Observation of the Antimatter Hypernucleus $^{4}_{\bar{\Lambda}}\overline{H}$

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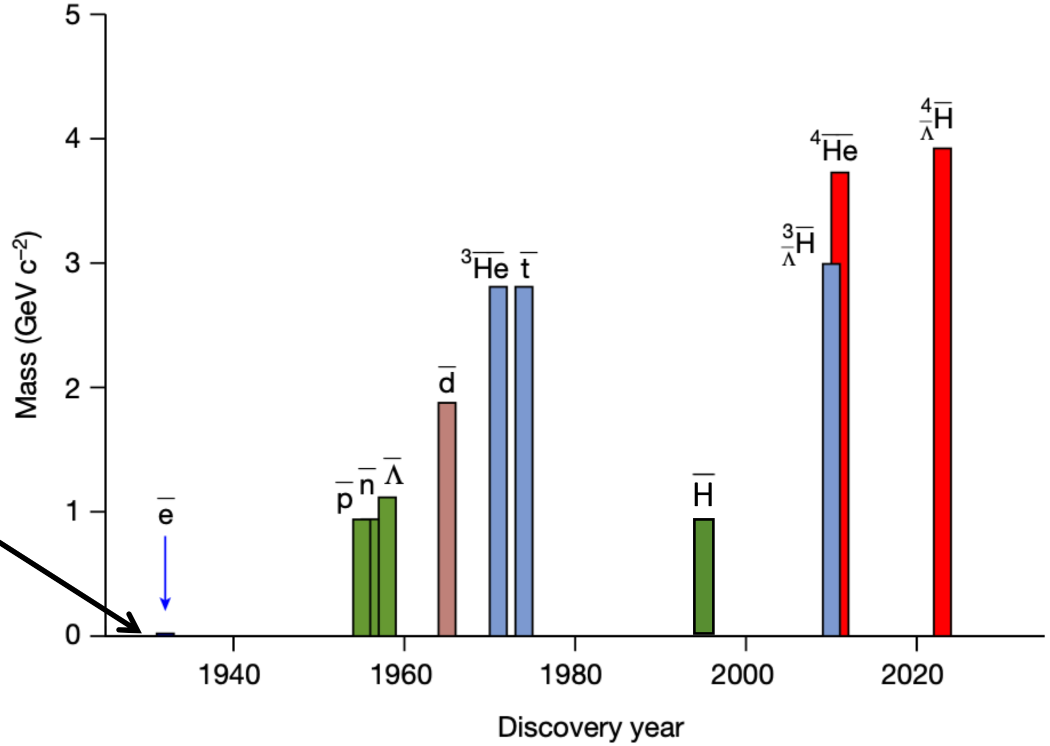
Institute of Modern Physics, CAS

for the STAR Collaboration

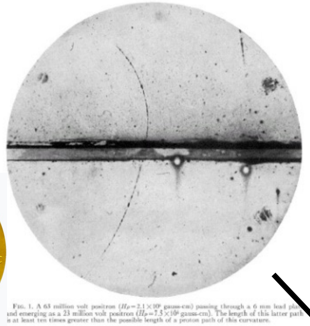
Introduction: History of Anti-matter Discovery

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



Introduction: History of Anti-matter Discovery

Carl D. Anderson



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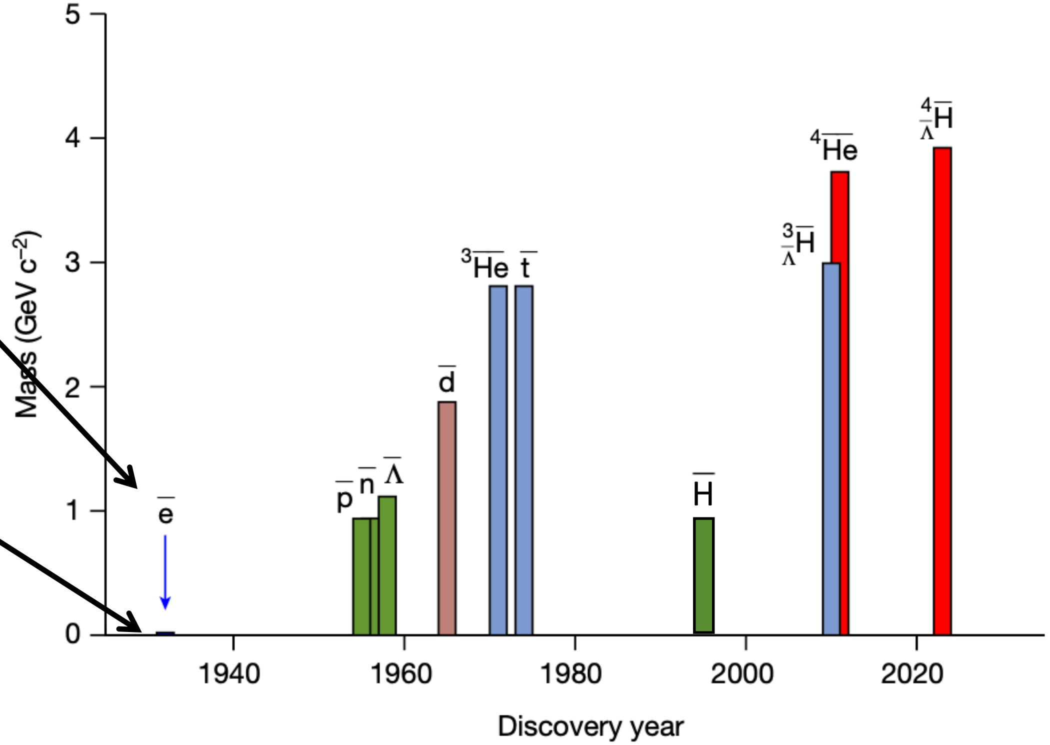

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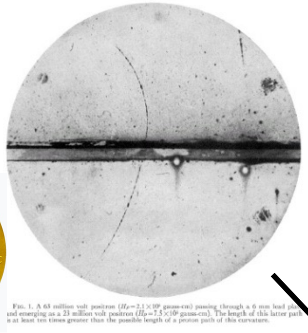

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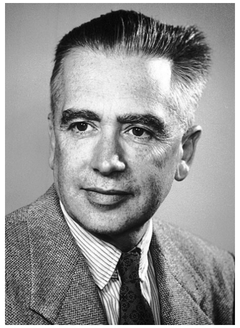
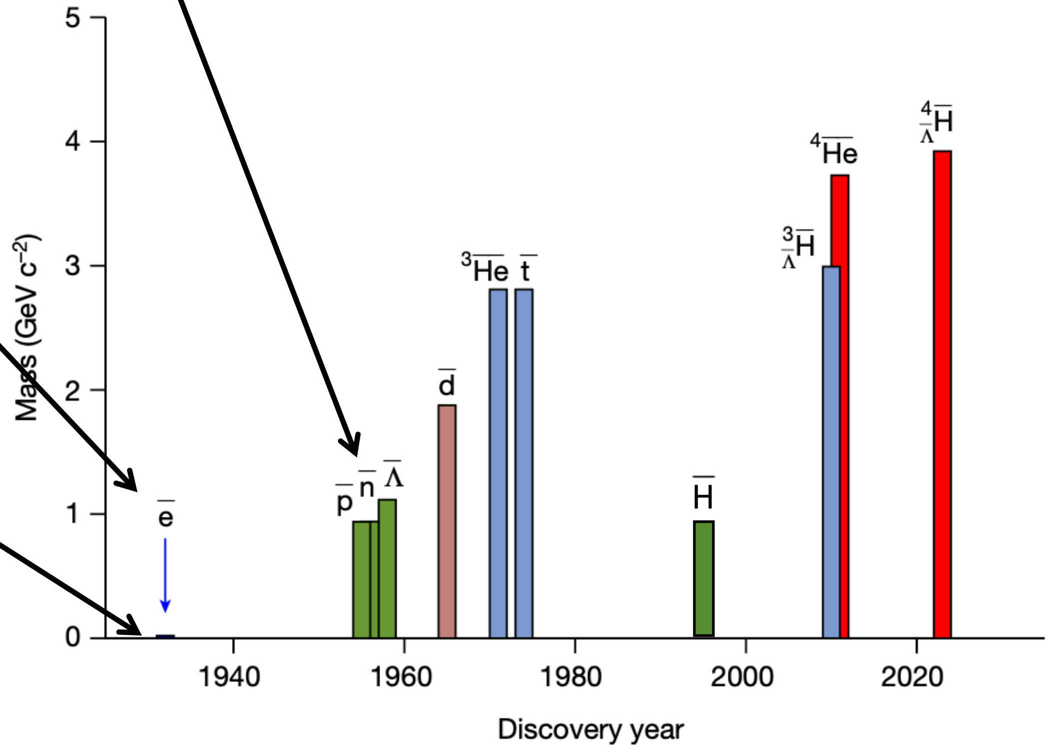


Emilio Segrè

Owen Chamberlain



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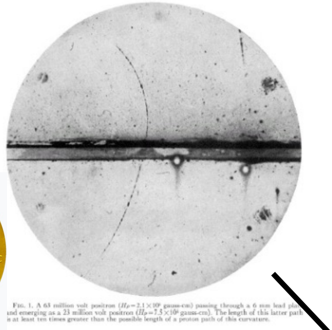

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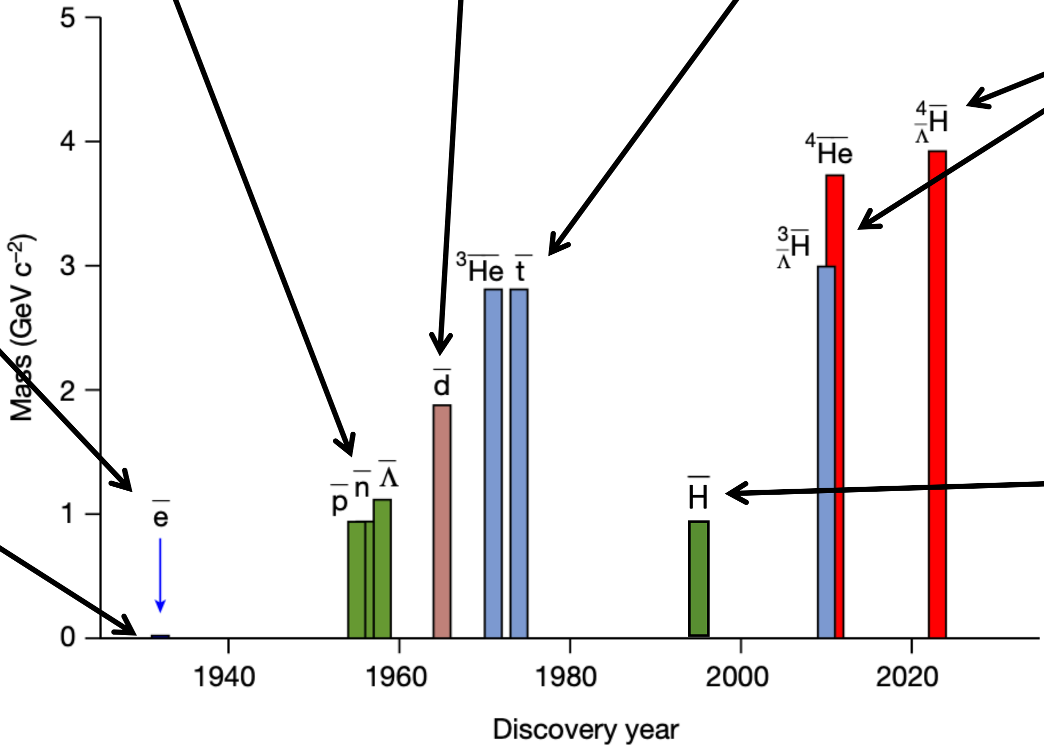

