Recent results on (anti)(hyper)nuclei production by the ALICE Collaboration

Mario Ciacco, on behalf of the ALICE Collaboration
University and INFN, Turin

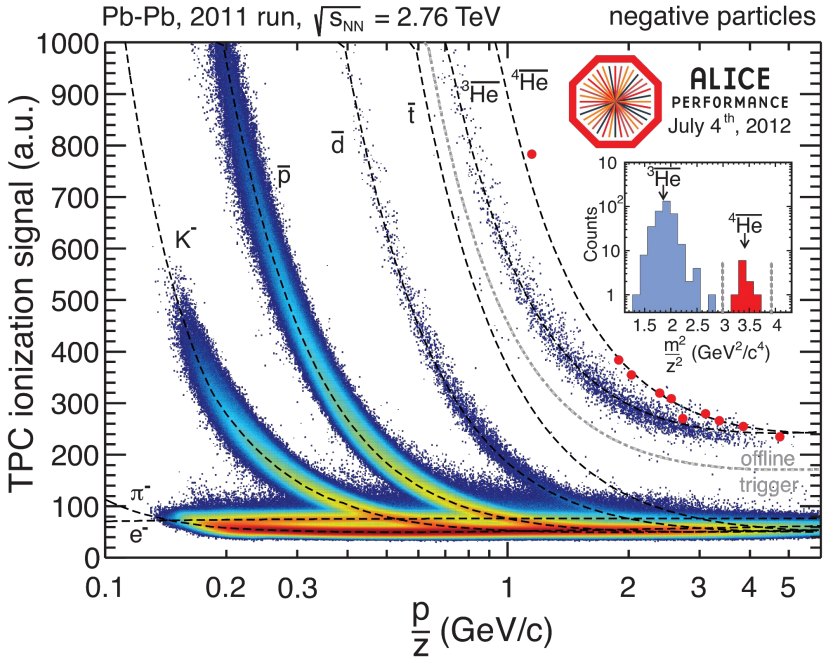
5th Workshop on Anti-Matter,
Hyper-Matter and Exotica Production

(Hyper)nuclei in the laboratory

- Light nuclei are observed in high-energy heavy-ion collision experiments
  - Hot and dense medium, T = O(100 MeV)
  - Binding energies O(1-10 MeV)
  - How can loosely-bound states emerge from such extreme conditions?
- Light (anti)(hyper)nuclei at the collider as a doorway to the Cosmos

Maximilian's lecture

  - Constraining models of astrophysical backgrounds in indirect dark-matter searches [1]
  - Hypernuclei properties → hyperon-nucleon interactions → input to model neutron-star matter [2]

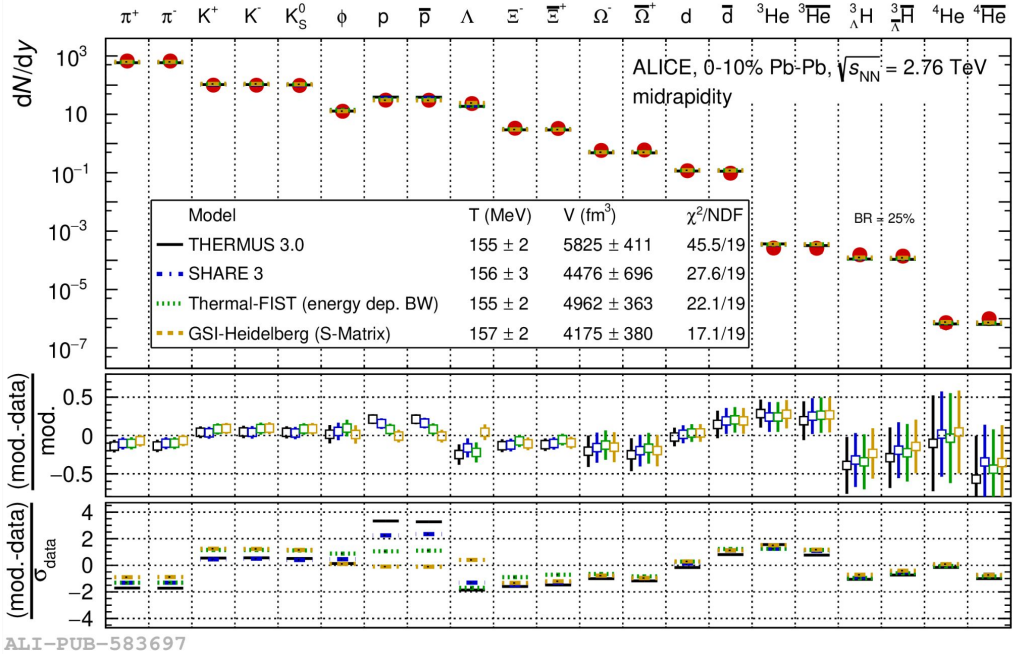


[1] Donato et al, Phys.Rev.D 62 (2000) 043003
[2] Logoteta et al, *Eur.Phys.J.A* 55 (2019) 11, 207

mario.ciacco@cern.ch

Nucleosynthesis models

- Statistical hadronisation
  - Yields of light-flavour hadrons including light (hyper)nuclei are instantly fixed at the freeze-out of inelastic interactions
  - Yields only depend on the mass and common thermal parameters *T* and *V*

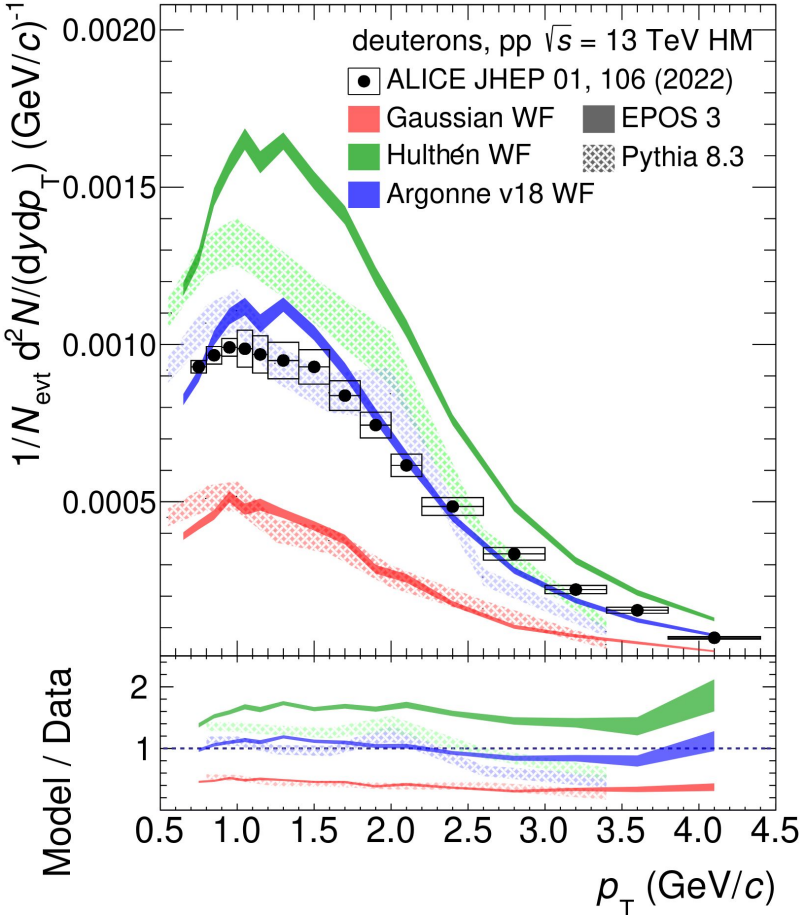


[1] *Eur.Phys.J.C* 84 (2024) 8, 813

mario.ciacco@cern.ch

Nucleosynthesis models (2)

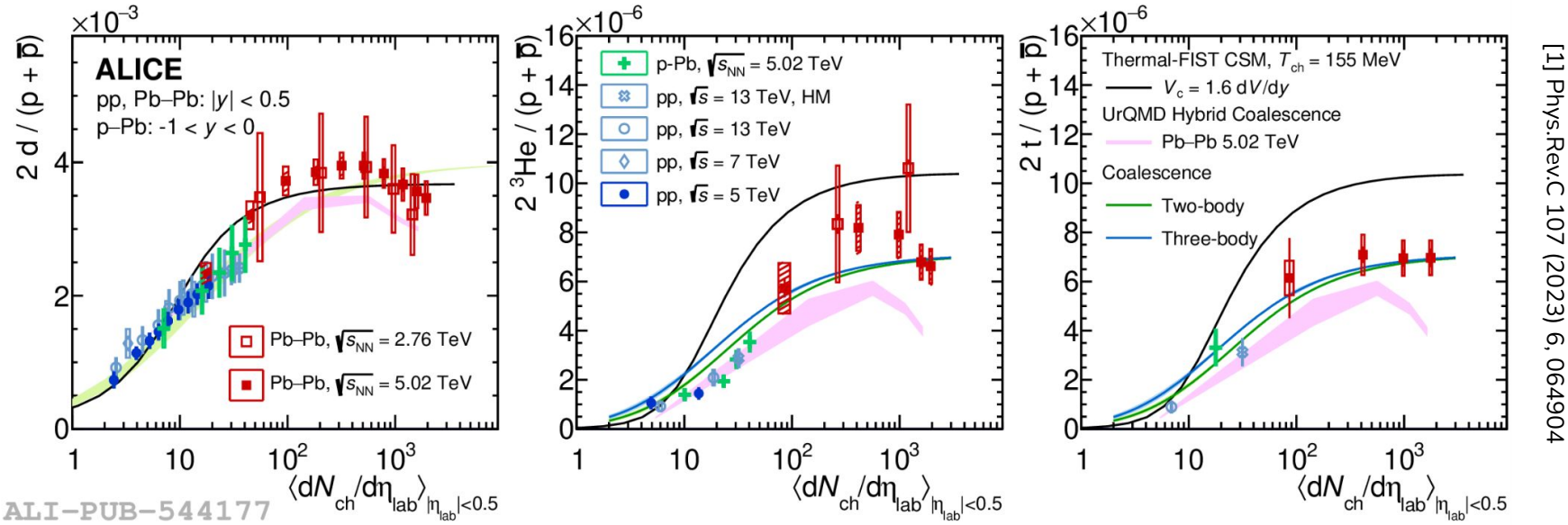
- Statistical hadronisation
  - Yields of light-flavour hadrons including light (hyper)nuclei are instantly fixed at the freeze-out of inelastic interactions
  - Yields only depend on the mass and common thermal parameters *T* and *V*
- Coalescence
  - Light (hyper)nuclei are formed by pre-existing nucleons overlapping in phase space
  - State-of-the-art models rely on Wigner function formulation



[1] Mahlein et al, Eur.Phys.J.C 83 (2023) 9, 804

(Anti)nuclei production in LHC Run 1 and 2

- Extensive studies of (anti)nuclei production across different colliding systems
  - A=2 → less separation power for different models within experimental uncertainties
  - A=3 → slight preference for coalescence with respect to statistical hadronization
- In the precision era of (hyper)nuclear physics at the LHC, can we pin down nucleosynthesis mechanisms?

