

From multicharm to QCD exotica with ALICE 3

Introduction: LHC and FCC

- The LHC is the only high energy collider for many years to come.
- Its potential for heavy-ion and hadron physics must therefore be fully exploited.
- Any *energy frontier* heavy-ion or hadronic physics measurement that will not be done with ALICE 3 will likely not be done before 2070.



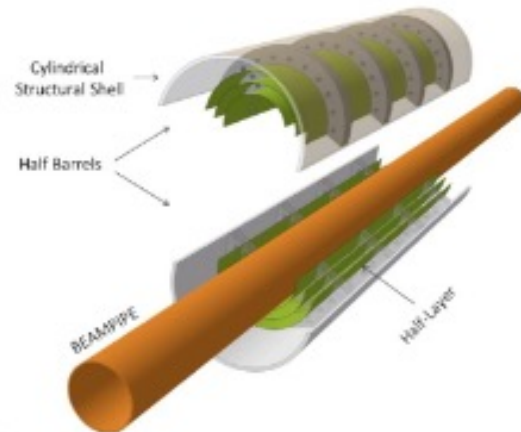
LHC schedule and ALICE upgrade

LS3: FoCal & ITS3, specific upgrades for Run 4

- Moving towards final sensors in view of start of production

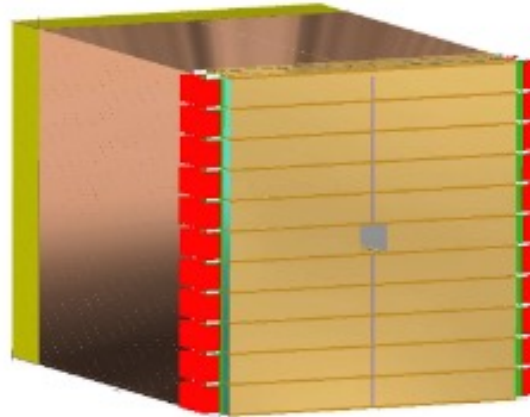
ITS 3

TDR: CERN-LHCC-2024-003



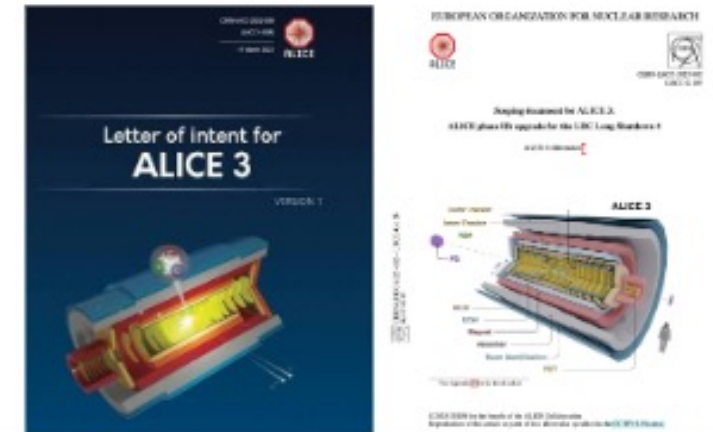
FoCal

TDR: CERN-LHCC-2024-004



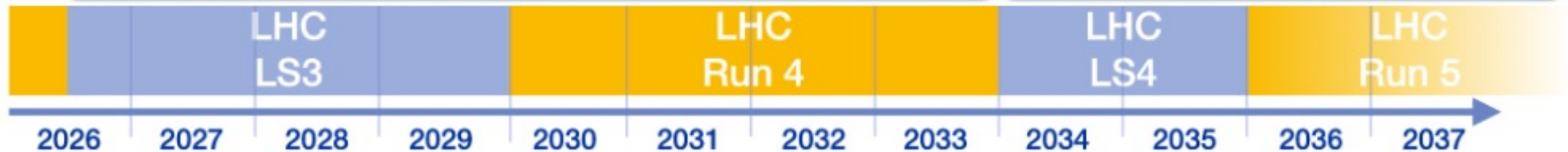
ALICE 3

Lol: CERN-LHCC-2022-009

SD: CERN-LHCC-2025-002

ALICE 2.1

ALICE 3



ALICE 3 in a nutshell

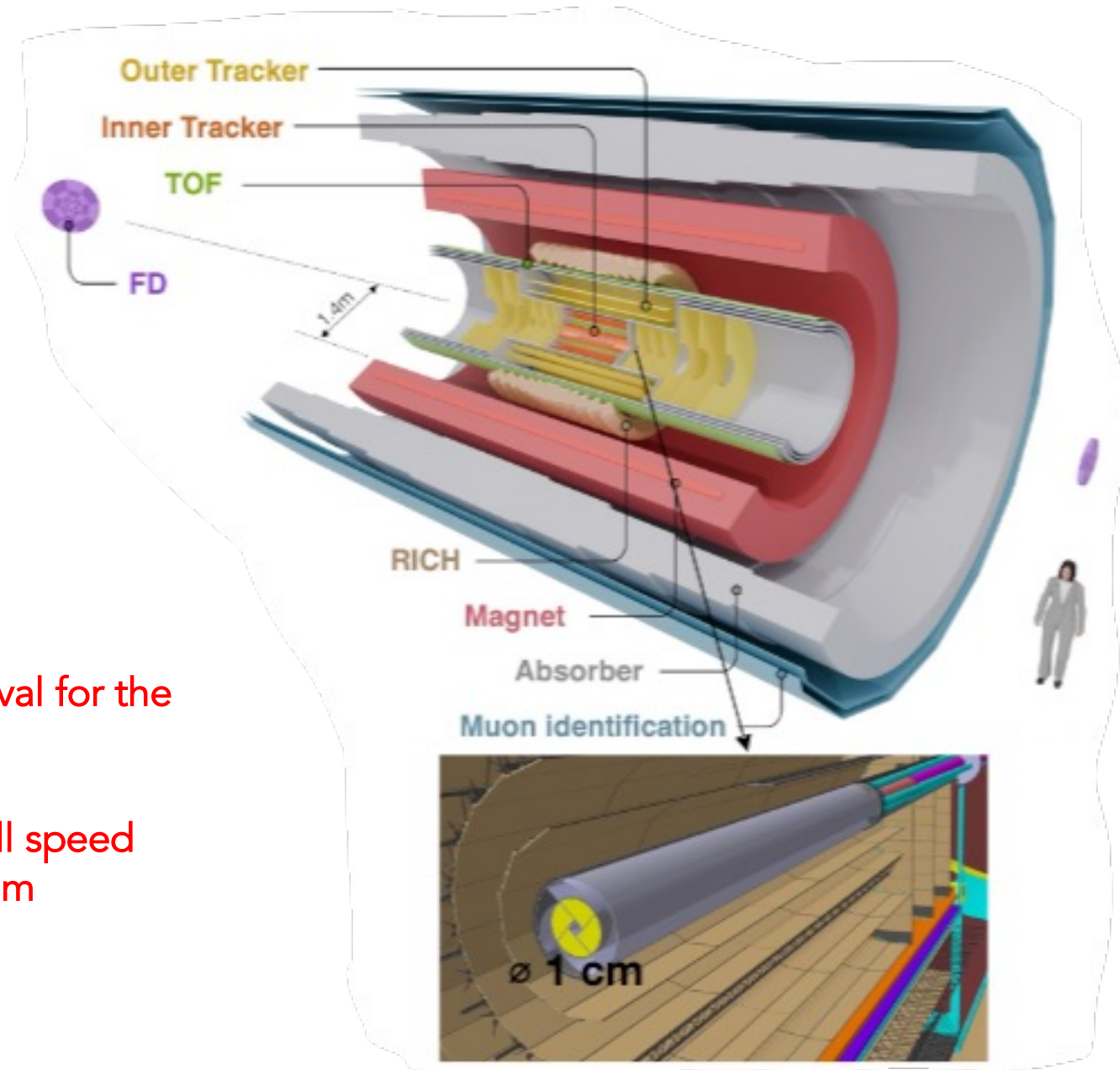
→ Novel detector concept:

- Compact and lightweight all silicon tracker
- Retractable vertex detector with $R_{\min}=5\text{mm}$ (inside the beam pipe!)
- Extensive PID and large acceptance
- New superconducting solenoid with $B=2\text{T}$

→ CERN Research Board in June gave formal approval for the preparation of the Technical Design Reports.

