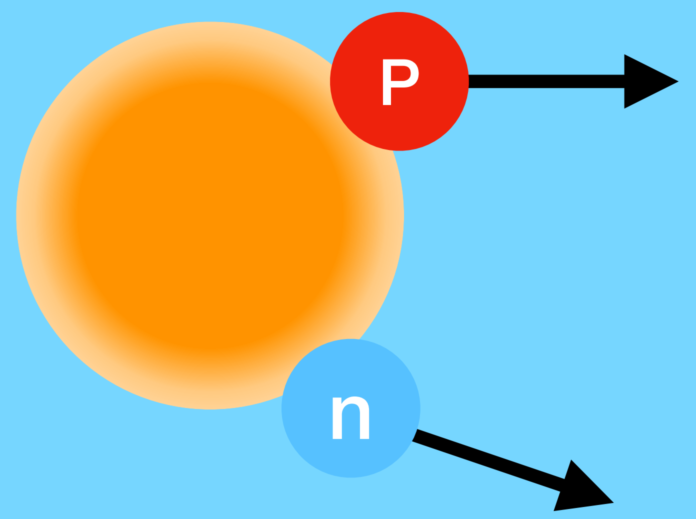
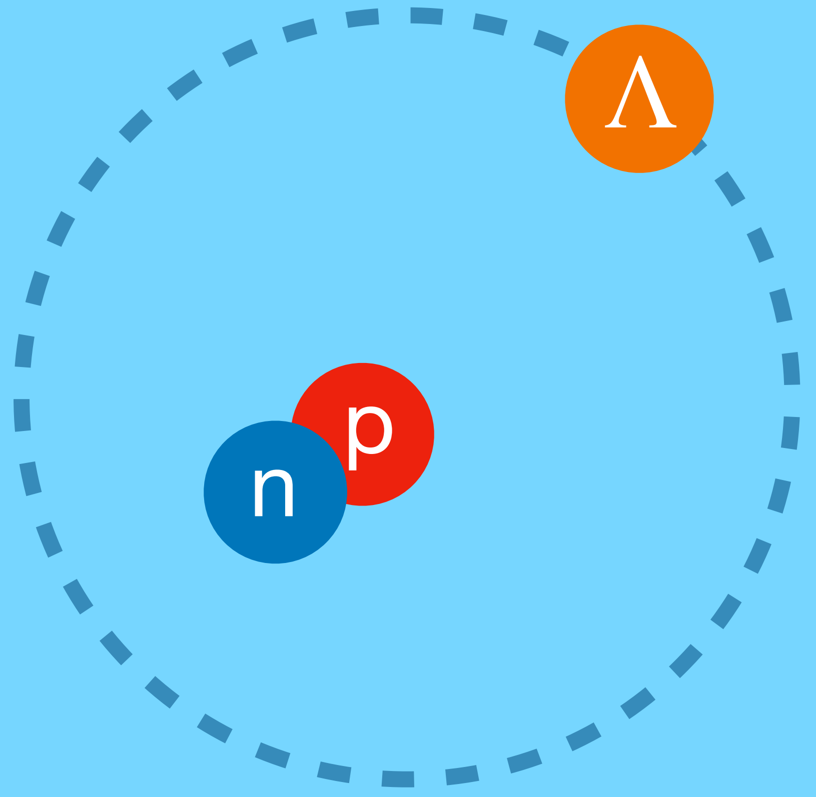
PANIC 2021 Conference 5-10 September 2021 Online

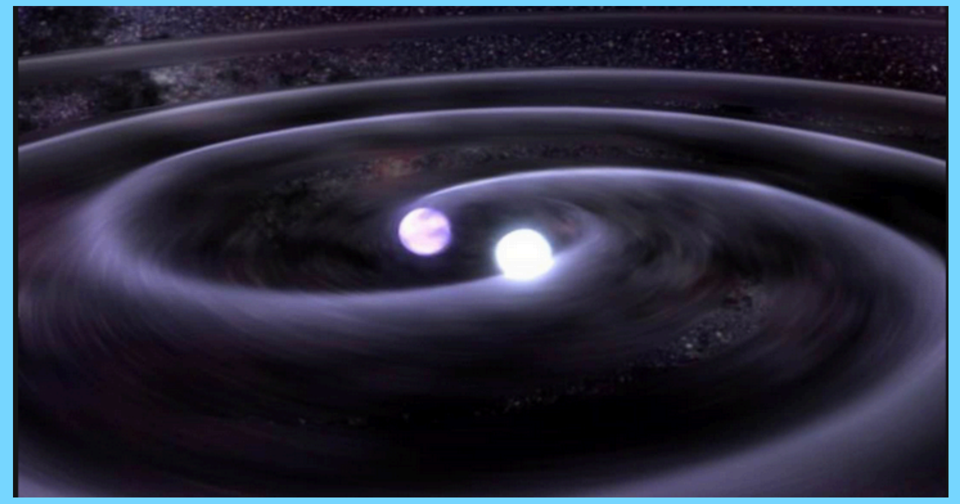


Overview on experimental results on hadrons in medium



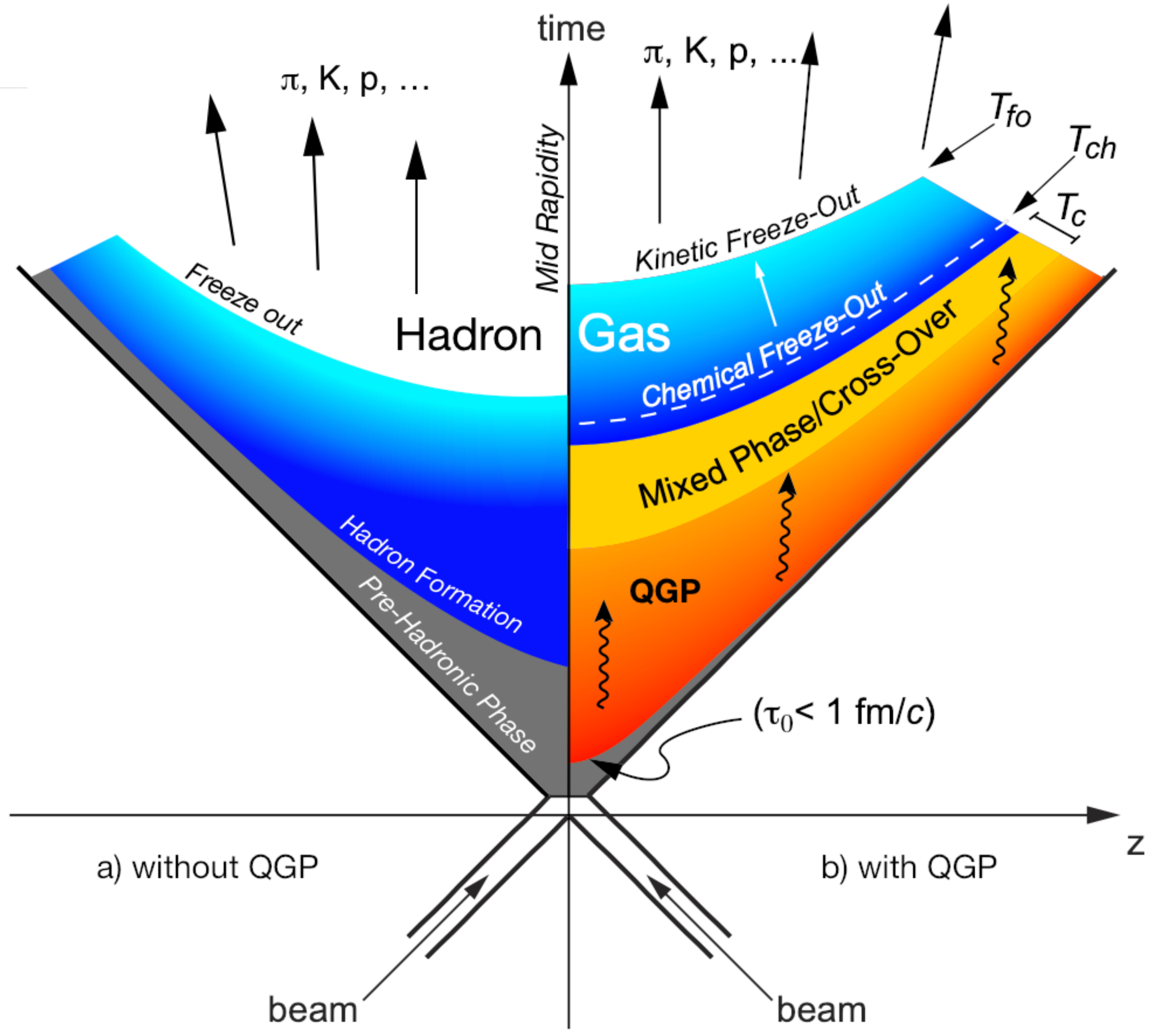
Stefania Bufalino

INFN and Politecnico di Torino (Italy)



Particle production in high energy collisions

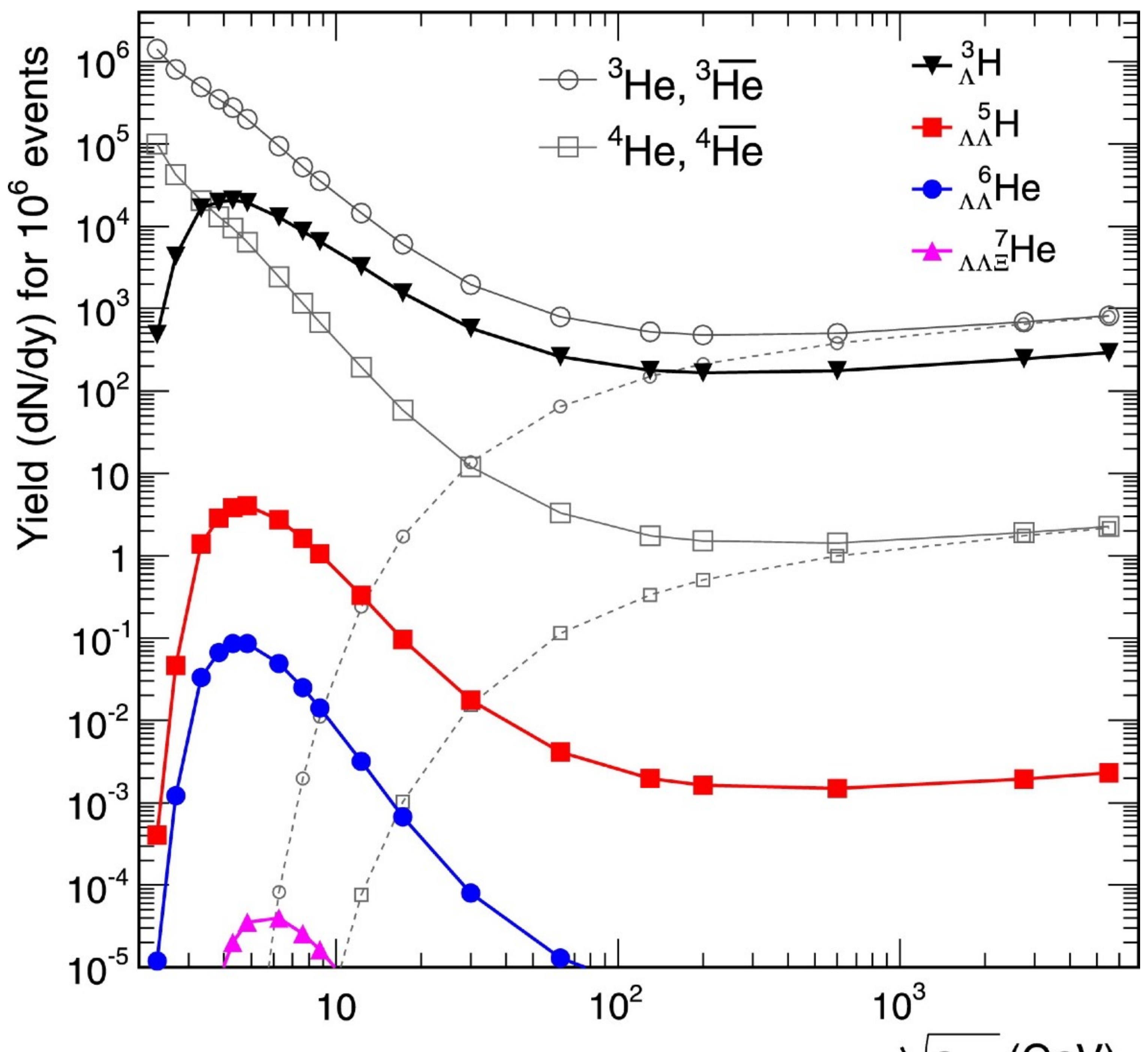
- Among other particle, light (anti-)nuclei and hypernuclei are abundantly produced both at the RHIC and at the LHC in all collision systems and at all the energies
- The **production mechanisms** of light (anti-)nuclei and hypernuclei in high-energy physics are still not completely understood
- Light (anti)nuclei have radii larger than those of ordinary hadrons and their sizes reach a significant fraction of the volume of the expanding medium
- Two classes of models are available for comparison:
    - the **coalescence** model
    - the **statistical hadronisation** model



The Statistical hadronisation model (SHM)

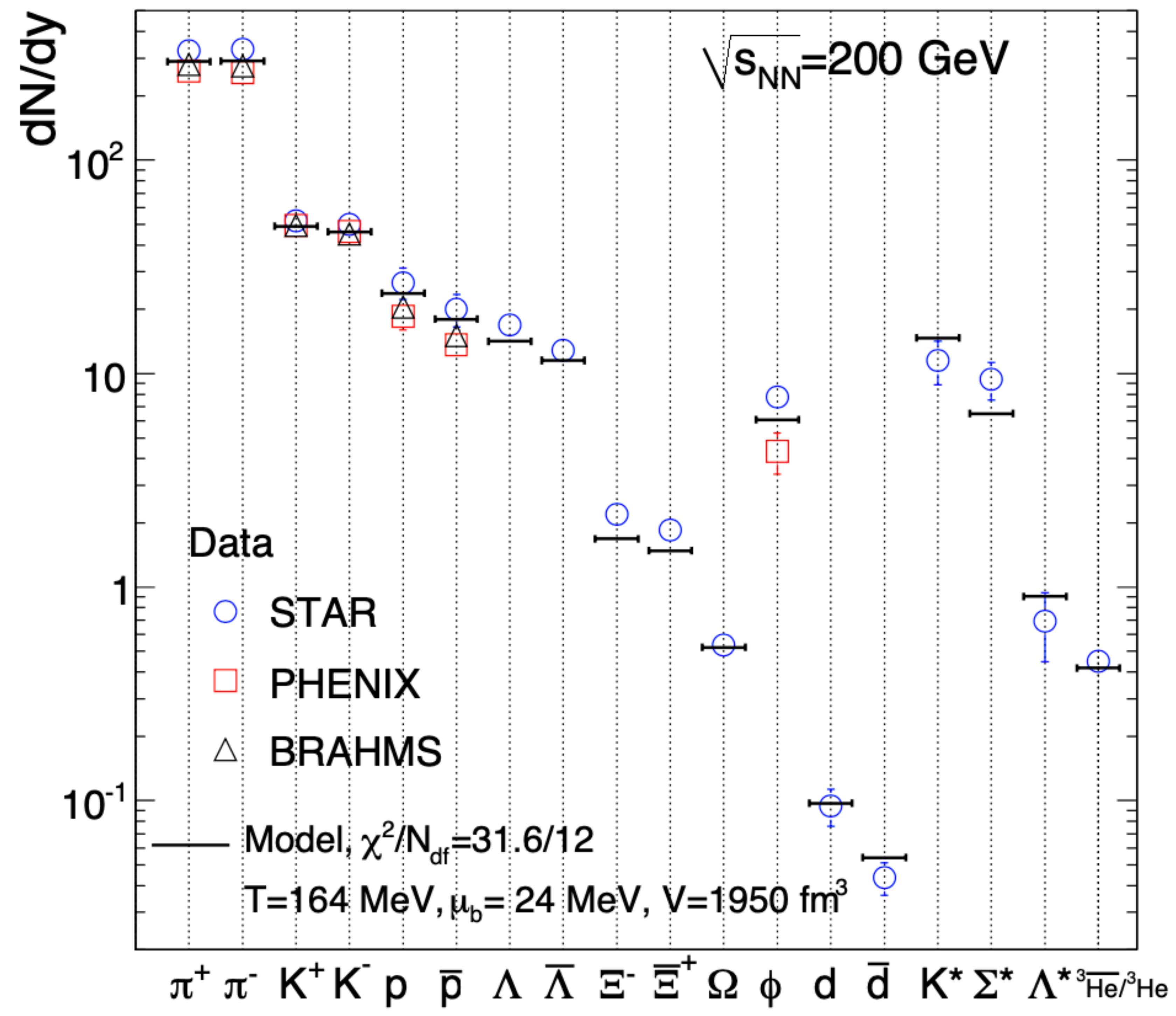
- Hadron abundances from **statistical equilibrium** at the **chemical freeze-out**
- Large reaction volume ($VT^3 > 1$) in HIC
  - **grand canonical ensemble**
- Successful in describing hadron yields in different collision systems and energies

