QM 2023

Measurements of (anti)(hyper)nuclei with ALICE

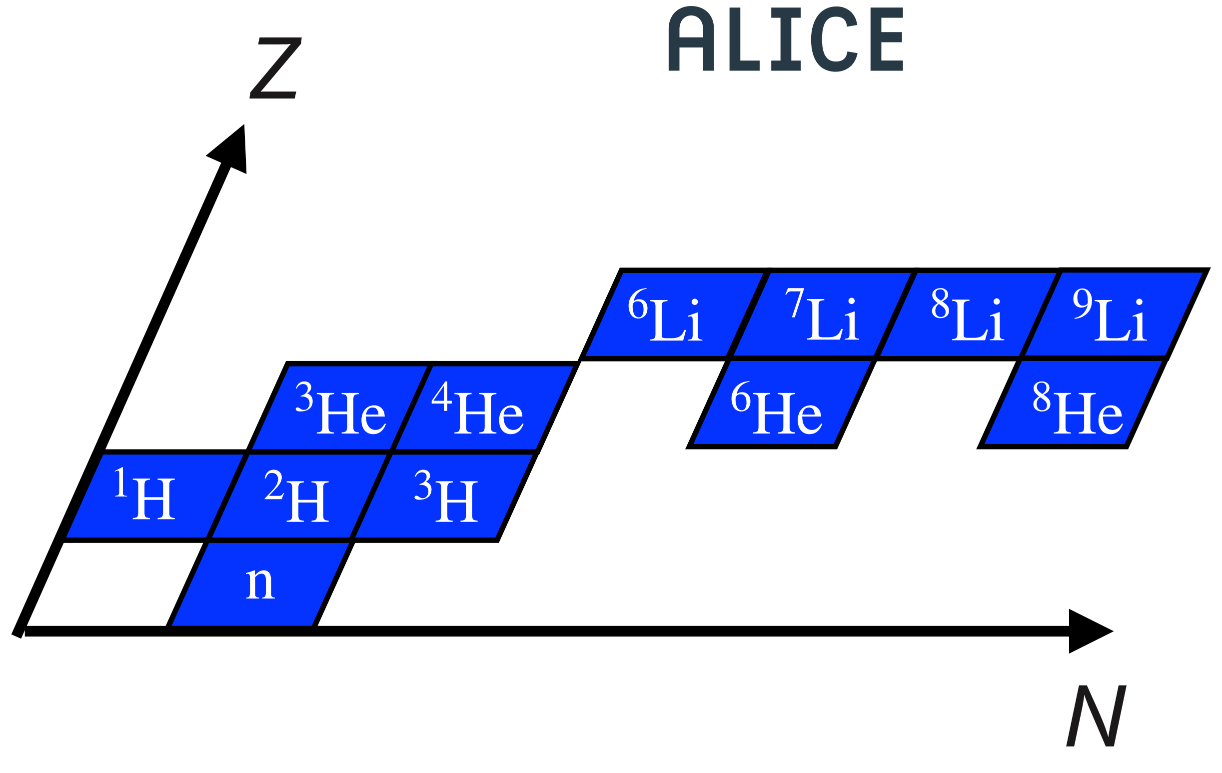
I. Vorobyev on behalf of the ALICE Collaboration
CERN

Quark Matter 2023
06.09.2023, Houston, TX, USA

Dimensions of (light) nuclear chart: nuclei

Nuclei: complex objects composed of protons and neutrons

- Production mechanism is still under investigation



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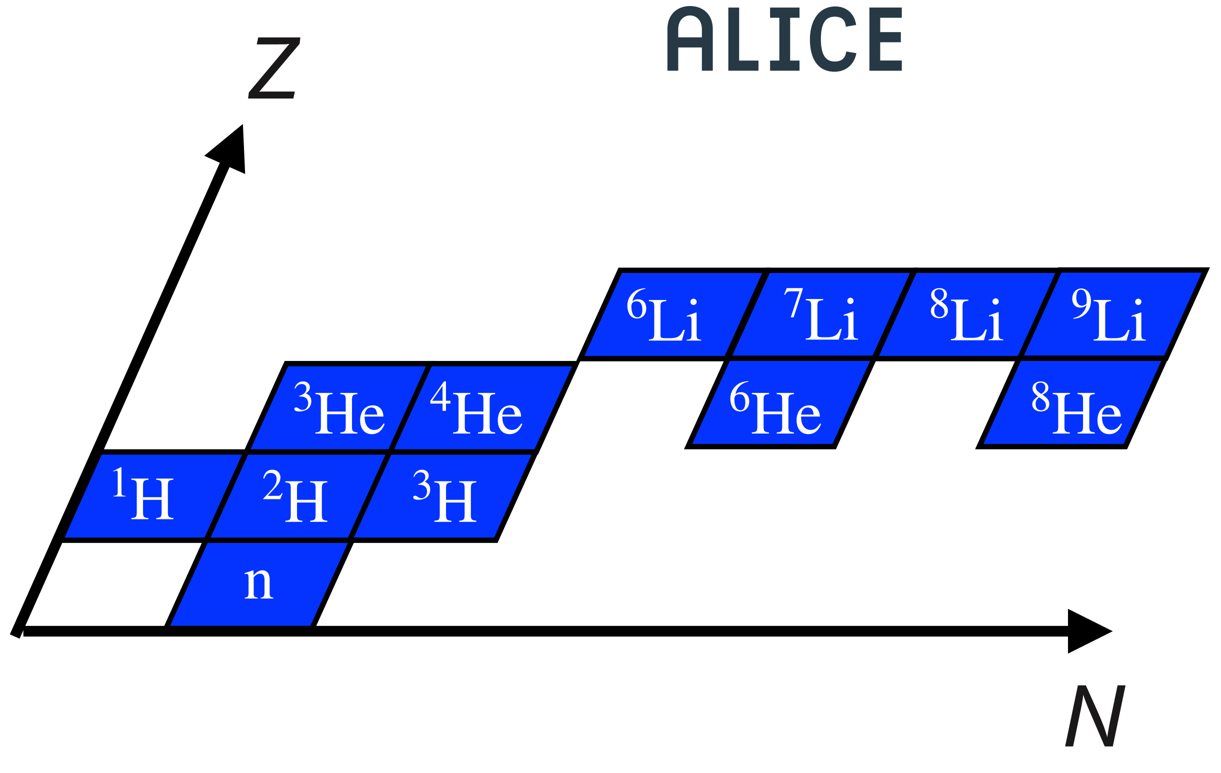

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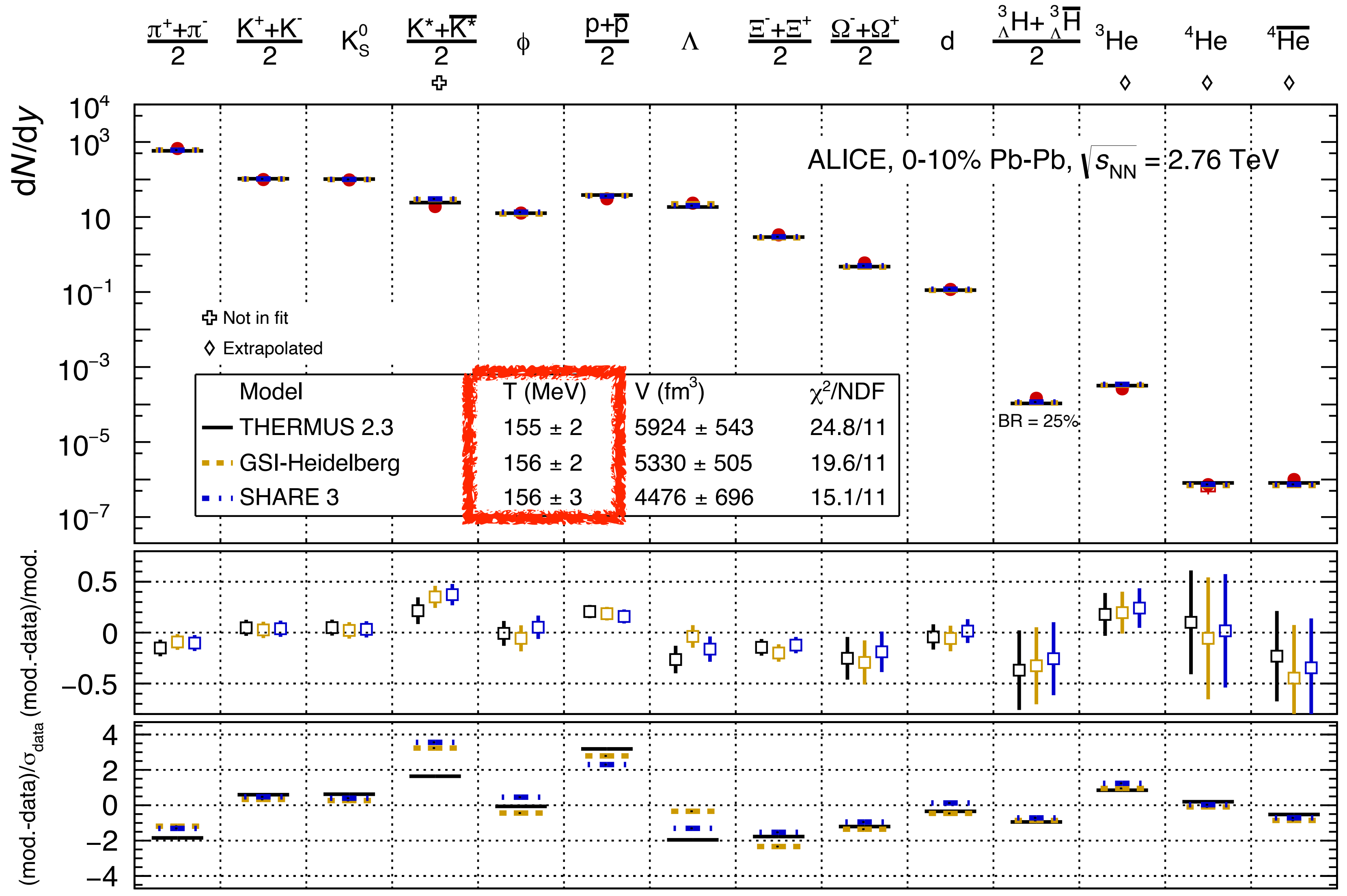
Statistical models [1, 2]

- Hadrons emitted from a source in local thermodynamical equilibrium
- $\mathrm{d}N/\mathrm{d}y \sim e^{-m/T_{\mathrm{chem}}}$



[1] Andronic et al., Nature 561 (2018) 321
[2] ALICE, Nucl. Phys. A 971 (2018) 1

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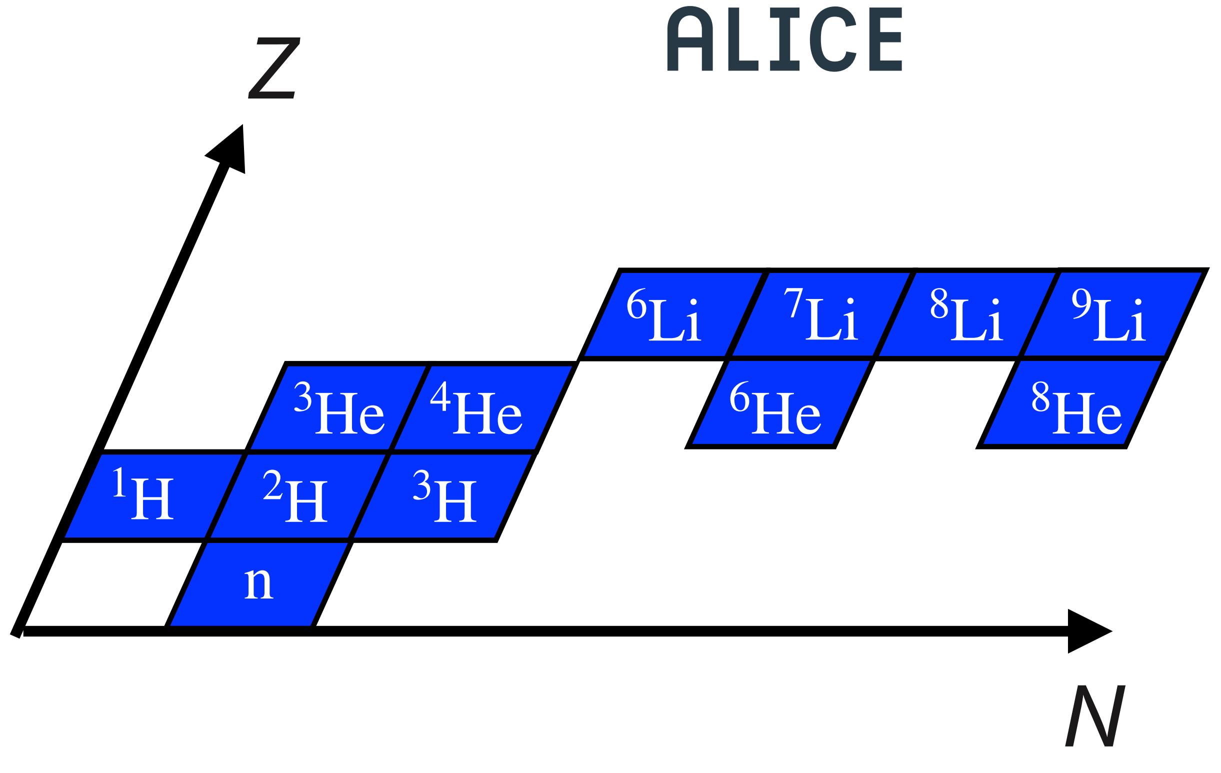

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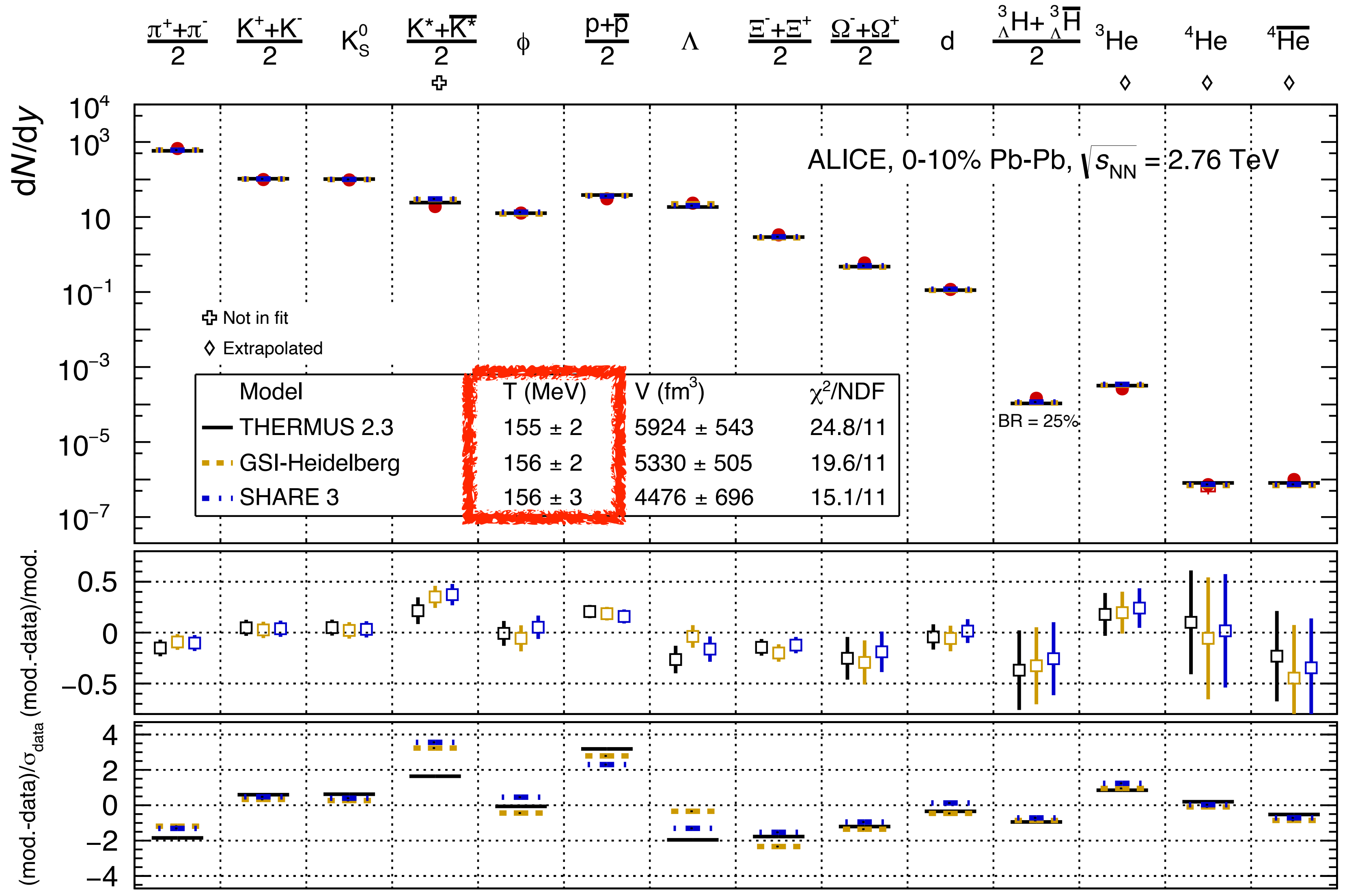
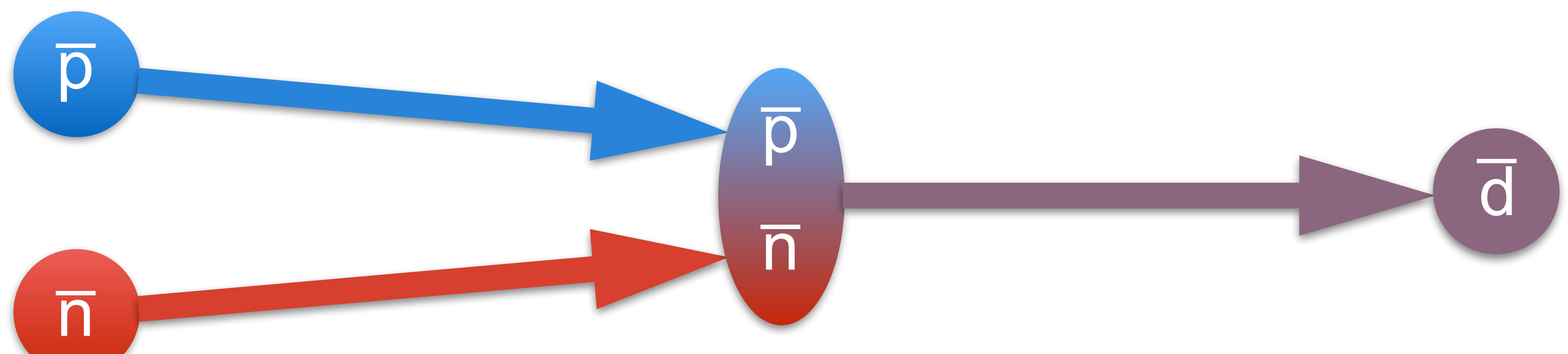


Coalescence models [3]

- Nuclei are produced from the overlap of nucleons' phase-space and Wigner density of the bound state



- Coalescence parameter B_A (↔ coalescence probability):

$$E_i \frac{\mathrm{d}^3 N_i}{\mathrm{d}p_i^3} = B_A \left(E_p \frac{\mathrm{d}^3 N_p}{\mathrm{d}p_\mathrm{p}^3} \right)^A \qquad B_A = \left(\frac{4\pi}{3} \frac{p_{\mathrm{coal}}^3}{8} \right)^{A-1} \frac{m_A}{m_p^Z m_n^{A-Z}}$$

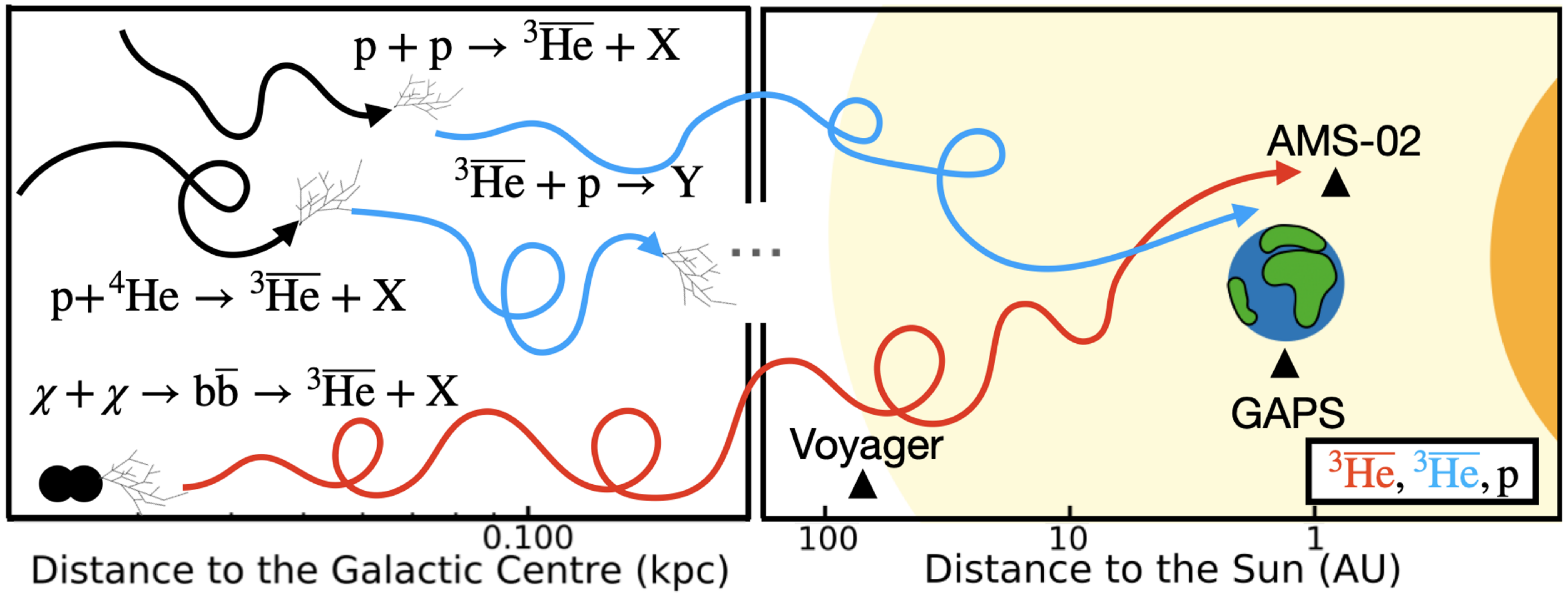
[1] Andronic et al., Nature 561 (2018) 321
[2] ALICE, Nucl. Phys. A 971 (2018) 1
[3] Butler et al., Phys. Rev. 129 (1963) 836

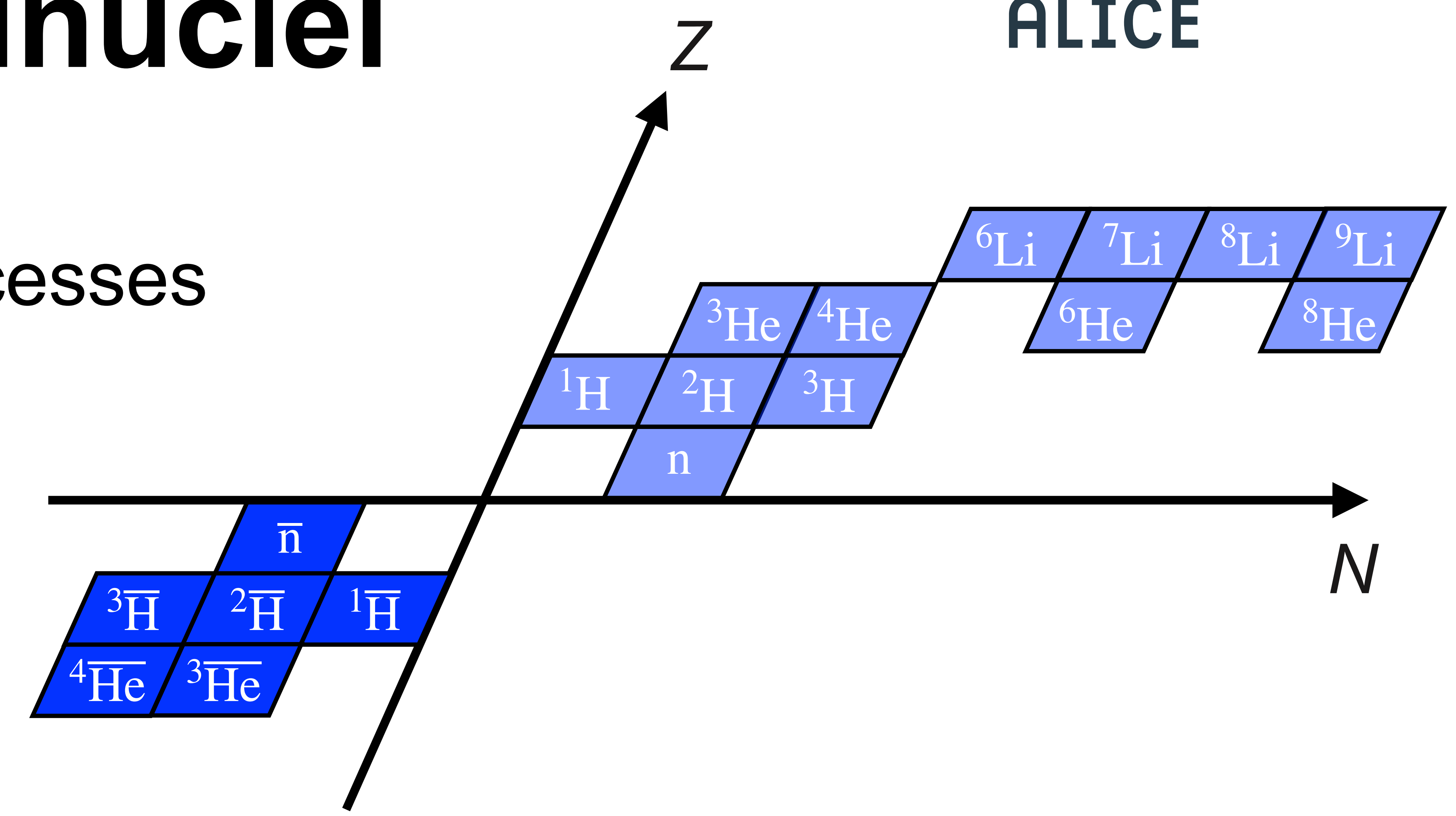
Dimensions of (light) nuclear chart: antinuclei

Antinuclei: antimatter counterpart of our matter world

- Extremely rare objects in nature, low background from “ordinary” processes
- Unique probe for new exotic physics! Dark matter, antistars, …

$^{3}\overline{\mathrm{He}}$ production and propagation in the Galaxy [1]





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ALICE

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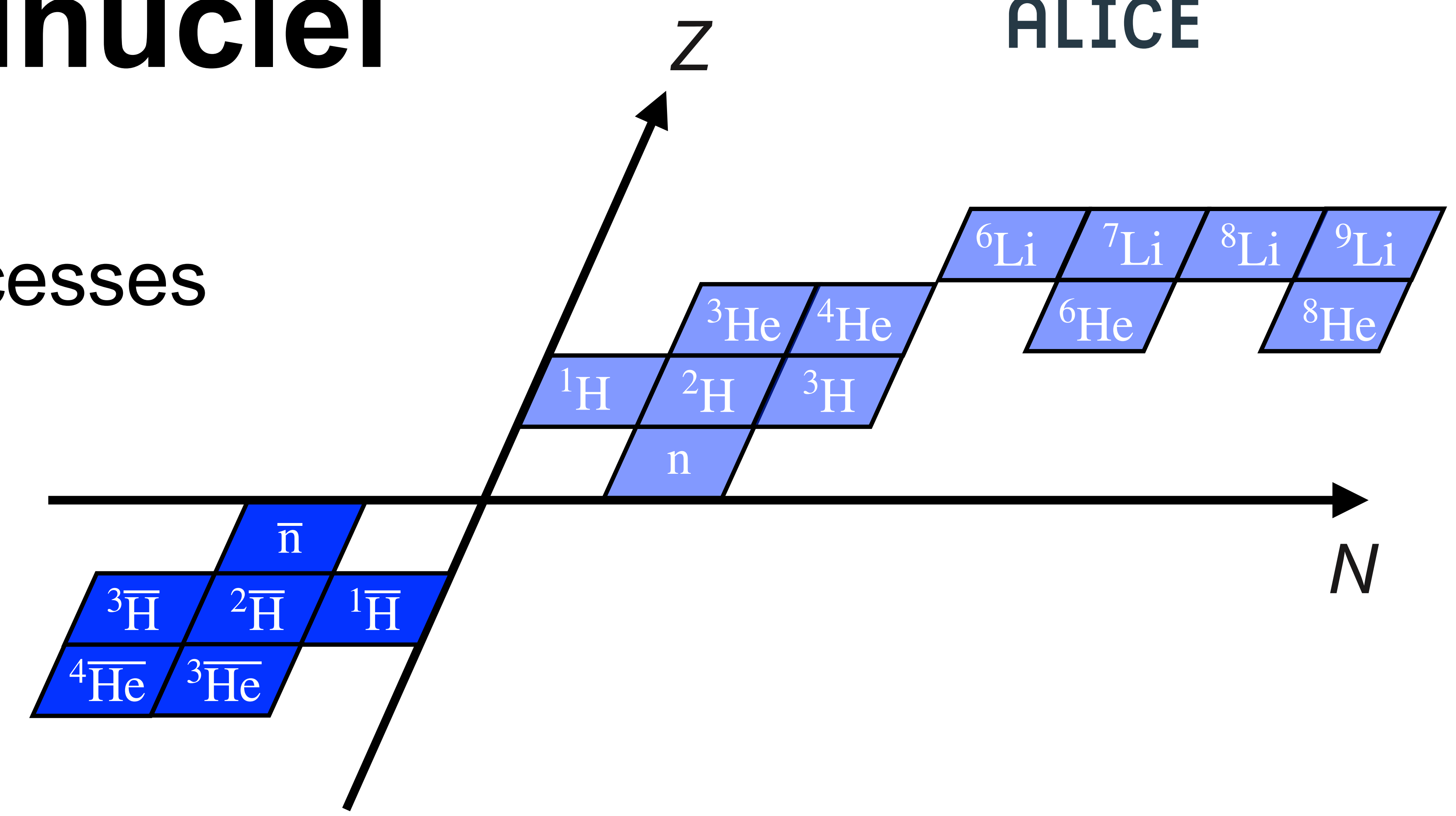

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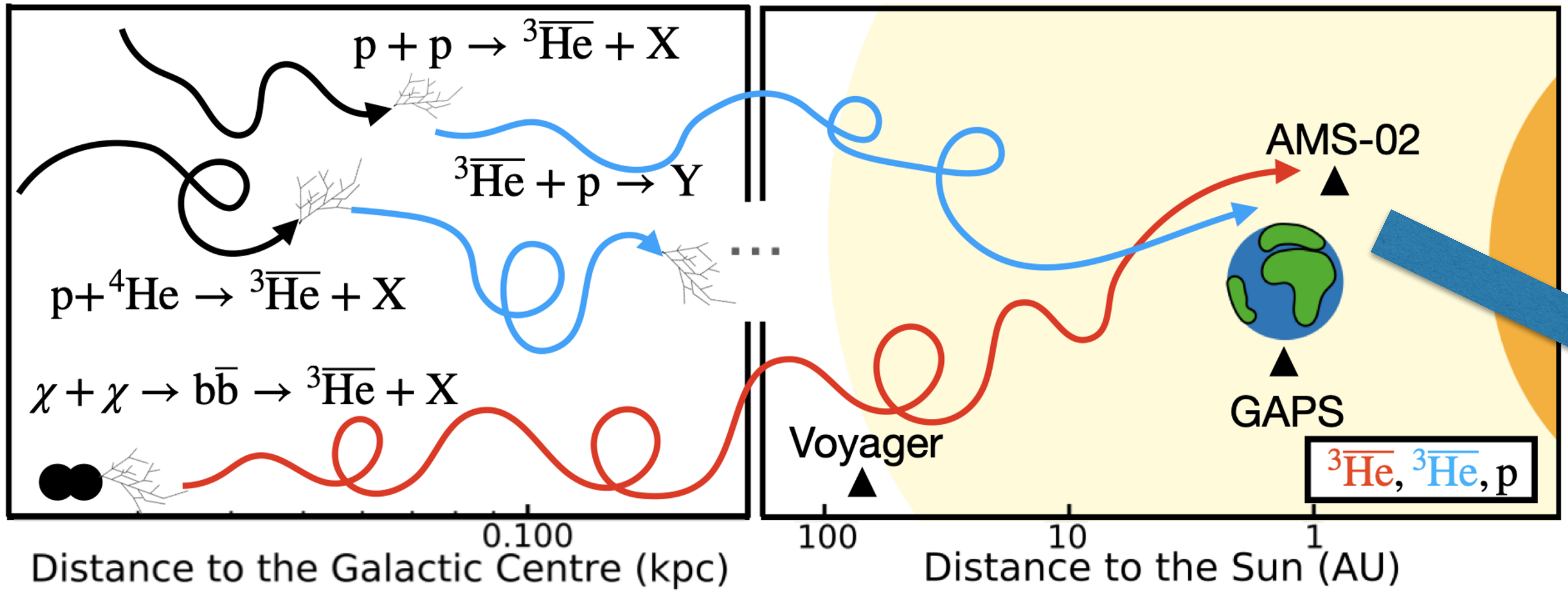
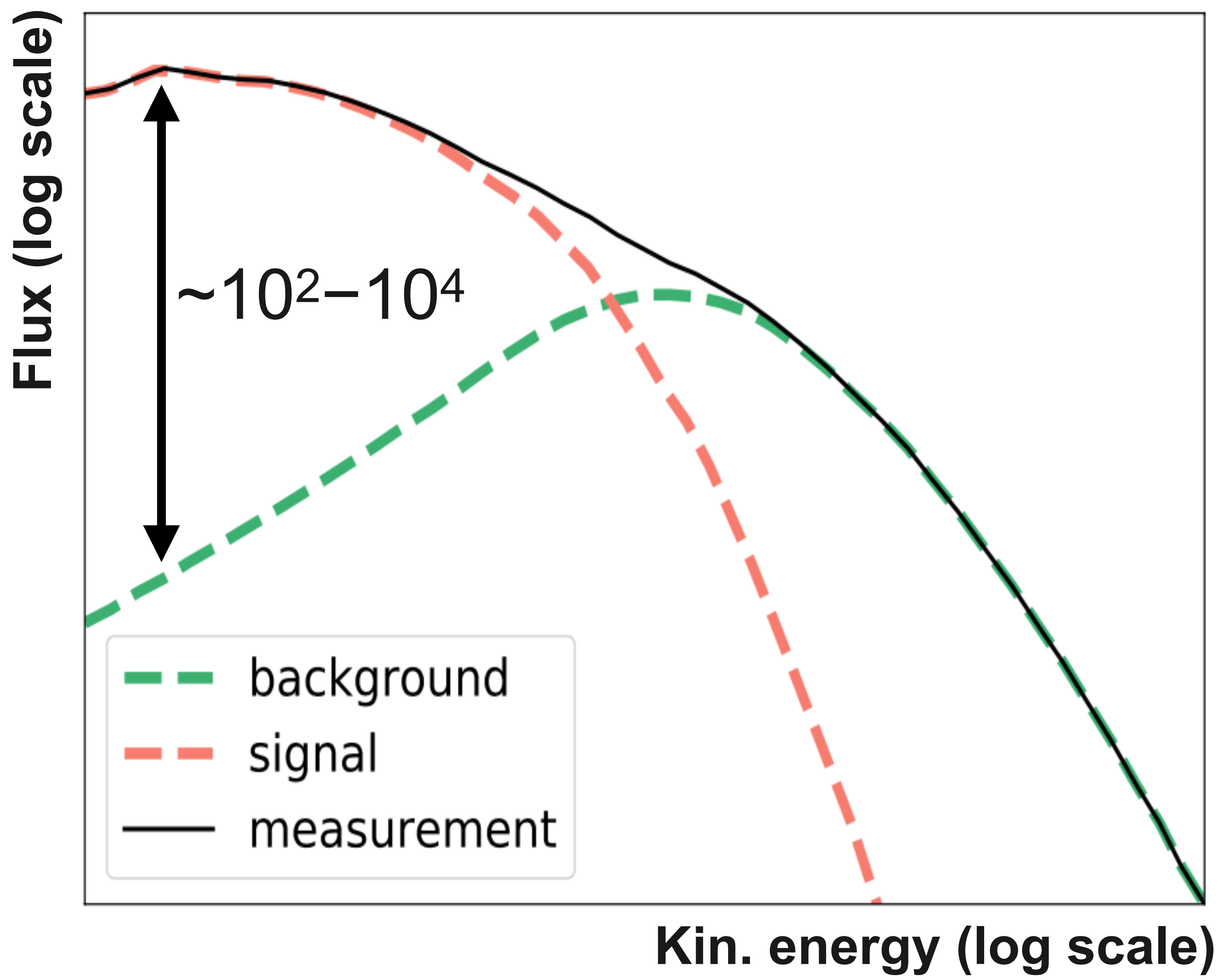


