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

STAR

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

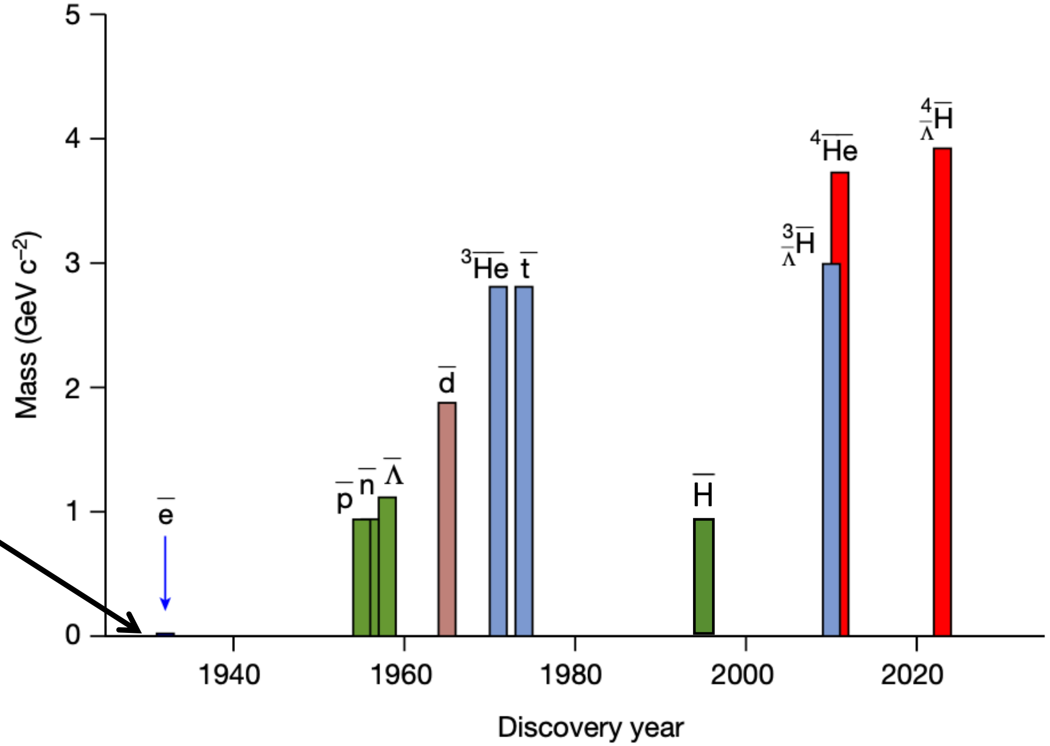
Qiu, Hao (仇浩)

Institute of Modern Physics, CAS

for the STAR Collaboration

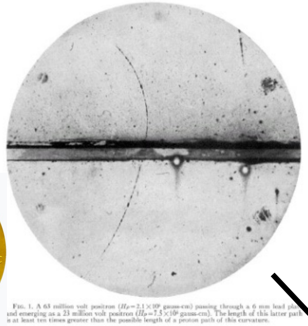
Introduction: History of Anti-matter Discovery

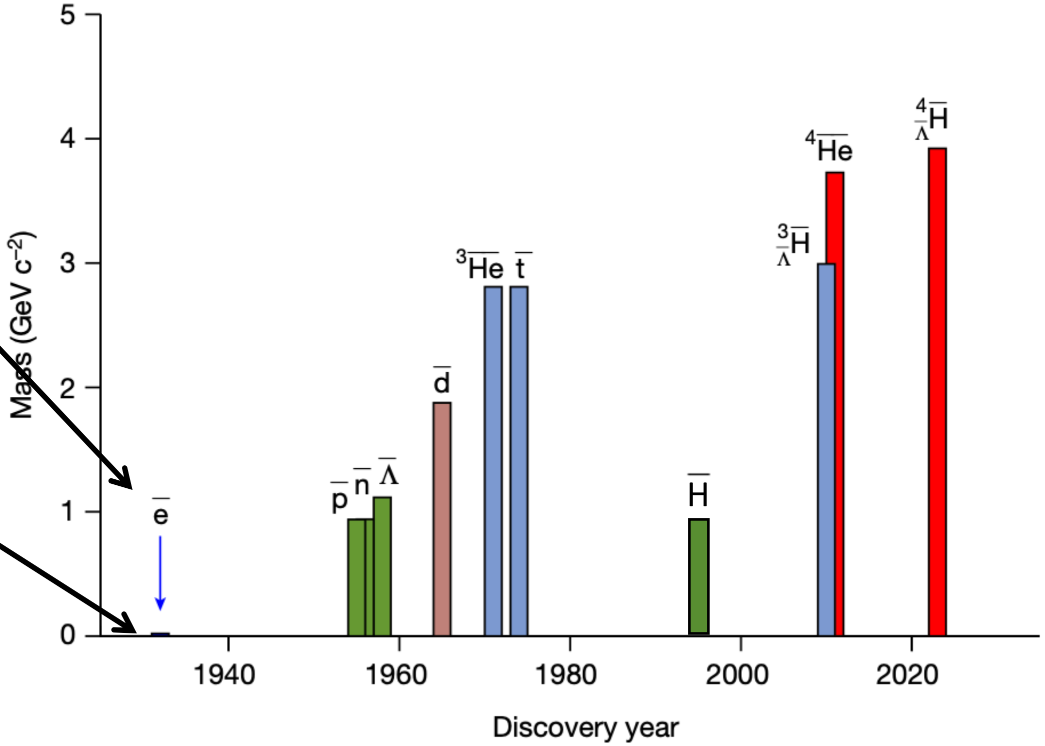
Dirac, P.A.M.,
The Quantum Theory of the Electron.
Proc. Roy. Soc. Lond. A 117, 610 (1928).



Introduction: History of Anti-matter Discovery

Carl D. Anderson





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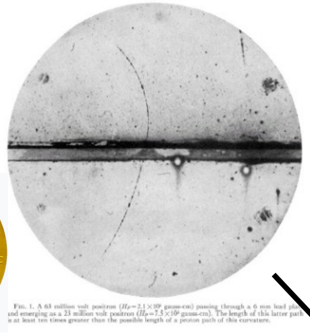

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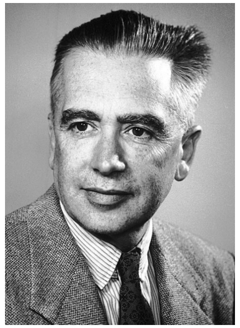
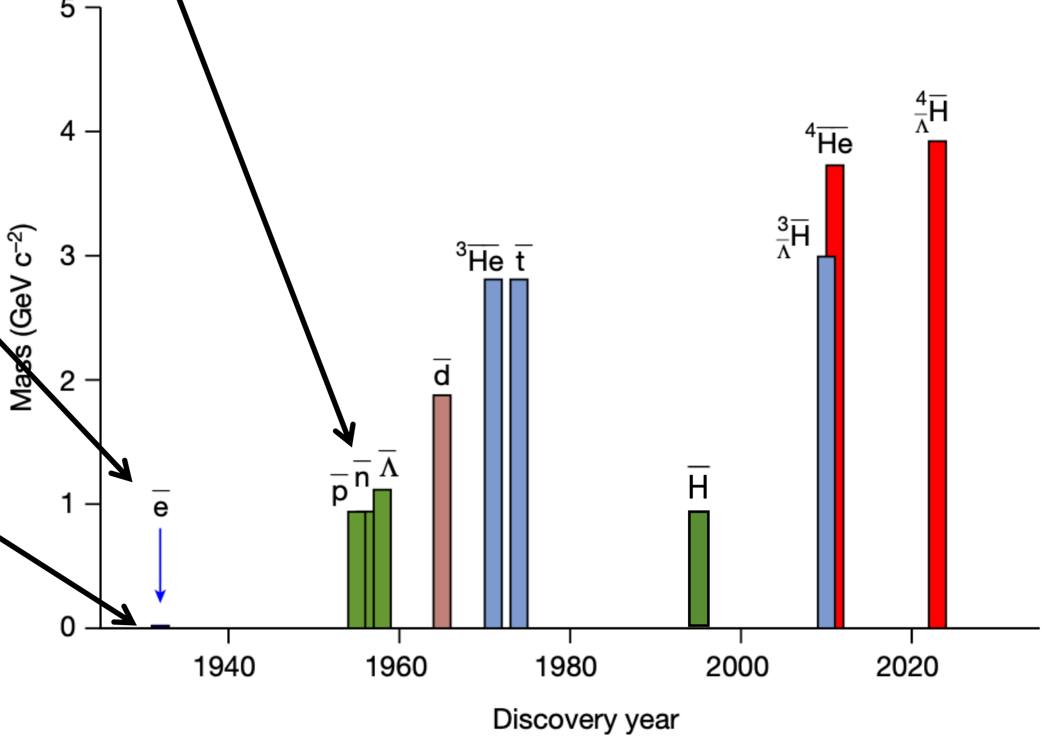


Emilio Segrè

Owen Chamberlain



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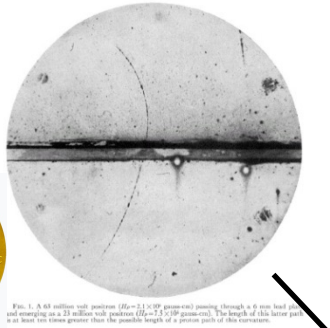

