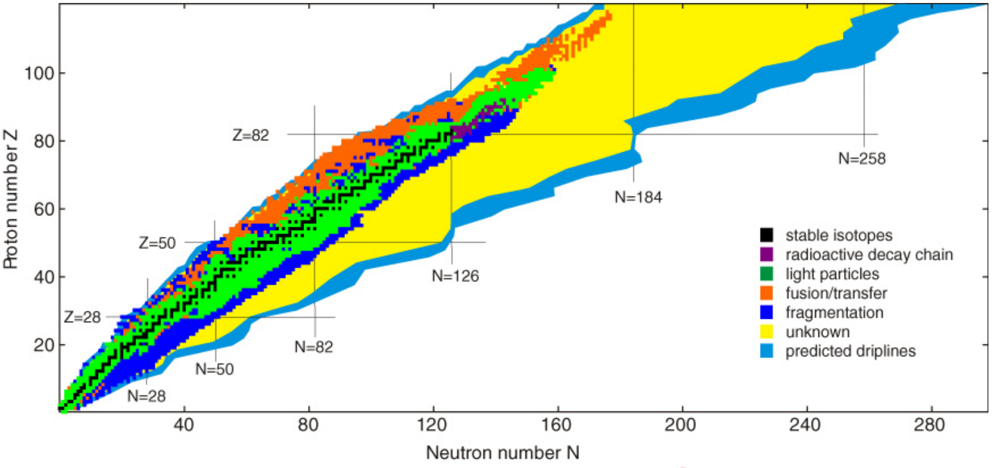
Production of charm and non-charm nuclei at LHC energies

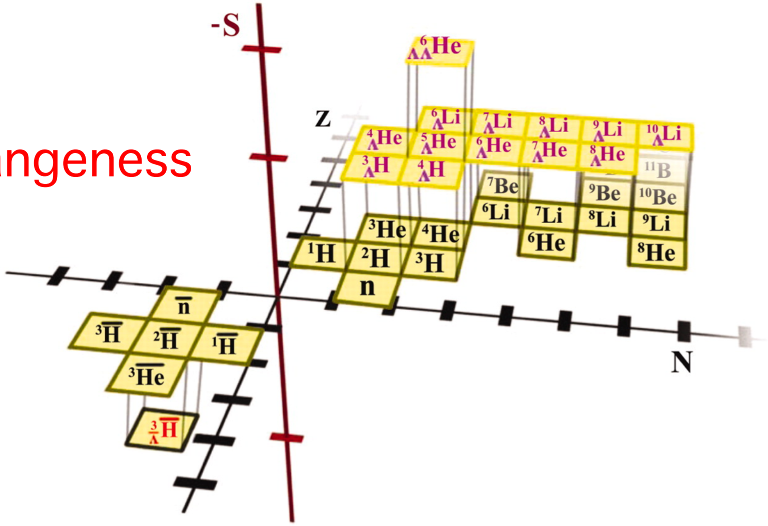
Alexander Kalweit, *CERN*

ECT* Trento workshop, 16th November 2021

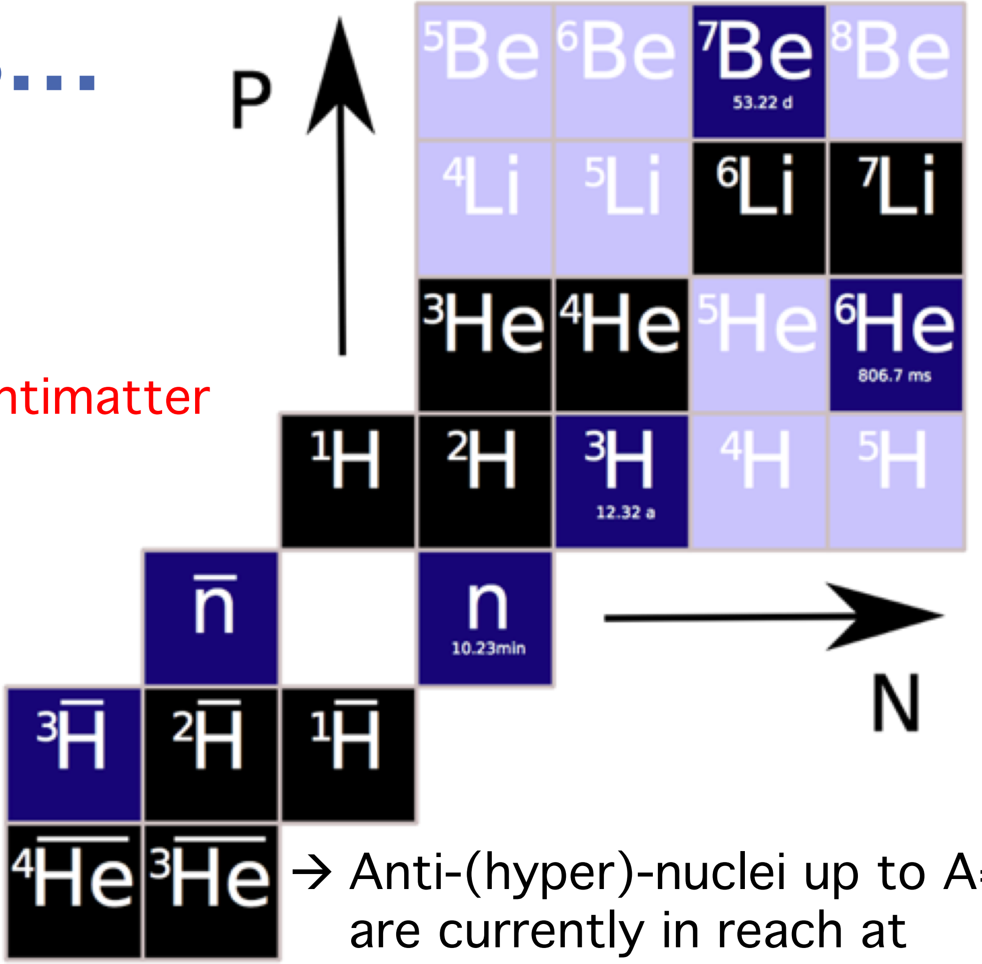
Extending the table of nuclides...



→ In the strangeness direction..



→ In the antimatter direction..



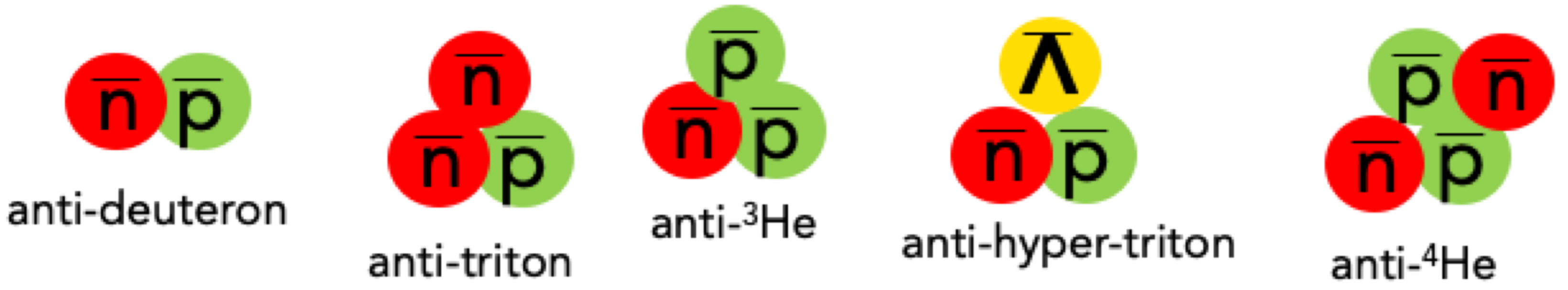
→ Anti-(hyper)-nuclei up to A=4 are currently in reach at accelerators.

→ Anti-hyper-nuclei of mass A=5 and anti-nuclei of mass A=6 will become in reach in the long term future.

