Precise measurement on hypertriton and antihypertriton mass and lifetime with the STAR Heavy Flavor Tracker

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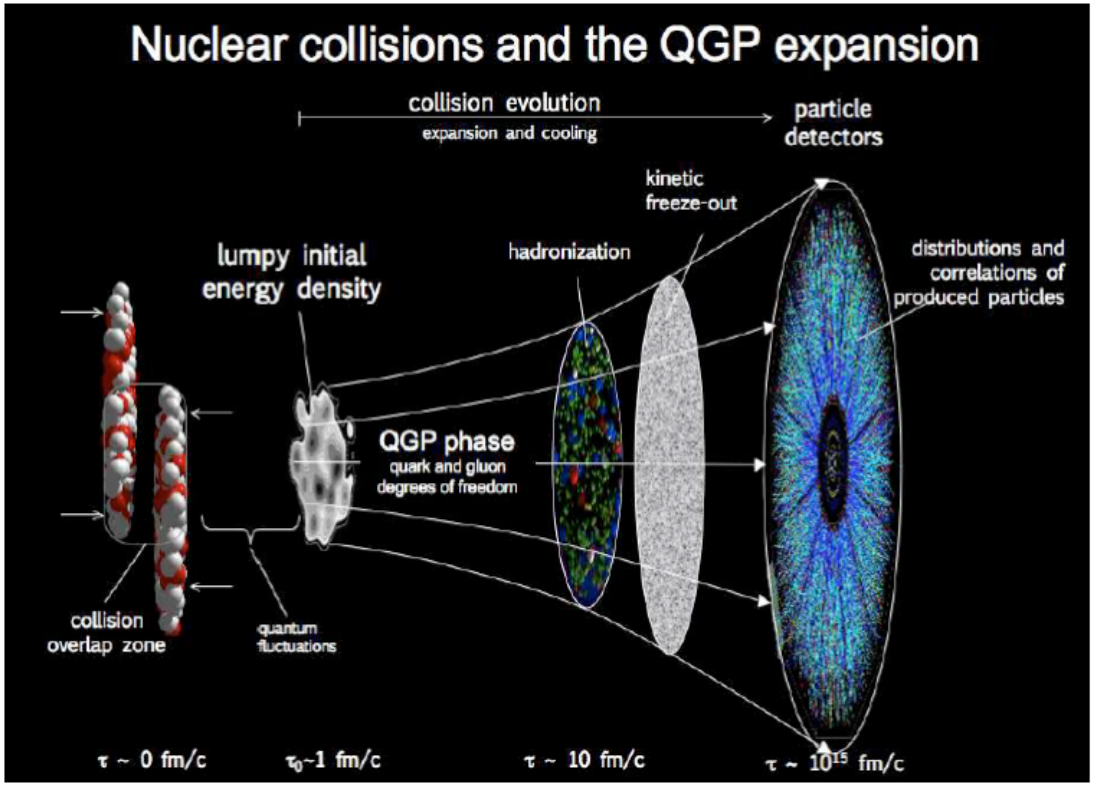
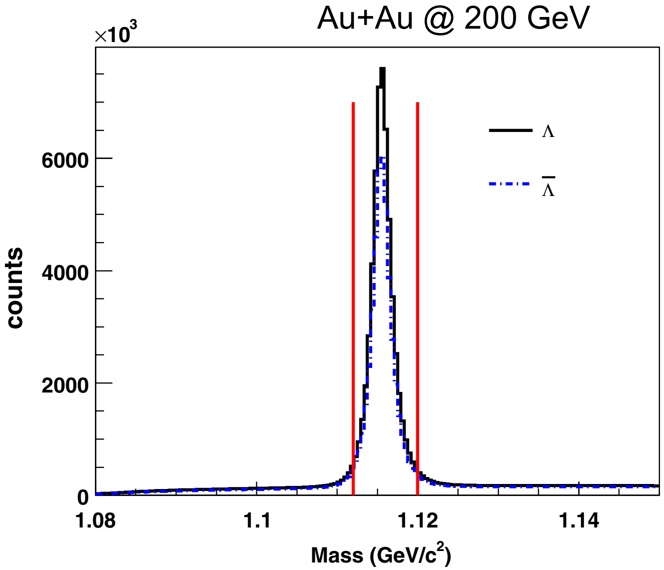
Heavy ion collider as a hyperon factory



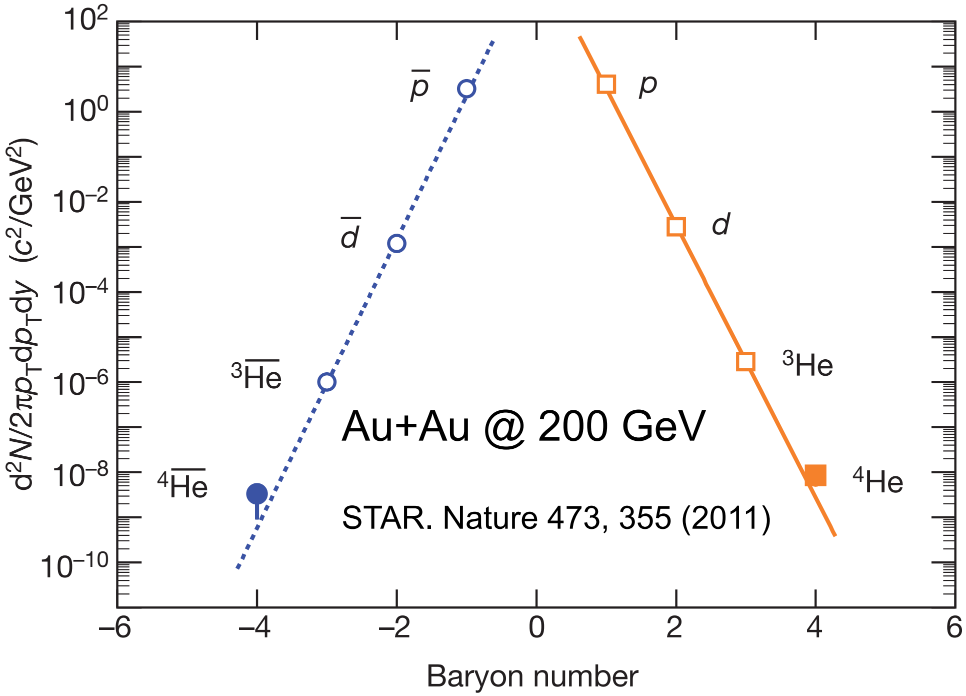
- ☑ RHIC, a QCD machine, small bang
- ☑ Hyperon rate is high, lab. for Y-N interaction
- ☑ Excellent secondary vertex reconstruction in STAR and ALICE

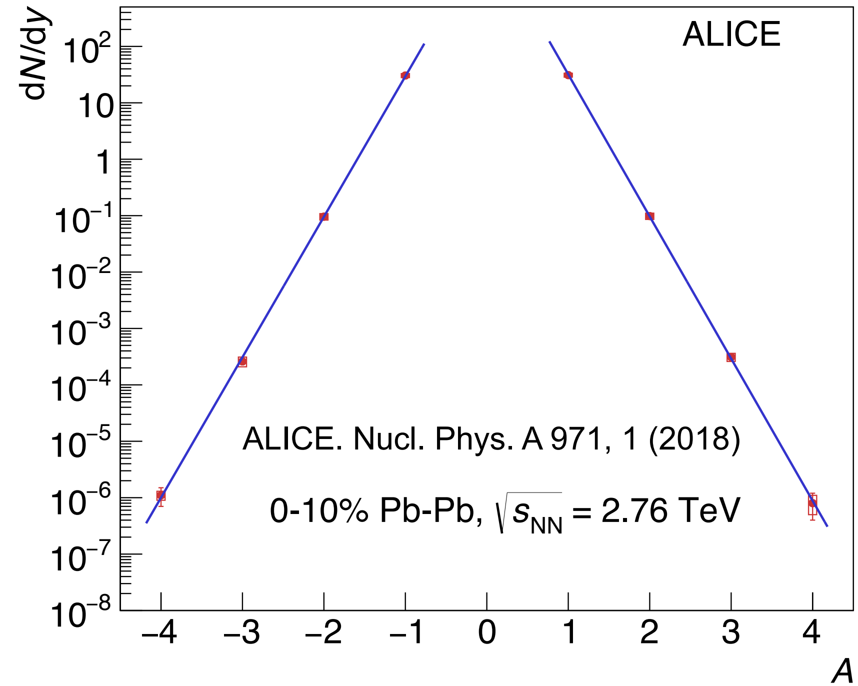
0-5% central collisions, Au+Au @ 200 GeV, Pb-Pb @ 2.76 TeV

$$\left.\frac{dN_Y}{dy}\right|_{y=0} \simeq \begin{cases} \mathbf{16.7,} & \mathbf{26,} & \Lambda\ \mathbf{(S=-1)} \\ \mathbf{2.2,} & \mathbf{3.3,} & \Xi\ \mathbf{(S=-2)} \\ \mathbf{0.3,} & \mathbf{0.6,} & \Omega\ \mathbf{(S=-3)} \end{cases}$$



(Hyper-)nuclei production in HIC





STAR. Science 328, 58 (2010)

Particle type	**Ratio**
${}^{3}_{\bar\Lambda}\overline{\text{H}}/{}^{3}_{\Lambda}\text{H}$	$0.49 \pm 0.18 \pm 0.07$
${}^{3}\overline{\text{He}}/{}^{3}\text{He}$	$0.45 \pm 0.02 \pm 0.04$
${}^{3}_{\bar\Lambda}\overline{\text{H}}/{}^{3}\overline{\text{He}}$	$0.89 \pm 0.28 \pm 0.13$
${}^{3}_{\Lambda}\text{H}/{}^{3}\text{He}$	$0.82 \pm 0.16 \pm 0.12$

☑ The production reduction factor is up to 10^3 at RHIC and 300 at LHC, limited to A<4 system

STAR ☆ Focus on the hypertriton lifetime (1)

☑ The lifetime measurements are interest 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.136B,1803 (1964),

  from Bevatron and AGS: Phys. Rev.139B,401 (1965)

  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. B16,46 (1970), $(1.28^{+0.35}_{-0.26})*10^{-10}$s

Focus on the hypertriton lifetime (2)

- But NEW measurements gave different values:

  Helium bubble chamber from Argonne ZGS:

  $(2.32^{+0.45}_{-0.34})*10^{-10}$s, Phys. Rev. Lett. 20,819 (1968)

  $(2.64^{+0.84}_{-0.52})*10^{-10}$s, Phys. Rev. D 1,66 (1970)

  $(2.46^{+0.62}_{-0.41})*10^{-10}$s, Nucl. Phys. B 67,269 (1973)

  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

  Phys. Rev. Lett. 20,1383 (1968)

- Theoretical side, the hypertriton being a loosely-bound nuclear system, its mean lifetime should not be significantly different from that of Lambda's

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

Updates on hypertriton analysis at STAR

Data sets for 2-body and 3-body analysis

TABLE I. Data set for the two-body decay channel analysis, with ^{3}He and $^3_\Lambda$H statistics.

