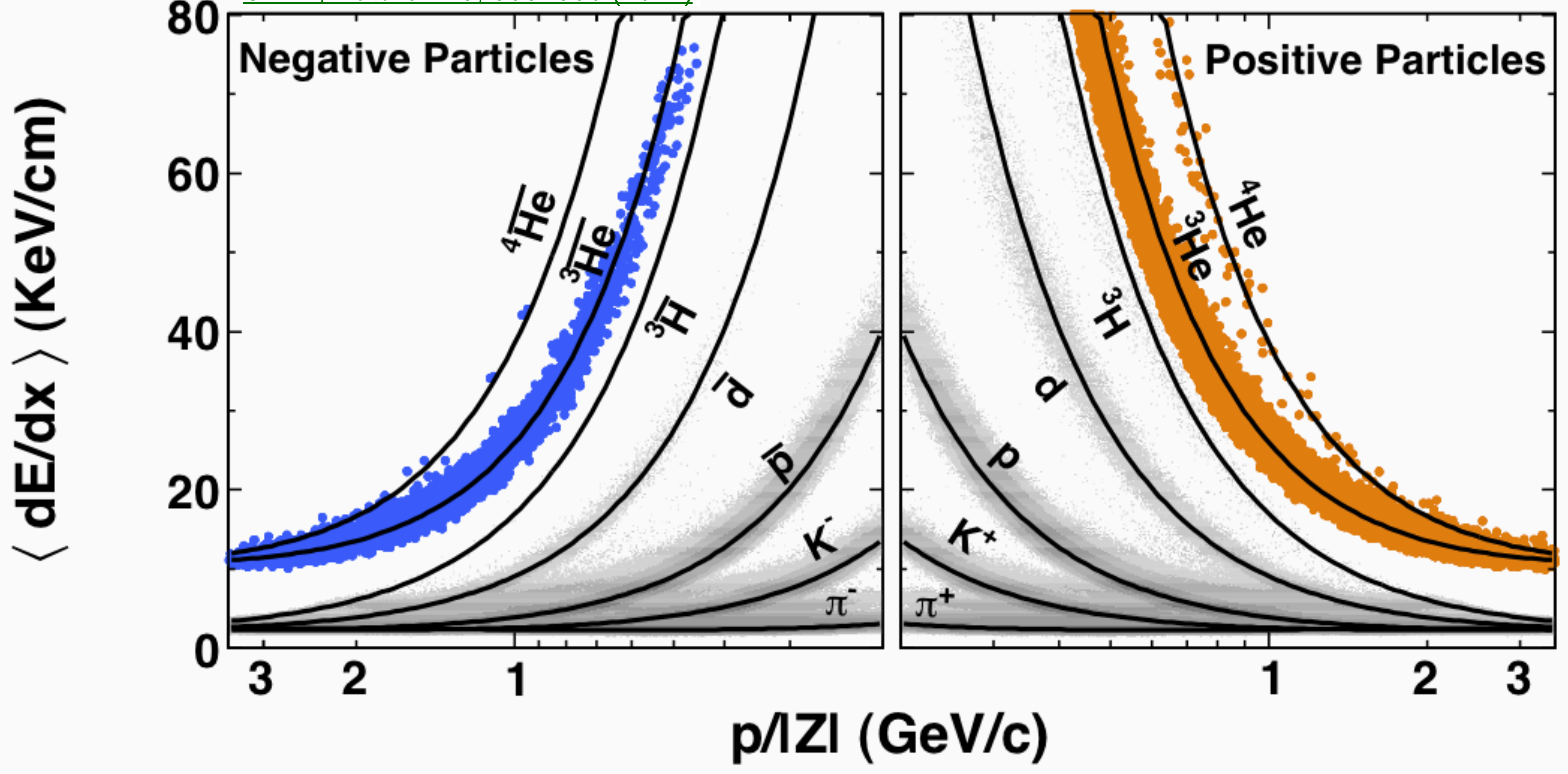
Bound states in hadronic collisions

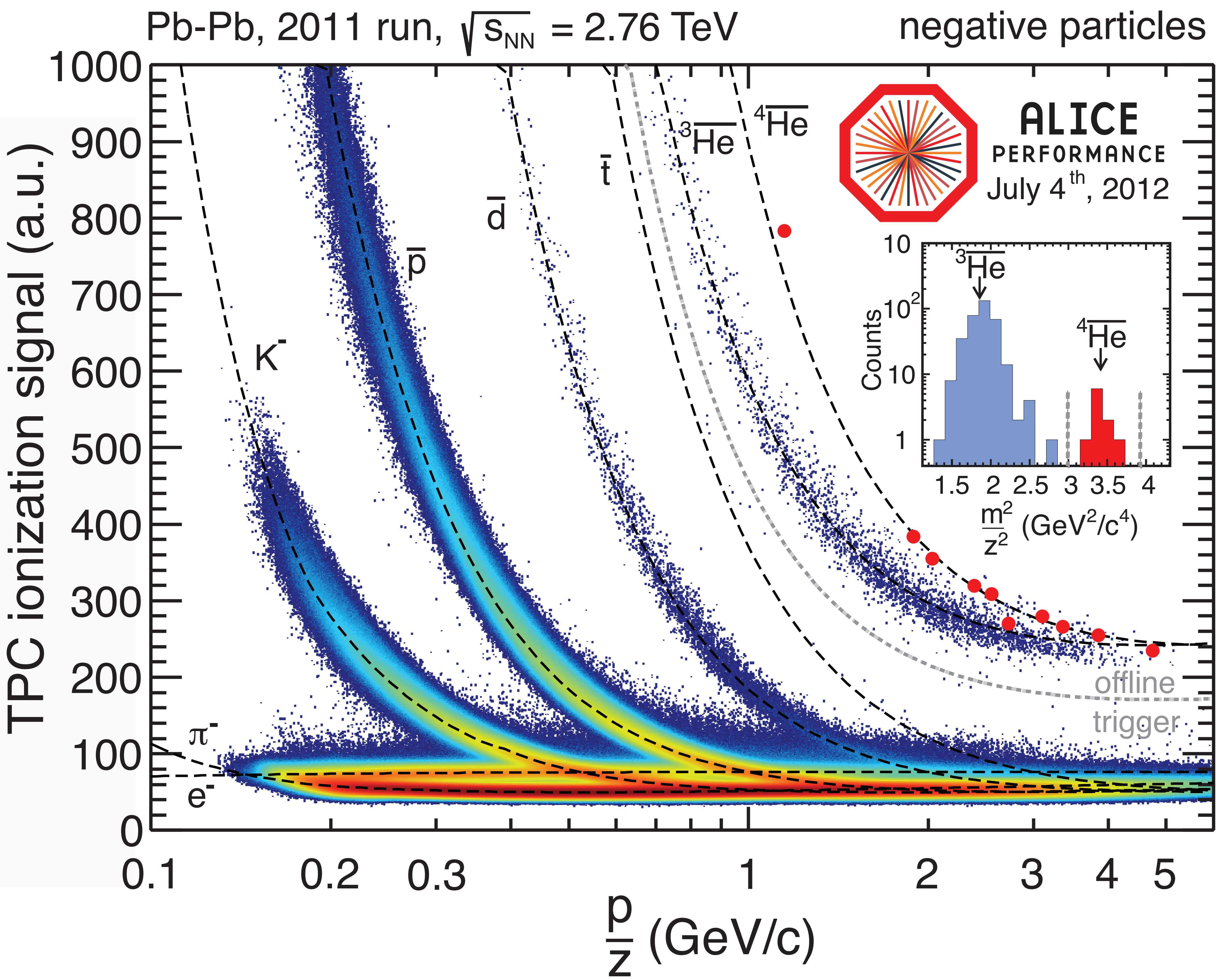
Maximiliano Puccio (CERN)

Bormio 60th International Winter Meeting on Nuclear Physics, 23rd January 2024

Which bound states do we measure?

STAR, Nature 473, 353–356 (2011)





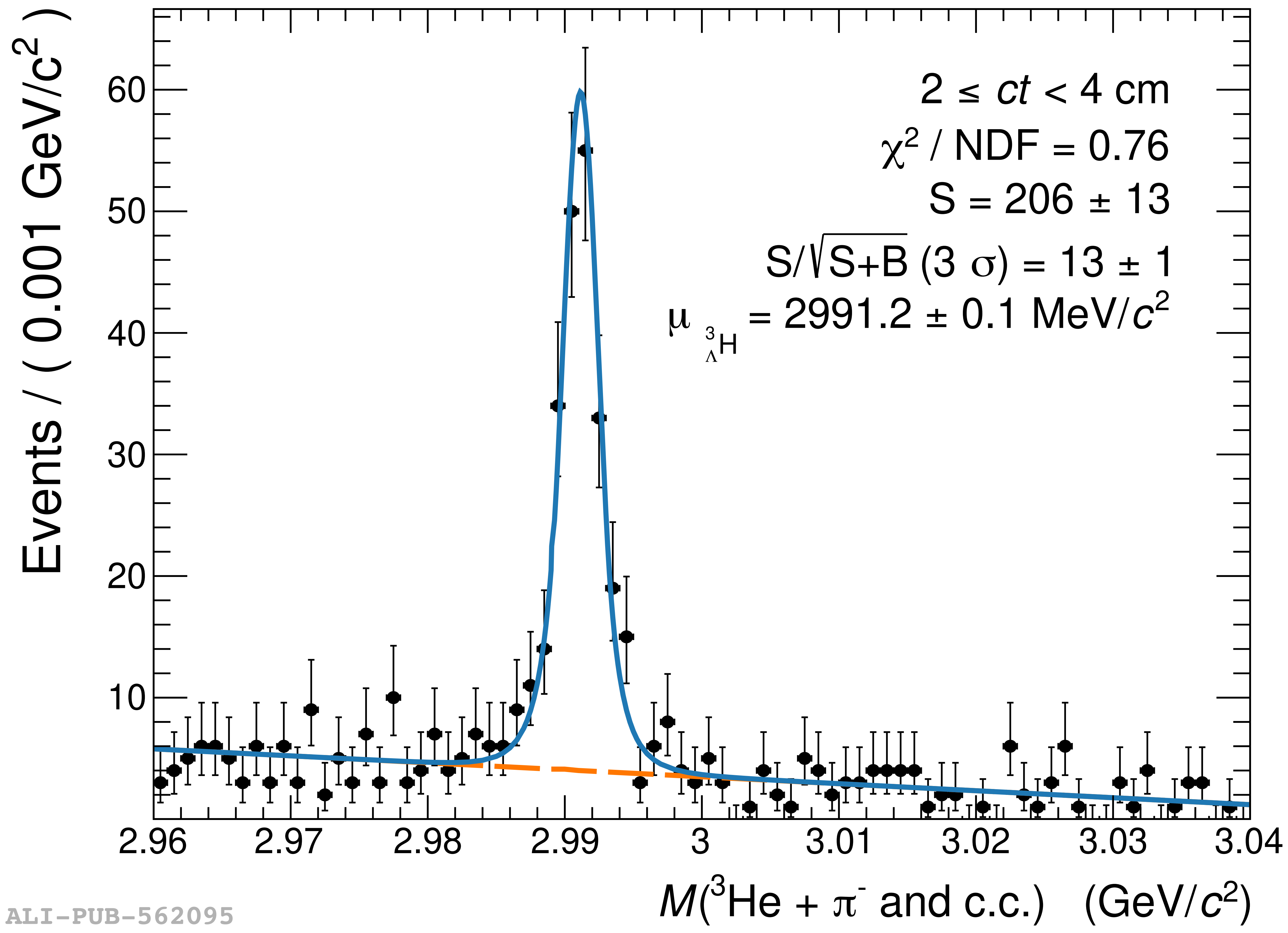
ALI-PERF-36713

Up to Z=4 nuclei and antinuclei are being measured both at RHIC and at the LHC

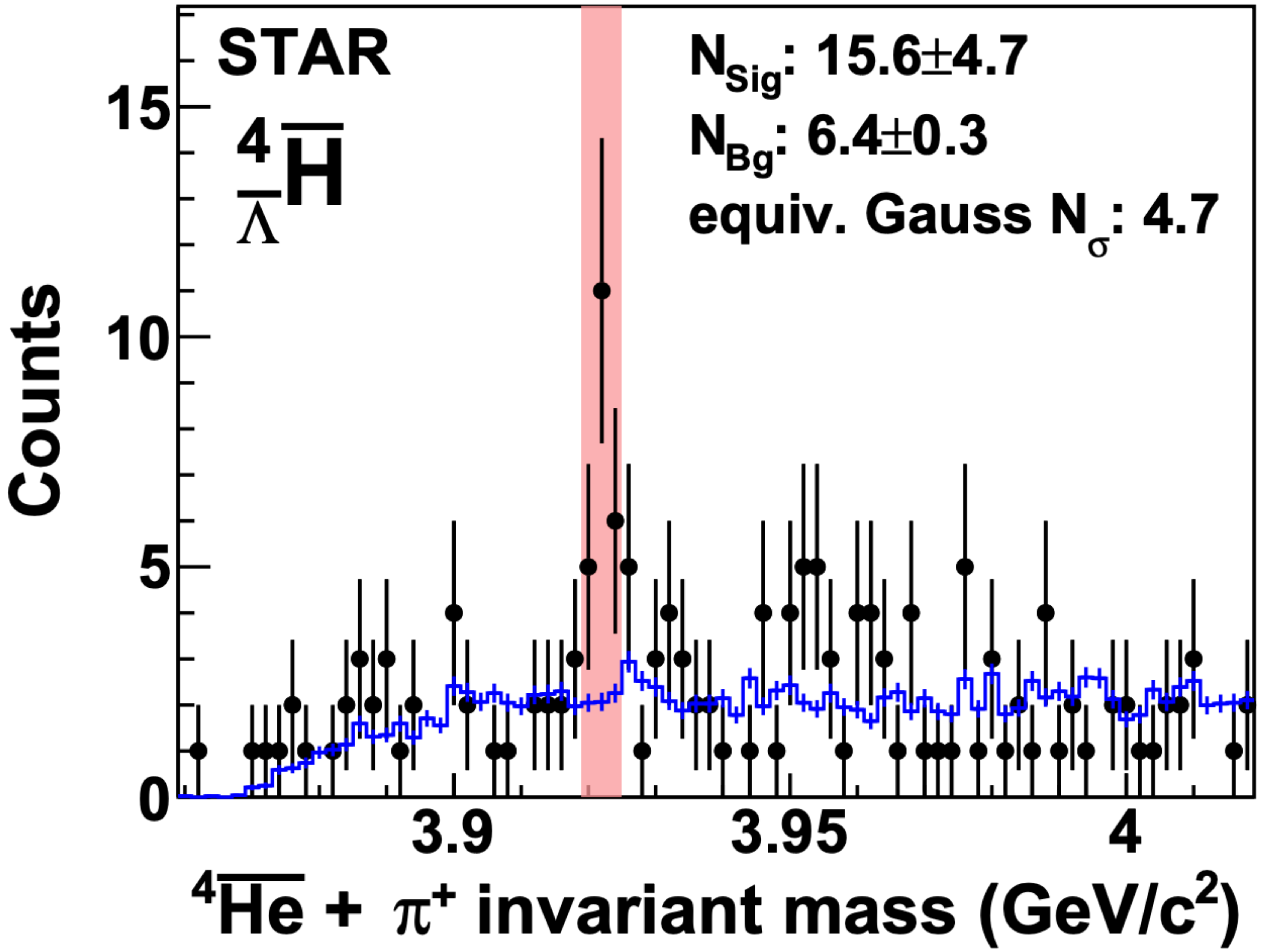
- Antinuclei are particularly interesting: they cannot be formed from fragments of the beam
  - A new kind of nucleosynthesis that was not possible to study before

Beyond the “standard” (anti)nuclei

ALICE, Phys. Rev. Lett. 131 (2023) 102302



STAR, https://arxiv.org/abs/2310.12674

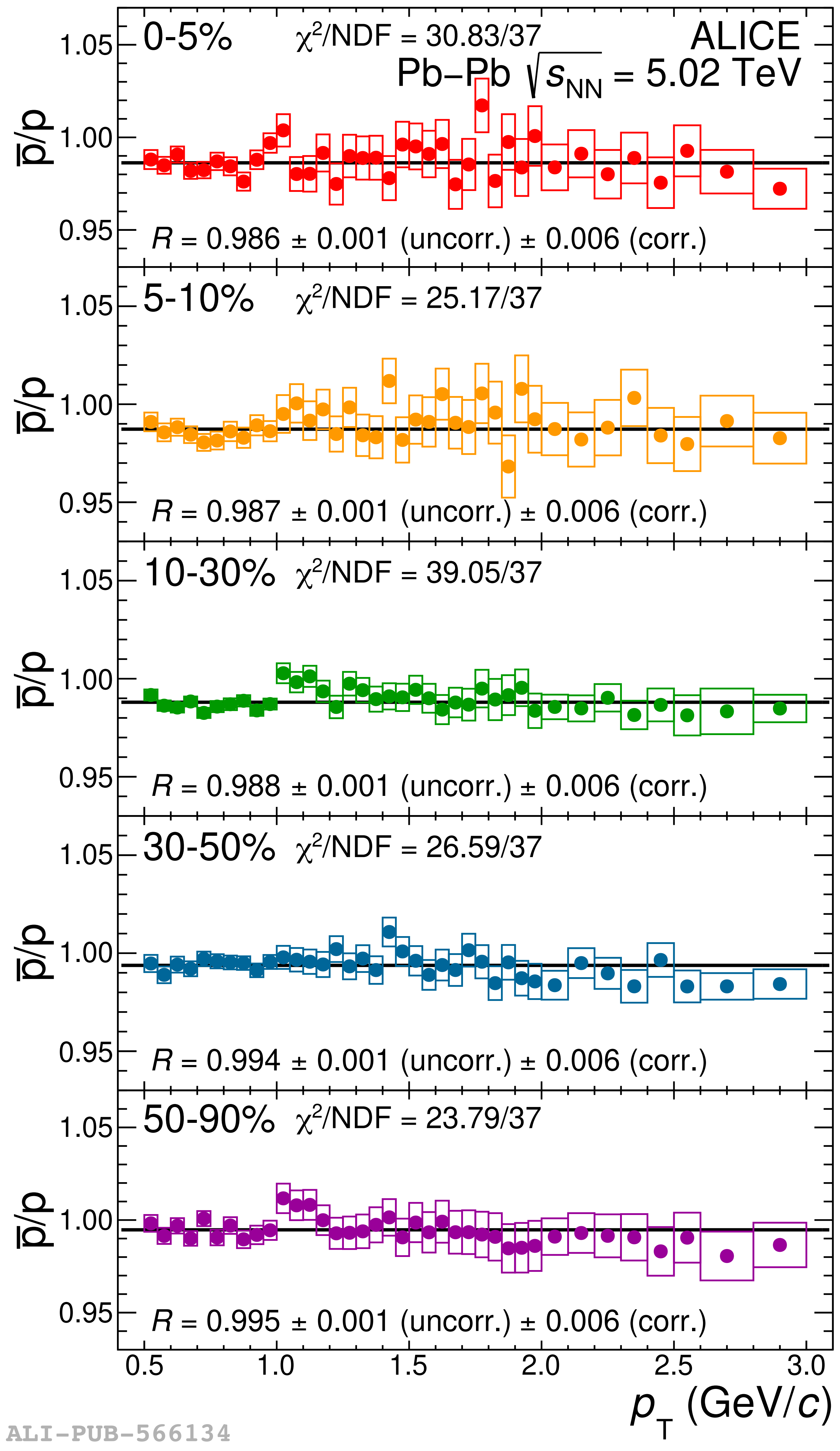


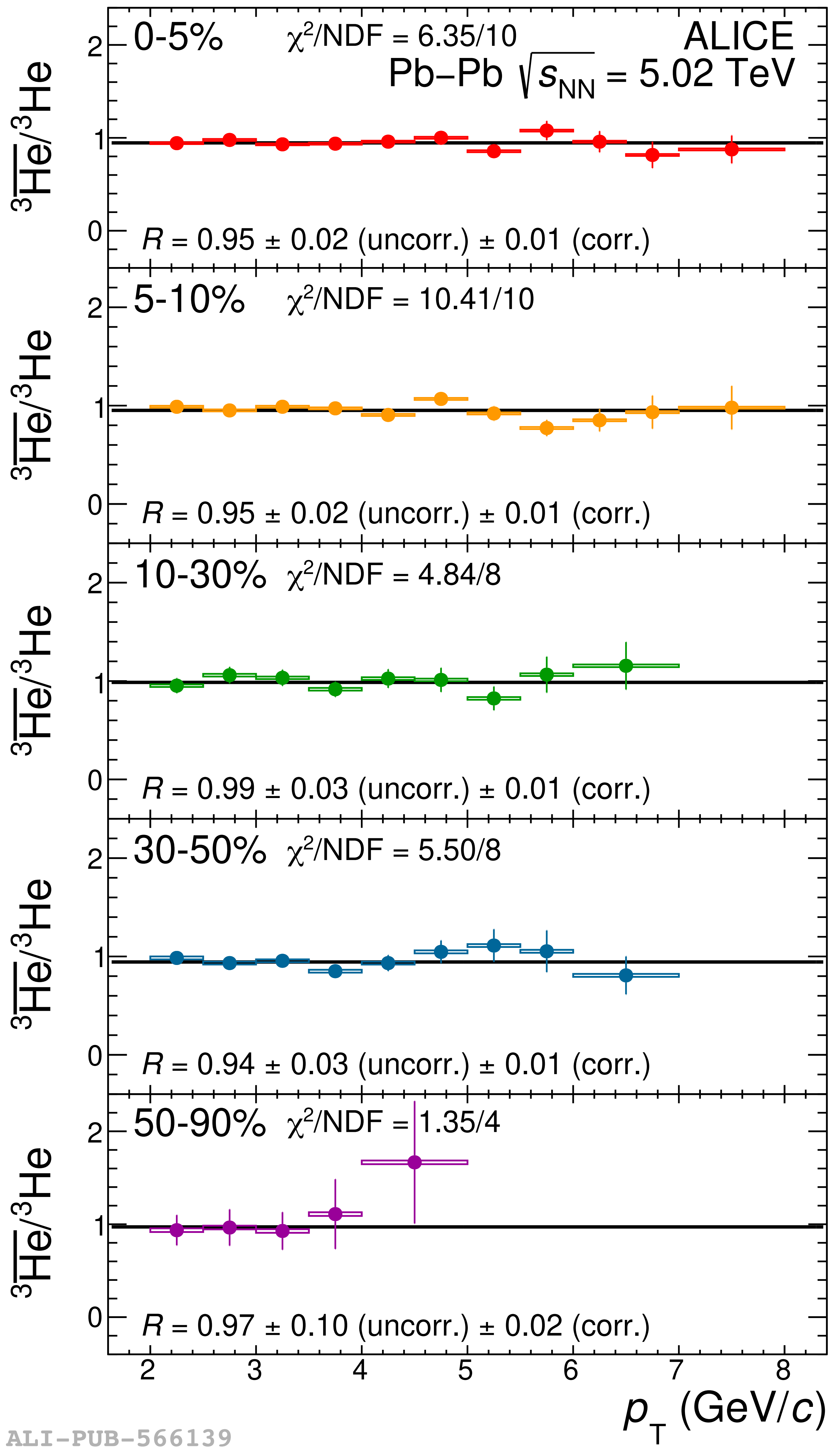
Up to A=4 antihypernuclei have been discovered in heavy ion collisions

- A new way to study the properties of hypernuclei (see also the talk by Prof. Herrmann)

High energy heavy-ion: antimatter factories

ALICE, arxiv:2311.13332





For a nucleus X with mass number A it has been found that:

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

- The antiproton/proton ratio ~1 at LHC
- The antiproton/proton ratio ~0.8 at RHIC top energy
- Tested up to A=4
- Specific studies were done to reduce the systematic uncertainties

In central Pb-Pb collisions at the LHC

~40 protons ~3e-4 ^{3}He

~0.1 deuterons ~1e-4 hypertritons

How do we can produce (anti)(hyper)nuclei in pp/AA?

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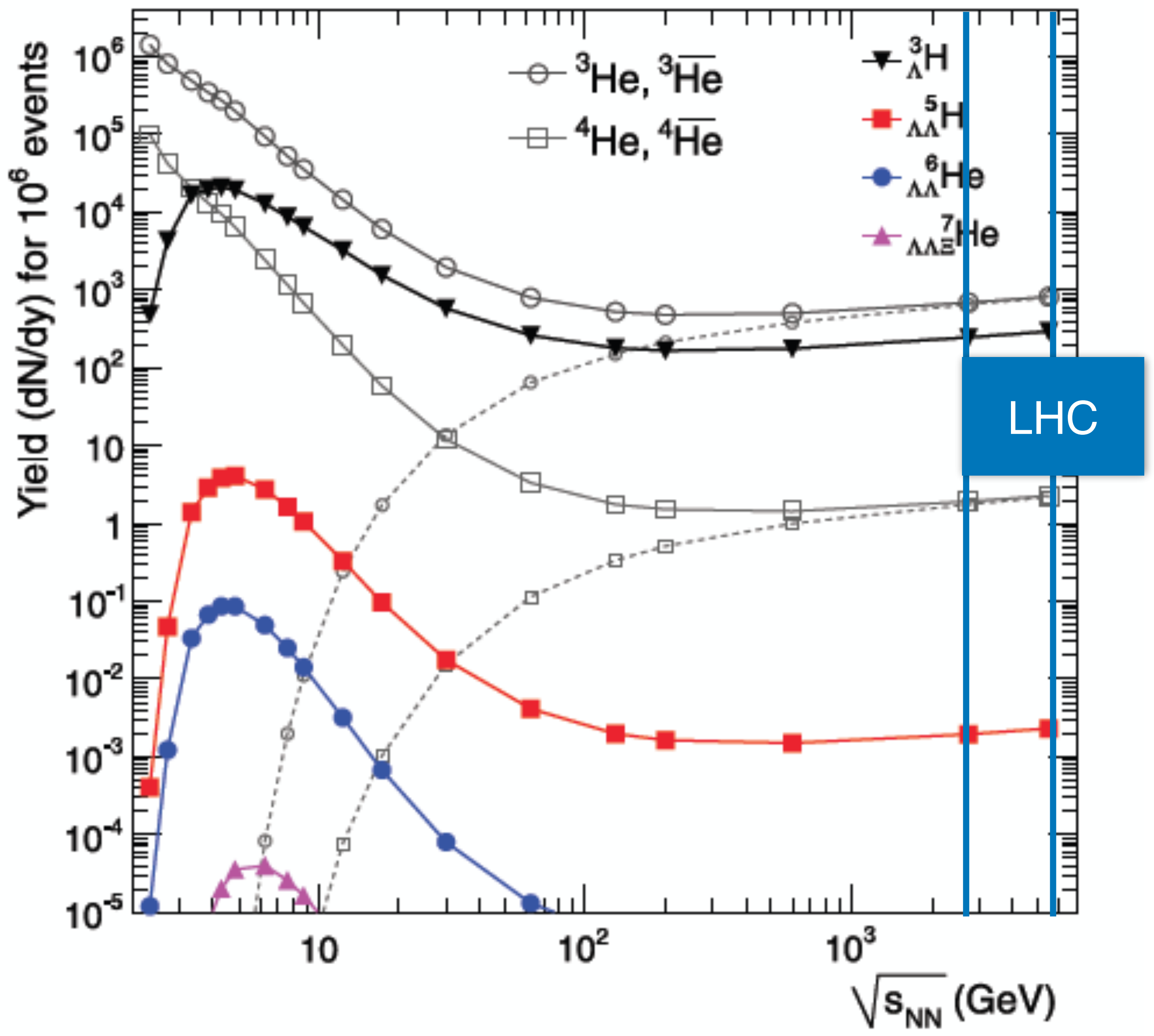
THERMAL MODELS

- 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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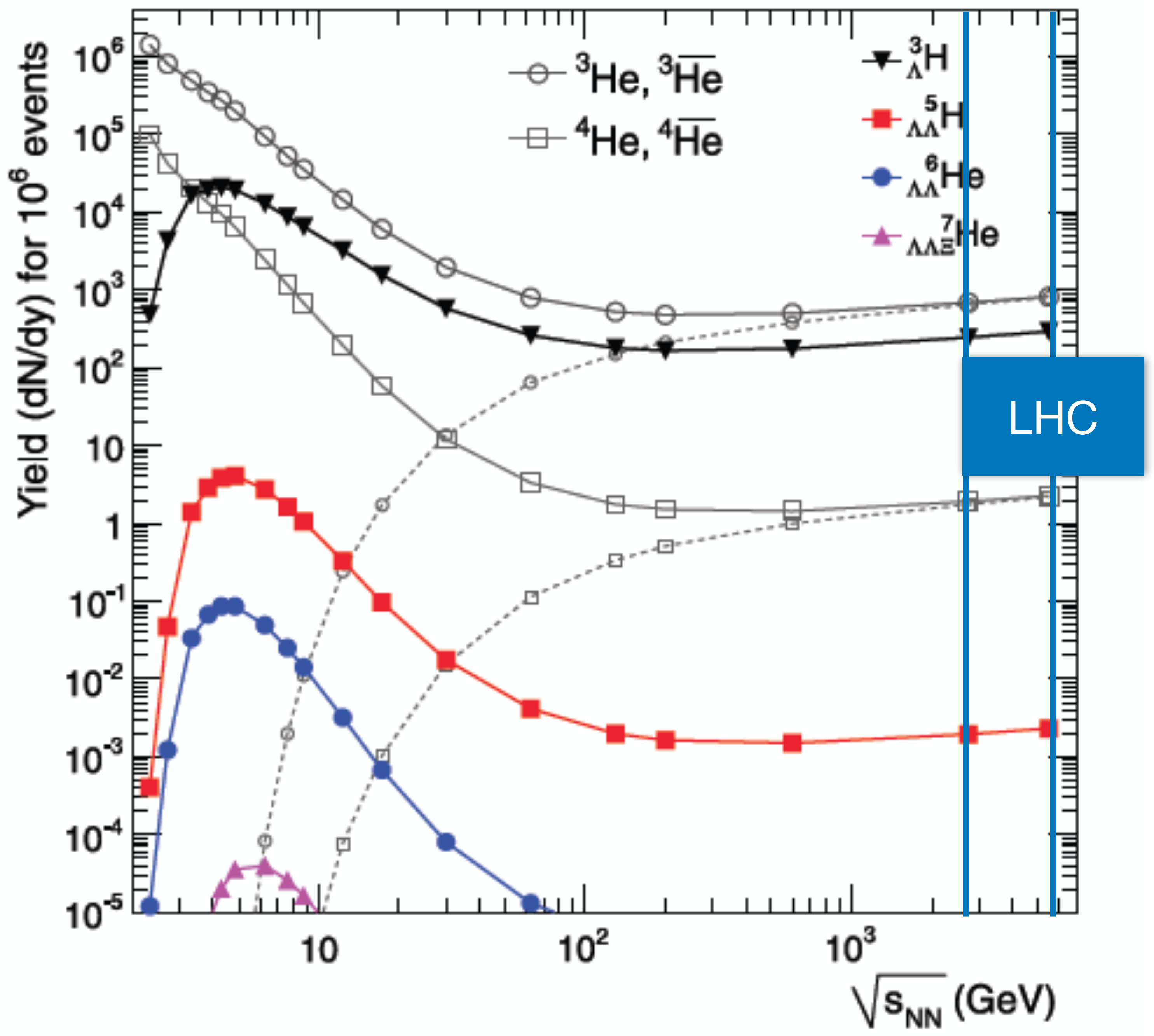

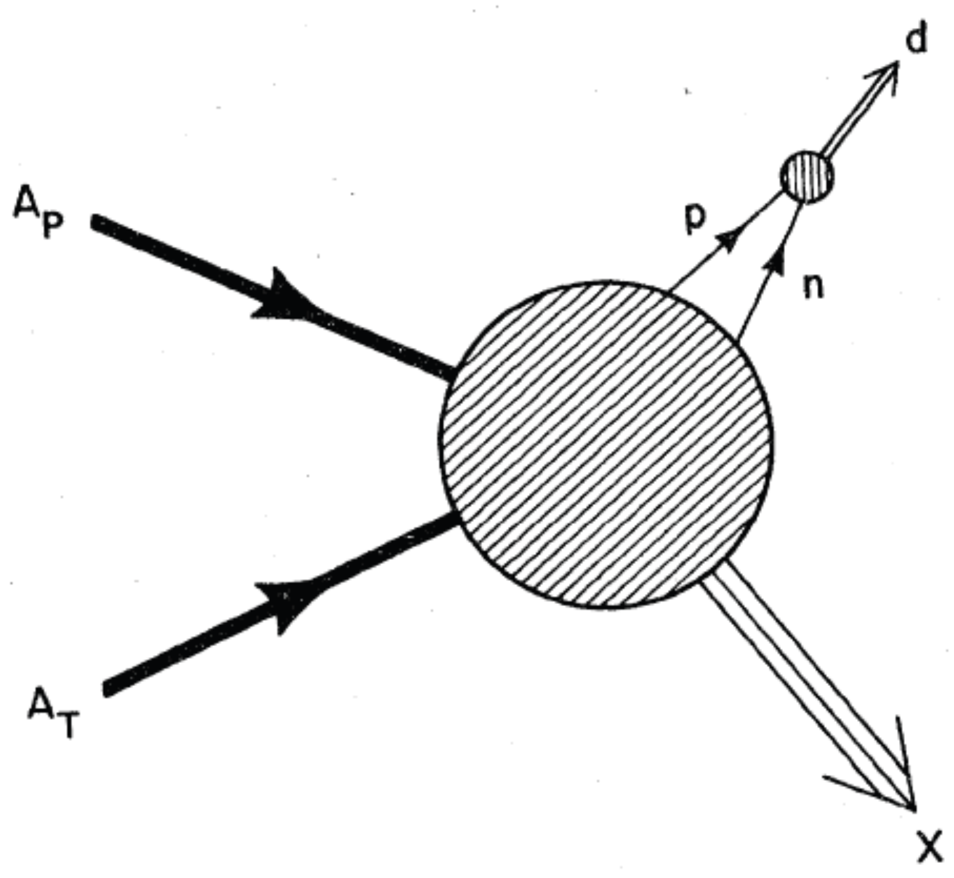

J. I. Kapusta, Phys.Rev. C21, 1301 (1980)

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
  - the larger the wave function the more we are sensitive to the system size

Thermal model vs coalescence at the LHC

We study the nucleus yield normalised by the proton production as a function of multiplicity

- Smooth evolution with multiplicity: same production mechanism in all collision systems?
  - Available SHM calculations with canonical ensemble do not describe A=3 nuclei
  - Coalescence model provide a good description of the measured ratios

The coalescence parameter

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

$$E_i \frac{\mathrm{d}^3 N_i}{\mathrm{d}p_i^3} = B_A \left(E_\mathrm{p} \frac{\mathrm{d}^3 N_\mathrm{p}}{\mathrm{d}p_\mathrm{p}^3} \right)^A \xrightarrow{\text{deuterons}} B_2 = \frac{E_\mathrm{d} \frac{\mathrm{d}^3 N_\mathrm{d}}{\mathrm{d}p_\mathrm{p}^3}}{\left(E_\mathrm{p} \frac{\mathrm{d}^3 N_\mathrm{p}}{\mathrm{d}p_\mathrm{p}^3} \right)^2}$$