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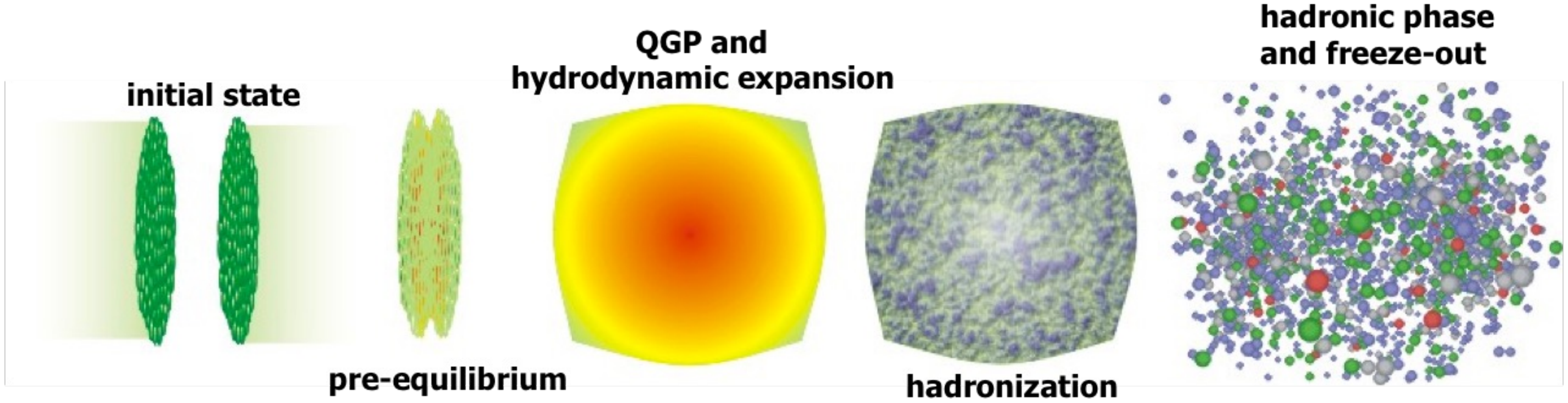
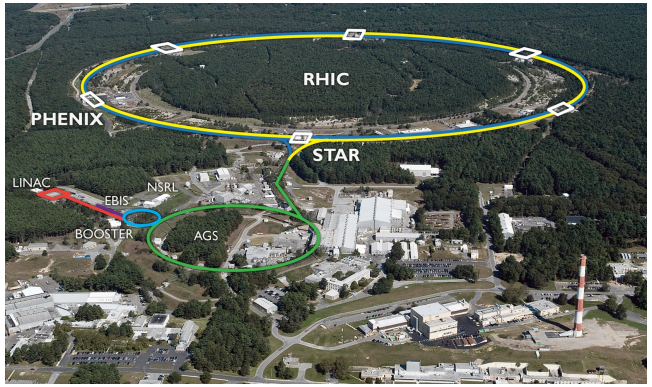
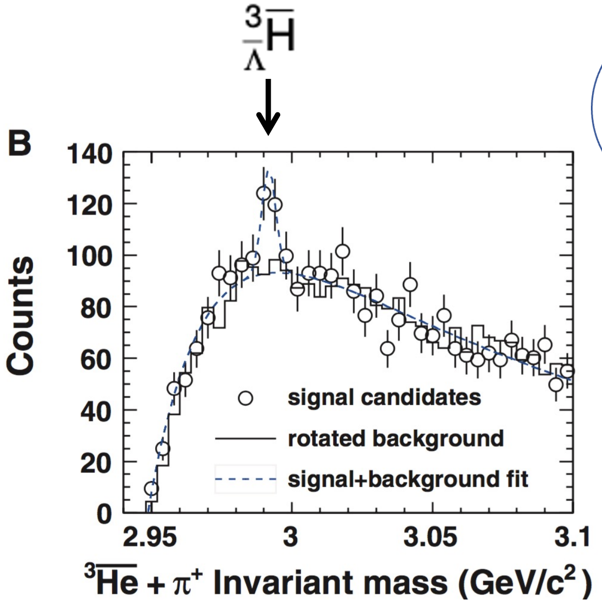
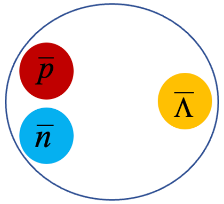


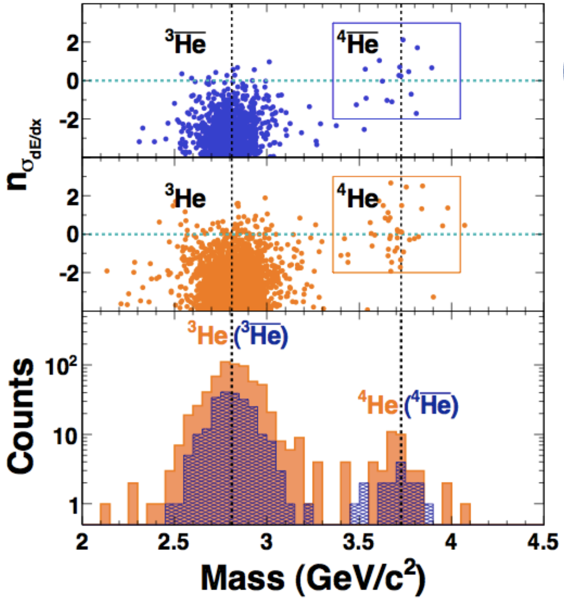


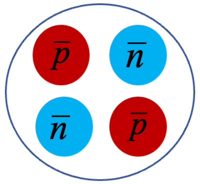
RHIC



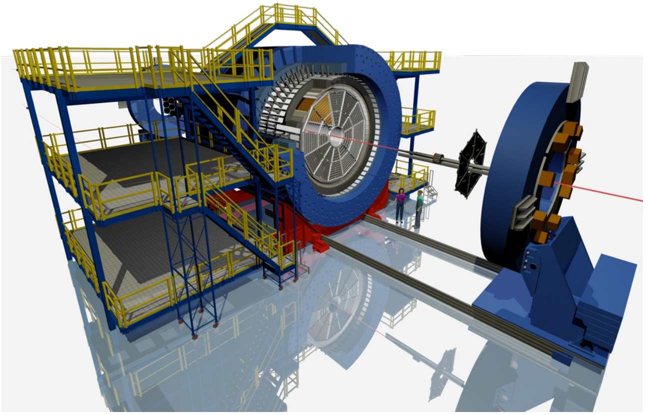


Science 328, 58 (2010)



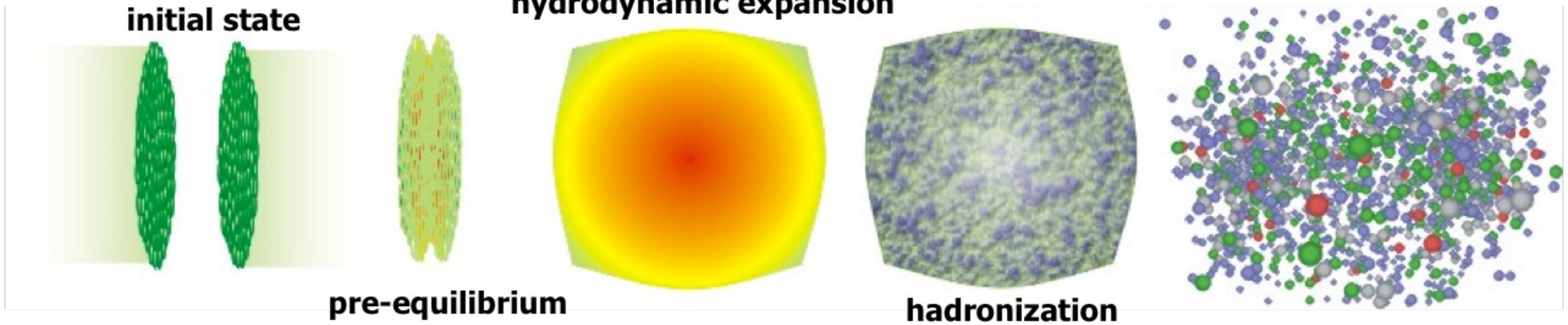


Nature 473, 353 (2011)

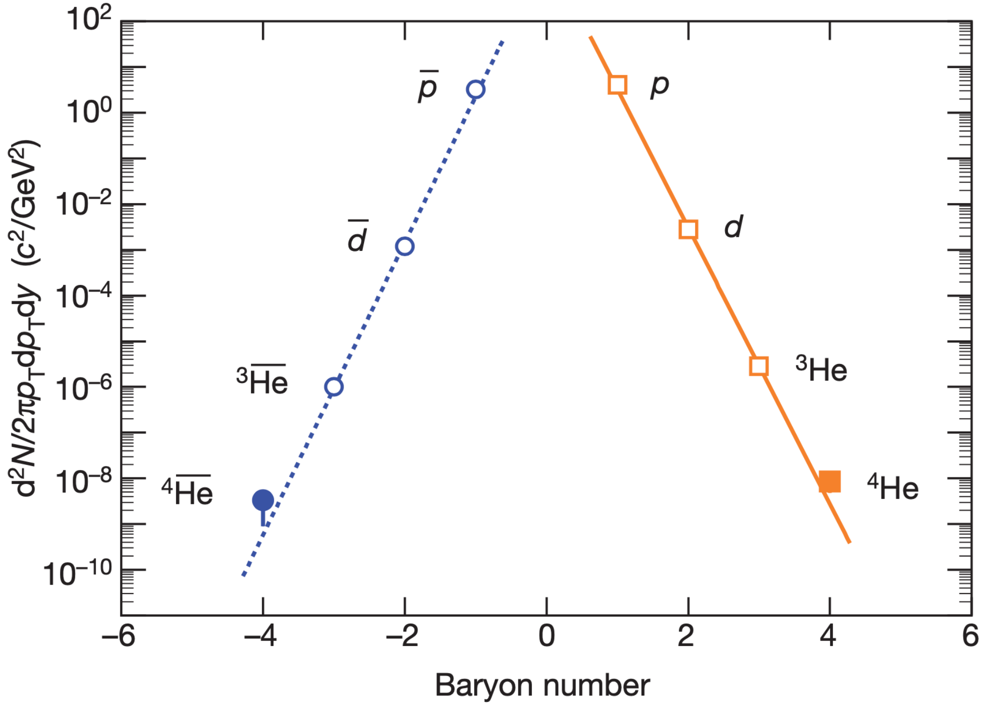


STAR

Introduction: Anti(hyper)nucleus Production

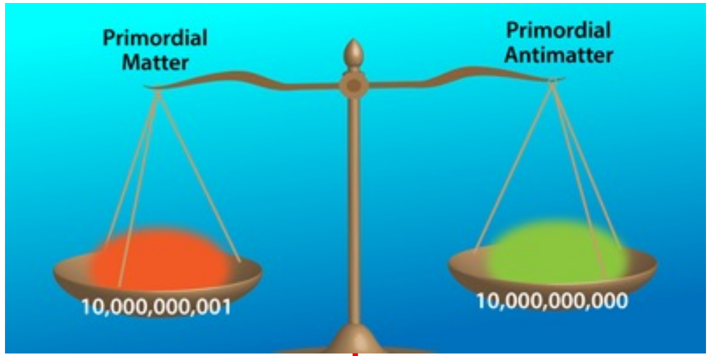


Nature 473, 353 (2011)



