Origin of (anti-)nuclear clusters in hadronic collisions

Starting comments and experimental overview

Alexander Kalweit, *CERN*

TH Institute 18th May 2020

Welcome!

- Many thanks from the organisers (Laura, Maximiliano, Kfir, AK) for joining and participating in this special *all-online* TH institute!

- The idea is to have in-depth discussions among experts from the experimental and theory community to understand the properties and the production of anti- and hyper-nuclei in pp, p-Pb, and Pb-Pb collisions at LHC energies.

- Feel free to add discussion points and questions (including plots which were not shown in the talks) in our google-doc:

https://docs.google.com/presentation/d/1Xr-nMaQCH_cSACO112PqsrIs6-3UPK7QrIDC2Q-_iu0/edit - slide=id.p

Agenda (1)

Tuesday, 19 May

09:00 → 10:00 **Starting comments / EXP overview** — 1h — Zoom only

Speaker: Alexander Philipp Kalweit (CERN)

10:00 → 11:00 **The thermal-statistical model applied to nuclear clusters** — 1h — Zoom only

Speaker: Anton Andronic (Westfaelische Wilhelms-Universitaet Muenster (DE))

11:00 → 12:00 **Coalescence as the origin of nuclear clusters** — 1h — Zoom only

Measurements of the production of light nuclei in relativistic heavy-ion collisions present us with an apparent puzzle: While the momentum spectra of these nuclei indicate a low "kinetic freeze-out" temperature coupled with strong collective flow, their yields reflect a much higher "chemical freeze-out" temperature, consistent with the quark-gluon plasma hadronization temperature. How can these fragile nuclei "survive" the rescattering in the hadronic phase, cooling down in the process and picking up additional collective flow, without getting destroyed and depleted? I will explain how the coalescence model reconciles these observations and how recent kinetic simulations of the process support this model.

Speaker: Ulrich Heinz (The Ohio State University)

12:00 → 13:30 **Lunch Break** — 1h 30m

Agenda (2)

12:00 → 13:30	**Lunch Break**	1h 30m	
13:30 → 14:00	**Light nuclei yields: EXP vs. TH expectation** **Speaker**: Luca Barioglio (Universita e INFN Torino (IT))	30m	Zoom only
14:00 → 15:00	**Coalescence--correlations relation: B2 vs. HBT/radii** Discussion of the EXP effort to test the predicted relation between pair correlations and coalescence yield. Main questions for TH and for the analysis, results and discussion. **Speaker**: Bernhard Hohlweger (TUM)	1h	Zoom only
15:00 → 16:00	**Discussion: coalescence vs. HBT**	1h	Zoom only
16:00 → 16:15	**Break**	15m	Zoom only
16:15 → 16:45	**The thermal model off-equilibrium** **Speakers**: Volodymyr Vovchencko, Dr Volodymyr Vovchenko (Lawrence Berkeley National Laboratory)	30m	Zoom only
16:45 → 17:15	**Cluster formation in a transport model** **Speakers**: Dr Dmytro Oliinychenko (Lawrence Berkeley National Laboratory), Dmytro Oliinychenko	30m	Zoom only
17:15 → 18:45	**Google Doc Discussion**	1h 30m	Zoom only

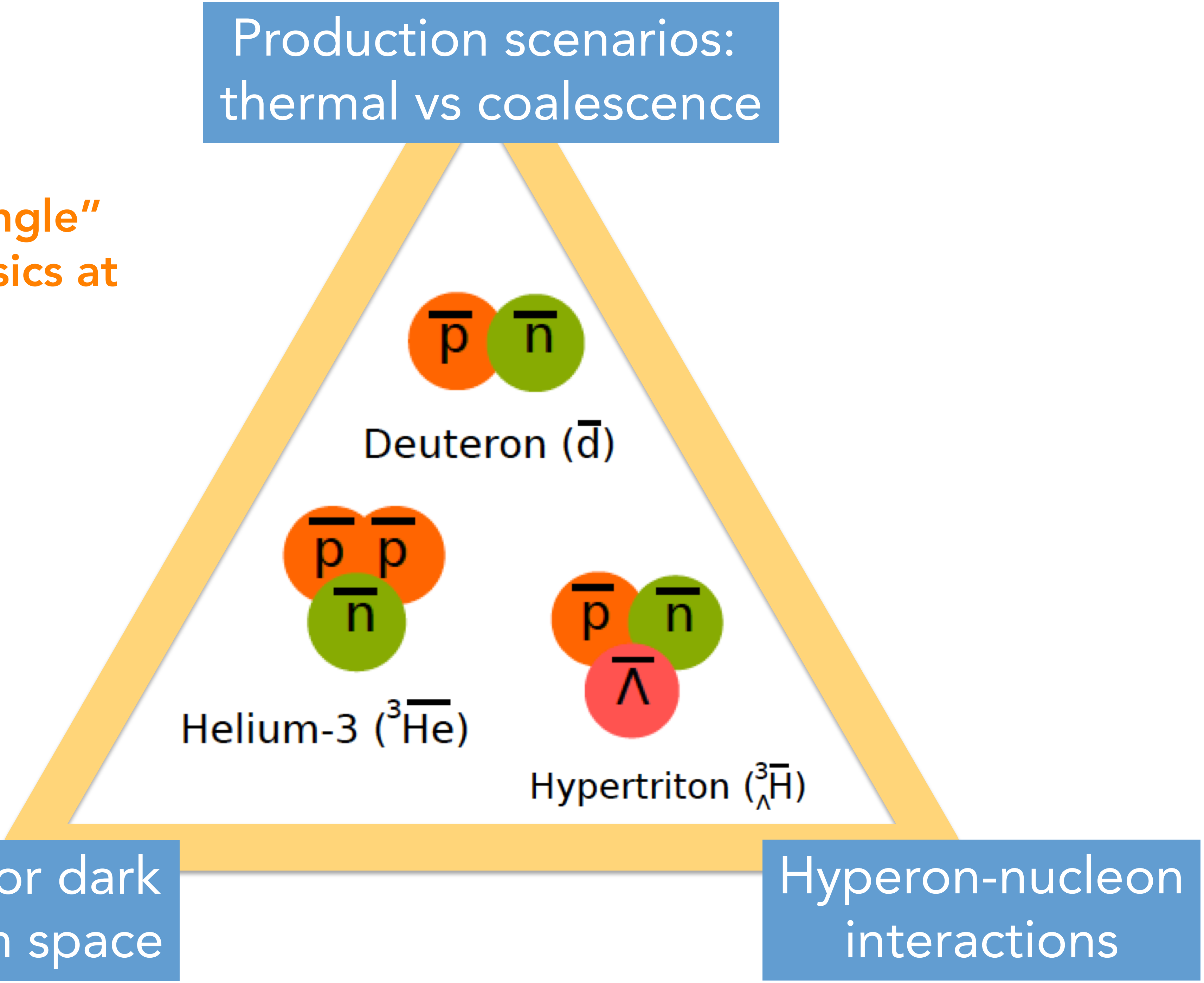
Agenda (3)

Wednesday, 20 May

09:00	→ 09:30	**Hypertriton structure** **Speaker**: Hans-Werner Hammer	30m	Zoom only
09:30	→ 10:00	**Hypertriton lifetime** **Speakers**: Jean-Marc Rene Richard (Centre National de la Recherche Scientifique (FR)), Jean-Marc Richard, jean-marc Richard (IPNL)	30m	Zoom only
10:00	→ 10:45	**Hypertriton yield at ALICE: EXP vs. TH**	45m	Zoom only
10:45	→ 11:30	**Discussion: Hypertriton as a probe of cluster formation**	45m	Zoom only
11:30	→ 12:00	**How to distinguish coalescence from thermal production of light nuclei** **Speaker**: Stanislaw Mrowczynski	30m	Zoom only
12:00	→ 13:30	**Break**	1h 30m	Zoom only
13:30	→ 15:00	**Google Doc Discussion & Workshop summary**	1h 30m	Zoom only
15:00	→ 16:00	**TH Colloquium: Jesse Thaler (https://indico.cern.ch/event/888504/)**	1h	Zoom only

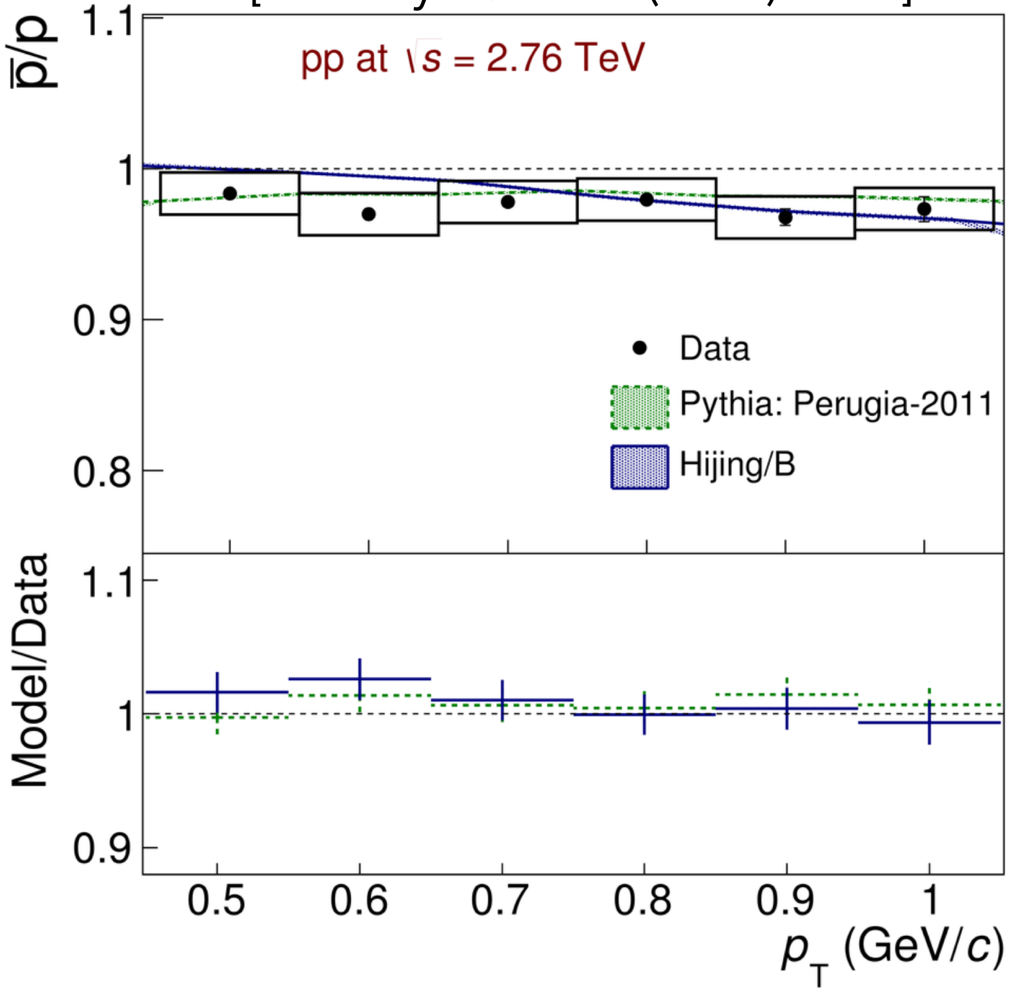
The LHC as an anti-matter factory

The "golden triangle" of anti-nuclei physics at the LHC.

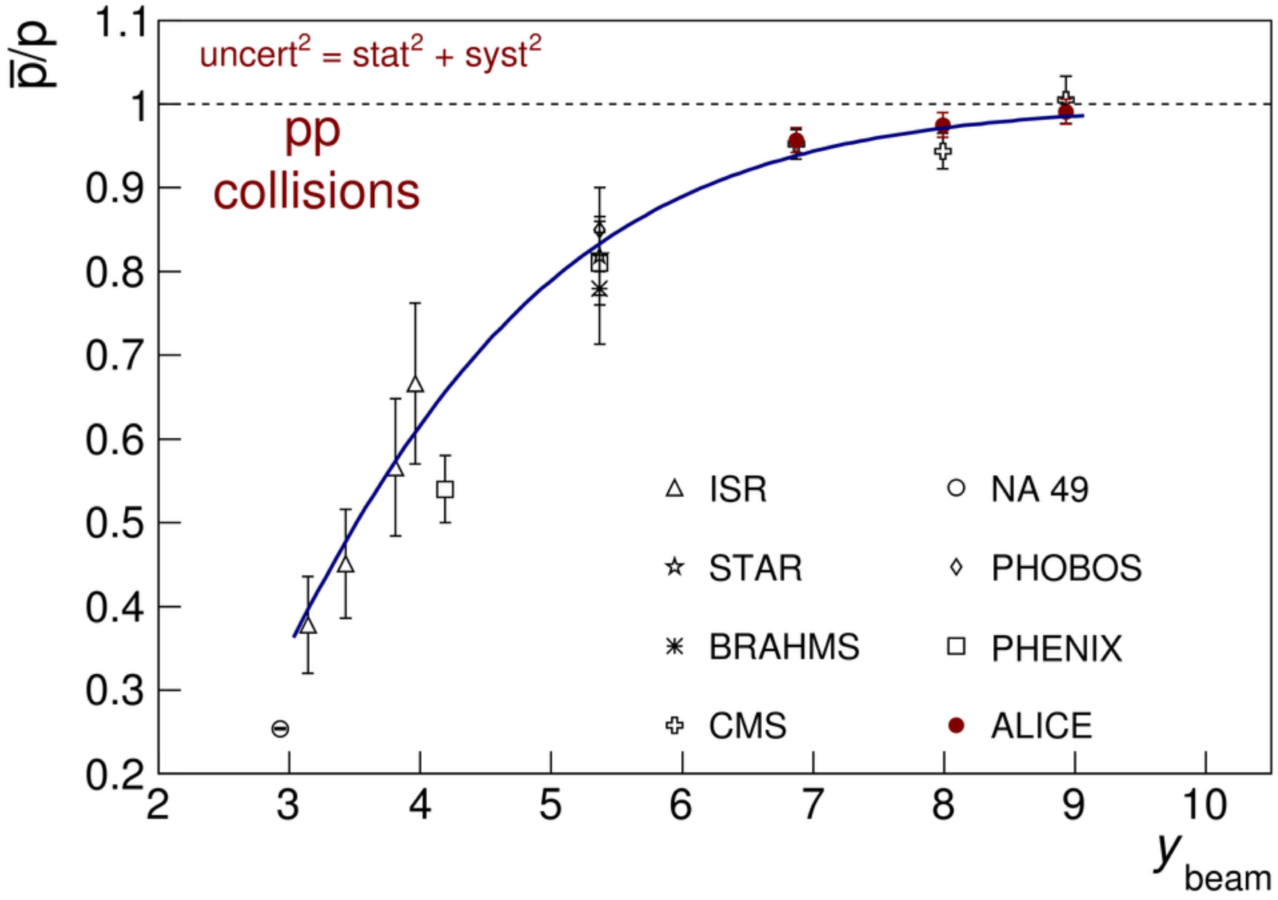


Particles and anti-particles

[Eur. Phys. J. C 73 (2013) 2496]

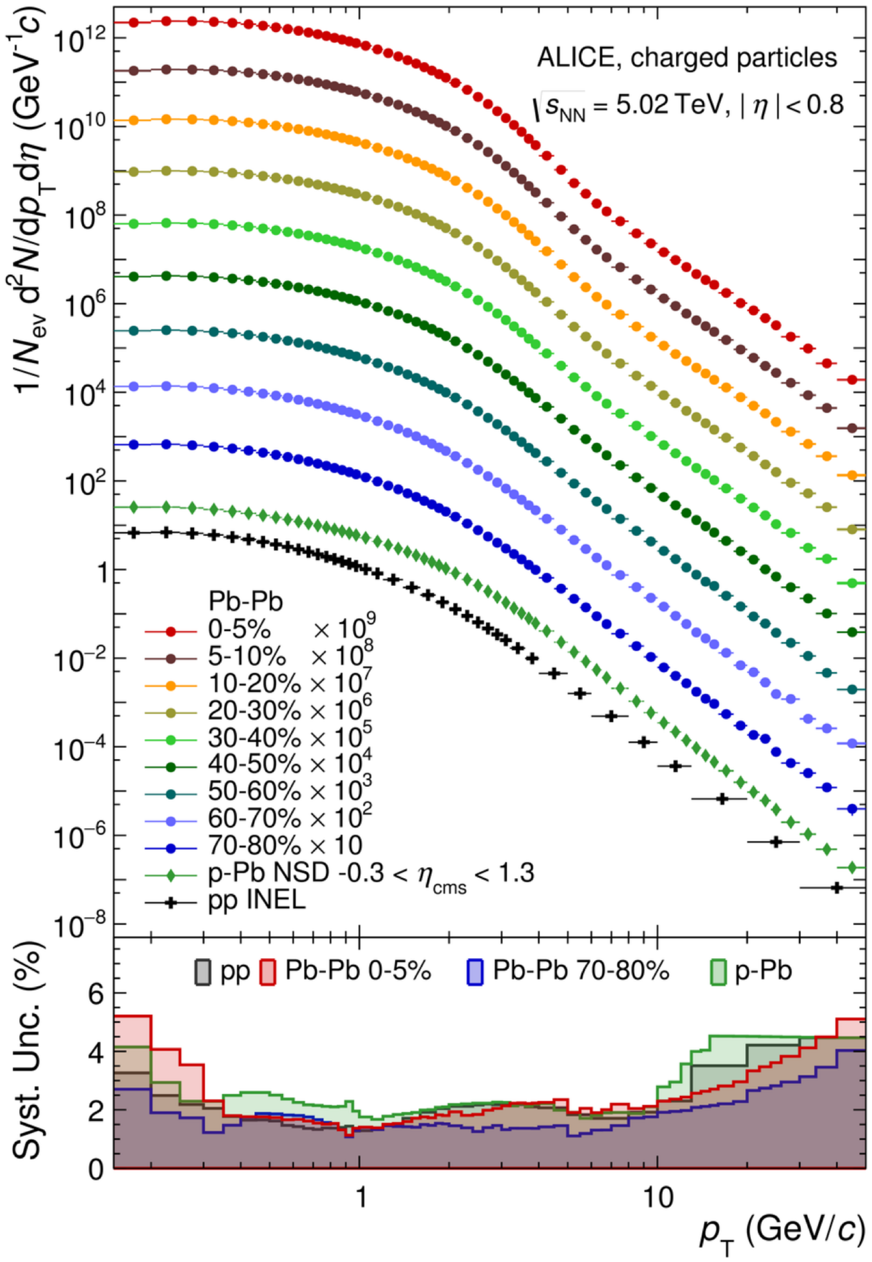


[Eur. Phys. J. C 73 (2013) 2496]



At LHC energies, particles and anti-particles are produced in equal abundance at mid-rapidity.