$$dN/dy \propto \exp\left(-m/T_{ch}\right)$$



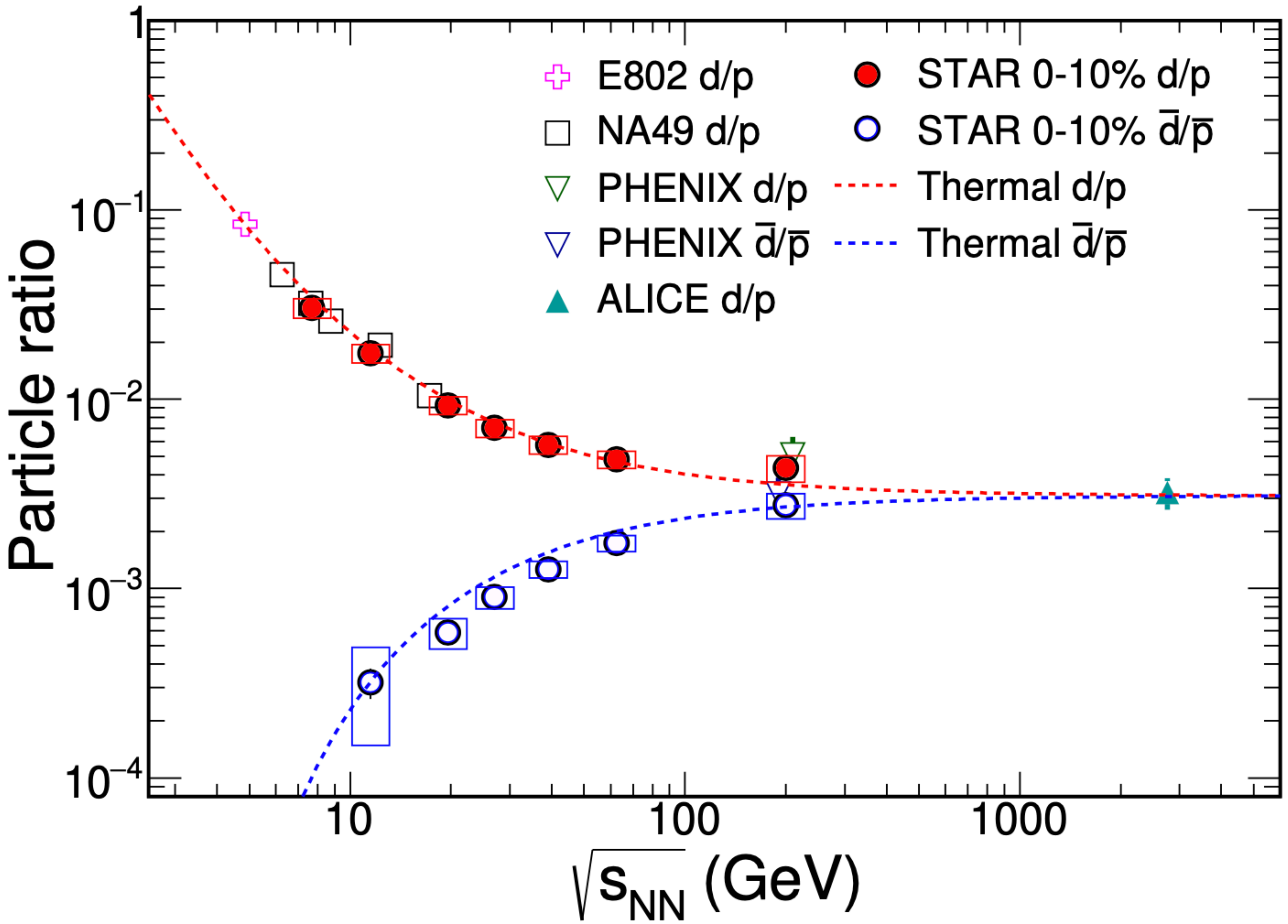
10.1016/j.physletb.2011.01.053

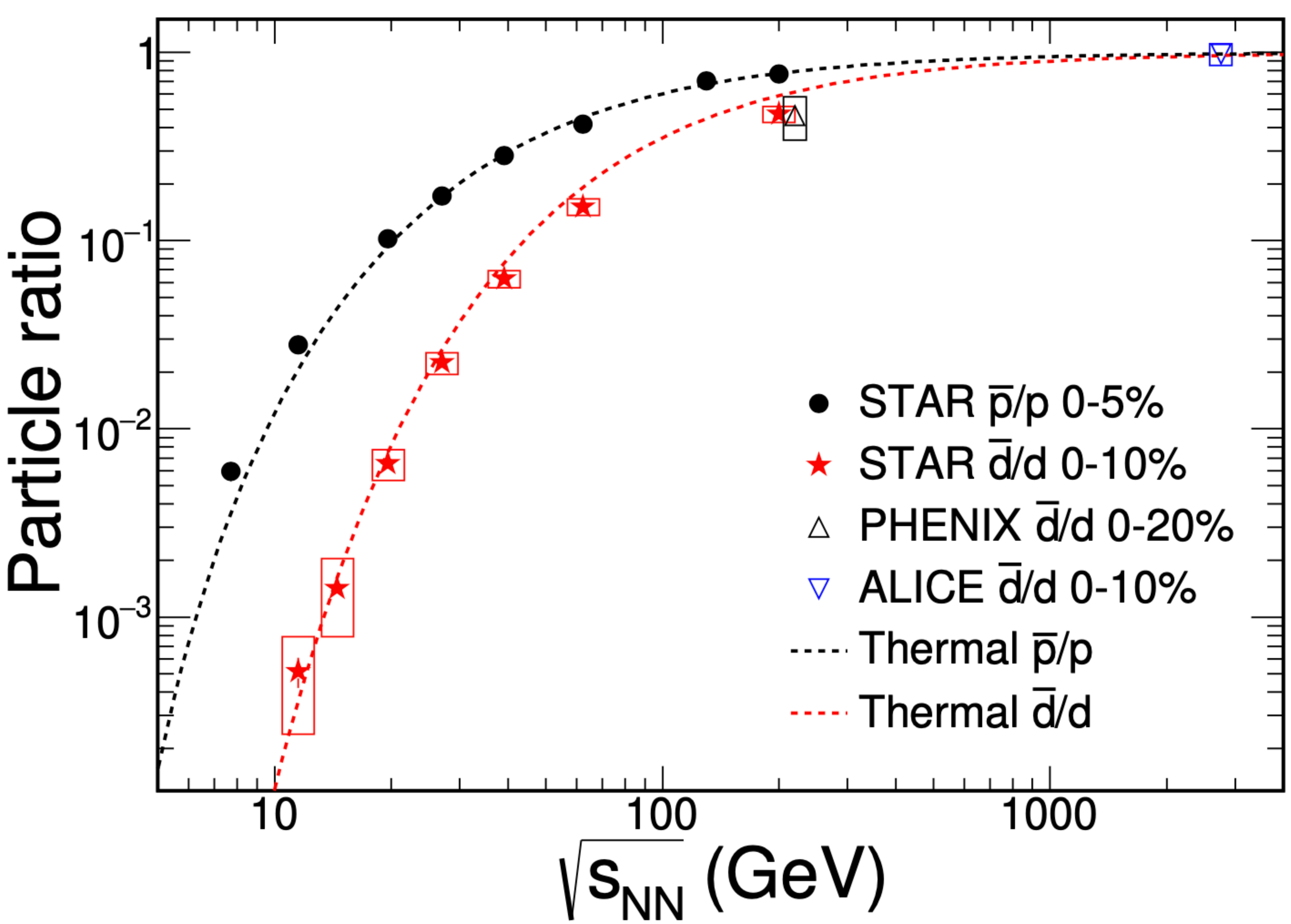
10.1016/j.physletb.2011.01.053



SHM vs collision energy

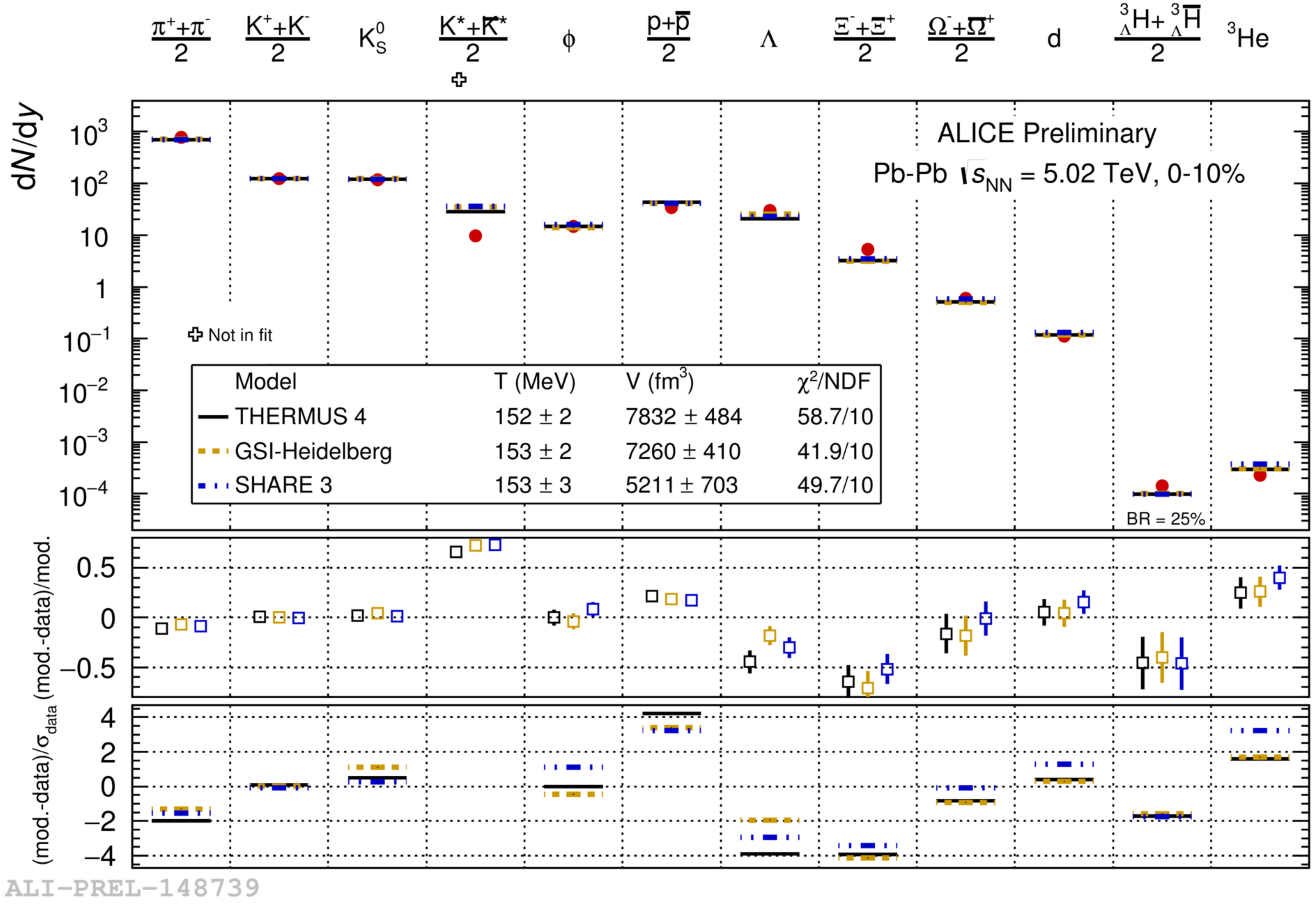
10.1103/PhysRevC.99.064905





Particle ratios are well described at different collision energies

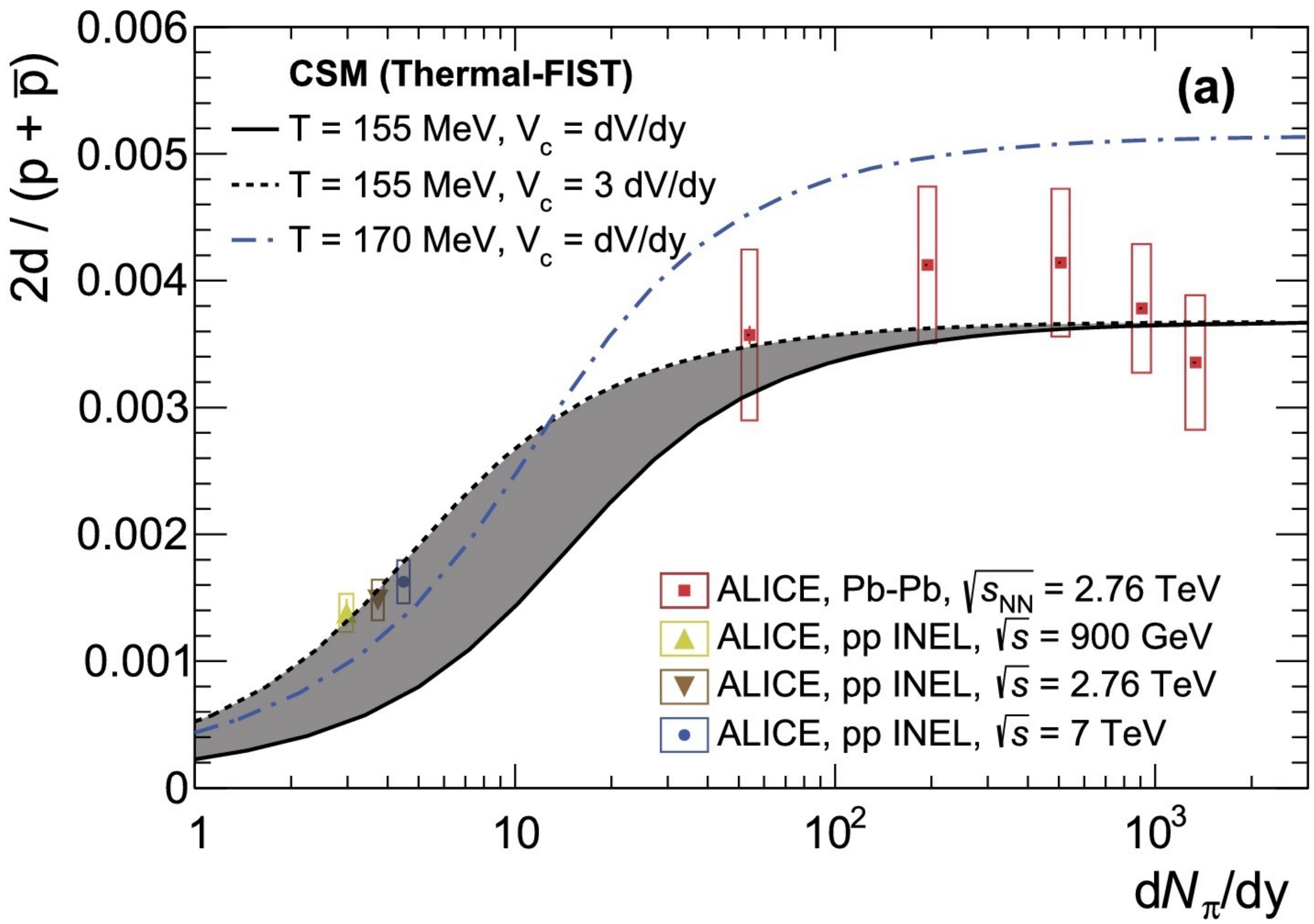
SHM for Pb-Pb collisions



- SHM describes **d*N*/dy** in Pb-Pb collisions over a wide range of d*N*/dy (**7 orders of magnitude**)
- Nuclei yields are well reproduced
  - thermally produced, together with the other particle species

THERMUS 4: Comput.Phys.Commun. 180 (2009) 84-106
GSI-Heidelberg: Nucl.Phys.A 772 (2006) 167-199
SHARE 3: Comput.Phys.Commun. 167 (2005) 229-251

The canonical statistical hadronisation model (CSM)



10.1016/j.physletb.2018.08.041

- In **small systems** ($VT^3 < 1$): local conservation of quantum numbers (S, Q and B)
  - **canonical ensemble**
- Small volumes → suppression of particles carrying the conserved charges: **canonical suppression**
- Large volumes → same as SHM
- Production vs multiplicity → dependence on the system size

Coalescence model

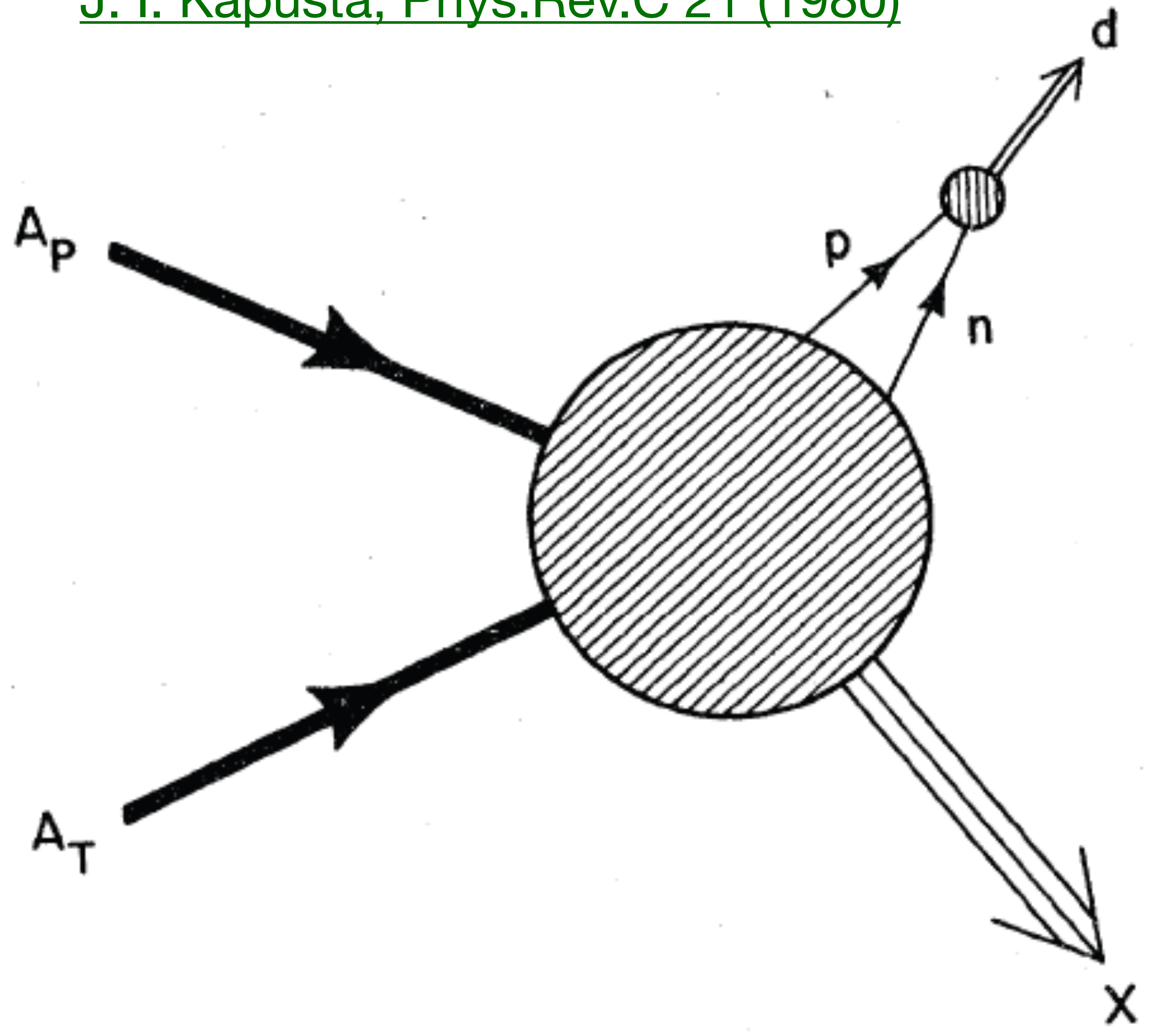
J. I. Kapusta, Phys.Rev.C 21 (1980)

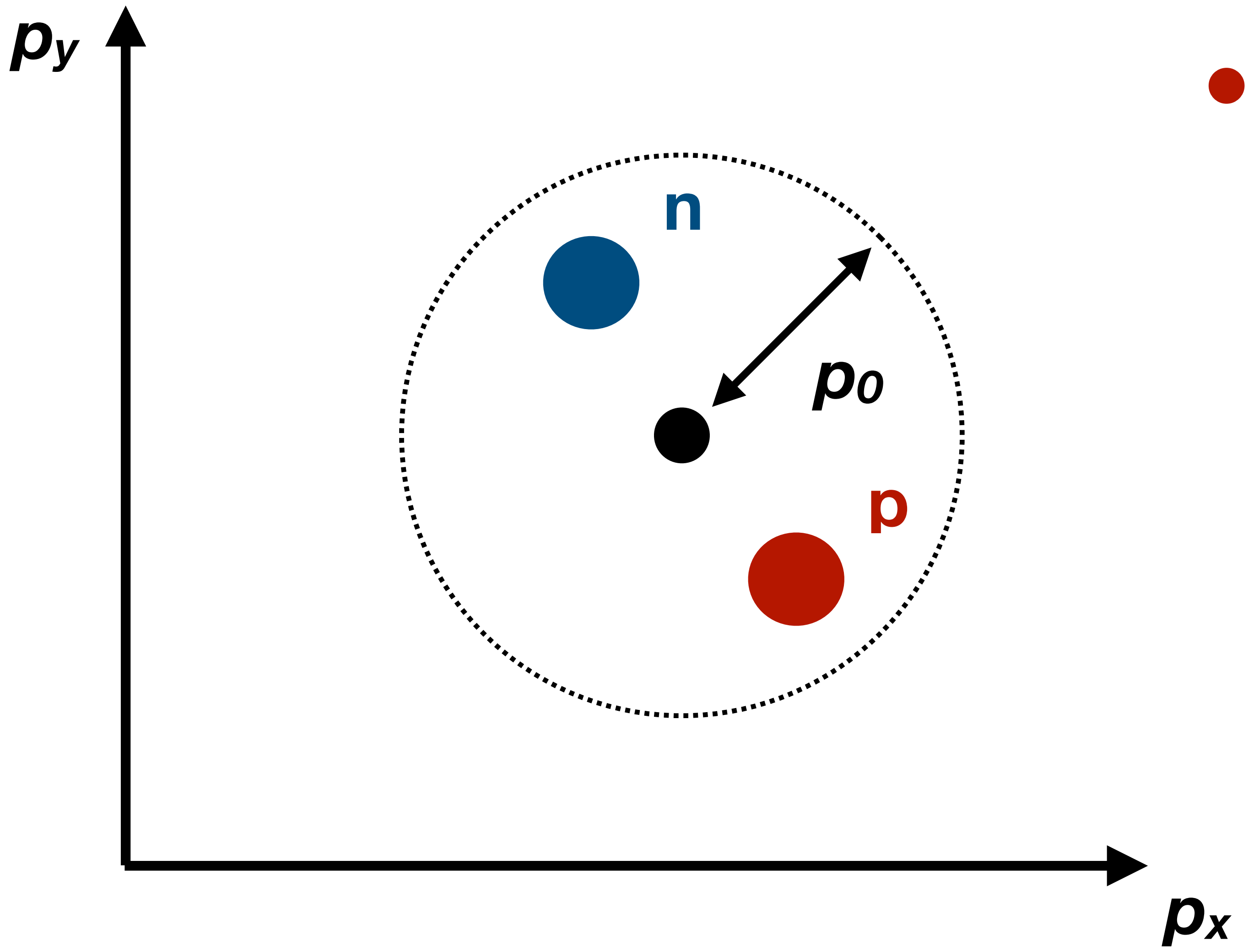
- Nucleons **close in phase space** at the **freeze-out** can form a nucleus via **coalescence**
- Coalescence parameter $\mathbf{B_A}$:

$$B_A = E_A \frac{\mathrm{d}^3 N_A}{\mathrm{d}p_A^3} \Bigg/ \left(E_p \frac{\mathrm{d}^3 N_p}{\mathrm{d}p_p^3} \right)^A$$

where:

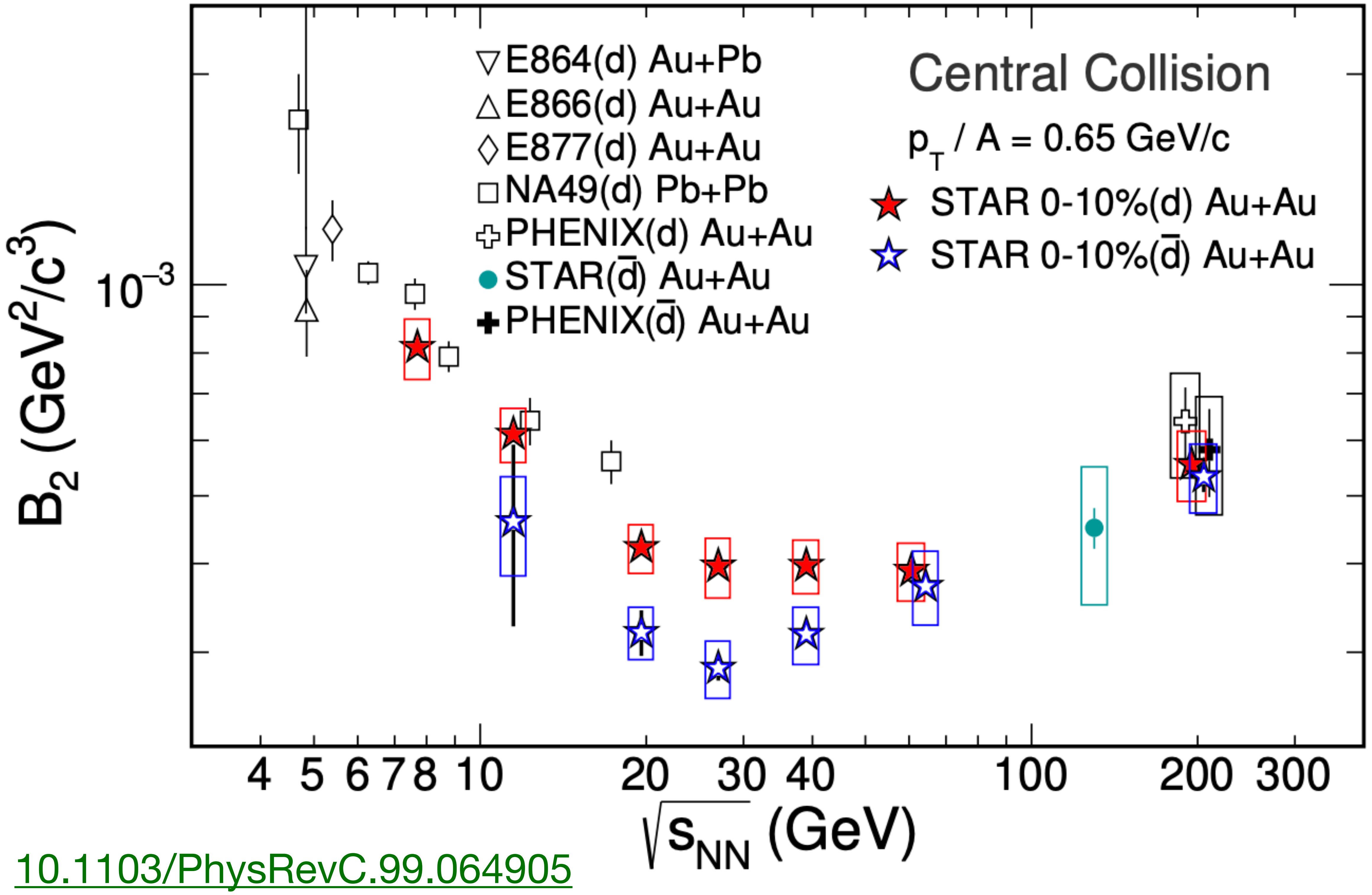
- A is the mass number of the nucleus
- $p_p = p_A / A$





- $\mathbf{B_A}$ is related to the **probability** to form a nucleus via coalescence
- **In the simplest formulation: No space-time** distribution fo the nucleons considered
  - Nucleons with similar momentum ($\Delta \mathbf{p} < \mathbf{p_0}$) can form a nucleus
  - Consequences: B_A vs p_T is **flat**
  - Applications: **pp collisions**: small volume (comparable with nucleus size) → nucleons are alway close to each other

Simple coalescence with Volume



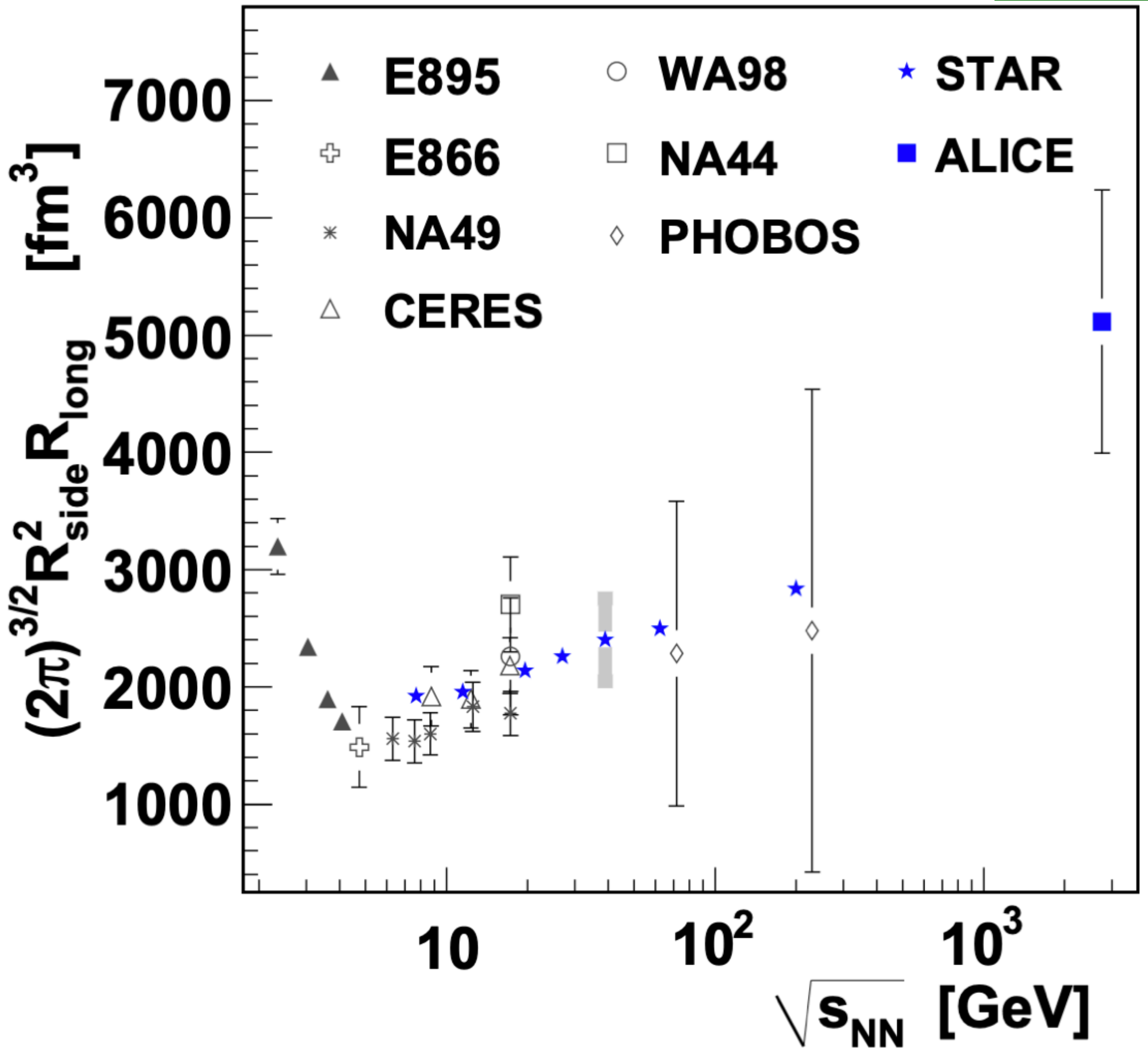
10.1103/PhysRevC.99.064905

- In simple coalescence model:

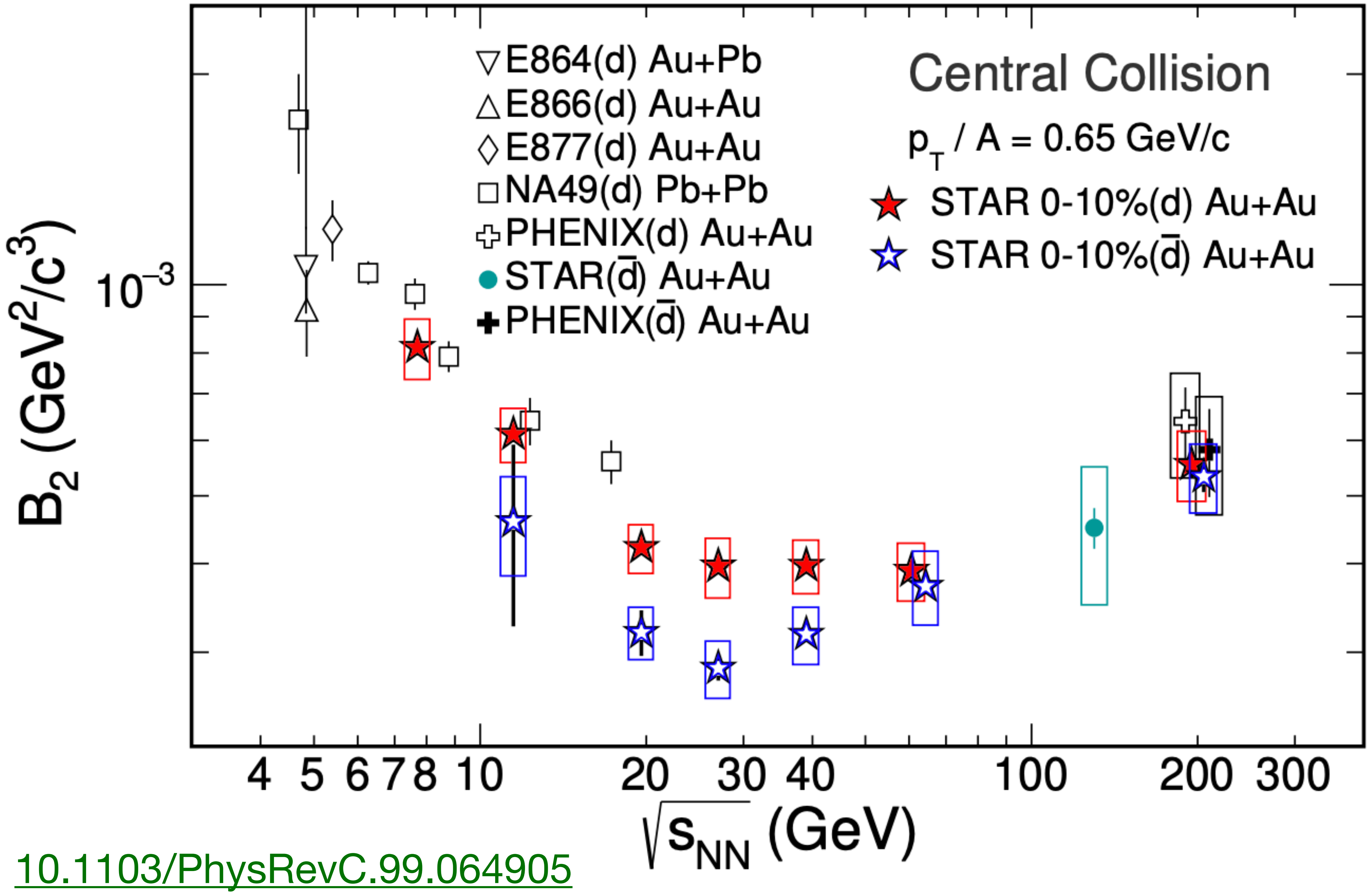
$$\frac{4\pi}{3}p_0^3 \leftrightarrow \frac{1}{V} \implies B_A \propto V^{1-A}$$

- V_{HBT} depends on m_T
  - Qualitative description of B_2 vs m_T
- B_2 vs $\sqrt{s_{NN}}$ not described

10.1103/PhysRevC.92.014904



Simple coalescence with Volume



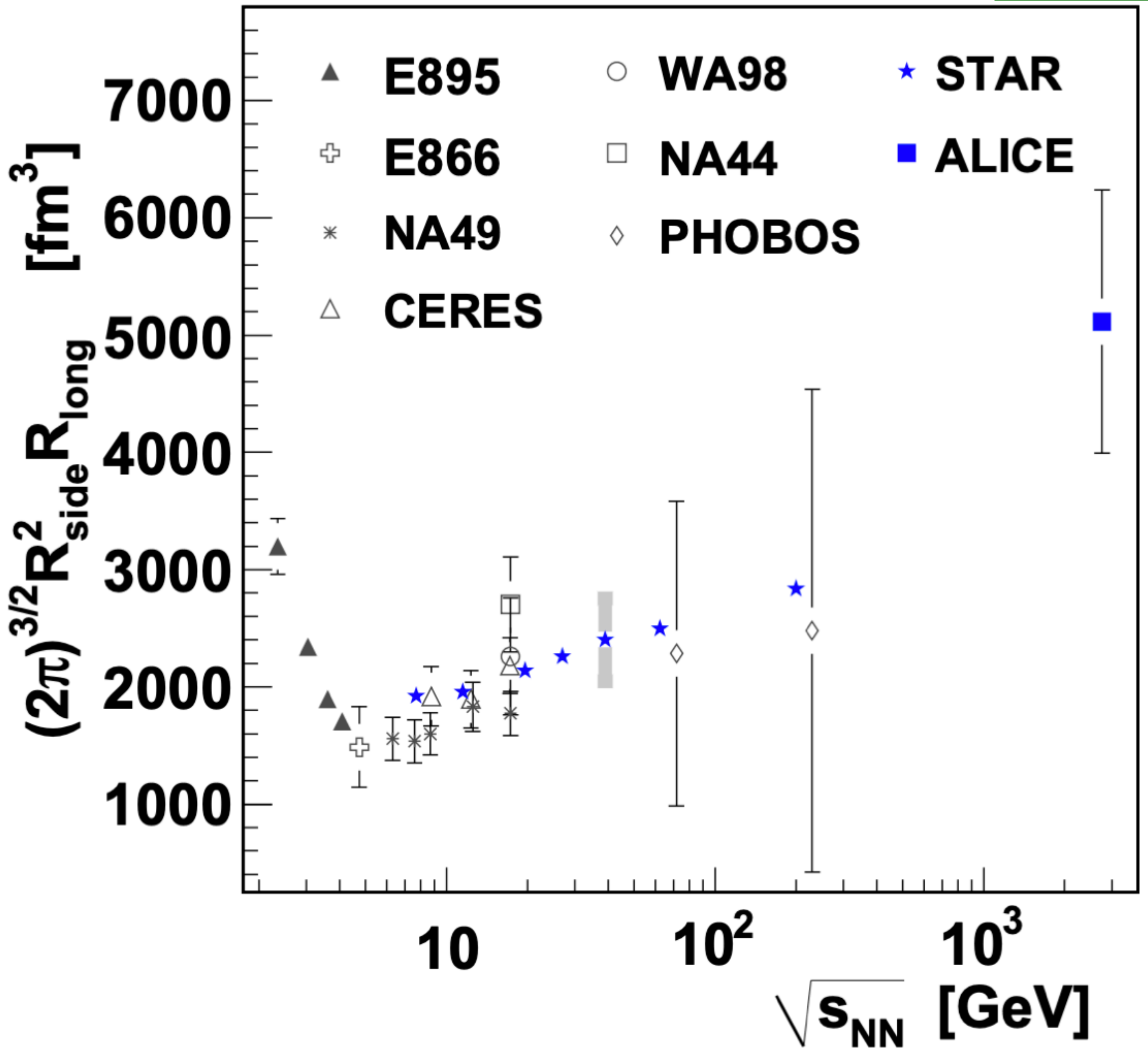
10.1103/PhysRevC.99.064905

- In simple coalescence model:

$$\frac{4\pi}{3} p_0^3 \leftrightarrow \frac{1}{V} \implies B_A \propto V^{1-A}$$

- V_{HBT} depends on m_T
  - Qualitative description of B_2 vs m_T
- B_2 vs $\sqrt{s_{NN}}$ not described

10.1103/PhysRevC.92.014904

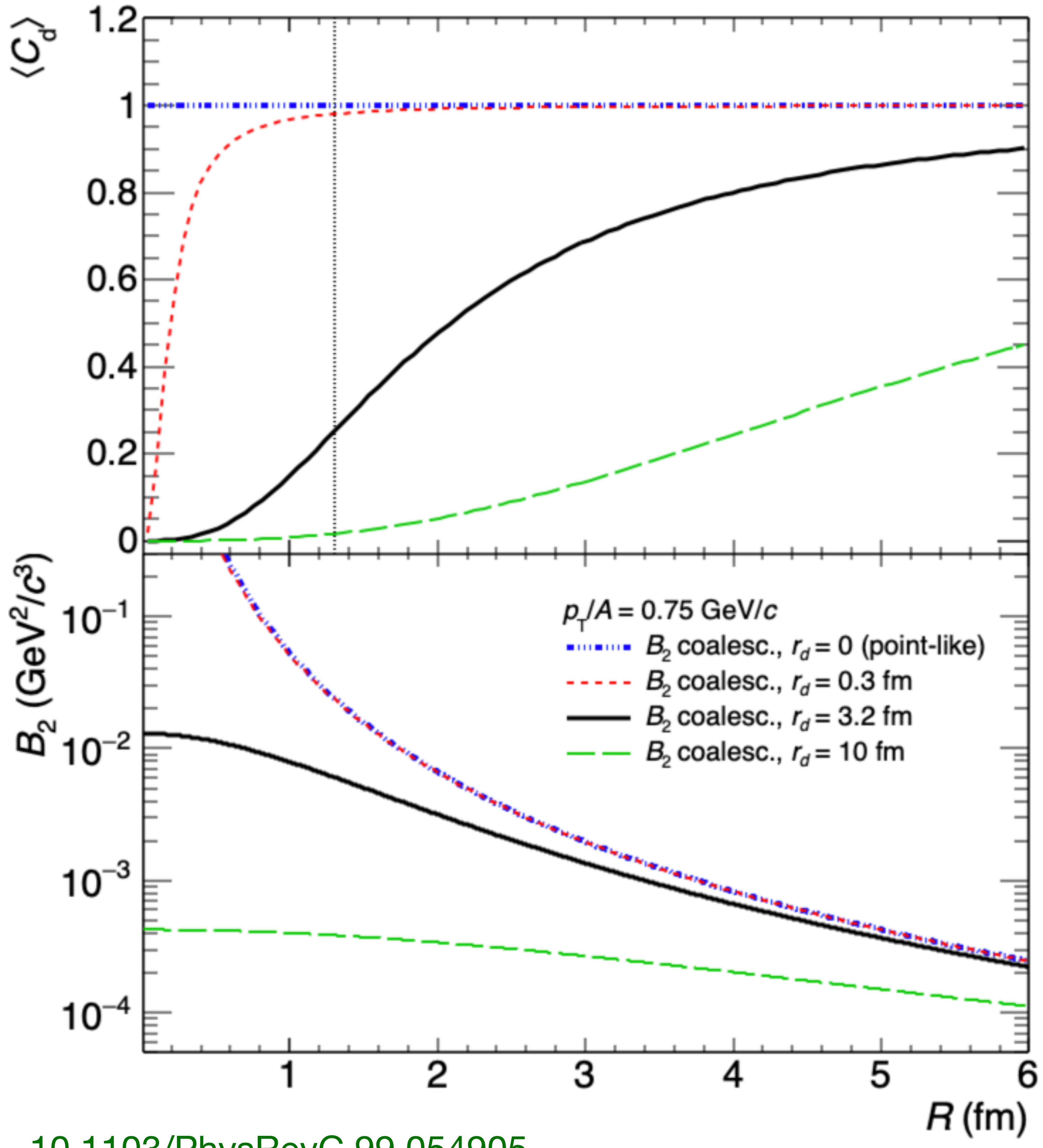


We need more advanced implementations of the coalescence model

An advanced coalescence model

- **Space-time** distribution considered
  - **overlap** between **nucleus wave-function** (Wigner formalism) and **nucleon phase-space distribution**
- Evolution with the system size **R**
- Dependence on the $\boldsymbol{p_T}$

$$B_A = \frac{2J_A + 1}{2^A\sqrt{A}}\frac{1}{m_T^{A-1}}\left[\frac{2\pi}{R^2(m_T) + \left(r_A/2\right)^2}\right]^{\frac{3}{2}(A-1)}$$



10.1103/PhysRevC.99.054905

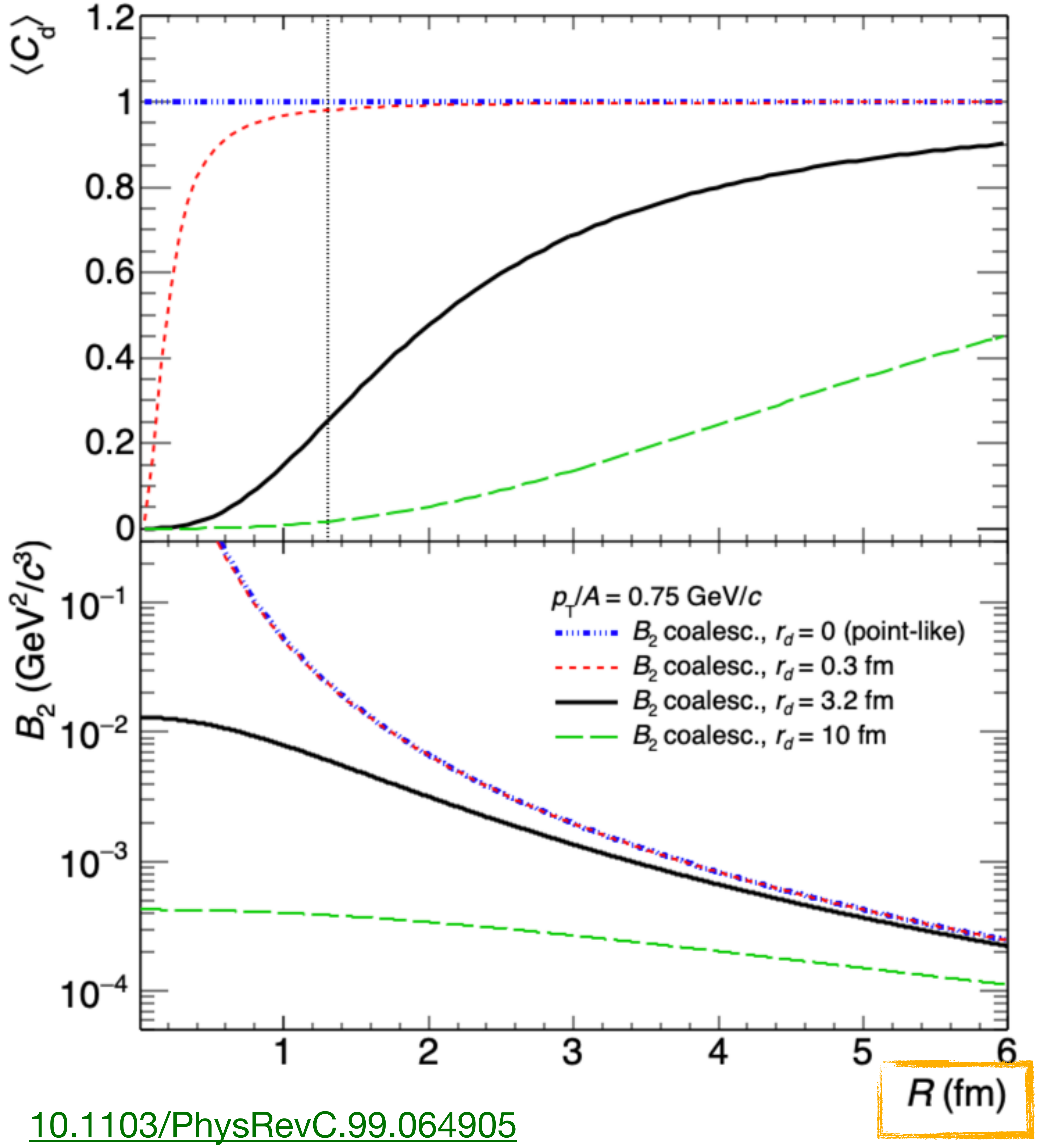
An advanced coalescence model

- **Space-time** distribution considered
  - **overlap** between **nucleus wave-function** (Wigner formalism) and **nucleon phase-space distribution**
- Evolution with the system size **R**
- Dependence on the $\boldsymbol{p}_{\mathbf{T}}$

$$B_A = \frac{2J_A+1}{2^A\sqrt{A}}\frac{1}{m_{\mathrm{T}}^{A-1}}\left[\frac{2\pi}{R^2(m_{\mathrm{T}})+\left(r_A/2\right)^2}\right]^{\frac{3}{2}(A-1)}$$

System size expressed as

$$R = a\,\langle \mathrm{d}N/\mathrm{d}\eta\rangle^{1/3} + b$$



10.1103/PhysRevC.99.064905

B_A vs multiplicity

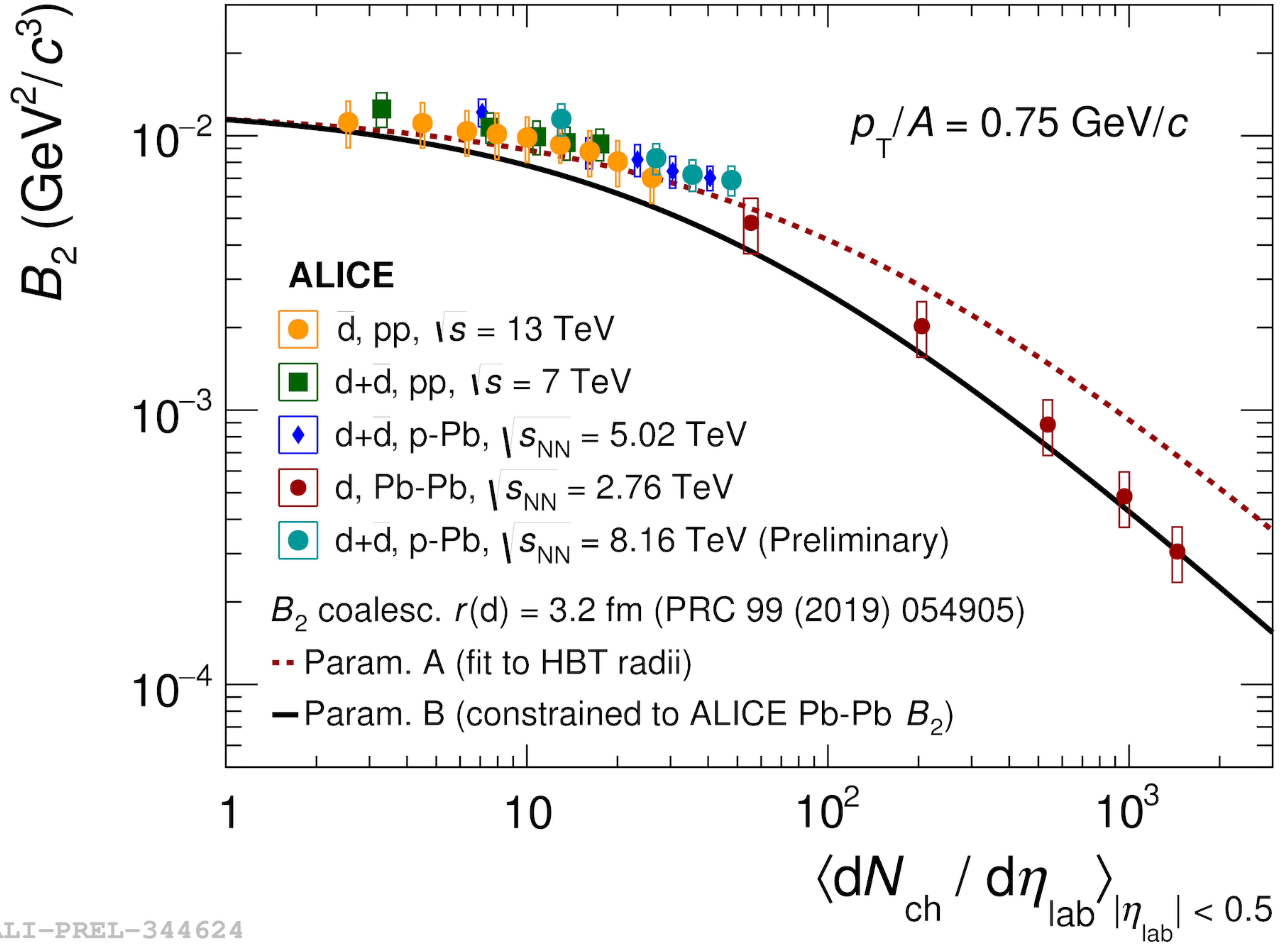
- **B_2** evolves **smoothly** with the **multiplicity**
- Two parameterisations:

$$R = a \, \langle \mathrm{d}N/\mathrm{d}\eta \rangle^{1/3} + b$$

A. *a* and *b* taken from a **fit** of R vs multiplicity

B. *a* and *b* are **fixed** to reproduce B_2 in 0-10% Pb-Pb

- Neither of the two reproduces B_2 over the full range but the match is quite good in the low multiplicities range



B_A vs multiplicity

- **B_2** evolves **smoothly** with the **multiplicity**
- Two parameterisations:

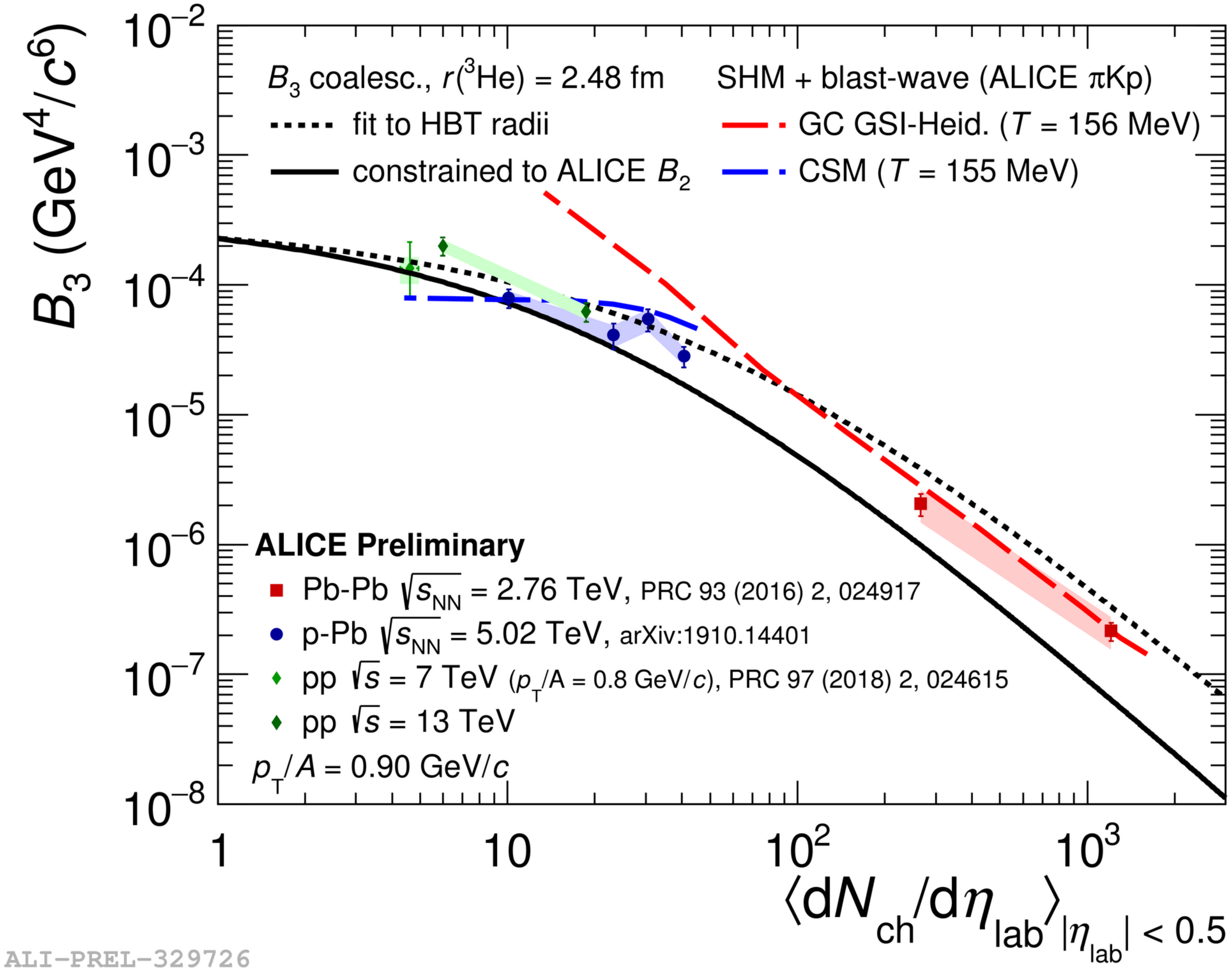
$$R = a \, \langle \mathrm{d}N/\mathrm{d}\eta \rangle^{1/3} + b$$

A. *a* and *b* taken from a **fit** of R vs multiplicity

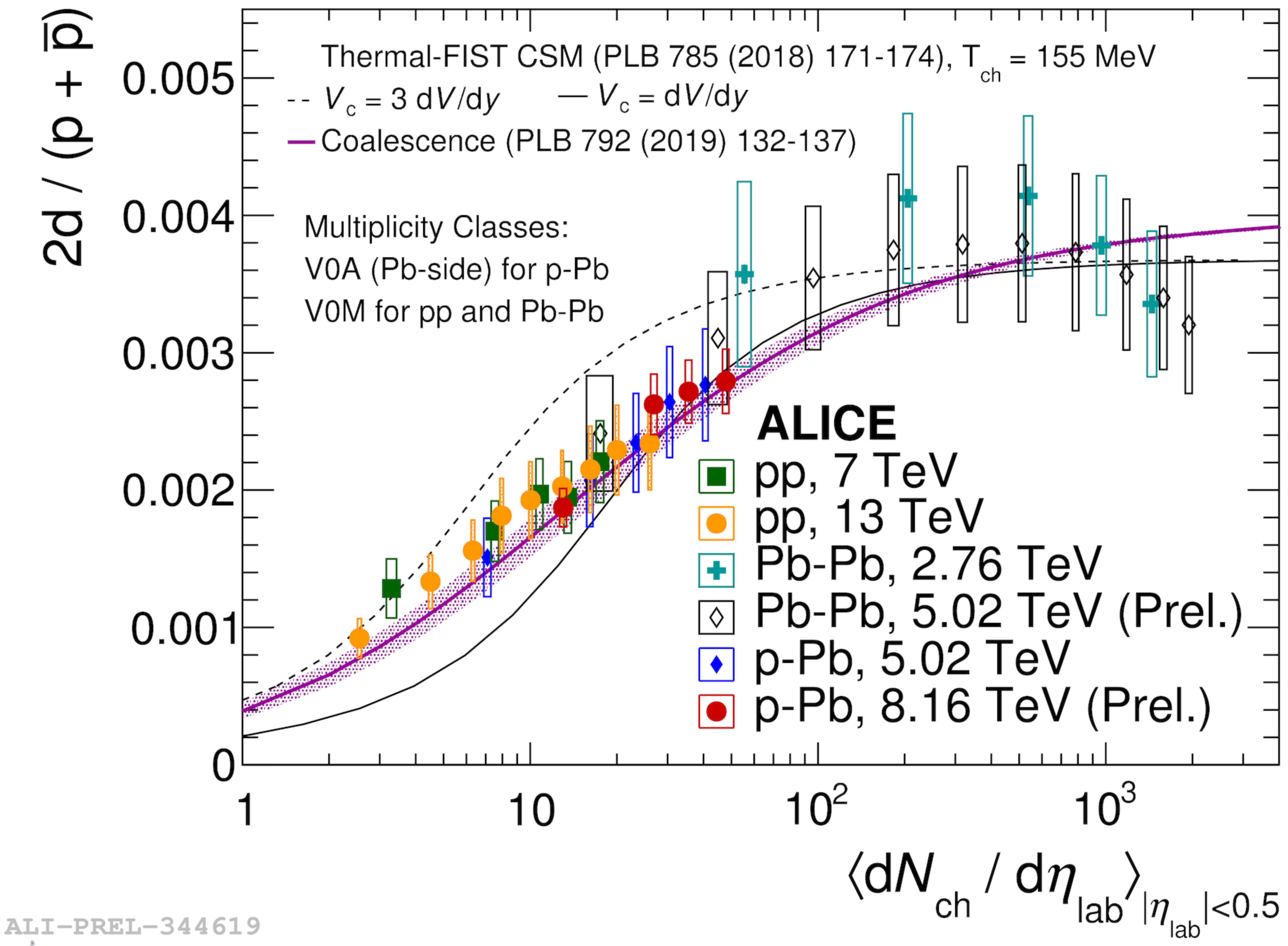
B. *a* and *b* are **fixed** to reproduce B_2 in 0-10% Pb-Pb

- Neither of the two reproduces B_2 over the full range but the match is quite good in the low multiplicities range

- Same for **B_3**

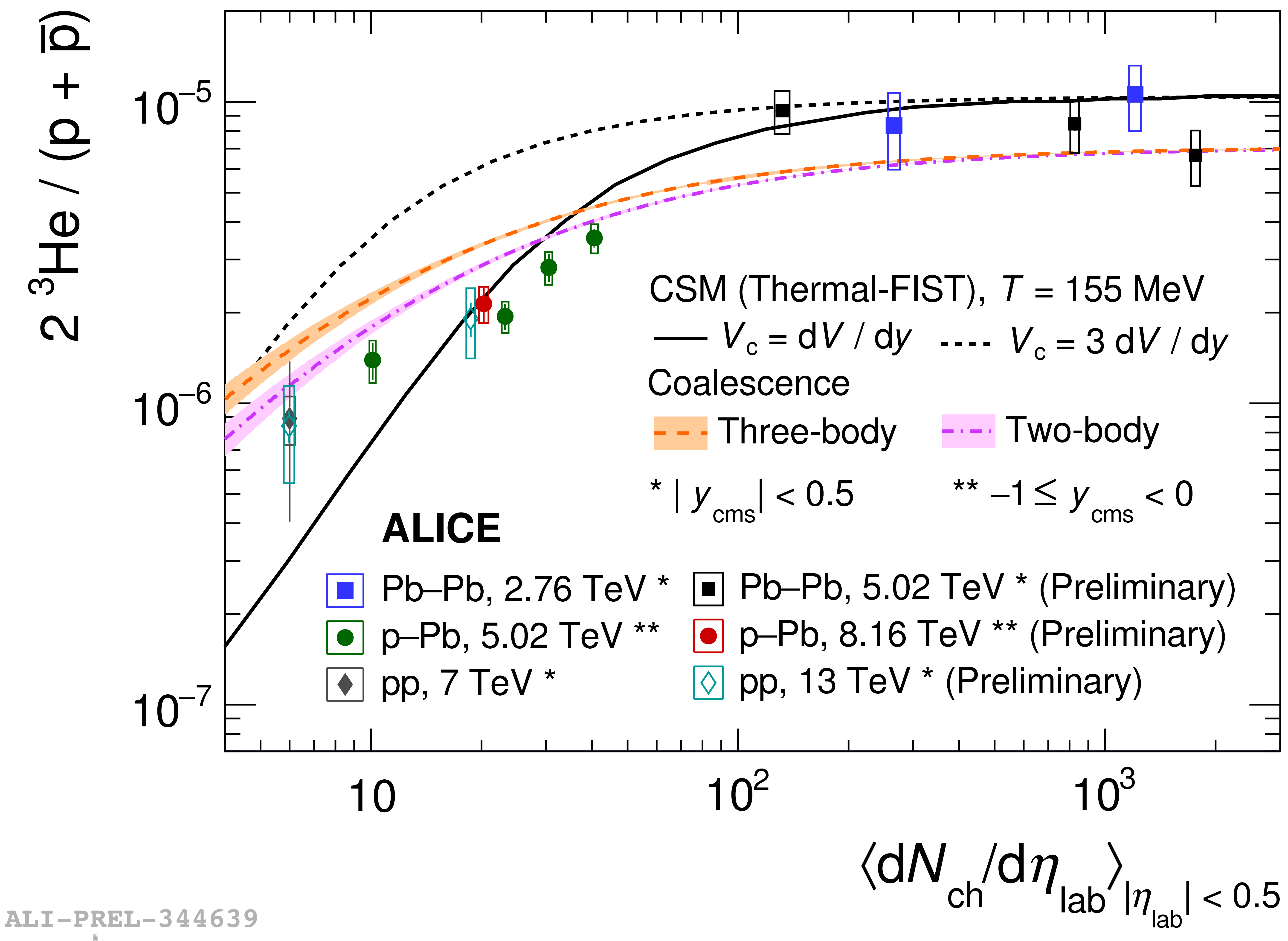


A/p vs multiplicity



- Smooth evolution of A/p with multiplicity
- Coalescence can explain well **d/p** over the **full range** of multiplicity

A/p vs multiplicity

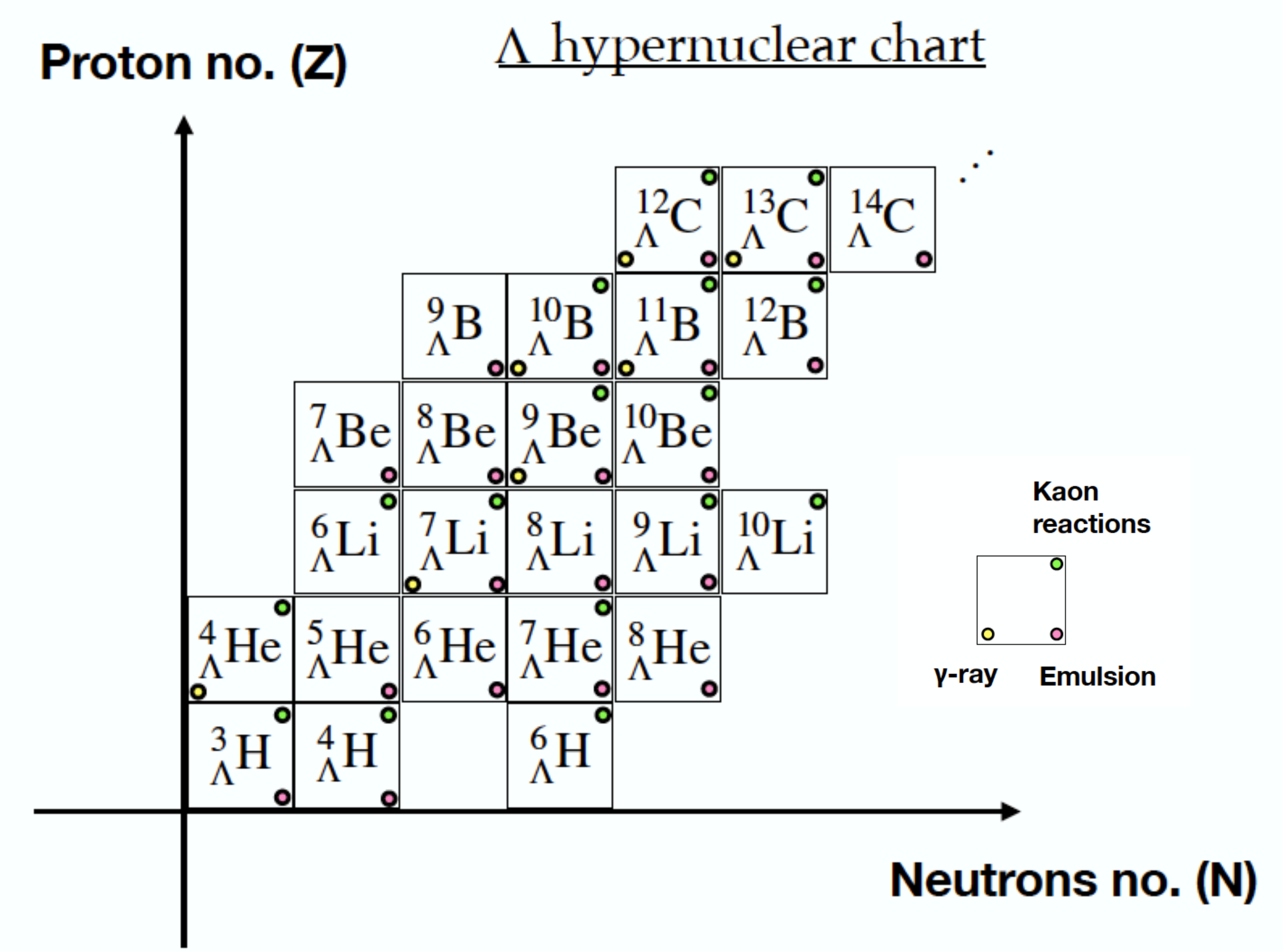


- Smooth evolution of A/p with multiplicity
- Coalescence can explain well **d/p** over the **full range** of multiplicity
- Coalescence does not describe **^{3}He/p**

Coalescence struggles for A > 2

Adding strangeness to nuclei…

Hypernuclei are nuclei containing at least one hyperon
First observation in 1952 by Danysz and Pniewski [Phil. Mag. 44 (1953) 348]



Credits to Isaac Vidaña

Different experimental techniques used to produce hyper nuclei and study they properties: γ ray, emulsion and strangeness exchange reaction

Provide access to the hyperon–nucleon (Y-N) interaction

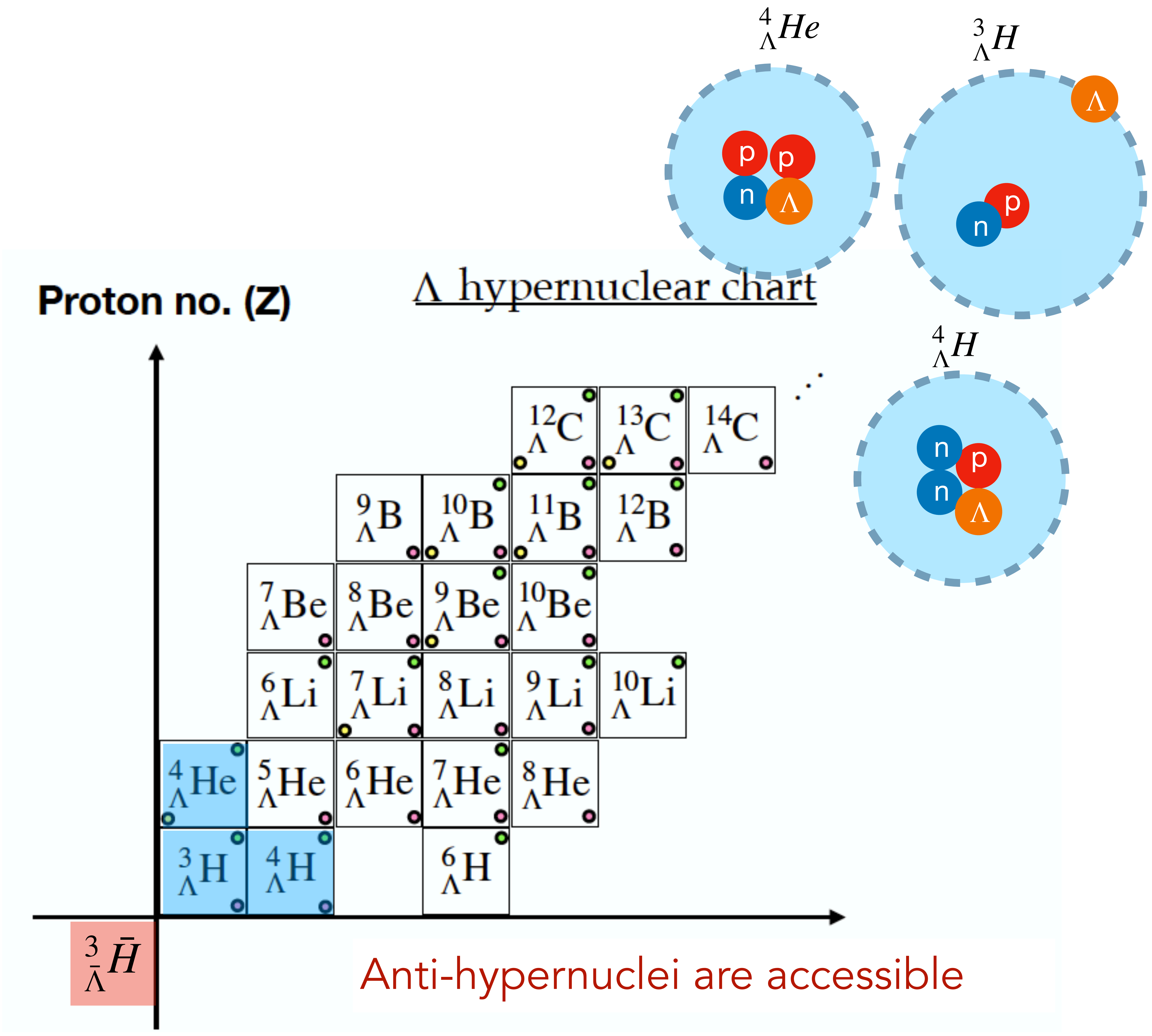
Strangeness in high density nuclear matter

- EOS of neutron star
- Hadronic phase of a heavy ion collision

First observation of hypernuclei in heavy ion collisions by STAR Collaboration in 2009

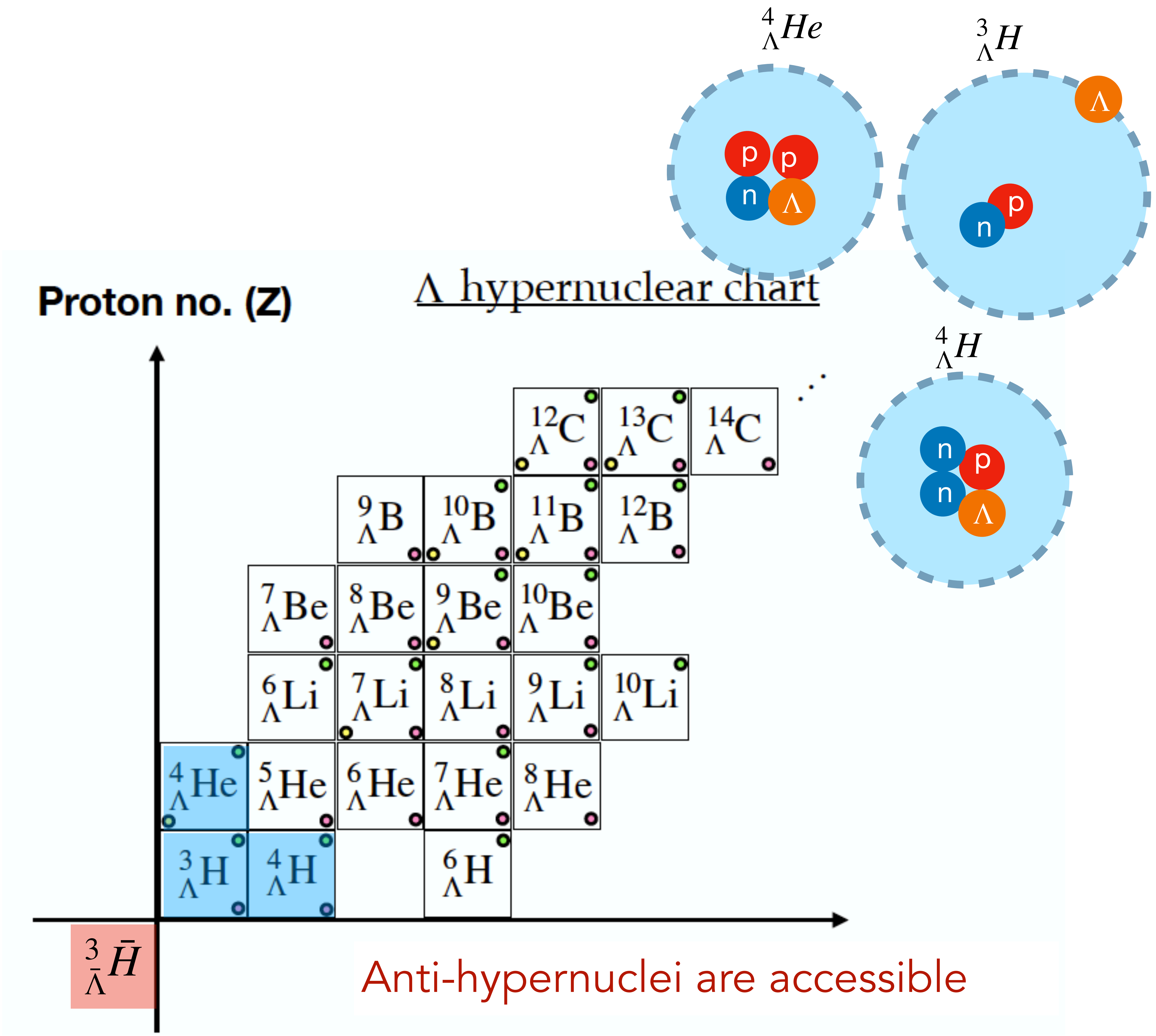
[STAR, Science 328 (2010) 58]