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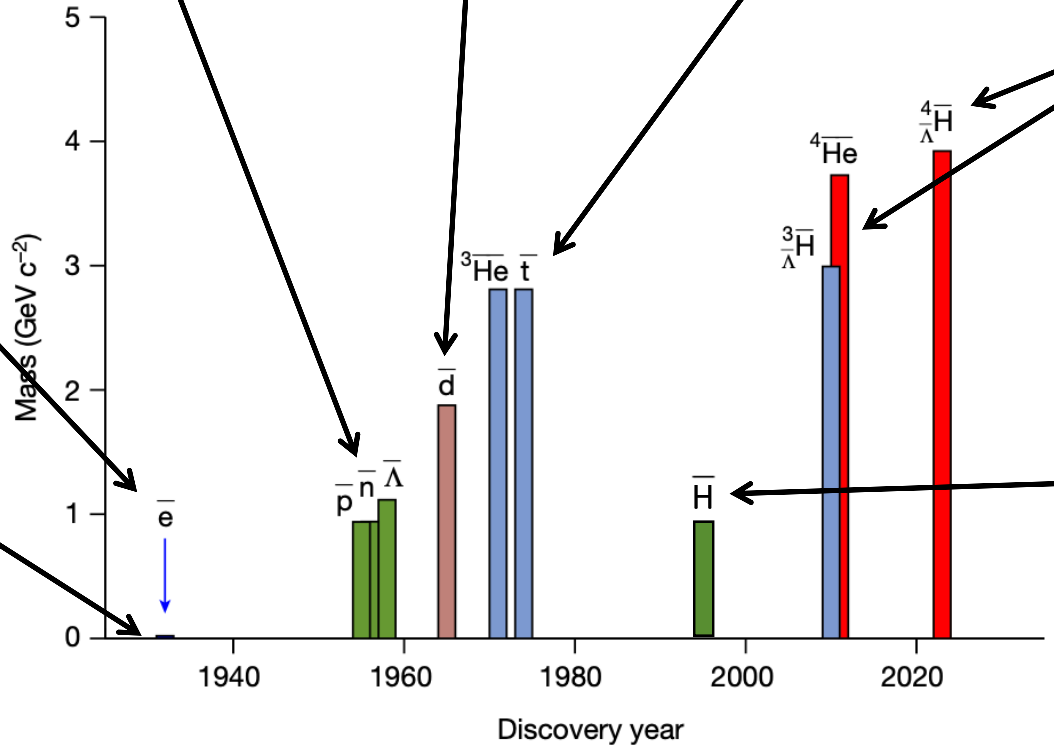
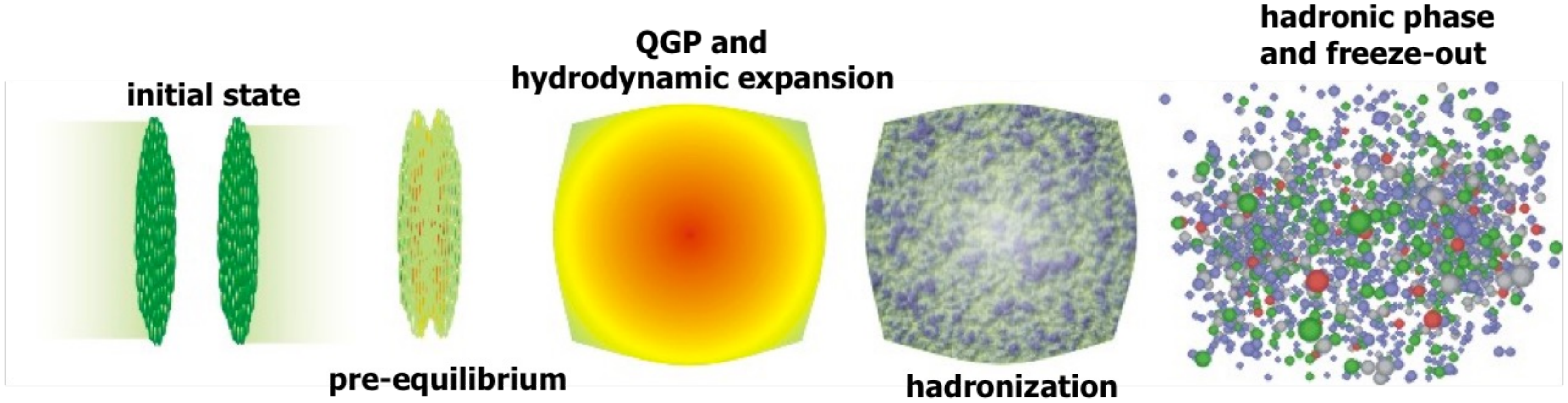
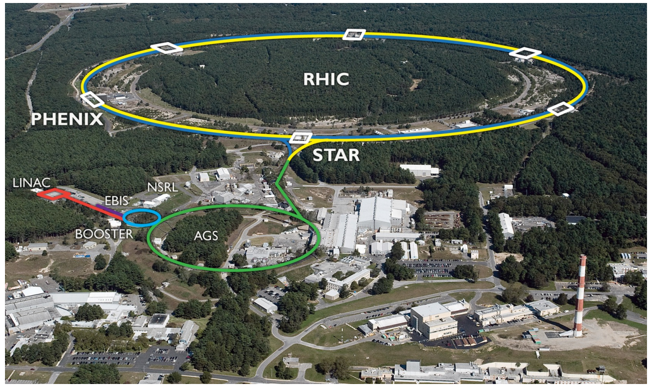


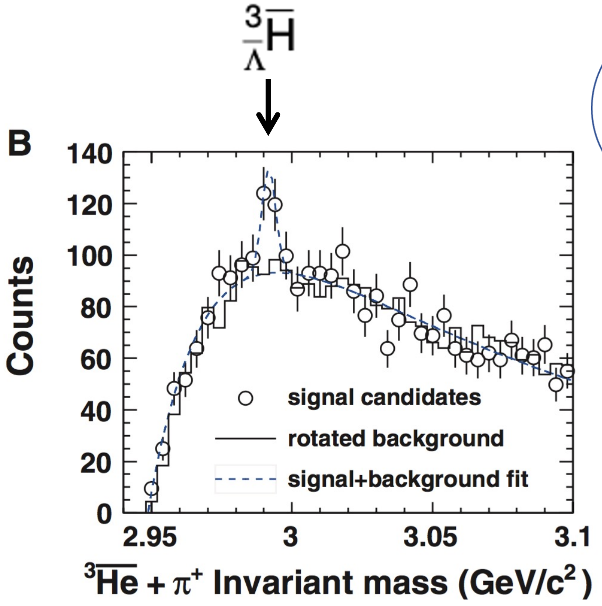
Qiu, Hao – IMP, CAS

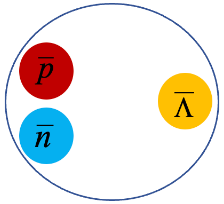
Introduction: History of Anti-matter Discovery



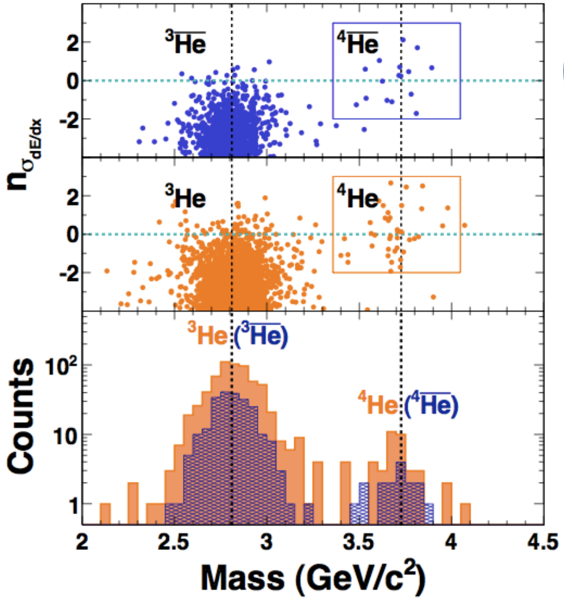


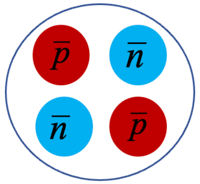
RHIC



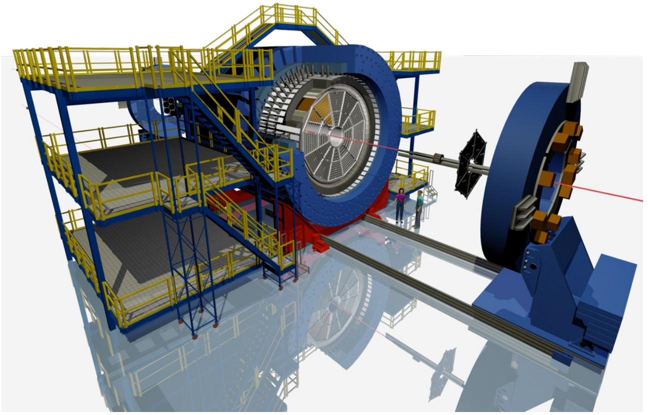


Science 328, 58 (2010)





Nature 473, 353 (2011)



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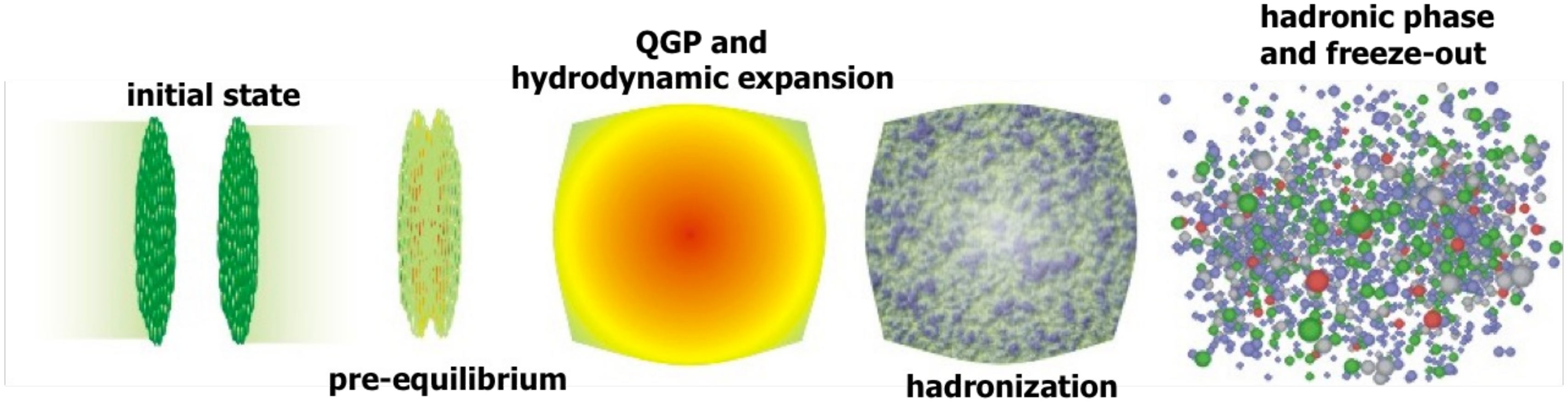
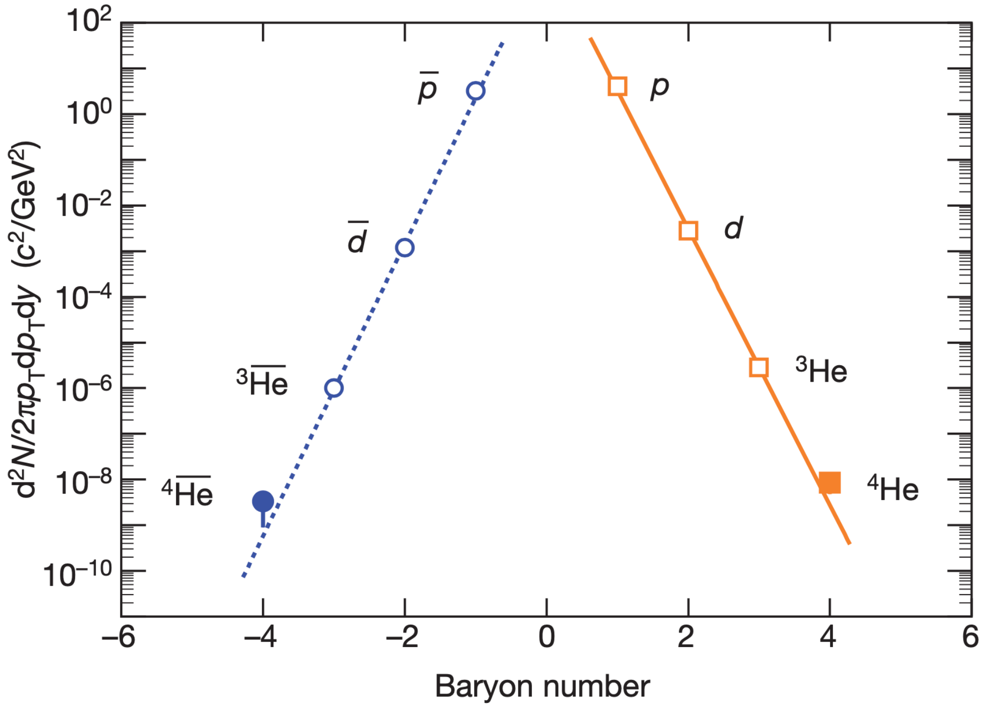
Introduction: Anti(hyper)nucleus Production

