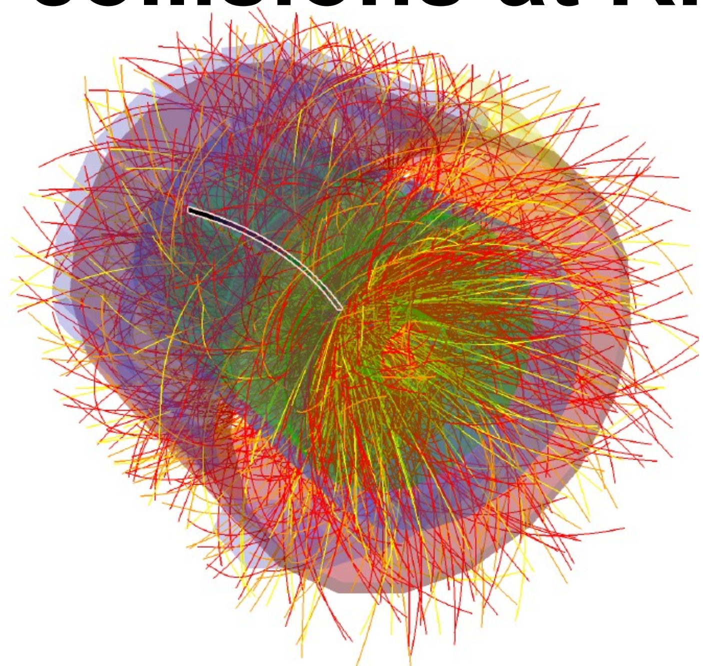
Production of loosely-bound objects in heavy-ion collisions at RHIC and LHC



July 16, 2024
GSI
EMMI Physics Day

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GOETHE UNIVERSITÄT FRANKFURT AM MAIN

IKF Institut für Kernphysik Frankfurt

Content

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

From Chemisty to Physics

Proton (p)

m=938.3 MeV/c^2

Deuteron (pn)

m=1875.6 MeV/c^2

Triton (pnn)

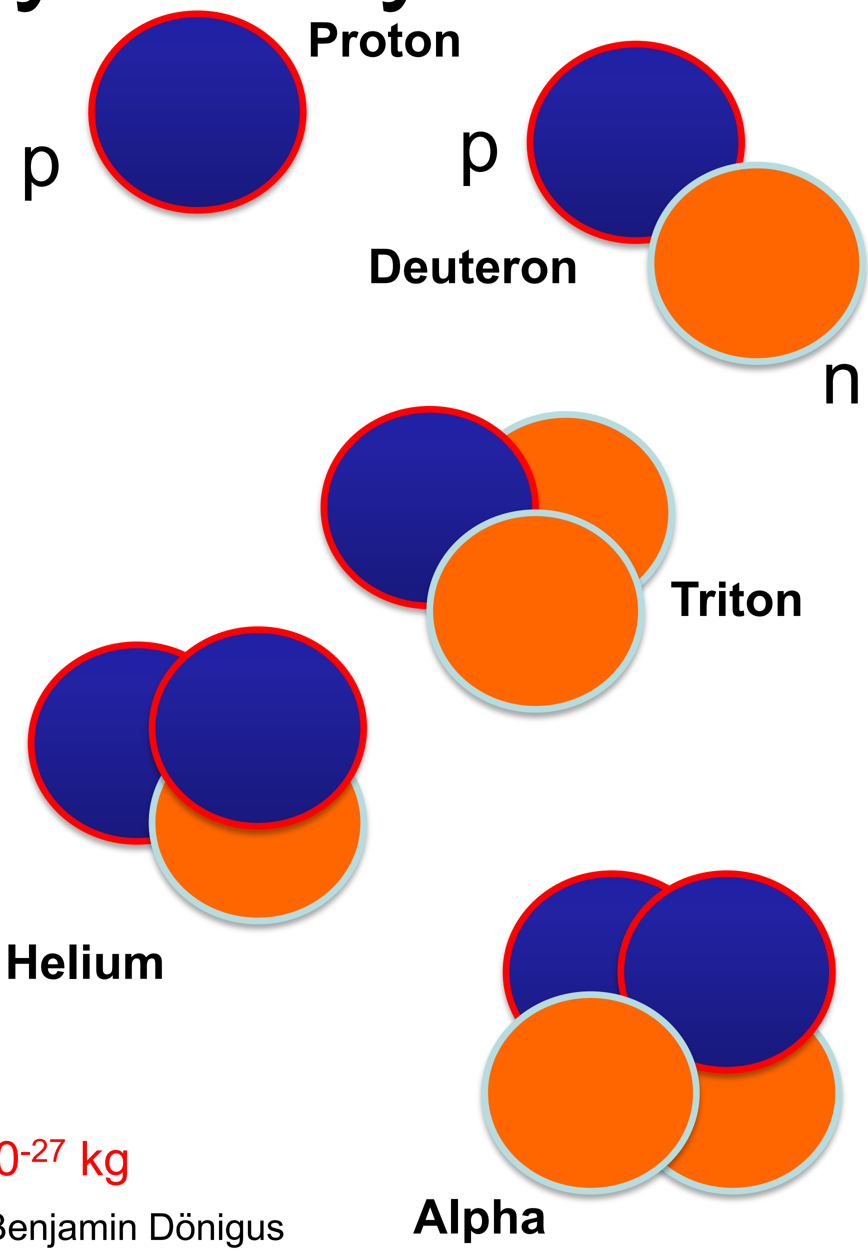
m=2808.9 MeV/c^2

Helium (ppn)

m=2808.4 MeV/c^2

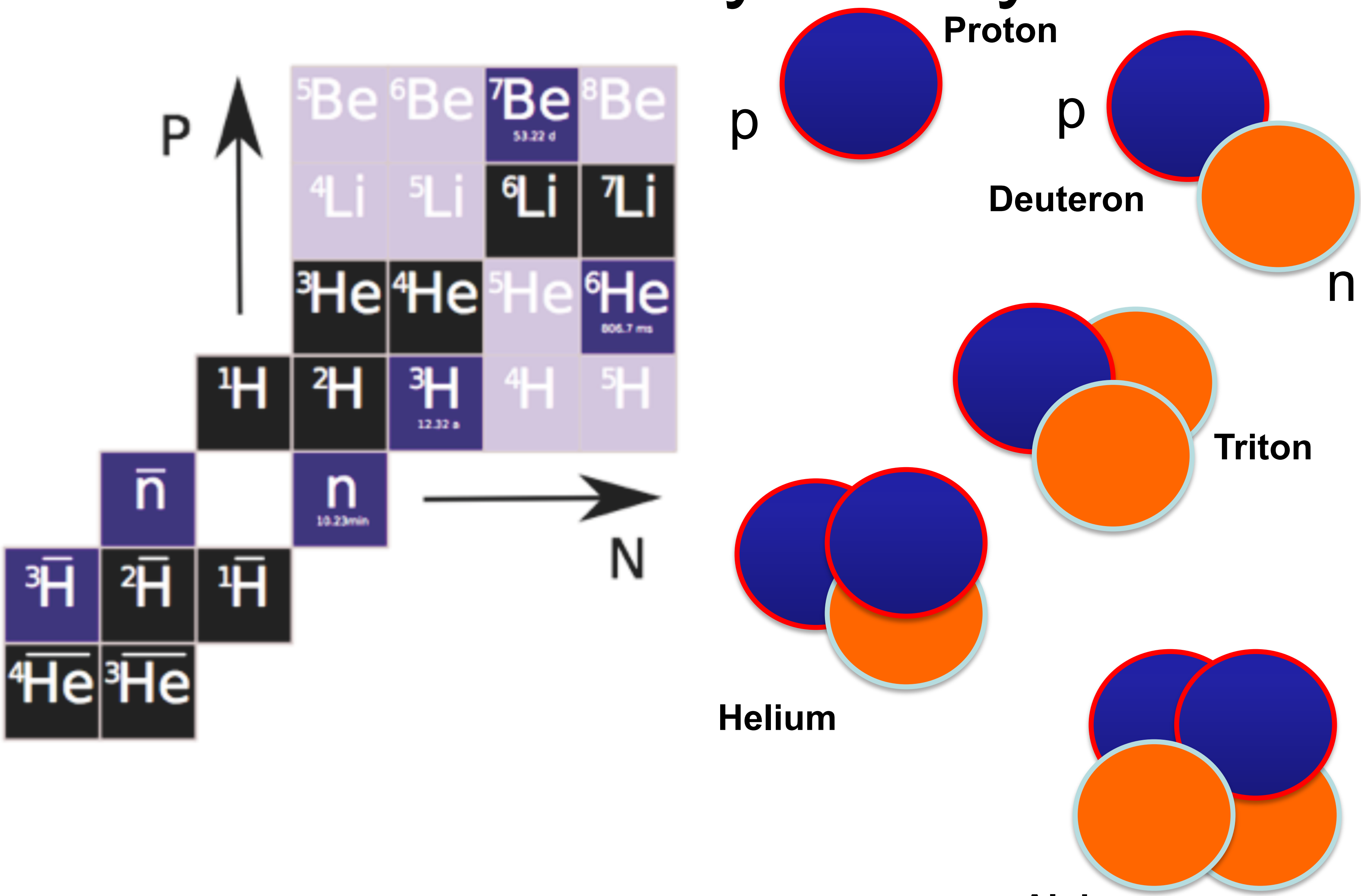
Alpha (ppnn)

m=3727.4 MeV/c^2

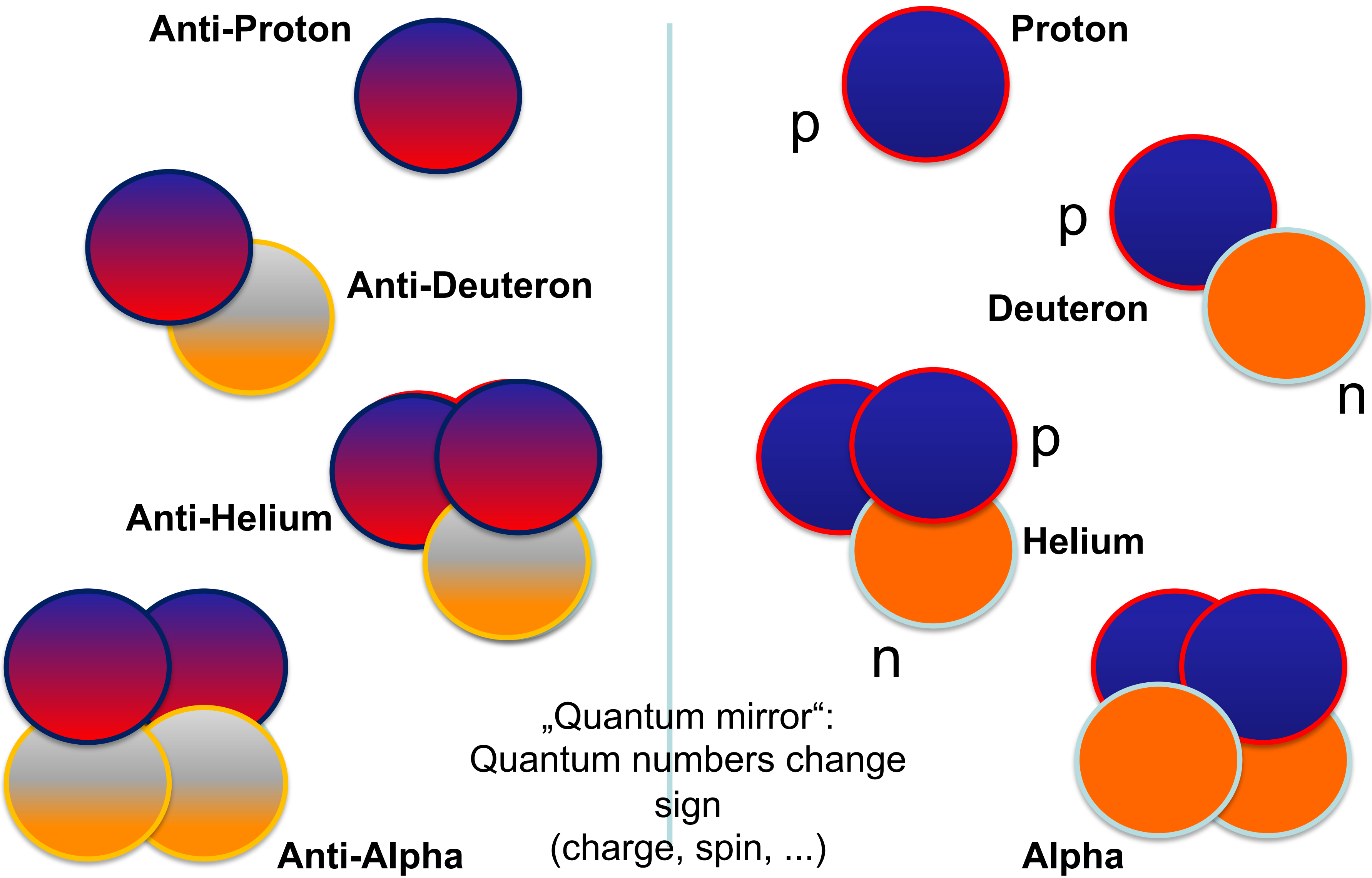


1 GeV/c^2 = 1.73 x 10^{-27} kg

From Chemisty to Physics



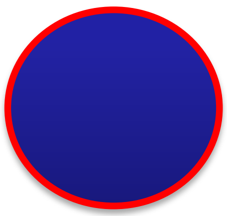
From Chemisty to Physics



„Quantum mirror“:
Quantum numbers change sign
(charge, spin, ...)

Zoo of hadrons

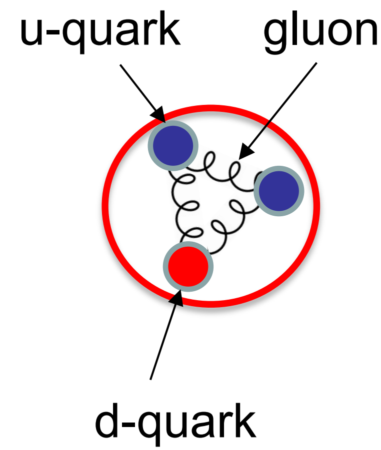
Baryons



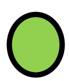
Proton (p) → uud

Neutron (n) → udd

Lambda (Λ) → uds



Mesons



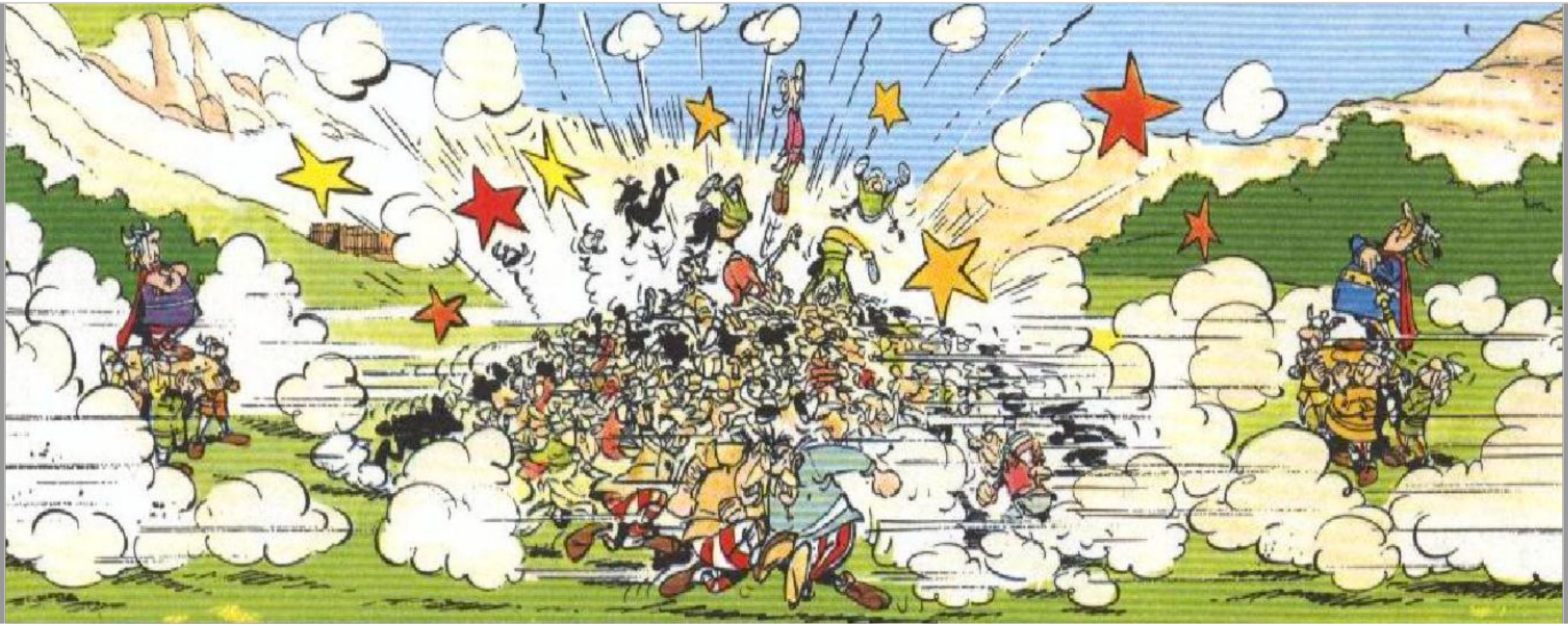
π-Meson → d$\bar{u}$

K-Meson → u$\bar{s}$

- Hadrons are consisting of quarks, anti-quarks und gluons
- Strangeness as new quark flavour not part of every-day matter, but is created for instance in high-energy particle collisions
- Theoretical description of hadrons through quantum chromo dynamics (QCD)

Collisions

- Nuclei are accelerated to high energies, i.e. speeds close to the speed of light, and are then collided
- This leads to the creation of (new) particles that can be detected in the experiments surrounding the collision point