Particle production at LHC energies (1)

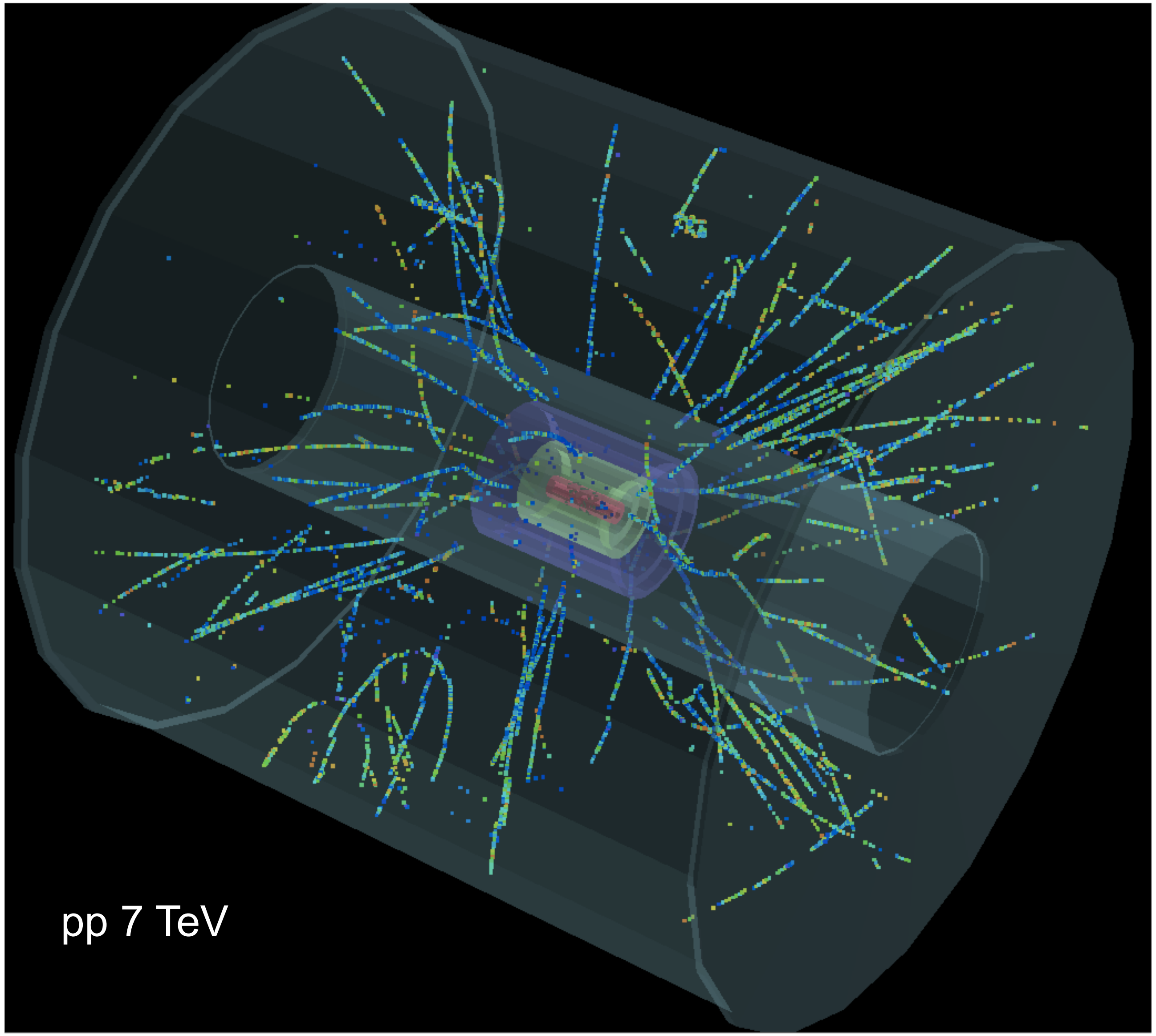


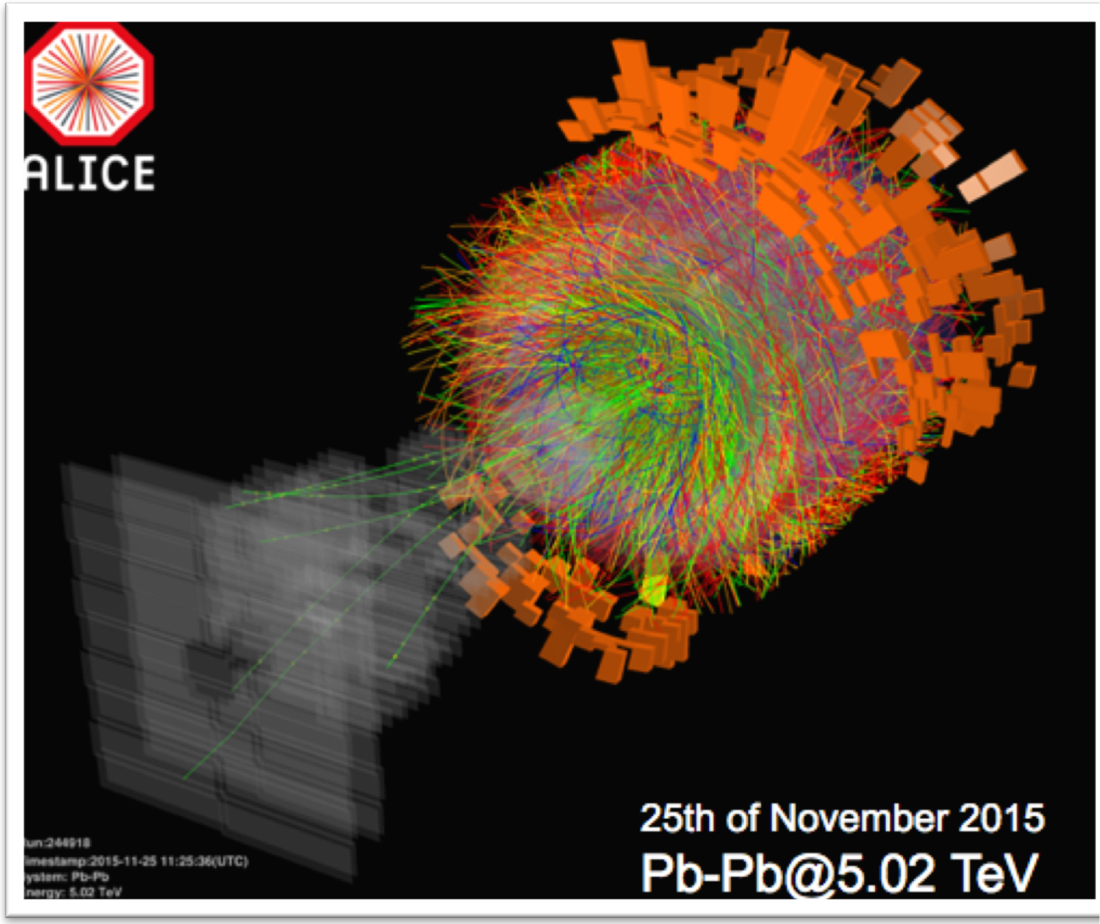
→ Even at LHC energies, 95% of all particles are produced with p_T < 2 GeV/c in pp and Pb-Pb collisions.

→ Bulk particle production and the study of collective phenomena are associated with ***"soft" physics*** in the non-perturbative regime of QCD.

[ALICE, JHEP 1811 (2018) 013]

Particle production at LHC energies (2)

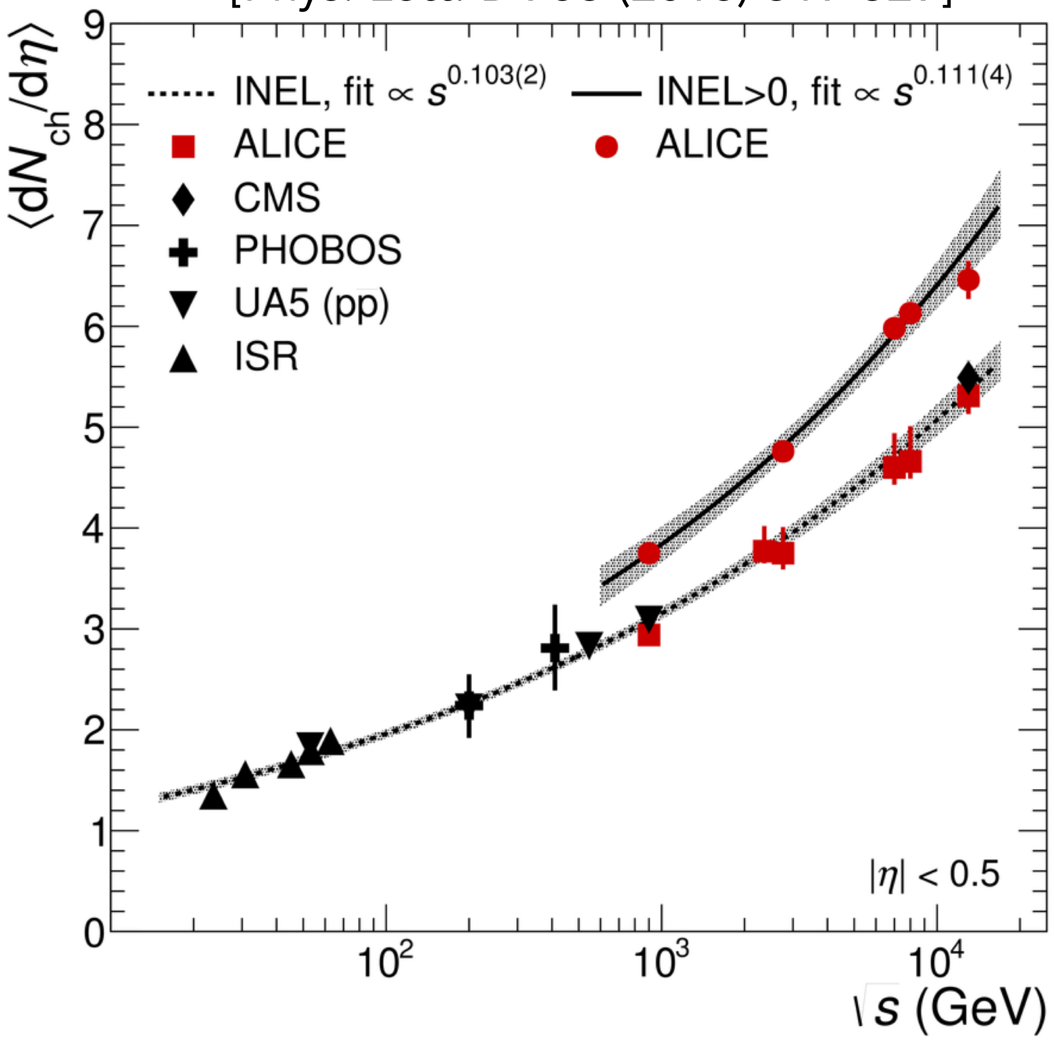




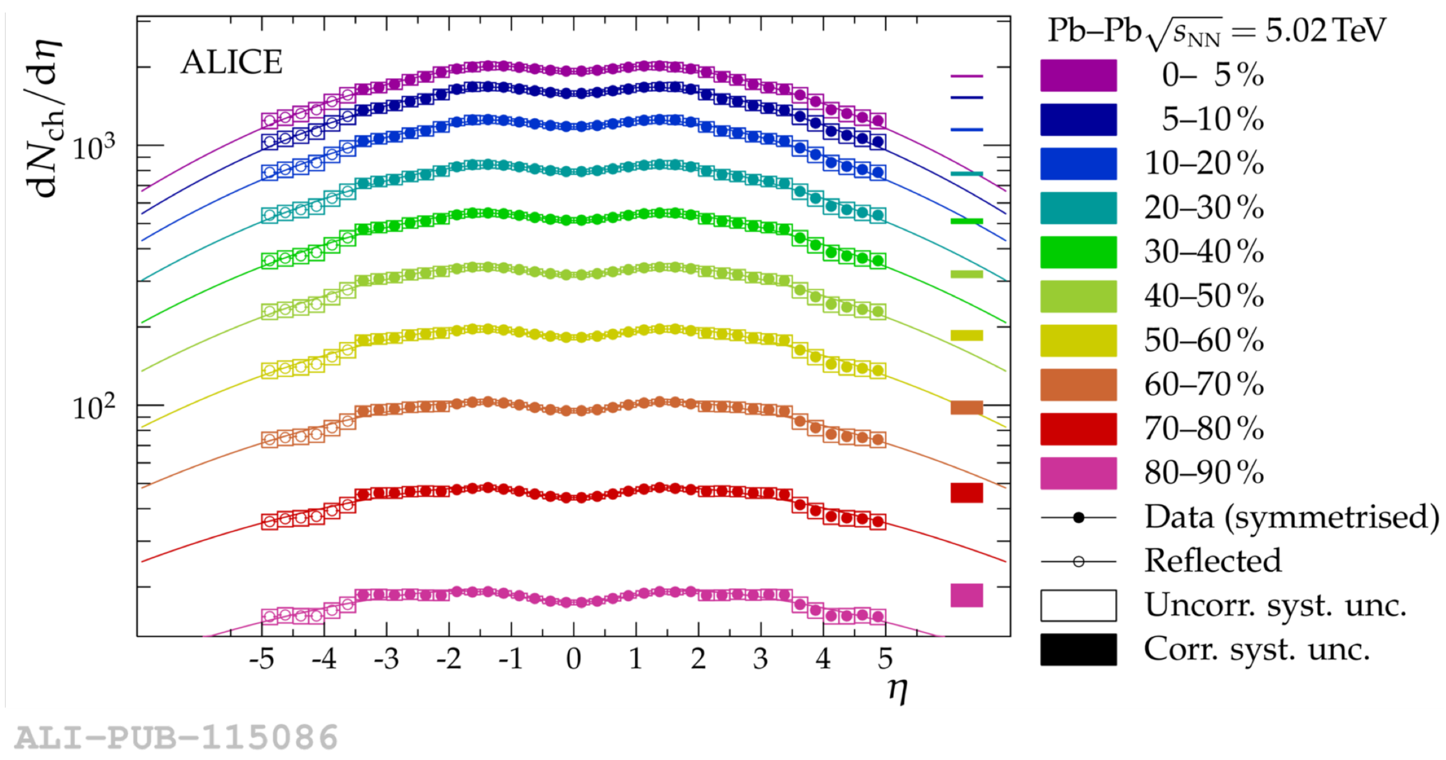
→ How many particles are produced in such a collision?