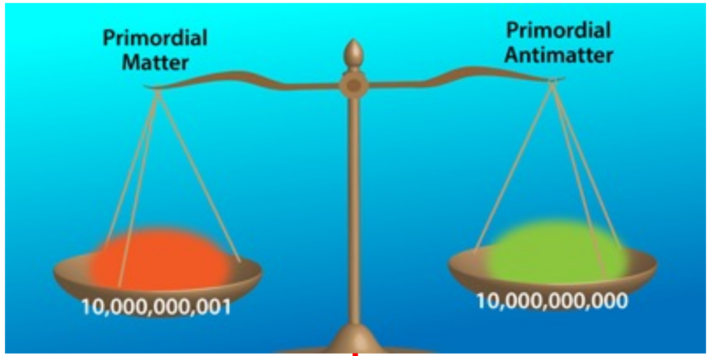


- Anti(hyper)nuclei binding energy ~ several MeV / nucleon
- QGP temperature ~ several hundred MeV
- ⇒ They are produced by coalescence of antibaryons in the last stage of the collision

Nature 473, 353 (2011)

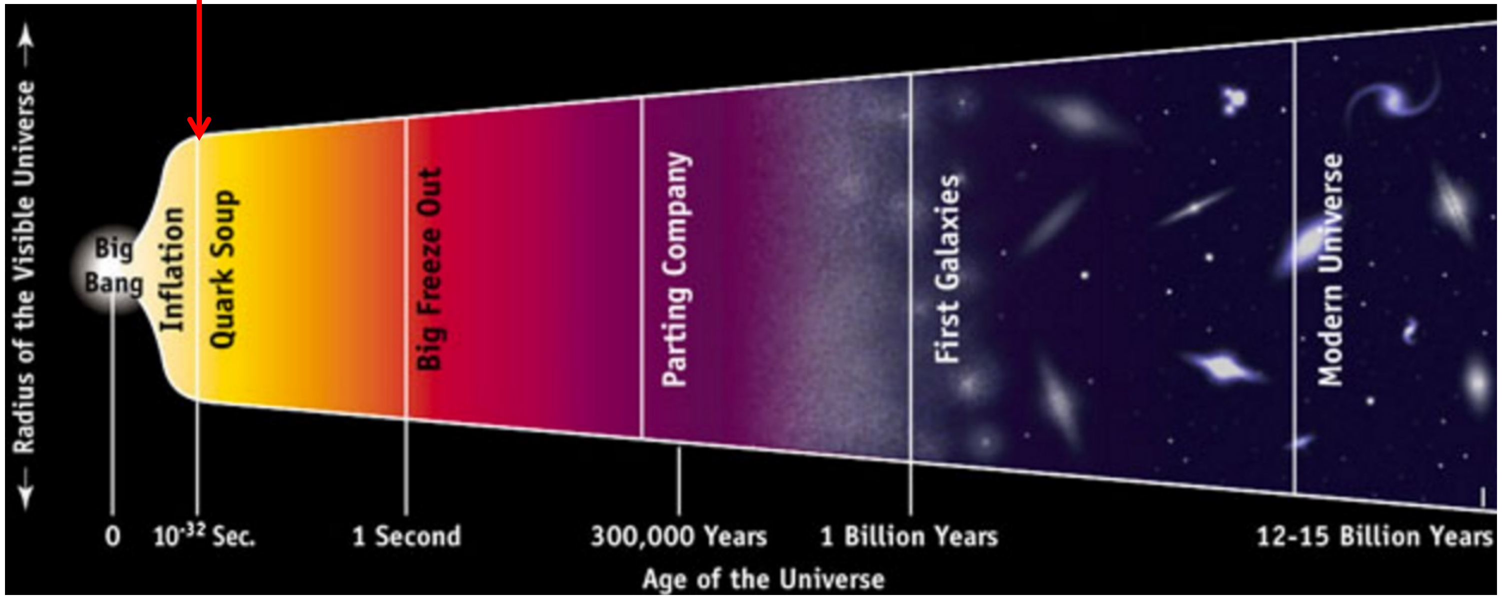


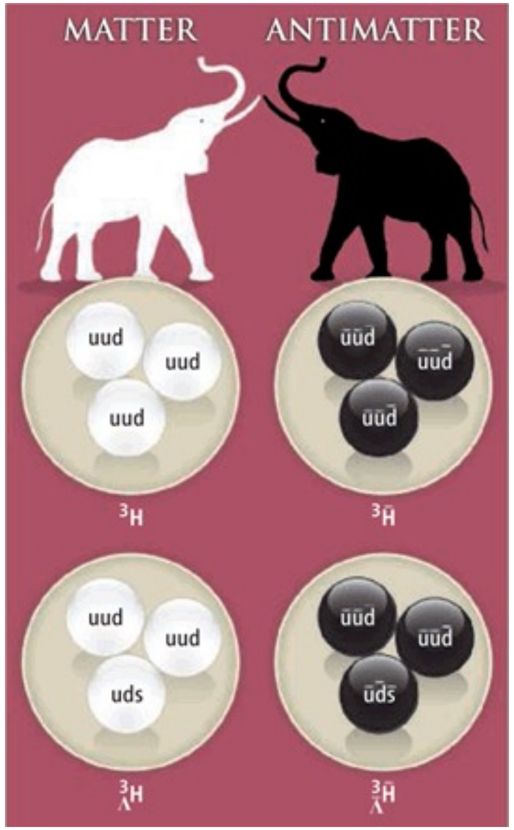
Introduction: Matter-antimatter Asymmetry in the Universe



?

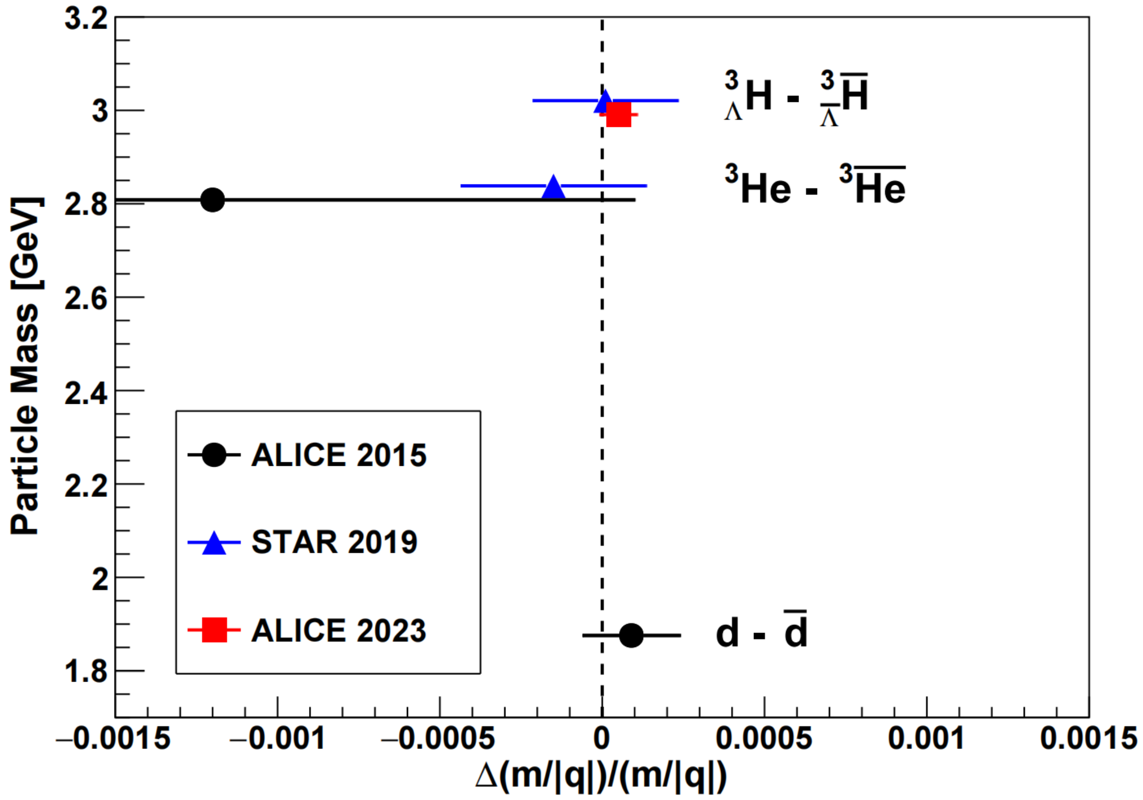
- Matter-antimatter asymmetry in early universe is the precondition for the existence of the matter world today
- The source of this asymmetry is still not clear