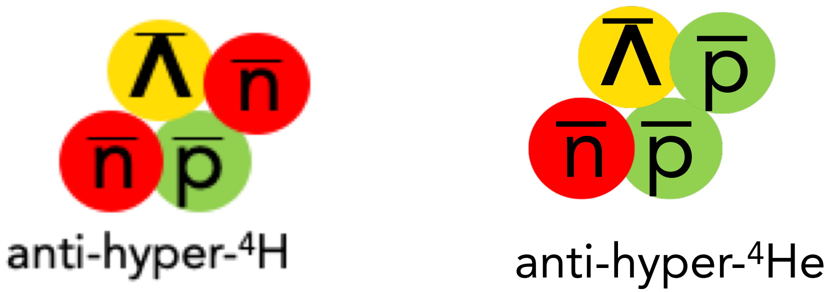
→ Can we also extend the table of nuclides in the charm direction in the next 15 years?

Zoo of exotic QCD bound states reachable at LHC

Run 1 & 2
(2010-2018)

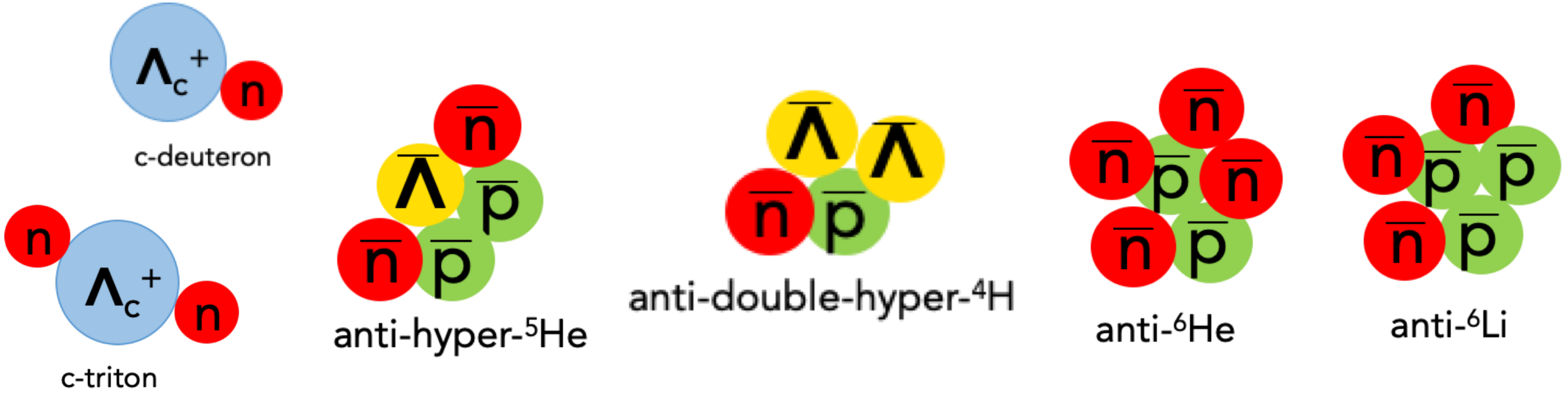


Run 3 & 4
(2021-2030)

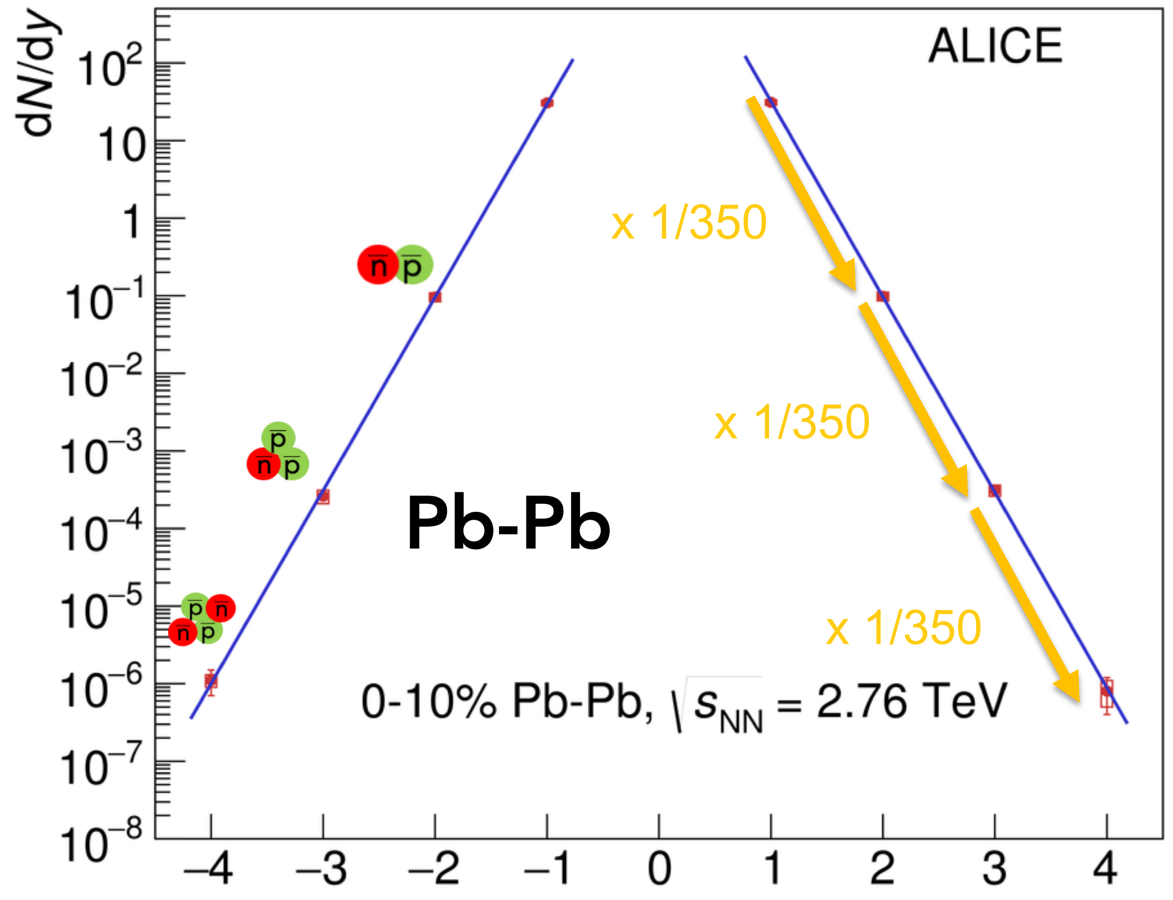


Run 5 & 6
(2032-2038)

