Observation of $^{4}_{\bar{\Lambda}}\overline{H}$ in Heavy Ions Collisions at RHIC

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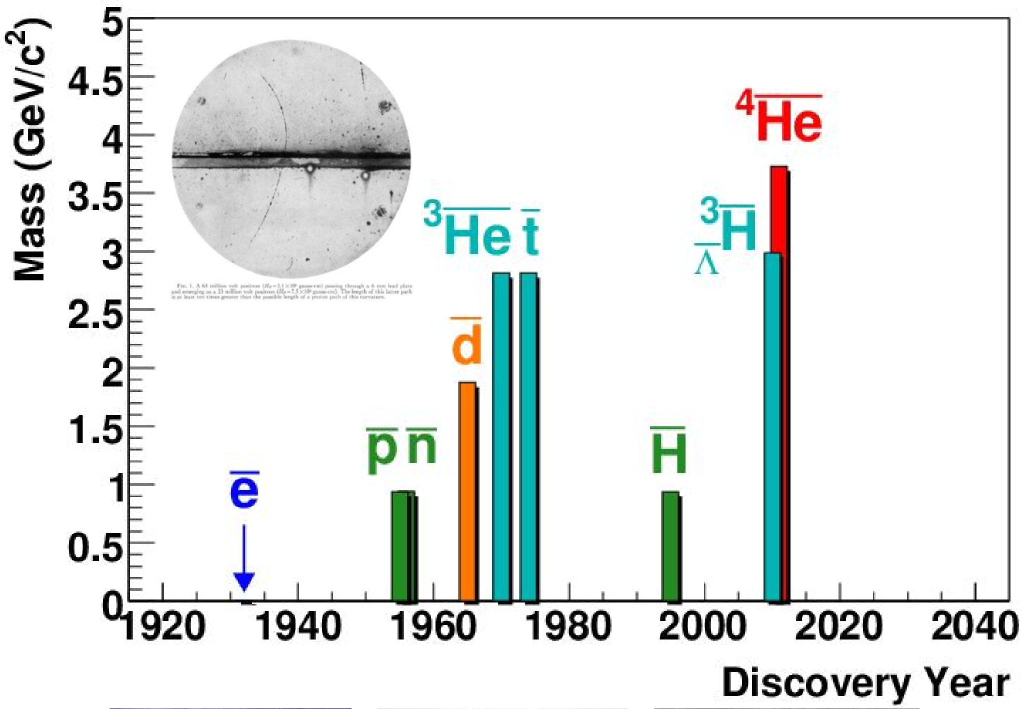
Outline

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

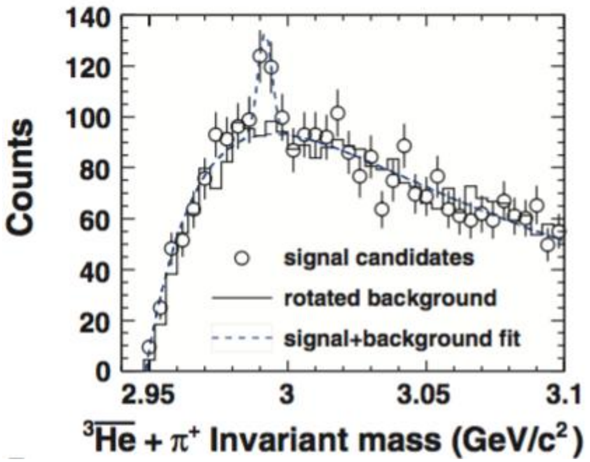
History of Anti-matter Discovery



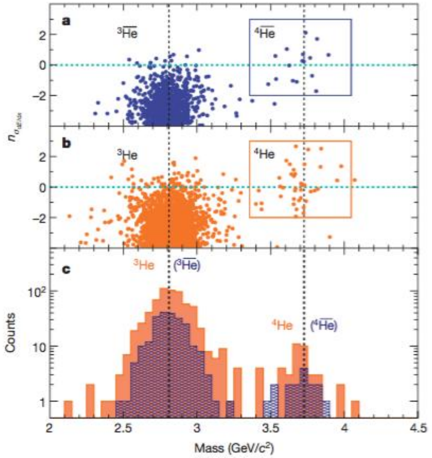
- P.A.M. Dirac, The Quantum Theory of the Electron. Proc. Roy. Soc. Lond. A 117, 610 (1928);
- C. D. Anderson and Chung-Yao Chao(赵忠尧)：Positron was discoveryed in 1932；
- ......

- In 2010, RHIC-STAR: 70 anti-hypertriton candidates;

- In 2011, RHIC-STAR: 15 counts of anti-Helium4.

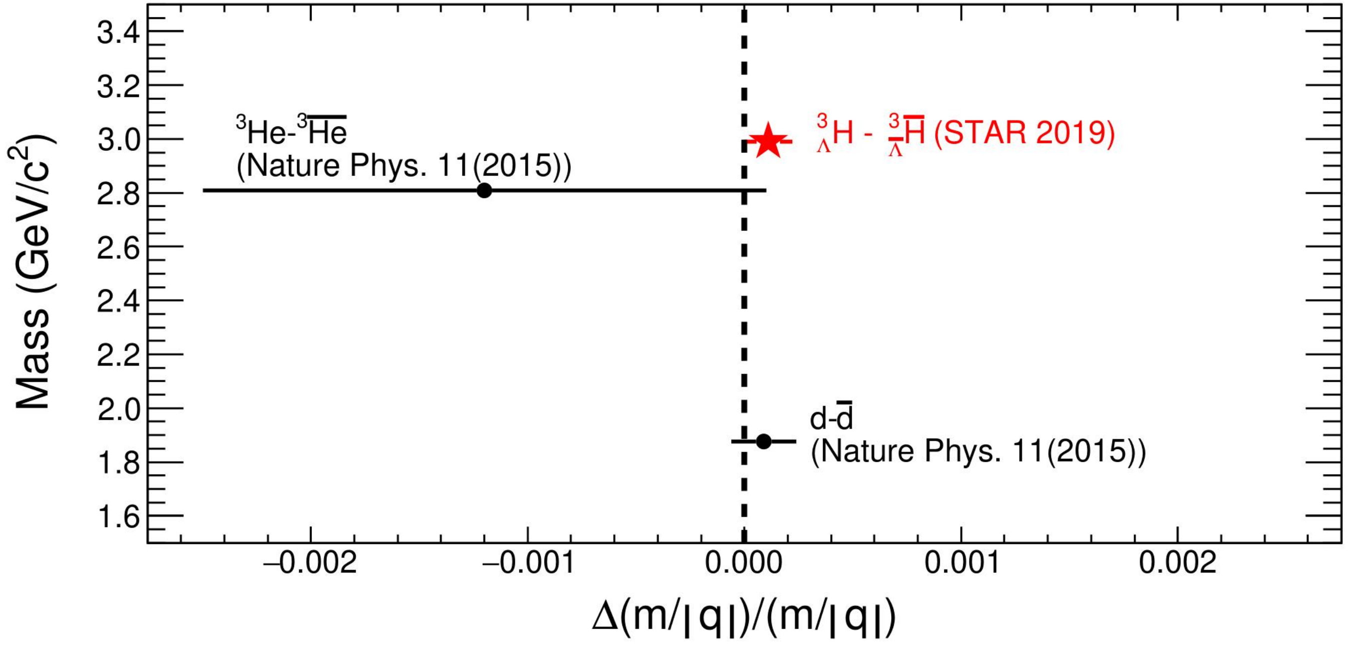


- *Science 328, 58 (2010)*



- *Nature 473, 353 (2011)*

Motivation



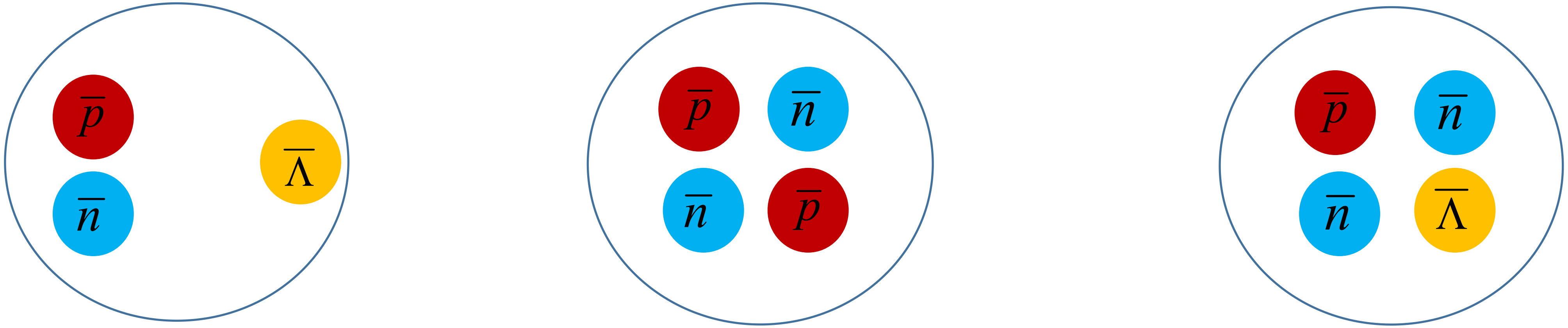
$$\frac{\Delta m}{m} = \frac{m_{^{3}_{\Lambda}\mathrm{H}} - m_{^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}}}{m} = [\,1.1 \pm 1.0(\mathrm{stat.}) \pm 0.5(\mathrm{syst.})] \times 10^{-4}$$

- *Nature Physics, VOL 16, April 2020, 409–412*

- Our universe has much more matter than antimatter. This is the basis for the existence of human civilization.
- Matter-antimatter asymmetry is a research topic of fundamental interest.
- Discovering new antimatter particles paves the way for studying matter-antimatter asymmetry.

