Observation of the Antimatter Hypernucleus

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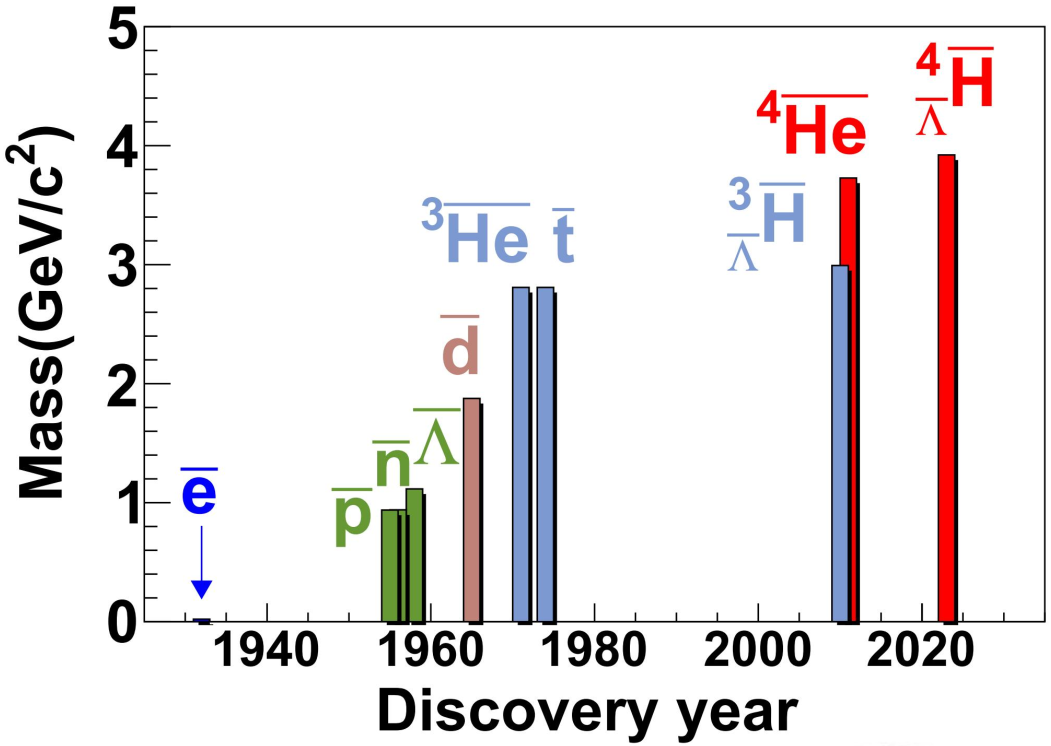
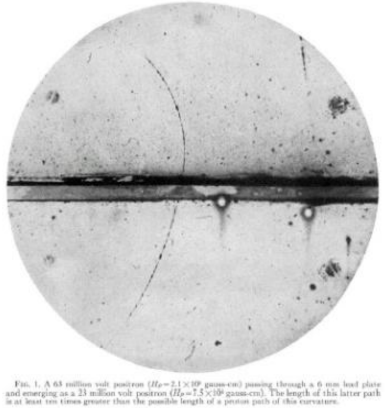
Outline

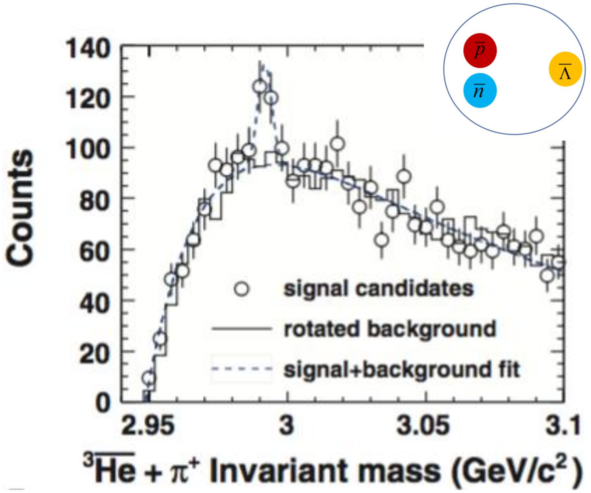
1. History of anti-matter discovery and motivation
2. Data sets
3. Particle identification and (anti-)hypernuclei reconstruction
4. Lifetime measurement of (anti-)hypernuclei
5. Yield ratio measurements among (anti-)hypernuclei and (anti-)nuclei
6. Summary

History of Anti-matter Discovery

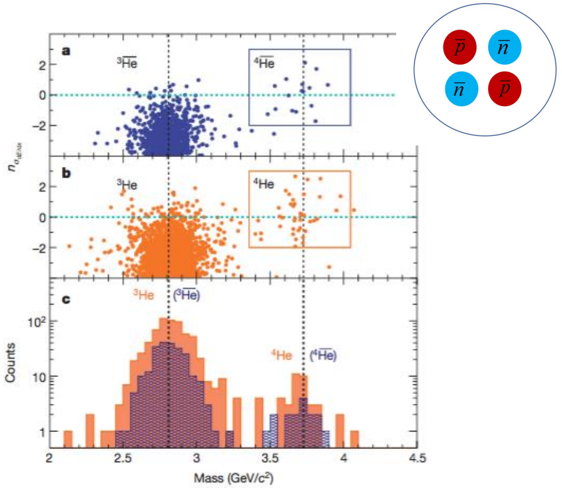


- P.A.M. Dirac, The Quantum Theory of the Electron. Proc. Roy. Soc. Lond. A 117, 610 (1928);
- C. D. Anderson： Positron was discoveryed in 1932；
- ......
- In 2010, RHIC-STAR: ~70 anti-hypertriton candidates;
- In 2011, RHIC-STAR: 15 counts of anti-Helium4.