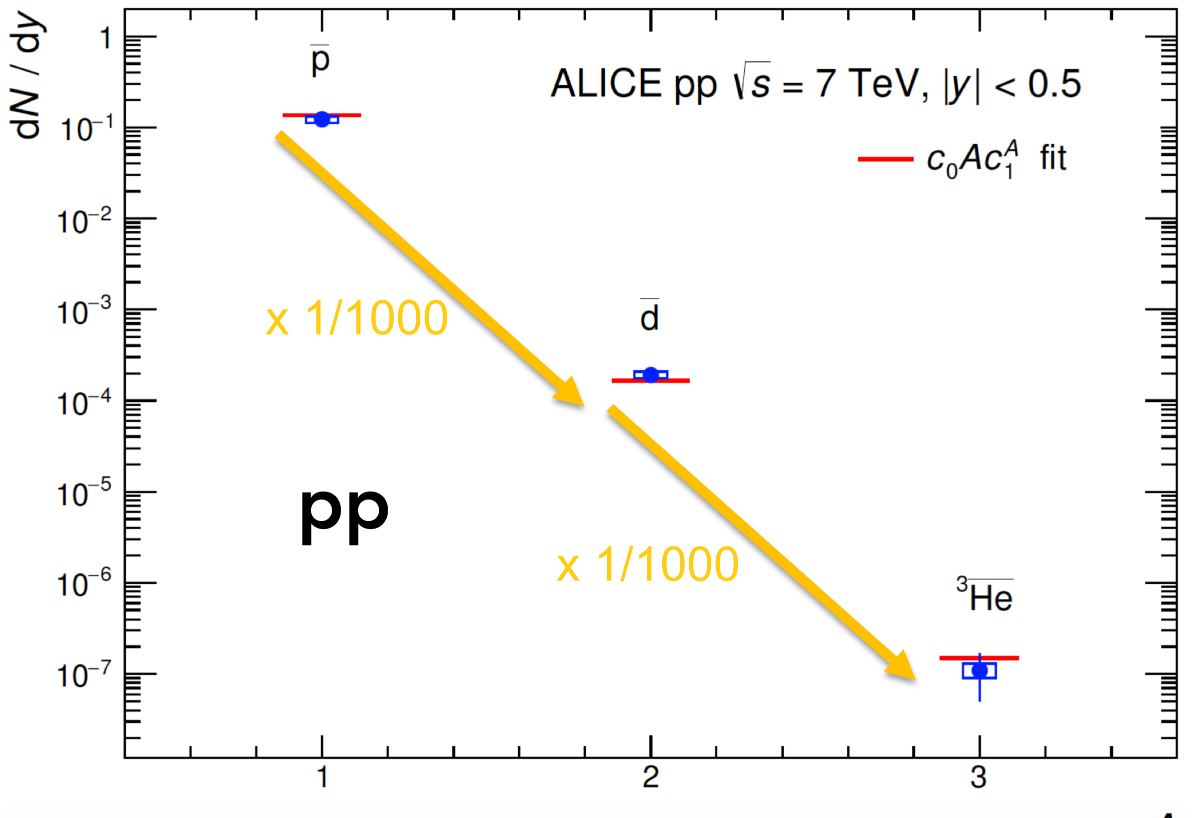
→ new ALICE 3
experiment at LHC-P2



Understanding nuclei production: penalty factor



[Nucl. Phys. A 971 (2018) 1-20]



[Phys. Rev. C 97 (2018) 024615]

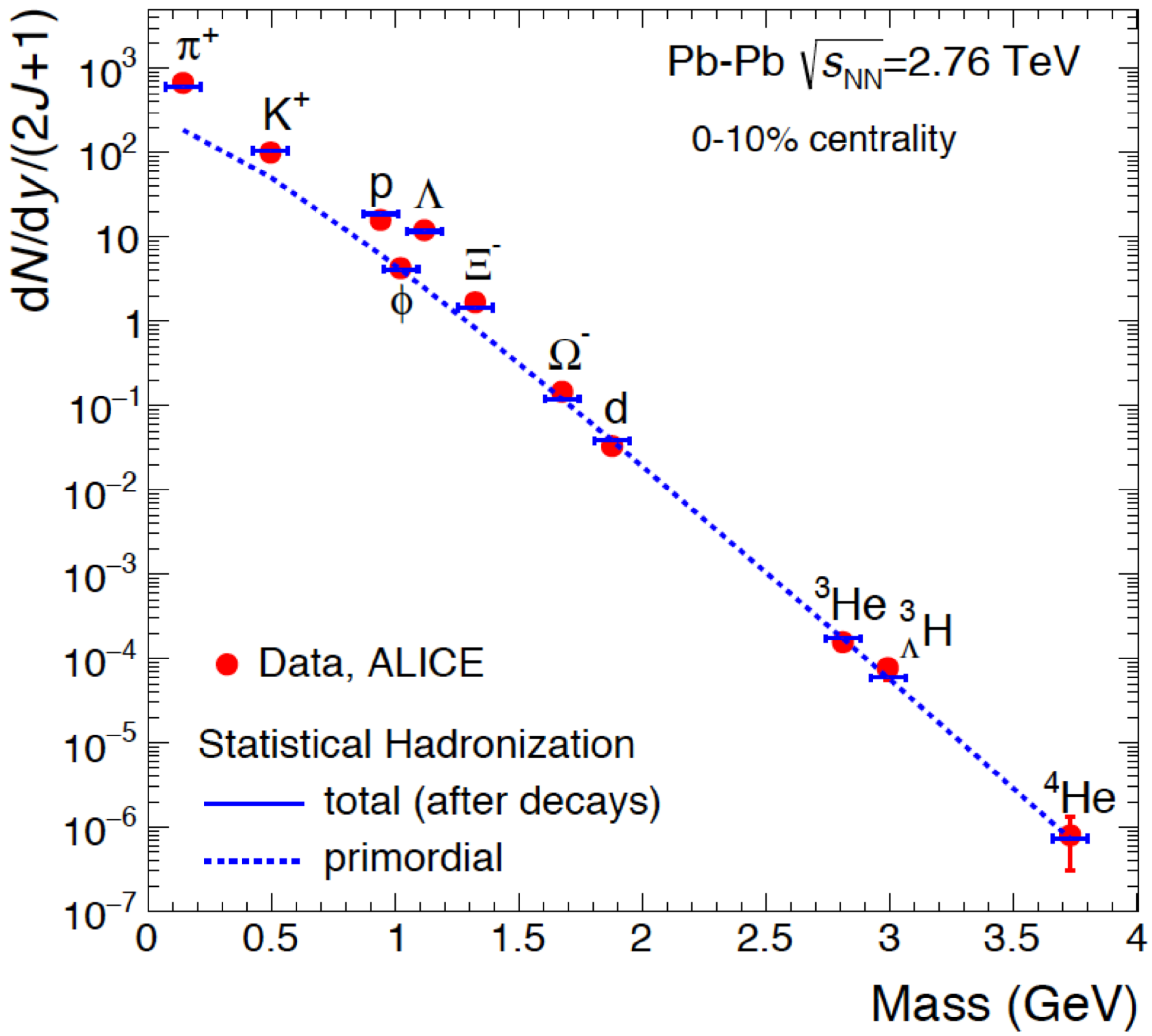
The production yield of (anti)-nuclei decreases at the LHC by a factor of about ~350 for each additional nucleon in Pb-Pb (~1000 in pp).

The statistical-thermal model as a production scenario

→ Production yields of light flavour hadrons from a chemically equilibrated fireball can be calculated by statistical-thermal models (roughly $dN/dy \sim \exp\{-m/T_{ch}\}$, in detail derived from partition function)

→ In Pb-Pb collisions, particle yields of light flavor hadrons are described over 7 orders of magnitude with a **common** chemical freeze-out temperature of $T_{ch} \approx 156$ MeV.

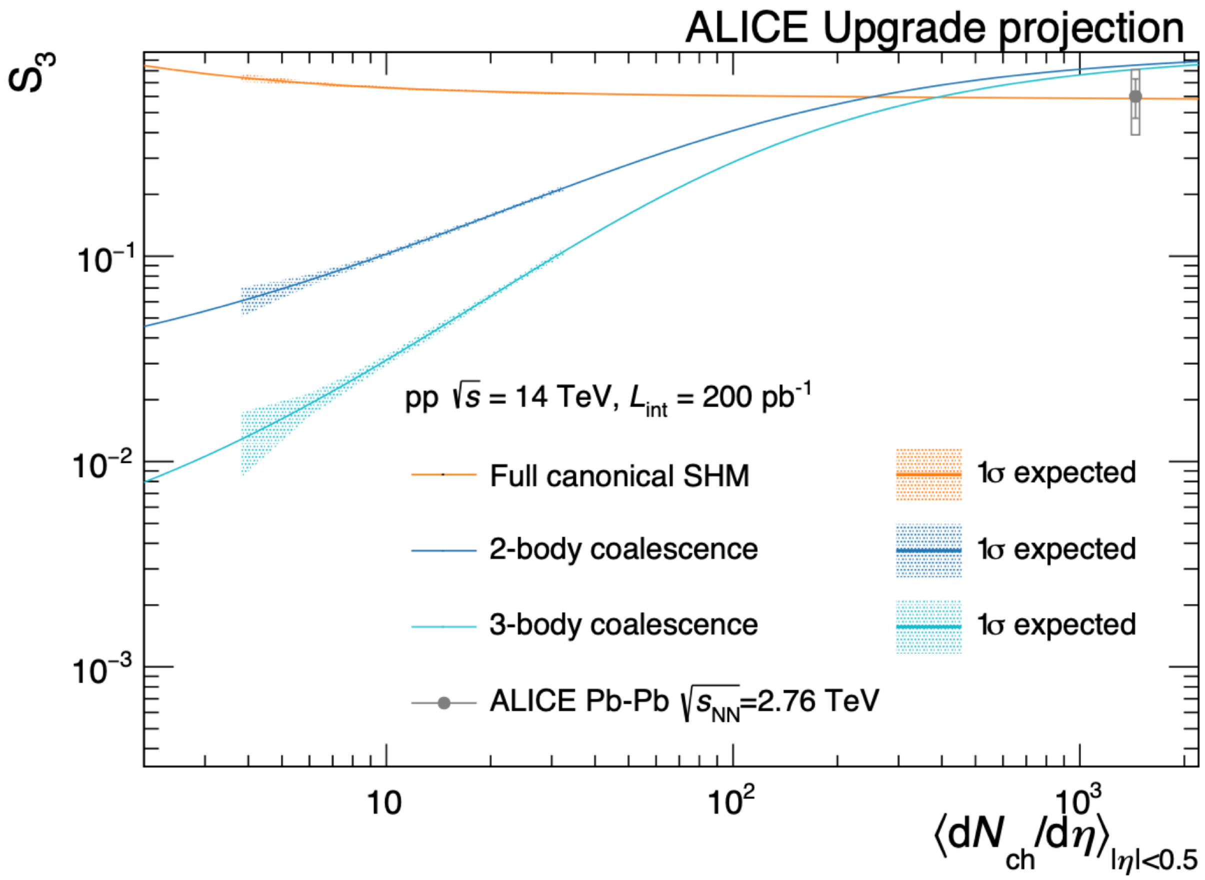
→ Light (anti-)nuclei are also well described despite their low binding energy ($E_{b,d} = 2.2$ MeV << T_{ch}).



