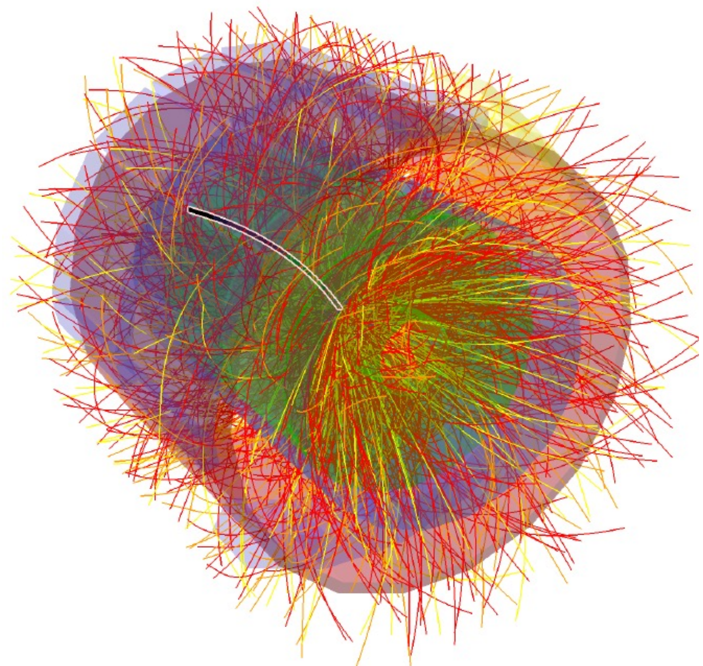
Production of (anti-)matter and exotics at the LHC



14. Dezember 2021
Physics Colloquium Mainz

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Institut für Kernphysik

Goethe Universität Frankfurt

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

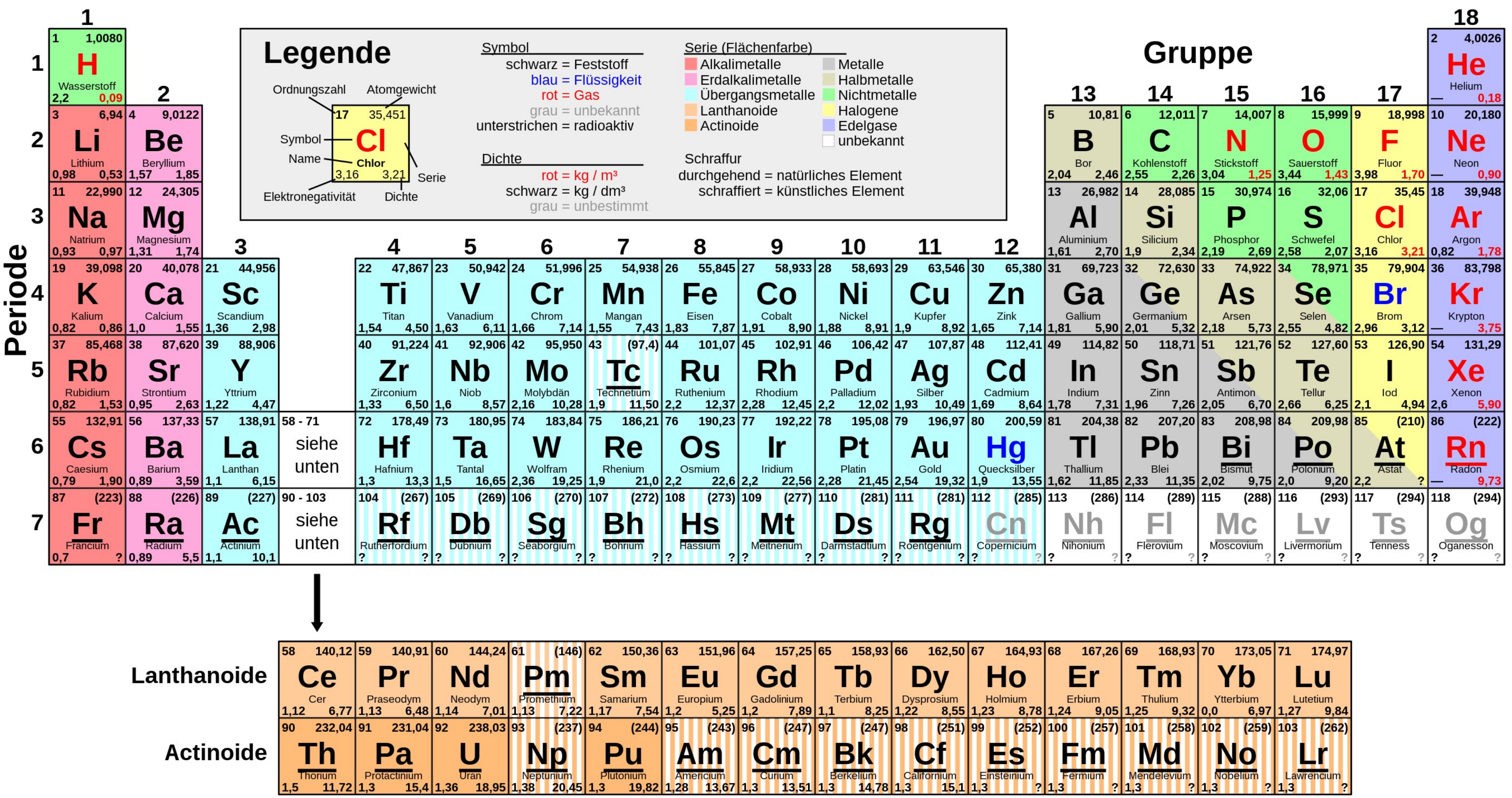
IKF Institut für Kernphysik Frankfurt

Content

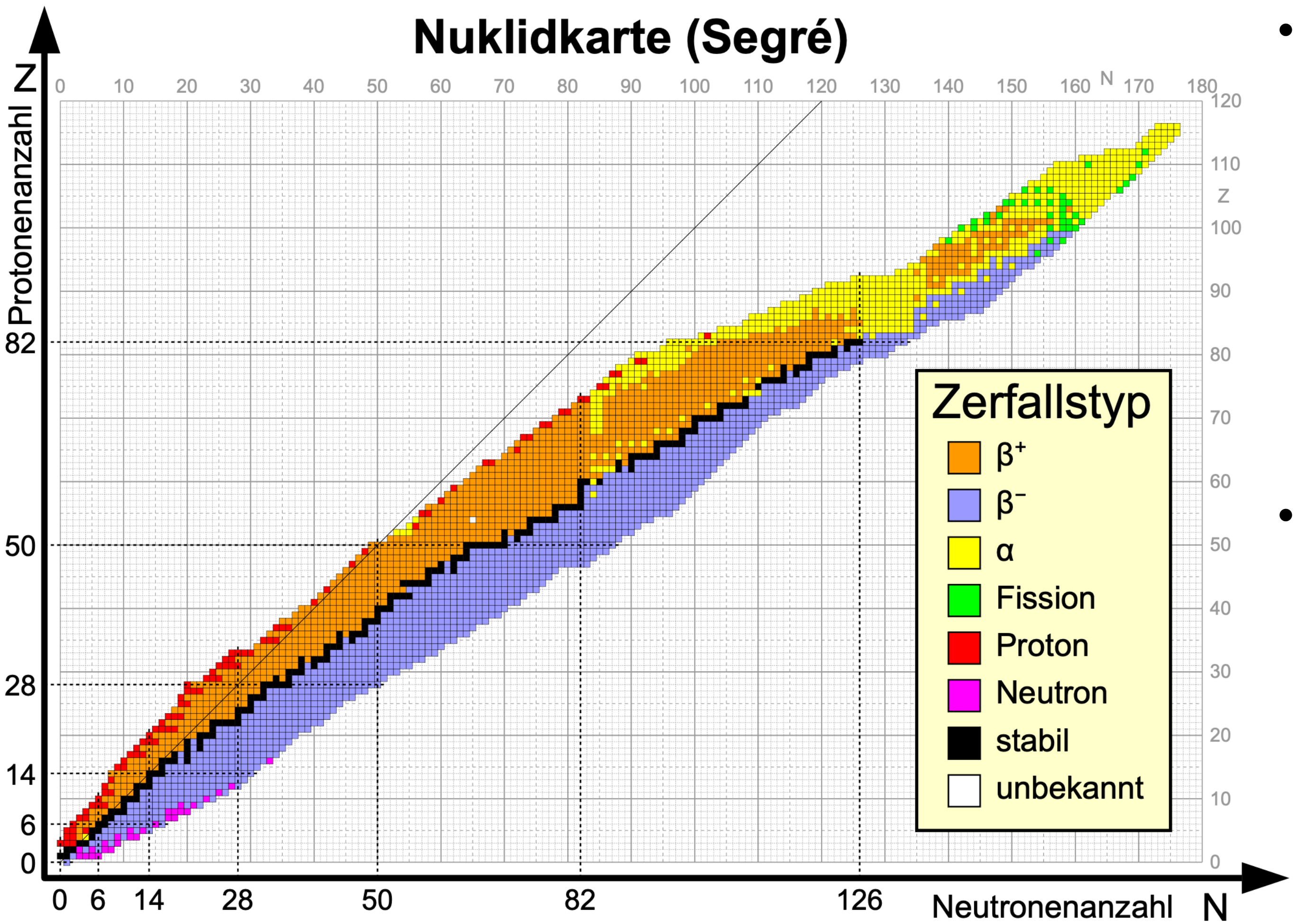
- Introduction
- Nuclei and Exotica
  - (Anti-)nuclei
  - (Anti-)hypertriton
  - (Anti-)hypermatter
- Summary & Outlook

From Chemisty to Physics

- Chemical elemente grupped in periodic table



From Chemisty to Physics



- Chemical elements and chemical properties are defined by the charge number, i.e. the number of protons
- Number of protons and neutrones define (nuclear) physical properties, such as stabilty or type of decay

From Chemisty to Physics

Proton (p)

m=938.3 MeV/c^2

Deuteron (pn)

m=1875.6 MeV/c^2

Triton (pnn)

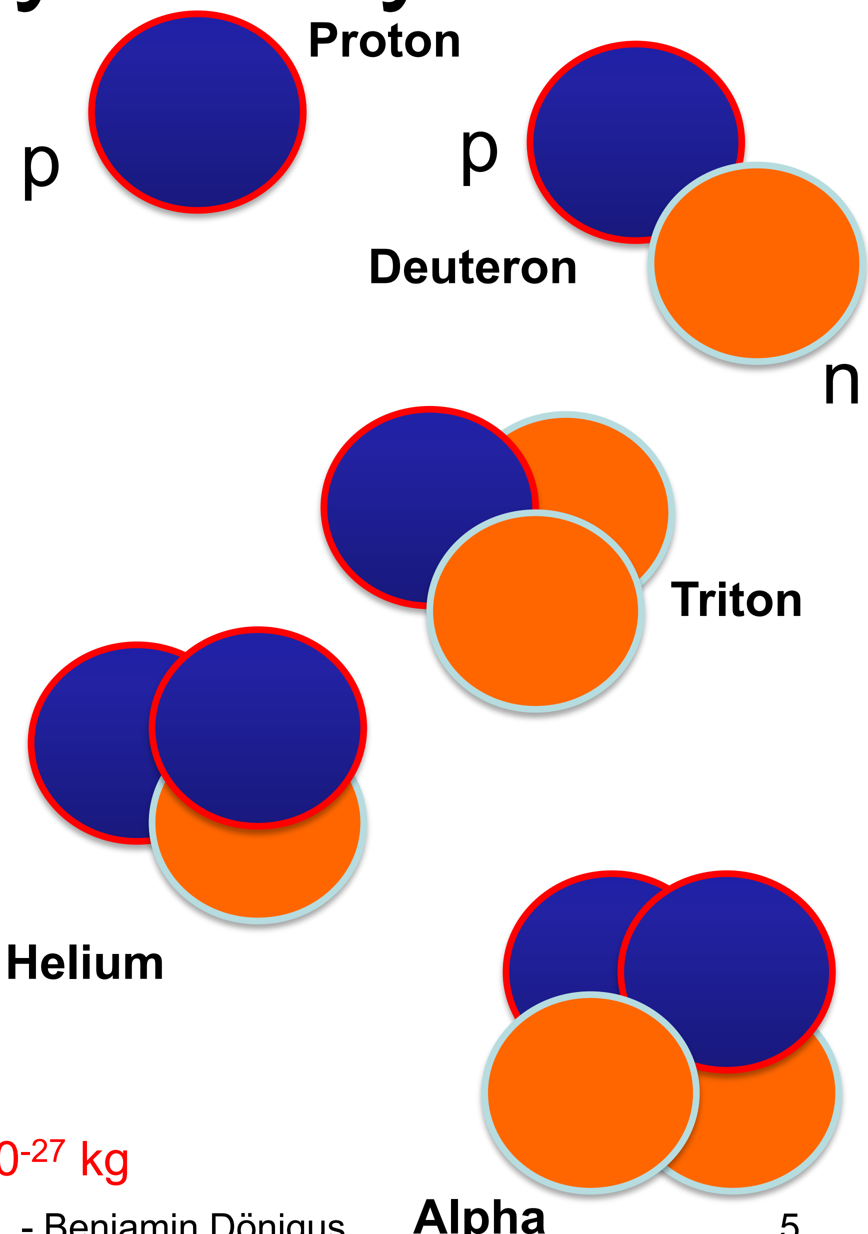
m=2808.9 MeV/c^2

Helium (ppn)

m=2808.4 MeV/c^2

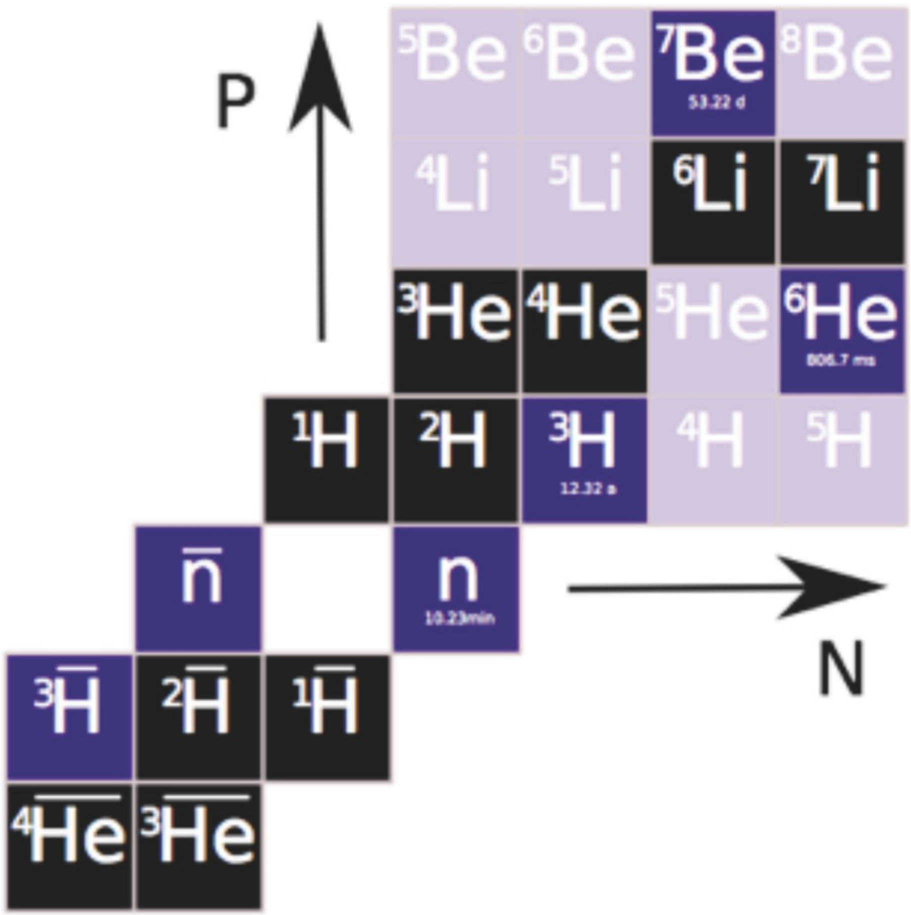
Alpha (ppnn)

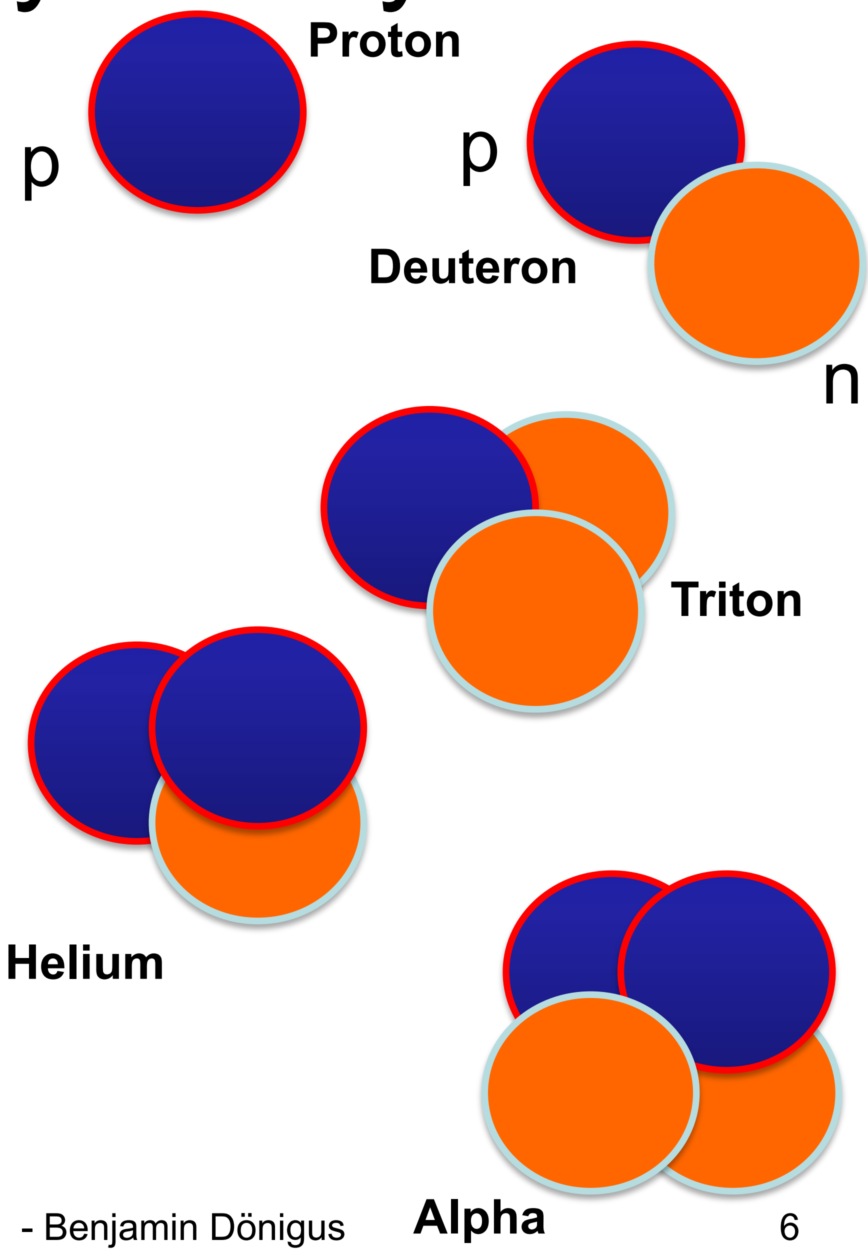
m=3727.4 MeV/c^2



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

From Chemisty to Physics





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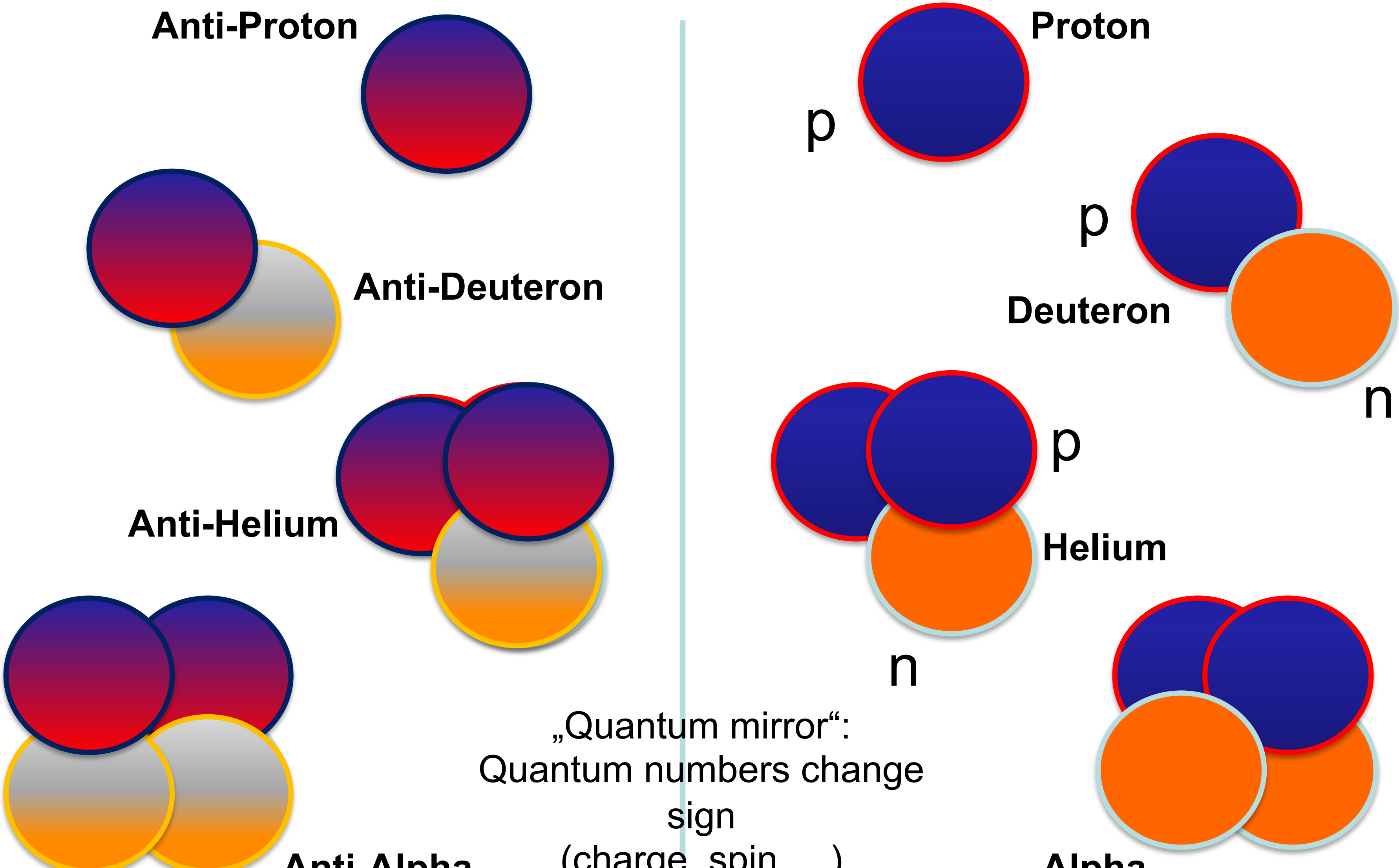
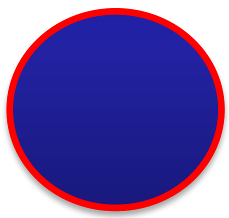


„Quantum mirror“:
Quantum numbers change sign
(charge, spin, ...)

