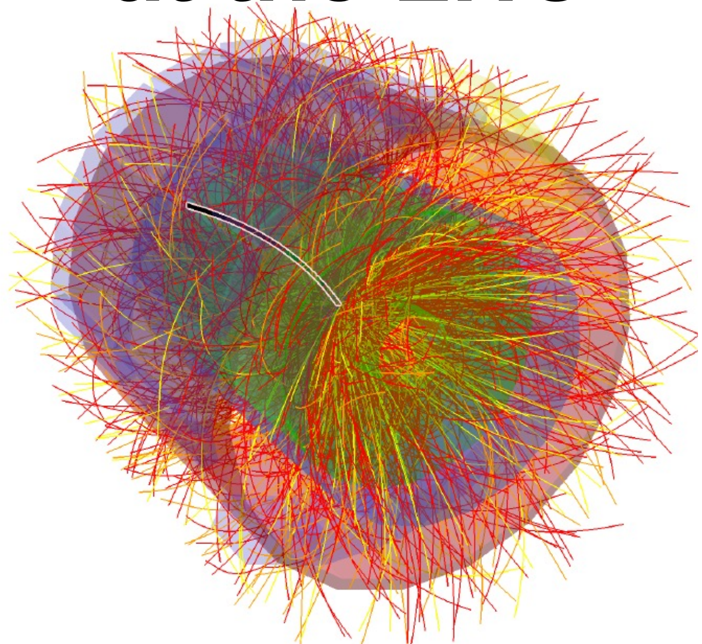
Production of loosely-bound objects at the LHC



May 26th, 2023, Yonsei University, Seoul

Heavy-Ion Meeting: Light Nuclei and resonance production in strongly interacting matter

Benjamin Dönigus

Institut für Kernphysik

Goethe Universität Frankfurt

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- Introduction
- Nuclei and Exotica
  - (Anti-)nuclei
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  - (Anti-)hypermatter
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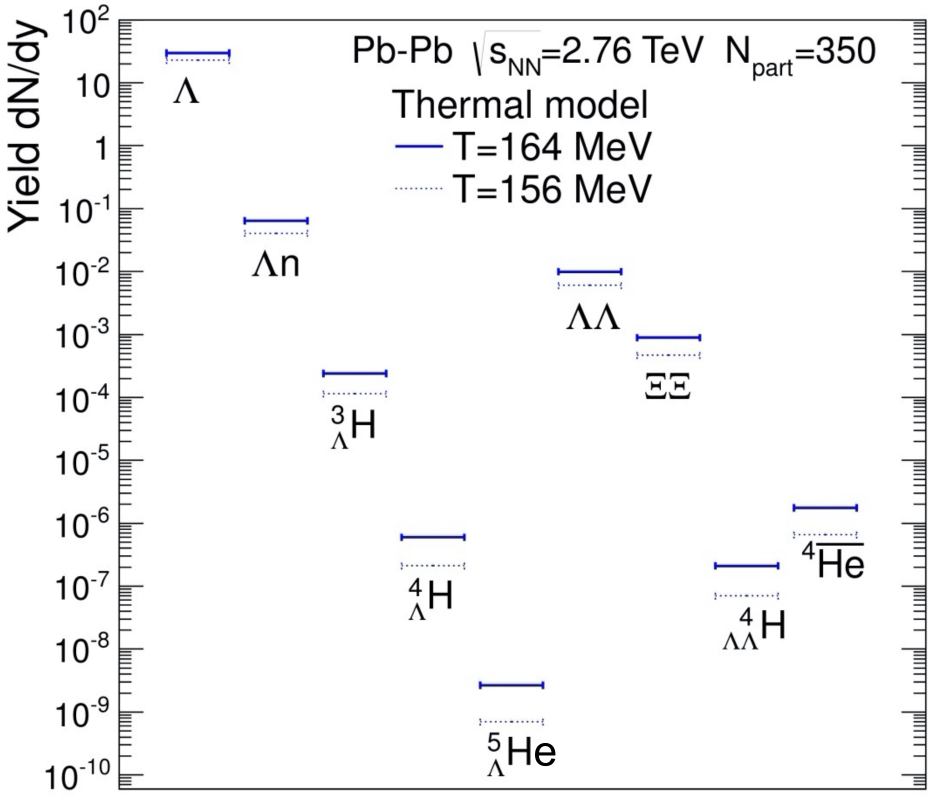
Motivation

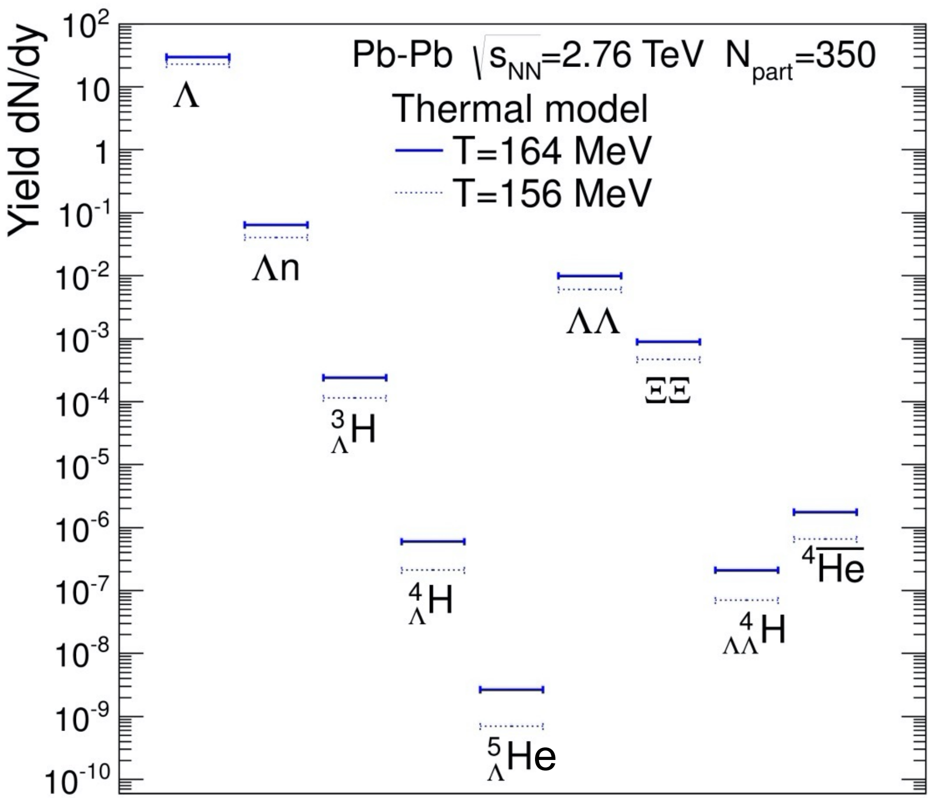


A. Andronic et al., PLB 697, 203 (2011) and references therein for the model, figure from A. Andronic, private communication

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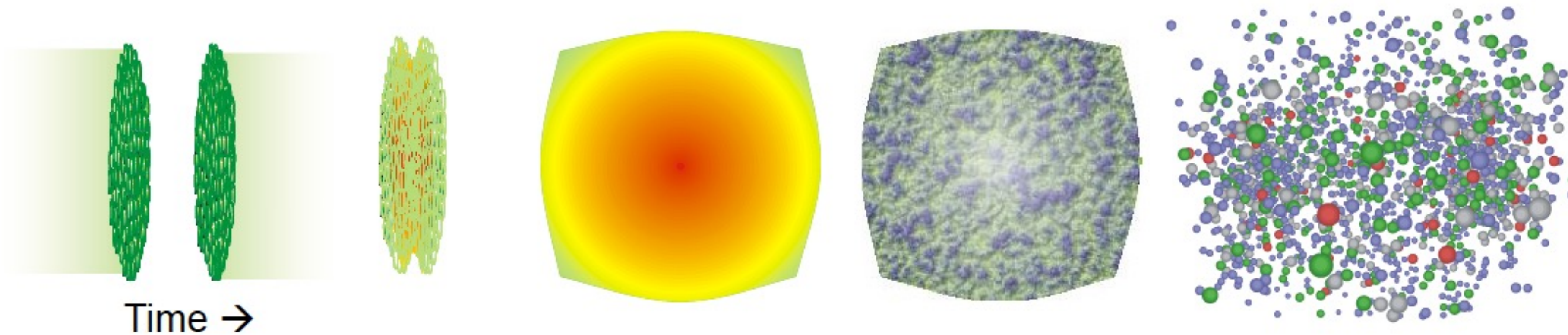
- Explore QCD and QCD inspired model predictions for (unusual) multi-baryon states
- Search for rarely produced anti- and hyper-matter
- Test model predictions, e.g. thermal and coalescence

→ Understand production mechanisms

→ Basis are light (anti-)nuclei

Introduction



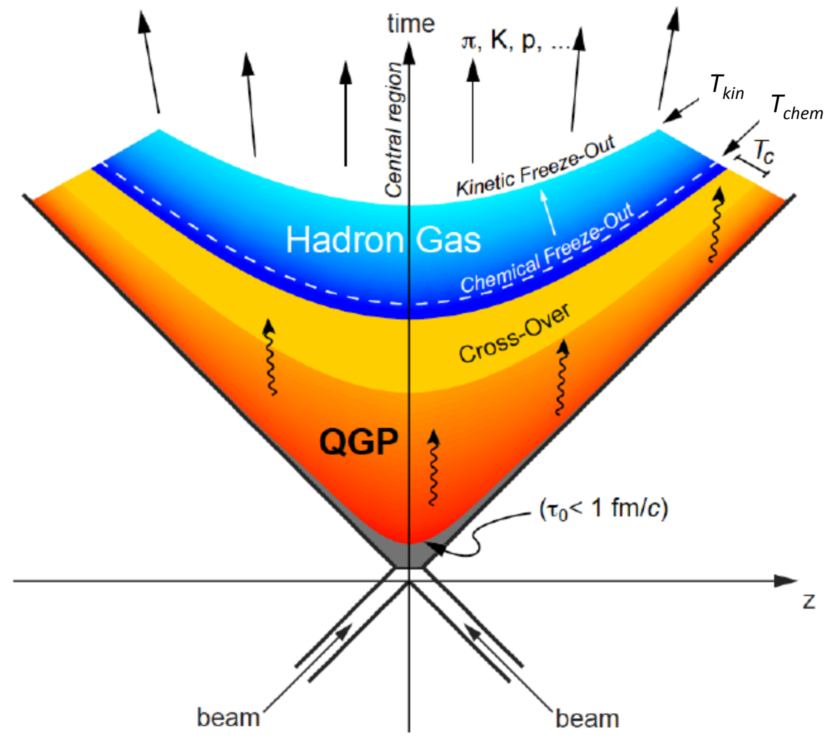
Cartoon of a Ultra-relativistic heavy-ion collision

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

Plot by S. Bass, Duke University; http://www.phy.duke.edu/research/NPTheory/QGP/transport/evo.jpg

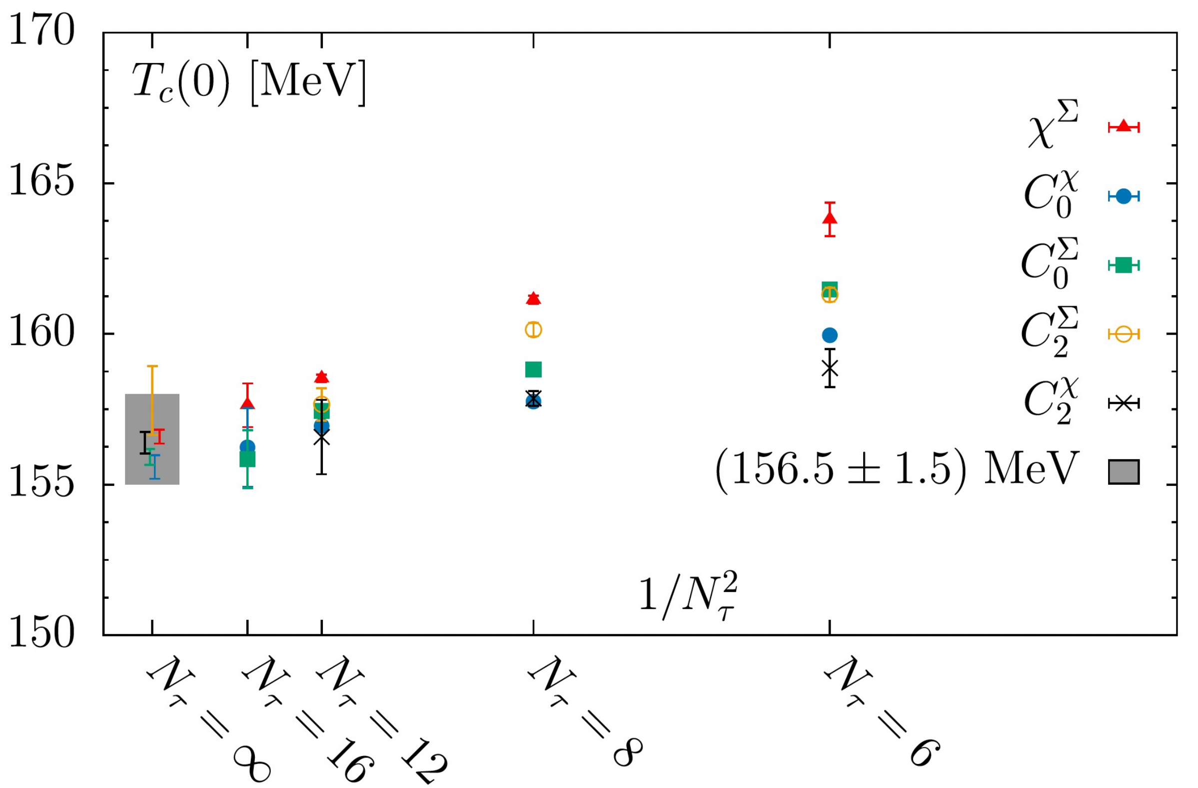
Introduction



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



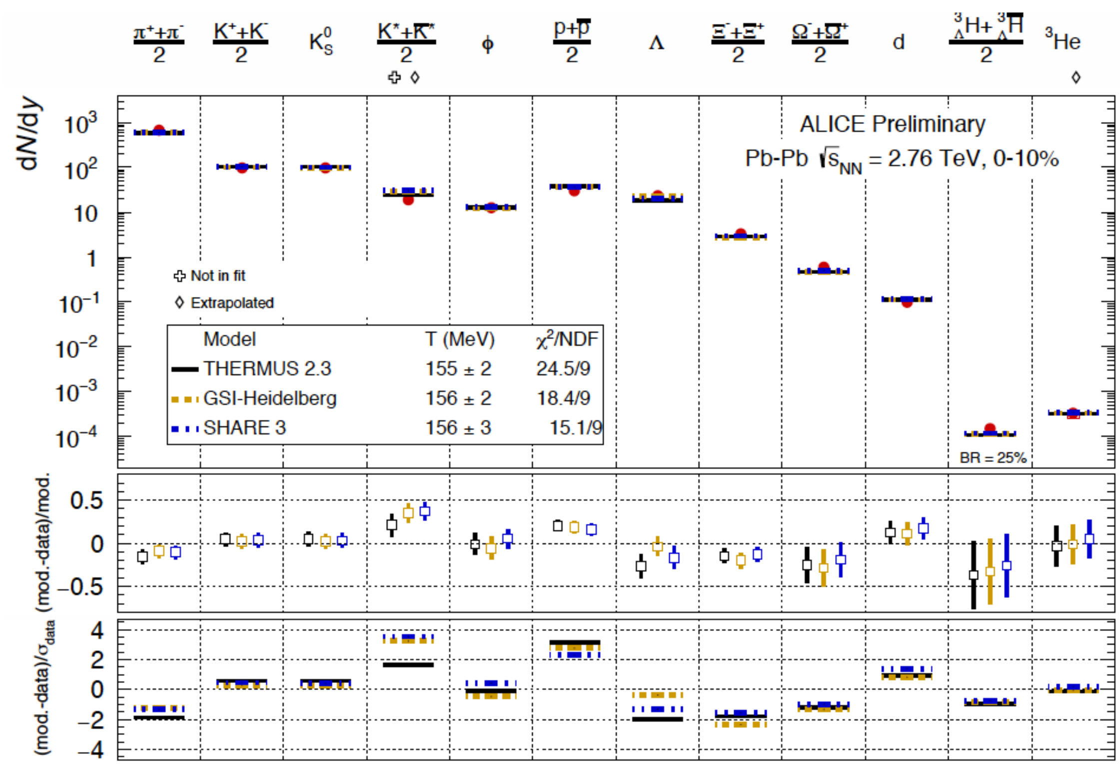
Lattice QCD tells us where to expect the phase transition

Critical 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

Thermal model

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

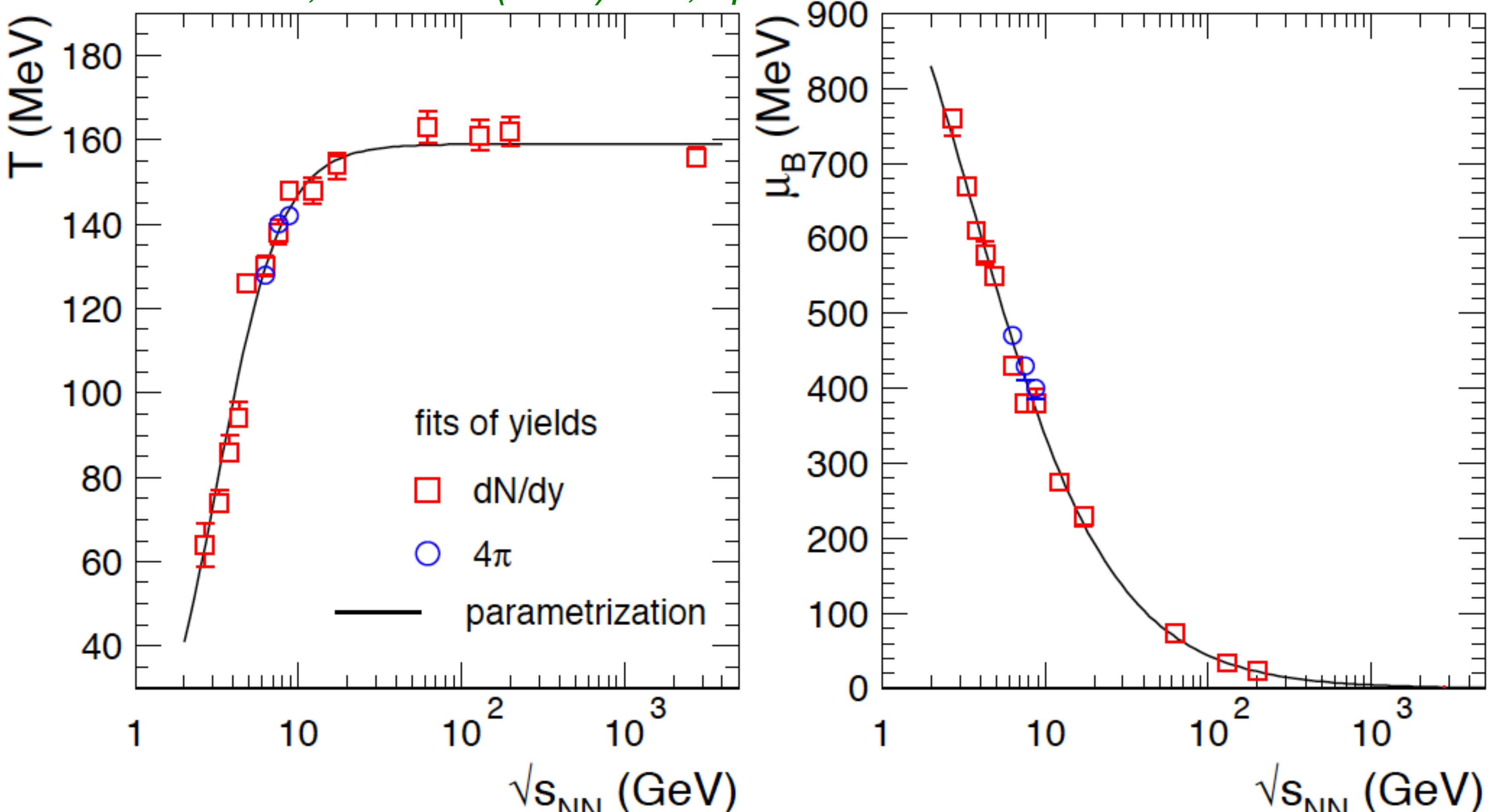


- chemical freeze-out temperature T_{ch}
- baryo-chemical potential μ_B
- Volume V

→ Using particle yields as input to extract parameters

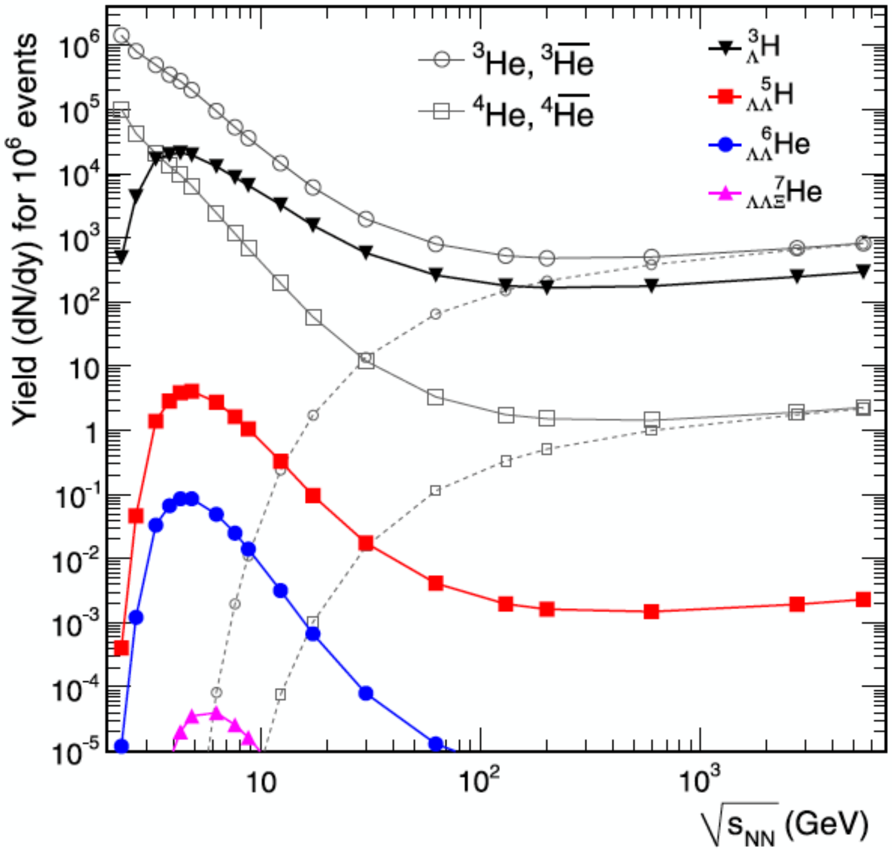
Energy dependence

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:

