Production of loosely bound states in relativistic nuclear collisions

- ALICE, status and prospects for the coming decade
- the statistical hadronization model and (u,d,s) hadrons
- including loosely bound hadrons, light nuclei and hyper-nuclei
- from pp to Pb-Pb collisions
- outlook

pbm

EMMI Workshop at the University of Wrocław

Aspects of Criticality II

Wroclaw Poland

July 2-4, 2024

work with:

Anton Andronic, Krzysztof Redlich, Johanna Stachel

Nature 561 (2018) 7723, 321-330, 1710.09425 [nucl-th]

in this talk:

newest results including those shown at SQM2024@Strasbourg

ALICE plans for the coming decade 2024 – 2033
LHC Run3 and Run4

ALICE upgraded → ALICE 2:

GEM based read-out chambers for the TPC, new inner tracker with ultra-thin Si layers, continuous read of (all) subdetectors

increase of data rates by factor >50

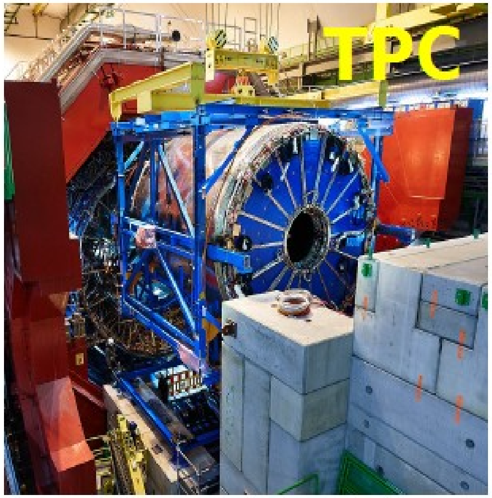
focus on rare objects, exotic quarkonia, single (and possibly double) charm hadrons to address a number of fundamental questions and issues such as:

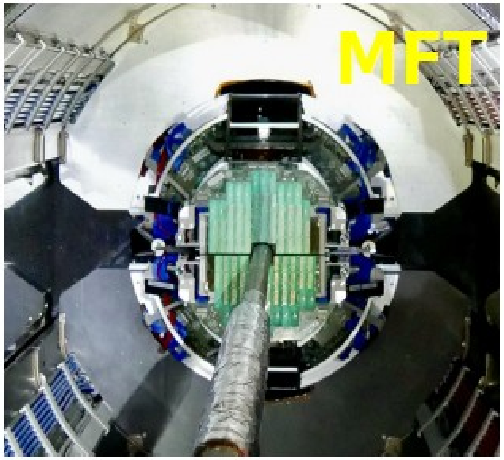
- what is the deconfinement radius for charm quarks
- are there colorless bound states in a deconfined medium?
- are complex, light nuclei and exotic charmonia (X,Y,Z) produced as compact multi-quark bags?
- can fluctuation measurements shed light on the mechanism of baryon production
- and critical behavior near the phase boundary?

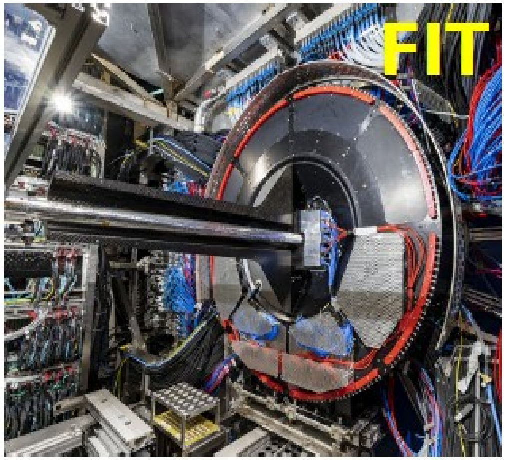
- low mass dileptons and low-p_T thermal photons
- collectivity from pp to AA collisions
- nuclear and hadronic physics
  - structure of light hyper-nuclei
  - hadron-hadron interaction from particle correlations
- ultra-peripheral and diffractive collisions

deciphering QCD in the strongly coupled regime

ALICE in Run 3 (ongoing)



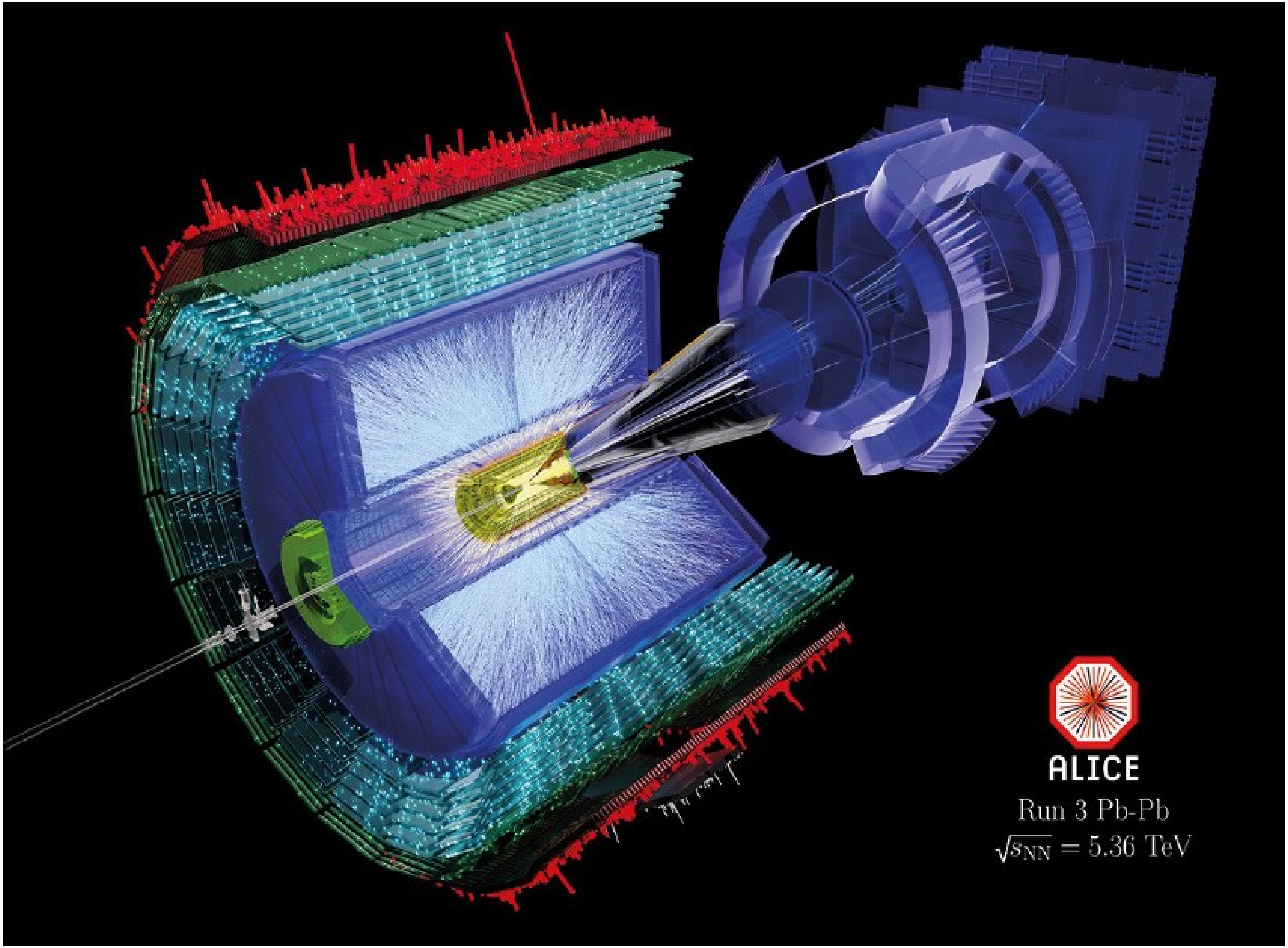




- Major upgrades installed in 2019-2021
- In production since 2022
- 50x increase in readout rate
- 3 to 6x improvement in pointing resolution
- Secondary vertexing for forward muons

