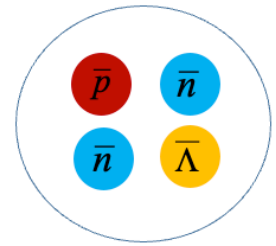
Observation of $^{4}_{\bar{\Lambda}}\overline{\mathrm{H}}$ in Heavy Ions Collisions at RHIC



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1st Symposium on Nuclear Physics
in Guangdong-Hong Kong-Macao Greater Bay Area

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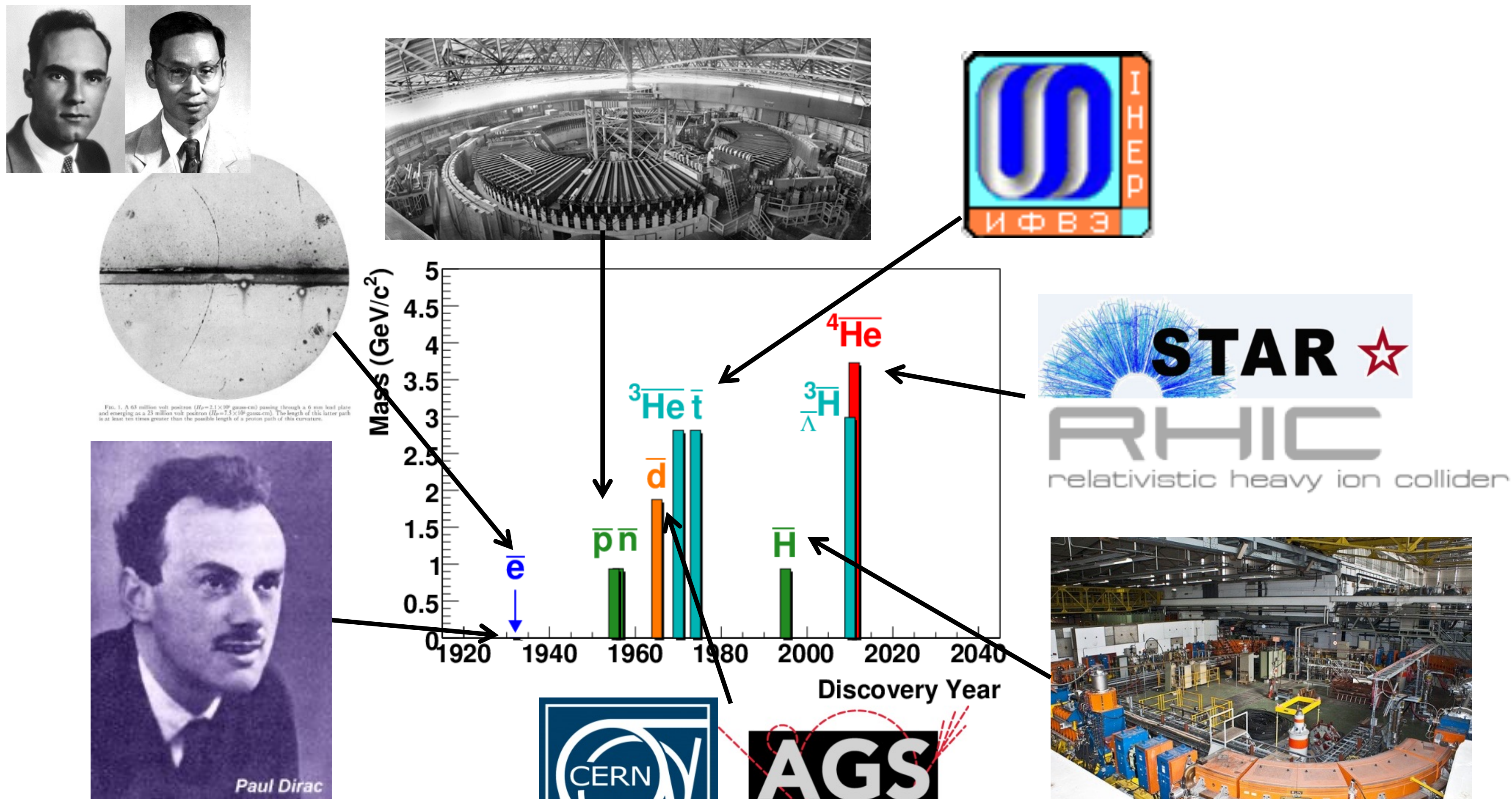
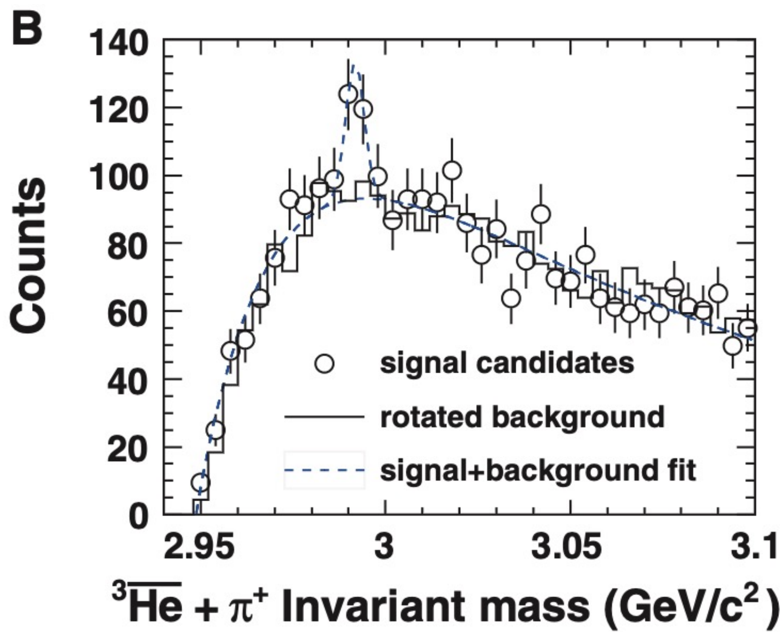
Introduction



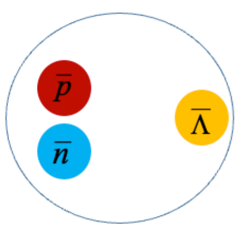
Dirac, P.A.M., The Quantum Theory of the Electron. Proc. Roy. Soc. Lond. A 117, 610 (1928).

- The search for antimatter particles has a history of nearly 100 years
- Antinuclei heavier than anti-proton have been observed only at accelerators

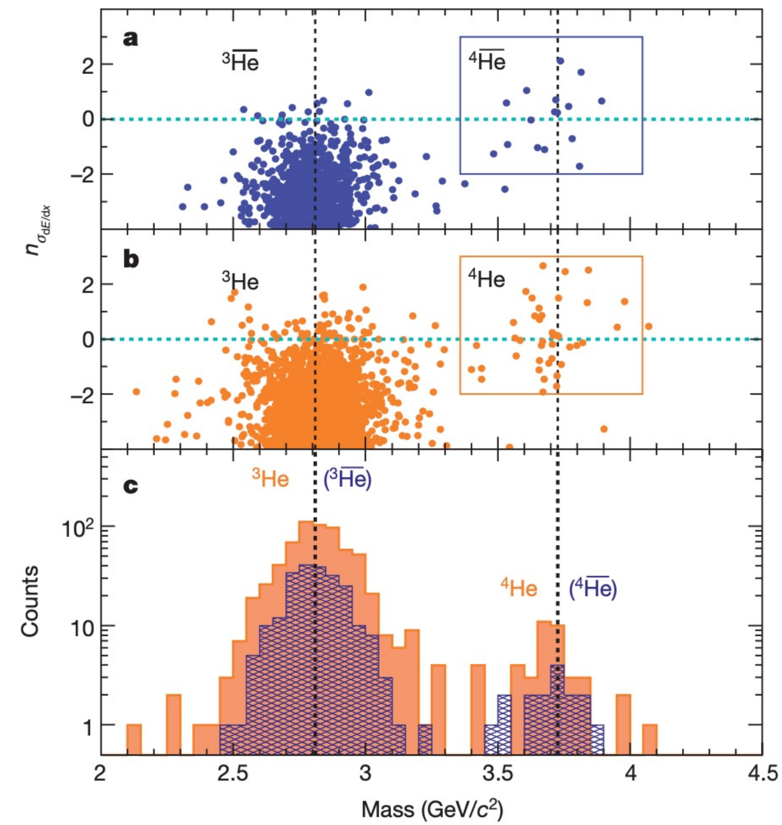
Introduction

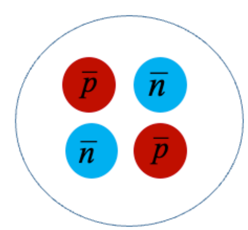


Science 328, 58 (2010)



70 ± 17 $^{3}_{\bar{\Lambda}}\overline{H}$ candidates



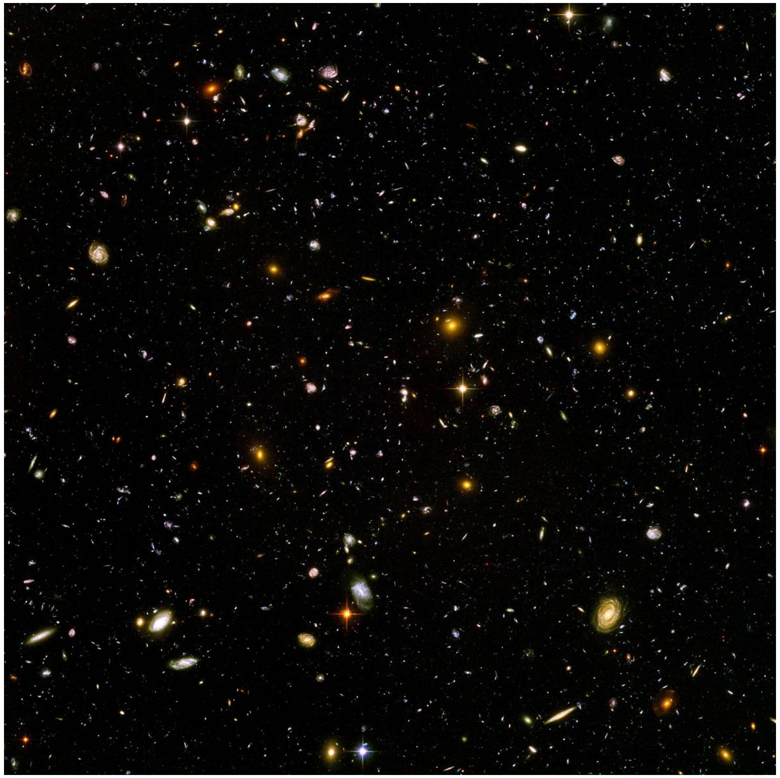


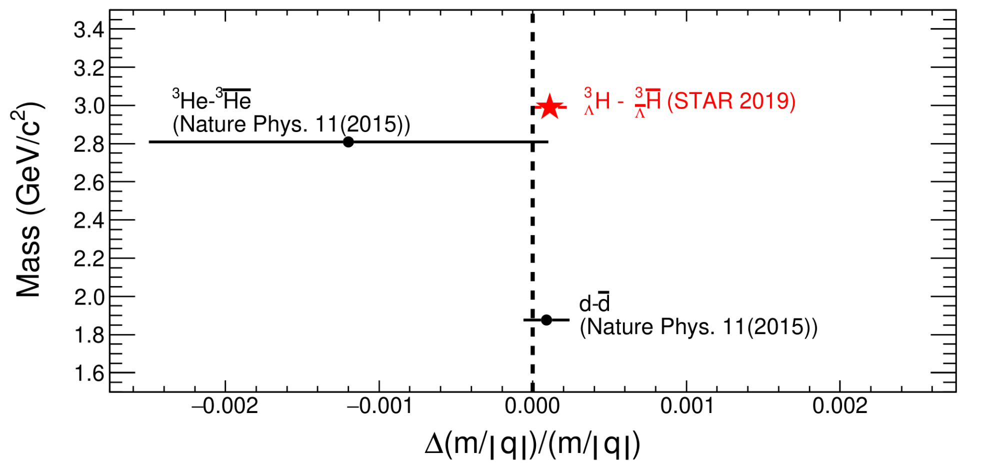
Nature 473, 353 (2011)

