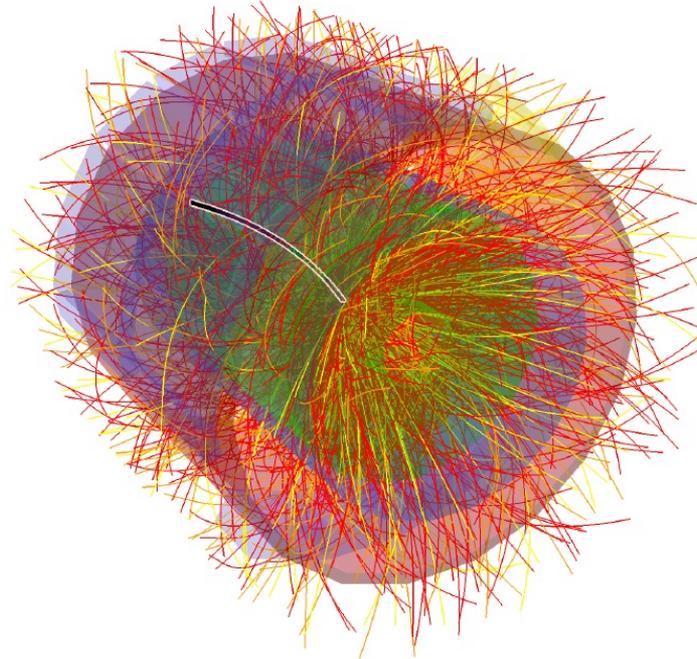


Production of (anti-)matter and exotics at the LHC



14. Dezember 2021

Physics Colloquium Mainz

Benjamin Dönigus

Institut für Kernphysik

Goethe Universität Frankfurt

Content

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

From Chemistry to Physics

- Chemical elements grouped in periodic table

Periode	Gruppe																	
	1	2											13	14	15	16	17	18
1	H Wasserstoff 1,008																	He Helium 4,0026
2	Li Lithium 6,94	Be Beryllium 9,0122											B Bor 10,81	C Kohlenstoff 12,011	N Stickstoff 14,007	O Sauerstoff 15,999	F Fluor 18,998	Ne Neon 20,180
3	Na Natrium 22,990	Mg Magnesium 24,305											Al Aluminium 26,982	Si Silicium 28,085	P Phosphor 30,974	S Schwefel 32,06	Cl Chlor 35,45	Ar Argon 39,948
4	K Kalium 39,098	Ca Calcium 40,078	Sc Scandium 44,956	Ti Titan 47,867	V Vanadium 50,942	Cr Chrom 51,996	Mn Mangan 54,938	Fe Eisen 55,845	Co Cobalt 58,933	Ni Nickel 58,693	Cu Kupfer 63,546	Zn Zink 65,380	Ga Gallium 69,723	Ge Germanium 72,630	As Arsen 74,922	Se Selen 78,971	Br Brom 79,904	Kr Krypton 83,798
5	Rb Rubidium 85,468	Sr Strontium 87,620	Y Yttrium 88,906	Zr Zirkonium 91,224	Nb Niob 92,906	Mo Molybdän 95,950	Tc Technetium (97,4)	Ru Ruthenium 101,07	Rh Rhodium 102,91	Pd Palladium 106,42	Ag Silber 107,87	Cd Cadmium 112,41	In Indium 114,82	Sn Zinn 118,71	Sb Antimon 121,76	Te Tellur 127,60	I Iod 126,90	Xe Xenon 131,29
6	Cs Caesium 132,91	Ba Barium 137,33	La Lanthan 138,91	Hf Hafnium 178,49	Ta Tantal 180,95	W Wolfram 183,84	Re Rhenium 186,21	Os Osmium 190,23	Ir Iridium 192,22	Pt Platin 195,08	Au Gold 196,97	Hg Quecksilber 200,59	Tl Thallium 204,38	Pb Blei 207,20	Bi Bismut 208,98	Po Polonium 209,98	At Astat (210)	Rn Radon (222)
7	Fr Francium 223	Ra Radium (226)	Ac Actinium (227)	Rf Rutherfordium (261)	Db Dubnium (269)	Sg Seaborgium (270)	Bh Bohrium (272)	Hs Hassium (273)	Mt Meitnerium (277)	Ds Darmstadtium (281)	Rg Roentgenium (281)	Cn Copernicium (285)	Nh Nihonium (286)	Fl Flerovium (289)	Mc Moscovium (288)	Lv Livermorium (293)	Ts Tenness (294)	Og Oganesson (294)

Legende

Ordnungszahl Atomgewicht
 Symbol Name
 Elektronegativität Dichte

Symbol schwarz = Feststoff
 blau = Flüssigkeit
 rot = Gas
 grau = unbekannt
 unterstrichen = radioaktiv

Dichte rot = kg / m³
 schwarz = kg / dm³
 grau = unbestimmt

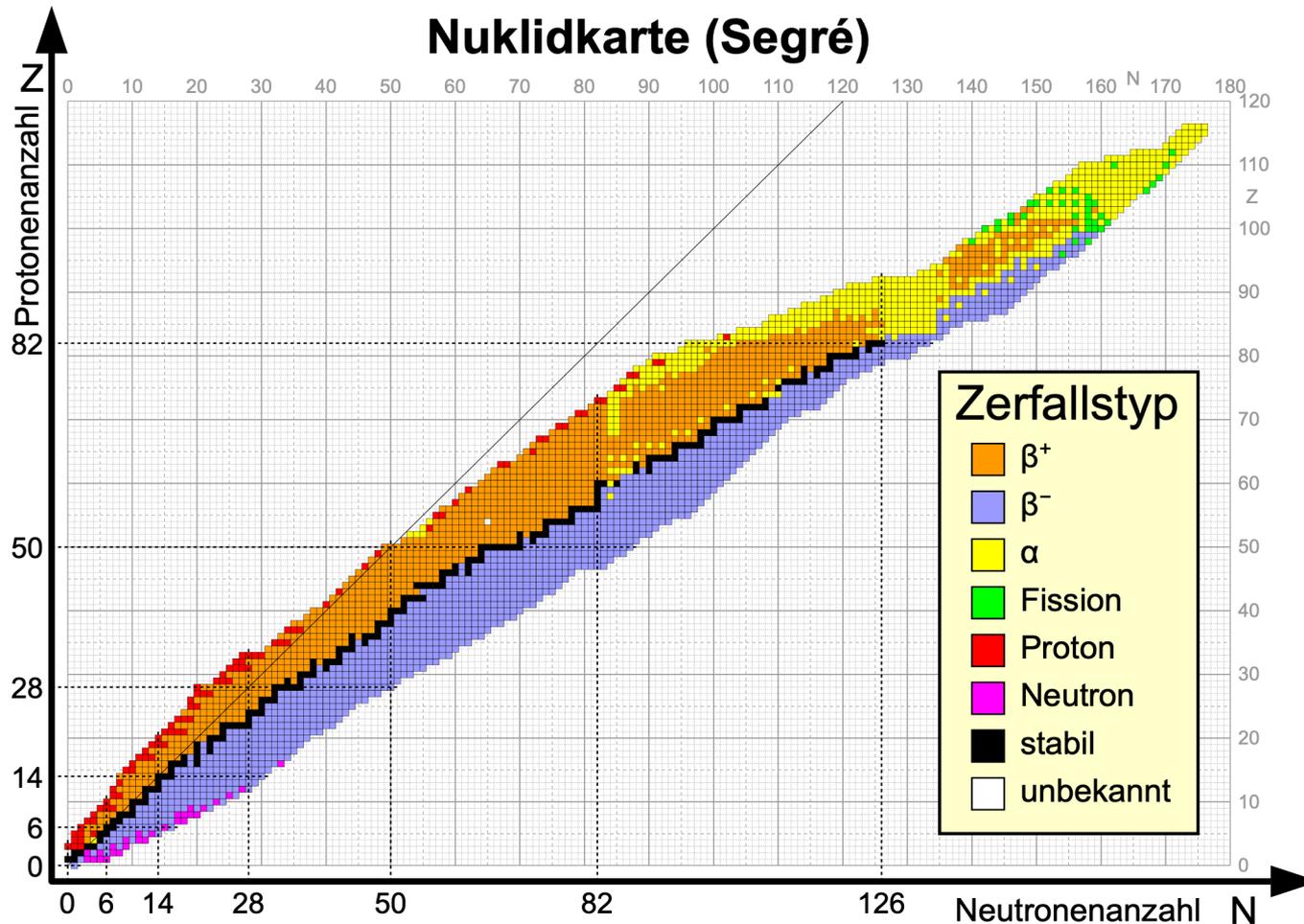
Serie (Flächenfarbe)
 Alkalimetalle Metalle
 Erdalkalimetalle Halbmethalle
 Übergangsmetalle Nichtmetalle
 Lanthanoide Halogene
 Actinoide Edelgase
 unbekannt

Schraffur
 durchgehend = natürliches Element
 schraffiert = künstliches Element

↓

Lanthanoide	Ce Cer 140,12	Pr Praseodym 140,91	Nd Neodym 144,24	Pm Promethium (146)	Sm Samarium 150,36	Eu Europium 151,96	Gd Gadolinium 157,25	Tb Terbium 158,93	Dy Dysprosium 162,50	Ho Holmium 164,93	Er Erbium 167,26	Tm Thulium 168,93	Yb Ytterbium 173,05	Lu Lutetium 174,97
Actinoide	Th Thorium 232,04	Pa Protactinium 231,04	U Uran 238,03	Np Neptunium (237)	Pu Plutonium (244)	Am Americium (243)	Cm Curium (247)	Bk Berkelium (247)	Cf Californium (251)	Es Einsteinium (252)	Fm Fermium (257)	Md Mendelevium (258)	No Nobelium (259)	Lr Lawrencium (262)

From Chemistry to Physics

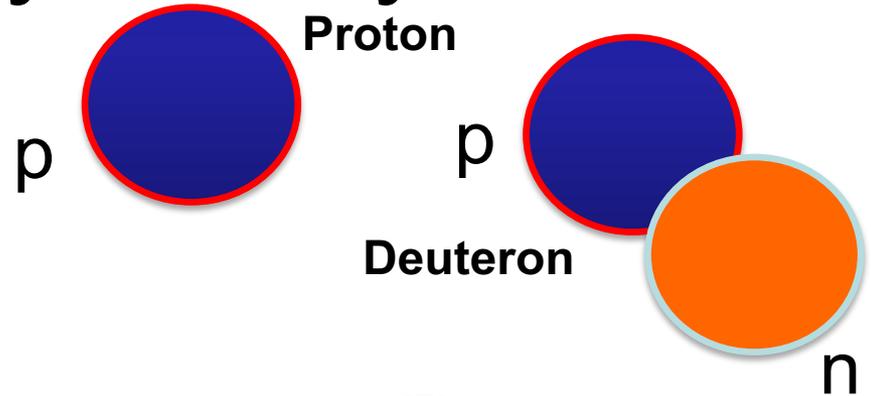


- Chemical elements and chemical properties are defined by the charge number, i.e. the number of protons
- Number of protons and neutrons define (nuclear) physical properties, such as stability or type of decay

From Chemistry to Physics

Proton (p)

$$m=938.3 \text{ MeV}/c^2$$

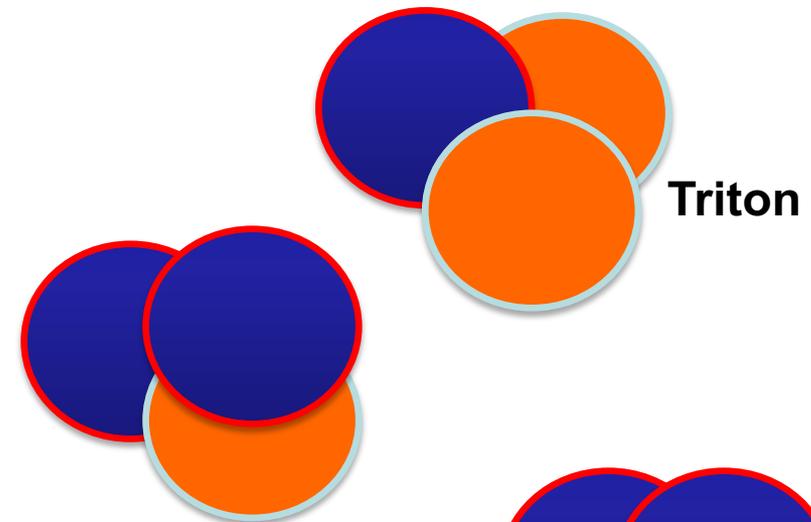


Deuteron (pn)

$$m=1875.6 \text{ MeV}/c^2$$

Triton (pnn)

$$m=2808.9 \text{ MeV}/c^2$$

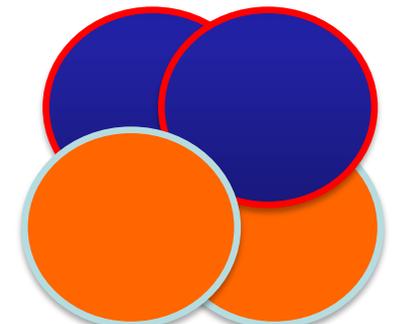


Helium (ppn)

$$m=2808.4 \text{ MeV}/c^2$$

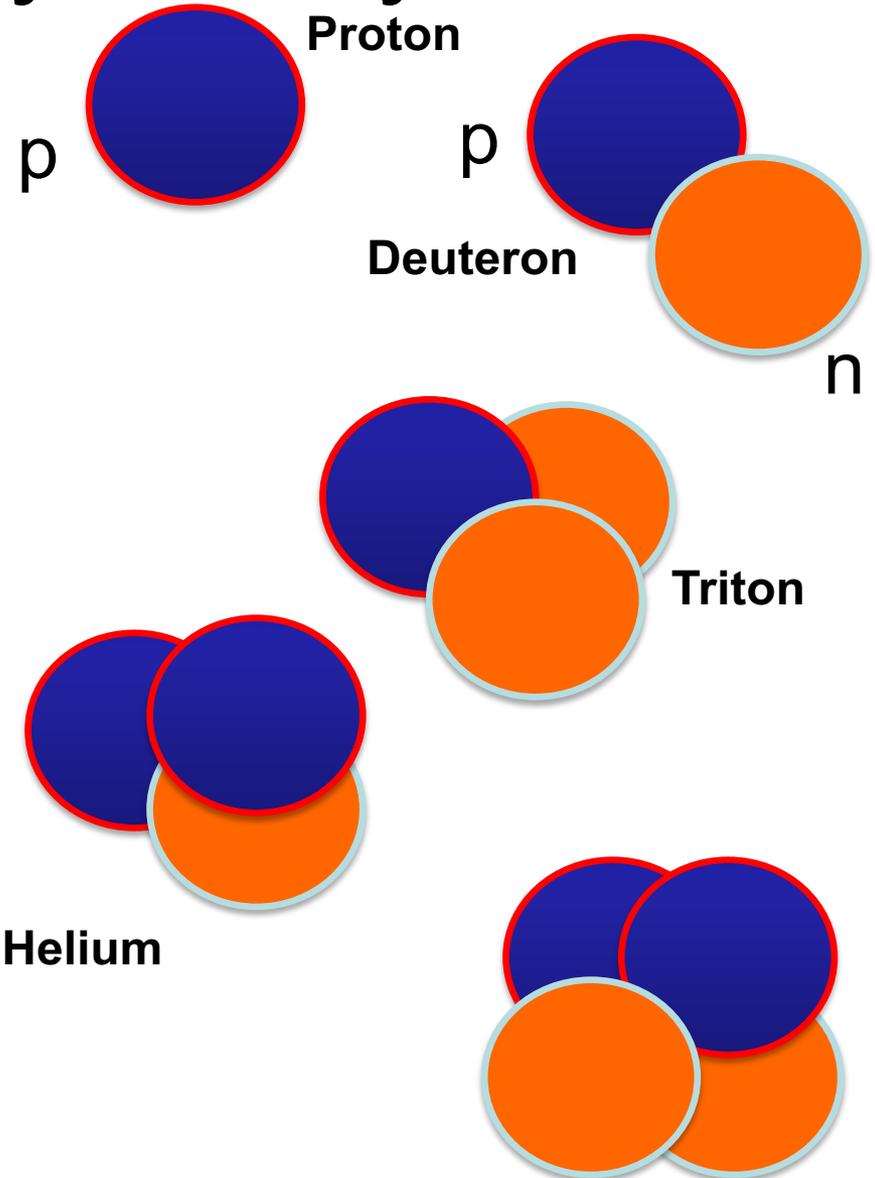
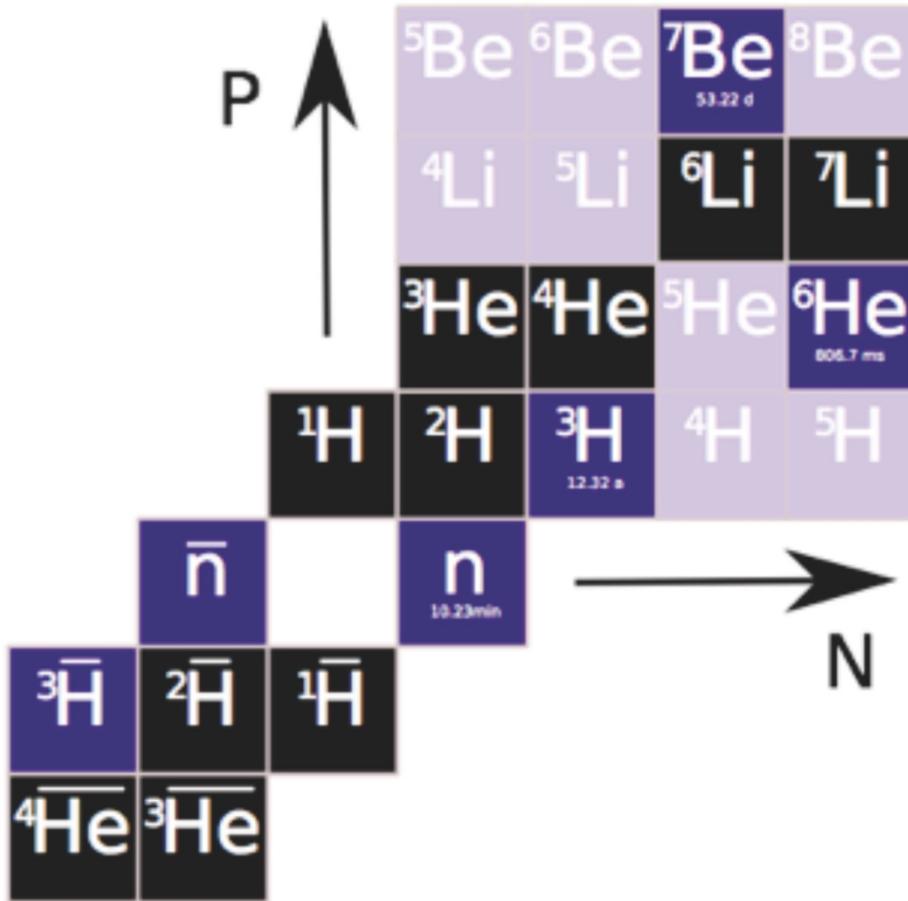
Alpha (ppnn)

$$m=3727.4 \text{ MeV}/c^2$$

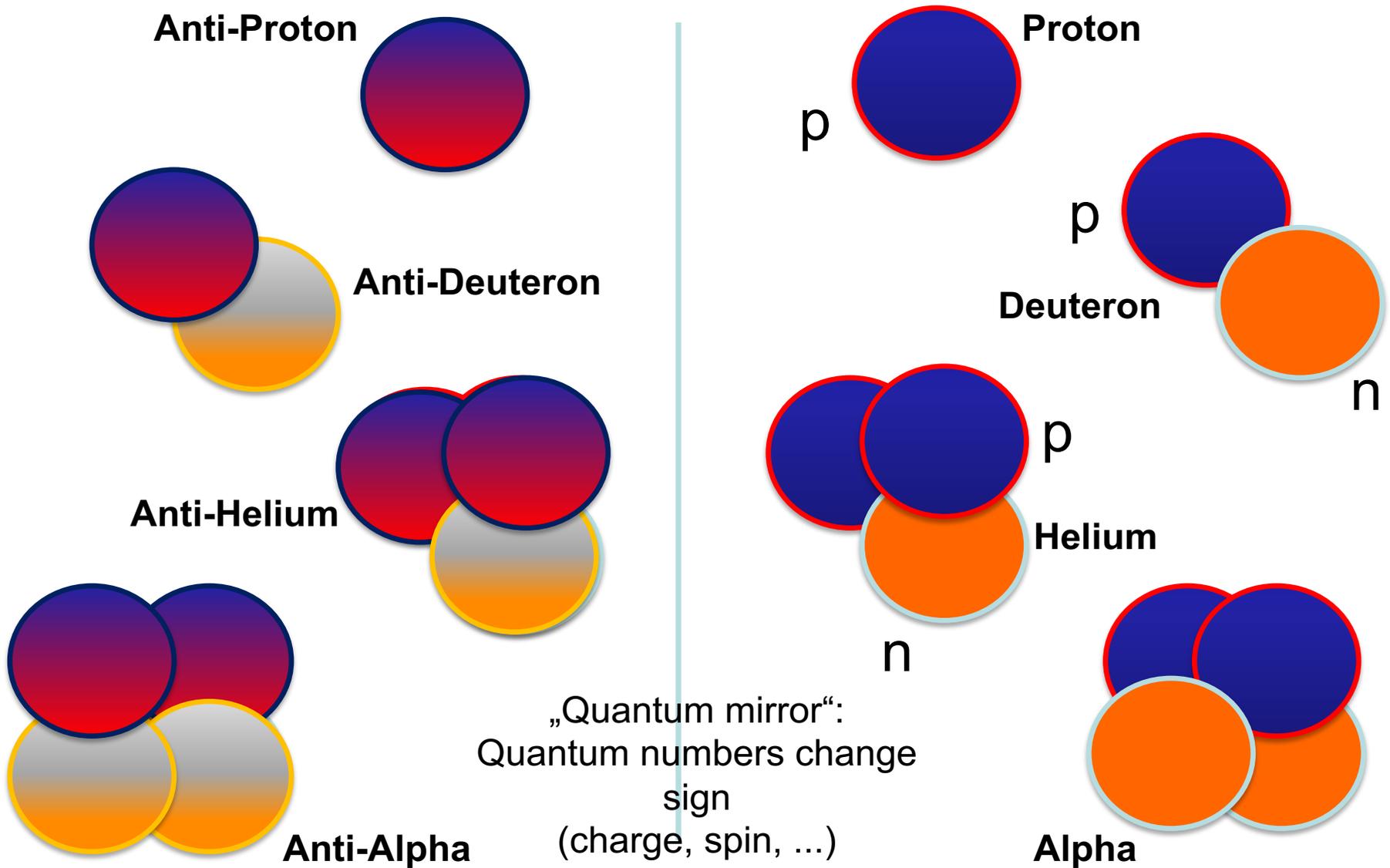


$$1 \text{ GeV}/c^2 = 1.73 \times 10^{-27} \text{ kg}$$

From Chemistry to Physics

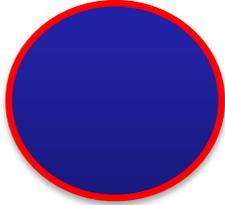


From Chemistry to Physics

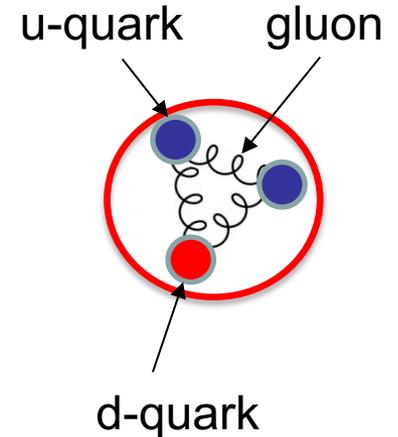


Zoo of hadrons

Baryons



Proton (p) \rightarrow uud
Neutron (n) \rightarrow udd
Lambda (Λ) \rightarrow uds