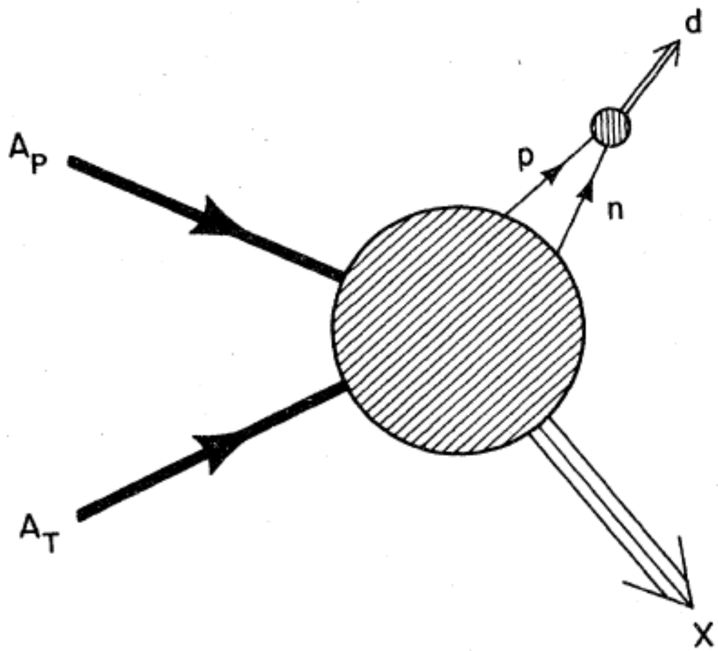
chemical freeze-out temperature T_{ch}

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}

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

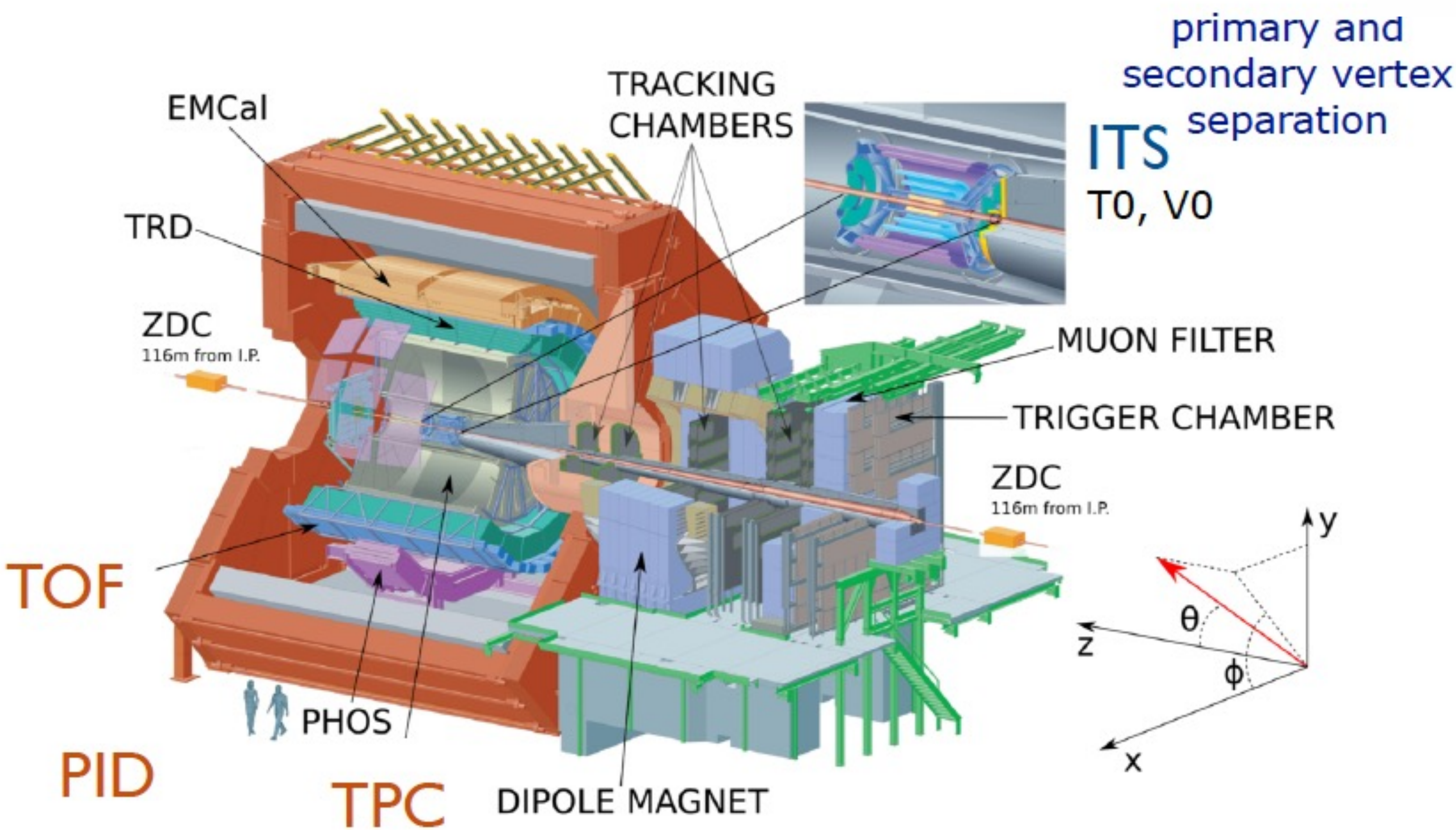
→ can break apart

→ created again by final-state coalescence

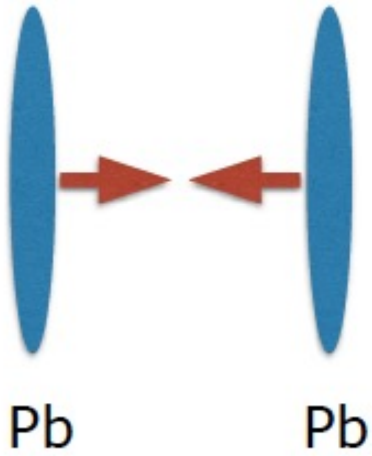
Large Hadron Collider at CERN

Large Hadron Collider at CERN

Experiment: ALICE



Interlude: Centrality

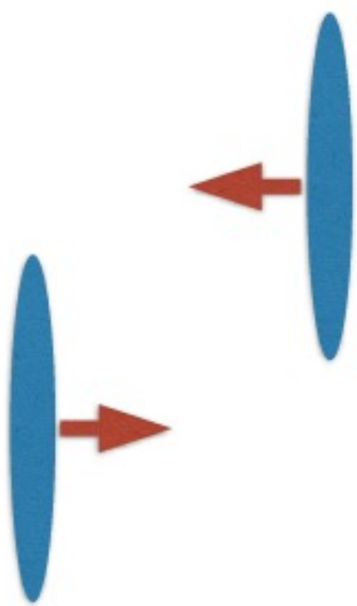


Central Pb-Pb collision:

High multiplicity = large dN/dη

High number of tracks

(more than 2000 tracks in the detector)



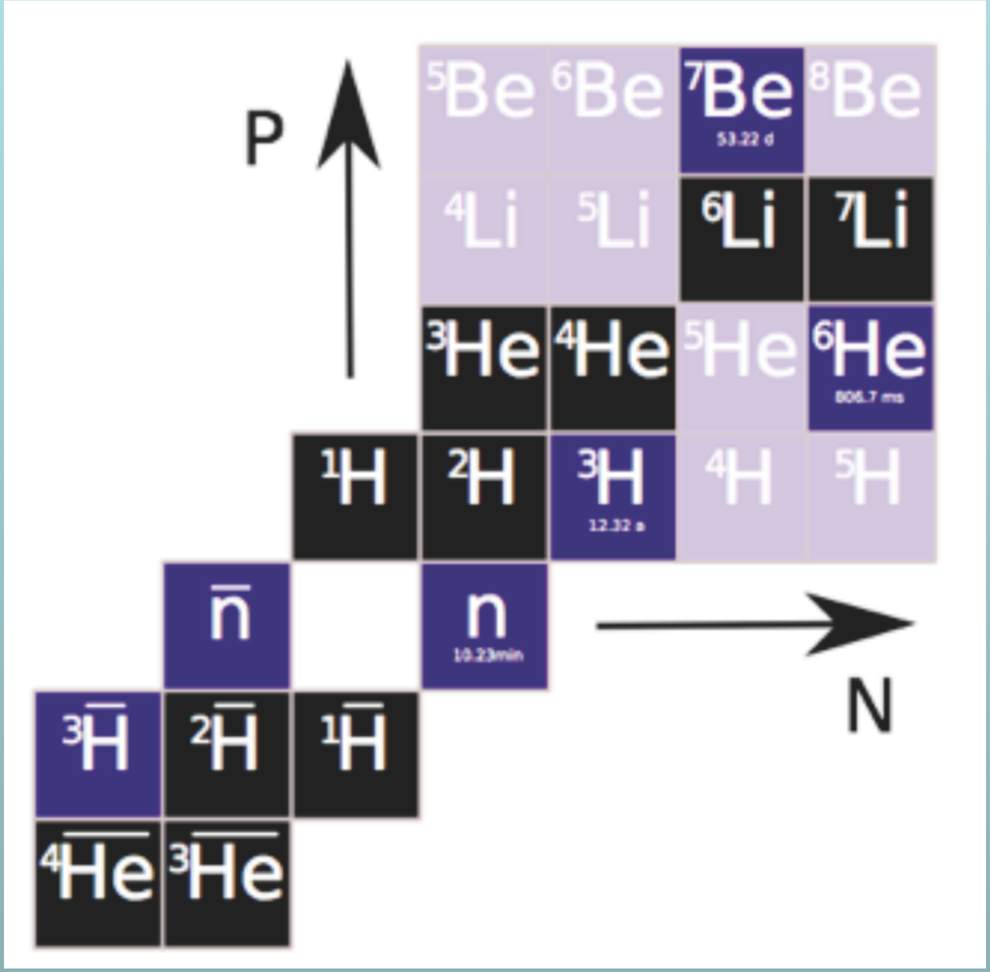
Peripheral Pb-Pb collision:

Low multiplicity = small dN/dη

Low number of tracks

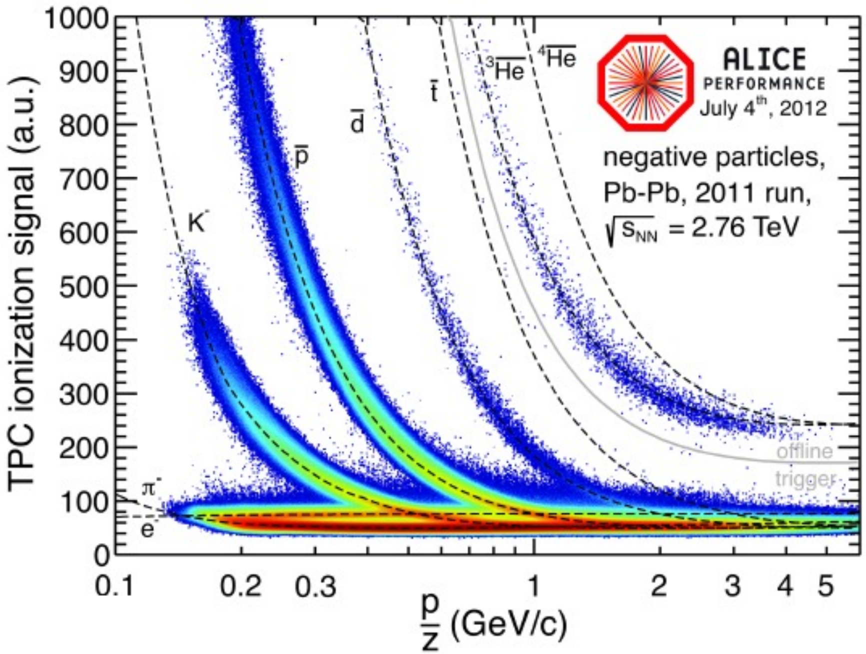
(less than 100 tracks in the detector)

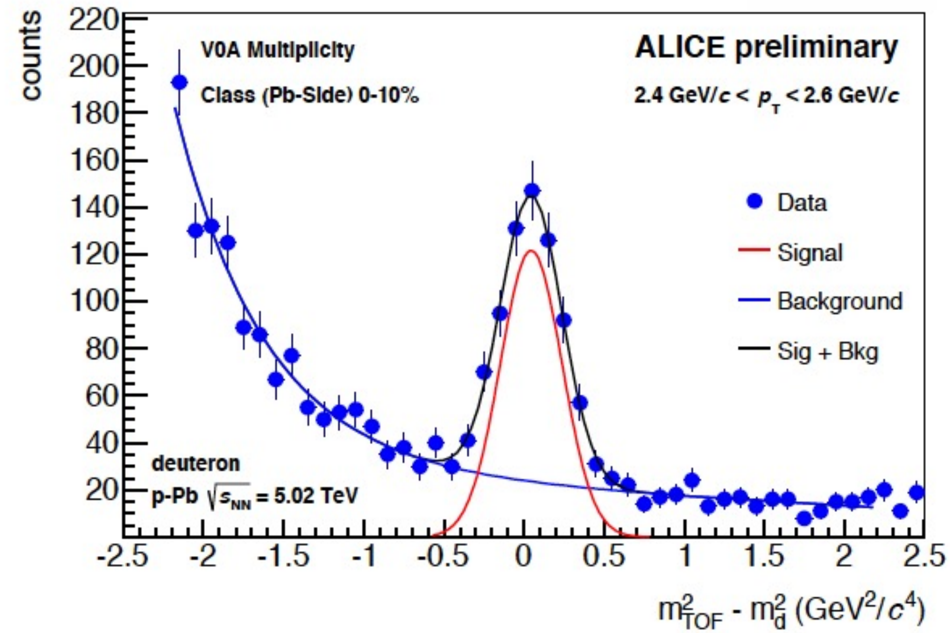
(Anti-)Nuclei



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
$^{3}\bar{H}$
$^{2}\bar{H}$
$^{1}\bar{H}$
$^{4}\overline{He}$
$^{3}\overline{He}$

Particle Identification





Low momenta:

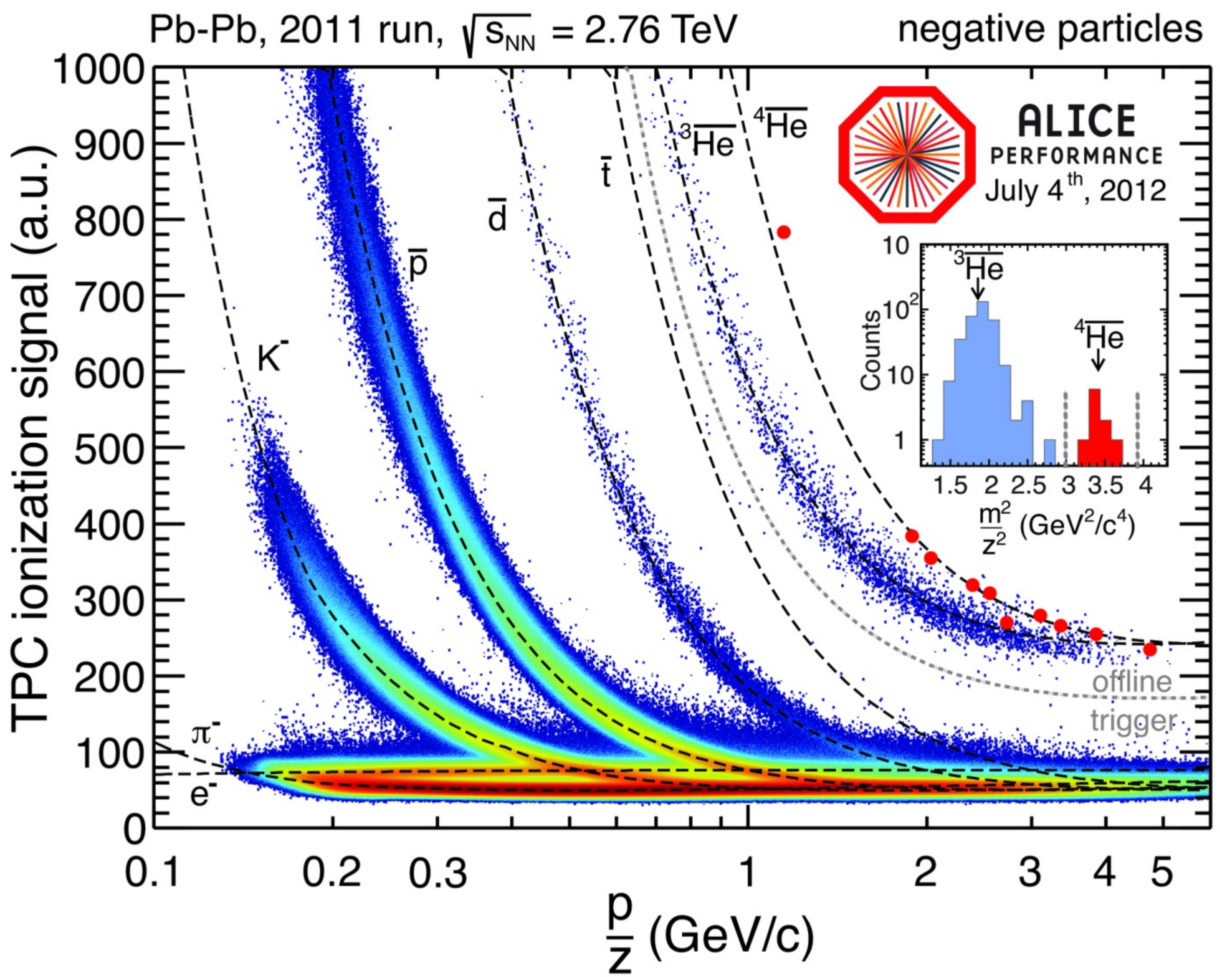
Nuclei are identified using the d*E*/d*x* measurement in the Time Projection Chamber (TPC)

Higher momenta:

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

Anti-Alpha

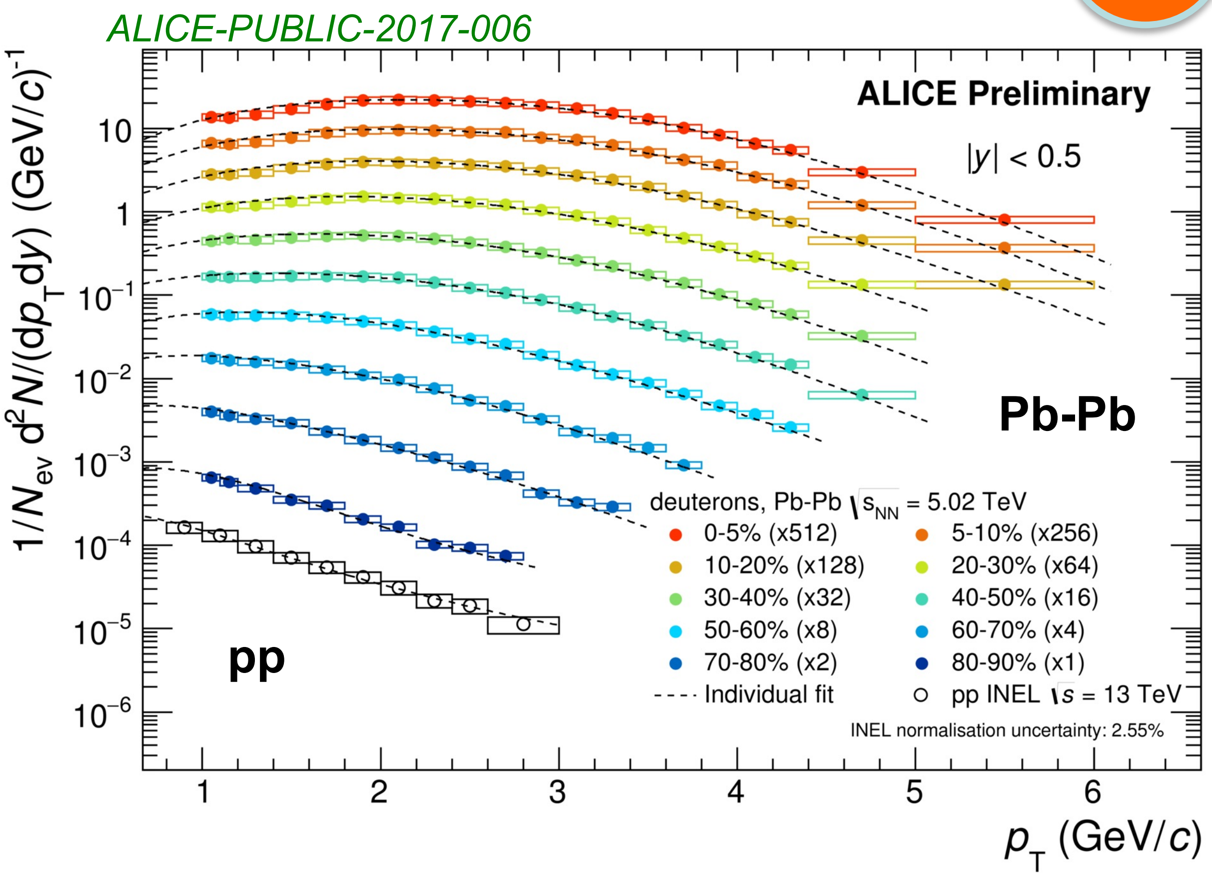
For the full statistics of 2011 ALICE identified 10 Anti-Alphas using TPC and TOF



STAR observed the Anti-Alpha in 2010:

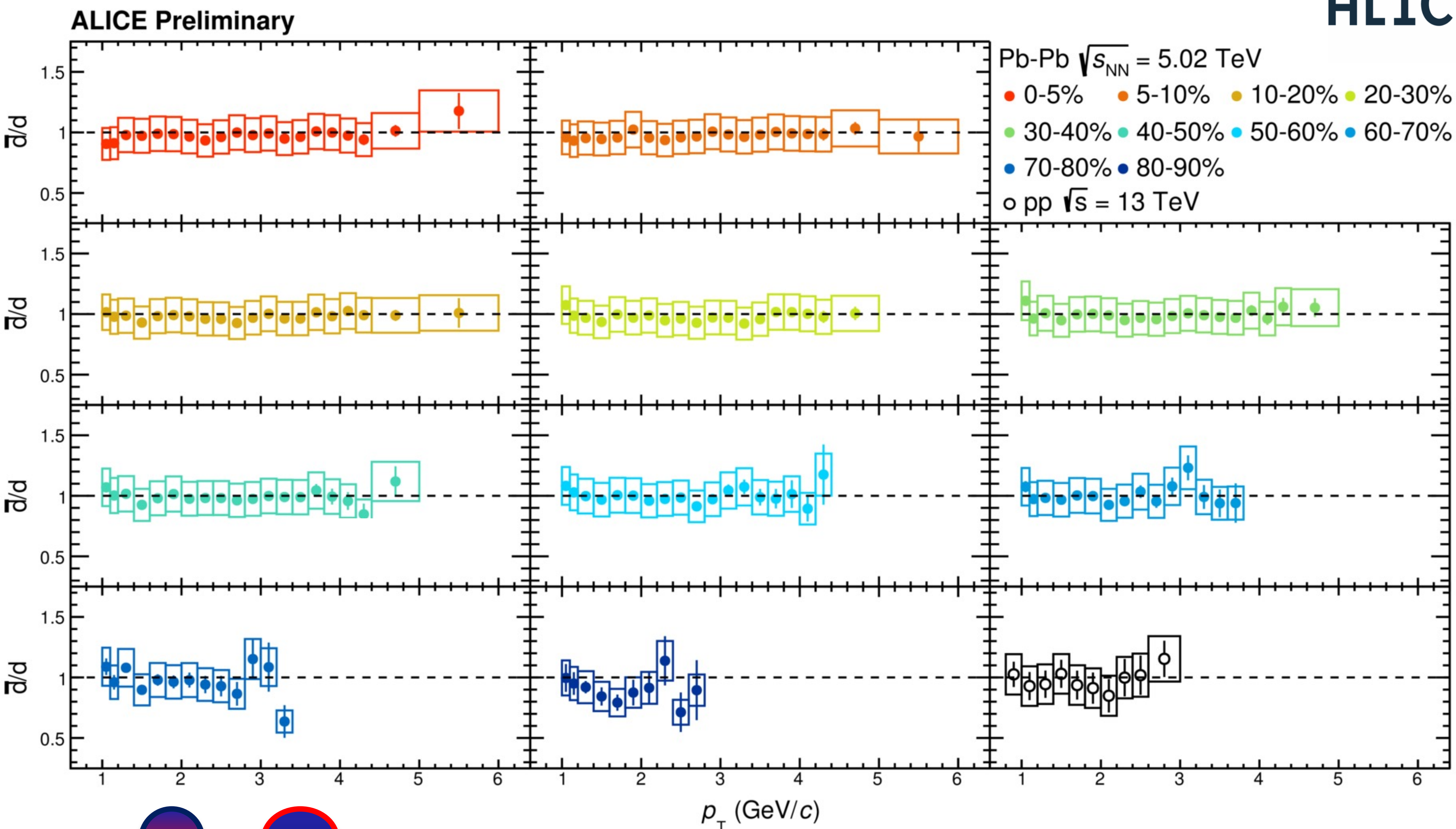
Nature 473, 353 (2011)

