Hadronisation and exotic nuclear states in high energy nuclear collisions with ALICE

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Seminar Bologna, 13th May 2022

Introduction

$$\mathcal{L}_{\mathrm{QCD}} = \bar{q}(i\gamma^{\mu} D_{\mu} - m)q - \frac{1}{4} F^{a}_{\mu\nu} F^{\mu\nu}_{a}$$

Quark-field

Quark-mass

Gluon field strength tensor

- In QCD, the fundamental degrees of freedom are quarks and gluons.

- Unfortunately, free quarks and gluons can not be observed in nature (*confinement*). Only their bound states (*hadrons*) are directly observable in nature.

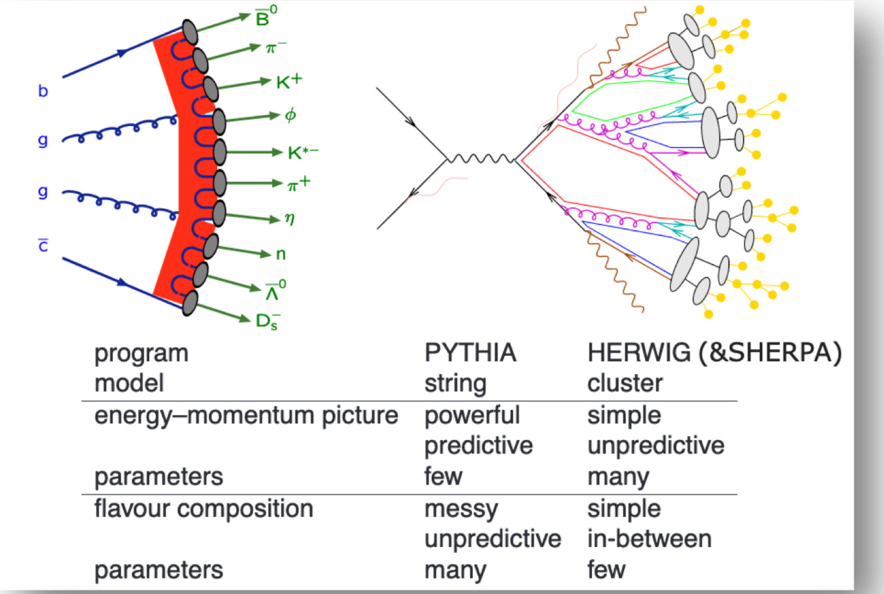
- The process of the formation of hadrons (either baryons *qqq* or mesons $q\bar{q}$) out of quarks and gluons is called *hadronization*.

Desperate attempts to describe hadronisation

- Lund string fragmentation

Breaking/tunneling with $\mathcal{P} \propto \exp\left(-\frac{\pi m_\perp^2}{\kappa}\right)$ gives hadrons.

strings with tension $\kappa \approx 1$ GeV/fm



- Herwig cluster hadronization

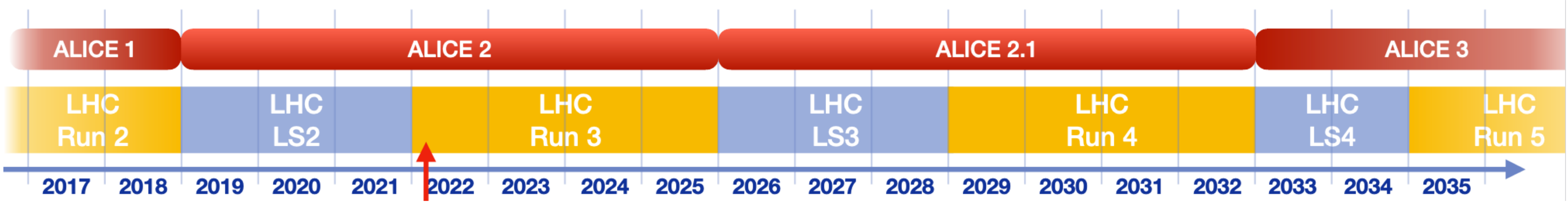
- Statistical hadronisation

$dN/dy \sim \exp\{-m/T_{ch}\}$

=> in all cases: neither an elegant (many tunable parameters) nor satisfactory (not first principles QCD) description

=> As experimentalists: let’s start with an easier question → is the hadronization pattern modified if the quark is surrounded by many other quarks (“quark coalescence”)

ALICE 1.. 2.. 3..


ALICE 1
ALICE 2
ALICE 2.1
ALICE 3
LHC Run 2
LHC LS2
LHC Run 3
LHC LS3
LHC Run 4
LHC LS4
LHC Run 5
2017
2018
2019
2020
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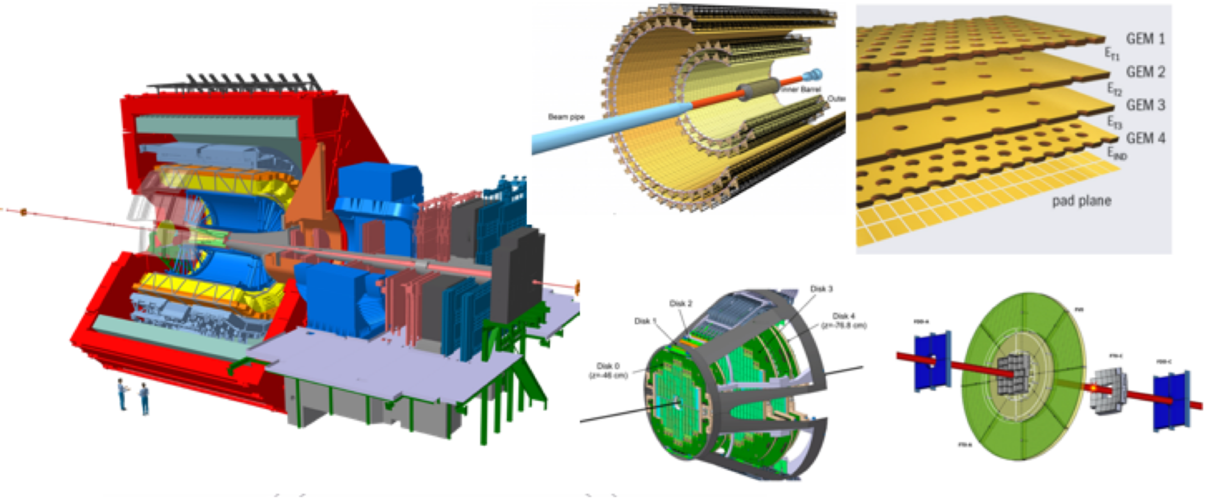
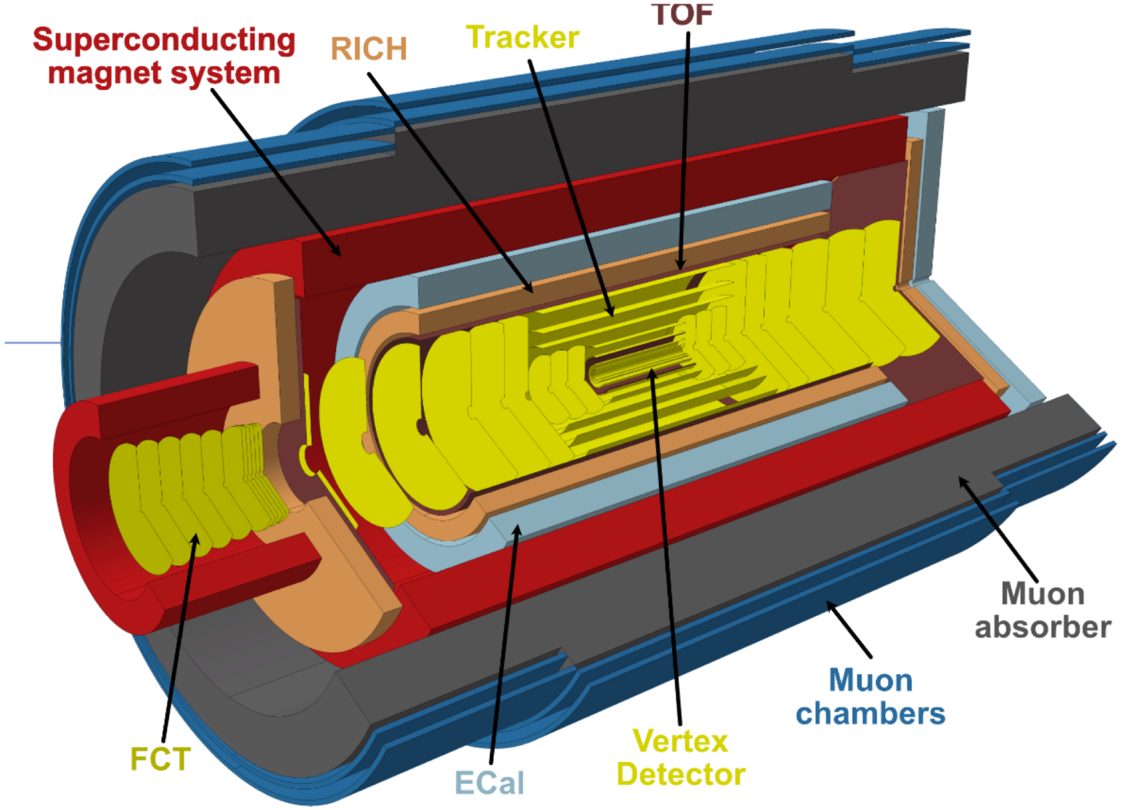
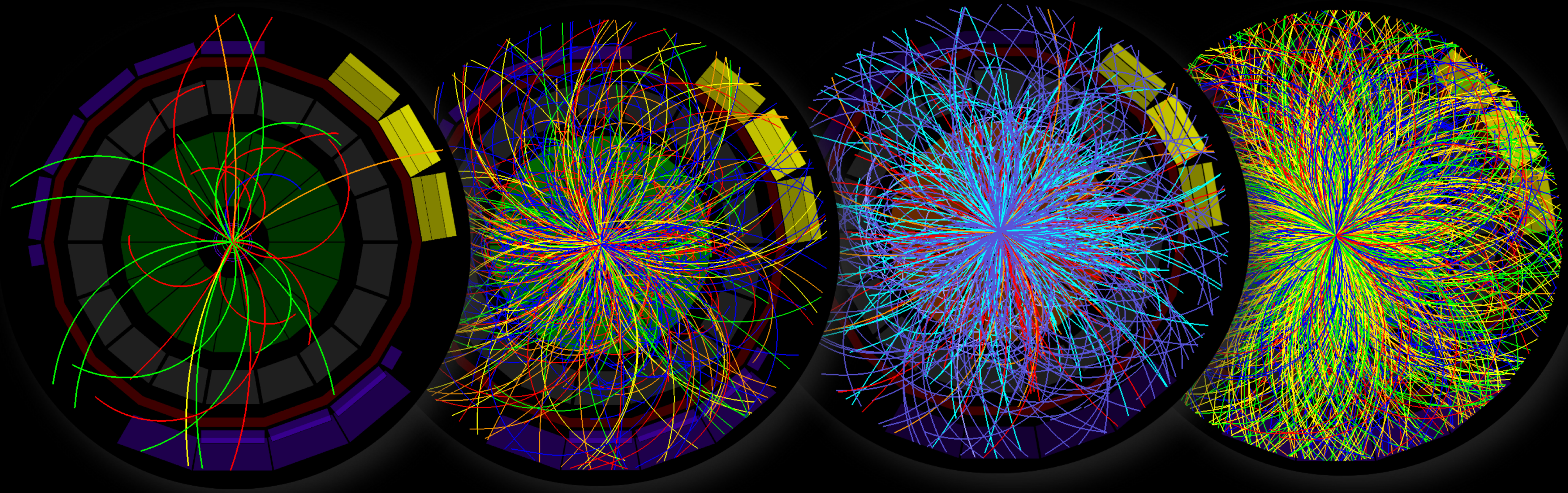