Zoo of hadrons

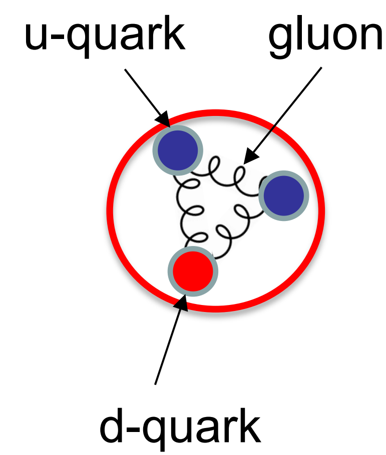
Baryons



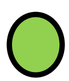
Proton (p) → uud

Neutron (n) → udd

Lambda (Λ) → uds



Mesons



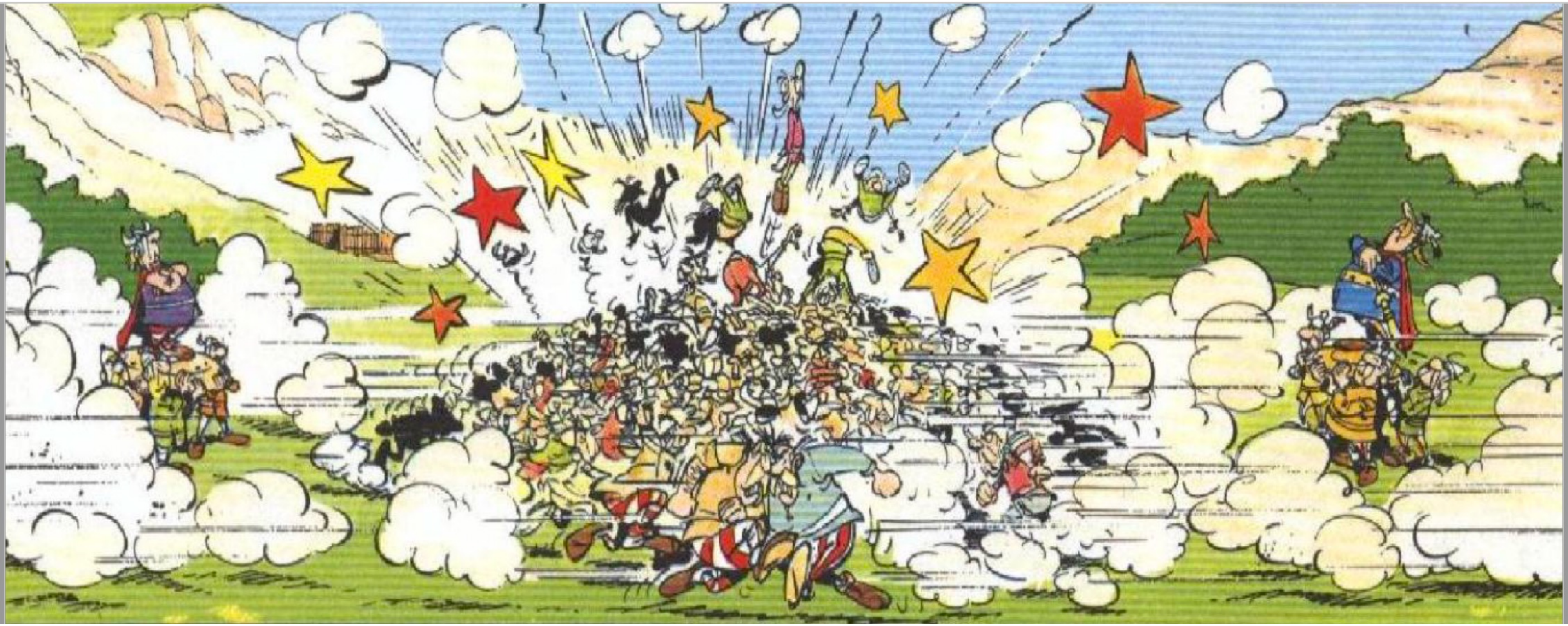
π-Meson → $d\bar{u}$

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 the collided
- This leads to the creation of (new) particles that can be detected in the experiments sorrounding the collision point



Asterix & Obelix, Der große Graben, Ehapa Verlag

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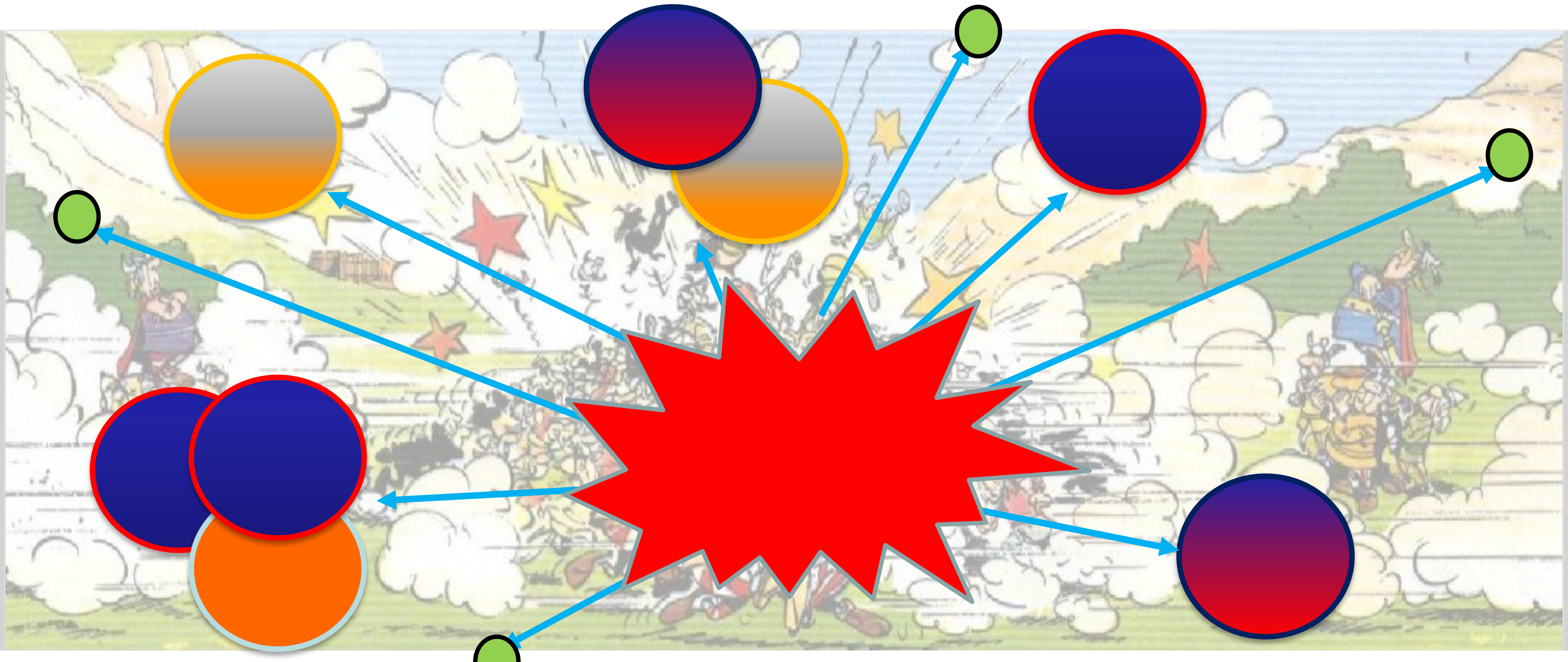
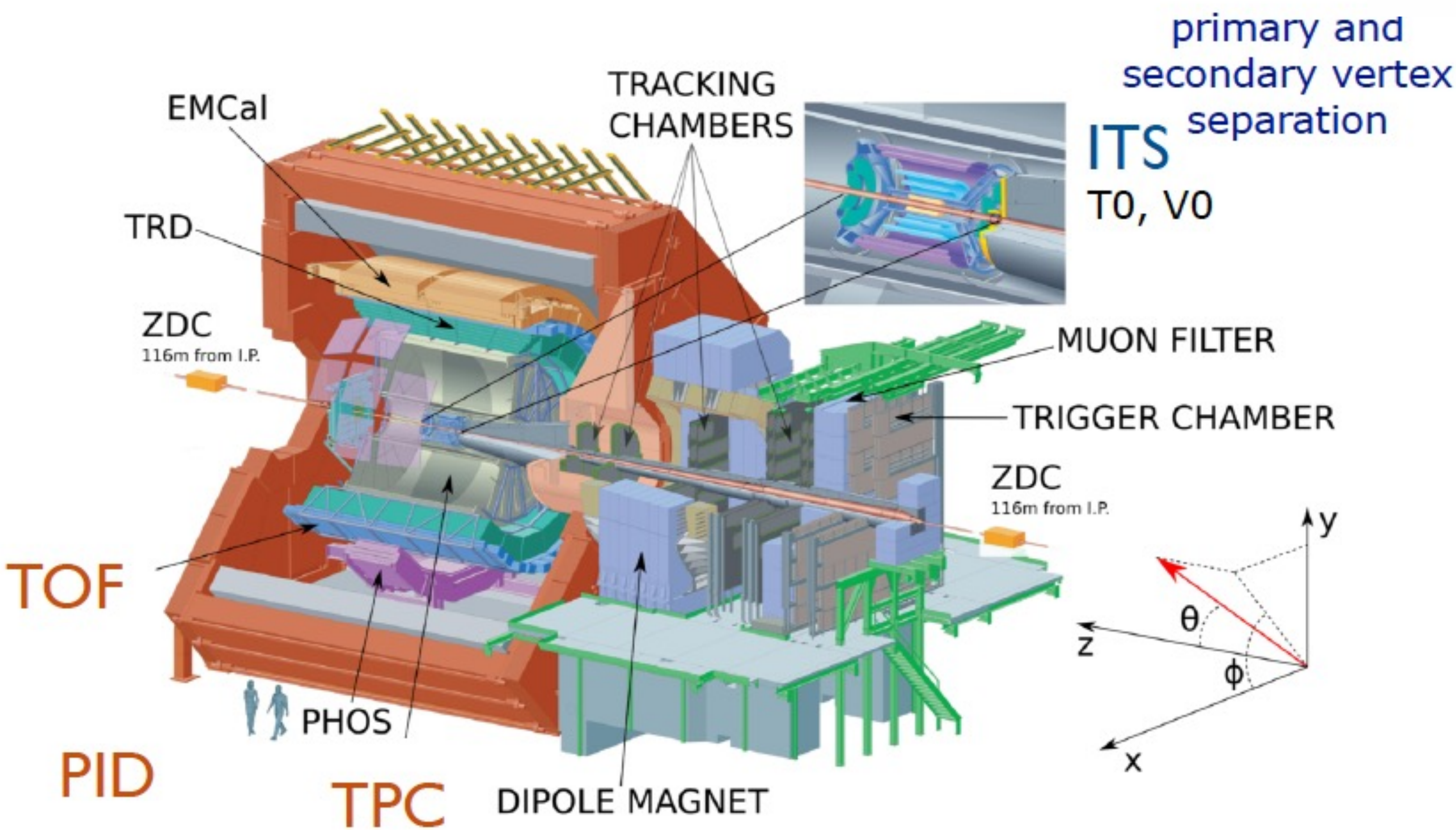


Asterix & Obelix, Der große Graben, Ehapa Verlag

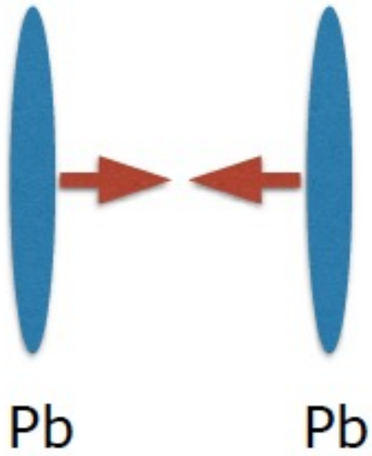
Large Hadron Collider at CERN

Large Hadron Collider at CERN

Experiment: ALICE



Interlude: Centrality

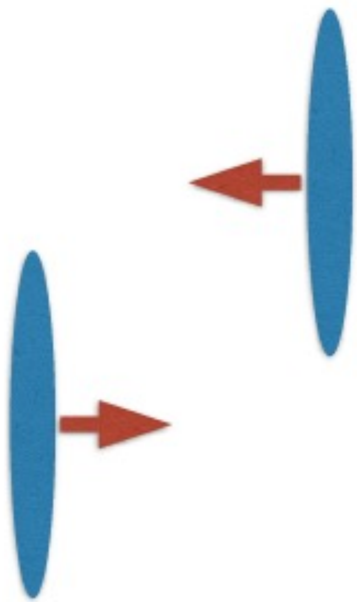


Central Pb-Pb collision:

High multiplicity = large dN/dη

High number of tracks

(more than 2000 tracks in the detector)



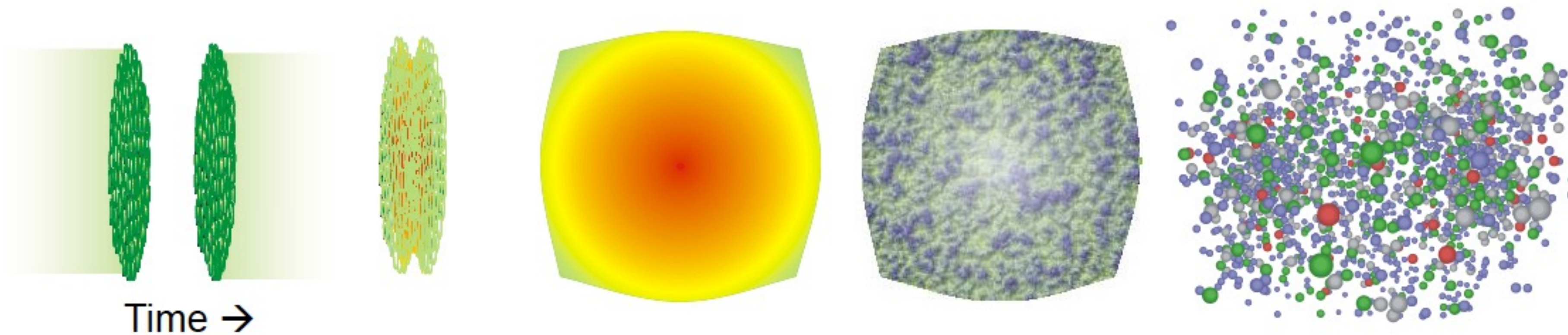
Peripheral Pb-Pb collision:

Low multiplicity = small dN/dη

Low number of tracks

(less than 100 tracks in the detector)

Introduction



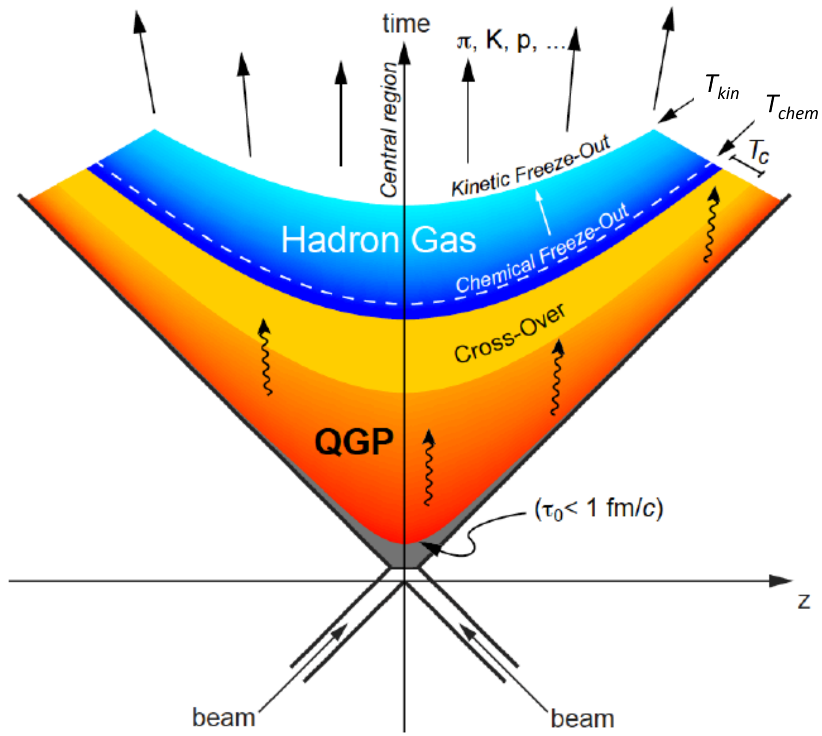
Cartoon of a Ultra-relativistic heavy-ion collision

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

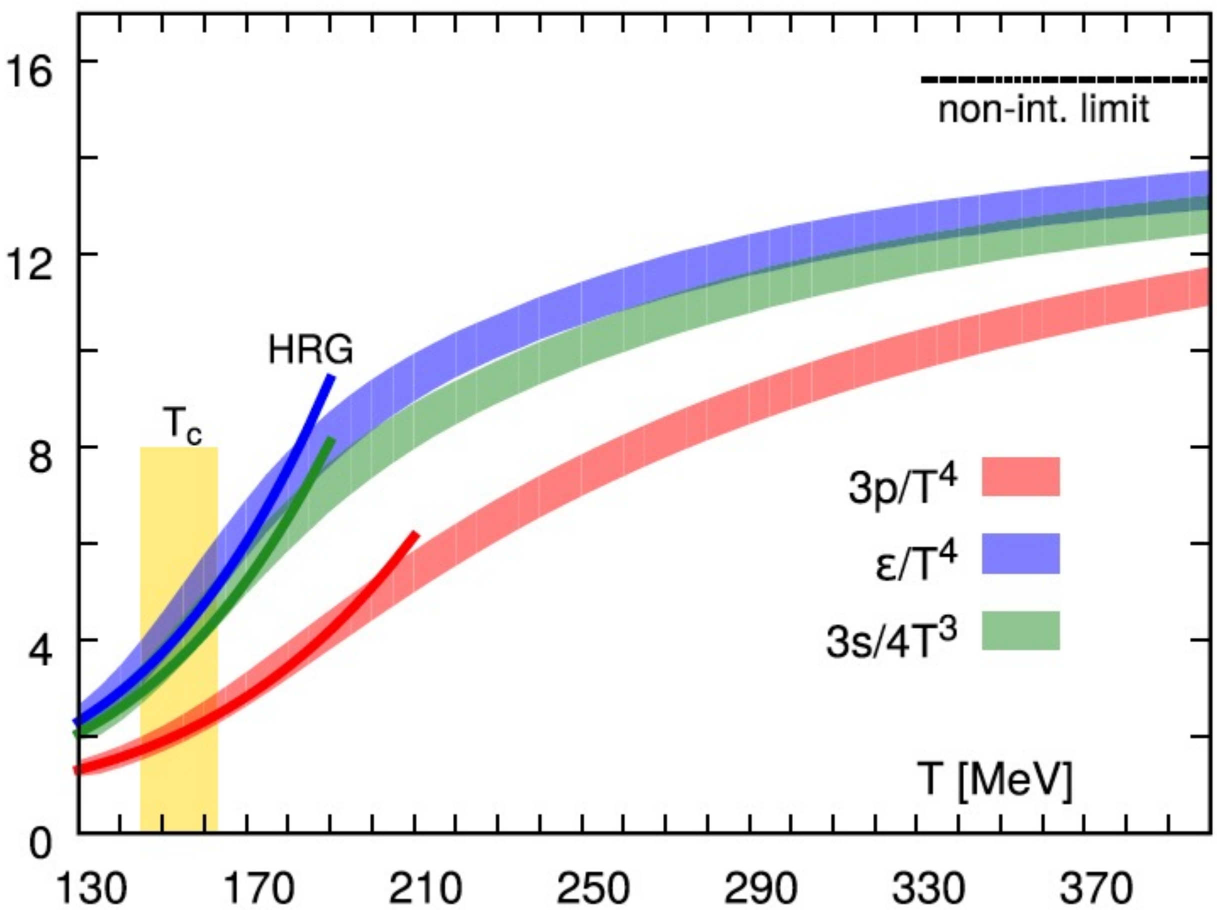
Introduction



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



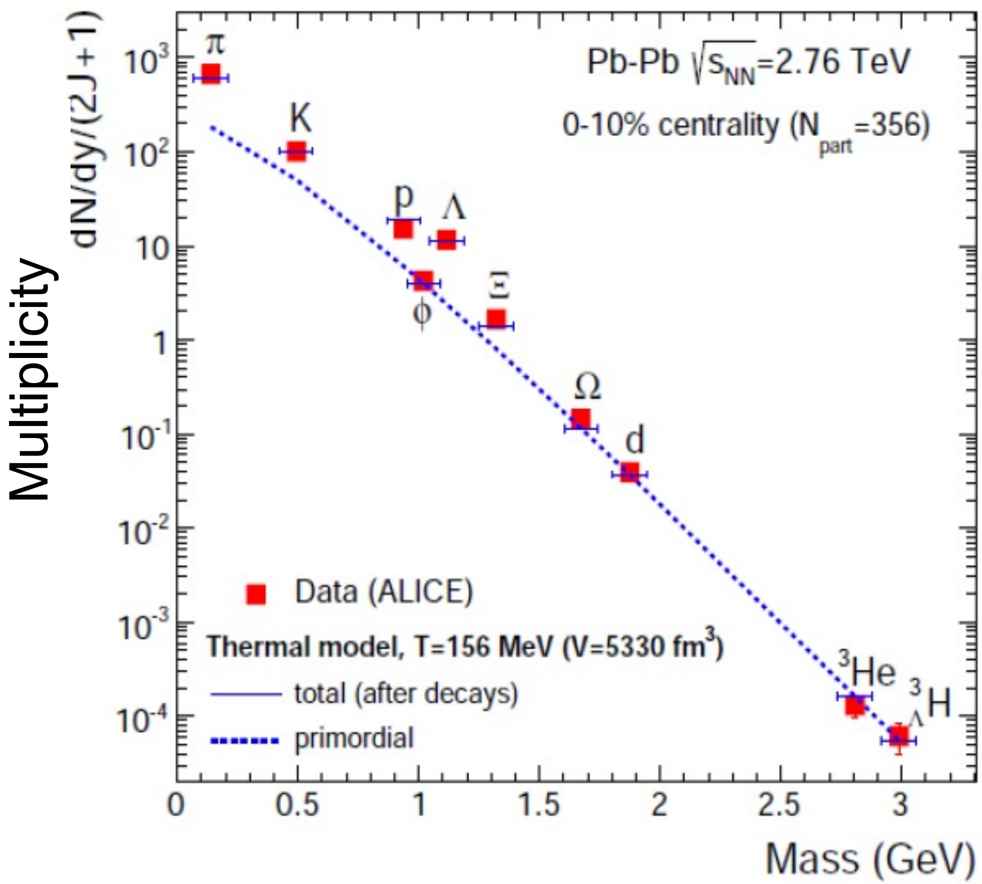
Lattice QCD tells us where to expect the phase transition

