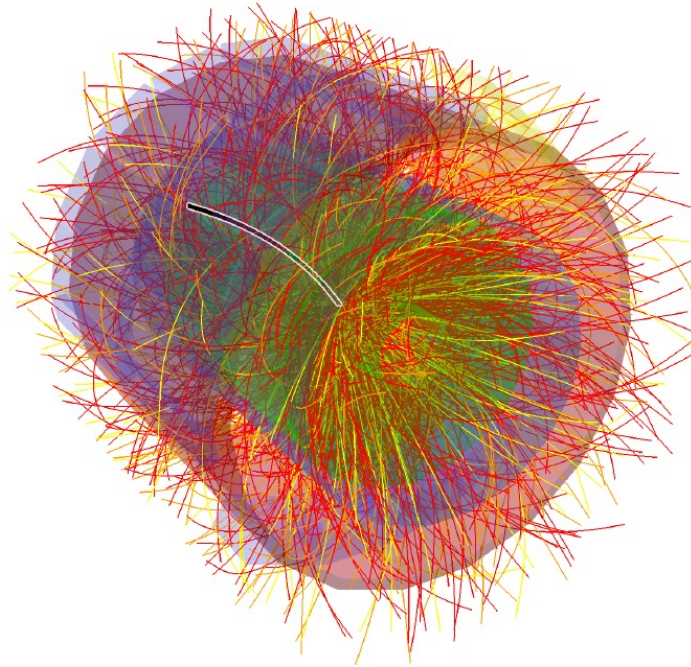


Production of loosely-bound objects in heavy-ion collisions at the LHC



September 7, 2026

**Georg-Christoph-Lichtenberg-Haus
Unlocking the QCD phase diagram**

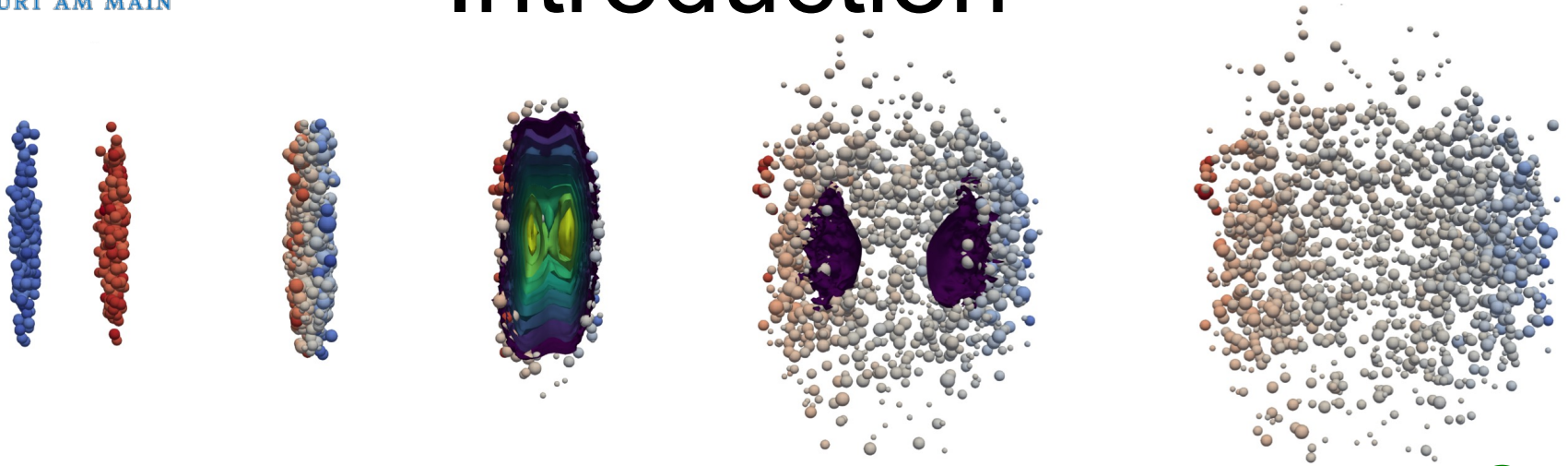
Benjamin Dönigus

**Institut für Kernphysik
Goethe Universität Frankfurt**

Content

- Introduction
- Nuclei
- Hypernuclei
- Summary & Outlook

Introduction

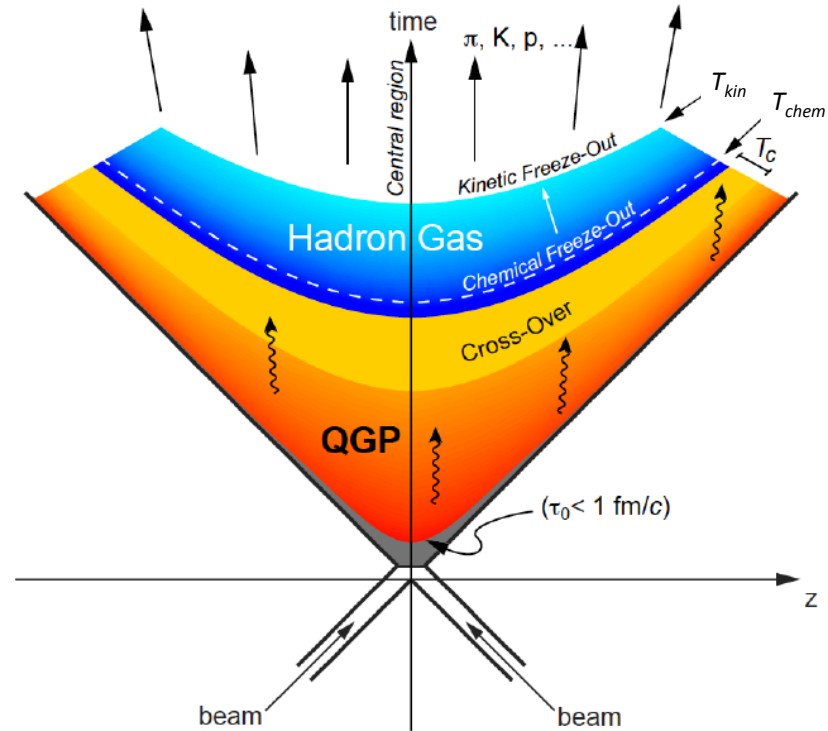


Cartoon of a Ultra-relativistic heavy-ion collision

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

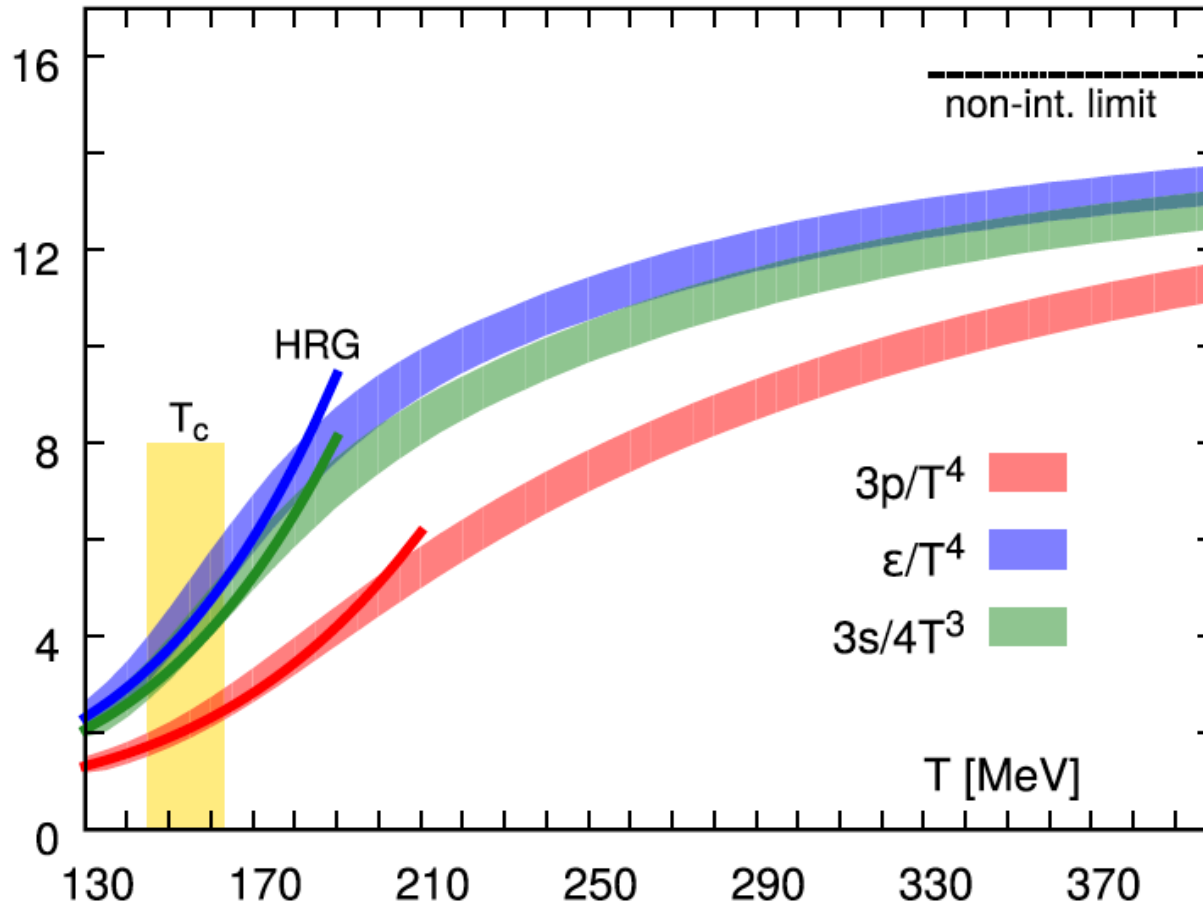
Introduction



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



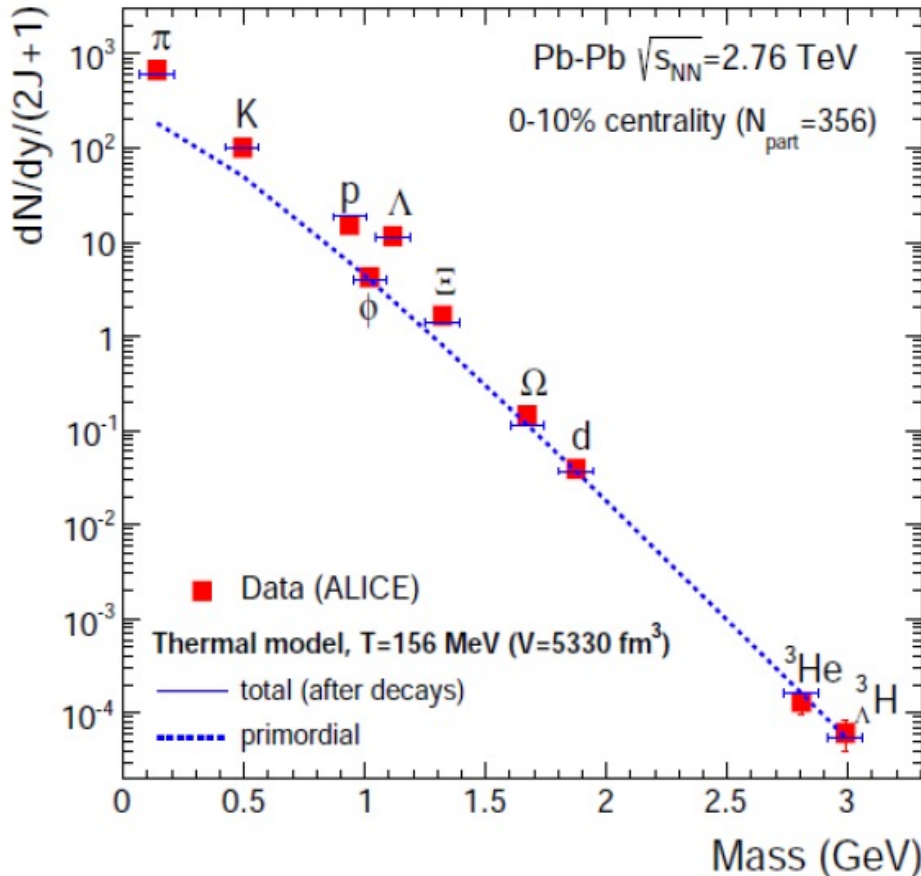
Lattice QCD
tells us where
to expect the
phase
transition

Critical energy density:
 $\epsilon_c = 0.34 \pm 0.16 \text{ GeV/fm}^3$

Critical temperature
 $T_c = (157 \pm 2) \text{ MeV}$

*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



Analogy:

Light source $\rightarrow$ particle source

- Multiplicity described best with
 $T = 1\,900\,000\,000\,000\,^{\circ}\text{C}$
(1,9 trillion degree centigrade)

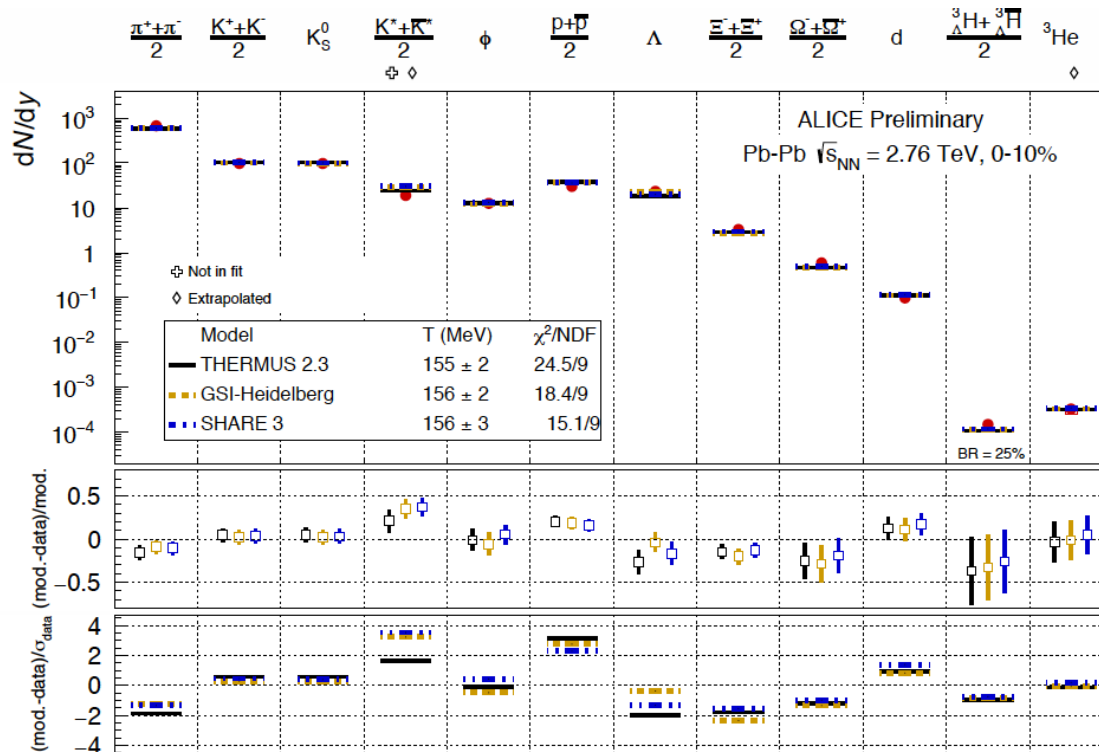
$\rightarrow$ 100 000 times hotter than in the interior of the sun!

1/40 eV = 20 $^{\circ}\text{C}$

Plot by A. Andronic, GSI-Heidelberg group
[arXiv:1407.5003 \[nucl-ex\]](https://arxiv.org/abs/1407.5003)

Thermal model

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

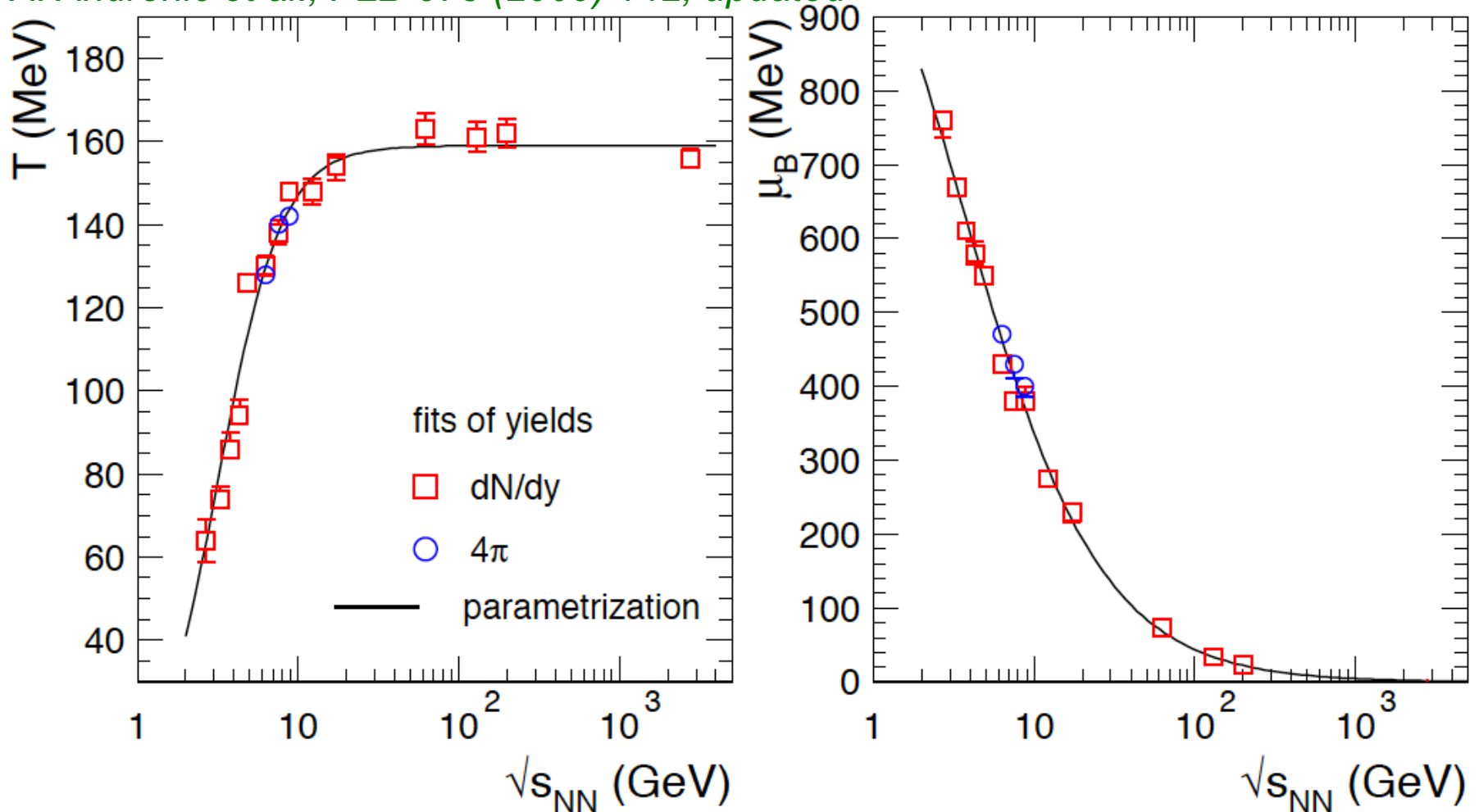


- chemical freeze-out temperature T_{ch}
- baryo-chemical potential μ_B
- Volume V

→ Using particle yields as input to extract parameters

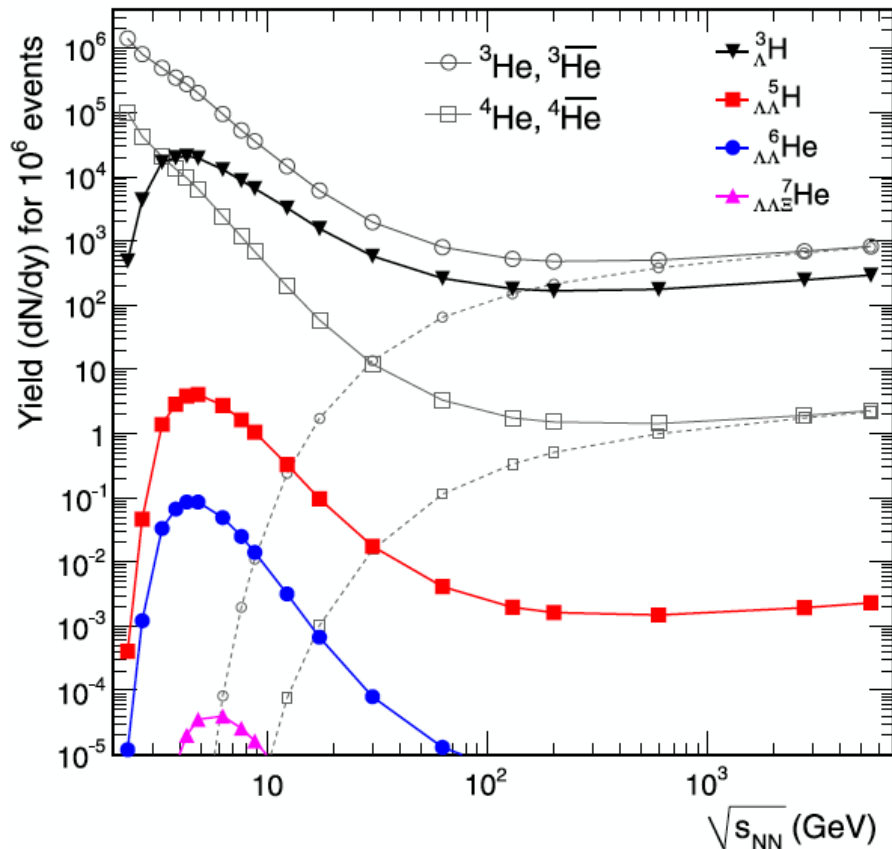
Energy dependence

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



Thermal model fits show limiting temperature: $T_{lim} = (159 \pm 2) \text{ MeV}$

Predicting yields of bound states



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

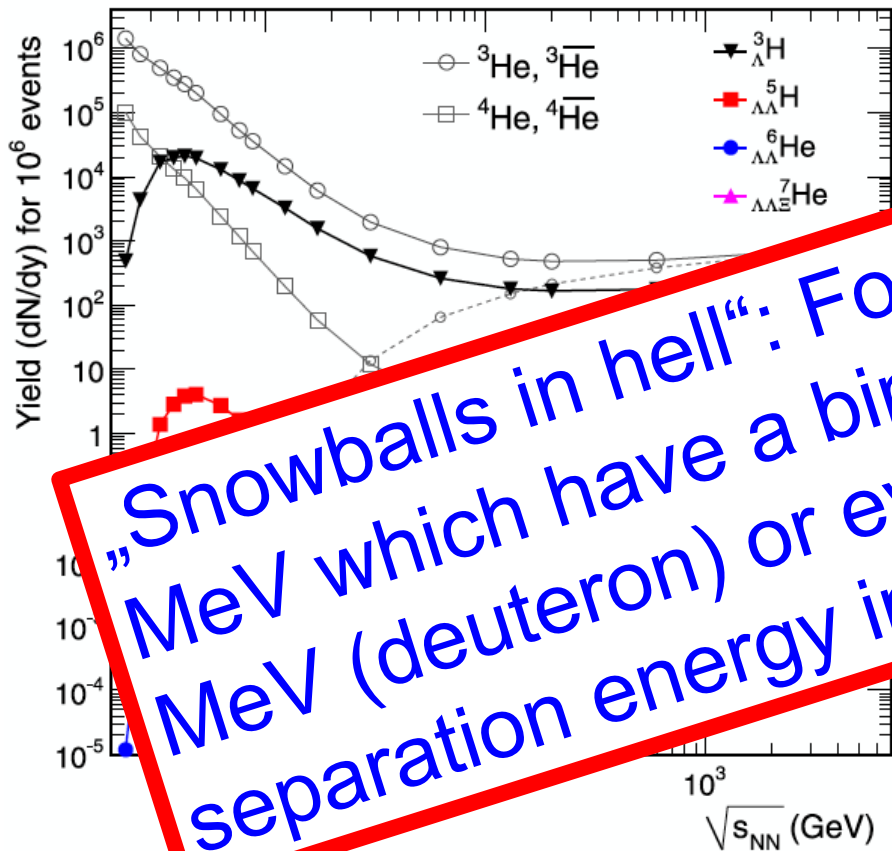
Key parameter at LHC energies:

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 $\sim \exp(-m/T_{\text{ch}})$
- Binding energies small compared to T_{ch}

Predicting yields of bound states



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

Key parameter at high energies

of T_{ch} due to:

1. large mass m
 2. exponential dependence of the yield $\sim \exp(-m/T_{ch})$
- Binding energies small compared to T_{ch}

Snowballs in hell

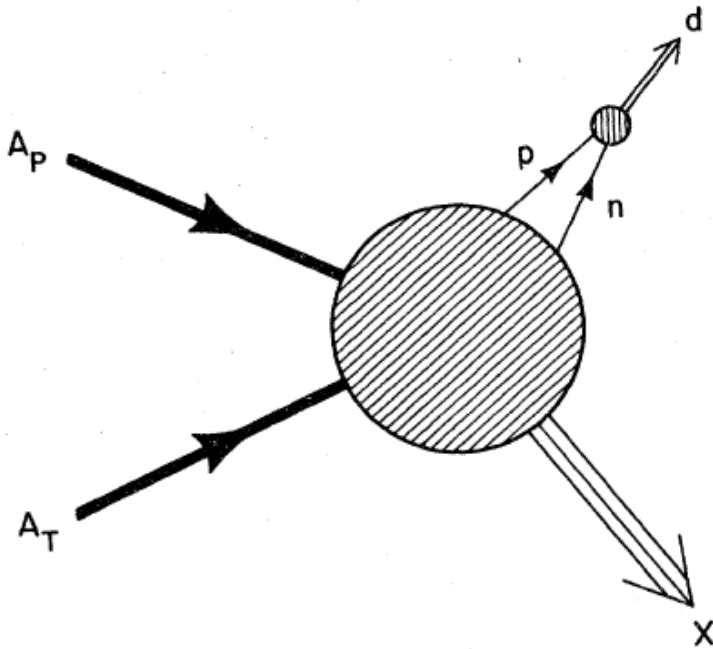
Recipe for a Hot Universe 93

- 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 3.3×10^{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.

