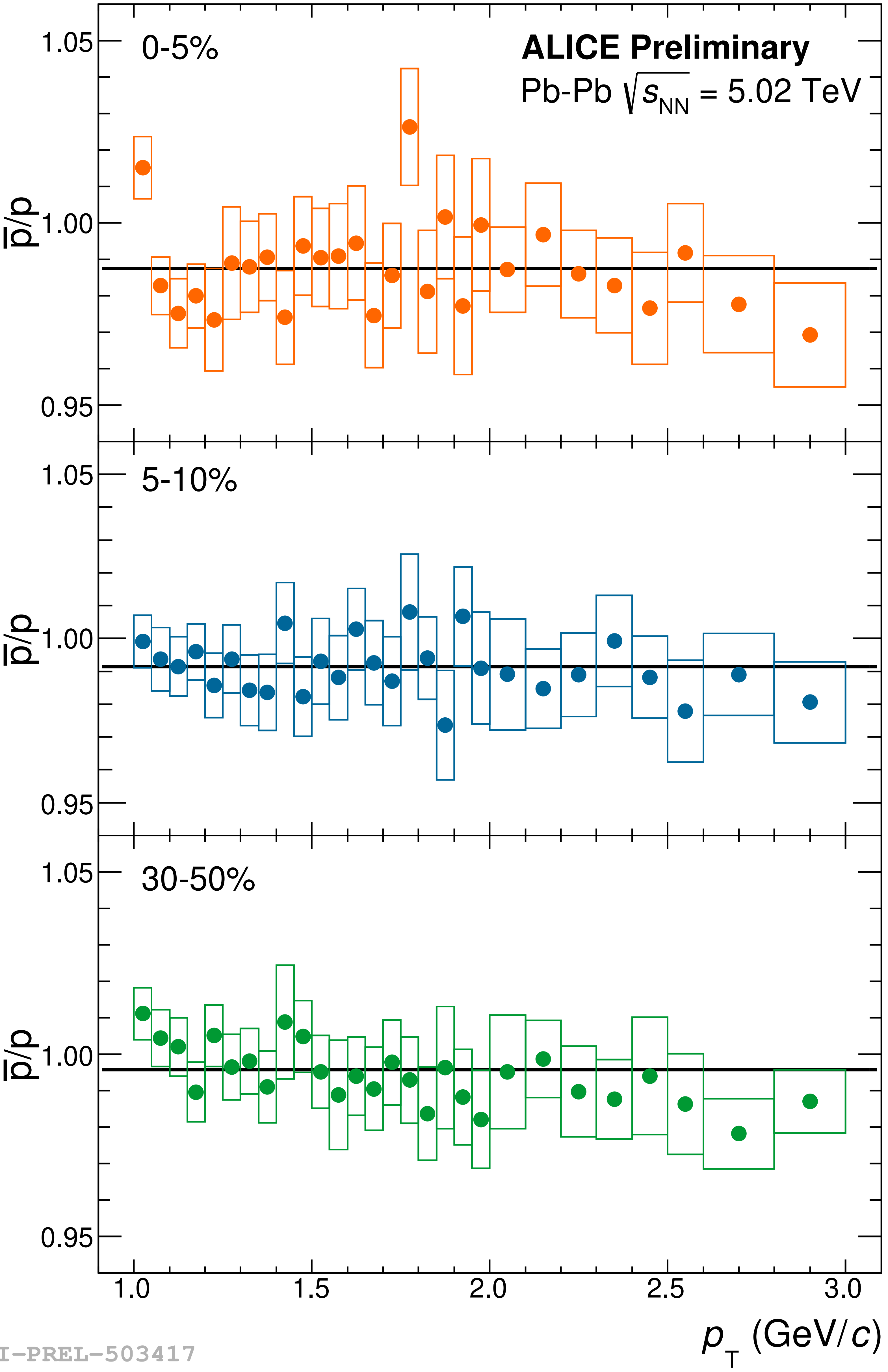
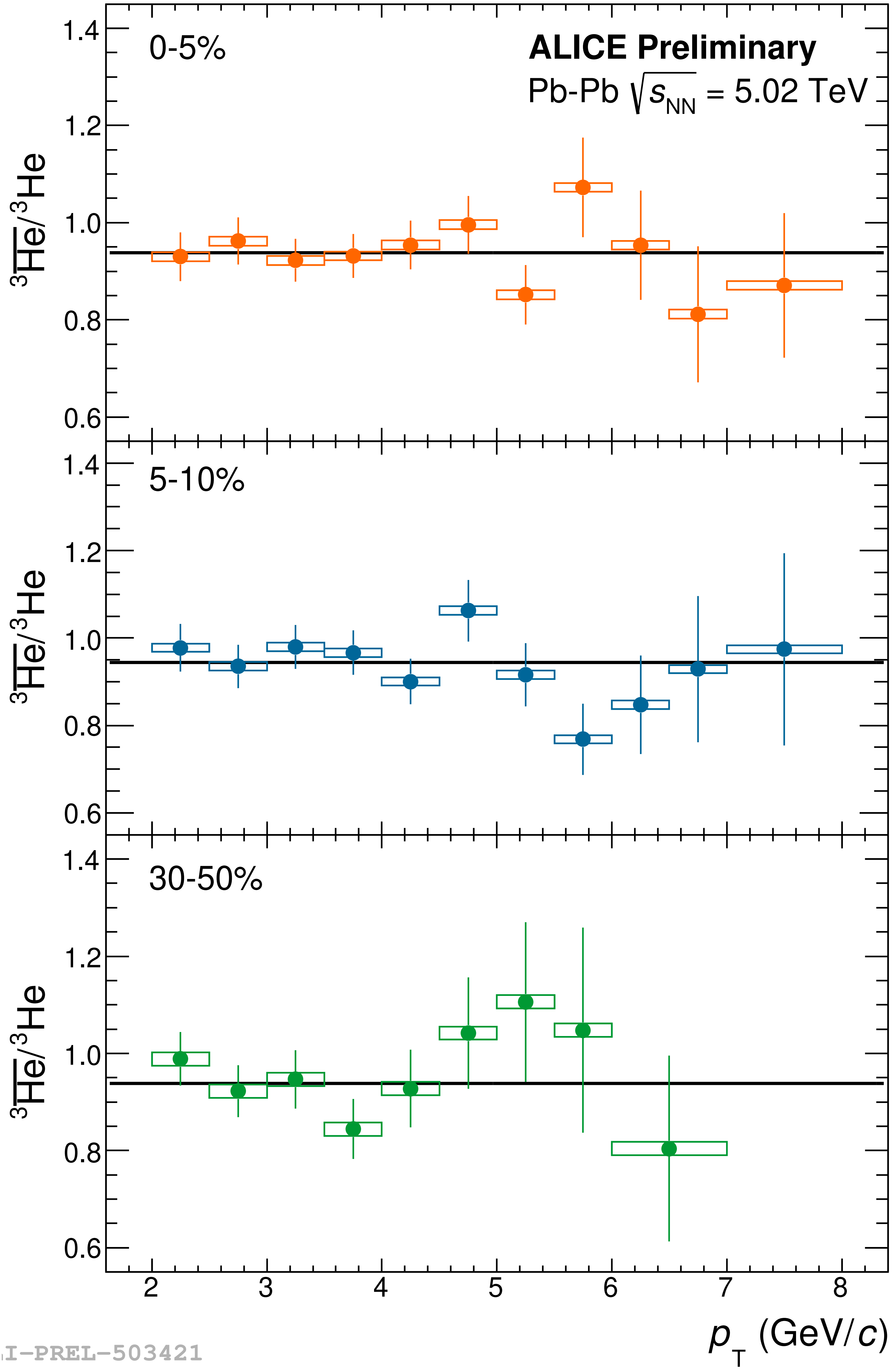
(Anti)(hyper)nucleosynthesis at the LHC with ALICE

Maximiliano Puccio (CERN)

HYP2022 - Prague 27th June 2022

Prelude: an antimatter factory





For a nucleus *X* with mass number *A* at the LHC it has been found that:

$$\frac{\overline{X}}{X} \approx \left(\frac{\overline{p}}{p}\right)^{A}$$

- The antiproton/proton ratio ~1 at LHC
- Tested up to A=3!
- Specific studies were done to reduce the systematic uncertainties

At the LHC matter and antimatter are produced in equal abundance at mid rapidity

In central Pb-Pb collisions

~40 protons	~3e-4 ^{3}He
~0.1 deuterons	~1e-4 hypertritons

Why should we care?

Three points we can address by studying (anti)(hyper)nuclei at the LHC:

1. How strong are the interactions among nuclei and hyperons?
    - ALICE delivers the most precise measurements of the properties of hypertriton
2. A nuclear physics problem: how loosely bound objects are formed in high energy collisions ("*snowball in hell*")?
    - Can we learn something about the particles being produced by studying their production rate?
3. How to interpret the flux of cosmic ray antinuclei for dark matter searches?
    - Beyond the study of antinuclei production: interaction of antinuclei with the material

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◉ Not discussed here! Come and ask me and L. Fabbietti about this in the breaks!

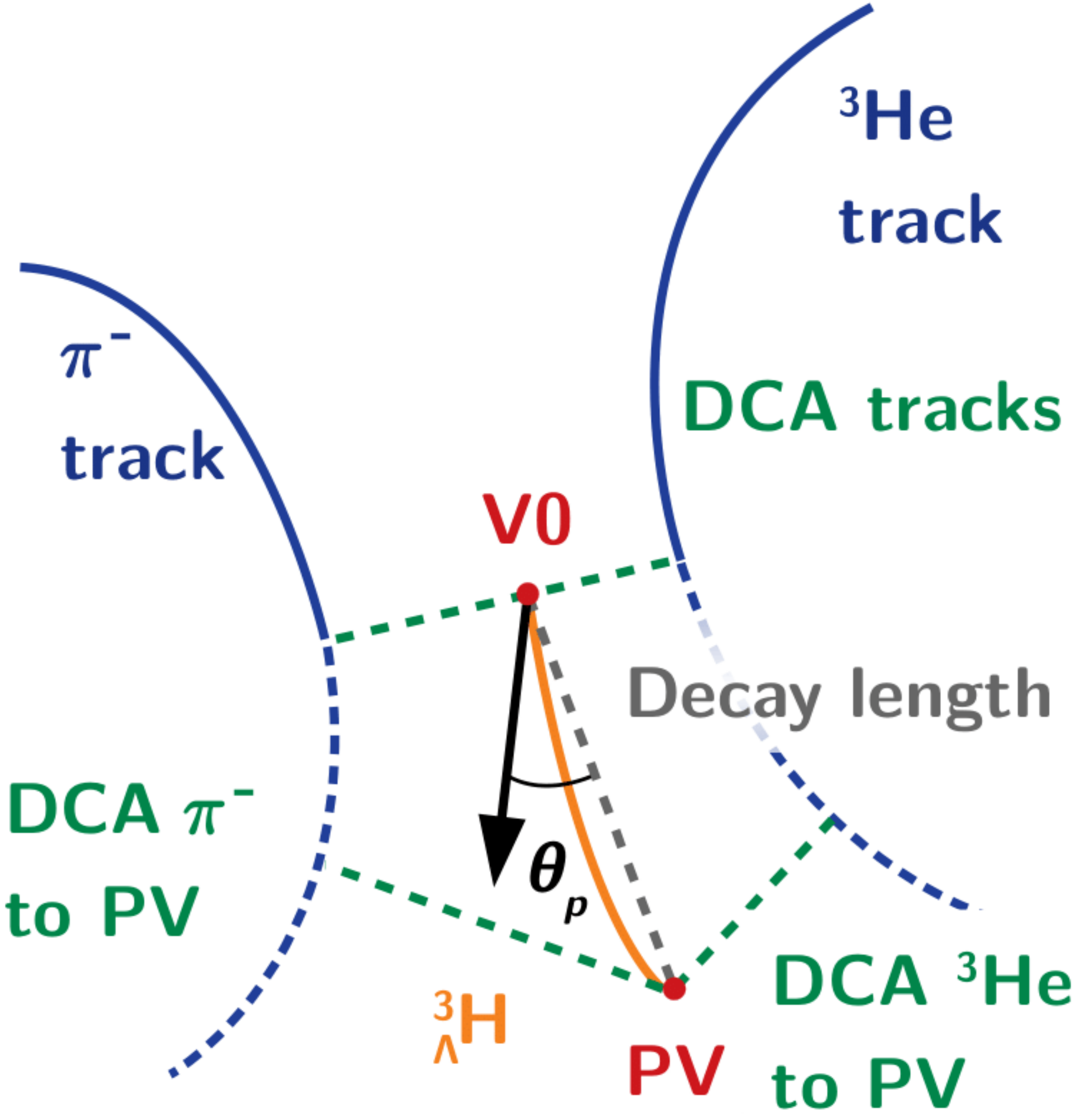
Lifetime and binding energy of $^{3}_{\Lambda}H$

Detecting $^{3}_{\Lambda}$H in heavy ion collisions

(Anti)Hypertriton decay in ^{3}Heπ^{-} is easily reconstructed by ALICE

Signal Extraction:

- Identify ^{3}He and π
- Evaluate (^{3}He,π) invariant mass
- Apply topological cuts in order to:
  - identify secondary decay vertex
  - reduce combinatorial background
- Or… train a ML discriminator