Deuterons



- 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

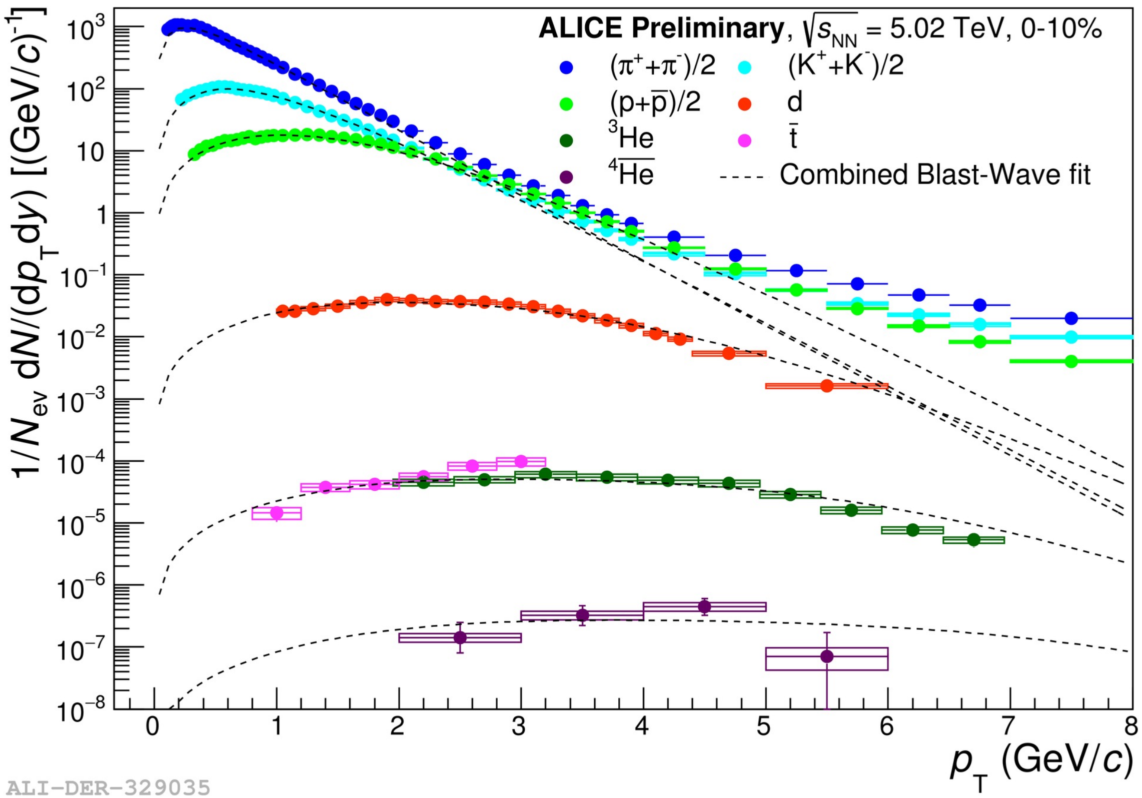
(Anti-)Deuteron ratio



: -ratios consistent with unity, as expected

Combined Blast-Wave fit

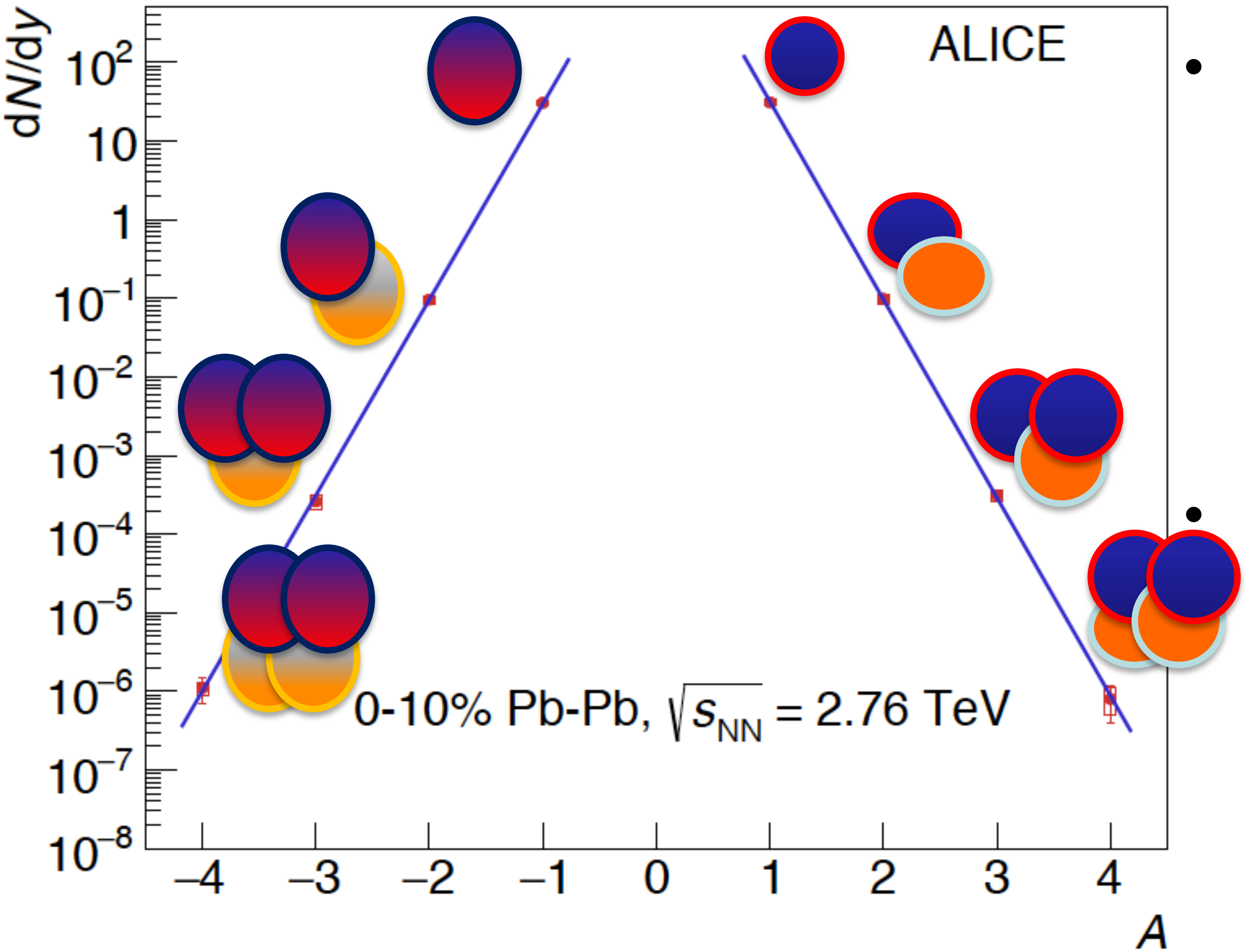
ALICE Collaboration, arXiv:1910.07678, Phys.Rev.C 101 (2020) 044907



- 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

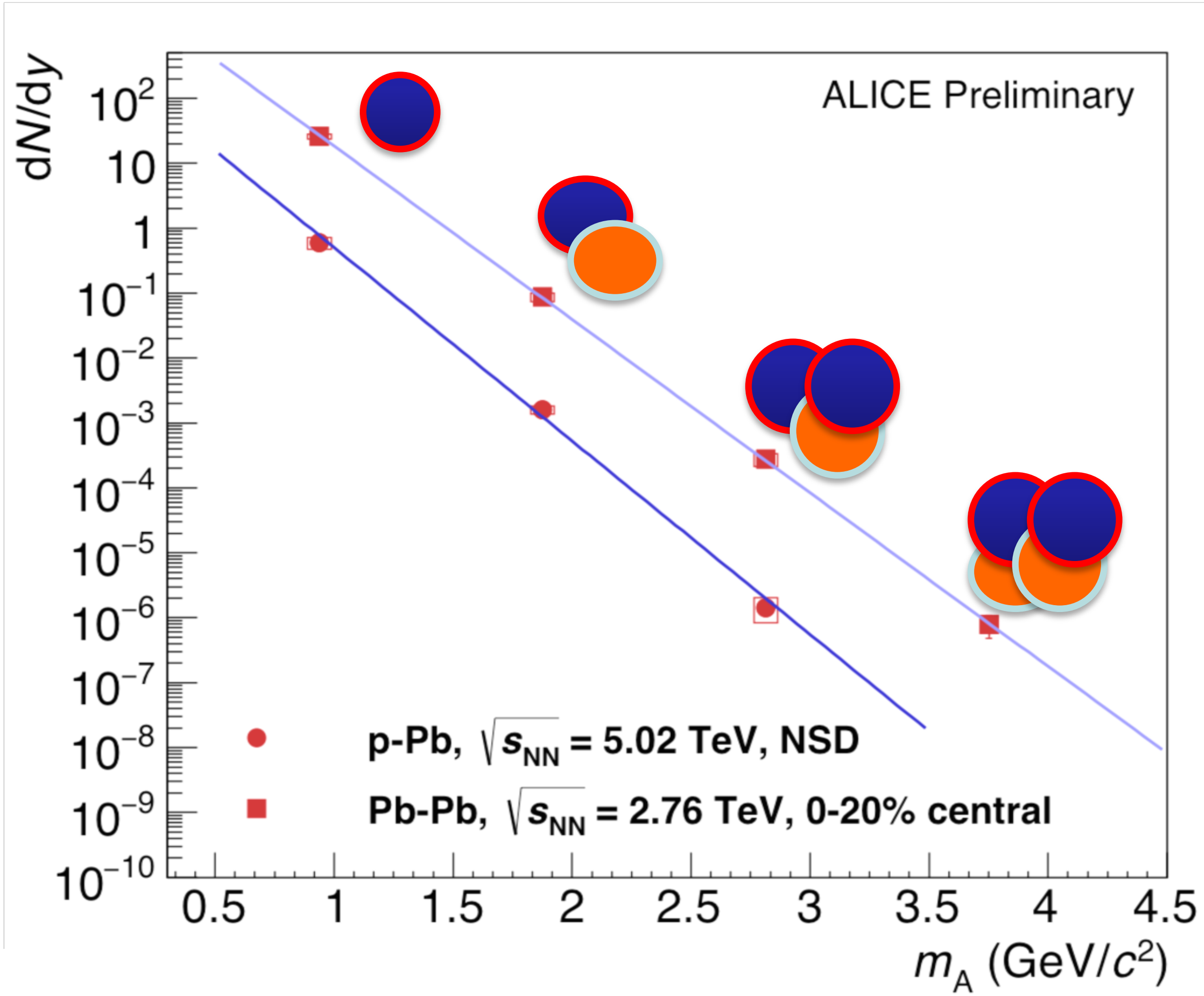
Mass dependence



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

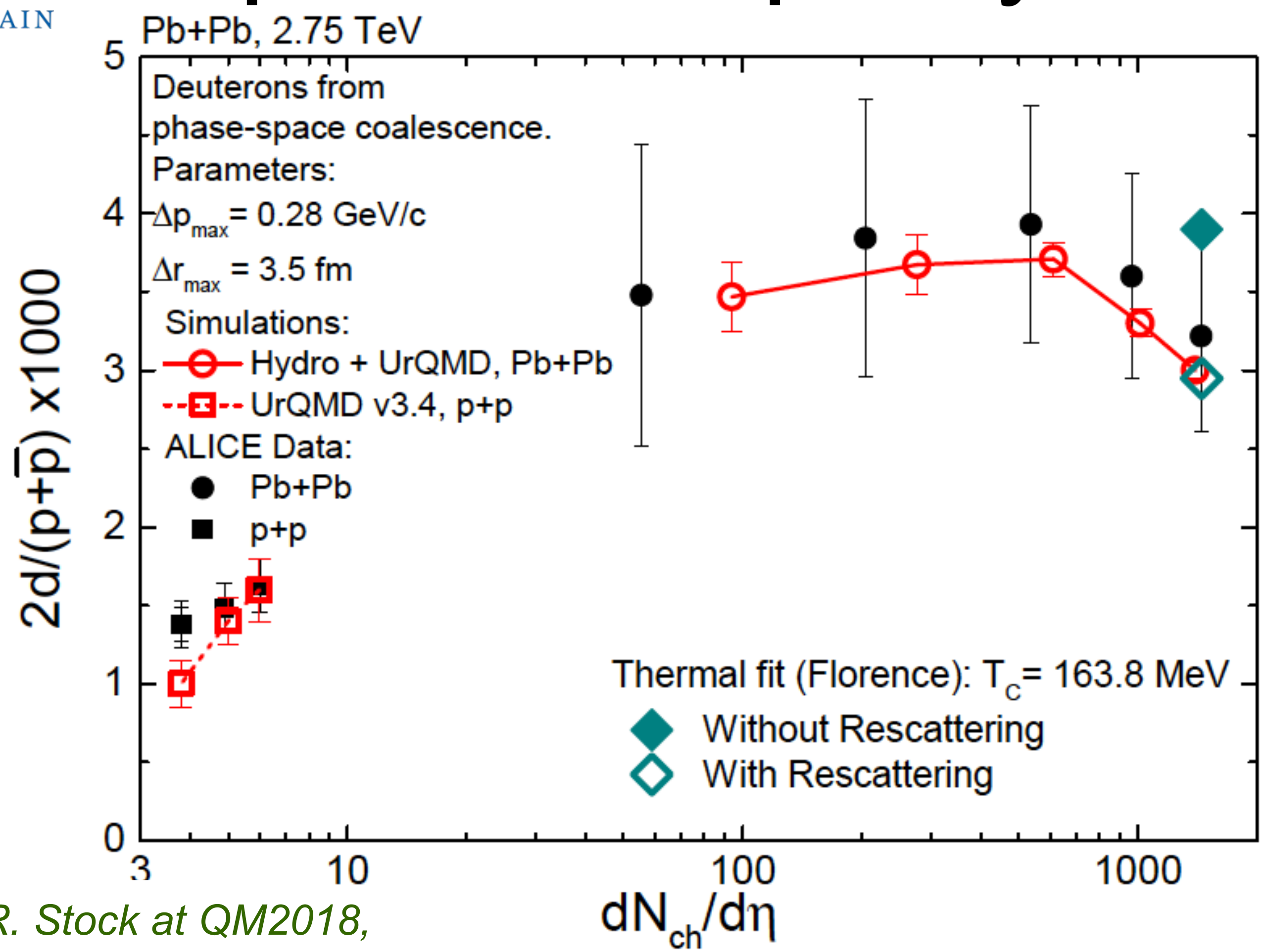
- Production of (anti-) nuclei is follwing an exponential, and decreases with mass as expected from thermal model
- In Pb-Pb the „penalty factor“ for each additional baryon ~300 (for particles and anti-particles)

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

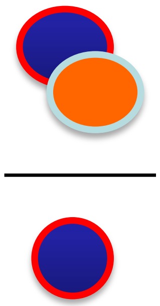
d/p vs. multiplicity

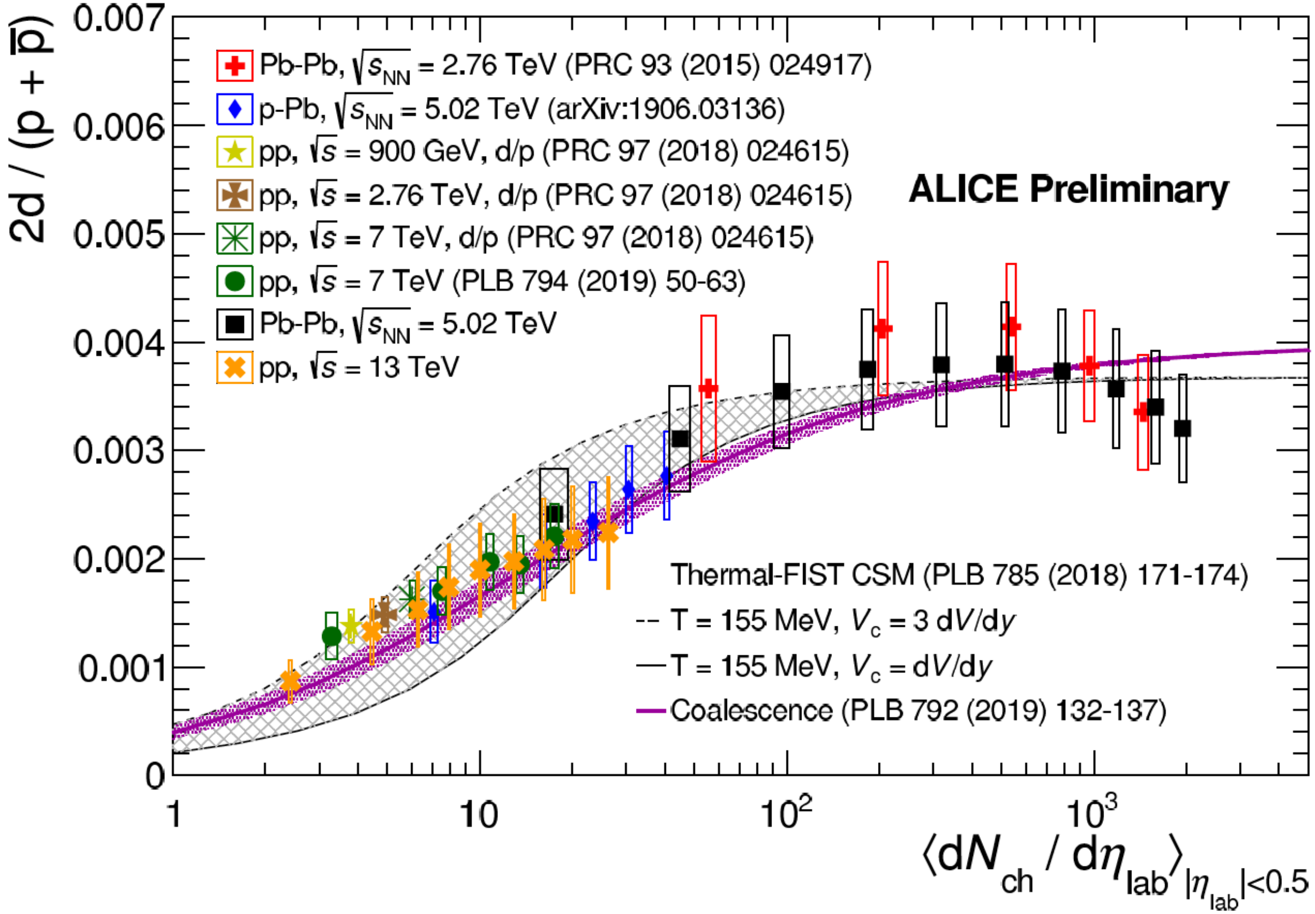


As shown by R. Stock at QM2018,
meanwhile coalsecence published: S. Sombun et al., Phys.Rev.C 99 (2019) 014901

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

d/p vs. multiplicity

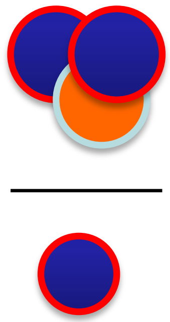


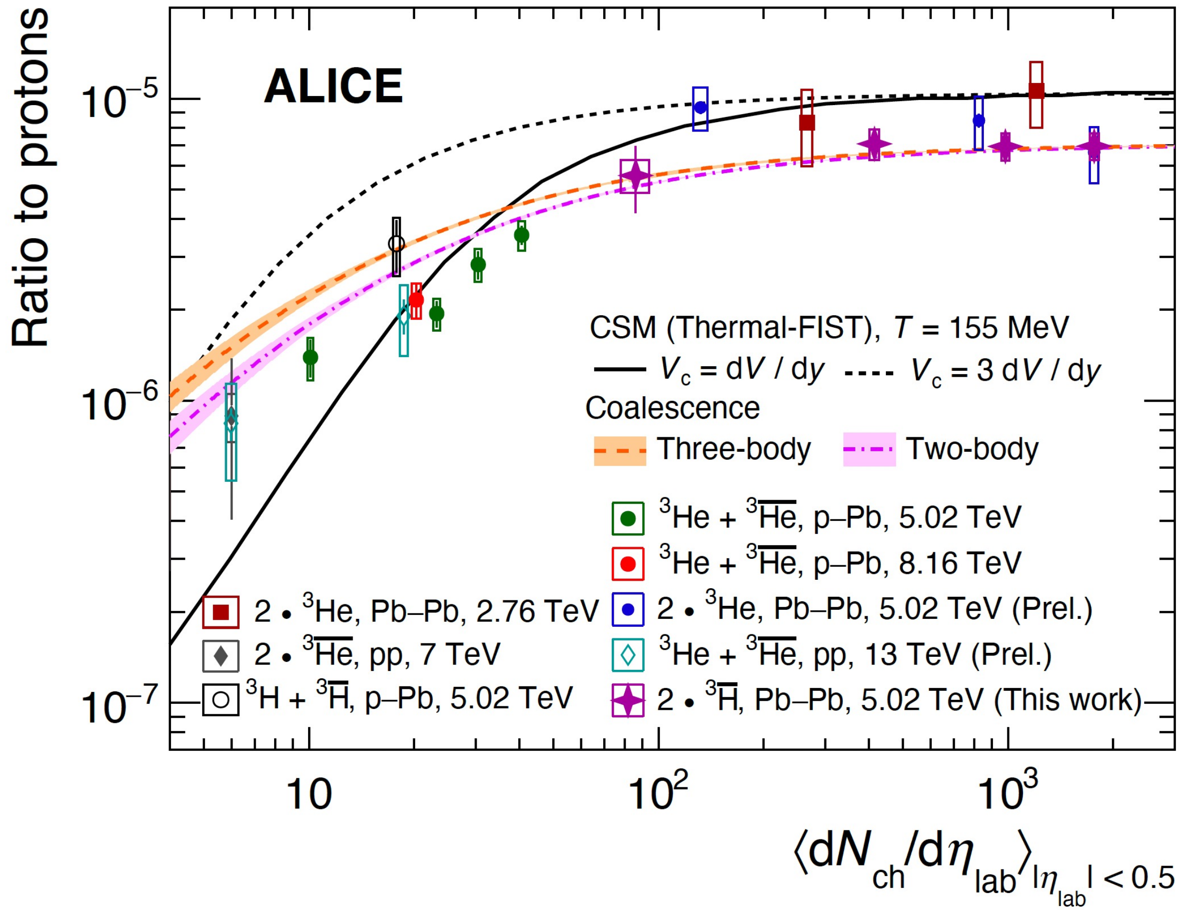


Models:
Coalescence: K.J. Sun, C.M. Ko, BD,
PLB 792 (2019) 132
CSM: V.Vovchenko, BD, H. Stöcker,
PLB 785 (2018) 171

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

^{3}He/p vs. multiplicity





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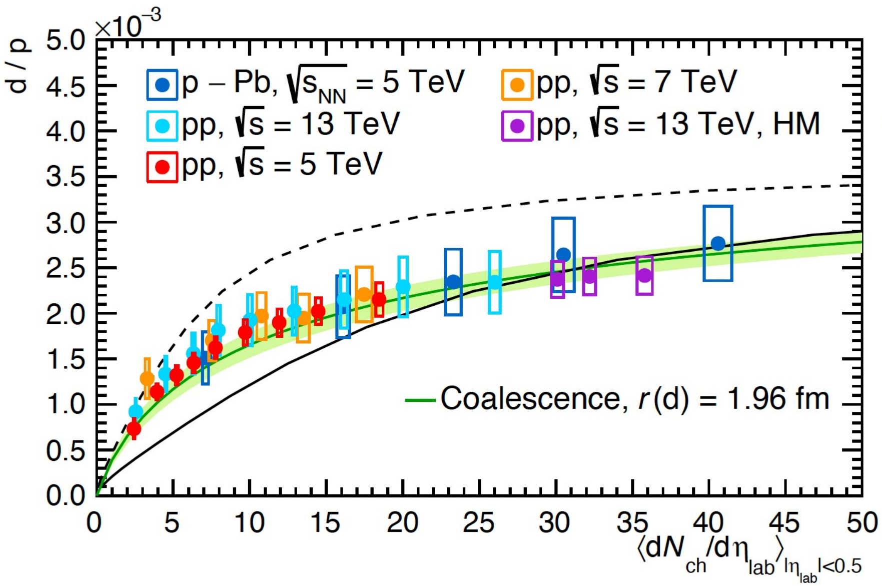
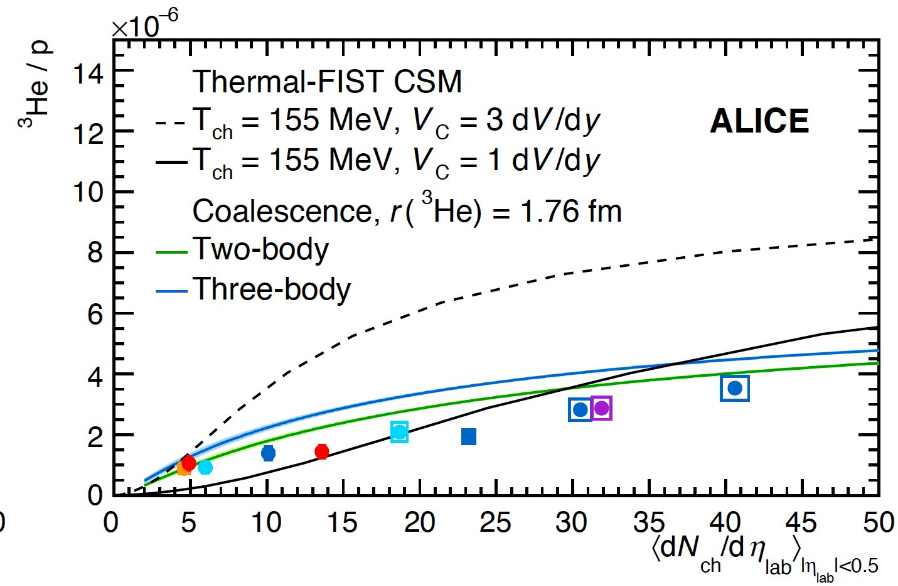
Coalescence: K.J. Sun, C.M. Ko, BD, PLB 792 (2019) 132
CSM: V.Vovchenko, BD, H. Stöcker, PLB 785 (2018) 171

