(anti)hypertriton lifetime puzzle

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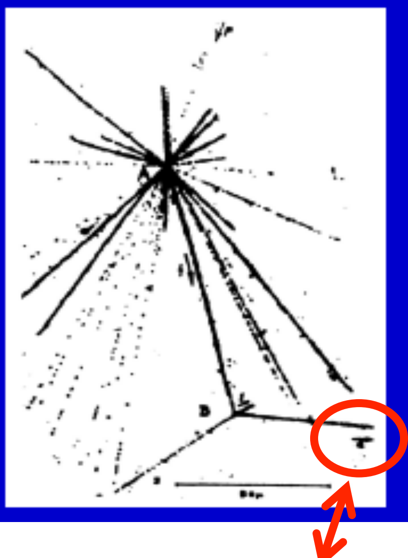
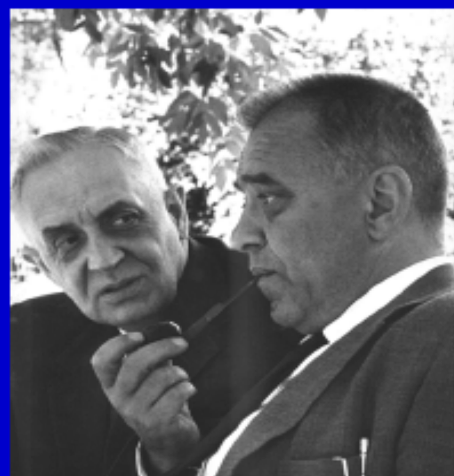
- Why we revisit the lifetime
- New measurement from STAR
  - Signal in separate bins
  - Updated results and world data
  - Discussions
- Concluding remarks

What are hypernucleus?

Nucleus which contains at least one hyperon in addition to nucleons.





- $\Lambda \rightarrow p + \pi^{-}$ *(64%);* $\Lambda \rightarrow n + \pi^{0}$ *(36%)*

The first hypernucleus was discovered by Danysz and Pniewski in 1952. It was formed in a cosmic ray interaction in a balloon-flown emulsion plate.

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

Hypernucleus of lowest A

$${}^{3}_{\Lambda}H(n+p+\Lambda)$$

$${}^{3}_{\overline{\Lambda}}\overline{H}(\overline{n}+\overline{p}+\overline{\Lambda})$$

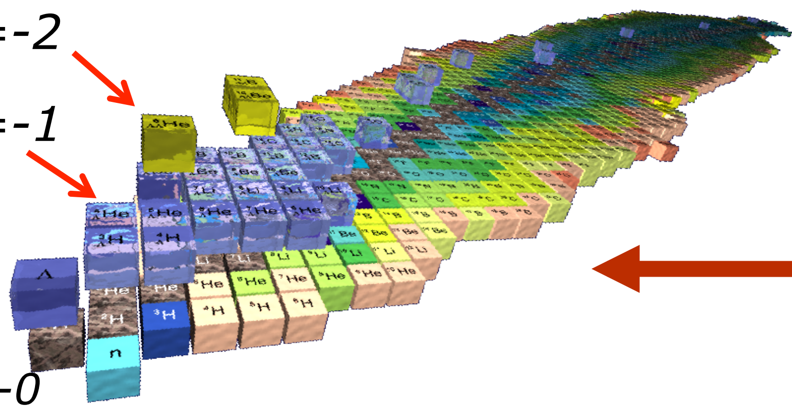
- Y-N interaction: a good window to understand the baryon potential
- Binding energy and lifetime are very sensitive to Y-N interactions
- Hypertriton: **ΔB=130±50 KeV; r~10fm**
- Production rate via coalescence at RHIC depends on overlapping wave functions of **n+p+Λ** in final state
- Hypertriton and anti-hypertriton ratios sensitive to matter and anti-matter profiles in heavy-ion collisions
- Important first step for searching for other exotic hypernuclei (double-Λ)

From Hypernuclei to Neutron Stars

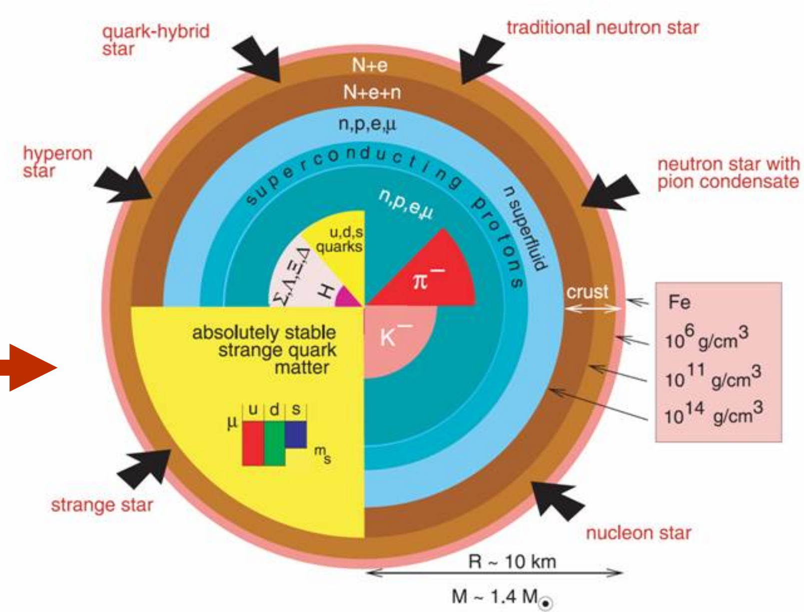
Nuclei ← Baryon-Baryon Interaction → Neutron Stars

S=-2

S=-1



S=-0



- ★ **Several possible configurations of Neutron Stars**
  - **hyperons, strange quark matter**
- ★ ***Single*** **and** ***double*** **hypernuclei in the laboratory:**
  - **study the strange sector of the baryon-baryon interaction**
  - **provide info on EOS of neutron stars**

The mesonic decay of hypertriton

Kamada et al., PRC 57, 1595(1998)

TABLE I. Partial and total mesonic and nonmesonic decay rates and corresponding lifetimes.

Channel	Γ [sec^{-1}]	Γ/Γ_Λ	$\tau=\Gamma^{-1}$ [sec]
^{3}He $+\pi^-$ and ^{3}H $+\pi^0$	0.146×10^{10}	0.384	0.684×10^{-9}
$d+p+\pi^-$ and $d+n+\pi^0$	0.235×10^{10}	0.619	0.425×10^{-9}
$p+p+n+\pi^-$ and $p+n+n+\pi^0$	0.368×10^{8}	0.0097	0.271×10^{-7}
All mesonic channels	0.385×10^{10}	1.01	0.260×10^{-9}
$d+n$	0.67×10^{7}	0.0018	0.15×10^{-6}
$p+n+n$	0.57×10^{8}	0.015	0.18×10^{-7}
All nonmesonic channels	0.64×10^{8}	0.017	0.16×10^{-7}
All channels	0.391×10^{10}	1.03	2.56×10^{-10}
Expt. [6]			$2.64\ {+0.92}\ {-0.54}\times10^{-10}$
Expt. (averaged) [11]			$2.44\ +\ 0.26\ {-0.22}\times10^{-10}$

[6] G. Keyes *et al.*, Phys. Rev. D **1**, 66 (1970); Phys. Rev. Lett. **20**, 819 (1968); Nucl. Phys. **B67**, 269 (1973).

[11] J. G. Congleton, J. Phys. G **18**, 339 (1992).

$$\frac{\Gamma({}^3_\Lambda\mathrm{H}\to\pi^-+{}^3\mathrm{He})}{\Gamma({}^3_\Lambda\mathrm{H}\to\pi^0+{}^3\mathrm{H})}=\frac{\Gamma({}^3_\Lambda\mathrm{H}\to\pi^-+p+d)}{\Gamma({}^3_\Lambda\mathrm{H}\to\pi^0+n+d)}=\frac{\Gamma({}^3_\Lambda\mathrm{H}\to\pi^-+p+p+n)}{\Gamma({}^3_\Lambda\mathrm{H}\to\pi^0+n+n+p)}=2.$$

$$\Gamma^{\mathrm{He}}\equiv\Gamma({}^3_\Lambda\mathrm{H}\to\pi^-+{}^3\mathrm{He}),$$

$$\Gamma^{p+d}\equiv\Gamma({}^3_\Lambda\mathrm{H}\to\pi^-+p+d),$$

$$\Gamma^{p+p+n}\equiv\Gamma({}^3_\Lambda\mathrm{H}\to\pi^-+p+p+n).$$

$$\Gamma=\frac{3}{2}(\Gamma^{\mathrm{He}}+\Gamma^{p+d}+\Gamma^{p+p+n})$$

Focus on the hypertriton lifetime (1)

- Though the mesonic decays are Pauli blocked in heavier hypernuclei, they are the dominant channels in hypertriton.
- In experiment, the 2-body helium3 channel and the 3-body deuteron channel are easier to access.