CPT theorem ⇒ Symmetry of matter-antimatter properties

Introduction: CPT symmetry test with heavy-ion collisions



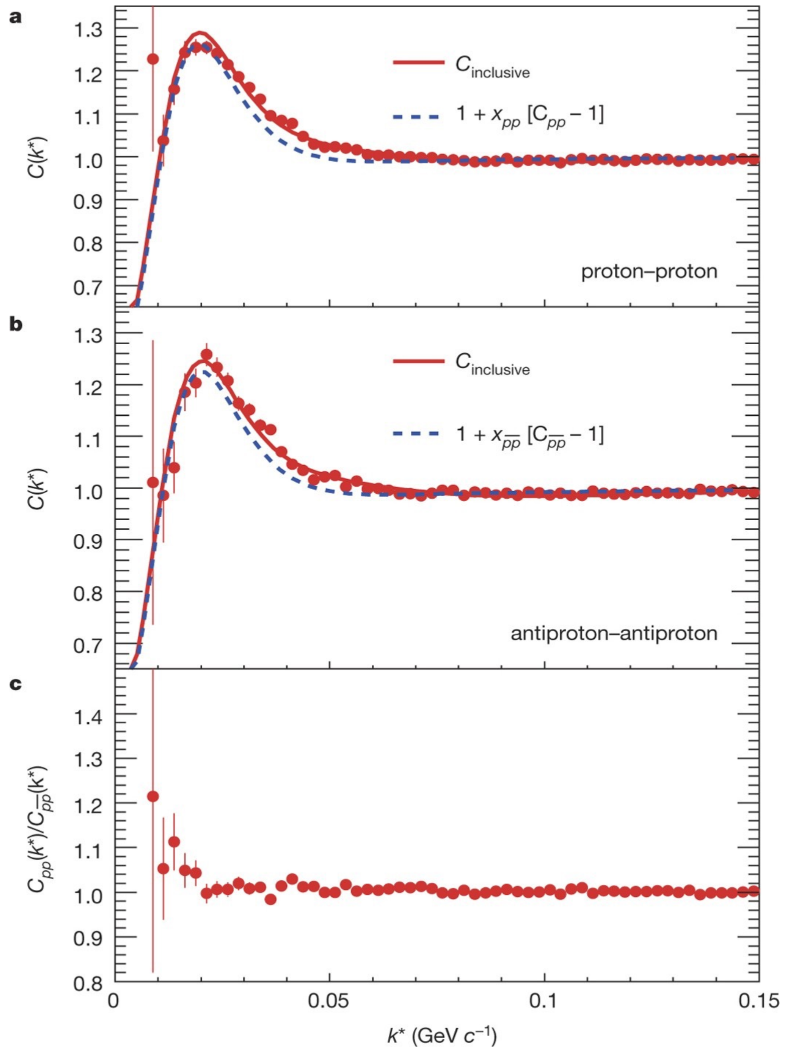
$$\frac{\tau_{^3_\Lambda \mathrm{H}} - \tau_{^3_{\bar{\Lambda}} \bar{\mathrm{H}}}}{\tau_{^3_\Lambda \mathrm{H}}} = [3 \pm 7(\mathrm{stat}) \pm 4(\mathrm{syst})] \times 10^{-2}$$

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 & $^{3}\overline{\mathrm{He}}$, $^{3}_{\Lambda}\mathrm{H}$ and $^{3}_{\bar{\Lambda}}\bar{\mathrm{H}}$
- No significant lifetime difference between $^{3}_{\Lambda}\mathrm{H}$ and $^{3}_{\bar{\Lambda}}\bar{\mathrm{H}}$

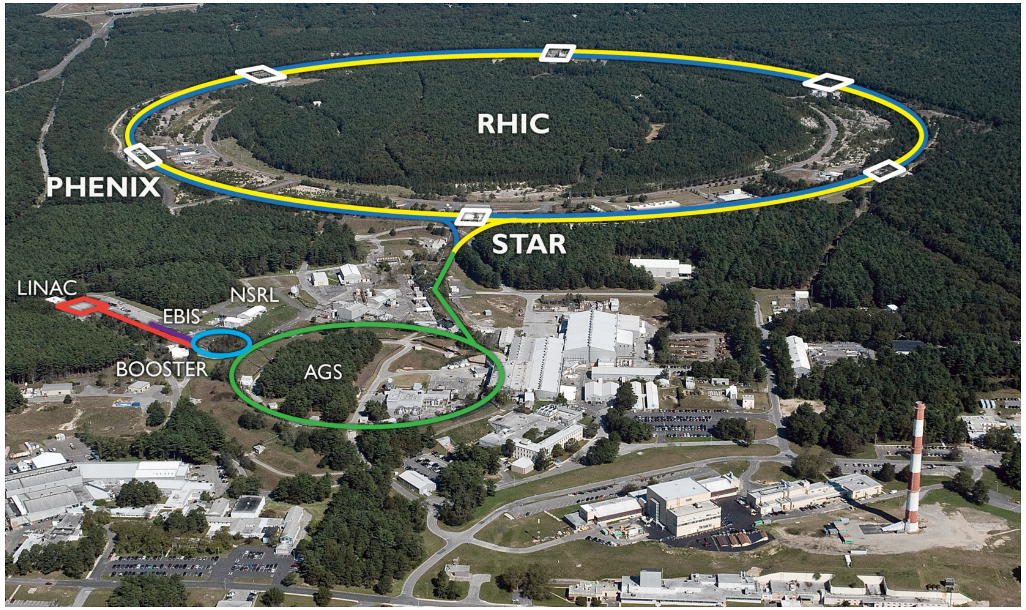
Introduction: CPT symmetry test with heavy-ion collisions

- No difference between p-p and $\overline{p}$-$\overline{p}$ correlation functions



Nature volume 527, pages345–348 (2015)

RHIC-STAR

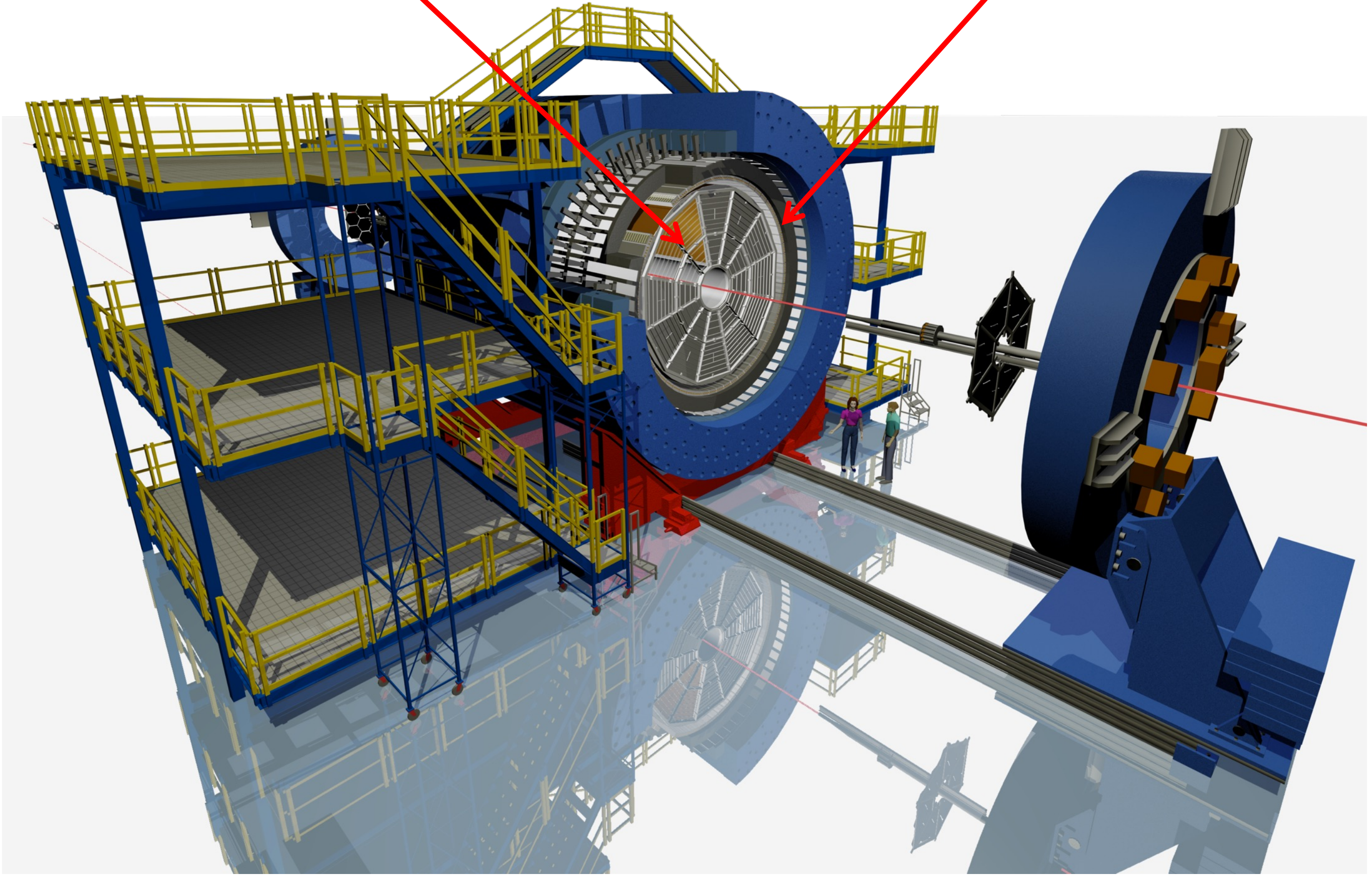


Time Projection Chamber

- 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

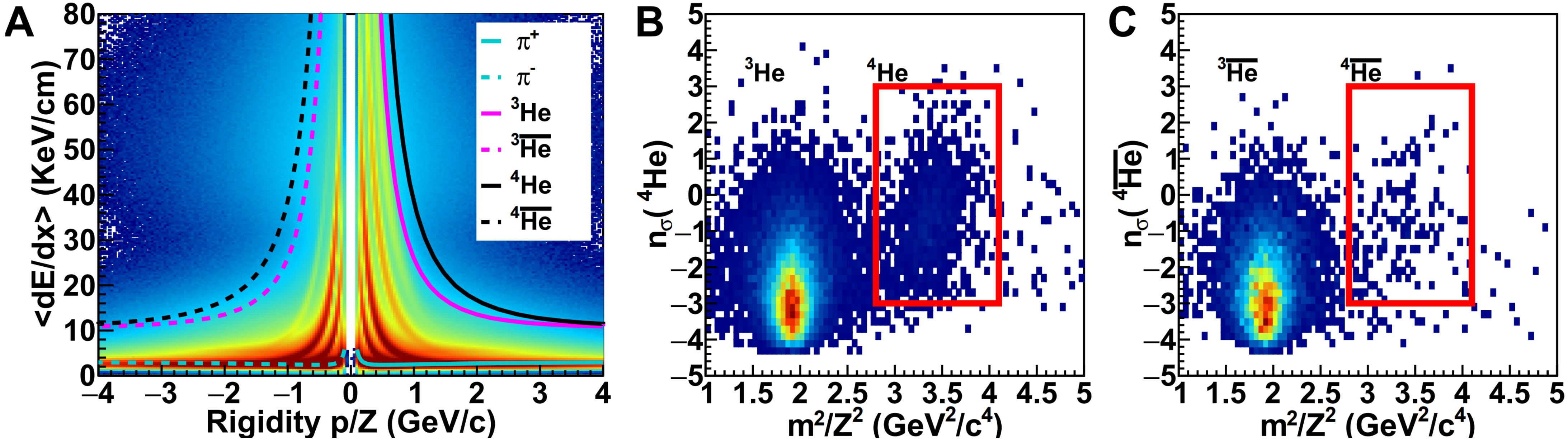
Trigger:

- 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

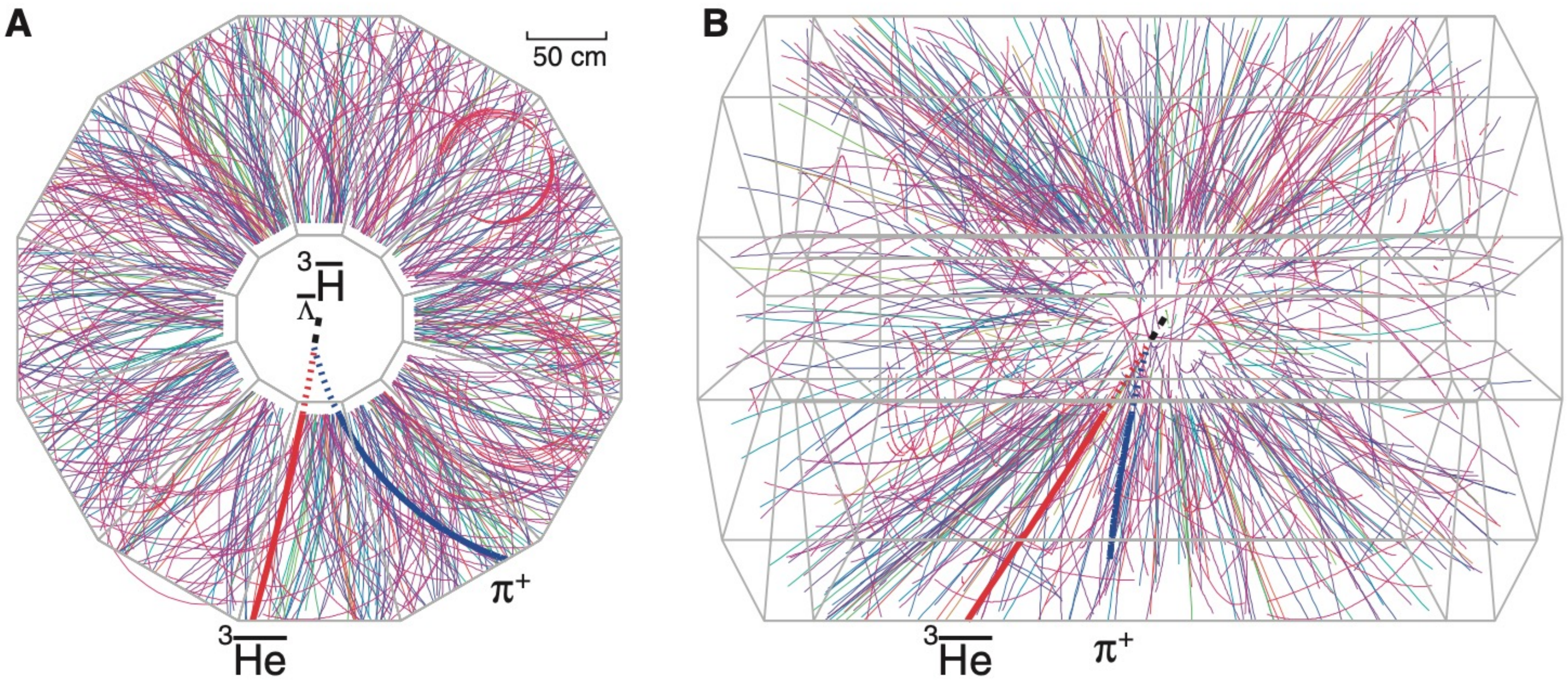
Decay Channels & Daughter Particle Identification

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

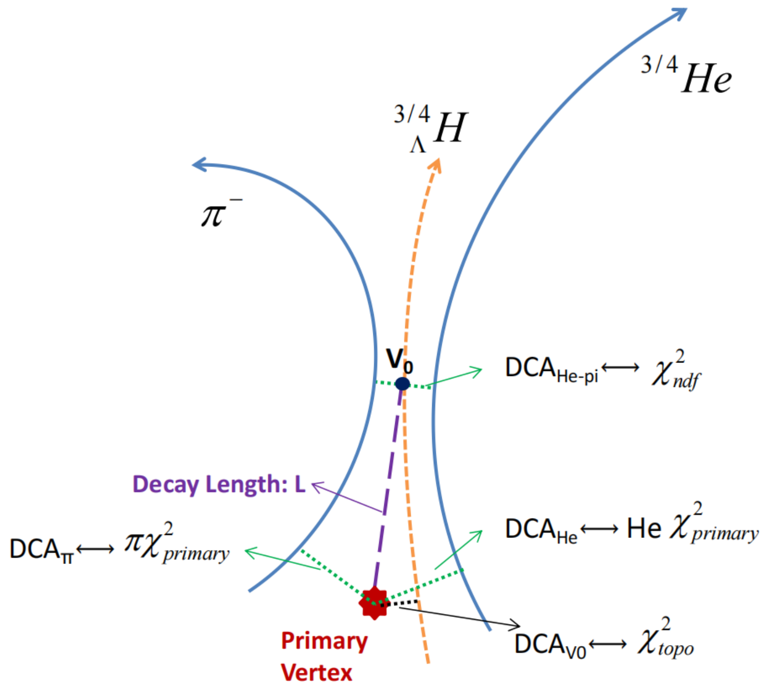


- ^{3}He PID: (Q<0 || p>2.) && $|n\sigma_{^{3}He}|<3$ && (if TOF matched, $1<M^2/Q^2<3$);
- ^{4}He PID: (Q<0 || p>2.) && $|n\sigma_{^{4}He}|<3$ && ($|n\sigma_{^{3}He}|>3.5$ || $2.8<M^2/Q^2<4.1$));
- π PID: $|n\sigma_{\pi}|<3$;

Decay Vertex Reconstruction



Science 328, 58 (2010)

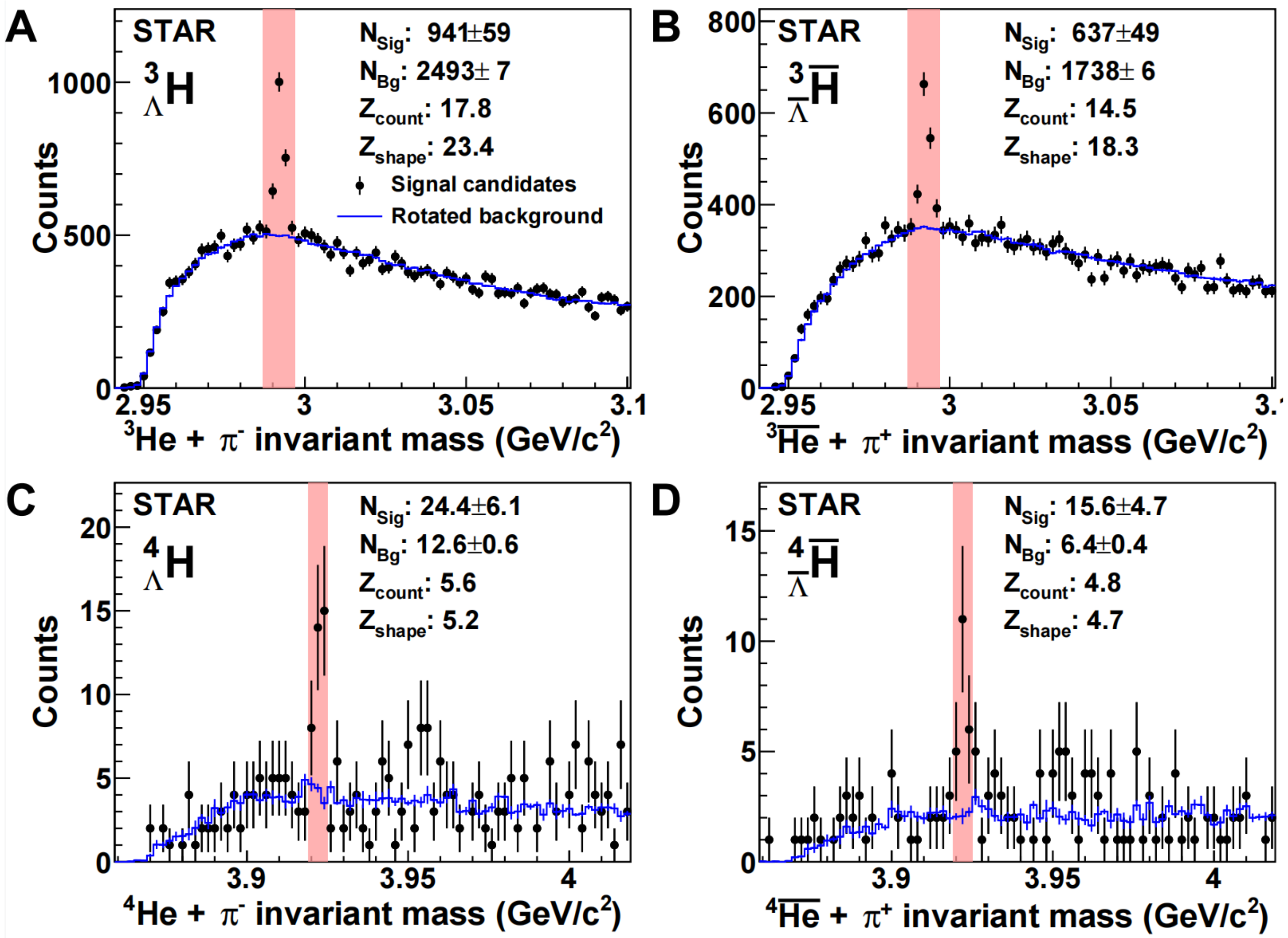


S. Gorbunov and I. Kisel, CBM-SOFT-note-2007-003, 7 May 2007
M. Zyzak, "Online selection of short-lived particles on many-core computer architectures in the CBM experiment at FAIR," Dissertation thesis, Goethe University of Frankfurt, 2016

- 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	$\chi^2_{\text{prim He}}$	$\chi^2_{\text{prim }\pi}$	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 $^{4}_{\bar{\Lambda}}\overline{H}$ signal candidates
- Significances Z_{count} = 4.8, Z_{shape} = 4.7