15 counts of $^{4}\overline{He}$

- STAR has observed 2 of the recently discovered antimatter particles: $^{3}_{\bar{\Lambda}}\overline{H}$ and $^{4}\overline{He}$

Introduction

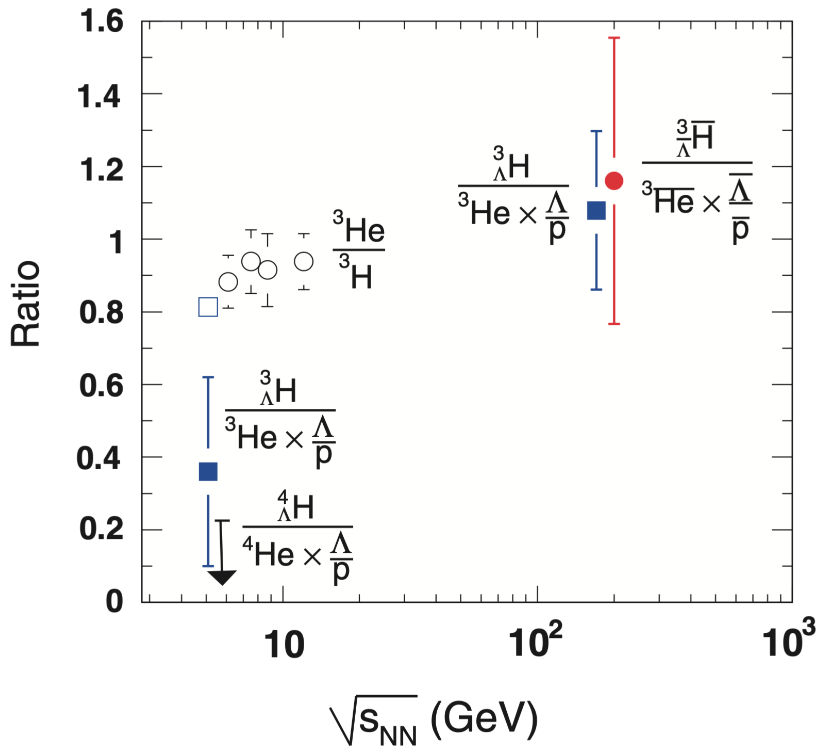




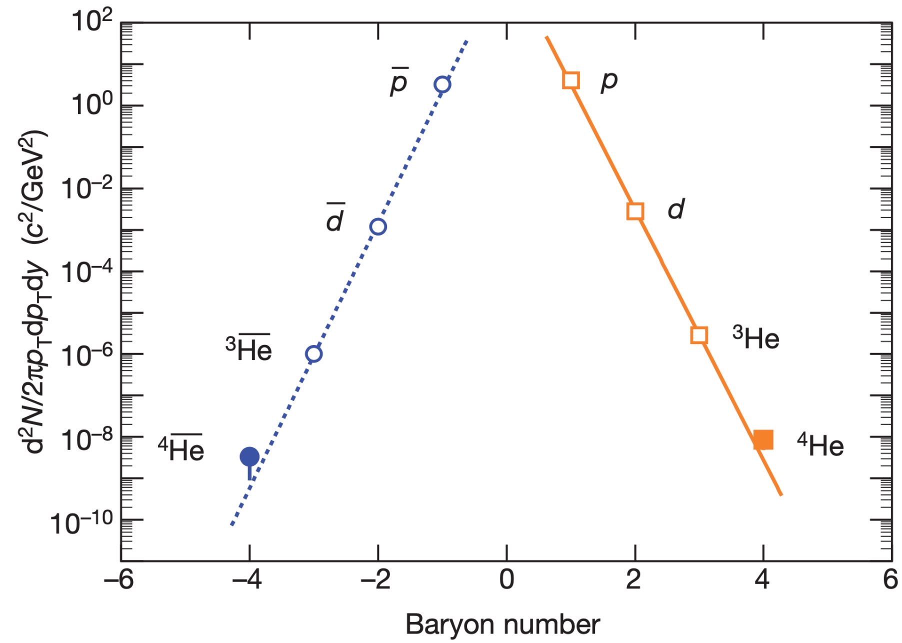
Nature Physics 16, 409 (2020)

- 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.

Introduction

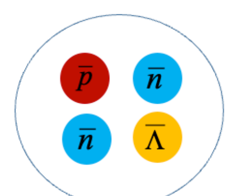


Science 328, 58 (2010)

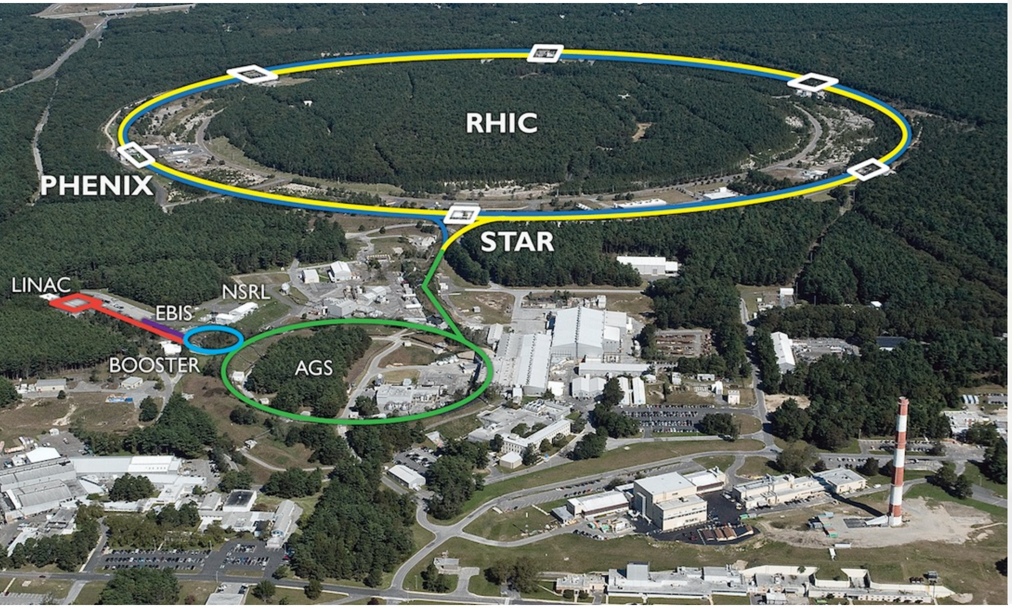


Nature 473, 353 (2011)

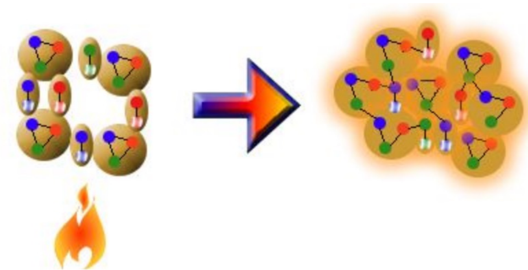
- Same order of magnitude of production yield for $^3_\Lambda\overline{H}$ and $^3\overline{He}$
- 3 order of magnitude lower production yield for each additional antibaryon number
- All A=5 nuclei are very unstable
- One candidate for the next easiest-to-find anti-particle is $^4_\Lambda\overline{H}$

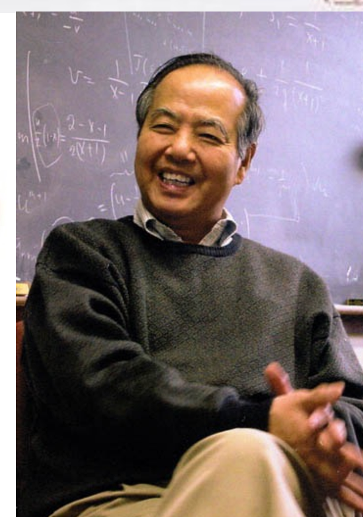


RHIC-STAR



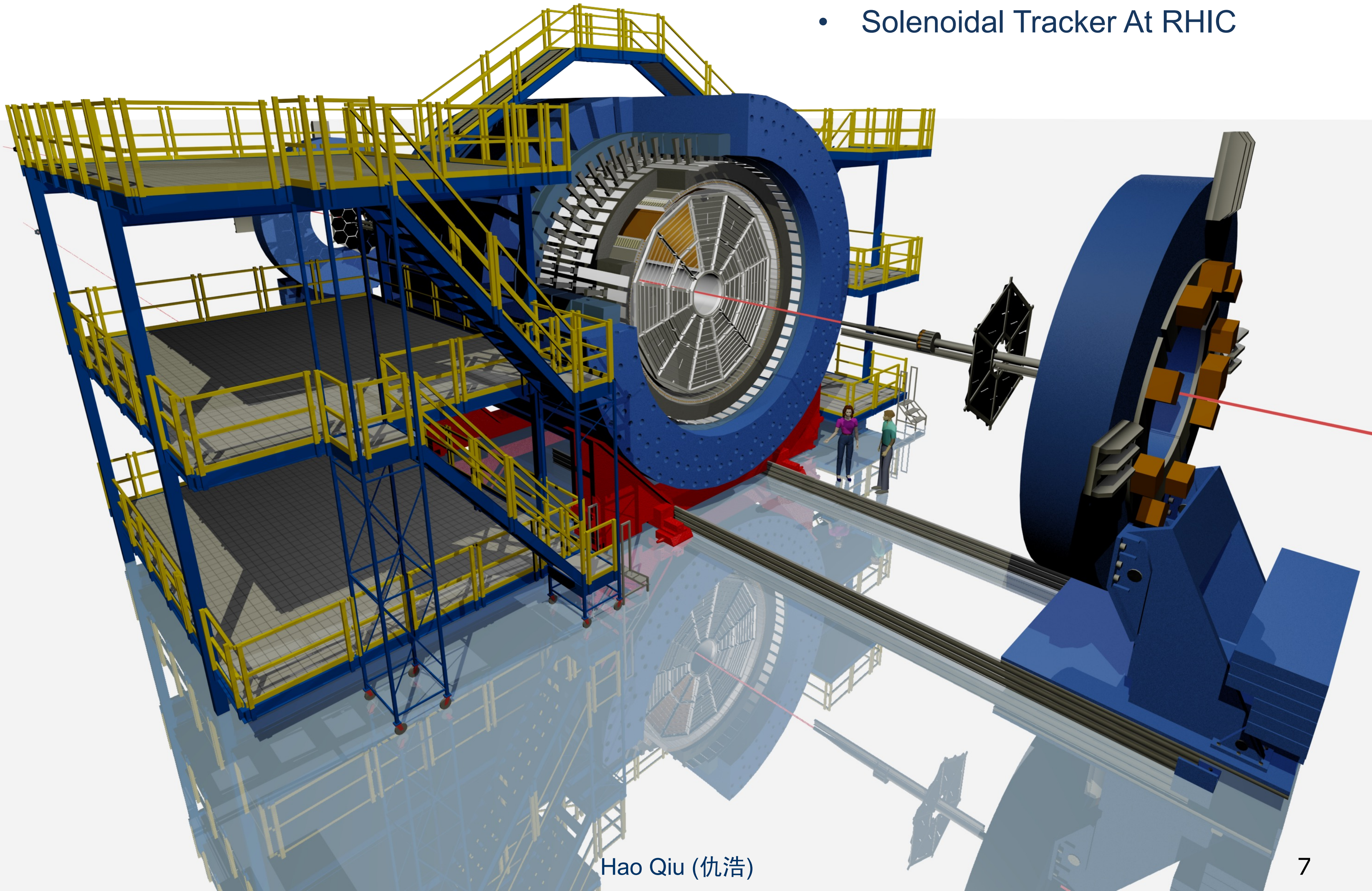
- Relativistic Heavy-Ion Collider
- 3.8 km circumference
- Typical collision: Au+Au @ 200 GeV
- Mainly built to create and study the properties of quark-gluon plasma