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

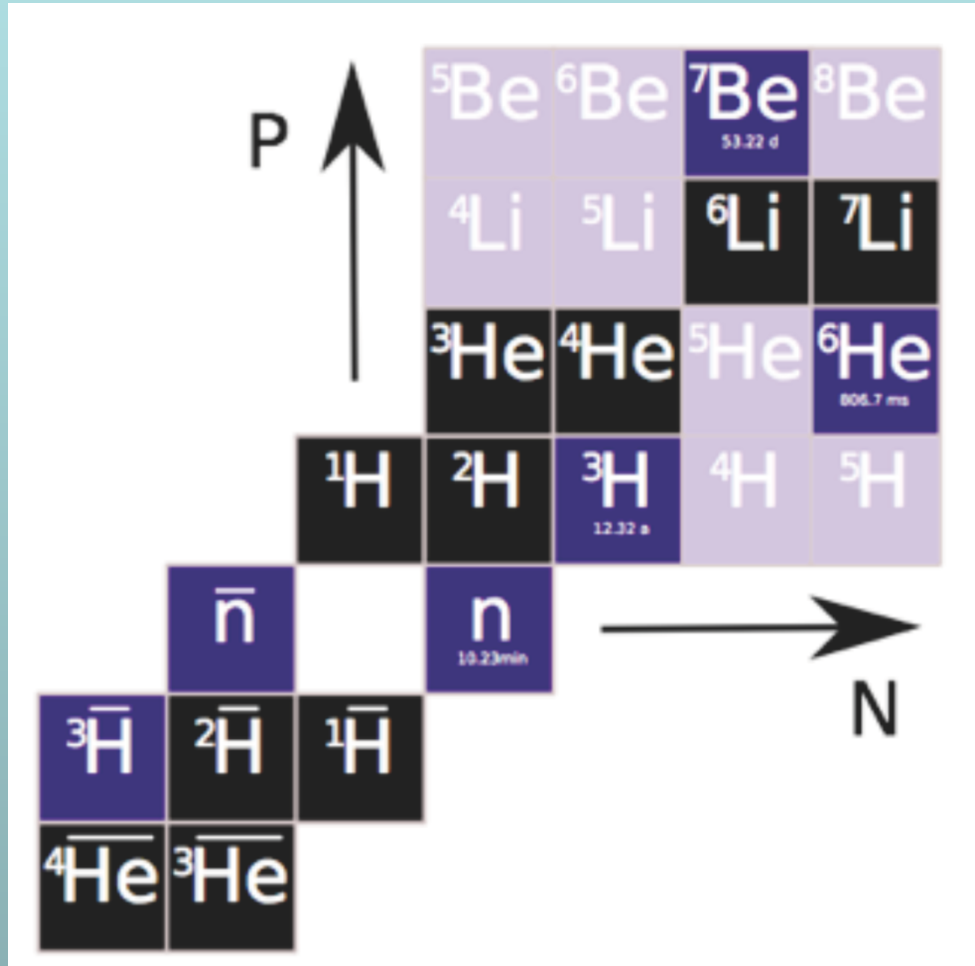
AGS predictions

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

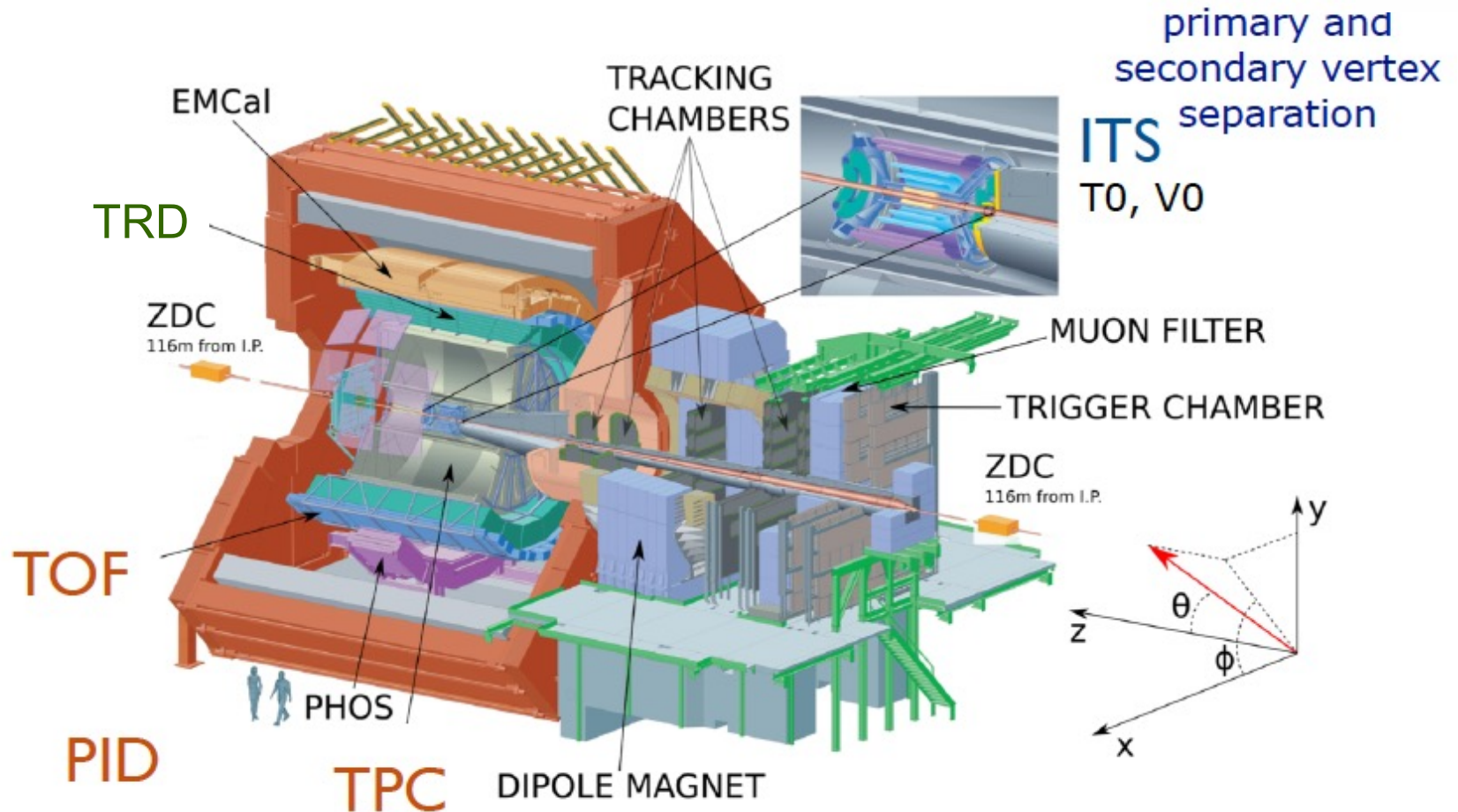
- Already at AGS the predictions from thermal model and coalescence were very close
- Looking at production yields alone might not be enough to disentangle models

Particles	Thermal model		Coalescence model
	$T = 0.120 \text{ GeV}$	$T = 0.140 \text{ GeV}$	
d	15	19	11.7
t+ ³ He	1.5	3.0	0.8
α	0.02	0.067	0.018
H ₀₁	0.09	0.15	0.07
${}^5_{\Lambda\Lambda}\text{H}$	3.5×10^{-5}	2.3×10^{-4}	4×10^{-4}
${}^6_{\Lambda\Lambda}\text{He}$	7.2×10^{-7}	7.6×10^{-6}	1.6×10^{-5}
${}^7_{\Xi^0\Lambda\Lambda}\text{He}$	4.0×10^{-10}	9.6×10^{-9}	4×10^{-8}
${}^{10}\text{St}^{-8}$	1.6×10^{-14}	7.3×10^{-13}	
${}^{12}\text{St}^{-9}$	1.6×10^{-17}	1.7×10^{-15}	
${}^{14}\text{St}^{-11}$	6.2×10^{-21}	1.4×10^{-18}	
${}^{16}_2\text{St}^{-13}$	2.4×10^{-24}	1.2×10^{-21}	
${}^{20}_2\text{St}^{-16}$	9.6×10^{-31}	2.3×10^{-27}	

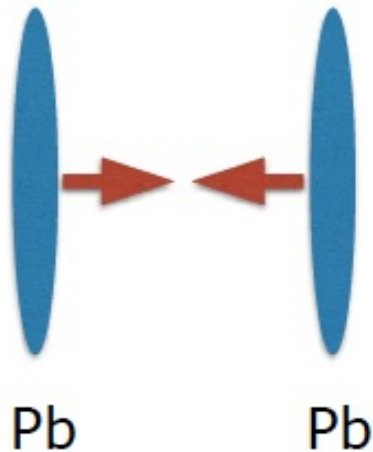
(Anti-)Nuclei



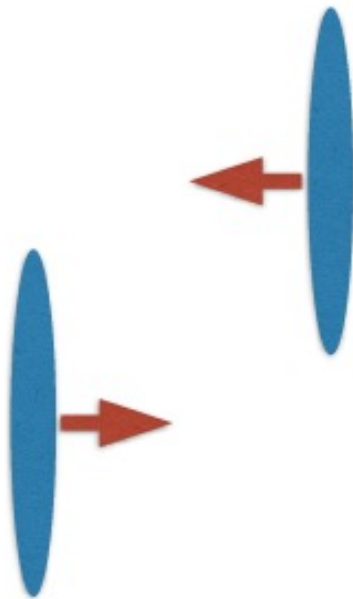
Experiment: ALICE



Interlude: Centrality

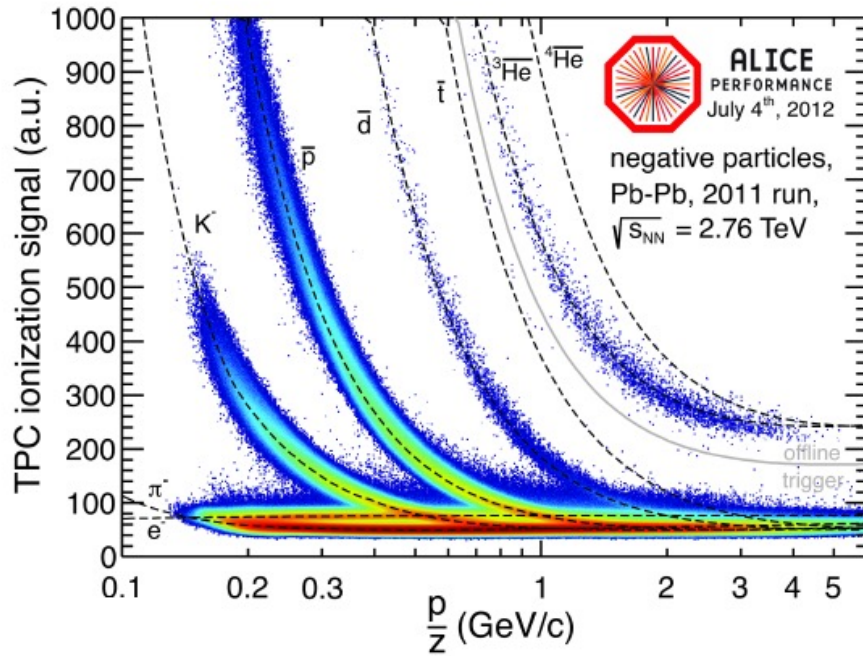


Central Pb-Pb collision:
High multiplicity = large $dN/d\eta$
High number of tracks
(more than 2000 tracks in the detector)



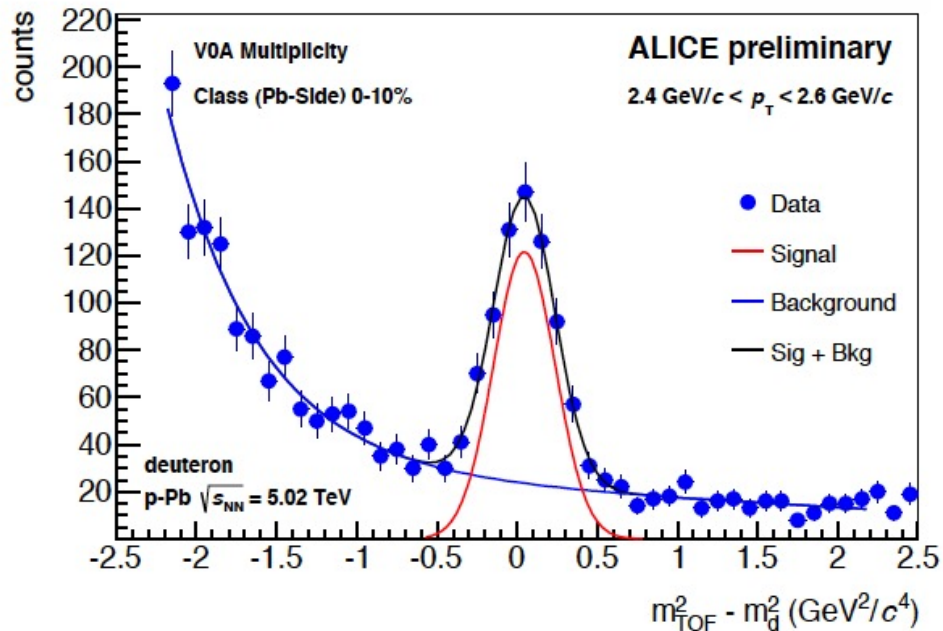
Peripheral Pb-Pb collision:
Low multiplicity = small $dN/d\eta$
Low number of tracks
(less than 100 tracks in the detector)

Particle Identification



Low momenta:

Nuclei are identified using the dE/dx measurement in the Time Projection Chamber (TPC)



Higher momenta:

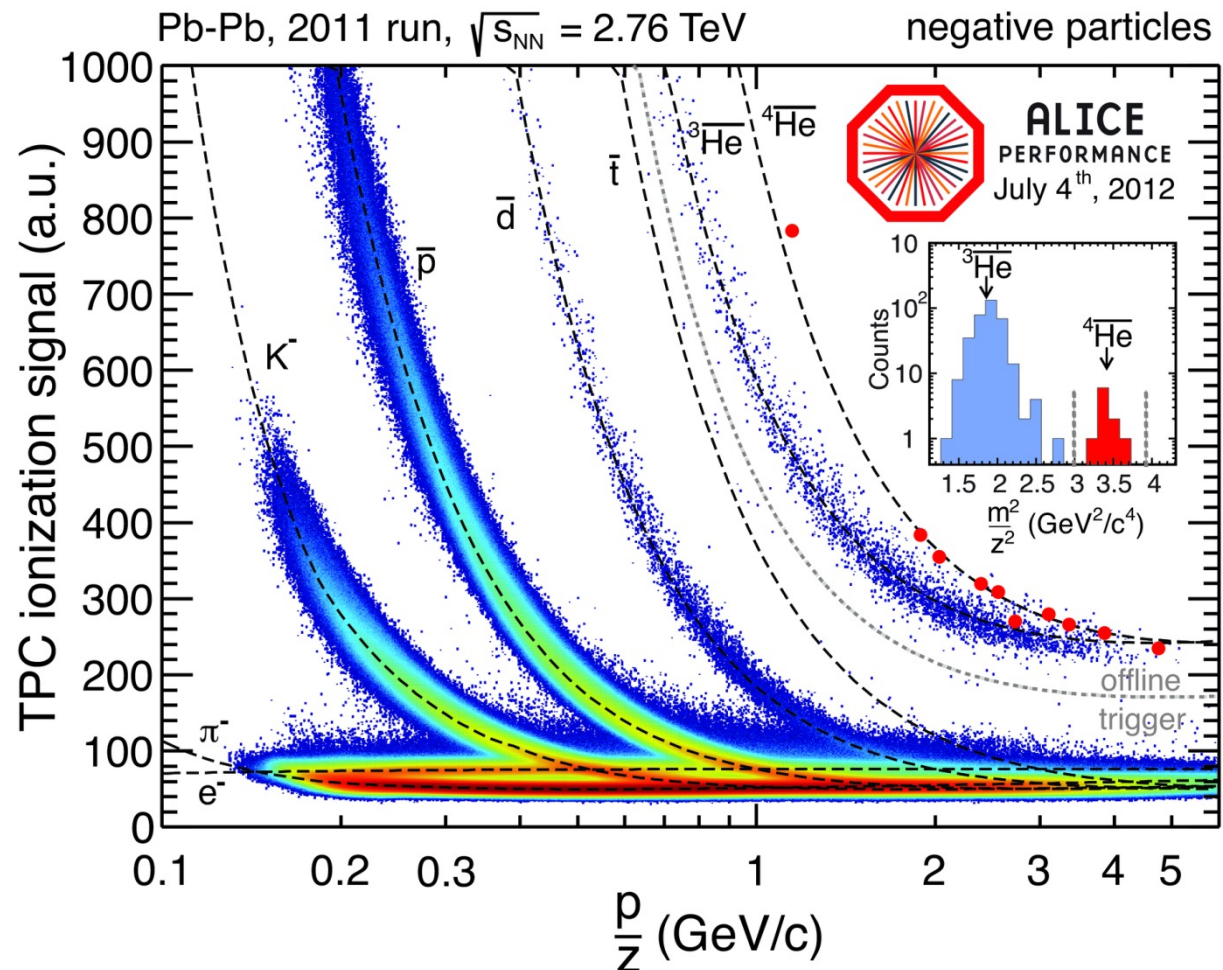
Velocity measurement with the Time-of-Flight (TOF) detector is used to calculate the m^2 distribution

Anti-Alpha

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

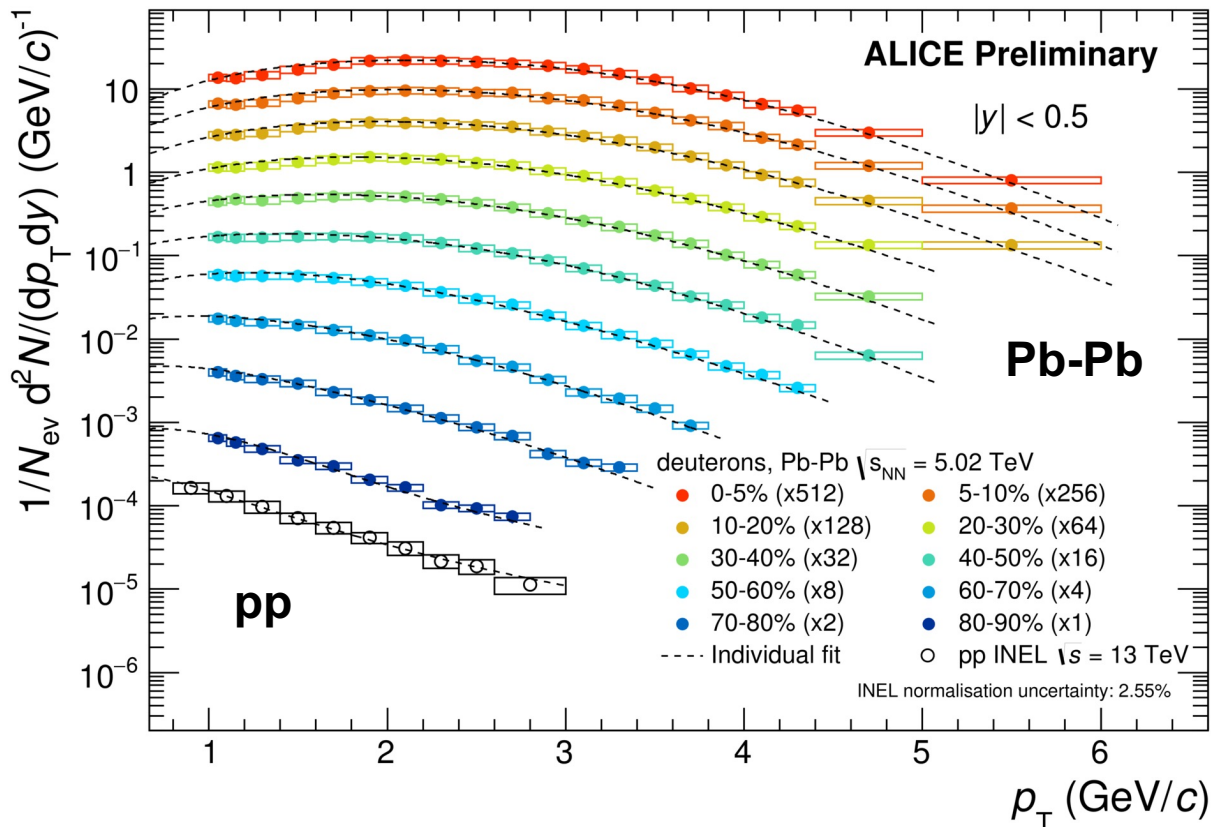
STAR observed the
Anti-Alpha in 2010:

Nature 473, 353 (2011)



