中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

Antimatter in Relativistic Heavy-ion Collisions

Qiu, Hao (仇浩)

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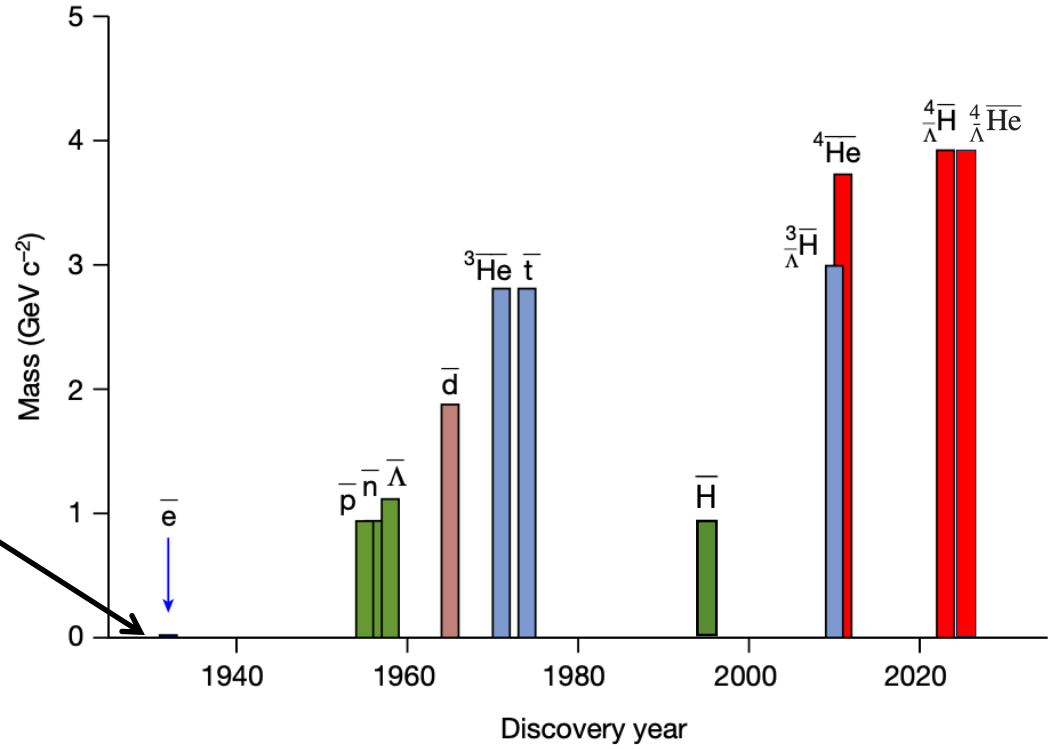
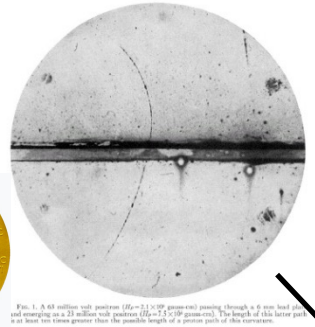
History of Anti-matter Discovery

Dirac, P.A.M.,
The Quantum Theory of the Electron.
Proc. Roy. Soc. Lond. A 117, 610 (1928).



History of Anti-matter Discovery

Carl D. Anderson



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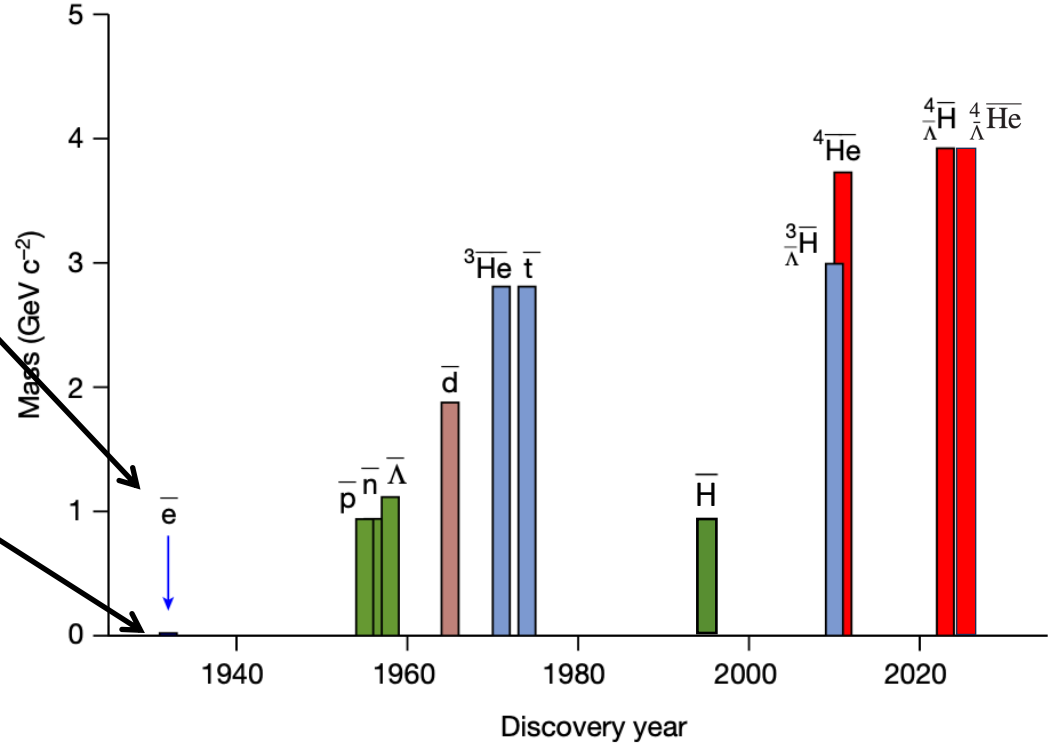

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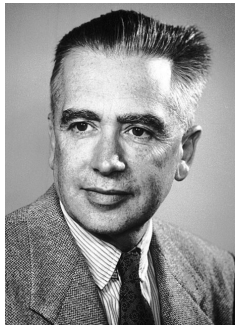
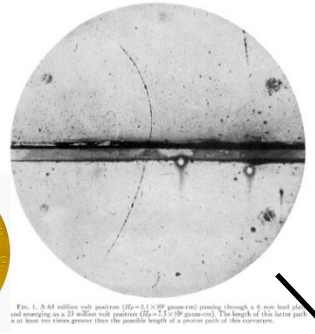


Emilio Segrè

Owen Chamberlain



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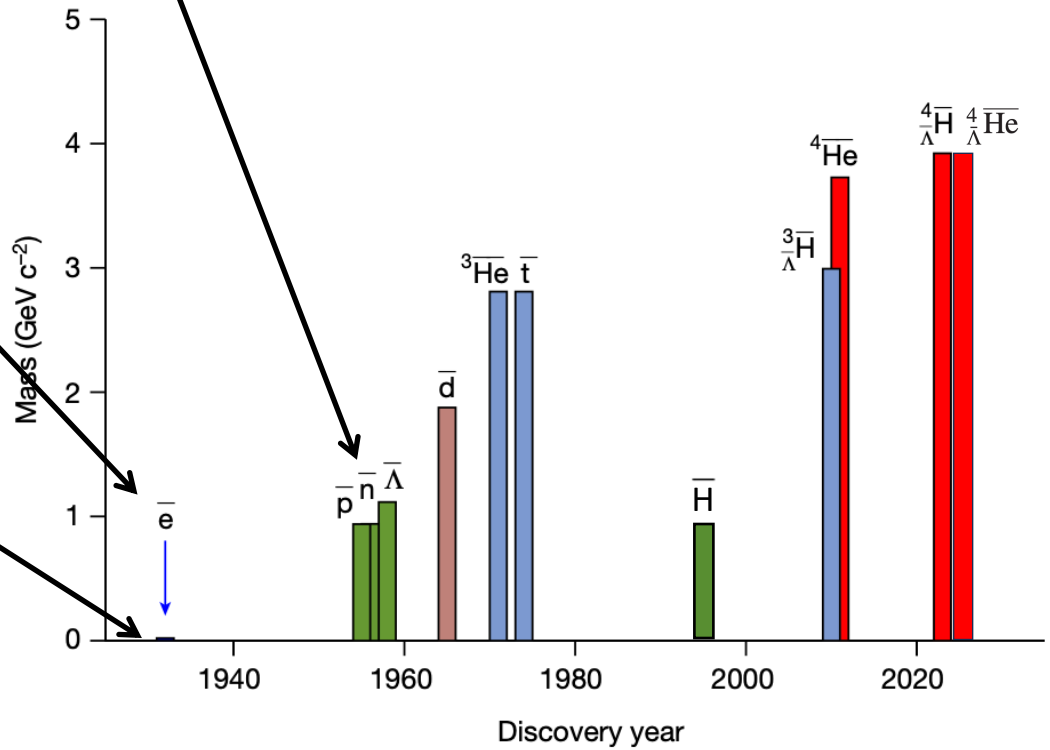
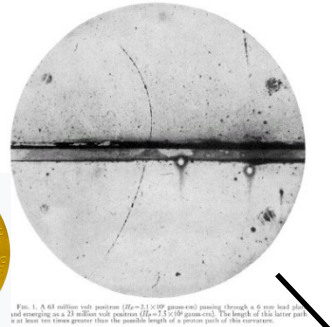


History of Anti-matter Discovery



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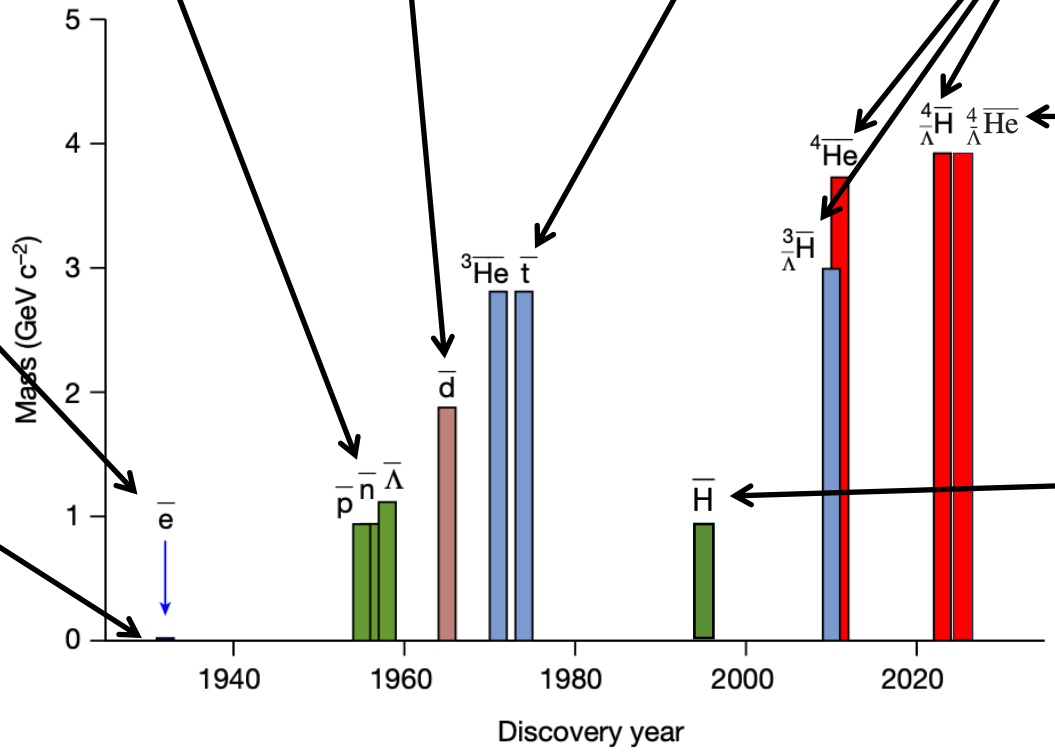
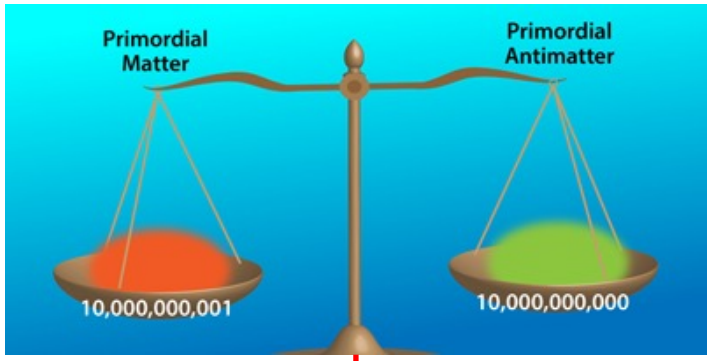
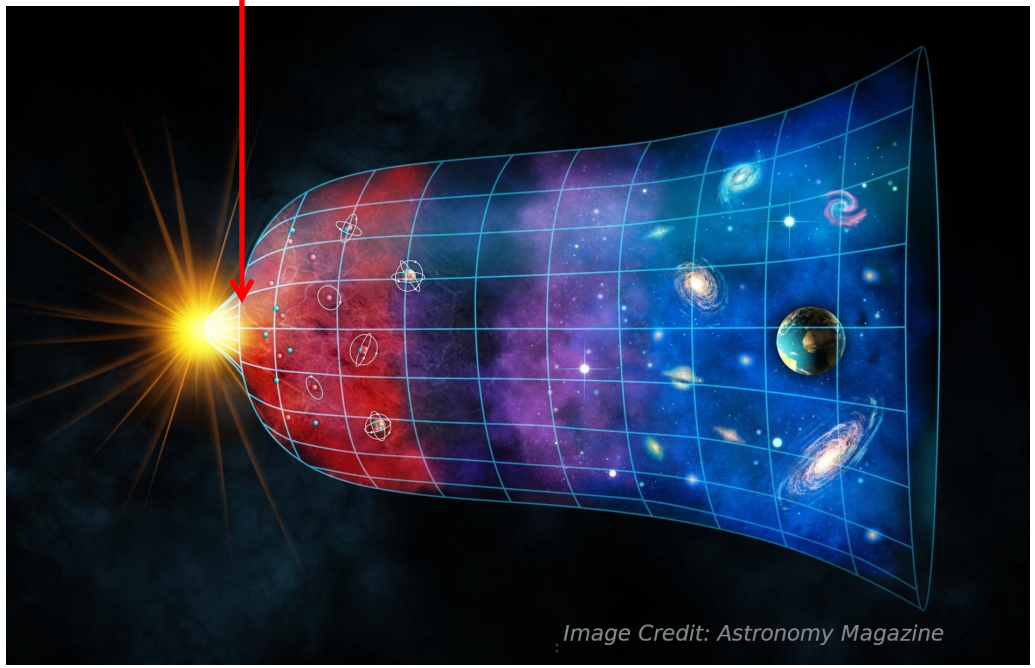