Hypernuclei production in heavy ion collisions

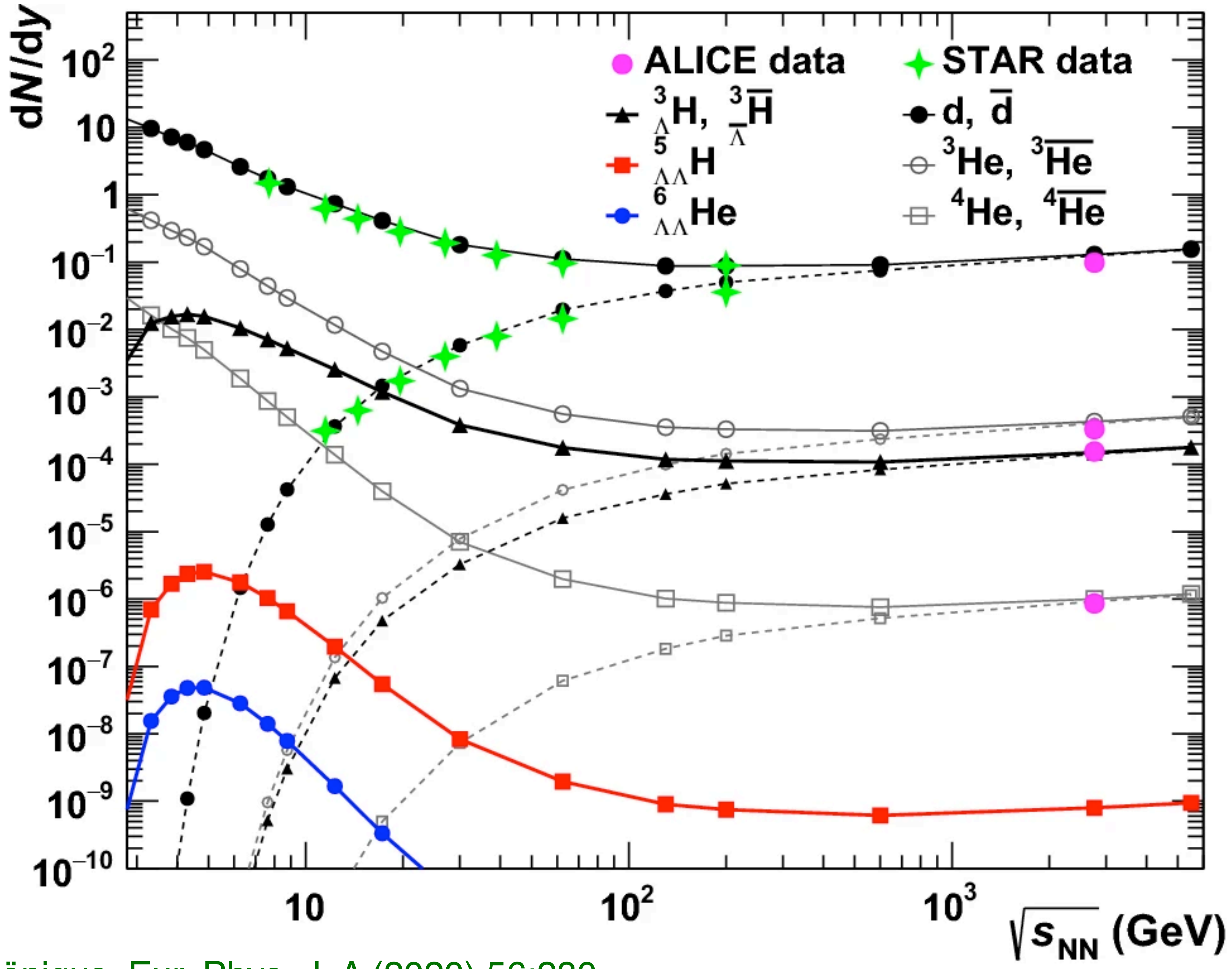


Anti-hypernuclei are accessible

Hypernuclei production in heavy ion collisions



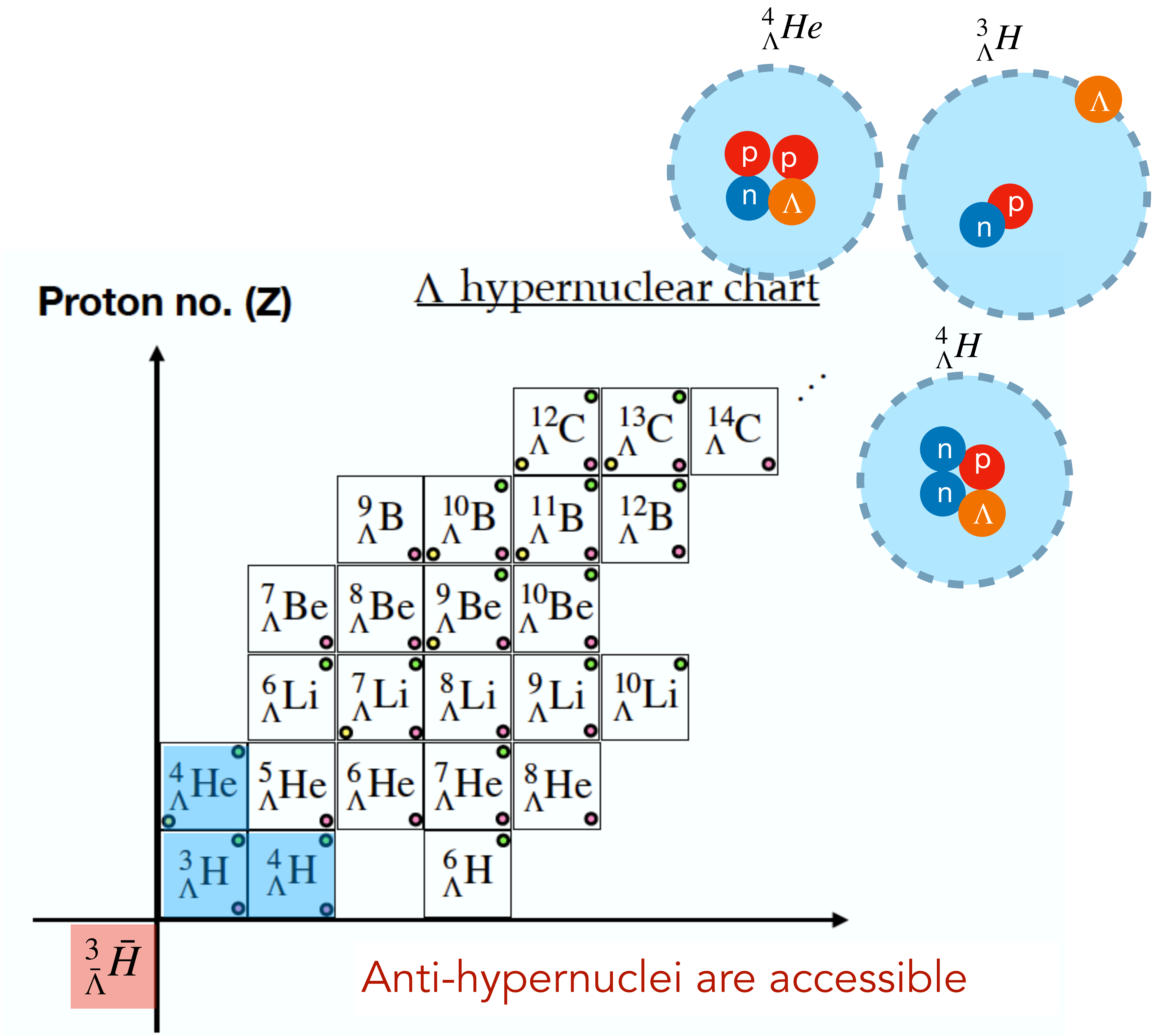
Thermal model



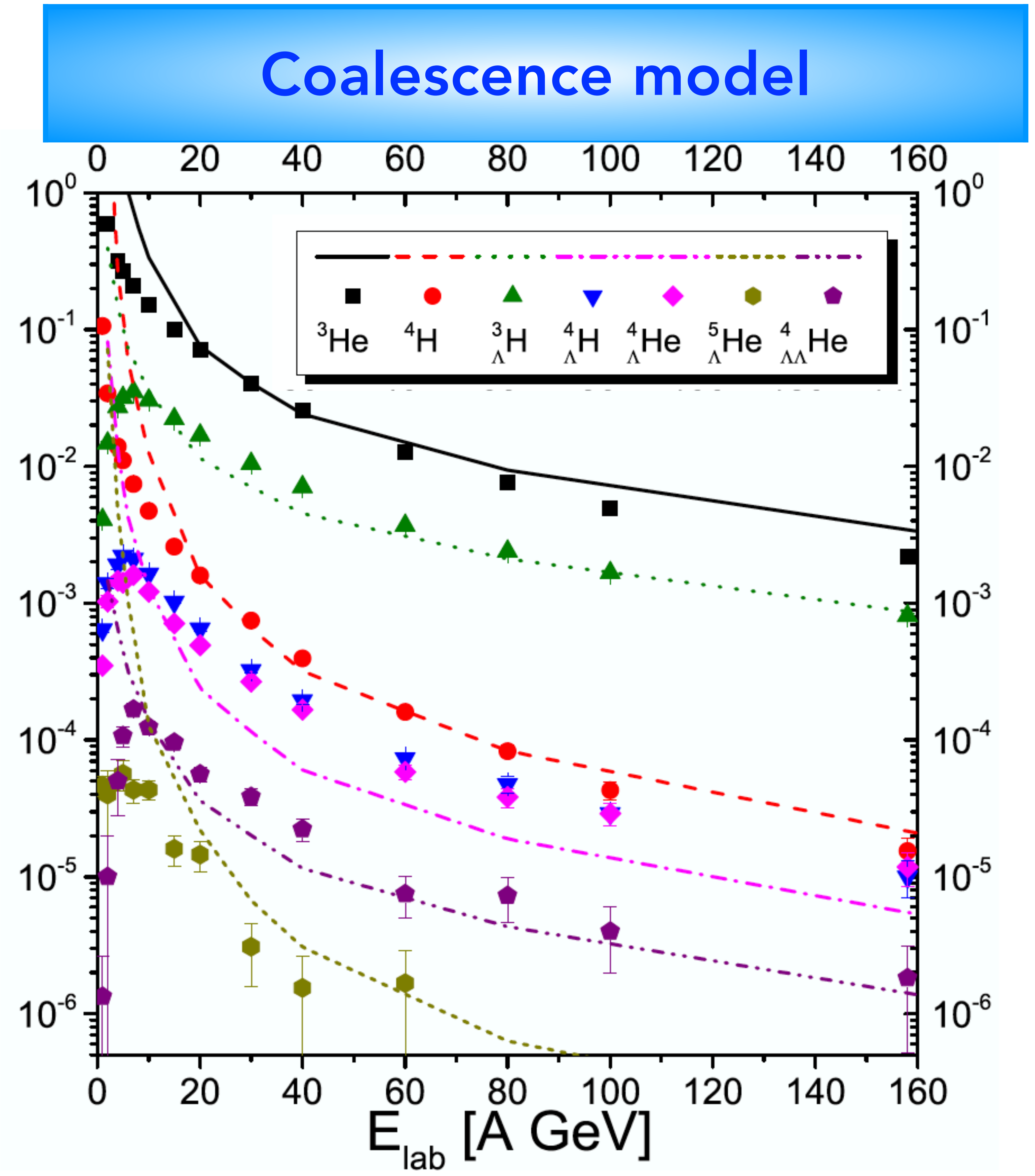
B. Dönigus, Eur. Phys. J. A (2020) 56:280

- Hypernuclei are very sensitive to T_{chem} because of their large mass
- Internal structure of hypernuclei plays no role

Hypernuclei production in heavy ion collisions



Anti-hypernuclei are accessible

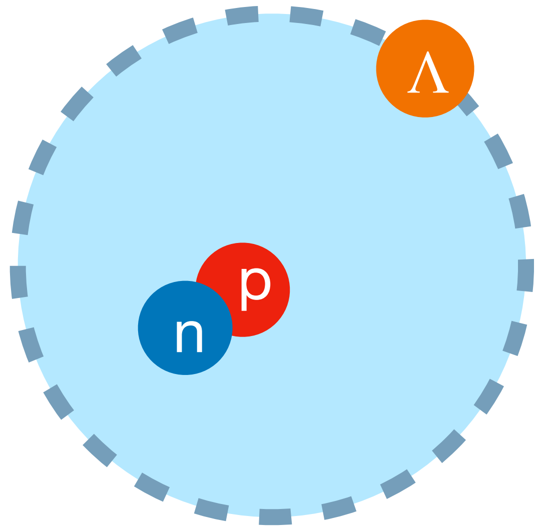


(Anti-)(hyper-)nuclei formed at the *chemical freeze-out*:

- might break up
- regenerate in the time interval between *chemical* and *kinetic freeze-out*

J. Steinheimer et al. Phys. Lett. B 714, 85-91 (2012)

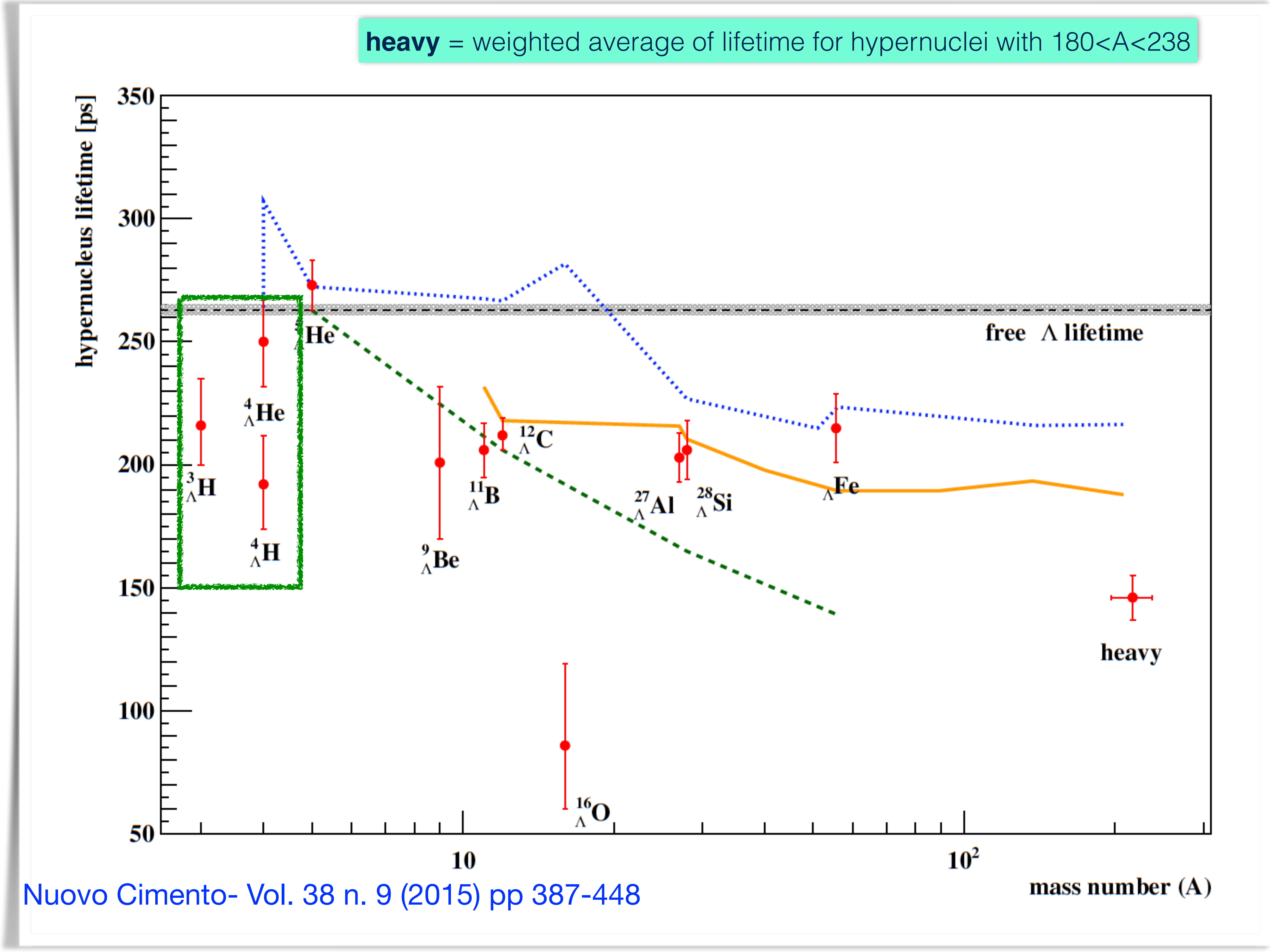
Hypertriton lifetime: theory vs experiments



- The hypertriton lifetime reflects its internal structure:
  - a low B_Λ should imply a small change of the Λ wave function inside the nucleus

Hypertriton lifetime is expected to be close to the free Λ one (263.2 ± 2 ps [1])

[1] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D, 98 (2018)



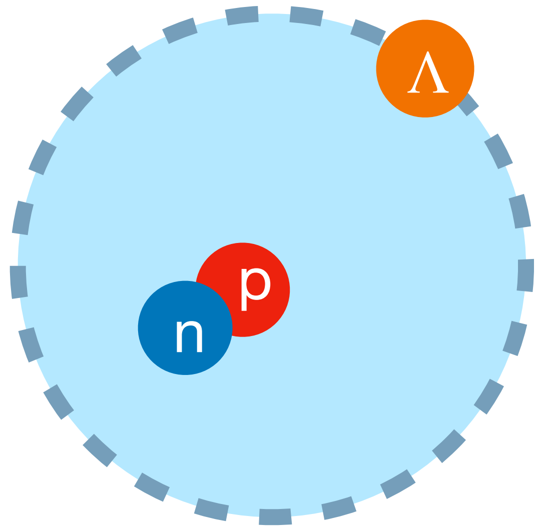
Nuovo Cimento- Vol. 38 n. 9 (2015) pp 387-448

.. recently

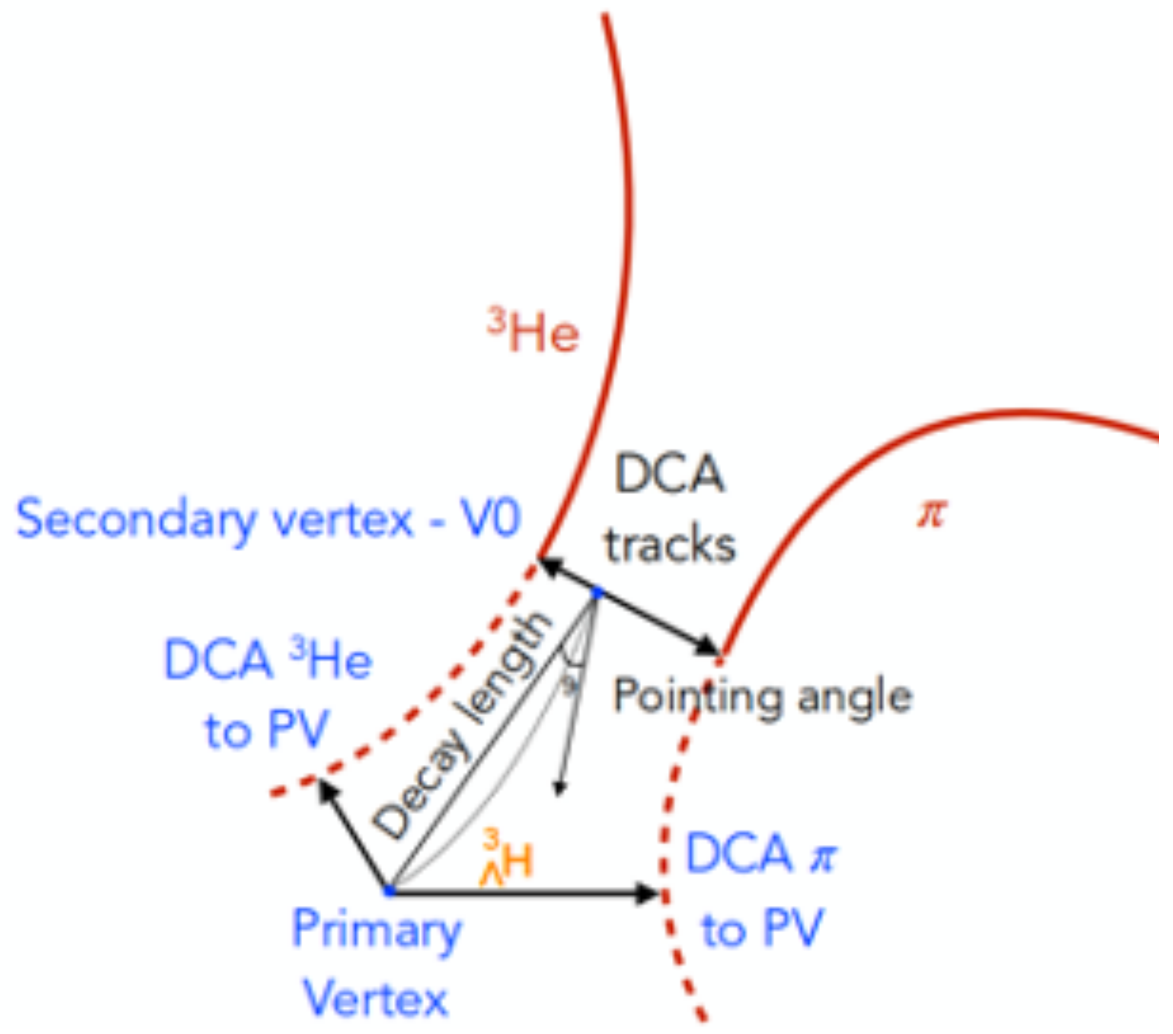
Λ_{UV} (MeV)	B_Λ (keV)	$\Gamma_{^3_\Lambda H \to ^3He+\pi^-}$ (GHz)	$\tau(^3_\Lambda H)$ (ps)
800	69	0.975	234 ± 27
900	135	1.197	190 ± 22
1000	159	1.265	180 ± 21
–	410	1.403	163 ± 18

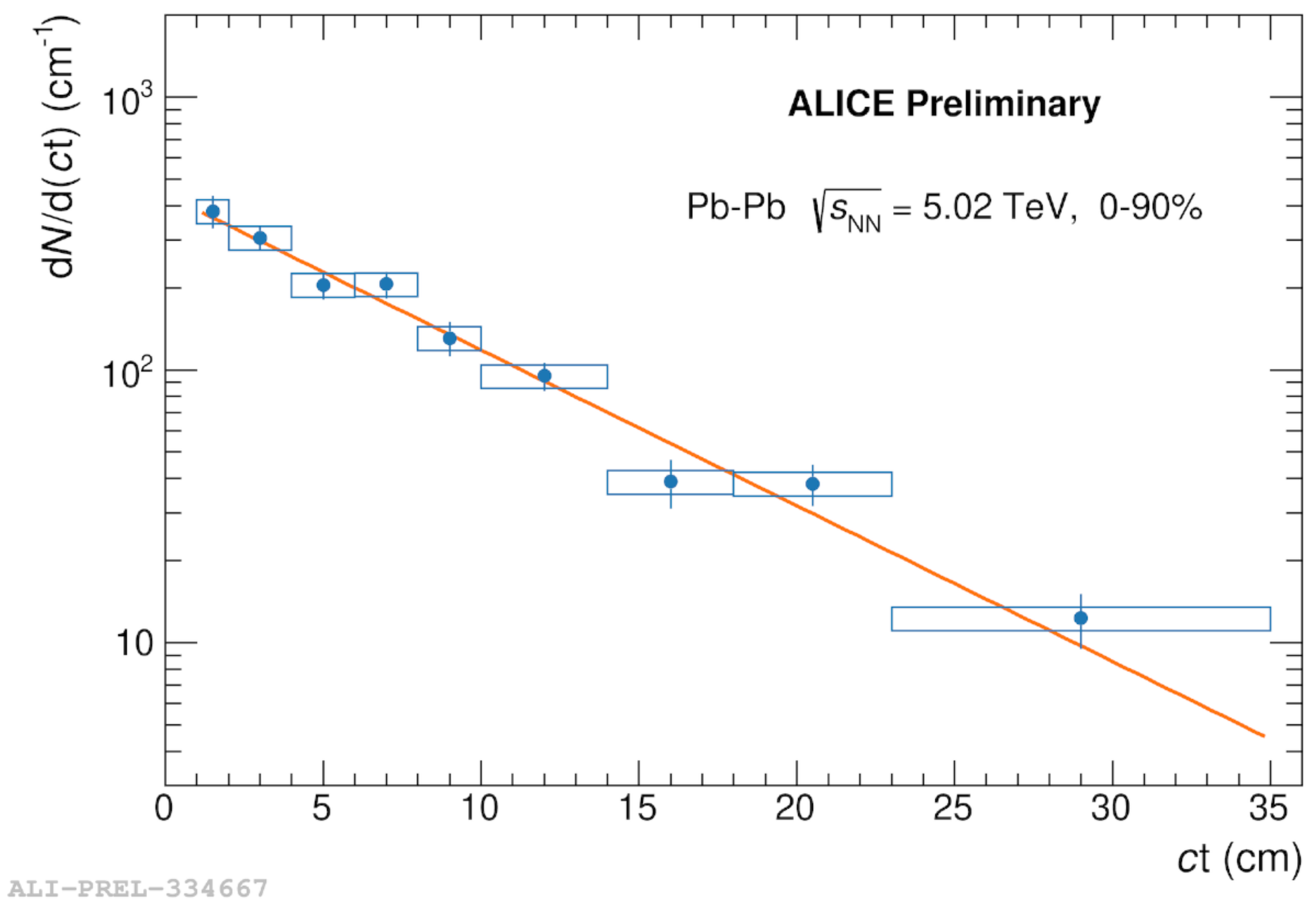
A. Pérez-Obiol et al, PLB811(2020)135916

