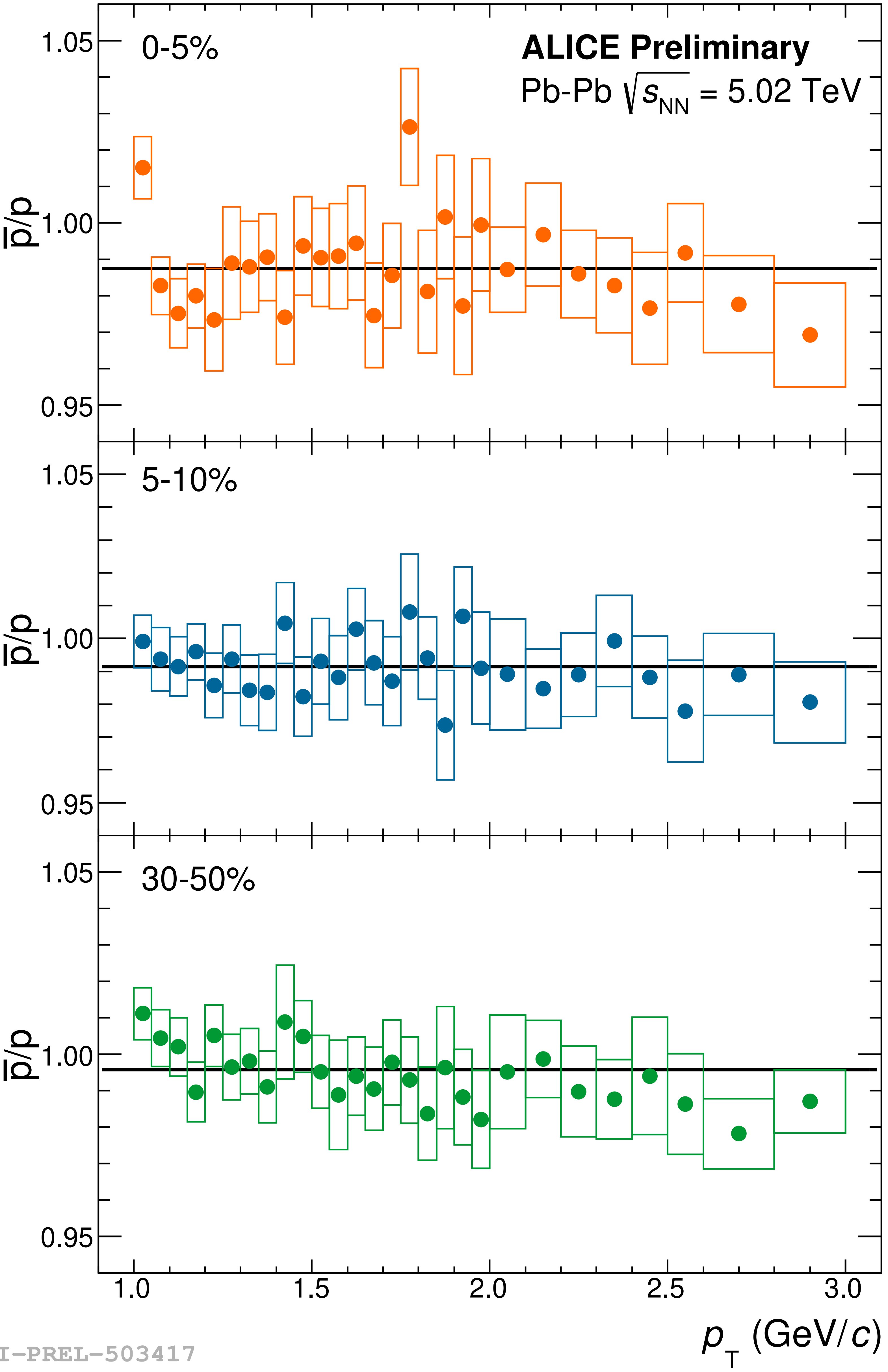
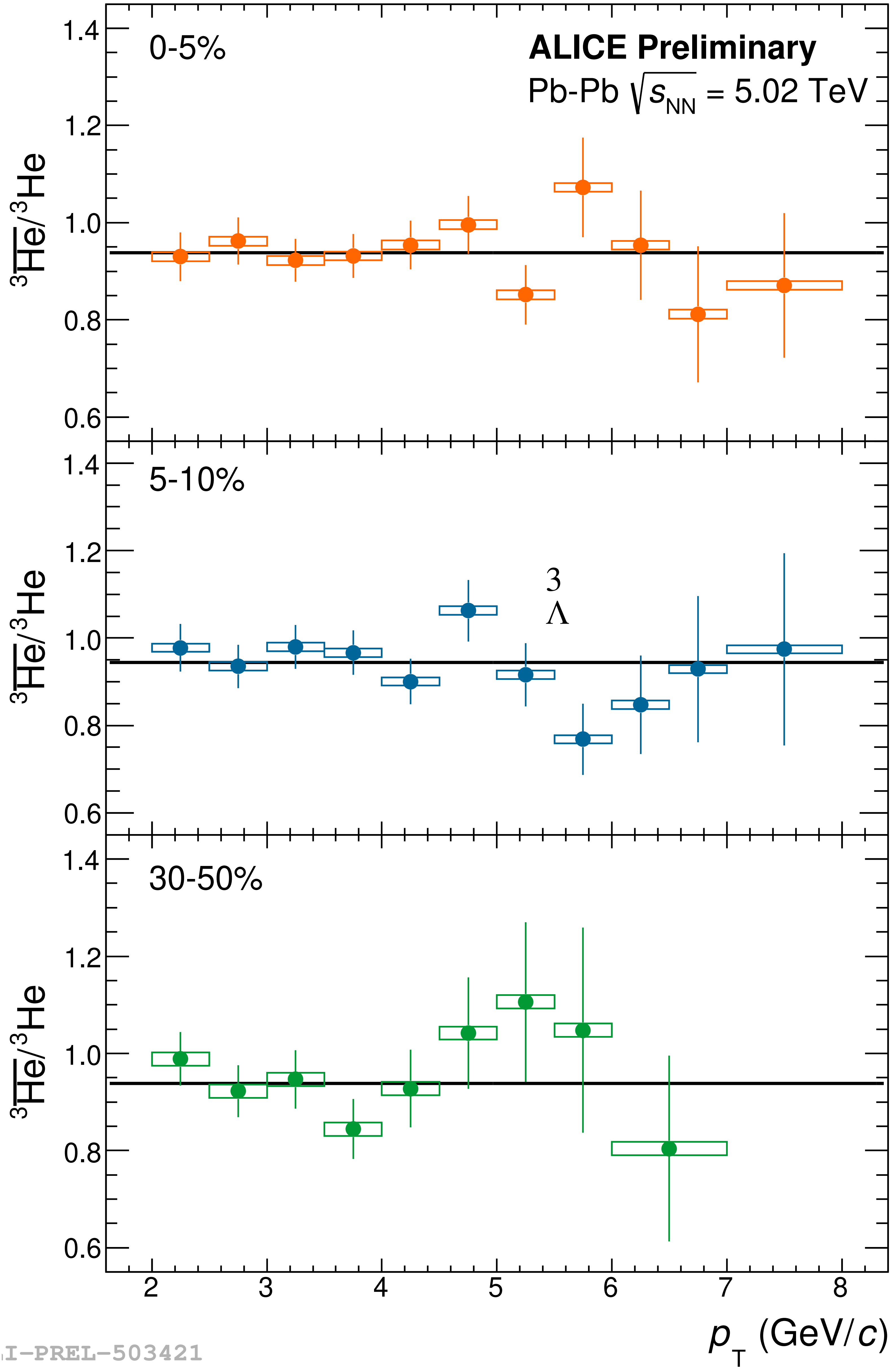
The future of hypernuclear physics at the LHC (and SPS)

Maximiliano Puccio (CERN)

HADRON 2023 - Genova 8th June 2023

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
- Valid up to A=3!
- Specific studies were done to reduce the systematic uncertainties

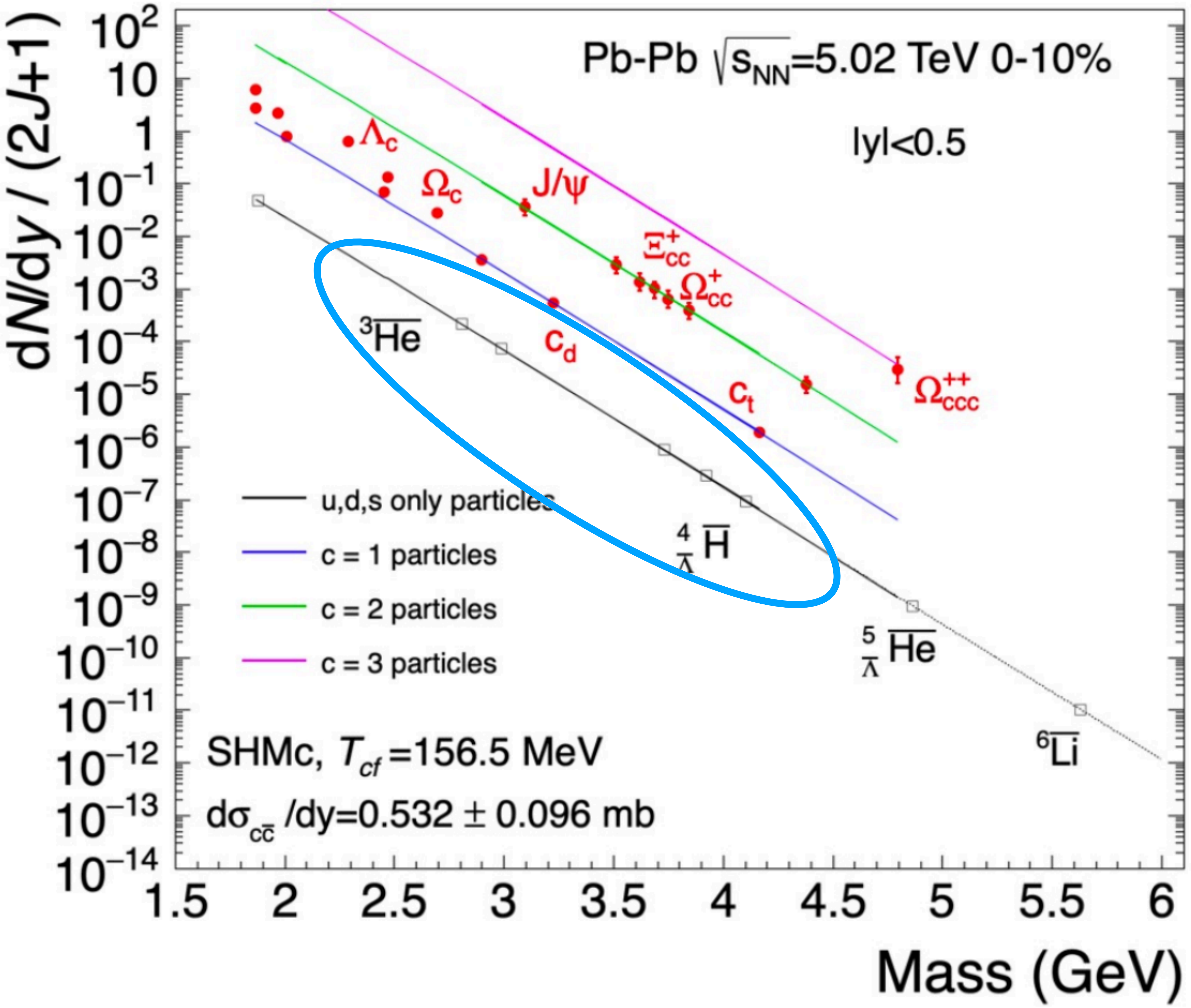
At the LHC matter and antimatter are produced in equal abundance at mid rapidity

In central Pb-Pb collisions

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

Prelude: the LHC is not a collider for hypernuclei

arxiv:2211.02491

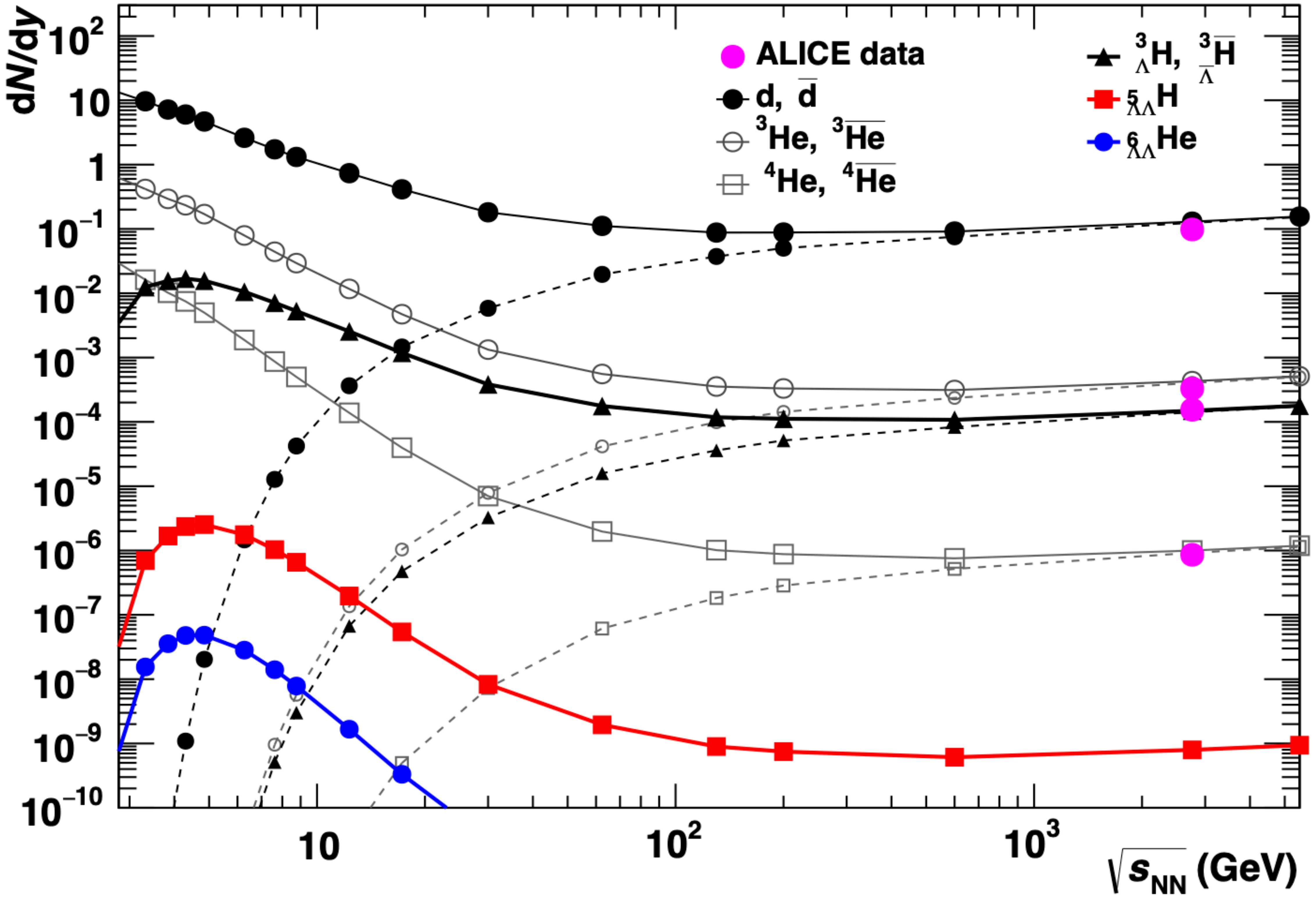


At the LHC we will manage to get the first measurement of A=5 antihypernuclei

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

Prelude: SPS can be a great facility for hypernuclei

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



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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)

What is this talk about?