GEM 1
GEM 2
GEM 3
GEM 4
pad plane


Superconducting magnet system
RICH
Tracker
TOF
Muon absorber
Muon chambers
Vertex Detector
ECal
FCT

ALICE 1

System size scan at the LHC



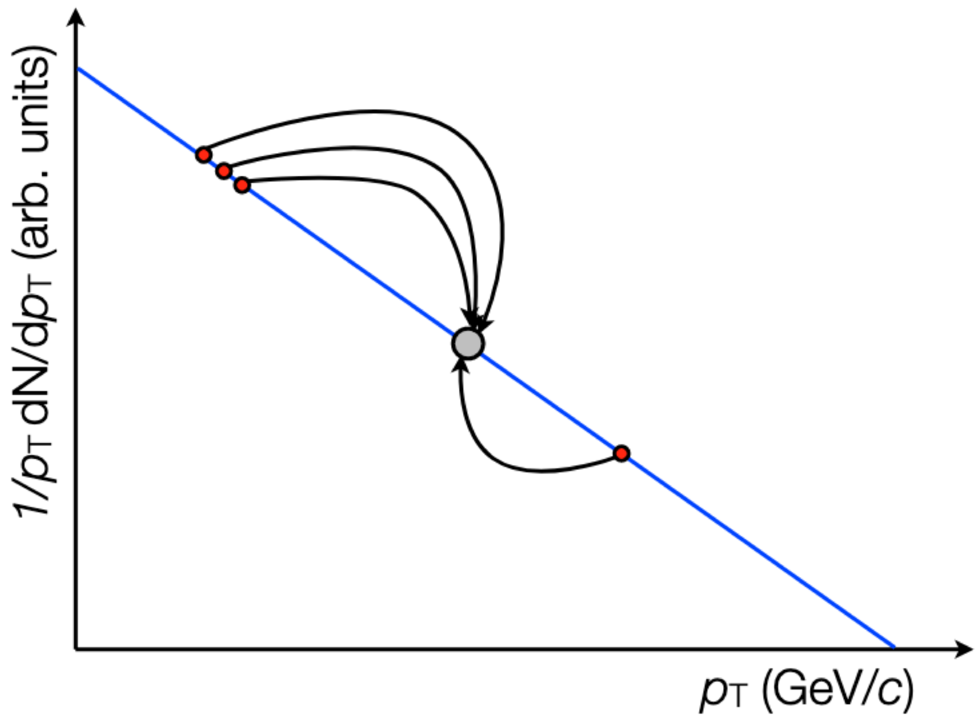
pp
13 TeV

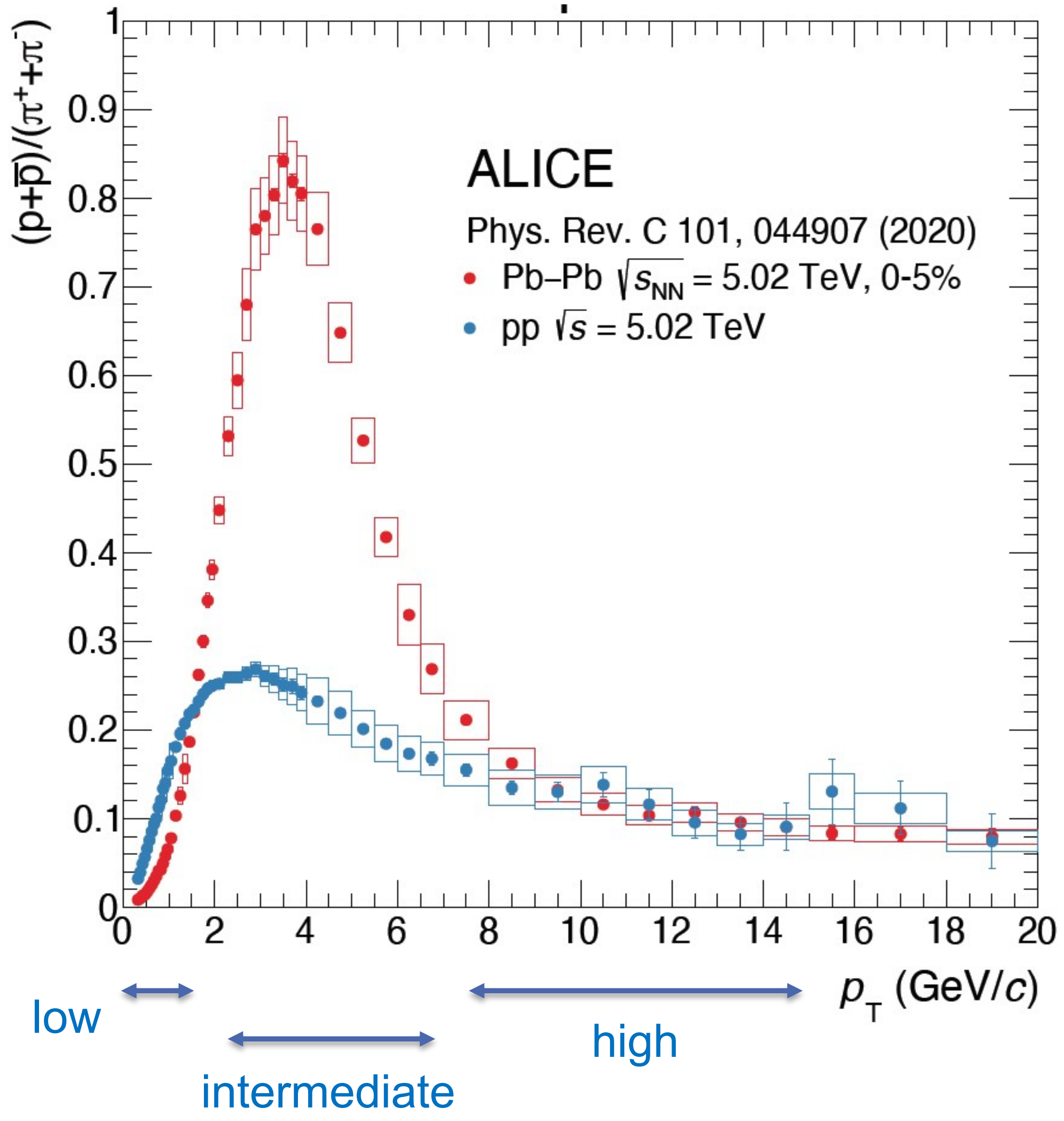
p-Pb
5.02 TeV

Xe-Xe
5.44 TeV

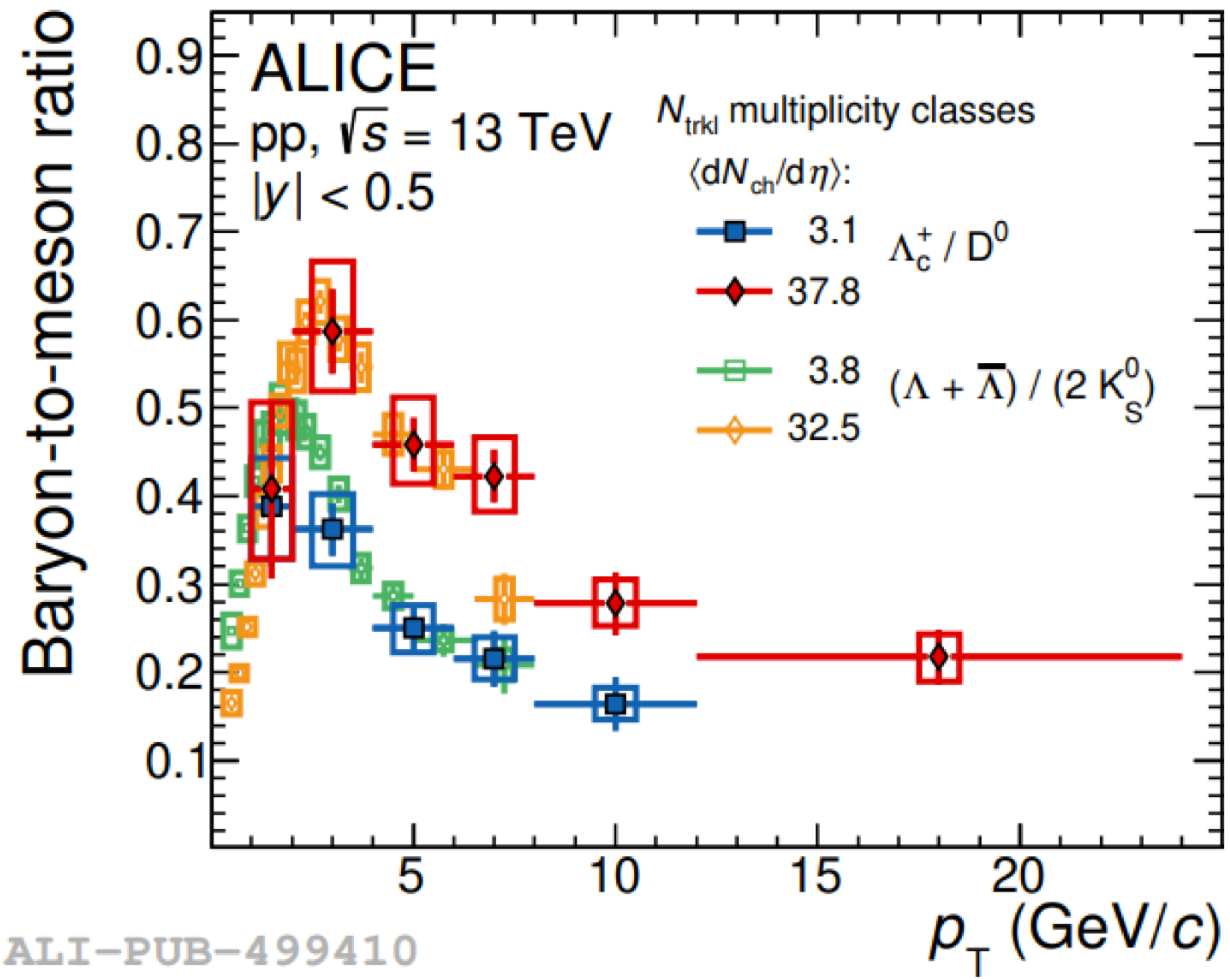
Pb-Pb
5.02 TeV

Baryon to meson ratio in the light flavor sector

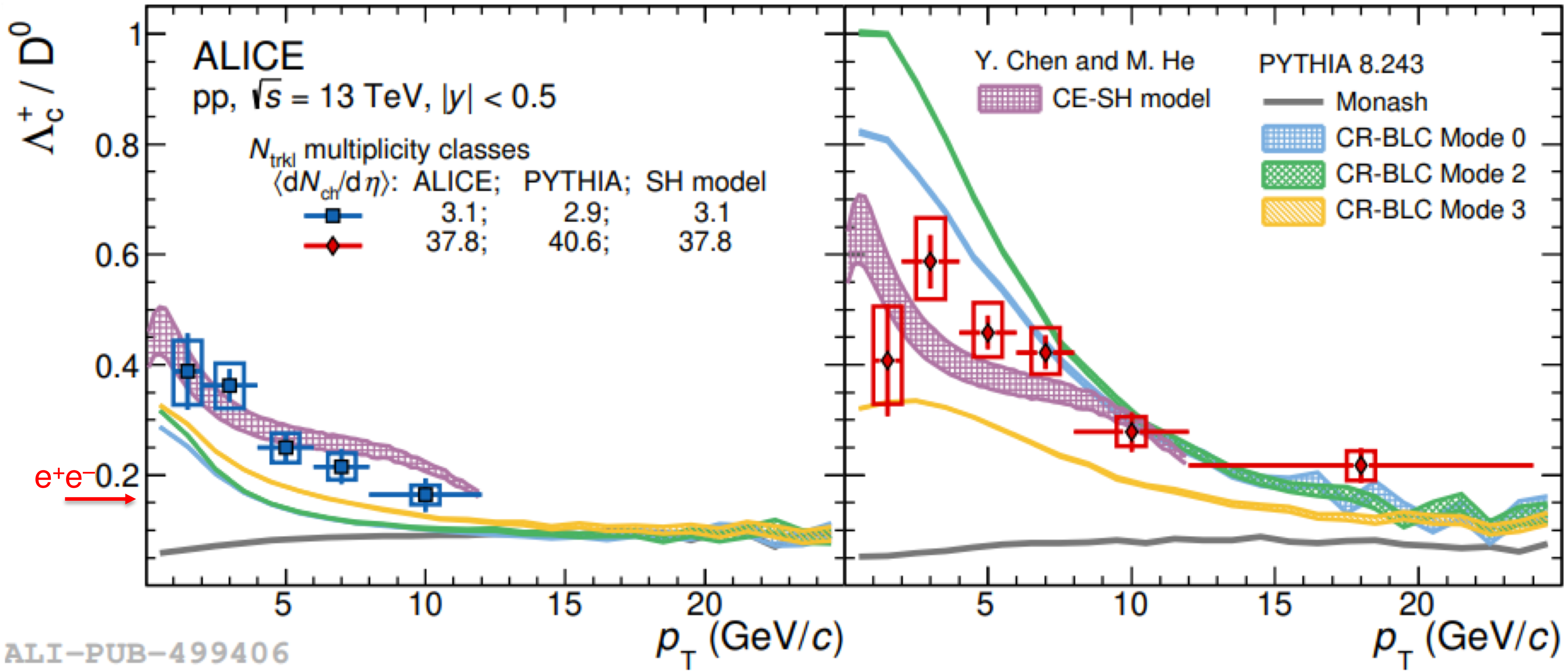




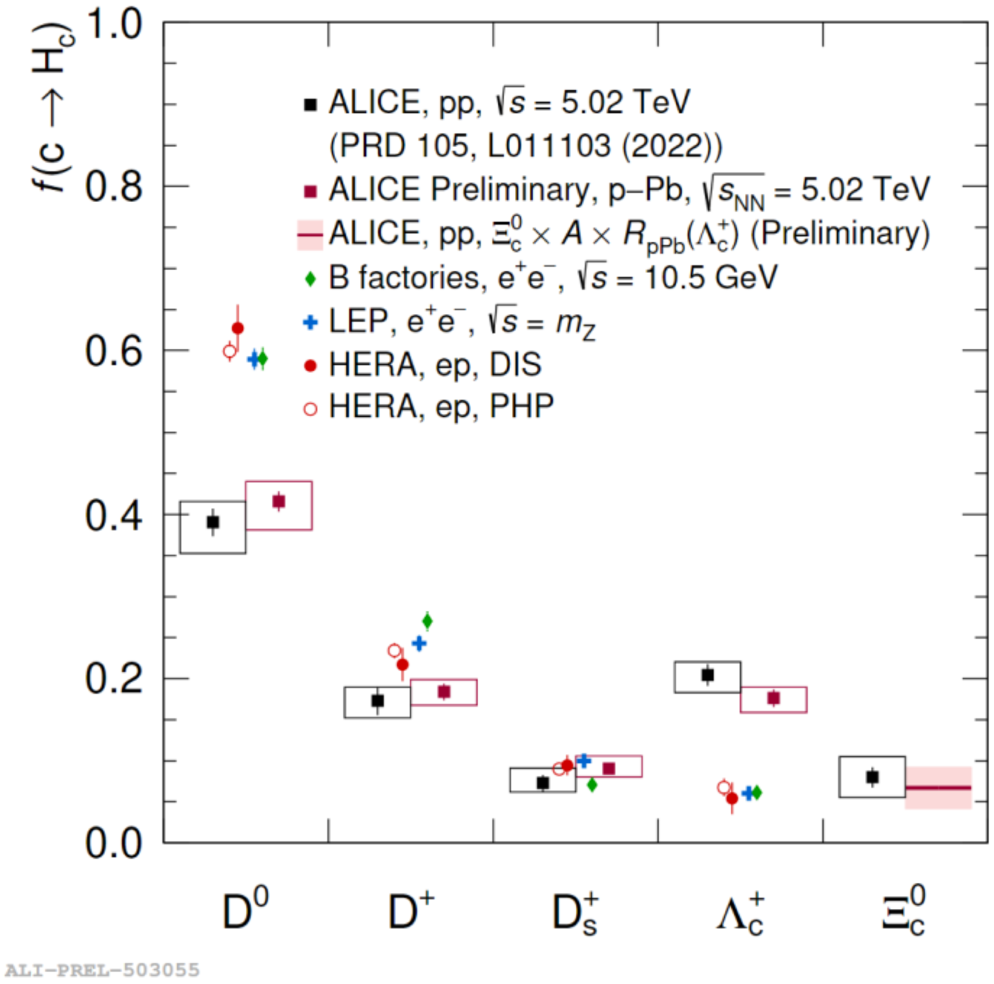
Baryon to meson ratio in the heavy flavor sector (1)



Baryon to meson ratio in the heavy flavor sector (2)



Charm fragmentation fractions



→ In summary:

Take home message number 1: partons like to “baryonise” at the LHC (much more than at LEP or at HERA).

TOWARDS ALICE 2

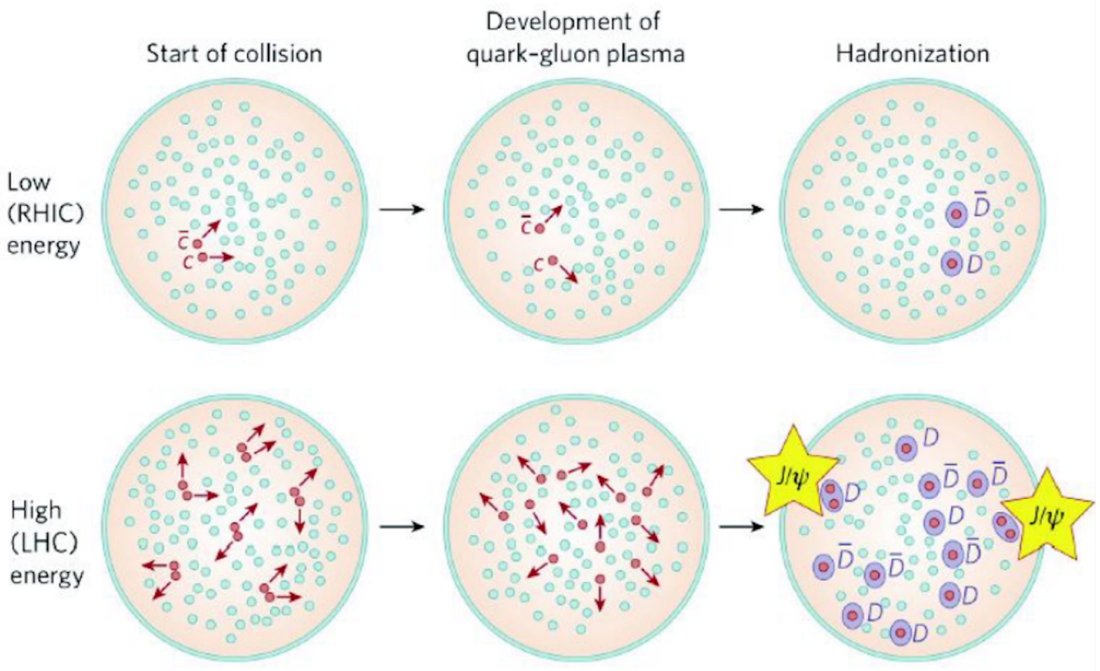