Asterix & Obelix, Asterix and the Great Divide

Collisions

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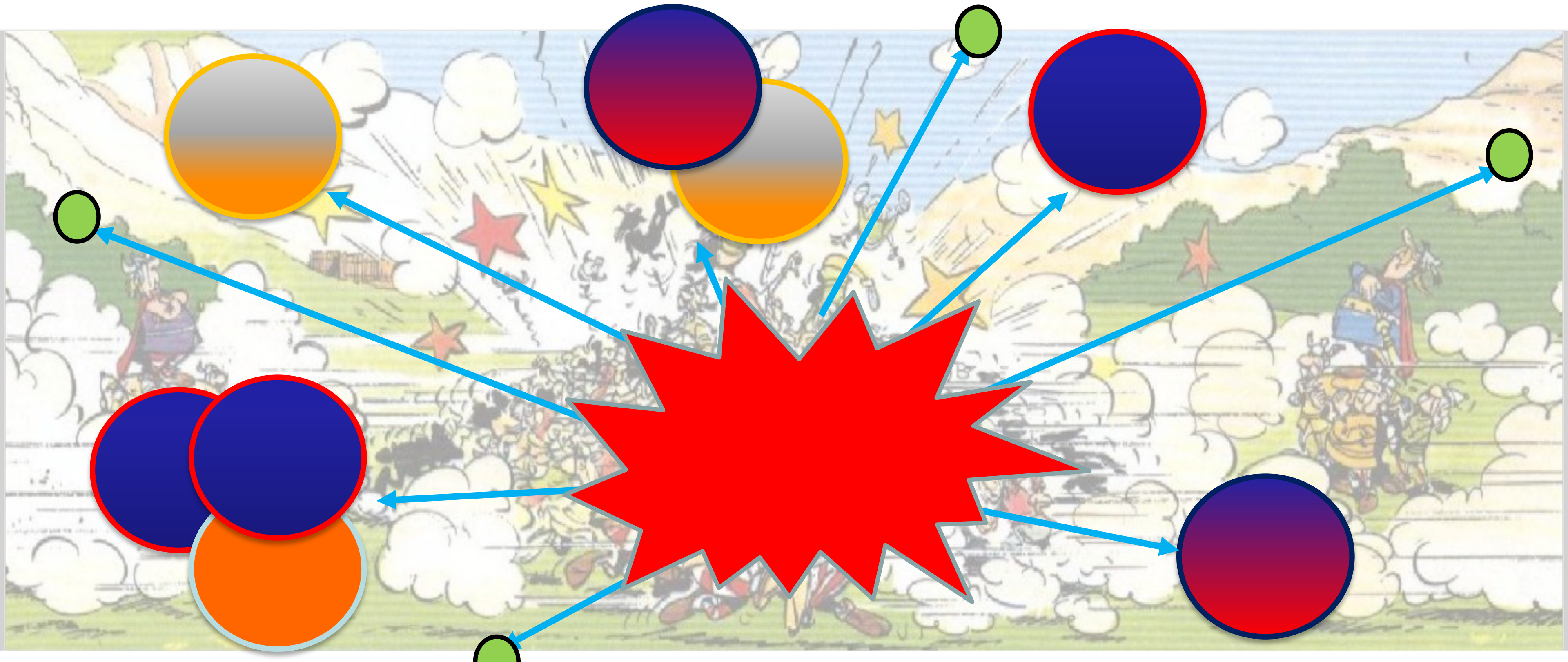
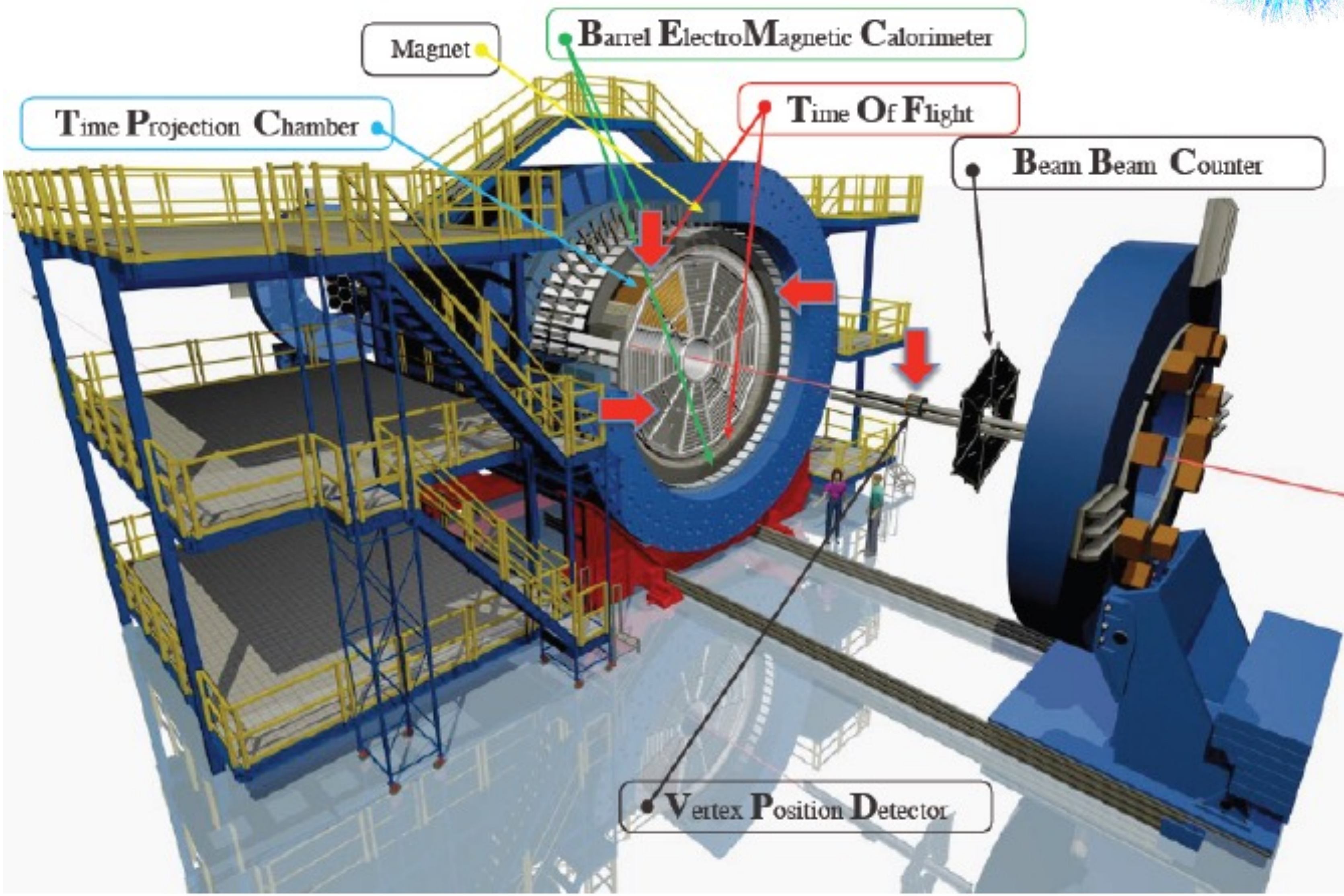
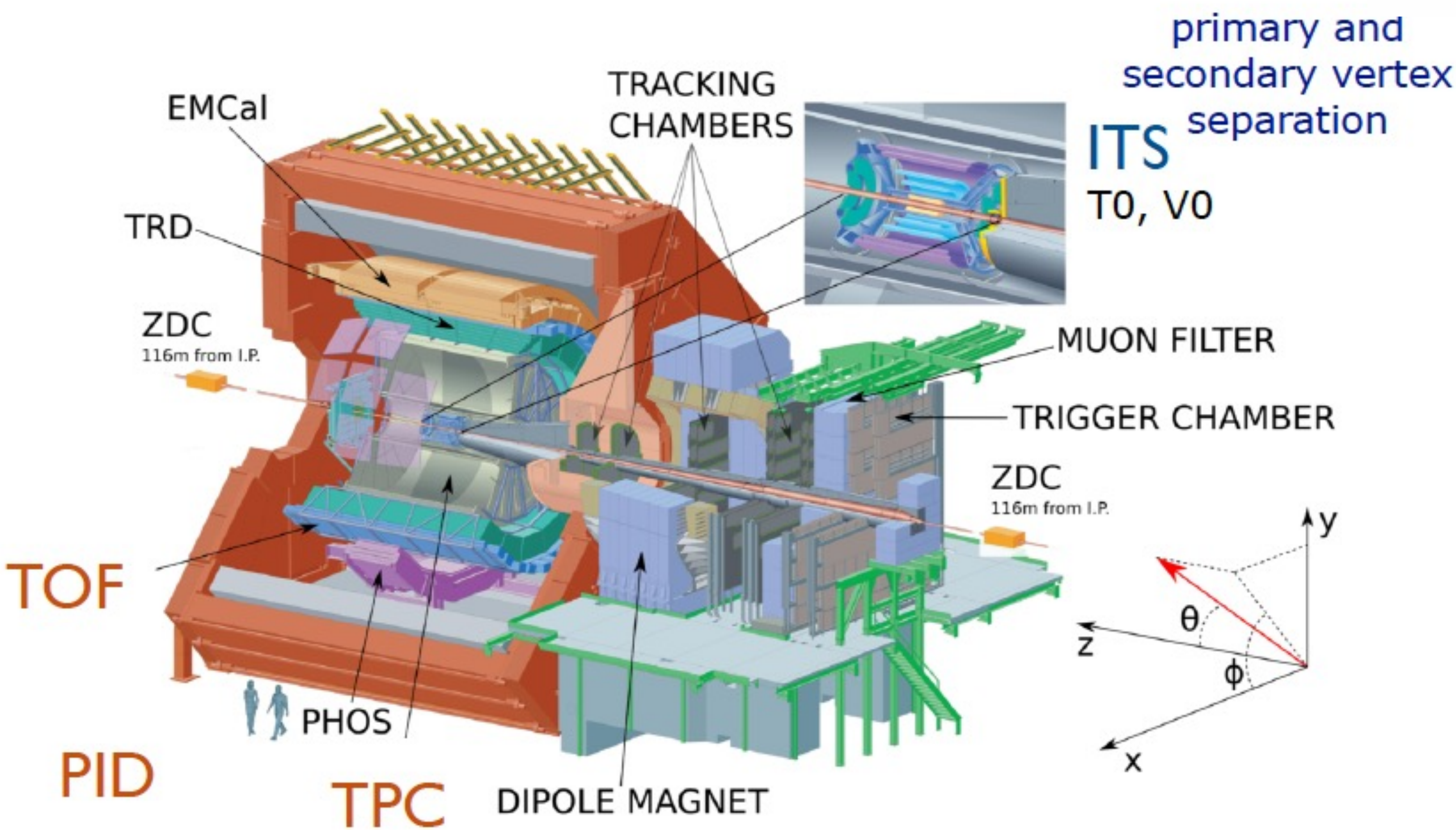


Asterix & Obelix, Asterix and the Great Divide

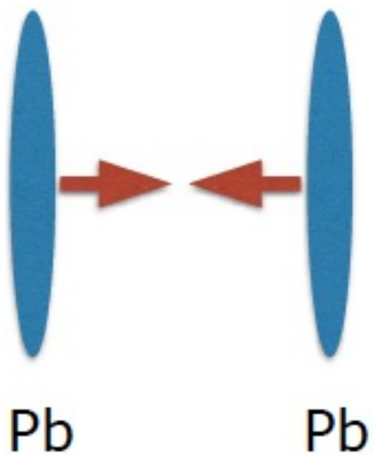
Experiments: STAR



Experiments: ALICE



Interlude: Centrality

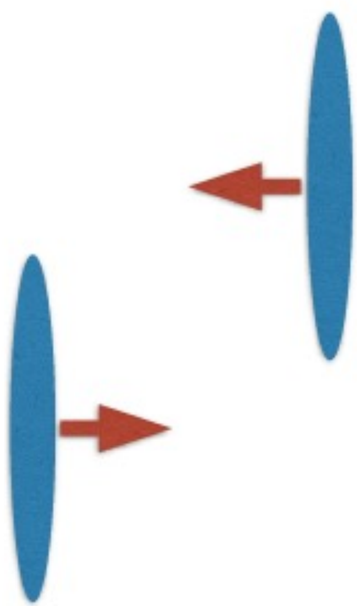


Central Pb-Pb collision:

High multiplicity = large dN/dη

High number of tracks

(more than 2000 tracks in the detector)



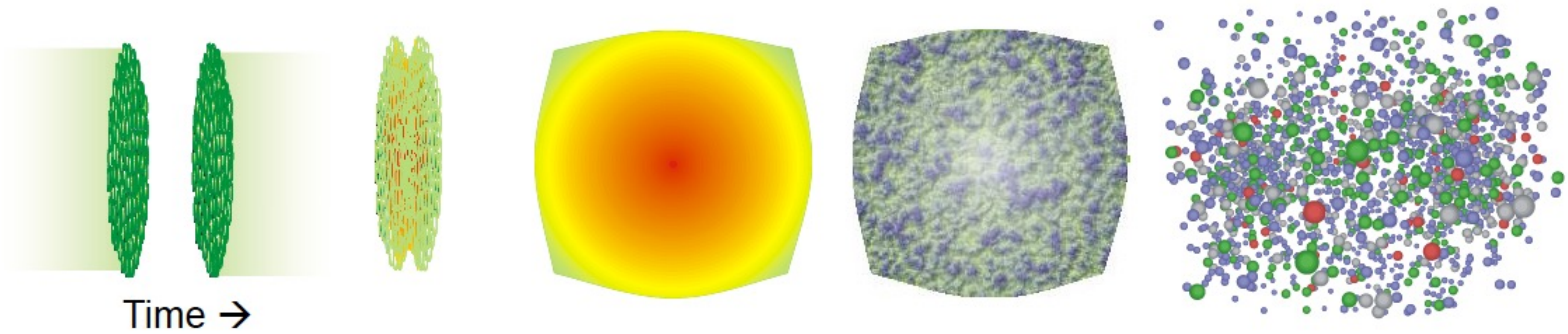
Peripheral Pb-Pb collision:

Low multiplicity = small dN/dη

Low number of tracks

(less than 100 tracks in the detector)

Introduction



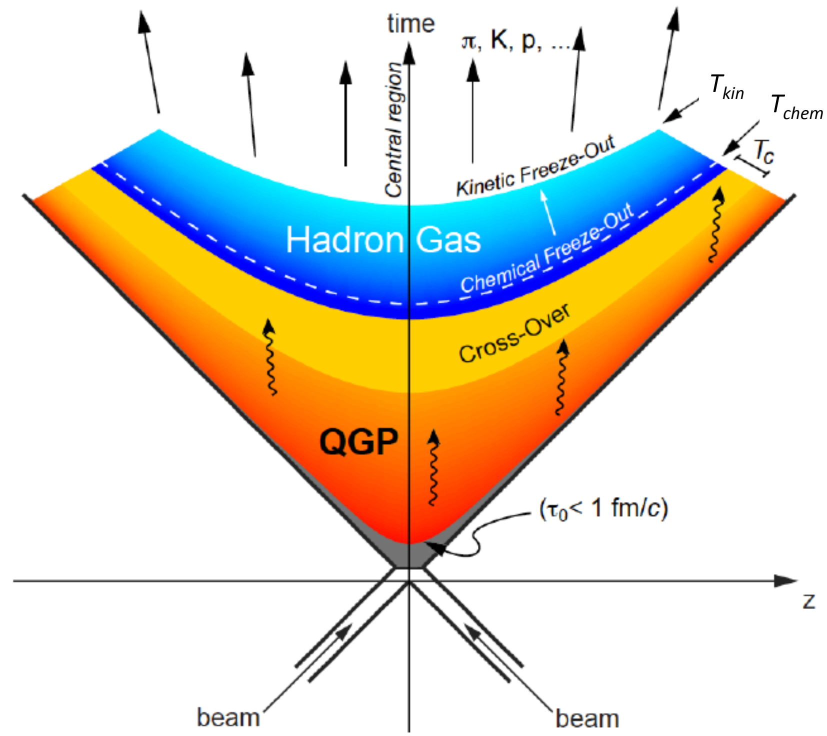
Cartoon of a Ultra-relativistic heavy-ion collision

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

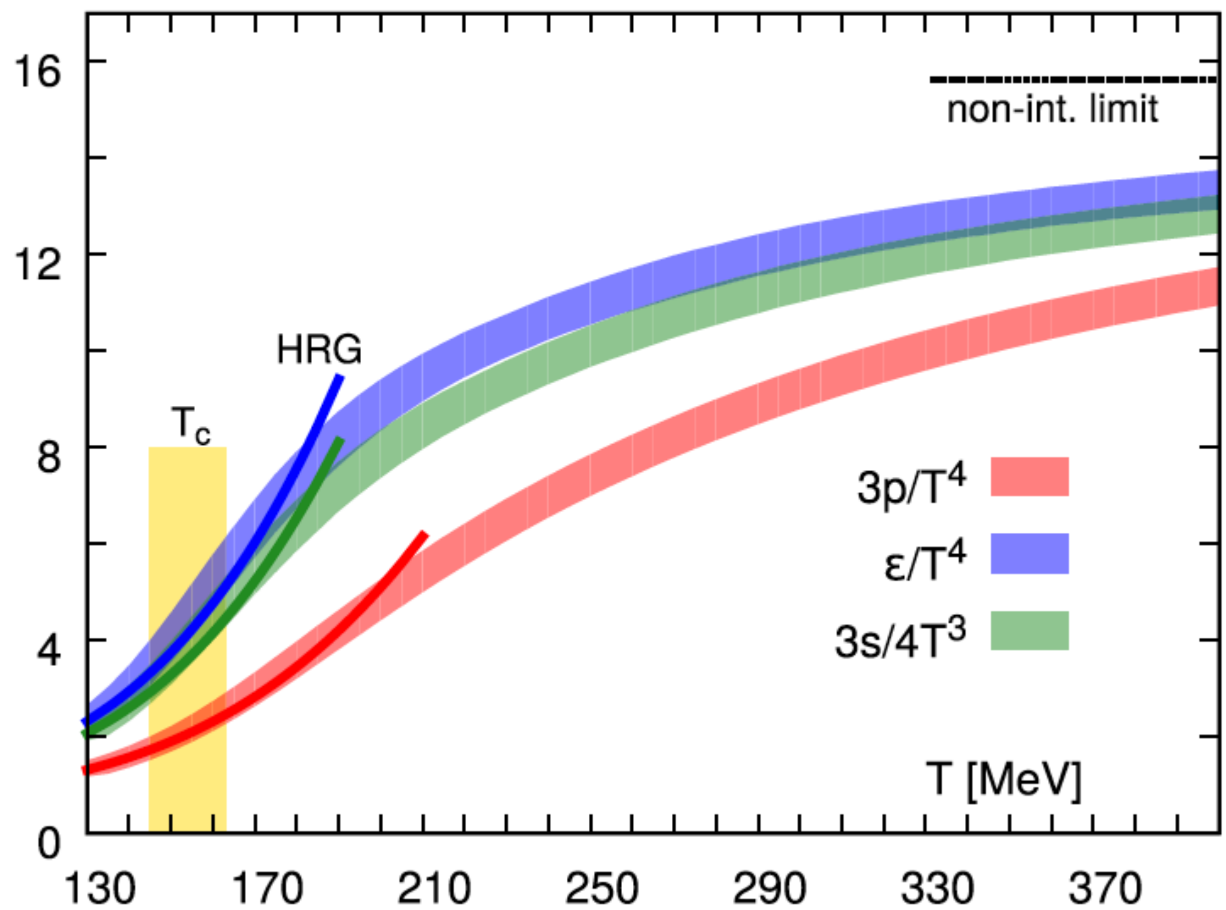
Introduction



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



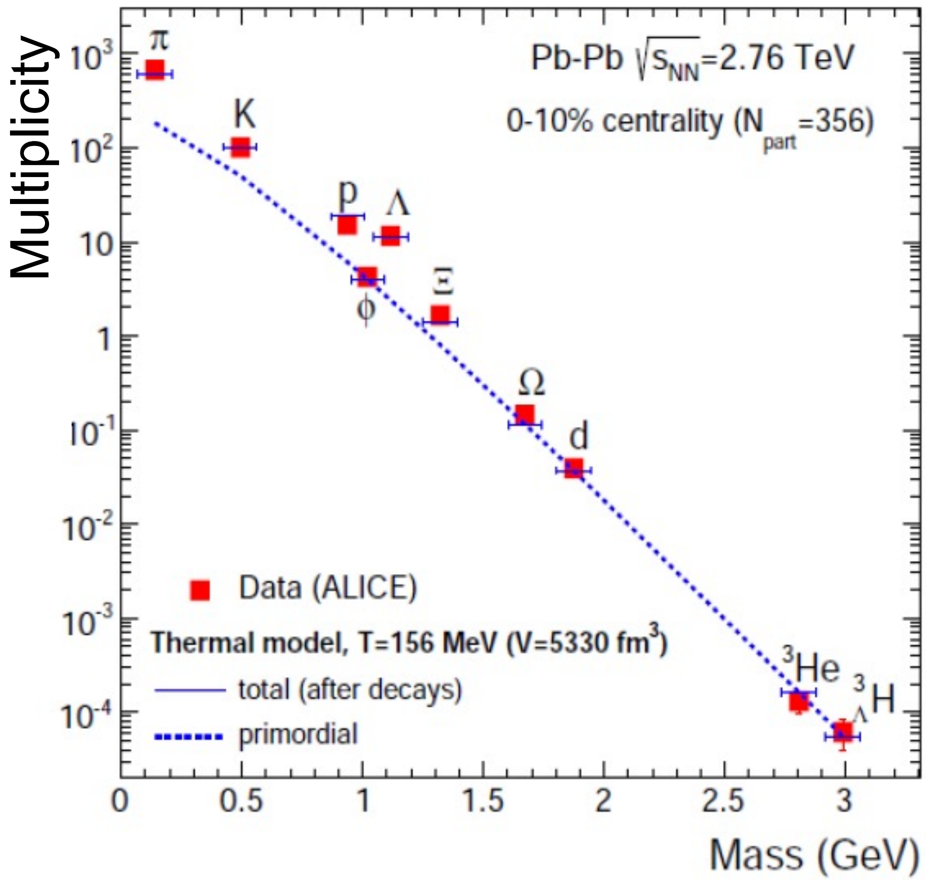
Lattice QCD tells us where to expect the phase transition