[A. Andronic *et al.*, *Nature* 561 (2018) 7723, 321-330]

Alternative production scenarios for antinuclei (1)

- It is often argued that statistical-thermal production for such weakly bound states is coincidental.
- Coalescence approaches or continuous generation and destruction via hadronic interactions are proposed as alternatives.
- This is an interesting physics topic, but not the subject of my talk today.
- What is relevant for charm nuclei here: in central heavy-ion collisions, the statistical-thermal model is at least a reliable baseline for the expected yields.



[Public note on ALICE pp program]

Alternative production scenarios for antinuclei (2)

- It is often argued that statistical-thermal production for such weakly bound states is coincidental.

- Coalescence approaches or continuous generation and destruction via hadronic interactions are proposed as alternatives.

- This is an interesting physics topic, but not the subject of my talk today.

- What is relevant for charm nuclei here: in central heavy-ion collisions, the statistical-thermal model is at least a reliable baseline for the expected yields.

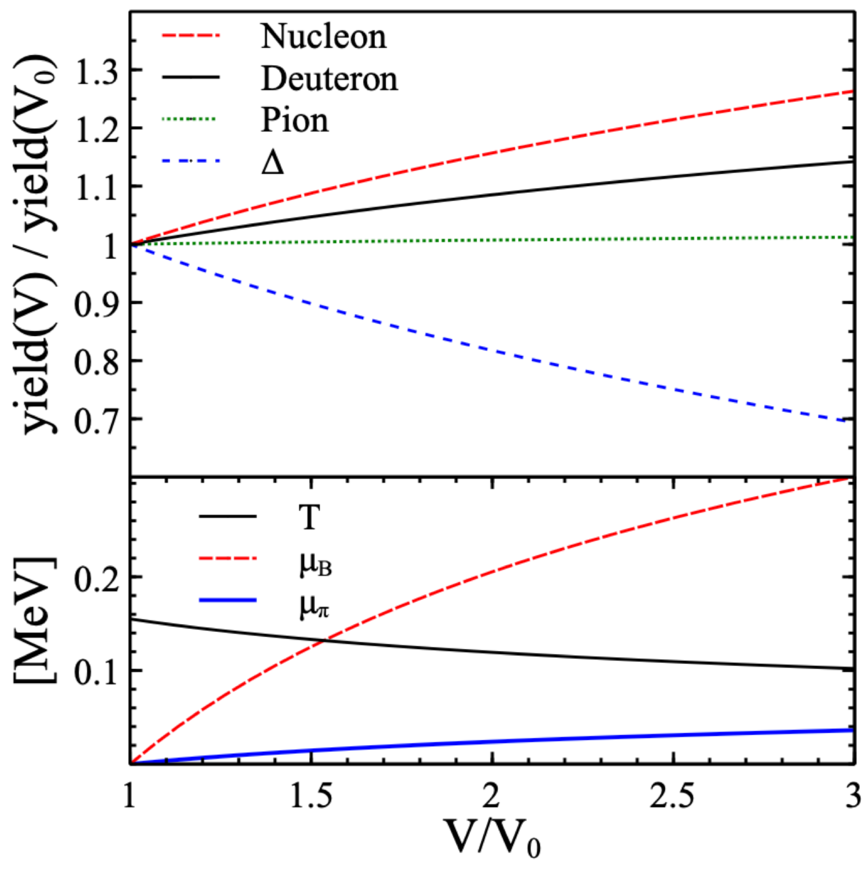


FIG. 8: Evolution of yields (upper panel) and thermodynamic variables (lower panel) in our toy model without annihilations for $T_0 = 155$ MeV. The deuteron yield grows, which is similar to our simulation within the fourth scenario in Fig. 7.

[Phys. Rev. C 99, 044907 (2019)]

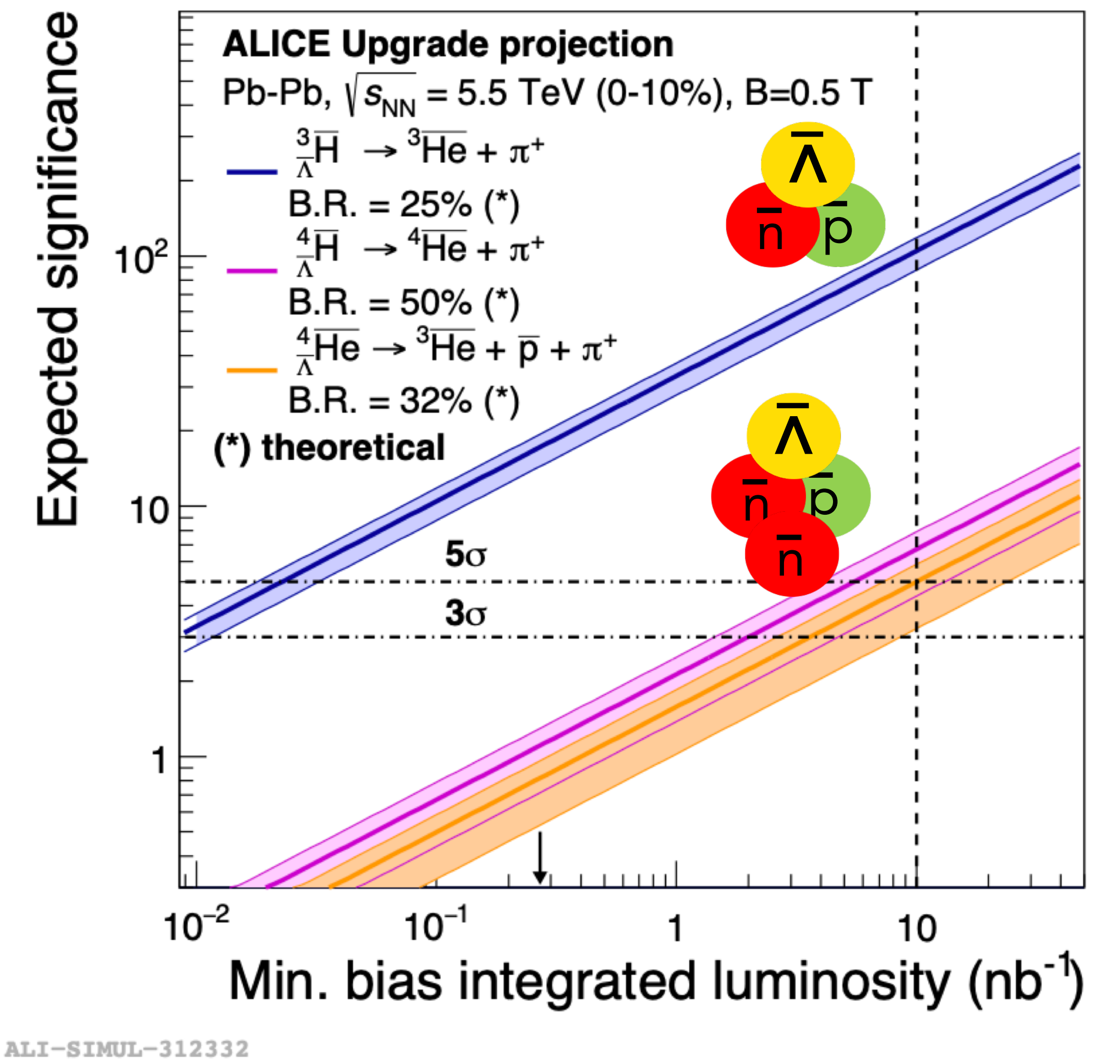
[CERN Yellow Report]

(anti-)hypernuclei

→ Light nuclei up to A = 4 (deuterons, tritons, ^{3}He and ^{4}He) are already observed today at the LHC, but with limited statistics. The same holds true for A = 3 hypernuclei (hypertriton).