Schematic antinuclei fluxes near Earth



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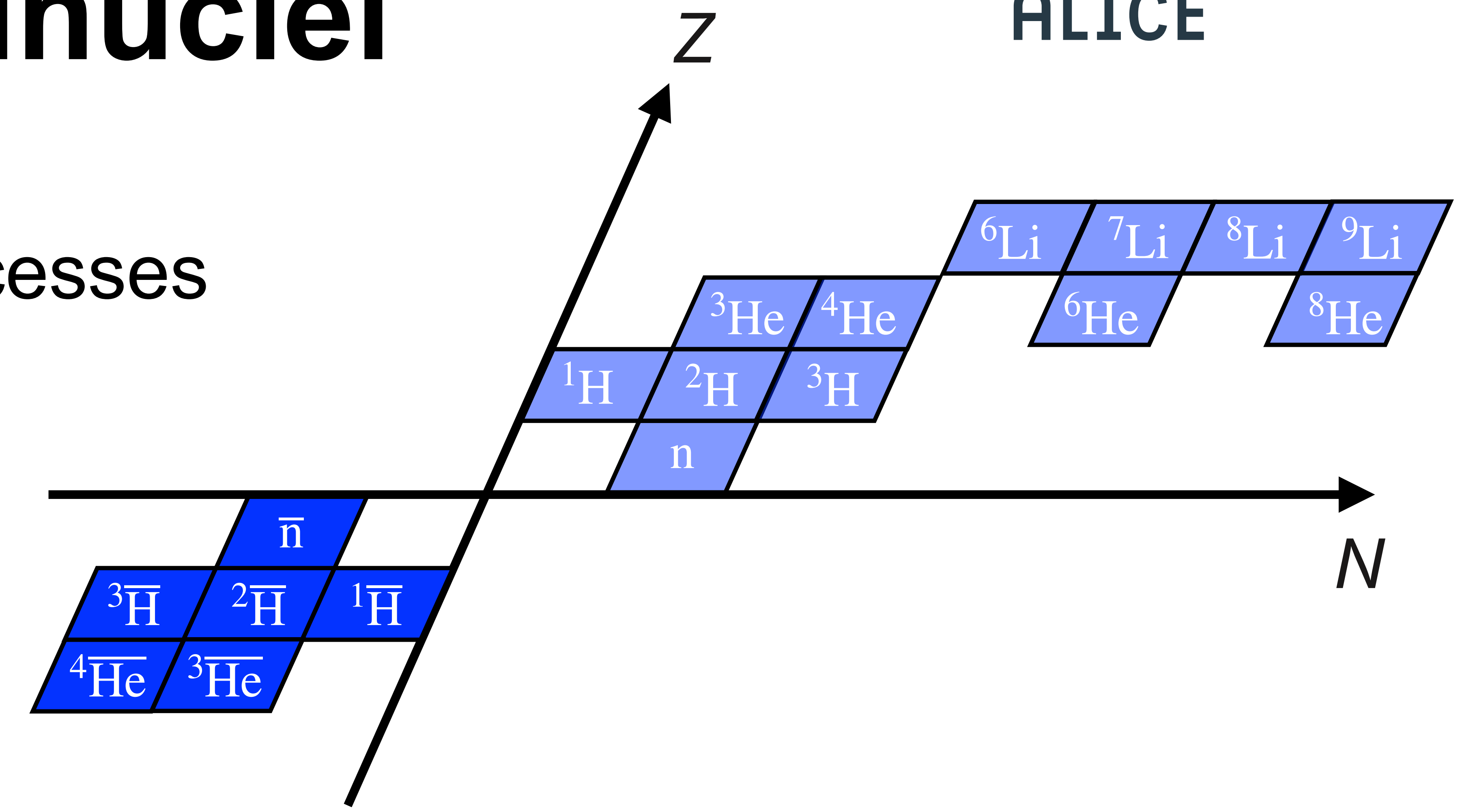
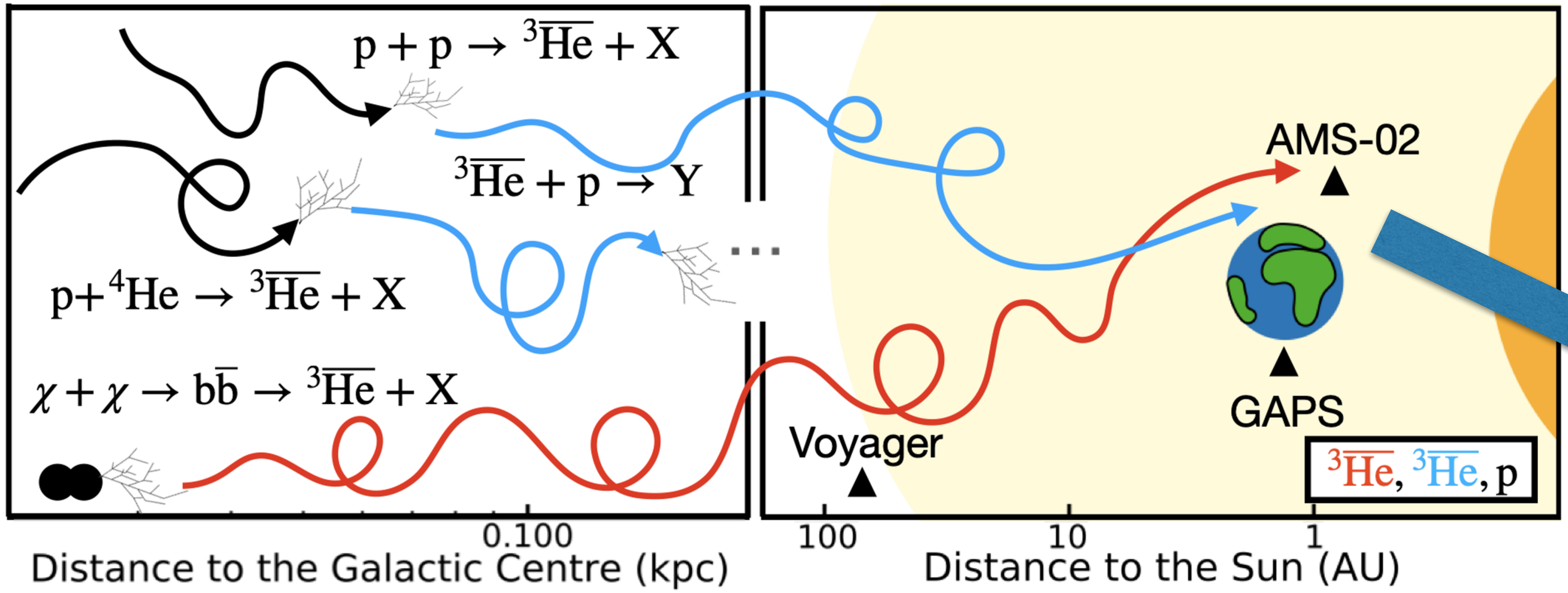


$^3\overline{\text{He}}$ **production and propagation in the Galaxy [1]**



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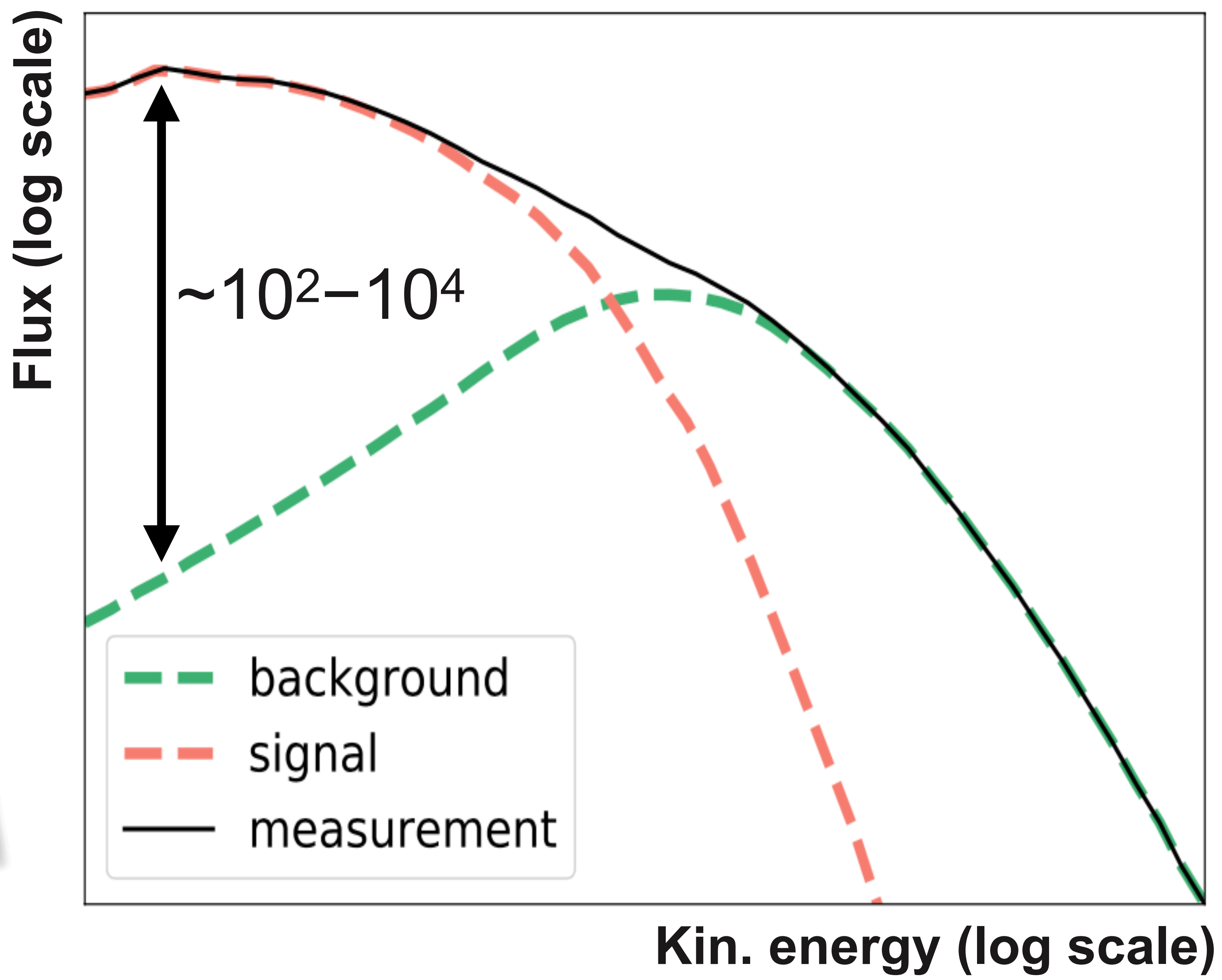


Measurements of light antinuclei production is of the utmost importance for astrophysics!

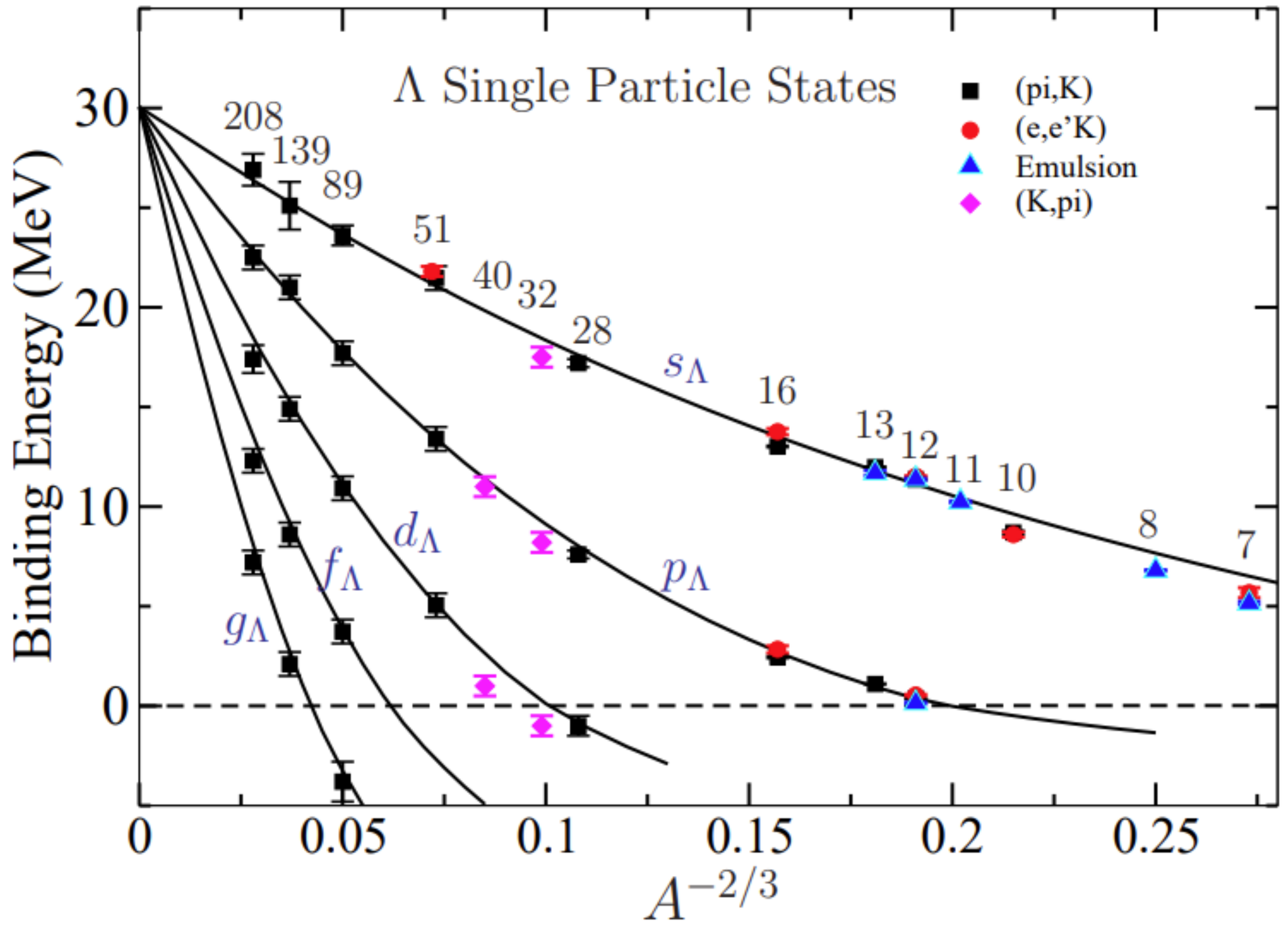
Chiara Pinto, Wed 6 Sept, 12:40

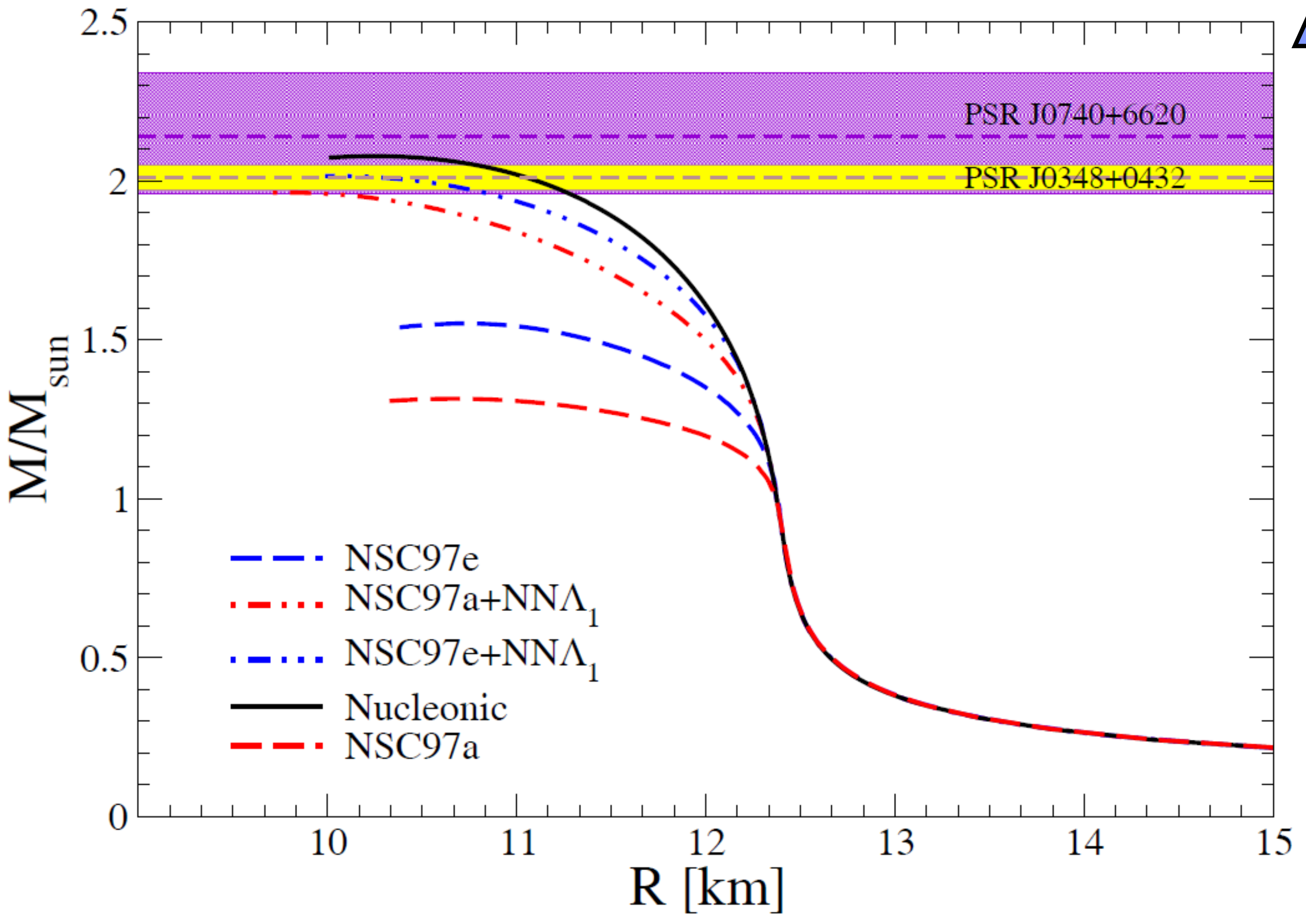
[1] ALICE, Nature Phys. 19 (2023) 1, 61

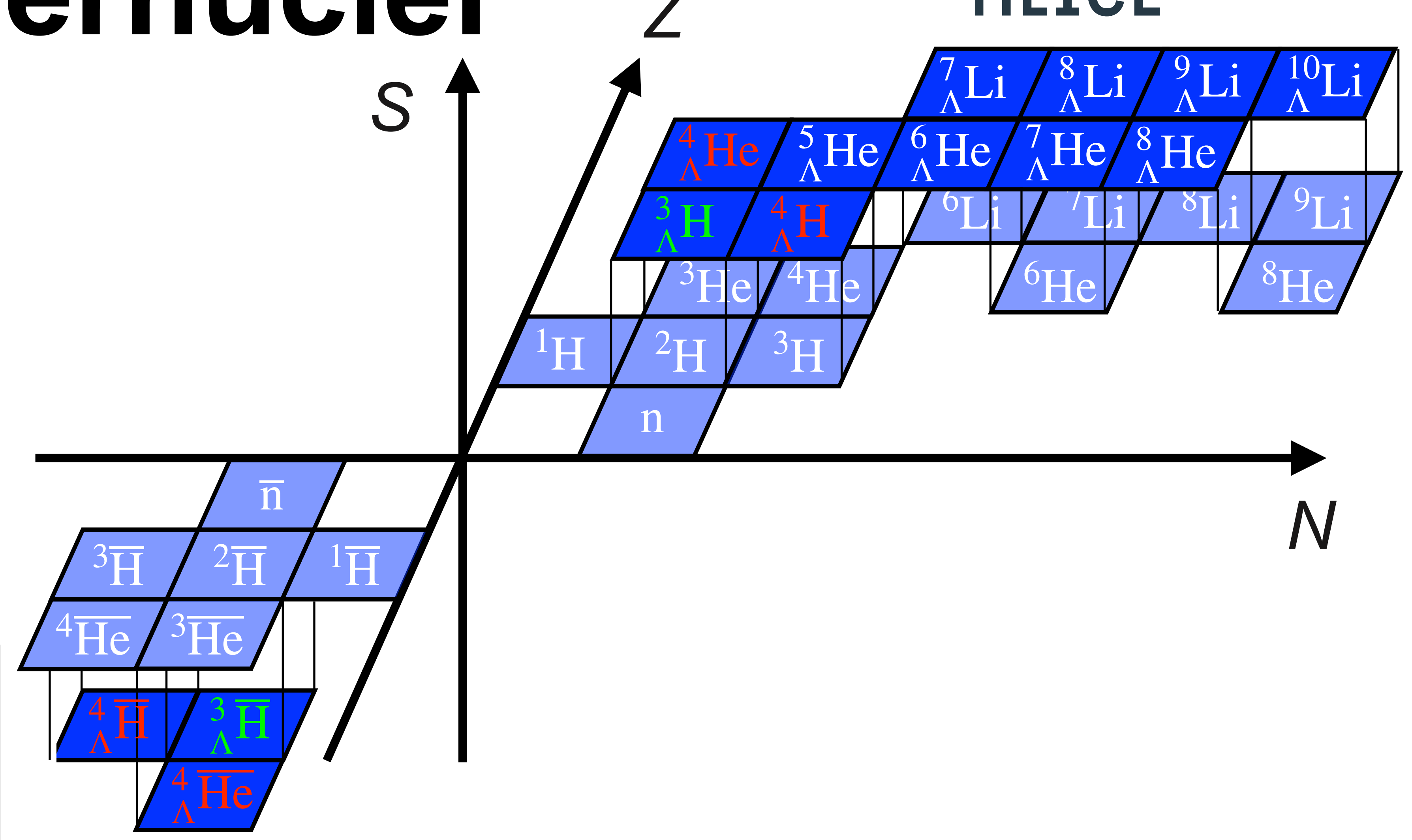
Dimensions of (light) nuclear chart: hypernuclei

Hypernuclei: bound states of nucleons and hyperons

- Formation of interesting states (hypertriton, hyperhelium, …), testing the nuclear shell model [1]
- Neutron stars' EOS [2] (understanding of Λ−N and Λ−Λ interaction!)







[1] Gal et al., Rev.Mod.Phys. 88 (2016) 3, 035004
[2] Logoteta et al., Eur.Phys.J.A 55 (2019) 11, 207

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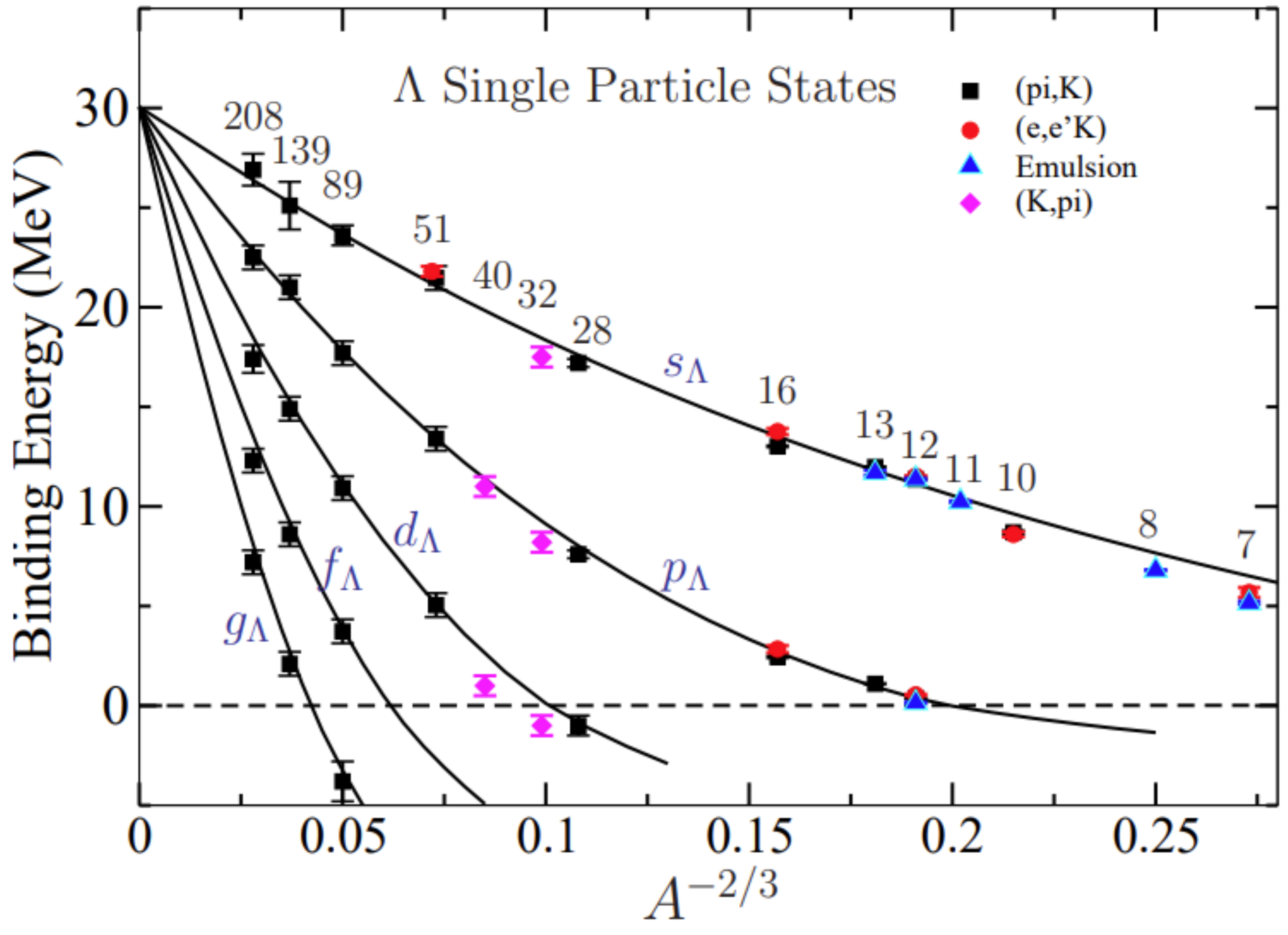
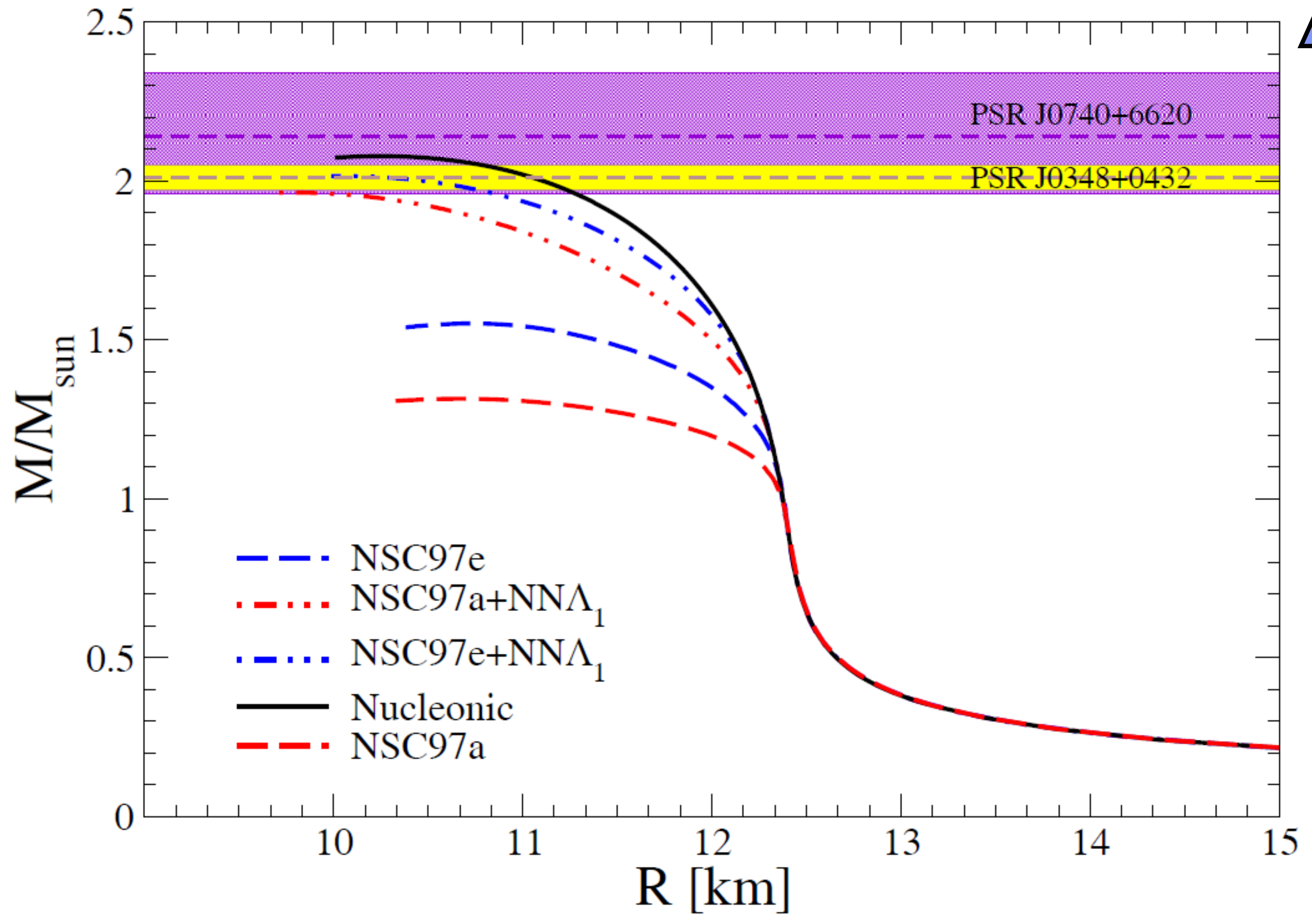
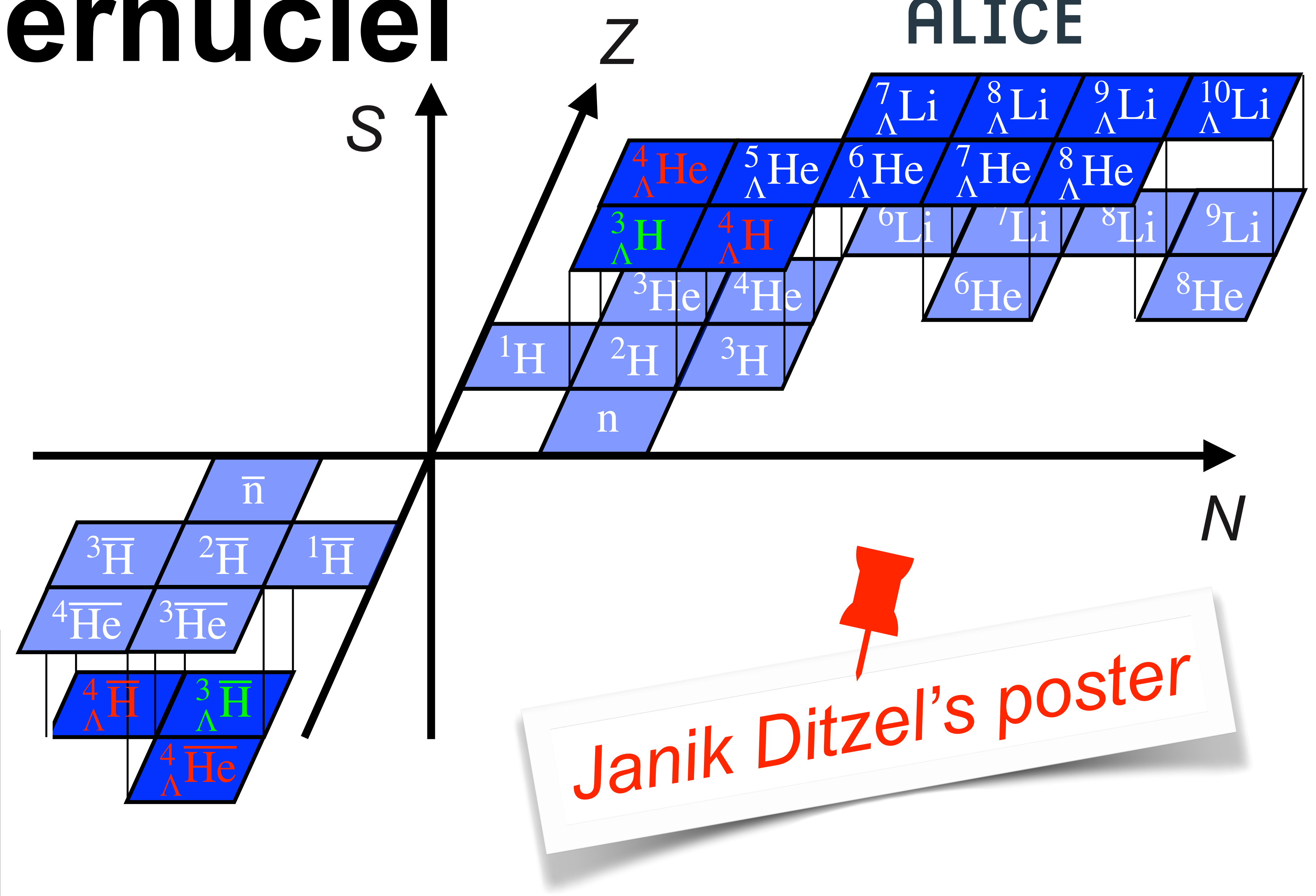






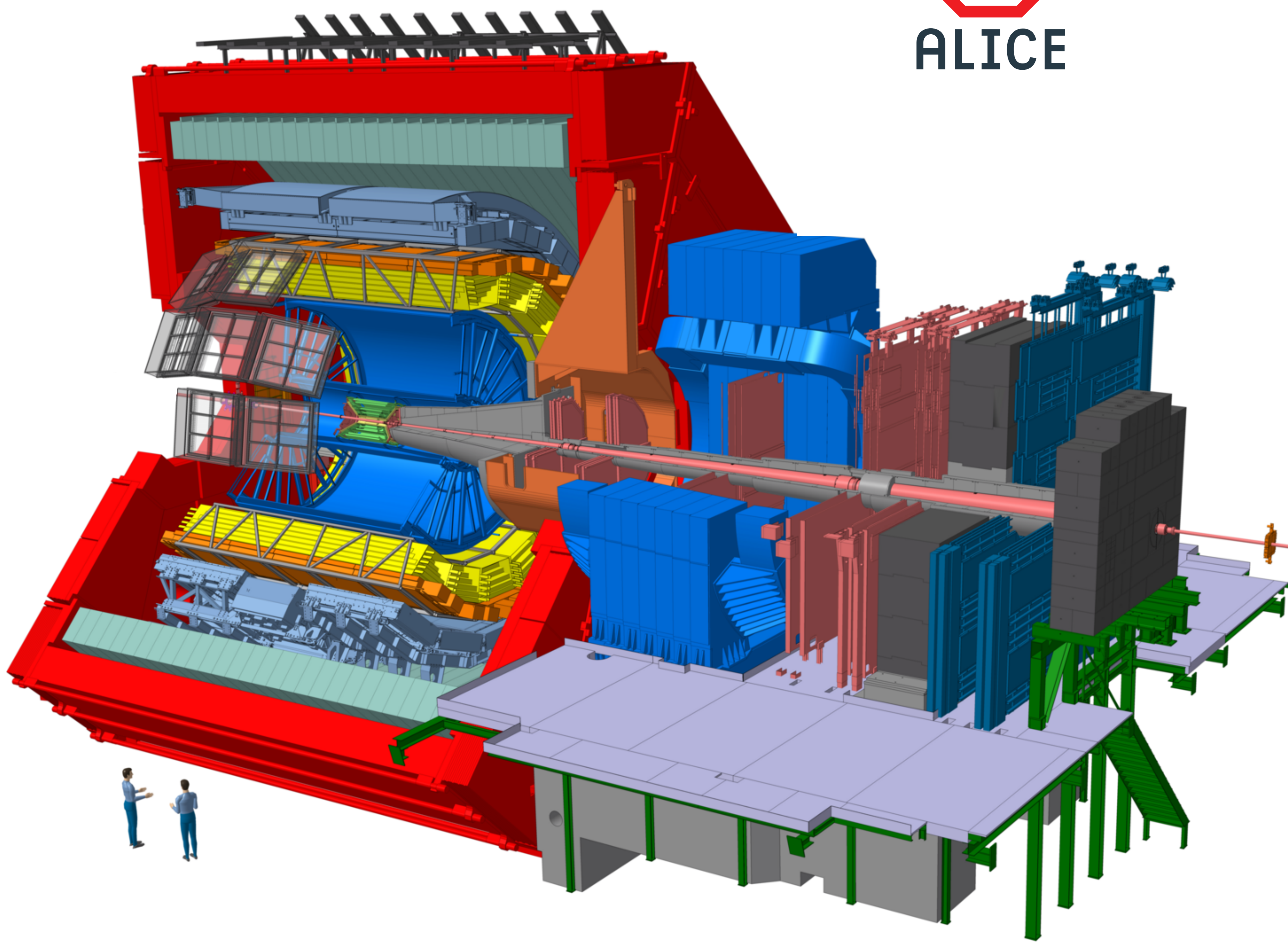
ALICE has measured the production and properties of (anti)hypertriton [3] ✅

*Can we study the **A = 4** hypernuclei with ALICE? Yes we can!*

[1] Gal et al., Rev.Mod.Phys. 88 (2016) 3, 035004
[2] Logoteta et al., Eur.Phys.J.A 55 (2019) 11, 207
[3] ALICE, Phys. Lett. B 754 (2016) 360, Phys. Lett. B 797 (2019) 134905, Phys. Rev. Lett. 128 (2022) 252003, Phys. Rev. Lett. 131 (2023) 102302

ALICE detector in Run 2

Unique tracking and PID capabilities to study the production of (anti)(hyper)nuclei at the LHC energies!