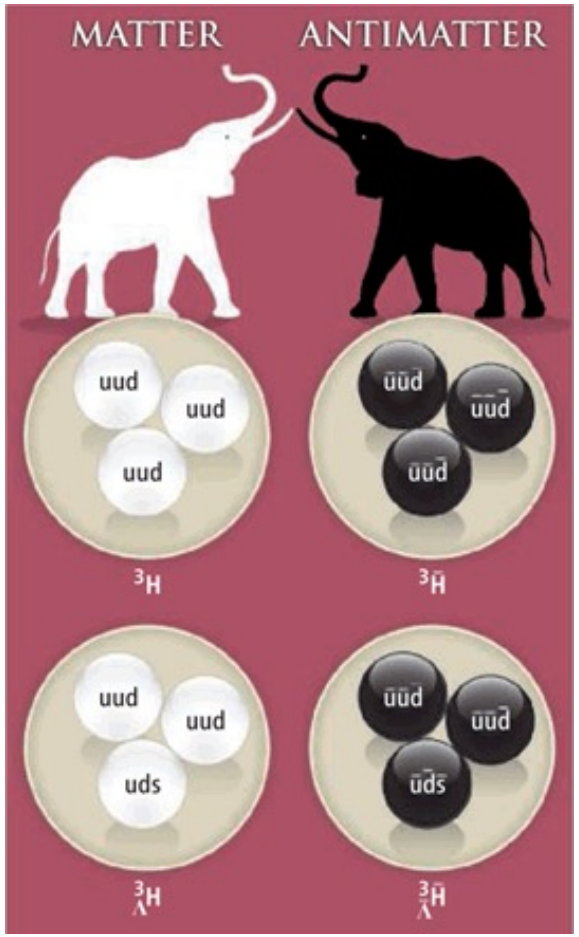
Matter-antimatter (A)symmetry



?

- Matter-antimatter asymmetry in early universe is the precondition for the existence of the matter world today
- The source of this asymmetry is still not clear

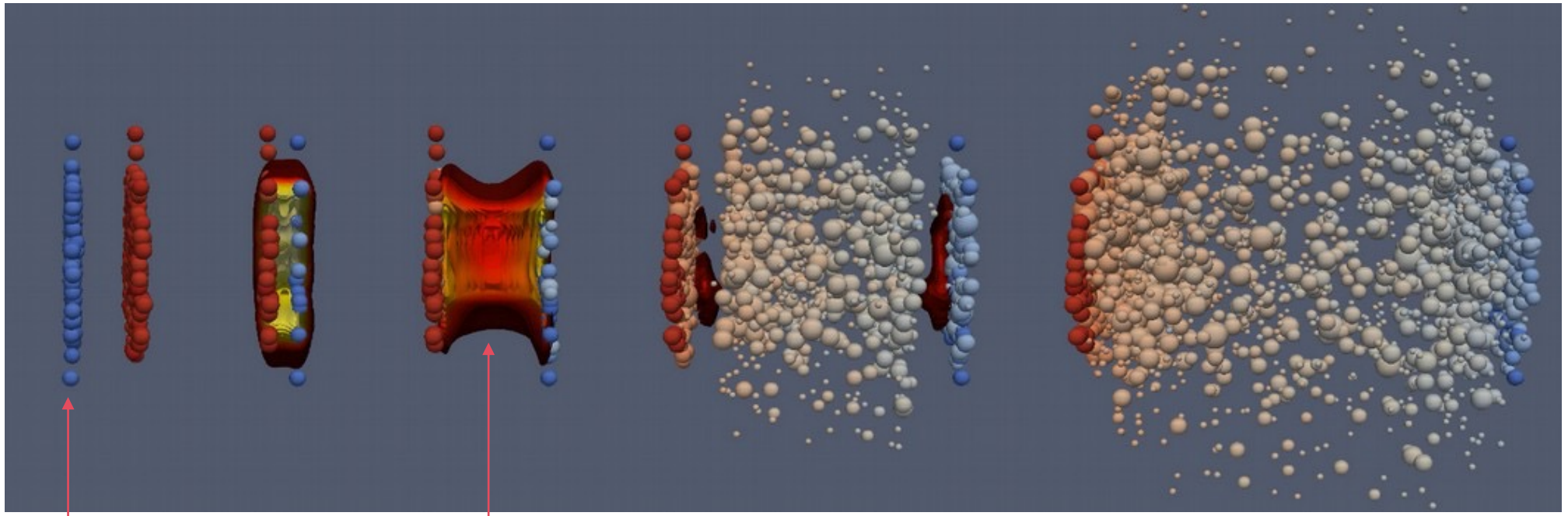




CPT theorem

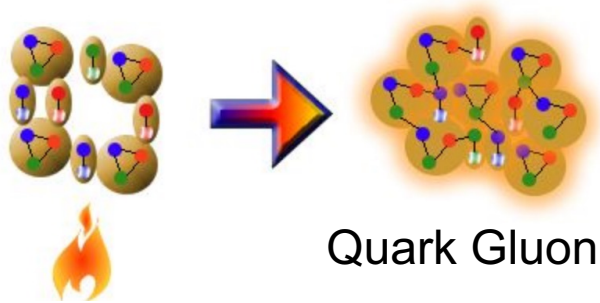
⇒ Symmetry of matter-antimatter properties

Relativistic Heavy-ion Collisions

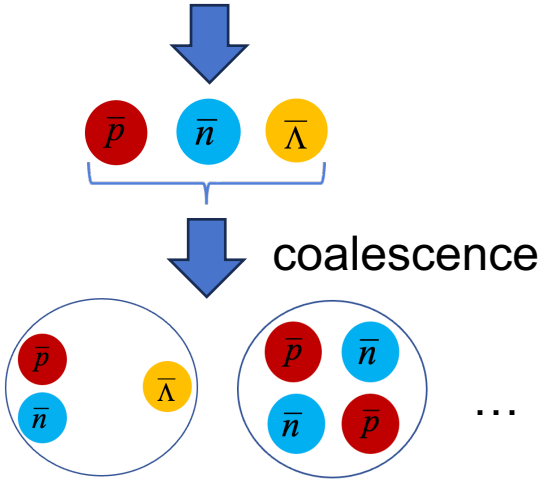


v ~ c

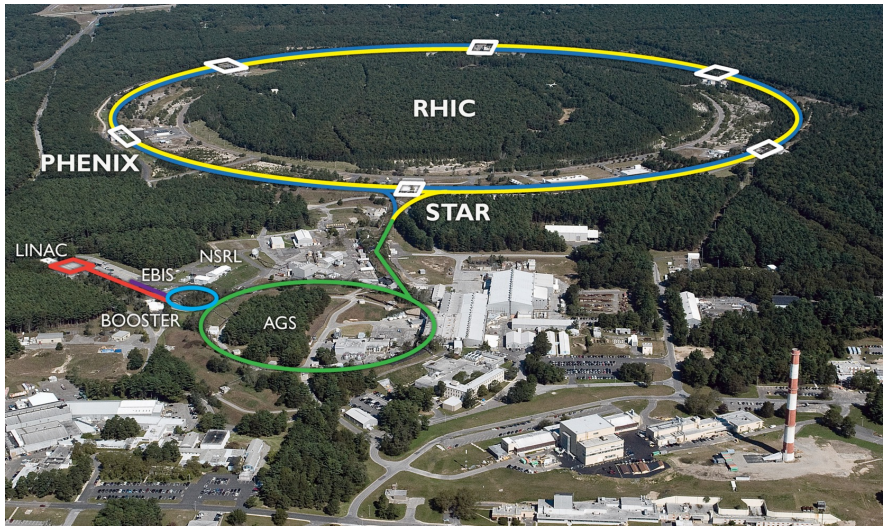
T ~ several hundred MeV ~ 10^{12} K



Quark Gluon Plasma (QGP)