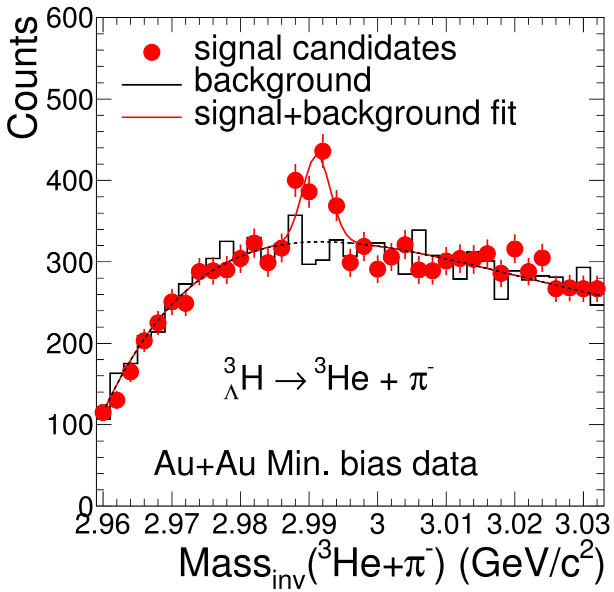
Energy	Events ($\times$10 M)	^{3}He	$^3\overline{\text{He}}$	$^3_\Lambda\text{H} + ^3_{\bar\Lambda}\overline{\text{H}}$
7.7 GeV	0.4	6388 ± 80	0	52 ± 17
11.5 GeV	1	5330 ± 73	0	44 ± 16
19.6 GeV	3	4941 ± 70	0	42 ± 14
27 GeV	5	4179 ± 65	19 ± 4	45 ± 16
39 GeV	12	5252 ± 72	133 ± 12	86 ± 21
200 GeV	22	6850 ± 83	2213 ± 47	85 ± 20

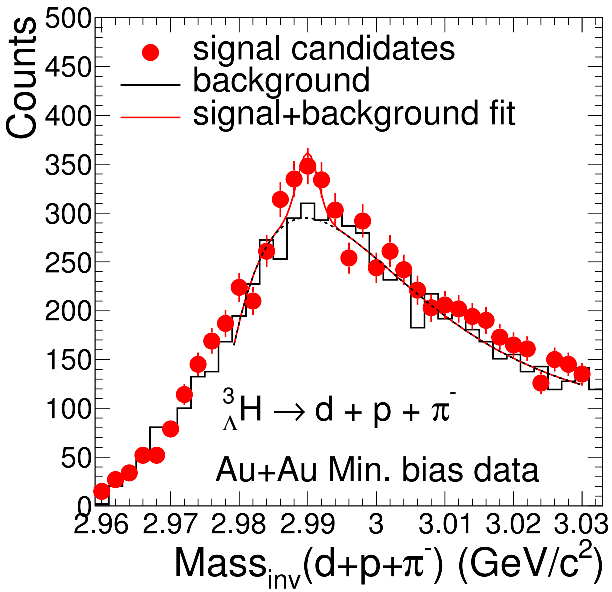
TABLE II. Data set for the three-body decay channel analysis, with $^3_\Lambda$H statistics.

Energy	Events ($\times$10 M)	$^3_\Lambda$H
27 GeV	5	42 ± 16
39 GeV	13	53 ± 13
200 GeV	52	128 ± 30

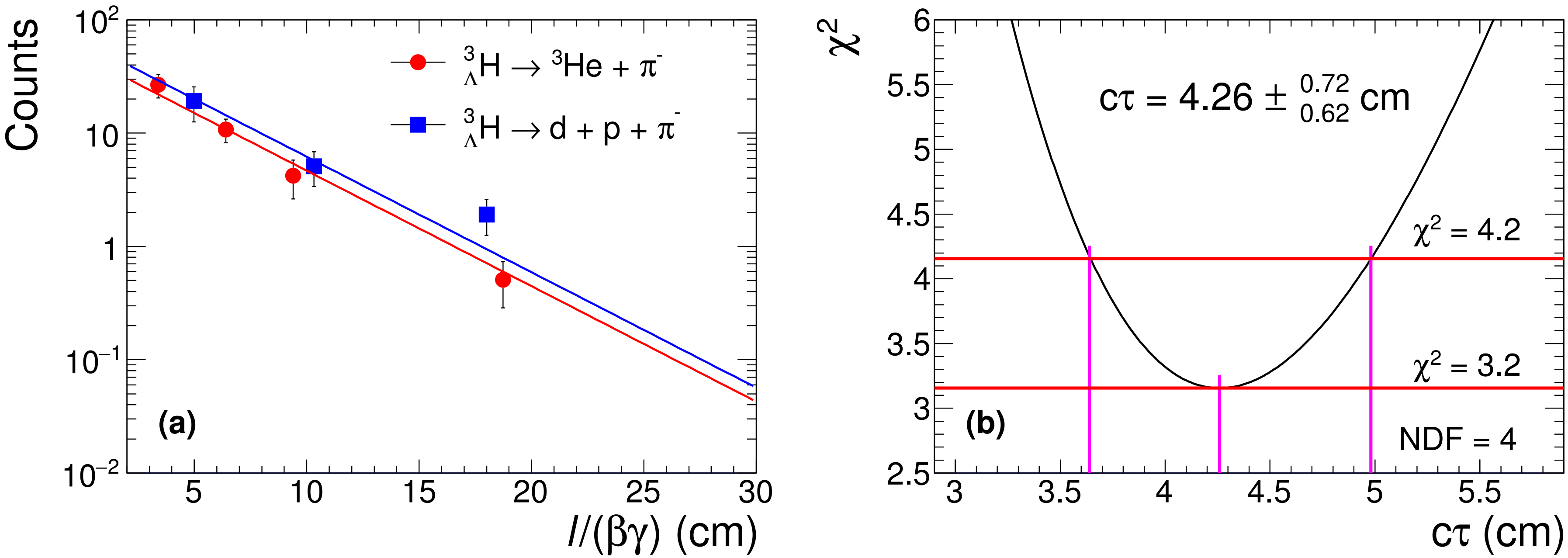
High statistics sample with good signal to background ratio in both channels: ~25% & ~15%

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





Updates on lifetime measurement at STAR

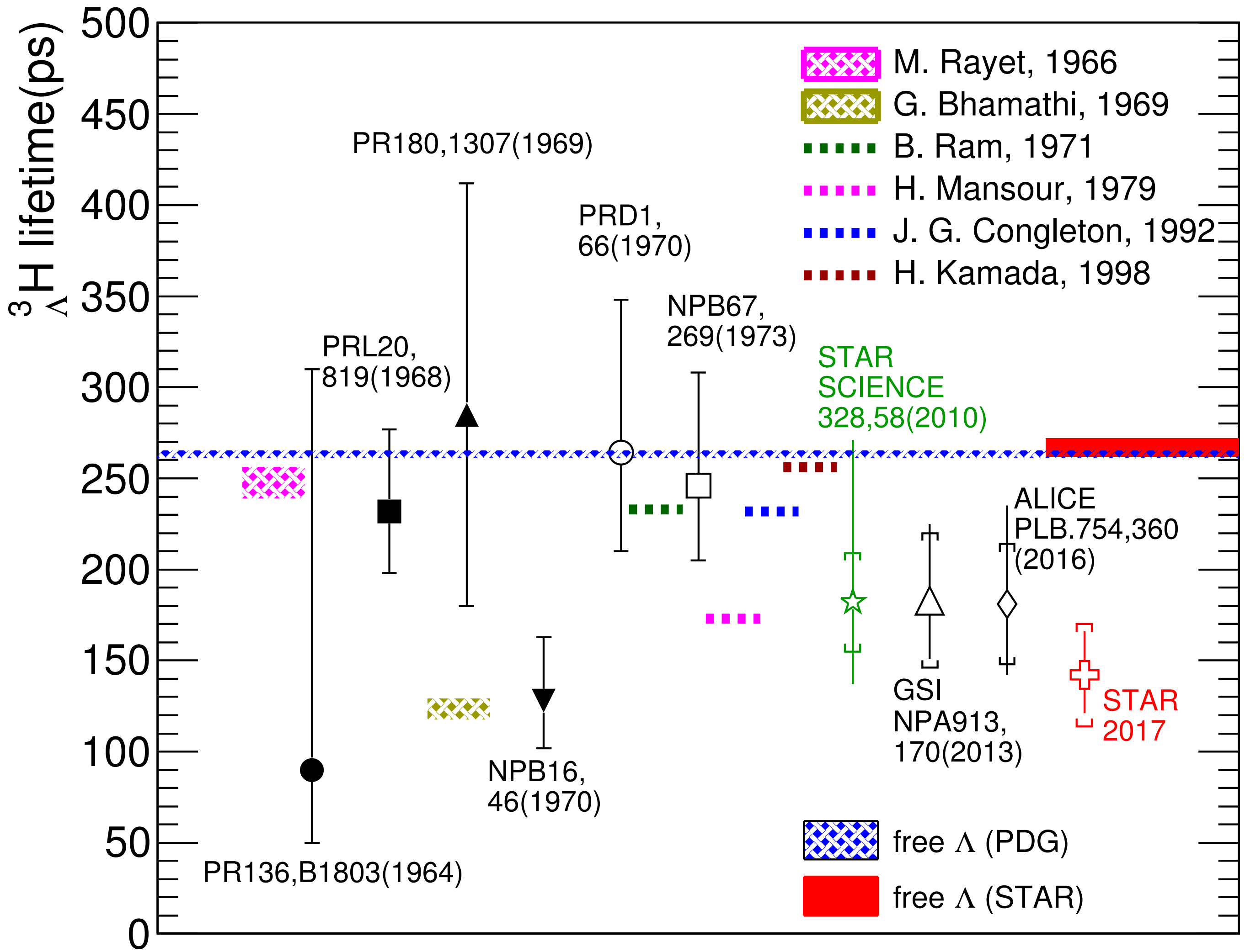


☑ The lifetime is determined from a combine analysis of 2-body and 3-body decay modes

