Measurements of resonances and exotic bound states with ALICE

NSTAR 2022 - The 13th International Workshop on the Physics of Excited Nucleons

Alberto Calivà for the ALICE Collaboration
University of Salerno and INFN
18 October 2022

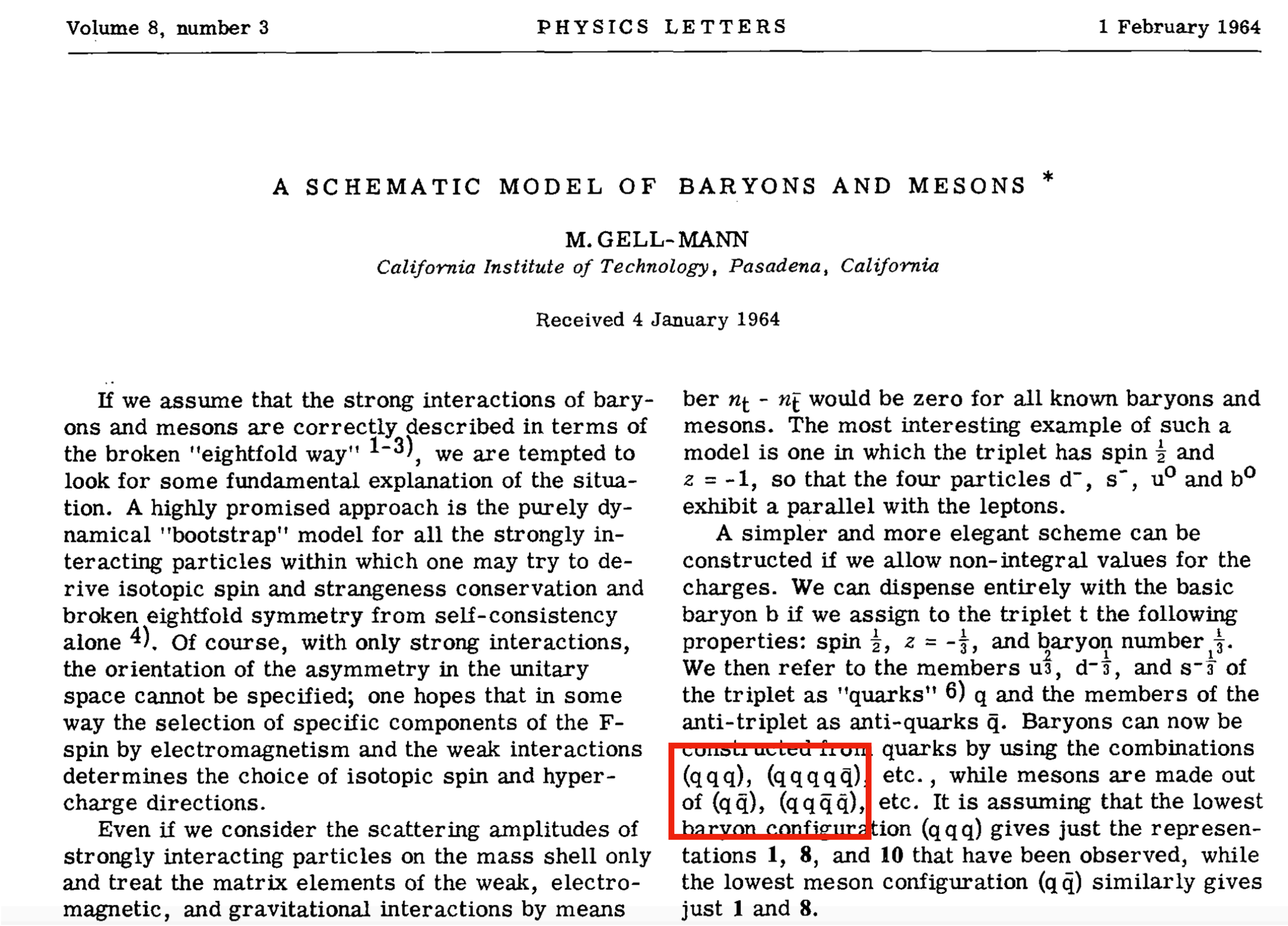
UNIVERSITÀ DEGLI STUDI DI SALERNO

Istituto Nazionale di Fisica Nucleare
SEZIONE DI NAPOLI
Gruppo Collegato di Salerno

CERN

ALICE

Introduction: Exotic hadrons


Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

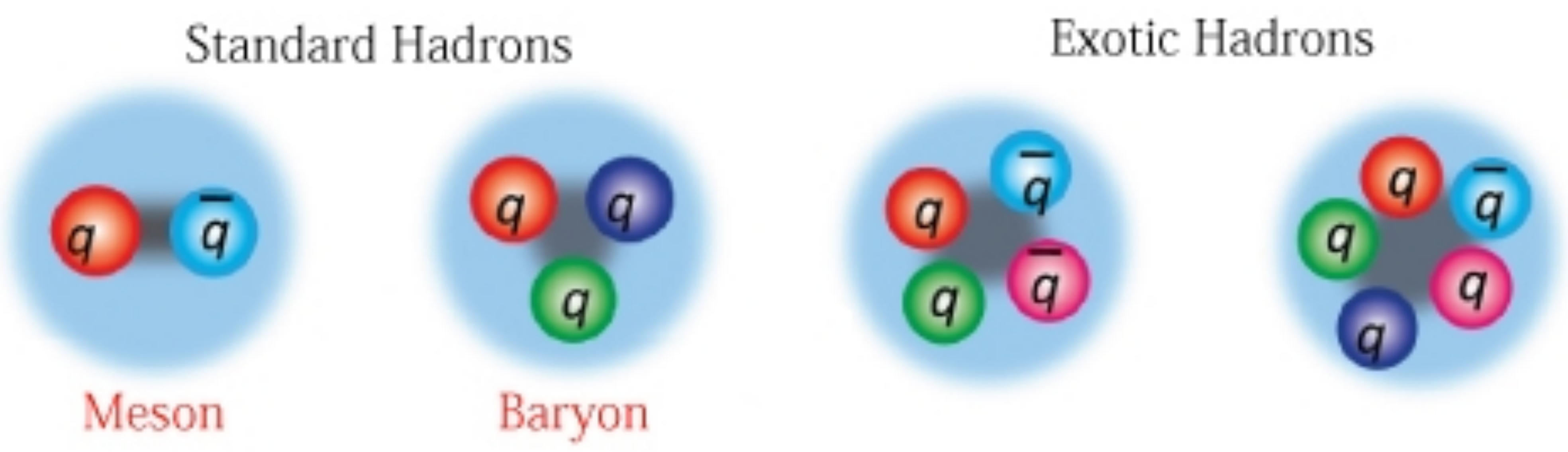
Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.



Detailed understanding of QCD requires study of **"exotic" hadrons** and their possible excitations

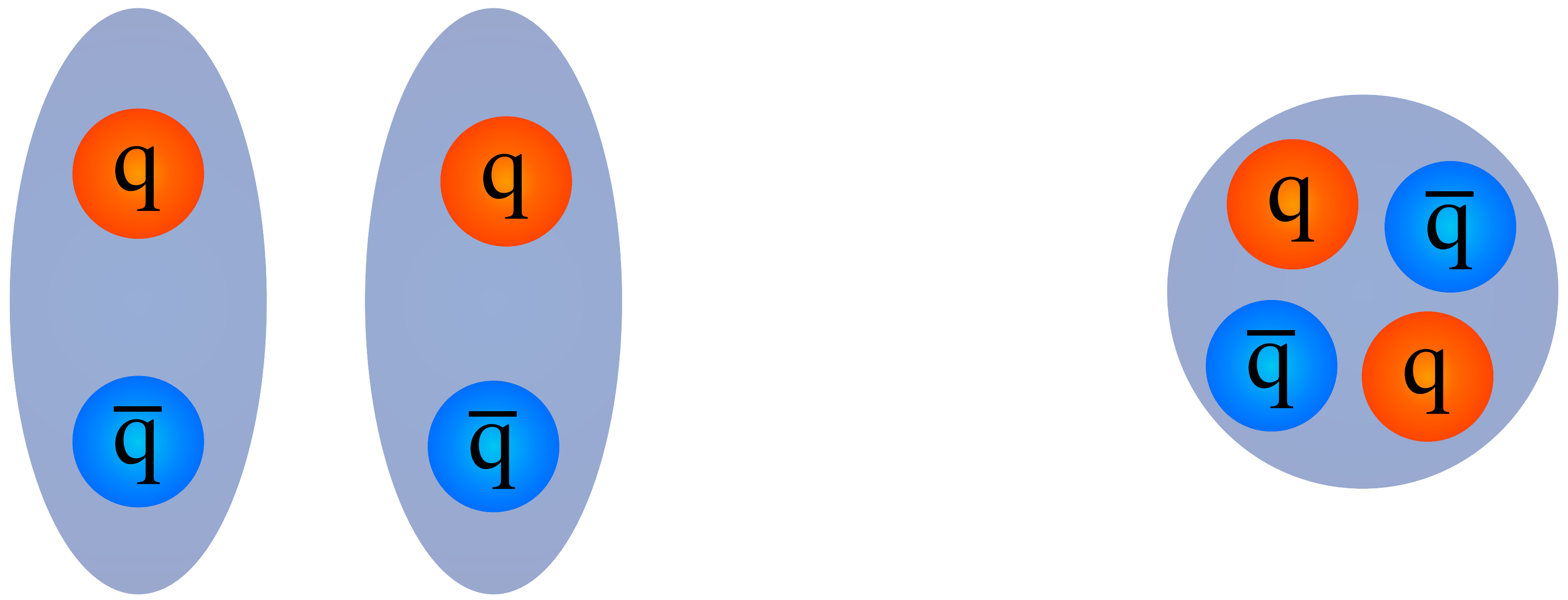
Exotic hadrons are combinations of quarks and antiquarks with "unusual" configurations

ALICE at LHC is the ideal laboratory for studies and searches for exotic hadrons

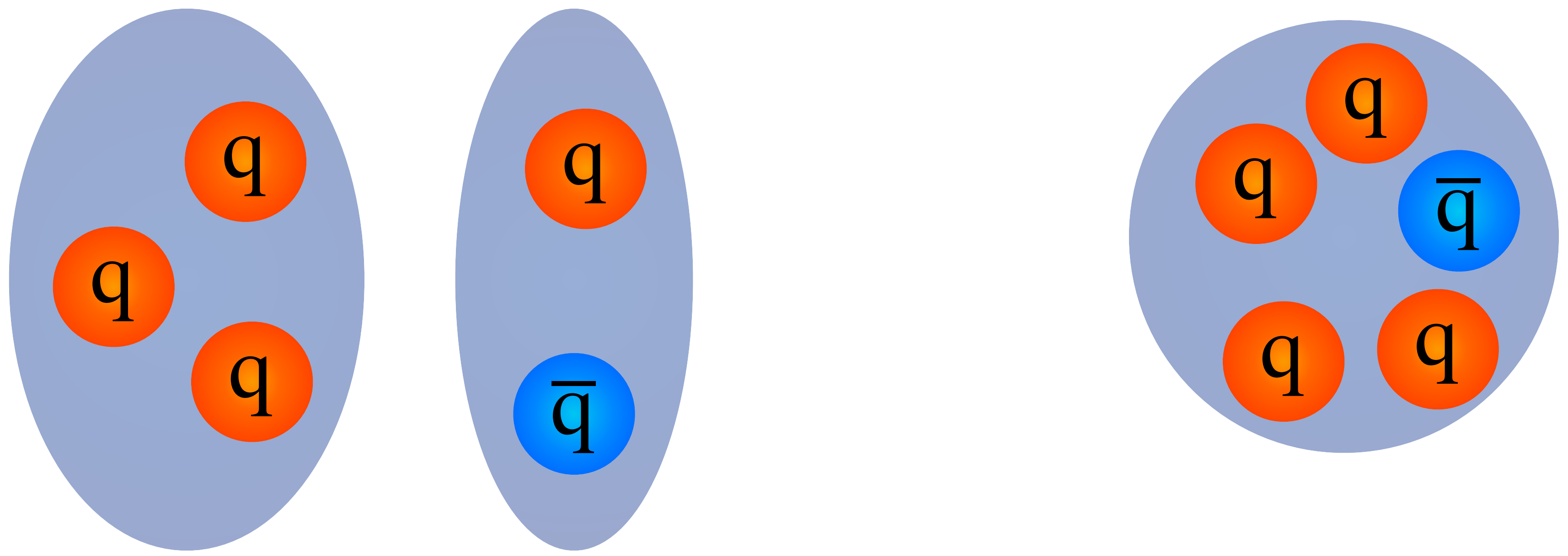
Exotic hadron structure

Study of the internal structure of exotic hadrons gives information
on the strong interaction and their production mechanism

Tetraquark: meson-meson molecule or compact $qq\bar{q}\bar{q}$ state



Pentaquark: meson-baryon molecule or compact $qqqq\bar{q}$ state



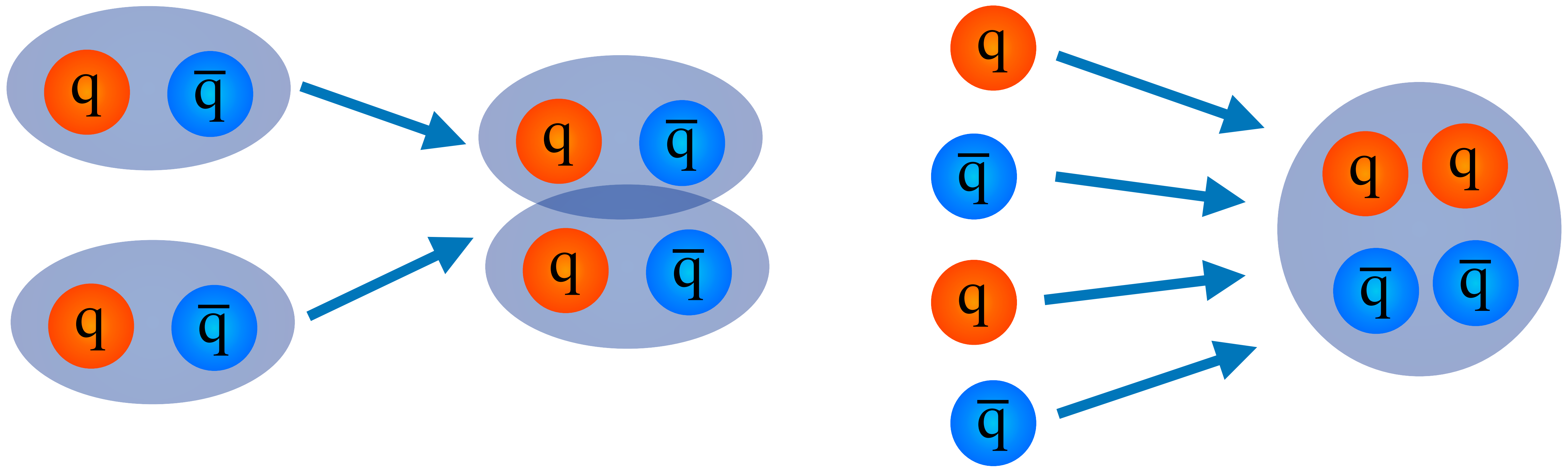
Yields predicted by competing phenomenological models:

- statistical hadronization model
- hadron coalescence

Hadron coalescence

<u>Hadron coalescence model</u>:

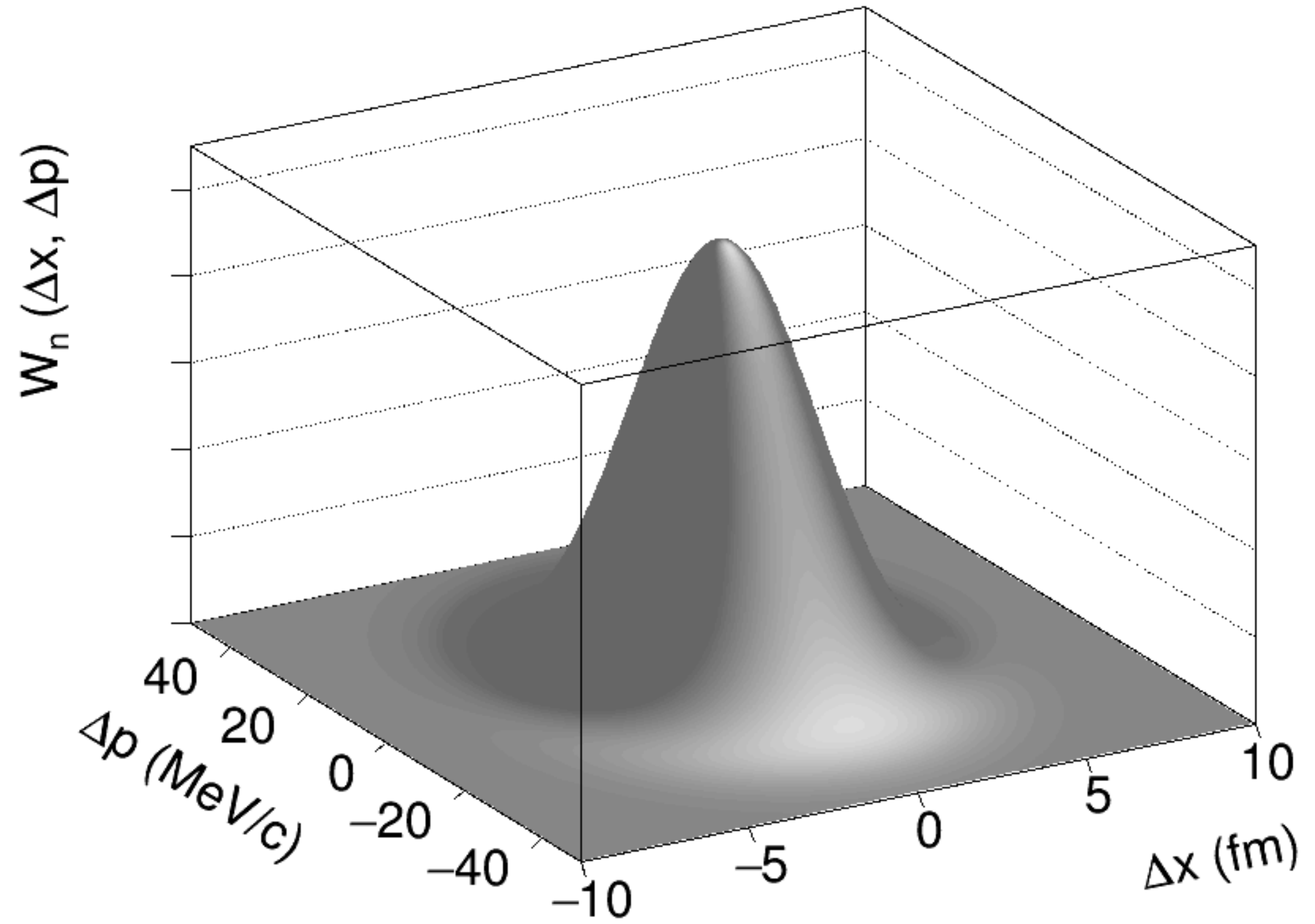
Exotic hadrons formed by coalescence of quarks or hadrons close in phase space



Yield of exotic hadrons in the state-of-the-art coalescence implementations:

$$N_H = g_H \cdot \int d^3x_1 \dots d^3x_n \cdot d^3k_1 \dots d^3k_n \cdot f_1(x_1, k_1) \cdot f_n(x_n, k_n) \cdot W_n(x_1, \dots, x_n, k_1, \dots k_n)$$

- g_H: spin (isospin) degeneracy factor
- $f_1(x_1, k_1) \cdot f_n(x_n, k_n)$: phase space distributions of (point-like) hadrons/quarks
- $W_n(x_1, \dots, x_n, k_1, \dots k_n)$: Wigner density of the bound state



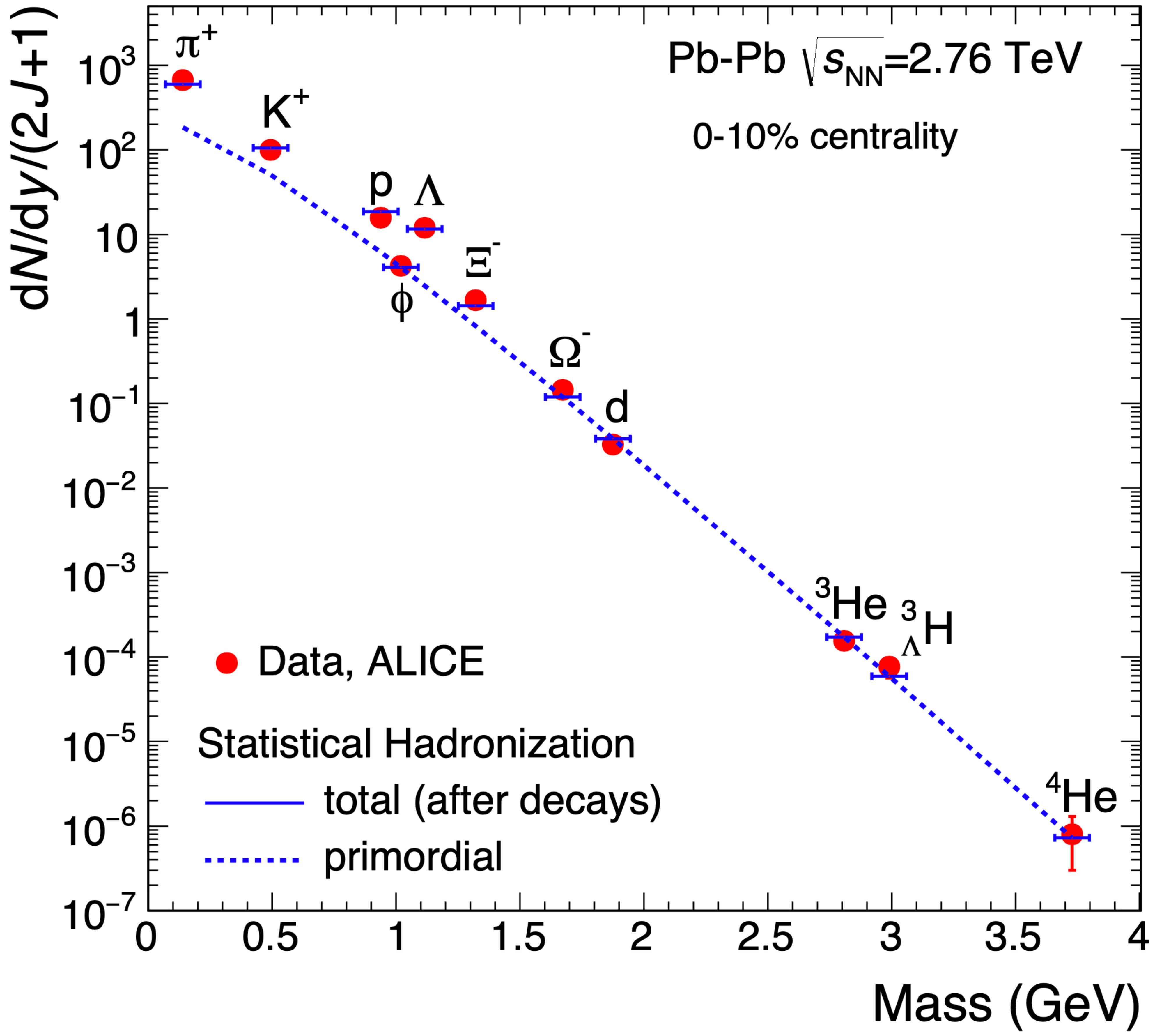
Exotic hadron wave function

- Gaussian approximation
- Solutions of the many-body problem using constituent models