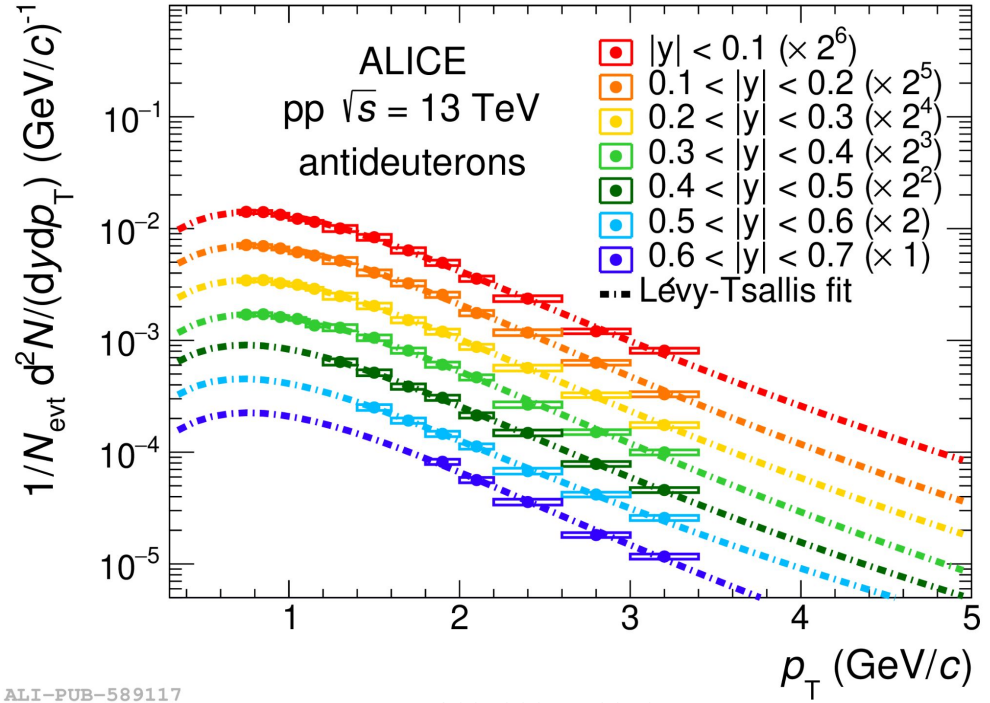


[1] Phys.Rev.C 107 (2023) 6, 064904

mario.ciacco@cern.ch

Antideuteron production vs. rapidity in pp

- First measurement of the rapidity dependence of antideuteron production in pp collisions up to $|y| = 0.7$
- $0.5 < |y| < 1.5 \rightarrow$ crucial input to model the flux of cosmic rays produced in interactions with the interstellar medium [2]



[1] Phys. Lett. B 860 (2025) 139191
[2] Blum, *Phys.Rev.C* 109 (2024) 3, L031904

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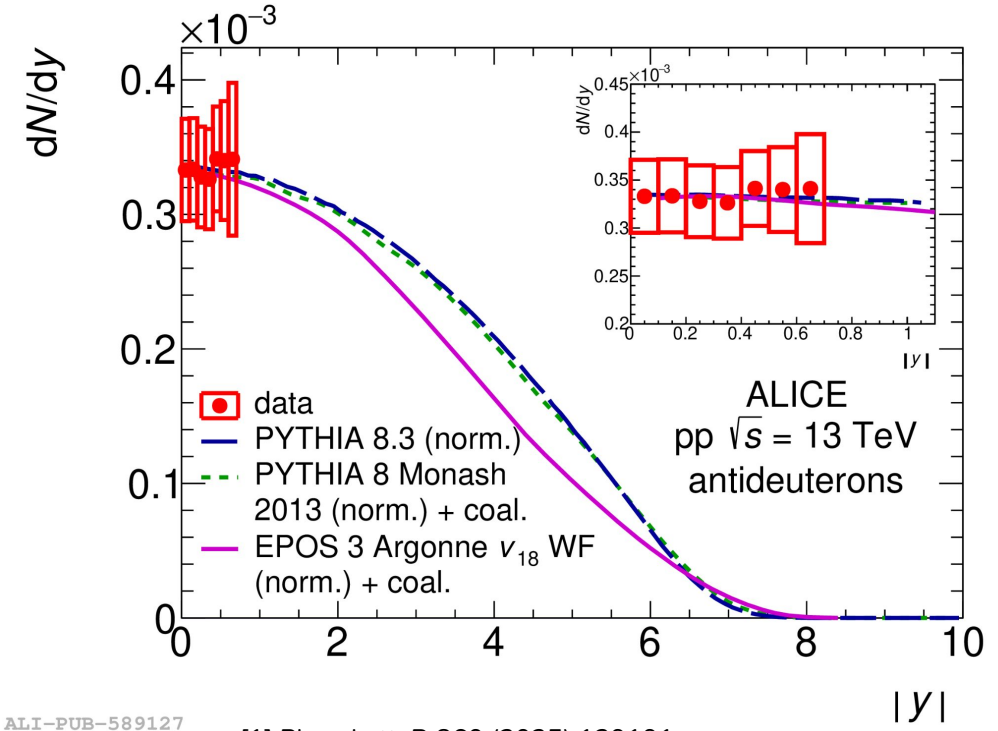
Antideuteron production vs. rapidity in pp (2)

- First measurement of the rapidity dependence of antideuteron production in pp collisions up to $|y| = 0.7$
- $0.5 < |y| < 1.5$ → crucial input to model the flux of cosmic rays produced in interactions with the interstellar medium [2]
- The antideuteron yield is independent of rapidity within uncertainties
  - Limited sensitivity to different models (with/without coalescence)
- Tighter constraints on models will require more forward measurements → LHCb and ALICE 3

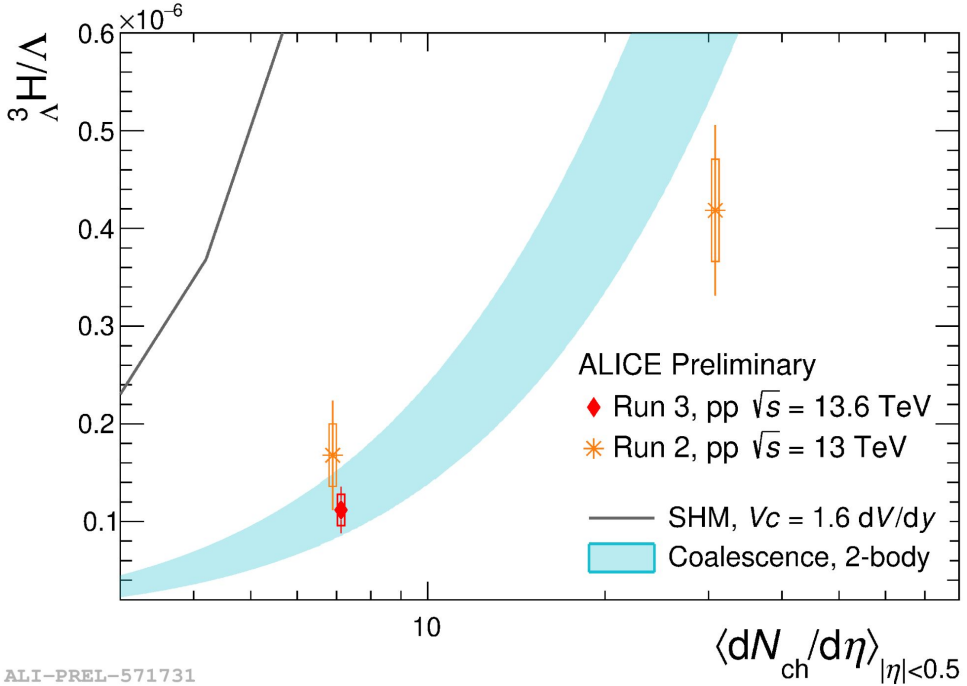


[1] Phys. Lett. B 860 (2025) 139191
[2] Blum, *Phys.Rev.C* 109 (2024) 3, L031904

mario.ciacco@cern.ch

Hypertriton production in pp

- ${}^{3}_{\Lambda}\mathrm{H} \rightarrow$ loosely bound "halo" hypernucleus
- High sensitivity to the production mechanism in small systems
  - Strong suppression in coalescence due to its large wave function compared to the source size



[1] Vovchenko et al, Phys.Lett.B 835 (2022) 137577
[2] Sun et al, Phys.Lett.B 792 (2019) 132-137

