Recent Results on Hypernucleus Physics in Heavy-Ion Collisions from STAR Exp.

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QCD与夸克物质物理研讨会

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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!

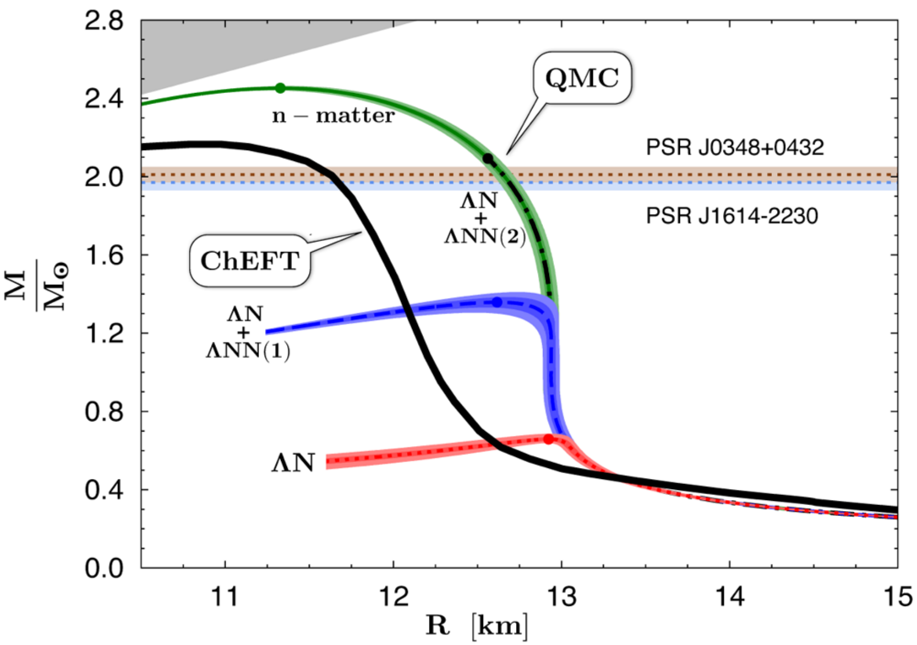
P. Demorest et al., Nature 467 (2010) 1081; Antoniadis et al., Science 340 (2013) 448

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

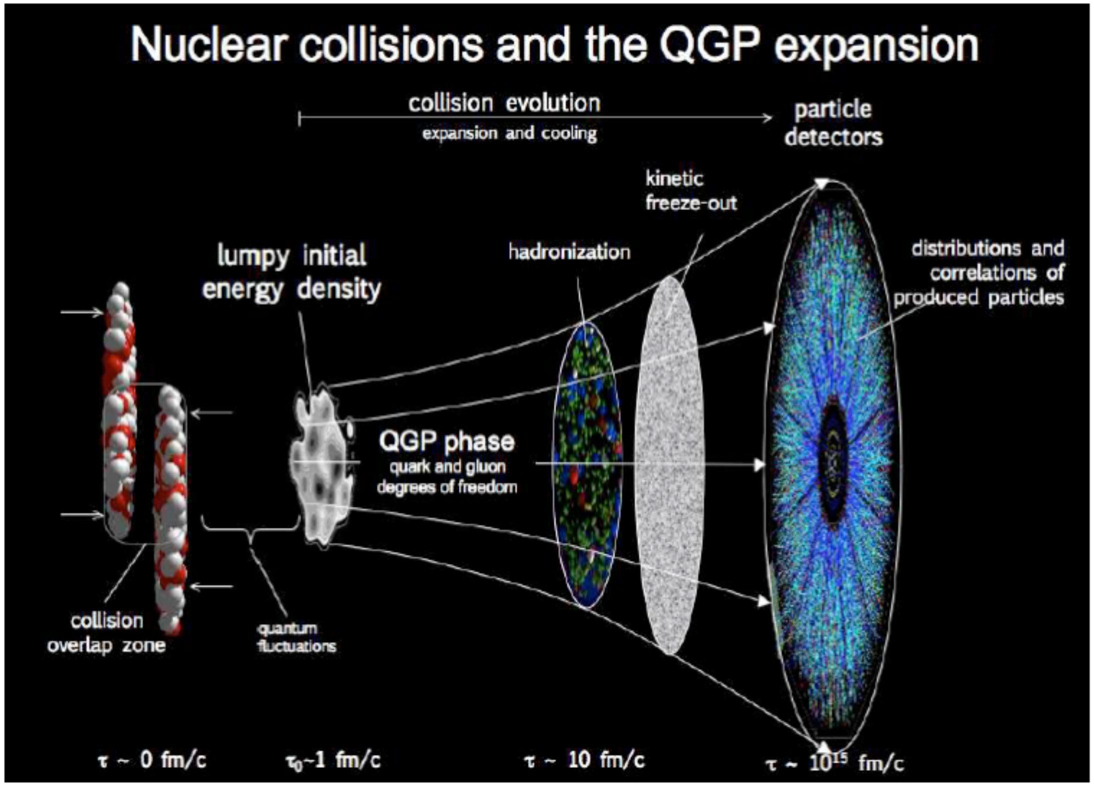
» Lonardoni et al., repulsive YNN interactions increase the mass of NS