- *Science 328, 58 (2010)*



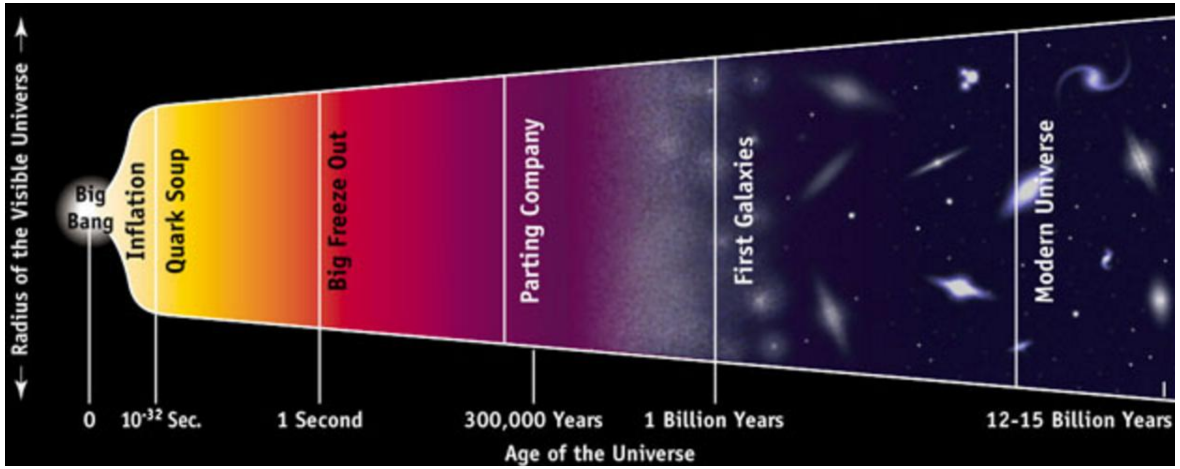
- *Nature 473, 353 (2011)*

Motivation

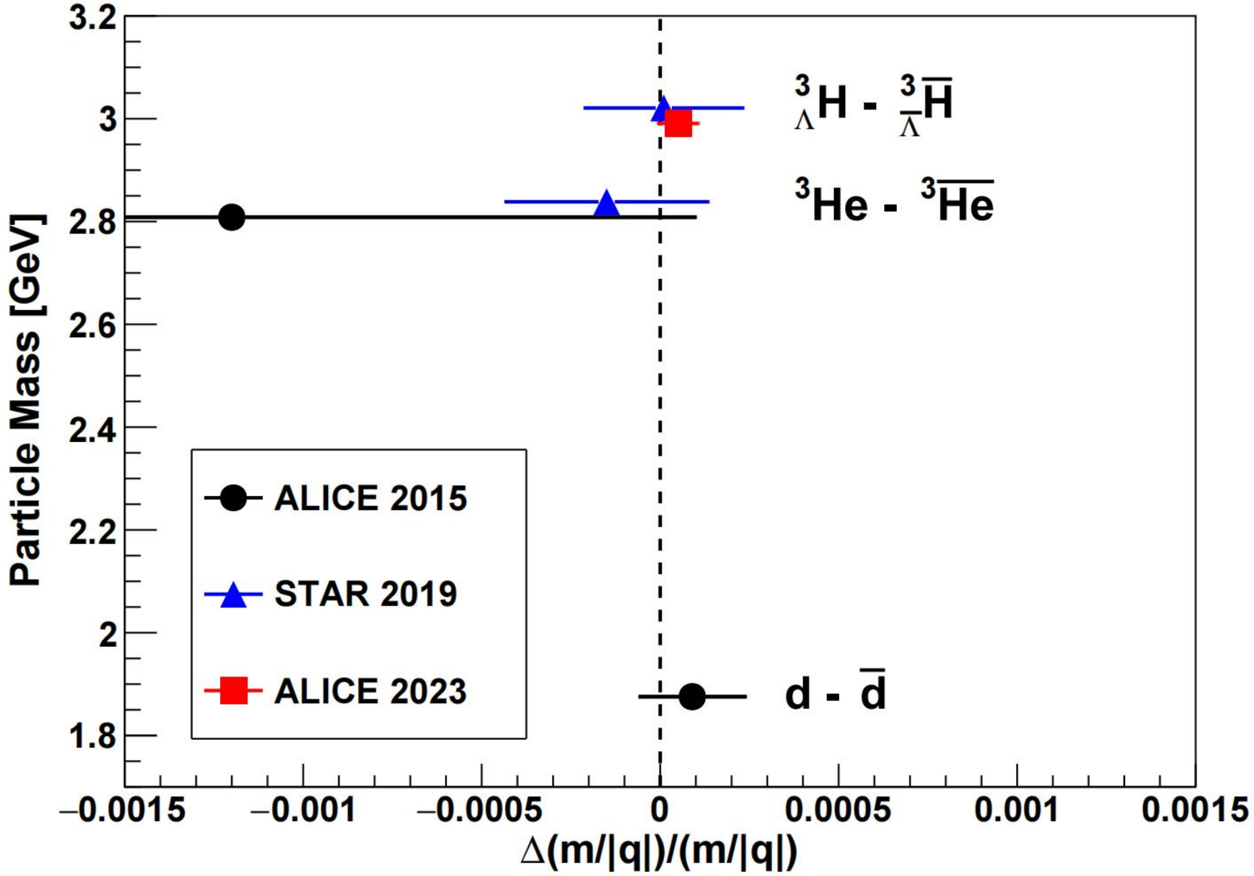
CPT theorem: A particle and its corresponding antimatter particle to have the same properties. (mass, lifetime , and interaction etc.)

Our current knowledge is that the initial Universe should have contained equal amounts of matter and antimatter (Baryon-Symmetric Universe, BSU). But our Universe is the matter-dominated (Baryon-Asymmetric Universe, BAU) world today, whose source is not completely understood so far.

Comparing the mass or lifetime of a particle and its corresponding antiparticle is an important experimental way to test the CPT symmetry.



Motivation



- *Nature Phys. 11 (2015) 10, 811-814*
- *Nature Phys. VOL 16, April 2020, 409–412*
- *PHYSICAL REVIEW LETTERS 131, 102302 (2023)*
- *Nature volume 527, pages345–348 (2015)*

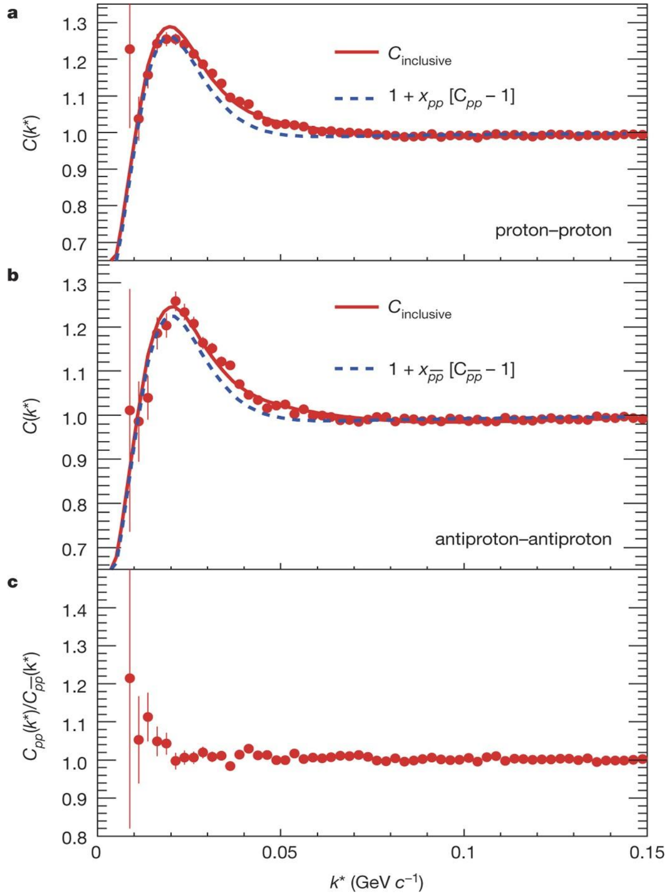
The ALICE and STAR experiments reported that there is no significant mass (binding energy) difference between d and dbar, He3 and anti-He3, H3L and anti-H3L.

Hypernucleus lifetimes also can be used to test the CPT symmetry. In 2023, ALICE also publish their new precise lifetime difference measurement between H3L and anti-H3L.

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

In 2015, STAR published the correlation function of p_bar-p_bar. There is no difference with p-p correlation function.

Motivation



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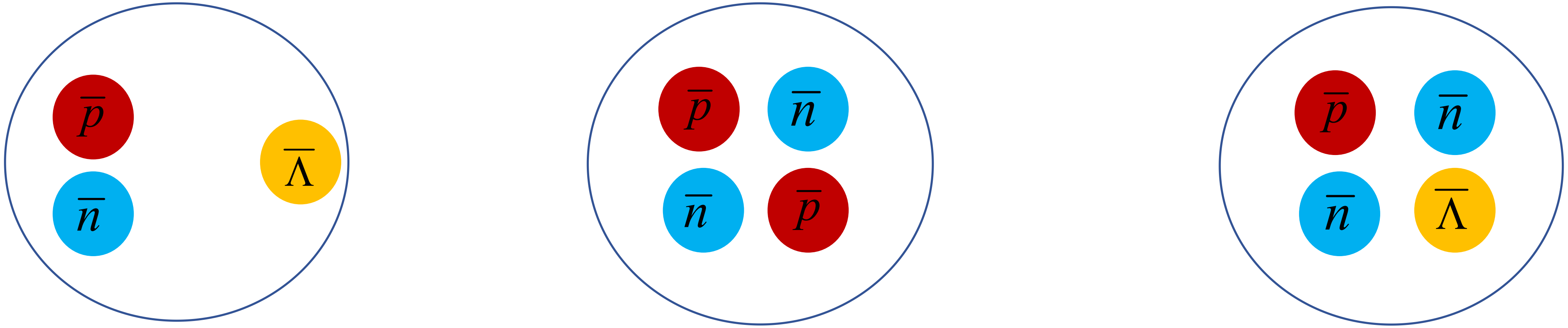
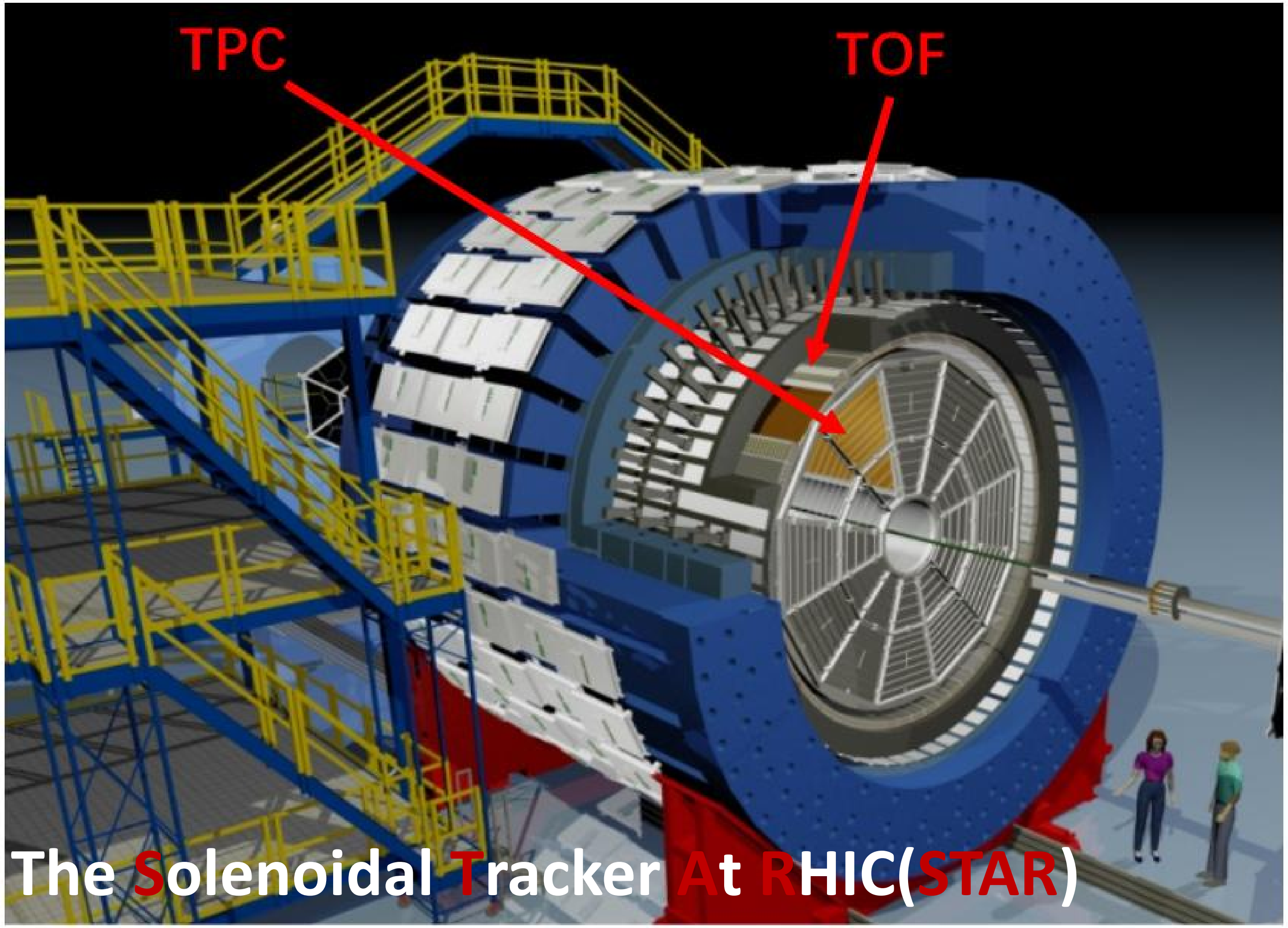
Motivation