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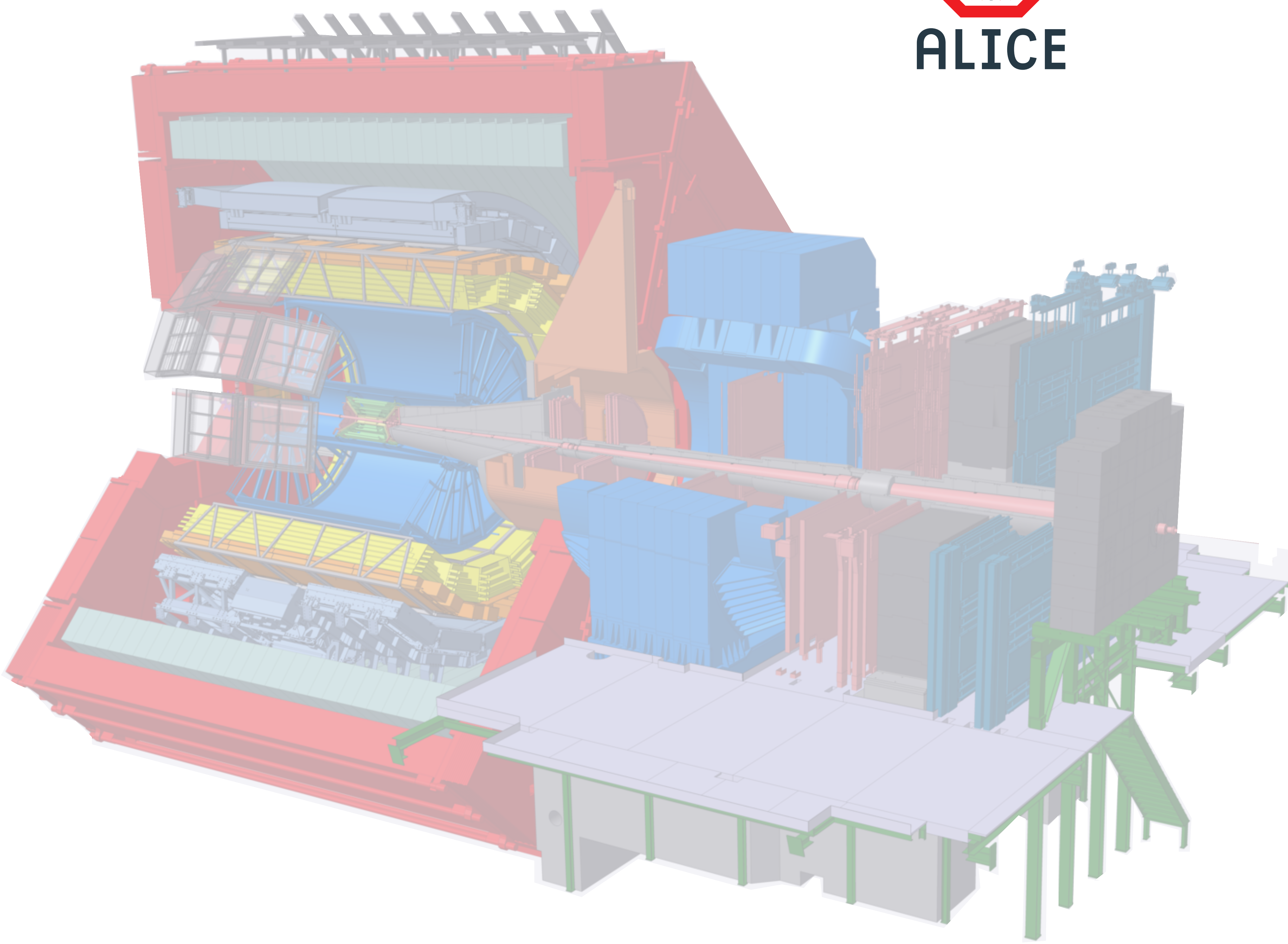
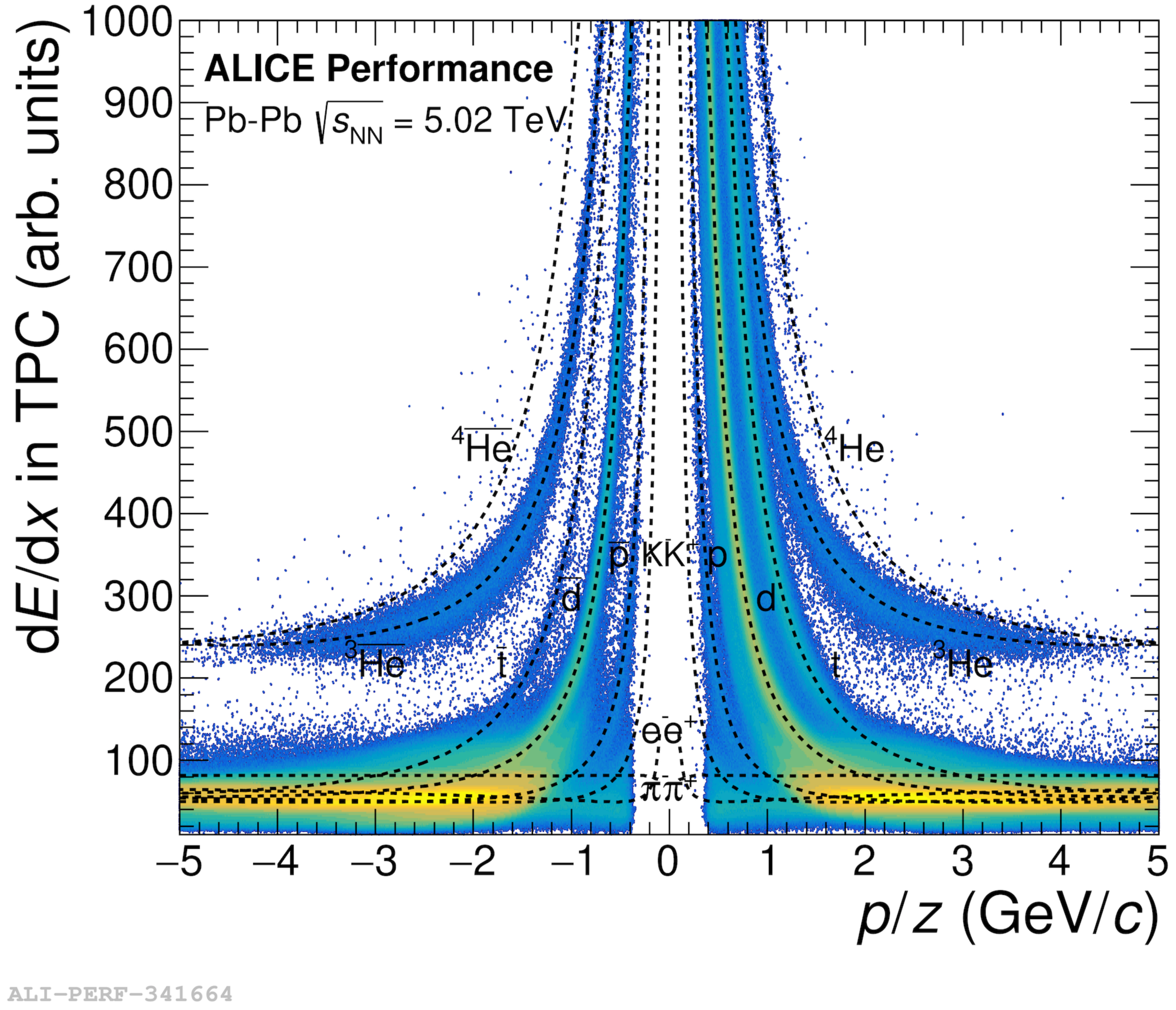
TPC: dE/dx in gas

- Separation of (anti)nuclei thanks to their large mass (and charge)



dE/dx in ALICE TPC



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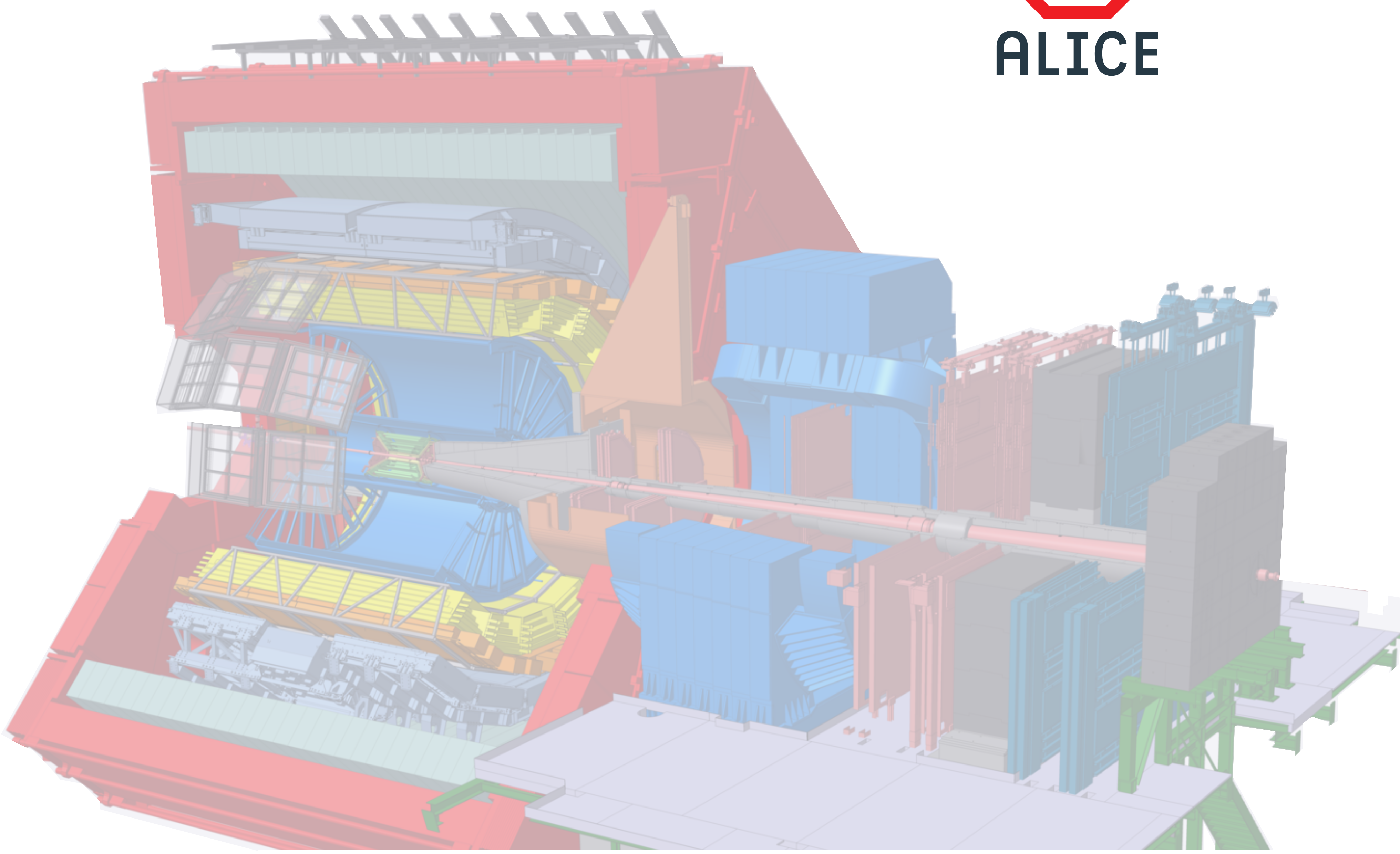
TOF measurements: $\beta = v/c$

- $p = \gamma\beta m \rightarrow$ mass



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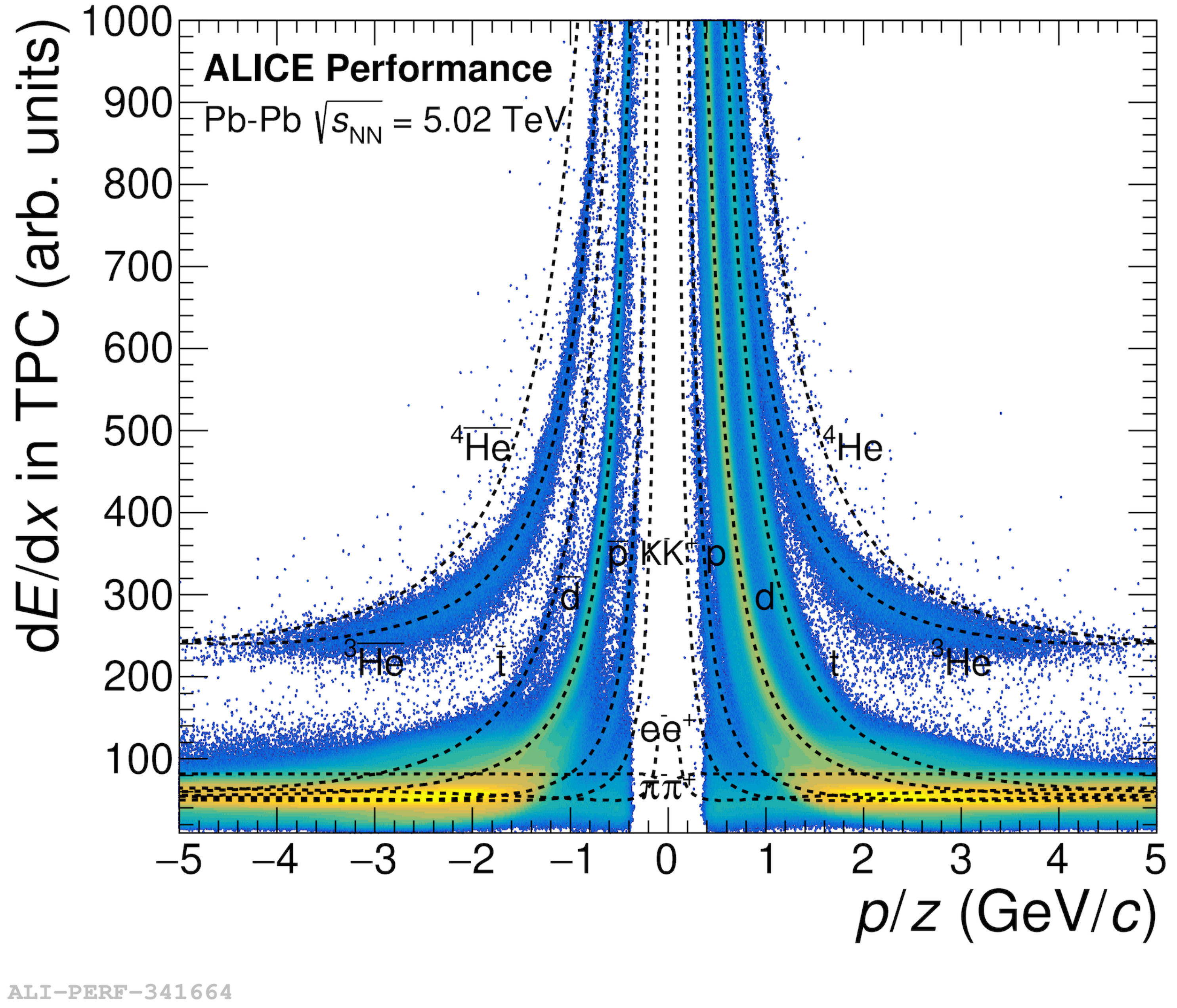
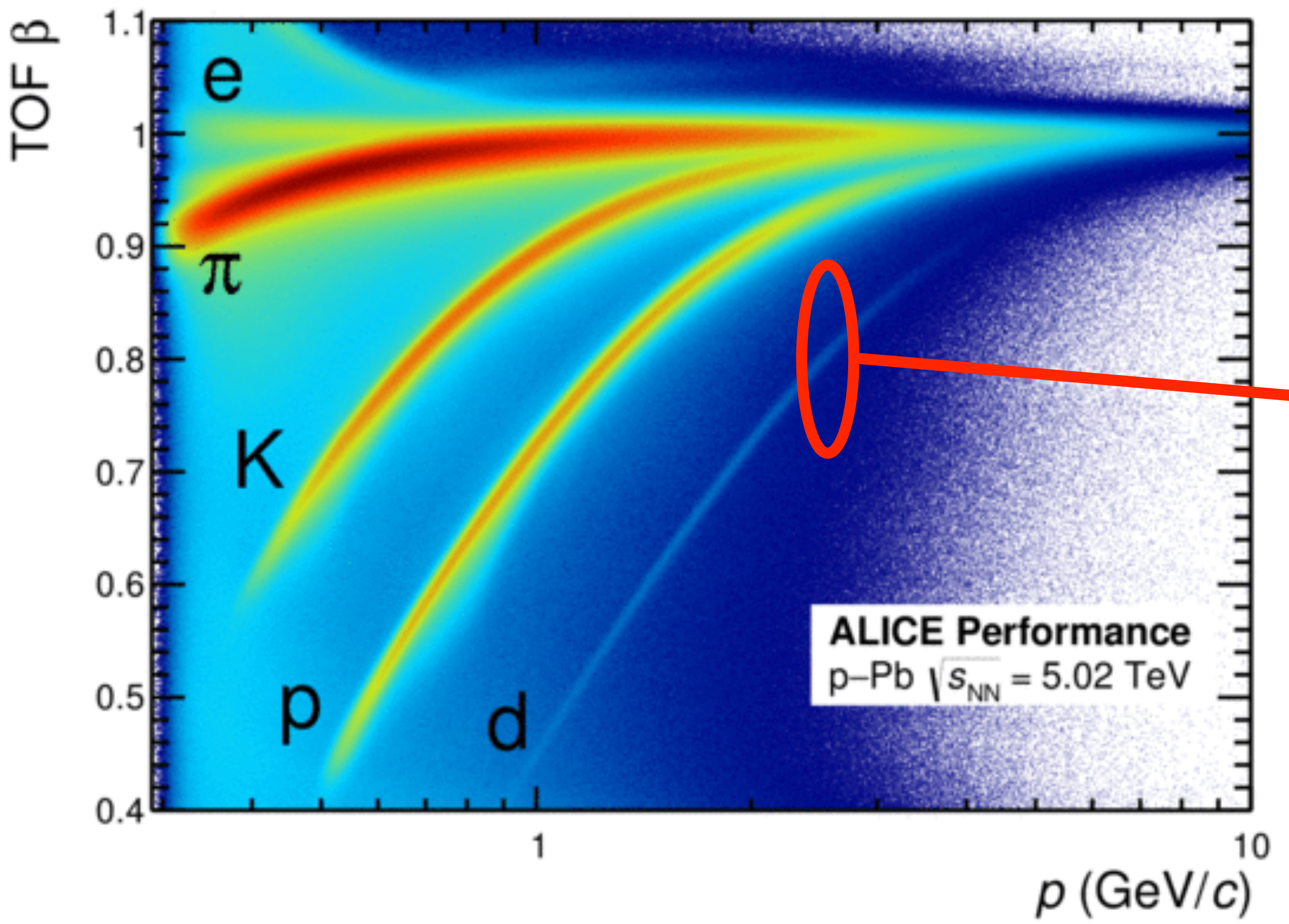
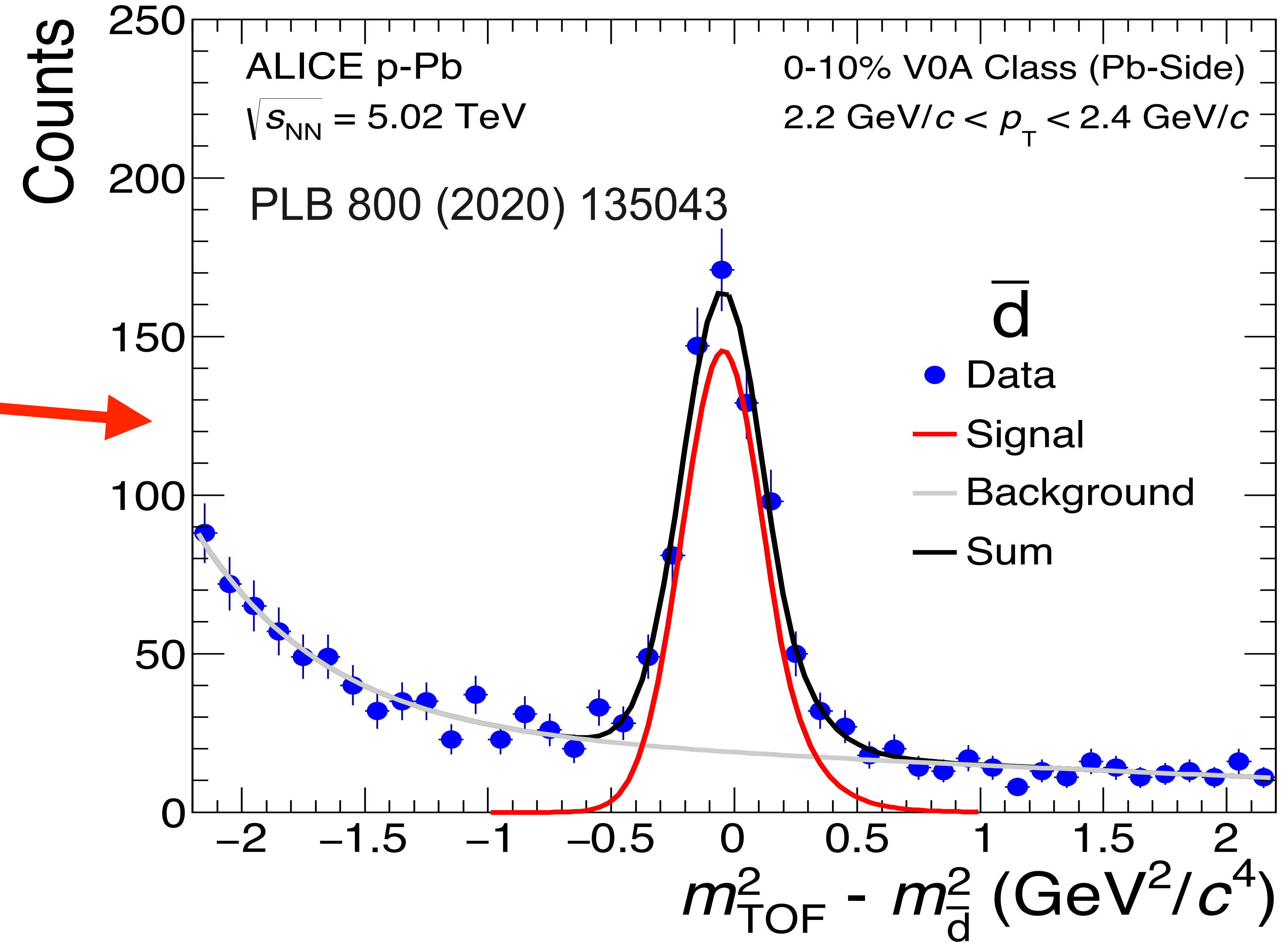


TOF β

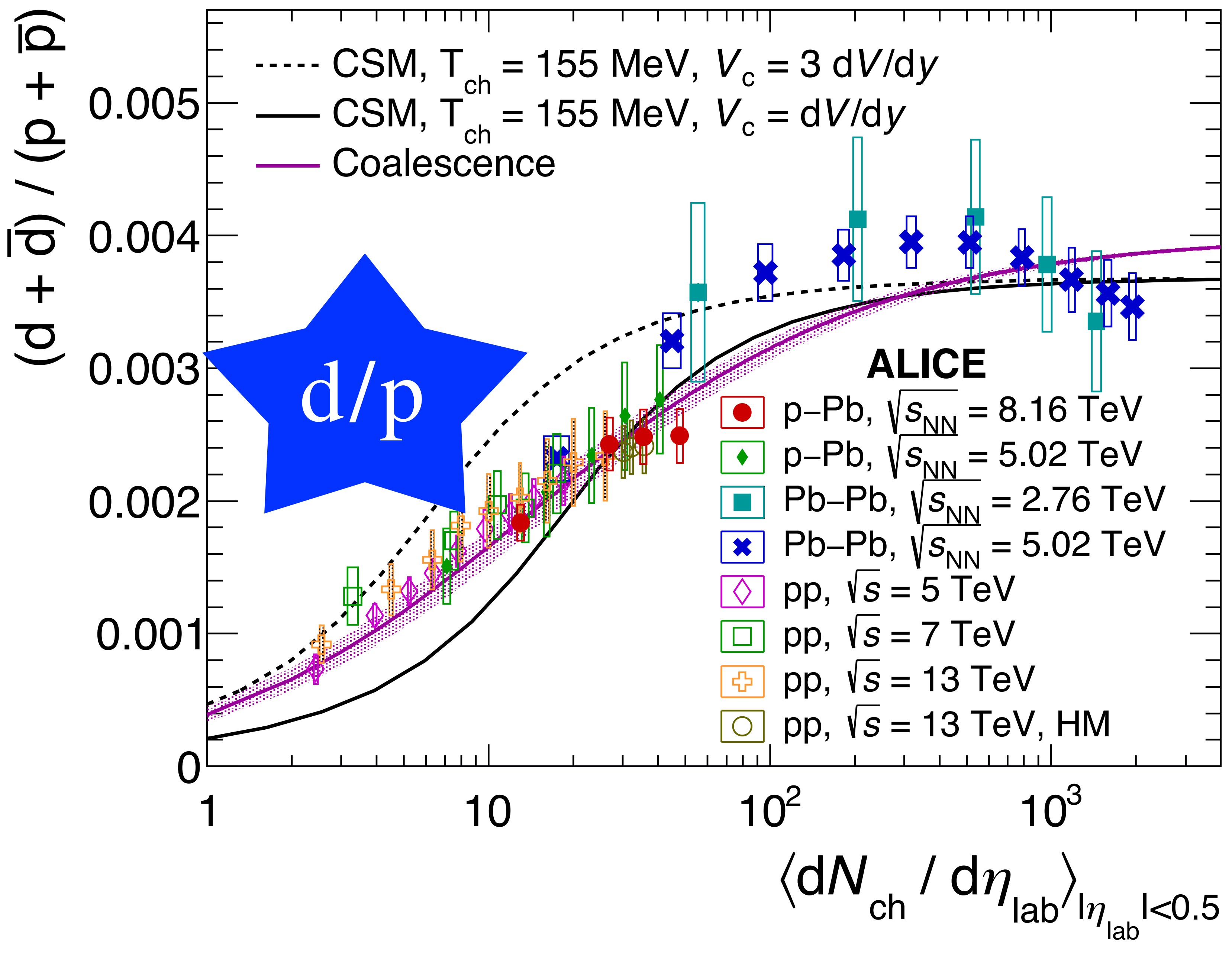


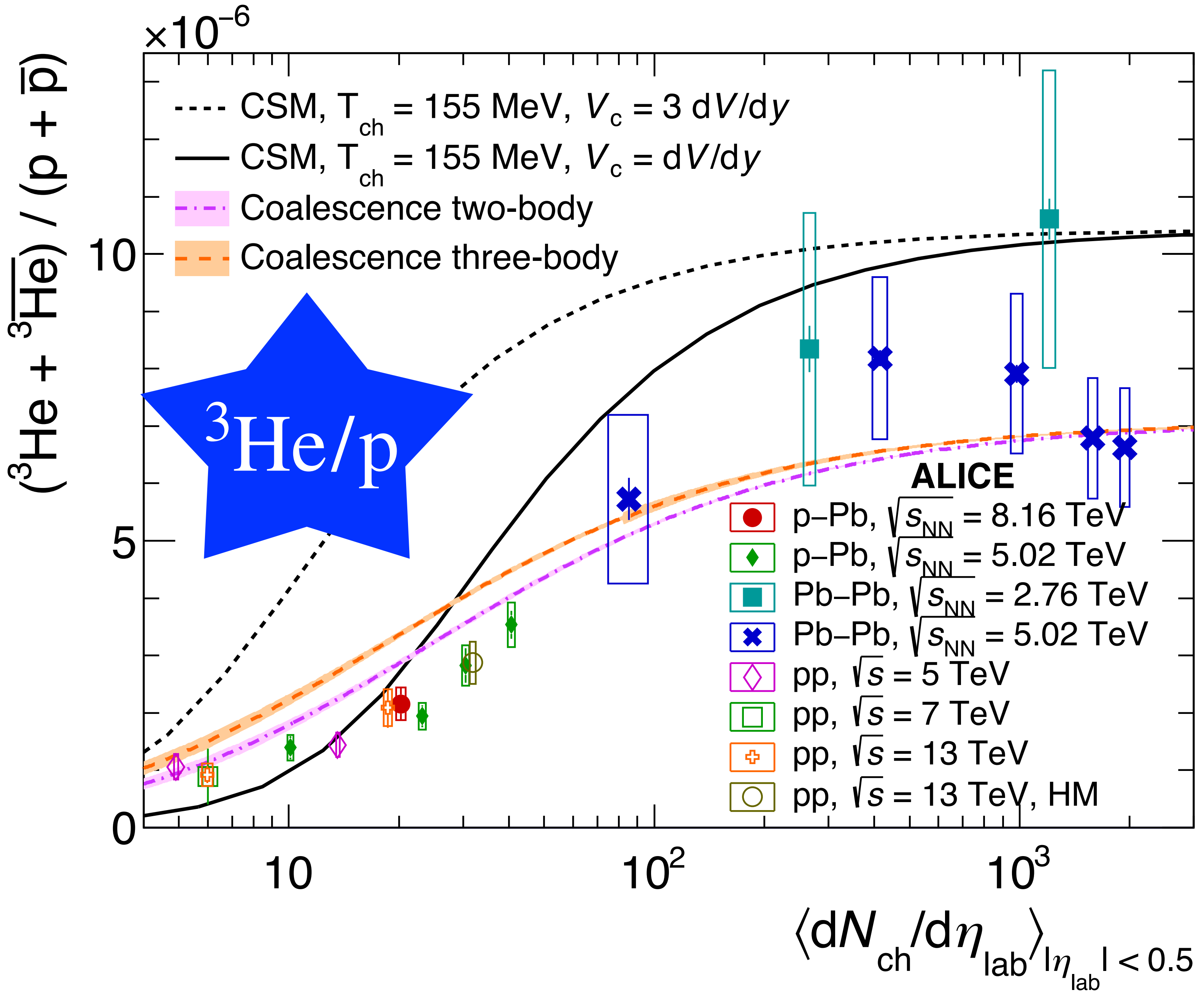


(Anti)(hyper)nuclei production across collision systems

Smooth evolution of d/p and ^{3}He/p ratios with multiplicity and system size [1]

- Good description of A = 2, 3 data with coalescence models
- Tension between statistical models and A = 3 experimental results