Particle production at LHC energies (3)

[Phys. Lett. B 753 (2016) 319-329]



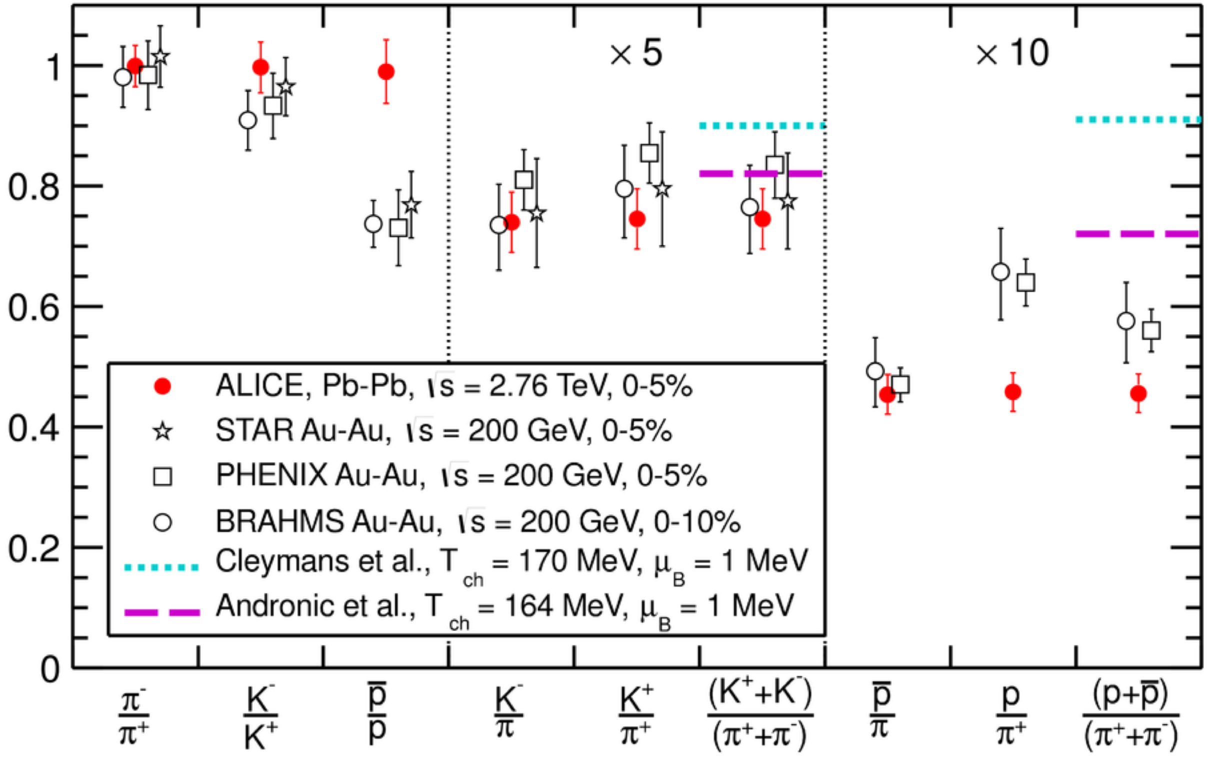
[Phys.Lett. B 772 (2017) 567-577]



$dN_{ch}/d\eta \approx$ 1943 ± 54 at midrapidity **in Pb-Pb**.

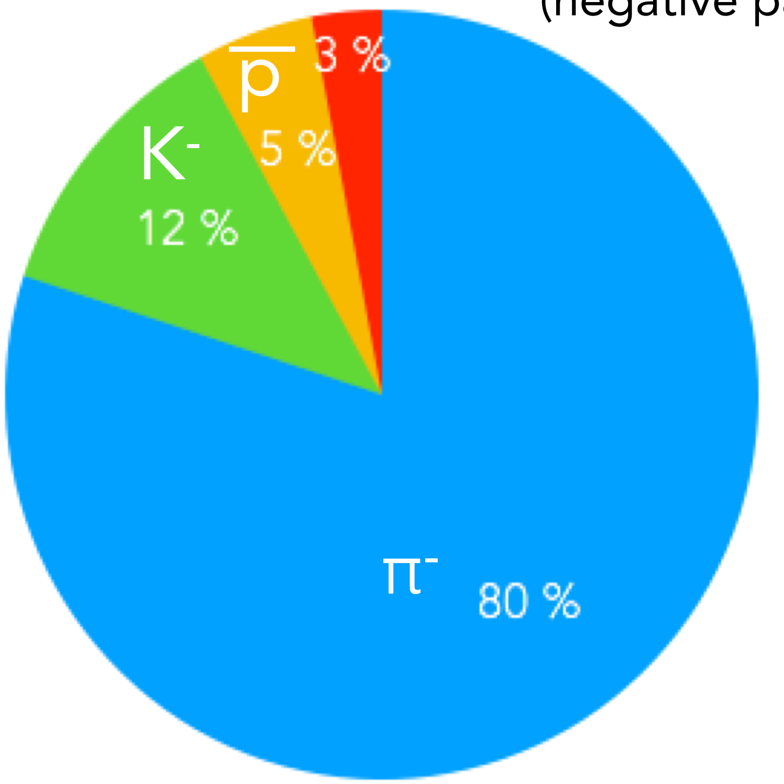
$dN_{ch}/d\eta \approx$ 4-7 in **pp collisions** at LHC energies

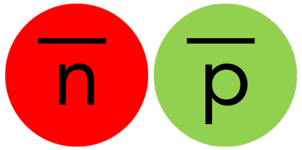
Particle production at LHC energies (4)



[Phys. Rev. Lett. 109 (2012) 252301]

(negative particles)



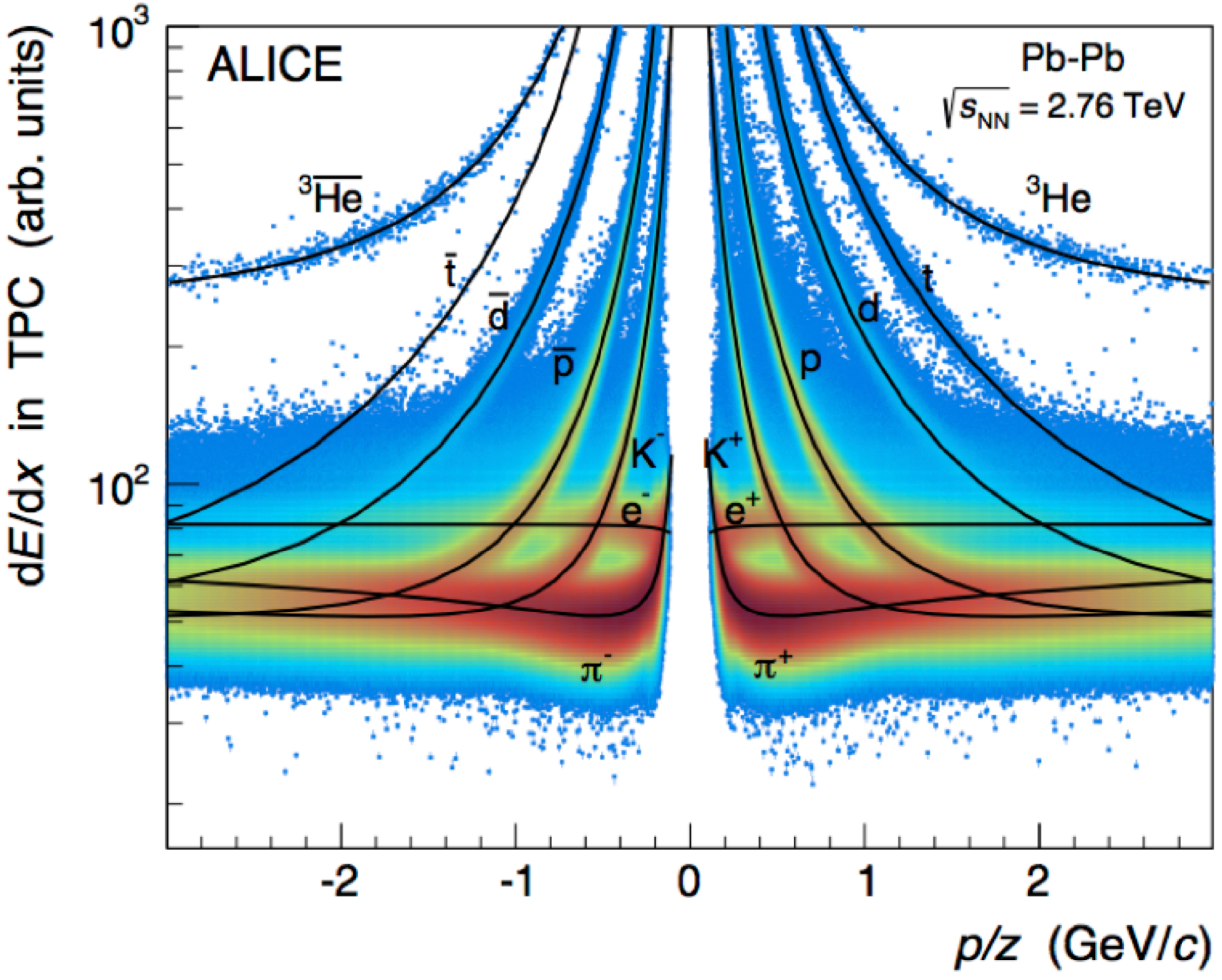


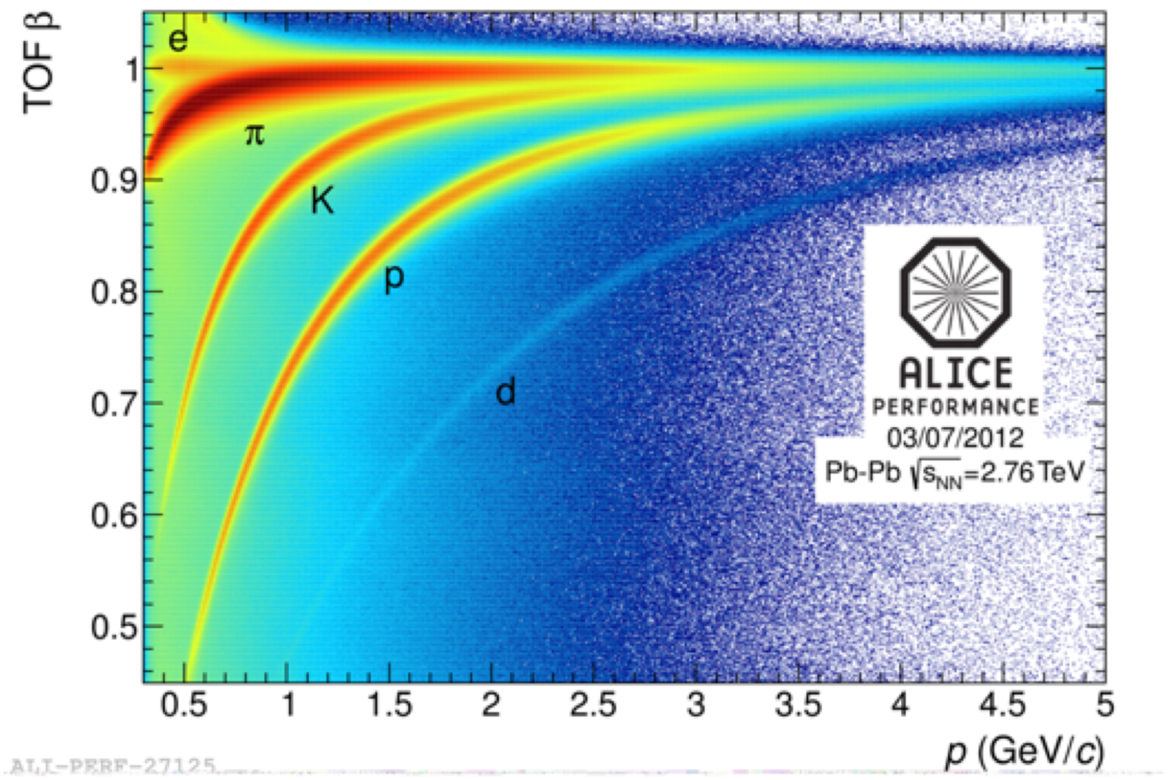
anti-deuteron

→Only ~5% of all negative particles are anti-protons (the "lightest anti-nucleus").

→The production of composite anti-particles is **very rare:** ~ **0.005% are anti-deuterons.** ➔ **Clean PID needed!**

Anti-nuclei identification in ALICE





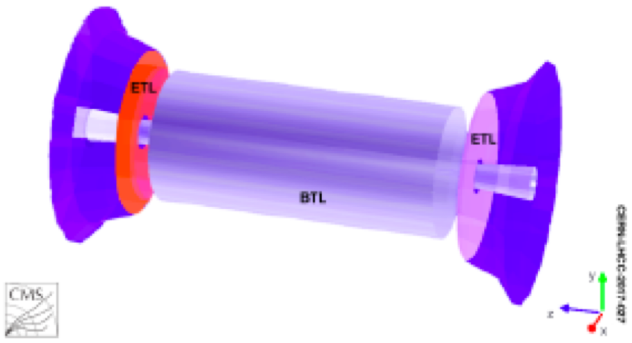
[Phys. Rev. C 93 (2015) 024917]

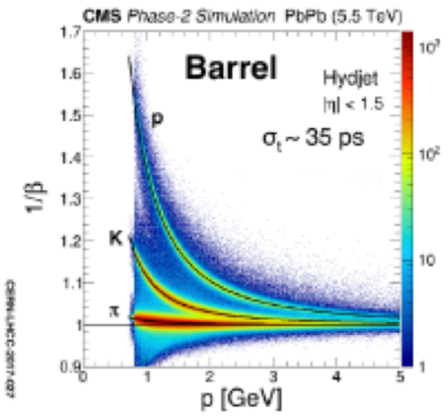
Prospects for (anti-)(Hyper-)nuclei measurements in CMS

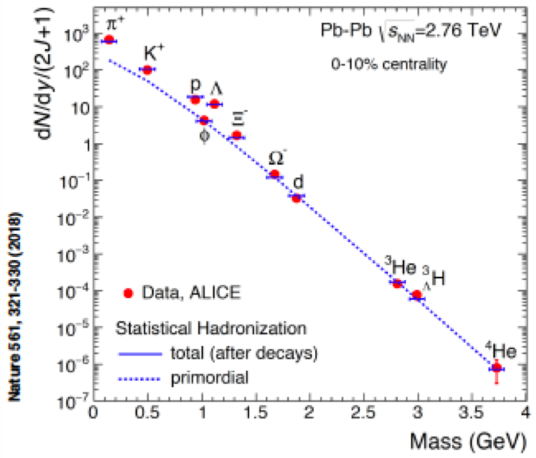
[QM talk, A. Govinda]

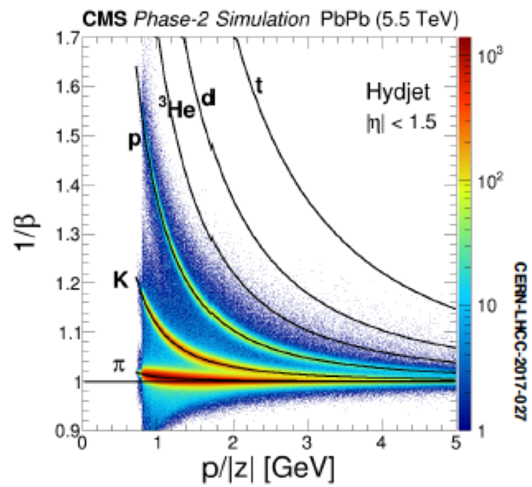
MIP Timing Detector (2026+)

- Time-of-flight: $\pi/K/p$ identification!
- Enhanced heavy flavour program...
  and more!



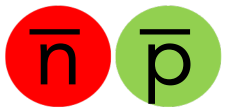




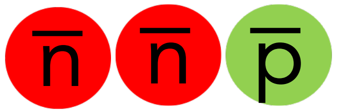


- Light (d, ^{3}He, t) and hyper ($^3_\Lambda$He, $^3_\Lambda$H) nuclei can be identified over a wide kinematic range via TOF using MTD.
- Also provide insights for dark matter searches and astrophysics.

