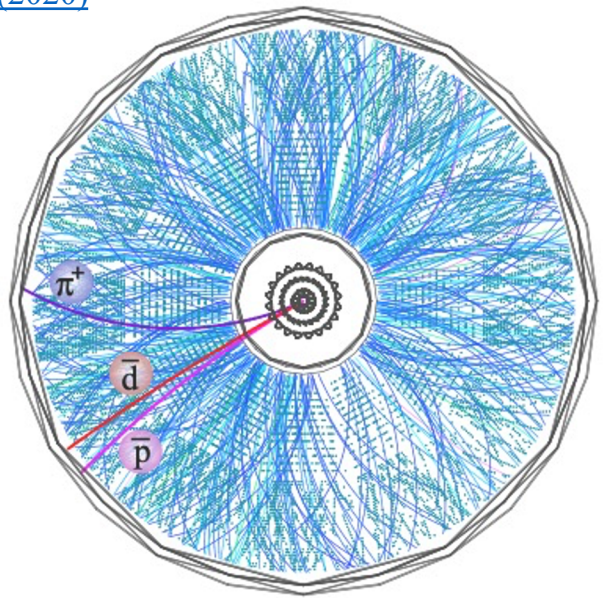
Measurement of the mass difference and the binding energy of the hypertriton and antihypertriton

The STAR Collaboration, *Nature Physics* **16**, 409-412 (2020)

Related paper and talks:
(1) Peng Liu et al., *Chinese Physics C* **43**, 124001 (2019)
(2) Peng Liu, talk of Quark Matter 2018, Italy, proceedings: *Nuclear Physics A* **982**, 811-814 (2019)
(3) Peng Liu, talk of NN2018, Japan, proceedings: *JPS Conference Proceedings* **32**, 010091 (2020)

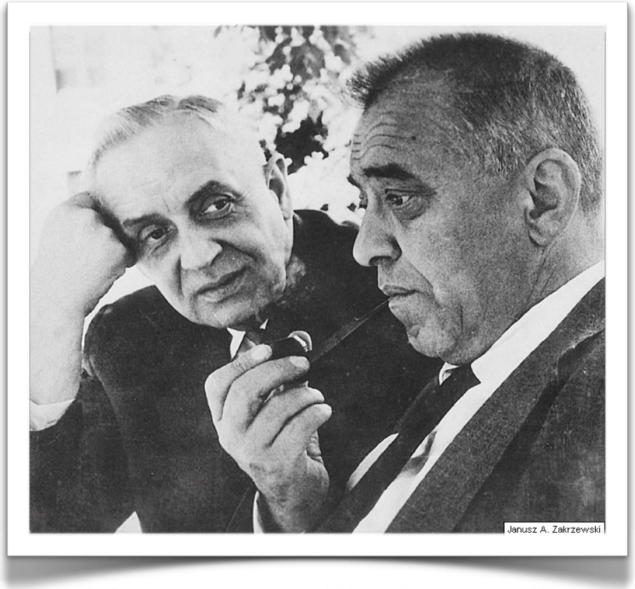
刘鹏

PAs: 陈金辉*、董昕、刘鹏*、马余刚、许长补 (以姓氏首字母排序)

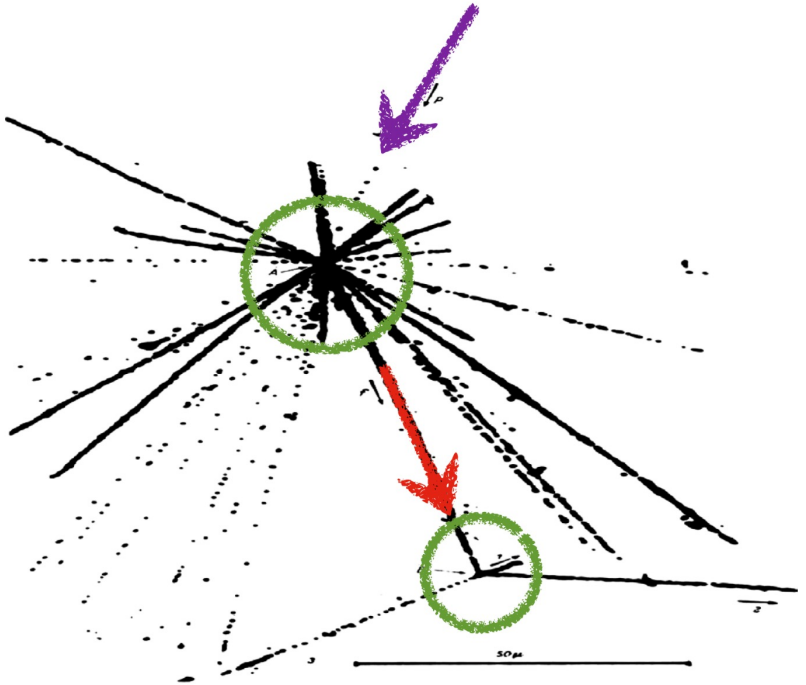


第十一届“晨光杯”青年优秀论文答辩
第十三届全国粒子物理学术会议 (2021)
2021年08月16日-20日

Motivation and Significance (Discovery of hypernucleus)