Mesons

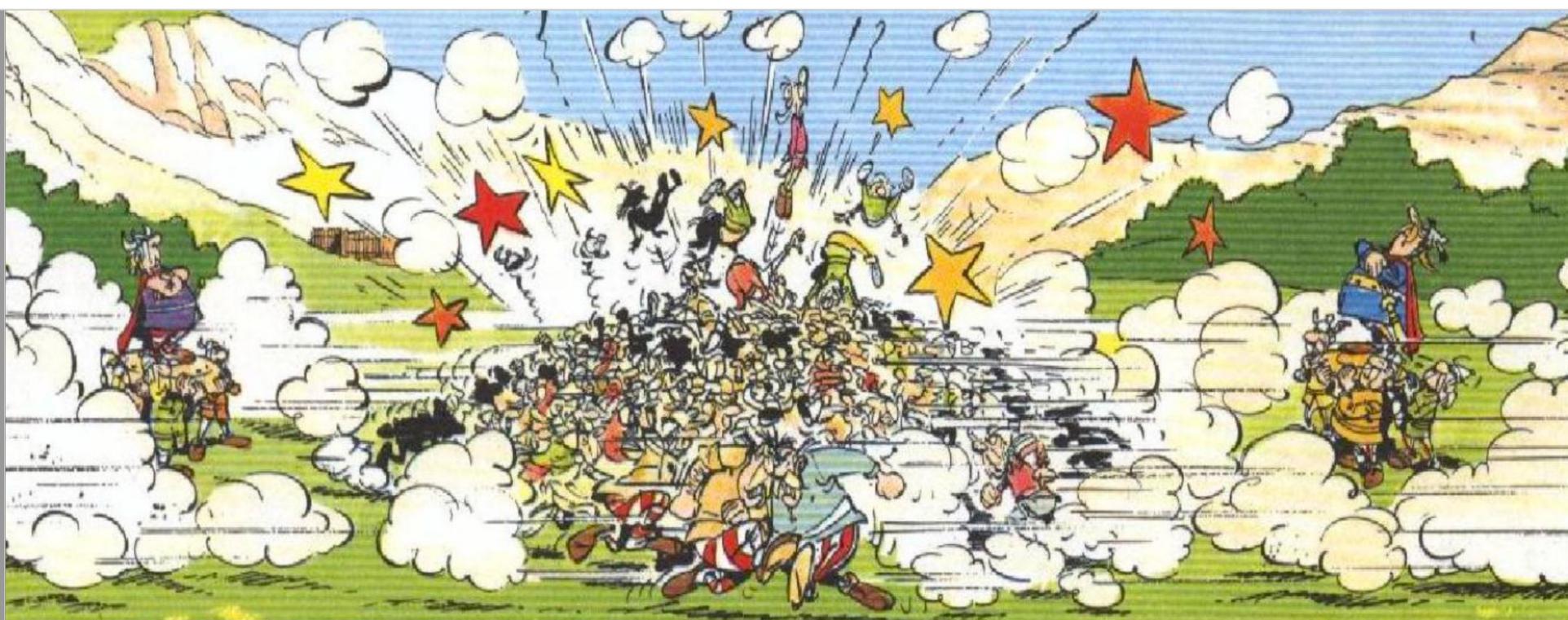


π -Meson \rightarrow $d\bar{u}$
K-Meson \rightarrow $u\bar{s}$

- 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)

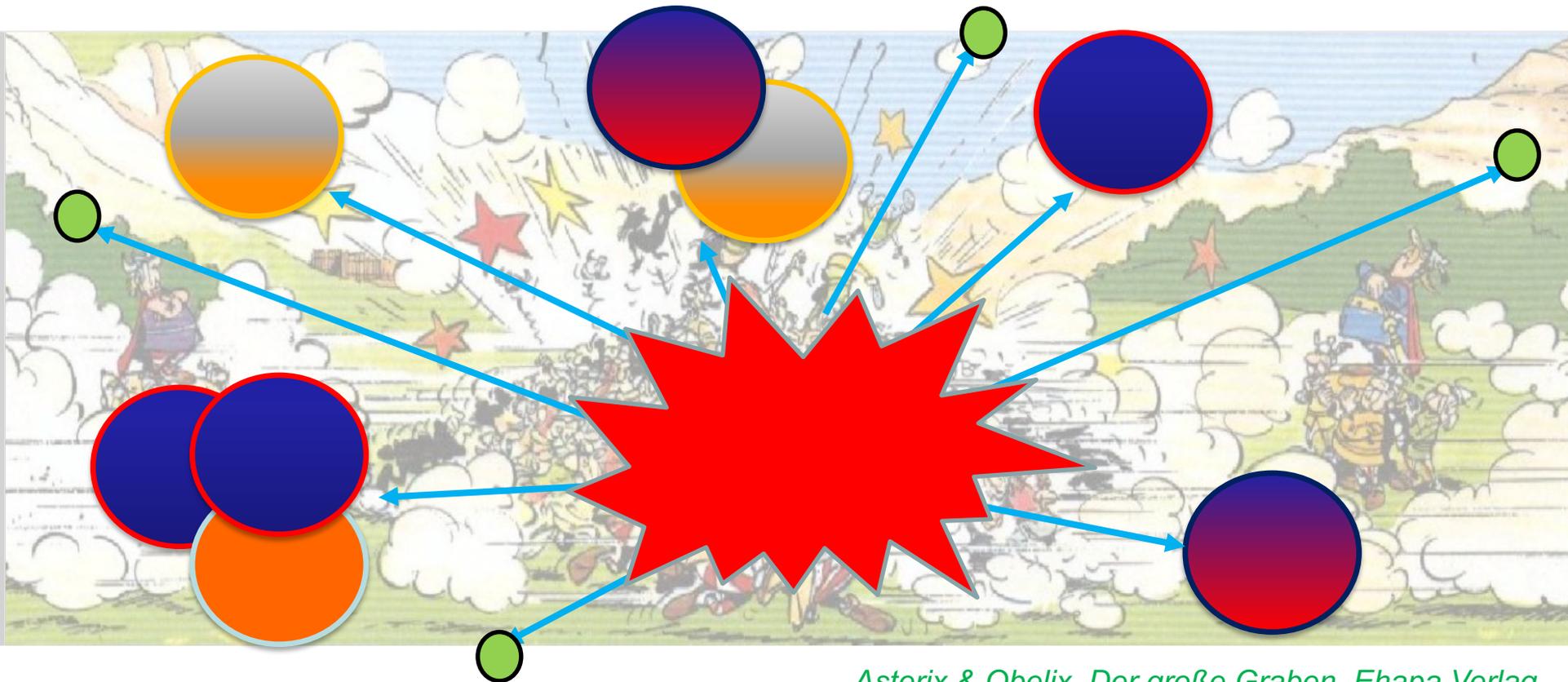
Collisions

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



Collisions

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



Asterix & Obelix, Der große Graben, Ehapa Verlag

Large Hadron Collider at CERN



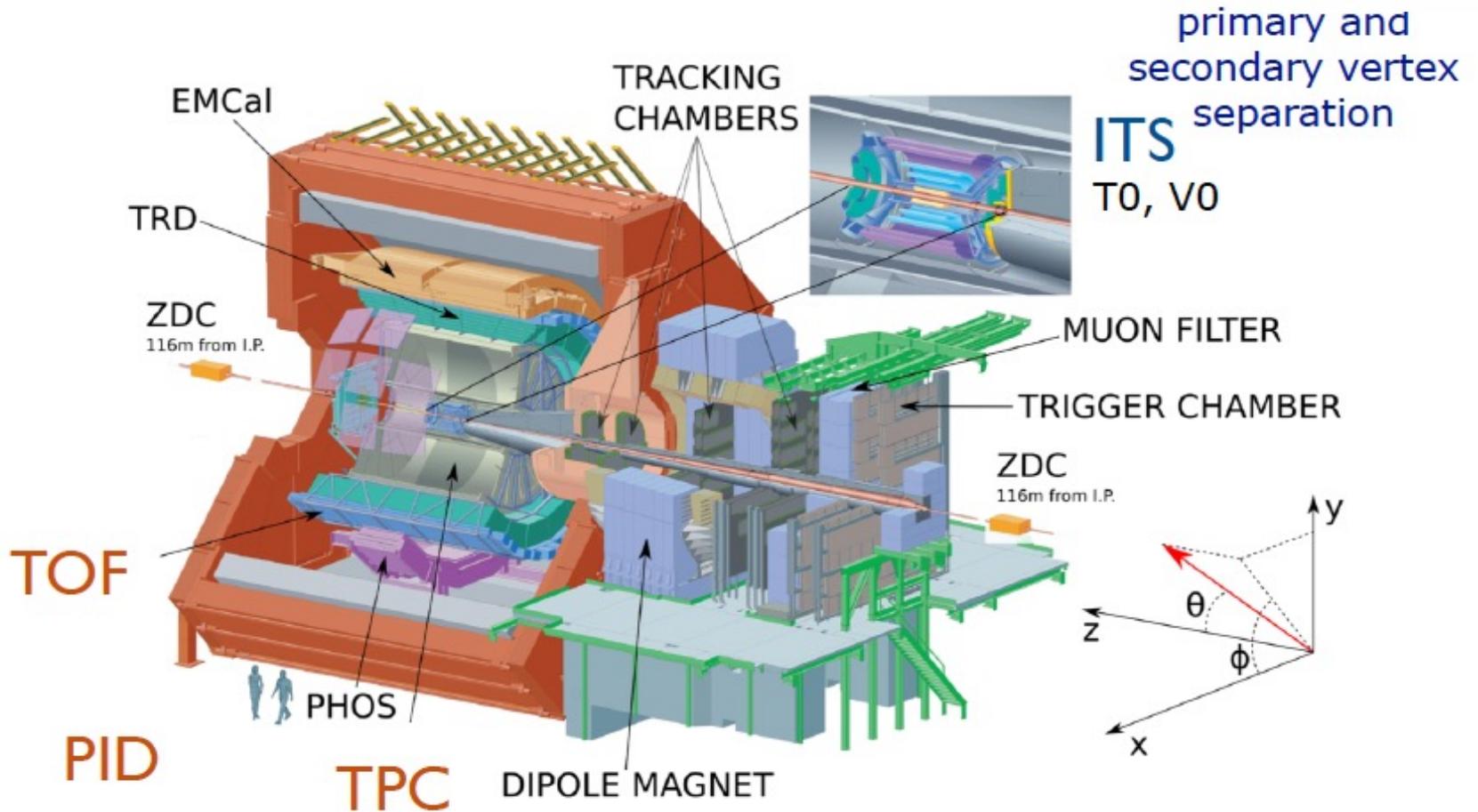
Large Hadron Collider at CERN



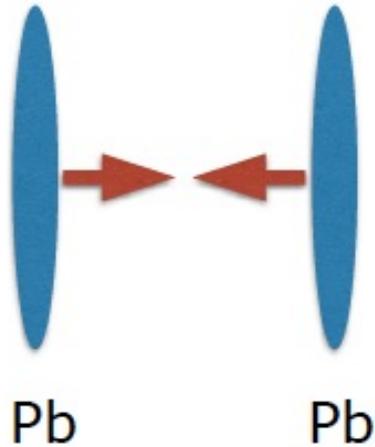
ALICE



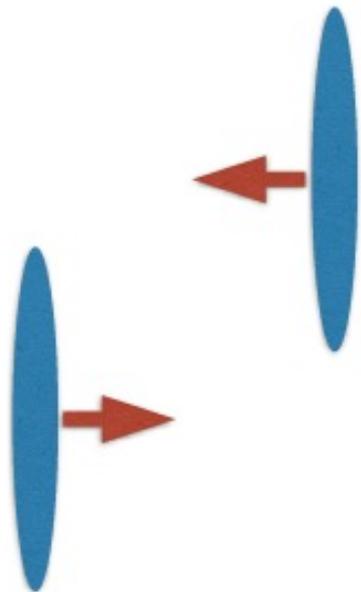
Experiment: ALICE



Interlude: Centrality

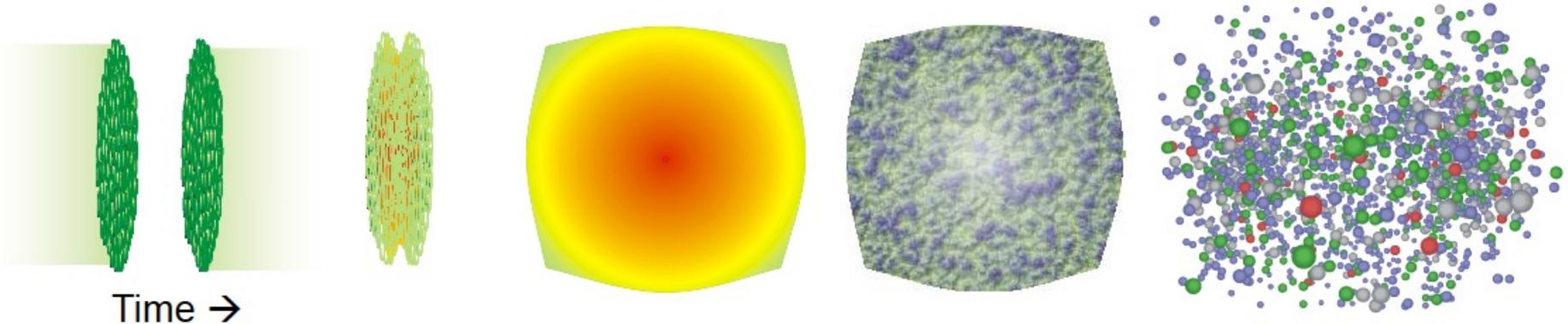


Central Pb-Pb collision:
High multiplicity = large $dN/d\eta$
High number of tracks
(more than 2000 tracks in the detector)



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

Introduction



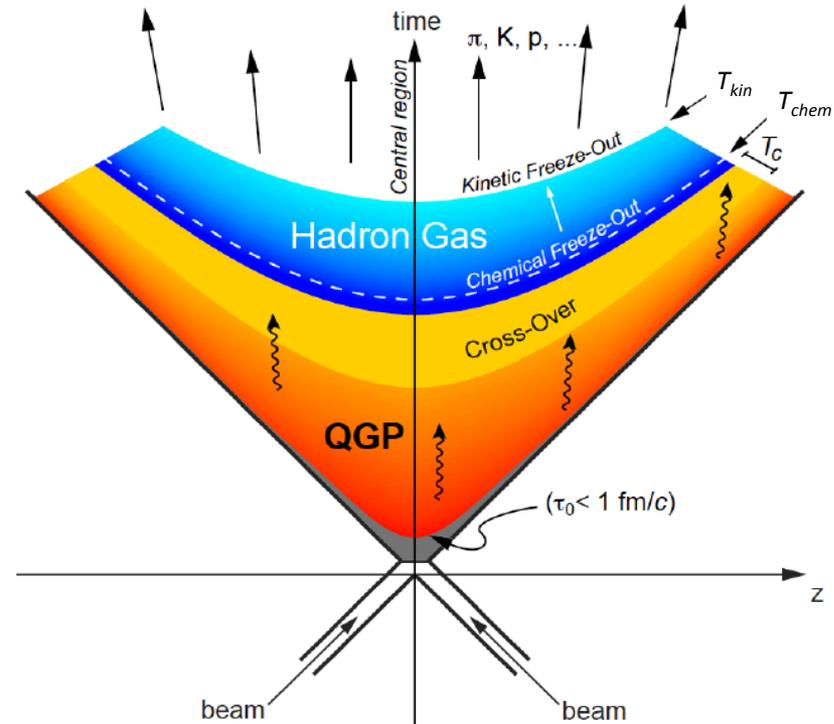
Cartoon of a Ultra-relativistic heavy-ion collision

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>

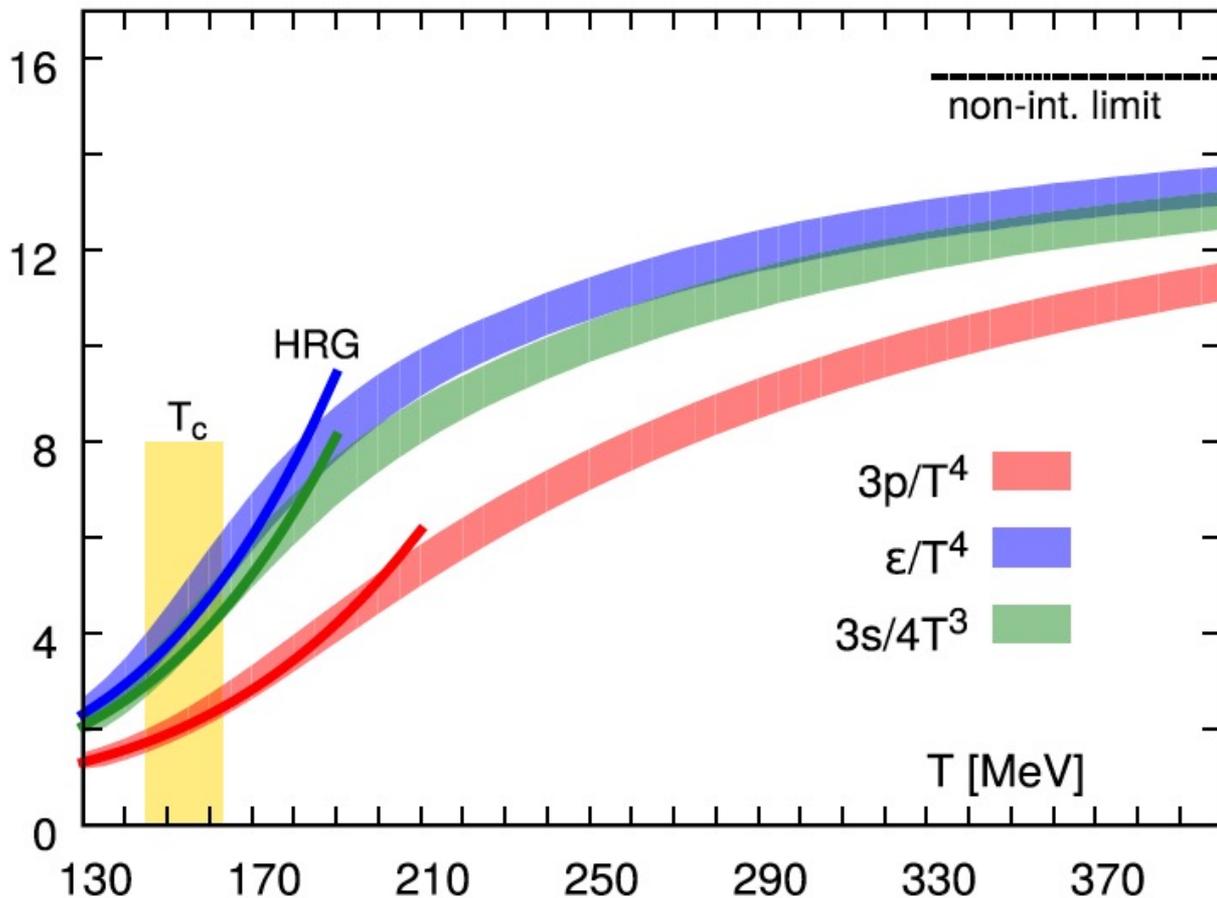
Introduction



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

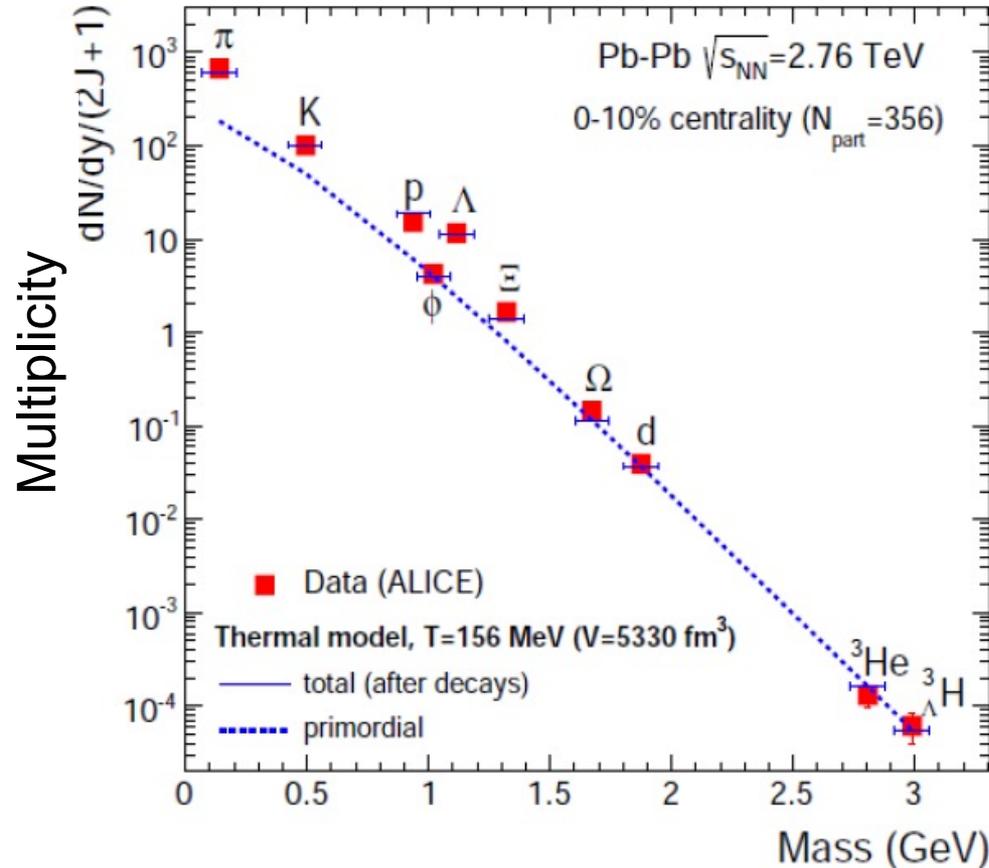
Critical energy density:
 $\varepsilon_C = 0.34 \pm 0.16 \text{ GeV/fm}^3$