Critical 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

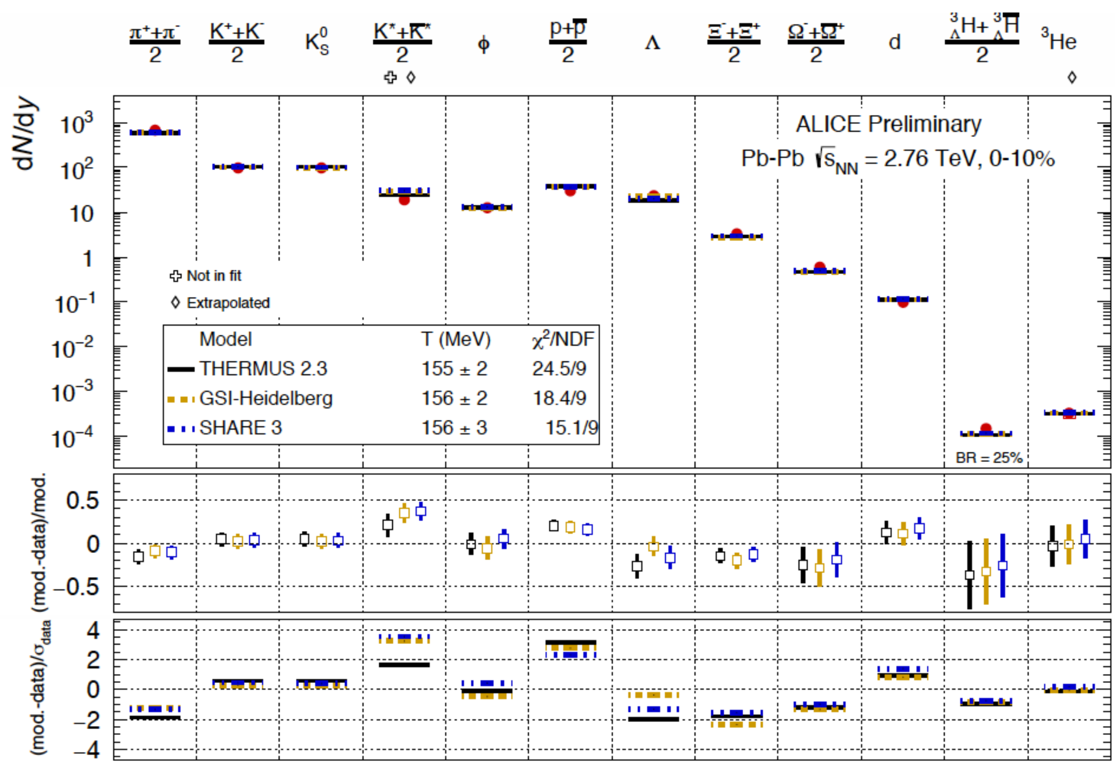
- Multiplicity described best with T = 1 900 000 000 000 °C (1,9 trillion degree centigrade)

→ 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)

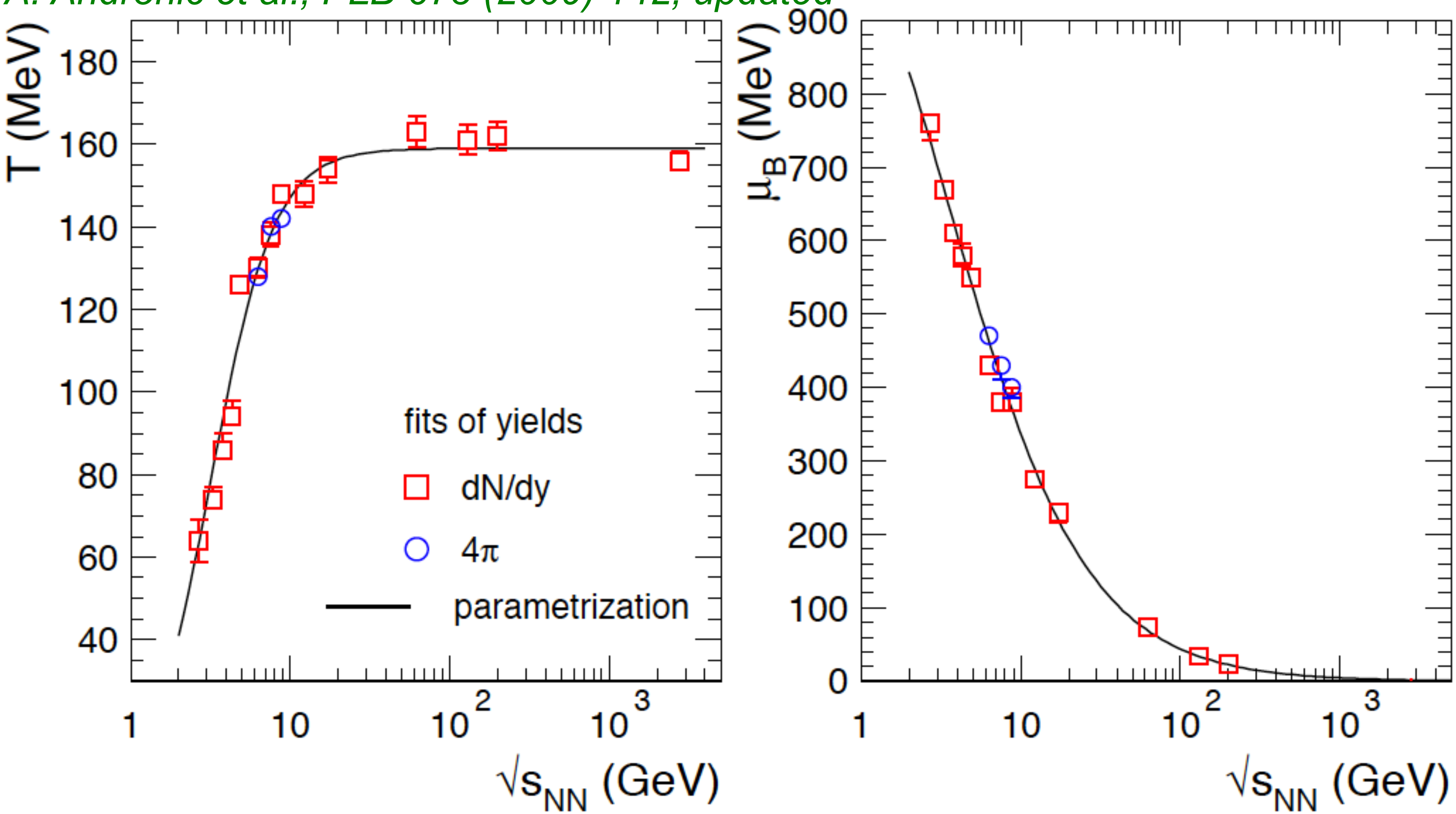


- chemical freeze-out temperature T_{ch}
- baryo-chemical potential μ_B
- Volume V

→ Using particle yields as input to extract parameters

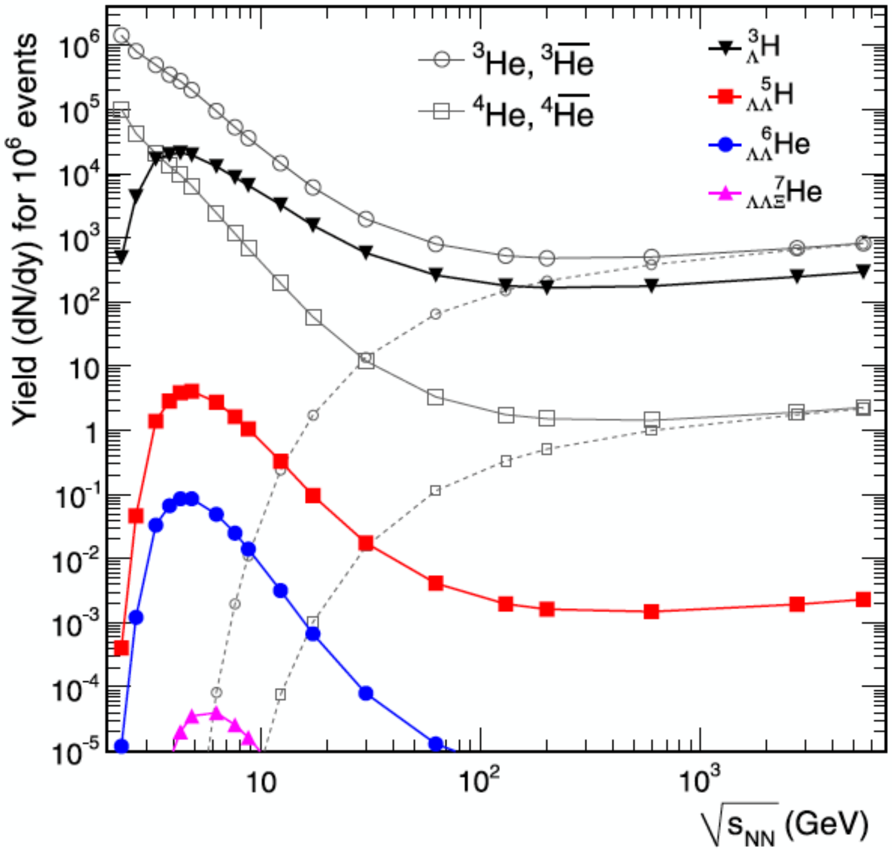
Energy dependence

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:

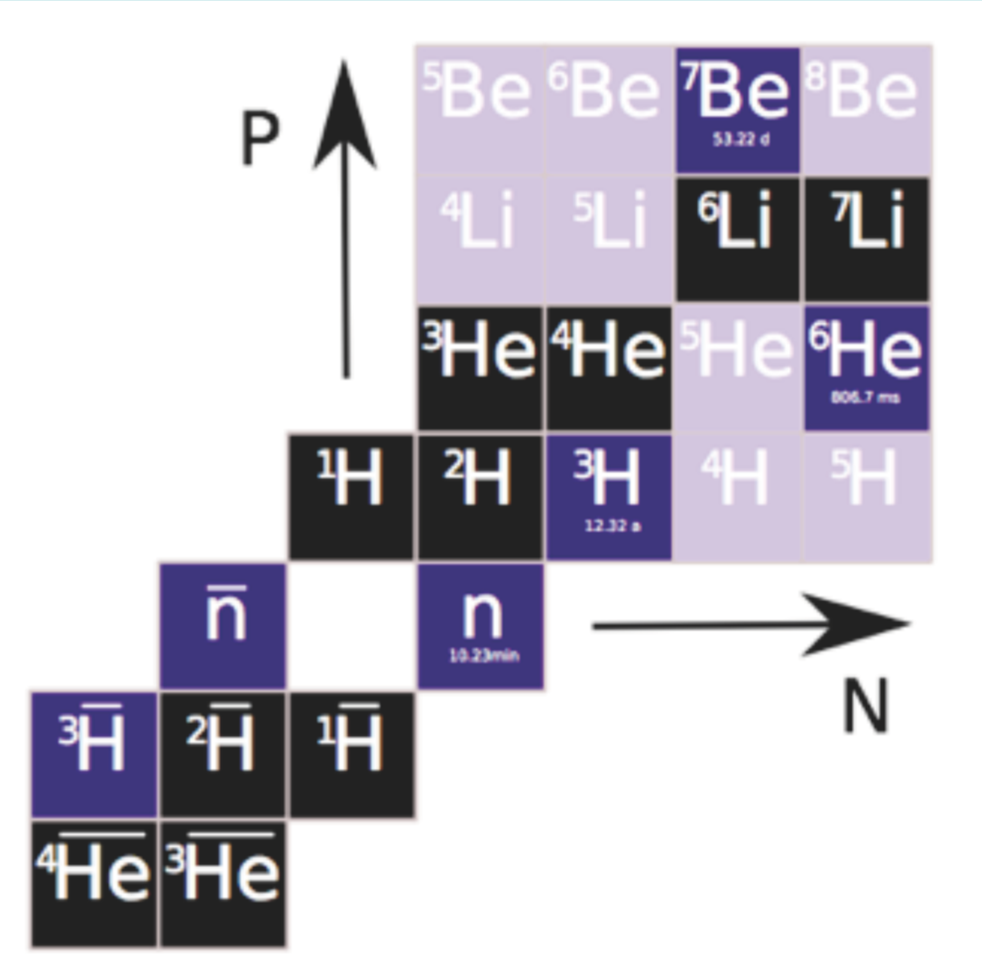
chemical freeze-out temperature T_{ch}

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

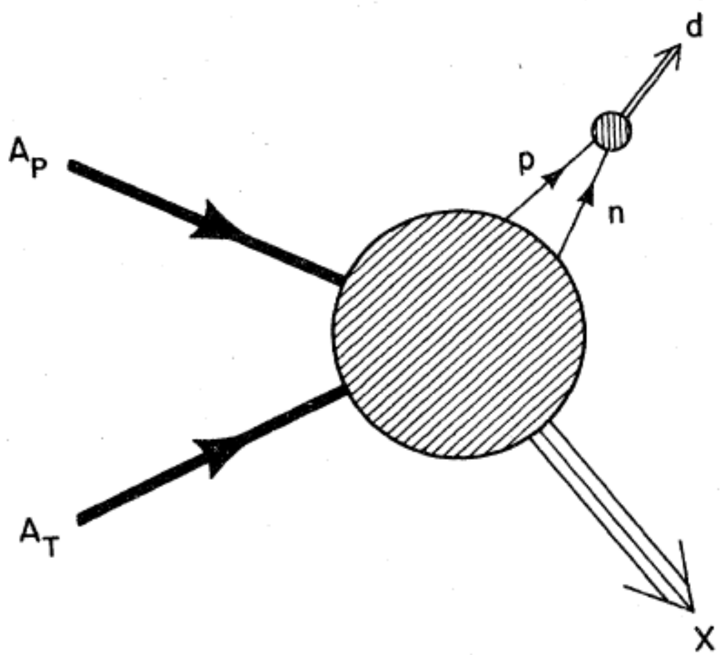
1. large mass *m*
2. exponential dependence of the yield ~ $\exp(-m/T_{ch})$

→ Binding energies small compared to T_{ch}

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

Coalescence



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

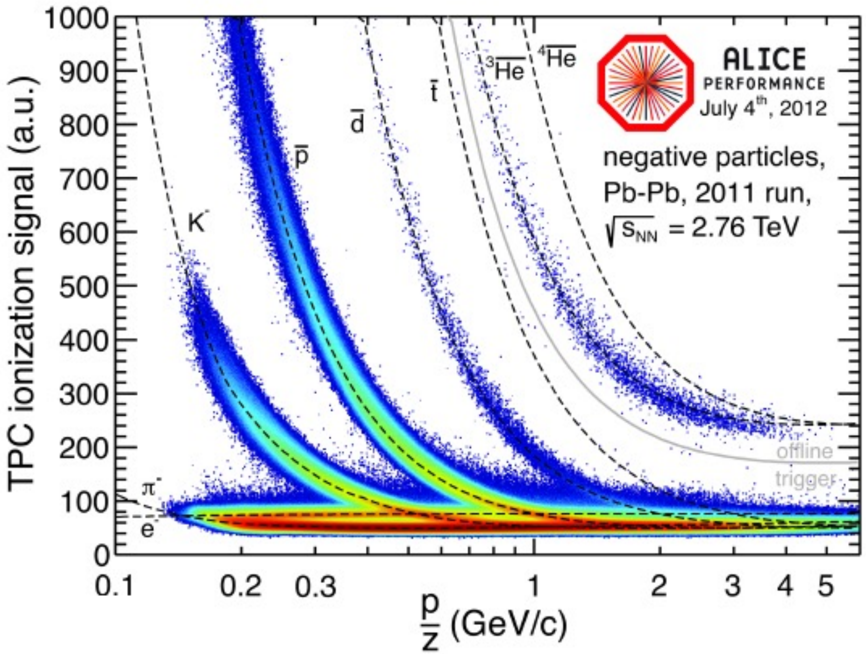
Nuclei are formed by protons and neutrons which are nearby and have similar velocities (after kinetic freeze-out)

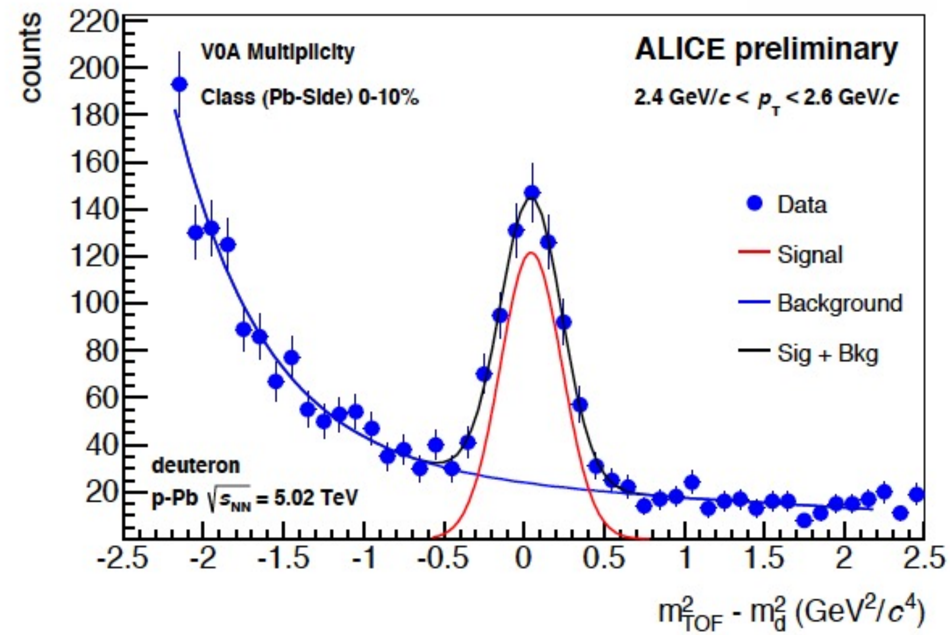
Produced nuclei

→ can break apart

→ created again by final-state coalescence

Particle Identification





Low momenta:

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

Higher momenta:

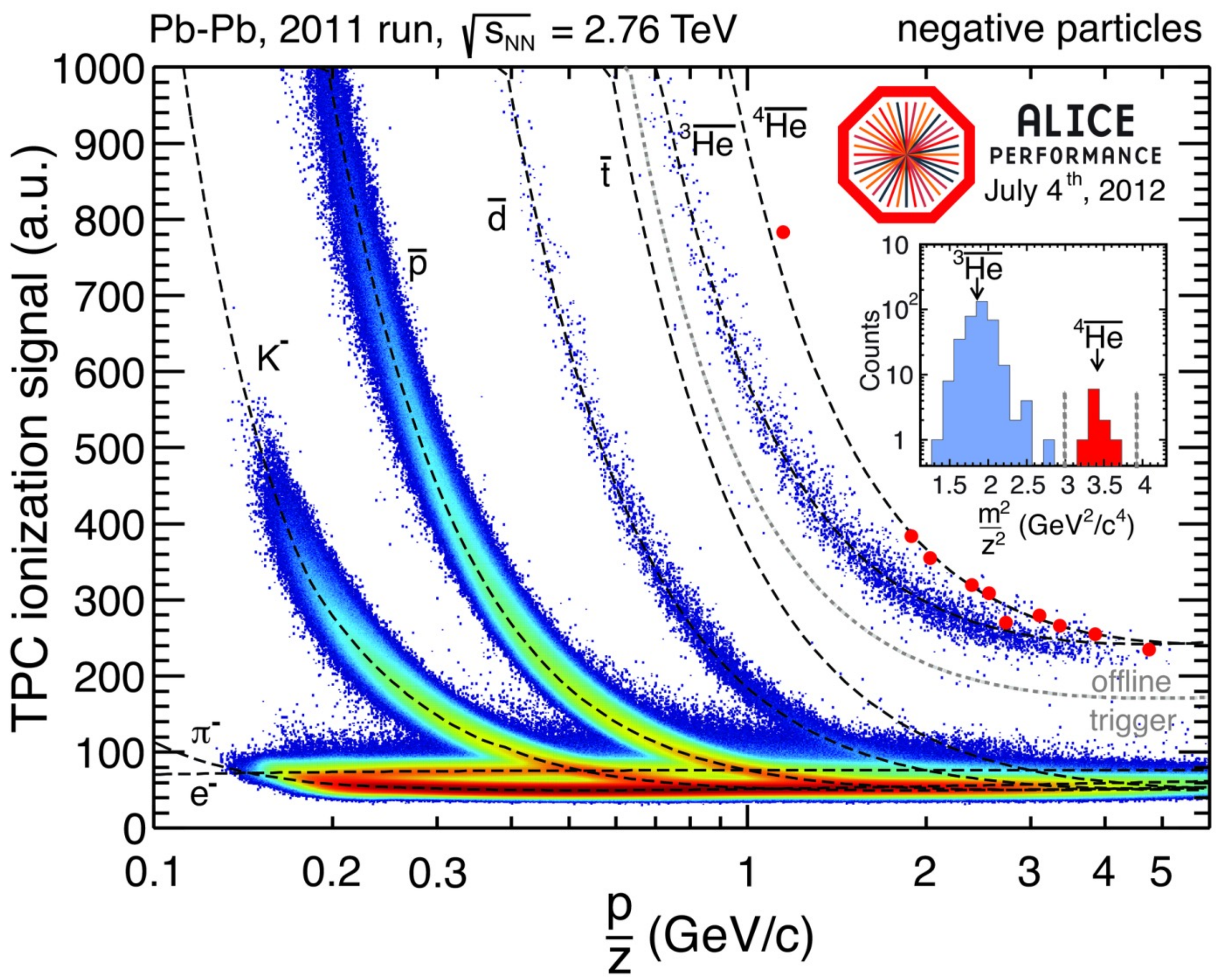
Velocity measurement with the Time-of-Flight (TOF) detector is used to calculate the m^2 distribution

Anti-Alpha

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

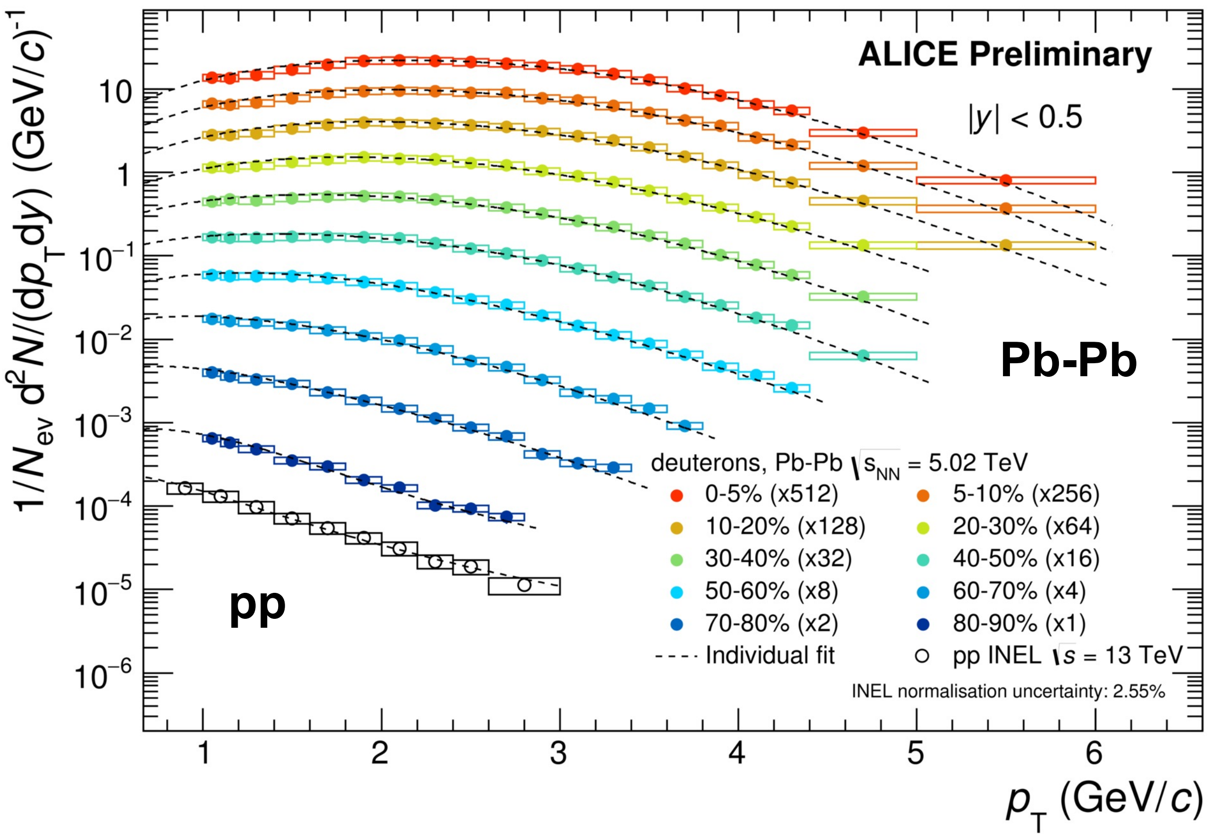
STAR observed the Anti-Alpha in 2010:

Nature 473, 353 (2011)



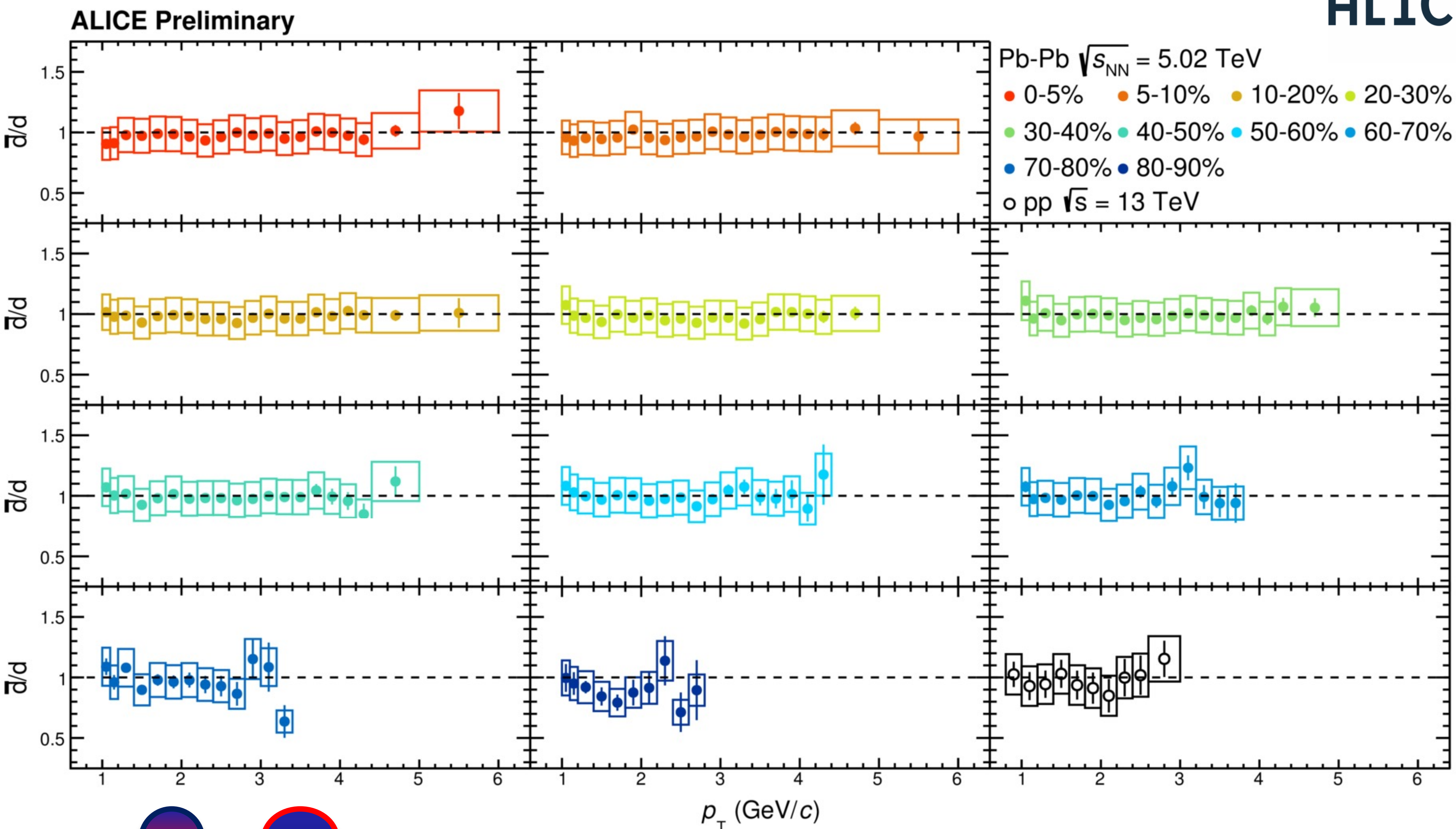
Deuterons

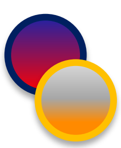
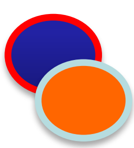
ALICE-PUBLIC-2017-006



- 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

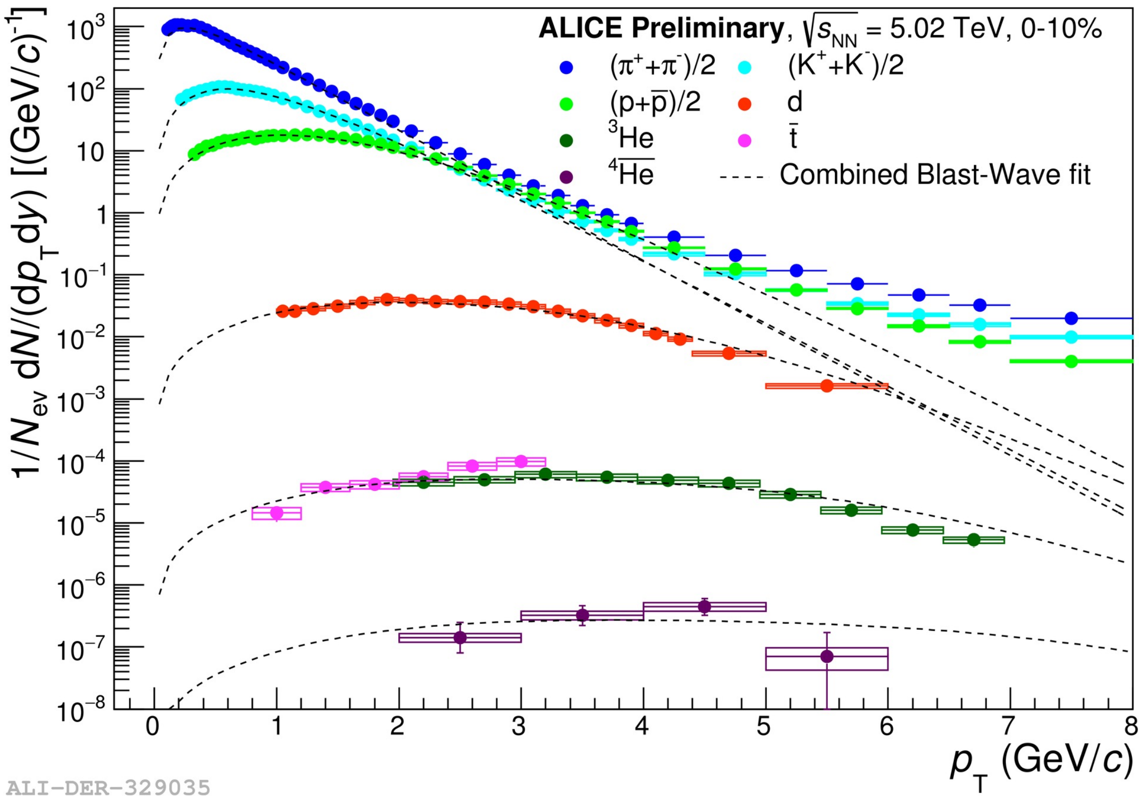
(Anti-)Deuteron ratio



 :  -ratios consistent with unity, as expected

Combined Blast-Wave fit

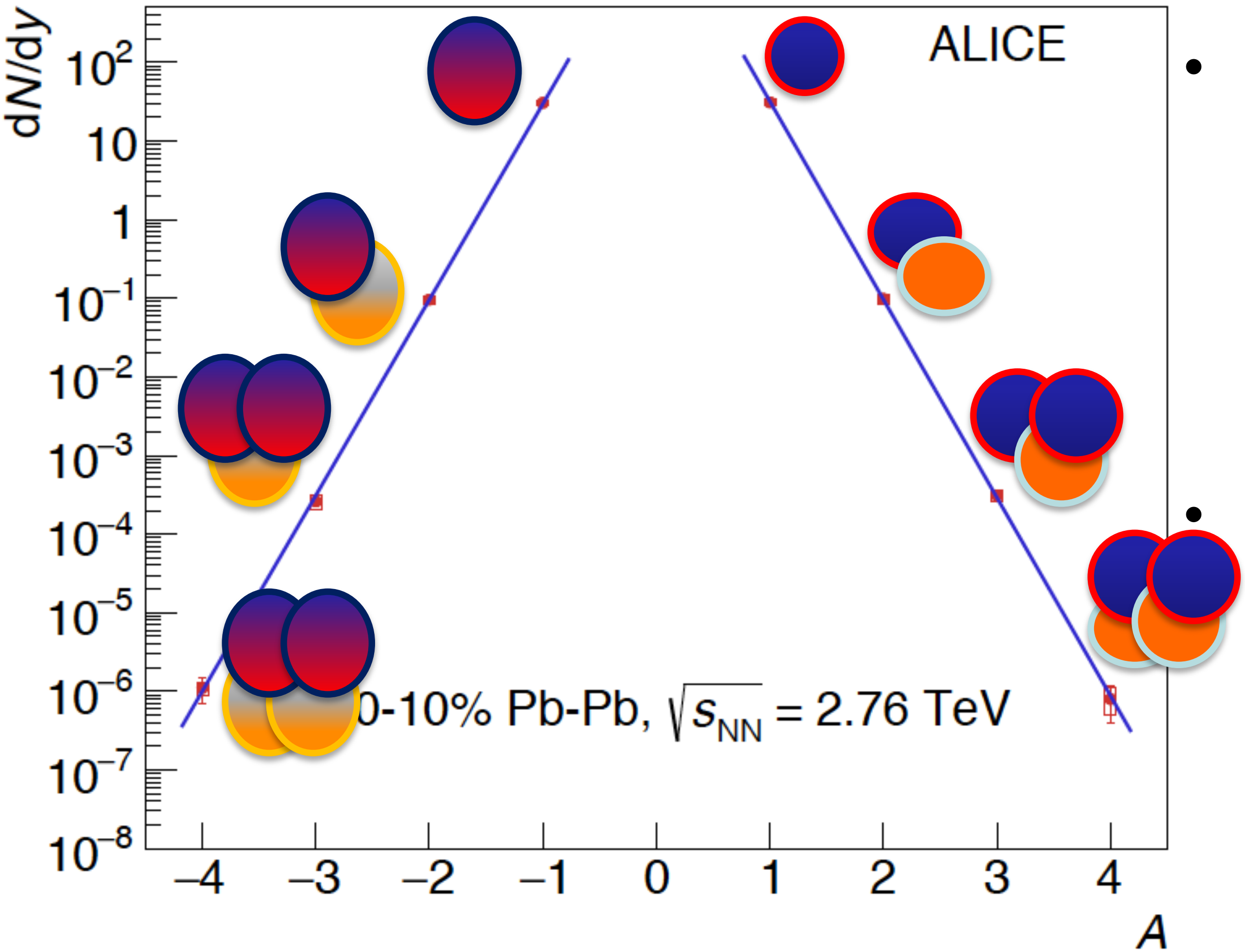
ALICE Collaboration, arXiv:1910.07678, see also arXiv:2311.11758



- 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

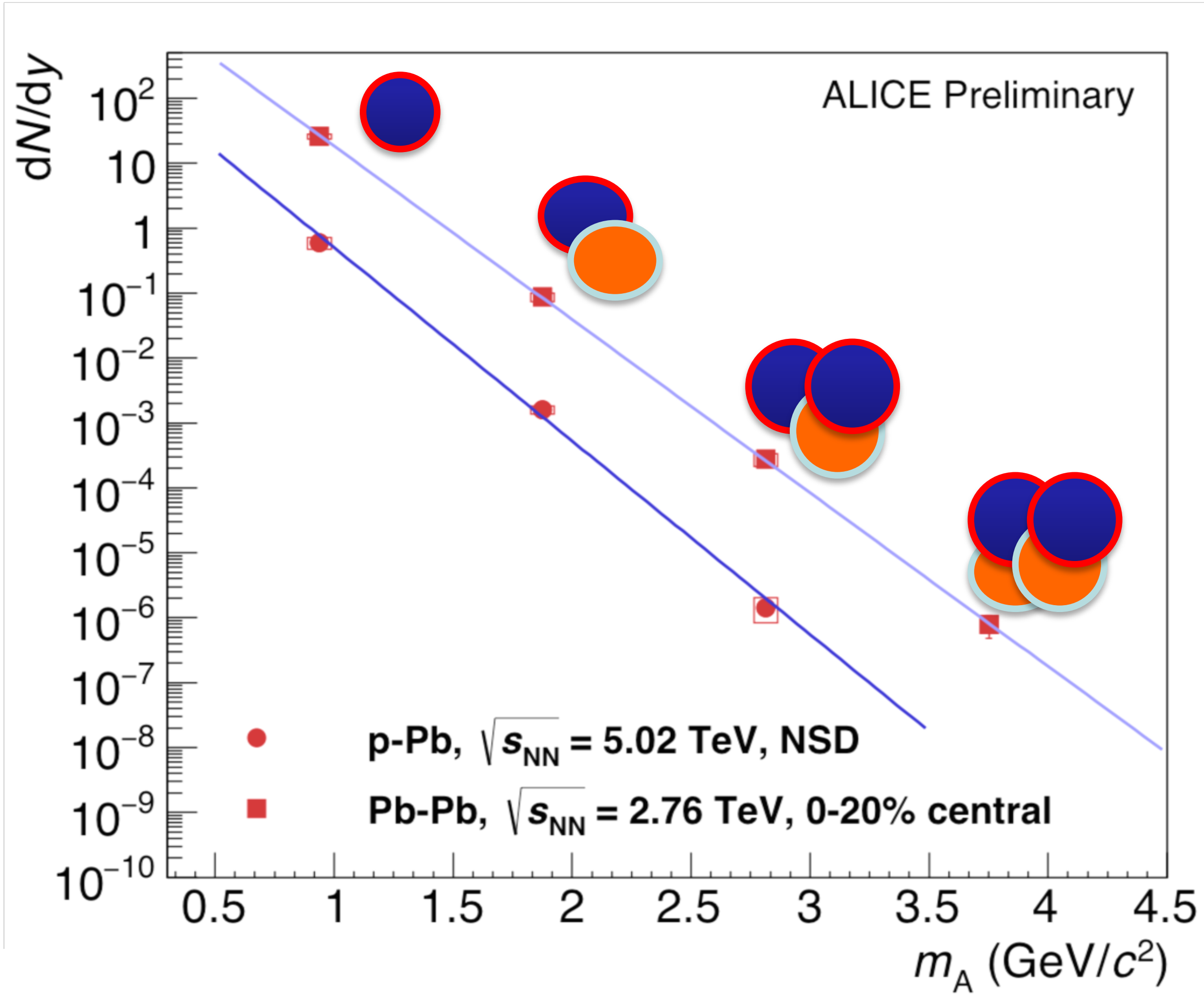
Mass dependence



- 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)