M. Danysz and J. Pniewski,
Phil. Mag. 44 (1953) 348

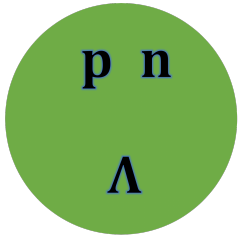


The first hypernucleus discovered in a balloon-flown emulsion plate in 1952

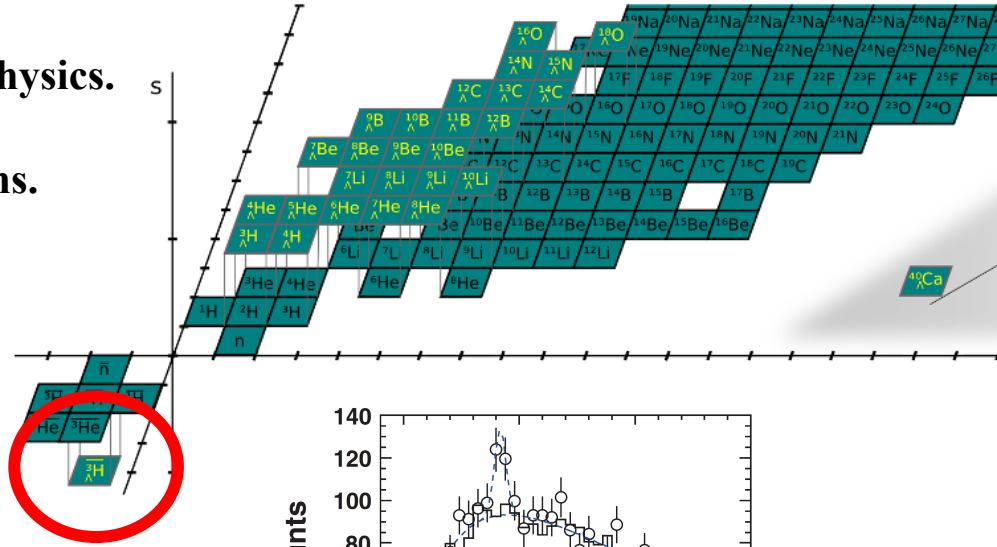
M. Danysz and J. Pniewski, *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* **44**, 348–350 (1953)
刘鹏，博士论文，中国科学院大学（2020）

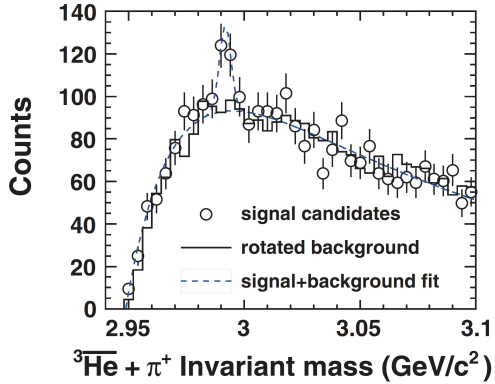
Motivation and Significance (Why study hypernuclei ?)

- ✓ **Enrich our knowledge about hypernuyclei physics.**
- ✓ **Excellent probe to investigate YN interactions.**
- ✓ **Implications for the EOS of neutron stars.**
- ✓ **CPT testing in hypernuclei sector.**



Hypertriton ($^{3}_{\Lambda}$H)