Critical temperature
 $T_C = (154 \pm 9) \text{ MeV}$

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



Analogy:

Light source \rightarrow particle source

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

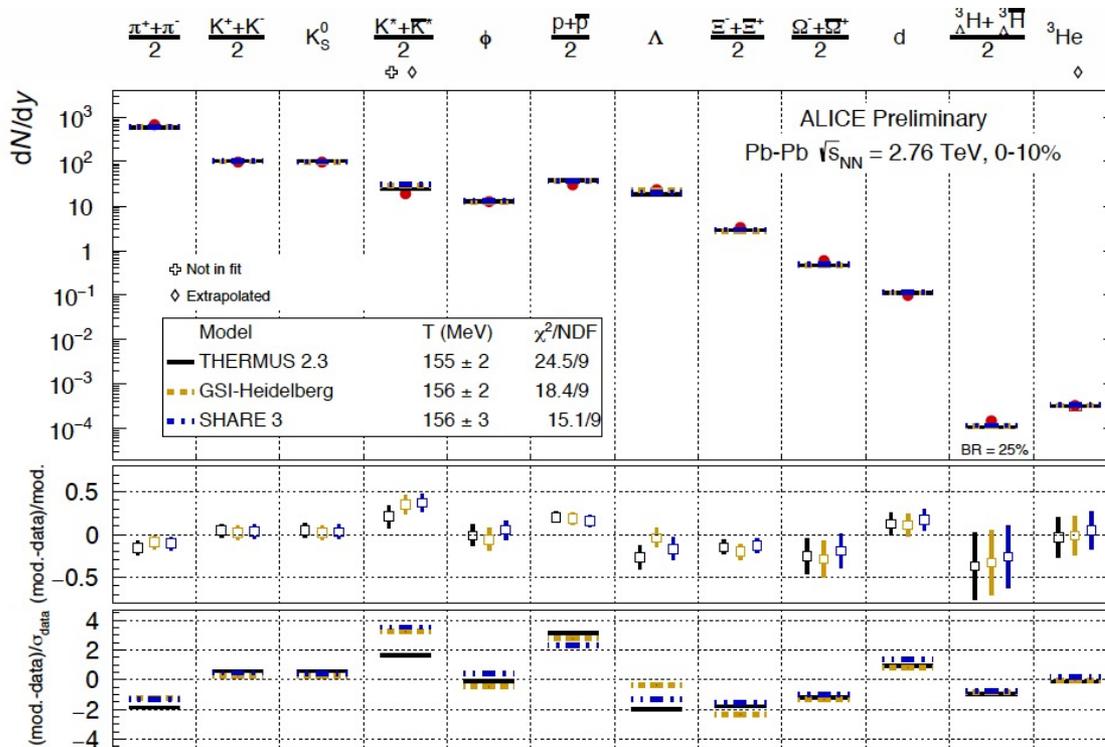
\rightarrow 100 000 times hotter than in the interior of the sun!

1/40 eV = 20 °C

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

Thermal model

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

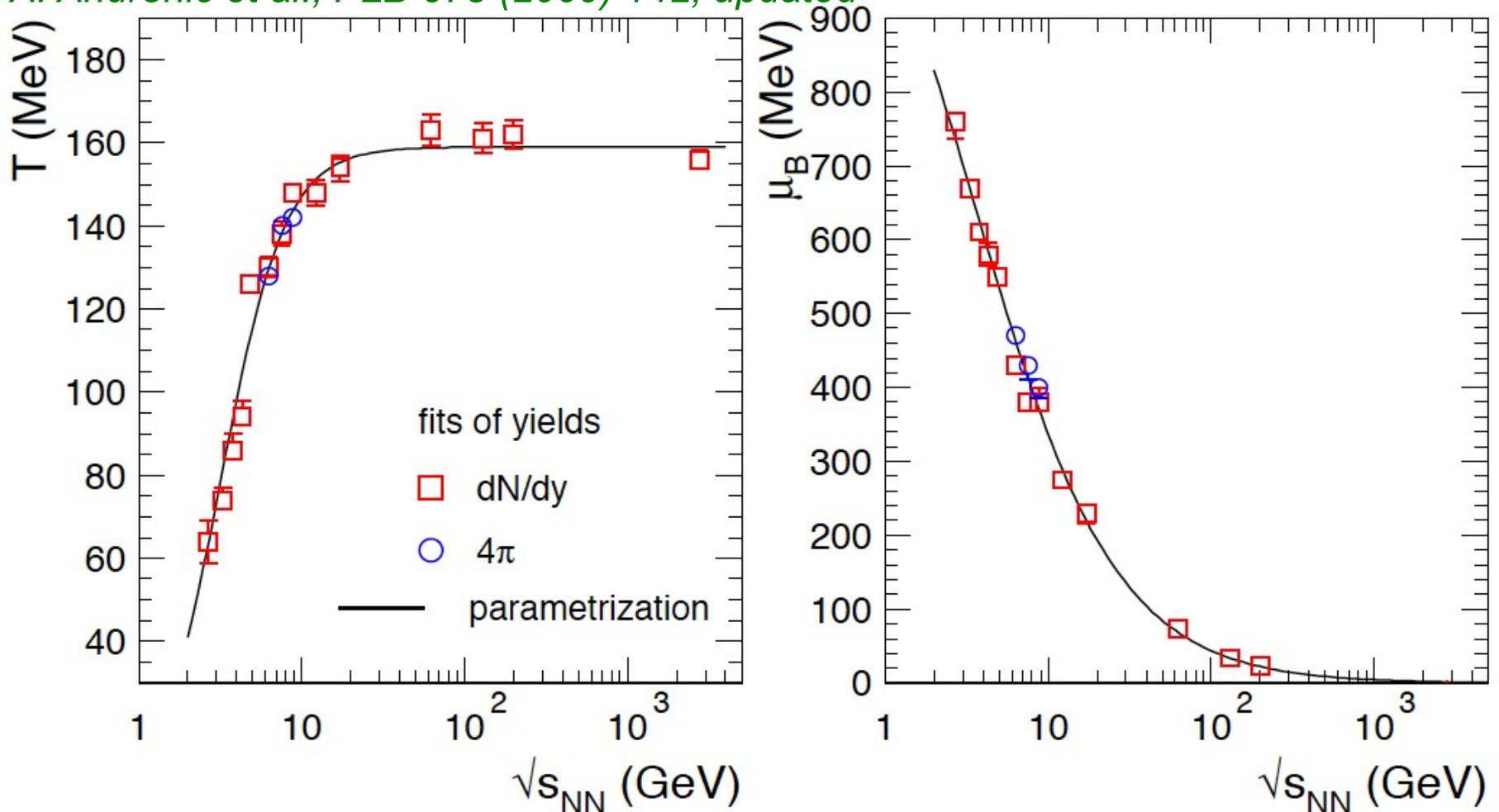


- chemical freeze-out temperature T_{ch}
- baryo-chemical potential μ_B
- Volume V

→ Using particle yields as input to extract parameters

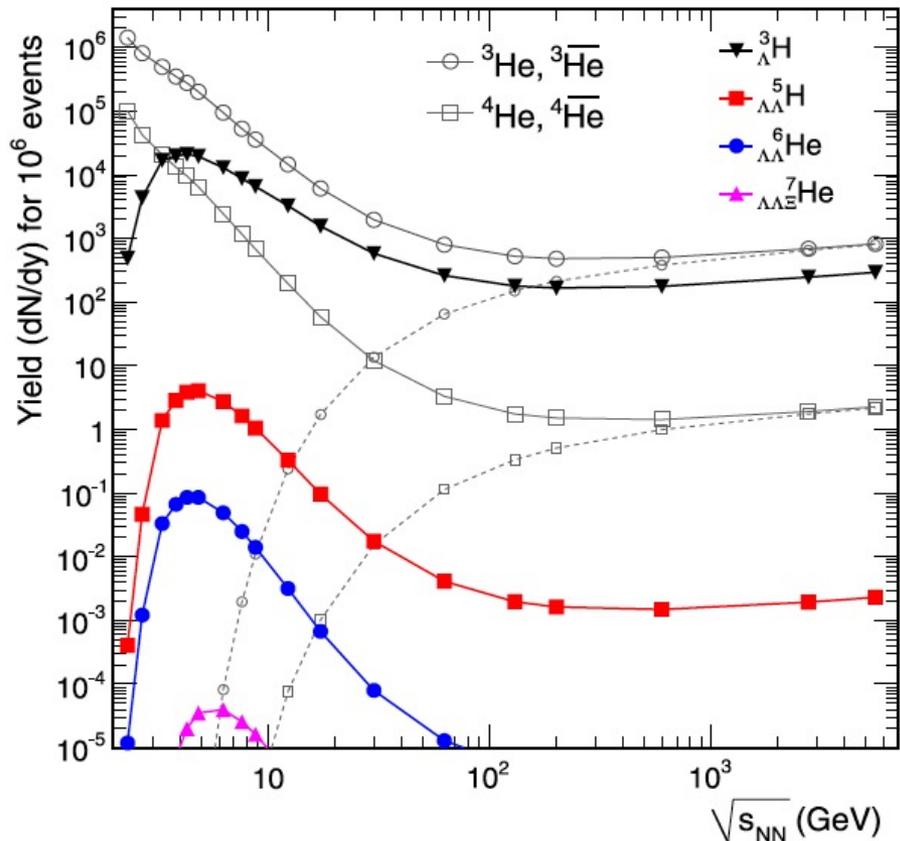
Energy dependence

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



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

Predicting yields of bound states



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

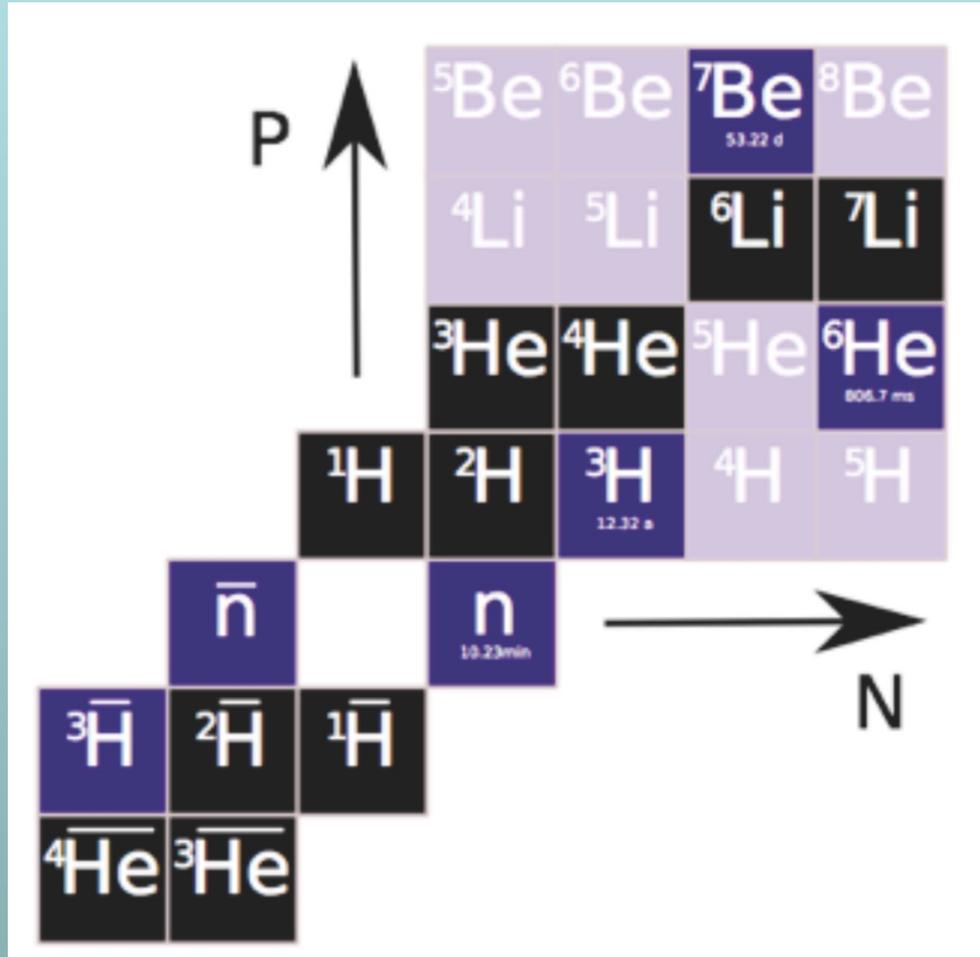
Key parameter at LHC energies:

chemical freeze-out temperature T_{ch}

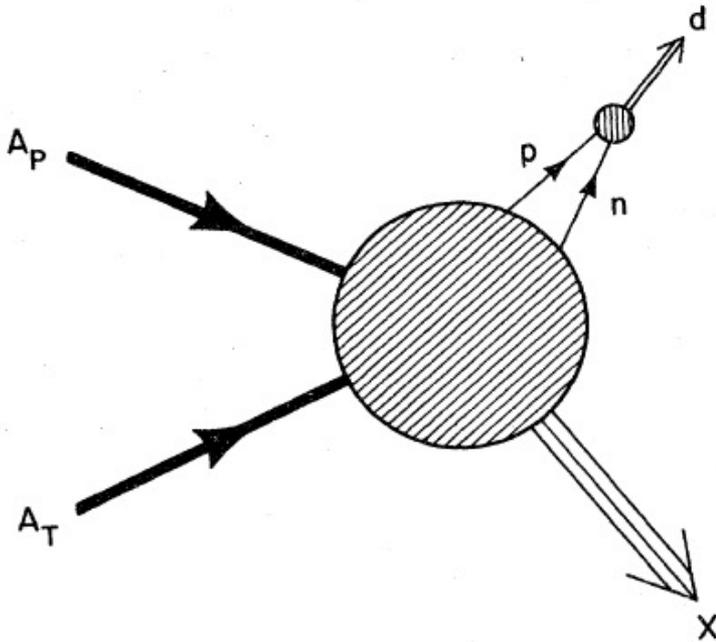
Strong sensitivity of abundance of nuclei to choice of T_{ch} due to:

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

(Anti-)Nuclei



Coalescence



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

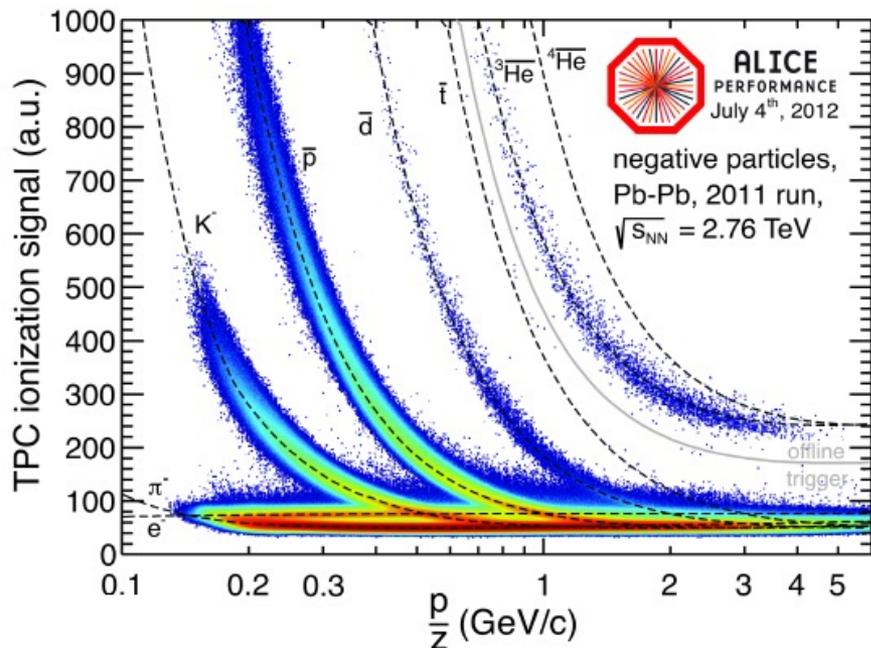
Nuclei are formed by protons and neutrons which are nearby and have similar velocities (after kinetic freeze-out)

Produced nuclei

→ can break apart

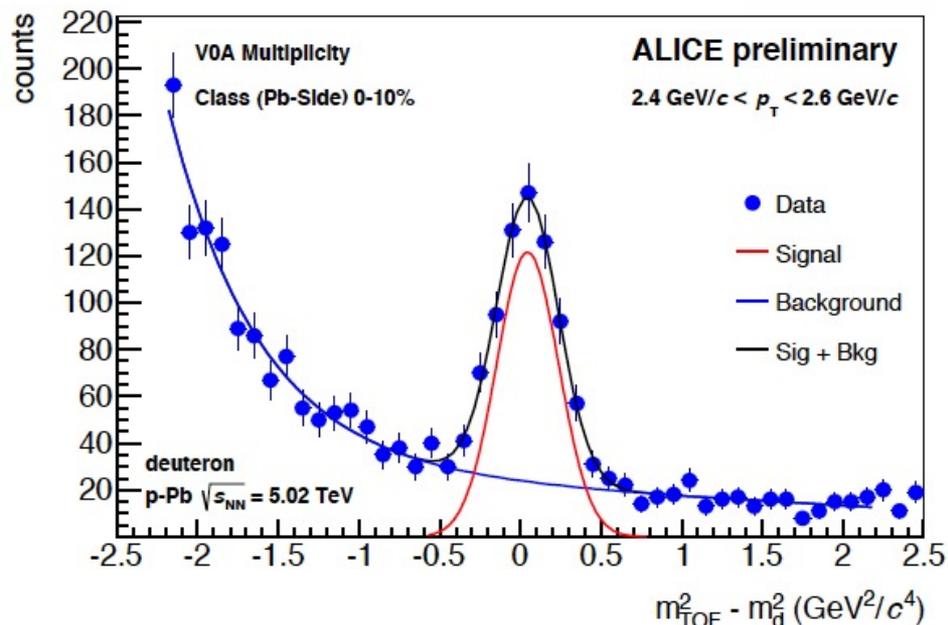
→ created again by final-state coalescence

Particle Identification



Low momenta:

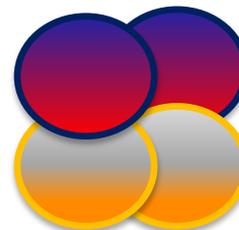
Nuclei are identified using the dE/dx measurement in the Time Projection Chamber (TPC)



Higher momenta:

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

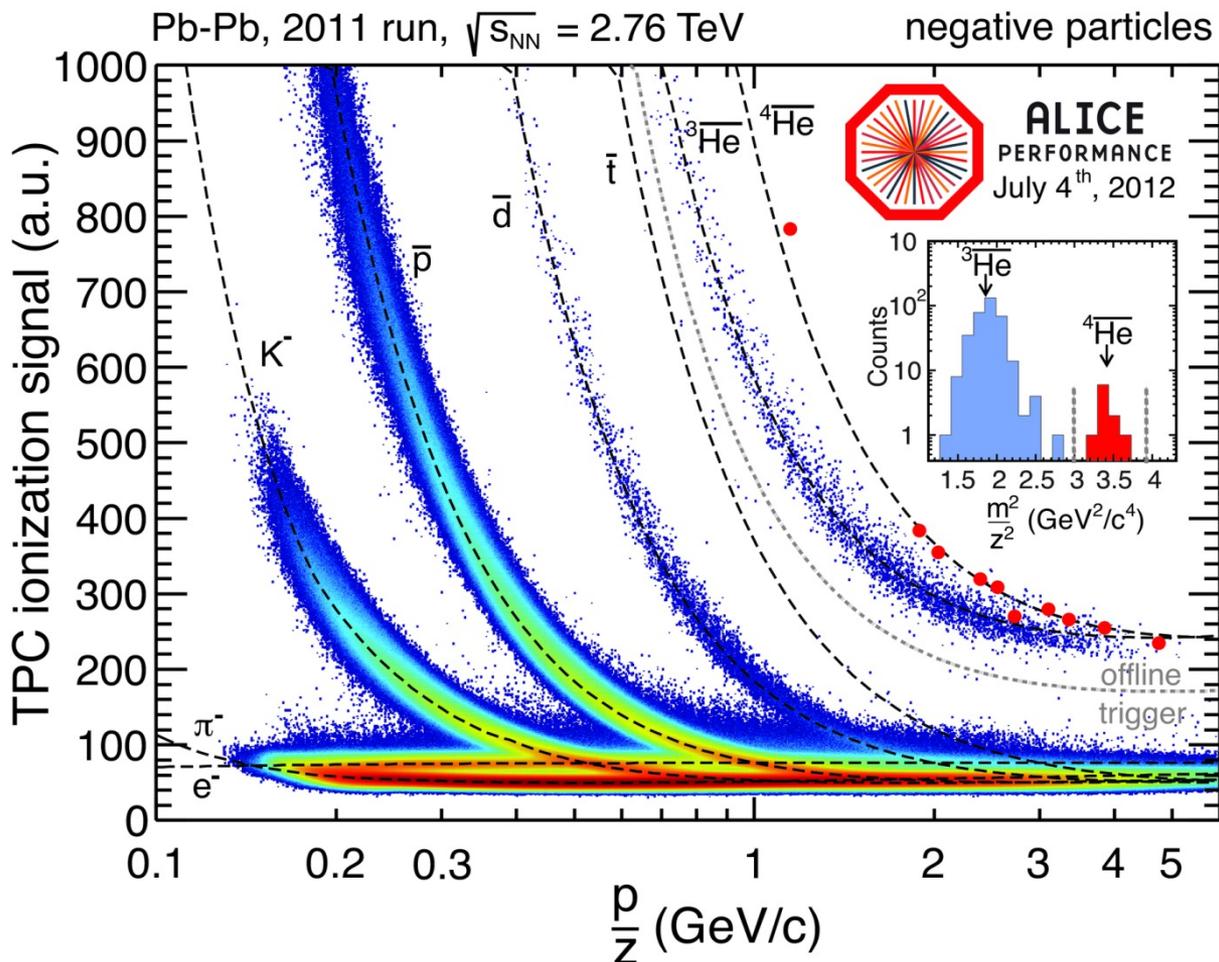
Anti-Alpha



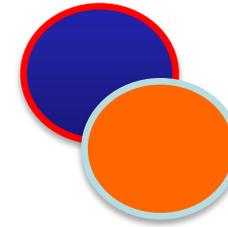
For the full statistics of 2011 ALICE identified 10 Anti-Alpha using TPC and TOF