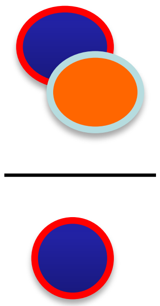
ALICE Collaboration, arXiv:1710.07531, NPA 971, 1 (2018)

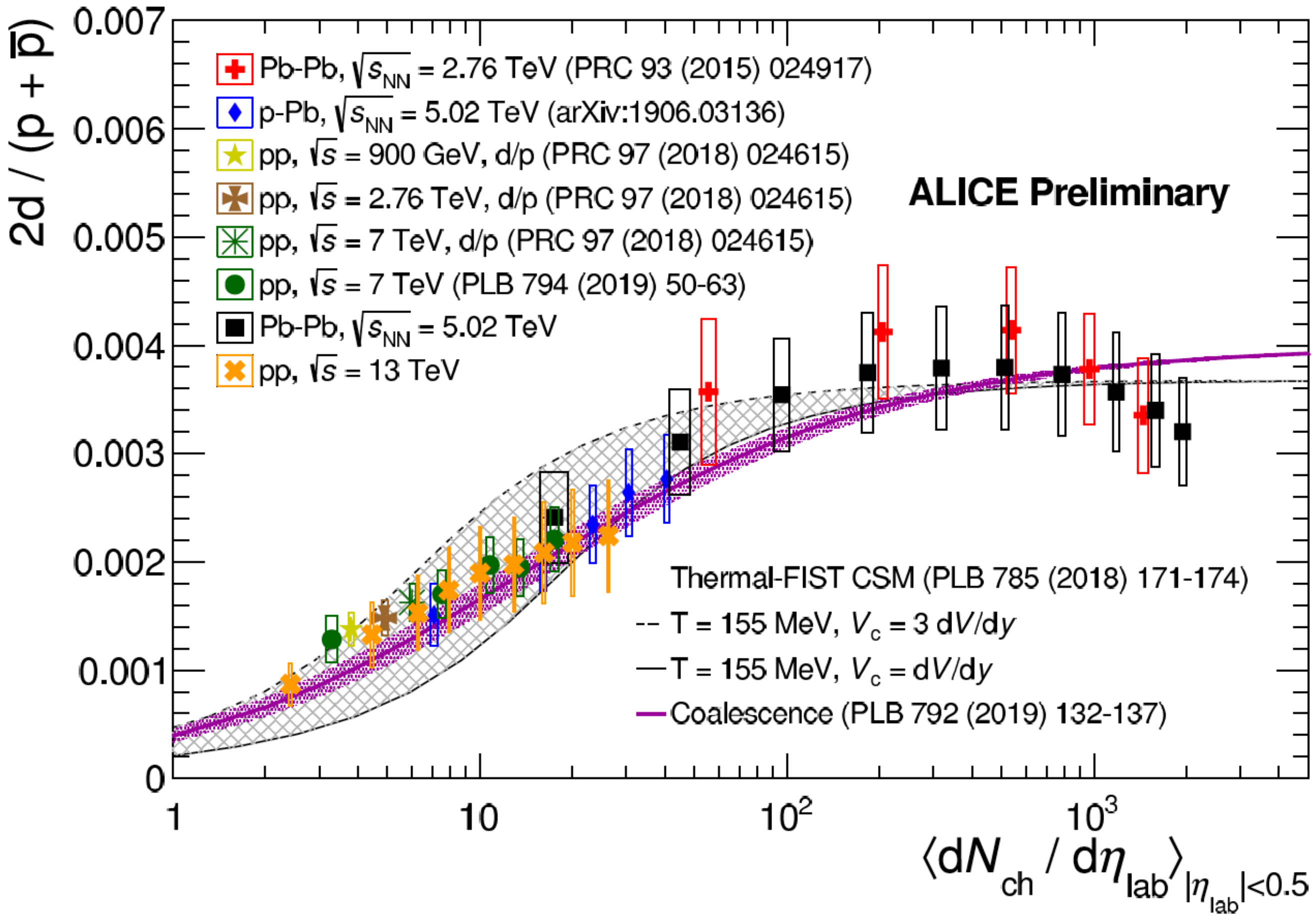
Mass dependence



- 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

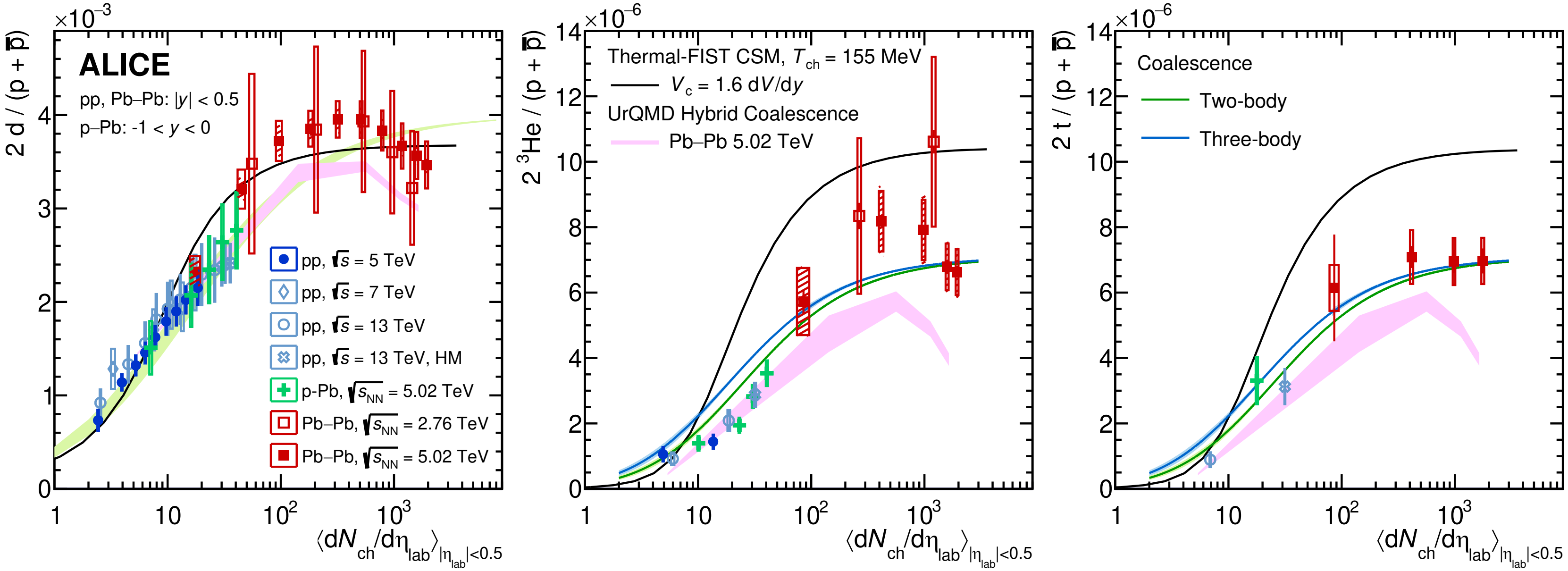




d/p ratio rather well described by coalescence and (canonical) thermal model

Ratios vs. multiplicity

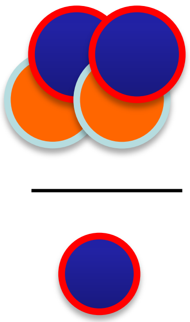
ALICE Collaboration, arXiv:2211.14015, Phys.Rev.C 107 (2023) 064904

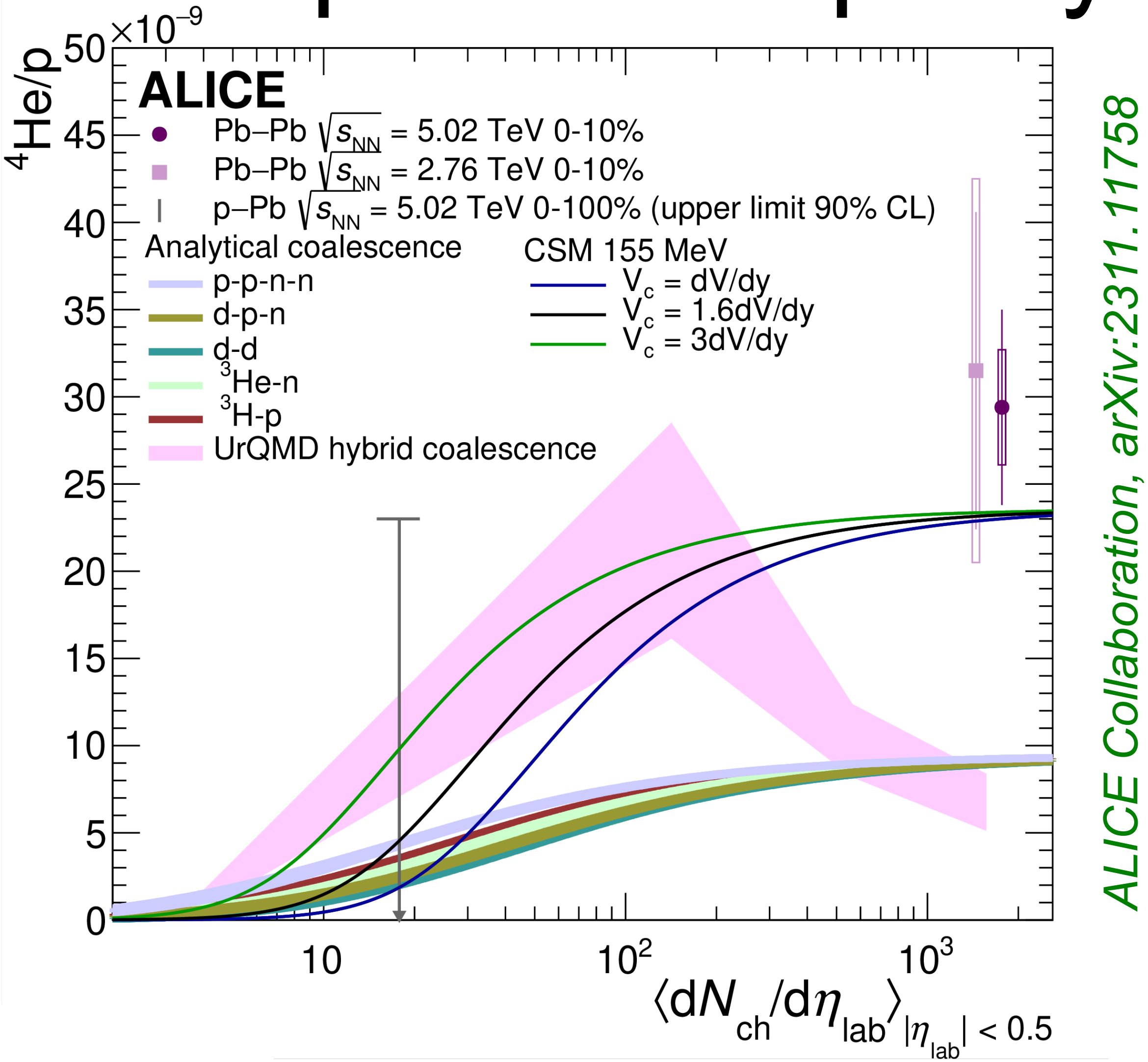


- d/p ratio rather well described by coalescence and (canonical) thermal model
- Some tension for ^{3}He/p and ^{3}H/p over p_T

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

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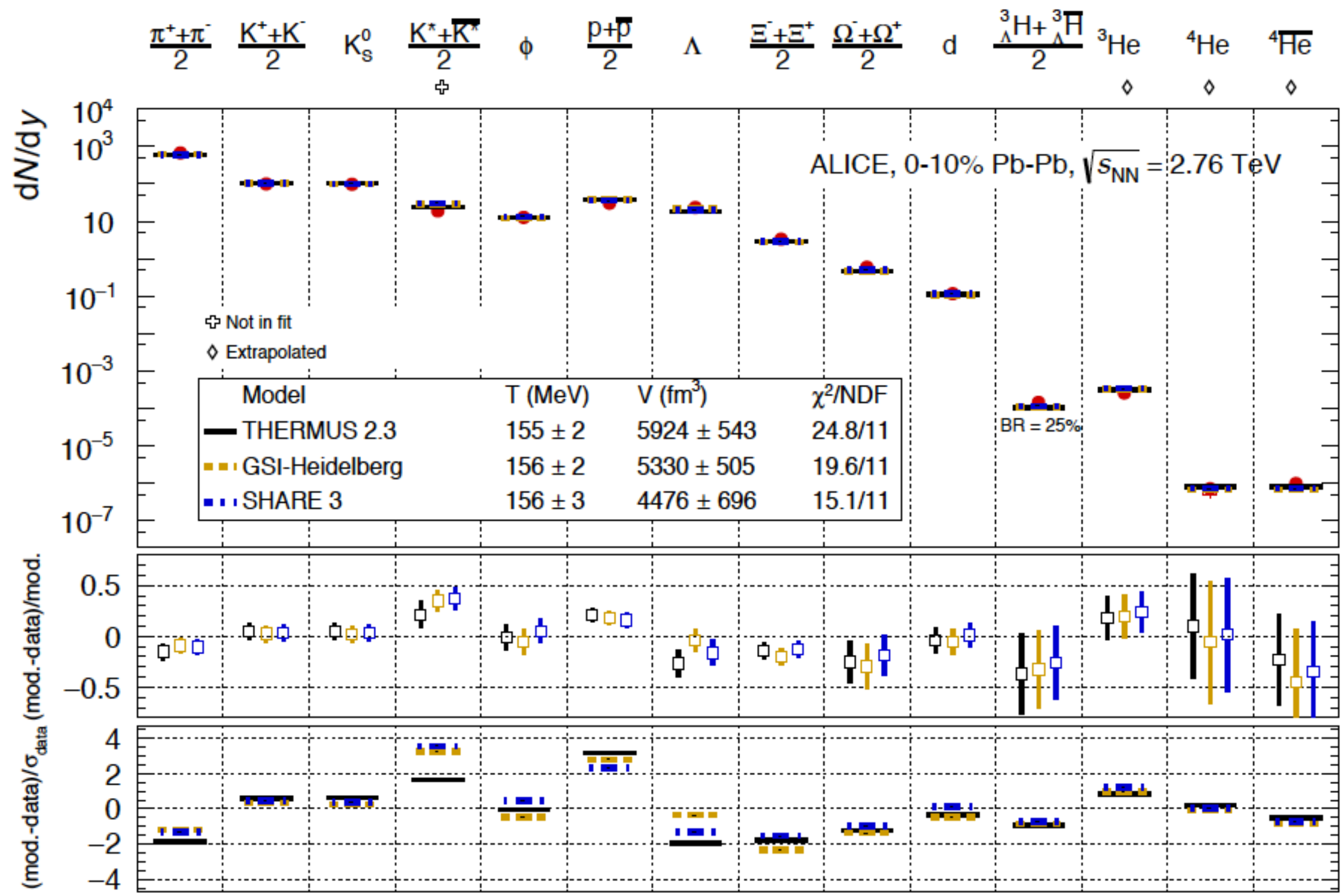
Thermal model

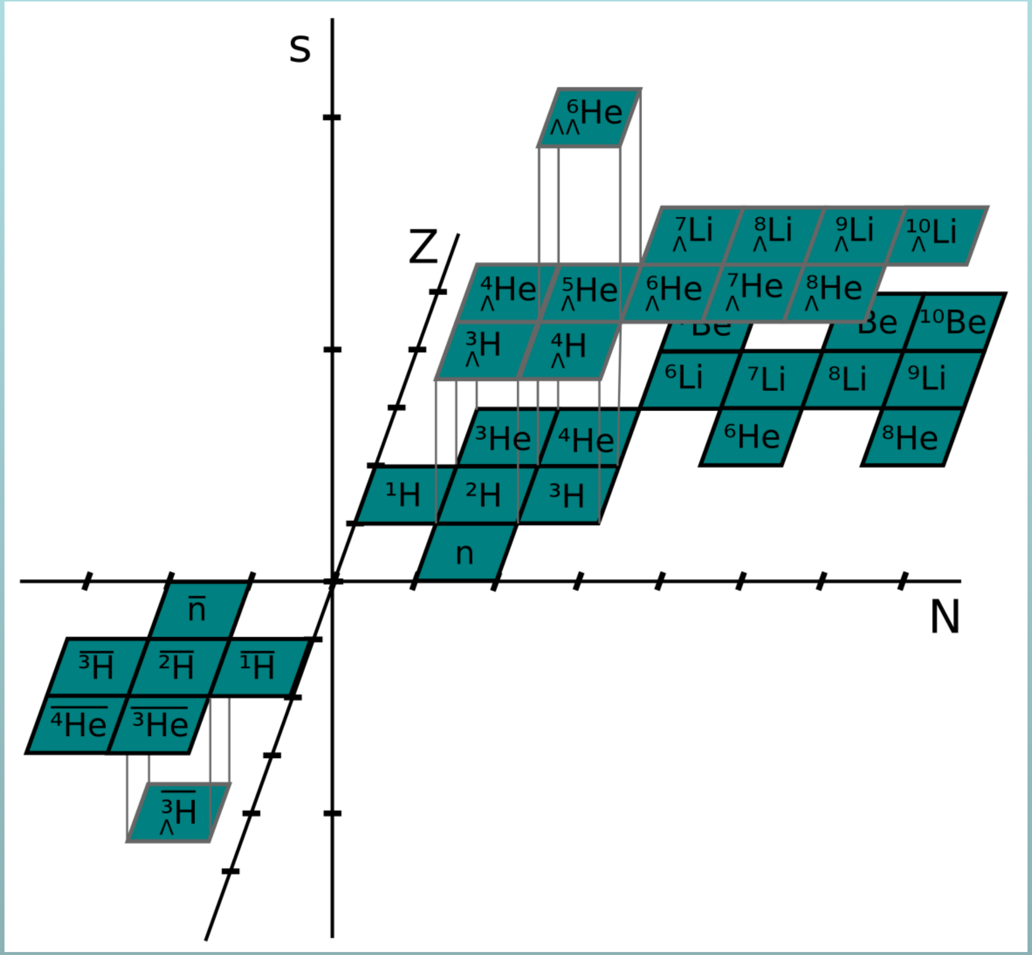


THERMUS: S. Wheaton, et al., CPC 180, 84 (2009)
GSI-Heidelberg: A. Andronic, et al., PLB 697, 203 (2011); PLB 673, 142 (2009) 142
SHARE3: G. Torrieri, et al., CPC 167, 229 (2005); CPC 175, 635 (2006); CPC 185, 2056 (2014)