1. 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?

2. How can we access the missing information about light hypernuclei (i.e. B.R., rare decays)?

   - Next generation detectors and reconstruction technique come to the rescue

3. Beyond LHC: hypernuclei at the SPS

(Anti)(hyper)nucleosynthesis processes

Two models with very different implications

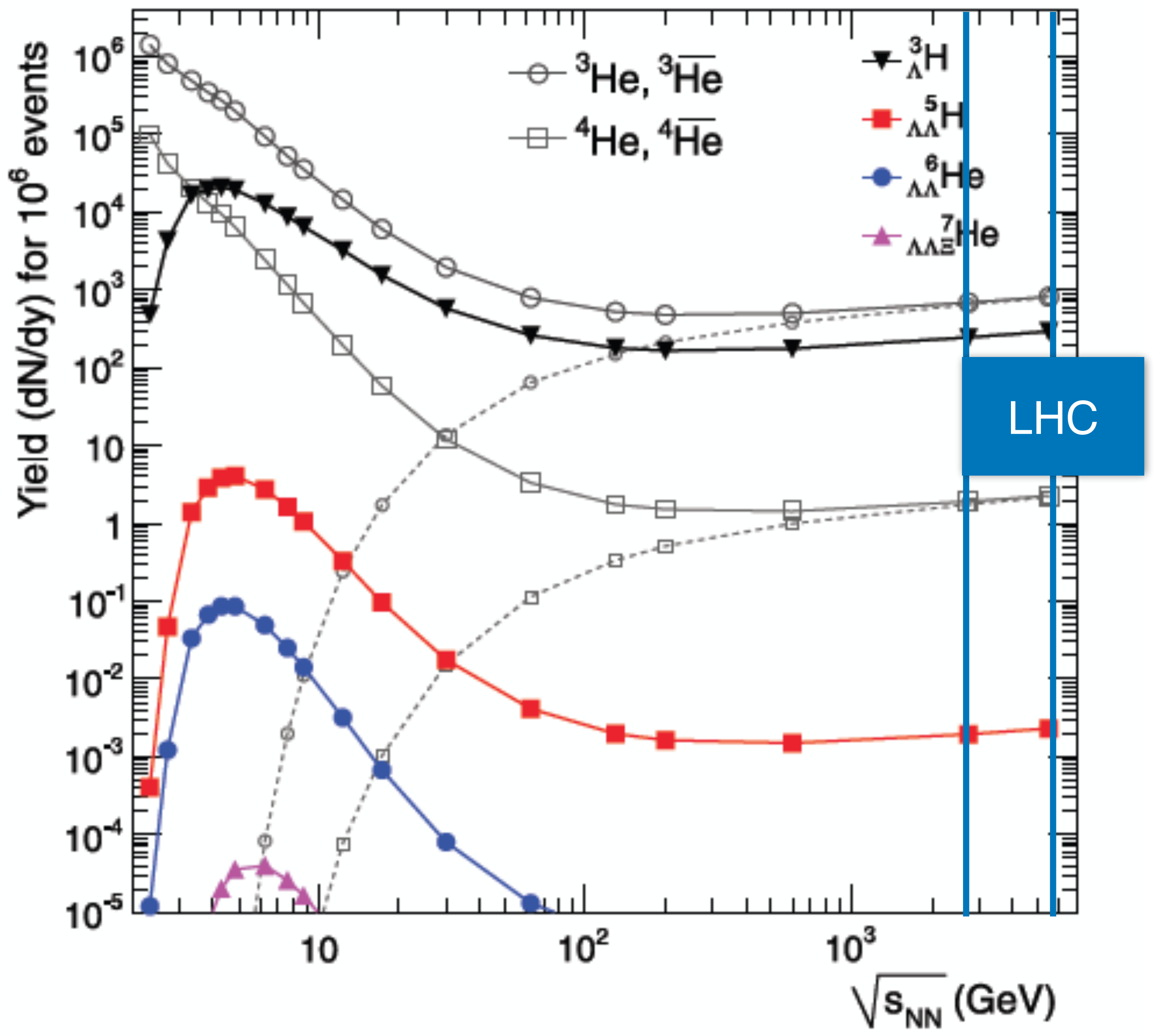
Two models with very different implications

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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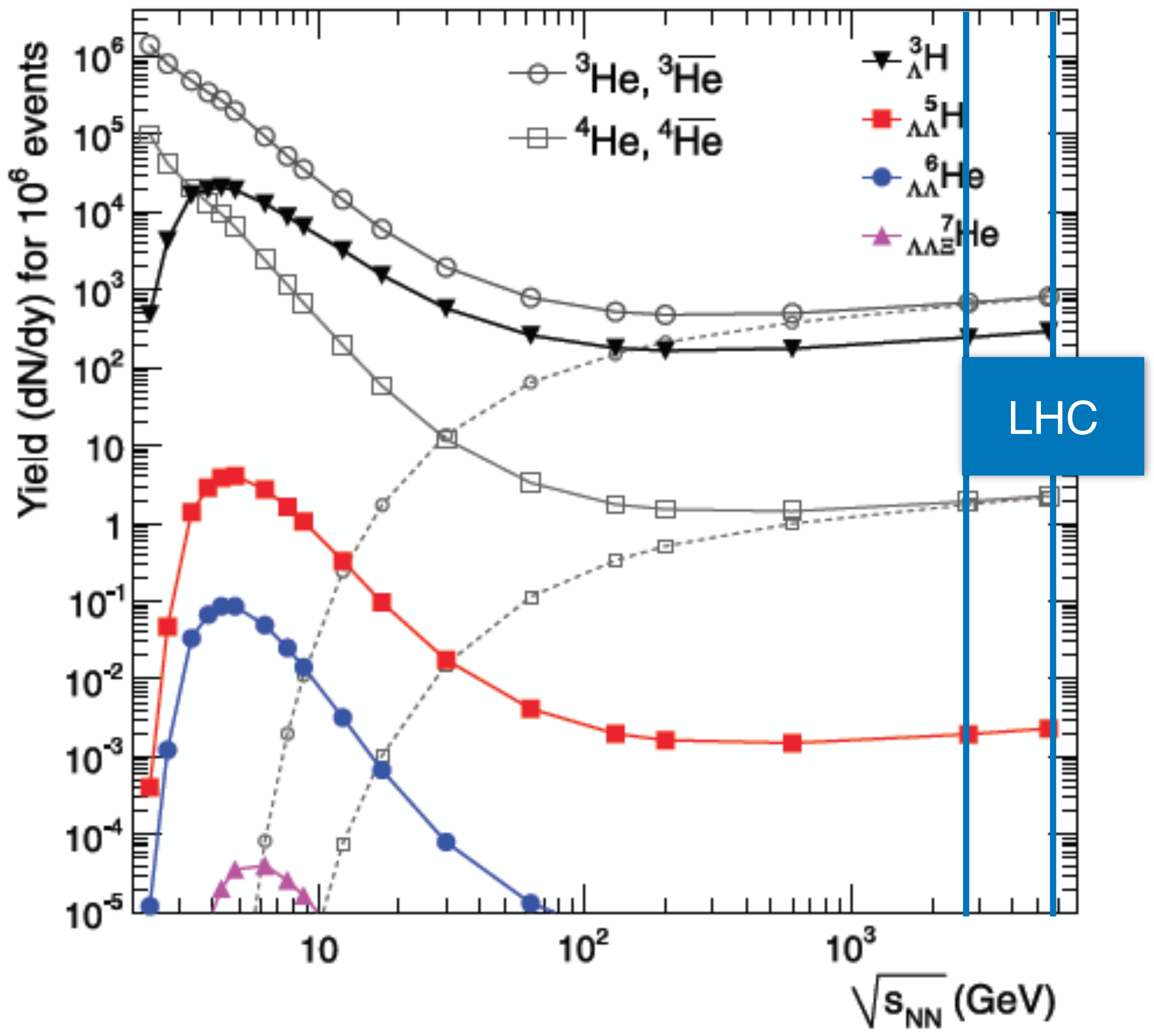
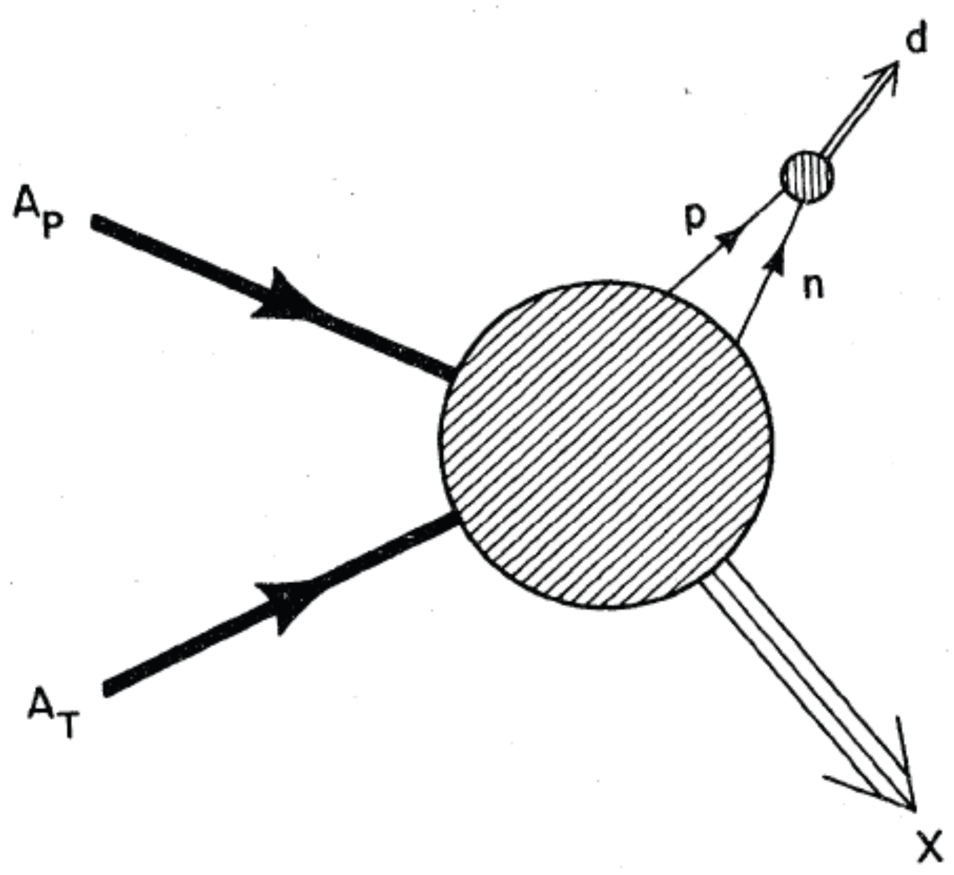




J. I. Kapusta, Phys.Rev. C21, 1301 (1980)

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

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

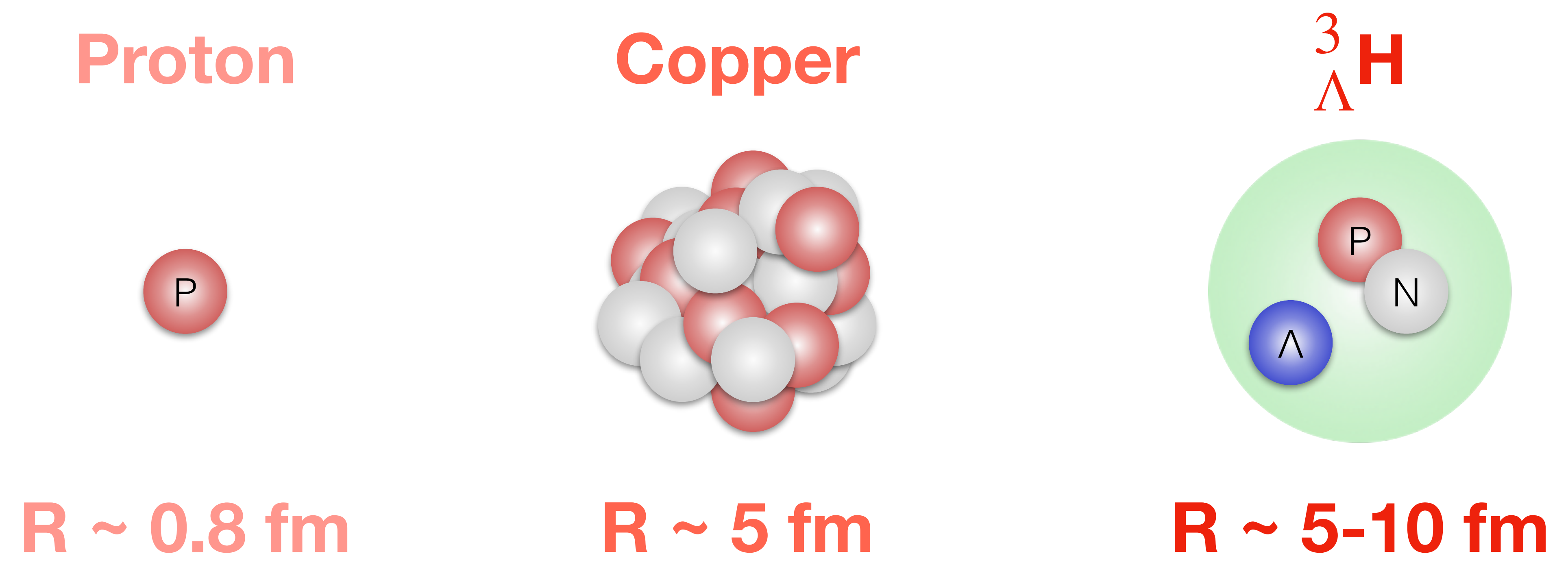
Sun. et al., Phys. Lett. B, 792, 132–137, (2019)

