Precise measurement of the mass difference and the binding energy B_{Λ} of $^{3}_{\Lambda}\mathrm{H}$ and $^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}$ with the Heavy Flavor Tracker in STAR at RHIC

Peng Liu (劉鵬)
(For the STAR Collaboration)
Shanghai Institute of Applied Physics, CAS, China
University of Chinese Academy of Sciences, China
Brookhaven National Laboratory, USA

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NN2018
SAITAMA, JAPAN
NUCLEUS-NUCLEUS COLLISIONS

Motivation and Significance

Hyperon-Nucleon interaction
(YN interaction)

Hyperon-Nucleon-Nucleon interaction
(YNN interaction)

Hyperon puzzle

- The presence of hyperon in neutron star (NS) is energetically favorable.
- Presence of hyperon leads to a smaller predicted maximum mass of NS.
- Observation of NS with about 2 solar mass.
- How to understand the difference ?

Rev. Mod. Phys. 88, 035004 (2016)
Eur. Phys. J. A 52 : 29 (2016)

Strong force

- A new degree of freedom, strangeness inside nuclear matter
- Insights into strong interaction

Eur. Phys. J. A 48, 41 (2012)
arXiv: 1711.07521

Very poor understanding on the YN and YNN interaction due to the difficulty in obtaining the stable hyperon beams.

Motivation and Significance

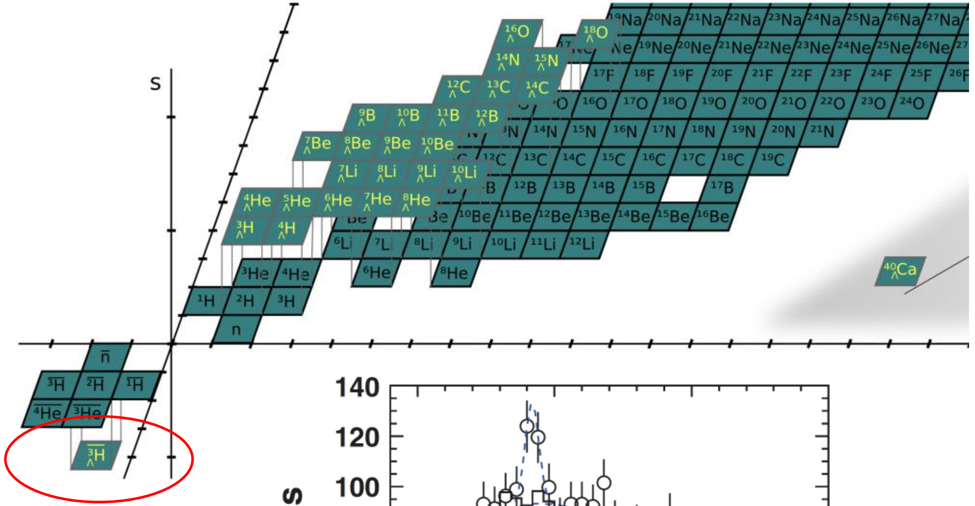
A good playground

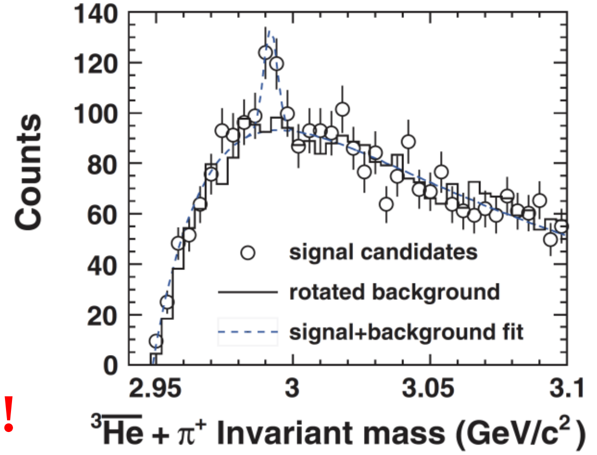
(Anti-) Hypernuclei

↓

Lifetime, Λ separation energy ….

YN, YNN interaction | CPT testing



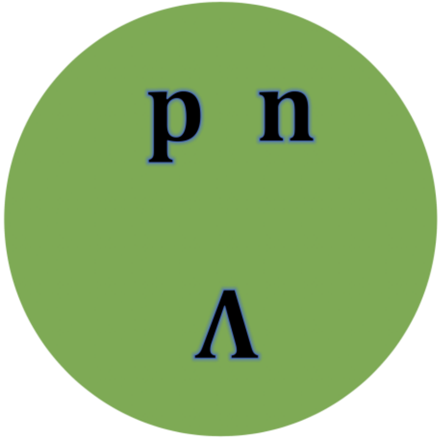


STAR collaboration, Science 328, 58 (2010)

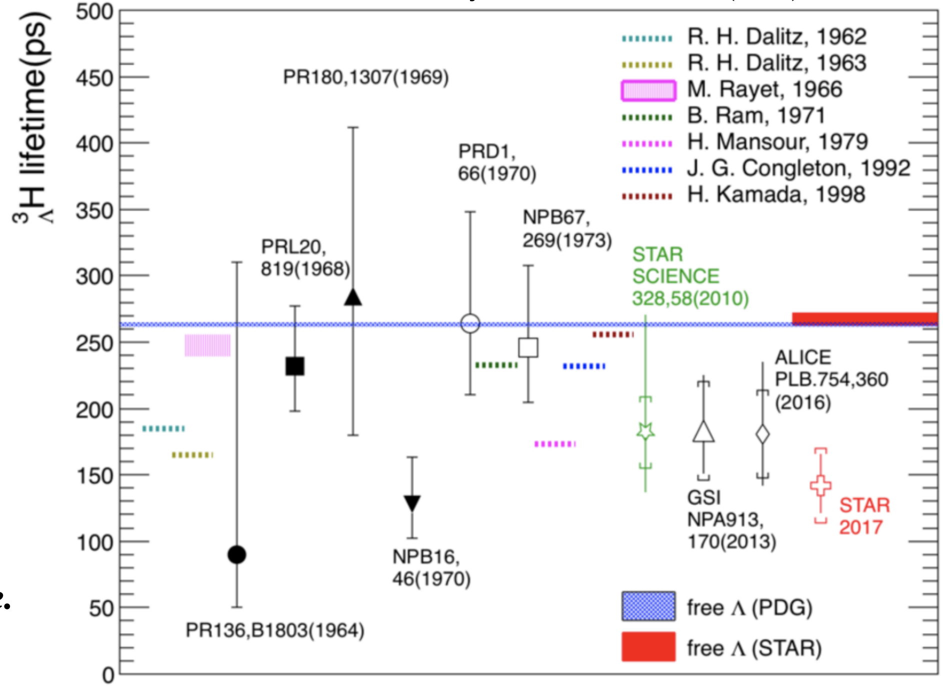
The measurements on those hypernuclei are needed !