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

ratios vs. (low) multiplicity

ALICE Collaboration, arXiv:2112.00610



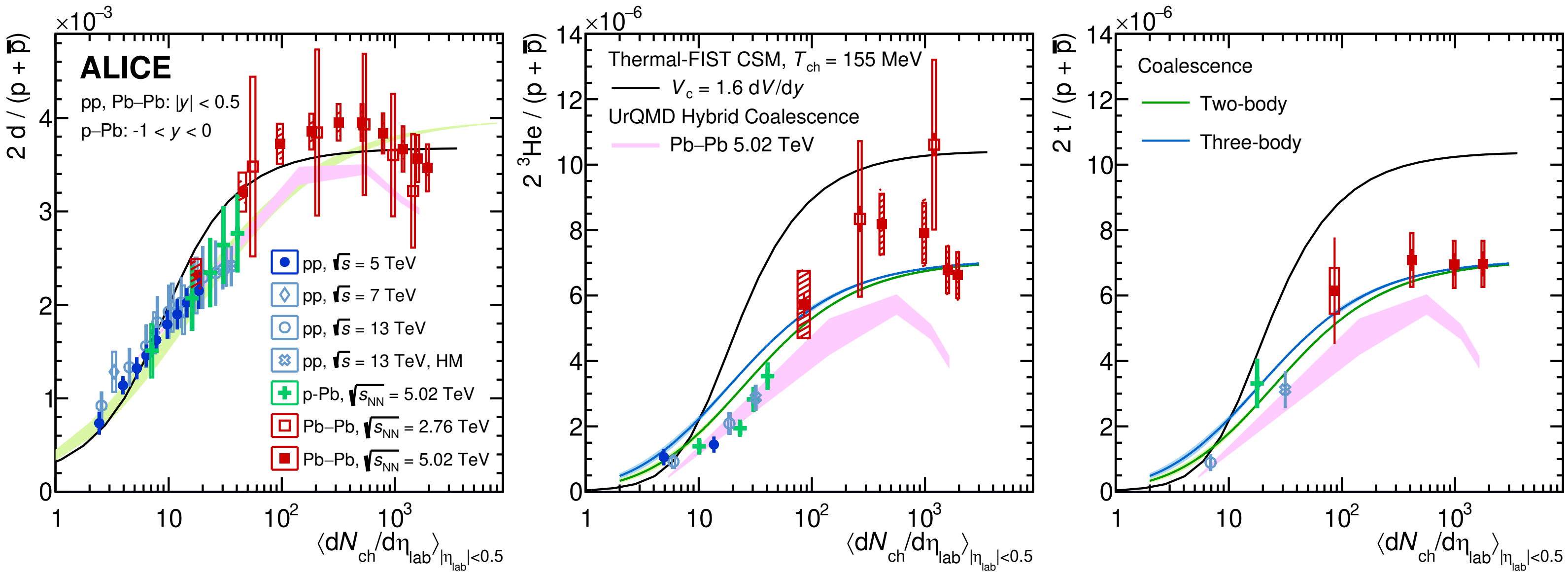


- d/p ratio rather well described by coalescence and (canonical) thermal model
- Some tension for ^{3}He/p at low p_T

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

ratios vs. multiplicity

ALICE Collaboration, arXiv:2211.14015, accepted by PRC



- 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

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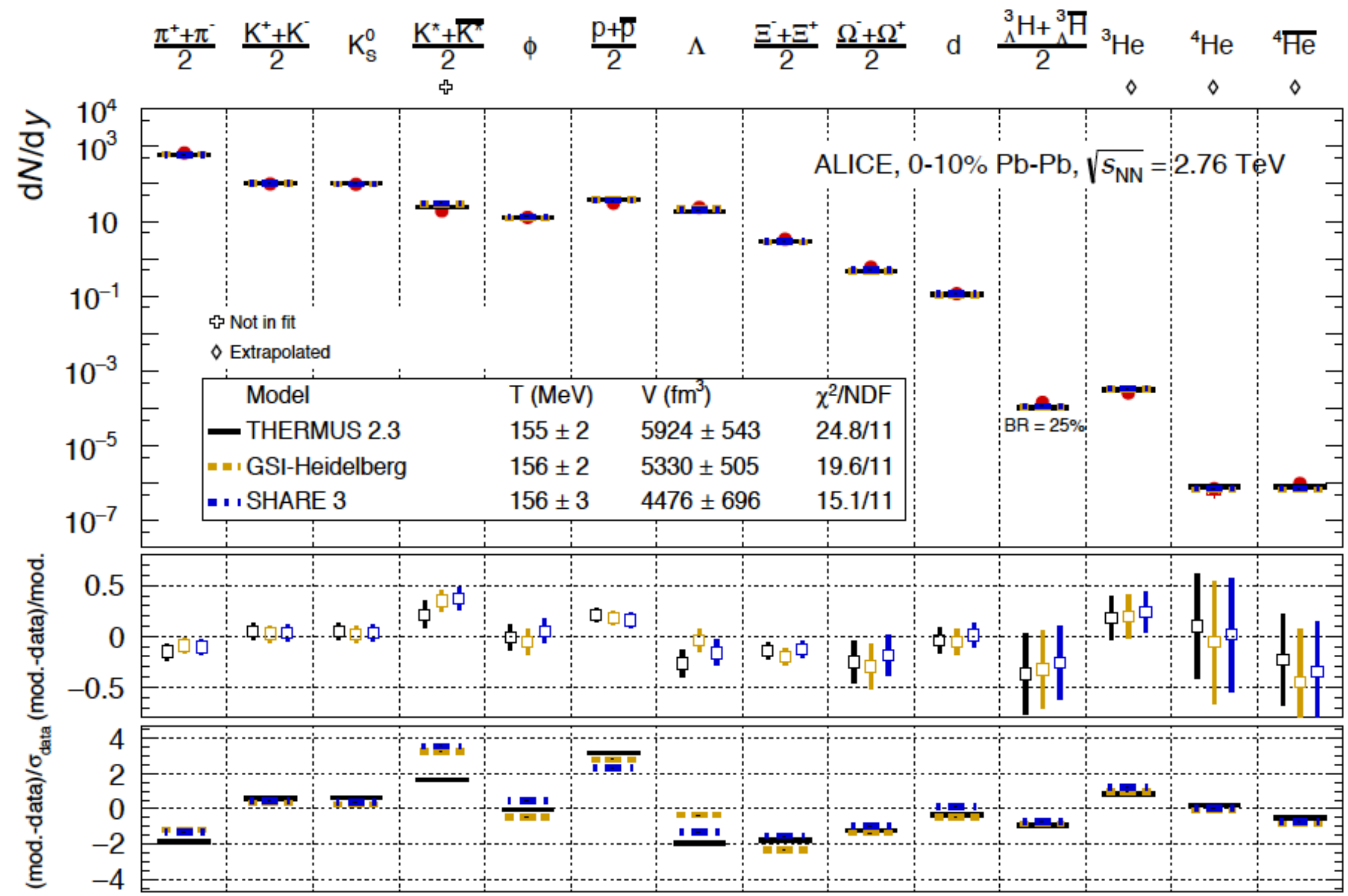
Thermal model

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)

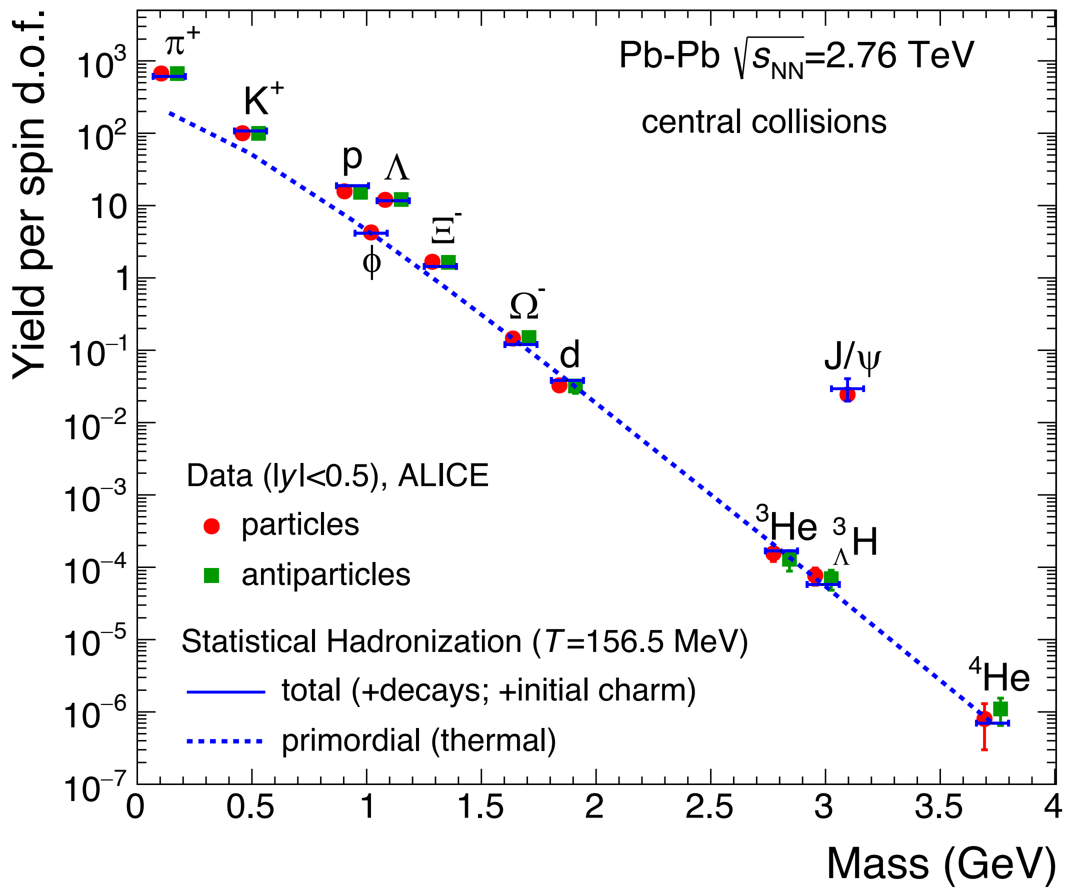


ALICE Collaboration, arXiv:1710.07531, NPA 971, 1 (2018)

- 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

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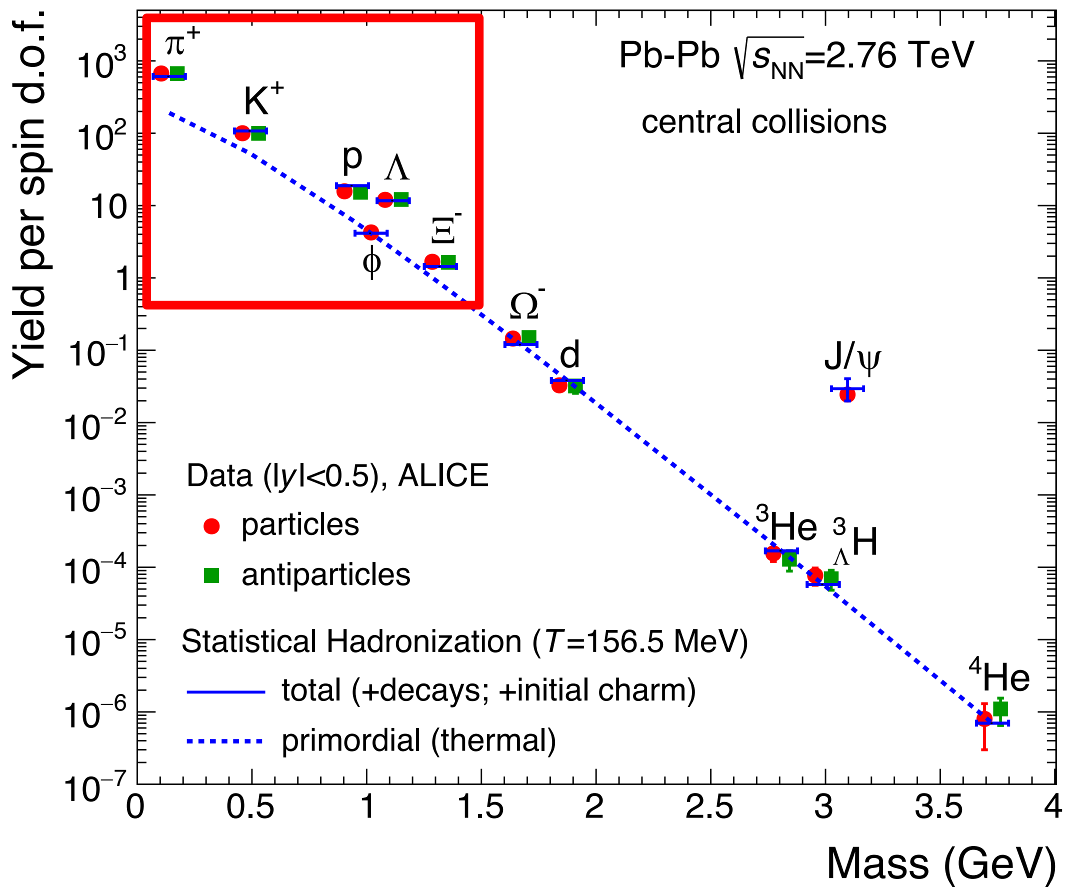

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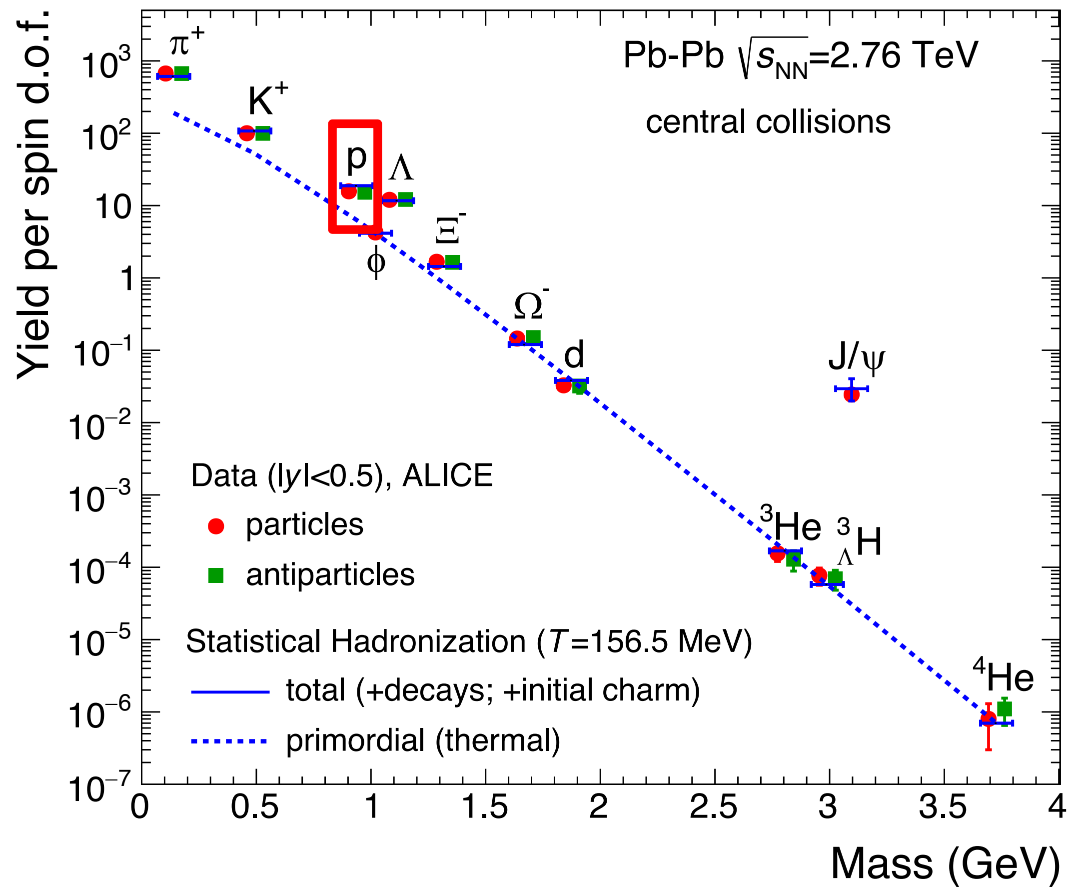

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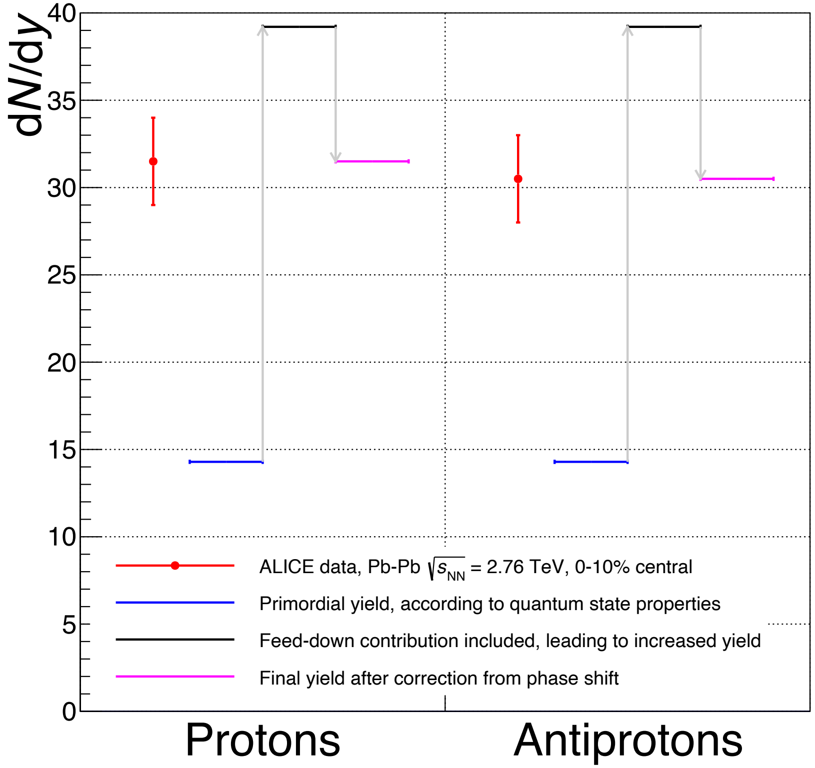
BD, G. Röpke, D. Blaschke, Phys. Rev. C 106 (2022) 044908



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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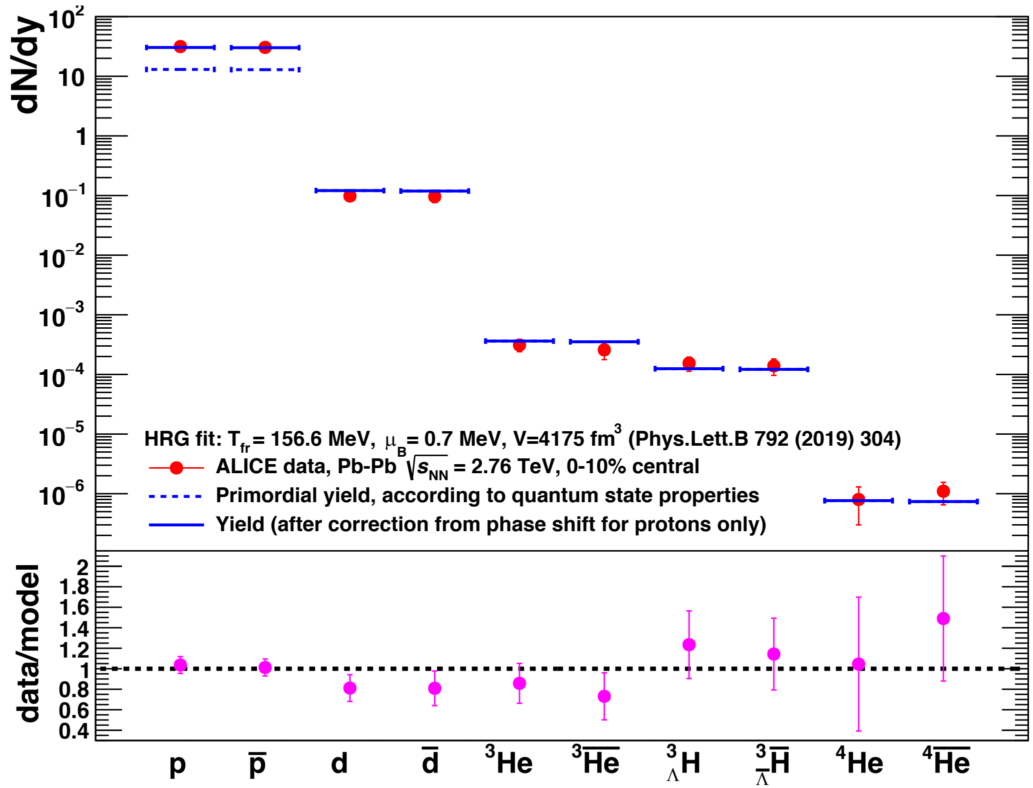

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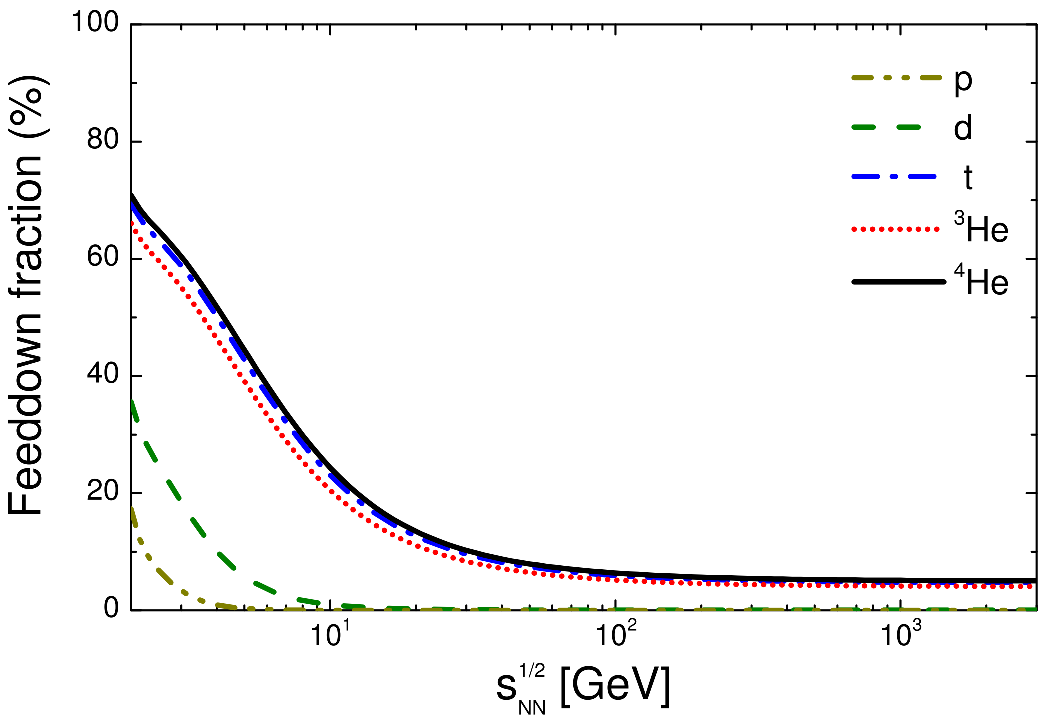
V. Vovchenko, BD, B. Kardan, M. Lorenz, H. Stoecker, Phys.Lett.B 809 (2020) 135746