Heavy flavor in heavy-ion collisions (1)

- Charm quarks ($m_c \approx 1.275$ GeV/c^2) are roughly 200-500 times heavier than u- or d-quarks. Beauty quarks are still roughly 4 times heavier than charm quarks ($m_b \approx 4.18$ GeV/c^2).

- Despite being so heavy, the many other light quarks give them apparently so many kicks that charm quarks participate in the medium expansion and they show a finite v_2.

- They are so heavy ($m_c, m_b >> T$) that they are produced only in the initial collisions. Then their number is conserved. This behavior is in contrast to light flavor quarks/hadrons that are continuously destroyed and created throughout the fireball evolution.

Heavy flavor in heavy-ion collisions (2)

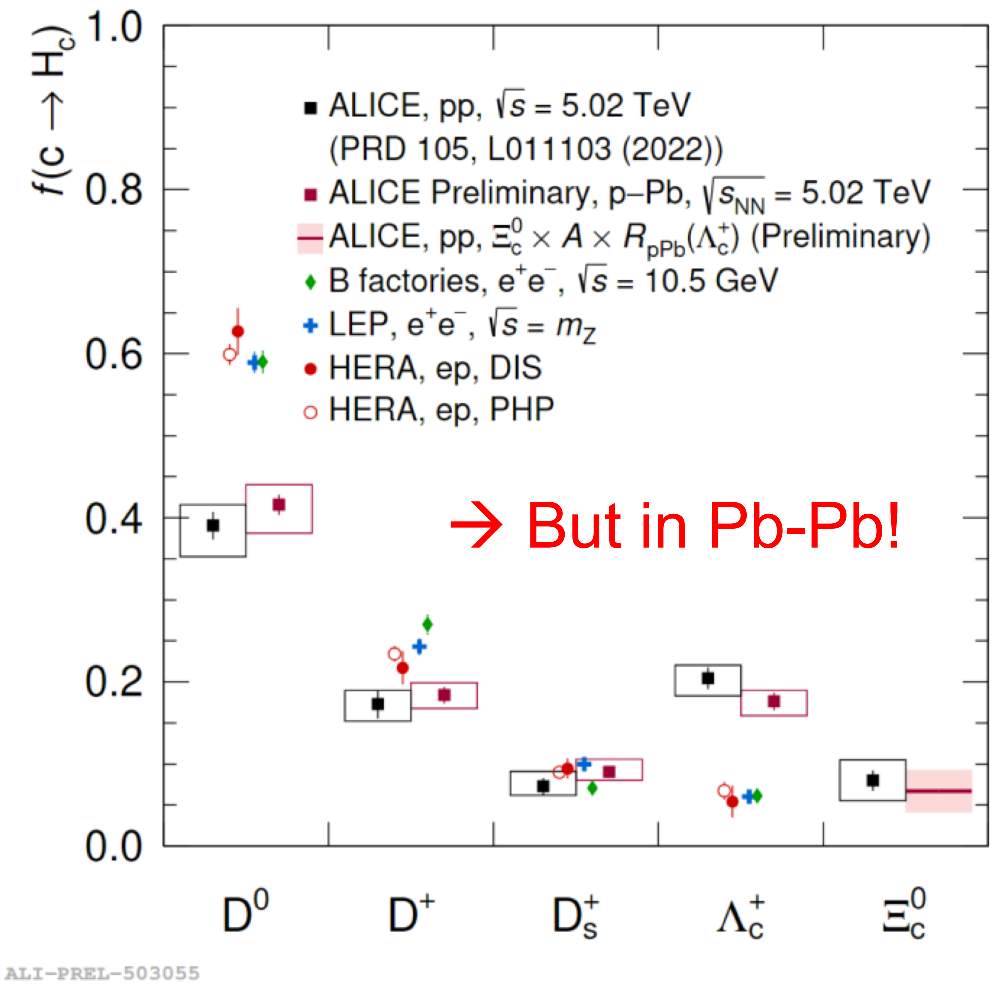


[Nature 448 (2007) 302-309]