Heavy-ion Colliders and Experiments



Relativistic Heavy Ion Collider

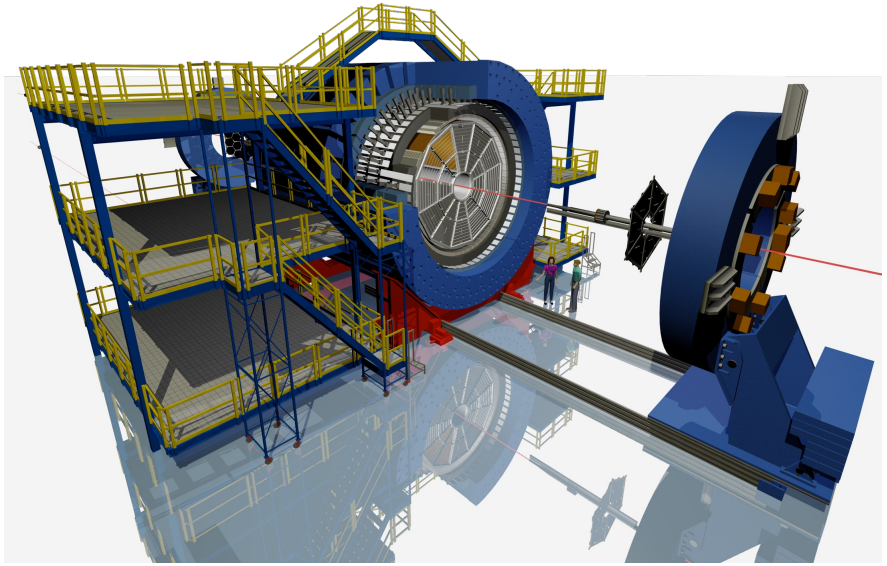
-RHIC

Top energy (HI): 200 GeV

Large Hadron Collider

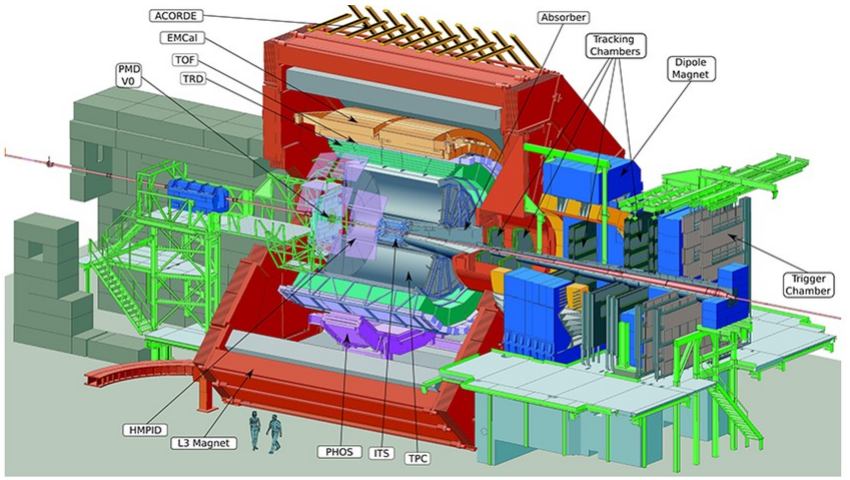
-LHC

Top energy (HI): several TeV



Solenoidal Tracker At RHIC

-STAR



A Large Hadron Collider Experiment

-ALICE

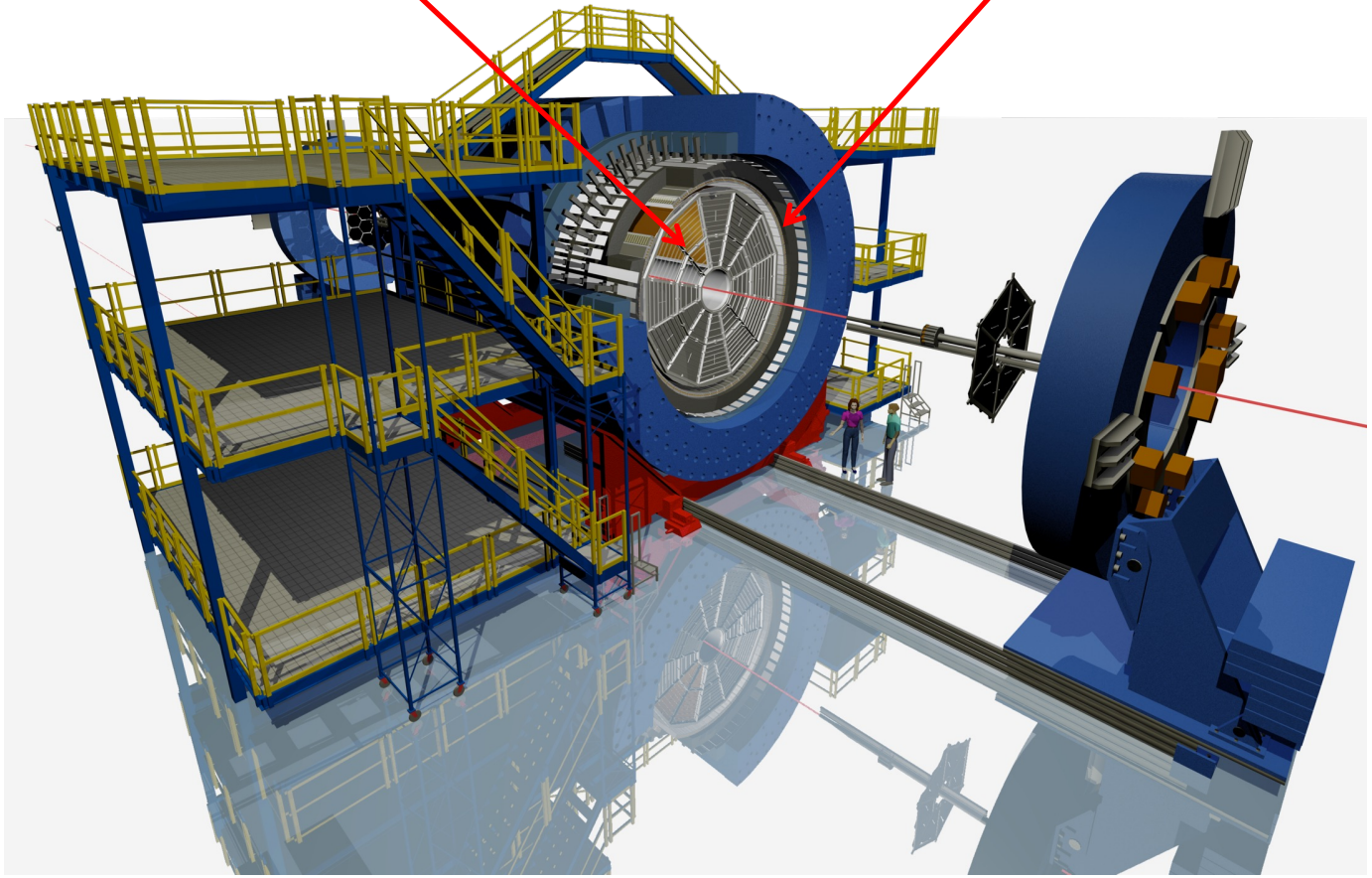
STAR Detectors

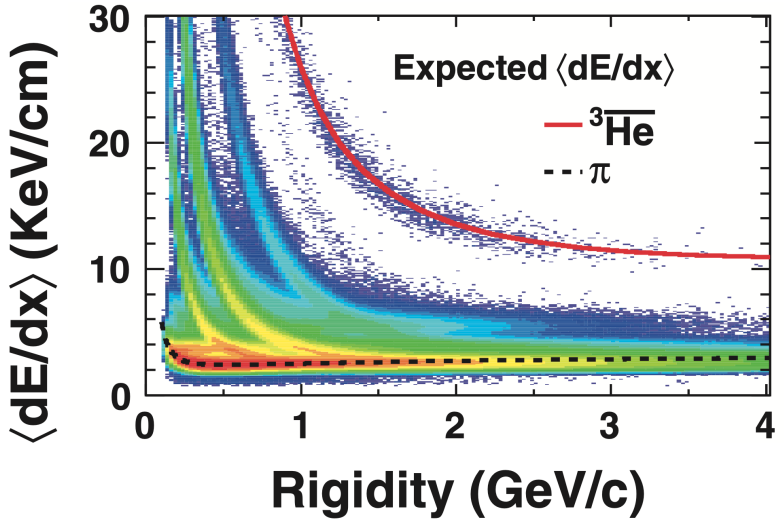
Time Projection Chamber

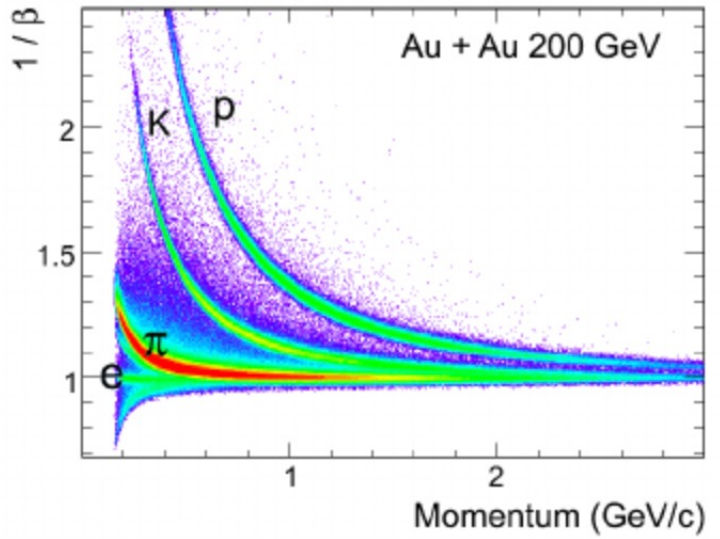
- tracking ⇒ p/Z, dE/dx

Time-Of-Flight detector

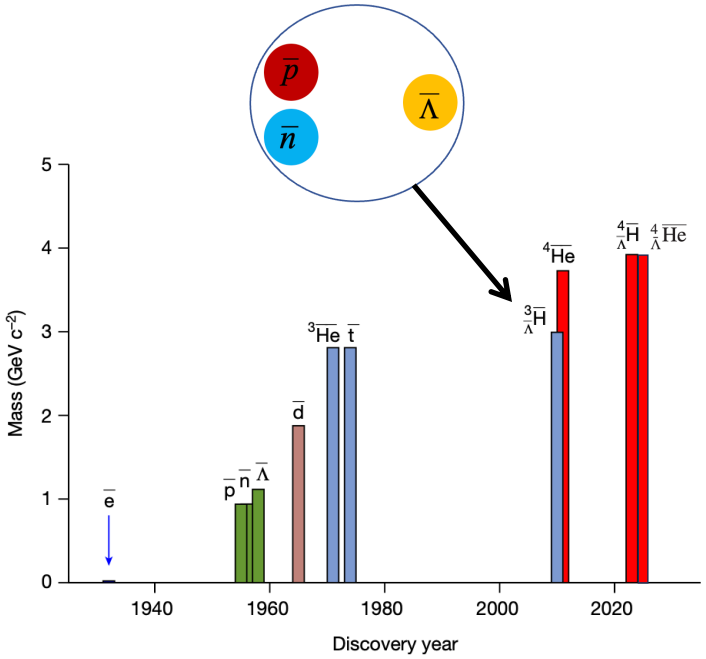
- TOF + L ⇒ β

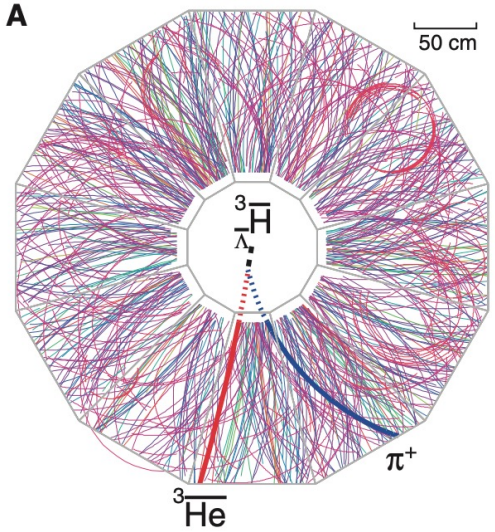


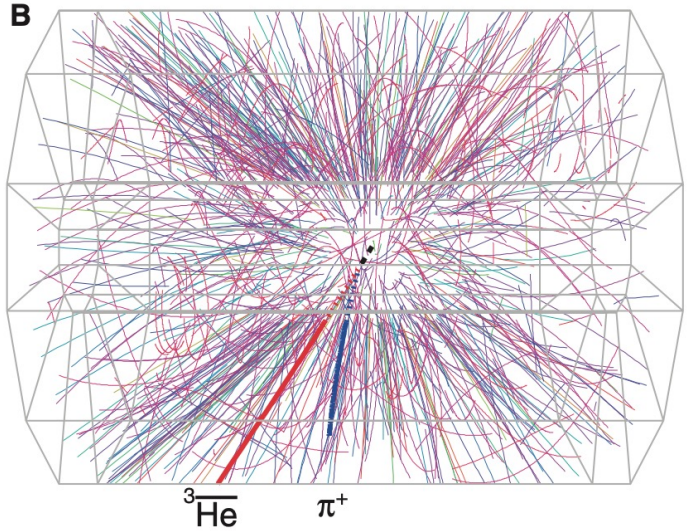


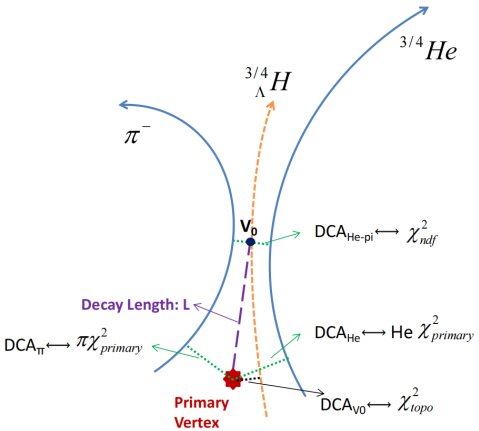


Observation of Antihypertriton



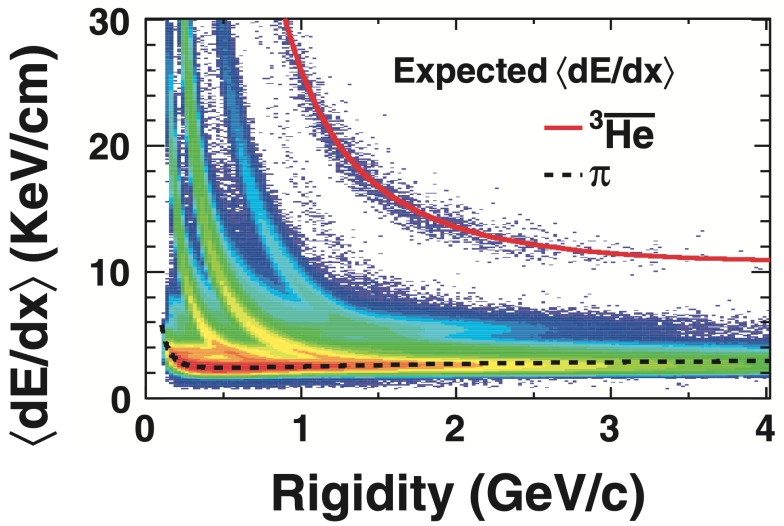






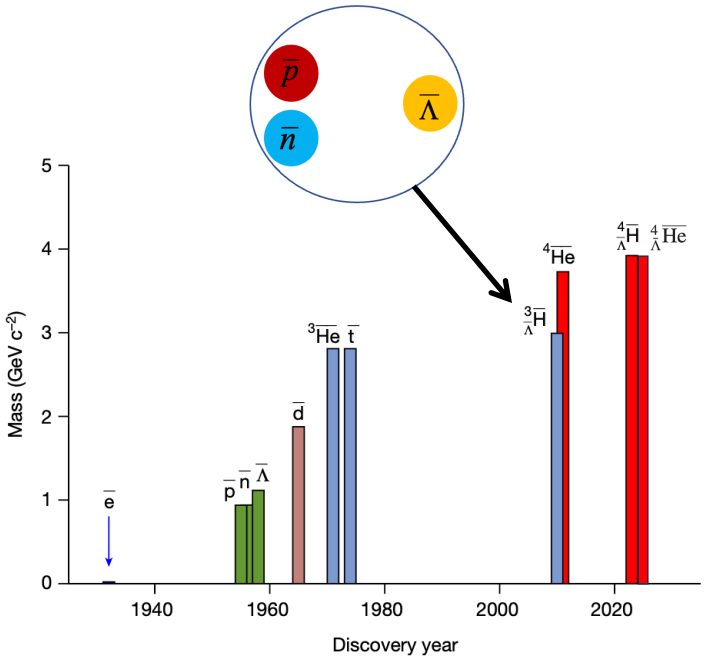
$$^{3}_{\Lambda}\overline{H} \rightarrow {}^{3}\overline{He} + \pi^{+}$$