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

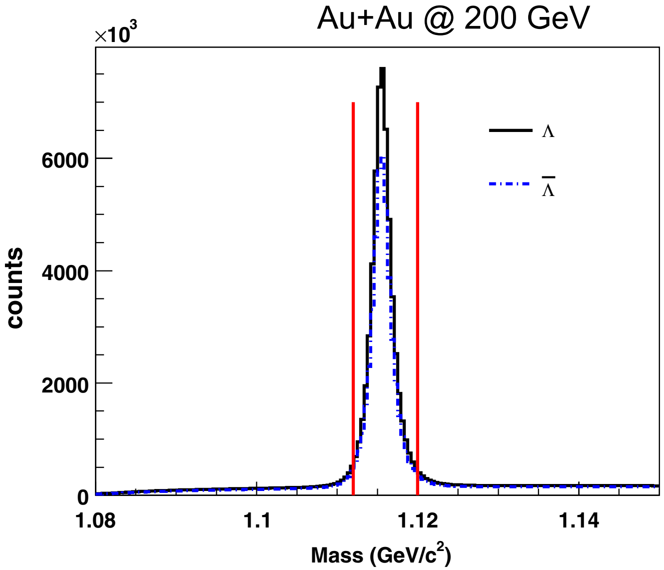
B.P. Abbott et al., Phys. Rev. Lett. 119, 161101 (2017); Phys. Rev. Lett. 121, 161101 (2018)



Heavy ion collider as a hyperon factory



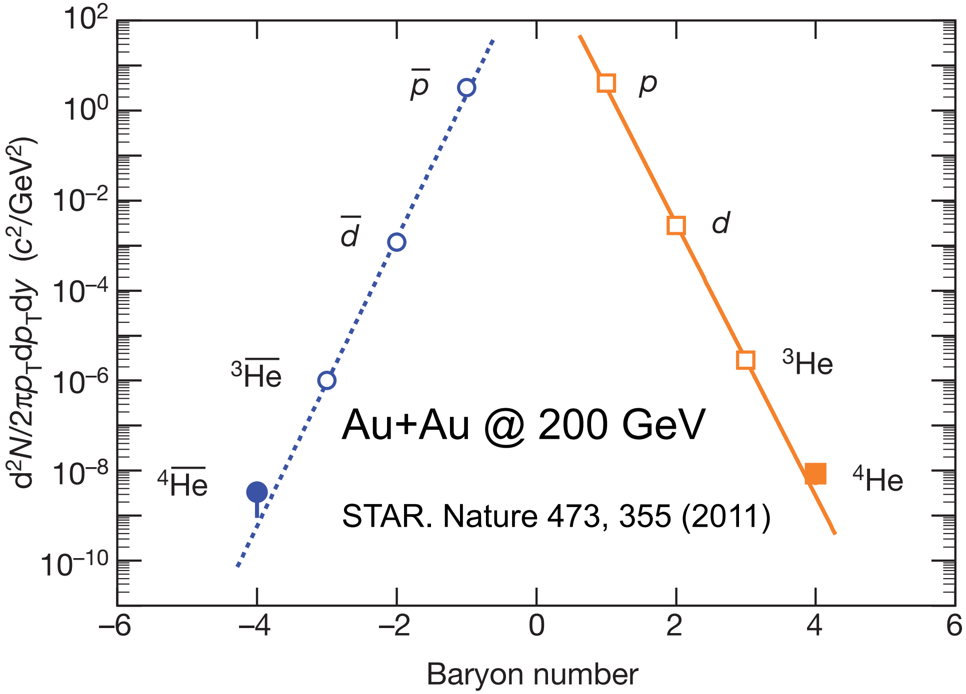
- ☑ RHIC, a QCD machine, small bang
- ☑ Hyperon rate is high, lab. for Y-N interaction
- ☑ Excellent secondary vertex reconstruction in STAR and ALICE