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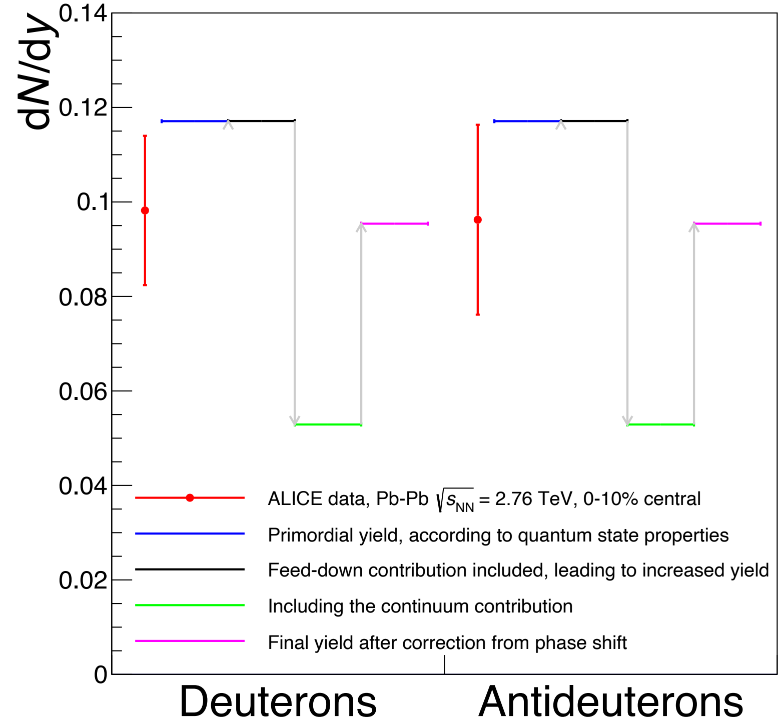
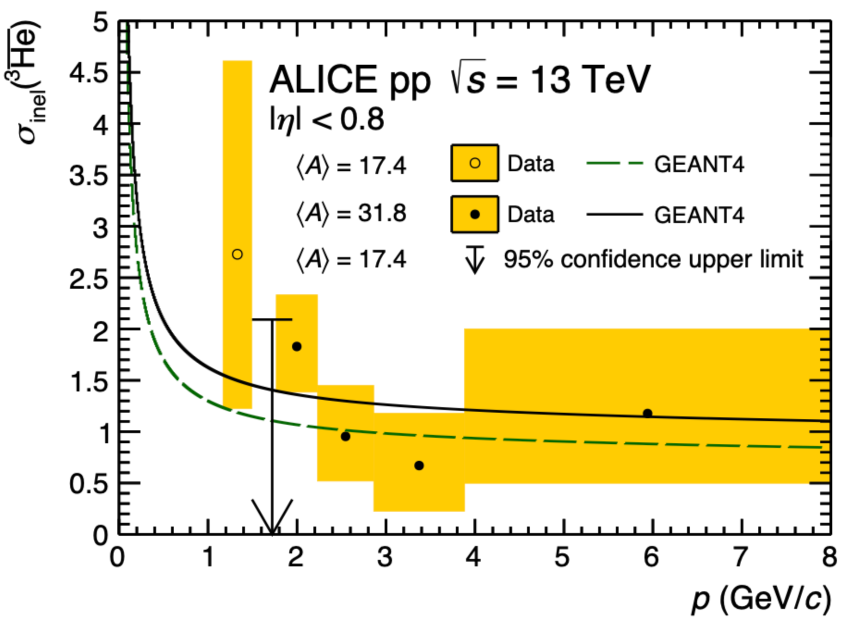
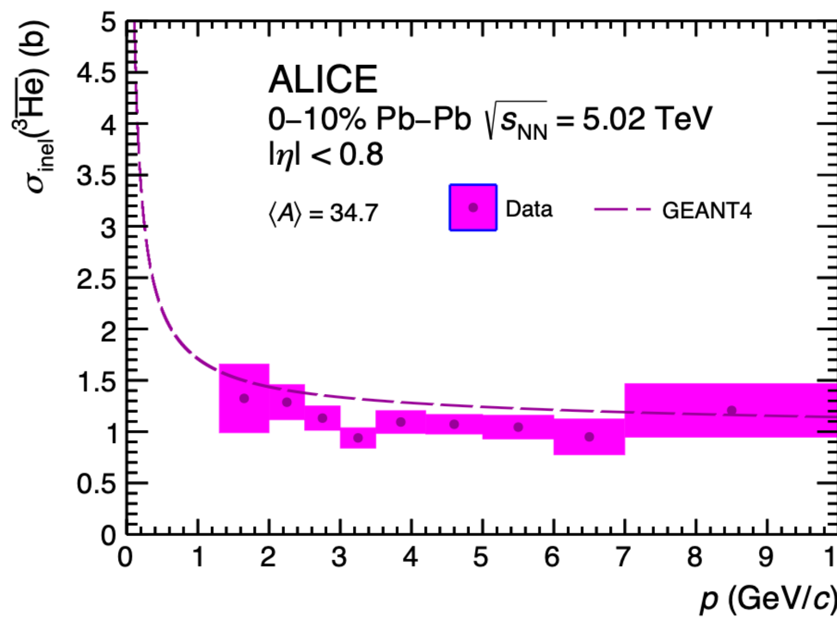


A. Andronic et al., Phys.Lett.B 797 (2019) 134836; Nature 561 (2018) 7723, 321; Phys.Lett.B 697 (2011) 203; Phys.Lett.B 792 (2019) 304

Anti-nuclei absorption

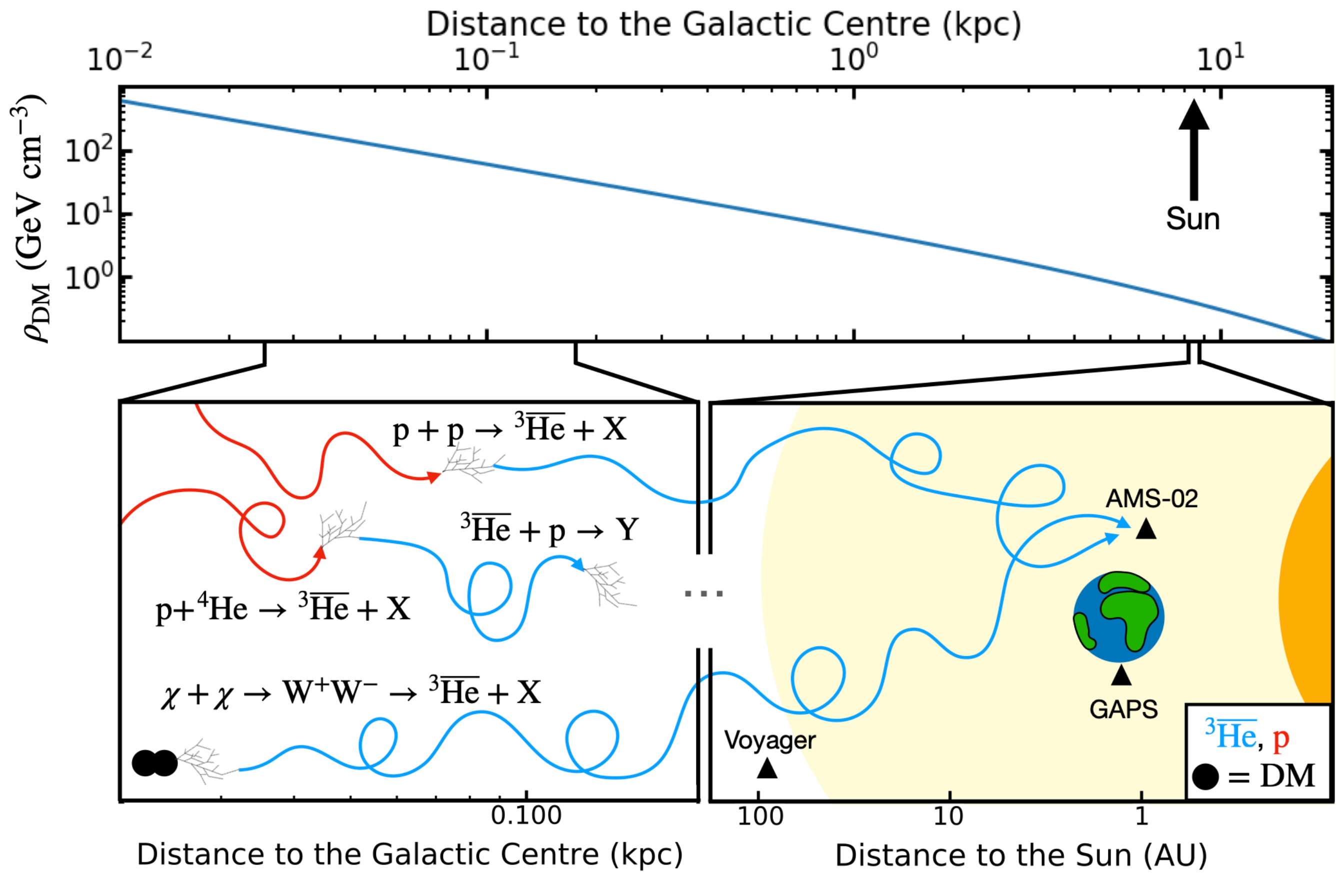
ALICE Collaboration, arXiv:2202.01549





- Absorption of Anti-3He measured with two different methods using the ALICE experiment as absorber
- GEANT4 does a really good job

Anti-^{3}He flux near earth

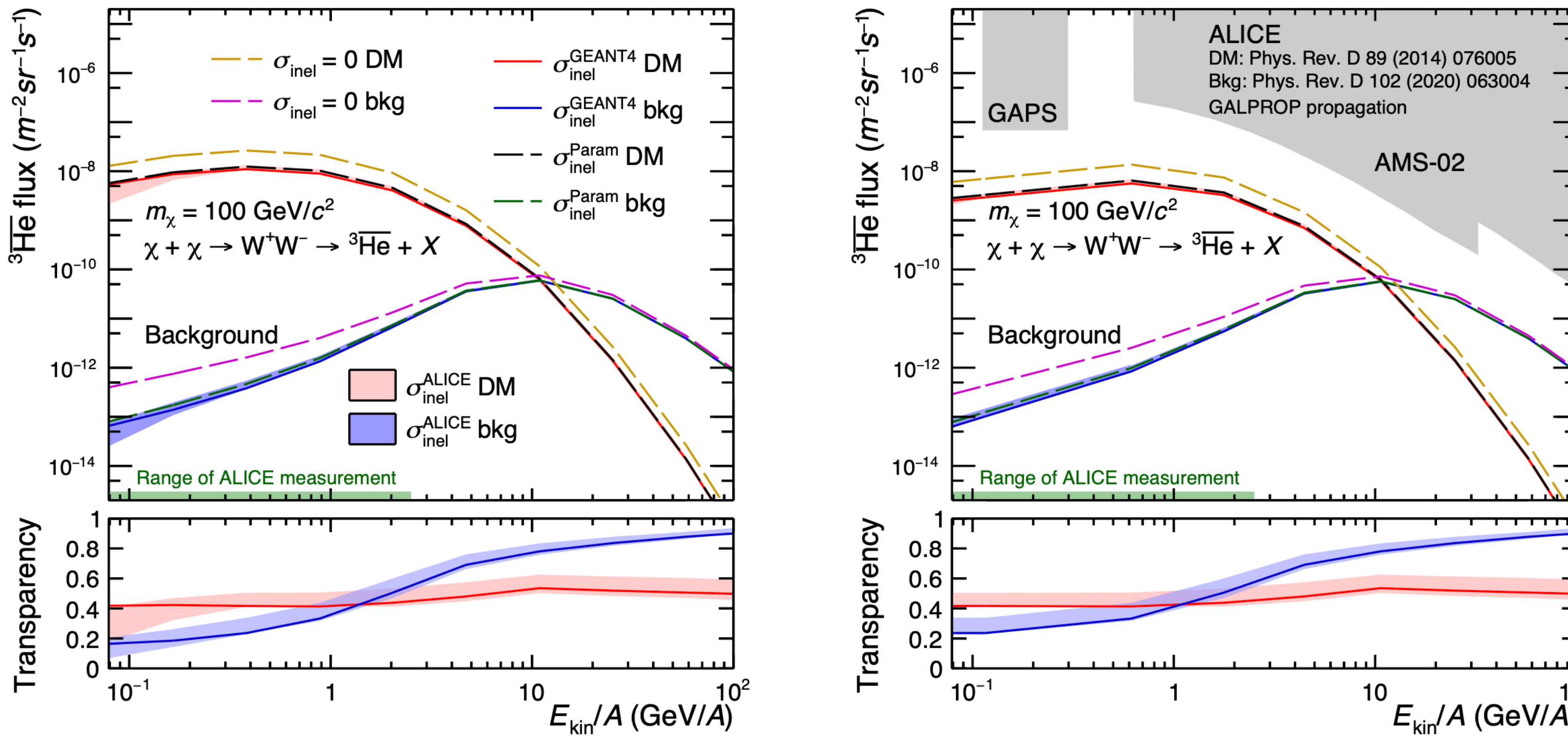


ALICE Collaboration, arXiv:2202.01549

- Measured absorption used to calculate the flux near earth, before and after solar modulation
- Large reduction of uncertainties due to ALICE measurement

Anti-^{3}He flux near earth

ALICE Collaboration, arXiv:2202.01549



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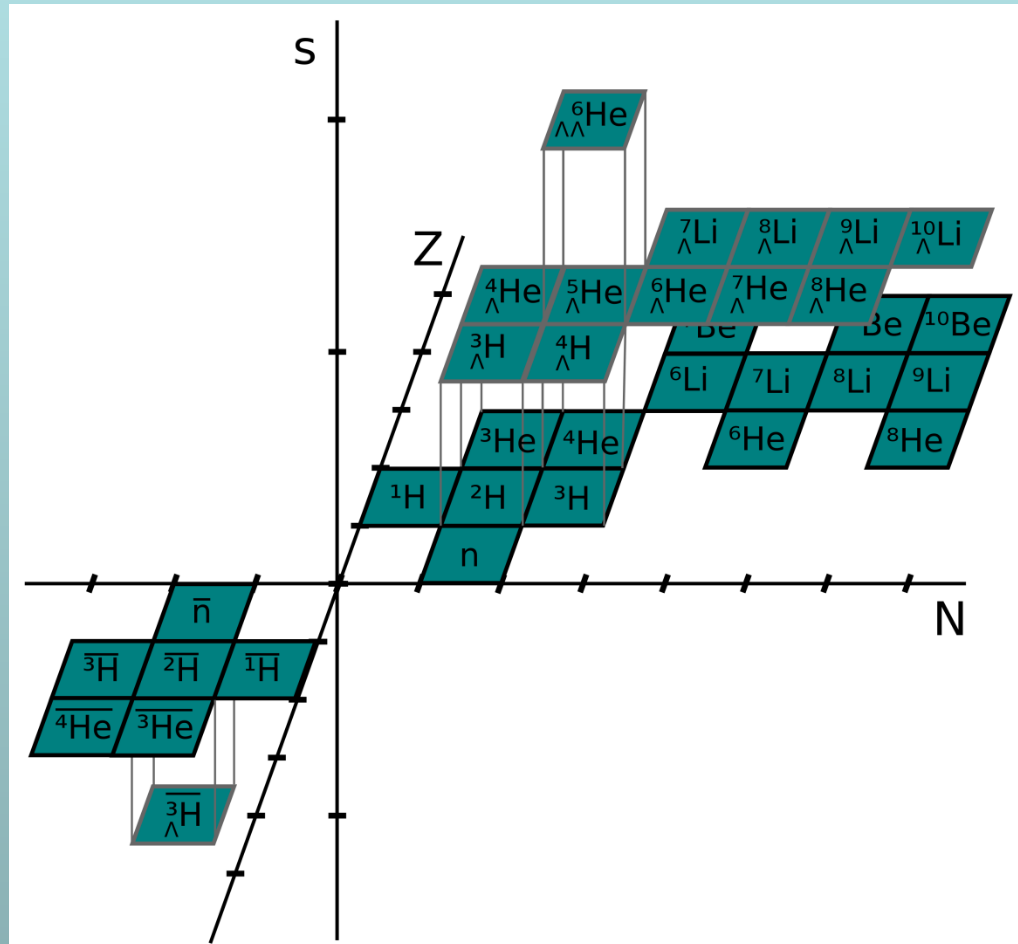
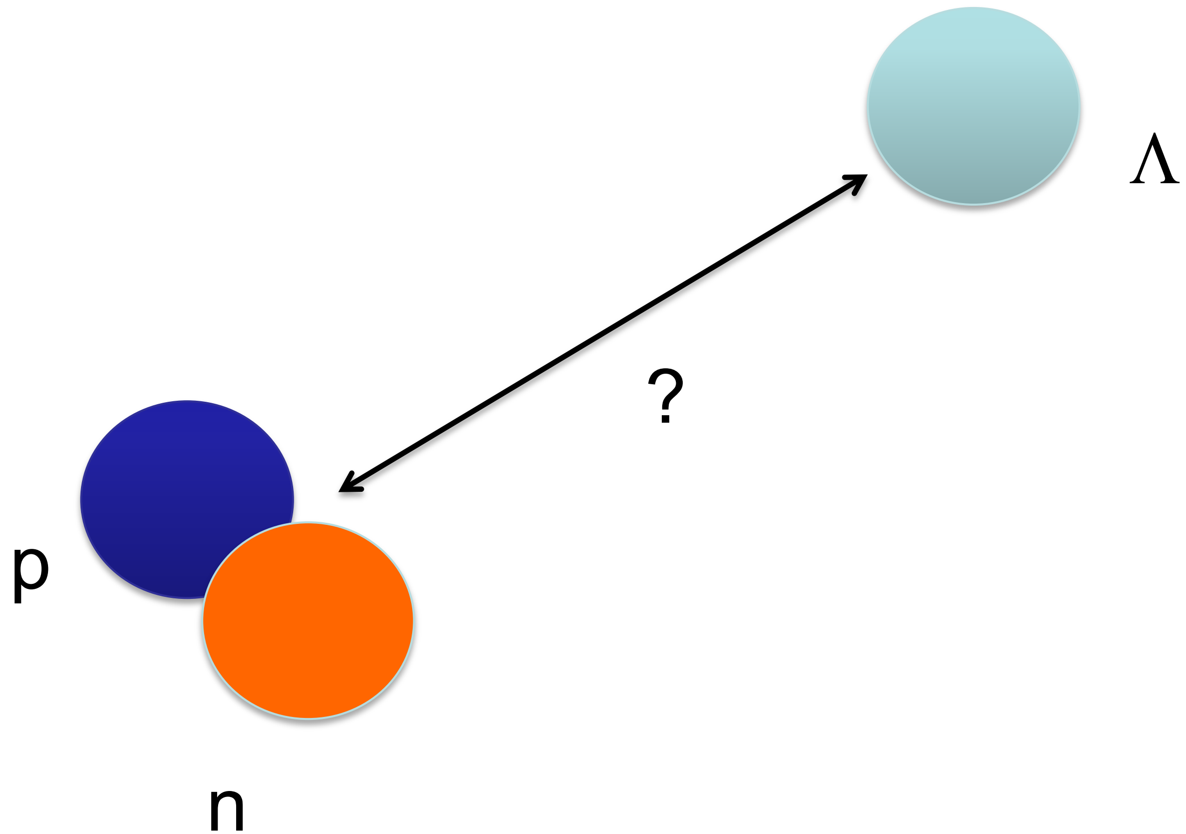
Hypernuclei



Hypertriton

Bound state of Λ, p, n

m = 2.991 GeV/c^2 (B_Λ =130 keV)



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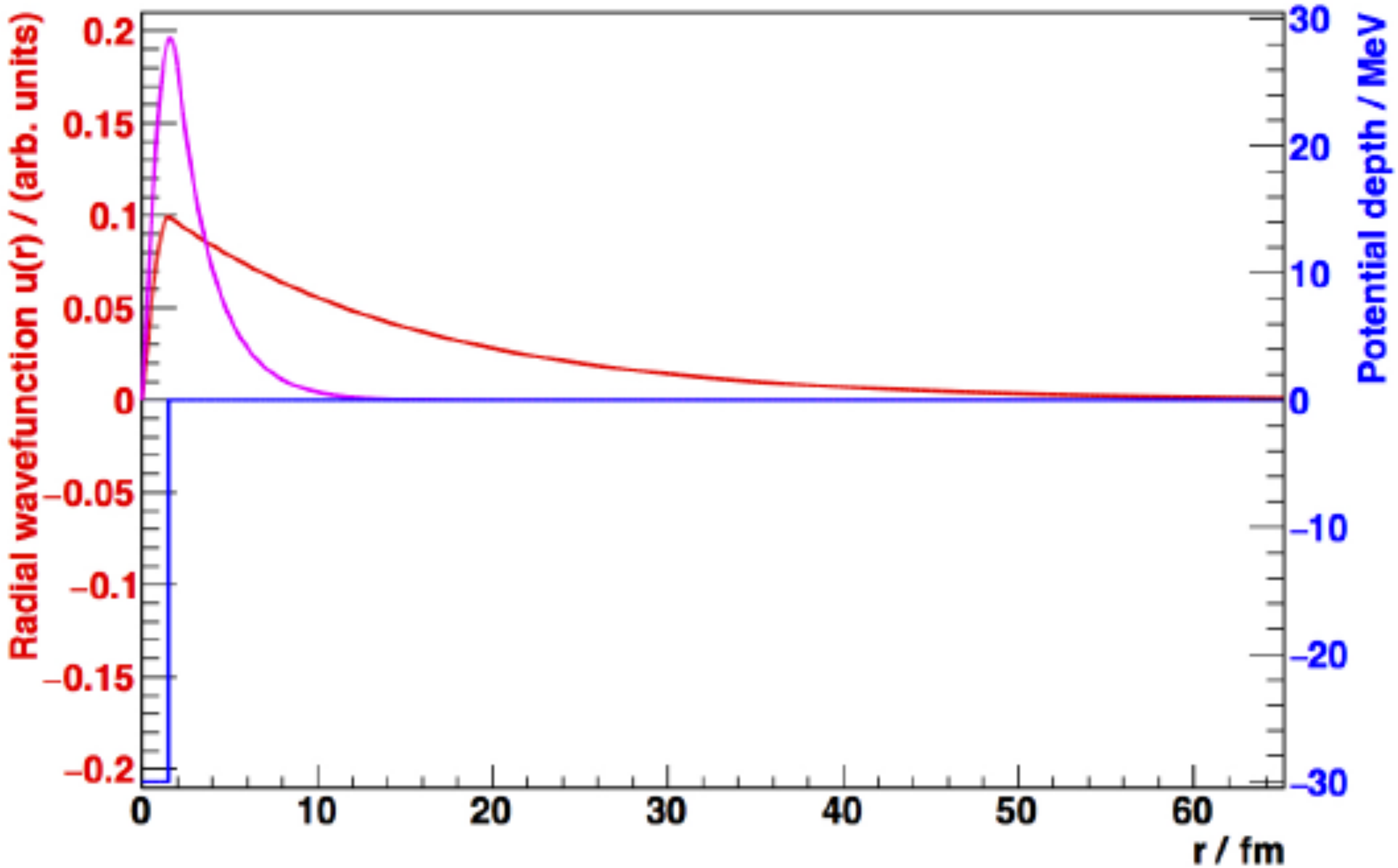

P. Braun-Munzinger, BD, Nucl. Phys. A 987 (2019) 144

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Bound state of Λ, p, n

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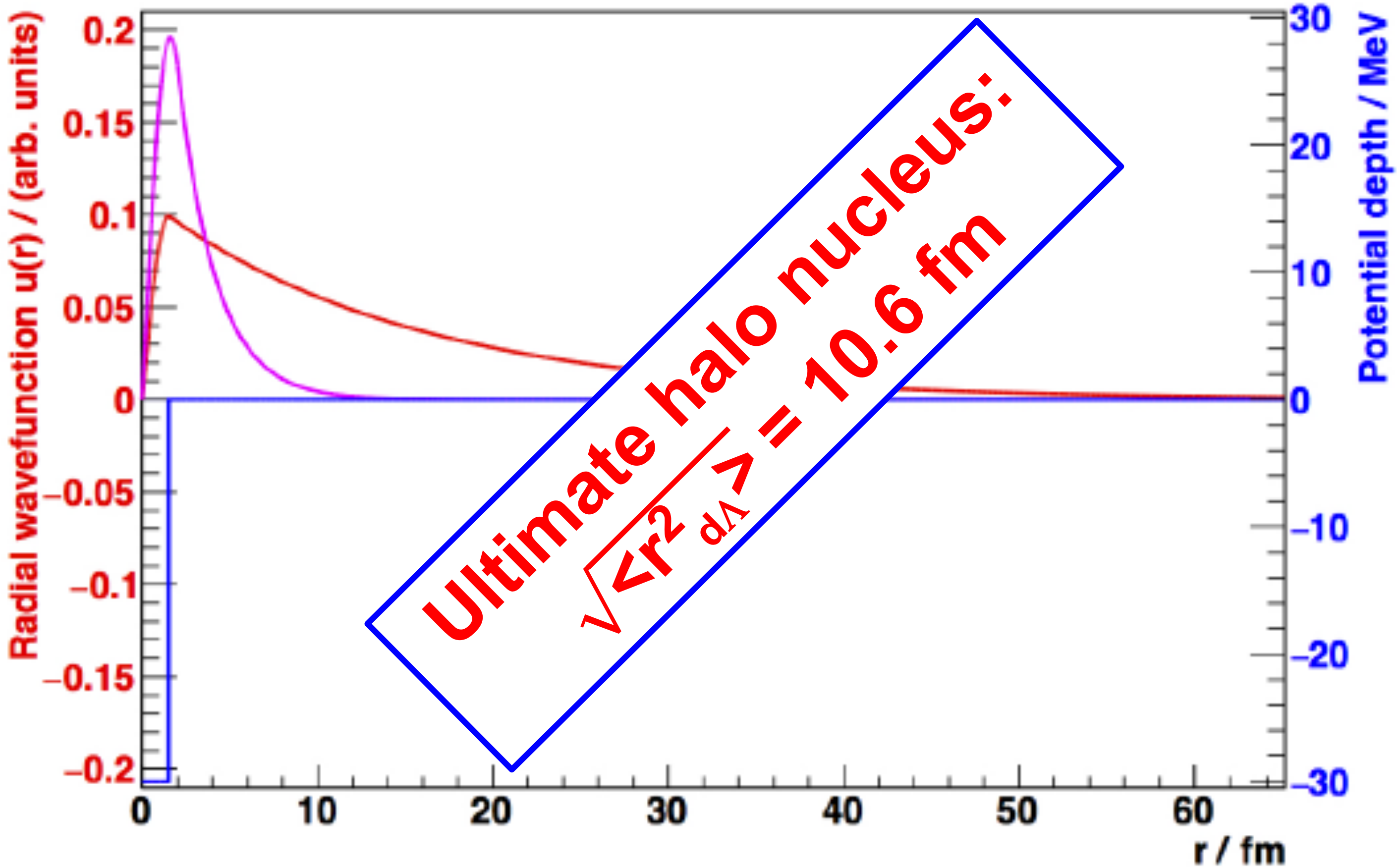
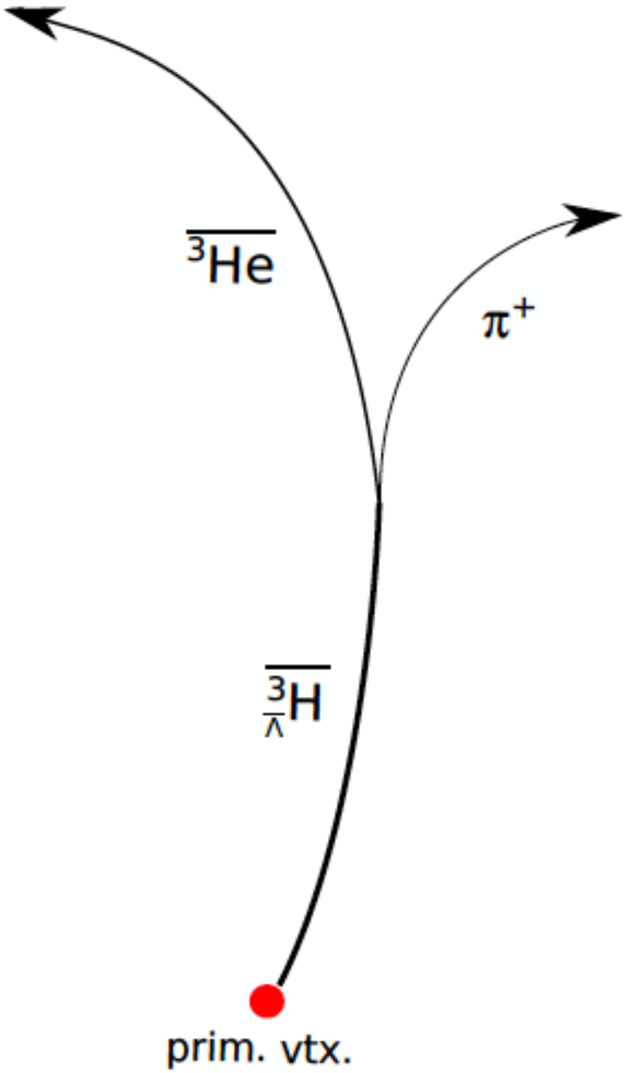