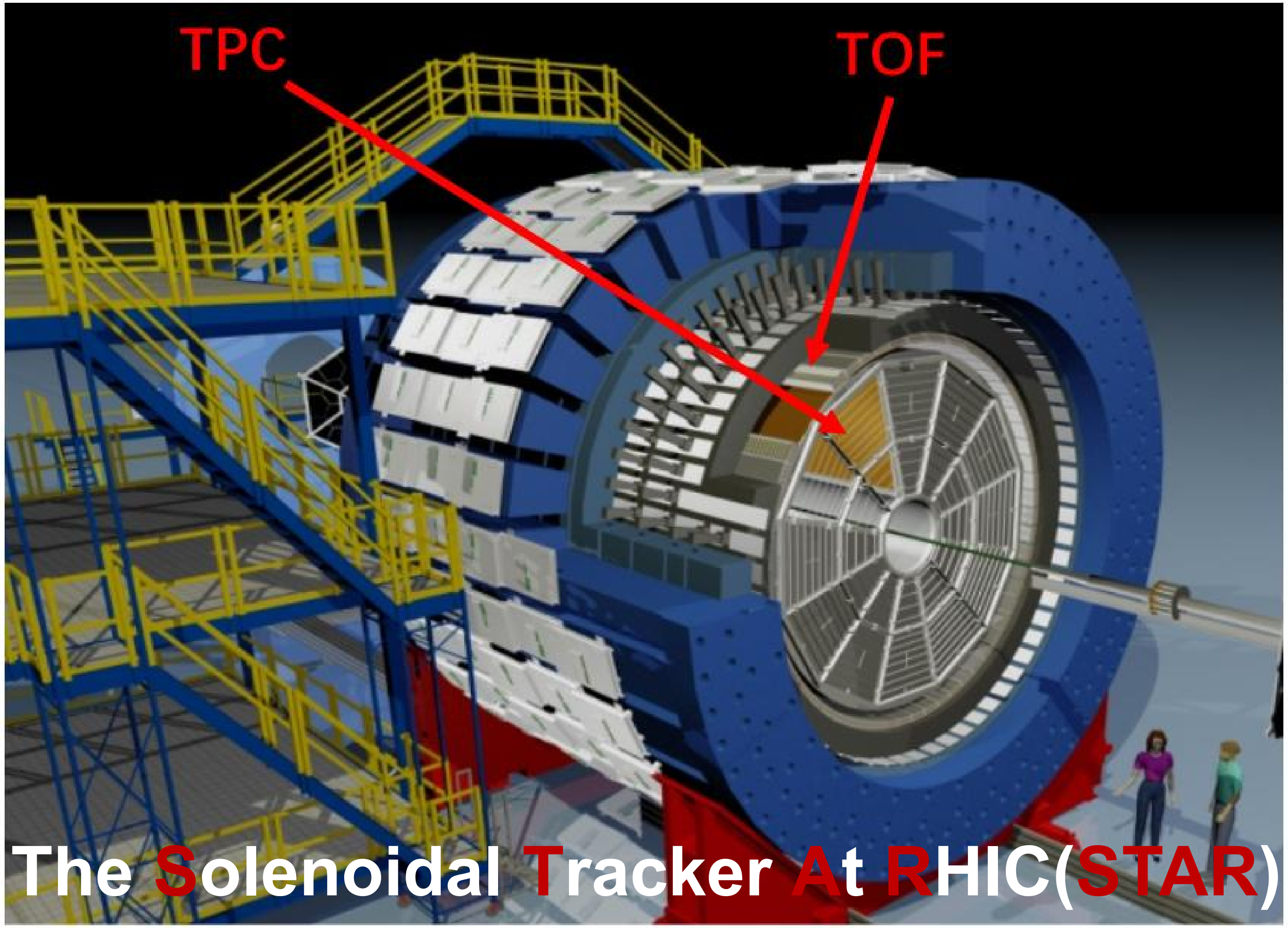
Motivation

- Nuclei are abundant in the universe, but antinuclei heavier than antiproton have been observed only at accelerators.
- 11 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

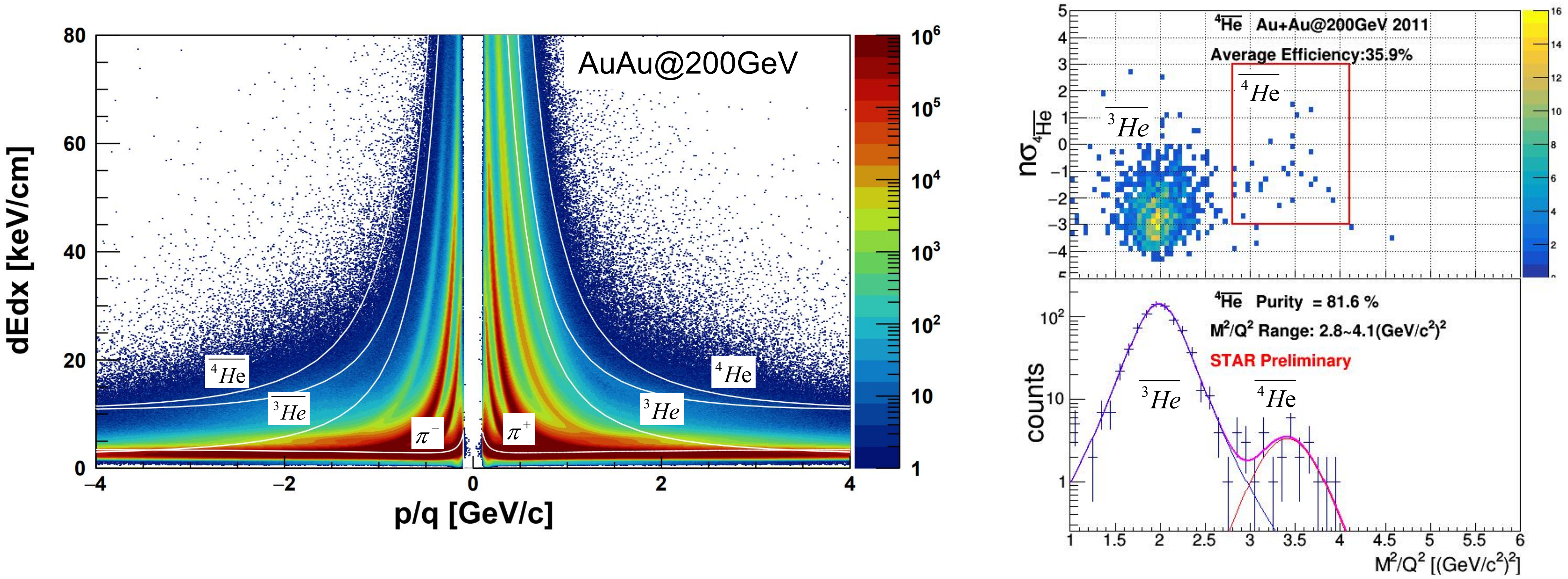
data set	year	N events
AuAu@200 GeV	2010	~660 M
AuAu@200 GeV	2011	~680 M
UU@193GeV	2012	~660 M
ZrZr+RuRu(Isobar)@200GeV	2018	~4.6 B