→ A = 4 (anti-)hypernuclei are in well in reach of LHC Run 3 & 4.

→ Any heavier object (A > 5) will need to be measured in LHC Run 5 & 6…



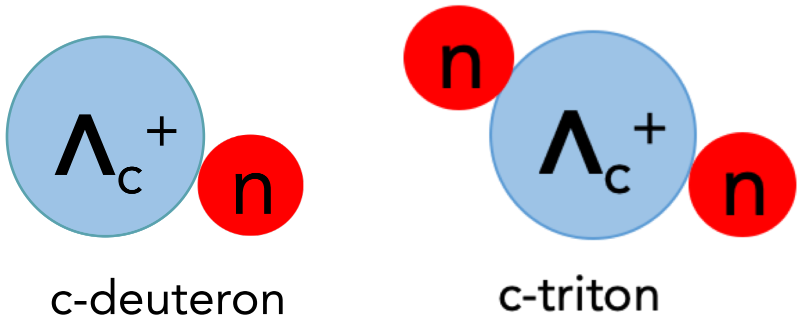
c-deuteron and c-triton

- The lightest possible bound states of a charm baryon and a nucleon without Coulomb repulsion are bound states of Λ_c^+ and a neutron: c-deuteron and c-triton.

- Their possible existence is widely and controversially discussed in the literature since the 1970s with the c-triton being more likely to exist than the c-deuteron, see e.g.:

  [Phys. Rev. Lett. 39, 1506]
  [Eur.Phys.J.A 54 (2018) 11, 199]

- Their possible (non-)existence sheds light on the charm-nucleon potential.



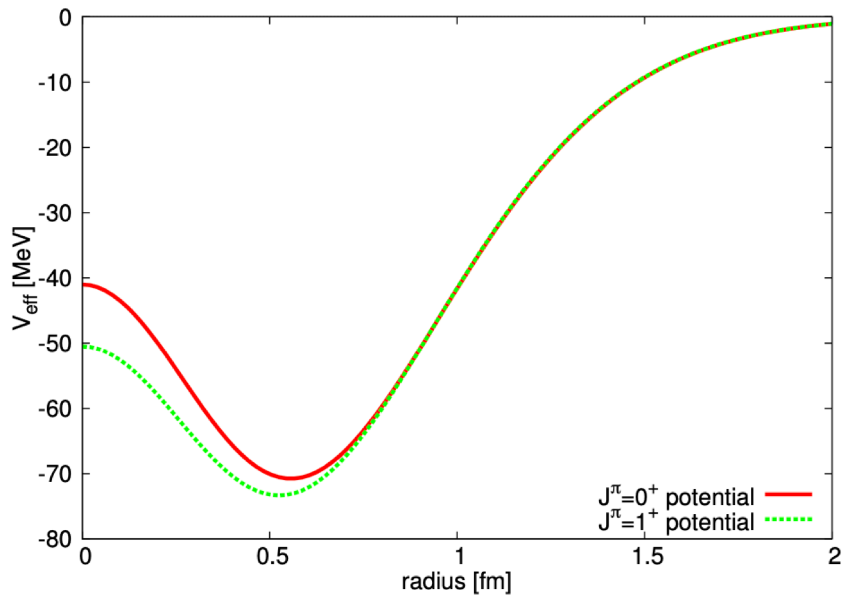


Fig. 9 $\Lambda_c N$ effective potentials for $J^\pi = 0^+$ and 1^+.

[*PTEP* 2016 (2016) 2, 023D02]

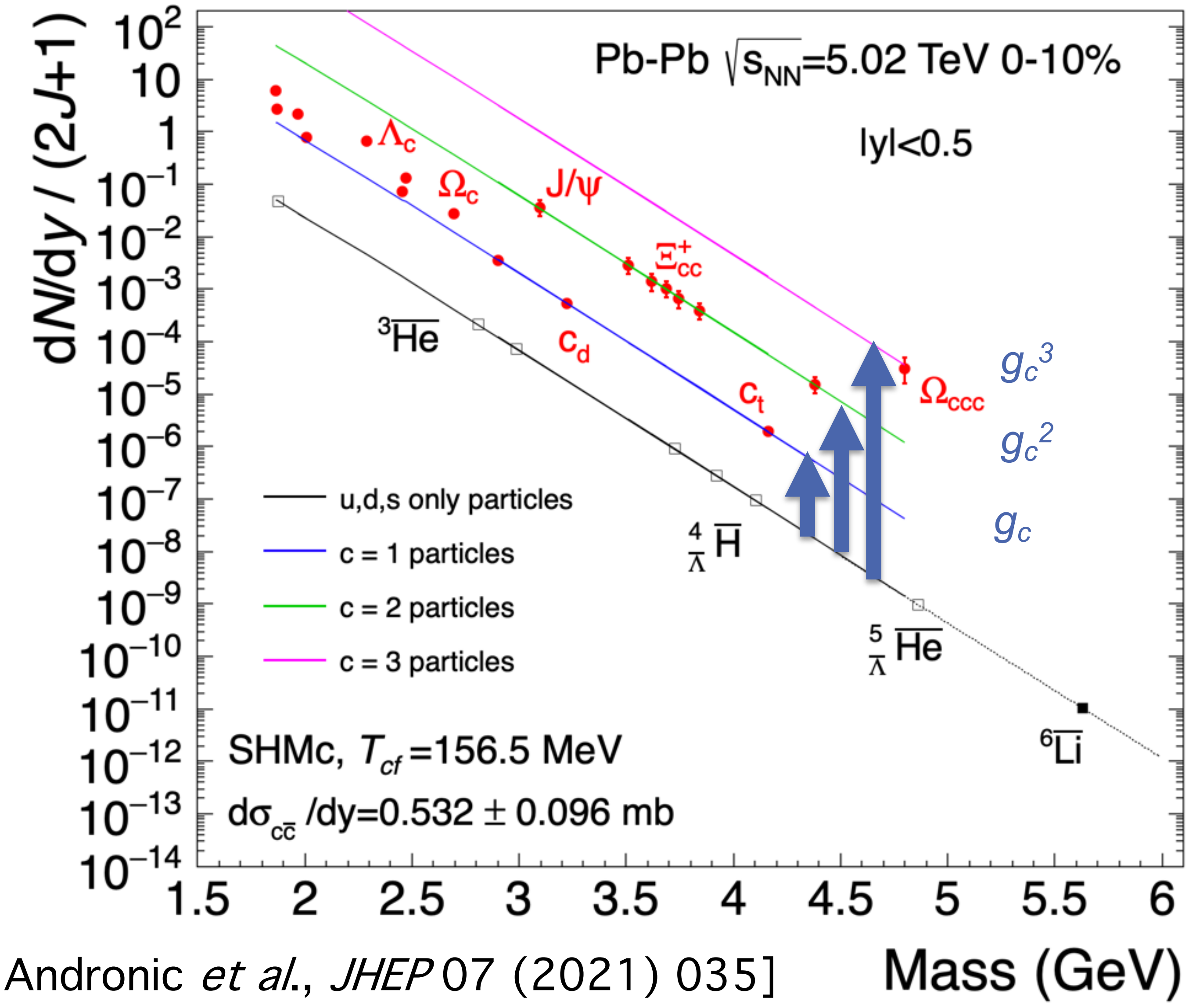
SHM production rates for charm nuclei

- Charm nuclei production rates are expected to be enhanced by the factor of the charm fugacity $g_c \approx 30$ as all other charm particles.