P. Braun-Munzinger, BD, Nucl. Phys. A 987 (2019) 144

Hypertriton Identification



Bound state of Λ, p, n

m = 2.991 GeV/c^2 (B_Λ =130 keV)

→ Radius of about 10.6 fm

Decay modes:

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

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

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

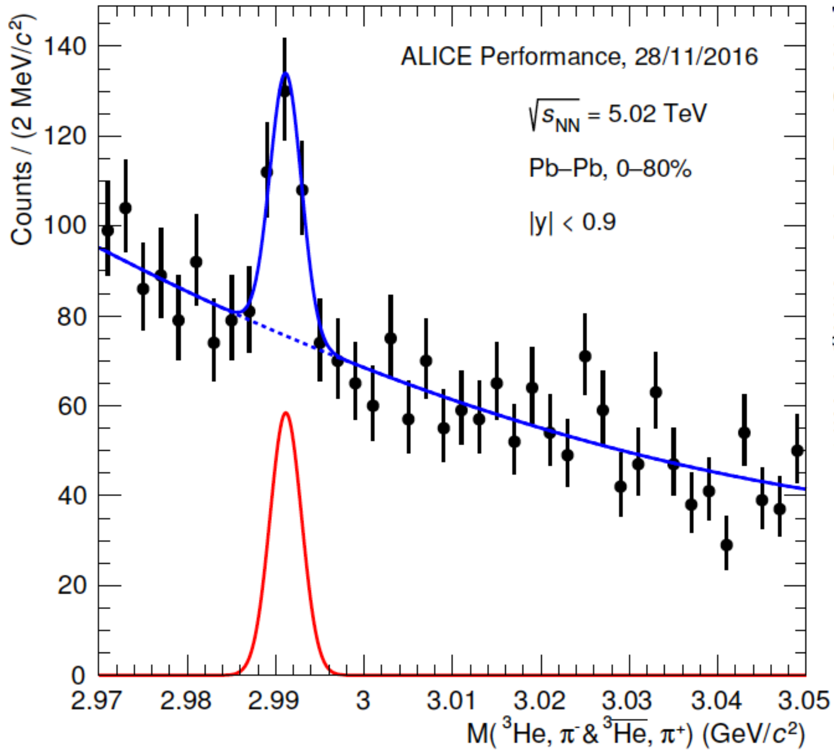
$$^3_\Lambda\text{H} \rightarrow \text{d} + \text{n} + \pi^0$$

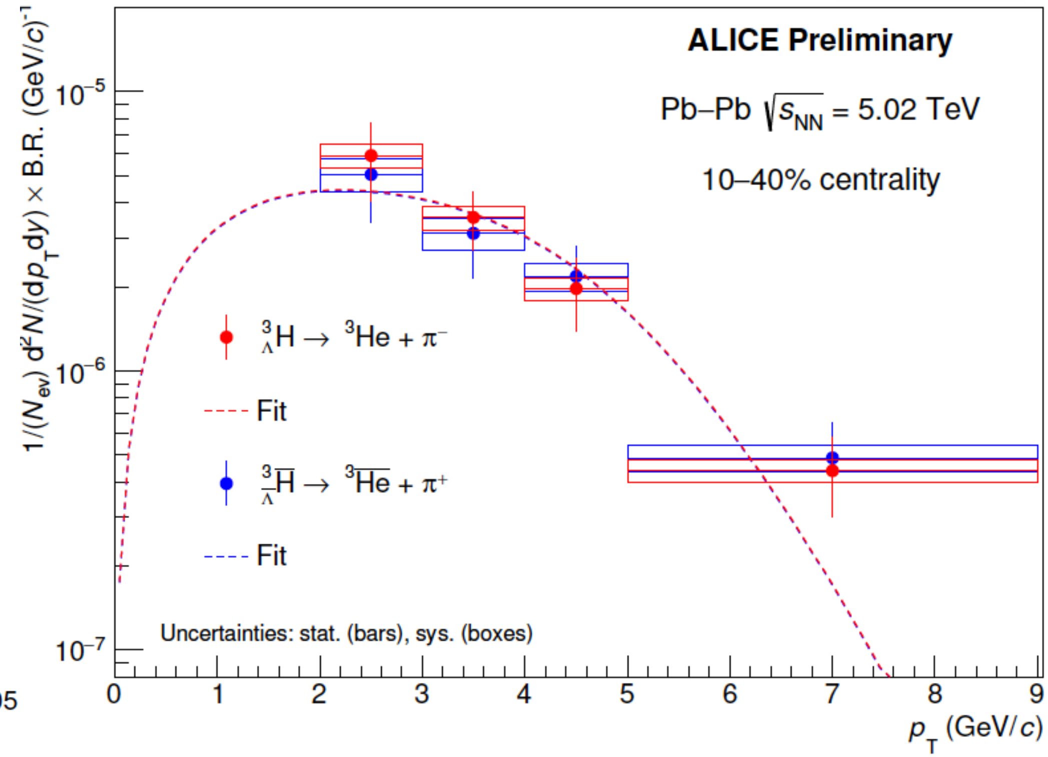
+ anti-particles

→ Anti-Hypertriton first observed by STAR Collaboration:

Science 328,58 (2010)

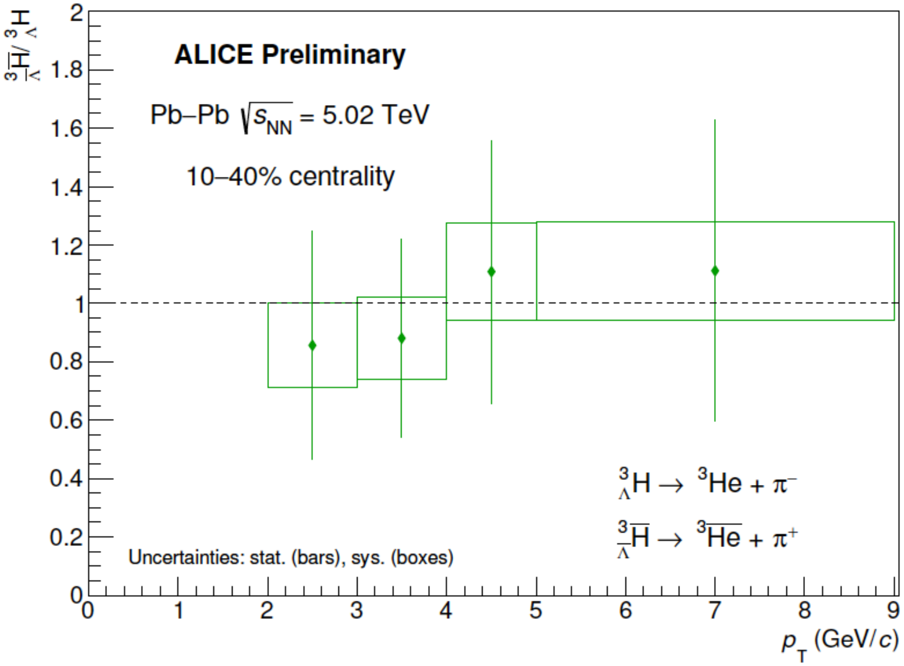
Hypertriton signal

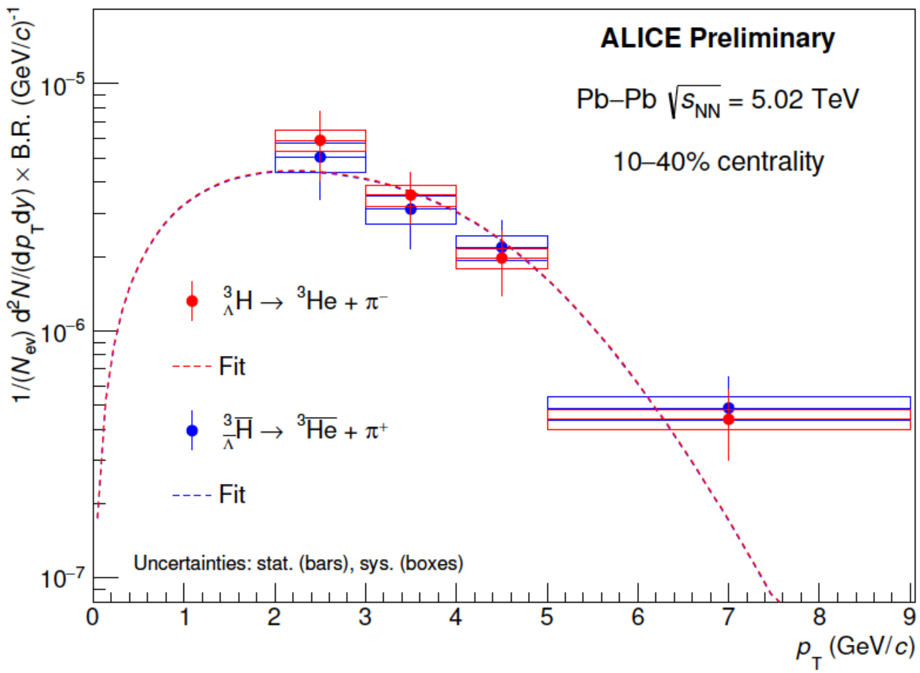




- Clear signal reconstructed by decay products
- Spectra can also be described by Blast-Wave model
  → Hypertriton flows as all other particles

Hypertriton spectra

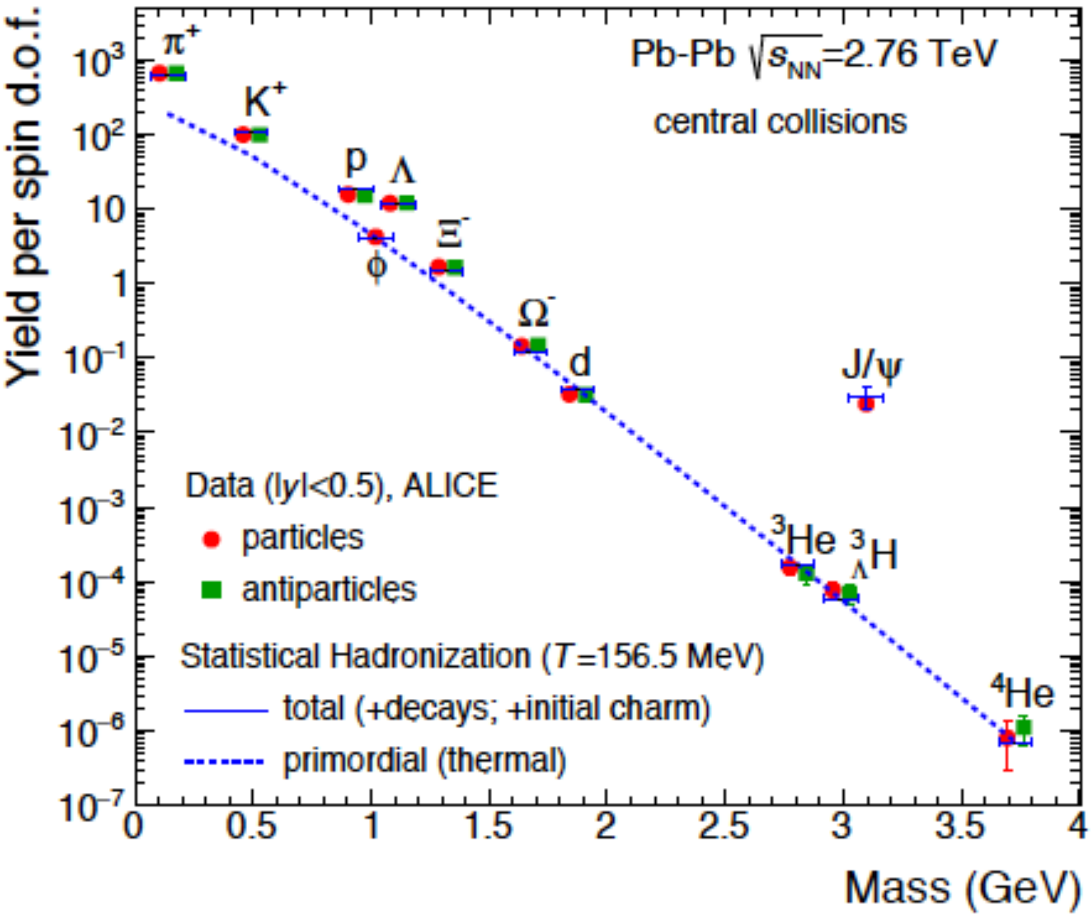




- Anti-hypertriton/Hypertriton ratio consistent with unity vs. p_T

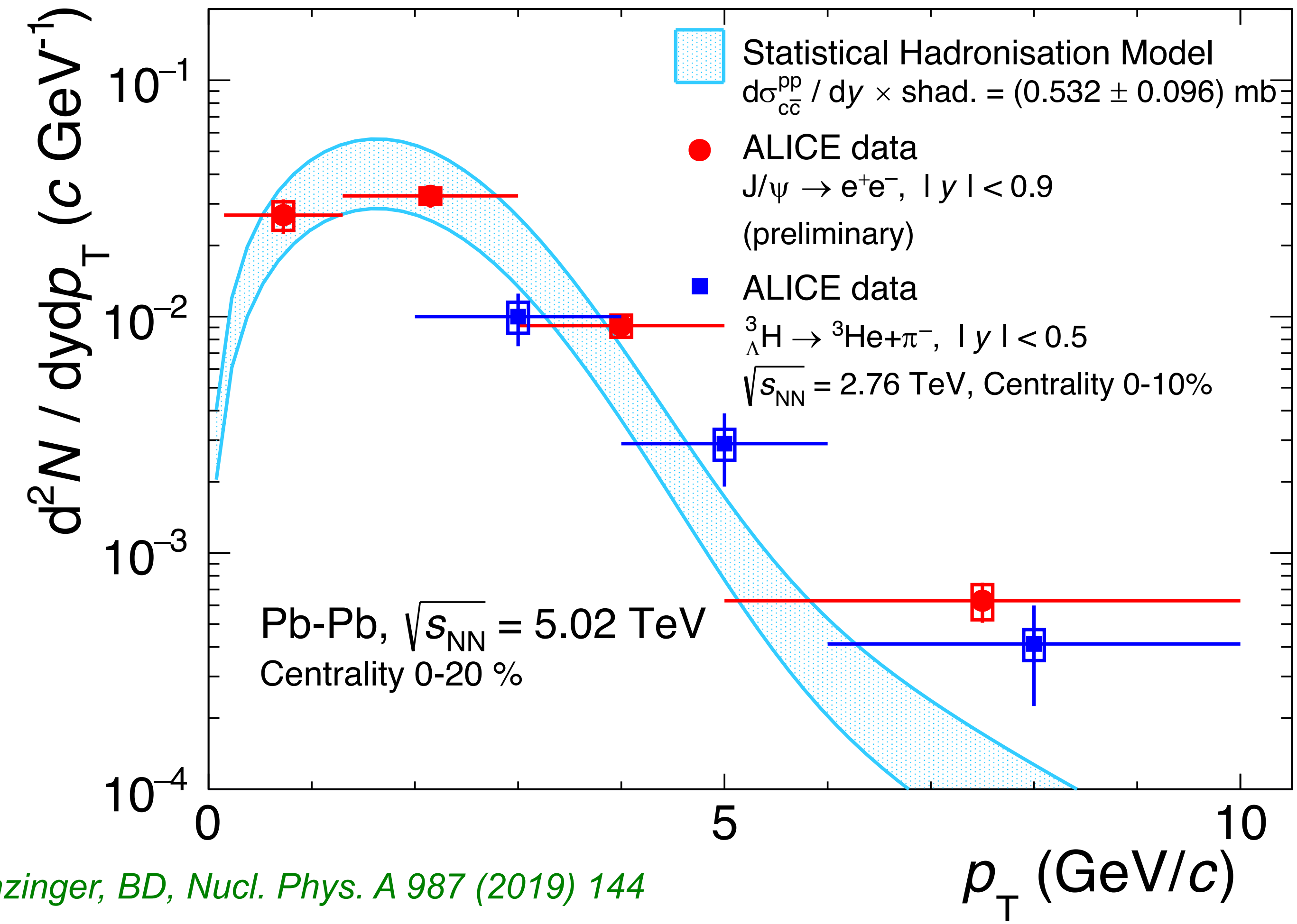
Fits: different view

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

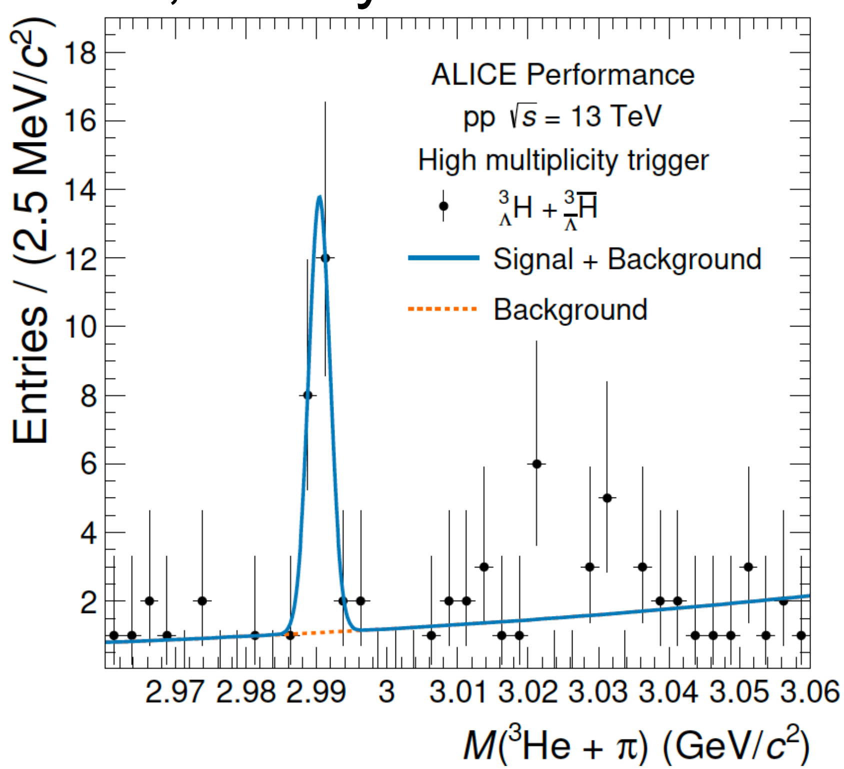


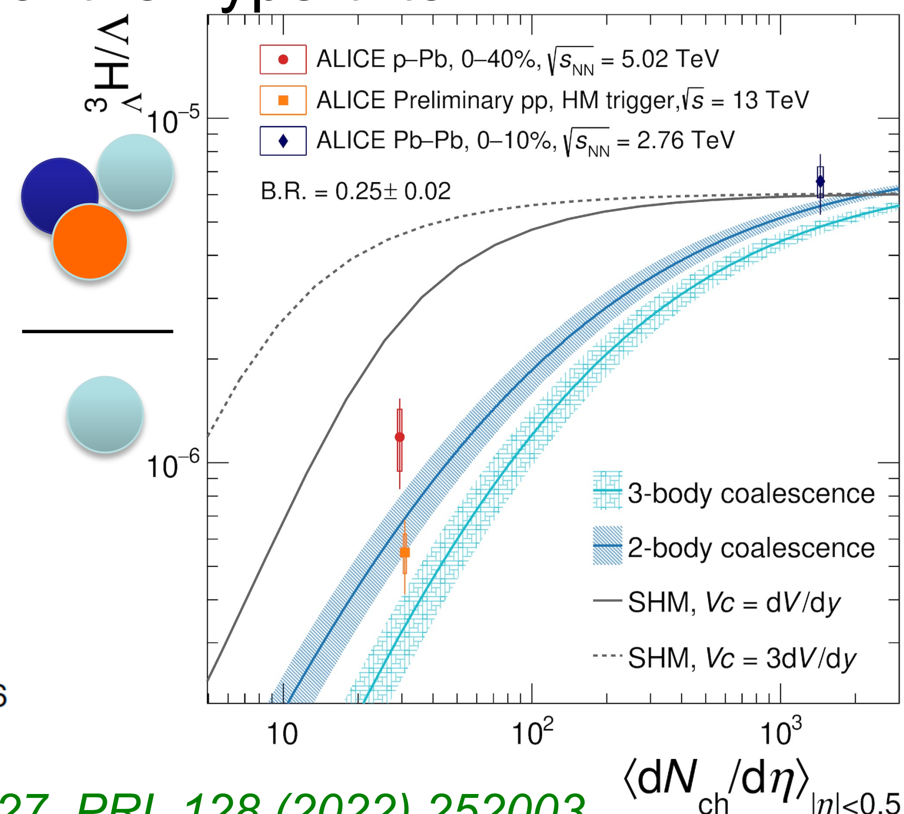
P. Braun-Munzinger, BD, Nucl. Phys. A 987 (2019) 144

- 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

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, arXiv:2107.10627, PRL 128 (2022) 252003