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

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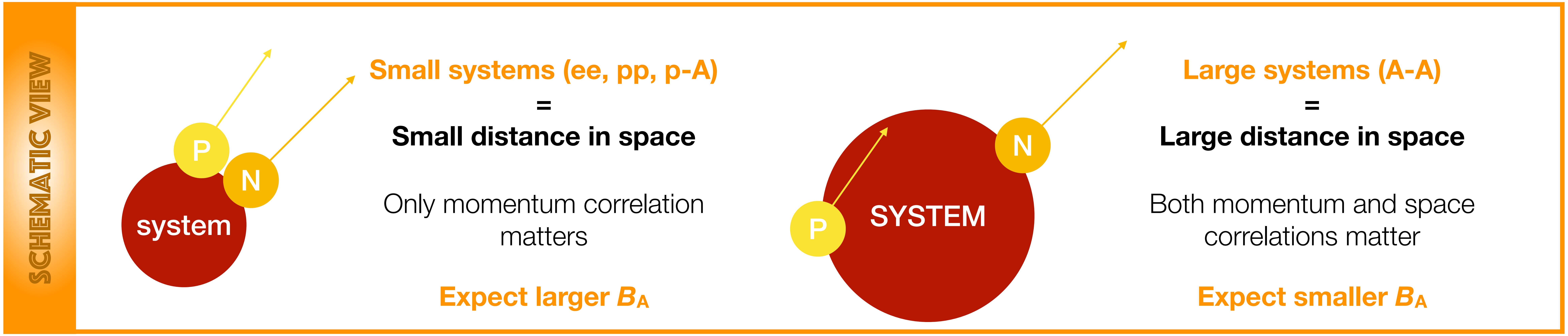


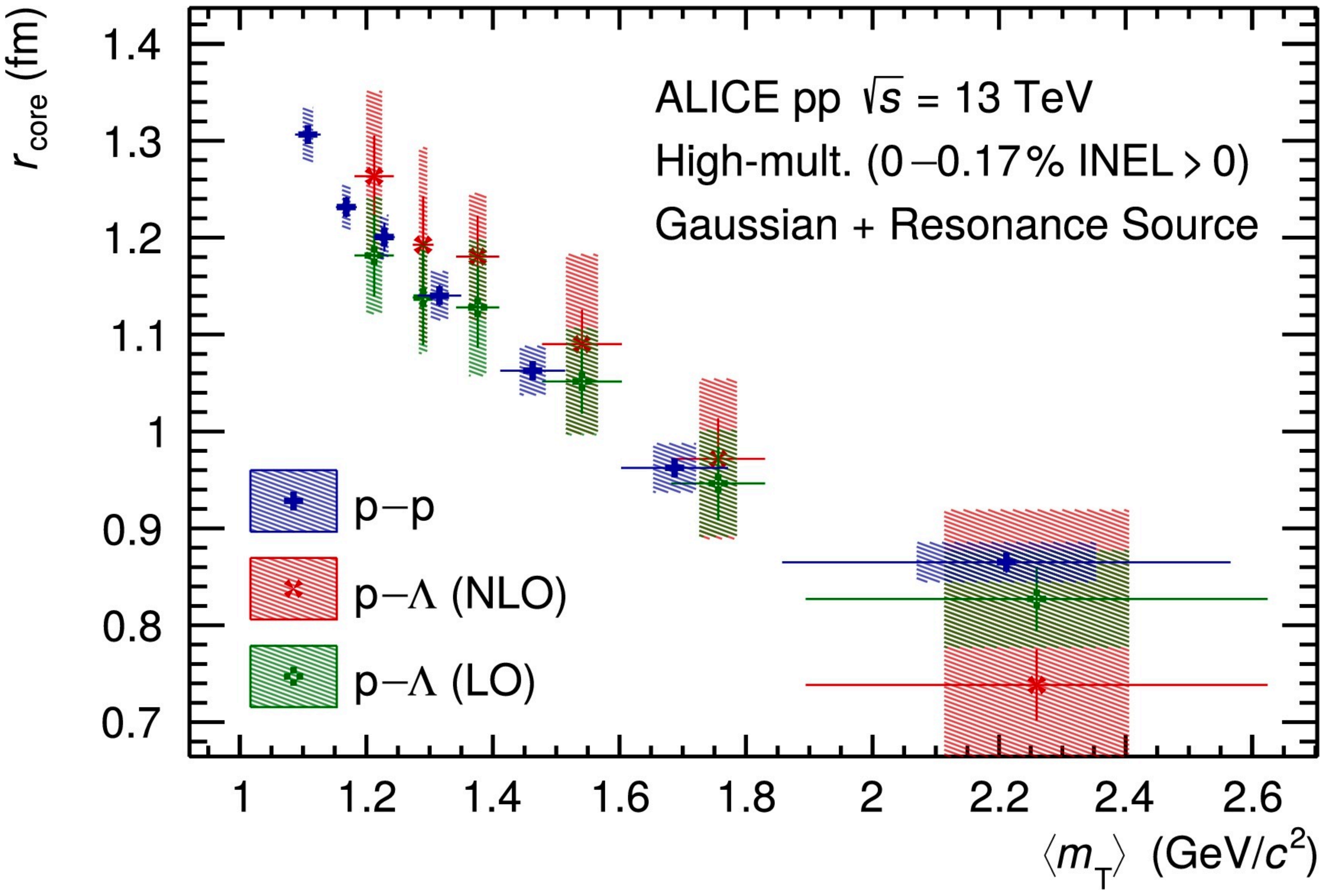
Coalescence model predictions

How to get a quantitative prediction in practice?

Source radius

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

ALICE, Phys.Lett.B 811 (2020)



See Georgios Mantzaridis' poster for the full story on how this measurement is done

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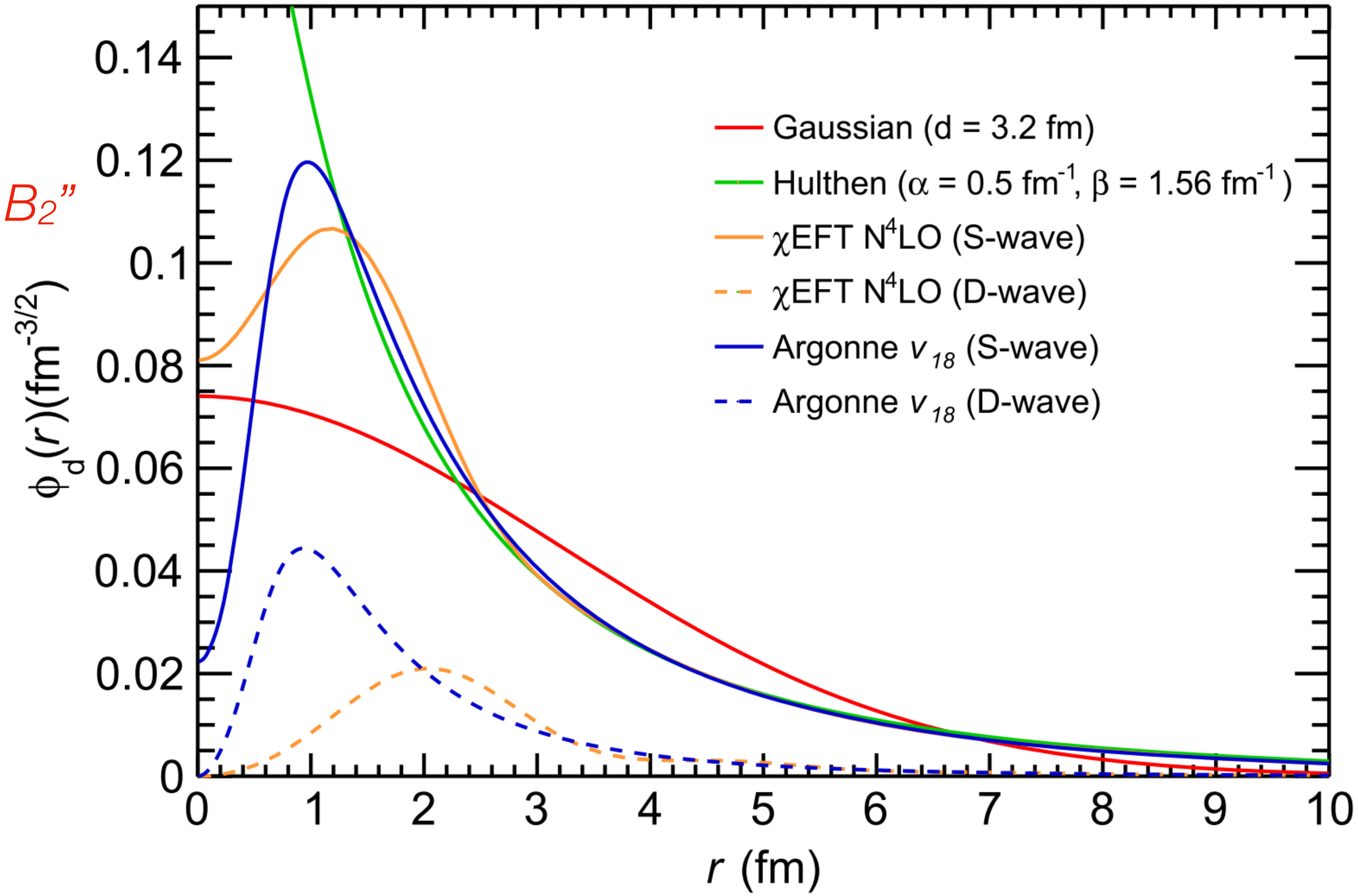
Wigner density

"Source Radius + Nucleus wave function -> B_2"

M, Mahlein et al, Eur.Phys.J.C 83 (2023) 9, 804



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Source radius

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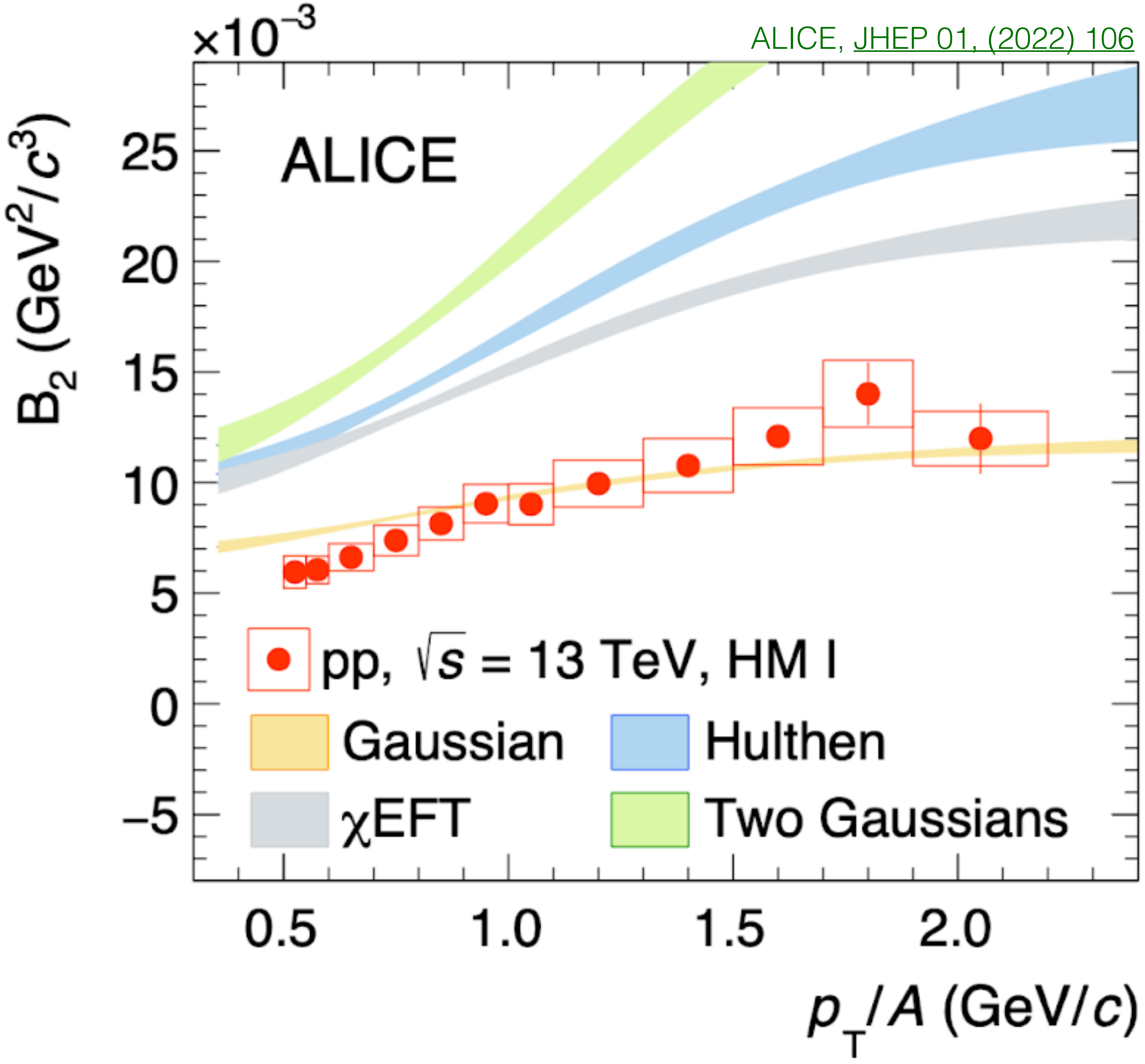
“Source Radius + Nucleus wave function -> B_2”

- Different wave functions give quite different expected coalescence parameter
  - It works within factor 2 for deuteron
  - Static coalescence does not take into account event-by-event correlations among nucleons (e.g. jets)

ALICE, JHEP 01, (2022) 106



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

Source radius ($\mathcal{C}_2^{\mathrm{PRF}}(\vec{p}, \vec{q})$)

Wigner density ($\mathcal{D}(\vec{q})$)

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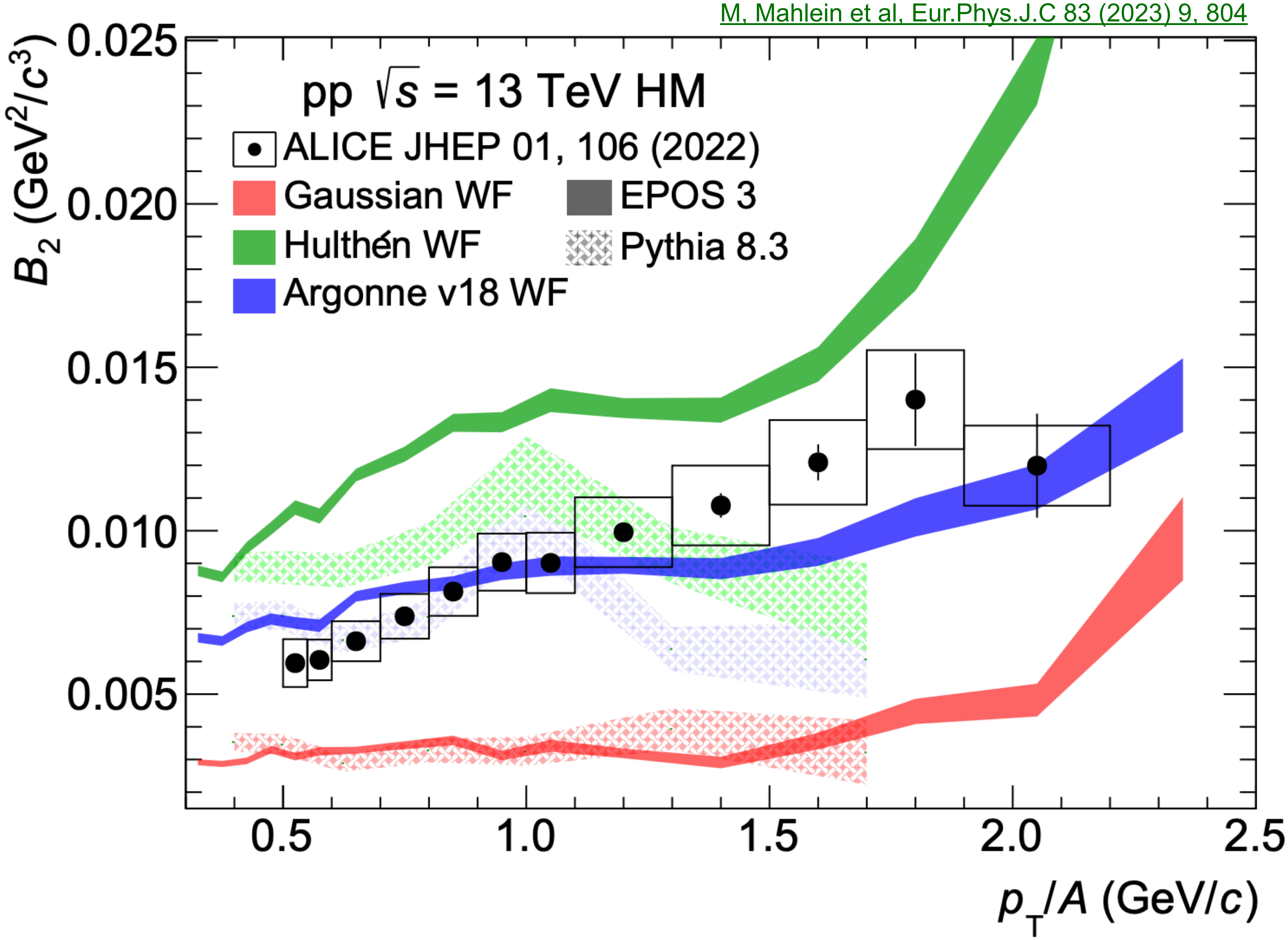


Event by event coalescence

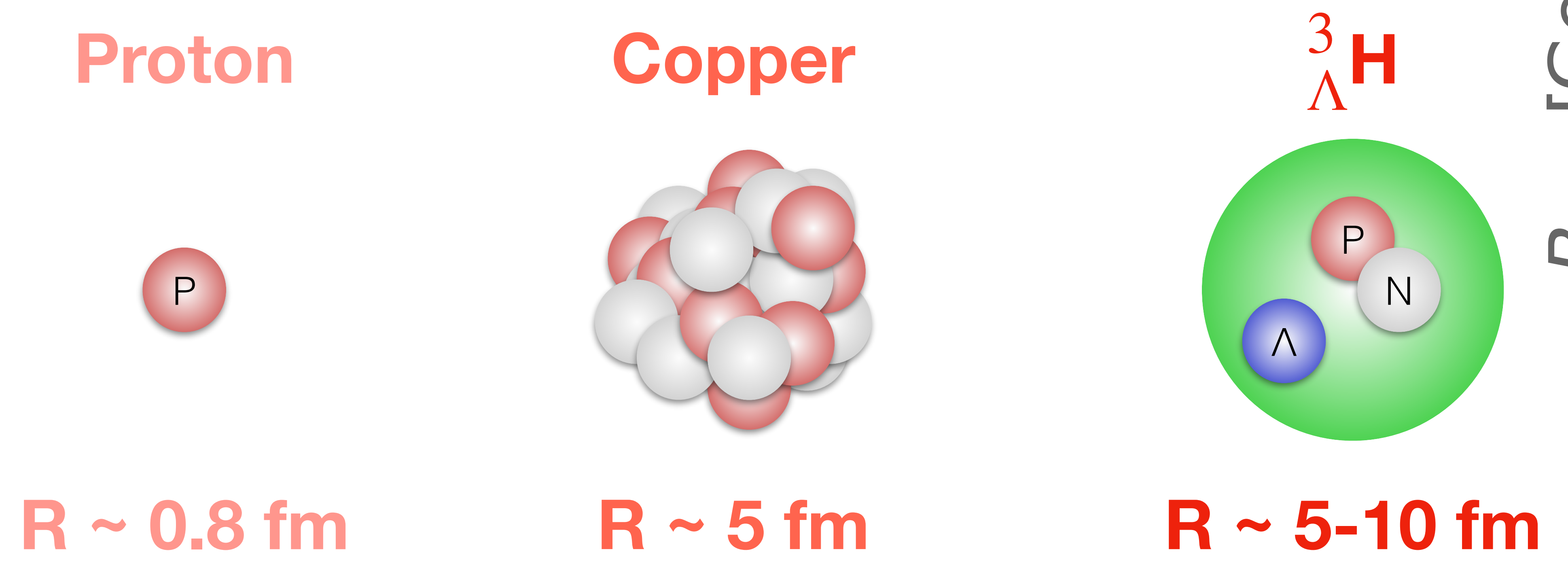
- Event generators with re-weighted nucleon distribution to get measured source: better description deuteron spectra using realistic wave function

The ultimate test: large bound systems

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

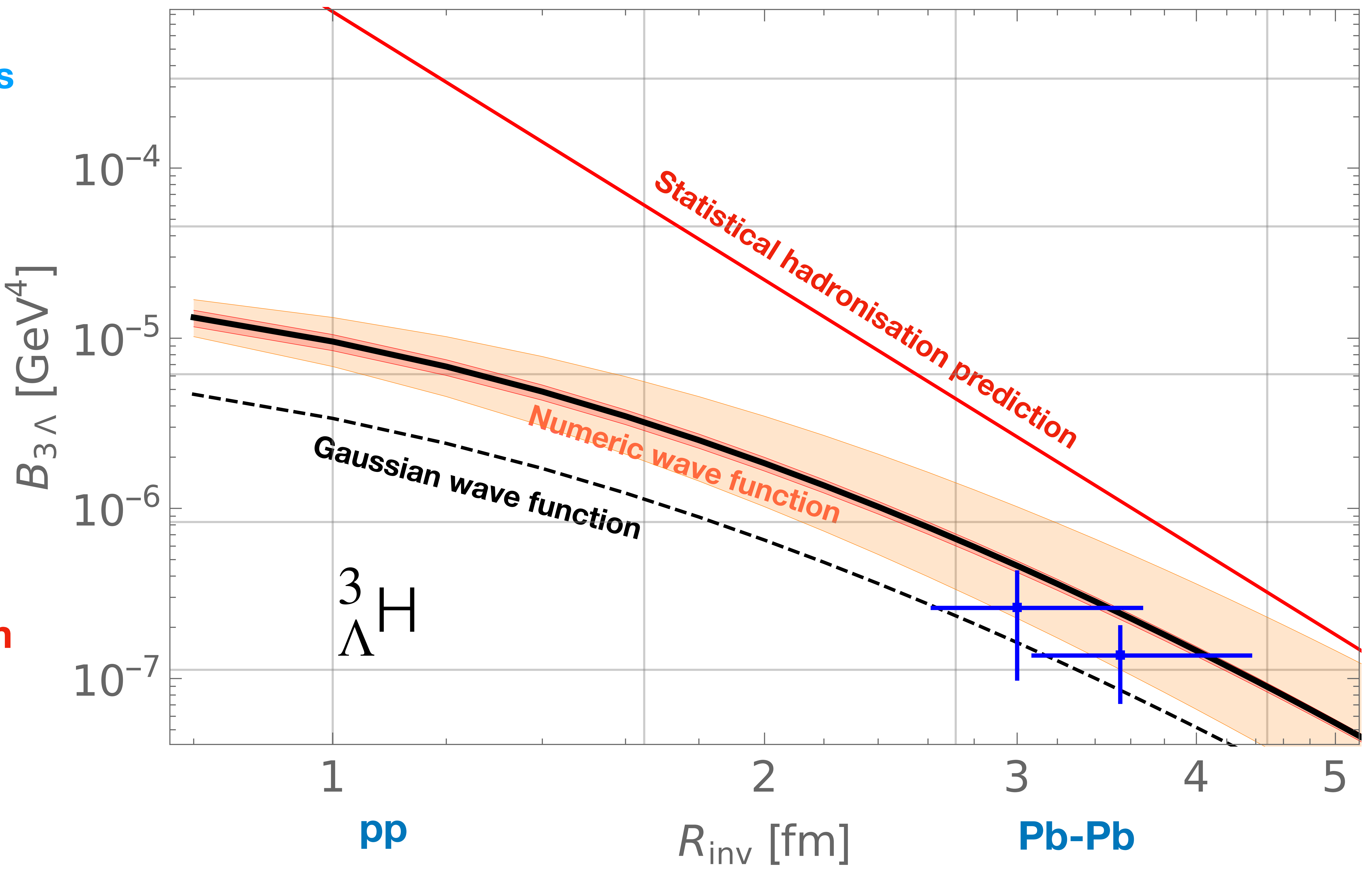
Source radius

Wigner density



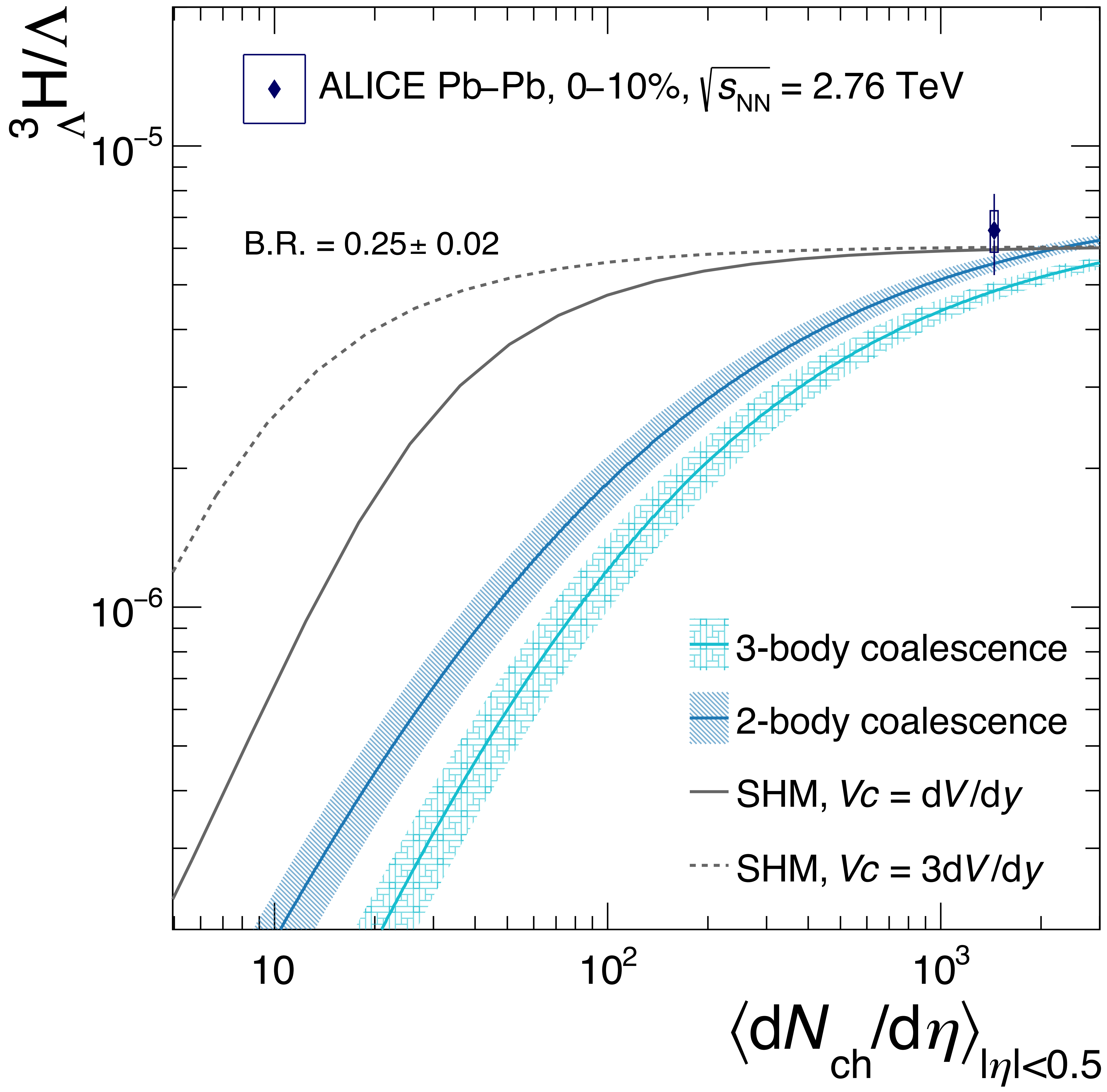
Halo nucleus: wide dΛ molecule

F. Bellini, K. Blum, A. Kalweit, M.P. PRC 103, 014907 (2021)



The case of hypertriton production in small systems

Models:
Vovchenko, et al., Phys. Lett., B785, 171-174, (2018)
Sun. et al., Phys. Lett. B, 792, 132–137, (2019)



$^3_\Lambda$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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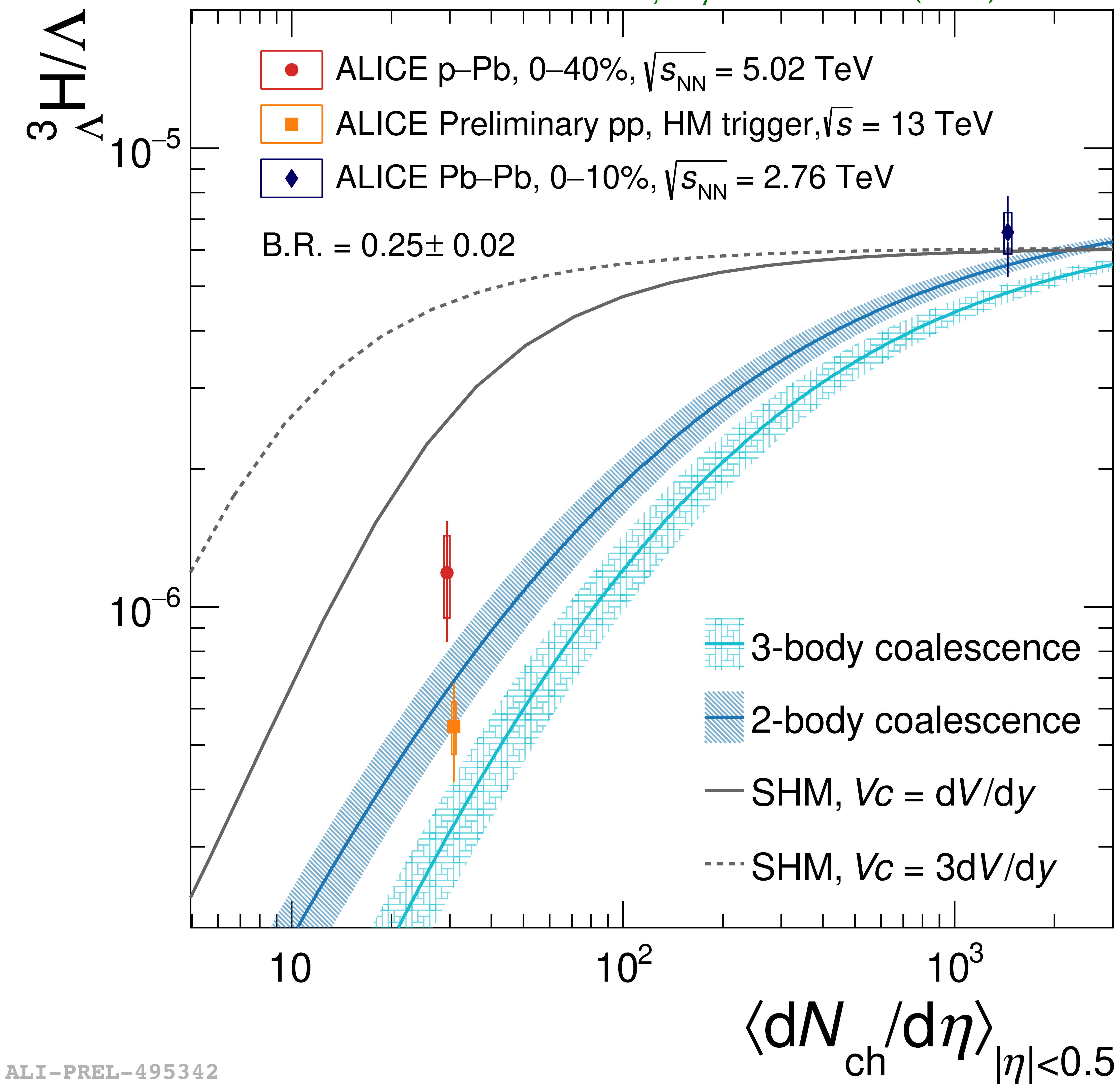
ALICE, Phys.Rev.Lett. 128 (2022) 252003



ALI-PREL-495342

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

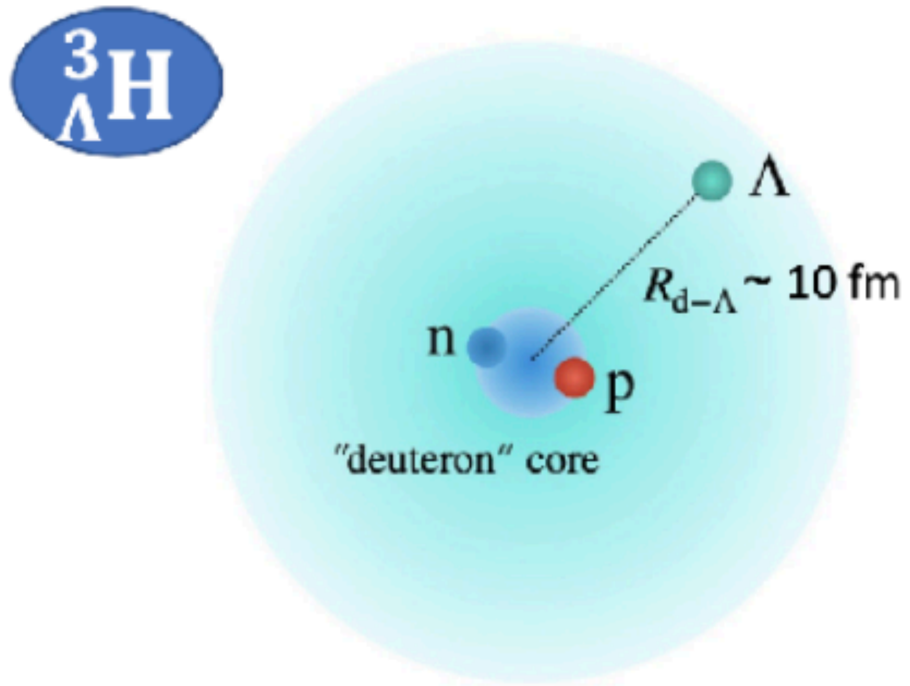
- SHM: insensitive to size of the hypertriton
- Coalescence: yield suppressed with assumed hypertriton radius ~10 fm
- Measurements in good agreement with 2-body coalescence
- Tension with SHM at low charged-particle multiplicity density
  - configuration with V_C = 3dV/dy is excluded at level of more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