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

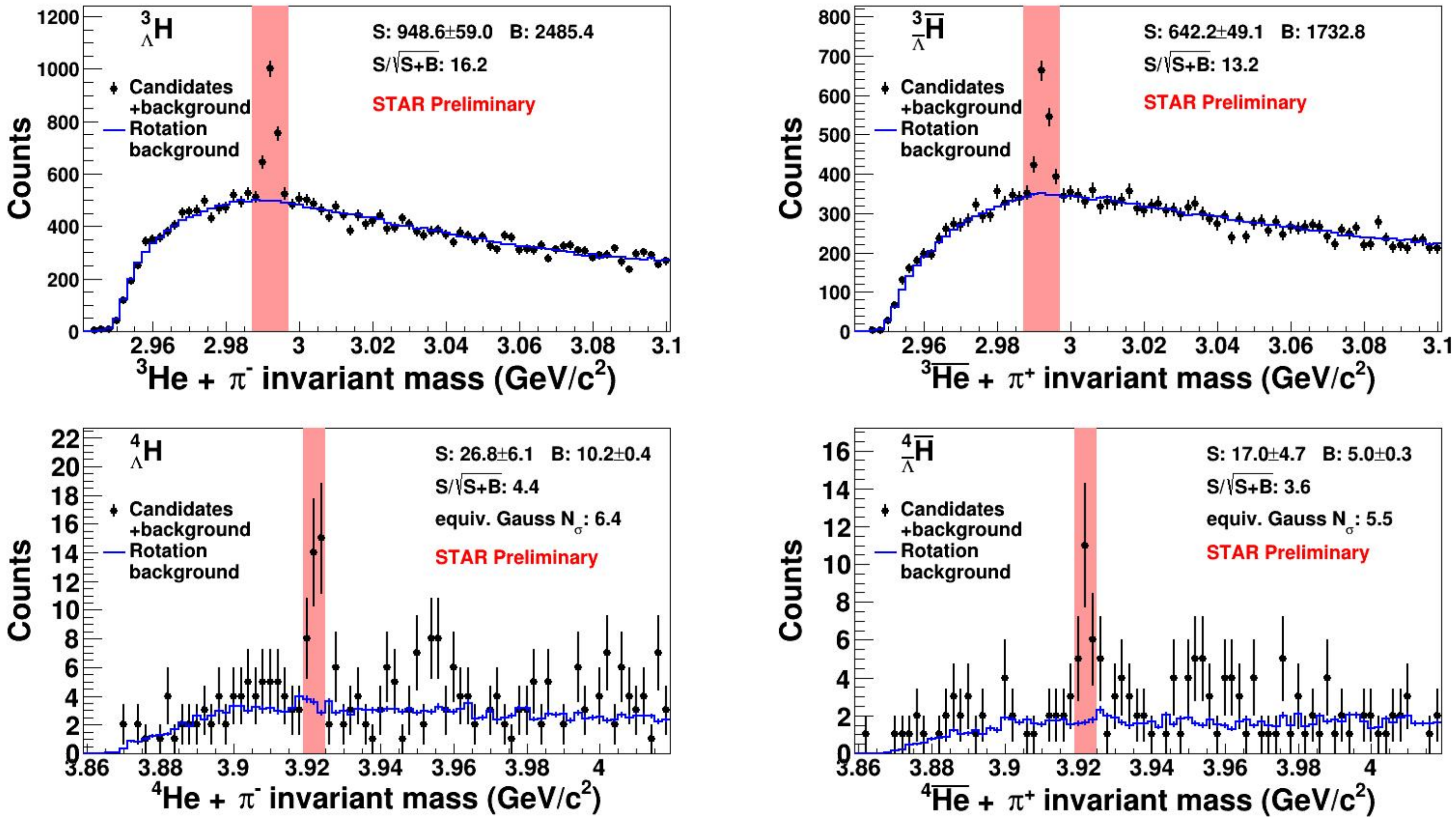
Particle Identification and Reconstruction



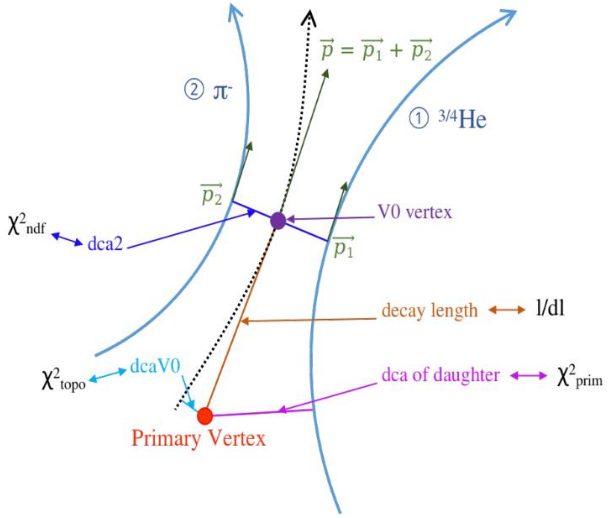
$$^3_\Lambda H \rightarrow {}^3He + \pi^-$$
$$^4_\Lambda H \rightarrow {}^4He + \pi^-$$
$$^3_{\bar\Lambda} \overline{H} \rightarrow {}^3\overline{He} + \pi^+$$
$$^4_{\bar\Lambda} \overline{H} \rightarrow {}^4\overline{He} + \pi^+$$

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

Particle Identification and Reconstruction



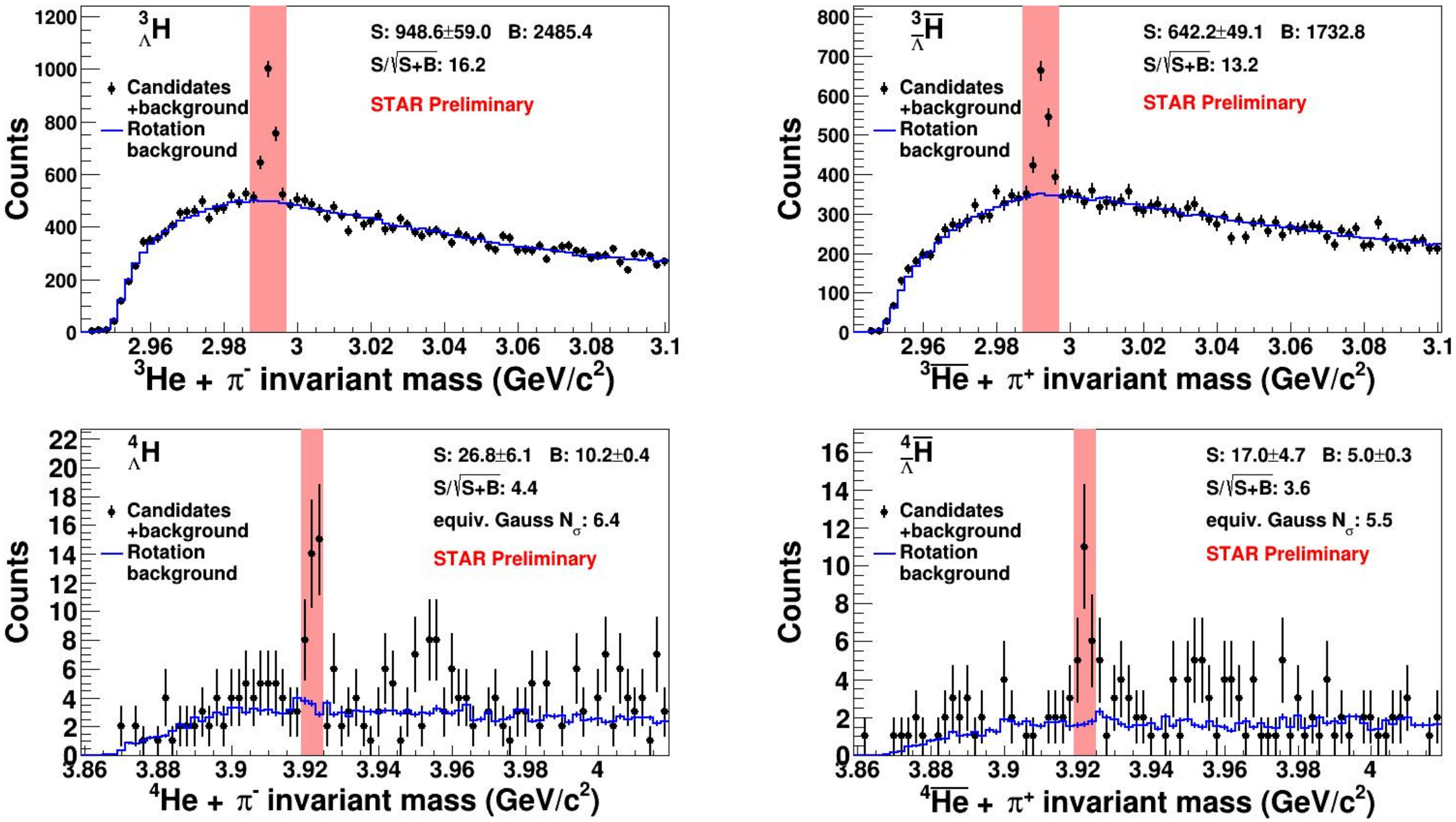
- **KF(Kalman Filter) Particle package** and rotation background are used.
- Topology cuts obtained by optimizing ${}^{3}_{\Lambda}\overline{H}$ significance (blind for ${}^{4}_{\Lambda}H$ and ${}^{4}_{\Lambda}\overline{H}$);