The heaviest antihypernucleus observed

Lifetime Measurements & CPT Symmetry Test

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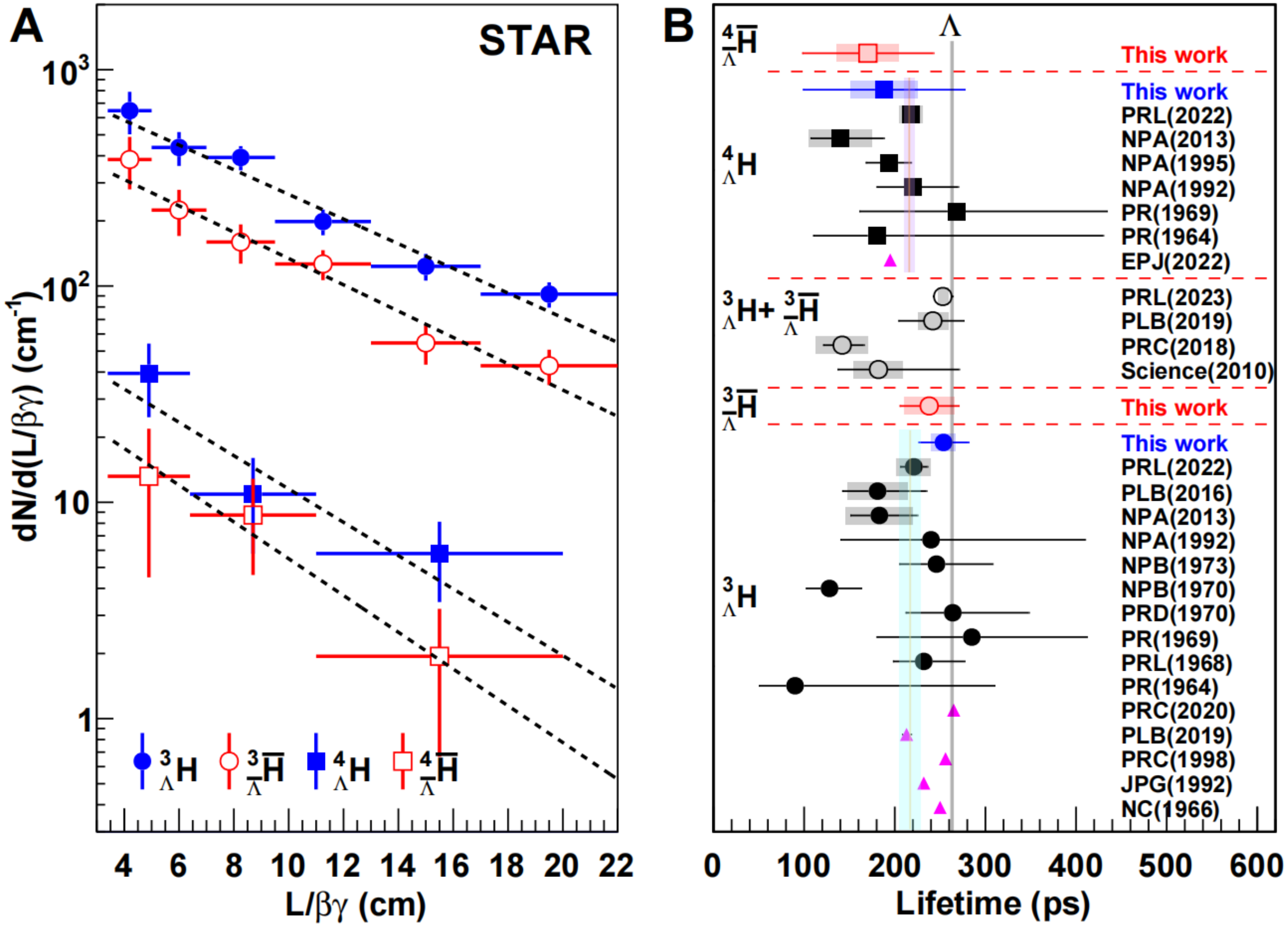


Nature 2024, DOI: 10.1038/s41586-024-07823-0

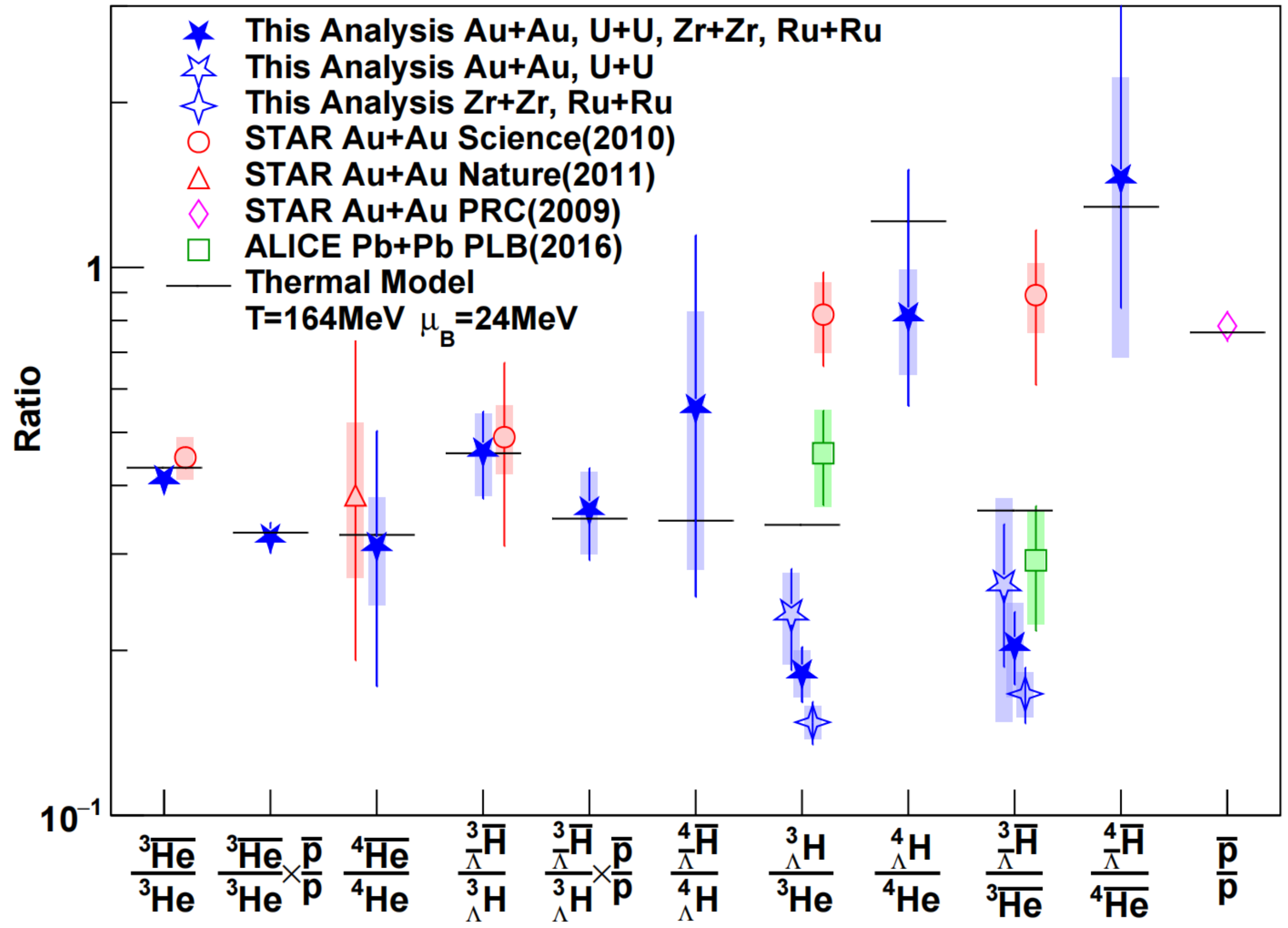
- Efficiency corrected
- Fit with exponential function: $N(t) = N_0 e^{-l/\beta\gamma c\tau}$
- Our results consistent with previous average

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

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

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

Yield Ratios



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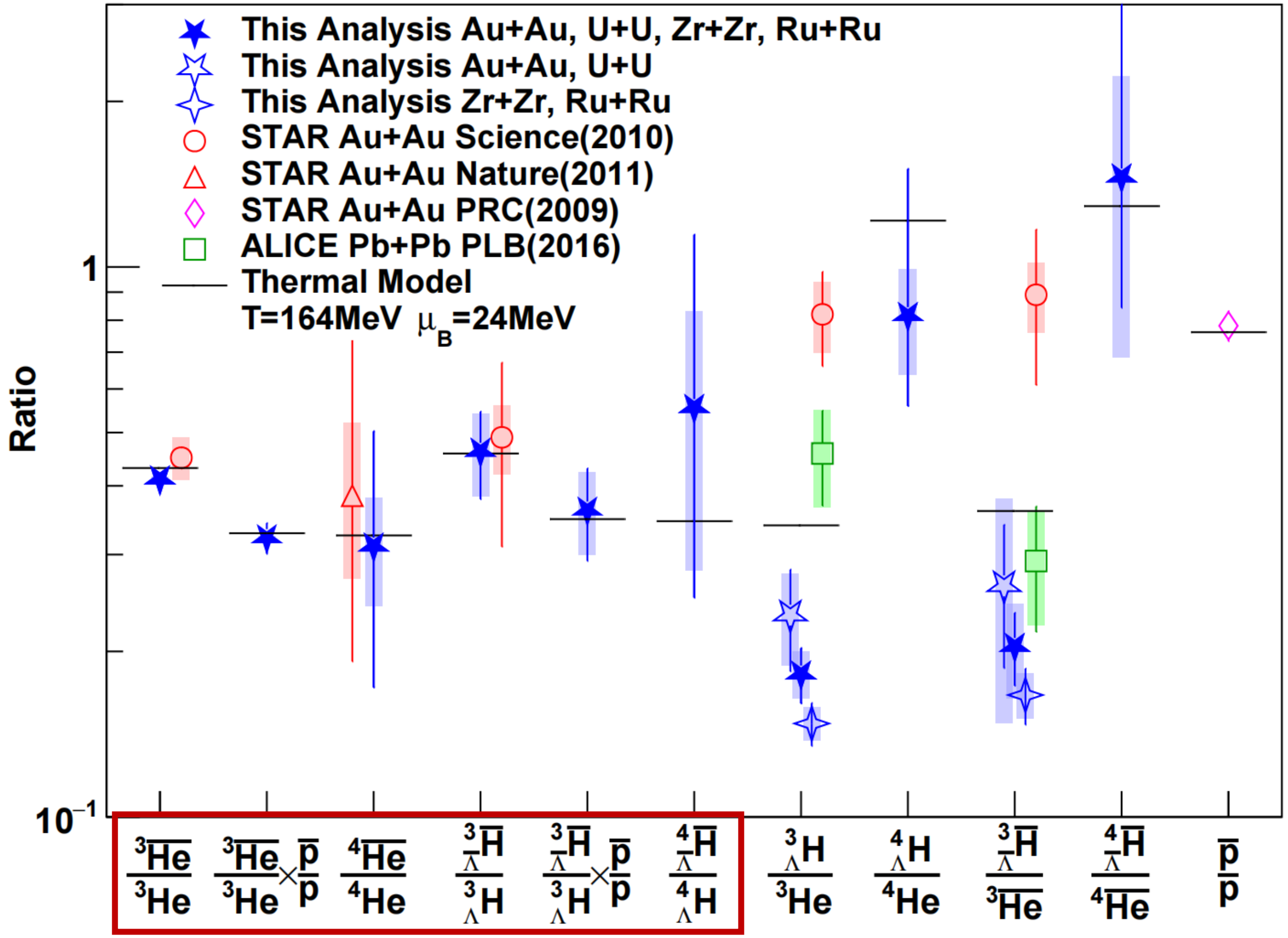
Science 328, 58 (2010)
Nature 473, 353–356 (2011)
Phys. Rev. Lett. 97, 152301
Phys. Lett. B 754 (2016) 360
Phys. Lett. B 697.3 (2011)