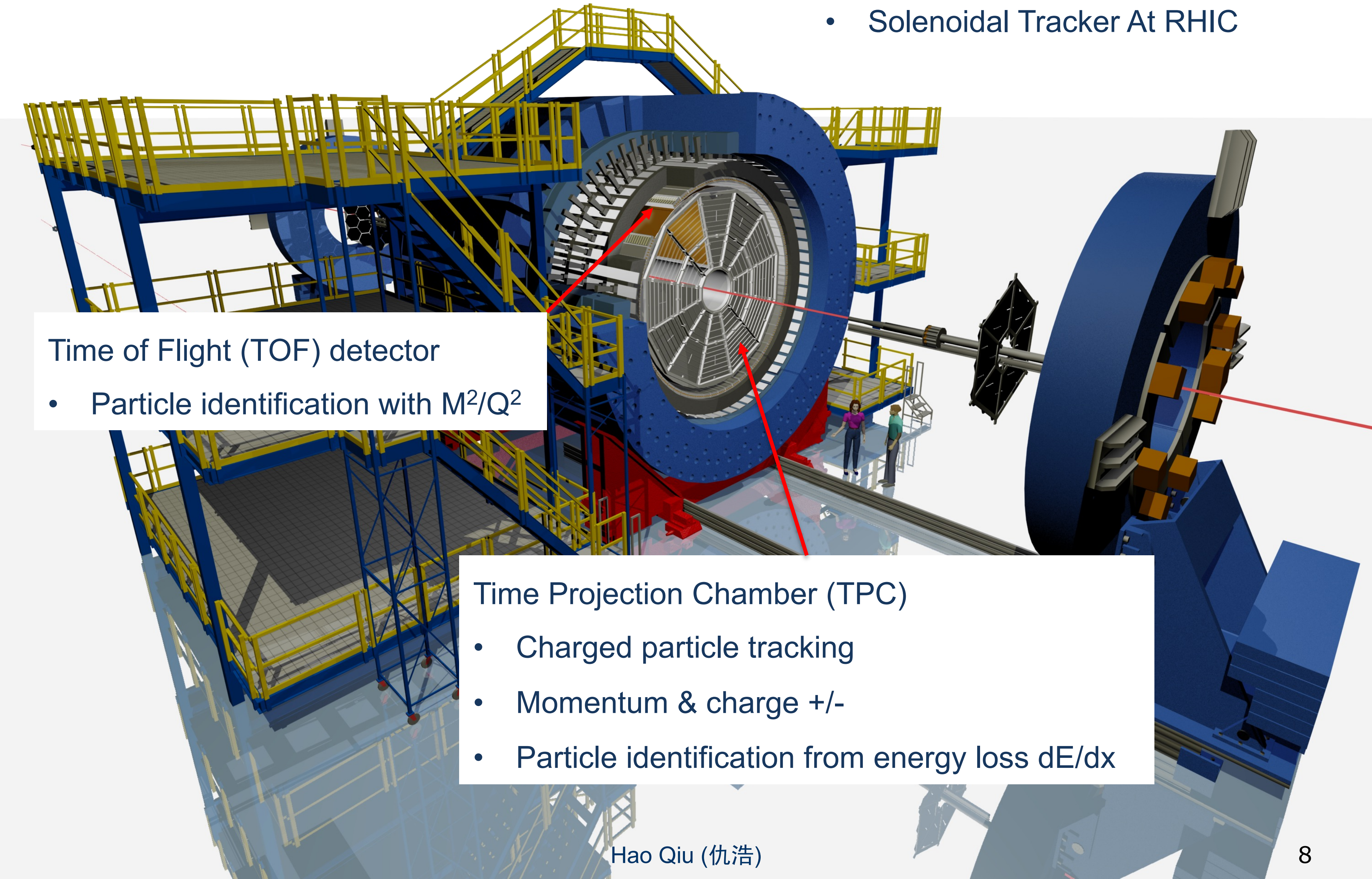
RHIC-STAR

- Solenoidal Tracker At RHIC



RHIC-STAR

- Solenoidal Tracker At RHIC



Time of Flight (TOF) detector

- Particle identification with M^2/Q^2

Time Projection Chamber (TPC)

- Charged particle tracking
- Momentum & charge +/-
- Particle identification from energy loss dE/dx

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

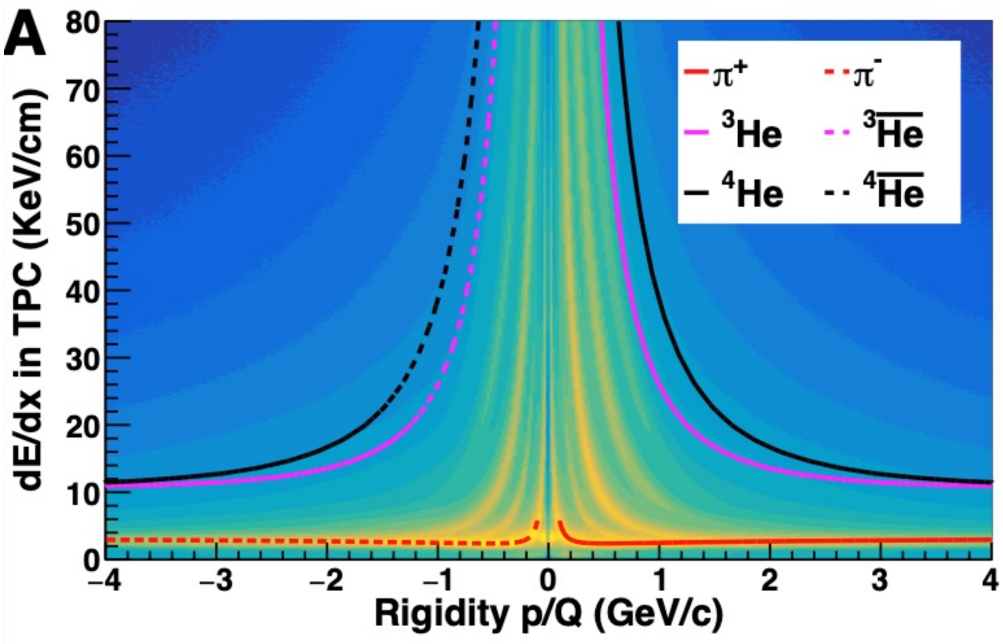
Triggers used:

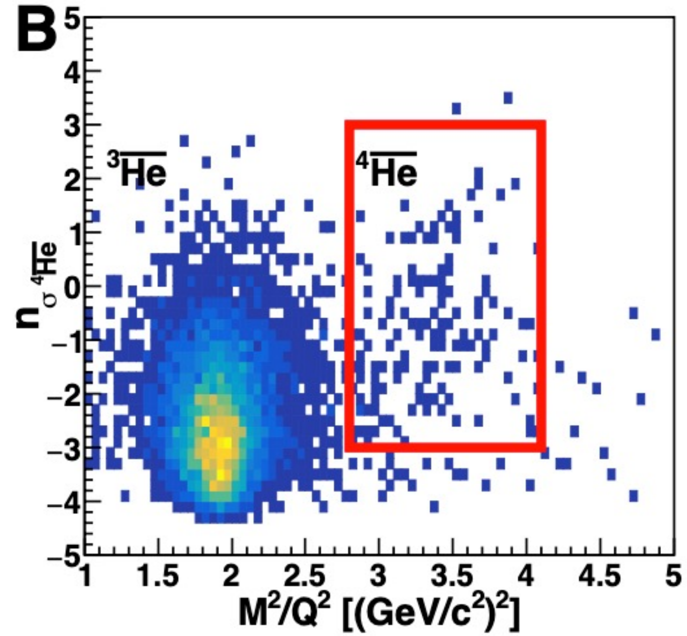
- Minimum bias
- Central
- Non-photonic electron
- Hadronic
- Di-muon
- High-level trigger

- Only minimum bias trigger used for yield ratios measurement

Daughter particle identification

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

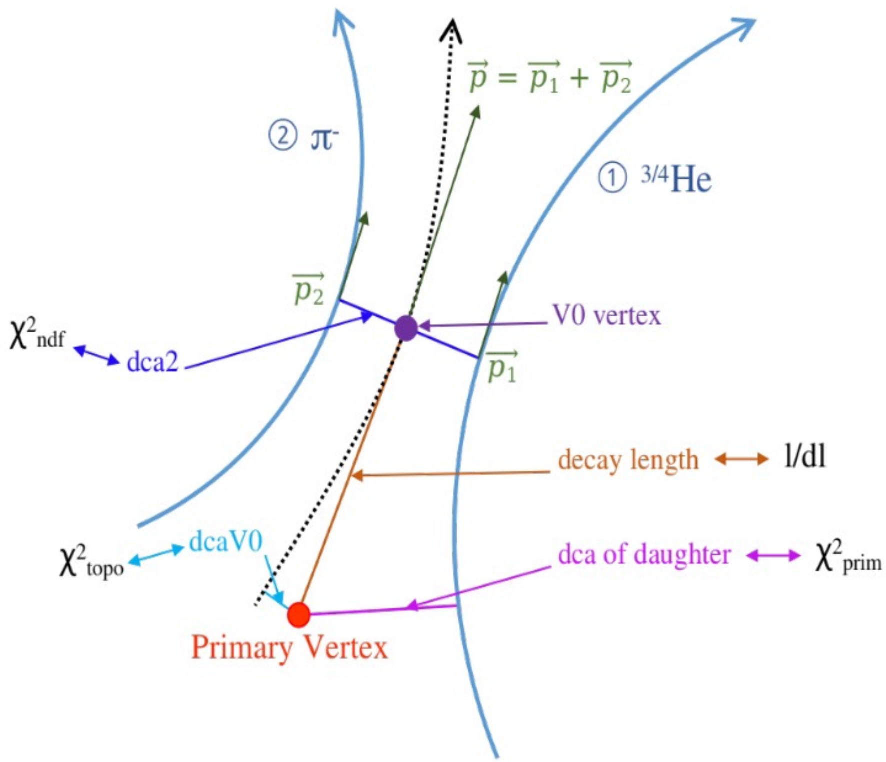




- ^{3}He & ^{4}He : p>2
- ^{3}He & $^{3}\overline{He}$: $|n_{\sigma 3He}|<3$; if TOF matched, $1<M^2/Q^2<3$
- ^{4}He & $^{4}\overline{He}$: $|n_{\sigma 4He}|<3$; $n_{\sigma 3He}>3.5$ or $2.8<M^2/Q^2<4.1$
- $\pi^{\pm}$: $|n_{\sigma\pi}|<3$