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

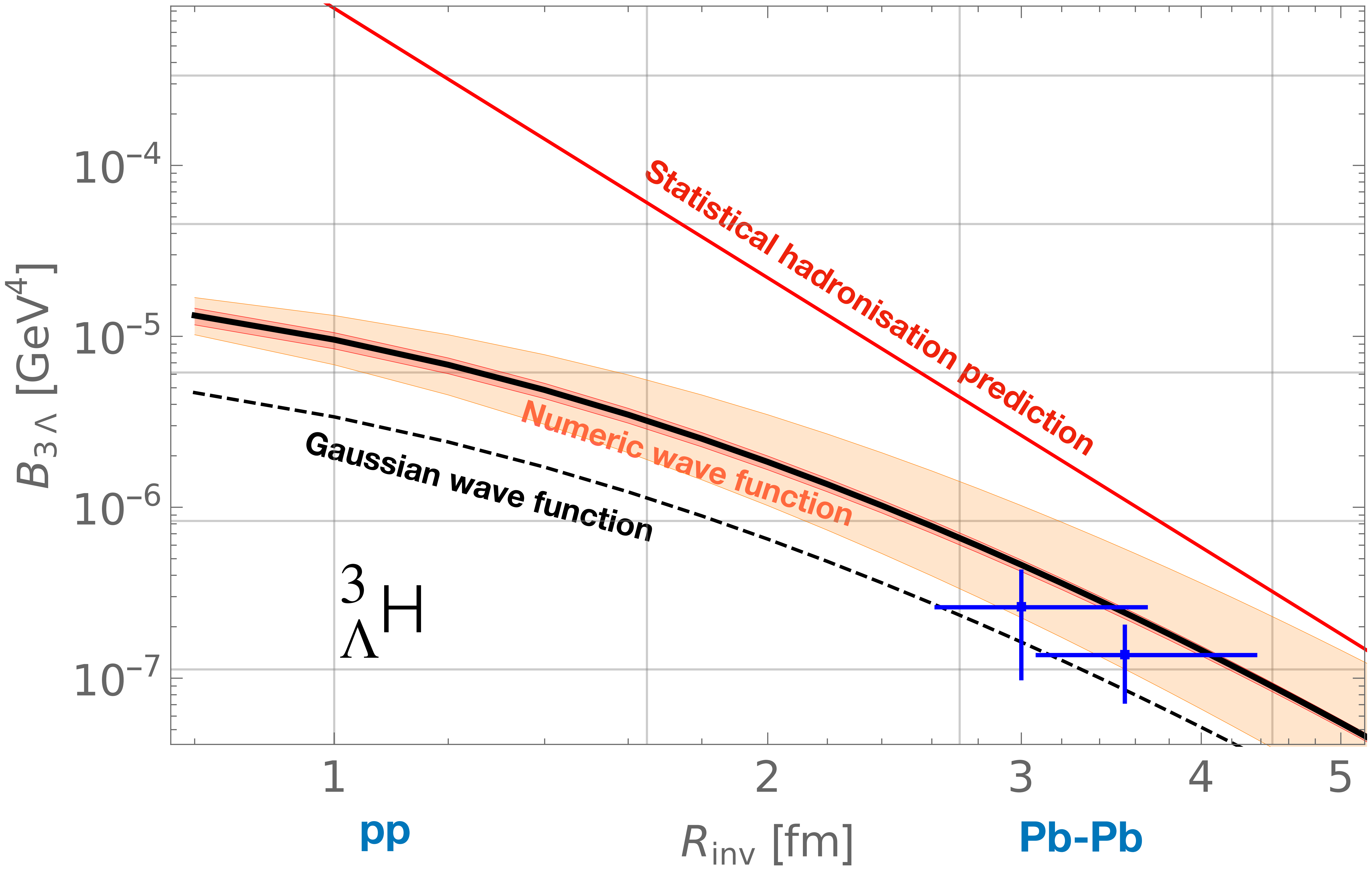
Correlation radius

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

Wigner density / wave function



Halo nucleus: wide dΛ molecule



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

From the correlation to the coalescence parameter

Correlation radius

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

Wigner density

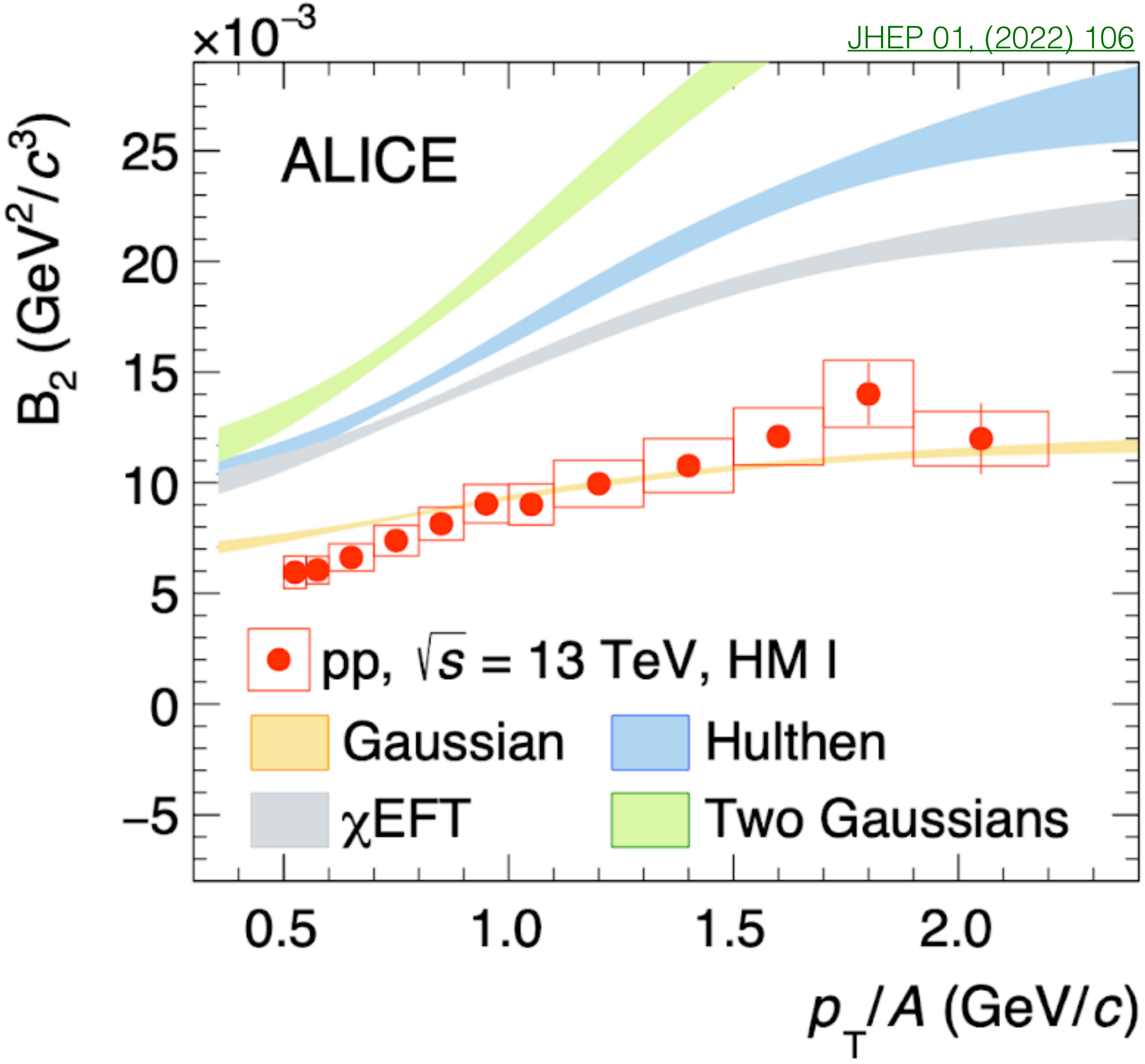
"Source Radius + Nucleus wave function -> B_2"

- 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

JHEP 01, (2022) 106



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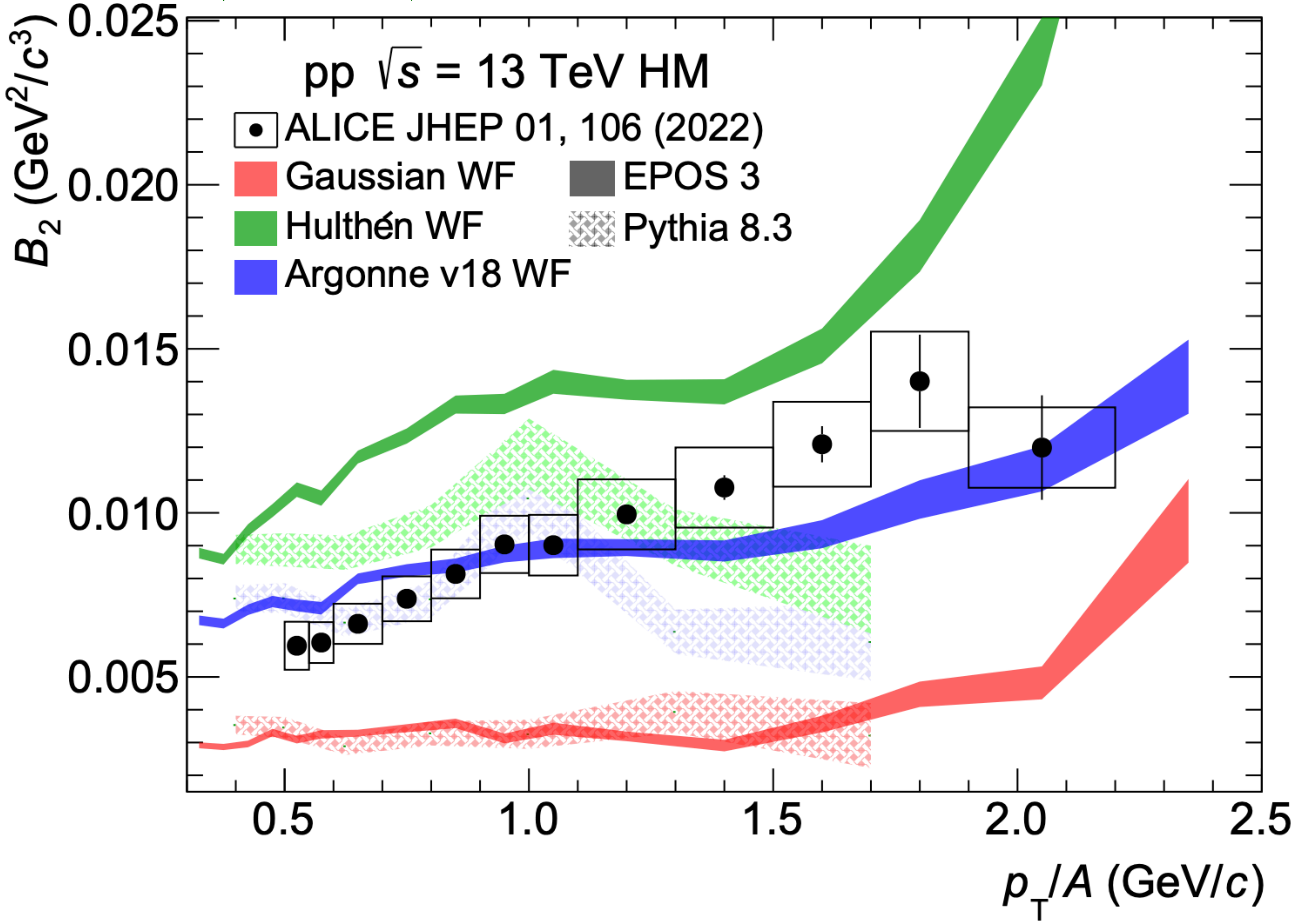
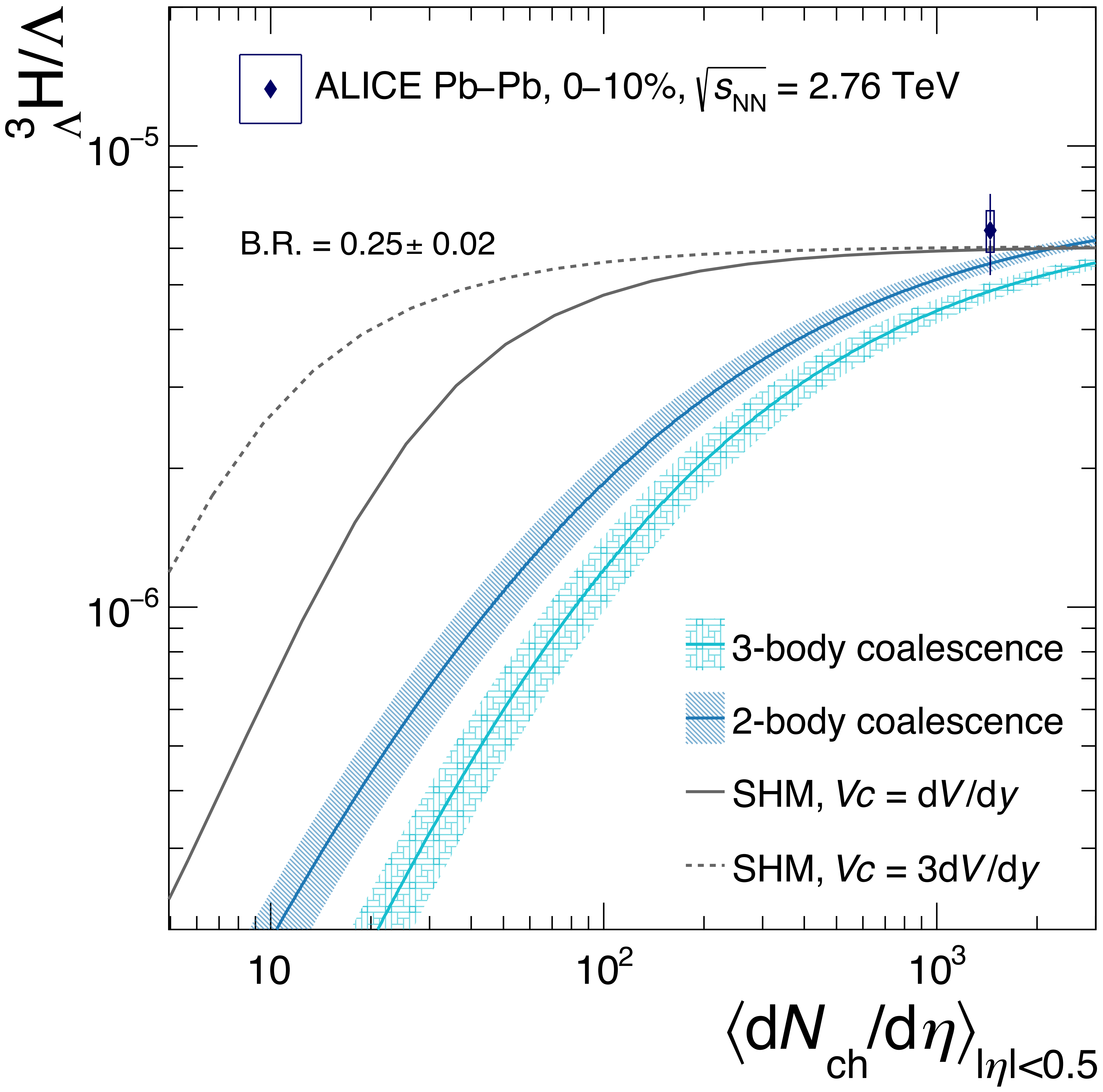
M, Mahlein et al, 2302.12696