- Nuclei are abundant in the universe, but antinuclei heavier than antiproton have been observed only at accelerators.
- 12 years after discovering ${}^{4}\overline{He}$, can we find heavier anti-(hyper)nuclei? Can we find ${}^{4}_{\Lambda}\overline{H}$?



2010: ${}^{3}_{\Lambda}\overline{H}$ 2011: ${}^{4}\overline{He}$ now? ${}^{4}_{\Lambda}\overline{H}$

STAR Detector and Data Sets



Time Projection Chamber (TPC)

- Charged particle tracking
- Momentum reconstruction
- Particle identification from energy loss (dE/dx vs. p/Q)

Time of Flight (TOF)

- Particle identification with M^2/Q^2

STAR Detector and Data Sets

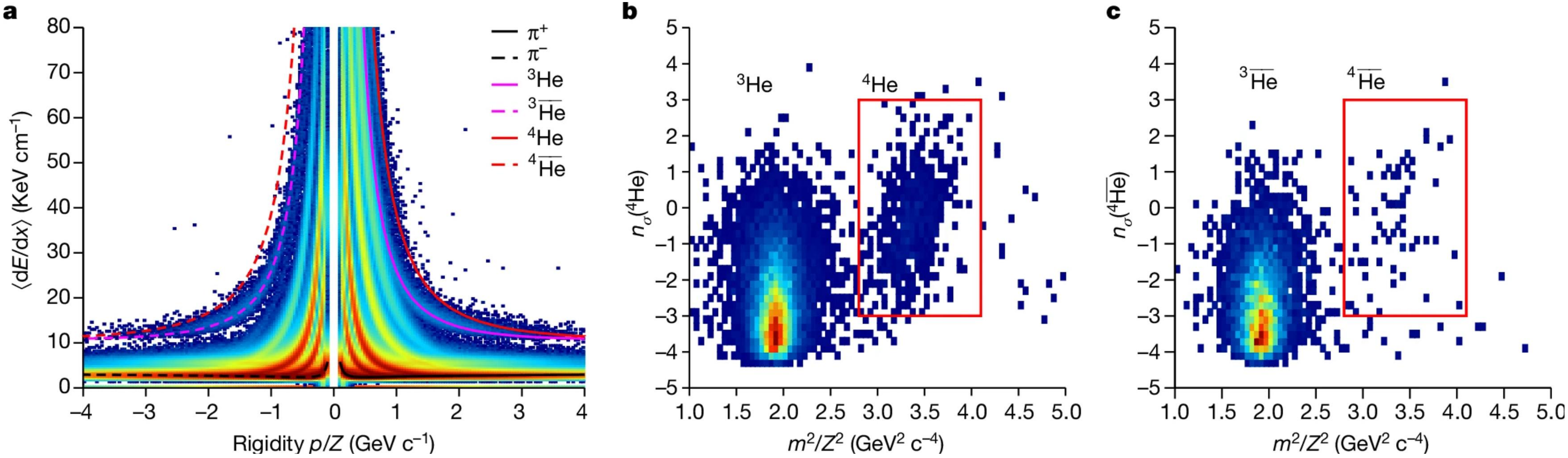
data set	year	N events
AuAu@200 GeV	2010	~606 M
AuAu@200 GeV	2011	~626 M
UU@193GeV	2012	~512 M
ZrZr+RuRu(Isobar)@200GeV	2018	~4.7 B

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 (in red) for yield ratios measurement

Particle Identification and Reconstruction

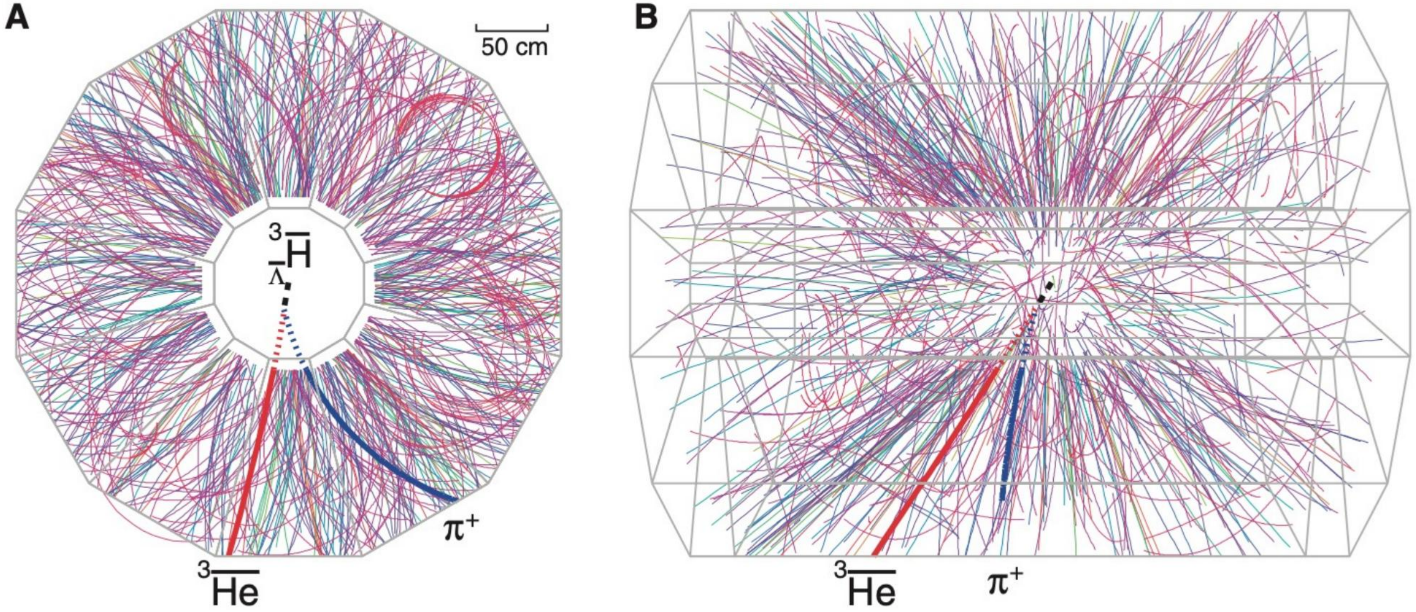


$$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-} \qquad {}^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$$