Deuterons

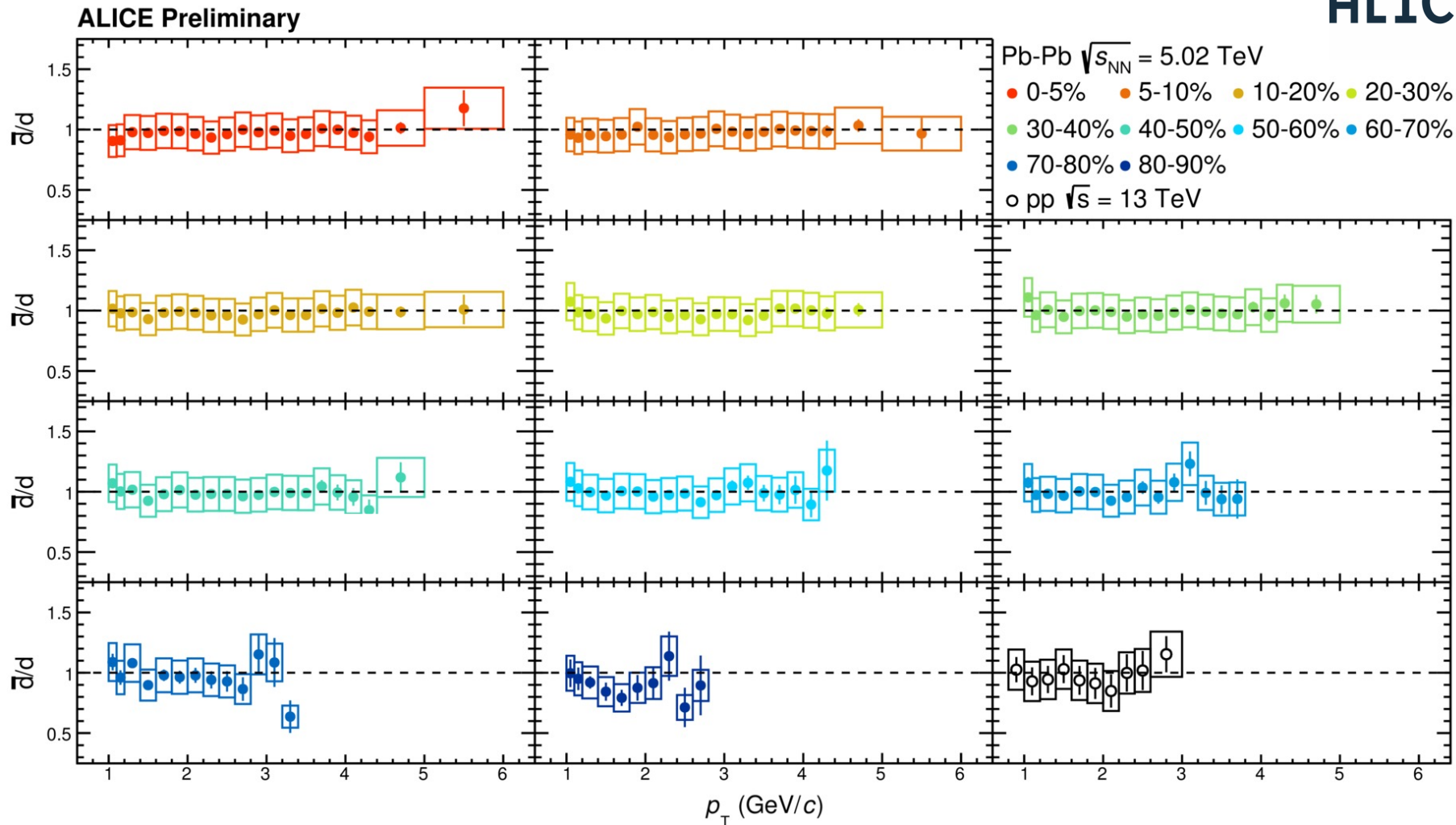
ALICE-PUBLIC-2017-006



See also ALICE Collaboration,
Phys.Rev.C 107 (2023) 064904

- 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

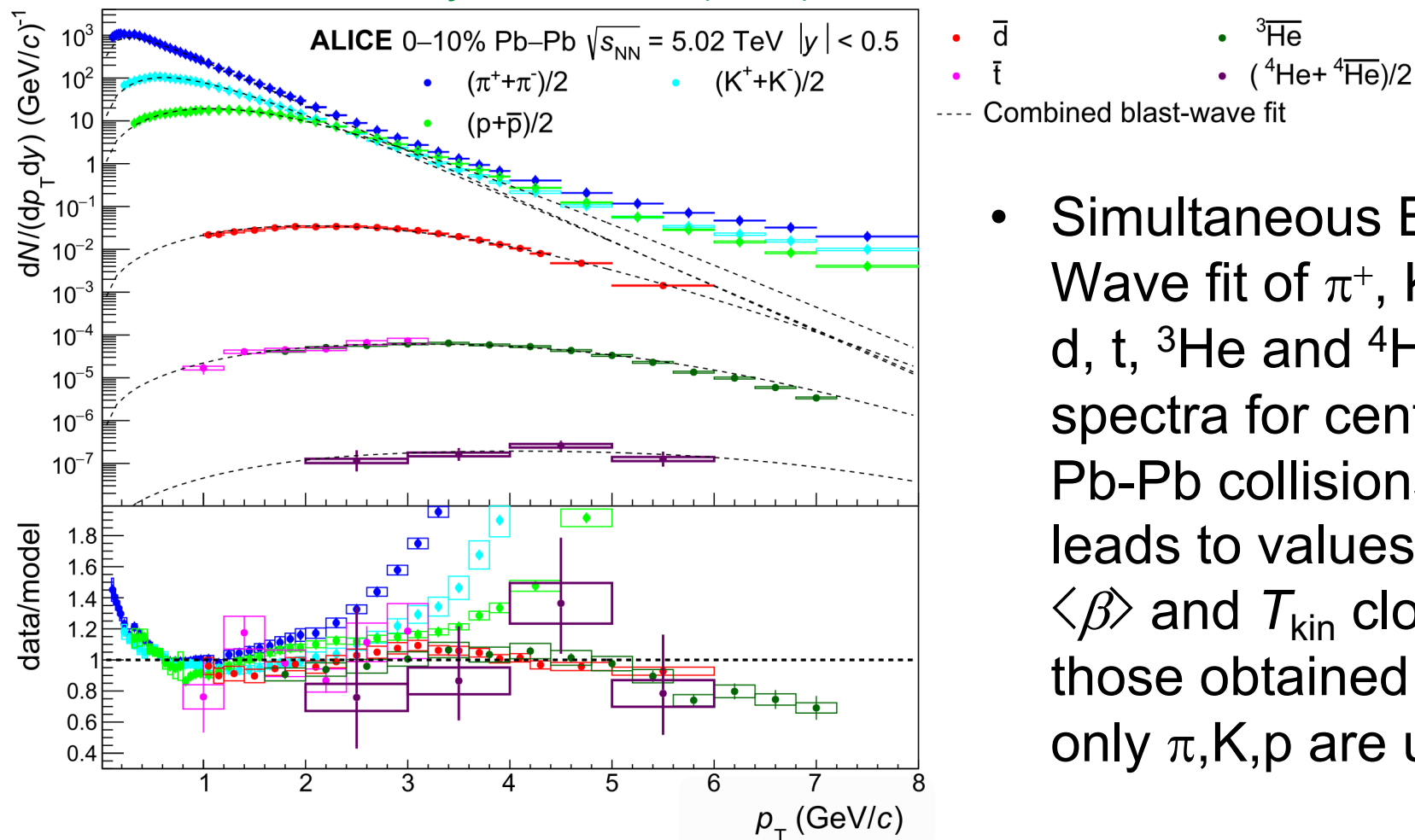
(Anti-)Deuteron ratio



Antideuteron-to-deuteron-ratios consistent with unity, as expected

Combined Blast-Wave fit

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



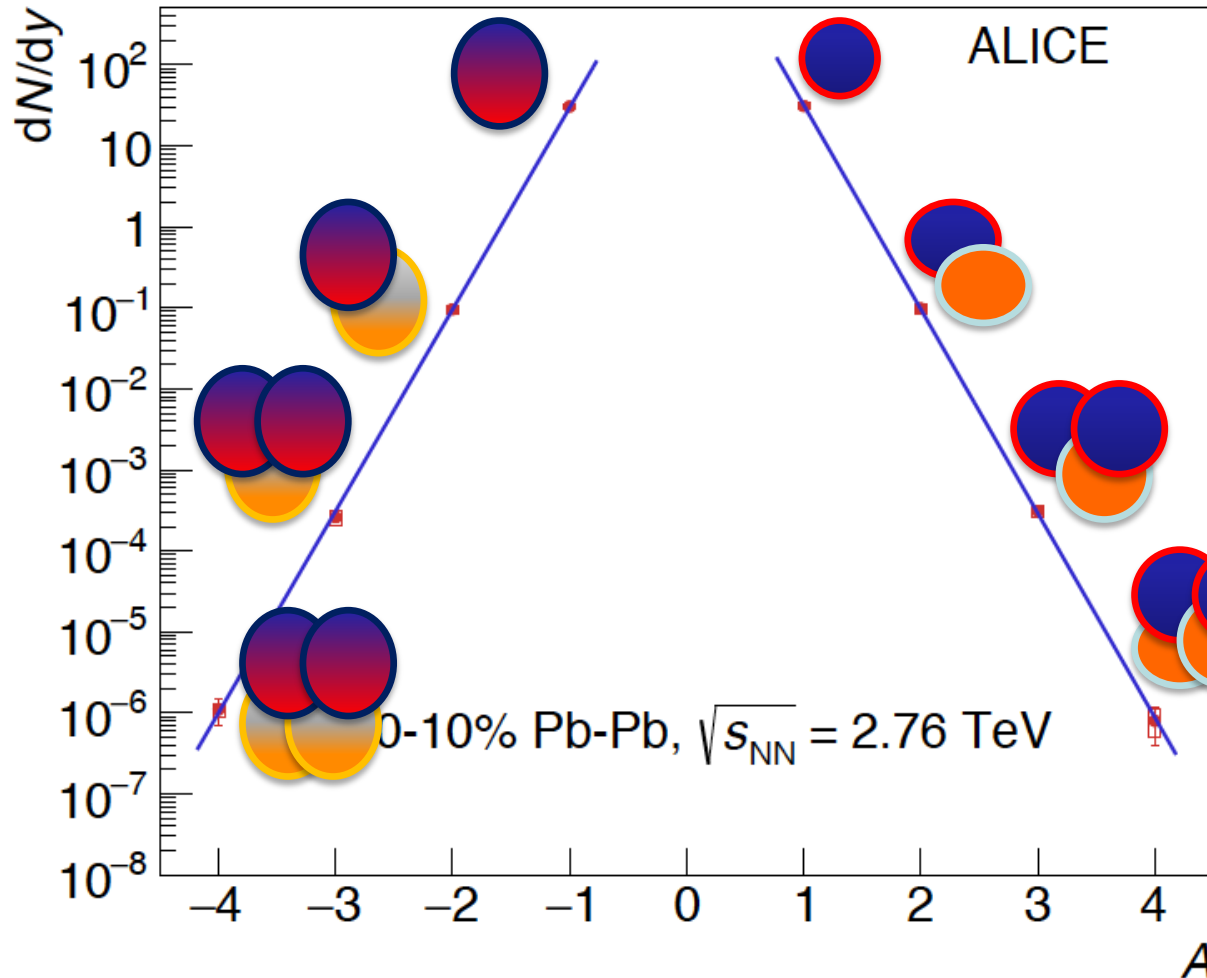
- Simultaneous Blast-Wave fit of π^+ , K^+ , p , d , t , ${}^3\text{He}$ and ${}^4\text{He}$ spectra for central Pb-Pb collisions leads to values for $\langle\beta\rangle$ and T_{kin} close to those obtained when only π, K, p are used

- All particles are described rather well with this simultaneous fit

Mass dependence



ALICE



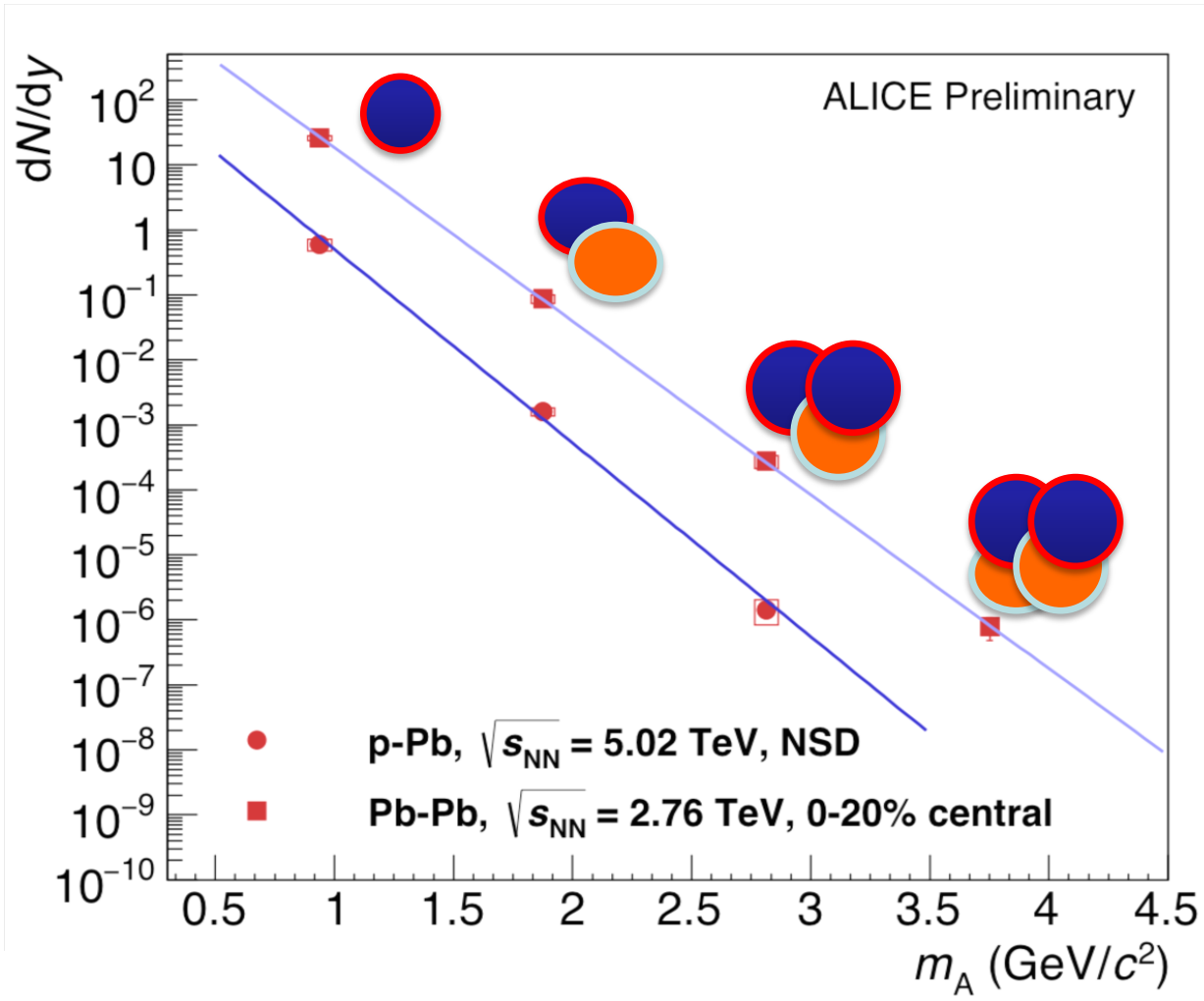
- Production of (anti-) nuclei is following an **exponential**, and decreases with mass as expected from thermal model
- In Pb-Pb the „penalty factor“ for each additional baryon ~ 300 (for particles and anti-particles)

ALICE Collaboration, [arXiv:1710.07531](https://arxiv.org/abs/1710.07531), NPA 971, 1 (2018)

Mass dependence

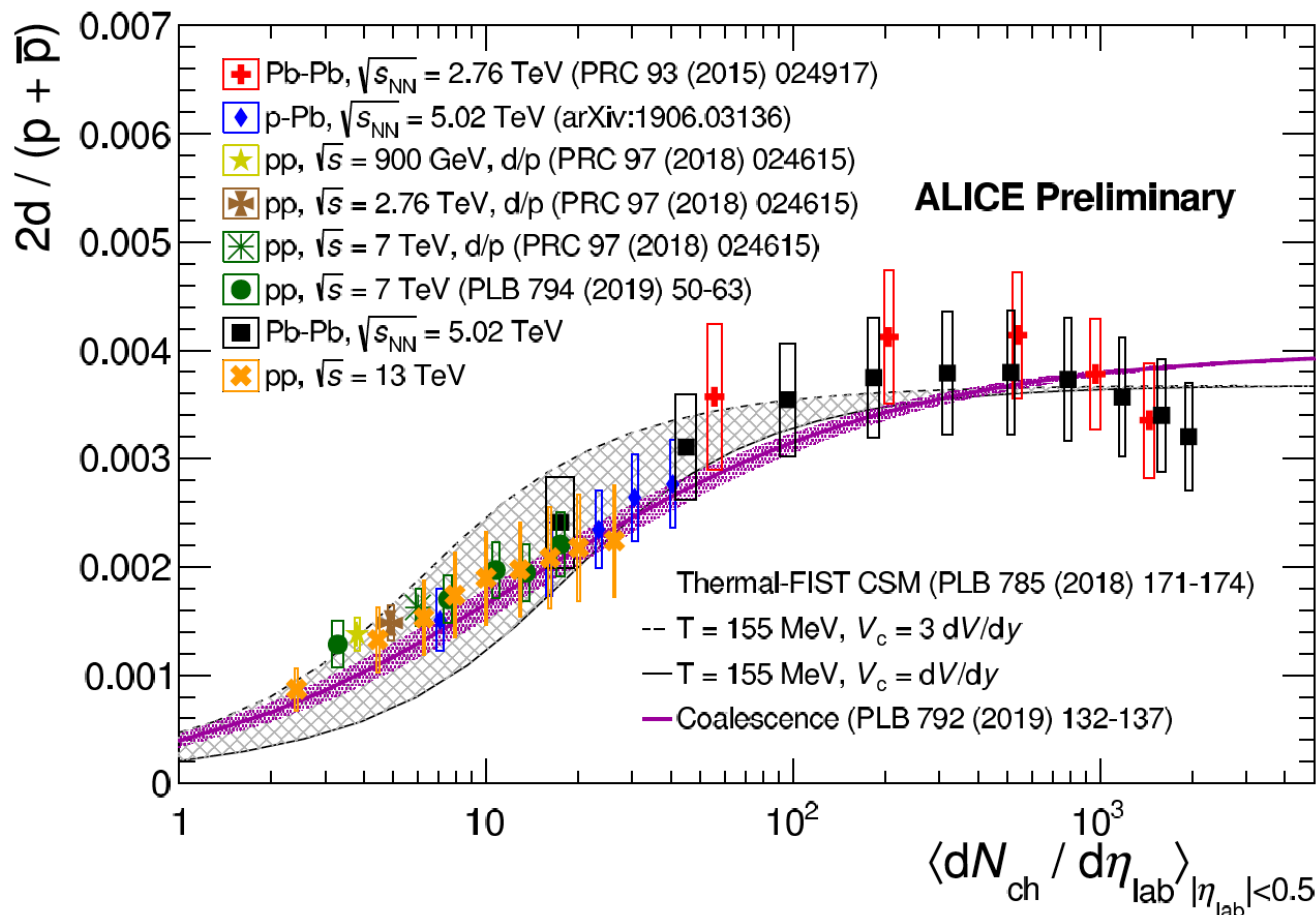


ALICE



- Production of (anti-) nuclei is following 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

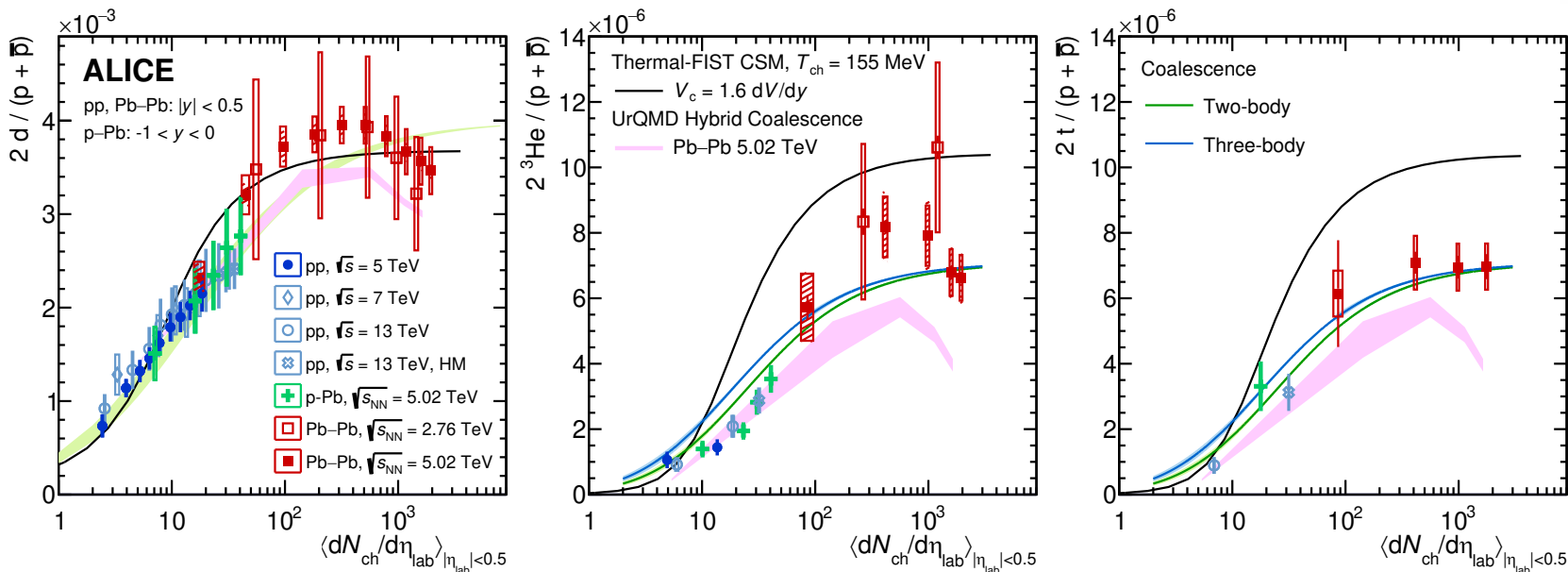
d/p vs. multiplicity



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

Ratios vs. multiplicity

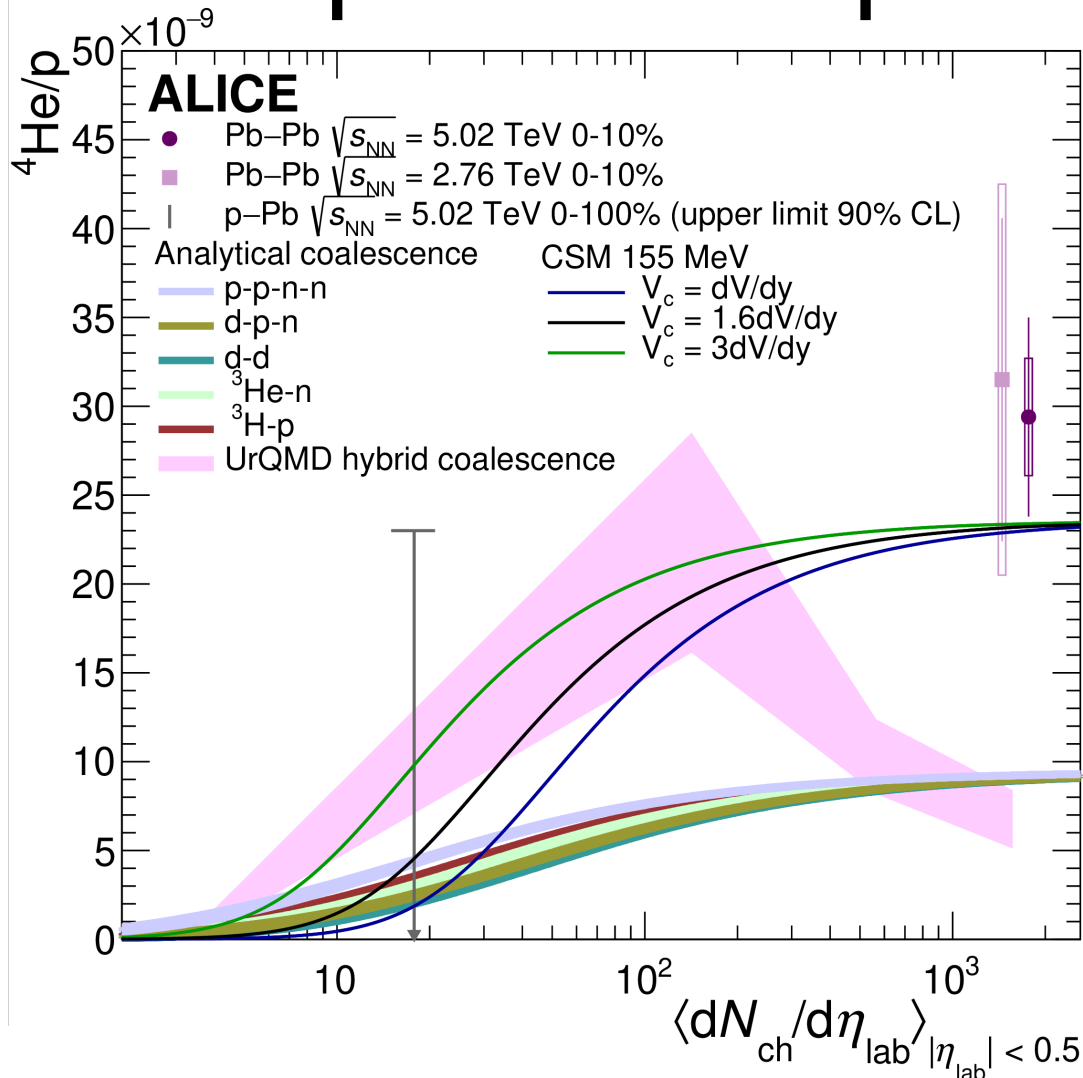
ALICE Collaboration, Phys.Rev.C 107 (2023) 064904