Hypertriton lifetime: theory vs experiments

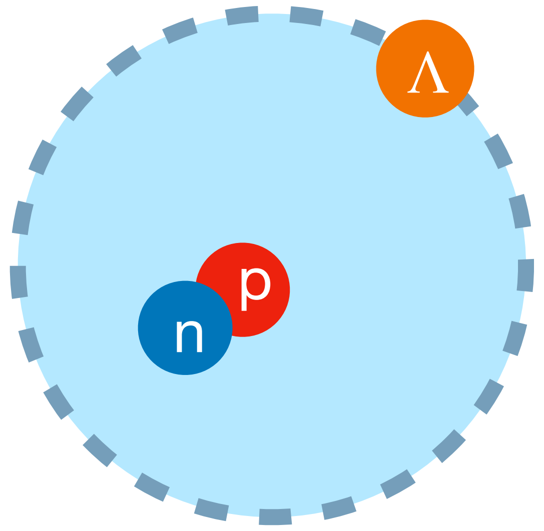


Lifetime extracted by measuring the yields as a function of the proper decay length

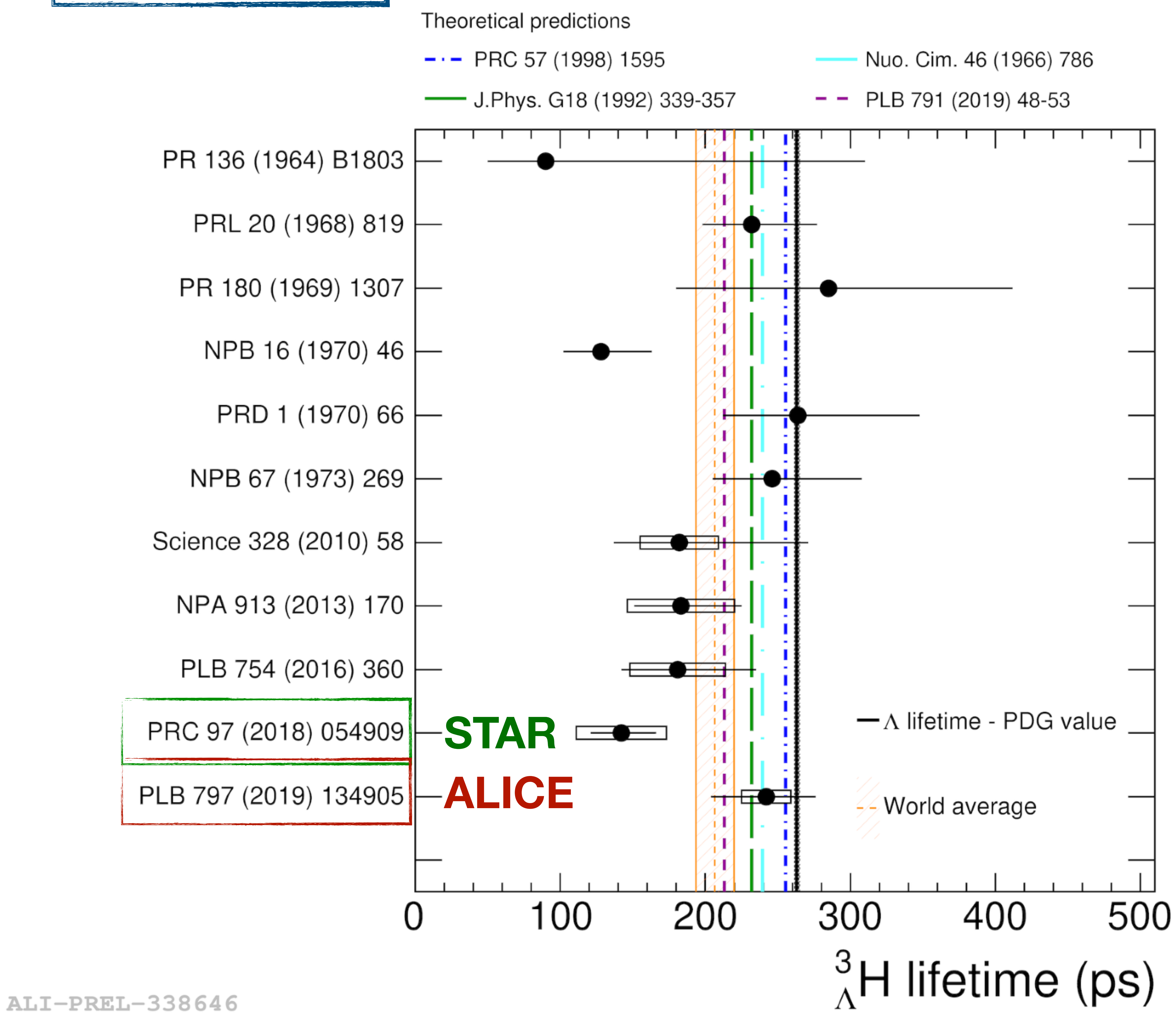




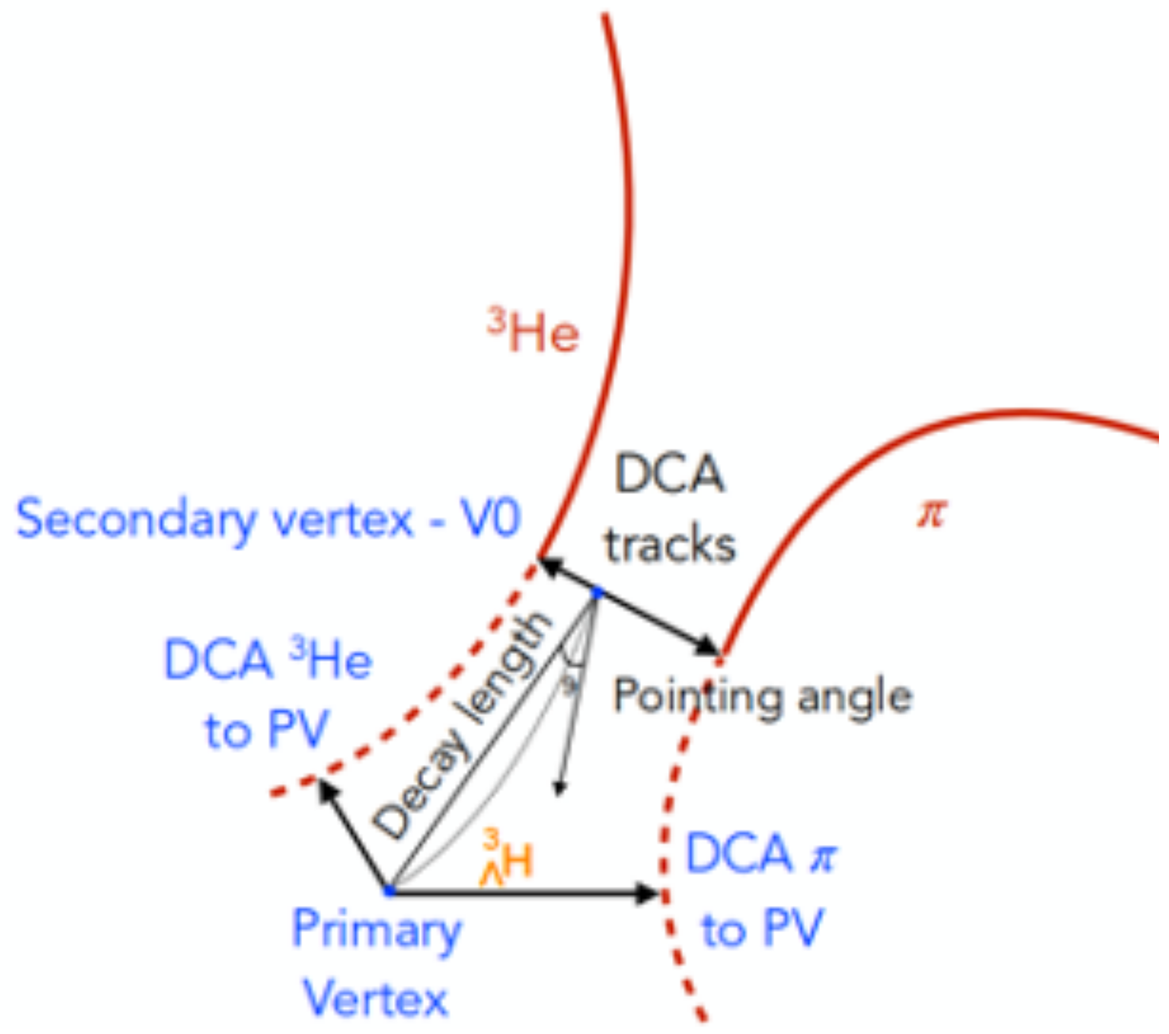
Hypertriton lifetime: theory vs experiments

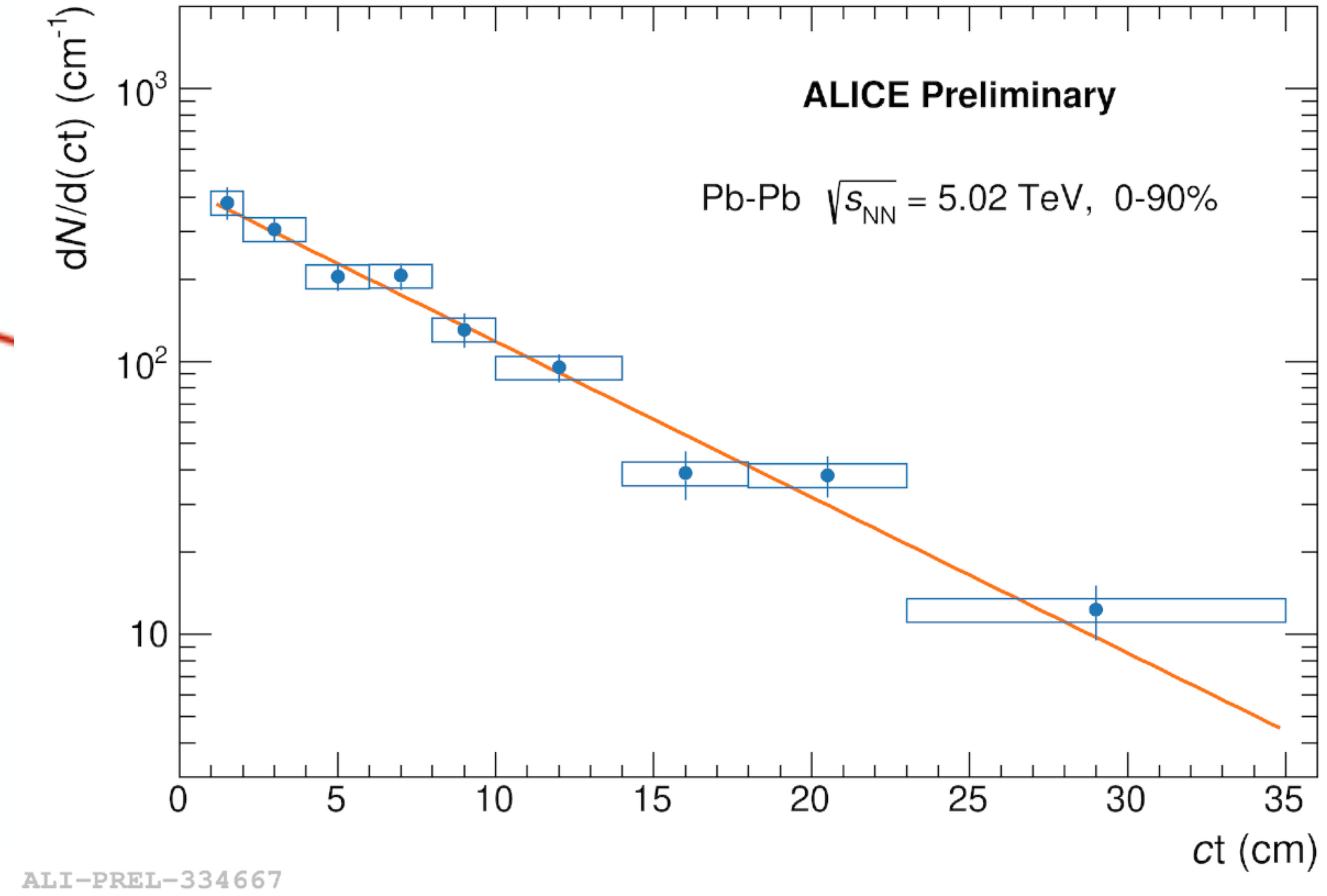


Published data



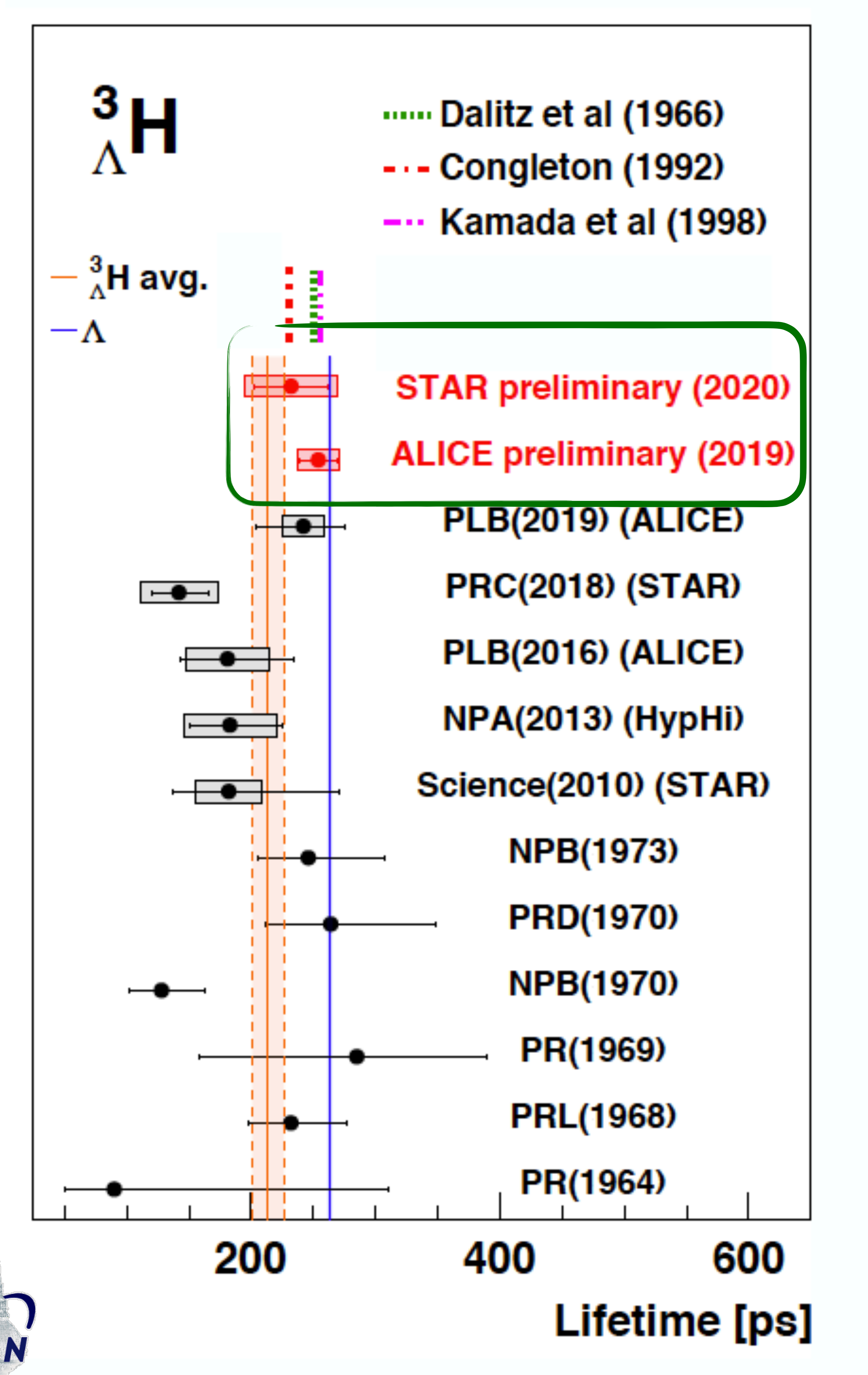
Lifetime extracted by measuring the yields as a function of the proper decay length

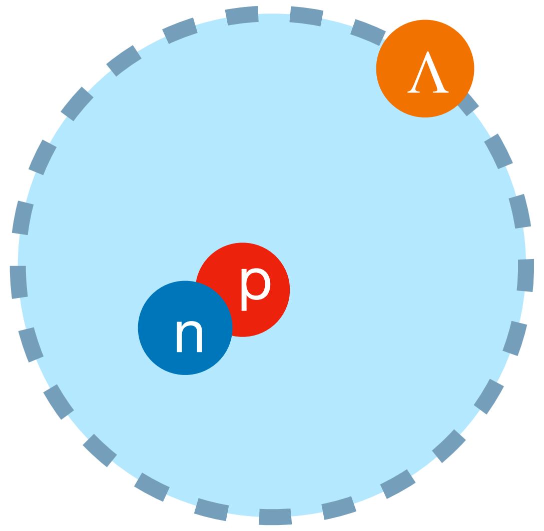




- Theory predicts hypertriton lifetime close to the Λ lifetime (>90%)
- STAR/HypHI reported lifetimes 30-40% shorter than Λ lifetime
- ALICE compatible with PDG value of Λ lifetime

Hypertriton lifetime: new experimental results





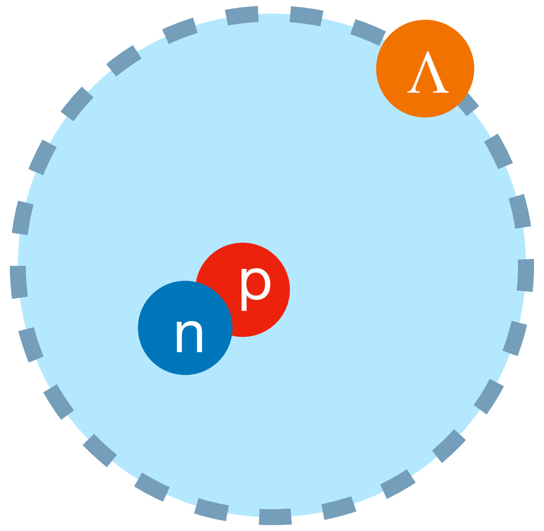
Published + NEW preliminary data

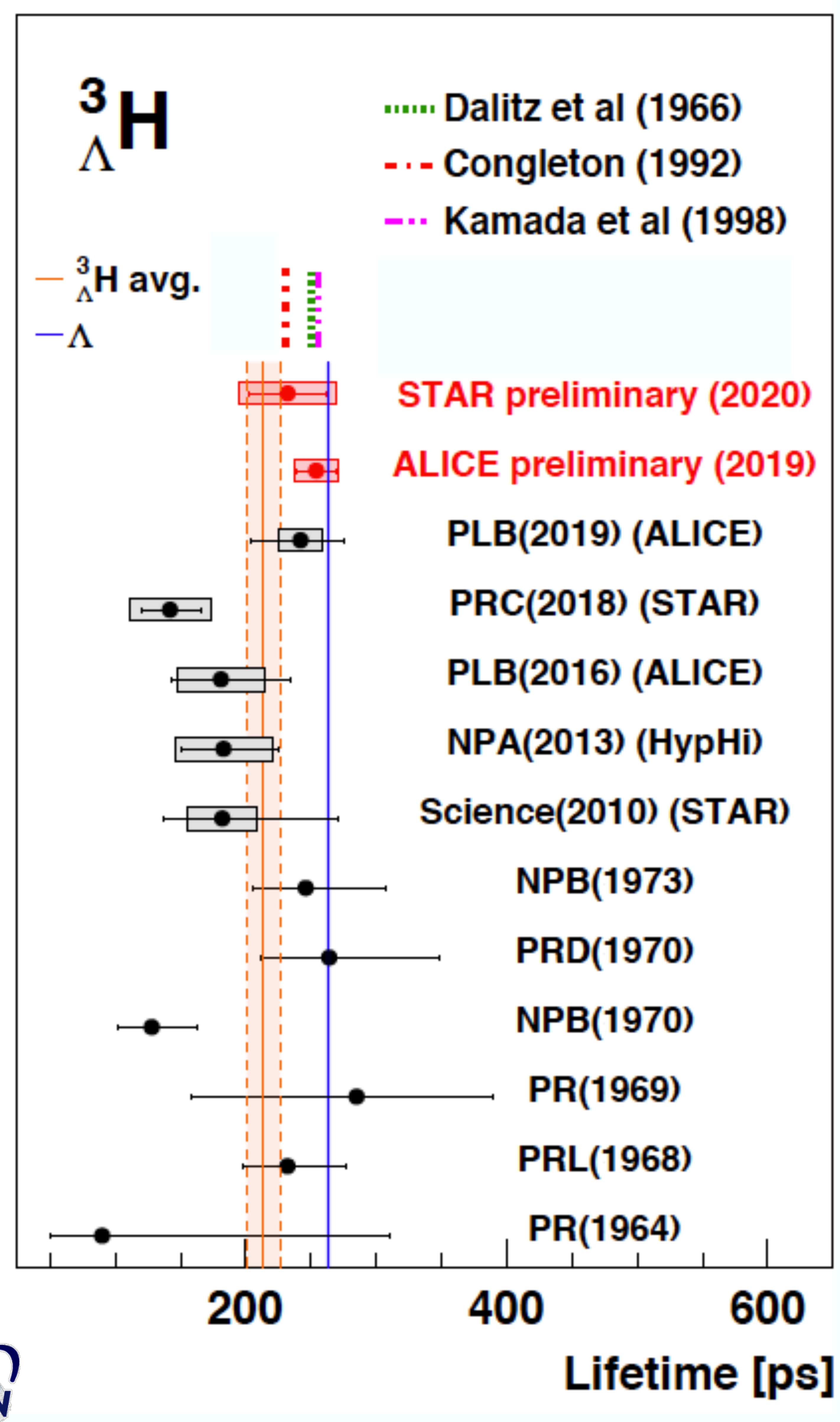
New STAR measurement compatible with Λ lifetime

ALICE preliminary: most precise measurement available

Strong hint that hypertriton is weakly bound, but **we still need binding energy measurement** to finally solve the puzzle

Hypertriton lifetime: new experimental results



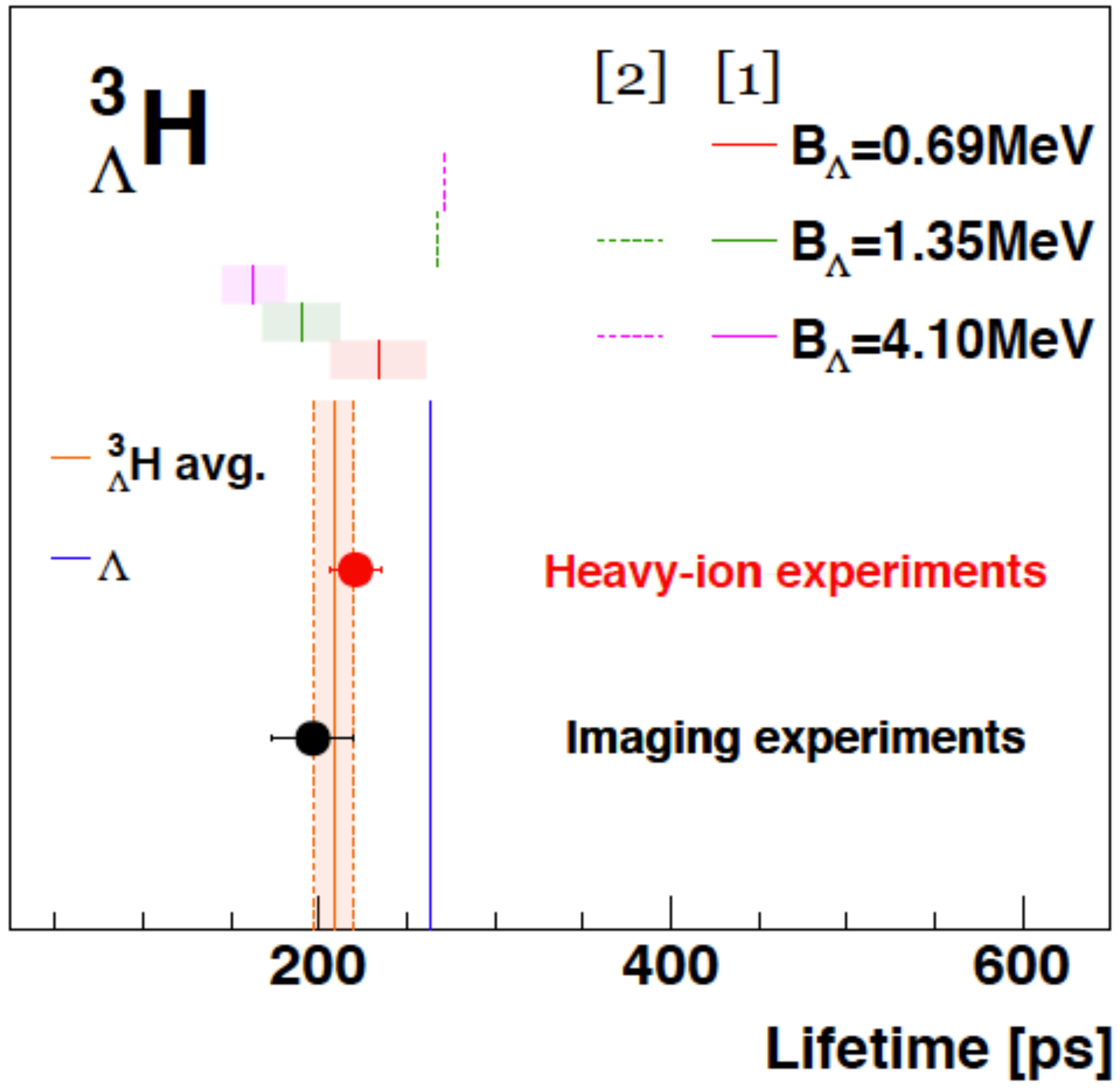


Published + NEW preliminary data

New STAR measurement compatible with Λ lifetime

ALICE preliminary: most precise measurement available

Strong hint that hypertriton is weakly bound, but **we still need binding energy measurement** to finally solve the puzzle