  [Phys. Rev. D 99, (2019) 094037]

Statistical hadronization model

A. Andronic *et al.*, Nature vol. 561, p. 321–330 (2018)



Hadron yields at chemical freeze-out (when inelastic interactions cease) calculated using the hadronic partition function:

$$n_i = -\frac{T}{V}\frac{\partial\, ln(Z_i)}{\partial\mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{dp\, p^2}{\exp[(E_i-\mu_i)/T]\pm 1} \rightarrow \frac{dN_i}{dy} = n_i \cdot \frac{dV}{dy}$$

primordial yields + feed-down from high-mass states

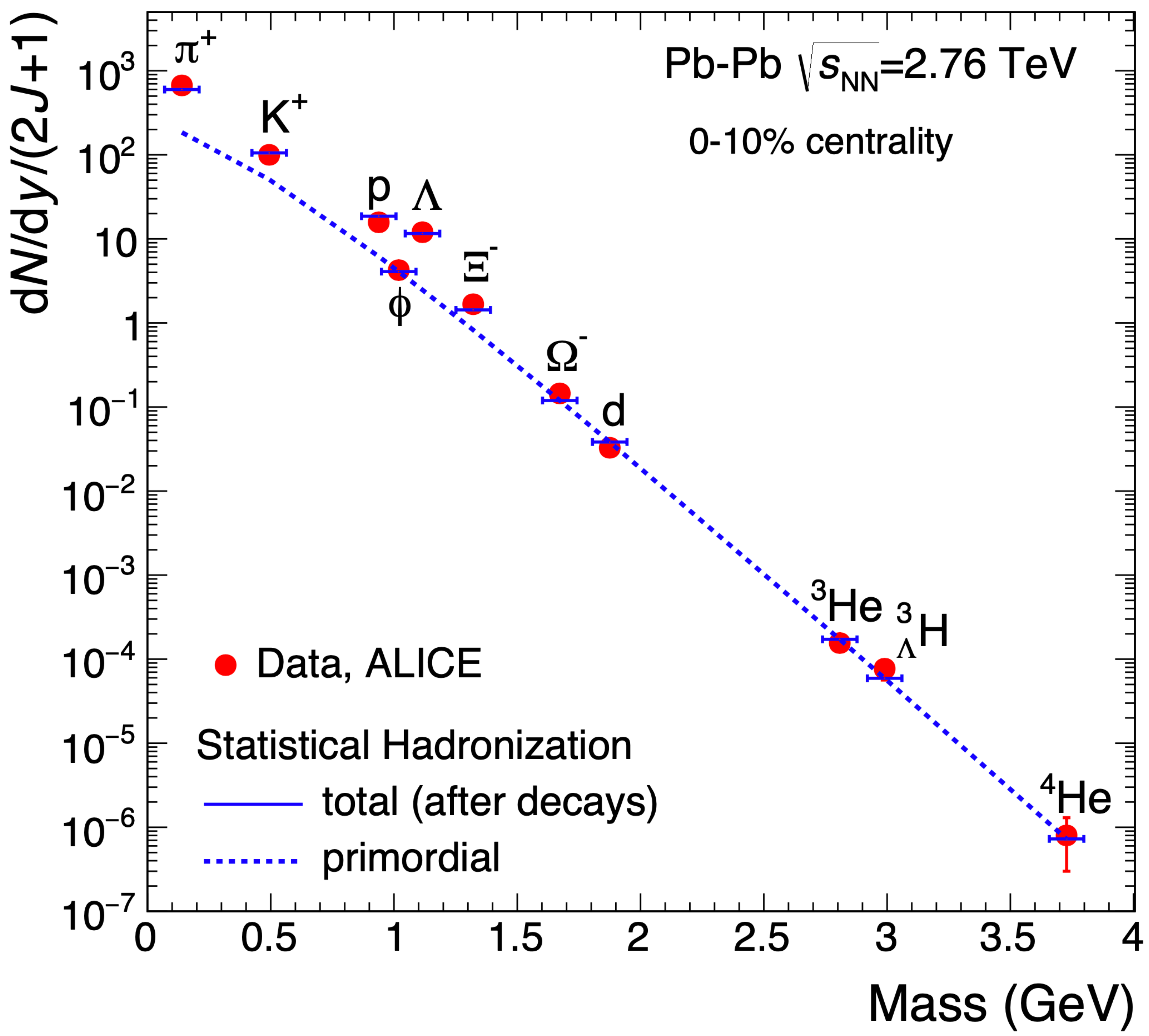
Fit experimental data using 3 free parameters: T_{chem}, V, μ_B

$$T_{chem} = 156.5 \pm 1.5\ \text{MeV} \rightarrow T_{chem} \approx T_{pc}$$

Chemical freeze-out close to phase boundary!

Statistical hadronization model

A. Andronic *et al.*, Nature vol. 561, p. 321–330 (2018)



Hadron yields at chemical freeze-out (when inelastic interactions cease) calculated using the hadronic partition function:

$$n_{\mathrm{i}} = -\frac{T}{V}\frac{\partial\, ln(\mathrm{Z_i})}{\partial\mu} = \frac{g_{\mathrm{i}}}{2\pi^2}\int_0^\infty \frac{\mathrm{d}p\, p^2}{\exp[(E_{\mathrm{i}}-\mu_{\mathrm{i}})/T]\pm 1} \rightarrow \frac{\mathrm{d}N_i}{\mathrm{d}y} = n_i \cdot \frac{\mathrm{d}V}{\mathrm{d}y}$$

primordial yields + feed-down from high-mass states

Fit experimental data using 3 free parameters: T_{chem}, V, μ_B

$$T_{\mathrm{chem}} = 156.5 \pm 1.5\ \mathrm{MeV} \rightarrow T_{\mathrm{chem}} \approx T_{\mathrm{pc}}$$

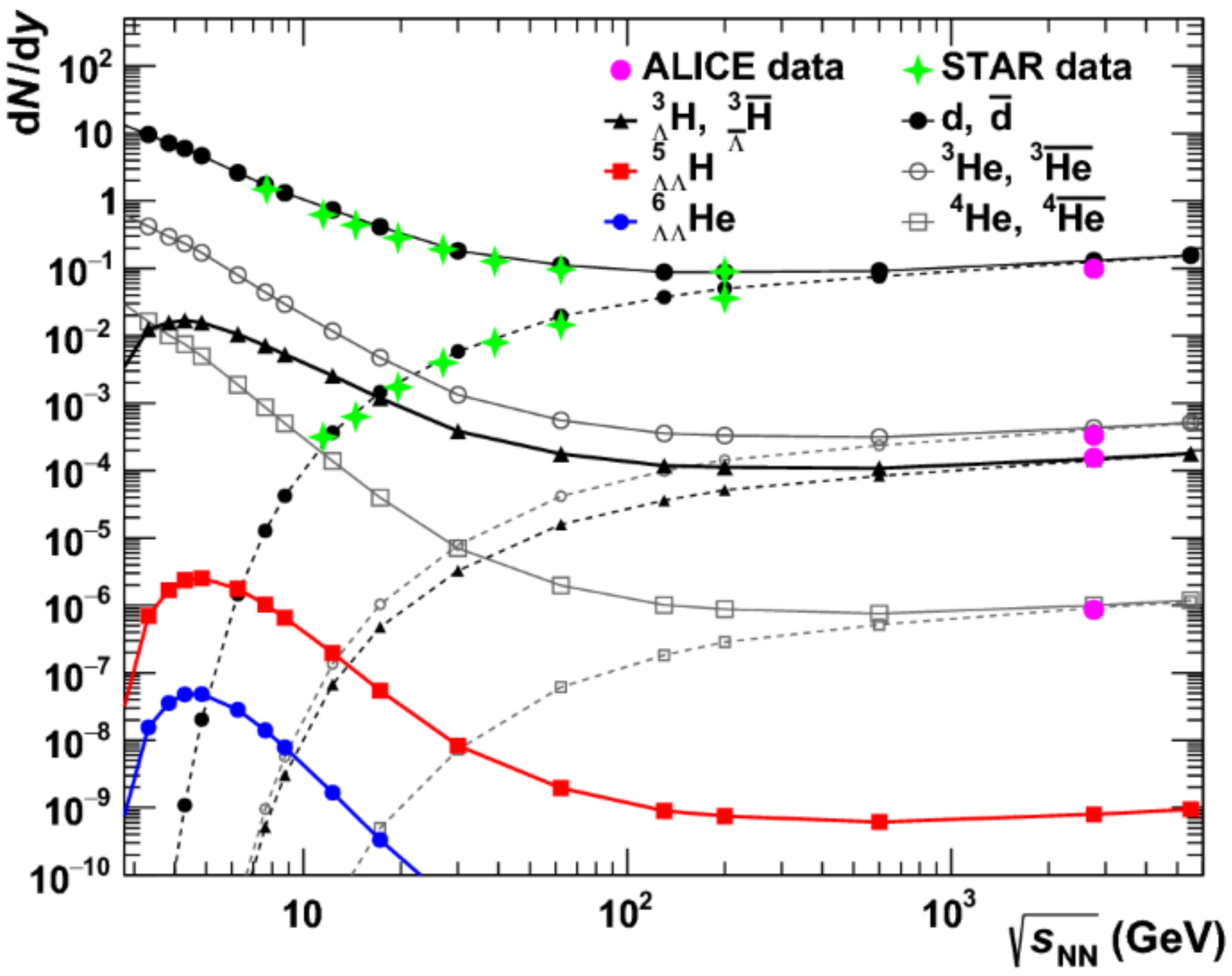
Chemical freeze-out close to phase boundary!

$$T_{\mathrm{nuclei}} = 159 \pm 5\ \mathrm{MeV}$$

… valid also for nuclei and loosely bound states, such as the hypertriton

(Anti)(hyper)nuclei

[Eur. Phys. J. A 56, 280 (2020)]

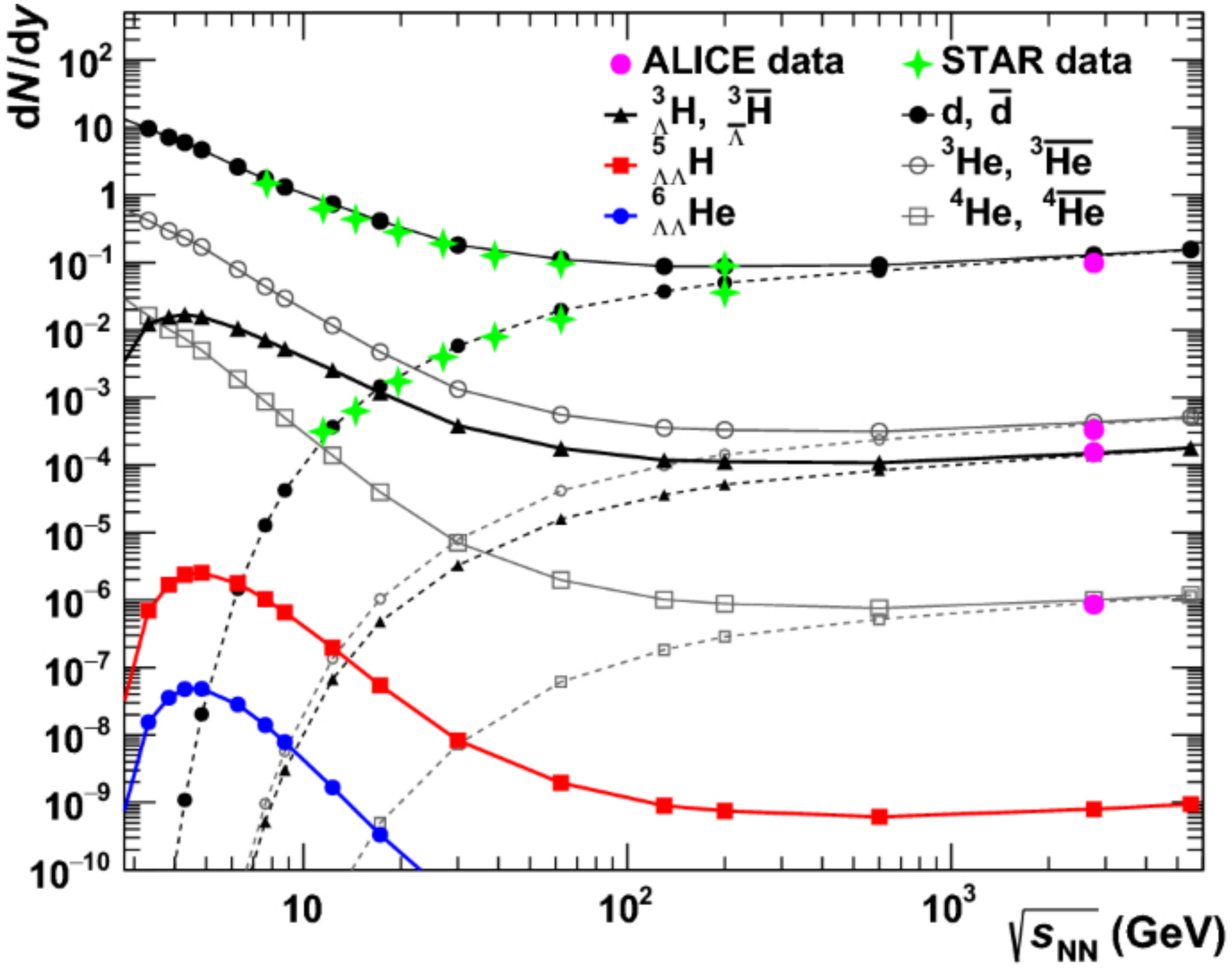


At LHC matter and antimatter produced in almost equal amount ($\mu_{\mathrm{B}} \approx 0$)

> LHC is an antimatter factory

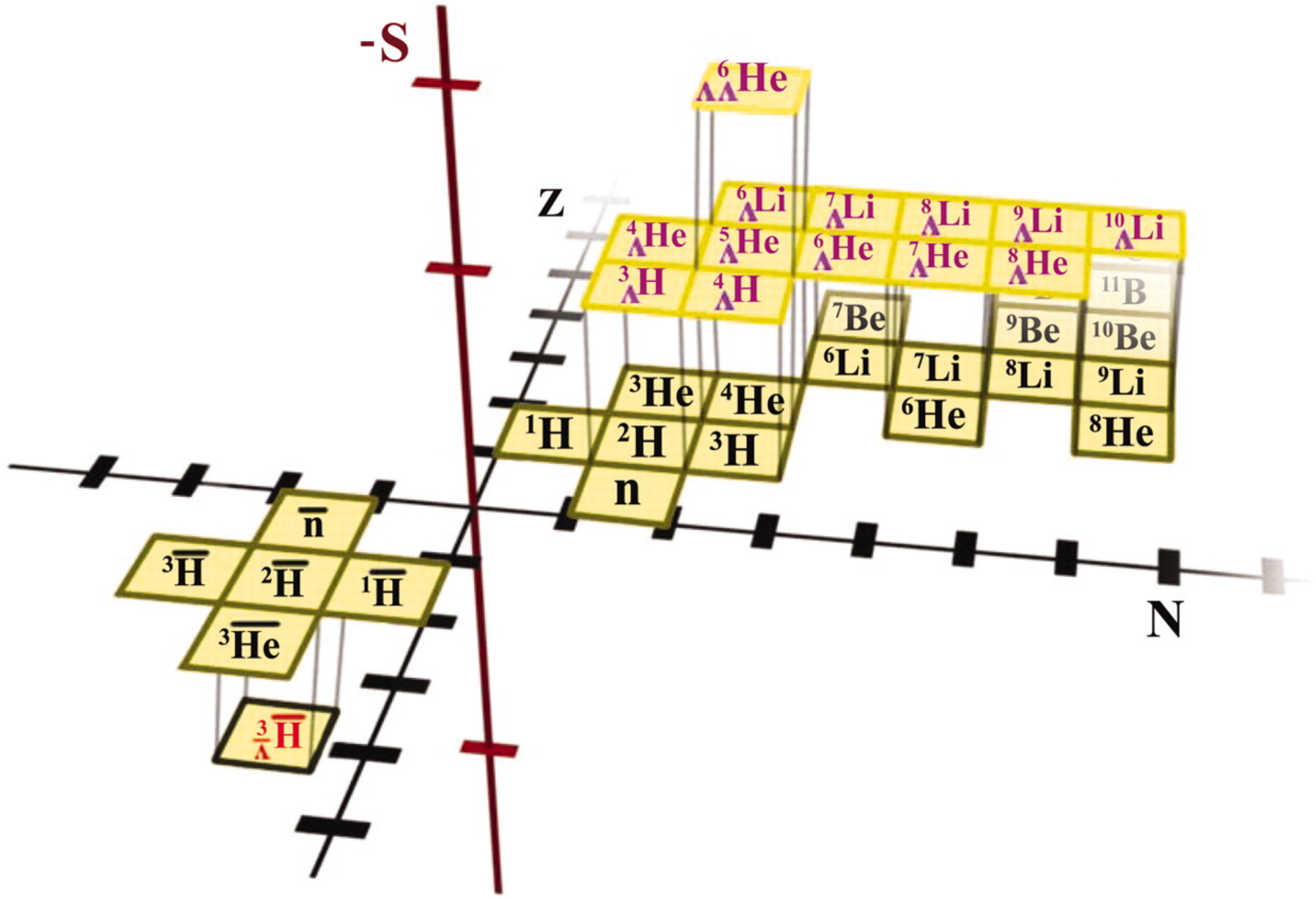
(Anti)(hyper)nuclei

[Eur. Phys. J. A 56, 280 (2020)]



Ultrarelativistic heavy-ion collisions are ideal to produce antimatter hypernuclei

> extend 3D nuclear chart into positive strangeness



At LHC matter and antimatter produced in almost equal amount ($\mu_B \approx 0$)

> LHC is an antimatter factory

[Science 328, 5974 (2010)]

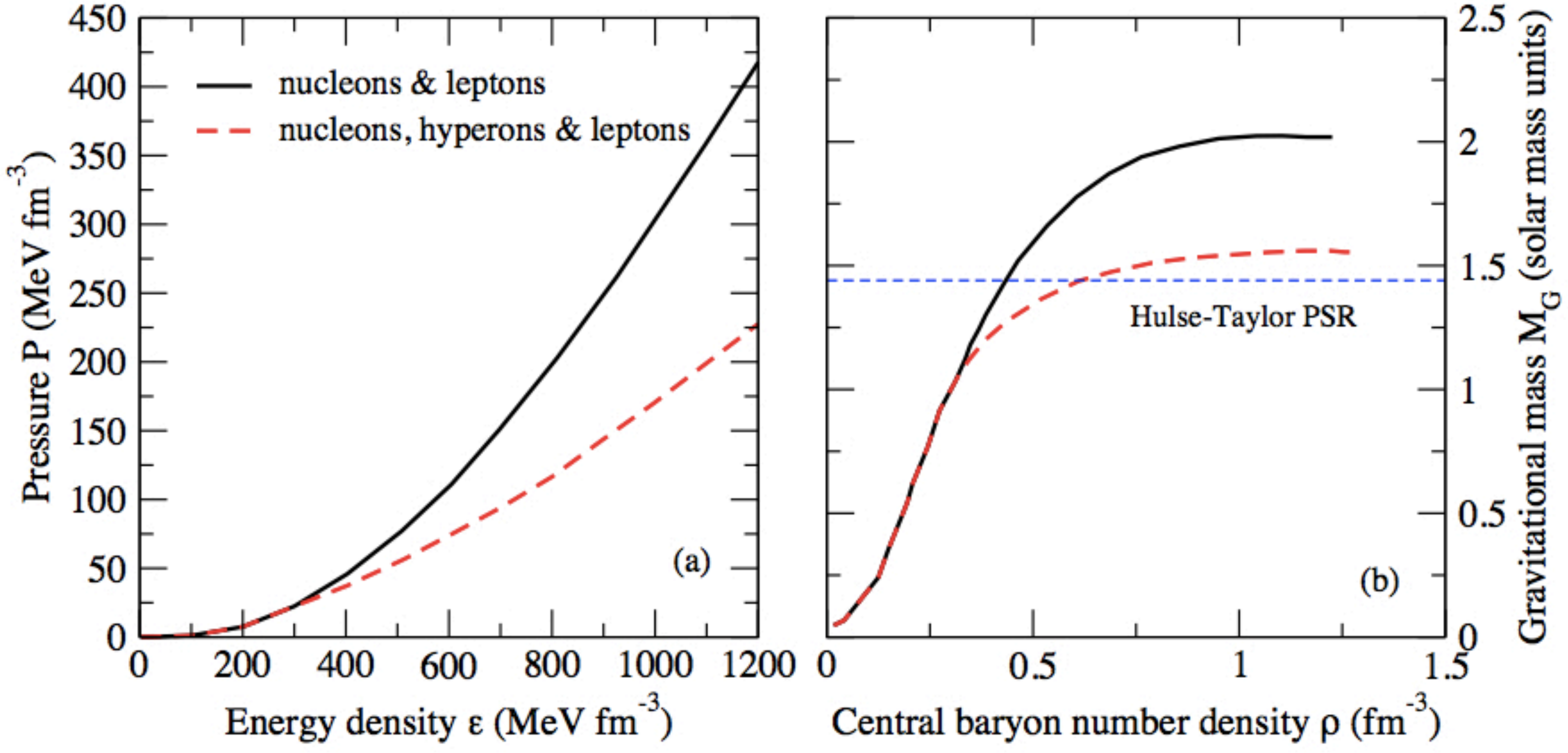
YN interaction and neutron stars

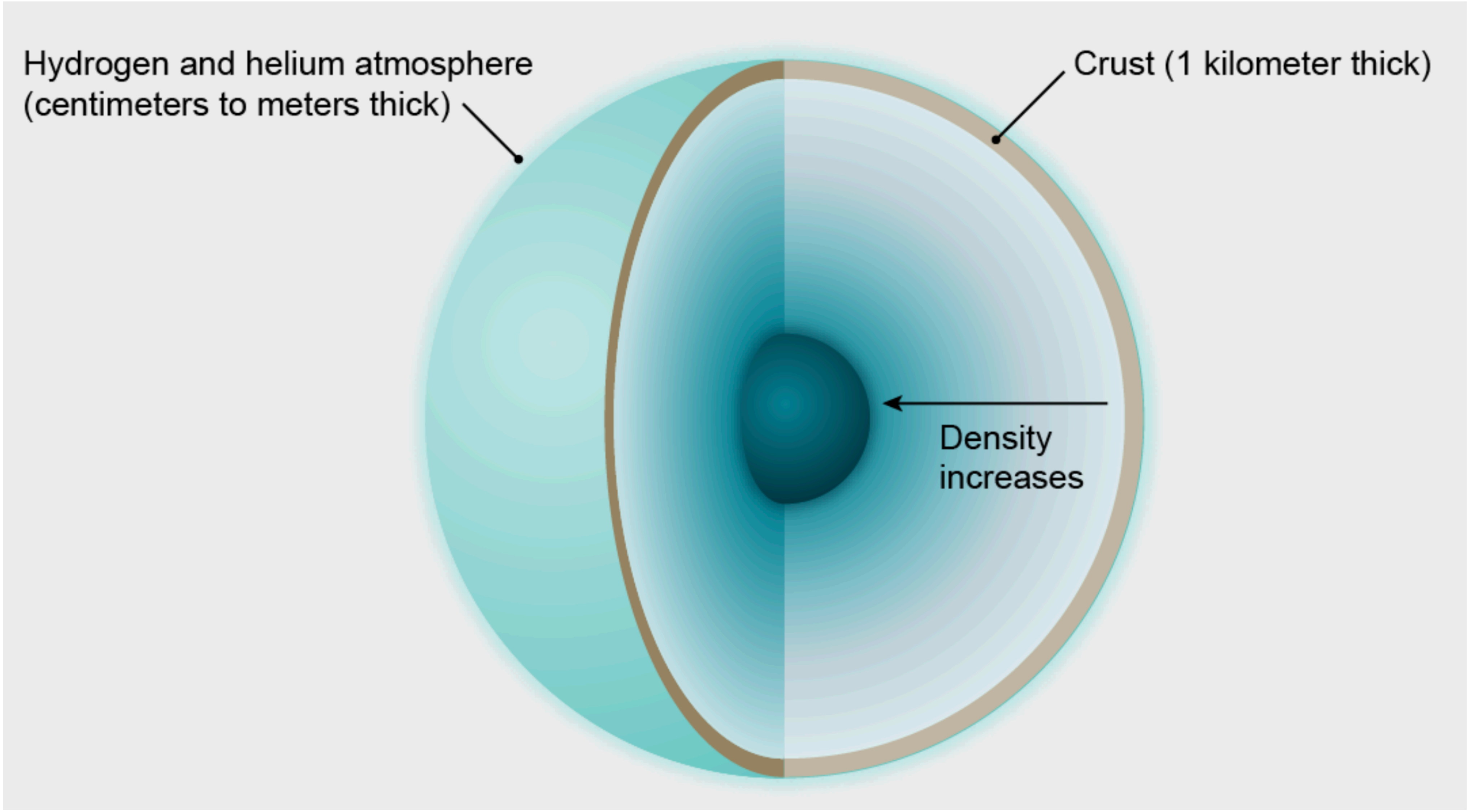
Hypernuclei are unique tools to study strong interaction between hyperons and nucleons (including three-body systems)