- This makes them observable at LHC energies despite small branching ratios.

- Excellent synergy between charm and anti-nuclei physics: anti- and hyper-nuclei provide the baseline to measure g_c with multi-charm hadrons!

Predictions of statistical-thermal hadronization model



[A. Andronic *et al.*, *JHEP* 07 (2021) 035]

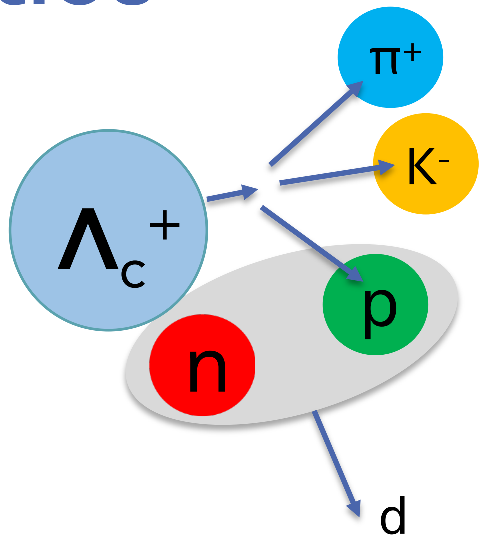
Decay channels and branching ratios

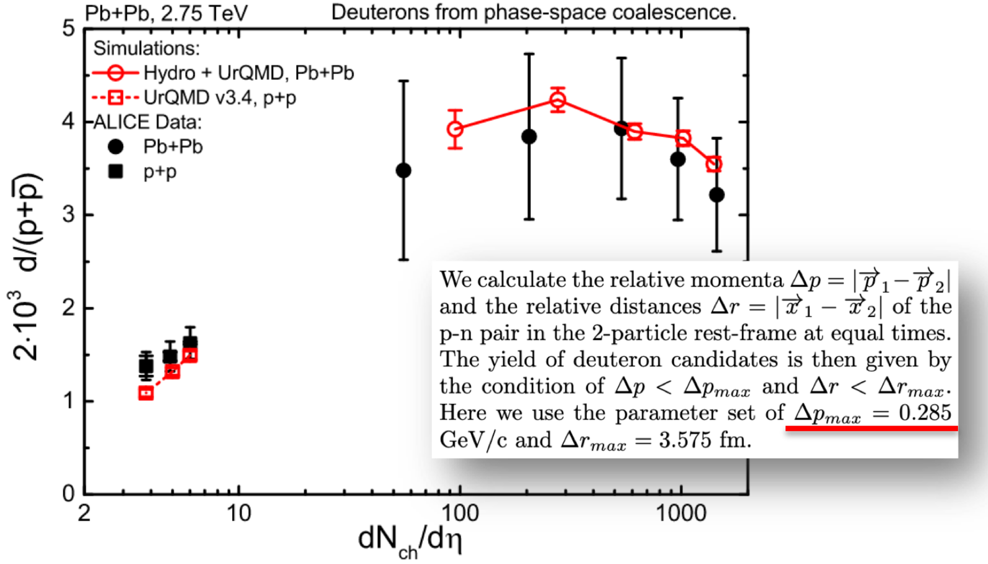
- Most promising decay channels:
  - $c_d \rightarrow d + K^- + \pi^+$
  - $c_t \rightarrow t + K^- + \pi^+$

- The relevant decay of the bound $\Lambda_c^+ \rightarrow p + K^- + \pi^+$ has a branching ratio of 6.28±0.32%.

- Probability of the decay proton to bind with the bound neutron can be estimated by requiring $p \lesssim 200$ MeV in the rest frame of the Λ_c^+ and is found to be ≈ 3-10%.

- This momentum scale for binding of protons and neutrons to deuterons is itself constrained by the deuteron production measurements at LHC energies ;-)



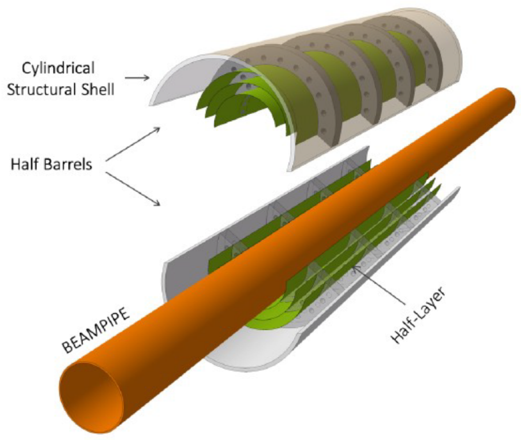


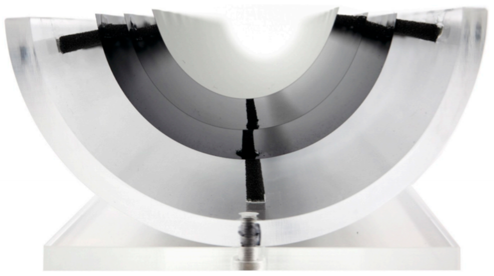
[Phys. Rev. C 99, 014901 (2019)]

The ALICE ITS3 upgrade

[ITS3 LoI]

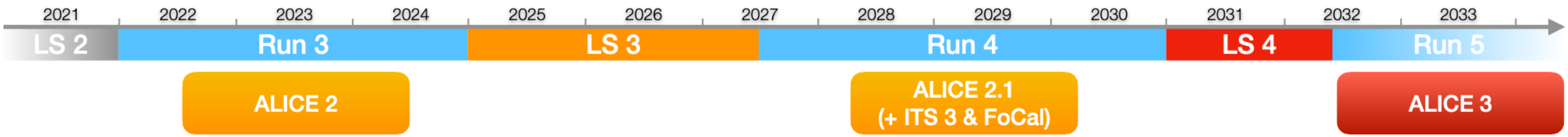
- Three truly cylindrical Si-pixel layers based on ultra-thin (50μm), curved sensors:
  - MAPS technology (integrate sensor and readout within one chip)
  - Reduce material budget from 0.35% X/X_0 to ≈0.05% X/X_0 and largely remove its inhomogeneities
  - Move layers closer to the primary vertex, innermost layer at R = 1.8cm (new beam-pipe with inner radius R = 1.6cm)
- Increase of tracking precision and efficiency at low transverse momenta
- Installation foreseen in Long Shutdown 3 for LHC Run 4 (2027-2030)