ALICE upgrades: *arXiv:2302.01238*

ITS: *NIM 1032(2022)166632*
TPC: *JINST 16 P03022 (2021)*
MFT: *CDS link*
FIT: *NIM 1039 (2022) 167021*

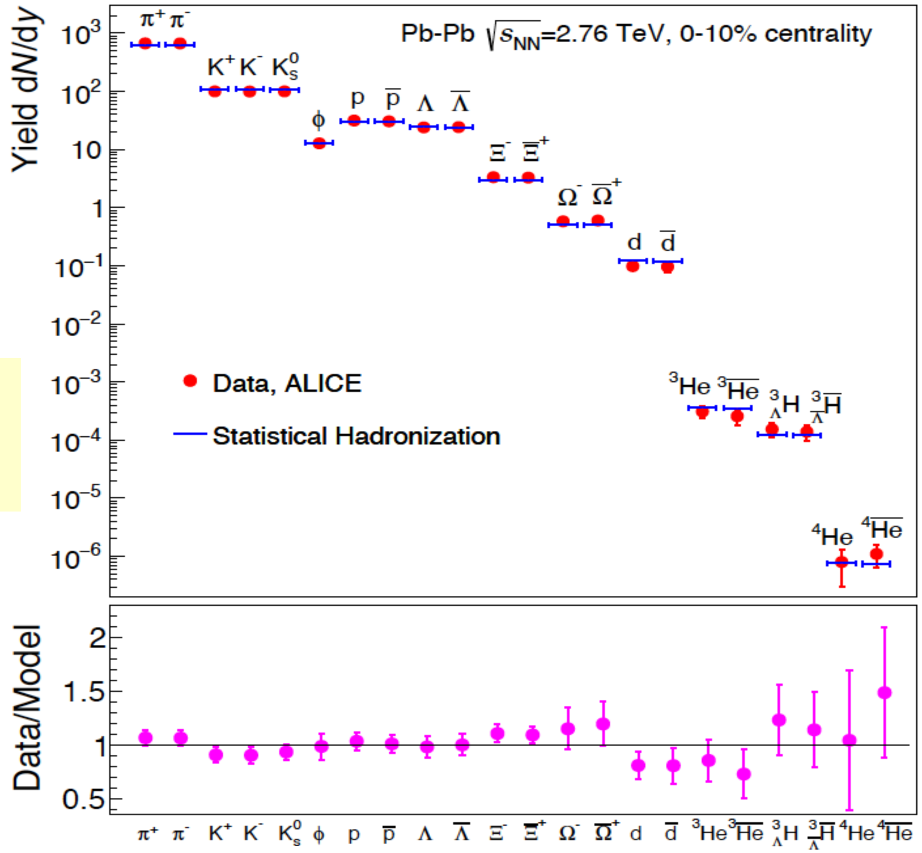


ALICE in 2023   Run 3

statistical hadronization of (u,d,s) hadrons

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nature 561 (2018) 321

status as of Sep. 2021



agreement over 9 orders of magnitude with QCD statistical operator prediction (- strong decays need to be added)

- matter and antimatter formed in equal portions
- even large very fragile (hyper) nuclei follow the systematics

Best fit:

$T_{CF} = 156.6 \pm 1.7$ MeV

$\mu_B = 0.7 \pm 3.8$ MeV

$V_{\Delta y=1} = 4175 \pm 380$ fm^3

$\chi^2/N_{df} = 16.7/19$

S-matrix treatment of inter-actions (non-strange sect.)

"proton puzzle" solved

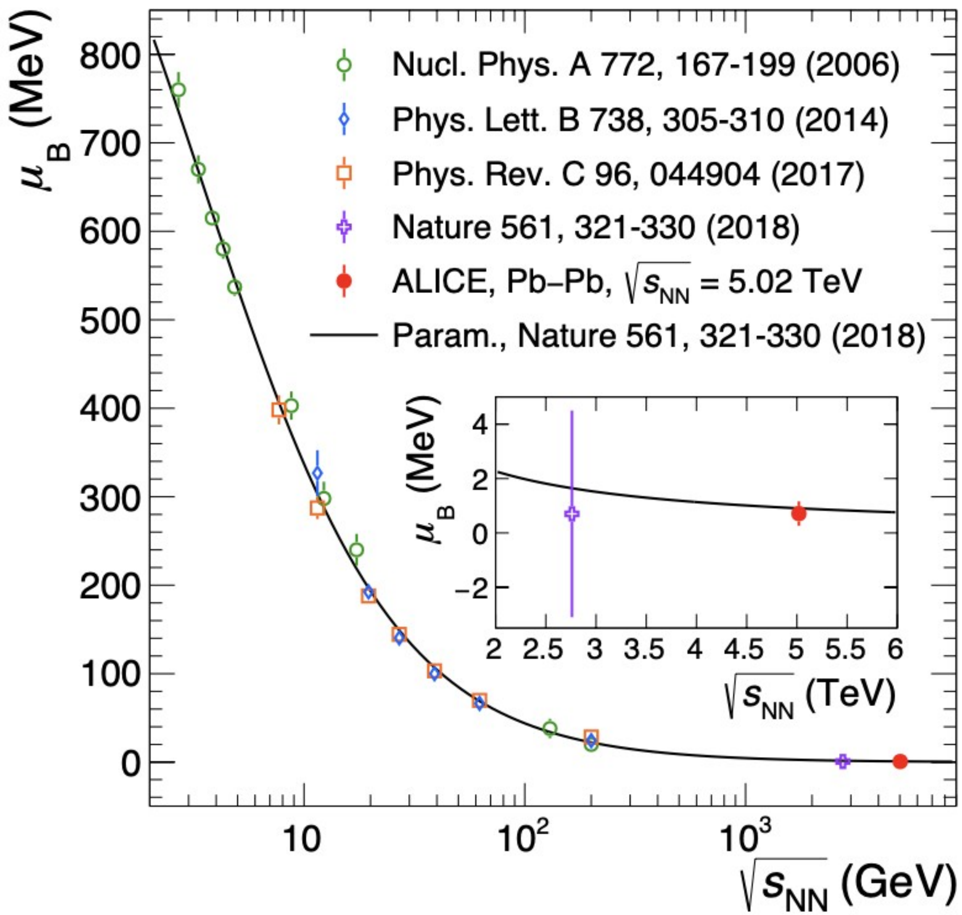
PLB 792 (2019) 304

data: ALICE coll.,
Nucl. Phys. A971 (2018) 1

similar results at lower energy, each new energy yields a pair of (T, μB) values

connection to QCD (QGP) phase diagram

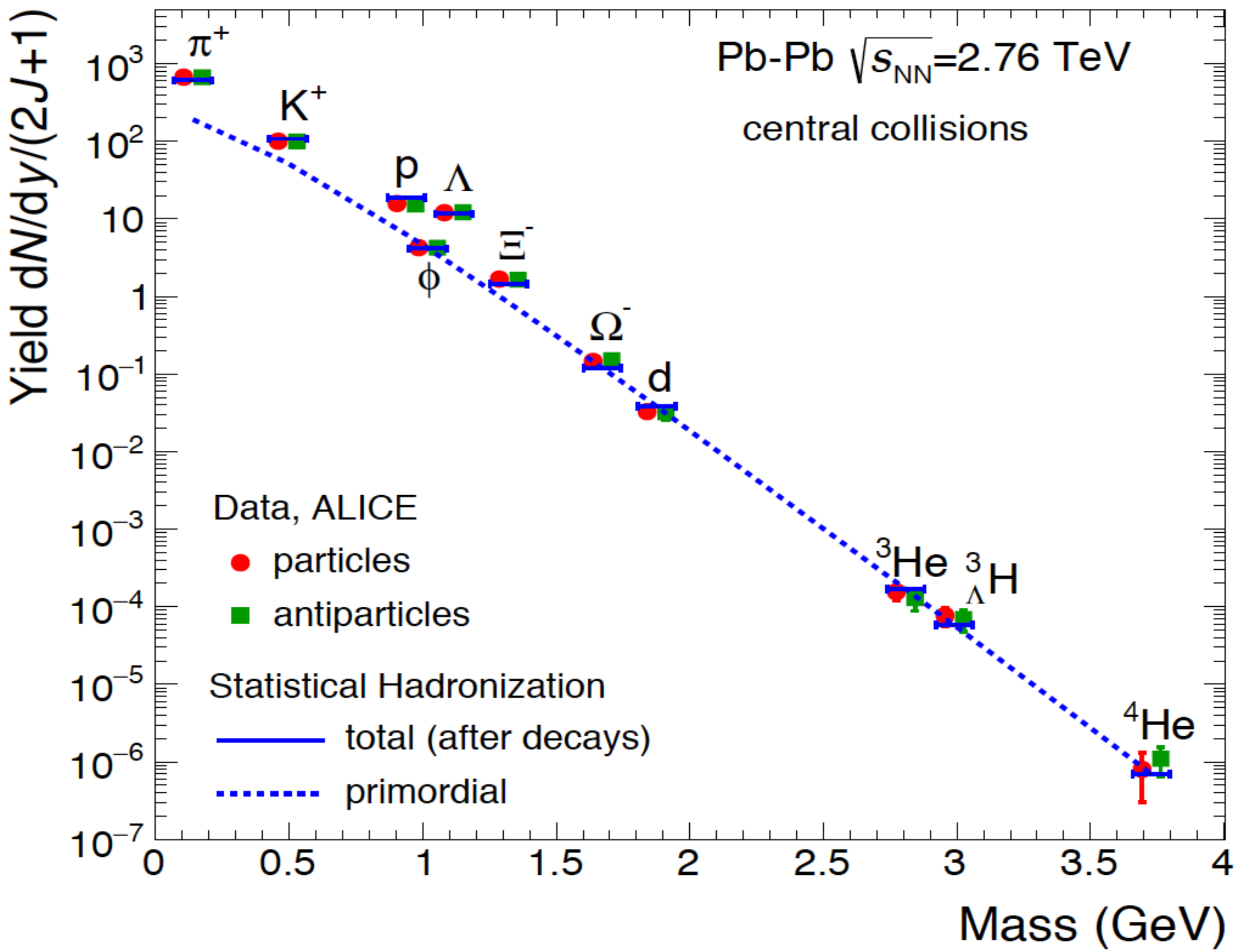
newest determination of baryon chemical potential



$$\mu_B = 0.66 \pm 0.45 \text{ MeV}$$

ALICE coll., 2311.13332 [nucl-ex], PRL in print

at LHC energy, production of (u,d,s) hadrons is governed
by mass and quantum numbers only
quark content does not matter



universal hadronization

1 parameter (T)