Knowledge of YN interaction is crucial for

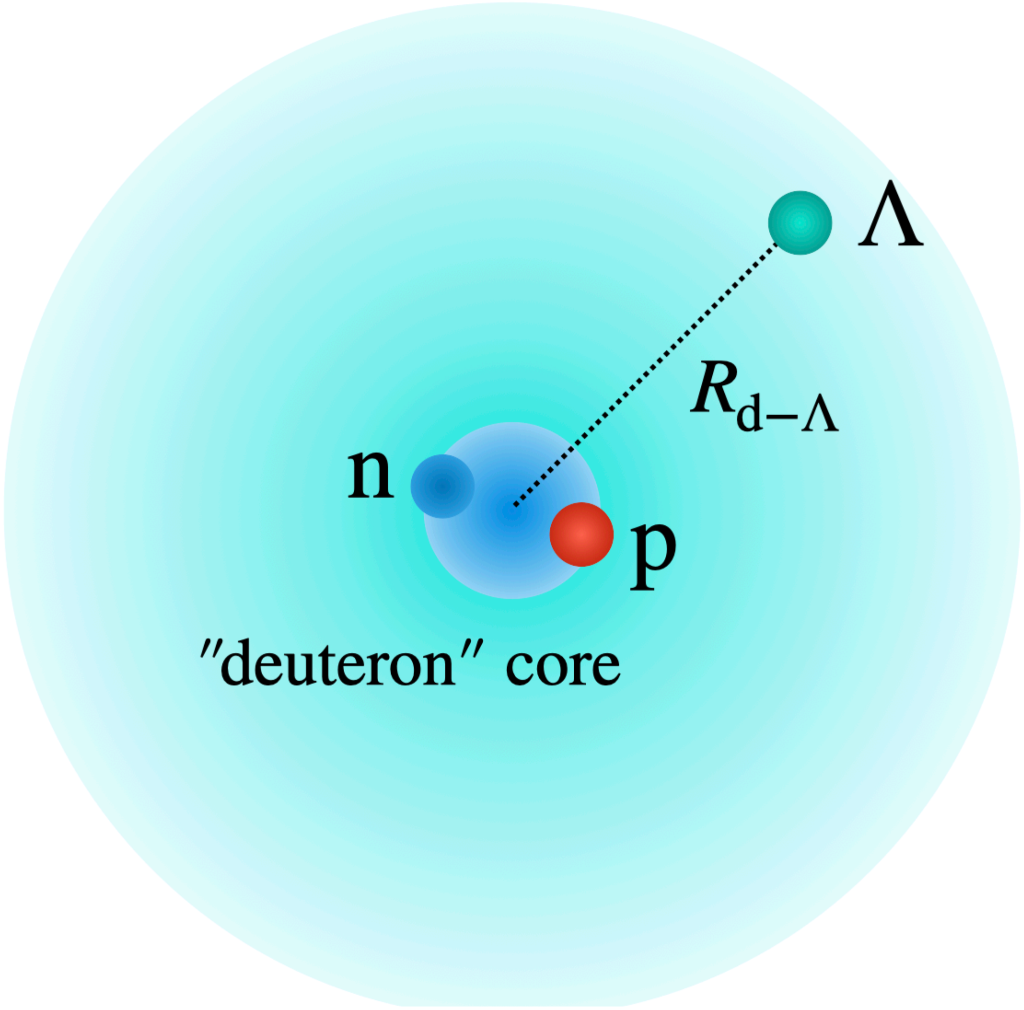
1. Studying the strangeness sector of QCD
2. Understanding internal structure of neutron stars (hyperon puzzle)

J. Phys.: Conf. Ser. 668 012031





The hypertriton



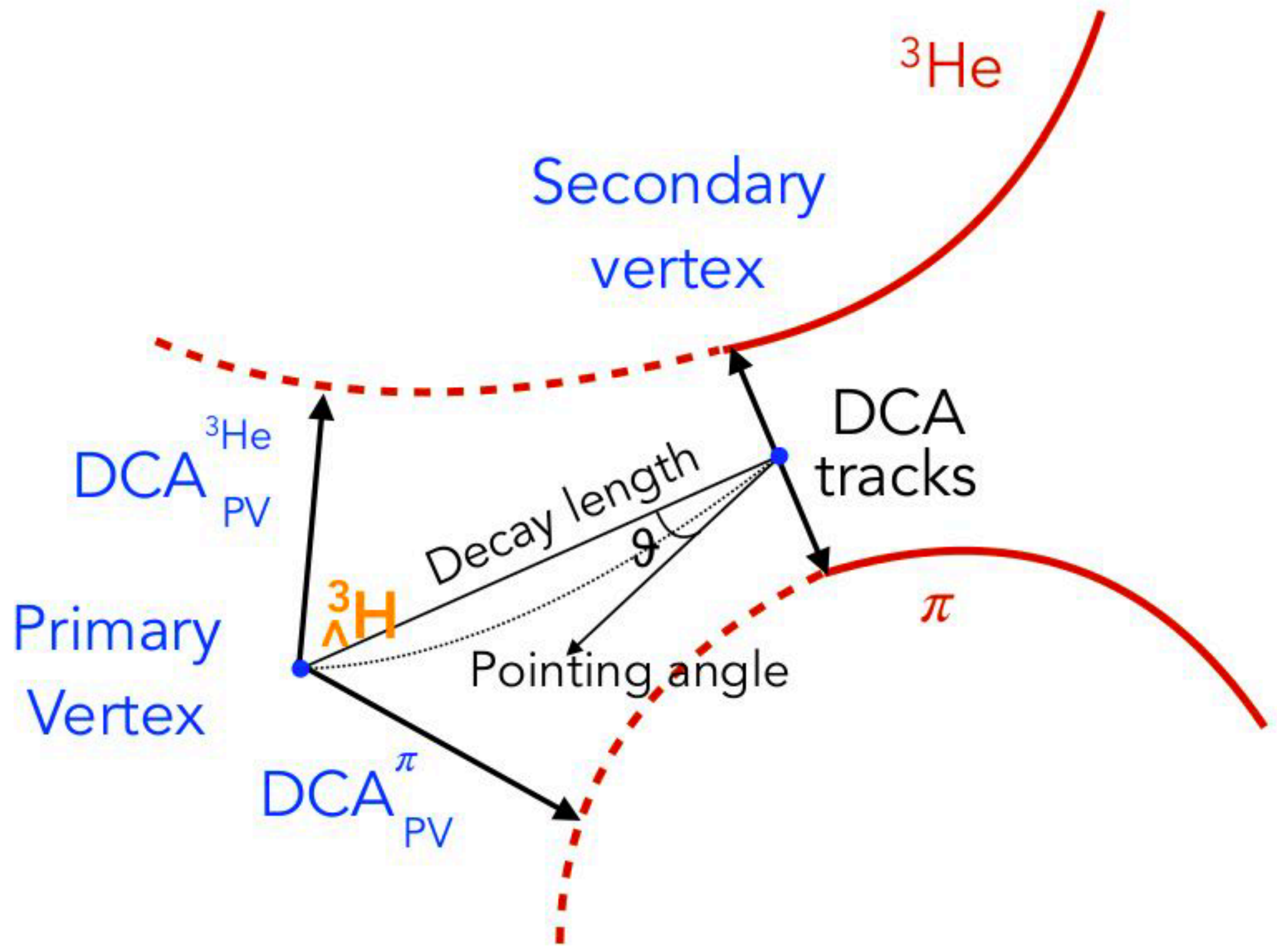
Lightest known hypernucleus

Bound state of proton, neutron and Λ hyperon

Ultimate halo nucleus with $\sqrt{\langle R^2_{d-\Lambda} \rangle} = 10.79^{+3.04}_{-1.53}$ fm

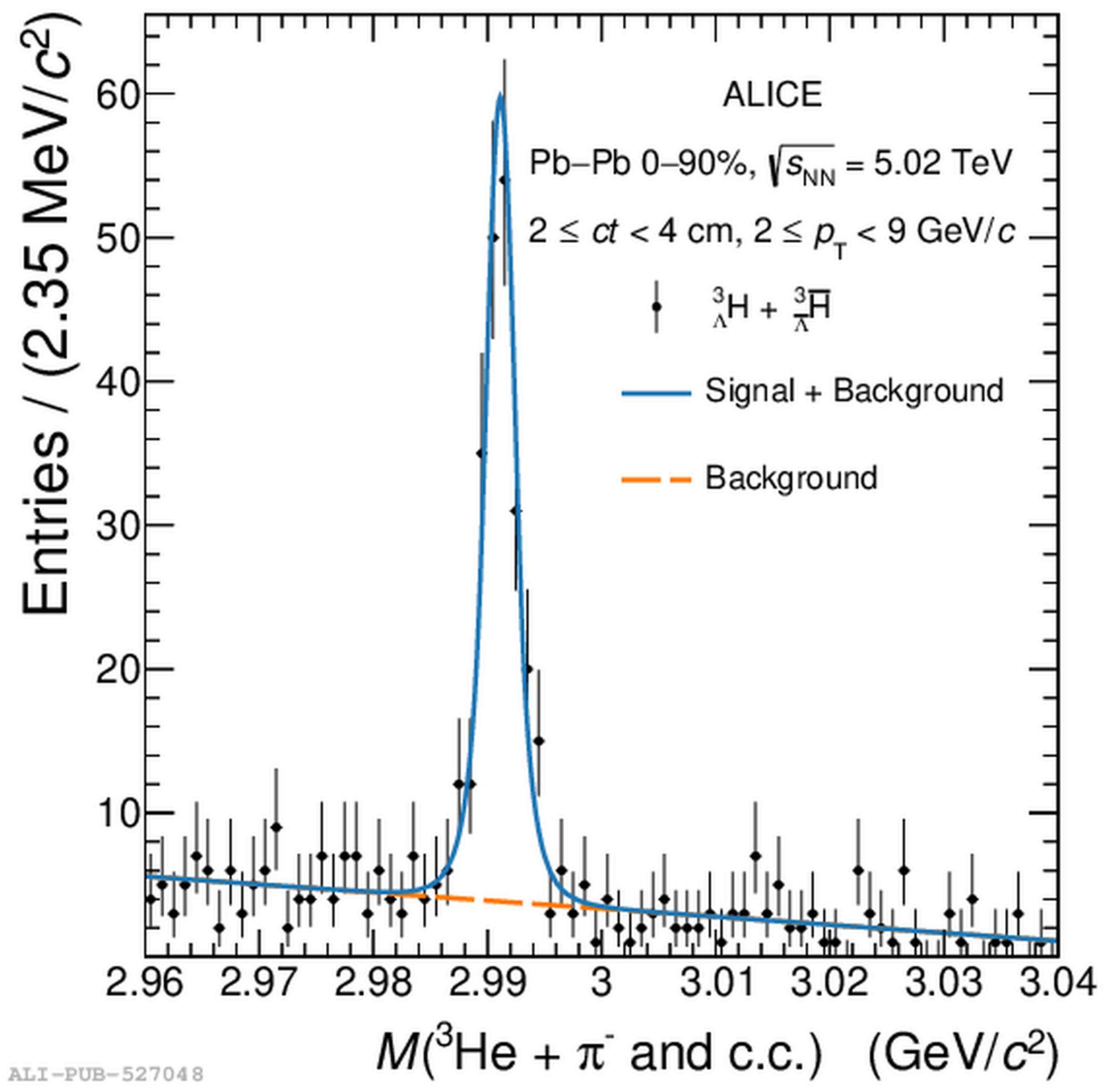
Phys. Rev. C 100 (2019) 034002

https://arxiv.org/abs/2209.07360



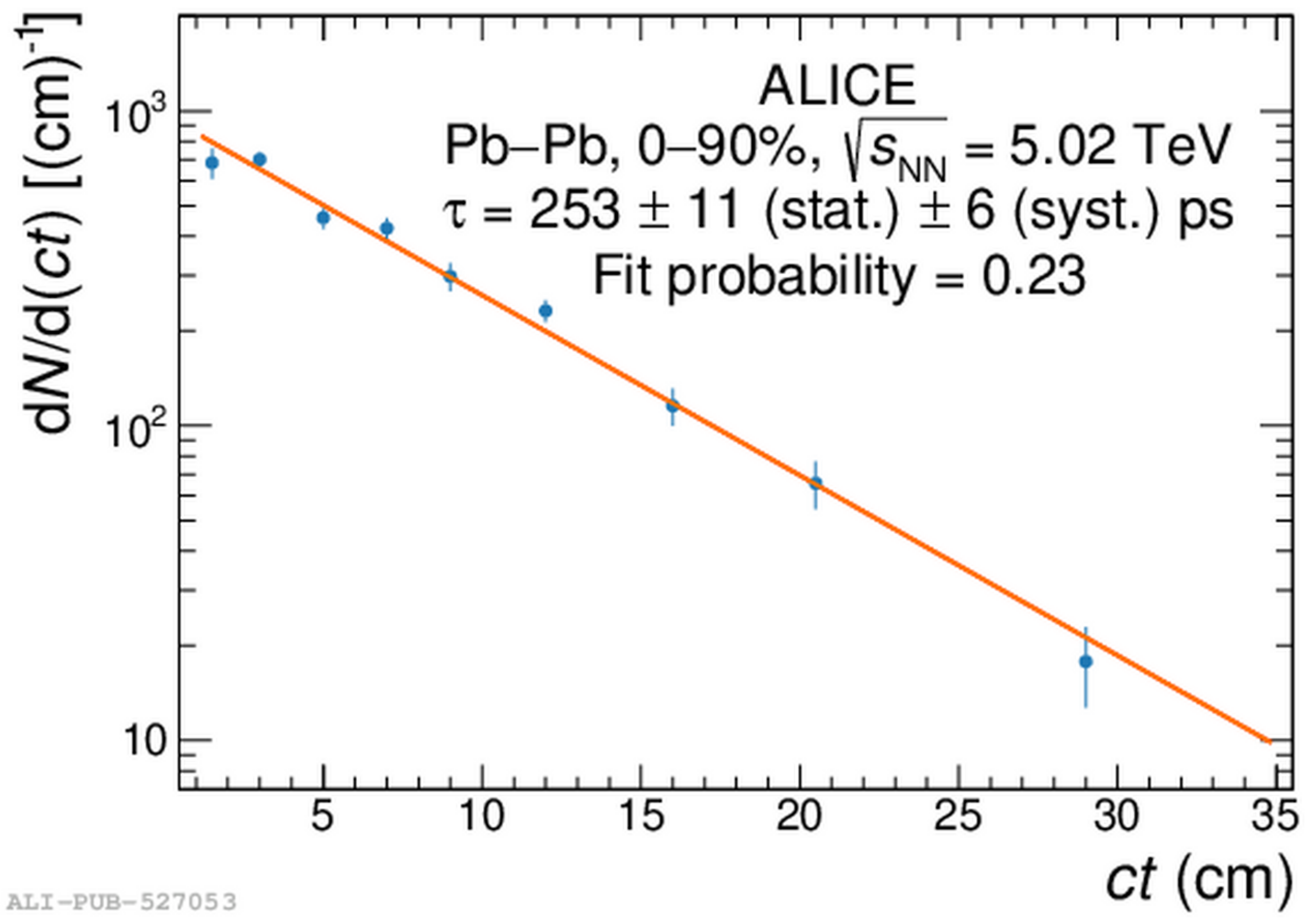
Reconstructed in ALICE using its charged mesonic decay channels:

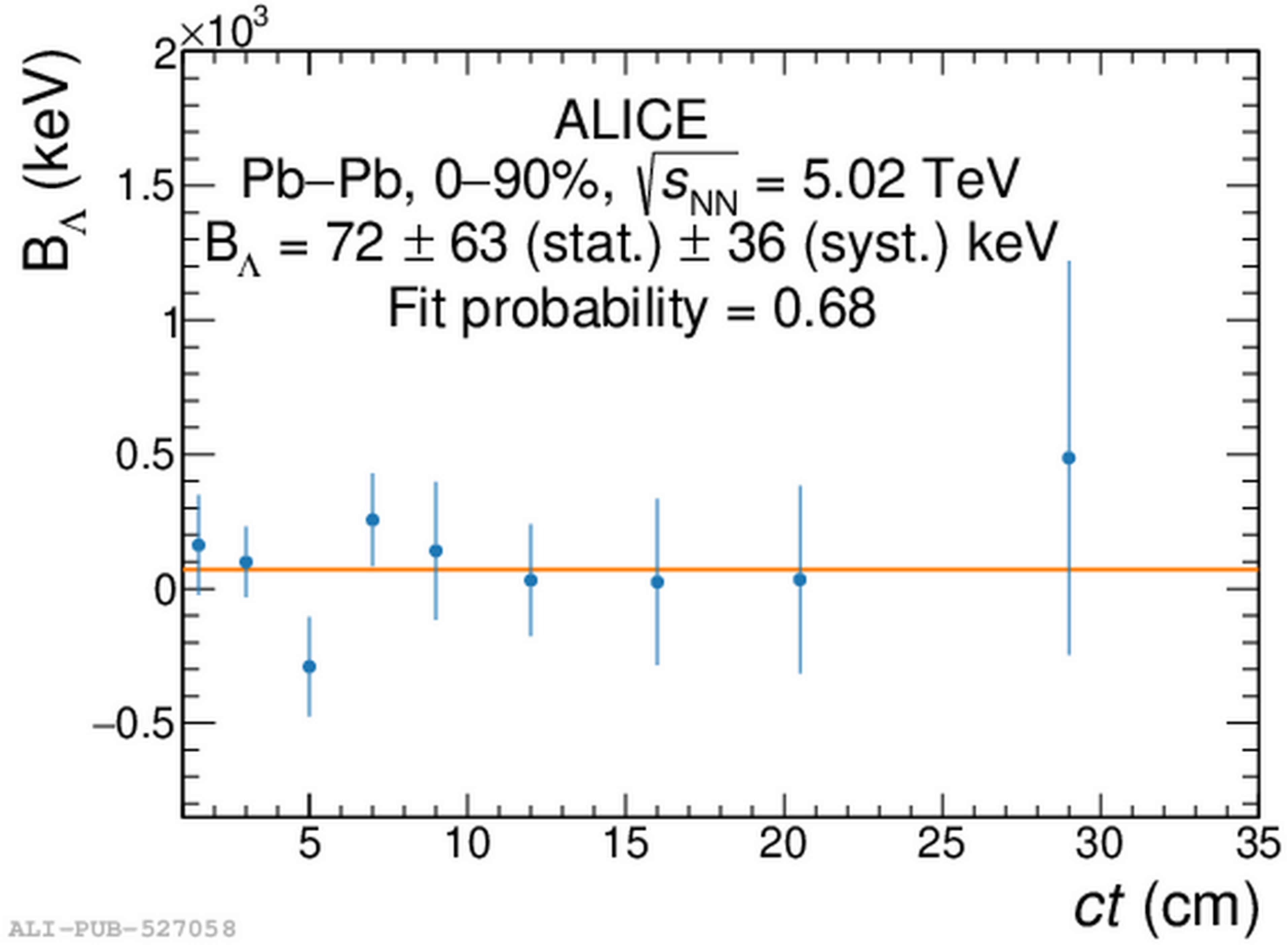
1. $^3_\Lambda\mathrm{H} \rightarrow {}^3\mathrm{He} + \pi$ (B.R. ≈ 25%)
2. $^3_\Lambda\mathrm{H} \rightarrow \mathrm{p} + \mathrm{d} + \pi$ (B.R. ≈ 40%)