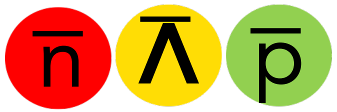
Light (anti-)nuclei



anti-deuteron

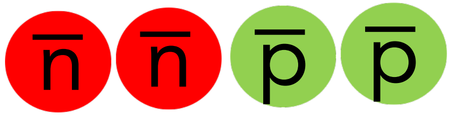


anti-triton

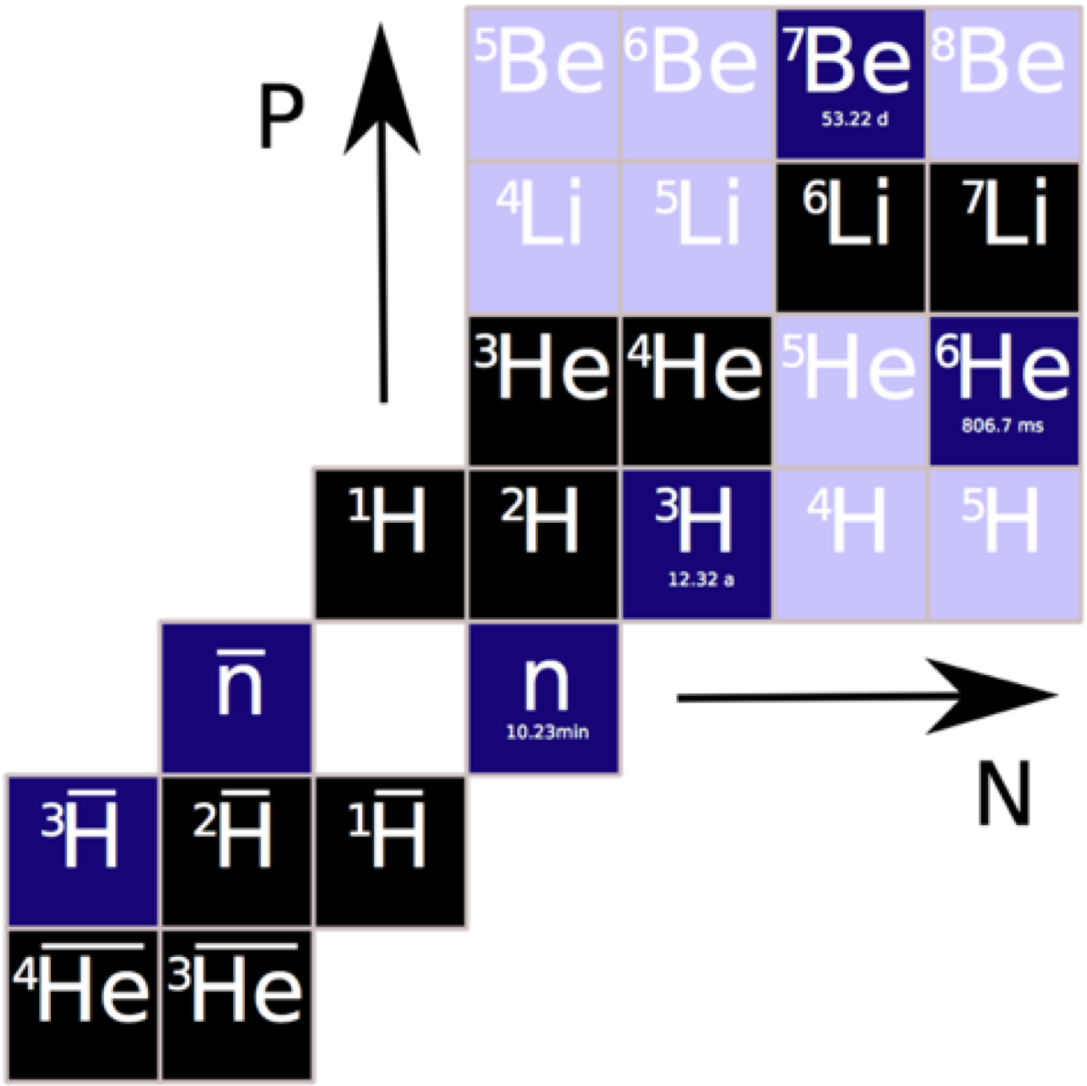


anti-hyper-triton

anti-helium3

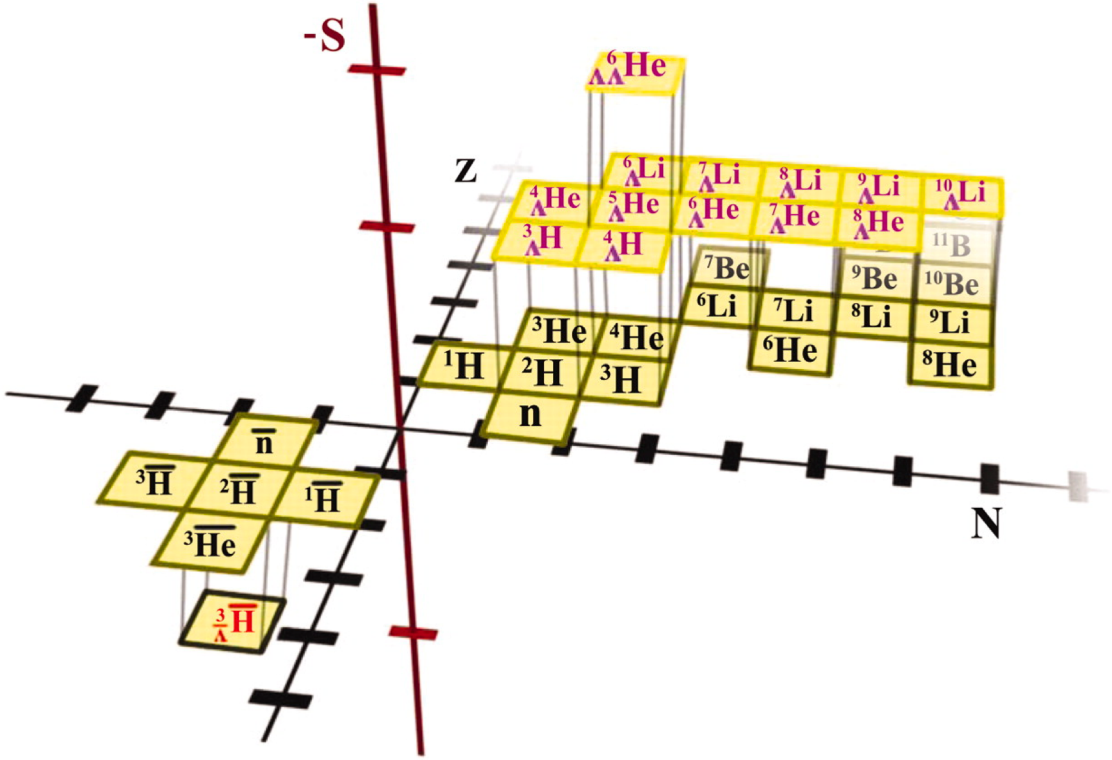


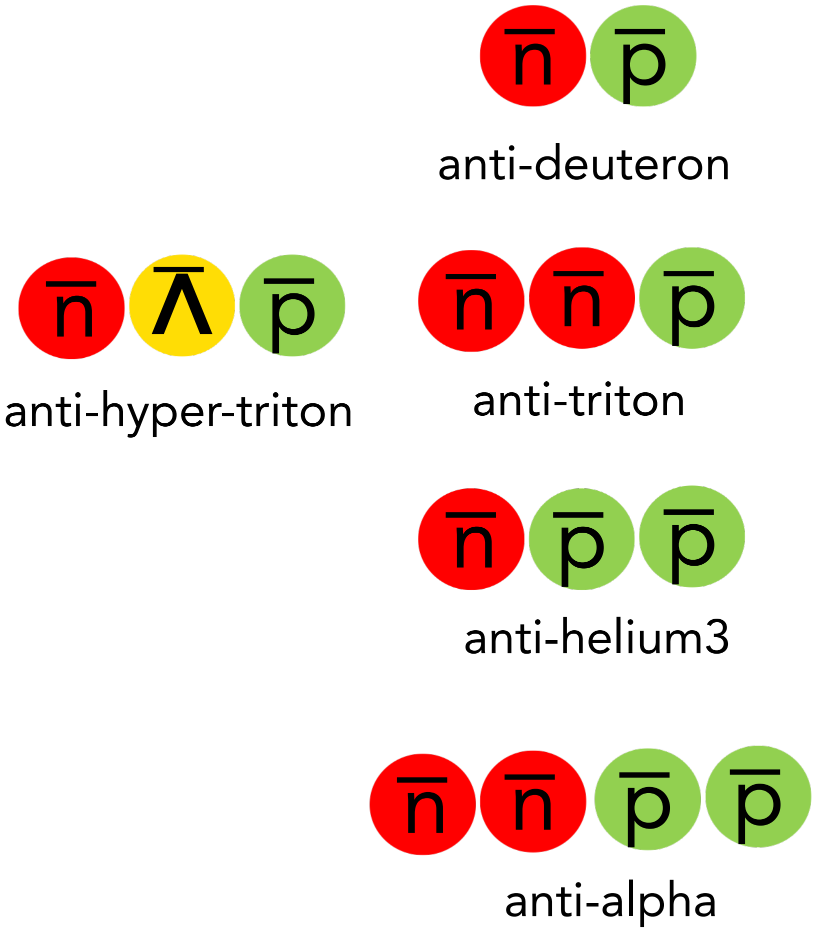
anti-alpha



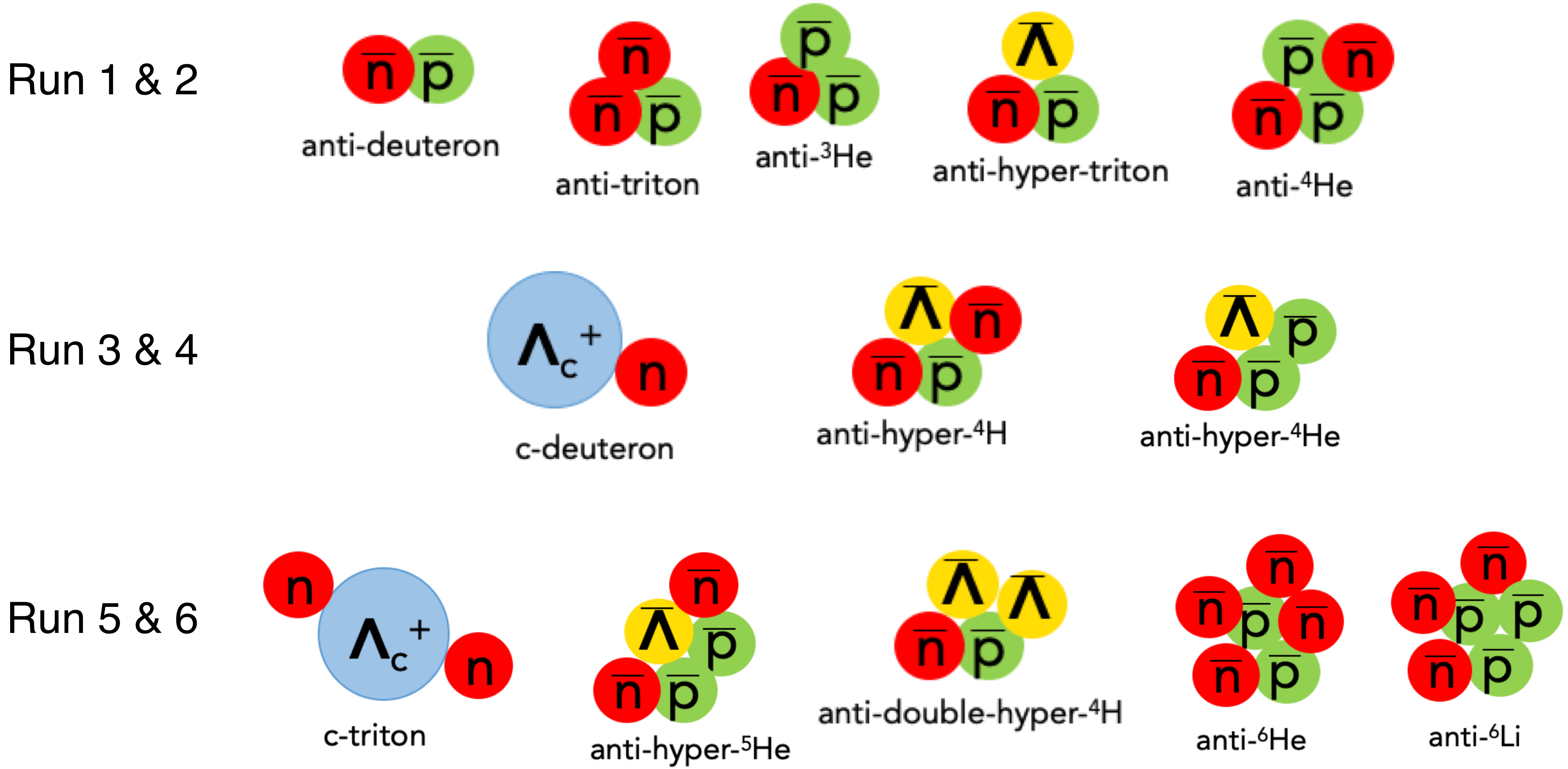
Anti-(hyper)-nuclei up to A=4 are currently in reach at accelerators. The anti-alpha is the heaviest observed so far and was first seen by the STAR experiment in 2011.