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

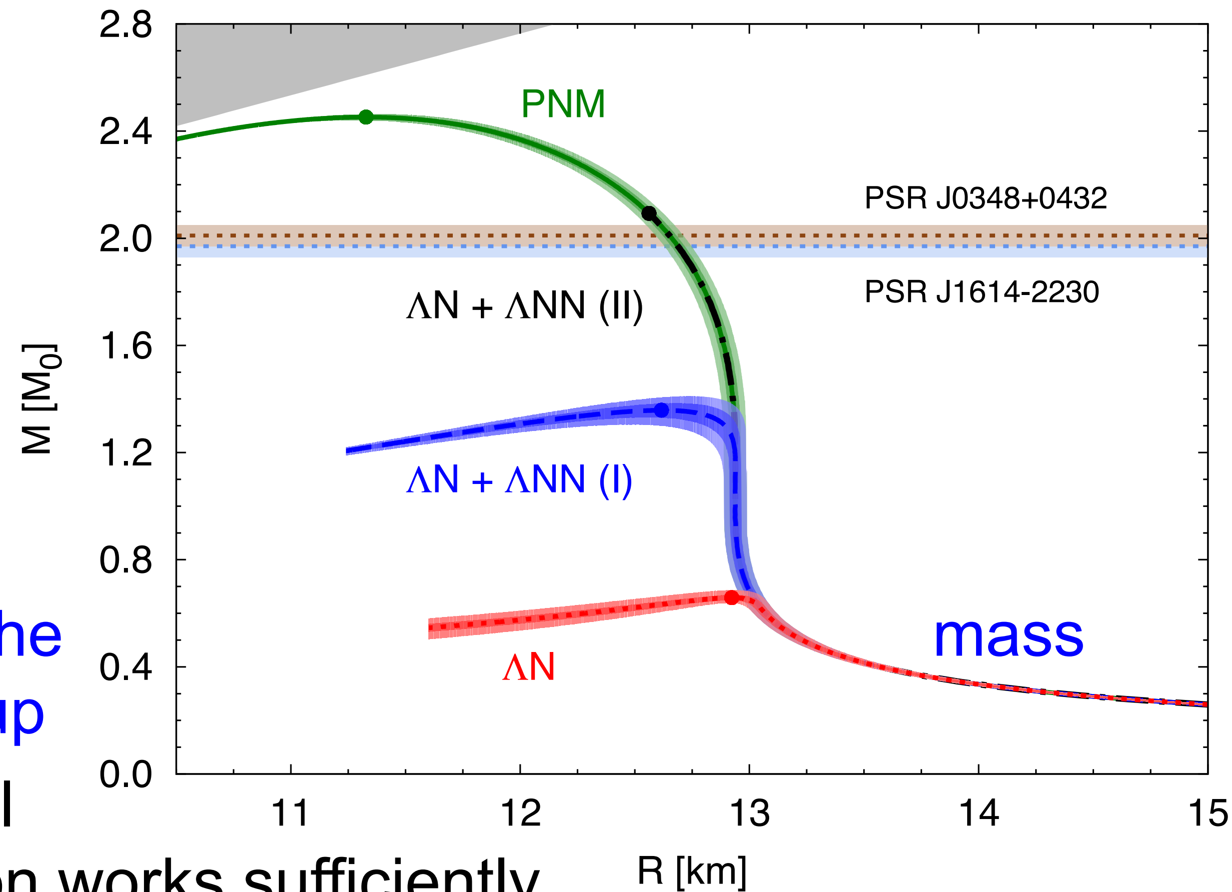
- Different model implementations describe the production probability, including light nuclei and hyper-nuclei, rather well at a temperture of about T_{ch} =156 MeV

Hypernuclei



Neutron stars and interactions

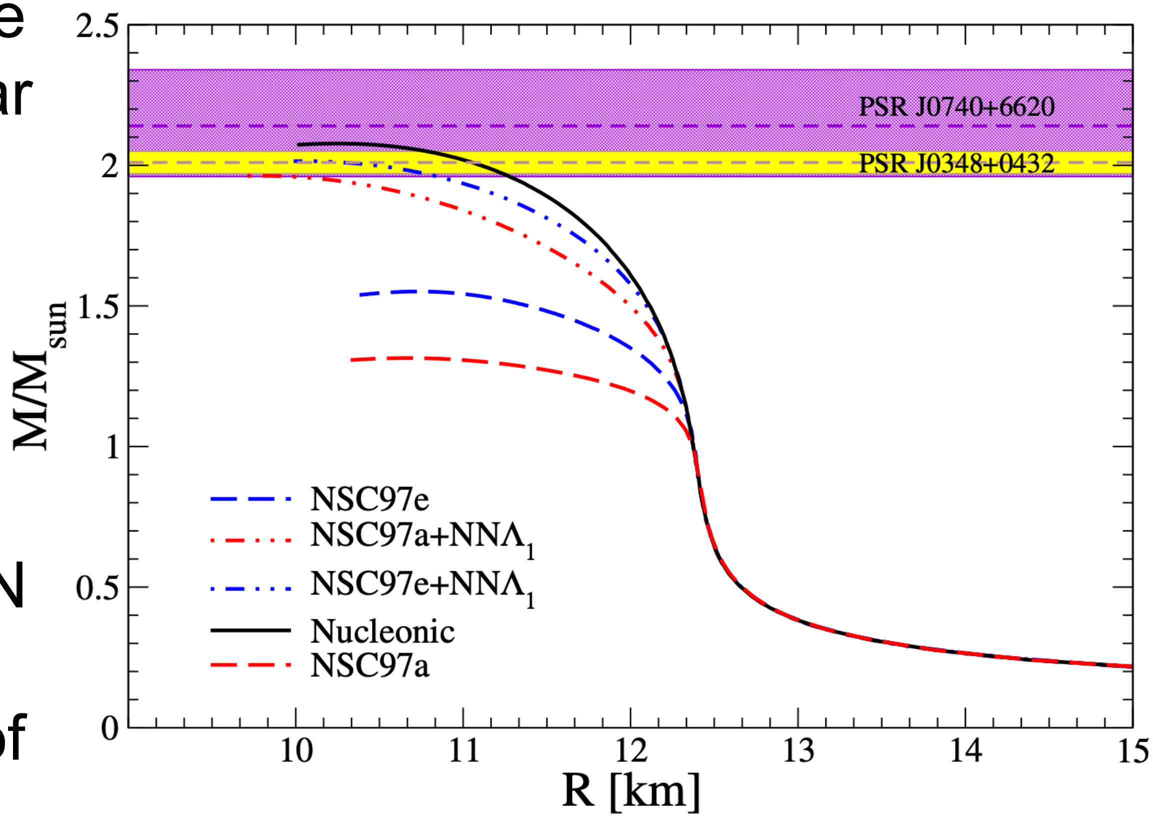
- Hyperon puzzle in neutron stars → hyperons make the EOS softer:
- Pure neutron matter (PNM) works well
- Known ΛN interaction → way to soft
- Including ΛNN forces brings the mass slightly up
- Only additional ΛNN interaction works sufficiently



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

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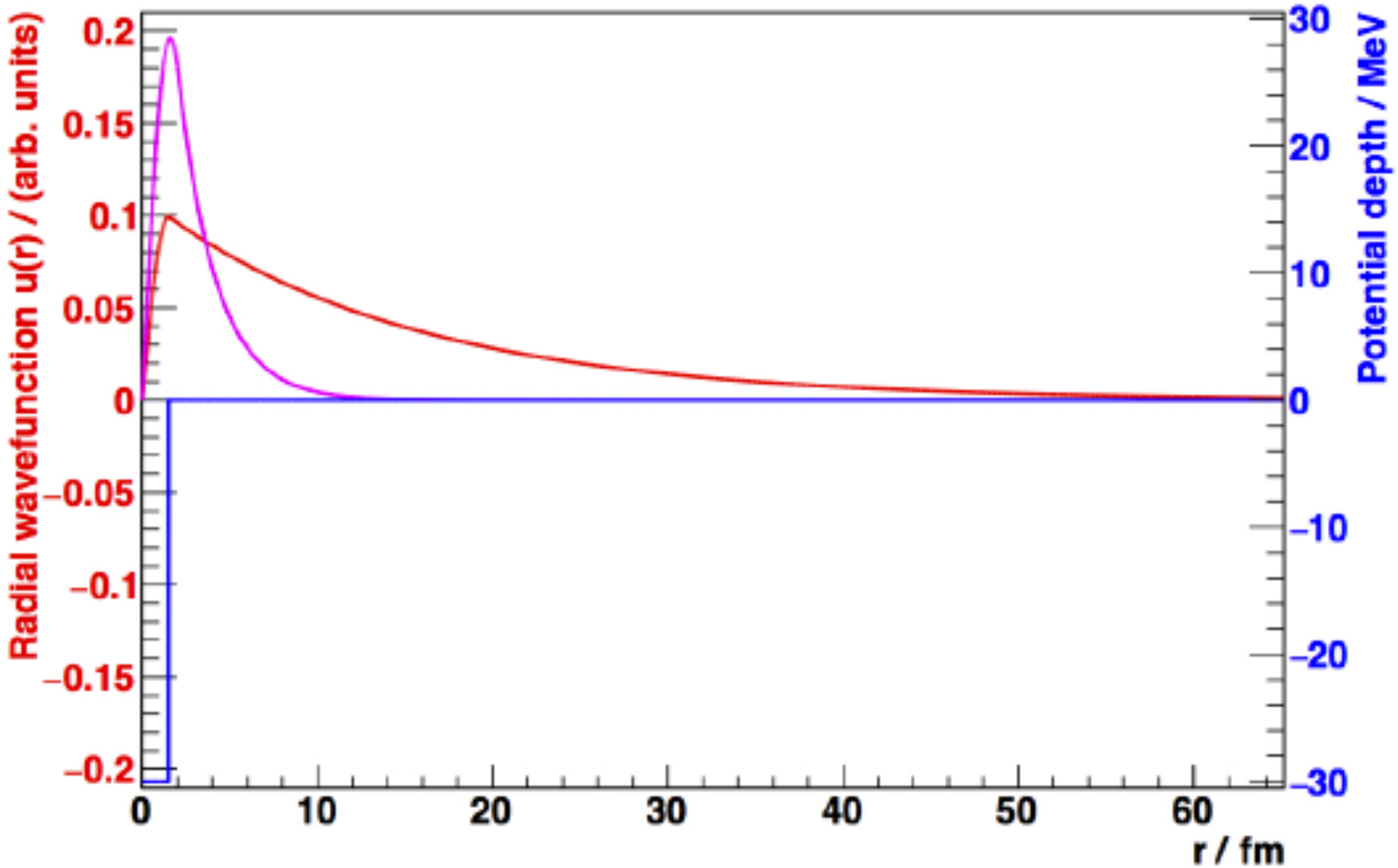

P. Braun-Munzinger, BD, Nucl. Phys. A 987 (2019) 144

Hypertriton

Bound state of Λ, p, n

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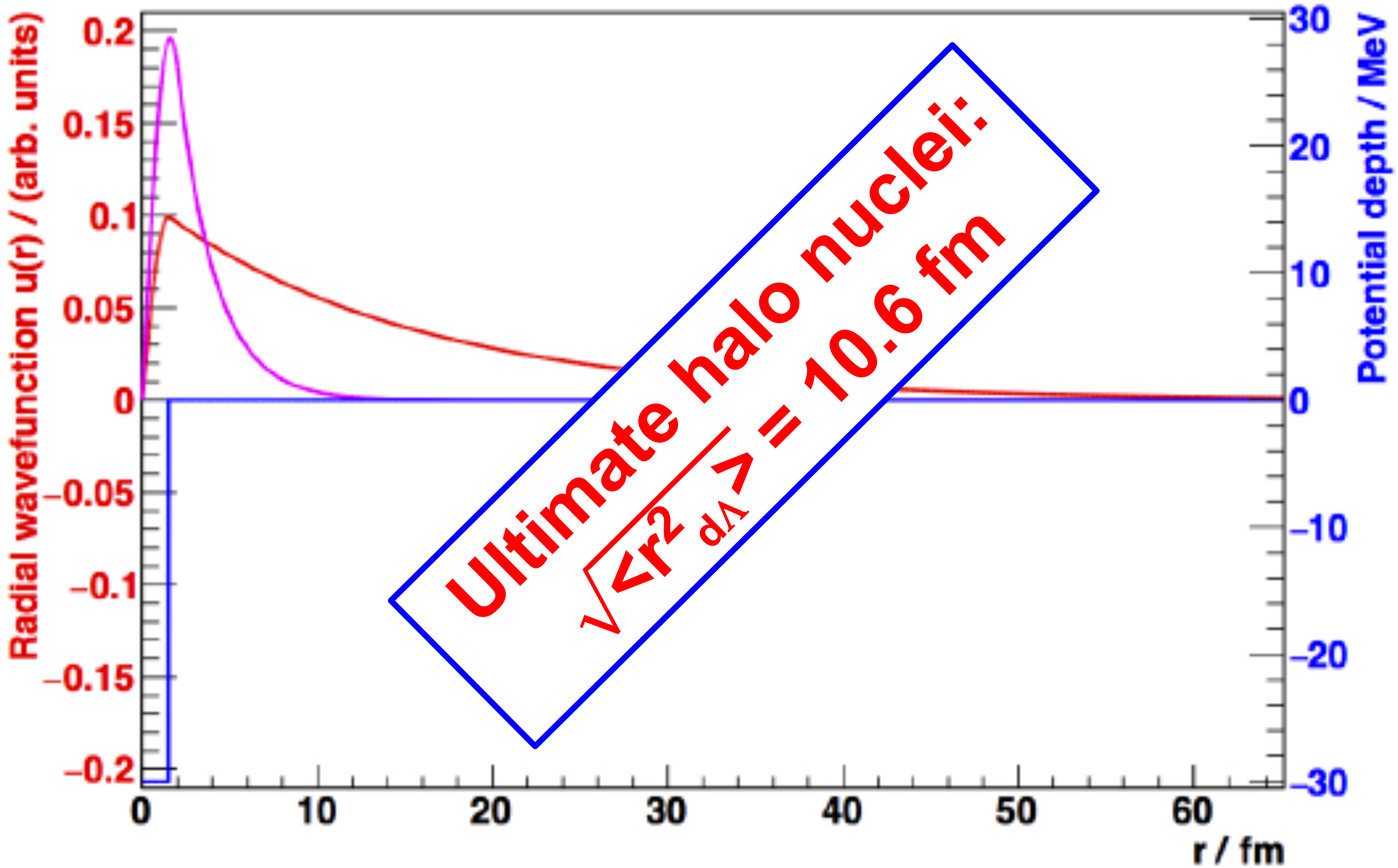
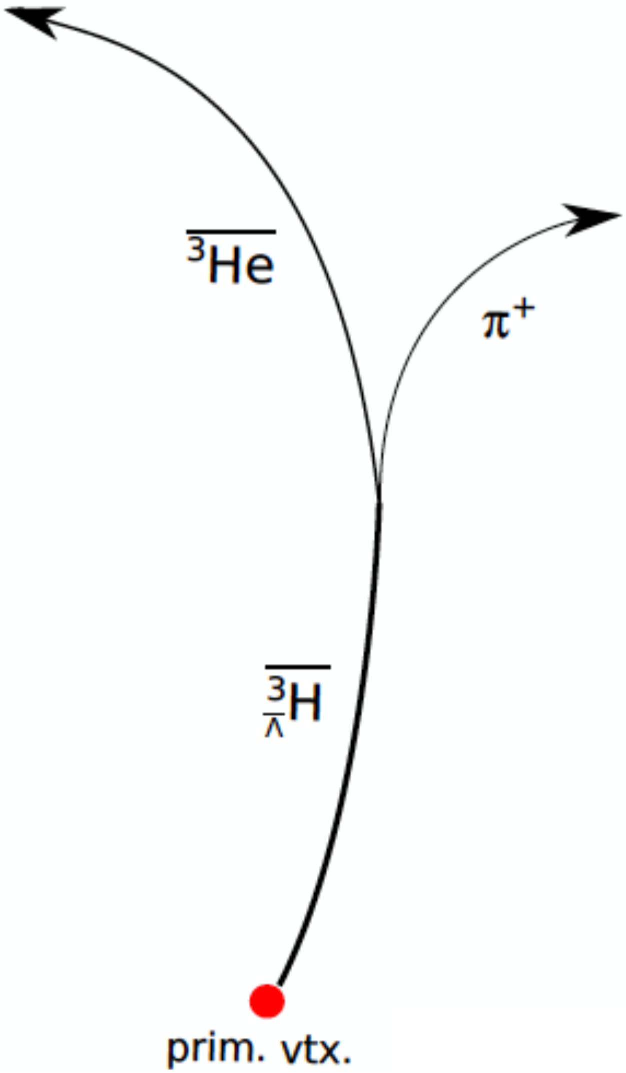


P. Braun-Munzinger, BD, Nucl. Phys. A 987 (2019) 144

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:

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

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

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

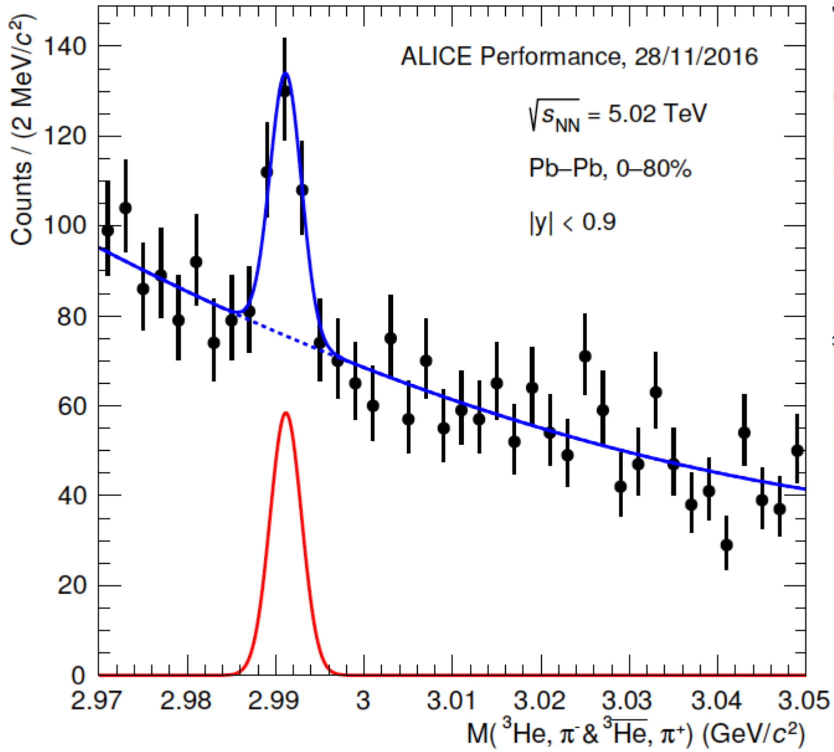
$$^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{n} + \pi^{0}$$