The lifetime measurements are interesting especially in view of the short values from early experiments :

The 1st measurements is $(0.95^{+0.19}_{-0.15})*10^{-10}$s from helium bubble chamber, by Block et al., presented in the proceeding of Conference on Hyperfragments at St, Cergue, 1963, p.62

Results from AGS nuclear-emulsion experiments: $(0.9^{+2.2}_{-0.4})*10^{-10}$s, Phys. Rev.136 (1964) B1803,

from Bevatron and AGS Phys. Rev. 139(1965) B401

2-body (3 in flight, 4 at rest) $(0.8^{+1.9}_{-0.3})*10^{-10}$s

★ 2-body combined with 3-body (5 in flight, 18 at rest) $(3.4^{+8.2}_{-1.4})*10^{-10}$s

Nuclear-emulsion with maximum likelihood procedure, Nucl. Phys. B 16 (1970) 46, $(1.28^{+0.35}_{-0.26})*10^{-10}$s,

Focus on the hypertriton lifetime (2)

- But other measurements gave different values:

  Helium bubble chamber from Argonne ZGS:

  $(2.32^{+0.45}_{-0.34})*10^{-10}$s, PRL 20 (1968)819

  $(2.64^{+0.84}_{-0.52})*10^{-10}$s, PRD 1(1970)66

  $(2.46^{+0.62}_{-0.41})*10^{-10}$s, NPB 67(1973)269

  Nuclear-emulsion from Bevatron:

  2-body is $(2.00^{+1.10}_{-0.64})*10^{-10}$s and 3-body $(3.84^{+2.40}_{-1.32})*10^{-10}$s,
  and a combined of $(2.74^{+1.10}_{-0.72})*10^{-10}$s

  PRL 20(1968)1383

- How about the theoretical understanding of these experimental results?

Focus on the hypertriton lifetime (3)

- The hypertriton being a loosely-bound nuclear system, its mean lifetime should not be significantly different from that of the free Lambda

  Theoretical calculations from Dalitz et al., initially gave a short value and updated later on a larger value close to the free Lambda's
  Phys. Lett. 1 (1962) 58 and Nuovo Cimento A 46,786 (1986)

  The calculations based on modern 3-body interaction force, the total lifetime is predicted to be $2.56*10^{-10}$s, Phys. Rev. C 57 (1998) 1595

- The hypertriton lifetime data are not sufficiently accurate to distinguish between models, more precise measurements are needed.

Results from RHIC-STAR Col.

- Previous measurement (before 1973)
  Use nuclear emulsion or bubble chamber.
  Accepted events: less than 80

- STAR 2010 measurement

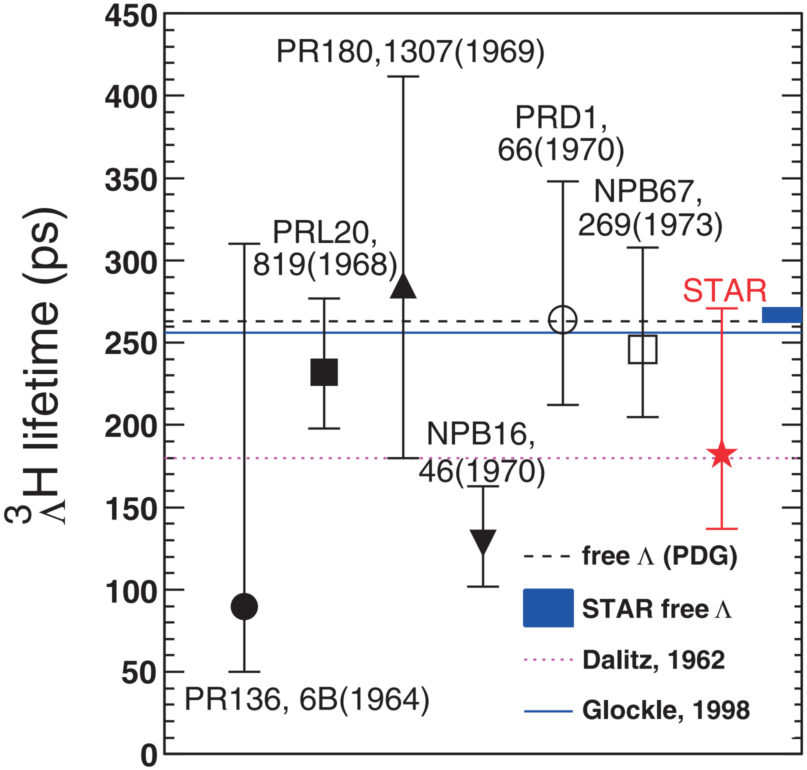
Run4 200GeV	MB	22M
Run4 200GeV	Central	23M
Run7 200GeV	MB	68M

- STAR 2012 measurement

Run10 200GeV	MB	~223M
Run10 200GeV	Central	~199M
Run10&11 low energies	MB	~213M

Previous measurement

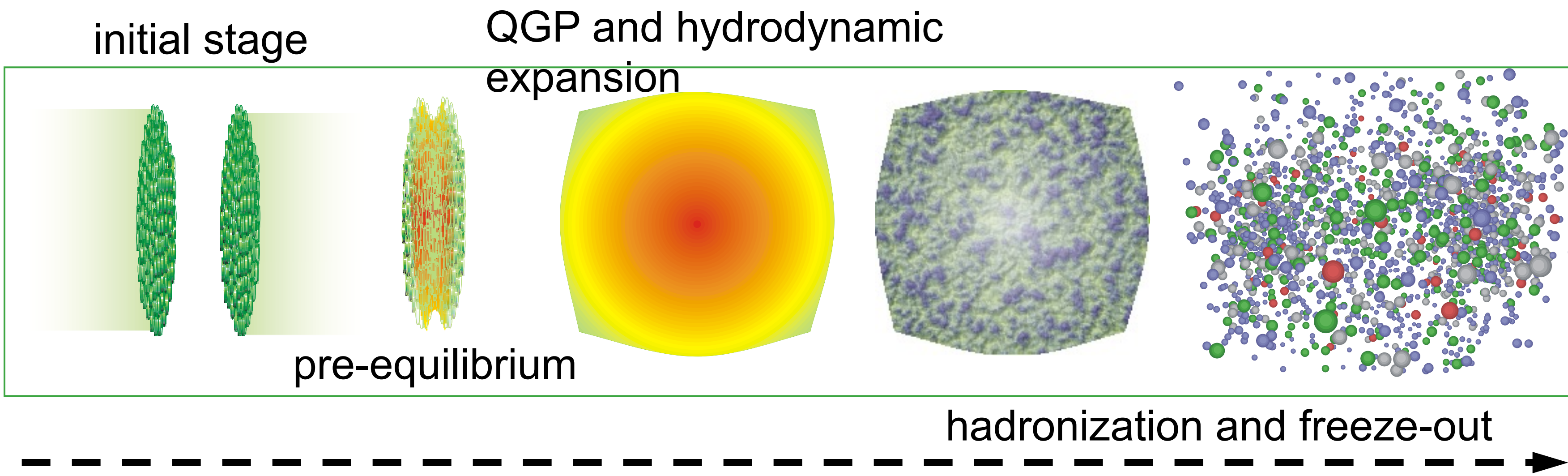
STAR Collaboration, Science 328 (2010)58



World data

- It is promising to obtain an improved lifetime measurement using the new data

Relativistic heavy-ion collisions

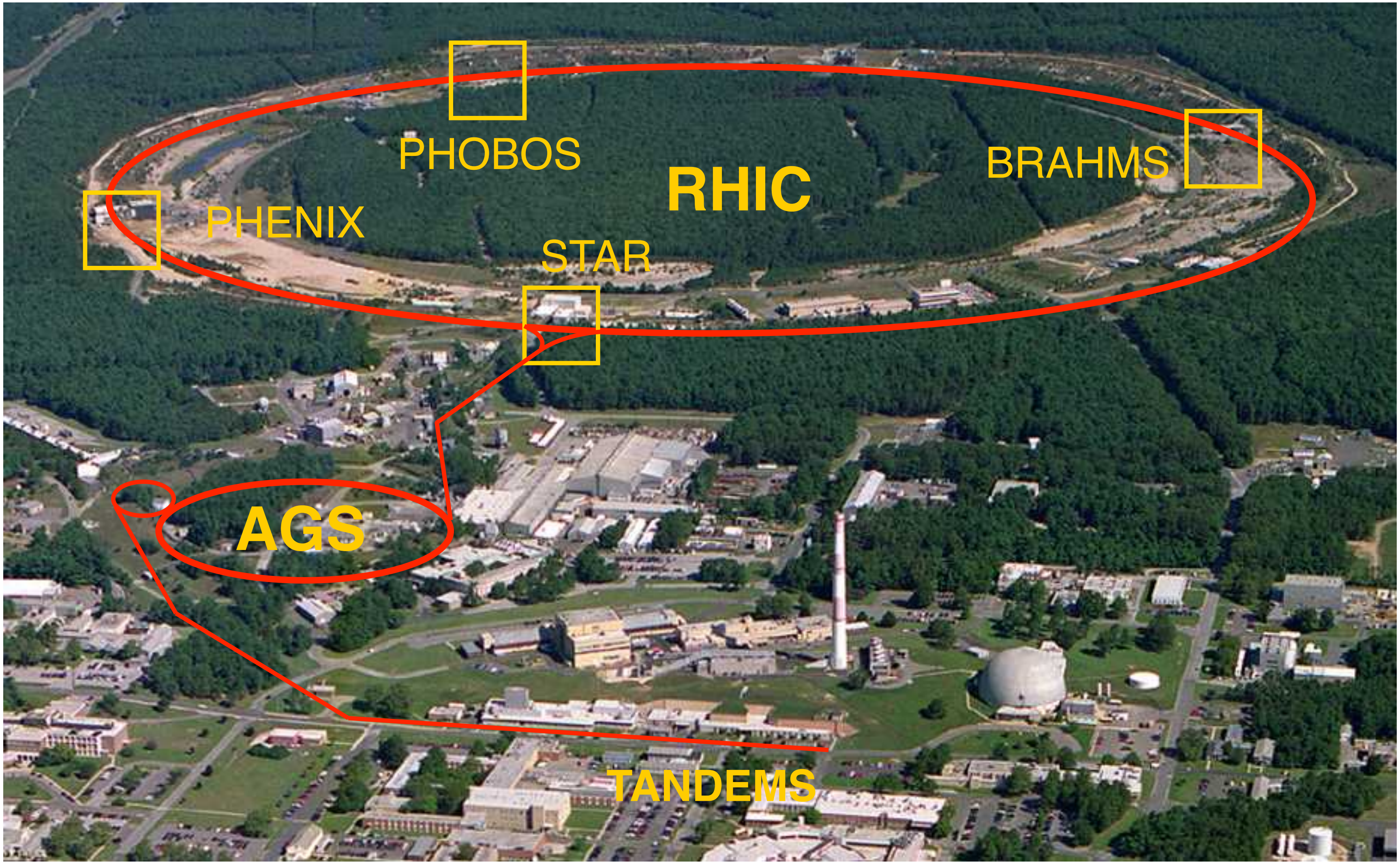


- Initial condition of collisions
- New state of matter : QGP
- Hadronization and hadronic interaction

