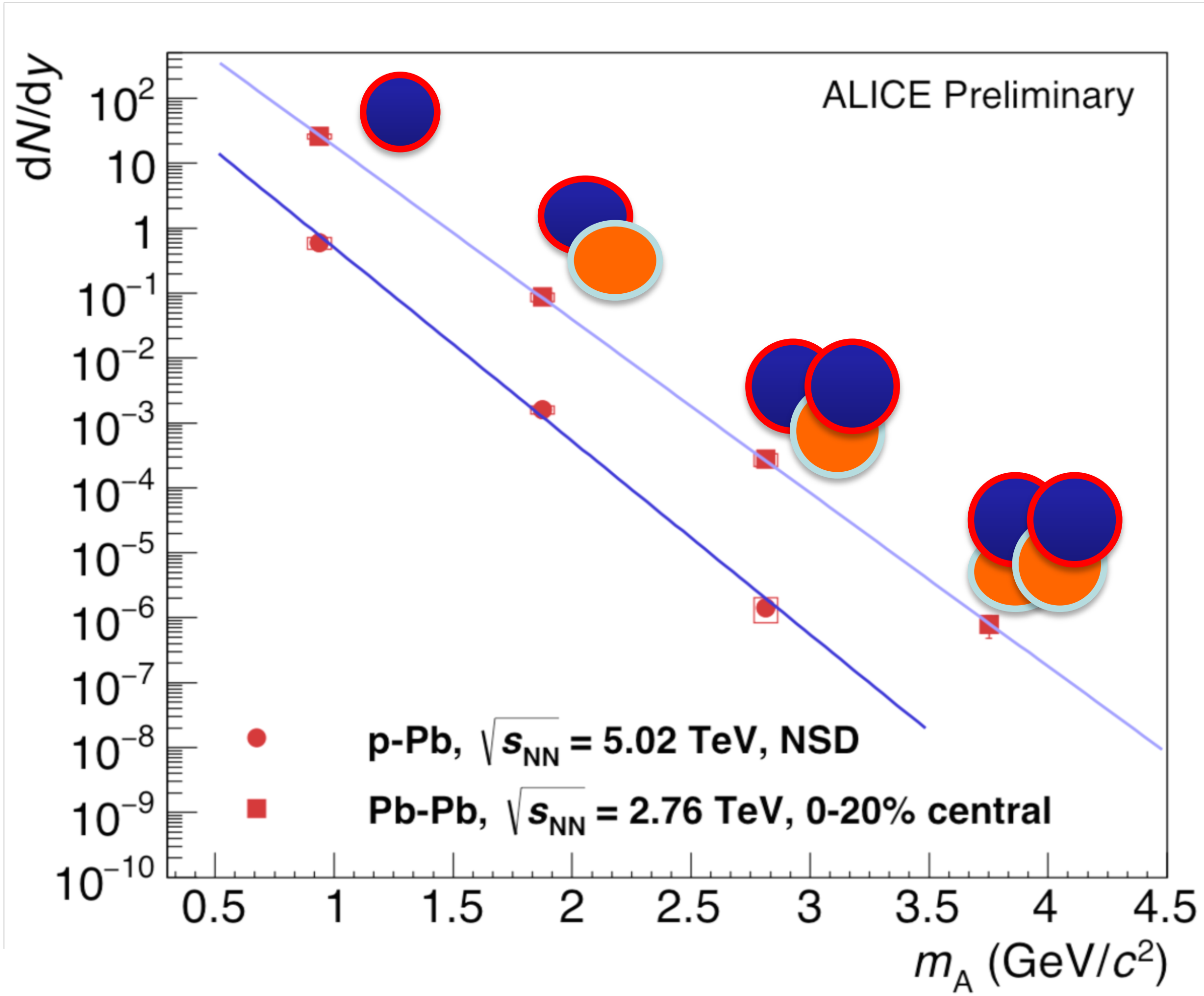
Mass dependence



- Production of (anti-) nuclei is follwing an exponential, and decreases with mass as expected from thermal model
- In Pb-Pb the „penalty factor“ for each additional baryon ~300 (for particles and anti-particles)

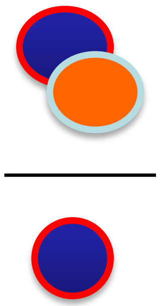
ALICE Collaboration, arXiv:1710.07531, NPA 971, 1 (2018)

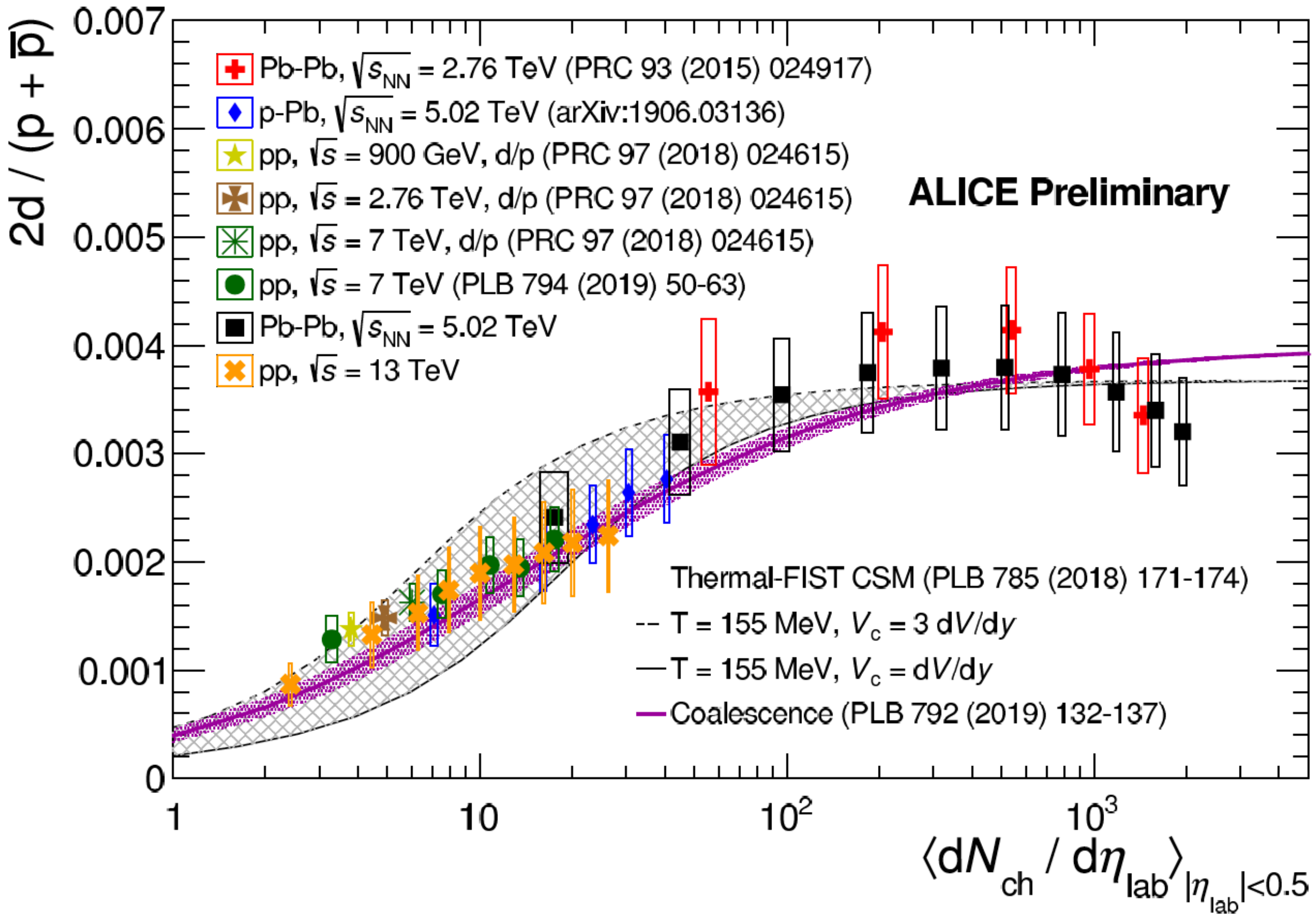
Mass dependence



- Production of (anti-) nuclei is follwing an exponential, and decreases with mass as expected from thermal model
- In Pb-Pb the „penalty factor“ for each additional baryon ~300, in p-Pb ~600 and in pp ~1000