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

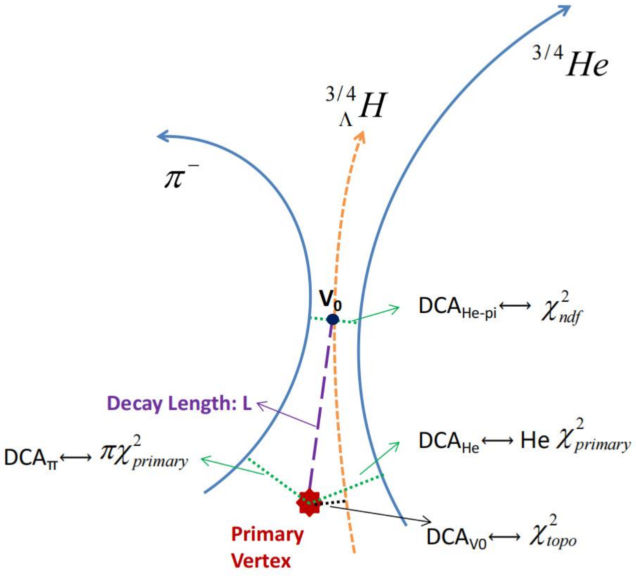
- ^{3}He PID： (Q<0 || p>2.) && $|n\sigma_{^{3}He}|<3$ && (if TOF matched, $1<M^2/Q^2<3$);
- ^{4}He PID： (Q<0 || p>2.) && $|n\sigma_{^{4}He}|<3$ && ($|n\sigma_{^{3}He}|>3.5$ || $2.8<M^2/Q^2<4.1$));
- π PID： $|n\sigma_{\pi}|<3$;

Particle Identification and Reconstruction



Science 328, 58 (2010)

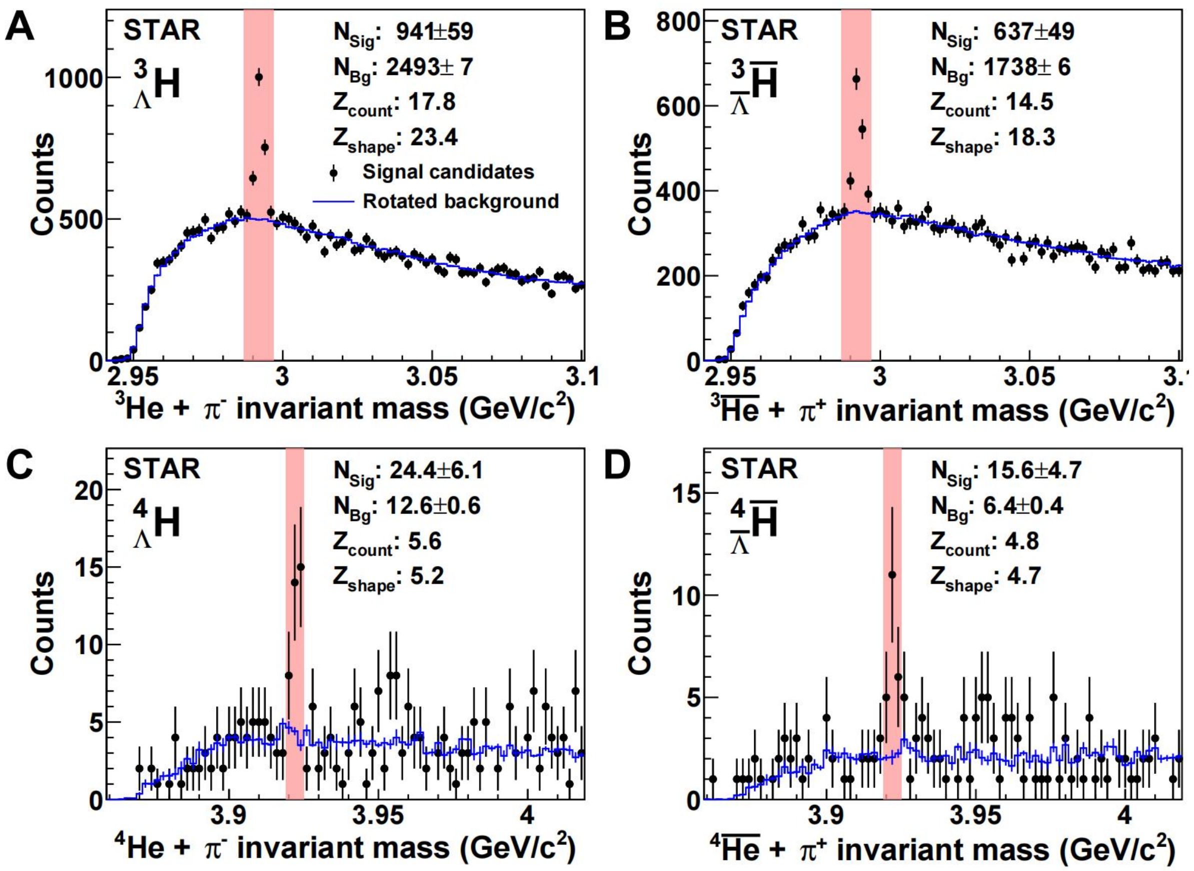
- **KF(Kalman Filter) Particle package** and rotation background are used.
- Topology cuts obtained by optimizing $^{3}_{\bar{\Lambda}}\bar{H}$ significance (blind for $^{4}_{\Lambda}H$ and $^{4}_{\bar{\Lambda}}\bar{H}$);



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

- *S. Gorbunov and I. Kisel, Reconstruction of decayed particles based on the Kalman filter. CBM-SOFT-note-2007-003, 7 May 2007*
- *KF Particle Finder — 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,*

Particle Identification and Reconstruction



$^{4}_{\bar{\Lambda}}\overline{H}$ is the heaviest antihypernuclei observed in laboratory!

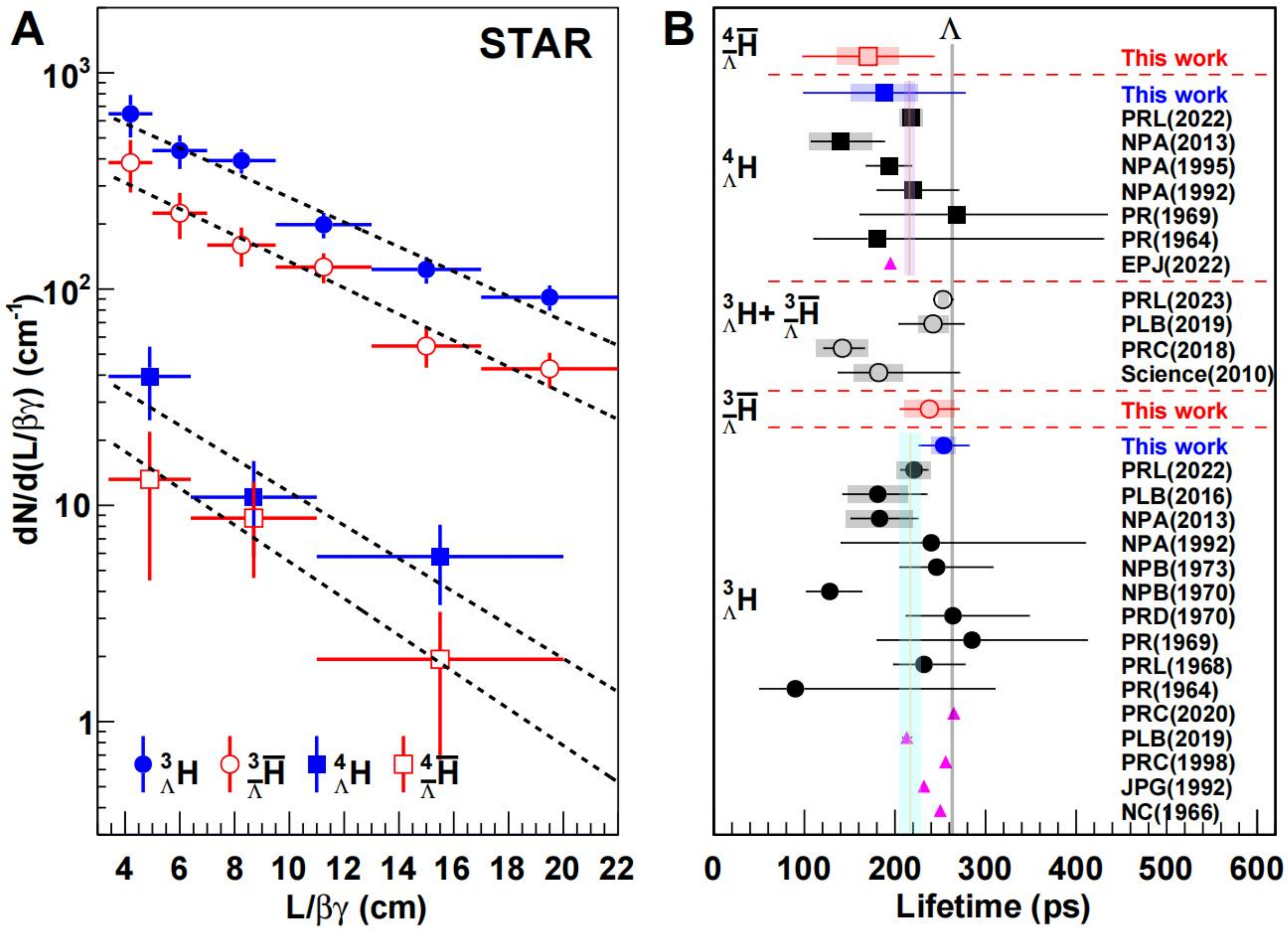
Got 15.6 candidates of $^{4}_{\bar{\Lambda}}\overline{H}$ and their significance reached 4.7.