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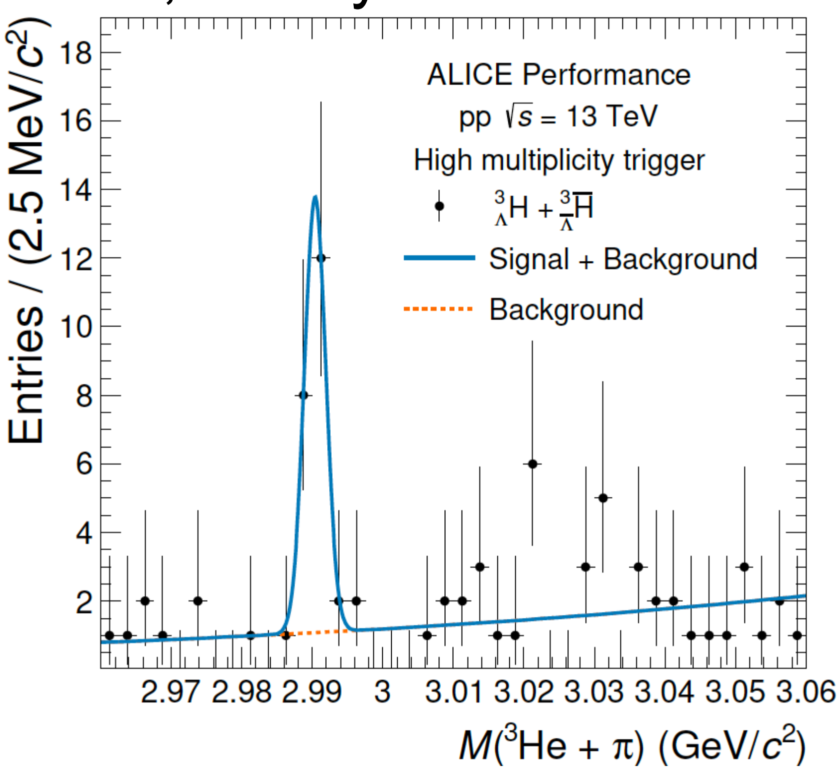
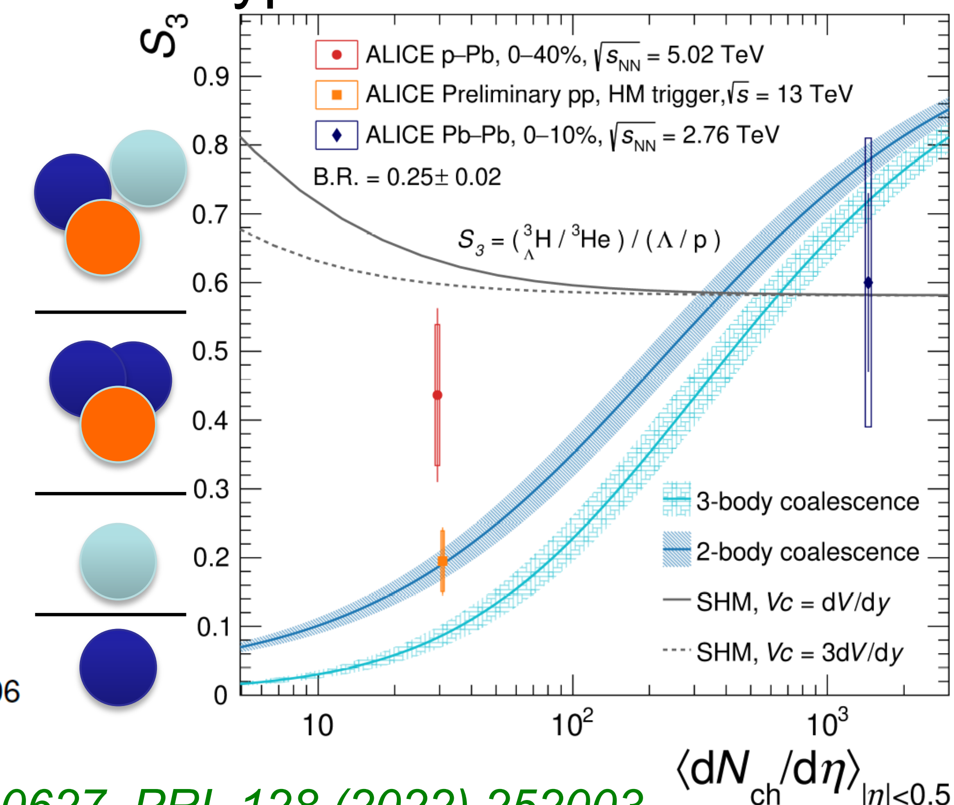
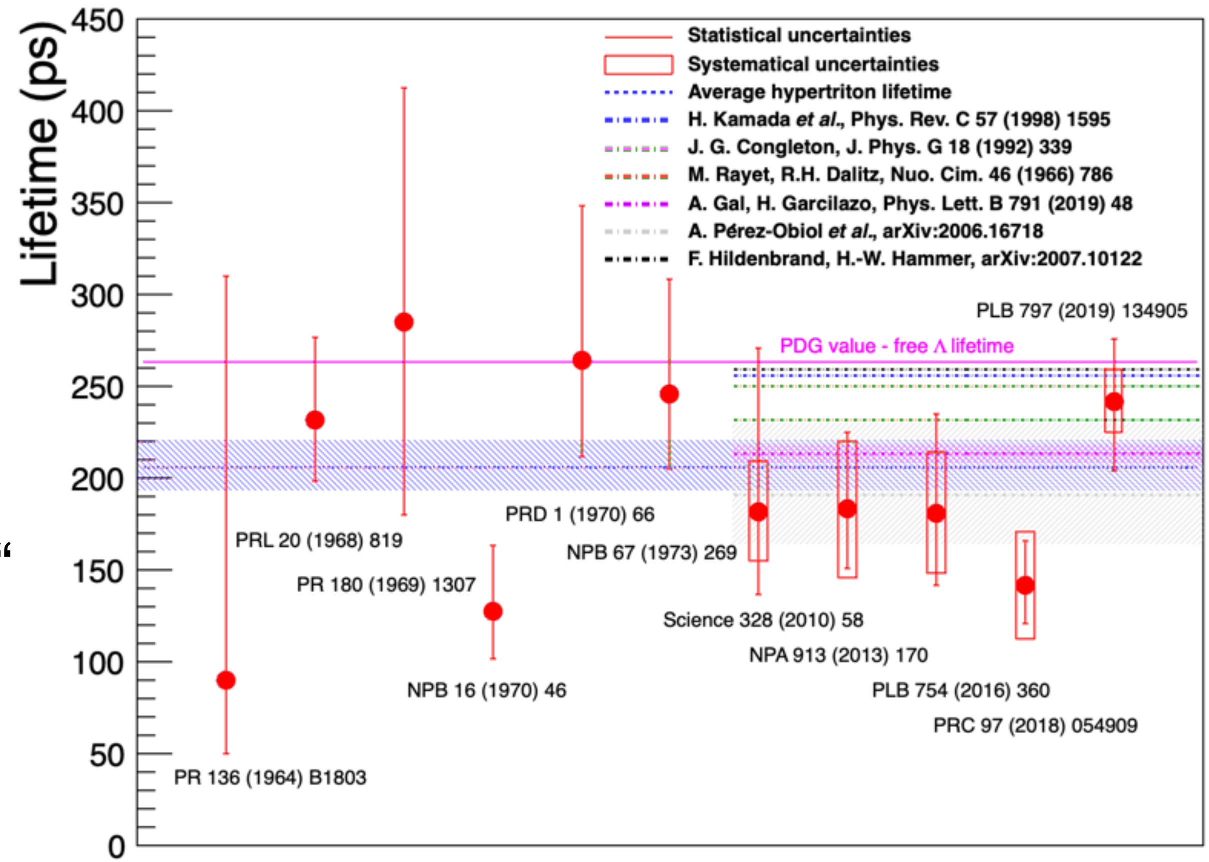




ALICE Collaboration, arXiv:2107.10627, PRL 128 (2022) 252003

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

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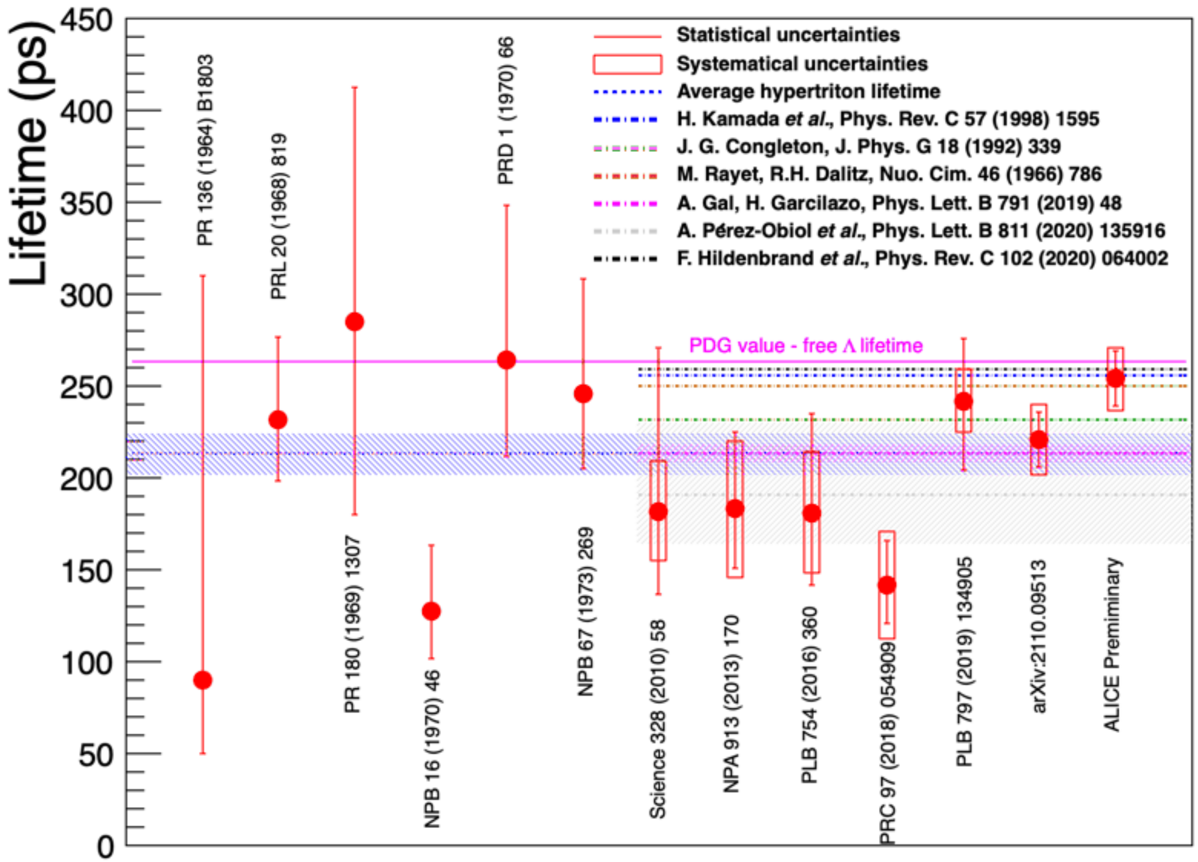
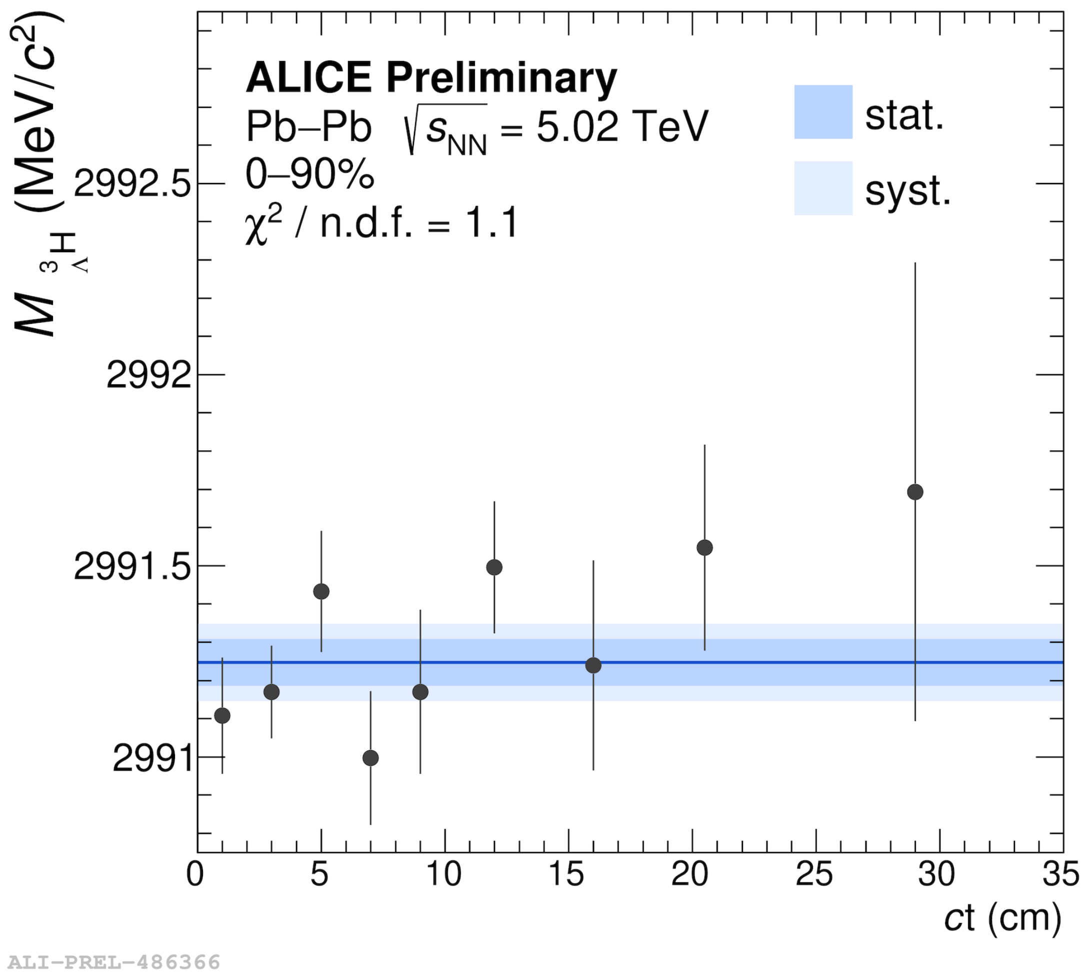


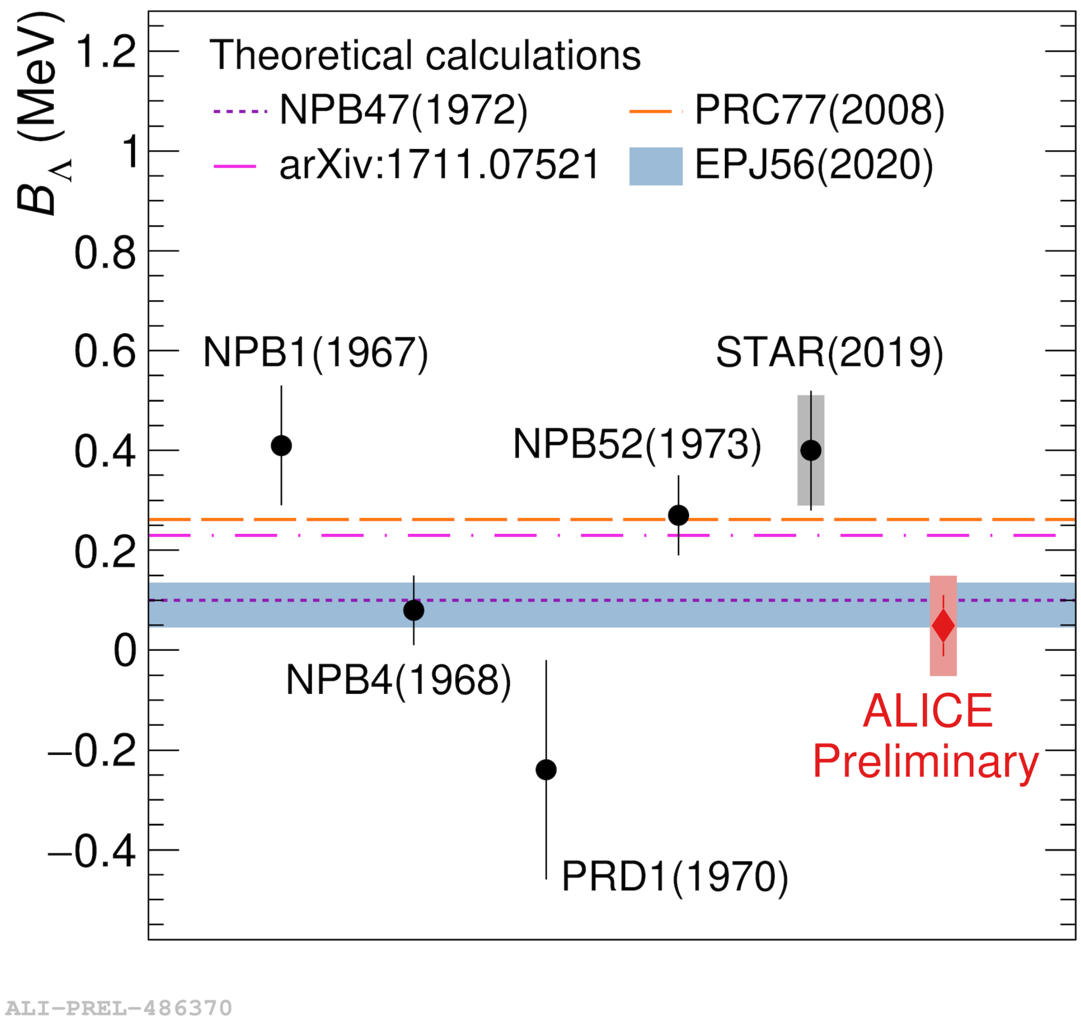
Binding Energy

- Current studies show a better constraint and smaller statistical uncertainties (will be published soon)
- The value obtained by this fit is B_Λ = 55 ± 62 keV

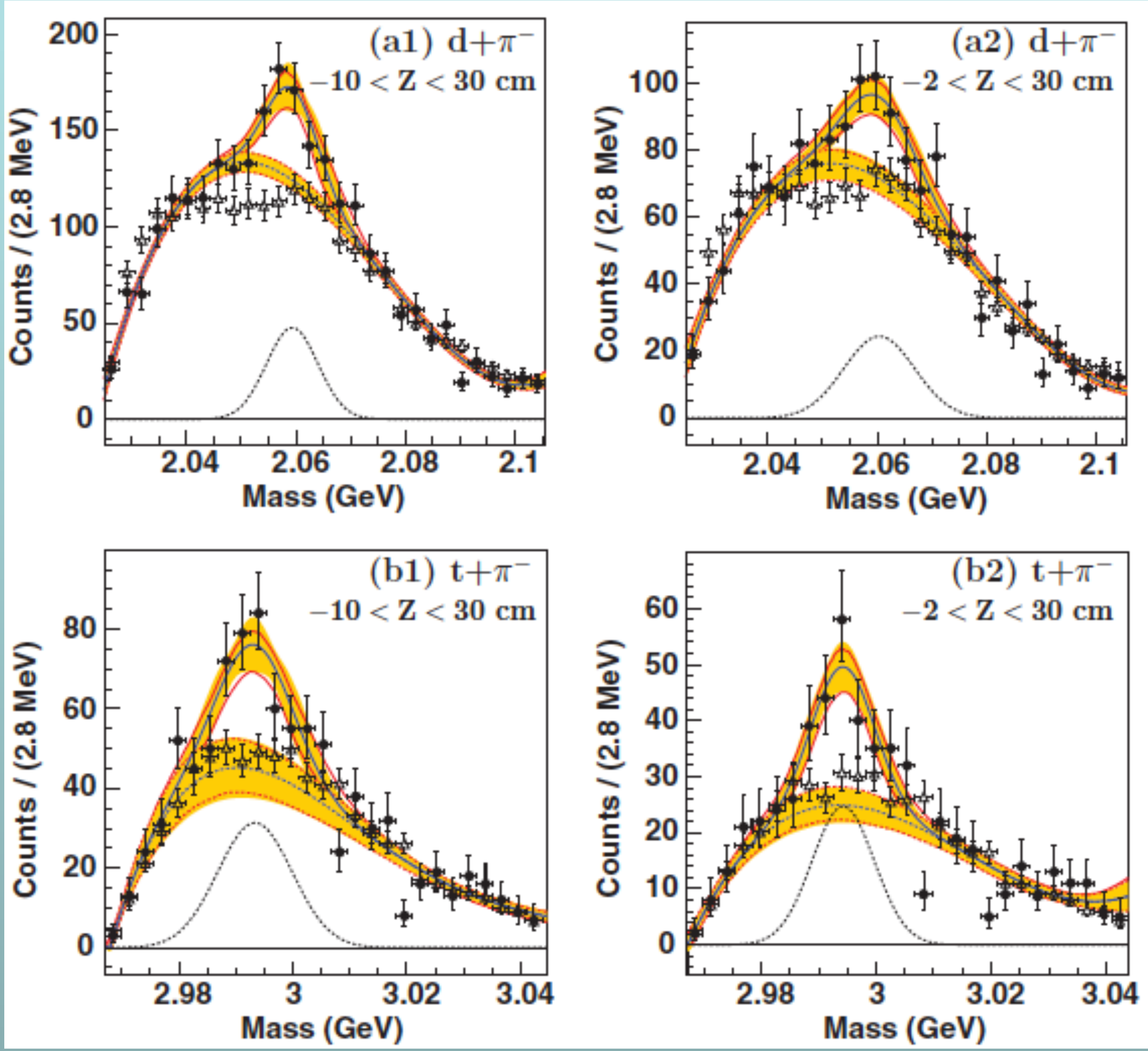


Binding Energy

- Current studies show a better constraint and smaller statistical uncertainties (will be published soon)
- The value obtained by this fit is $B_{\Lambda} = 55 \pm 62$ keV
- Is compatible within the theoretical predictions



Exotica Searches



HypHI Collaboration observed signals in the t+π and d+π invariant mass distributions

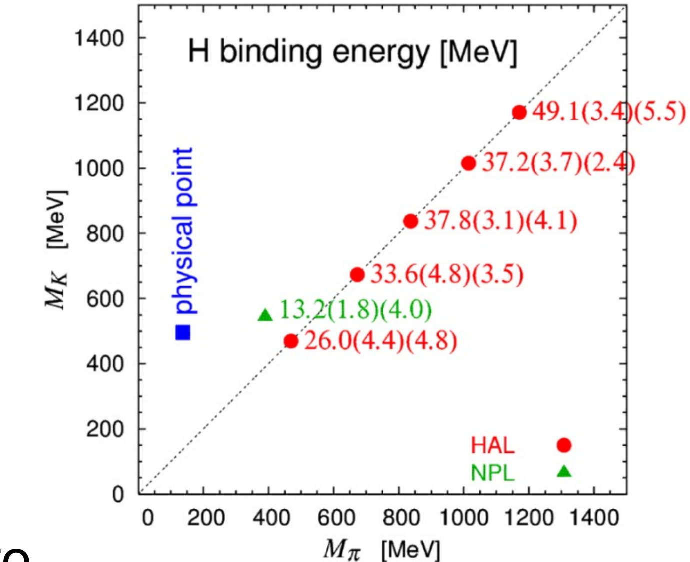
C. Rappold et al., PRC 88, 041001 (2013)

H-Dibaryon

- Hypothetical bound state of *uuddss* ($\Lambda\Lambda$)
- First predicted by Jaffe in a bag model calculation (*PRL 195, 38 +617 (1977)*)
- Recent lattice calculations suggest *(Inoue et al., PRL 106, 162001 (2011) and Beane et al., PRL 106, 162002 (2011))* a bound state (20-50 MeV/c^2 or 13 MeV/c^2)
- *Shanahan et al., PRL 107, 092004 (2011) and Haidenbauer, Meißner, PLB 706, 100 (2011)* made chiral extrapolation to a physical pion mass and got as result:
  - the H is unbound by 13±14 MeV/c^2 or lies close to the Ξp threshold