$$\tau = 142^{+24}_{-21}\,(\text{stat.}) \pm 29\,(\text{syst.})\ \text{ps}$$

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

Updates on world data of lifetime

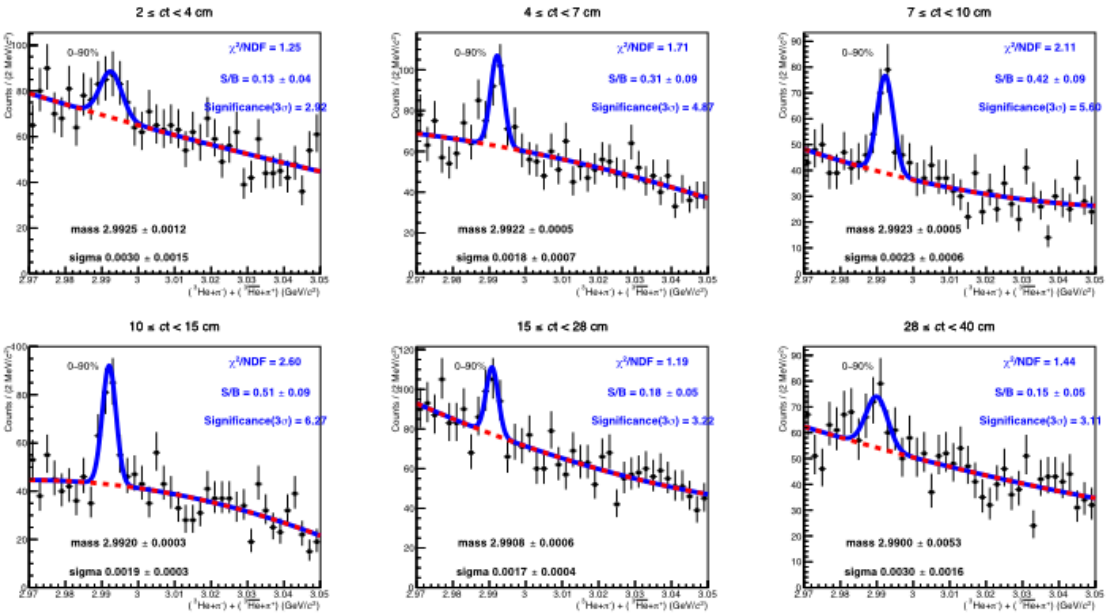


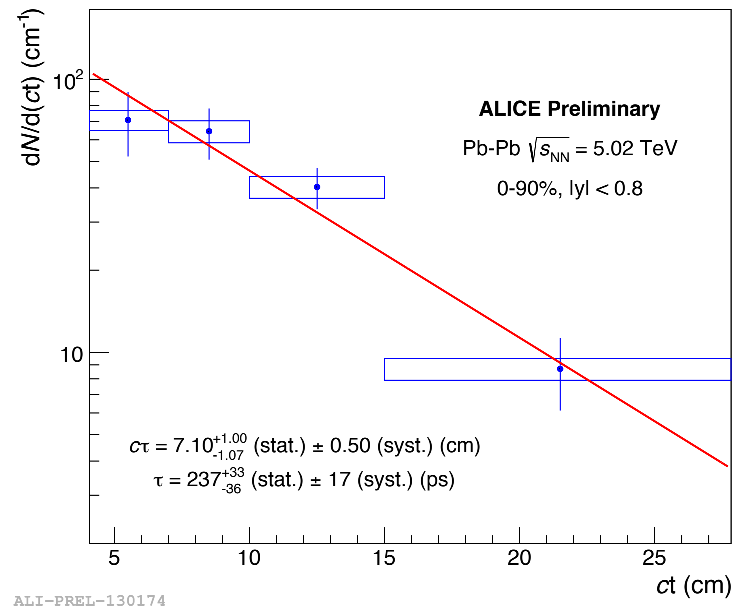
World average:

$$211^{+18}_{-16}\ \text{ps}$$

The discrepancy may be related to the Lambda separation energy, the B_Λ?

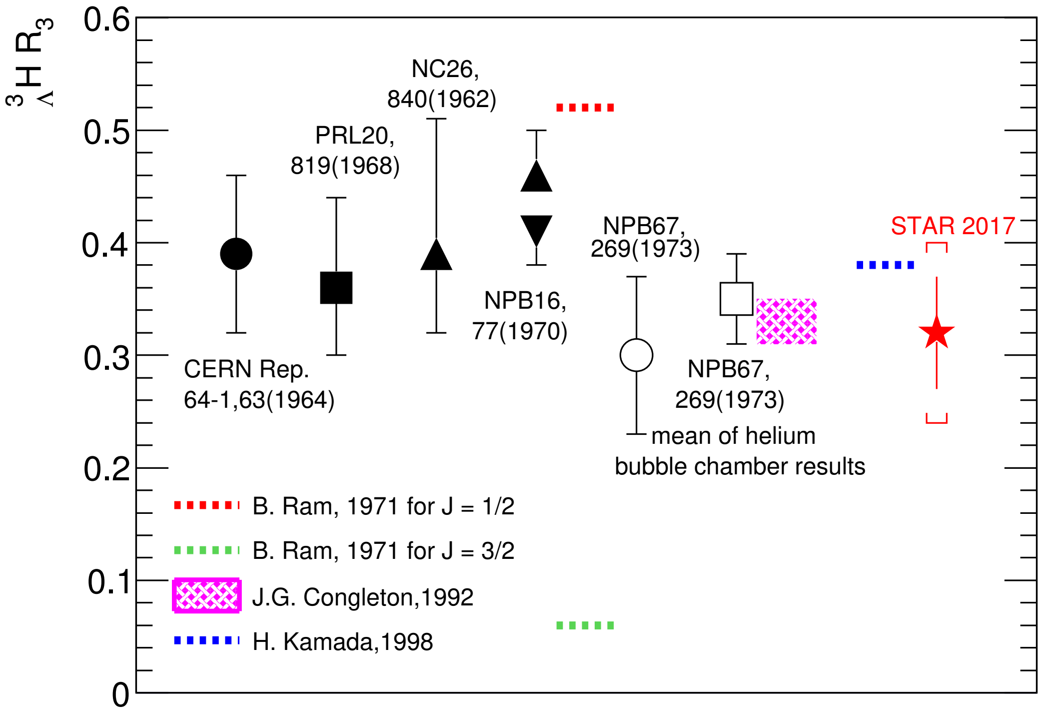
STAR ☆ Updates on lifetime measurement @ALICE





- ☑ ALICE new measurement : $\tau = 223 \pm^{41}_{33}\,(stat.) \pm 20(syst.)ps$
- ☑ It is 2σ higher than the latest STAR published data (in term of the STAR uncertainty)

STAR ☆ The decay branching ratio is related to B_Λ



$$R_3 = \frac{\Gamma(^3_\Lambda\mathrm{H} \to {}^3\mathrm{He} + \pi^-)}{\Gamma(^3_\Lambda\mathrm{H} \to \text{all } \pi^- \text{channels})}.$$

☑ The R_3 is sensitive to the spin of hypertriton. It can also be used to obtain an indirect measurement of the B_Λ

Table 2: Measurements of variable R_3.

R_3	Technique
0.39 ± 0.07	helium bubble chamber
$0.36^{+0.08}_{-0.06}$	helium bubble chamber
$0.39^{+0.12}_{-0.07}$	emulsion
$0.41^{+0.04}_{-0.03}$ to $0.46^{+0.04}_{-0.03}$	emulsion
0.30 ± 0.07	helium bubble chamber
0.35 ± 0.04	mean of helium bubble chamber results
0.32 ± 0.05	time projection chamber

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

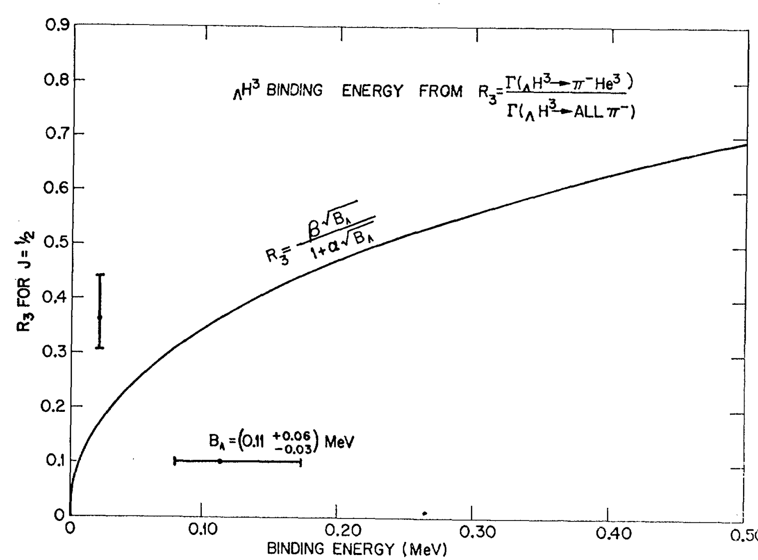


*Fig. is from Phys. Rev. D 1,66 (1970) with $R_3 = 0.36 \pm^{0.08}_{0.06}$

**Curve is from Phys. Rev. 113,1604 (1959) with B_Λ=0.25 MeV, spin 1/2 scenario

Can we measure B_Λ better?

☑ The early data suffers from large statistical uncertainty!