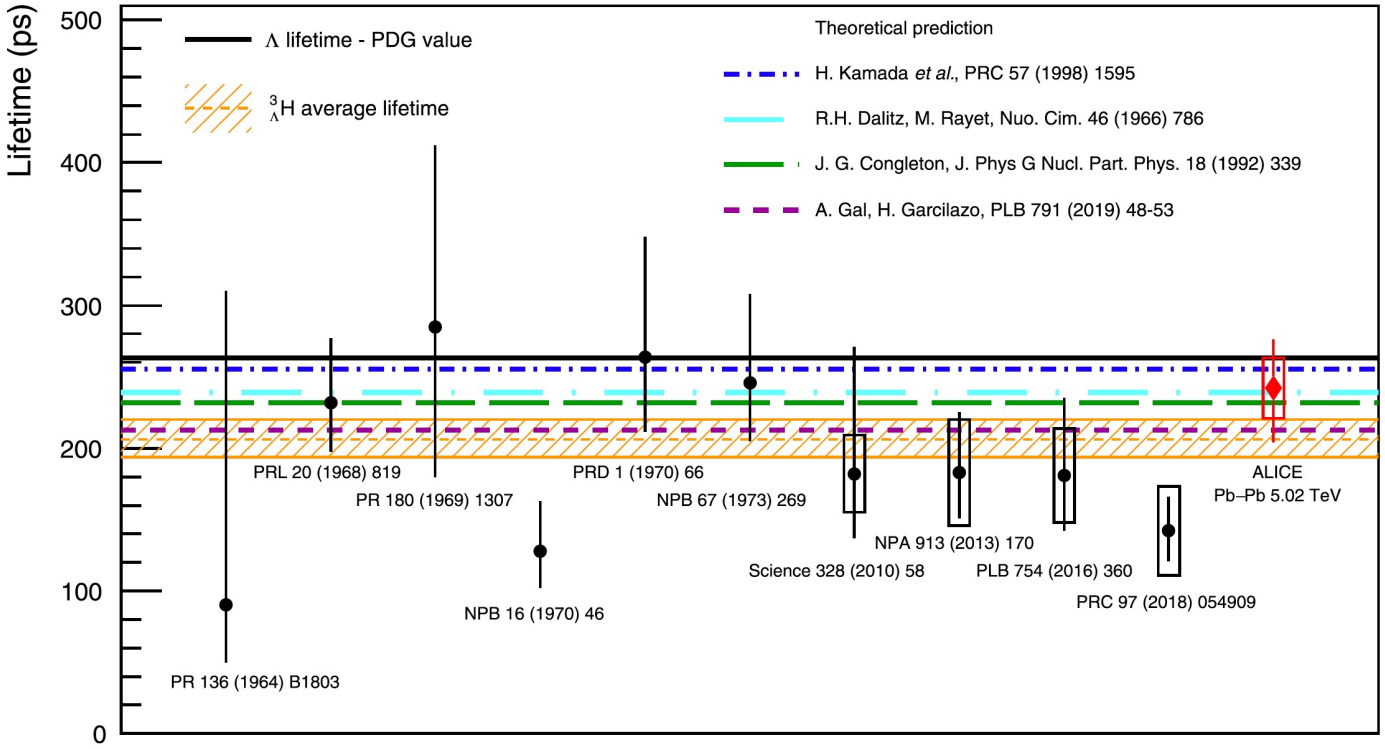


STAR collaboration, *Science* **328**, 58 (2010)

Motivation and Significance (Measurements of hypertriton)

YN interaction ---- lifetime of hypertriton

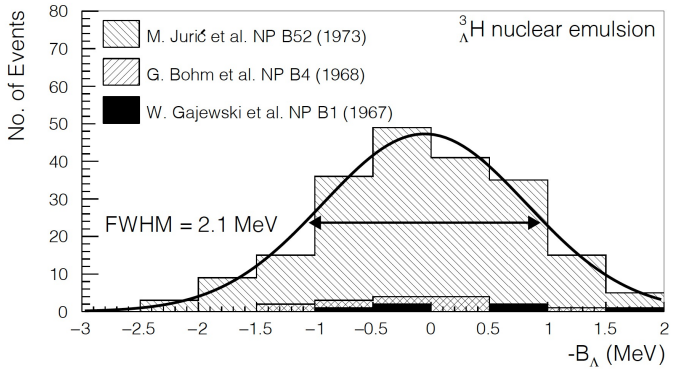
"A measurement of the lifetime to a precision of a few percent will guide and constrain the theoretical input leading to a more precise determination of the Y-N interaction, eventually contributing to solving the hyperon puzzle."



ALICE Collaboration, *Physics Letters B* **797**, 134905 (2019)

Motivation and Significance (Measurements of hypertriton)

YN interaction ---- Λ binding energy B_Λ of hypertriton



Patrick Achenbach et al., *POS* (**Hadron2017**) 207

Table 3. The original and the recalibrated Λ separation energy for hypernuclei data from 1967 [18], 1968 [19], and 1973 [20]. The listed errors are the reported statistical uncertainties only, and the recalibrated Λ separation energy should be considered as subject to the same errors as the original measurements. The Λ separation energy is in units of MeV.