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

Critical temperature
T_C = (154 ± 9) MeV

A. Bazavov et al. (hotQCD) Phys. Rev. D90 (2014) 094503
Similar results from Budapest-Wuppertal group: S. Borsányi et al. JHEP 09 (2010) 073

Temperature of the source



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

Analogy:

Light source → particle source

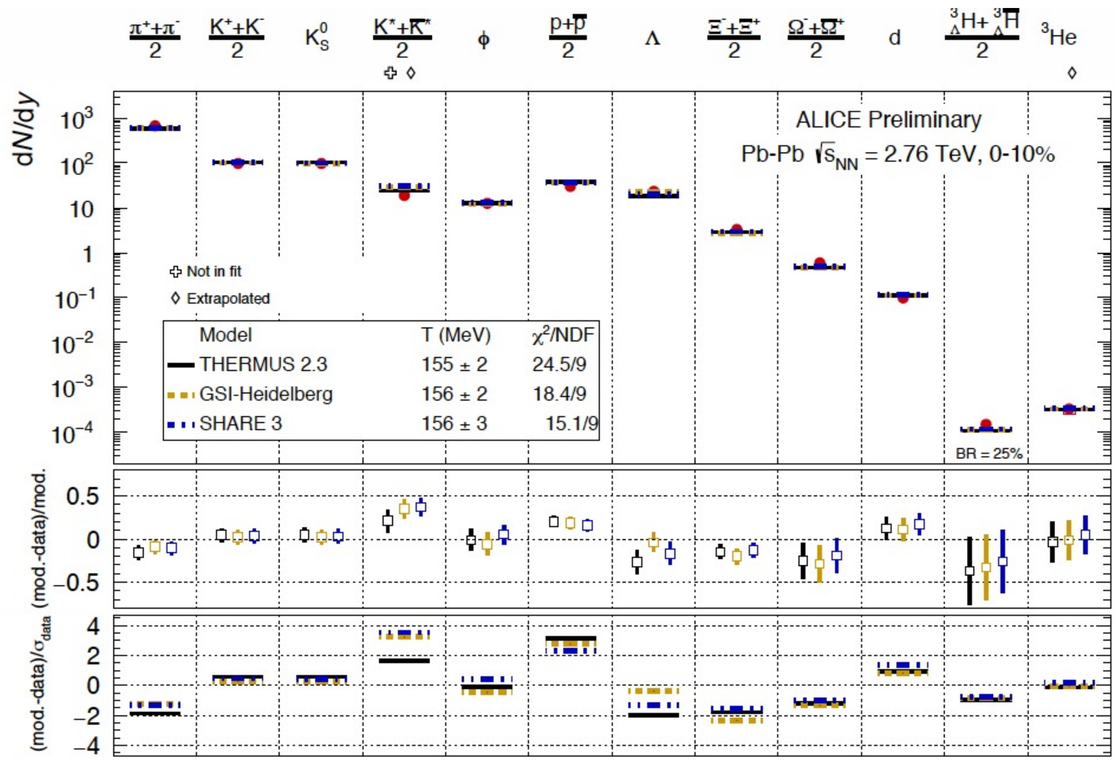
- Multiplicity described best with T = 1 900 000 000 000 °C (1,9 trillion degree centigrade)

→ 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)

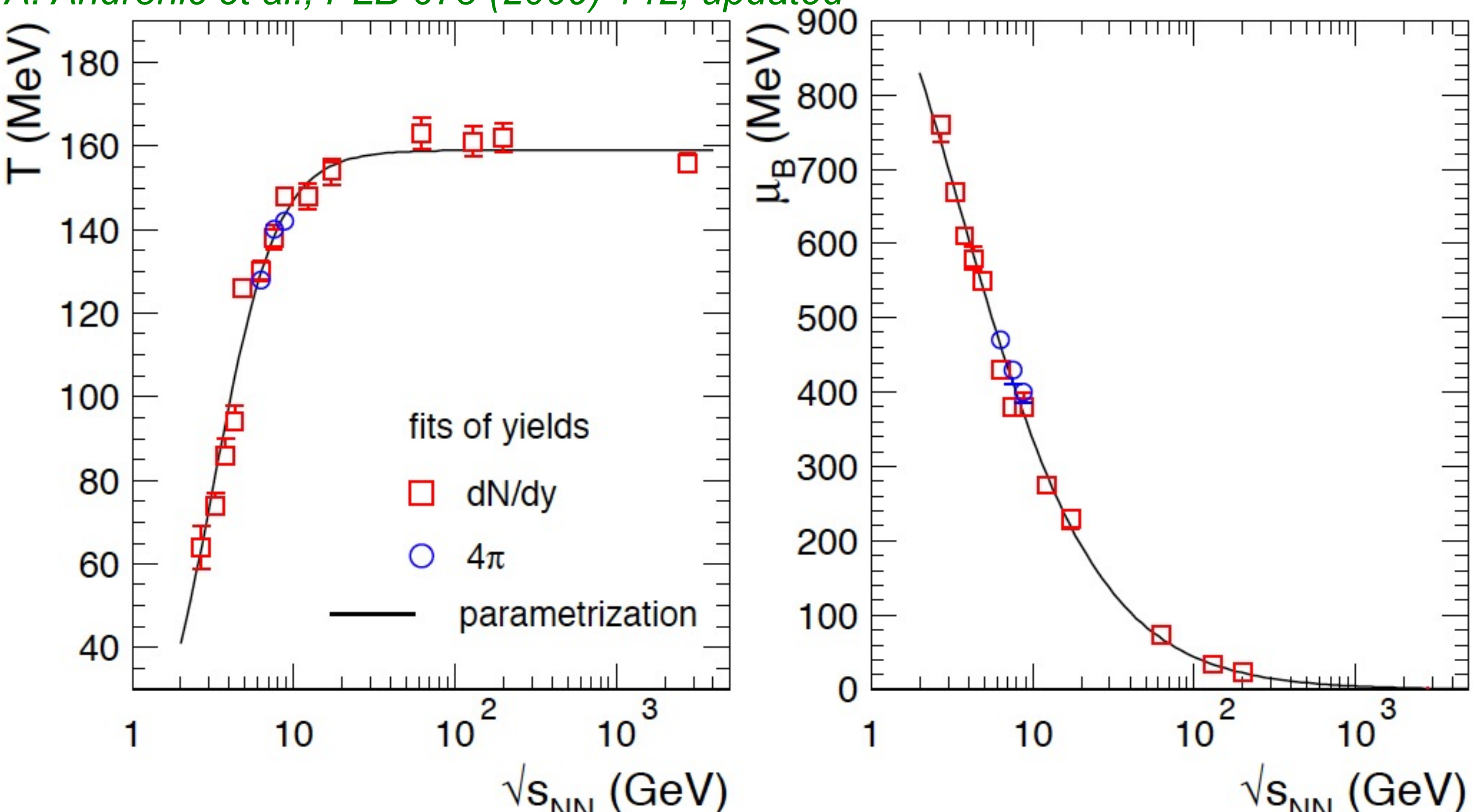


- chemical freeze-out temperature T_{ch}
- baryo-chemical potential μ_B
- Volume V

→ Using particle yields as input to extract parameters

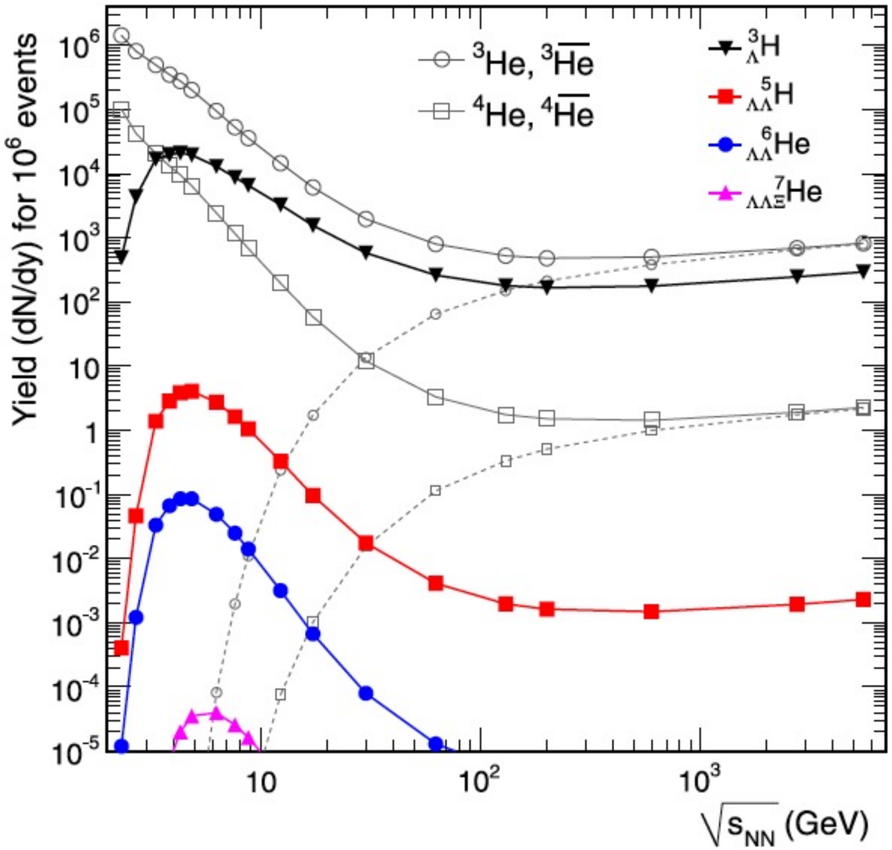
Energy dependence

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}

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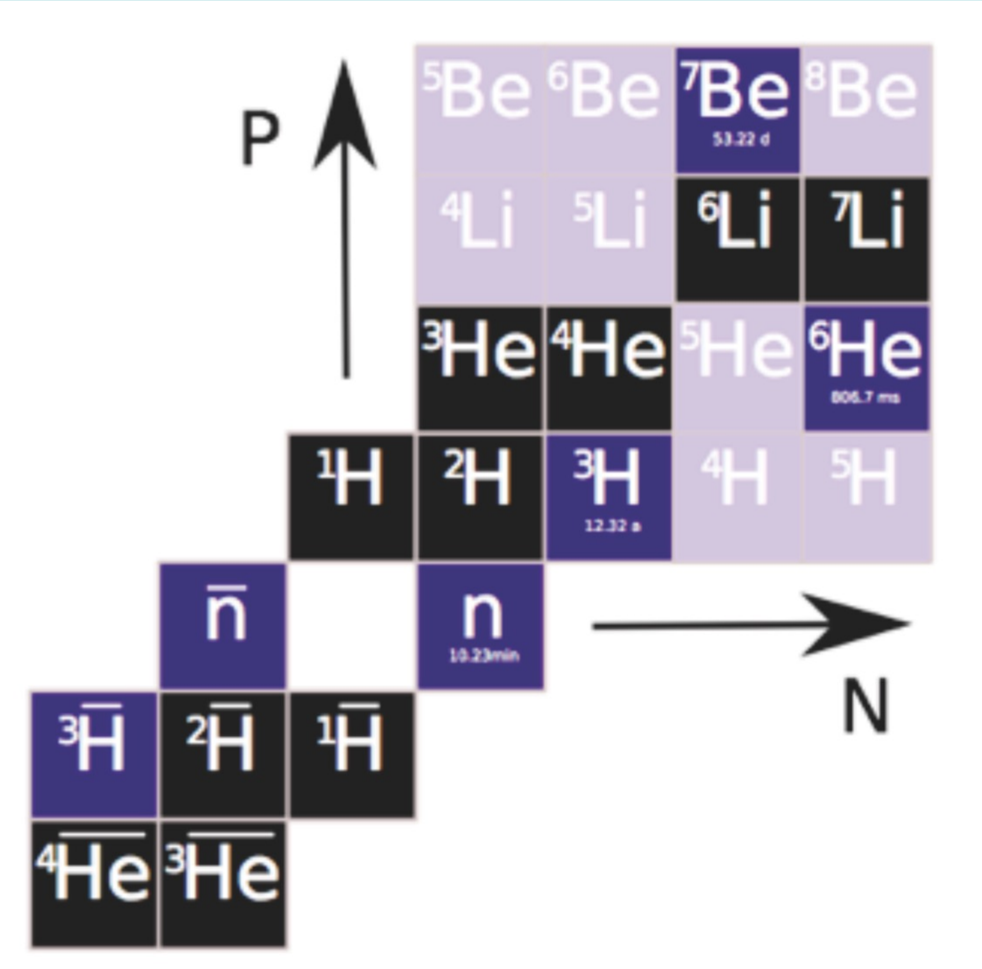
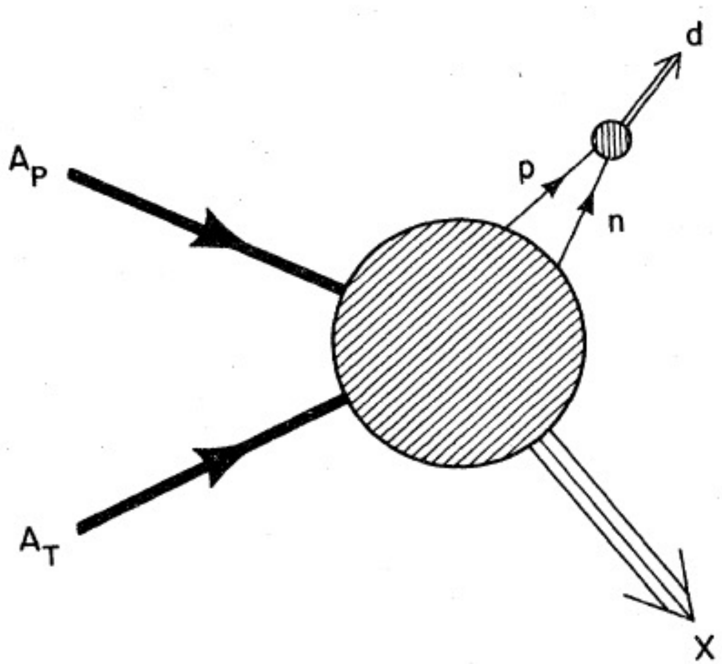
(Anti-)Nuclei



Coalescence



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

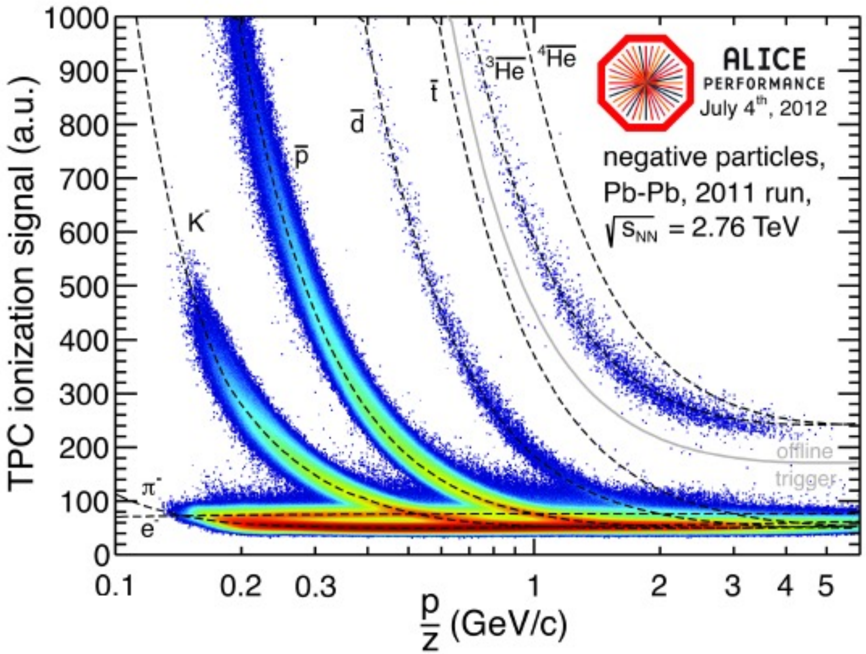
Nuclei are formed by protons and neutrons which are nearby and have similar velocities (after kinetic freeze-out)

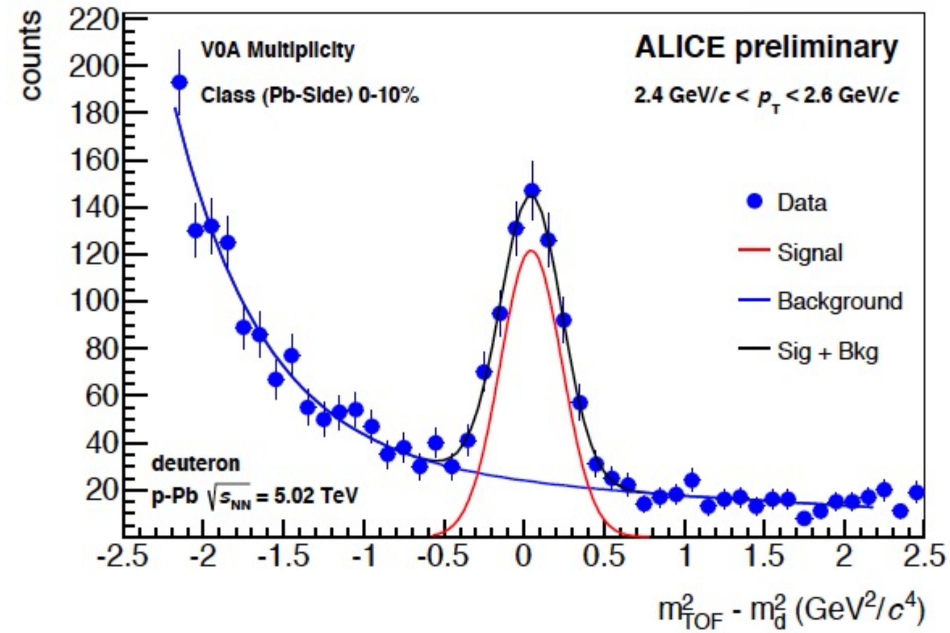
Produced nuclei

→ 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:

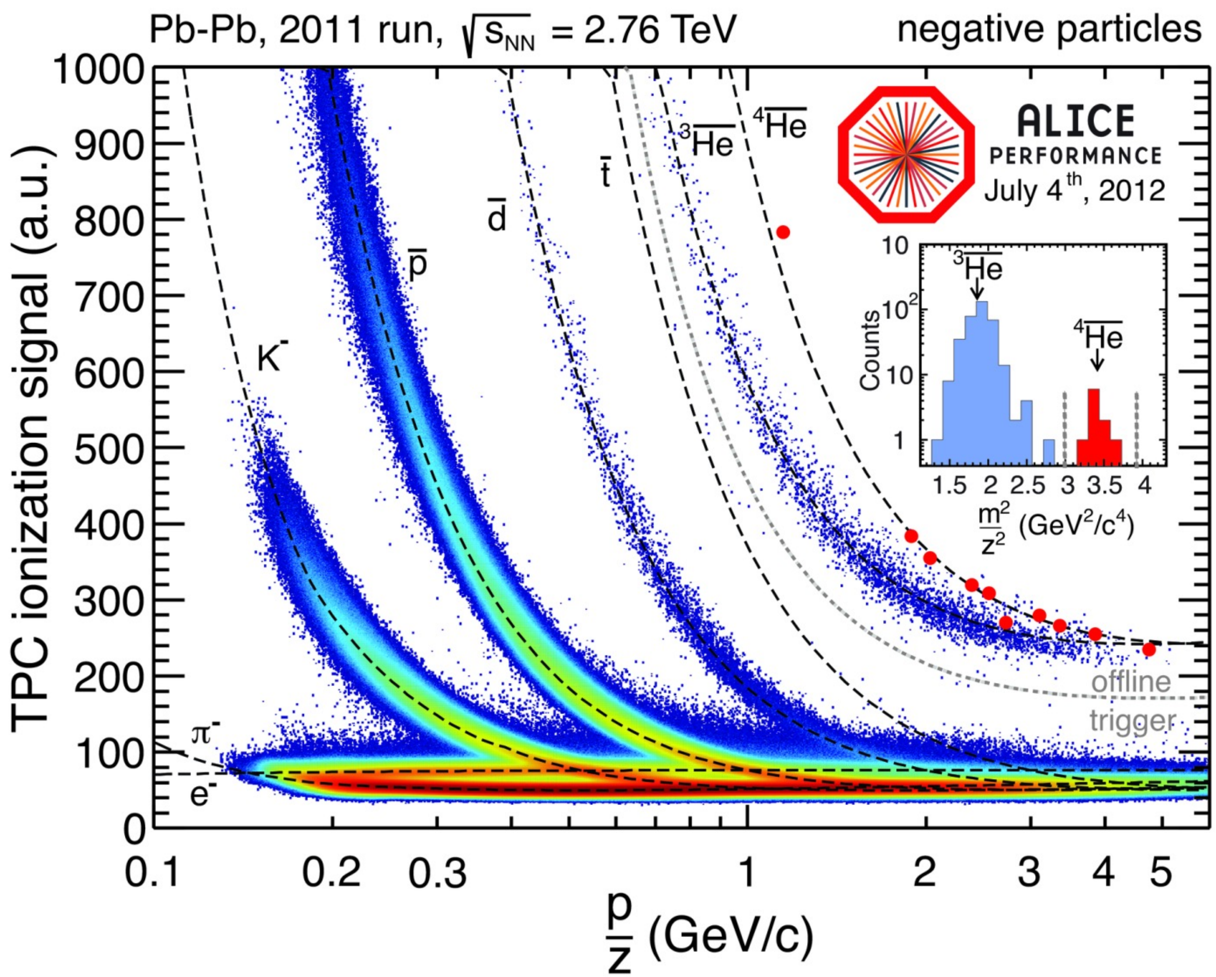
Velocity measurement with the Time-of-Flight (TOF) detector is used to calculate the m^2 distribution