N_sig/sqrt(N_bg) or N_sig/sqrt(N_sig+N_bg) is not work when N_sig<<N_bg doesn't hold. In general, calculating significance requires calculating Likelihood function ratios between the pure background hypothesis and signal + background hypothesis asymptotic formula.

Rotation background and Gauss shape signal.
In this way, we use RooStats()::AsymptoticCalculator() calculate the significance as **Z_shape**.
Specially, In the counting experiment, the counts follow a Poisson distribution, and we already know the N_sig and N_bg, the significance is calculated by the formula

$$Z_{count} = \sqrt{2\left[\left(N_{Sig} + N_{Bg}\right)\ln\left(1 + \frac{N_{Sig}}{N_{Bg}}\right) - N_{Sig}\right]}$$

Lifetime Measurements



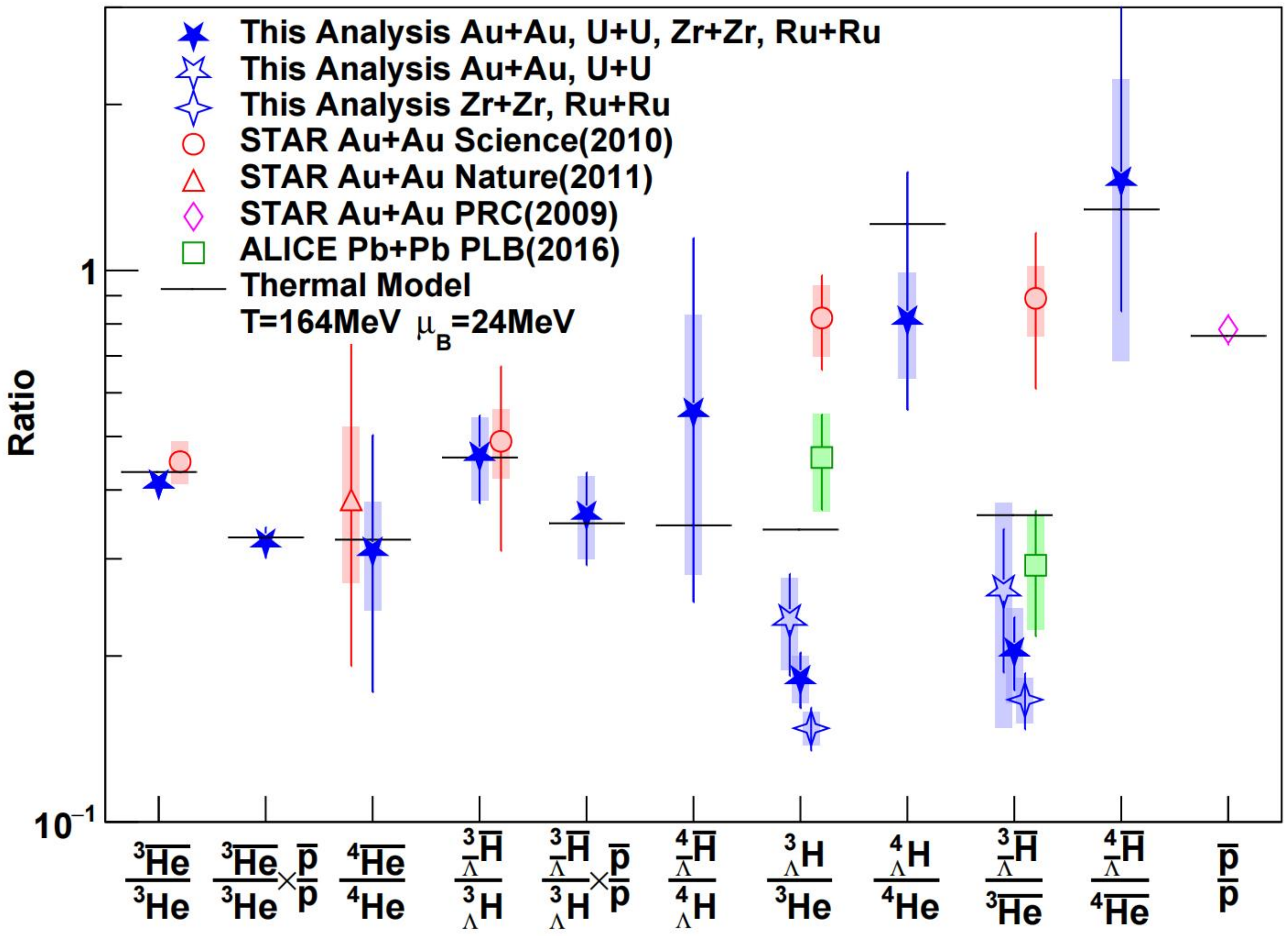
- Decay time: $t = l/\beta\gamma$
- Efficiency corrected
- Well described by the exponential function: $N(t) = N_0 e^{-l/\beta\gamma c\tau}$

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

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

No lifetime difference within uncertainties!