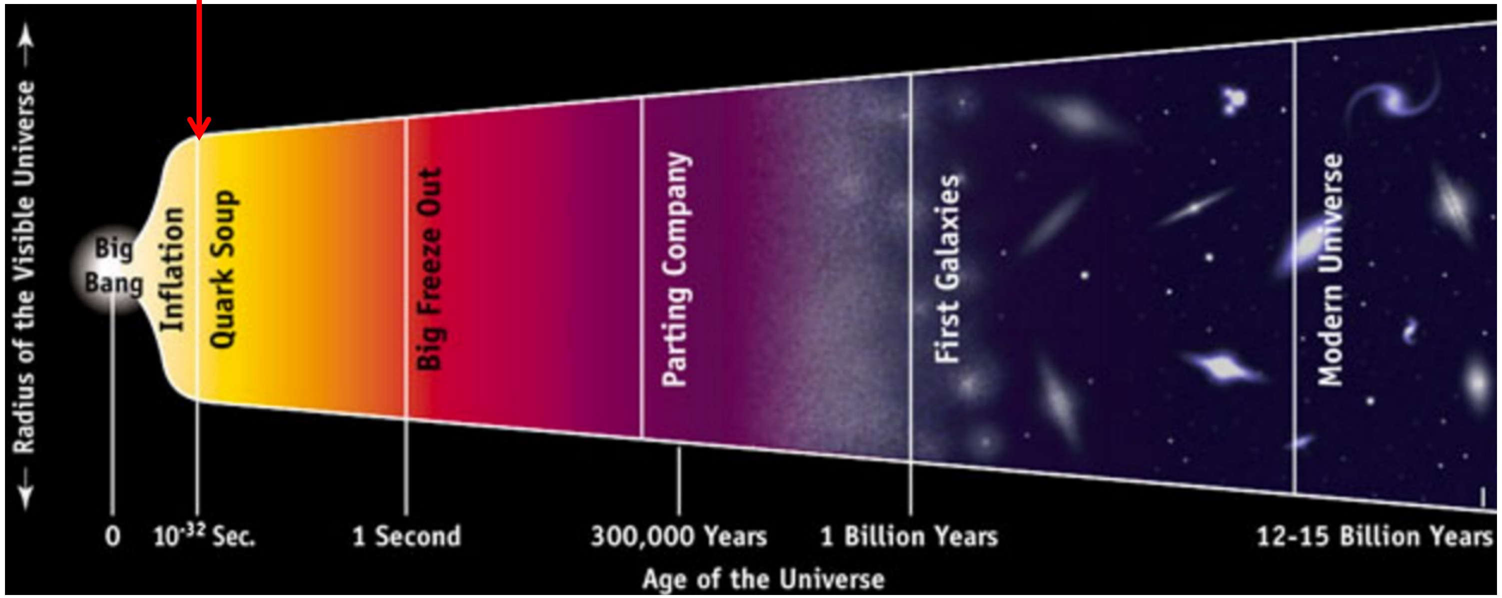
- Anti(hyper)nuclei binding energy ~ several MeV / nucleon
- QGP temperature ~ several hundred MeV
- ⇒ They are produced by coalescence of antibaryons in the last stage of the collision

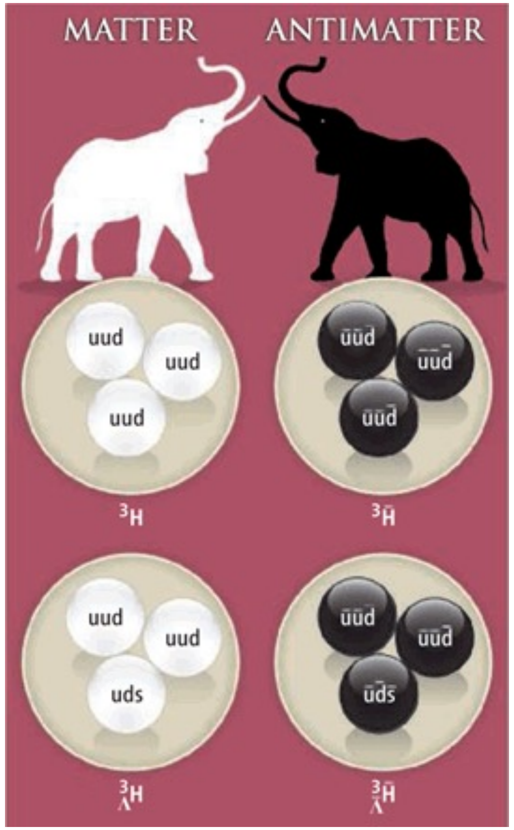
Introduction: Matter-antimatter Asymmetry in the Universe



?

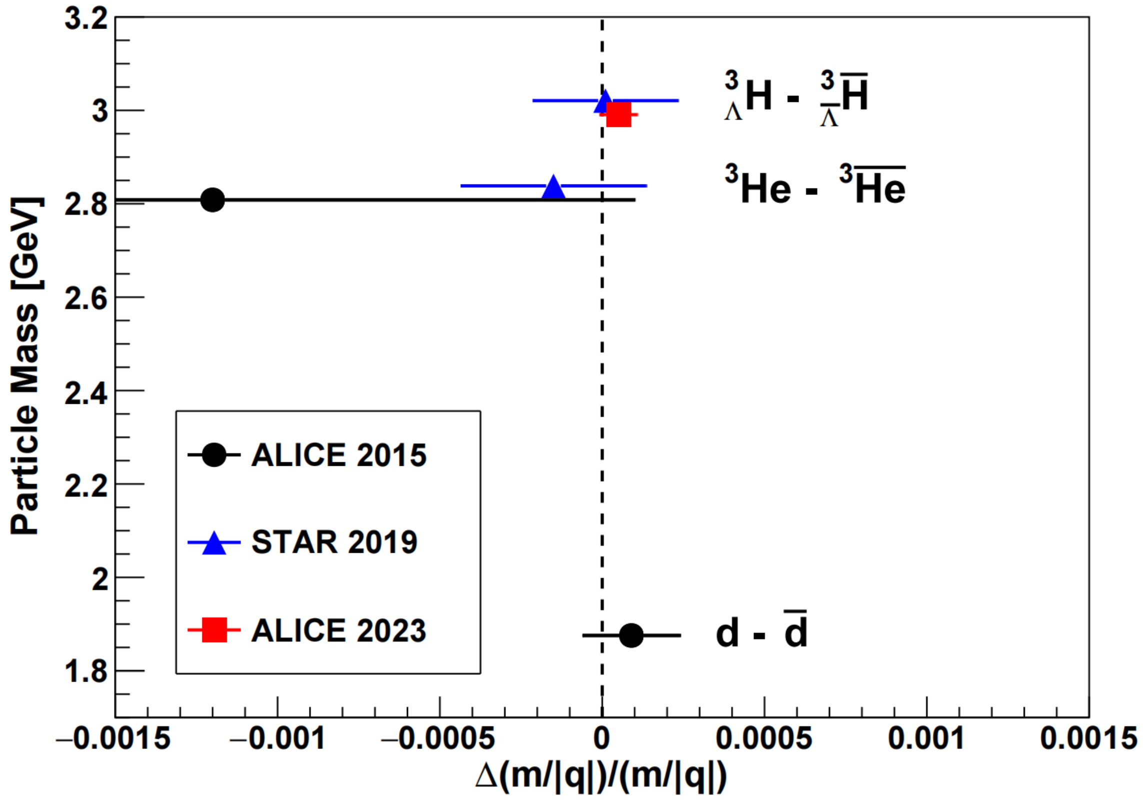
- Matter-antimatter asymmetry in early universe is the precondition for the existence of the matter world today
- The source of this asymmetry is still not clear





CPT theorem ⇒ Symmetry of matter-antimatter properties

Introduction: CPT symmetry test with heavy-ion collisions



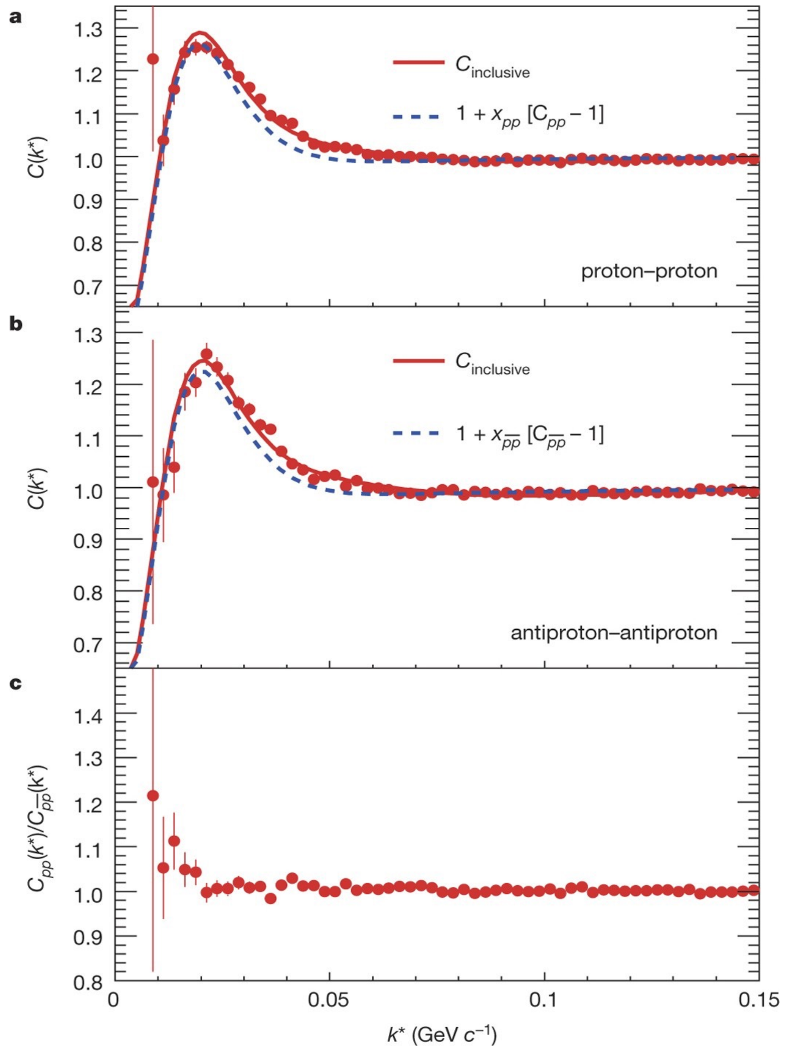
$$\frac{\tau_{^3_\Lambda H} - \tau_{^3_{\bar{\Lambda}}\bar{H}}}{\tau_{^3_\Lambda H}} = [3 \pm 7(\text{stat}) \pm 4(\text{syst})] \times 10^{-2}$$