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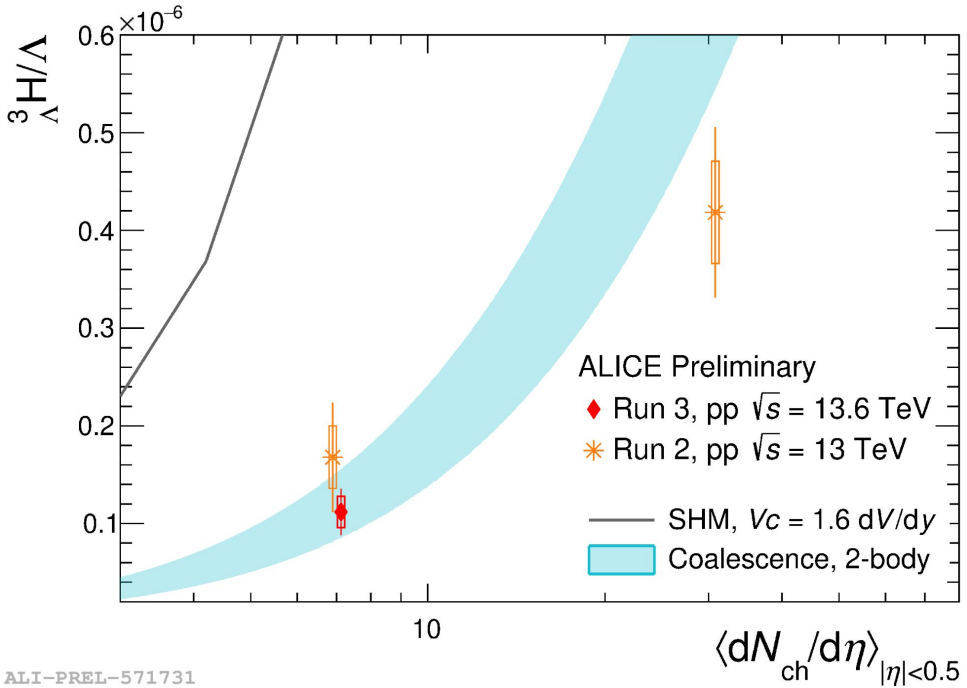
Hypertriton production in pp (2)

- ${}^{3}_{\Lambda}\mathrm{H} \rightarrow$ loosely bound "halo" hypernucleus
- High sensitivity to the production mechanism in small systems
  - Strong suppression in coalescence due to its large wave function compared to the source size
- Dedicated asynchronous software trigger in the Run 3 pp data taking
  - Statistical uncertainties reduced by a factor > 2
  - Coalescence is strongly favoured by the data



[1] Vovchenko et al, Phys.Lett.B 835 (2022) 137577
[2] Sun et al, Phys.Lett.B 792 (2019) 132-137

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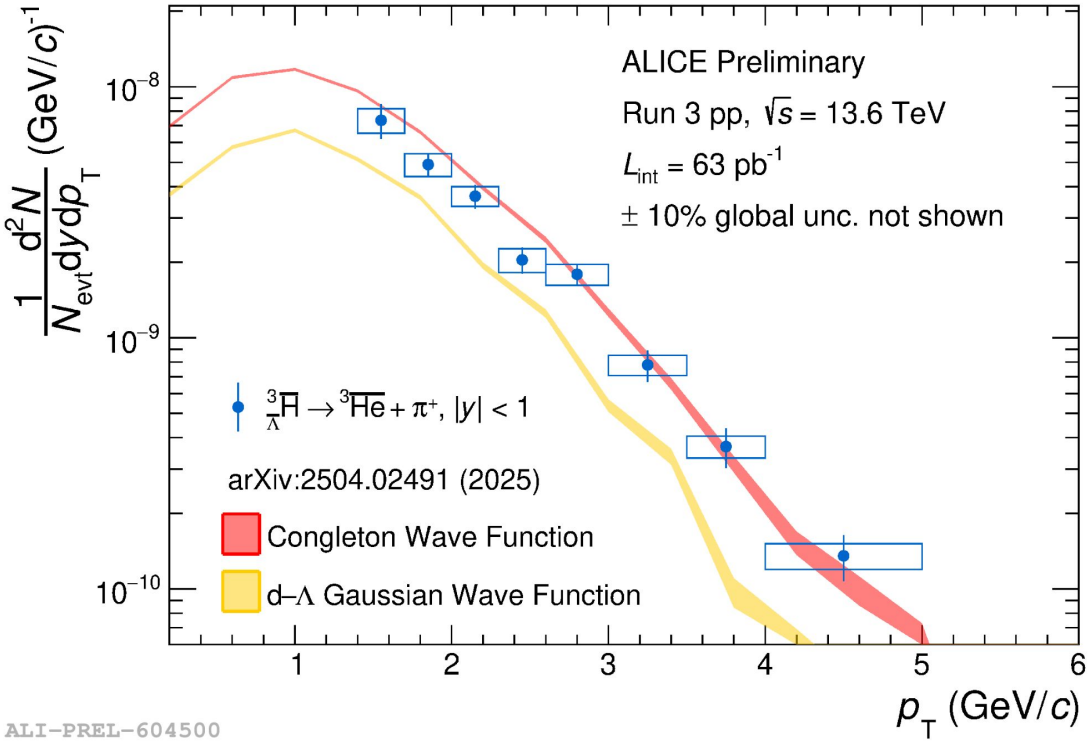
Hypertriton production in pp (3)

- First precise measurement of the p_T spectrum of ${}^3_\Lambda$H in pp
- Constraints on the wave function using realistic coalescence afterburner code [1]
  - ${}^3_\Lambda$H as a d-Λ system
  - Congleton wave function favoured by the data with respect to Gaussian

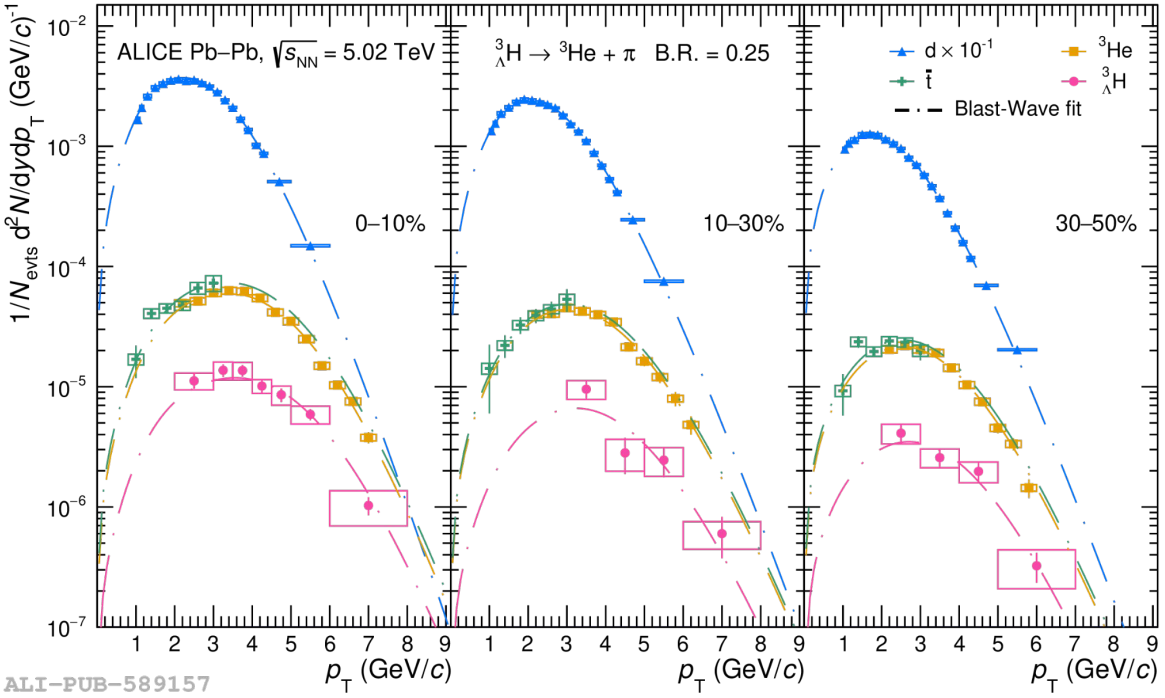


[1] Mahlein et al, Eur.Phys.J.C 84 (2024) 11, 1136

mario.ciacco@cern.ch

Hypertriton production in Pb–Pb

- The p_T spectrum of $^3_\Lambda$H has been measured also in Pb–Pb collisions as a function of centrality
- The p_T shape is consistently described by the blast-wave model across different nuclear species within present uncertainties

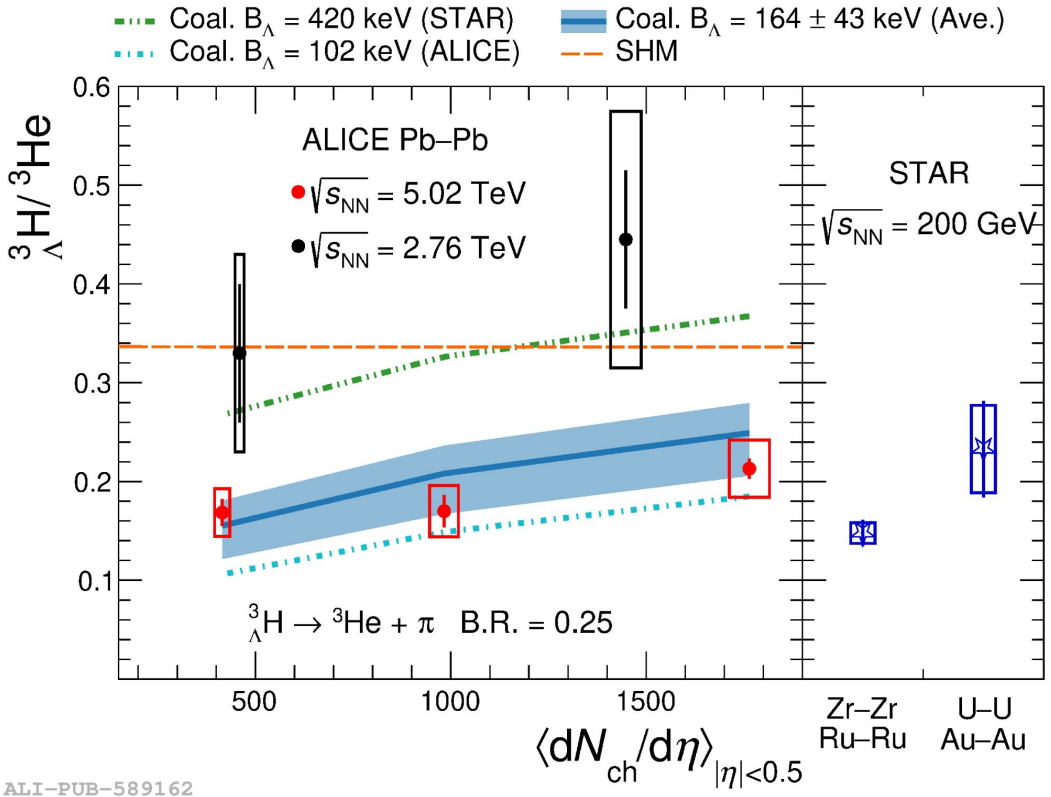


[1] Phys. Lett. B 860 (2025) 139066

mario.ciacco@cern.ch

Hypertriton production in Pb–Pb (2)