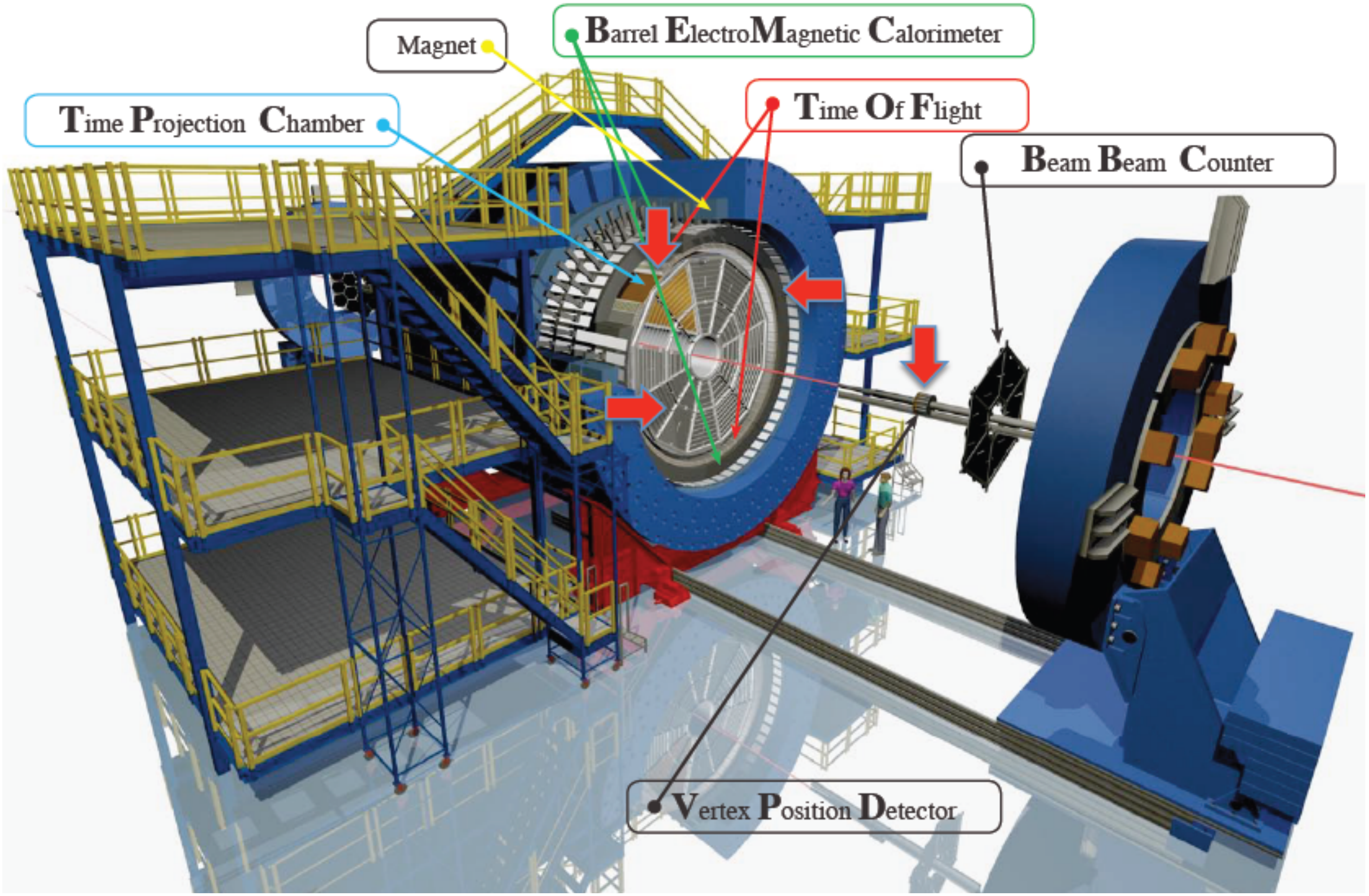
★ RHIC creates hot and dense matter, containing dozens of hyperons in central events : ideal source of hypernuclei studies.

RHIC white paper: Nucl. Phys. A 757

Relativistic Heavy Ion Collider (RHIC)



The STAR Detector



★ TPC: effectively 3-D ionization camera with over 50 million pixels.

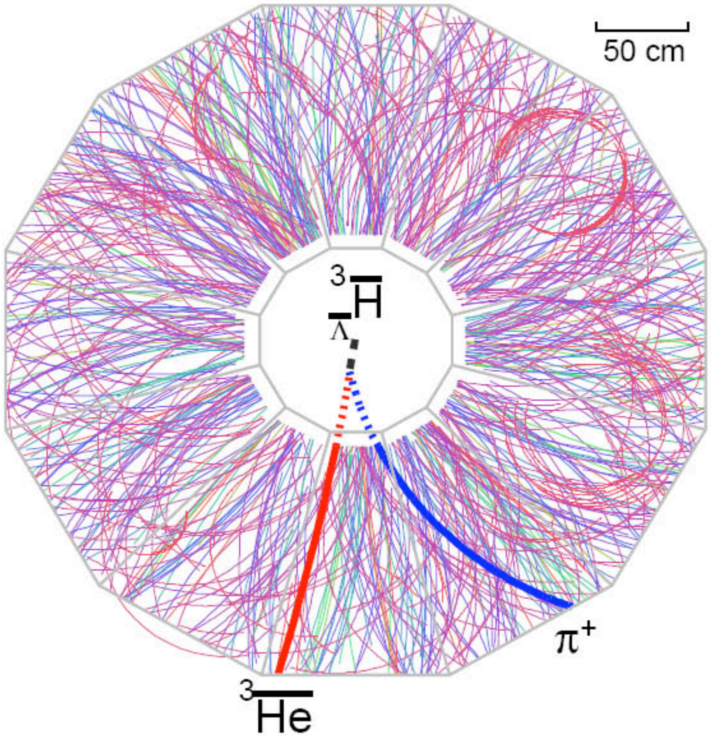
★ STAR: a complex set of various detectors, a wide range of measurements and a broad coverage of different physics topics.