Anti-Alpha

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

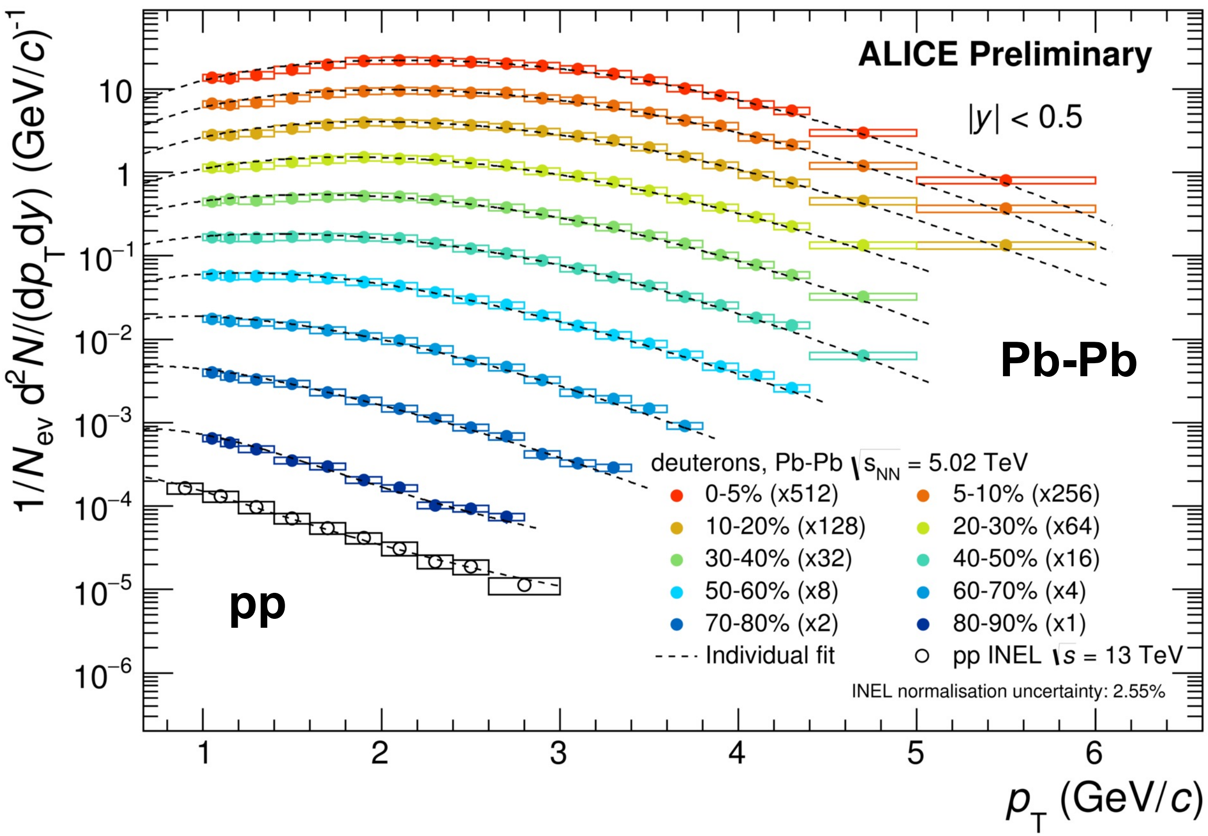
STAR observed the Anti-Alpha in 2010:

Nature 473, 353 (2011)



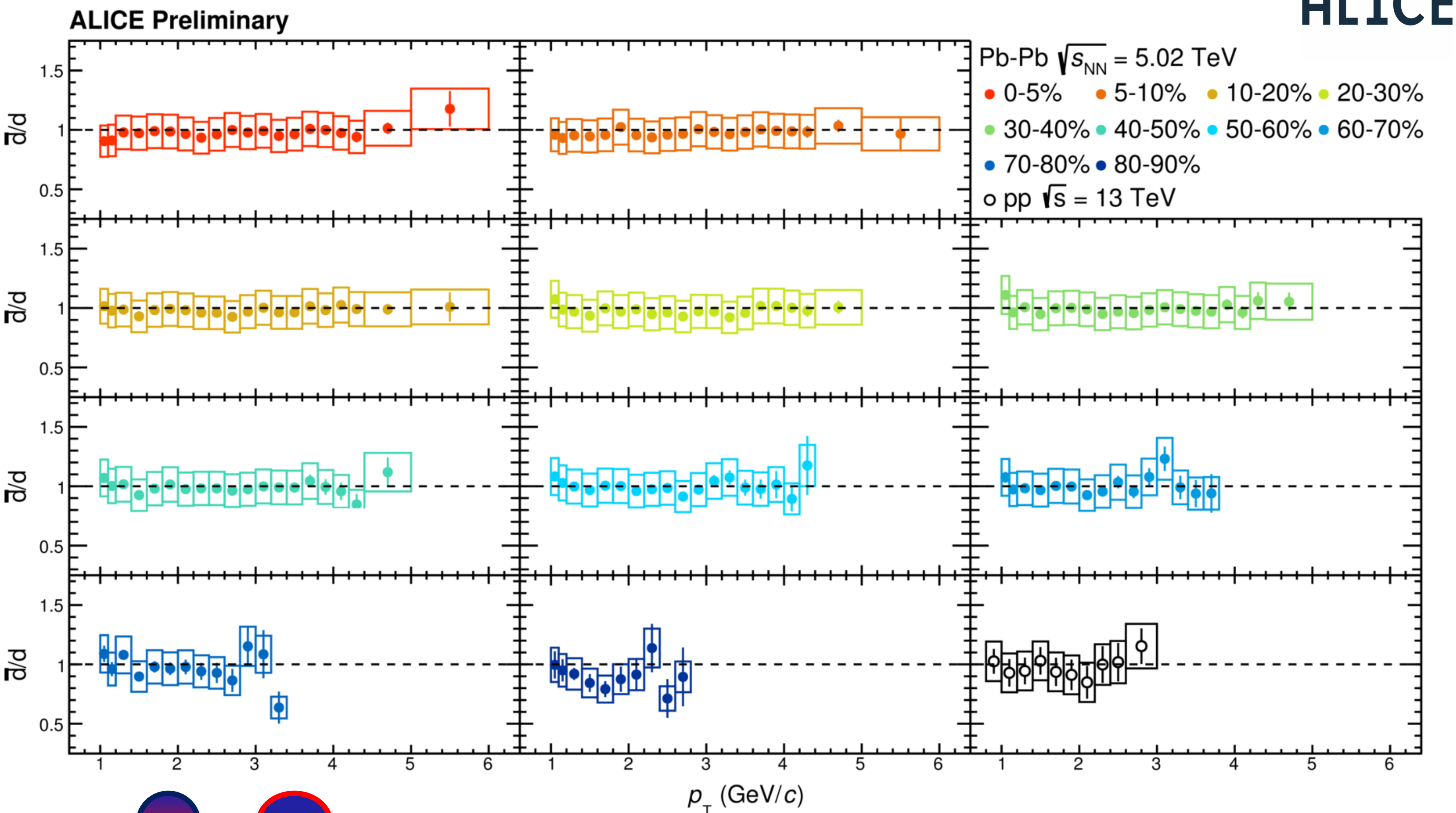
Deuterons

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

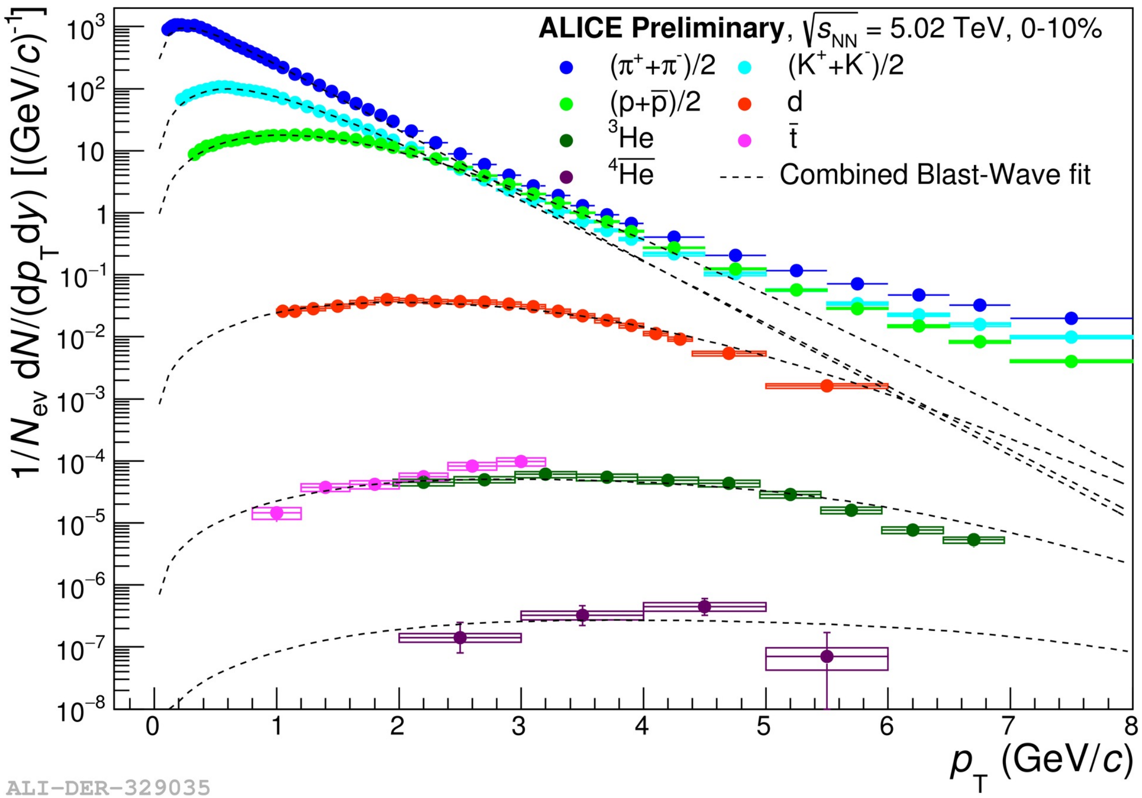
(Anti-)Deuteron ratio



-ratios consistent with unity, as expected

Combined Blast-Wave fit

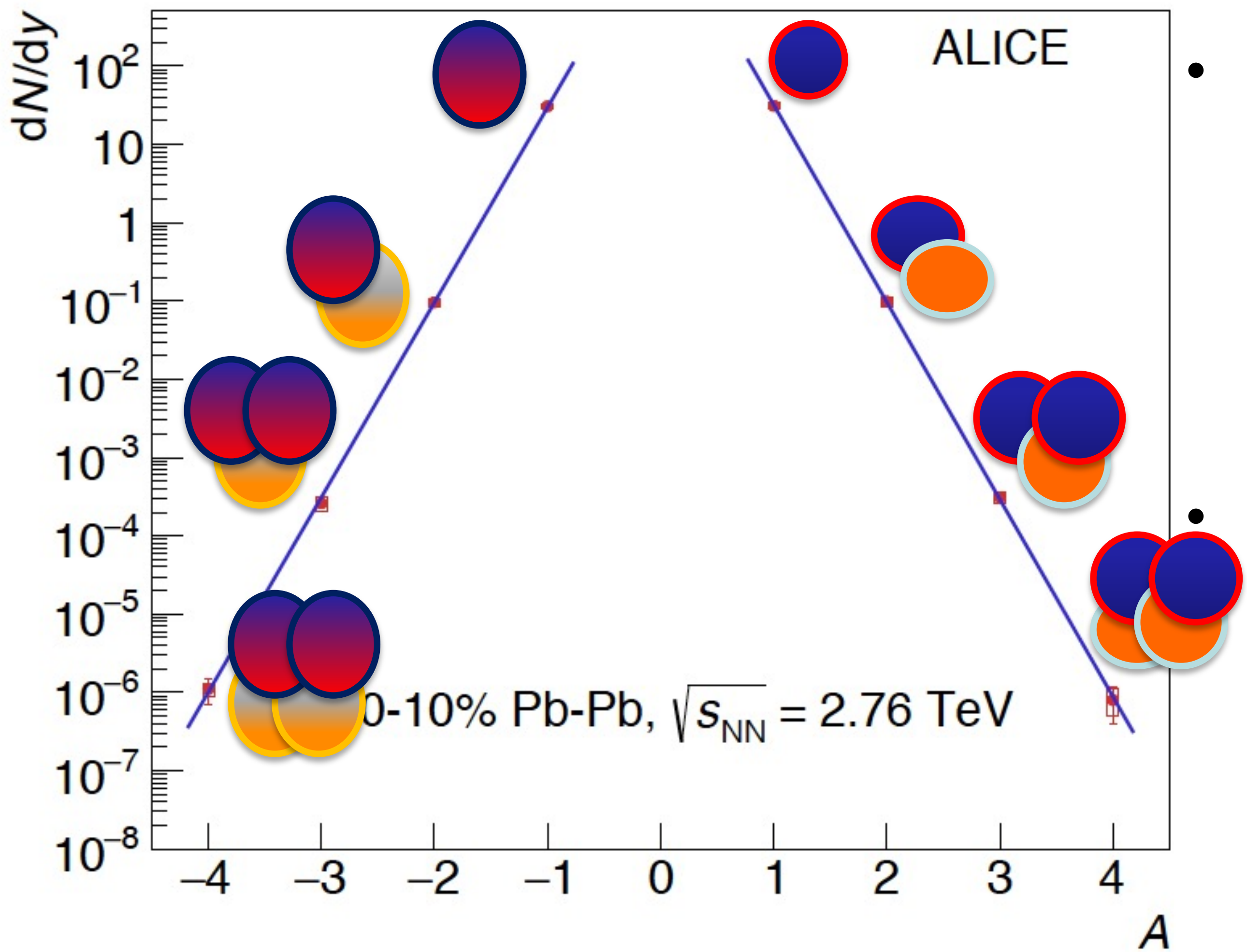
ALICE Collaboration, arXiv:1910.07678



- 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

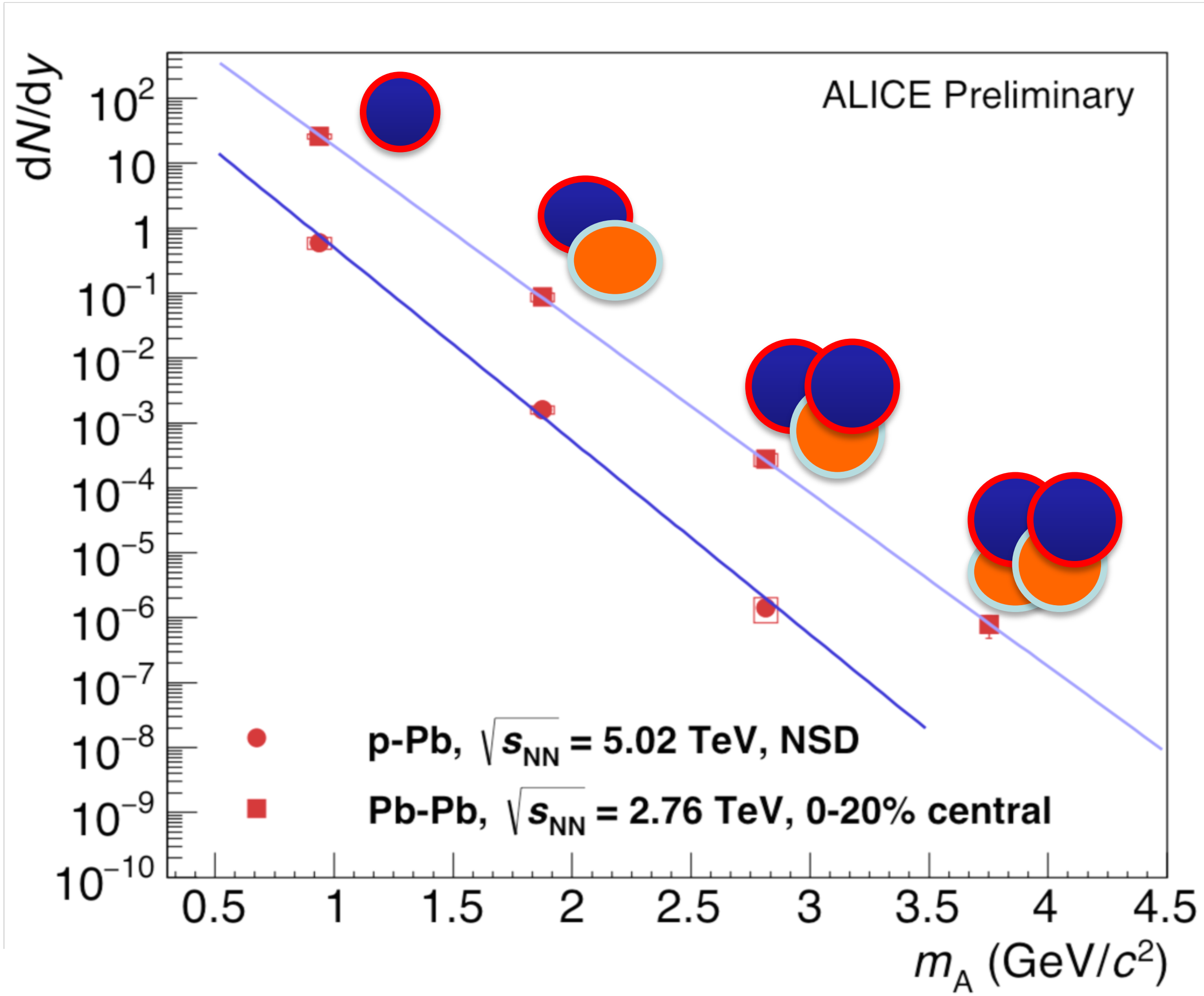
Mass dependence



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

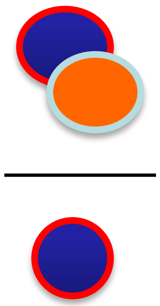
- Production of (anti-) nuclei is follwing an exponential, and decreases with mass as expected from thermal model
- In Pb-Pb the „penalty factor“ for each additional baryon ~300 (for particles and anti-particles)