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

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

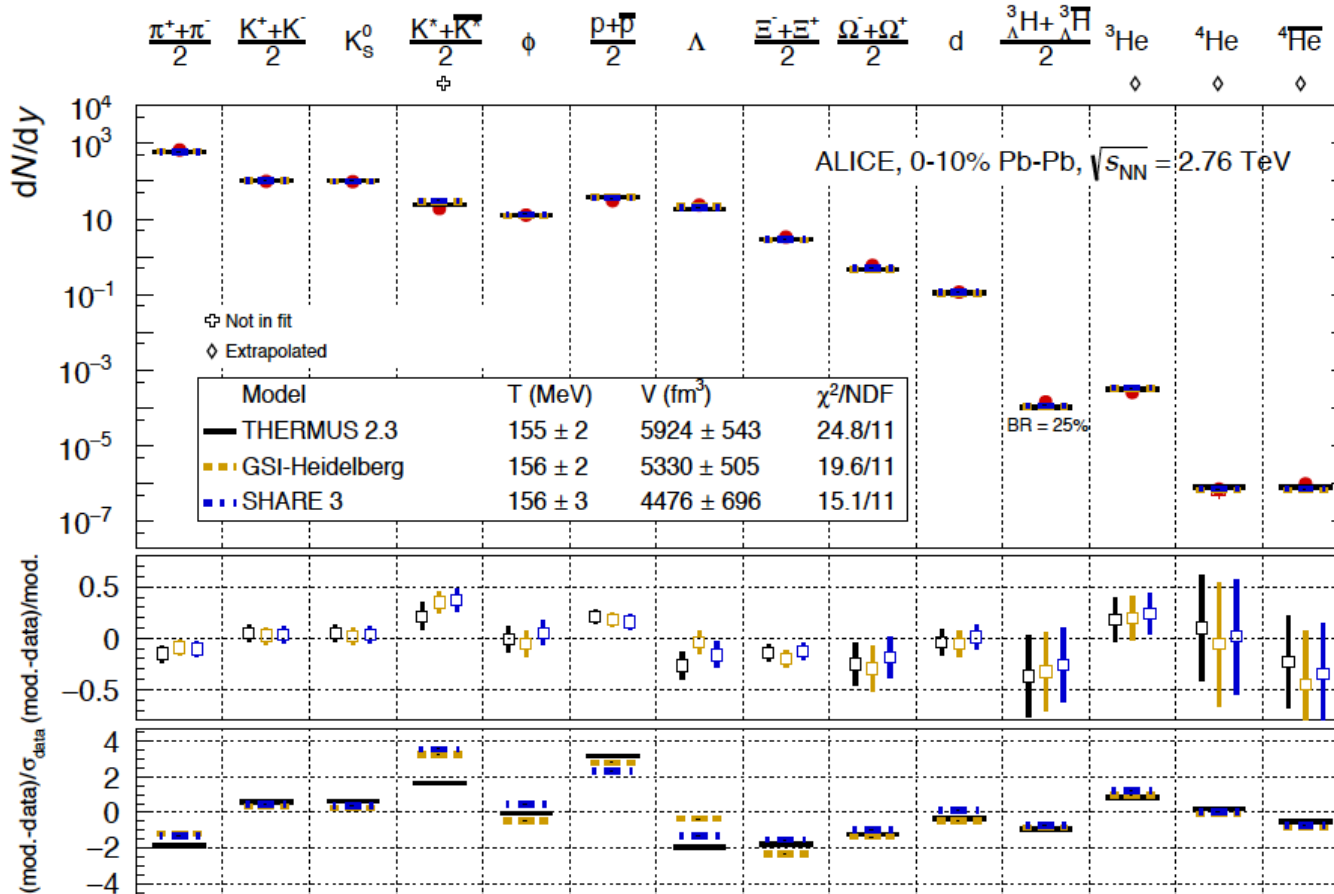
$^4\text{He}/p$ vs. multiplicity



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

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

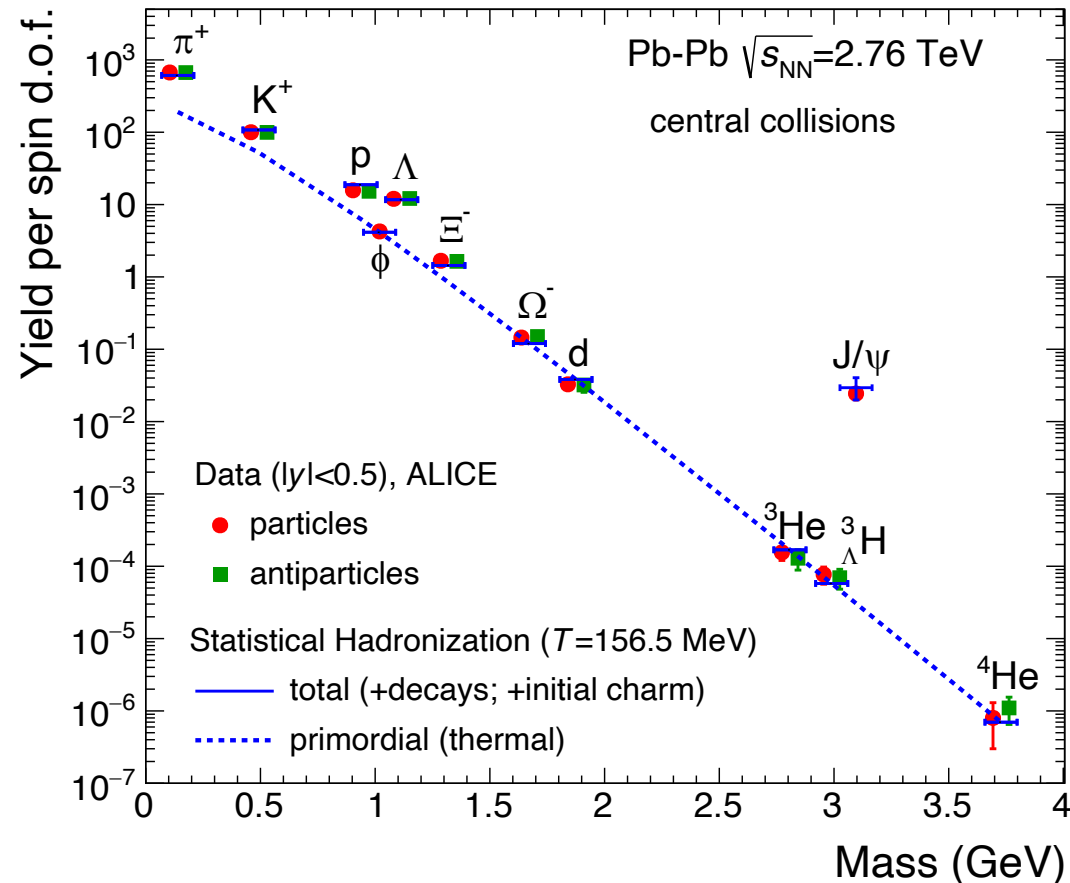
Thermal model



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

Thermal model

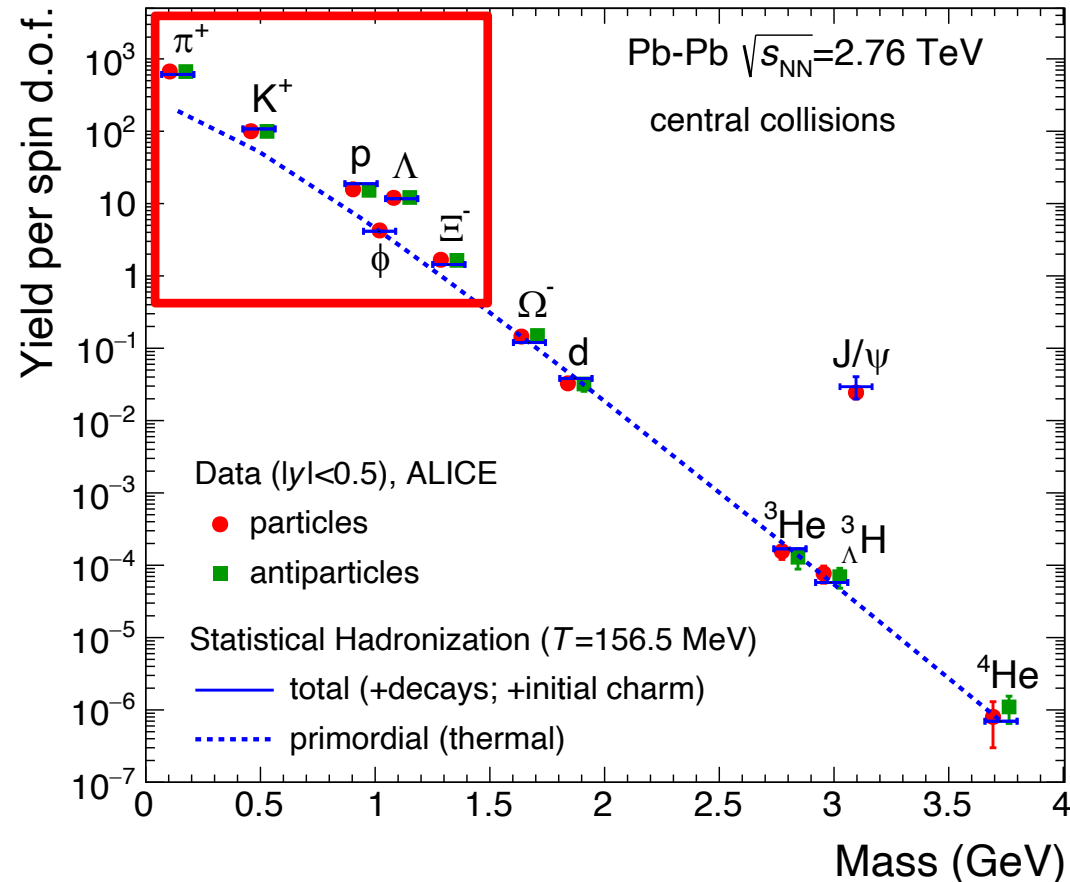
- For the thermal model description of production yields, feed-down is an important ingredient
- All light hadron production yields are populated strongly by resonances
- Seems to not be the case for (hyper-)nuclei



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

Thermal model

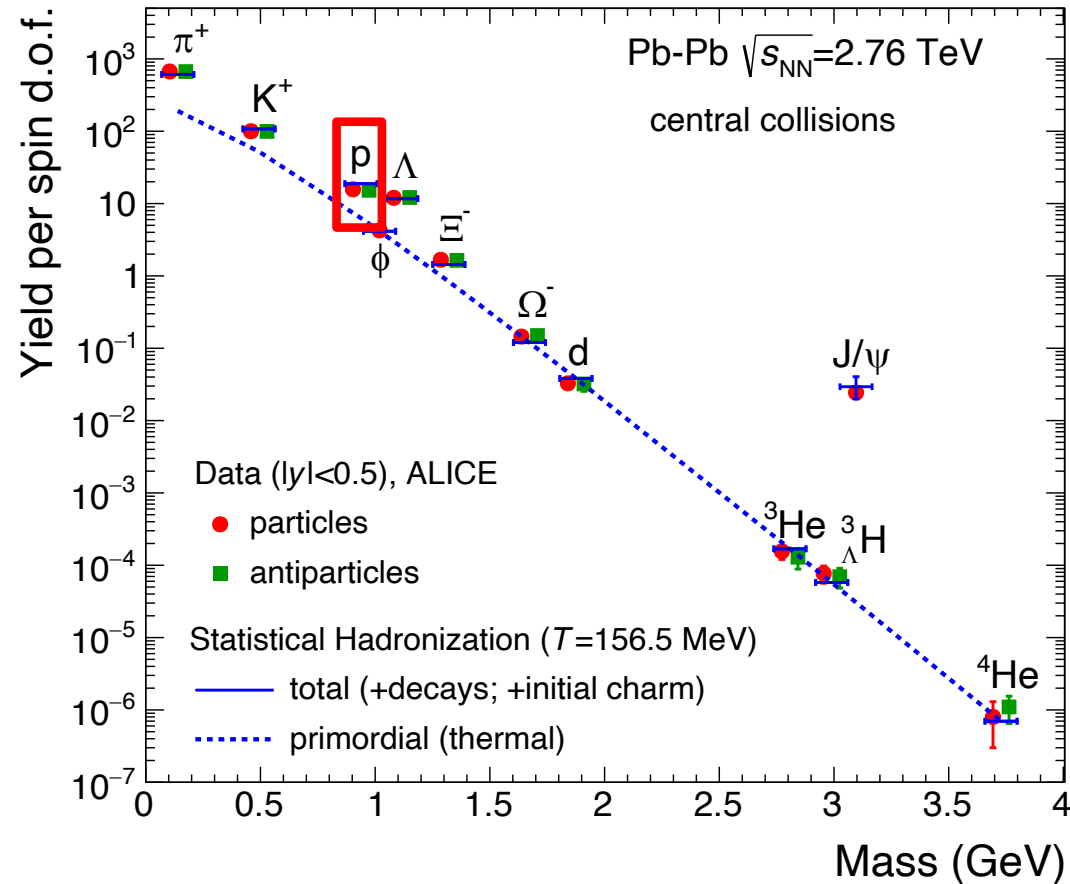
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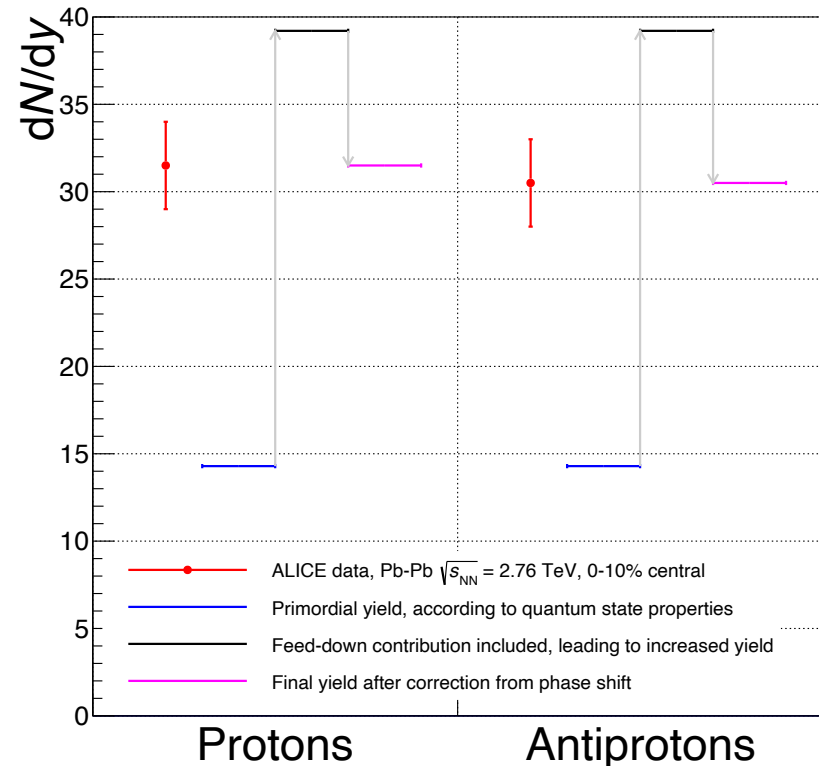


A. Andronic et al., Phys.Lett.B 797 (2019) 134836

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

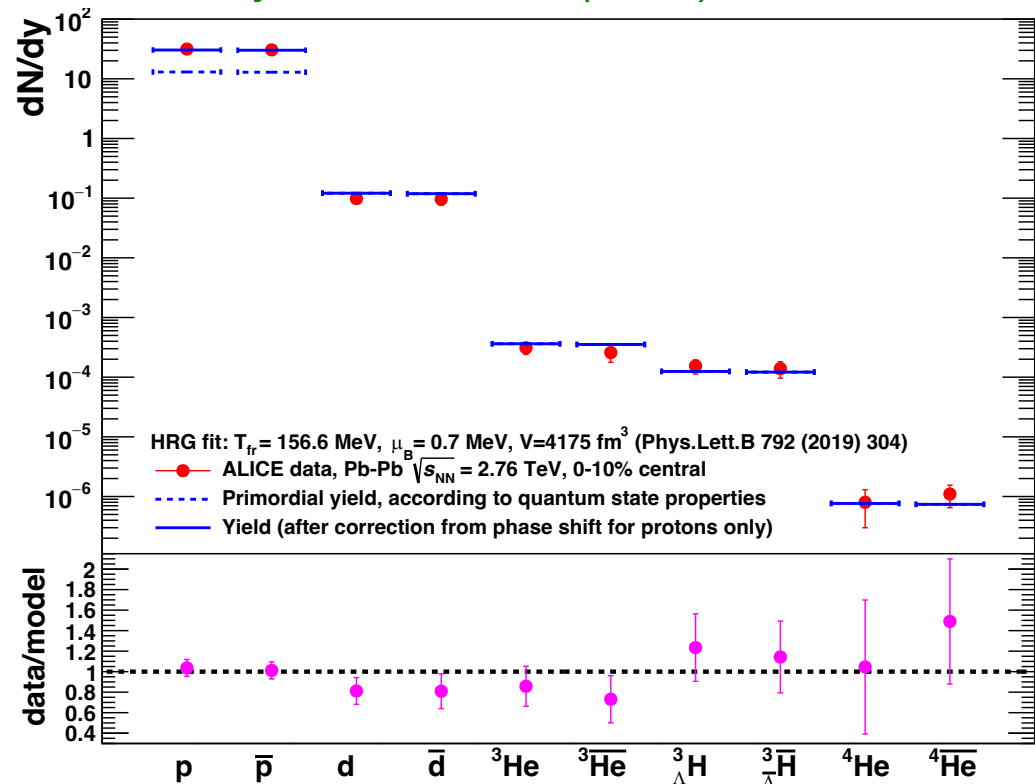


*A. Andronic et al., Phys.Lett.B 797 (2019) 134836;
Nature 561 (2018) 7723, 321; Phys.Lett.B 697 (2011) 203;
Phys.Lett.B 792 (2019) 304*

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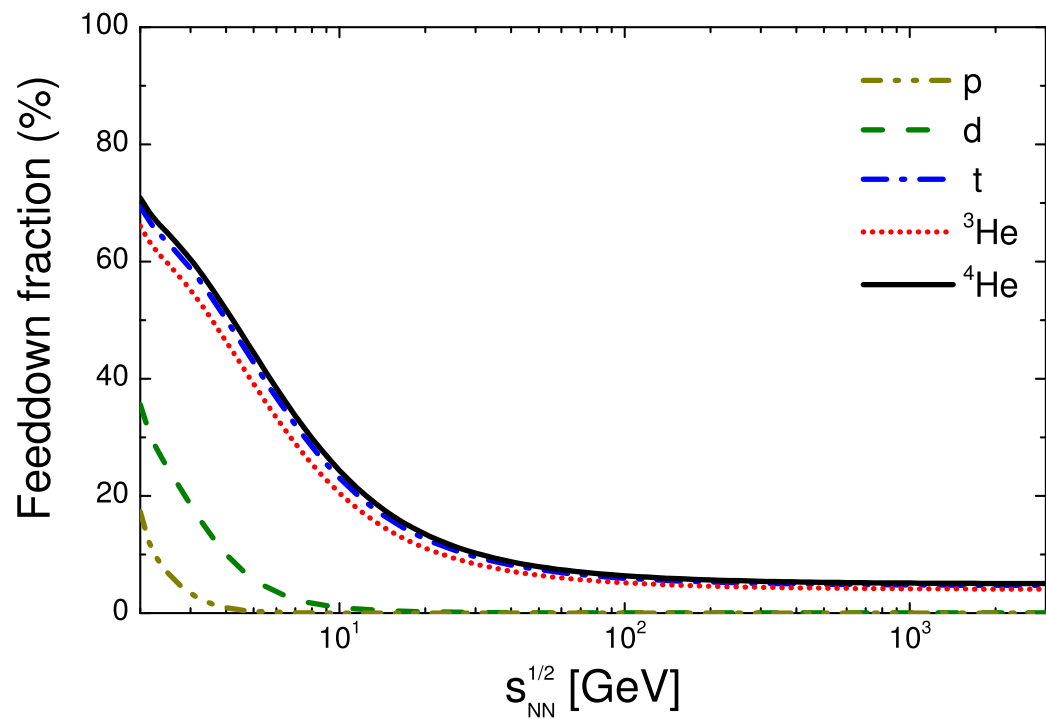


*A. Andronic et al., Phys.Lett.B 797 (2019) 134836;
Nature 561 (2018) 7723, 321; Phys.Lett.B 697 (2011) 203;
Phys.Lett.B 792 (2019) 304*

Thermal model

- 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

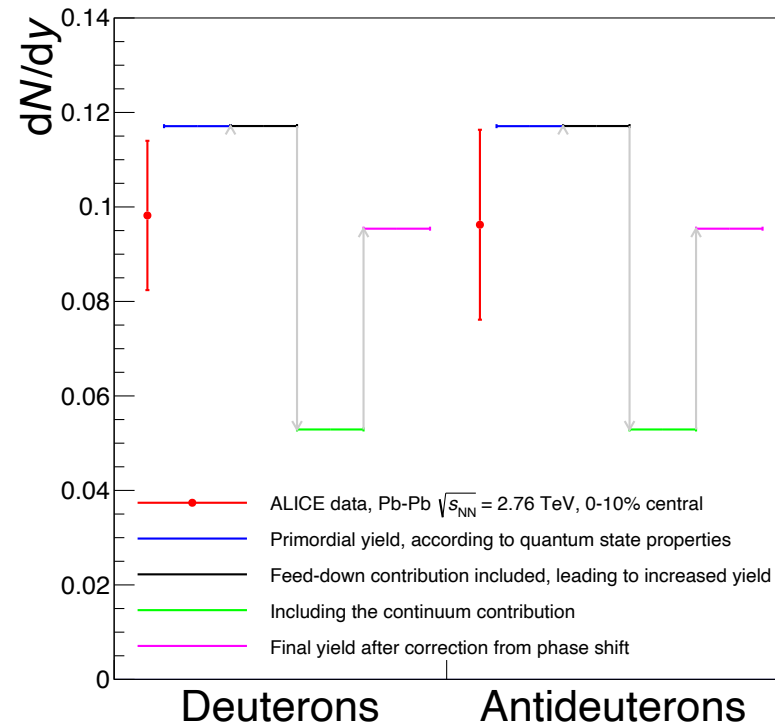
V. Vovchenko, BD, B. Kardan, M. Lorenz, H. Stoecker, Phys.Lett.B 809 (2020) 135746



Thermal model

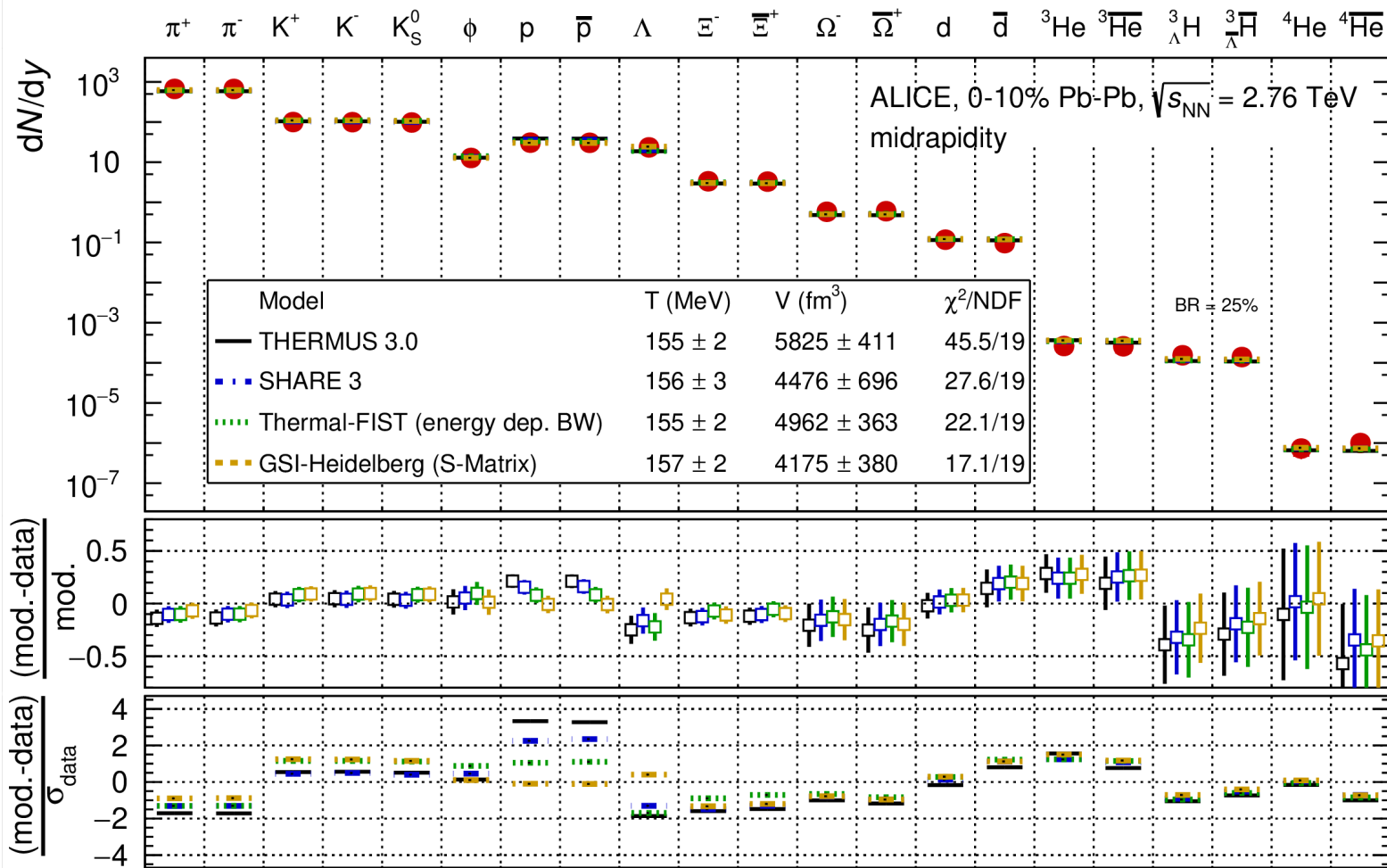
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*A. Andronic et al., Phys.Lett.B 797 (2019) 134836;
Nature 561 (2018) 7723, 321; Phys.Lett.B 697 (2011) 203;
Phys.Lett.B 792 (2019) 304*

Thermal model



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

-connecting
to phase
shifts from
 ρ - π
scattering
data

Energy-dependent Breit-Wigner works similar well

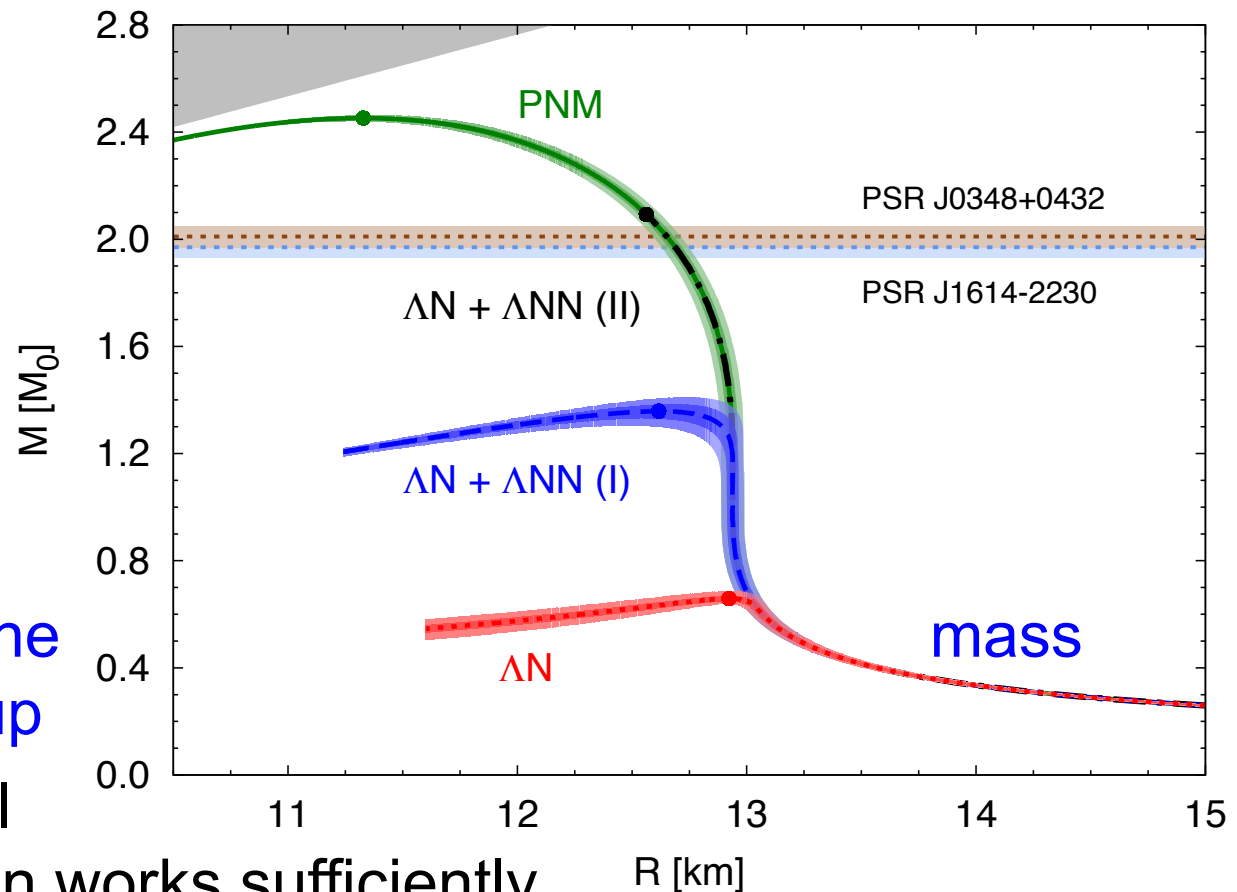
ALICE Collaboration, *Eur.Phys.J.C* 84 (2024) 813