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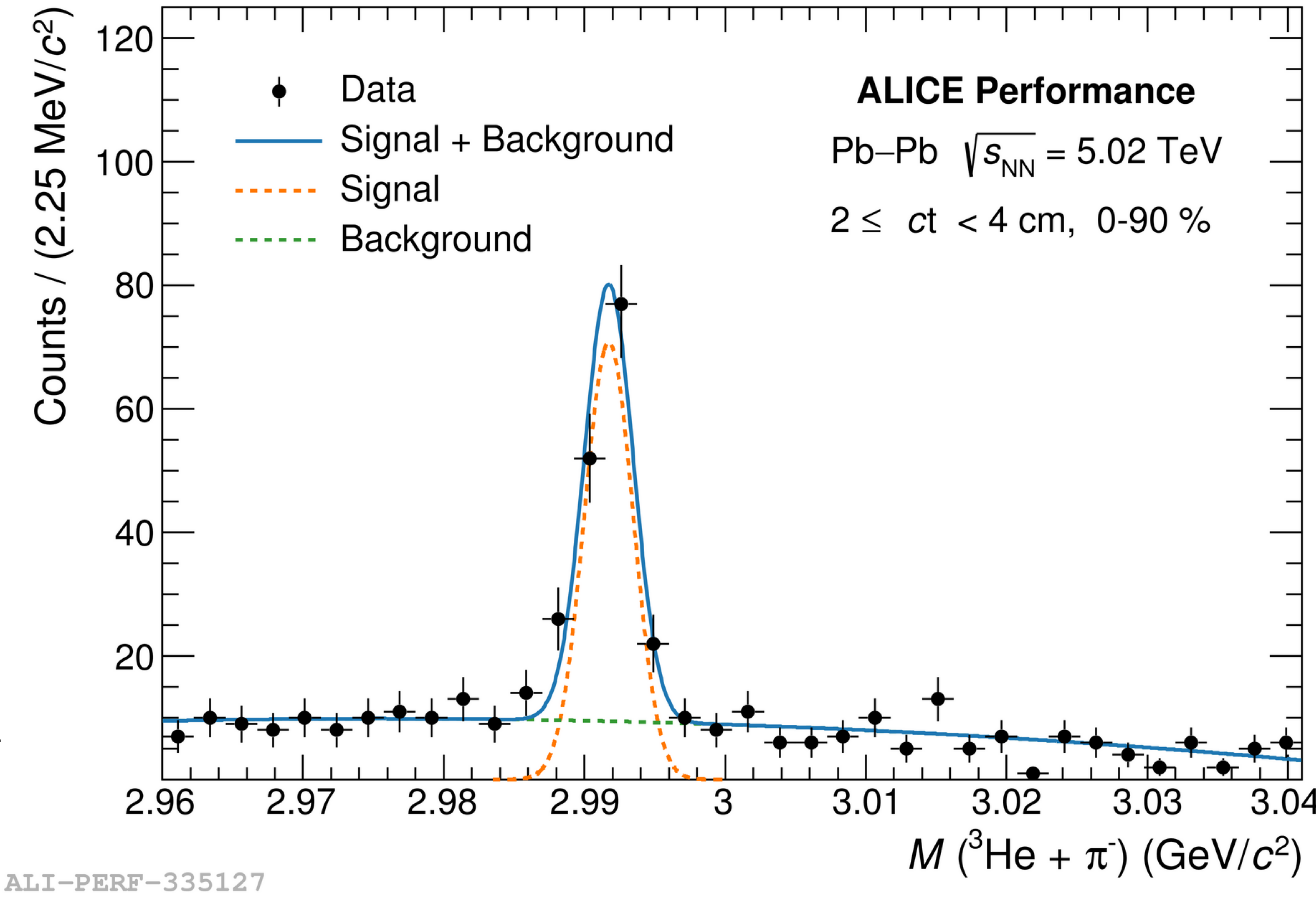
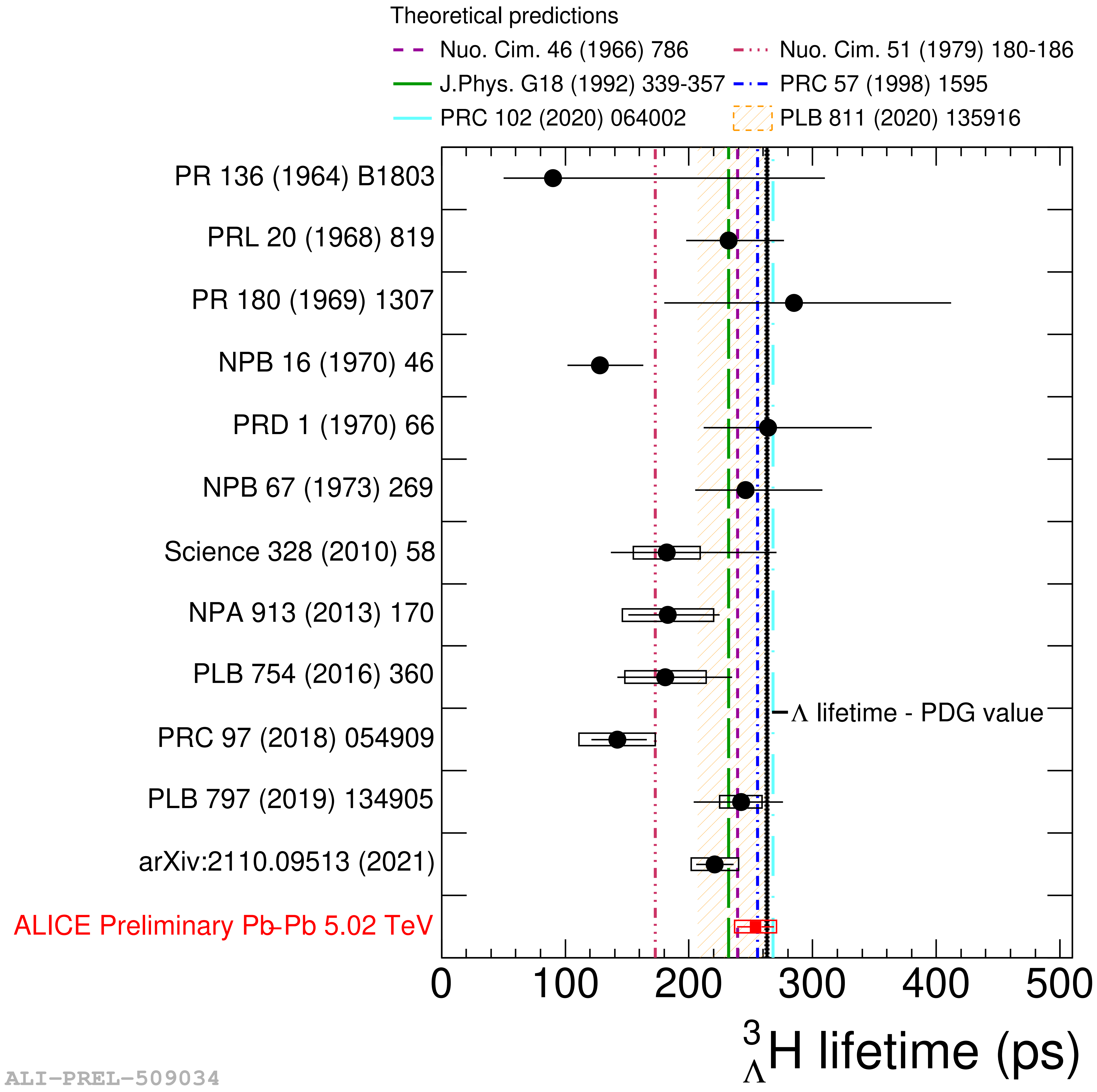
- XGBoost discriminator trained on data and MC
- Significance enhanced by up to 50%

Analysis details in S. Bufalino talk on 29/06/2022, 18:20



$^{3}_{\Lambda}$H lifetime and binding energy in the high precision era



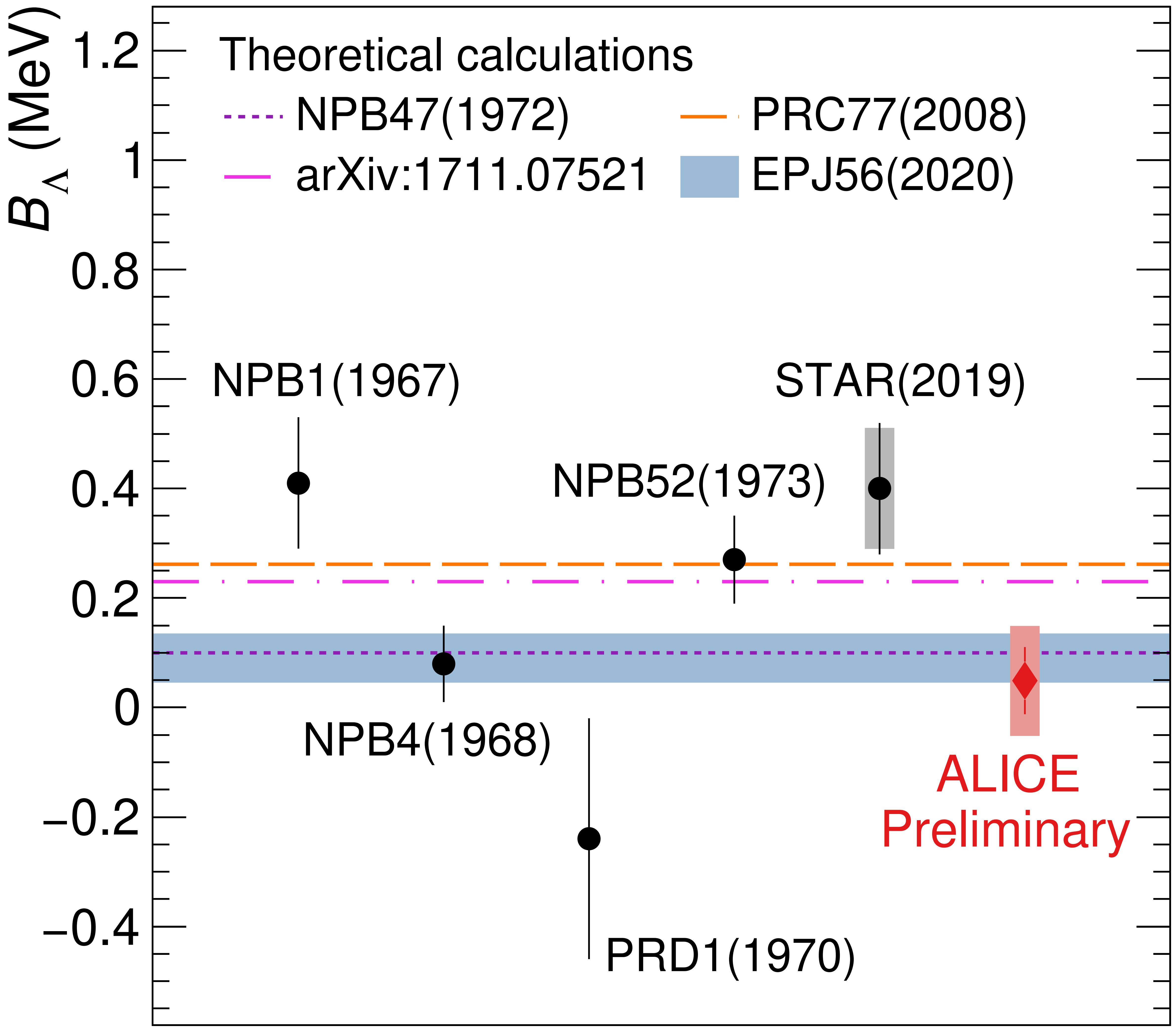
Paper out in few weeks!

Using the 2018 Pb-Pb data + ML methods

- World's most precise measurement
- Exclude large deviations from free Λ lifetime
- Test of different models with different $^{3}_{\Lambda}$H structure

$^{3}_{\Lambda}$H lifetime and binding energy in the high precision era

$$B_\Lambda = m_d + m_\Lambda - m_H$$



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ALI-PREL-486370

Using the 2018 Pb-Pb data + ML methods

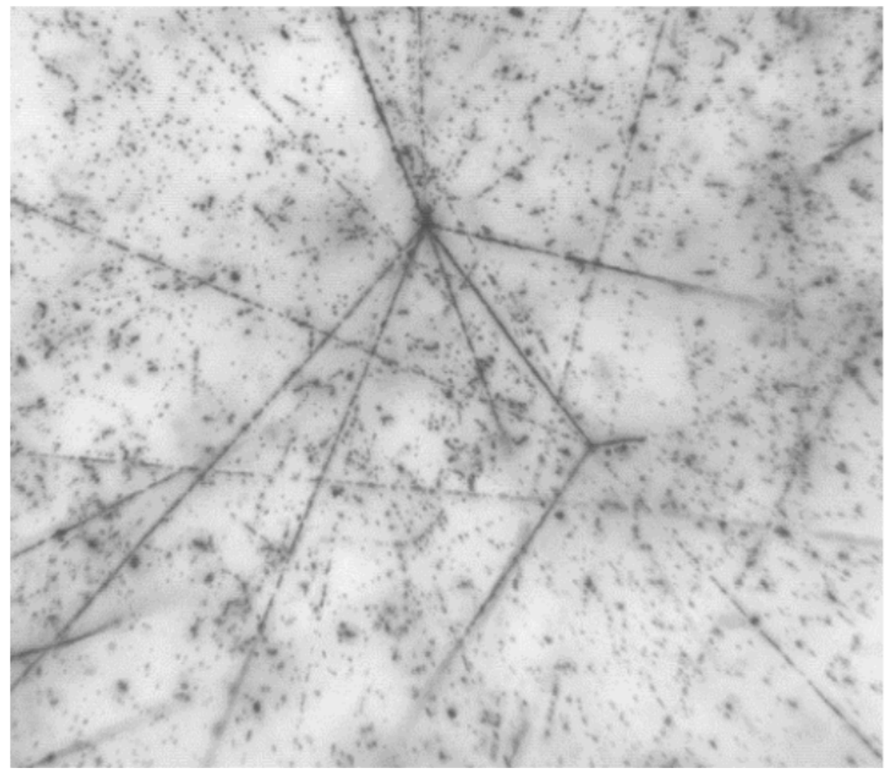
- World's most precise measurement
- Exclude large deviations from free Λ lifetime
- Test of different models with different $^{3}_{\Lambda}$H structure

The measured B_Λ is extremely small

- Compatible with a loosely bound deuteron-Λ molecule

B_Λ uncertainties are O(100 keV)

- Visualising techniques still have the best uncertainties



Developing kinematic closure techniques by tracking the $^{3}_{\Lambda}$H before its decay