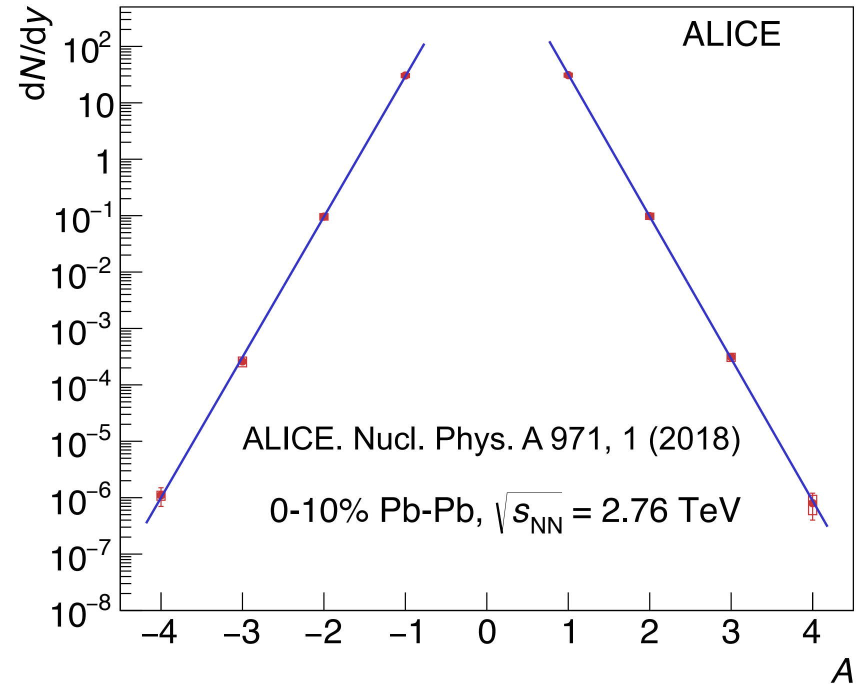


0-5% central collisions, Au+Au @ 200 GeV, Pb-Pb @ 2.76 TeV

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

(Hyper-)nuclei production in HIC





STAR. Science 328, 58 (2010)

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

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

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 ^3He and $^3_\Lambda H$ statistics.