Motivation and Significance

“Hi, I am Hypertriton ($^{3}_{\Lambda}H$) ”



STAR collaboration, Phys. Rev. C 97, 054909 (2018)

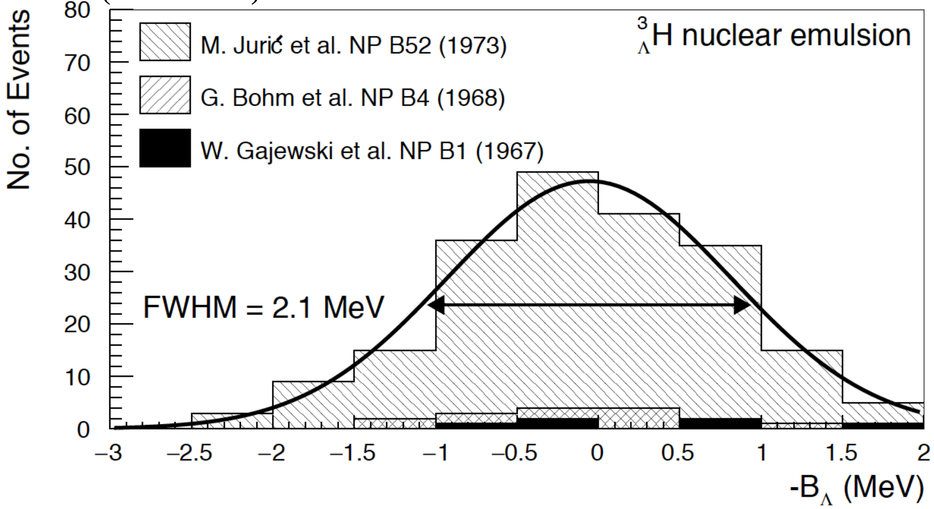


- ✓ *A lot of measurements of lifetimes were carried out.*
- ✓ *Recent data suggest shorter value than free Λ's lifetime.*
- ✓ *Stronger YN interaction in hypernucleus system?*

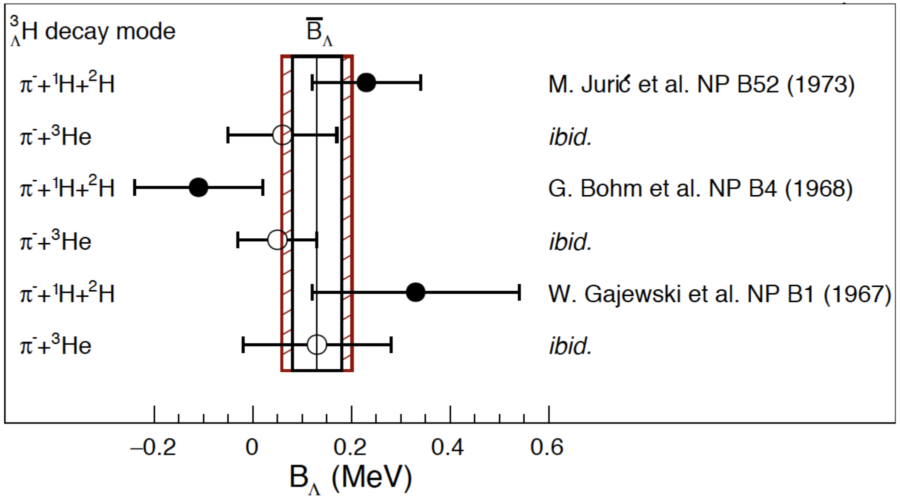
How about the Λ separation energy which is directly connected to the YN interaction ?

Motivation and Significance

PoS(Hadron2017)207



PoS(Hadron2017)207



- **Larger statistical uncertainties.**
- **No knowledge on the systematic error and may suffer from a large systematic error.**
- **B_Λ spread in the big range.**
- **No measurements in recent 45 years.**