➡Equivalent to a O(MHz) bubble chamber

(Anti)(hyper)nucleosynthesis processes

Two models with very different implications

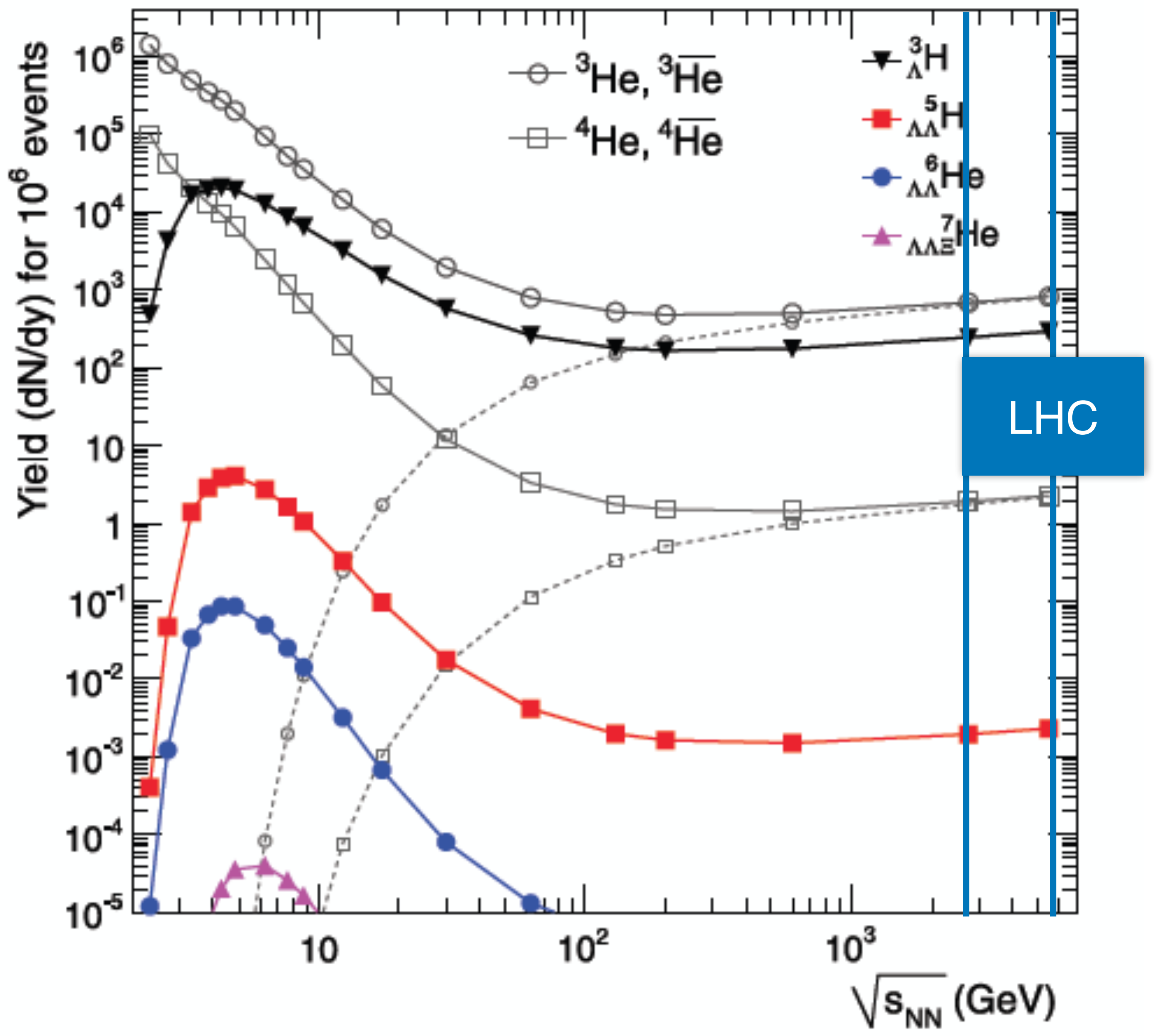
Two models with very different implications

THERMAL MODELS

- Hadrons emitted from the interaction region in statistical equilibrium when the system reaches a limiting temperature
- Freeze-out temperature T_{chem} is a key parameter
- Abundance of a species $\propto \exp(-m/T_{chem})$:
  - ➡For nuclei (large m) strong dependence on T_{chem}

Mainly used for Pb-Pb, it can be used in smaller systems by using the canonical ensemble

A. Andronic, P. Braun-Munzinger, J. Stachel and H. Stoecker, Phys. Lett. B607, 203 (2011), 1010.2995



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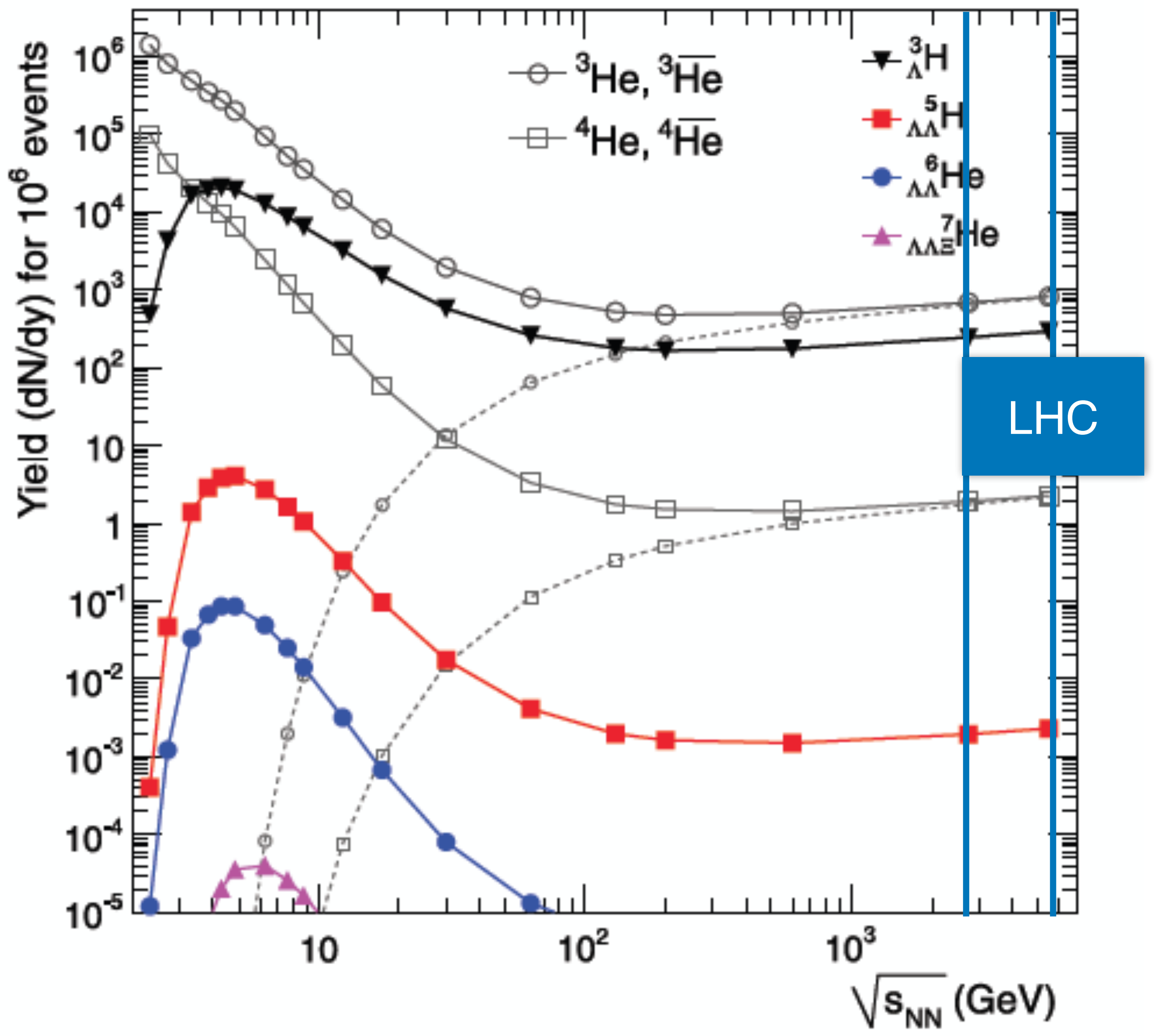
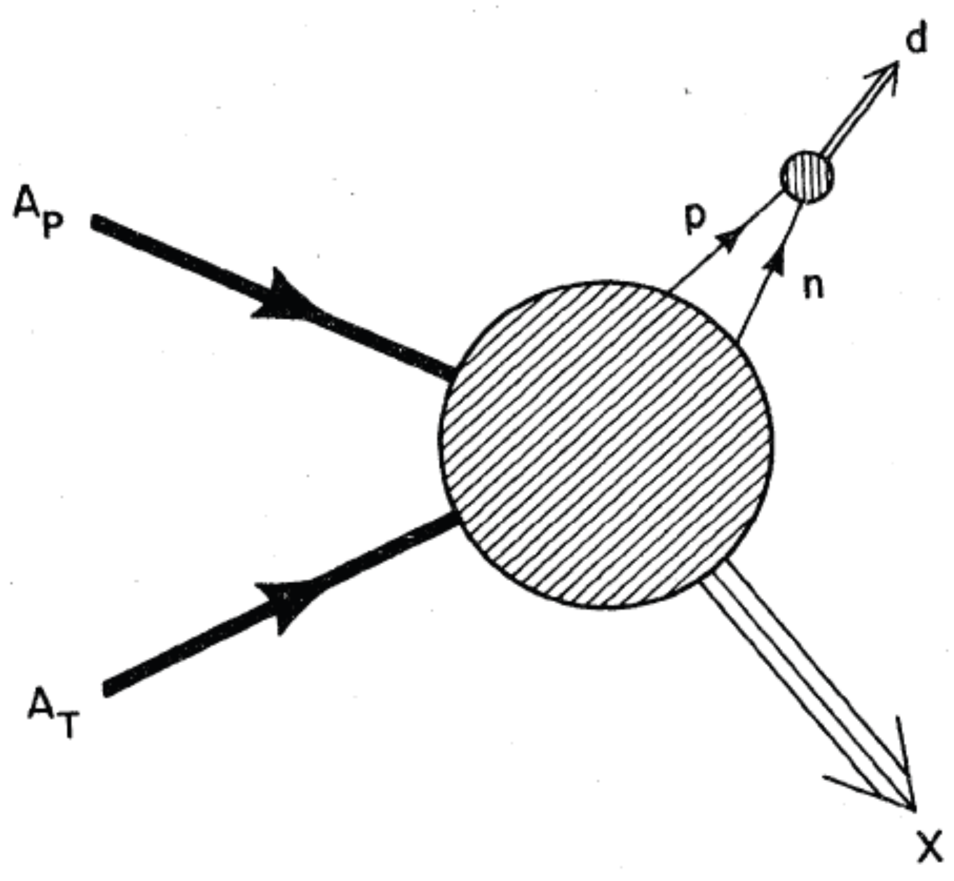