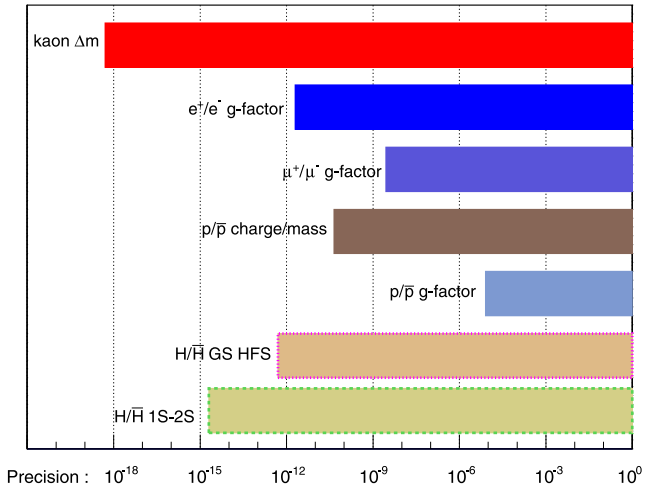
Hypernucleus	NPB1 (1967) [18]		NPB4 (1968) [19]		NPB52 (1973) [20]	
	Original	Recalibrated	Original	Recalibrated	Original	Recalibrated
$^{3}_{\Lambda}$H	0.20 ± 0.12	0.41	0.01 ± 0.07	0.08	0.15 ± 0.08	0.27
$^{4}_{\Lambda}$H	2.13 ± 0.06	2.35	2.23 ± 0.03	2.31	2.08 ± 0.06	2.20
$^{4}_{\Lambda}$He	2.20 ± 0.06	2.45	2.36 ± 0.04	2.47	2.42 ± 0.04	2.53
$^{5}_{\Lambda}$He	3.08 ± 0.03	3.33	3.08 ± 0.02	3.19	3.17 ± 0.02	3.28
$^{6}_{\Lambda}$He	4.09 ± 0.27	4.08	4.38 ± 0.19	4.23	4.42 ± 0.13	4.39

Peng Liu et al., *Chinese Physics C* **43**, 124001 (2019)

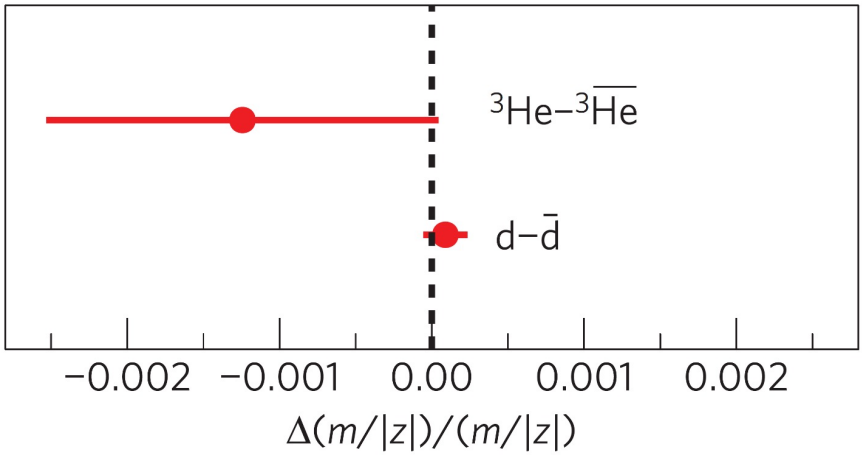
- **Larger statistical uncertainties.**
- **No knowledge on the systematic error and may suffer from a large systematic error.**
- **B_Λ spread in a big range.**
- **No measurements in recent 45 years.**

Motivation and Significance (Antihypertriton)

CPT testing in hypernuclei sector



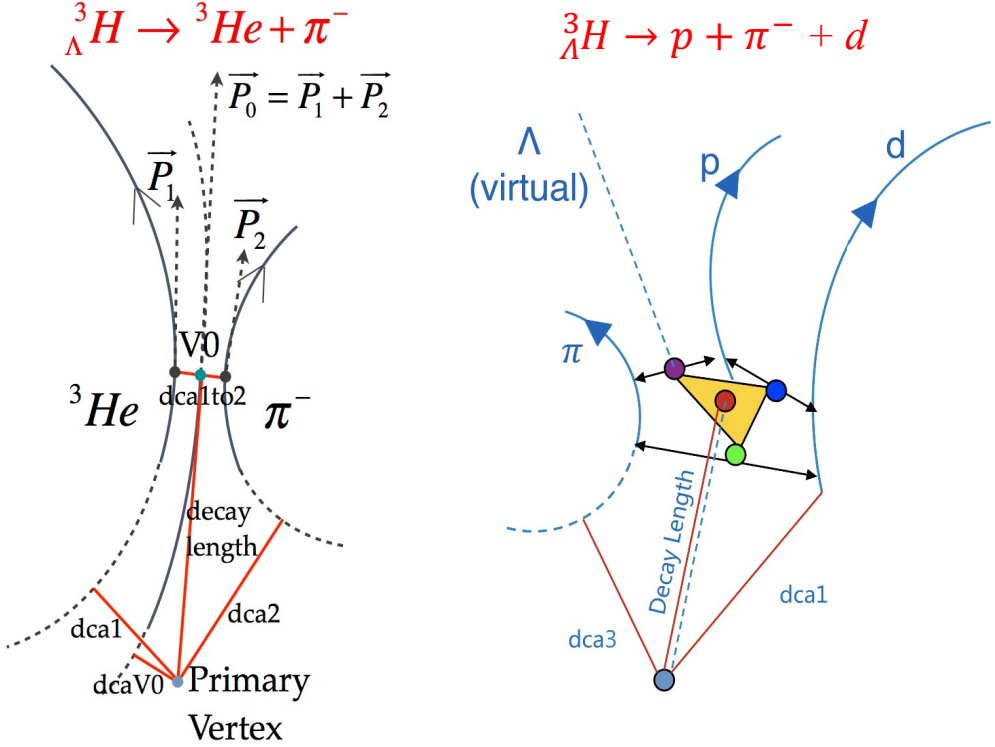
Jinhui Chen et al., *Physics Reports* **760**, 1-39 (2018)