→ Detector development and preparations are in full speed (ALICE upgrade week next week, several test beam campaigns during 2026)

See also talks by Magnus and Raphaëlle..

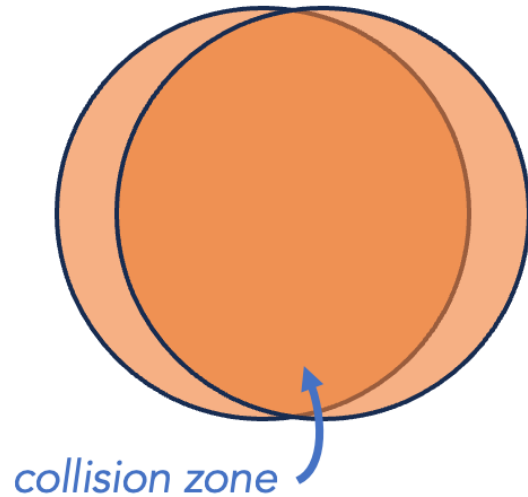


A very rich and *unique* physics program..

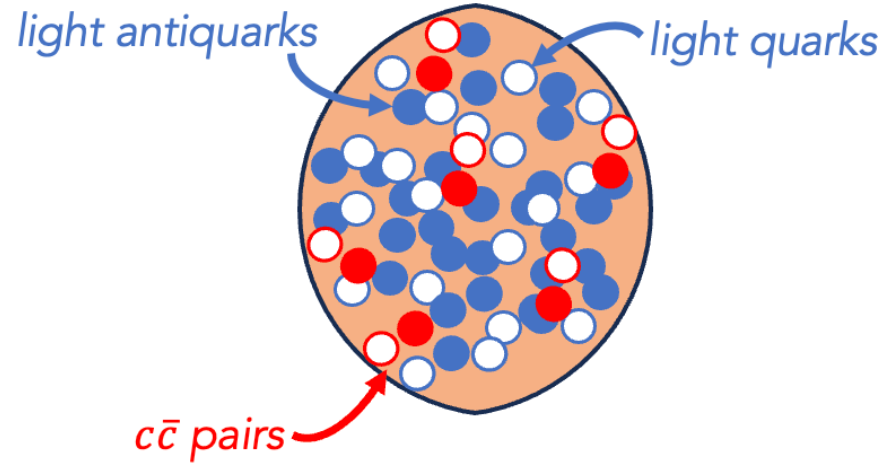
1. Measurement of multi-charm hadron production: Is their production enhanced?
2. High precision beauty production and flow: Is beauty less thermalized than charm?
3. $D\bar{D}$ - correlations: can we directly “see” energy loss and diffusion of charm quarks in the QGP?
4. High precision di-electron mass spectrum: What is the initial QGP temperature and its time dependence? Is there chiral symmetry restoration?
5. Charm nuclei like c-deuteron or c-triton: Do they exist?
6. Tetra- and Pentaquarks: can we clarify their structure with femtosopic and production measurements?
7. Net-baryon and net-charm fluctuations: How sharp/smooth is the crossover at LHC energies? Are lattice QCD predictions correct?
8. And so much more...

Multicharm baryons (1)

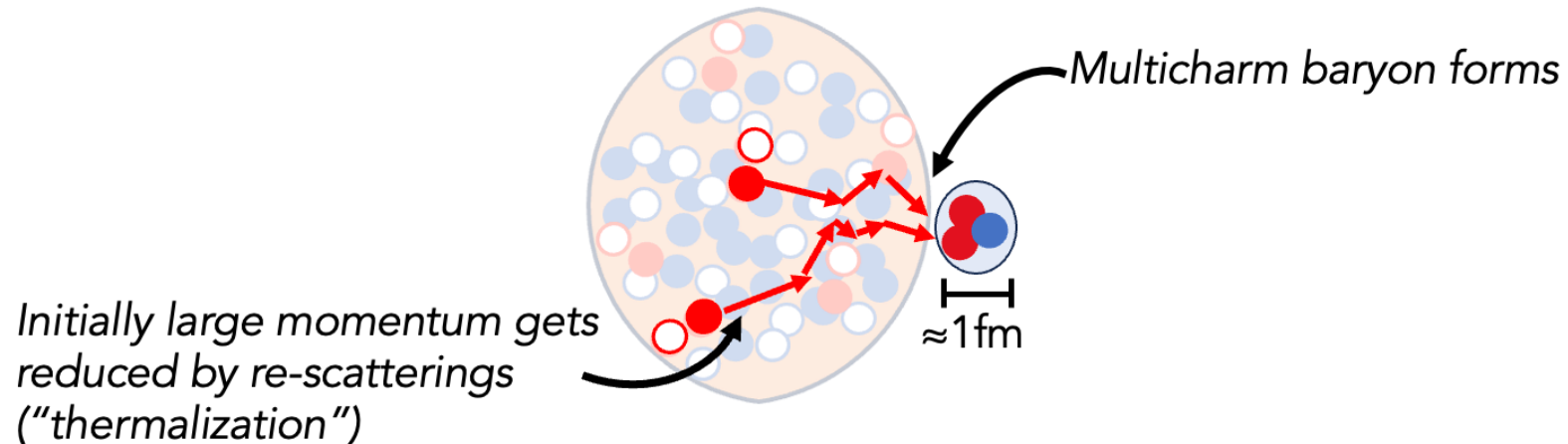
(1.) collision of two Pb-Pb nuclei
(transverse plane)