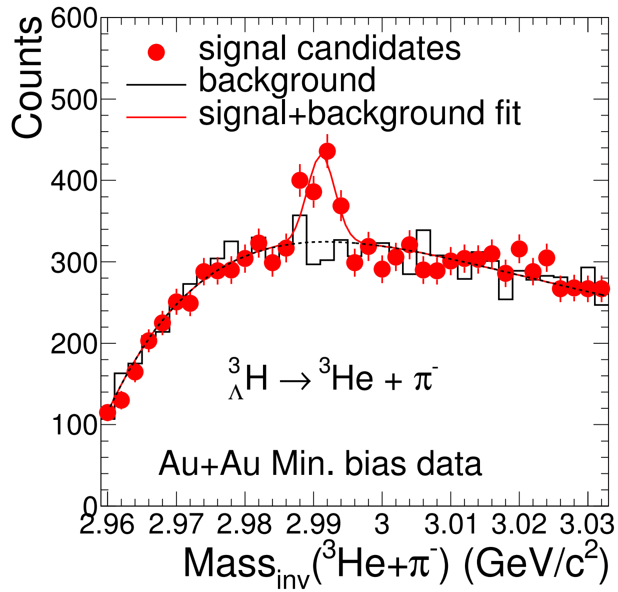
Energy	Events (×10 M)	^3He	$^3\overline{He}$	$^3_\Lambda H + ^3_{\overline{\Lambda}}\overline{H}$
7.7 GeV	0.4	6388 ± 80	0	52 ± 17
11.5 GeV	1	5330 ± 73	0	44 ± 16
19.6 GeV	3	4941 ± 70	0	42 ± 14
27 GeV	5	4179 ± 65	19 ± 4	45 ± 16
39 GeV	12	5252 ± 72	133 ± 12	86 ± 21
200 GeV	22	6850 ± 83	2213 ± 47	85 ± 20

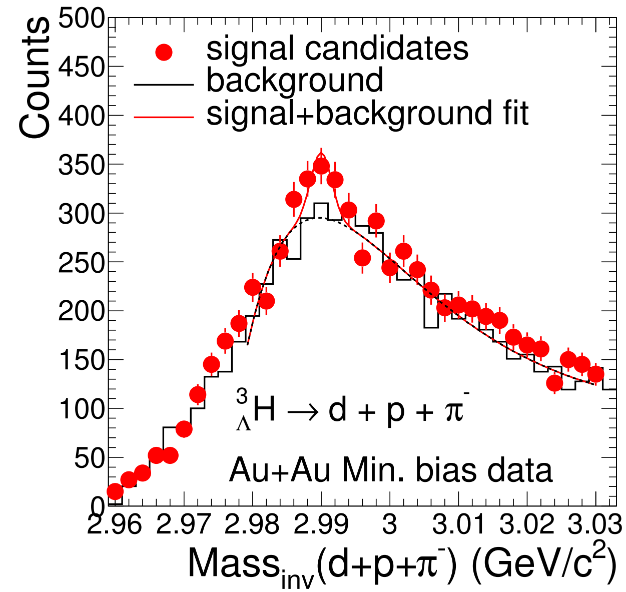
TABLE II. Data set for the three-body decay channel analysis, with $^3_\Lambda H$ statistics.

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

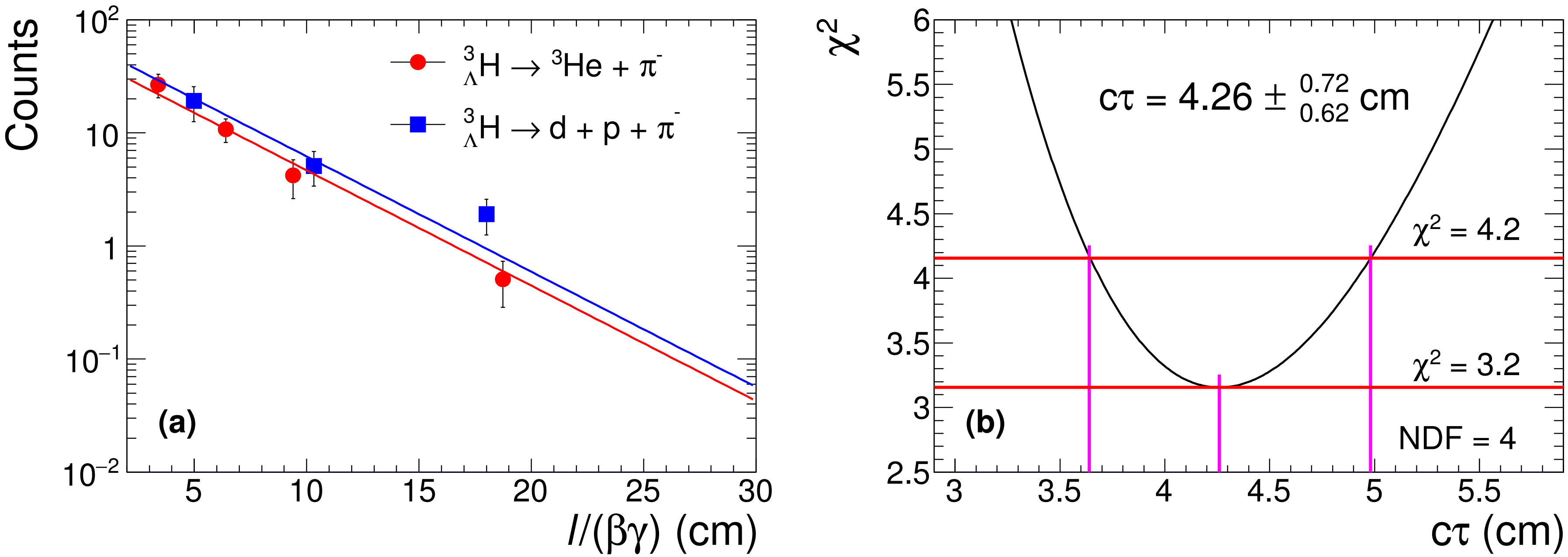
☑ High statistics sample with good signal to background ratio in both channels: ~25% & ~15%