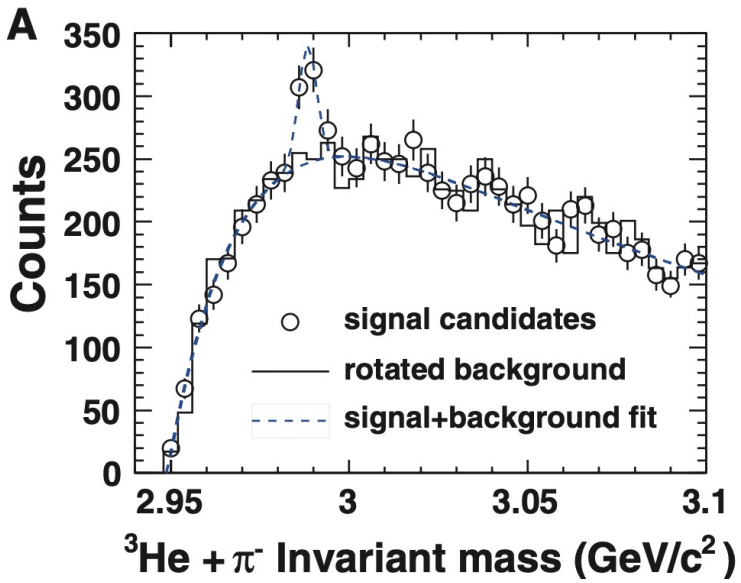
- ~111 M events used

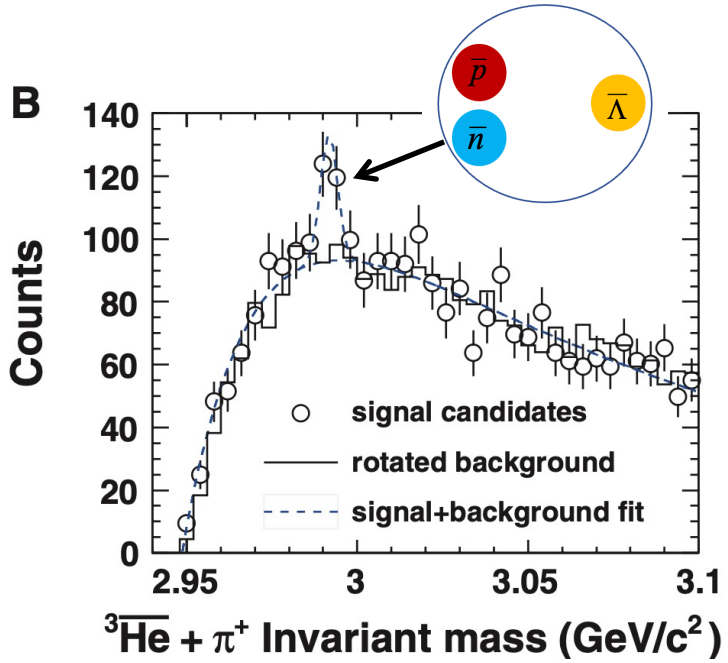


STAR Collaboration, Science 328, 58 (2010)

Observation of Antihypertriton

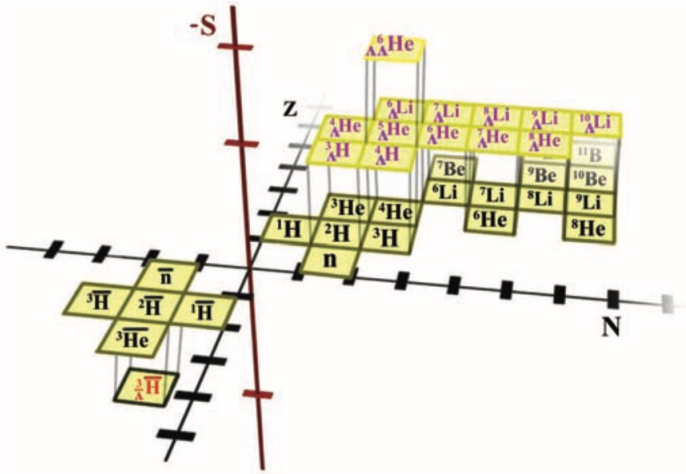






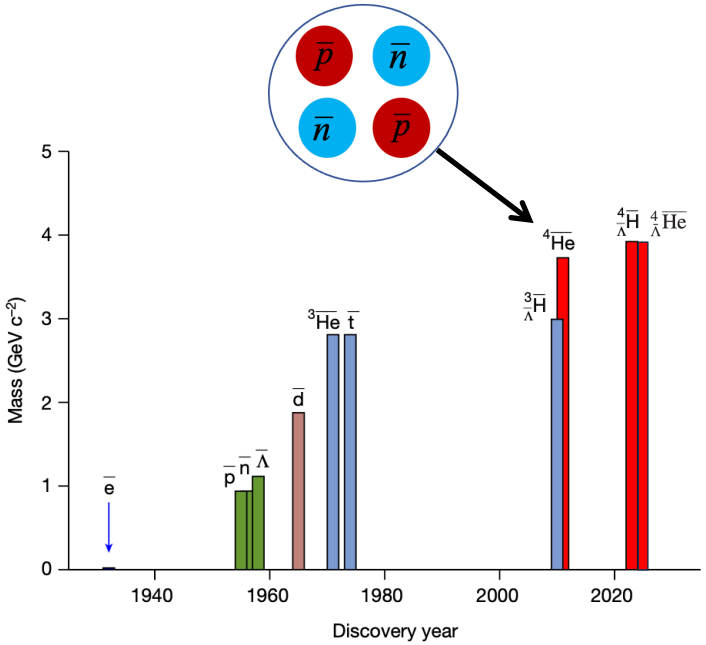
$$ {}^{3}_{\Lambda}\overline{\mathrm{H}} \rightarrow {}^{3}\overline{\mathrm{He}} + \pi^{+} $$

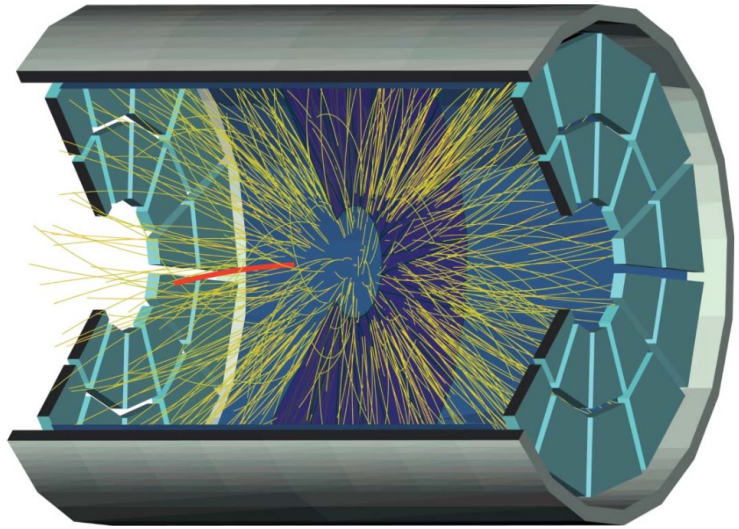
- ~111 M events used
- 70 ± 17 antihypertritons were observed
  - The 1st antihypernucleus observed in experiments

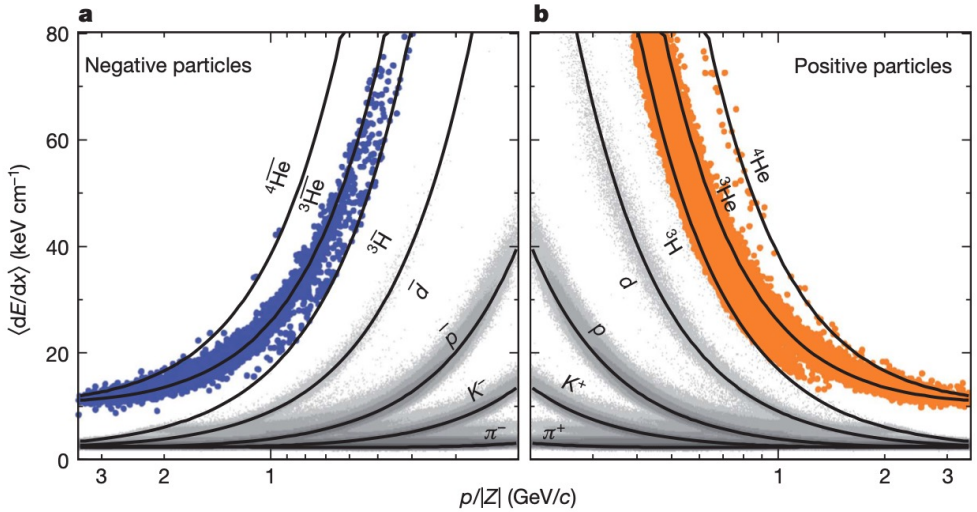


STAR Collaboration, Science 328, 58 (2010)

Observation of Antihelium-4



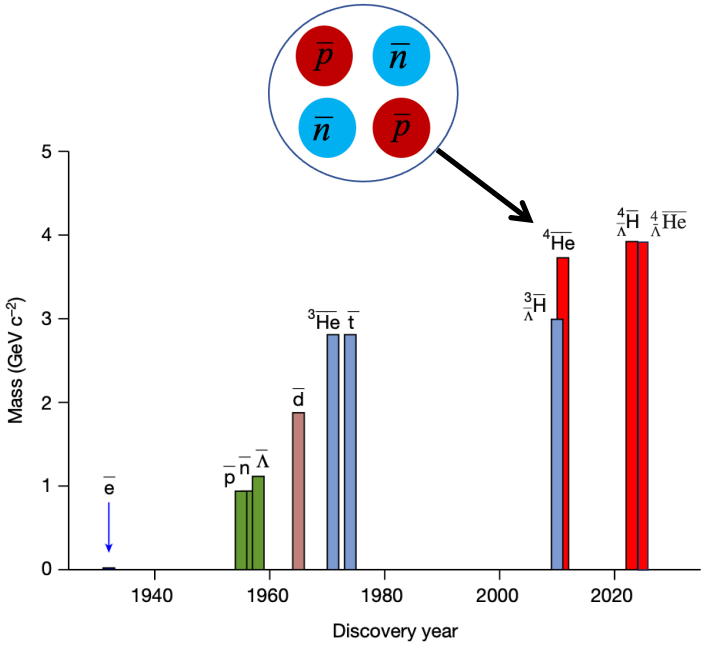




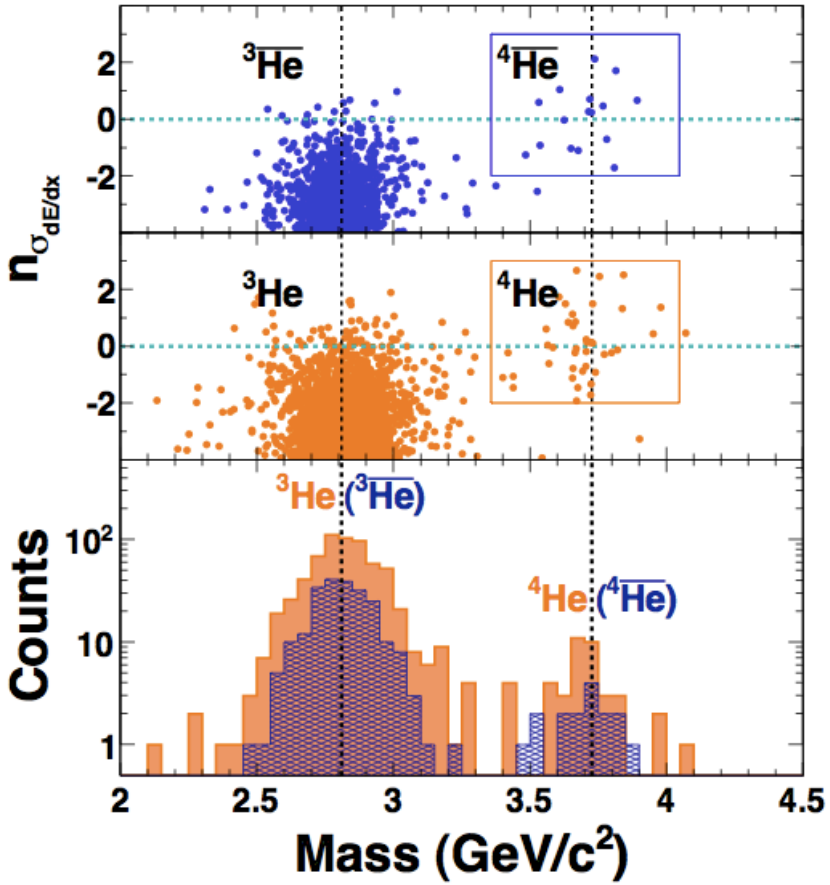
- ~1 B events used

STAR Collaboration, Nature 473, 353 (2011)

Observation of Antihelium-4



normalized dE/dx deviation from expectation for ^{4}He & $^4\overline{\mathrm{He}}$