	$B_\Lambda \pm \Delta B_\Lambda$ (MeV)		δB_Λ (MeV)
	Bohm et al.[a)]	This work	
${}^{3}_{\Lambda}H$	0.01 ± 0.07	0.15 ± 0.08	0.14 ± 0.11

a) G. Bohm et al., Nucl. Phys. B4, 511 (1968)
b) This work : M. Juric, G. Bohm et al., Nucl. Phys. B52,1 (1973)

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]

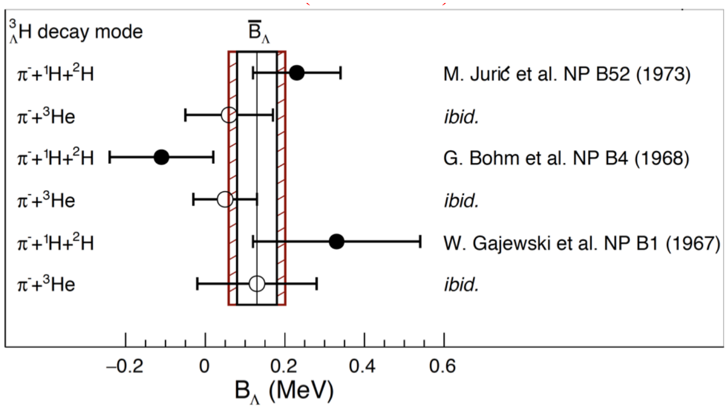
G. Keyes et al., Phys. Rev. D 1,66 (1970)

${}_{\Lambda}{}^{3}H$	$\pi^- \; {}^3He$ b)	26	0.13 ± 0.15
	$\pi^- \; {}^1H \; {}^2H$	6	0.33 ± 0.21
	total	32	0.20 ± 0.12

G. Gajewski et al., Nucl. Phys. B 1,105 (1967)

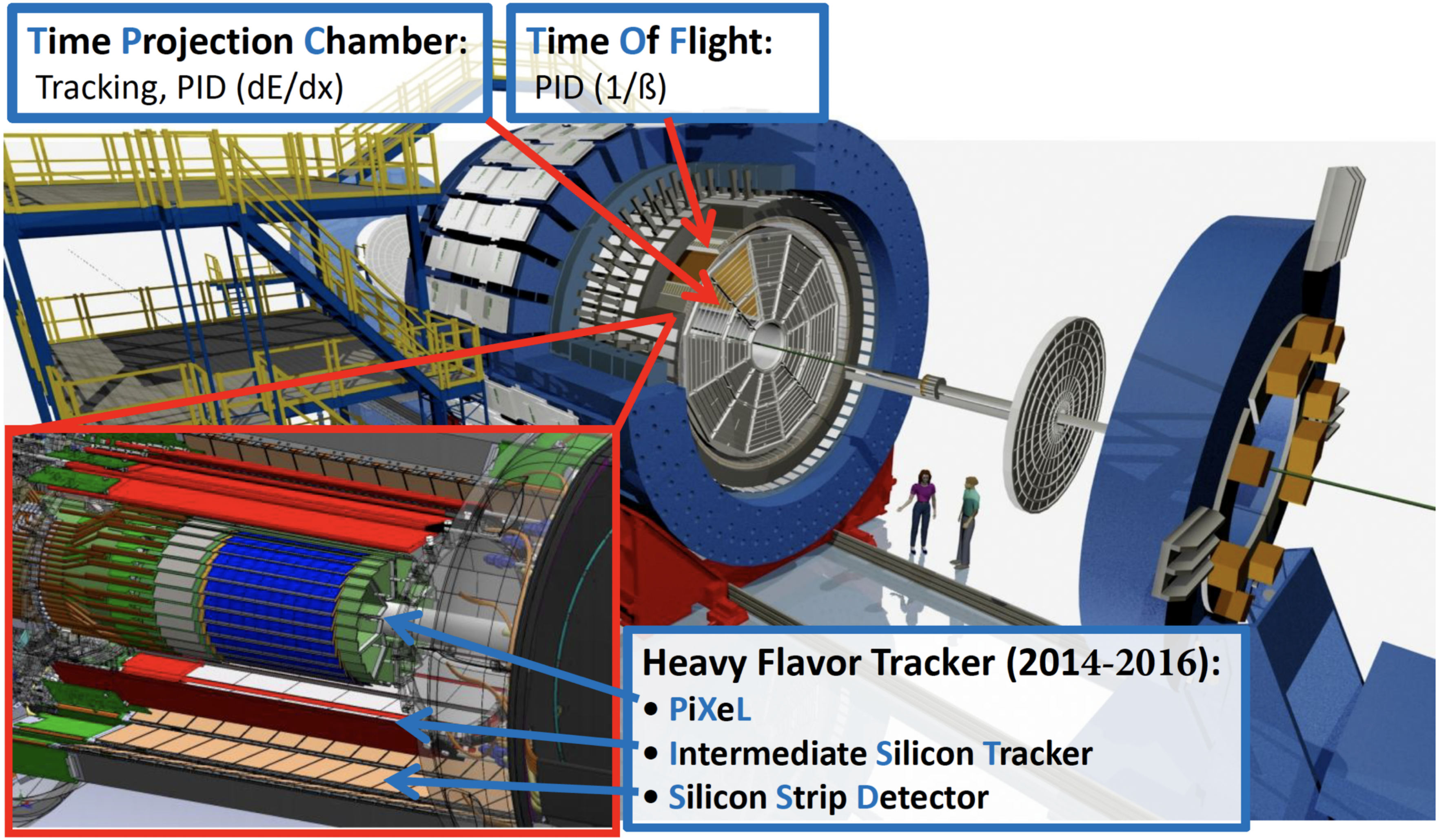
$$B_\Lambda = 0.13 \pm 0.05 \text{MeV}$$

P. Achenbach, PoS (Hadron 2017) 207



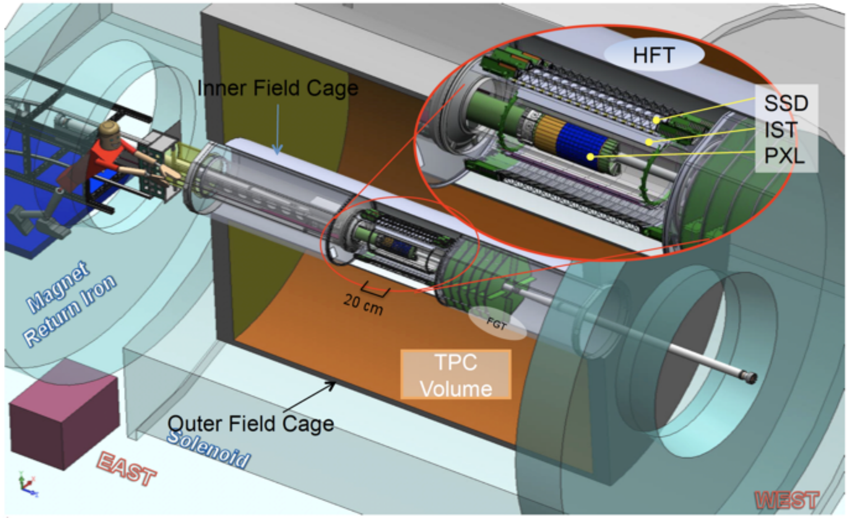
"I feel that we are far from seeing the end of this road. A good deal of theoretical work on this 3-body system would still be well justified." R.H. Dalitz Nucl. Phys. A 754, 14 (2005)

STAR ☆ The Solenoidal Tracker at RHIC (STAR)



☑ STAR: uniform and large acceptance, HFT: precise vertex measurement

STAR ☆ The Heavy Flavor Tracker at STAR (HFT)



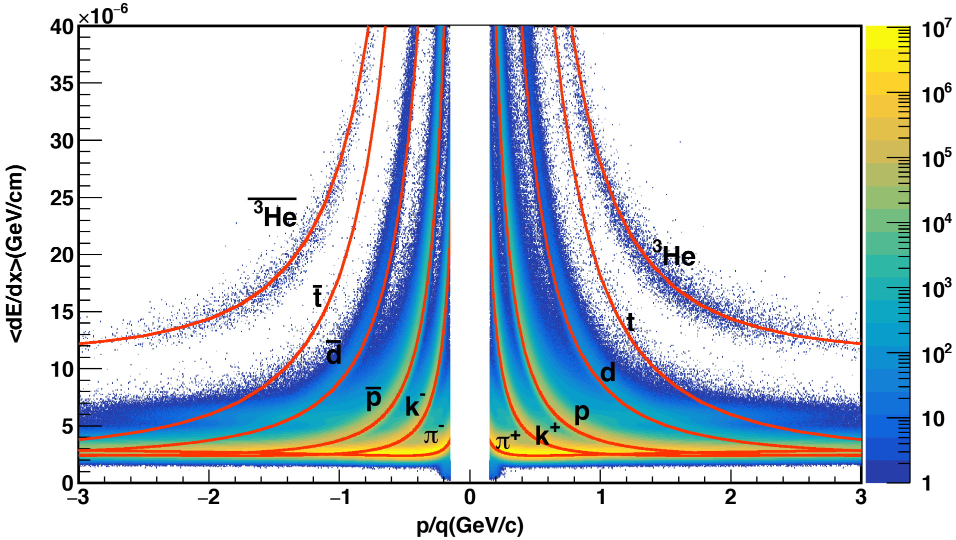
PXL: PiXeL
IST: Intermediate Silicon Tracker
SSD: Silicon Strip Detector

Detector	Radius (cm)	Hit Resolution (R × ϕ) / Z (μm/μm)	Thickness
SSD	22	30/860	1% X_0
IST	14	170/1800	<1.5% X_0
PXL	8	6.2/6.2	0.5% X_0
	2.8	6.2/6.2	0.4% X_0