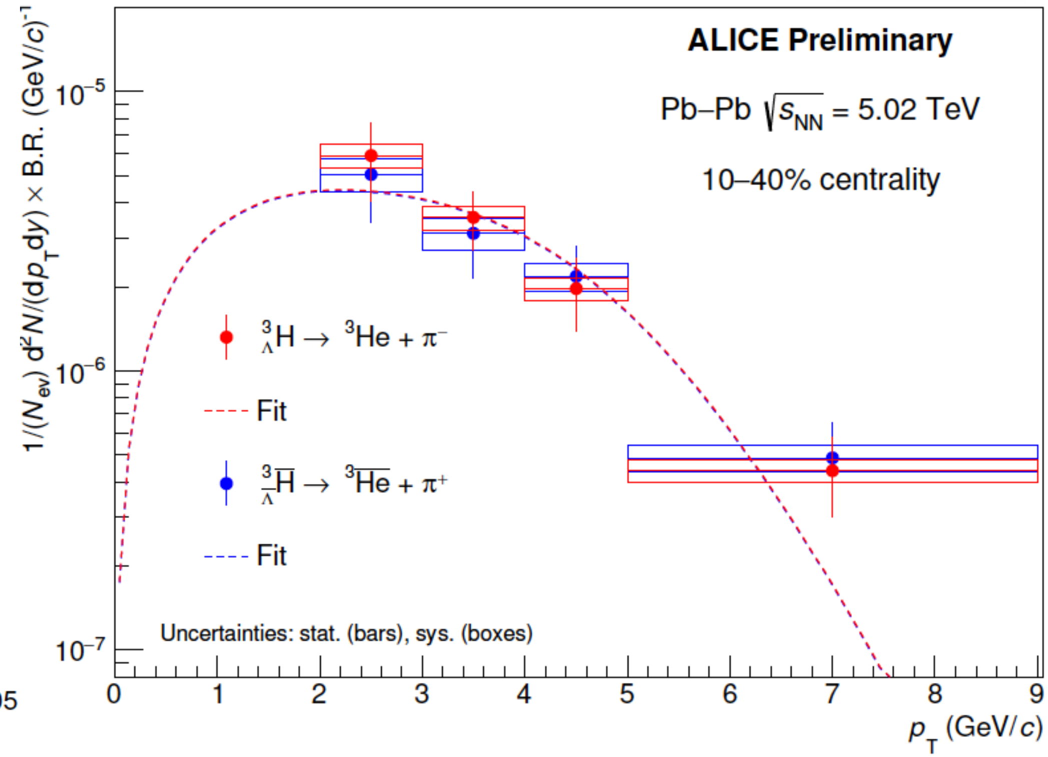
\+ anti-particles

→ Anti-Hypertriton first observed by STAR Collaboration:

Science 328,58 (2010)

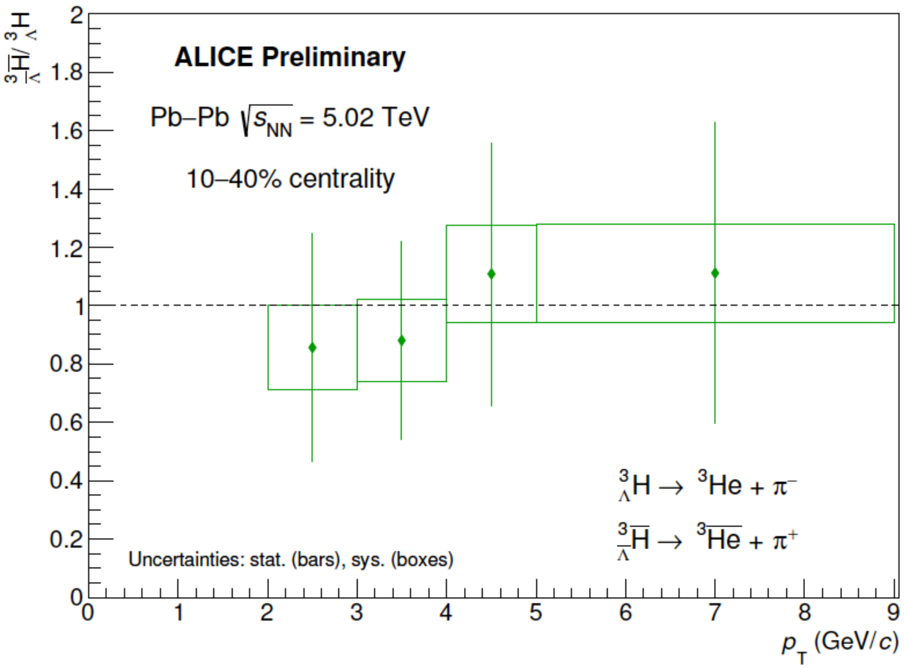
Hypertriton signal

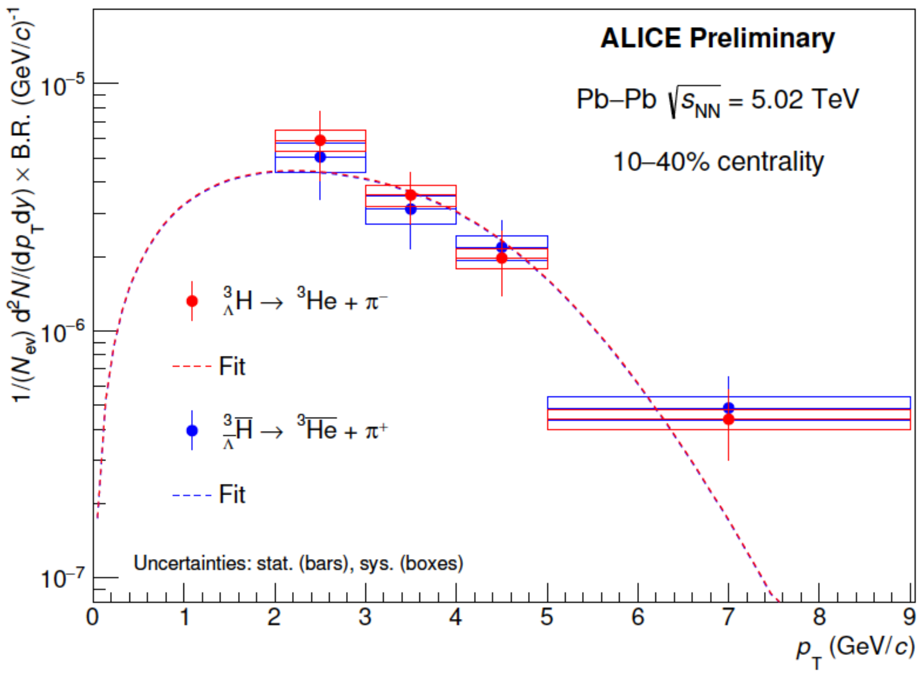




- Clear signal reconstructed by decay products
- Spectra can also be described by Blast-Wave model
  → Hypertriton flows as all other particles

Hypertriton spectra

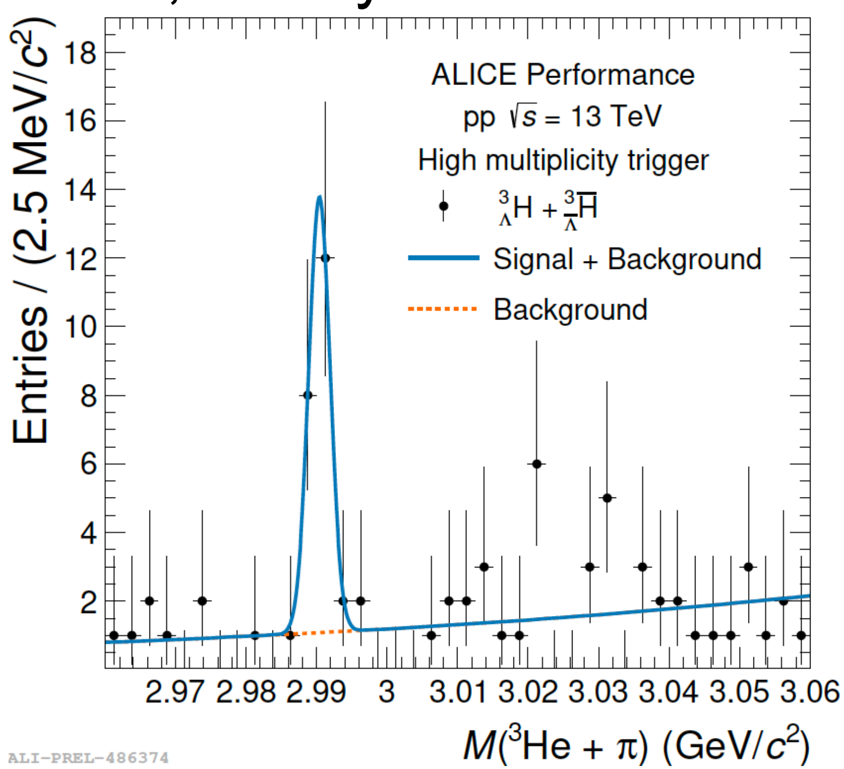


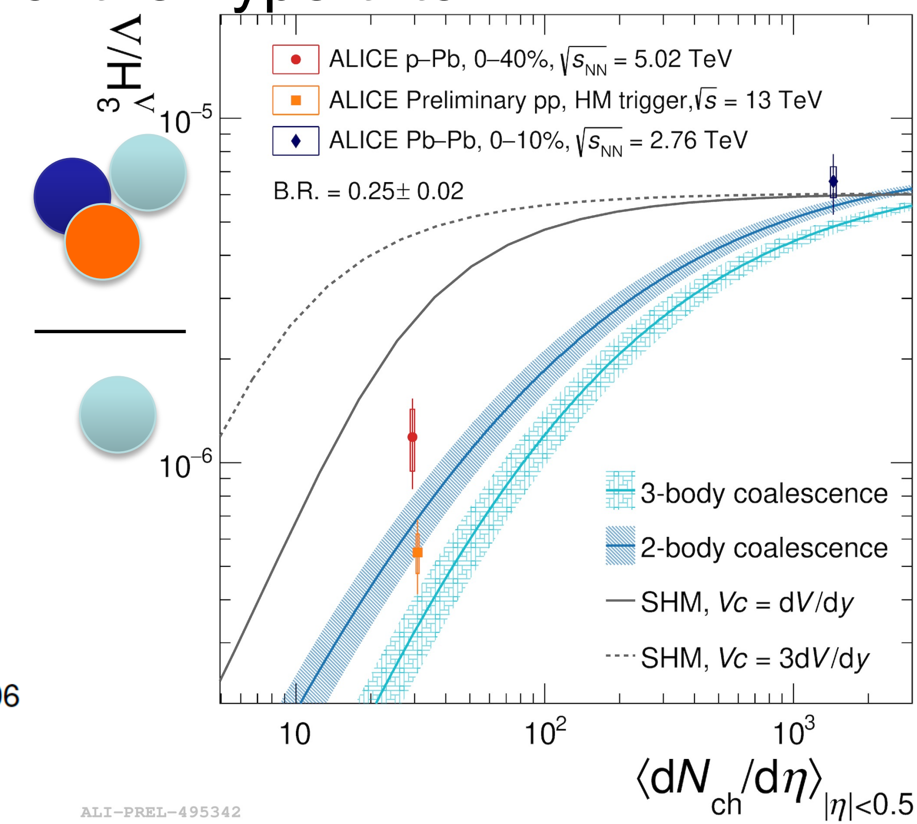


- Anti-hypertriton/Hypertriton ratio consistent with unity vs. p_T

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
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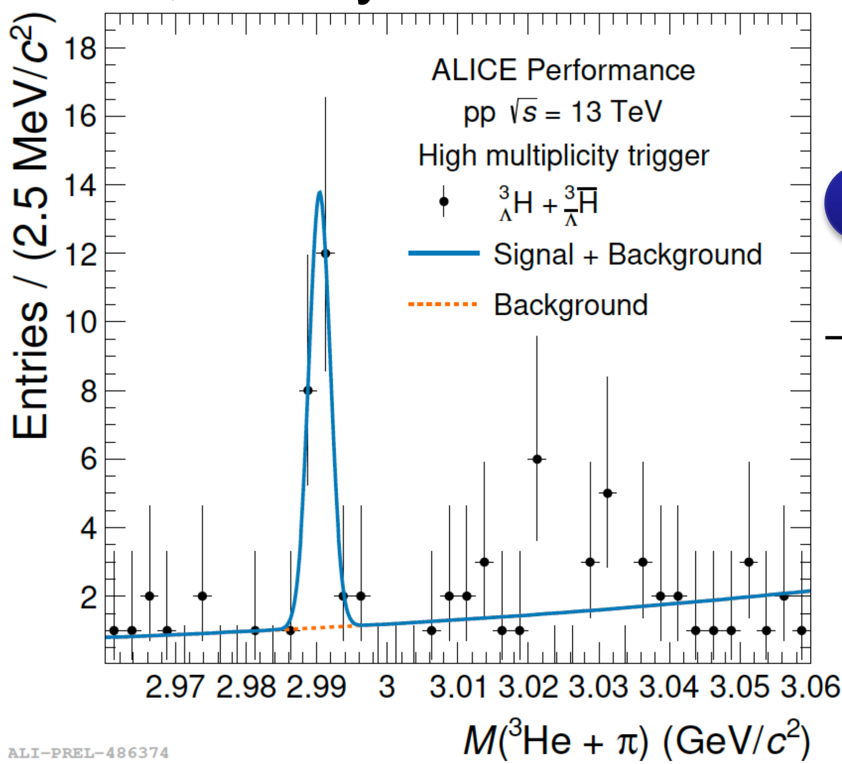
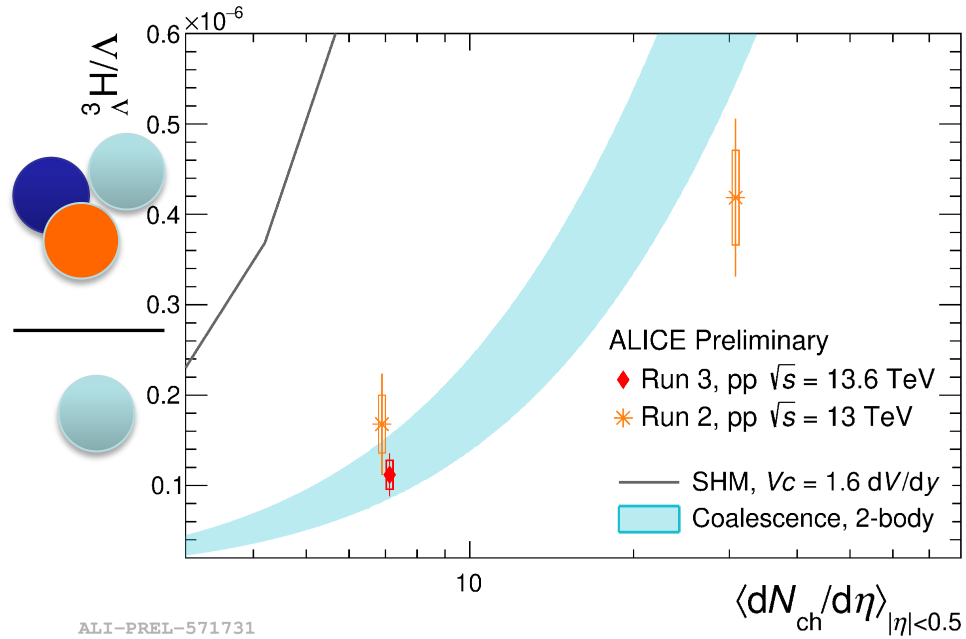
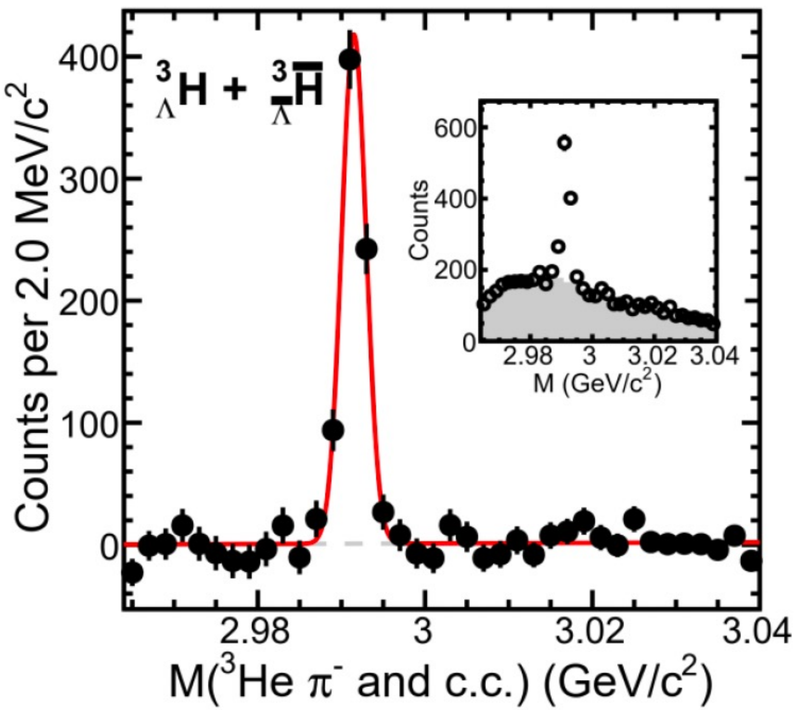




Hypertriton at RHIC

- Hypertriton signal recently also extracted in isobar collisions



As presented by Dongsheng Li @ SQM2024

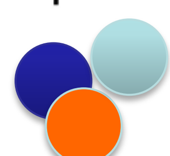
0-80% Zr+Zr & Ru+Ru @ $\sqrt{s_{NN}}$ = 200 GeV

$p_T \leq 5$ (GeV/c)

Same Event (SE)

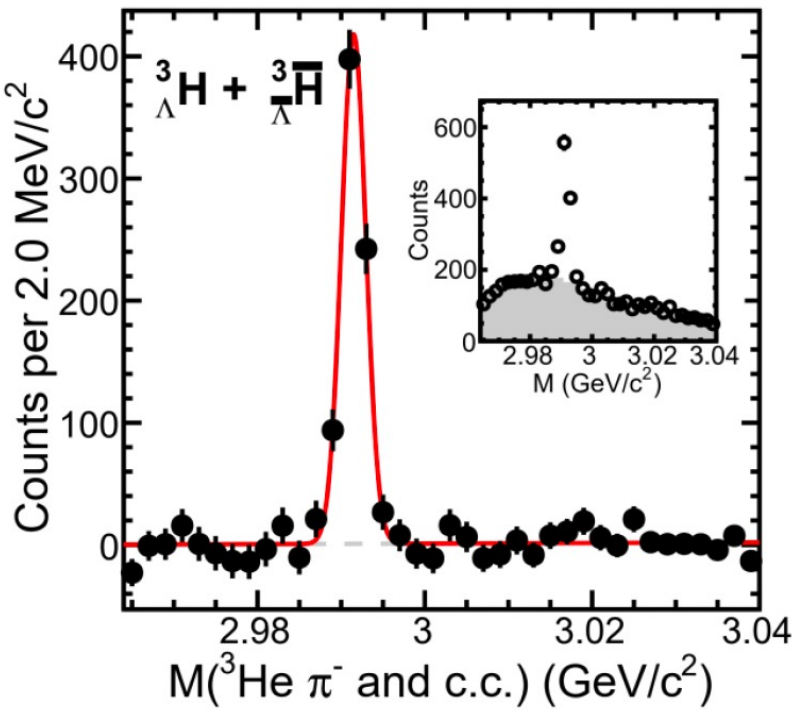
Mixed Event (ME)