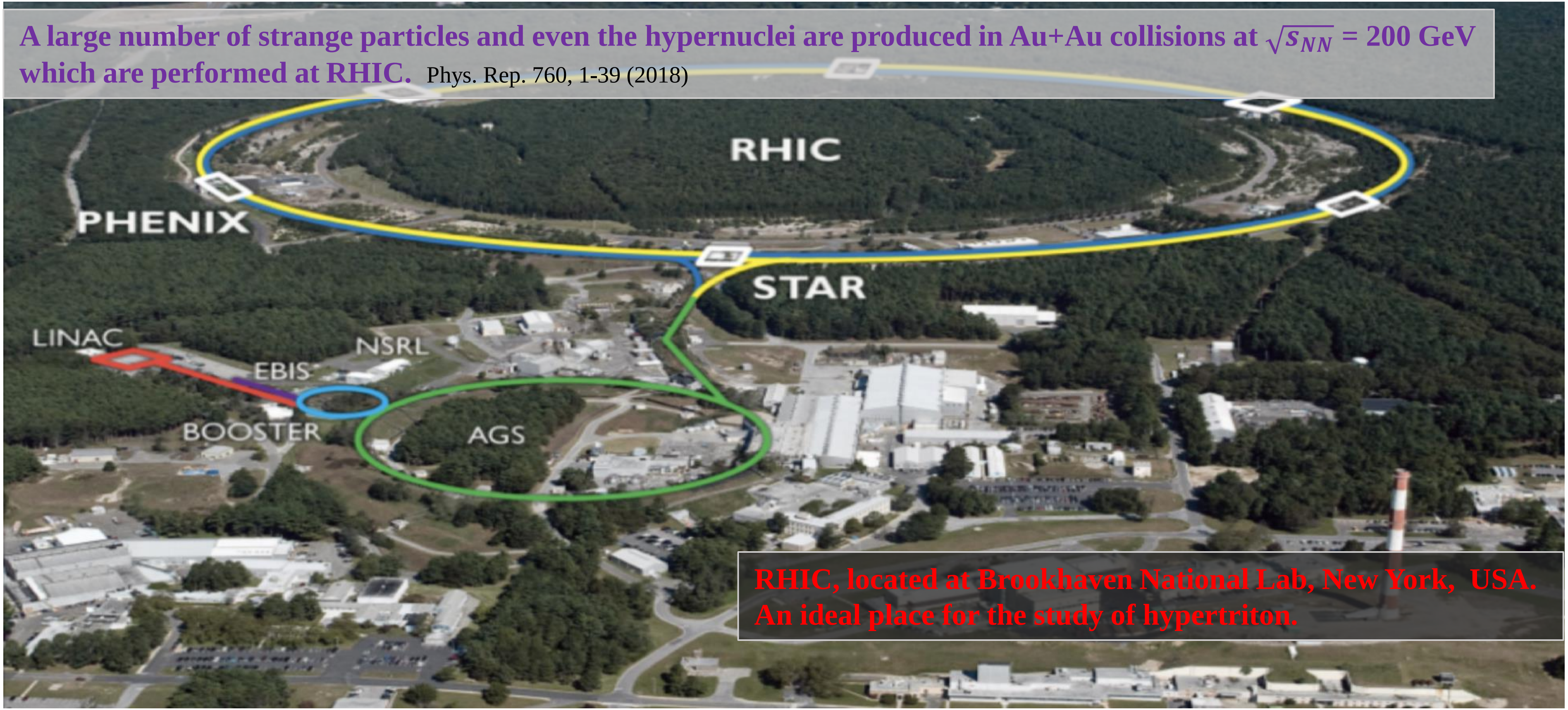
for the deuteron mass. The two-body decay events give $B_\Lambda = 0.25 \pm 0.31$ MeV, while the combined decays give $B_\Lambda = -0.07 \pm 0.27$ MeV. These results should be compared to the two emulsion measurements 0.06 ± 0.06 [20] and 0.24 ± 0.12 MeV.[21]

G. Keyes et al., Phys. Rev. D 1,66 (1970)

More precise measurements on B_Λ are highly needed !

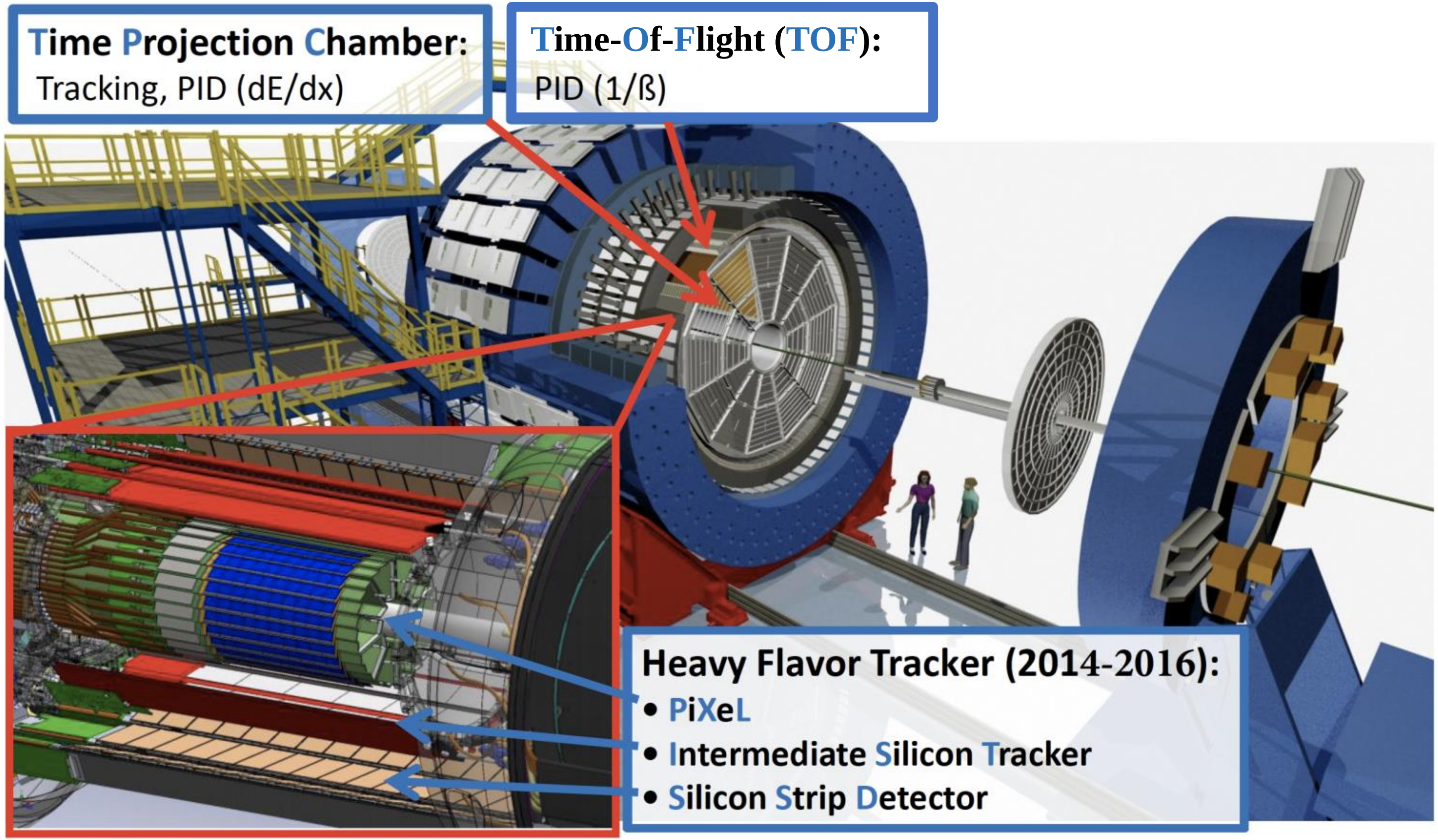
The Relativistic Heavy Ion Collider (RHIC)