- The uncertainty on the $^{3}_{\Lambda}$H/^{3}He ratio is reduced by a factor > 4 compared to the LHC Run 1
  - Coalescence predictions with world-average B_{Λ} input agree with the data
  - ALICE measurements are in agreement with STAR data in other ion-ion systems at lower centre-of-mass energy



[1] Phys. Lett. B 860 (2025) 139066

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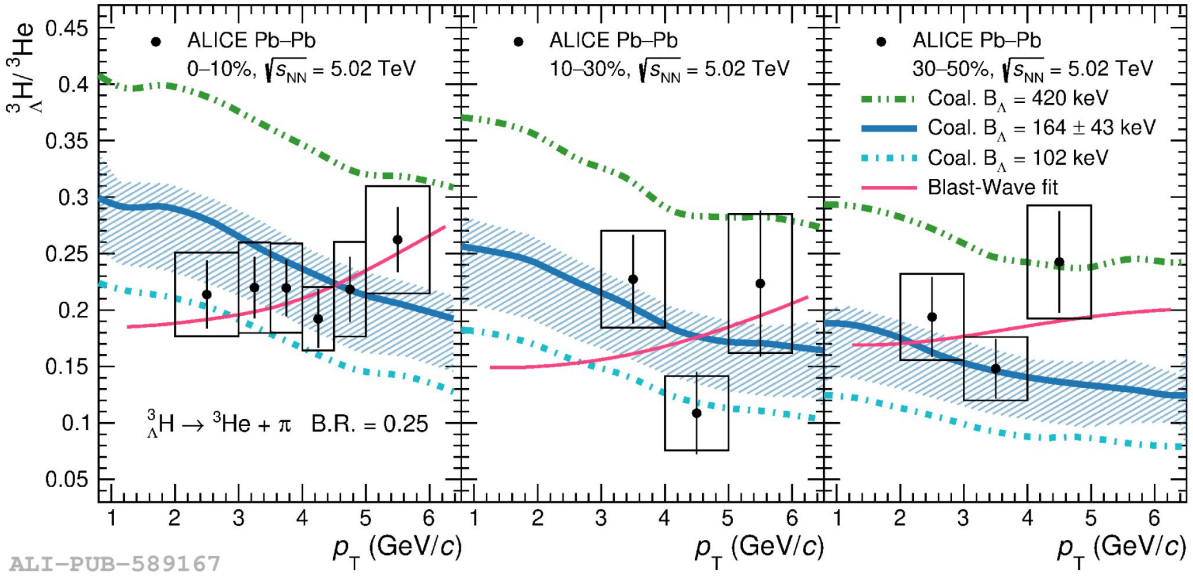
Hypertriton production in Pb–Pb (3)

- The $^{3}_{\Lambda}$H/^{3}He ratio is also measured as a function of p_T
  - Different trends expected by coalescence with respect to blast-wave [2]
- Uniform p_T trend within current uncertainties
  - Could be further explored leveraging the data samples collected during the Run 3+4

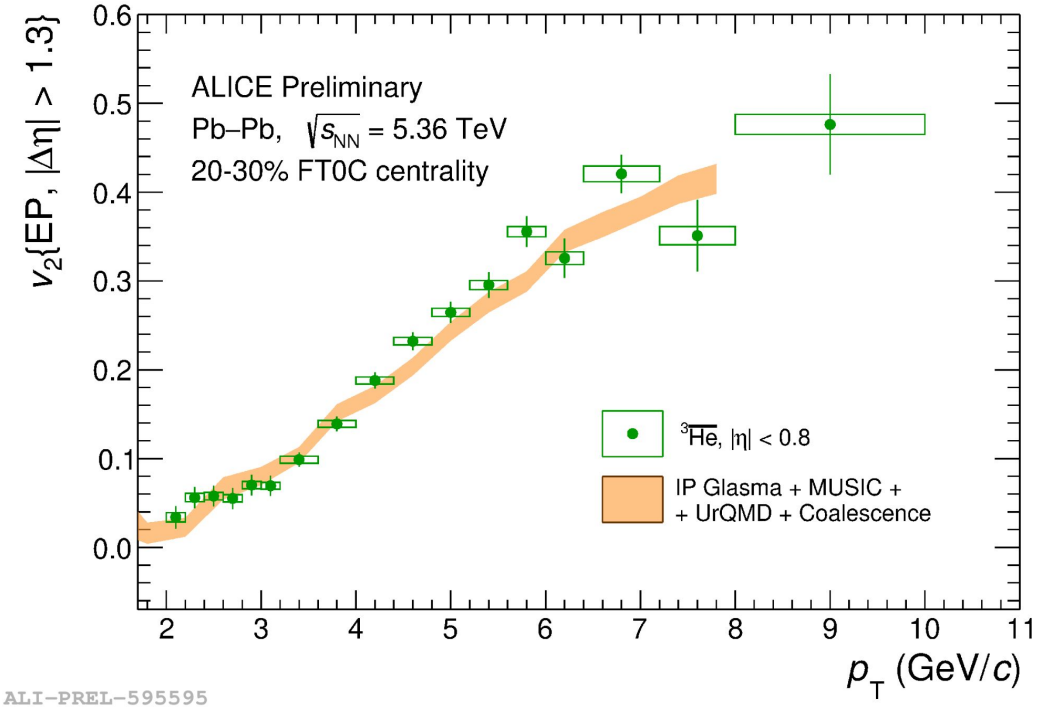


[1] Phys. Lett. B 860 (2025) 139066
[2] Liu et al, Phys.Lett.B 855 (2024) 138855

mario.ciacco@cern.ch

Elliptic flow of A=3 as a probe of nucleosynthesis

- Azimuthal momentum anisotropies in heavy-ion collisions are driven by the initial system geometry
- These anisotropies can be modified by the nucleosynthesis process
  - Hydro + coalescence hypothesis describes ^{3}He elliptic flow



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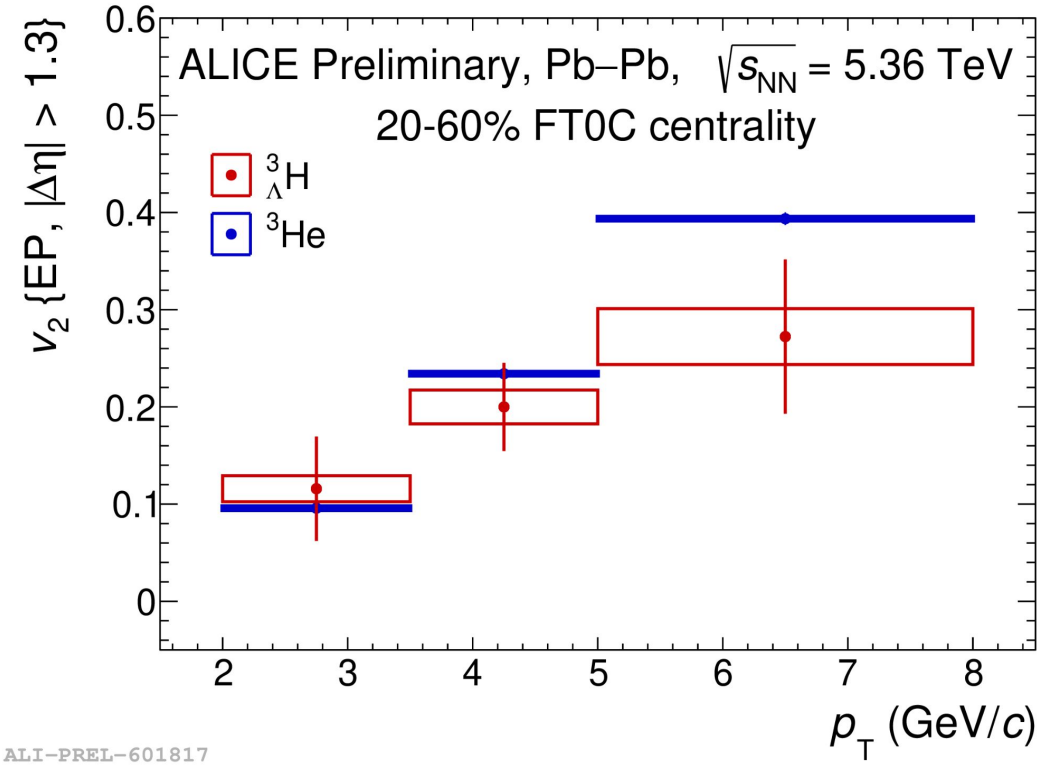
- Azimuthal momentum anisotropies in heavy-ion collisions are driven by the initial system geometry
- These anisotropies can be modified by the nucleosynthesis process
  - Hydro + coalescence hypothesis describes ^{3}He elliptic flow
- First measurement of the hypertriton elliptic flow enabled by large Pb–Pb samples collected in Run 3 with continuous readout
  - Consistent with ^{3}He within current uncertainties