(Anti-)hypernuclei reconstruction

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

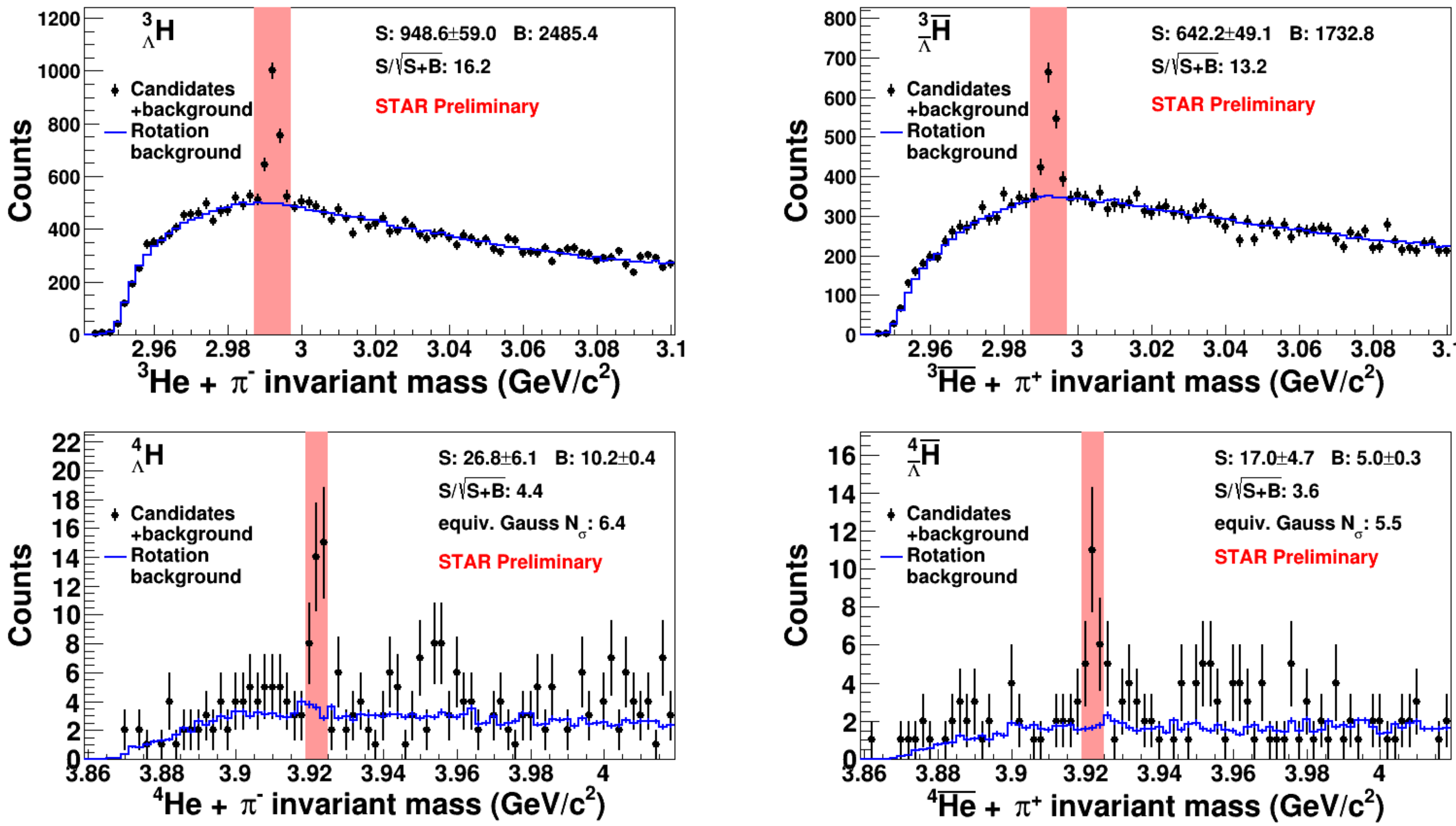


- KF(Kalman Filter) Particle package is used for the reconstruction
- Topology cuts obtained by optimizing $^{3}_{\Lambda}\overline{H}$ significance
  - Blind analysis for $^{4}_{\Lambda}\overline{H}$ search

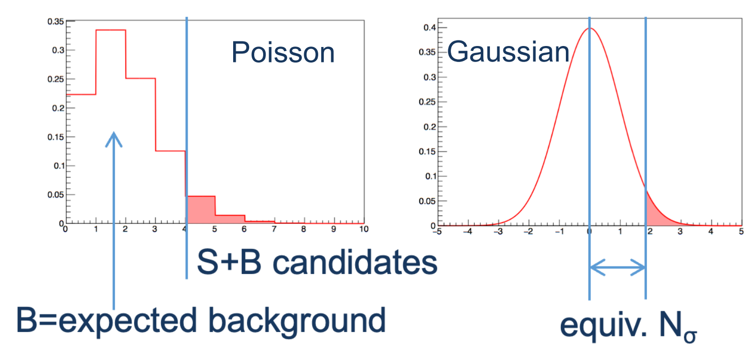
S. Gorbunov and I. Kisel, CBM-SOFT-note-2007-003, 2007
M. Zyzak, Dissertation thesis, Goethe University of Frankfurt, 2016

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	-

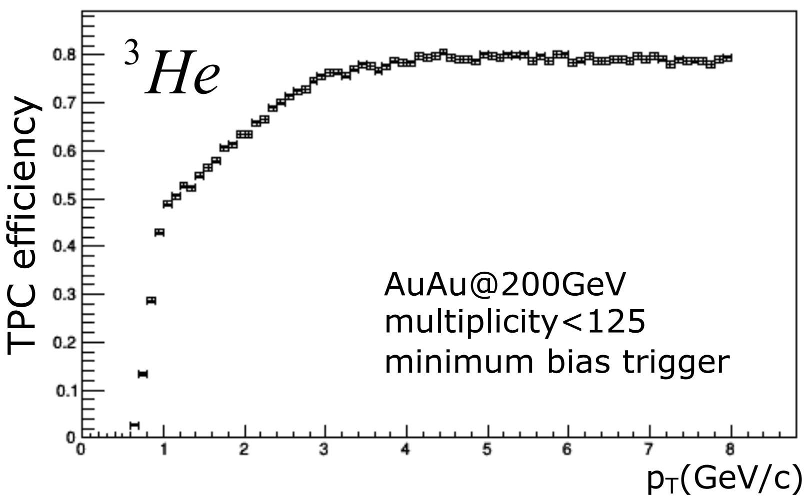
The signal

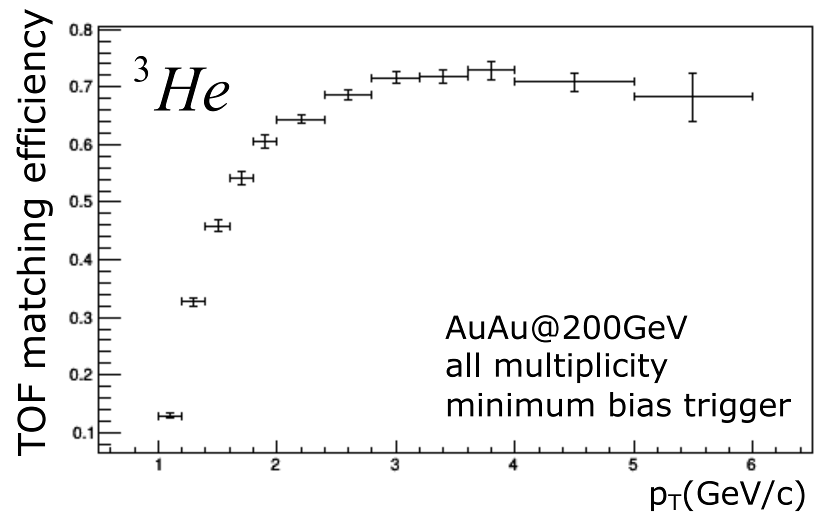


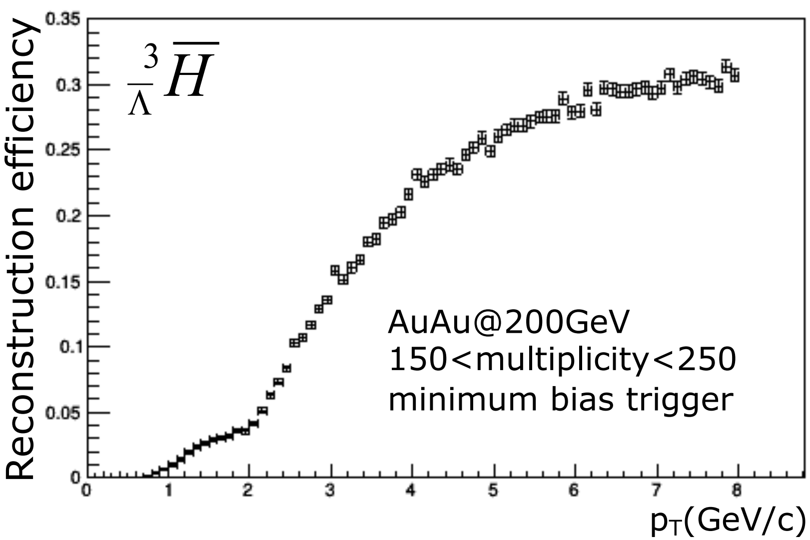
- A signal of 17 $^{4}_{\bar{\Lambda}}\overline{H}$ obtained
- Equivalent Gaussian significance = 5.5σ
    - Meaning the possibility of 17 candidates all coming from background fluctuation is 4.0×10^{-8}