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





Updates on lifetime measurement at STAR

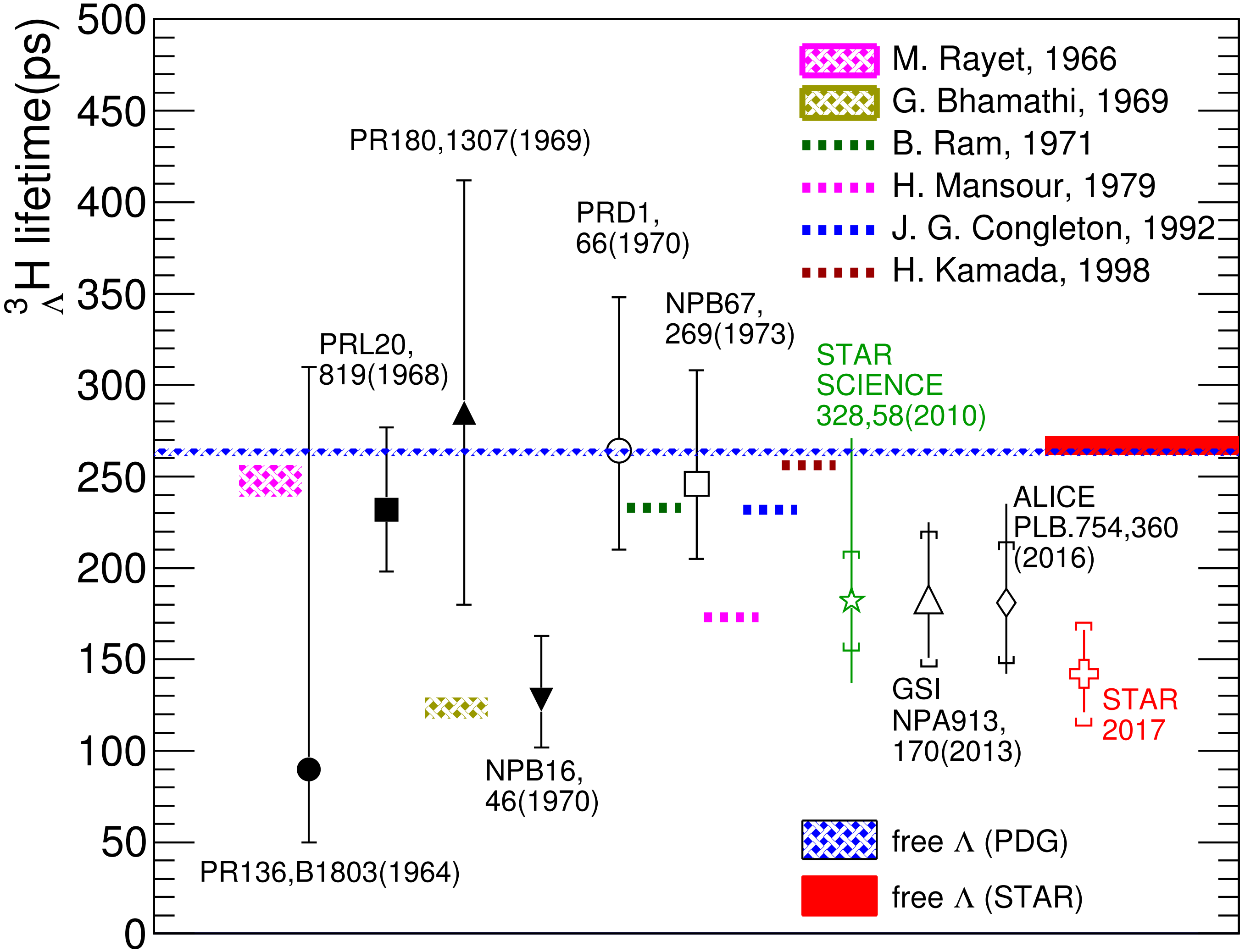


☑ The lifetime is determined from a combine analysis of 2-body and 3-body decay modes