Nature Phys. 11 (2015) 10, 811-814
Nature Phys. VOL 16, April 2020, 409–412
PHYSICAL REVIEW LETTERS 131, 102302 (2023)

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

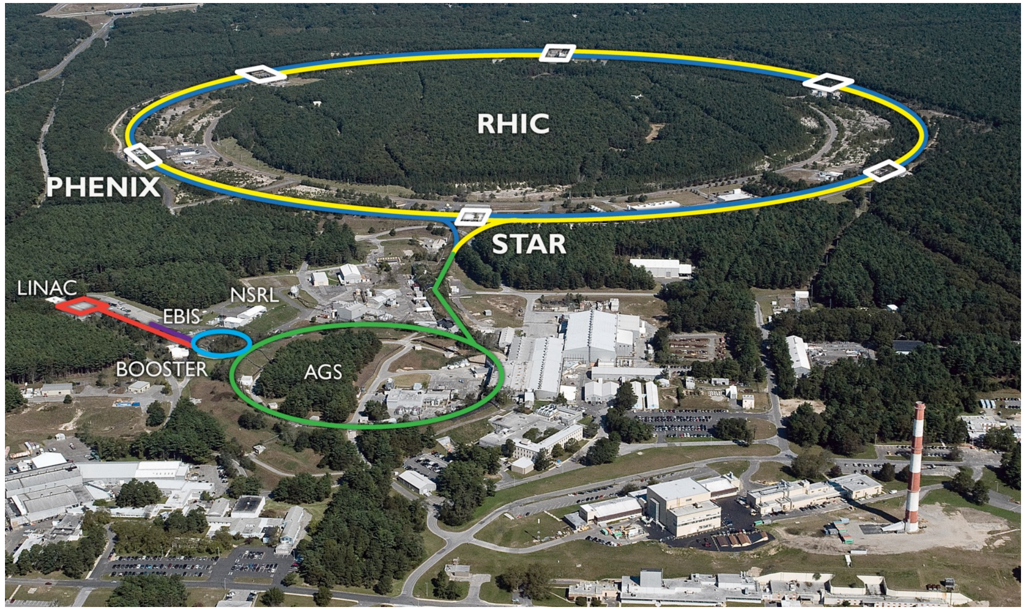
Introduction: CPT symmetry test with heavy-ion collisions

- No difference between p-p and $\bar{p}$-$\bar{p}$ correlation functions
  - ⇒ No difference between p-p and $\bar{p}$-$\bar{p}$ interactions



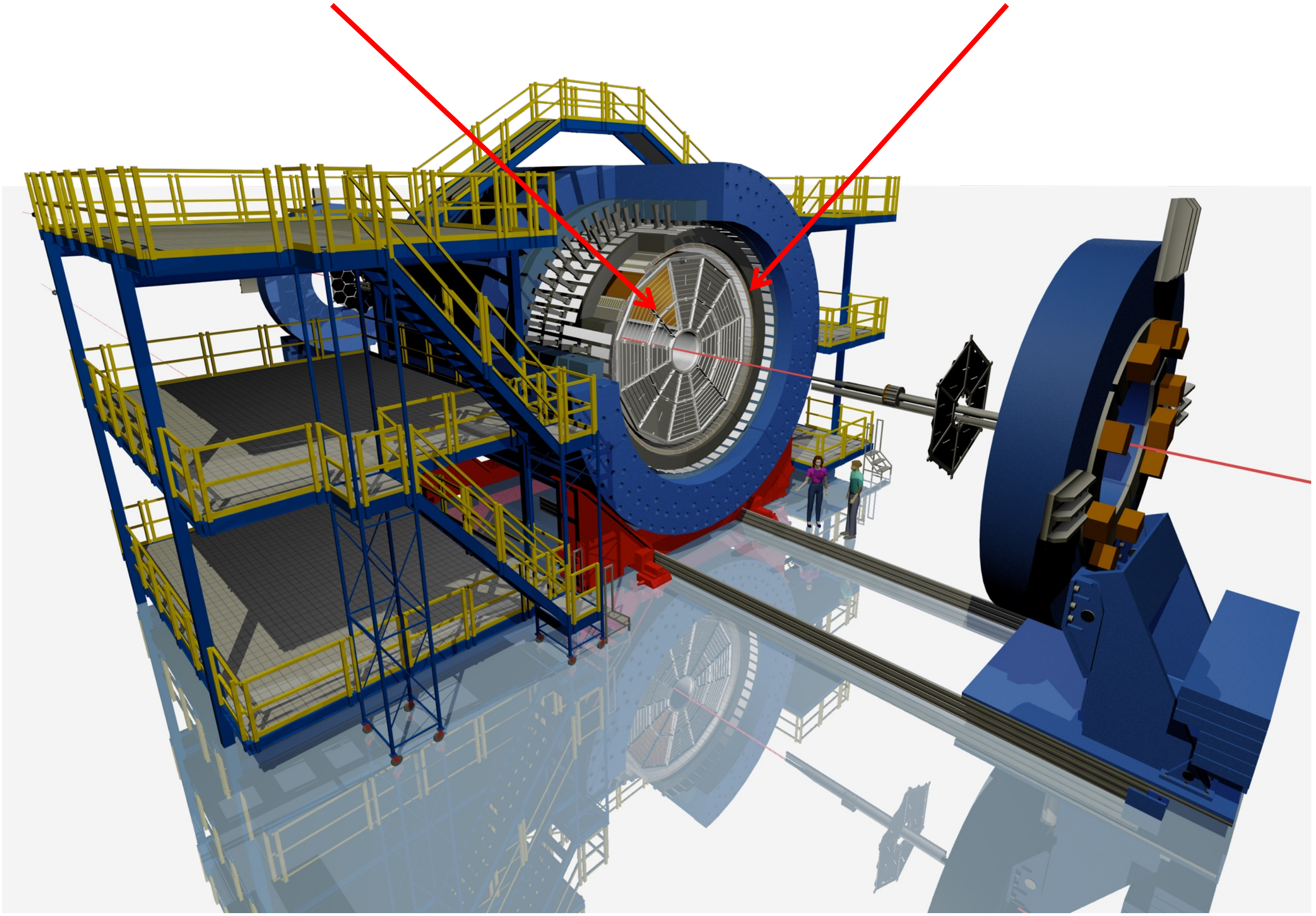
Nature volume 527, pages345–348 (2015)

RHIC-STAR



Time Projection Chamber
- tracking ⇒ p/Z, dE/dx

Time-Of-Flight detector
- TOF + p/Z + L ⇒ m^2/Z^2



Data Sets

data set	year	N events
AuAu@200 GeV	2010	~606 M
AuAu@200 GeV	2011	~626 M
UU@193GeV	2012	~512 M
ZrZr+RuRu(Isobar)@200GeV	2018	~4.7 B

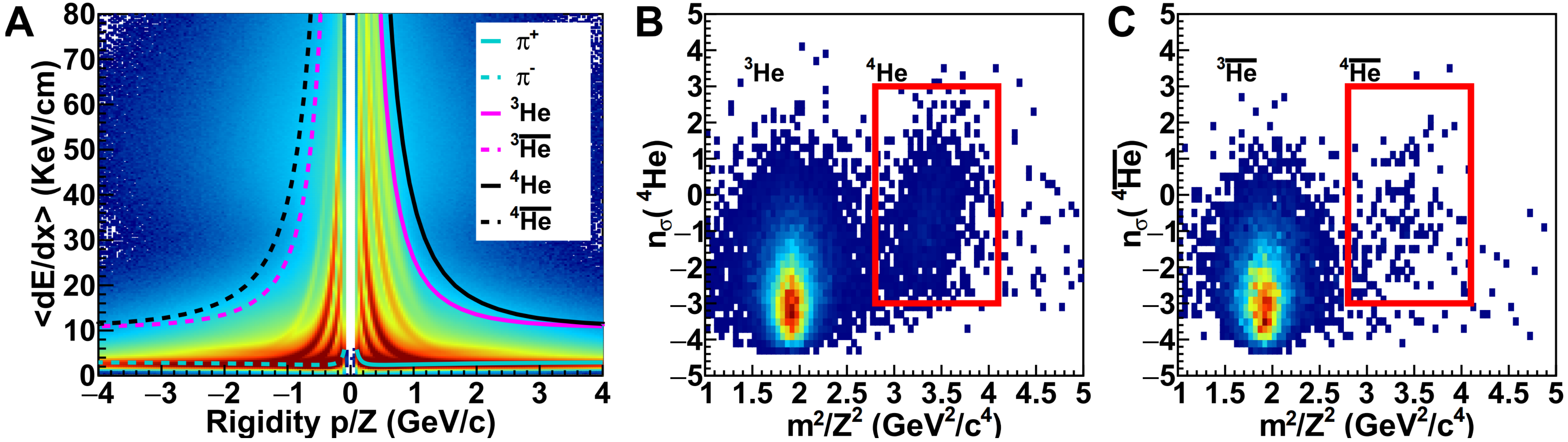
Trigger:

- Minimum bias trigger
- Central trigger
- Electromagnetic and hadronic triggers
- ......

- Use as many triggers as possible to find signal and measure lifetime
- Use minimum bias trigger for production yield ratios measurement

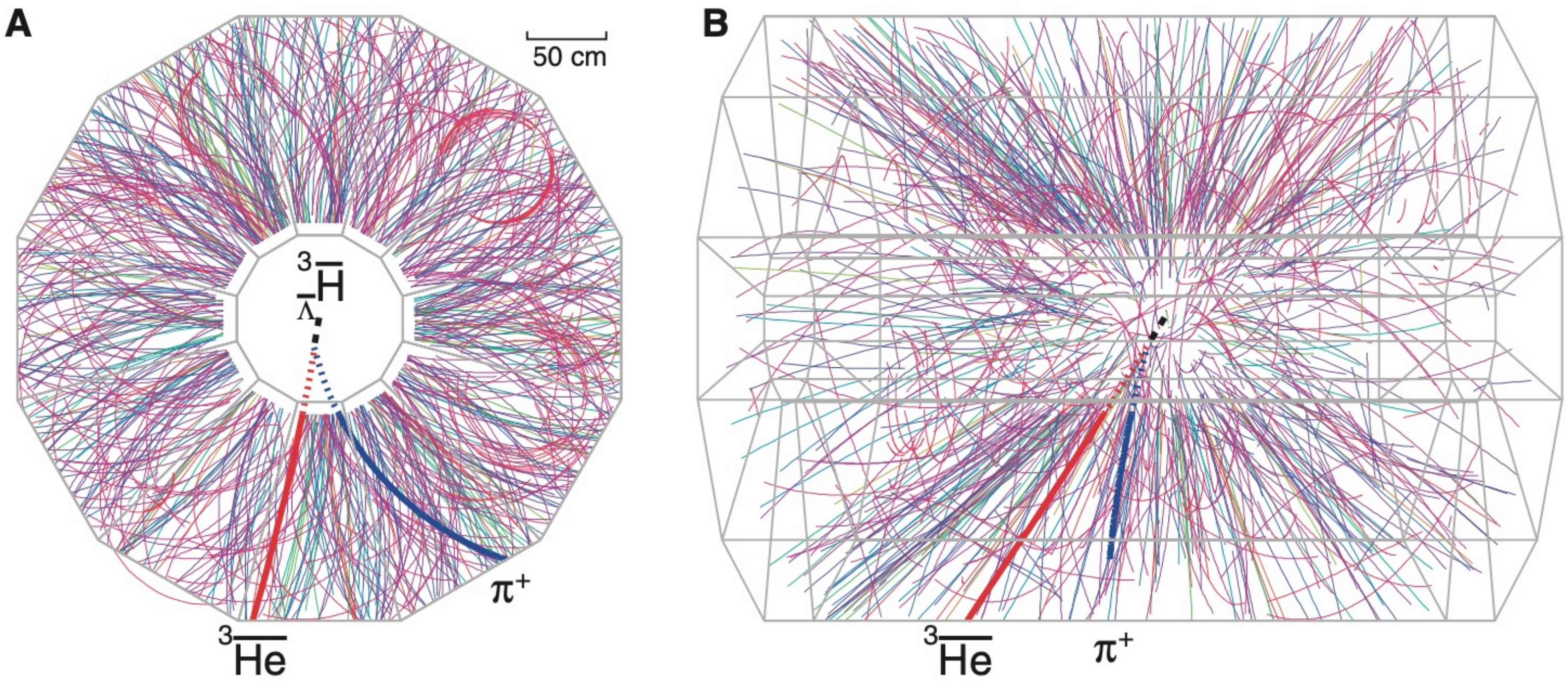
Decay Channels & Daughter Particle Identification