d/p vs. multiplicity

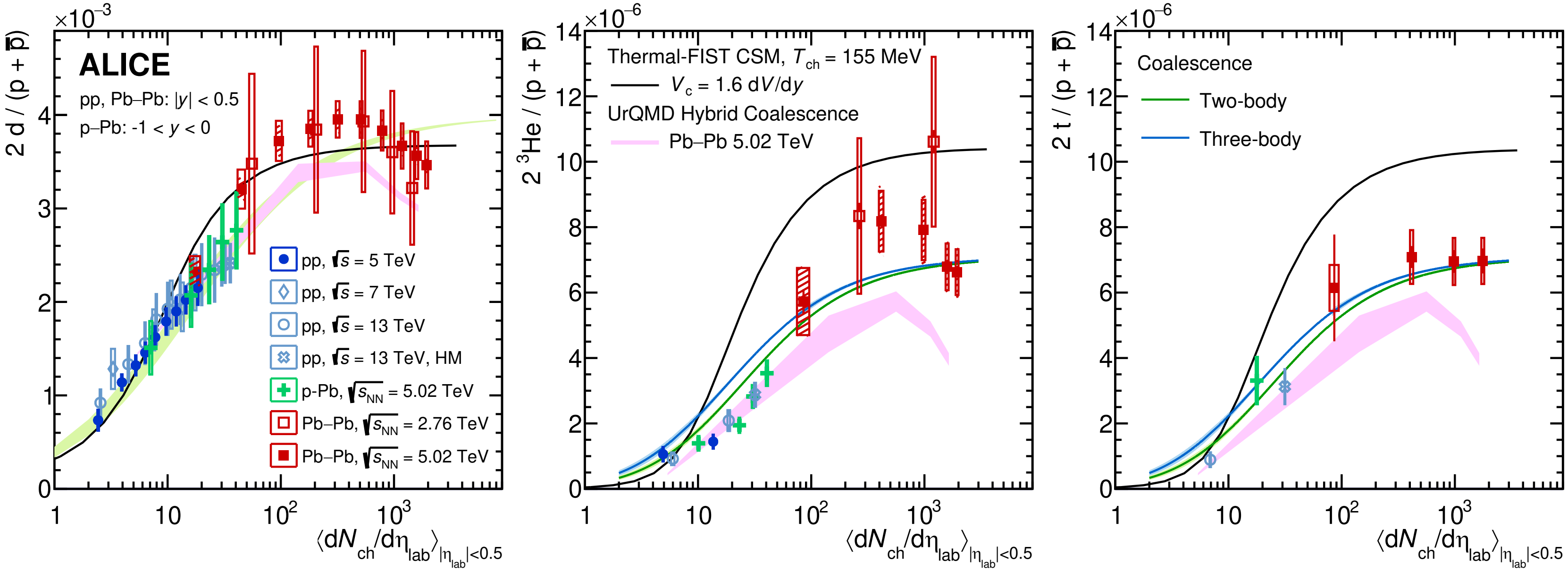




d/p ratio rather well described by coalescence and (canonical) thermal model

Ratios vs. multiplicity

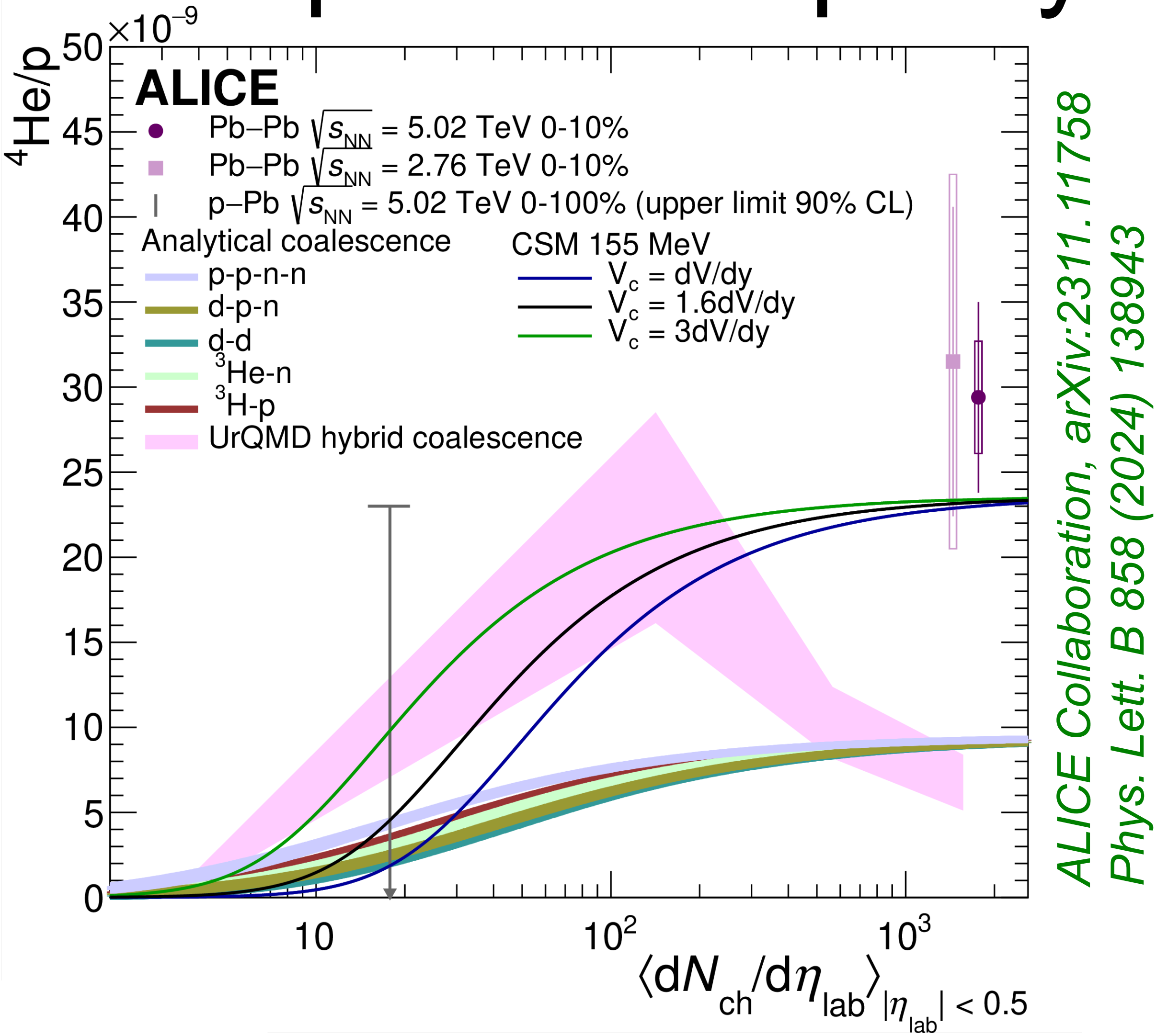
ALICE Collaboration, arXiv:2211.14015, Phys.Rev.C 107 (2023) 064904



- d/p ratio rather well described by coalescence and (canonical) thermal model
- Some tension for ^{3}He/p and ^{3}H/p over p_{T}

Models:
Coalescence: K.J. Sun, C.M. Ko, BD, PLB 792 (2019) 132
CSM: V.Vovchenko, BD, H. Stöcker, PLB 785 (2018) 171
UrQMD Hybrid: T. Reichert, J. Steinheimer, V.Vovchenko, BD, M. Bleicher, Phys. Rev. C 107 (2023) 1

^{4}He/p vs. multiplicity

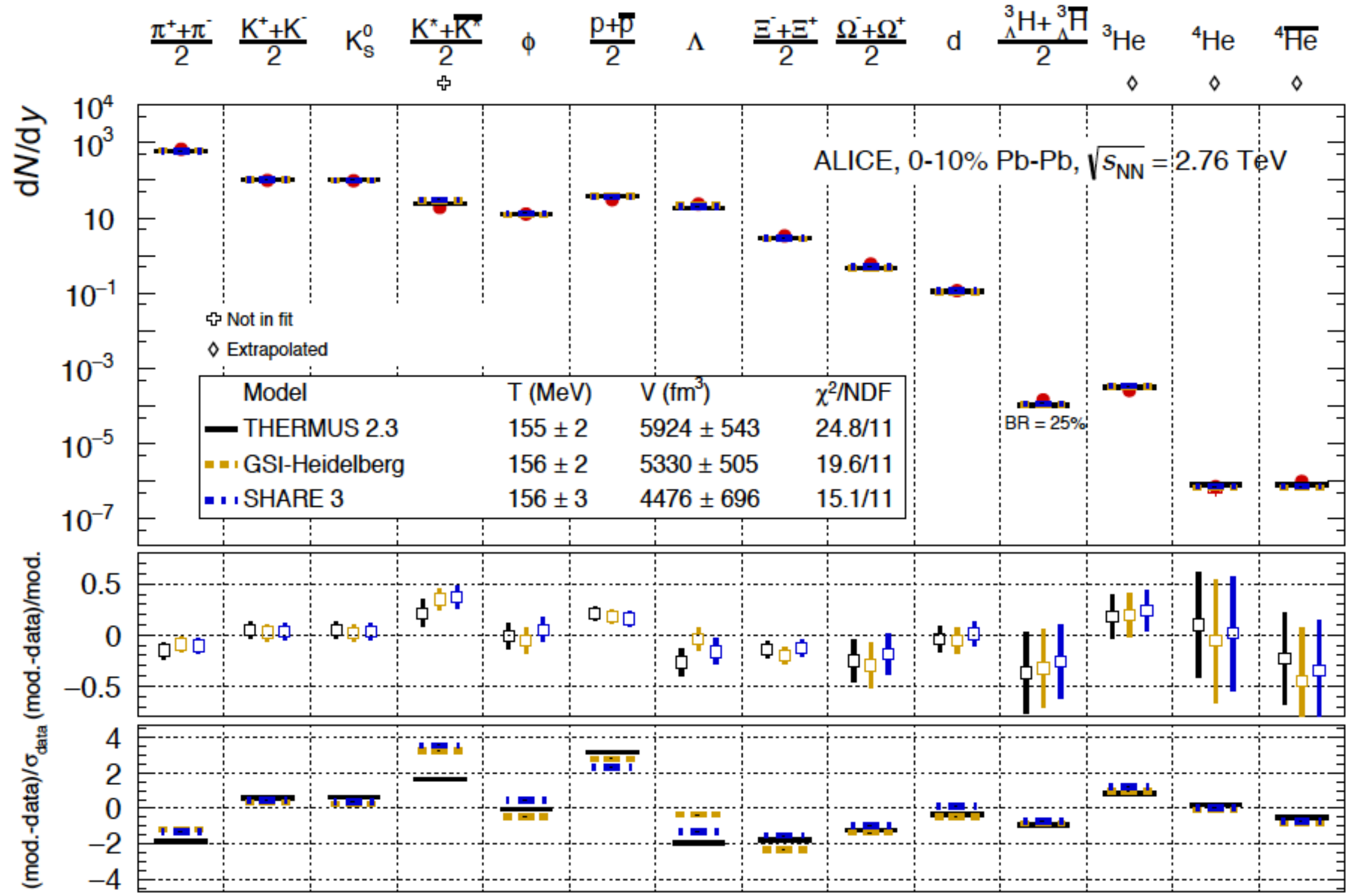


^{4}He/p ratio significantly better described by the thermal model

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Thermal model

THERMUS: S. Wheaton, et al., CPC 180, 84 (2009)
GSI-Heidelberg: A. Andronic, et al., PLB 697, 203 (2011); PLB 673, 142 (2009) 142
SHARE3: G. Torrieri, et al., CPC 167, 229 (2005); CPC 175, 635 (2006); CPC 185, 2056 (2014)