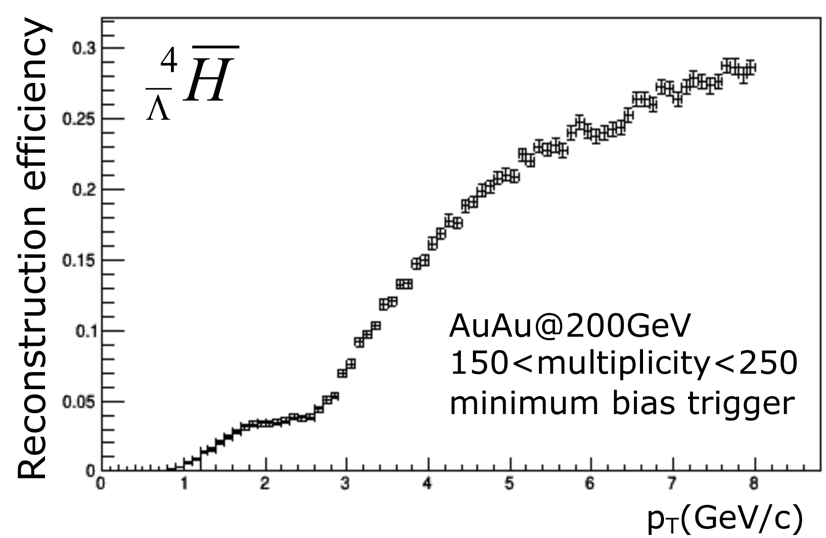


Yield ratio measurement - efficiencies

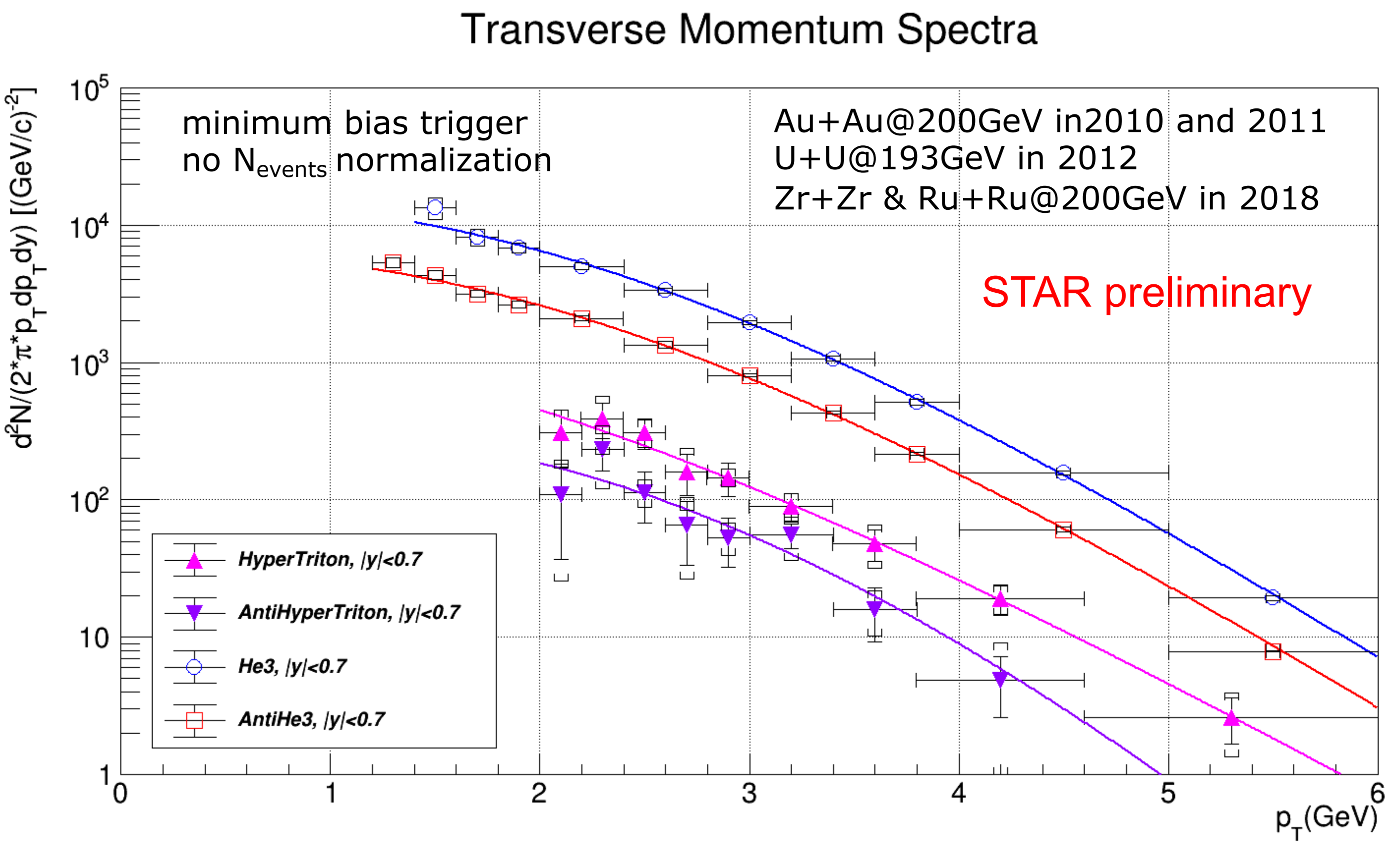








Transverse momentum spectra – A=3

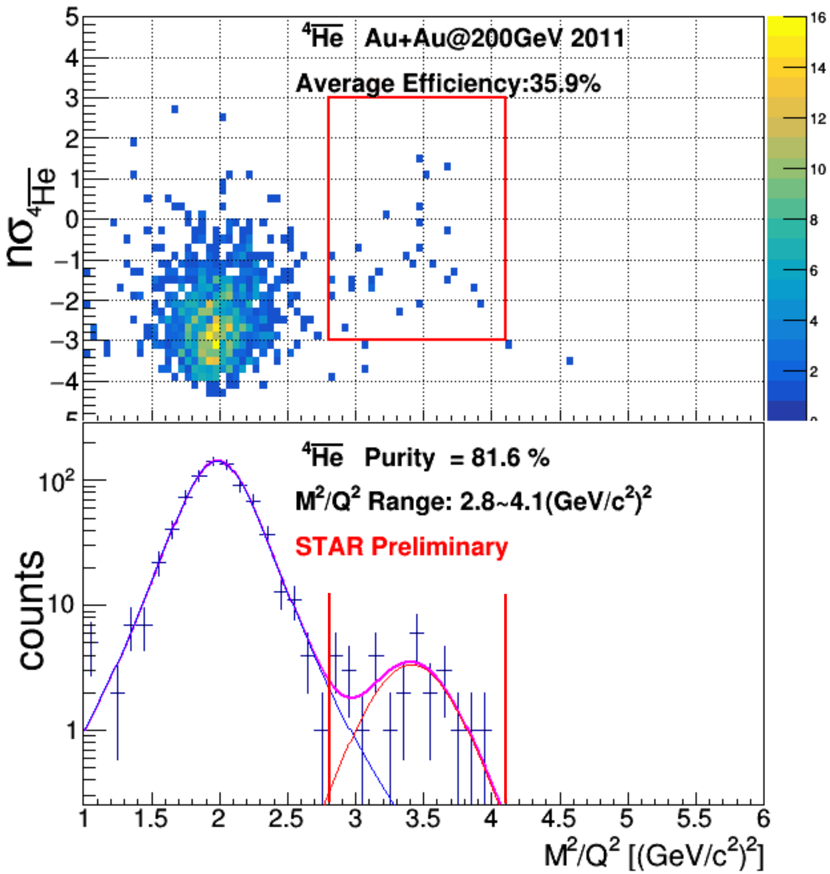


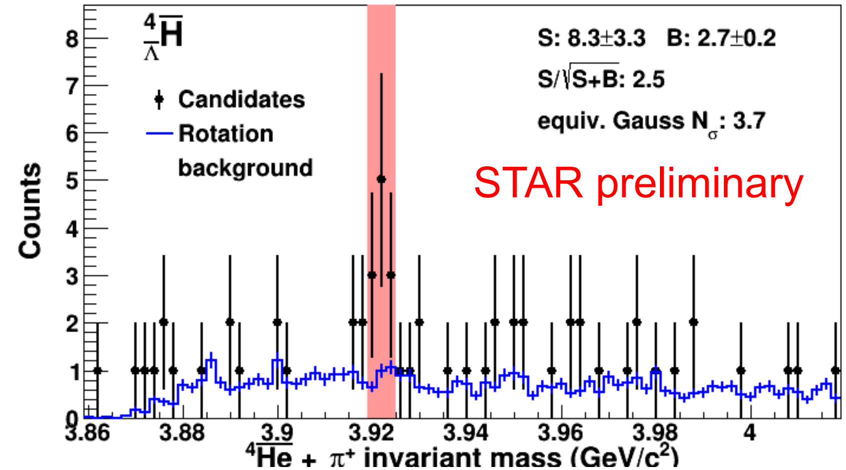
|rapidity|<0.7

Blast Wave function fit: $$\frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy} \propto \int_0^R r dr m_0 I_0\left(\frac{p_T \sinh\rho}{T}\right) K_1\left(\frac{m_T \cosh\rho}{T}\right)$$ PRC 48, 2462 (1993)

- For ^3He, $^3\overline{He}$, $^3_\Lambda H$ & $^3_\Lambda \overline{H}$, yields are obtained by integrating over the measured p_T range: $0.7<p_T/M<1.5$