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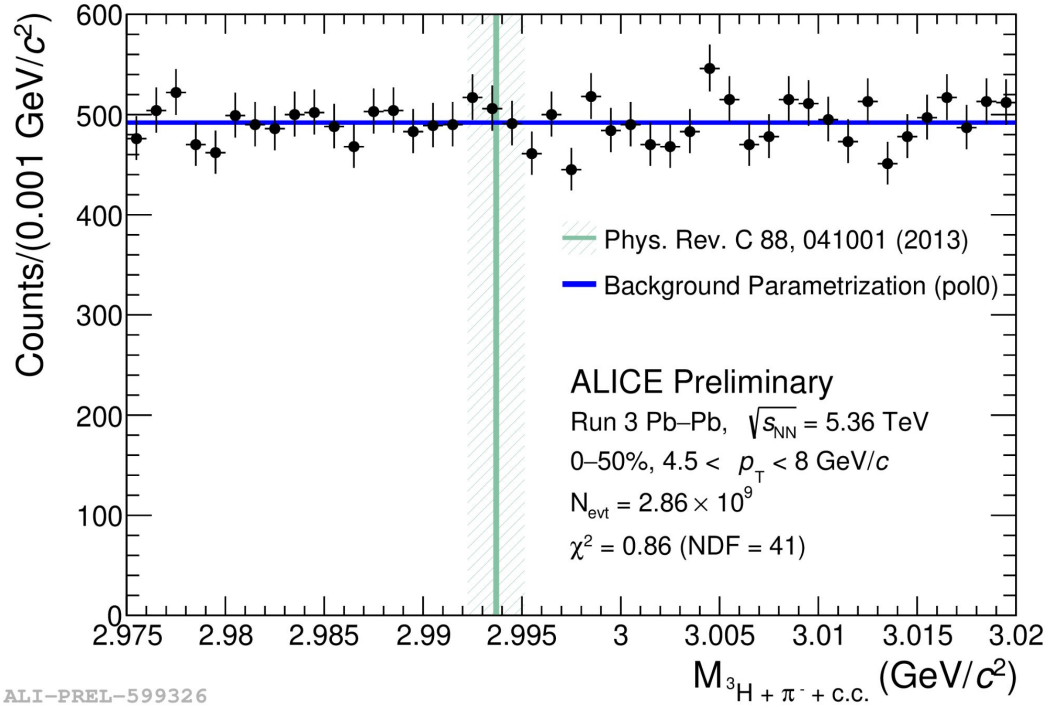
Search for exotic A=3 bound states

- Large data samples collected in the Run 3 also enable exotic states searches
- Λnn (bound) state → unconfirmed signals obtained by HypHI [1]
- Searched by ALICE through its charged-mesonic 2-body decay channel in the phase-space region with highest expected significance



[1] Rappold et al, Phys. Rev. C 88, 041001 (2013)

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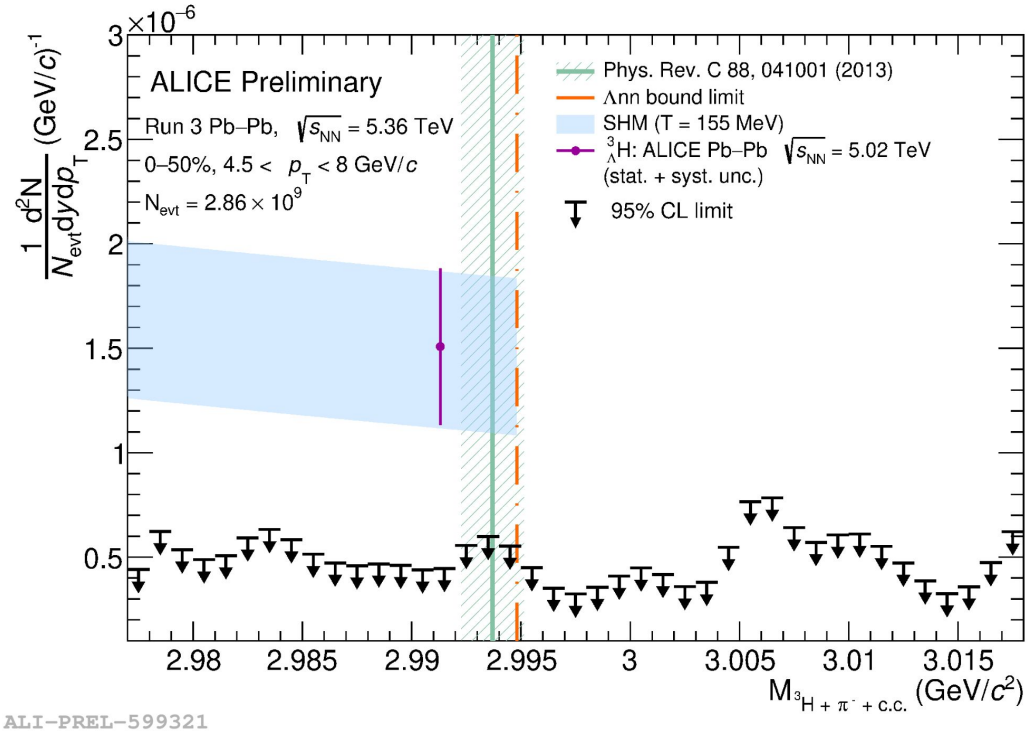
- Λnn (bound) state → unconfirmed signals obtained by HypHI [1]
- Searched by ALICE through its charged-mesonic 2-body decay channel in the phase-space region with highest expected significance
- No evidence of Λnn from the LHC
  - Yields lower than a half of the $^{3}_{\Lambda}$H yield excluded by 95% CL



[1] Rappold et al, Phys. Rev. C 88, 041001 (2013)

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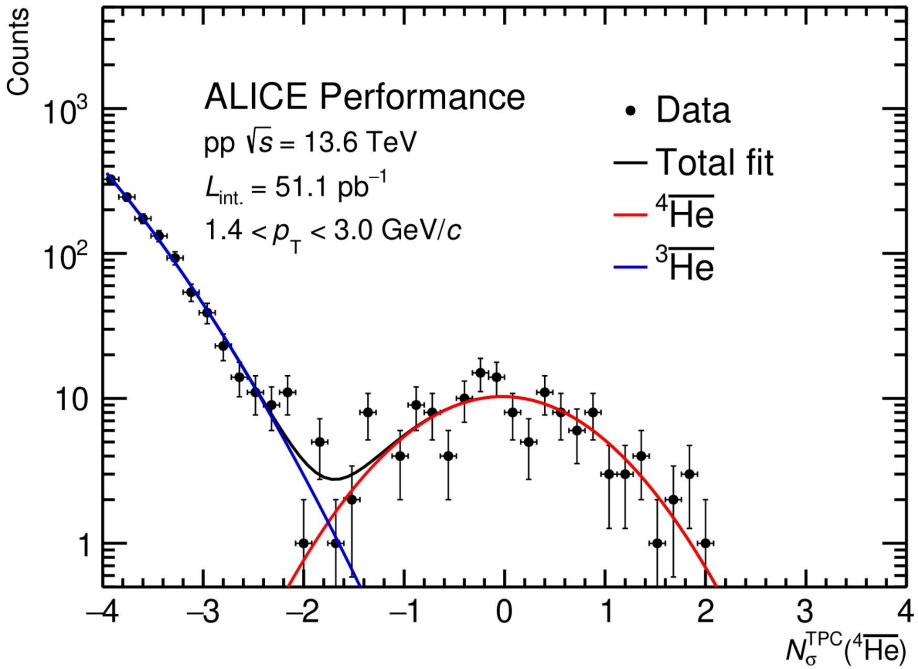
Anti-alpha production in pp

- Asynchronous software triggers for highly-ionising particles in the TPC
- First observation of anti-^{4}He in pp collisions thanks to the high inspected luminosity O(50 pb^{-1})



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mario.ciacco@cern.ch

Anti-alpha production in pp (2)

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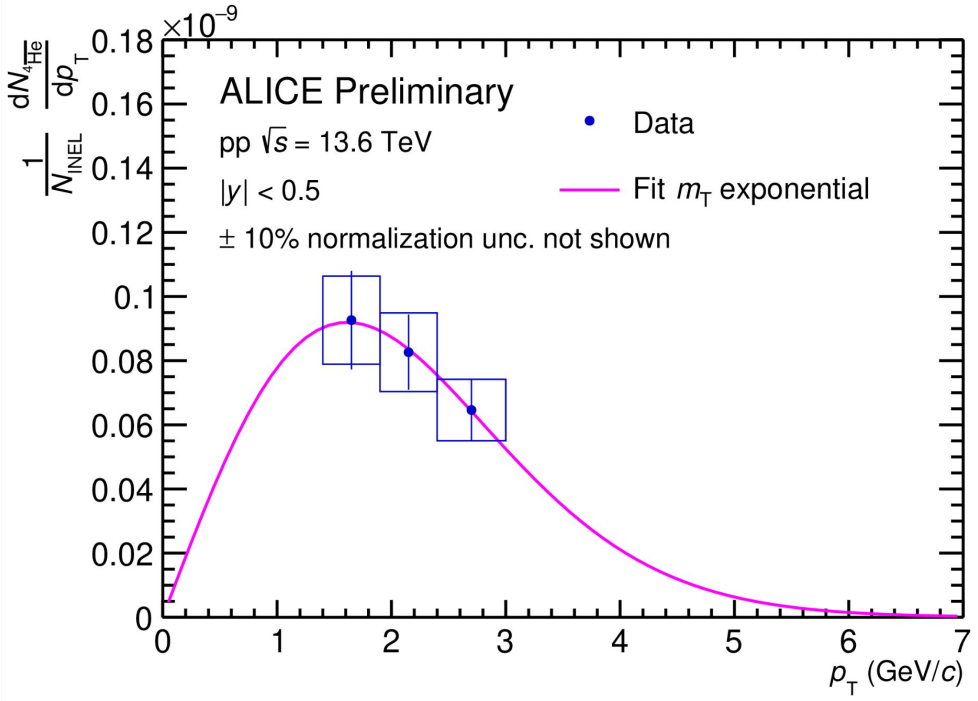
  - Enabling a p_T differential measurement in 3 intervals



