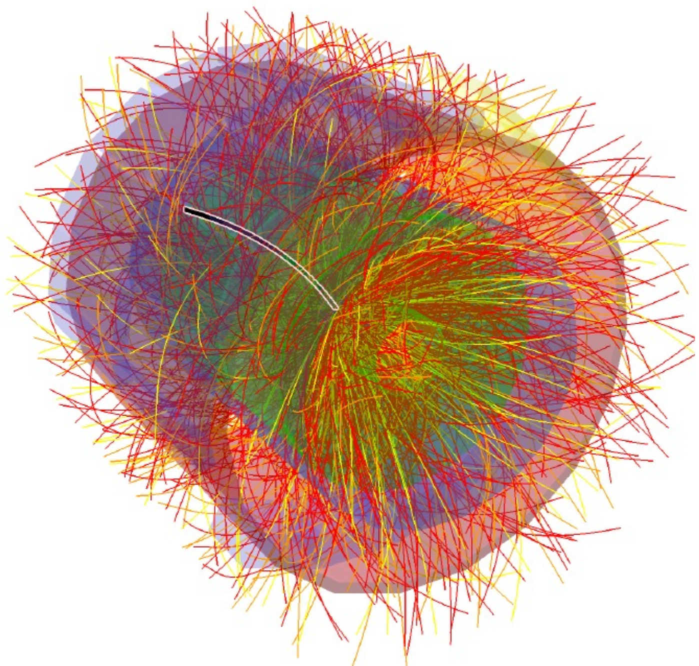
Production of loosely bound objects in heavy-ion collisions



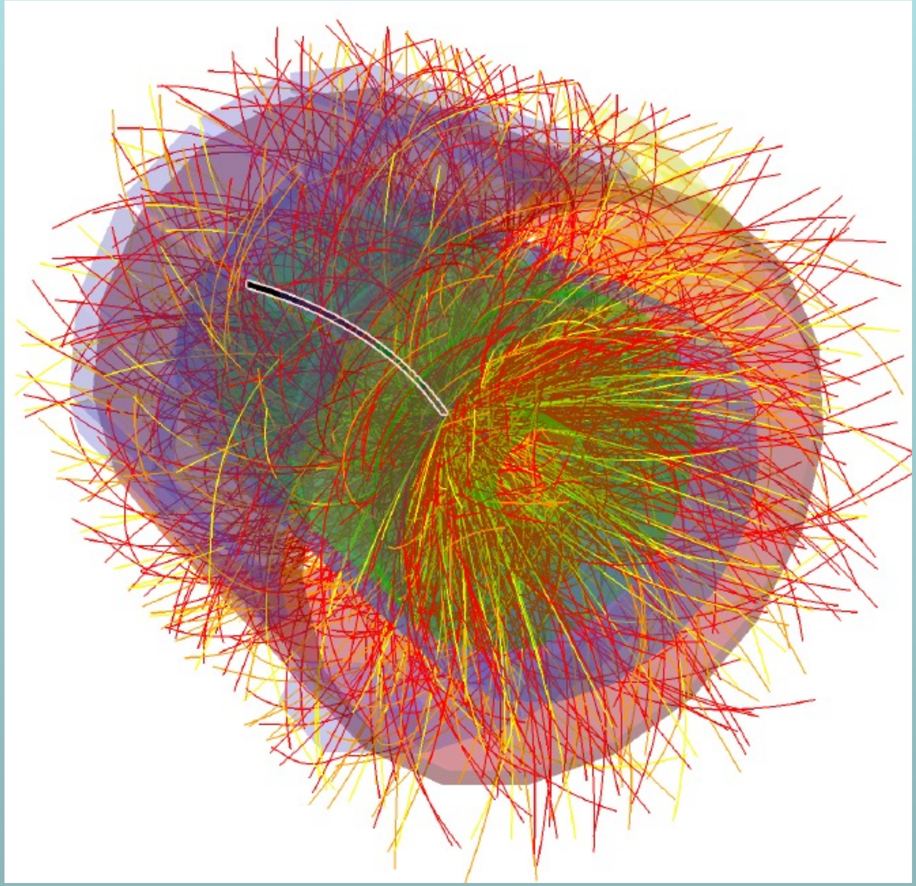
September 30th, 2022
ExHIC Workshop (APCTP)

Benjamin Dönigus

Institut für Kernphysik

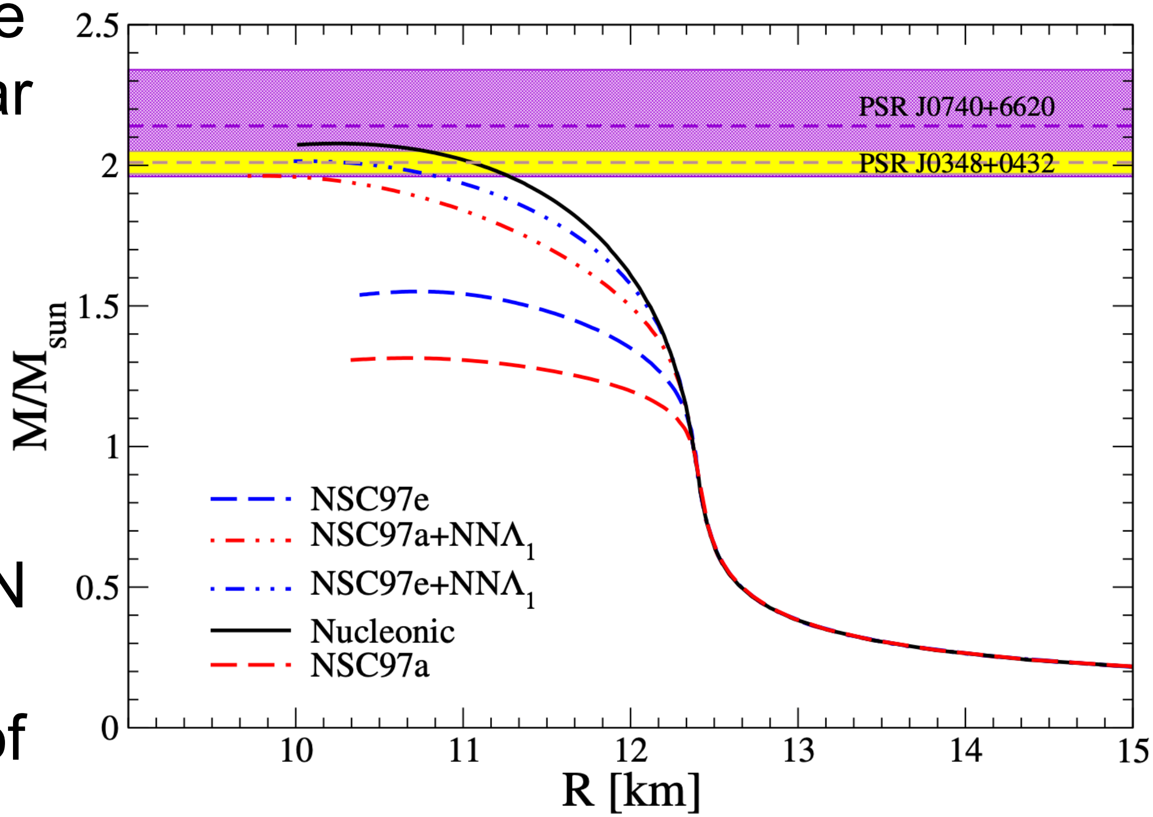
Goethe Universität Frankfurt

Introduction



Hypernuclei

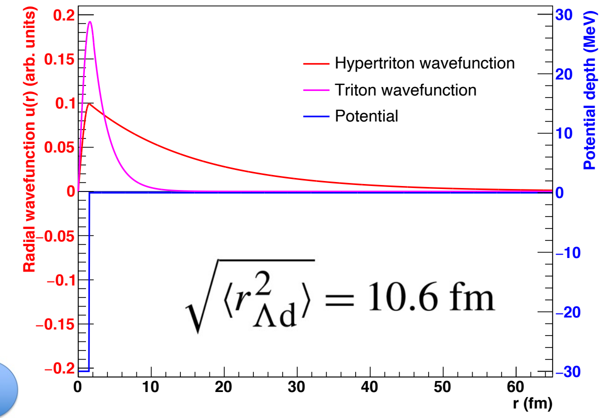
- Hypernuclei are unique probes to study nuclear structure
- Single Λ-hypernuclei are major source of extracting Λ-N interaction
- Correct Λ-N and Λ-N-N interaction needed to understand structure of neutron stars

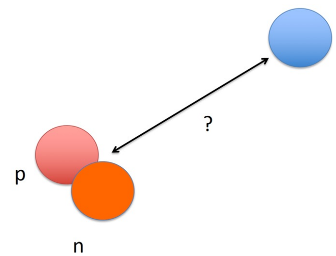


D. Logoteta et al., Astron. Astrophys. 646 (2021) A55

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

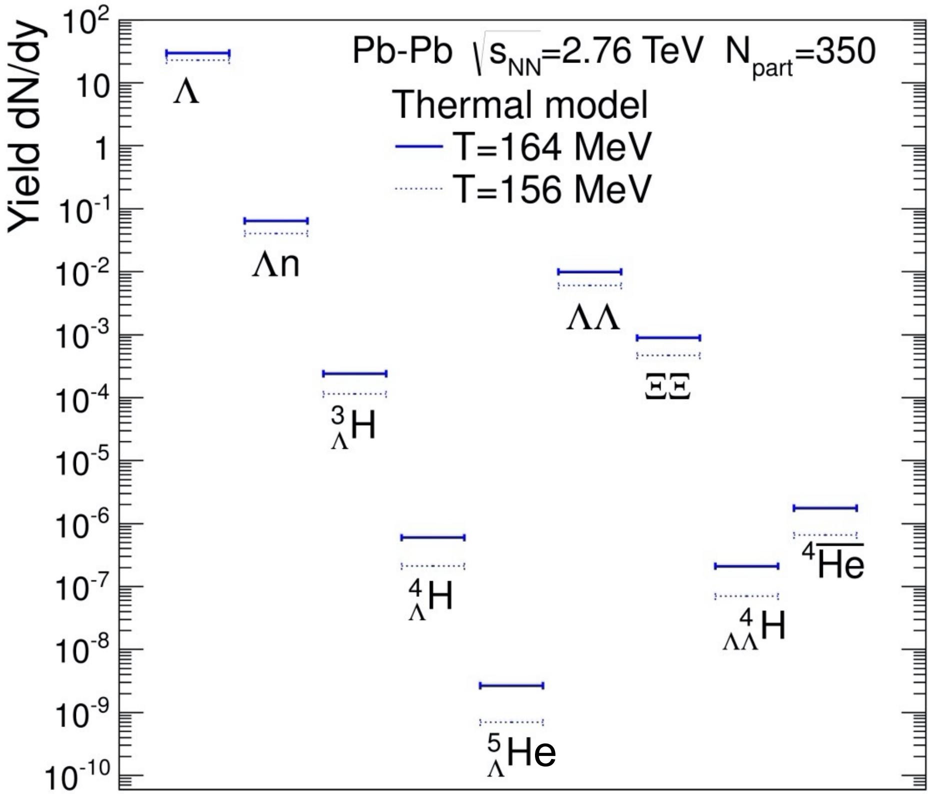




P. Braun-Munzinger, BD, Nucl. Phys. A 987 (2019) 144
F. Hildenbrand, H.-W. Hammer Phys.Rev.C 100 (2019) 3

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

Motivation

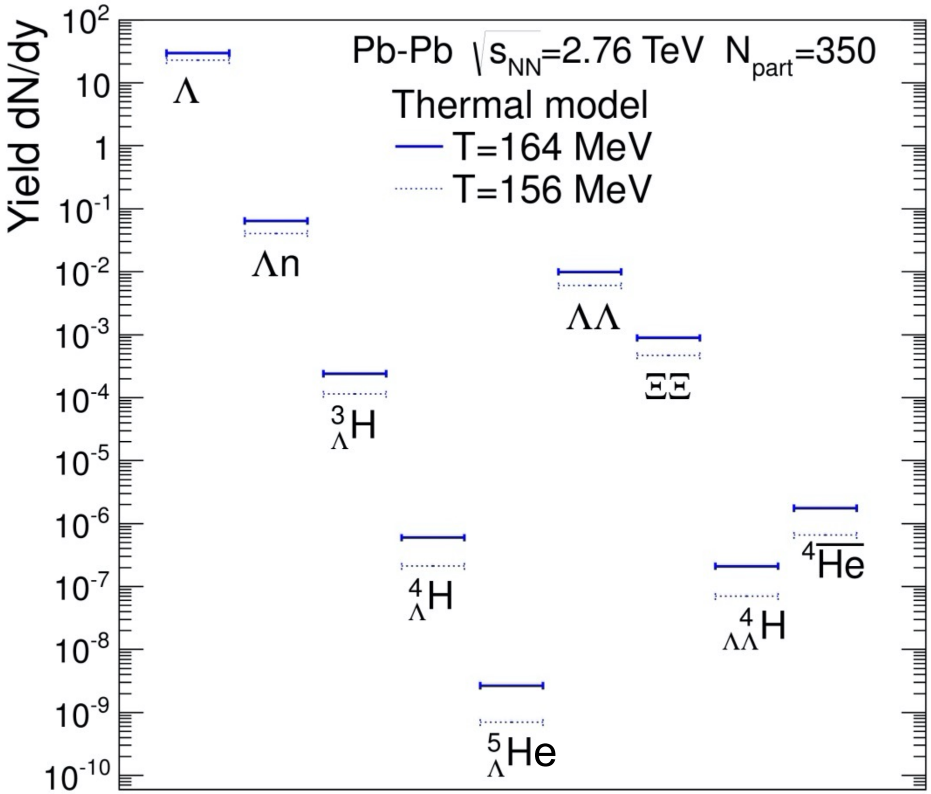


A. Andronic et al., PLB 697, 203 (2011) and references therein for the model, figure from A. Andronic, private communication

- 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

→ Understand production mechanisms

Motivation



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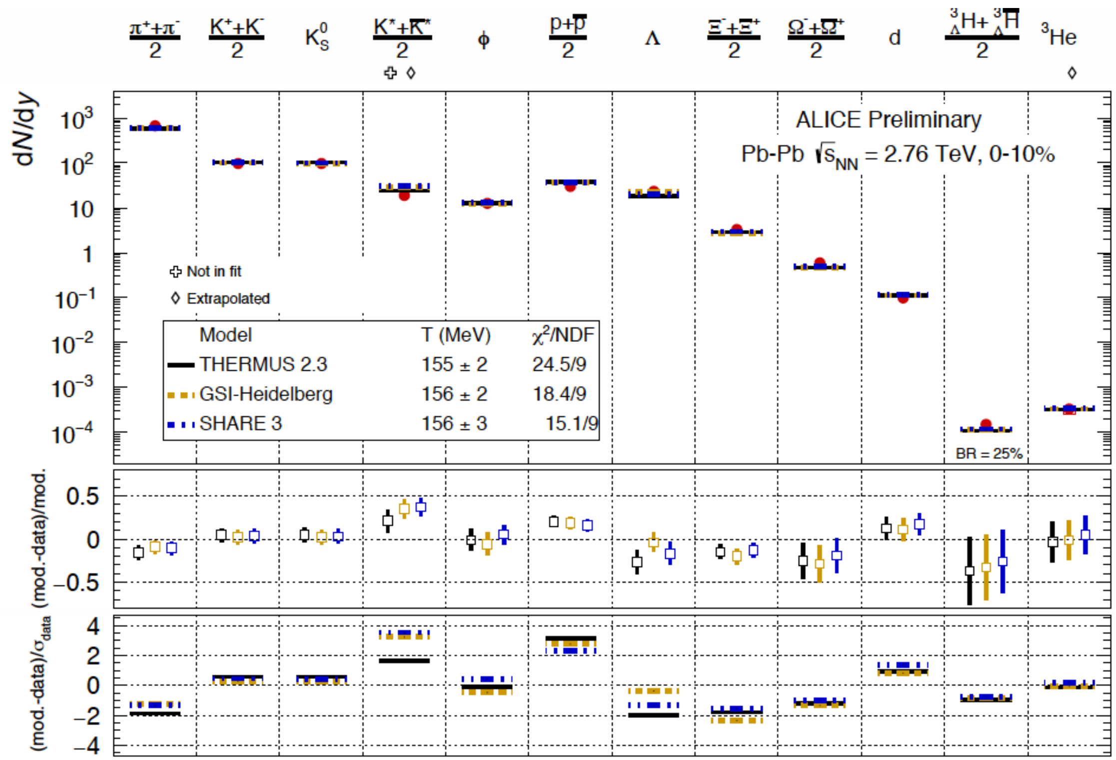
- Explore QCD and QCD inspired model predictions for (unusual) multi-baryon states
- Search for rarely produced anti- and hyper-matter
- Test model predictions, e.g. thermal and coalescence