Yield measurement – A=4



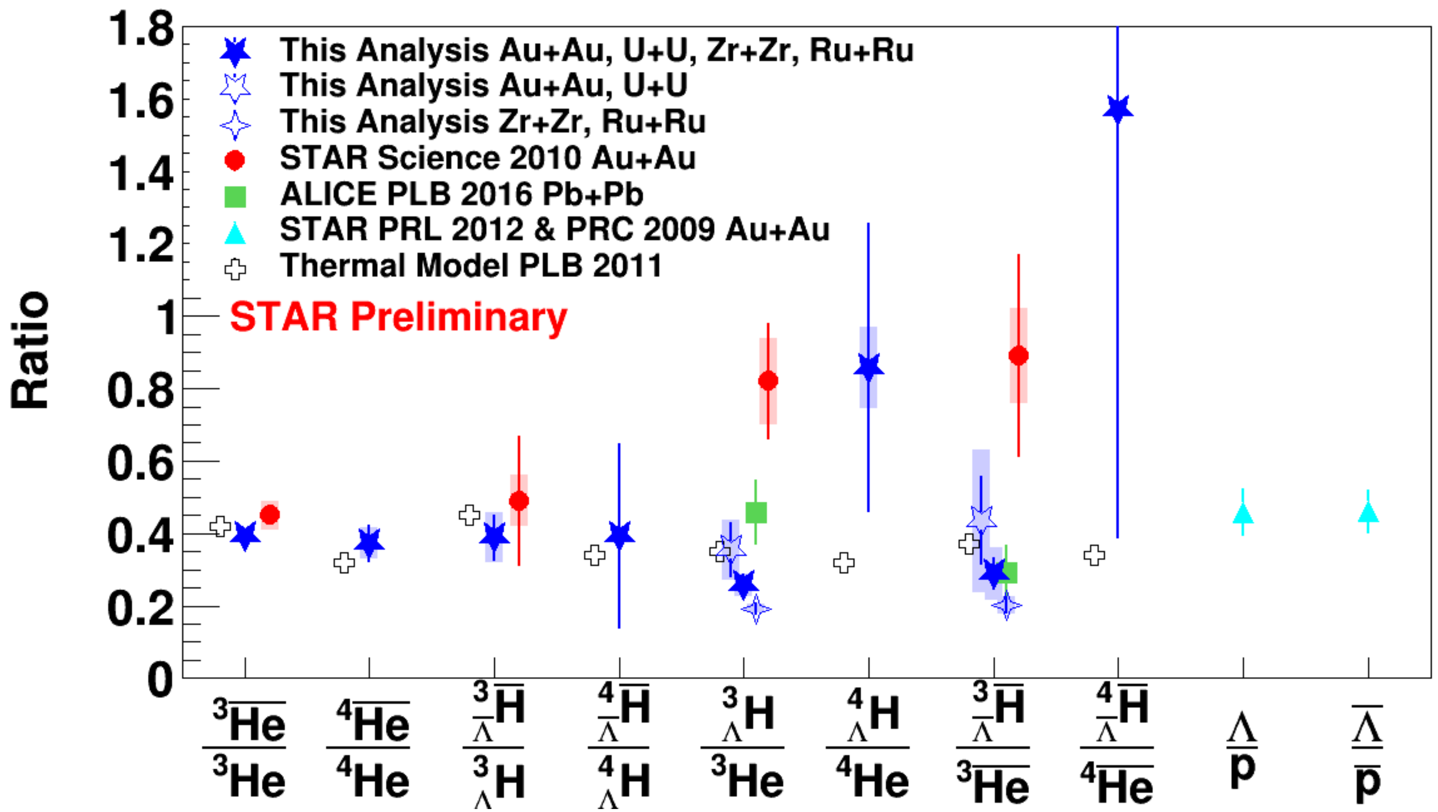


$0.7<p_T/M<1.5$

$|rapidity|<0.7$

- 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

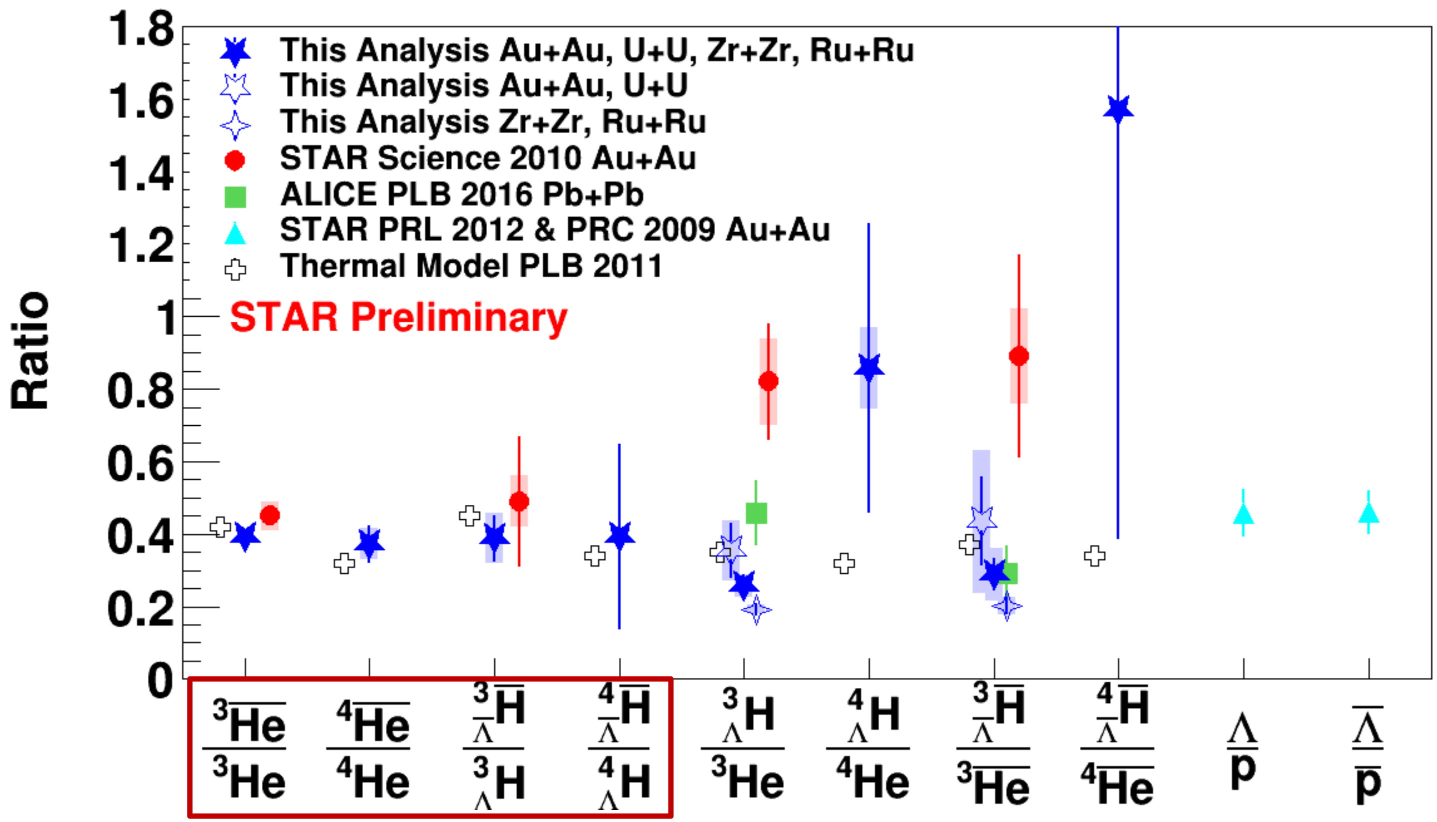


- Branching fractions:
  - 25% for ${}^{3}_{\Lambda}H$ 2 body decay
  - 50% for ${}^{4}_{\Lambda}H$ 2 body decay
- Phase space of this analysis:
  - $0.7<p_T/M<1.5$, |rapidity|<0.7

- STAR Science 2010: Au+Au@200GeV
- ALICE PLB: Pb+Pb@2.76TeV
- Thermal Model: T=164MeV, μ_B=24MeV

Scince 328, 58 (2010)
PLB 754, 360 (2016)
PLB 697, 203 (2011)

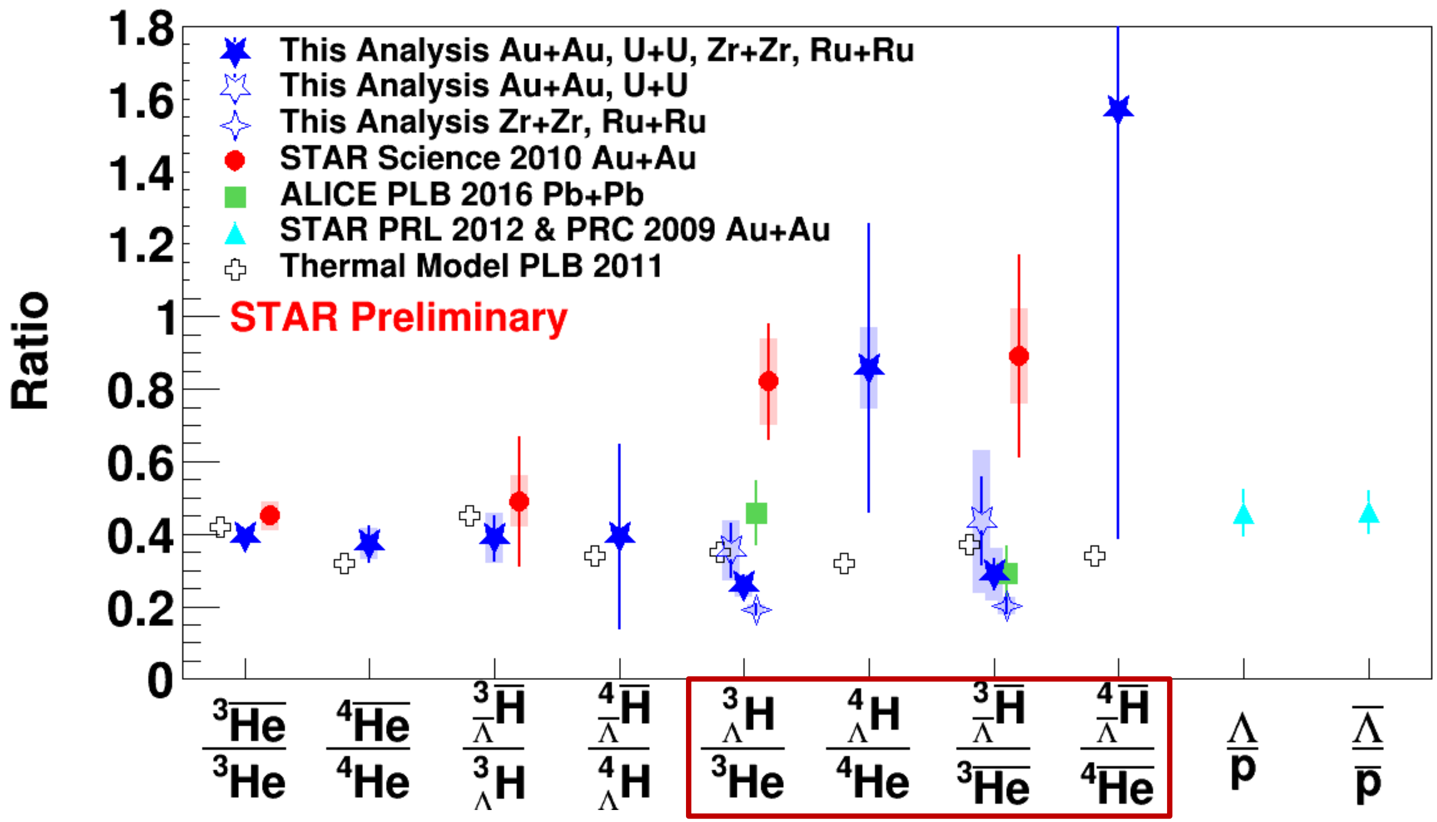
Yield ratios



- For the ratios of anti-matter over matter:
  - Our results are consistent with thermal model and STAR measurement in 2010
  - ${}^{4}_{\Lambda}\overline{H}$ / ${}^{4}_{\Lambda}H \sim {}^{4}\overline{He}$ / ${}^{4}He$ ${}^{3}_{\Lambda}\overline{H}$ / ${}^{3}_{\Lambda}H \sim {}^{3}\overline{He}$ / ${}^{3}He$

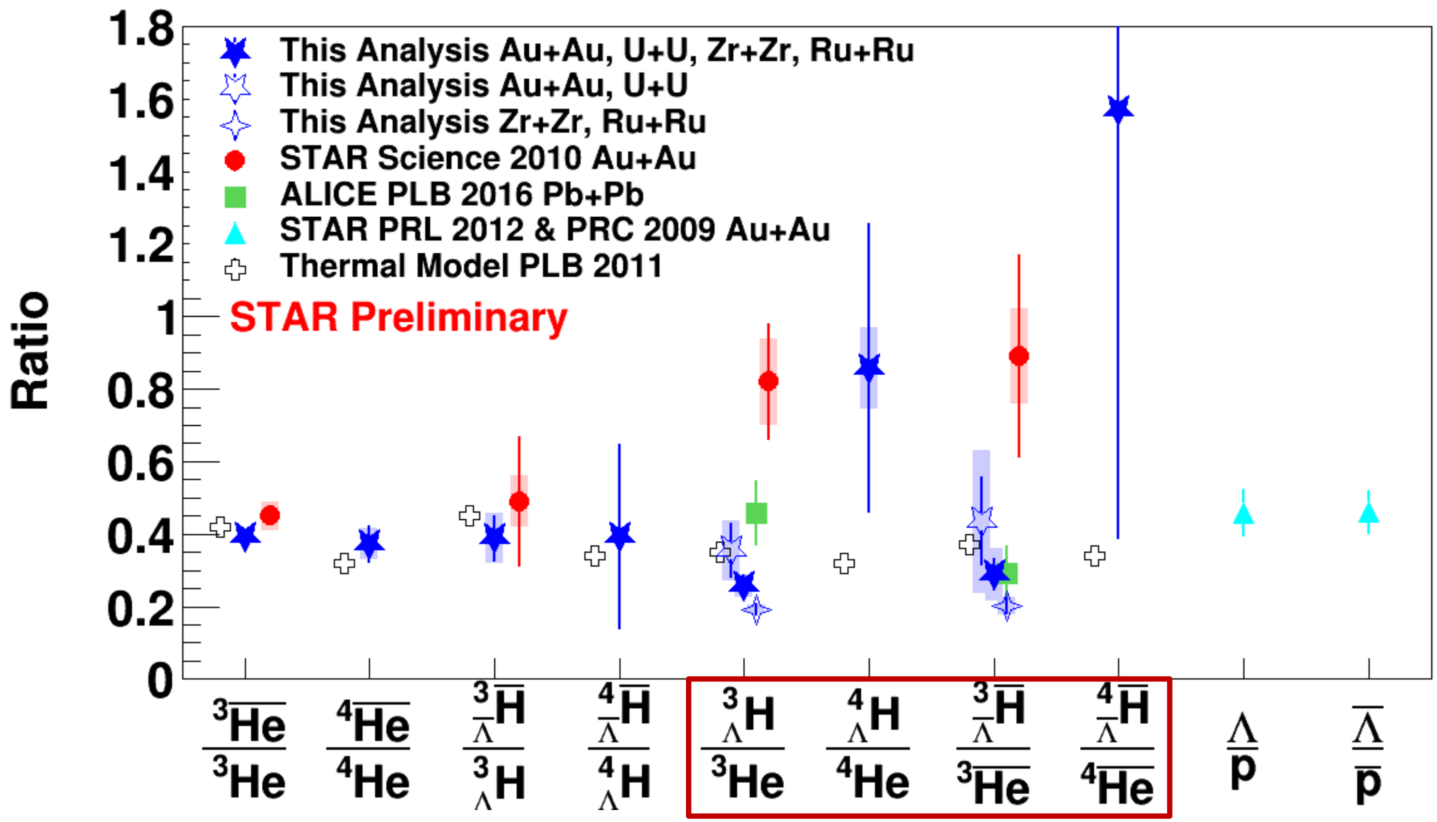
Scince 328, 58 (2010)
PLB 754, 360 (2016)
PLB 697, 203 (2011)