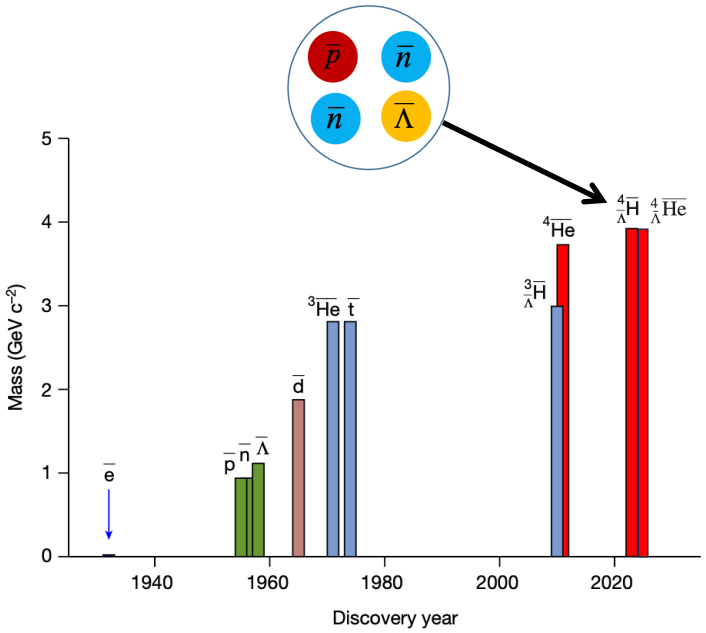


$$m = (p/c)\sqrt{(t^2c^2/L^2 - 1)}$$

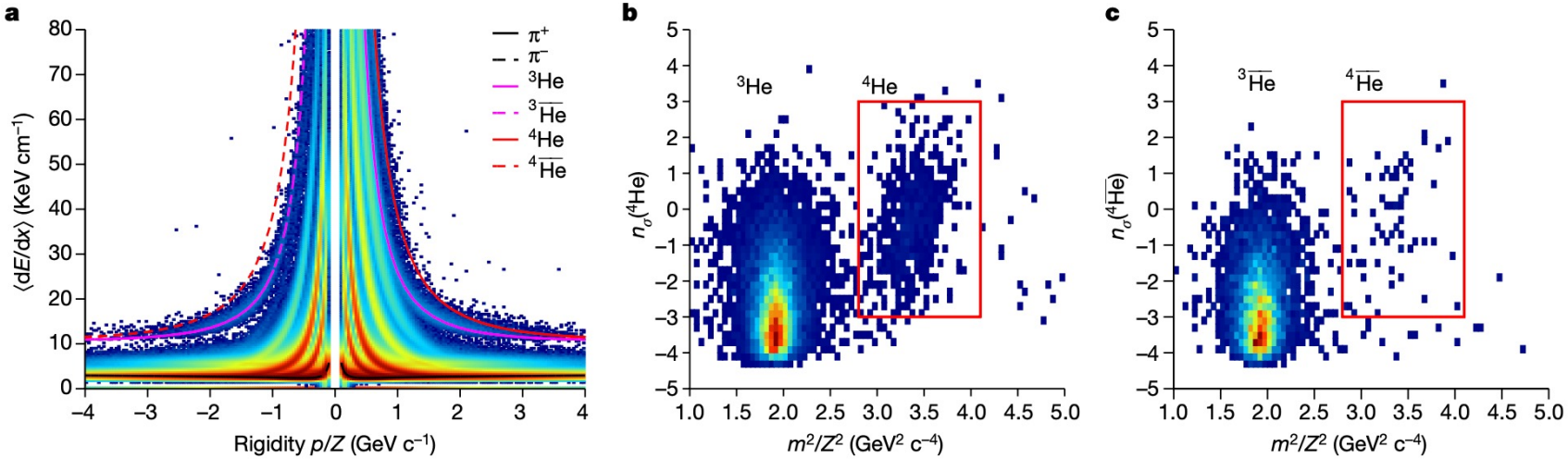
- ~1 B events used
- A total of 18 antihelium-4 candidates identified
  - 15 (200 GeV, yr 2010) + 1 (62 GeV, yr 2010) + 2 (yr 2007)
- Expected background counts:
  - 1.4 (200 GeV, yr 2010) + 0.05 (62 GeV, yr 2010)

STAR Collaboration, Nature 473, 353 (2011)

Observation of Antihyperhydrogen-4



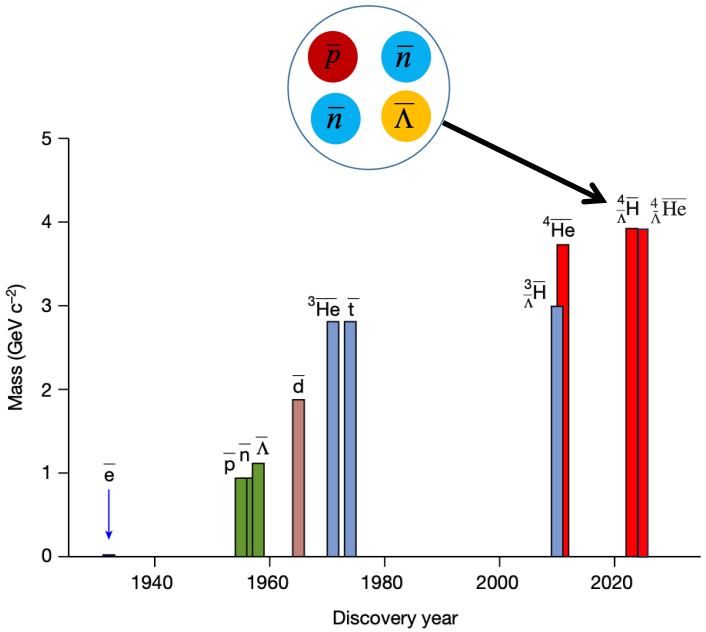
$$ {}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-} \qquad {}^{3}_{\bar{\Lambda}}\overline{H} \rightarrow {}^{3}\overline{He} + \pi^{+} \qquad {}^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-} \qquad {}^{4}_{\bar{\Lambda}}\overline{H} \rightarrow {}^{4}\overline{He} + \pi^{+} $$

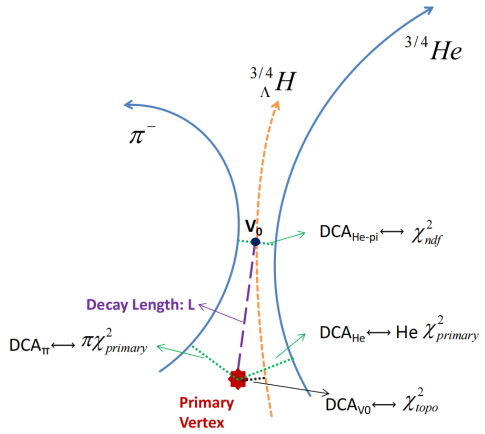


- A total of ~6.4 B collision events used

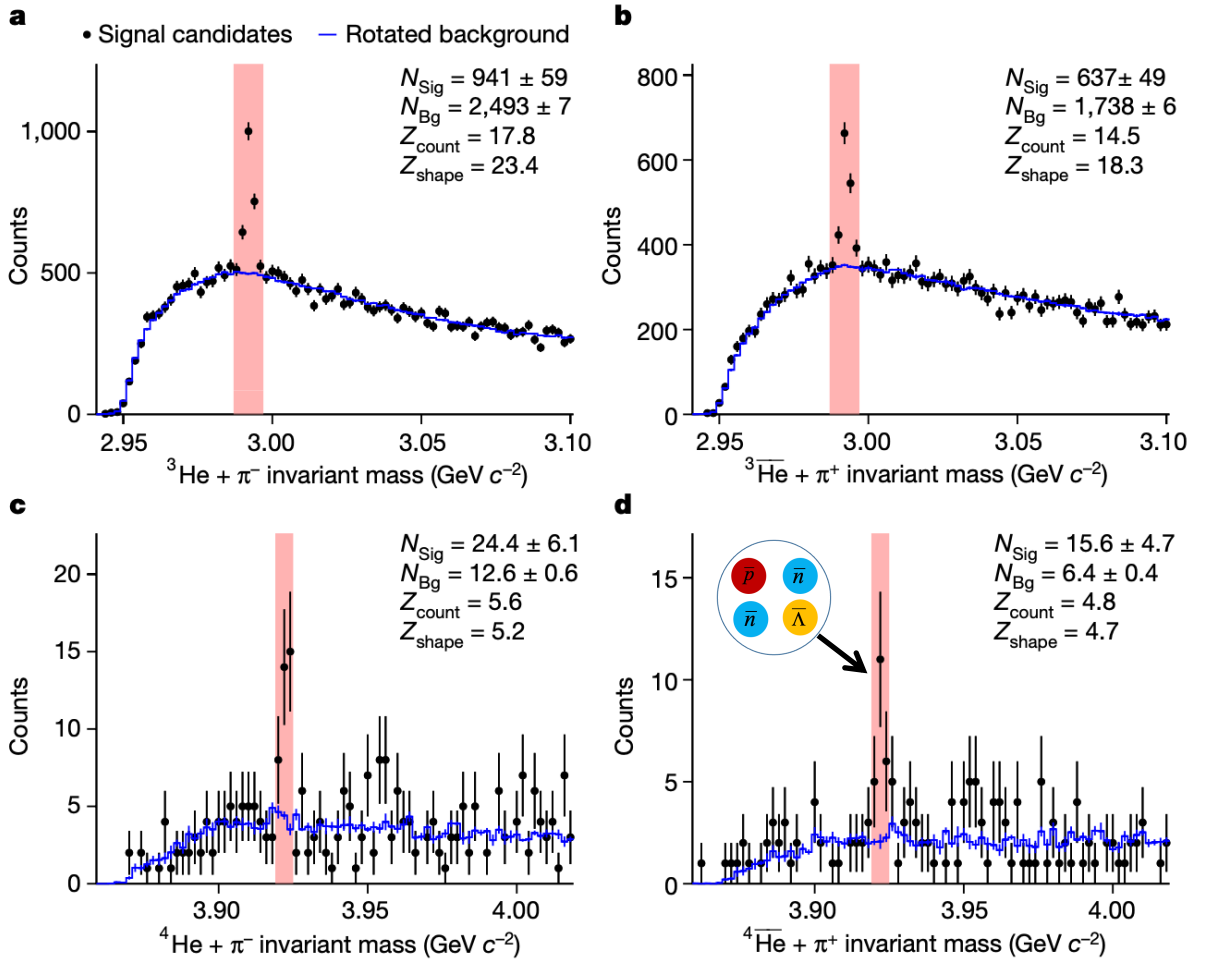
STAR Collaboration, Nature 632, 1026 (2024)

Observation of Antihyperhydrogen-4





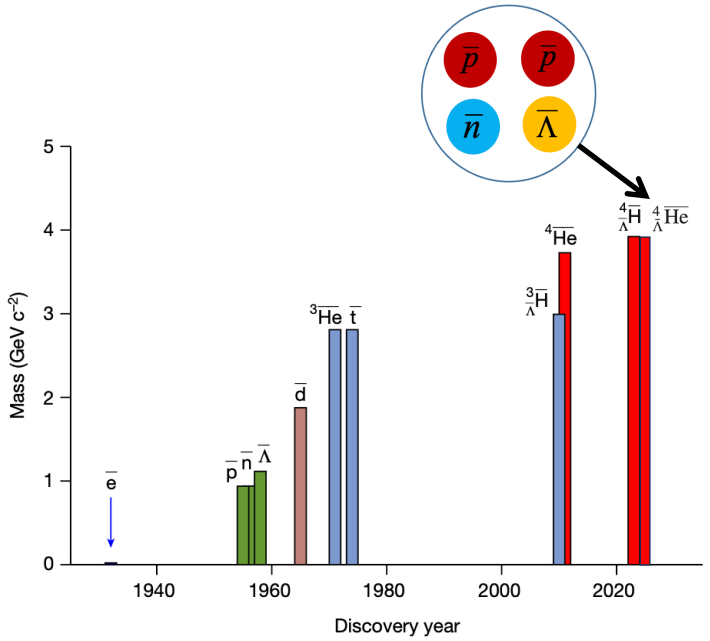
$$ {}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-} \qquad {}^{3}_{\bar{\Lambda}}\overline{H} \rightarrow {}^{3}\overline{He} + \pi^{+} \qquad {}^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-} \qquad {}^{4}_{\bar{\Lambda}}\overline{H} \rightarrow {}^{4}\overline{He} + \pi^{+} $$

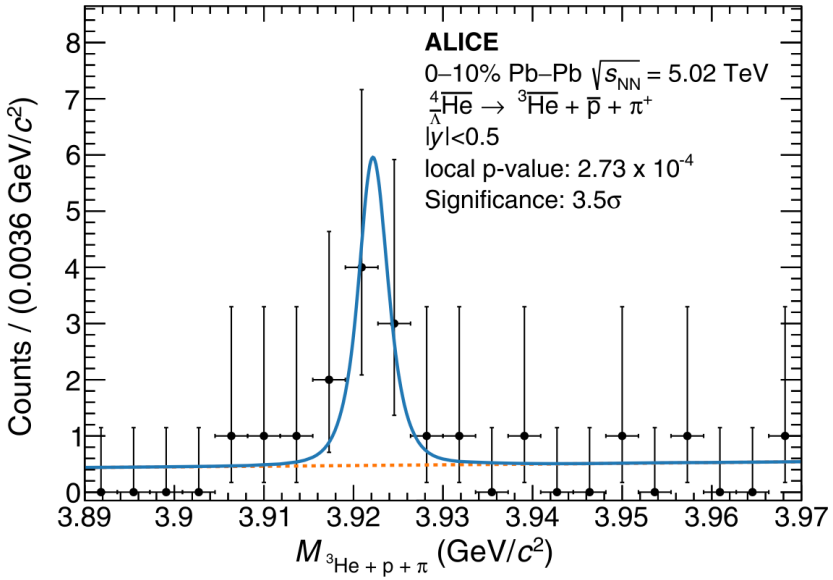


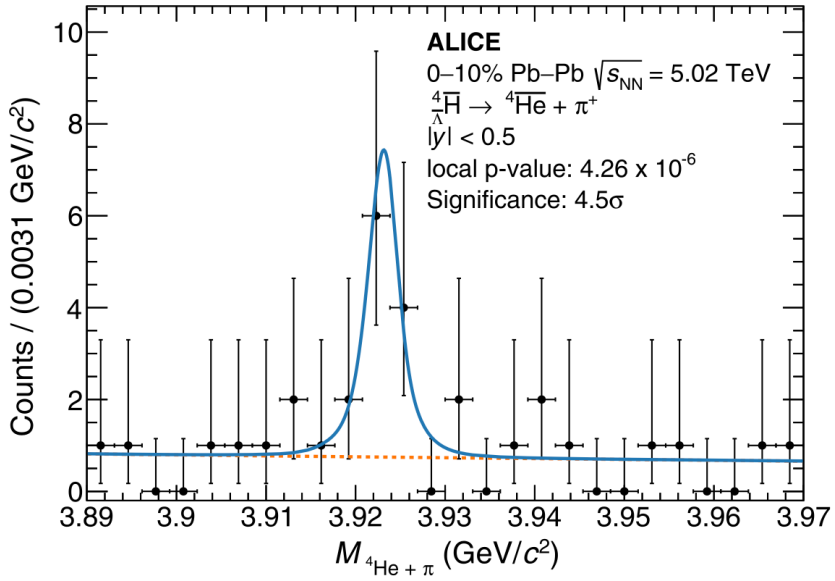
- A total of ~6.4 B collision events used
- 15.6 ± 4.7 antihyperhydrogen-4 signal candidates observed
  - significance Z_{count} = 4.8
- The heaviest antimatter hypernucleus observed