A large number of strange particles and even the hypernuclei are produced in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV which are performed at RHIC. Phys. Rep. 760, 1-39 (2018)

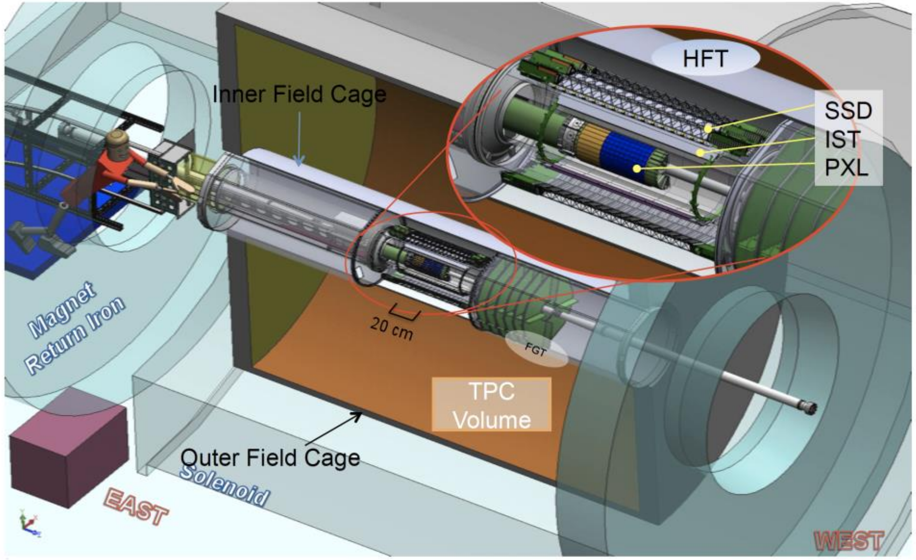


RHIC, located at Brookhaven National Lab, New York, USA.
An ideal place for the study of hypertriton.

The Solenoidal Tracker at RHIC (STAR)



The Heavy Flavor Tracker at STAR (HFT)



Detector	Radius (cm)	Hit Resolution ($R \times \phi$) / Z (μm/μm)	Thickness
SSD	22	30/860	1% X_0
IST	14	170/1800	1.32% X_0
PXL	8	6.2/6.2	0.52% X_0
	2.8	6.2/6.2	0.39% X_0

PXL: PiXeL
IST: Intermediate Silicon Tracker
SSD: Silicon Strip Detector

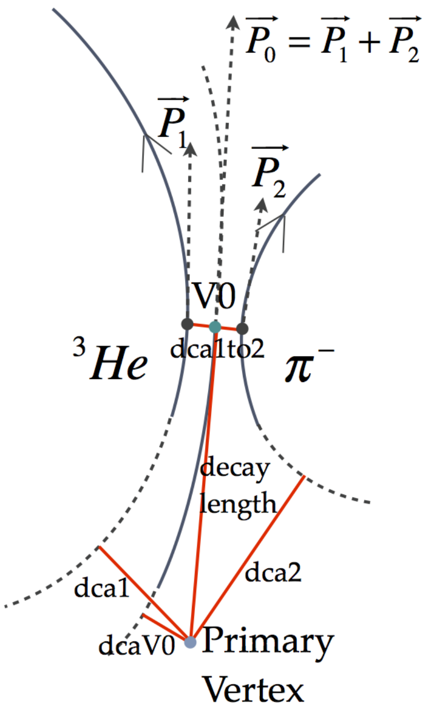
Details on the HFT : https://drupal.star.bnl.gov/STAR/starnotes/public/sn0600

Taking data:
Au+Au collision, about 1.2 billion in 2014, about 3.4 billion in 2016.

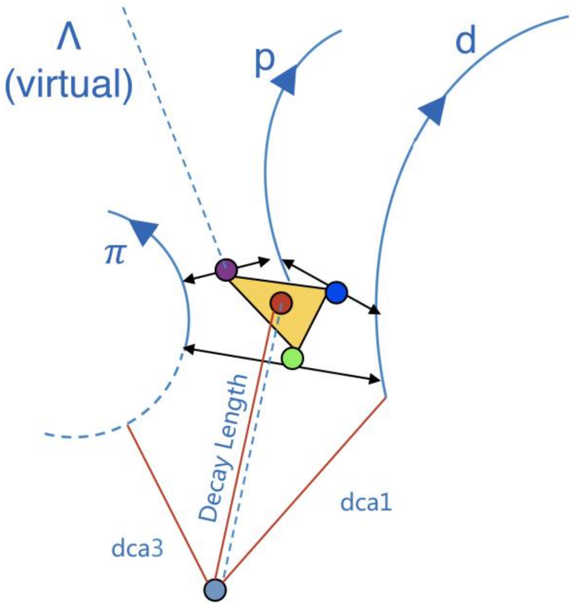
TPC → ~1mm → SSD → ~300μm → IST → ~250μm → PXL → < 30μm → vertex

Reconstruction of ${}^{3}_{\Lambda}H$ and ${}^{3}_{\bar{\Lambda}}\bar{H}$

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



$${}^{3}_{\Lambda}H \rightarrow p + \pi^{-} + d$$



${}^{3}_{\Lambda}H$ has many decay channels:

- ✓ Non-meson decay channels:
  - ${}^{3}_{\Lambda}H \rightarrow d + n$
  - ${}^{3}_{\Lambda}H \rightarrow p + n + n$
- ✓ Meson decay channels:
  - ${}^{3}_{\Lambda}H \rightarrow {}^{3}He\ ({}^{3}H) + \pi^{-}\ (\pi^{0})$
  - ${}^{3}_{\Lambda}H \rightarrow d + p\ (n) + \pi^{-}\ (\pi^{0})$
  - ${}^{3}_{\Lambda}H \rightarrow p + n + p\ (n) + \pi^{-}\ (\pi^{0})$