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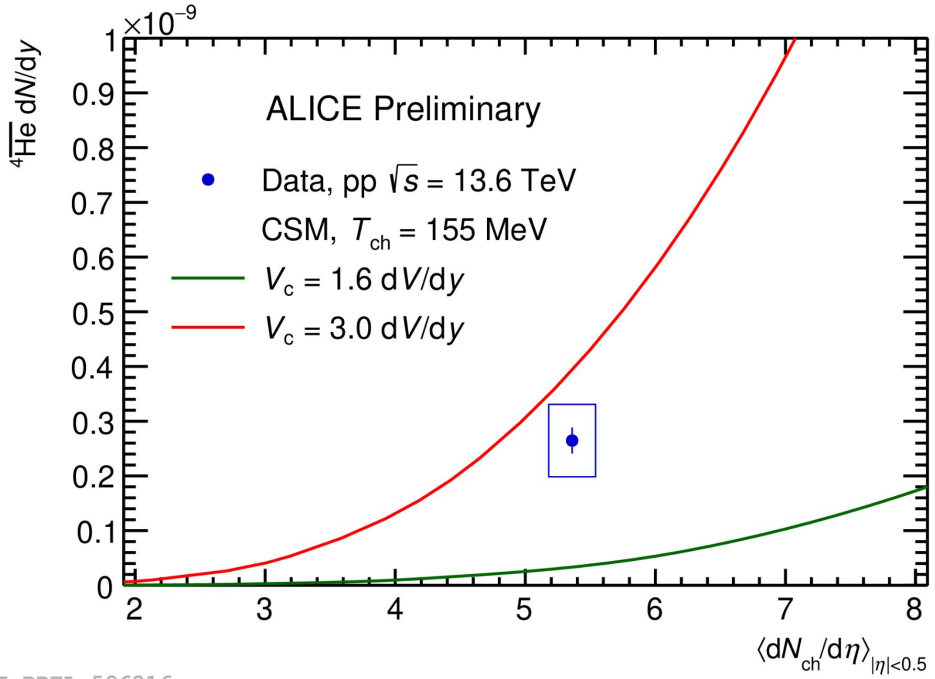
- First observation of anti-^{4}He in pp collisions thanks to the high inspected luminosity O(50 pb^{-1})
  - Enabling a p_T differential measurement in 3 intervals
- Differently from A=3, canonical statistical hadronization in agreement with dN/dy
  - Canonical volume V_C = 3 dV/dy similar to other light-flavour hadrons [1]

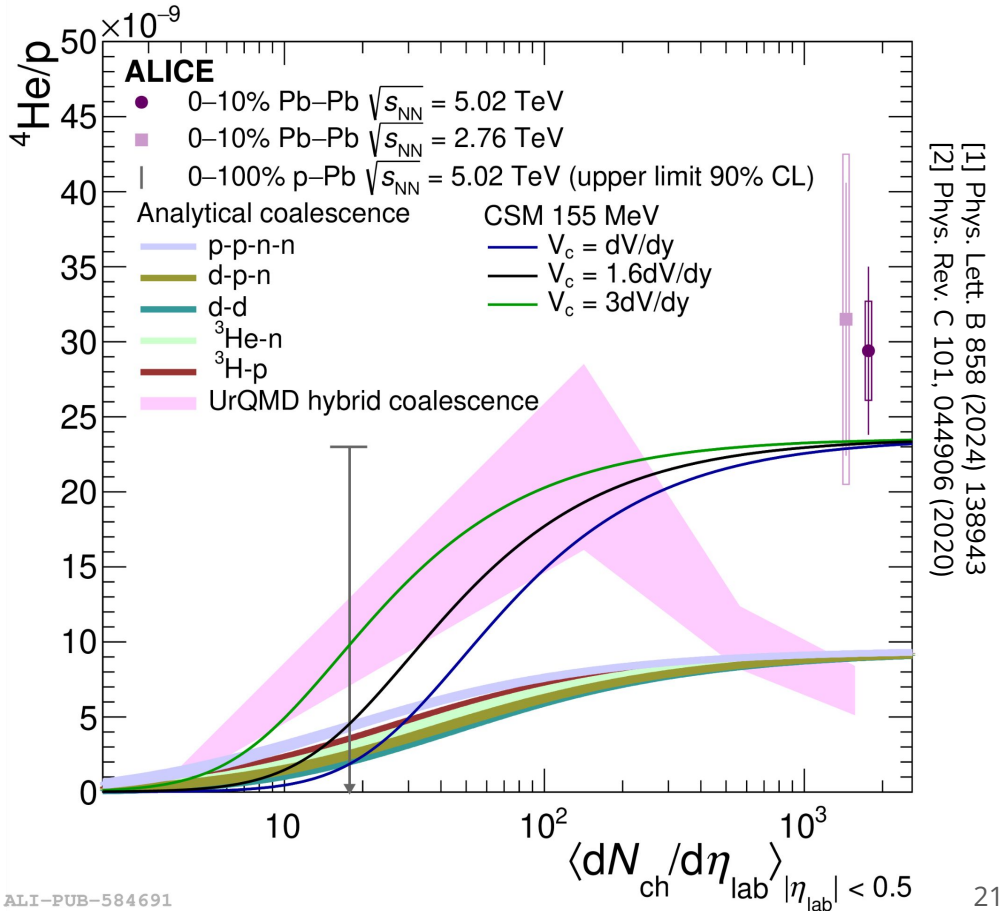


[1] Vovchenko et al, Phys.Rev.C 100 (2019) 5, 054906

mario.ciacco@cern.ch

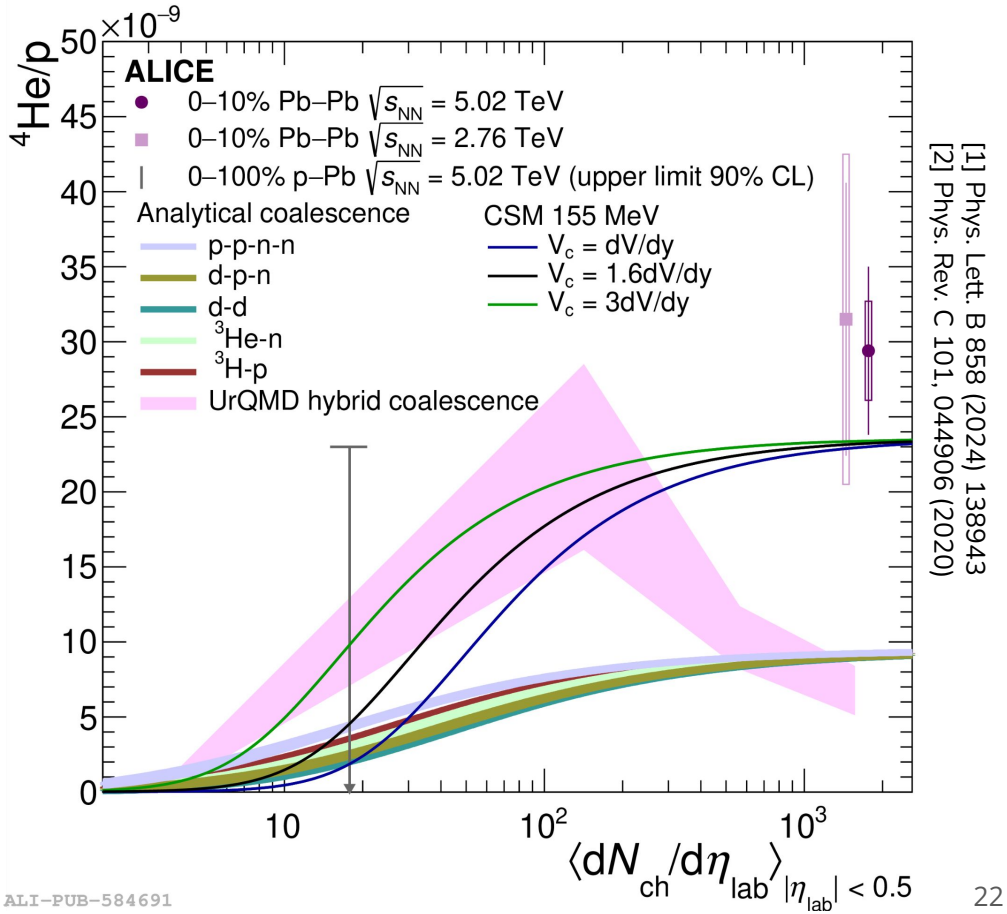
Alpha production in Pb–Pb

- ^{4}He production in Pb–Pb using the Run 2 sample
- The average ^{4}He/p yield ratio is consistent with Run 1 with uncertainties improved by a factor of 2



Alpha production in Pb–Pb (2)

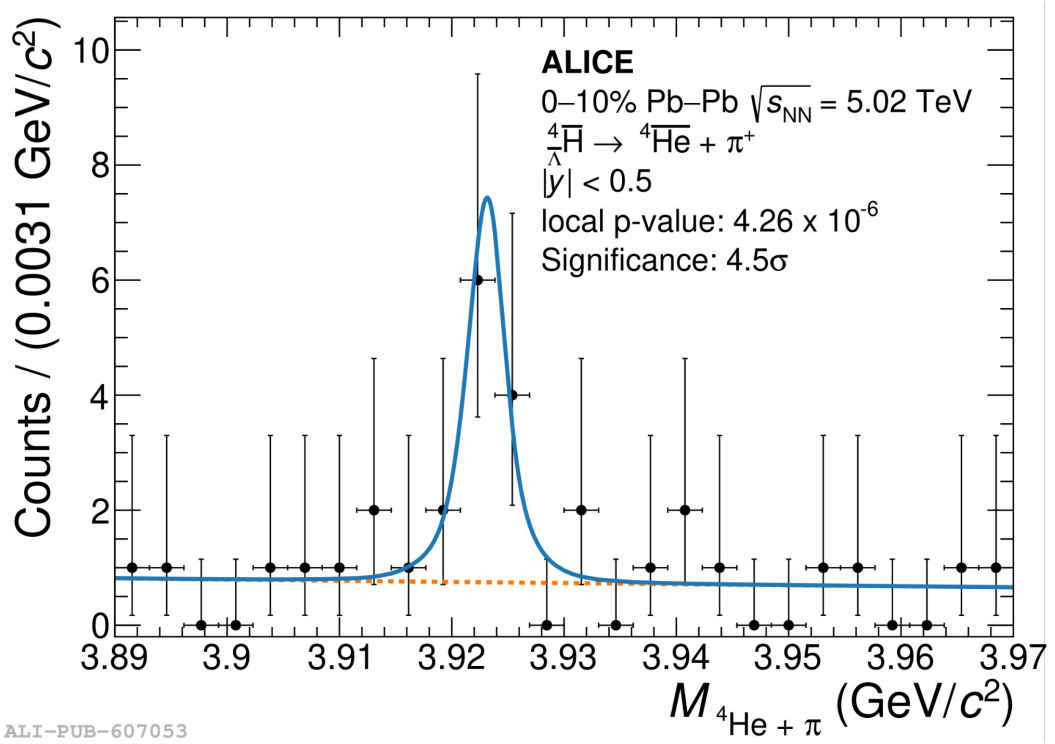
- ^{4}He production in Pb–Pb using the Run 2 sample
- The average ^{4}He/p yield ratio is consistent with Run 1 with uncertainties improved by a factor of 2
- Statistical hadronisation is consistent with the data
- Coalescence calculations underpredict the yield
- Multiplicity-differential measurement → understanding the nucleosynthesis of compact states



mario.ciacco@cern.ch

A=4 hypernuclei production in Pb–Pb

- (Anti)$^4_\Lambda$H and (anti)$^4_\Lambda$He reconstructed in Pb–Pb through charged 2-body and 3-body decay channels
  - Identification of the candidates relying on machine learning