Neutron stars and interactions

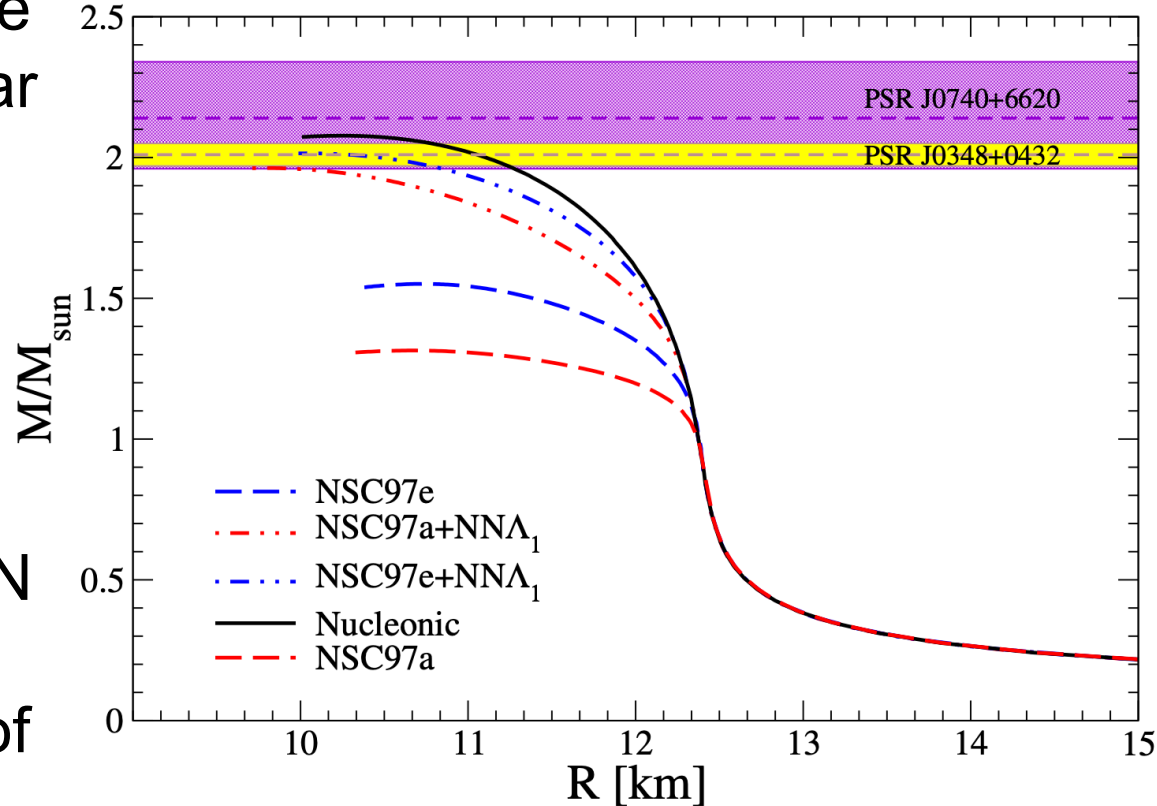
- Hyperon puzzle in neutron stars $\rightarrow$ hyperons make the EOS softer:

- Pure neutron matter (PNM) works well
- Known ΛN interaction $\rightarrow$ way to soft
- Including ΛNN forces brings the mass slightly up
- Only additional ΛNN interaction works sufficiently



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

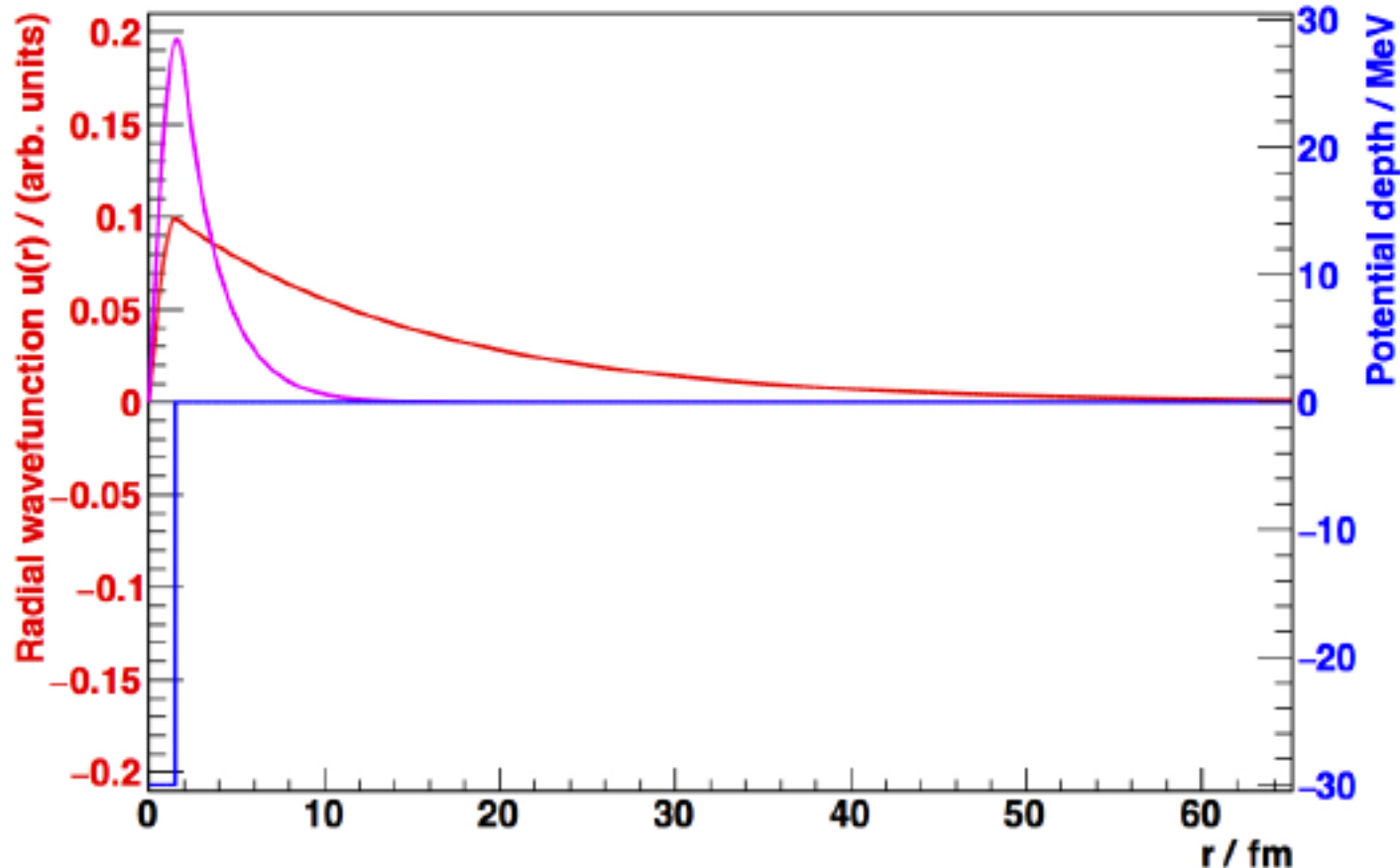
Bound state of Λ , p, n

$$m = 2.991 \text{ GeV}/c^2 \text{ (} B_{\Lambda} = 130 \text{ keV)}$$

Hypertriton

Bound state of Λ , p, n

$$m = 2.991 \text{ GeV}/c^2 \quad (B_\Lambda = 130 \text{ keV})$$

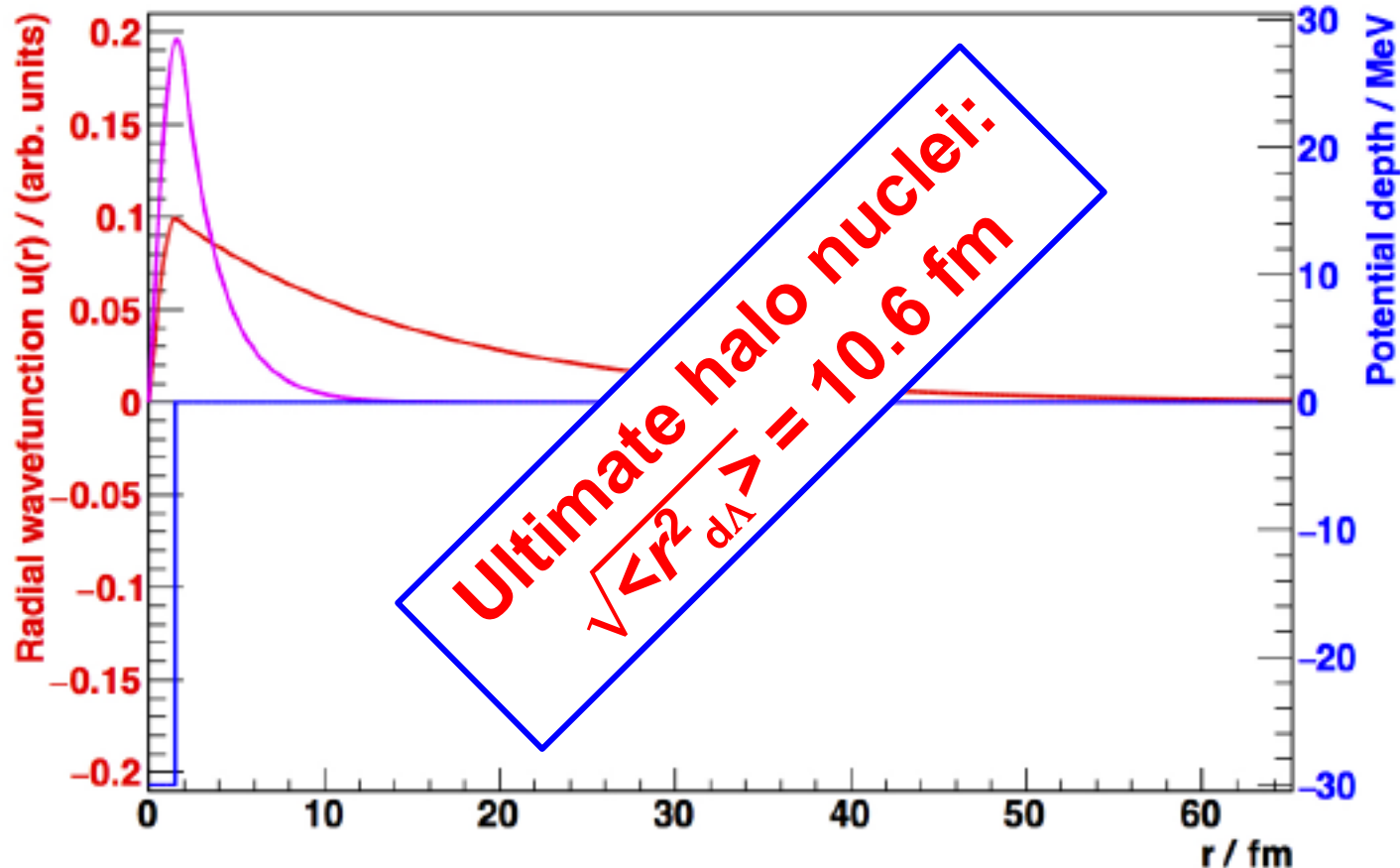


P. Braun-Munzinger, BD, Nucl. Phys. A 987 (2019) 144

Hypertriton

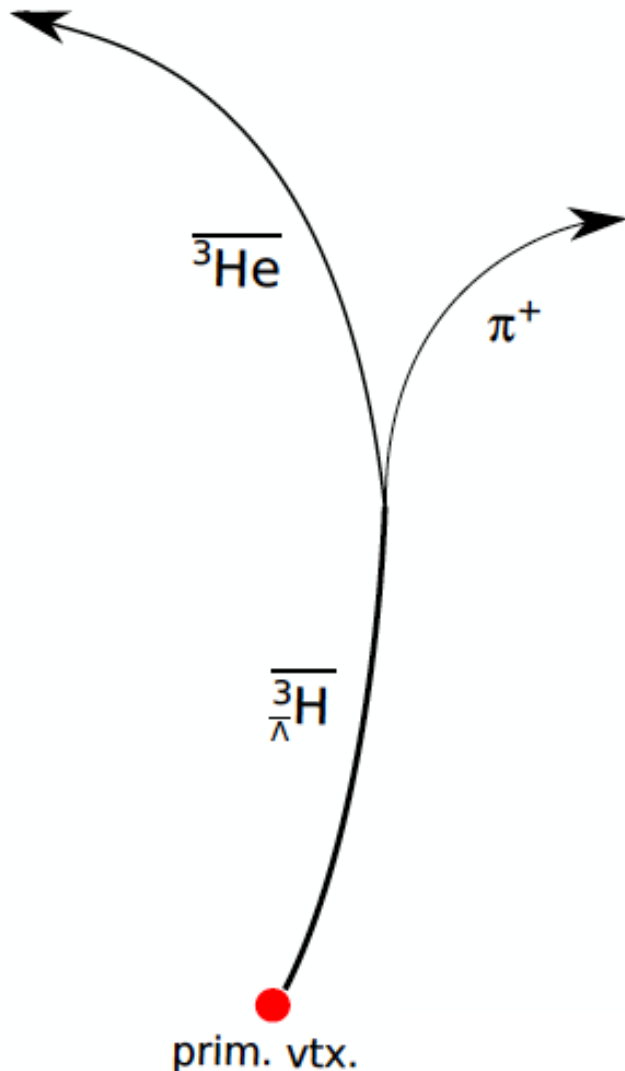
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P. Braun-Munzinger, BD, Nucl. Phys. A 987 (2019) 144

Hypertriton Identification

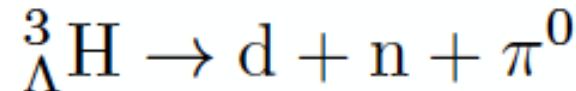
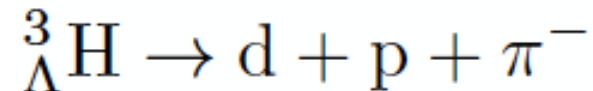
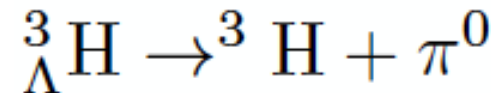
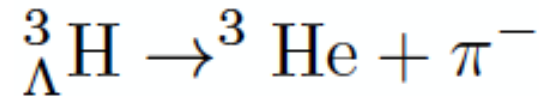


Bound state of Λ , p, n

$m = 2.991 \text{ GeV}/c^2$ ($B_\Lambda = 130 \text{ keV}$)

→ Radius of about 10.6 fm

Decay modes:



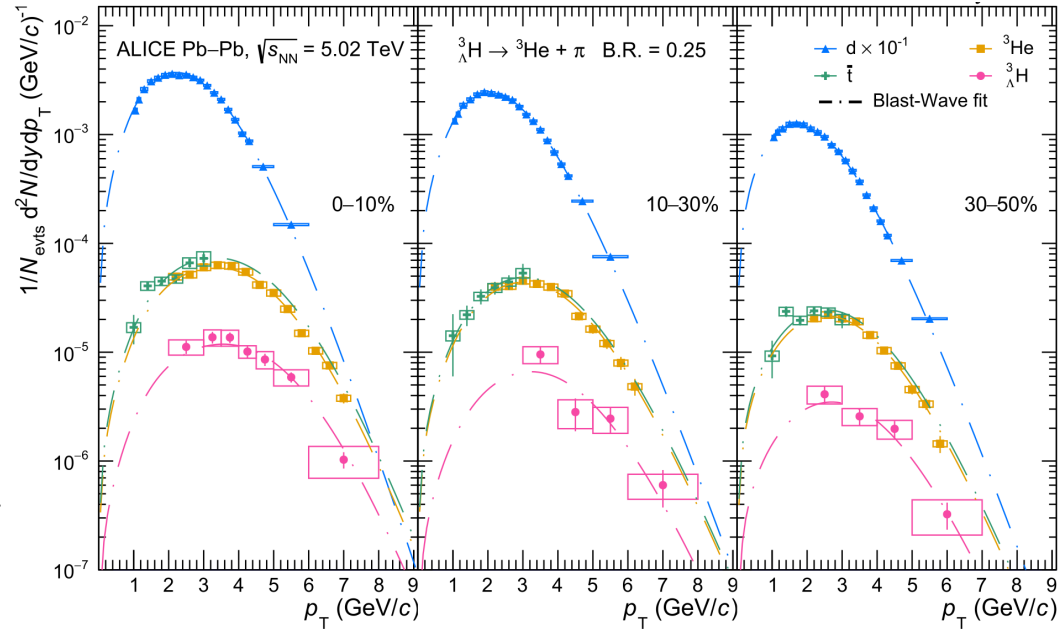
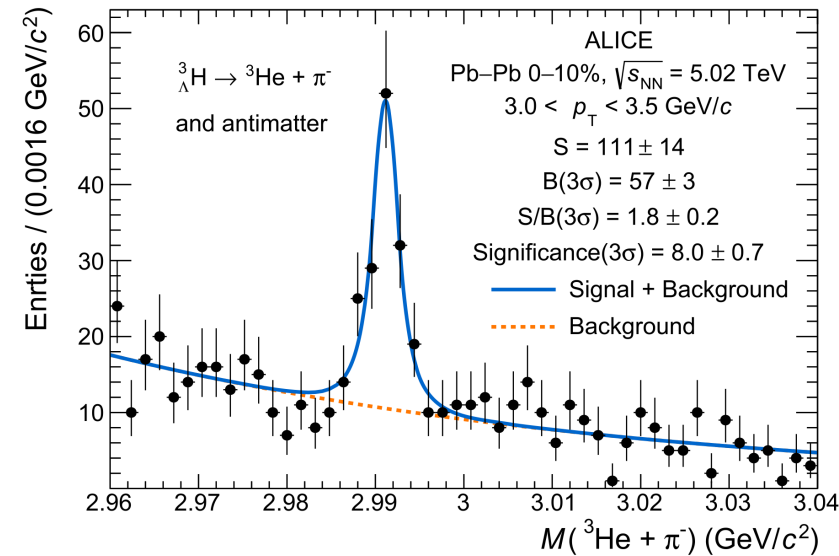
+ anti-particles

→ Anti-Hypertriton first observed by
STAR Collaboration:

Science 328,58 (2010)

Hypertriton signal

ALICE Collaboration, *Phys.Lett.B* 860 (2025) 139066

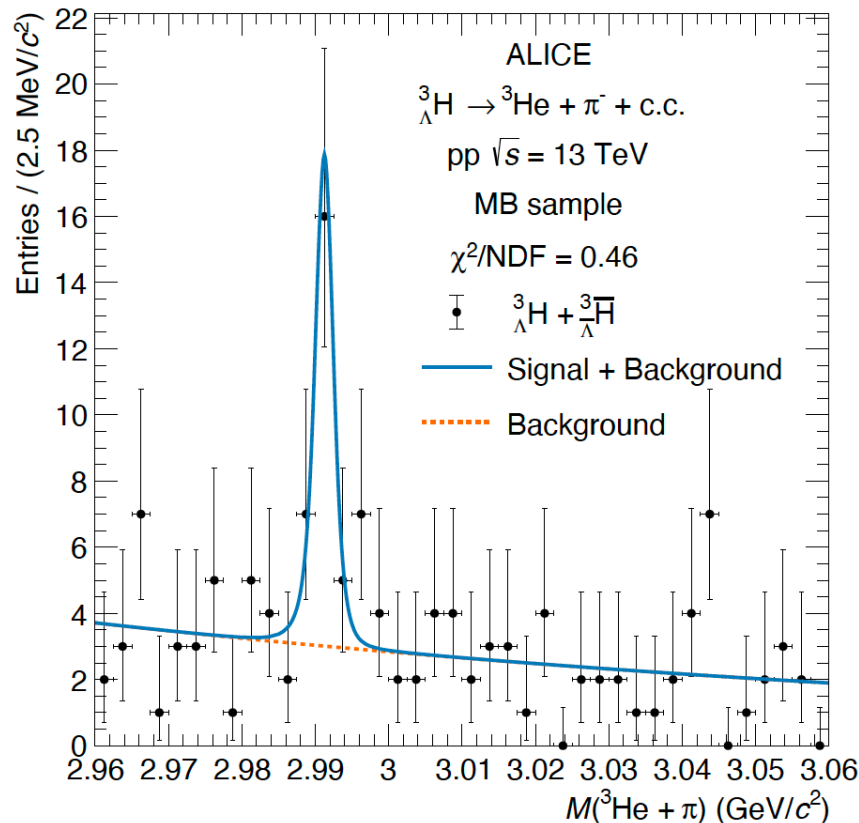
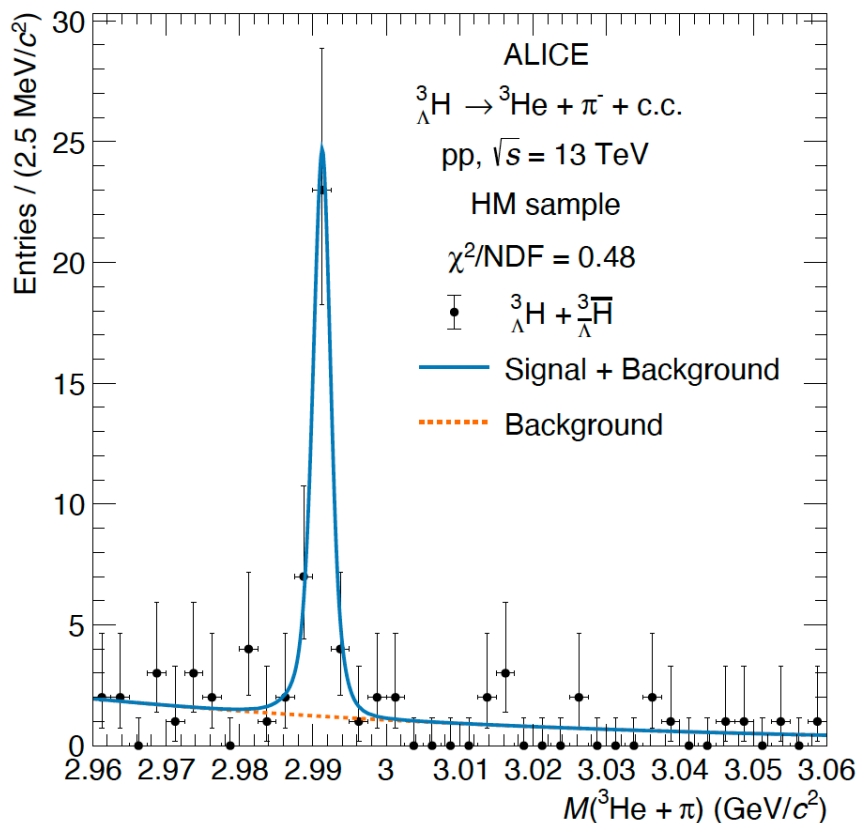


- Clear signal reconstructed by decay products
- Spectra can also be described by Blast-Wave model
→ Hypertriton flows as all other particles



Hypertriton in pp & p-Pb

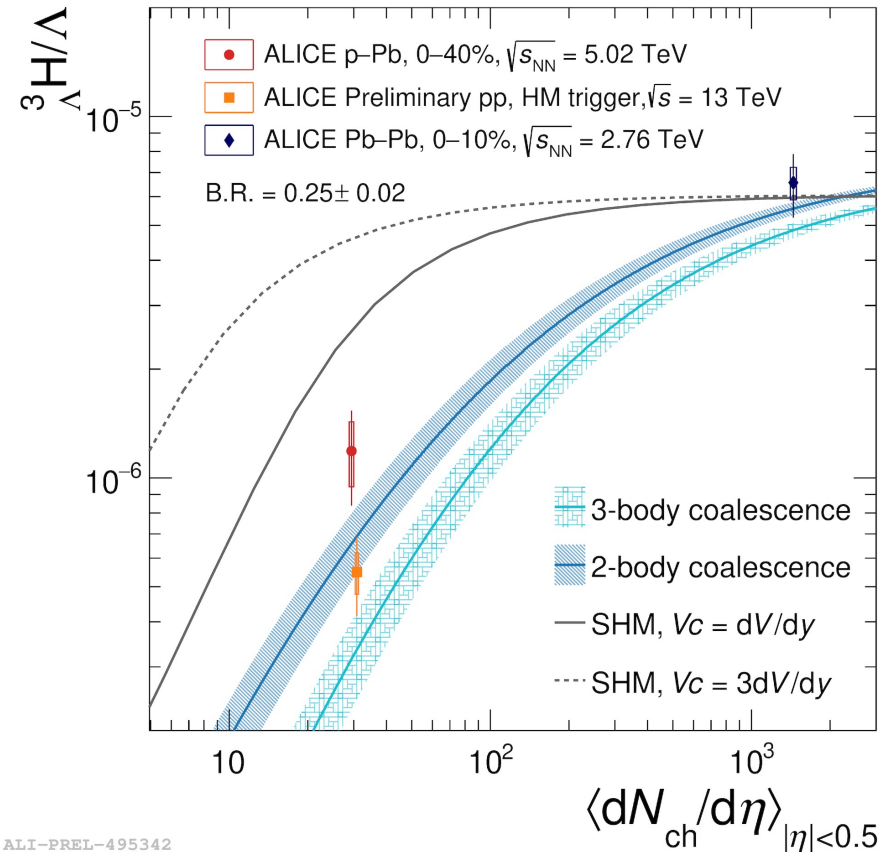
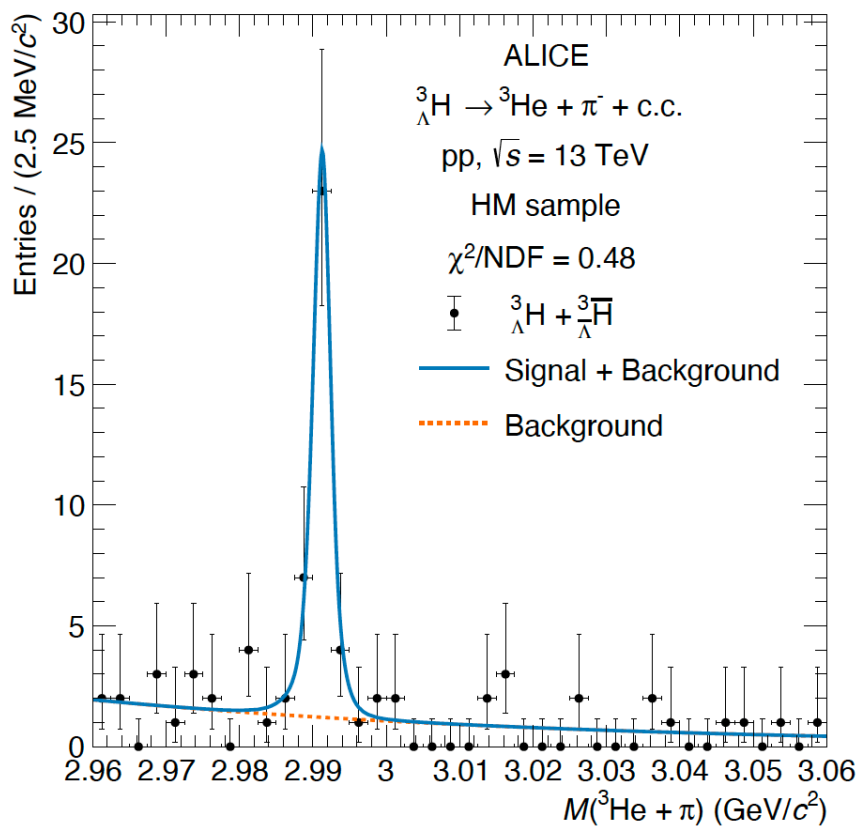
- Hypertriton signal extracted in pp and p-Pb collisions
- Stronger separation between models as for other particle ratios, mainly due to the size of the hypertriton