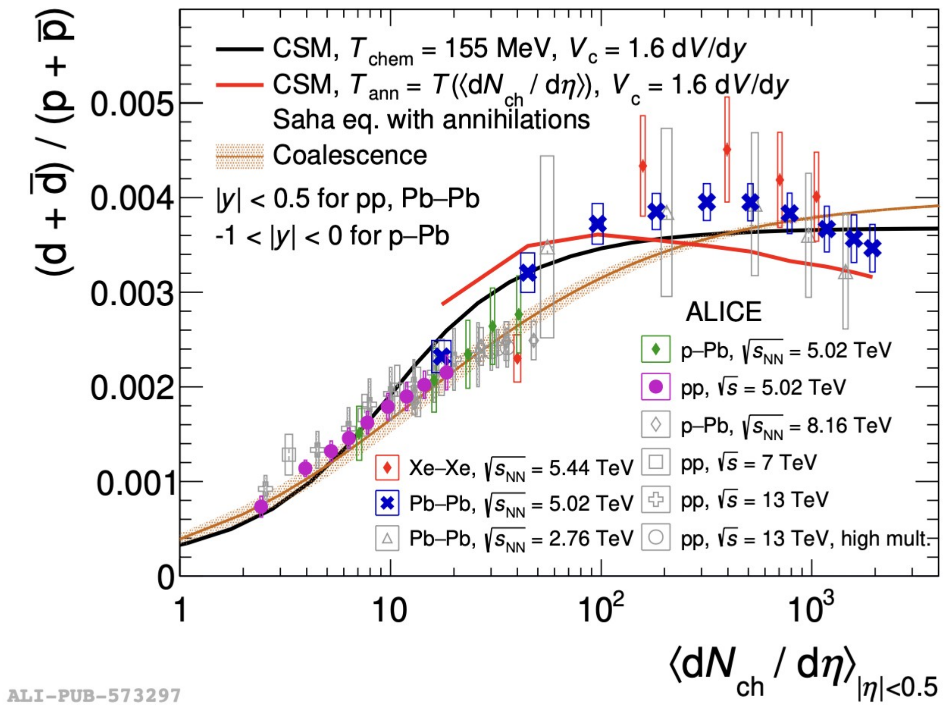
at LHC energy, matter and anti-matter is
produced with equal yields, all chemical potentials vanish

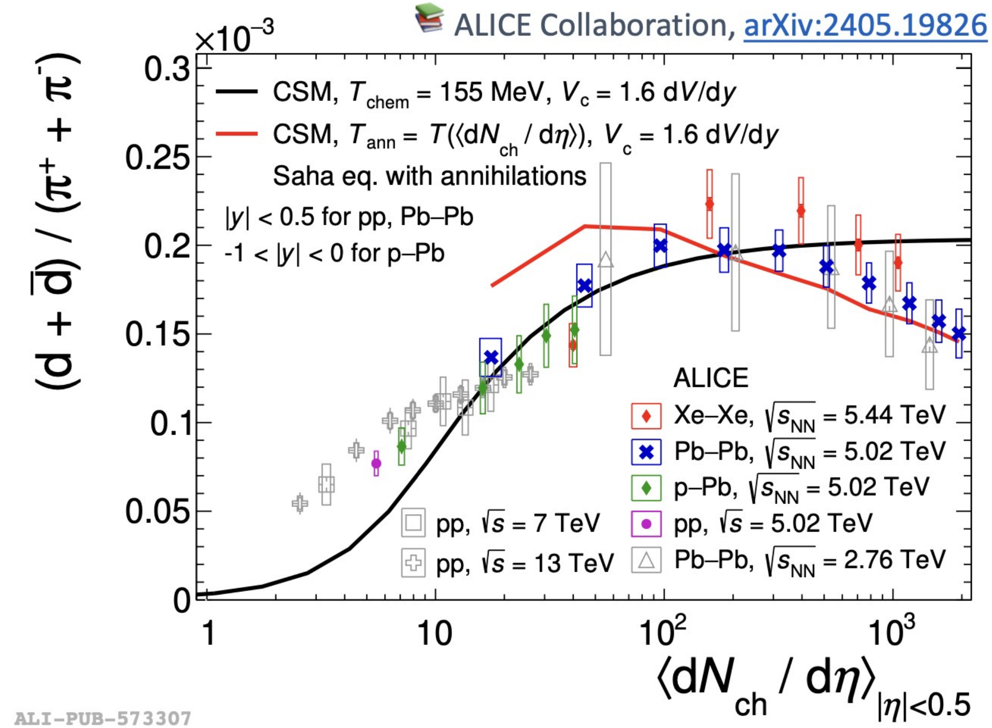
now on to very loosely bound states and their production in high energy collisions

- already the deuteron with 2.2 MeV binding enery is very loosely bound compared to the average energy of particles at the LHC (TeV)
- the hyper-triton is an even more extreme case, see below
- the quantum mechanical formation time of such states far exceeds 100 fm/c, i.e. they cannot be generated or destroyed more than once in a collision

deuterons – the test case for (hyper-)nuclei

ALICE Collaboration, [arXiv:2405.19826](https://arxiv.org/abs/2405.19826)





if thermal description works for deuterons, it should work for all nuclei and hyper-nuclei.

no clear evidence for annihilation

coalescence and thermal description work equally well, thermal description is parameter-free

The hyper-triton

mass = 2990 MeV, binding energy = 2.3 MeV

Lambda sep. energy = 0.13 MeV

molecular structure: (p+n) + Lambda

2-body threshold: (p+p+n) + pi- = ^{3}He + pi-

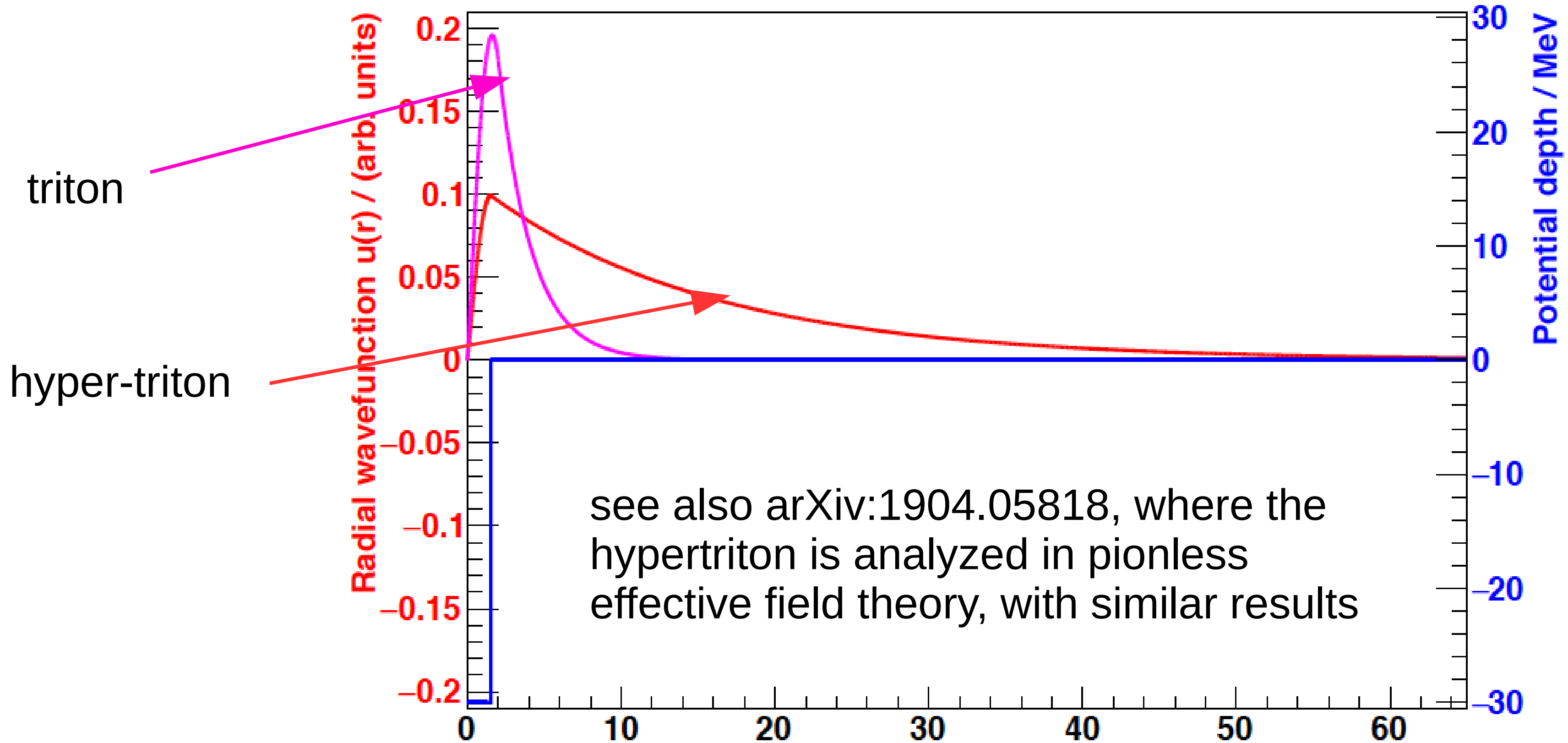
rms radius = $(4 \text{ B.E. } M_{red})^{-1/2}$ = 10.3 fm =
rms separation between d and Lambda

in that sense: hypertriton = (p n Lambda) =
(d Lambda) is the ultimate halo state

yet production yield is fixed close to 156 MeV temperature
(about 1000 x Lambda separation energy.)