→ Understand production mechanisms

→ Basis are light (anti-)nuclei

Thermal model

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

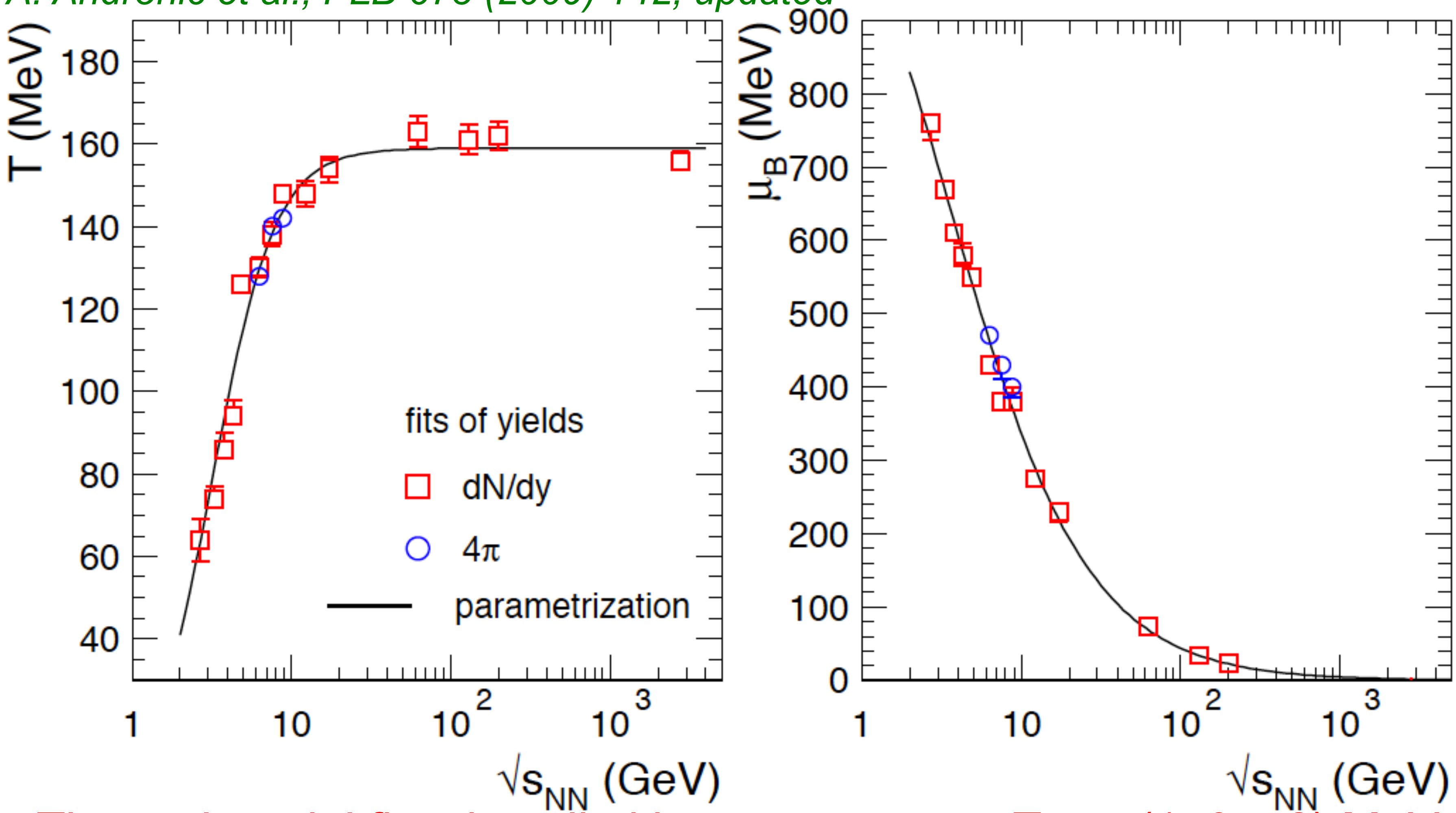


- chemical freeze-out temperature T_{ch}
- baryo-chemical potential μ_B
- Volume V

→ Using particle yields as input to extract parameters

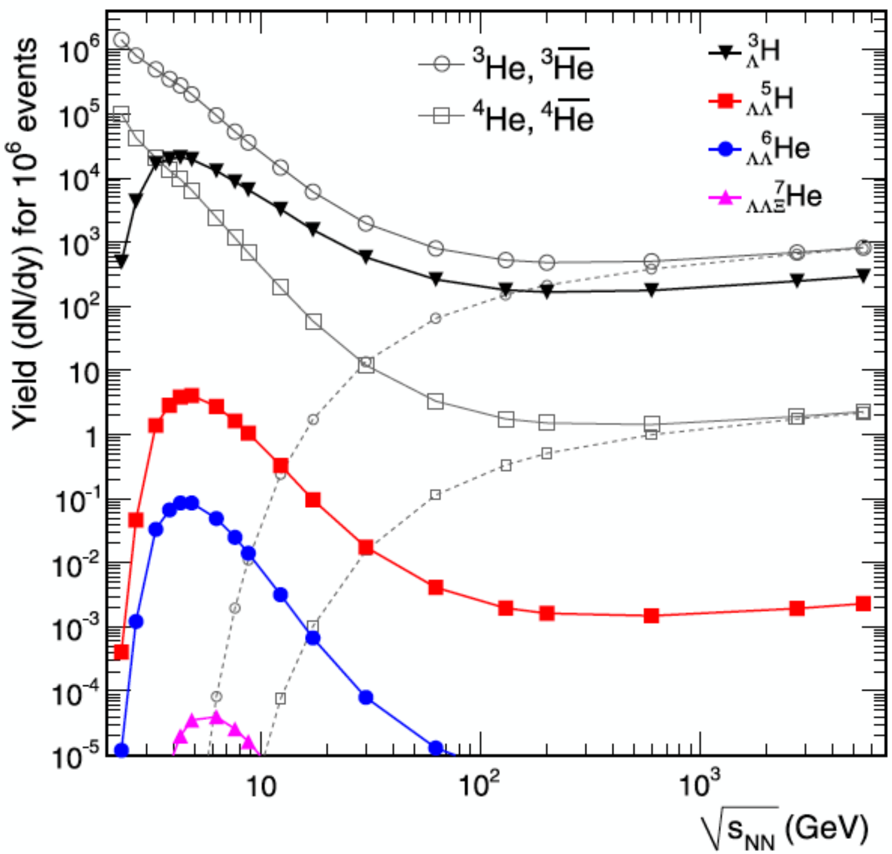
Energy dependence

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}

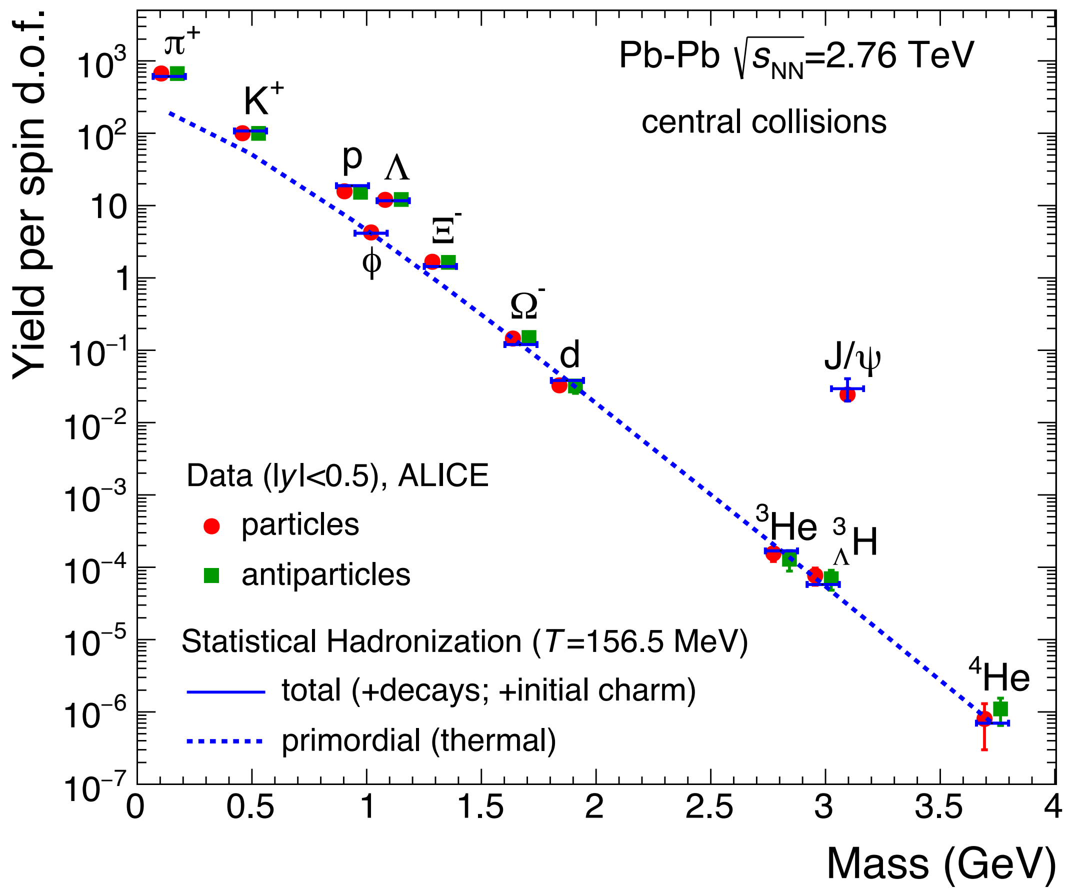
Strong sensitivity of abundance of nuclei to choice of T_{ch} due to:

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

→ Binding energies small compared to T_{ch}

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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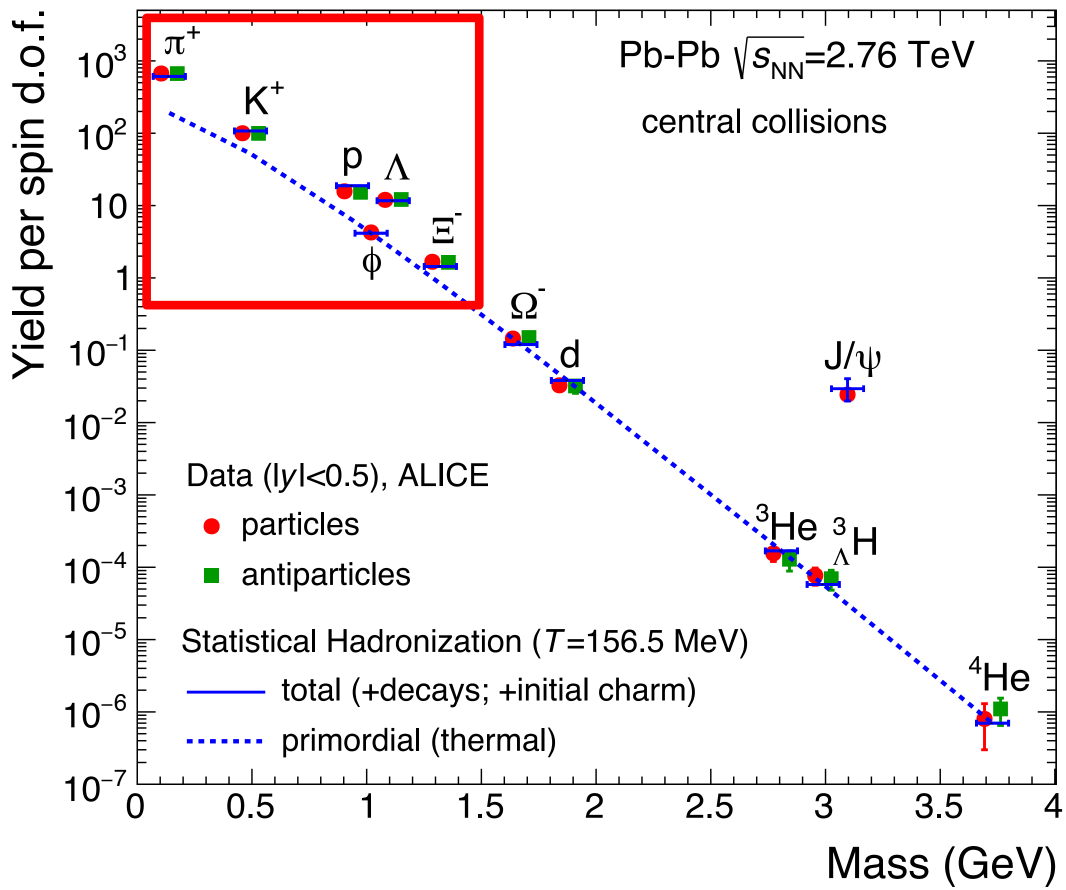