[1] ALICE, arXiv:2212.04777

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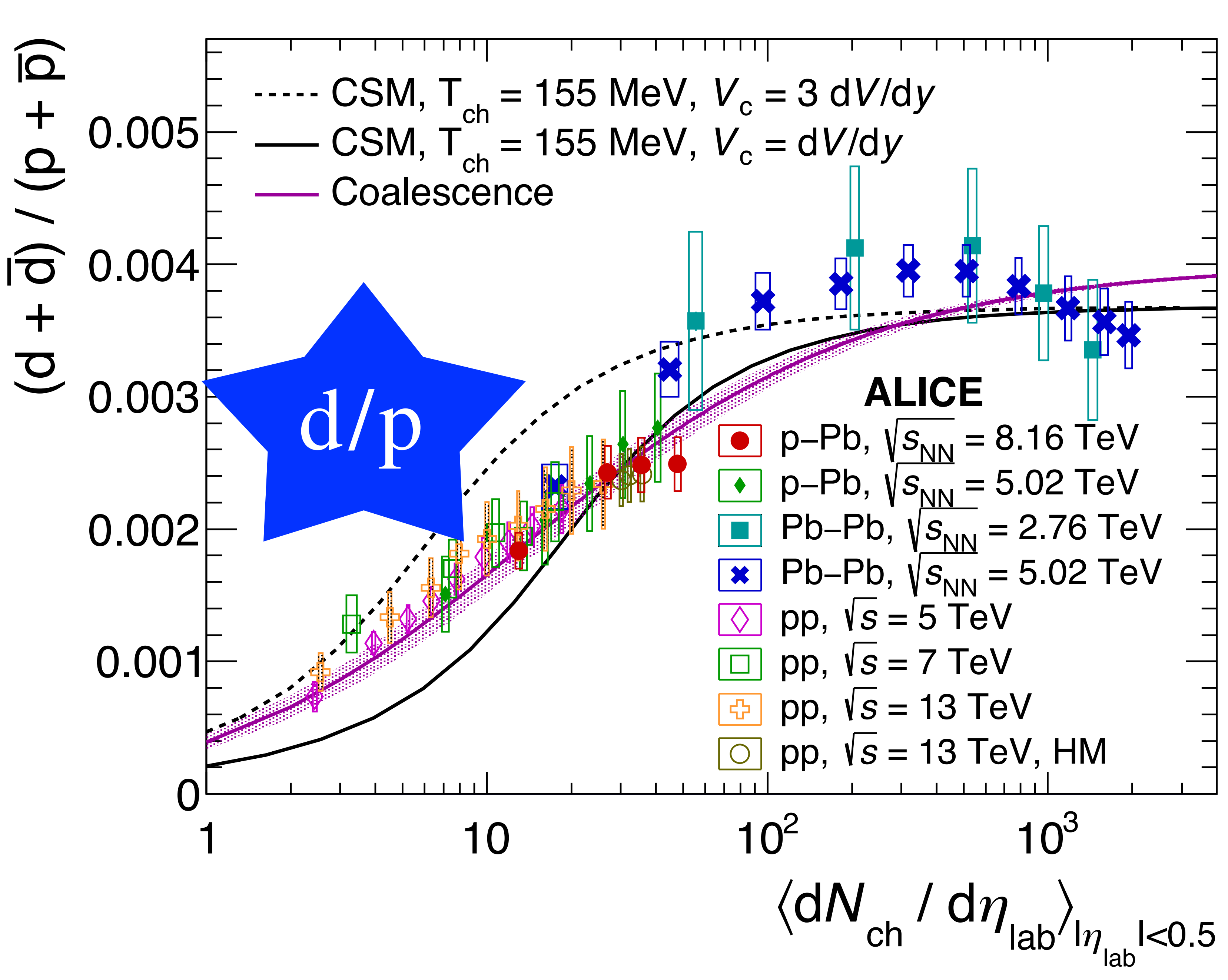
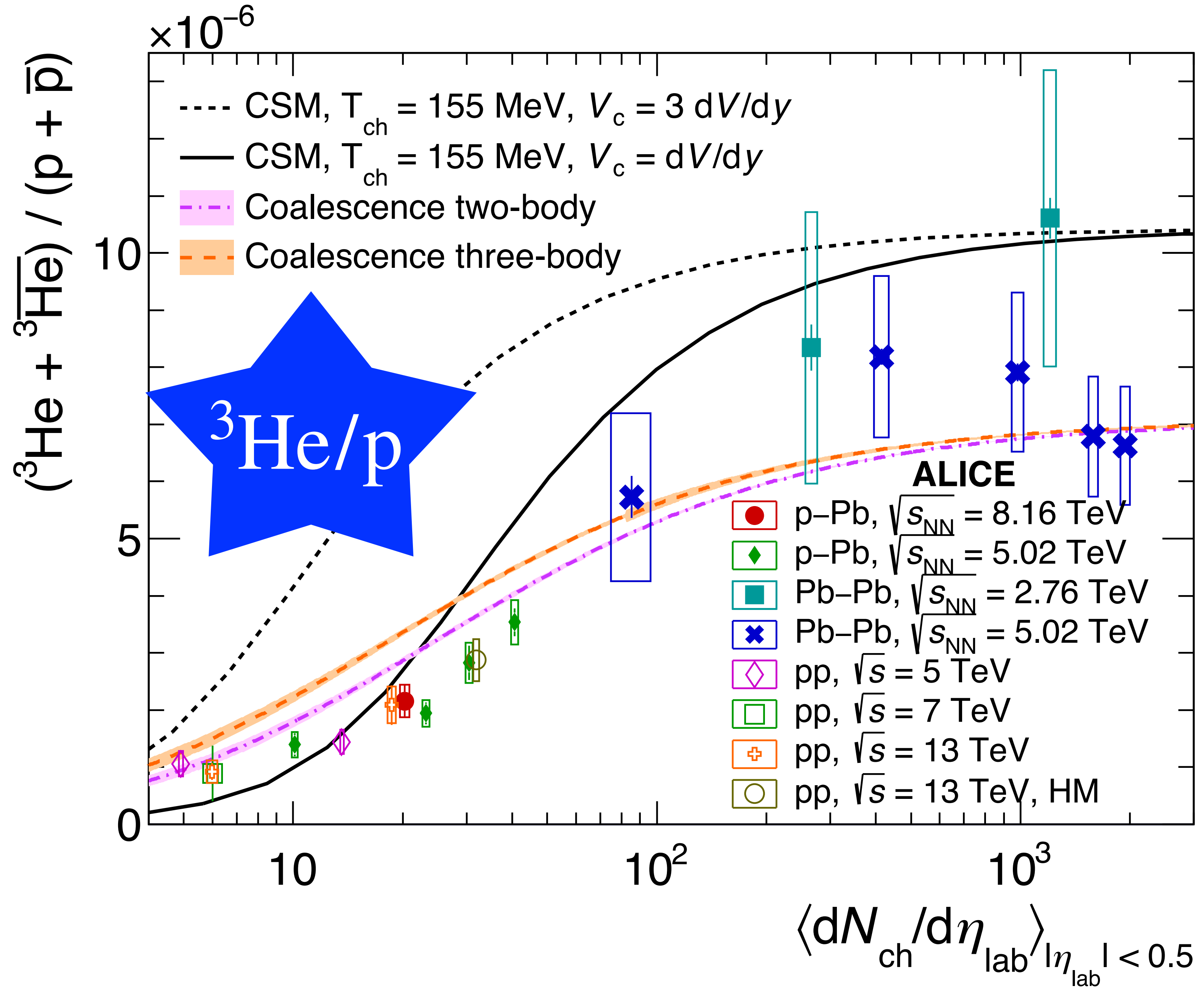
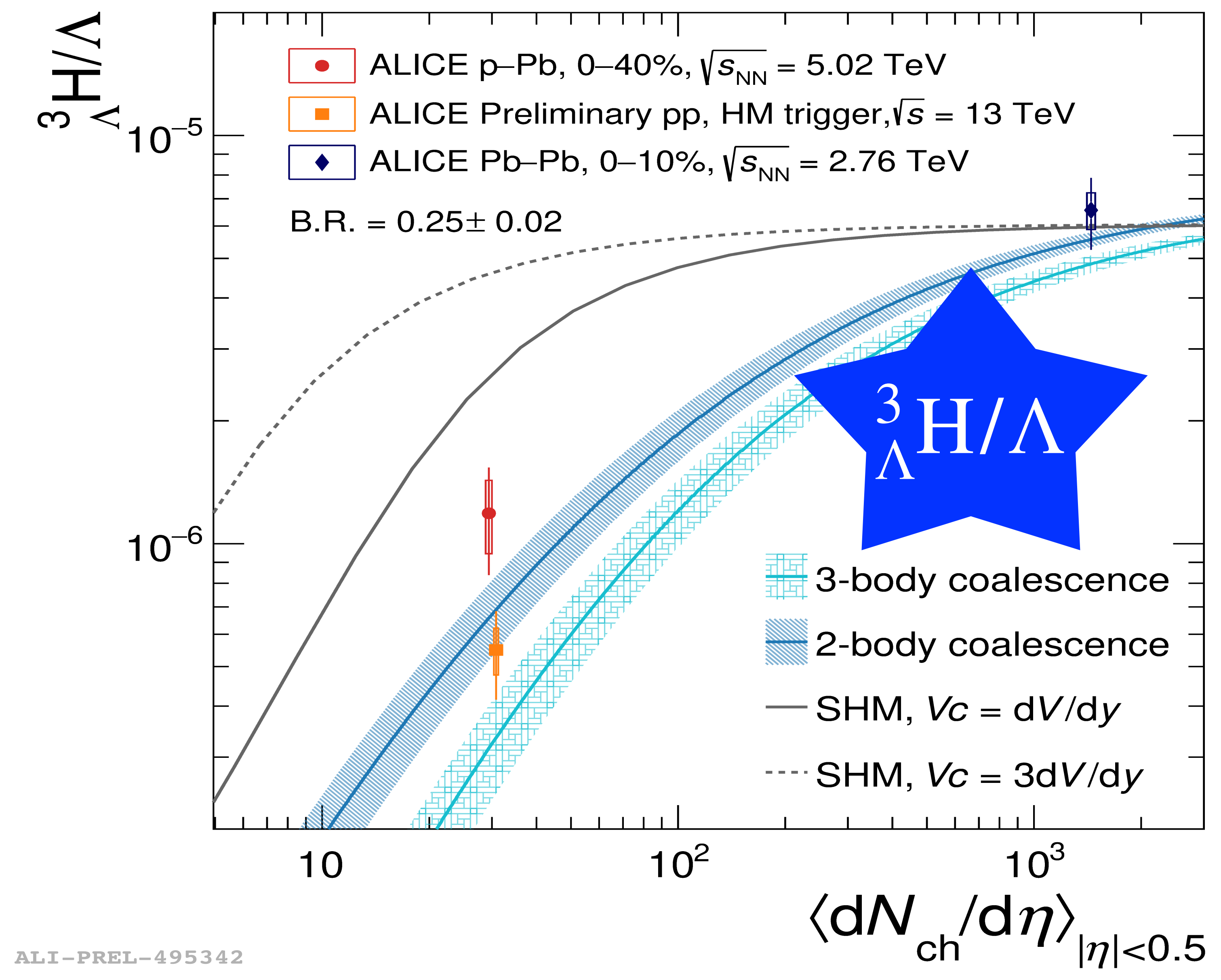
- Good description of *A* = 2, 3 data with coalescence models
- Tension between statistical models and *A* = 3 experimental results
- *Recent* $^{3}_{\Lambda}\mathrm{H}/\Lambda$ *measurements [2] support coalescence model in small systems!*







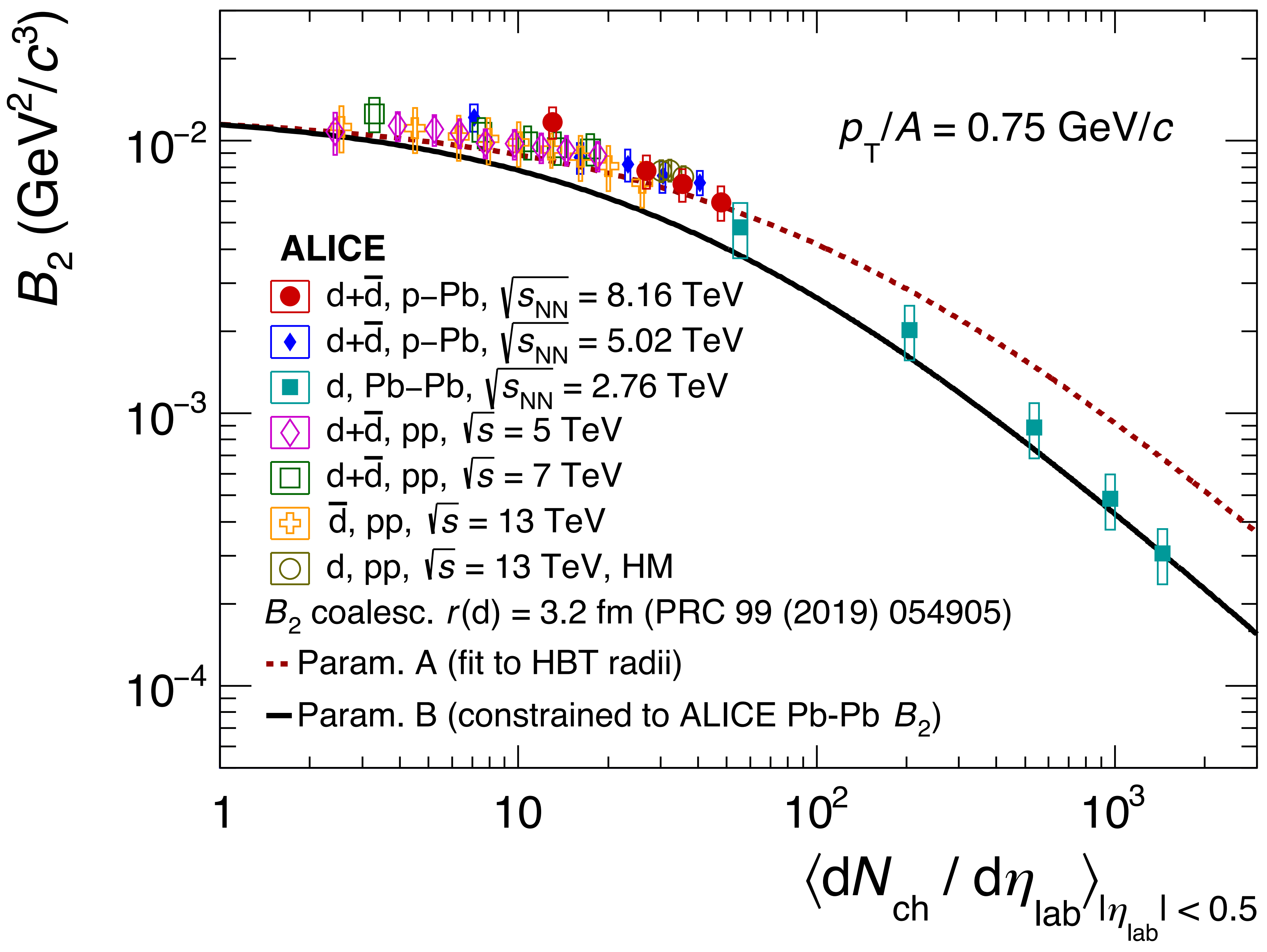
[1] ALICE, arXiv:2212.04777
[2] ALICE, Phys. Rev. Lett. 128 (2022) 252003

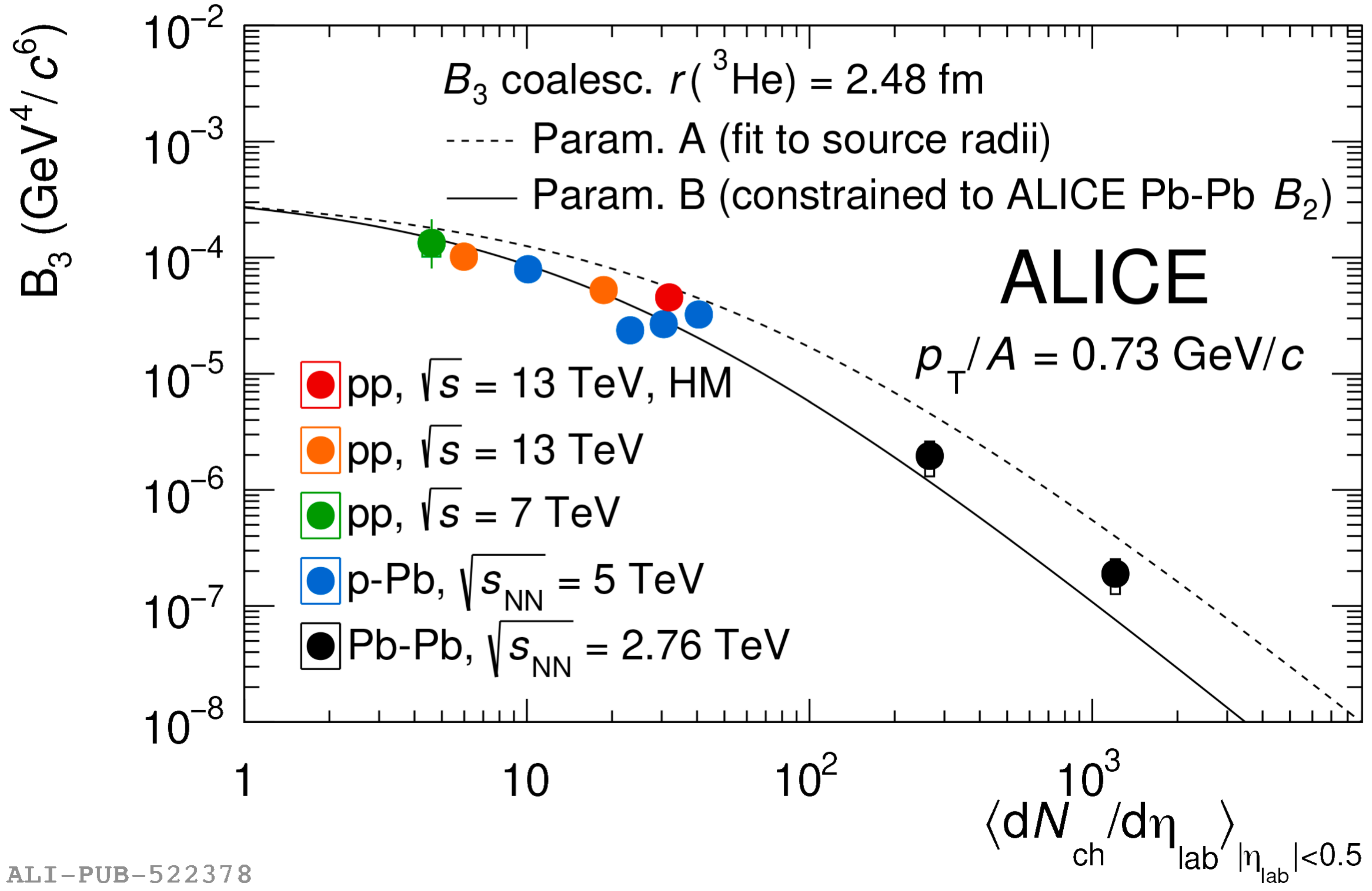
ALICE

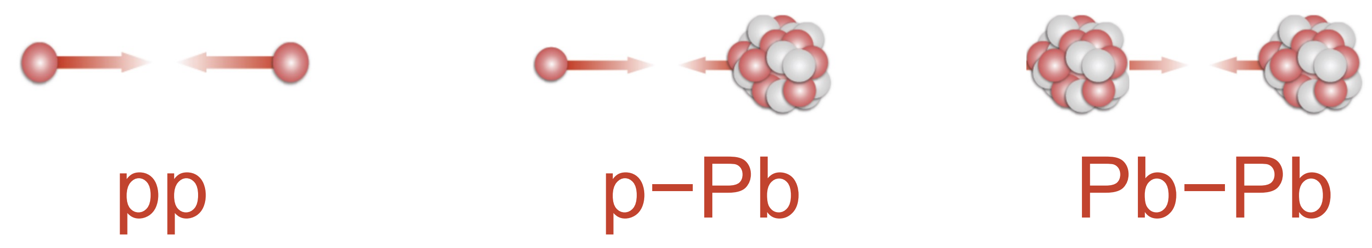
Coalescence parameter B_A

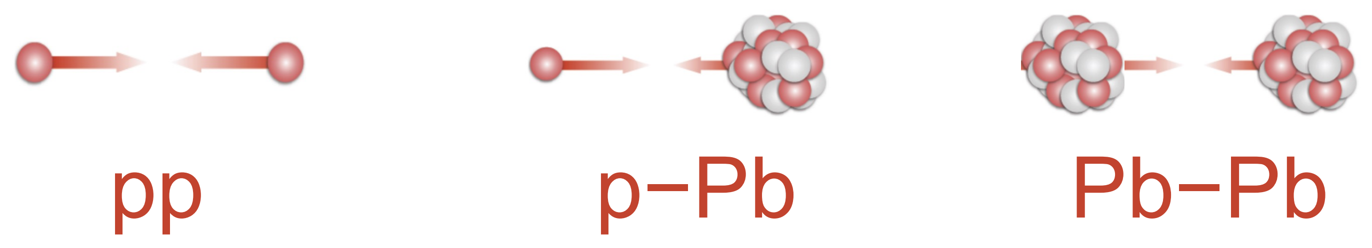
Smooth evolution of B_2 and B_3 with multiplicity and system size [1, 2]

- Large system size (r ~2−5 fm) → decrease of B_A due to space separation between nucleons









[1] ALICE, arXiv:2212.04777
[2] ALICE, PRC 101, (2020) 044906

State-of-the-art coalescence modelling

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Precise measurements of
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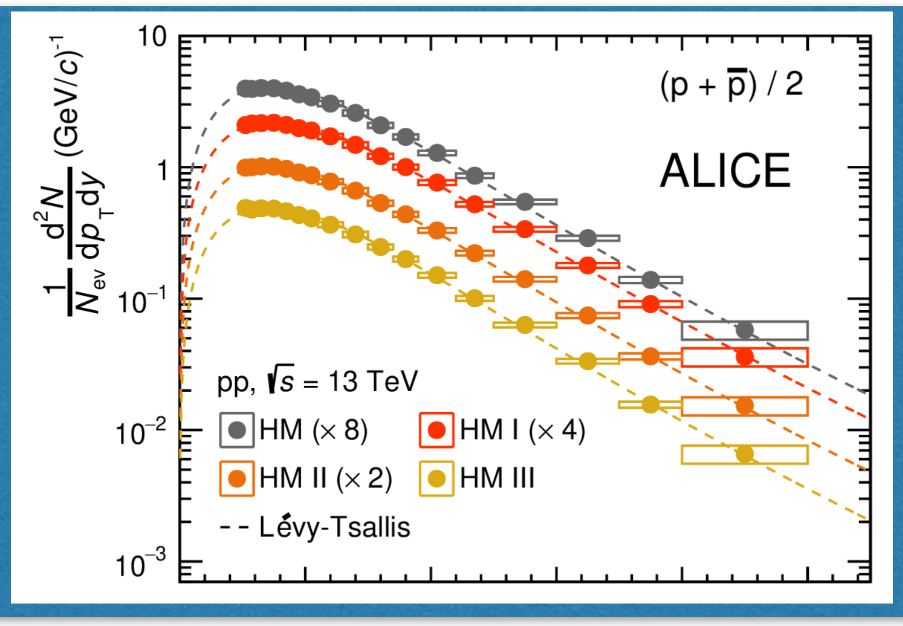

[1] JHEP 01 (2022) 106

ALICE

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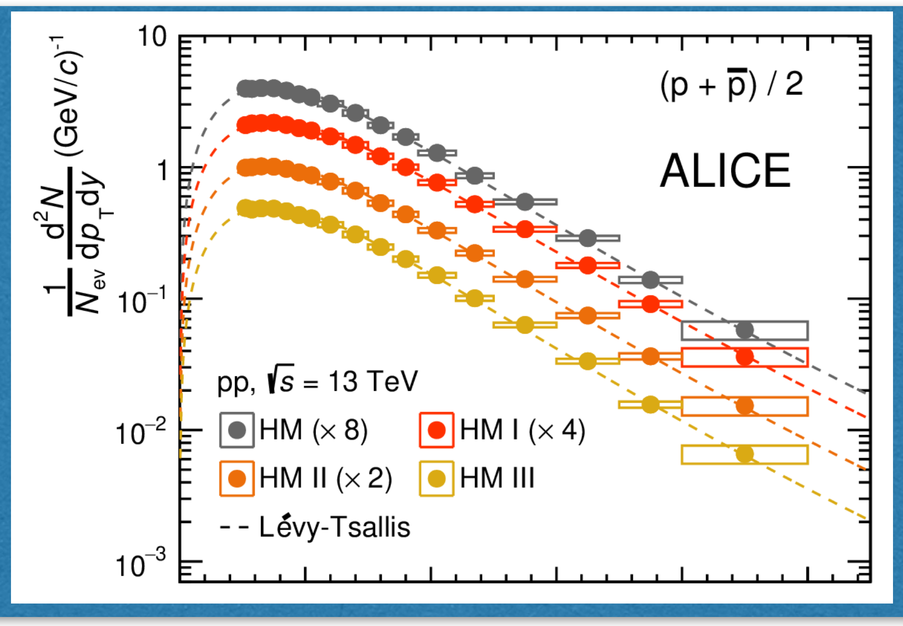
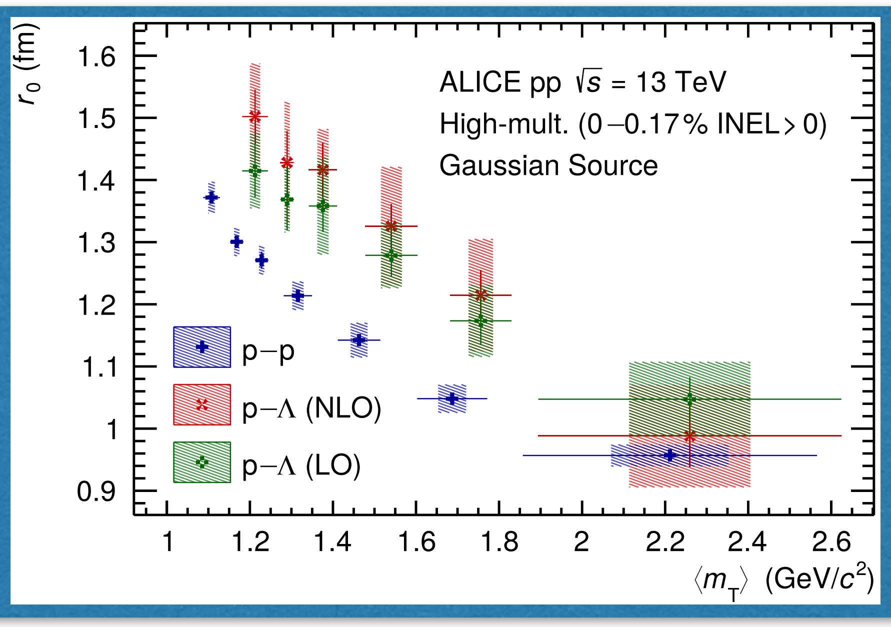


Particle-emitting source radius [2]



[1] JHEP 01 (2022) 106
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ALICE

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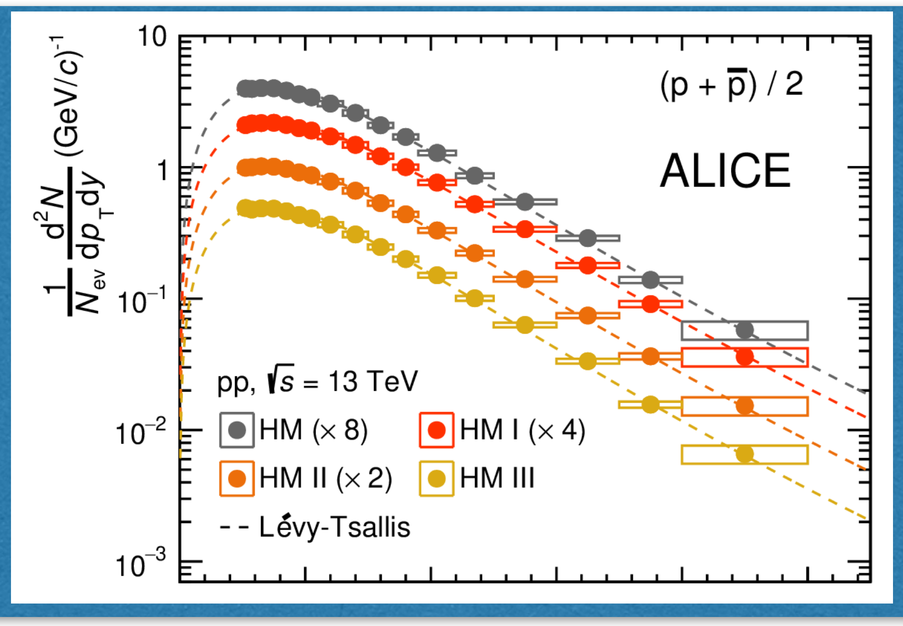

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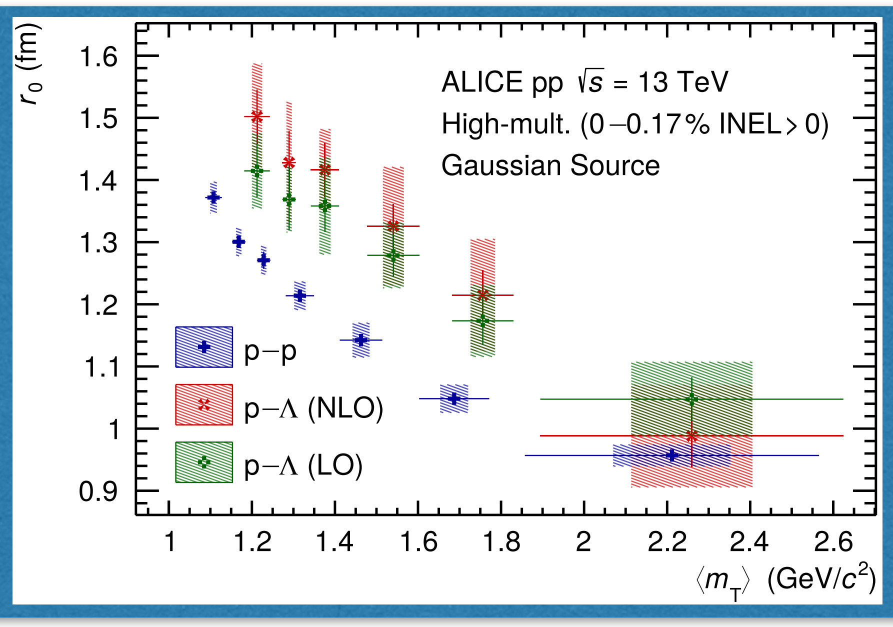
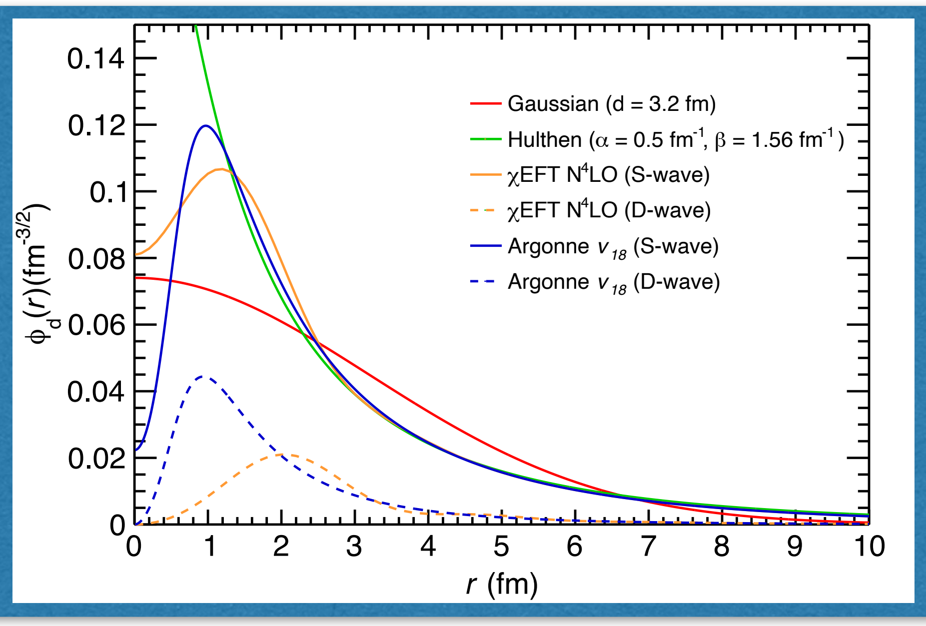


Hypotheses for d wave functions



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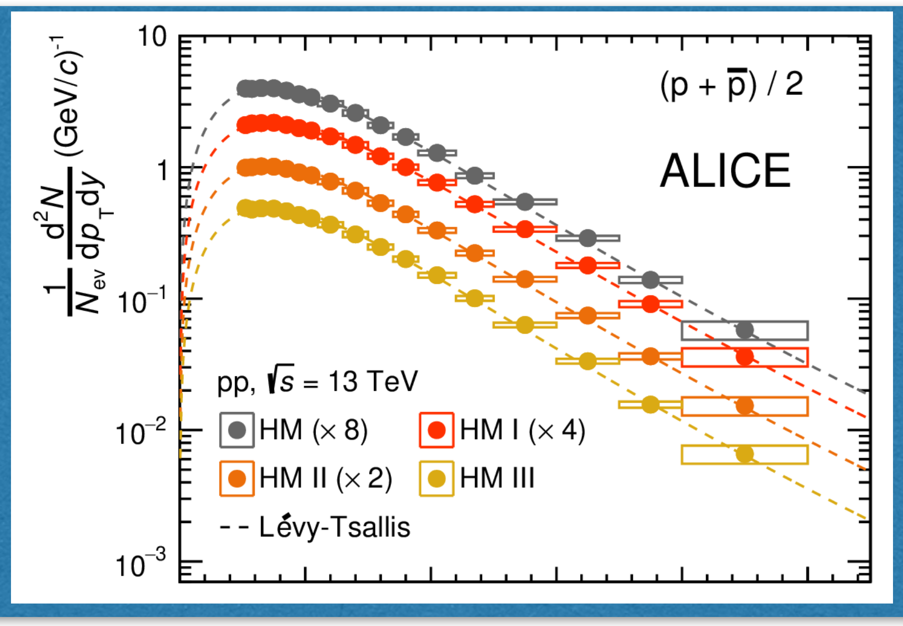

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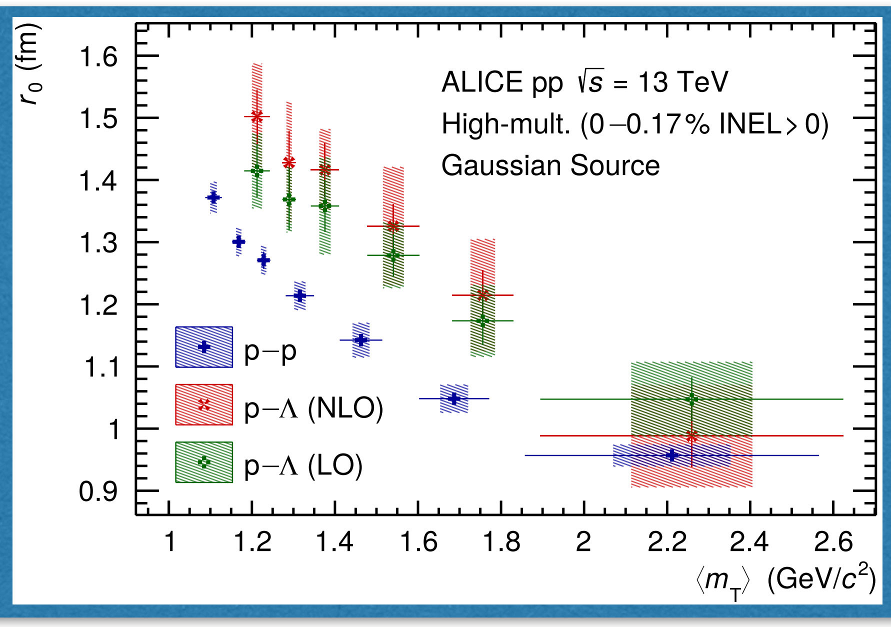