Light (anti-)nuclei

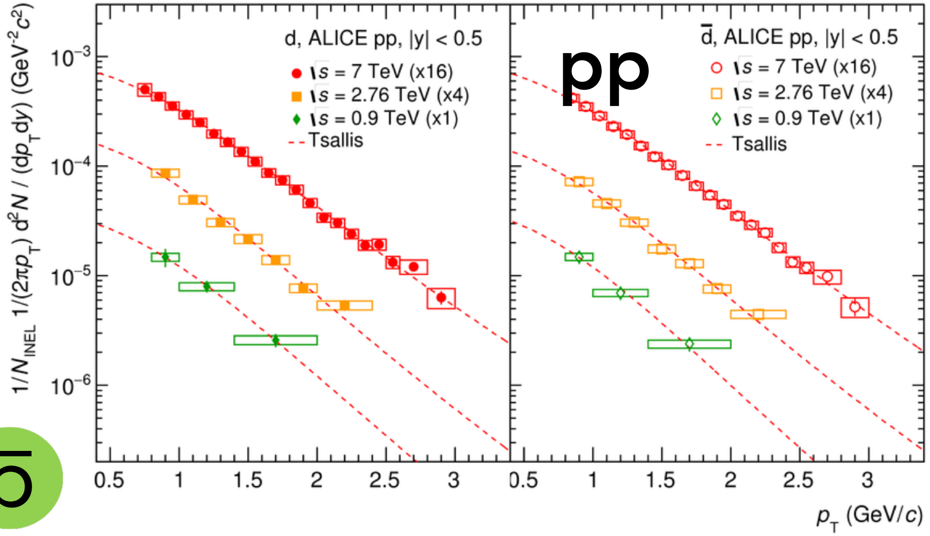




Zoo of exotic QCD bound states



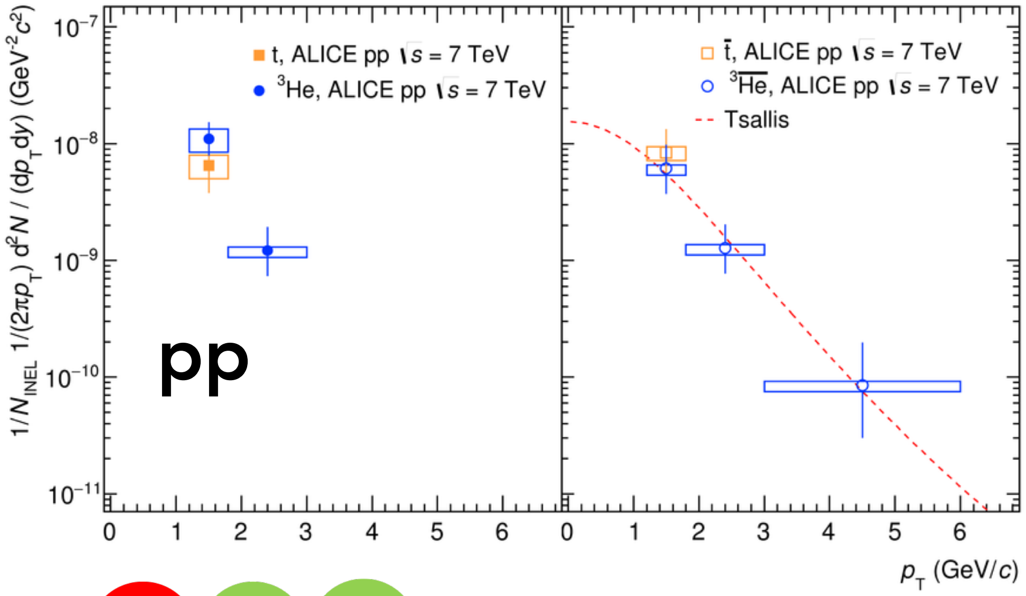
A wealth of data: p_T spectra



pp

$\bar{n}$ $\bar{p}$

anti-deuteron



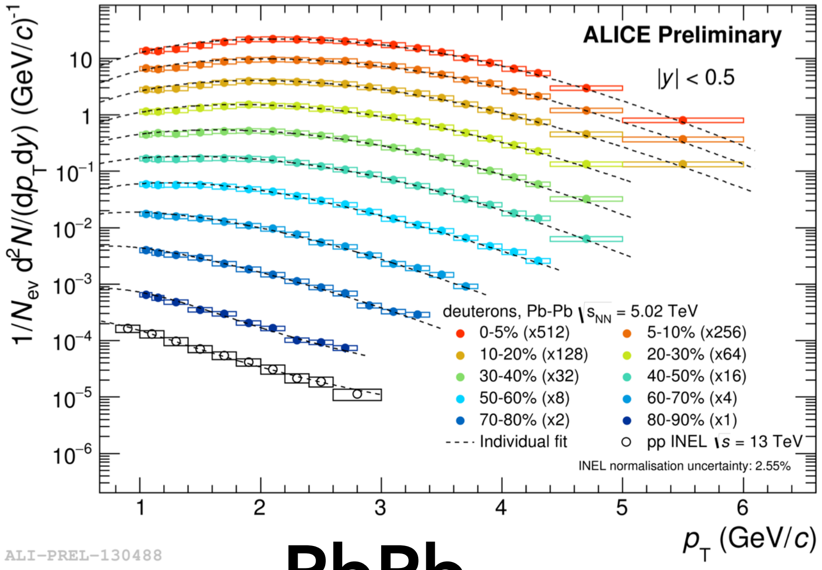
pp

$\bar{n}$ $\bar{p}$ $\bar{p}$

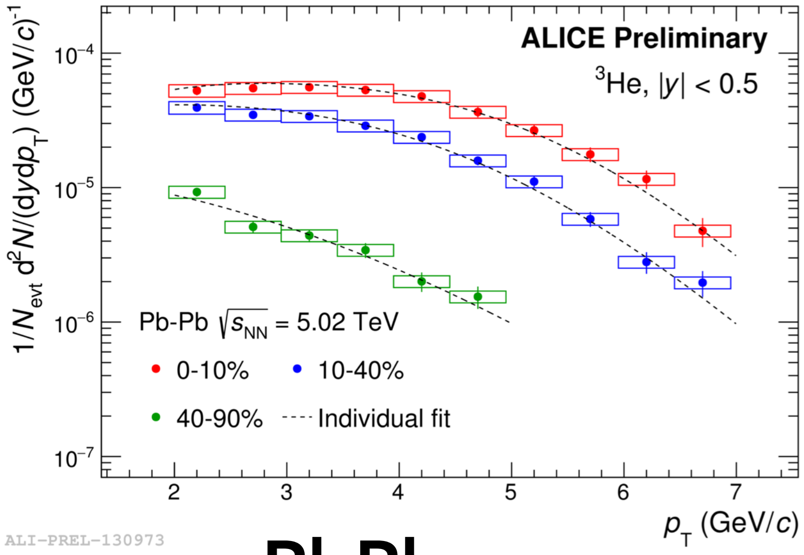
anti-helium3

$\bar{n}$ $\bar{\Lambda}$ $\bar{p}$

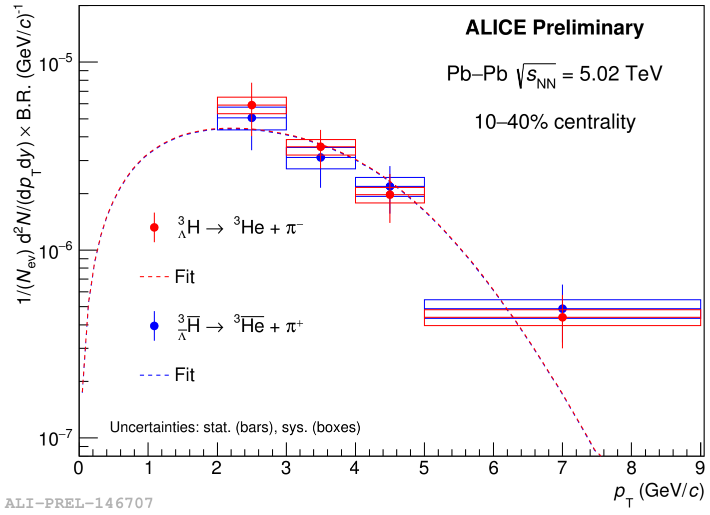
anti-hyper-triton



PbPb

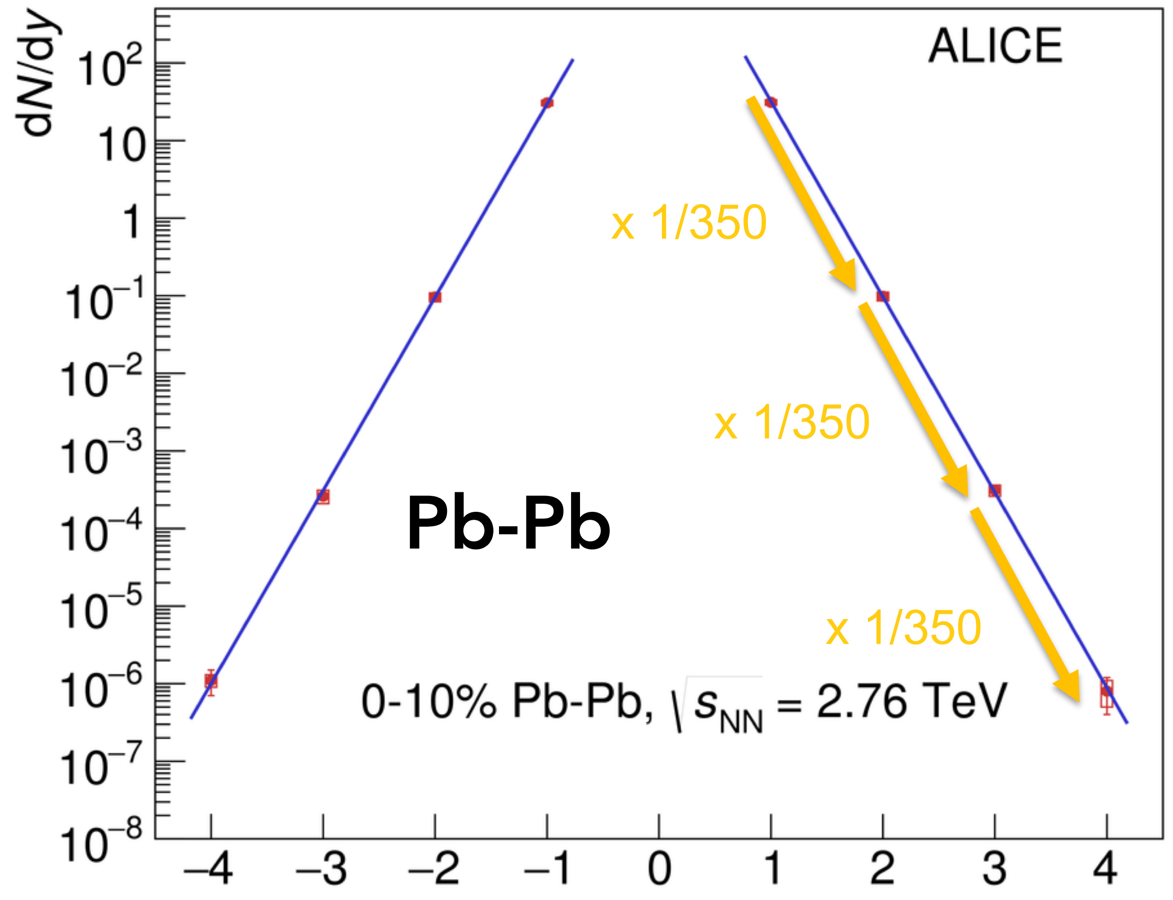


PbPb

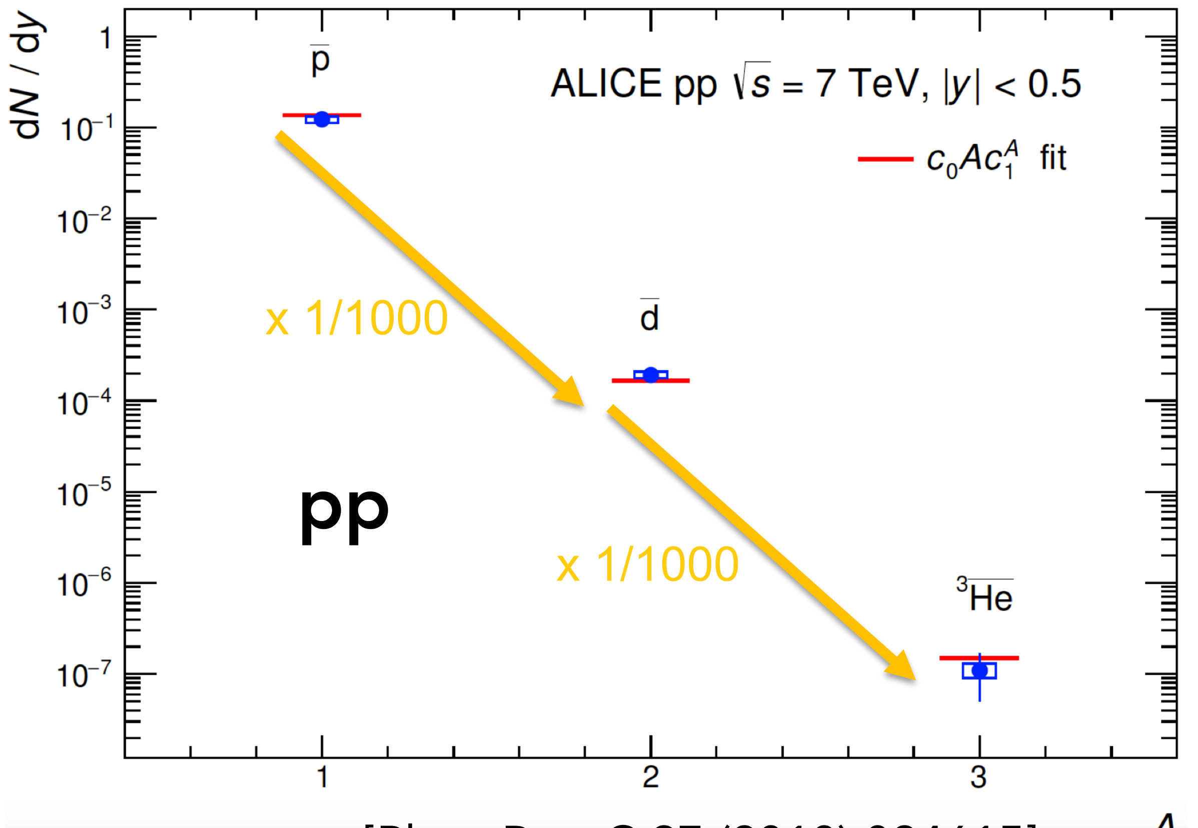


PbPb

Penalty factor at the LHC



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



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

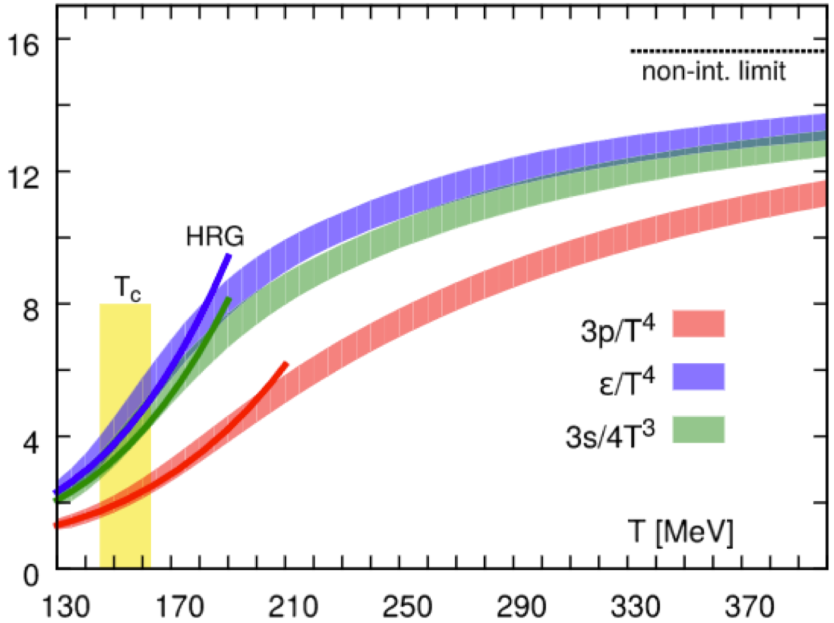
The production yield of (anti)-nuclei decreases by a factor of about ~350 for each additional nucleon in Pb-Pb (~1000 in pp).

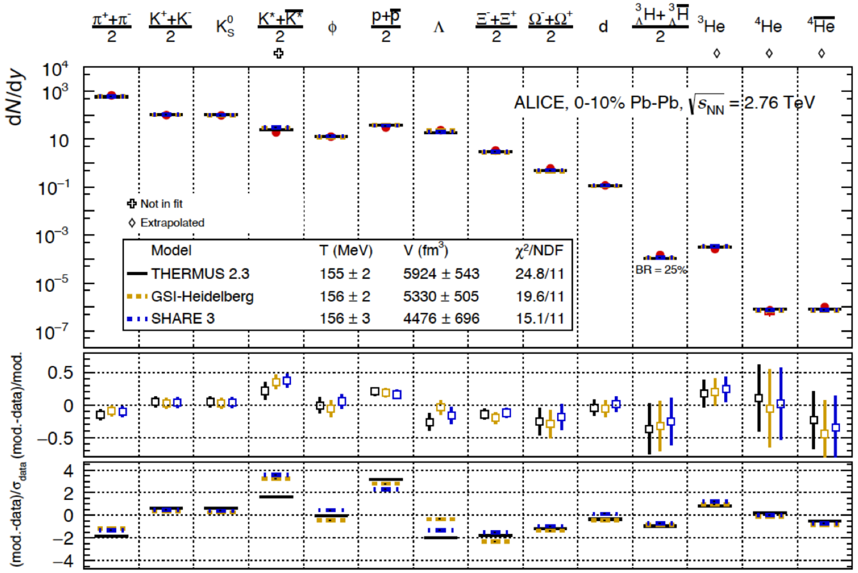
An introduction to the “anti-nuclei puzzle”

A problem of two scales

1. "Temperatures", mean-transverse momenta etc. are of the 100-200 MeV scale:

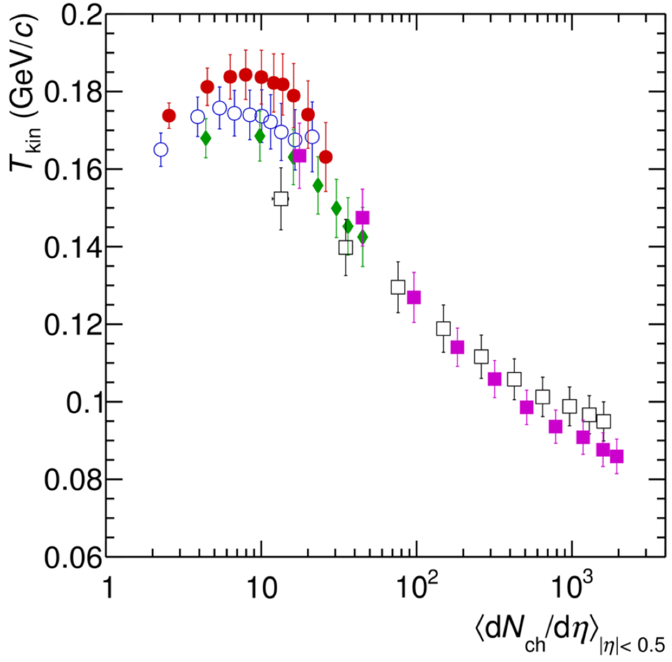
[Lattice QCD, PRD 90 094503 (2014)]





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

[arXiv:2003.02394]



2. Binding energies of the composite objects are of the order of ~1-10 MeV:

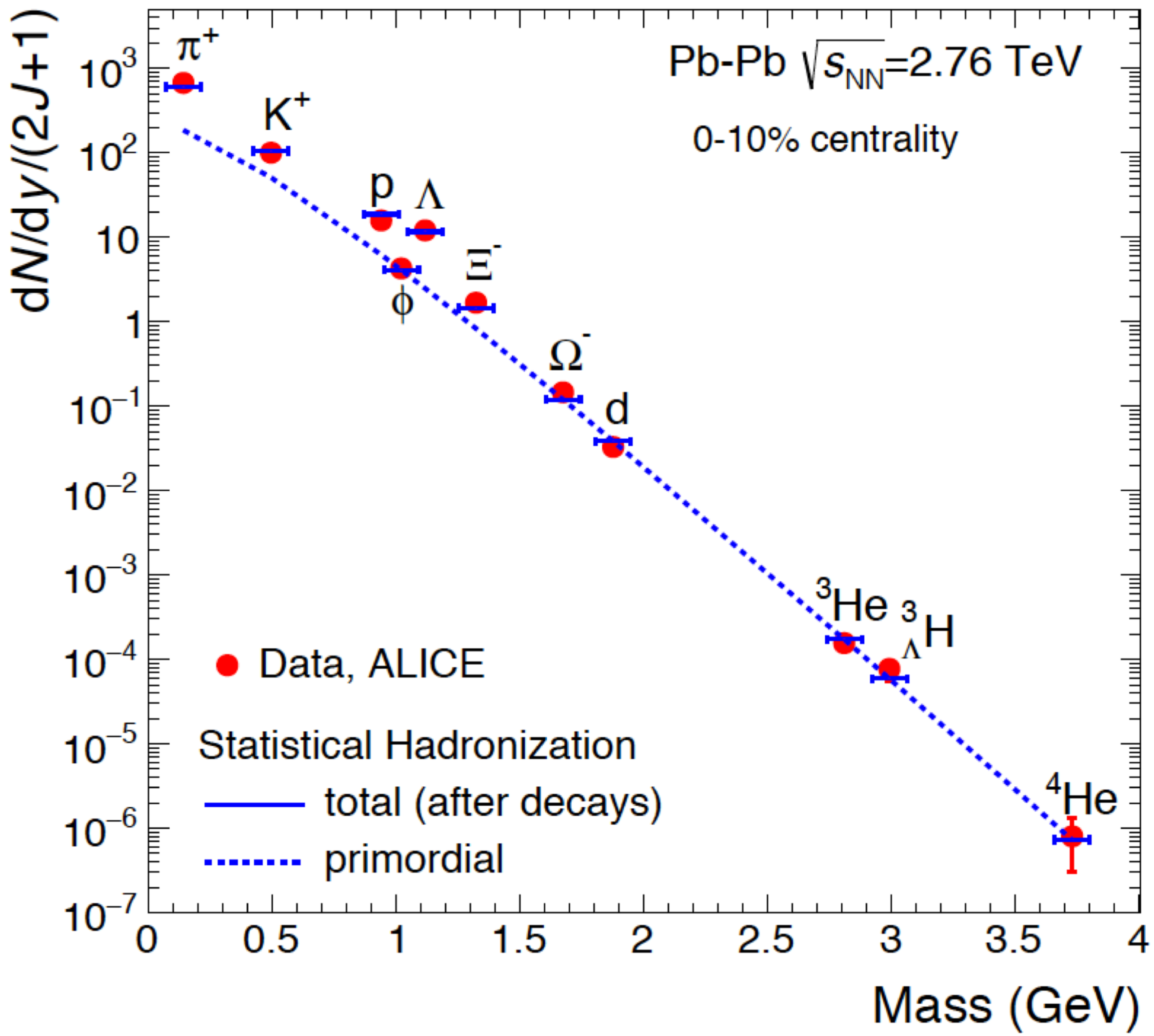
Mass number	Nucleus	Composition	Binding energy (MeV)	Spin
A = 2	d	pn	2.224575 (9)	1
A = 3	^{3}H	pnn	8.4817986 (20)	1/2
	^{3}He	ppn	7.7180428 (23)	1/2

Chemical equilibrium at the LHC: anti-nuclei puzzle

Production yields of light flavour hadrons from a chemically equilibrated fireball can be described 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}).