wave function of the hyper-triton – schematic picture

figure by Benjamin Doenigus, August 2017



Wavefunction (red) of the hypertriton assuming a s-wave interaction for the bound state of a Λ and a deuteron. The root mean square value of the radius of this function is $\sqrt{\langle r^2 \rangle} = 10.6$ fm. In blue the corresponding square well potential is shown. In addition, the magenta curve shows a "triton" like object using a similar calculation as the hypertriton, namely a deuteron and an added nucleon, resulting in a much narrower object as the hypertriton.

now most recent results on hyper-triton structure from ALICE precision measurements

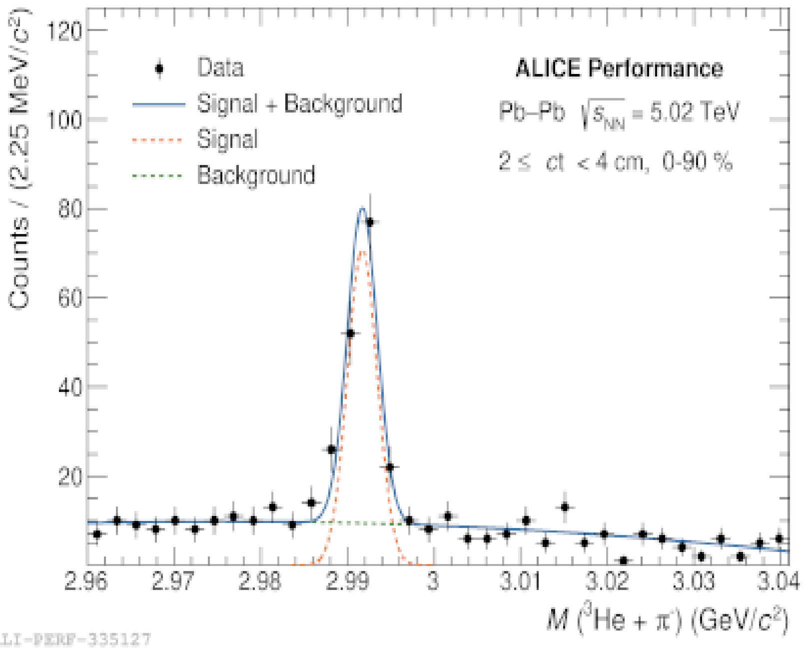
- binding energy
- Λ separation energy
- lifetime

hyper-triton identification in ALICE using machine-learning techniques

BDT

for boosting the signal extraction

- Boosted Decision Trees (BDT) models trained on dedicated sample to discriminate signal and background
- State-of-the-art hyperparameter optimization
- BDT selection optimized to improve the significance of the hypertriton signal
- Signal extracted with high significance over a wide ct range

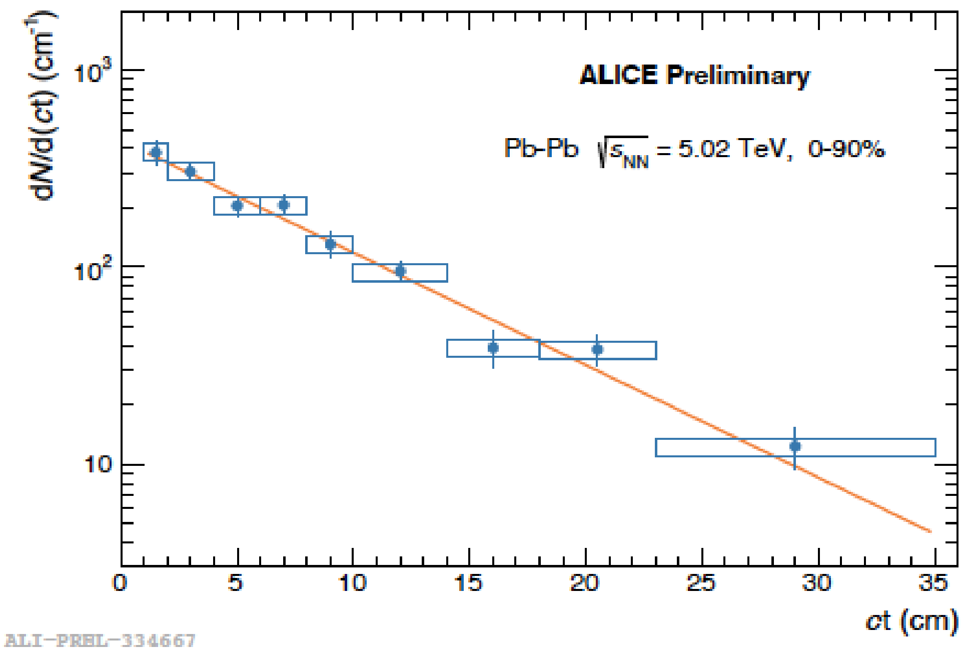


very small background contribution

newest result on lifetime measurement – needs precision determination of ALICE detector material

Lifetime
measurement

- Signal extracted in a wide ct range thanks to the BDT
- Most precise hypertriton lifetime determination so far
  - 5% stat. 6% syst.
  - Statistical uncertainty lower than the world average uncertainty
- Consistent with free Λ lifetime and previous ALICE measurement



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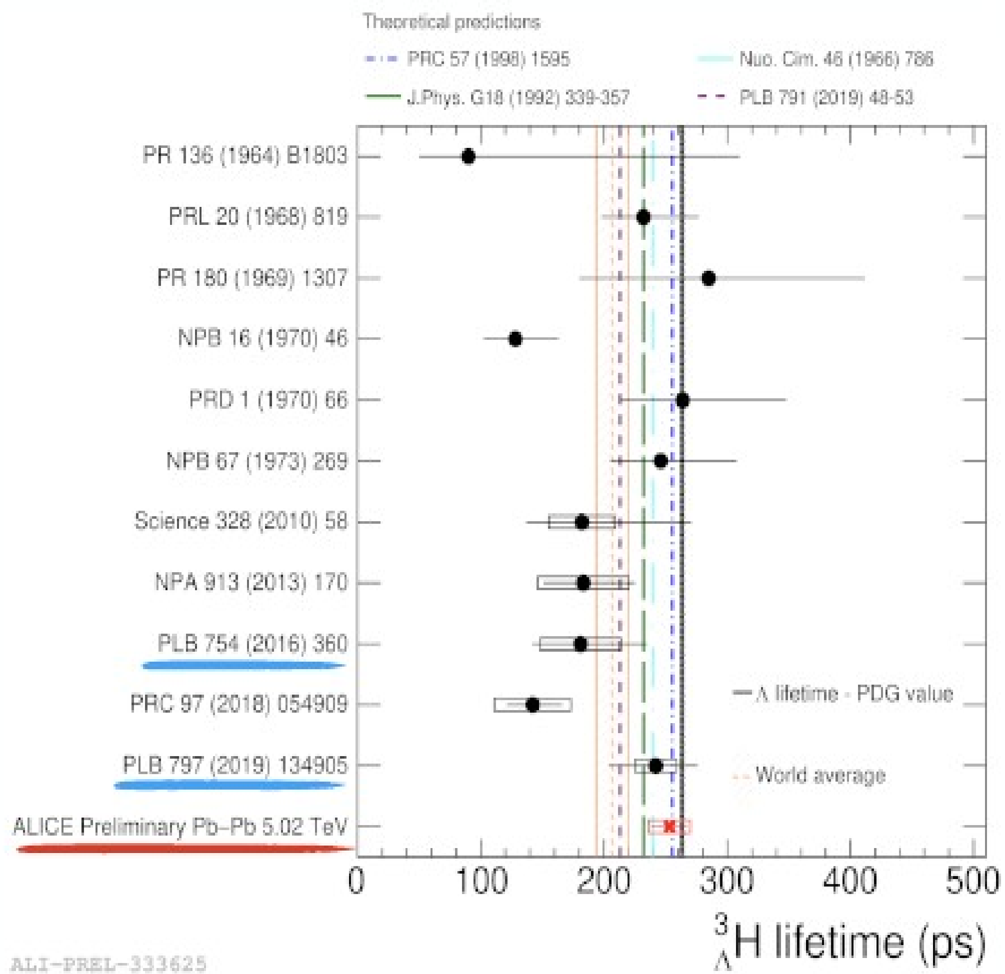
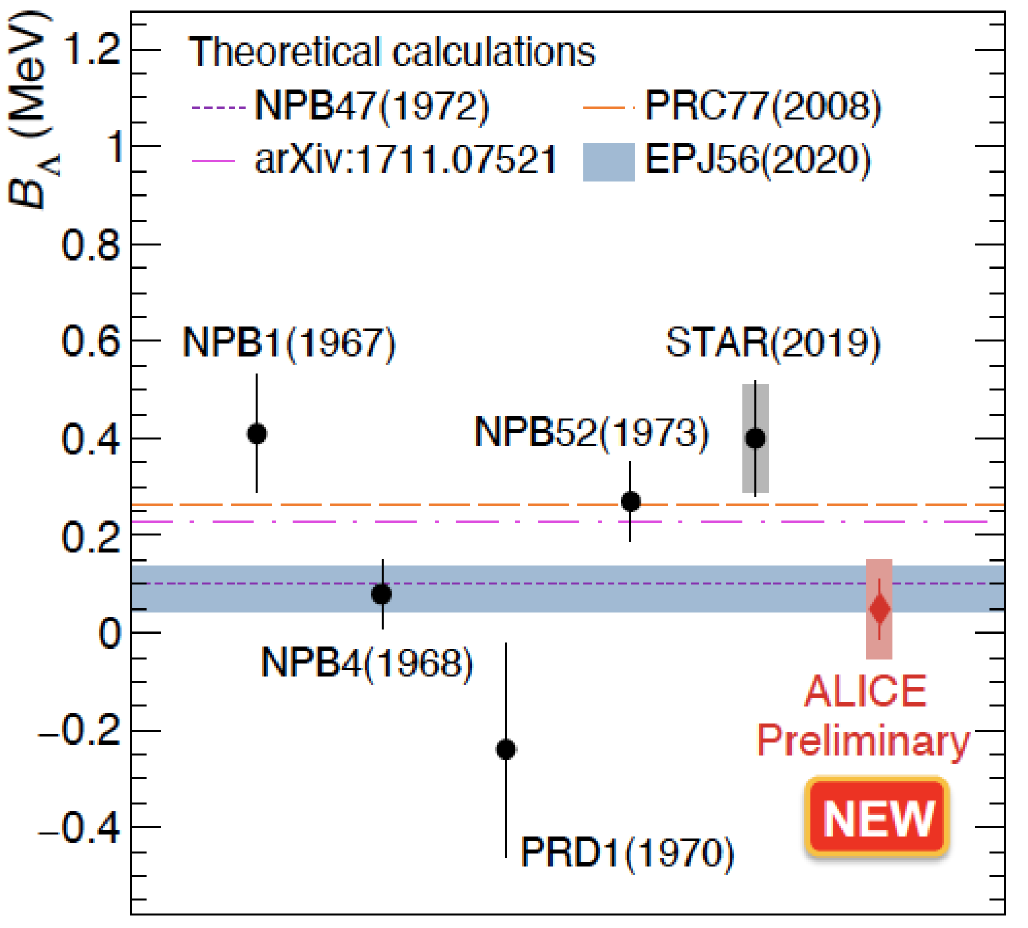