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

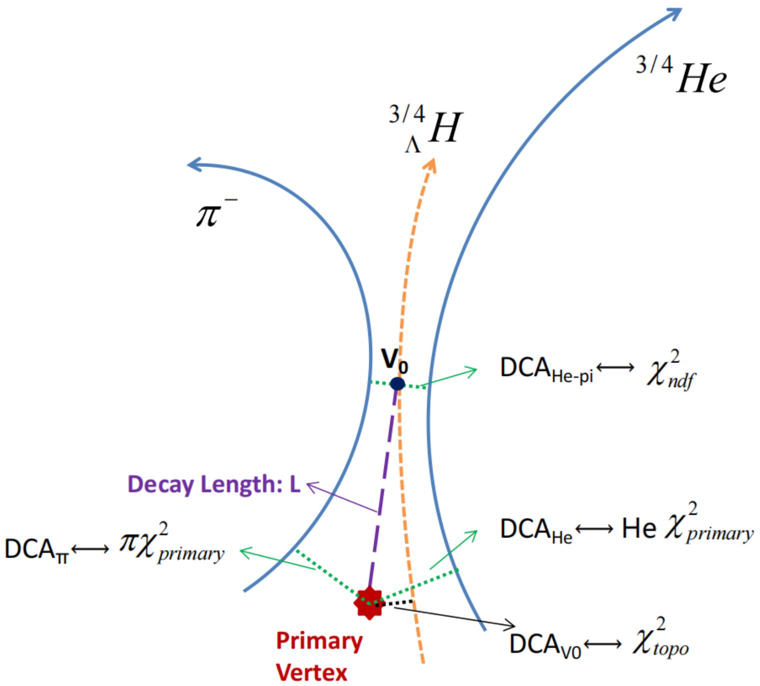


- ^{3}He PID： (Z<0 || p>2.) && $|n\sigma_{^3He}|<3$ && (if TOF matched, $1<M^2/Z^2<3$);
- ^{4}He PID： (Z<0 || p>2.) && $|n\sigma_{^4He}|<3$ && ($|n\sigma_{^3He}|>3.5$ || $2.8<M^2/Z^2<4.1$));
- π PID： $|n\sigma_{\pi}|<3$;

Decay Vertex Reconstruction



Science 328, 58 (2010)

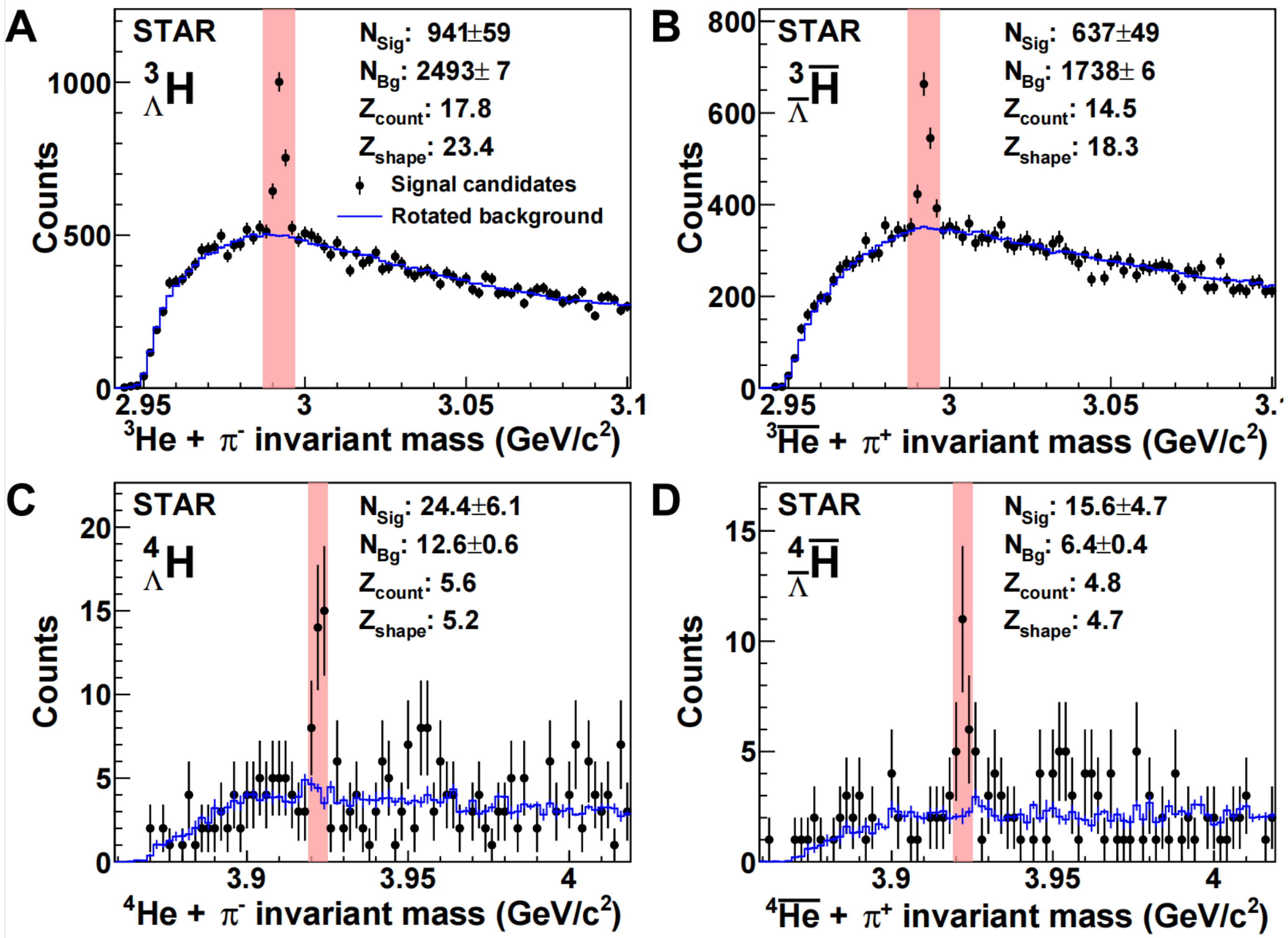


S. Gorbunov and I. Kisel, CBM-SOFT-note-2007-003, 7 May 2007
M. Zyzak, "Online selection of short-lived particles on many-core computer architectures in the CBM experiment at FAIR," Dissertation thesis, Goethe University of Frankfurt, 2016

- KF(Kalman Filter) Particle package for decay vertex reconstruction
- Topology cuts obtained by optimizing $^{3}_{\Lambda}\overline{H}$ significance
  - blind for $^{4}_{\Lambda}H$ and $^{4}_{\Lambda}\overline{H}$

Particle	$\chi^2_{prim\ He}$	$\chi^2_{prim\ \pi}$	χ^2_{ndf}	χ^2_{topo}	L/dL	L	He DCA
$^{3}_{\Lambda}H$ & $^{4}_{\Lambda}H$	<2000	>10	<5	<2	>3.5	>3.4cm	<1cm
$^{3}_{\Lambda}\overline{H}$ & $^{4}_{\Lambda}\overline{H}$	<2000	>10	<5	<3	>3.5	>3.4cm	-