(2.) Production of > 1000 light quarks
and ≈ 20 $c\bar{c}$ pairs at midrapidity

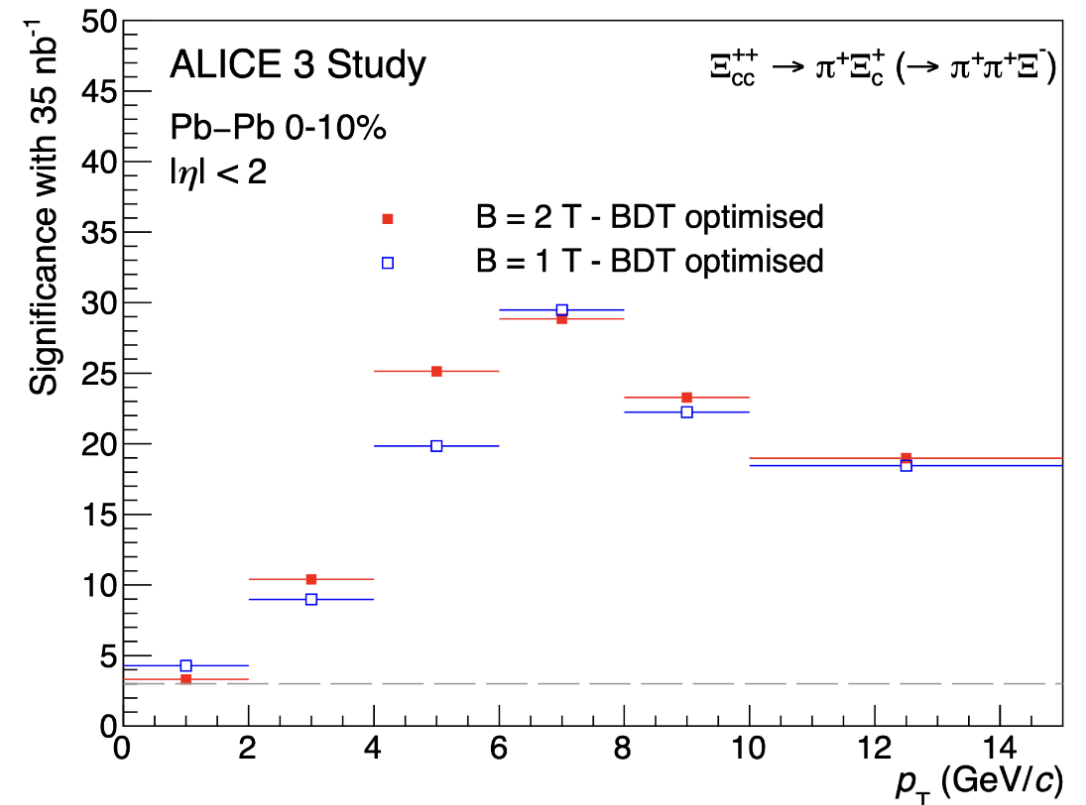
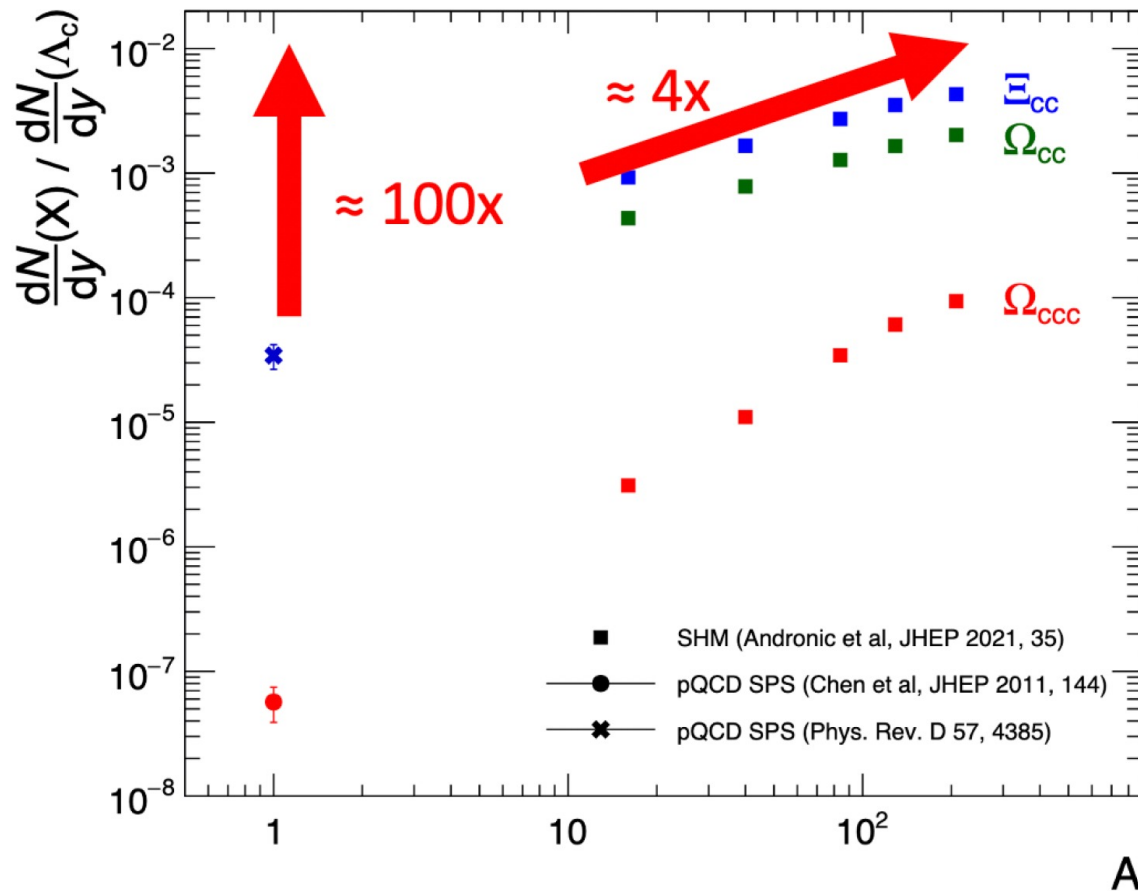


(3.) Many re-scatterings occur: charm gets thermalized and multicharm baryons
form by coalescence from independently produced charm quarks



Multicharm baryons (2)

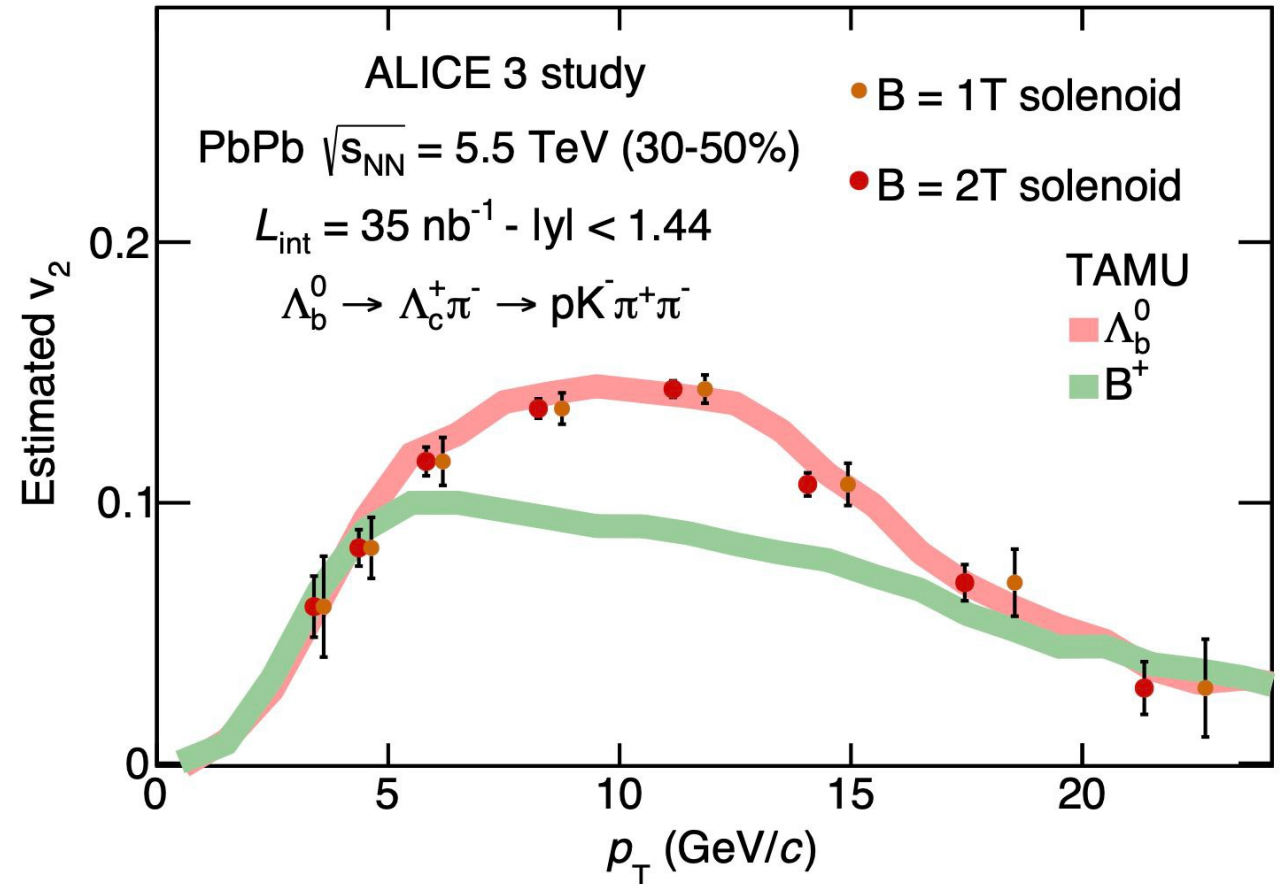
→ The unprecedented vertexing and tracking capabilities of ALICE 3 will allow the first time ever measurement of multicharm baryons such as Ξ_{cc} and Ω_{cc} in heavy-ion collisions.