STAR observed the Anti-Alpha in 2010:

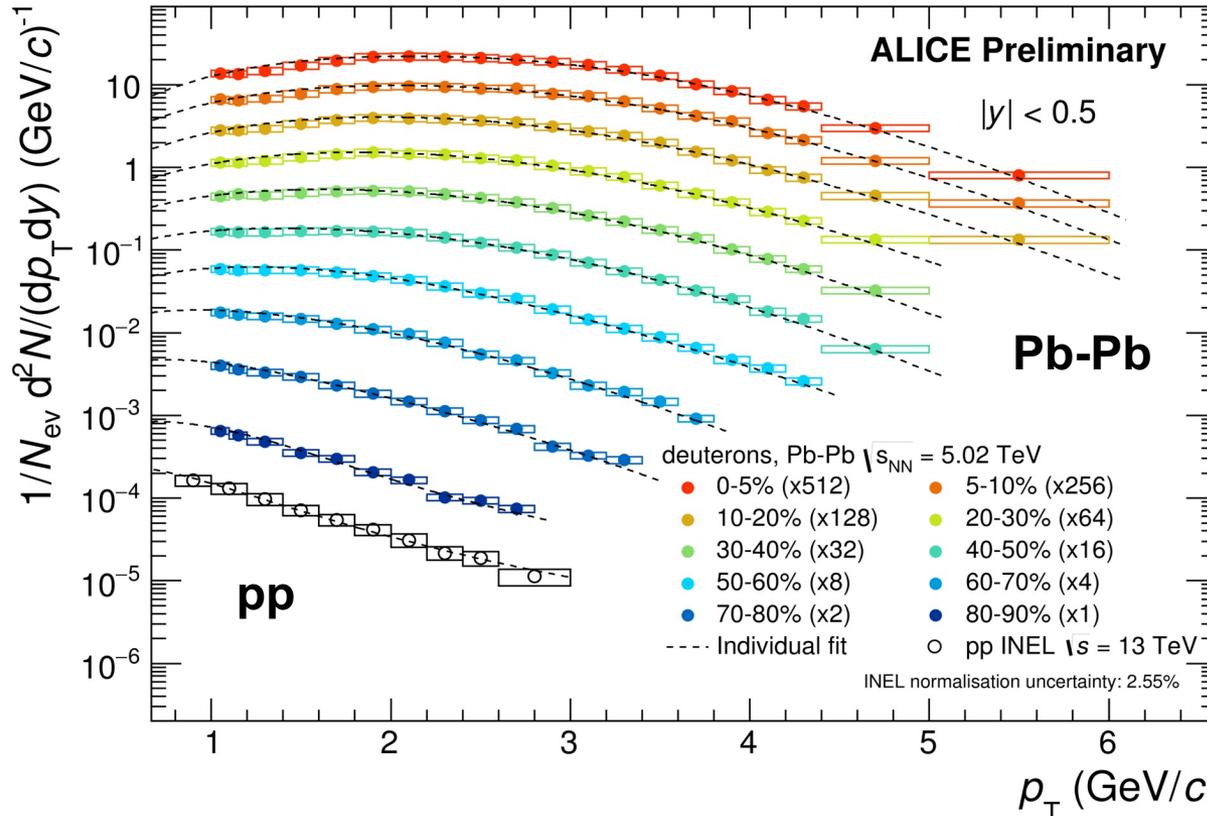
Nature 473, 353 (2011)



Deuterons



ALICE-PUBLIC-2017-006

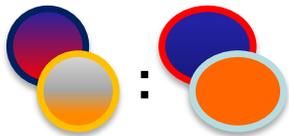
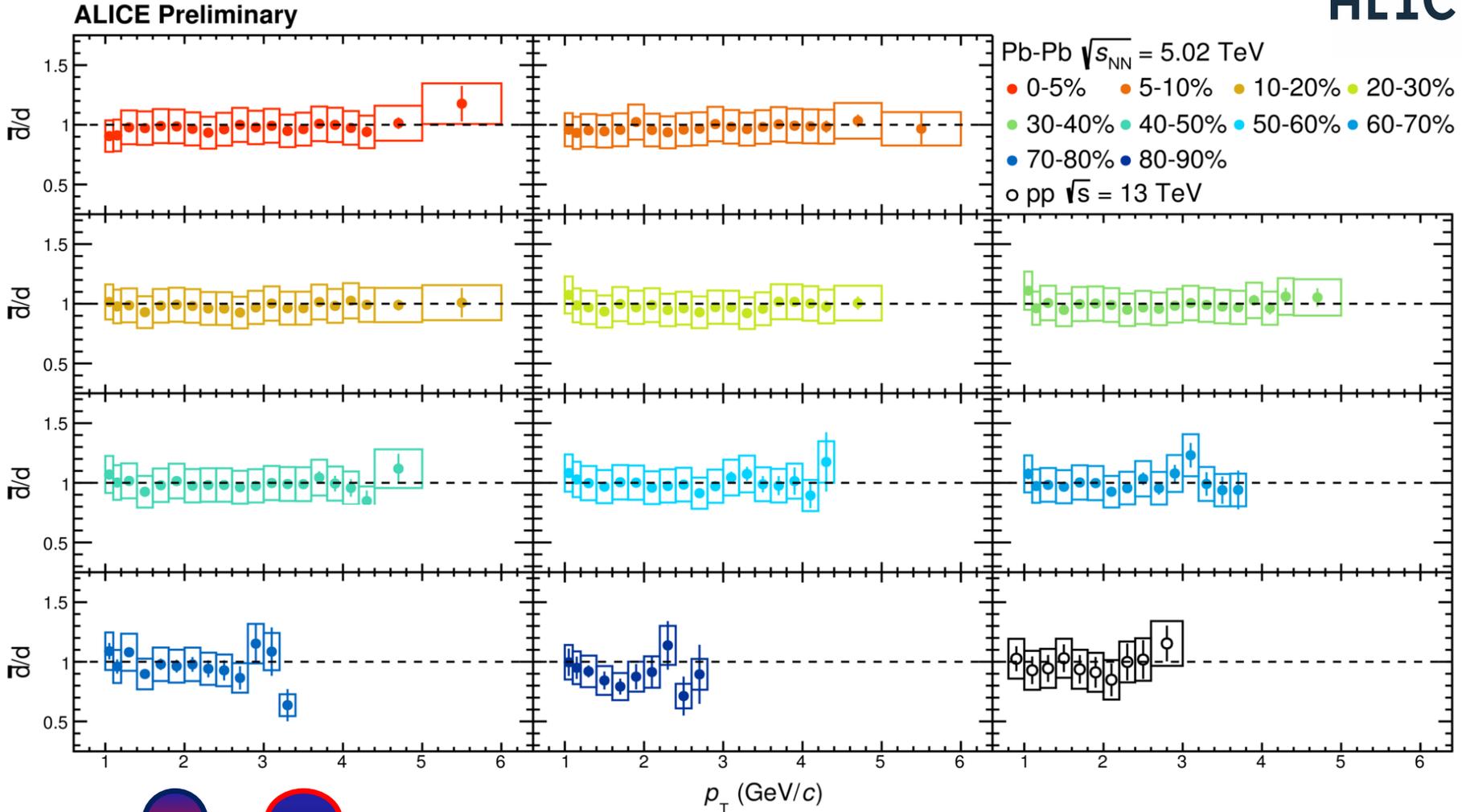


- p_T -spectra getting harder for more central collisions (from pp to Pb-Pb) → showing clear radial flow
- Blast-Wave fits describe the data in Pb-Pb very well
- No hint for radial flow in pp

(Anti-)Deuteron ratio



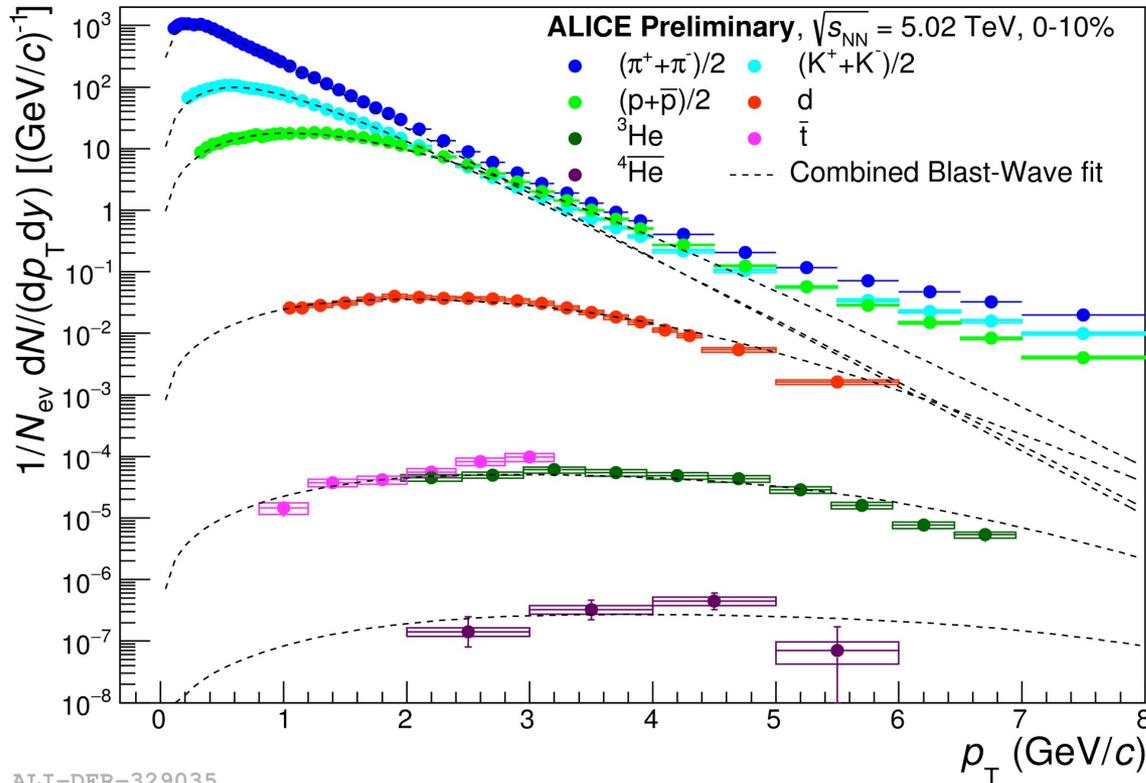
ALICE



-ratios consistent with unity, as expected

Combined Blast-Wave fit

ALICE Collaboration, arXiv:1910.07678



ALI-DER-329035

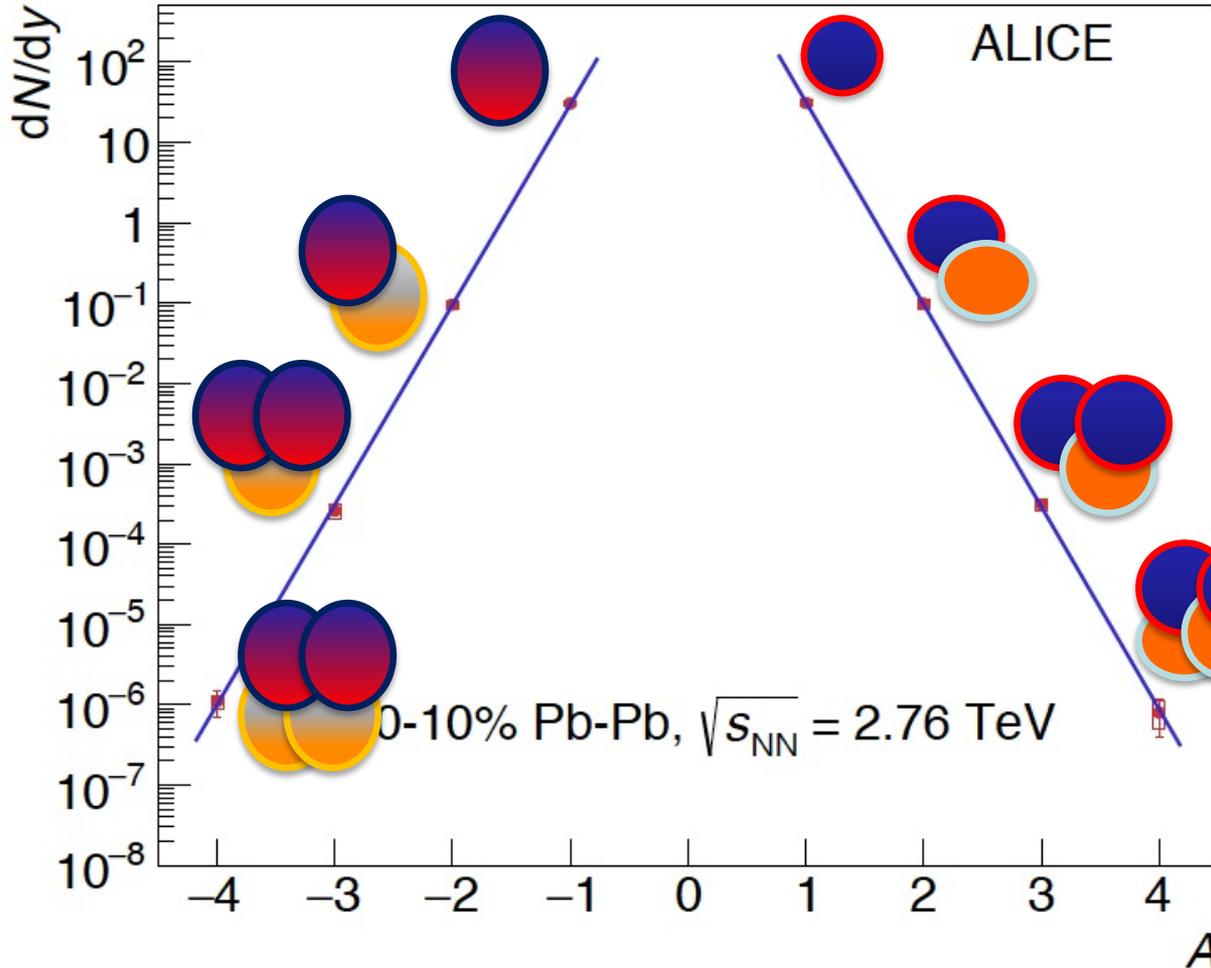
- Simultaneous Blast-Wave fit of π^+ , K^+ , p , d , t , ${}^3\text{He}$ and ${}^4\text{He}$ spectra for central Pb-Pb collisions leads to values for $\langle\beta\rangle$ and T_{kin} close to those obtained when only π, K, p are used

- All particles are described rather well with this simultaneous fit

Mass dependence



ALICE



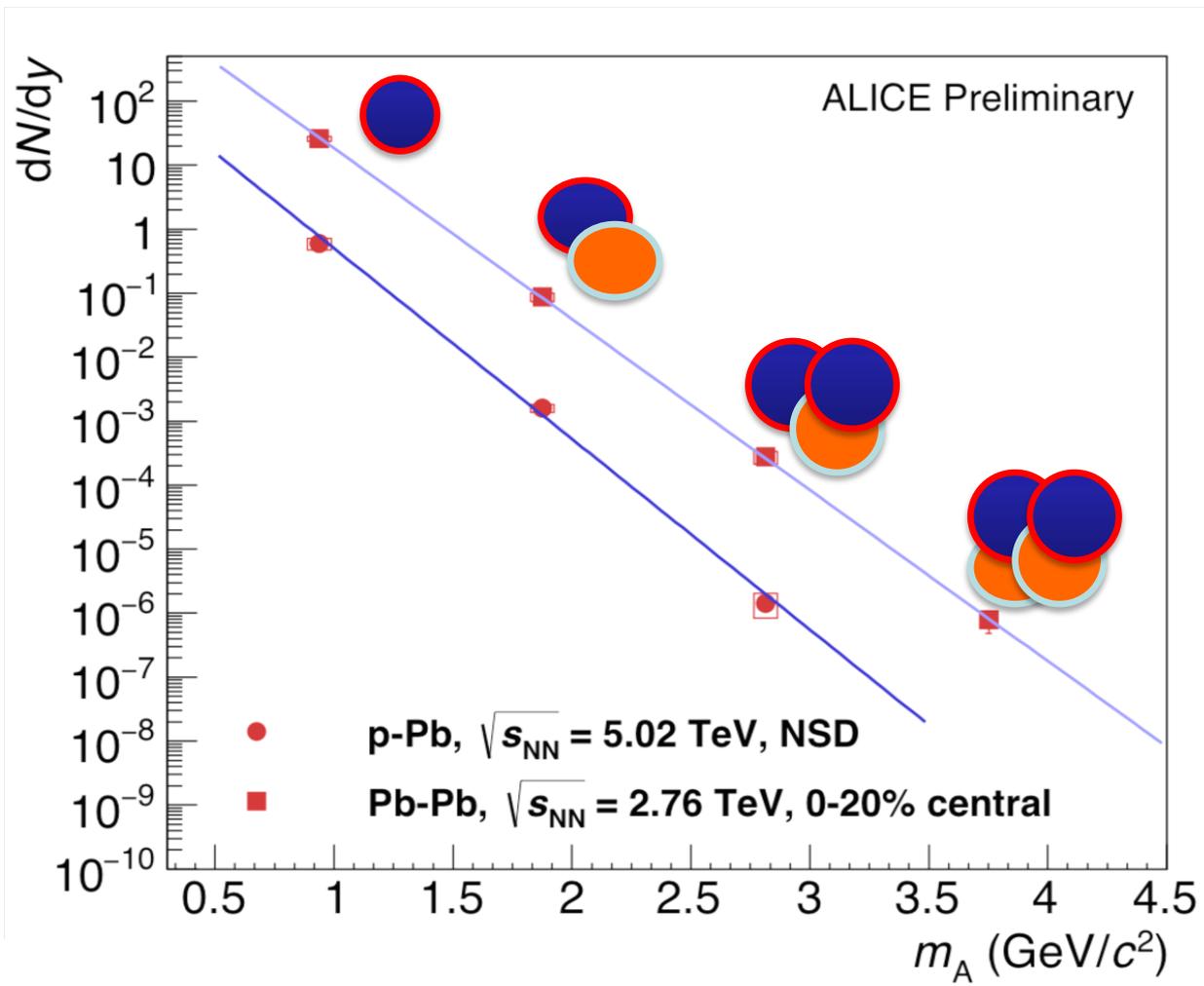
- Production of (anti-) nuclei is following an **exponential**, and decreases with mass as expected from thermal model
- In Pb-Pb the „penalty factor“ for each additional baryon ~ 300 (for particles and anti-particles)

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

Mass dependence

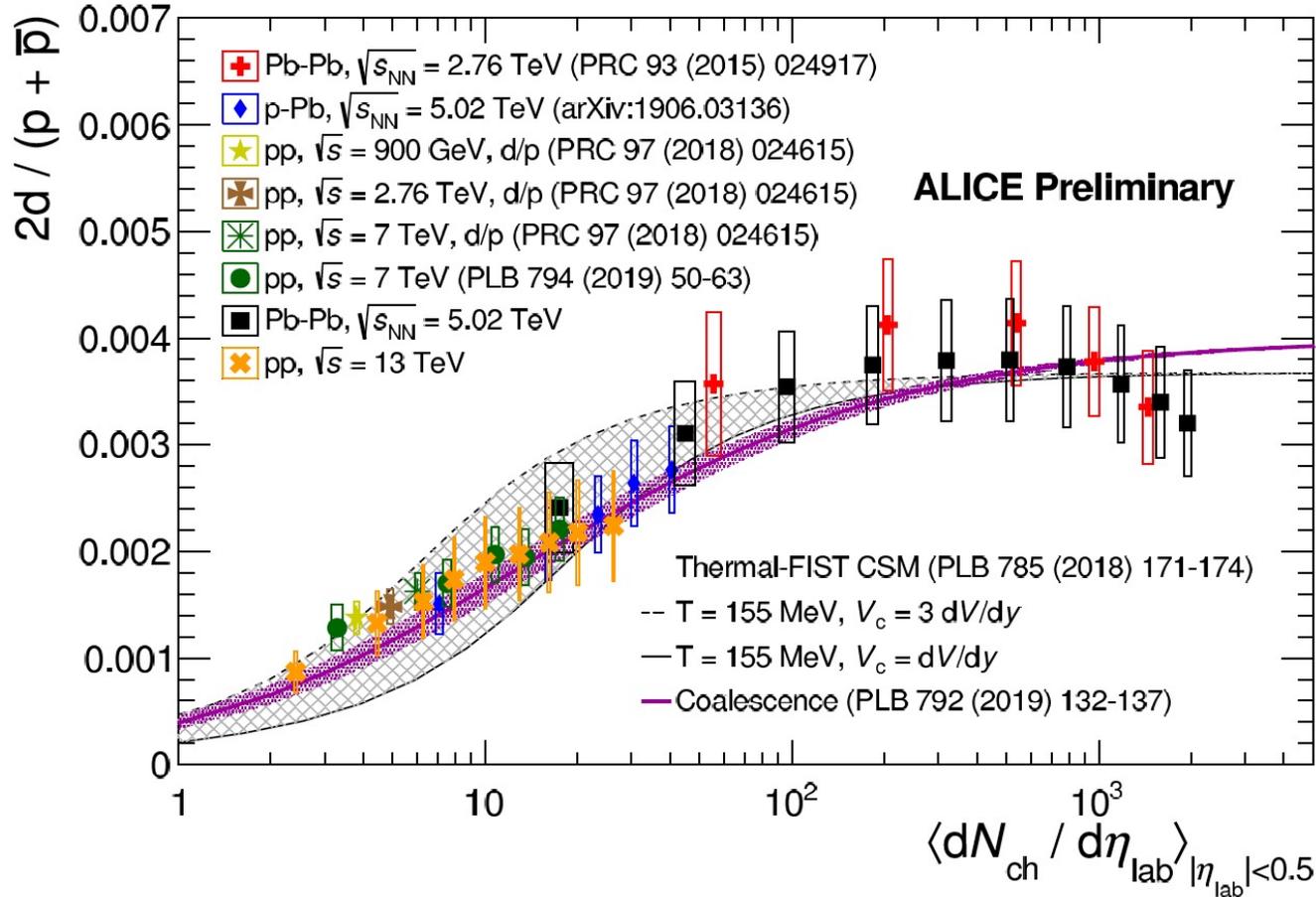
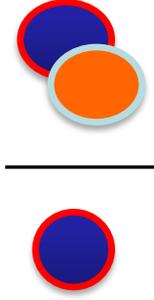