- Branch fraction assumed:
  - 25% for $^3_\Lambda H \to {}^3He + \pi^-$
  - 50% for $^4_\Lambda H \to {}^4He + \pi^-$
- Phase space: $0.7<p_T/M<1.5$, $|y|<0.7$

- $\frac{^3_\Lambda H}{^3He}$ & $\frac{^3_{\bar{\Lambda}}\overline{H}}{^3\overline{He}}$ 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 $\frac{^3_\Lambda H}{^3He}$ & $\frac{^3_{\bar{\Lambda}}\overline{H}}{^3\overline{He}}$ ratios are lower than Science 2010 results by 2.8 & 1.9 σ

Yield Ratios



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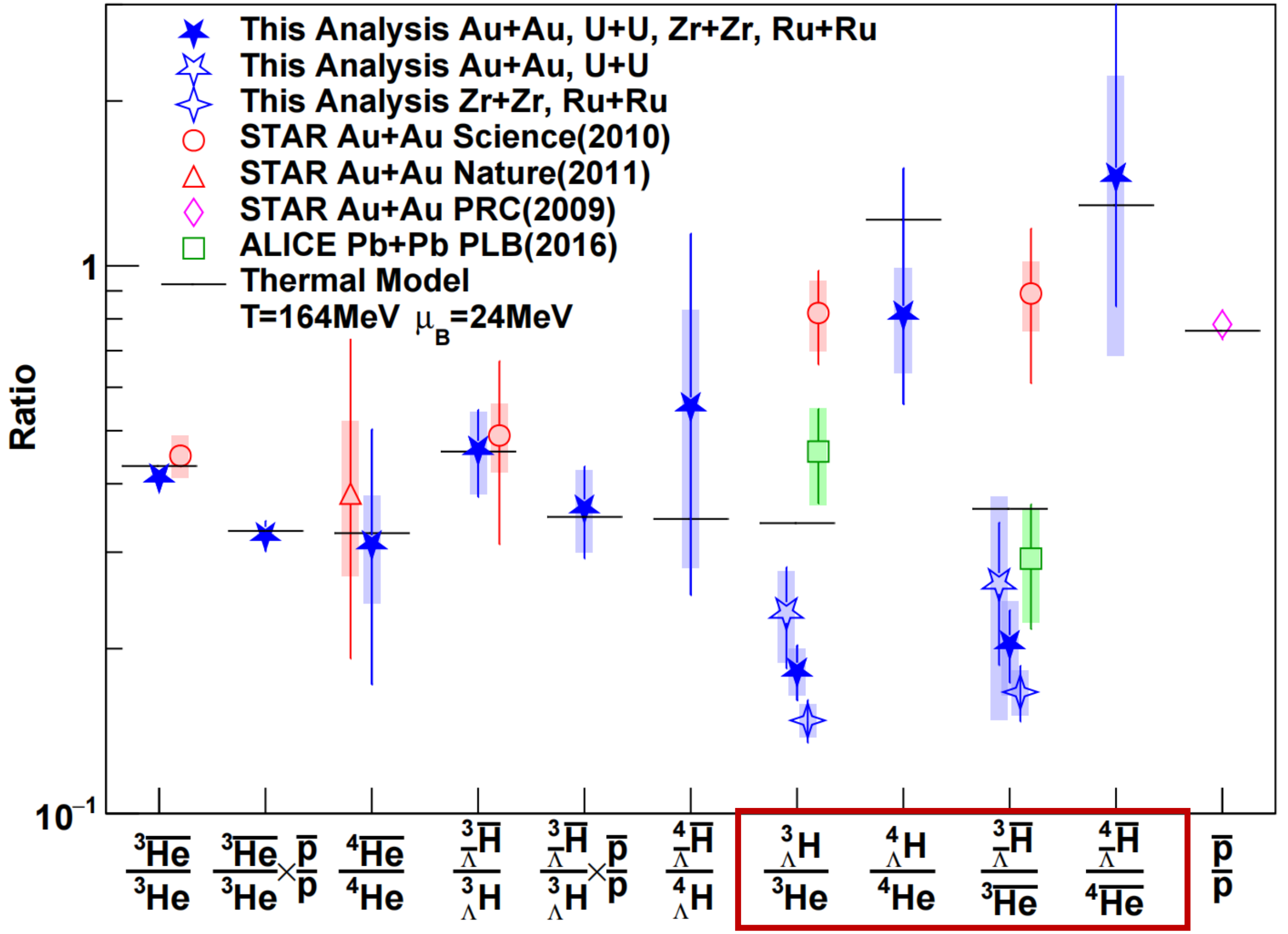
$$^4\overline{\mathrm{He}}/^4\mathrm{He} \sim {}^3\overline{\mathrm{He}}/^3\mathrm{He} \times \bar{p}/p$$

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

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

Yield Ratios



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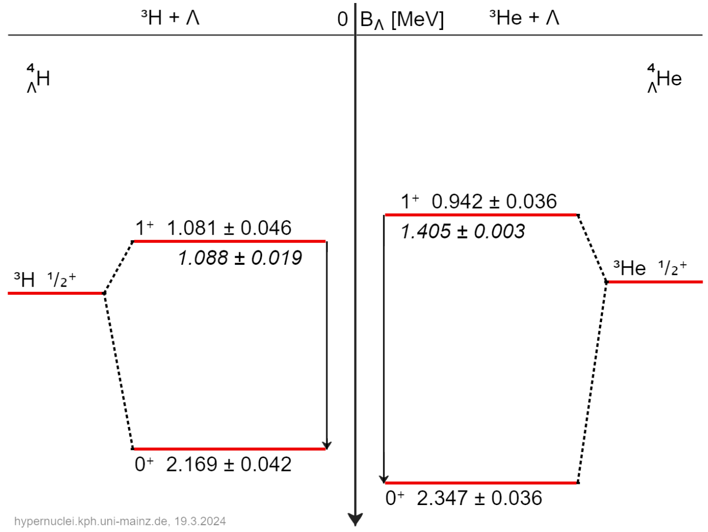
$$^4_\Lambda\mathrm{H}/^4\mathrm{He} \sim 4 \times {}^3_\Lambda\mathrm{H}/^3\mathrm{He}$$

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

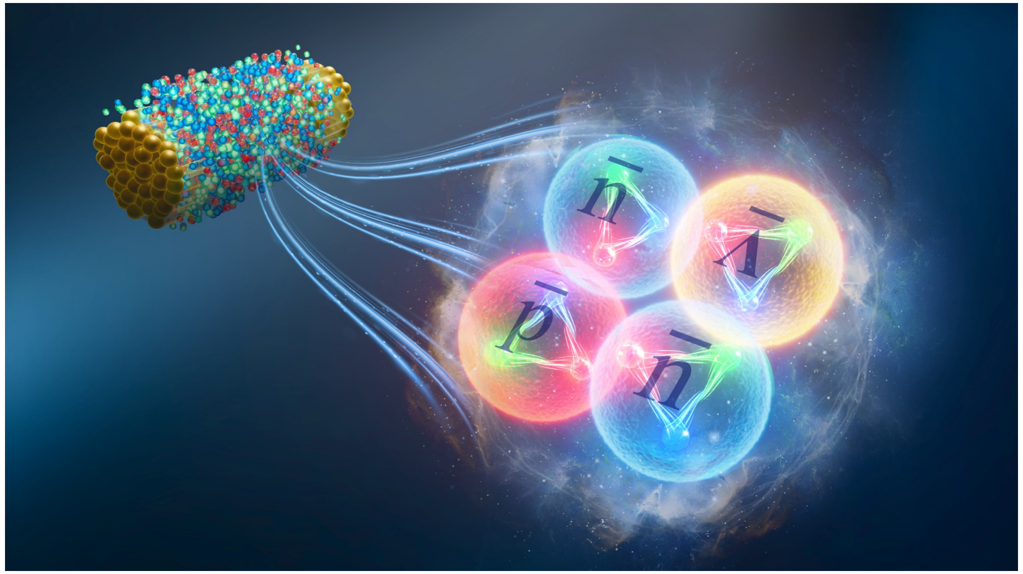
- Factor 4 due to spin-1 excited states of $^4_\Lambda H$ & $^4_\Lambda \overline{H}$

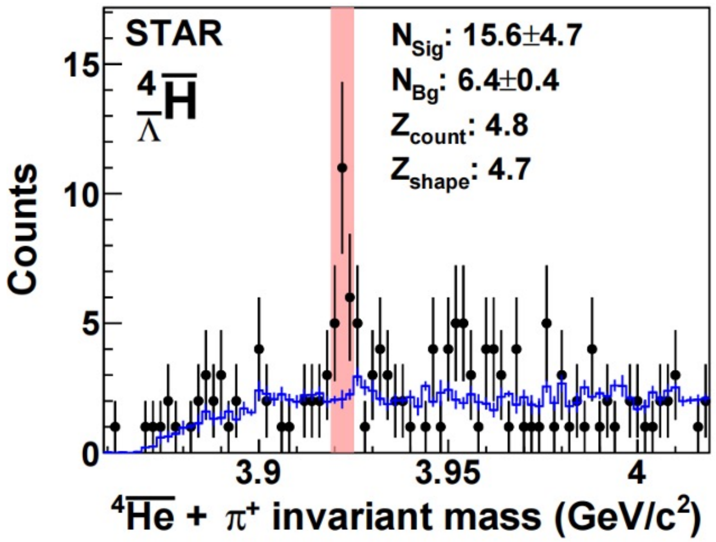


- Consistent with expectation of coalescence picture
- Consistent with thermal model predictions