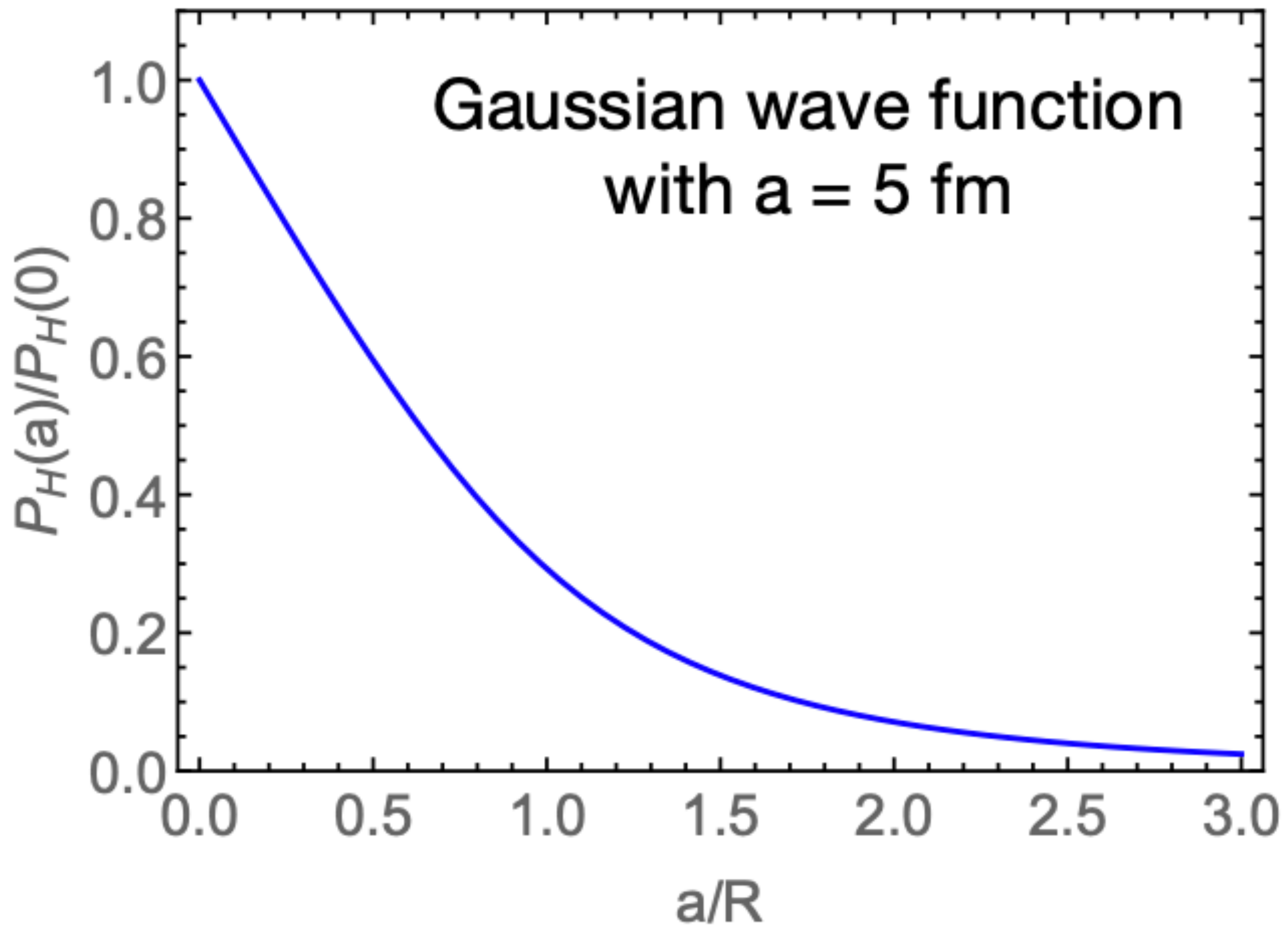
Production of hypertriton in pp and p-Pb collisions as a doorway to the study of its structure

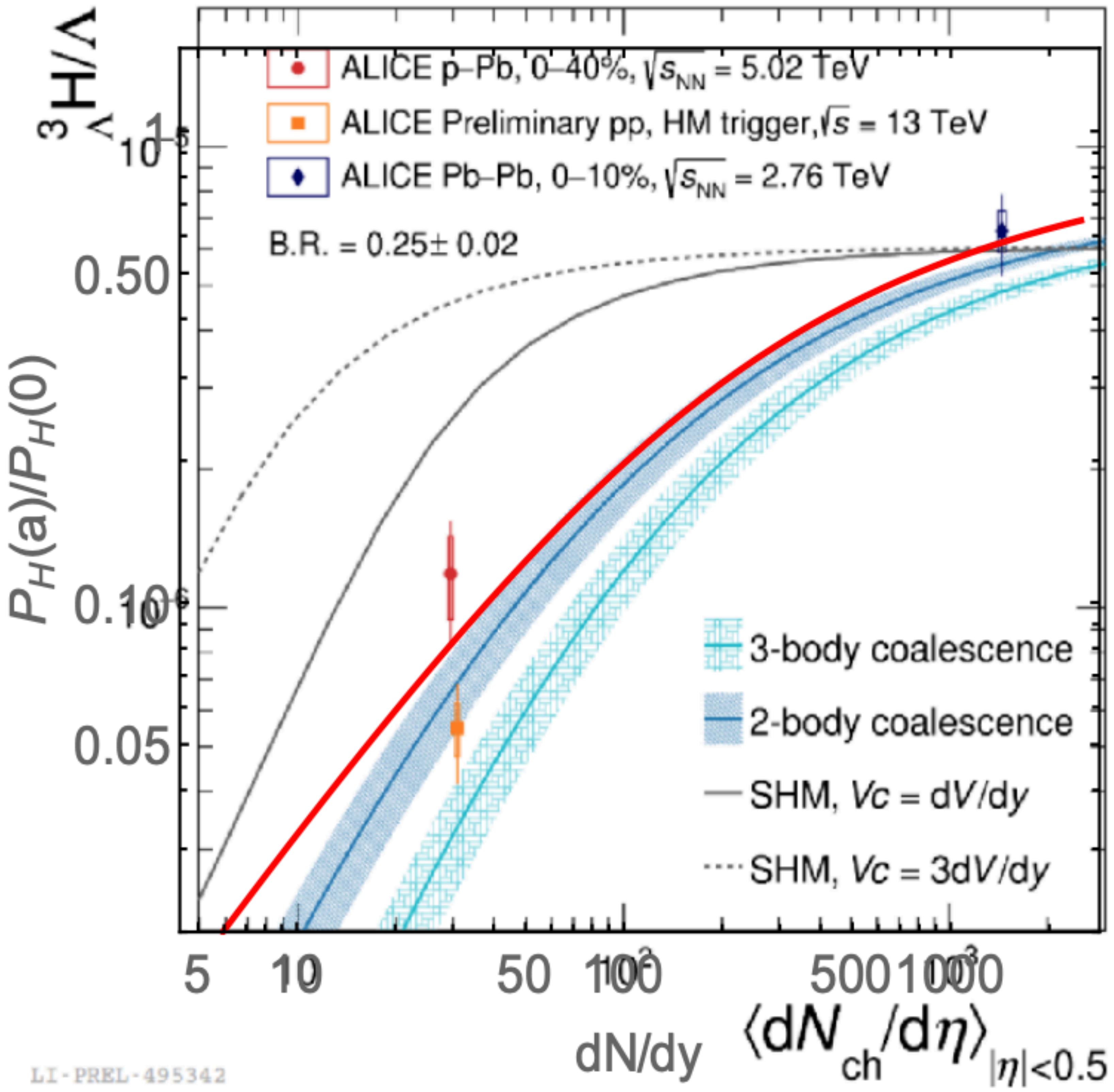
The case of hypertriton production in small systems

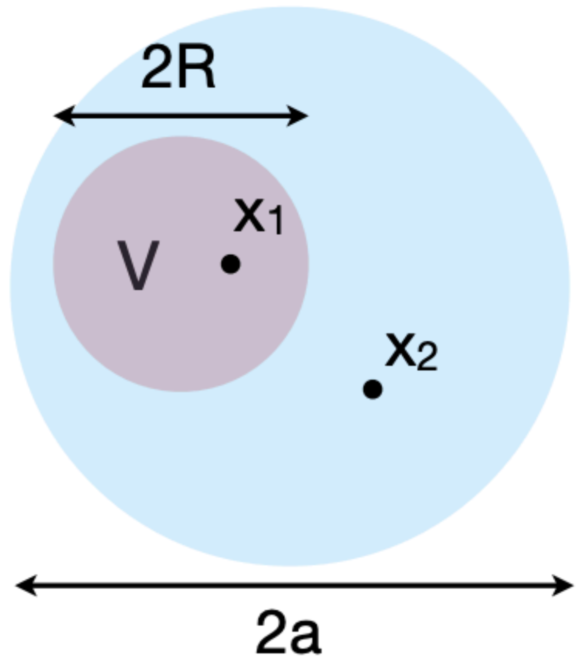
Particle size matters

Berndt Mueller SQM22 summary talk









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

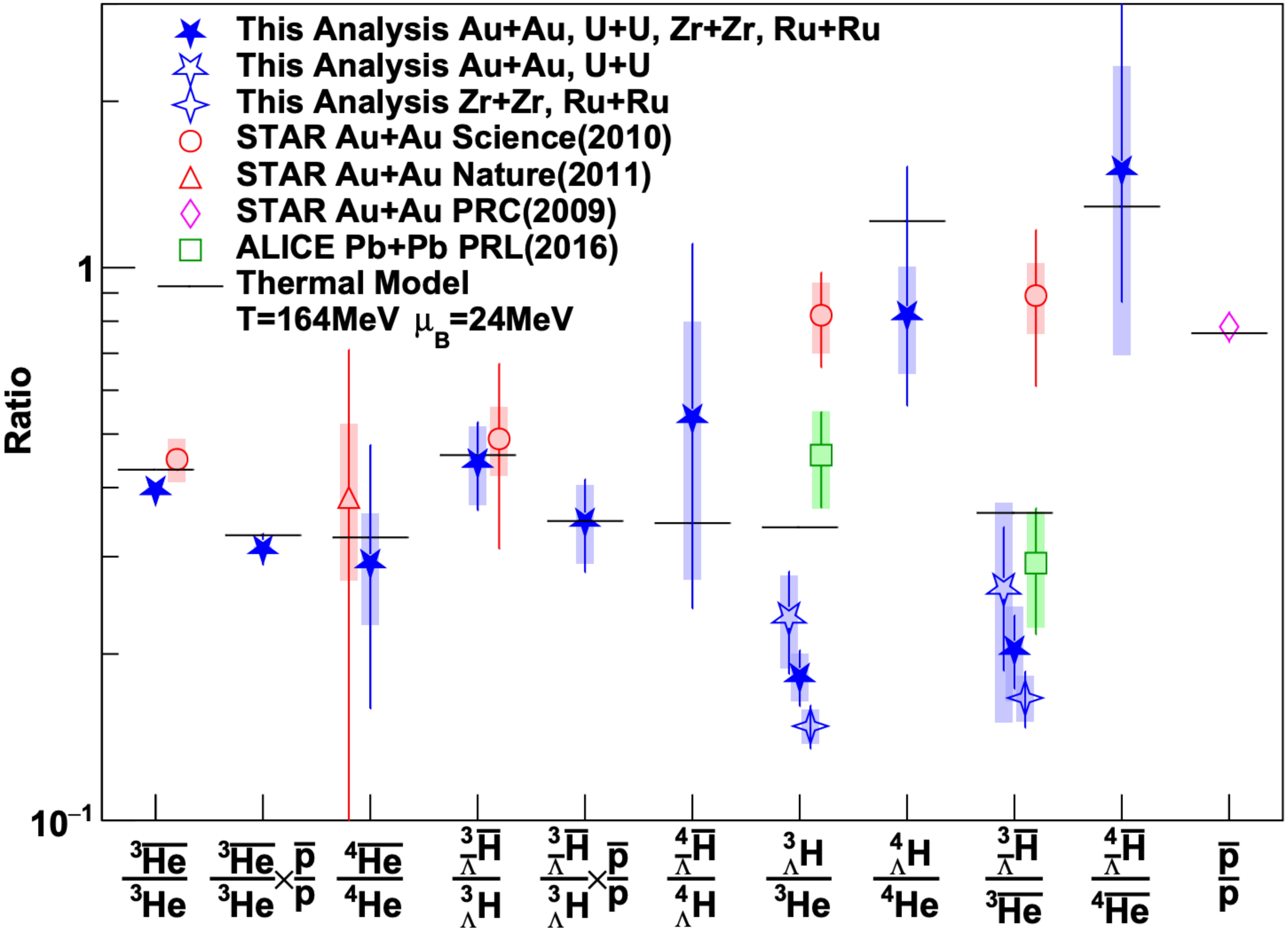
$$P_H \approx \int d^3p\, e^{-E_p/T} \int d^3x_1\, d^3x_2\, |\psi_p(0)|^2 \theta_V(x_1)\theta_V(x_2)$$

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

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

Hypertriton production suppression at RHIC?

STAR, https://arxiv.org/abs/2310.12674



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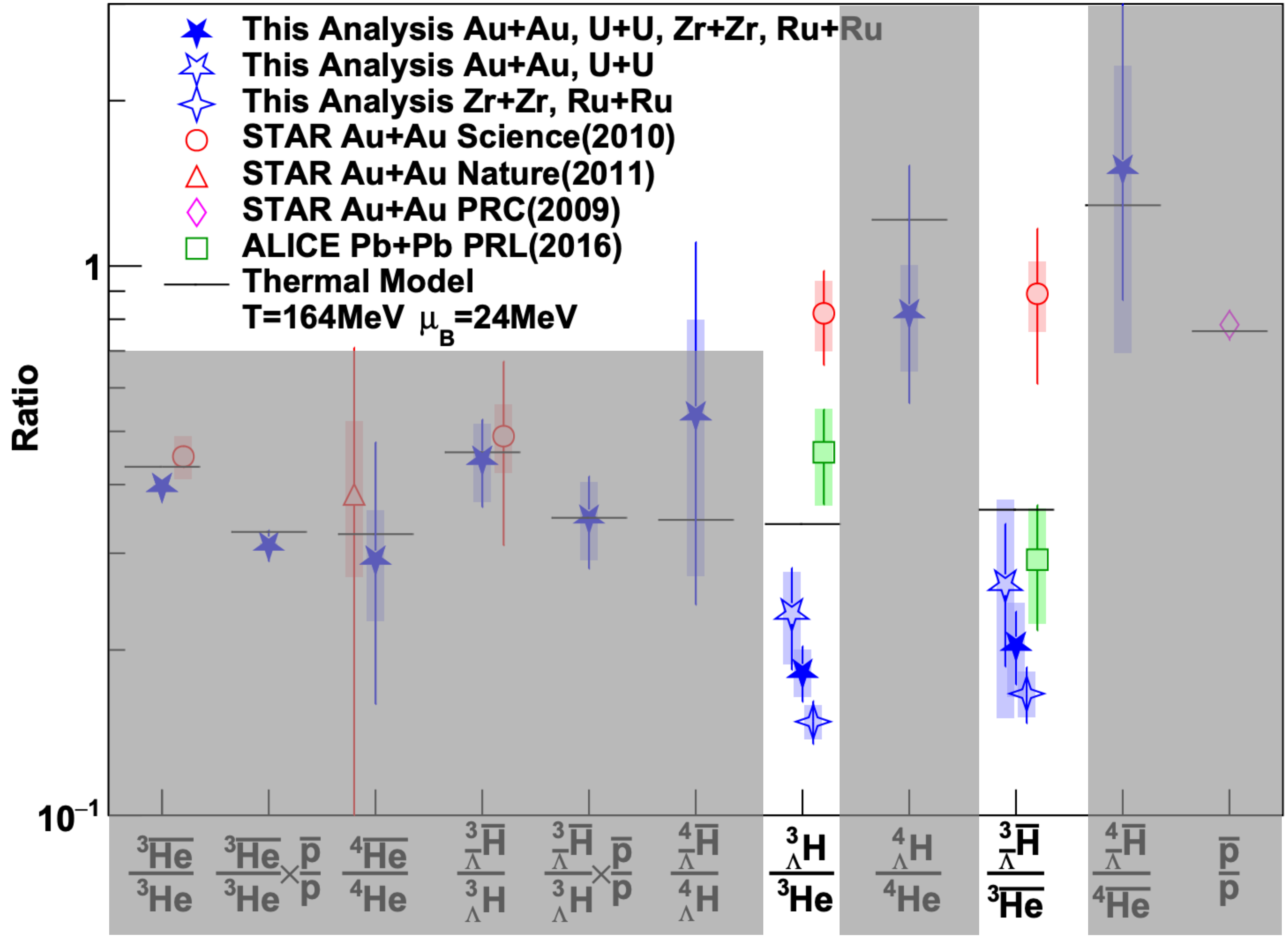
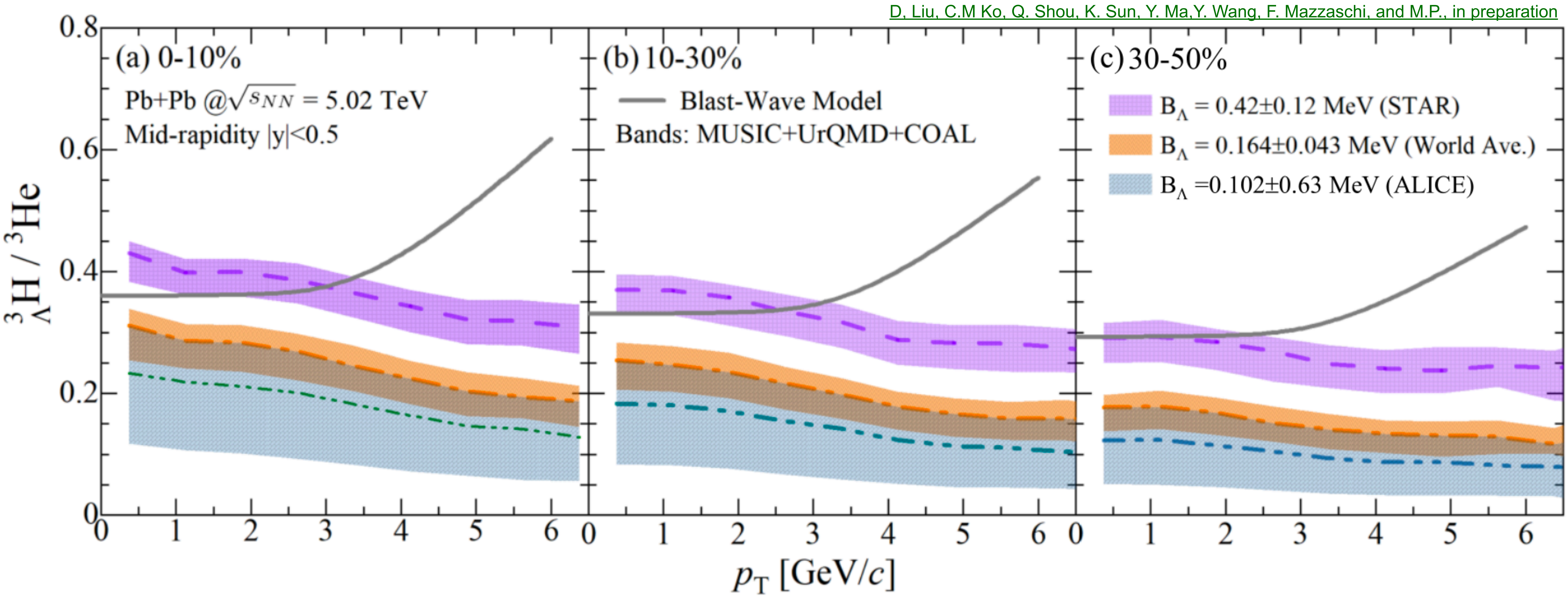


Indication of larger deviation from the SHM prediction in the collision among “small” ions

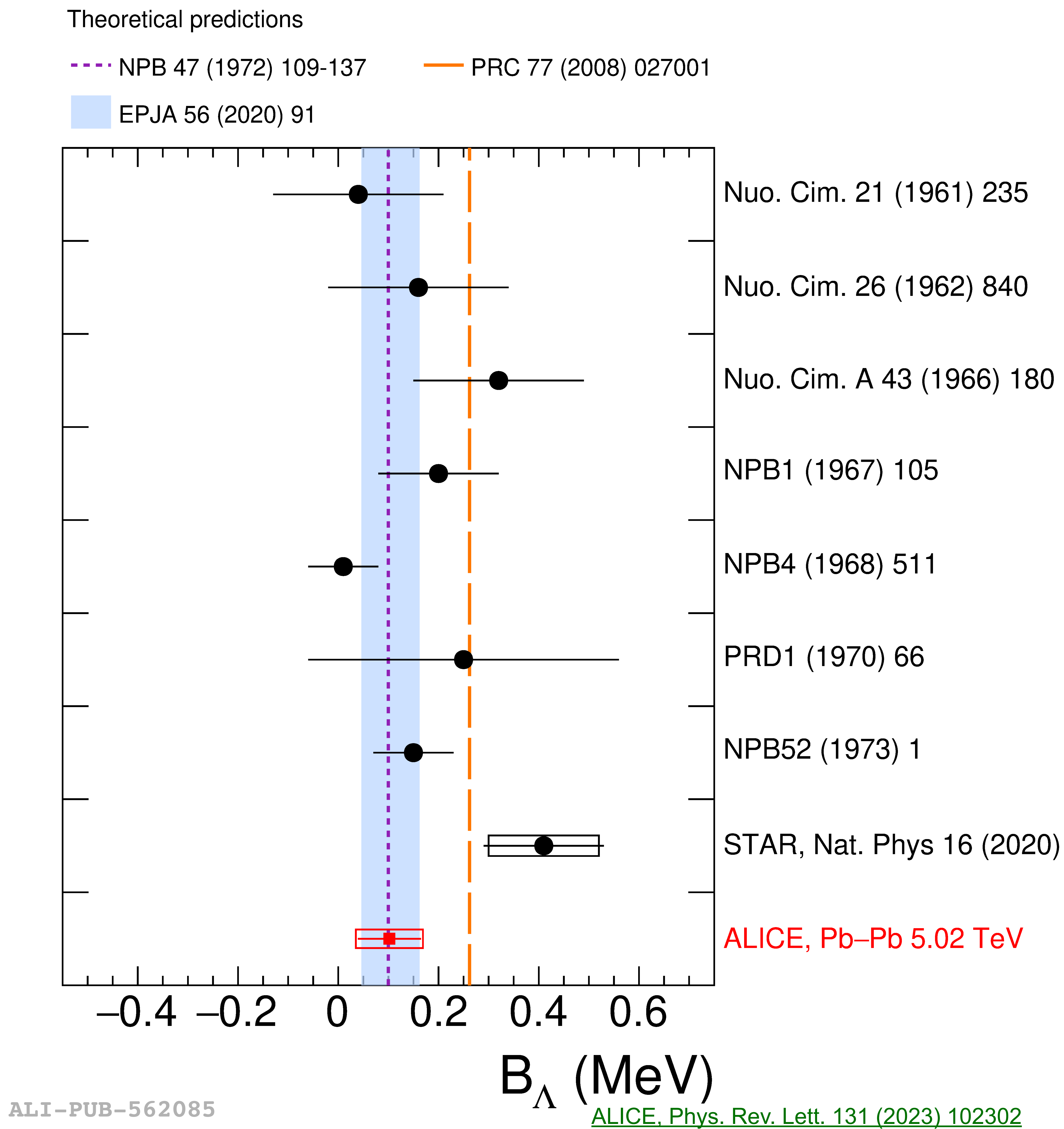
- Same effect as going to p-Pb or pp collisions at the LHC!

$^{3}_{\Lambda}H$ momentum spectra in coalescence vs radial flow



- Radial flow picture (Blast-Wave): higher mass states have an harder momentum spectrum
- Coalescence: at large momentum smaller source radius, hence the state with the larger wave-function will get suppressed

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



ALICE, Phys. Rev. Lett. 131 (2023) 102302

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

The measured B$_{\Lambda}$ is extremely small

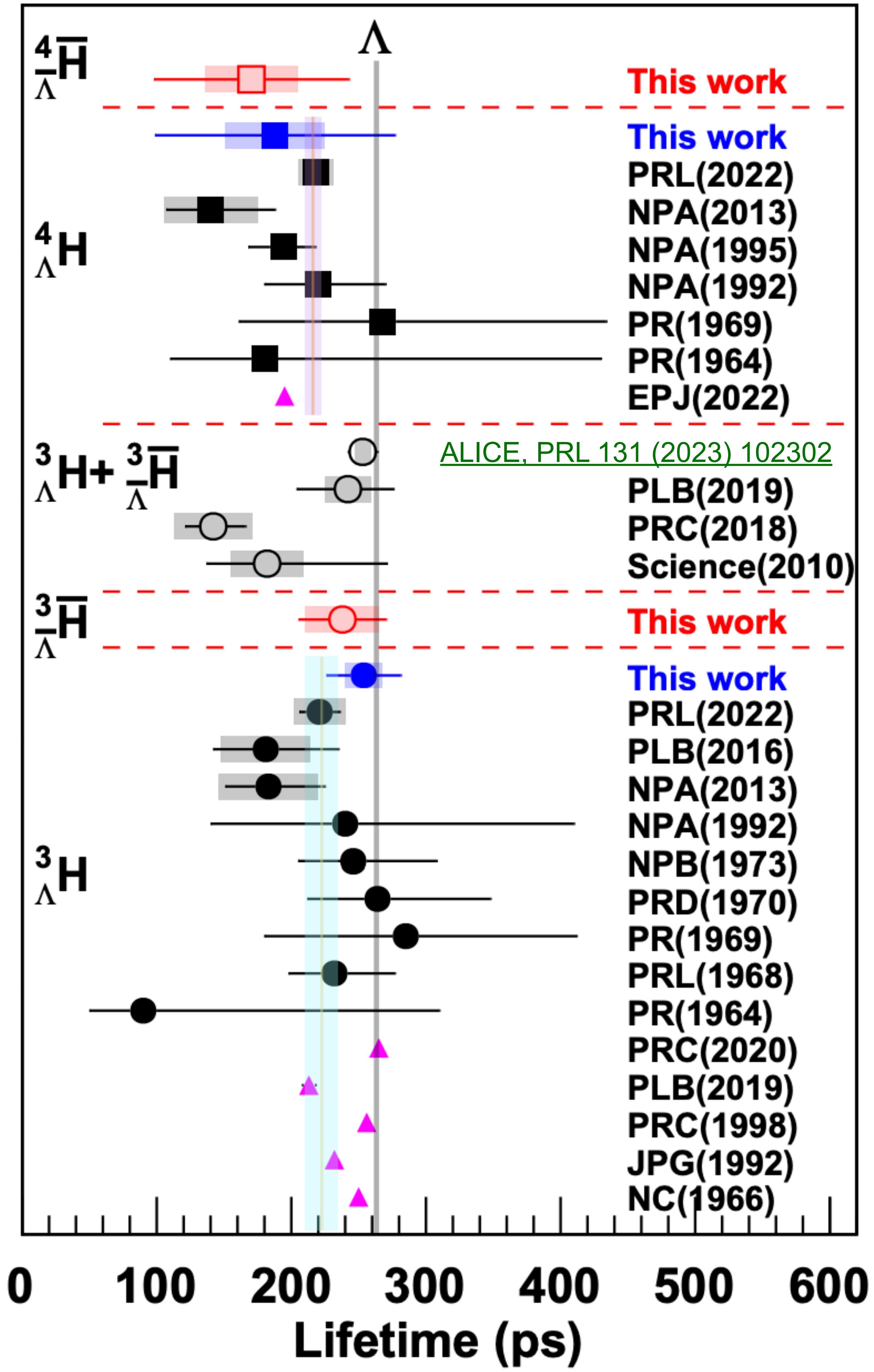
- Compatible with a loosely bound deuteron-Λ molecule

B$_{\Lambda}$ uncertainties are O(100 keV)

- Visualising techniques still have the best uncertainties
- New techniques needed in heavy-ion to reduce the systematic uncertainties
  - Ask me in the coffee break!

A<5 lifetime and binding energy in the high precision era

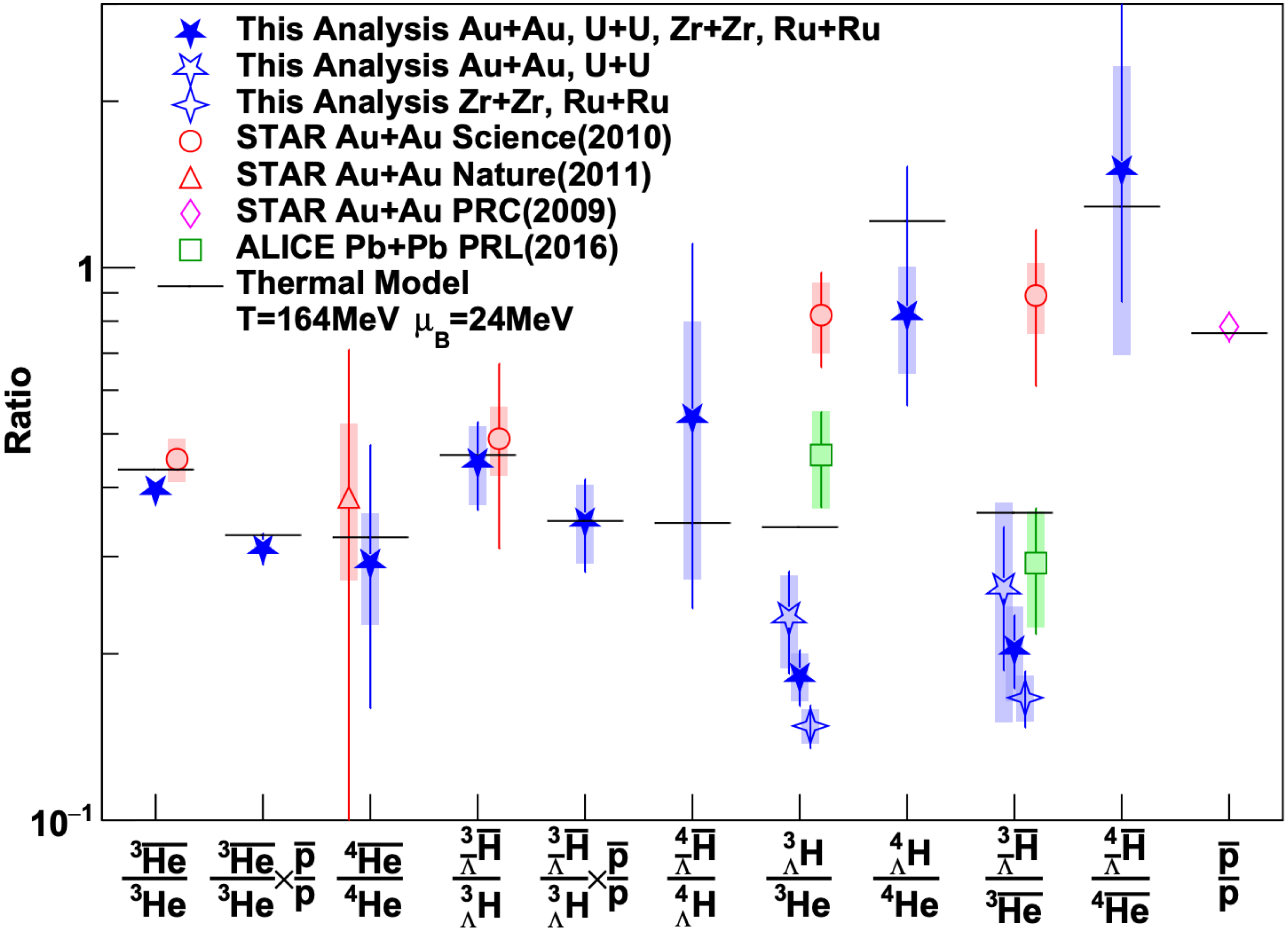
STAR, https://arxiv.org/abs/2310.12674



- World's leading measurements of the lifetime of hypernuclei with A<5 come from Heavy Ion experiment
- Exclude large deviations from free Λ lifetime
- Test of different models with different ${}^{3}_{\Lambda}H$ structure