Yield ratios



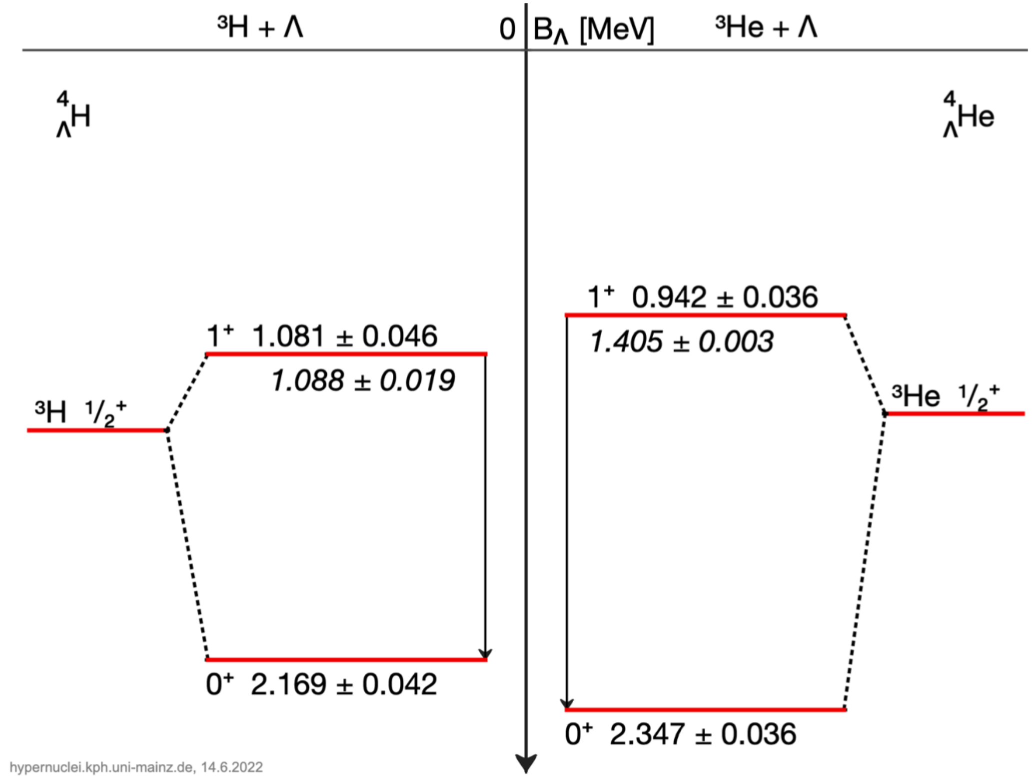
- For the ratios of (anti-)hypernuclei over (anti-)nuclei:
  - The Au+Au and U+U results constitute a fair comparison to previous results in Au+Au and Pb+Pb collisions due to similar system sizes.
  - The newly measured ${}^{3}_{\Lambda}H$ / ${}^{3}He$ & ${}^{3}_{\Lambda}\overline{H}$ / ${}^{3}\overline{He}$ and are consistent with previous measurements, as well as the thermal model calculations.

Yield ratios



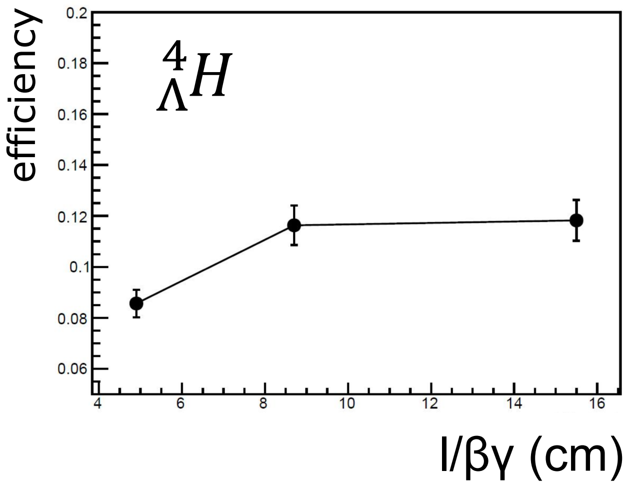
- For the ratios of (anti-)hypernuclei over (anti-)nuclei:
  - With all the collision systems combined, $^{4}_{\Lambda}H$ / ^{4}He & $^{4}_{\Lambda}\overline{H}$ / $^{4}\overline{He}$ seem larger than $^{3}_{\Lambda}H$ / ^{3}He & $^{3}_{\Lambda}\overline{H}$ / $^{3}\overline{He}$.
  - This may hint at the production of $^{4}_{\Lambda}H$ & $^{4}_{\Lambda}\overline{H}$ with both spin 0 and 1 states.
  - Thermal model here has not considered $^{4}_{\Lambda}H$ & $^{4}_{\Lambda}\overline{H}$ with both spin 0 and 1 states yet.

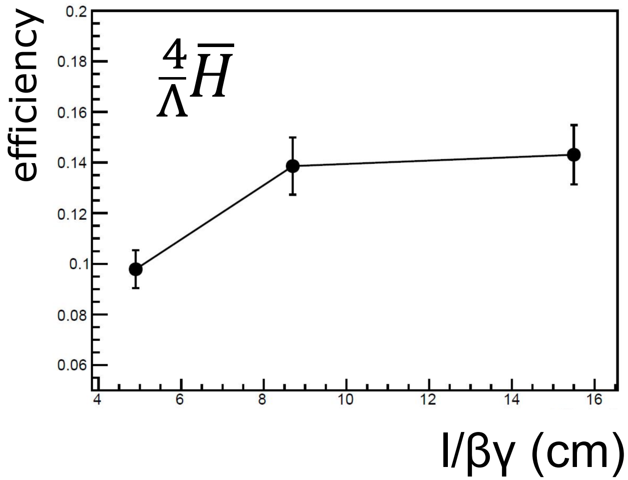
${}^{4}_{\Lambda}H$ & ${}^{4}_{\overline{\Lambda}}\overline{H}$ feed down

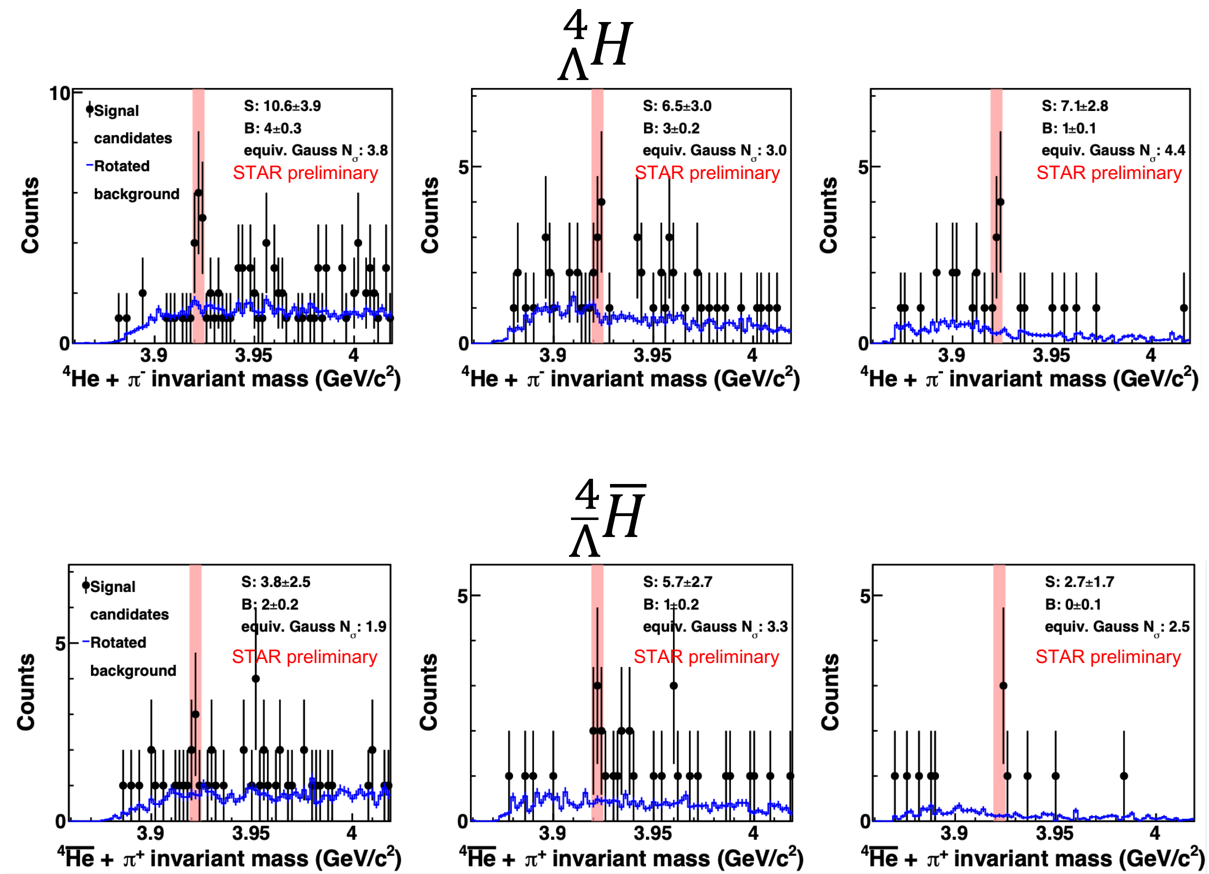


- ${}^{4}_{\Lambda}H$ exited state (J=1) has higher population due to degeneracy 2J+1 = 3
- Considering feed-down from J=1 state, the total yield is enhanced by a factor of 4