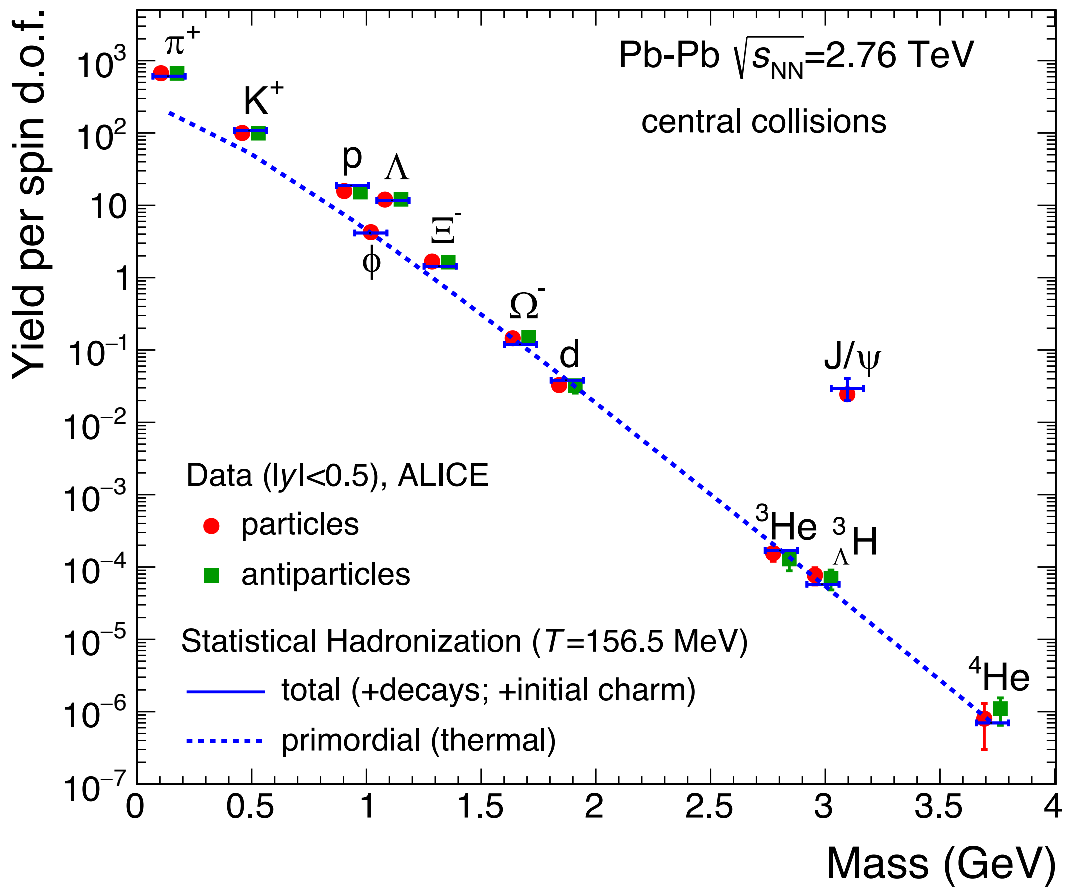


ALICE Collaboration, arXiv:1710.07531, NPA 971, 1 (2018)

- Different model implementations describe the production probability, including light nuclei and hyper-nuclei, rather well at a temperture of about T_{ch} =156 MeV

Thermal model

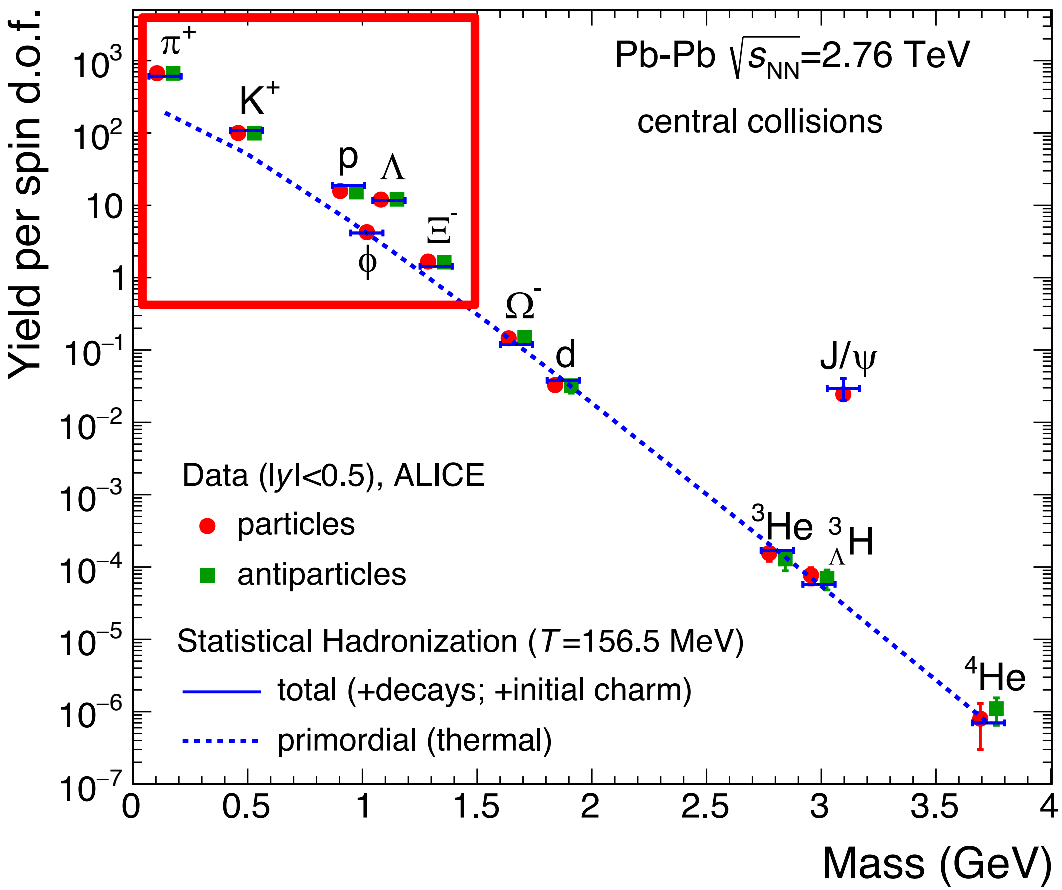
- For the thermal model description of production yields, feed-down is an important ingredient
- All light hadron production yields are populated strongly by resonances
- Seems to not be the case for (hyper-)nuclei



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

Thermal model

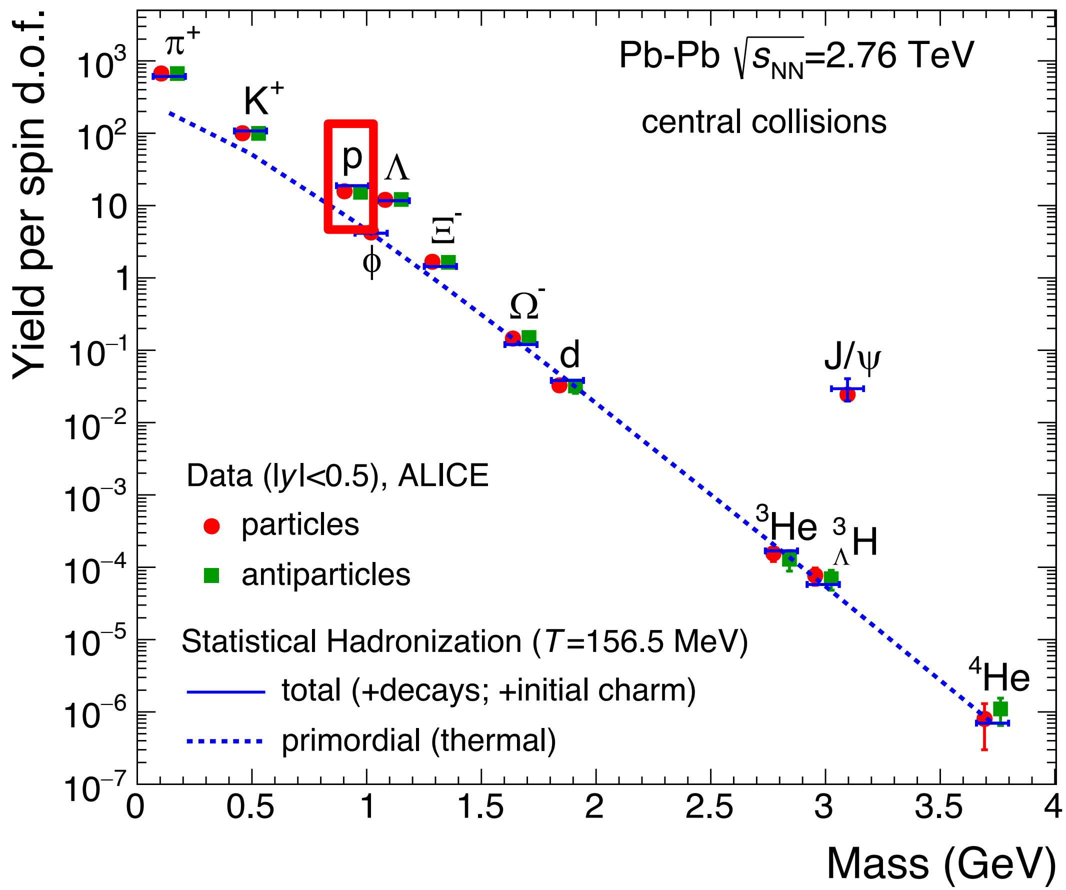
- For the thermal model description of production yields, feed-down is an important ingredient
- All light hadron production yields are populated strongly by resonances
- Seems to not be the case for (hyper-)nuclei