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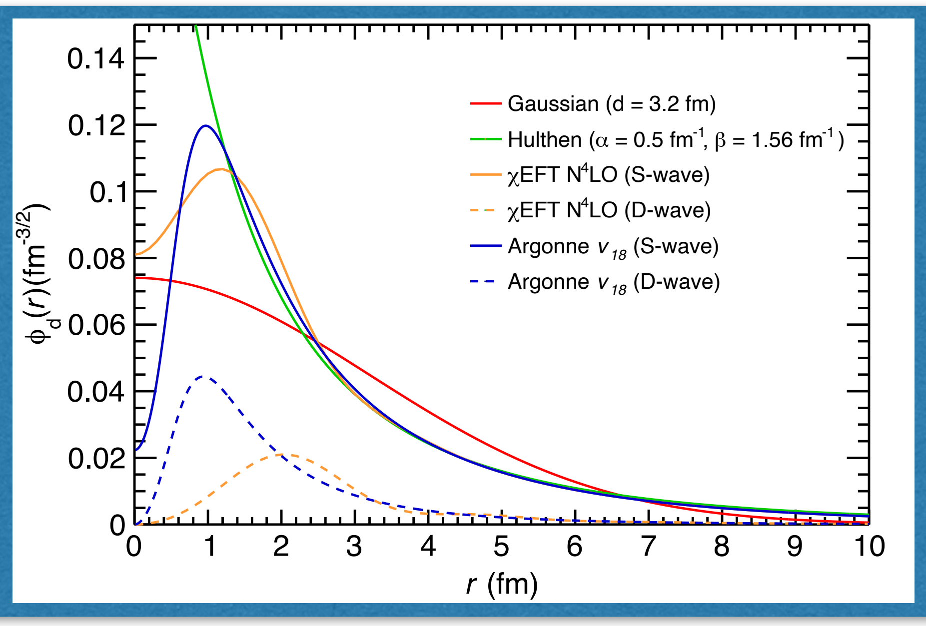
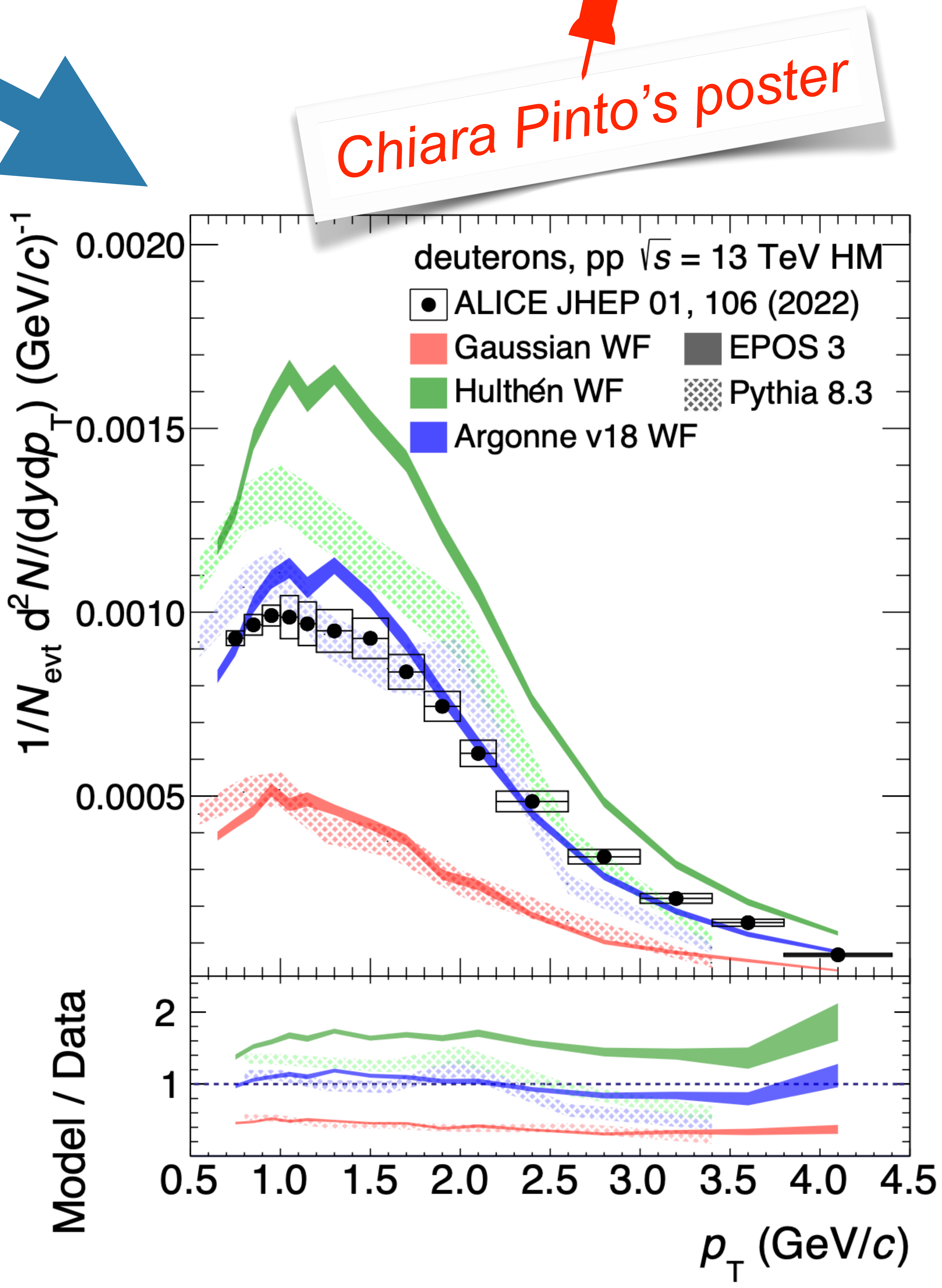


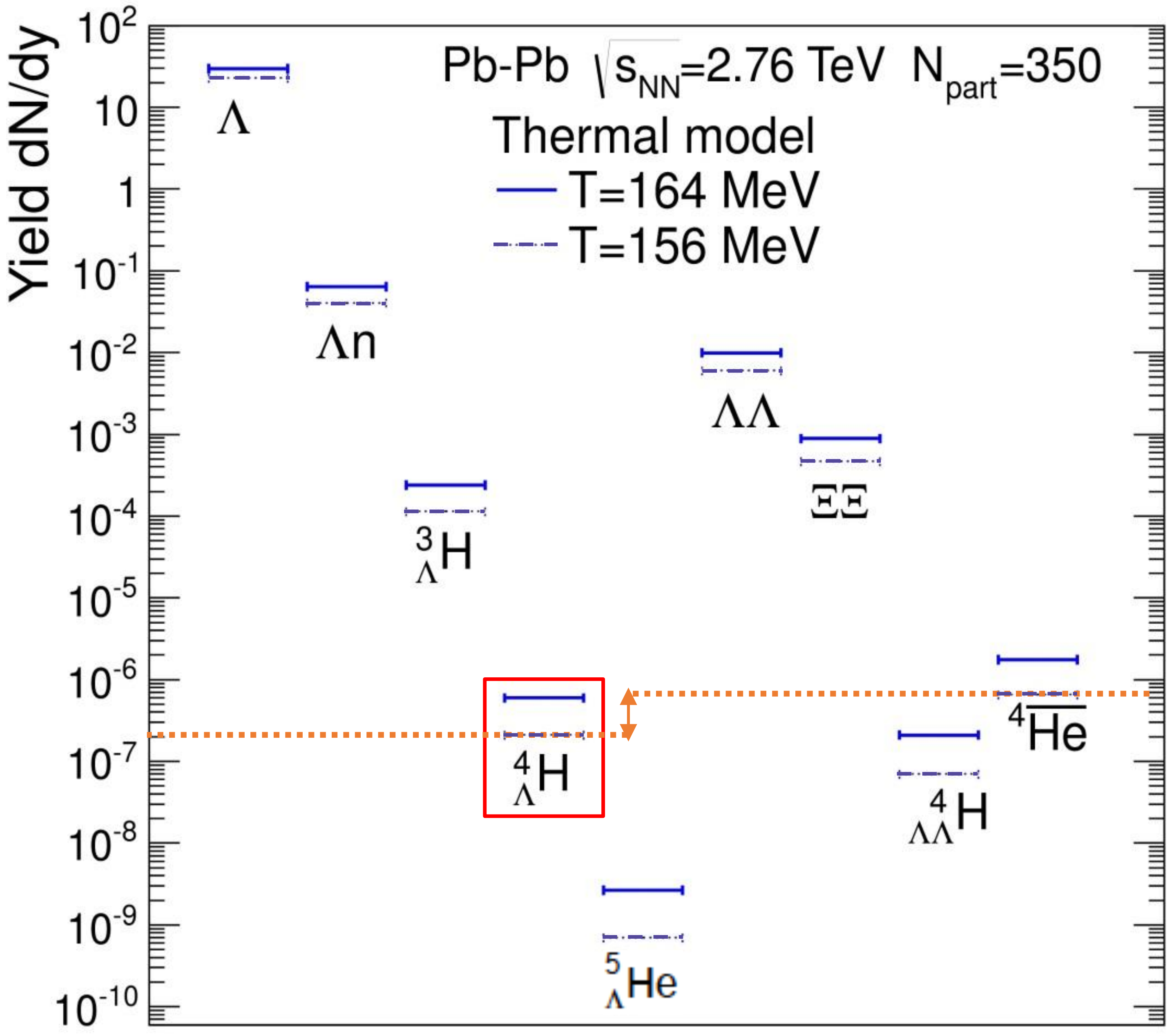


Description of d spectrum with coalescence model with no free parameters [3]

[1] JHEP 01 (2022) 106
[2] ALICE. Phys. Lett. B 811 (2020) 135849
[3] Horst et al., arXiv:2302.12696

A = 4 hypernuclei yield in theory

- Penalty factor for adding one nucleon to a particle: ~300 for Pb−Pb collisions [1]
- Additional suppression due to strangeness content



[1] Andronic et al., Phys. Lett. B 697 (2011) 203

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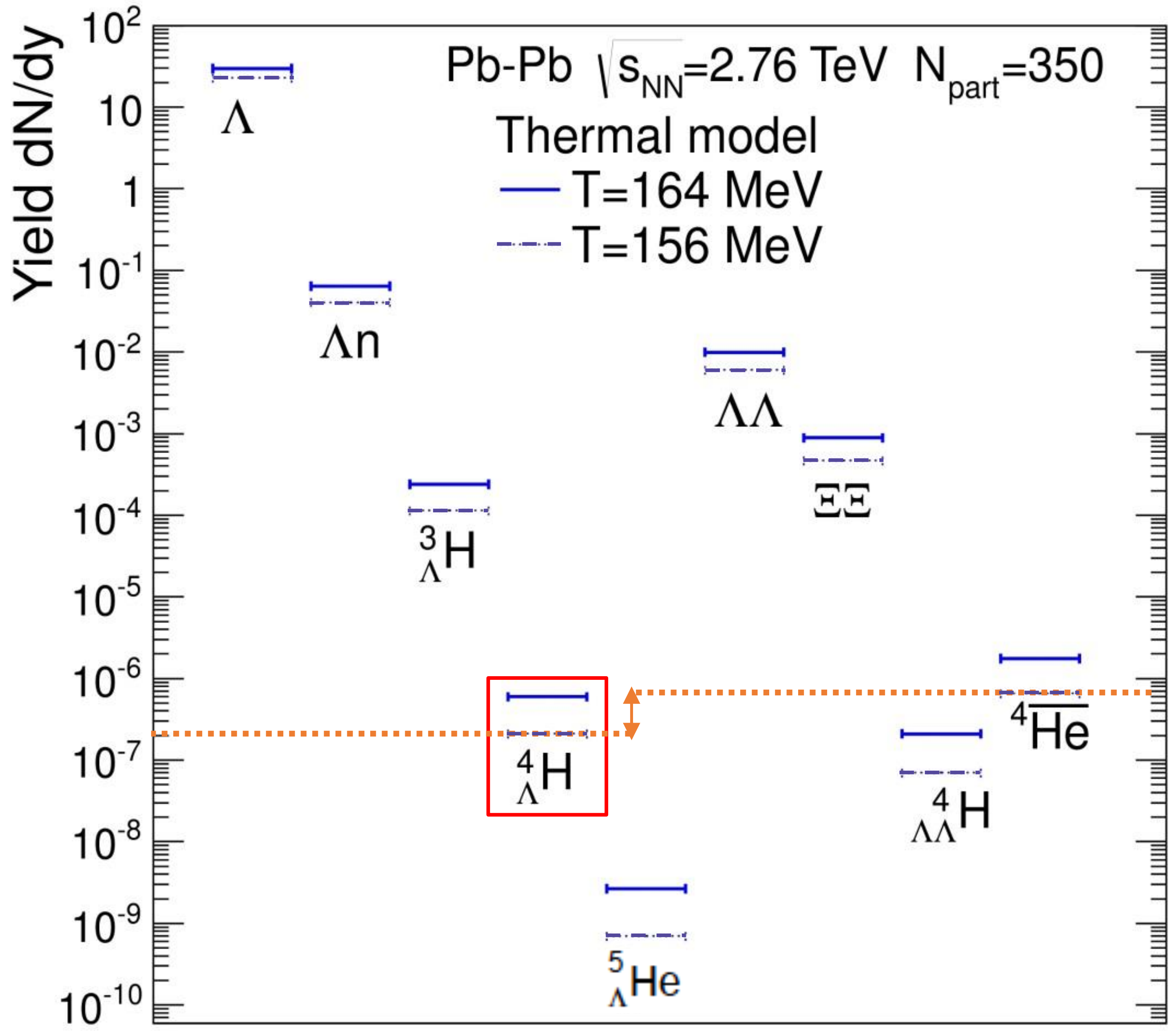
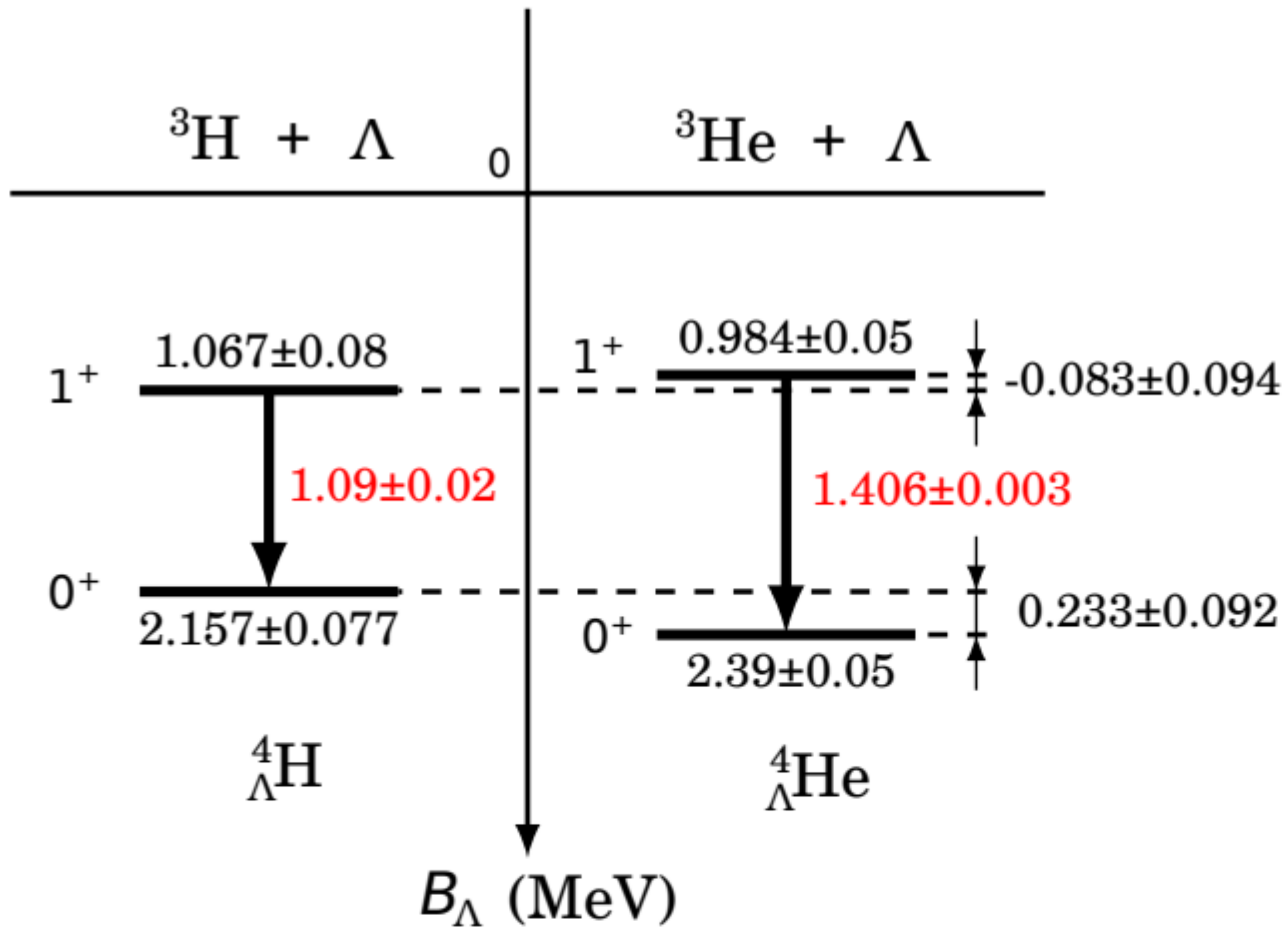




Chances to see A = 4 hypernuclei with Pb−Pb data from Run 2?

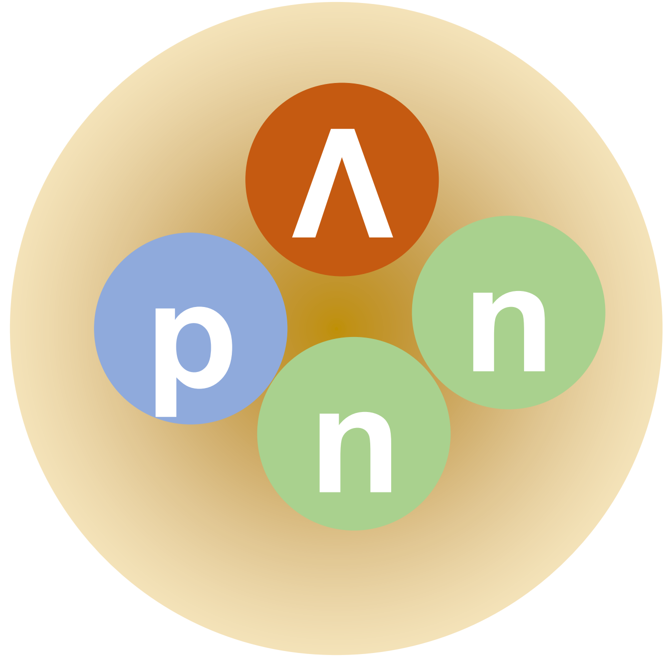
Feed-down from excited states [2, 3] → enhancement of a factor up to ~4 w.r.t. ground state [4]!

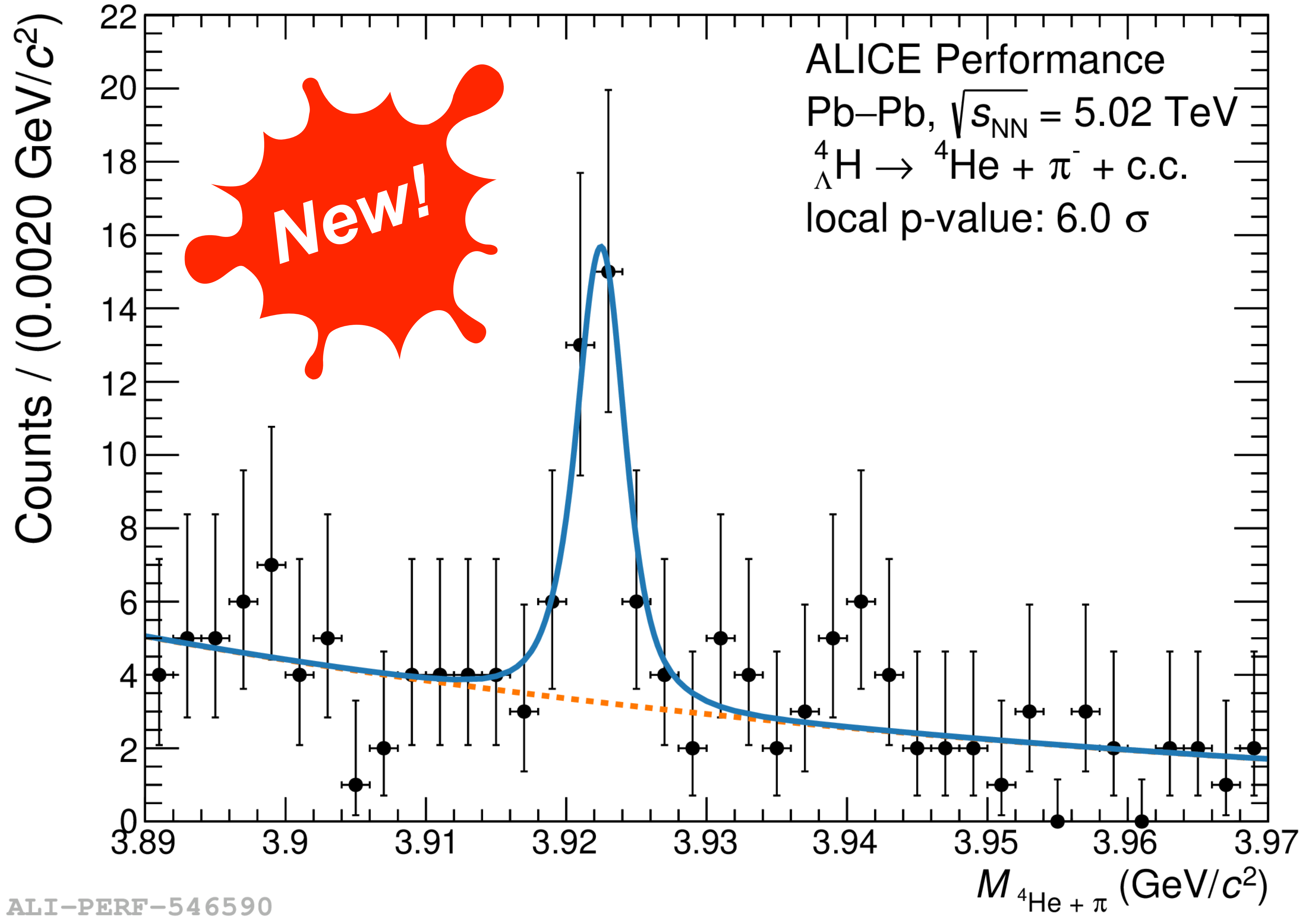
[1] Andronic et al., Phys. Lett. B 697 (2011) 203
[2] J-PARC E13, Phys.Rev.Lett. 115 (2015) 22, 222501
[3] Schaefer et al., Phys.Rev.C 106 (2022) 3, L031001
[4] Dönigus, EPJ Web Conf. 276 (2023) 04002

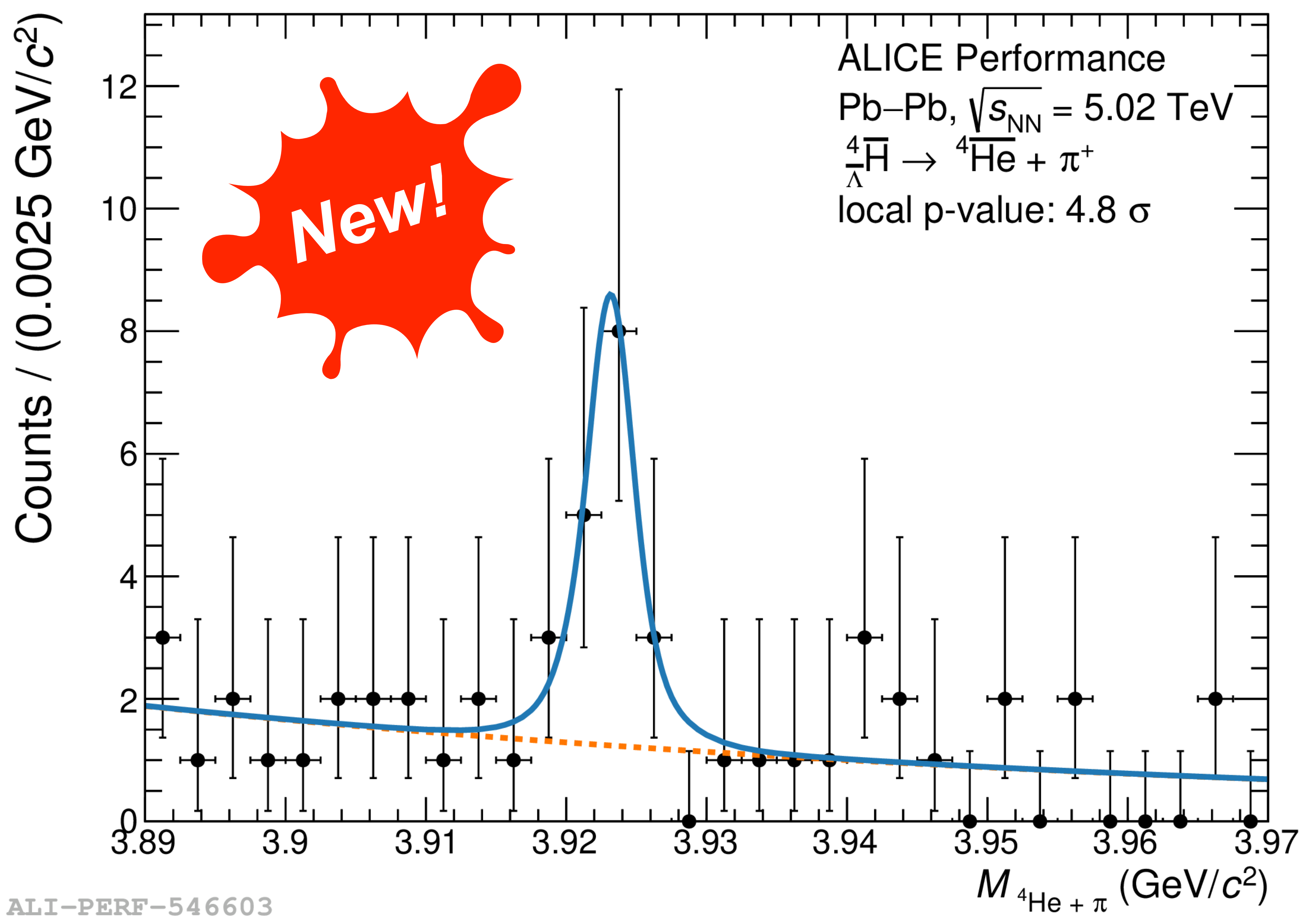
A = 4 hypernuclei in ALICE: ${}^{4}_{\Lambda}\mathrm{H}$!

Careful topological and kinematic selection, machine learning approach (BDT) for the signal extraction

First signal of ${}^{4}_{\Lambda}\mathrm{H}$ at the LHC energies!







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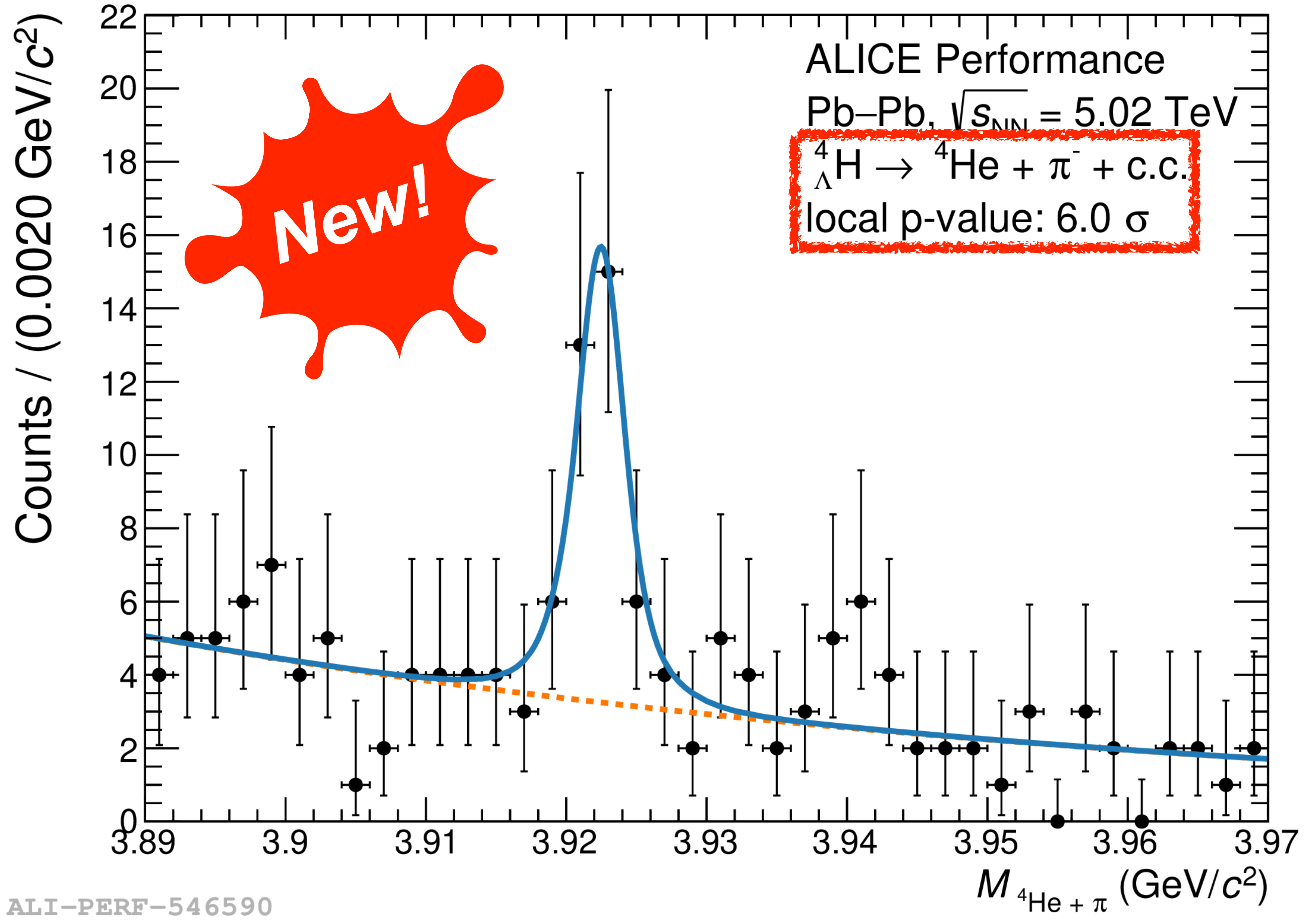
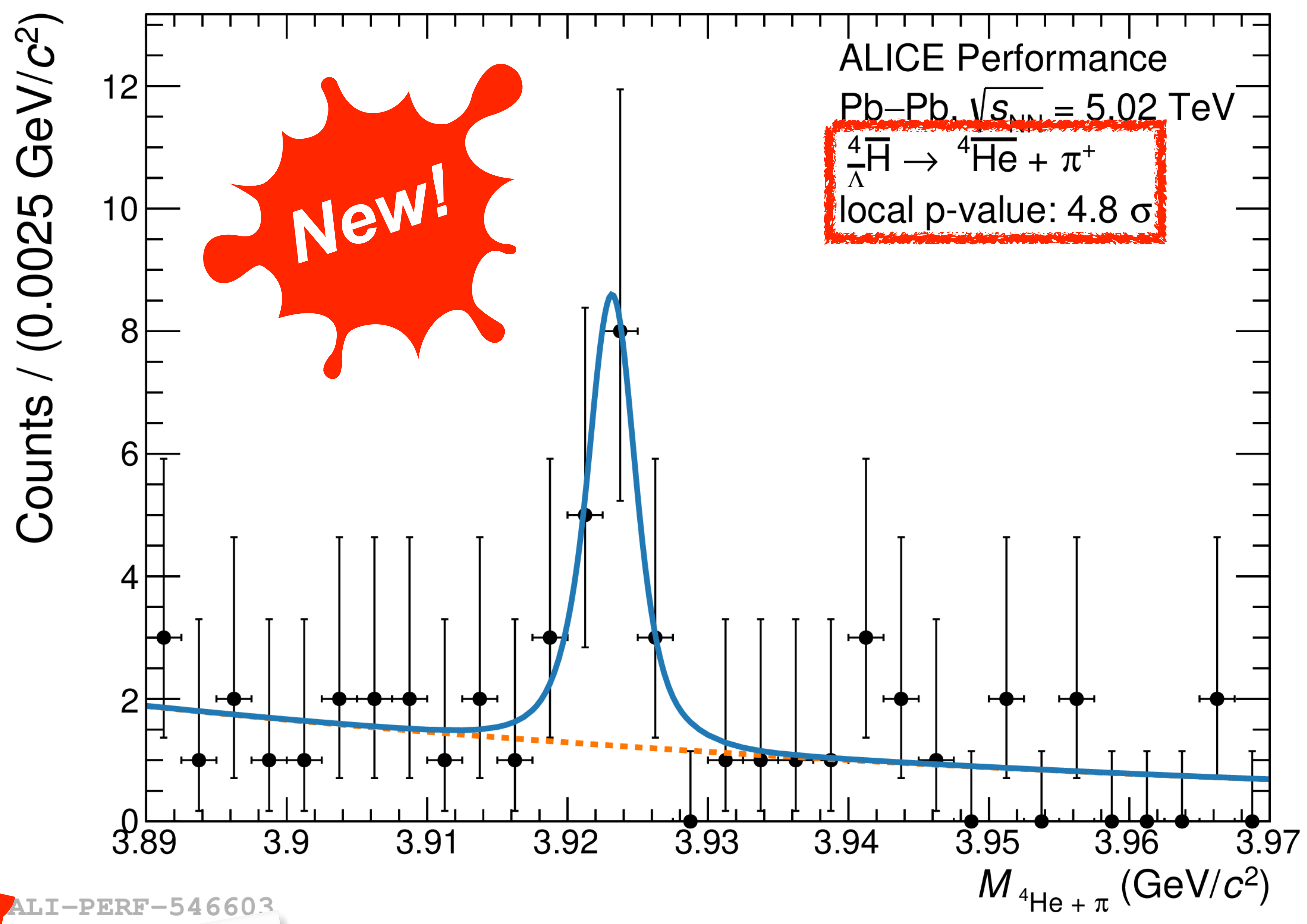
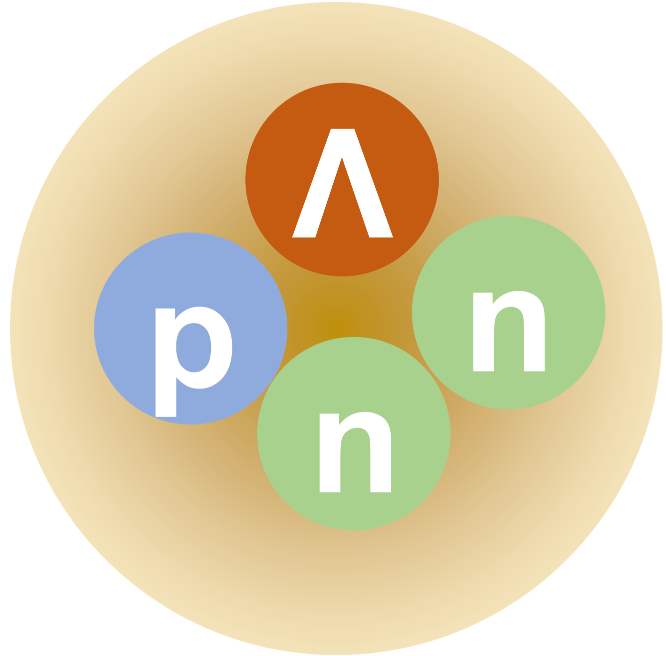
Two-body decay: ${}^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^{-} +$ c.c, local p-values of **6.0σ** and **4.8σ**!