→ Renewed interest in experimental searches

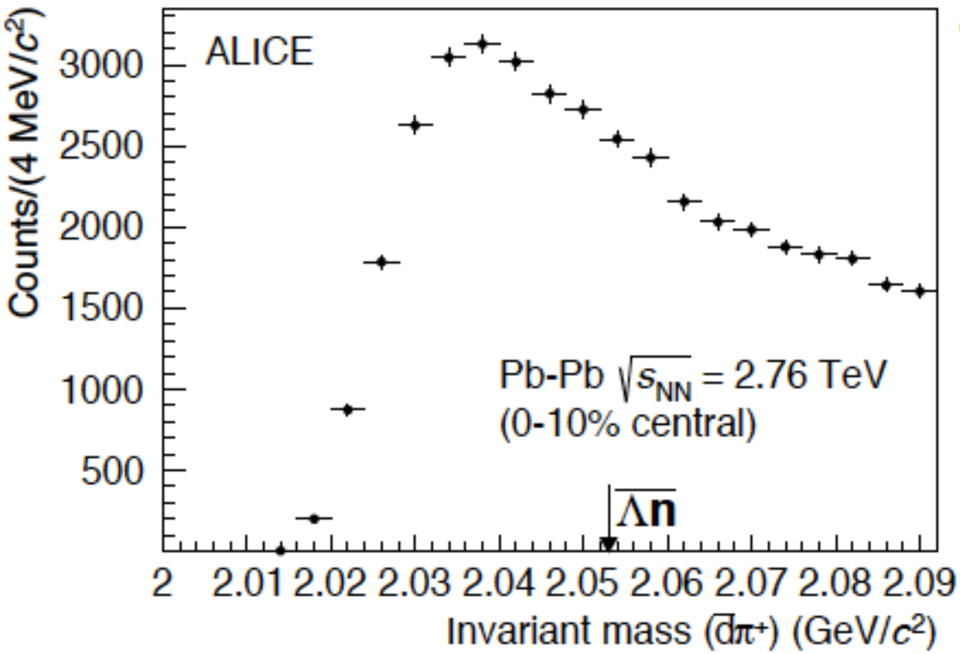
T. Inoue, private communication

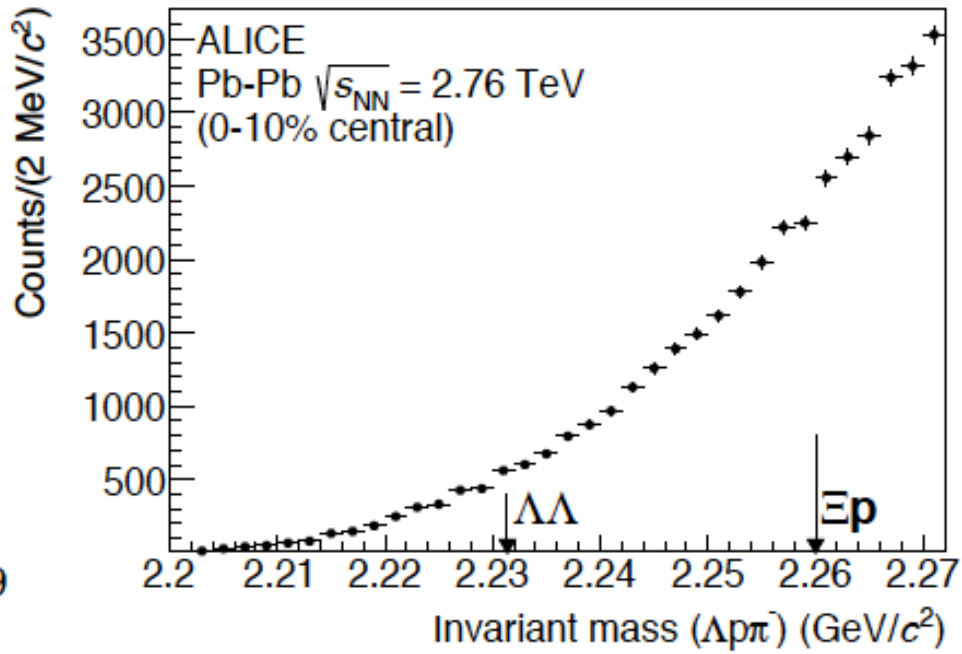


- Most recent lattice QCD result points back to a weakly bound state (4.56±1.29 MeV/c^2): *J.R. Green et al., PRL 127 (2021) 242003*

Searches for bound states

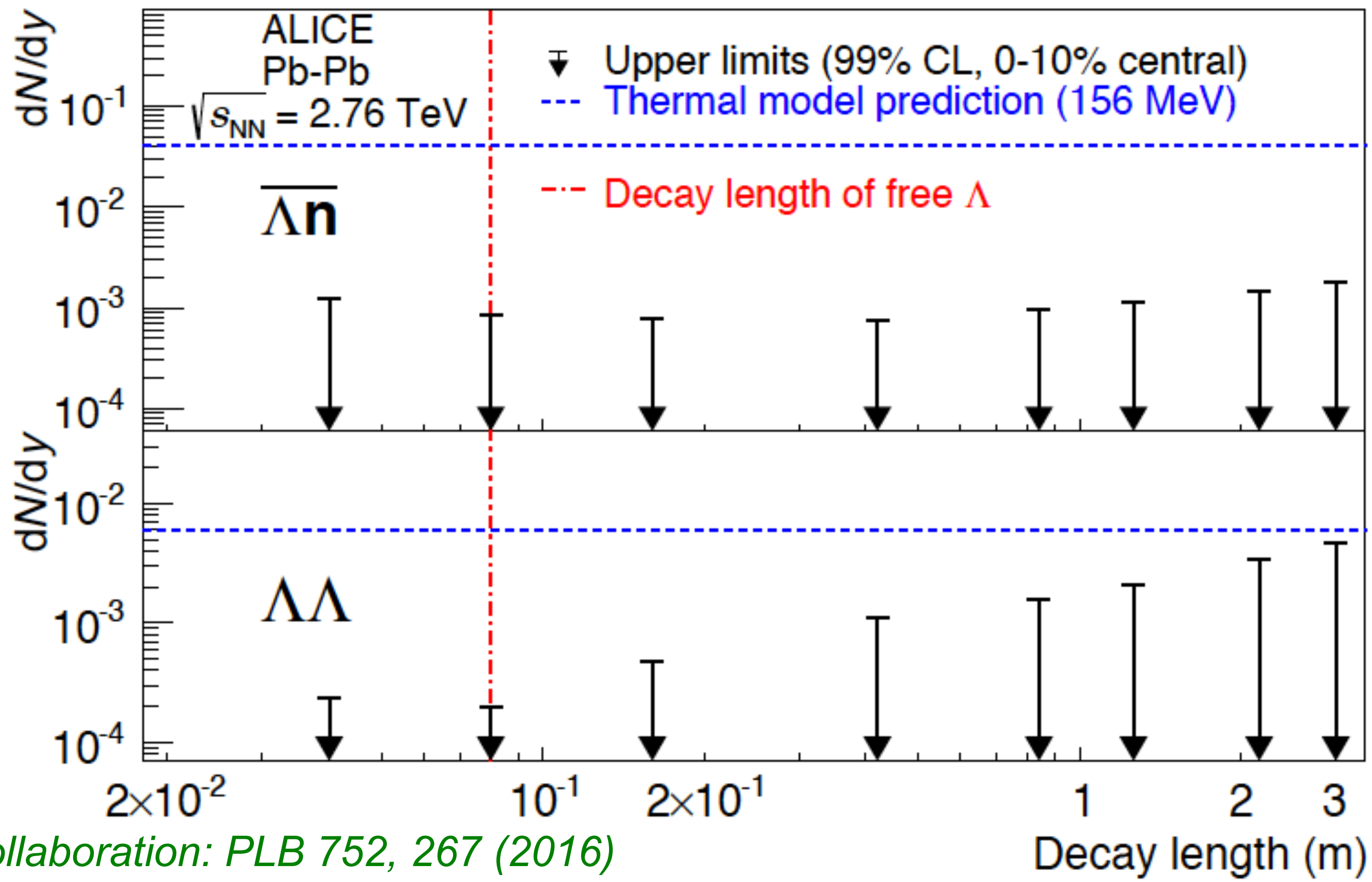
ALICE Collaboration: PLB 752, 267 (2016)





Invariant mass analyses of the two hypothetical particles lead to no visible signal → Upper limits set

Decay length dependence

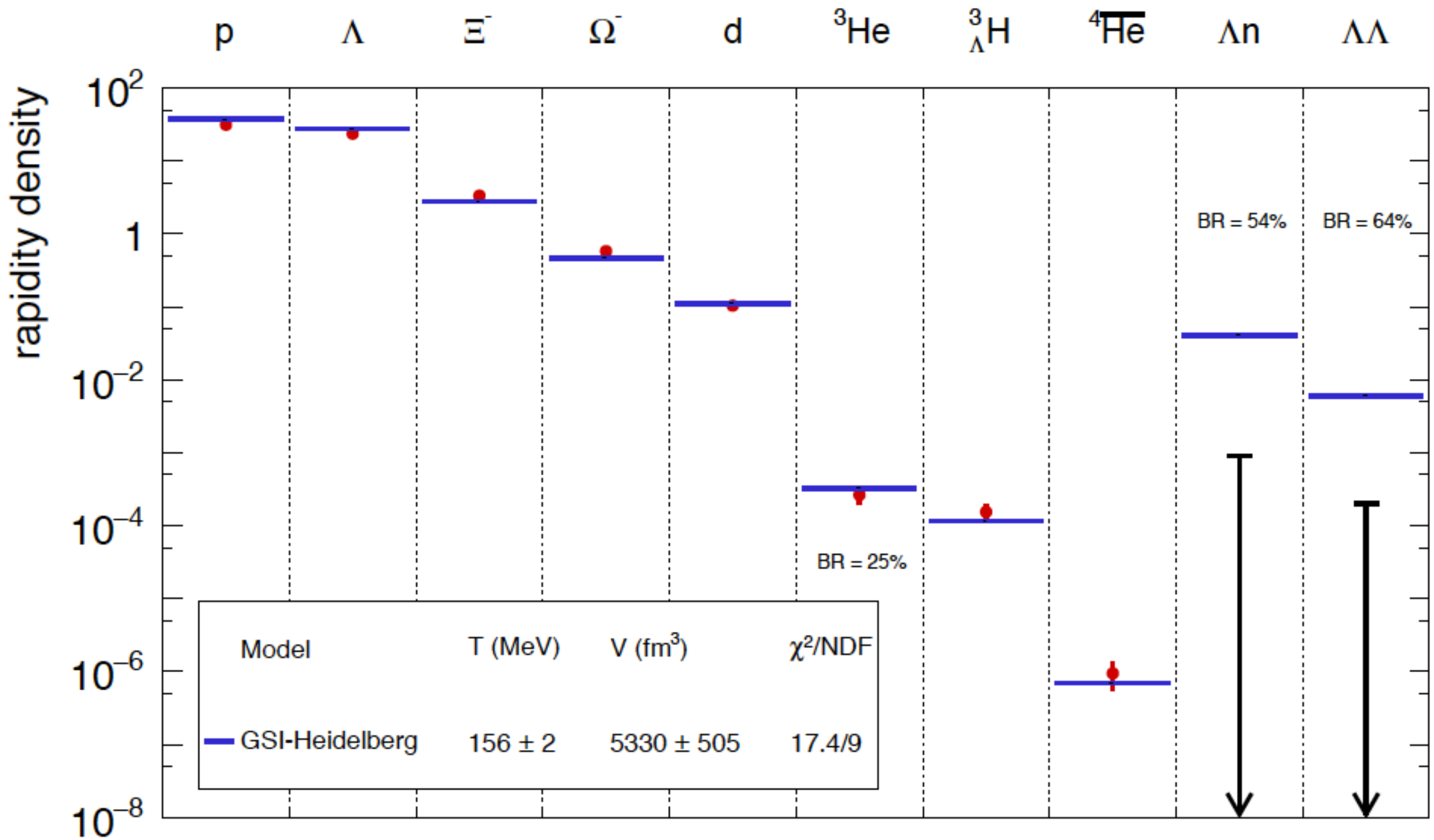


ALICE Collaboration: PLB 752, 267 (2016)

Search for a bound state of Λn and ΛΛ, shows no hint of signal

→ upper limits set (for different lifetimes assumed for the bound states)

Comparison with fit



Simplified plot, CERN Courier (September 2015)

Hypertriton (B_Λ: 130 keV) and Anti-Alpha (B/A: 7 MeV) yields fit well with the thermal model expectations

→ Upper limits of ΛΛ and Λn are factors of >25 below the model values

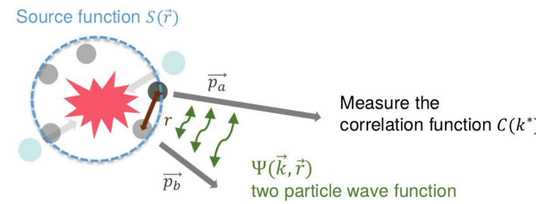
ΛΛ correlations

Statistical definition — *Experimental definition* — *Theoretical definition*

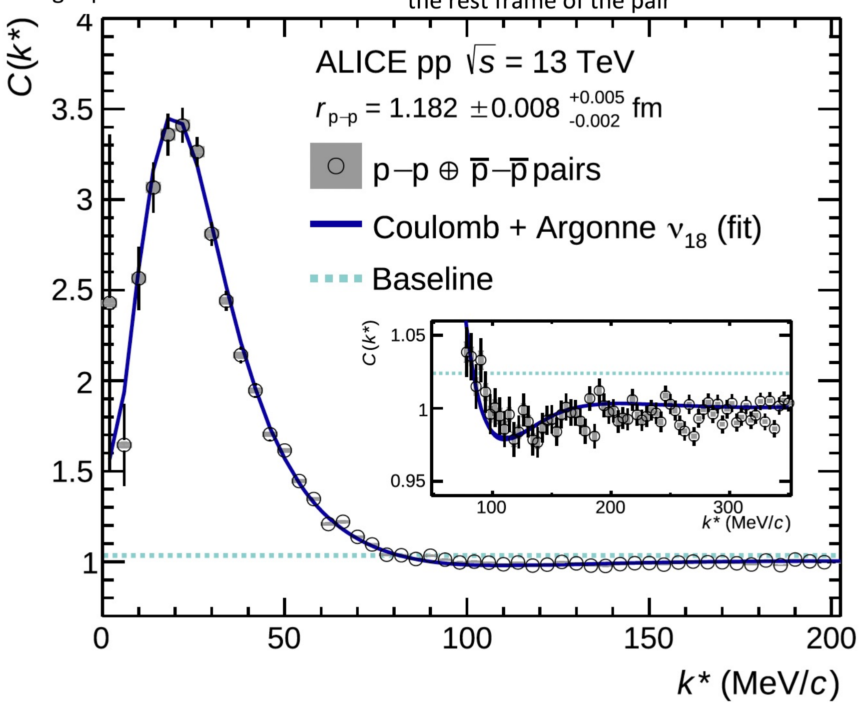
$$C(k^*) = \frac{\mathcal{P}(\vec{p}_a,\vec{p}_b)}{\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)} = \mathcal{N}\,\frac{N_{\mathrm{Same}}(k^*)}{N_{\mathrm{Mixed}}(k^*)} = \int S(\vec{r})\left|\Psi(\vec{k}^*,\vec{r})\right|^2 \mathrm{d}^3\vec{r} \xrightarrow{k^*\to\infty} 1$$

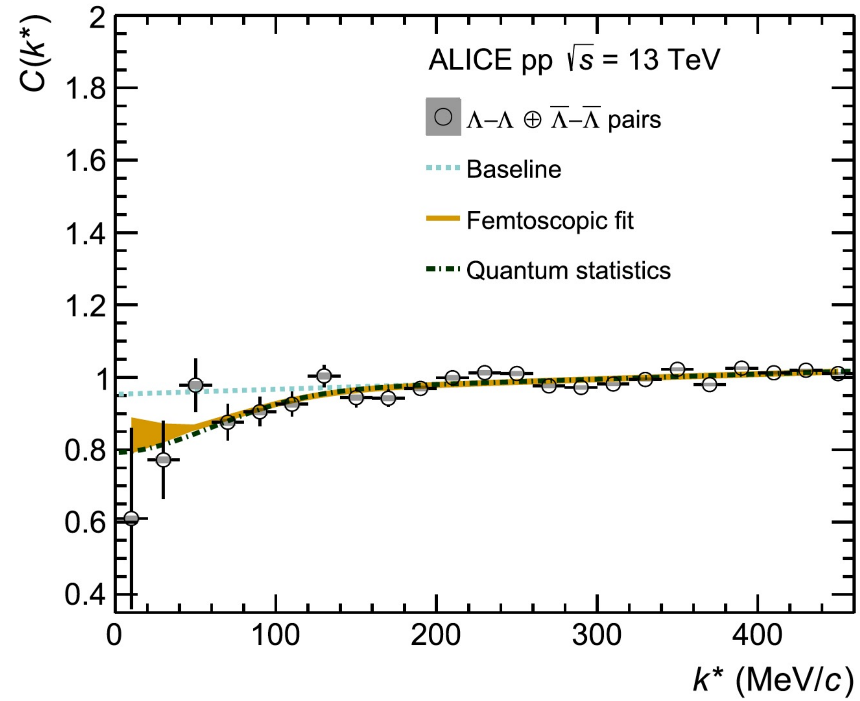
Single-particle momenta

Relative distance / reduced momentum in the rest frame of the pair



ALICE Collaboration: PLB 797 (2019) 134822





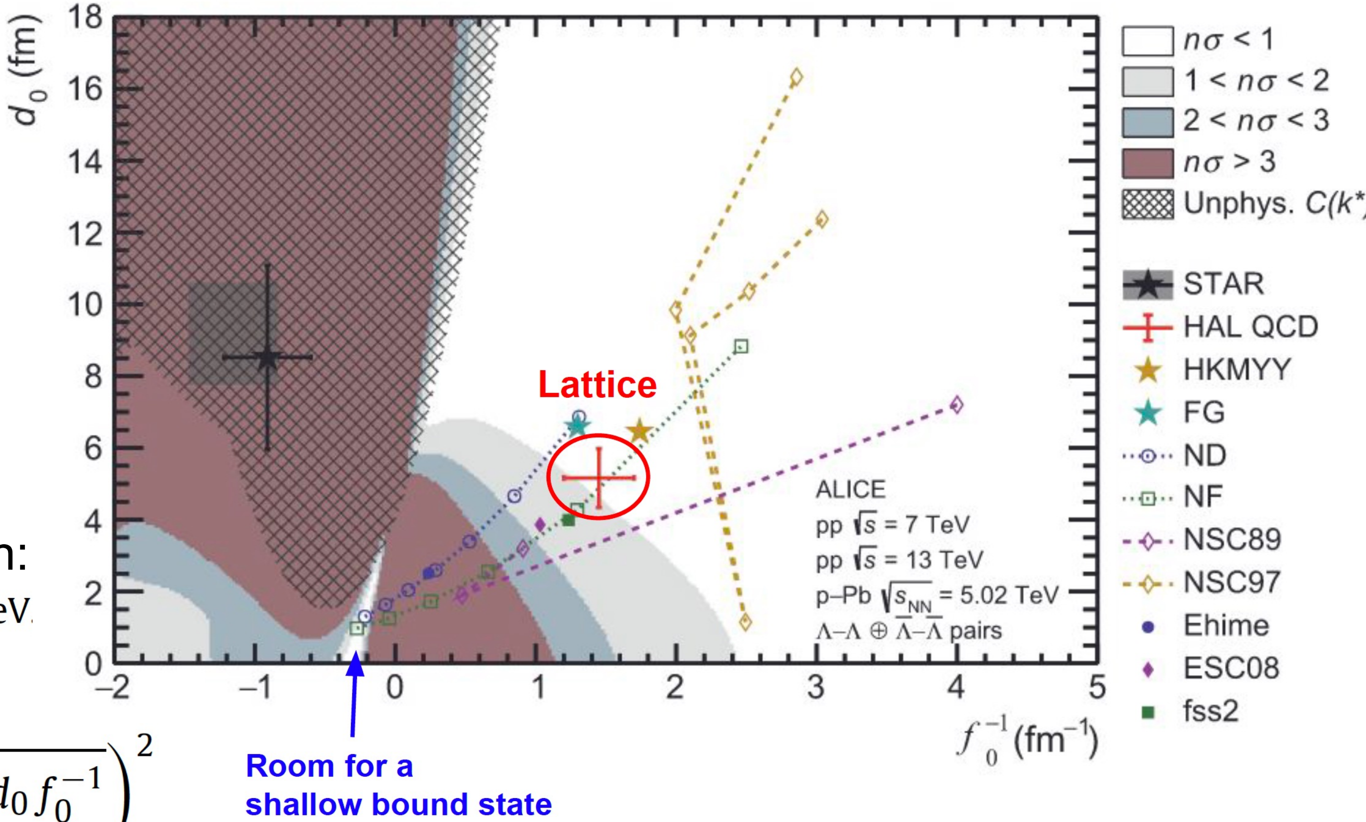
- Source determined by pp correlation, such that the ΛΛ interaction can be extracted from the corresponding correlation

ΛΛ correlations

ALICE Collaboration: PLB 797 (2019) 134822

- **Parameter scan** to test the compatible scattering length (f_0) and effective range (d_0)
- **Compatible** with the **Lattice** calculations, and results from **hypernuclei**
- An **upper limit** for the binding energy of the **hypothetical H-dibaryon** of

$$B_{\Lambda\Lambda} < 3.2\text{MeV}$$



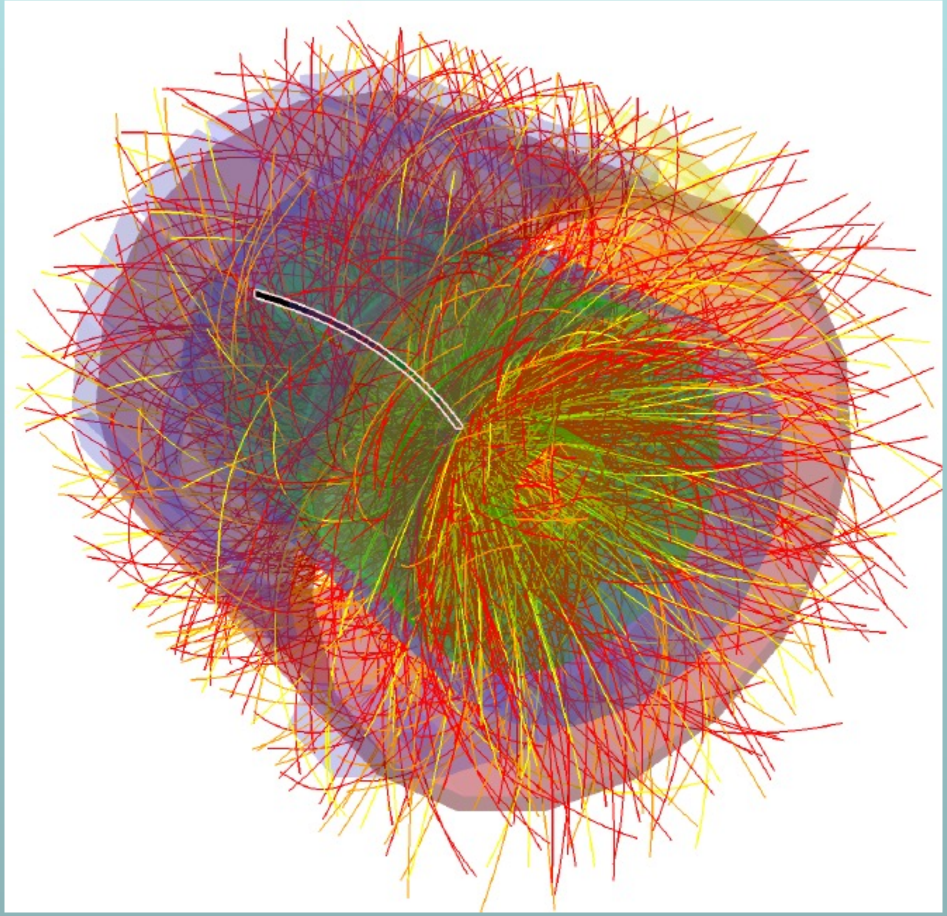
Best value from the scan:

$$B_{\Lambda\Lambda} = 3.2^{+1.6}_{-2.4}(\text{stat})^{+1.8}_{-1.0}(\text{syst})\ \text{MeV}$$

using

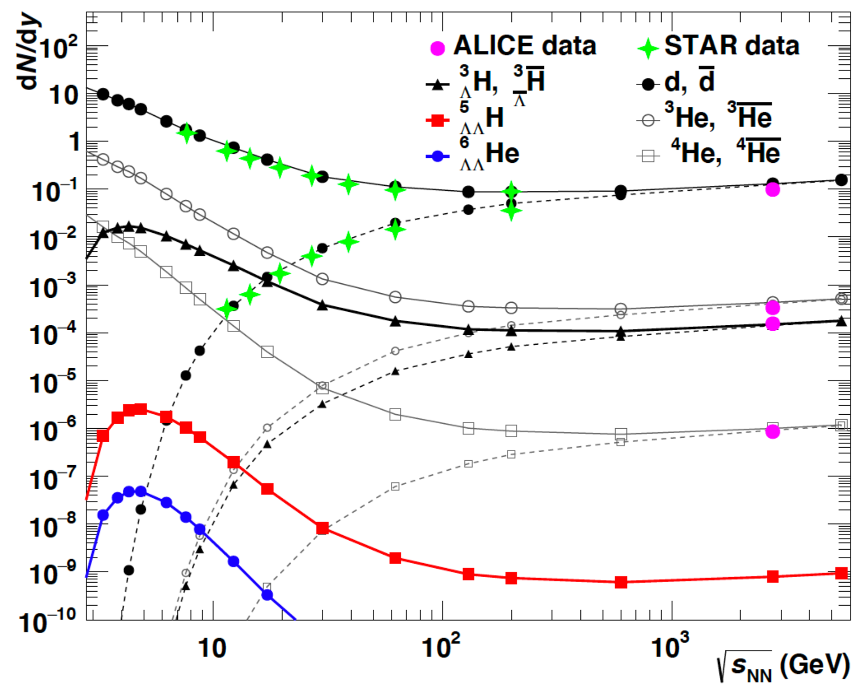
$$B_{\Lambda\Lambda} = \frac{1}{m_\Lambda d_0^2}\left(1 - \sqrt{1 + 2 d_0 f_0^{-1}}\right)^2$$

Outlook & Summary



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 by ALICE as predicted by the thermal model
- 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 (e.g. LHC Run 3 just started)



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