The case of ${}^{4}_{\Lambda}H$ and ${}^{4}_{\Lambda}He$

STAR, https://arxiv.org/abs/2310.12674



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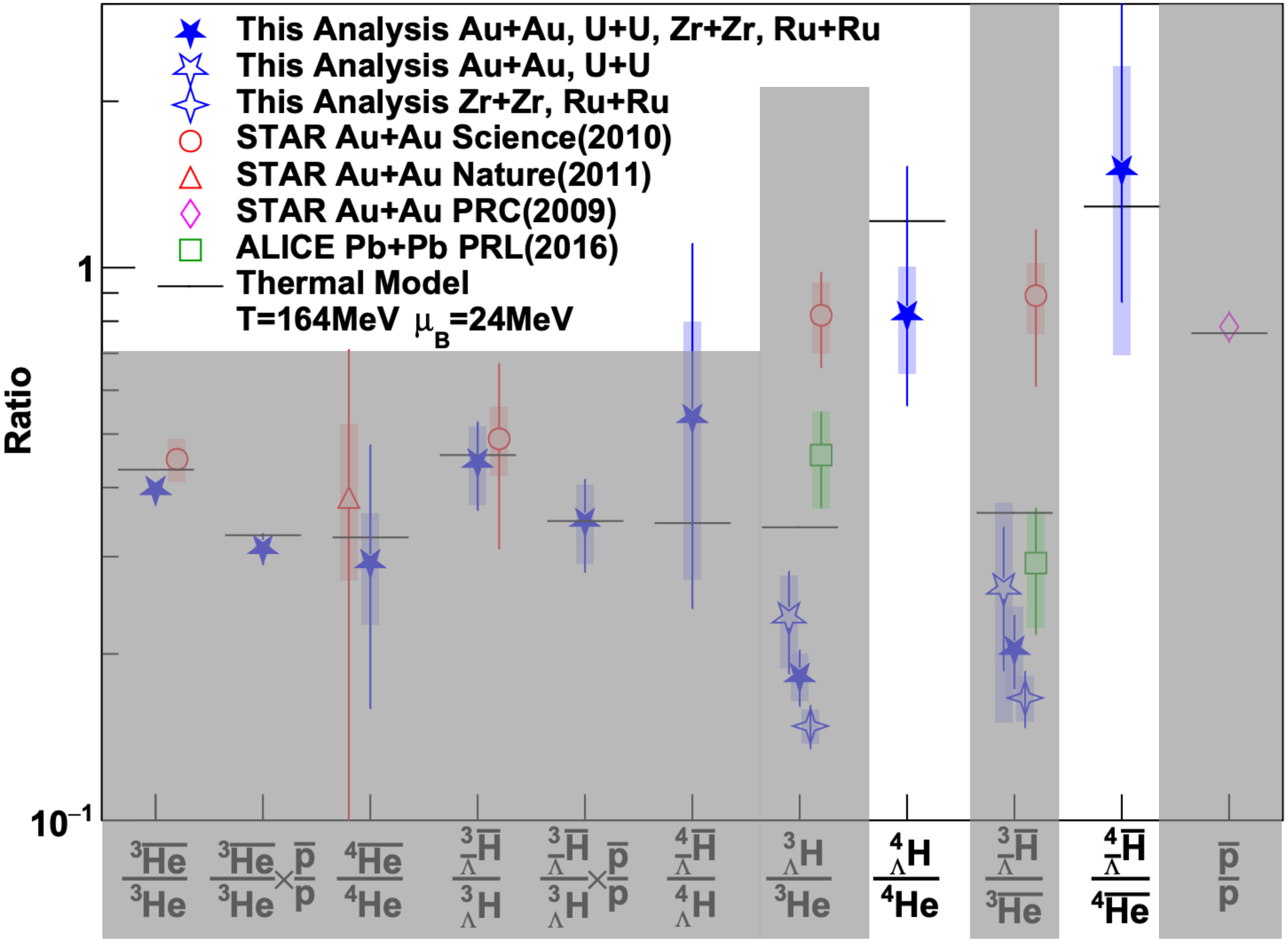
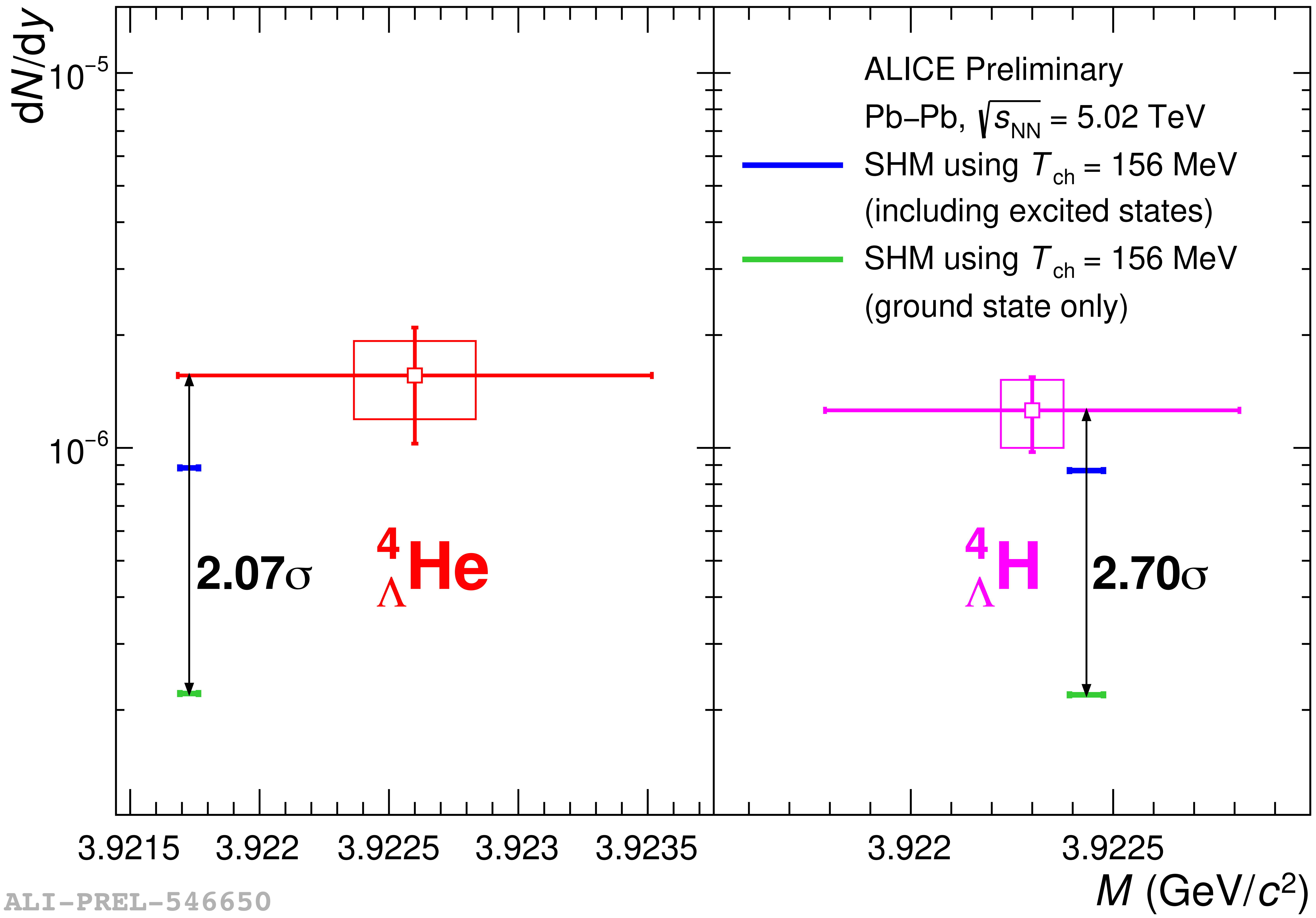


${}^{4}_{\Lambda}H$ is expected to be a compact state

- SHM could give a good estimation of the yield

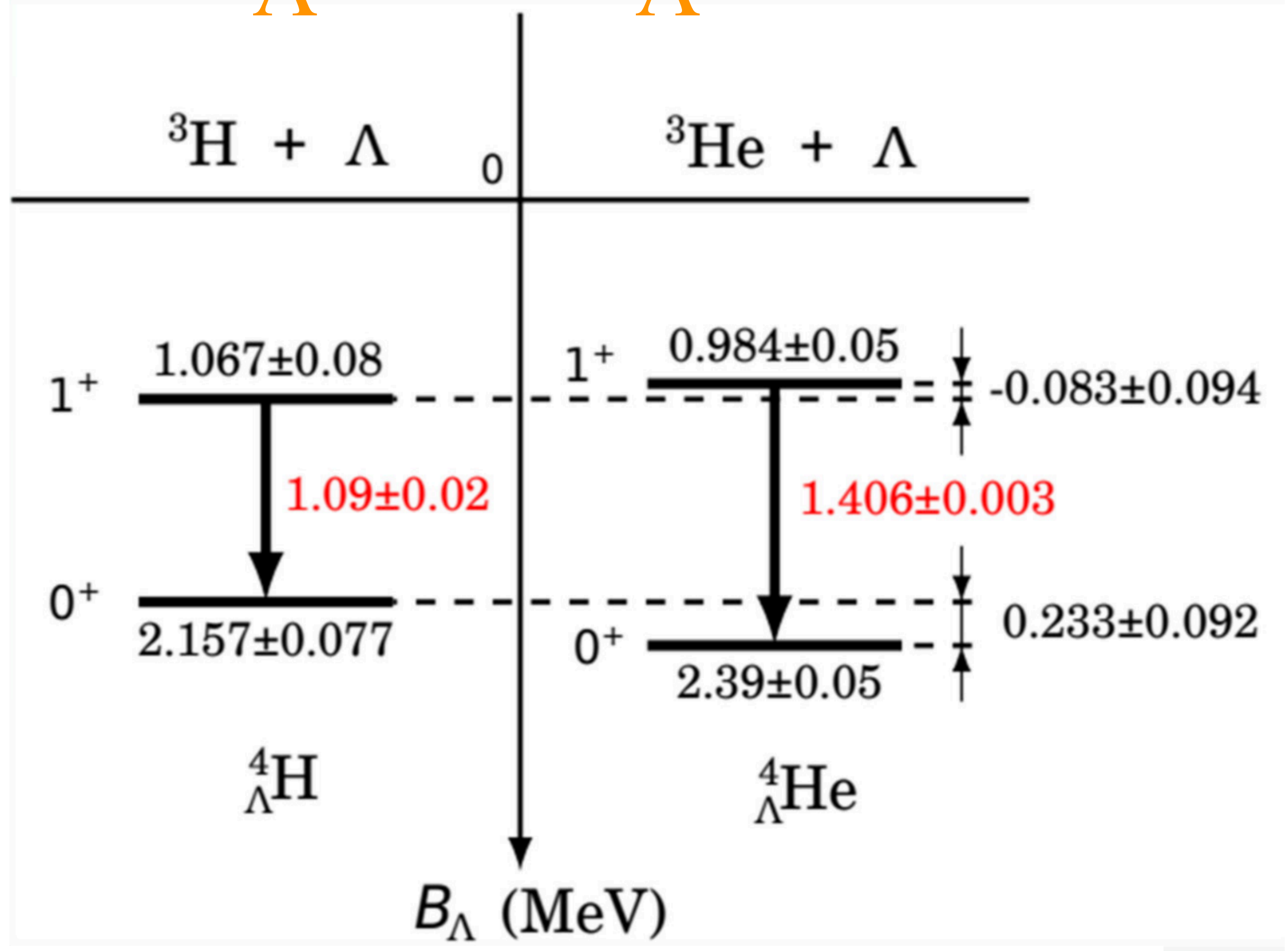
The case of $^4_\Lambda$H and $^4_\Lambda$He



$^4_\Lambda$H is expected to be a compact state

- SHM could give a good estimation of the yield

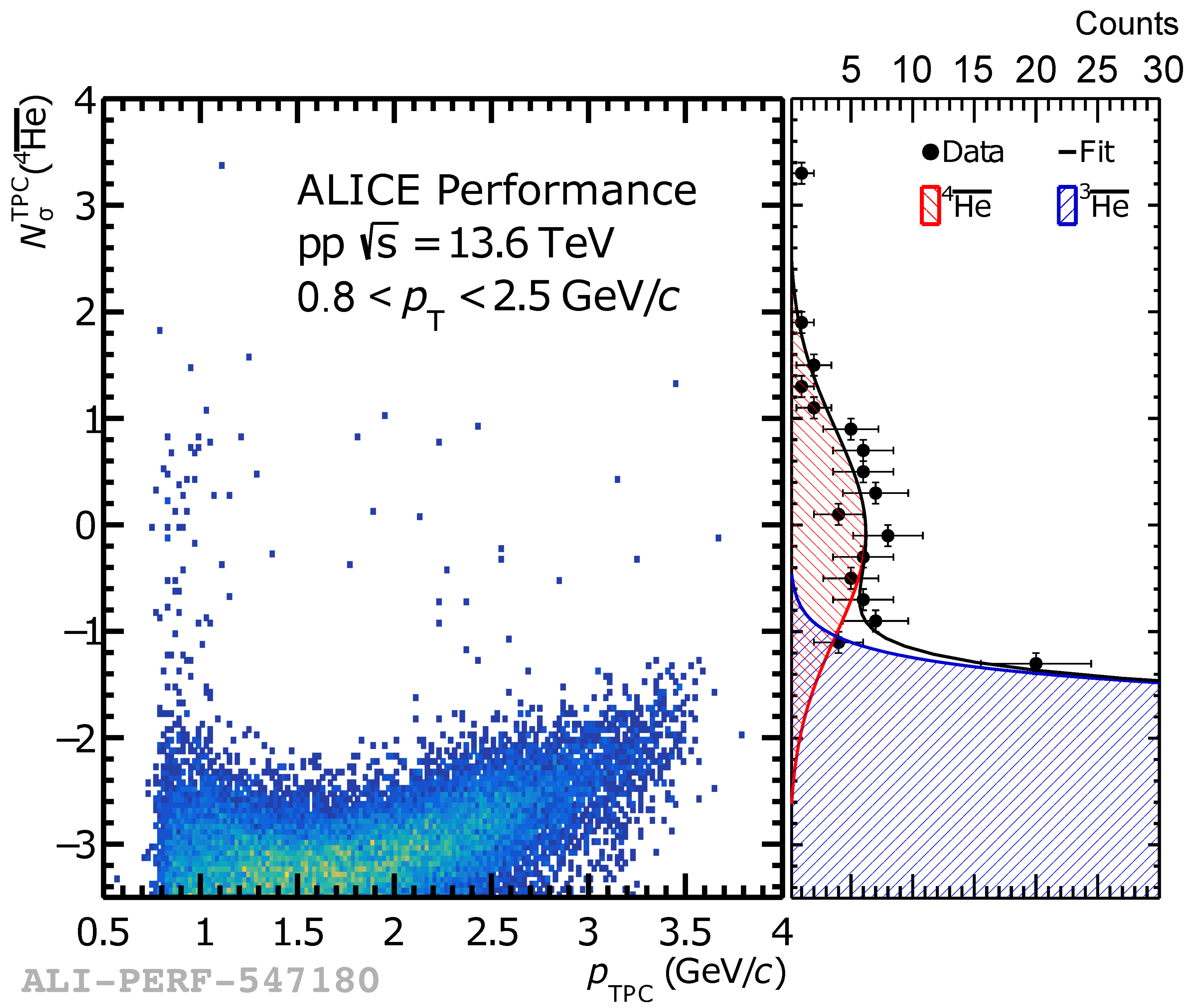
However, the SHM correctly describes the yield only when including the higher spin states of the $^4_\Lambda$H and $^4_\Lambda$He

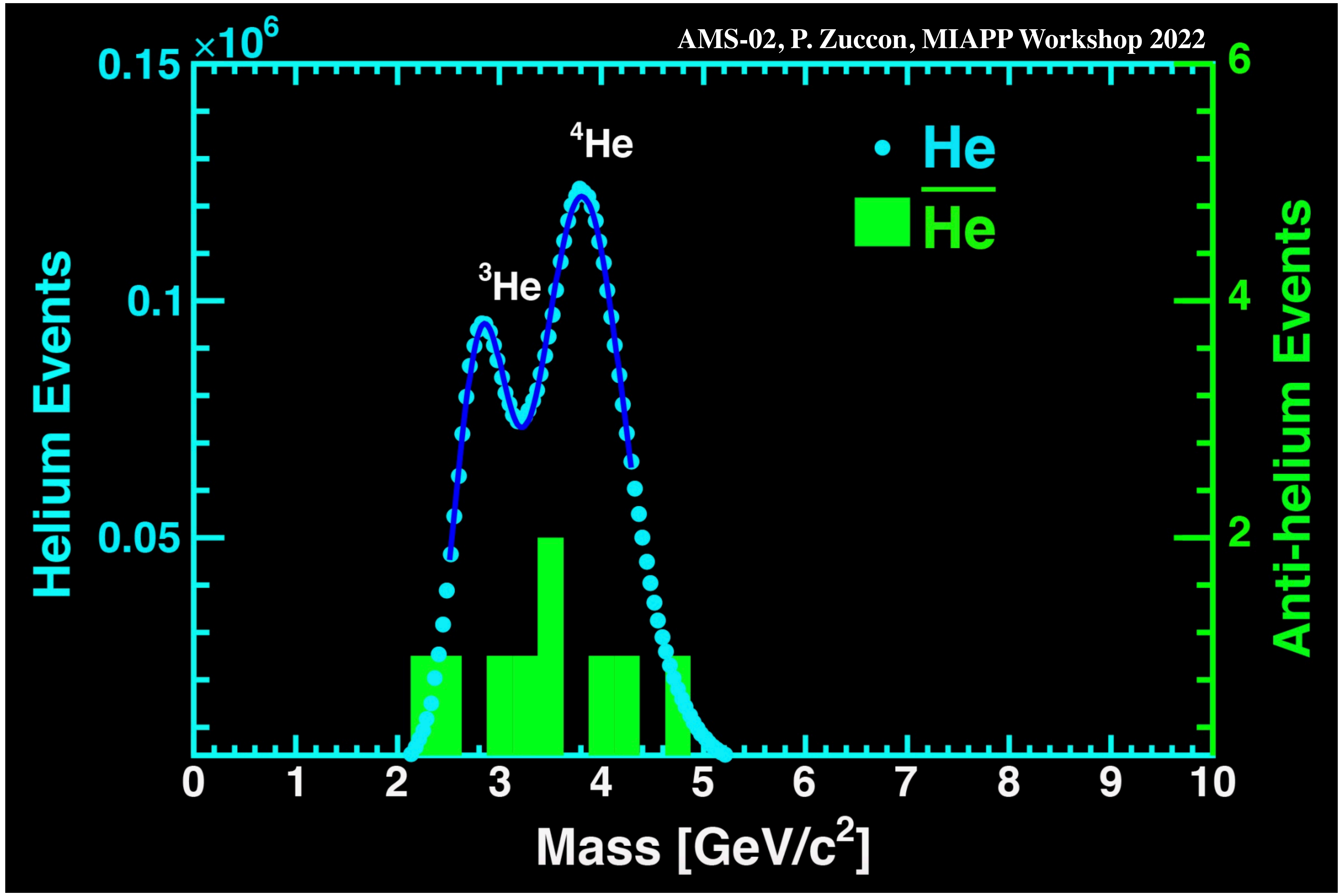


M. Schäfer, N. Barnea, A. Gal, Phys.Rev.C 106, L031001 (2022)

The Future

Precision (anti)(hyper)nuclei in pp collisions

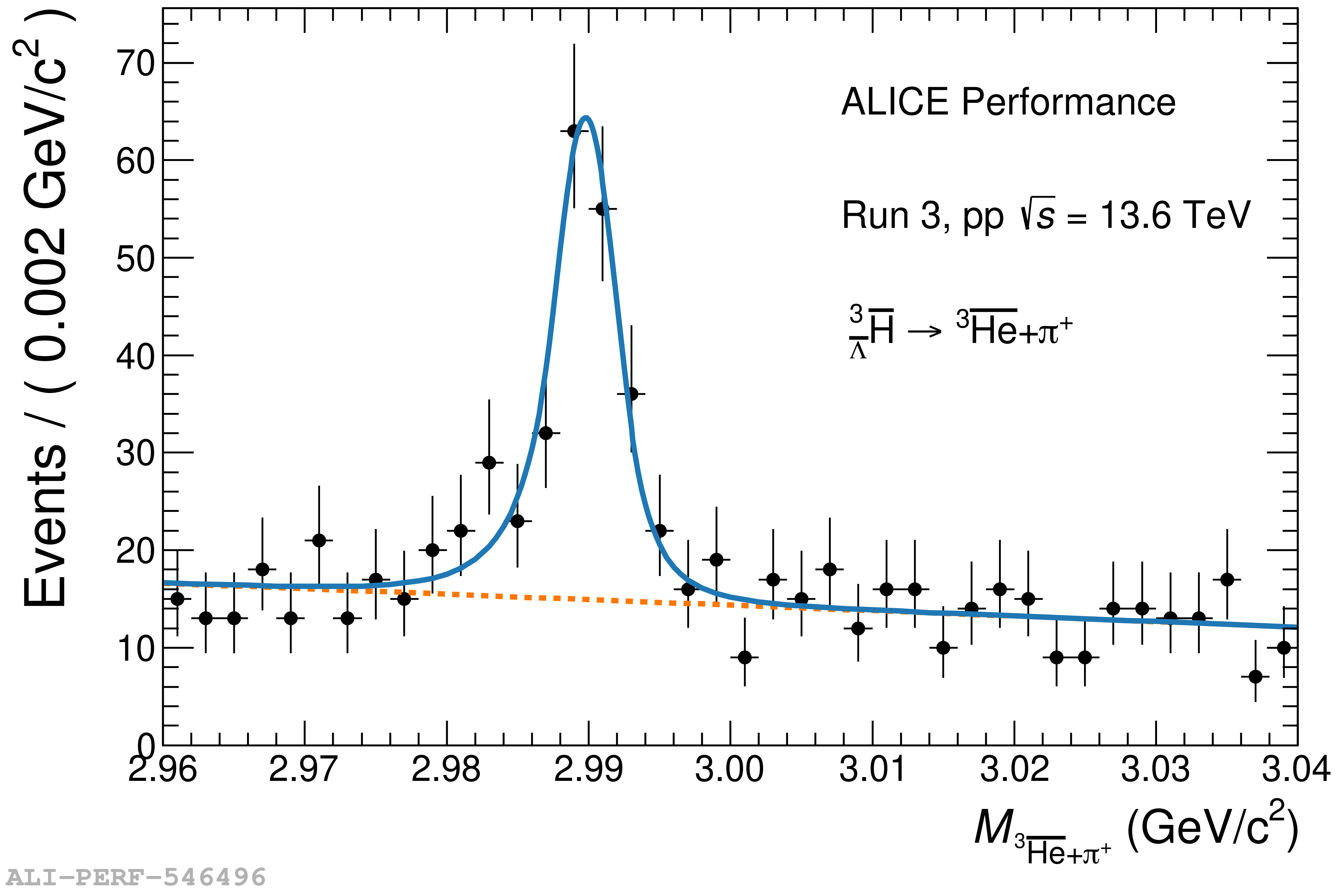




First signals of the production of anti-alpha detected in pp collisions

- Necessary input to understand how many anti alpha we expect in AMS-02

Precision (anti)(hyper)nuclei in pp collisions



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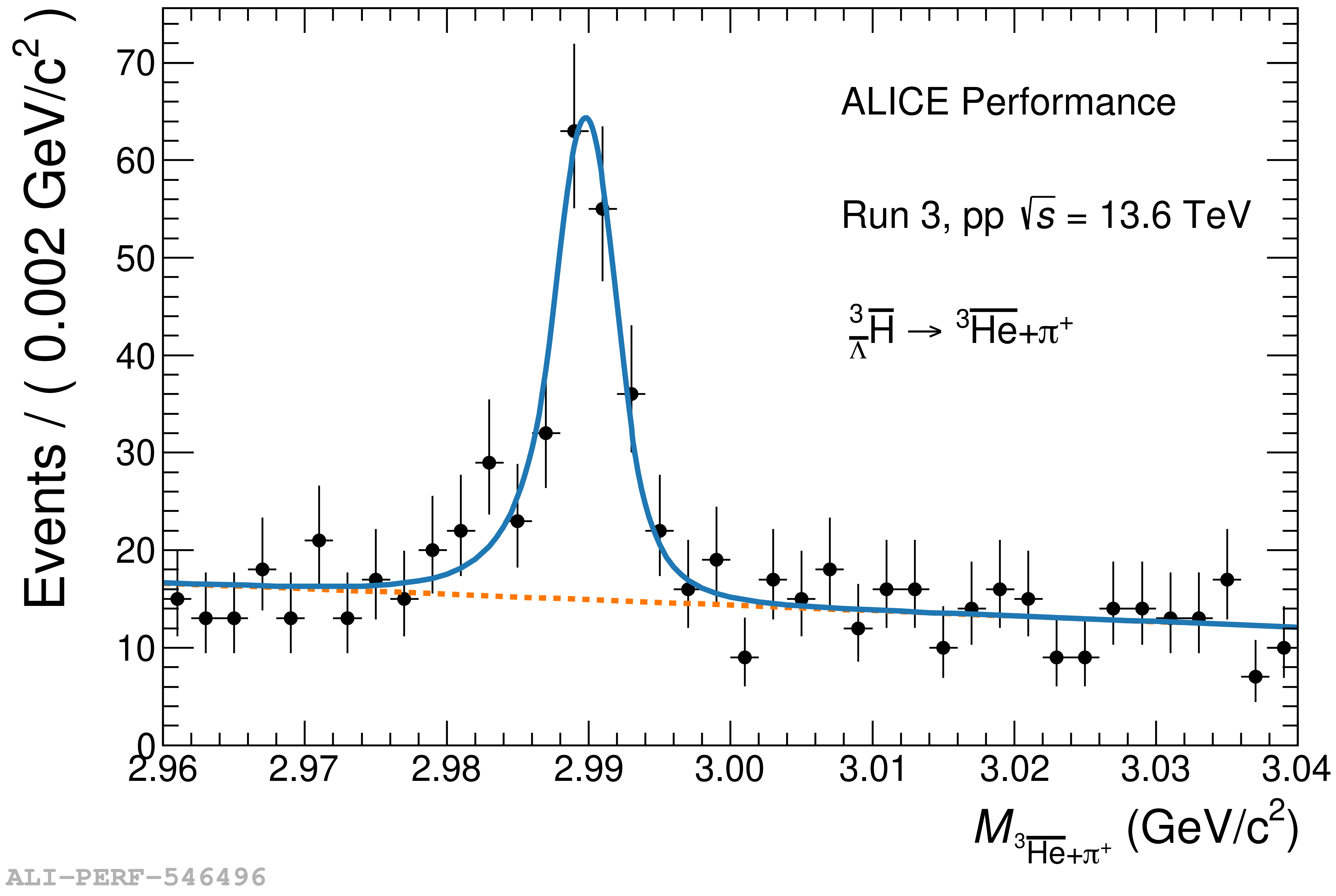
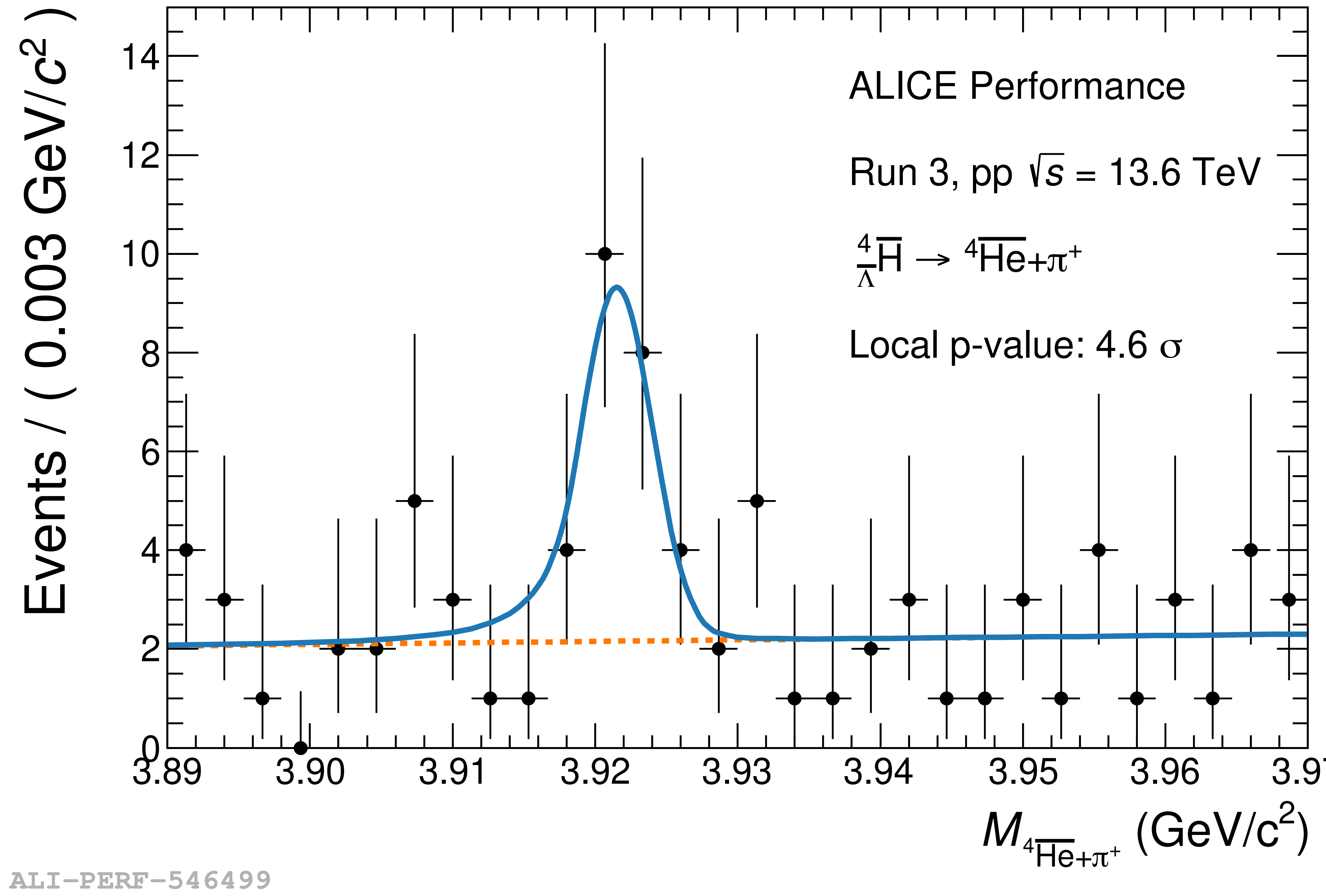
A=3 hypernuclei in pp: from the first signals in Run 2 to precision measurement in Run 3

Precision (anti)(hyper)nuclei in pp collisions





First signals of the production of anti-alpha detected in pp collisions

- Necessary input to understand how many anti alpha we expect in AMS-02

A=3 hypernuclei in pp: from the first signals in Run 2 to precision measurement in Run 3

- Even first A=4 antihypernuclei seen in pp

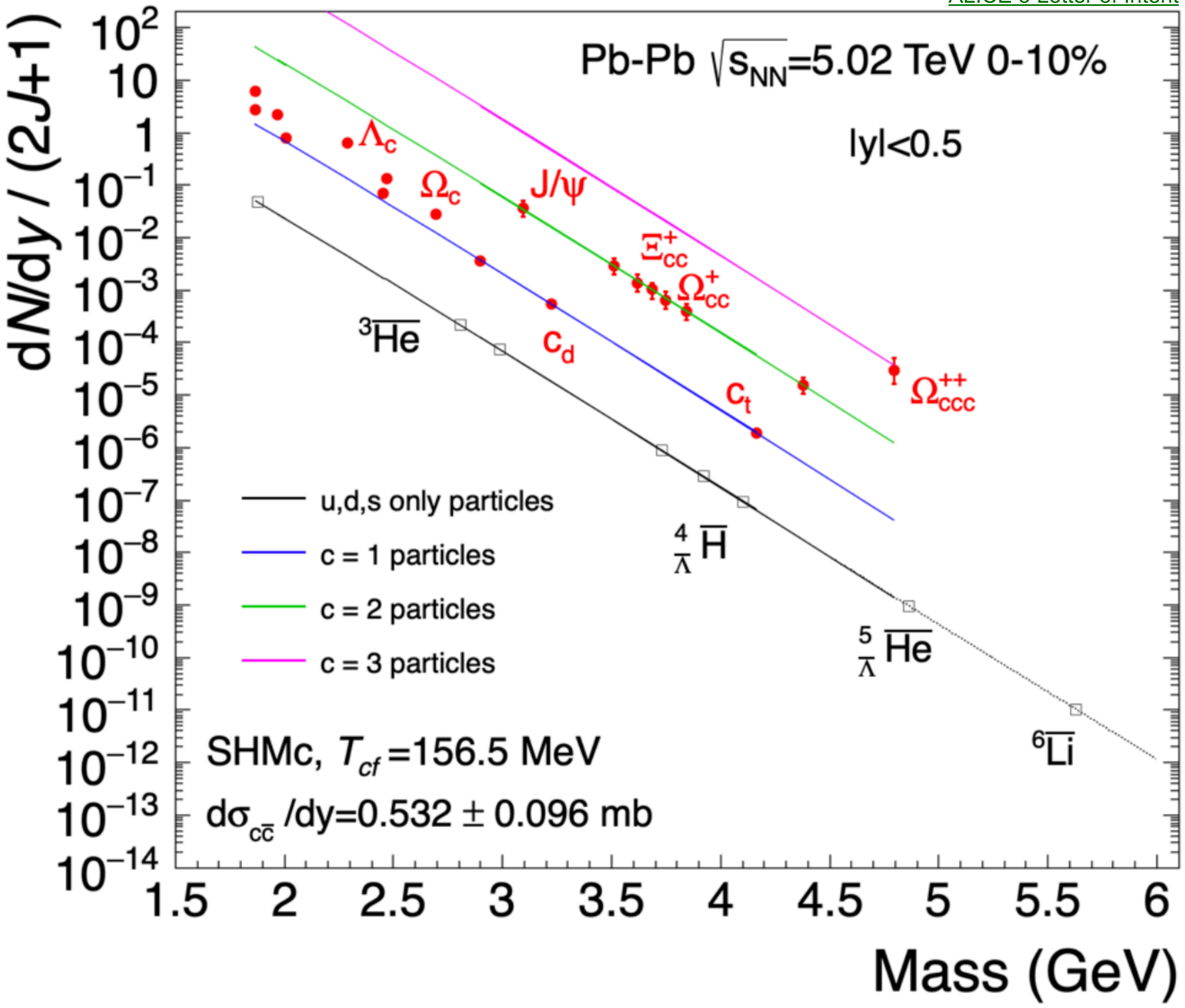
Forward production of ${}^{3}_{\Lambda}H$

https://cds.cern.ch/record/2868251/

First observation of hypertriton decays in LHCb!