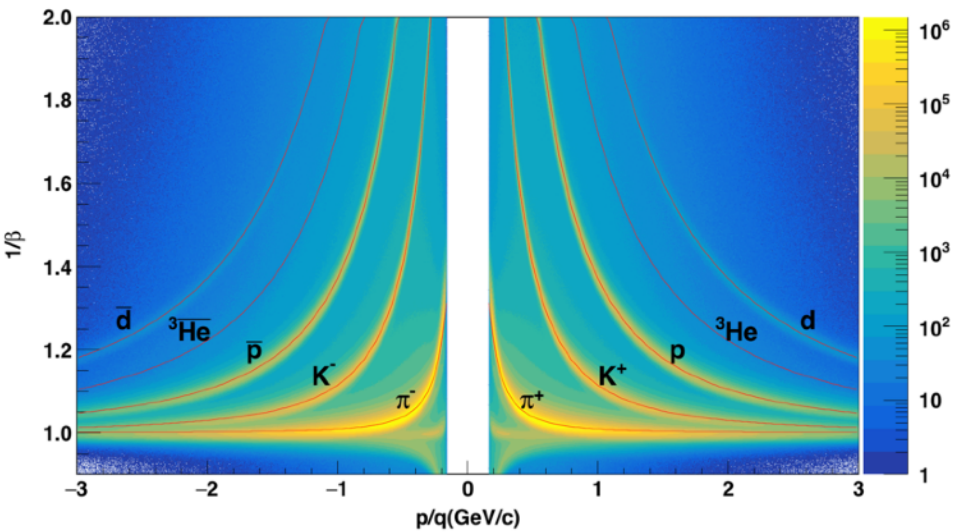
TPC → ~1mm → SSD → ~300μm → IST → ~250μm → PXL → < 30μm → vertex

☑ Data : ~1.2 billion Au+Au collision events in 2014, and ~3.4 billion Au+Au collision events in 2016

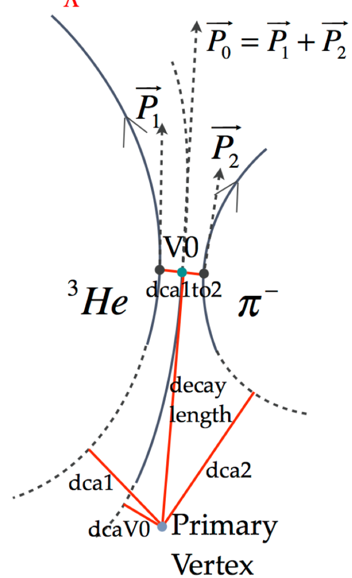
The particle identification in STAR



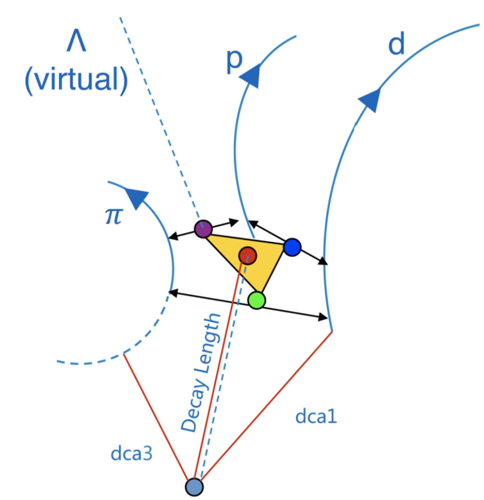
- ☑ Clean PID of charge particles from TPC and ToF in STAR
- ☑ The topology of hypertriton in STAR detector



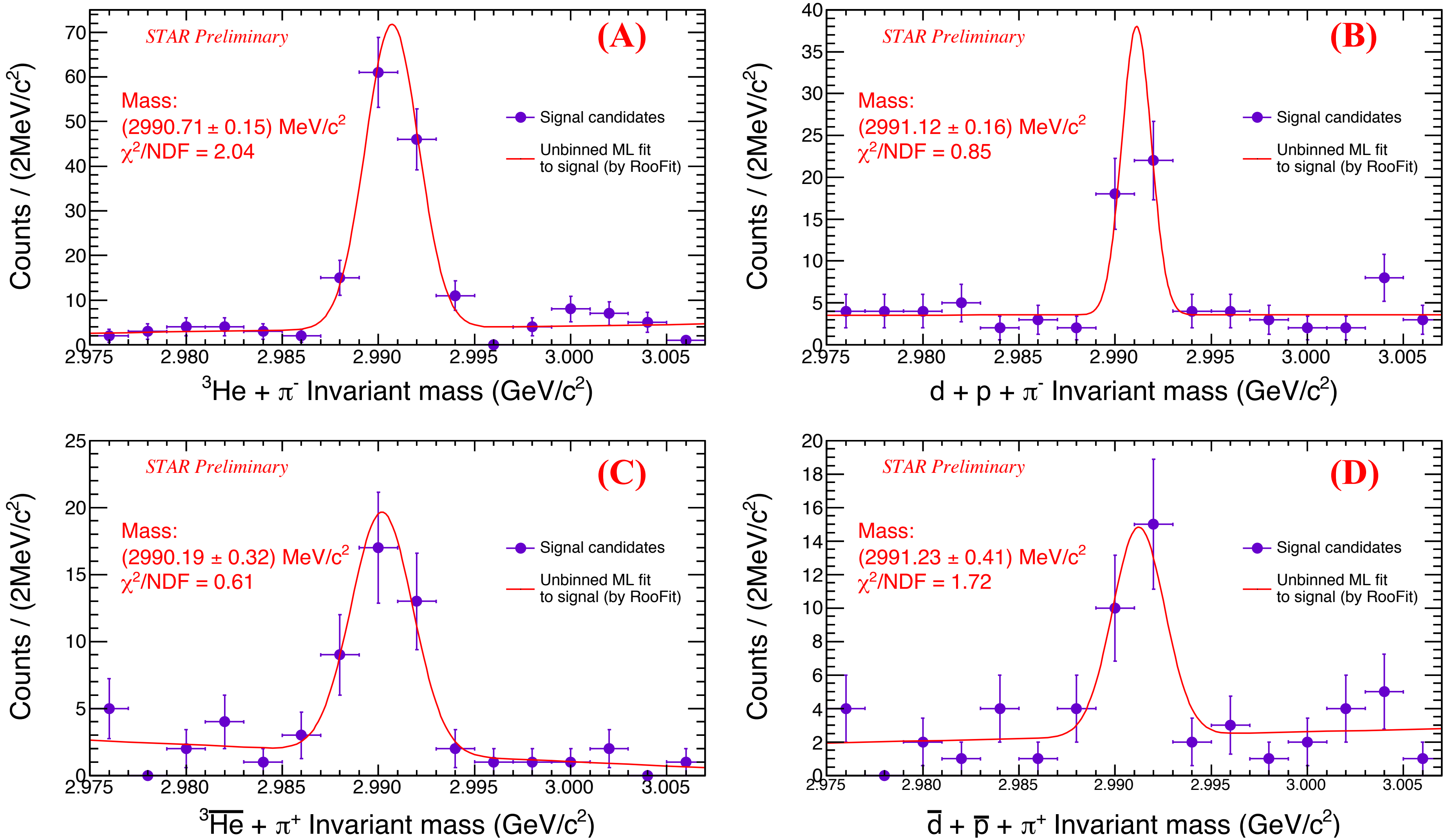
$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$



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

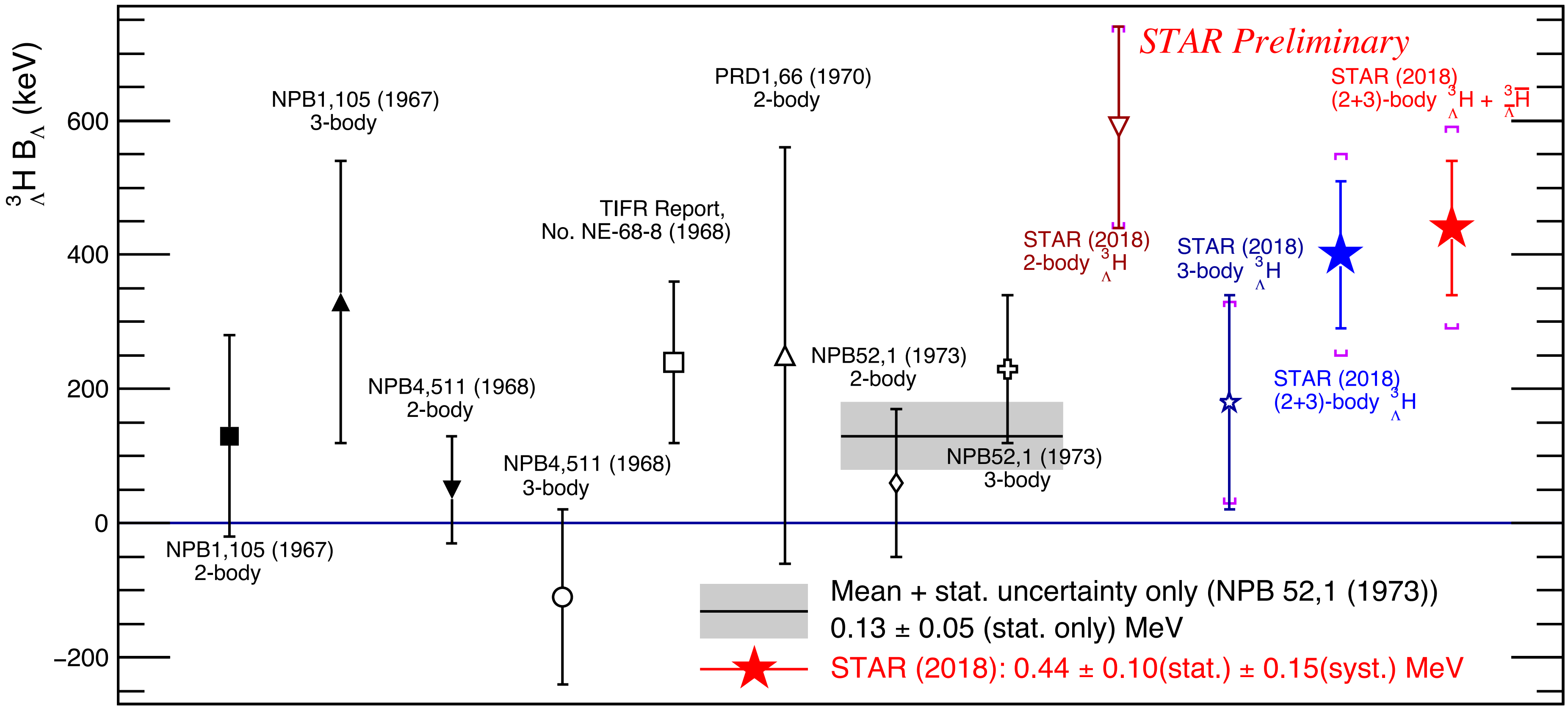


Invariant mass distr. with energy loss correction



☑ Energy loss in the material in front of and in TPC

The B_Λ data



$$\mathbf{m_\Lambda + m_d - m_{{}^{3}_{\Lambda}H}}$$

☑ The difference between STAR measurement and the previous measurement is 0.31±0.11 (stat. only) MeV