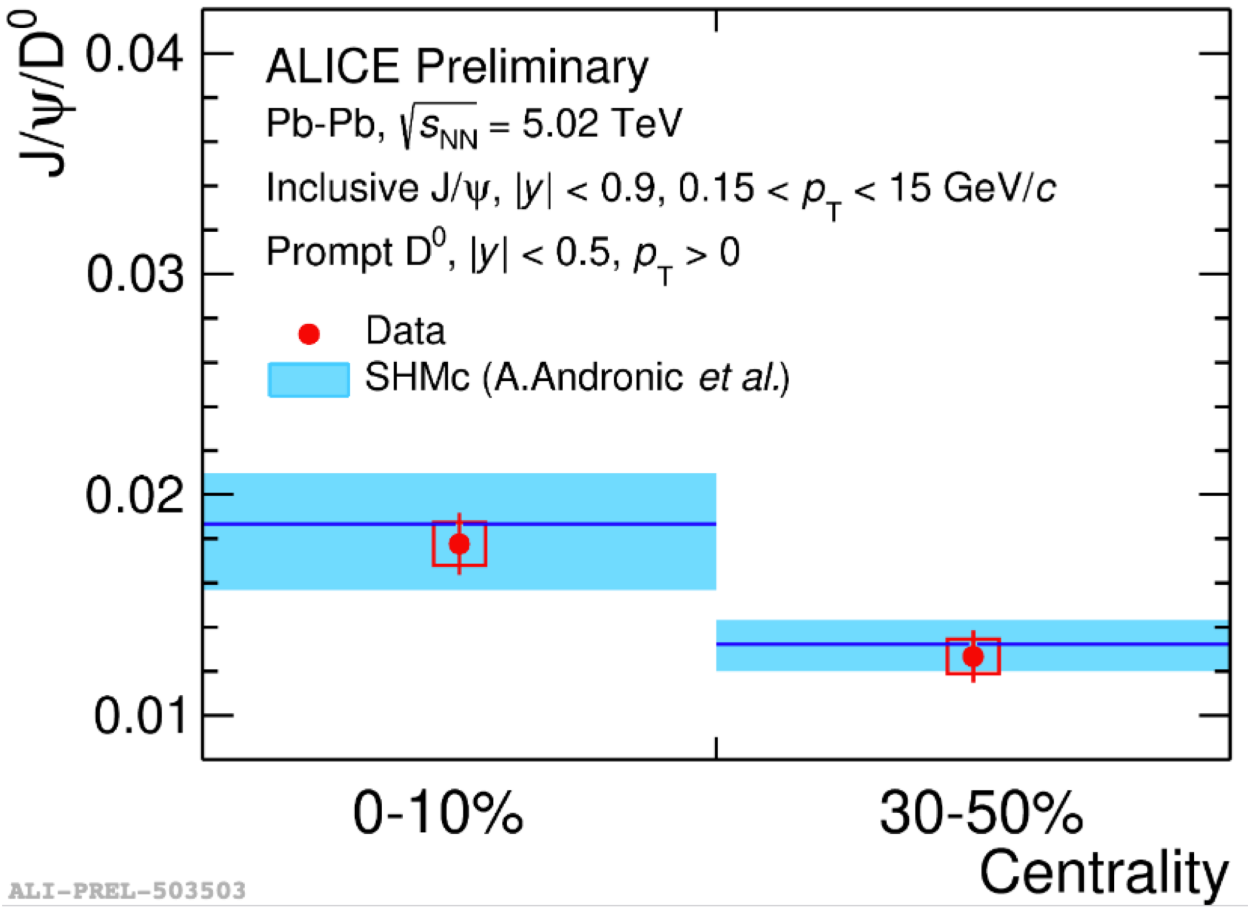
- Charm offers another possibility → we know how many we implant into the QGP and then we see how many come out in which form.
- Point the road to the future → we have already measured pp fragmentation fractions and we will do it in Pb-Pb

Charm hadronization and proving deconfinement

What is needed?



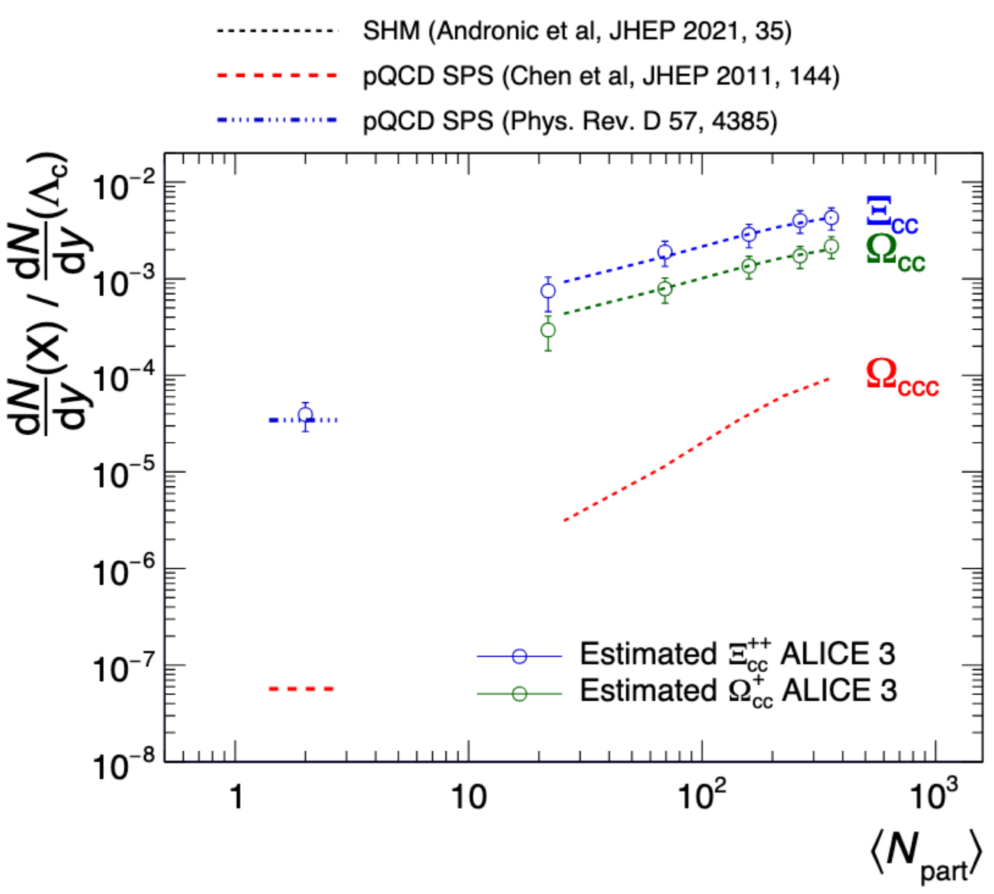
Where we are?



How can we reach textbook quality for this?

- Effects on J/psi recombination are intriguing, but they remain smallish, because of the interplay of dissociation and recombination.

- Much more elegant: measure multi-charm hadrons

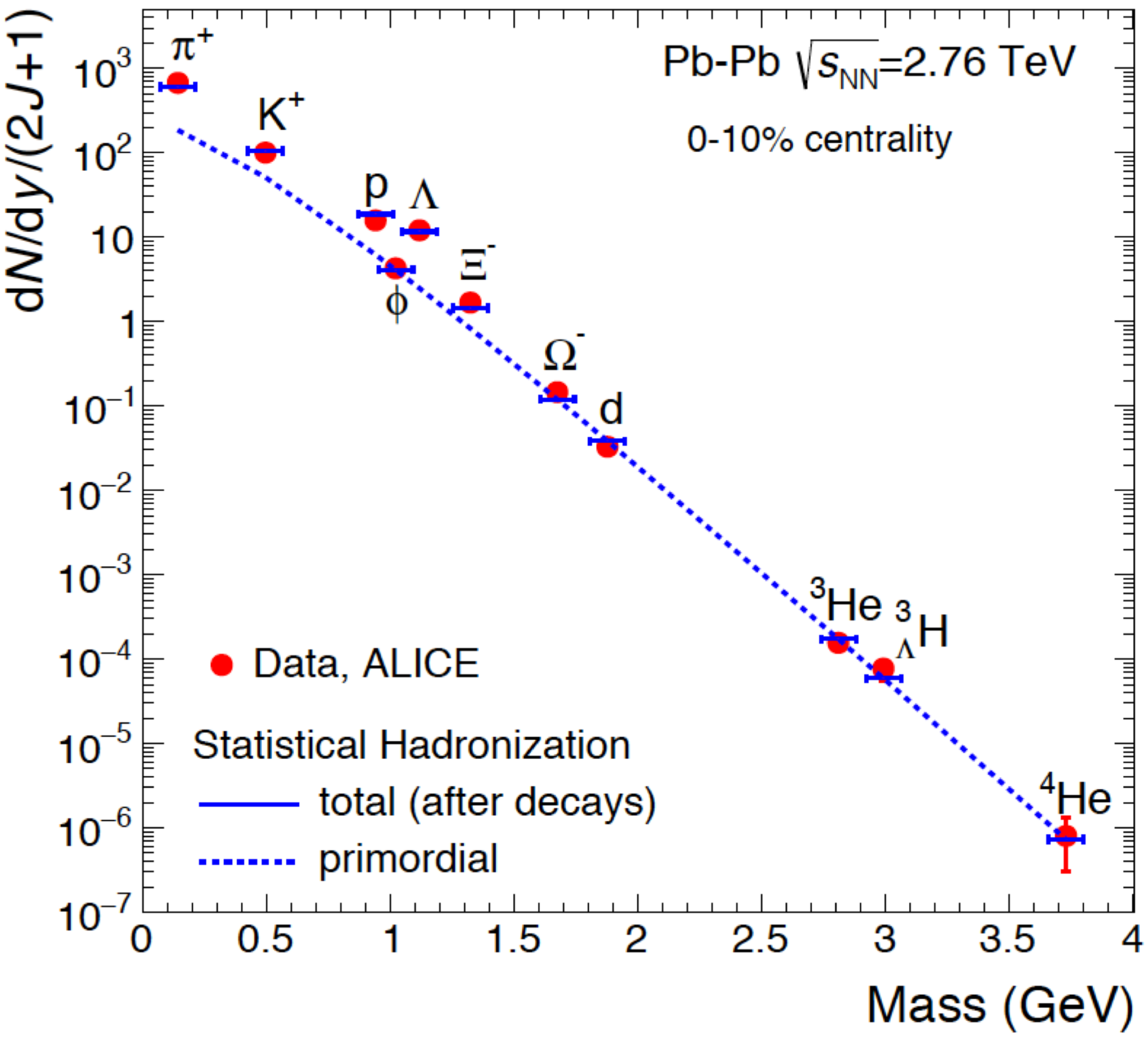


Large enhancements: unique sensitivity to **thermalisation and hadronisation dynamics**

THE FAR FUTRE: ALICE 3

Thermal hadron production of light flavor hadrons

- 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 9 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}).