ALICE Collaboration, *Nature Physics* **11**, 811-814 (2015)

- ***"Qualitatively different tests of CPT symmetry are a continuing priority for fundamental physics, as are revisitations of past tests with improved accuracy."*** STAR collaboration, *Nature Physics* **16**, 409-412 (2020)
- **The first observation of antihypertriton in 2010 by STAR collaboration provides us an opportunity to test CPT symmetry in hypernuclei sector, which is never tested.**

Reconstruction of hypertriton and antihypertriton



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

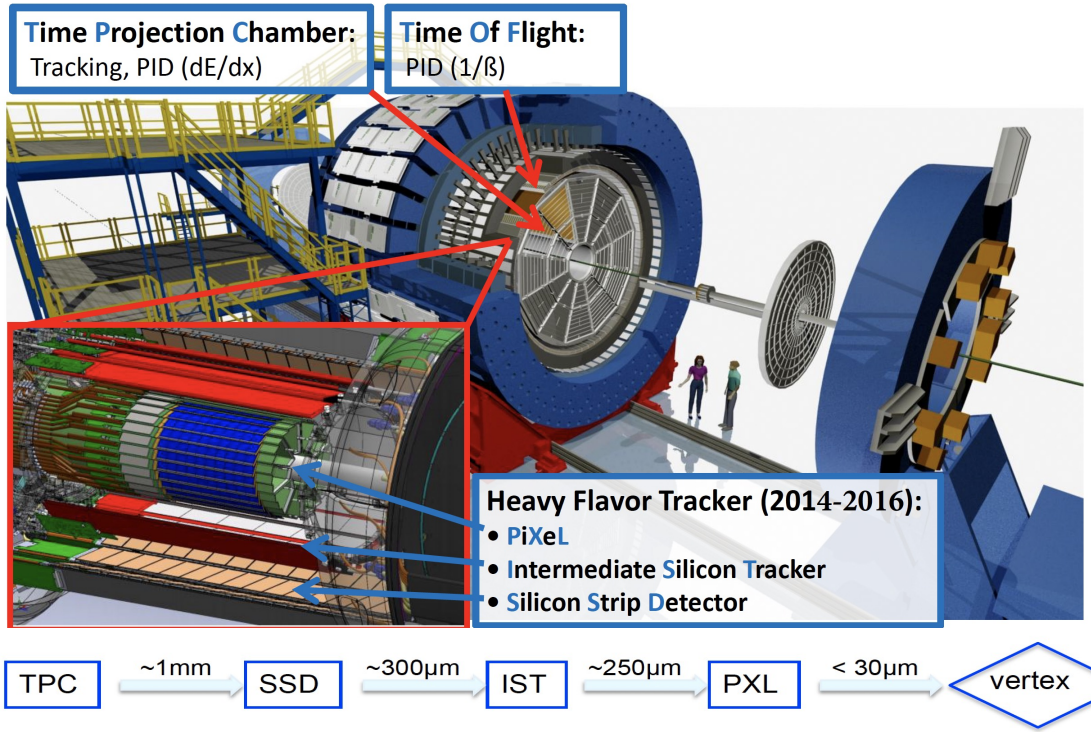
- ✓ **Non-mesonic decay channels (1.63%):**
  - $^{3}_{\Lambda}H \rightarrow d + n$
  - $^{3}_{\Lambda}H \rightarrow p + n + n$
- ✓ **Mesonic decay channels (98.37%):**
  - $^{3}_{\Lambda}H \rightarrow {}^{3}He\ (^{3}H) + \pi^{-}\ (\pi^{0})$ (37.34%)
  - $^{3}_{\Lambda}H \rightarrow d + p\ (n) + \pi^{-}\ (\pi^{0})$ (60.09%)
  - $^{3}_{\Lambda}H \rightarrow p + n + p\ (n) + \pi^{-}\ (\pi^{0})$ (0.94%)

Good PID of charged particles in STAR detector.
Reconstructing $^{3}_{\Lambda}H$ ($^{3}_{\Lambda}\bar{H}$) through:
- $^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$
- $^{3}_{\Lambda}H \rightarrow d + p + \pi^{-}$