ALICE



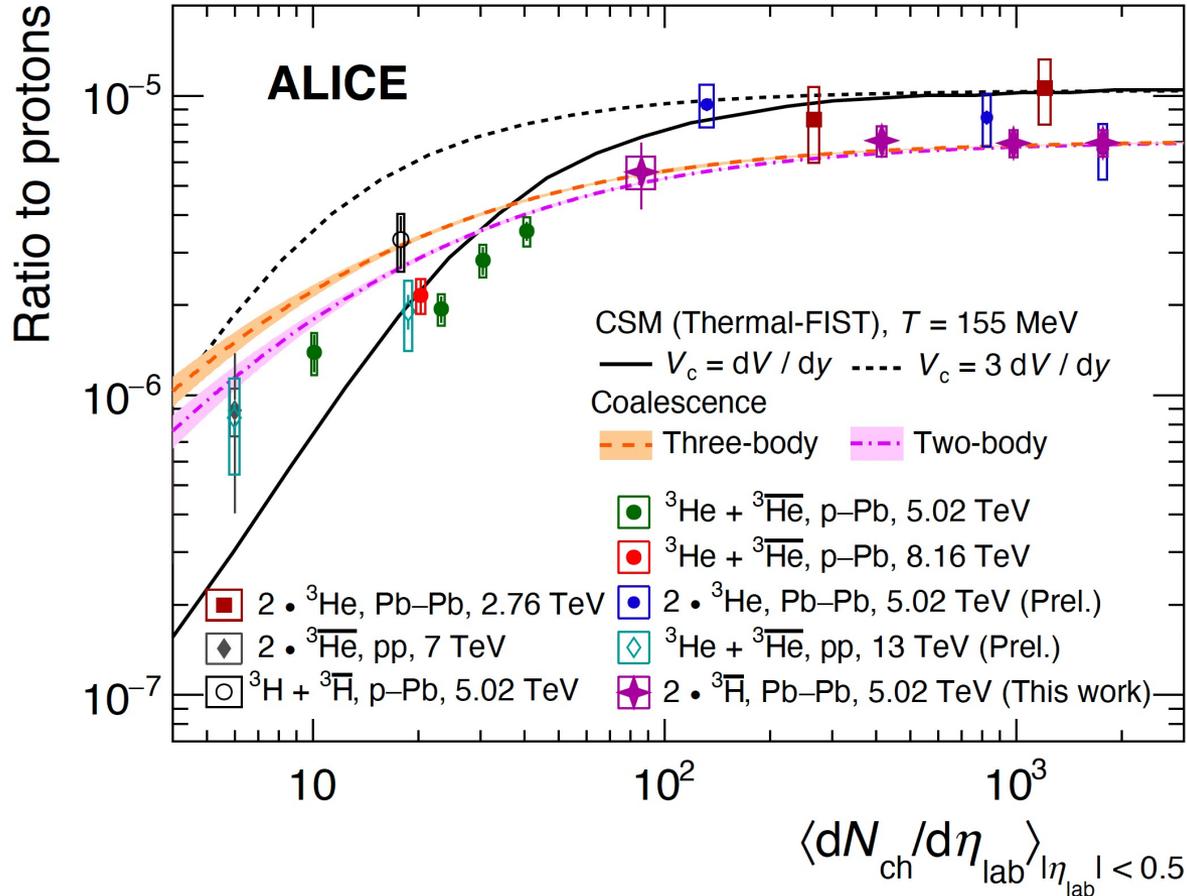
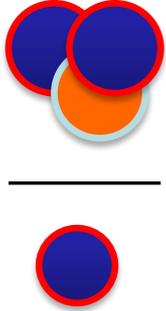
- Production of (anti-) nuclei is following an **exponential**, and decreases with mass as expected from thermal model
- In Pb-Pb the „penalty factor“ for each additional baryon ~ 300 , in p-Pb ~ 600 and in pp ~ 1000

d/p vs. multiplicity



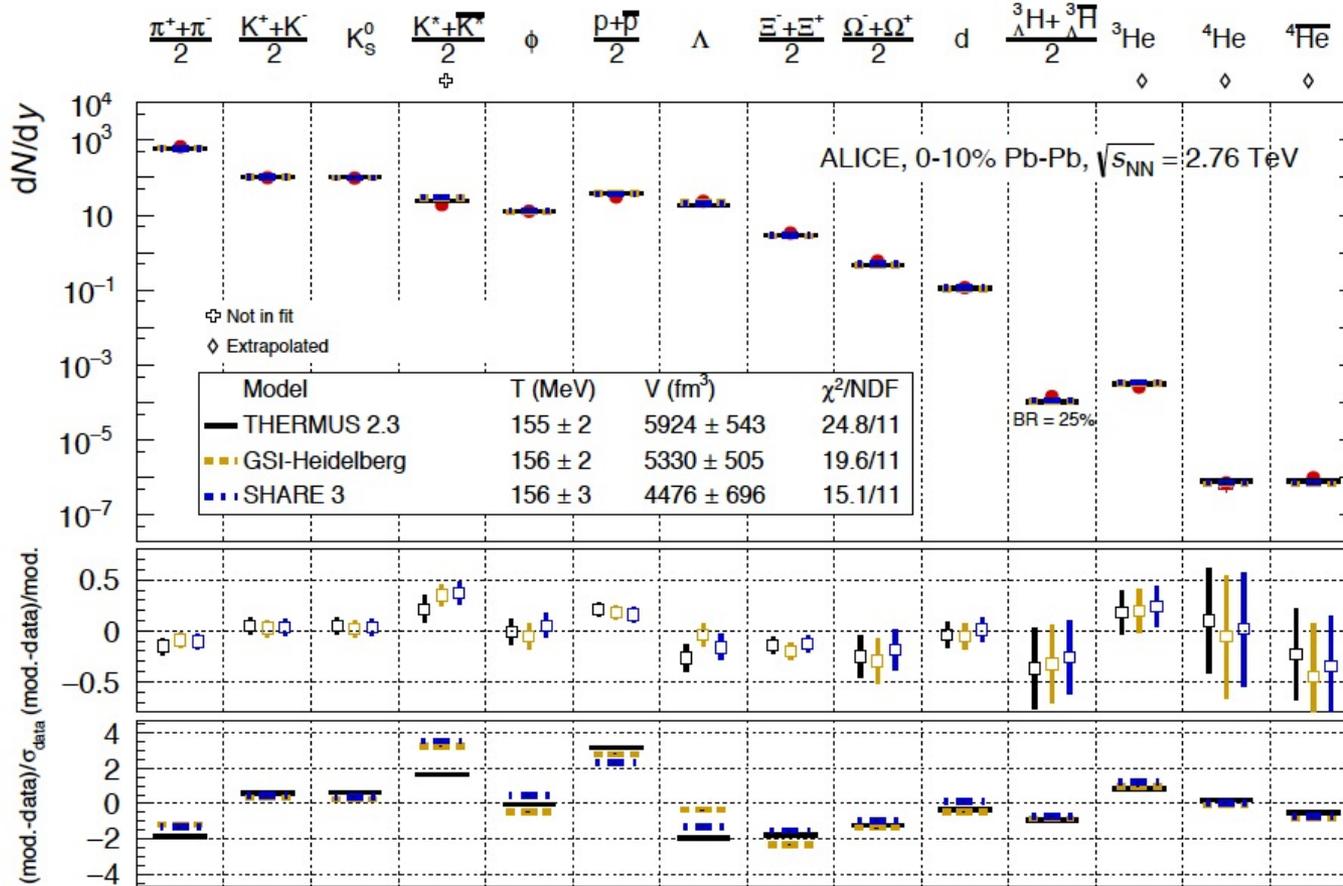
d/p ratio rather well described by coalescence and (canonical) thermal model

$^3\text{He}/p$ vs. multiplicity



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

Thermal model

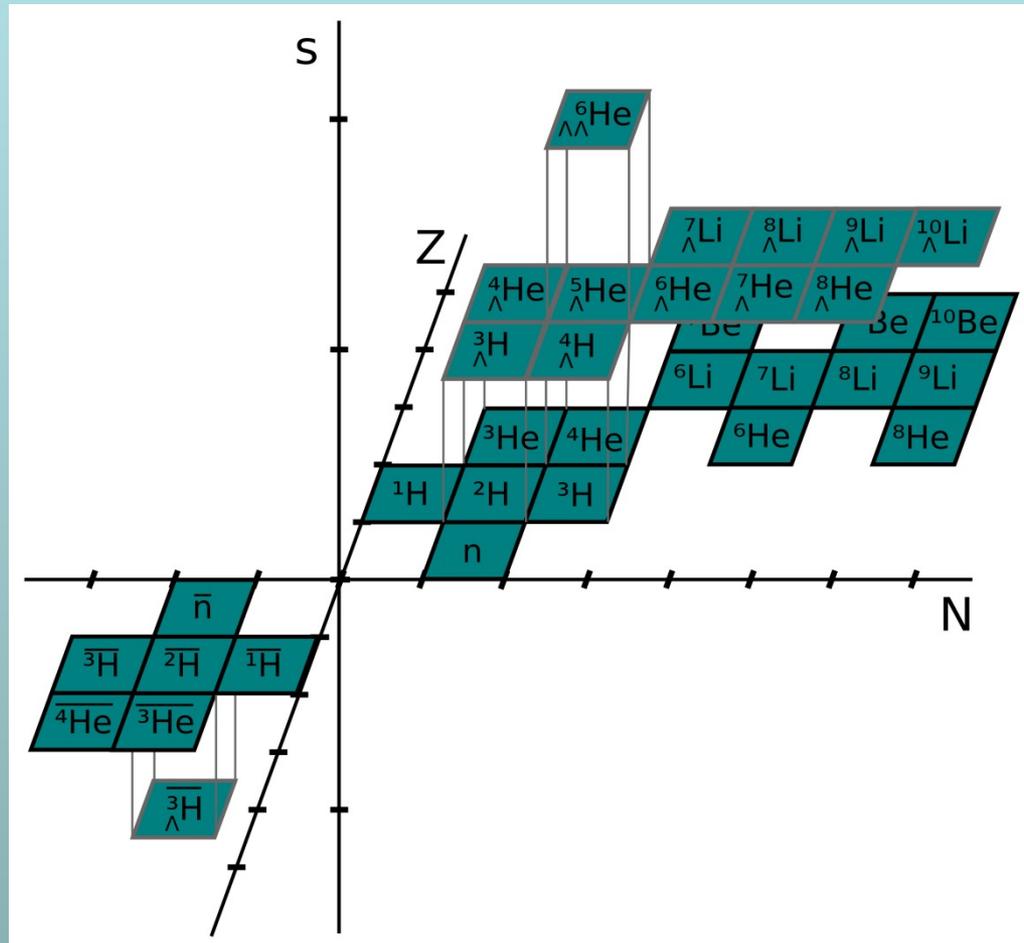


THERMUS: S. Wheaton, et al., CPC 180, 84 (2009)
 GSI-Heidelberg: A. Andronic, et al., PLB 697, 203 (2011); PLB 673, 142 (2009) 142
 SHARE3: G. Torrieri, et al., CPC 167, 229 (2005); CPC 175, 635 (2006); CPC 185, 2056 (2014)

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 temperature of about $T_{ch} = 156$ MeV

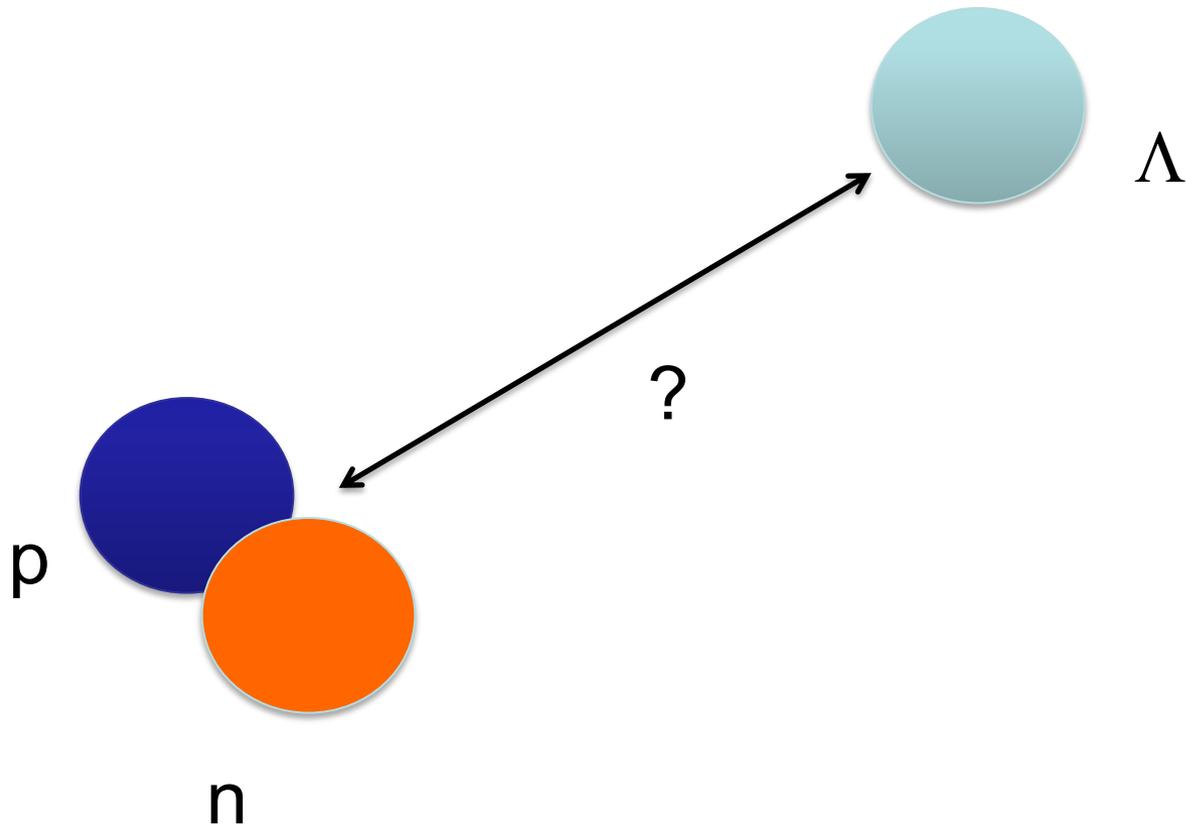
Hypernuclei



Hypertriton

Bound state of Λ , p, n

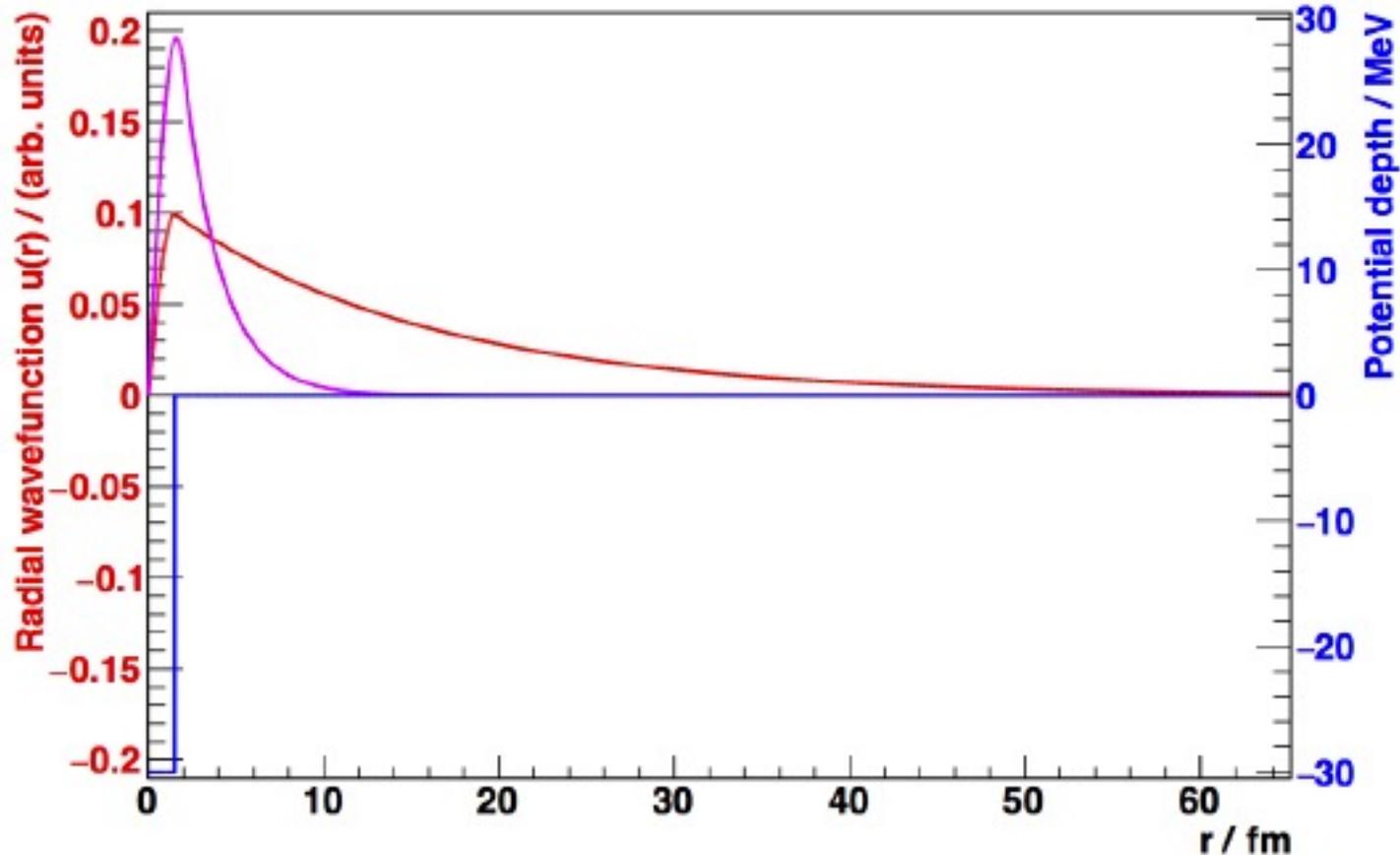
$$m = 2.991 \text{ GeV}/c^2 \quad (B_\Lambda = 130 \text{ keV})$$



Hypertriton

Bound state of Λ , p, n

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

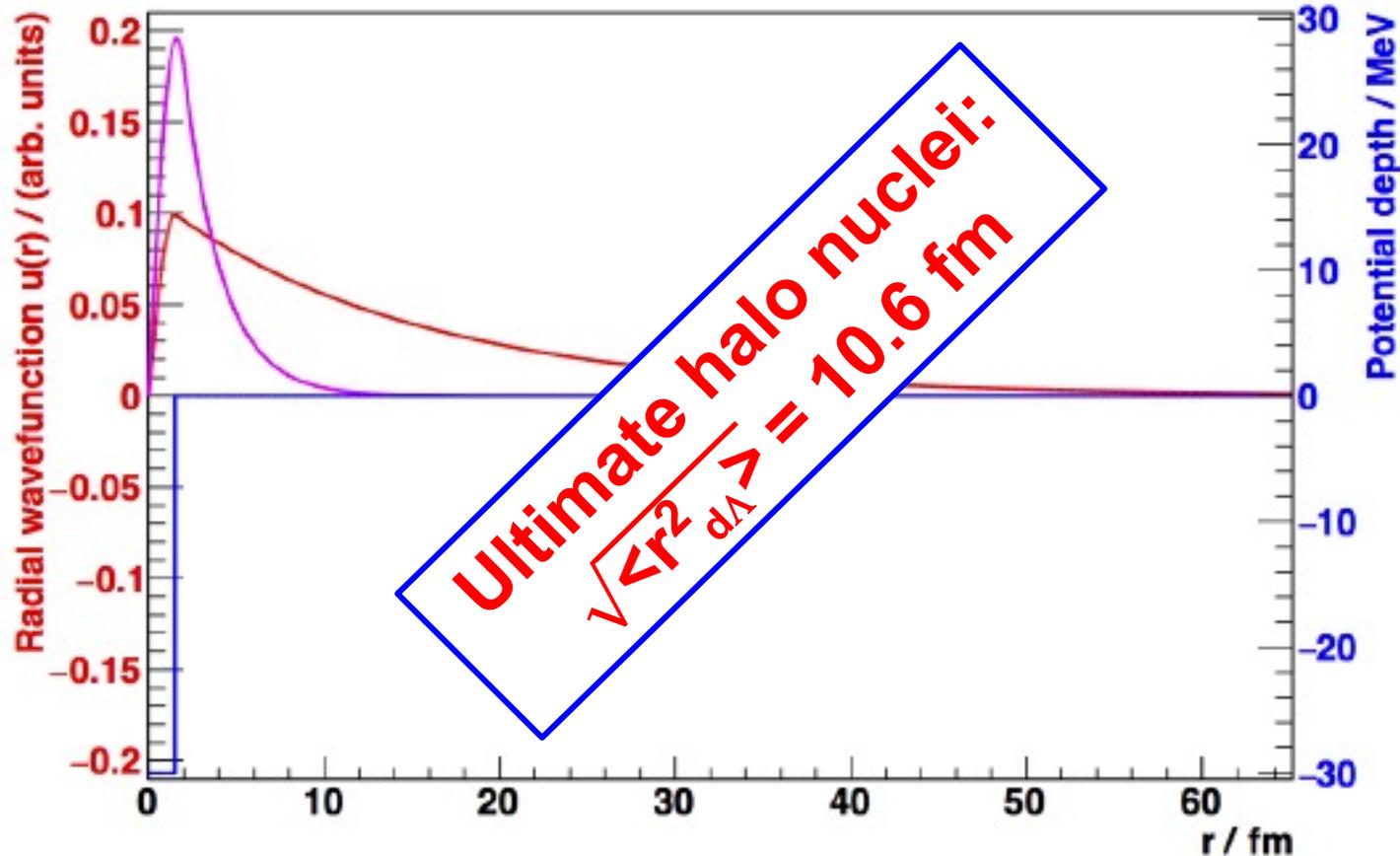


P. Braun-Munzinger, BD, Nucl. Phys. A 987 (2019) 144

Hypertriton

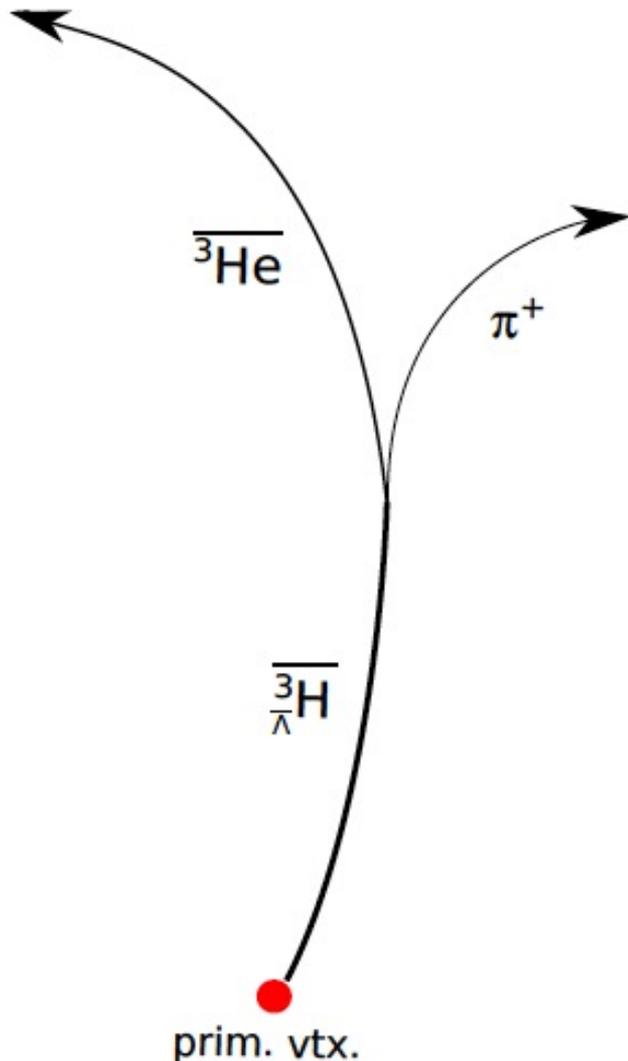
Bound state of Λ , p, n

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



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

Hypertriton Identification

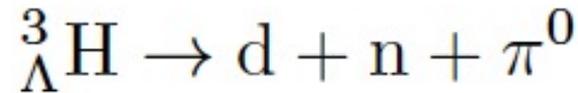
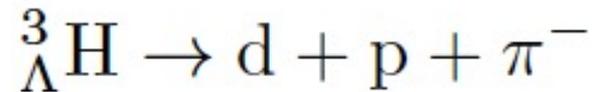
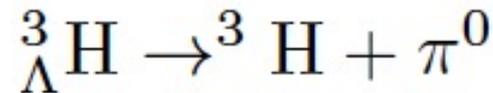
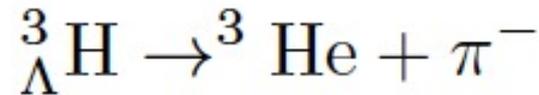