Signals

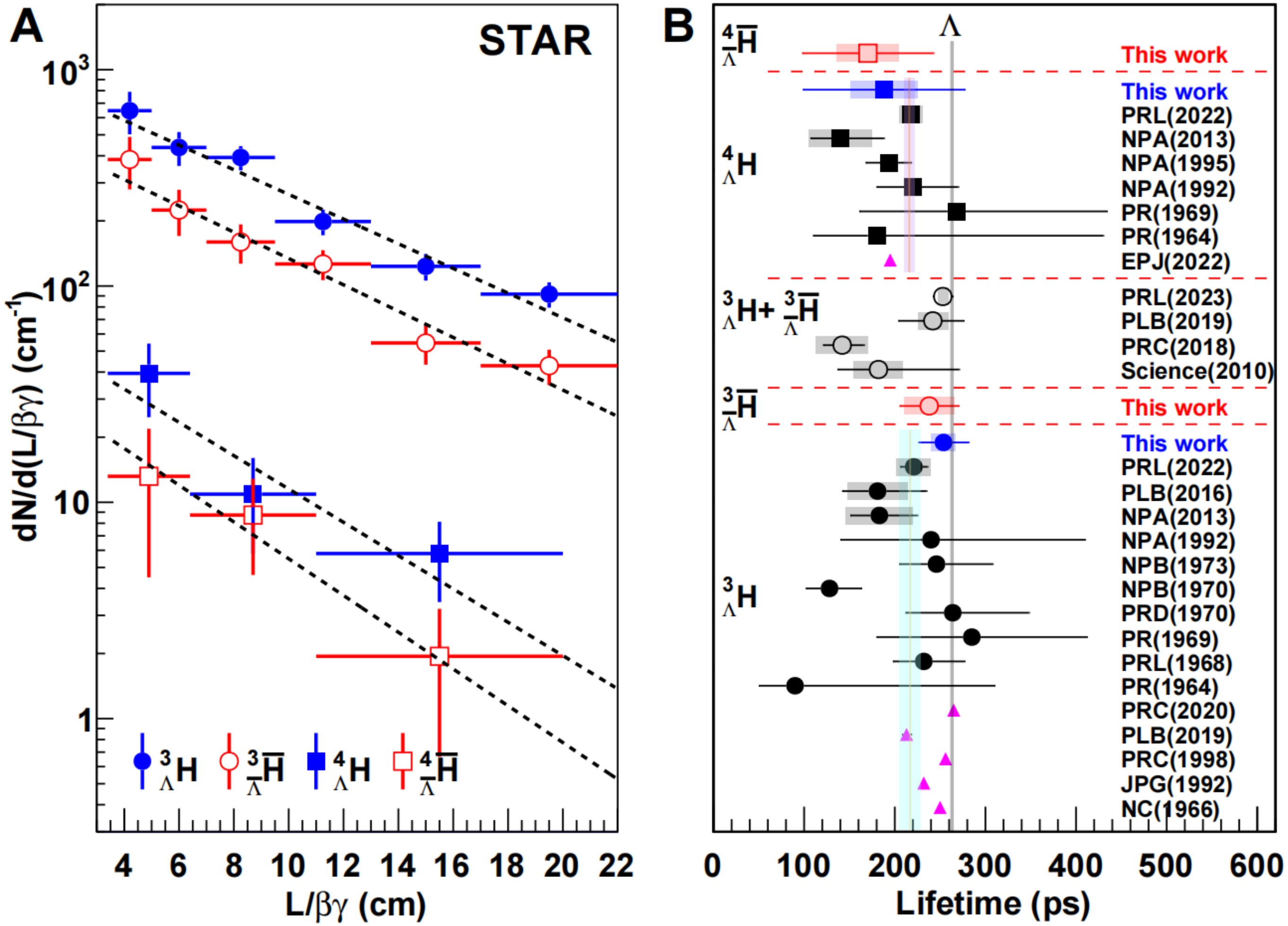


Nature 2024, DOI: 10.1038/s41586-024-07823-0

- Background invariant-mass distributions obtained by rotating the (anti)He daughter track before reconstructing the decay vertex
- $$Z_{count} = \sqrt{2\left[\left(N_{Sig} + N_{Bg}\right)\ln\left(1 + \frac{N_{Sig}}{N_{Bg}}\right) - N_{Sig}\right]}$$
- Z_shape obtained with RooStats()::AsymptoticCalculator() assuming pure background vs. background + Gaussian signal
- 15.6 $^{4}_{\bar{\Lambda}}\bar{H}$ signal candidates
- Significances Z_{count} = 4.8, Z_{shape} = 4.7

The heaviest antihypernucleus observed

Lifetime Measurements & CPT Symmetry Test



Nature 2024, DOI: 10.1038/s41586-024-07823-0

- Efficiency corrected
- Fit with exponential function: $N(t)=N_0 e^{-l/\beta\gamma c\tau}$

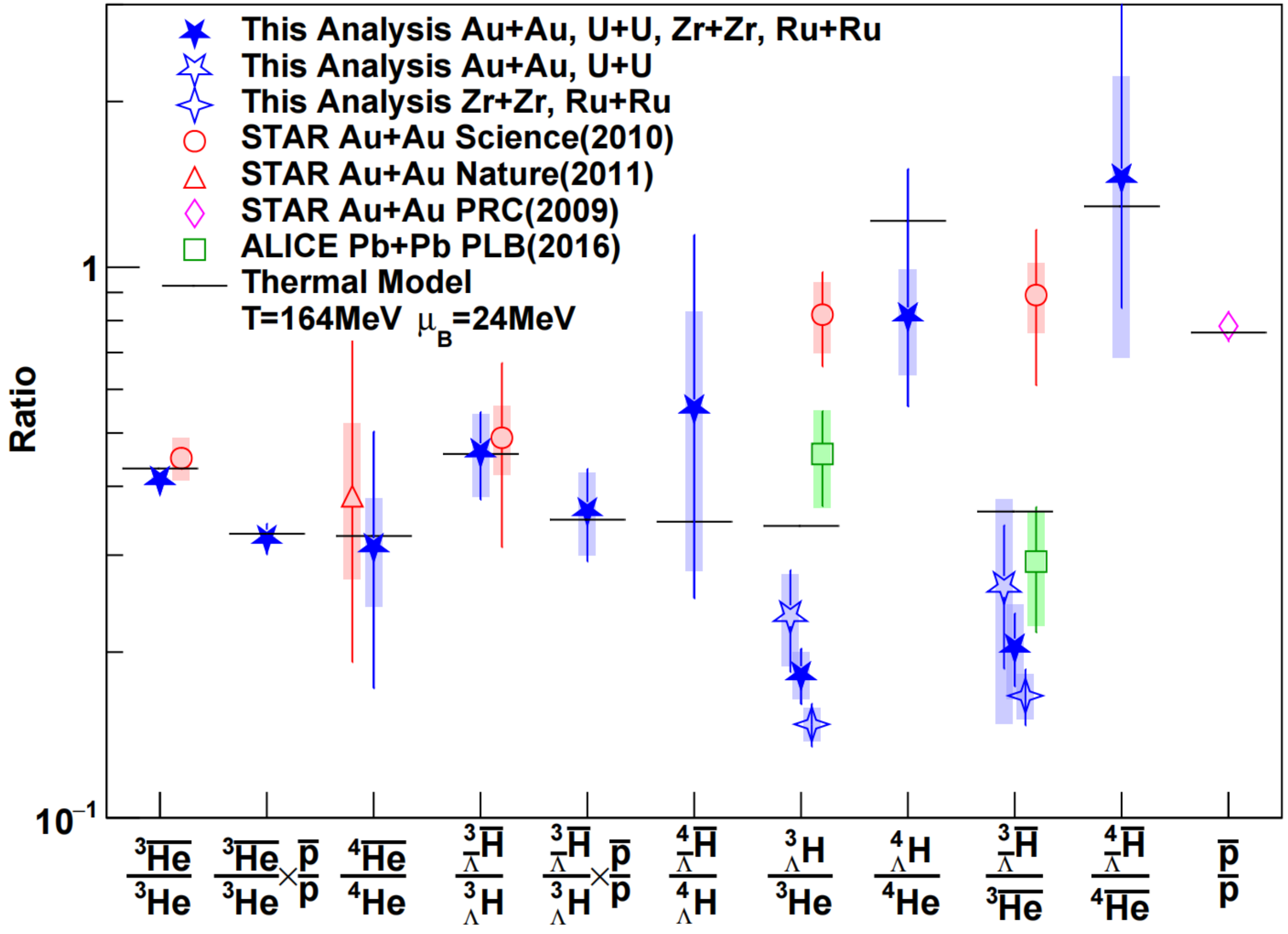
- Our results consistent with previous average

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

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

- No lifetime difference between antihypernuclei and their corresponding hypernuclei within uncertainties

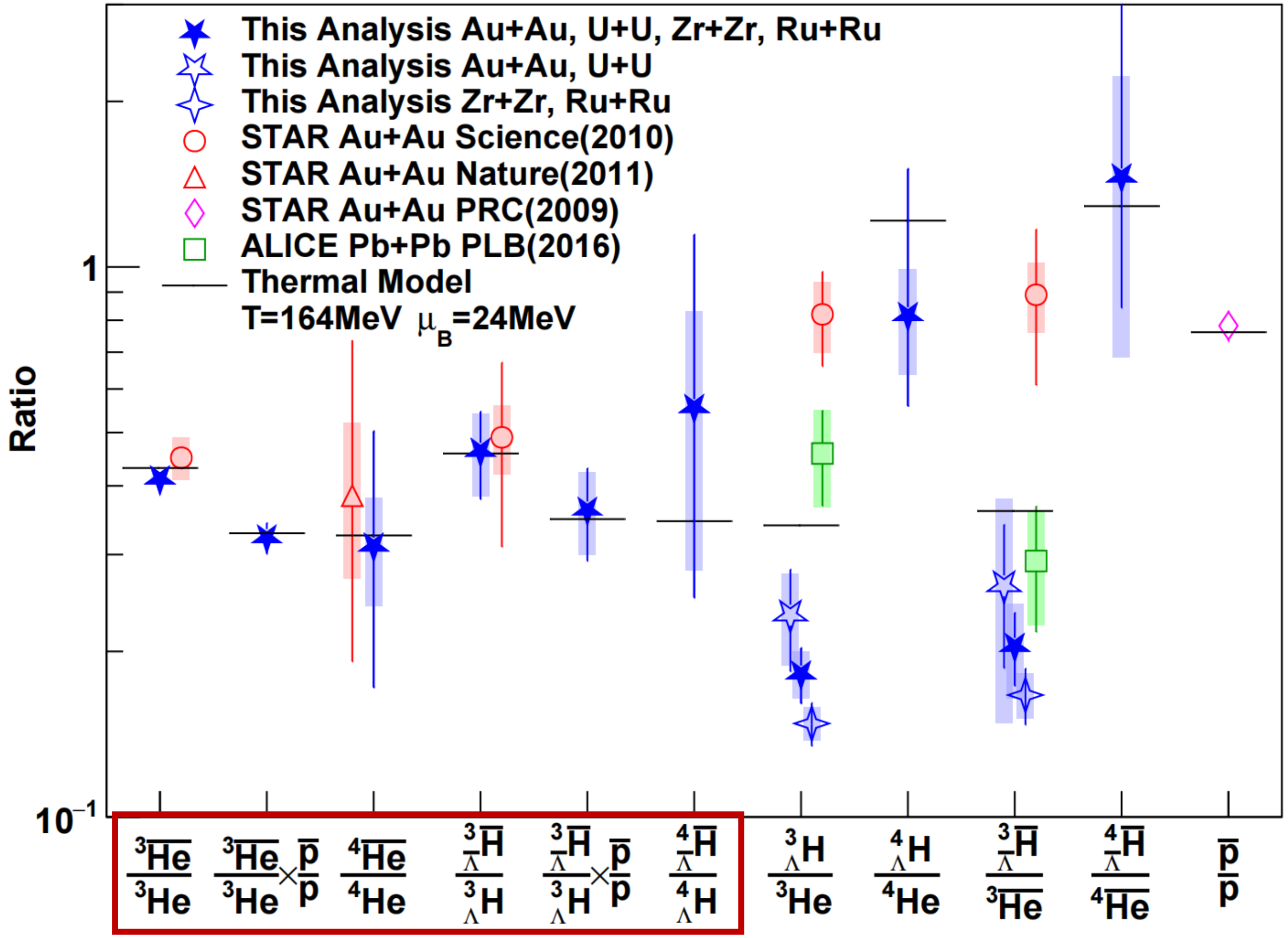
Yield Ratios



Nature 2024, DOI: 10.1038/s41586-024-07823-0
Science 328, 58 (2010)
Nature 473, 353–356 (2011)
Phys. Rev. Lett. 97, 152301
Phys. Lett. B 754 (2016) 360
Phys. Lett. B 697.3 (2011)

- Branch fraction assumed:
  - 25% for ${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$
  - 50% for ${}^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$
- Phase space: $0.7<p_T/M<1.5$, $|y|<0.7$
- $\frac{{}^{3}_{\Lambda}H}{{}^{3}He}$ & $\frac{{}^{3}_{\bar{\Lambda}}\bar{H}}{{}^{3}\overline{He}}$ ratios measured in large and small collision systems separately to have a fair comparison with previous measurements
- Our results are consistent with previous results, except that the $\frac{{}^{3}_{\Lambda}H}{{}^{3}He}$ & $\frac{{}^{3}_{\bar{\Lambda}}\bar{H}}{{}^{3}\overline{He}}$ ratios are lower than Science 2010 results by 2.8 & 1.9 σ