A. Andronic et al., Phys.Lett.B 797 (2019) 134836

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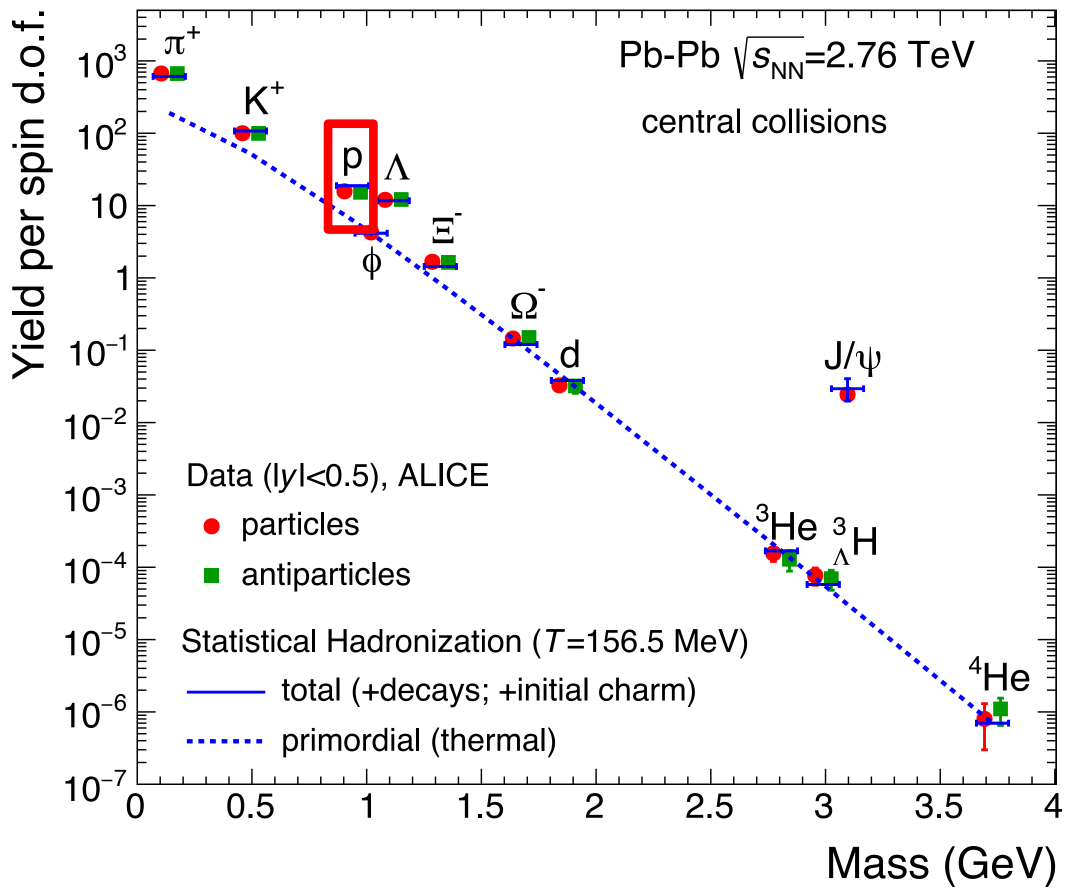

A. Andronic et al., Phys.Lett.B 797 (2019) 134836

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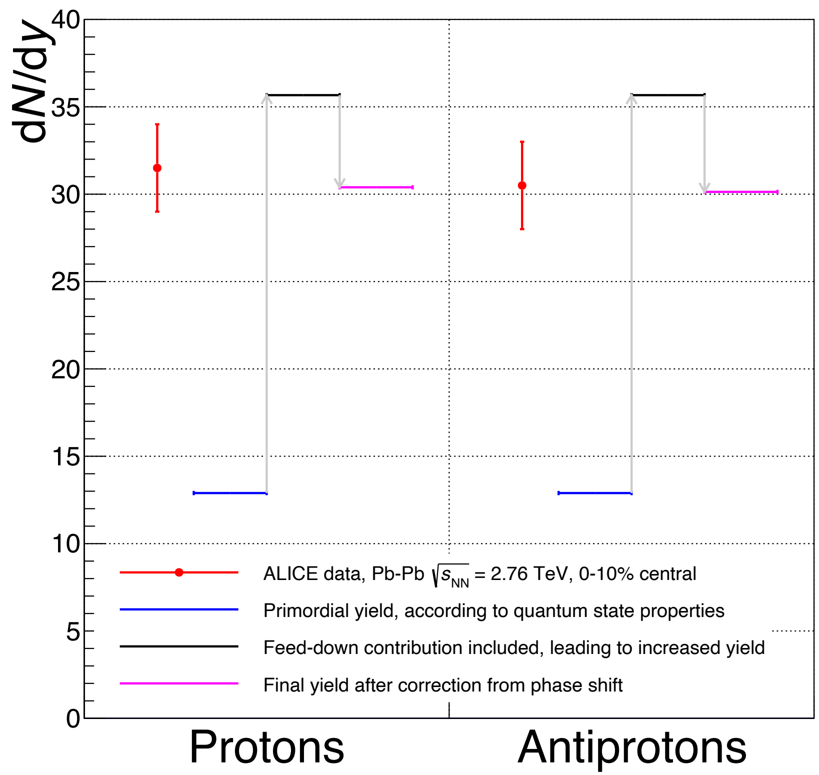
BD, G. Röpke, D. Blaschke, arXiv:2206.10376, accepted by PRC



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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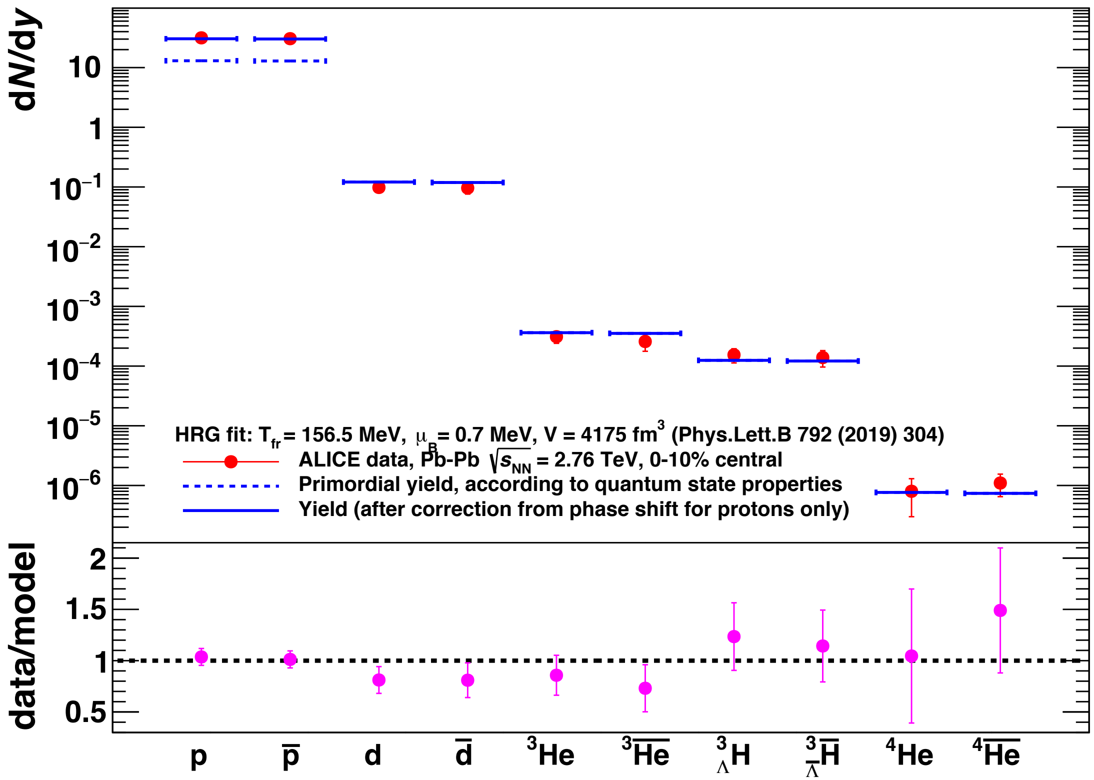

A. Andronic et al., Phys.Lett.B 797 (2019) 134836; Nature 561 (2018) 7723, 321; Phys.Lett.B 697 (2011) 203; Phys.Lett.B 792 (2019) 304

Thermal model

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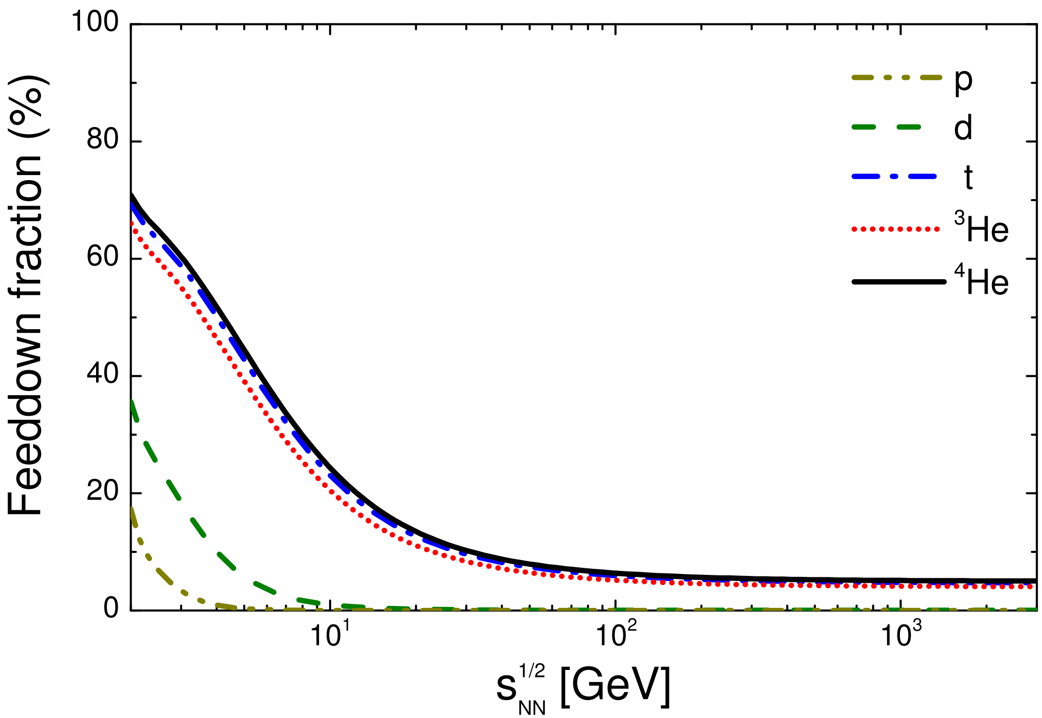
- Seems to not be the case for (hyper-)nuclei at LHC

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



Thermal model

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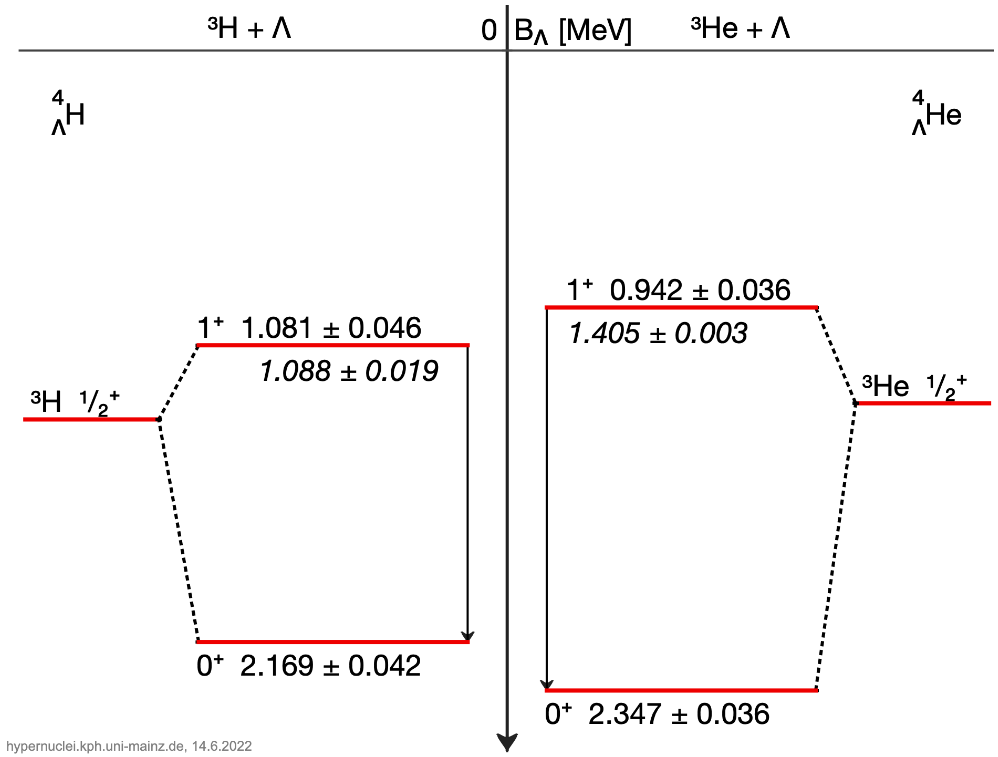
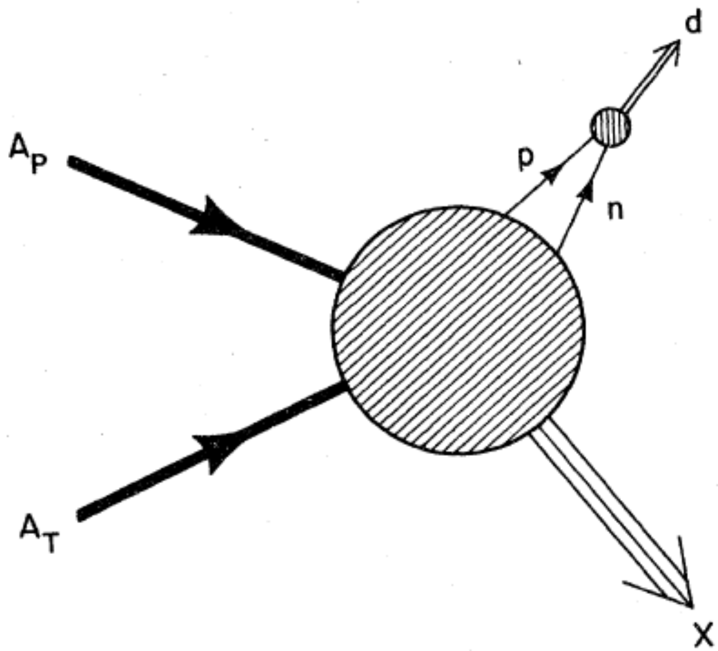
- All light hadron production yields are populated strongly by resonances
- Seems to not be the case for (hyper-)nuclei
- Important for A=4 hypernuclei !