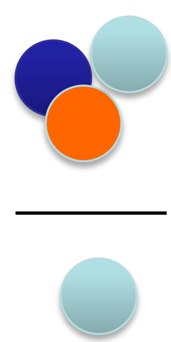
SE - ME

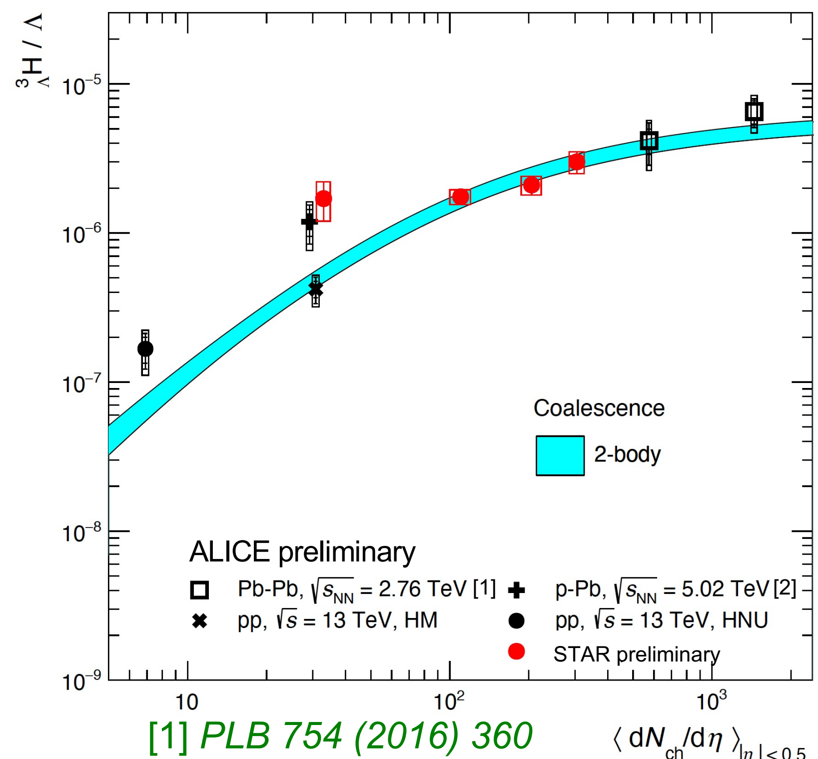


Hypertriton/Λ ratio

- 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



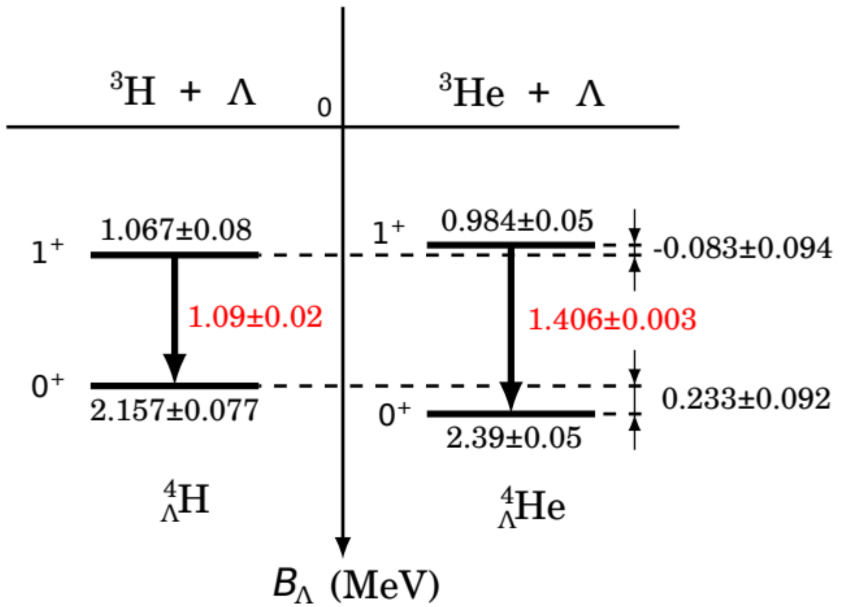




[1] *PLB 754 (2016) 360*
[2] *PRL 128 (2022) 252003*

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



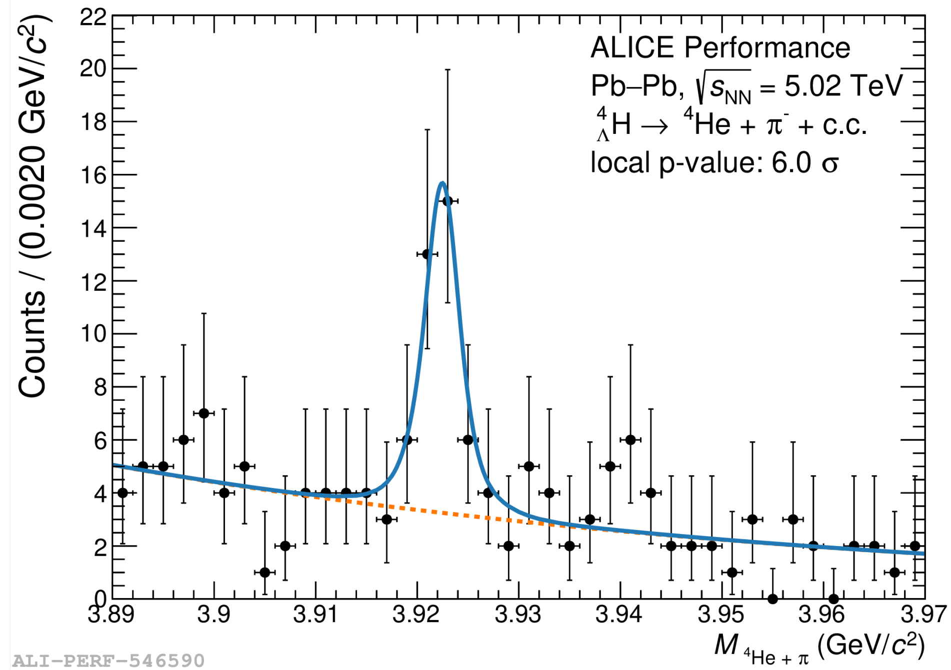
M. Schäfer, N. Barnea, A. Gal, Phys.Rev.C 106, L031001 (2022)

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

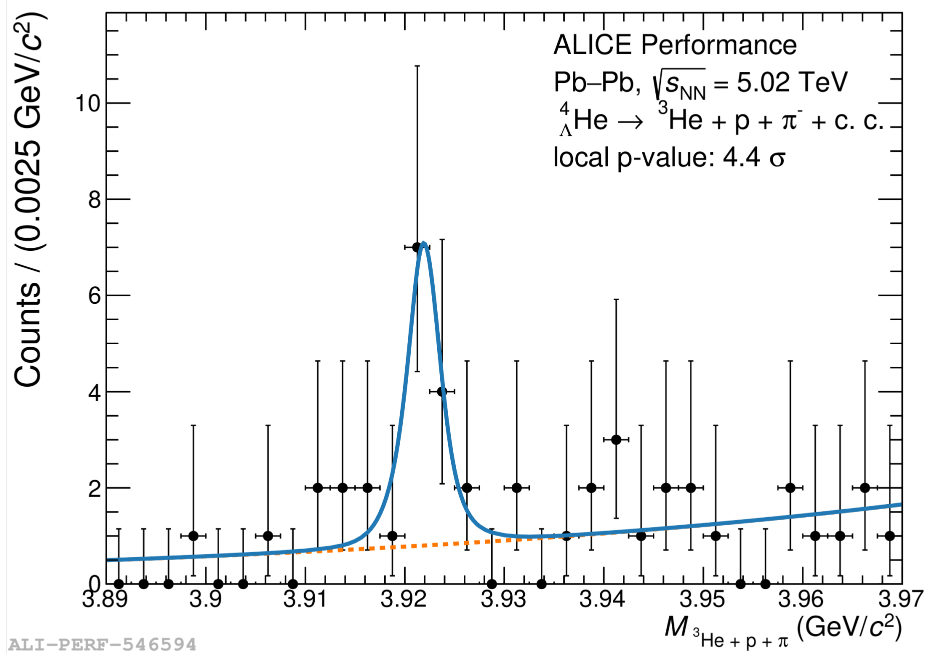
- For the first time, we are able to reconstruct A = 4 (anti)hypernuclei at the LHC and determine their production yield

- **(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 local p-value of **4.4σ**

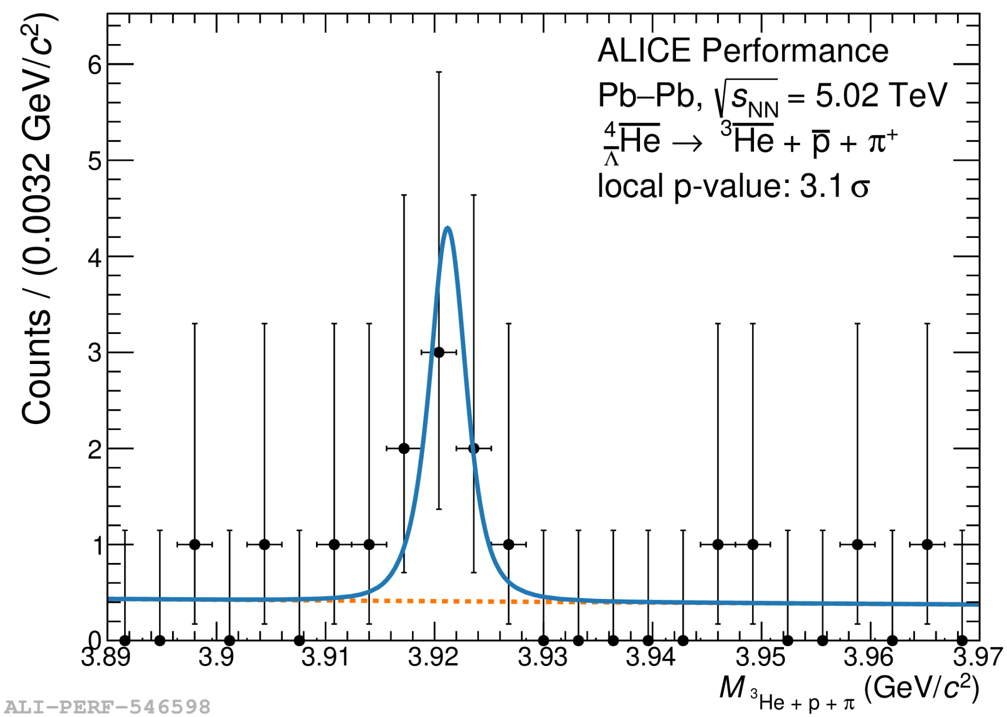


A = 4 hypernuclei

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

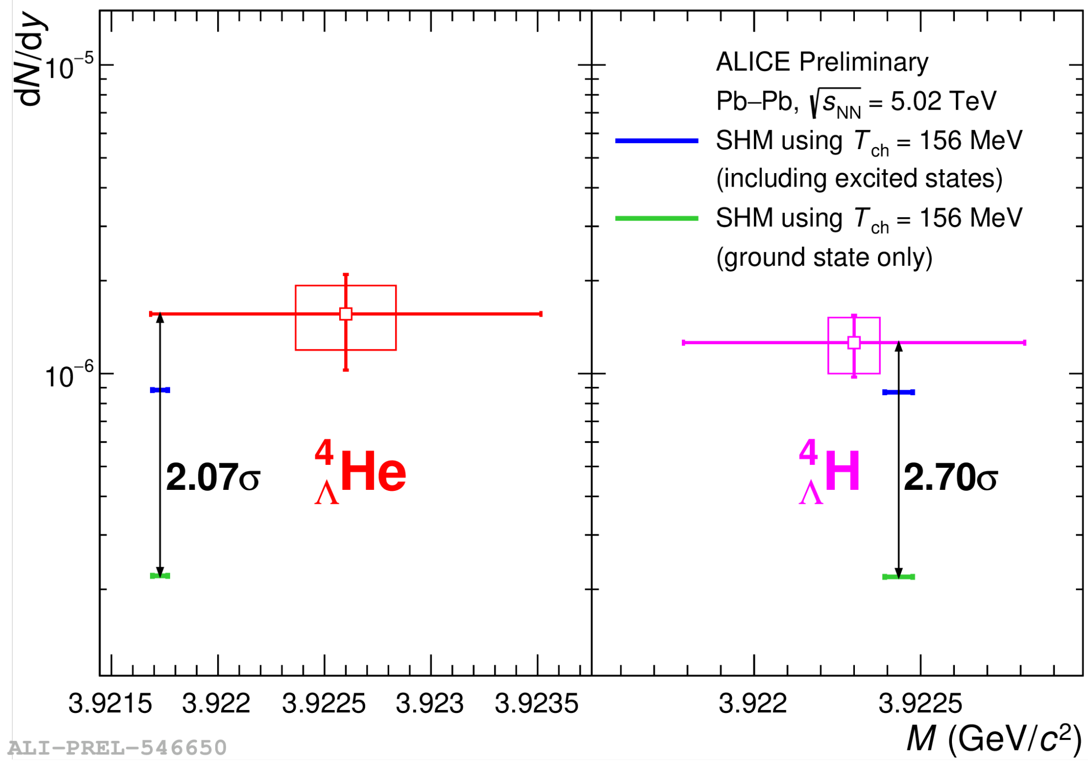
- **First observation of the antihyperhelium-4** in Run 2 Pb-Pb collisions at 5.02 TeV

- Reaching a local p-value of **3.1σ**

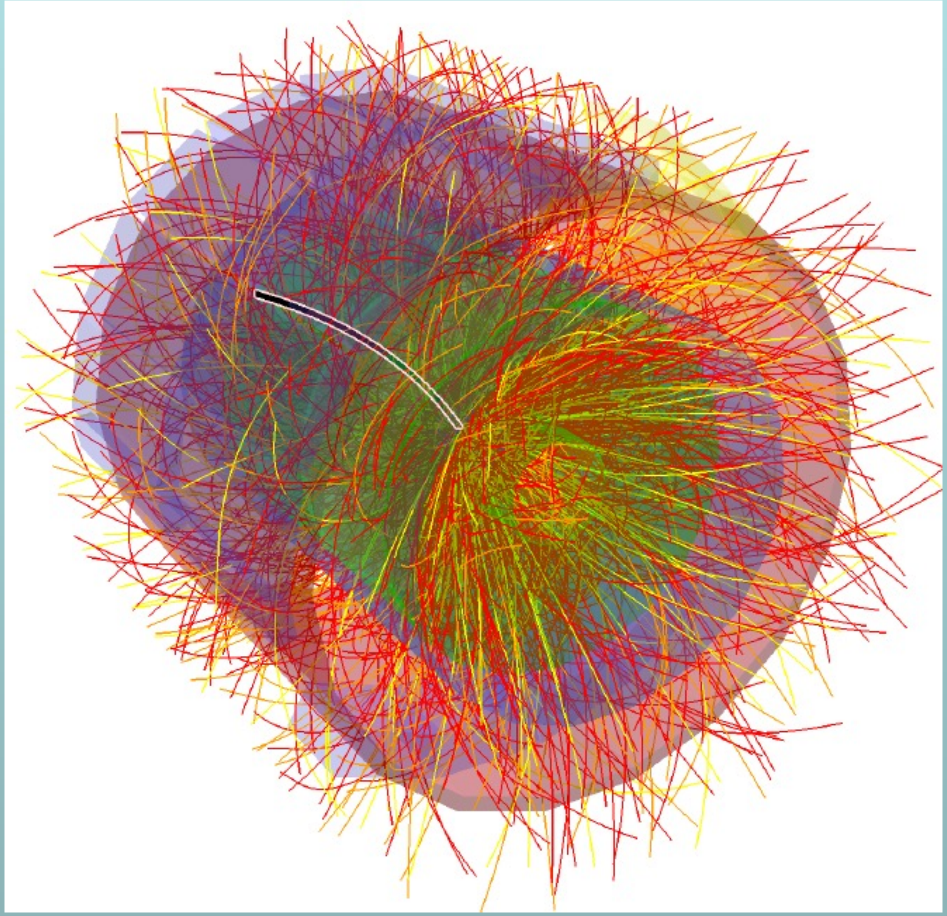


A = 4 hypernuclei

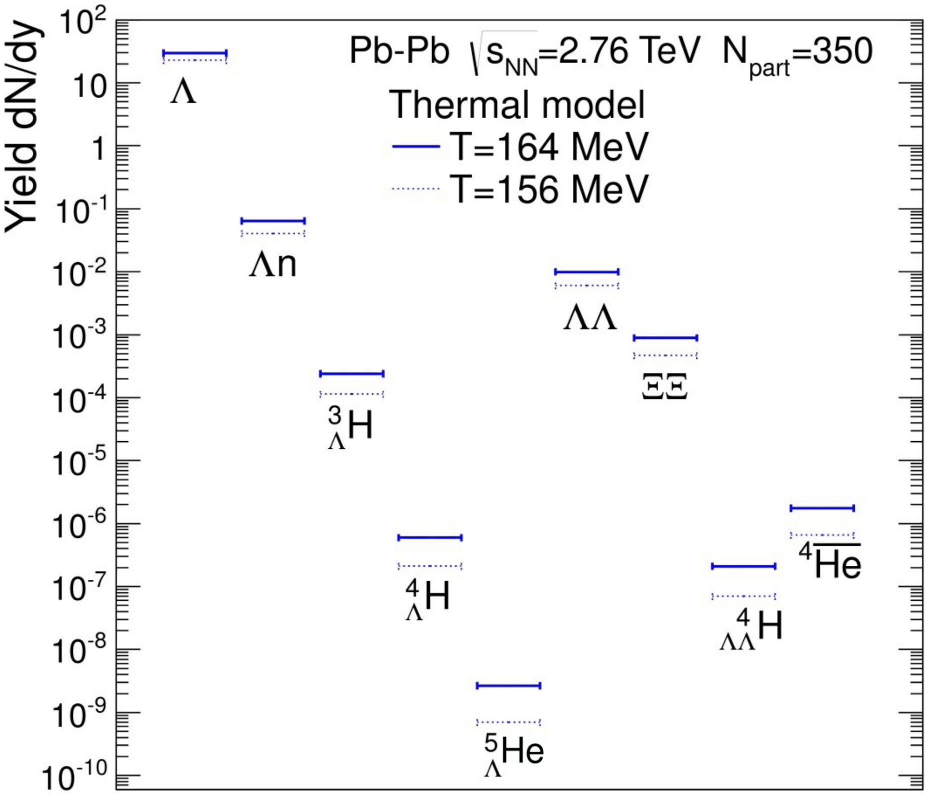
- First measurement of the (anti)hyperhelium-4 production yield
- Testing the dependence of the yields of the SHM with the spin-degeneracy
- Our yields confirm the hypothesis of excited states for both (anti)hypernuclei within 2σ
- currently dominated by statistical uncertainties
- with more data, a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



Outlook & Summary



Outlook

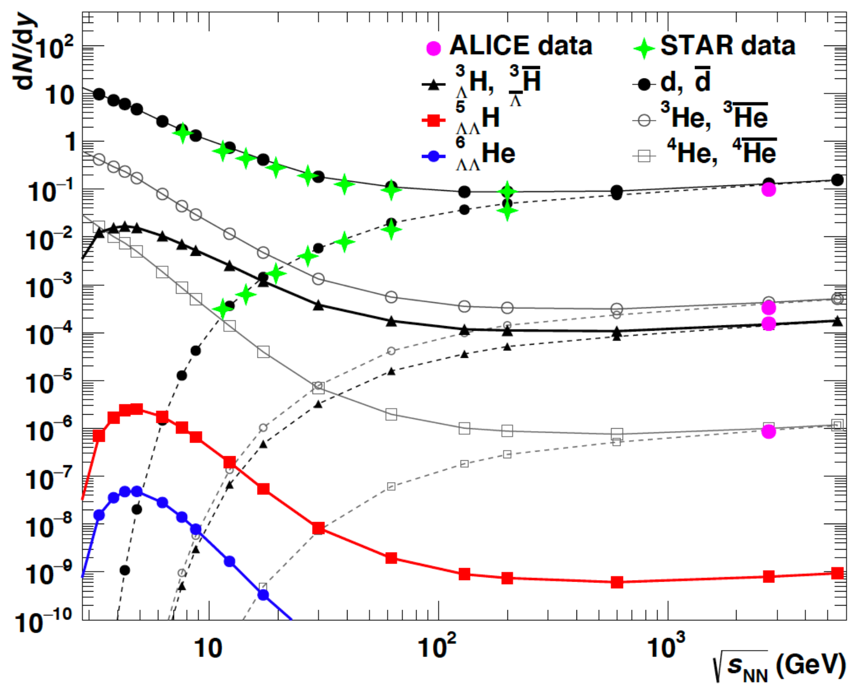


A. Andronic, private communication, model described in A. Andronic et al., PLB 697, 203 (2011) and references therein

- 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 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 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