Long term perspective: supernuclei

ALICE 3 Letter of Intent



Extending the nuclear chart to charm

- SHMc: yield comparable to that of nuclei already observed
  - B.R. expected to be O(%)
  - Lifetime O(100um/c): larger bkg

Discovery requires upgraded vertexing and rate capabilities: ALICE3

- In the meanwhile: constrain interaction models between N and charmed hadrons (see Emma Chizzali's talk)

Summary

- Heavy-ion experiments proved to be a powerful tool to study the properties of light hypernuclei
  - Best measurements of the lifetime, competing measurements of the binding energies
- Quantitative understanding of the new a completely new nucleosynthesis process
  - Let’s write a new section about it here: https://en.wikipedia.org/wiki/Nucleosynthesis#Major_types
- New ways into hypernuclei structure? Study of the production in small collision systems
  - More data coming from the experiments

Backup

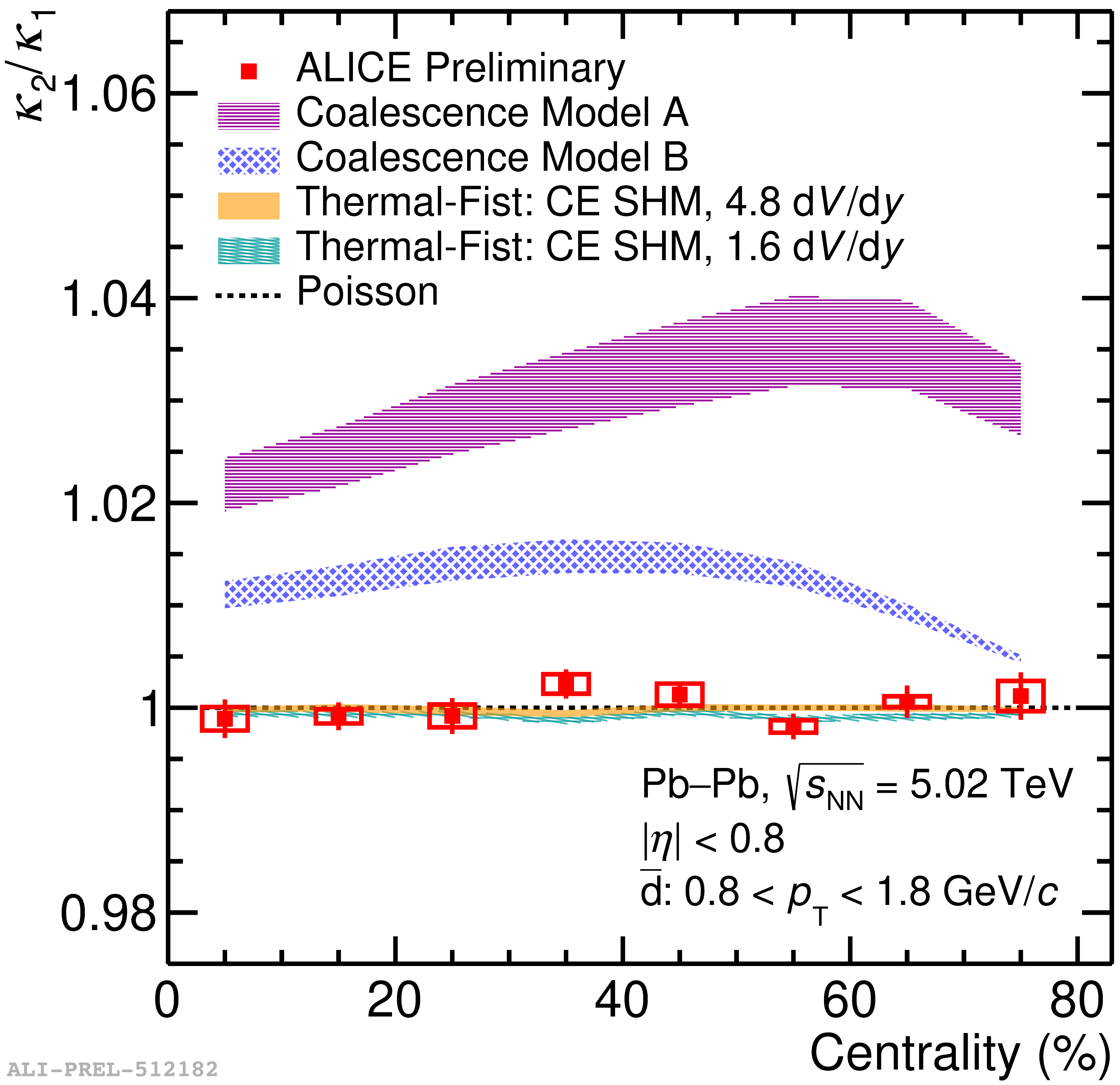
Beyond the average: antinuclei number fluctuations

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)

Phys. Rev. Lett. 131 (2023) 041901



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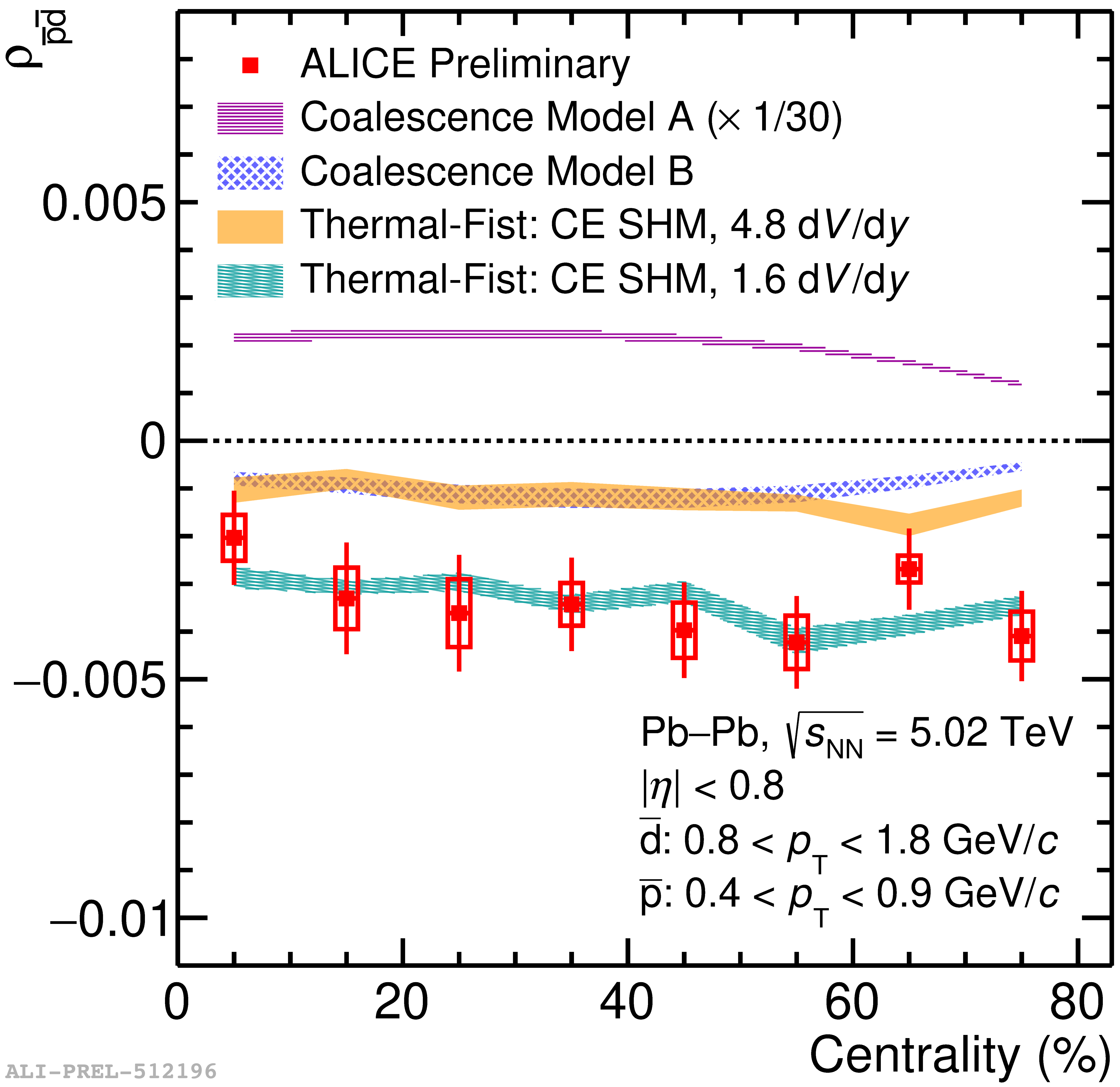
$$\rho_{\bar{p}\bar{d}} = \frac{\langle (n_{\bar{d}} - \langle n_{\bar{d}} \rangle)(n_{\bar{p}} - \langle n_{\bar{p}} \rangle) \rangle}{\sqrt{\kappa_{2\bar{d}} \kappa_{2\bar{p}}}}$$

- 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

Phys. Rev. Lett. 131 (2023) 041901



ALI-PREL-512196

The missing piece in all previous (and future) experiments

From the Mainz hypernuclei database:

$^{3}_{\Lambda}H$	
Ground State: Λ Binding Energy	our value: 0.148 ± 0.040 MeV
Ground State: Lifetime	our value: 237^{+10}_{-9} ps
Branching Ratios - (Non)-Mesonic Weak Decays	
R3: MWD into π^- Two-Body to all π^- MWD	our value: $0.357^{+0.028}_{-0.027}$

Display options: ◉ Branching Ratio ○ Decay Width

Only relative B.R.s available! Extrapolation to absolute BR through ΔI = 1/2 rule

Knowledge of the BR is one of the fundamental missing pieces to be measured to constrain the theories of interactions within the hypernuclei

But how do we access the absolute B.R. in the future?

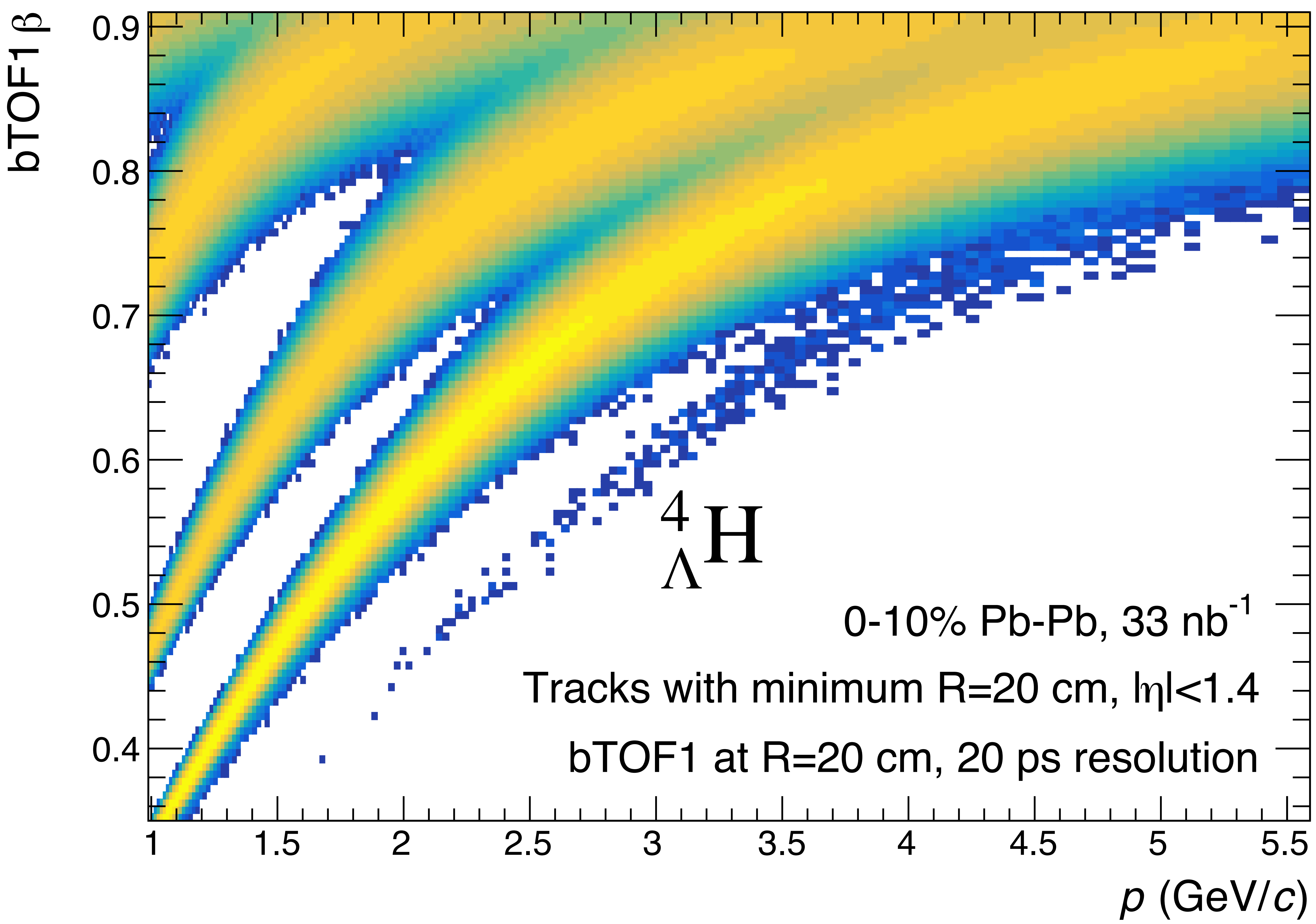
- In Pb-Pb at the LHC hypernuclei have an average momentum ~ their mass (βγ~1)
- Hypernuclei with A5 have a lifetime comparable to the free Λ

We might identify hypernuclei before they decay: direct access to the absolute yield/B.R. using a time of flight detector close to the interaction region

Direct identification of hypernuclei at the LHC

First look using Delphes and correct yields of particles

- Assuming a few % momentum resolution and a time measurement at 20 cm from the particle production point
- Using 20ps resolution the ${}^{4}_{\Lambda}\mathrm{H}$ is clearly separated from the triton
- For ${}^{4}_{\Lambda}\mathrm{He}$ good separation of Z=2 charges is required
- For ${}^{3}_{\Lambda}\mathrm{H}$ a better timing resolution in is necessary



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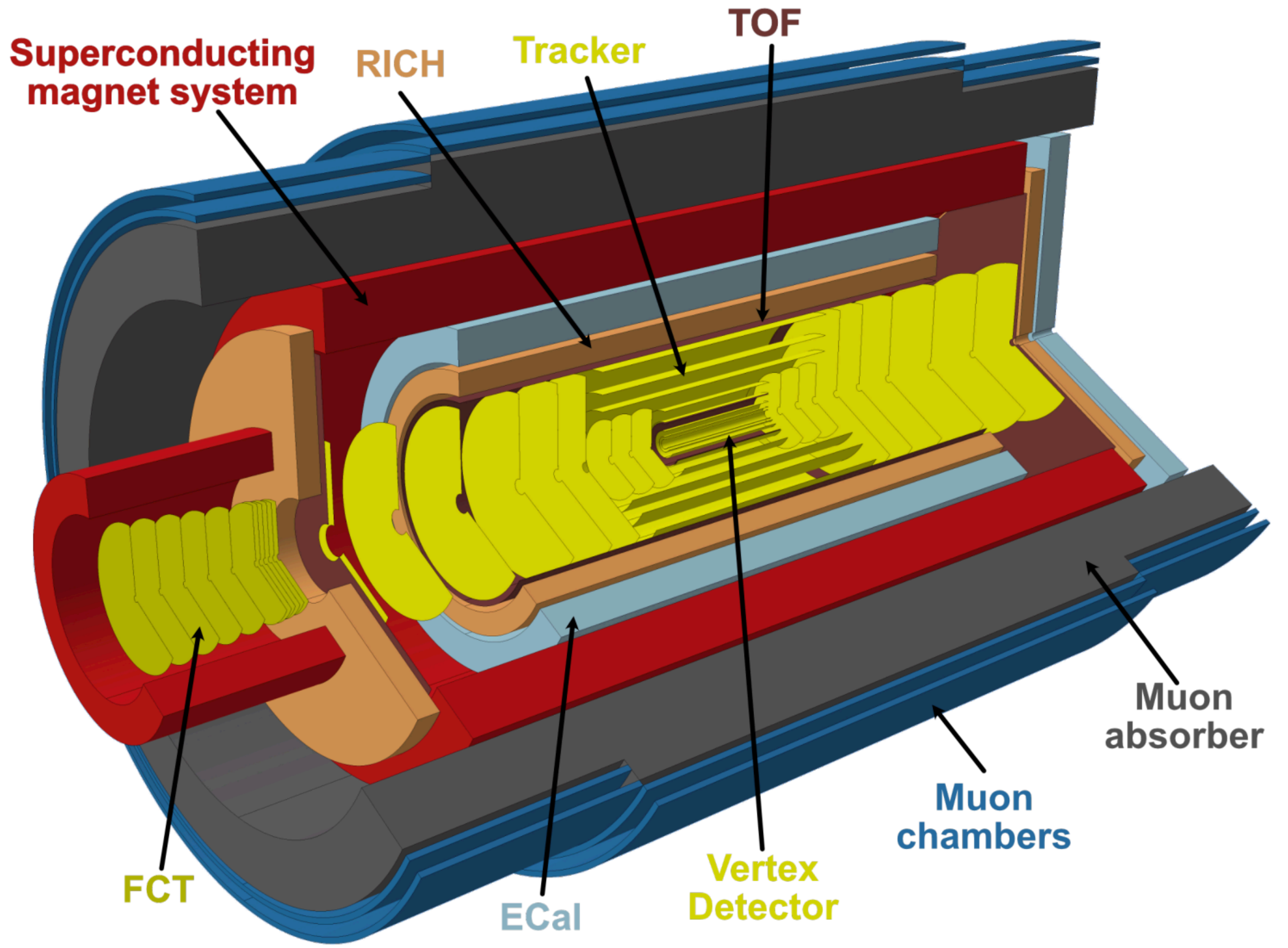
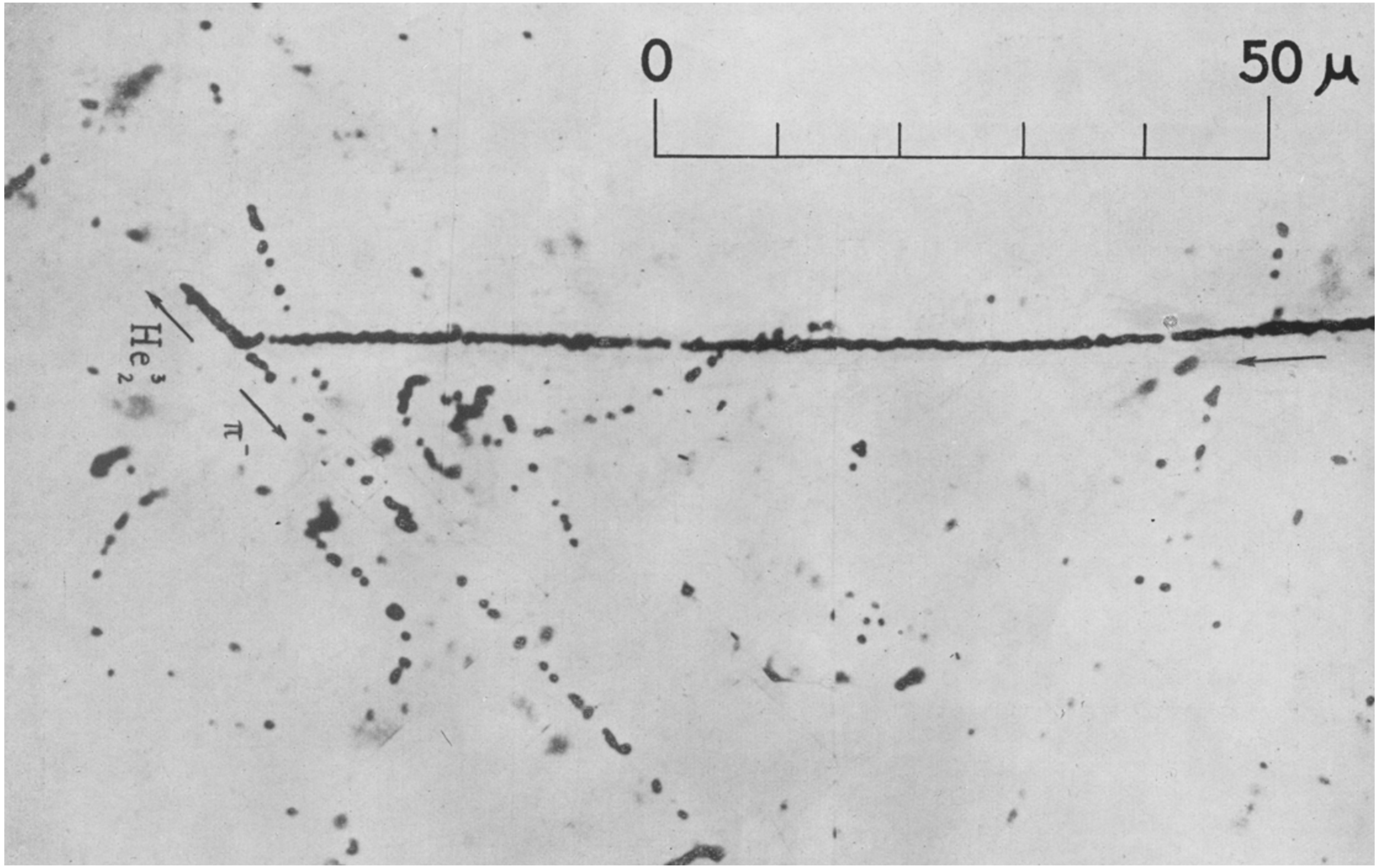
ALICE3 Letter Of Intent arxiv:2211.02491



Not a wild dream, but a project: ALICE3

- (Almost) all silicon experiment with detection plans as close as 5 mm to the interaction region and two TOF detectors with required time resolution of approximately 20ps

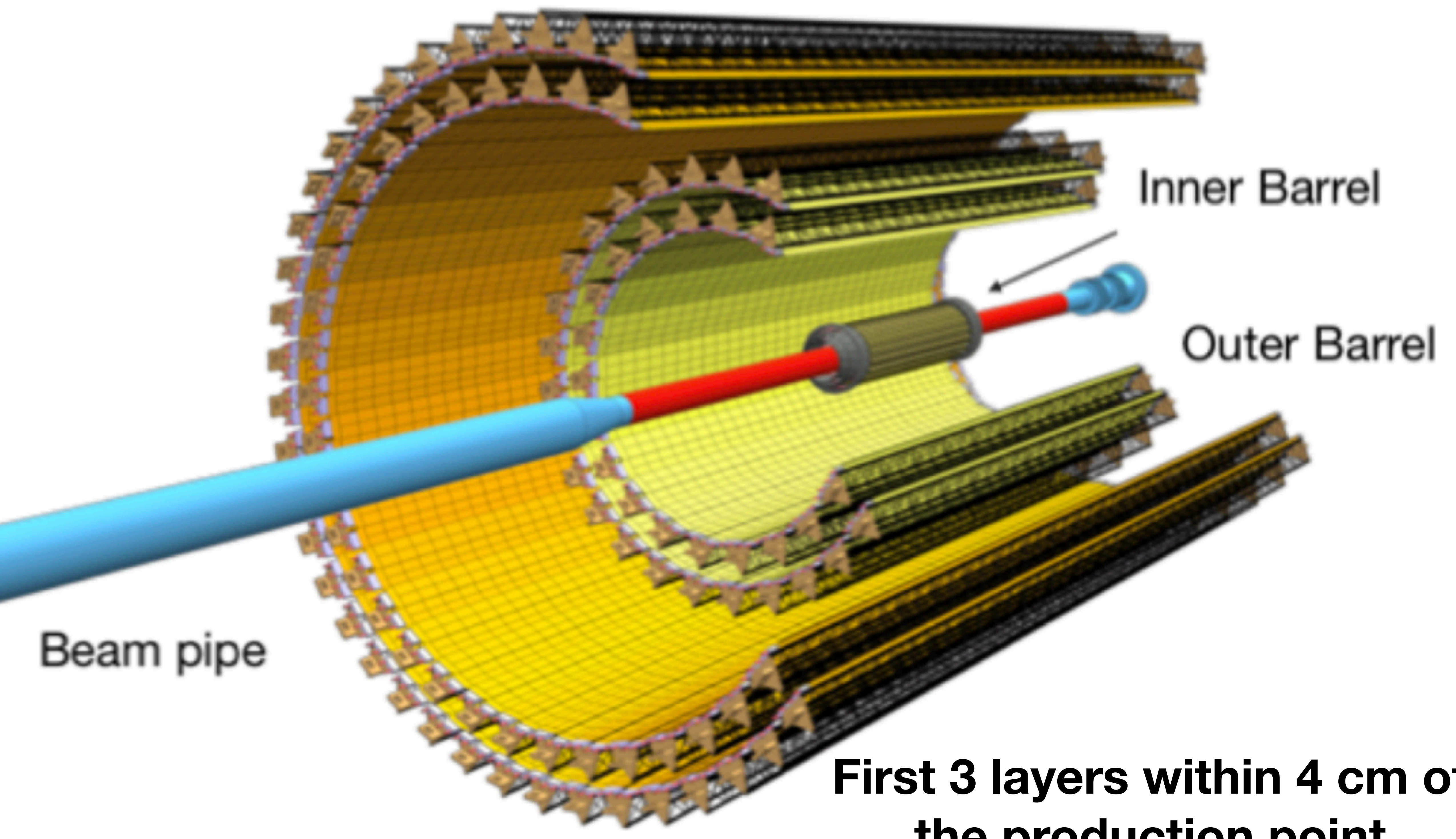
Maybe we don't have to wait that long



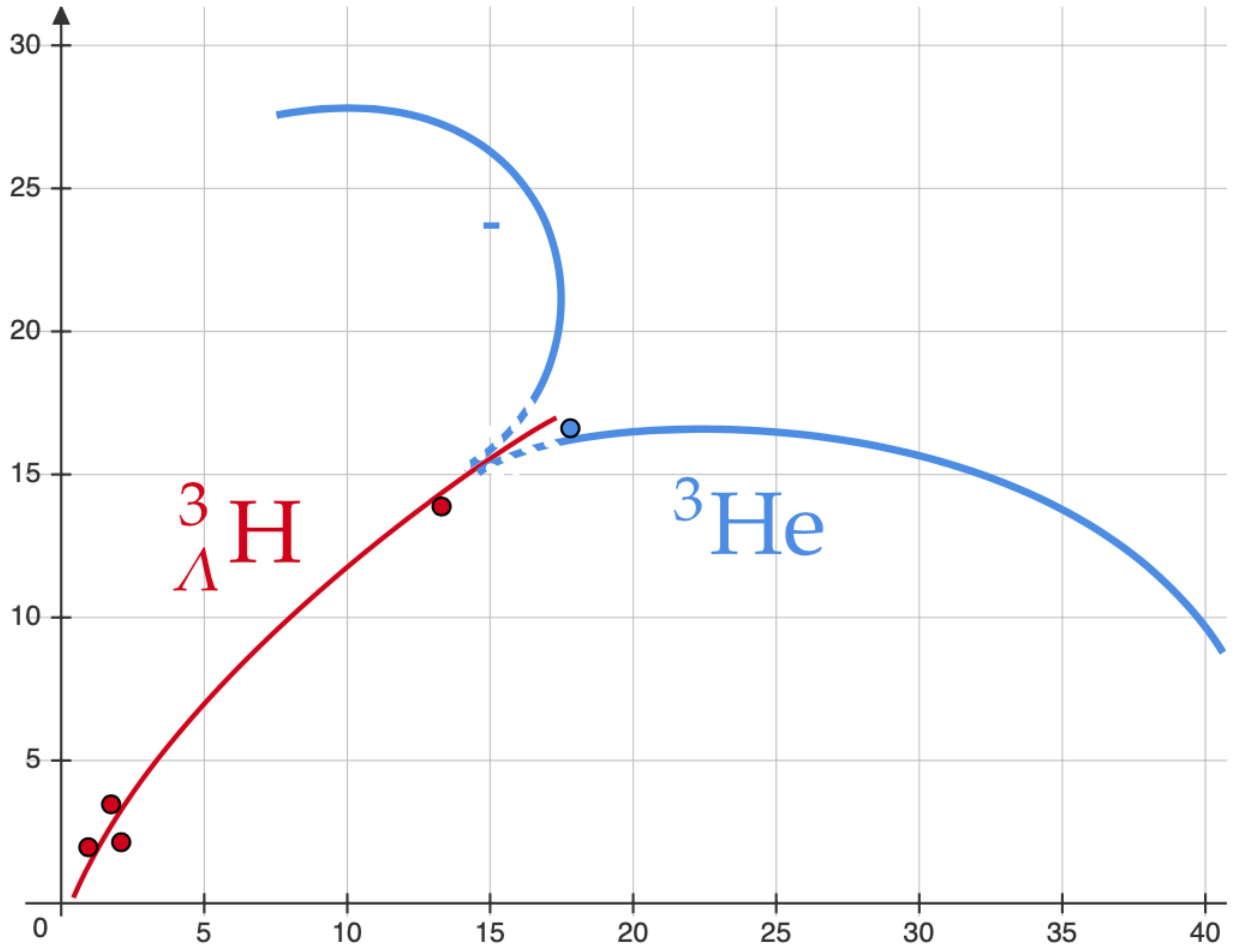
A Bonetti, R Levi Setti, M Panetti, L Scarsi, and G Tomasini. „On the possible ejection of a meson-active triton from a nuclear disintegration“. In: *Il Nuovo Cimento (1943-1954)* 11.2 (1954), pp. 210–212

A MHz silicon bubble chamber

ALICE ITS2



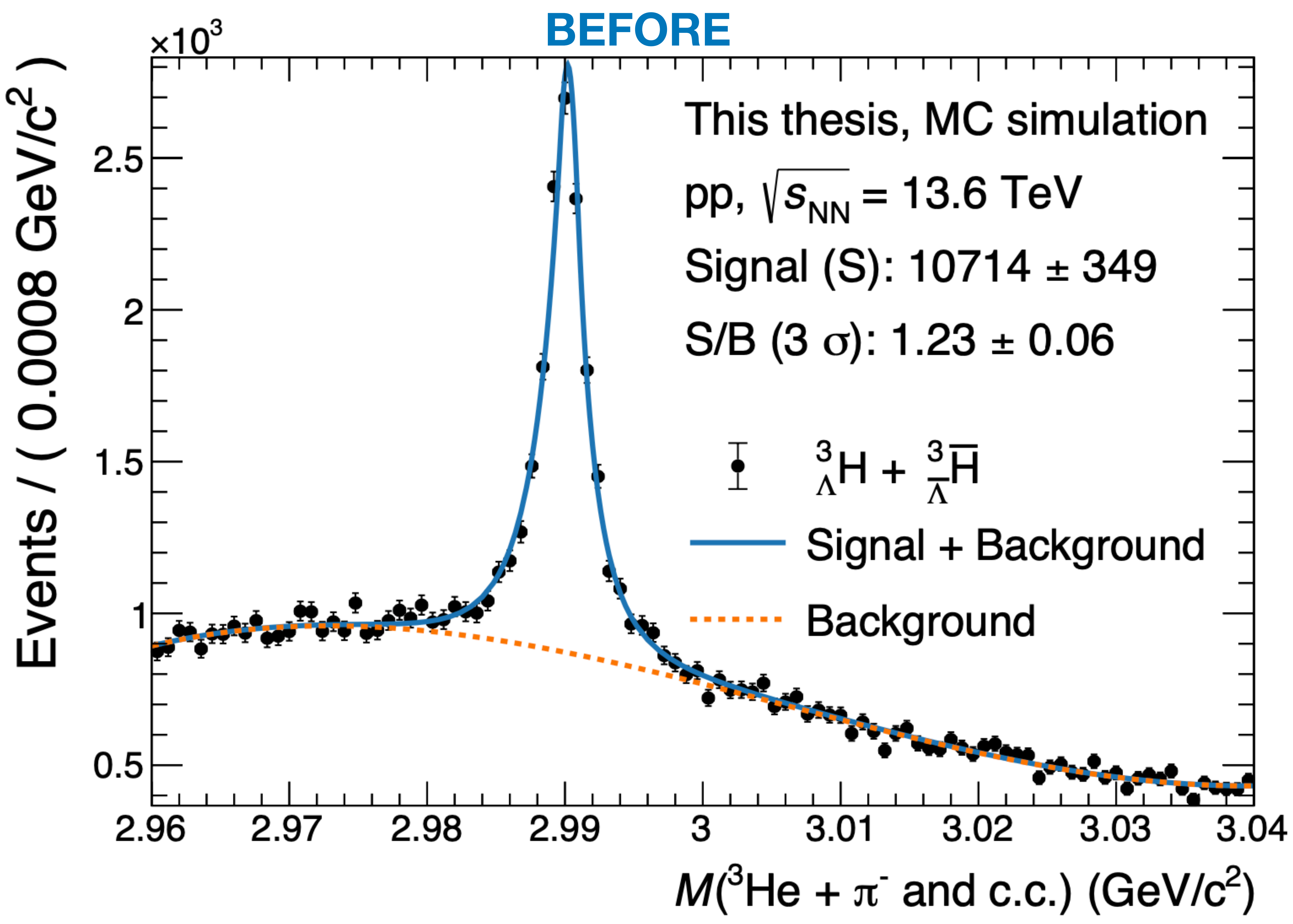
First 3 layers within 4 cm of the production point

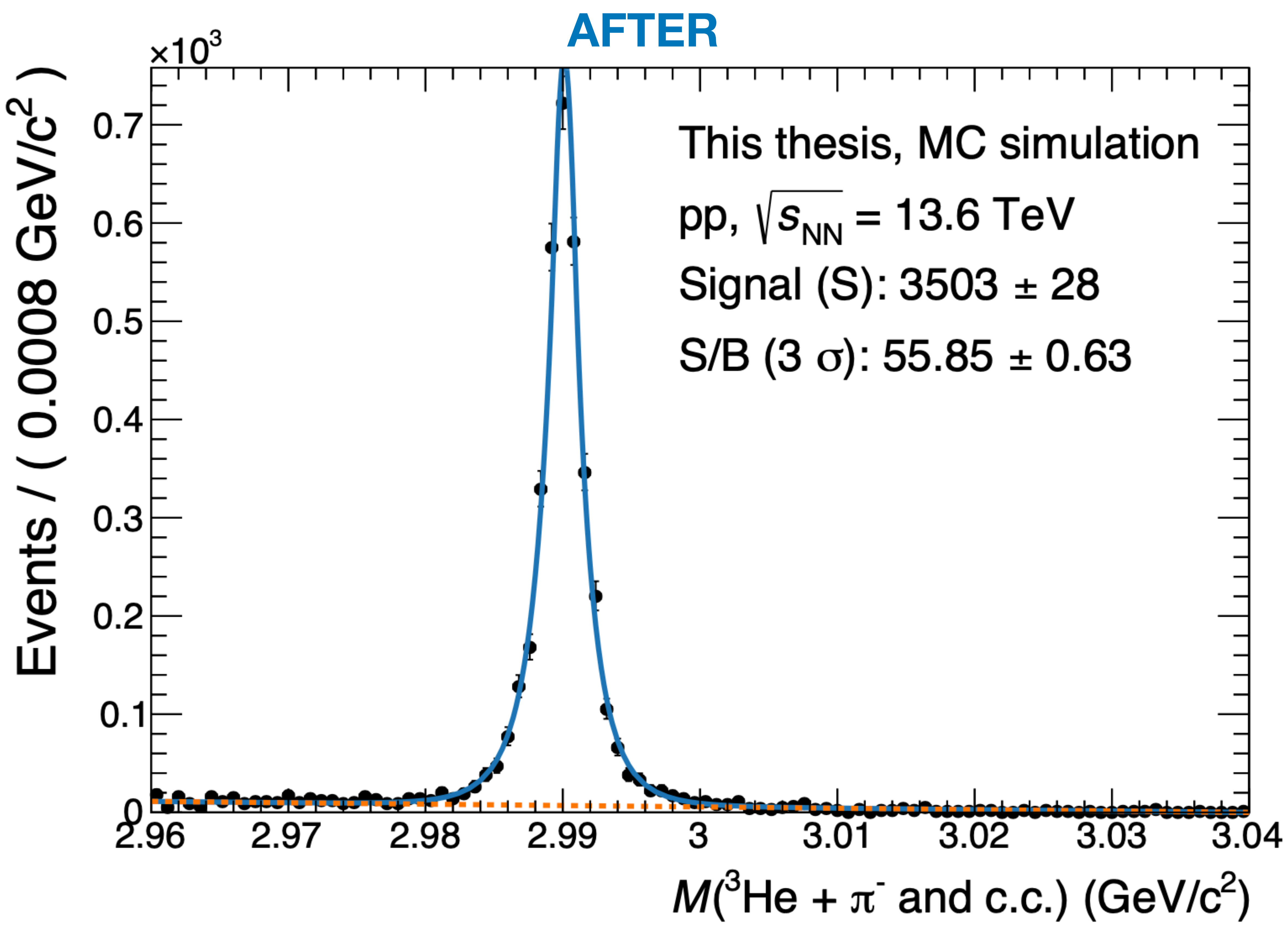


From decay vertex reconstruction to full kinematic closure by tracking the mother track