But already improving: accouting for event-by-event correlations on top of the proper source parameterisation brings the more realistic wave functions closer to data

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 d-Λ separation for hypertriton ~10 fm

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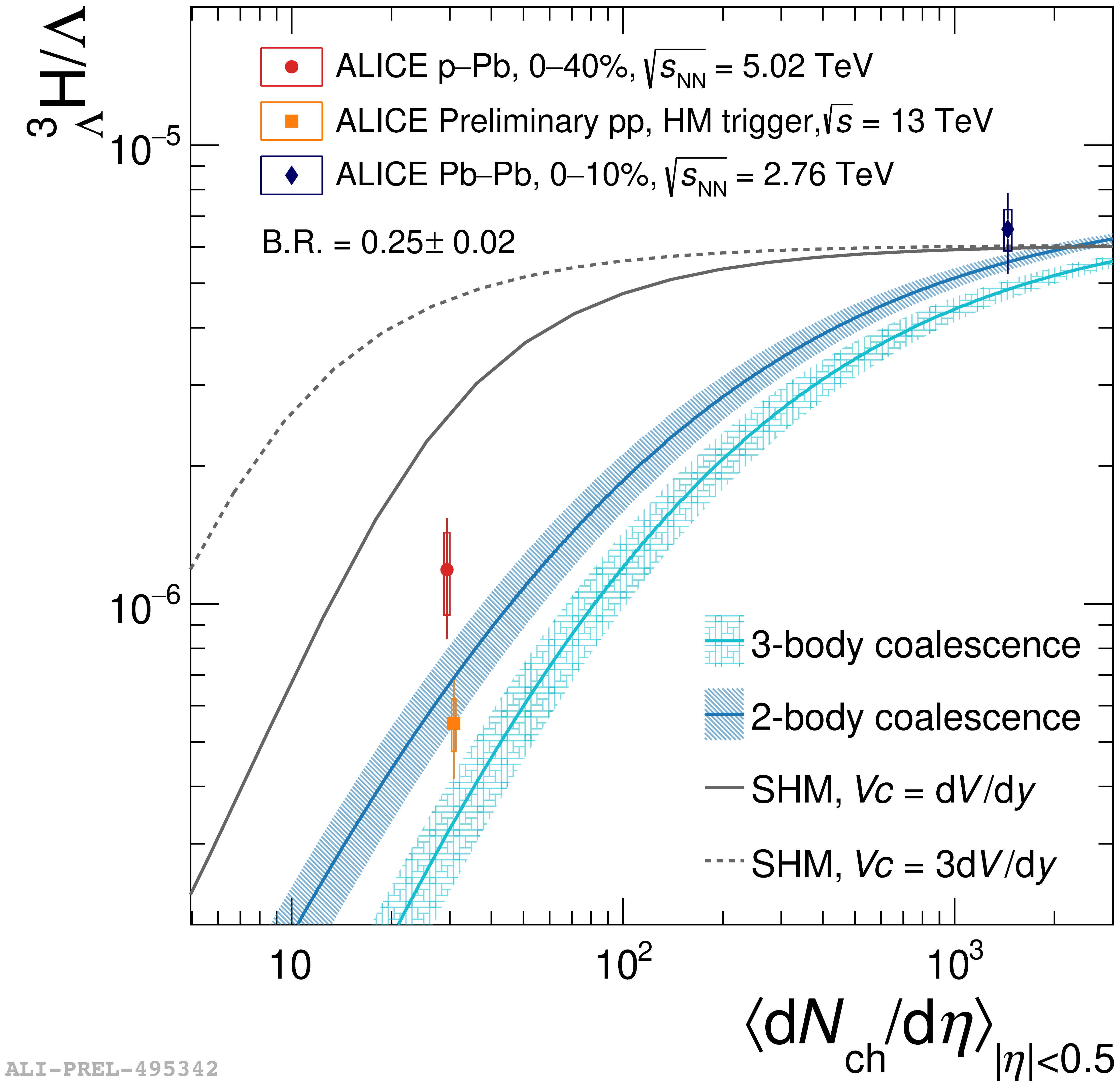
arXiv:2107.10627



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

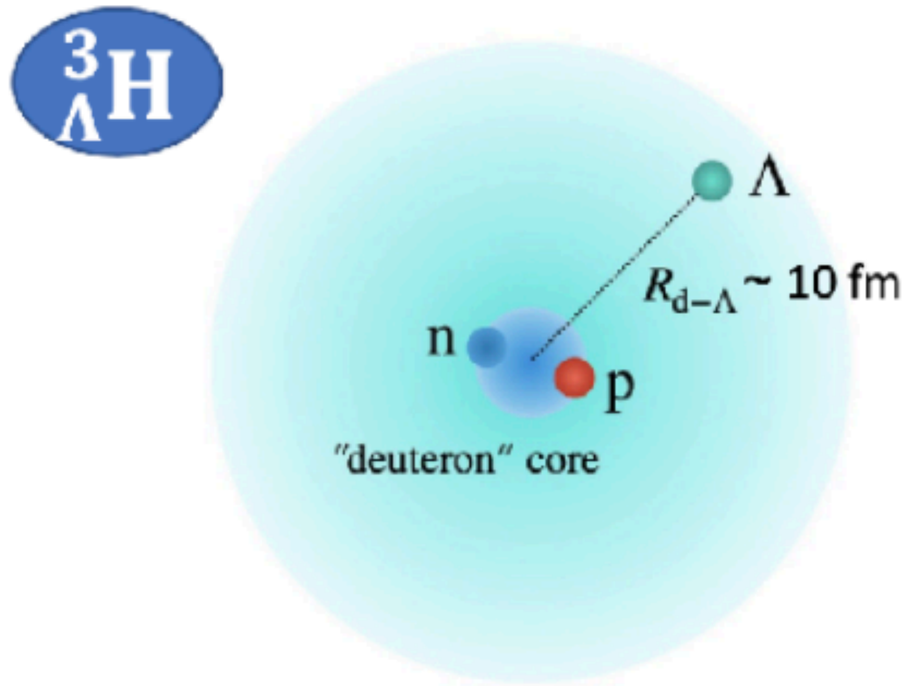
- SHM: insensitive to size of the hypertriton
- Coalescence: yield suppressed with assumed d-Λ separation for hypertriton ~10 fm
- Measurements in good agreement with 2-body coalescence
- Tension with SHM at low charged-particle multiplicity density
  - configuration with V_C = 3dV/dy is excluded at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

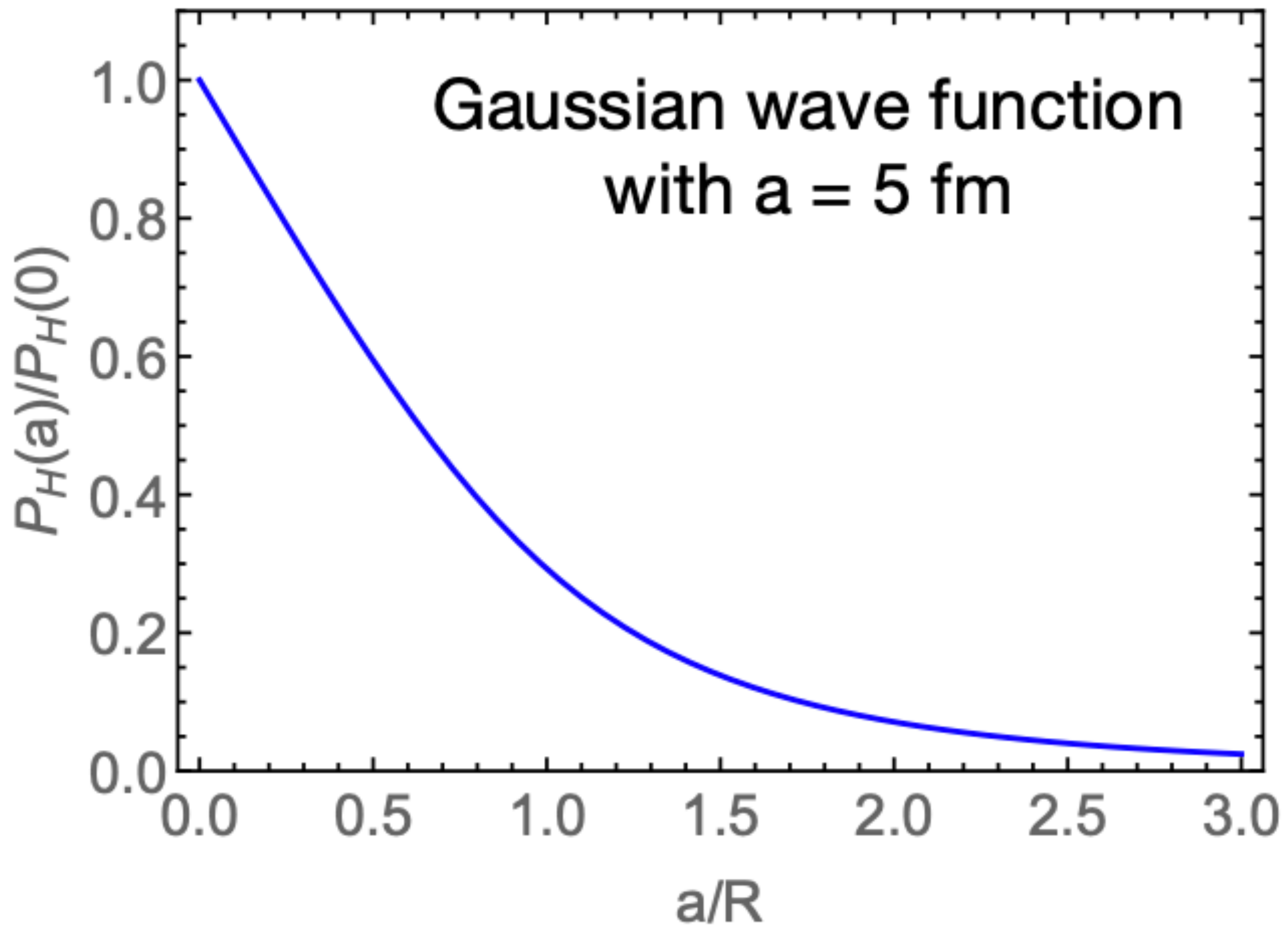
Production of hypertriton in pp and p-Pb collisions as a doorway to the study of its structure

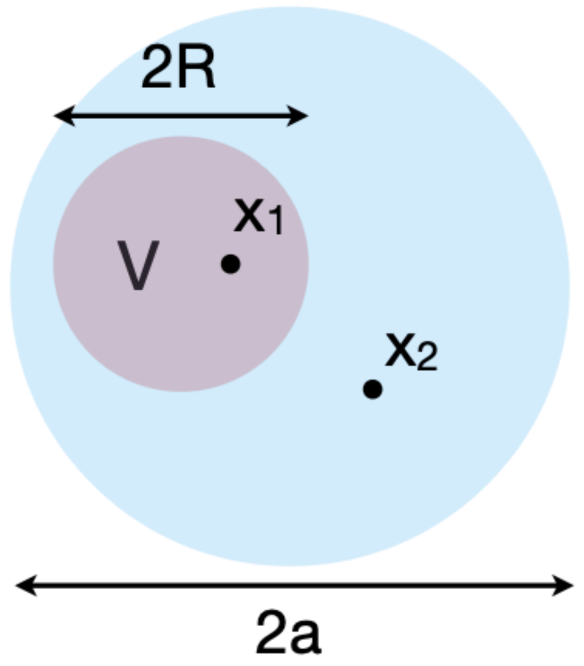
The case of hypertriton production in small systems

Particle size matters

Berndt Mueller SQM22 summary talk



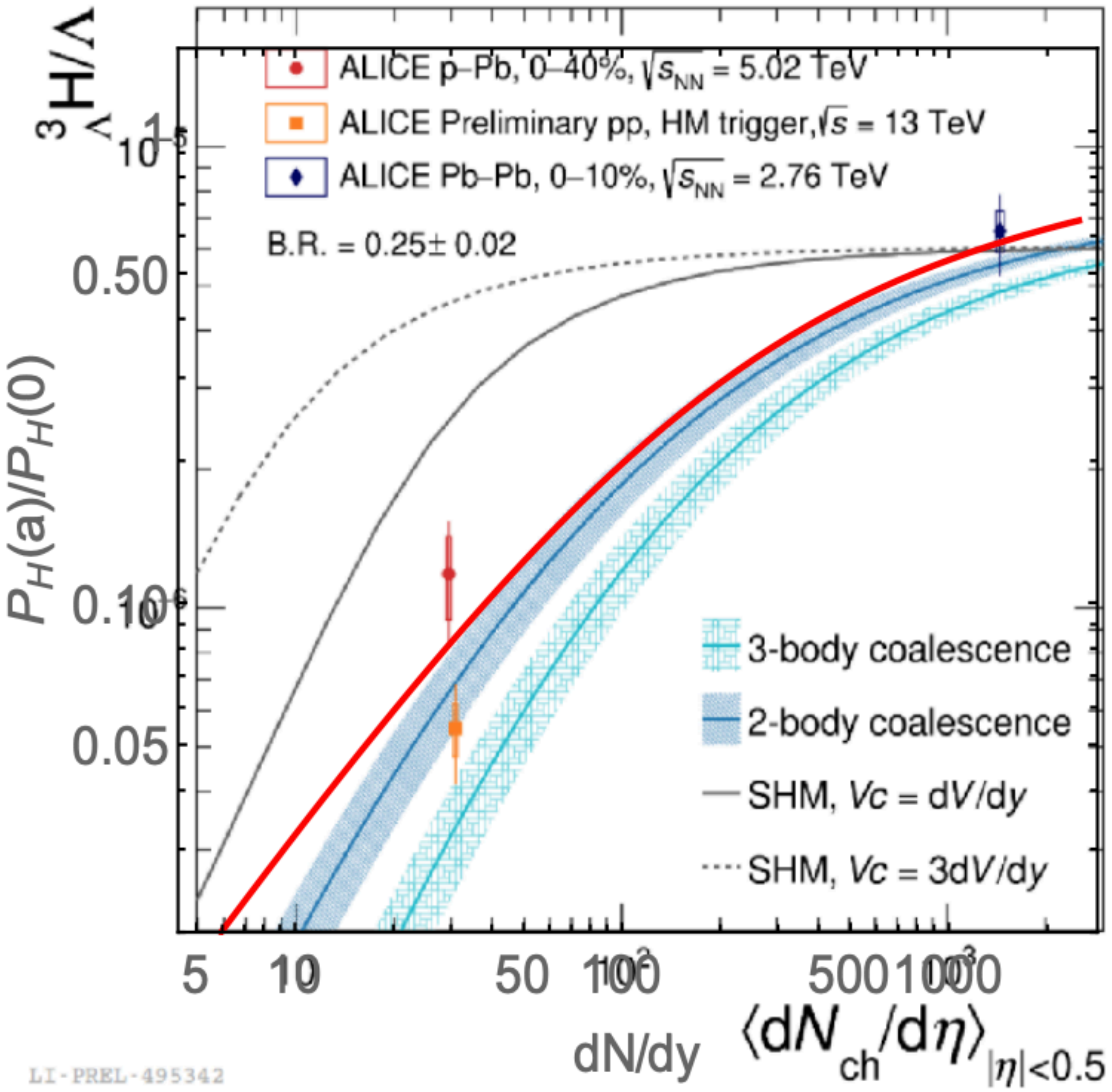




When $a \gg R$, requires $|x_1 - x_2| < R$:

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

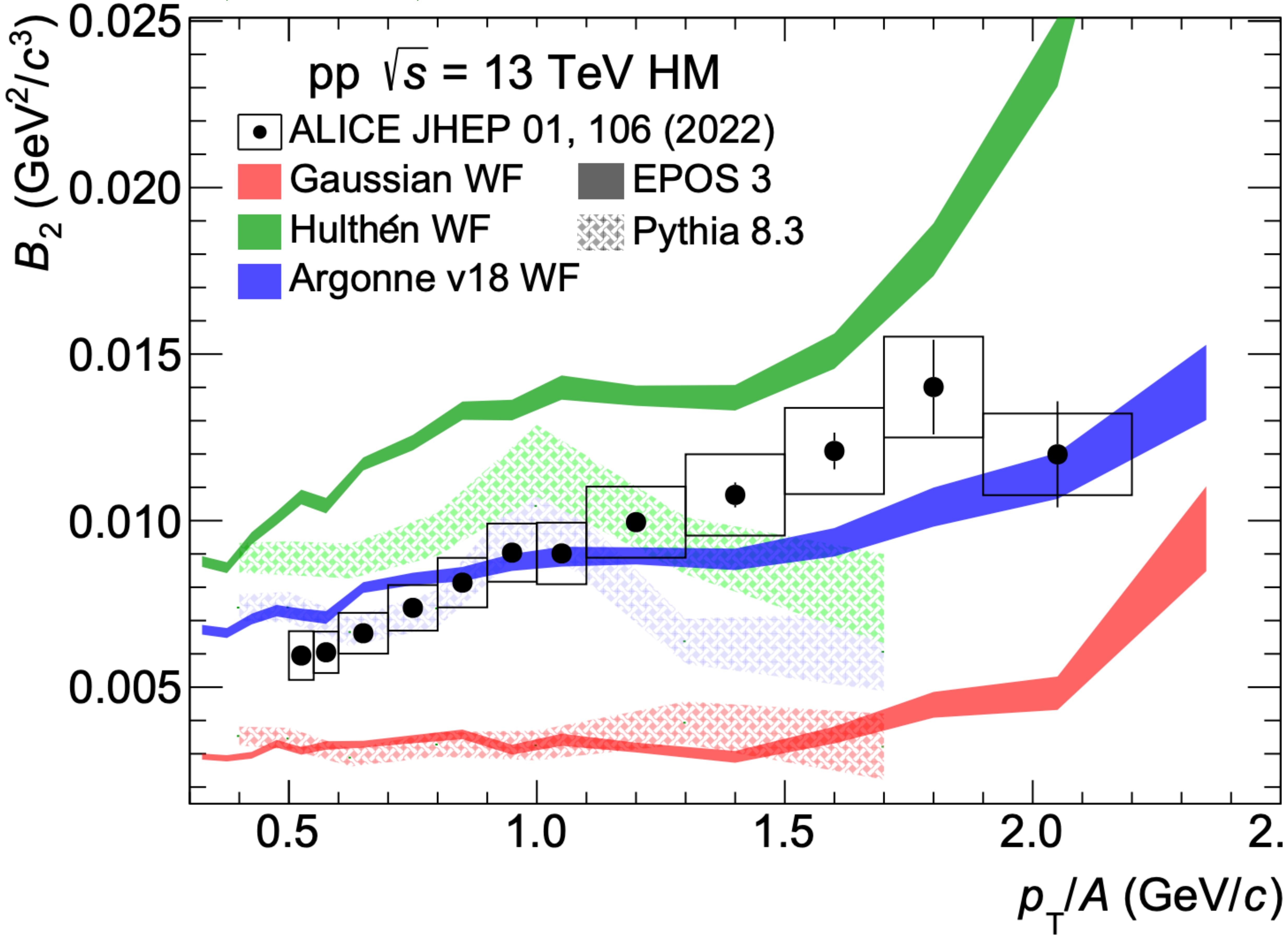
$$P_H \approx V_H^2 \int d^3p\, e^{-E_p/T} |\psi_p(0)|^2 \propto \frac{V_H^2}{a^3} \int d^3p\, e^{-E_p/T}$$

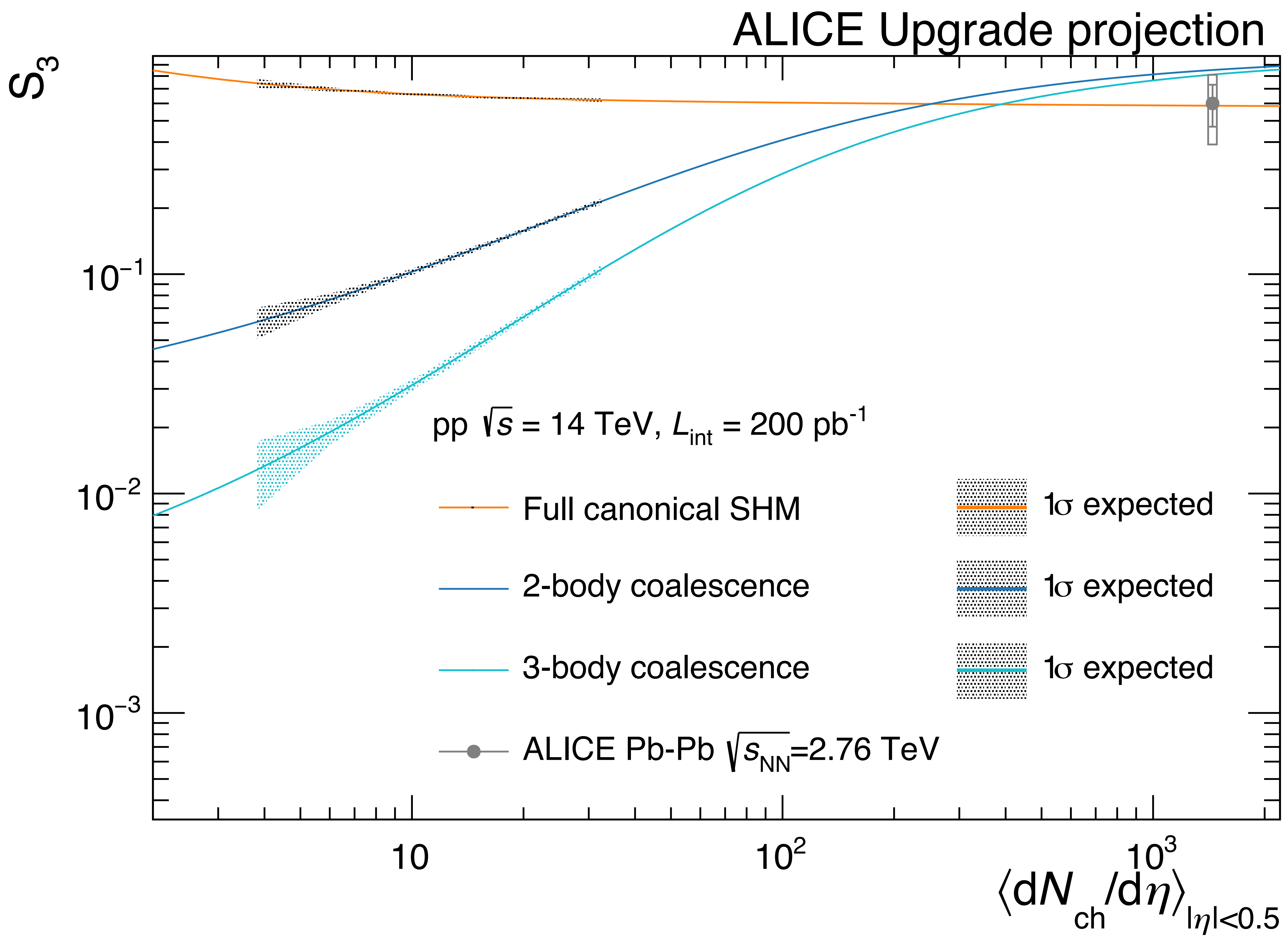


Particle size aware SHM is coming up: a further confirmation that we can study hypernuclei wave functions

LHC Run3: hypertriton is the new deuteron

M, Mahlein et al, 2302.12696





- In Run 3 ALICE will have x100 more hypertritons in pp collisions: few percent precision on the yield
  - Essentially like the deuteron
- Already next year theory will be the limiting factor!

Modern detectors and new reconstruction techniques

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
$\Delta I = 1/2$ rule

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

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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 ($\beta\gamma$~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
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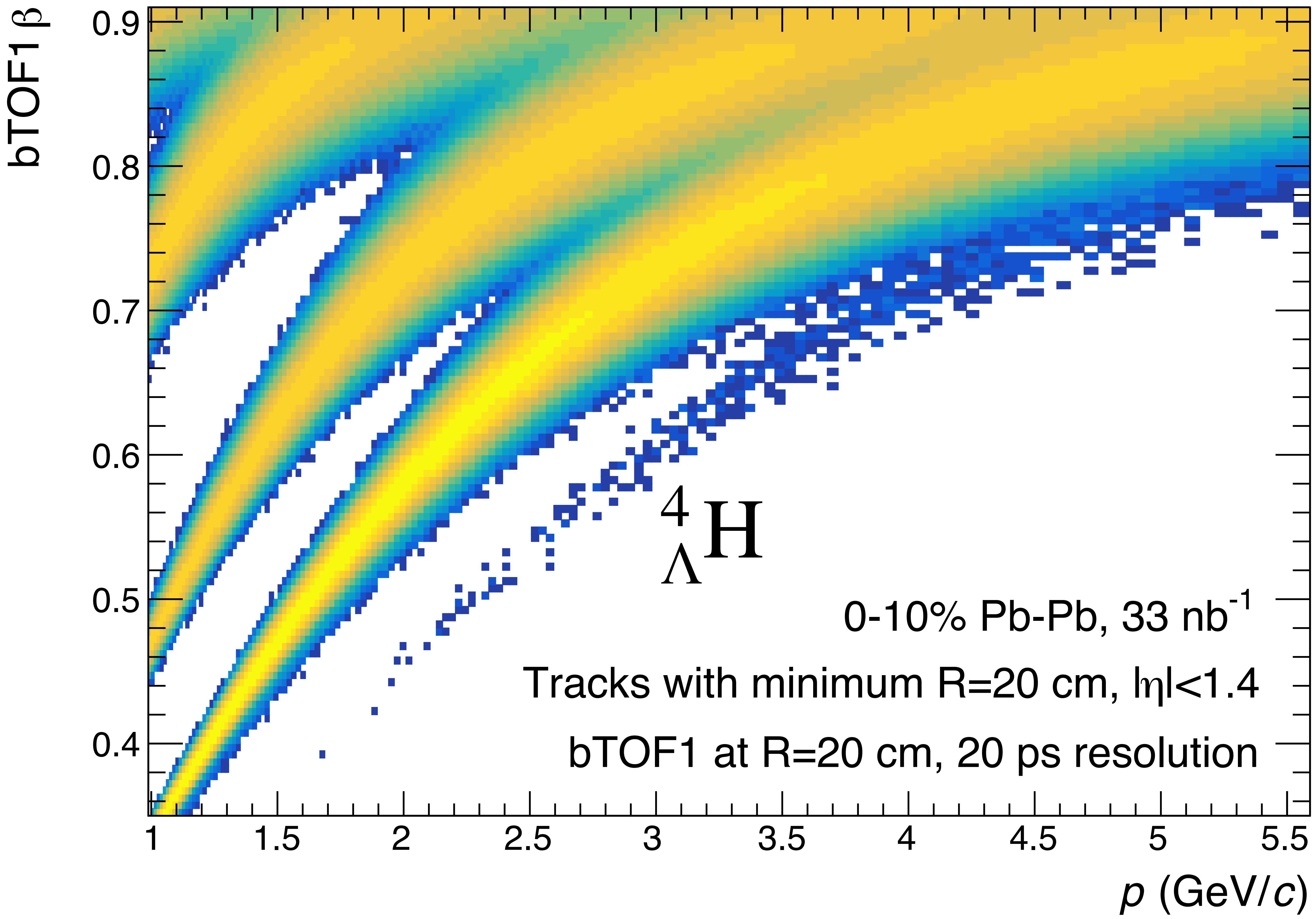