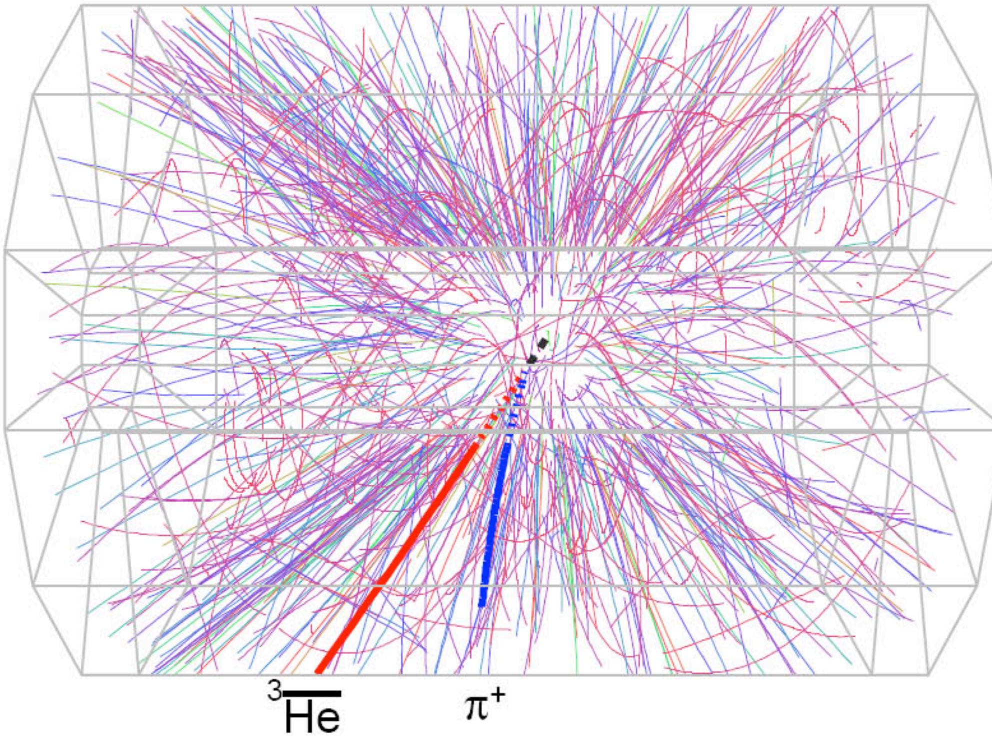
STAR-TPC: *NIMA 499 (2003) 659*

STAR-detector: *NIMA 499 (2003) 624*

Event display

STAR Collaboration, Science 328 (2010) 58





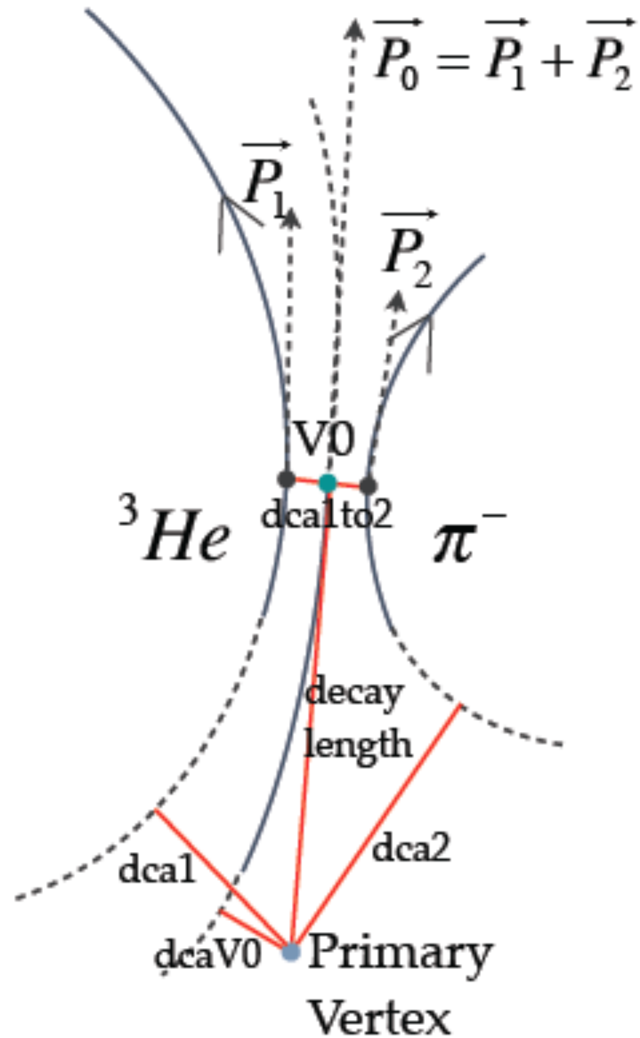
★ A beautiful event in the STAR TPC that includes the production and decay of a antihypertriton candidate. (Data taken from Run4 Au+Au 200GeV MB collision)

Datasets and track selection

★ Datasets and event statistics

Run10 7.7GeV	MB	~4M
Run10 11.5GeV	MB	~11M
Run11 19.6GeV	MB	~31M
Run11 27GeV	MB	~49M
Run10 39GeV	MB	~118M
Run10 200GeV	MB	~223M
Run10 200GeV	Central	~199M
Run7 200GeV	MB	~56M

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

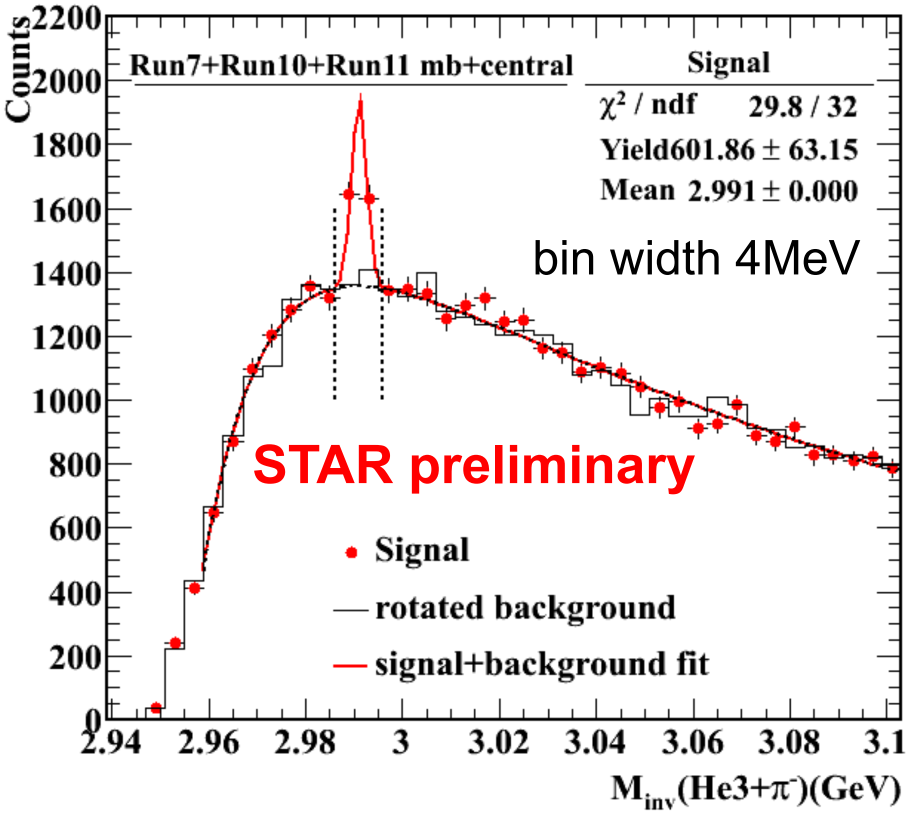


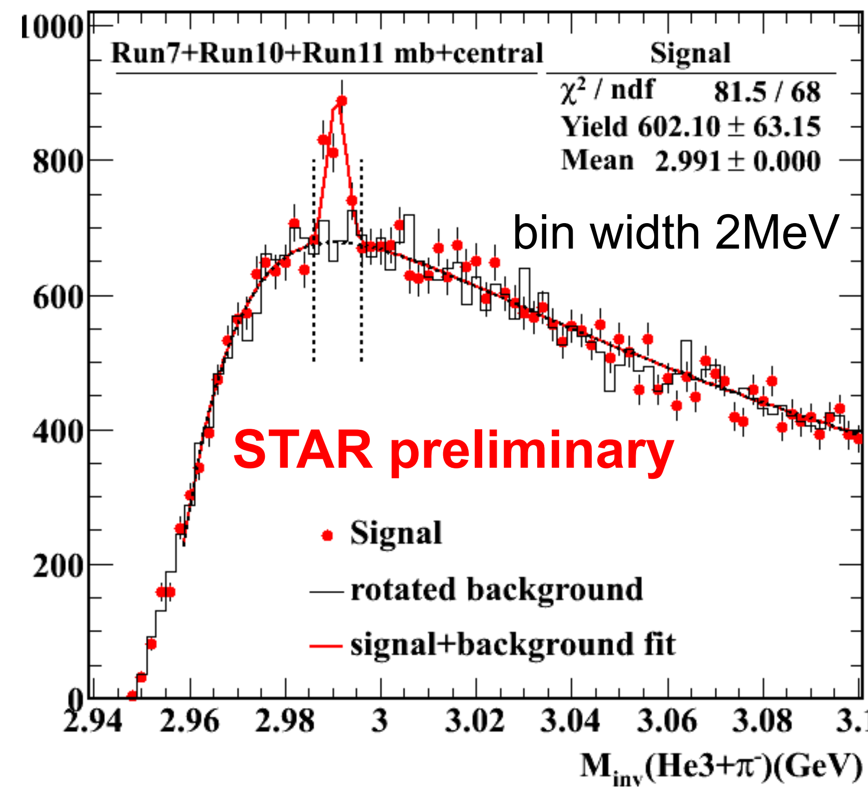
★ Analysis method: secondary vertex finding technique

- Identify ^{3}He and π candidate
- Find the V0 position from daughters pairing
- Plot the invariant mass dis. of daughters
- Combinatorial background analysis