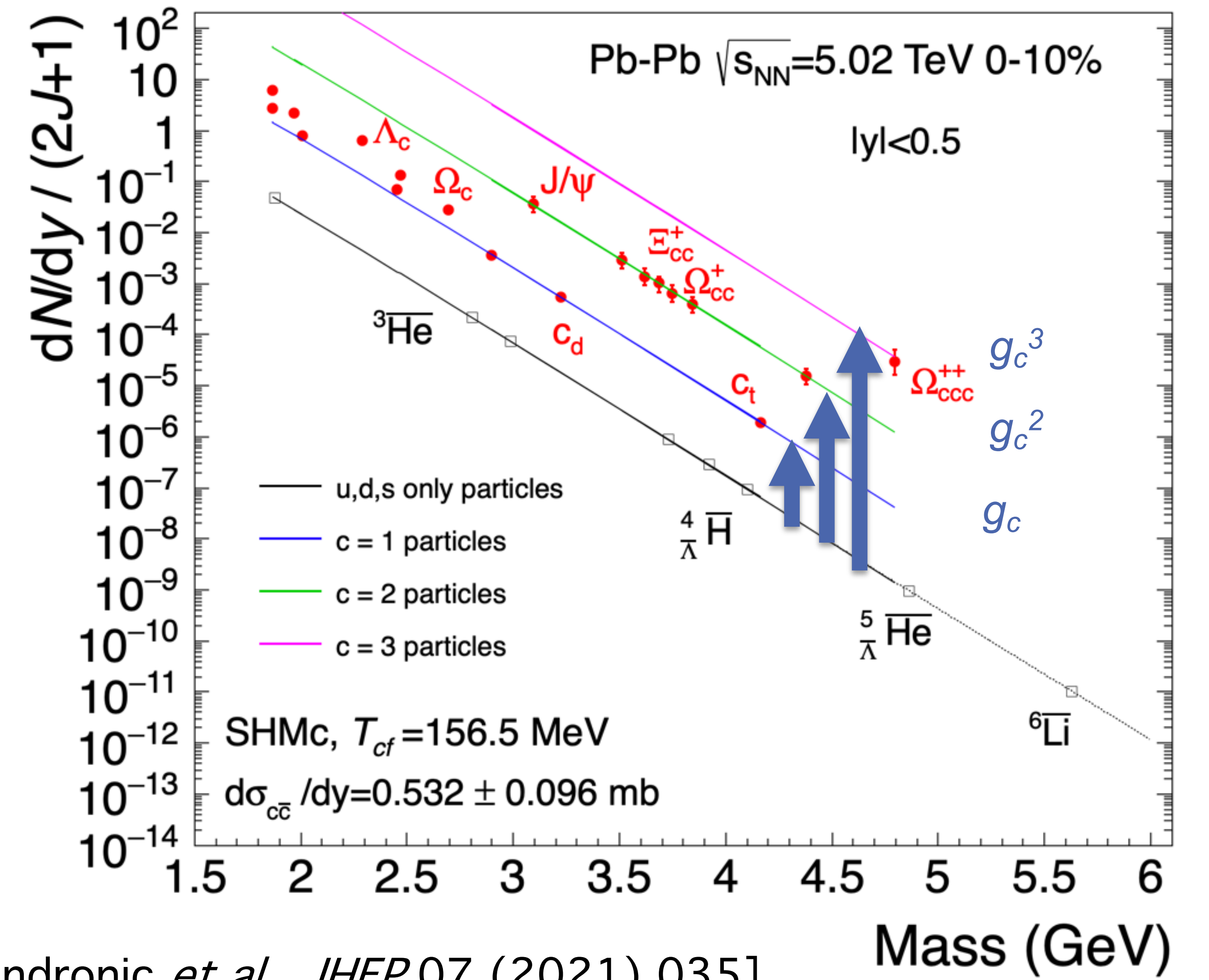
[A. Andronic *et al.*, *Nature* 561 (2018) 7723, 321-330]

Will we observer the same behavior for heavy-flavor with ALICE 3?

Thermal production of charm particles

- Charm particle production rates are expected to be enhanced by the factor of the charm fugacity $g_c \approx 30$ (including charm nuclei).
- This makes multi-charm 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!

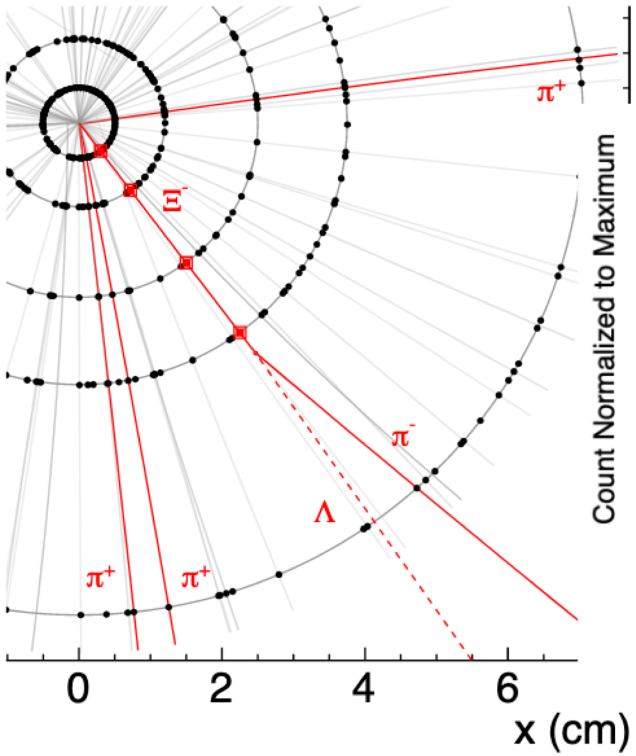
Predictions of statistical-thermal hadronization model



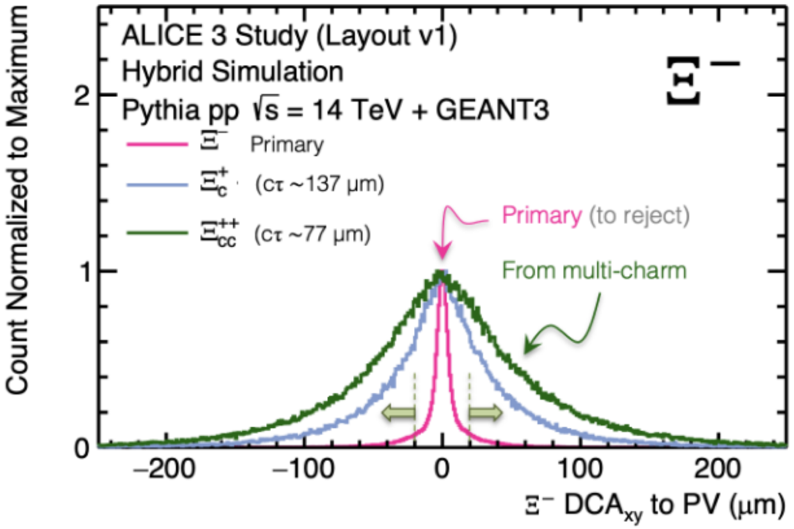
[A. Andronic *et al.*, *JHEP* 07 (2021) 035]

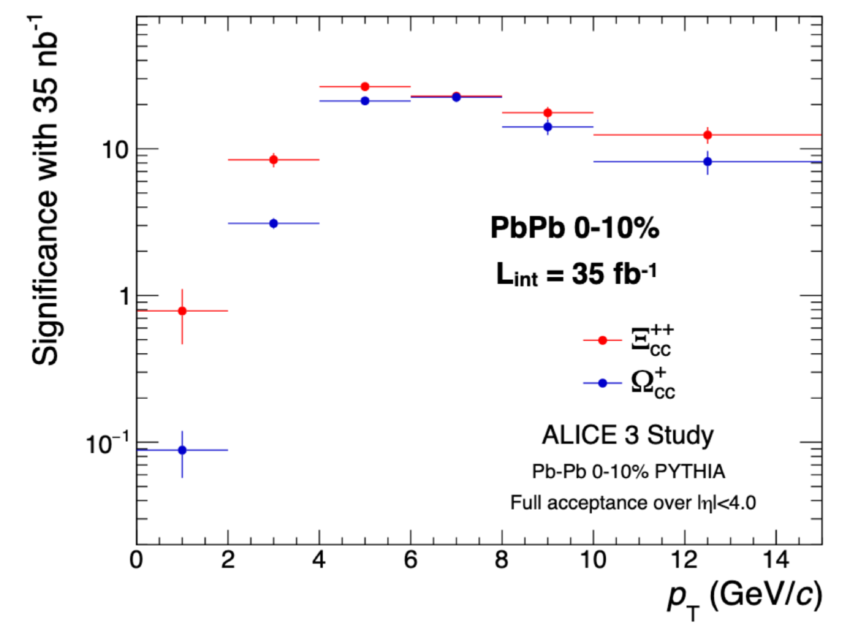
Measuring multi-charm with strangeness tracking

New technique: strangeness tracking



Impact parameter of Ξ





Pointing of Ξ baryon provides high selectivity

$$\Xi^+_{cc} \rightarrow \Xi^+_c + \pi^+ \qquad \Xi^+_c \rightarrow \Xi^- + 2\pi^+$$

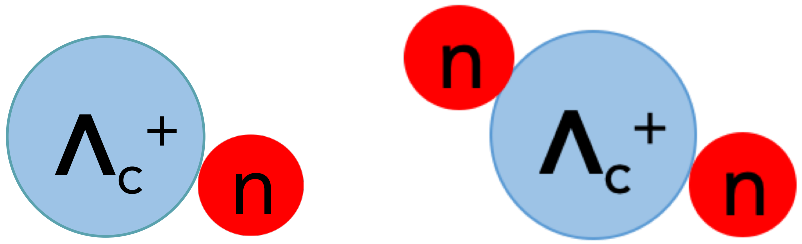
c-deuteron and c-triton

- 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.



c-deuteron c-triton

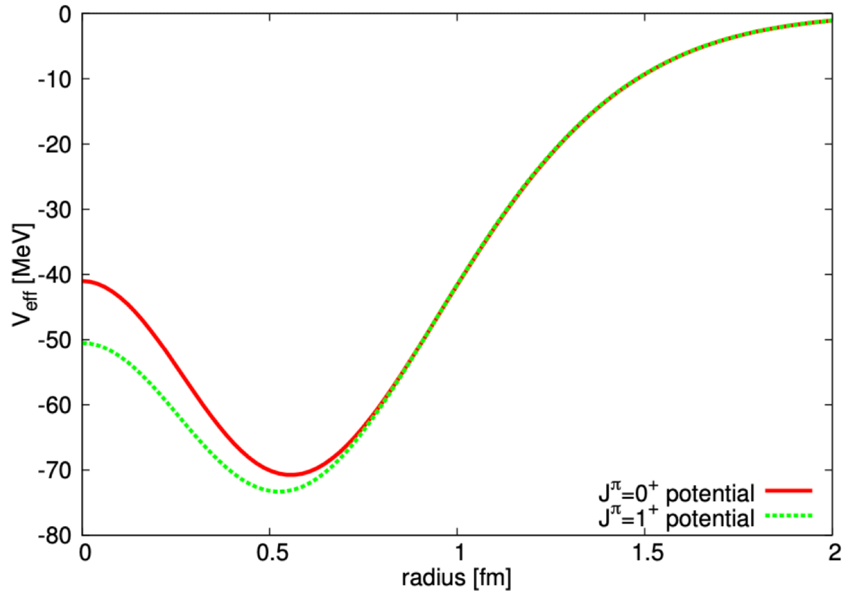


Fig. 9 $\Lambda_c N$ effective potentials for $J^\pi = 0^+$ and 1^+.