[1] Phys. Rev. Lett. 134 (2025) 162301

mario.ciacco@cern.ch

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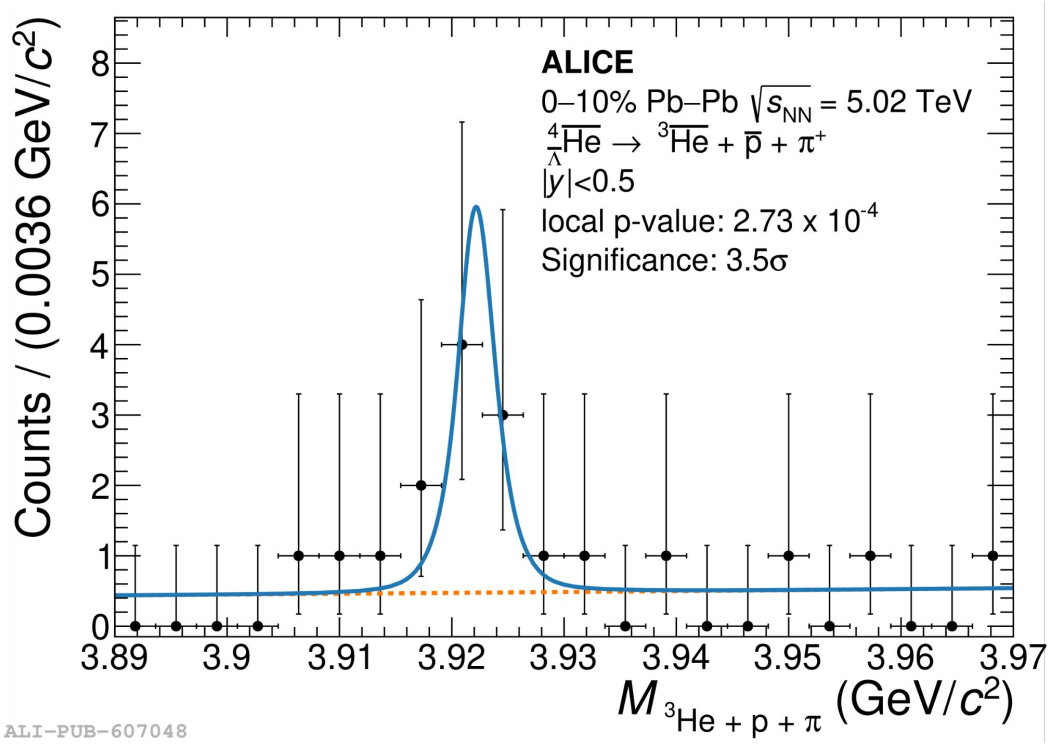
  - Identification of the candidates relying on machine learning
  - Anti$^4_\Lambda$He → first evidence of this antimatter state



[1] Phys. Rev. Lett. 134 (2025) 162301

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A=4 hypernuclei production in Pb–Pb (3)

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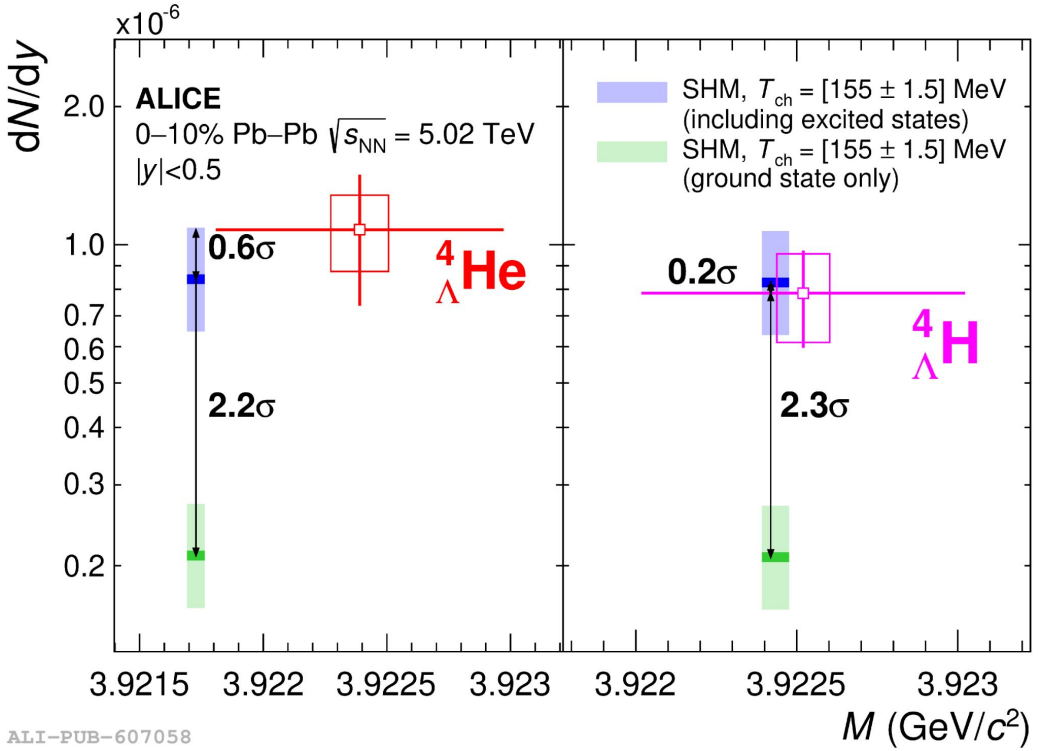
  - Identification of the candidates relying on machine learning
  - Anti$^4_\Lambda$He → first evidence of this antimatter state
- The yields are enhanced with respect to statistical hadronisation predictions for the ground states
- Including excited states improves the agreement

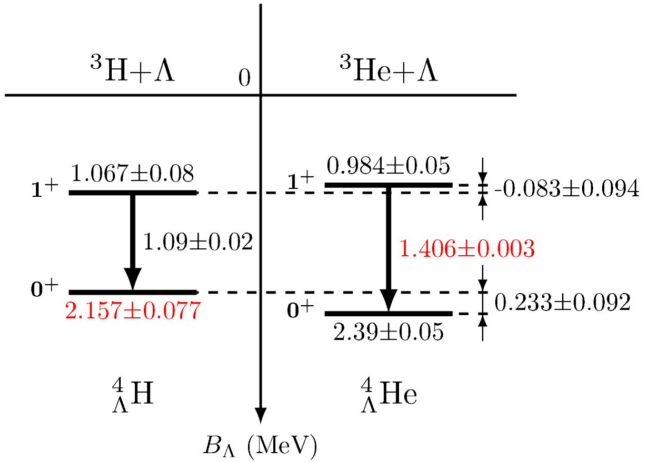


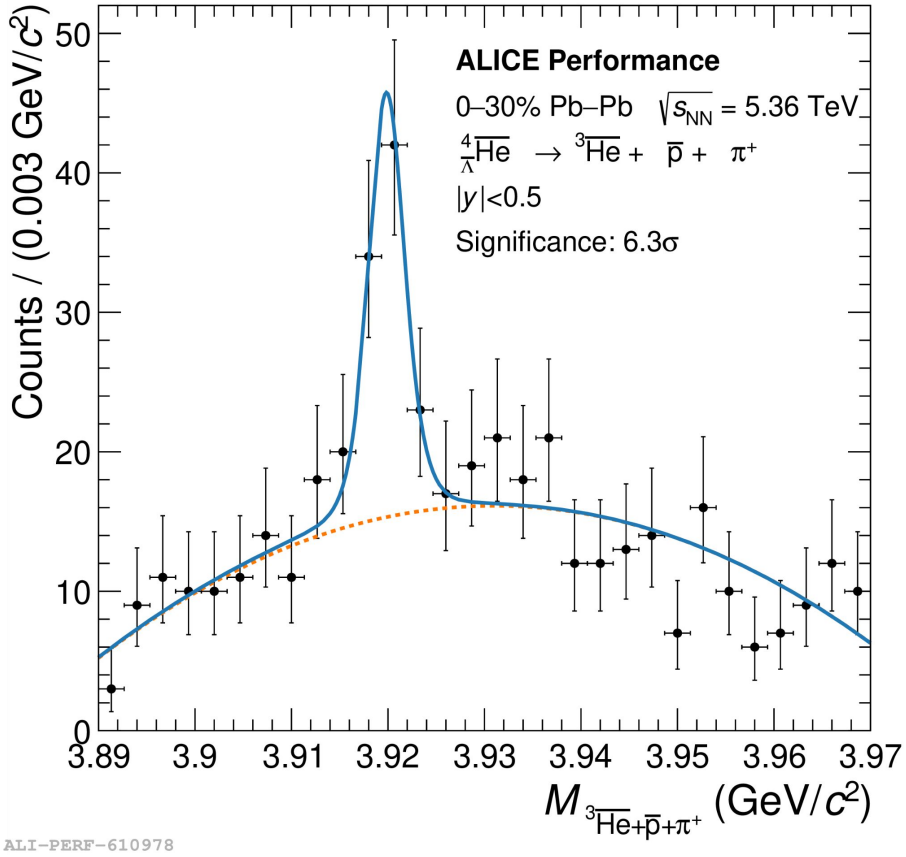
[1] Phys. Rev. Lett. 134 (2025) 162301

mario.ciacco@cern.ch

A=4 hypernuclei in the LHC Run 3

- Larger integrated luminosity in Run 3 → observation of anti$^4_\Lambda$He with > 5σ significance
- Enabling precision study of strong interaction properties, e.g., charge symmetry breaking of Λ-nucleon interaction [1]