The largest Hypertriton sample

- Statistics: Run7+Run10+Run11 MB+Central, ~610M events



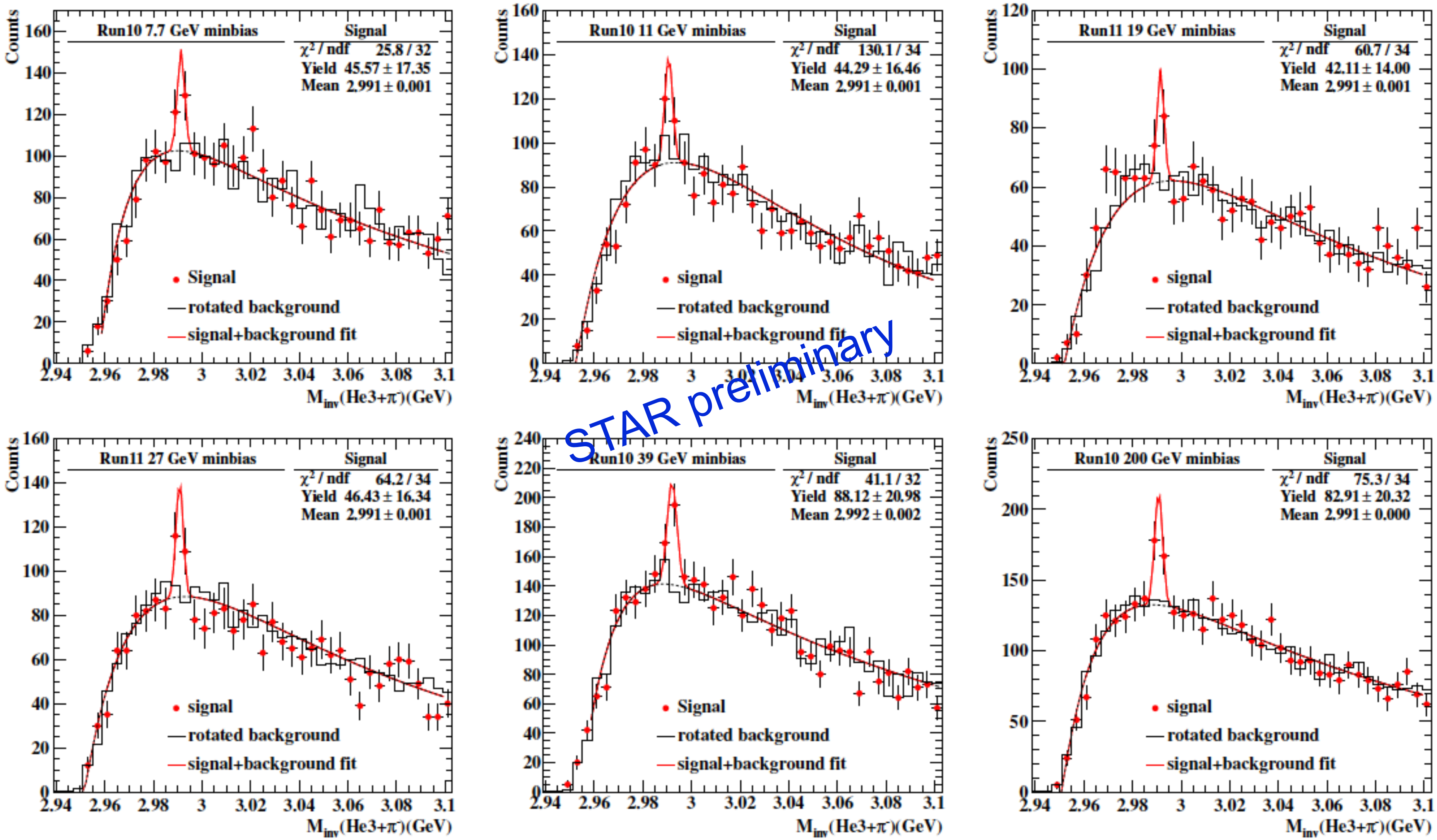


- Signal observed from the data (bin-by-bin counting [2.986,2.996]GeV): **602±63**, which is the largest hypertriton sample ever created
- Background estimation: rotated background

background: form:

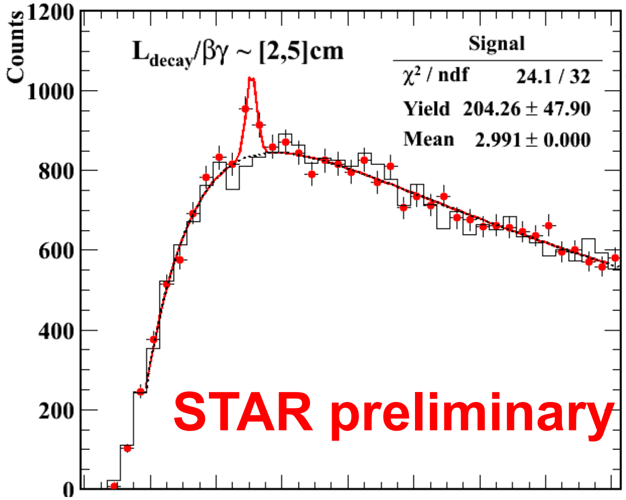
$$f(x) \propto \exp(-\frac{x}{p_1}) - \exp(-\frac{x}{p_2})$$

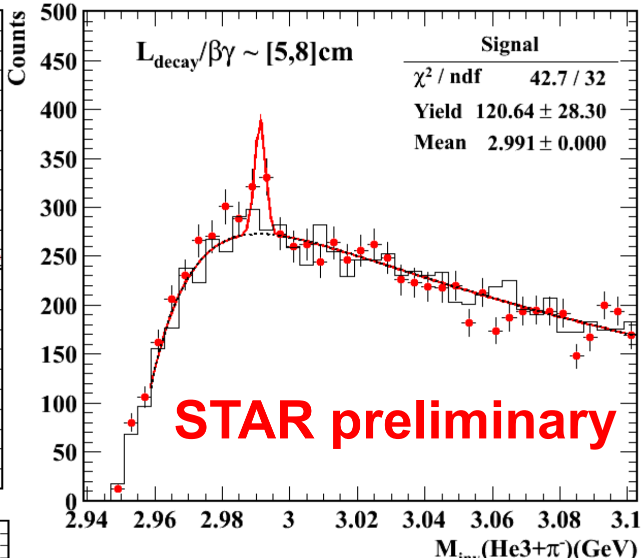
Hypertriton signal from STAR BES at $\sqrt{s_{NN}}$ =7.7, 11.5, 19.6, 27, 39, 200GeV

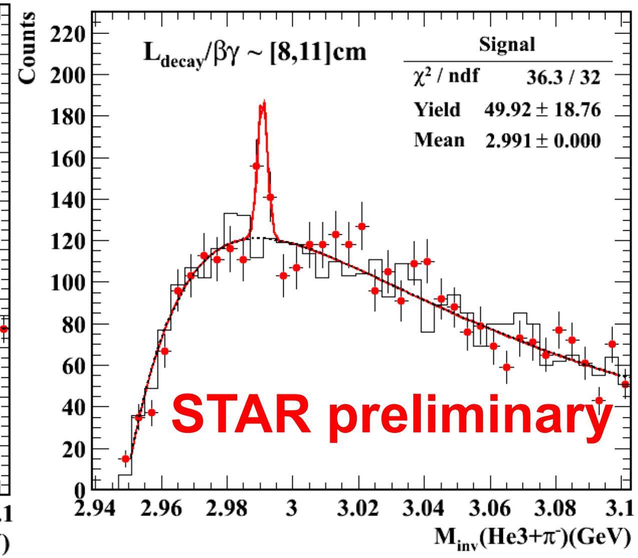


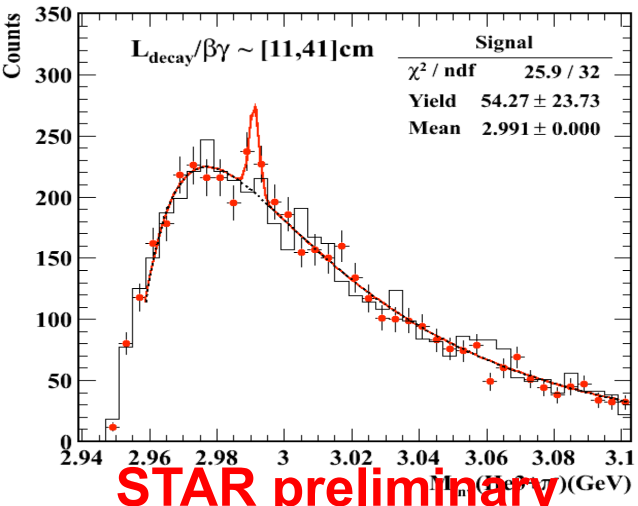
Signal in separated decay length bins

$$\star\ N(t) = N(0)\times e^{-t/\tau} = N(0)\times e^{-L/\beta\gamma c\tau}$$









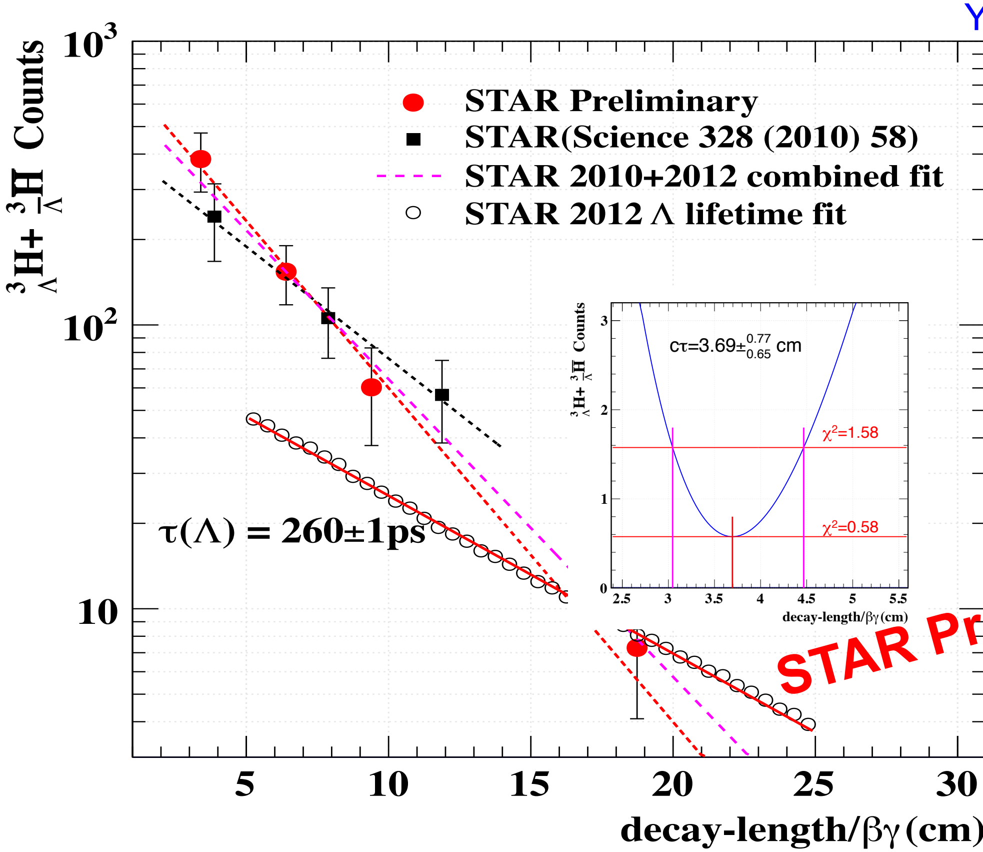
- Measure the hypertriton signal in different L/βγ bins: 2-5-8-11-41cm
- Combined dataset