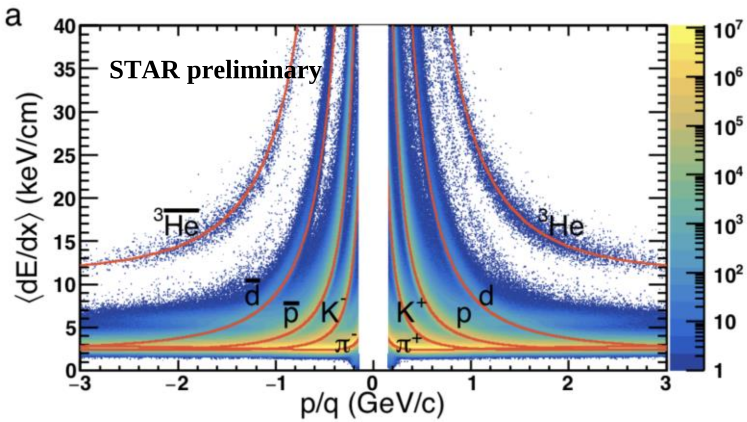
Good PID of charged particles in STAR detector.

Reconstructing ${}^{3}_{\Lambda}H$ (${}^{3}_{\bar{\Lambda}}\bar{H}$) through:

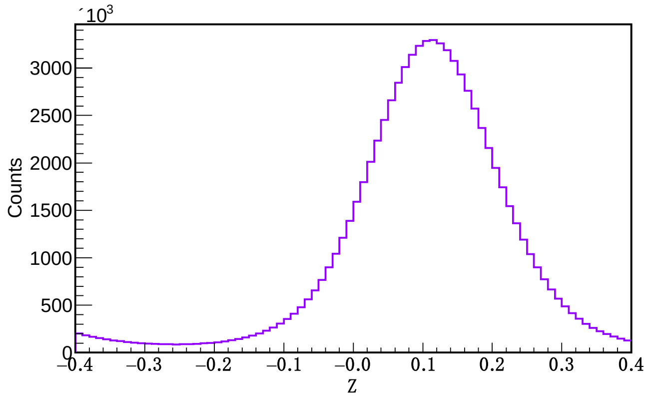
- ${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$
- ${}^{3}_{\Lambda}H \rightarrow d + p + \pi^{-}$

Precisely determining of decay vertex due to the high spatial resolution (< 30 μm) of HFT.

PID of decay daughters



$$Z = log\left(\frac{<\frac{dE}{dx}>_{exp.}}{<\frac{dE}{dx}>_{th.}}\right)$$



TPC:

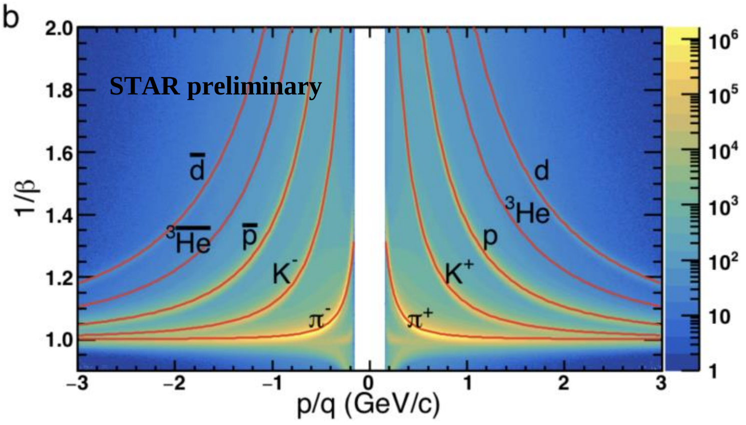
<dE/dx>: the average energy loss

P : track momentum

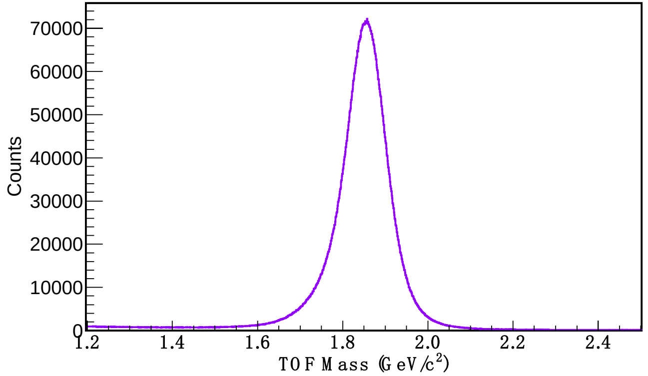
L : track length

TOF:

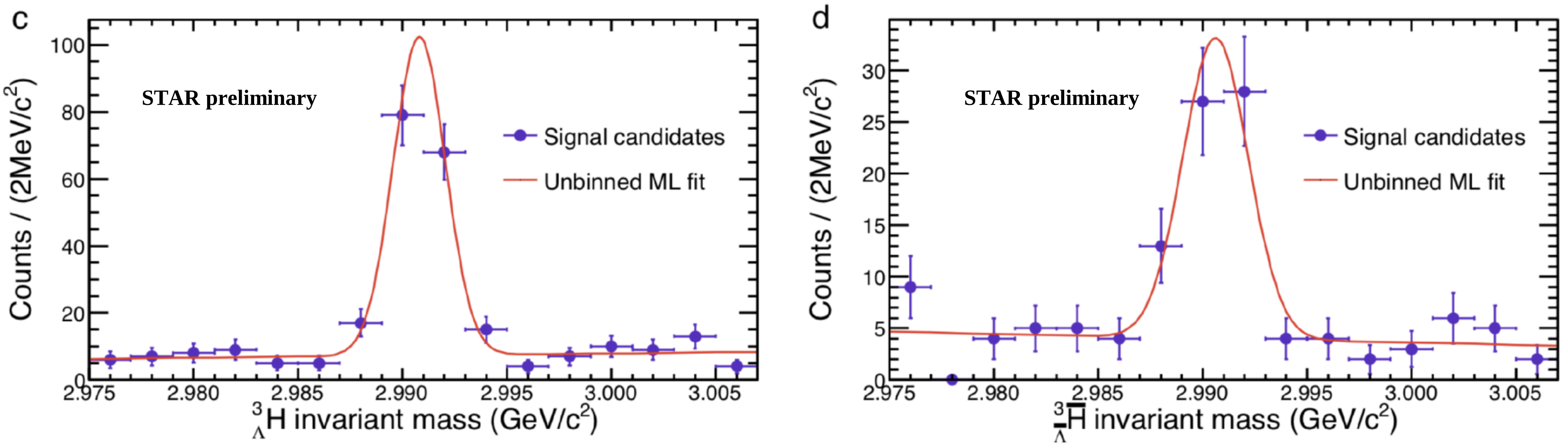
t : track's time of flight



$$m^2 = \frac{p^2}{\gamma^2\beta^2} = p^2\left(\frac{c^2t^2}{L^2} - 1\right)$$



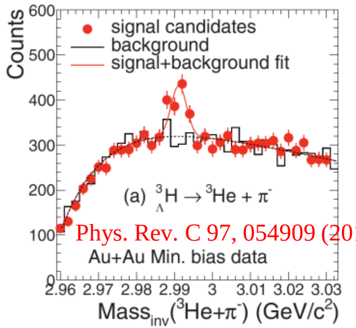
Invariant masses of ${}^{3}_{\Lambda}H$ and ${}^{3}_{\Lambda}\overline{H}$



Due to the good performance of PID and high spatial resolution in STAR:

- **Invariant mass distributions obtained with excellent signal/background ratio.**
- **Signal/background is higher by factor of 23 relative to the early reconstructed distributions.**
- **Significance of signal : 11.5 for ${}^{3}_{\Lambda}H$ and 6.9 for ${}^{3}_{\Lambda}\overline{H}$.**

Precise measurement on ${}^{3}_{\Lambda}H$ and ${}^{3}_{\Lambda}\overline{H}$ are made based on these distributions.



Phys. Rev. C 97, 054909 (2018)

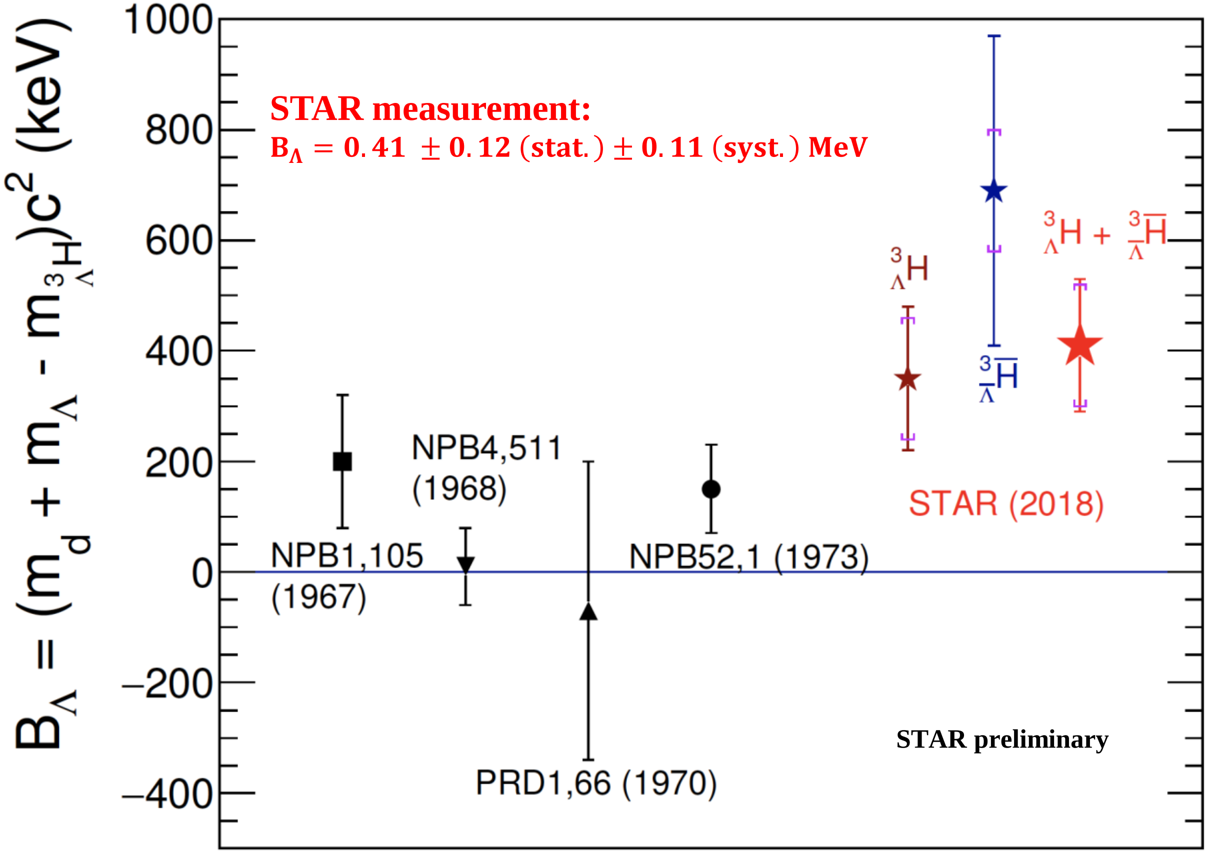
Binding energy, B_Λ, of ${}^3_\Lambda H$ and ${}^3_{\bar{\Lambda}}\bar{H}$

Current STAR measurement of B_Λ:

- ✓ **Larger than the values from 45 years ago.**
- ✓ **Substantially and significantly differs from zero.**

Difference between our measurement and the old measurement ?

Recalling the old measurement process.



Binding energy, B_Λ, of ${}^3_\Lambda H$ and ${}^3_{\bar{\Lambda}}\bar{H}$

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Recalling the old measurement process.