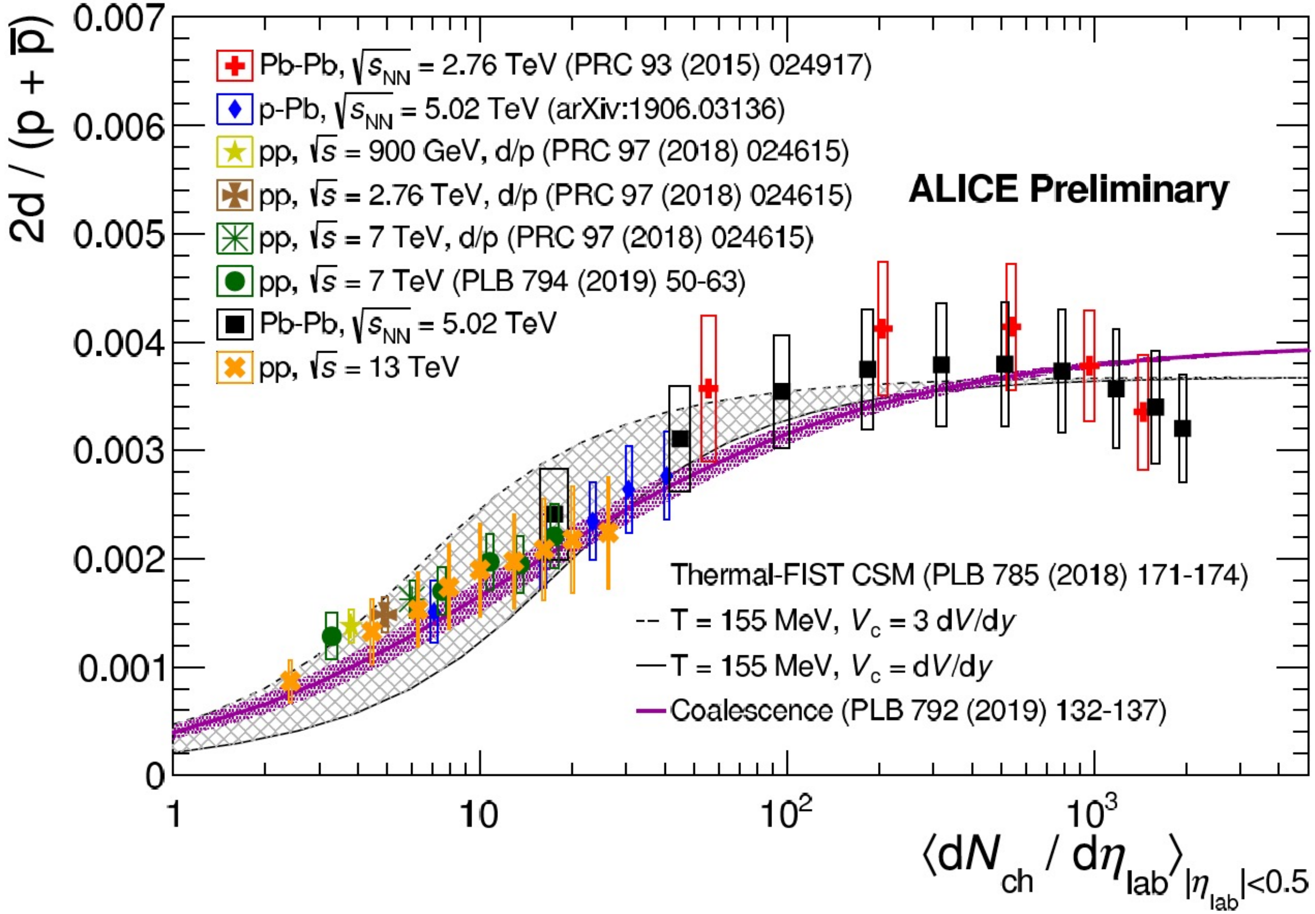
Mass dependence



- 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

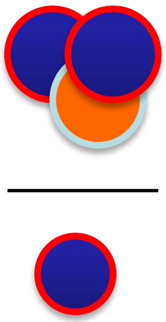
d/p vs. multiplicity

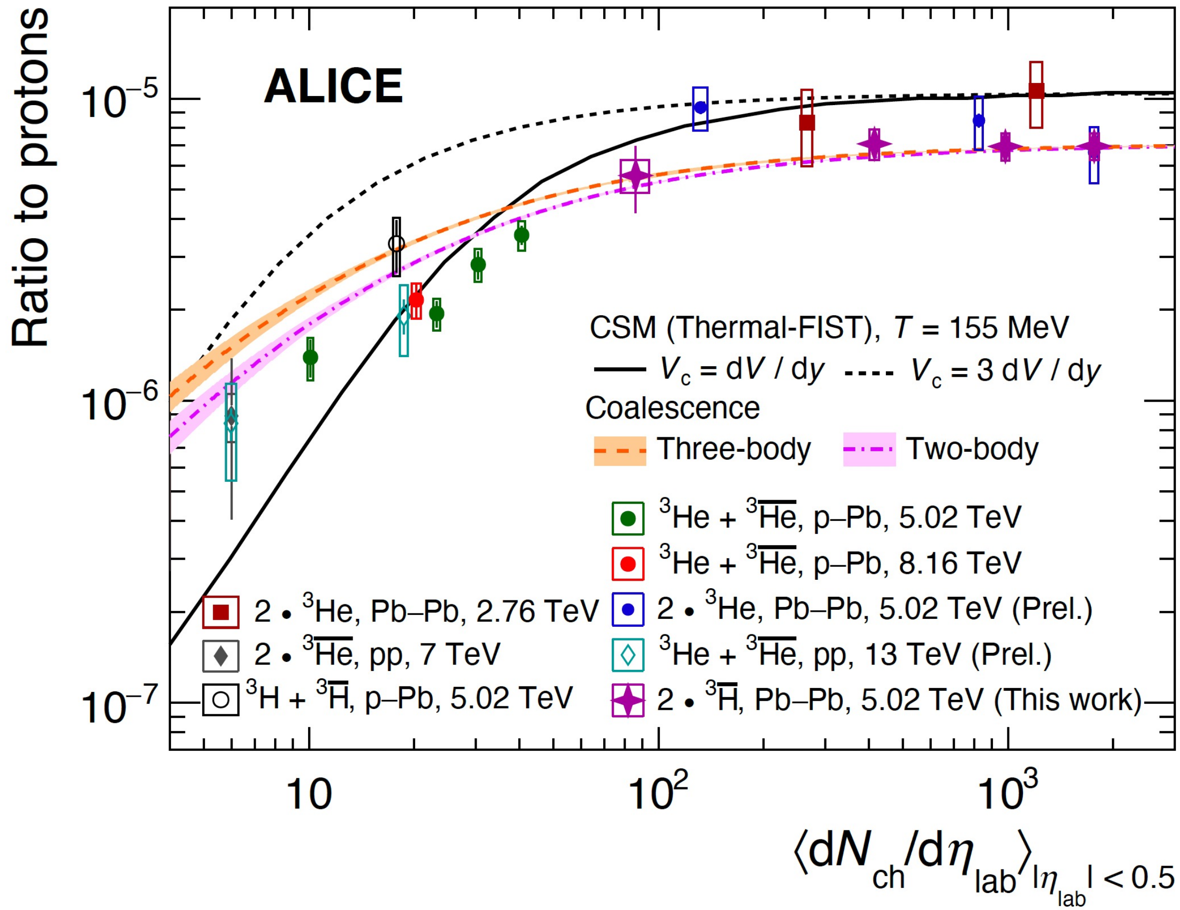




d/p ratio rather well described by coalescence and (canonical) thermal model

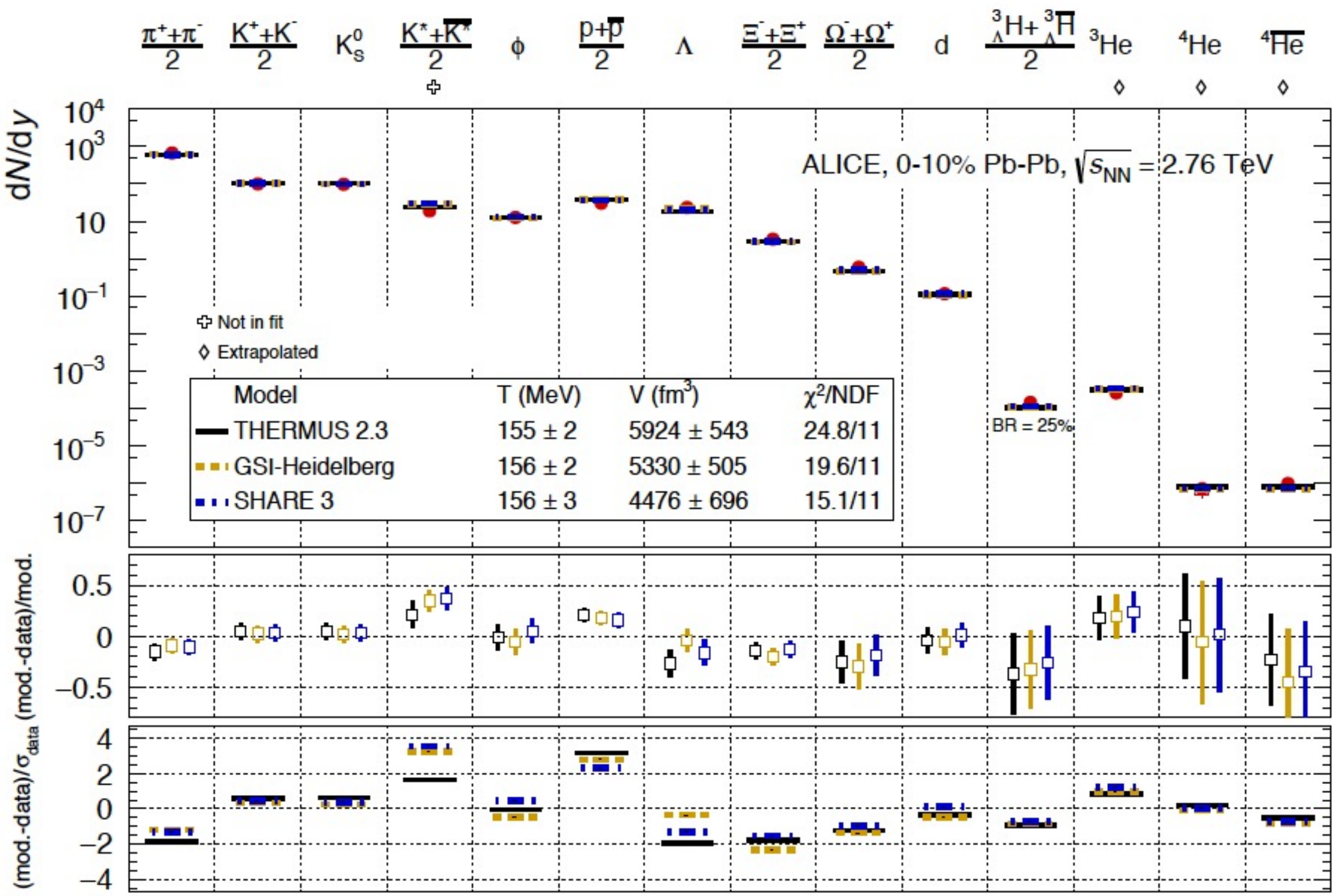
^{3}He/p vs. multiplicity





^{3}He/p and ^{3}H/p ratios are similarly 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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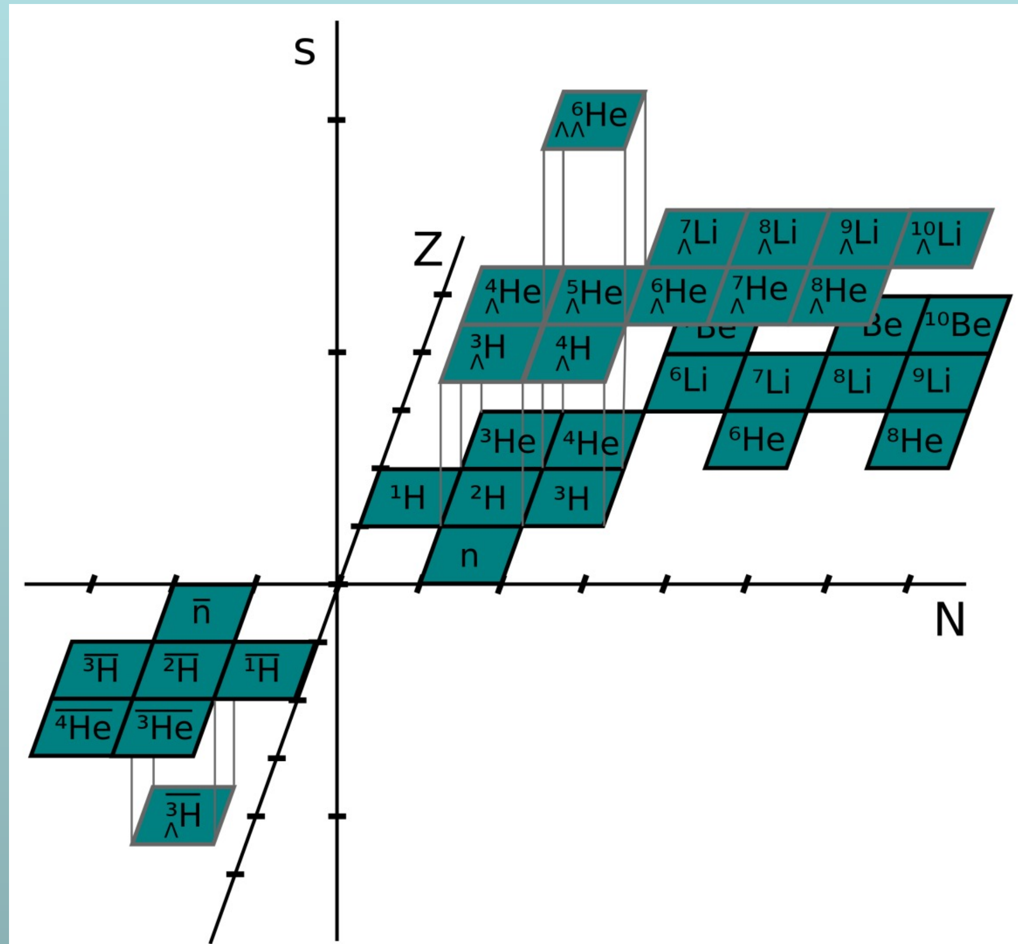
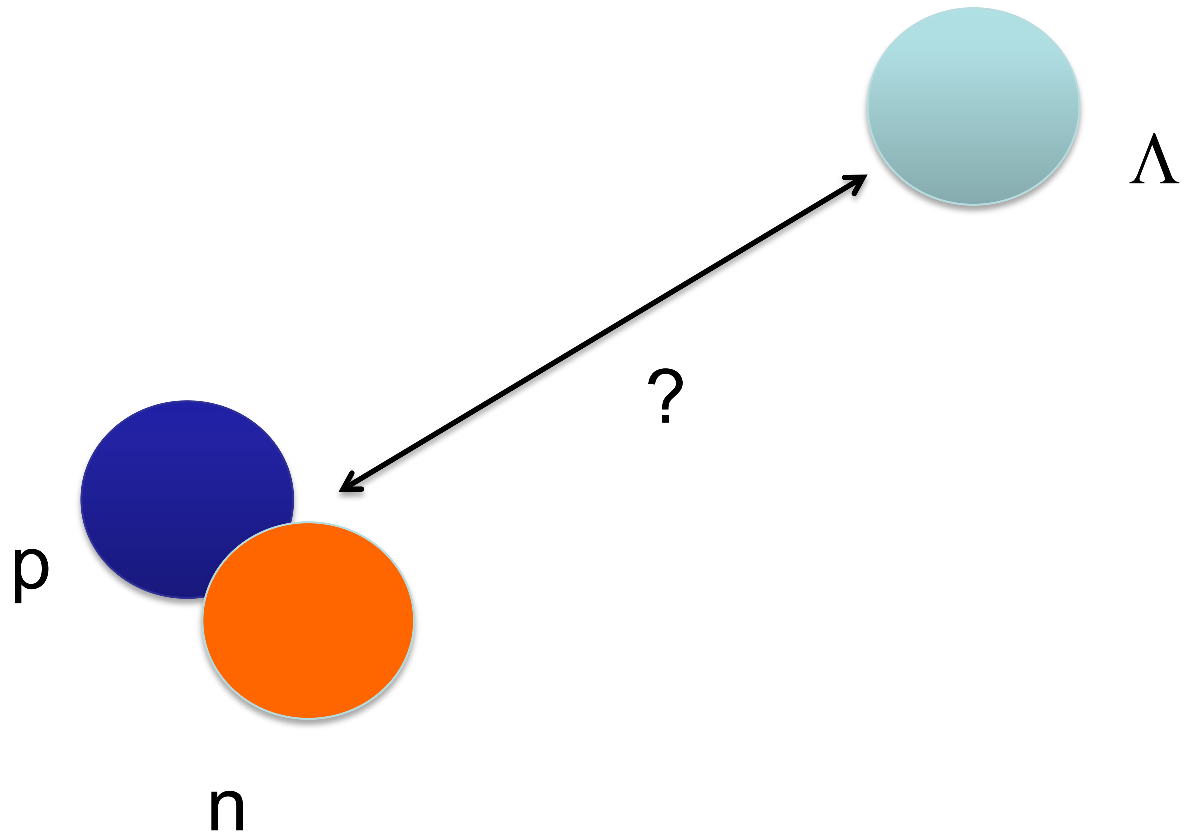
Hypernuclei



Hypertriton

Bound state of Λ, p, n

m = 2.991 GeV/c^2 (B_Λ =130 keV)



Hypertriton

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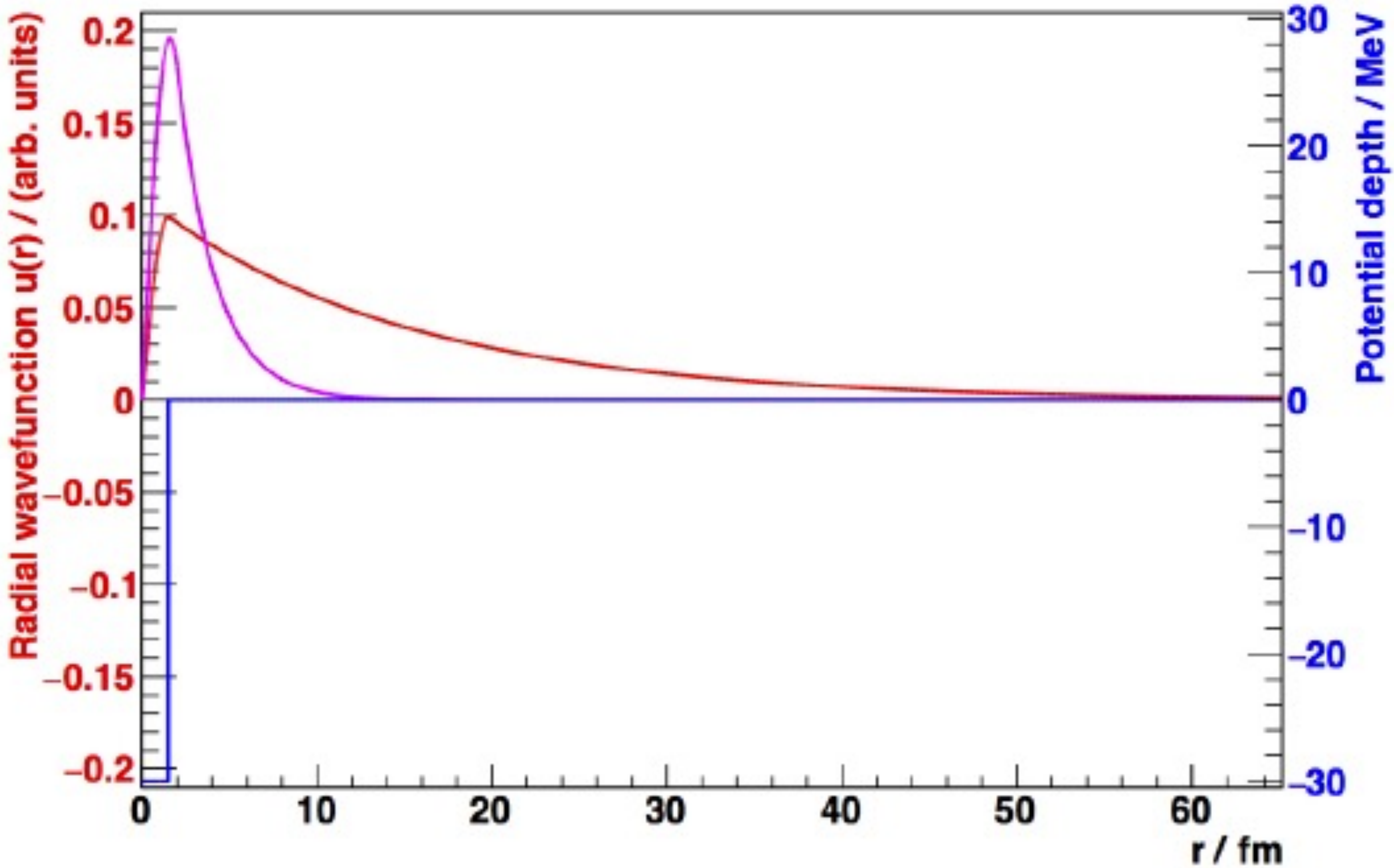

P. Braun-Munzinger, BD, Nucl. Phys. A 987 (2019) 144

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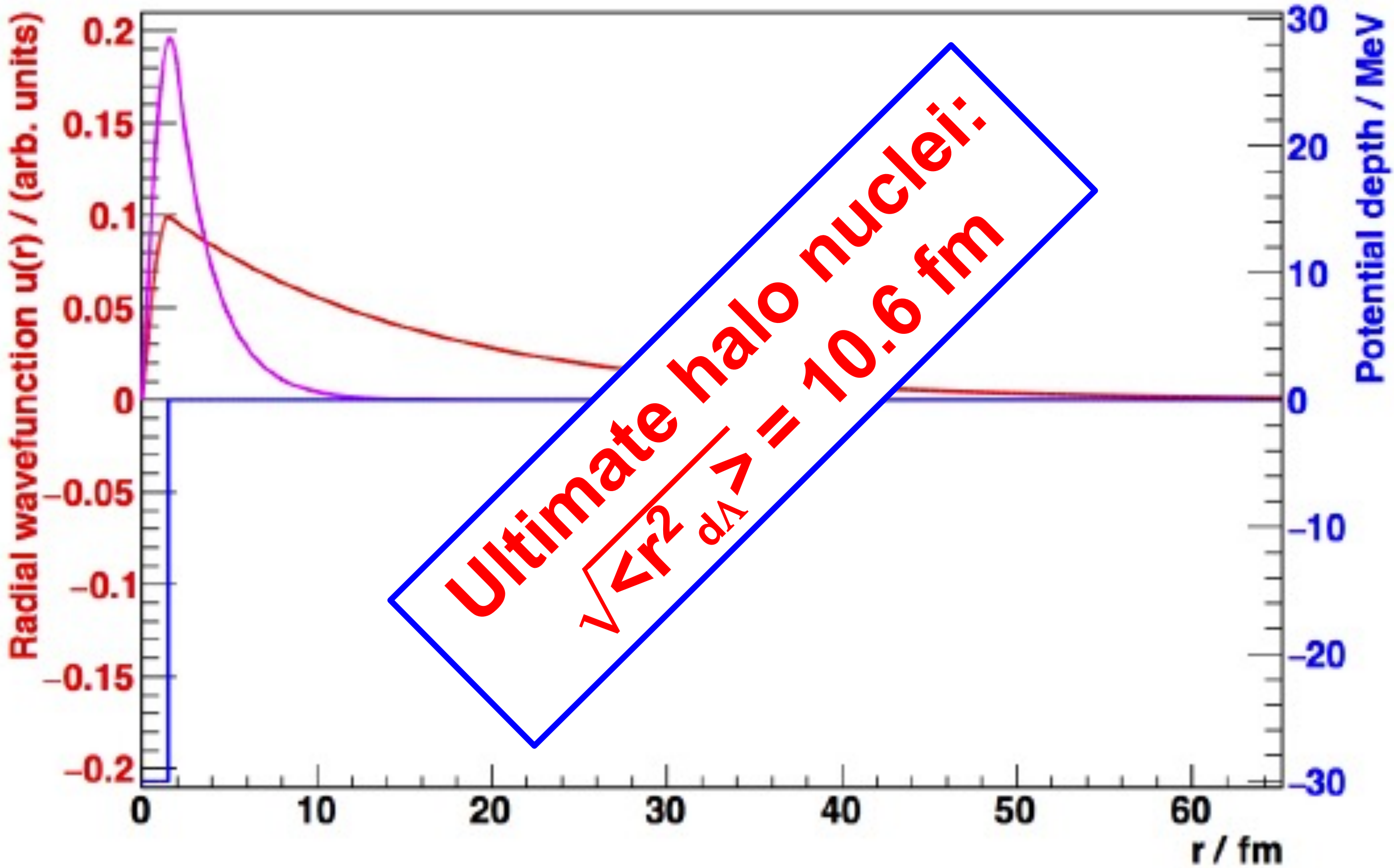
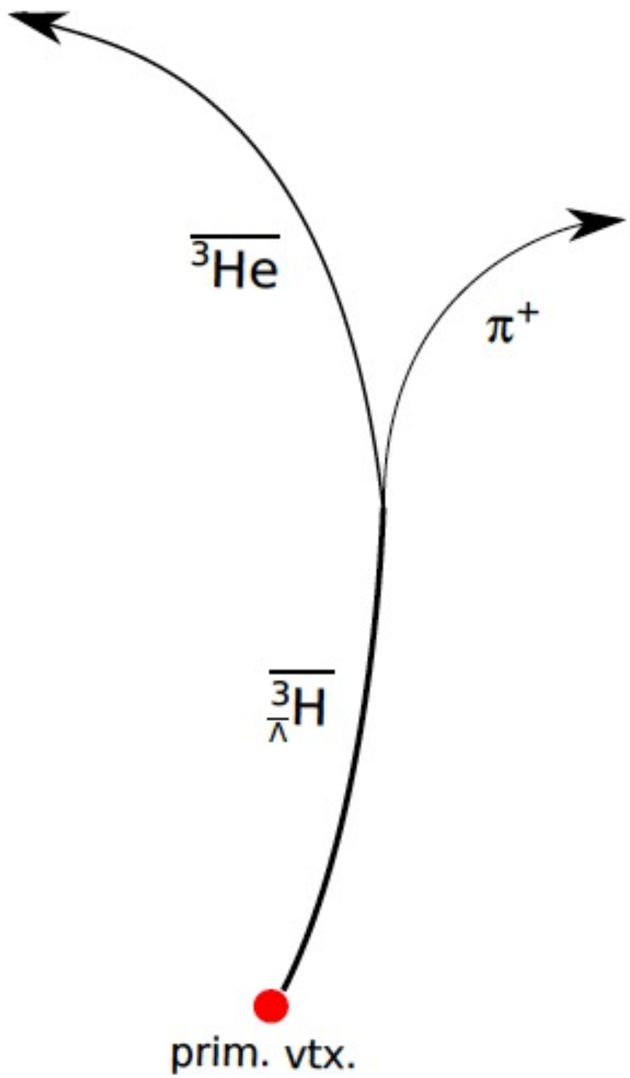