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

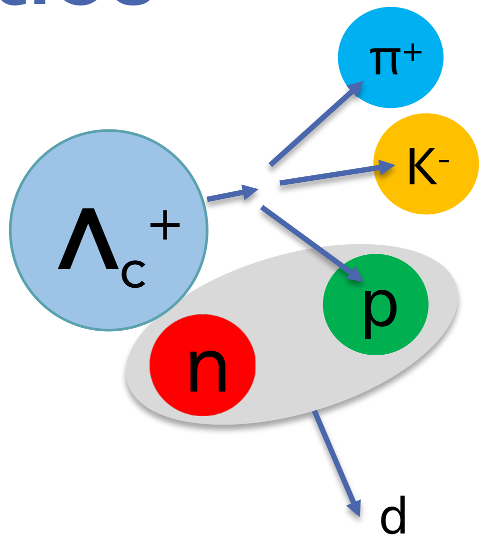
Decay channels and branching ratios

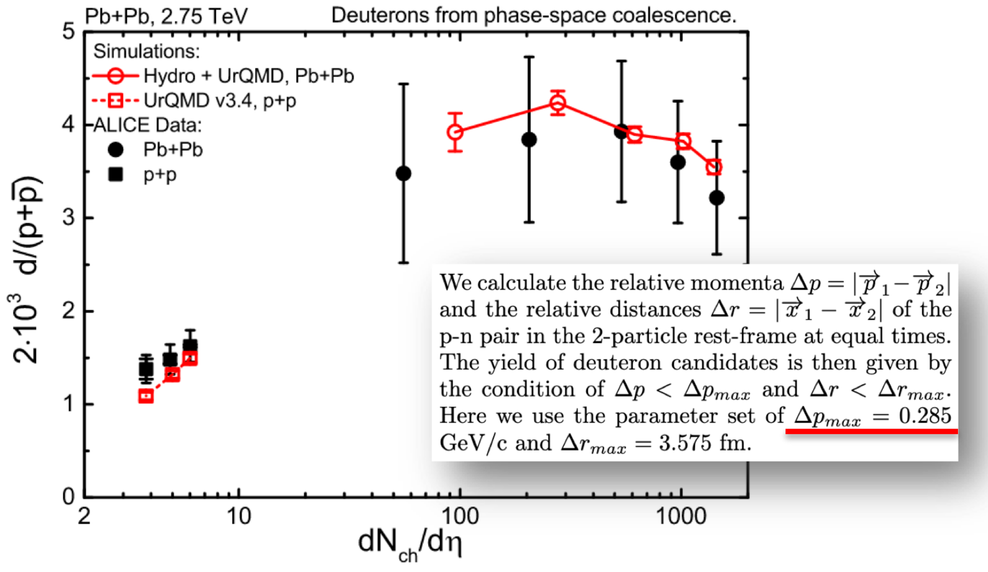
- Most promising decay channels:
  – $c_d \rightarrow d + K^- + \pi^+$
  – $c_t \rightarrow t + K^- + \pi^+$

- 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 ;-)

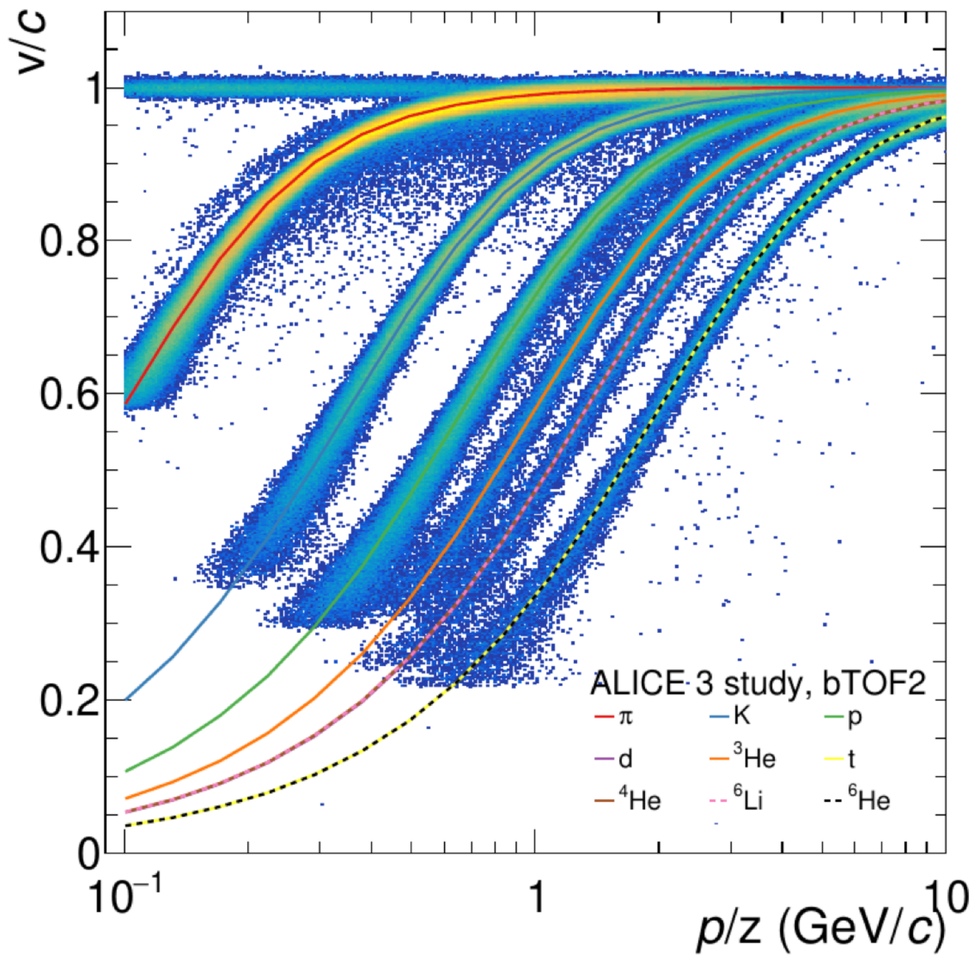


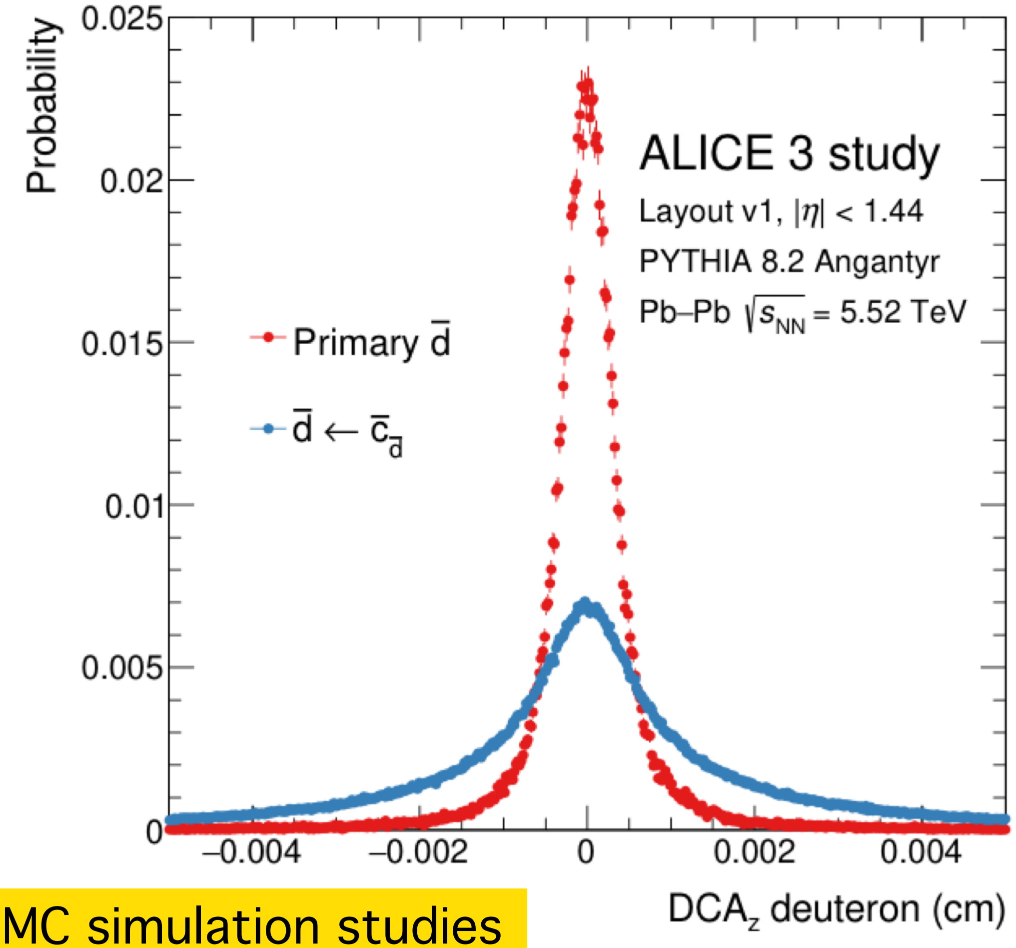


[Phys. Rev. C 99, 014901 (2019)]

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.

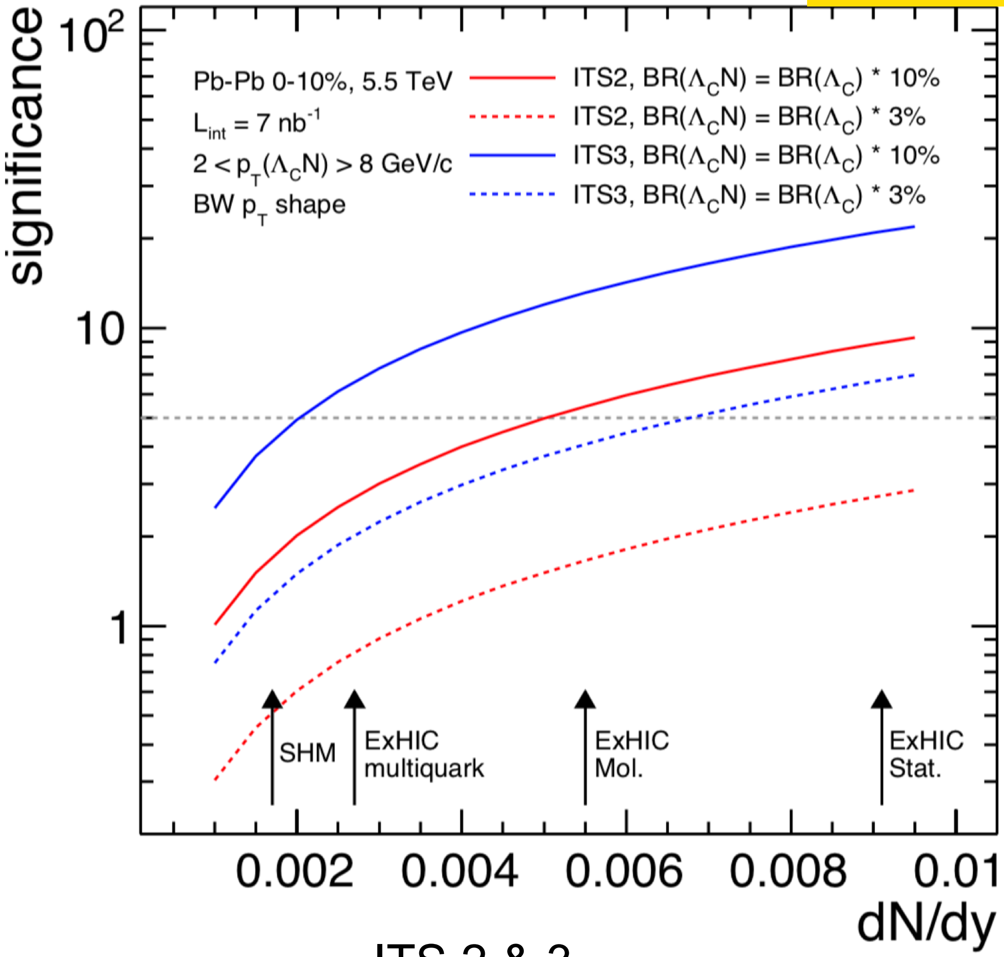




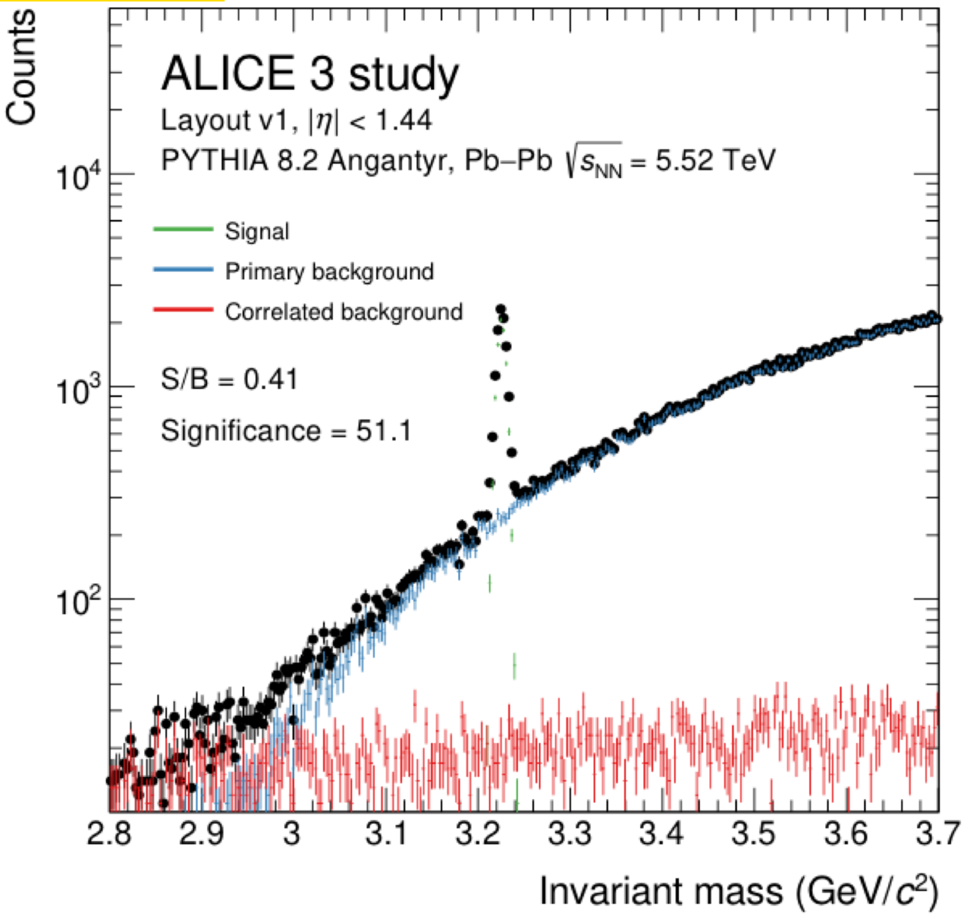
MC simulation studies

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.