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	-

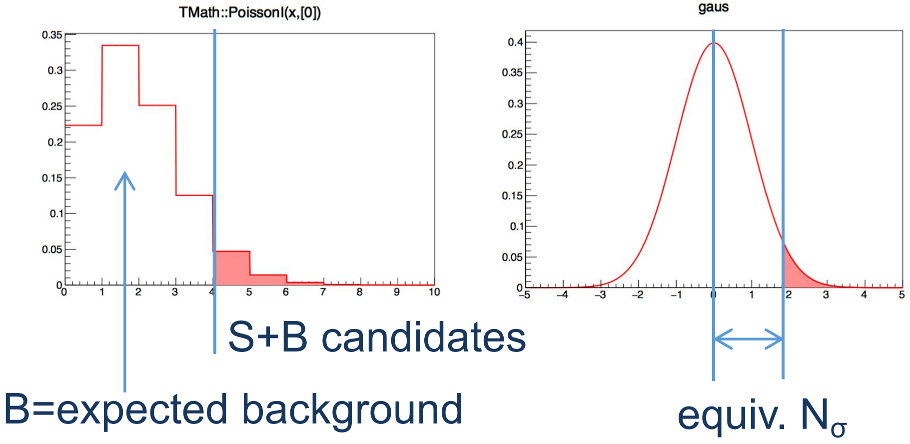
- *S. Gorbunov and I. Kisel, Reconstruction of decayed particles based on the Kalman filter. CBM-SOFT-note-2007-003, 7 May 2007*
- *KF Particle Finder — M. Zyzak, "Online selection of short-lived particles on many-core computer architectures in the CBM experiment at FAIR," Dissertation thesis, Goethe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

Particle Identification and Reconstruction



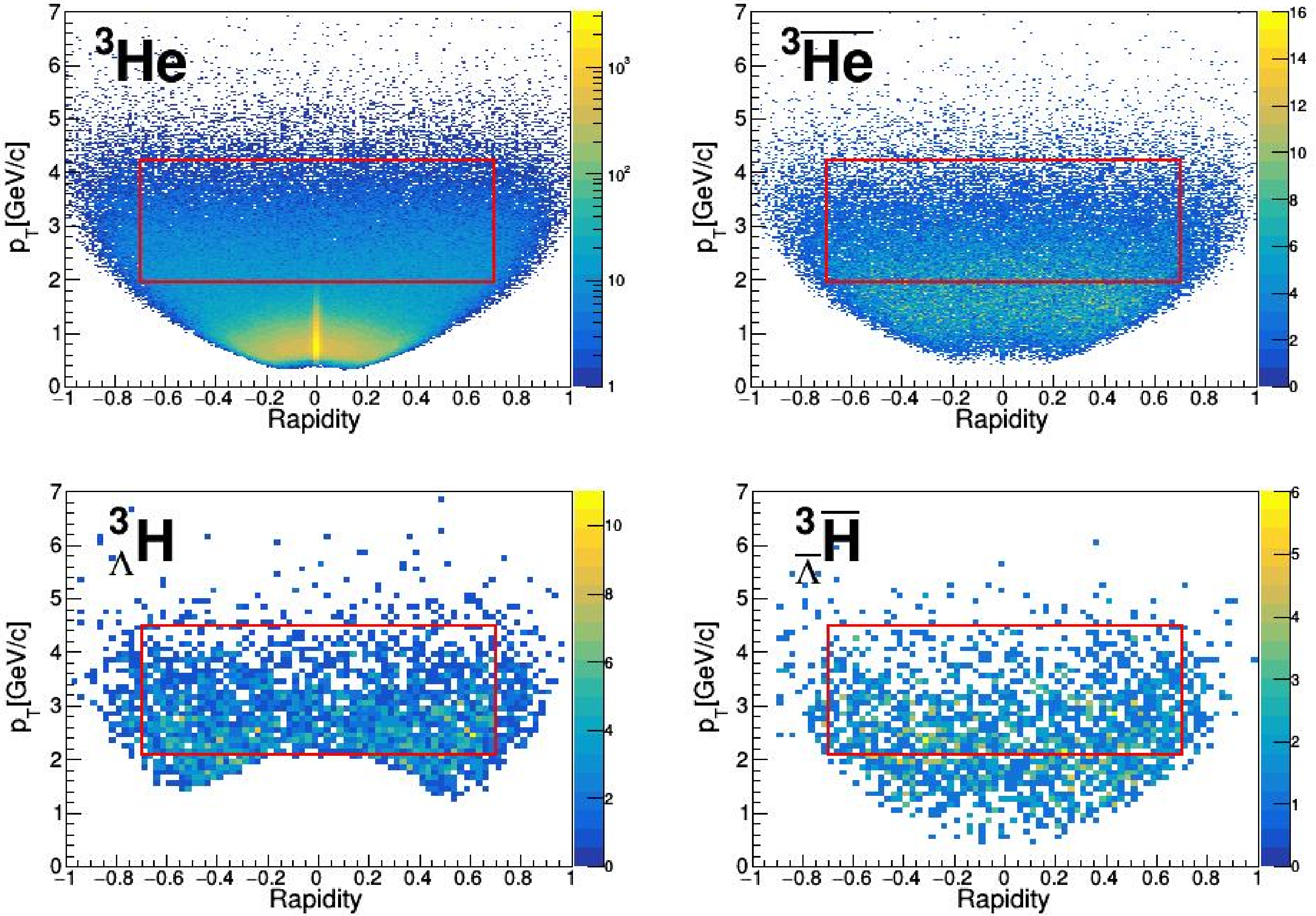
- Got 17 candidates of $^{4}_{\Lambda}\overline{H}$ and their significance (equivalent Gauss N_σ) reached 5.5, that means the possibility of 17 candidates all coming from fluctuation of background is just $4.0*10^{-8}$;

$$\sum_{n=S+B}^{+\infty} Poisson(n,B) = \int_{N_\sigma}^{+\infty} Gaus(x,\sigma)dx$$



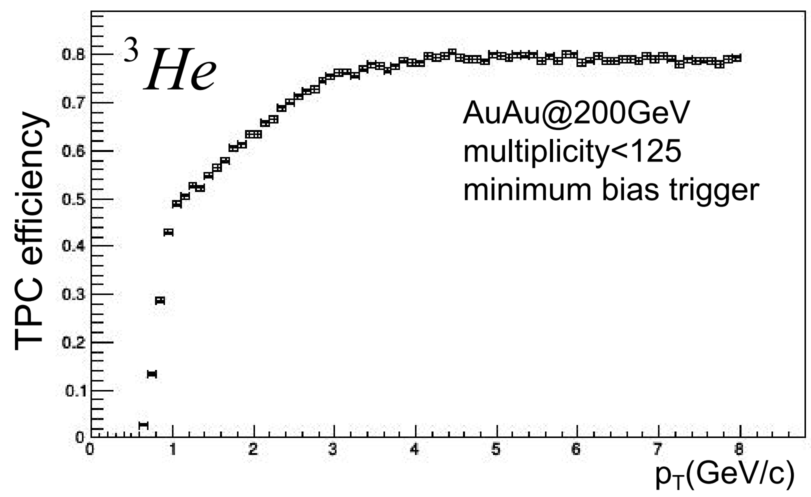
$^{4}_{\Lambda}\overline{H}$ is the heaviest antihypernuclei observed in laboratory!