P. Braun-Munzinger, BD, Nucl. Phys. A 987 (2019) 144

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:

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

$$^3_\Lambda H \rightarrow ^3H + \pi^0$$

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

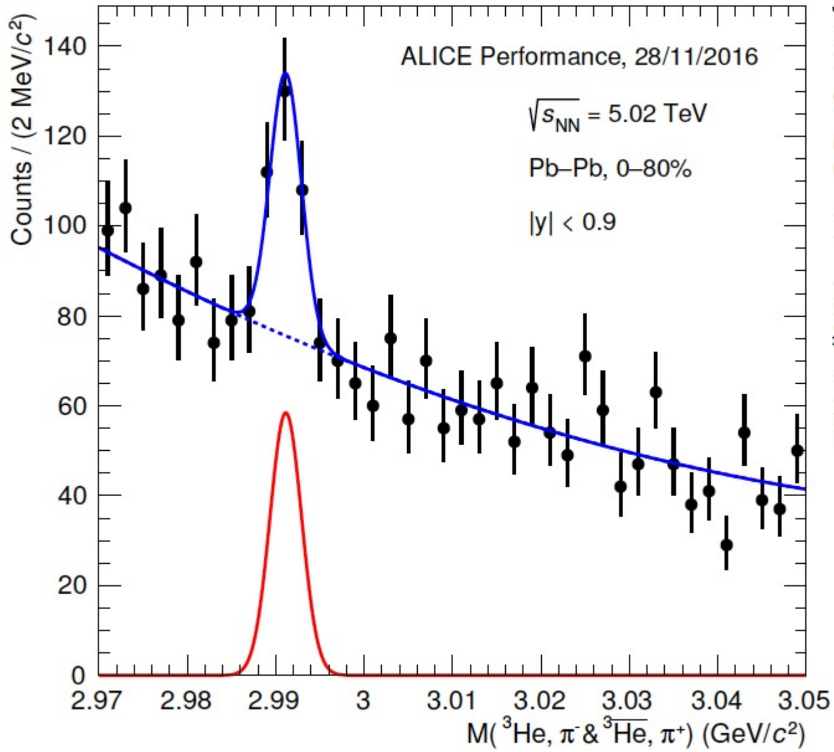
$$^3_\Lambda H \rightarrow d + n + \pi^0$$

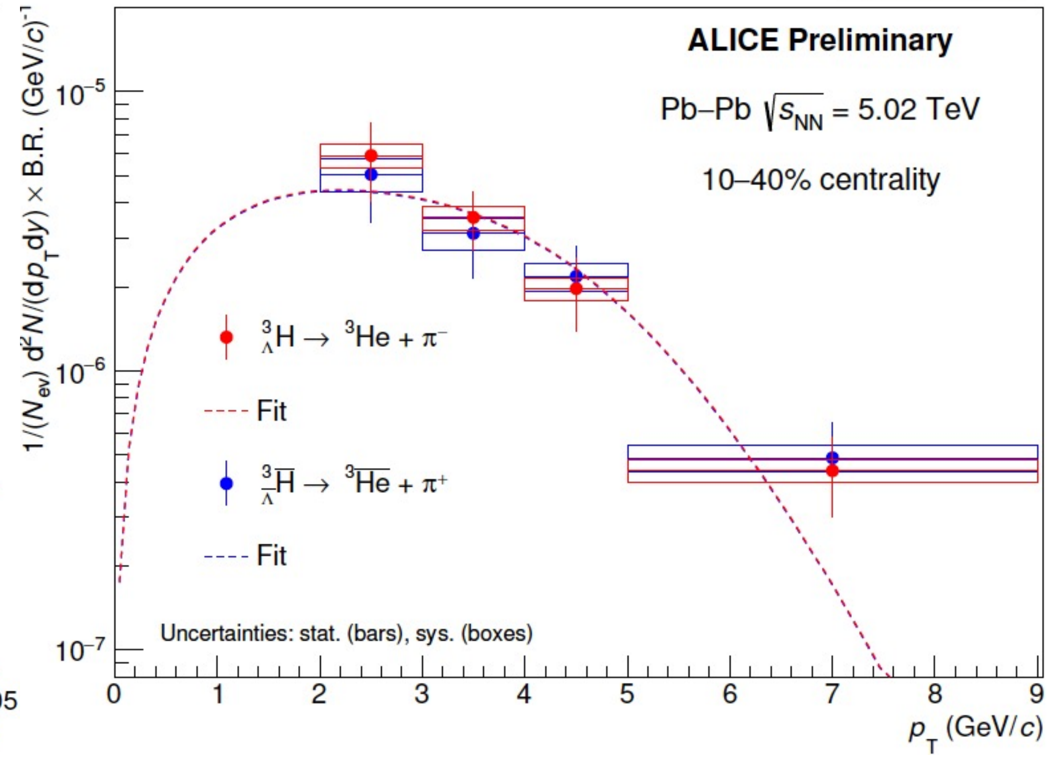
+ anti-particles

→ Anti-Hypertriton first observed by STAR Collaboration:

Science 328,58 (2010)

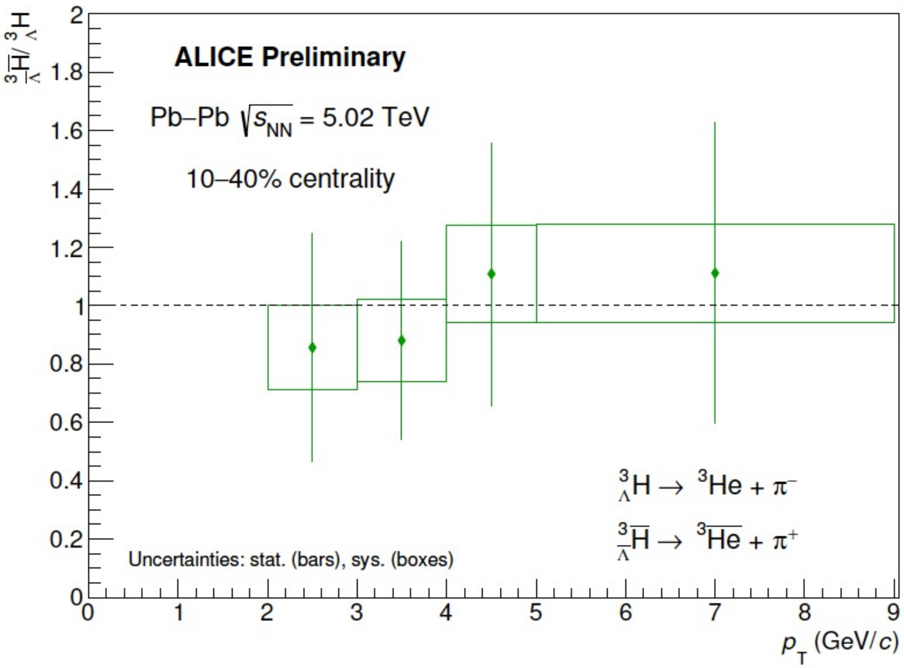
Hypertriton signal

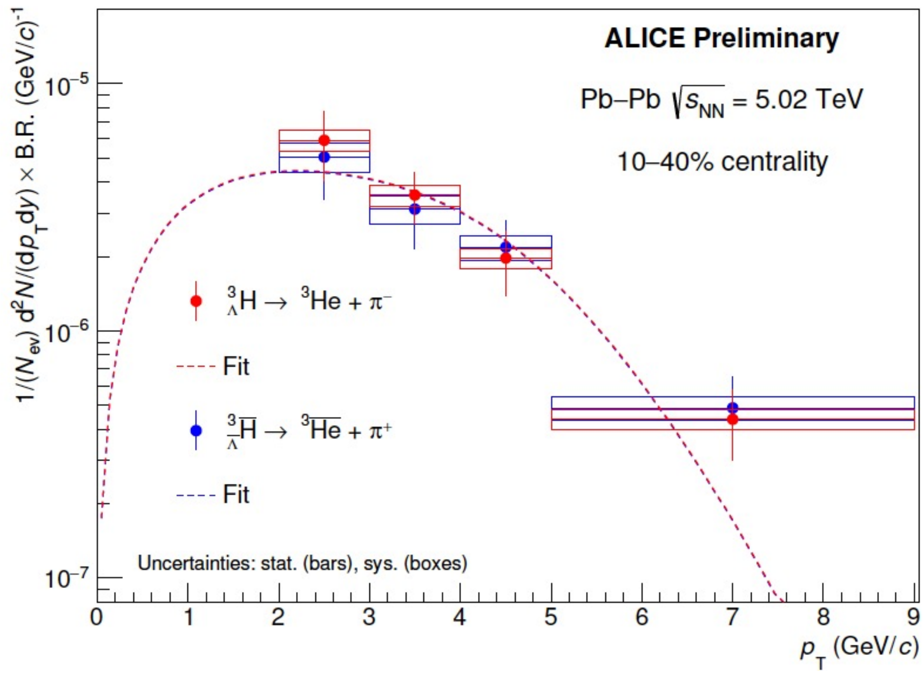




- Clear signal reconstructed by decay products
- Spectra can also be described by Blast-Wave model
  → Hypertriton flows as all other particles

Hypertriton spectra

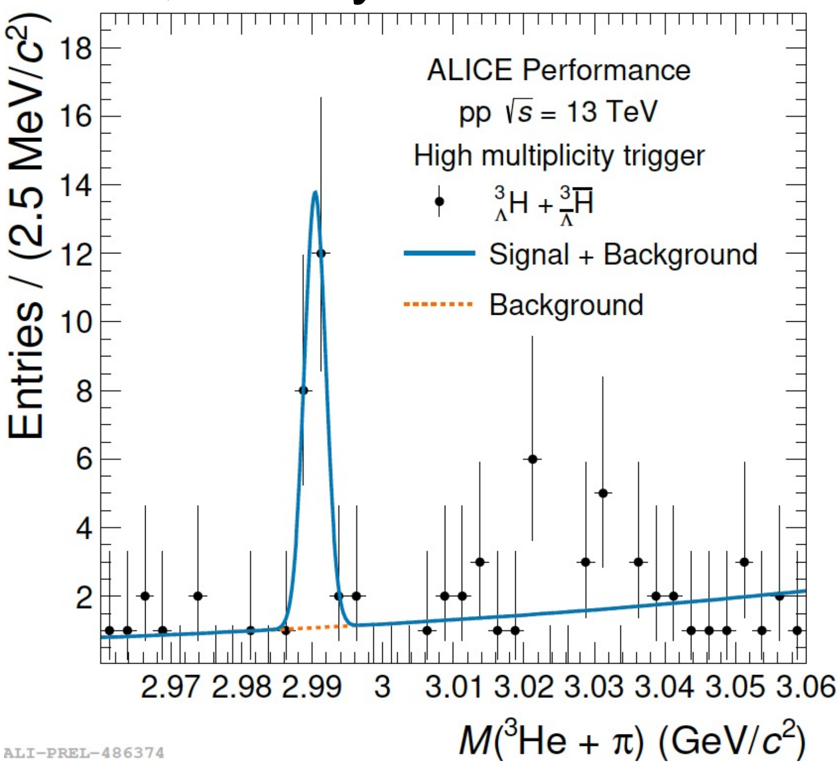


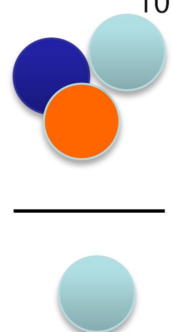


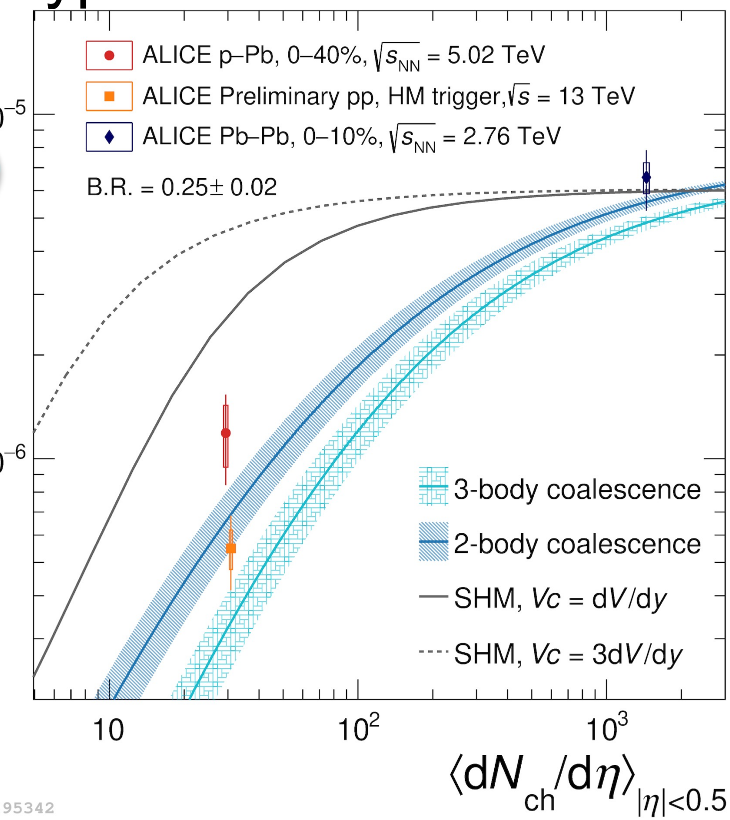
- Anti-hypertriton/Hypertriton ratio consistent with unity vs. p_T

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







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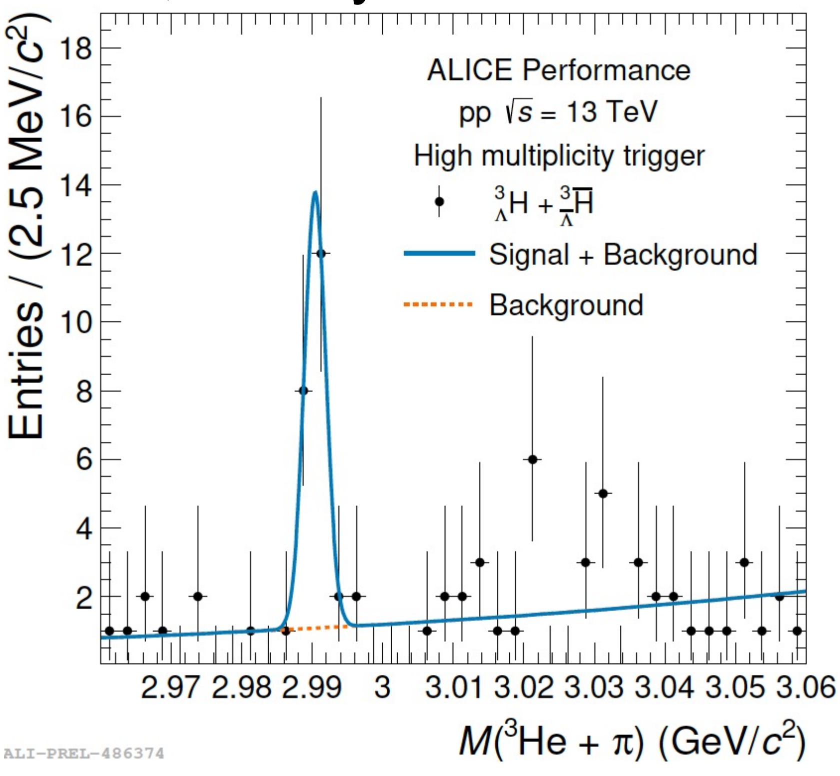
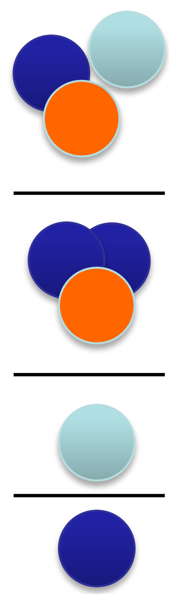
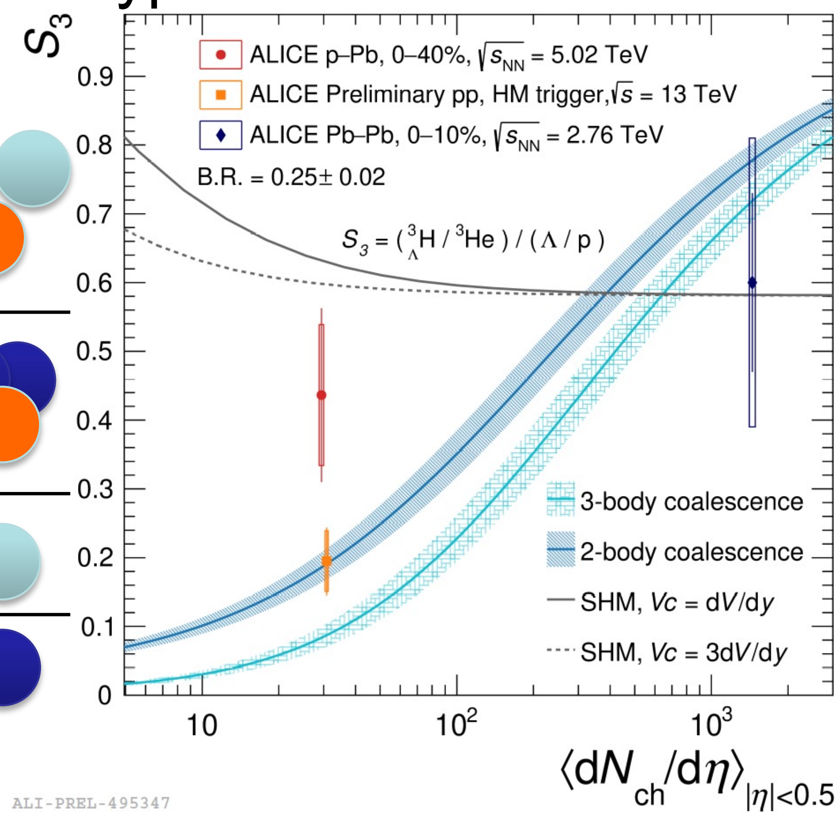
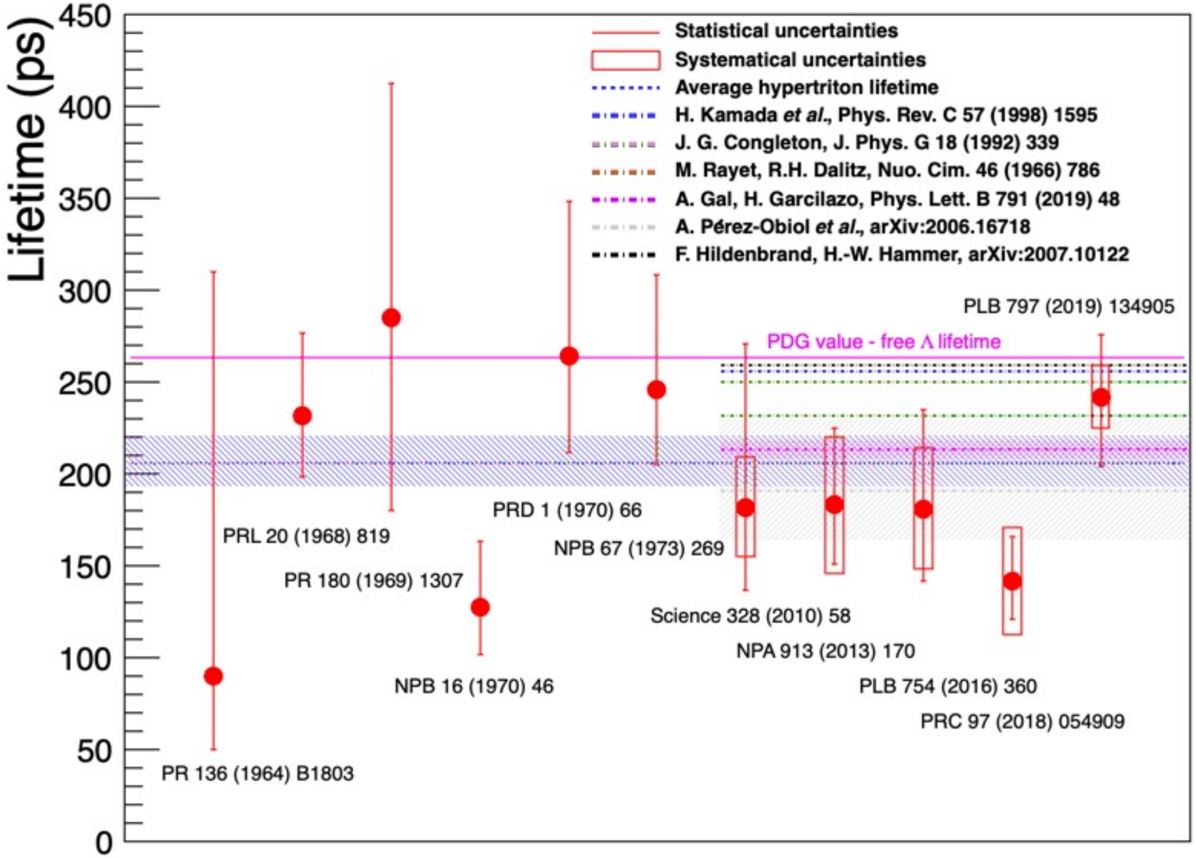