Thermal production of beauty particles

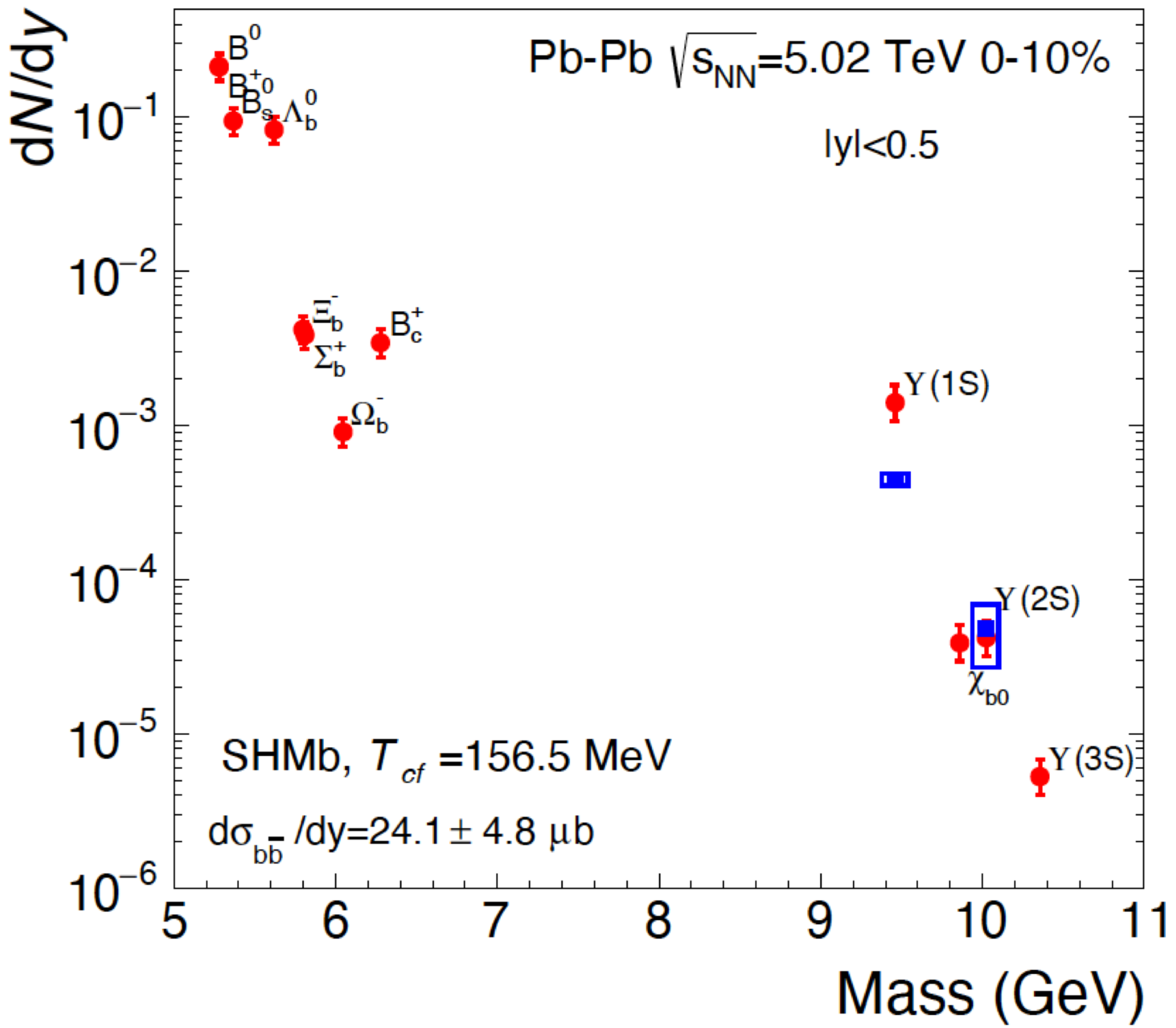
- The same calculation as for light and charm quarks can be repeated for beauty particles.
- The thermalization of beauty quarks is likely not achieved. Therefore, a deviation from the model predictions is expected.
- ALICE 3 is in a unique position to verify the thermalization of charm and to falsify the thermalization of beauty at the same time.

Quantifying the differences: light, charm, beauty

- A compensation of two large numbers: the thermal penalty factor and the beauty fugacity factor g_b.
- Number of quarks produced per unit rapidity in central Pb-Pb:
  - Light: ≈ 4000
  - Charm (c-cbar): ≈ 14
  - Beauty (b-bbar): ≈ 0.6
- Thermal penalty factor approximated as $\exp(-m/T_c)$: (very rough)
  - Light (proton): ≈ 0.0025
  - Charm (J/psi): ≈ $2.3 \cdot 10^{-9}$
  - Beauty (Upsilon): ≈ $6.8 \cdot 10^{-27}$
- Fugacity factors:
  - Light: n/a
  - Charm: ≈ 30
  - Beauty: ≈ $1.05 \cdot 10^{9}$

[for exact numbers → A. Andronic, presentation at QM'22]

Predictions for beauty particles

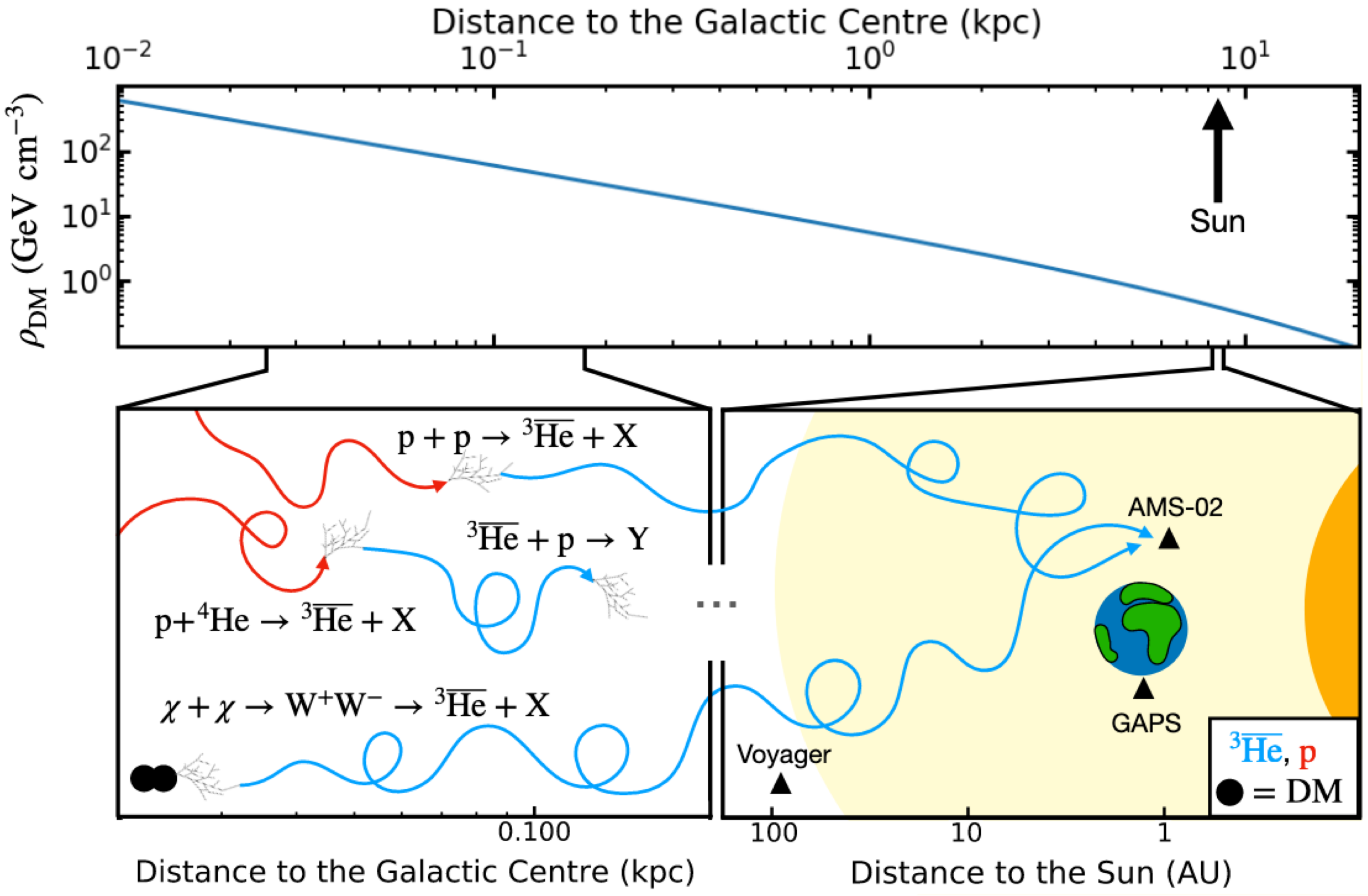


[A. Andronic, presentation at QM'22]

- In contrast to charmonia, the production of bottomonia is overpredicted by a factor 2-3.
- This would imply that roughly only 30-50% of beauty quarks are thermalized.
- It would be very important to measure the full family of B-mesons and beauty baryons.