Bound state of Λ , p, n

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

→ Radius of about 10.6 fm

Decay modes:

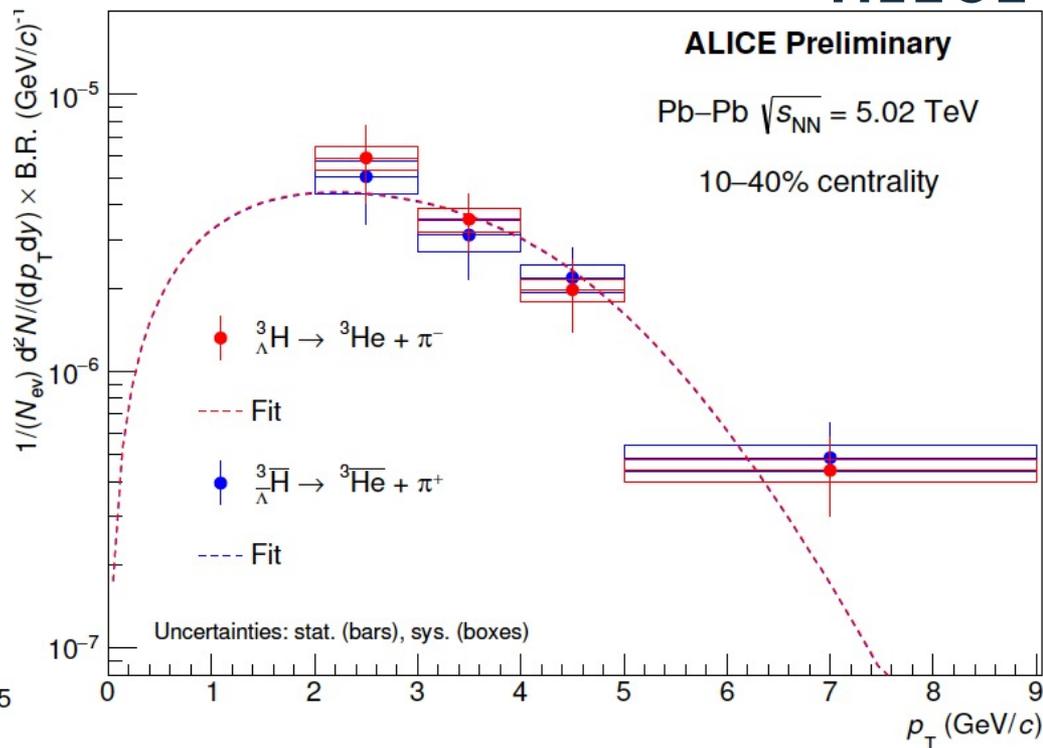
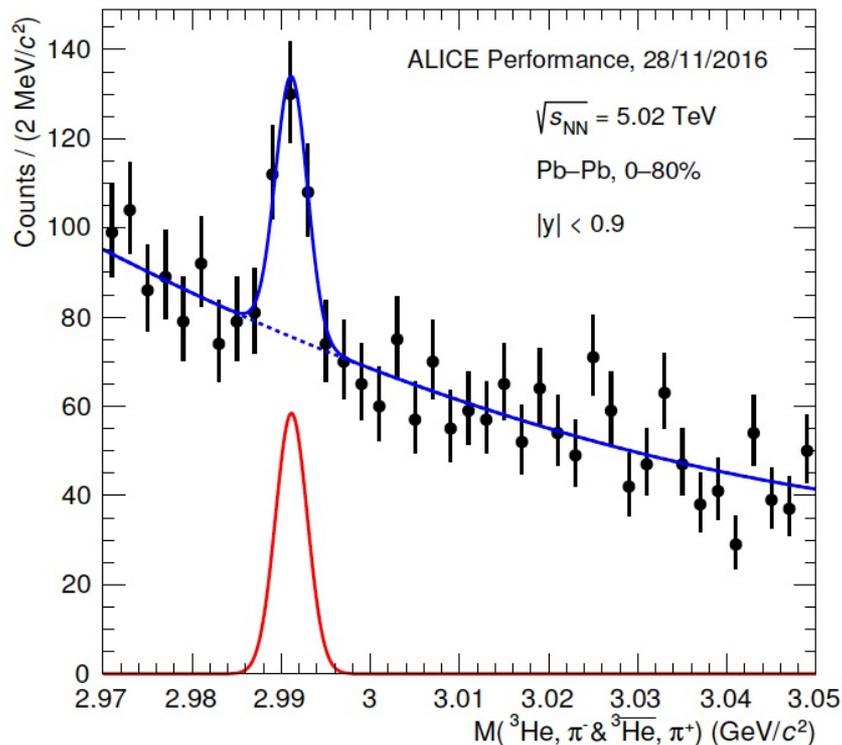


+ anti-particles

→ Anti-Hypertriton first observed by
STAR Collaboration:

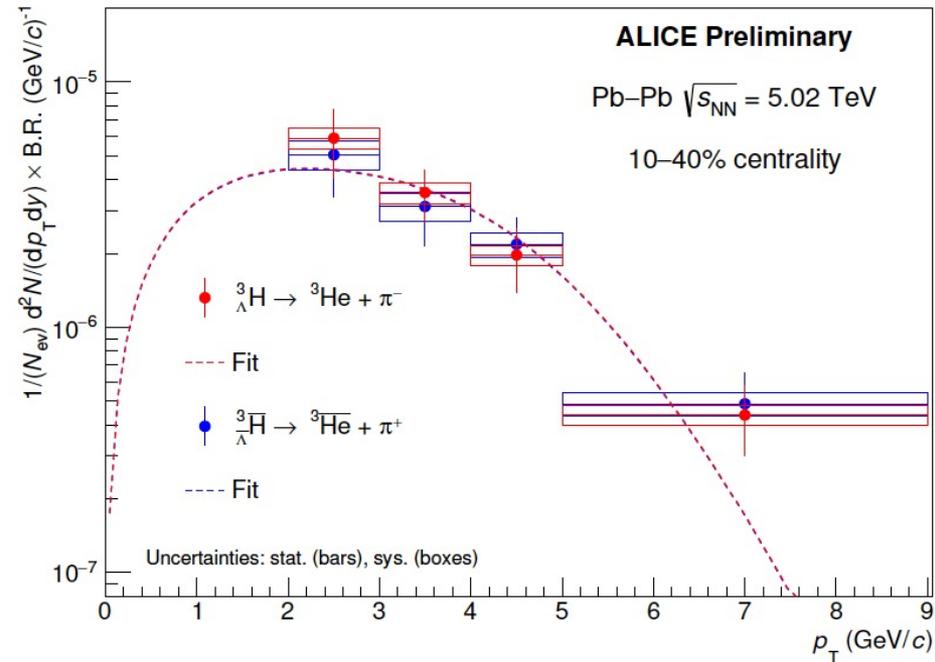
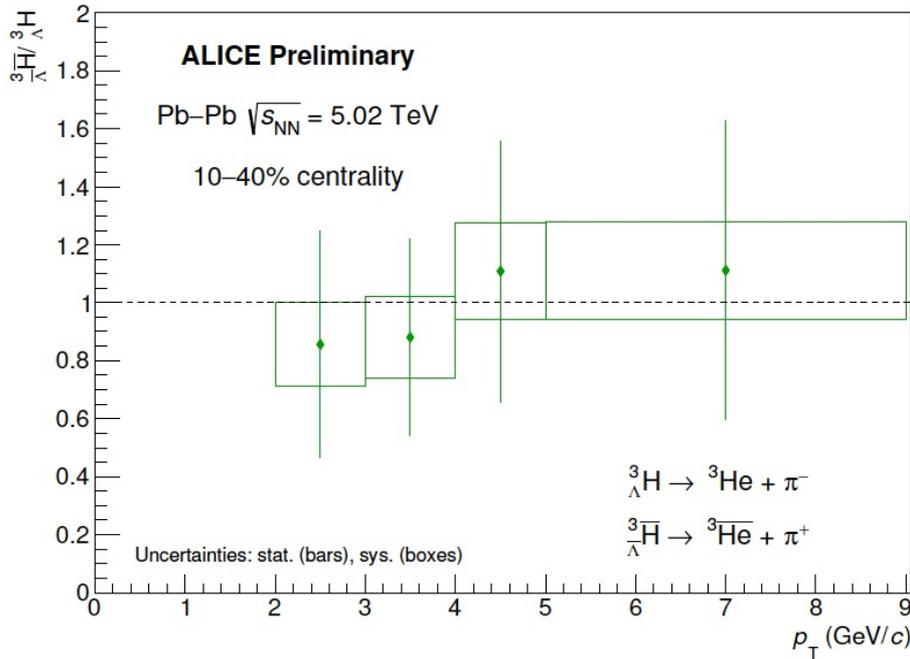
Science 328,58 (2010)

Hypertriton signal



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

Hypertriton spectra



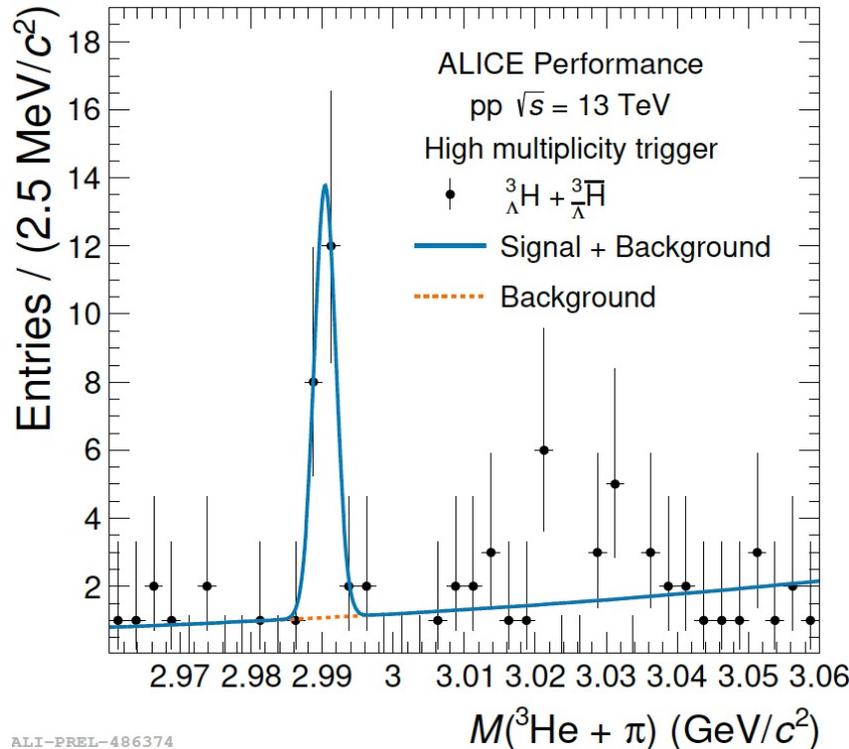
- Anti-hypertriton/Hypertriton ratio consistent with unity vs. p_T



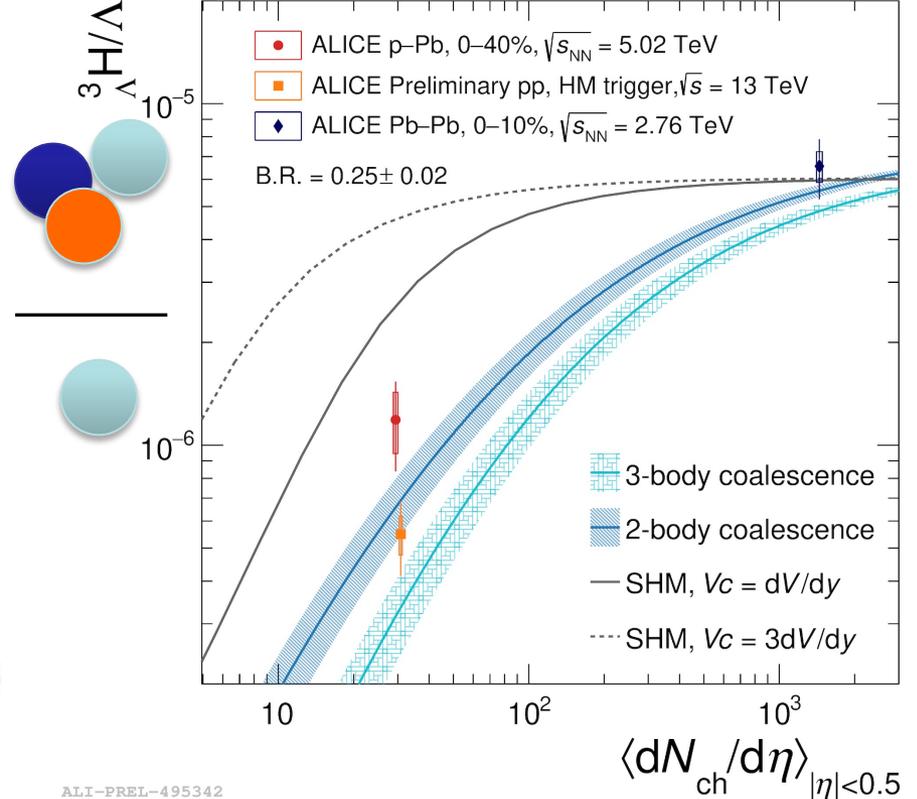
Hypertriton in pp & p-Pb



- 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



ALI-PREL-486374

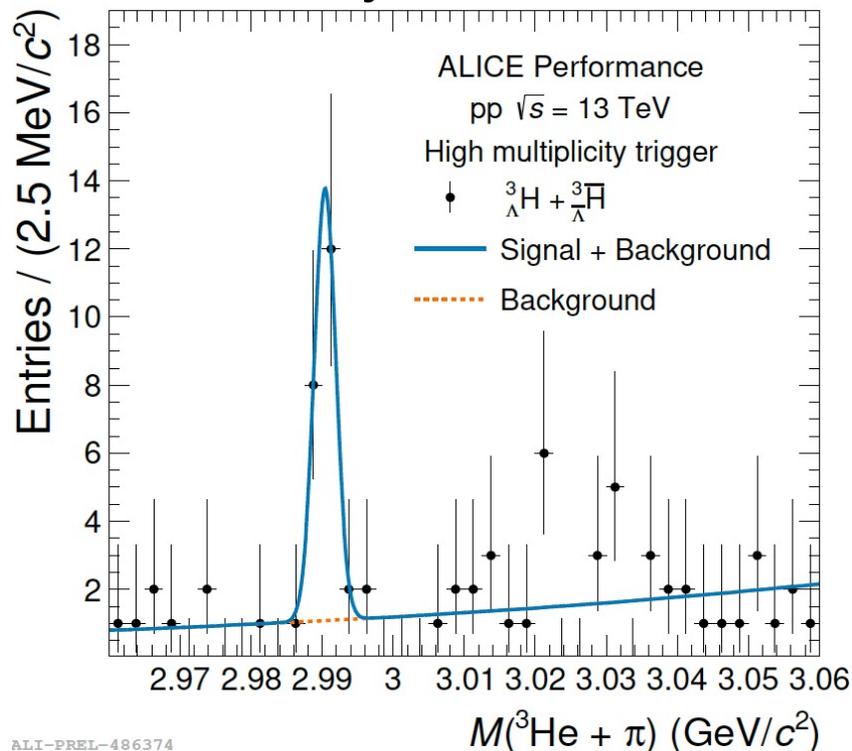


ALI-PREL-495342

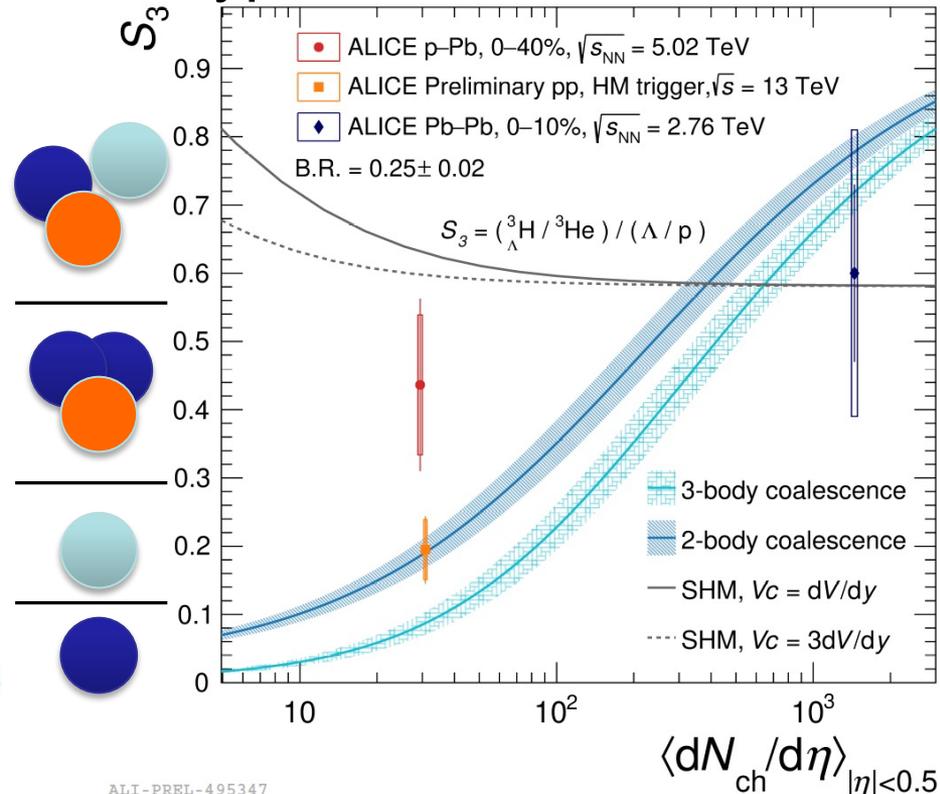


Hypertriton in pp & p-Pb

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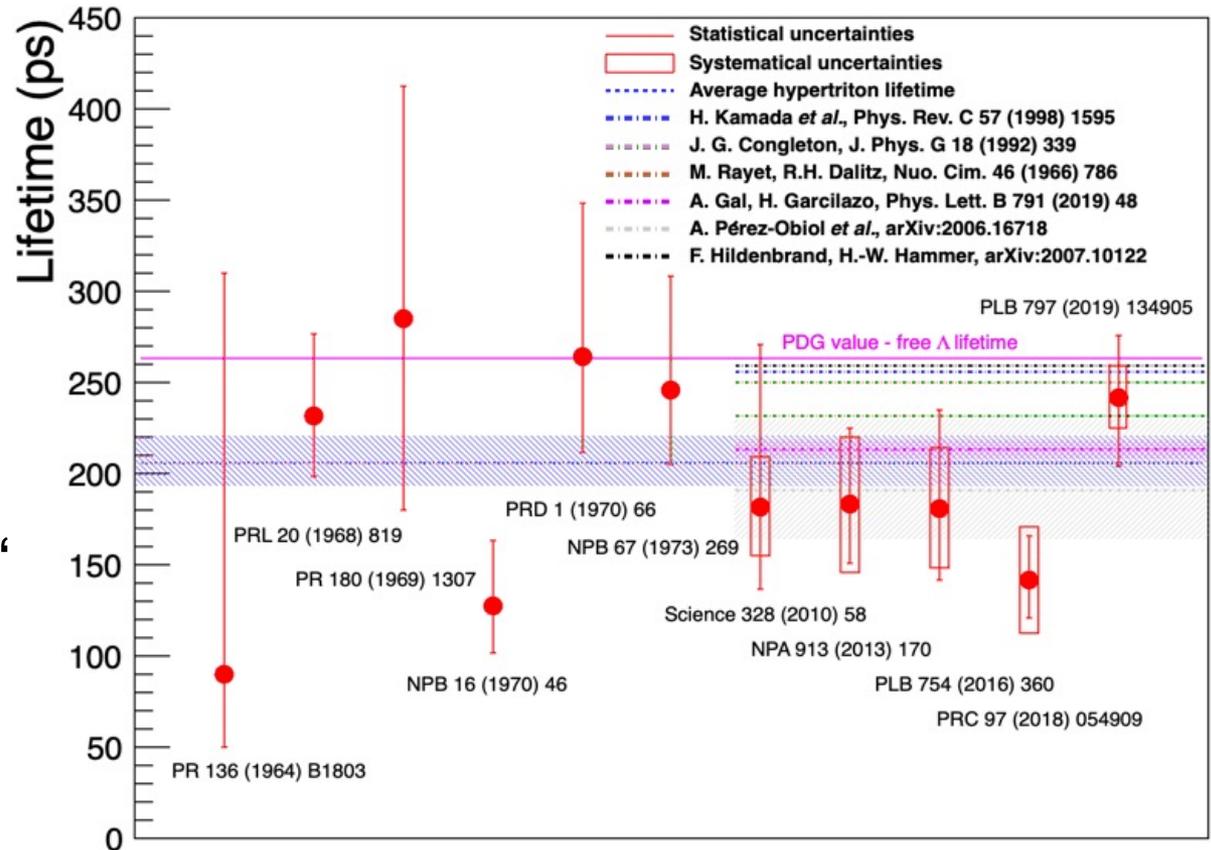
ALI-PREL-486374