STAR Collaboration, Nature 632, 1026 (2024)

Observation of Antihyperhelium-4





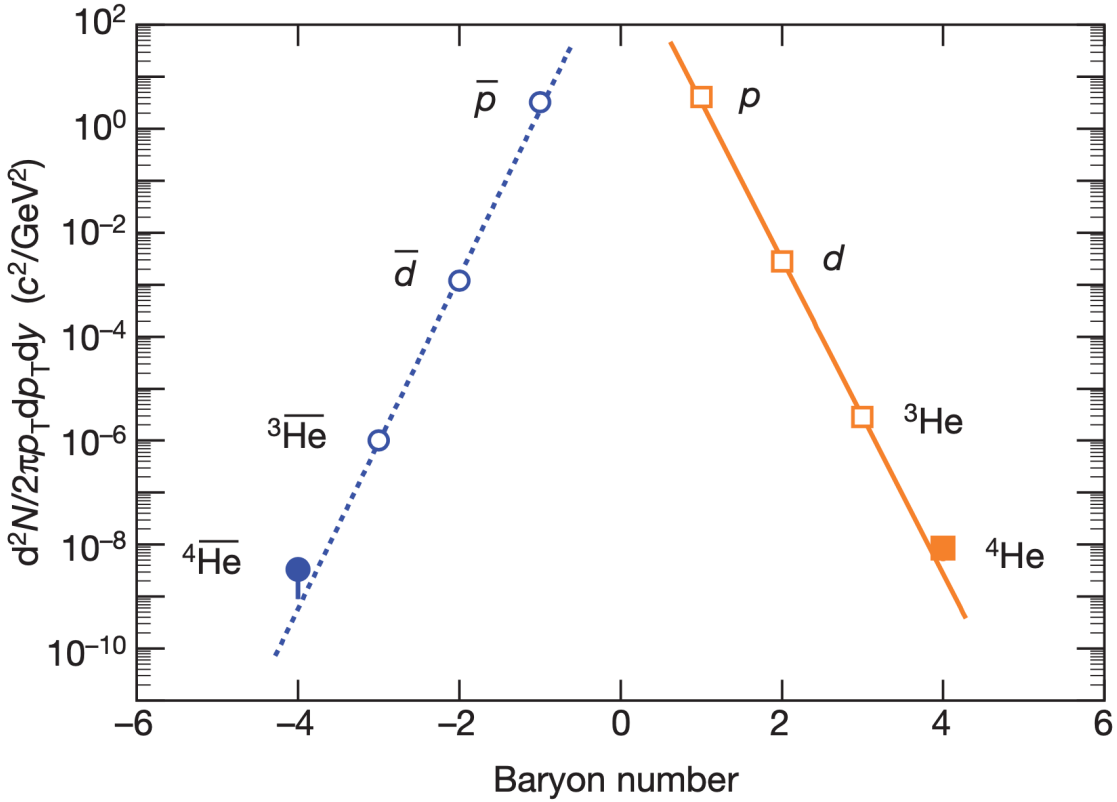


ALICE Collaboration, Phys. Rev. Lett. 134 (2025) 162301

- 108 M events used
- Antihyperhelium-4 significance: 3.5σ

Production Yields

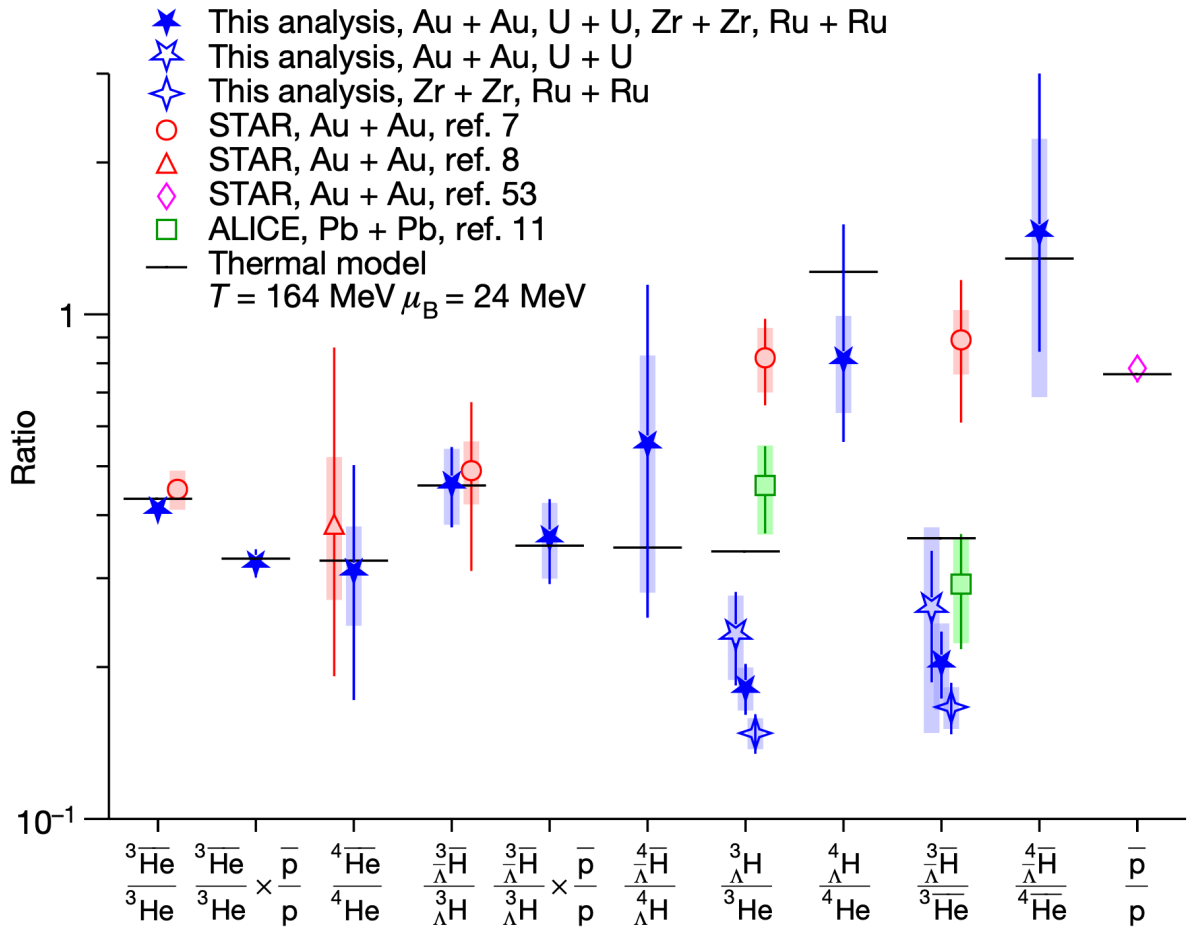
- A reduction factor of ~10^3 for each additional antibaryon in the production yields
  - Very difficult for the antibaryons to be “by chance” close enough in both position and momentum space, and coalesce



STAR Collaboration, Nature 473, 353 (2011)

Production Yields

- (Anti)(hyper)nuclei with the same (anti)baryon number have the production yields on the same order of magnitude
- At RHIC energy, anti(hyper)nuclei are produced slightly less than corresponding (hyper)nuclei
- At RHIC energy, (anti)hypernuclei are produced slightly less than corresponding (anti)nuclei



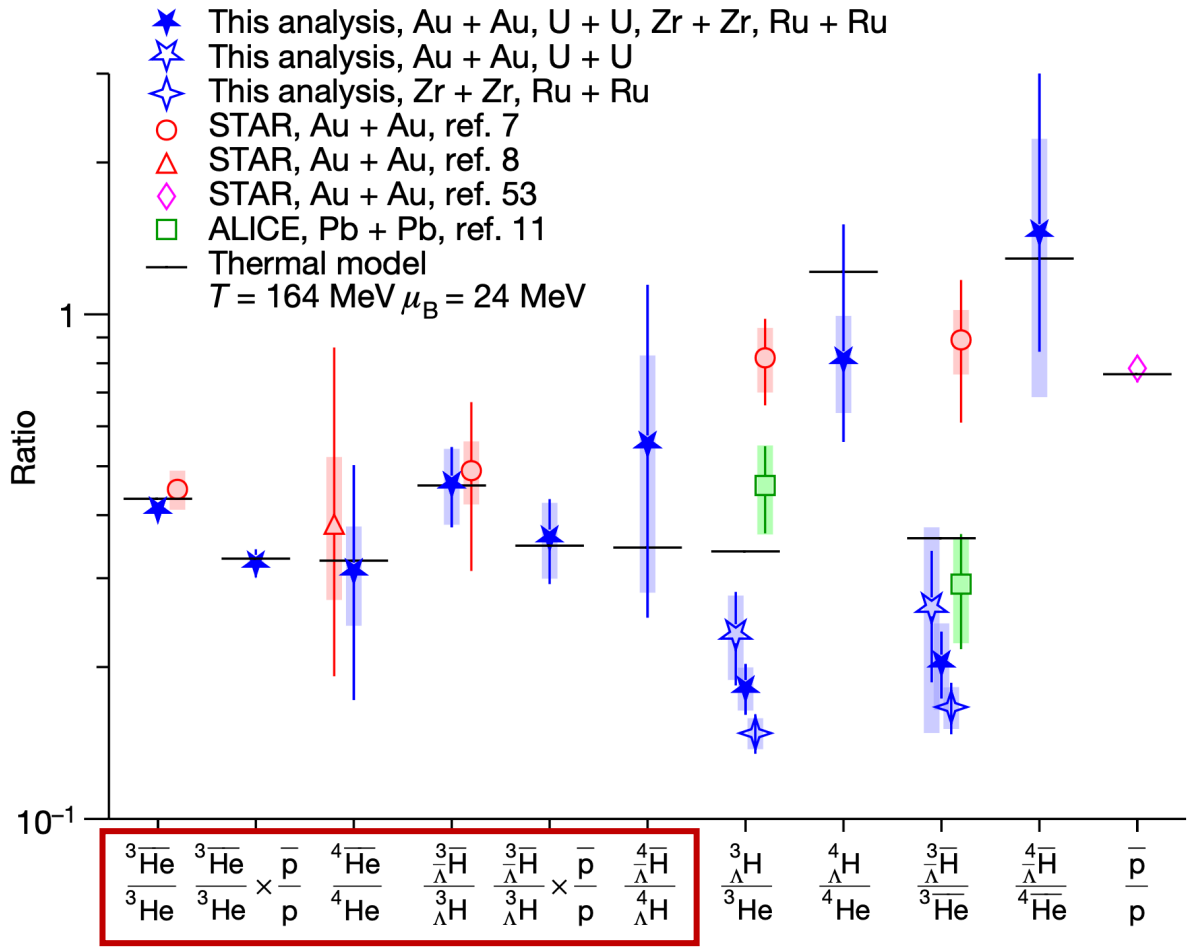
STAR Collaboration, Nature 632, 1026 (2024)

Production Yields

$$^{4}\overline{\mathrm{He}}/^{4}\mathrm{He} \sim {}^{3}\overline{\mathrm{He}}/^{3}\mathrm{He} \times \bar{\mathrm{p}}/\mathrm{p}$$

$$^{4}_{\bar{\Lambda}}\overline{\mathrm{H}}/^{4}_{\Lambda}\mathrm{H} \sim {}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}/^{3}_{\Lambda}\mathrm{H} \times \bar{\mathrm{p}}/\mathrm{p}$$

- Consistent with the coalescence picture & the thermal model prediction



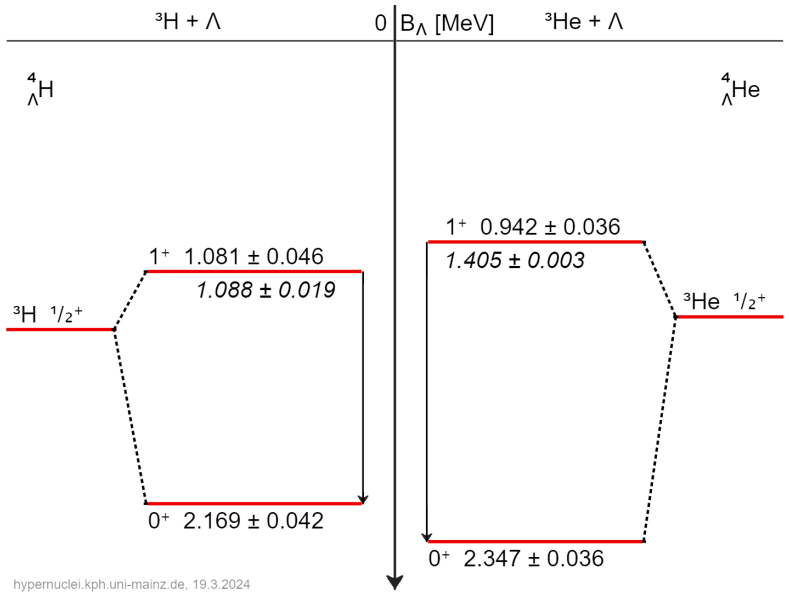
STAR Collaboration, Nature 632, 1026 (2024)