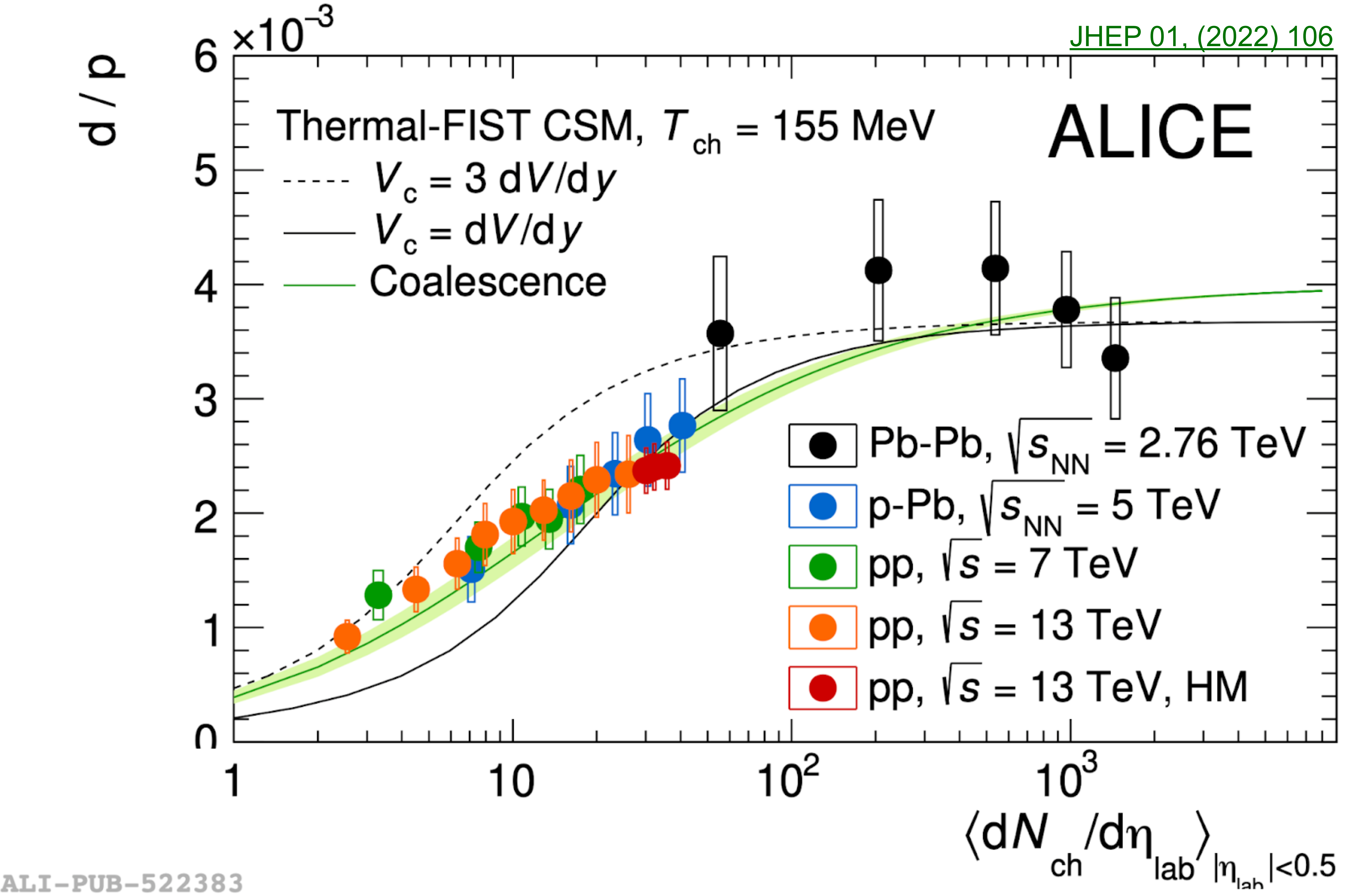


J. I. Kapusta, Phys.Rev. C21, 1301 (1980)

COALESCENCE

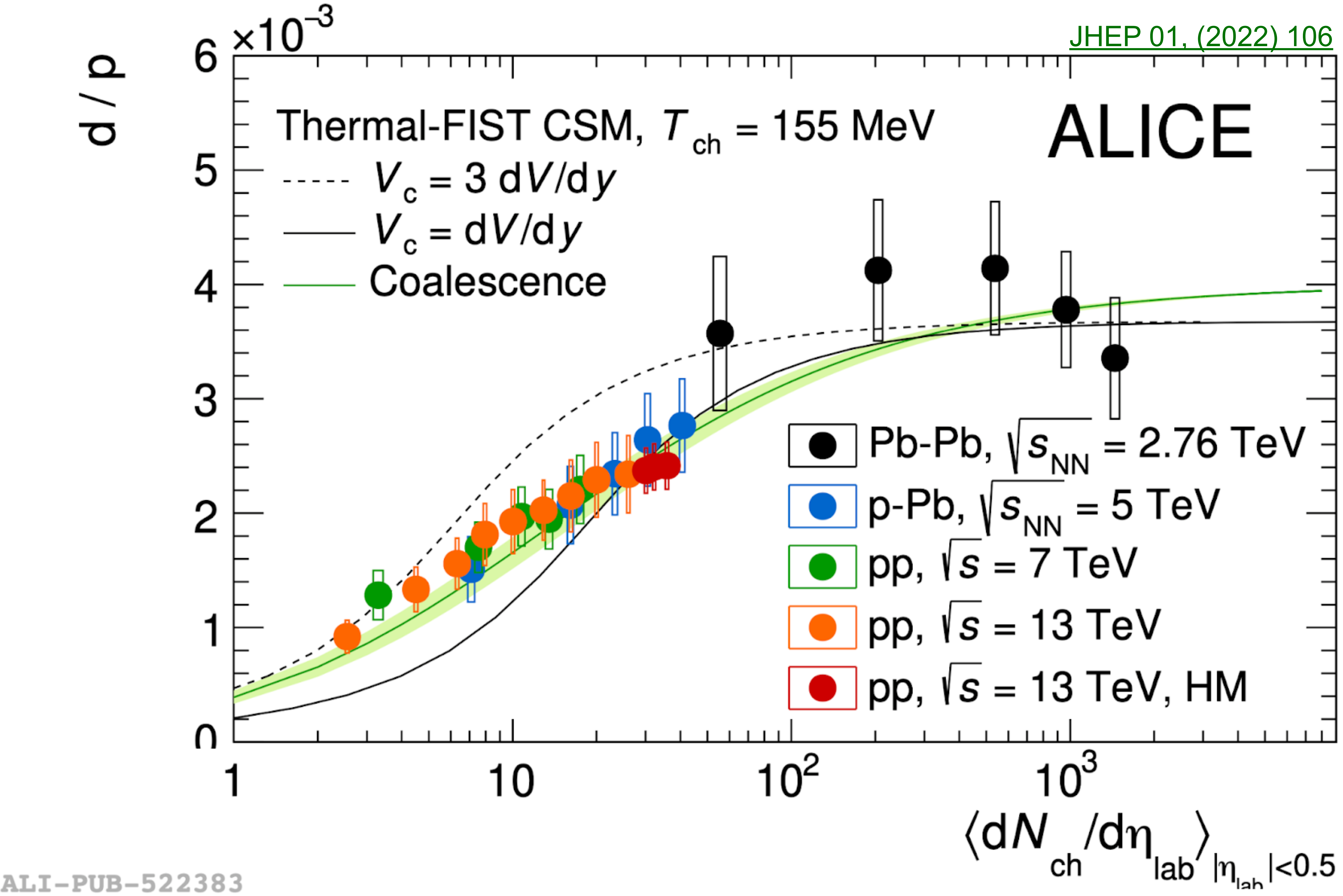
- If (anti)baryons are close in phase space they can form a (anti)nucleus
- Interplay between the configuration of the phase space of (anti)baryons and the wave function of the (anti)nuclei to be formed
  - TL;DR: the larger the wave function the more we are sensitive to the system size

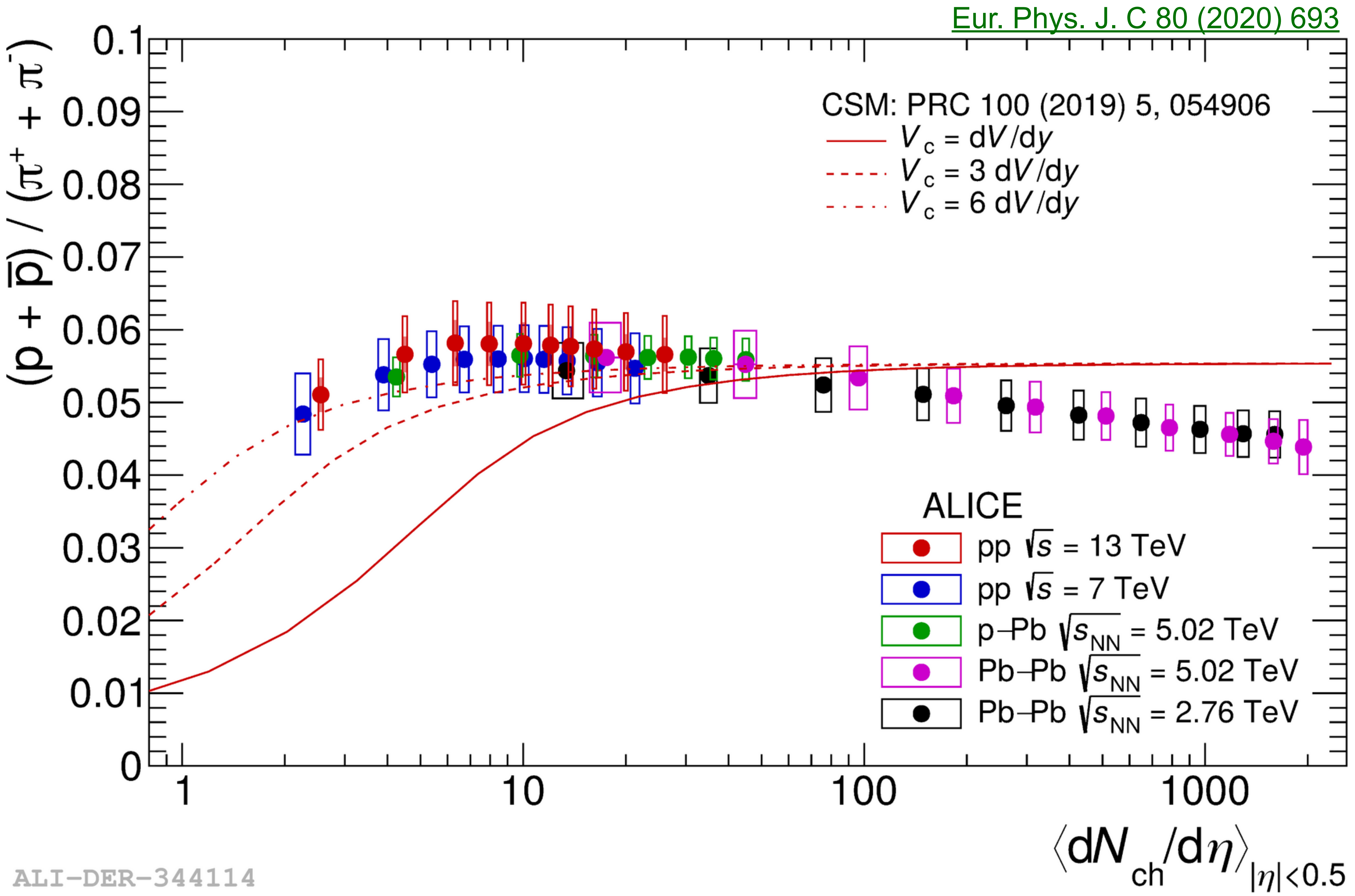
Thermal model vs coalescence



- Is this smooth transition suggesting a single description for the nucleosynthesis in HEP?
  - Thermal model with canonical suppression gets the rise of the nucleus/proton ratio

Thermal model vs coalescence





- Is this smooth transition suggesting a single description for the nucleosynthesis in HEP?
  - Thermal model with canonical suppression gets the rise of the nucleus/proton ratio
    - With the same parameters proton over pion ratio is not reproduced at low multiplicity

➡ However we do not expect Statistical Hadronisation Models to necessarily work in pp: system equilibrium might not be reached in small systems!

The coalescence parameter

The coalescence parameter for a nucleus *i* with A nucleons is defined as:

$$E_i \frac{\mathrm{d}^3 N_i}{\mathrm{d}p_i^3} = B_A \left(E_\mathrm{p} \frac{\mathrm{d}^3 N_\mathrm{p}}{\mathrm{d}p_\mathrm{p}^3} \right)^A$$

deuterons →

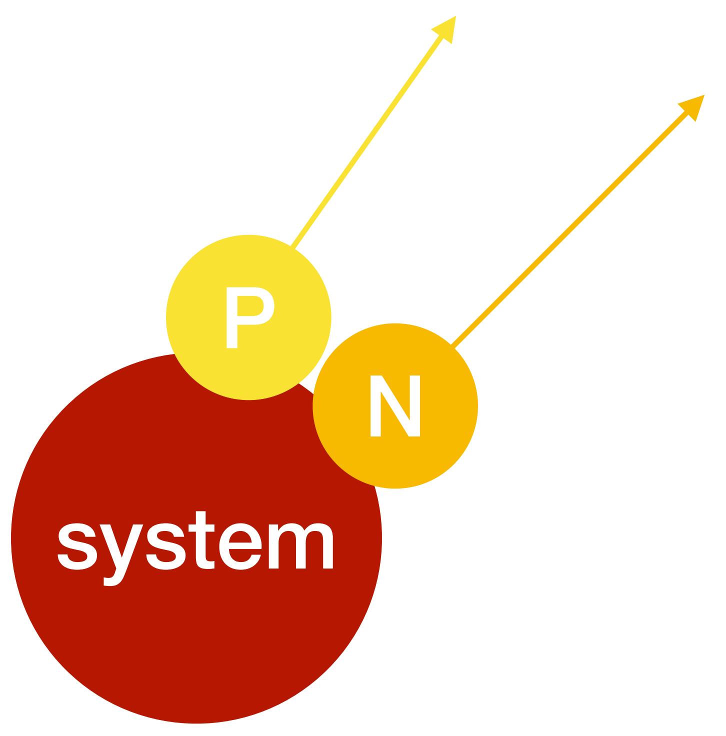
$$B_2 = \frac{E_\mathrm{d} \frac{\mathrm{d}^3 N_\mathrm{d}}{\mathrm{d}p_\mathrm{p}^3}}{\left(E_\mathrm{p} \frac{\mathrm{d}^3 N_\mathrm{p}}{\mathrm{d}p_\mathrm{p}^3} \right)^2}$$

Experimental parameter that is tightly connected to the coalescence probability:

Larger B_A $\Longleftrightarrow$ Larger coalescence probability

The closer the nucleons are in phase space the higher is the coalescence probability

SCHEMATIC VIEW



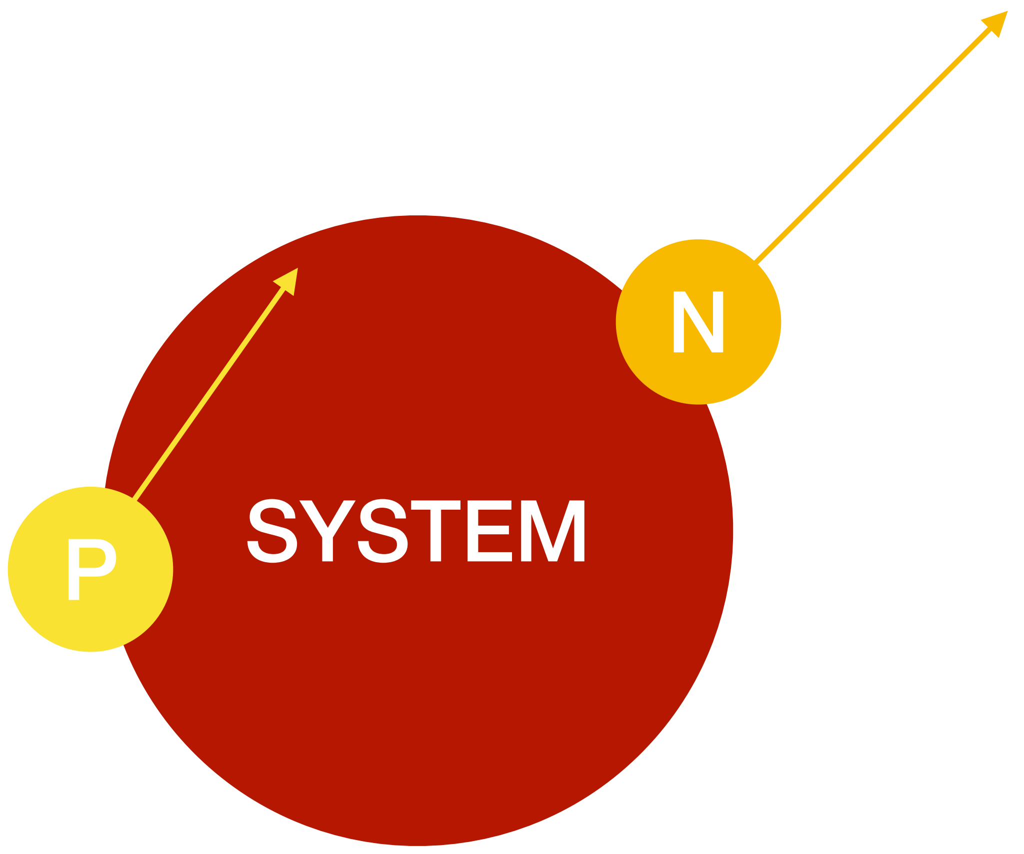
Small systems

=

Small distance in space

Only momentum correlation matters

Expect larger B_A



Large systems

=

Large distance in space

Both momentum and space correlations matter

Expect smaller B_A

Understanding nucleosynthesis at LHC

How to get a quantitative prediction in practice?