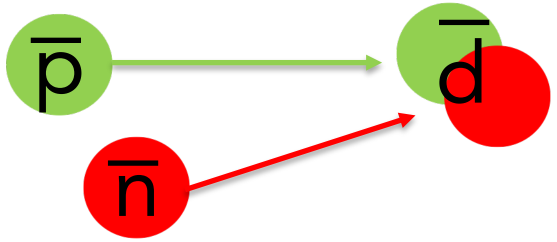
[A. Andronic *et al.*, arXiv:1710.09425]

Coalescence parameters B_A

- A production by coalescence could explain this puzzle.

- (anti-)nuclei production by coalescence of (anti-)protons and (anti-)neutrons which are close by in momentum and configuration space. Roughly speaking: *"deuteron ∝ proton x neutron => deuteron ∝ proton²"*

$$E_{\mathrm{d}} \frac{\mathrm{d}^3 N_{\mathrm{d}}}{\mathrm{d}p_{\mathrm{d}}^3} = B_2 \left(E_{\mathrm{p}} \frac{\mathrm{d}^3 N_{\mathrm{p}}}{\mathrm{d}p_{\mathrm{p}}^3} \right)^2$$



- Spherical approximation: maximum momentum difference (coalescence momentum p_0) is approx. 100 MeV (5.3 MeV kinetic energy of a nucleon in the rest frame of the other).

Fermi momentum and uncertainty principle

- “Close in phase-space” <-> “Close in configuration and momentum space” sounds nice, but is quantum-mechanically ill defined due to the uncertainty principle!

- Imagine a point-like emission source (pp): phase-space reduces to momentum space and the **coalescence momentum**, becomes equal to the momentum of the nucleons in the bound nucleus (the “Fermi momentum” in large nuclei).

- Quantum-mechanically correct treatment: overlap of the source function with the **Wigner-function** of the nucleus.

$$P(x,p) = \frac{1}{\pi\hbar}\int_{-\infty}^{\infty} dy\, \psi^*(x+y)\psi(x-y)e^{2ipy/\hbar}$$

- A point for the discussion: *Should we still call it “coalescence” if there is no (or negligible) dependence on the internal structure of the formed object?*

Measuring the wave-function of nuclei

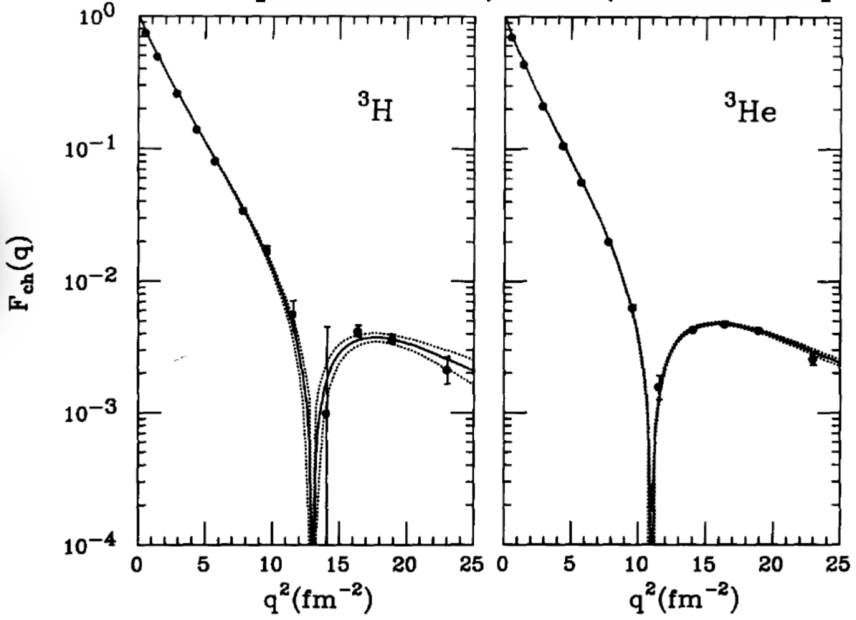
- Data from (old) electron scattering experiments for deuterons, tritons, ^{3}He, ^{4}He.

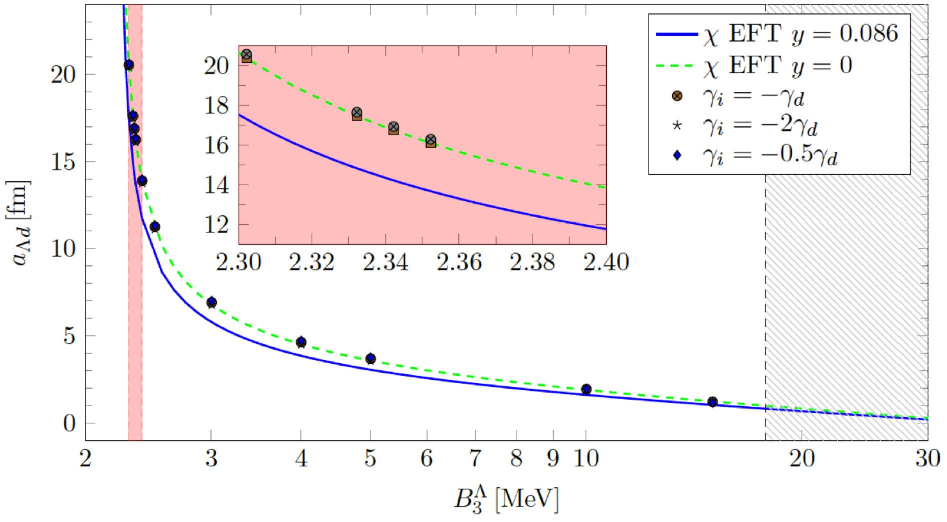
> The design of a tritium target containing of the order of 370 TBq (10 000 curies) of ^{3}H required a thorough study of options and safety considerations.

- For hyper-triton, the X(3872), and other QCD exotics, we have to rely on theory.

- A win-win situation?
  - If the coalescence model will turn out to be the correct description in small systems, can we then infer the wave-function of any QCD bound state by relating its production to the production of its constituents?
  - If thermal-statistical production turns out to be the correct scenario, we have to rethink the nature of QCD bound states.

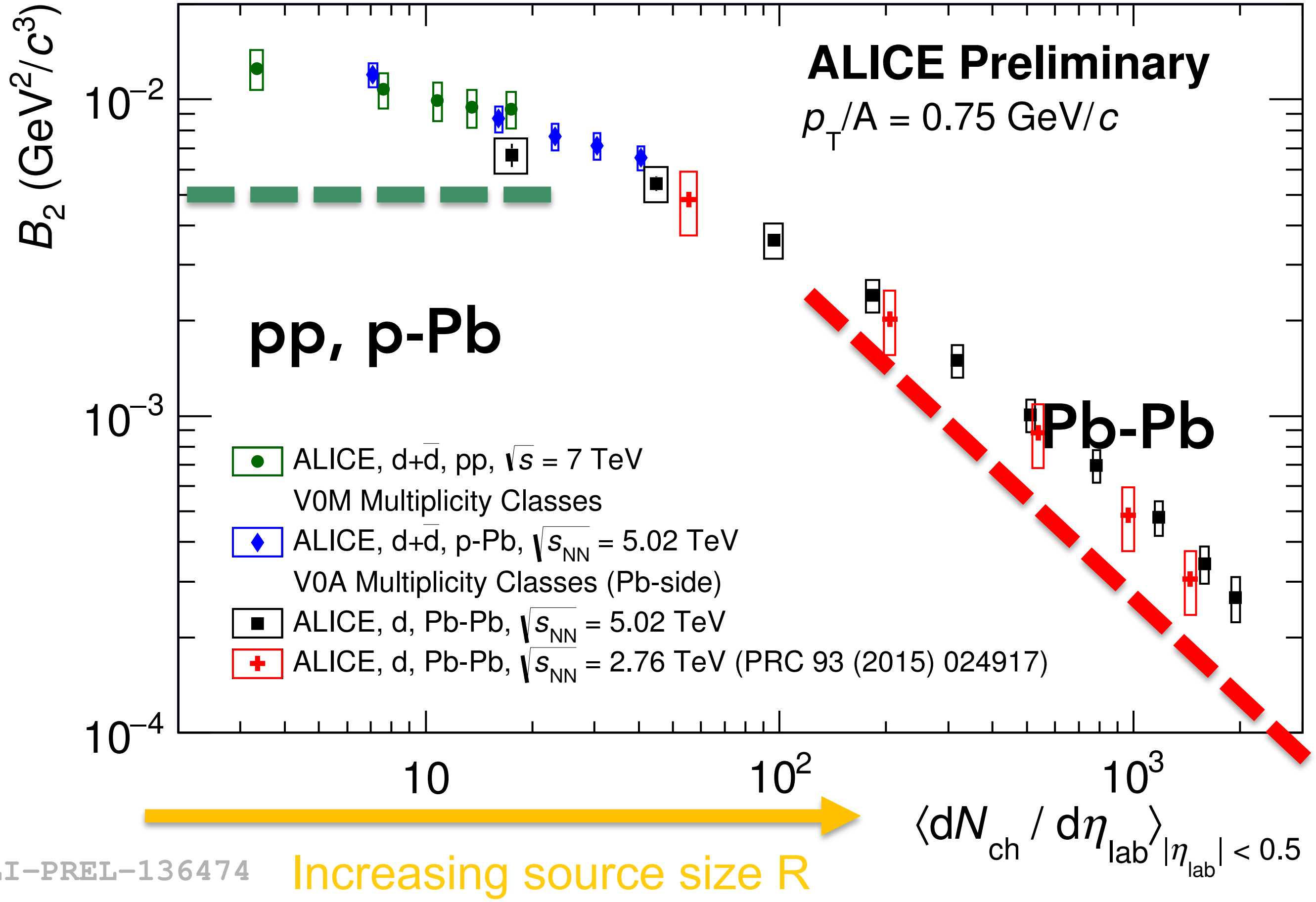
[NPA 579 (1994) 596-626]





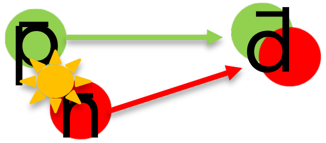
[Phys. Rev. C 100, 034002 (2019)]

Coalescence models in heavy-ion collisions

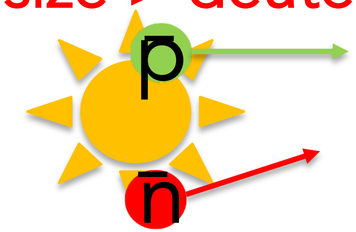


→ Two production regimes observed:

(a.) system size < deuteron size



(b.) system size > deuteron size



→ Strong dependence of B_2 on collision geometry.

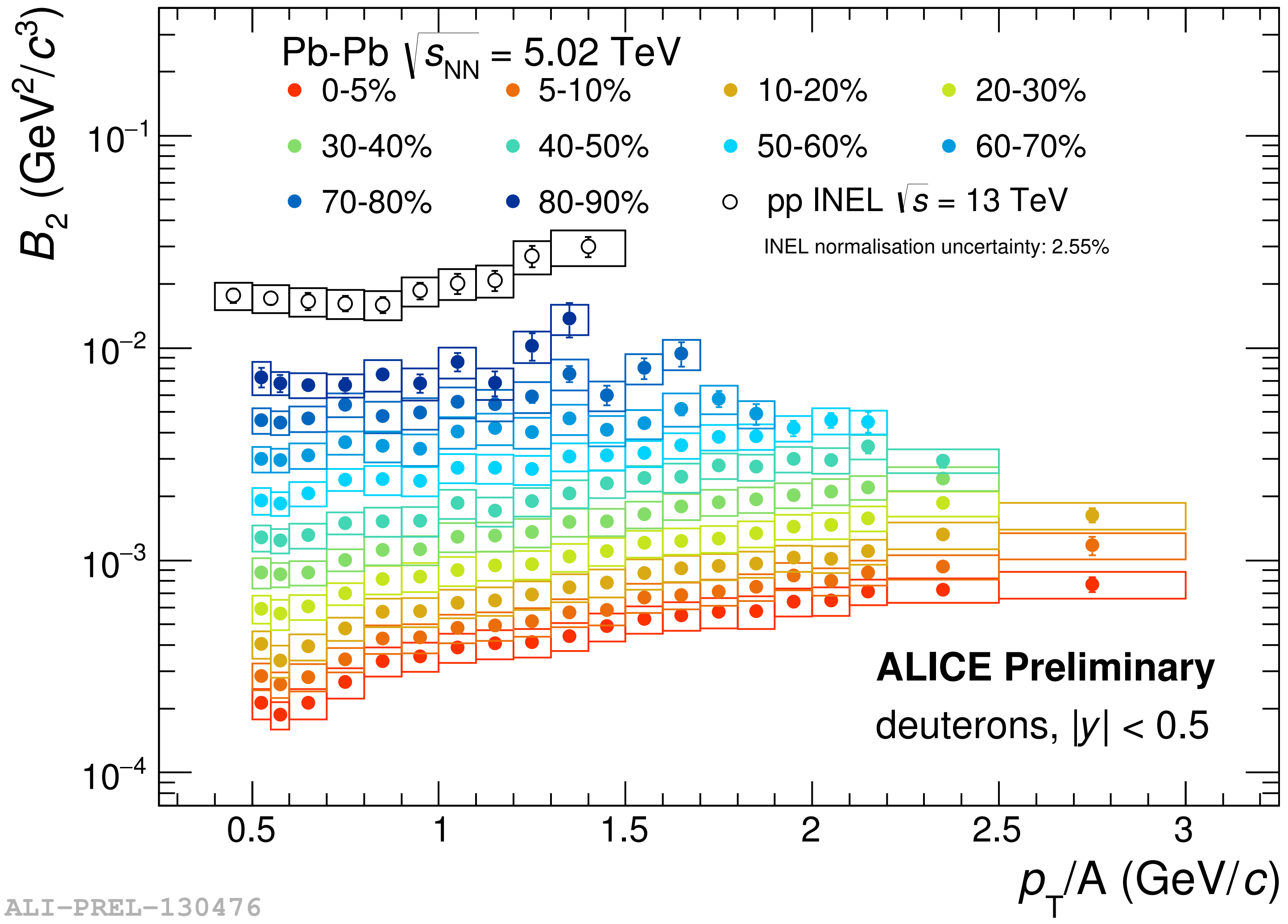
$$N_A \sim (R^2 + r_A^2/4)^{-3/2}$$

R – size of the system

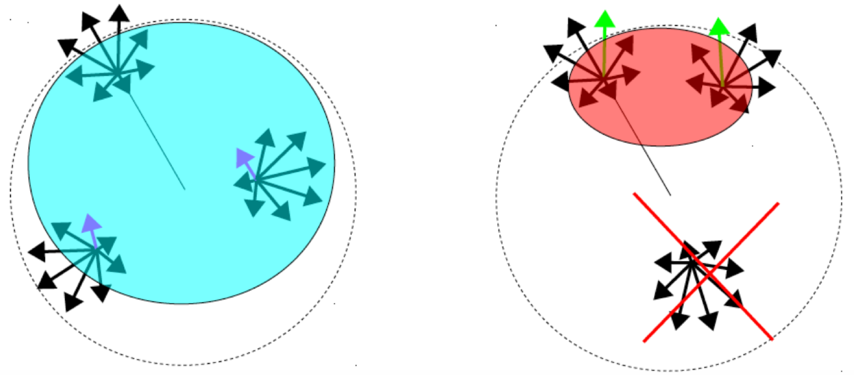
r_A – size of nucleus

The trend with multiplicity is explained as an increase in the source size R in coalescence models (e.g. *Scheibl,Heinz PRC 59 (1999) 1585*).

p_T dependence of B_2 in Pb-Pb



- A particle emitted from a medium will have a collective velocity β_f and a thermal (random) one β_t
- As observed p_T grows, the region from where pairs with small relative momentum can be emitted gets smaller and shifted to the outside of the source