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

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

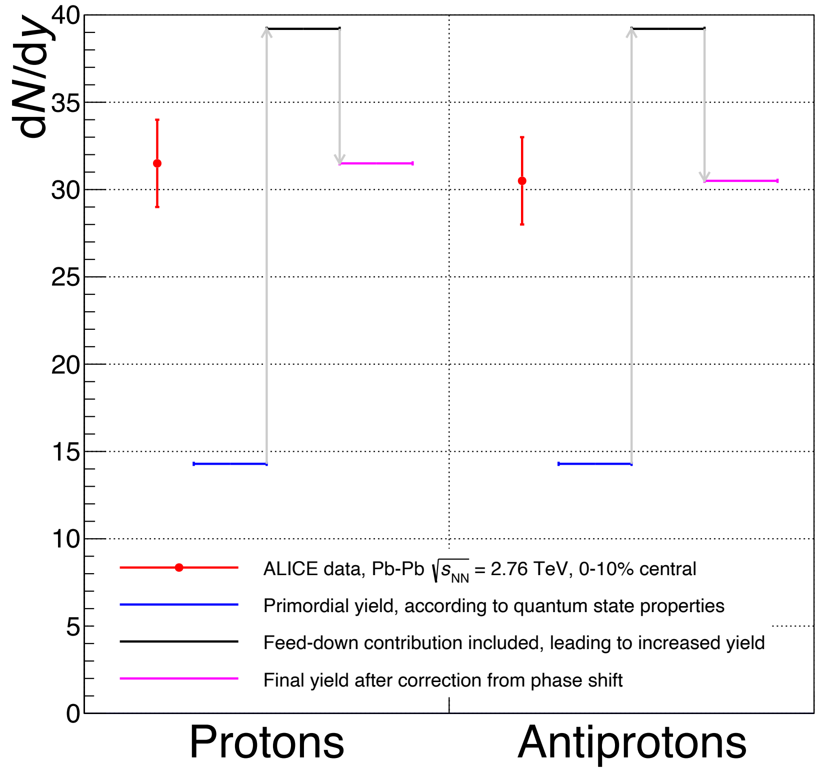


A. Andronic et al., Phys.Lett.B 797 (2019) 134836

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

BD, G. Röpke, D. Blaschke, Phys. Rev. C 106 (2022) 044908

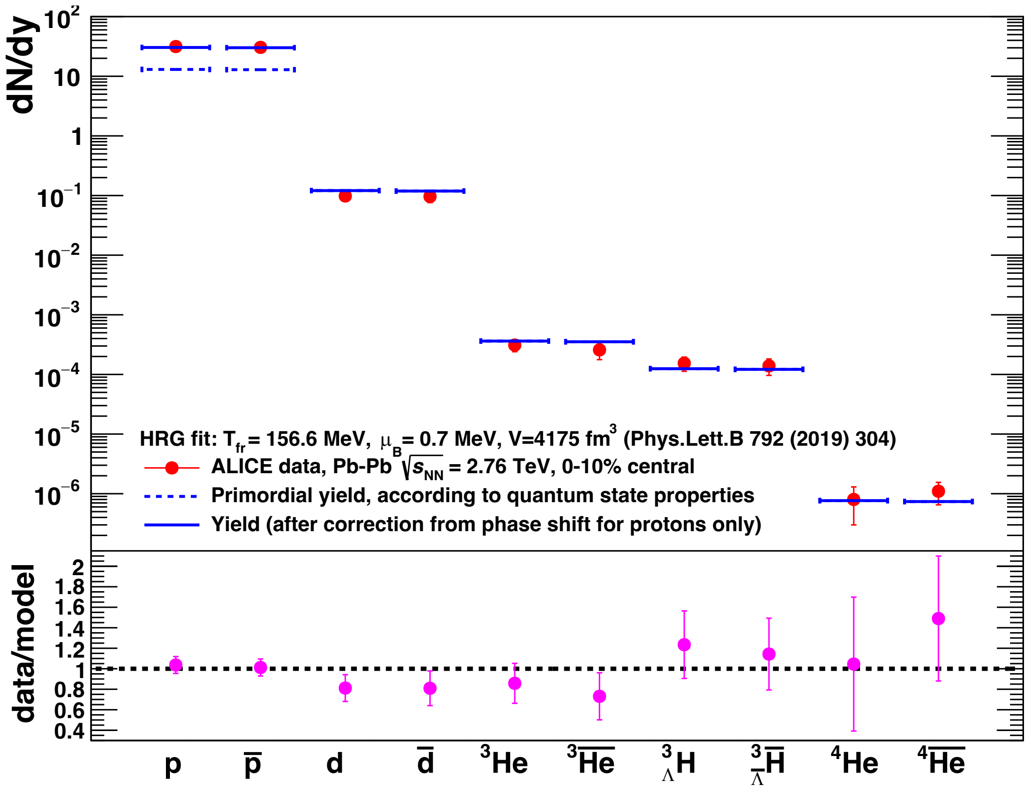


A. Andronic et al., Phys.Lett.B 797 (2019) 134836; Nature 561 (2018) 7723, 321; Phys.Lett.B 697 (2011) 203; Phys.Lett.B 792 (2019) 304

Thermal model

- 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

BD, G. Röpke, D. Blaschke, Phys. Rev. C 106 (2022) 044908

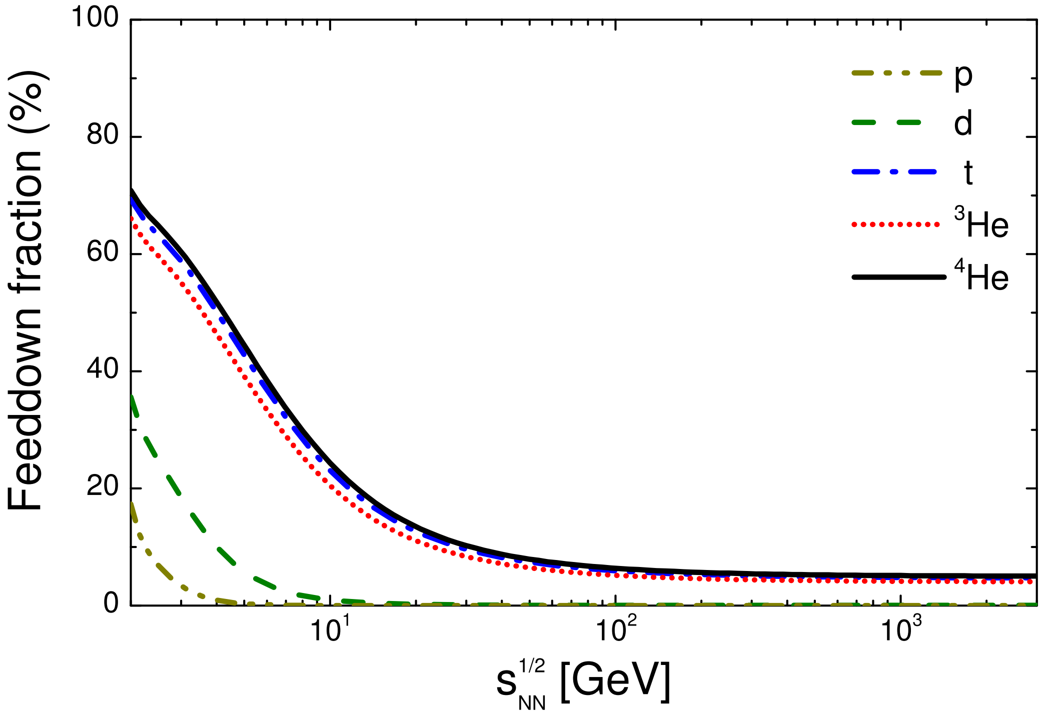


A. Andronic et al., Phys.Lett.B 797 (2019) 134836; Nature 561 (2018) 7723, 321; Phys.Lett.B 697 (2011) 203; Phys.Lett.B 792 (2019) 304

Thermal model

- 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 at LHC

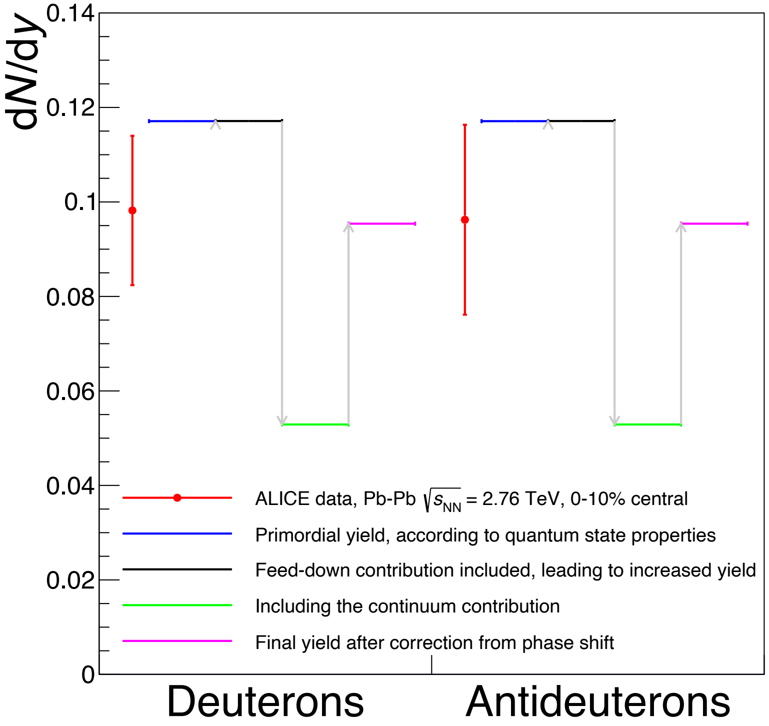
V. Vovchenko, BD, B. Kardan, M. Lorenz, H. Stoecker, Phys.Lett.B 809 (2020) 135746