[ALICE 3 Lol and Scoping document]

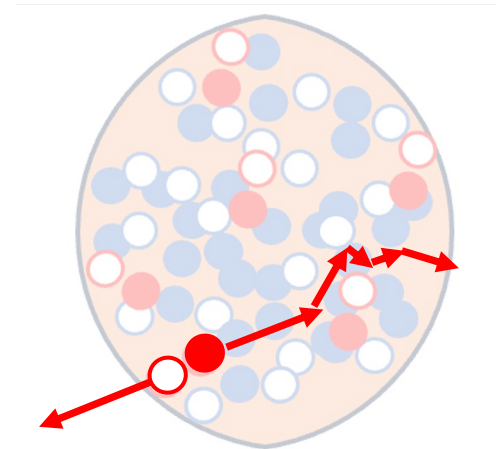
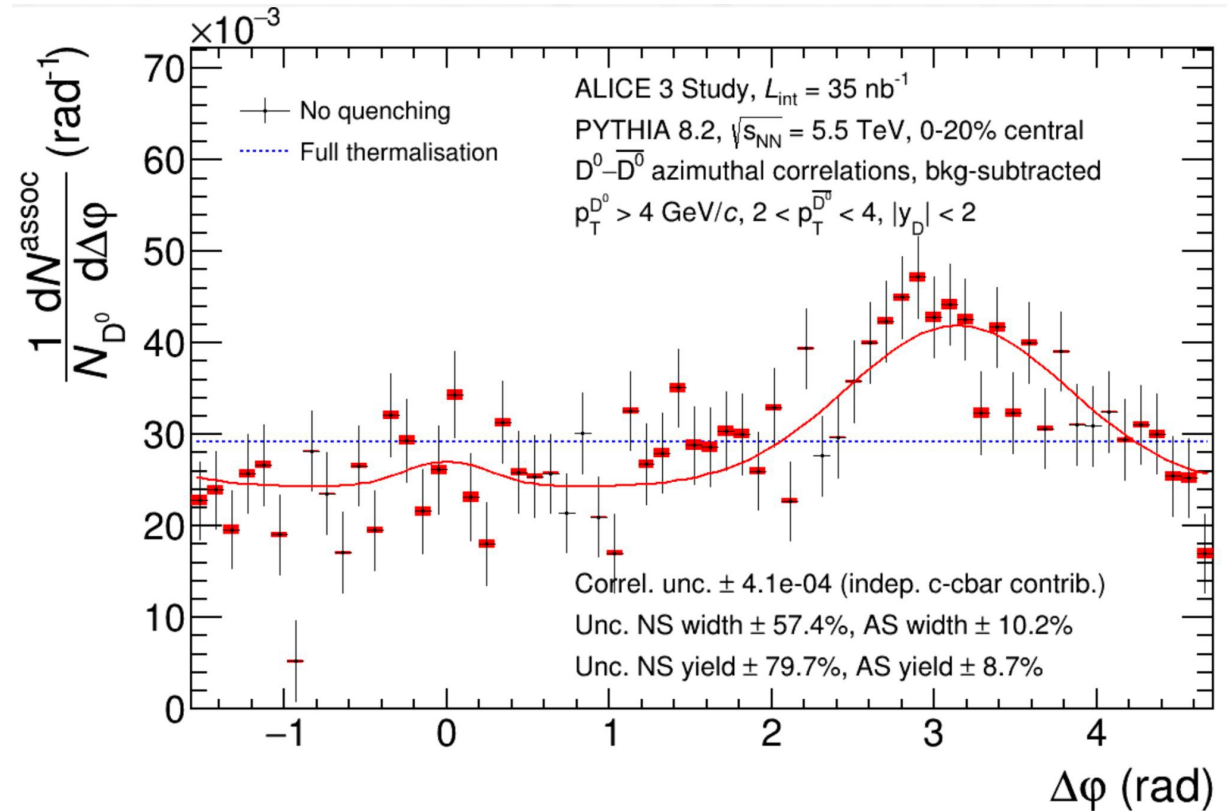
Beauty production and flow

- Due to their larger mass, beauty quarks should be less thermalised than charm quarks. This is already visible comparing the elliptic flow v_2 of prompt and non-prompt charm hadrons.
- Measuring this with direct beauty reconstruction would verify this important question in the field.
- ALICE 3 will be able to test baryon/meson splitting at intermediate p_T in the beauty sector.