Hypertriton lifetime and B_Λ

https://arxiv.org/abs/2209.07360





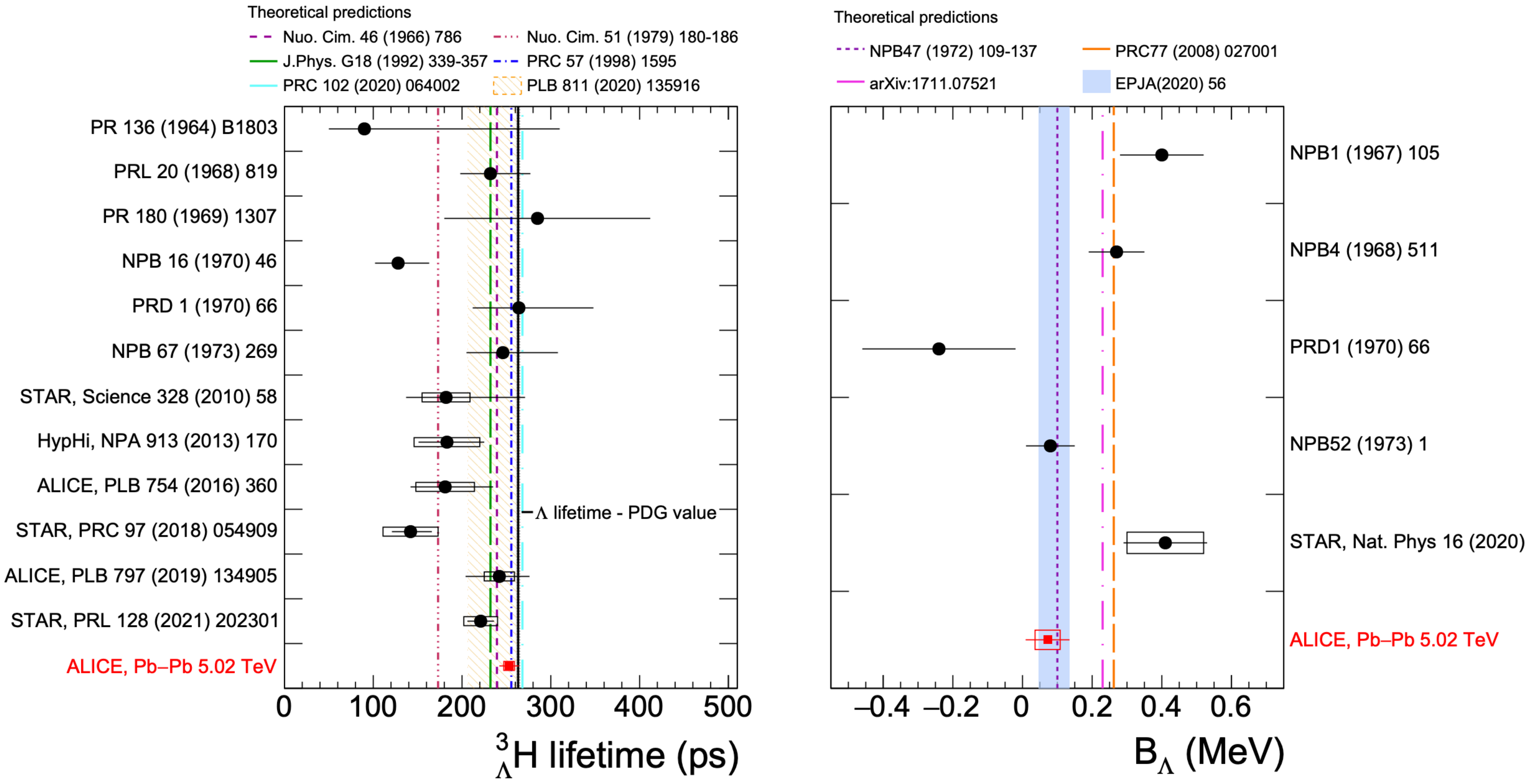
$^{3}_{\Lambda}\mathrm{H}$ lifetime extracted from exponential fit to the measured *ct* distribution

Λ separation energy (B_Λ) from the $^{3}_{\Lambda}\mathrm{H}$ mass measurement: $B_\Lambda = m_\mathrm{d} + m_\Lambda - m_{^{3}_{\Lambda}\mathrm{H}}$

- Deuteron mass from CODATA
- Λ mass from PDG

Comparison with world average

https://arxiv.org/abs/2209.07360

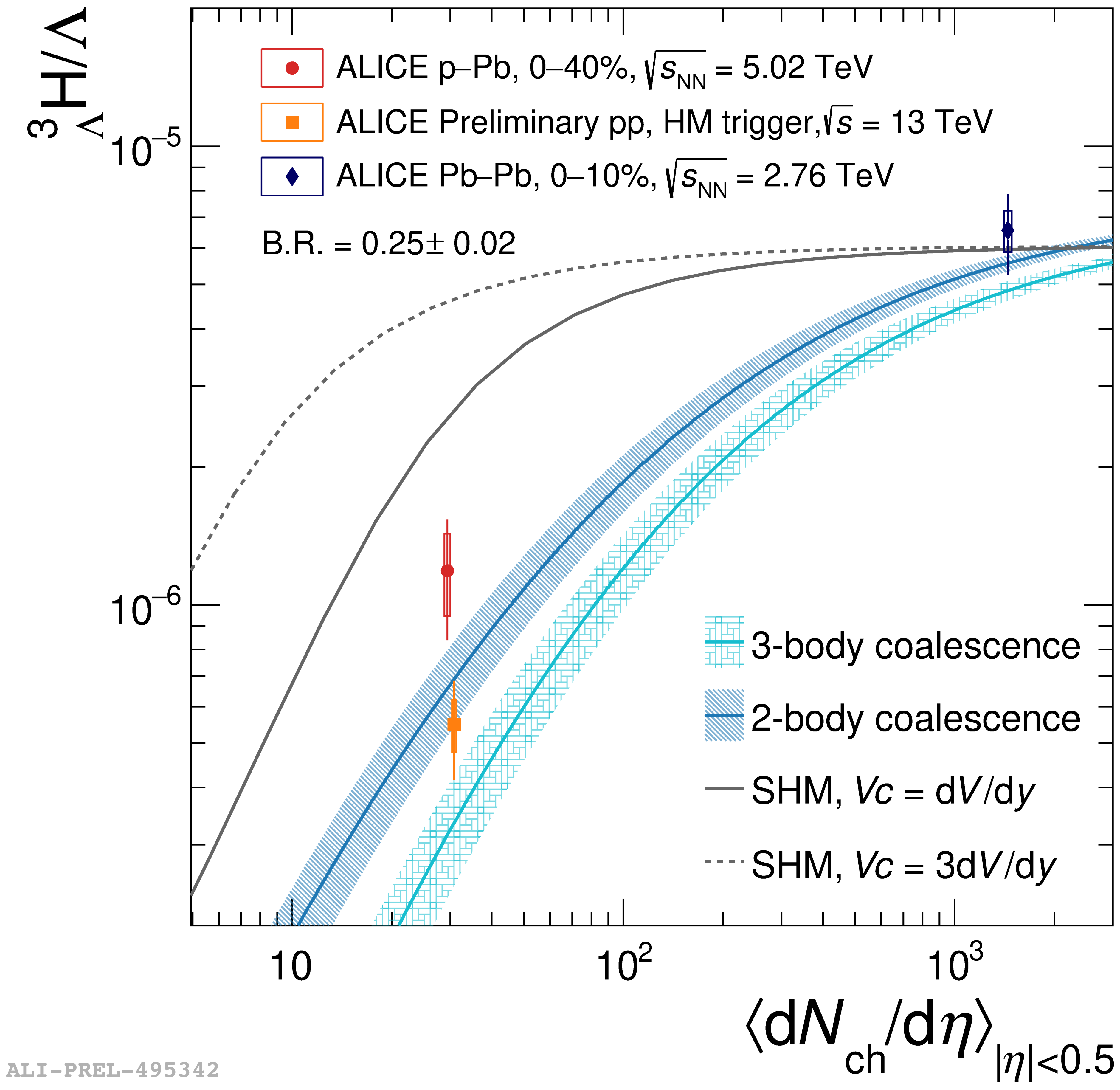


Most precise measurements of lifetime and B_Λ

Consistently indicate a weakly bound state → large wave function

Hypertriton in small systems

Phys. Rev. Lett. 128 (2022) 252003



Hypertriton production measured in small collision systems

- HM pp at 13 TeV
- p-Pb at 5.02 TeV

Large separation between predictions from statistical hadronization model and coalescence

> hypertriton production sensitive to production models

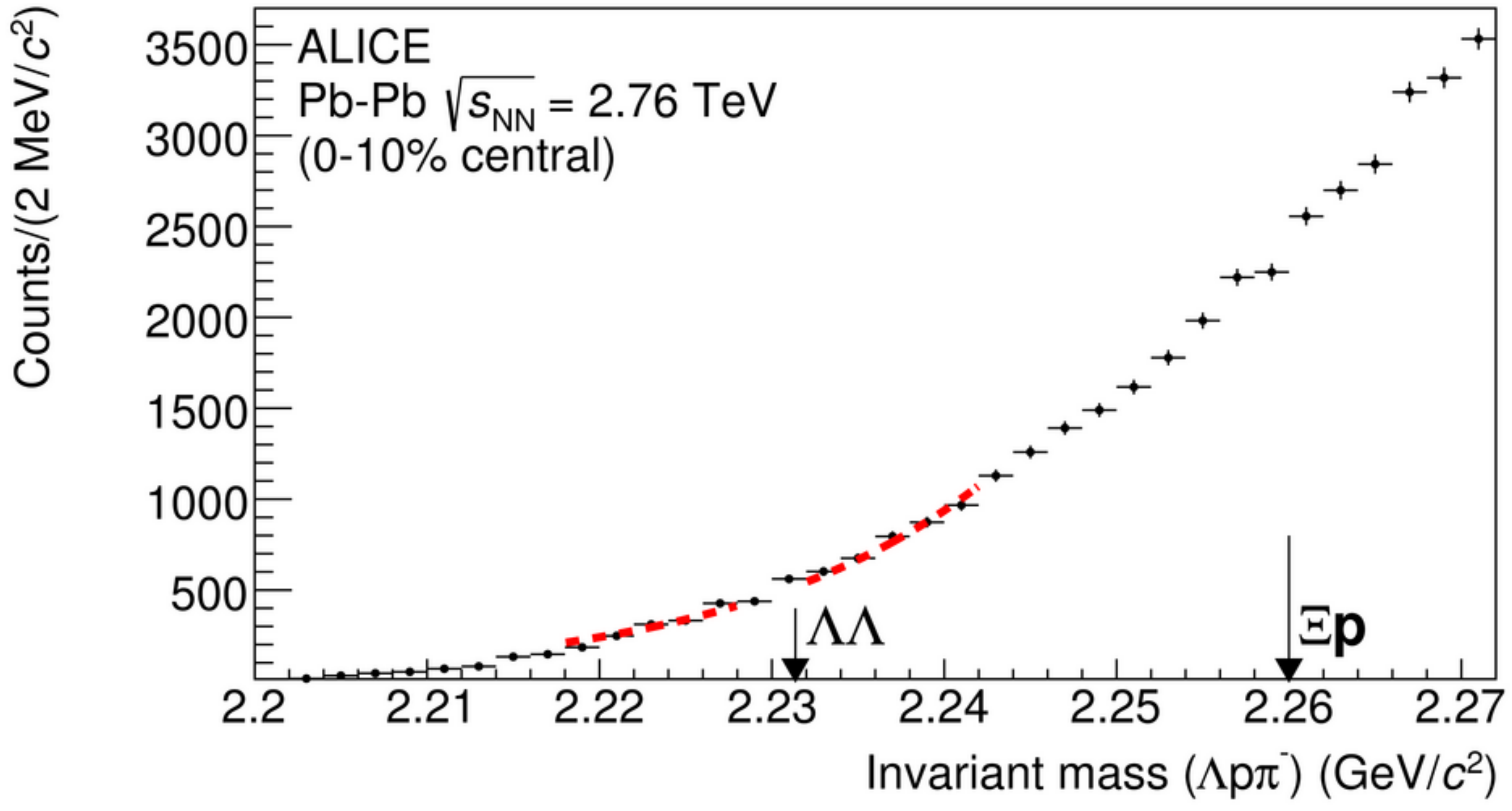
Clear tension with SHM at low multiplicity

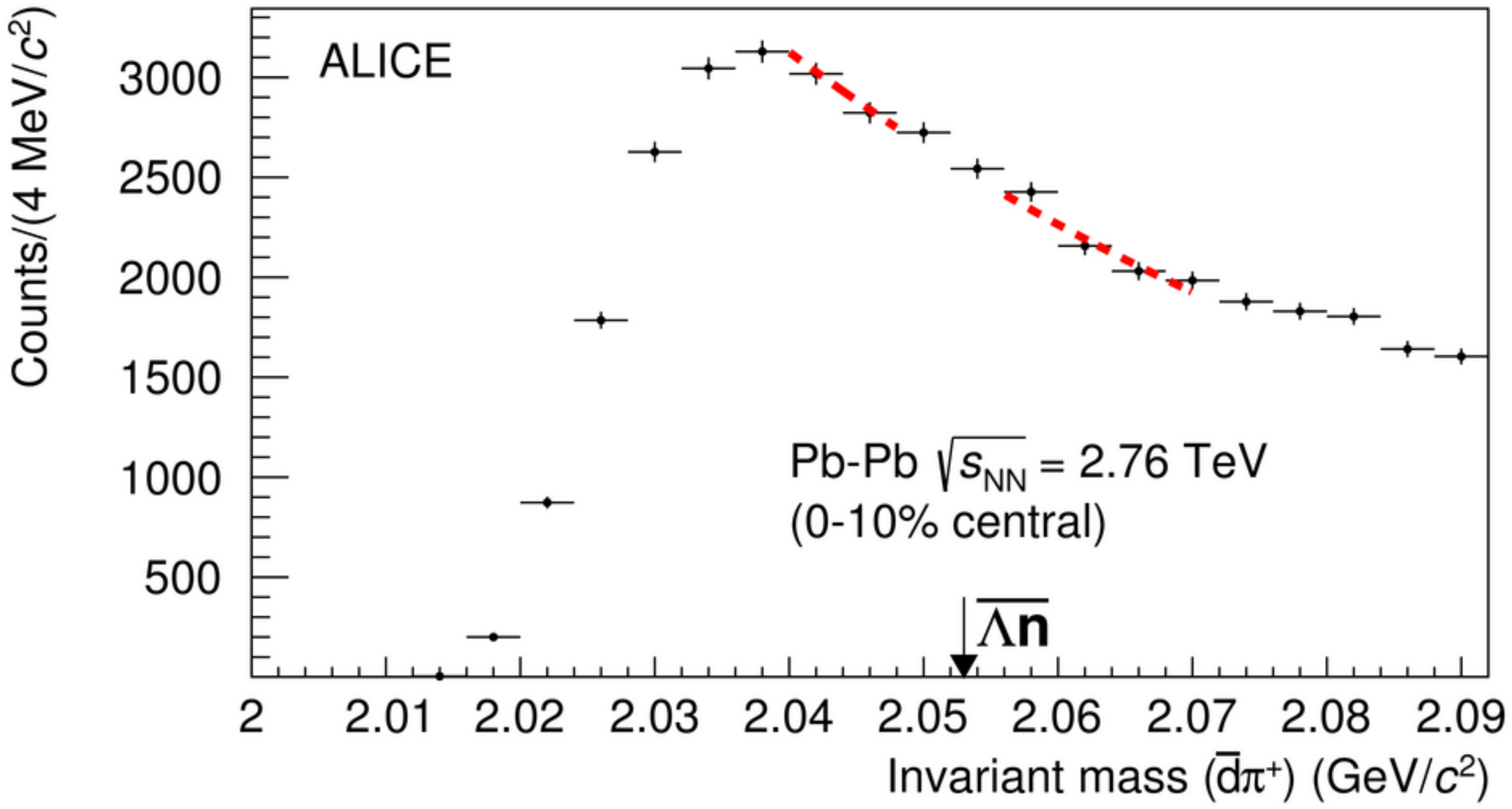
> configuration with V_C = 3dV/dy is excluded (discrepancy > 6σ)

Full multiplicity evolution will be studied in Run 3

Searches for exotic dibaryons

[Phys. Lett. B 752 (2016) 267-277](#)





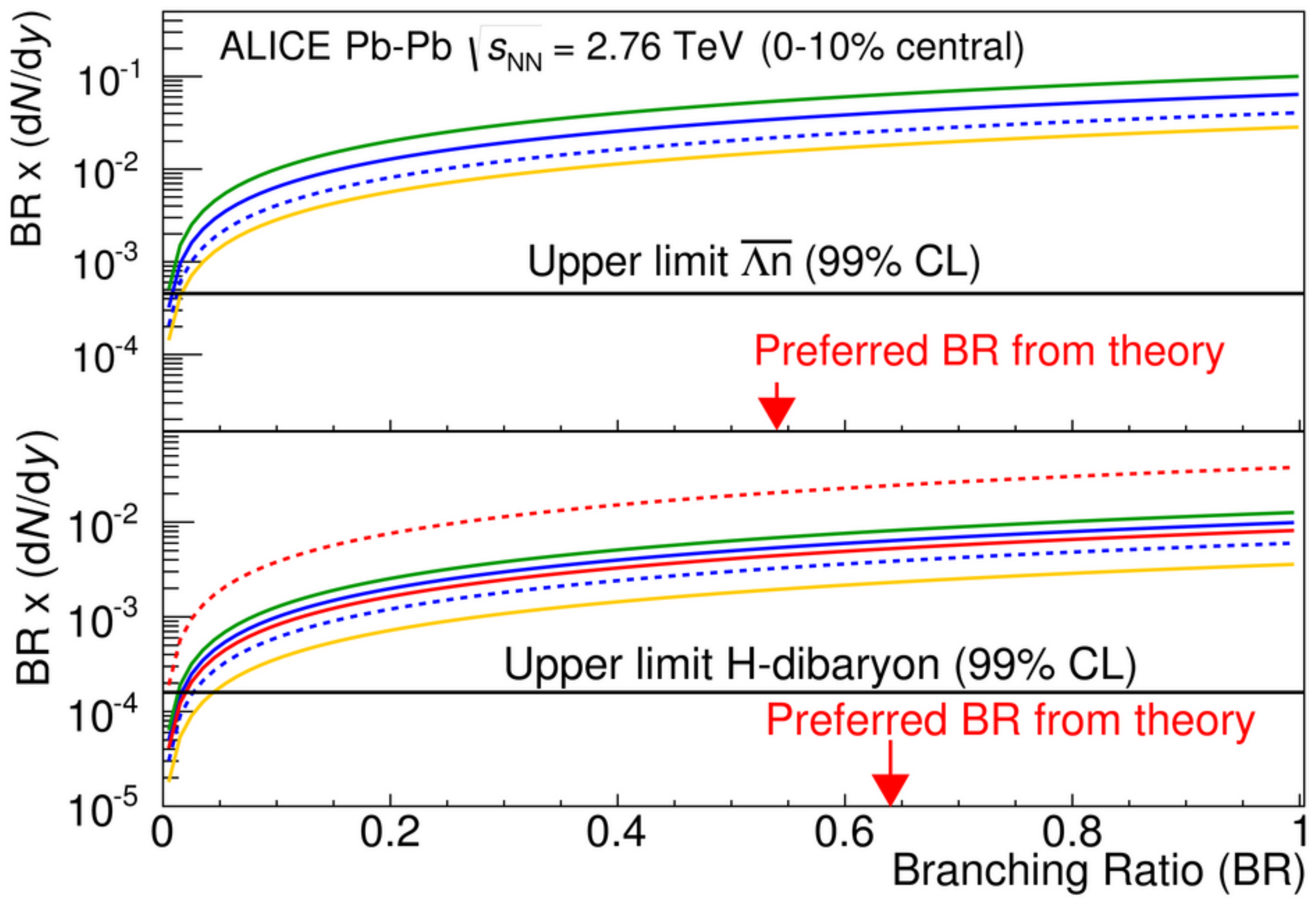
Searches for two hypothetical strange dibaryon states in Pb-Pb collisions at 2.76 TeV: $\Lambda\Lambda$ (H-dibaryon) and $\overline{\Lambda n}$

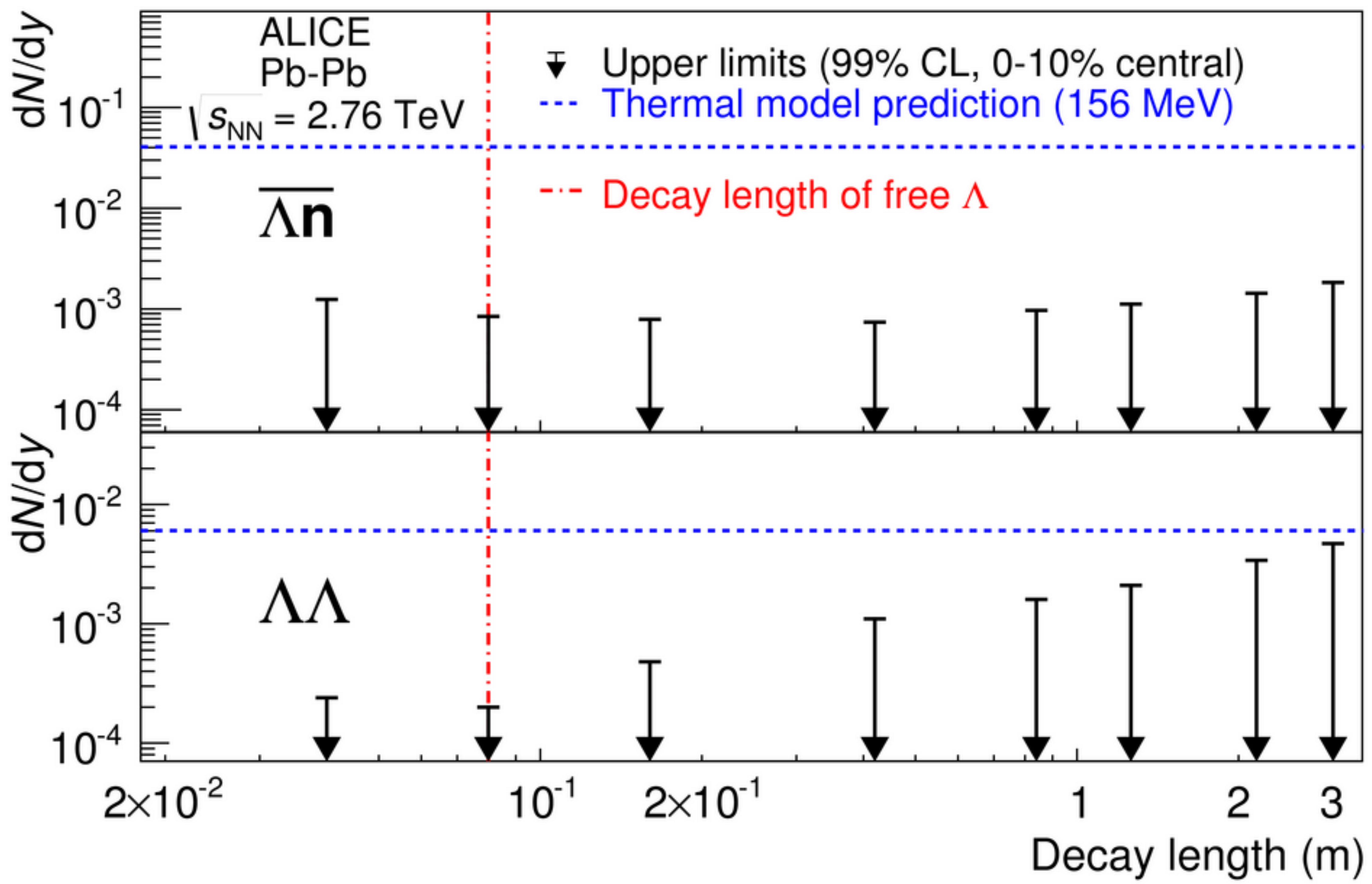
Weak decay channels are used

- $\Lambda\Lambda \rightarrow \Lambda + p + \pi^-$
- $\overline{\Lambda n} \rightarrow \bar{\mathrm{d}} + \pi^+$