Hypertriton „Puzzle“

- 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



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Hypertriton „Puzzle“

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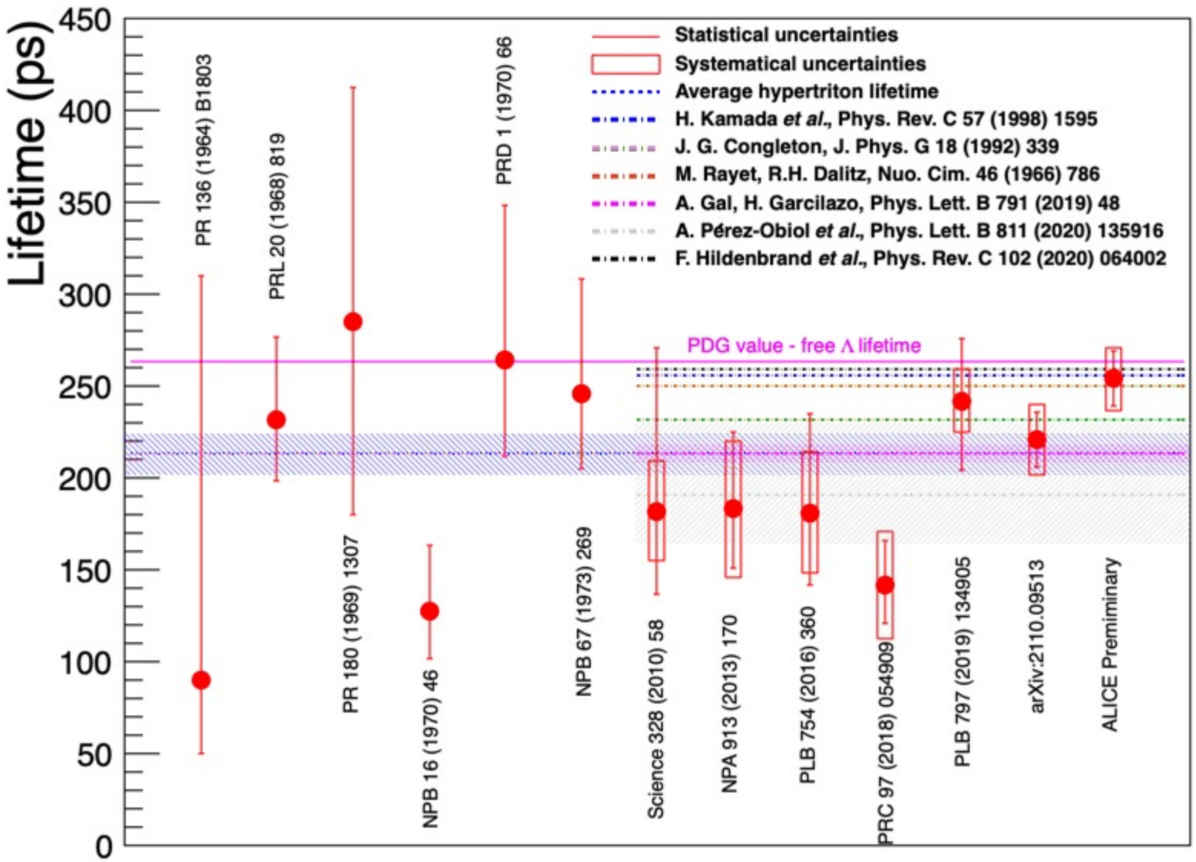
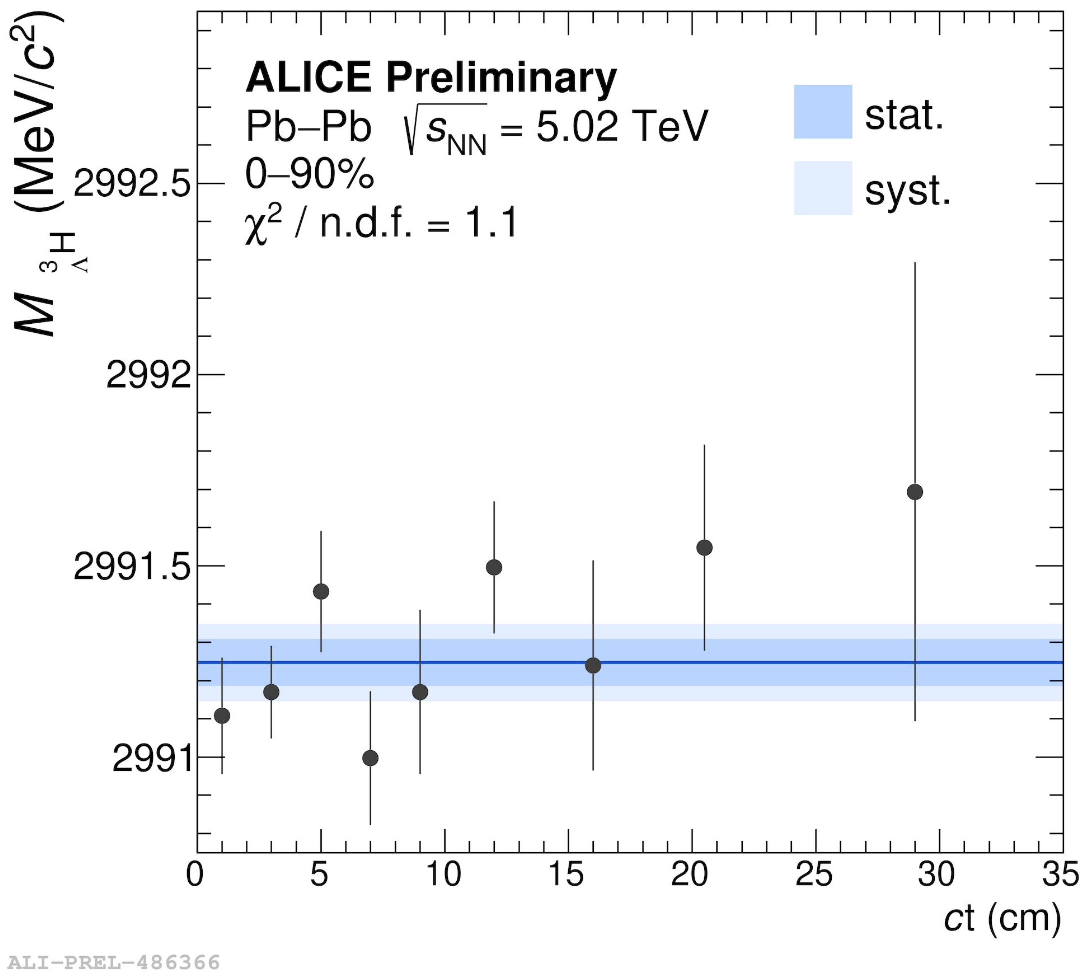


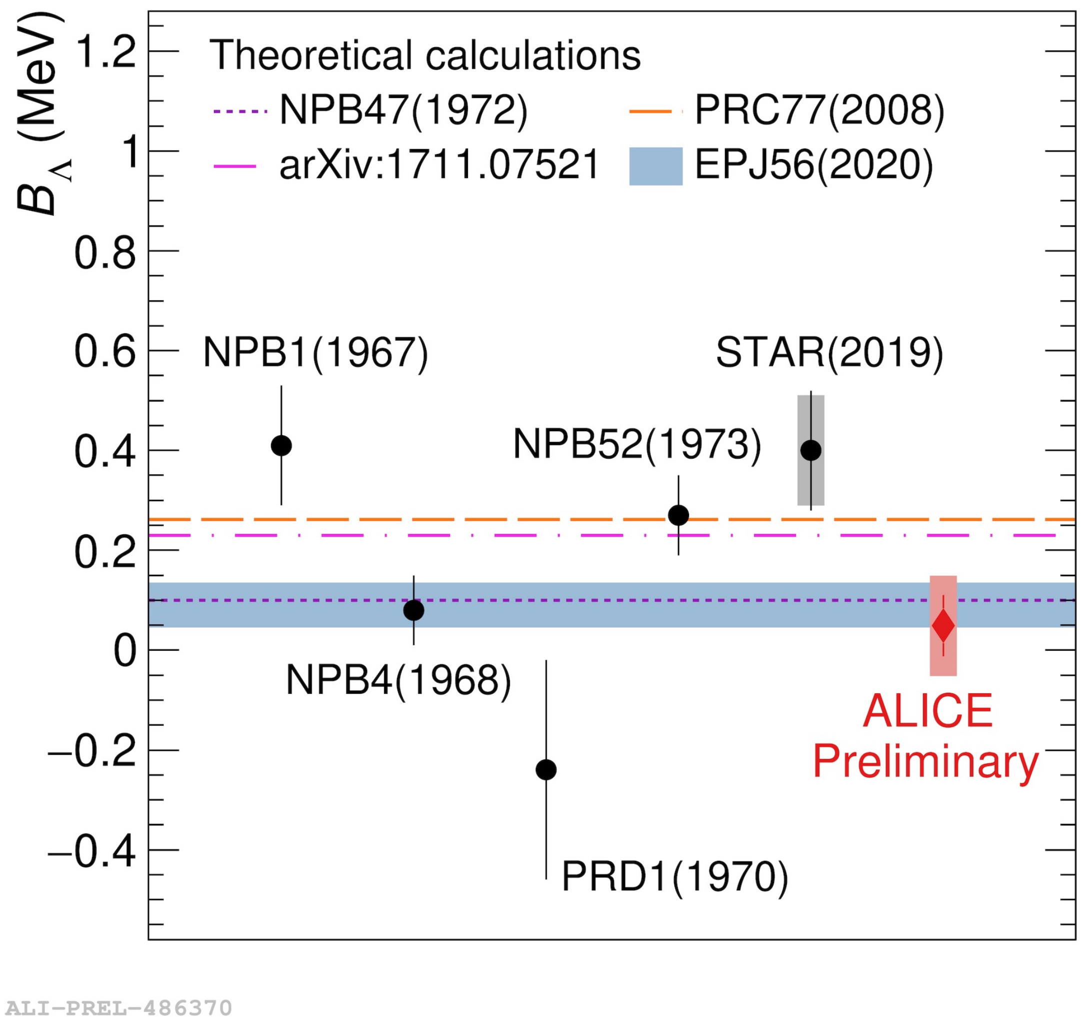
Binding Energy

- Preliminary Result for SQM2019
- 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

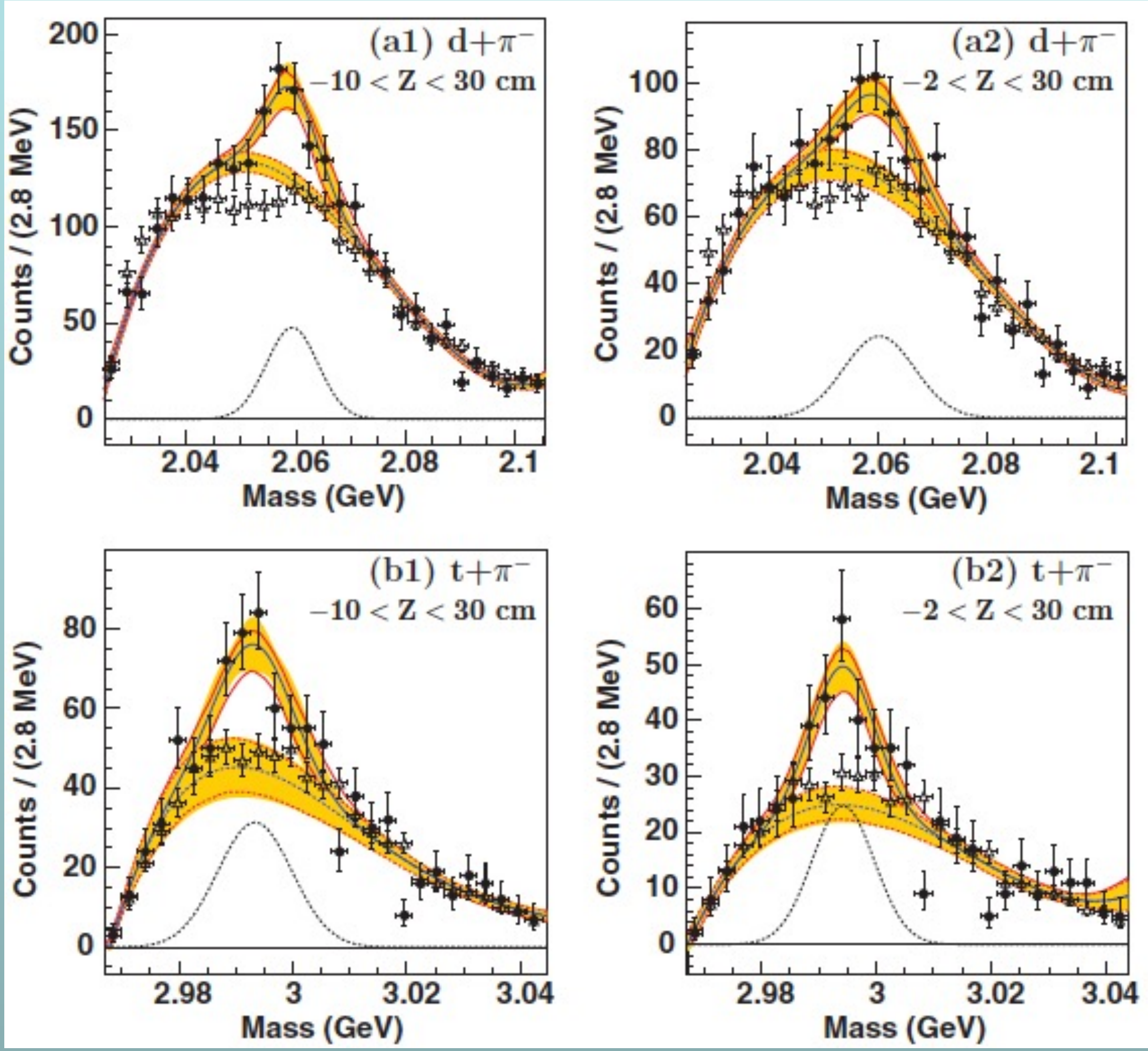


Binding Energy

- Preliminary Result for SQM2019
- 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
- Is compatible within the theoretical predictions



Exotica Searches



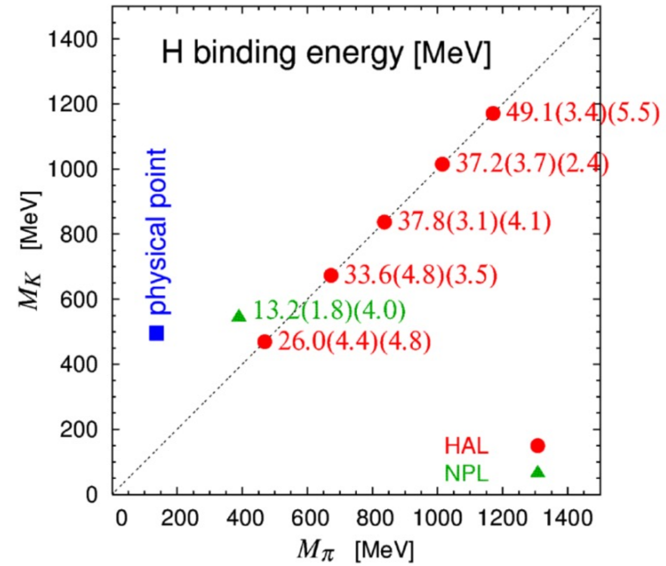
HypHI Collaboration observed signals in the t+π and d+π invariant mass distributions

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

H-Dibaryon

- Hypothetical bound state of *uuddss* (ΛΛ)
- 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

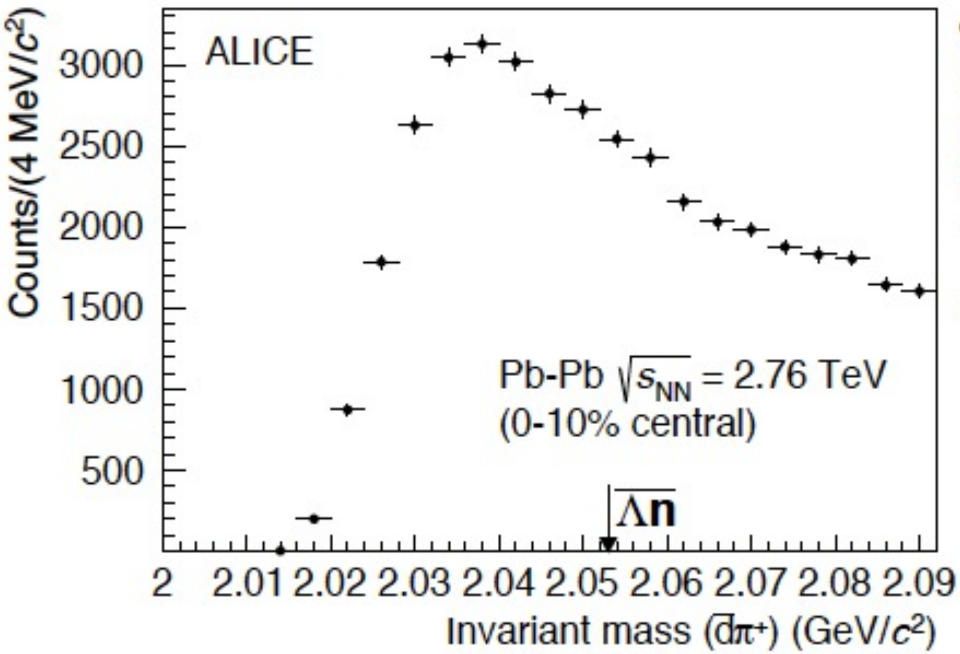
→ Renewed interest in experimental searches

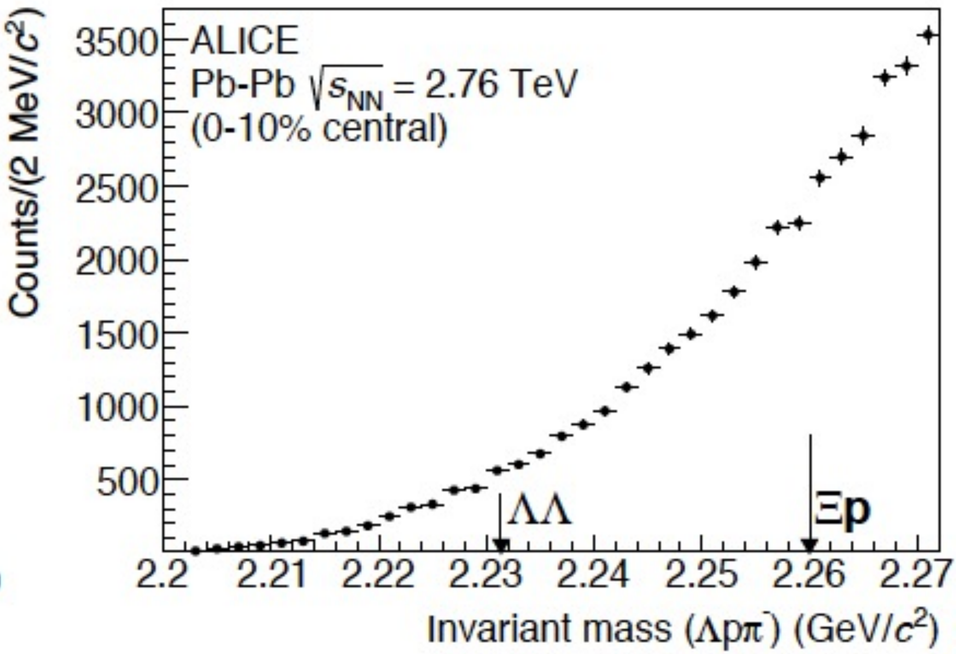


T. Inoue, private communication

Searches for bound states

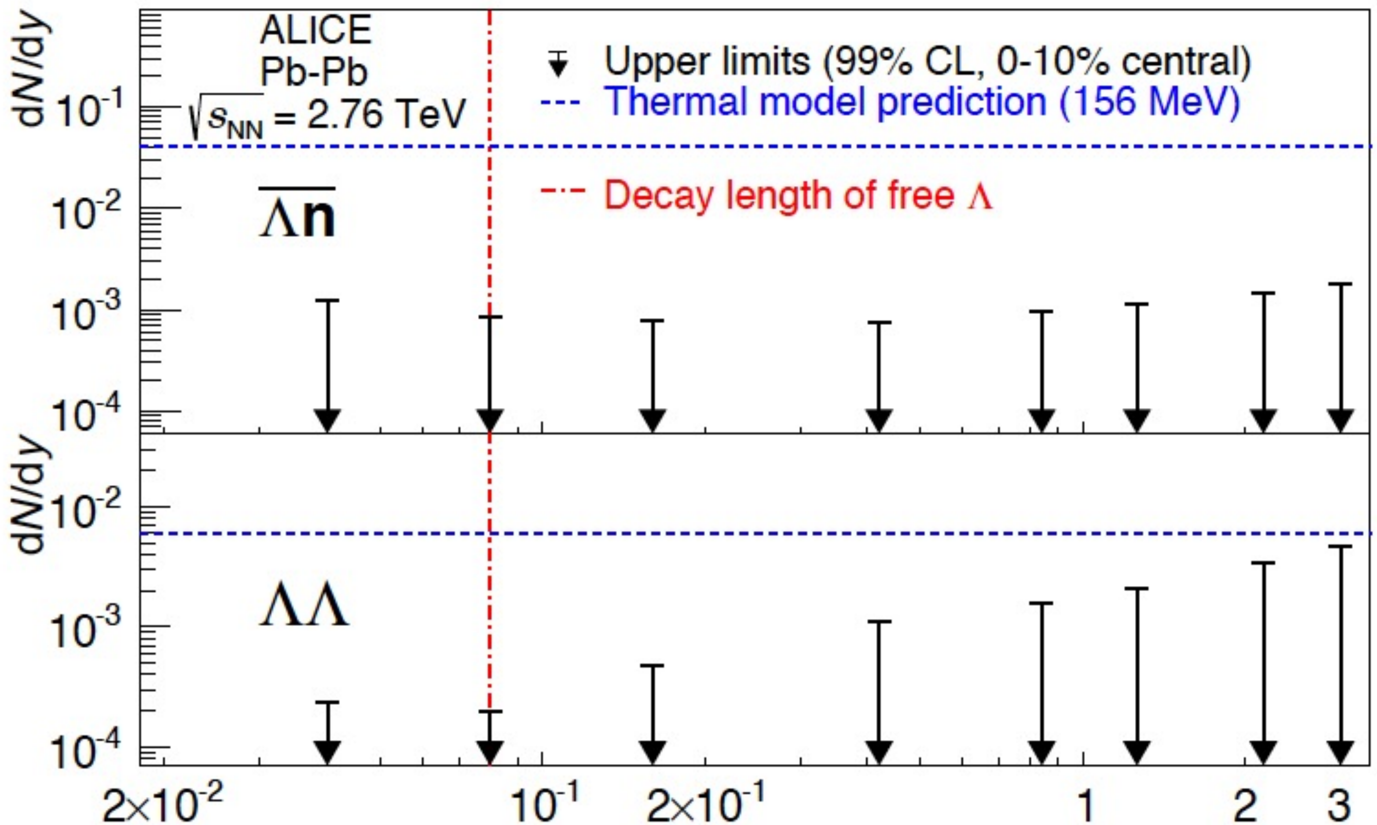
ALICE Collaboration: PLB 752, 267 (2016)