D-meson correlations

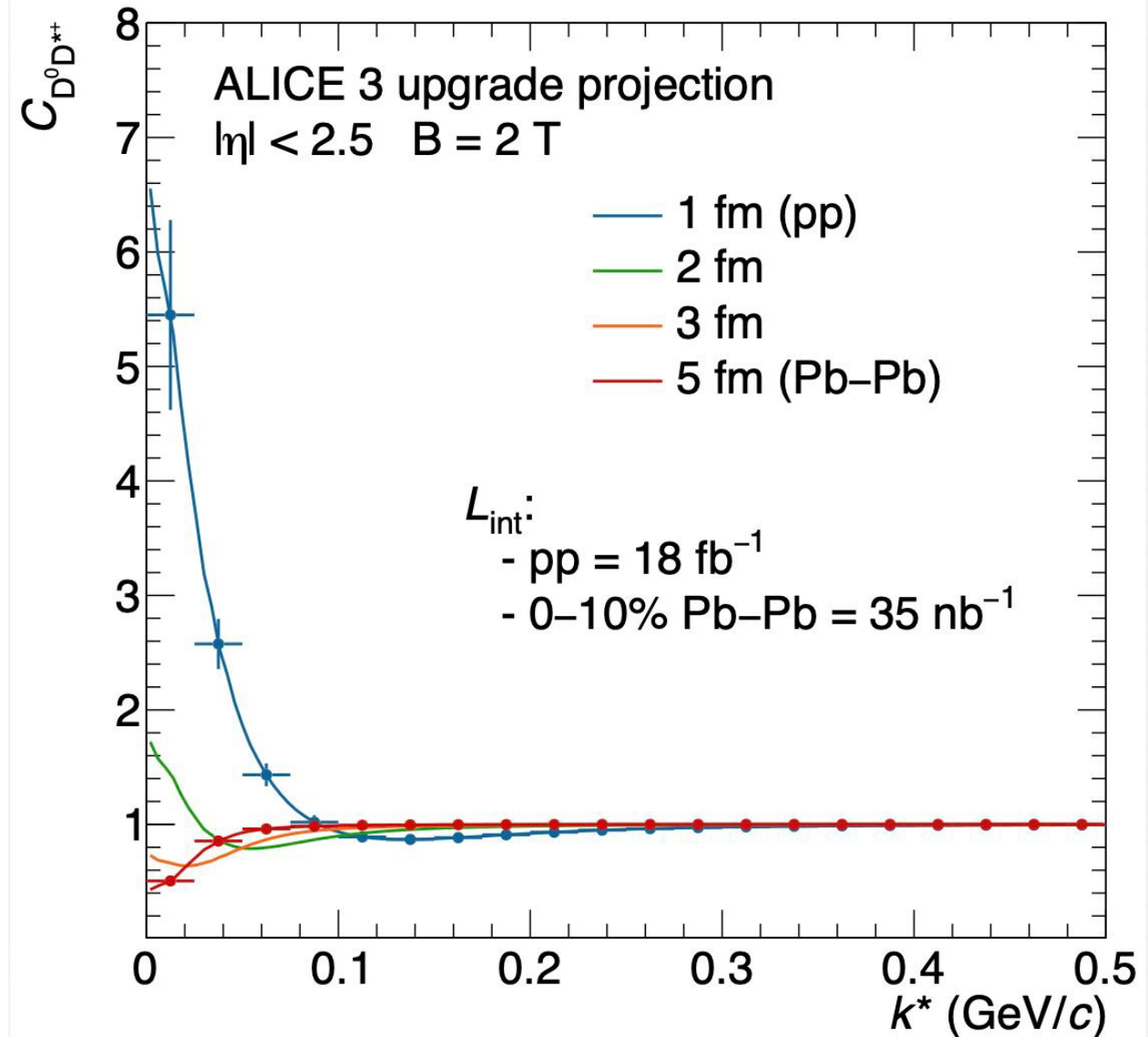
- In leading order, $c\bar{c}$ pairs and correspondingly $D\bar{D}$ pairs are produced back to back in azimuth.
- While traversing the medium, this back to back correlation is expected to be washed out, in particular at low p_T .
- By measuring the width and height of this correlation as a function of centrality and p_T , charm quark diffusion can be directly investigated.



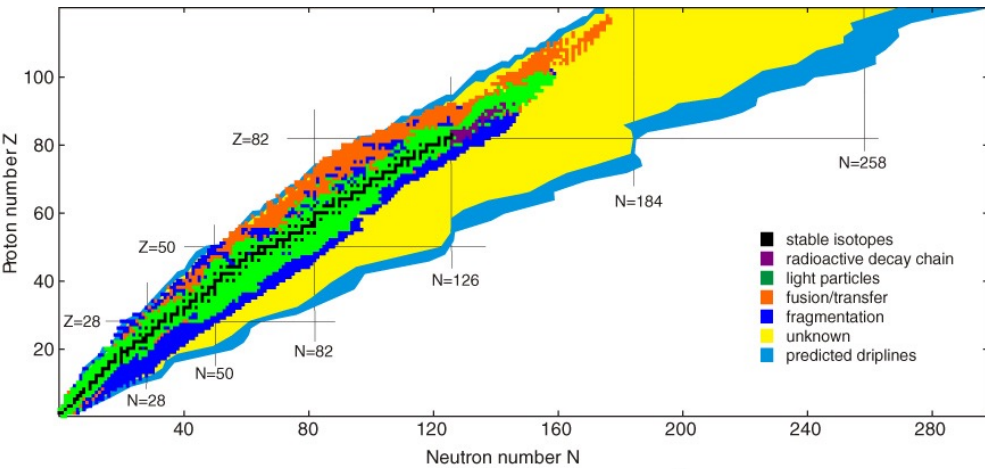
[ALICE 3 Lol and Scoping document]

Hadron-hadron correlations

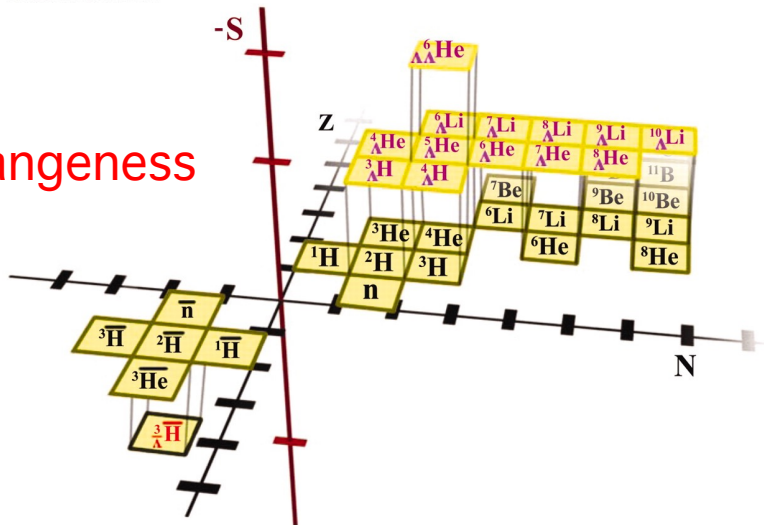
- Two particle correlations of charm hadrons such as $D^0 D^{*+}$ with small momentum difference k^* provide insights for hadron physics.
- The nature of several tetraquark candidates also have an alternative interpretation as bound state of two charm mesons.
- By investigating the correlation function of these mesons in system smaller (pp) and larger (Pb-Pb) than tetraquark candidate, one can clarify the existence of a bound state of these two mesons.