Hypertriton in pp & p-Pb

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

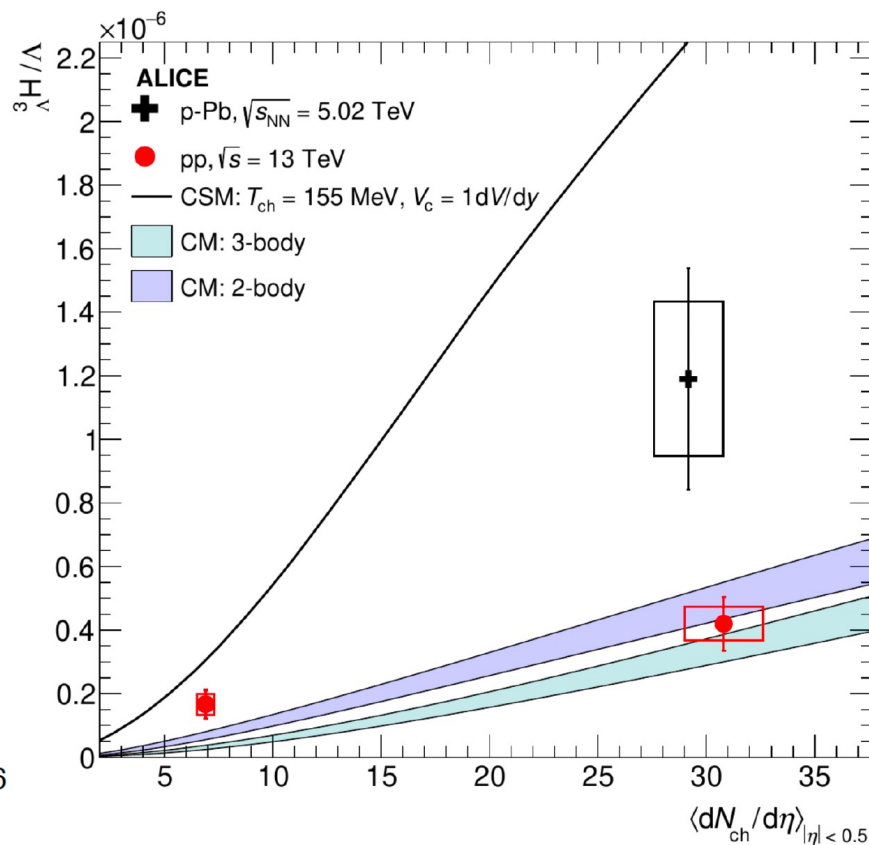
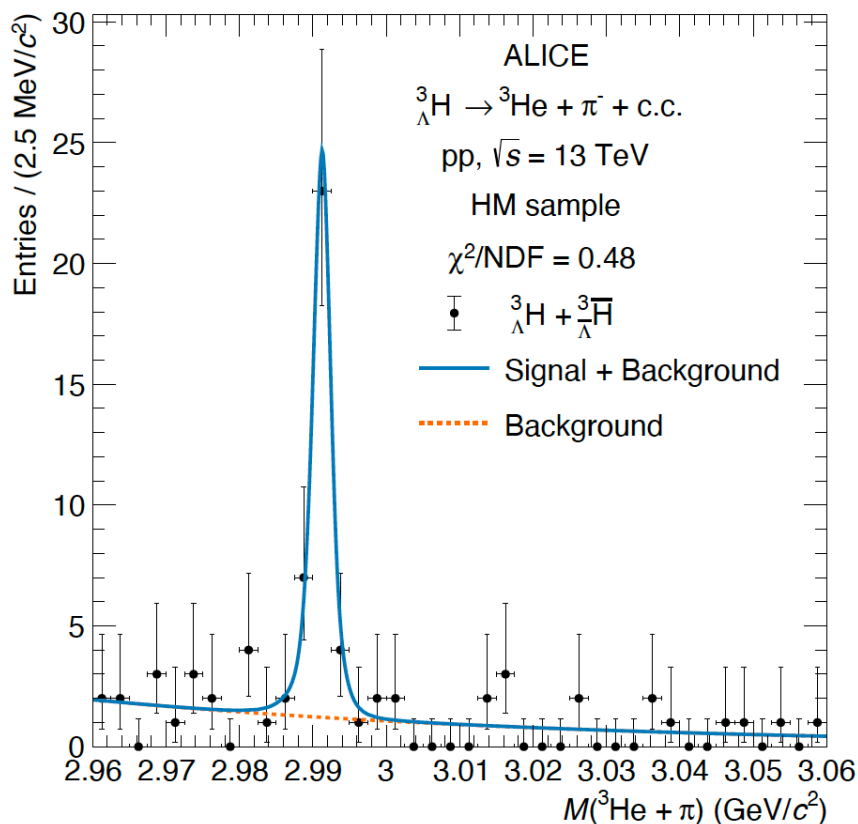


ALI-PREL-495342



Hypertriton in pp & p-Pb

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

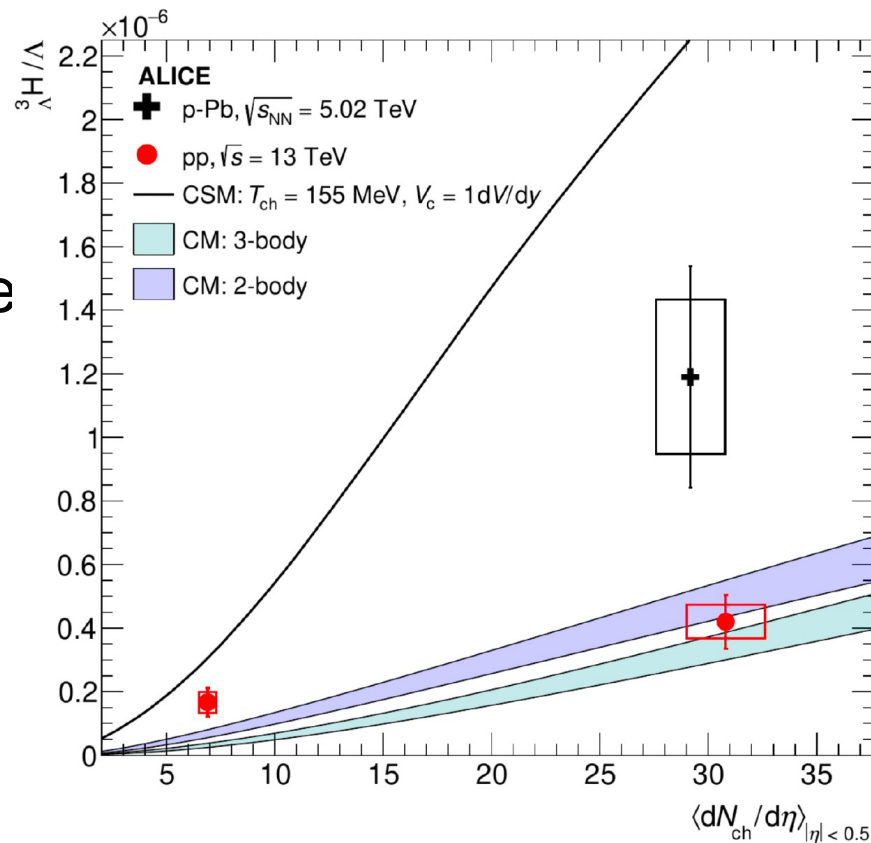


ALICE Collaboration, arXiv:2604.07949

Hypertriton size?

- Hypertriton signal extracted in pp and p-Pb collisions
- Stronger separation between models as for other particle ratios, mainly due to the size of the hypertriton
- If one uses the analytical form of the coalescence model (using Gaussian wave functions for d and $^3_\Lambda\text{H}$) one can perform a fit to determine the size

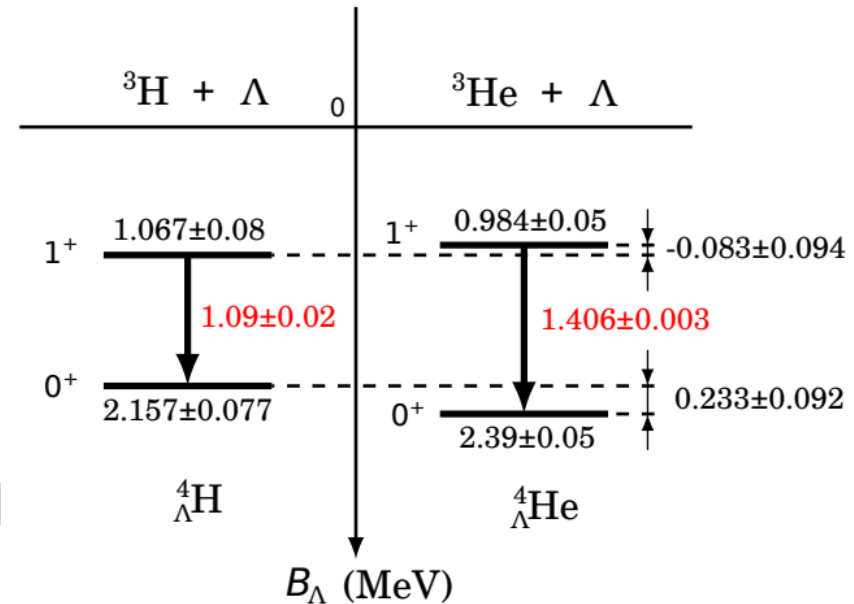
$$\rightarrow \sqrt{\langle r^2_{d\Lambda} \rangle} = (9.54 \pm 2.67) \text{ fm}$$



ALICE Collaboration, arXiv:2604.07949

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



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

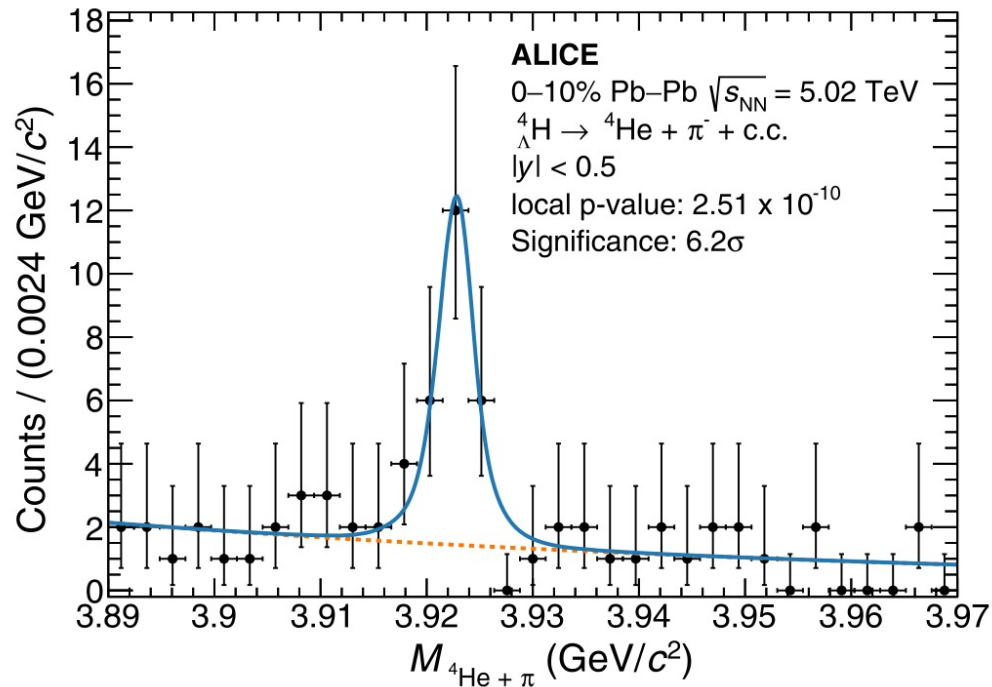
- Also the yields of the SHM scale with the **spin-degeneracy**
- Resulting in a total enhancement of a factor 4 for both hypernuclei

[BD, EPJ Web Conf. 276 \(2023\) 04002](#)

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 (anti)hyperhydrogen-4** in Run 2 Pb-Pb collisions at 5.02 TeV
- Reaching a significance of **6.2 σ**

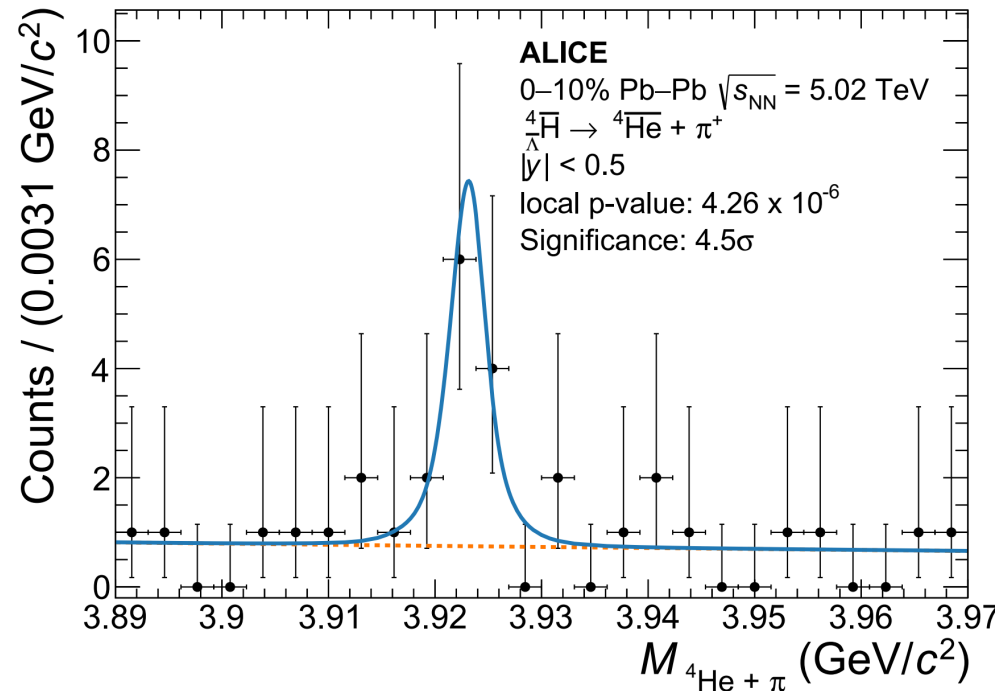
ALICE Collaboration, PRL 134 (2025) 162301



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 antihyperhydrogen-4** in Run 2 Pb-Pb collisions at 5.02 TeV
- Reaching a significance of **4.5 σ**

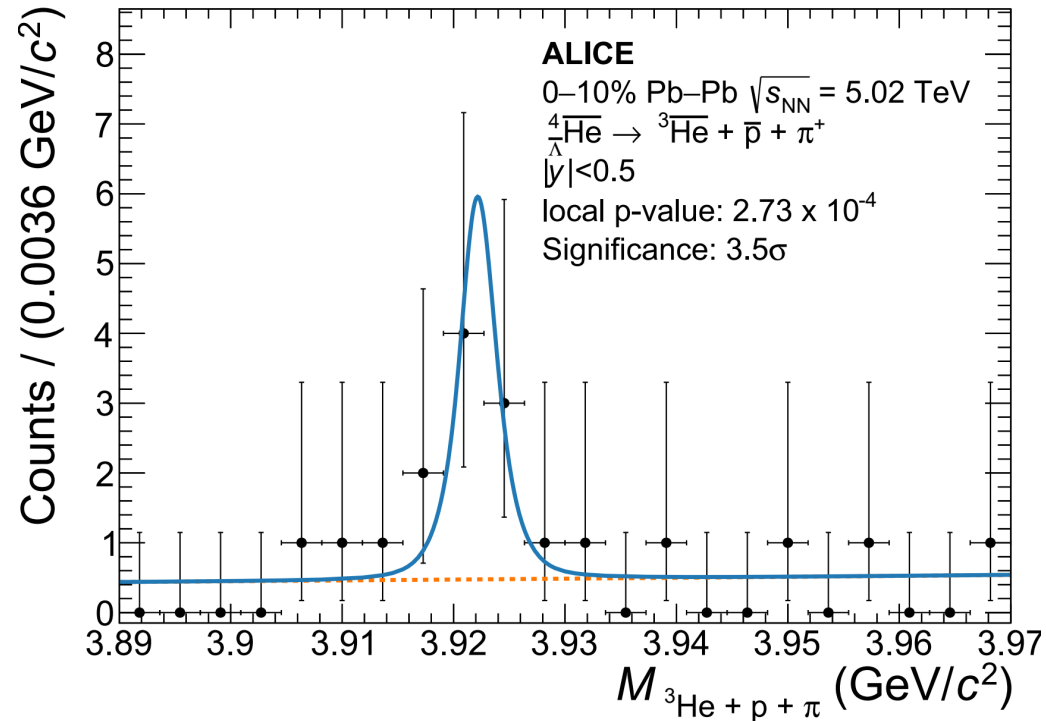
ALICE Collaboration, PRL 134 (2025) 162301



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 **3.5 σ**

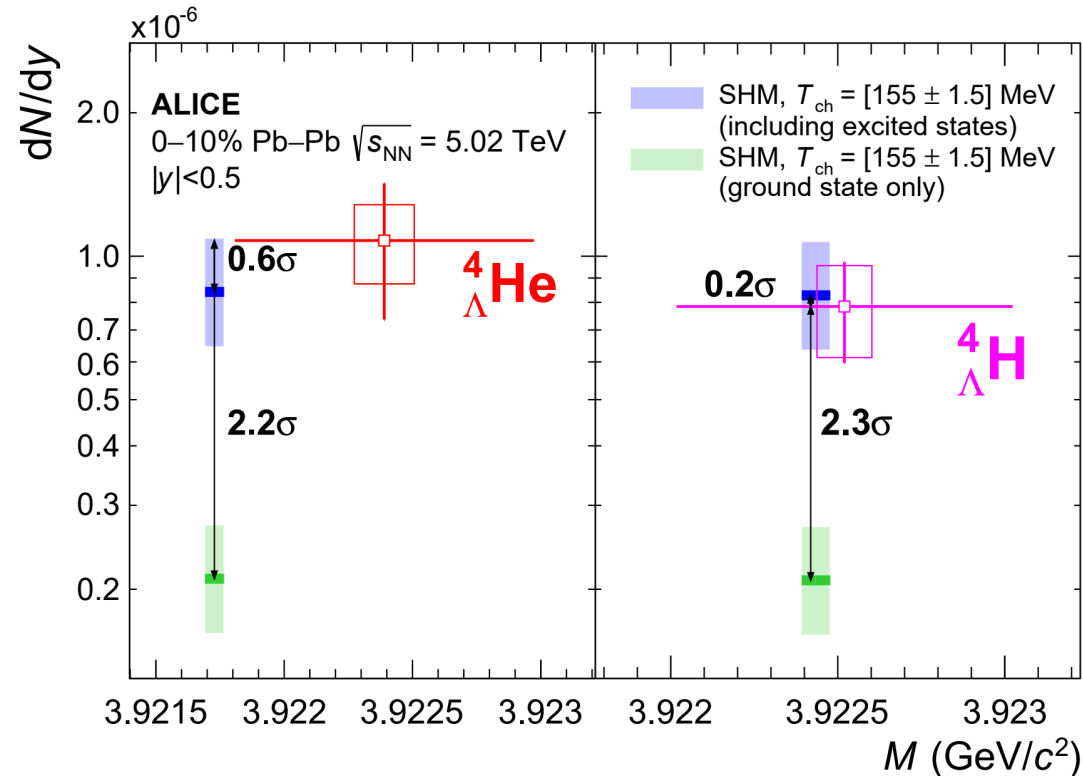
ALICE Collaboration, PRL 134 (2025) 162301



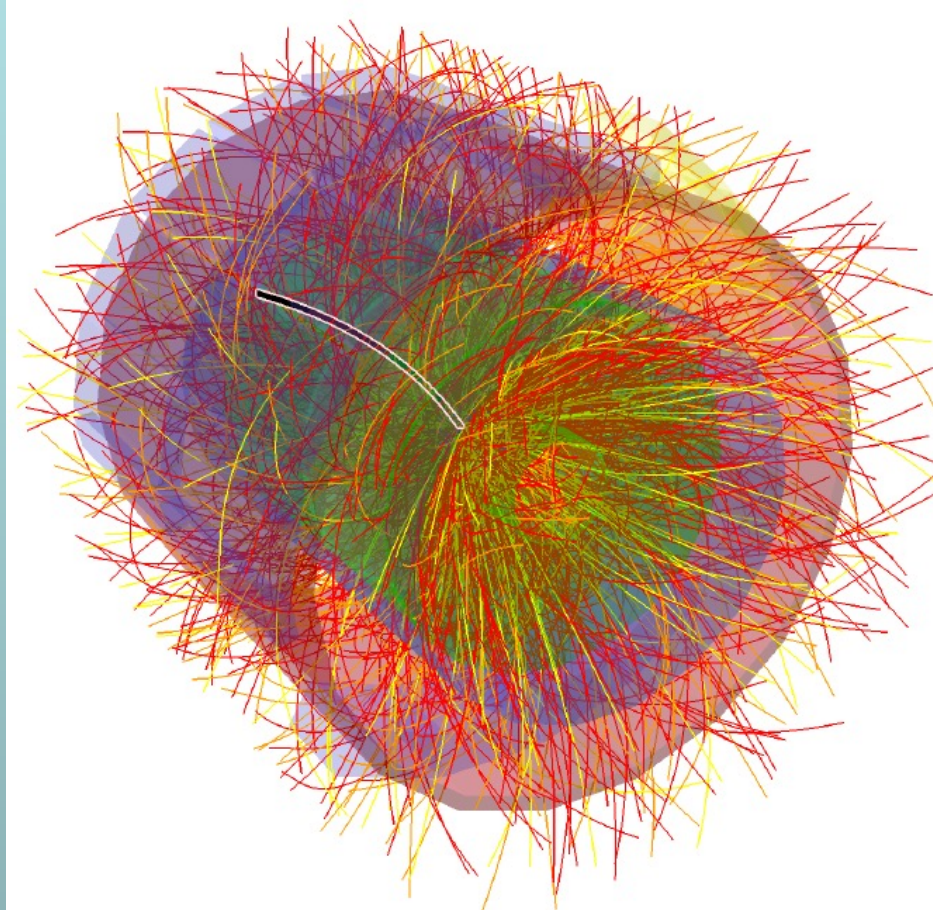
A = 4 hypernuclei

- First measurement of the (anti)hyperhelium-4 production yield at LHC
- 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)

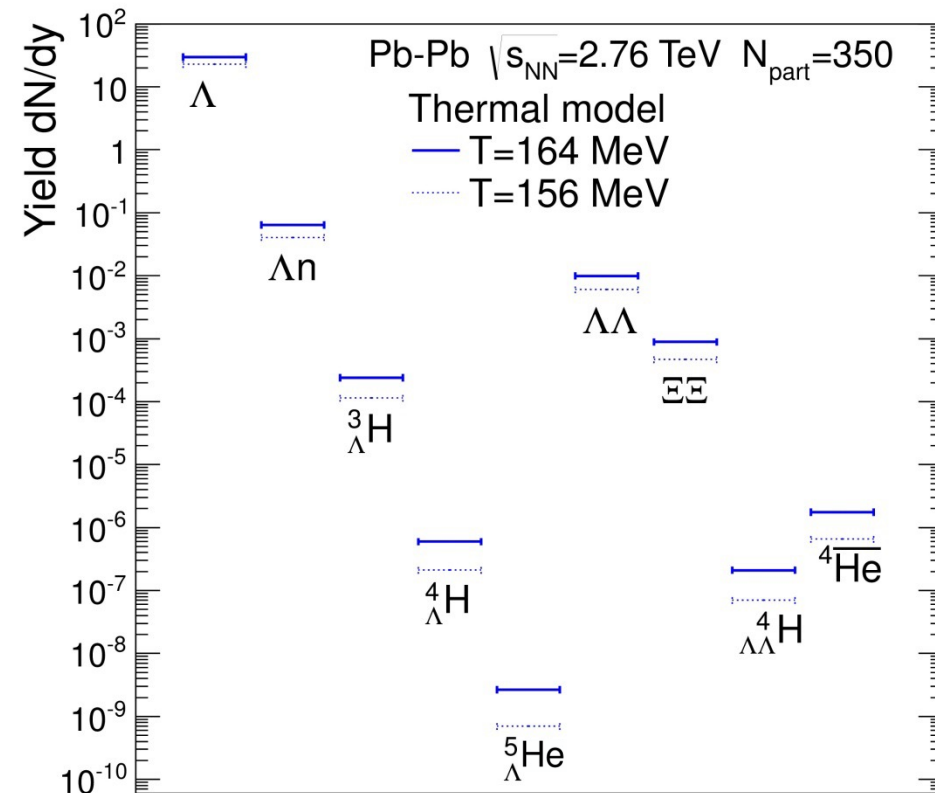
ALICE Collaboration, PRL 134 (2025) 162301



Outlook & Summary



Outlook

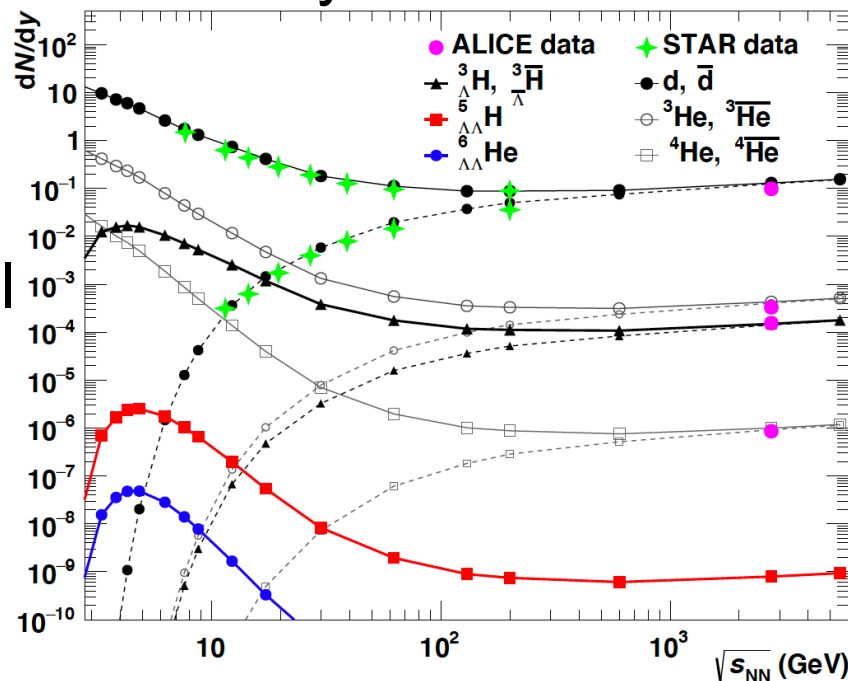


- Explore QCD and QCD inspired model predictions for (unusual) multi-baryon states
- Search for rarely produced anti- and hyper-matter
- Test model predictions, e.g. thermal and coalescence

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

Conclusion

- ALICE@LHC is well suited to study light (anti-)(hyper-) nuclei and perform searches for exotic bound states ($A < 5$)
- Copious production of loosely bound objects measured as predicted by the thermal model
- Ratios vs. multiplicity trend described by both models
 - main tension: Alpha, ${}^4_{\Lambda}\text{H}$, ${}^4_{\Lambda}\text{He}$ vs. t, ${}^3\text{He}$, ${}^3_{\Lambda}\text{H}$
 - more compact objects clearly favour thermal model
- New and more precise data to be expected in the next years - Run 3 of the LHC just finished



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

Happy Birthday Peter!