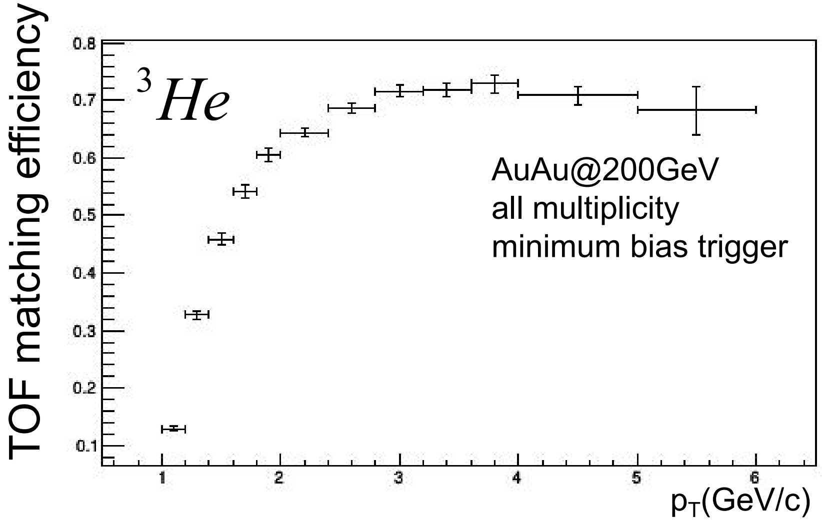
Yield Ratios Measurement - Phase Space

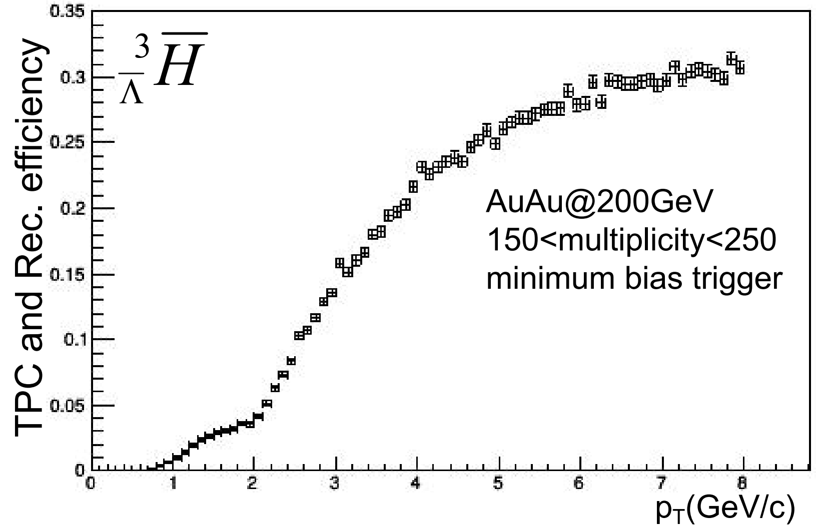


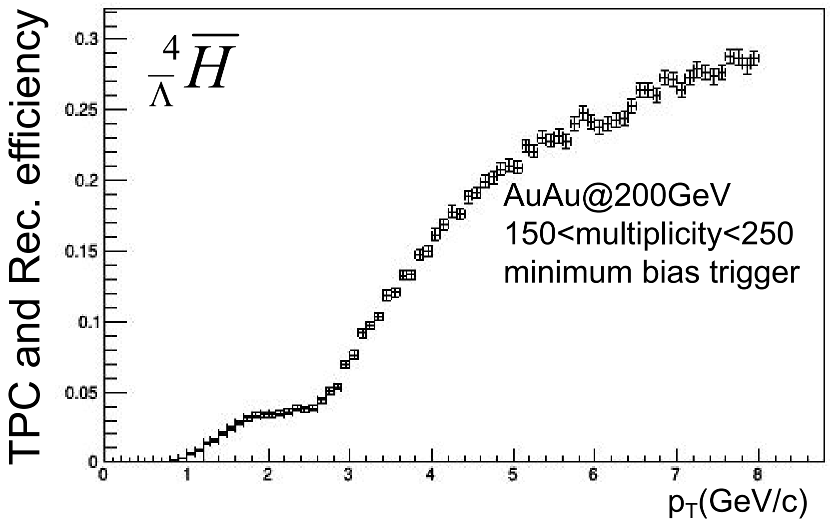
- Yield measurement in phase space region : $0.7<p_T/M<1.5$, $|rapidity|<0.7$

Yield Ratios Measurement - Efficiencies

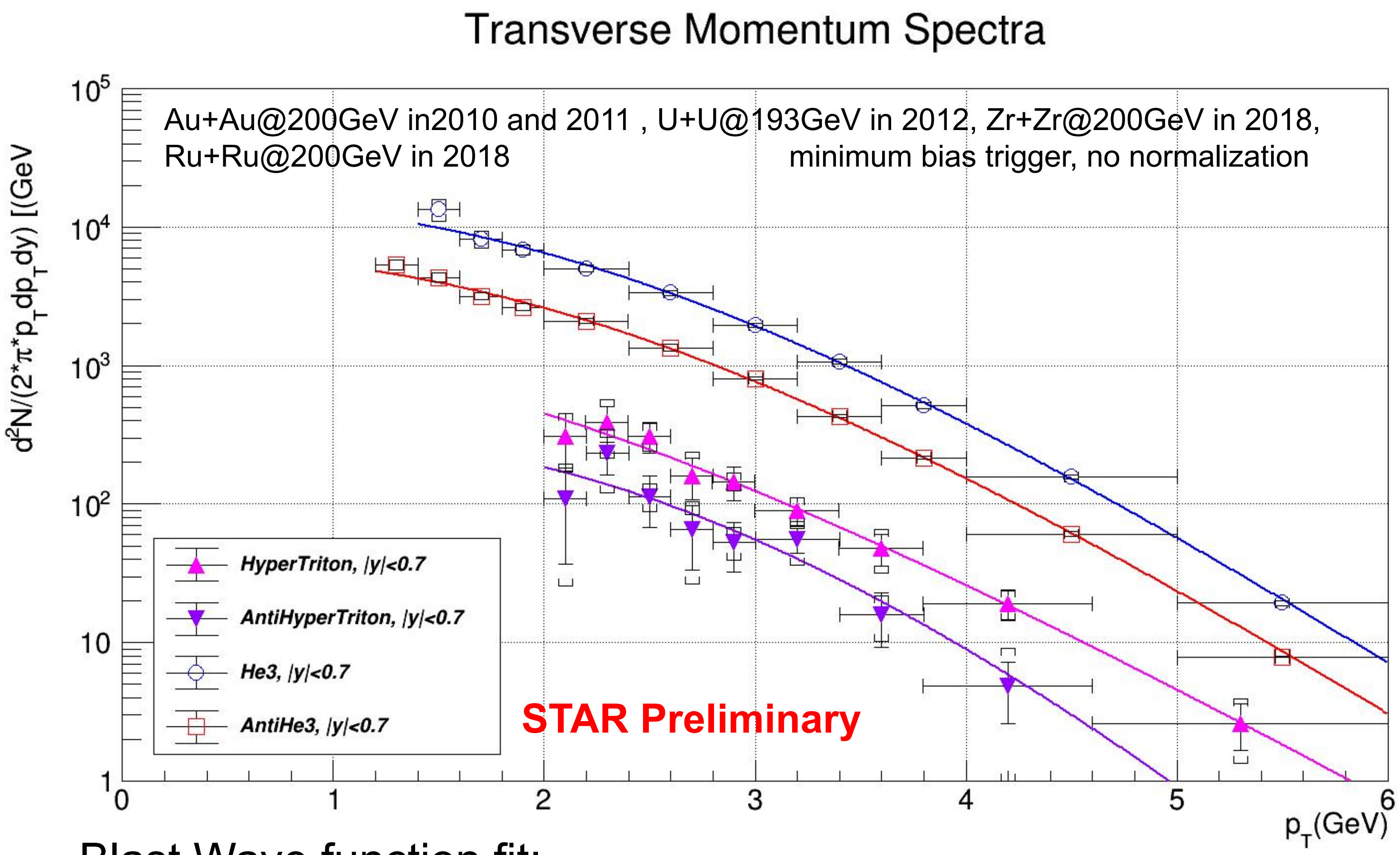








Yield Ratios Measurement - A = 3 Particles



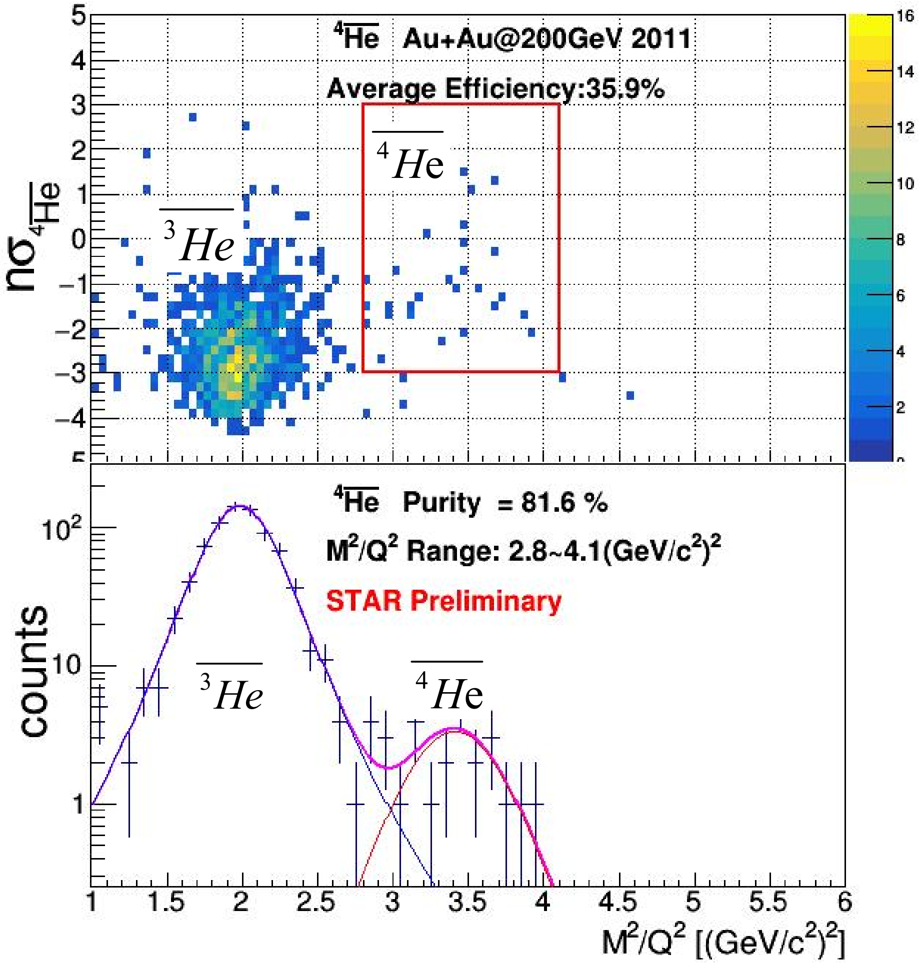
Blast Wave function fit:

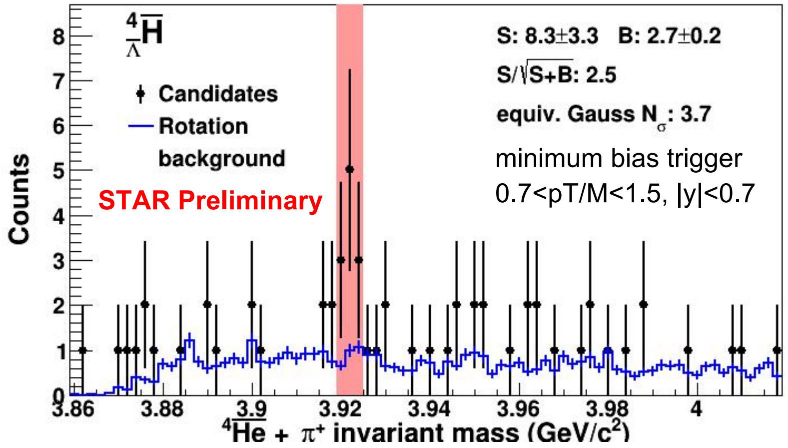
$$\frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy} \propto \int_0^R r dr m_0 I_0\left(\frac{p_T \sinh\rho}{T}\right) K_1\left(\frac{m_T \cosh\rho}{T}\right)$$

- *Physical Review C Volume48, Number5, 1993*

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

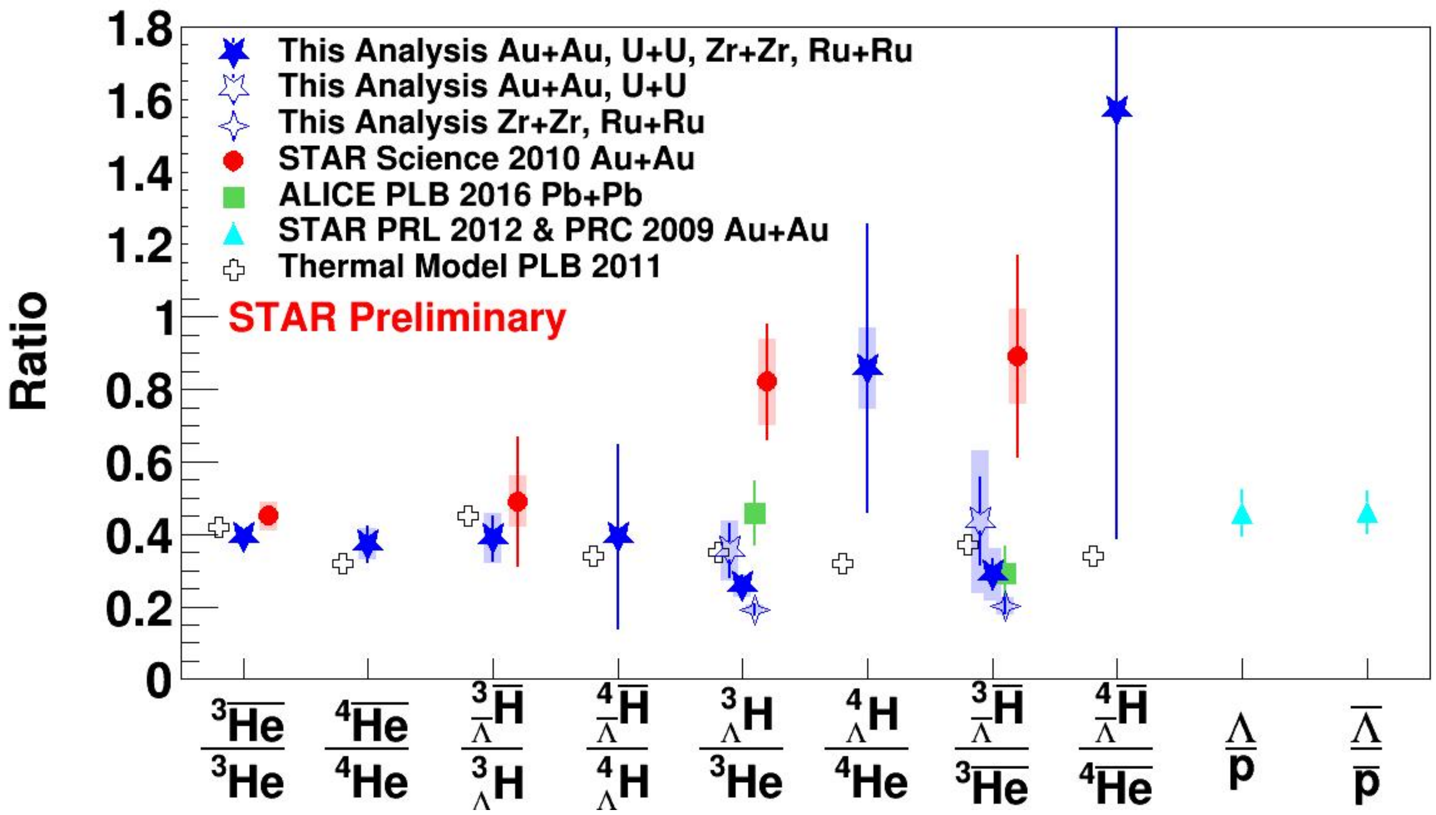
Yield Ratios Measurement - A = 4 Particles





- 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.

Yield Ratios Measurement



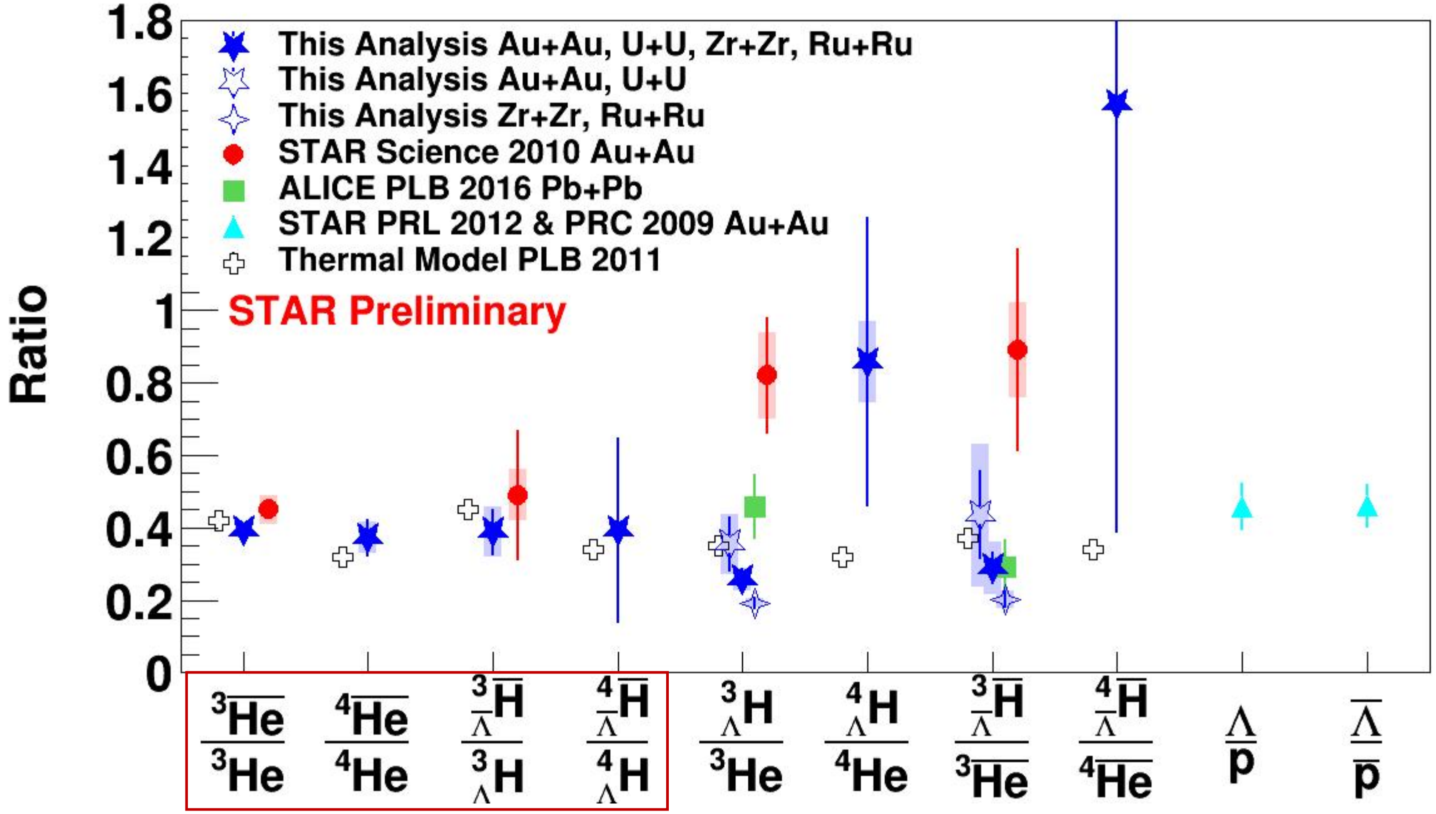
- STAR Science 2010: Au+Au@200GeV
- ALICE PLB: Pb+Pb@2.76TeV
- Thermal Model:

  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)*
- *Physics Letters B 754 (2016) 360-372*
- *Physics Letters B 697 (2011) 203-207*

Yield Ratios Measurement

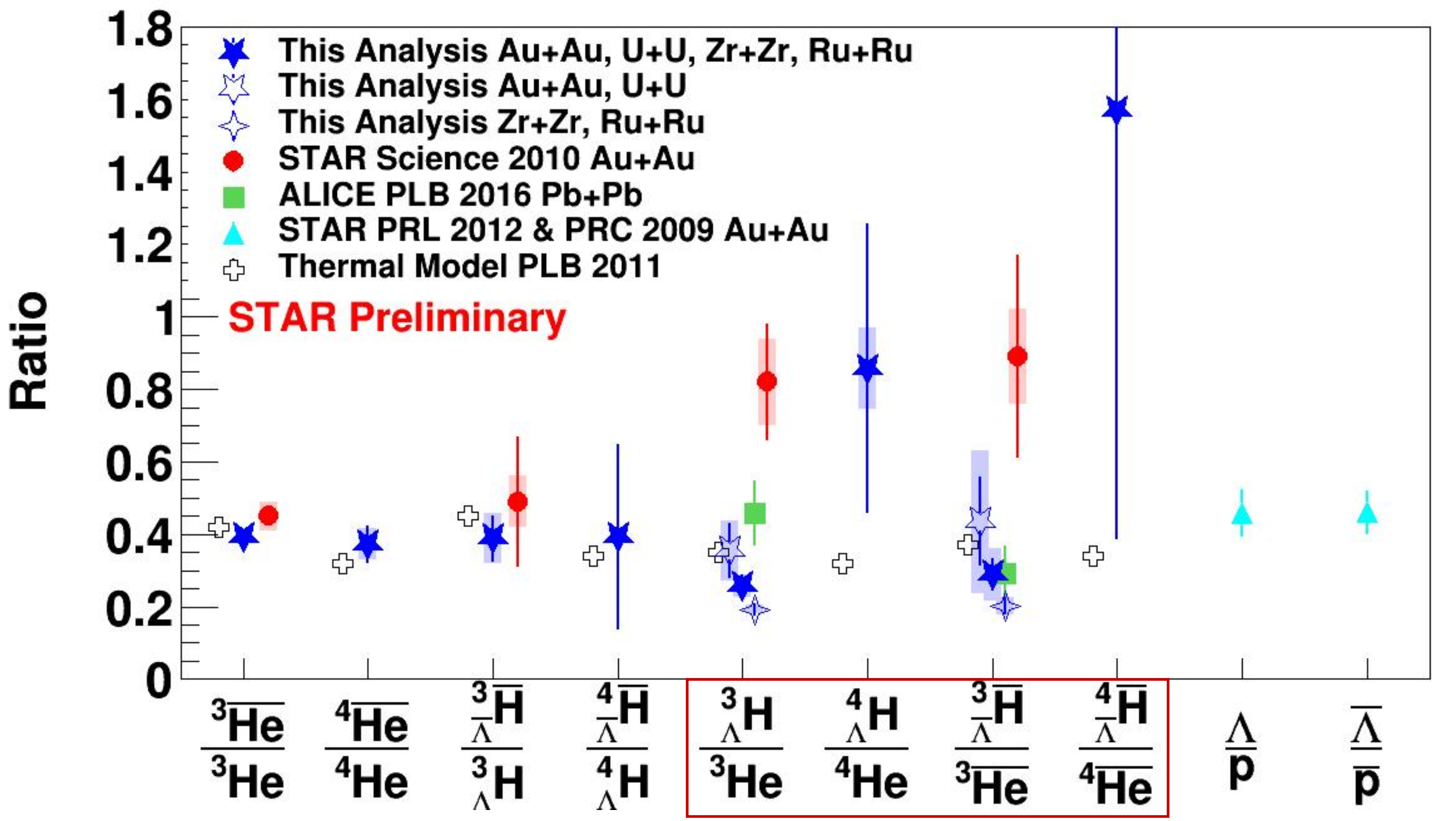


For the ratios of anti-matter over matter:

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

$$\frac{{}^{3}_{\bar{\Lambda}}\overline{H}}{{}^{3}_{\Lambda}H} \approx \frac{{}^{3}\overline{He}}{{}^{3}He} \qquad \frac{{}^{4}_{\bar{\Lambda}}\overline{H}}{{}^{4}_{\Lambda}H} \approx \frac{{}^{4}\overline{He}}{{}^{4}He}$$