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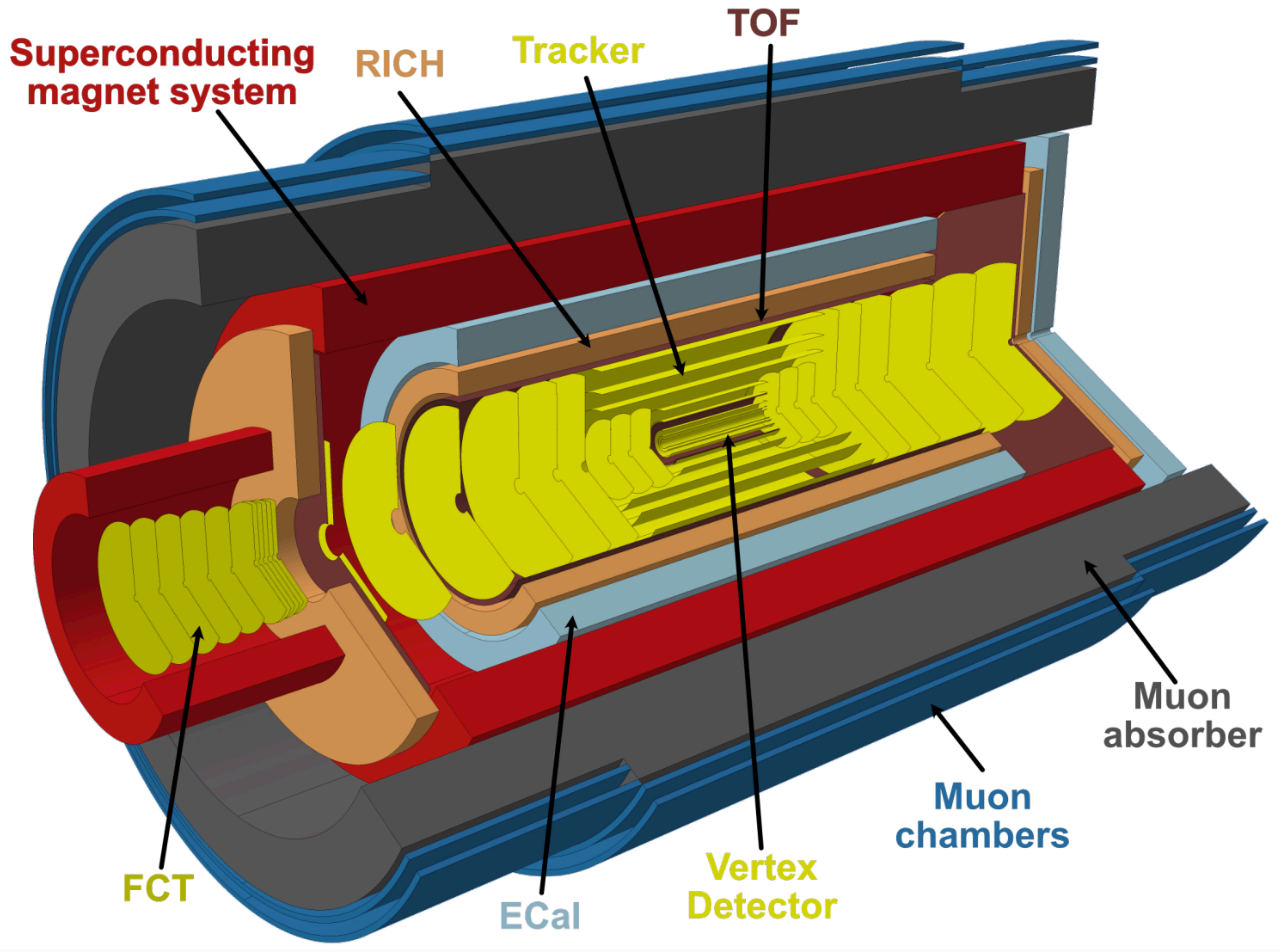
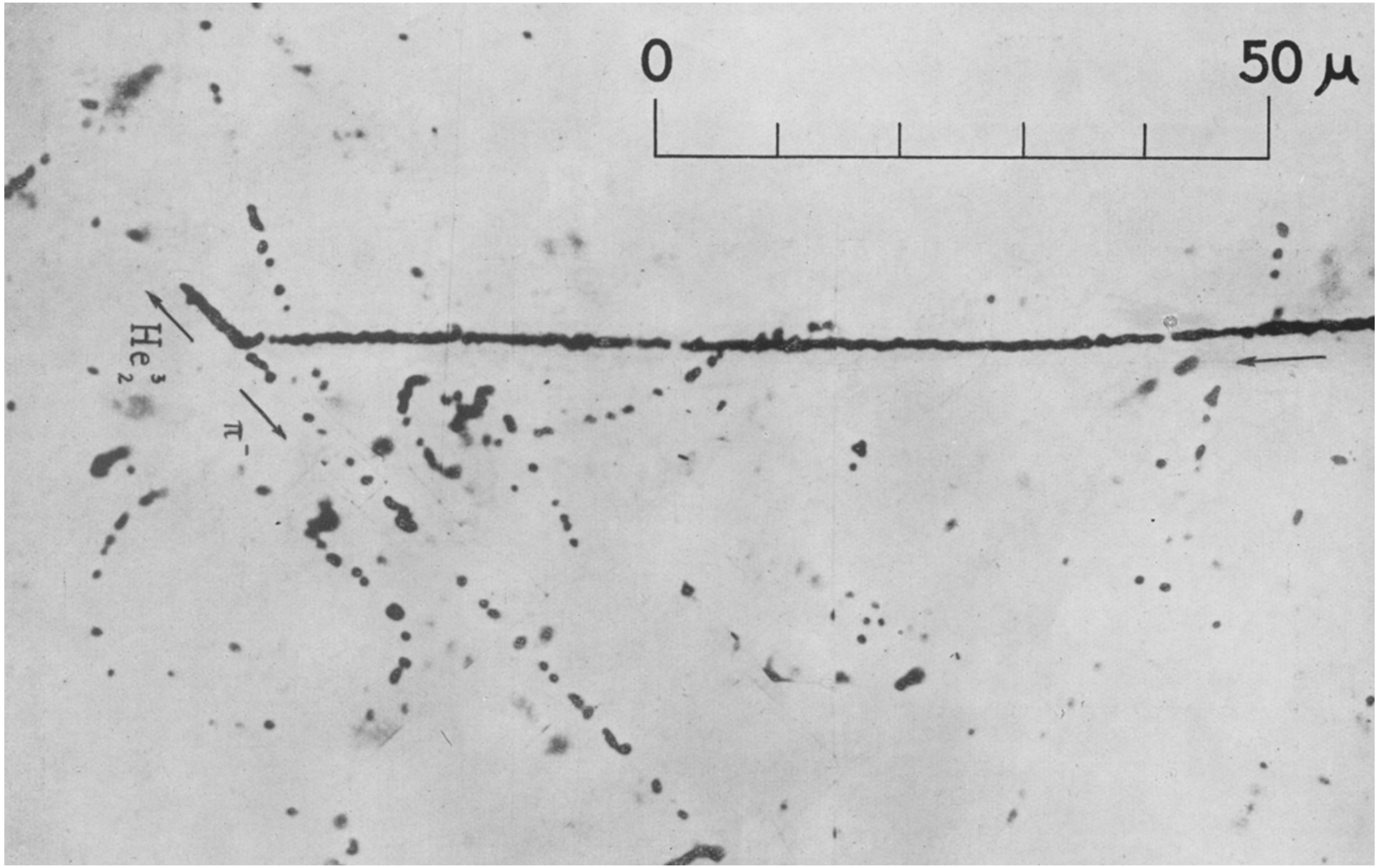
ALICE3 Letter Of Intent arxiv:2211.02491



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

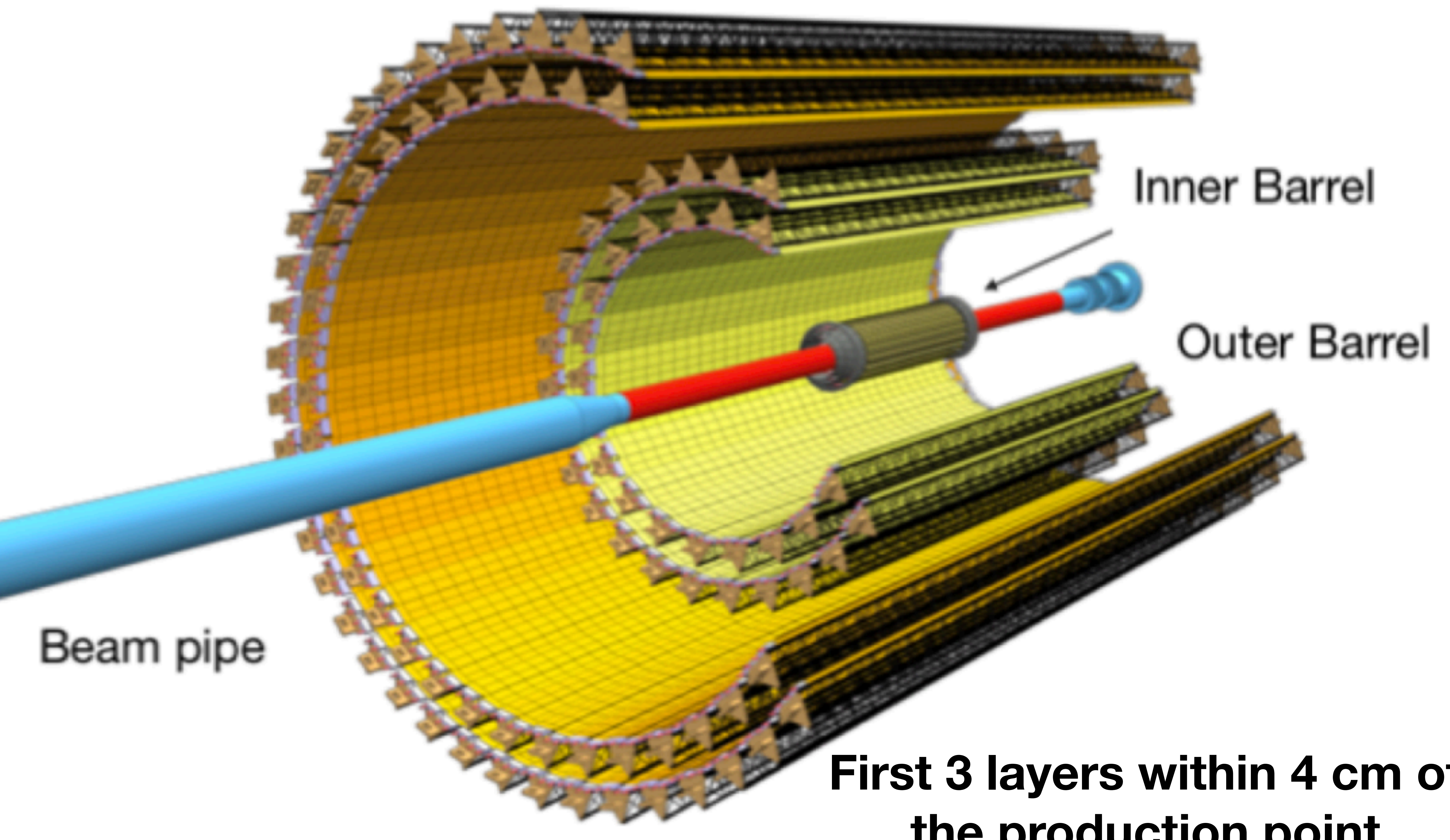
Maybe we don’t have to wait that long



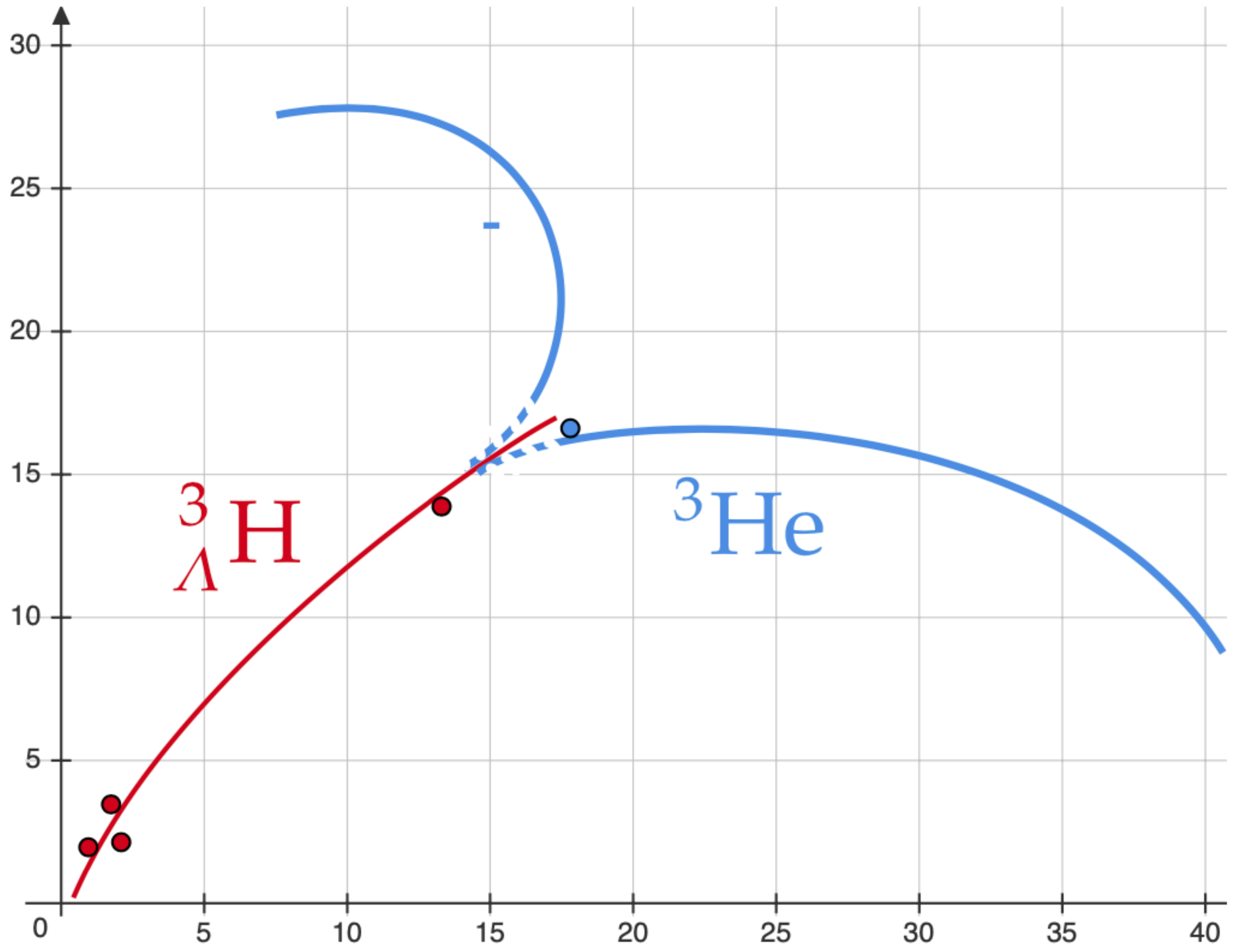
A Bonetti, R Levi Setti, M Panetti, L Scarsi, and G Tomasini. „On the possible ejection of a meson-active triton from a nuclear disintegration“. In: *Il Nuovo Cimento (1943-1954)* 11.2 (1954), pp. 210–212