Yield Ratios



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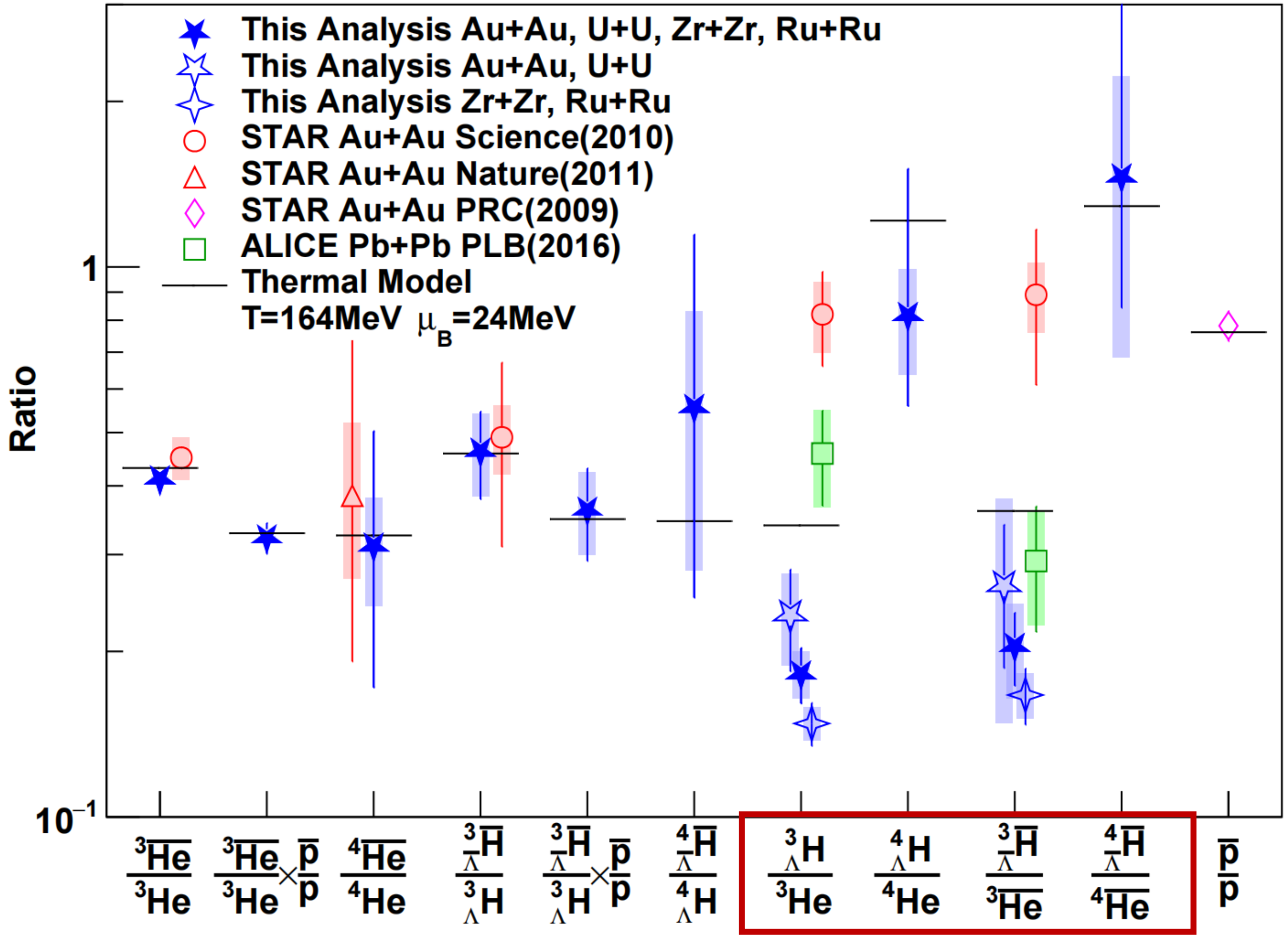
$$^{4}\overline{\mathrm{He}}/^{4}\mathrm{He} \sim {}^{3}\overline{\mathrm{He}}/^{3}\mathrm{He} \times \bar{\mathrm{p}}/\mathrm{p}$$

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

- Consistent with expectation of coalescence picture
- Consistent with thermal model predictions

Yield Ratios



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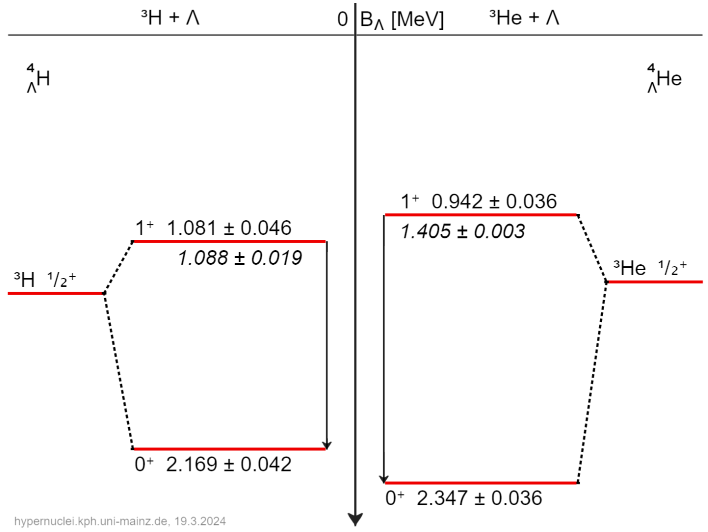
Phys. Lett. B 754 (2016) 360
Phys. Lett. B 697.3 (2011)

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

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

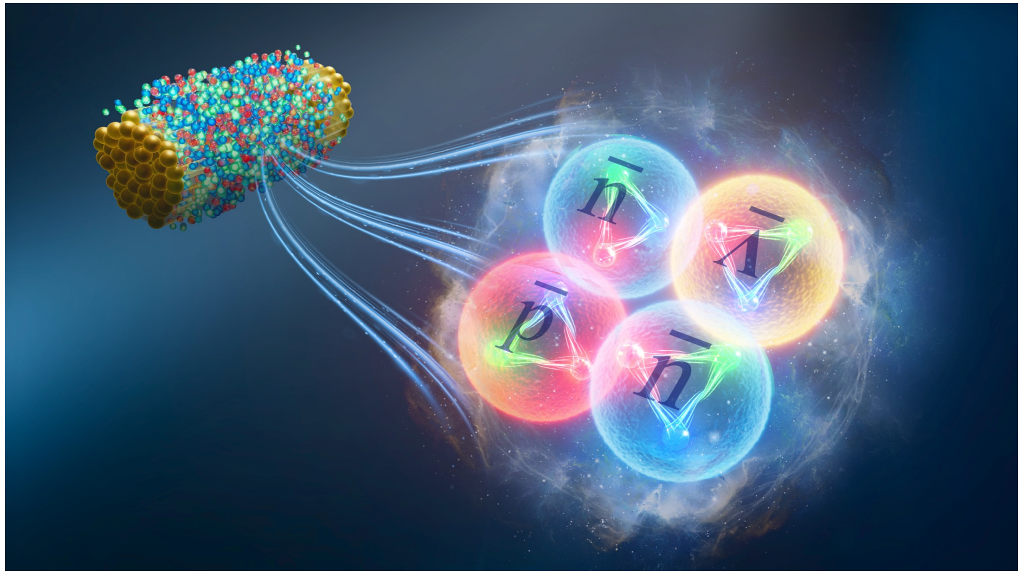
- Factor 4 due to spin-1 excited states of $^{4}_{\Lambda}H$ & $^{4}_{\Lambda}\overline{H}$

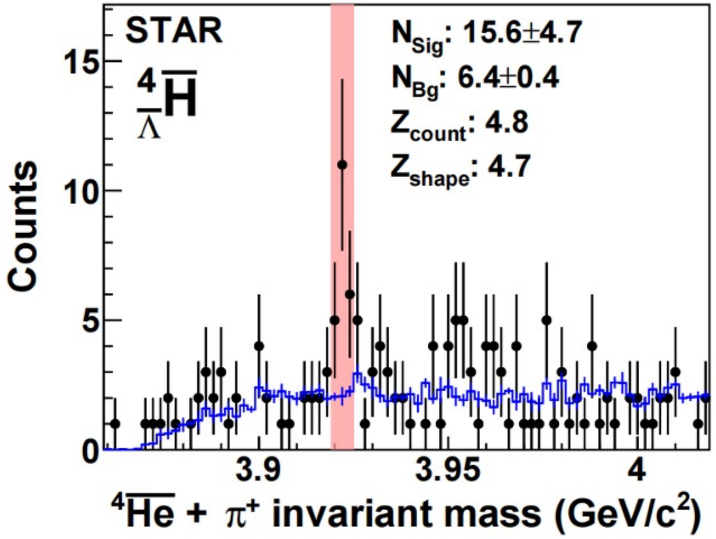


- Consistent with expectation of coalescence picture
- Consistent with thermal model predictions