Production Yields

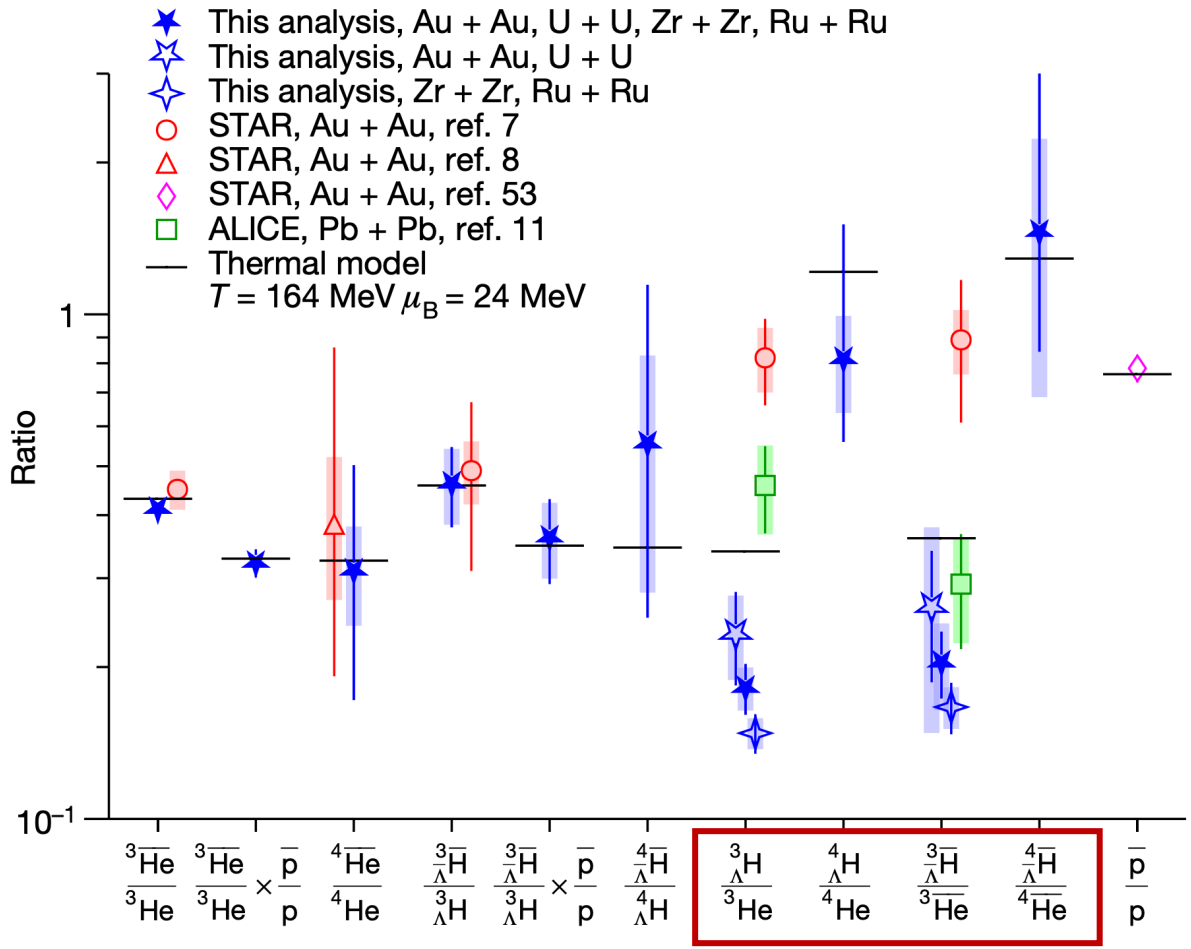
$$^{4}_{\Lambda}\mathrm{H}/^{4}\mathrm{He} \sim 4 \times {}^{3}_{\Lambda}\mathrm{H}/^{3}\mathrm{He}$$

$$^{4}_{\bar{\Lambda}}\overline{\mathrm{H}}/^{4}\overline{\mathrm{He}} \sim 4 \times {}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}/^{3}\overline{\mathrm{He}}$$

- Factor 4 due to spin-1 excited states of $^{4}_{\Lambda}H$ & $^{4}_{\bar{\Lambda}}\overline{H}$



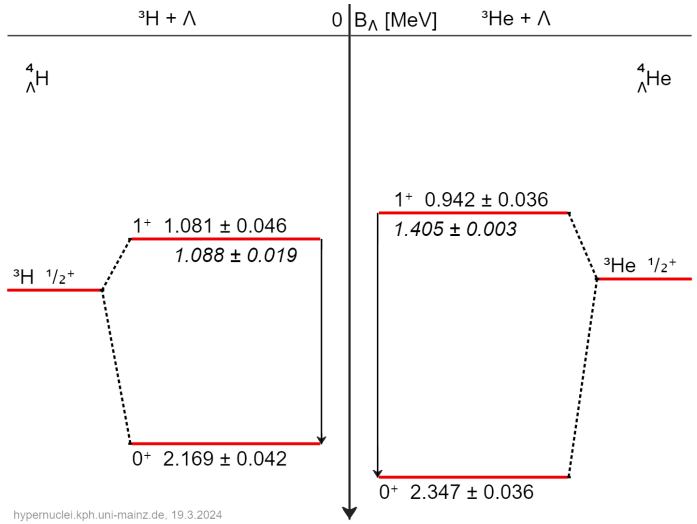
- Consistent with the coalescence picture & the thermal model prediction



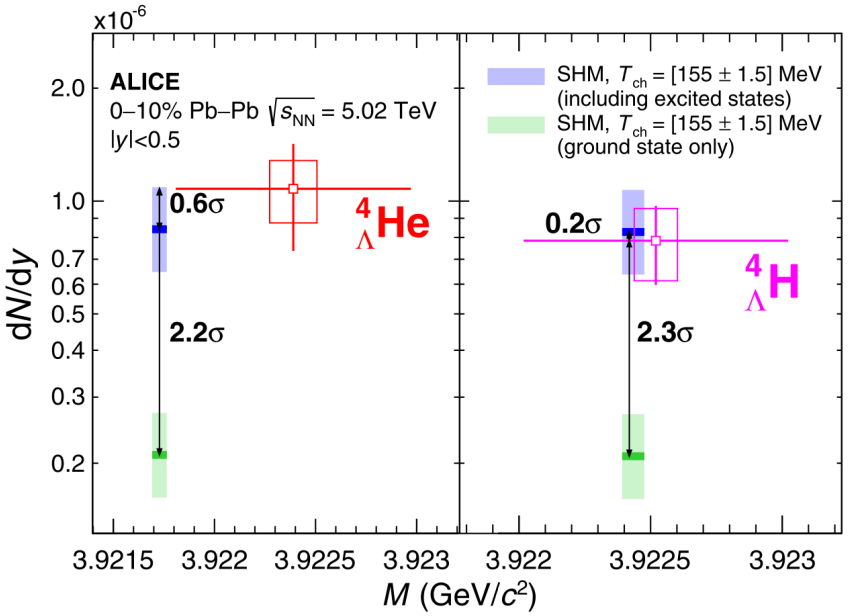
STAR Collaboration, Nature 632, 1026 (2024)

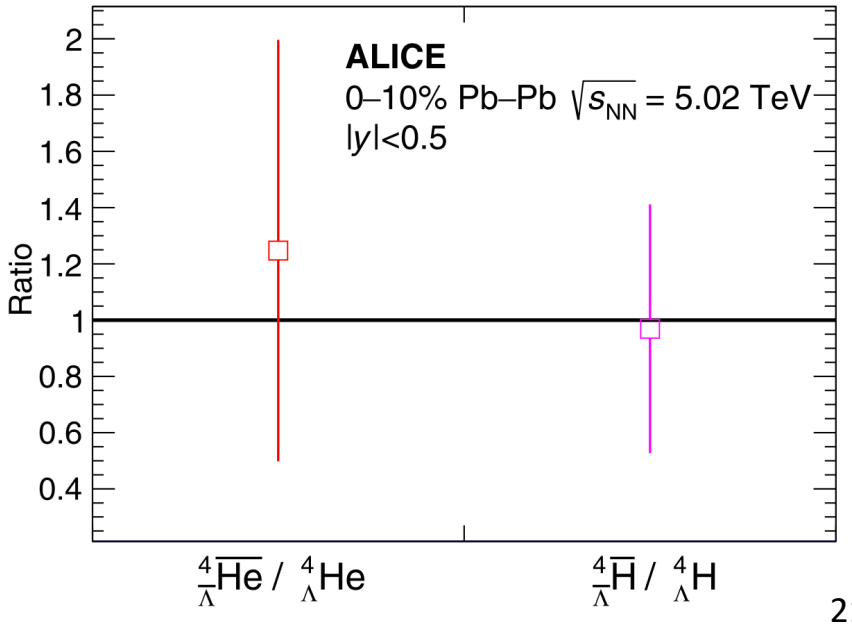
Production Yields

- The measured production yields are consistent with statistical thermal model predictions with the factor of 4 enhancement due to spin-1 excited states of ${}^{4}_{\Lambda}H$ & ${}^{4}_{\bar{\Lambda}}\overline{H}$



- At LHC energy, no significant production yield difference between antihypernuclei and corresponding hypernuclei observed
  - Expected as $\mu_B \sim 0$

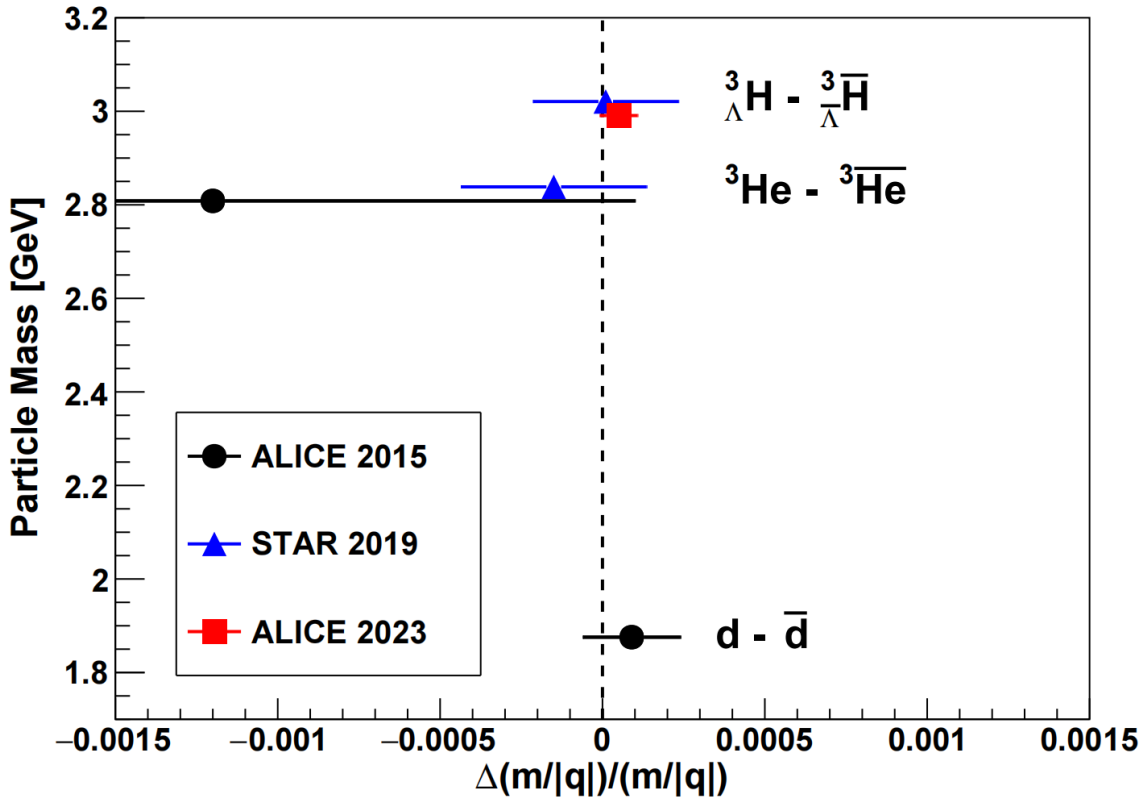




ALICE Collaboration, Phys. Rev. Lett. 134 (2025) 162301

CPT Symmetry Test – Mass Differences

- No significant mass or binding energy difference between d & $\bar{d}$, ^{3}He & $^3\overline{\text{He}}$, $^3_\Lambda$H and $^3_{\bar{\Lambda}}\bar{\text{H}}$
- Consistent with CPT theorem



ALICE Collaboration, Nature Phys. 11 (2015) 811
STAR Collaboration, Nature Phys. 16 (2020) 409
ALICE Collaboration, Phys. Rev. Lett. 131, 102302 (2023)