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

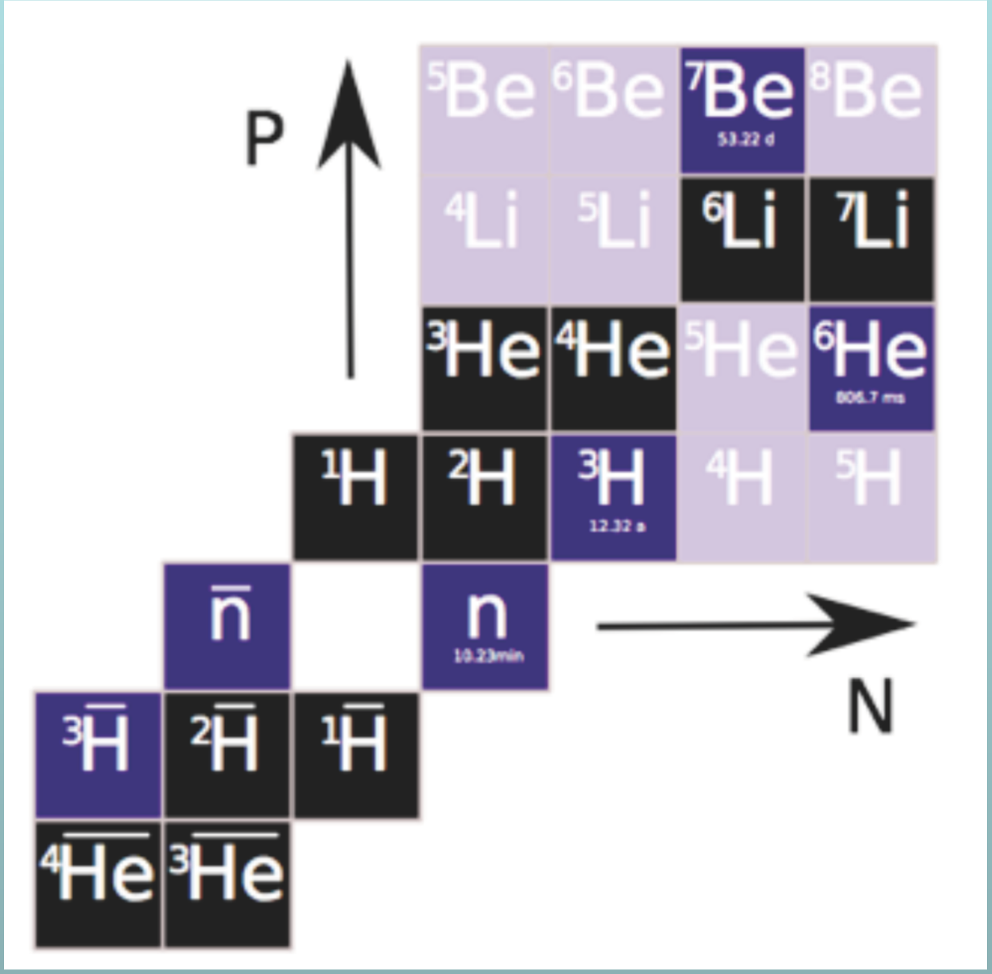


J. I. Kapusta, PRC 21, 1301 (1980)

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

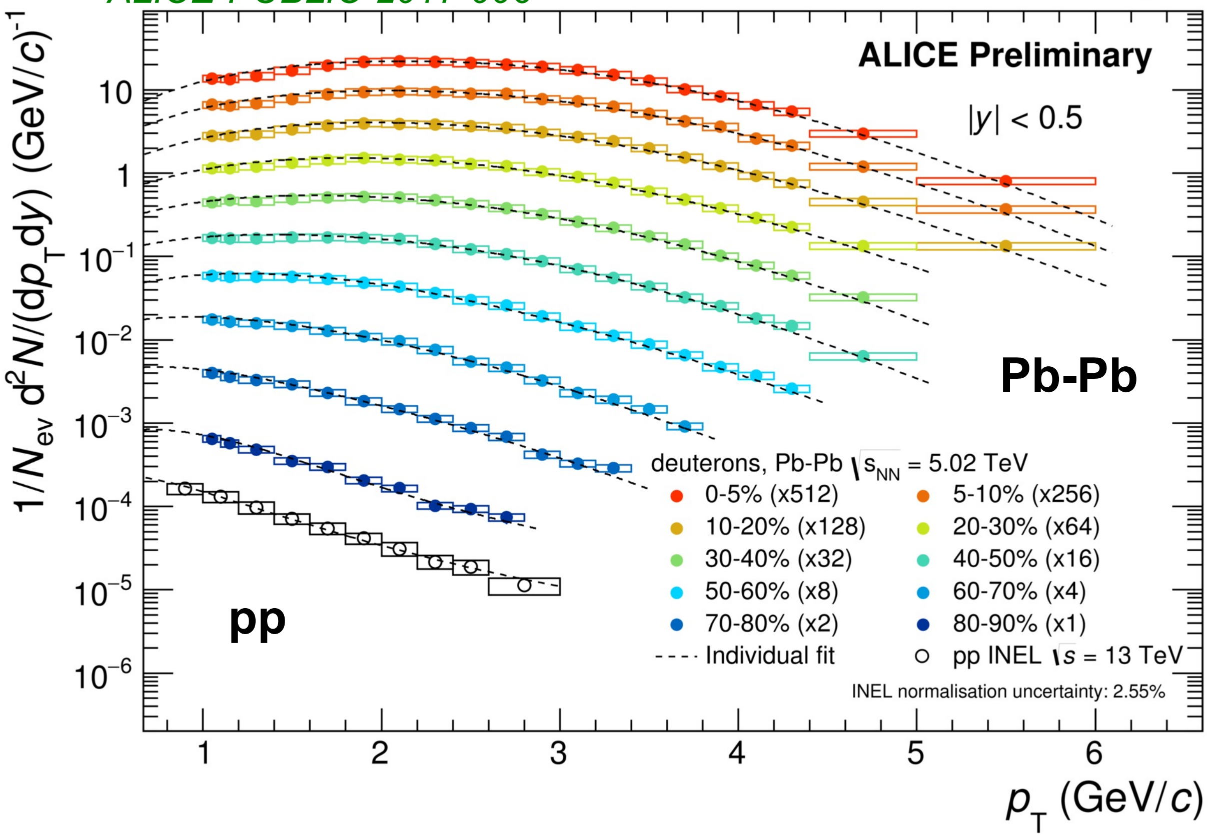
(Anti-)Nuclei



P
N
⁵Be
⁶Be
⁷Be
53.22 d
⁸Be
⁴Li
⁵Li
⁶Li
⁷Li
³He
⁴He
⁵He
⁶He
806.7 ms
¹H
²H
³H
12.32 a
⁴H
⁵H
n̄
n
10.23min