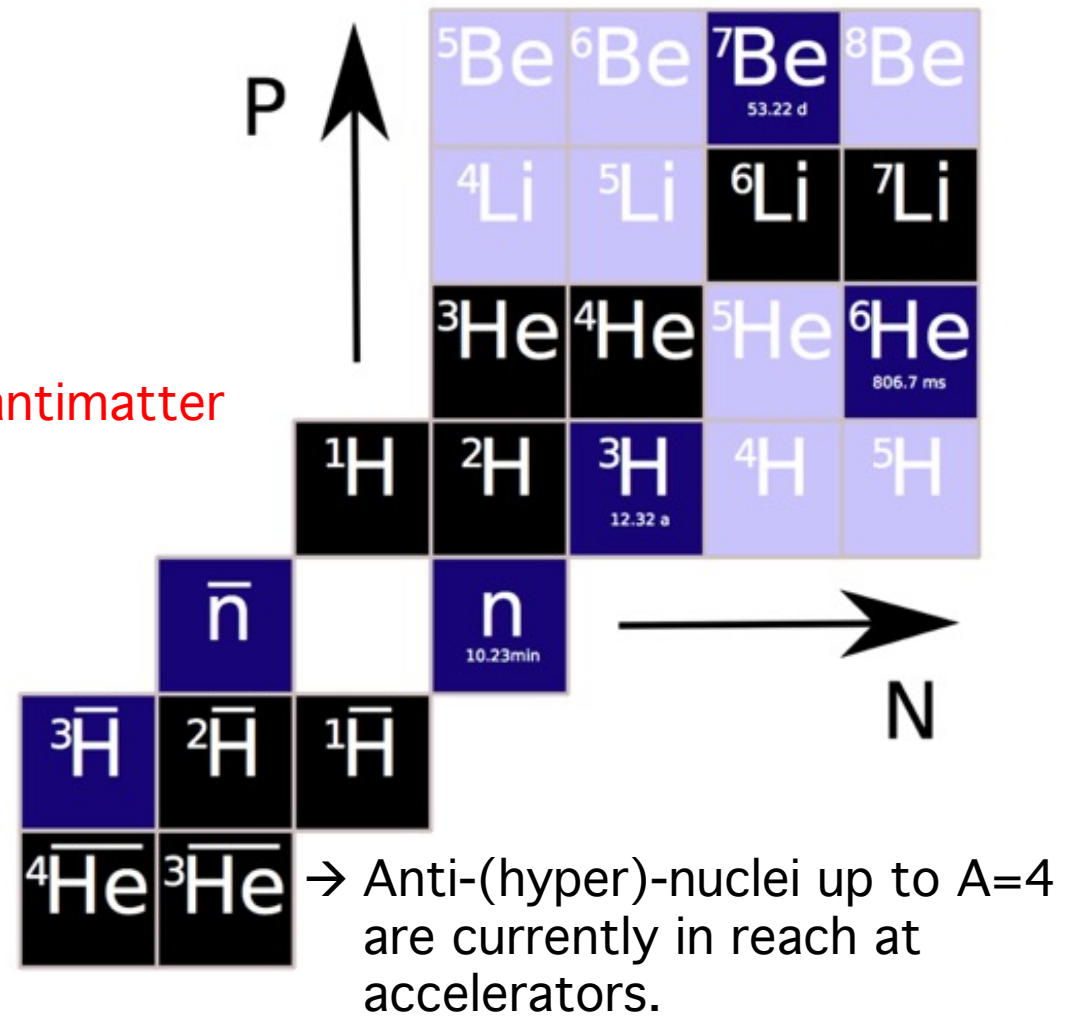
Extending the table of nuclides...



→ In the strangeness direction..



→ In the antimatter direction..



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

c-deuteron and c-triton

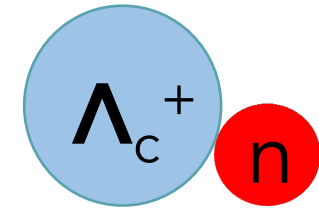
- The lightest possible bound states of a charm baryon and a nucleon without Coulomb repulsion are bound states of Λ_c^+ and a neutron: c-deuteron and c-triton.

- Their possible existence is widely and controversially discussed in the literature since the 1970s, see e.g.:

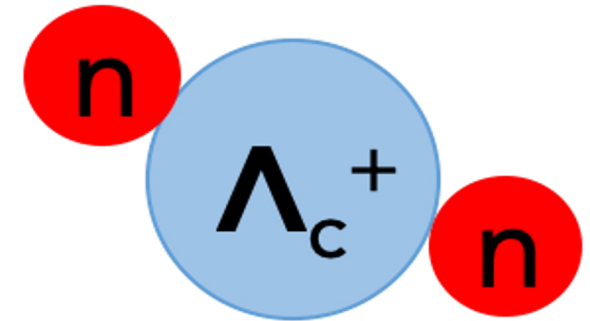
[Phys. Rev. Lett. 39, 1506]

[Eur.Phys.J.A 54 (2018) 11, 199]

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



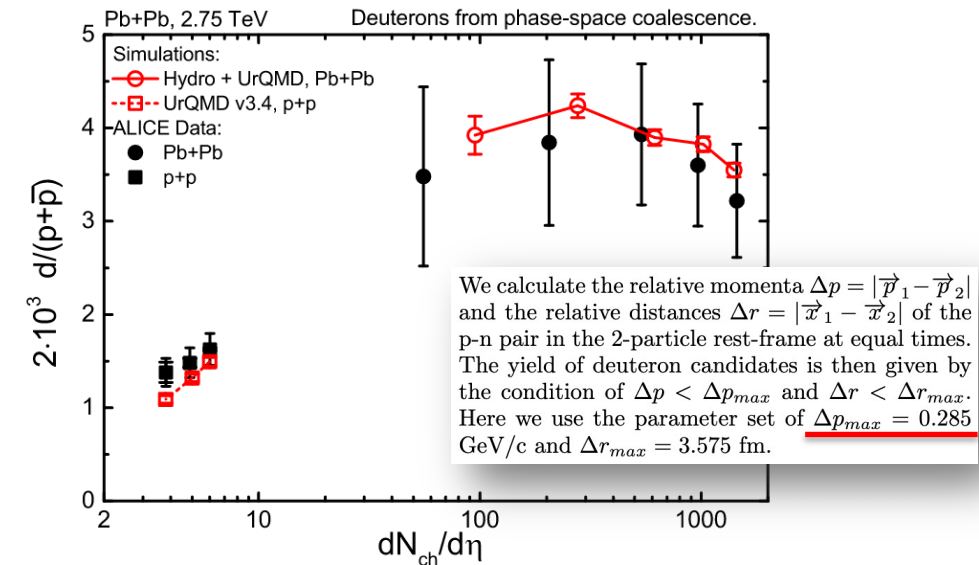
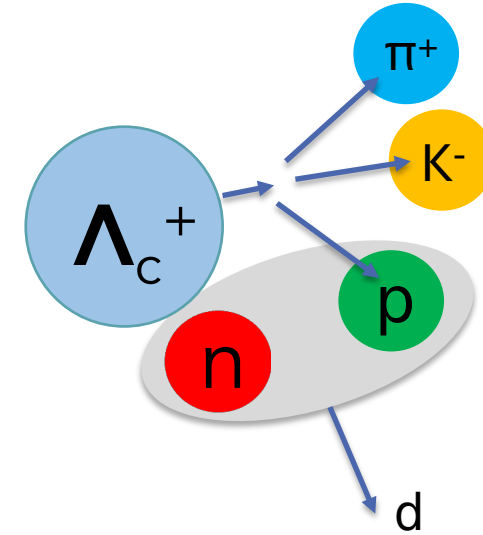
c-deuteron