Summary

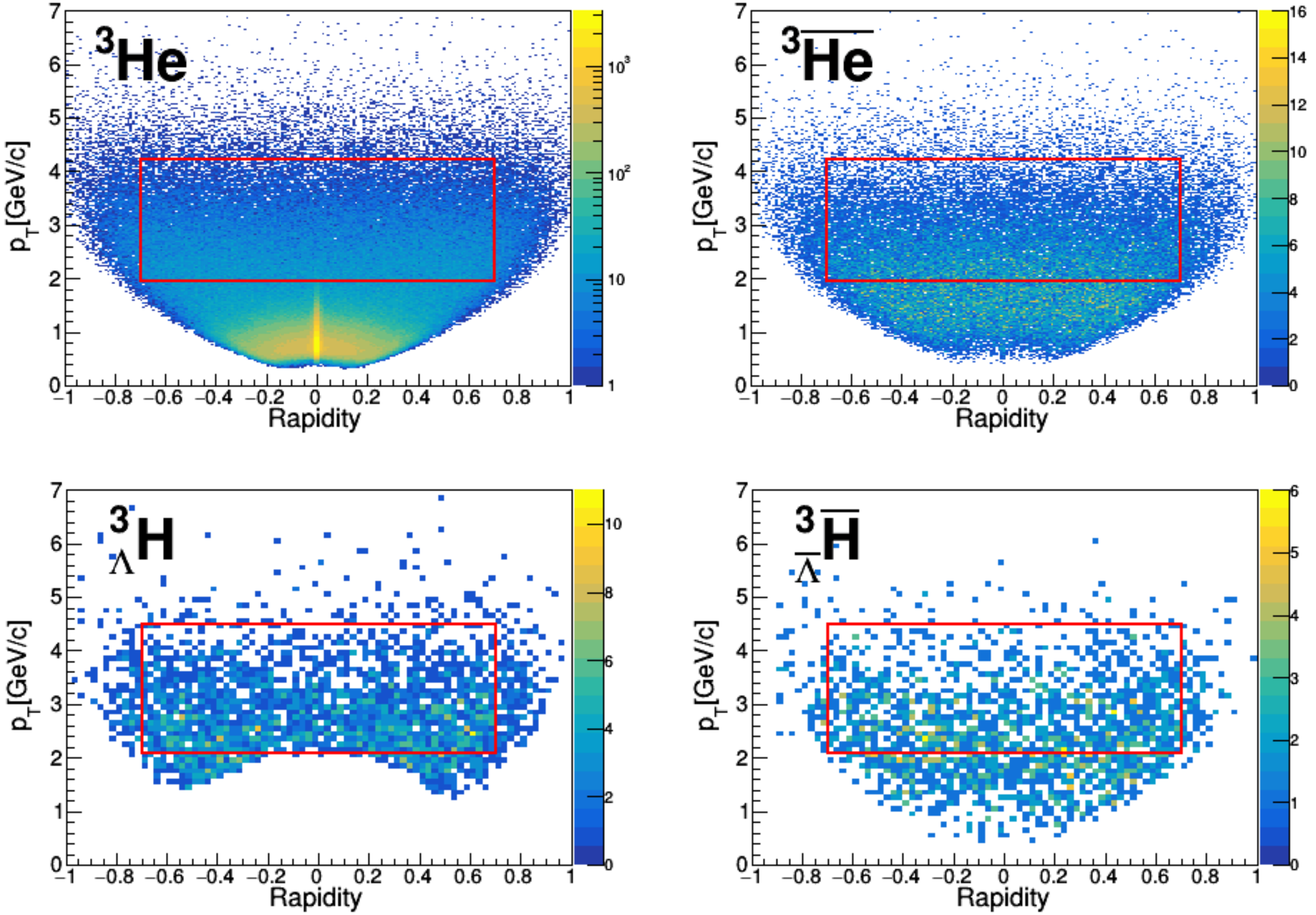
- 15.6 $^{4}_{\bar{\Lambda}}\overline{H}$ signal candidates observed, with a significance of 4.7 σ
- Lifetimes of (anti)hypernuclei compared
  - $\tau_{^{3}_{\Lambda}H} \approx \tau_{^{3}_{\bar{\Lambda}}\overline{H}}$, $\tau_{^{4}_{\Lambda}H} \approx \tau_{^{4}_{\bar{\Lambda}}\overline{H}}$
  - Confirming 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





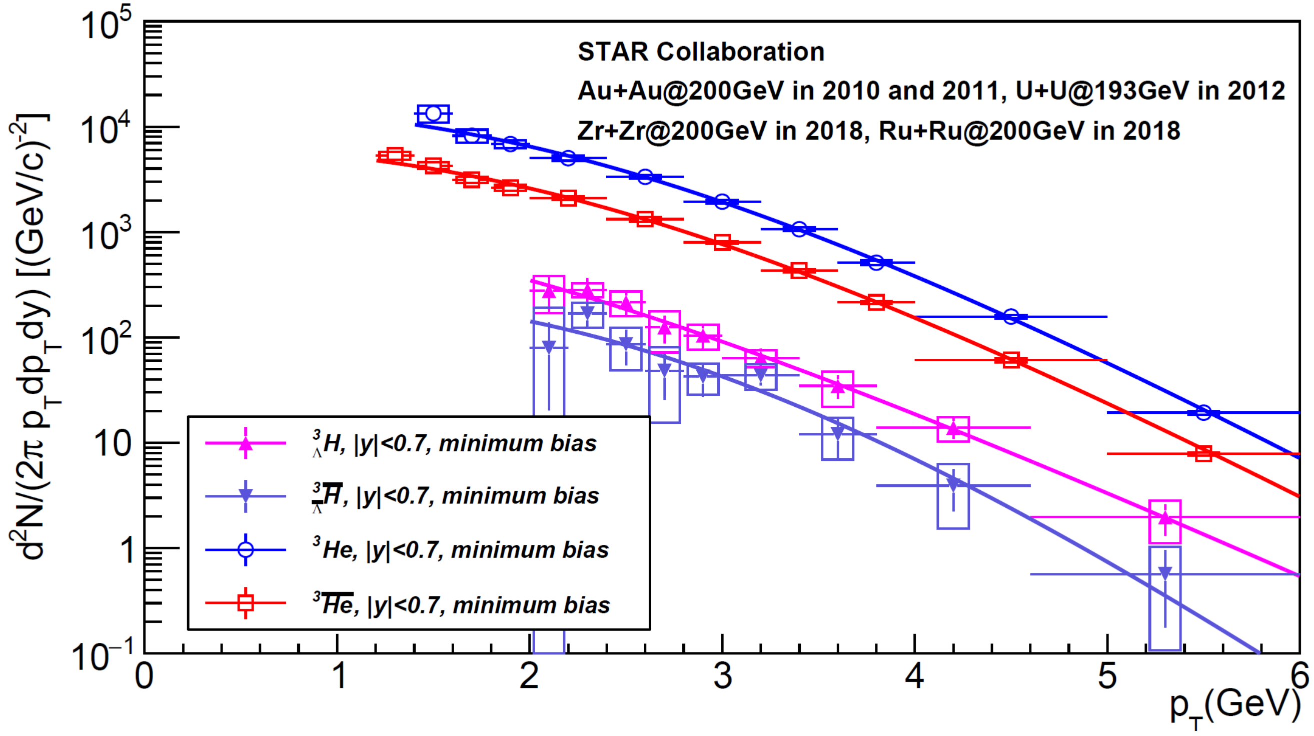
Thanks ☺

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



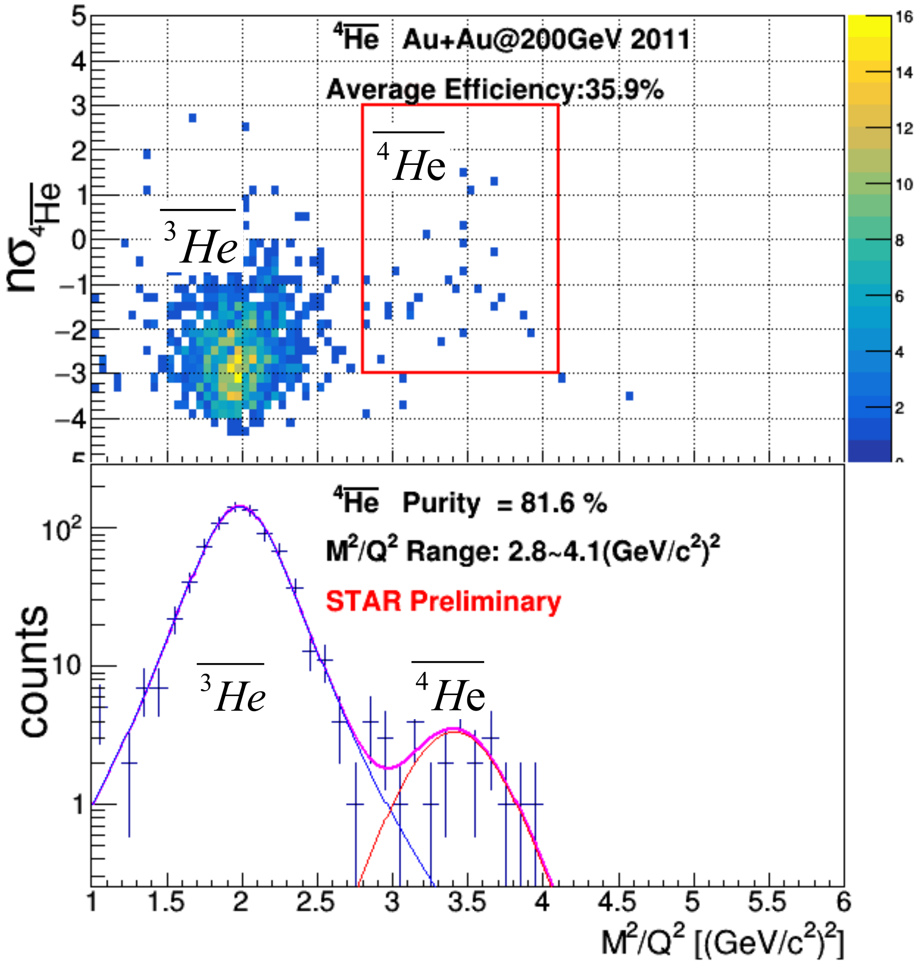
Blast Wave function fit:

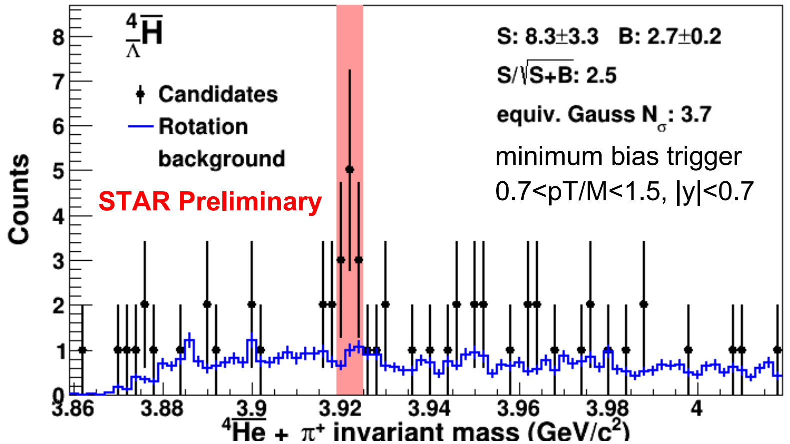
$$\frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy} \propto \int_0^R r dr m_0 I_0\left(\frac{p_T \sinh\rho}{T}\right) K_1\left(\frac{m_T \cosh\rho}{T}\right)$$

- *Physical Review C Volume48, Number5, 1993*

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

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.