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

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

Updates on world data of lifetime

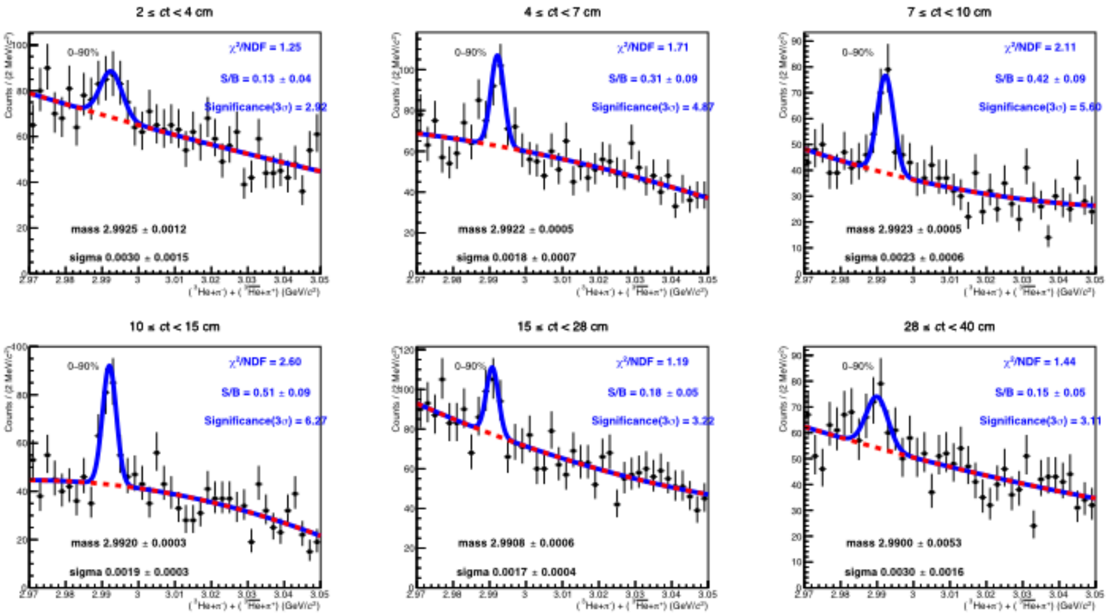


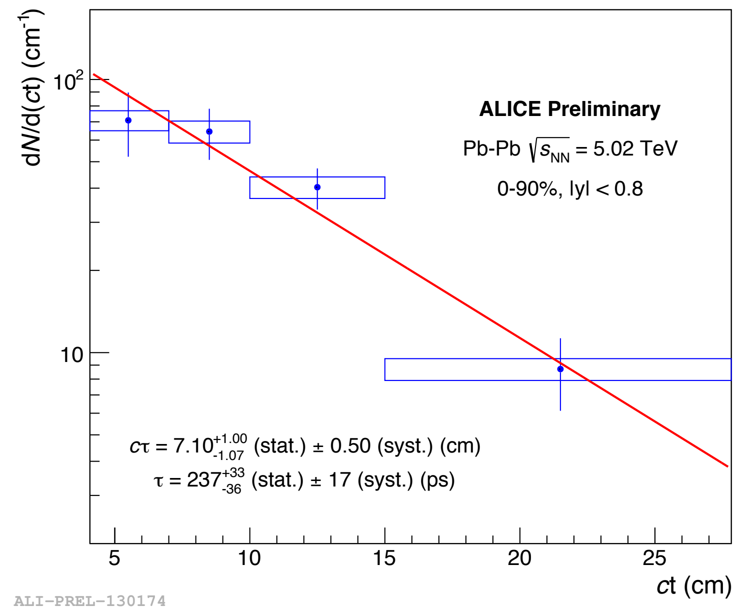
World average:

211^{+18}_{-16} ps

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

Updates on lifetime measurement @ALICE





QM18, HYP18