Upper limits

[Phys. Lett. B 752 (2016) 267-277]



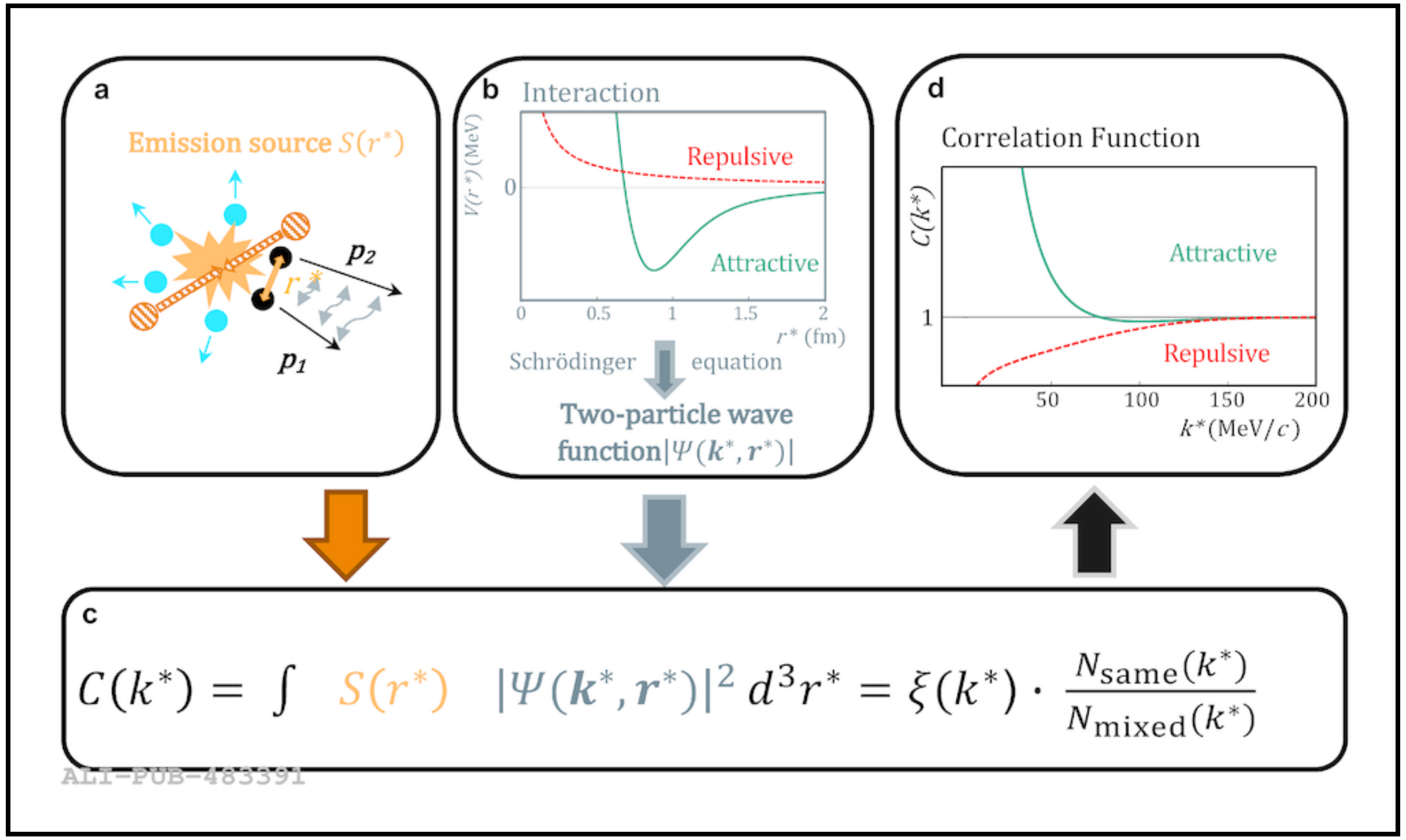


No evidence for these bound states is observed

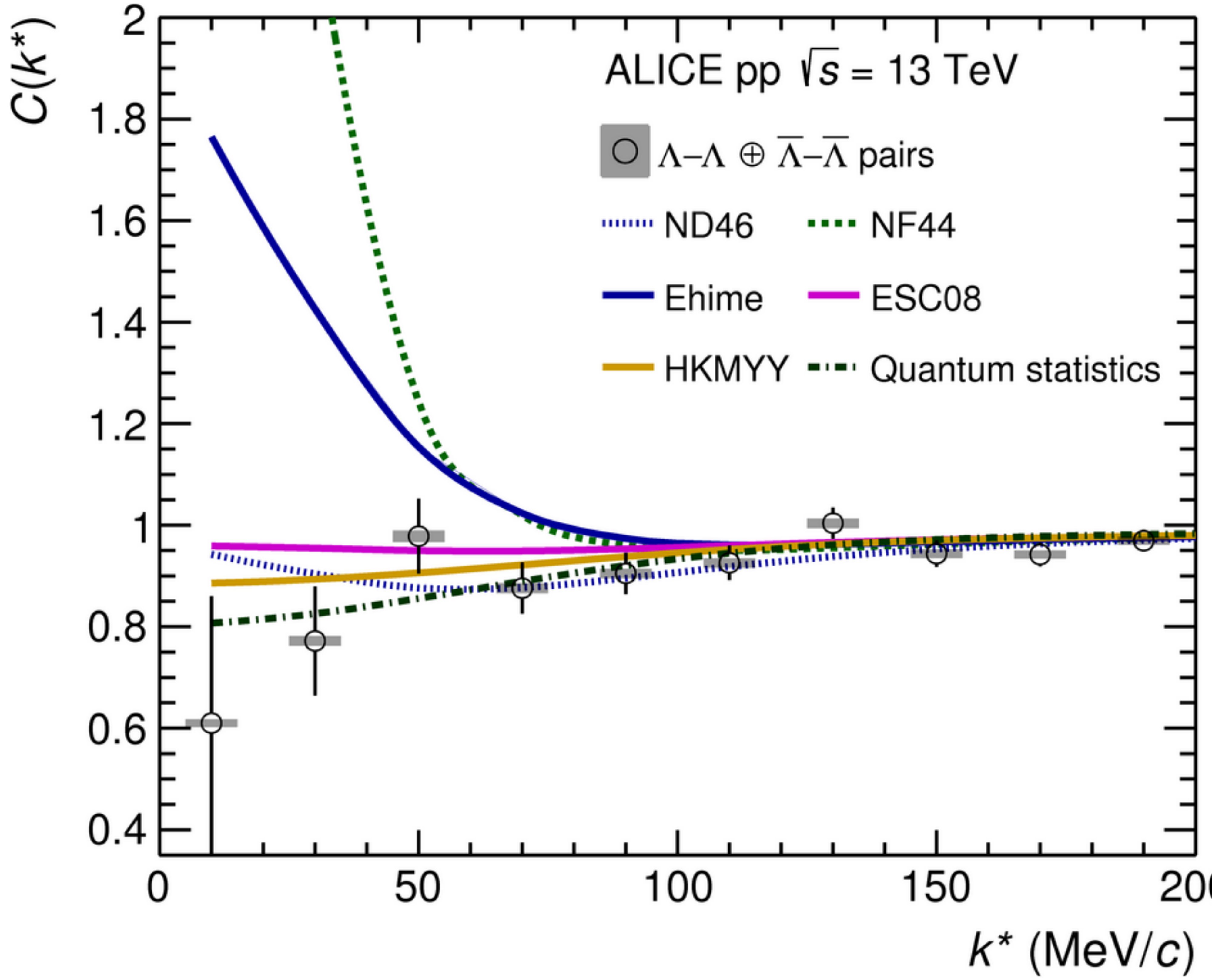
- Upper limits are determined at 99% C.L. for a wide range of lifetimes and for the full range of branching ratios
- results compared to thermal, coalescence and hybrid UrQMD model expectations

H-dibaryon from correlations

Nature 588 (2020) 232-238



Phys. Lett. B 797 (2019) 134822

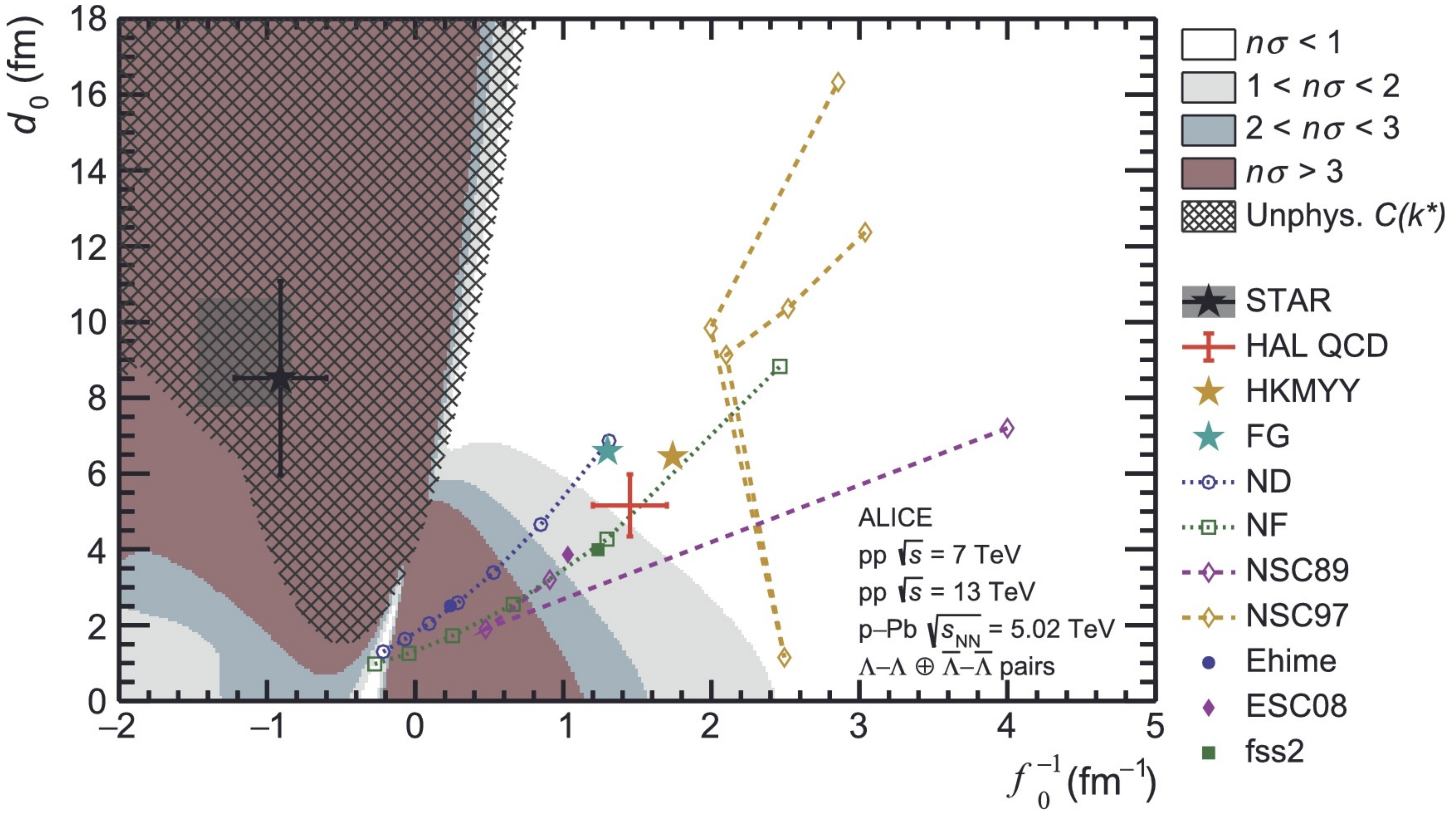


Constraints on the existence of the H-dibaryon derived from $\Lambda\Lambda$ momentum correlations in the femtoscopic region

Source size constrained by fit of pp correlation function

ΛΛ: a shallow bound state

Phys. Lett. B 797 (2019) 134822



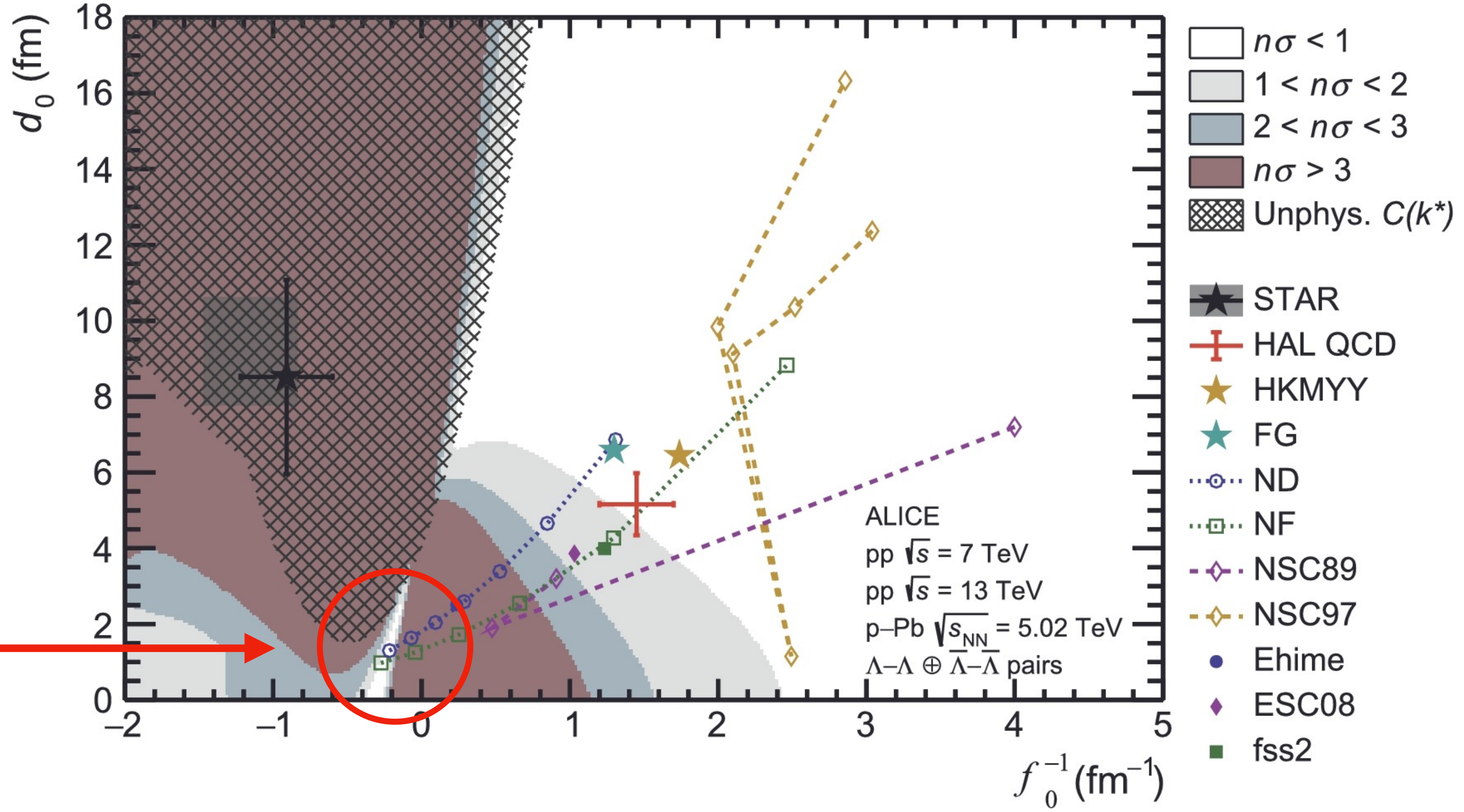
Constraints on the $\Lambda\Lambda$ scattering parameter space obtained by comparing data with model calculations

Data are compatible with hypernuclei results and lattice calculations, both predicting a shallow attractive interaction: $\mathrm{B}_{\Lambda\Lambda} = 3.2^{+1.6}_{-2.4}\ (\mathrm{stat})^{+1.8}_{-1.0}\ (\mathrm{syst})$

ΛΛ: a shallow bound state

Phys. Lett. B 797 (2019) 134822

Room for a shallow bound state

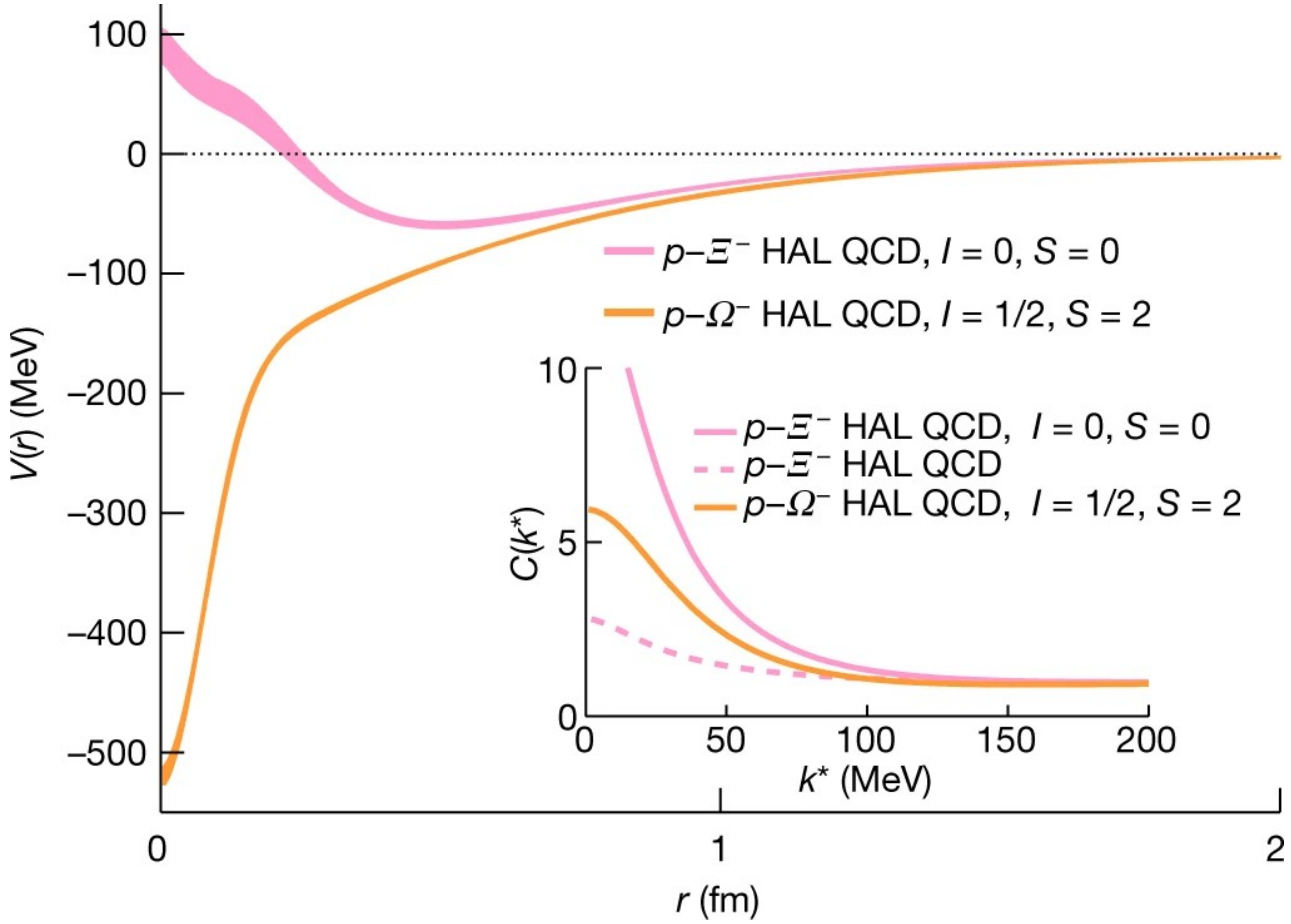


Constraints on the $\Lambda\Lambda$ scattering parameter space obtained by comparing data with model calculations