- We have a fruitful collaboration for more than 20 years



Happy Birthday Peter!

- We have a fruitful collaboration for more than 20 years

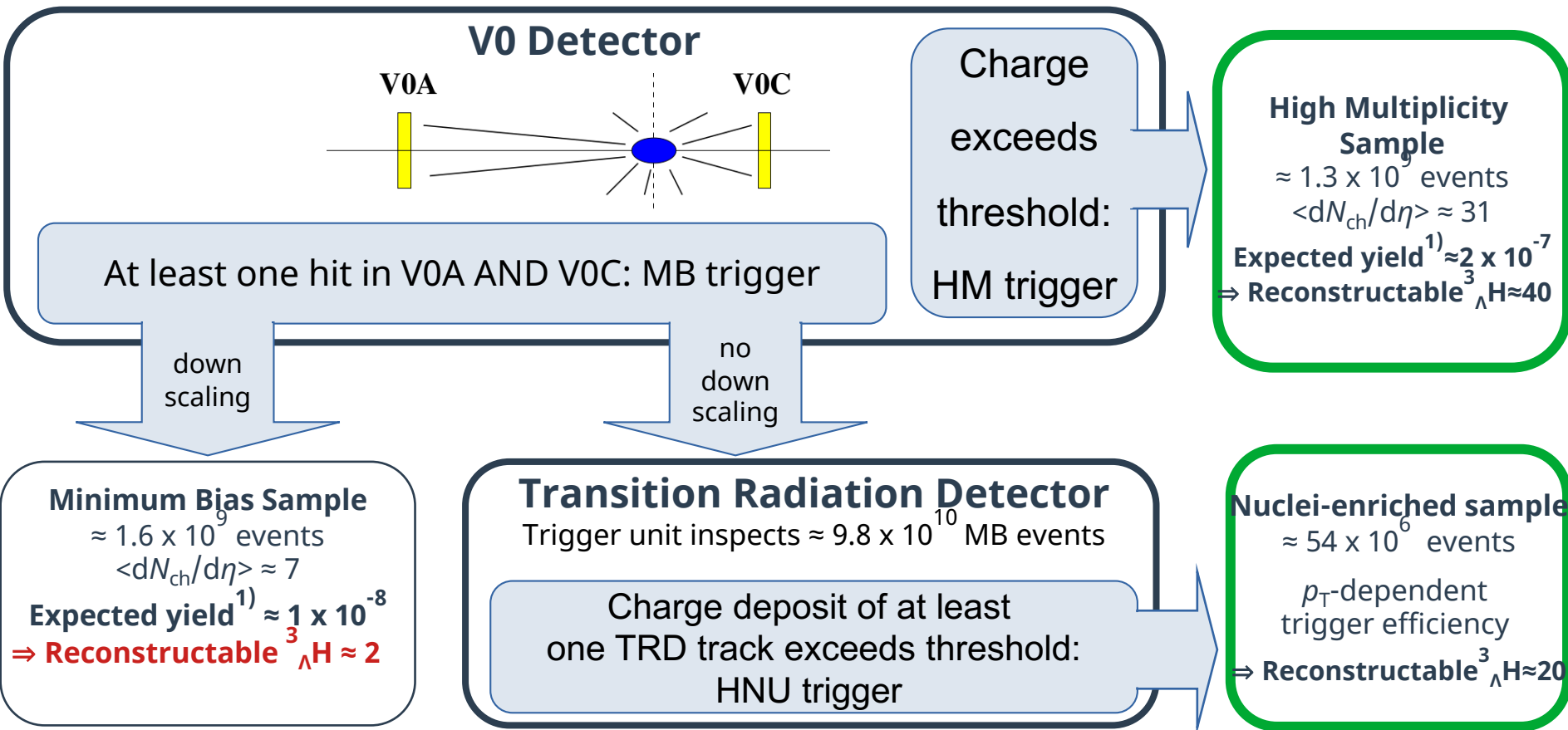


Happy Birthday Peter!



Backup

Trigger

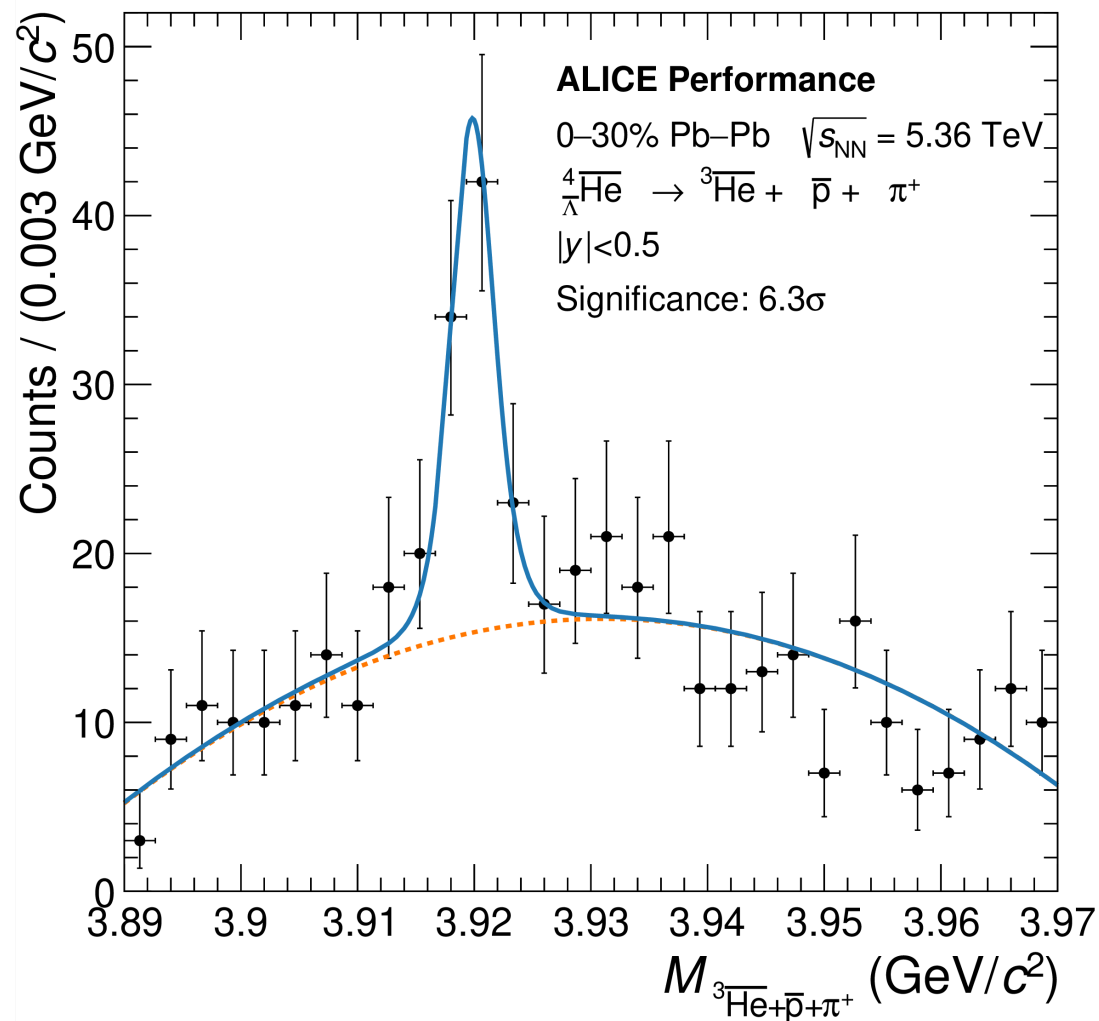


1) Predictions from coalescence model: K.-J. Sun, C.-M. Ko, B. Dönigus, Phys. Lett. B. 792 (2019) 132

Run 3: antihyperhelium-4

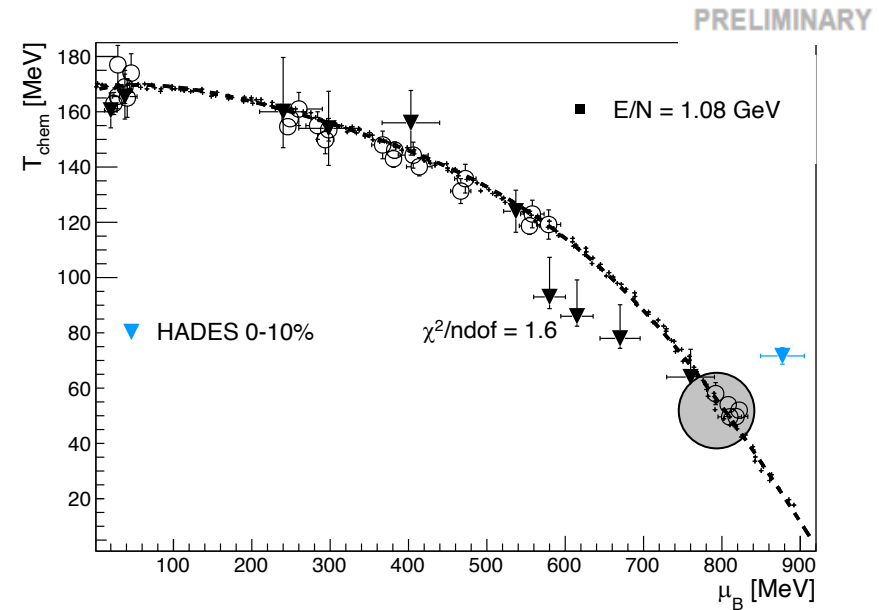
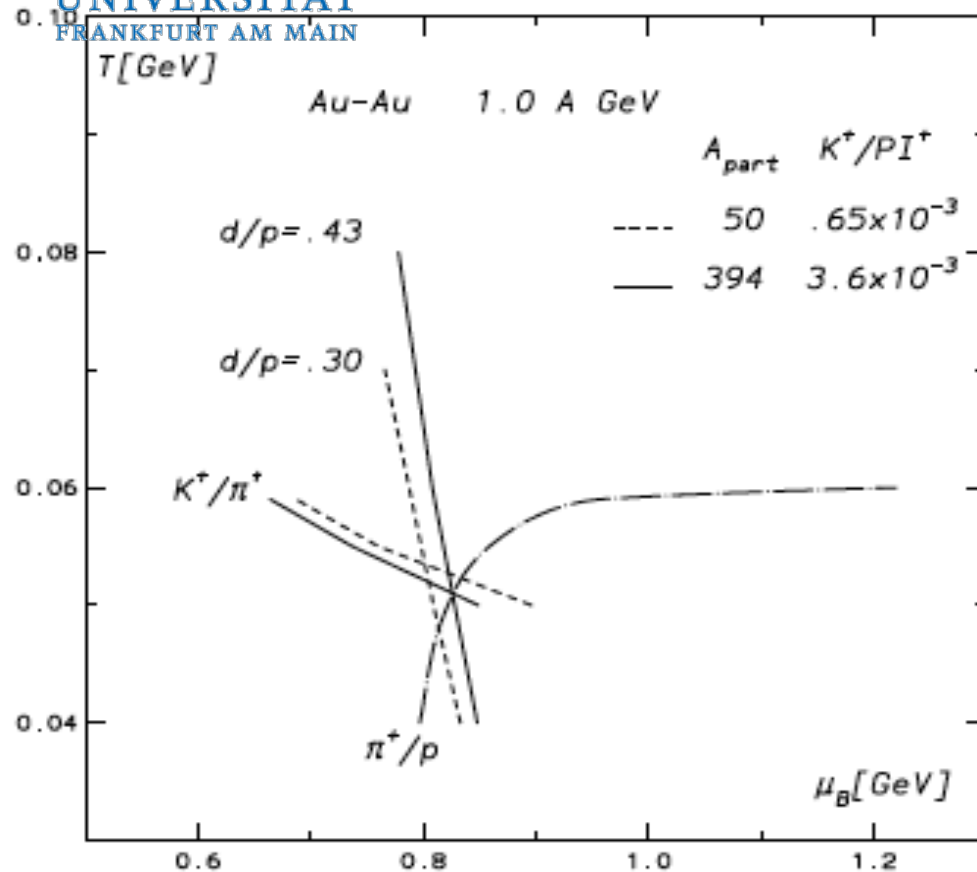
Finally, in Run 3 data a 6.3σ significance is reached

More to come from the new data



ALI-PERF-610978

Phase diagram: HADES



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

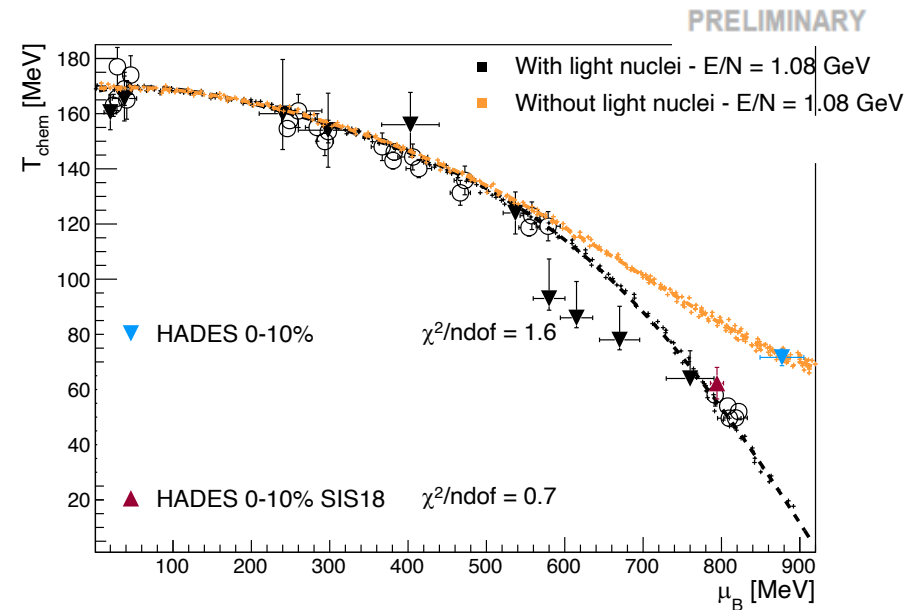
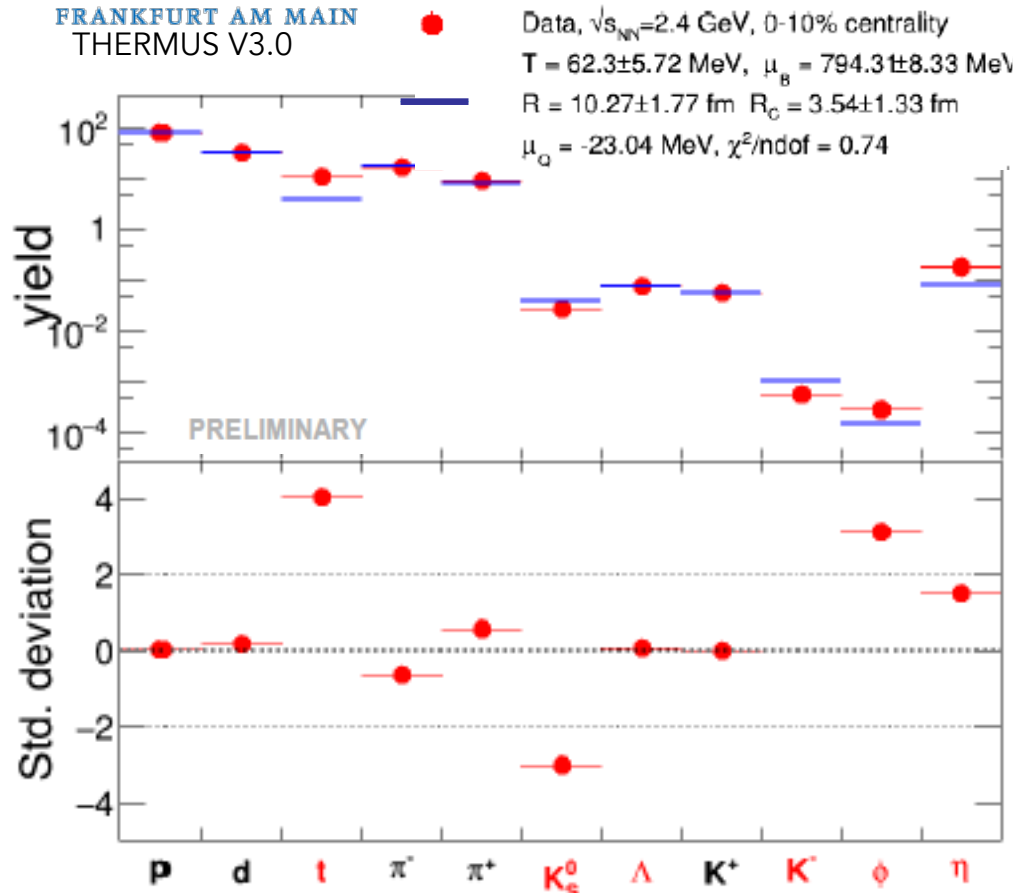
- Freeze-out points previously estimated based on ratios of p , d , K^+ , π^+
- Light nuclei are not included in Thermus V2.3

Switch to Thermus V3.0 or Thermal-Fist <https://github.com/vlvovch/Thermal-FIST>

Unlocking the QCD phase diagram - Benjamin Dönigus

M. Lorenz 2019

Phase diagram: HADES



- 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 .

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

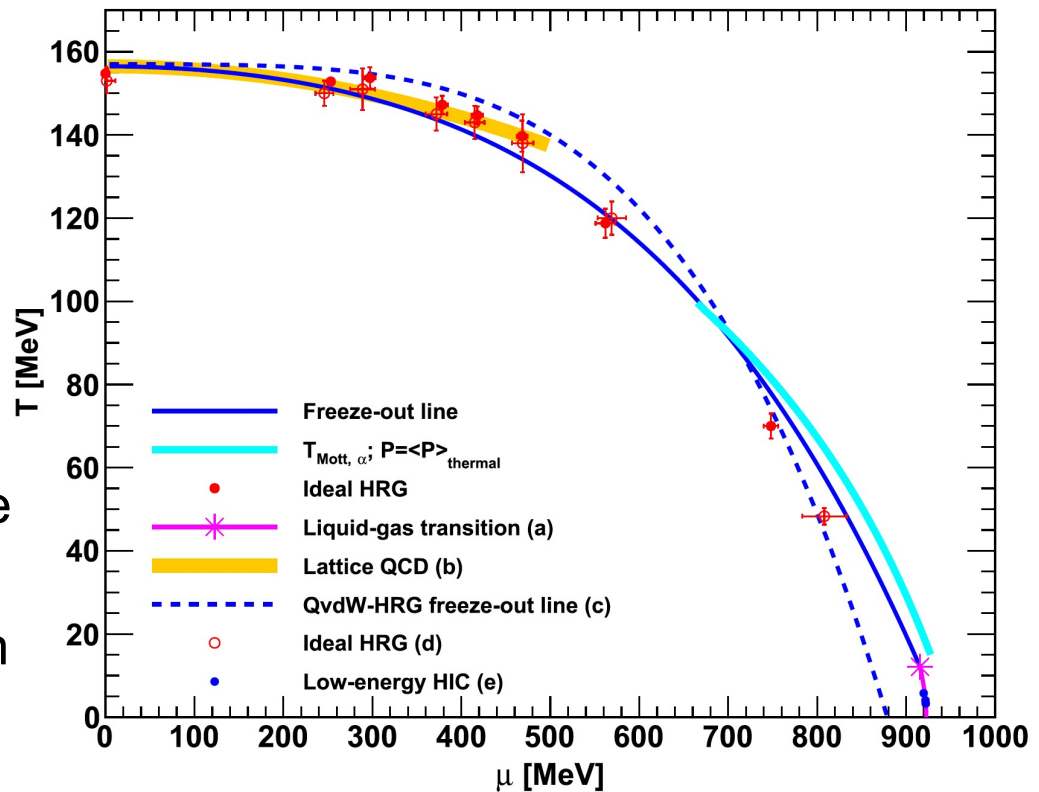
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Unlocking the QCD phase diagram - Benjamin Dönigus

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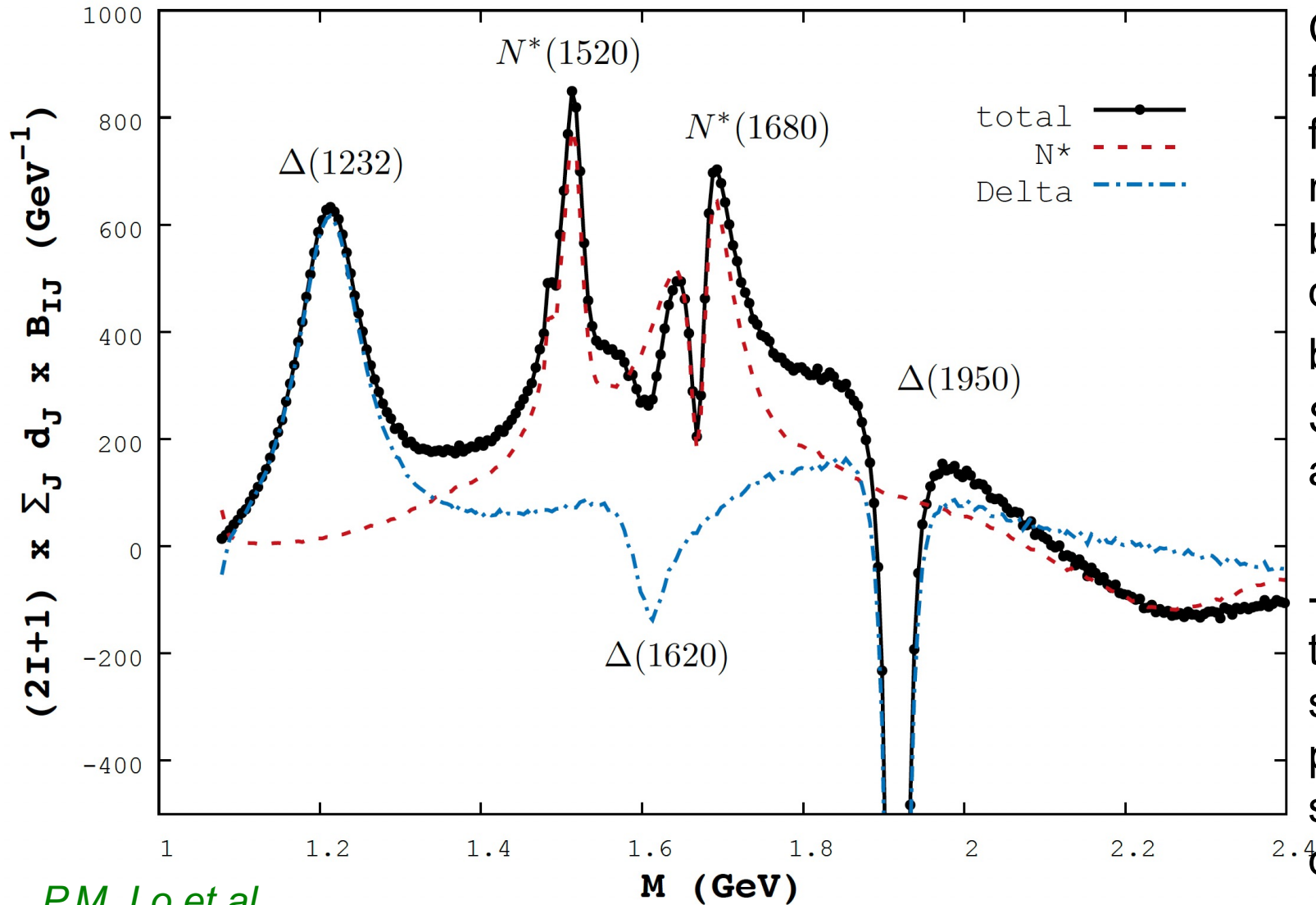
Phase diagram: Mott α