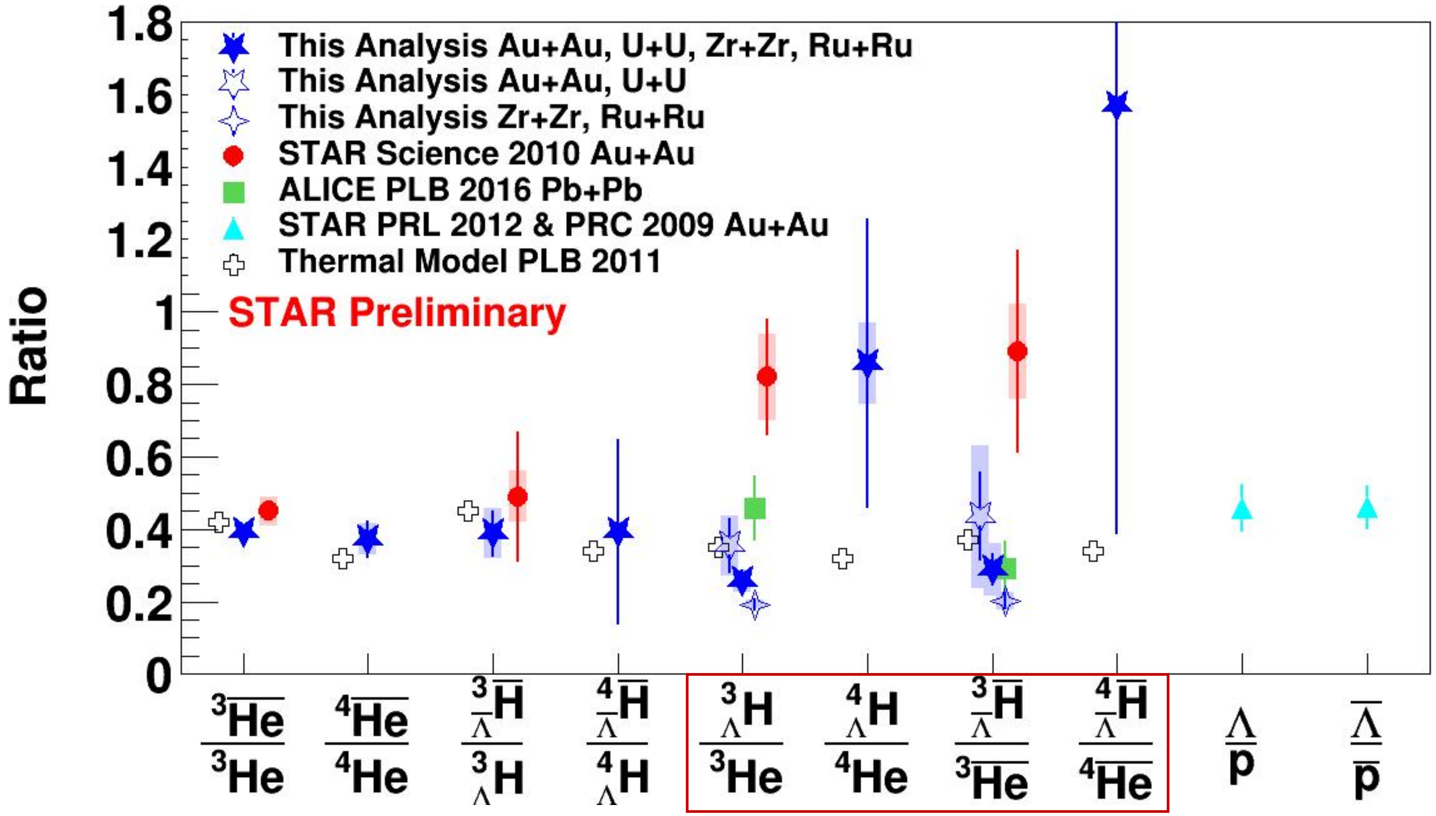
Yield Ratios Measurement



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 consistent with previous measurements, as well as the thermal model calculation.

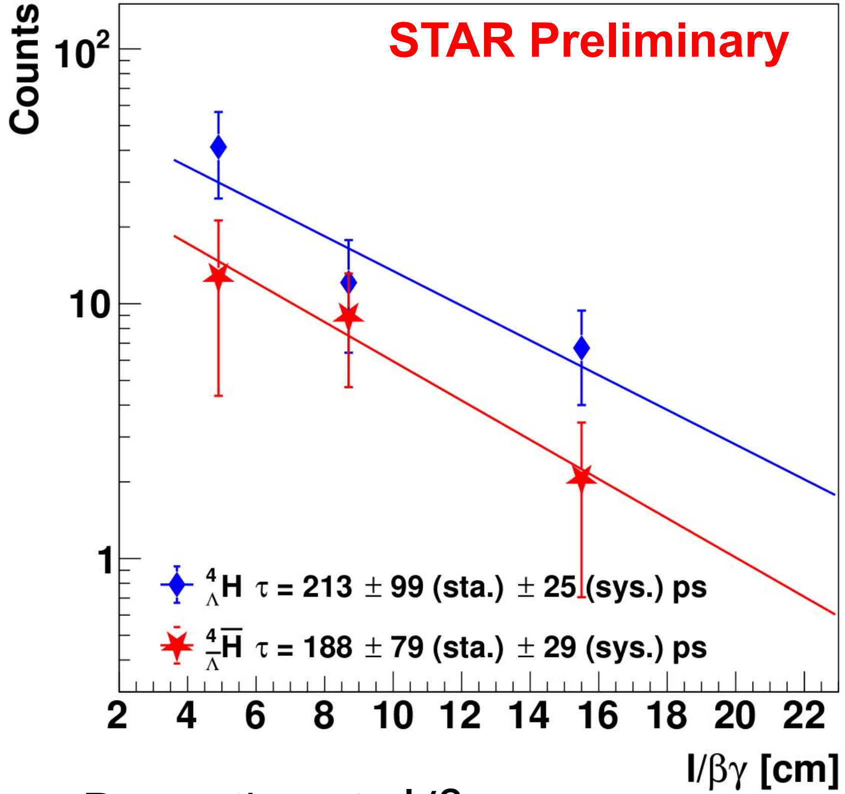
Yield Ratios Measurement



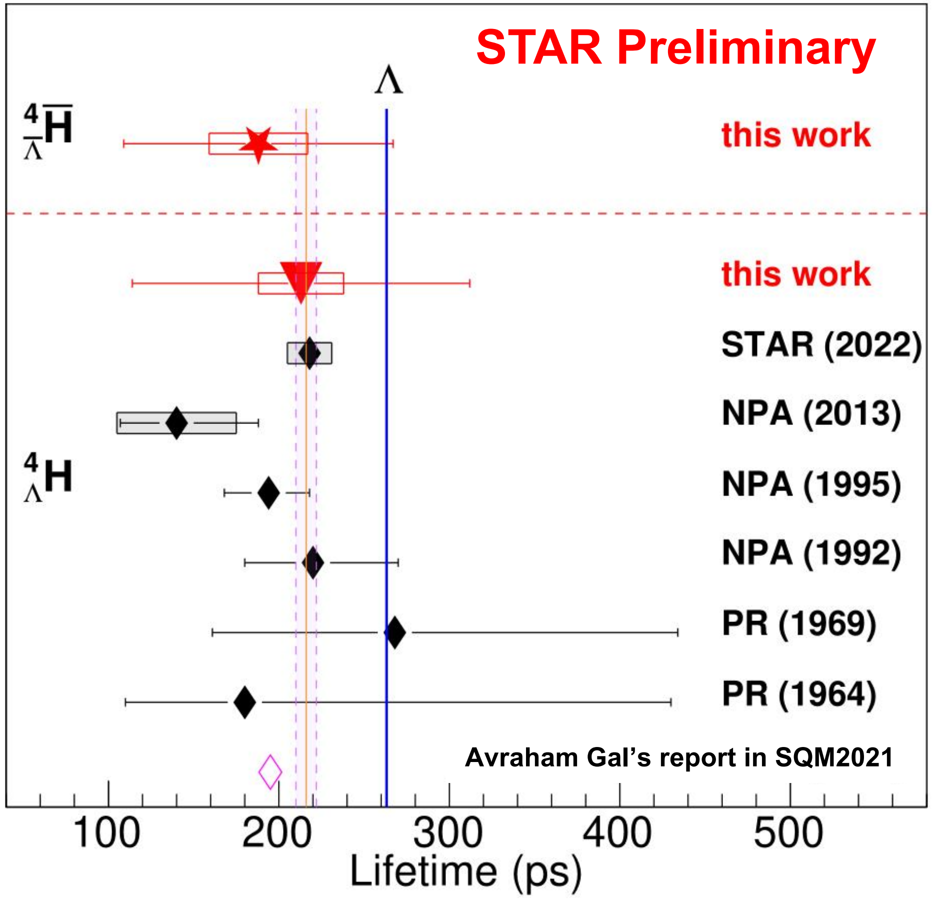
For the ratios of (anti-)hypernuclei over (anti-)nuclei:

- With all the collision systems combined, ${}^{4}_{\Lambda}H/{}^{4}He$ and ${}^{4}_{\Lambda}\overline{H}/{}^{4}\overline{He}$ seem to be larger than ${}^{3}_{\Lambda}H/{}^{3}He$ and ${}^{3}_{\Lambda}\overline{H}/{}^{3}\overline{He}$. This may hint at the production of ${}^{4}_{\Lambda}H$ or ${}^{4}_{\Lambda}\overline{H}$ with both spin 0 and 1 states.

Lifetime Measurements



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



- *Avraham Gal, EPJ Web of Conferences 259, 08002 (2022)*

Summary

- 17±4.7 signal candidates of ${}^{4}_{\bar{\Lambda}}\overline{H}$ observed, with equivalent Gaussian significance of 5.5 σ.
- Various anti-particle or particle ratios are presented.
  - ${}^{3}_{\bar{\Lambda}}\overline{H} \Big/ {}^{3}_{\Lambda}H \approx {}^{3}\overline{He} \Big/ {}^{3}He$, ${}^{4}_{\bar{\Lambda}}\overline{H} \Big/ {}^{4}_{\Lambda}H \approx {}^{4}\overline{He} \Big/ {}^{4}He$
  - ${}^{4}_{\Lambda}H \Big/ {}^{4}He \gtrsim {}^{3}_{\Lambda}H \Big/ {}^{3}He$, ${}^{4}_{\bar{\Lambda}}\overline{H} \Big/ {}^{4}\overline{He} \gtrsim {}^{3}_{\bar{\Lambda}}\overline{H} \Big/ {}^{3}\overline{He}$
- Lifetimes of hypernuclei are measured: $\tau_{{}^{4}_{\Lambda}H} \approx \tau_{{}^{4}_{\bar{\Lambda}}\overline{H}}$.

Thank you for your attention!

• Back Up - Lifetime

Use physical spectra to weight eff. vs p_T , we can get the mean efficiency of every L/β*γ bin.

(anti-) ${}^{3}_{\Lambda}H$ L/β*γ bin：
3.4~5.0, 5.0~8.0, 8.0~12.0, 12.0~17.0, 17.0~22.0, 22.0~27.0

(anti-) ${}^{4}_{\Lambda}H$ L/β*γ bin：
3.4~6.4, 6.4~11.0, 11.0~20.0