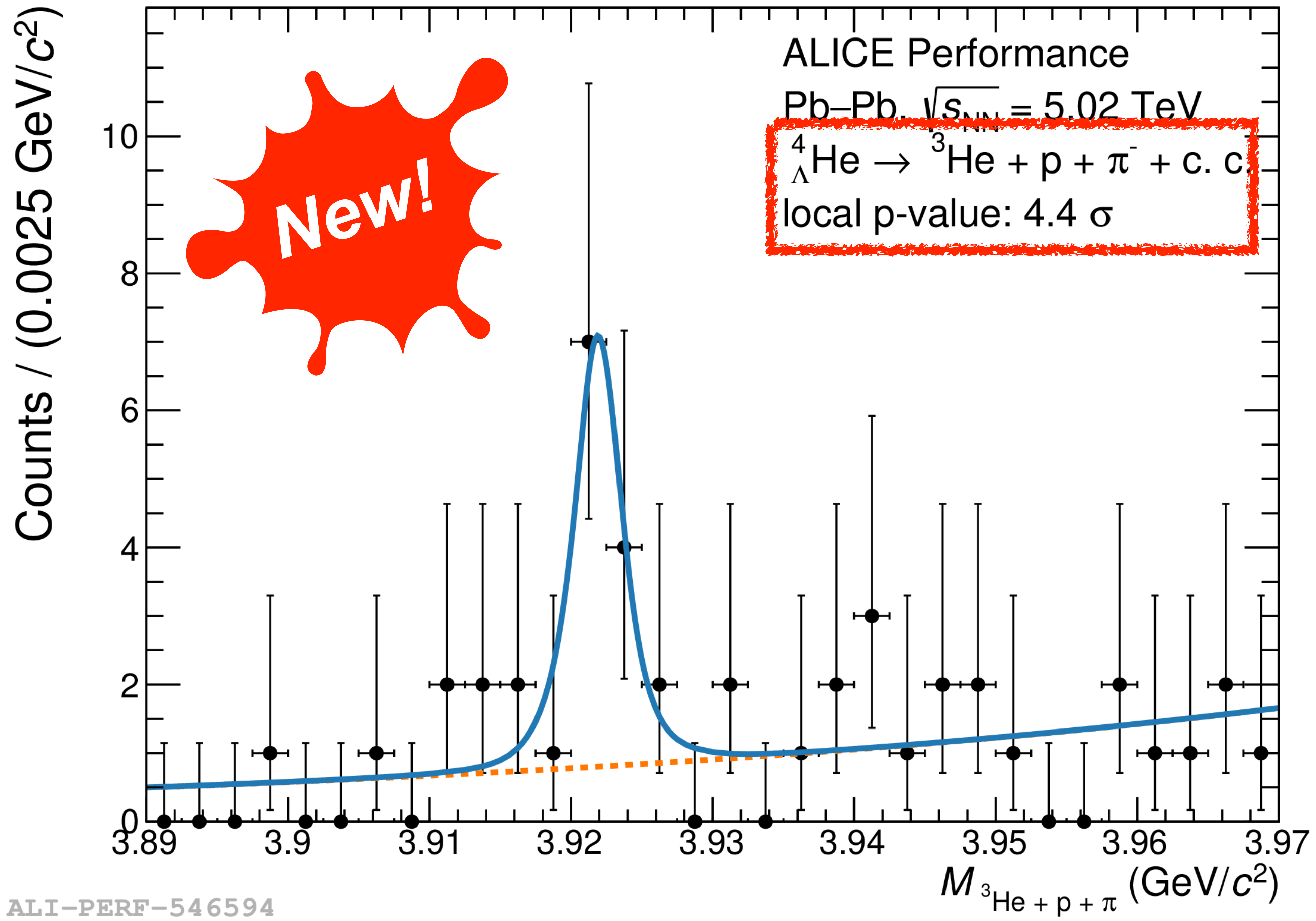
Janik Ditzel's poster

A = 4 hypernuclei in ALICE: $^{4}_{\Lambda}\mathrm{He}$!

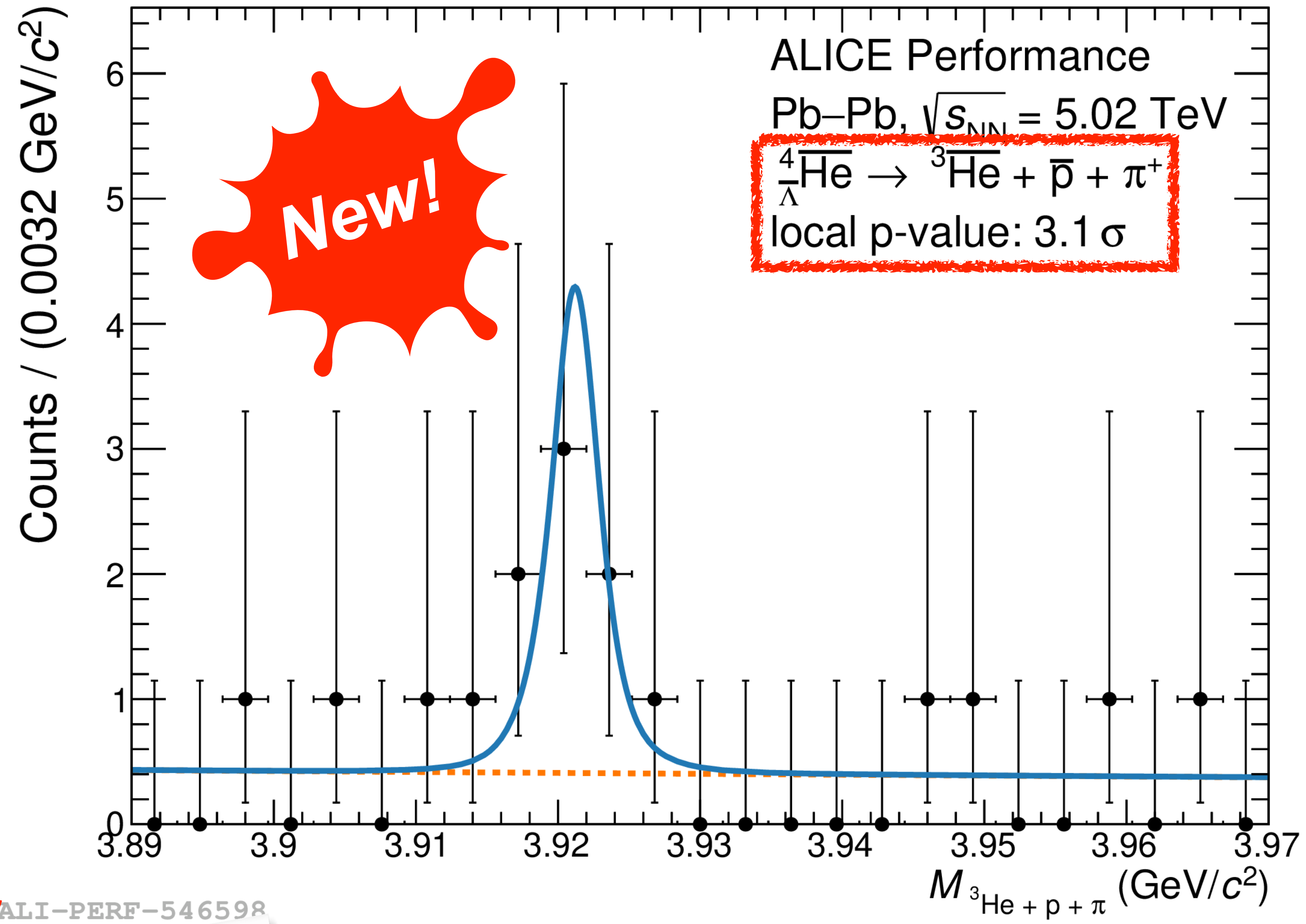
Careful topological and kinematic selection, machine learning approach (BDT) for the signal extraction

First signal of $^{4}_{\Lambda}\mathrm{He}$ at the LHC energies!

Three-body decay: $^{4}_{\Lambda}\mathrm{He} \rightarrow {}^{3}\mathrm{He} + \mathrm{p} + \pi^{-} +$ c.c, local p-values of **4.4σ** and **3.1σ**!



ALI-PERF-546594



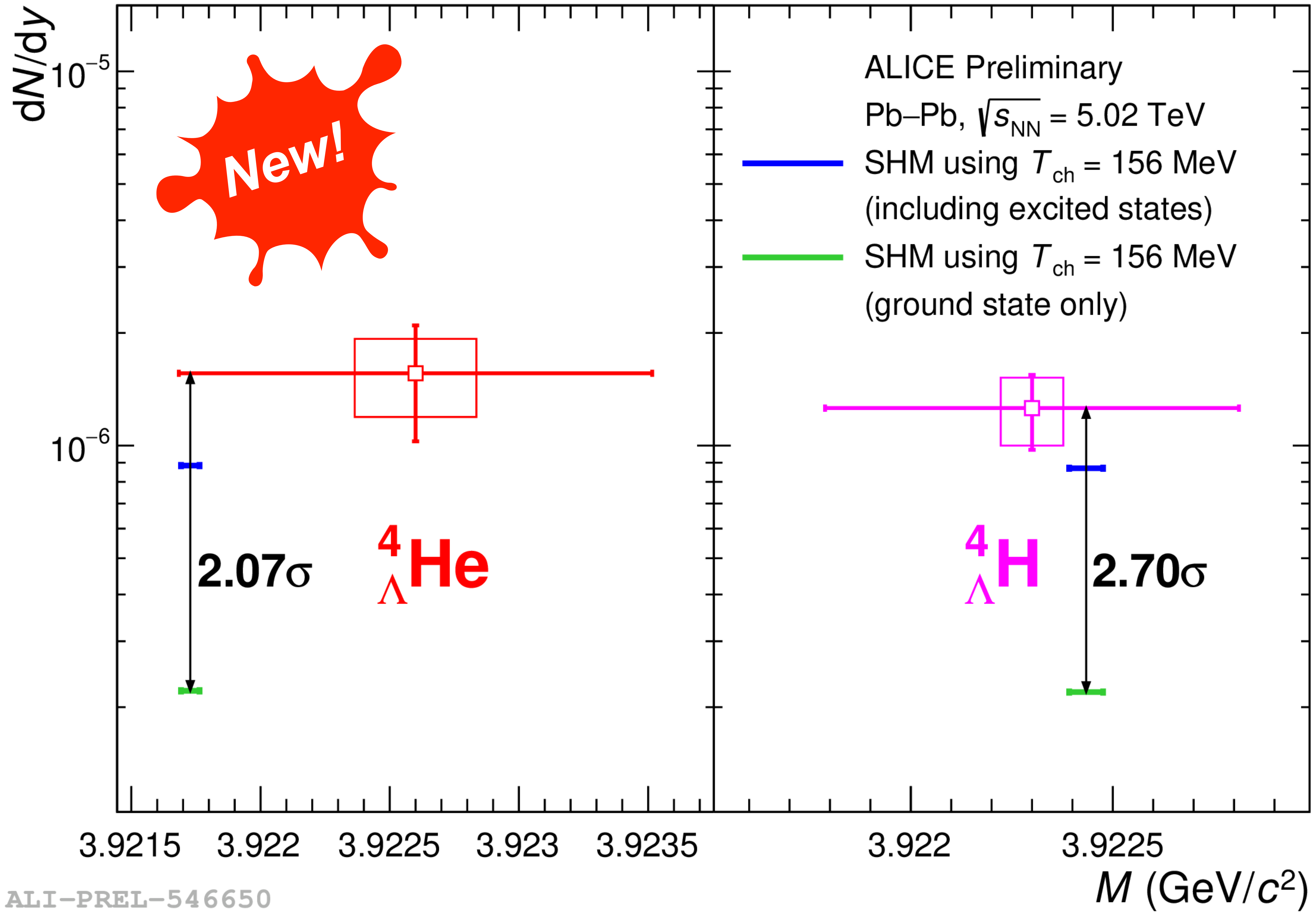
ALI-PERF-546598

Janik Ditzel's poster

A = 4 hypernuclei in ALICE: comparison with SHM

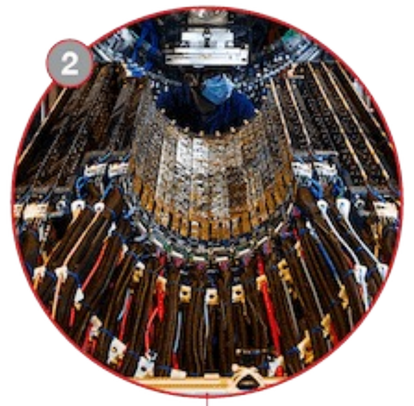
Testing the dependence of the yields of the SHM with the spin-degeneracy

- Results agree with hypothesis of excited states for both (anti)hypernuclei
- Shedding light on the charge symmetry breaking
  - Not understood from theoretical point of view
  - Large statistical uncertainties, more to come with Run 3 data!



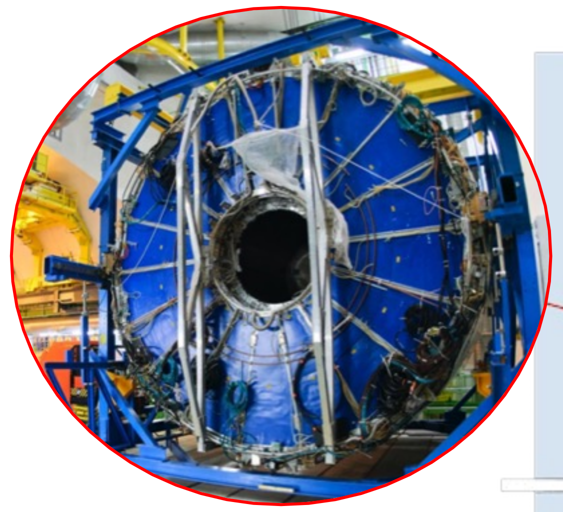
Janik Ditzel's poster

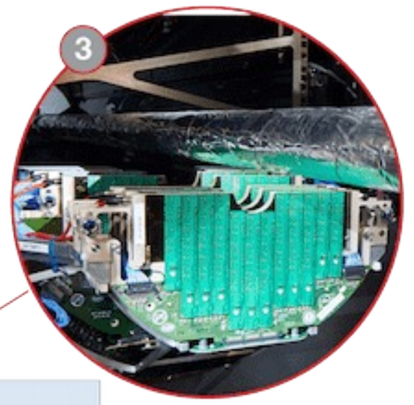
ALICE in 2010’s → ALICE in 2020’s



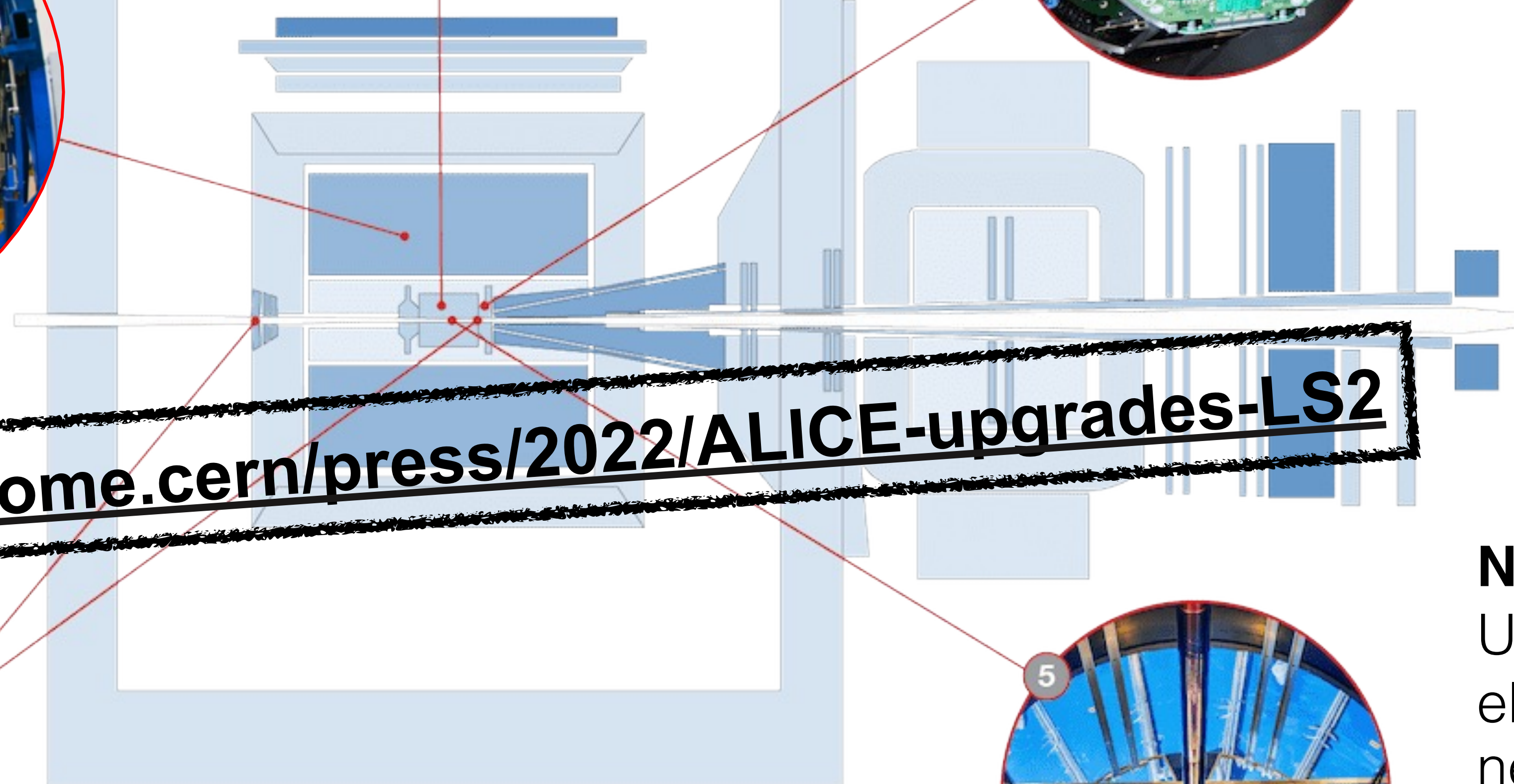
New Inner Tracking System (ITS)
– 7 barrels, 10 m² silicon tracker
based on MAPS (12.5 G pixels`

New GEM-based TPC
with continuous readout



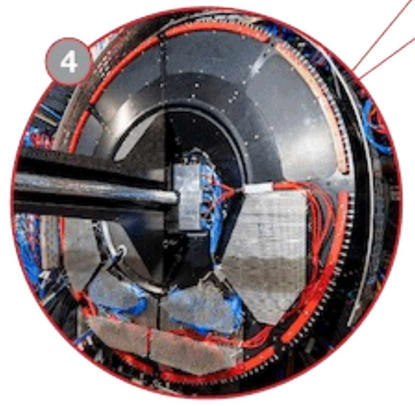


New Muon Forward Tracker (MFT) - 5 disks
based on MAPS

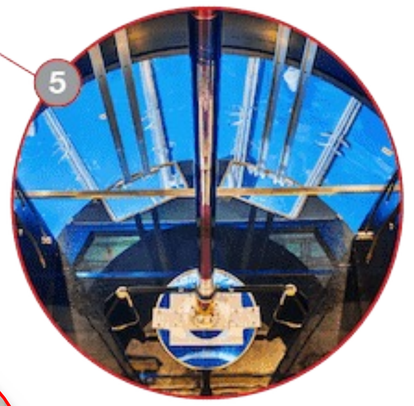


https://home.cern/press/2022/ALICE-upgrades-LS2

New Trigger and Readout
Upgrade of readout electronics of all detector, new Central Trigger Processor



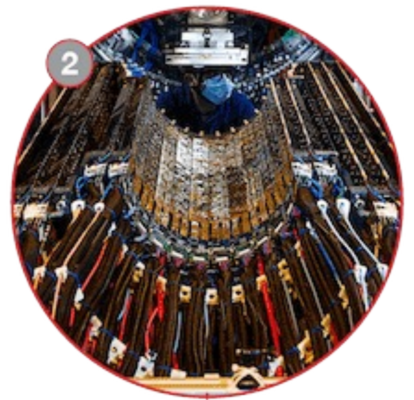
New Online/Offline (O2)



New Fast Interaction Trigger (FIT)
– 3 detector technologies: interaction trigger, online luminometer, forward multiplicity

New Beampipe
smaller diameter (36.4 mm), first detection layer at 20 mm

ALICE in 2010's → ALICE in 2020's



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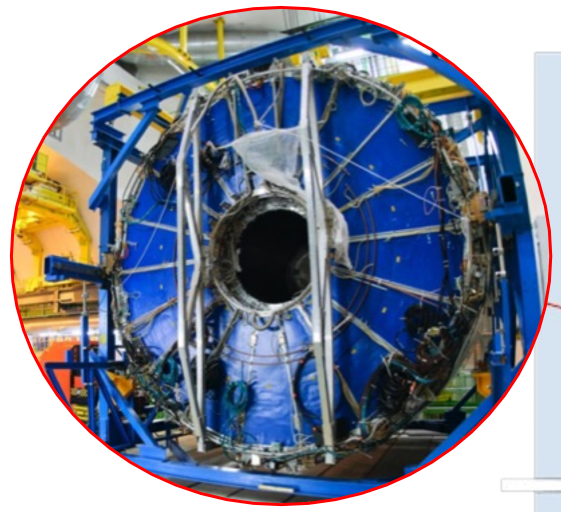

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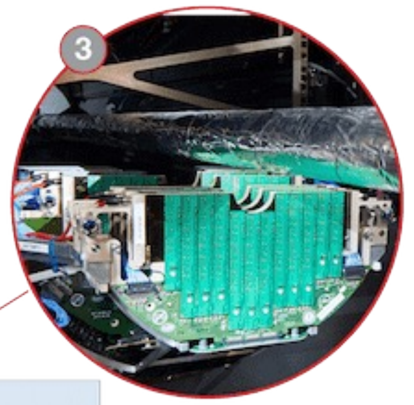

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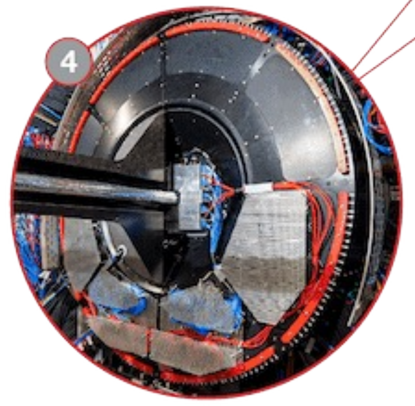

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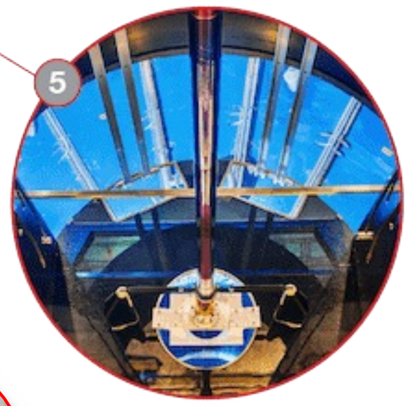
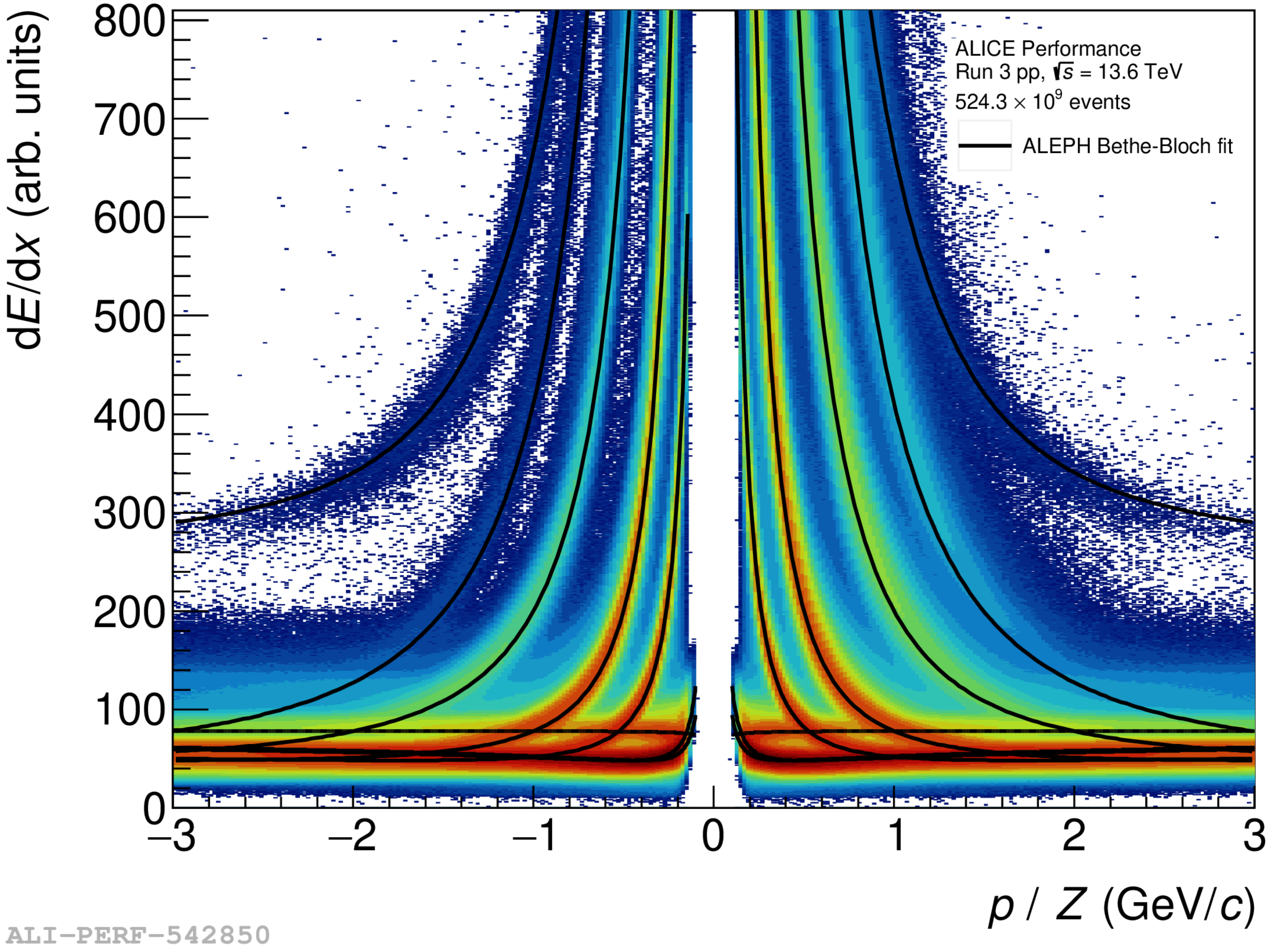


New Beampipe
smaller diameter (36.4 mm), first detection layer at 20 mm

TPC dE/dx from ***524 × 10⁹ events*** *collected in 2022*

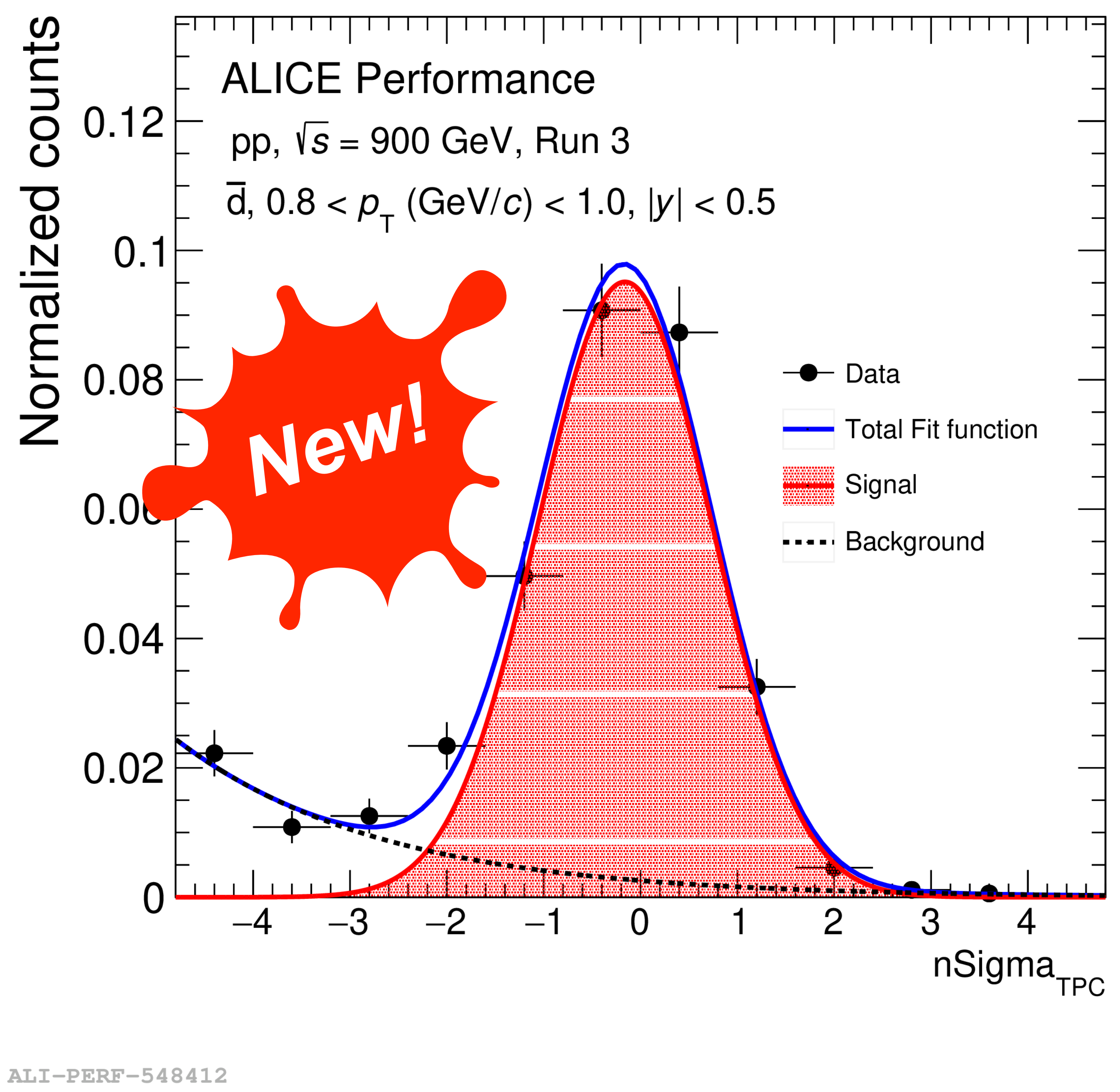


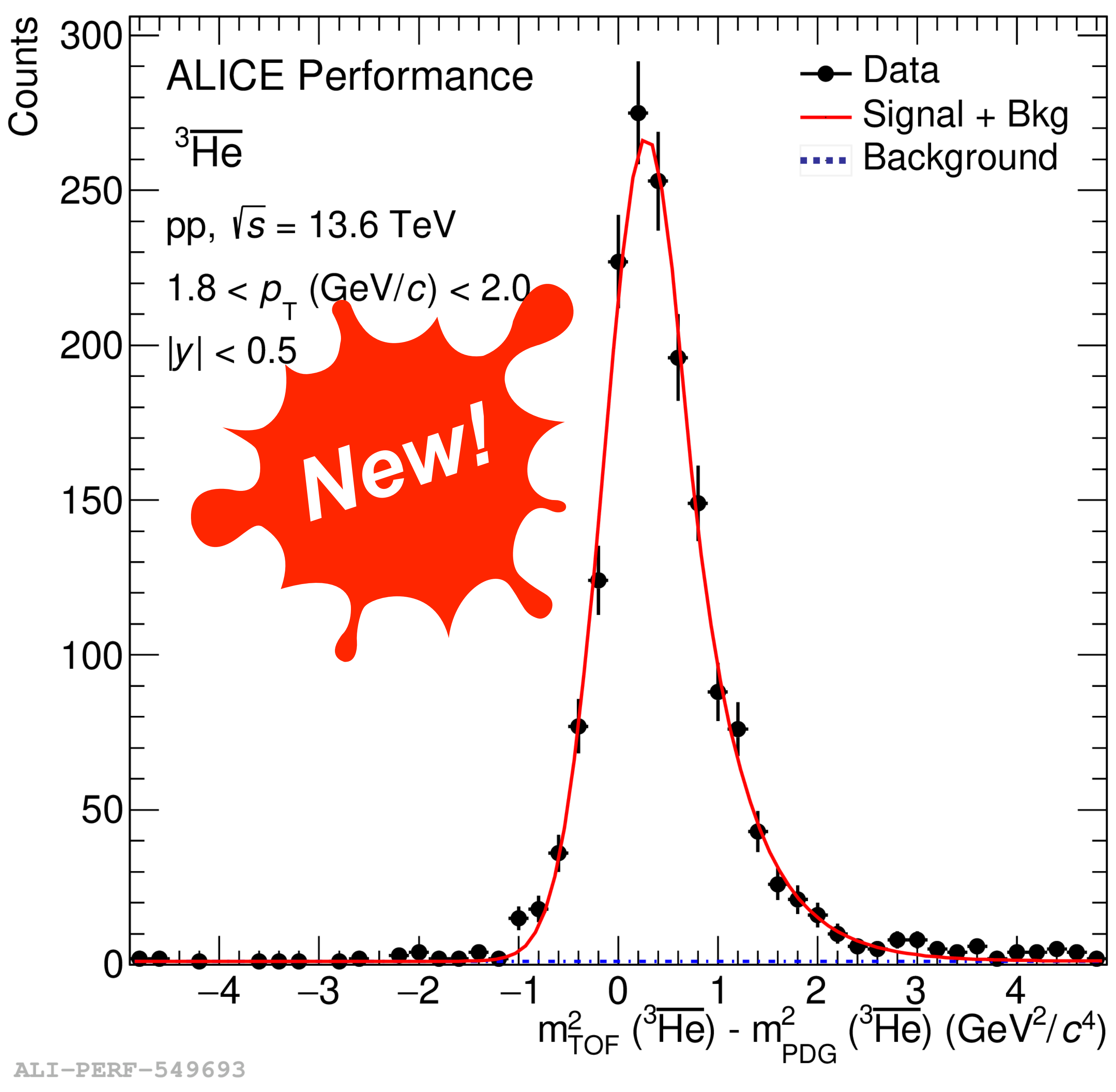
Latest news from Run 3 data: (anti)nuclei identification