Thermal model

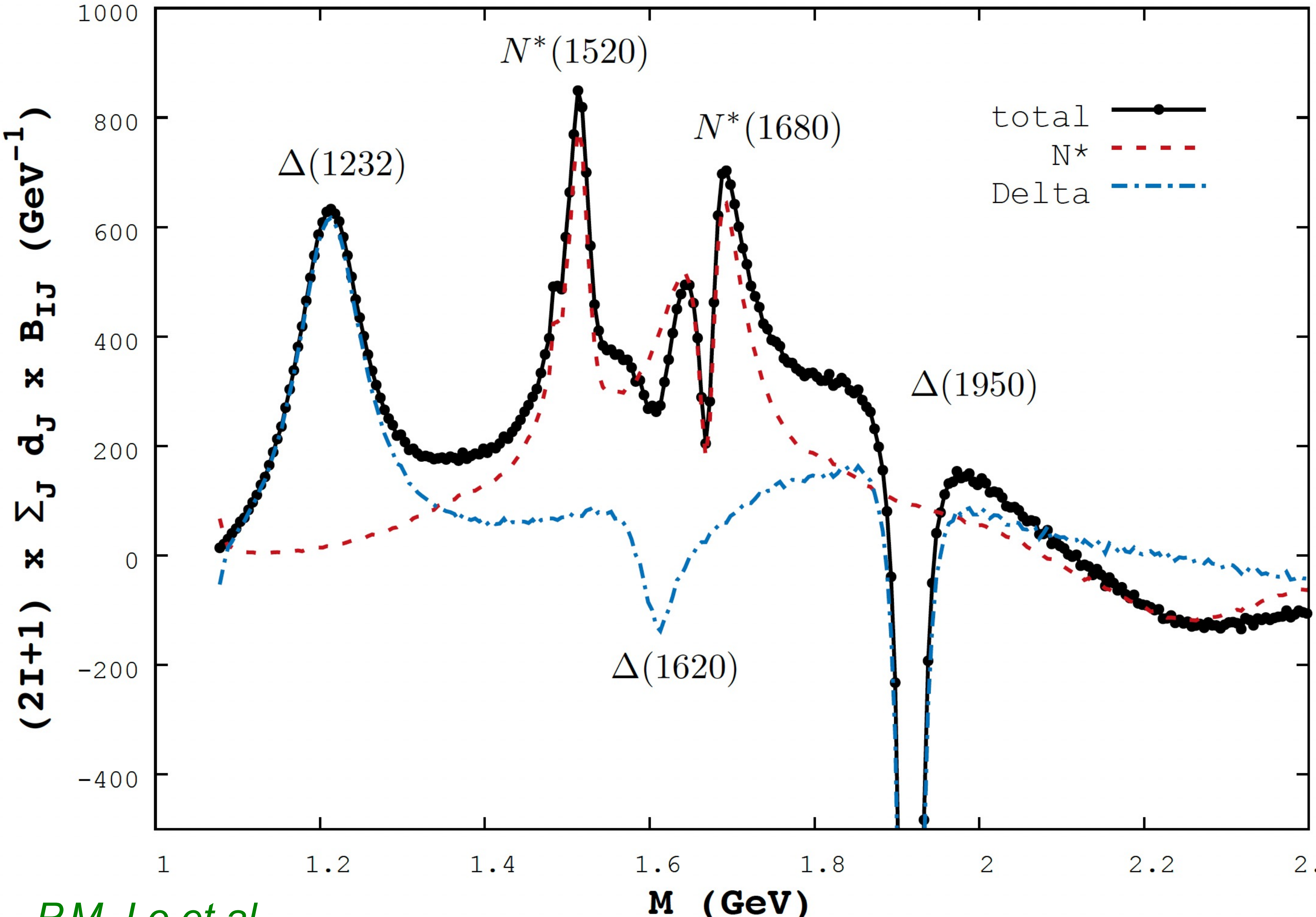
- For the thermal model description of production yields, feed-down is an important ingredient
- All light hadron production yields are populated strongly by resonances
- Seems to not be the case for (hyper-)nuclei

BD, G. Röpke, D. Blaschke,
Phys. Rev. C 106 (2022) 044908



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

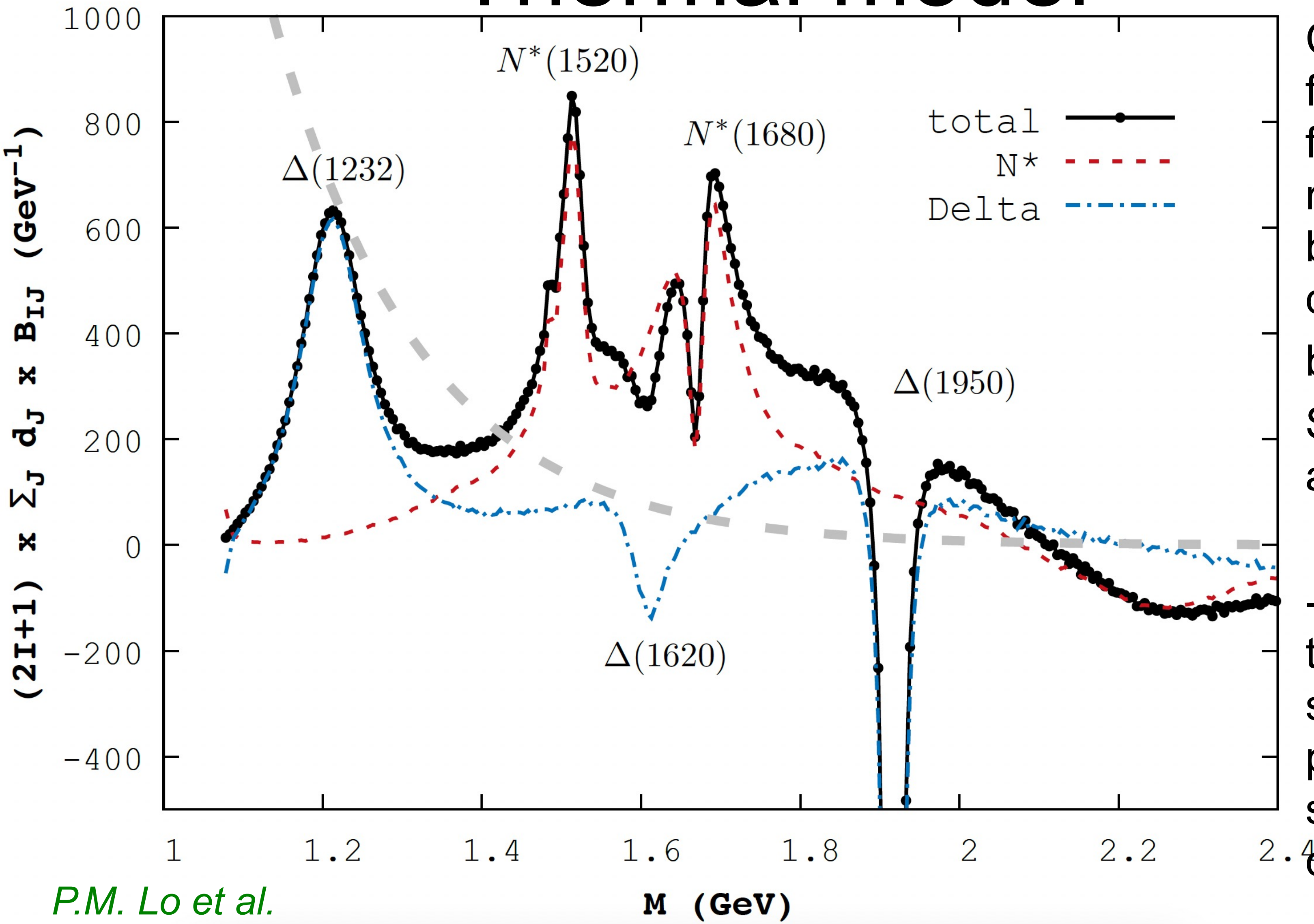


Contribution for protons from resonances best described by the S-Matrix approach

-connecting to phase shifts from p-π scattering data

P.M. Lo et al.