new ALICE results on hyper-triton binding energy

- Use Machine Learning (BDTs) to identify ${}^{3}_{\Lambda}$H candidates in Pb–Pb
- Most precise measurement of ${}^{3}_{\Lambda}$H lifetime
  - Favors ${}^{3}_{\Lambda}$H lifetime near free Λ lifetime
- Very precise measurements of ${}^{3}_{\Lambda}$H mass and binding energy
  - Binding energy compatible with 0.
  - Support loosely bound ${}^{3}_{\Lambda}$H



note: measurement of BΛ: 100 keV precision out of 2.99 GeV mass, dm/m = 1/30000

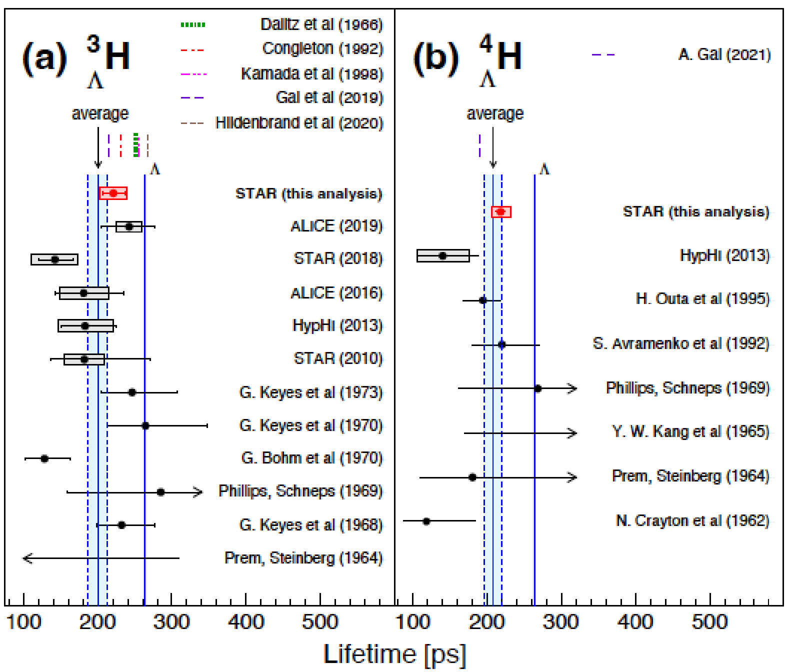
hyper-triton is large (about 10 fm radius)
and very loosely bound

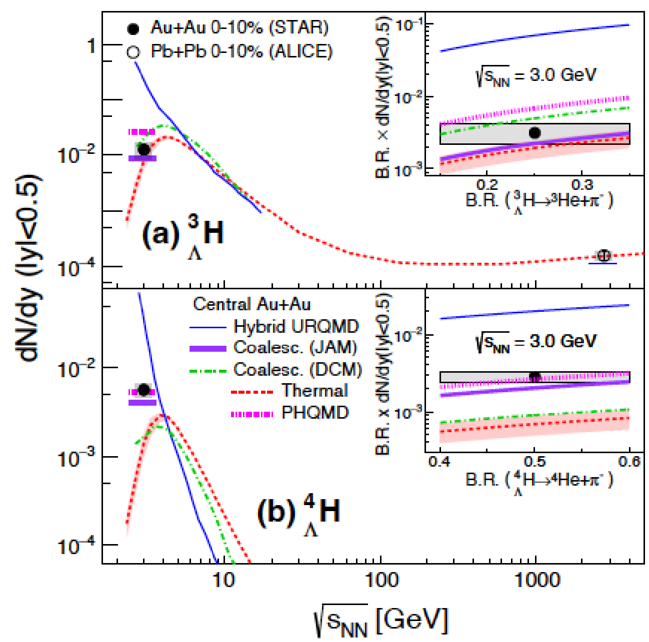
ALICE coll., Phys.Rev.Lett. 131 (2023) 10, 102302

$$\tau = [253 \pm 11 \text{ (stat.)} \pm 6 \text{ (syst.)}] \text{ ps},$$

$$B_\Lambda = [72 \pm 63 \text{ (stat.)} \pm 36 \text{ (syst.)}] \text{ keV}.$$

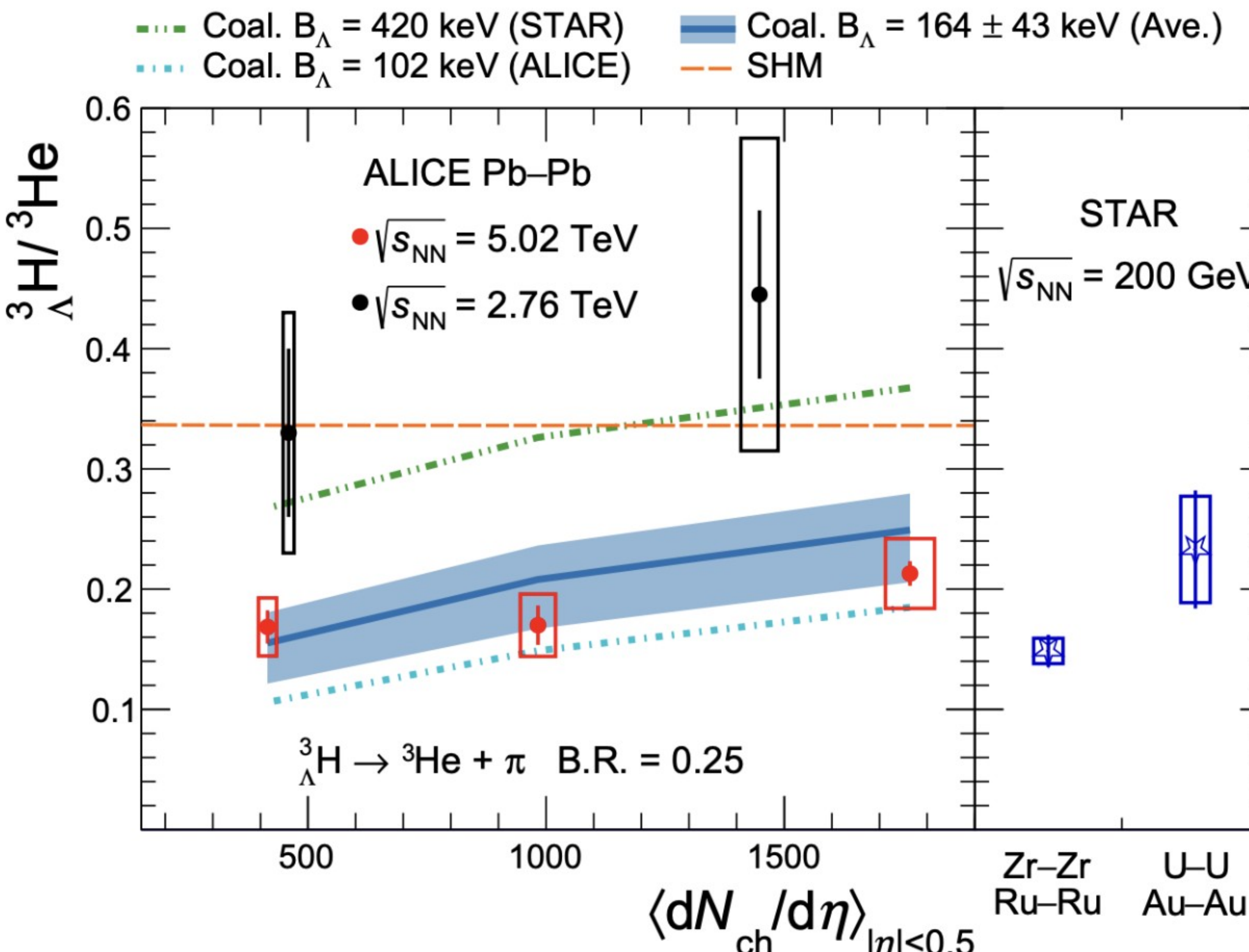
Hyper-nuclei in Au-Au collisions at low energy $\sqrt{s_{NN}}$ = 3 GeV