ALI-PREL-495347

Hypertriton „Puzzle“

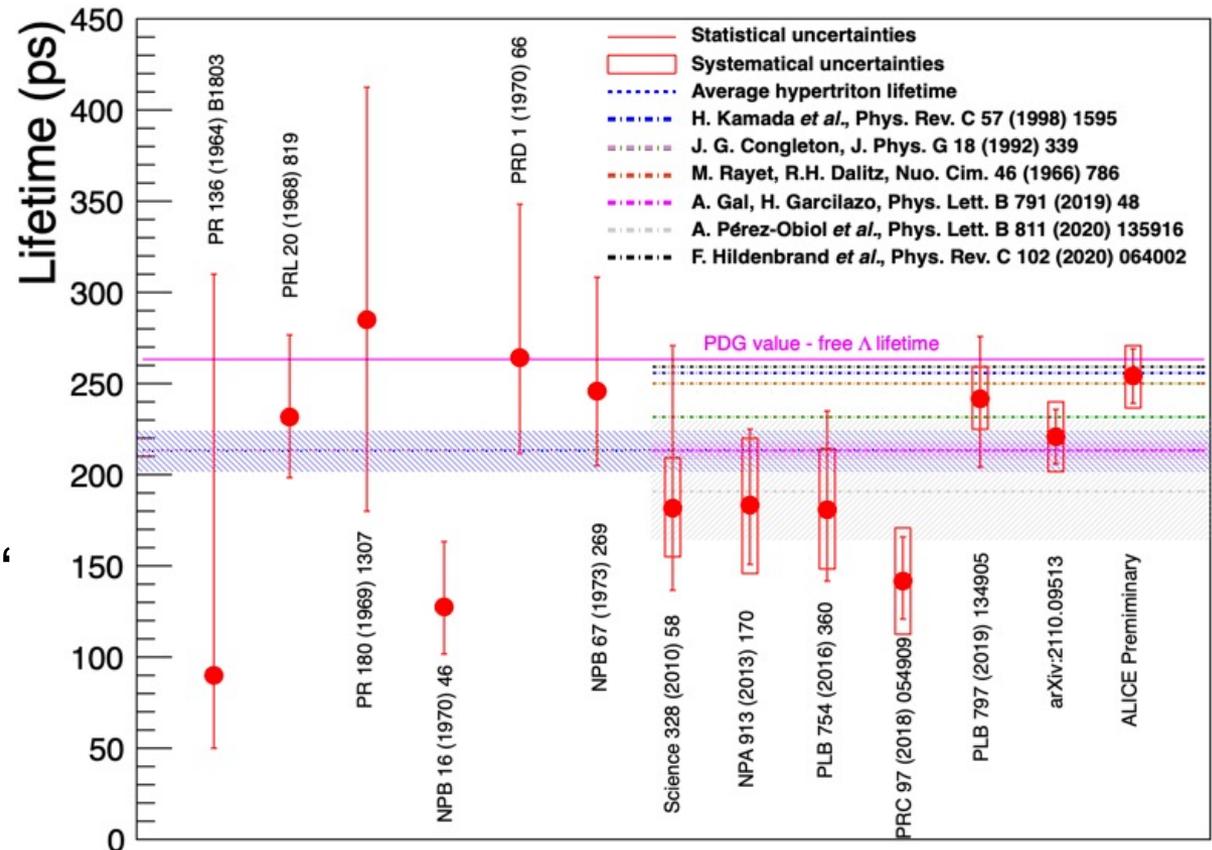
- Recently measured lifetimes are significantly below the lifetime of the free $\Lambda \rightarrow$ new ALICE results agree with the world average of all known measurements and with the free Λ lifetime
- Most recent calculations include „final-state“ interaction and agree well with the data



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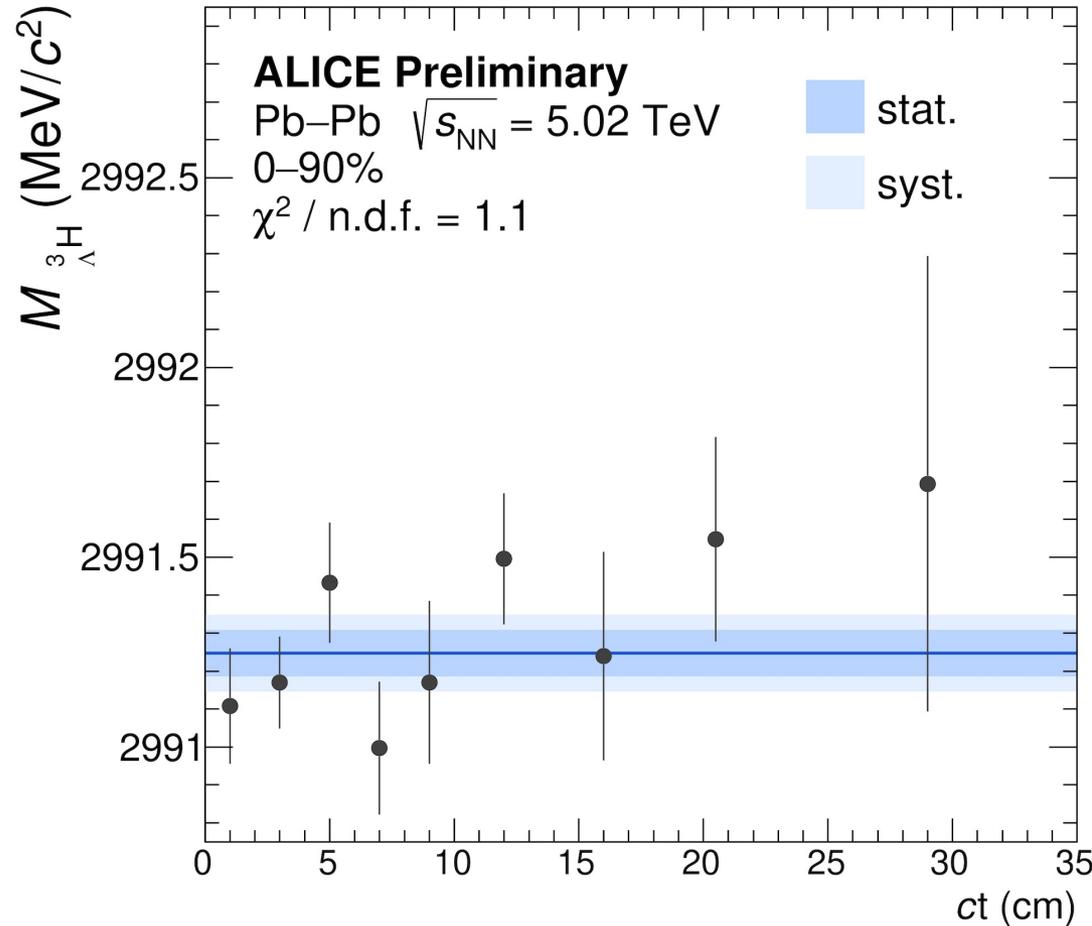
Hypertriton „Puzzle“

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Binding Energy

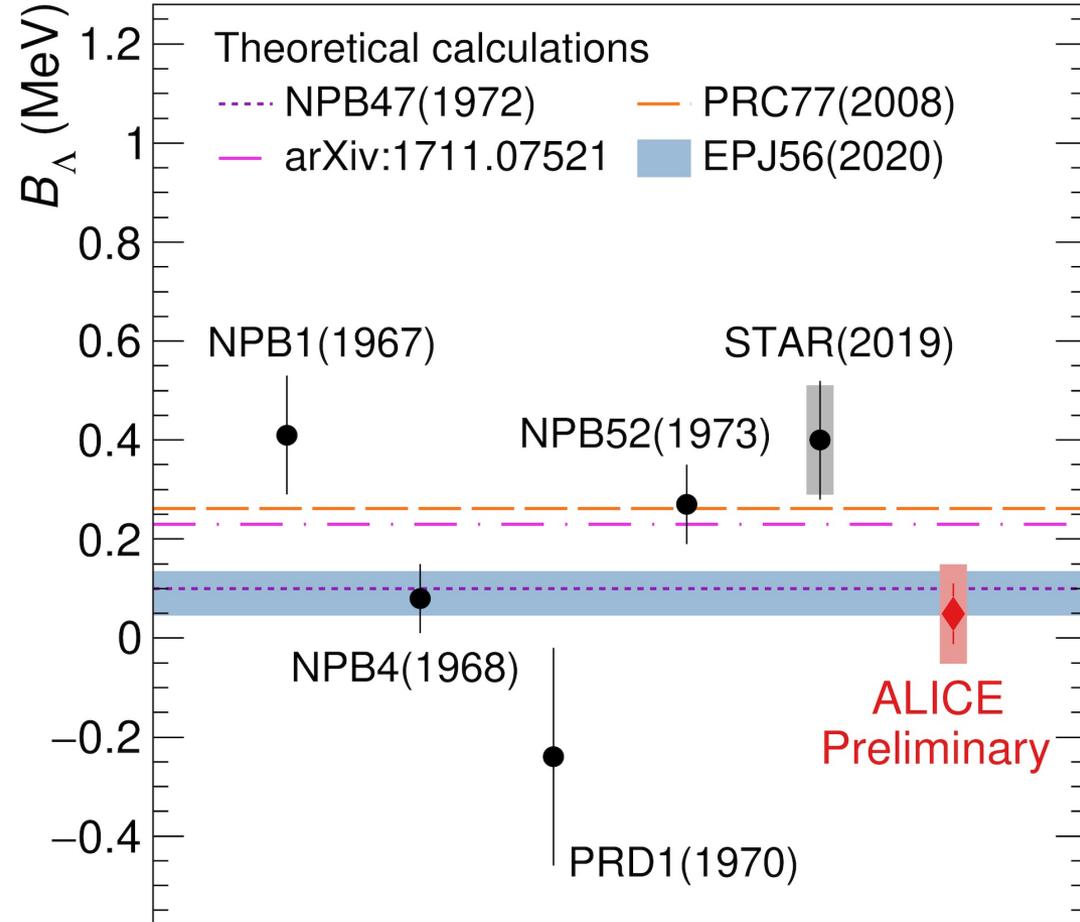
- Preliminary Result for SQM2019
- Current studies show a better constraint and smaller statistical uncertainties (will be published soon)
- The value obtained by this fit is $B_{\Lambda} = 55 \pm 62 \text{ keV}$



ALI-PREL-486366

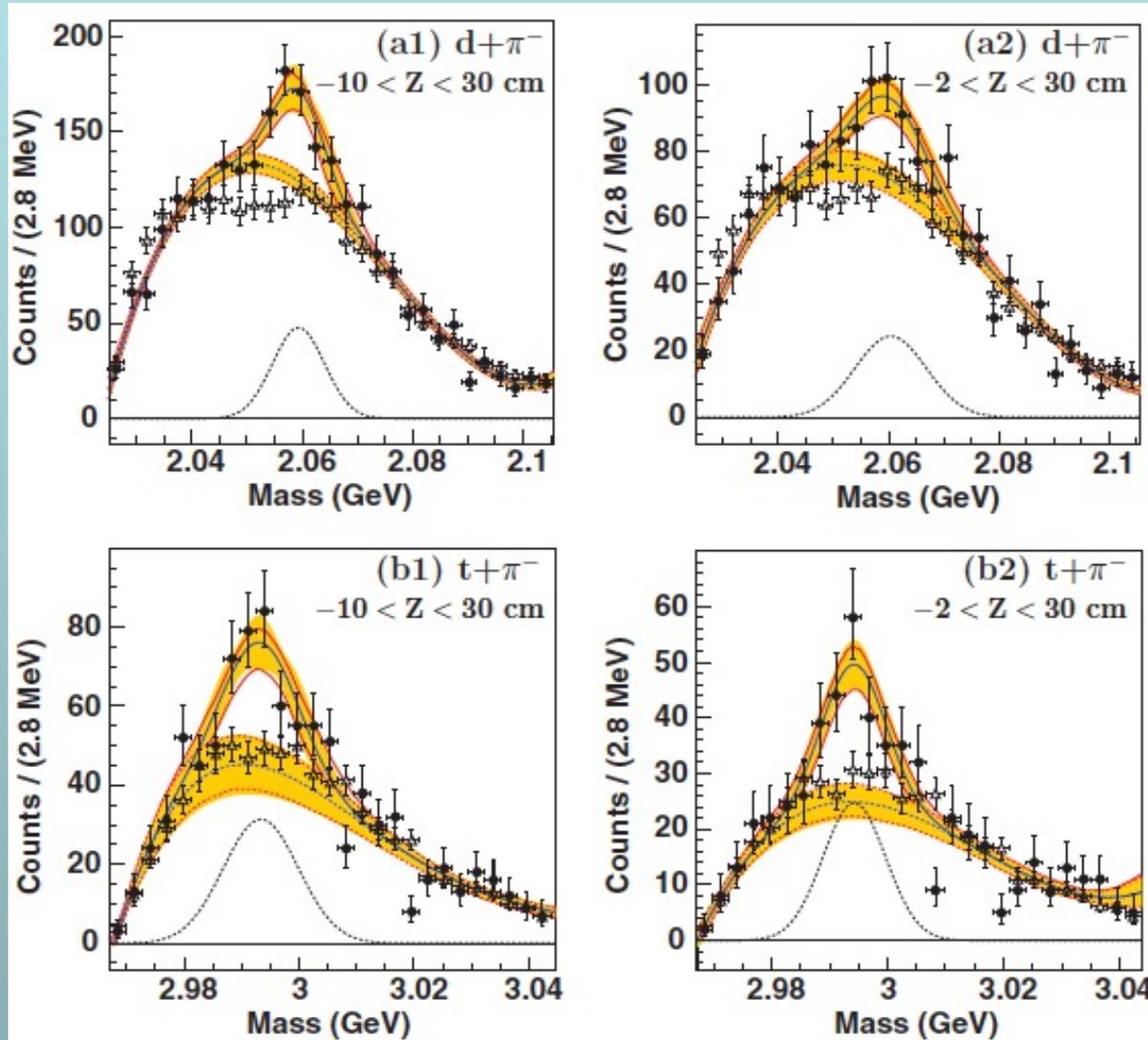
Binding Energy

- 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
 $B_{\Lambda} = 55 \pm 62 \text{ keV}$
- Is compatible within the theoretical predictions



ALI-PREL-486370

Exotica Searches



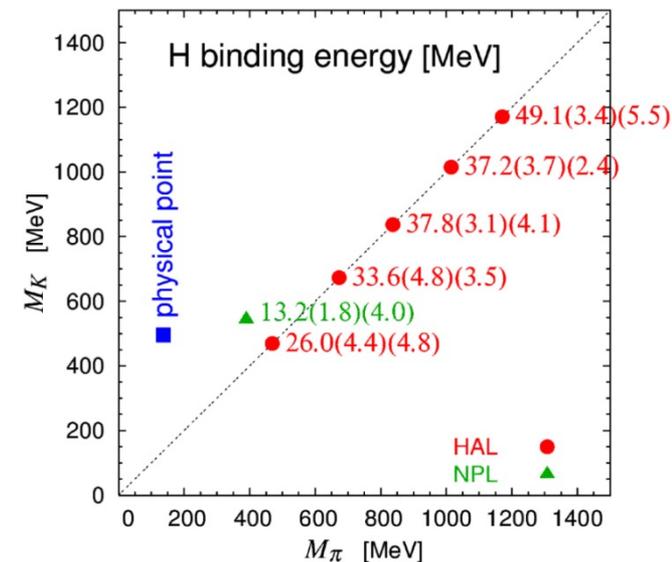
HypHI
Collaboration
observed signals
in the $t+\pi^-$ and $d+\pi^-$
invariant mass
distributions

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/c² or 13 MeV/c²)
- *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/c² or lies close to the Ξp threshold

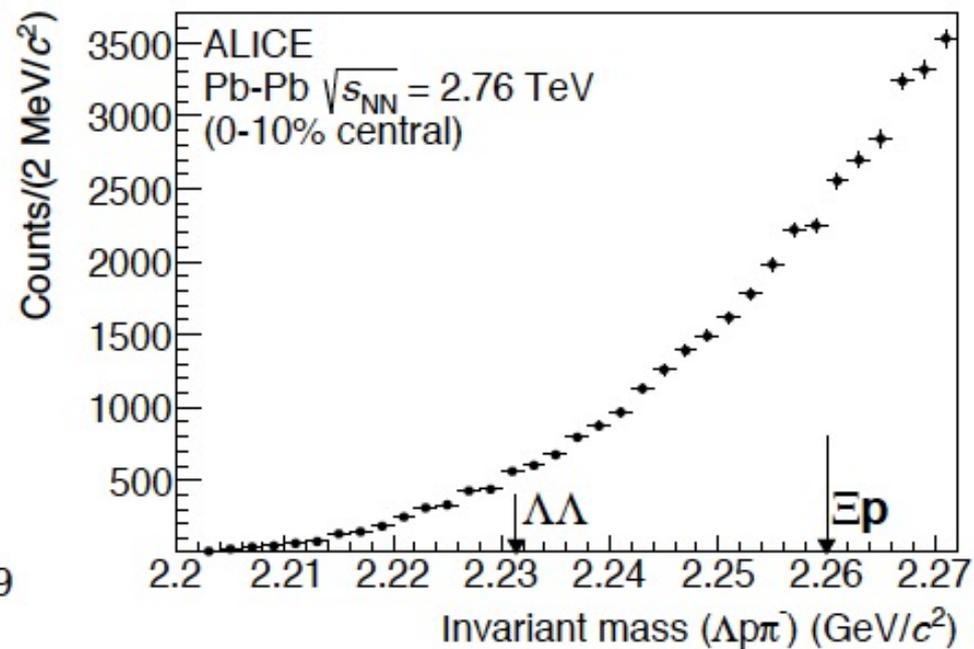
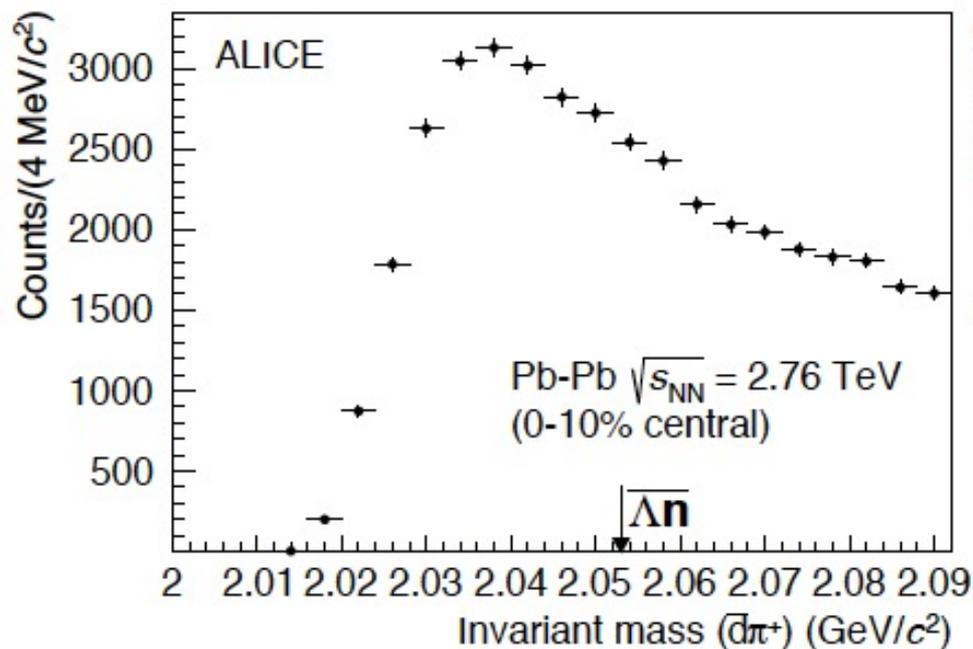
→ Renewed interest in experimental searches