A. Kisiel, Hirschegg 2019

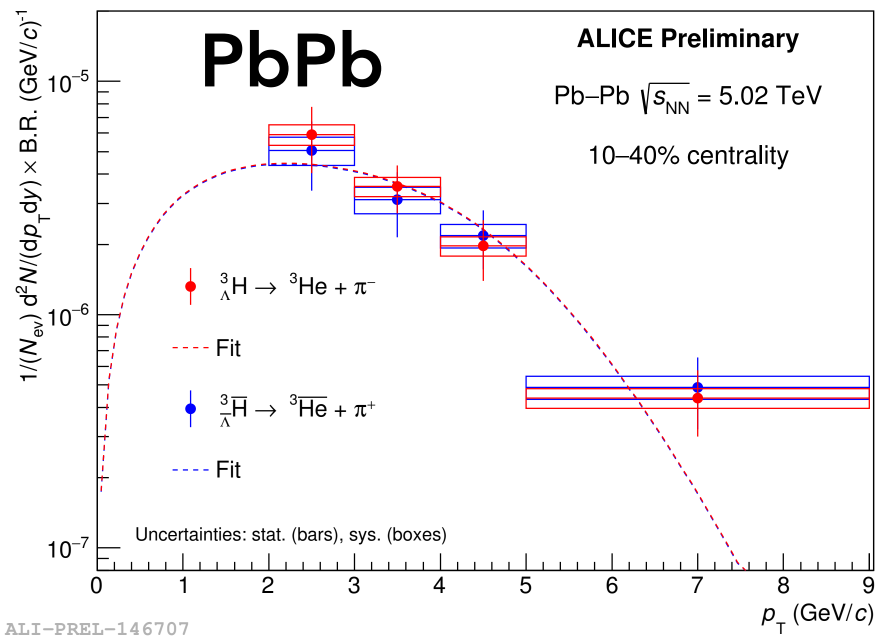
High momenta means => thermal (random) and collective component must align
=> more likely that they come from the same volume element
=> higher coalescence probability

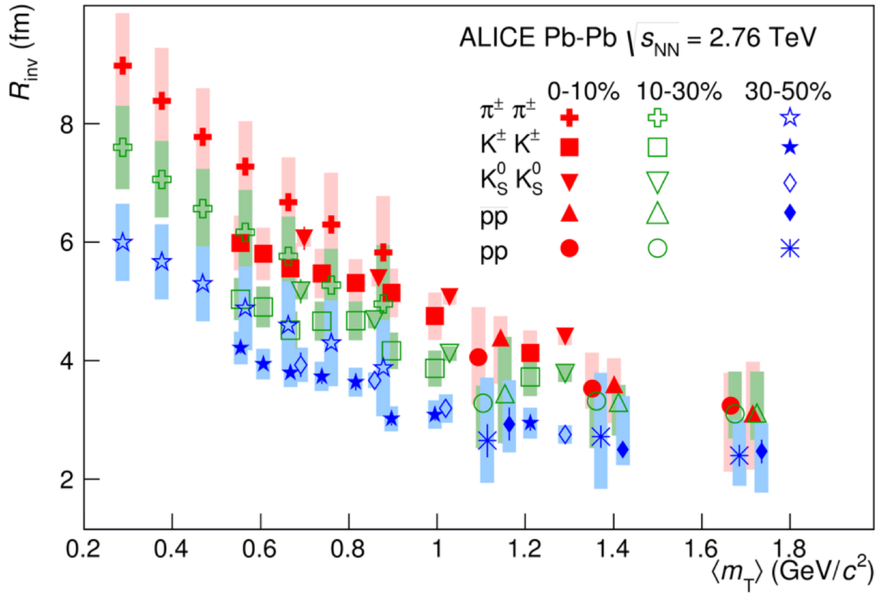
Typical momenta and HBT radii

- Roughly speaking, the maximum of the production probability in a range around 0.5 to 2.0 GeV/*c* per nucleon (system size dependent!).

- This corresponds to an m_T range around 1 to 2 GeV/c and thus to radii around 2-6 fm.

  → Important to do such "rough" studies precisely in future and it is one of the goals of the workshop to establish a roadmap for these projects.

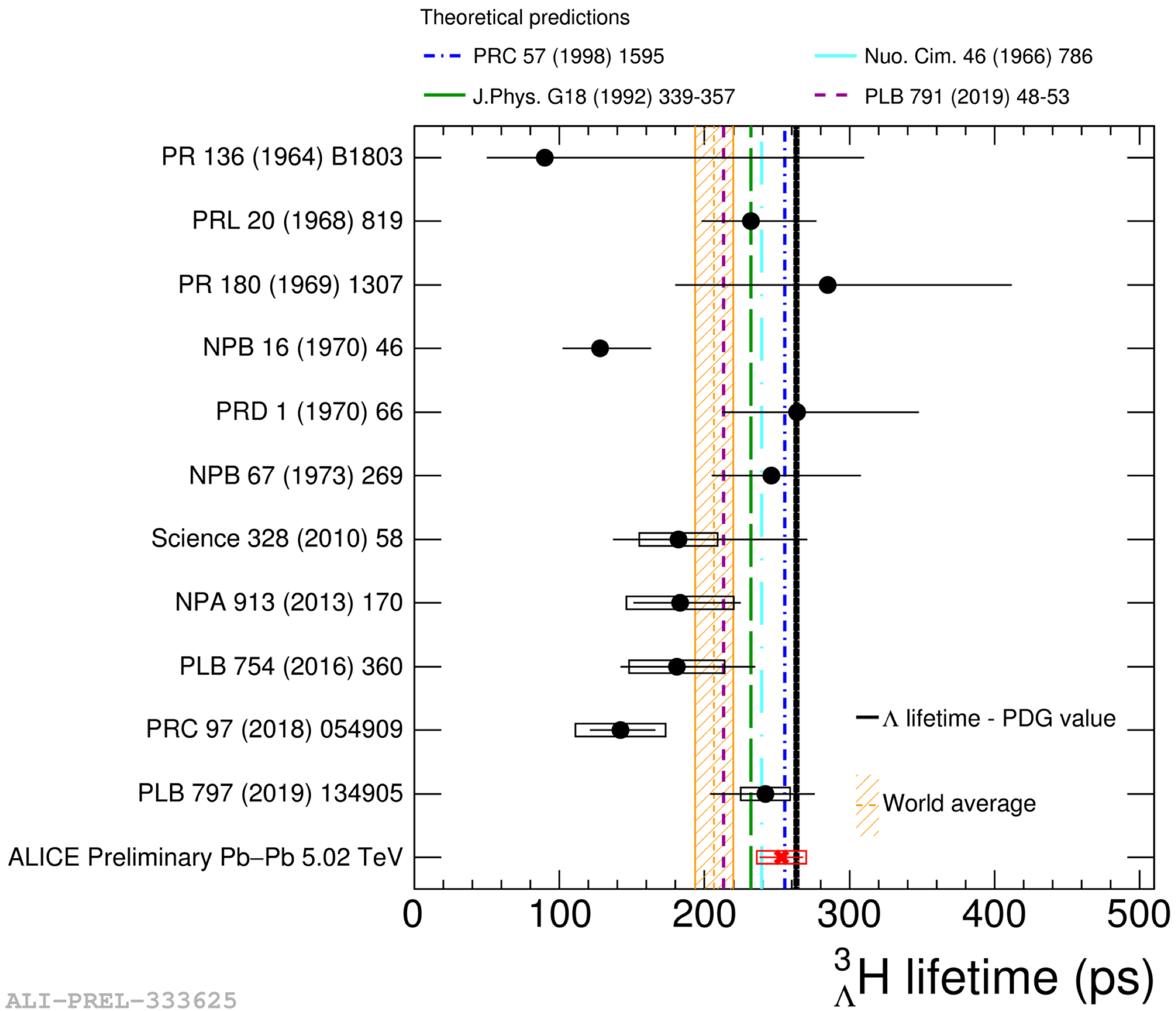


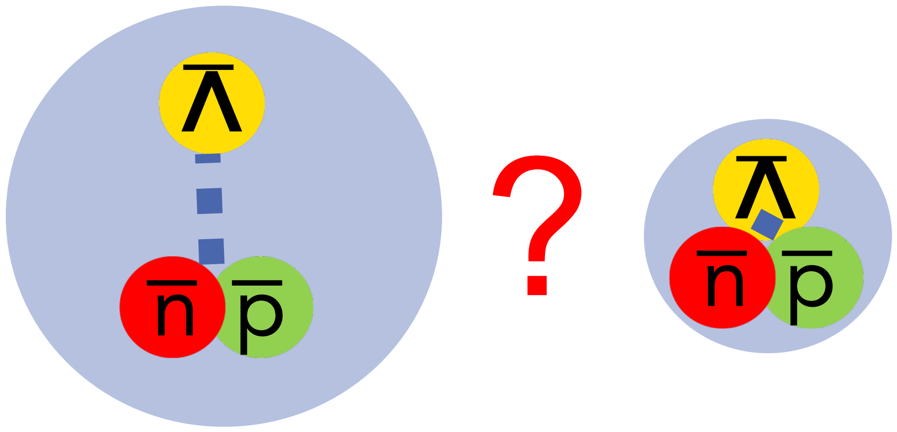


[Phys. Rev. C 92 (2015) 054908]

Towards more exotic QCD bound states:
The X(3872) and the anti-hyper-triton

(Anti-)Hypertriton lifetime measurement from ALICE



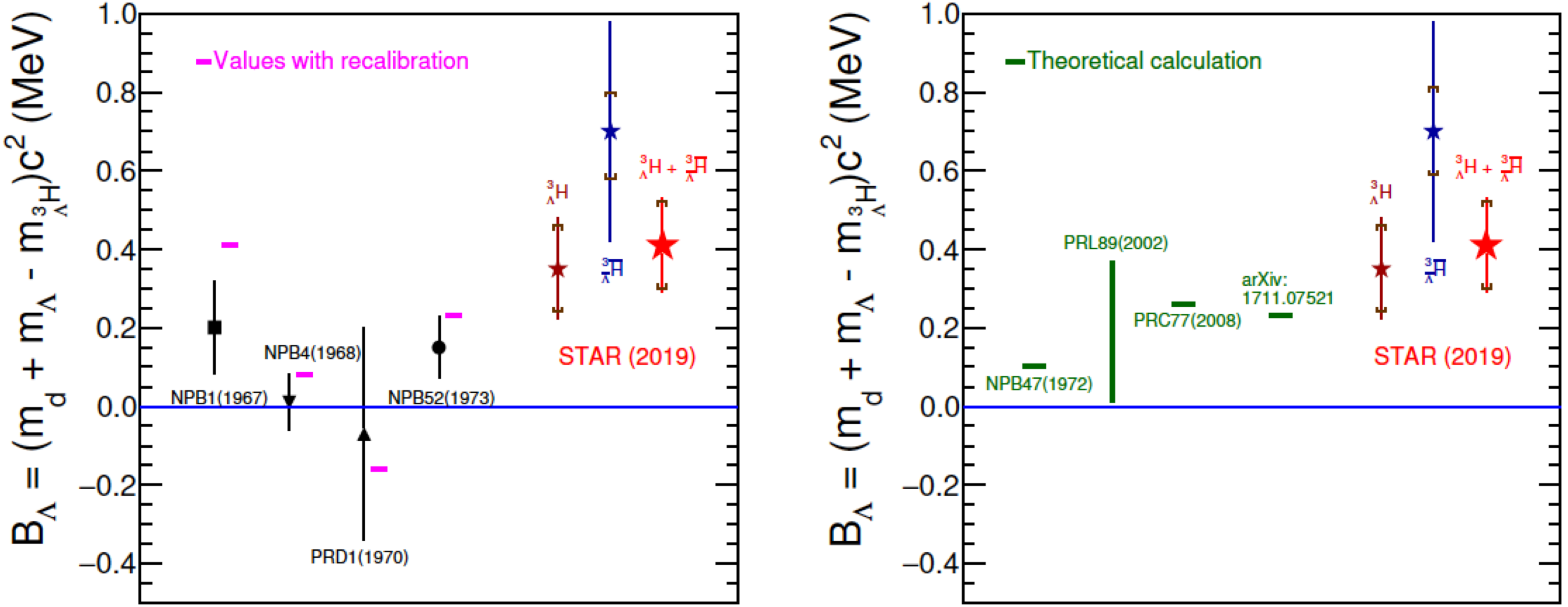


m = 2.991 GeV/c^2, B_Λ = 130 keV
→rms-radius = 10.3 fm

- Exclude large deviations from free Λ life time
- Test of different models with different Hypertriton structure and final state interaction

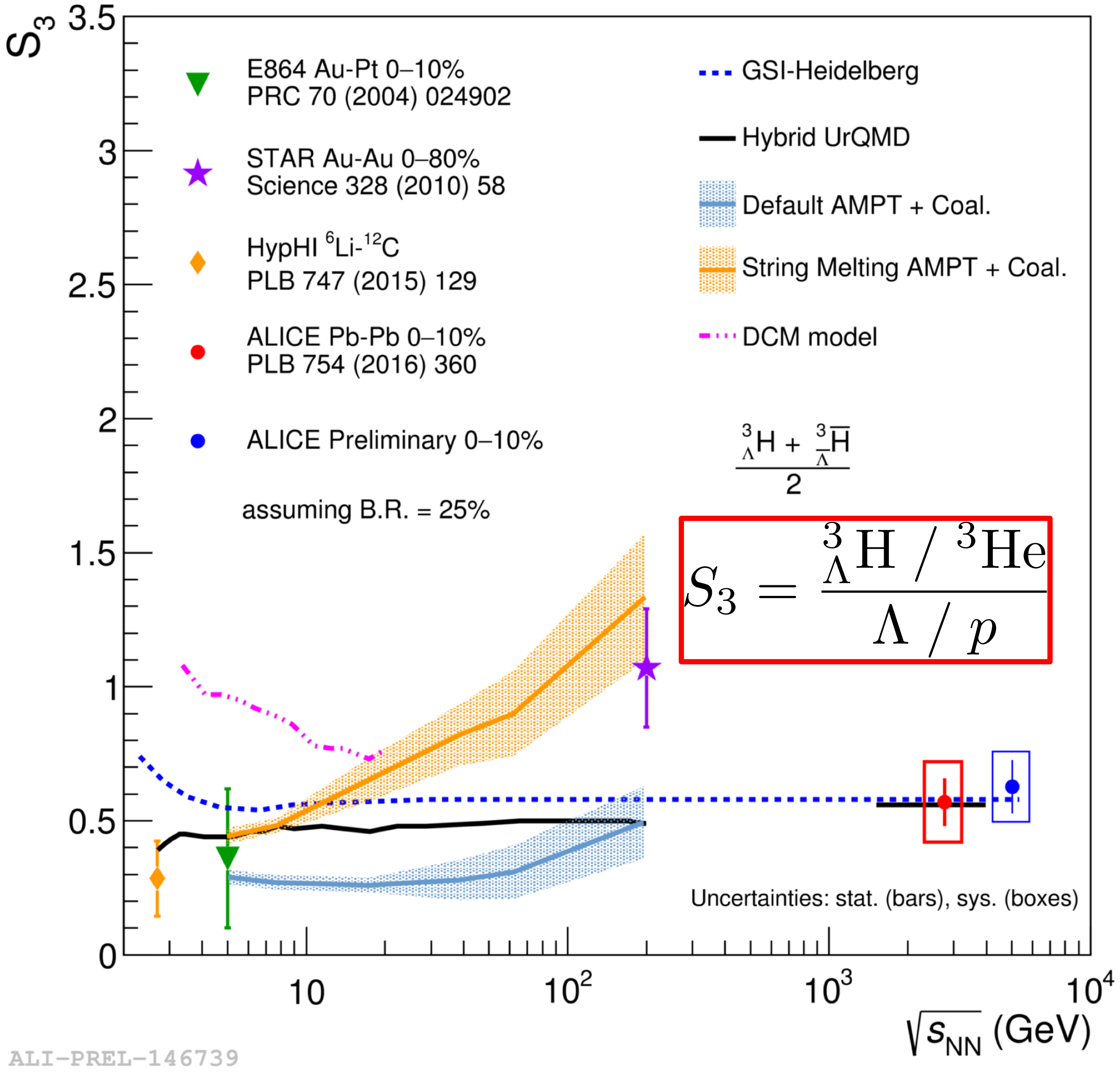
(anti-)Hyper-triton measurements from STAR

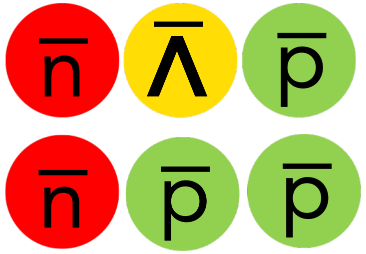
[*STAR, Nature Phys.* 16 (2020) 4]



How precisely do we really know the Lambda separation energy in the hyper-triton?
→ Homework for the experimentalists..

(anti-)hyper-triton in Pb-Pb collisions at 5.02 TeV





anti-hyper-triton

anti-^{3}He

→ Yields of heavy and fragile objects such as (anti-)(hyper-)nuclei in agreement with thermal-statistical model predictions at *chemical* freeze-out.