Data are compatible with hypernuclei results and lattice calculations, both predicting a shallow attractive interaction: $\mathrm{B}_{\Lambda\Lambda} = 3.2^{+1.6}_{-2.4}\ (\mathrm{stat})^{+1.8}_{-1.0}\ (\mathrm{syst})$

p-Ω Strange dibaryon

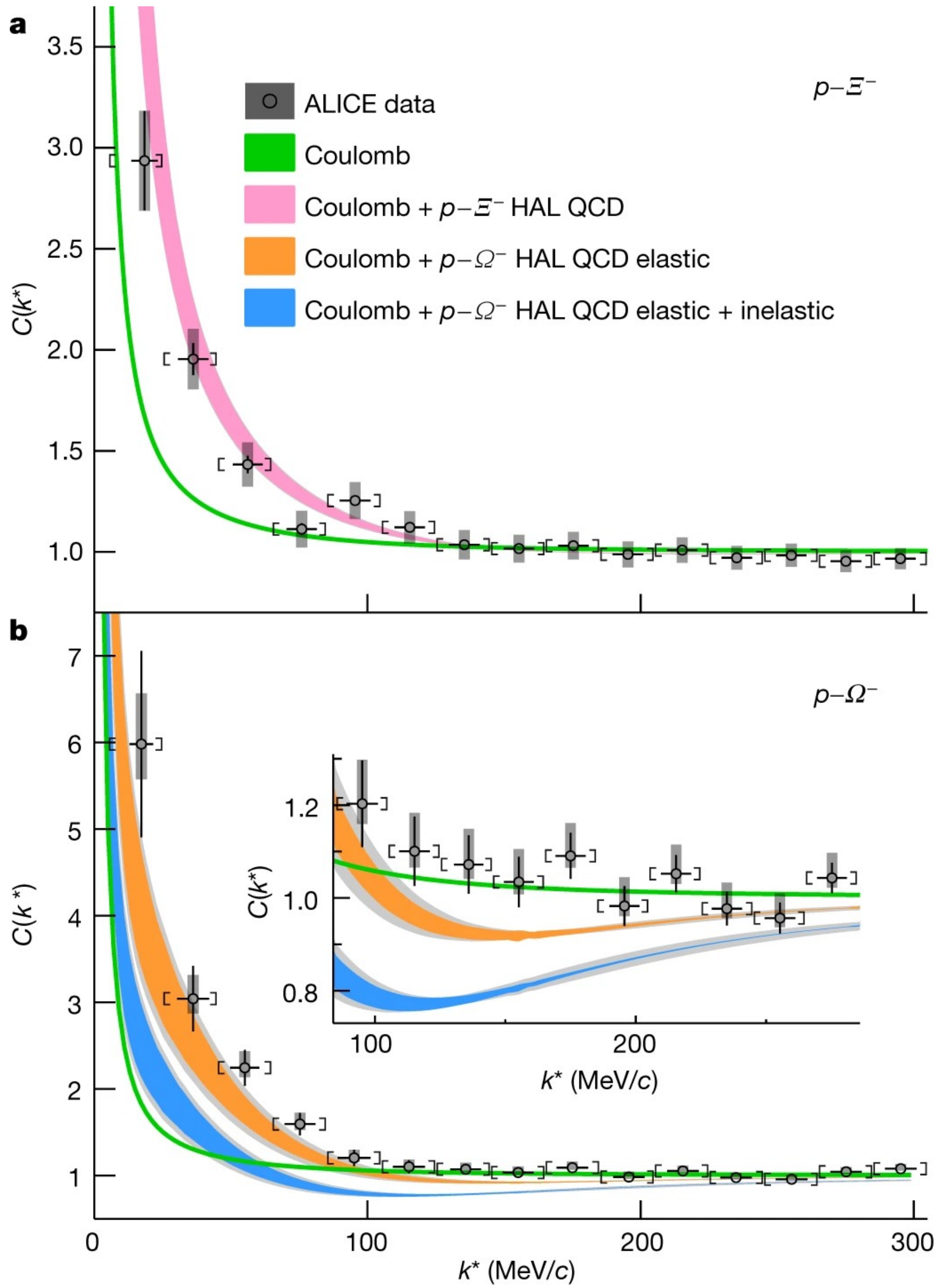
Nature 588 (2020) 232-238



p-Ω interaction: purely attractive (HAL QCD)

calculations underestimate the data in 100 < k^* < 300 MeV/c

1. Inelastic interaction not accounted for quantitatively
2. p-Ω dibaryon assumed (E_b = 2.5 MeV): depletion of C(k^*)

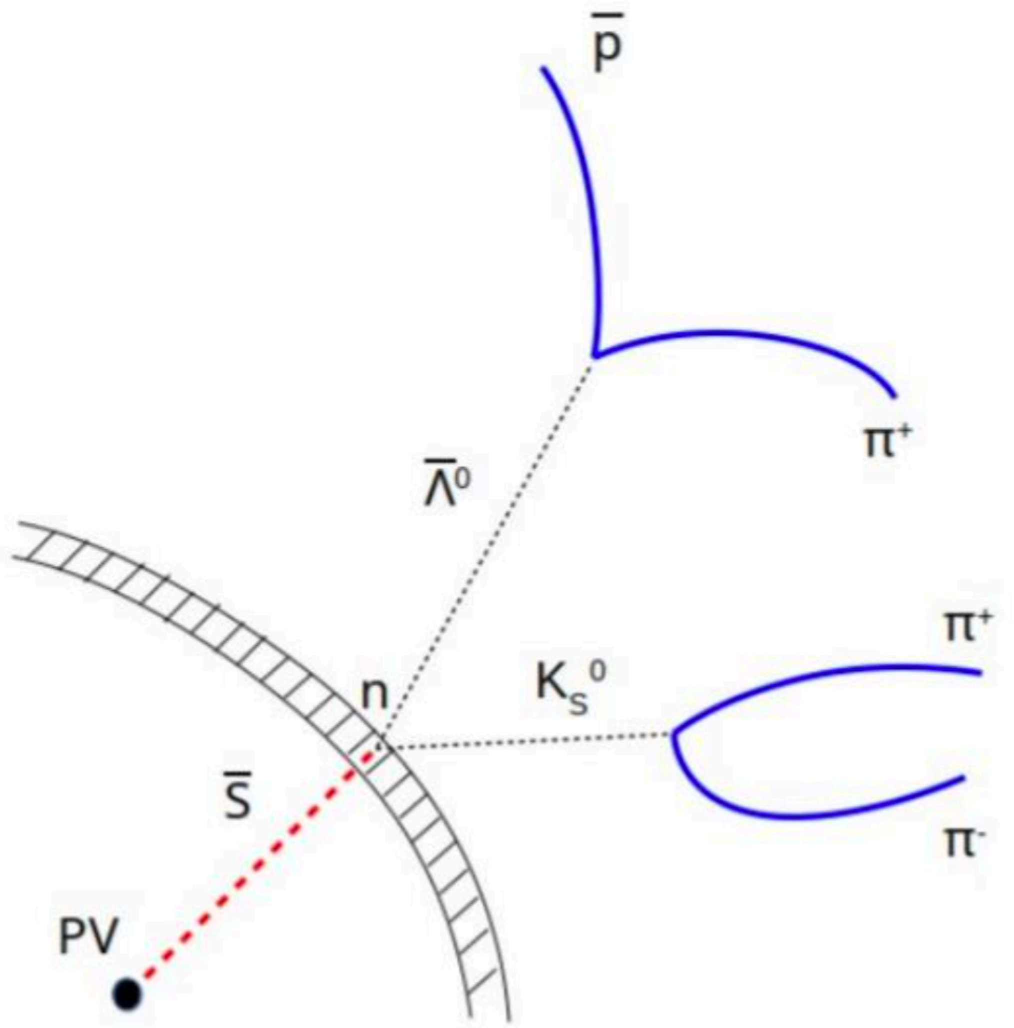


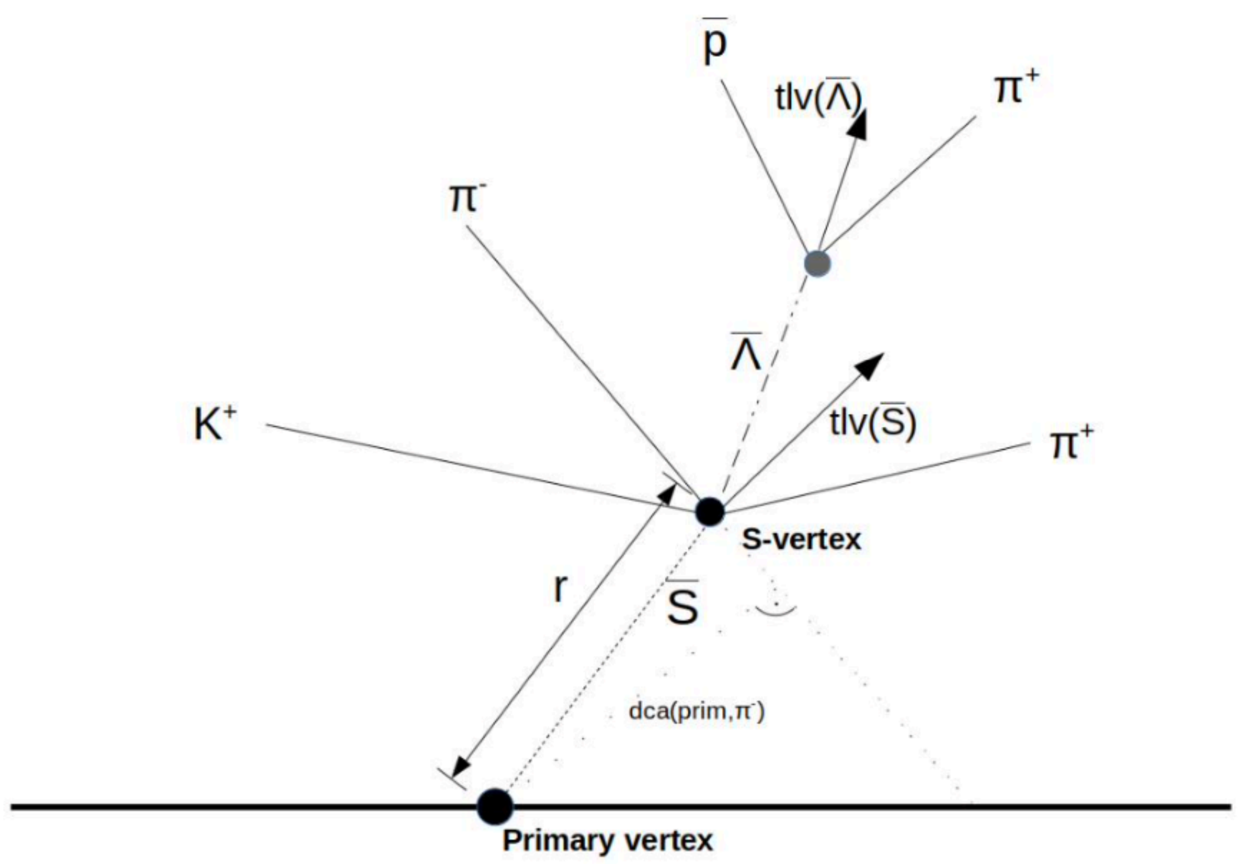
Stable H-dibaryon: sexaquark

In 2017, G. Farrar proposed a new (*uuddss*) state called Sexaquark

as a dark matter candidate (arXiv:1708.08951 [hep-ph]) → highly debated

- Spin-0, flavor-singlet, *Q*=0, *B*=2, and *S*=-2
- if $m_S < 2(m_p + m_e) \rightarrow$ absolutely stable
- If $m_S < m_p + m_e + m_\Lambda \rightarrow$ its lifetime would be longer than the age of the universe
- Searches based on its interaction with detector material (https://arxiv.org/abs/2201.01334)





$\bar{S} + n \rightarrow$	$\bar{S} + p \rightarrow$
$\bar{\Lambda}\, K^+\, \pi^-\, \pi^0$	$\bar{\Lambda}\, K^+\, \pi^-\, \pi^+$
$\bar{\Lambda}\, K^0\, \pi^-\, \pi^+$	$\bar{\Lambda}\ K^+\, \pi^0\, \pi^0$
$\bar{\Lambda}\, K^0\, \pi^0\, \pi^0$	$\bar{\Lambda}\, K^0\, \pi^+\, \pi^0$
$\bar{p}\, K^0\, K^0\, \pi^+$	$\bar{p}\, K^+\, K^+\, \pi^0$
$\bar{p}\, K^0\, K^+\, \pi^0$	$\bar{p}\, K^+\, K^0\, \pi^+$

M.Sc. Thesis of F.Partous (2018)

Pentaquark with hidden strangeness

ALICE

Phys. Rev. D 97, (2018) 094019

Several hidden-strangeness molecular pentaquarks are proposed with different spin configurations

Decay channels and expected masses provided for the searches

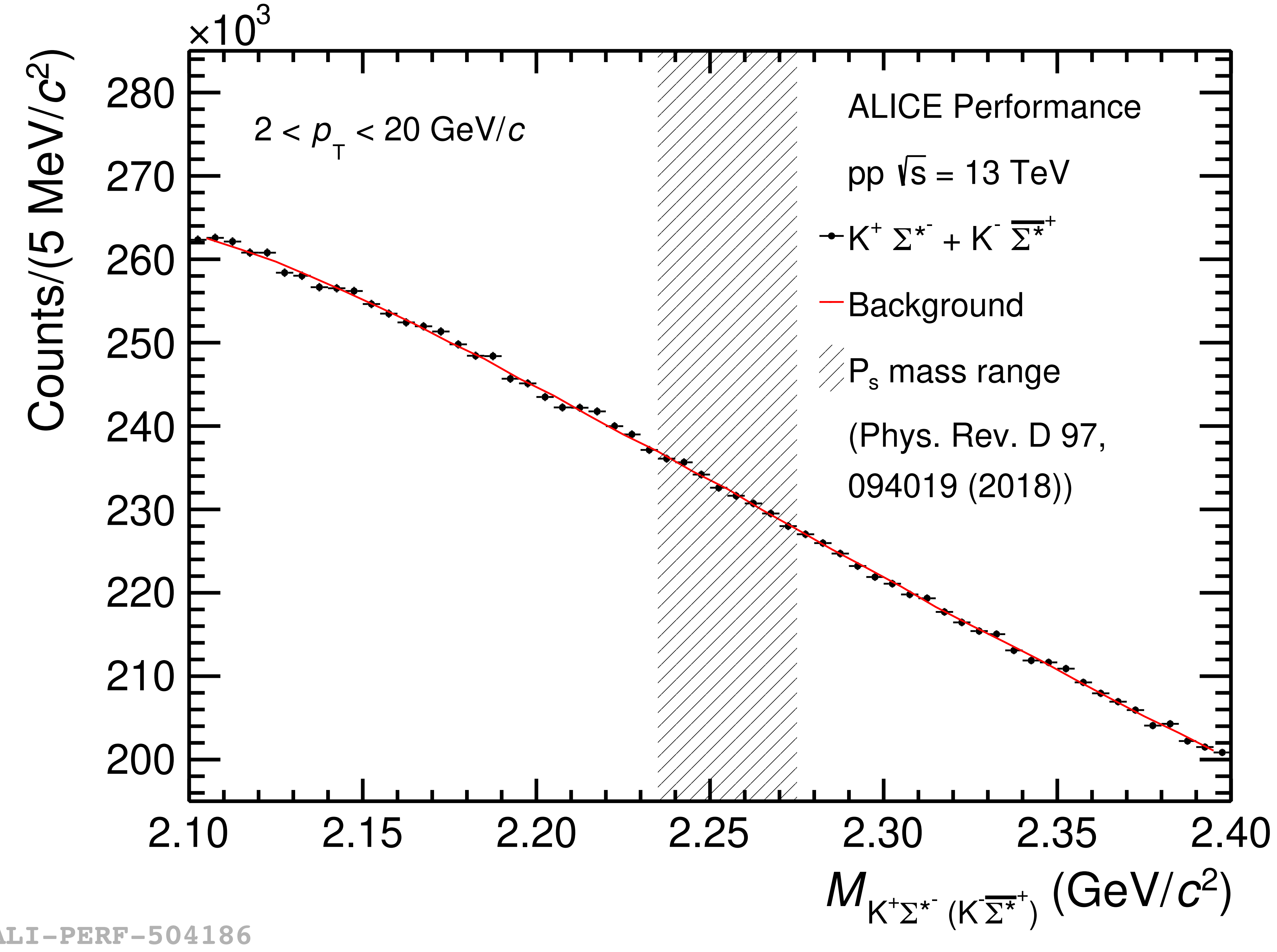
TABLE IV. The resonance mass and decay width (in MeV) of the molecular pentaquarks with $J^P = \frac{1}{2}^-$.

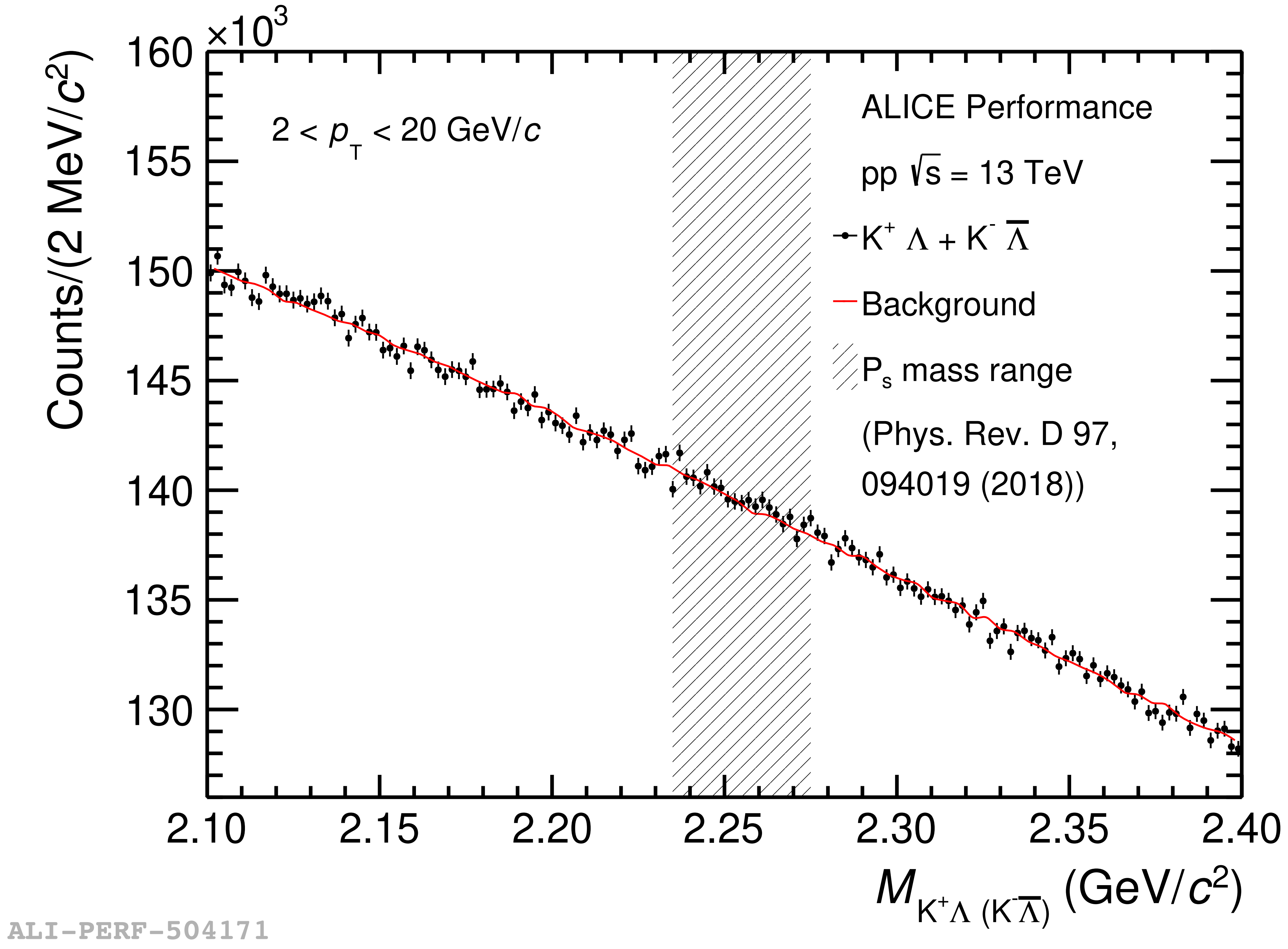
	ΣK		ΣK^*		$\Sigma^* K^*$	
S wave	M_r	Γ_i	M_r	Γ_i	M_r	Γ_i
$N\eta'$	⋯	⋯	2079.4	1.1	2246.8	20.0
$N\phi$	⋯	⋯	2080.0	3.6	2237.0	30.0
ΛK	1668.0	1.3	2083.4	1.0	2261.5	20.0
ΛK^*	⋯	⋯	2056.6	0.2	2219.0	58.0
ΣK	⋯	⋯	2071.6	4.6	2252.3	6.0
ΣK^*	⋯	⋯	⋯	⋯	2253.9	16.0
D wave						
$N\phi$	⋯	⋯	2076.3	0.3	2254.4	0.006
ΛK^*	⋯	⋯	2076.3	0.4	2253.6	0.6
ΣK^*	⋯	⋯	⋯	⋯	2254.0	0.06
$\Sigma^* K$	⋯	⋯	2076.8	0.01	2253.3	0.8

TABLE V. The resonance mass and decay width (in MeV) of the molecular pentaquarks with $J^P = \frac{3}{2}^-$.