A MHz silicon bubble chamber

ALICE ITS2



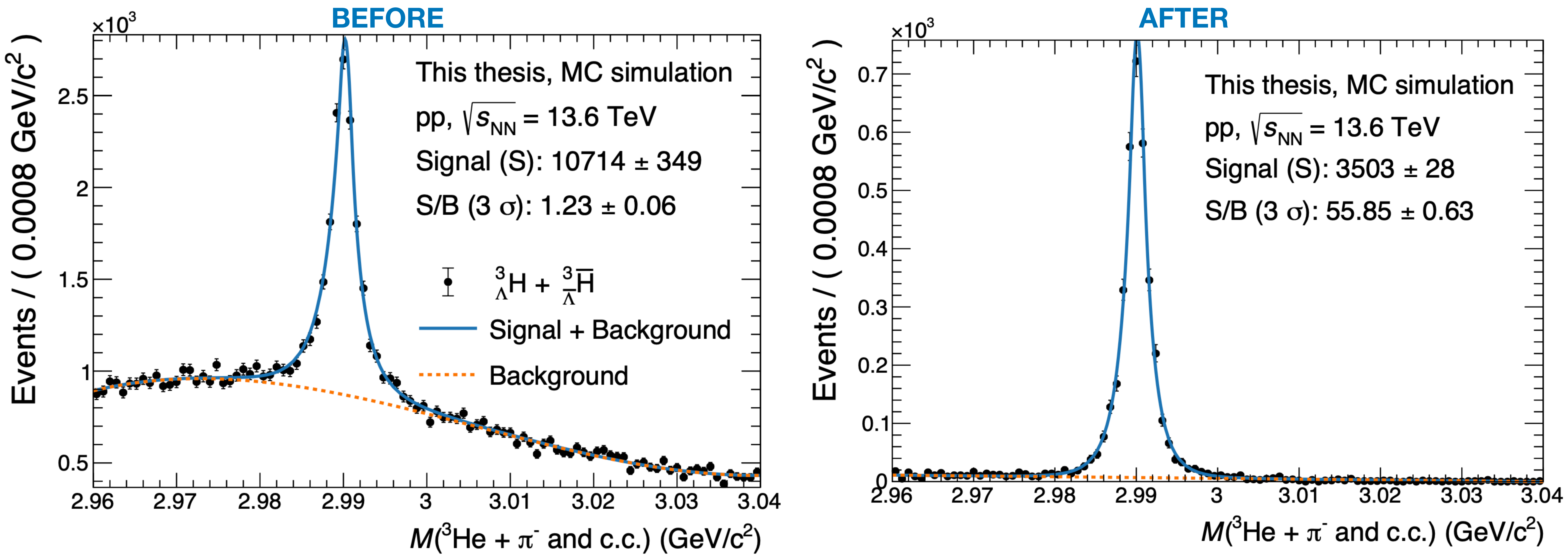
First 3 layers within 4 cm of the production point



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

A MHz silicon bubble chamber

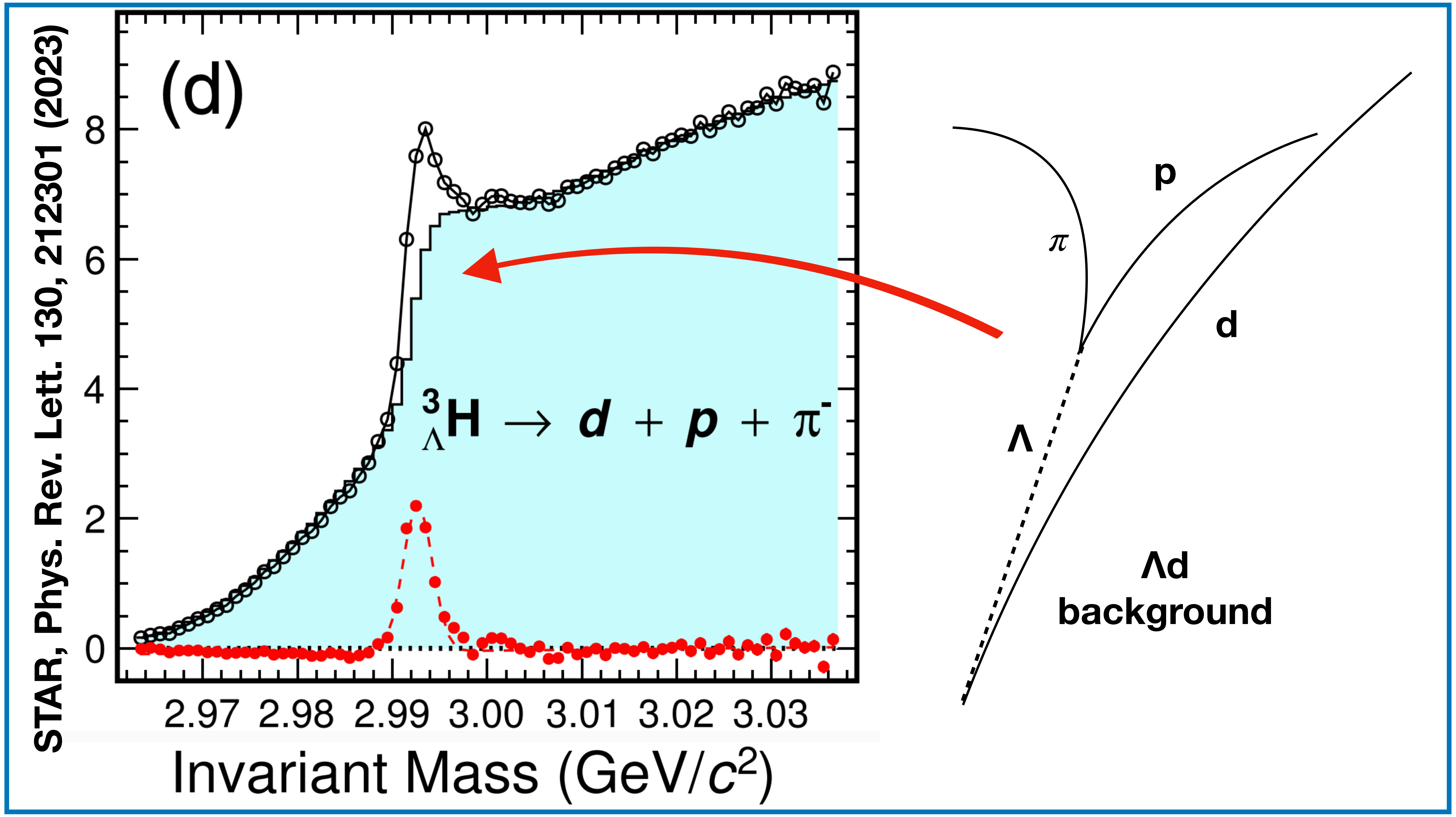
F. Mazzaschi PhD thesis

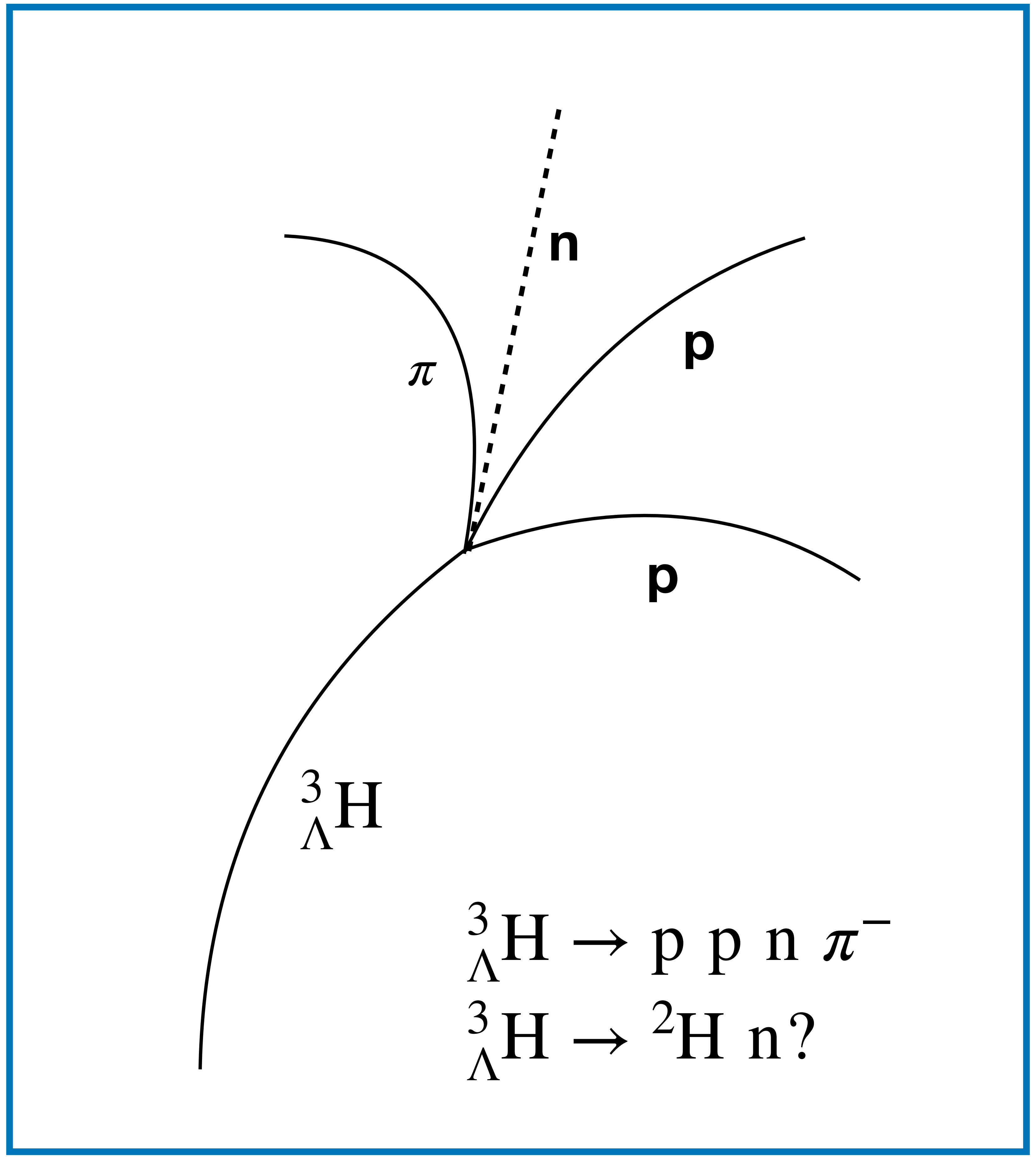


From decay vertex reconstruction to full kinematic closure by tracking the mother track

- Extreme reduction of the combinatorial background with no additional selections

A MHz silicon bubble chamber



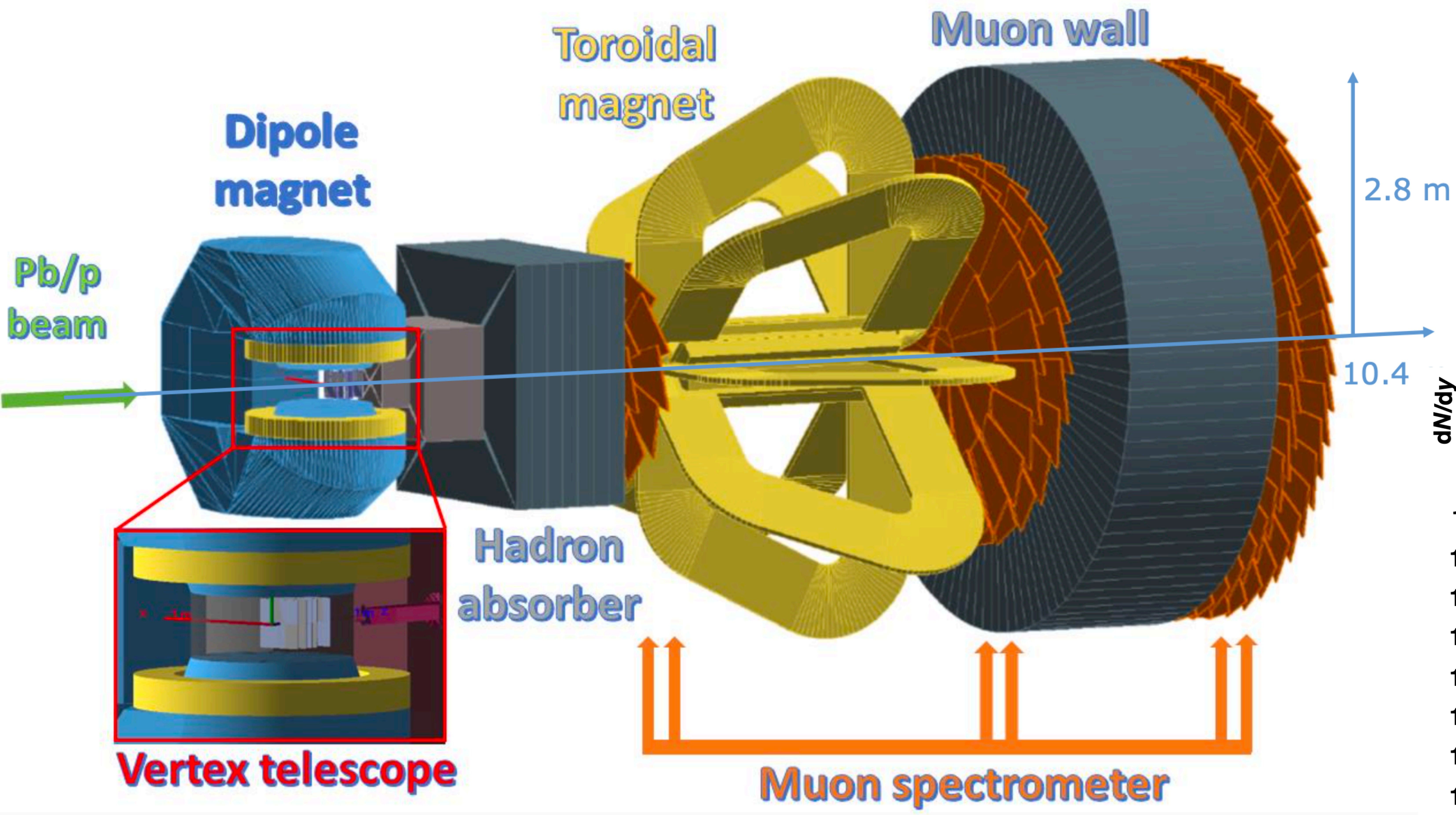


From decay vertex reconstruction to full kinematic closure by tracking the mother track