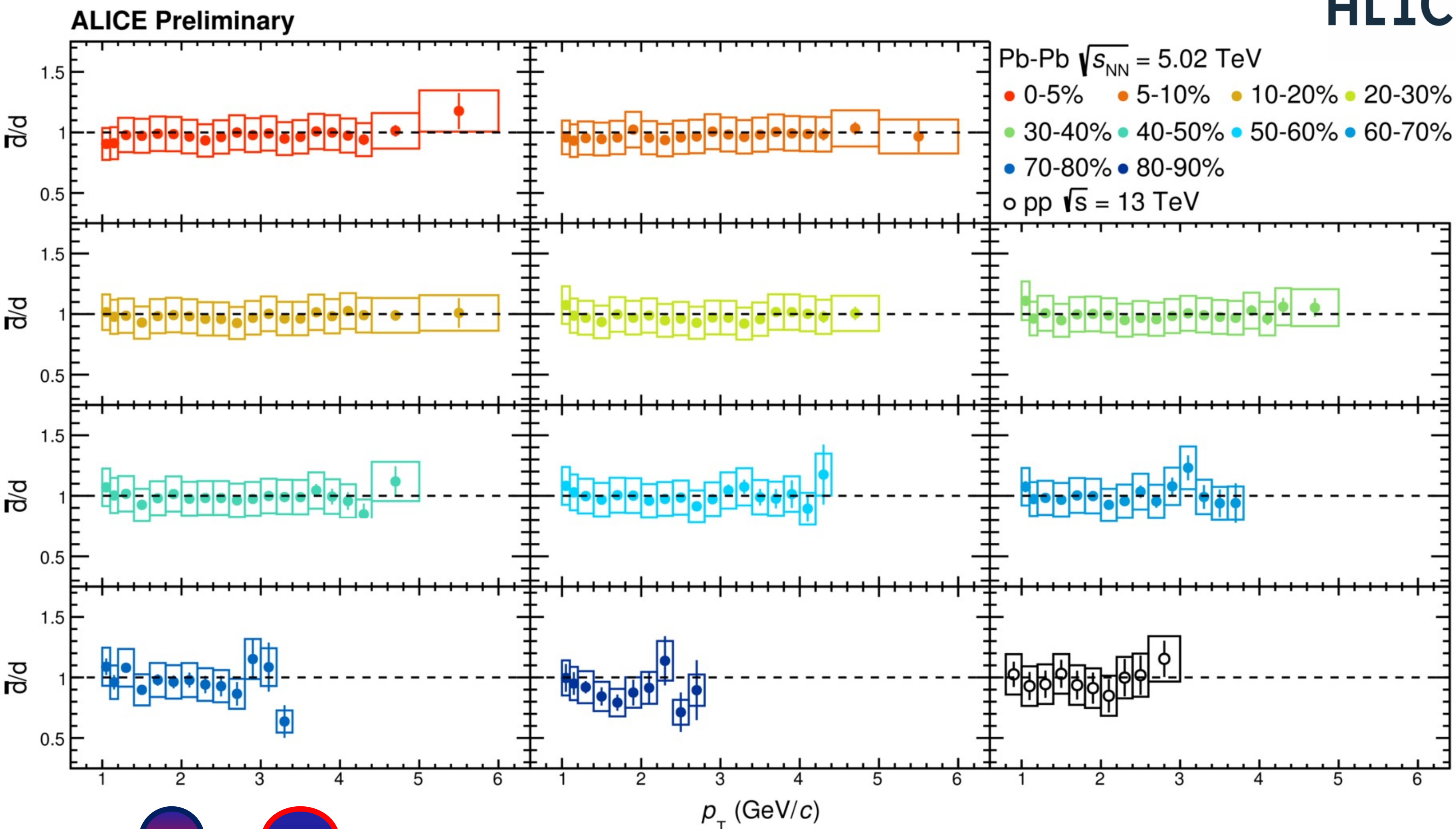
Deuterons

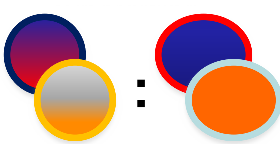
ALICE-PUBLIC-2017-006



- pT-Spektra 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

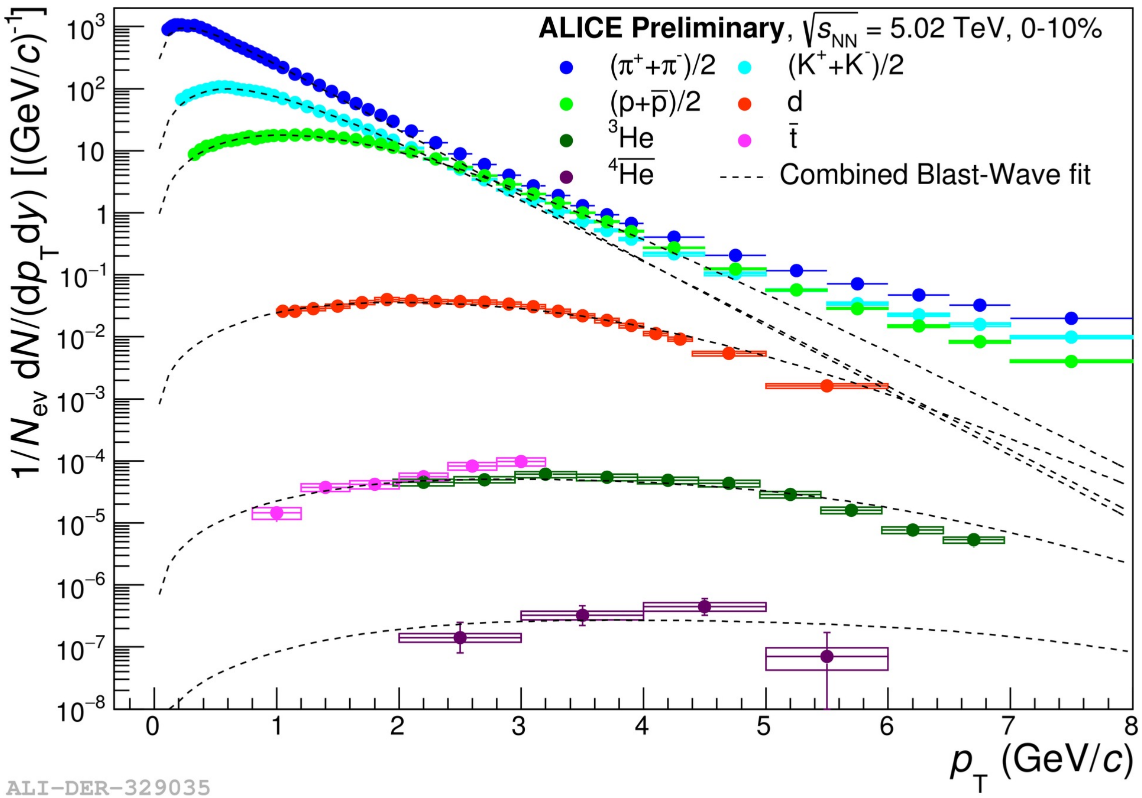
(Anti-)Deuteron ratio



 : -ratios consistent with unity, as expected

Combined Blast-Wave fit

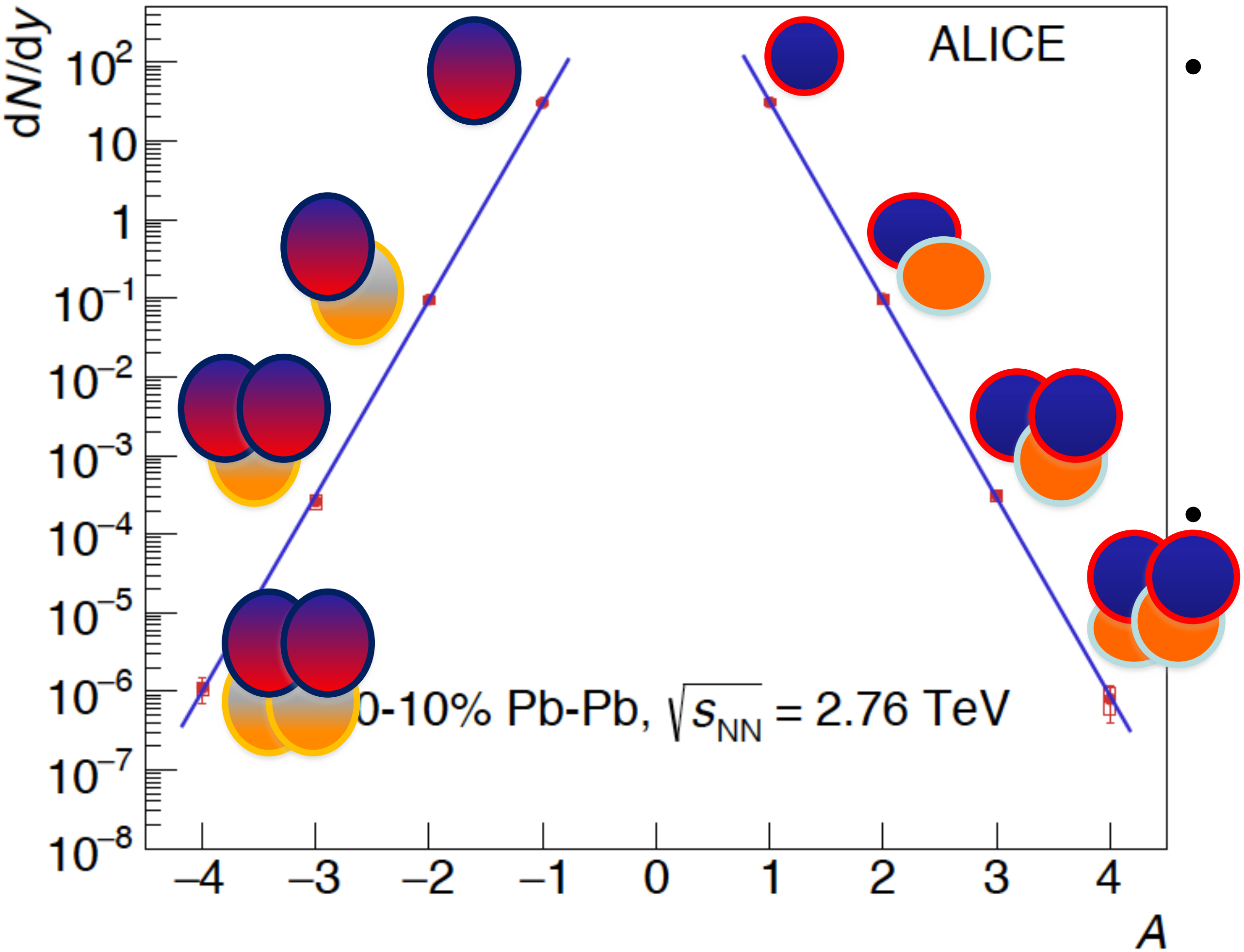
ALICE Collaboration, arXiv:1910.07678



- 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

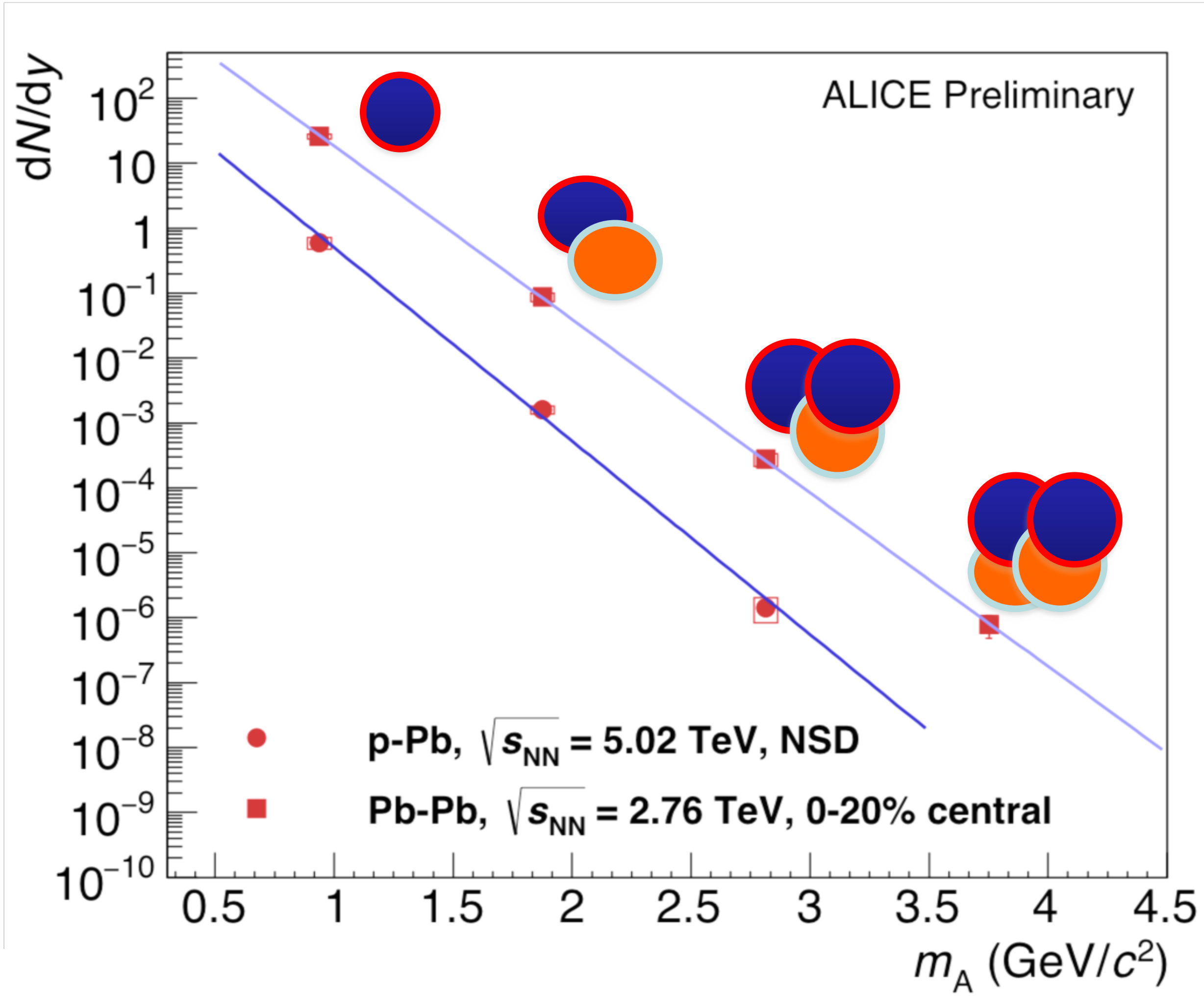
Mass dependence



- 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)

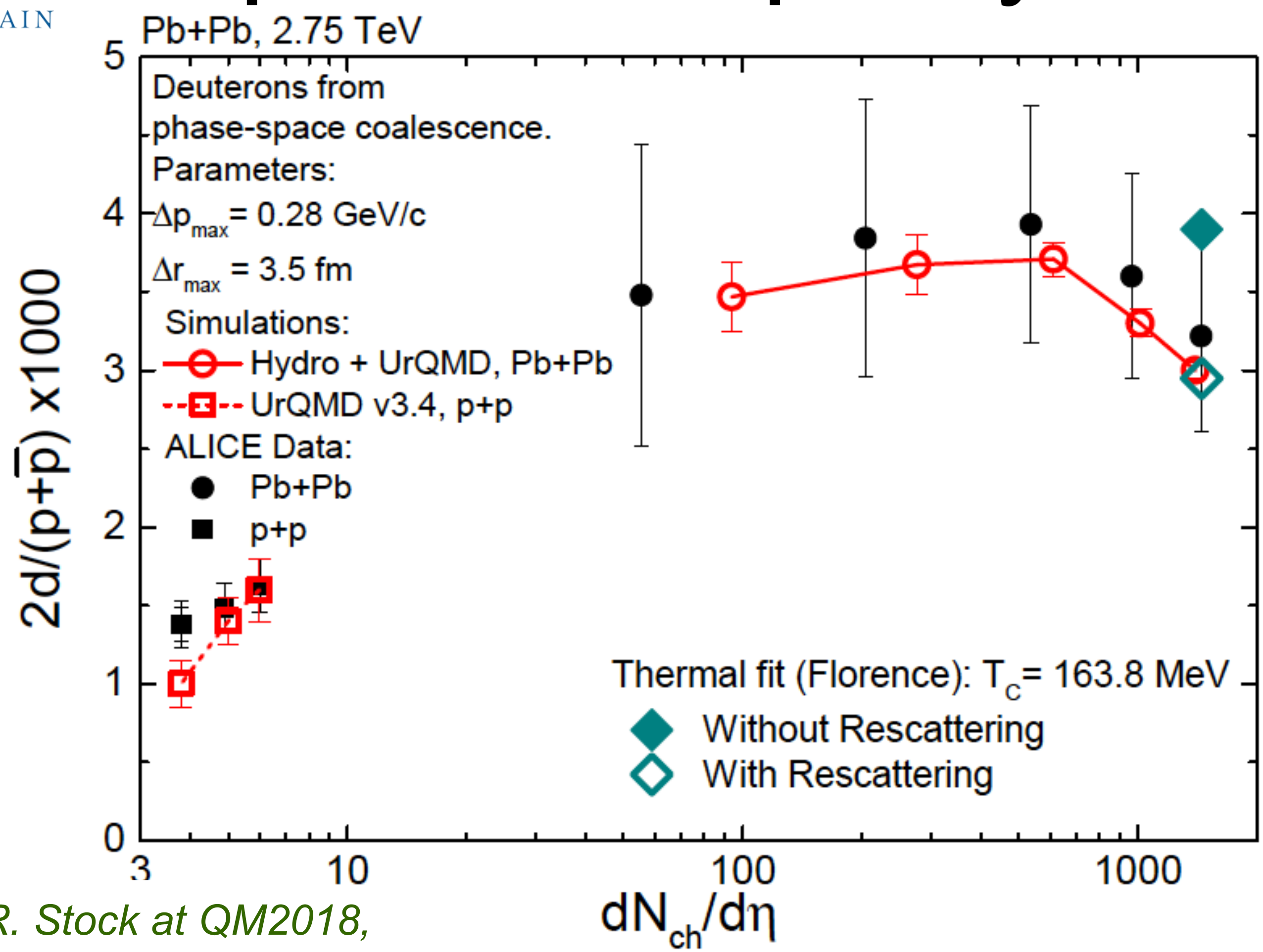
ALICE Collaboration, arXiv:1710.07531, NPA 971, 1 (2018)

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

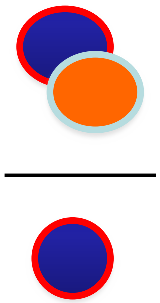
d/p vs. multiplicity

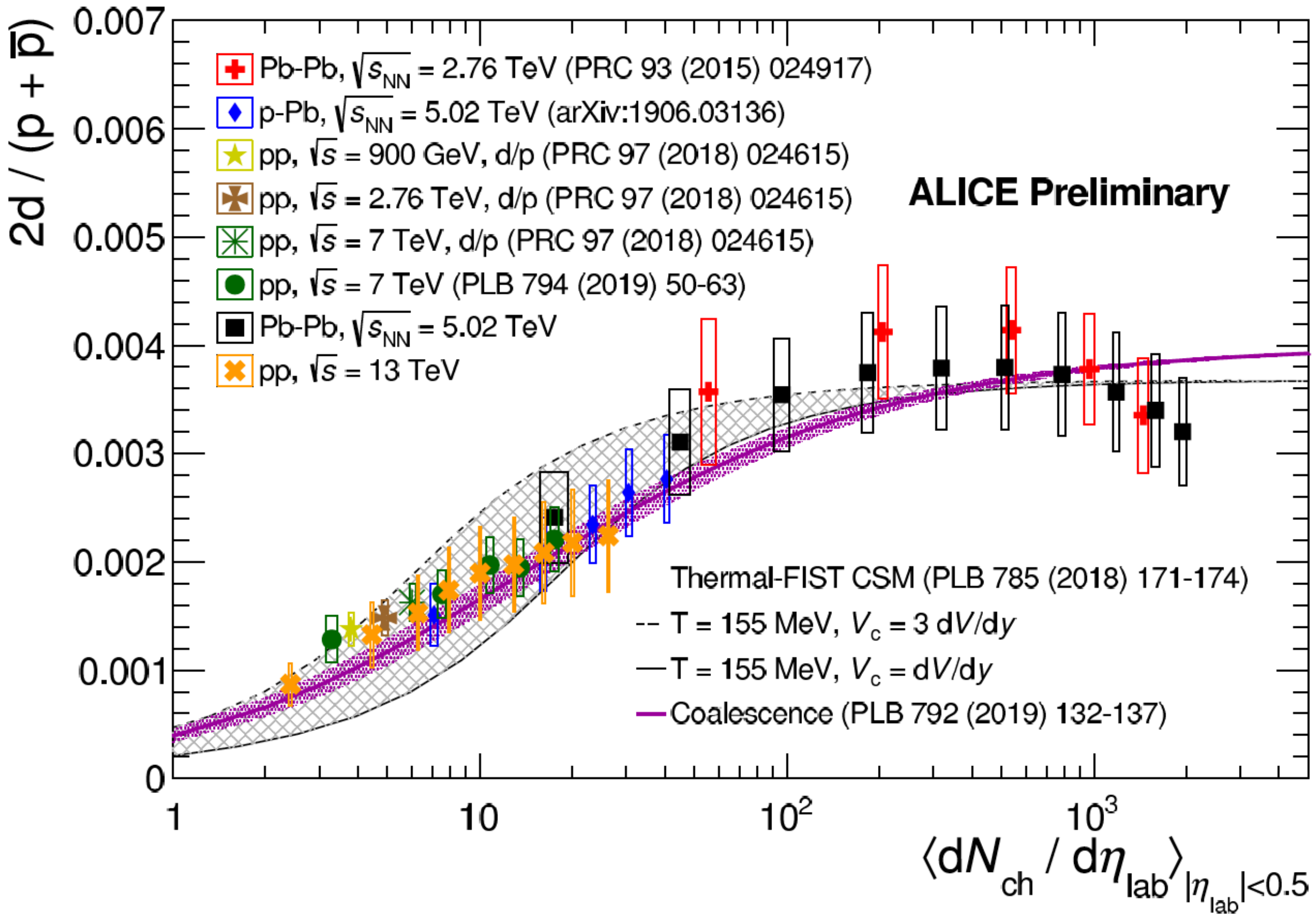


As shown by R. Stock at QM2018,
meanwhile coalsecence published: S. Sombun et al., Phys.Rev.C 99 (2019) 014901

d/p ratio described by applying afterburner on Hybrid UrQMD simulations – similar results for thermal approach

d/p vs. multiplicity

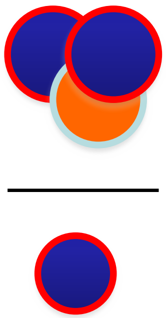


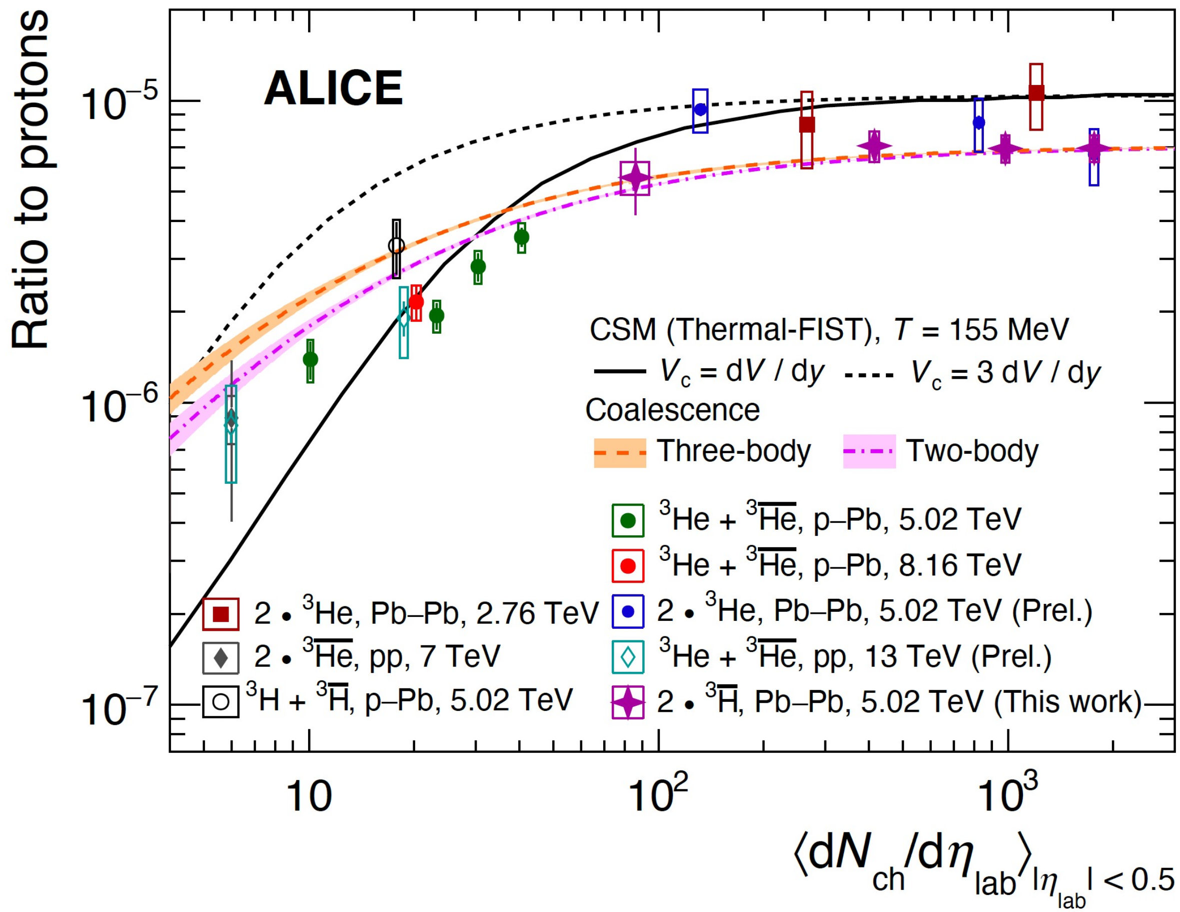


Models:
Coalescence: K.J. Sun, C.M. Ko, BD, PLB 792 (2019) 132
CSM: V.Vovchenko, BD, H. Stöcker, PLB 785 (2018) 171