Summary

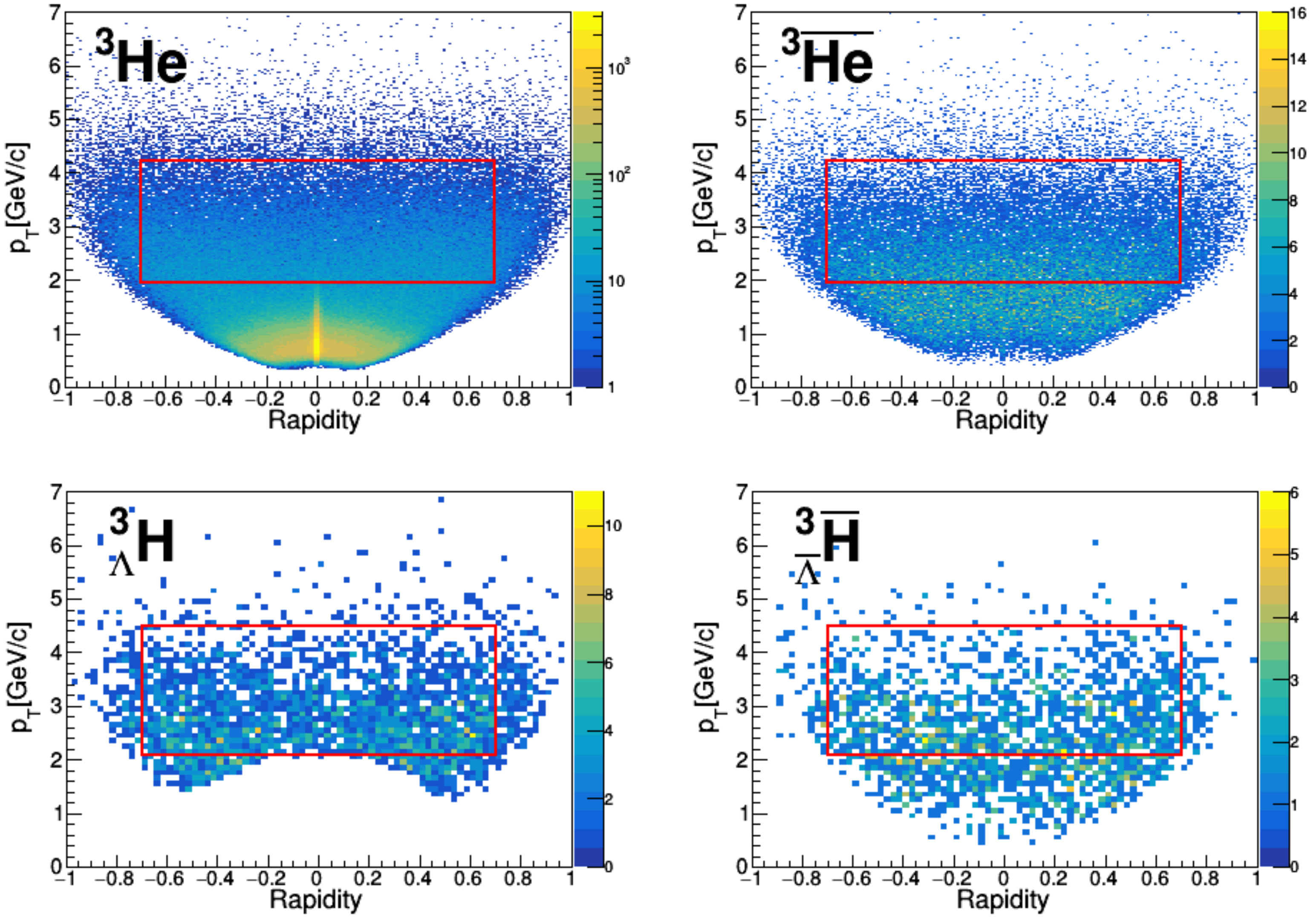
- 15.6 $^{4}_{\bar{\Lambda}}\overline{H}$ signal candidates observed, with a significance of 4.7 σ
- Lifetimes of (anti)hypernuclei compared
  - $\tau_{^{3}_{\Lambda}H} \approx \tau_{^{3}_{\bar{\Lambda}}\overline{H}}$, $\tau_{^{4}_{\Lambda}H} \approx \tau_{^{4}_{\bar{\Lambda}}\overline{H}}$
  - Confirming CPT symmetry
- Various (anti)particle production yield ratios presented
  - $^{4}\overline{\mathrm{He}}/^{4}\mathrm{He} \sim {}^{3}\overline{\mathrm{He}}/^{3}\mathrm{He} \times \bar{\mathrm{p}}/\mathrm{p}$
  - $^{4}_{\bar{\Lambda}}\overline{\mathrm{H}}/^{4}_{\Lambda}\mathrm{H} \sim {}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}/^{3}_{\Lambda}\mathrm{H} \times \bar{\mathrm{p}}/\mathrm{p}$
  - $^{4}_{\Lambda}\mathrm{H}/^{4}\mathrm{He} \sim 4 \times {}^{3}_{\Lambda}\mathrm{H}/^{3}\mathrm{He}$
  - $^{4}_{\bar{\Lambda}}\overline{\mathrm{H}}/^{4}\overline{\mathrm{He}} \sim 4 \times {}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}/^{3}\overline{\mathrm{He}}$
  - Consistent with coalescence picture and thermal model





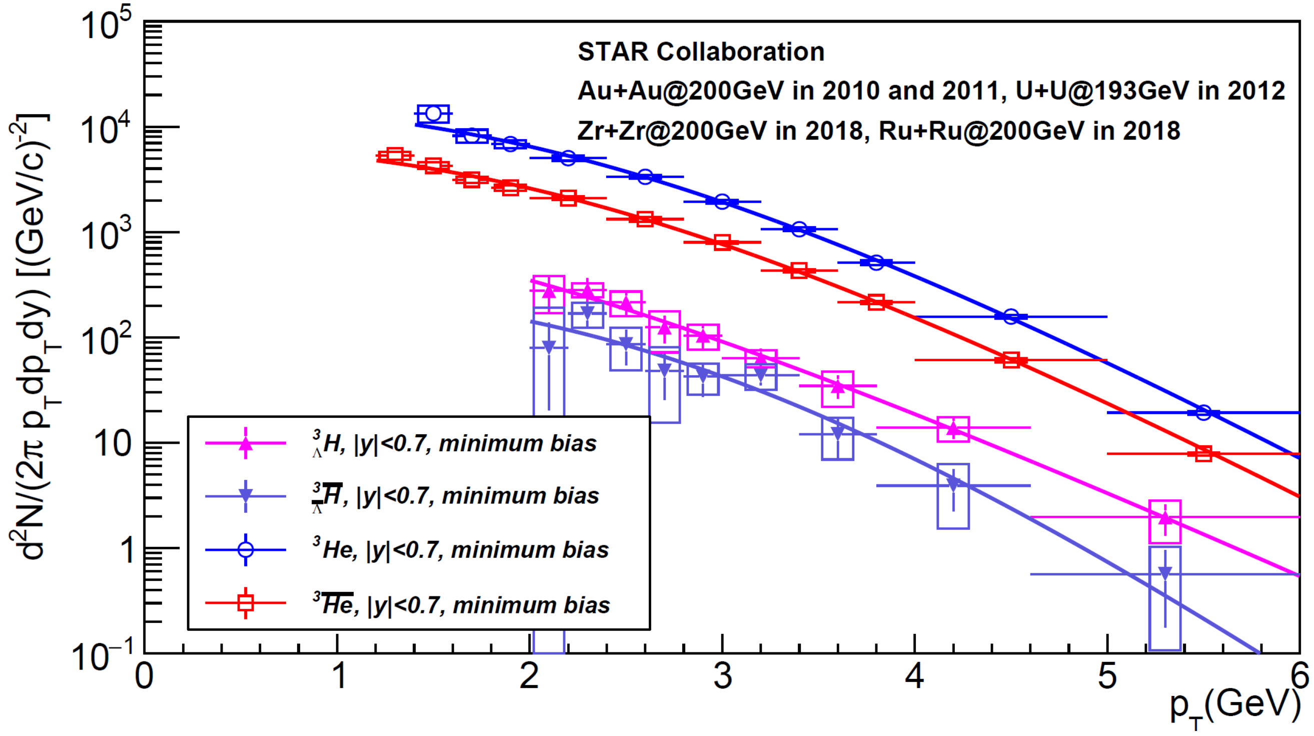
Thanks ☺

Back Up: Yield Ratios Measurement - Phase Space



- Yield measurement in phase space region : $0.7<p_T/M<1.5$, |rapidity|<0.7

Back Up: Yield Ratios Measurement - A = 3 Particles



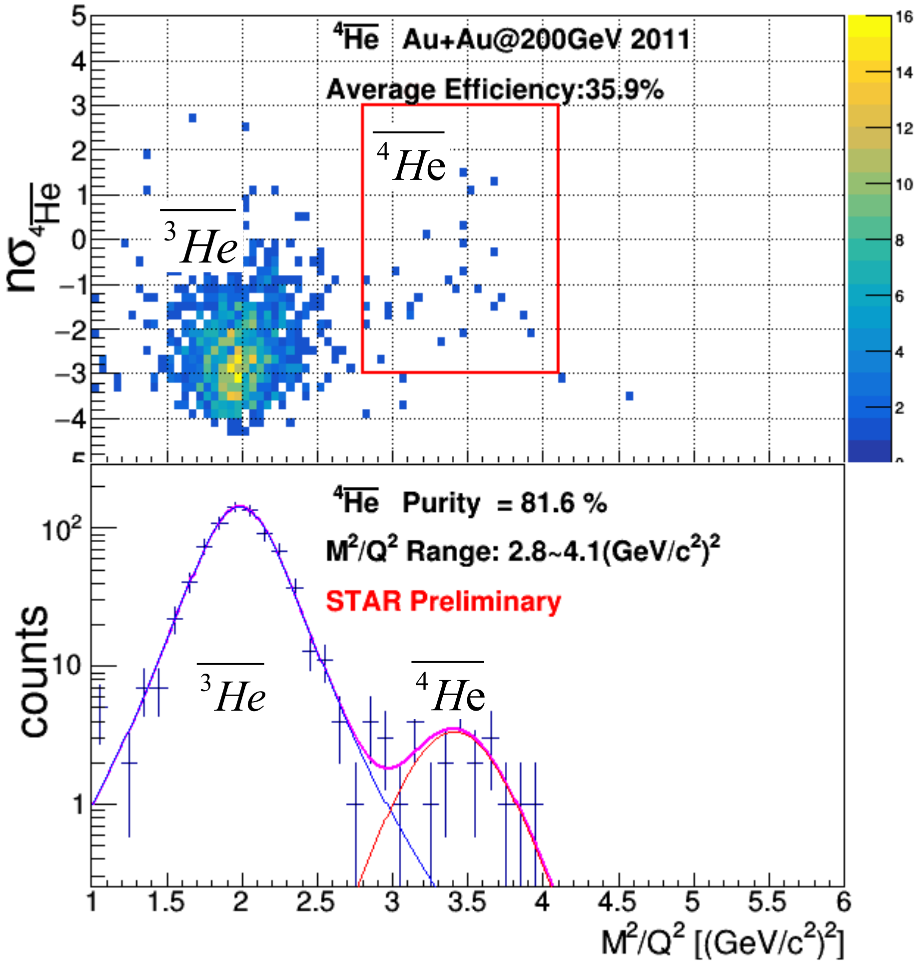
- ^{3}He, $^{3}\overline{He}$, $^{3}_{\Lambda}H$ and $^{3}_{\bar{\Lambda}}\overline{H}$: Yields are obtained by integrating over the measured p_T spectrum.

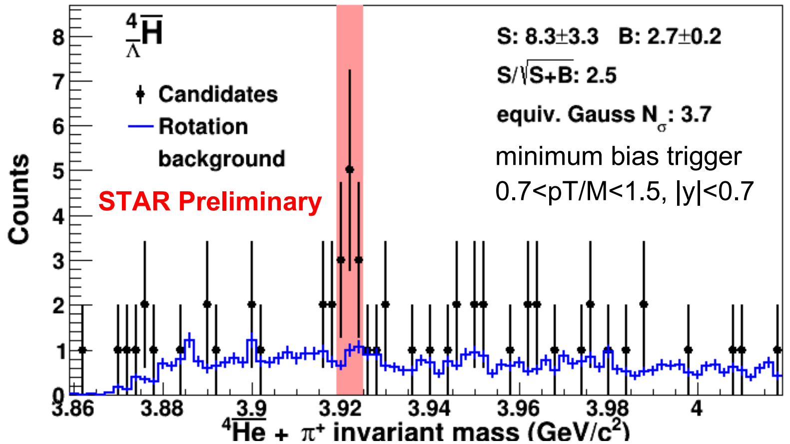
Blast Wave function fit:

$$\frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy} \propto \int_0^R r dr m_0 I_0\left(\frac{p_T \sinh\rho}{T}\right) K_1\left(\frac{m_T \cosh\rho}{T}\right)$$

- *Physical Review C Volume48, Number5, 1993*

Back Up: Yield Ratios Measurement - A = 4 Particles





- For A = 4 particles, the yields are too low to obtain a p_T spectrum.
- An average efficiency is obtained for the whole measured p_T range, assuming Blast Wave functional shape with the same T and β as those of A = 3 particles.