engineering model

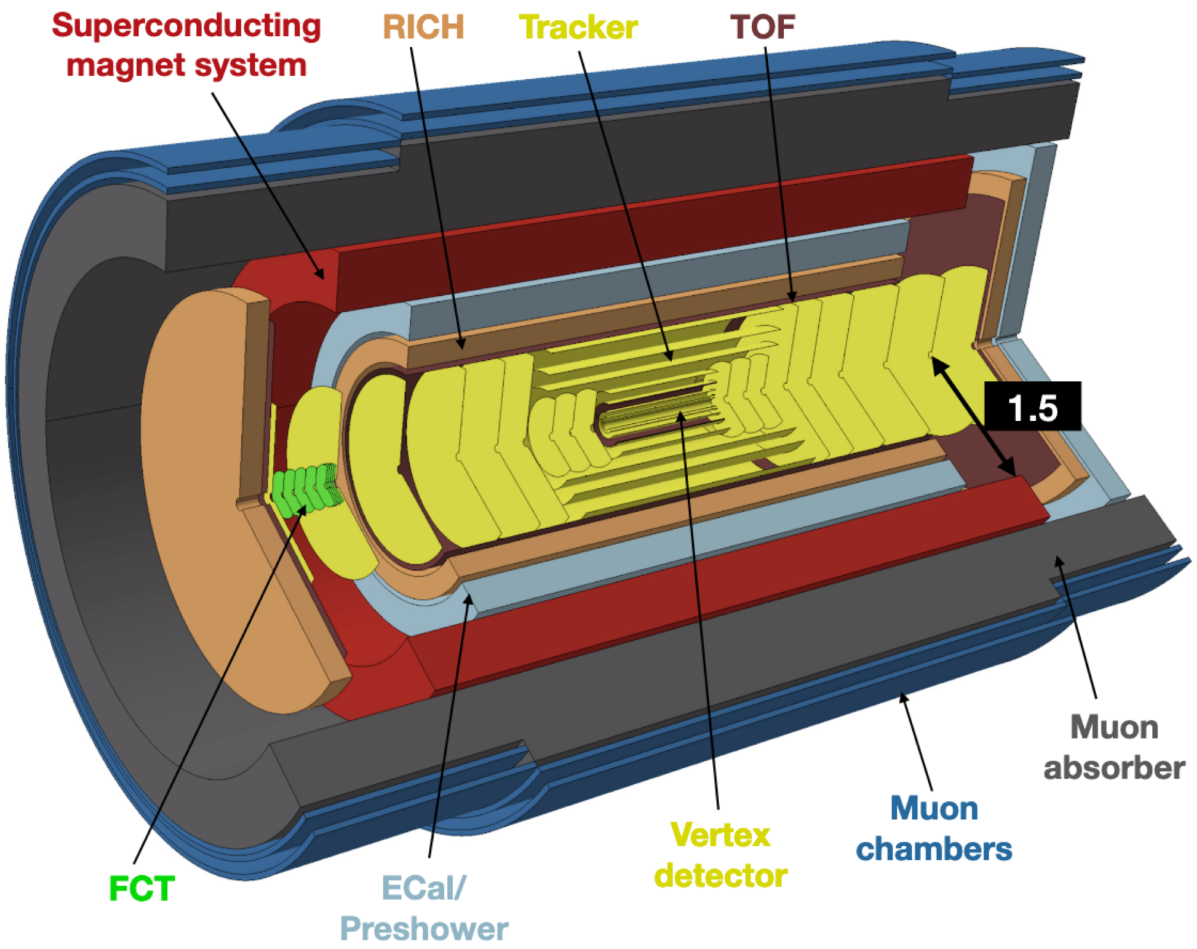
inner layers	ITS1	ITS2	ITS3
X/X_0	1.14%	0.38%	0.05%
innermost radius	39 mm	22 mm	18 mm
pixel size	50x425 μm^2	30x30 μm^2	O(15x15 μm^2)

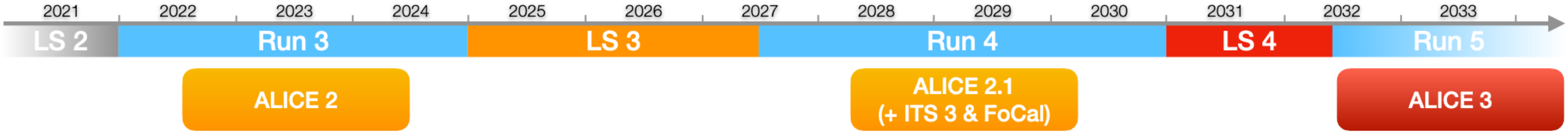


The ALICE 3 detector

[Public workshop on ALICE 3]

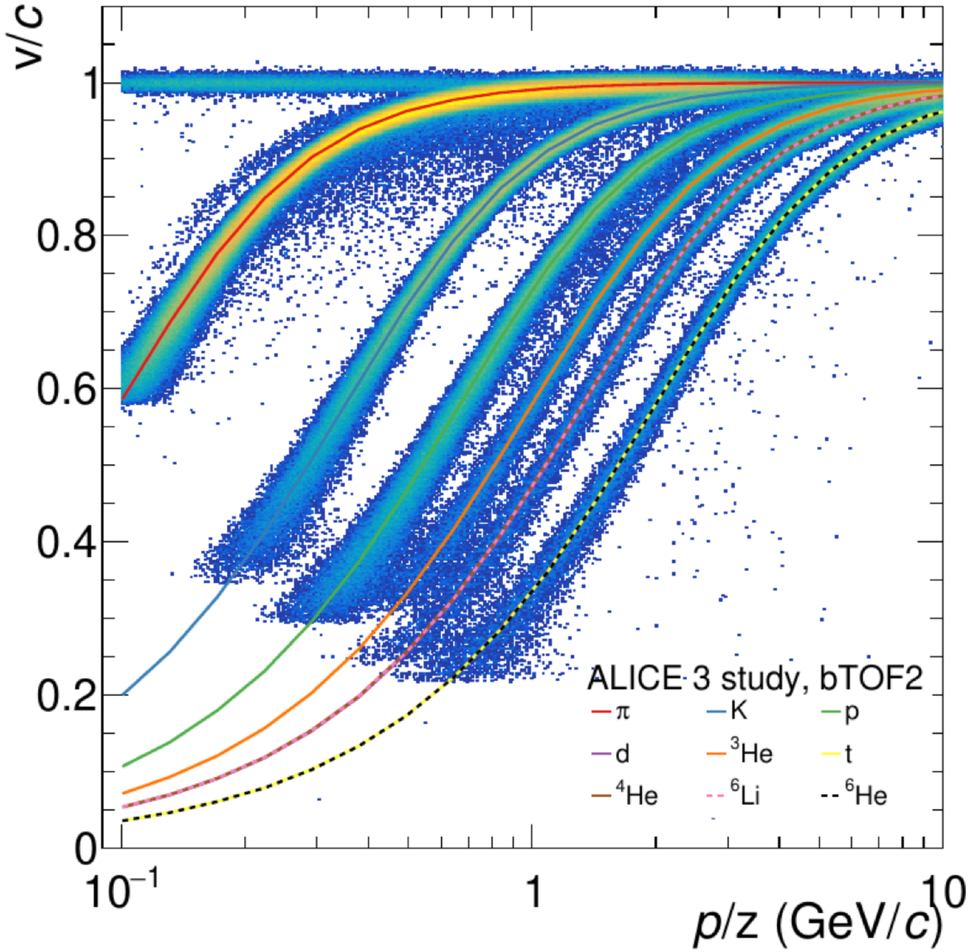
- Compact all-silicon tracker with high-resolution vertex detector
- Superconducting magnet system
- Particle Identification over large acceptance
- Fast read-out and online processing