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

^{3}He/p vs. multiplicity





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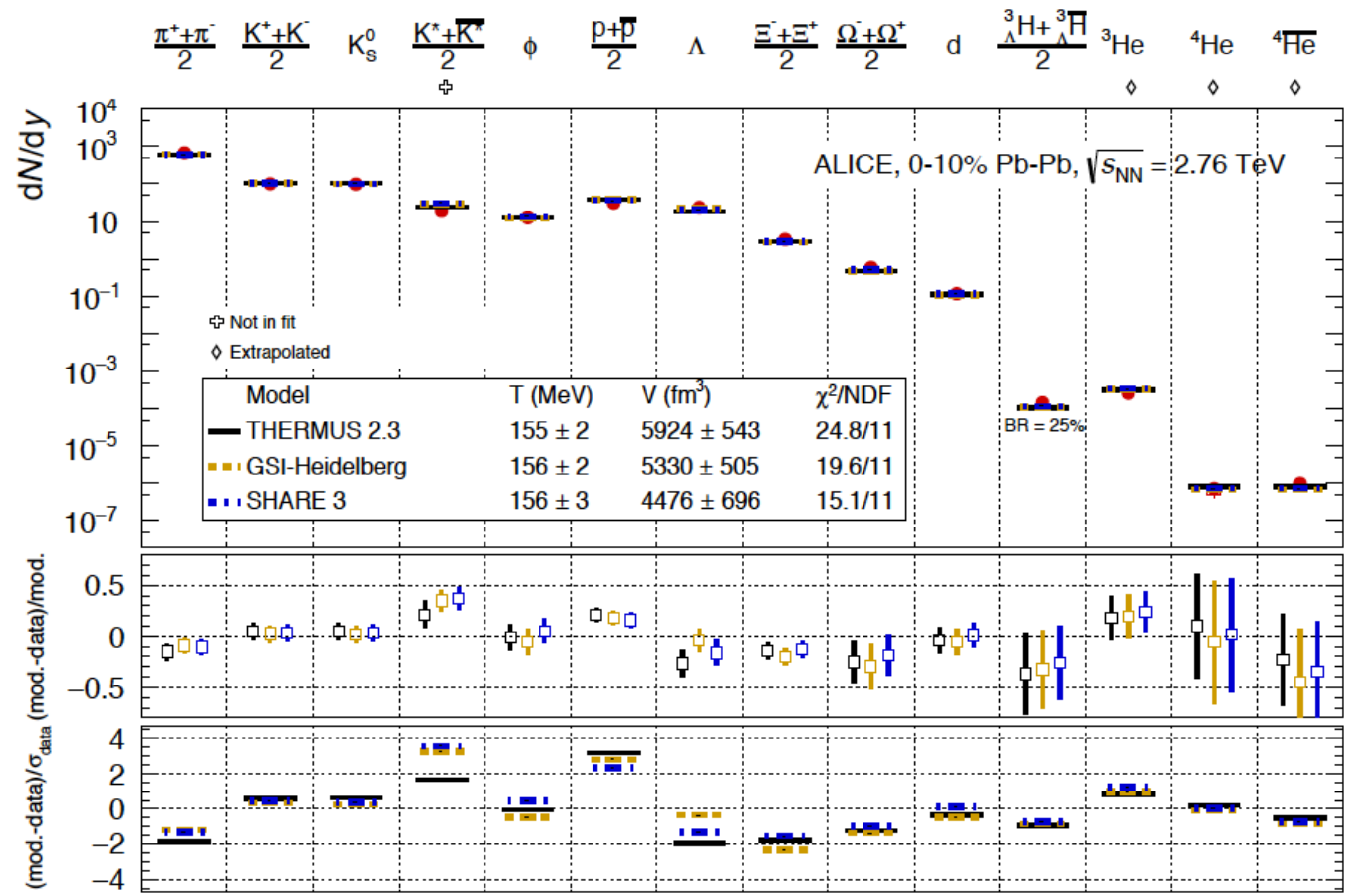
^{3}He/p and ^{3}H/p ratios are similarily well described by coalescence and (canonical) thermal model

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

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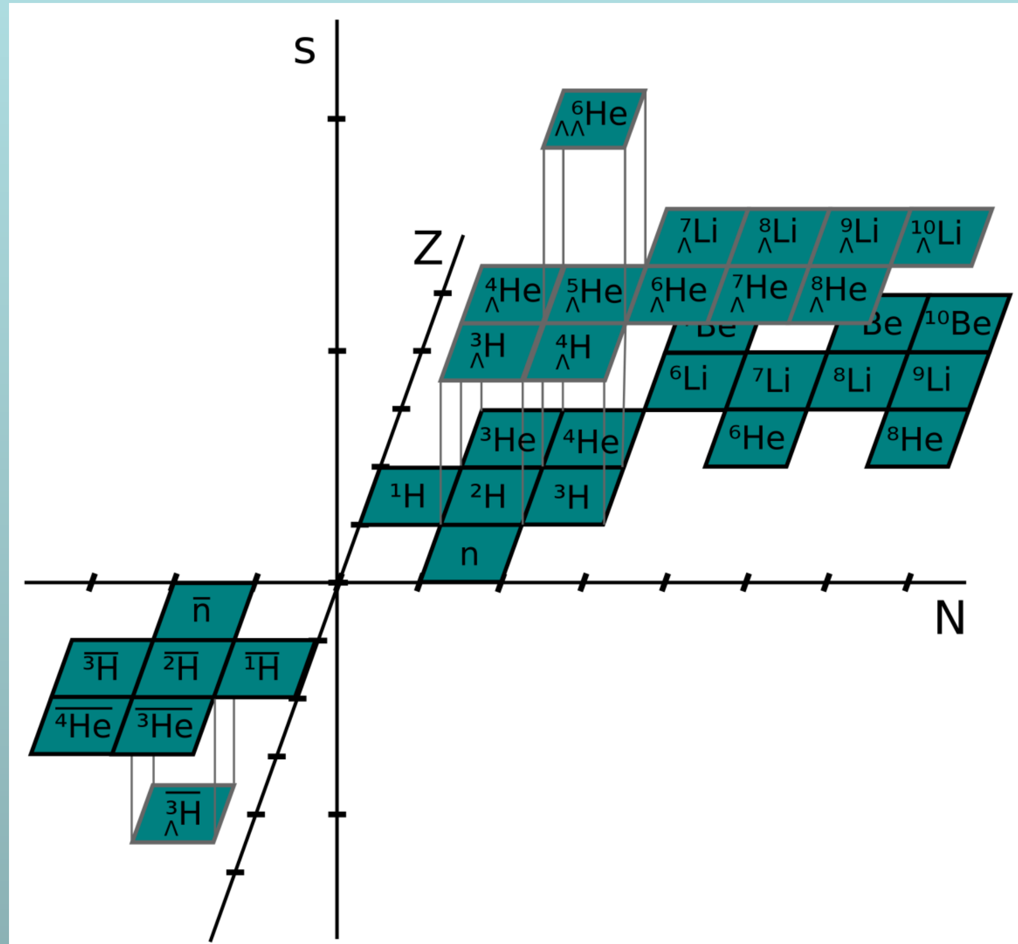
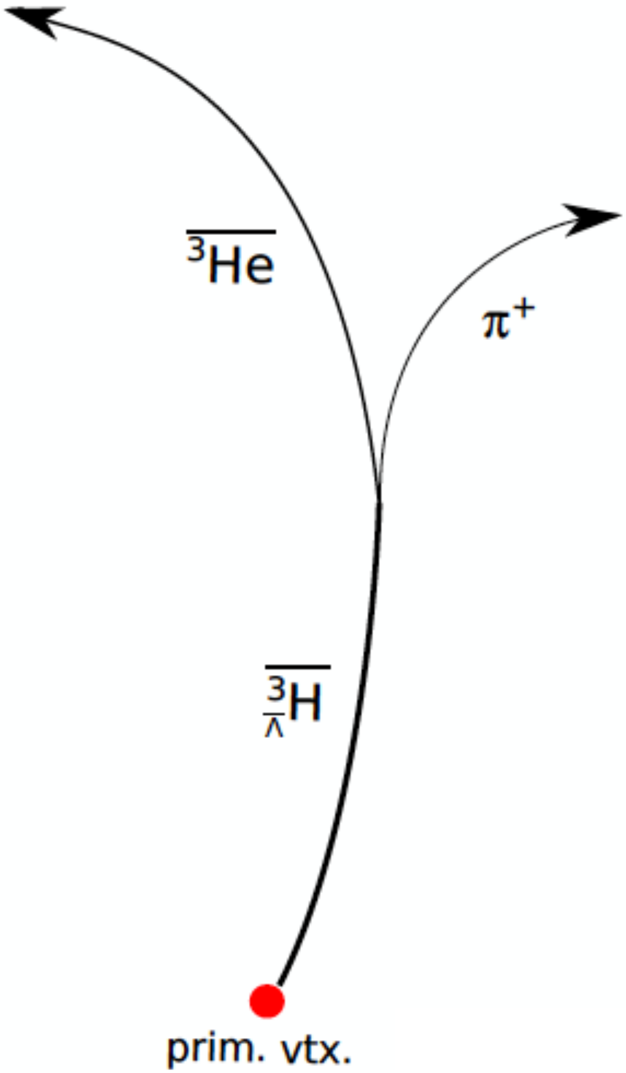
Hypernuclei



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:

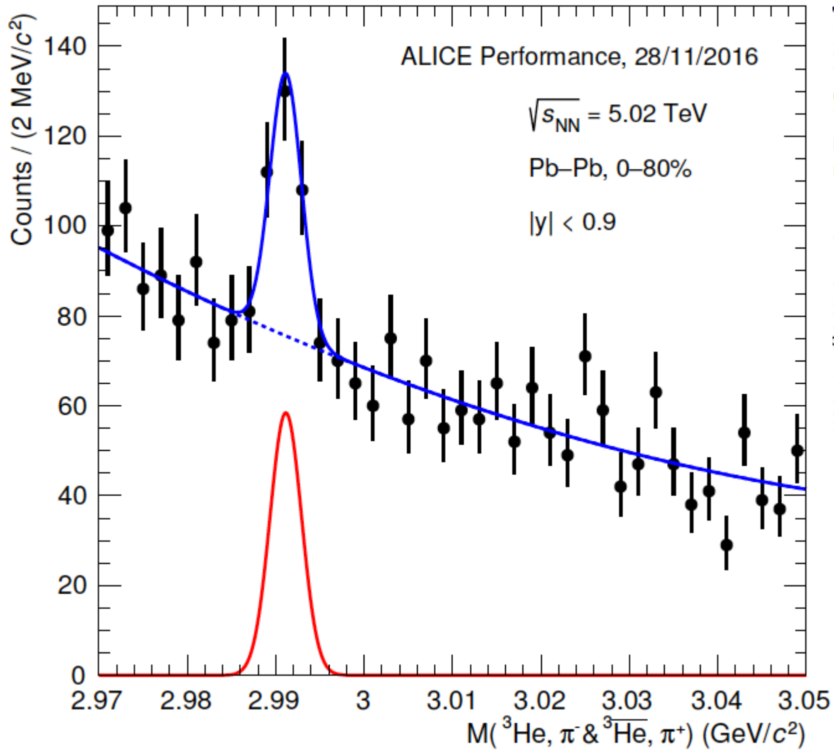
$$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\,\mathrm{He} + \pi^{-}$$
$$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\,\mathrm{H} + \pi^{0}$$
$$^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^{-}$$
$$^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{n} + \pi^{0}$$

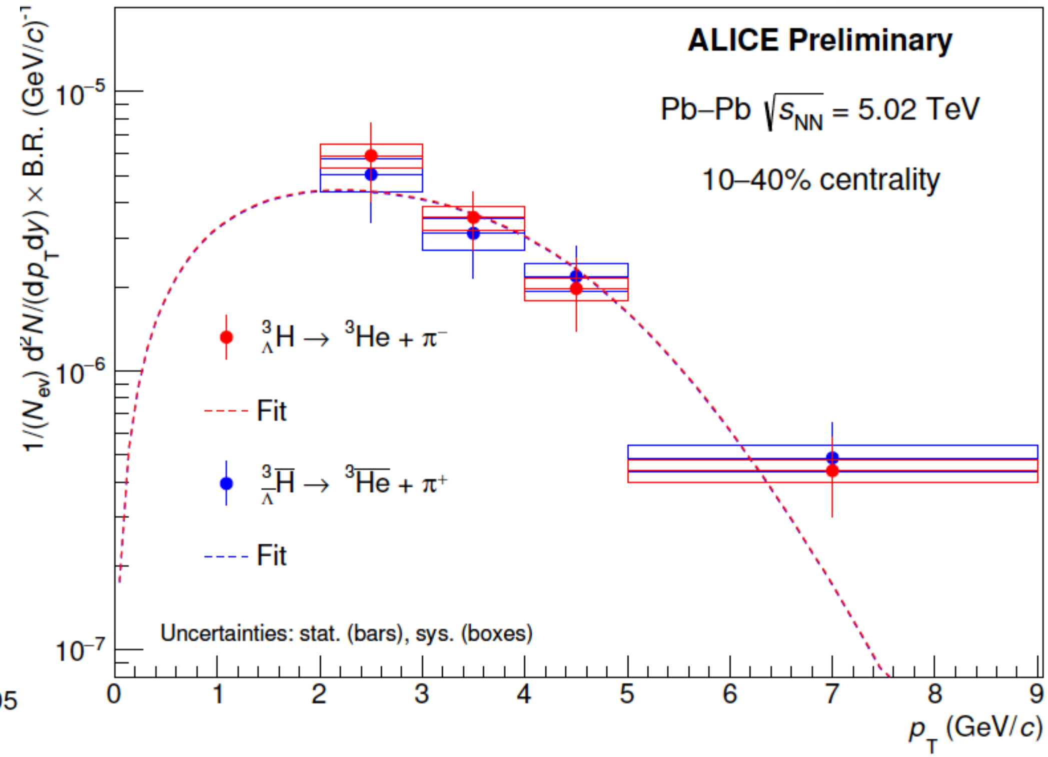
+ anti-particles

→ Anti-Hypertriton first observed by STAR Collaboration:

Science 328,58 (2010)