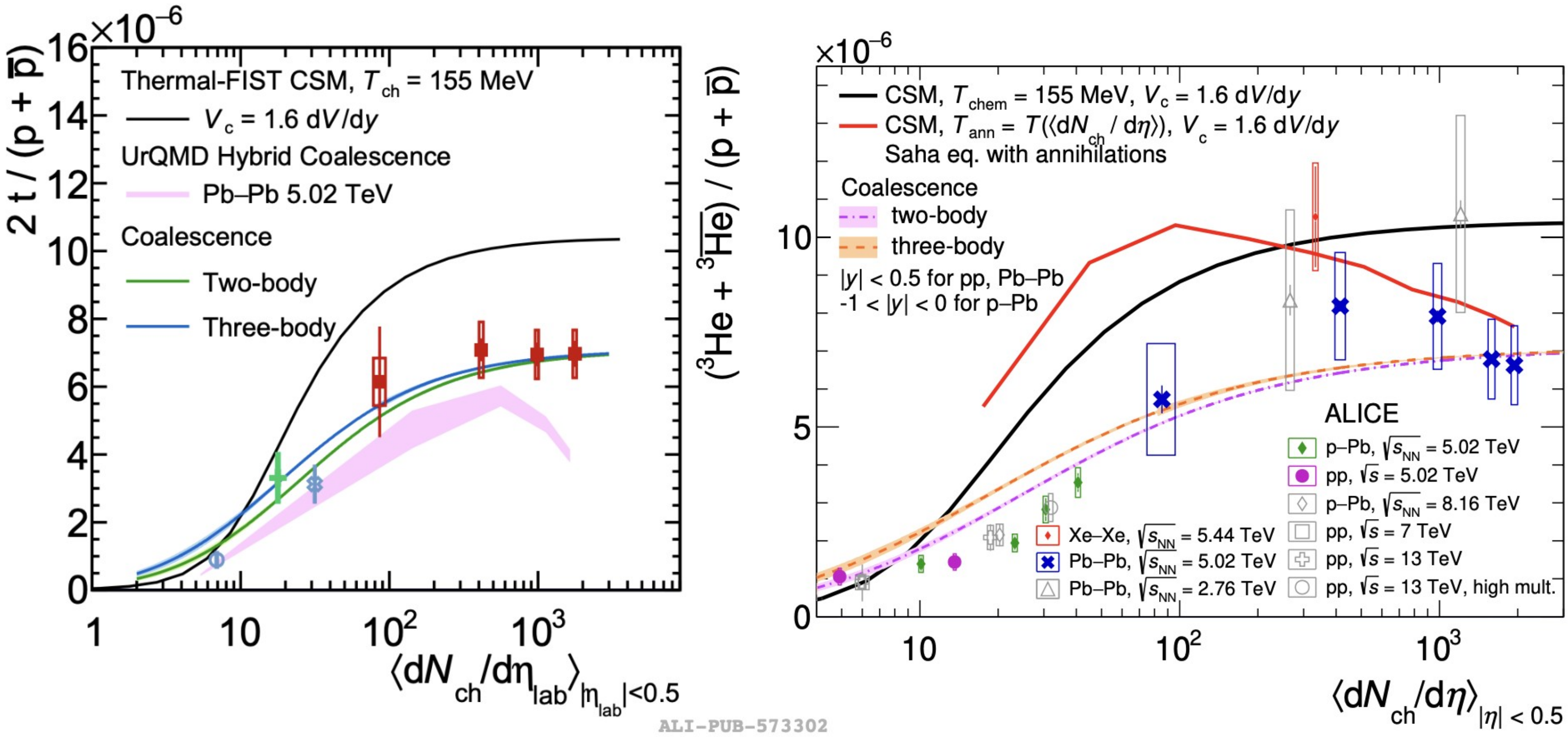
results from STAR at $\sqrt{s_{NN}}$ = 3 GeV,
Phys.Rev.Lett. 128 (2022) 20, 202301
excited state needed!

new results on hyper-triton at RHIC and LHC



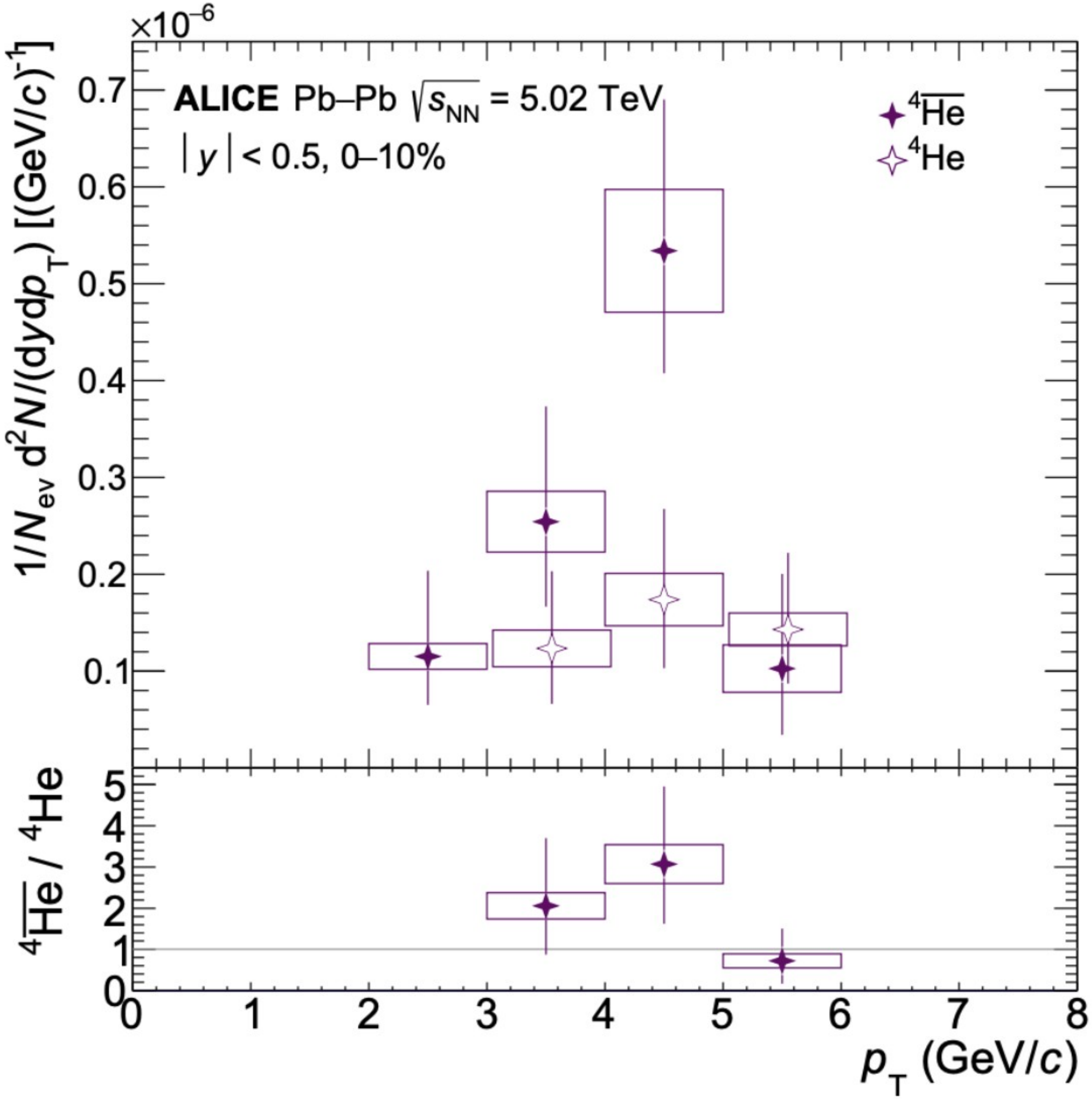
new ALICE points significantly lower at 5.02 vs 2.76 TeV, difference is mostly absorption correction…, note: particle ratio is independent of temperature