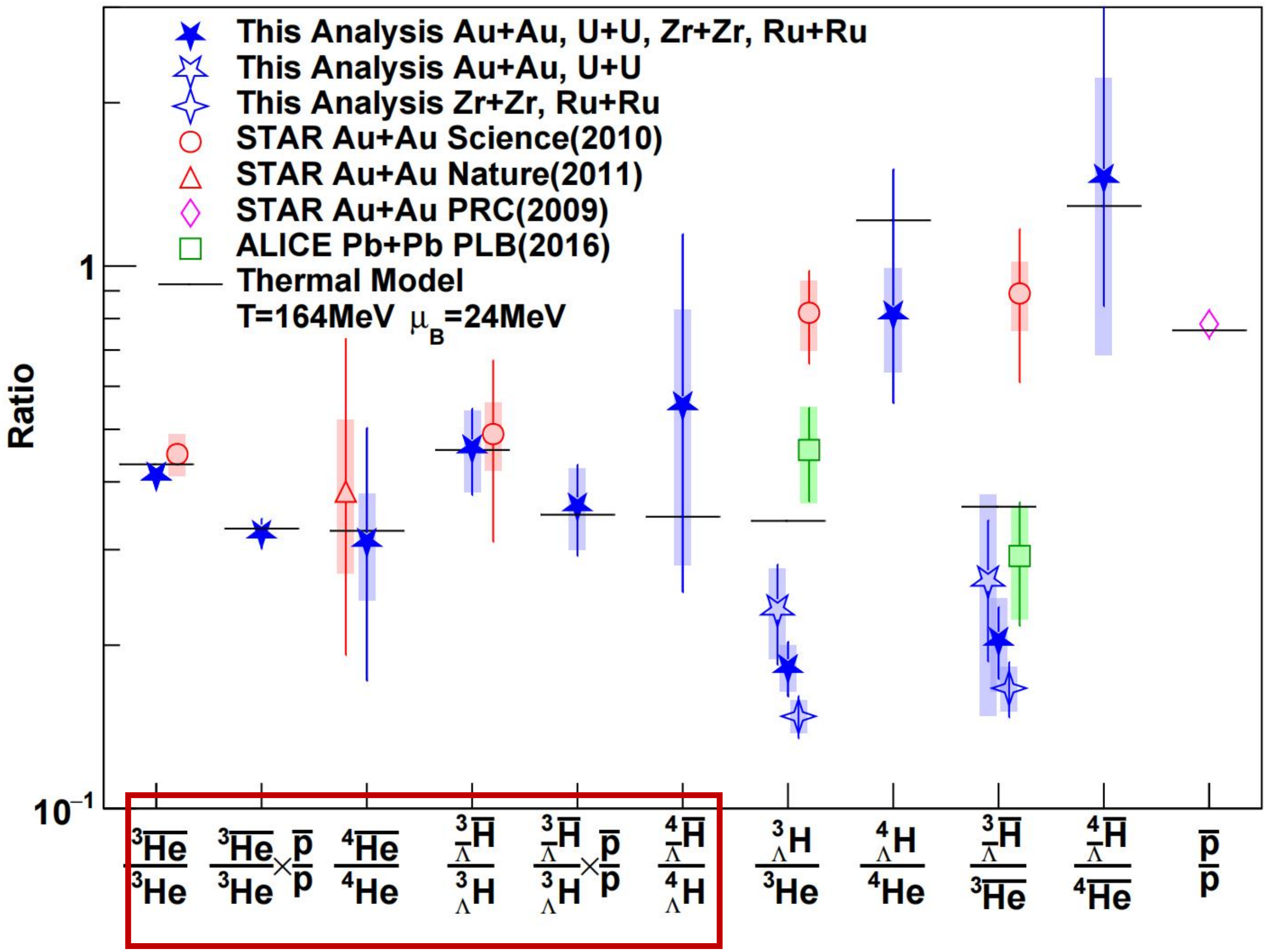
Yield Ratios Measurement



- STAR Science 2010: Au+Au@200GeV
- STAR Nature 2011: Au+Au@200GeV
- ALICE PLB: Pb+Pb@2.76TeV
- Thermal Model:
  T=164MeV, μ_B=24MeV
- B.R. : 25% for ${}^{3}_{\Lambda}H$ 2 body decay
- B.R. : 50% for ${}^{4}_{\Lambda}H$ 2 body decay
- Phase space of this analysis: 0.7<p_T/M<1.5, |rapidity|<0.7

- *Scince 328, 58 (2010)*
- *Nature 473, 353–356 (2011)*
- *Phys. Rev. Lett. 97, 152301*
- *Phys. Lett. B 754(2016)360–372*
- *Phys. Lett. B 697.3 (2011)*

Yield Ratios Measurement



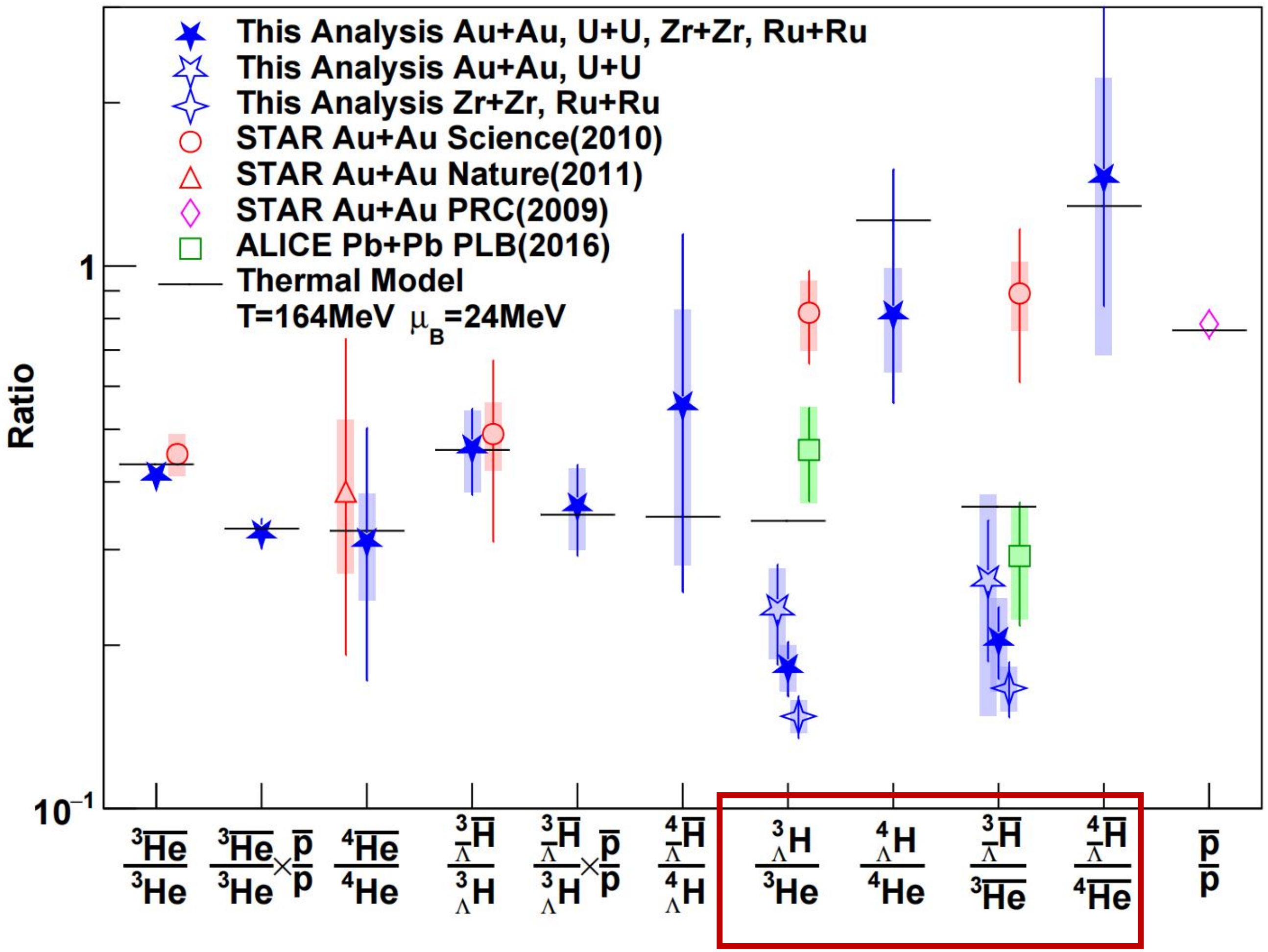
For the ratios of anti-matter over matter:

- Our results are consistent with thermal model and STAR measurement in 2010 and 2011.