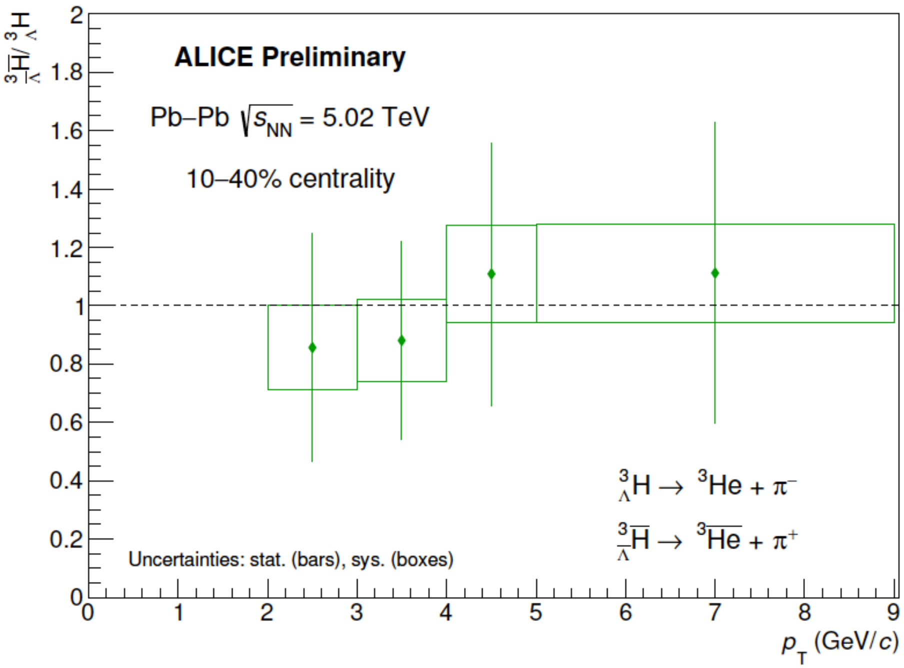
Hypertriton signal

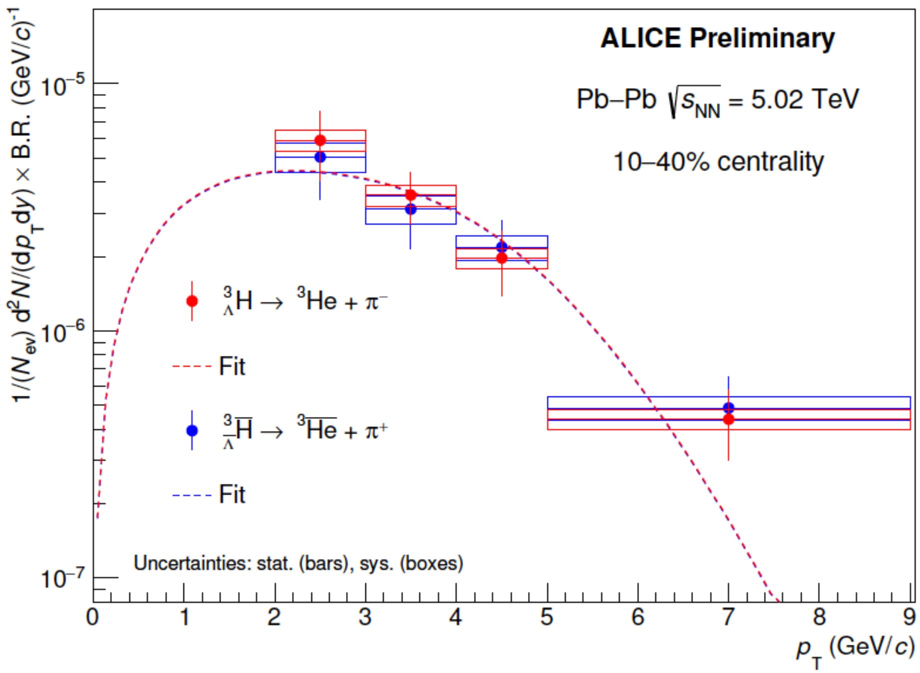




- Clear signal reconstructed by decay products
- Spectra can also be described by Blast-Wave model
  → Hypertriton flows as all other particles

Hypertriton spectra

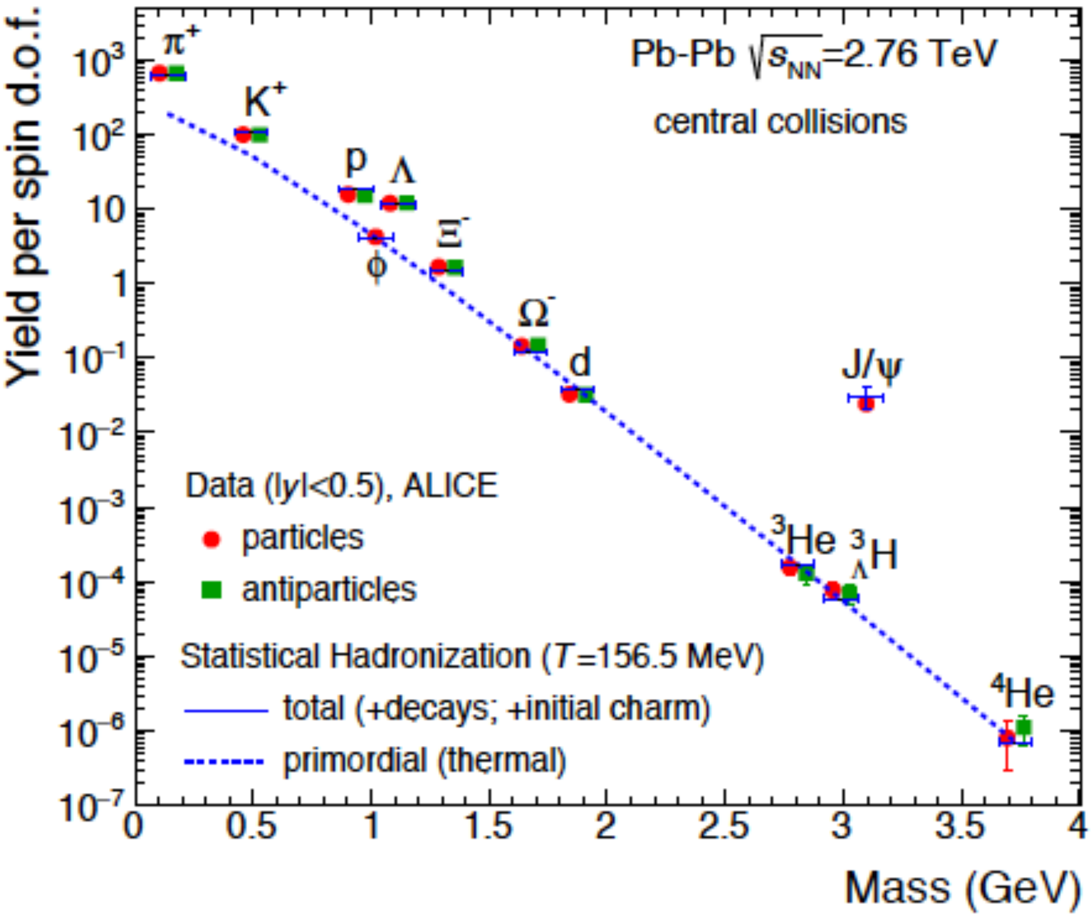




- Anti-hypertriton/Hypertriton ratio consistent with unity vs. p_T

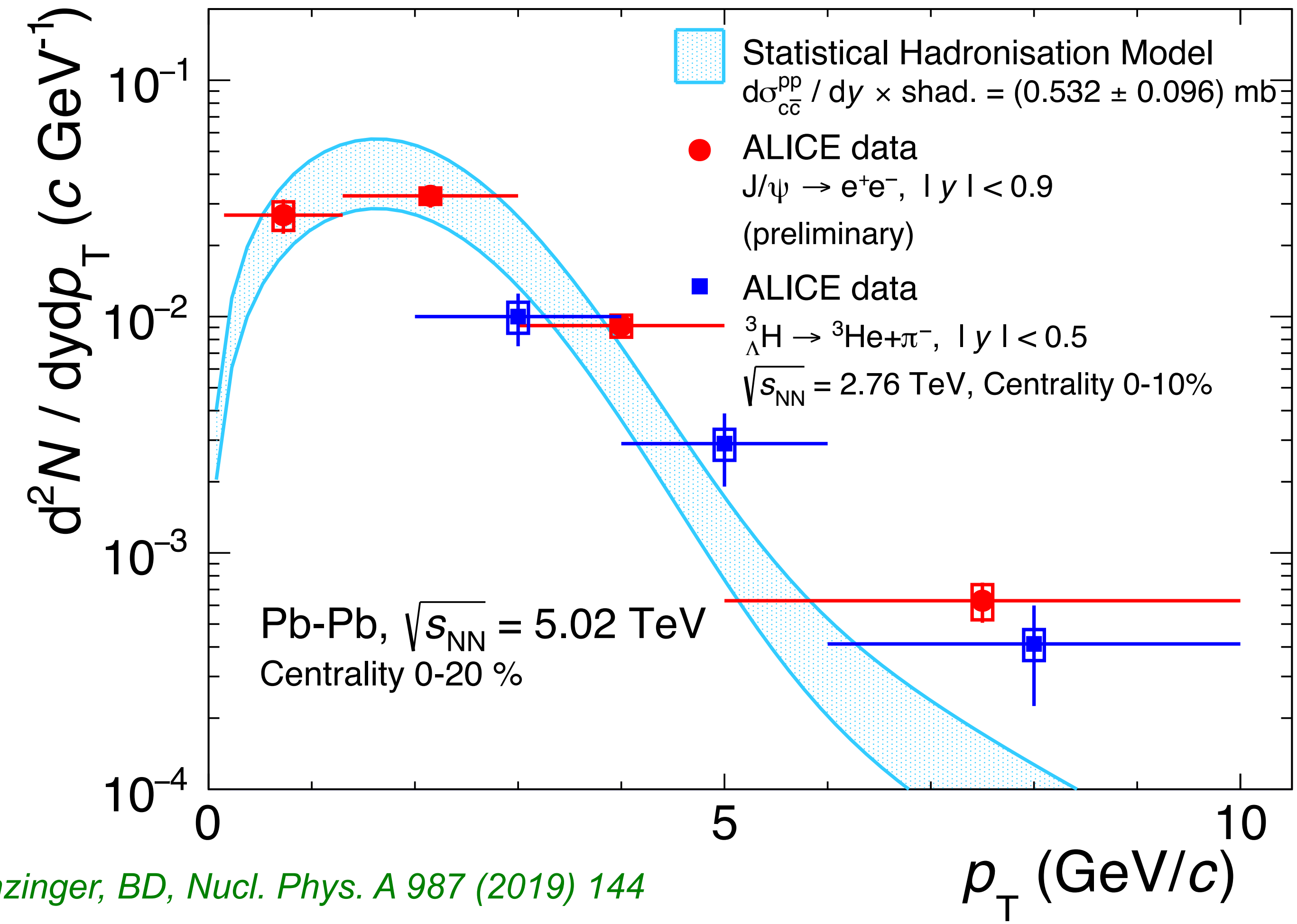
Fits: different view

A. Andronic et al., arXiv:1901.09200



- Excellent agreement over 9 orders of magnitude
- Fit of nuclei (d, ^{3}He, ^{4}He): T_{ch}=159 ± 5 MeV
- No feed-down for (anti-)(hyper-)nuclei
- charm quarks, out of chemical equilibrium, undergo statistical hadronization → only input: number of ccbar pairs

Hypertriton - J/ψ comparison

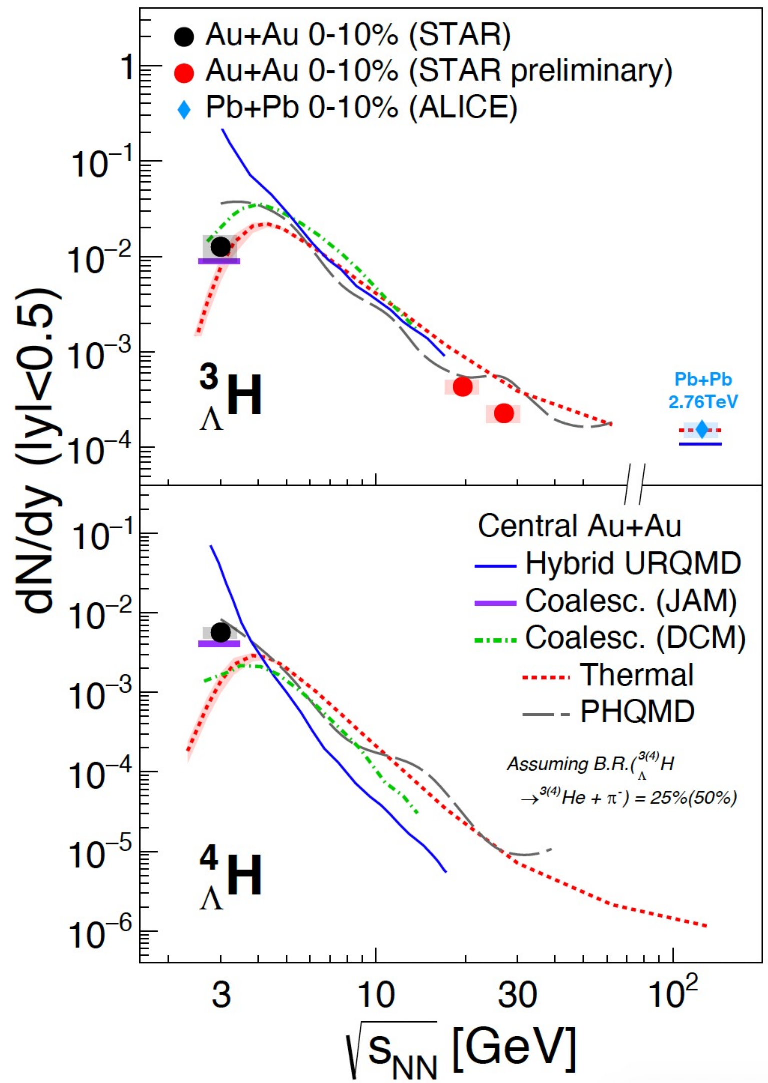


P. Braun-Munzinger, BD, Nucl. Phys. A 987 (2019) 144

- Shape of the p_T spectra of J/ψ and hypertriton agree very well, despite the binding energy of the hypertriton is 2.35 MeV and of the J/ψ 600 MeV

Hypernuclei yields

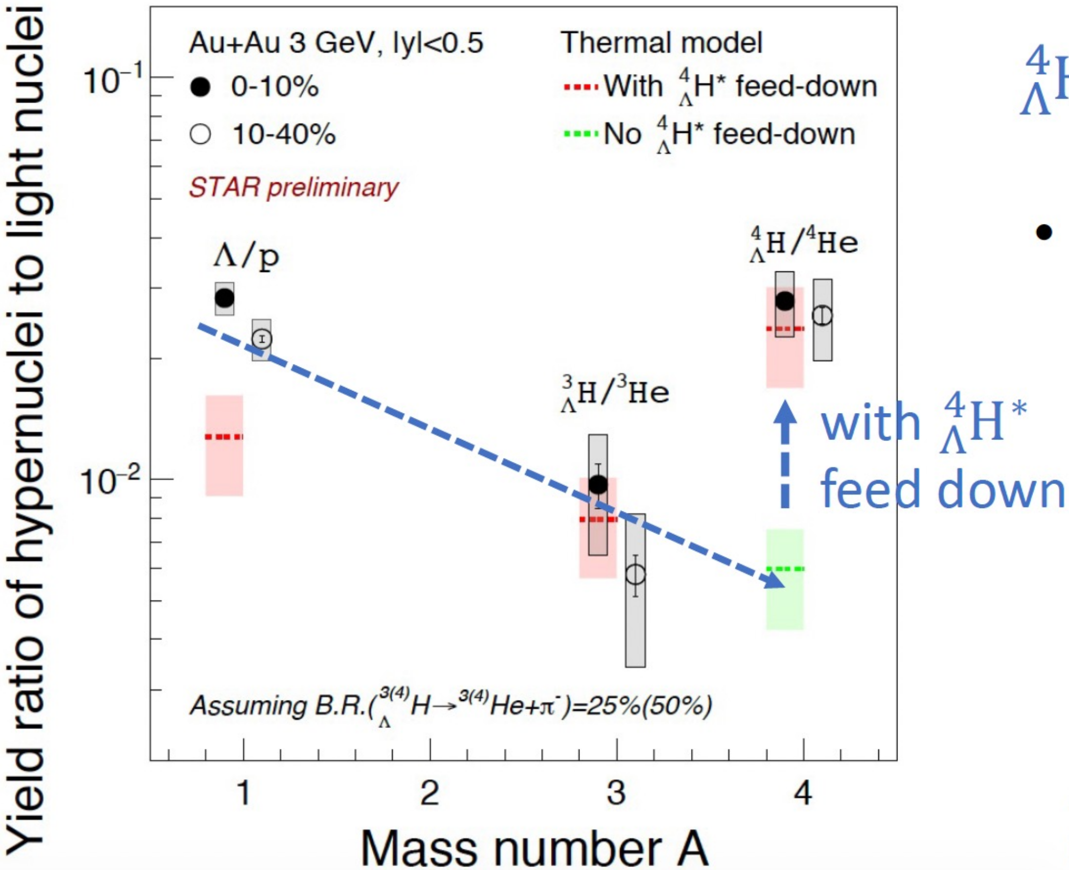
- Recent STAR preliminary results are slightly overestimated by models
- Trend vs. energy described qualitatively by all models