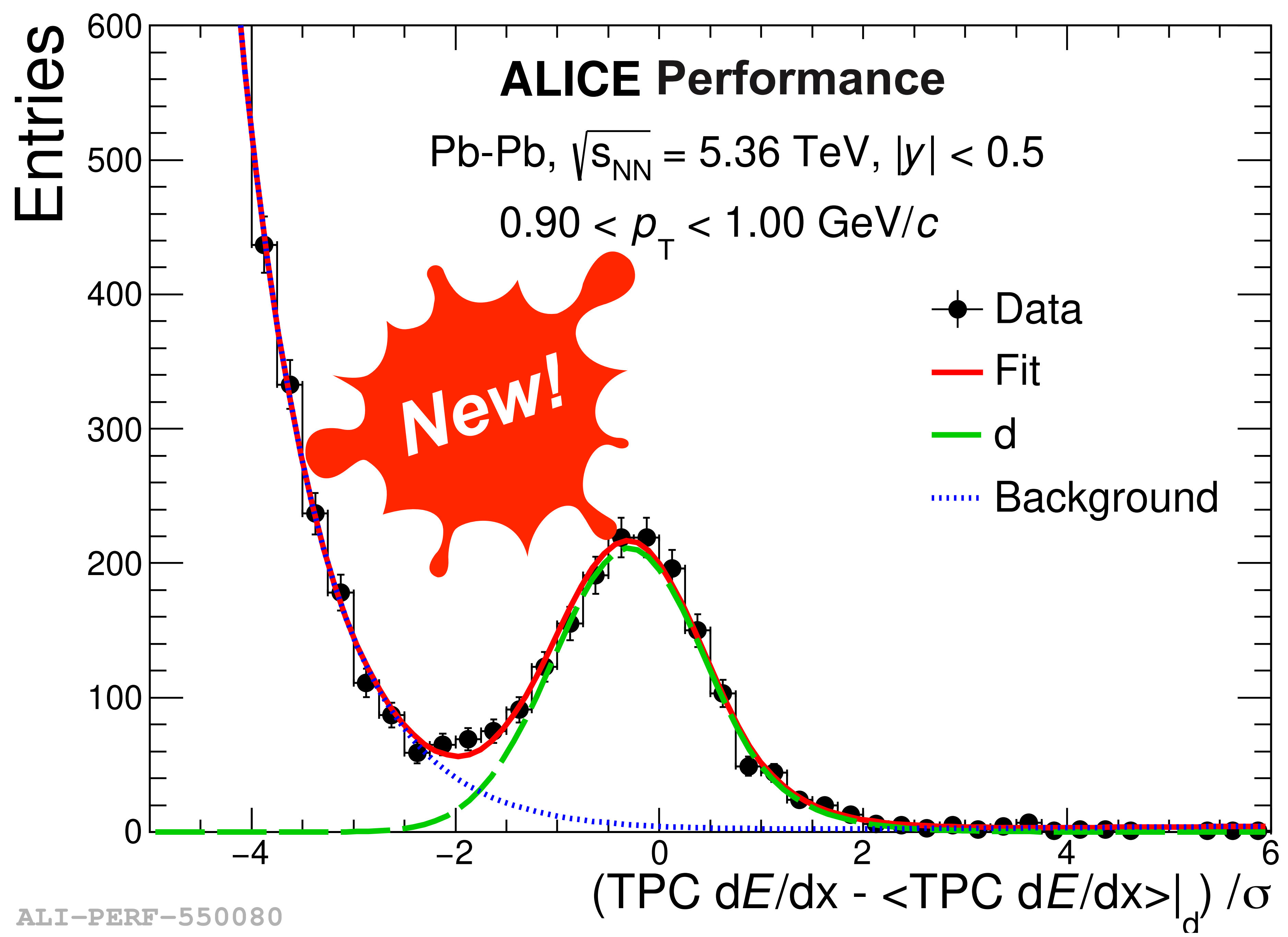
ALICE

(Anti)nuclei identification with upgraded ALICE detector in TPC and TOF systems

- Clean signal of (anti)nuclei in pp and Pb−Pb collisions ✅







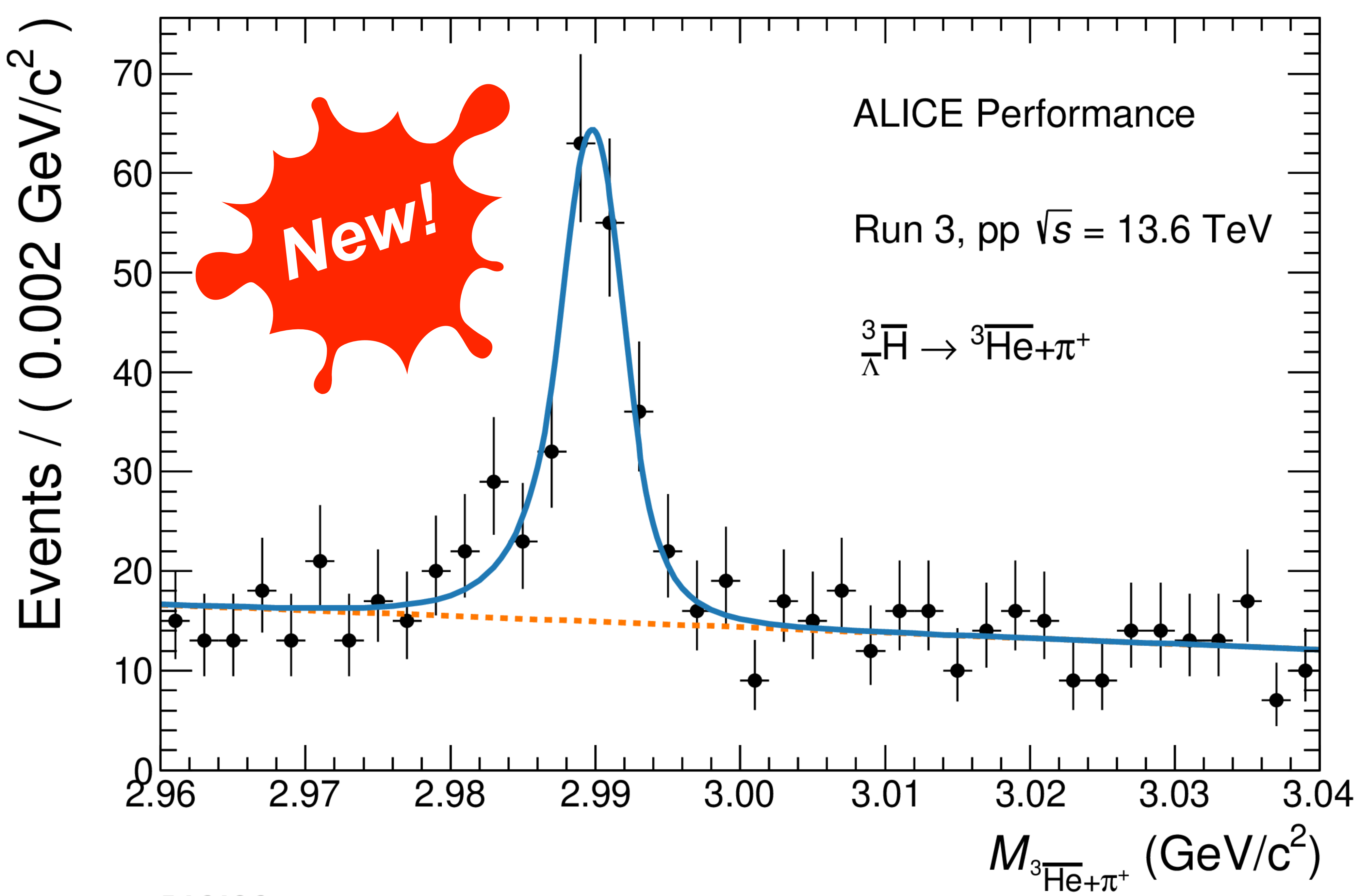
Giovanni Malfattore's poster

Latest news from Run 3 data: (anti)hypernuclei in pp!

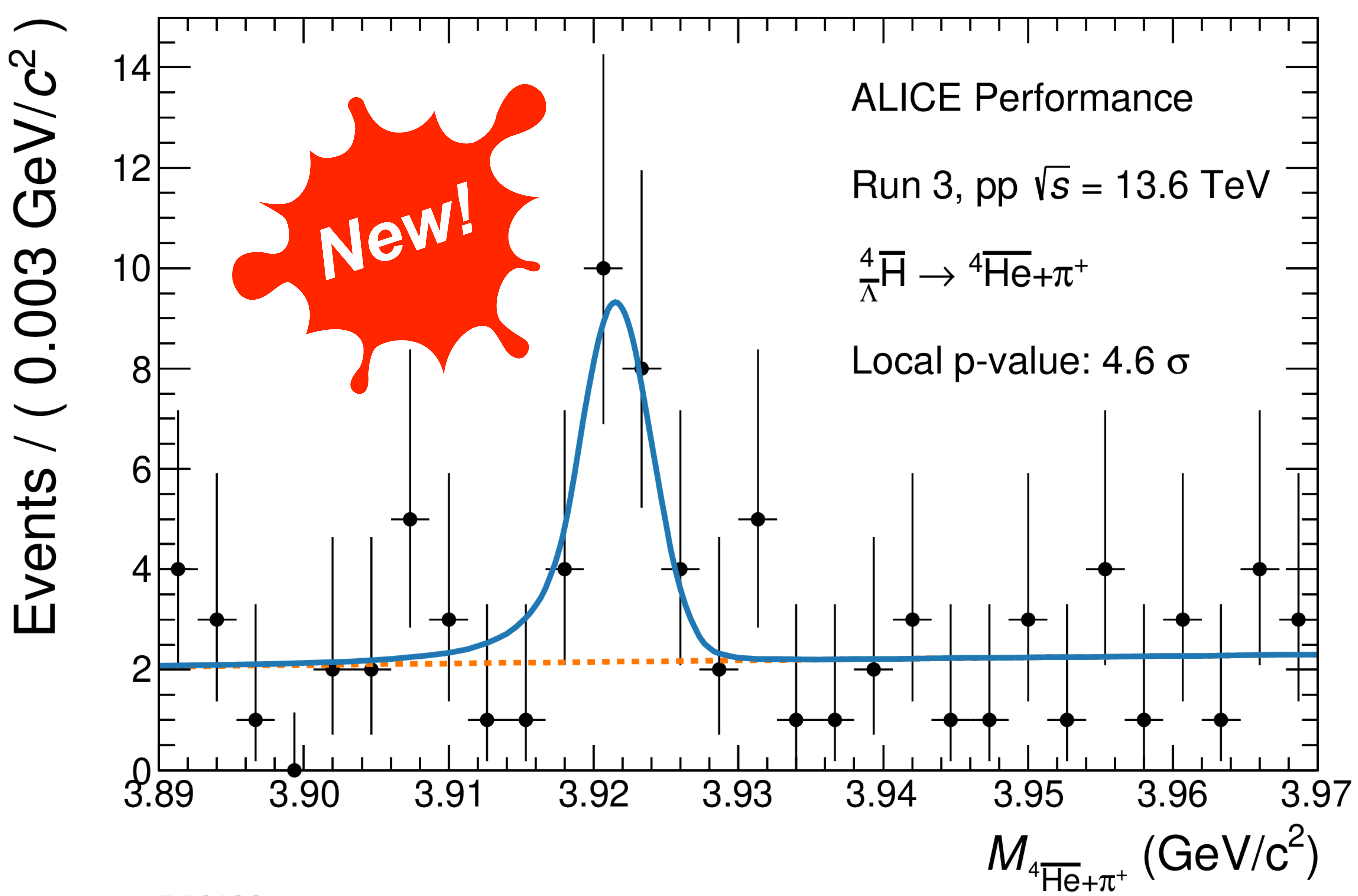
First invariant-mass spectra of $^{3}_{\Lambda}\mathrm{H}$ and $^{4}_{\Lambda}\mathrm{H}$ in pp collisions at 13.6 TeV!

Large data sample to be analysed:

- Precise studies of lifetime and binding energy in small systems
- Production yield as a function of multiplicity
- Comparison with theoretical models to unprecedented precision!



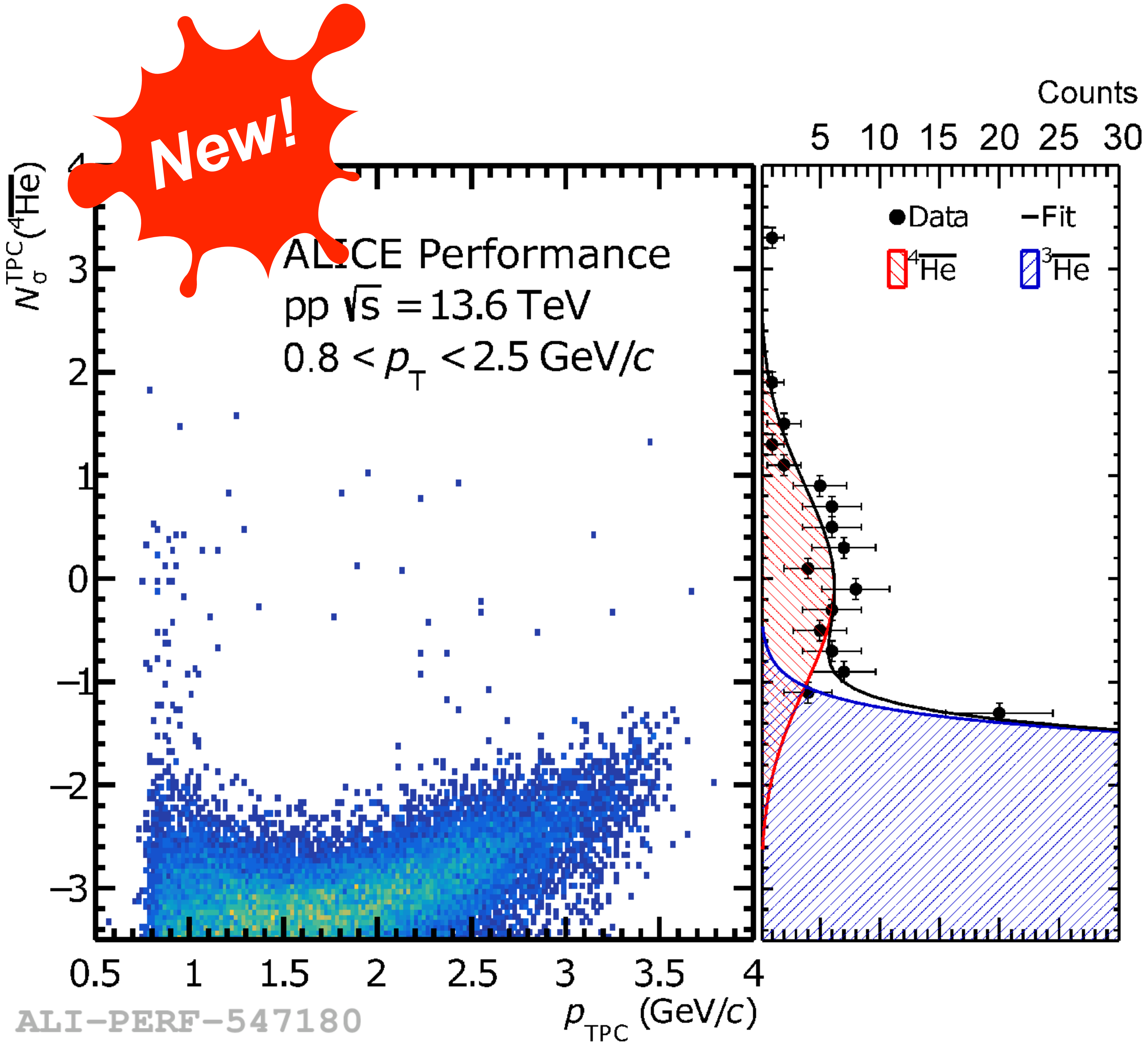
ALI-PERF-546496



ALI-PERF-546499

Latest news from Run 3 data: $^{4}\overline{\mathrm{He}}$ in pp!

First signal of $^{4}\overline{\mathrm{He}}$ in pp collisions!



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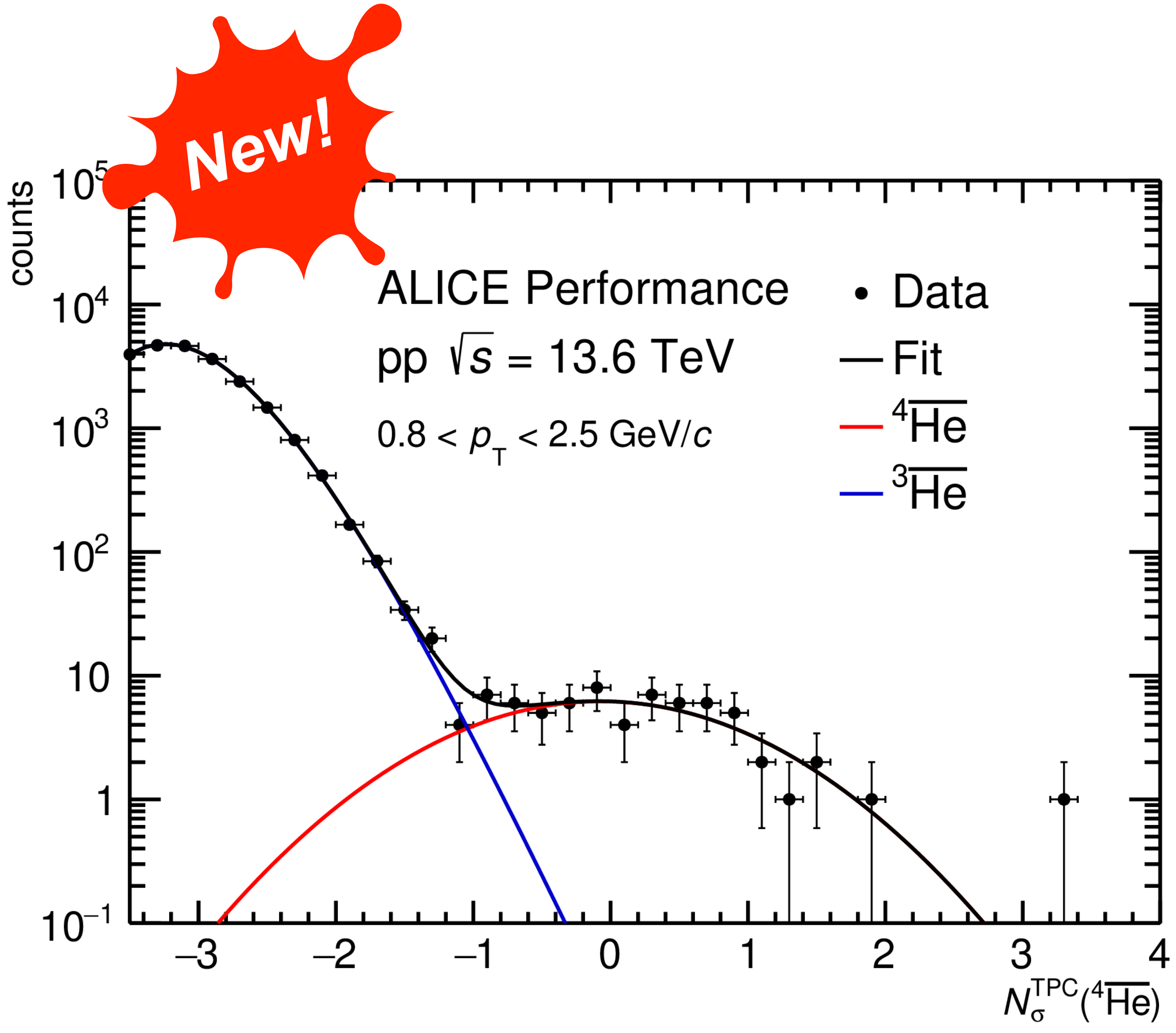


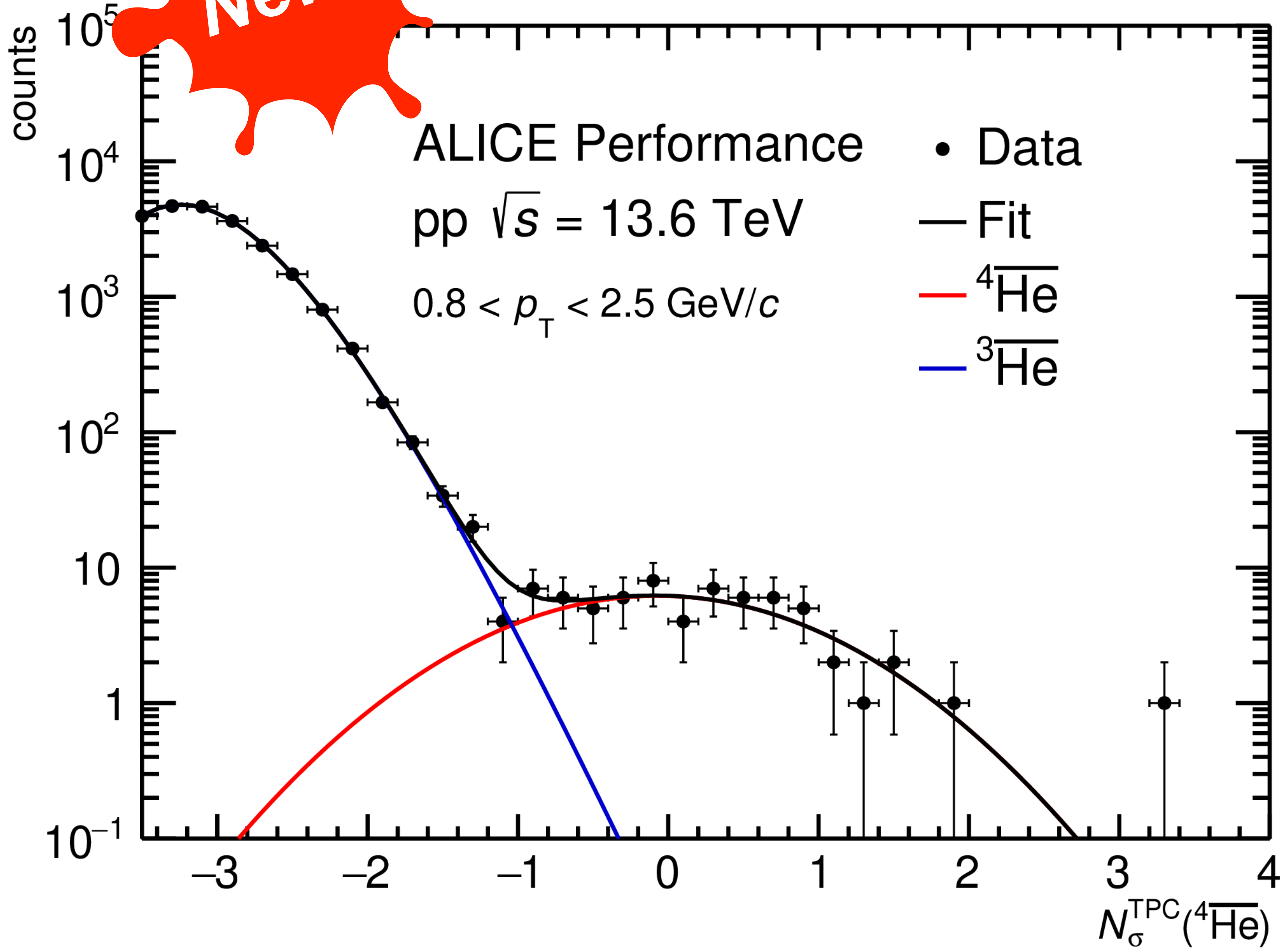
Latest news from Run 3 data: $^{4}\overline{\mathrm{He}}$ in pp!

ALICE

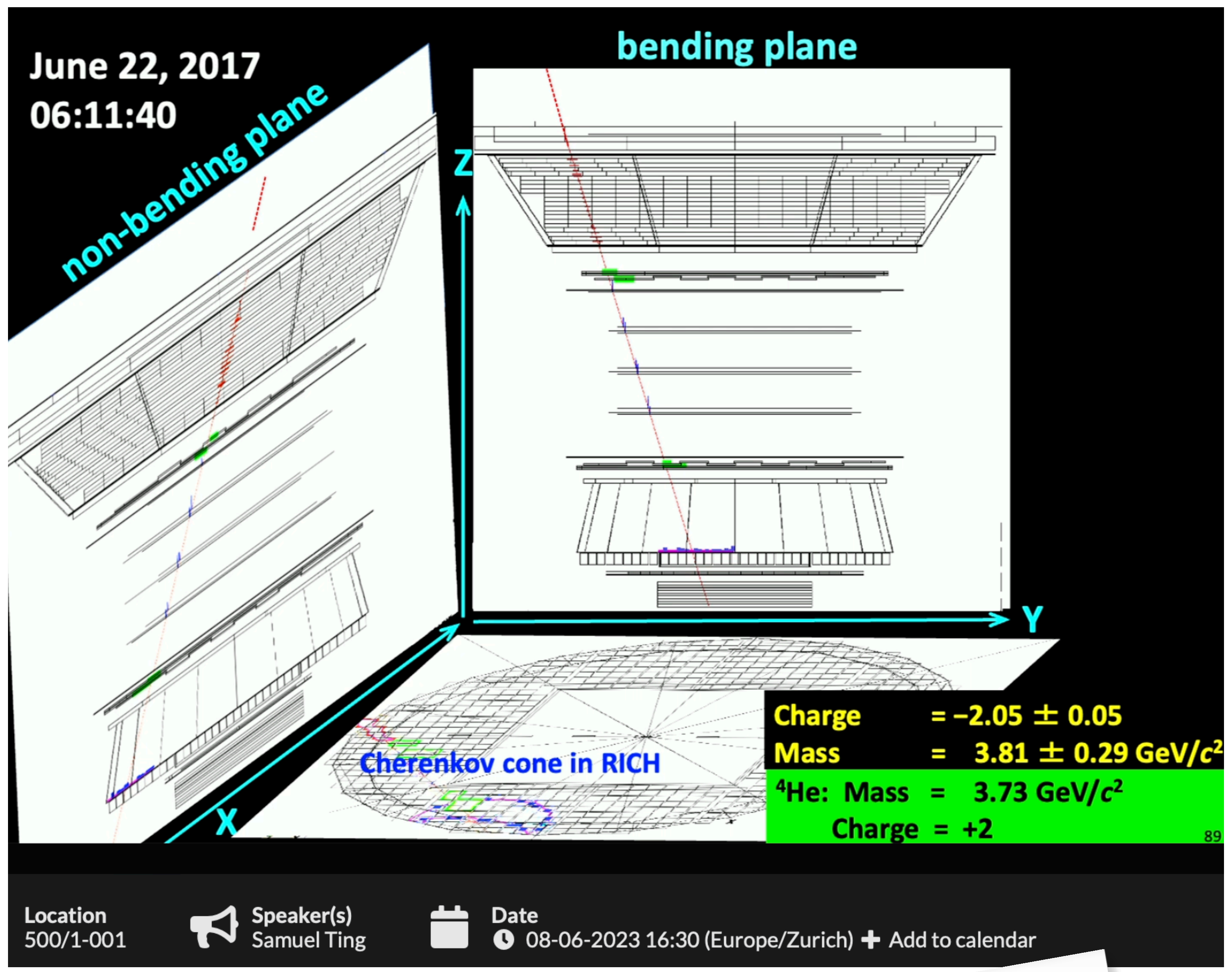
First signal of $^{4}\overline{\mathrm{He}}$ in pp collisions!

- Of great importance for astrophysics, in context of potential $^{4}\overline{\mathrm{He}}$ events in AMS-02! [1]
- Will help to constrain astrophysical background based on experimental data [2]

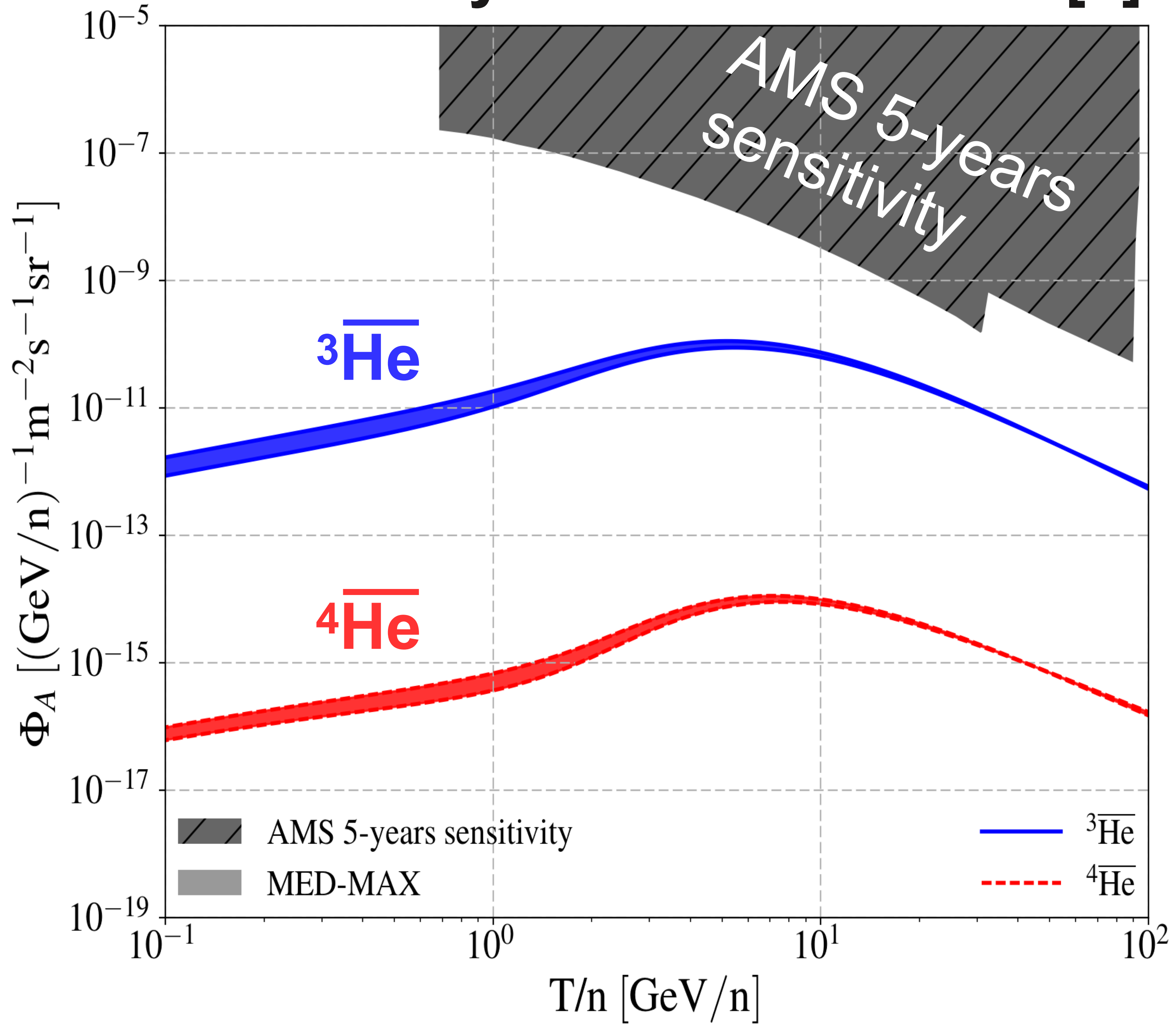
New!



$^{4}\overline{\mathrm{He}}$ event in AMS-02 [1]



Secondary antihelium fluxes [2]



Chiara Pinto, Wed 6 Sept, 12:40

[1] S. Ting, CERN Colloquium 2023
[2] Poulin et al., Phys. Rev. D99 (2019) 023016

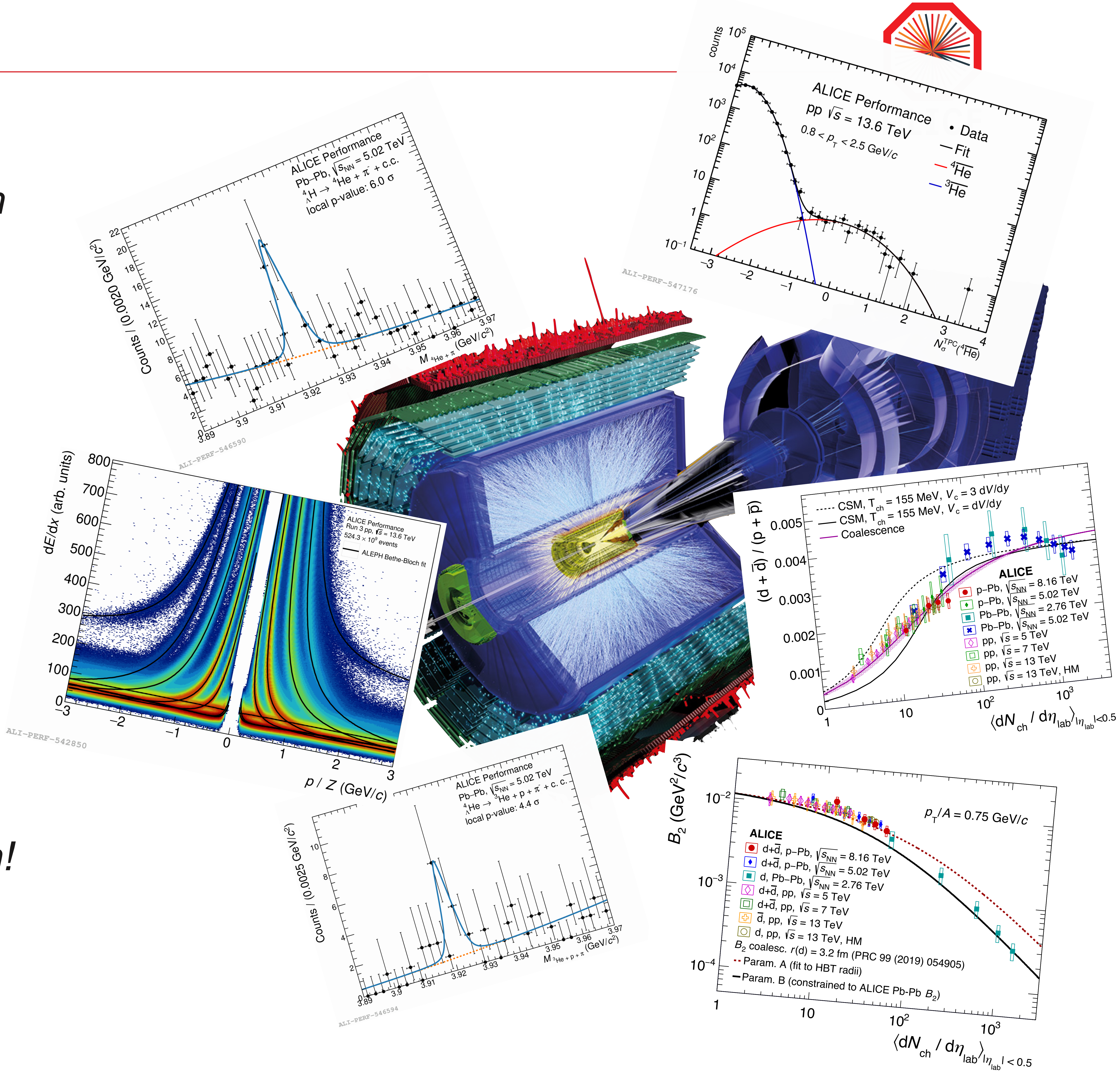
Summary

ALICE is in unique position to study the production of (anti)(hyper)nuclei at the LHC!

Results are an important input for:

- Nuclear physics
  - Understanding the production mechanisms
  - Testing theoretical nuclear models
- Astrophysical applications
  - Equation of state of neutron stars
  - Indirect dark matter searches with antinuclei in space

Much more to come with ongoing Run 3 campaign!



Summary

ALICE is in unique position to study the production of (anti)(hyper)nuclei at the LHC!