yield of A = 3 nuclei vs multiplicity



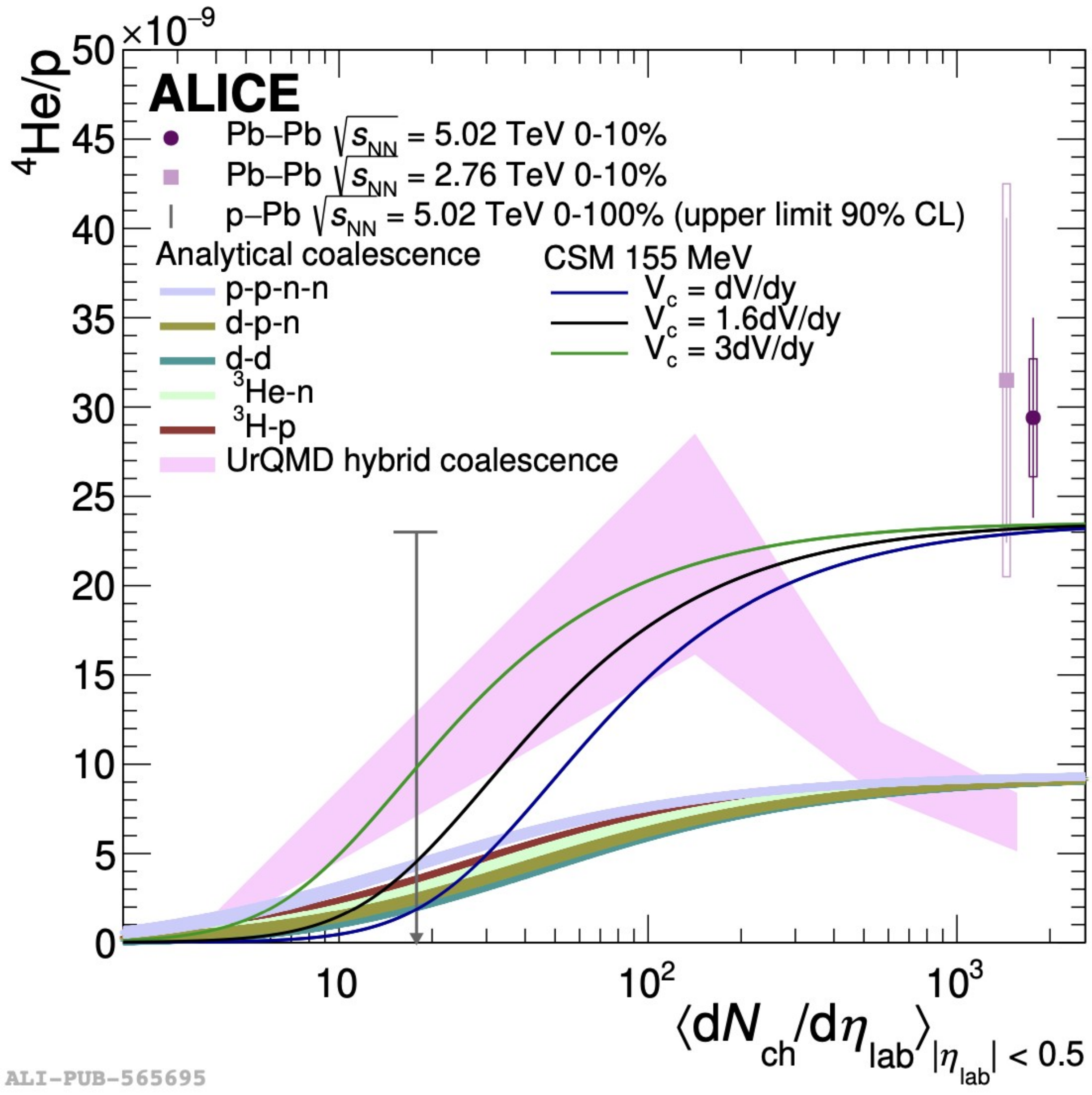
S-matrix correction for protons is missing!

alpha and anti_alpha at LHC-ALICE



2311.11758 [nucl-ex]

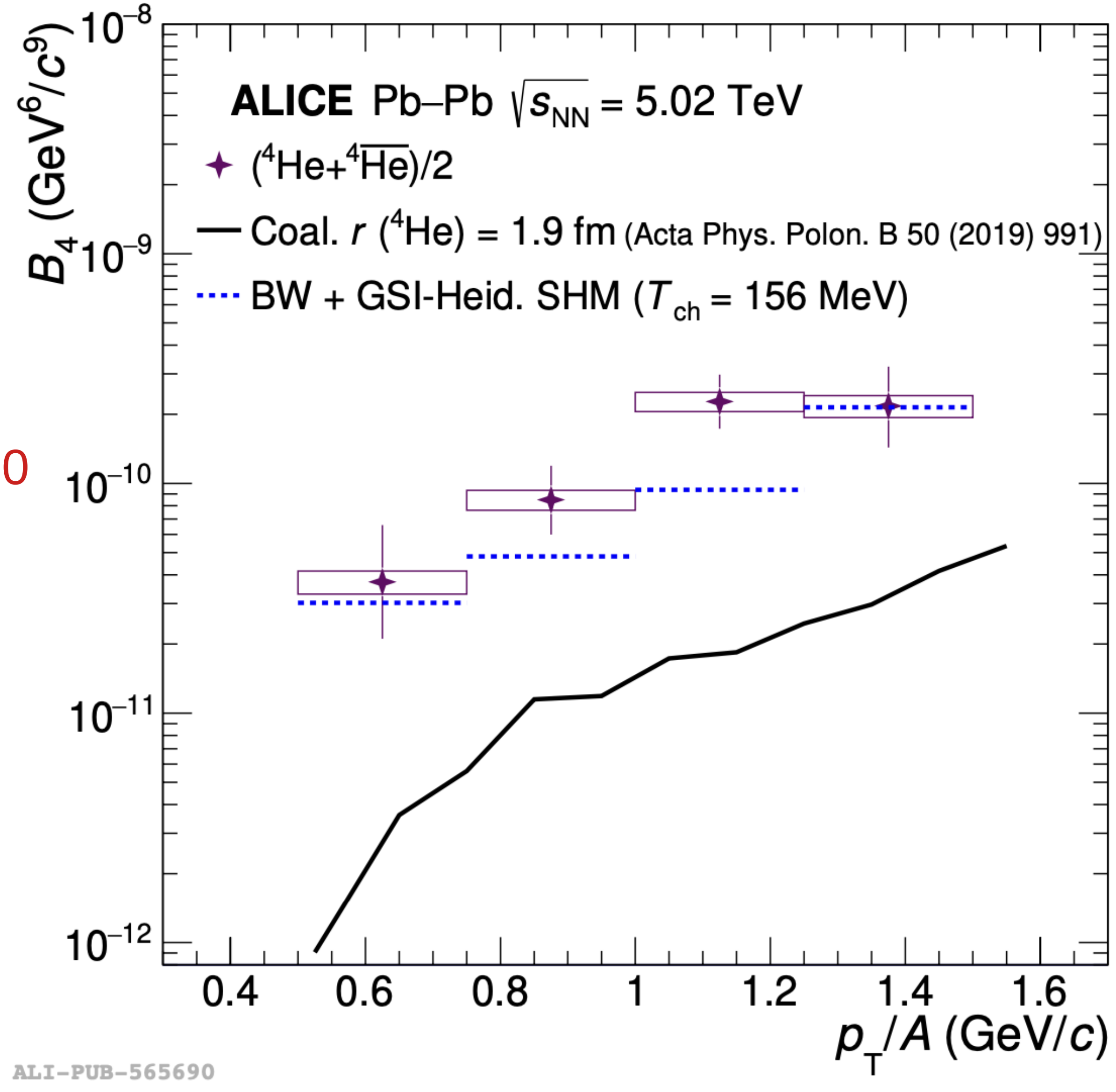
alpha production vs SHM and coalescence models