	ΣK^*		$\Sigma^* K$		$\Sigma^* K^*$	
S wave	M_r	Γ_i	M_r	Γ_i	M_r	Γ_i
$N\phi$	2060.6	10.4	⋯	⋯	2270.5	0.03
ΛK^*	2046.1	15.0	⋯	⋯	2256.5	2.0
ΣK^*	⋯	⋯	⋯	⋯	2270.6	0.1
$\Sigma^* K$	2054.1	2.3	⋯	⋯	2263.6	3.7
D wave						
$N\eta'$	2061.4	0.001	1875.7	0.0004	2269.2	0.01
$N\phi$	2061.0	0.2	⋯	⋯	2269.3	0.01
ΛK	2060.6	0.9	1871.6	0.08	2269.2	0.02
ΛK^*	2059.1	0.3	⋯	⋯	2269.1	0.05
ΣK	2060.3	0.9	1871.6	0.05	2269.2	0.02
ΣK^*	⋯	⋯	⋯	⋯	2269.2	0.003

Searches for P_s with ALICE





Searches have been performed by ALICE in the decay channels:
$K^0_S\ \Sigma^{*+}$, $K^+_S\ \Sigma^{*-}$, $K^{*0}\ \Lambda$, $K^{*+}\ \Lambda$, $K^+\ \Lambda$, $K^0_S\ \Lambda$, $\phi\ p$

No signal is observed
→ ongoing work to set upper limits

f_0: a mysterius particle

$f_0(980)$: scalar meson with unknown lifetime and quark content

- $n\bar{n} = (u\bar{u} + d\bar{d})/\sqrt{2}$ state: PRD 67, 094011 (2003)
- exotic four-quarks state: PRD 103, 014010 (2021)
- Molecular state (mainly $K\bar{K}$): PRD 101 094034 (2020)

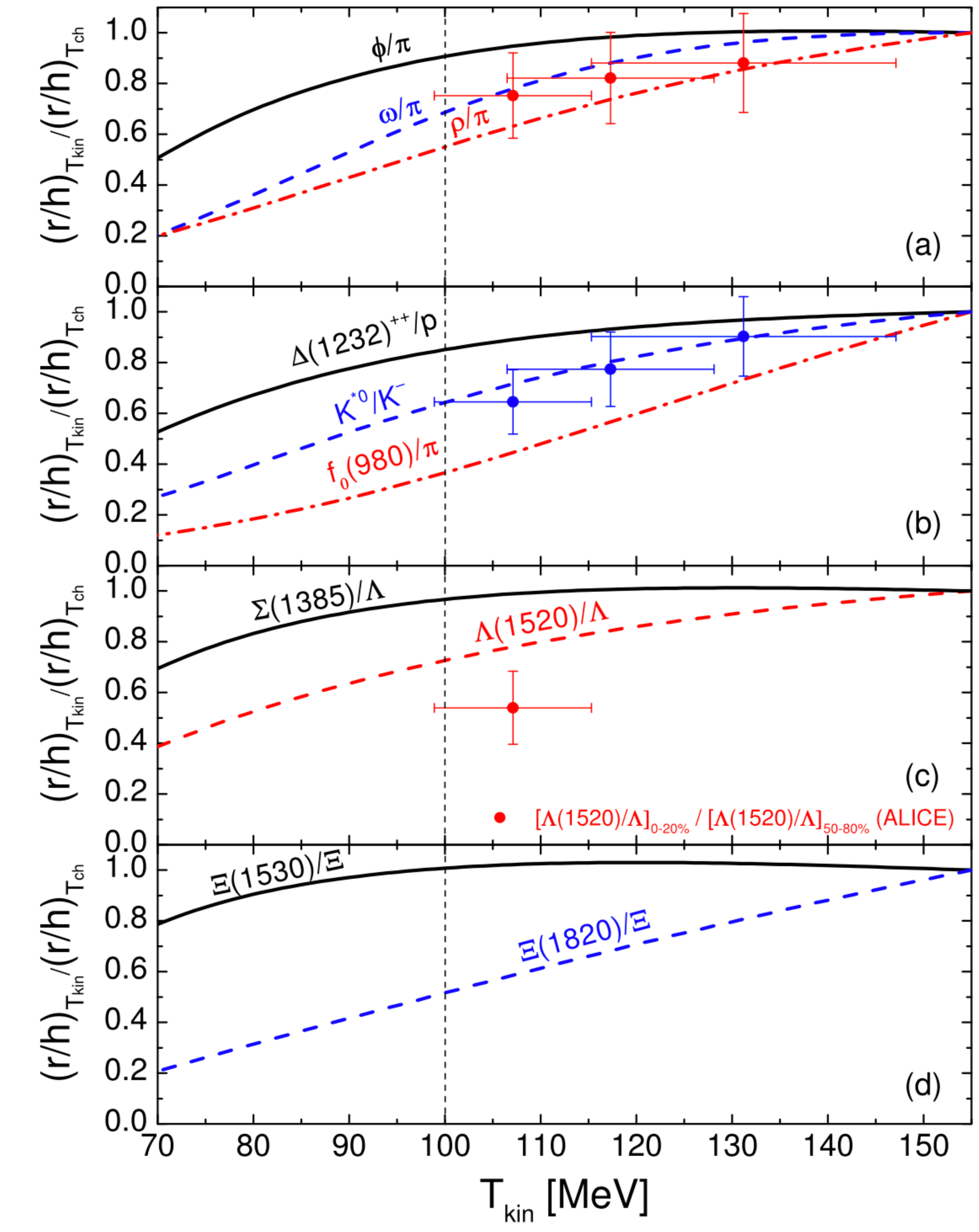
Measurement of $f_0(980)$ in small systems

study its internal structure using the canonical statistical model (CSM): PRC 100, 054906 (2019)

Measurement of $f_0(980)$ in heavy-ion collisions

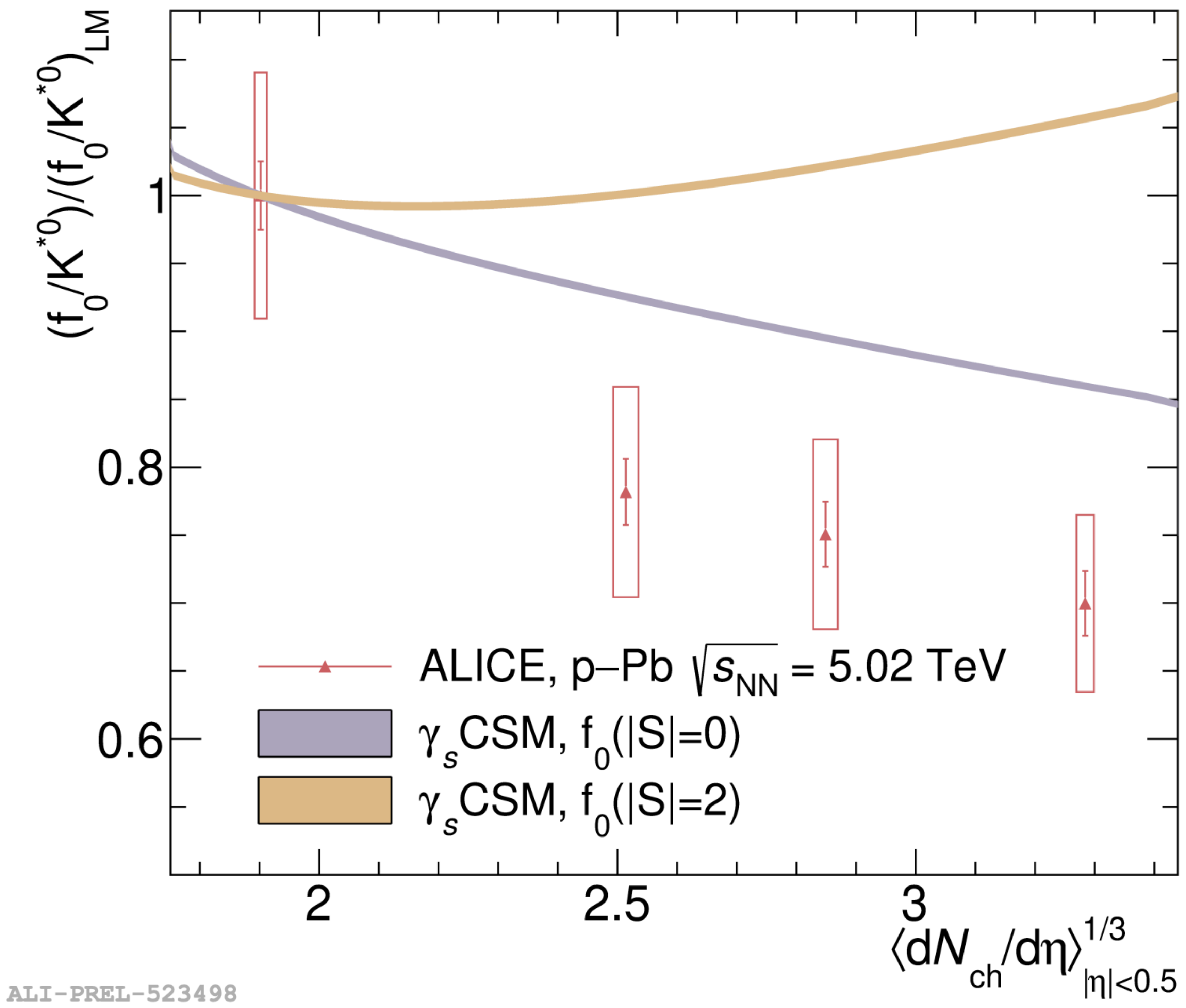
"*A significant suppression of the $f_0(980)/\pi$ ratio in central collisions relative to peripheral ones can be interpreted as evidence for a short $f_0(980)$ lifetime*": PRC 102, 024909 (2020)

PRC 102, 024909 (2020)

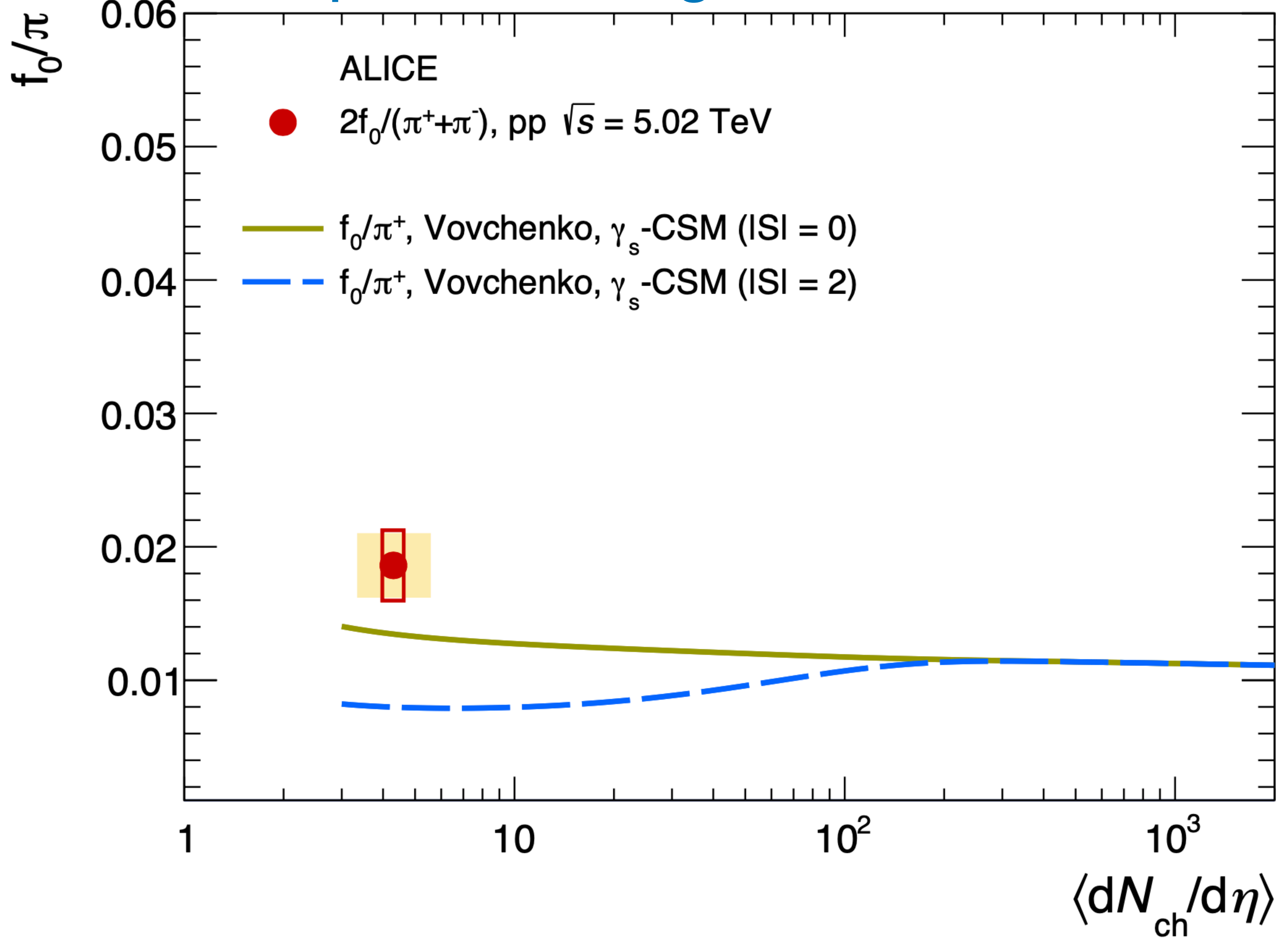


ALICE

Measurements of f_0 in small systems



https://arxiv.org/abs/2206.06216



$f_0(980)/K^{*0}$ and $f_0(980)/\pi$ compared with γ_S-CSM predictions: PRC 100, 054906 (2019)

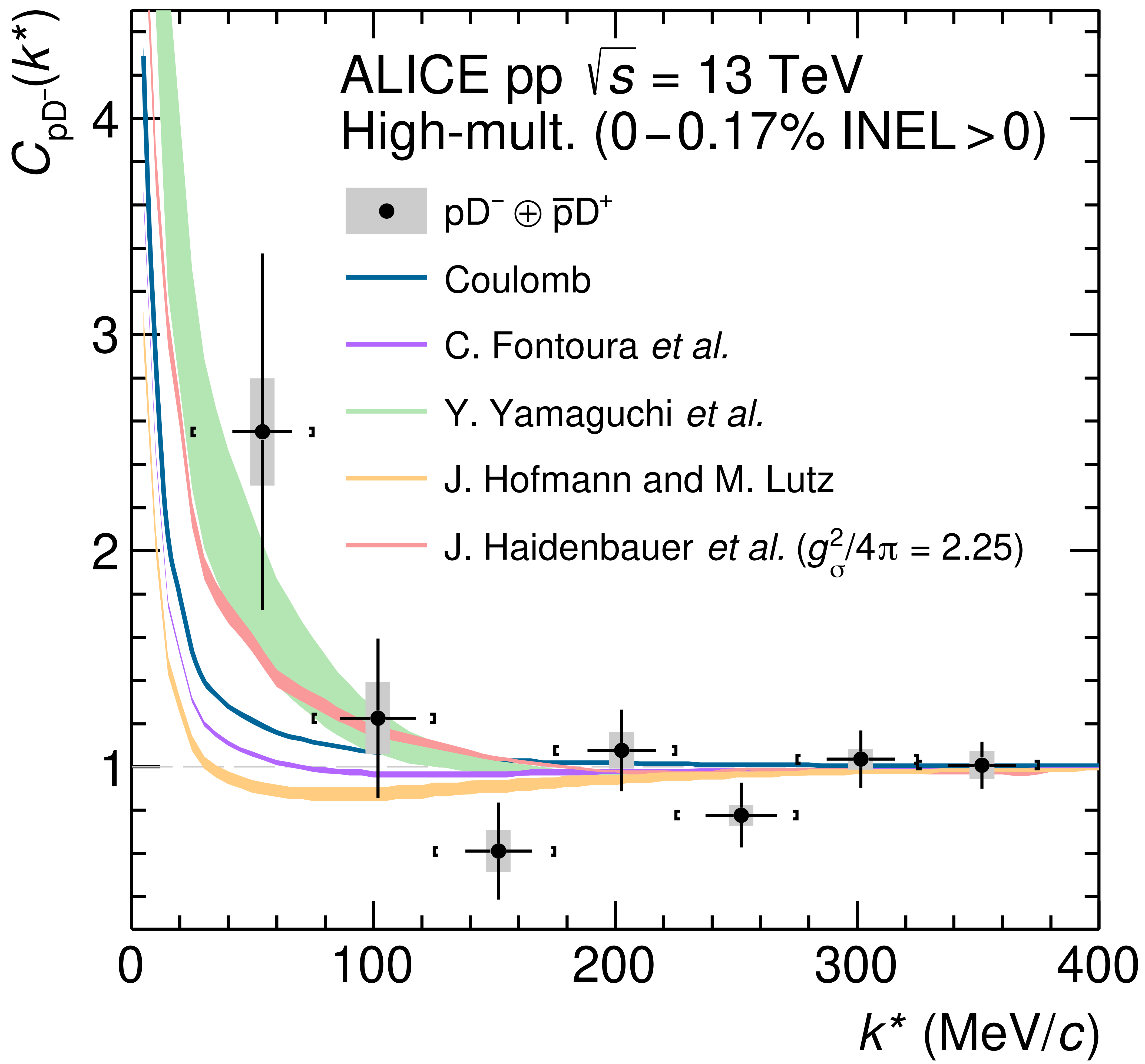
- |S| = 0 (no strangeness)
- |S| = 2 ($s\bar{s}$)

Data disfavor the |S| = 2 ($s\bar{s}$) scenario

N.B.: No rescattering effects in γ_S-CSM

Bound states in the charm sector

[Phys. Rev. D 106 (2022) 052010](#)



First measurement of D-p femtoscopic correlation function
> suggests a shallow attractive interaction

- *C*(k*) compatible with Coulomb-only within 1.5σ
- agreement improves when an attractive D-N strong interaction is considered
  [Phys. Rev. D **84**, (2011) 014032](#)

The model by Yamaguchi et al. also foresees the formation of a D-N bound state with a mass of 2804 MeV/c^2.

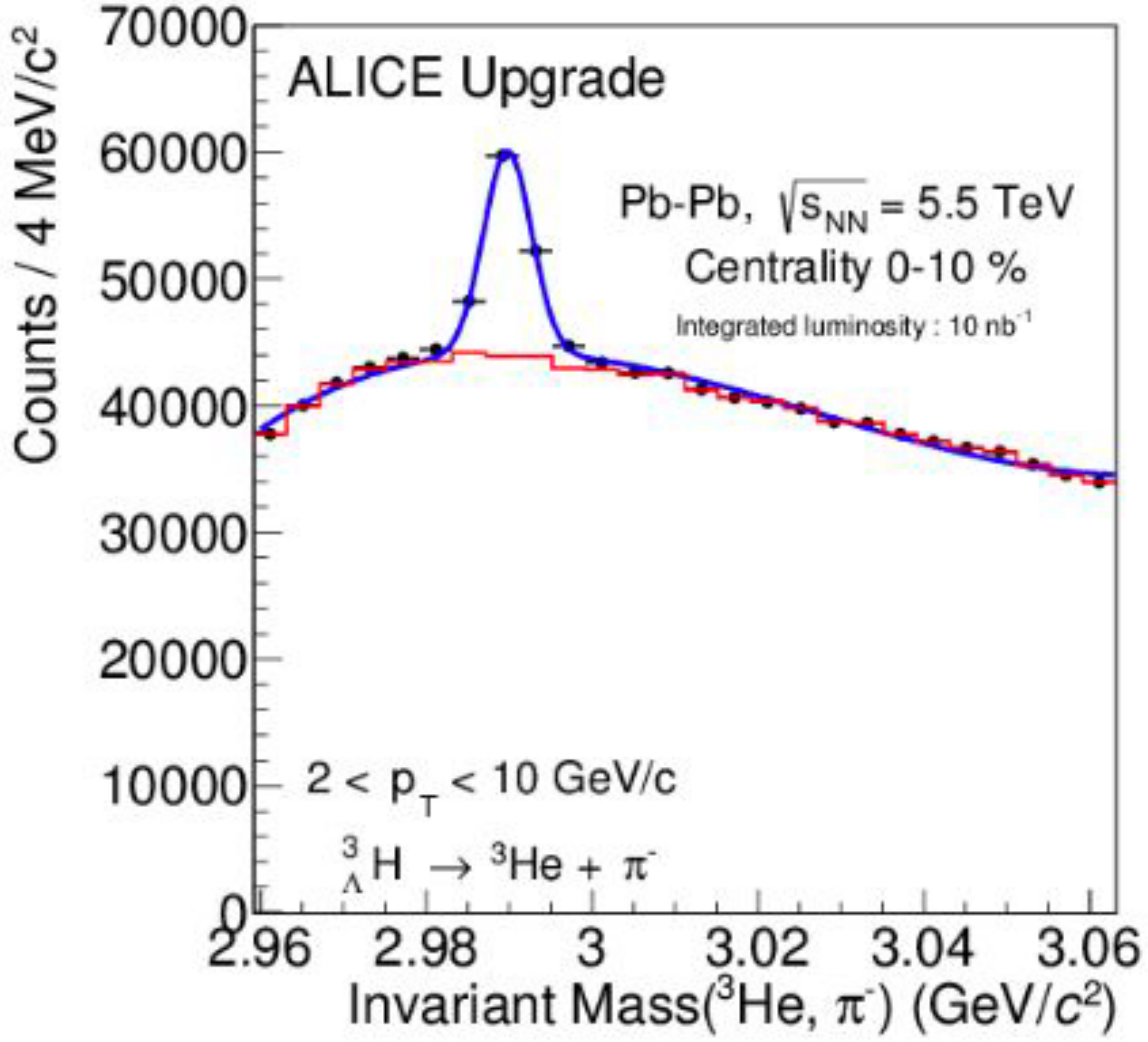
Data not conclusive yet due to large stat. uncertainties
> will be addressed with improved precision in Run 3

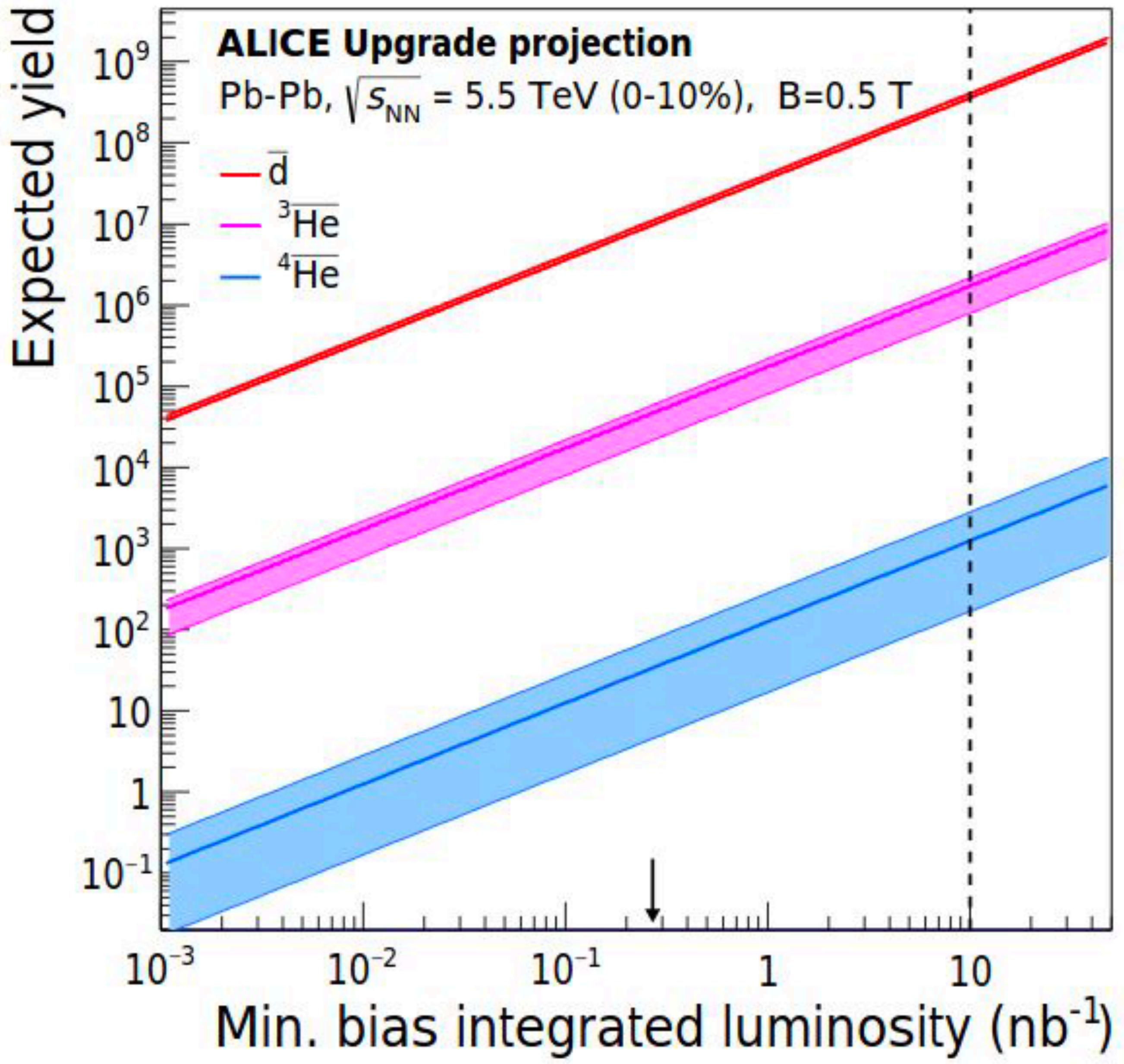
(Hyper)nuclei measurements in run3+4

[J. Phys. G: Nucl. Part. Phys. 41 (2014) 087002](#)