Thermal model

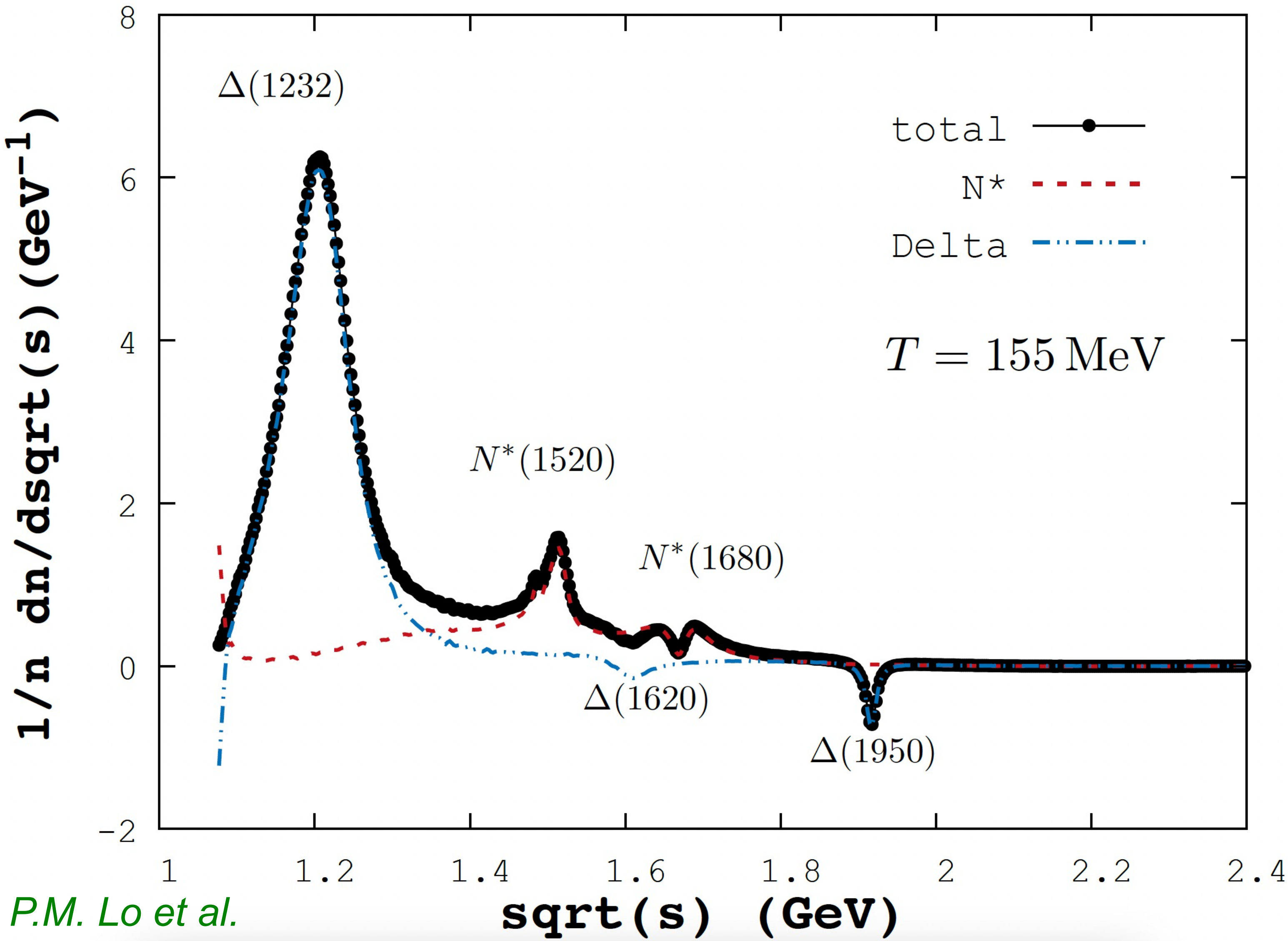


P.M. Lo et al.

Contribution for protons from resonances best described by the S-Matrix approach

-connecting to phase shifts from p-π scattering data

Thermal model

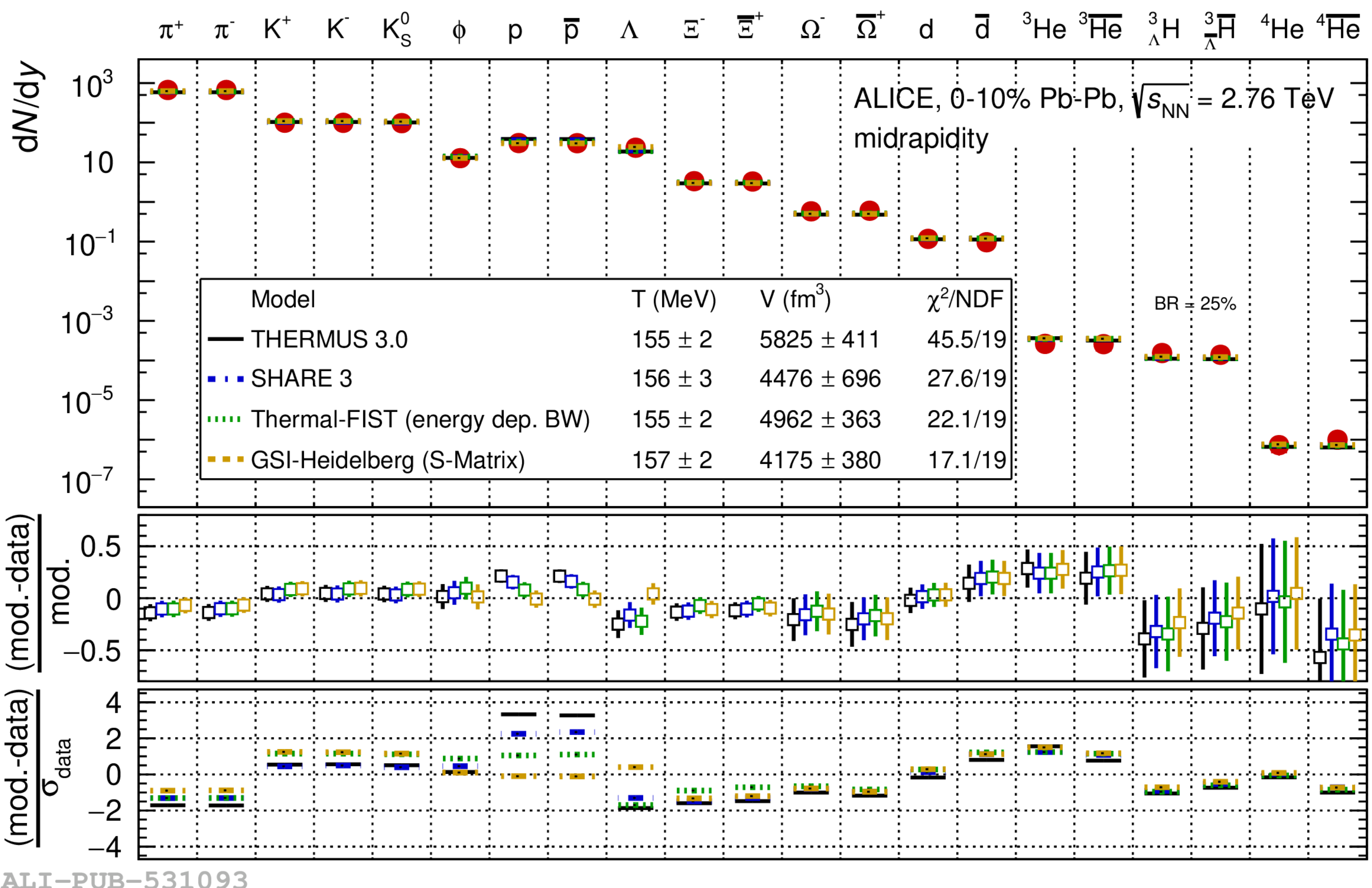


Contribution for protons from resonances best described by the S-Matrix approach

-connecting to phase shifts from p-π scattering data

P.M. Lo et al.

Thermal model



Energy-dependent Breit-Wigner works similar well

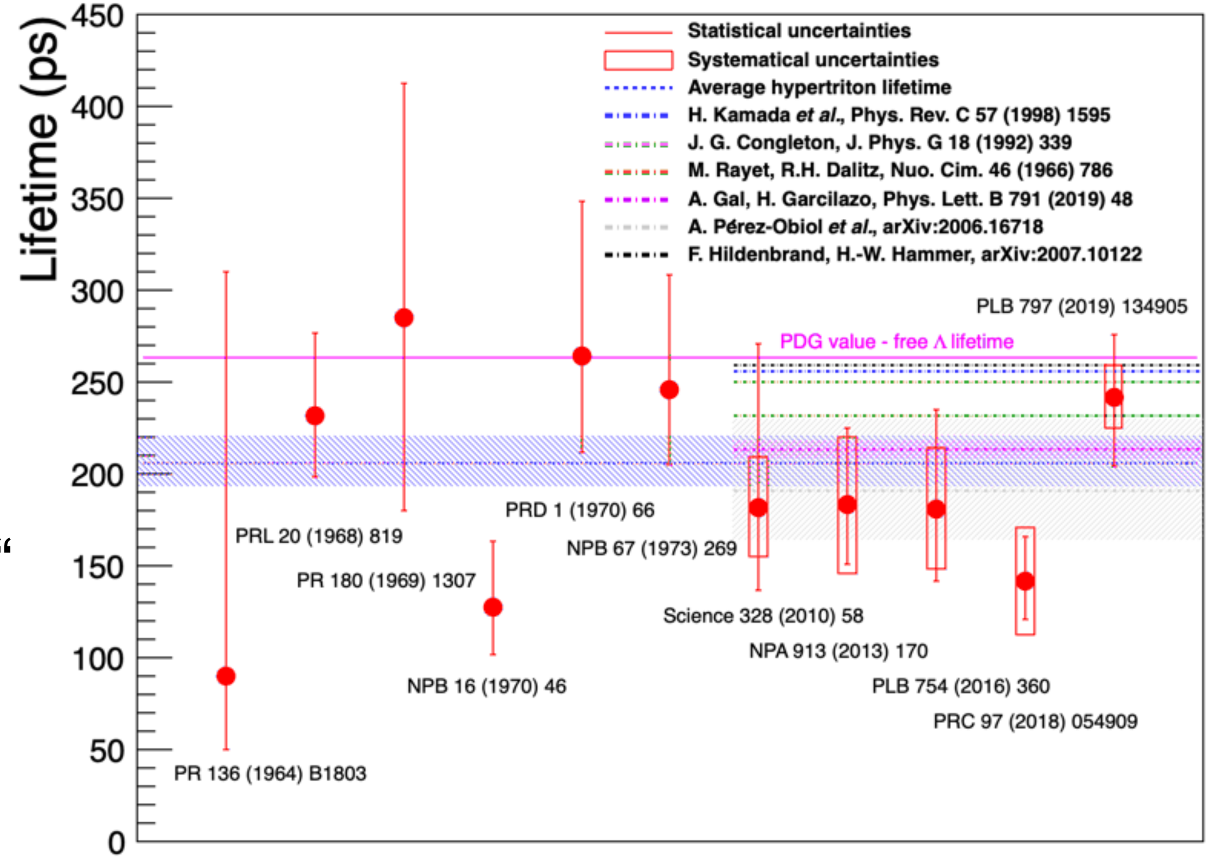
Contribution for protons from resonances best described by the S-Matrix approach

-connecting to phase shifts from p-π scattering data

ALICE Collaboration, arXiv:2211.04384 [nucl-ex]