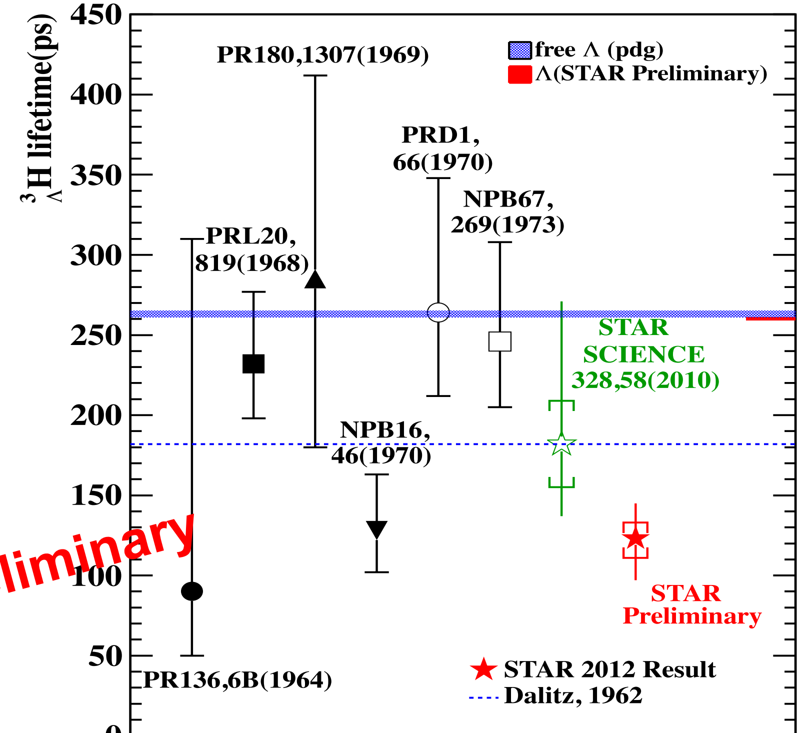
run10： 7.7, 11.5, 39, 200GeV MiniBias,

run10： 200GeV central；run11: 19.6, 27GeV MB

New hypertriton lifetime result

Y.H. Zhu (SINAP), Nucl. Phys. A 904–905 (2013) 551c





Y.H. Zhu (SINAP) for STAR Col., QM2012, USA
J.H. Chen (SINAP) v, Spain

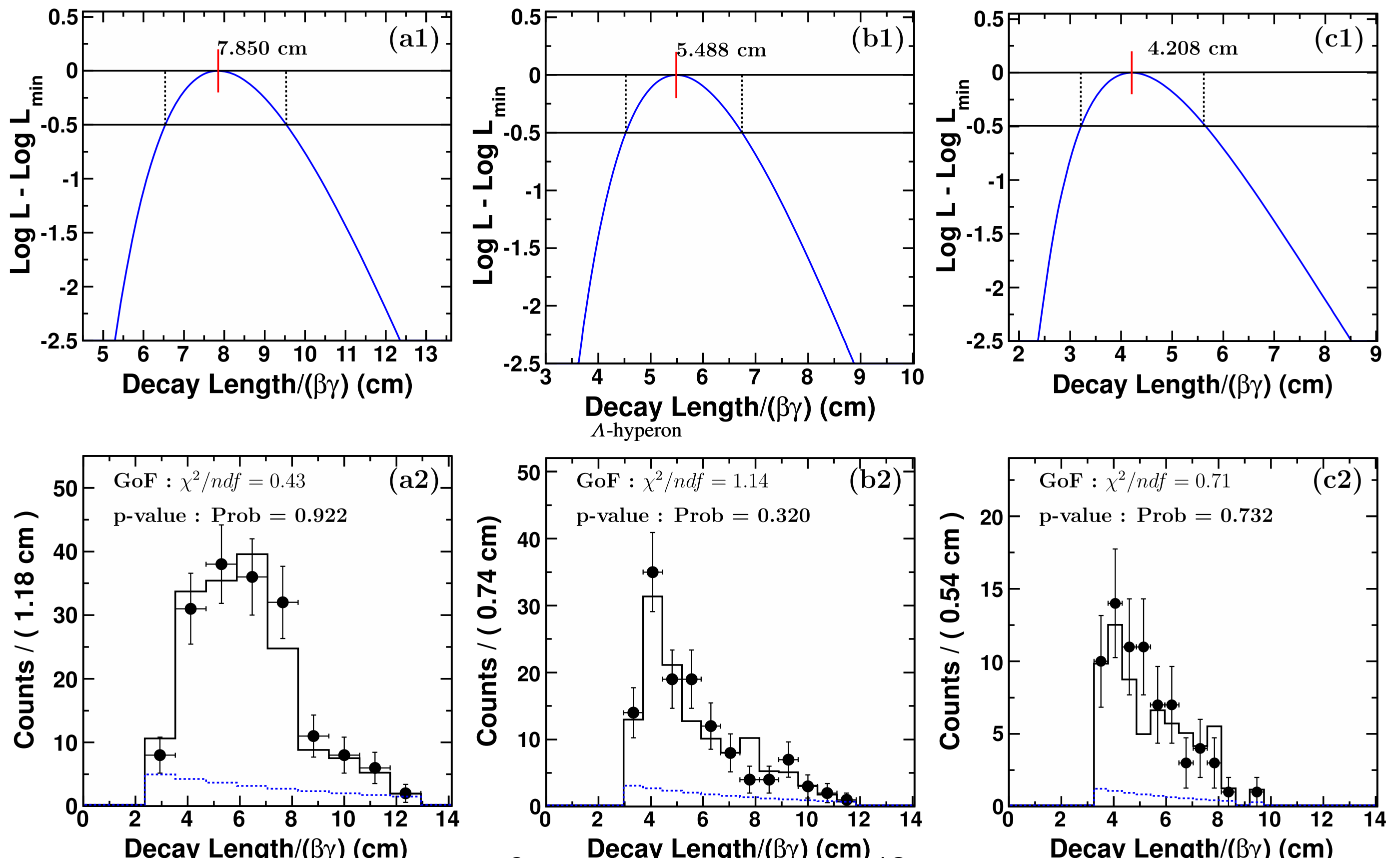
★STAR 2012 preliminary result: $\tau = 123 \pm^{26}_{22} \pm 10\, ps$

★STAR 2010+2012 combined fit: $\tau = 138 \pm^{23}_{20}\, ps$

As a further cross-check, Λ is reconstructed via the $\Lambda \to p + \pi^-$ decay channel. We use exactly the same method to obtain the Λ lifetime and the result is 260 ± 1 ps which is consistent with the $\tau = 263 \pm 2$ ps compiled by the Particle Data Group [10].

Measurement from HpyHI project

Lambda | Hypertriton | ^{4}H(Lambda)



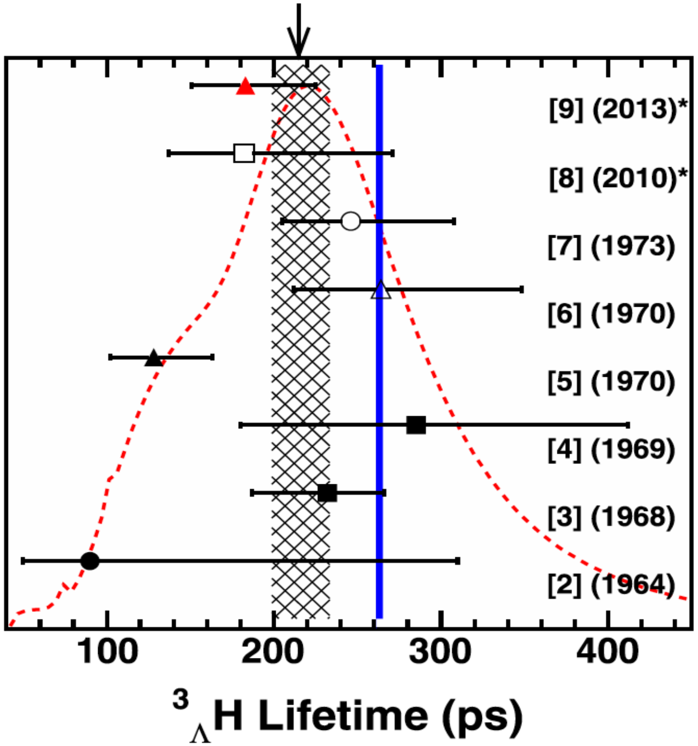
Hypernuclear spectroscopy at GSI: ^{6}Li projectiles on ^{12}C target at 2 A GeV presents the hypertriton lifetime measurement from 2-body channel:

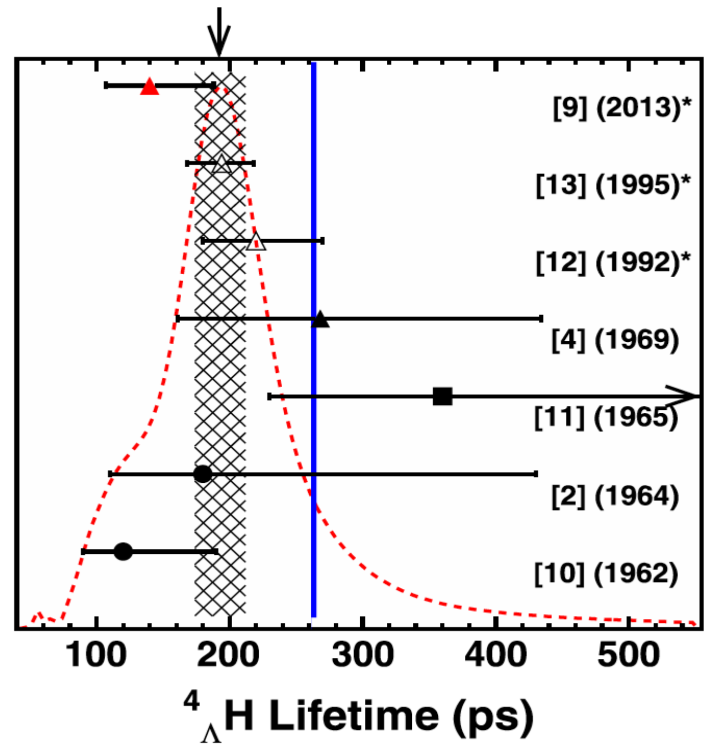
$$\tau = 183 \pm^{42}_{32} \pm 37\, ps$$

Nucl. Phys. A 913(2013)170

On the measured lifetime of light hypernuclei 3ΛH and 4ΛH

C. Rappold, R. Saito et al., Phys. Lett. B 728, 543(2014)





- The combined analysis of the world data for the lifetime of 3ΛH and 4 ΛH gave the average of 3 ΛH and 4ΛH lifetime was respectively 216+19−16 ps and 192+20−18ps.
- With these studies, it has been revealed that the measured lifetime of 3 ΛH and 4ΛH can be significantly shorter than that of the Λ–hyperon.

The physics for short lifetime?

★ Revisit the previous theoretical calculation:

A statistical combination analysis of the experimental lifetime data give average of 216^{+19}_{-18} ps for hypertriton, indicated that the lifetime of light hypernuclei is significantly shorter than the free Lambda's

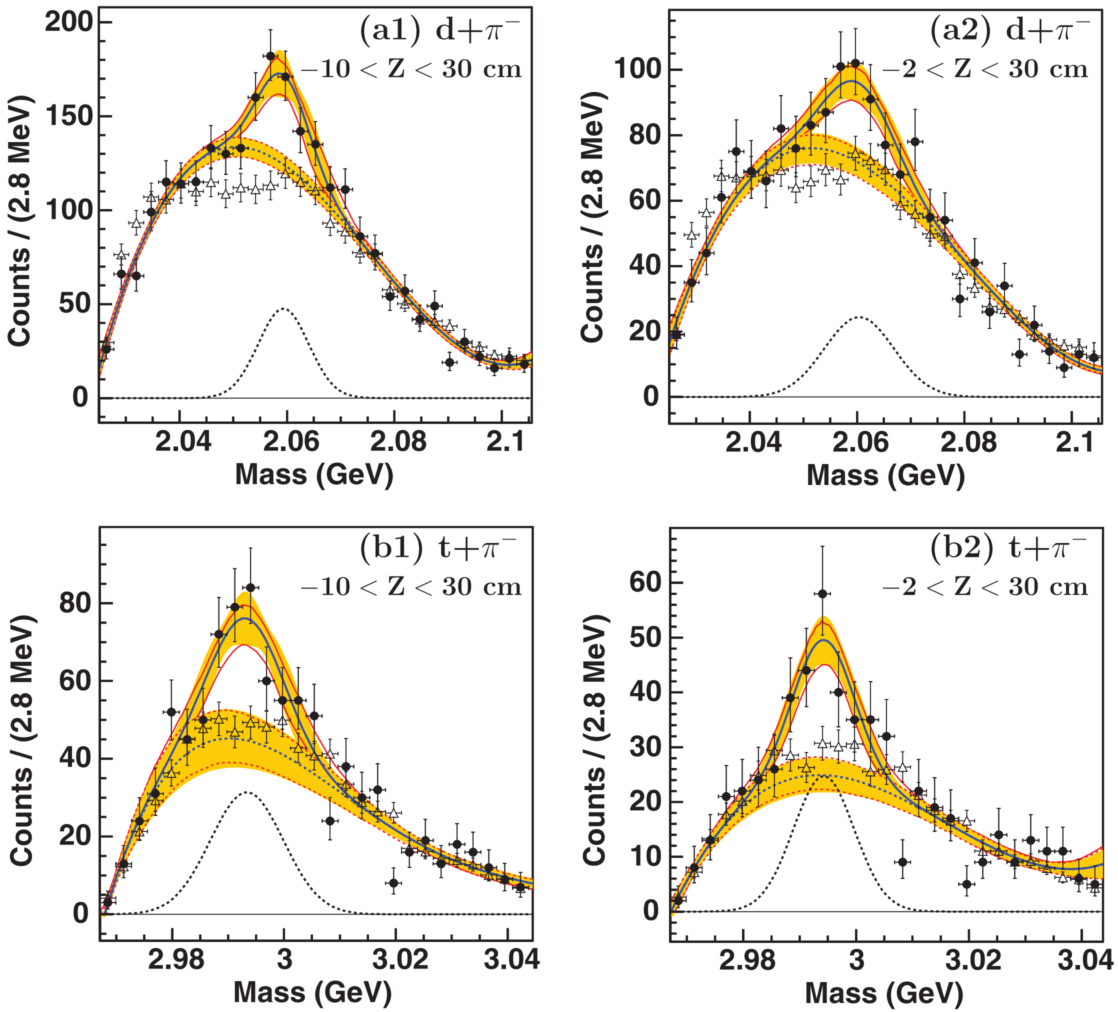
★ Revisit binding energy (130 ± 50 kev), STAR exp. 3-body analysis have significant progress.

★ Physics implications:
(1) Loose Lambda inside hypernucleus,
hypernuclear lifetime ~ free Labmda
(2) Stronger lambda-n interaction,
hypernuclear lifetime < free Labmda
………

(1)

(2)

(nnΛ) signal in HI reaction?



HypHI exp. observed a signal in the invariant mass distribution of d+pi and t+pi channel.

PRC 88,041001R(2013)

Data from HIRES Col. Excluded the (Lp) candidates

PLB 687, 31(2010)

PRD 84, 032002(2011)

A possible interpretation might be the two- and three-body decays of an unknown bound state of 2 neutrons associated with a Lambda:

$$\text{via } {}^{3}_{\Lambda}n \to t + \pi^- \text{ and } {}^{3}_{\Lambda}n \to t^* + \pi^- \to d + n + \pi^-,$$

STAR preliminary

Yifei Xu (SINAP&BNL)

Two Bodies:

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

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

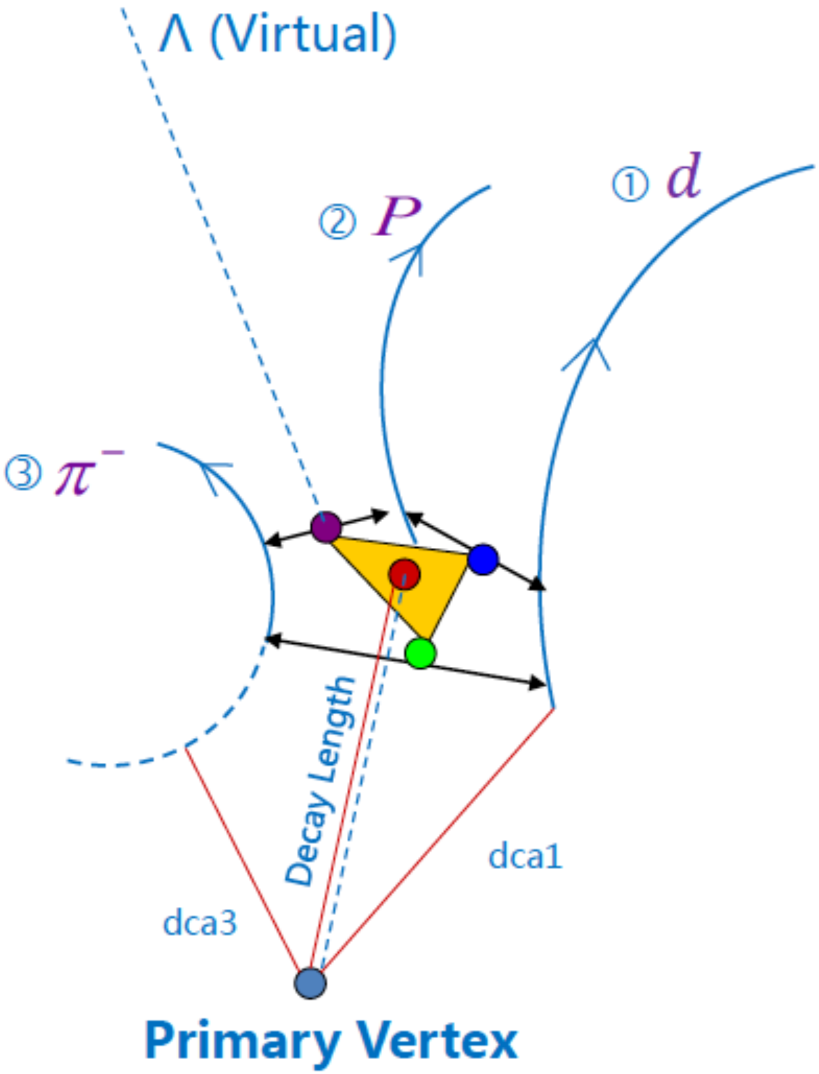
Three Bodies:

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

$${}^{3}_{\bar{\Lambda}}\overline{H} \rightarrow \bar{d} + \overline{P} + \pi^{+}$$