- 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

Prospects at the SPS

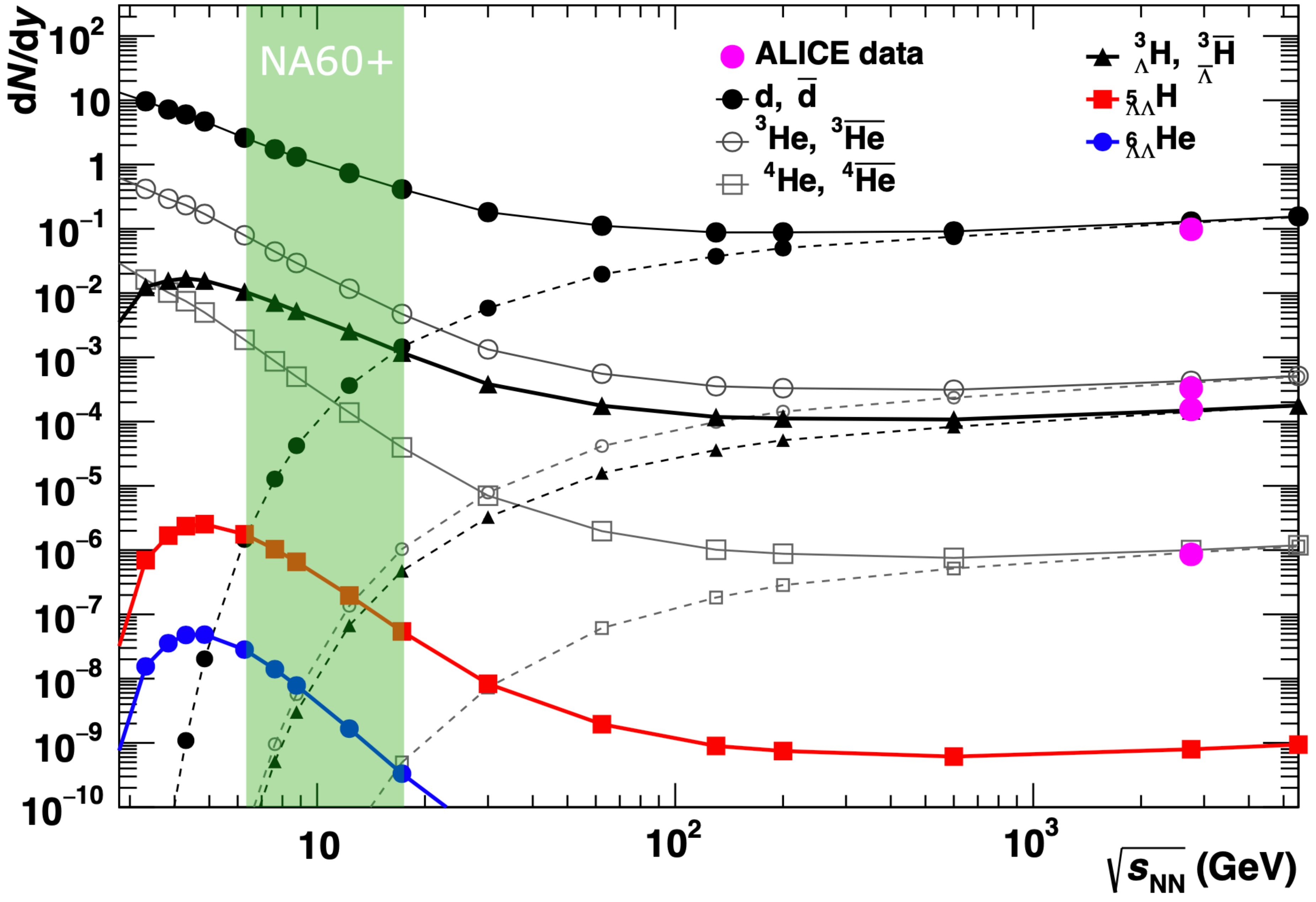
Hypernuclei in NA60+



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

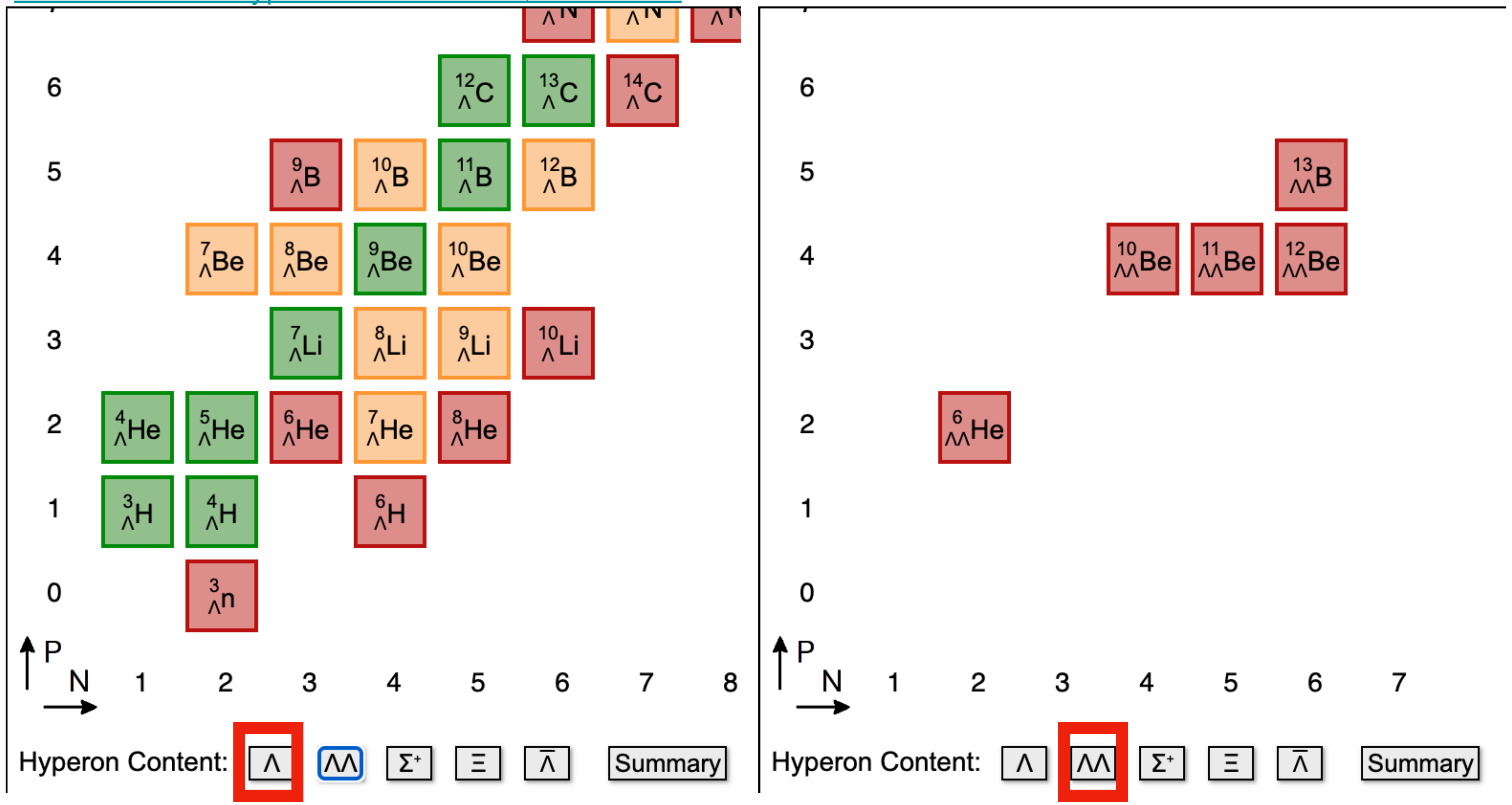
Heavy ion experiment at the SPS with a focus on heavy-flavour and di-leptons and high rate capabilities

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

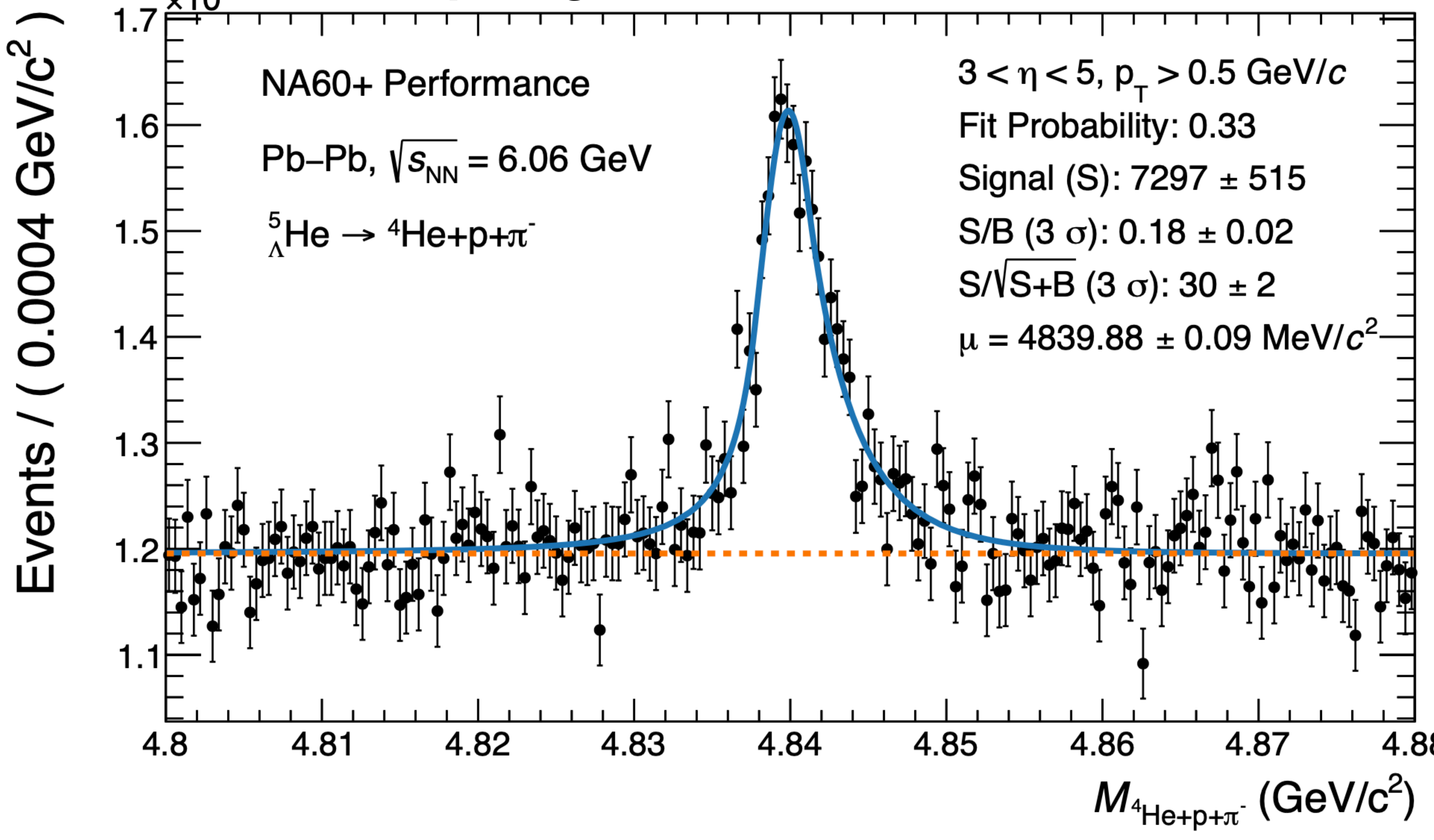


Hypernuclei in NA60+

From the Mainz hypernuclei database, June 2023



Topological selections + cluster size PID



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

Summary and outlook

Summary

- 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

- New detectors and new analysis techniques will open new avenues
  - New measurement of hypernuclei properties
  - Potential of discovery in the multistrange (and charm) sector

- Ultimately, there is still a lot to be explored at hadronic colliders in the hypernuclear sector
  - Not covered here, but seen this morning: LHCb might join the quest!

Backup

Direct identification of hypernuclei in ALICE3

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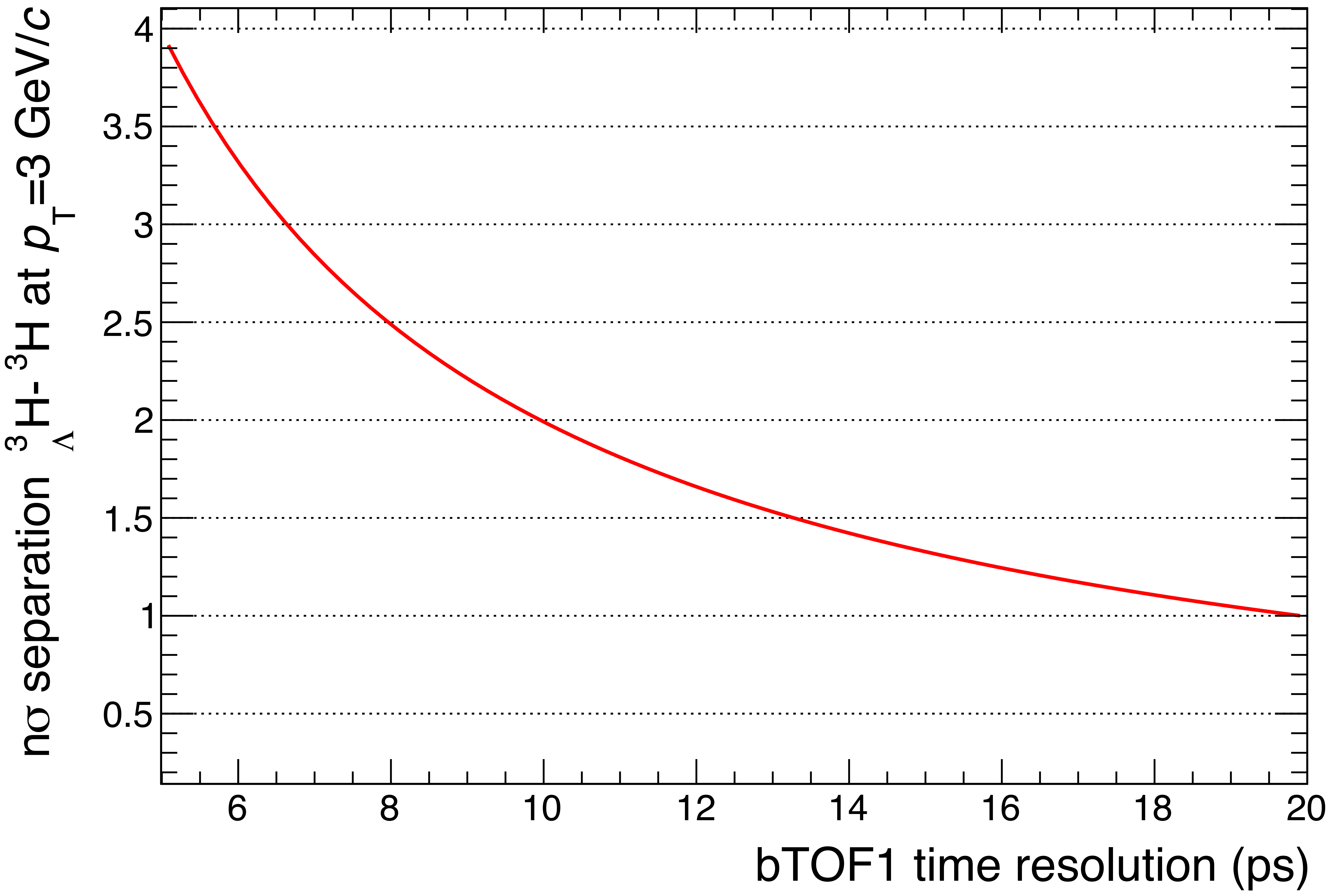

Currently ~1 sigma separation between triton and hypertriton at their mean p_T

- A time resolution of 10 ps or better is required to have a separation of at least 2σ between triton and hypertriton at their average momenta