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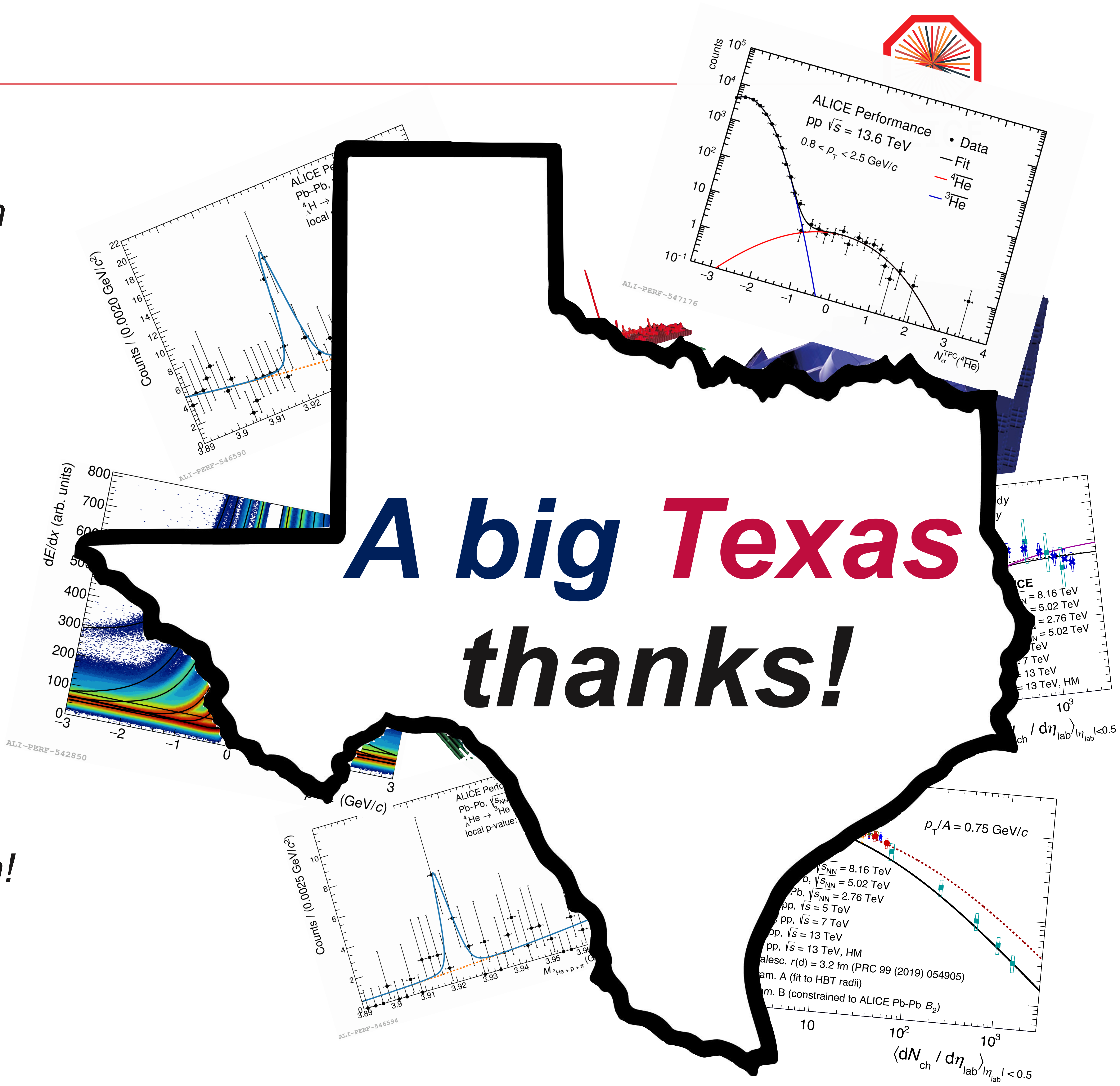
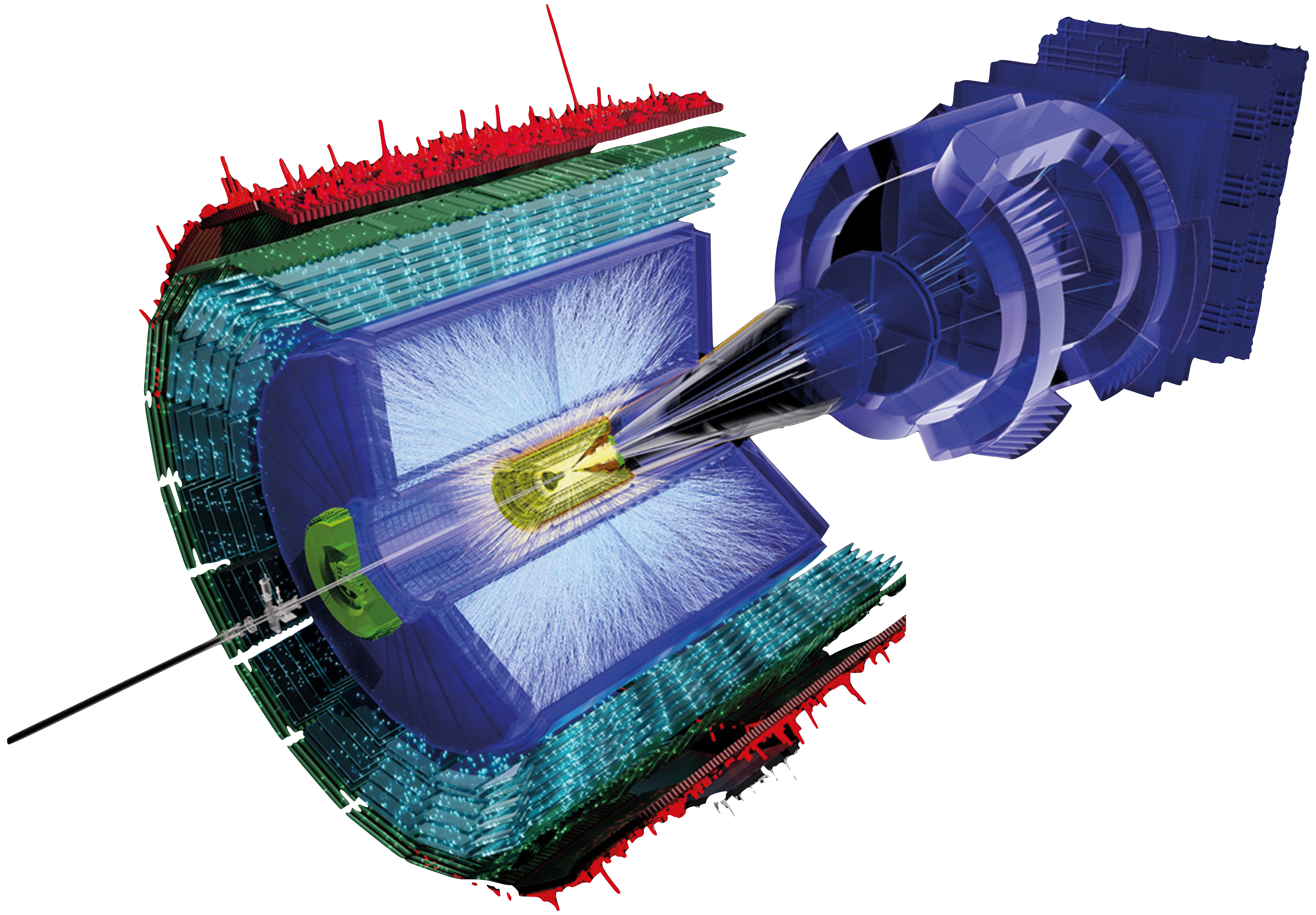
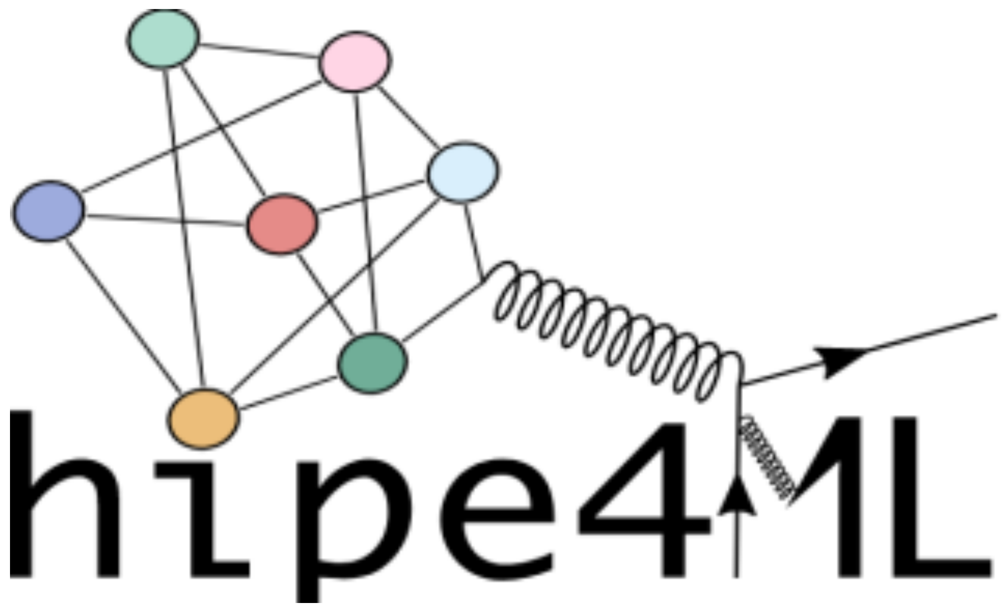


Back-up slides

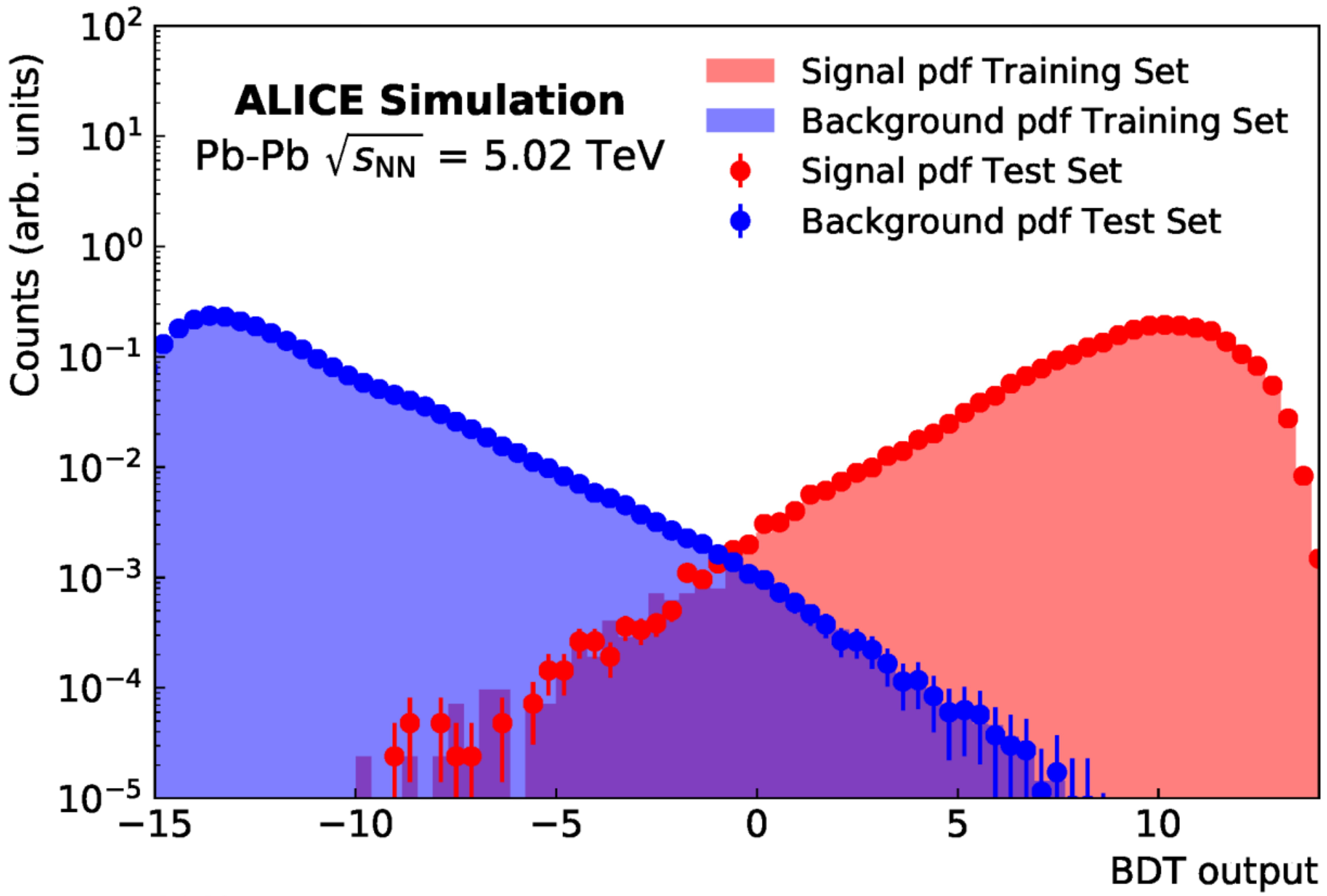


Signal extraction: hypernuclei

- Using a machine learning approach (Boosted Decision Tree) for the signal extraction
- A machine is trained and tested using a dedicated MC sample with injected hypernuclei and a background sample
- The result is a model that is applied on the data and allows a selection via the BDT output value



https://hipe4ml.github.io/

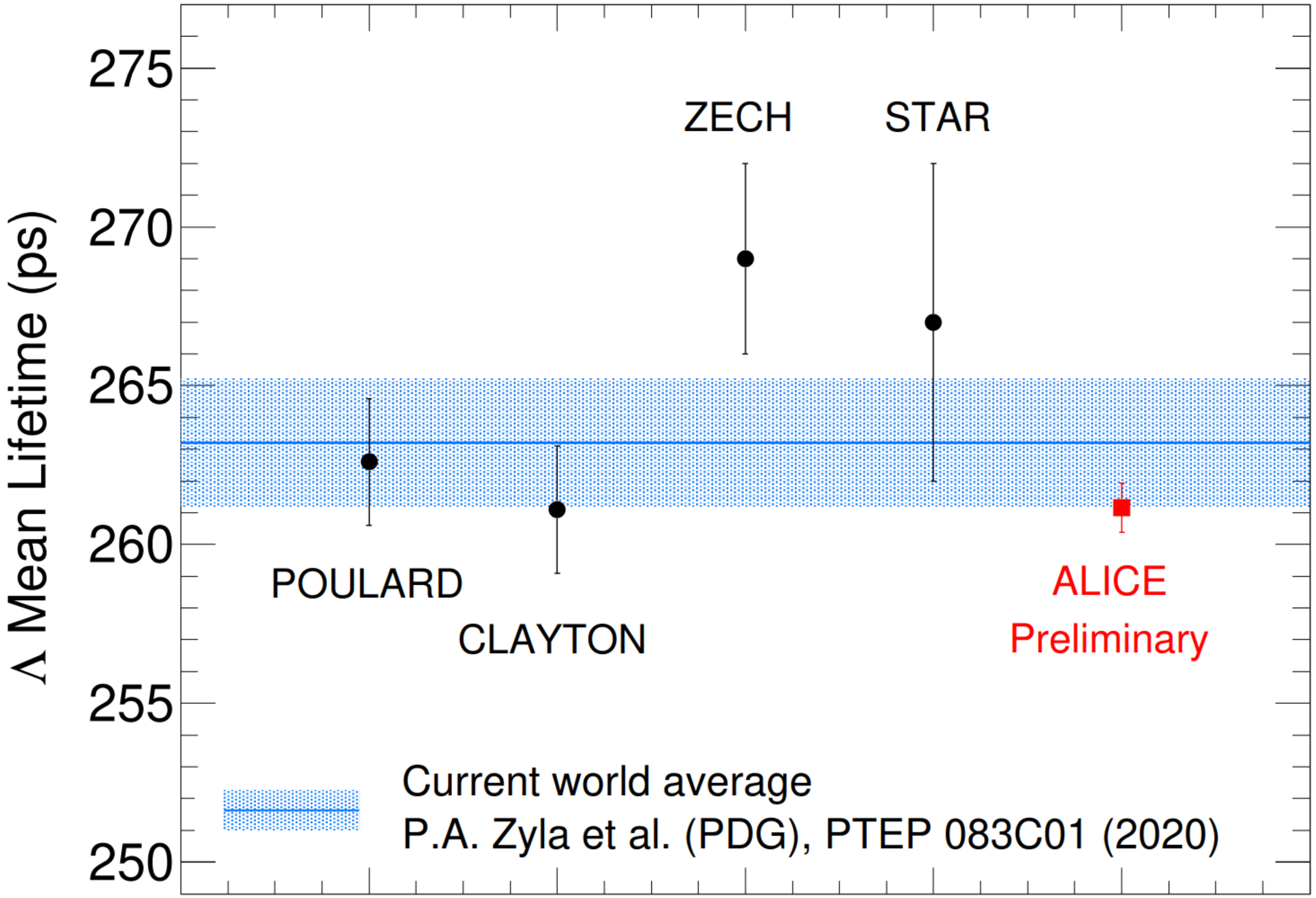


ALI-SIMUL-316844

Free Λ lifetime

New, extremely precise measurement of the free Λ lifetime in Pb−Pb 5.02 TeV

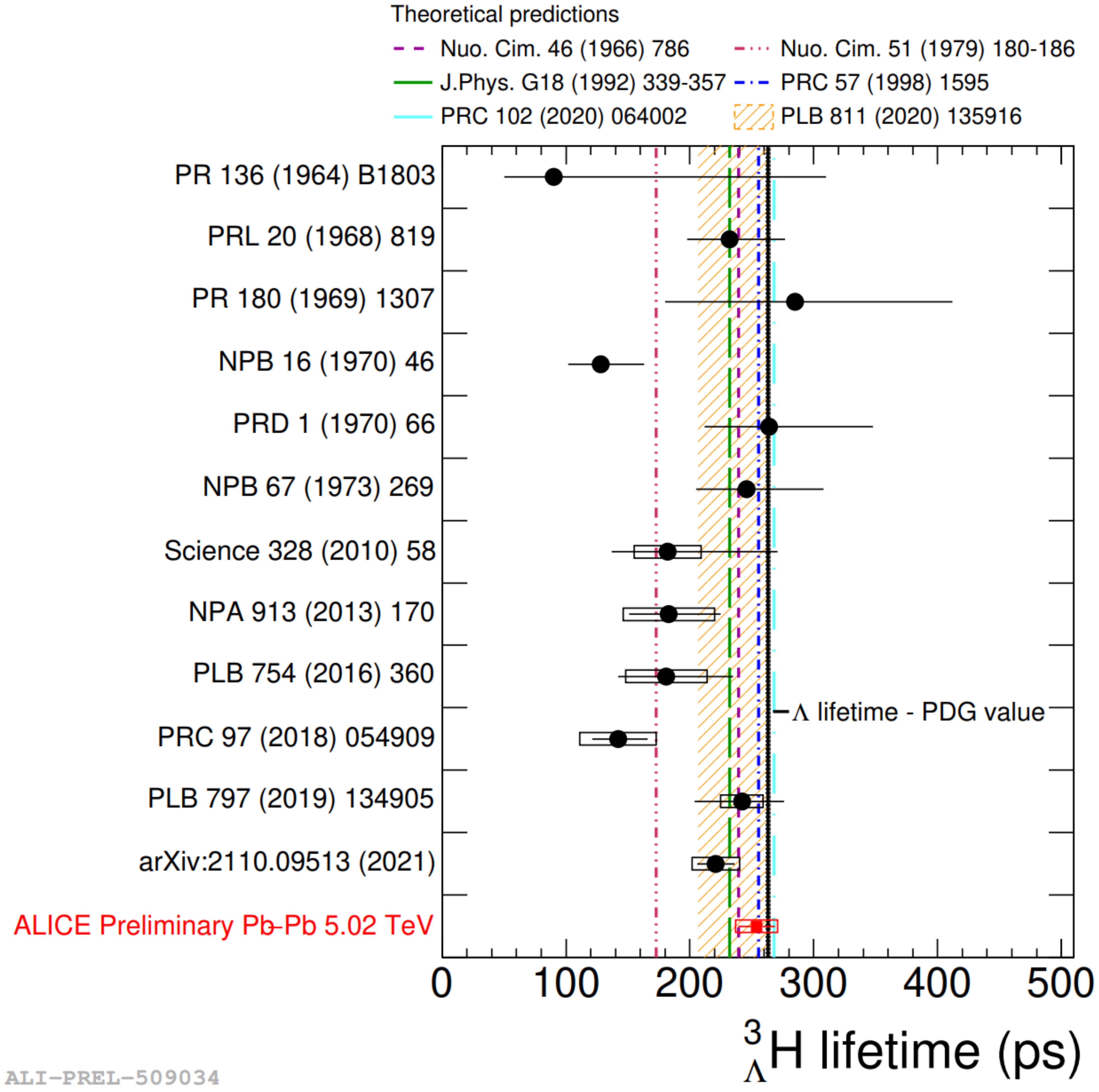
- Reference for the hypertriton lifetime
- About ×3 more precise than the current PDG value!



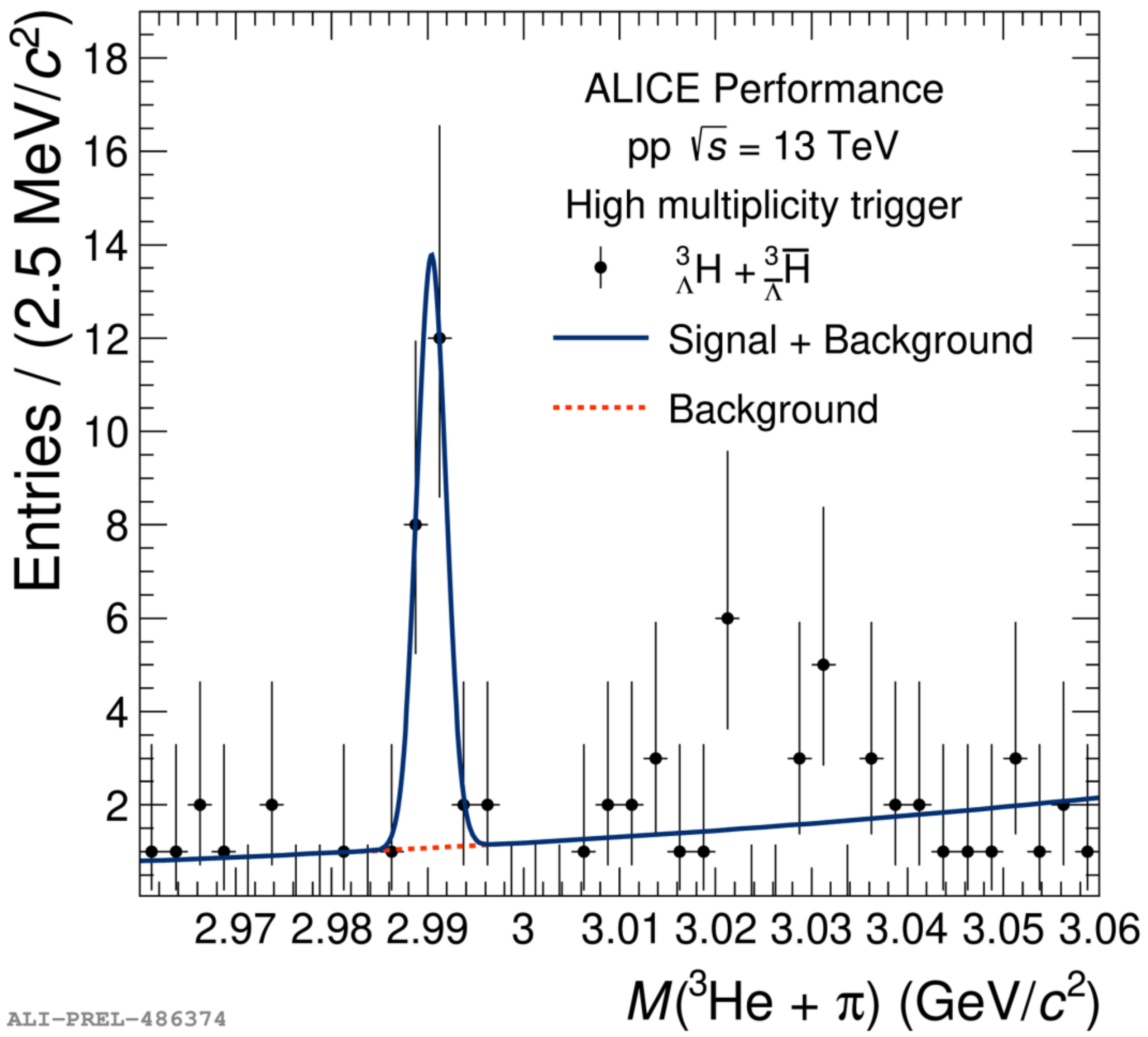
ALI-PREL-505548

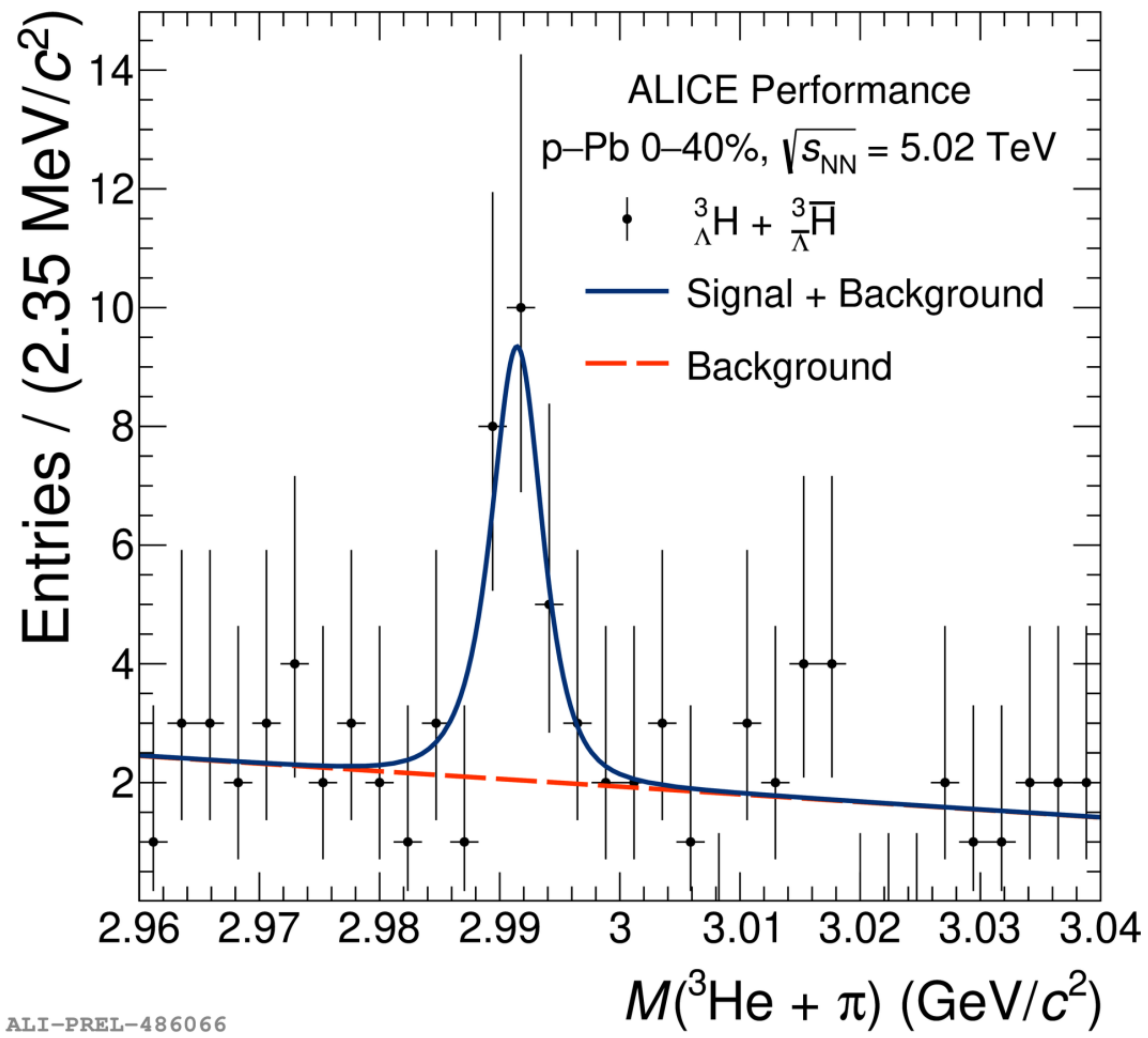
Hypertriton lifetime

Recent measurement in Run 2 Pb−Pb 5.02 TeV
- Compatible with free Λ lifetime



Hypertriton measurements in pp and p−Pb





Wigner function formalism

Projecting the (anti)nucleon density matrix on the deuteron density matrix [1] we have

$$d^3N/dP^3 = S\int d^3q \int d^3r_p \int d^3r_n \, W(q,r) \; W_{np}(p_n,p_p,r_n,r_p)/(2\pi)^6$$

From event generators

- $W(q,r)$: Deuteron Wigner function
- $W_{np}(p_n,p_p,r_n,r_p)$: Wigner function of the p-n state

being $$W_{np}(\vec{P}/2+\vec{q}, \vec{P}/2-\vec{q}, r_n, r_p) = H_{np}(\vec{r}_n, \vec{r}_p) G_{np}(\vec{P}/2+\vec{q}, \vec{P}/2-\vec{q})$$

G_{np}: Nucleon momentum phase-space

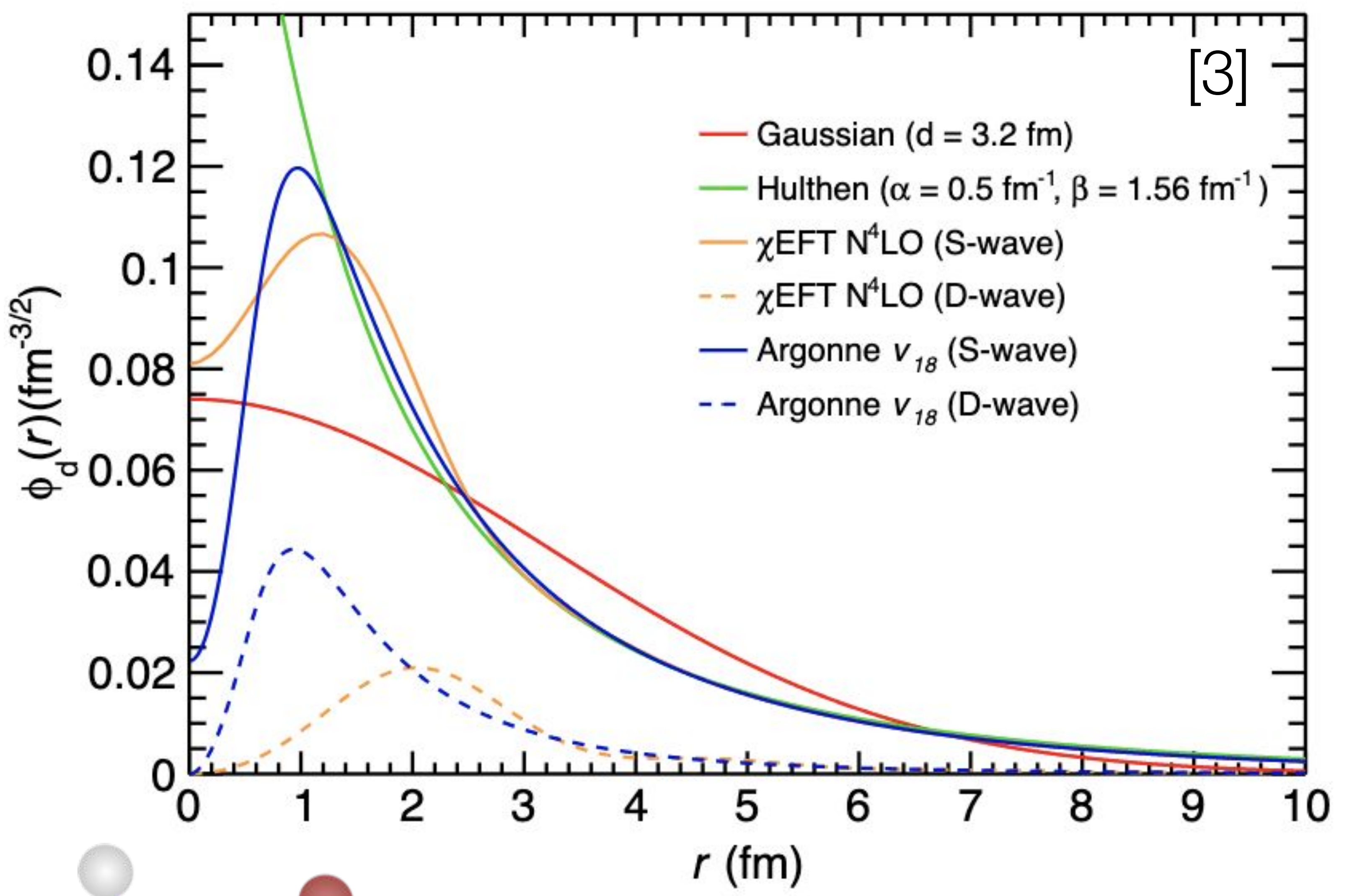
H_{np} is the spatial distribution of nucleons. Assuming a Gaussian source [2] the coalescence probability p(q,σ) as a function of the relative momentum q and size of the emission source σ can be derived

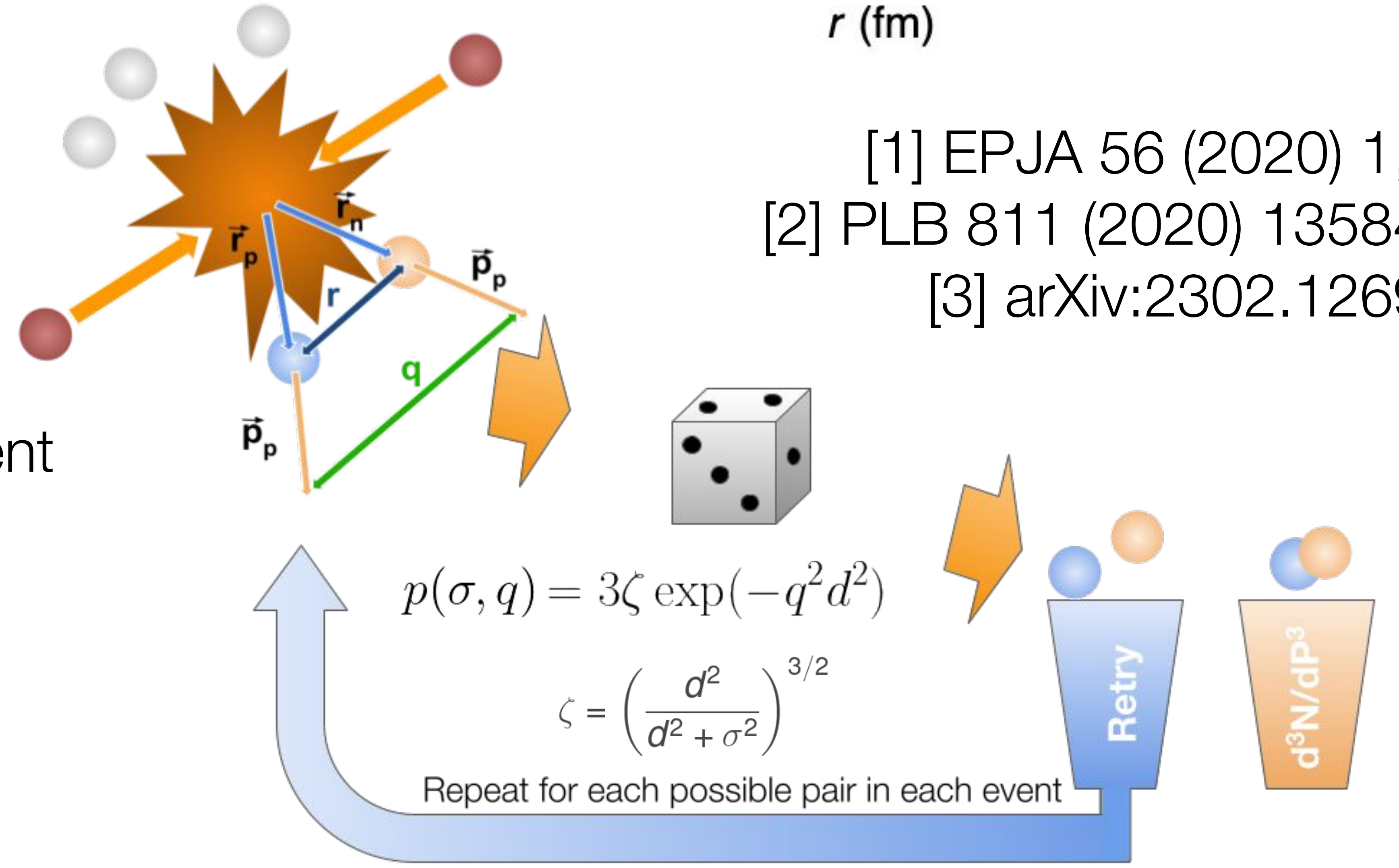
$$p(\sigma,q) = \int d^3r_p d^3r_n h(r_n) h(r_p) W(q,r)$$

This allows us to calculate the coalescence probability for any Wigner function and to probe different wavefunctions ψ for the final state (several options)

$$W(\vec{q},\vec{r}) = \int d^3\zeta \; \Psi(\vec{r}+\vec{\zeta}/2)\Psi^*(\vec{r}-\vec{\zeta}/2)e^{i\vec{q}\vec{\zeta}}$$

This probability can be applied on each (anti)proton-(anti)neutron pair (triplet) in each event





[1] EPJA 56 (2020) 1, 4
[2] PLB 811 (2020) 135849
[3] arXiv:2302.12696