- 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*

Thermal model

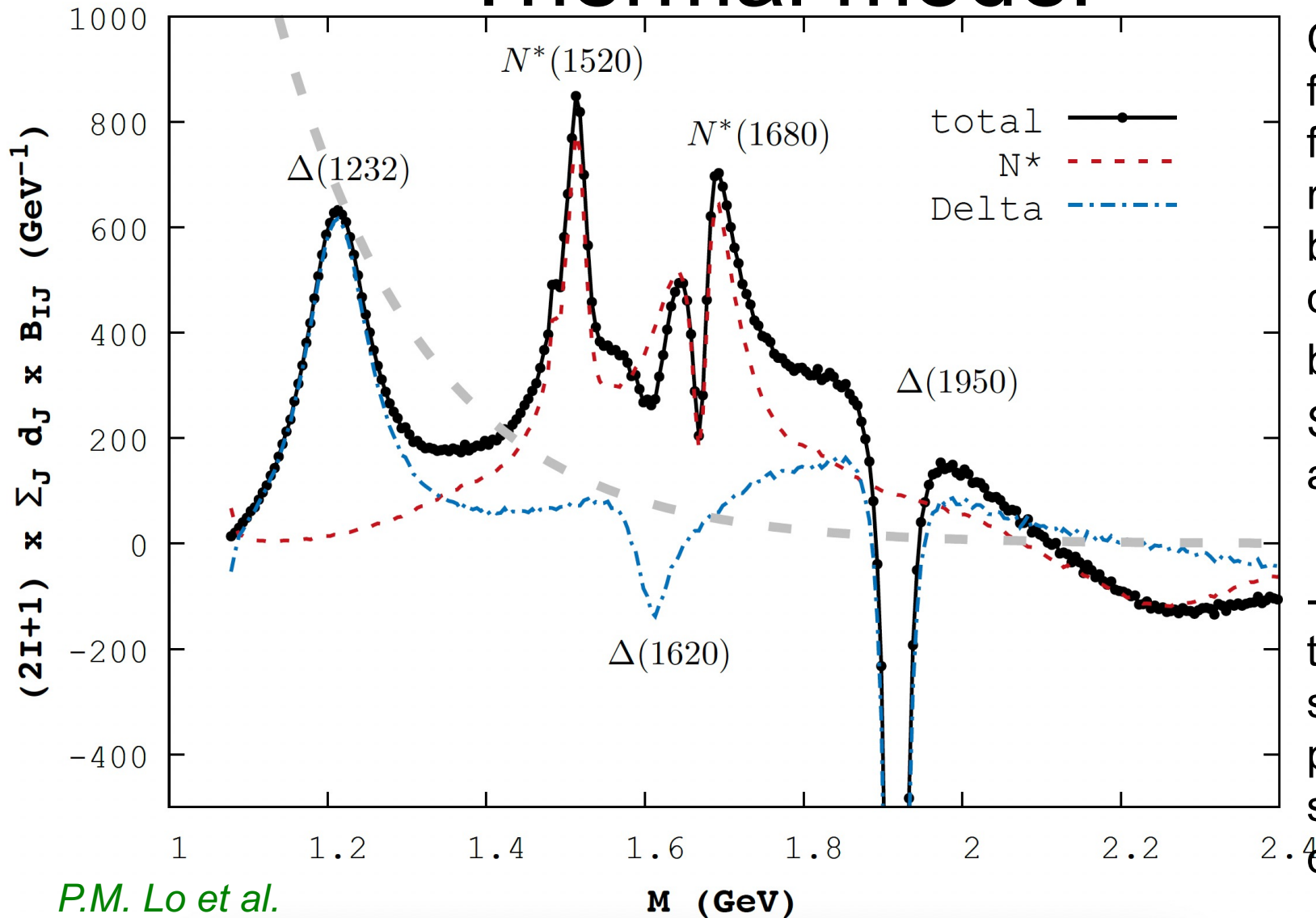


Contribution
for protons
from
resonances
best
described
by the
S-Matrix
approach

-connecting
to phase
shifts from
 p - π
scattering
data

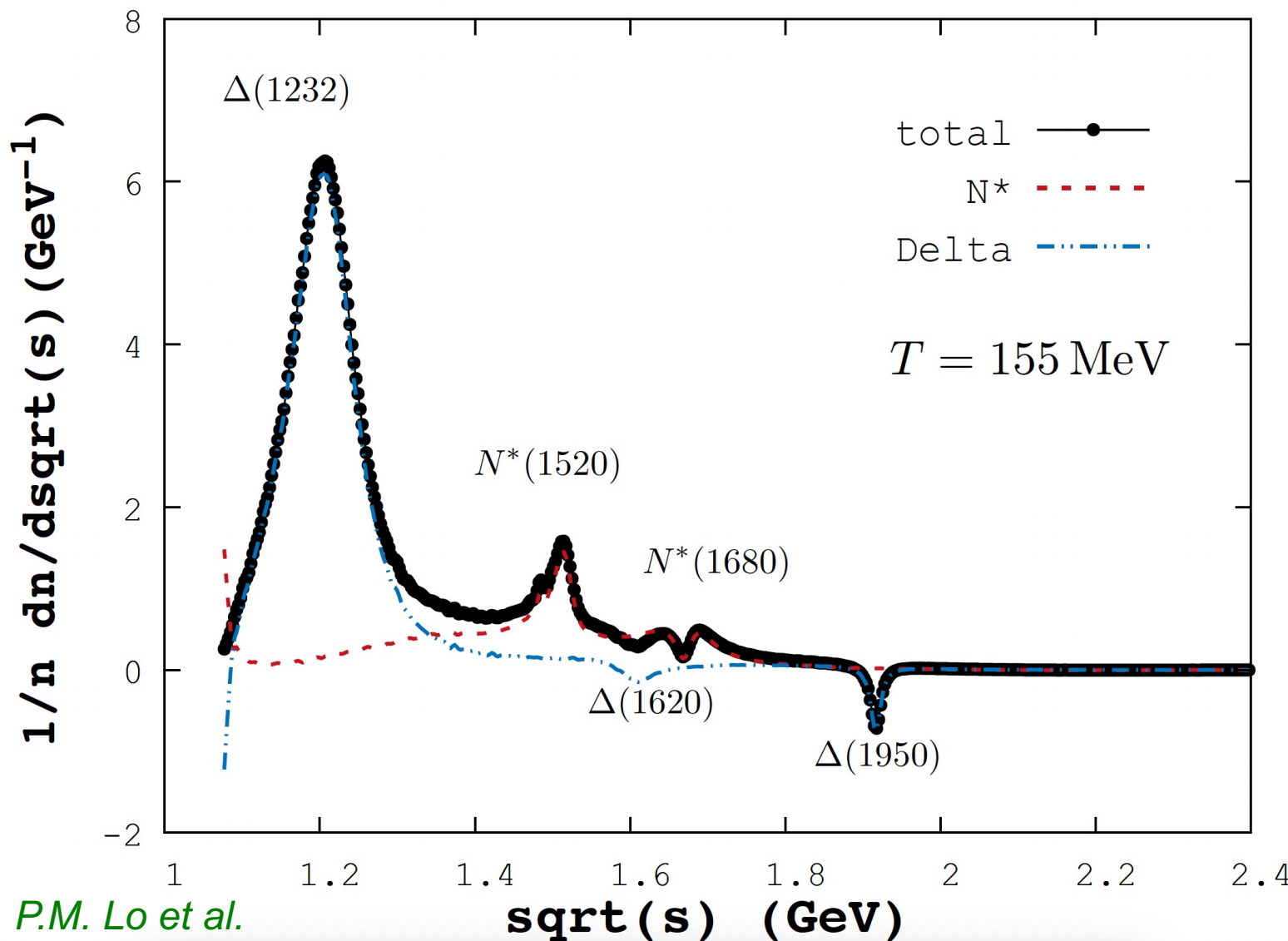
P.M. Lo et al.

Thermal model



P.M. Lo et al.

Thermal model

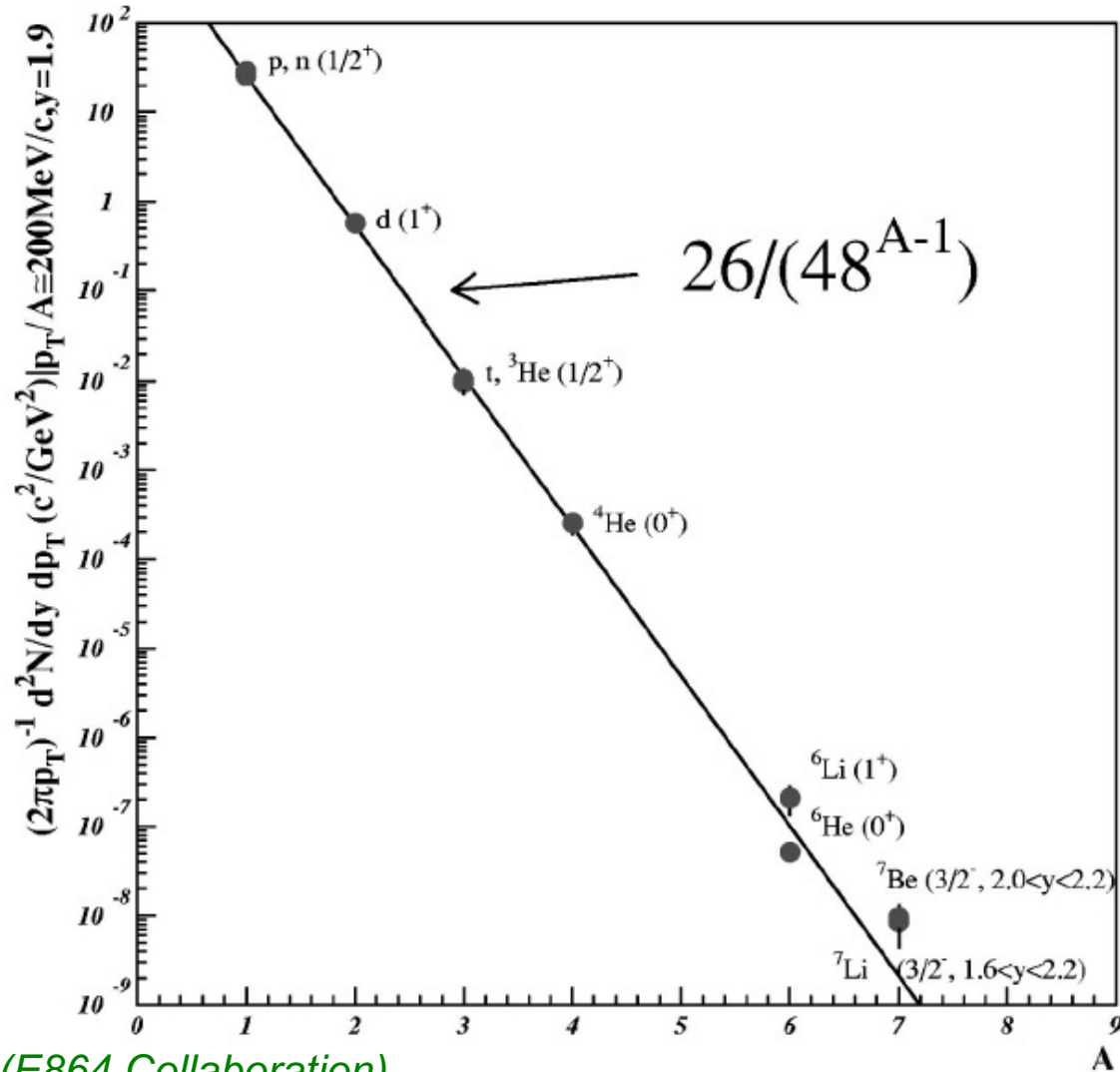


P.M. Lo et al.

Contribution
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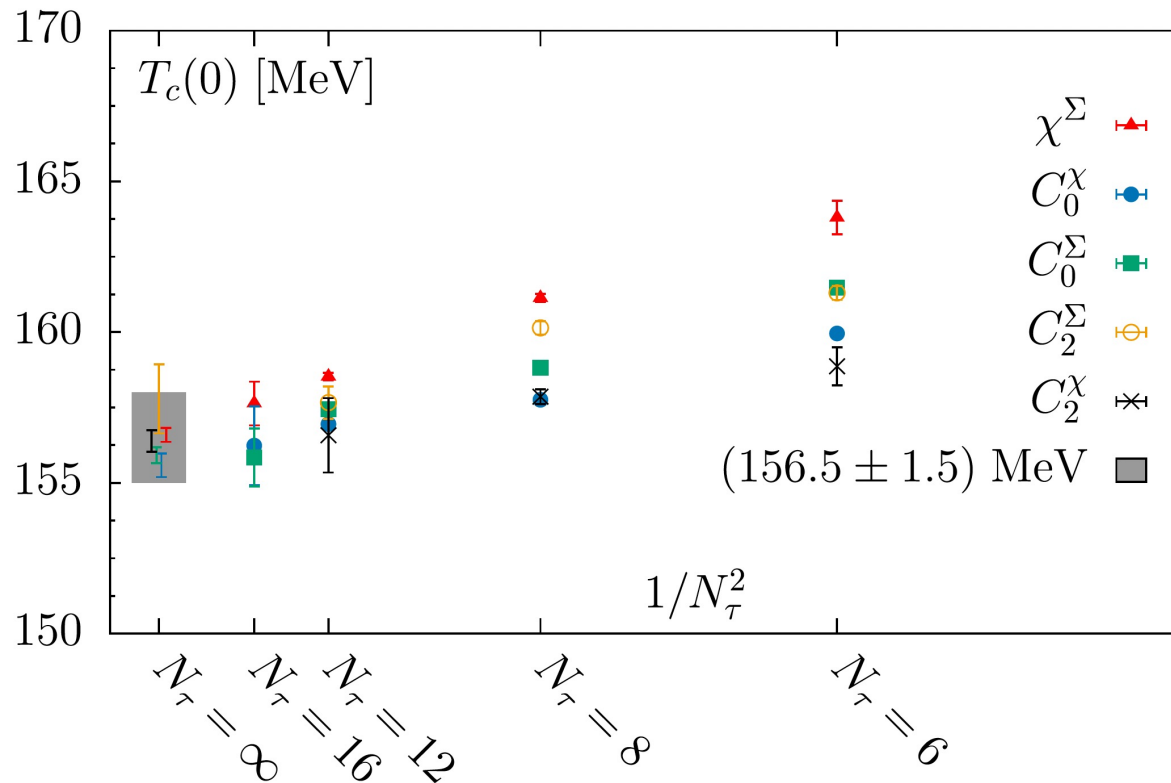
-connecting
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E864 nuclei result



*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

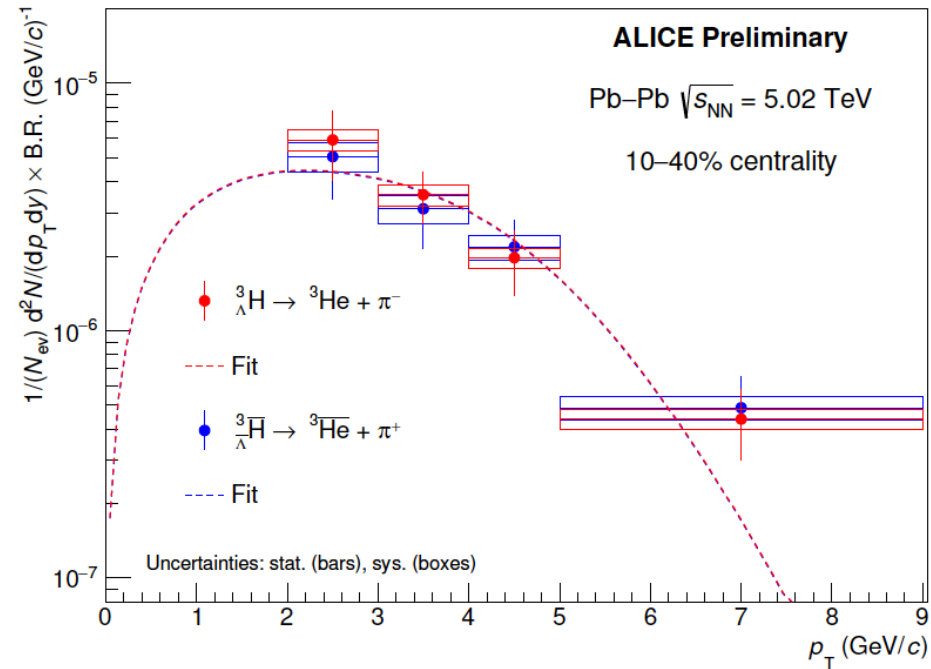
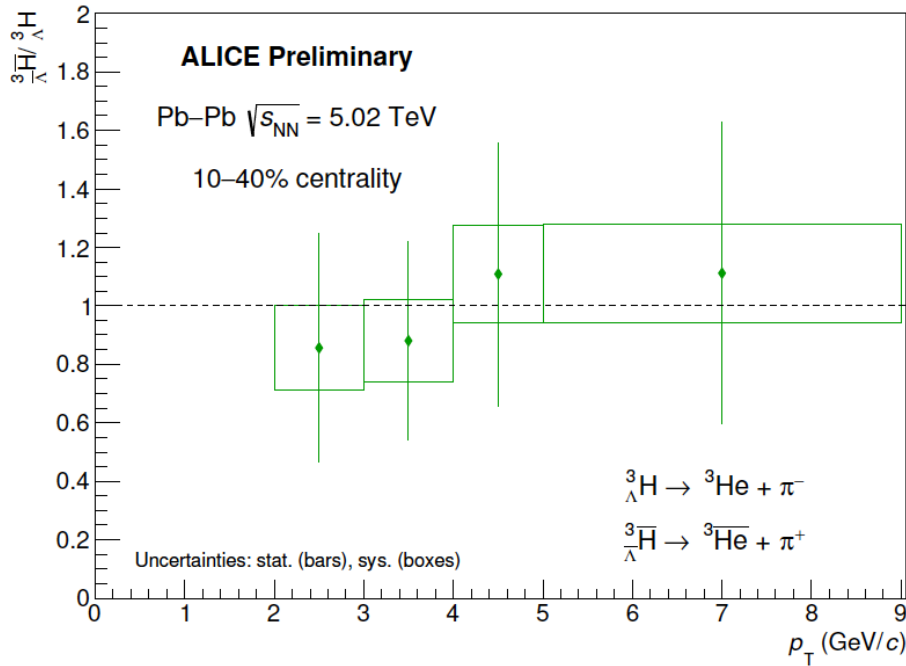
Critical energy density:
 $\epsilon_c = 0.34 \pm 0.16$ GeV/fm³

Critical temperature
 $T_c = (156.5 \pm 1.5)$ MeV

A. Bazavov et al. (hotQCD) PLB 795 (2019) 15

Similar results: S. Borsányi et al. (Budapest-Wuppertal group) PRL 125 (2020) 052001

Hypertriton spectra



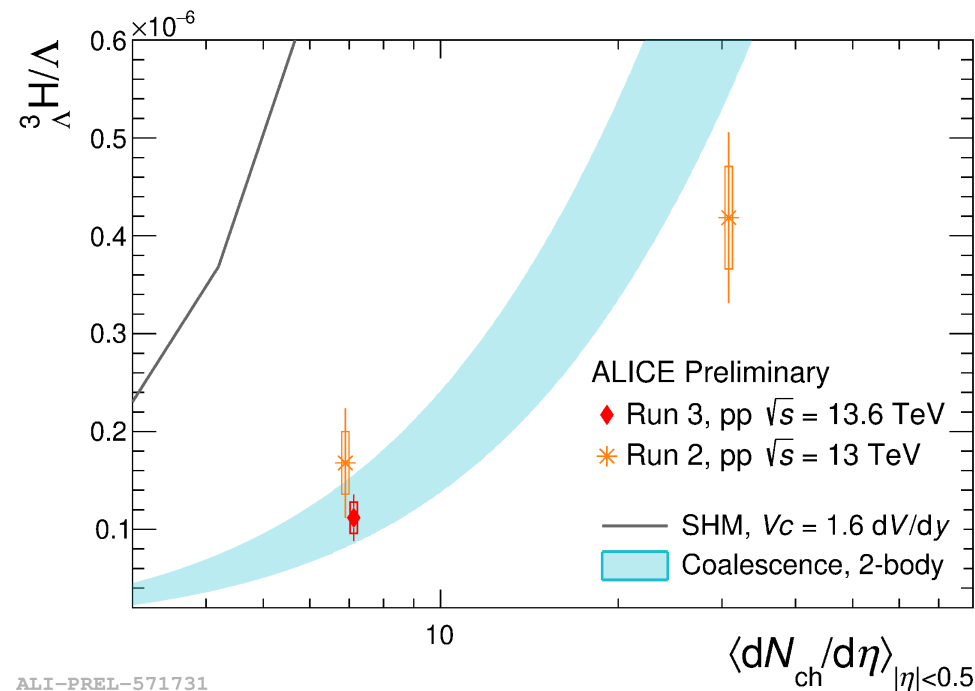
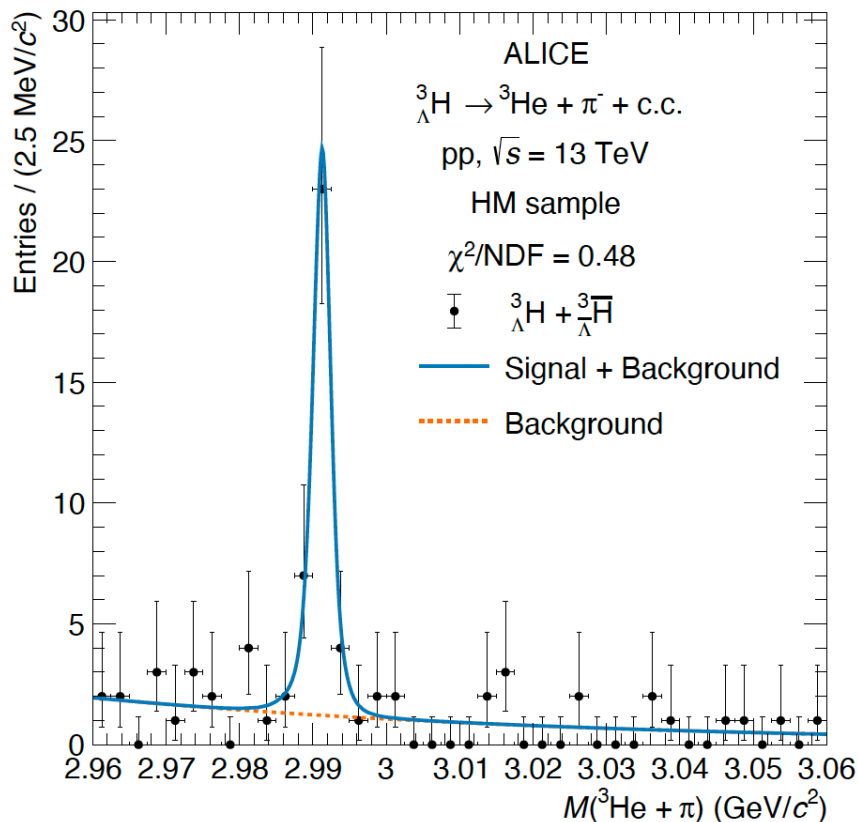
- Anti-hypertriton/Hypertriton ratio consistent with unity vs. p_T



Hypertriton in pp & p-Pb



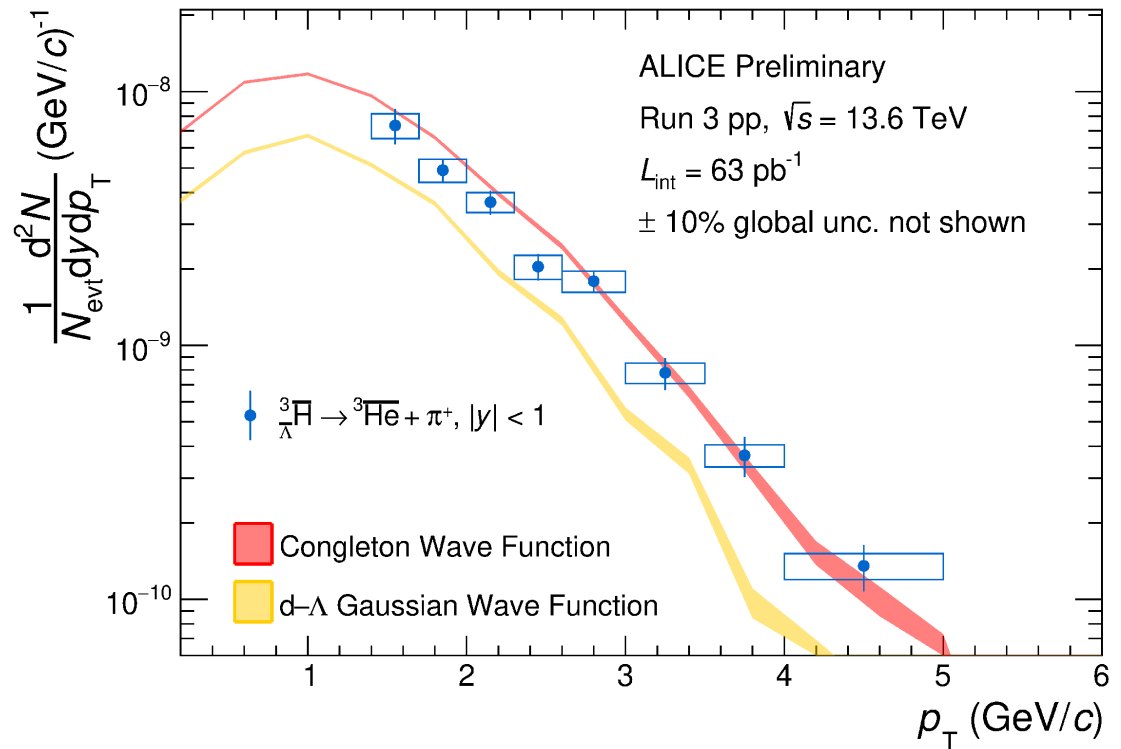
- Hypertriton signal extracted in pp and p-Pb collisions
- Stronger separation between models as for other particle ratios, mainly due to the size of the hypertriton



Hypertriton: 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

M. Mahlein et al. arxiv:2504.02491



Hypertriton size