A MHz silicon bubble chamber

F. Mazzaschi PhD thesis

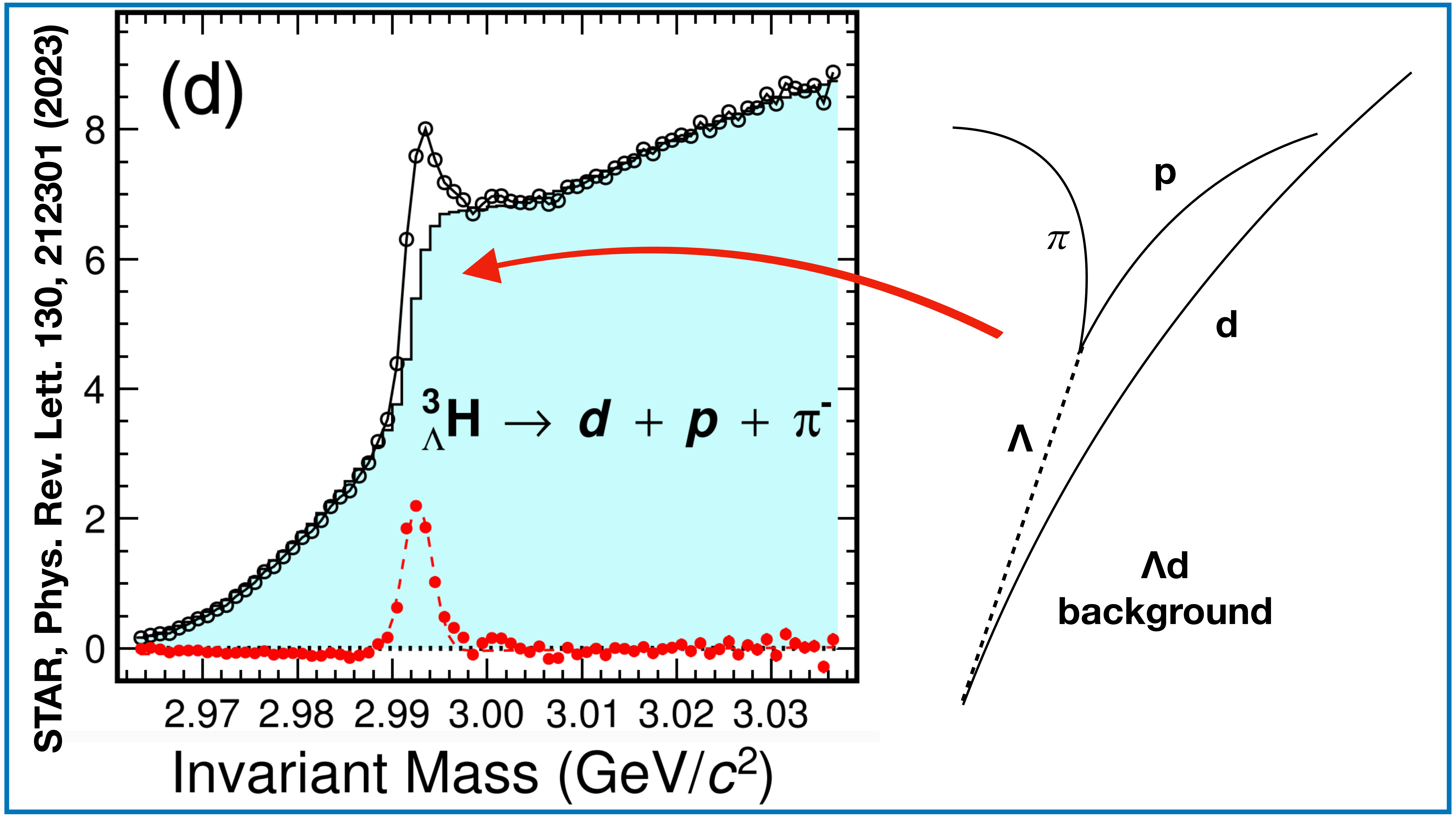


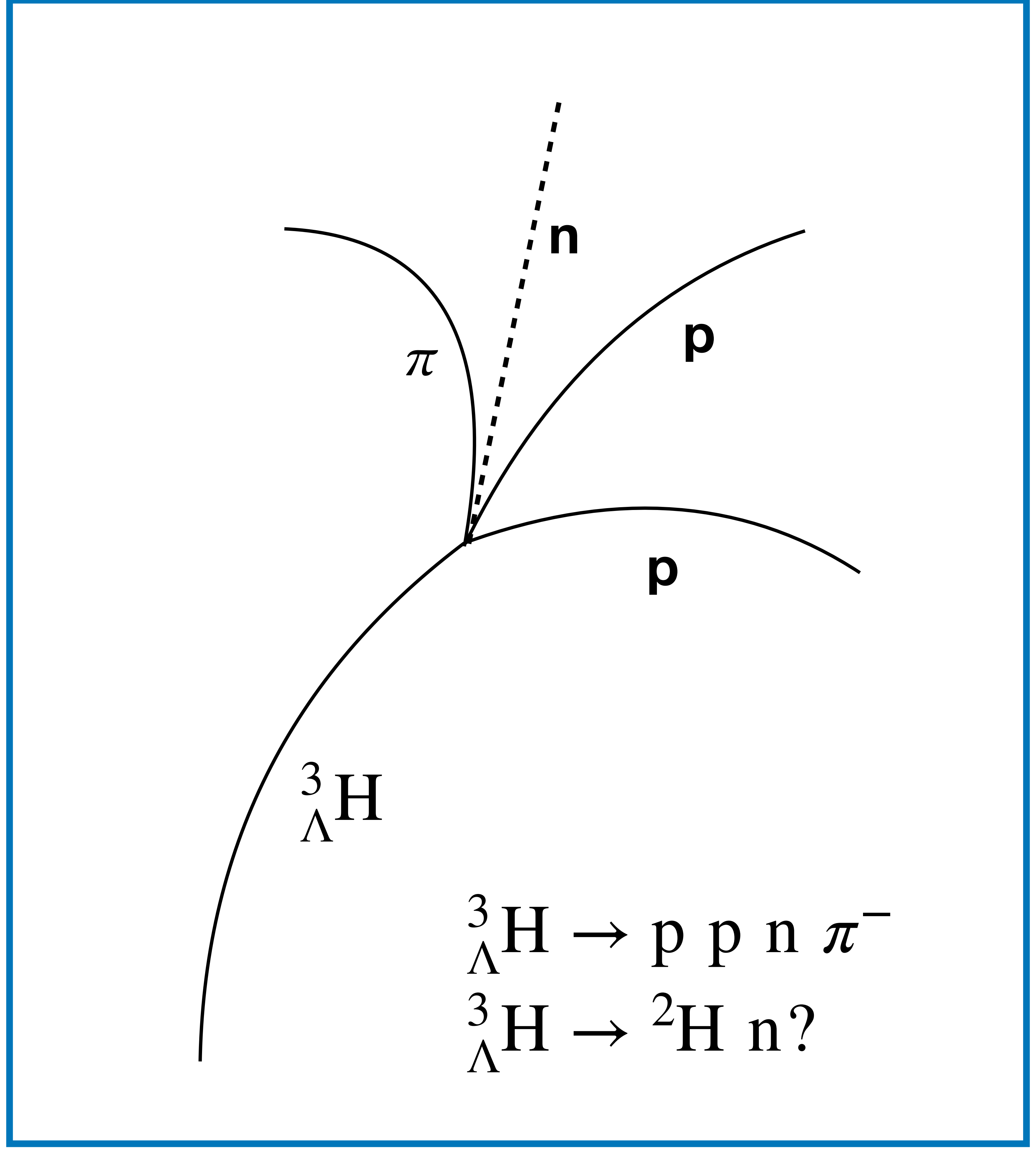


From decay vertex reconstruction to full kinematic closure by tracking the mother track

- Extreme reduction of the combinatorial background with no additional selections

A MHz silicon bubble chamber



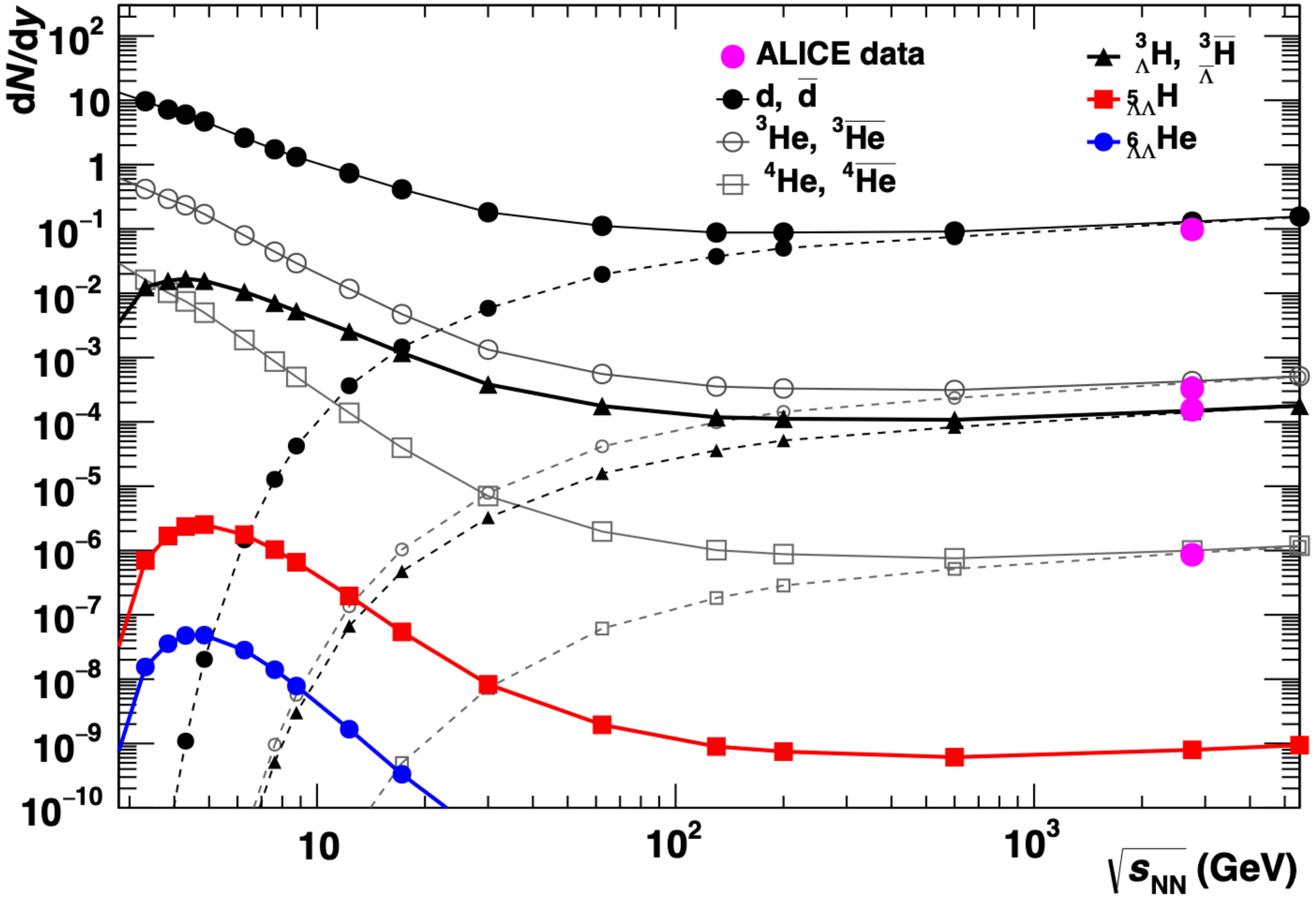


From decay vertex reconstruction to full kinematic closure by tracking the mother track

- Extreme reduction of the combinatorial background with no additional selections
- Potential of removing correlated background in the 3-body decay of Hypertriton and to study decays with neutral particles in the final state

SPS can be a great facility for hypernuclei

B. Dönigus, P. Braun-Munziger *Nucl.Phys.A* 987 (2019) 144-201



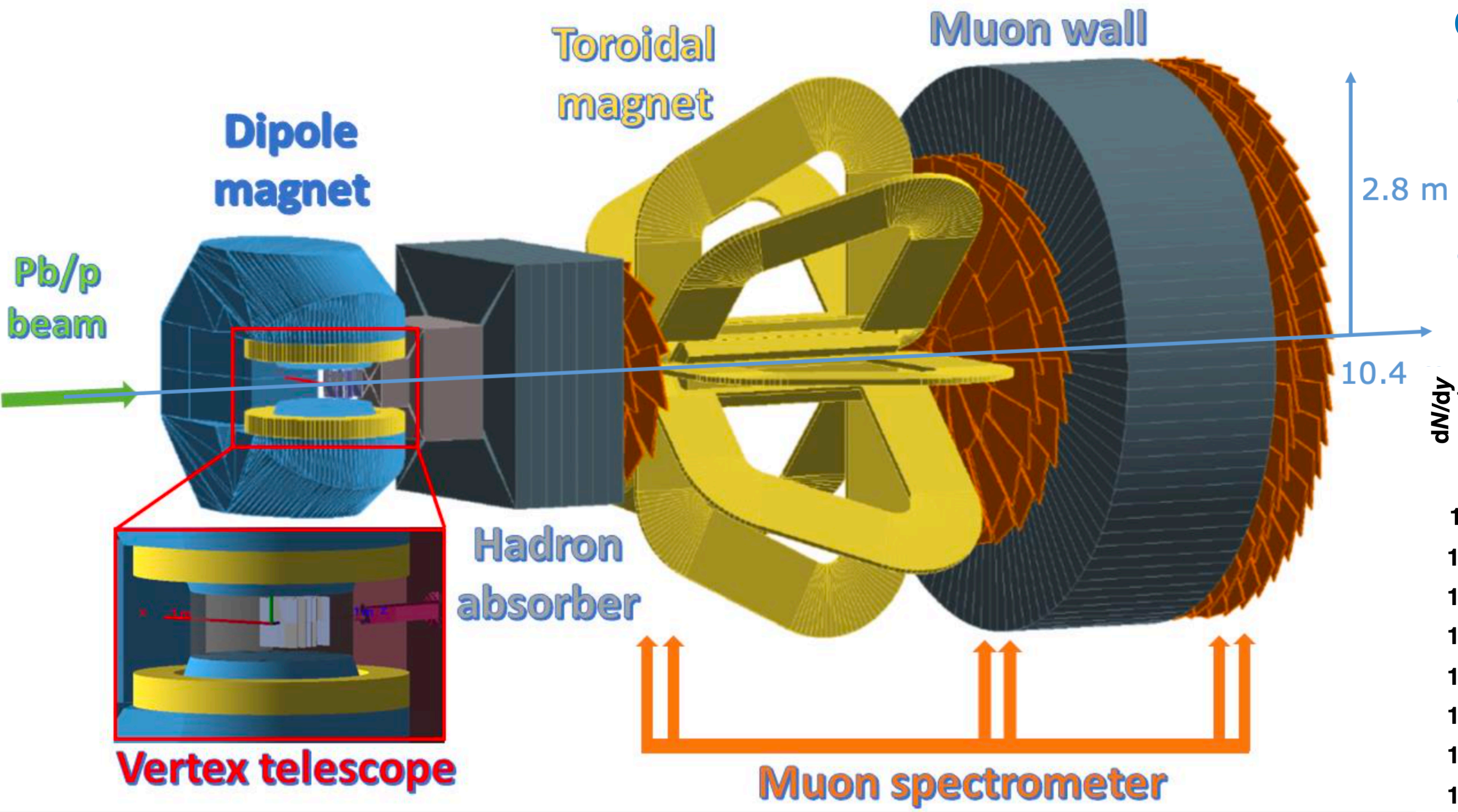
At the LHC we will manage to get the first measurement of A=5 antihypernuclei

- However we are far from precision physics for A=5: they will be few hundreds
- Ultimately not so interesting for the community

Lower energy heavy-ion experiments have a great statistics advantage

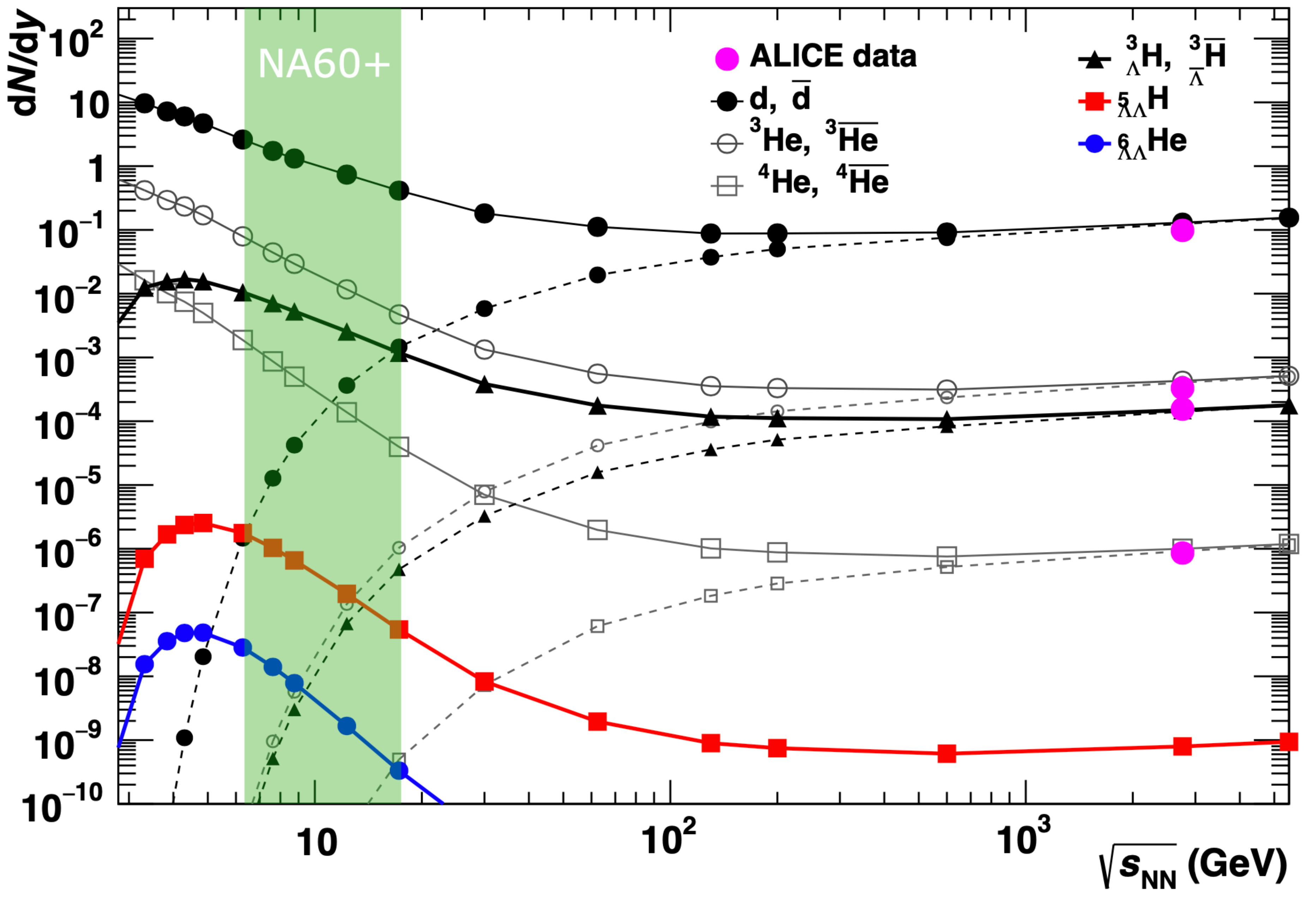
- SPS we will be unbeatable in terms of statistical precision for hypernuclei up to A=6
- Only other low energy facilities can compete (see CBM@SIS100)

Hypernuclei in NA60+



Heavy ion experiment at the SPS with a focus on heavy-flavour and di-leptons and high rate capabilities

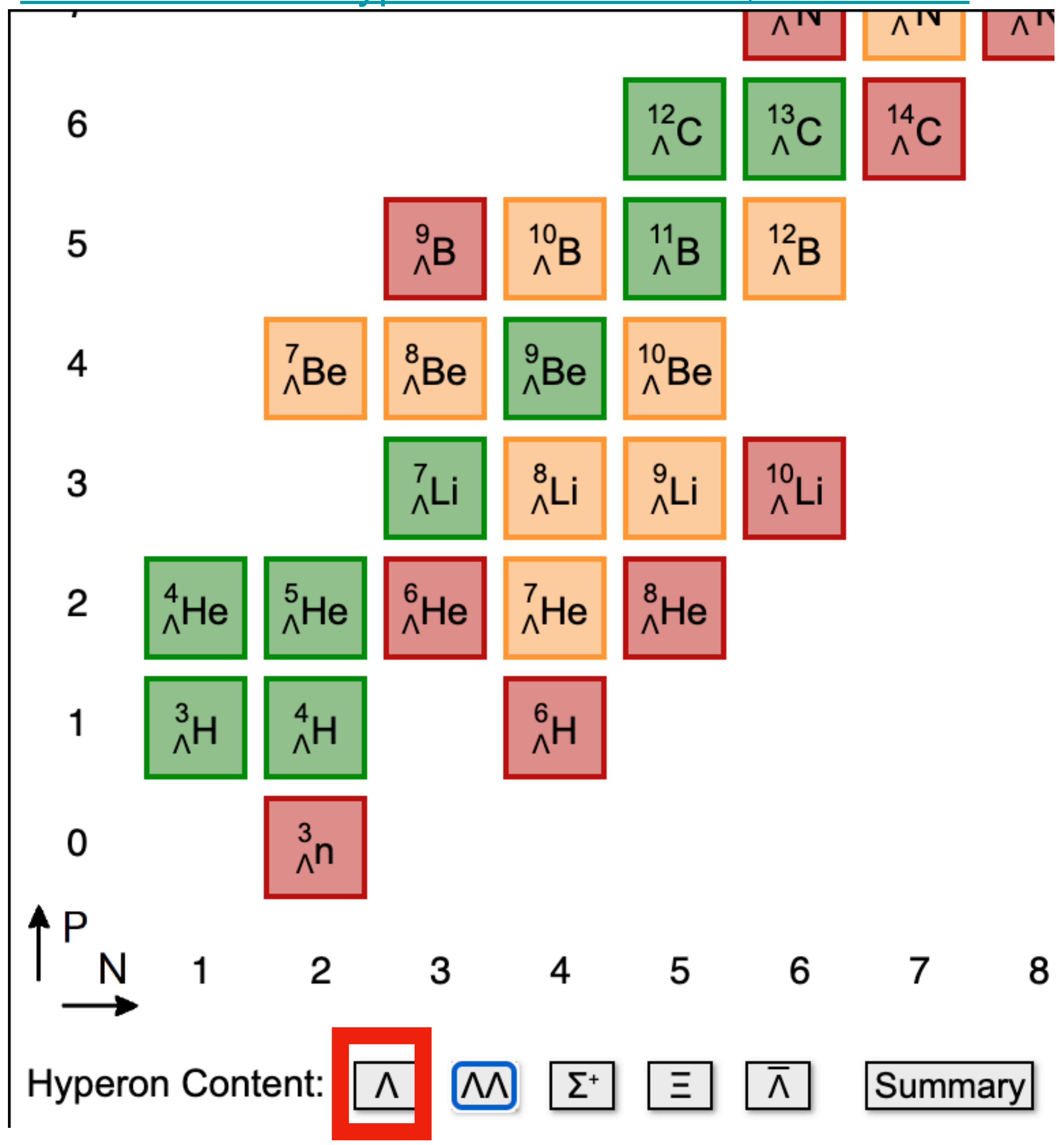
- 10^{11} MB Pb-Pb events per month of data taking
- Collision $\sqrt{s_{NN}}$ scan in the range 6-17 GeV

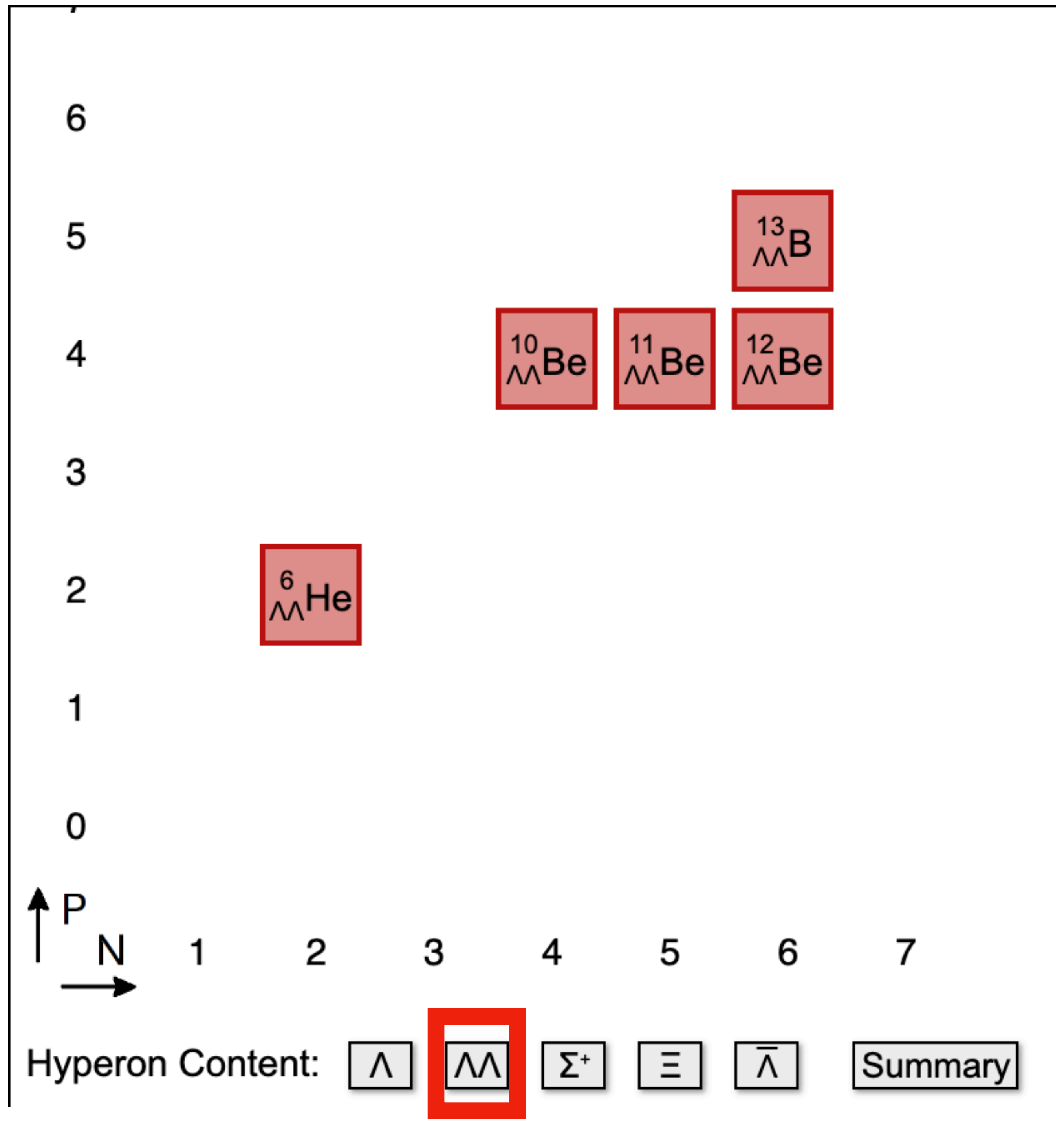


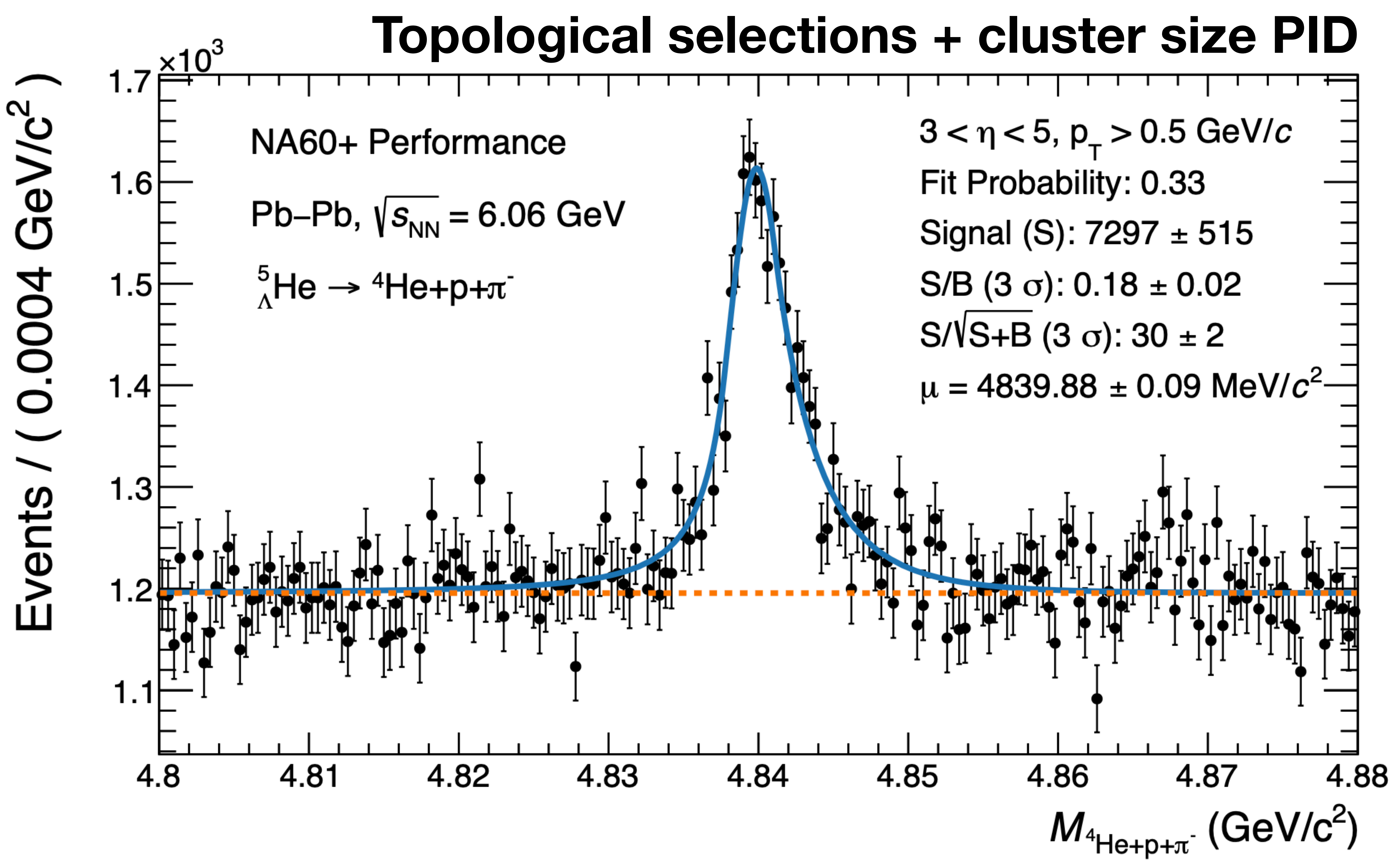
More details on the project in E. Scomparin talk on 6th June

Hypernuclei in NA60+

From the Mainz hypernuclei database, June 2023







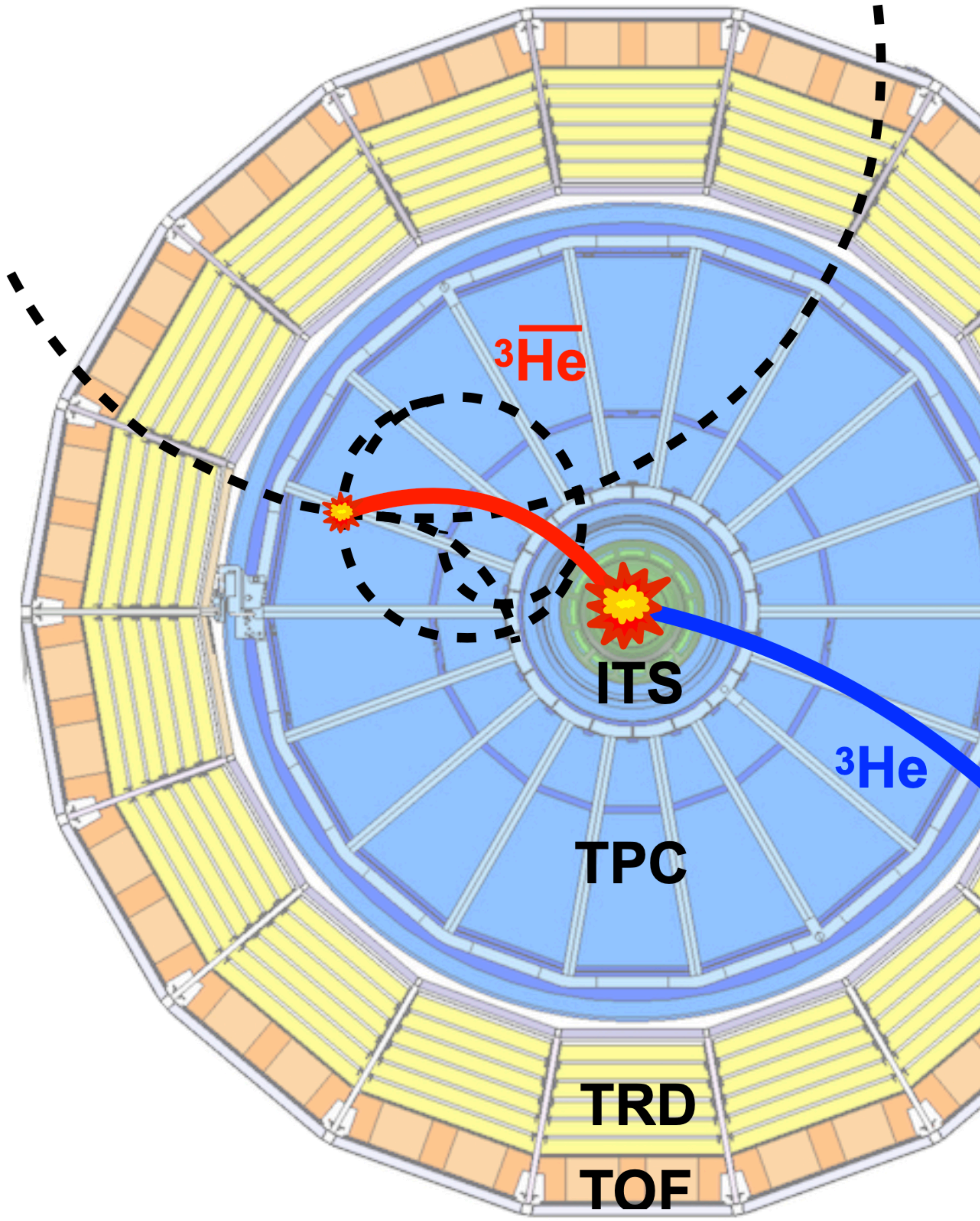
Open points in hypernuclear physics that can be addressed with NA60+:

- Precise characterisation of **known states**: properties of Λ hypernuclei, **charge symmetry breaking**
- Properties and confirmation of **poorly known**/**unknown** hypernuclei: **A=6**, **light ΛΛ hyper nuclei**
- **Possible discovery of light Ξ and Σ hypernuclei** bound according to theory [1,2] (e.g. NNNΞ)

[1] E. Hiyama et al. *Phys. Rev. Lett.* 124, 092501
[2] H. Le et al. *Eur. Phys. J. A* (2021) 57: 339

Low energy anti-^{3}He interaction cross section

- Opportunity to extract the cross section using the ALICE detector material as a target
  - Antimatter is expected to interact a lot with the material via annihilation processes!!