Peng Liu (for the STAR Collaboration), talk of NN2018 and *JPS Conference Proceedings* **32**, 010091 (2020)
Peng Liu (for the STAR Collaboration), talk of QM2018 and *Nuclear Physics A* **982**, 811-814 (2019)
For details: 刘鹏，博士论文，中国科学院大学 (2020)

Reconstruction of hypertriton and antihypertriton

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



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

Data:

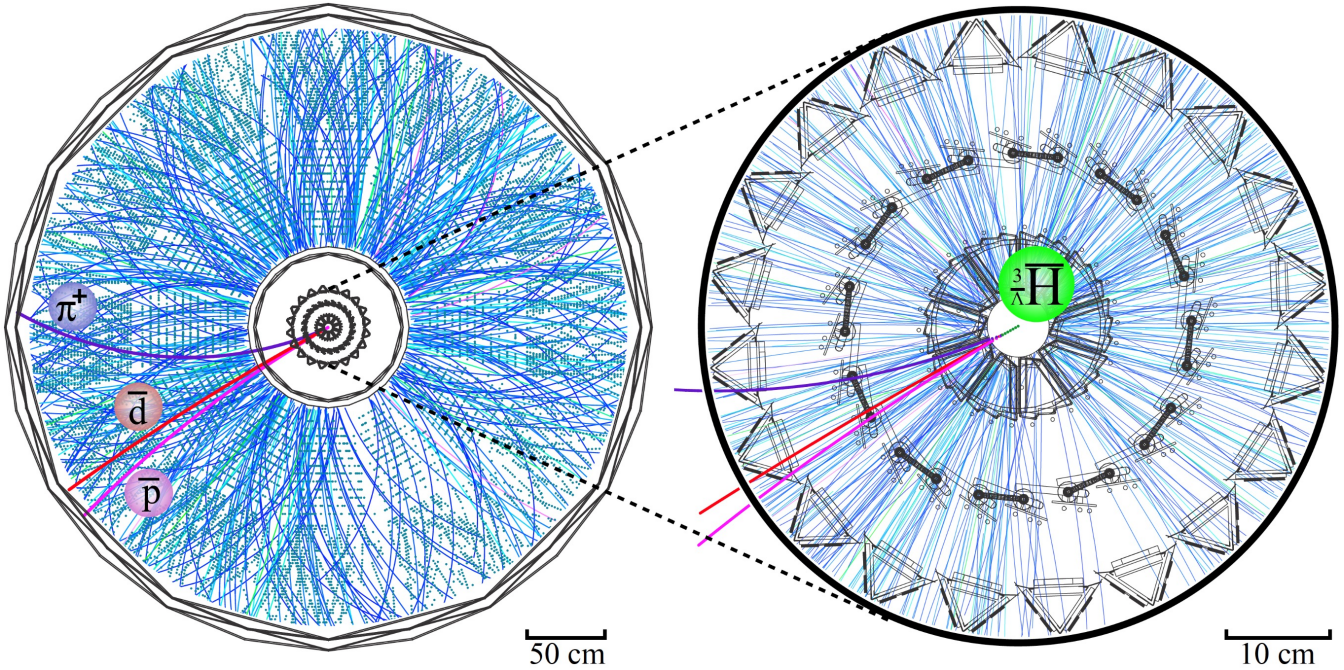
Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV,

1.2 billion in 2014, 3.4 billion in 2016.

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

Event display of antihypertriton decay through 3-body decay channel

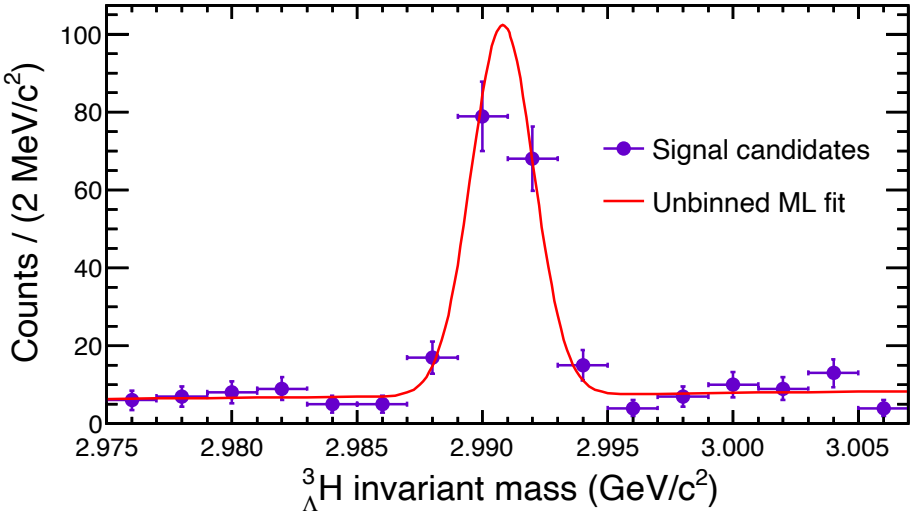
A typical antihypertriton 3-body decay in the detectors. The left side shows a less magnified view of the STAR detector, including a projected view of the large number of tracks detected by the TPC in a typical gold-gold collision. The right side shows a magnified view of the four cylindrical layers of the HFT located at the centre of the TPC