Lifetime measurements



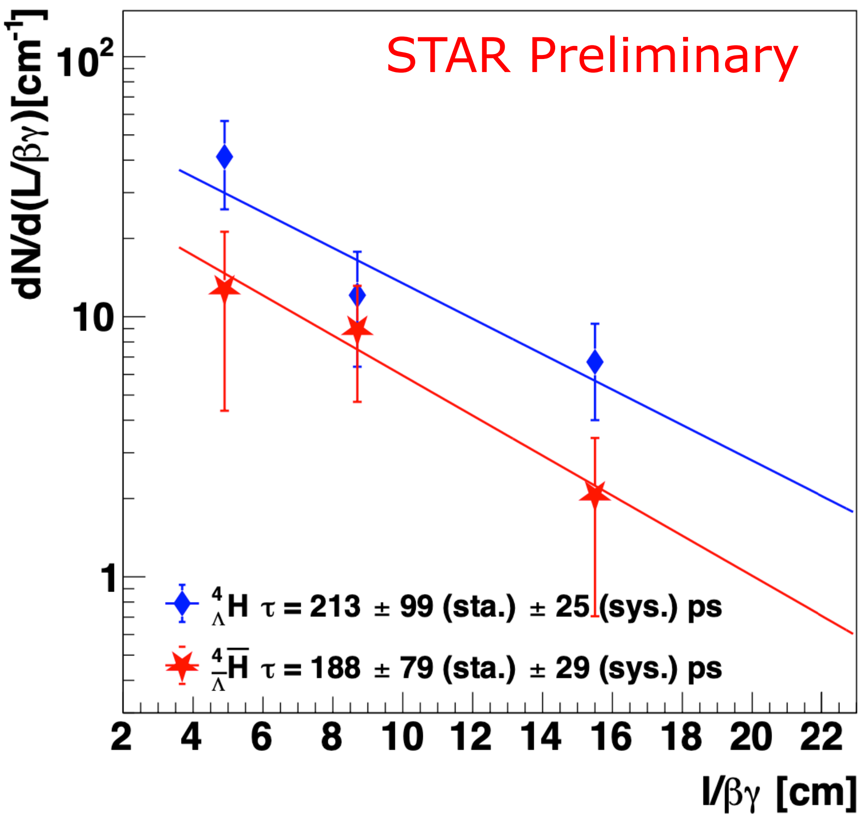


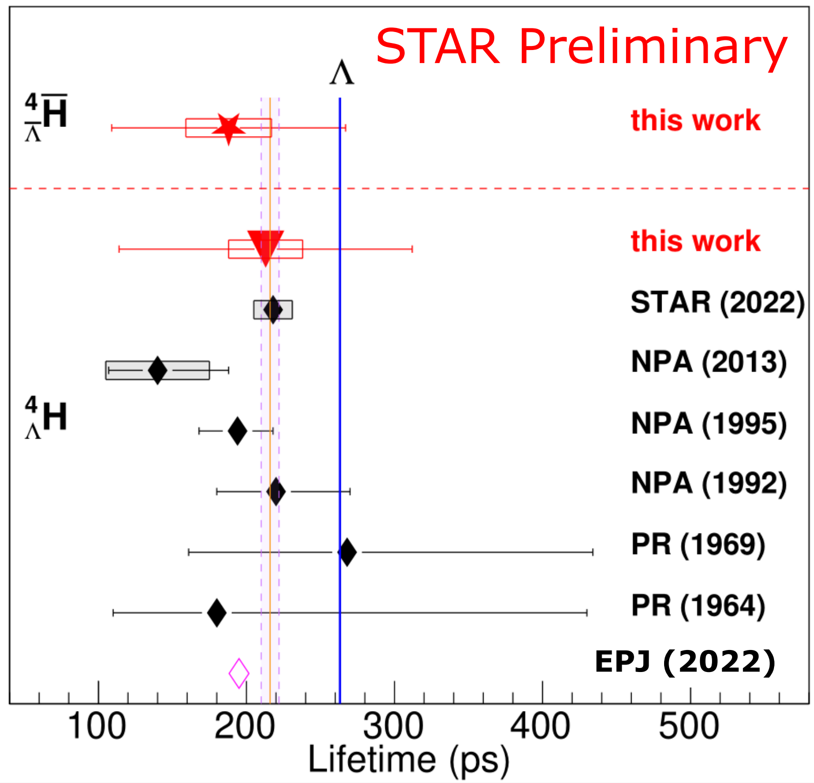


l/βγ: 3.4~6.4 6.4~11.0 11.0~20.0

- Lifetime is calculated by measuring relative signal yields in 3 l/βγ bins
  - l/βγ ∝ decay time in the hypernuclei rest frame

Lifetime measurements

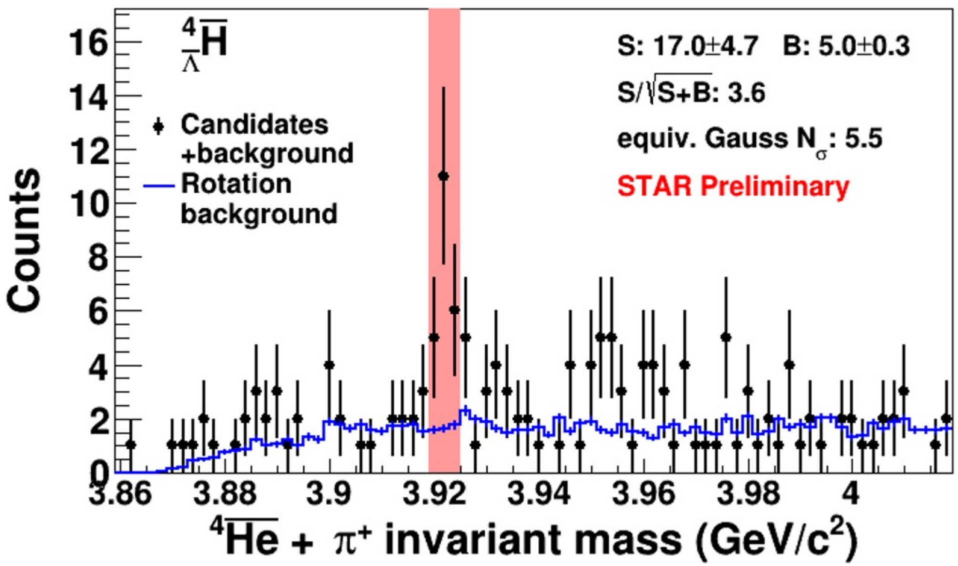




EPJ 259 (2022) 08002
PR 136 (1964) B1803
PR 180 (1969) 1307
NPA 547 (1992) 95c
NPA 585 (1995) 109c
NPA 913 (2013) 170
PRL 128 (2022) 202301

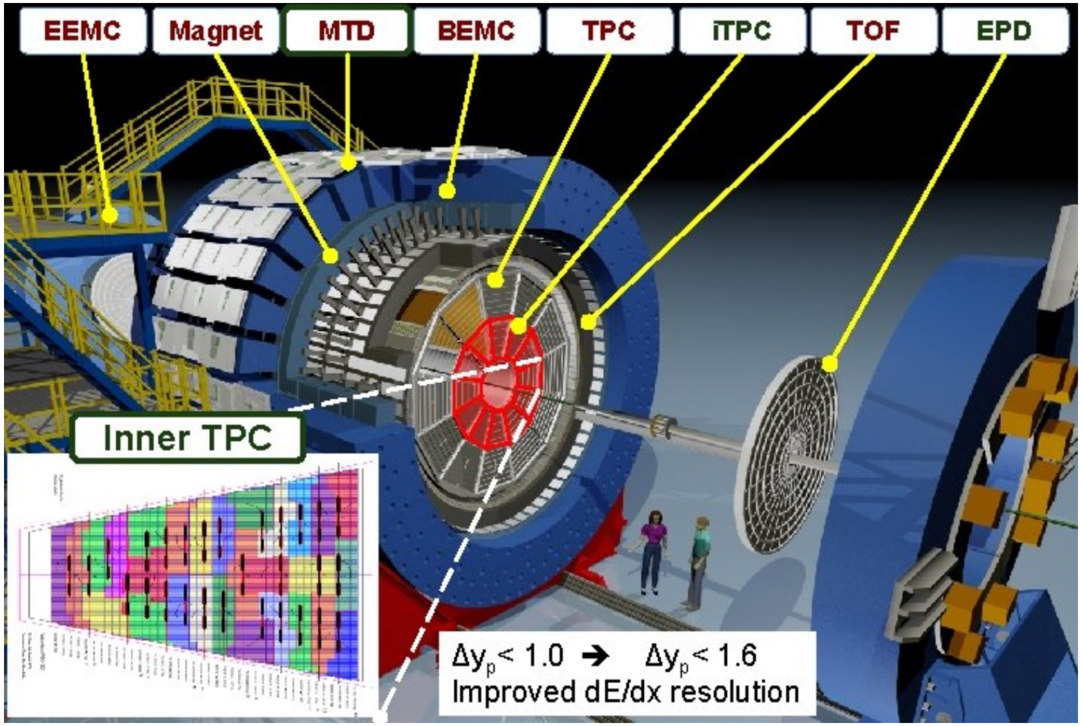
- Well described by the exponential function: $N(l/\beta\gamma)=N_0 e^{-l/\beta\gamma c\tau}$
- $\tau_{^{4}_{\Lambda}H} \sim \tau_{^{4}_{\Lambda}\bar{H}}$
- Consistent with earlier measurements and a theoretical prediction

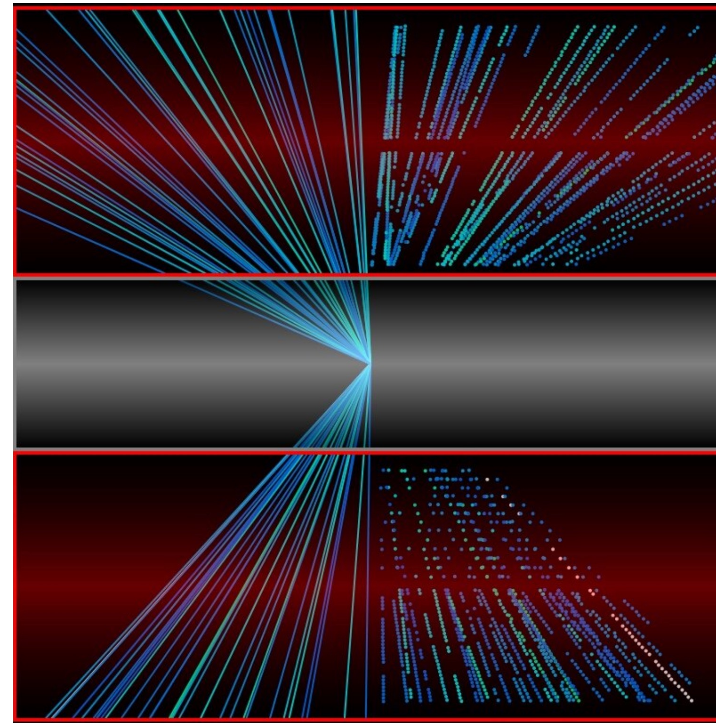
Summary



- ~17 signal candidates of $^{4}_{\Lambda}\overline{H}$ observed, with equivalent Gaussian significance of 5.5 σ
  - Second & heaviest anti-hypernuclei observed in experiment
- Various ratios among (anti-)particles are measured
  - $^{4}_{\Lambda}\overline{H}$ / $^{4}_{\Lambda}H$ ~ $^{4}\overline{He}$ / ^{4}He $\quad$ $^{3}_{\Lambda}\overline{H}$ / $^{3}_{\Lambda}H$ ~ $^{3}\overline{He}$ / ^{3}He
  - $^{4}_{\Lambda}H$ / $^{4}He \gtrsim$ $^{3}_{\Lambda}H$ / ^{3}He $\quad$ $^{4}_{\Lambda}\overline{H}$ / $^{4}\overline{He} \gtrsim$ $^{3}_{\Lambda}\overline{H}$ / $^{3}\overline{He}$
    - Hint at the production of $^{4}_{\Lambda}H$ & $^{4}_{\Lambda}\overline{H}$ with both spin 0 and 1 states
- Lifetimes measured: $\tau_{^{4}_{\Lambda}H} \sim \tau_{^{4}_{\Lambda}\overline{H}}$

Outlook





- STAR inner TPC upgrade finished in 2019
  - Reach to lower $p_T \Rightarrow$ critical to reconstruct the soft daughter pions from (anti-)hypernuclei
  - Larger η coverage
- STAR will take ~20B Au+Au 200 GeV data from 2023 to 2025
  - Search for ${}^{4}_{\Lambda}\overline{He}$, mult-strange hypernuclei…

Thanks ☺