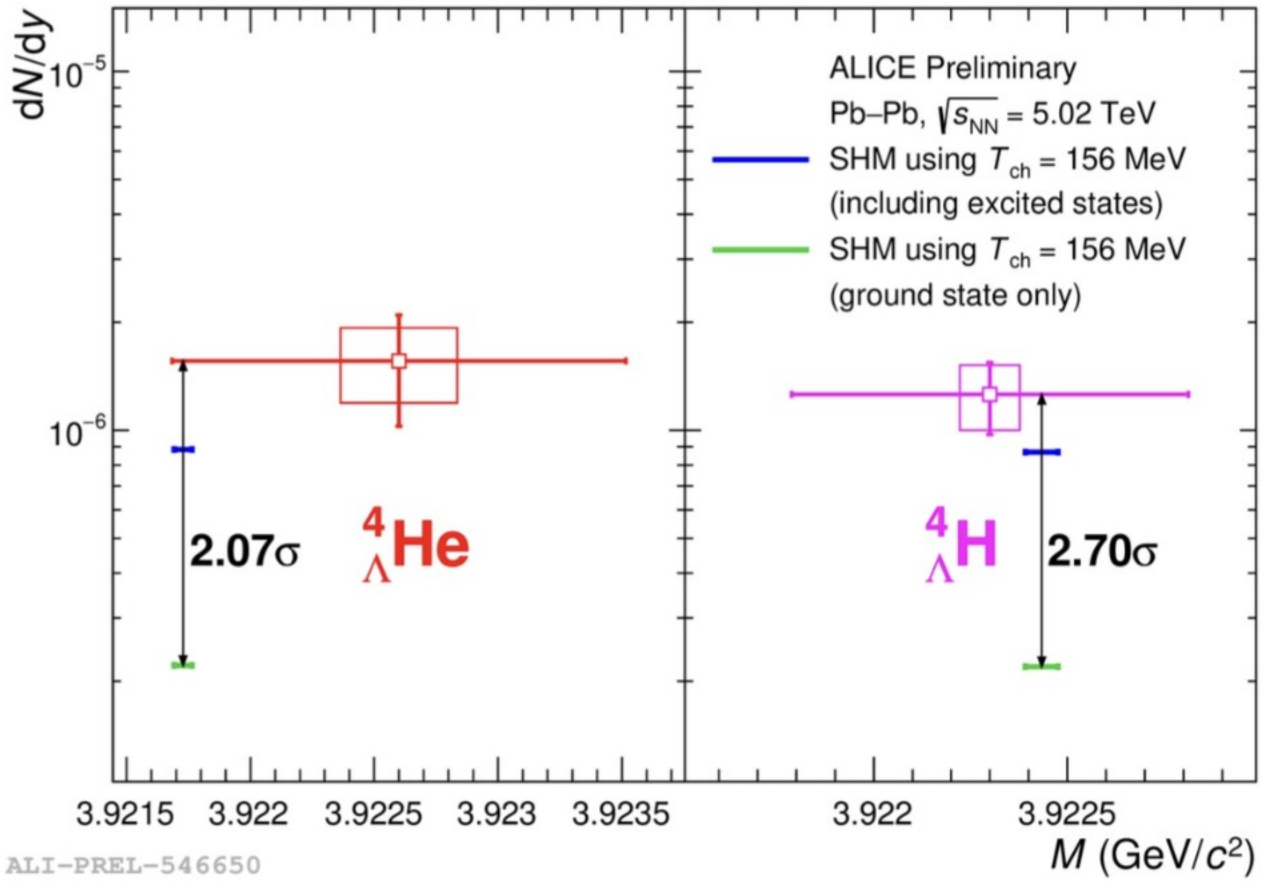
2311.11758 [nucl-ex]

alpha transverse momentum distribution vs coalescence models and SHM

coal off by about factor of 10



mass number 4 hypernuclei at LHC energy
excited states very important



how are loosely bound states produced in high energy nuclear collisions?

doorway state hypothesis:
all nuclei and hyper-nuclei, penta-quark and T,X,Y,Z states are formed as virtual, compact multi-quark states at the phase boundary. Then slow time evolution into hadronic representation. Excitation energy about 20 MeV, time evolution about 10 fm/c

Andronic, pbm, Redlich, Stachel
Nature 561 (2018) 321, arXiv :1710.09425

how can this be tested?

precision measurement of spectra and flow pattern for light nuclei and hyper-nuclei, multi-charm hadrons, penta-quark and X,Y,Z states from pp via pPb to Pb-Pb

a major new opportunity for ALICE Run3/4 and beyond 2030 for X,Y,Z, T_{cc} and penta-quark states

also new opportunities for GSI/FAIR and JINR/NICA experiments

summary and outlook

quantitative description of hadron production
in Pb-Pb and Au-Au collisions with SHM
all hadrons are produced very close to the QCD phase boundary

much progress in description of light nuclei and hypernuclei

SMH: good and parameter-free description for A = 2 and 4, open question about A = 3
Coalescence: good description for A = 2, and 3, description fails for A = 4

universal hadronization at temperature $T = T_{chem}$ with T_{chem} as single parameter

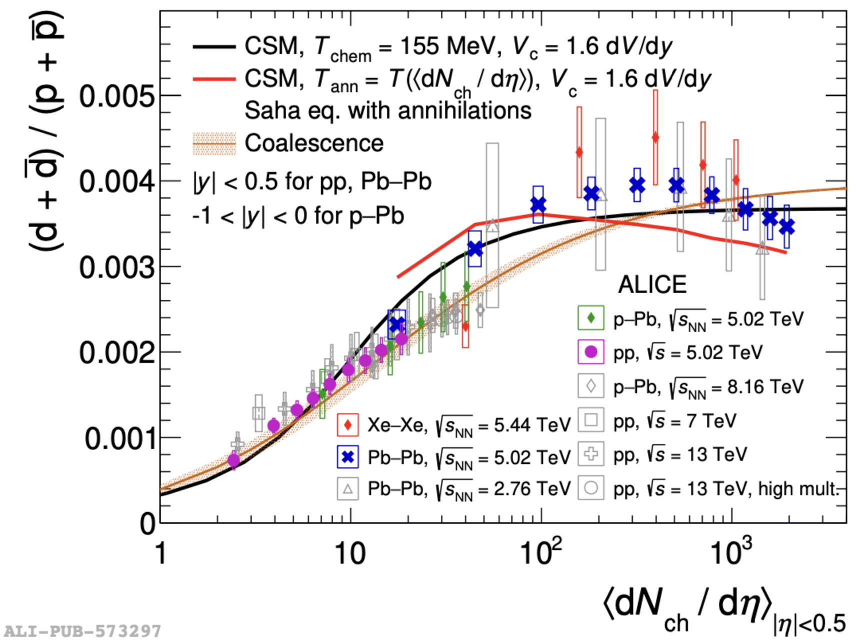
excited states need to be included in the description for both models,
details of wave functions important for coalescence approach

for production from small systems (pp, pPb, …) SHM with canonical thermodynamics is needed, correlation volume is under investigation

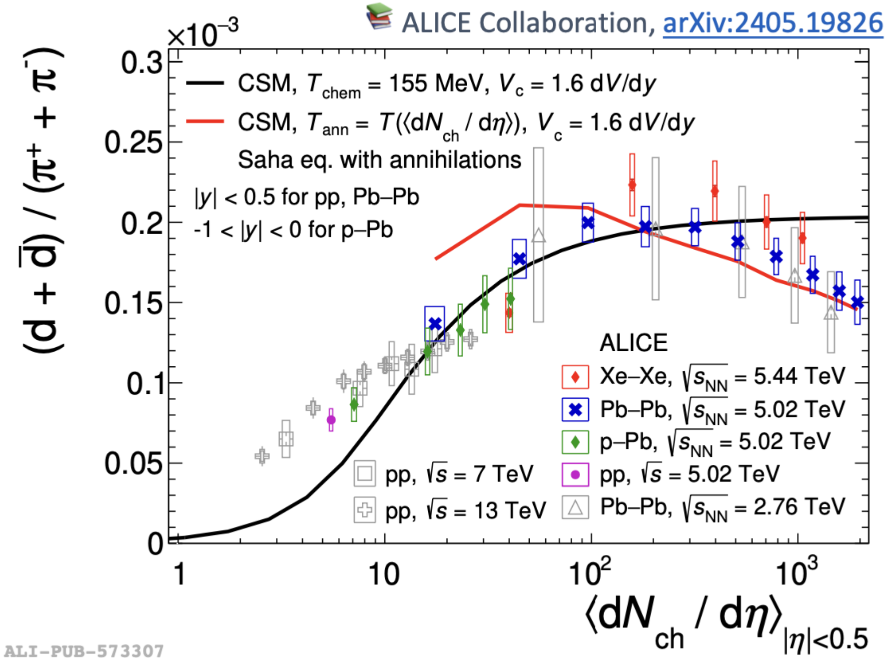
much new information expected with upgraded detectors in LHC Run 3 and Run 4

additional material

the deuteron story



ALICE Collaboration, [arXiv:2405.19826](https://arxiv.org/abs/2405.19826)



- **V_c=1.6 dV/dy** is the correlation volume needed to describe the net-deuteron number fluctuations in Pb–Pb collisions[1]
- **CSM →** either with fixed chemical temperature (CSM-I) or with **annihilation** temperature depending on multiplicity[2] (CSM-II)
- Both CSM and **coalescence**[3] predictions qualitatively reproduce the trend and overall yields, but neither of the models catch all data points
- CSM-I at low multiplicity does not reproduce d/π ratio, but CSM-II at high multiplicity catches the decreasing trend

[1] ALICE Collaboration, PRL 131 (2023) 041901 [2] Vovchenko, Koch, PLB 835, 137577 (2022) [3] Sun, Ko, Doenigus, PLB 792 (2019) 132-137

slide taken from Chiara Pinto
SQM2024