c-triton

Decay channels and branching ratios

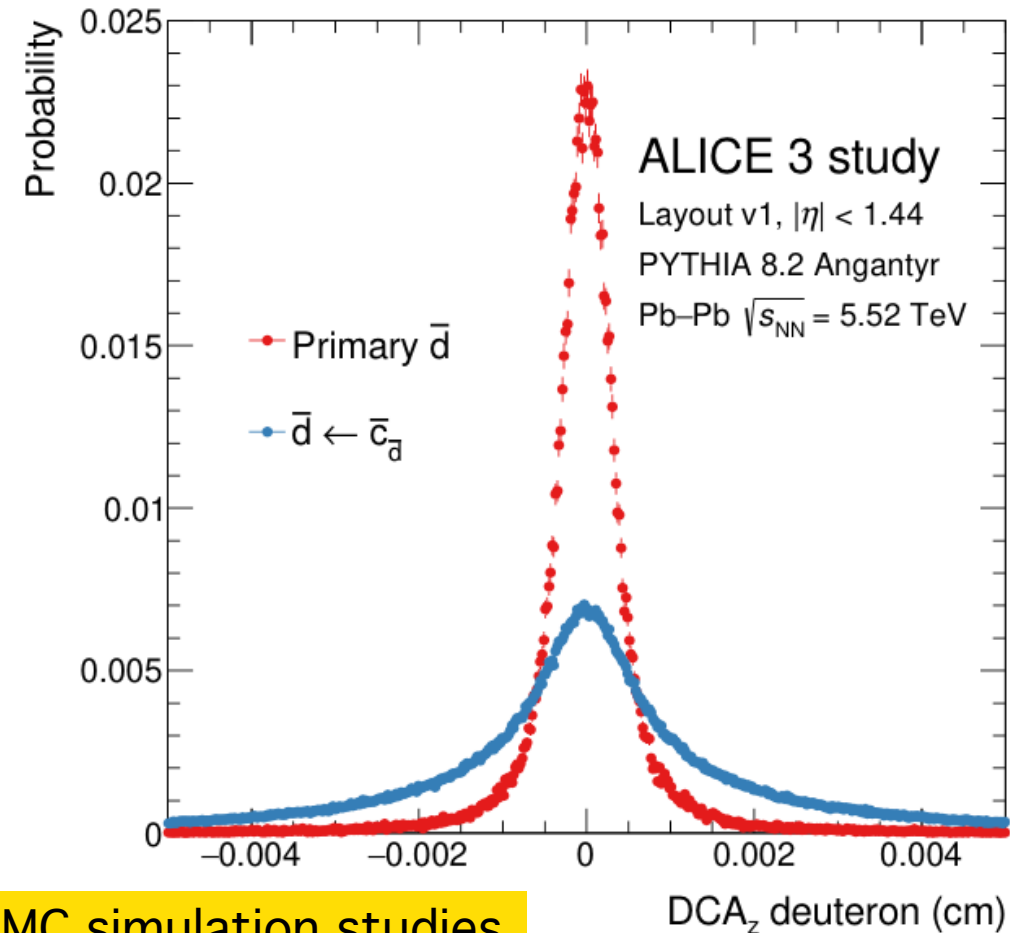
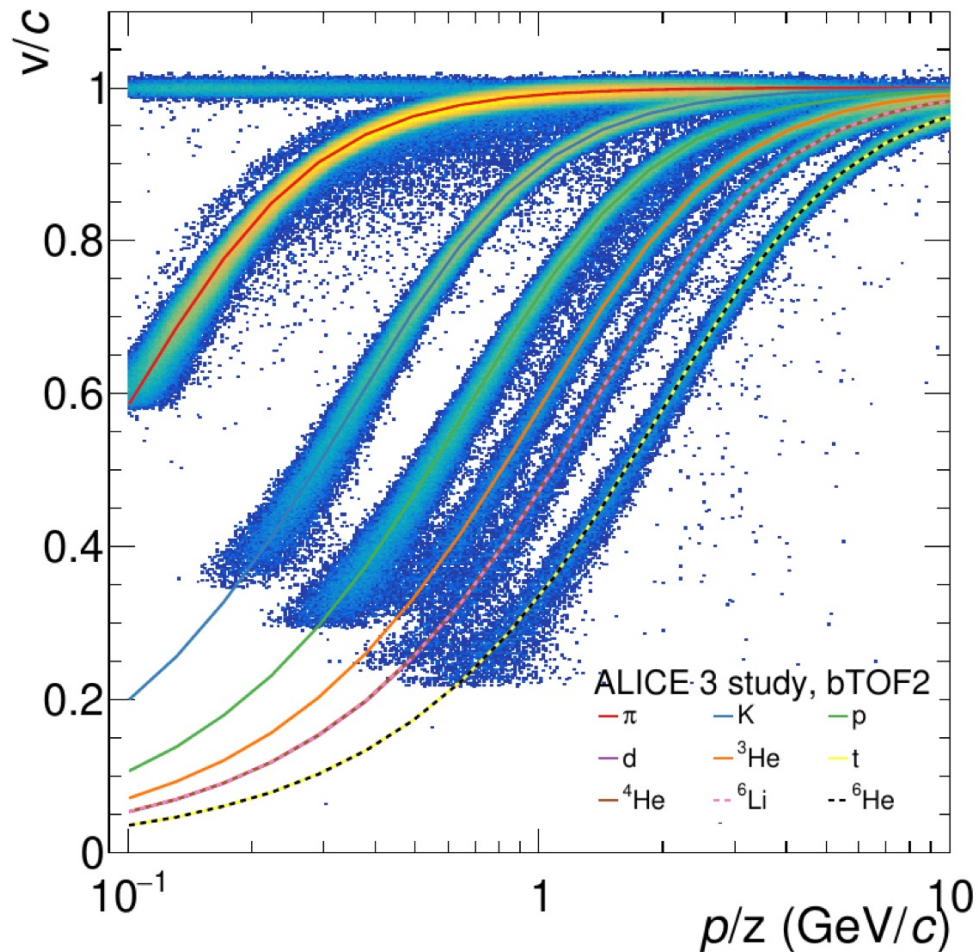
- Most promising candidates and decay channels:
 - $c_d \rightarrow d + K^- + \pi^+$
 - $c_t \rightarrow t + K^- + \pi^+$
- The relevant decay of the bound $\Lambda_c^+ \rightarrow p + K^- + \pi^+$ has a branching ratio of $6.28 \pm 0.32\%$.
- Probability of the decay proton to bind with the bound neutron can be estimated by requiring $p \lesssim 200$ MeV in the rest frame of the Λ_c^+ and is found to be $\approx 3\text{-}10\%$.
- 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)]