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

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

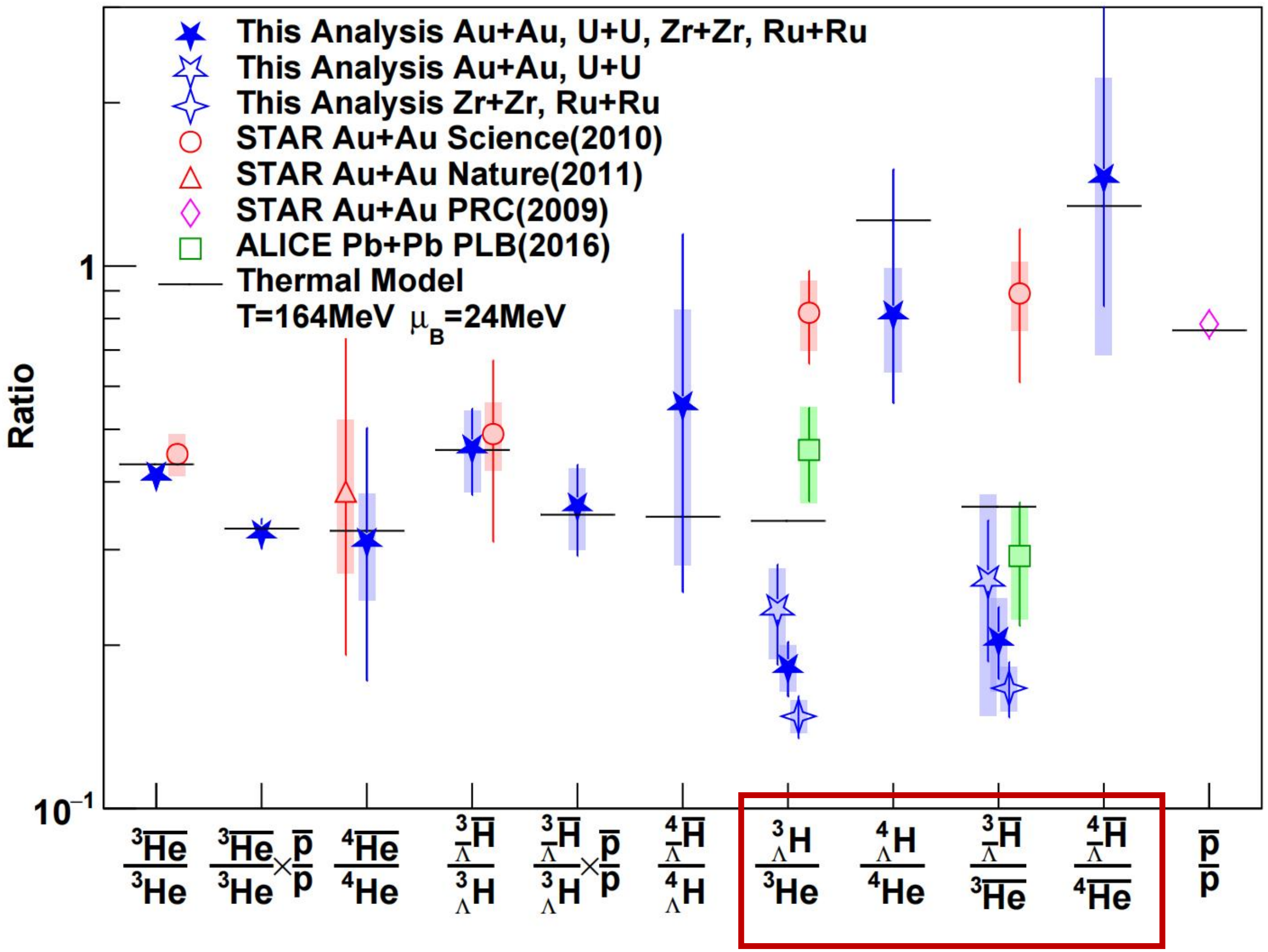
Yield Ratios Measurement



For the ratios of (anti-)hypernuclei over (anti-)nuclei:

- The Au+Au and U+U results constitute a fair comparison to previous results in Au+Au and Pb+Pb collisions due to similar system sizes.
- The newly measured $^{3}_{\Lambda}H/^{3}He$ and $^{3}_{\Lambda}\overline{H}/^{3}\overline{He}$ are lower than previous STAR measurements by 2.8 and 1.9 σ.

Yield Ratios Measurement

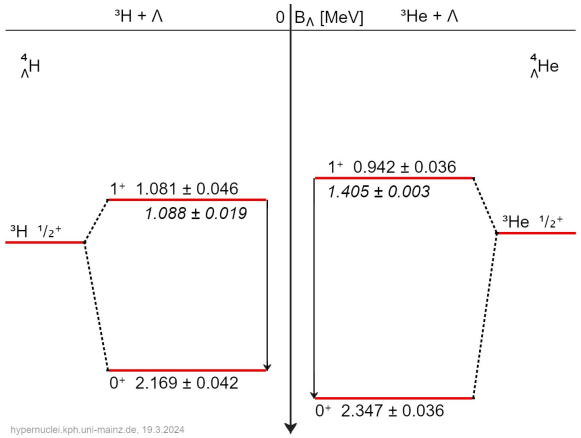


For the ratios of (anti-)hypernuclei over (anti-)nuclei:

- With all the collision systems combined,

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

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



Summary

- 15.6 signal candidates of ${}^{4}_{\bar{\Lambda}}\overline{H}$ observed, with significance of 4.7 σ.
- Lifetimes of hypernuclei are measured: $\tau_{{}^{3}_{\Lambda}H} \approx \tau_{{}^{3}_{\bar{\Lambda}}\overline{H}}$, $\tau_{{}^{4}_{\Lambda}H} \approx \tau_{{}^{4}_{\bar{\Lambda}}\overline{H}}$.
- Various anti-particle or particle ratios are presented. Consistent with coalescence picture and thermal model.
- This work has been published in

Nature volume 632, pages1026–1031 (2024)

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

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

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

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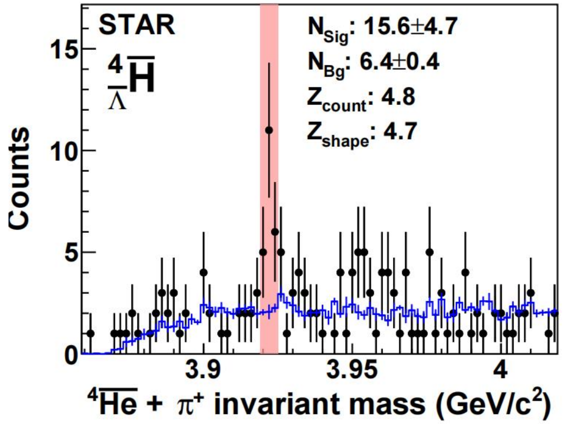
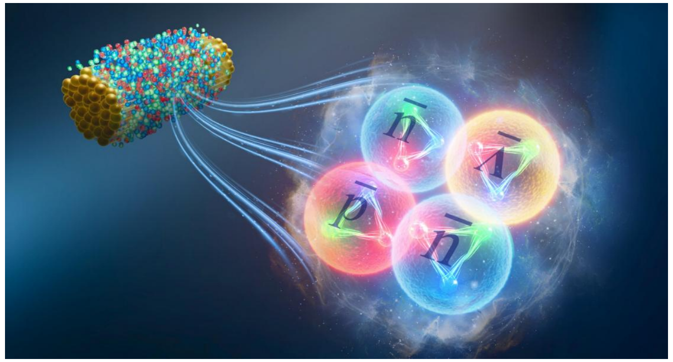
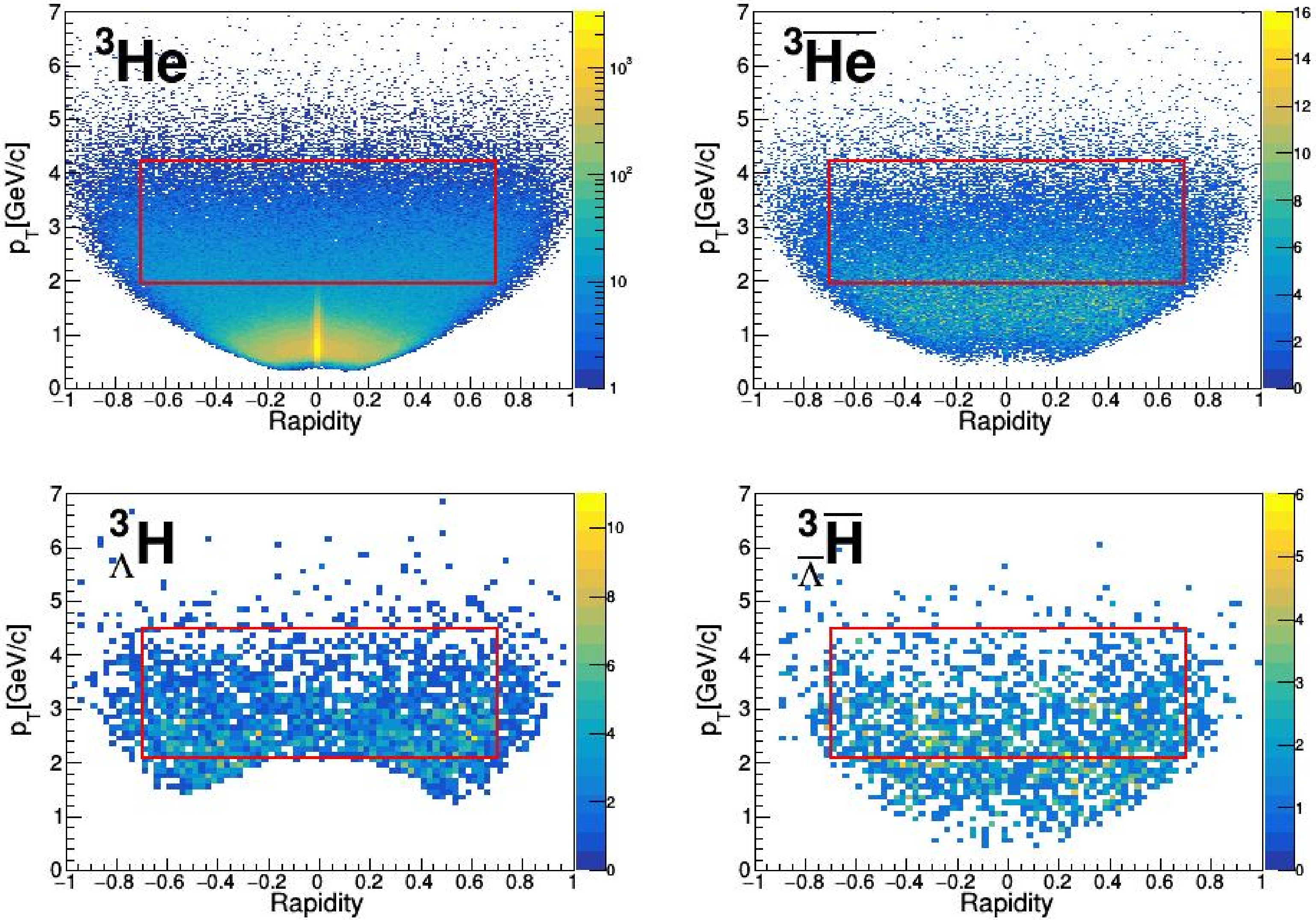