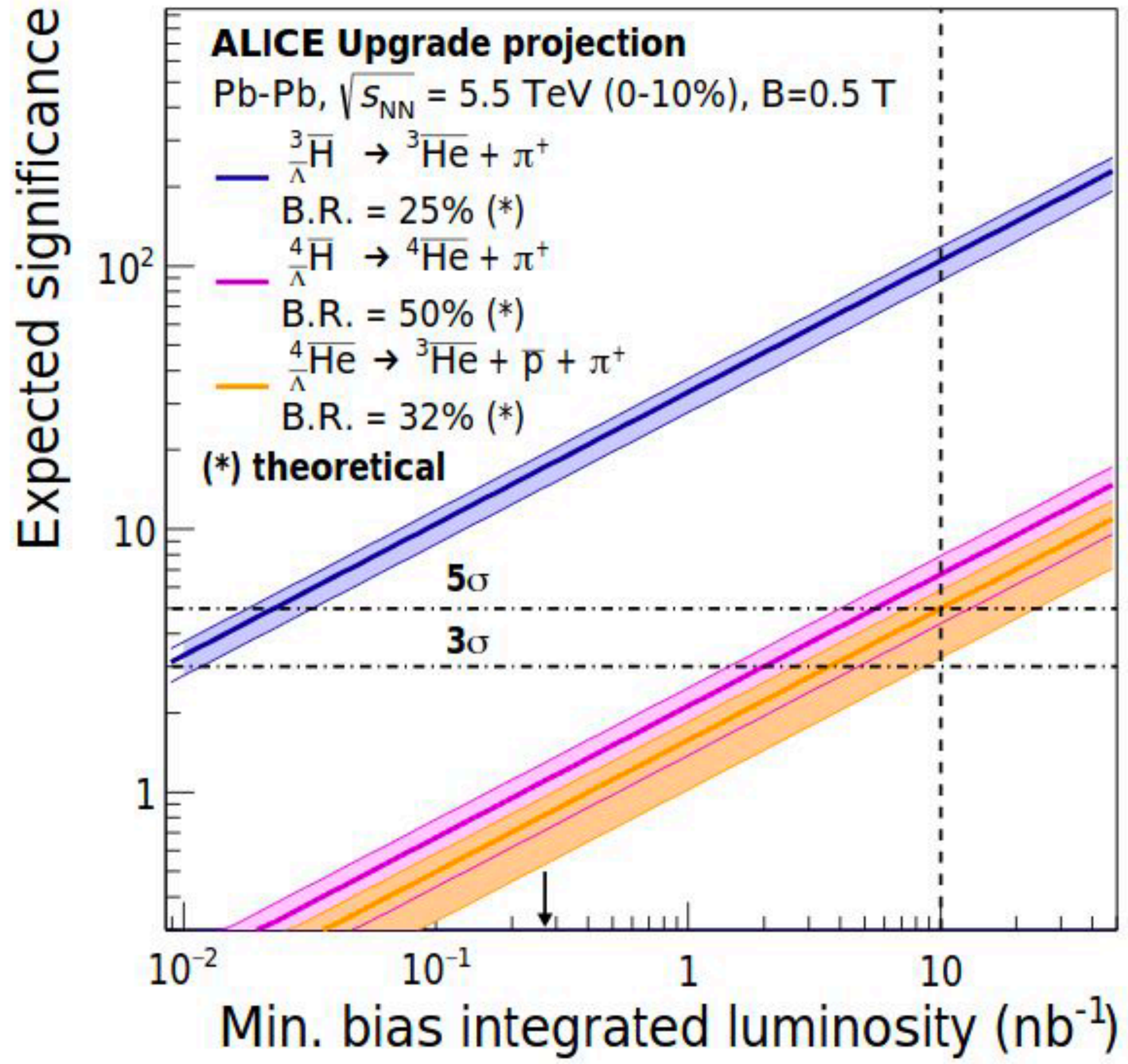
Improved precision expected in Run 3 and Run 4 for (hyper)nuclei measurements

- ~×50 larger data sample (Pb-Pb collision rate ≈ 50 kHz)
- New ITS: better sec. vertex resolution and lower material





ALI-SIMUL-312336

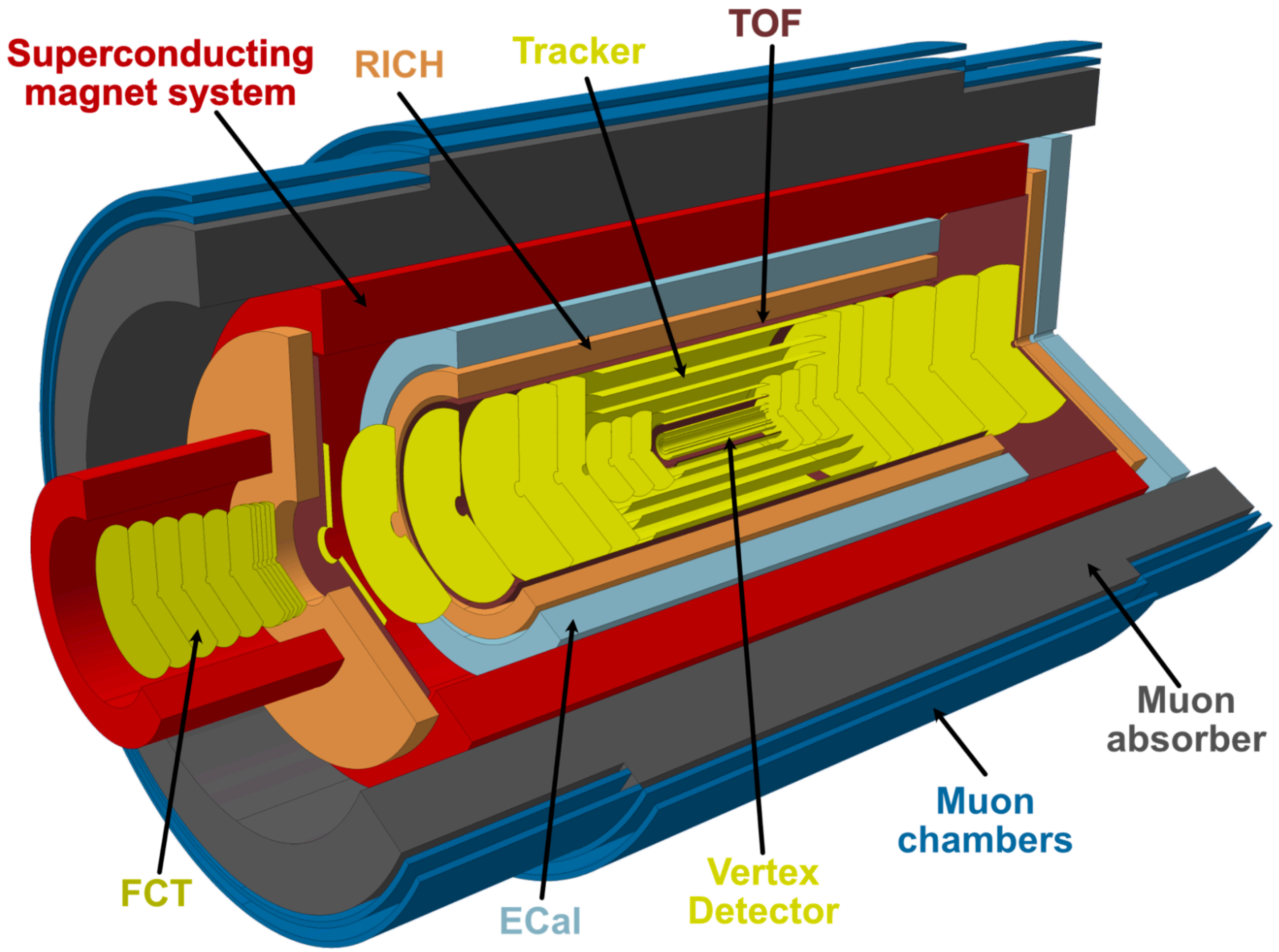


ALI-SIMUL-312332

State	dN/dy [81]	B.R.	$\langle Acc \times \varepsilon \rangle$	Yield
$^{3}_{\Lambda}H$	1×10^{-4}	25 % [82]	11 %	44000
$^{4}_{\Lambda}H$	2×10^{-7}	50 % [82]	7 %	110
$^{4}_{\Lambda}He$	2×10^{-7}	32 % [83]	8 %	130

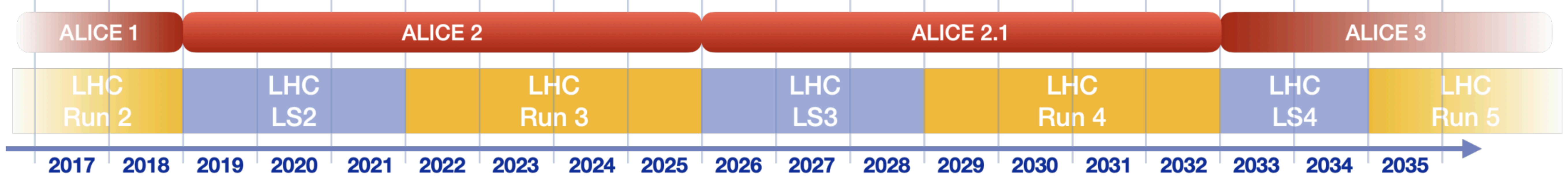
Next generation HI experiment

Letter of intent for ALICE 3:
A next generation heavy-ion experiment at the LHC
CERN-LHCC-2022-009 ; LHCC-I-038



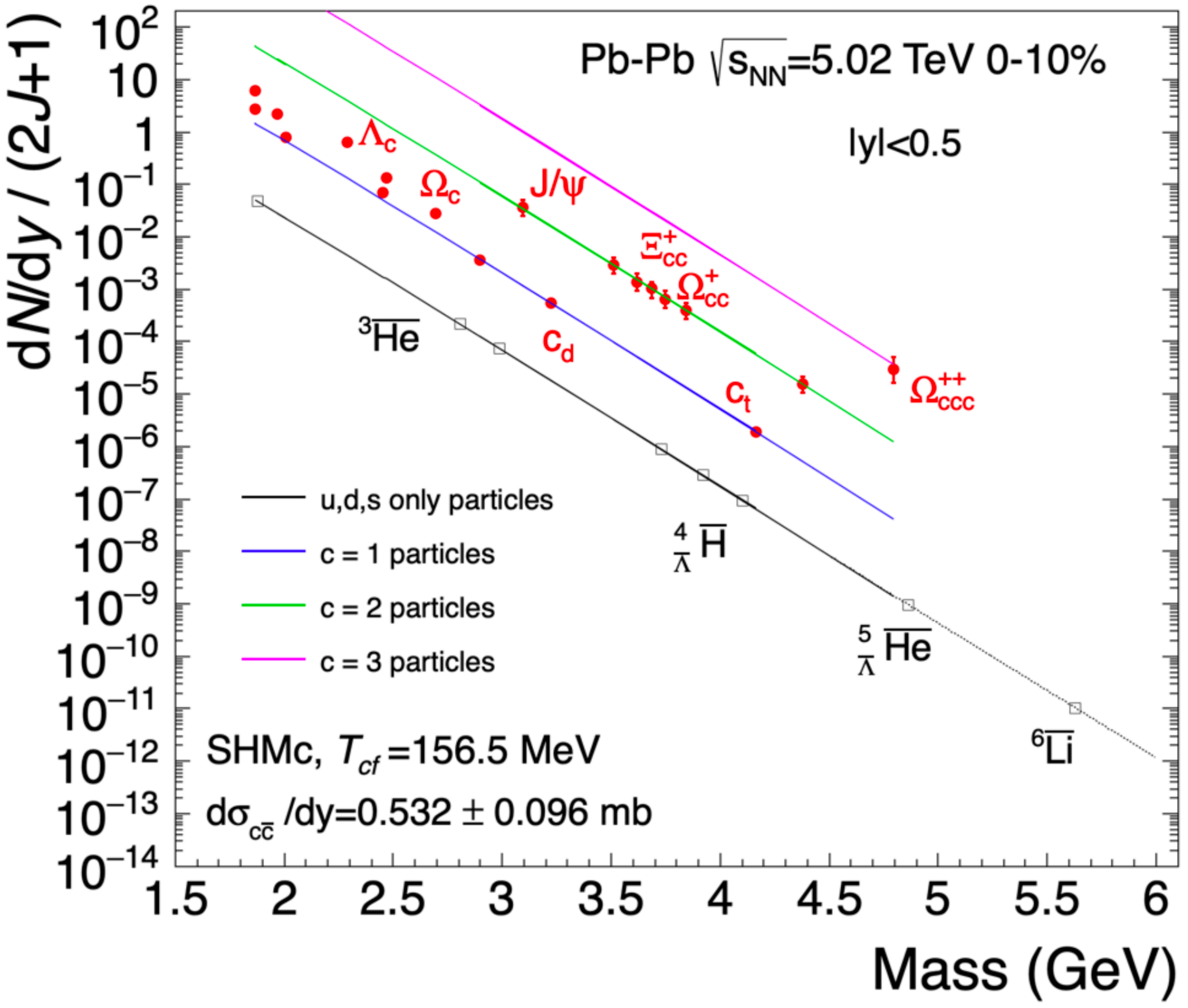
ALICE 3 detector concept:

- Silicon tracker composed of cylinders and disks
- B field provided by a superconducting magnets
- Vertex detector contained within the beam pipe
- Particle identification: TOF, RICH, photon detector, and muon system
- Forward conversion tracker housed in a dedicated dipole magnet



Exotic hyper- and super-nuclei

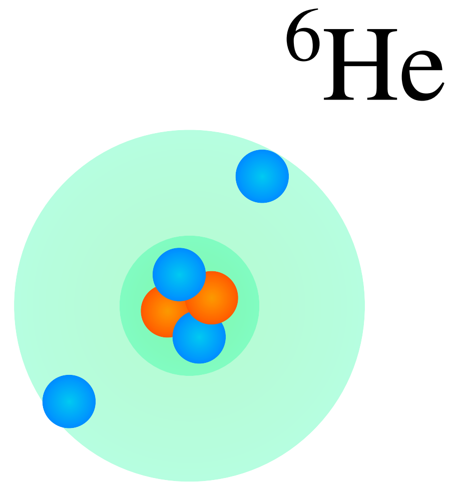
Letter of intent for ALICE 3:
A next generation heavy-ion experiment at the LHC
CERN-LHCC-2022-009 ; LHCC-I-038



ALICE 3 ideally suited for the study of hyper-nuclei like $^4_\Lambda$H or $^5_\Lambda$He and A=6 (anti)nuclei
> Test production models

SHM: Ω_{ccc}^{++} about $g_c^3 \approx 3 \times 10^4$ more abundant than $^5_\Lambda$He (approximately same mass)

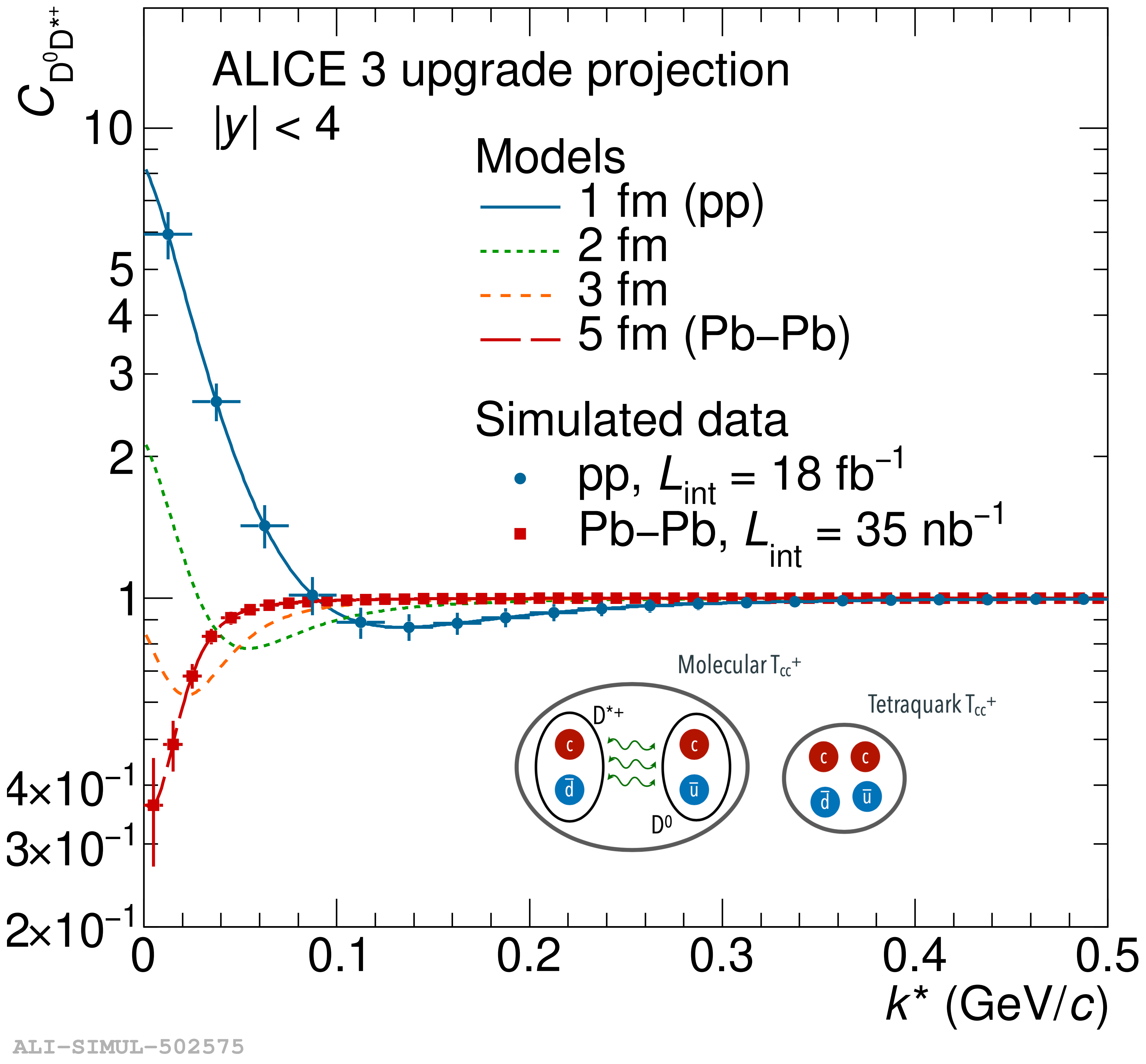
^{6}He is the lightest known halo nucleus
> coalescence predicts lower yield than SHM

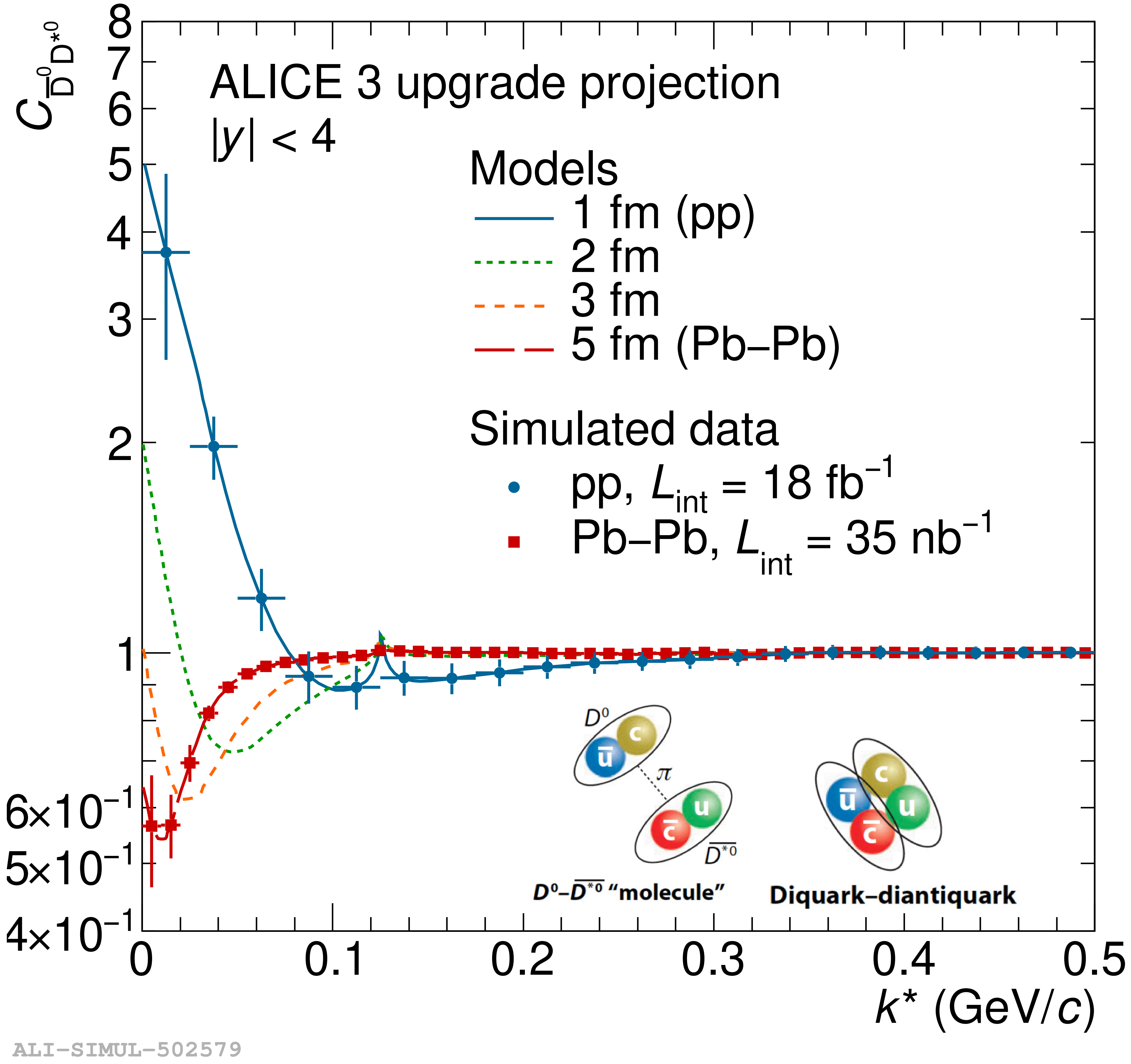


Search for super-nuclei (light nuclei with charm)
most promising candidates: c-deuteron, c-triton and c-^{3}He

$$c_d \rightarrow d + K^- + \pi^+$$
$$c_t \rightarrow {}^3H + K^- + \pi^+$$

Exotic molecules/tetraquarks





Interplay between system size and scattering length gives size-dependent modification of the correlation function in presence of a bound state (https://arxiv.org/abs/2203.13814)

Expected precision enough to study T_{cc}^{+} and X(3872) molecular structures

Summary

Outstanding contribution of ALICE to the studies and searches for exotic hadrons

Exciting times are ahead with the re-start of LHC

Further investigations with future upgrades and ALICE 3

Summary

Outstanding contribution of ALICE to the studies and searches for exotic hadrons

Exciting times are ahead with the re-start of LHC

Further investigations with future upgrades and ALICE 3

Thank you for your attention!

Backup slides