In "W. E. Slater, Nuovo Cimento, 10 (Suppl 1), 1 (1958)"

momentum, is described in Appendix B. B_Λ is most conveniently computed ([13]) from the equation:

$$M_{F'} + M_\Lambda - B_\Lambda = \sum_i M_i + Q = M_F \qquad (c = 1), \tag{1}$$

where the various M's are the rest energies of the particles involved in the event and Q is the total kinetic energy released. F' represents the nuclear core to which the Λ^0 particle is bound; F is the hypernucleus in question, and the index i labels the i'th decay particle. Rearranging (1) and defining $Q_0(F, M_i) = M_{F'} + M_\Lambda - \sum_i M_i$, one has

$$B_\Lambda = Q_0 - Q\,. \tag{1'}$$

☑ for the 2-body decay channel:

$$B_\Lambda = M_\Lambda + M_d - M_{^3He} - M_\pi - Q = Q_0 - Q$$

☑ for the 3-body decay channel:

$$B_\Lambda = M_\Lambda + M_d - M_d - M_p - M_\pi - Q = Q_0 - Q$$

Binding energy, B_Λ, of ${}^3_\Lambda H$ and ${}^3_{\bar\Lambda}\bar{H}$

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Recalling the old measurement process.

☑ for the 2-body decay channel:

$$B_\Lambda = M_\Lambda + M_d - M_{^3He} - M_\pi - Q = Q_0 - Q$$

☑ for the 3-body decay channel:

$$B_\Lambda = M_\Lambda + M_d - M_d - M_p - M_\pi - Q = Q_0 - Q$$

By comparing the difference of Q_0 between old and new values, the best estimations of B_Λ of old measurements are obtained.

	Lambda (MeV)	Deuteron (MeV)
NPB 1,105 (1967)	1115.44 [1]	1875.50 [5,6,7]
NPB 4,511 (1968)	1115.57 [1]	1875.50 [5,6,7]
PRD 1,66 (1970)	1115.67 [2]	1875.58 [2]
NPB 52, 1 (1973)	1115.57 [3]	1875.50 [5,6,7]
Today	1115.68 [PDG 2017]	1875.61 [CODATA]

	Pion (MeV)	Proton (MeV)	Helium3 (MeV)
NPB 1,105 (1967)	139.59 [4]	938.26 [4]	2808.22 [5,6,7]
NPB 4,511 (1968)	139.58 (PDG 1967)	938.26 (PDG 1967)	2808.22 [5,6,7]
PRD 1,66 (1970)	139.58 (PDG 1969)	938.26 (PDG 1969)	2808.22 [5,6,7]
NPB 52, 1 (1973)	139.58 (PDG 1972)	938.26 (PDG 1972)	2808.22 [5,6,7]
Today	139.57 (PDG 2017)	938.27 (PDG 2017)	2808.39 (CODATA)

[1] G. Bohm et al., Nucl. Phys. B 4, 511 (1968), Ilford K5 emulsion @ CERN P. S.
[2] G. Keyes et al., Phys. Rev. D 1, 66 (1970), helium bubble chamber @ Argonne ZGS
[3] M. Juric et al., Nucl. Phys. B 52, 1 (1973), Ilford K5 emulsion @ Brookhaven AGS
[4] C. Mayeur et al., Nuovo Cimento II, 43, 180 (1966), Ilford K5 emulsion @ CERN P. S.
[5] F. Everling, L. A. Konig, J. H. E. Mattauch and A. H. Wapstra, Nucl. Phys. 18, 529 (1960)
[6] A. H. Wapstra, Physica, 21, 378 (1955)
[7] W. E. Slater, Nuovo Cimento, 10 (Suppl 1), 1 (1958)

Binding energy, B_Λ, of ${}^3_\Lambda H$ and ${}^3_{\bar{\Lambda}}\bar{H}$

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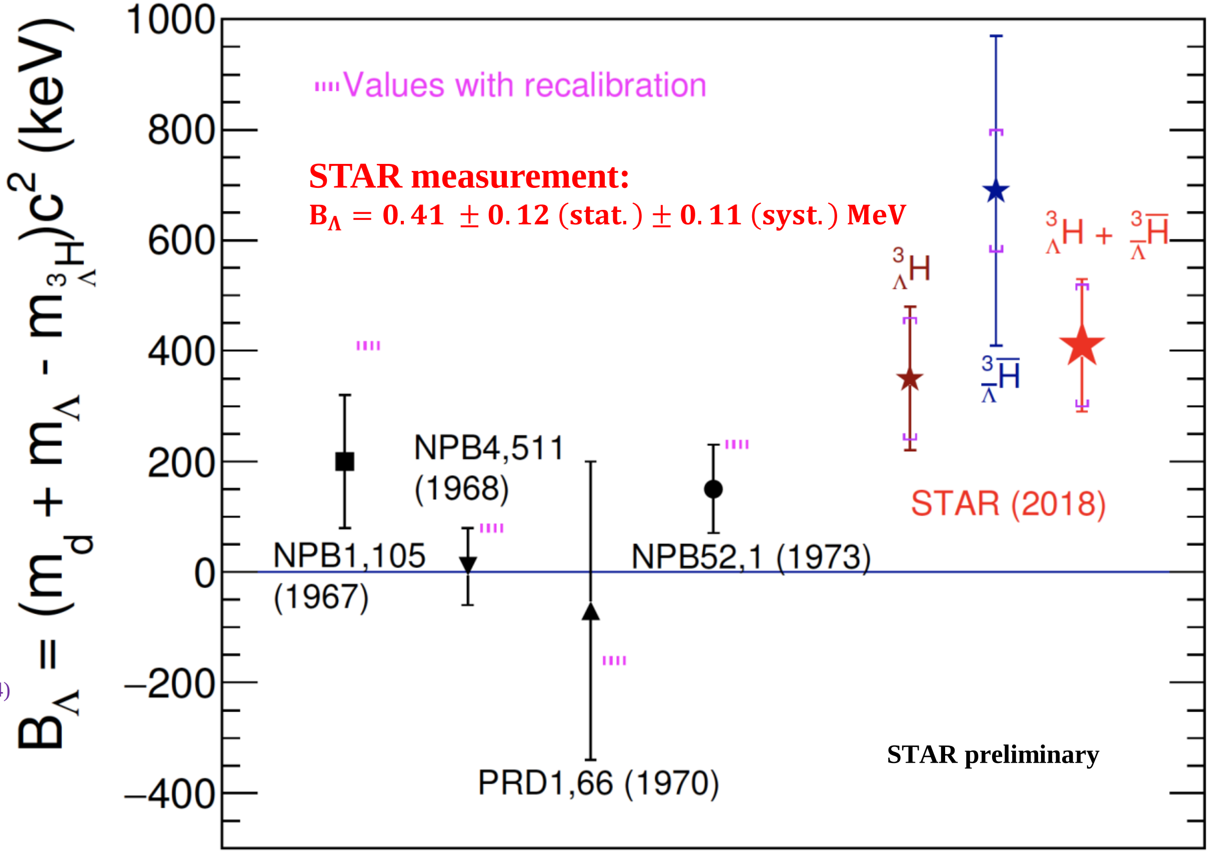
- ✓ STAR measurements substantially and significantly differ from zero.
- ✓ The larger B_Λ, the stronger YN interaction.
- ✓ Our results constrain the hyperon-nucleon interaction.