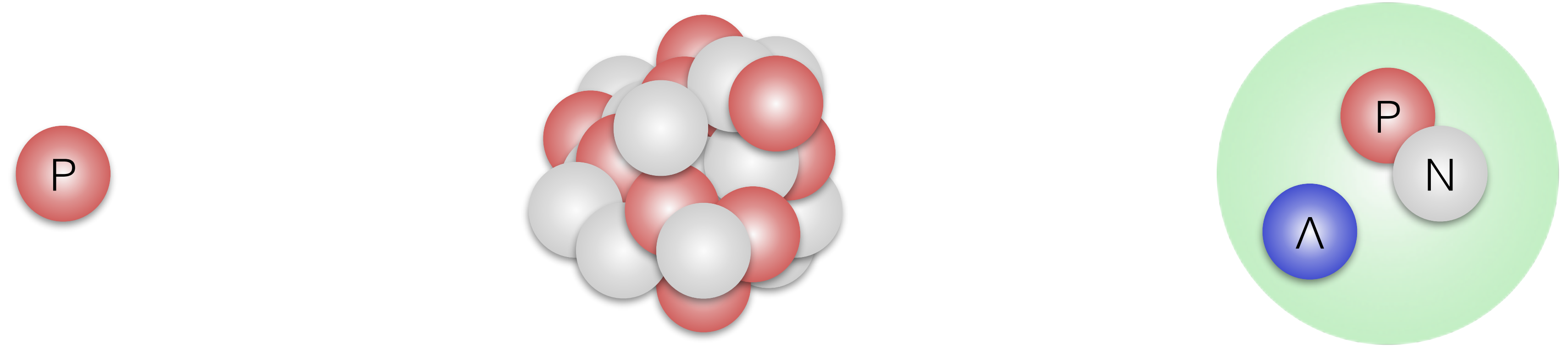
Our recent development that allows us to zoom into the production of nuclei through coalescence

Correlation radius

$$B_A(p) \approx \frac{3}{2m}\int \mathrm{d}^3q\,\mathscr{D}(\vec{q})\,\mathscr{C}_2^{\mathrm{PRF}}(\vec{p},\vec{q})$$

Wigner density / wave function

Proton	Copper	$^{3}_{\Lambda}$H

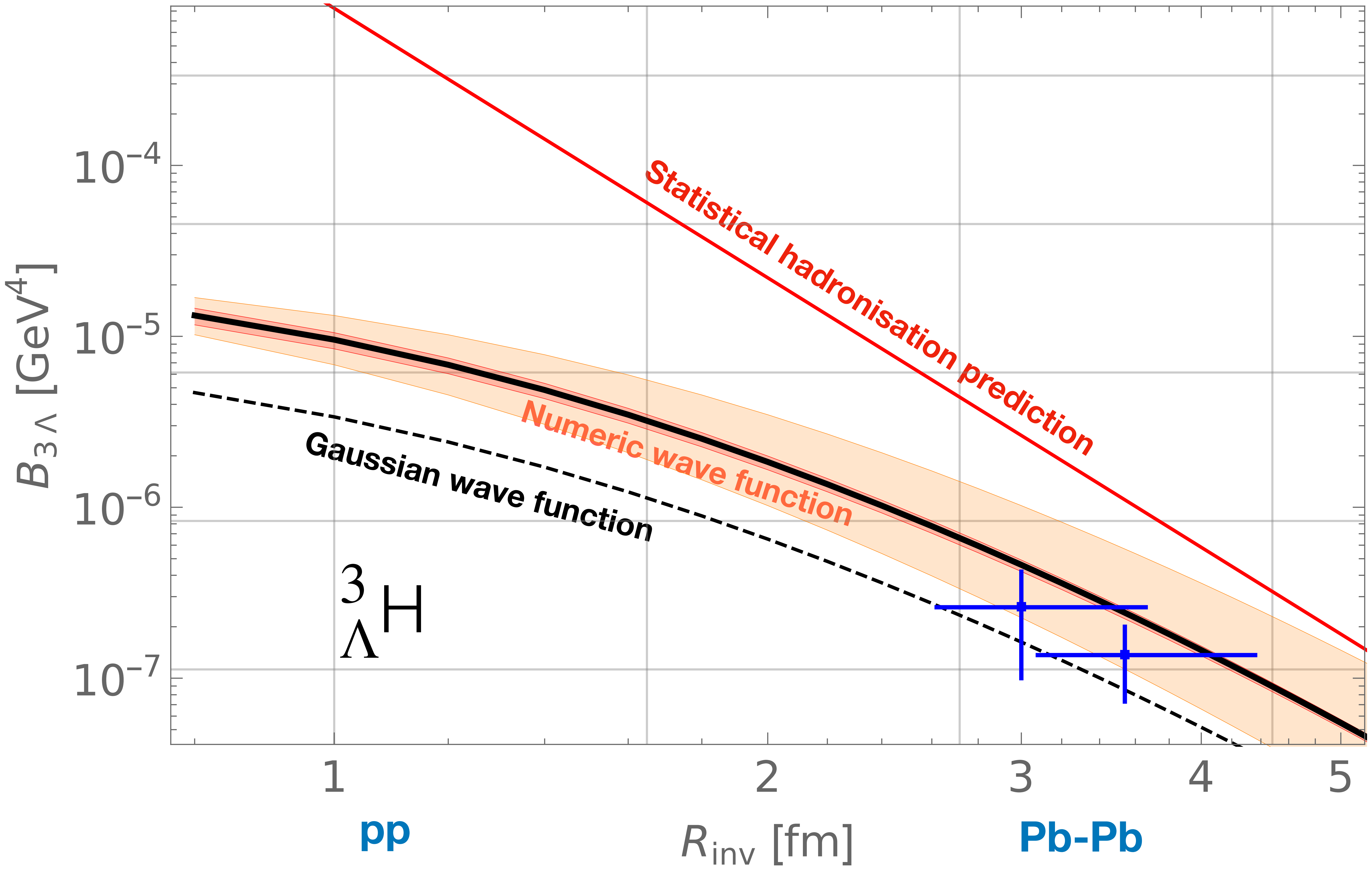


R ~ 0.8 fm	R ~ 5 fm	R ~ 5-10 fm

Halo nucleus: wide dΛ molecule

Sun. et al., Phys. Lett. B, 792, 132–137, (2019)

F. Bellini, K. Blum, A. Kalweit, M.P. PRC 103, 014907



From understanding nucleosynthesis to understanding the $^{3}_{\Lambda}$H wave function

From the correlation to the coalescence parameter

$$B_2(p) \approx \frac{3}{2m} \int \mathrm{d}^3 q \, \mathscr{D}(\vec{q}) \, \mathscr{C}_2^{\mathrm{PRF}}(\vec{p}, \vec{q})$$

Correlation radius

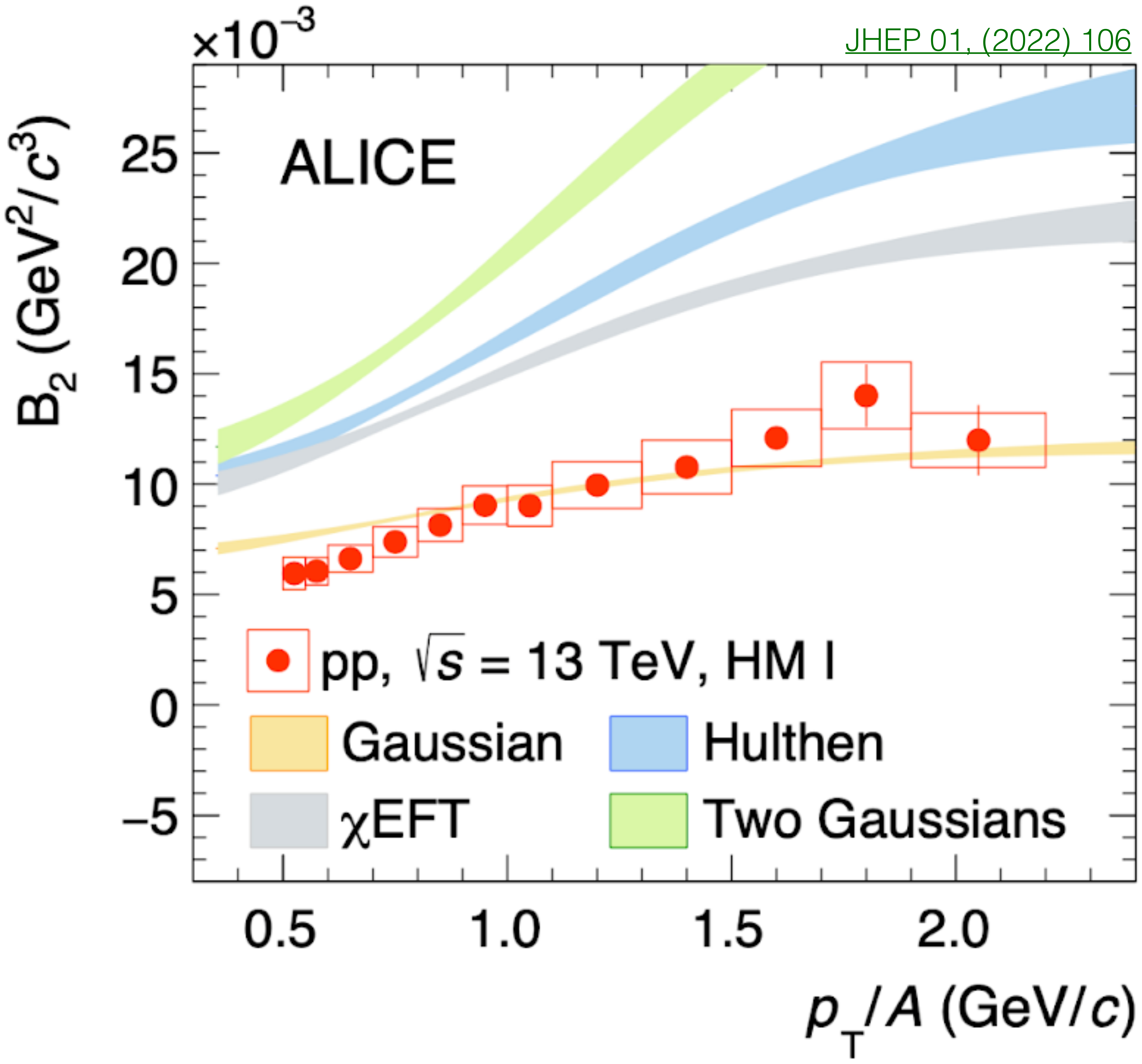
Wigner density

"Source Radius + Nucleus wave function -> B_2"

- Different wave functions give quite different expected coalescence parameter
  - It works within factor 2 for deuteron

Coalescence it is still an incomplete model

- Known approximations and limitations that can be worked out
- We have standard candles to gauge the models



The case of hypertriton production in small systems

Models:
V. Vovchenko, et al., Phys. Lett., B785, 171-174, (2018)
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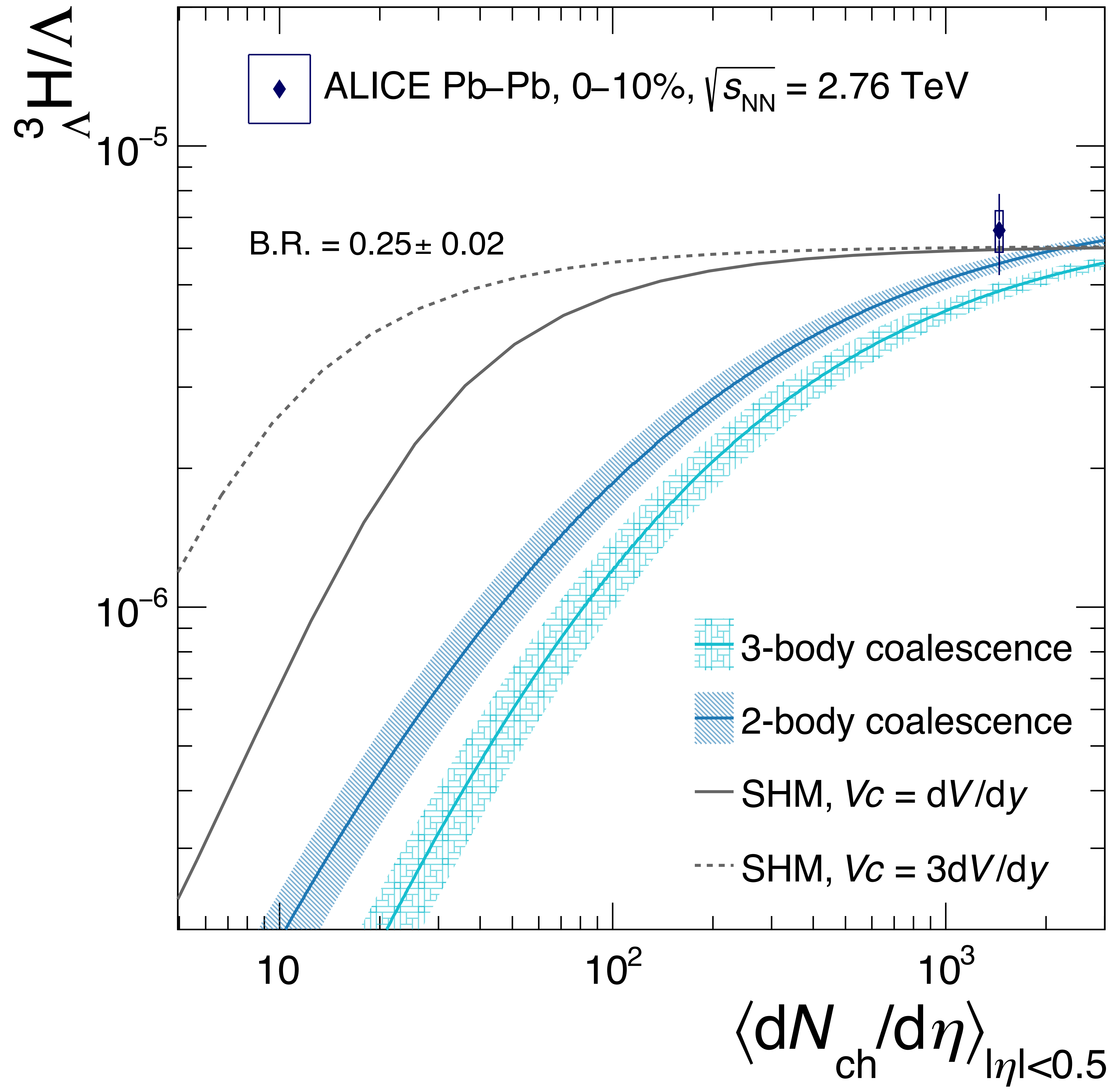

$^{3}_{\Lambda}$H / Λ in small systems: large separation between production models

- SHM: insensitive to size of the hypertriton
- Coalescence: yield suppressed with assumed hypertriton radius ~10 fm