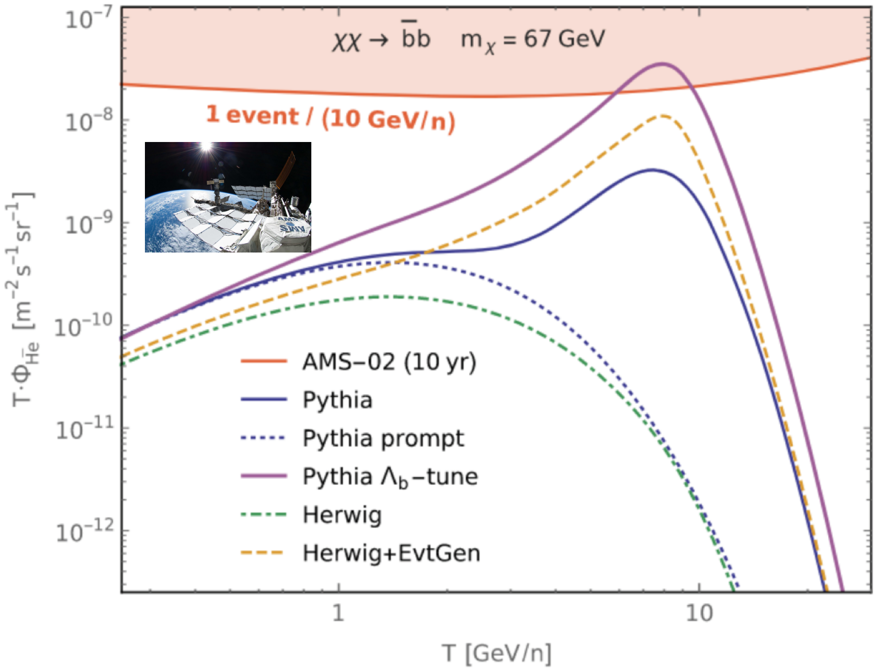
BEYOND HEAVY-ION PHYSICS

Search for anti-nuclei in space

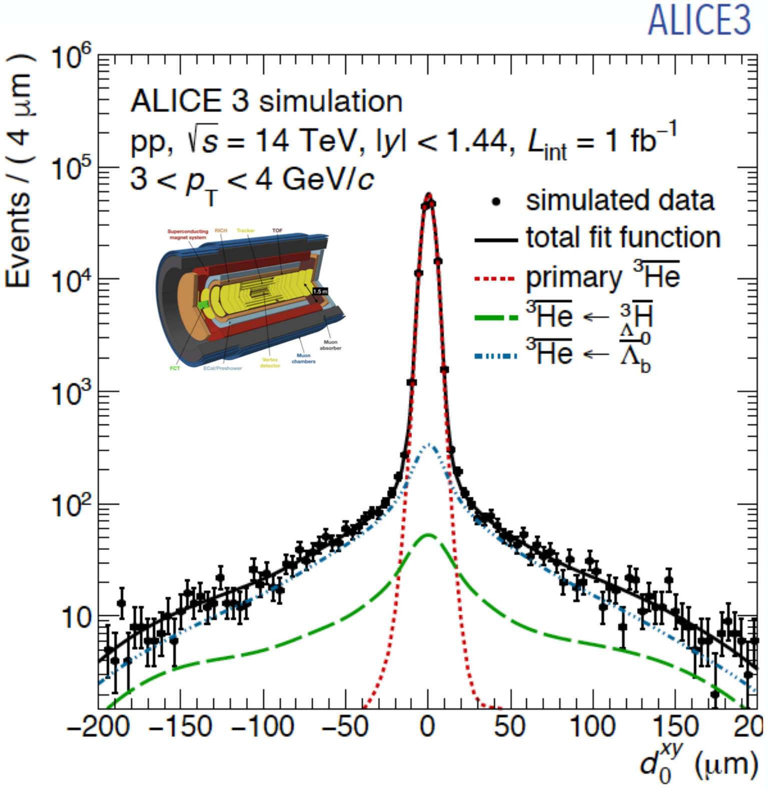


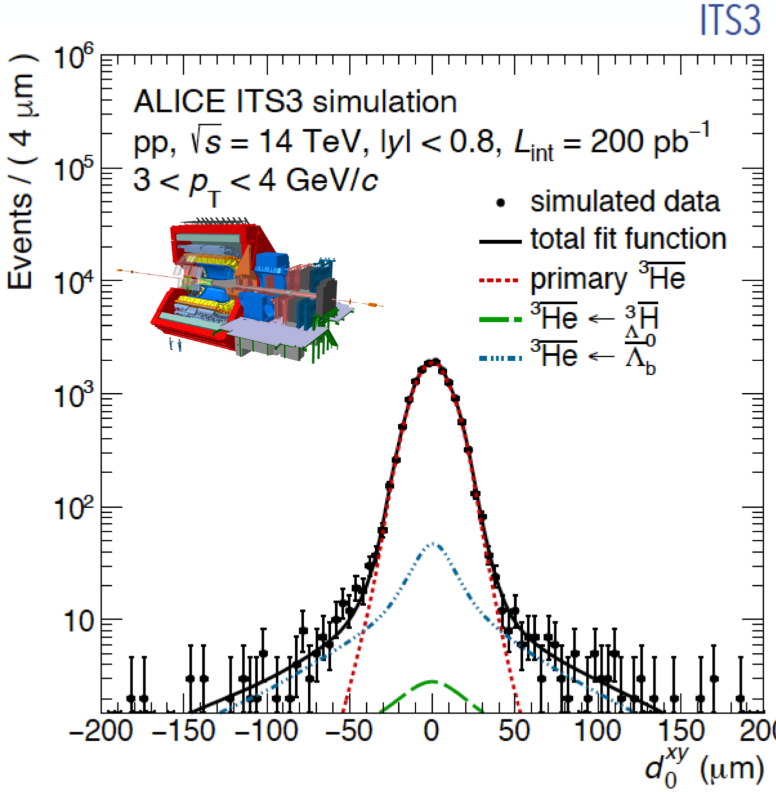
Antinuclei production in b-quark decays (1)

$$\chi\chi \rightarrow b\bar{b} \rightarrow \overline{\Lambda}_b^0 + X \rightarrow {}^3\overline{\mathrm{He}} + X$$



[M. Winkler, T. Linden, PRL 126 (2021)]





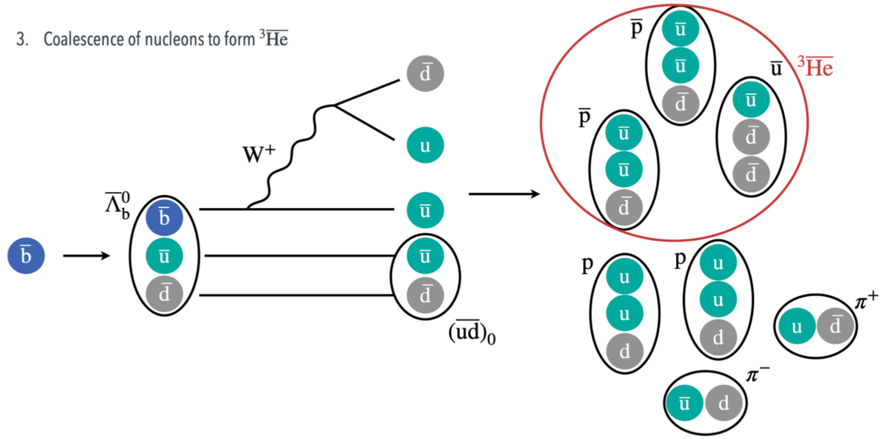
→ Anti-^{3}He originating from Λ_b decays from dark matter annihilation might lead to an enhanced flux of anti-^{3}He near earth.

→ Accelerator based experiments like ALICE are in the best position to determine the branching ratios of these rare decays.

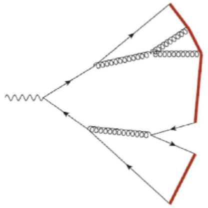
→ Precise dca-resolution of ALICE 3 is key to perform the measurement. First layer in beam-pipe removes all potential ambiguities from Moliere scattering that are difficult to simulate.

Antinuclei production in b-quark decays (2)

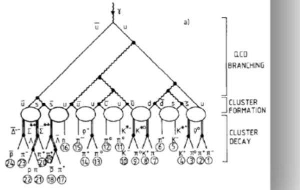
$$\chi\chi \rightarrow b\bar{b} \rightarrow \overline{\Lambda}{}_b^0 + X \rightarrow {}^3\overline{\mathrm{He}} + X$$

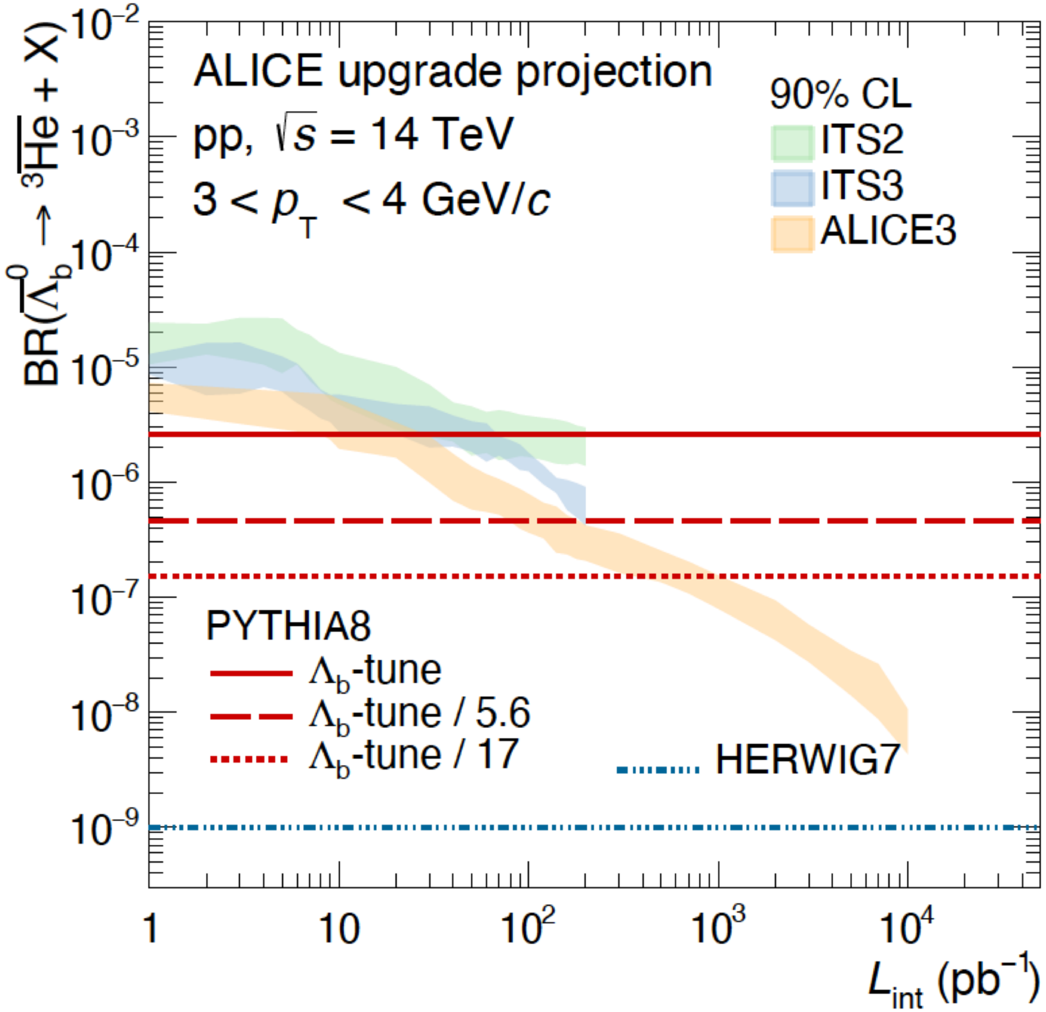


- **String fragmentation** (e.g. Lund model in PYTHIA)
  - Strings = colour-flux tubes between q and $\bar{q}$ end-points
  - Gluons represent kinks along the string
  - Strings break via vacuum-tunneling of (di)quark-anti(di)quark pairs



- **Cluster decay** in HERWIG
  - Shower evolved up to a softer scale
  - All gluons forced to split into $q\bar{q}$ pairs
  - Identify colour-singlet clusters of partons following color flow
  - Clusters decay into hadrons according to available phase space





After LHC Run 3 & 4, we will have understood the formation mechanisms of A < 5 anti- and hyper-nuclei from collisions, but will only **start to probe** their production in b-quark decays. Run 5 & 6 will provide the **definitive answer.**

Summary and conclusion

- ALICE has strong PID capabilities and measures things down to low momenta -> ideal to study non-perturbative hadronization effects.

- One one hand, this is useful to understand particle production in QCD with wide ranging applications including the search for DM in our galaxy.

- On the other hand, this will also pave the way for a textbook quality proof of the creation of a deconfined phase.

Thank you!