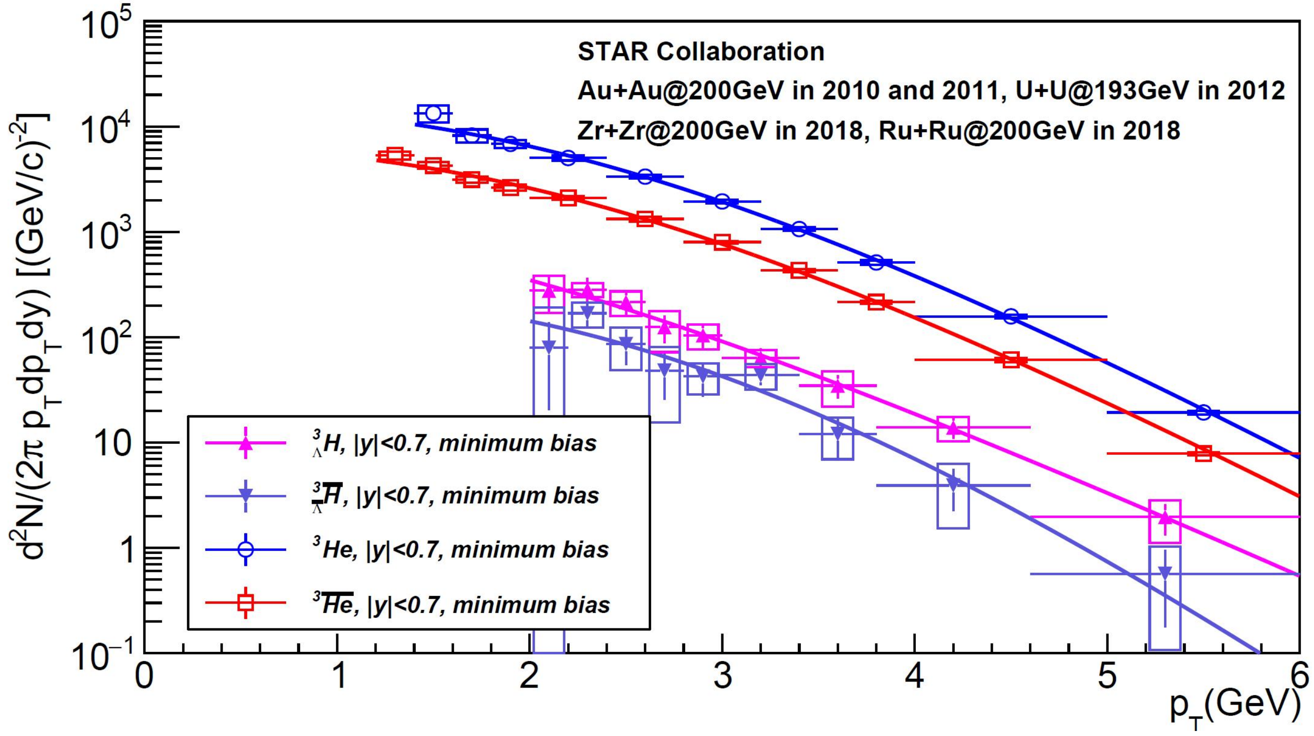
Thank you for your attention!

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



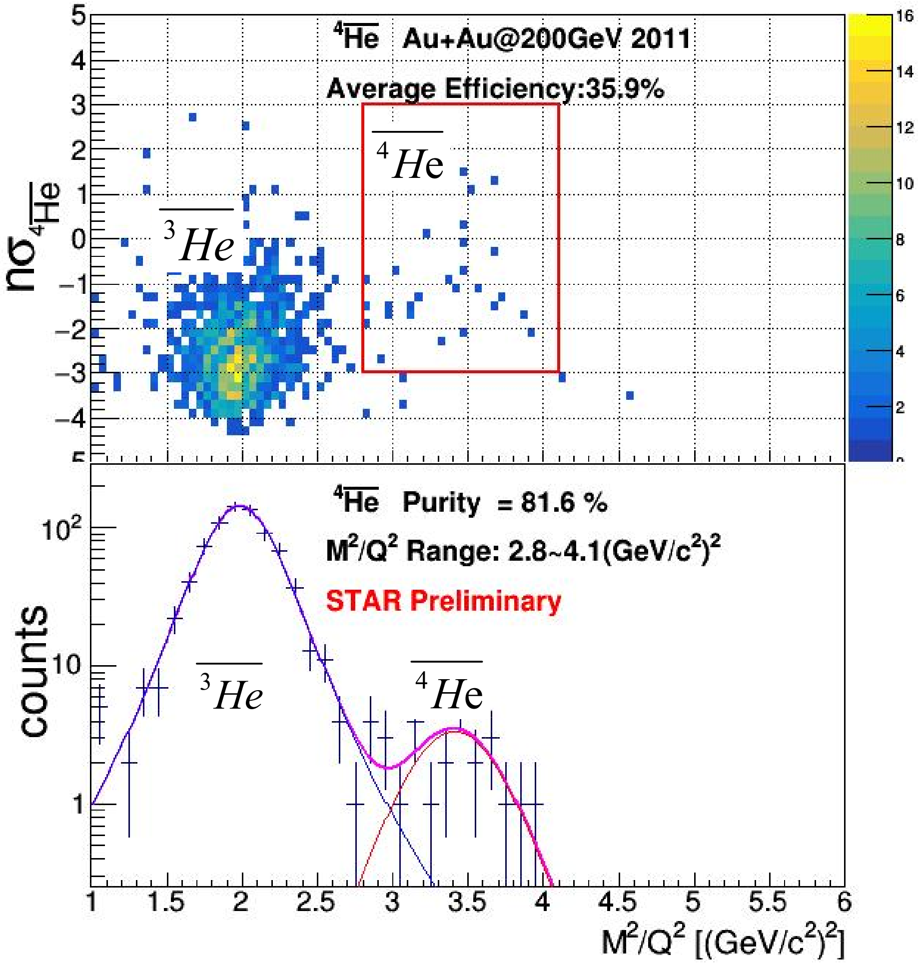
- ^3He, $^3\overline{He}$, $^3_\Lambda H$ and $^3_{\overline{\Lambda}}\overline{H}$: Yields are obtained by integrating over the measured p_T spectrum.

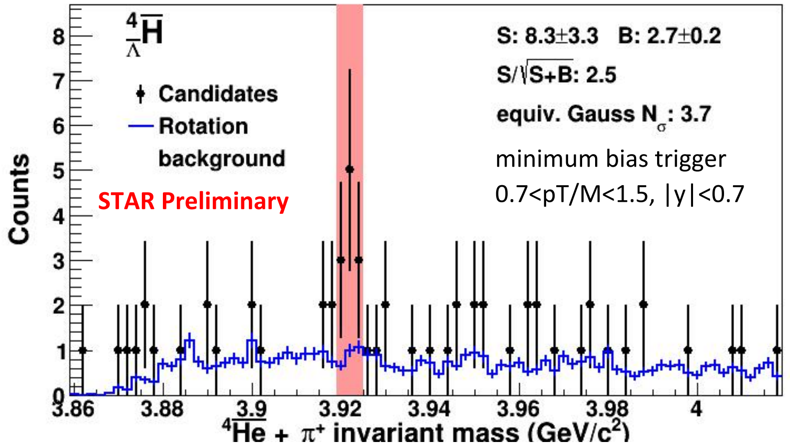
Blast Wave function fit:

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

- *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.

Back Up: ALICE A=4 antimatter hypernuclei