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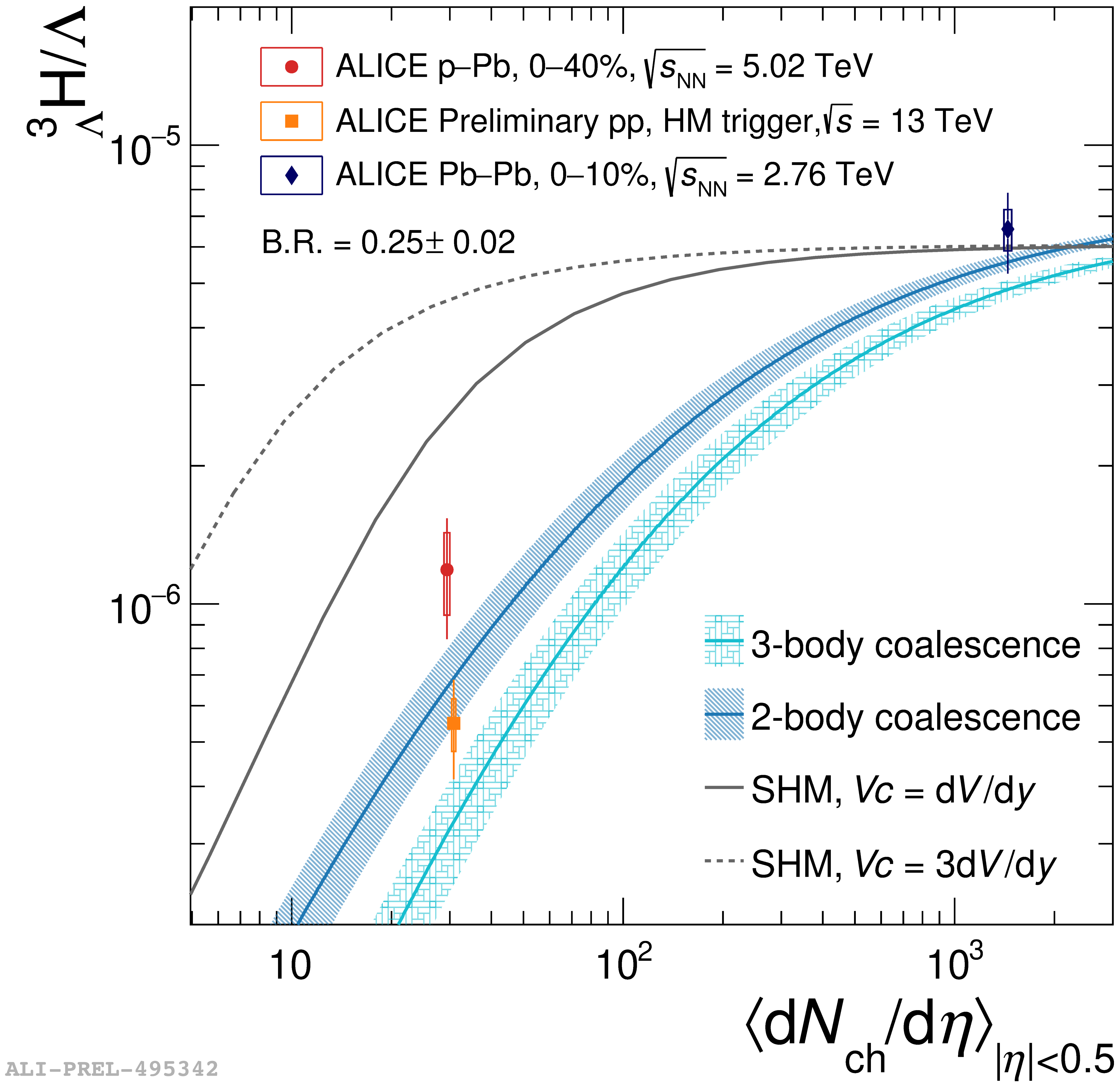
arXiv:2107.10627



$^{3}_{\Lambda}H$ / Λ in small systems: large separation between production models

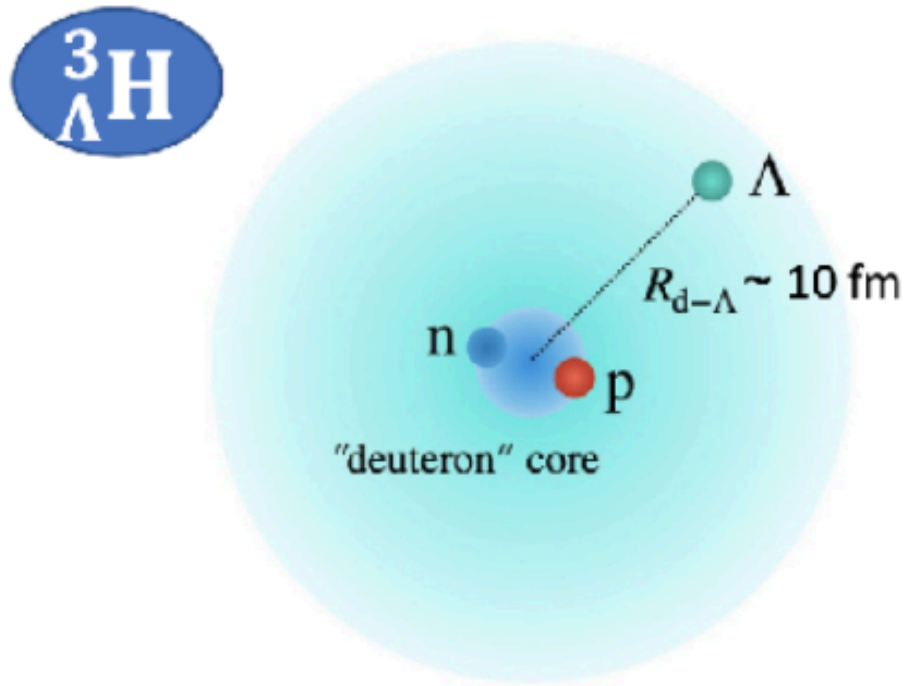
- SHM: insensitive to size of the hypertriton
- Coalescence: yield suppressed with assumed hypertriton radius ~10 fm
- Measurements in good agreement with 2-body coalescence
- Tension with SHM at low charged-particle multiplicity density
  - configuration with V_C = 3dV/dy is excluded at level of more than 6σ

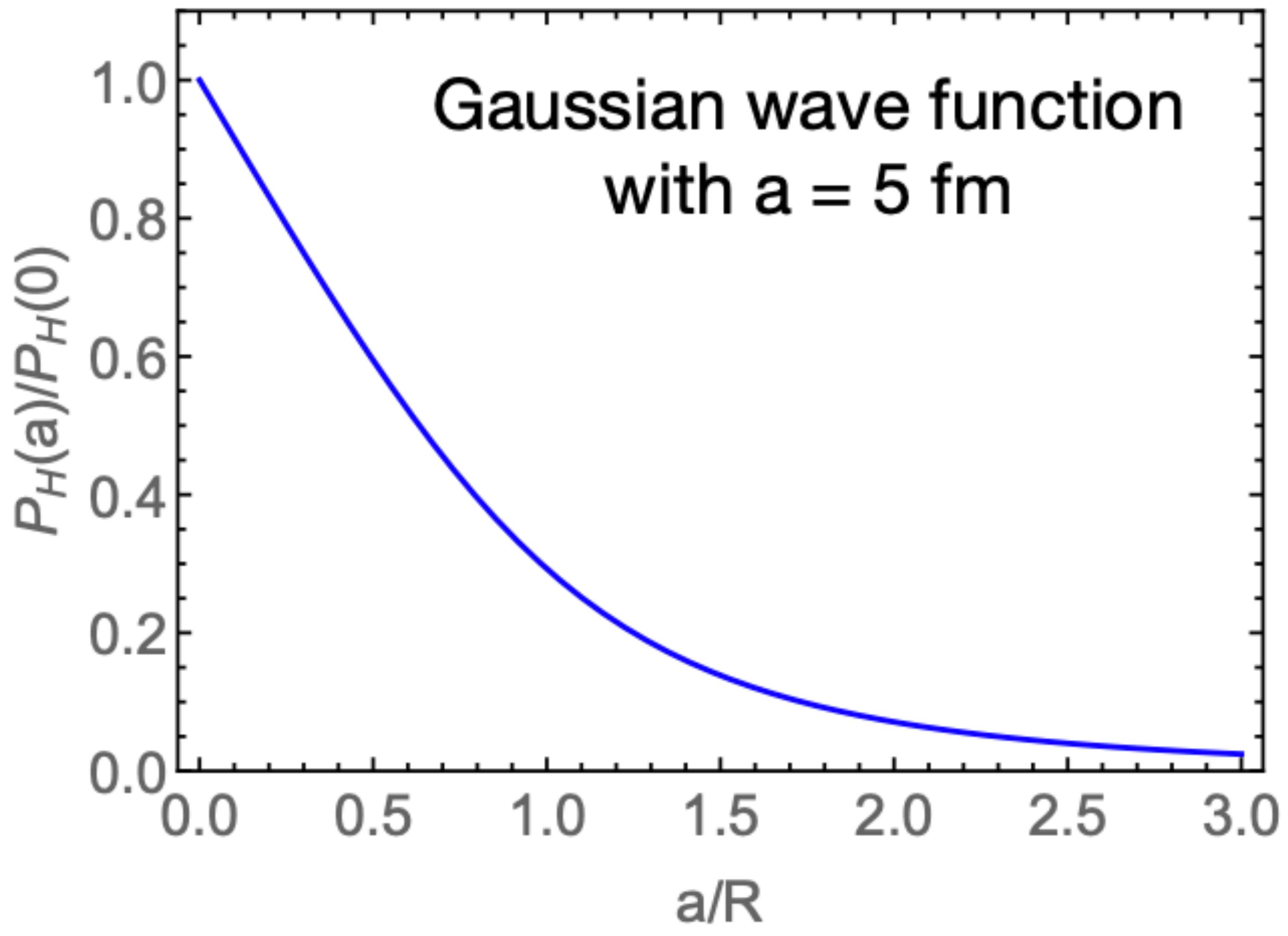
Production of hypertriton in pp and p-Pb collisions as a doorway to the study of its structure

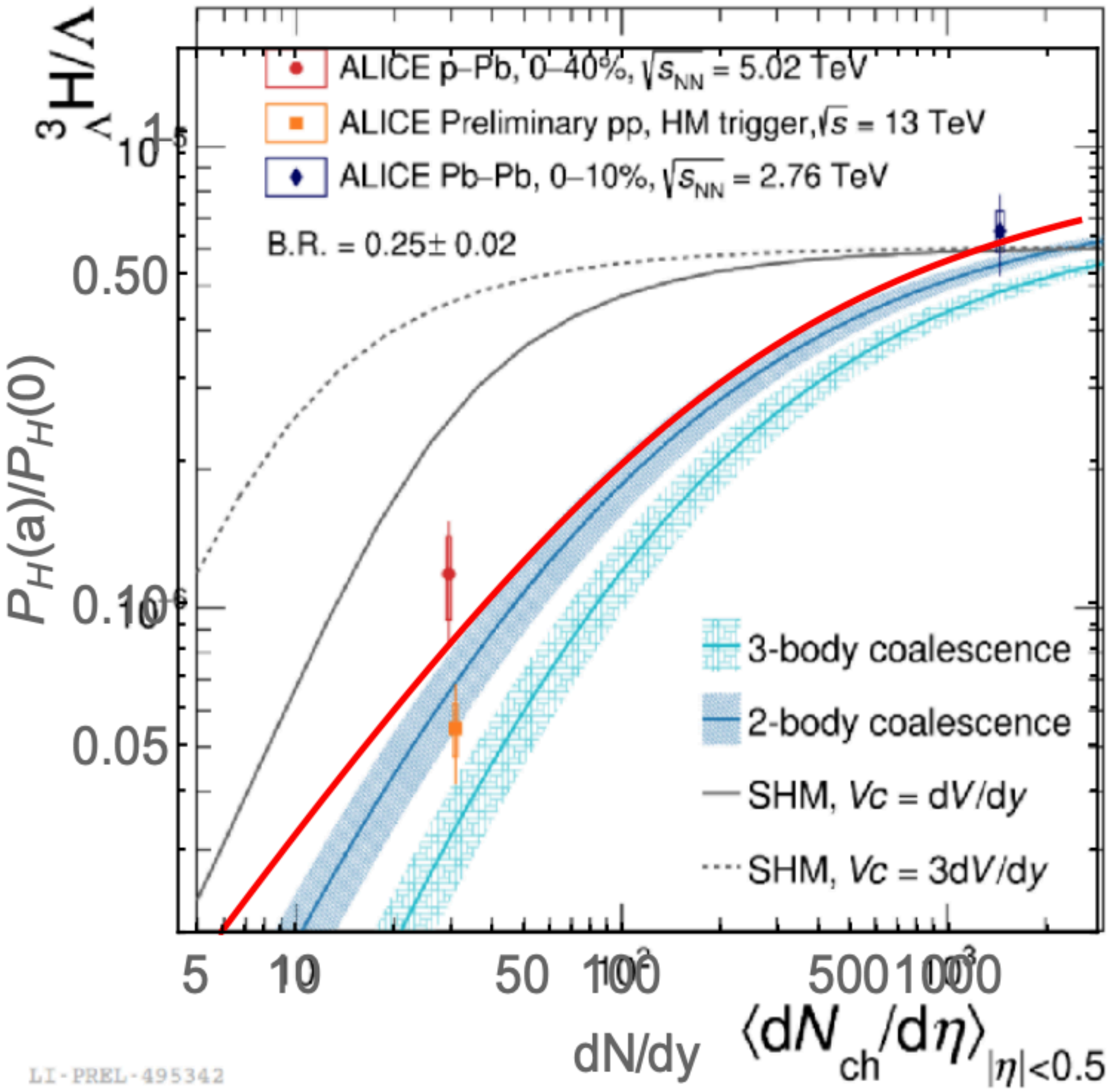
The case of hypertriton production in small systems

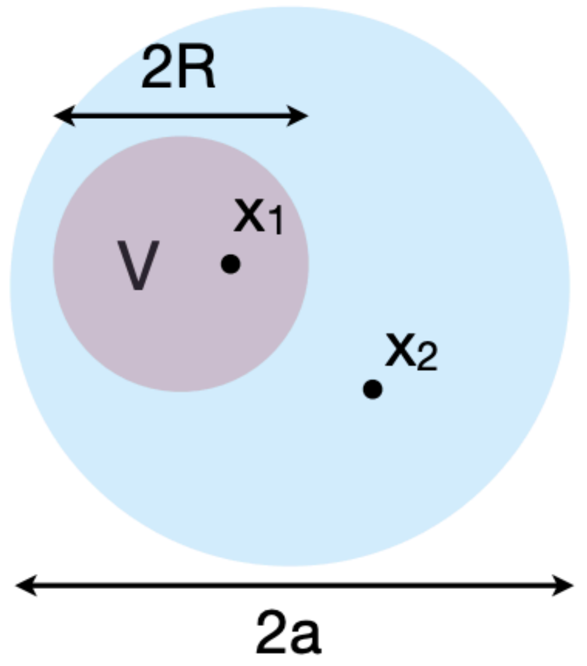
Particle size matters

Berndt Mueller SQM summary talk









When $a \gg R$, requires $|x_1 - x_2| < R$:

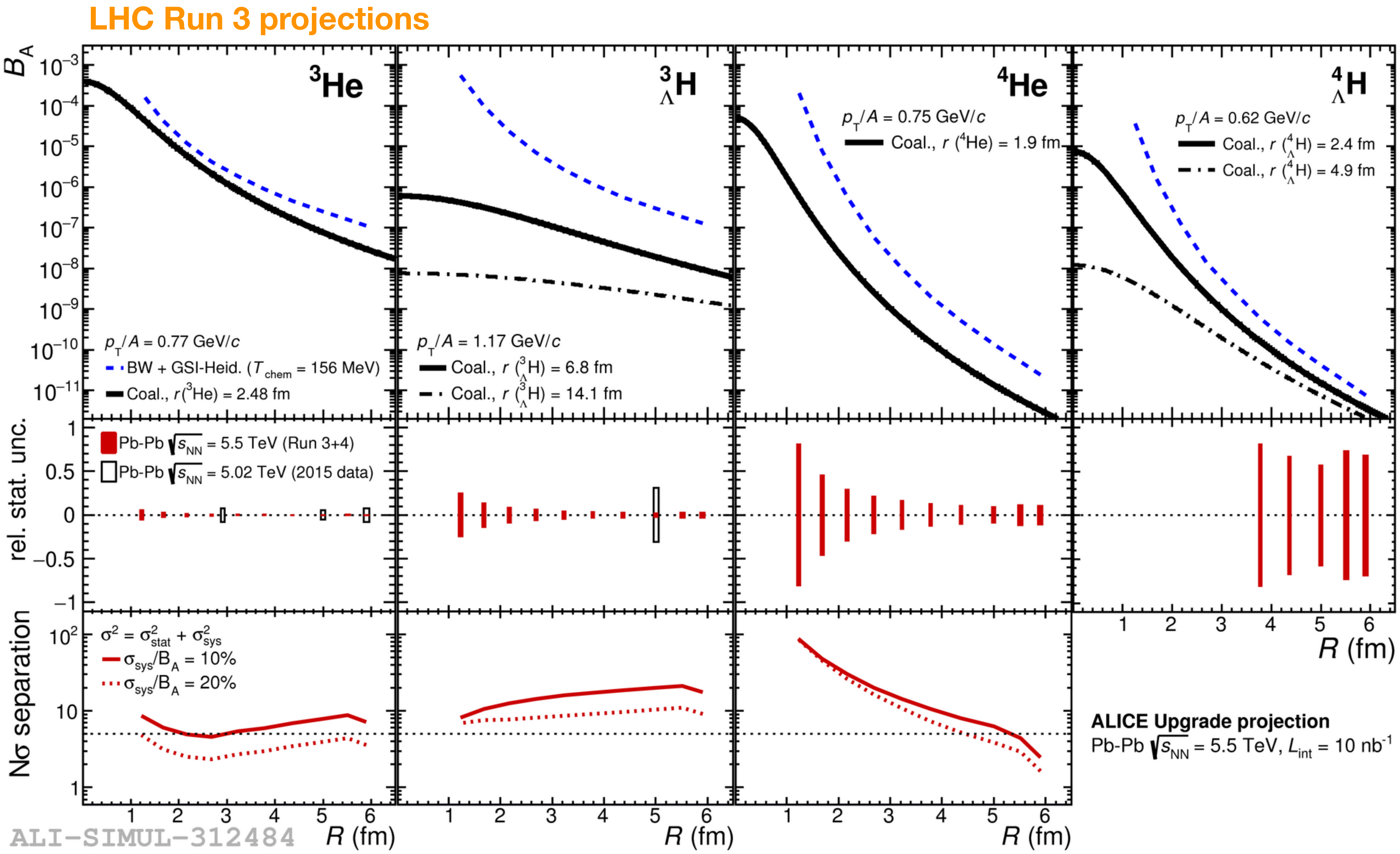
$$P_H \approx \int d^3p\, e^{-E_p/T} \int d^3x_1\, d^3x_2\, |\psi_p(0)|^2 \theta_V(x_1)\theta_V(x_2)$$

$$P_H \approx V_H^2 \int d^3p\, e^{-E_p/T} |\psi_p(0)|^2 \propto \frac{V_H^2}{a^3} \int d^3p\, e^{-E_p/T}$$

Particle size aware SHM is coming up: a further confirmation that we can study hypernuclei wave functions

Summary and outlook

We are in the high precision era for hypernuclei in HI



Expect A=4 (hyper)nuclei measurements with precision similar to A=3 during Run 2

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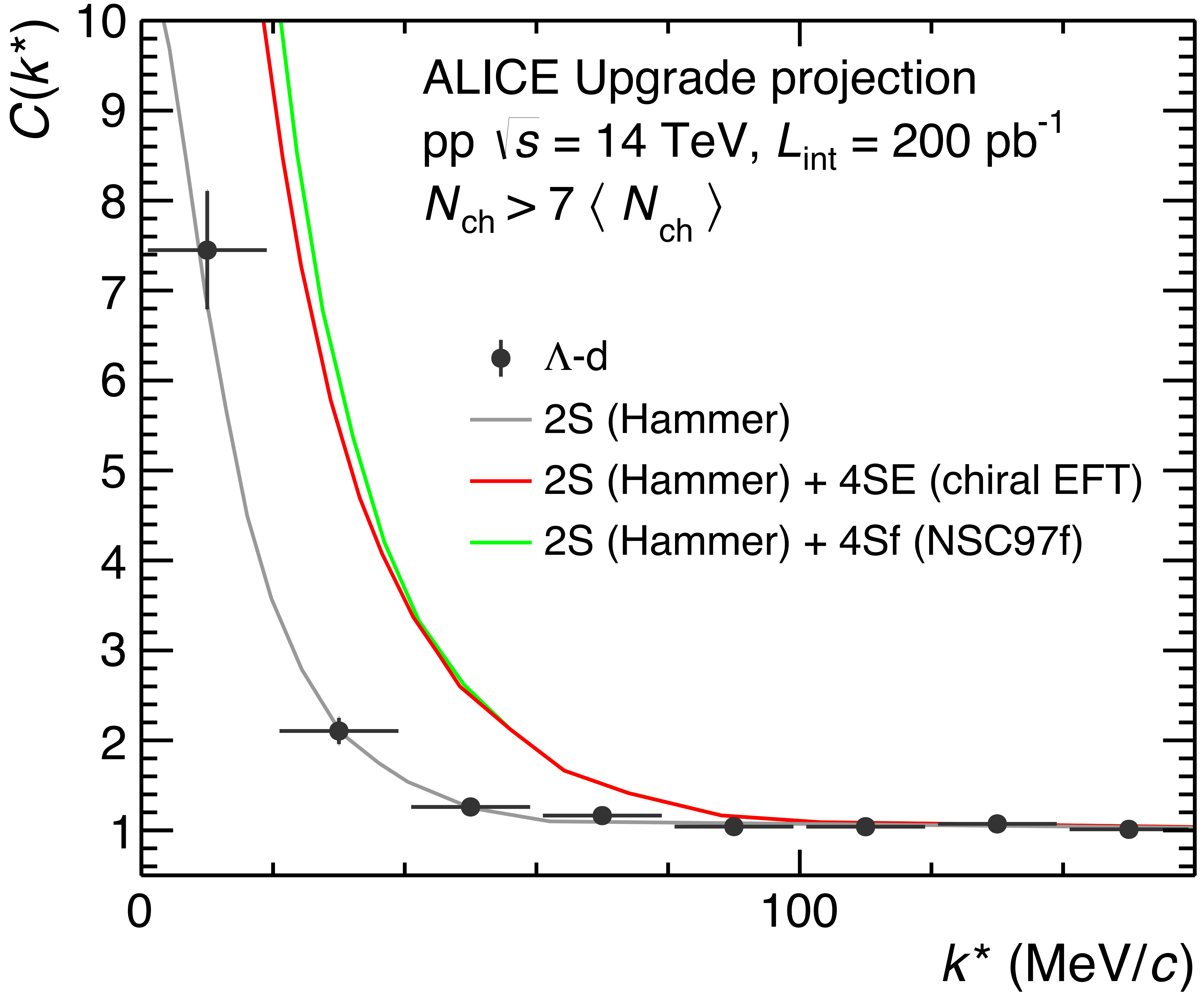
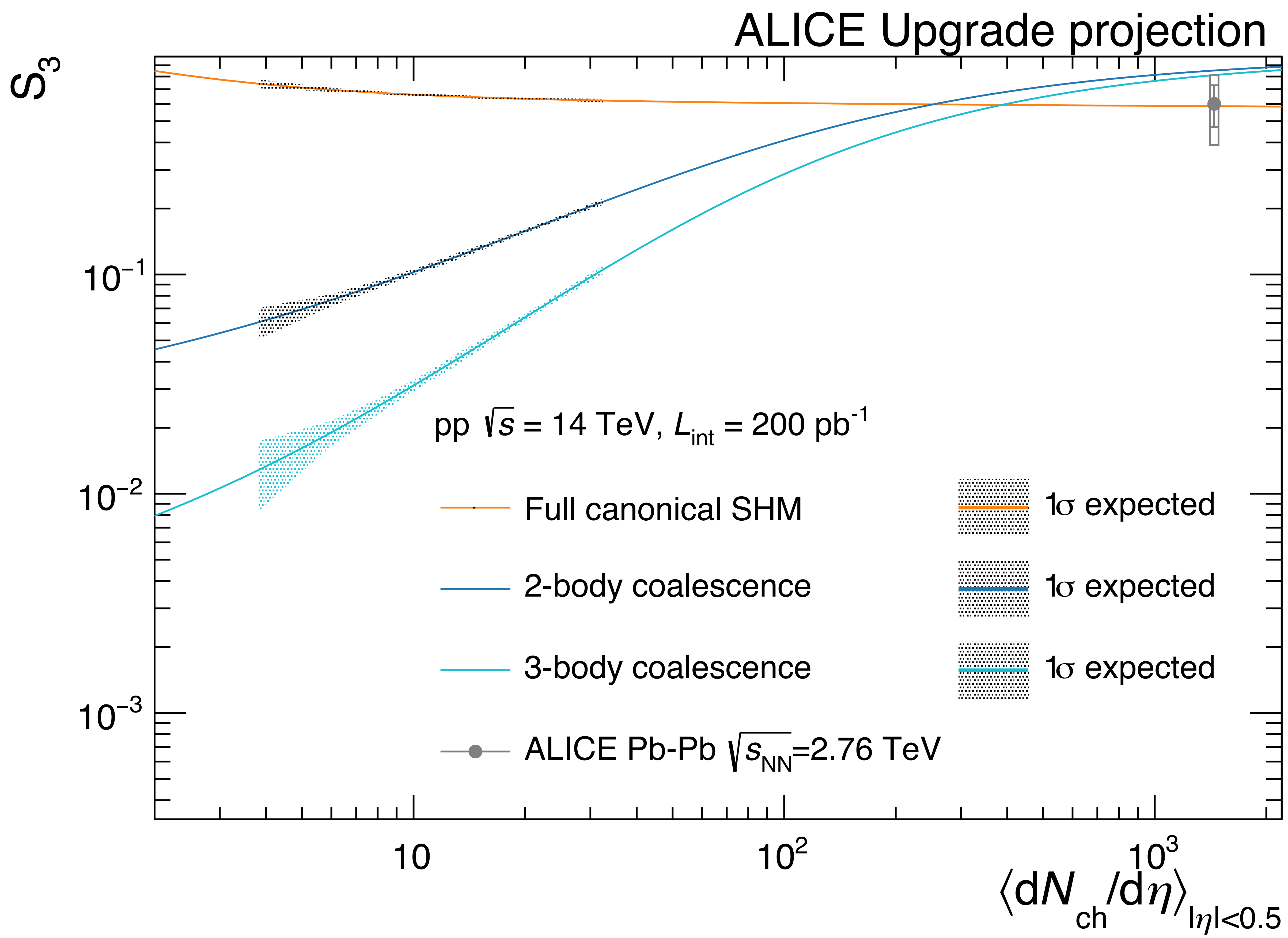




- In Run 3 ALICE will have x100 more hyper tritons in pp collisions
  - Few percent precision on the production yields
- Precise determination of ΛNN 3-body forces through Λd correlations
  - Possible background in the dpπ decay of hypertriton?
  - See B. Sigh talk for more on this

Summary

- ALICE proved to be an precision experiment for the determination of $^{3}_{\Lambda}H$ properties
  - Starting from the end of this year this will expand to A=4 hypernuclei

- New ways into hypernuclei structure: study of the production in small collision systems
  - More data coming from the experiment
  - More theoretical development required and ongoing