Hypertriton „Puzzle“

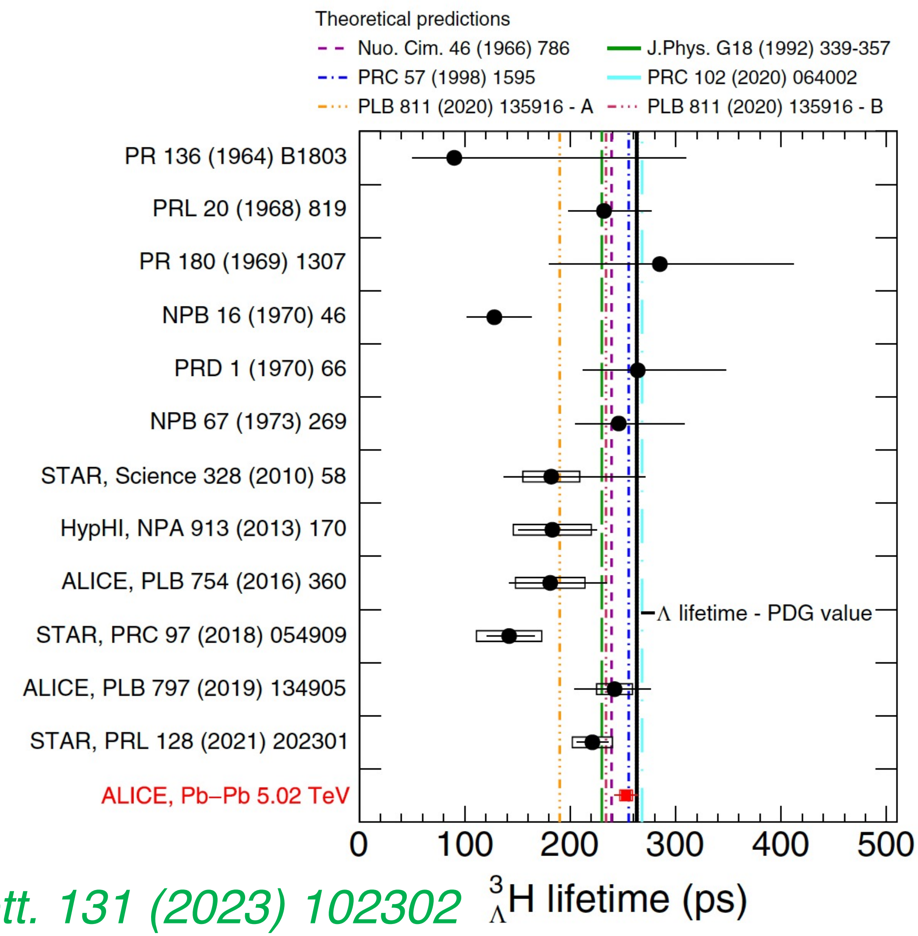
- Recently measured lifetimes are significantly below the lifetime of the free Λ → new ALICE results agree with the world average of all known measurements and with the free Λ lifetime
- Most recent calculations include „final-state“ interaction and agree well with the data



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

Hypertriton „Puzzle“

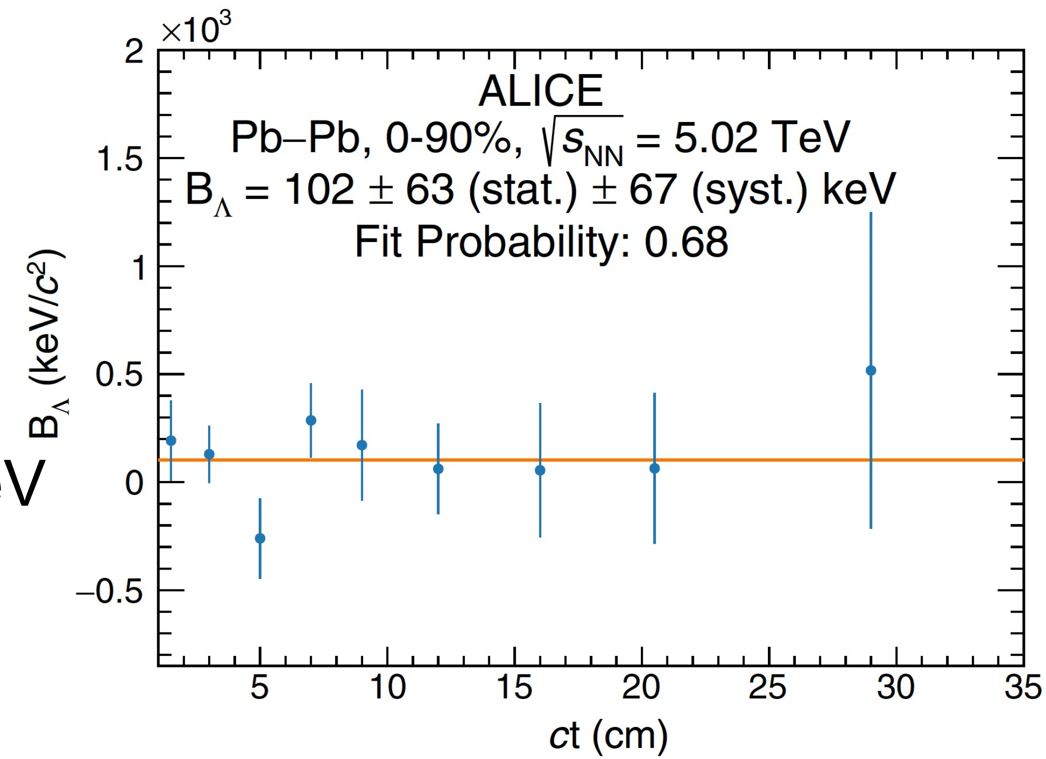
- Recently measured lifetimes are significantly below the lifetime of the free Λ → new ALICE results agree with the world average of all known measurements and with the free Λ lifetime
- Most recent calculations include „final-state“ interaction and agree well with the data



ALICE Collaboration, Phys. Rev. Lett. 131 (2023) 102302

Binding Energy

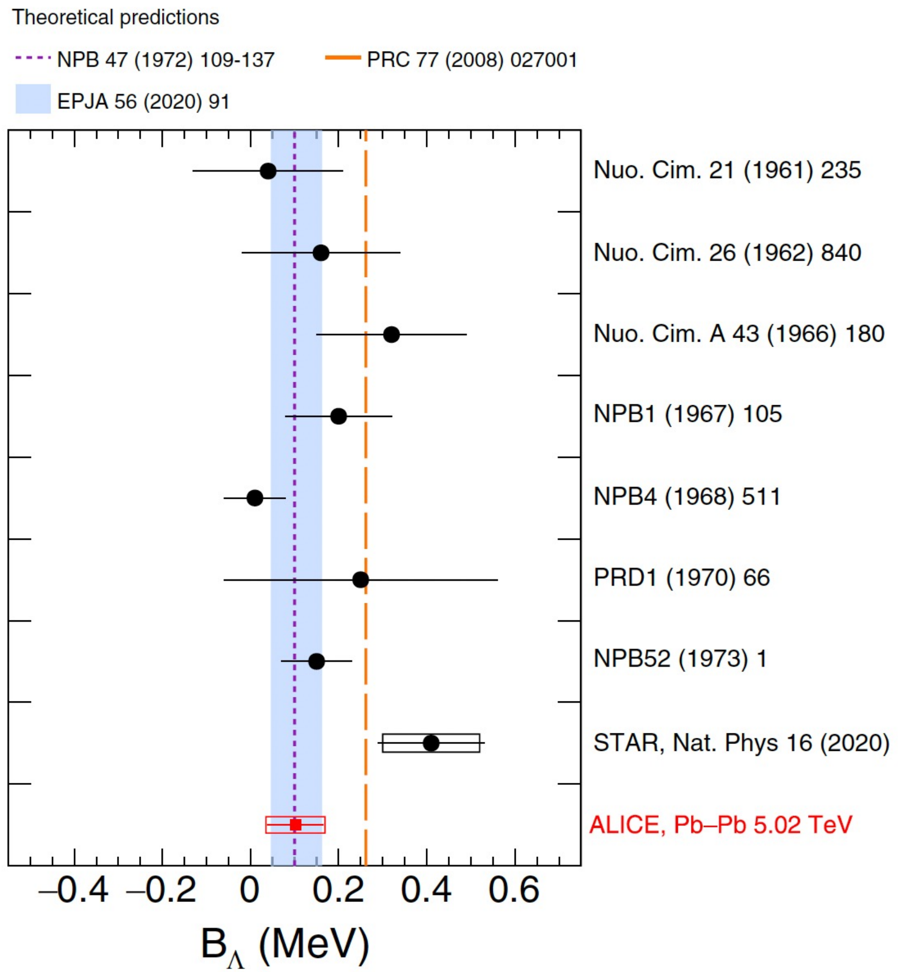
- Current studies show a better constraint and smaller statistical uncertainties
- The value obtained by this fit is $B_{\Lambda} = (102 \pm 63 \pm 67)$ keV
- Is compatible with the theoretical predictions