CPT Symmetry Test – Lifetime Differences

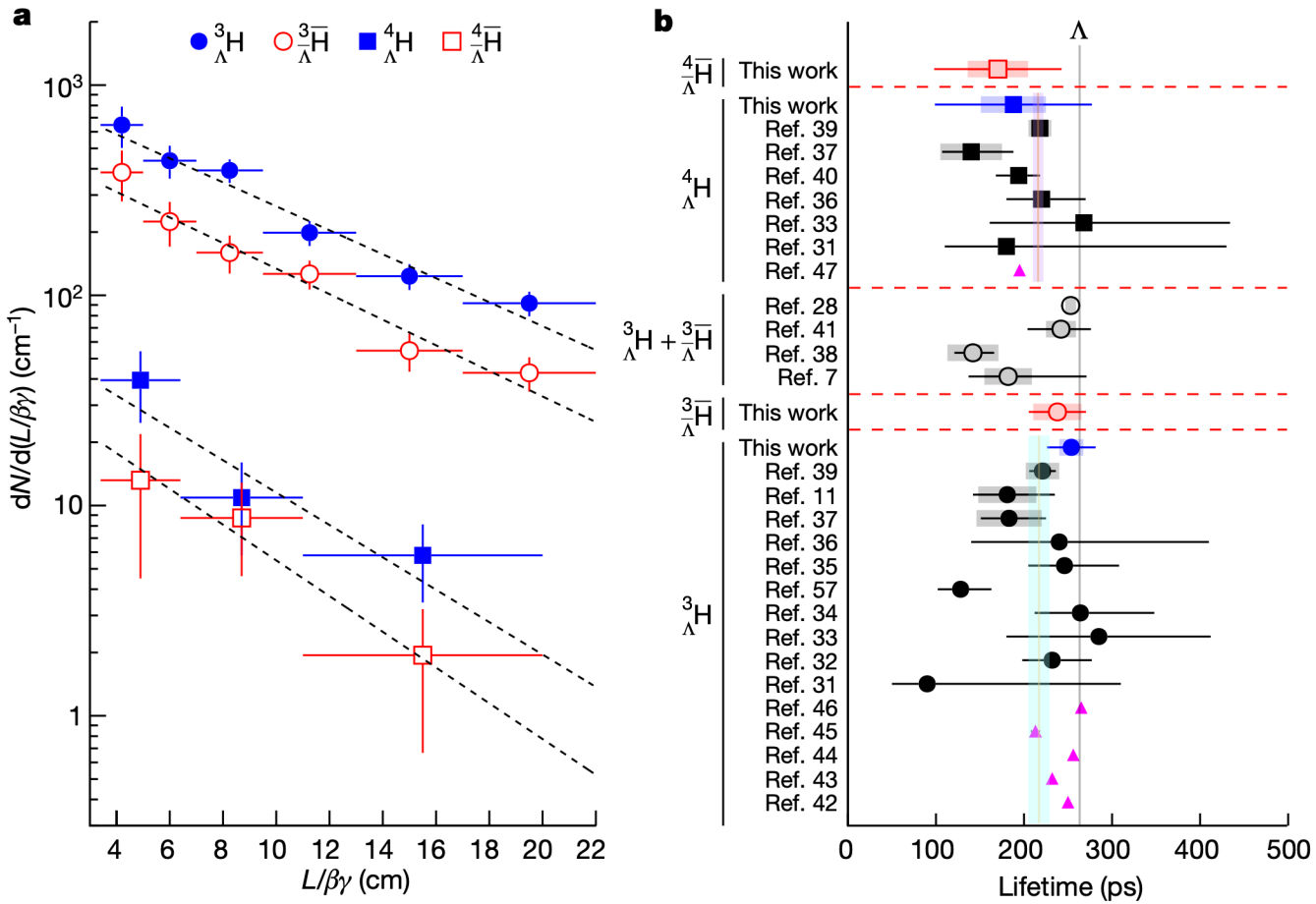
$$\tau_{{}^{3}_{\Lambda}\mathrm{H}} - \tau_{{}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}} = 16 \pm 43(\mathrm{stat.}) \pm 20(\mathrm{sys.})\ \mathrm{ps}$$

$$\tau_{{}^{4}_{\Lambda}\mathrm{H}} - \tau_{{}^{4}_{\bar{\Lambda}}\overline{\mathrm{H}}} = 18 \pm 115(\mathrm{stat.}) \pm 46(\mathrm{sys.})\ \mathrm{ps}$$

STAR Collaboration, Nature 632, 1026 (2024)

$$\frac{\tau_{{}^{3}_{\Lambda}\mathrm{H}} - \tau_{{}^{3}_{\bar{\Lambda}}\bar{\mathrm{H}}}}{\tau_{{}^{3}_{\Lambda}\mathrm{H}}} = [3 \pm 7(\mathrm{stat}) \pm 4(\mathrm{syst})] \times 10^{-2}$$

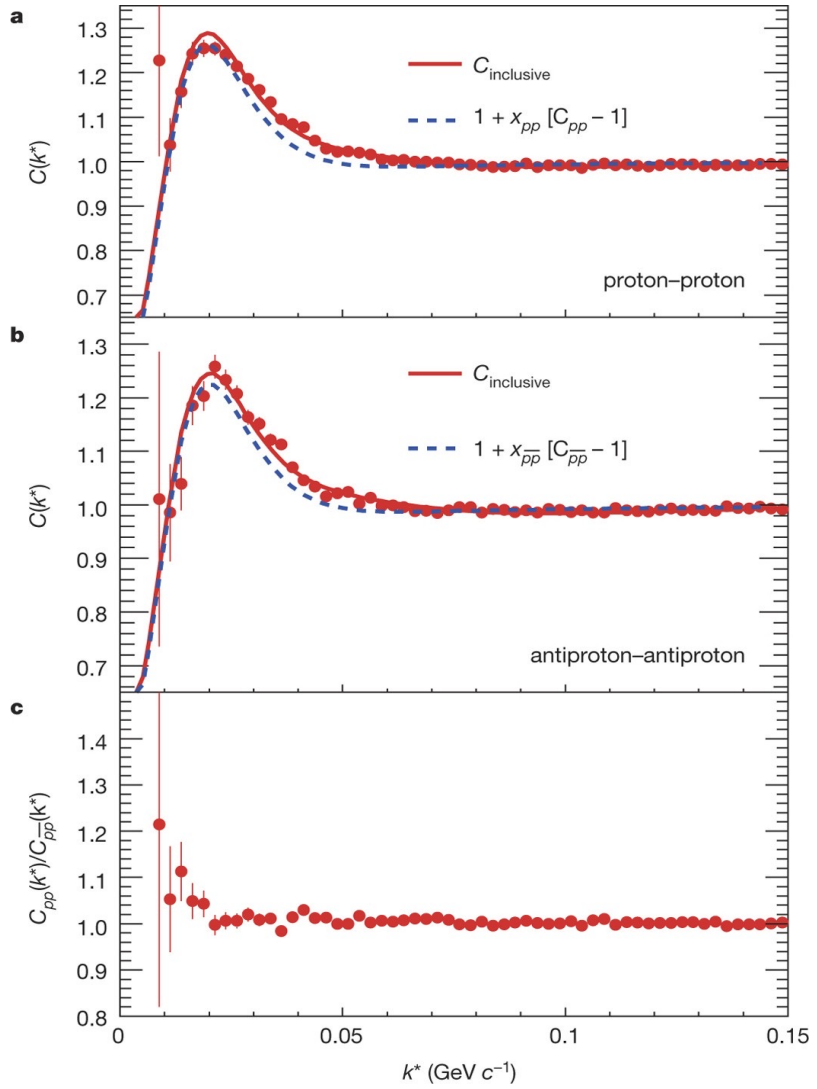
ALICE Collaboration,
Phys. Rev. Lett. 131, 102302 (2023)



- No significant lifetime difference between antihypernuclei and their corresponding hypernuclei
- Consistent with CPT theorem

CPT Symmetry Test – Interaction Differences

- No difference between p-p and $\bar{p}$-$\bar{p}$ correlation functions
  - ⇒ No difference between p-p and $\bar{p}$-$\bar{p}$ interactions
- Consistent with CPT theorem



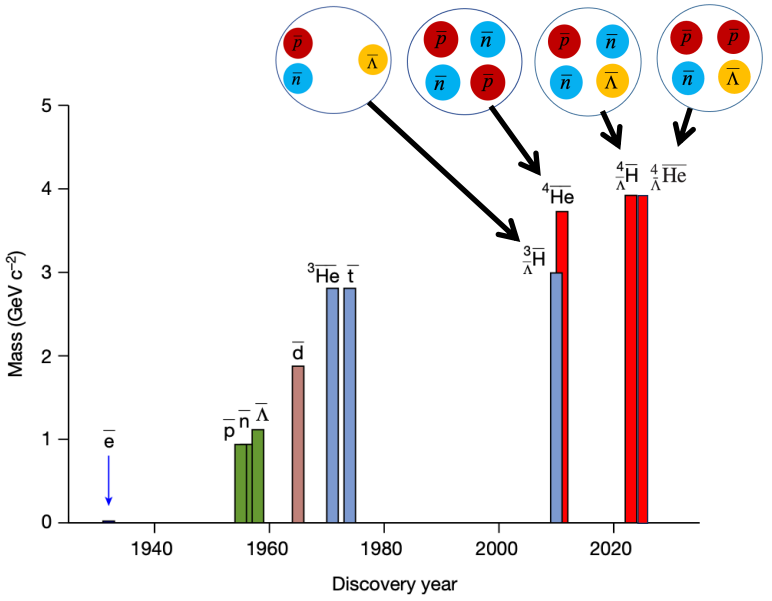
STAR Collaboration, Nature 527, 345 (2015)

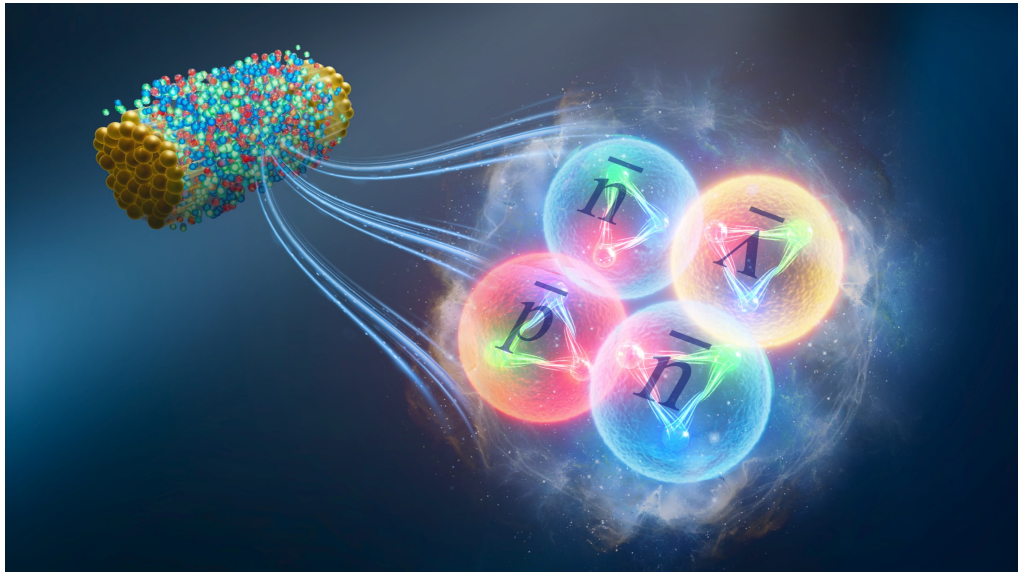
Summary

- $^{3}_{\bar{\Lambda}}\overline{H}$, $^{4}\overline{He}$, $^{4}_{\bar{\Lambda}}\overline{H}$ & $^{4}_{\bar{\Lambda}}\overline{\mathrm{He}}$ have been observed sequentially by STAR & ALICE experiments at RHIC & LHC

- Production yield (ratios) are consistent with expectations of the coalescence production picture and the statistical thermal model

- CPT symmetry is confirmed by comparing the masses, lifetimes and interactions of (hyper)nuclei and anti(hyper)nuclei

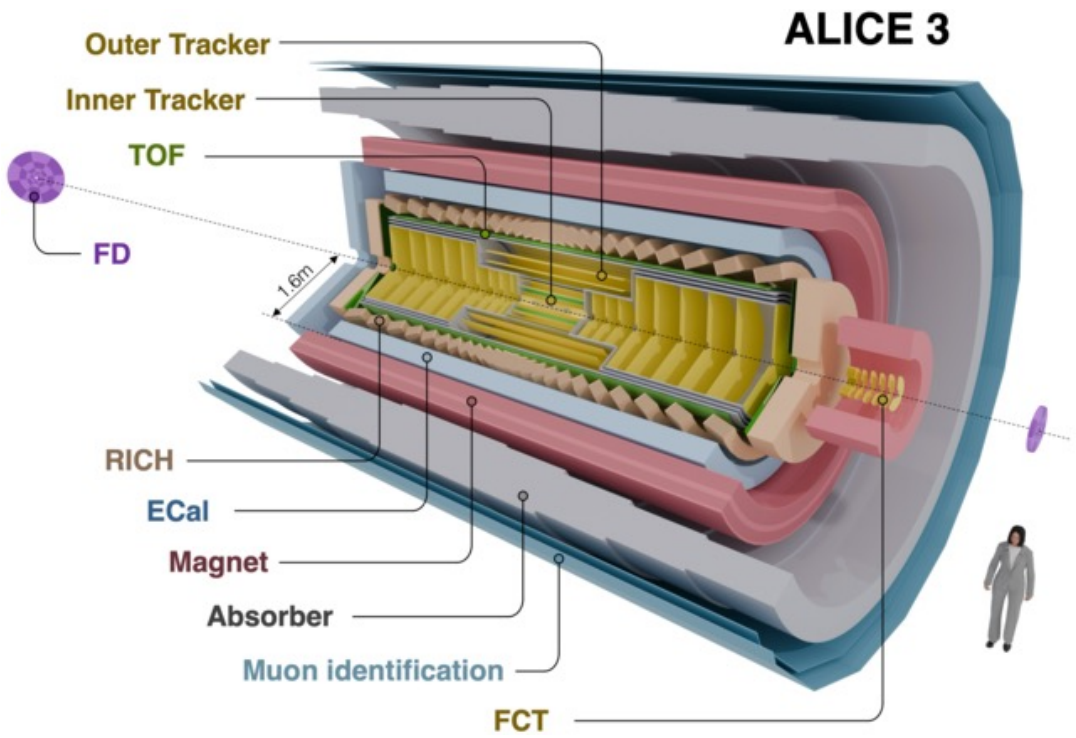




Outlook

- STAR aims to take 16-18 B 200 GeV Au+Au collision events by 2026
- After the continuous-readout upgrade, ALICE-II takes heavy-ion collision data at an event rate of 50 kHz, instead of 8 kHz before
- ALICE-III with all-silicon tracker instead of TPC aims to run at luminosities a factor of 20 to 50 times higher than now

- These much larger data samples in the future will offer potential for precise measurements and discoveries about antimatter in relativistic heavy-ion collisions



Thanks ☺