How to determine the B_Λ of hypertriton

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

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

STAR ☆ The charged particle's range-energy relation in emulsion

- Range-energy relation: measure the daughter's range in the emulsion to determine the kinetic energy of daughter

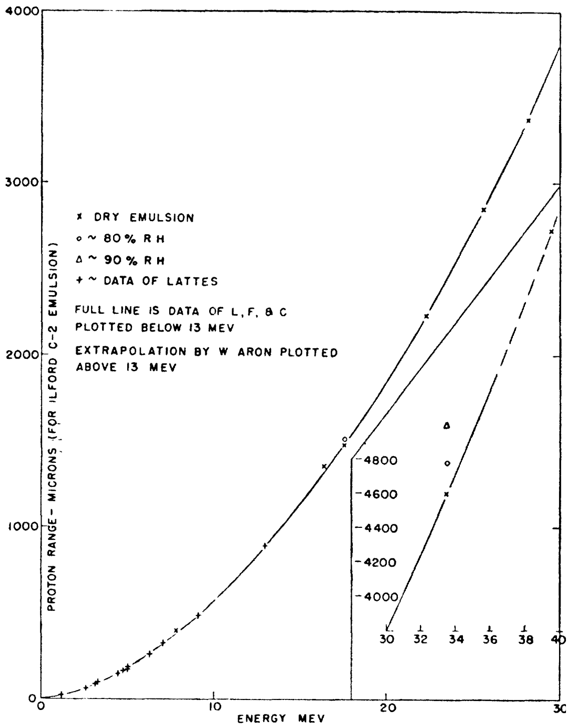


FIG. 2. Range of protons *vs.* energy.

E (Mev)	R (μ)	
7.8	389	±2.7
16.4	1358	8.1
17.6	1465	4.5
17.6	1497	6.0
22.3	2244	8.9
25.6	2849	7.1
28.2	3369	10.0
33.5	4597	13.8
33.5	4762	24.0
33.5	4996	10.0
39.5	6123	18.0

[1] H. Brander, F. M. Smith, W. H. Barkas and S. Bishop, Phys. Rev. 77, 462 (1950)
[2] J. Rotblat, Nature 167, 550 (1951)
[3] W. H. Barkas and A. H. Rosenfeld, UCRL-8030 for the U. S. Atomic Energy Commission with Contract No. W-7405-eng-48

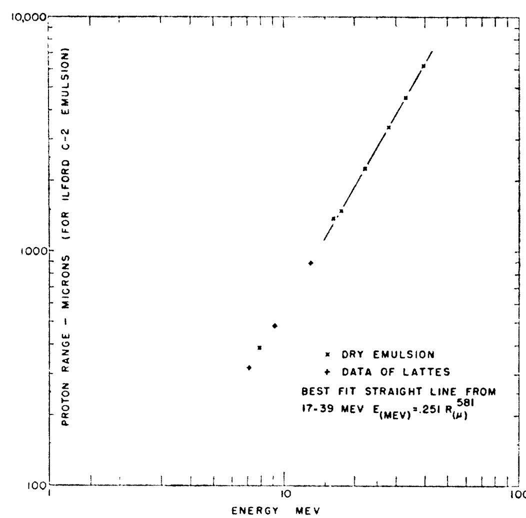


FIG. 3. Power law approximation for range-energy relation.

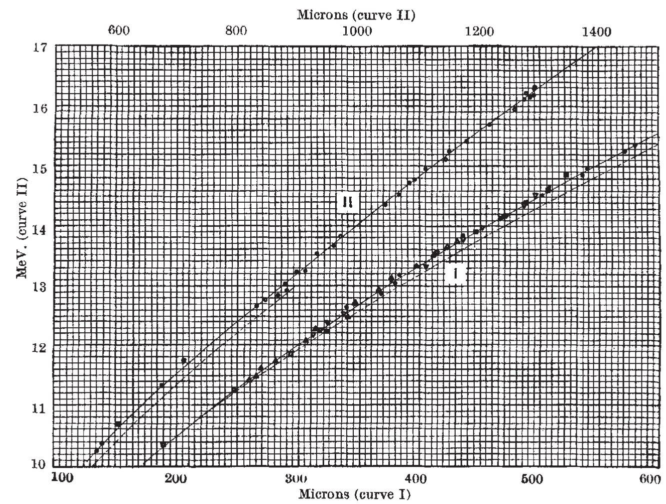


Fig. 1. Proton range–energy relation. ○—○—, $^{14}_{7}N(d,p)^{15}_{7}N$; ●—●—, $^{12}_{6}C(d,p)^{13}_{6}C$; ▽—▽—, $^{16}_{8}O(d,p)^{17}_{8}O$; △—△—, $^{16}_{8}O(d,p)^{17}_{8}O^*$; □—□—, $d+p$ elastic scattering; ■—■—, $^{2}_{1}H(d,p)^{3}_{1}H$. Full curve gives the best range–energy relation; broken curve is that of Lattes, Fowler and Cuer

Revisit the mass values

	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)

STAR ☆ Updated the Q_0 estimation with new mass value (1)

☑ for the 2-body decay channel:

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

	Q_0 (MeV)	Q_0 difference (MeV)
NPB 1,105 (1967)	43.13	–0.2
NPB 4,511 (1968)	43.27	–0.06
PRD 1,66 (1970)	43.45	0.12
NPB 52, 1 (1973)	43.27	-0.06
Today	43.33	

	B_Λ (MeV)	Corrected B_Λ (MeV)
NPB 1,105 (1967)	0.13 ± 0.15	0.33 ± 0.15
NPB 4,511 (1968)	0.05 ± 0.08	0.11 ± 0.08
PRD 1,66 (1970)	0.25 ± 0.31	0.13 ± 0.31
NPB 52, 1 (1973)	0.06 ± 0.11	0.12 ± 0.11

STAR ☆ Updated the Q_0 estimation with new mass value (2)

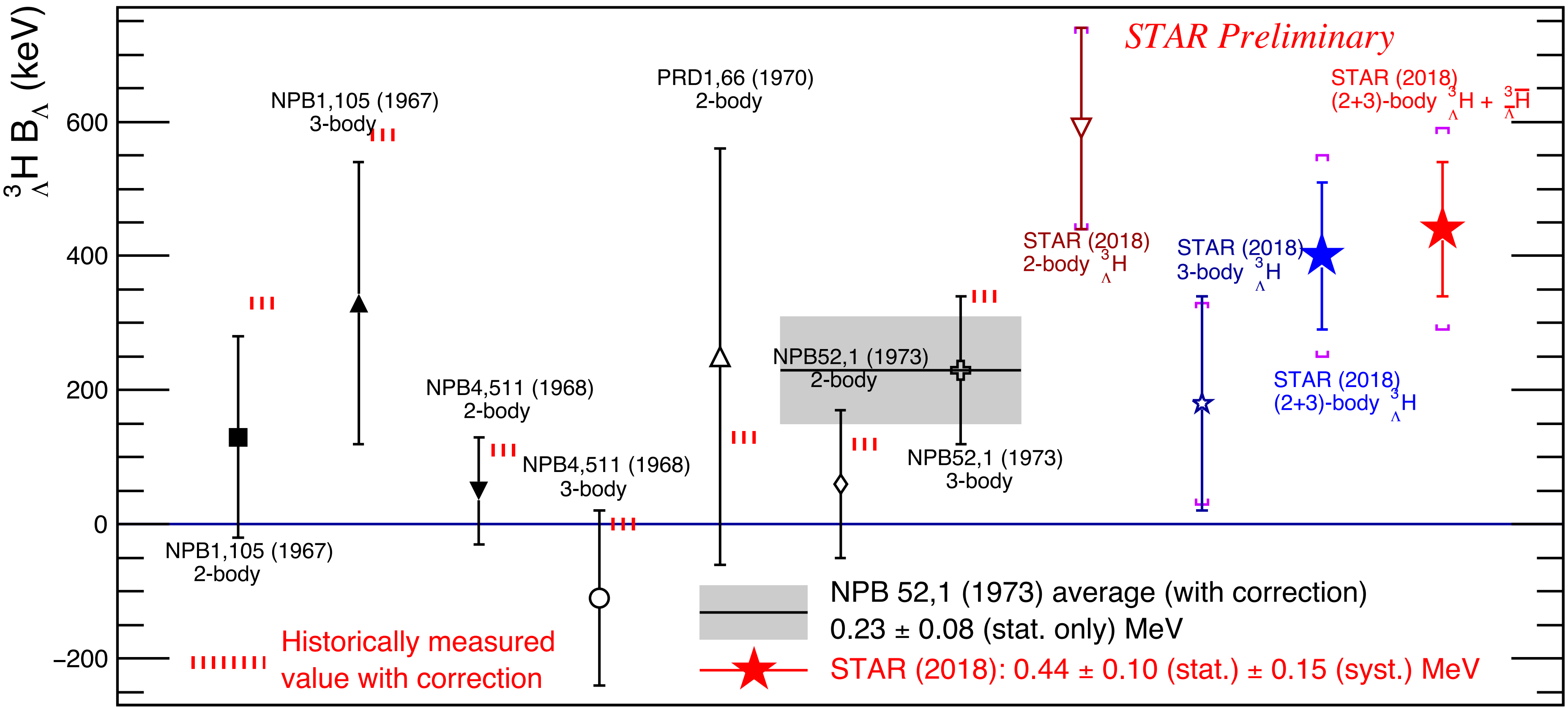
☑ for the 3-body decay channel:

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

	Q_0 (MeV)	Q_0 difference (MeV)
NPB 1,105 (1967)	37.59	-0.25
NPB 4,511 (1968)	37.73	-0.11
PRD 1,66 (1970)	37.83	-0.01
NPB 52, 1 (1973)	37.73	-0.11
Today	37.84	

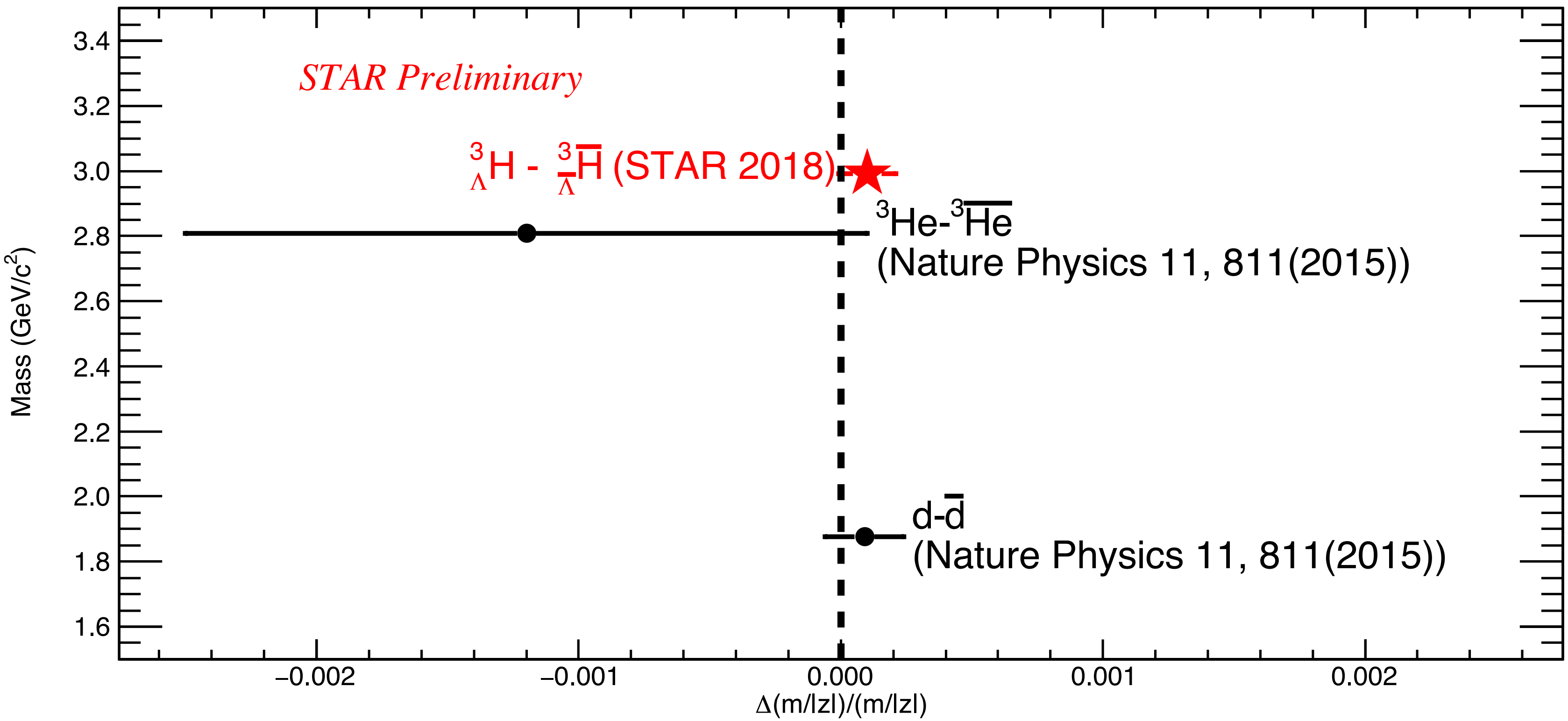
	B_Λ (MeV)	Corrected B_Λ (MeV)
NPB 1,105 (1967)	0.33 ± 0.21	0.58 ± 0.21
NPB 4,511 (1968)	-0.11 ± 0.13	0 ± 0.13
PRD 1,66 (1970)	N/A	**N/A**
NPB 52, 1 (1973)	0.23 ± 0.11	0.34 ± 0.11

The B_Λ data with correction



☑ World average on early data with new mass value: 0.18±0.05 (stat.) MeV, average on 1973 data with new mass value: 0.23±0.08 (stat.) MeV.

Mass difference measurement



☑ ALICE: $$\left(\frac{\Delta(\mathbf{m}/|\mathbf{z}|)}{\mathbf{m}/|\mathbf{z}|}\right)_{\mathbf{d}} = (\mathbf{0.9} \pm \mathbf{0.5}\ (\mathbf{stat.}) \pm \mathbf{1.4}\ (\mathbf{syst.}))\times\mathbf{10^{-4}}$$

$$\left(\frac{\Delta(\mathbf{m}/|\mathbf{z}|)}{\mathbf{m}/|\mathbf{z}|}\right)_{\mathbf{^{3}He}} = (-\mathbf{1.2} \pm \mathbf{0.9}\ (\mathbf{stat.}) \pm \mathbf{1.0}\ (\mathbf{syst.}))\times\mathbf{10^{-3}}$$

☑ STAR: $$\left(\frac{\Delta(m/|z|)}{m/|z|}\right)_{{}^{3}_{\Lambda}H} = (1.0 \pm 0.9(stat.) \pm 0.7(syst.)) \times 10^{-4}$$

Summary

- An updated hypertriton lifetime using the two- and three-body decay channels is shorter than the Lambda's

$$\tau = 142 \pm^{24}_{21} (stat.) \pm 29(syst.)\mathrm{ps}$$

- Ratio between the 2-body and the 3-body mesonic decay prefers a spin = 1/2 assignment for hypertriton

$$R_3 = 0.32 \pm 0.05(stat.) \pm 0.08(syst.)$$

- The mass and binding energy of (anti)hypertriton have been measured

$$^{3}_{\Lambda}H : 2990.90 \pm 0.11(stat.) \pm 0.15(syst.)\mathrm{MeV/c^2}$$

$$^{3}_{\bar{\Lambda}}\bar{H} : 2990.59 \pm 0.25(stat.) \pm 0.15(syst.)\mathrm{MeV/c^2}$$

$$B_{\Lambda} : 0.44 \pm 0.10(stat.) \pm 0.15(syst.)\mathrm{MeV}$$

- Mass difference between hypertriton and antihypertriton is estimated

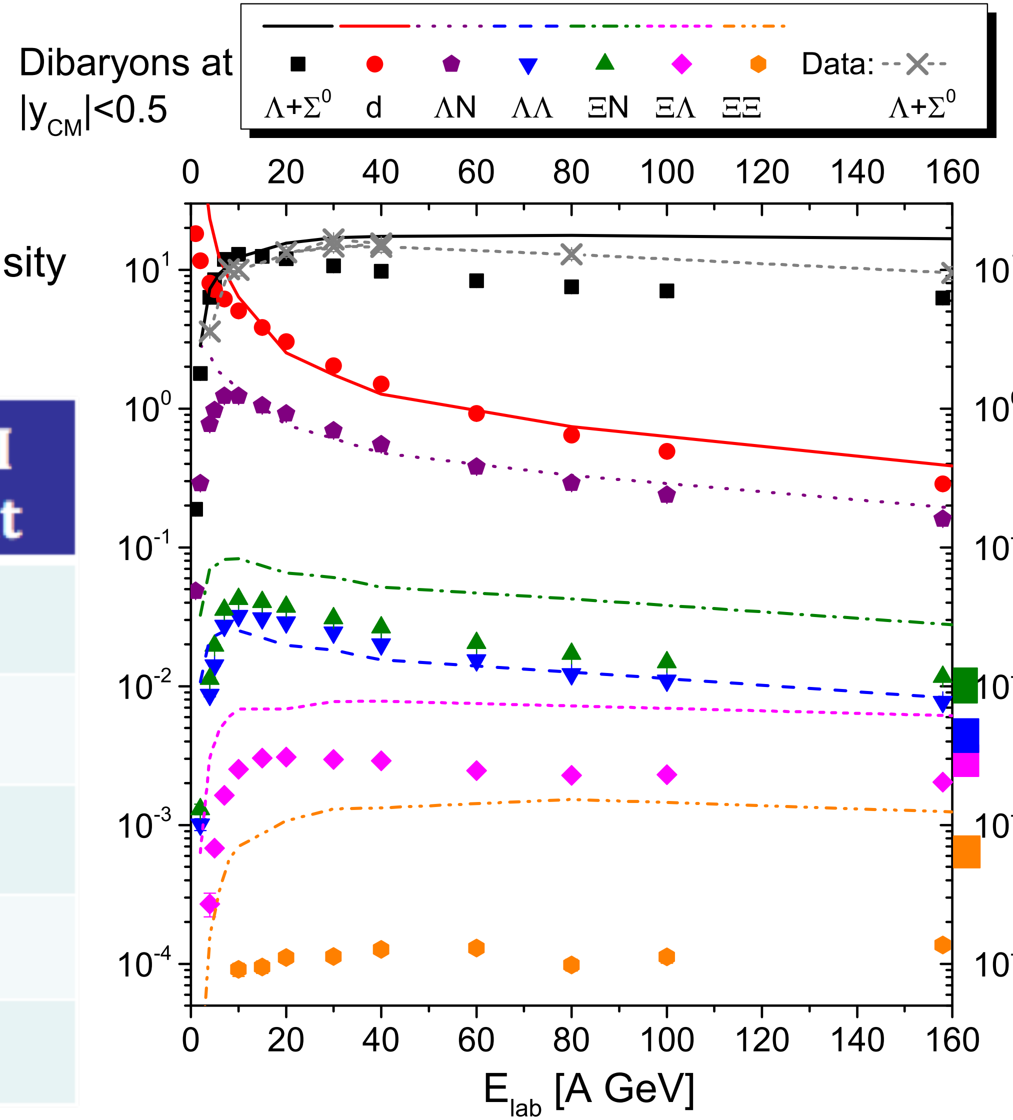
$$\left(\frac{\Delta(m/|z|)}{m/|z|}\right)_{^{3}_{\Lambda}H} = (1.0 \pm 0.9(stat.) \pm 0.7(syst.)) \times 10^{-4}$$