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

Decay length dependence

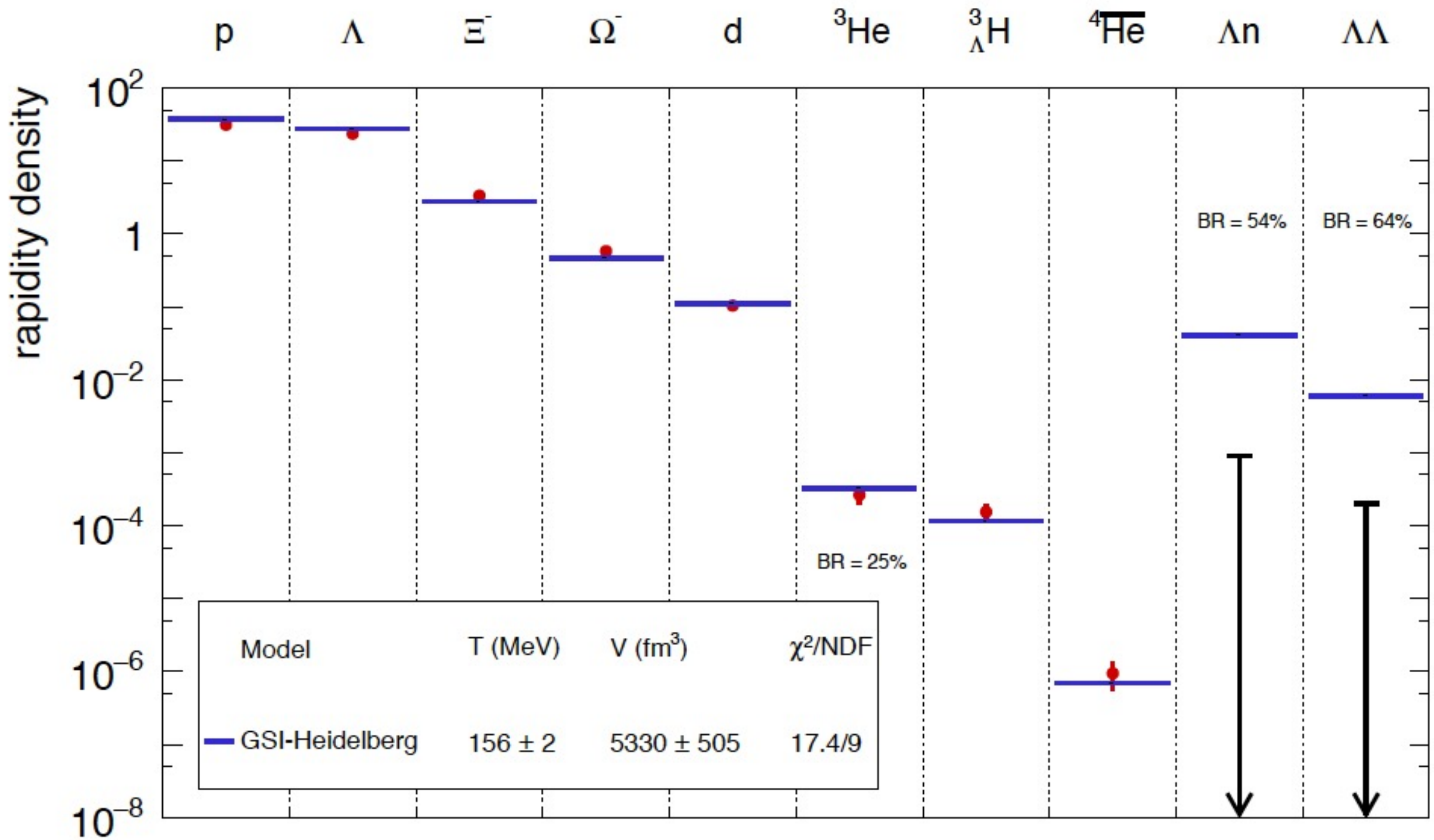


ALICE Collaboration: PLB 752, 267 (2016)

Search for a bound state of Λn and $\Lambda\Lambda$, shows no hint of signal

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

Comparison with fit

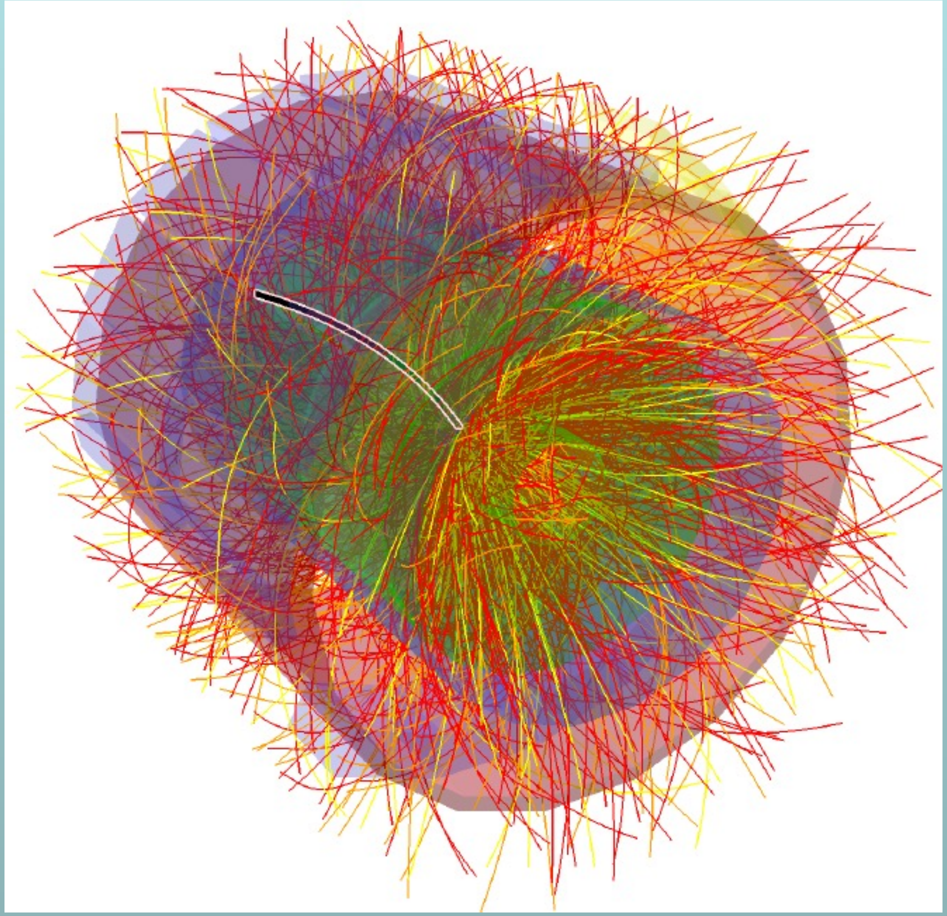


Simplified plot, CERN Courier (September 2015)

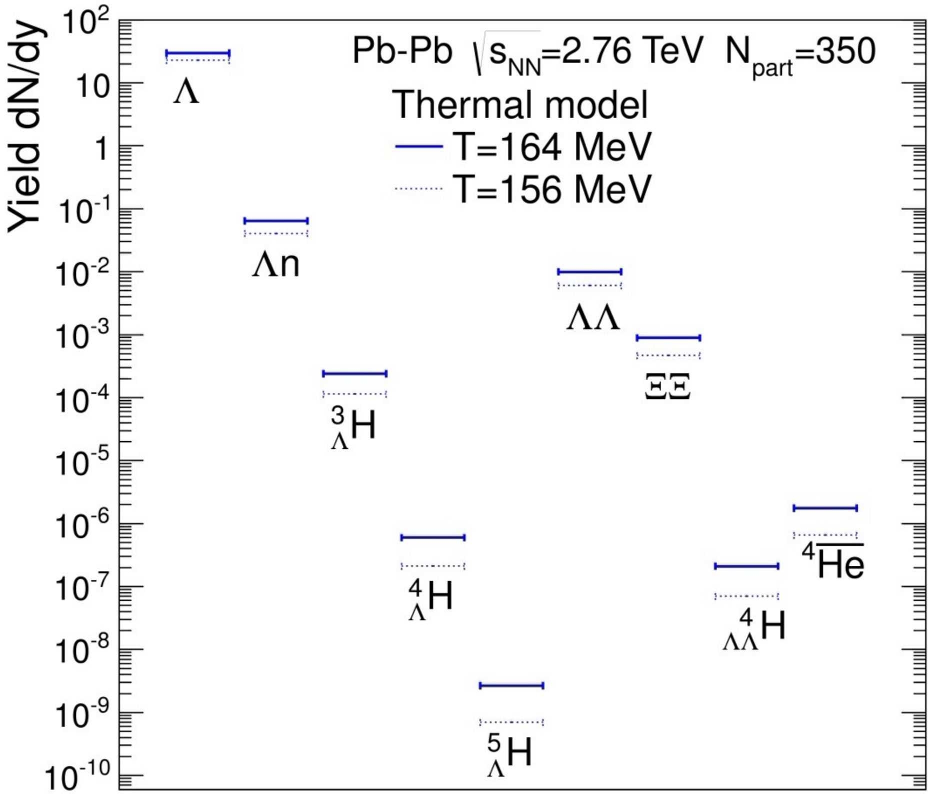
Hypertriton (B_Λ: 130 keV) and Anti-Alpha (B/A: 7 MeV) yields fit well with the thermal model expectations

→ Upper limits of $\Lambda\Lambda$ and Λn are factors of >25 below the model values

Outlook & Summary



Outlook

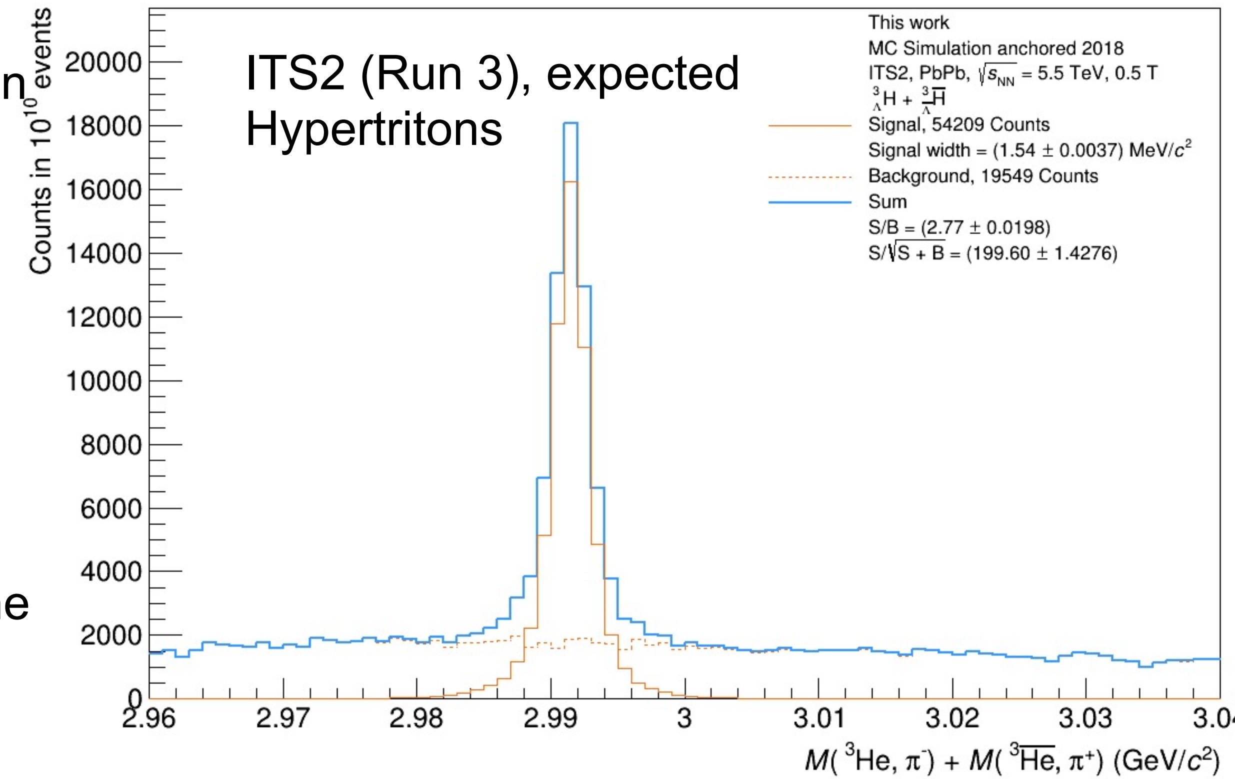


A. Andronic, private communication, model described in A. Andronic et al., PLB 697, 203 (2011) and references therein

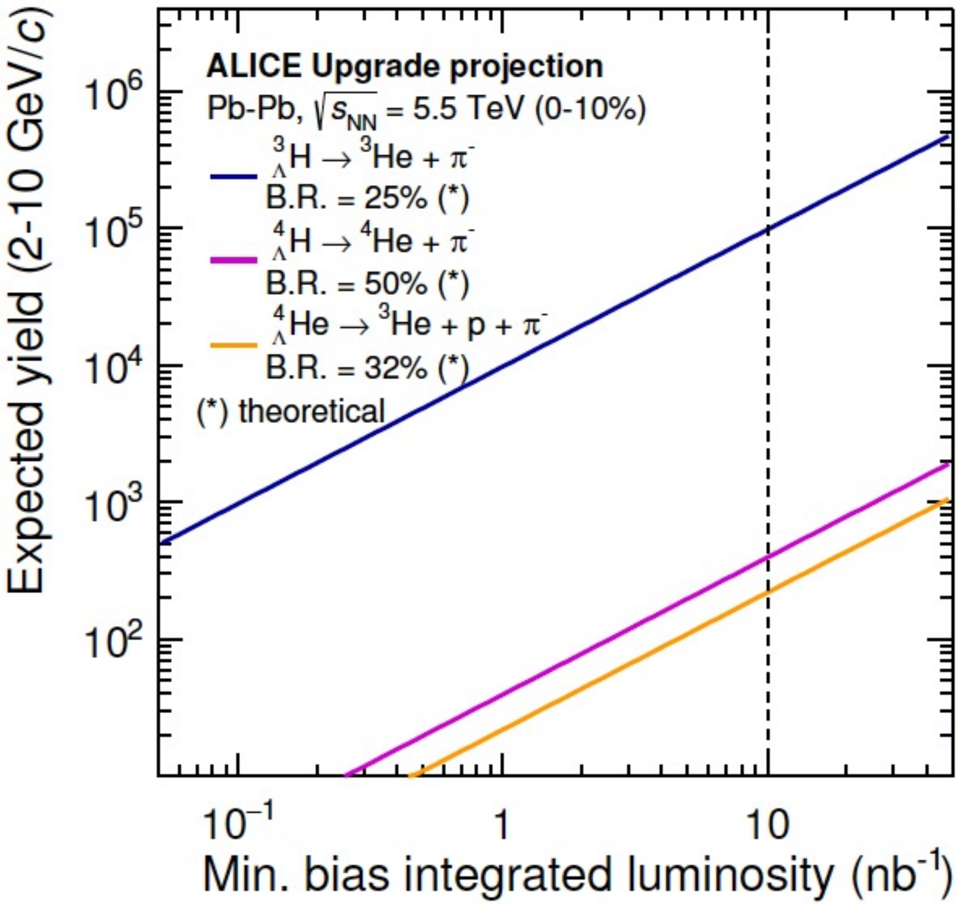
- Explore QCD and QCD inspired model predictions for (unusual) multi-baryon states
- Search for rarely produced anti- and hyper-matter
- Test model predictions, e.g. thermal and coalescence

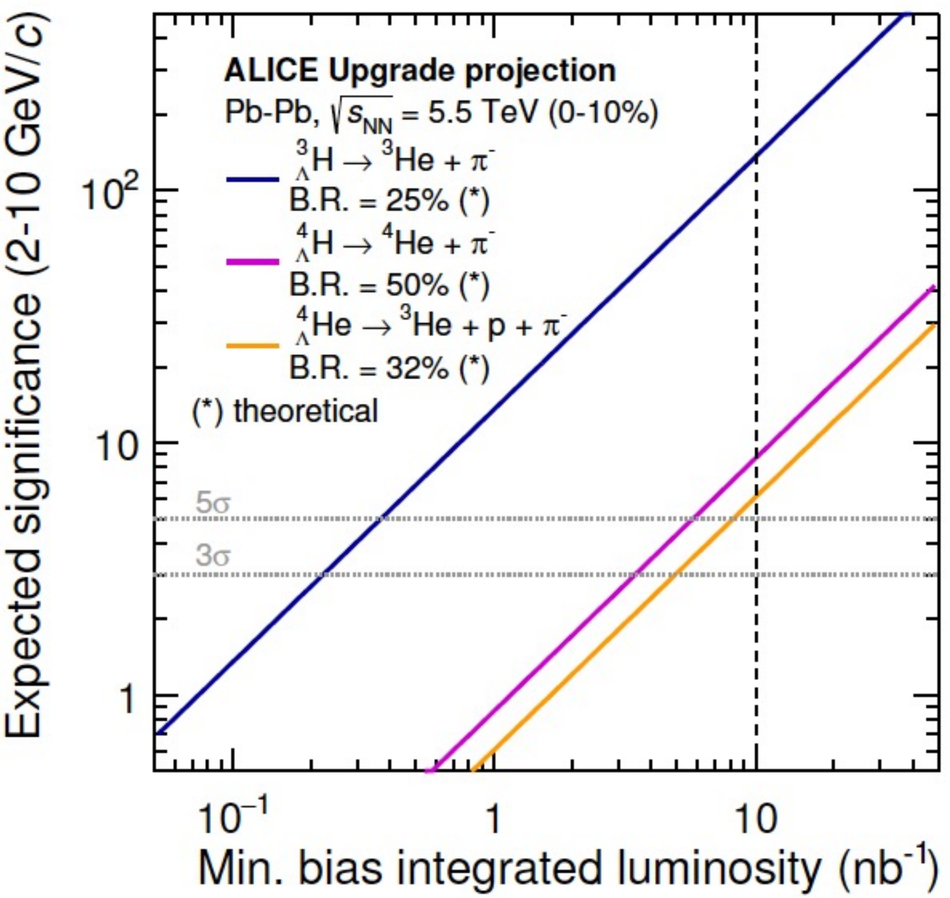
Expectations

- Results shown before are based on data gathered in Run 1 and Run 2 of the LHC with different peculiarities
- Run 3 & Run 4 of LHC will deliver much more statistics (50 kHz Pb-Pb collision rate)
- Upgraded ALICE detector will be able to cope with the high luminosity
- TPC Upgrade: GEMs for continous readout
- ITS Upgrade: less material budget and more precise tracking for the identification of hyper-nuclei
- Physics which is now done for A = 2 and A = 3 (hyper-)nuclei will be done for A = 4



Expectations

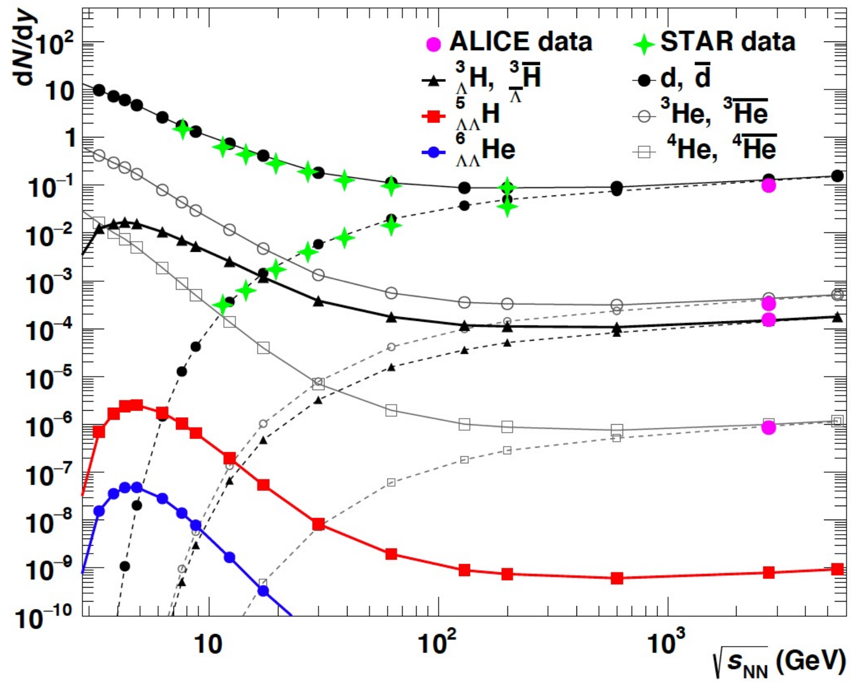




Expected significance >5σ for the full data set to be collected in Run 3 & 4

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



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