Experimental challenges: PID and vertexing

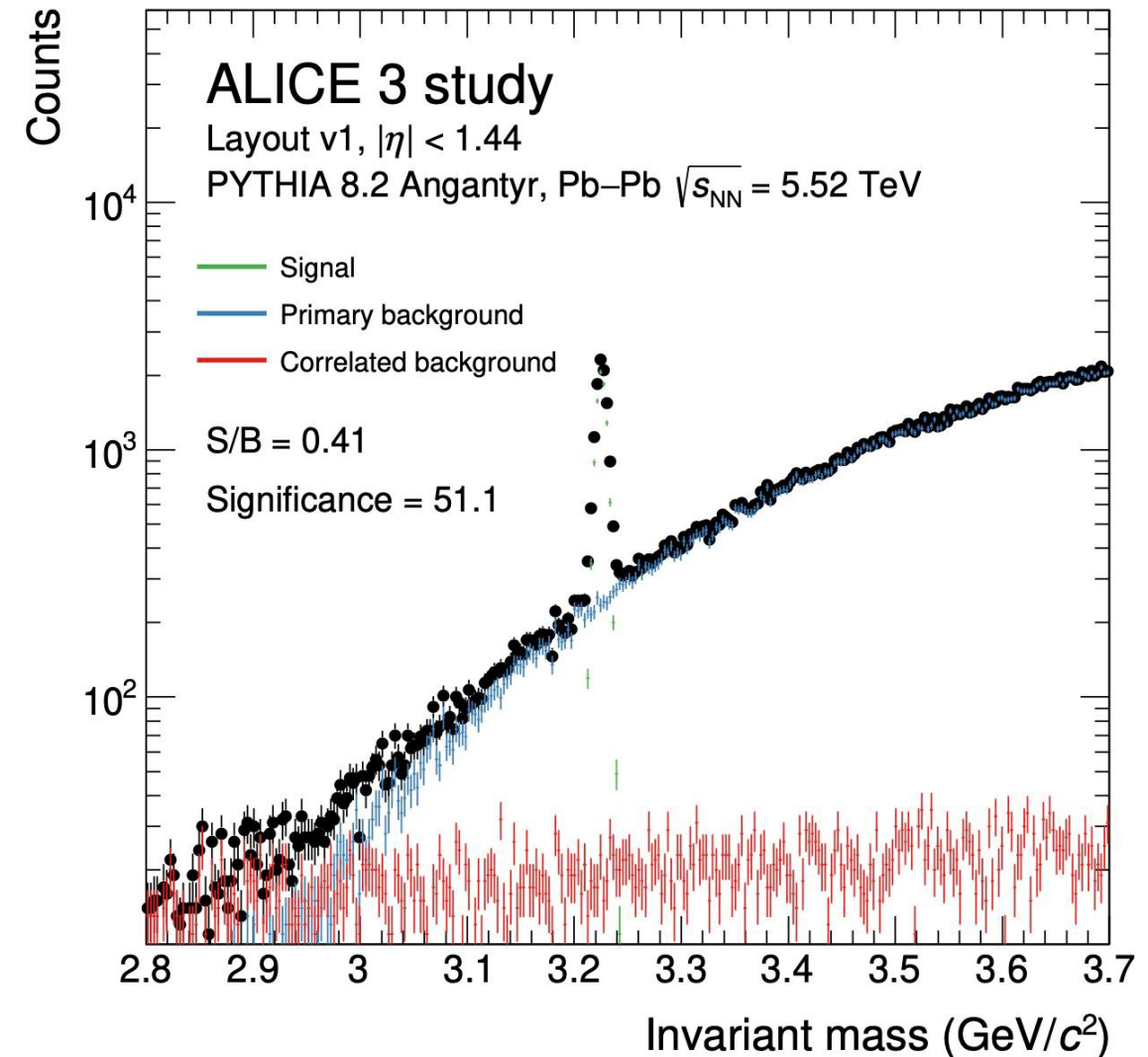
- Rare production of anti-nuclei requires excellent particle identification
- Main background source: primary deuterons that are combined with random pions and kaons → excellent dca-resolution. => **ALICE 3 is ideally suited for a charm-nuclei program!**



MC simulation studies

ALICE 3 and c-deuteron

- ALICE 3 is ideally suited to find the c-deuteron as simulation studies clearly indicate. Even the c-triton is in reach.
- If these objects do not exist, then ALICE 3 is in a unique position to set stringent limits as the expected production yields can be well constrained by thermal model estimates.



Summary and conclusions

- ALICE 3 is well on its way and we are looking forward to great physics with it.
- Peter was together with a few other people (most of them in the audience today) the initiator of the project (roughly 2018) and is still today one of the main drivers.
- A big personal thank you for 21 years of scientific mentorship (Nuclear physics course “Kernphysik I” at TU Darmstadt in 2005 together with M. Mager and M. Knichel) for me and the field of heavy-ion physics as a whole!

Nuclear Physics Course
Summer Semester 2005

Prof. Dr. Peter Braun-Munzinger
Dr. Dariusz Miskowiec, Dr. Christian Lippmann
Oliver Busch, Dr. Mario Babilon



TECHNISCHE
UNIVERSITÄT
DARMSTADT

Problem Set #1

General Remark: Use units of $\hbar = c = 1$

1. An atomic nucleus ($A=200$) has kinetic energy of 1, 10, 10^3 , 10^6 MeV.
Compute its momentum, total energy, velocity, and kinetic energy per nucleon E/A .
2. The Compton wavelength equals $\lambda = \frac{1}{m}$.
Compute it for an electron, a proton, and a Pb nucleus. Please express the results in fm.
3. A massless quark is bound inside a nucleon with radius $r = 1$ fm. Using the uncertainty principle, estimate the momentum, kinetic energy, and the total energy of the quark.
4. Same as 3. with a nucleon mass of 930 MeV inside a nucleus with radius $R = 10$ fm.

Thank you!

FCC timeline

2028 Decision by the CERN Member States, including France and Switzerland, meeting in the CERN Council, on whether to carry out the project

2026–2032 Preparatory phase; Further, more in-depth studies commissioned by the CERN Member States

2033 to 2040 Civil engineering phase

After 2038 FCC installation phase

After 2045 FCC commissioning and operation

New baseline layout v3

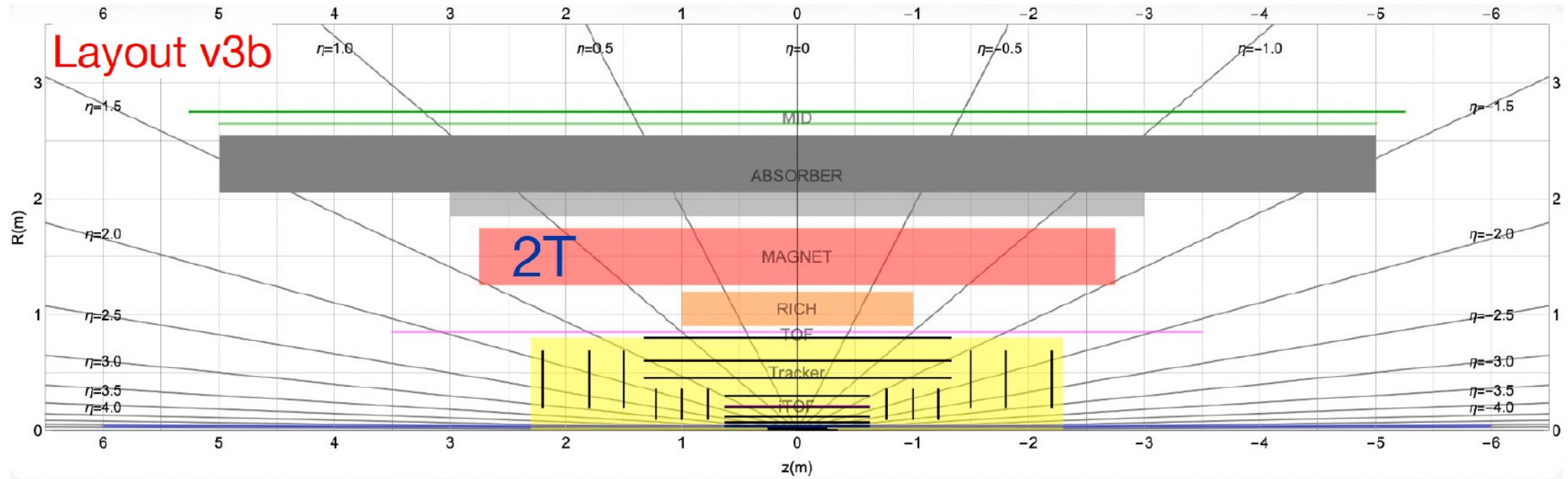


Figure 2: ALICE 3 in layout version v3b (including RICH).

- The new favoured baseline version (v3b) that matches best the resource estimate consist of (a.) a shorter 2T magnet (TBD), (b.) a reduced tracker acceptance $|\eta| < 2.5$, (c.) a reduced TOF acceptance of $|\eta| < 2.0$, and a RICH with $|\eta| < 0.8$.