Outlook (1)

STAR BES-II at 2019 and 2020

- detector upgrades
- low energy electron cooling
- hyperon production at high baryon density

Collision Energies	Proposed Event	BES-I Event
7.7	100	4
9.1	160	N/A
11.5	230	12
14.5	300	20
19.6	400	36



J. Steinheimer et al., Phys. Lett. B 714 (2012) 85

STAR ☆

Outlook (2)

On the lifetime measurements:

- Proposed (π^-,K^0) reaction on nuclear targets for precise determination of the lifetime of the hydrogen hyper-isotopes and other neutron-rich Λ-hypernuclei at J-PARC

  M. Agnello et al., Nucl. Phys. A 954 (2016) 176
  Prof. Alessandro Feliciello, Friday

- New experiment to measure decay-pion time spectrum w/MM tag at ELPH-Tohoku with tagged gamma

  Dr. Sho Nagao, Thursday (A1)

On the mass measurements:

- Decay-pion spectroscopy at MAMI

  P. Achenbach, Hadron 2017, Spain

- Plans to measure at JLab with e-beam, ^{3}He target (LoI for JLab PAC46)

  Prof. Satoshi Nakamura, Tuesday

Back-up slides

Hyperons in neutron stars

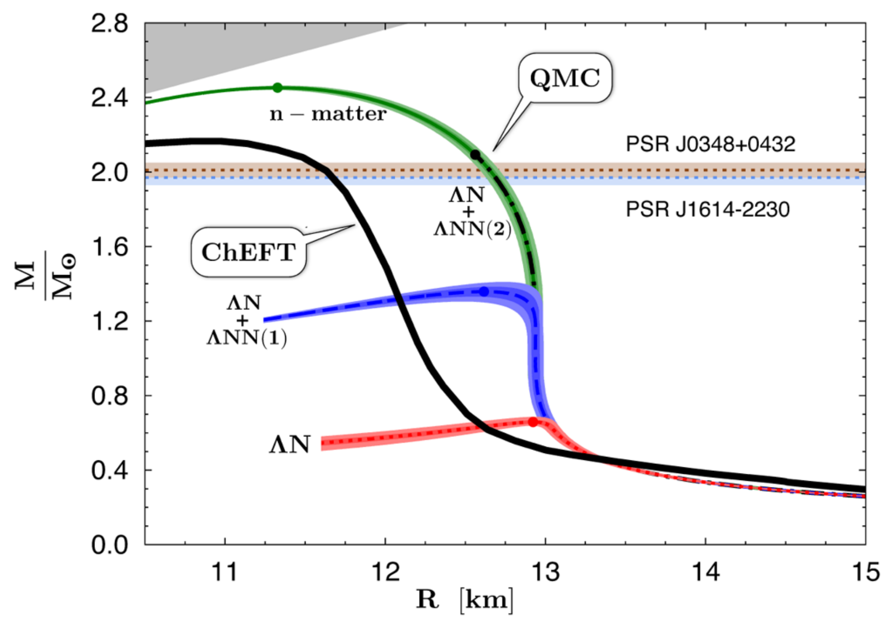
Hyperon puzzle

- Hyperons are predicted to exist inside neutron stars at densities exceeding 2-3ρ_0
- The inner core of NS is so dense, Pauli blocking prevents hyperons from decaying by limiting the phase space available to nucleons
- The presence of hyperon reduces the maximum mass of neutron stars ~0.5-1.2M_0
- However, new observation for large mass of NS!

P. Demorest et al., Nature 467 (2010) 1081; Antoniadis et al., Science 340 (2013) 448

» Rijken and Schulze: inclusion of YY interactions increase the mass of NS

» Lonardoni et al., repulsive YNN interactions increase the mass of NS



GW from NS merger, provides new information on NS EOS, and new constrains on radius and mass

Phys. Rev. Lett. 119, 161101 (2017)

Future direction (2)

- Proposed (π^-,K^0) reaction on nuclear targets for precise determination of the lifetime of the hydrogen hyperisotopes and other neutron-rich Λ-hypernuclei at J-PARK

M. Agnello et al., NPA 954 (2016) 176

$$K^- + {}^{3,4}\mathrm{He} \rightarrow \pi^0 + {}^{3,4}_{\Lambda}\mathrm{H}$$
$$\hookrightarrow \gamma\gamma$$
$$\pi^- + {}^{3,4}\mathrm{He} \rightarrow K^0 + {}^{3,4}_{\Lambda}\mathrm{H}$$
$$\hookrightarrow \pi^+\pi^-$$

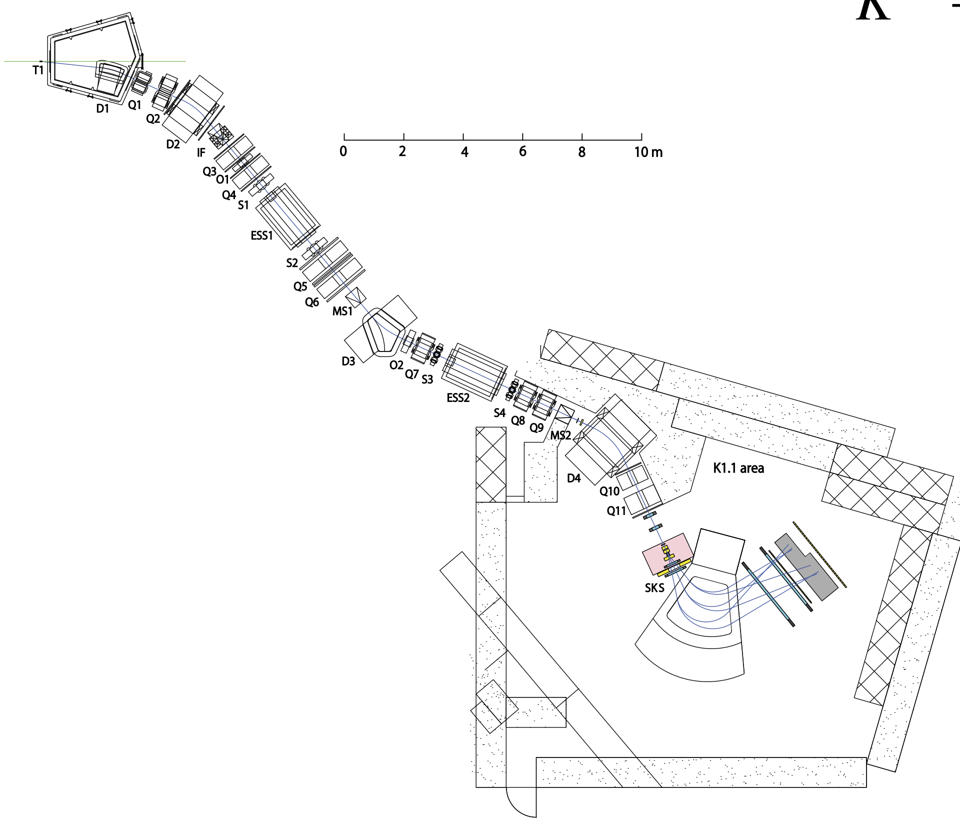
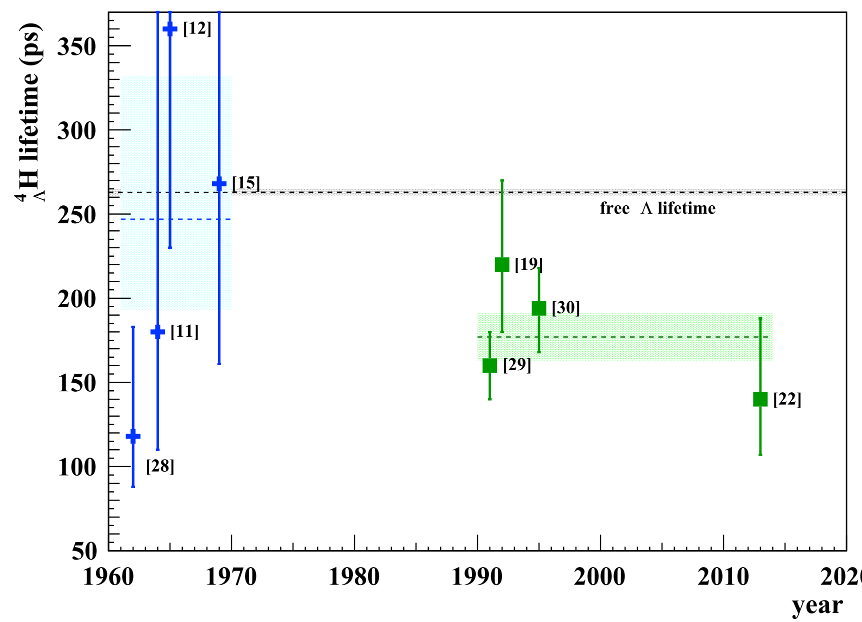
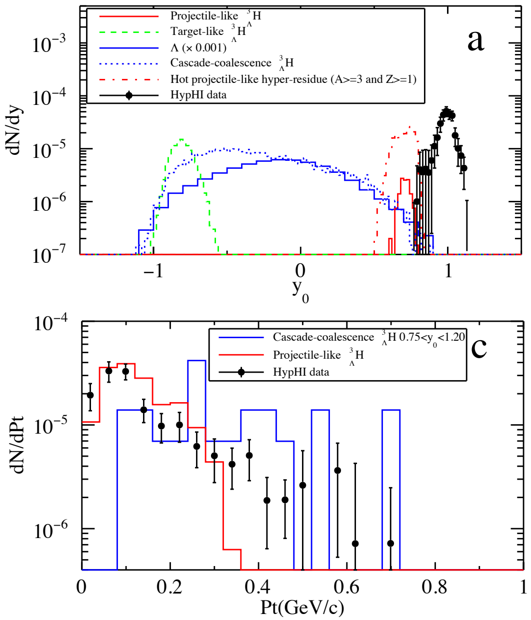


Fig. 4. Layout of the J-PARC K1.1 beam line and K1.1 experimental area. From [46].



Future direction (3)



☑ Light hypernuclei production in peripheral ion collisions

arXiv: 1712.04658