Thanks to B. Doenigus, L. Fabbietti, A. Kalweit for the input and discussion

Backup

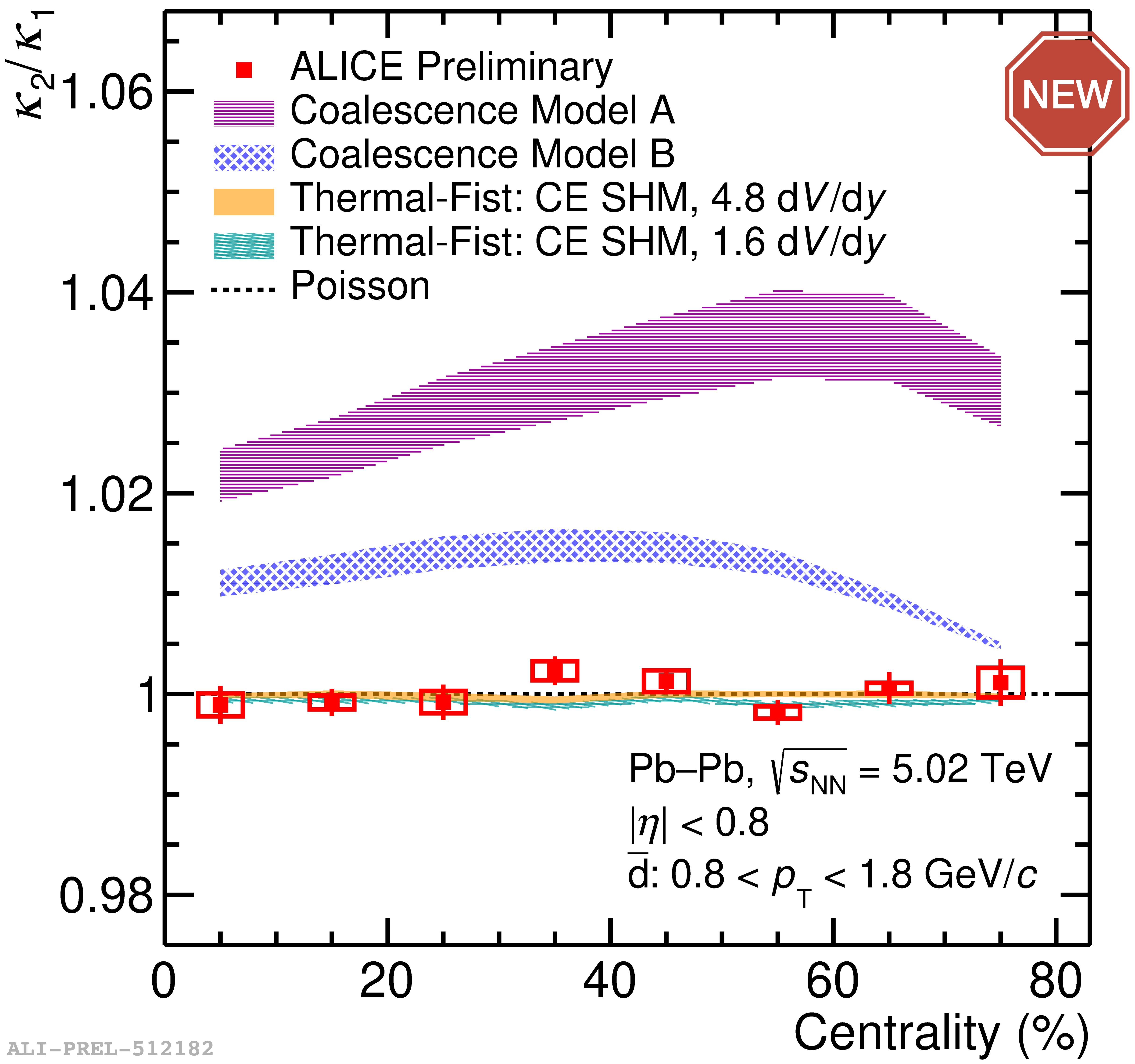
Beyond the average: antinuclei number fluctuations

New observables based on event-by-event fluctuations to distinguish Statistical hadronisation and hadron coalescence

$$\frac{\kappa_2}{\kappa_1} = \frac{\langle (n - \langle n \rangle)^2 \rangle}{\langle n \rangle}$$

- Cumulant ratio currently favours the SHM
  - Coalescence depends on nucleon phase space conditions (correlations p-n)

arXiv:2204.10166



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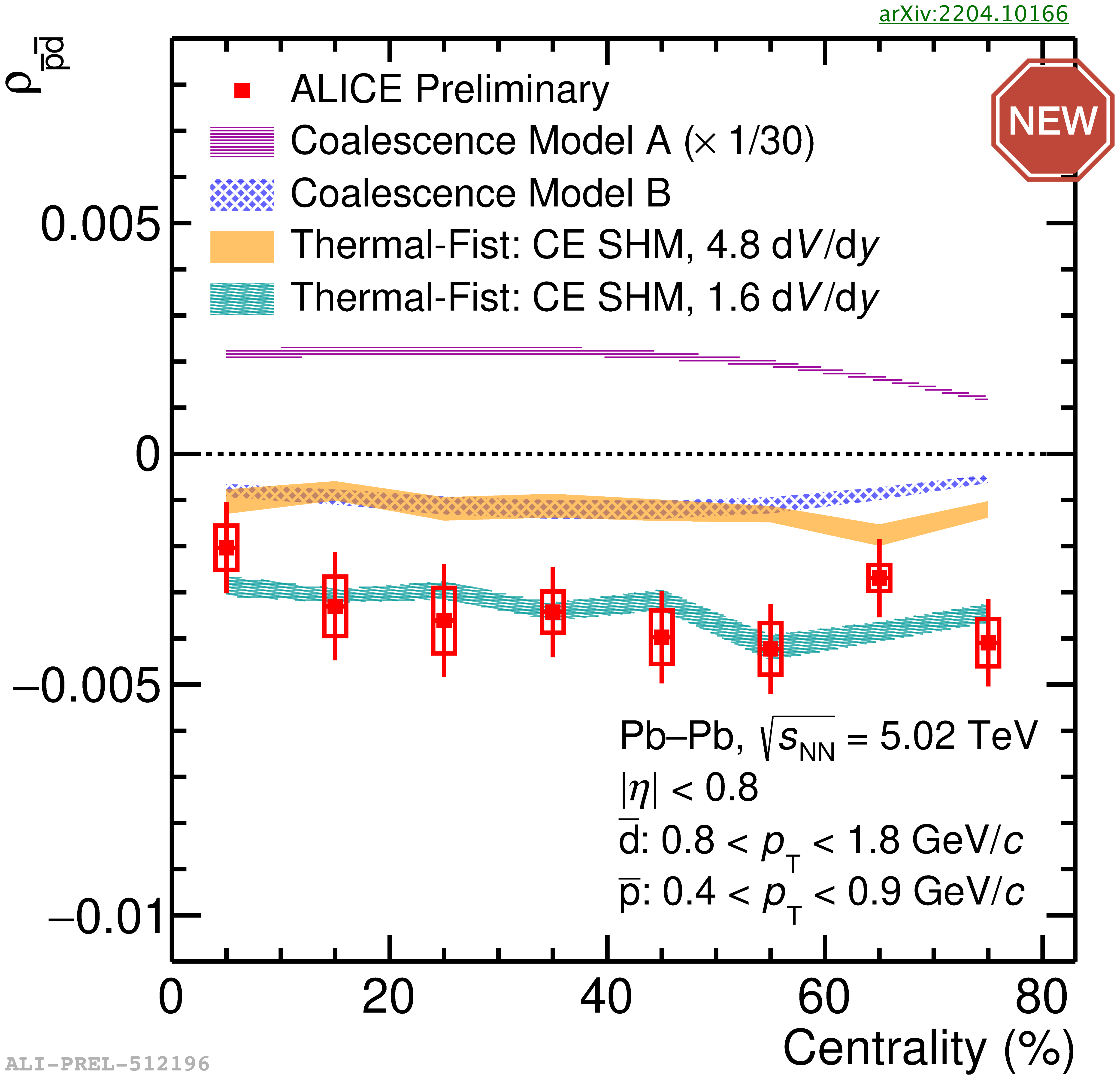
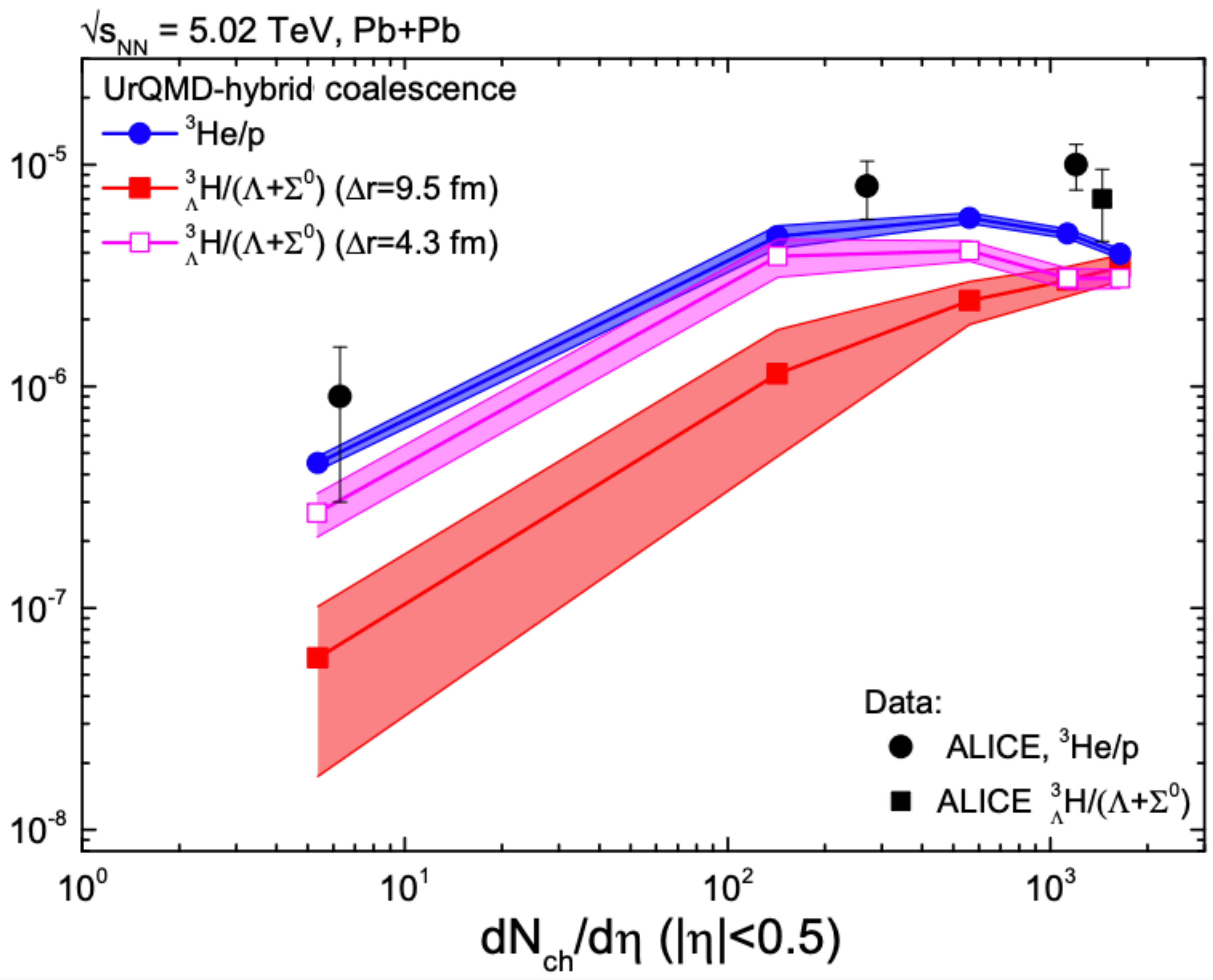
$$\rho_{\bar{p}\bar{d}} = \frac{\langle (n_{\bar{d}} - \langle n_{\bar{d}} \rangle)(n_{\bar{p}} - \langle n_{\bar{p}} \rangle) \rangle}{\sqrt{\kappa_{2\bar{d}} \kappa_{2\bar{p}}}}$$

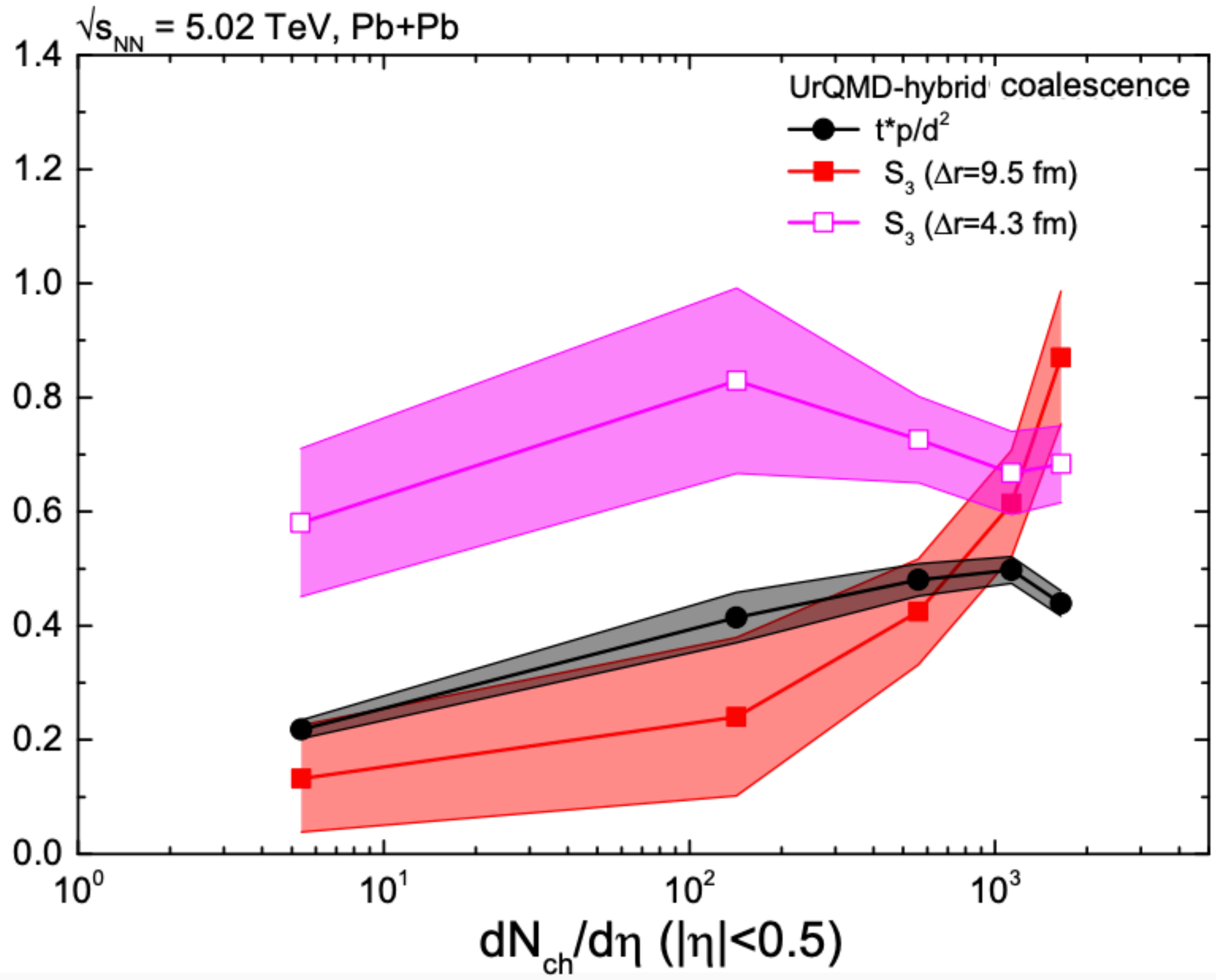
- Pearson correlation constrains the correlation volume for baryon number
  - Agrees with results from (anti)nuclei yields
  - Different wrt results from (anti)proton yields and fluctuations



UrQMD + Box coalescence

See T. Reichert talk at SQM





Similar conclusion as for the coalescence model: strong sensitivity to the object size

How precise are we in measuring lifetimes?