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

SQM talk by Y. Ji



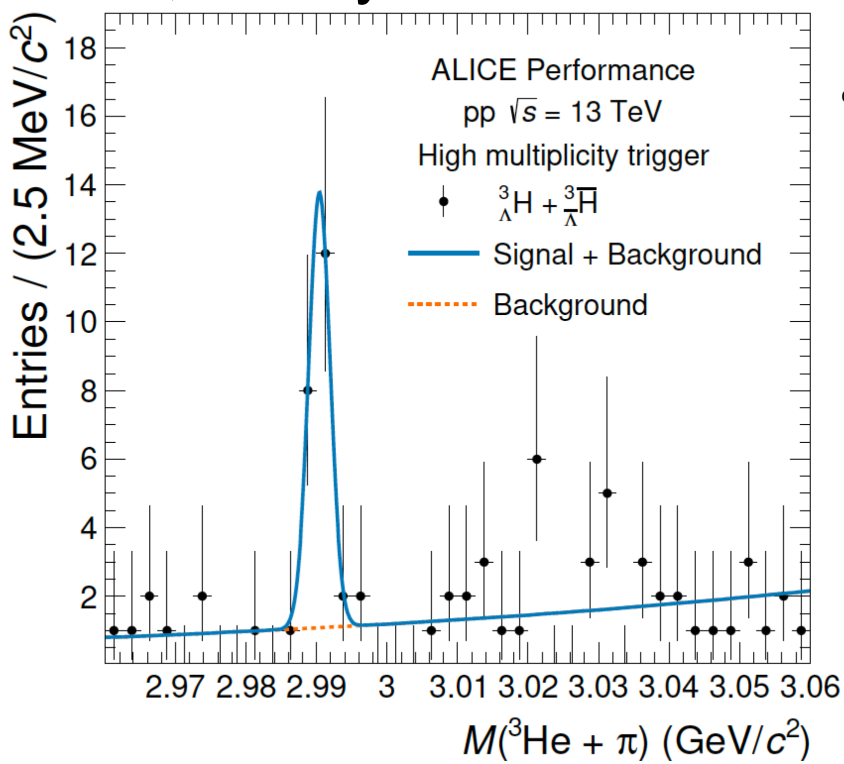
$$^4_\Lambda H^*(J^+ = 1) \rightarrow {^4_\Lambda H}(J^+ = 0) + \gamma$$

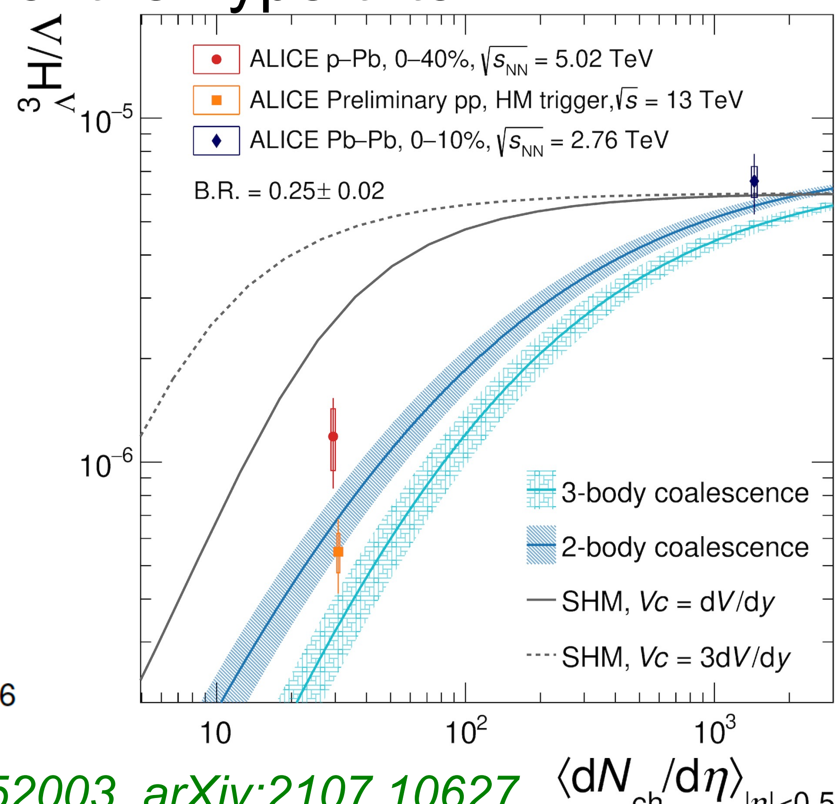
- Thermal model calculation, including excited $^4_\Lambda H^*$ feed down, shows a similar trend.

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

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





ALICE Collaboration, PRL 128 (2022) 252003, arXiv:2107.10627

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

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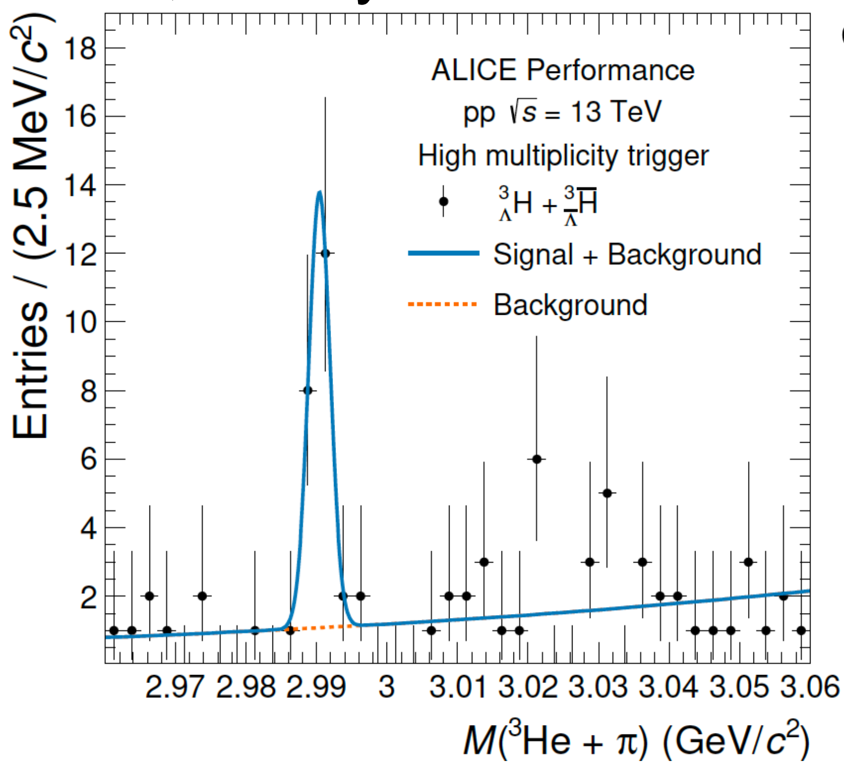

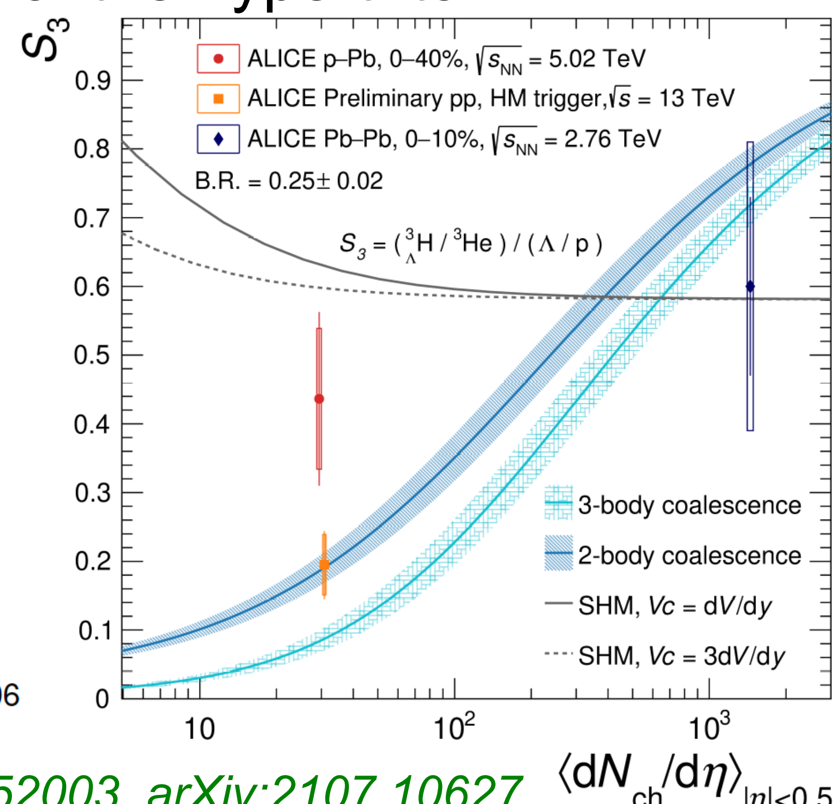

ALICE Collaboration, PRL 128 (2022) 252003, arXiv:2107.10627

V. Vovchenko, BD, H. Stoecker, PLB 785 (2018) 171
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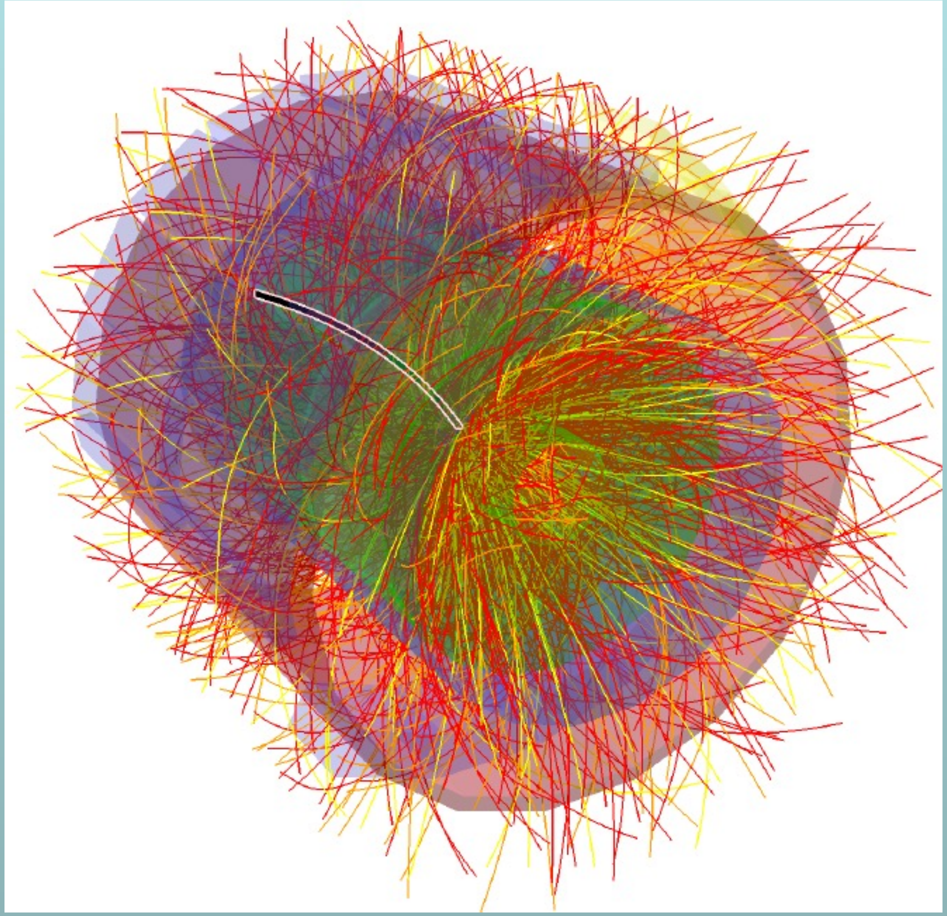
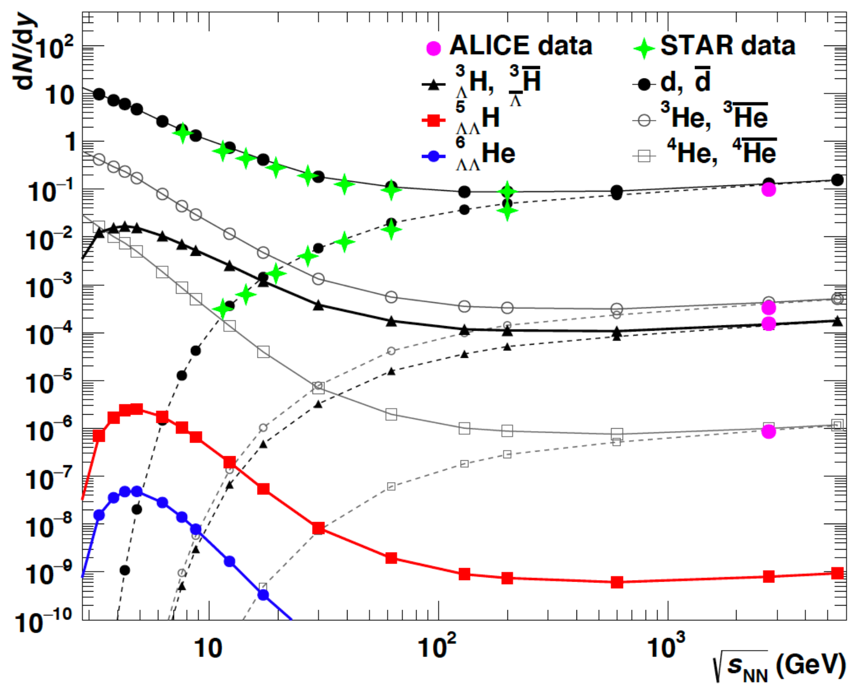
Summary



Conclusion

- Copious production of loosely bound objects measured in heavy-ion collisions as predicted by models
- Production models (thermal & coalescence) are giving rather good description at different energies/multiplicities
  - Results at small systems seem to slightly prefer coalescence
- Models describe the (anti-)(hyper-)nuclei data rather well
- Ratios vs. multiplicity trend described by both models
- New and more precise data can be expected in the next years



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