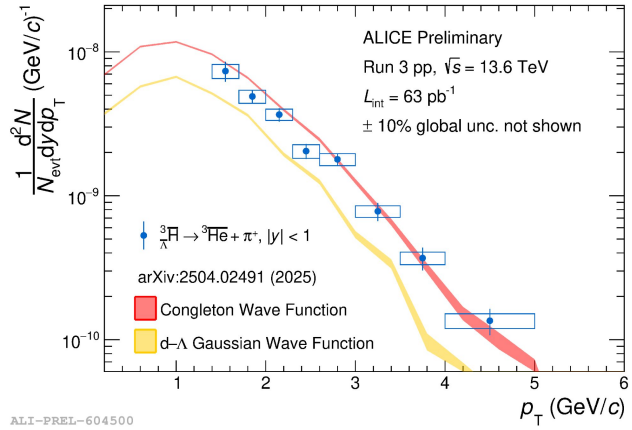


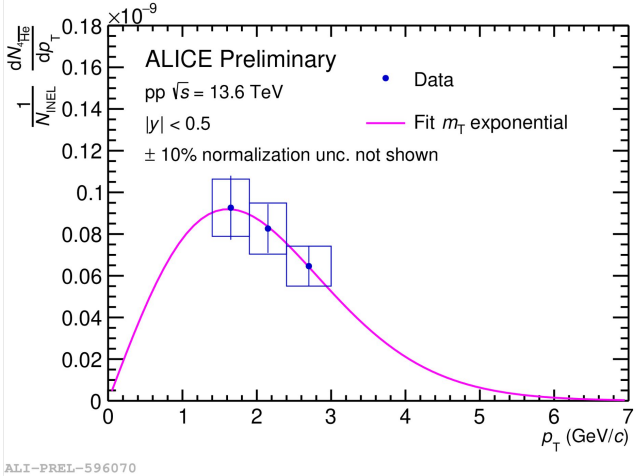


[1] Gal et al, J. Phys. Conf. Series 966 (2018) 012006

Summary and outlook

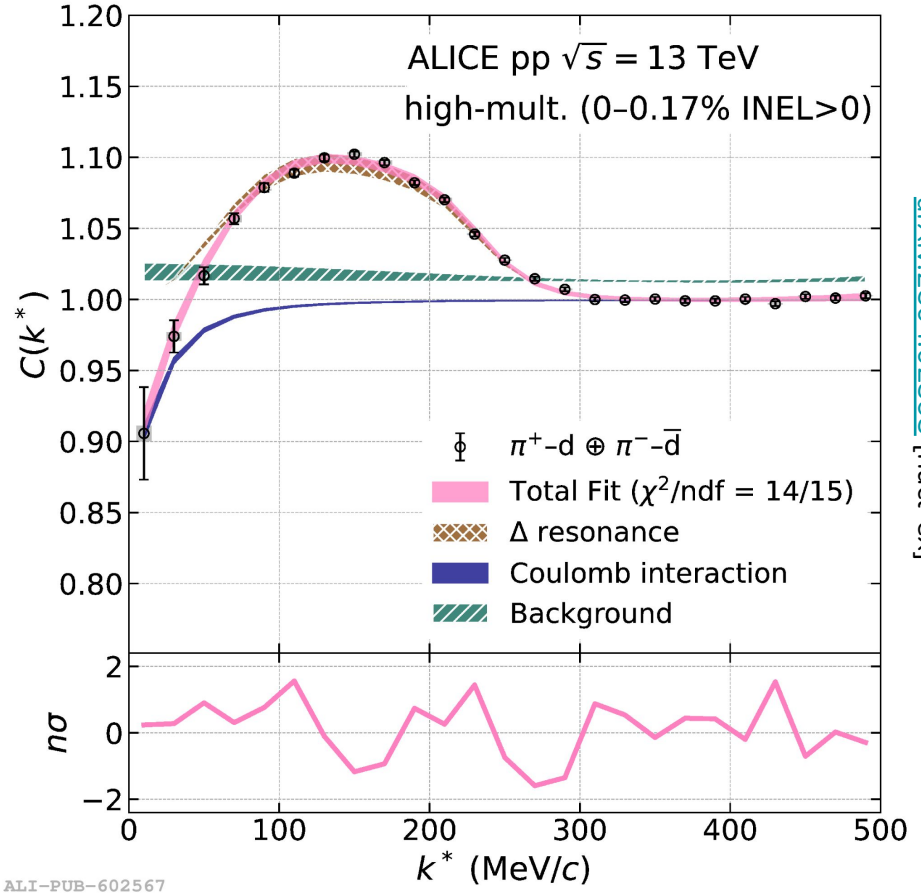
- A wealth of new precision measurements is becoming available to the community
  - Coalescence models are favoured up to A=4
- Novel constraints to nucleosynthesis models coming from hypertriton and antialpha in small systems and A=4 hypernuclei in Pb–Pb
  - The upgraded ALICE apparatus plays a central role in (hyper)nuclear physics at the LHC
- Many opportunities ahead thanks to the full array of data samples collected in the Run 3
  - pp, p-O, OO, Ne–Ne, Pb–Pb





Bonus: nucleosynthesis unveiled through femtoscopy

- Observation of Δ resonance contribution in pion-deuteron correlation functions
  - Deuterons must be formed from pre-existing nucleons
  - Direct evidence of the nuclear coalescence process in the deuteron formation
- More details in Maximilian's talk



arXiv:2504.02393 [nucl-ex]

More ALICE results at this EMMI workshop

- (Anti)nuclei production in jets
  - How does the dense and boosted jet-cone environment modify light-nuclei formation with respect to the underlying event?

Chiara's talk

- Pion-deuteron femtoscopic correlations
  - Can we disentangle the deuteron formation mechanism by analysing the correlation with nearby light mesons?

Maximilian's talk

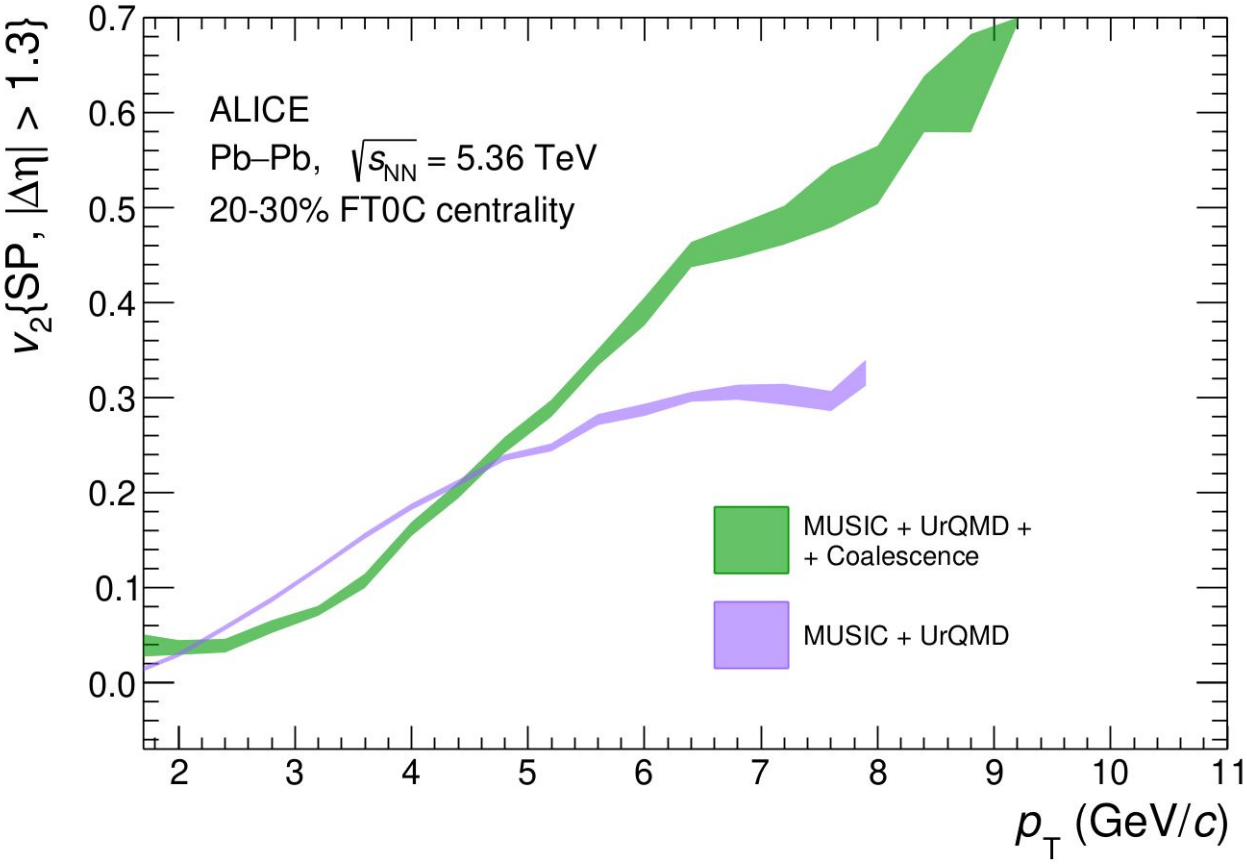
- Hypertriton 3-body decay and R_3
  - How do we separate and reduce the different background contributions in the data to correctly identify the hypertriton signal?

Carolina's talk

mario.ciacco@cern.ch

Additional slides

^{3}He flow: hydrodynamics w/ and w/o coalescence



mario.ciacco@cern.ch