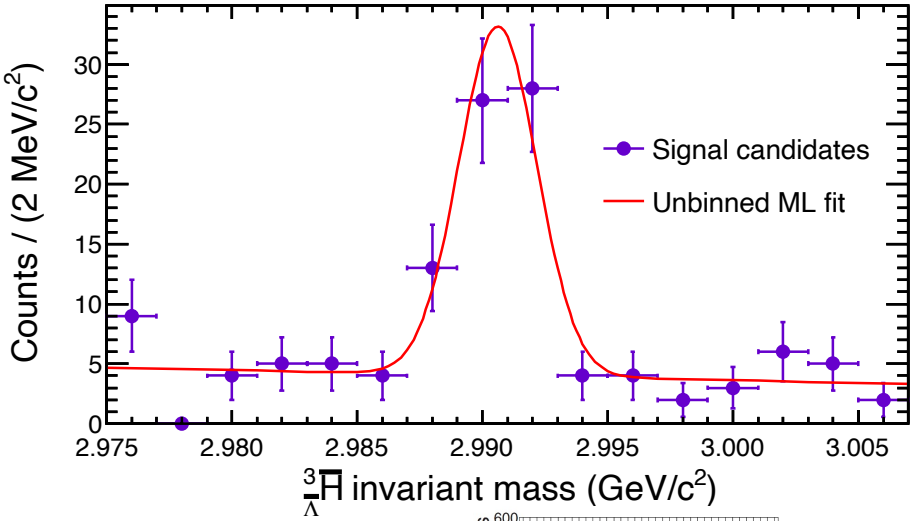


STAR collaboration, *Nature Physics* **16**, 409-412 (2020)

Invariant mass distributions with excellent signal/background ratio

STAR collaboration, *Nature Physics* **16**, 409-412 (2020)



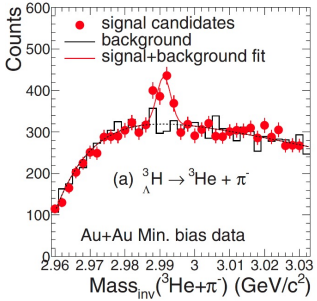


- **The hypertriton S/B ratio is close to a factor of 23 better than the previous measurement using only the TPC**

$m_{^3_\Lambda H} = 2,990.95 \pm 0.13\,(stat.) \pm 0.11\,(syst.)\ MeV/c^2$ $m_{^3_{\bar\Lambda}\bar H} = 2,990.60 \pm 0.28\,(stat.) \pm 0.11\,(syst.)\ MeV/c^2$

$m_{^3_\Lambda H + ^3_{\bar\Lambda}\bar H} = 2,990.89 \pm 0.12\,(stat.) \pm 0.11\,(syst.)\ MeV/c^2$

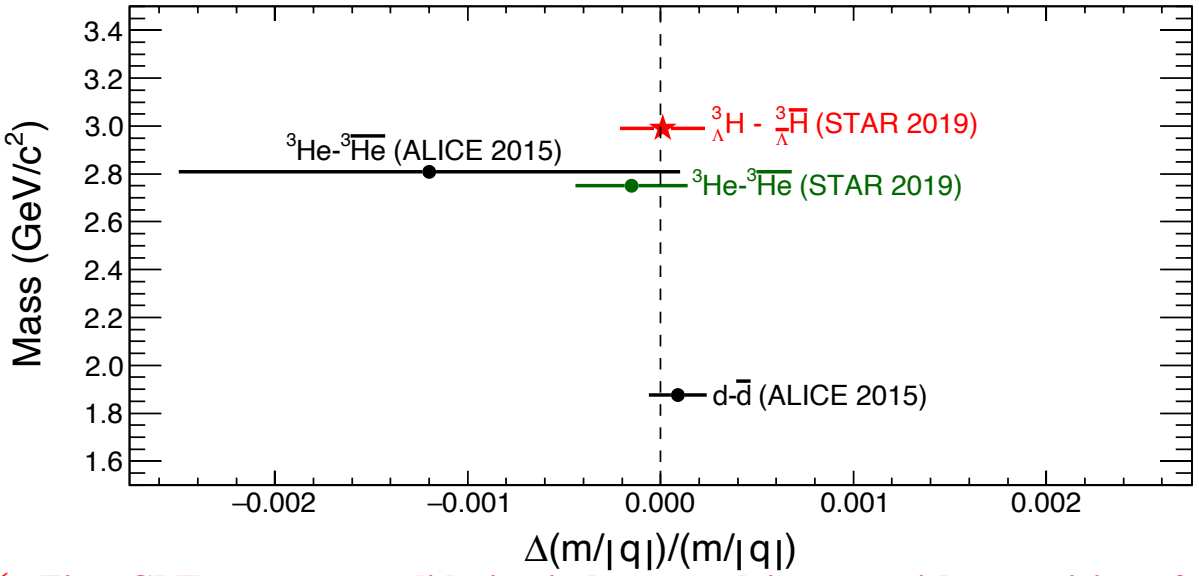
For details: 刘鹏，博士论文，中国科学院大学 (2020)