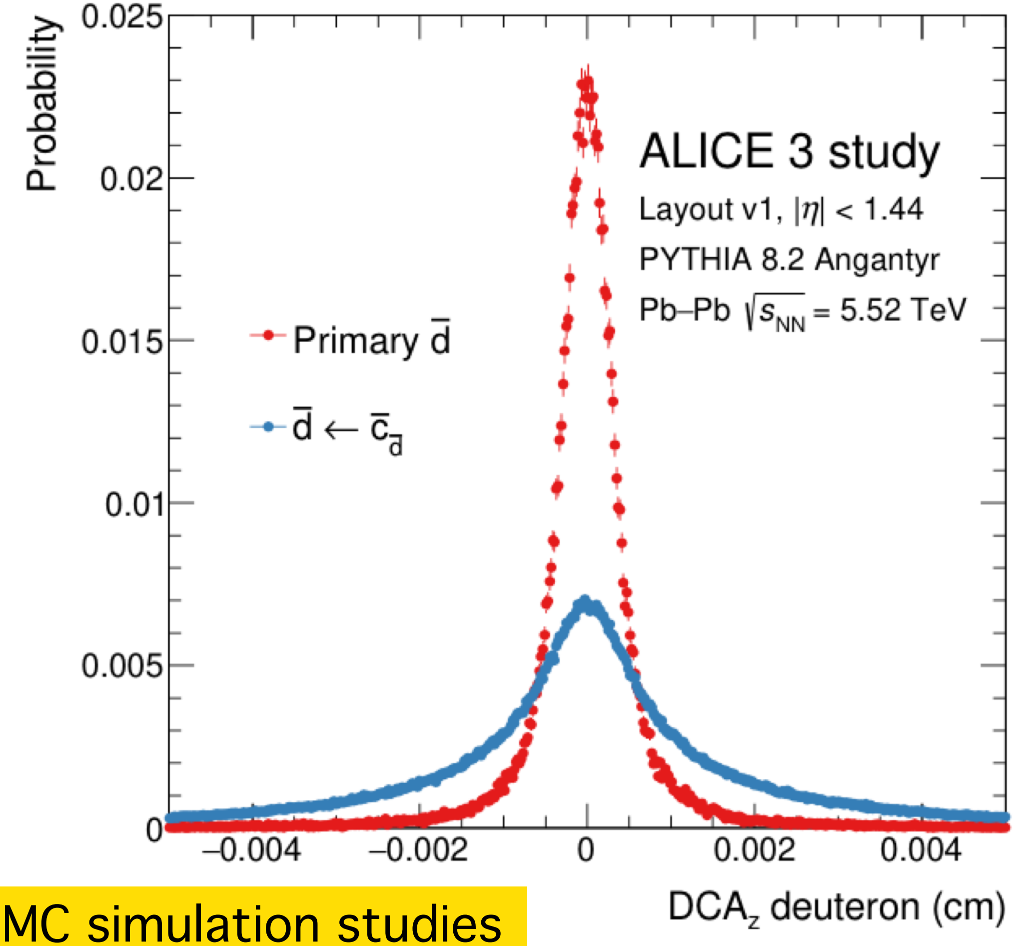




Experimental challenges: PID and vertexing

- Rare production of anti-nuclei requires excellent particle identification
- Main background source: primary deuterons that are combined with random pions and kaons → excellent dca-resolution.

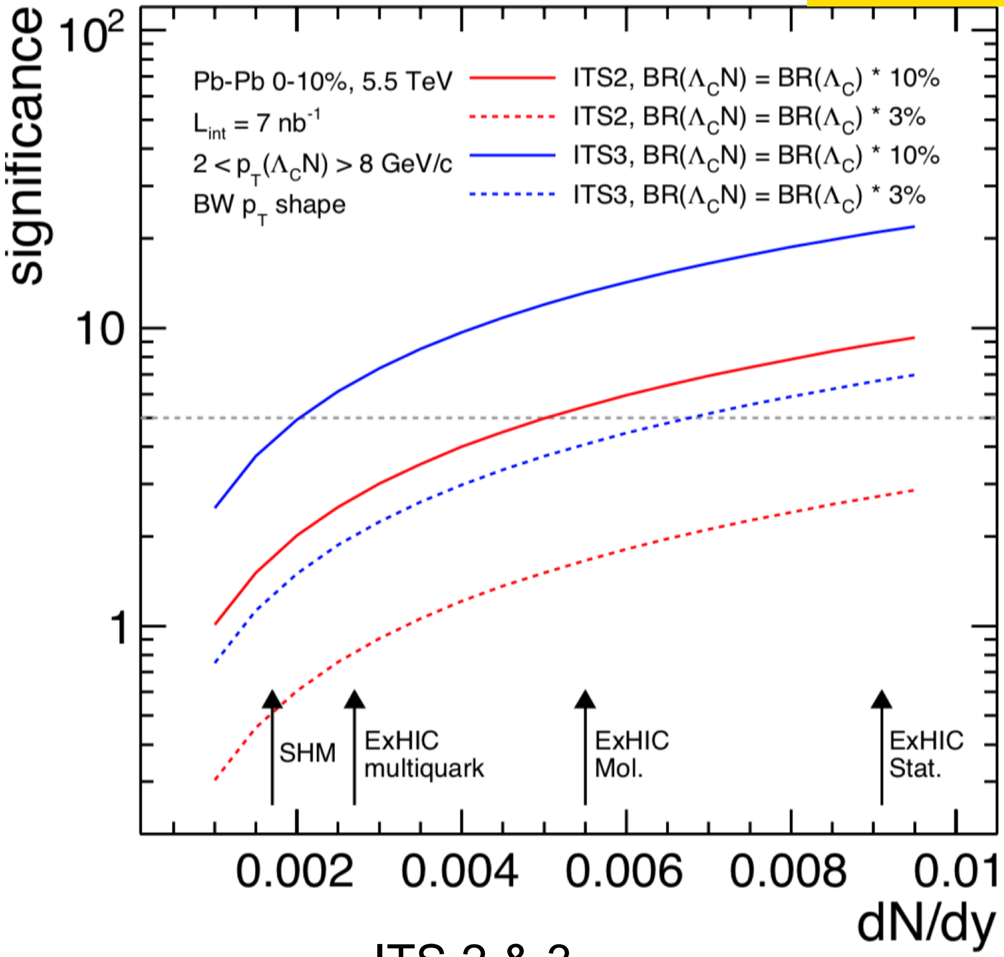




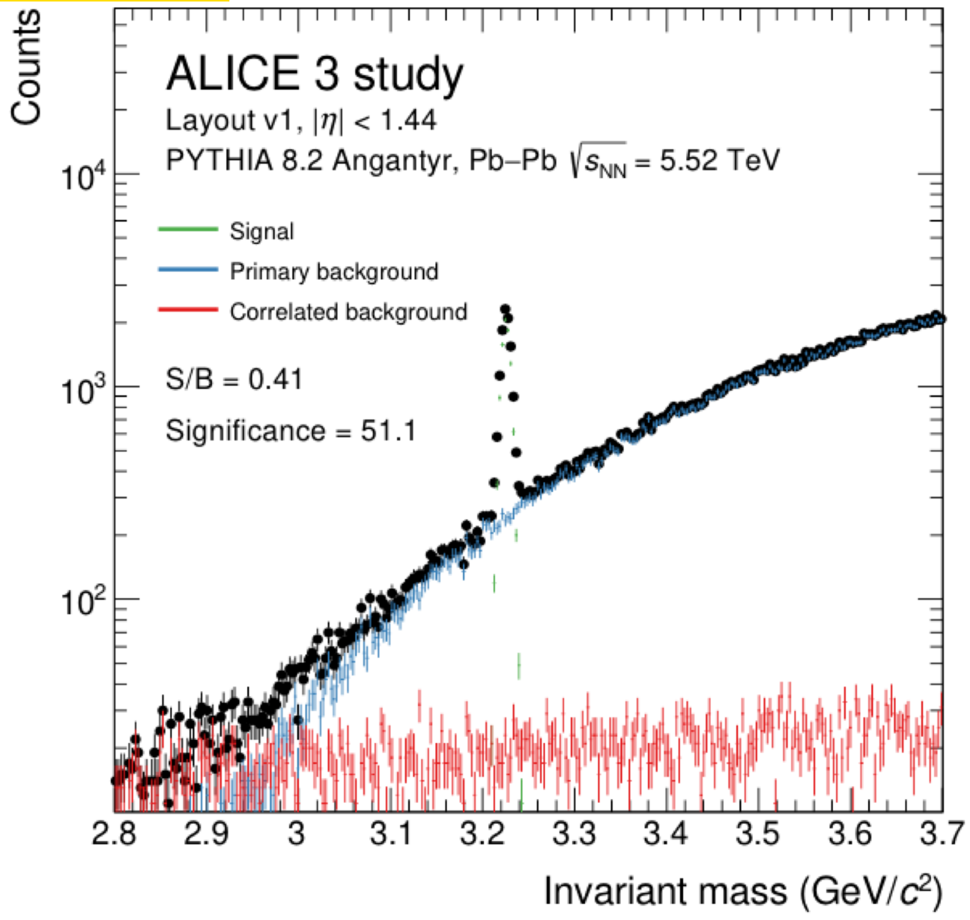
MC simulation studies

c-deuteron: physics performance simulation

MC simulation studies



ITS 2 & 3



ALICE3 (SHM)

The ITS3 upgrade will allow ALICE to start to become sensitive to c-deuteron production (if it exists); a definitive answer will be provided by ALICE 3.

Summary and conclusions

- Interesting physics prospects at LHC energies to observe for the first time charm nuclei.
- The planned ITS 3 and ALICE 3 projects are perfectly suited for these studies.
- Strong synergies with the core heavy-flavor programme that is discussed at this workshop.
- In case of their non-existence, the limits that can be established with respect to their production expected in statistical-thermal models are very powerful.

Thank you!