ALICE Collaboration, Phys. Rev. Lett. 131 (2023) 102302

Binding Energy

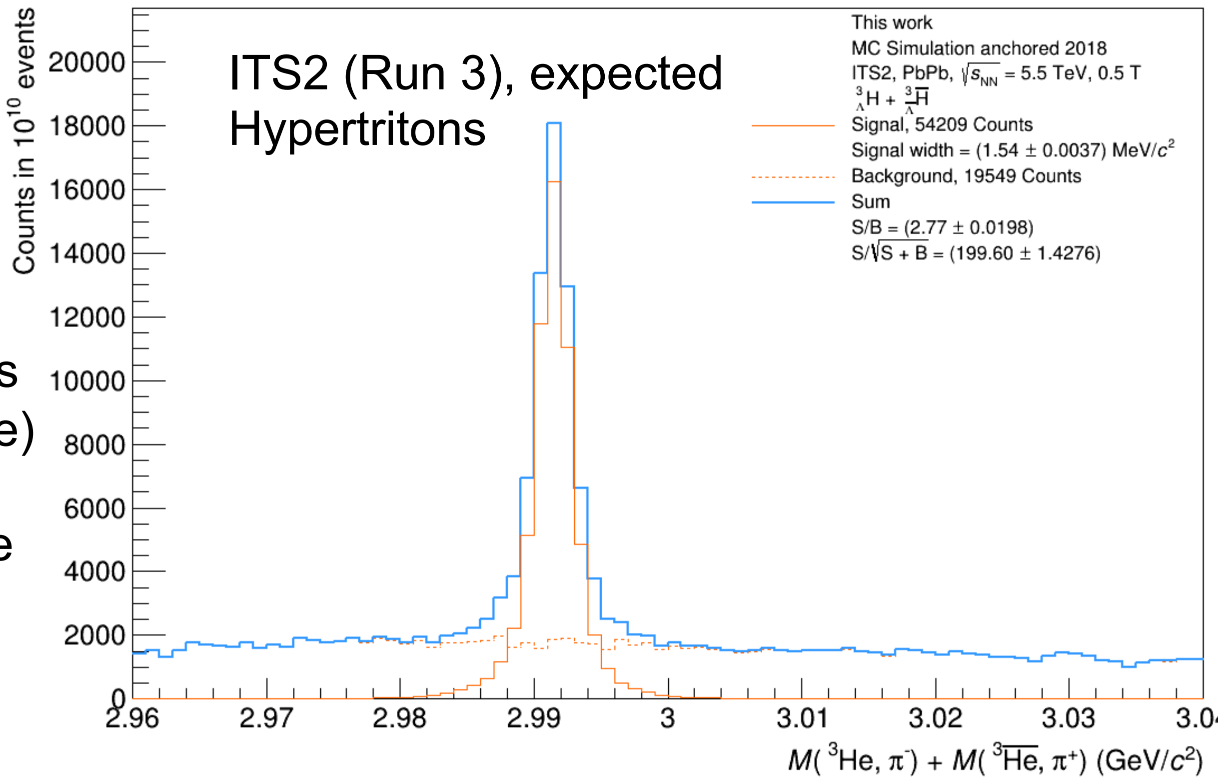
- Current studies show a better constraint and smaller statistical uncertainties
- The value obtained by this fit is $B_\Lambda = (102 \pm 63 \pm 67)$ keV
- Is compatible with the theoretical predictions



ALICE Collaboration, Phys. Rev. Lett. 131 (2023) 102302

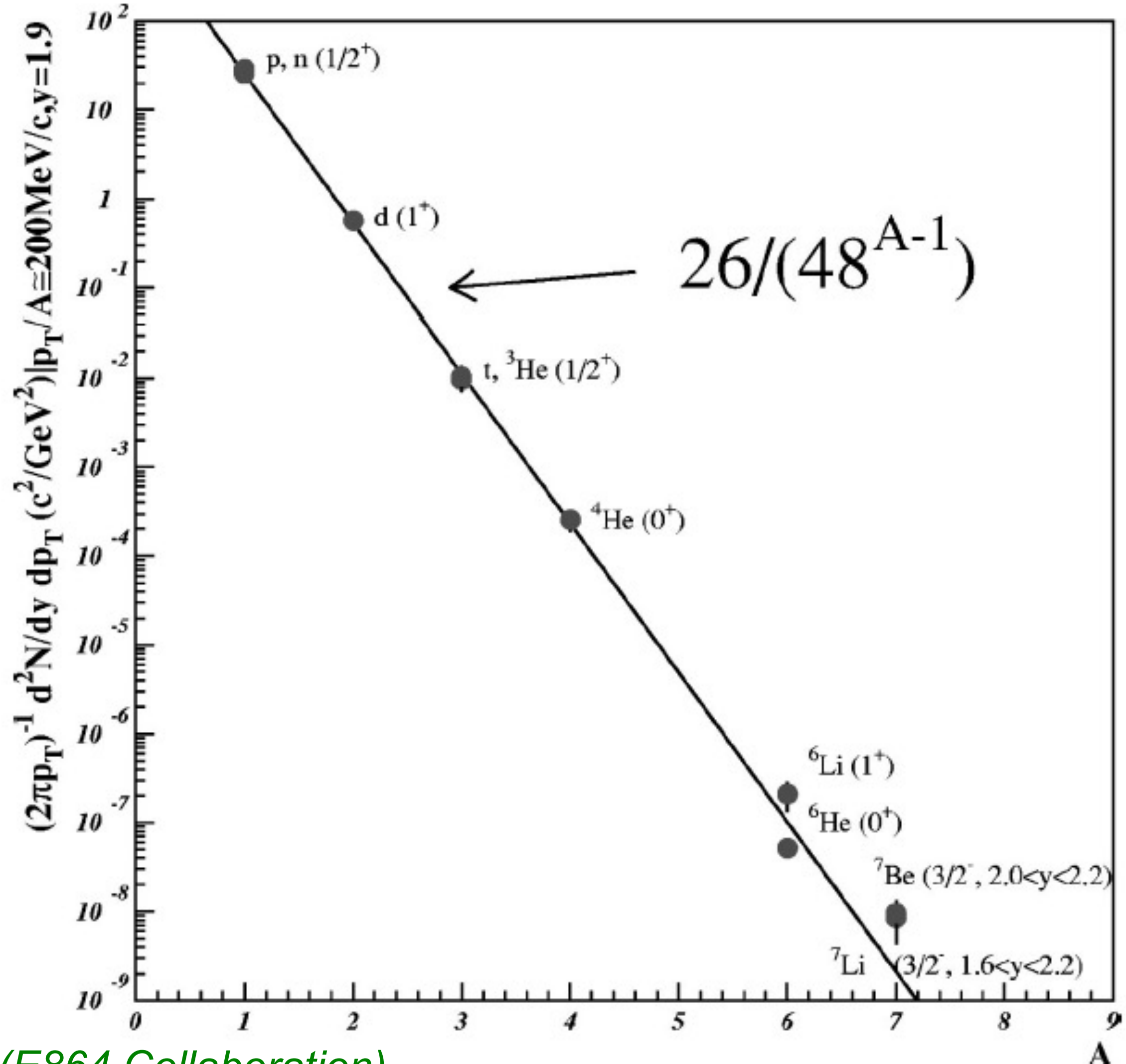
Expectations

- Run 2 of the LHC has started in 2015 and for Pb-Pb collisions ~ factor 10 increase expected in statistics
- Run 3 & Run 4 of LHC will deliver much more statistics (50 kHz Pb-Pb collision rate)
- Upgraded ALICE detector will be able to cope with the high luminosity
- TPC Upgrade: GEMs for continous readout



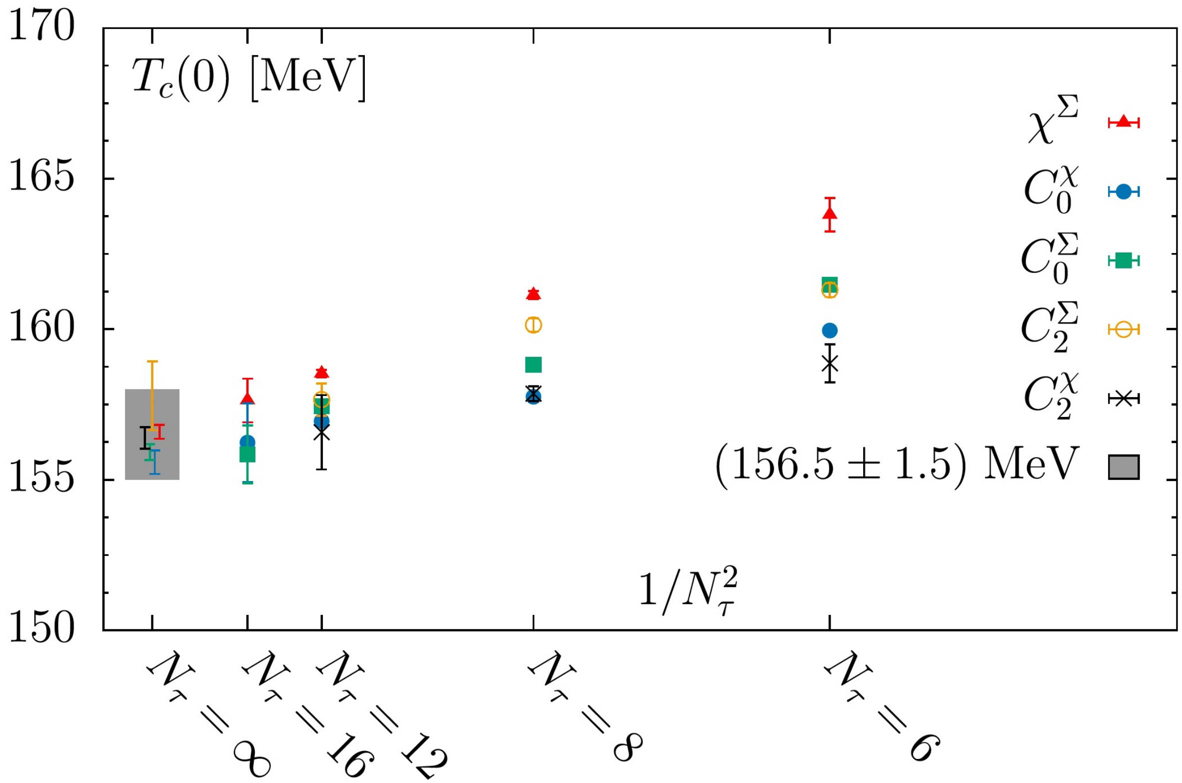
- ITS Upgrade: less material budget and more precise tracking for the identification of hyper-nuclei
- Physics which is now done for A = 2 and A = 3 (hyper-)nuclei will be done for A = 4

E864 nuclei result



T.A. Armstrong et al. (E864 Collaboration), Phys. Rev. C 61 (2000) 064908

Lattice QCD results



Lattice QCD tells us where to expect the phase transition

Critical energy density:
ε_C = 0.34 ± 0.16 GeV/fm^3

Critical temperature
T_C = (156.5 ± 1.5) MeV

A. Bazavov et al. (hotQCD) PLB 795 (2019) 15
Similar results: S. Borsányi et al. (Budapest-Wuppertal group) PRL 125 (2020) 052001

Hypertriton/Λ ratio

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