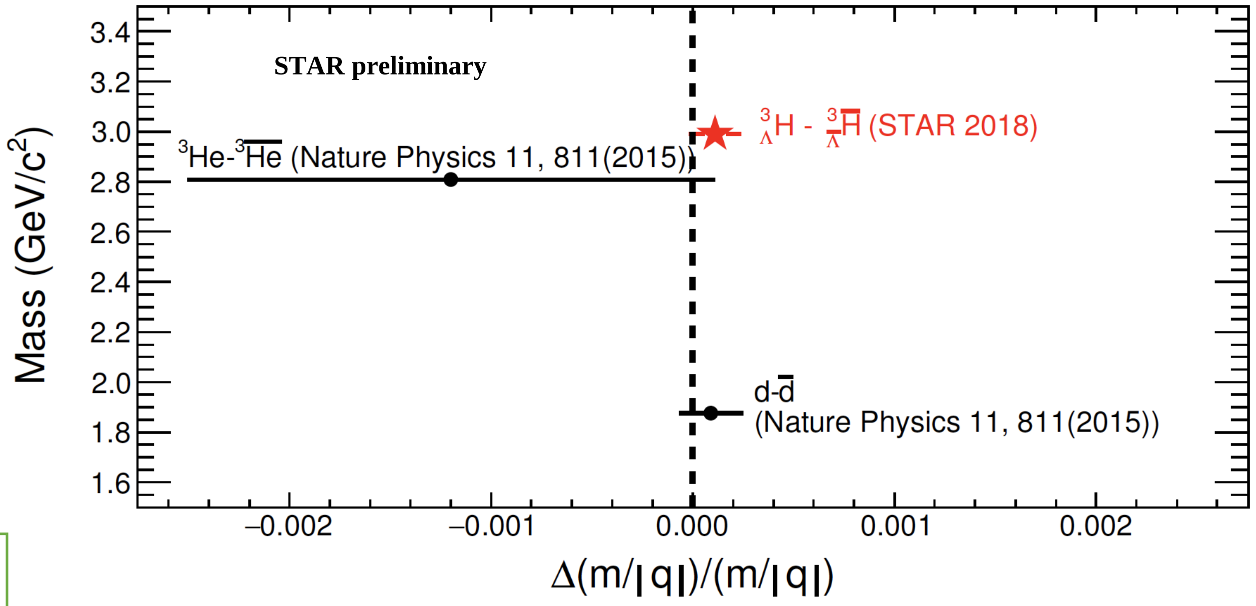
Theoretical calculations:

- ❖ **0.10 MeV by Dalitz in 1972.** Nucl. Phys. B 47, 109(1972)
- ❖ **0.01-0.37 MeV with ab initio calculation in 2002.** Phys. Rev. Lett. 89, 142504 (2002).
- ❖ **0.262 MeV with SU(6) quark model baryon-baryon interactions.** Phys. Rev. C 77, 027001 (2008).
- ❖ **-1.2 MeV with AFDMC in 2014.** Phys. Rev. C 89, 014314 (2014)
- ❖ **0.23 MeV with improved AFDMC calculation in 2018.** arXiv: 1711.07521



Mass difference between ${}^{3}_{\Lambda}H$ and ${}^{3}_{\bar{\Lambda}}\bar{H}$

- **CPT testing in hypernuclei sector for the first time.**
- **No violation of CPT symmetry observed with high precision.**



${}^{3}_{\Lambda}H$: 2990.95 ± 0.13 (stat.) ± 0.11 (syst.) MeV/c^2
${}^{3}_{\bar{\Lambda}}\bar{H}$: 2990.61 ± 0.28 (stat.) ± 0.11 (syst.) MeV/c^2

$$\left(\frac{\Delta(m/|q|)}{m/|q|}\right)_d = (0.9 \pm 0.5\,(\text{stat.}) \pm 1.4\,(\text{syst.})) \times 10^{-4} \qquad \left(\frac{\Delta(m/|q|)}{m/|q|}\right)_{^3He} = (-1.2 \pm 0.9\,(\text{stat.}) \pm 1.0\,(\text{syst.})) \times 10^{-3}$$

$$\left(\frac{\Delta m}{m}\right)_{^3_\Lambda H} = (1.0 \pm 0.9\,(\text{stat.}) \pm 0.7\,(\text{syst.})) \times 10^{-4}$$

Summary

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1. Hypertriton and anti-hypertriton mass.

$^{3}_{\Lambda}\mathrm{H}$: 2990.95 $\pm$ 0.13 (stat.) $\pm$ 0.11 (syst.) MeV/c^2

$^{3}_{\Lambda}\overline{\mathrm{H}}$: 2990.61 $\pm$ 0.28 (stat.) $\pm$ 0.11 (syst.) MeV/c^2

2. CPT examination in hypernuclei sector for the first time.

$$\left(\frac{\Delta m}{m}\right)_{^{3}_{\Lambda}\mathrm{H}} = (1.0 \pm 0.9\,(\mathrm{stat.}) \pm 0.7\,(\mathrm{syst.})) \times 10^{-4}$$

3. Higher Λ separation energy observed.

$B_{\Lambda} = 0.41 \pm 0.12\,(\mathrm{stat.}) \pm 0.11\,(\mathrm{syst.})$ MeV

Higher B_{Λ}, stronger YN/YNN interaction in hypertriton which was seen as a weekly-bound state ever.

中国科学院上海应用物理研究所
Shanghai Institute of Applied Physics, Chinese Academy of Sciences

BROOKHAVEN NATIONAL LABORATORY

Thanks for your attention !

Contact info. penglhep@gmail.com

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