Material budget at mid-rapidity:
- Beam pipe (~0.3% X_0)
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ALICE, arXiv:2202.01549, Nat. Phys. (2022)

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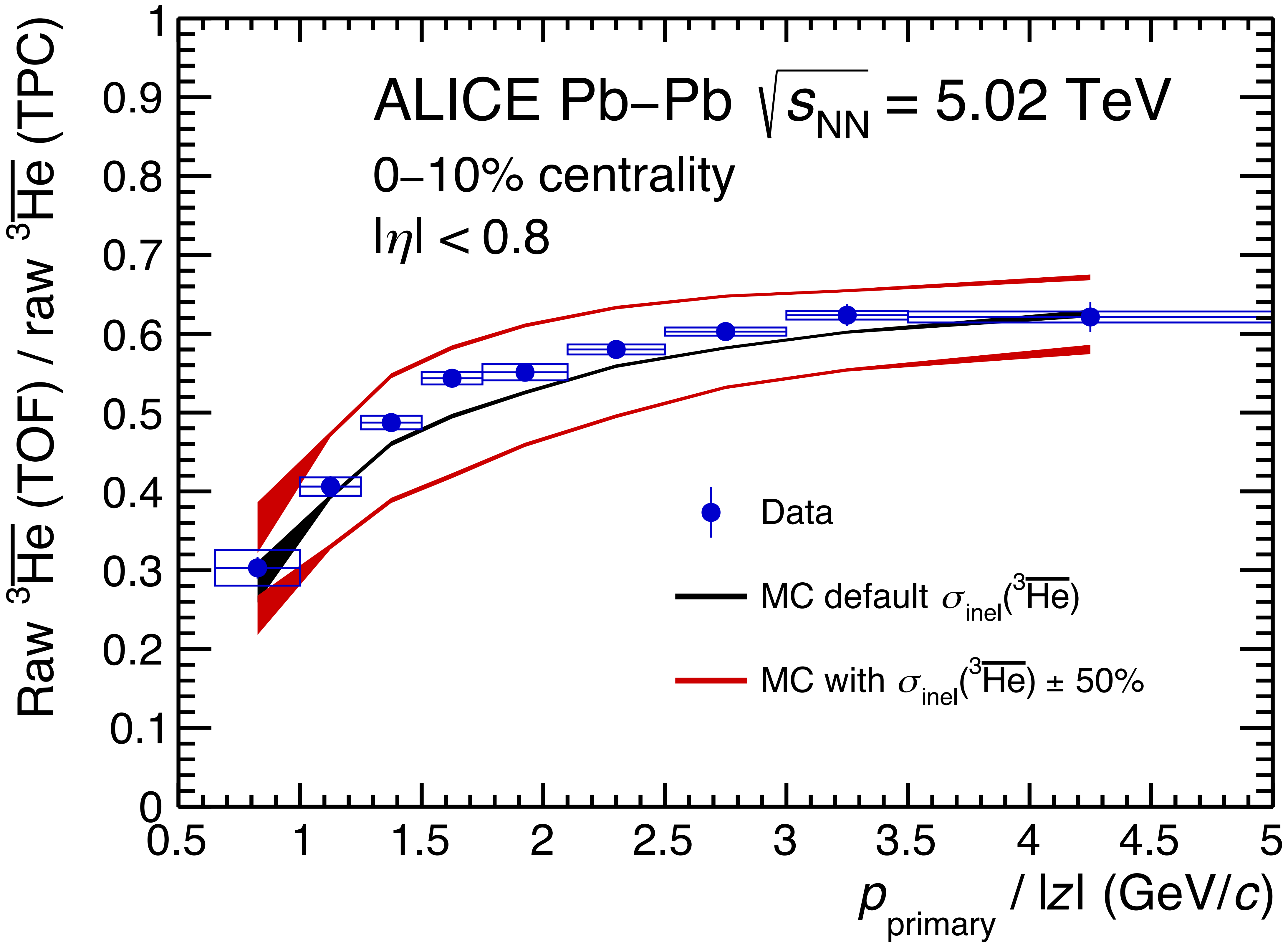
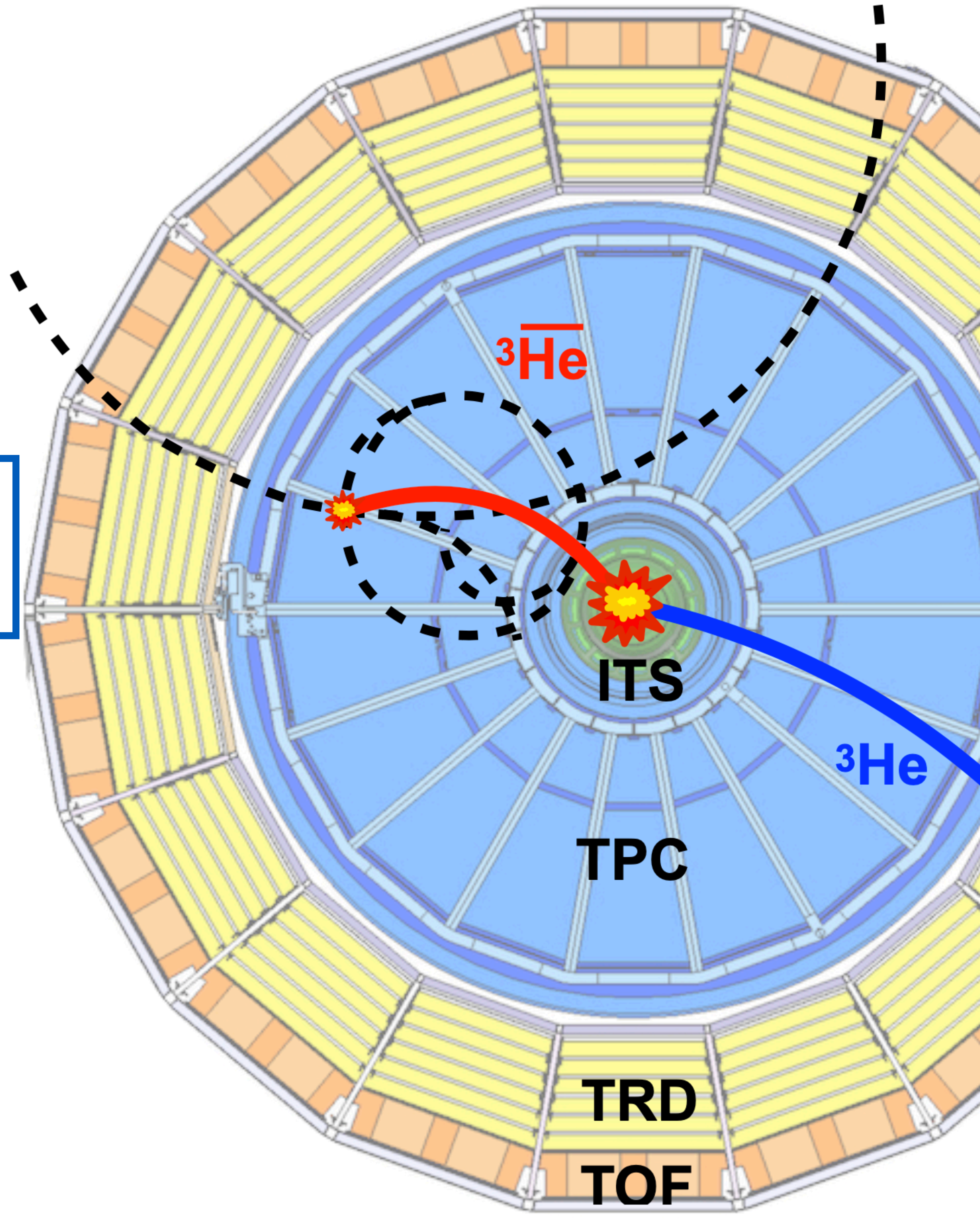


Measurement of the anti-^{3}He before and after TOF matching



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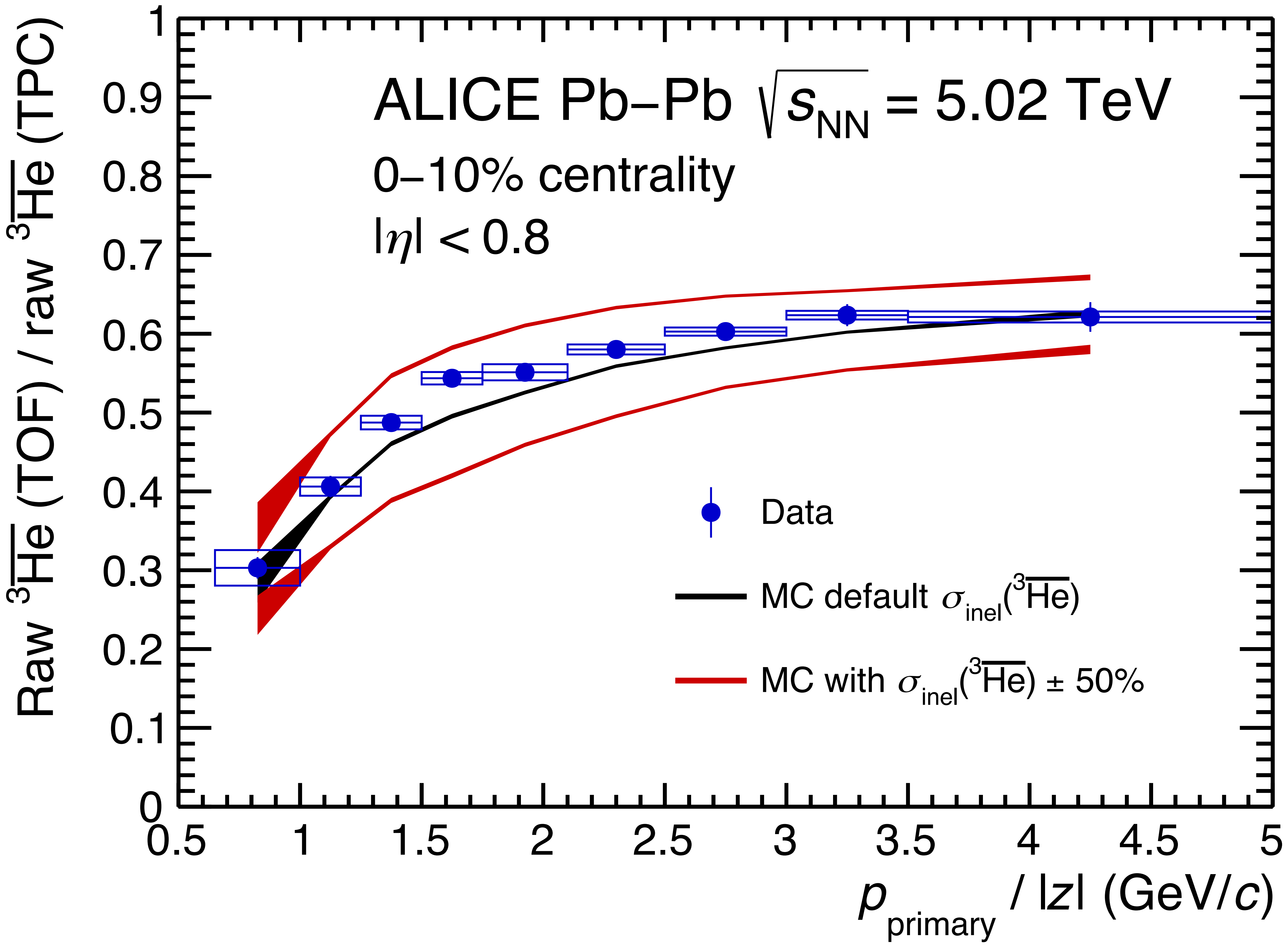

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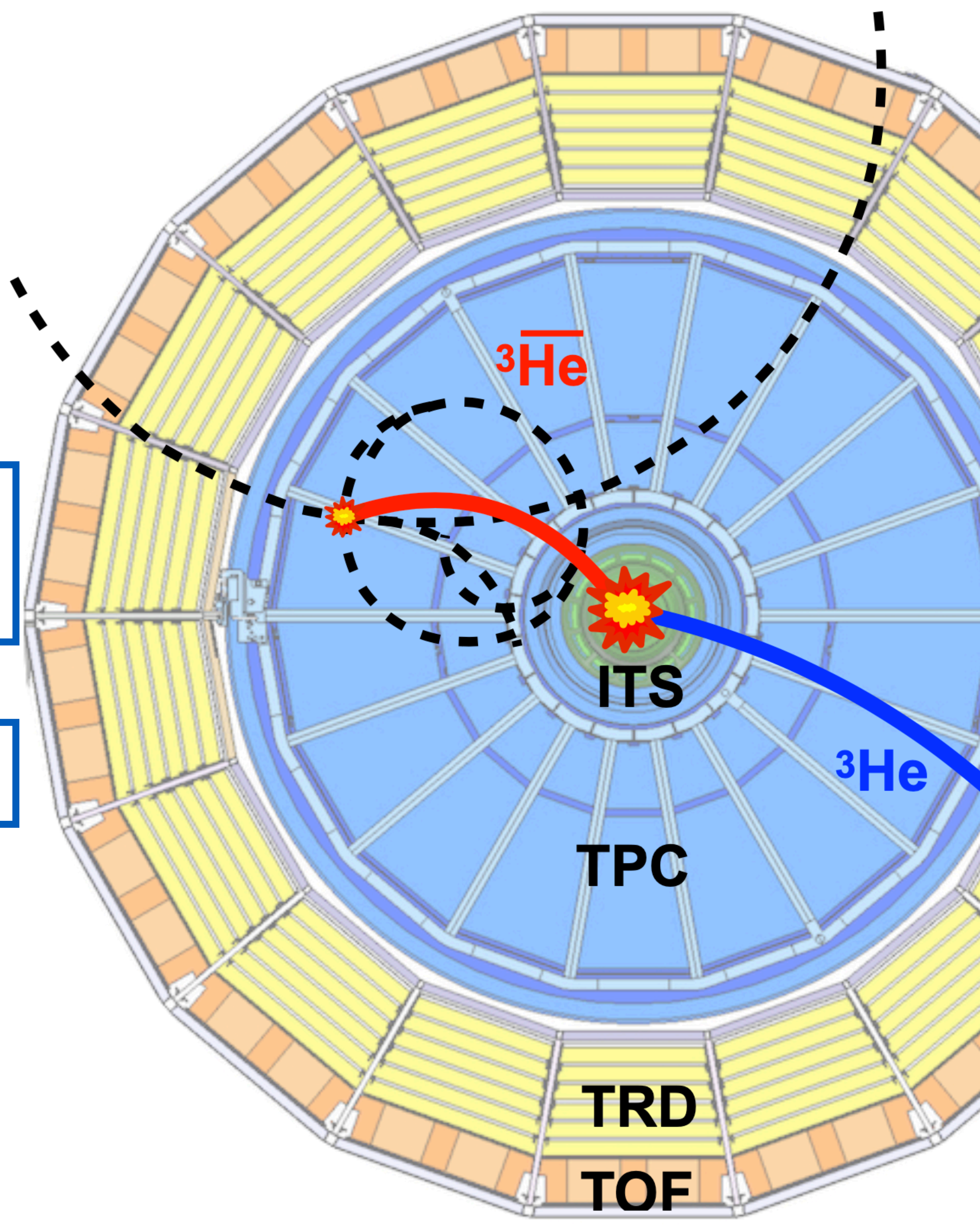
Comparison with GEANT4 MC



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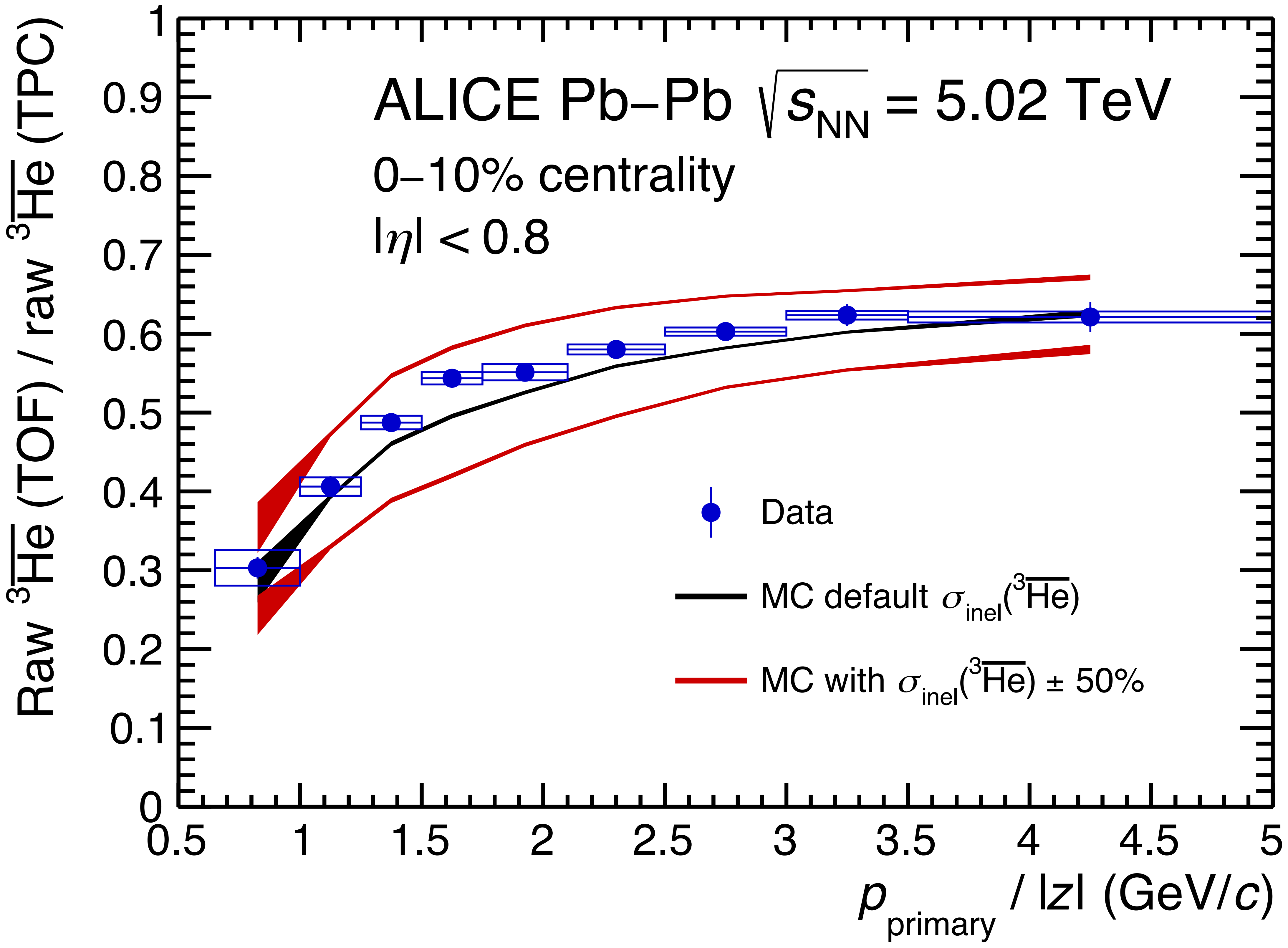

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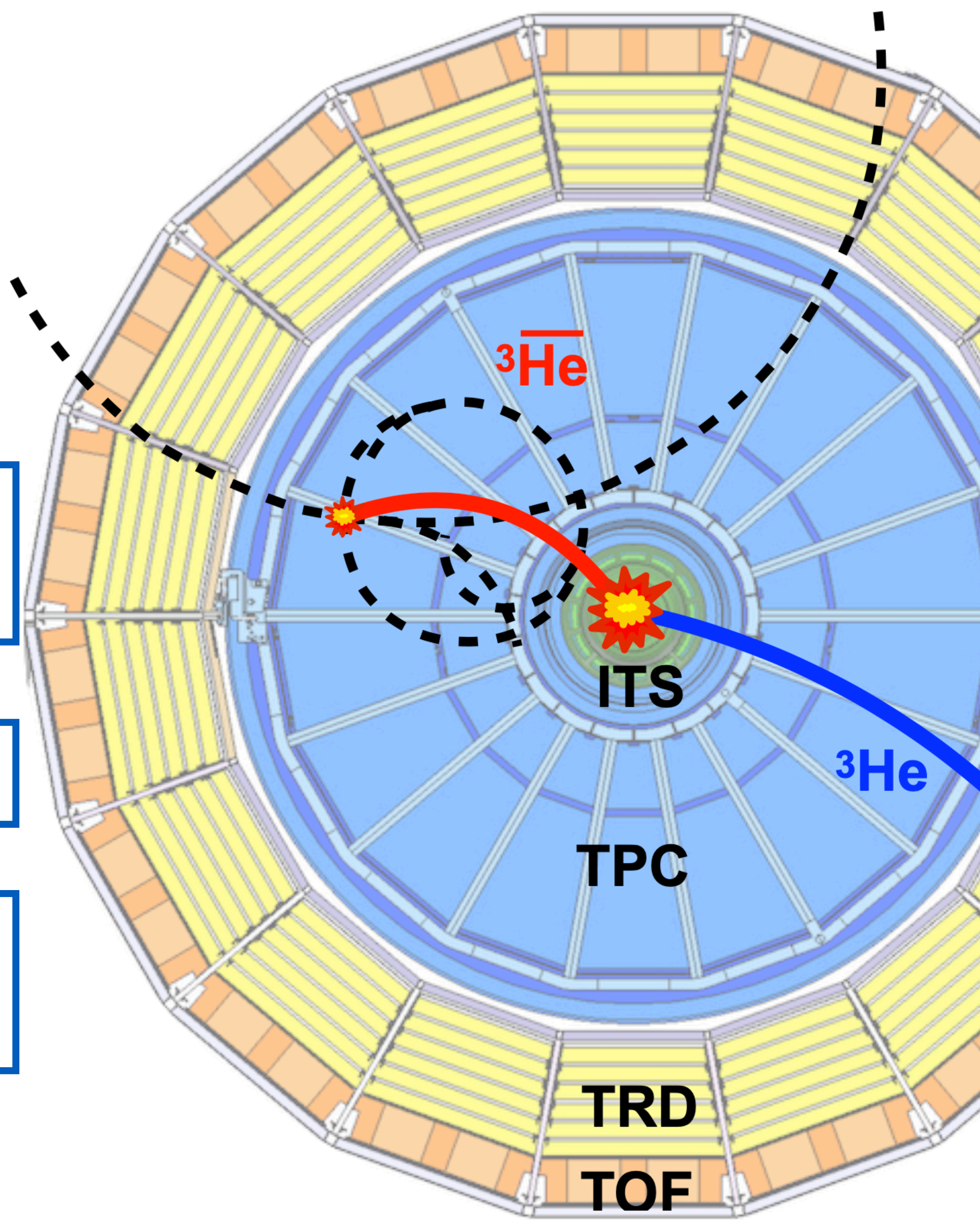
Variations of the GEANT4 anti-^{3}He inelastic cross sections



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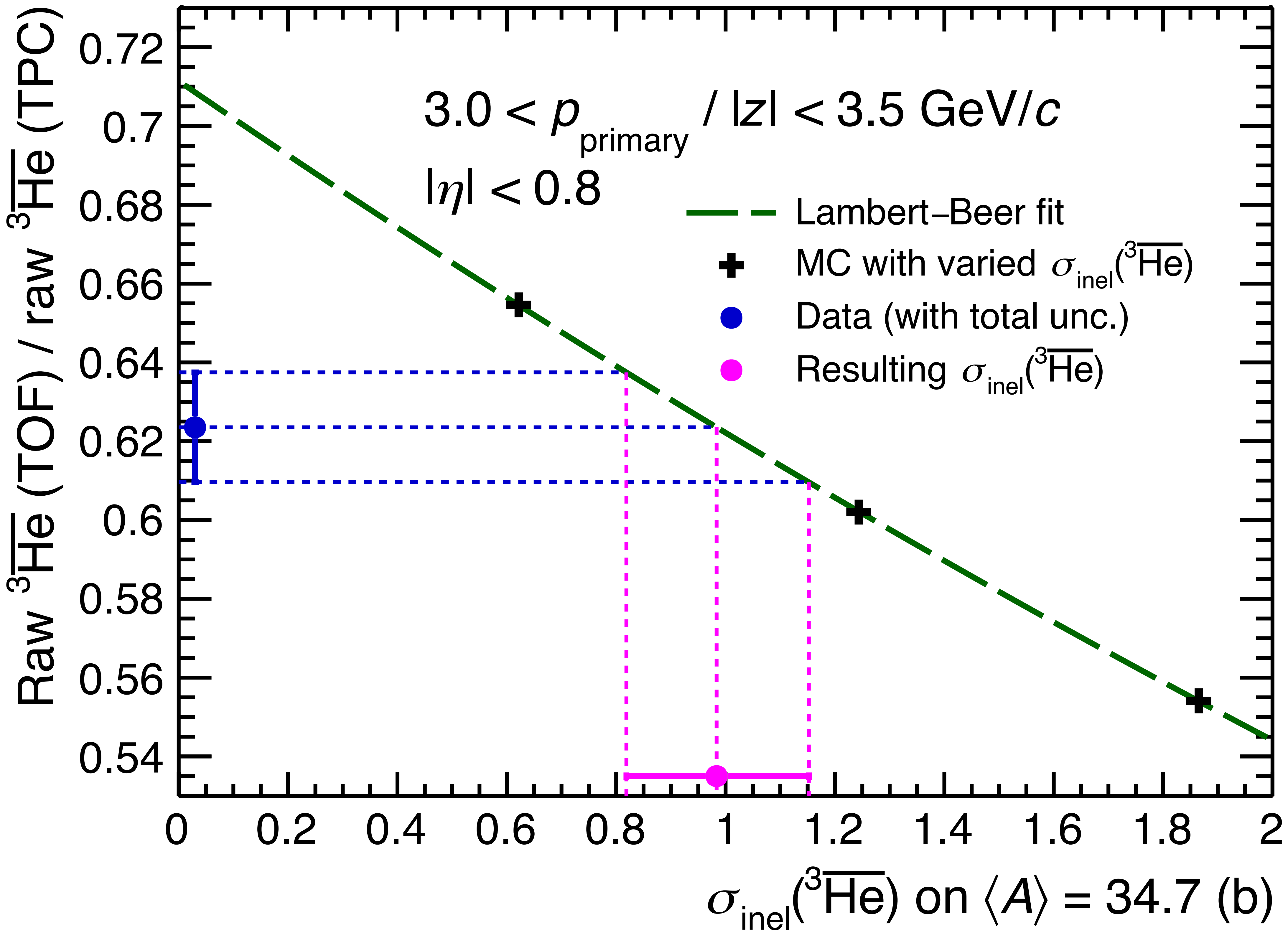

Measurement of the anti-^{3}He before and after TOF matching

Comparison with GEANT4 MC

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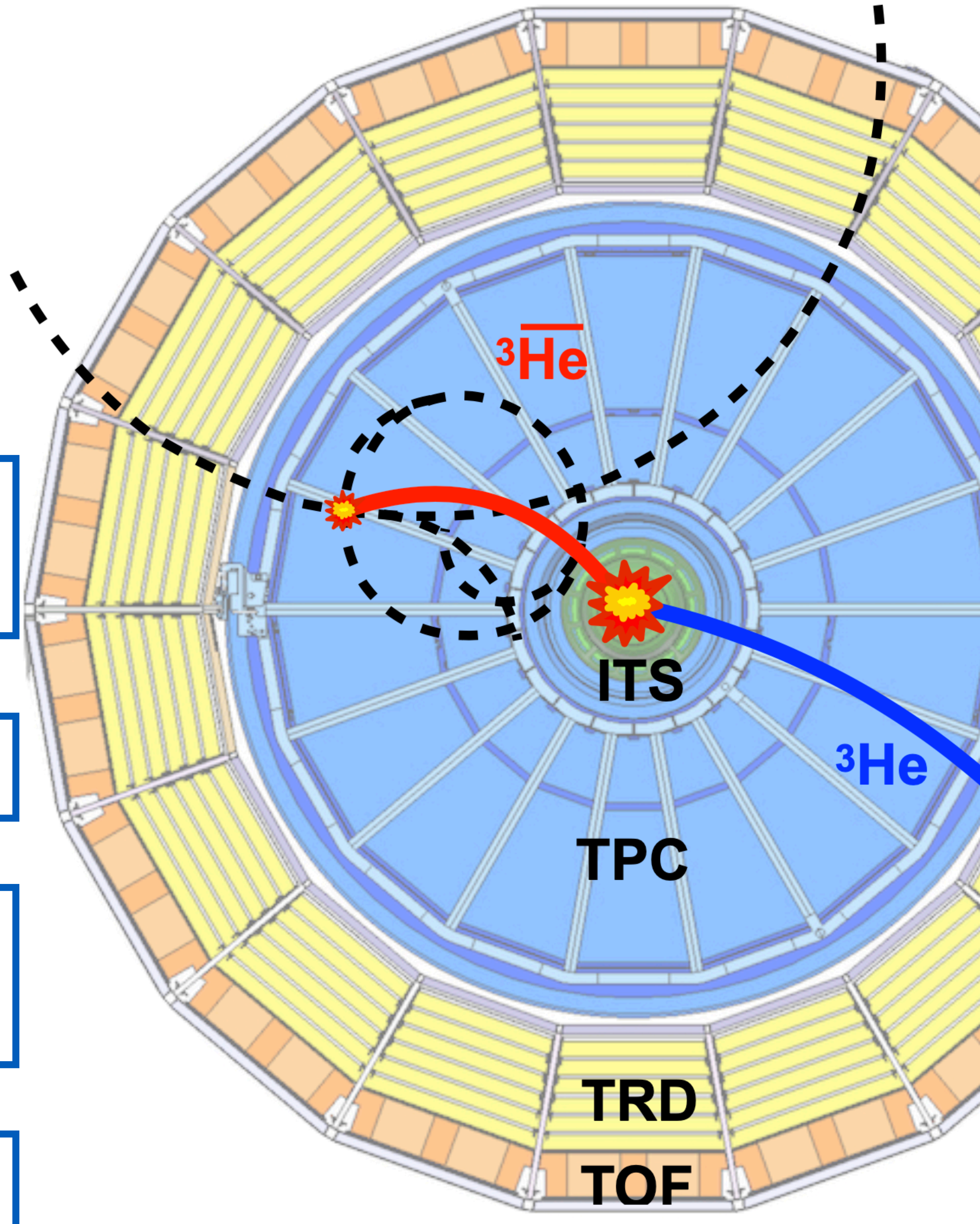
Interpolation of the variations to measure the anti-^{3}He inelastic cross section



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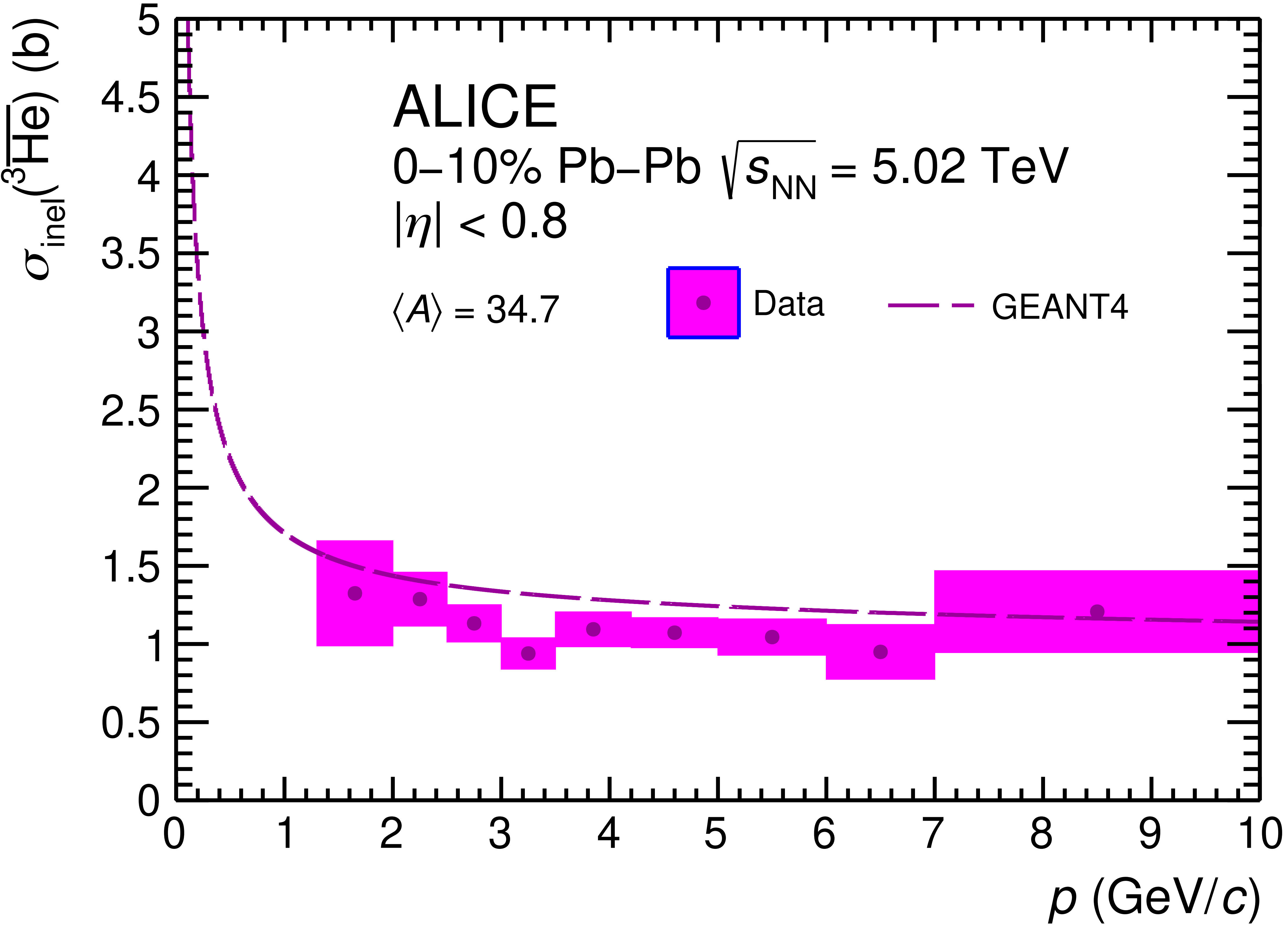