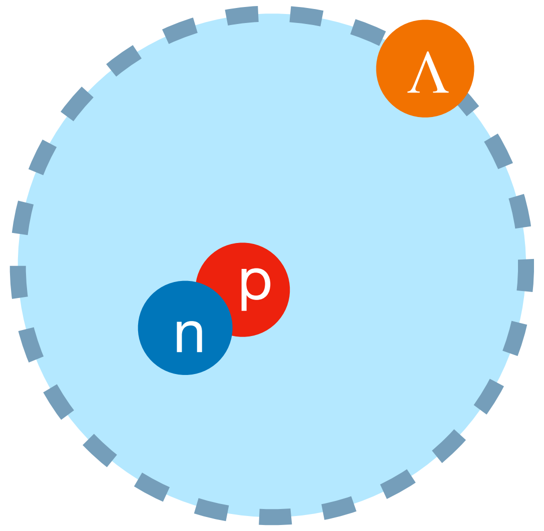


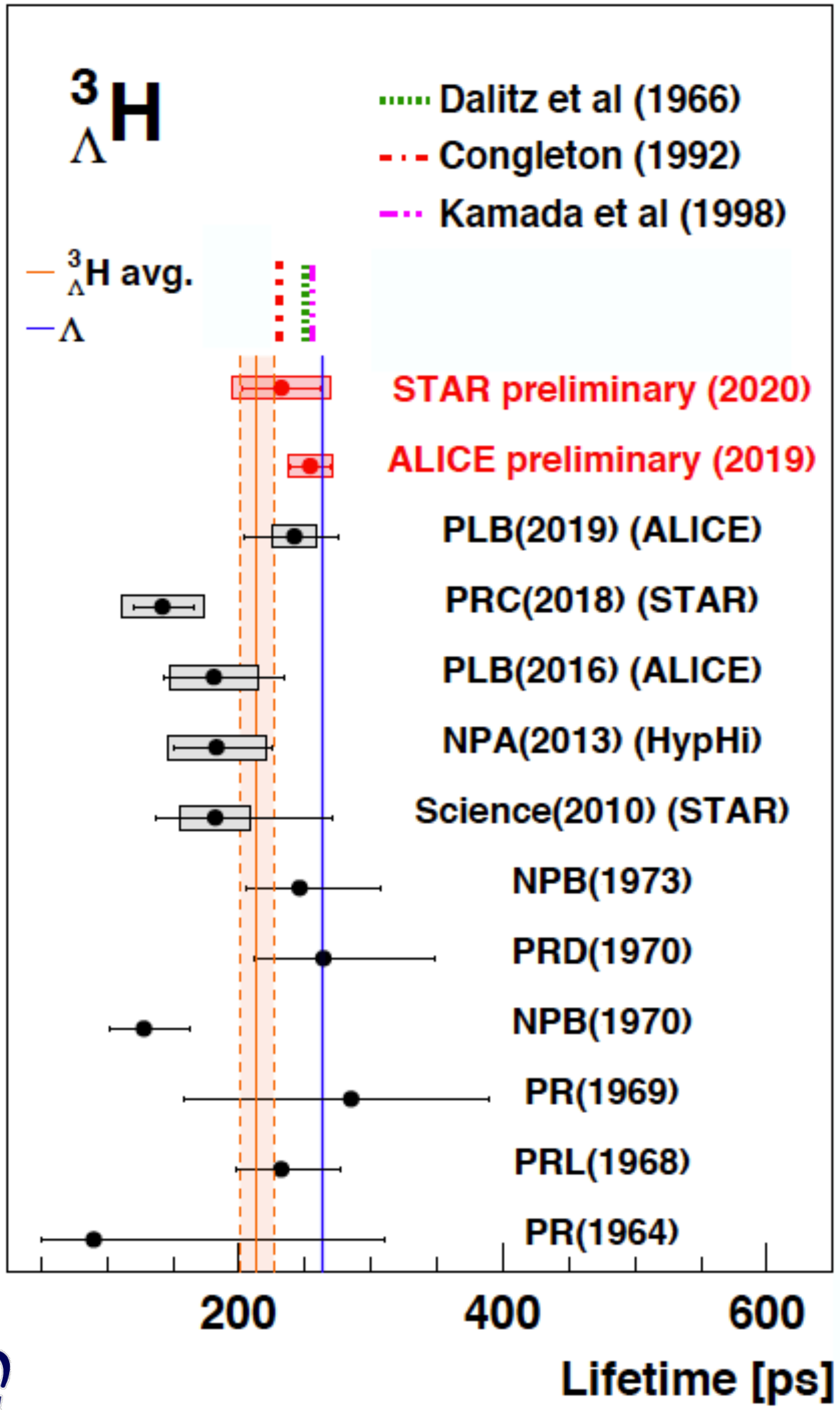
- Recent prediction from Gal et. al. indicates that pion FSI may decreases lifetime by ~10%

- Suggestion of a close relationship between the lifetime and B_Λ

[1] A. Pérez-Obiol et al, PLB811(2020)135916
[2] F. Hildenbrand et al, PRC102(2020)064002

Hypertriton lifetime: new experimental results



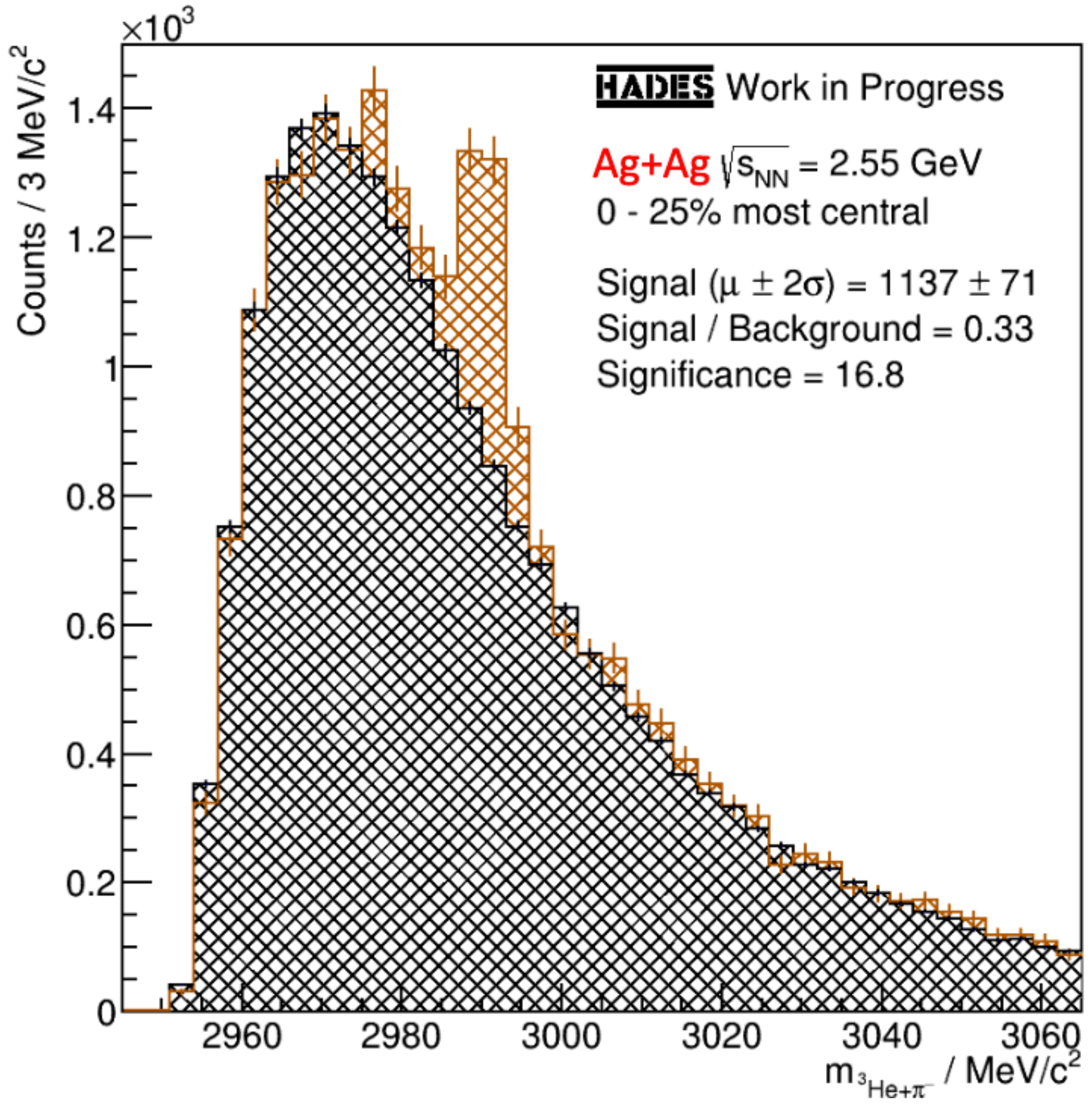


Published + NEW preliminary data

New STAR measurement compatible with Λ lifetime

ALICE preliminary: most precise measurement available

Strong hint that hypertriton is weakly bound, but **we still need binding energy measurement** to finally solve the puzzle



First observation at midrapidity at this energy

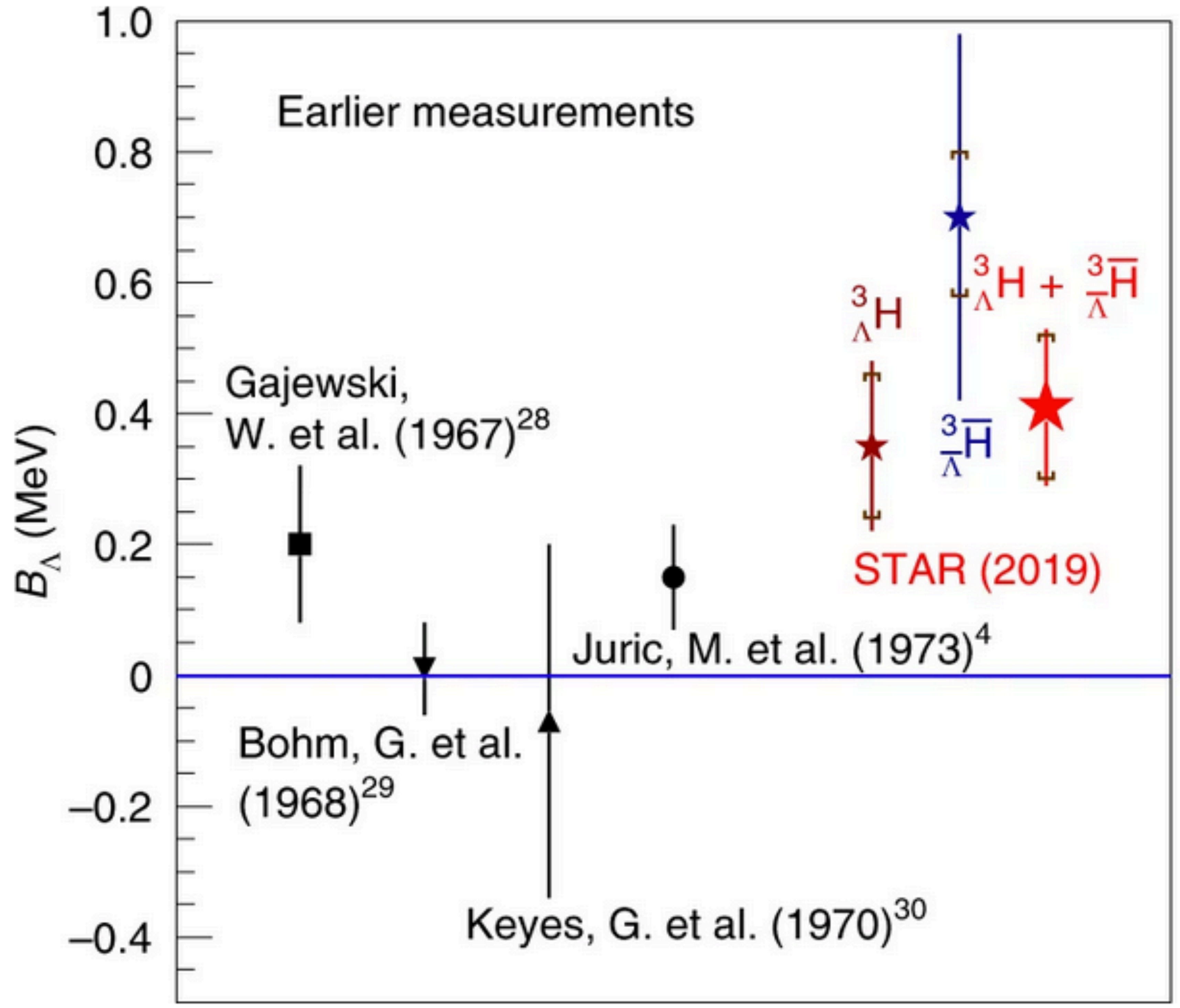
HADES expected to further reduce the uncertainty

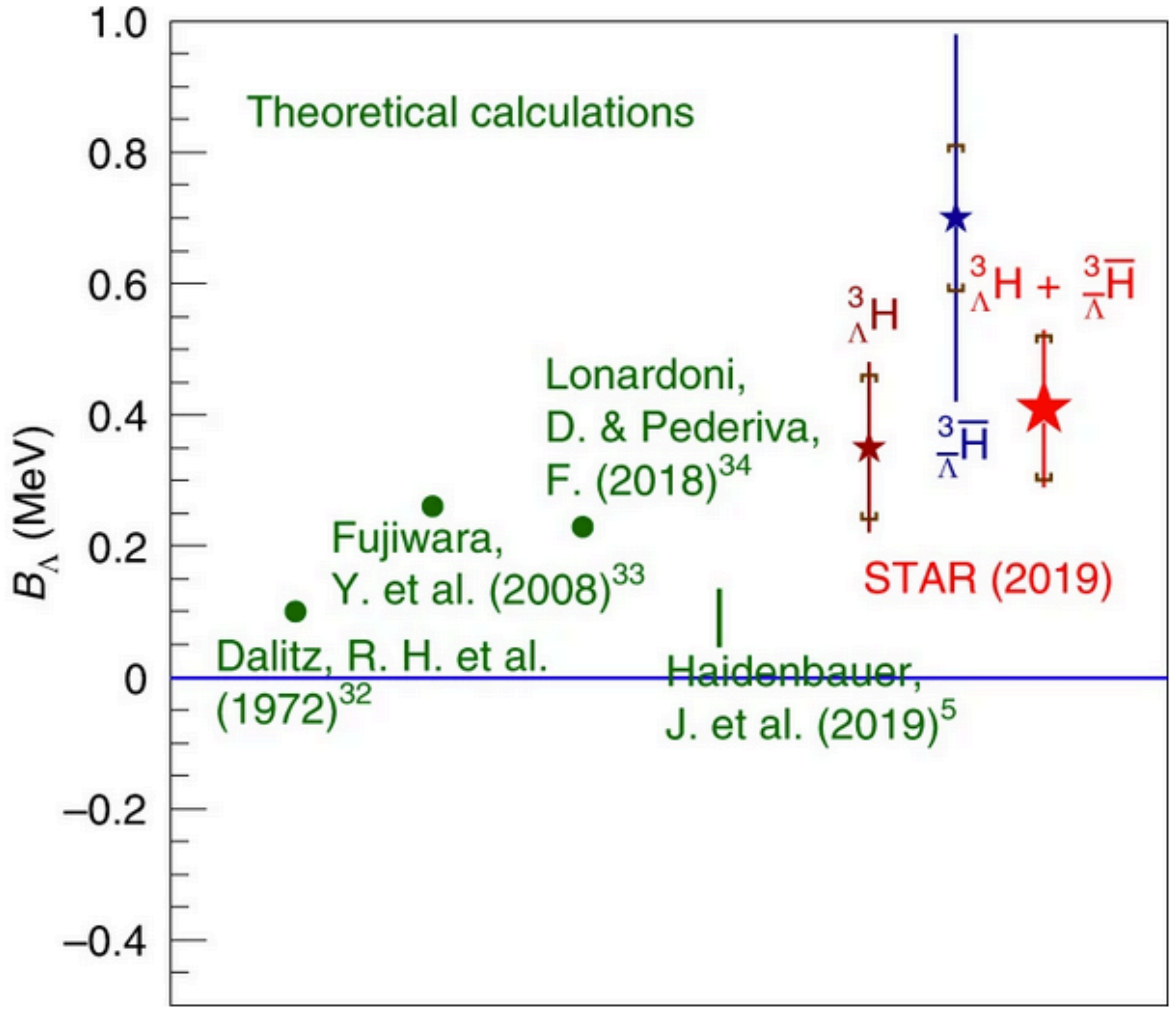
Hypertriton Λ separation energy

- STAR measurement[1] : hypertriton is more compact than expected

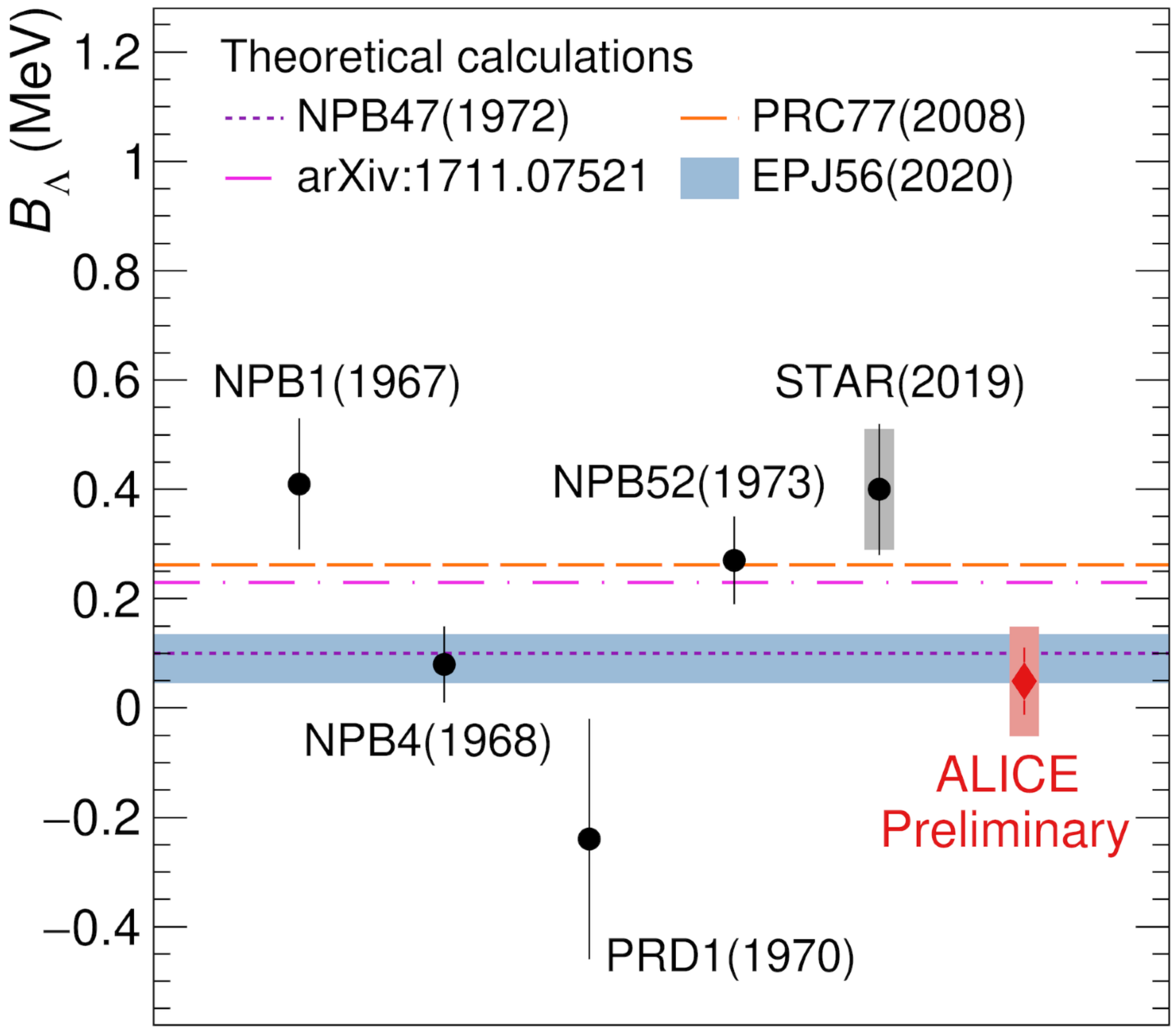
m = 2,990.89 ± 0.12(stat.) ± 0.11(syst.) MeV/c^2
B_Λ = 0.41 ∓ 0.12 (stat.) ∓ 0.11 (syst.) MeV