Run	Energy	Vertex-R	Vertex-Z	Ref-Mult	Trigger Type	Trigger ID	Event Number
Run11	27GeV	≤2.0	≤50	All	Min-Bias	360001, 360002	53.31 M
Run10	39GeV	≤2.0	≤40	All	Min-Bias	280001	134.41 M
Run10	62.4GeV	≤2.0	≤40	All	Min-Bias	270001, 270011 270021	70.23 M
Run11	200GeV	≤2.0	≤30	All	Min-Bias	350003, 350013 350023, 350033 350043	516.87 M

Topologic cuts



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

- v012 : Mid-point of DCA 1 to 2
- v023 : Mid-point of DCA 2 to 3
- v013 : Mid-point of DCA 1 to 3

We assume the three points above to be the three vertexes of a triangle, then:

- v0123 : Centre of gravity of the triangle

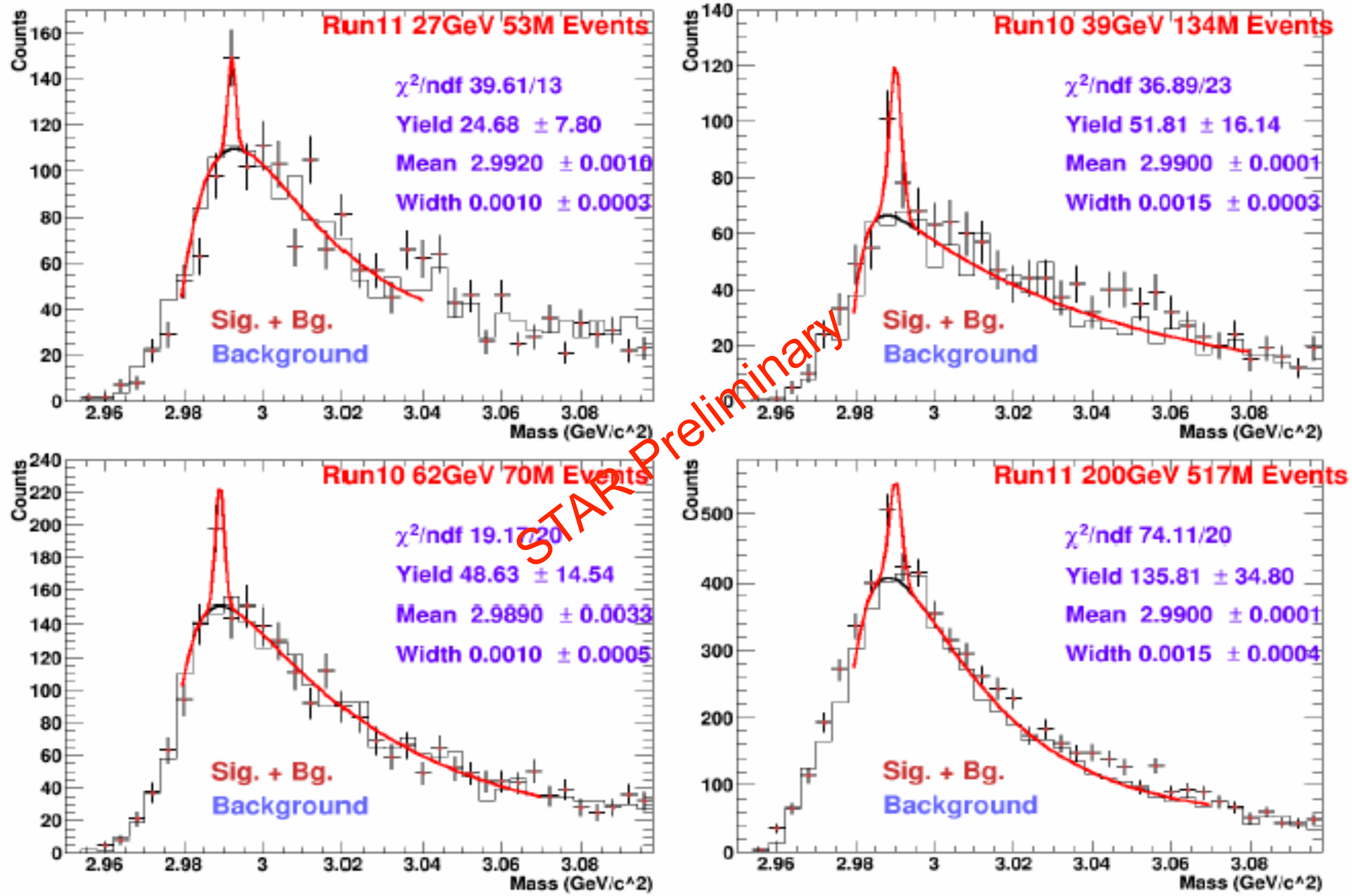
Then we have:

dca1, dca2, dca3, Decay Length
dca1to2, dca2to3, dca1to3........

STAR preliminary

Yifei Xu (SINAP)

Signal with Background fitting function : $f_{sig}(x) = f_{bkg}(x) + gaus()$



Bin Width 4 MeV

Preliminary 3-body analysis also shows a short lifetime.
Detailed results will be shown in HYP2015, Sept. 2015 by Mr. Yifei Xu

Concluding Remarks

- Measurements of hypertriton lifetime are an interesting project in the field. Independent exp. present different results.

- Several theoretical interpretations have achieved in the field and tend to conclude a value close to the free Lambda's

- New and precise measurements (>600 signals) from STAR Col. in the Relativistic Heavy-Ion Collider give a short value:

$$\tau = 123 \pm^{26}_{22} \pm 10$$

- Data from HypHI from GSI fixed target exp. Also show a short lifetime value:

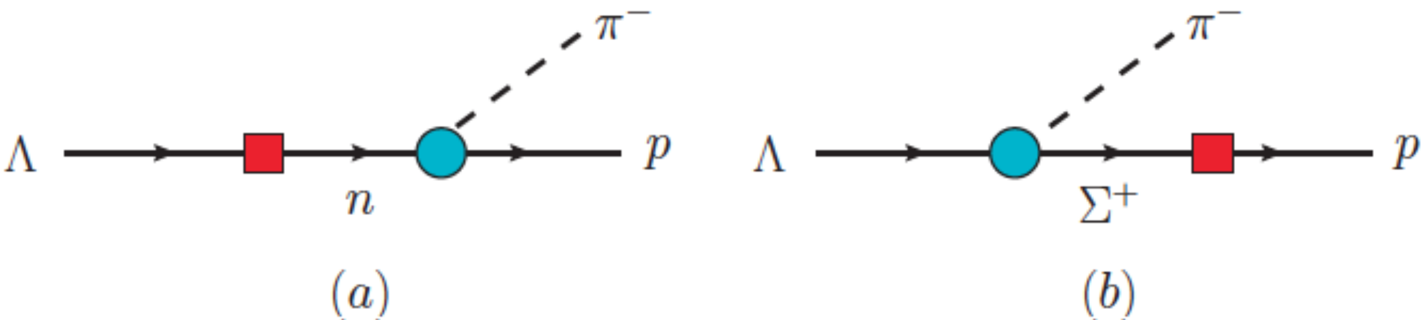
$$\tau = 183 \pm^{42}_{32} \pm 37 ps$$

- The discrepancy among different exp. is still there, the hypertriton lifetime is still a puzzle. New measurements from STAR Col., esp. for 3-body decay channel should shed new light on the puzzle.

Understanding the shortened lifetime of ${}^{3}_{\Lambda}$H

Jean-Marc Richard[1*], Qian Wang[2†], and Qiang Zhao[3‡]

Q. Zhao, Private communication



baryon internal conversion process

FIG. 1: Feynman diagrams for the free Λ hadronic weak decay.

absent. For the weakly bound ^{3}H ground state, its lowest energy level 1s-shell is occupied by the two anti-parallel neutrons. Since the mass of the Λ is close to the nucleon, the intermediate pole of ^{3}H should play a role. Therefore, when the initial Λ converts to a neutron it should be affected by the existing neutron due to Pauli principle. The saturation of the intermediate ^{3}H means that an anti-symmetrization of the intermediate pnn relative S-wave system has been properly treated at leading order. In contrast, the process of Fig. 1 (b) will not be affected by the Pauli blocking. Such an unbalanced effect on the processes in Figs. 1 (a) and (b) can violate the cancelation pattern and eventually increase the amplitude significantly. We find this is the most efficient mechanism that shorten the lifetime of ${}^{3}_{\Lambda}$H.

The shortened lifetimes of hyper-3H and hyper-4H are due to the Pauli blocking effects which will suppress one pole amplitude but unaffect the other. As a consequence, the "perfect cancelation" between those two pole terms will be violated and the increased amplitude will broaden the width and then shorten the lifetime of the hypernuclei.

Systematic Study on Lifetime

Absorption

Hypertriton interacts with air and detector structure materal

$$e^{-\frac{\sigma_{{}^{3}_{\Lambda}H+material}}{\sigma_{p+material}}\cdot\frac{l}{\lambda_T/\rho}} \sim e^{-\frac{\sigma_{{}^{3}_{\Lambda}H+p}}{\sigma_{p+p}}\cdot\frac{l}{\lambda_T/\rho}} < e^{-\frac{\sigma_{pd}+\sigma_{p\Lambda}}{\sigma_{pp}}\cdot\frac{l}{\lambda_T/\rho}}$$

Absorption effect is less than 1.5% and can be neglected

Bin Width

Present is 4MeV bin, τ fit result is 123 ± 24ps

For 2MeV bin, τ fit result is 116 ± 23ps

Systematic error due to binning is 5.7%

Different Cuts

Change cuts 1): τ : 120 ± 30ps Change cuts 2): τ : 130 ± 28ps

Systematic error due to cuts is 6.2%

Total Systematic Error: ~8.4%