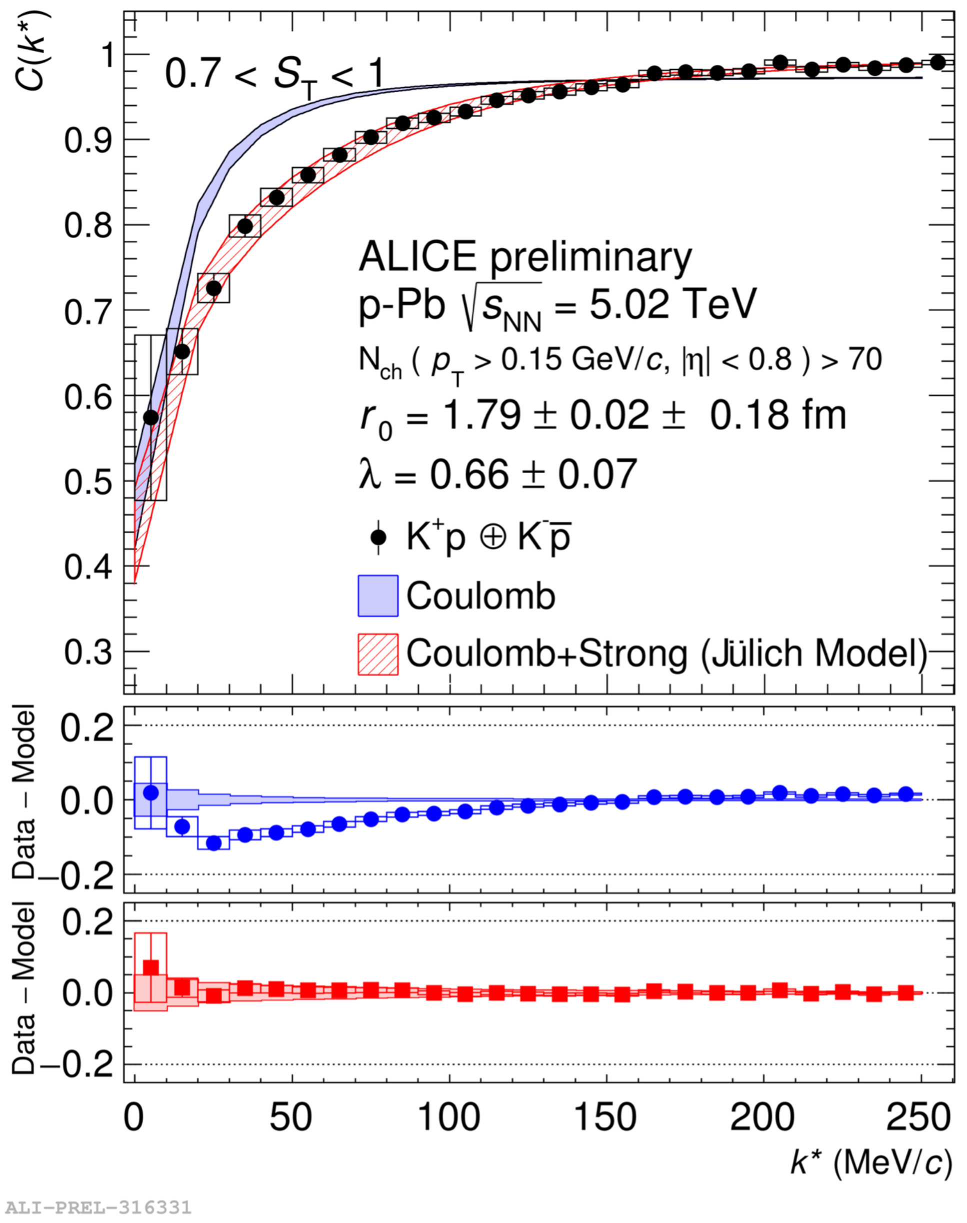
→ No re-scattering of anti-nuclei in hadronic phase despite large dissociation cross-section.

→ Final-state coalescence after kinetic freeze-out requires more detailed modeling: *naive coalescence* ($S_3 \approx 1$) does not describe data.

Correlation functions

Already now, ALICE is investigating anti-nuclei correlations (e.g. with kaons) and these studies can be taken to a next level.

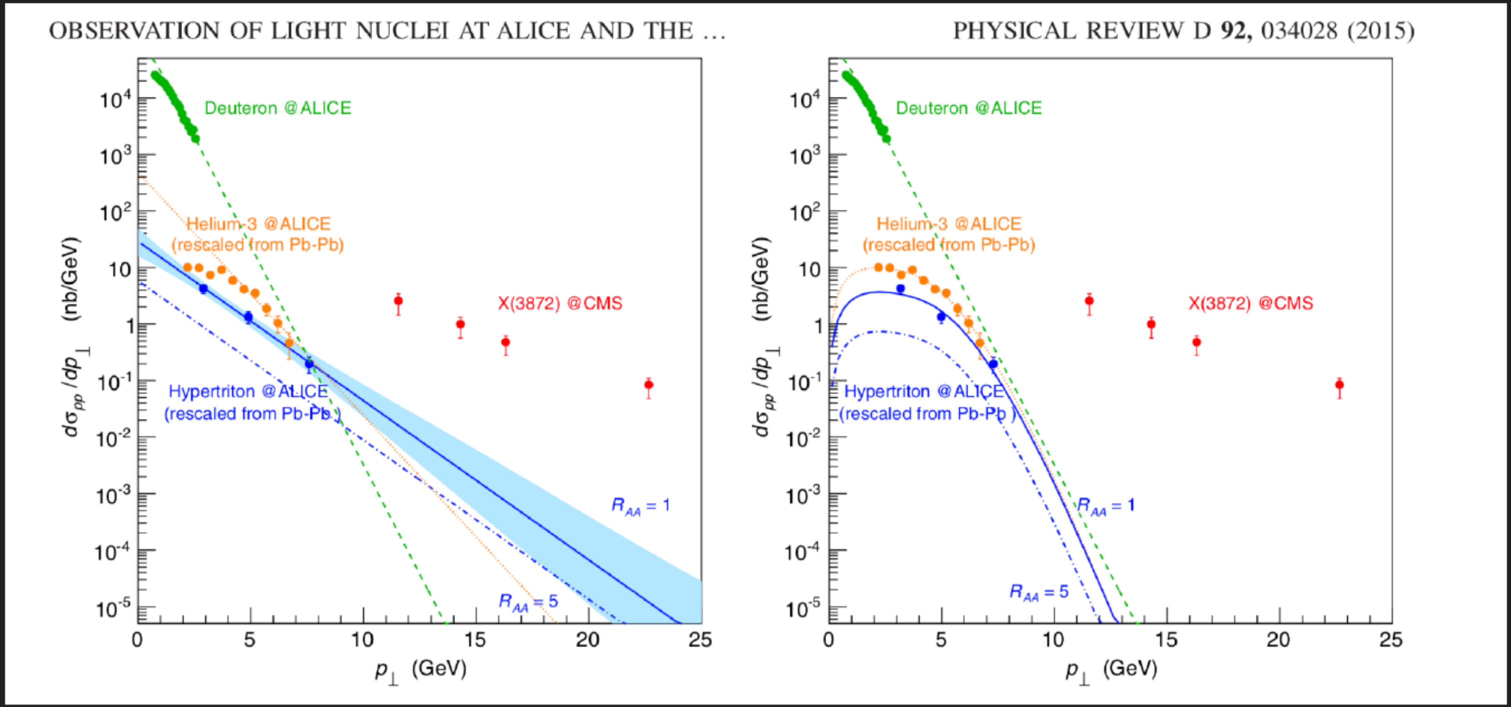
→ The formation of any exotic bound QCD object can be studied in **unprecedented detail** by studying correlation functions of for instance $(d,\Lambda) \to {}^{3}_{\Lambda}H$ or $({}^{3}He,\Lambda) \to {}^{4}_{\Lambda}He$.



The X(3872)

The X(3872) sort of anomalous charmonium with **1⁺⁺** quantum numbers

right at DD^* threshold and rather close to $J/\psi+\rho$.



Esposito et al. PRD92 (2015) 034028

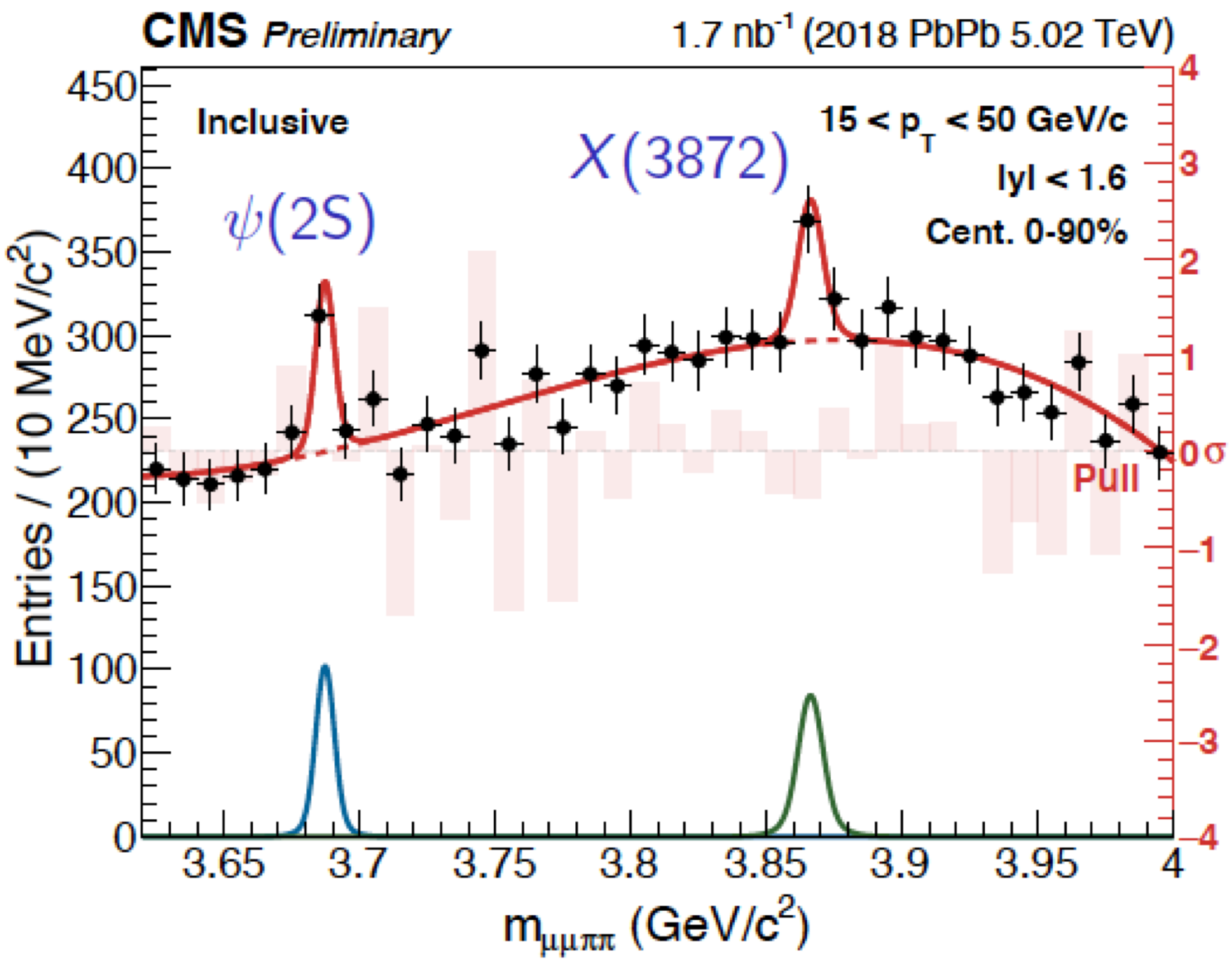
Bignamini, Grinstein, Piccinini, ADP, Sabelli, PRL103 (2009) 162001
Esposito, Grinstein, Maiani, Piccinini, Pilloni, ADP, Riquer, 1709.09631

[Talk of A. Polosa at the charm hadronization workshop]

Loosely bound objects in heavy-ion collisions

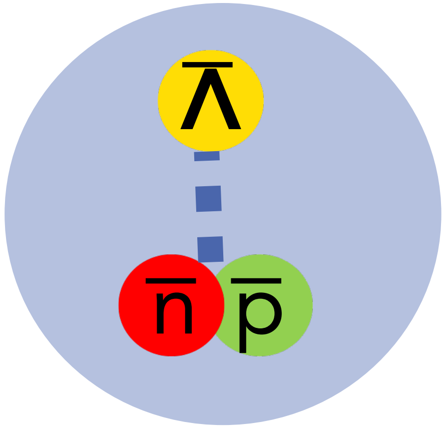
[Y. Jie Lee]
[J. Durham]

→ The X(3872) will not be suppressed if its behavior is like a hyper-triton!



- Mass is consistent with sum of D^0 and $\overline{D}^{*0}$ masses:

$$M_{\chi_{c1}(3872)} - (M_{D^0} + M_{\bar{D}^{*0}}) = 0.01 \pm 0.27 \text{ MeV}$$



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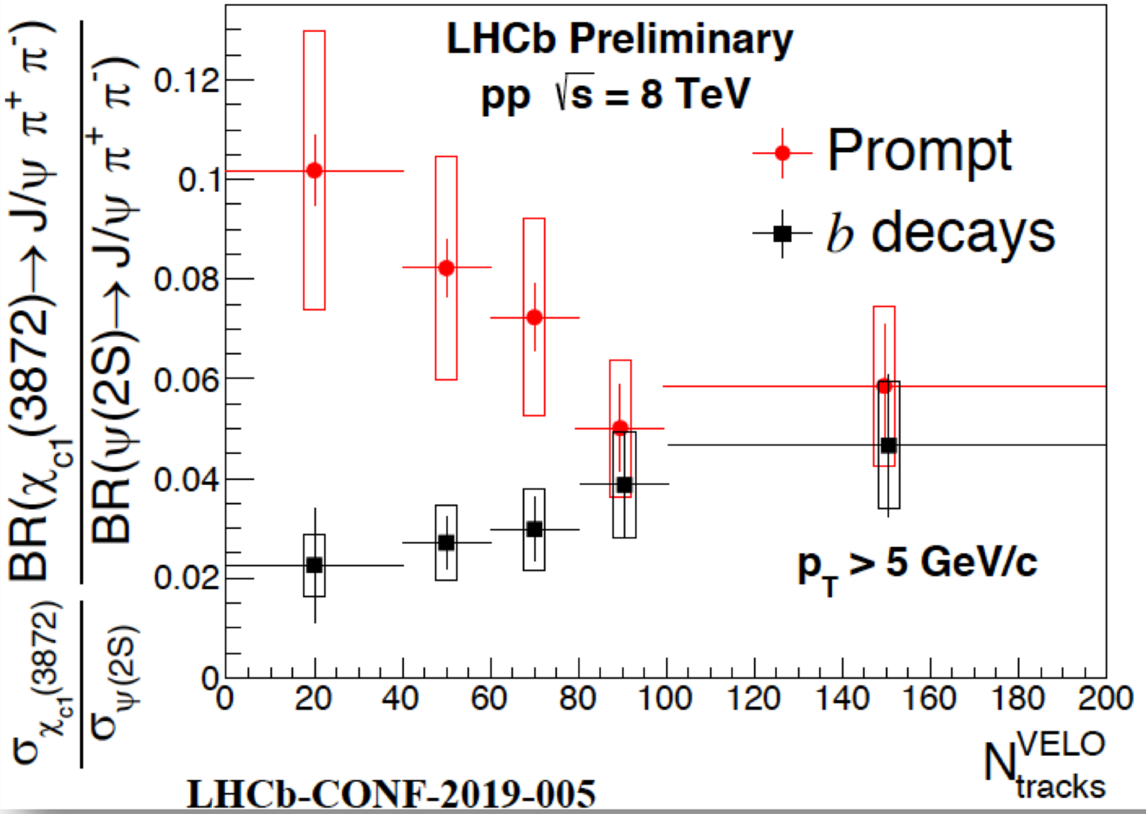
Another snowball in hell?

→ The X(3872) will not be suppressed if its behavior is like a hyper-triton!

Ratio of cross sections

$$\frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \times \frac{\mathcal{B}[\chi_{c1}(3872) \to J/\psi\pi^+\pi^-]}{\mathcal{B}[\psi(2S) \to J/\psi\pi^+\pi^-]} = \frac{N_{\chi_{c1}(3872)}\, f_{\rm prompt}^{\chi_{c1}(3872)}}{N_{\psi(2S)}\, f_{\rm prompt}^{\psi(2S)}} \times \frac{\varepsilon_{\psi(2S)}}{\varepsilon_{\chi_{c1}(3872)}}$$



Prompt Component:
Increasing suppression of $X(3872)$ production relative to $\psi(2S)$ as event activity increases

b-decay component:
No significant change in relative production, as expected for decays in vacuum. Ratio is set by b decay branching fractions.
Consistent with ATLAS measurement
R = 0.0395±0.0032±0.0008 (p_T>10GeV/c)
JHEP 2017:117 (2017)

Summary and conclusions

- A lot of and fast evolving experimental and phenomenological activity in this research area.

- After the reporting of the initial findings, it is now time to enter an era of increased precision in comparisons of data and theory:

  1. Remove approximations, e.g. by measuring HBT radii and production yields in the same events

  2. If approximations cannot be removed, they need to be quantified, e.g. uncertainties in the hyper-triton wave-function.

Thank you and enjoy the workshop!