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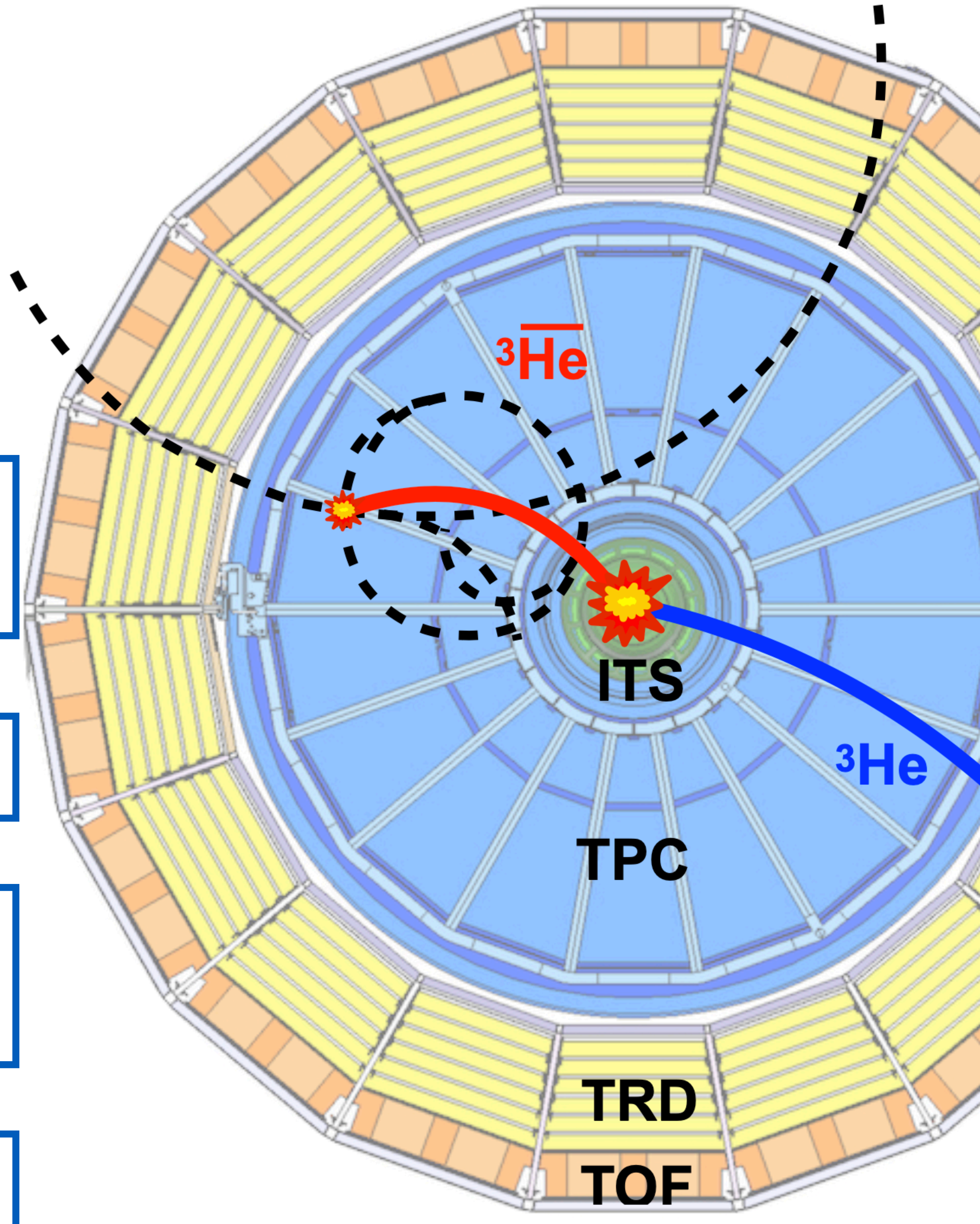

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First measurement of the anti-^{3}He interaction cross section with ordinary matter

ALICE, arXiv:2202.01549, Nat. Phys. (2022)

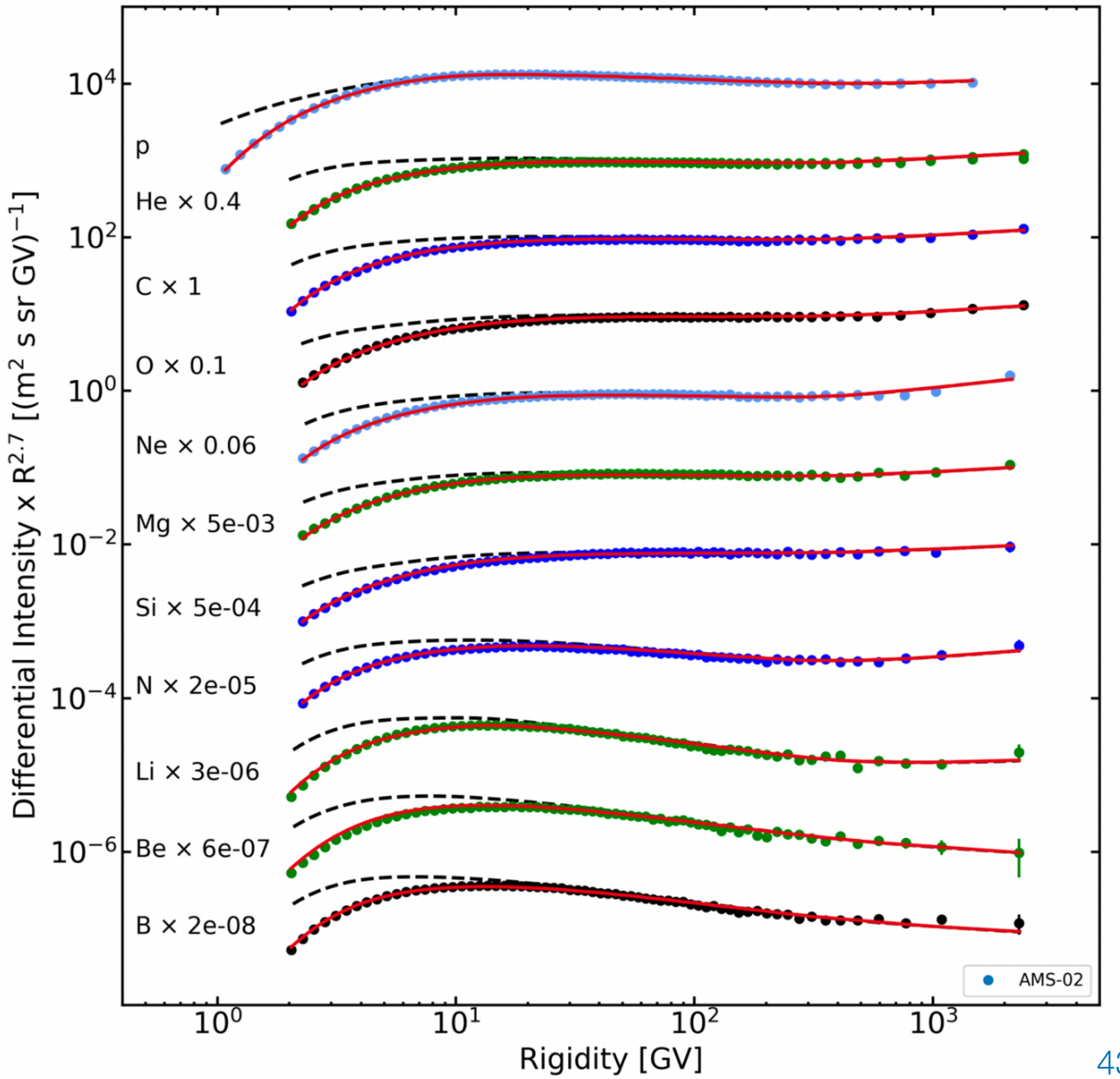
How do we go from collider data to cosmic-antinuclei flux?

$$\frac{\partial \psi}{\partial t} = q(\mathbf{r}, p) + \mathbf{div}(D_{xx}\mathbf{grad}\psi - \mathbf{V}\psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{\psi}{p^2} - \frac{\partial}{\partial p}\left[\psi \frac{dp}{dt} - \frac{p}{3}(\mathbf{div} \cdot \mathbf{V})\psi\right] - \frac{\psi}{\tau_f} - \frac{\psi}{\tau_r}$$

Step 1: take a publicly available cosmic ray propagation code, **GALPROP [1]**

GALPROP solves numerically the transport equation up to the heliosphere:

- The diffusion, convection, and propagation parameters are fixed looking at nuclei (way more abundant) [2]



[1] A. Strong, et. al. Nuclear and Particle Physics Proceedings, 297-299, 2018
[2] Boschini et al. ApJS 250 27 (2020)
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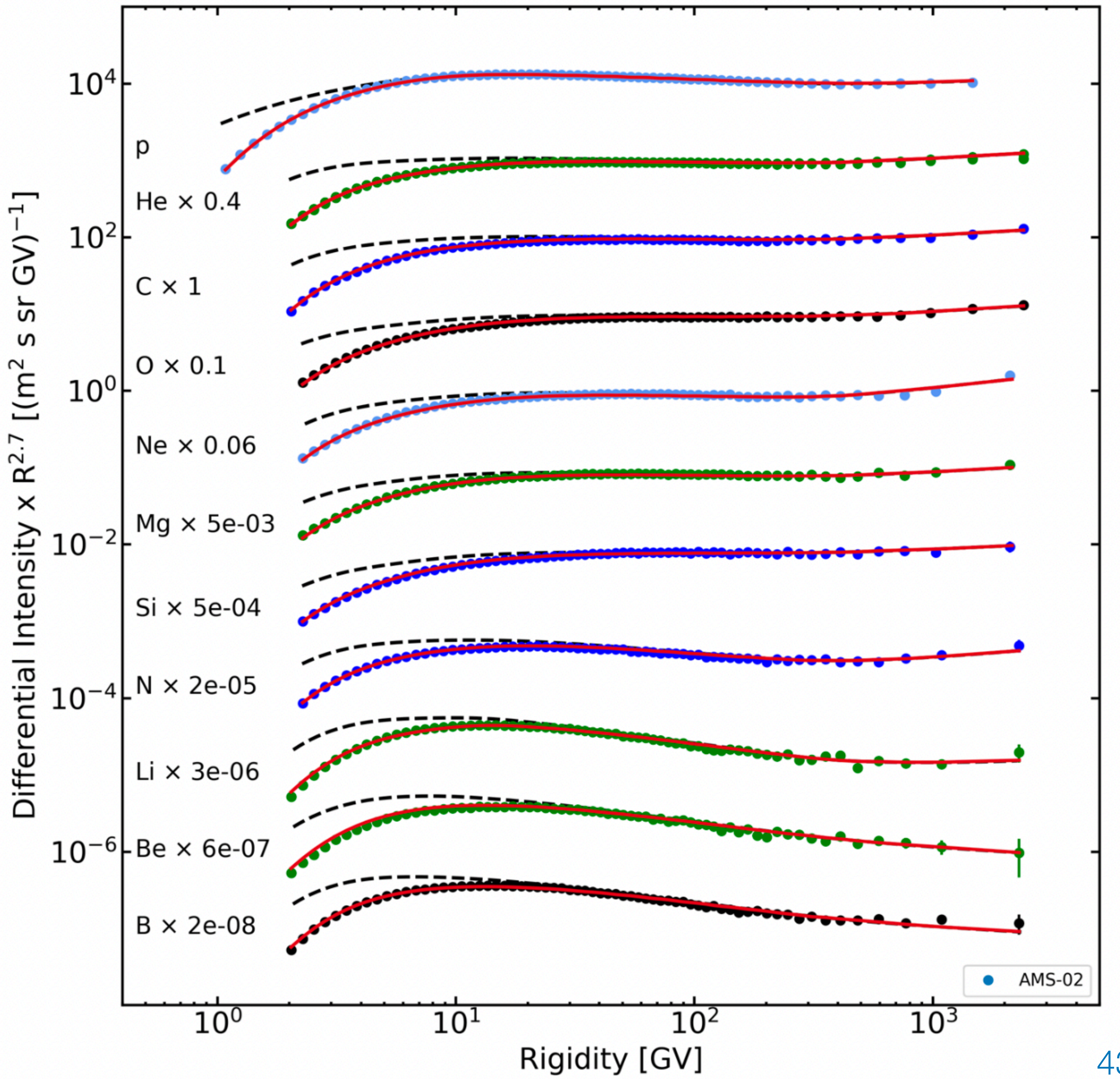
The propagation until Earth is then done using the Force Field approximation [3] in our example calculation

$$F_{mod}(E_{mod}, \phi) = F(E)\frac{(E - Z\phi)^2 - m_{^3He}^2}{E^2 - m_{^3He}^2} \text{, where } E_{mod} = E - Z\phi$$

with ϕ = 0.4 GV



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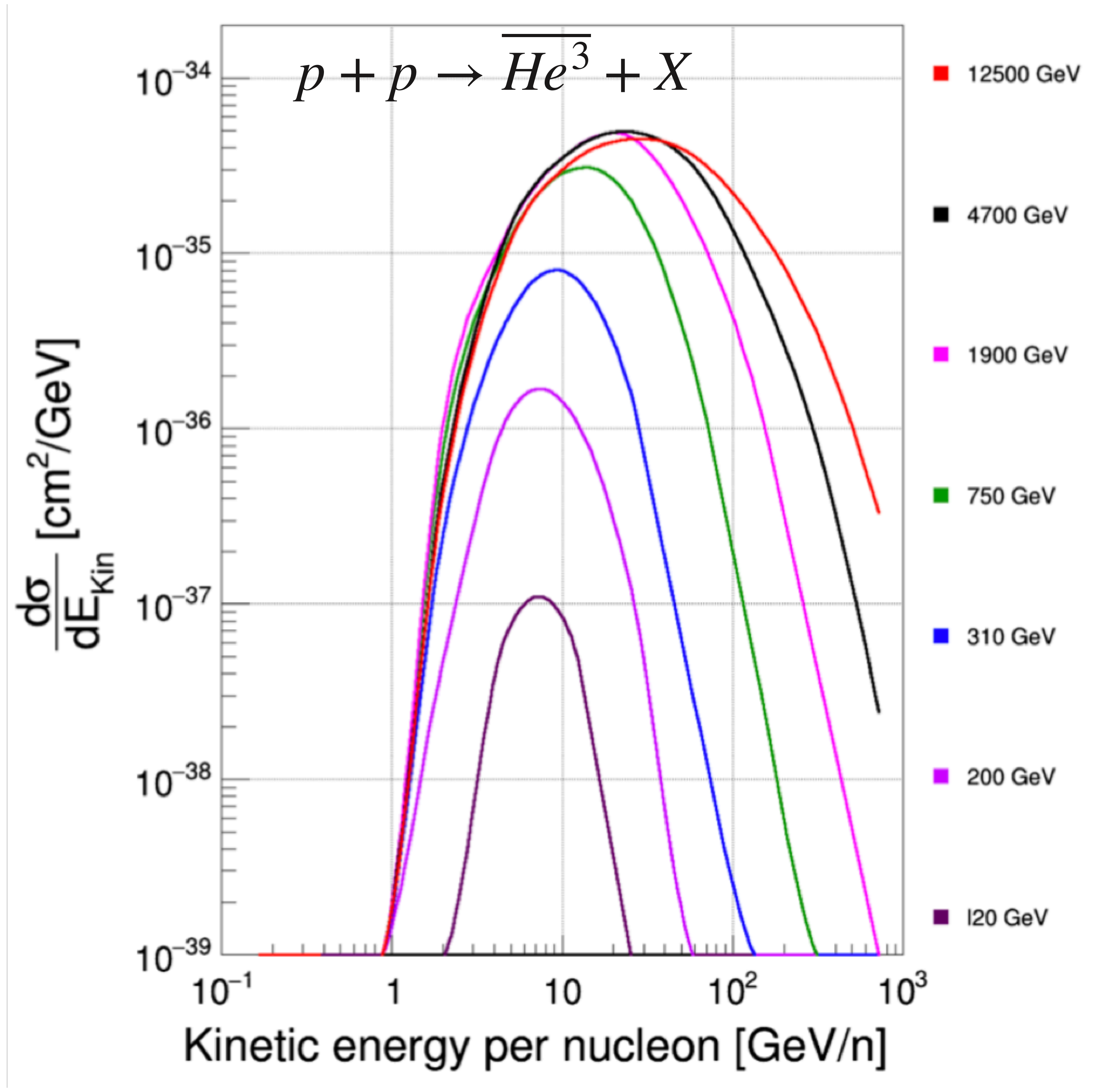

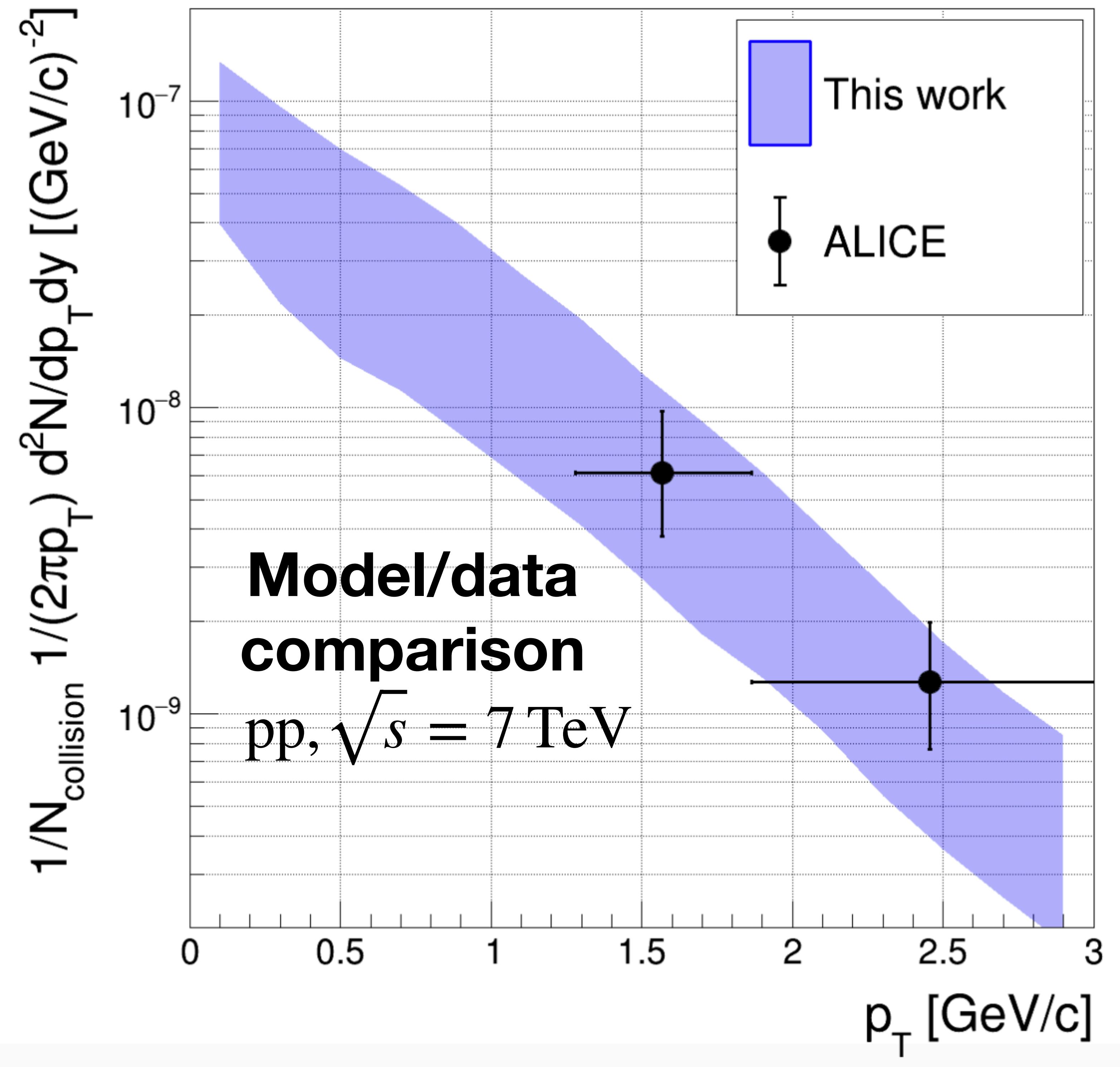

Relevant collision systems: pp, p-He, He-p, He-He

- Production cross section in pp collisions from [1] (EPOS LHC + event-by-event coalescence)
- Other collision types scaled $(A_T A_P)^{2.2}/3$
- Validated by ALICE data

[1] Shukla et al, Phys. Rev. D. 102, 063004 (2020) [2] ALICE, Phys. Rev. C 97, 024615 (2018)

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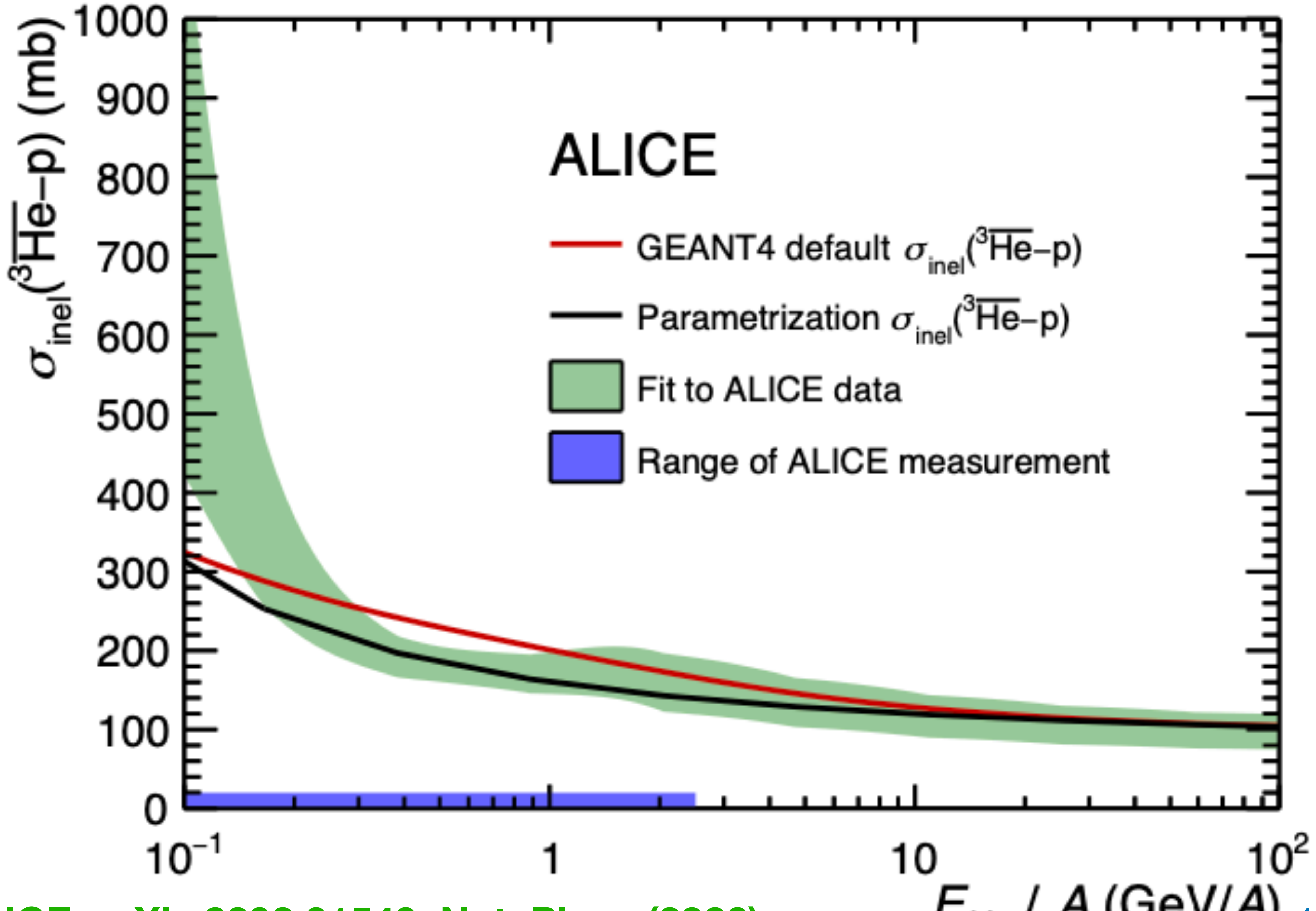
Step 3: use our measurement to determine how likely are the anti-^{3}He inelastic interaction with the interstellar medium

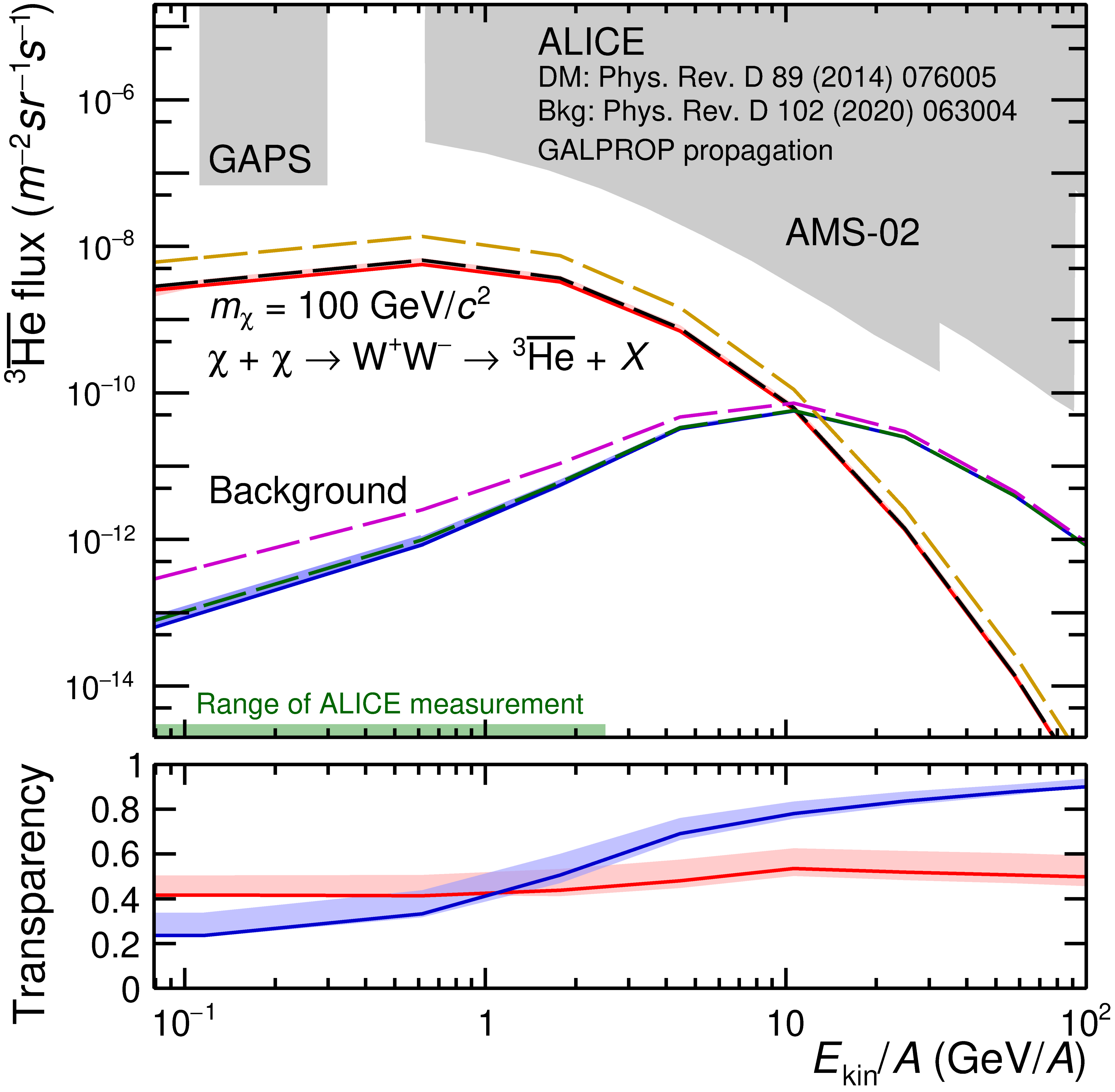
We need to scale our measurements of σ_{inel} (on heavy targets) for proton and helium targets typical of ISM

- Get a correction factor for Geant4 parameterisation using ALICE measurements
- Use this correction factor for all targets, with additional 8% uncertainty on possible A scaling



ALICE, arXiv:2202.01549, Nat. Phys. (2022)

ALICE's dark side: applications for dark matter searches



$$\text{Transparency} = \frac{\text{Flux}(\sigma_{\text{inel}})}{\text{Flux}(\sigma_{\text{inel}} = 0)}$$

Result: Sizeable decrease of the expected flux at low energy when scaling for the measured anti^{3}He modification of inelastic cross section

ALICE, arXiv:2202.01549, Nat. Phys. (2022)

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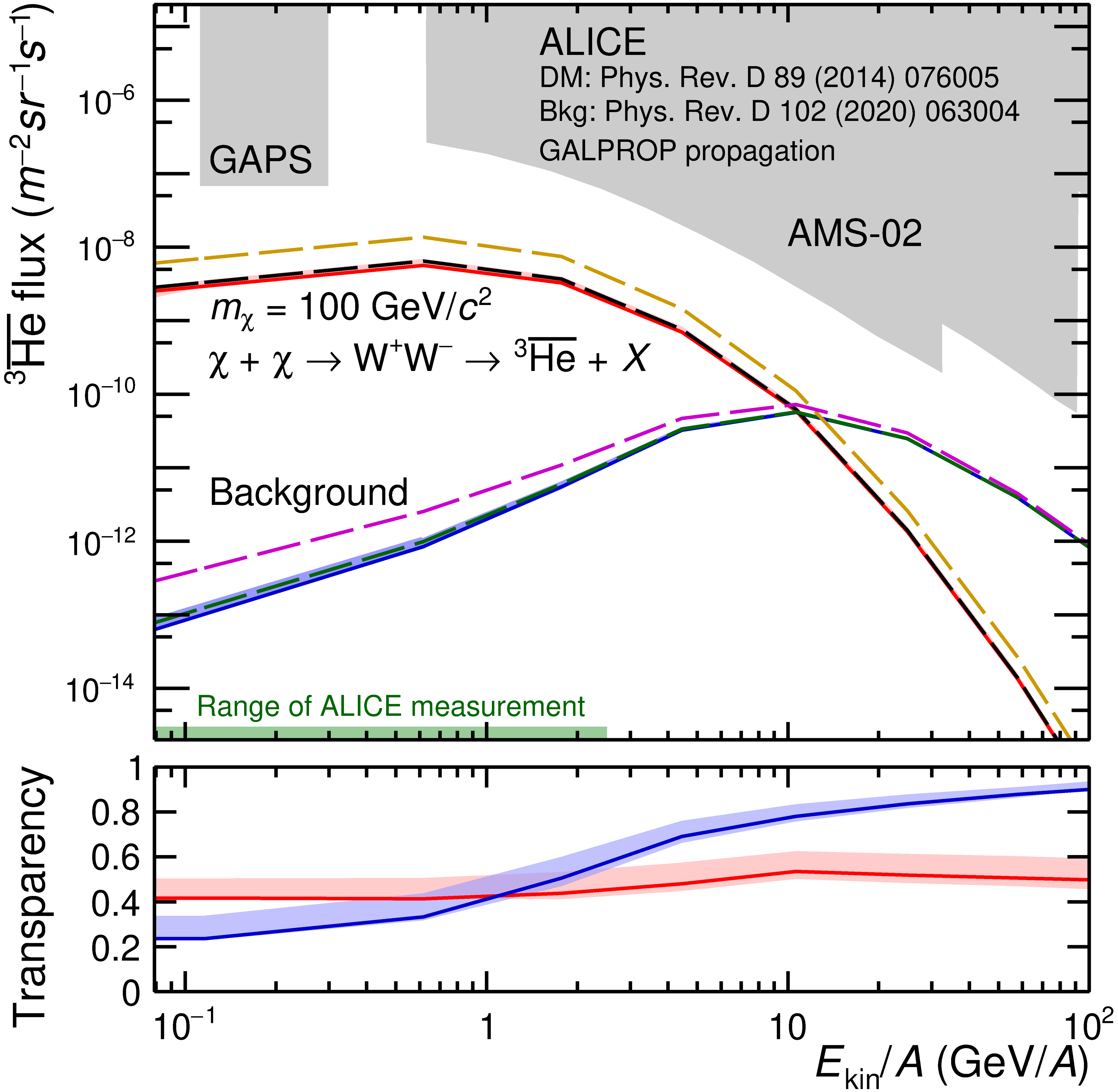

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- This is an example of flux calculation to illustrate the contribution of the antinuclei interaction cross section
  - 50% transparency for anti-^{3}He from DM!
- Only uncertainties on the cross-section shown
  - ~20% contribution to the flux uncertainties

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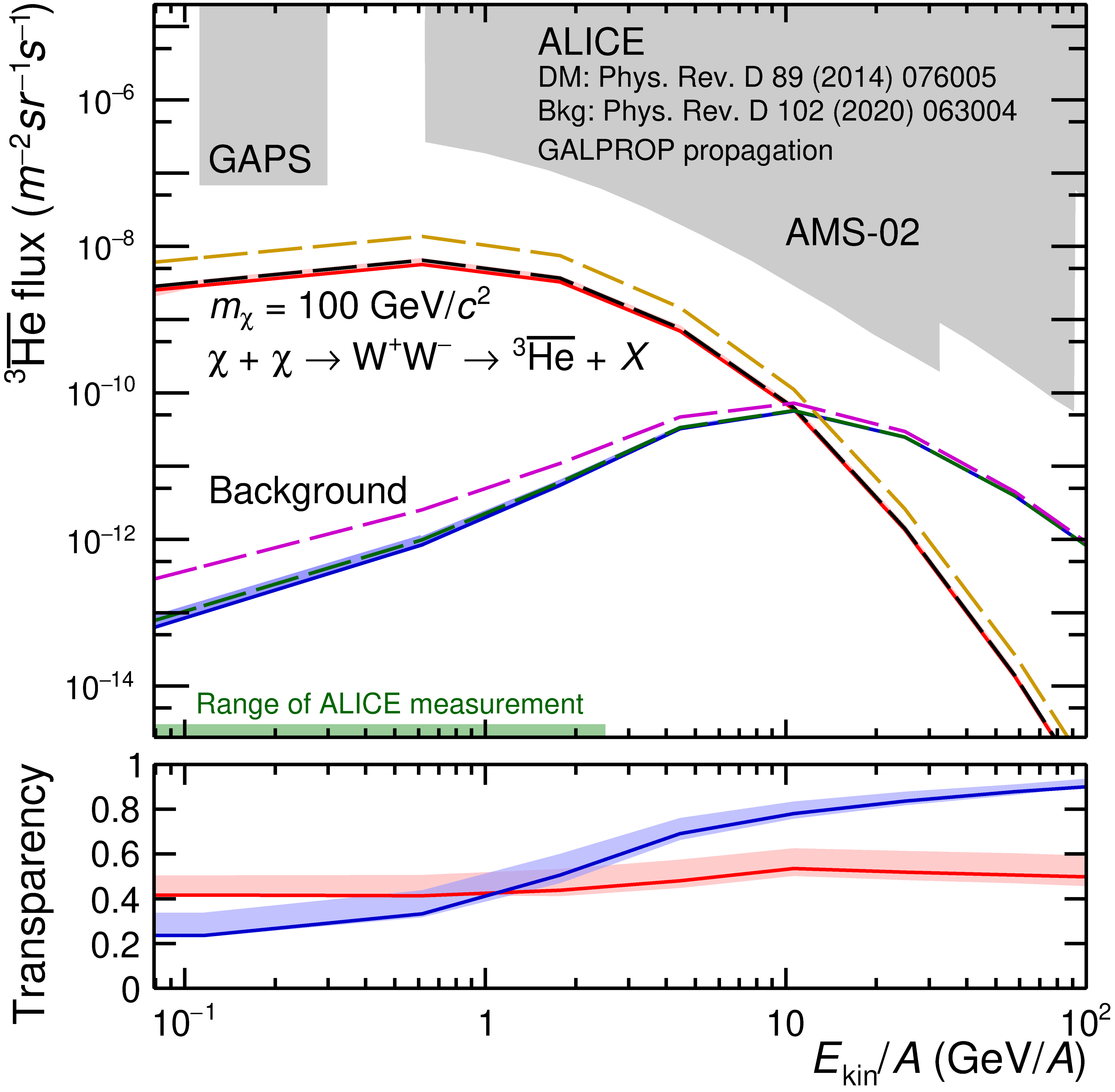

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➡ Now this is a subdominant uncertainty for the expected fluxes of antinuclei

ALICE, arXiv:2202.01549, Nat. Phys. (2022)