[1] STAR Collaboration, Nature Physics 16 (2020), 409–412





Hypertriton Λ separation energy



ALI-PREL-486370

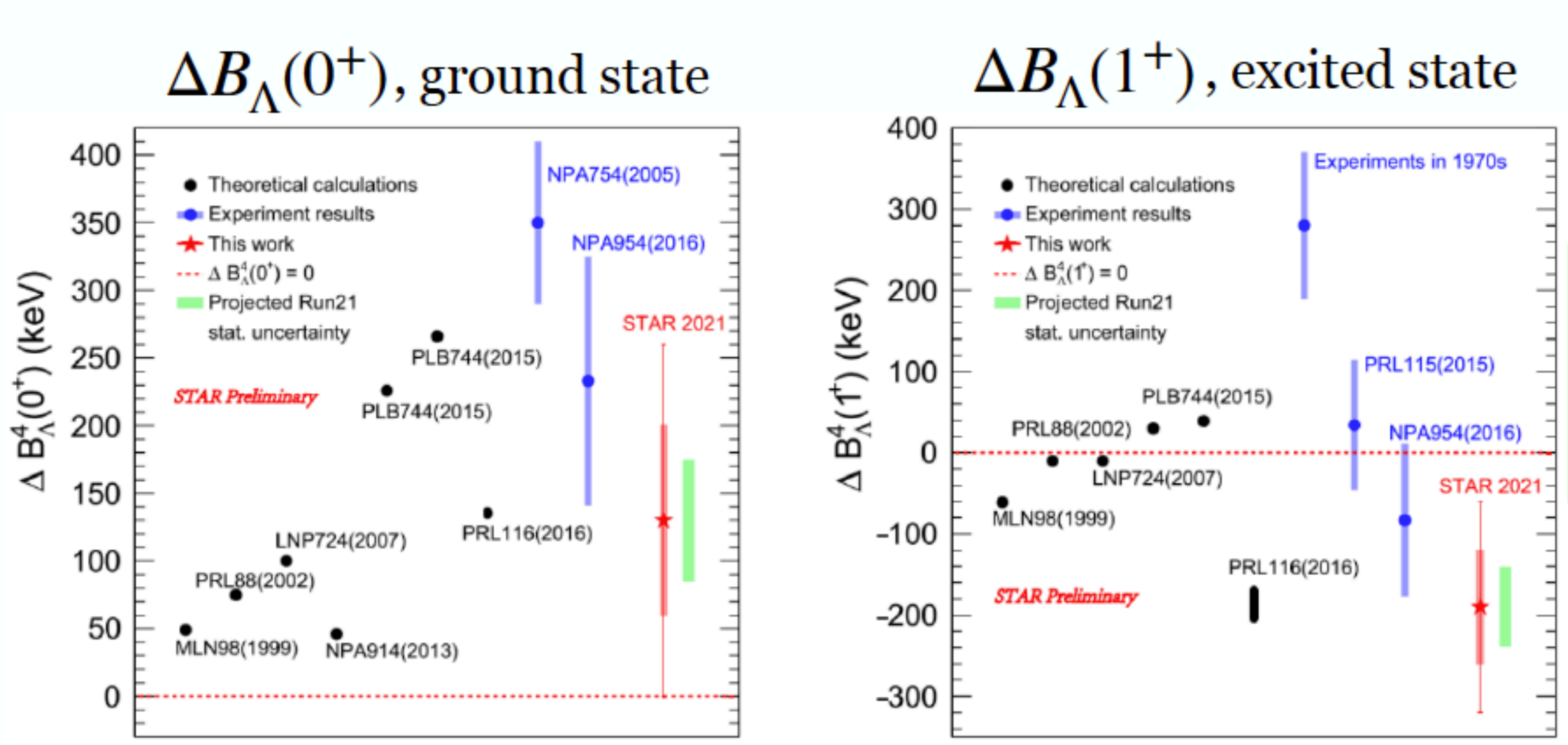
- From the mass measurement to B_Λ

STAR (2019) $B_\Lambda(^3_\Lambda\mathrm{H}) = 0.41 \pm 0.12(\mathrm{stat}) \pm 0.11(\mathrm{syst})$ **[MeV]**

ALICE (2021) $B_\Lambda(^3_\Lambda\mathrm{H}) = 0.05 \pm 0.06(\mathrm{stat}) \pm 0.10(\mathrm{syst})$ **[MeV]**

- Weakly bound nature of $^3{}_\Lambda$H is confirmed by the latest ALICE measurement
  - B_Λ consistent with zero
  - consistent with SU(3) chiral effective field theory and Dalitz predictions

Λ hypernuclei with A=4



$\tau({}^4_\Lambda\mathrm{H}) = 217 \pm 8(\mathrm{stat}) \pm 12(\mathrm{syst})[\mathrm{ps}]$

$B_\Lambda({}^4_\Lambda\mathrm{H}) = 2.24 \pm 0.06(\mathrm{stat}) \pm 0.18(\mathrm{syst})[\mathrm{MeV}]$

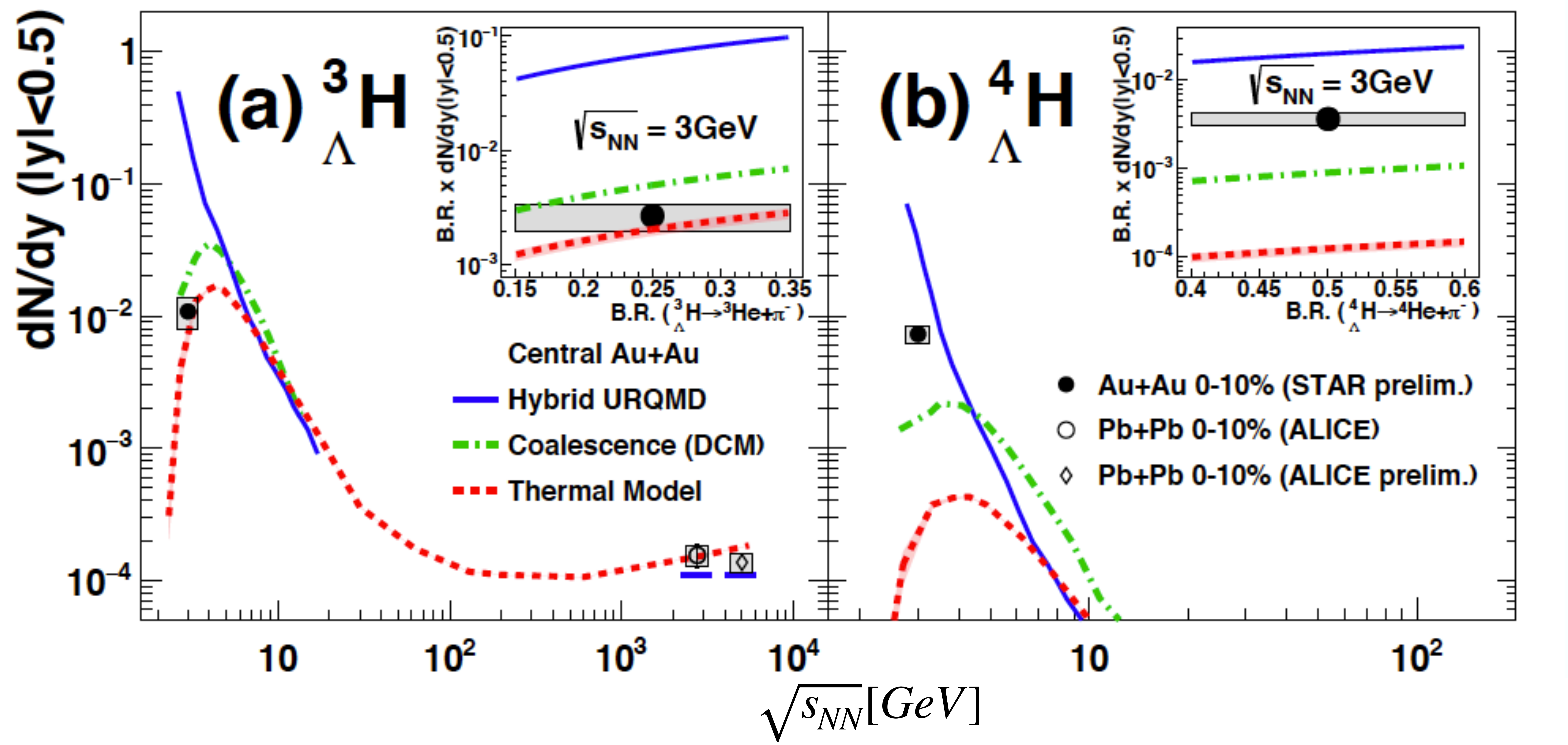
$B_\Lambda({}^4_\Lambda\mathrm{He}) = 2.37 \pm 0.12(\mathrm{stat}) \pm 0.14(\mathrm{syst})[\mathrm{MeV}]$

STAR (2021)

$$\Delta B_\Lambda(0^+) = 130 \pm 130(stat) \pm 70(syst)[\mathrm{keV}]$$

Charge symmetry breaking (CSB) effects in ground and excited states are consistent with theoretical calculations

Production of Λ hypernuclei in large systems



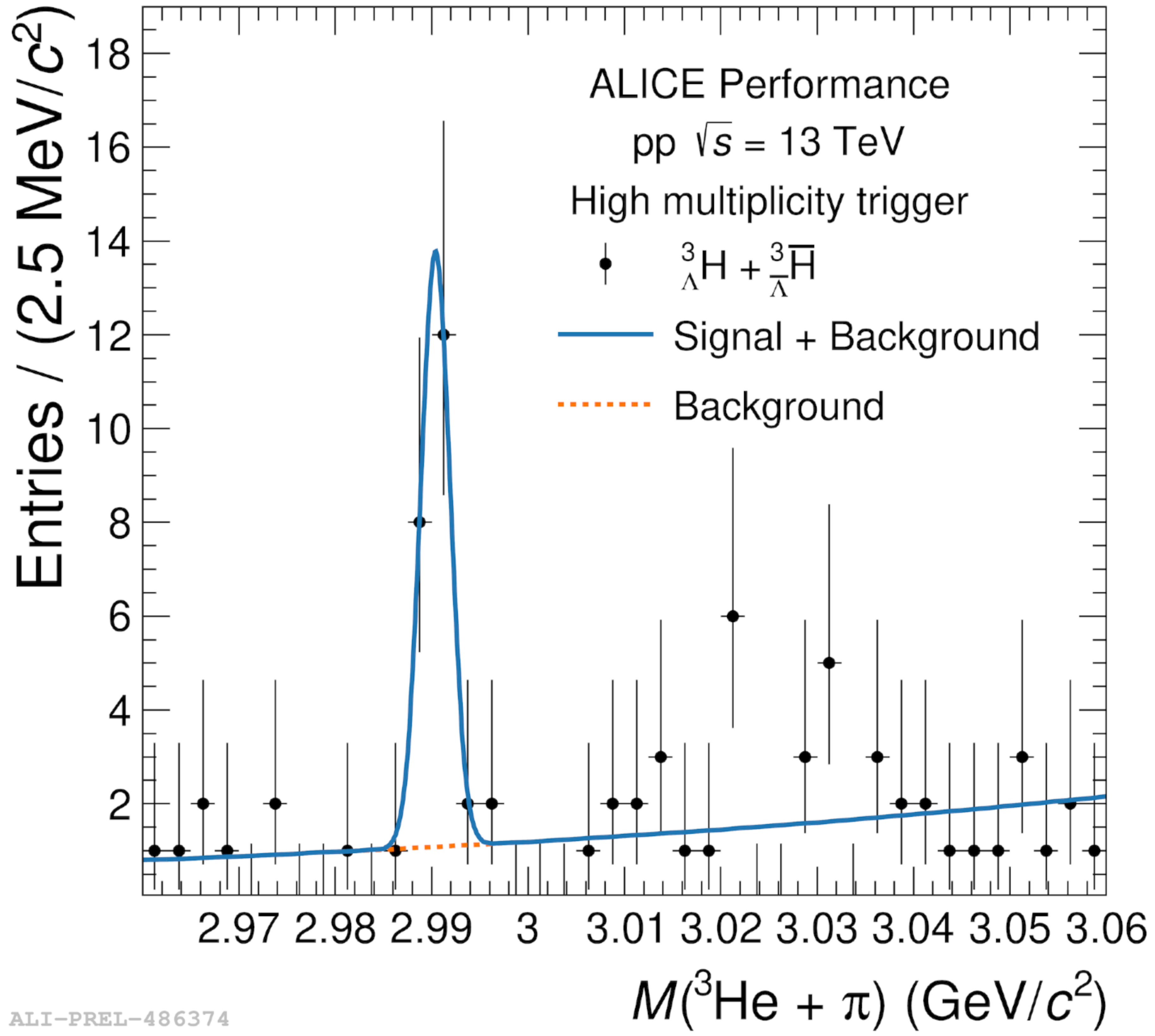
STAR @ 3 GeV (2021)

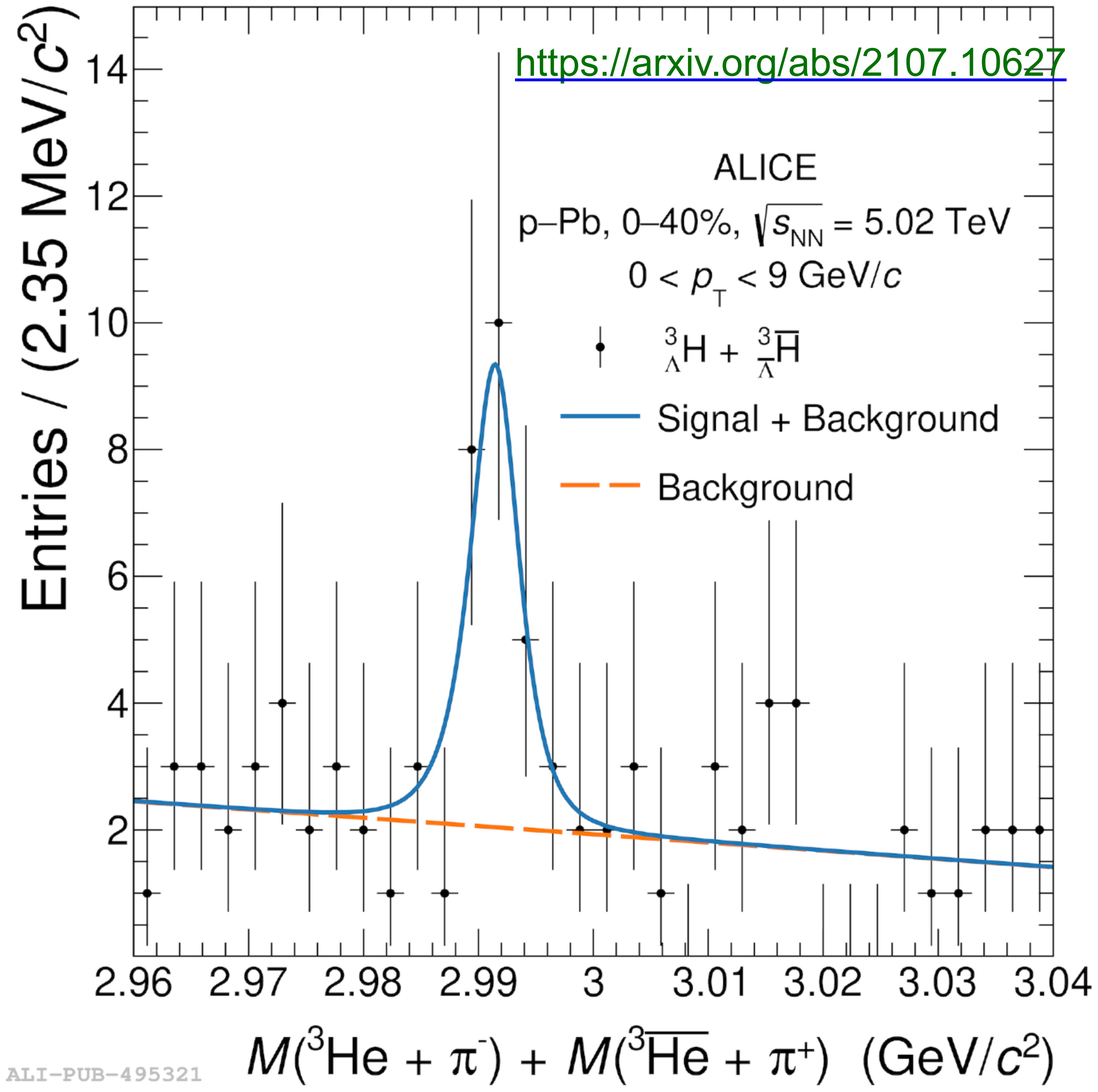
ALICE @ 2.76 TeV,
NPA 1005 (2021) 121791

ALICE @ 5.02 TeV
PLB 754 (2016) 360

- $^{3}_{\Lambda}H$: Thermal model (GSI-Heidelberg) describes both ALICE and STAR data
- $^{3}_{\Lambda}H$: STAR data at 3 GeV are compatible also with coalescence
- Results of $^{4}_{\Lambda}H$ are not described by any model

Production of Λ hypernuclei in small systems





- **Trigger on high multiplicity events using V0 detectors**
- Selection using topological cuts on triggered events

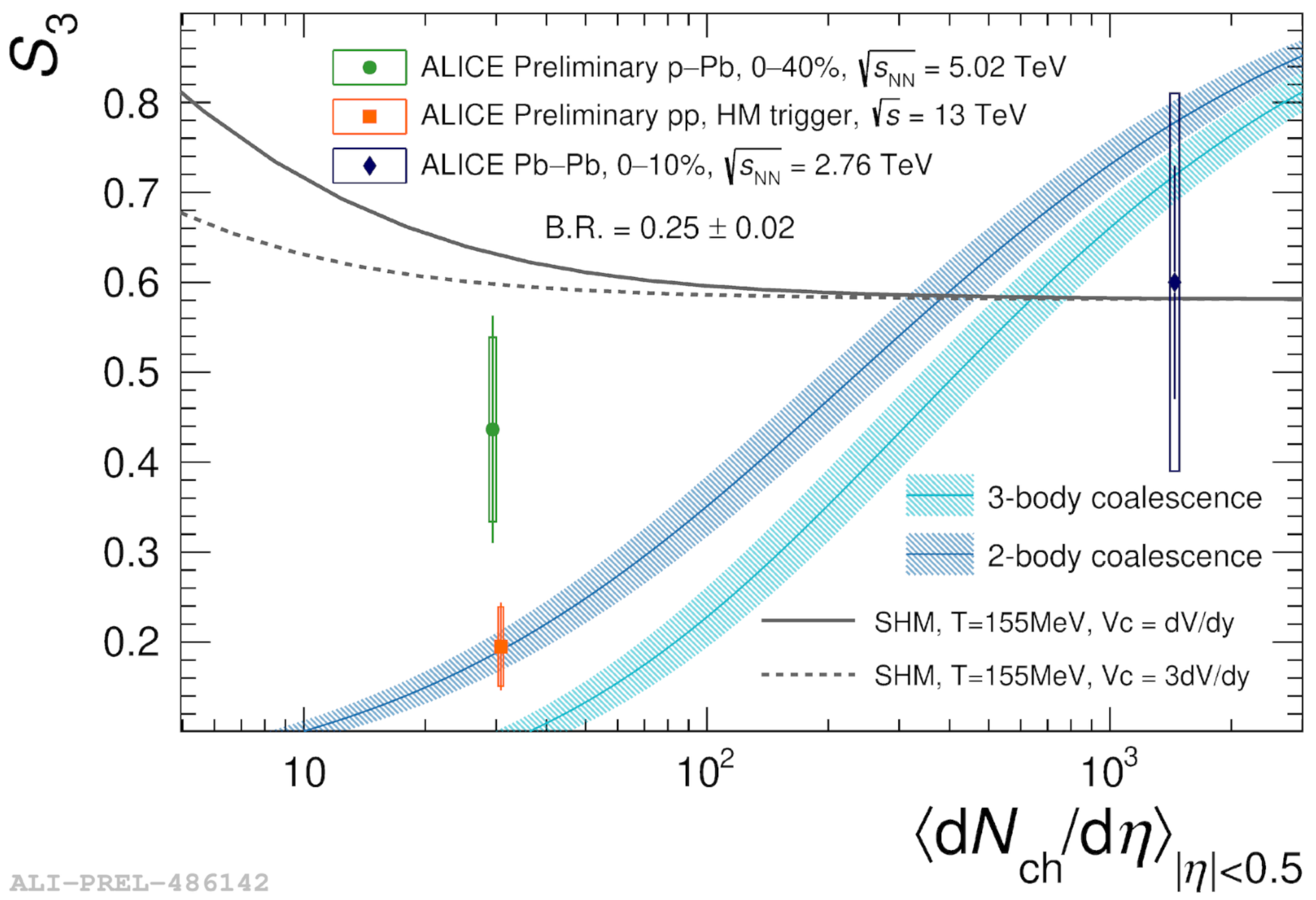
- Signal selection using a BDT Classifier
- **fundamental contribution of ML to extract the signal with good significance: 4.6σ**

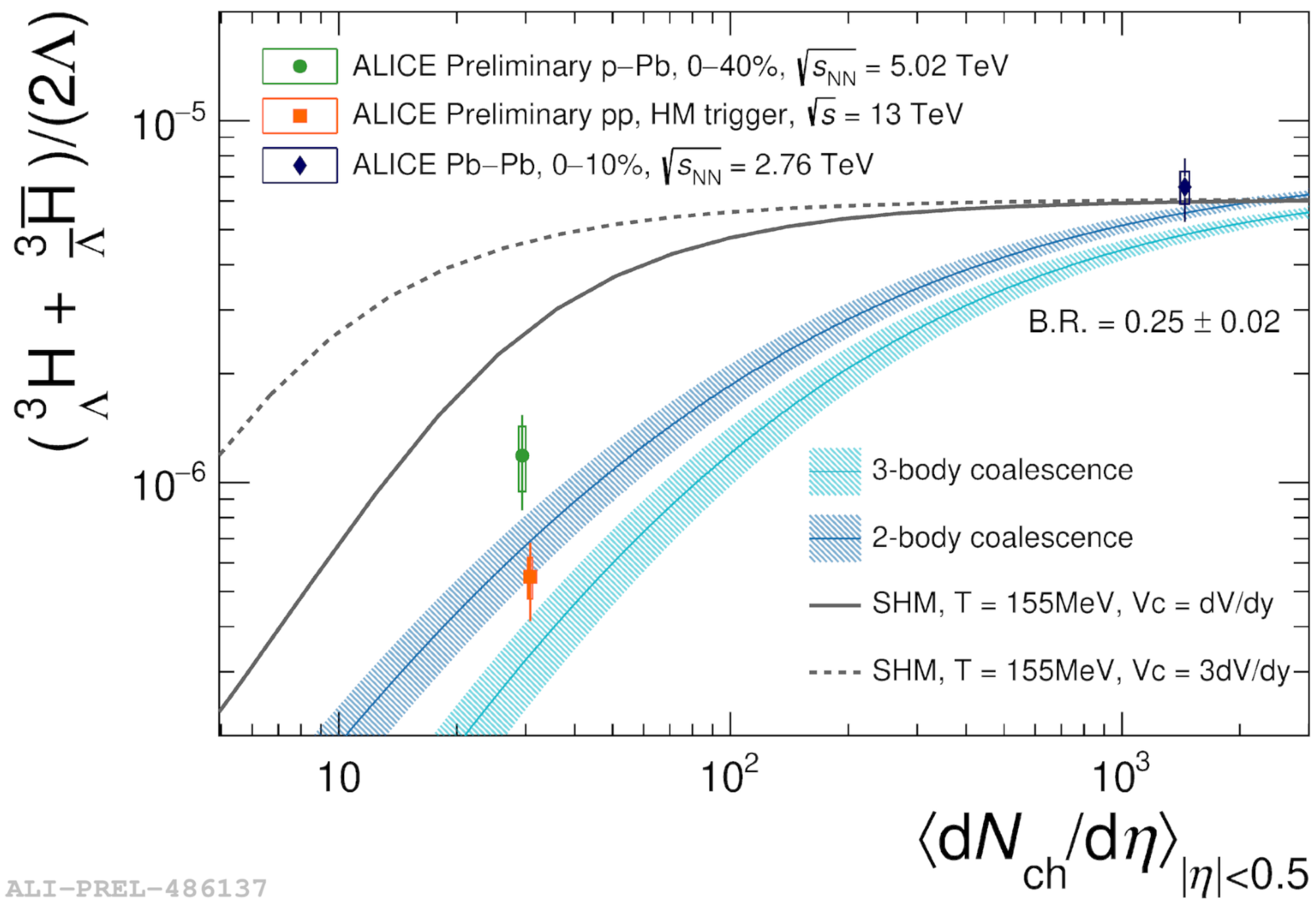
Production of Λ hypernuclei in small systems

https://arxiv.org/abs/2107.10627

$$S_3 = \frac{^3_\Lambda \mathrm{H}}{^3\mathrm{He}} \times \frac{p}{\Lambda}$$

(SHM) Vovchenko, V., Dönigus, B., & Stoecker, H. (2018). *Phys. Lett., B785, 171-174.*
(Coalescence) Sun, K.J., Ko, C., & Dönigus, B. (2019). *Phys. Lett. B, 792, 132–137.*





- large separation between production models
- **measurements in good agreement with 2-body coalescence**
- **p+p data tension with SHM**

Summary

- Many new interesting results for not ordinary baryons and hypernuclei in different colliding systems in high energy collisions

- Theory vs experimental results

    - The **coalescence model** provides a good description of B_A and **nuclei/proton ratio** as a function of multiplicity for small collision systems

    - **CSM** can describe the evolution of **d/p** and **^{3}He/p** with multiplicity

    - The measurements of ${}^{3}_{\Lambda}\mathrm{H}/\Lambda$ and $\mathbf{S_3}$ in pp and p-Pb collisions **favour two-body coalescence** w.r.t. CSM

- Structure of hypernuclei

    - precise τ and B_Λ of light/anti hypernuclei: high statistics data

    - Tighter constraints on the Y-N interaction and hypernuclear structure

Thank you!