STAR Collaboration, *Physical Review C* **97**, 054909 (2018)

Results (mass difference)

STAR collaboration, *Nature Physics* **16**, 409-412 (2020)



$$\frac{\Delta m}{m} = [0.1 \pm 2.0(\text{stat.}) \pm 1.0(\text{syst.})] \times 10^{-4}$$

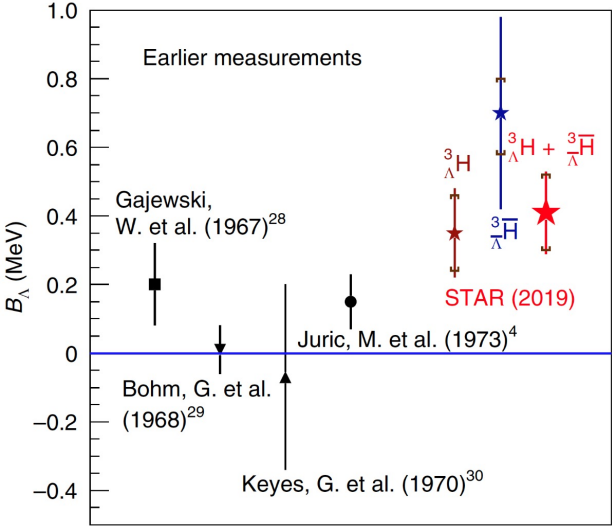
$$\frac{\Delta m}{m} = [-1.5 \pm 2.6(\text{stat.}) \pm 1.2(\text{syst.})] \times 10^{-4}$$

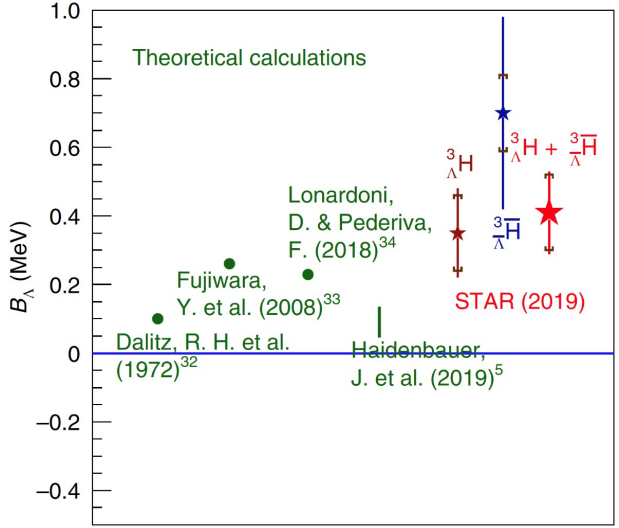
For details: 刘鹏，博士论文，中国科学院大学 (2020)

- ✓ **First CPT symmetry validation in hypernuclei sector with a precision of 10^{-4}, which is an order of magnitude improved over the early data with same mass number.**
- ✓ **New mass difference between ^{3}He and $^{3}\overline{\text{He}}$ is placed by STAR measurement.**
- ✓ **Place constraint to Standard-Model Extension (SME).** Colladay, D. et al., *Physical Review D* **55**, 6760 (1997)

Results (Λ binding energy)

STAR collaboration, *Nature Physics* **16**, 409-412 (2020)





$$B_\Lambda = m_d + m_\Lambda - m_{^3_\Lambda H}$$
$$= 0.41 \pm 0.12\,(\text{stat.})$$
$$\pm 0.11(\text{syst.})\ \text{MeV}$$

For details: 刘鹏，博士论文，中国科学院大学 (2020)

- ✓ **Early measurements are in agreement with 0 within statistical errors.**
- ✓ **The current STAR result differs from 0 with a statistical significance of 3.4σ.**
- ✓ **The central value of current STAR measurement is larger than the commonly used measurement from 1973.**
- ✓ **Theoretical calculations span in a wide range.**
- ✓ **Physics Today: "Strange matter interacts strongly with nucleons"(https://doi.org/10.1063/PT.6.1.20200327a)**

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