T. Inoue, private communication

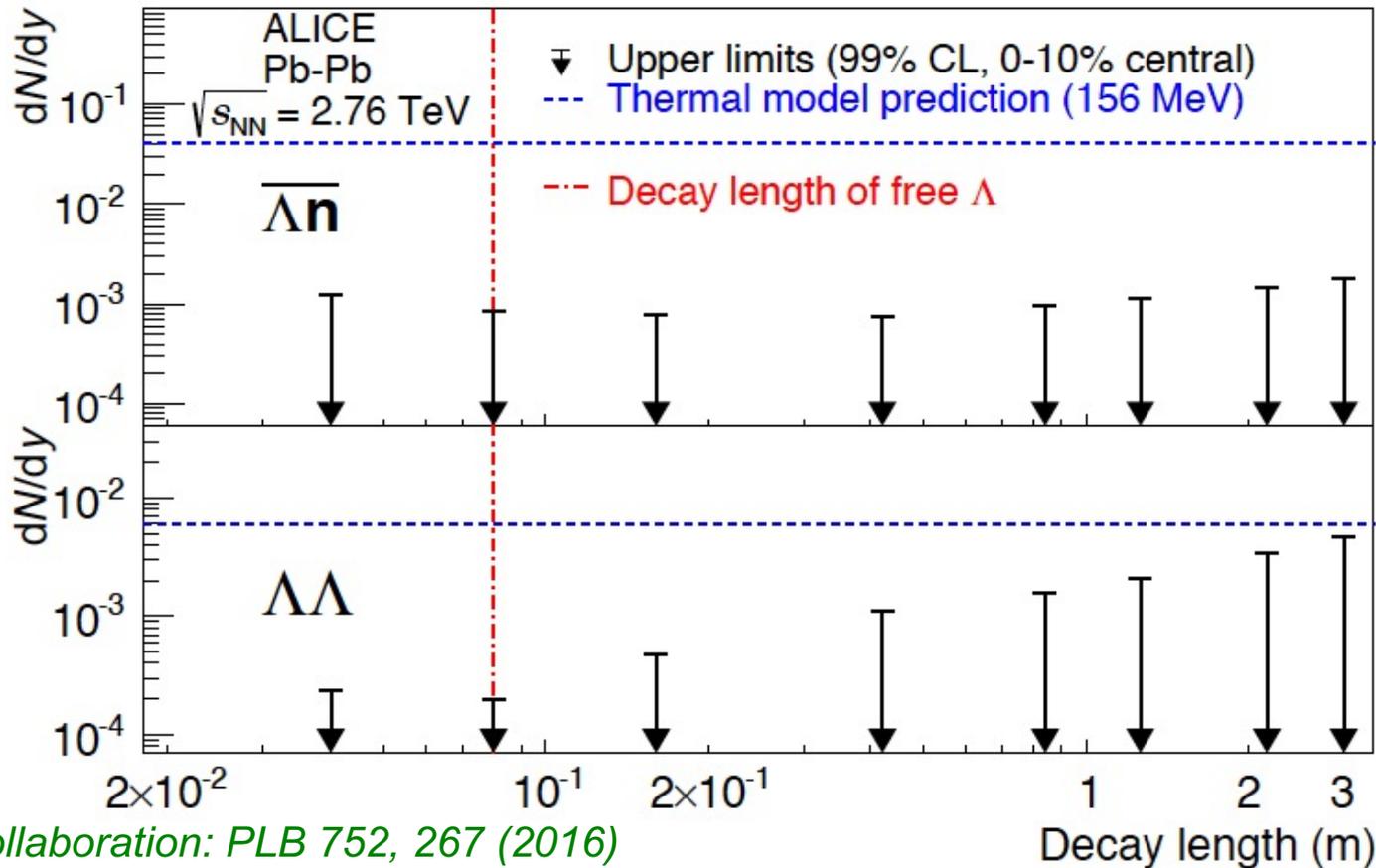
Searches for bound states

ALICE Collaboration: PLB 752, 267 (2016)



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

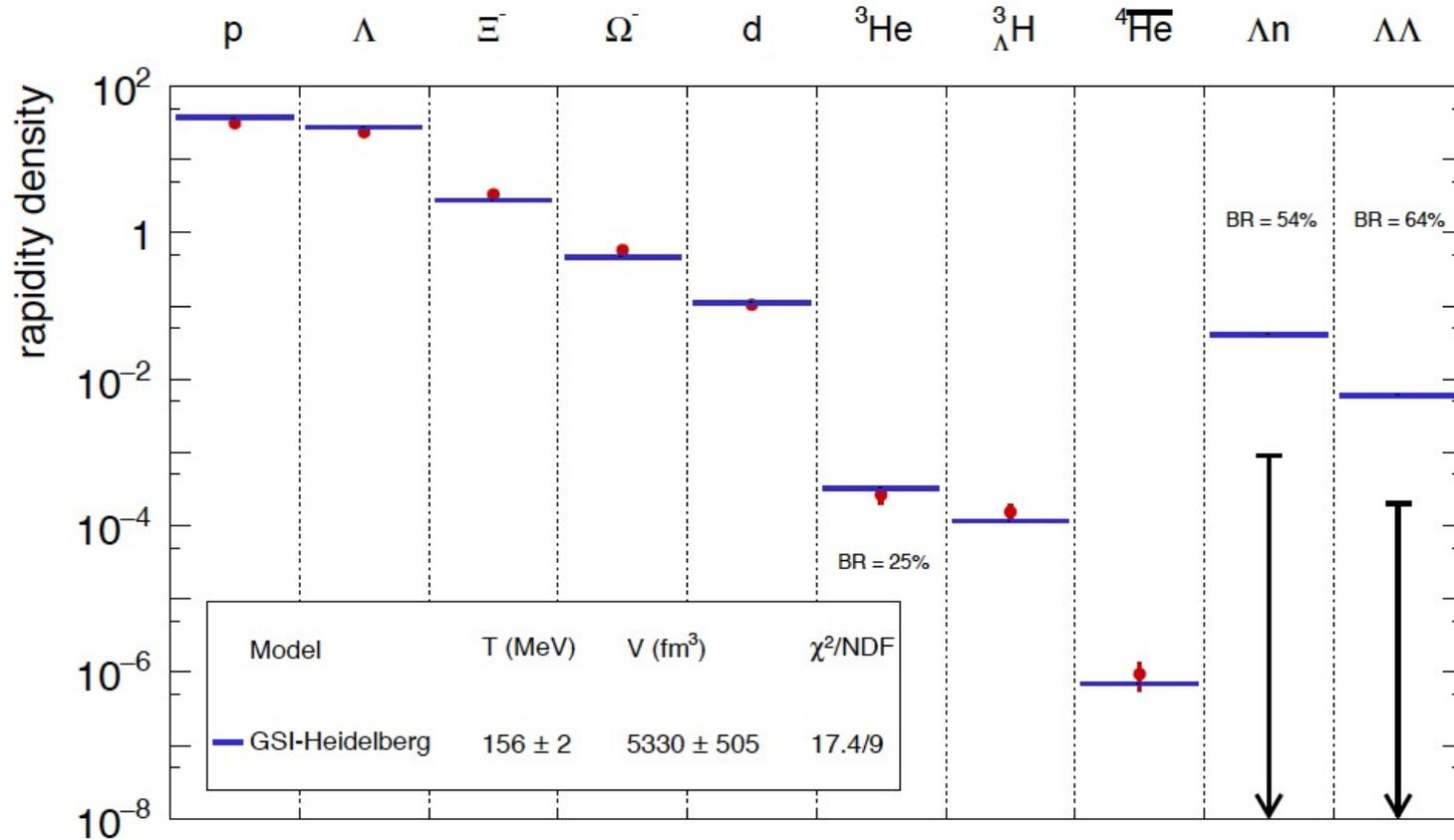
Decay length dependence



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

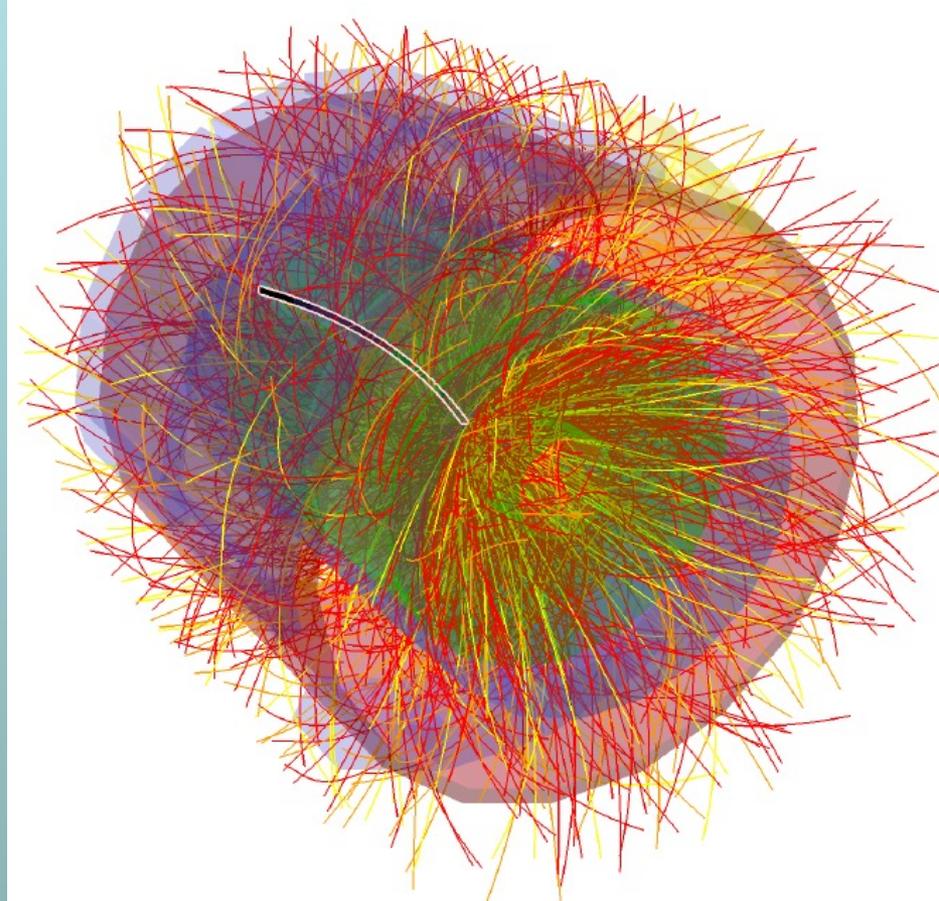


Simplified plot, CERN Courier (September 2015)

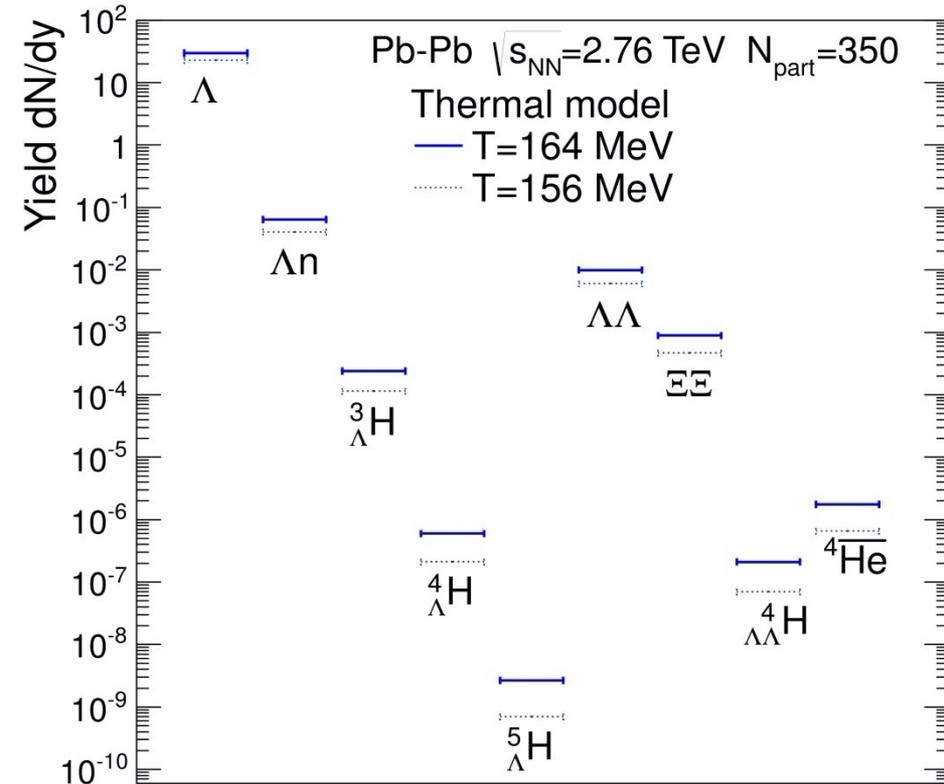
Hypertriton (B_{Λ} : 130 keV) and Anti-Alpha (B/A : 7 MeV) yields fit well with the thermal model expectations

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

Outlook & Summary



Outlook

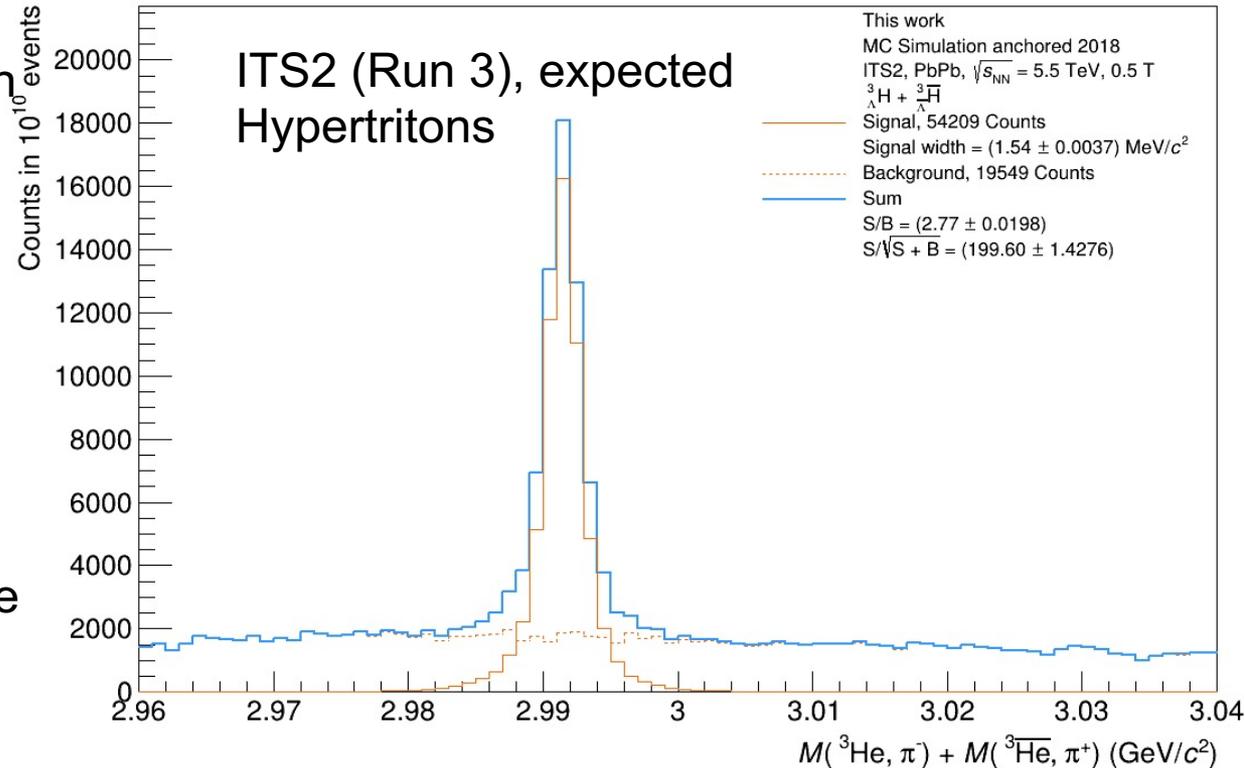


- Explore QCD and QCD inspired model predictions for (unusual) multi-baryon states
- Search for rarely produced anti- and hyper-matter
- Test model predictions, e.g. thermal and coalescence

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

Expectations

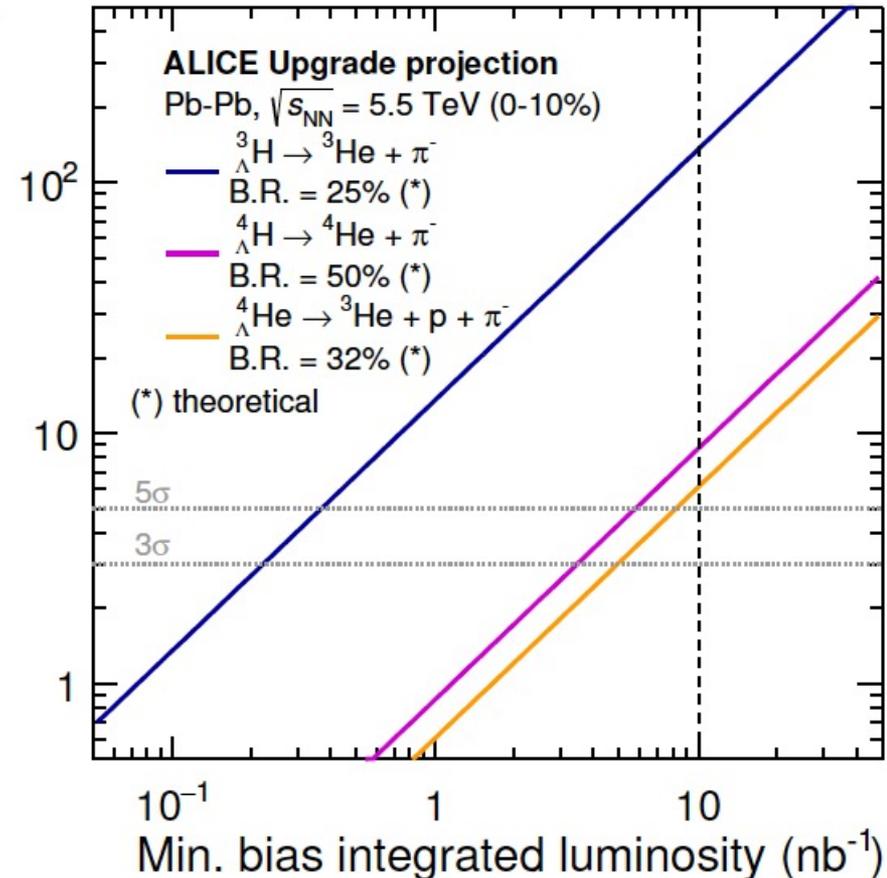
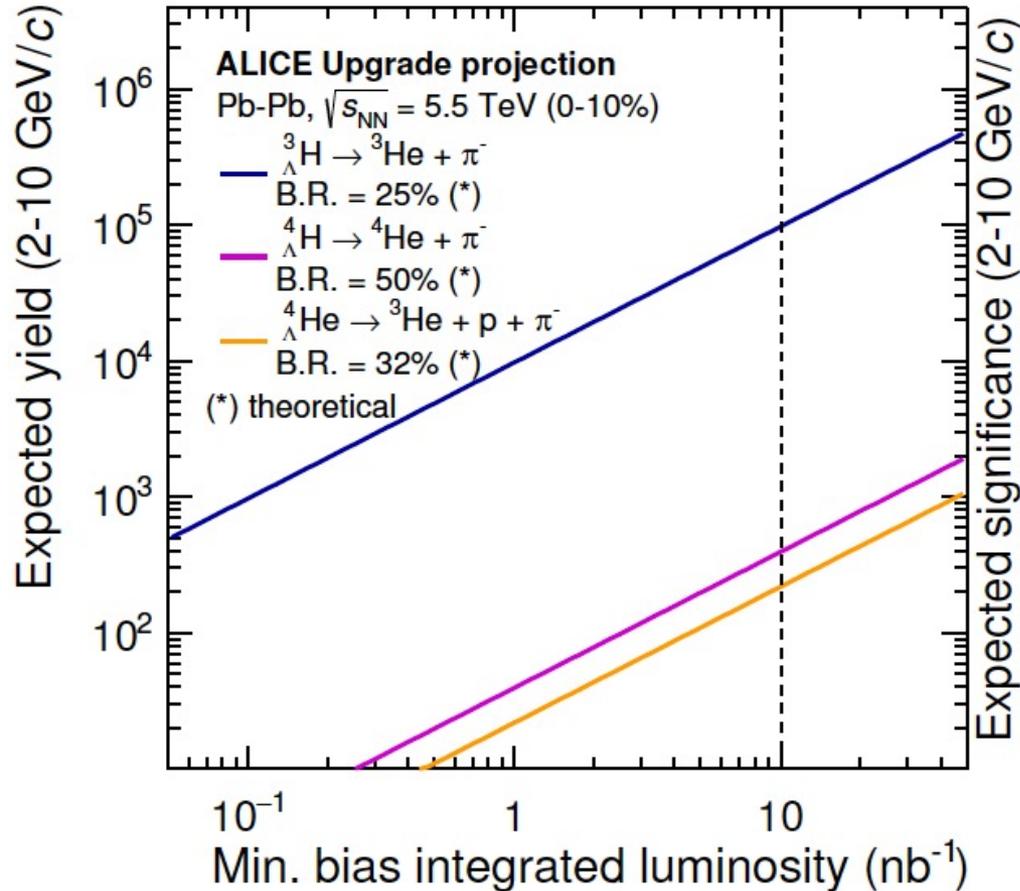
- Results shown before are based on data gathered in Run 1 and Run 2 of the LHC with different peculiarities
- Run 3 & Run 4 of LHC will deliver much more statistics (50 kHz Pb-Pb collision rate)
- Upgraded ALICE detector will be able to cope with the high luminosity
- TPC Upgrade: GEMs for continuous 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



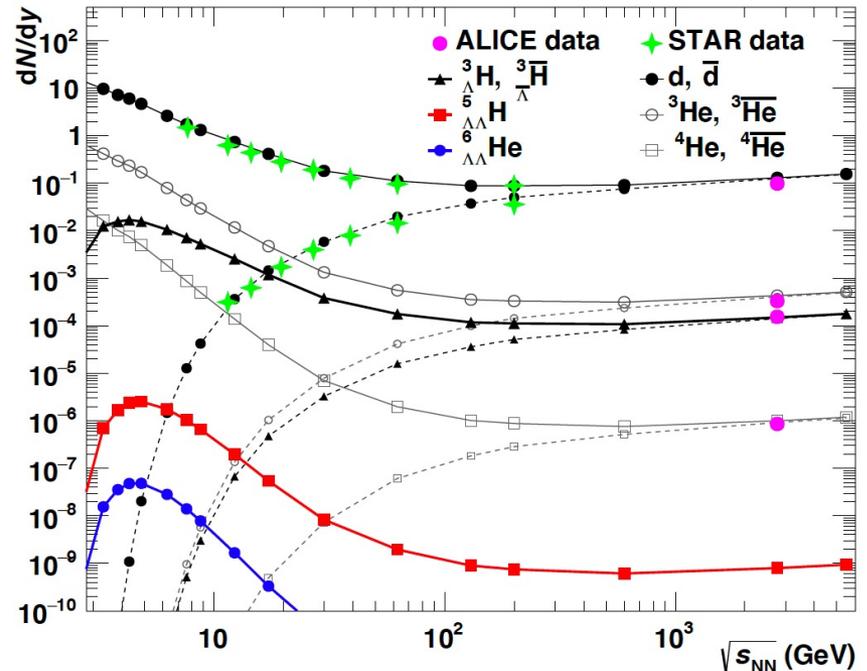
ALICE



Expected significance $>5\sigma$ 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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