☑ 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)

The decay branching ratio is related to B$_\Lambda$

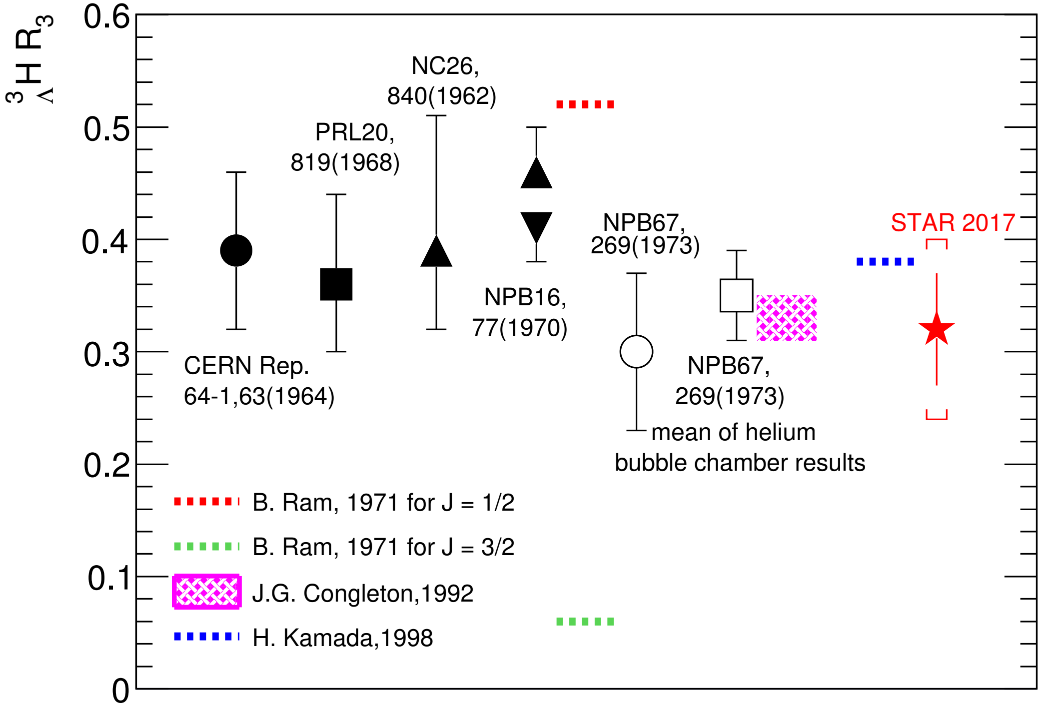


Table 2: Measurements of variable R_3.

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)

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

☑ The R$_3$ is sensitive to the spin of hypertriton. It can also be used to obtain an indirect measurement of the B$_\Lambda$

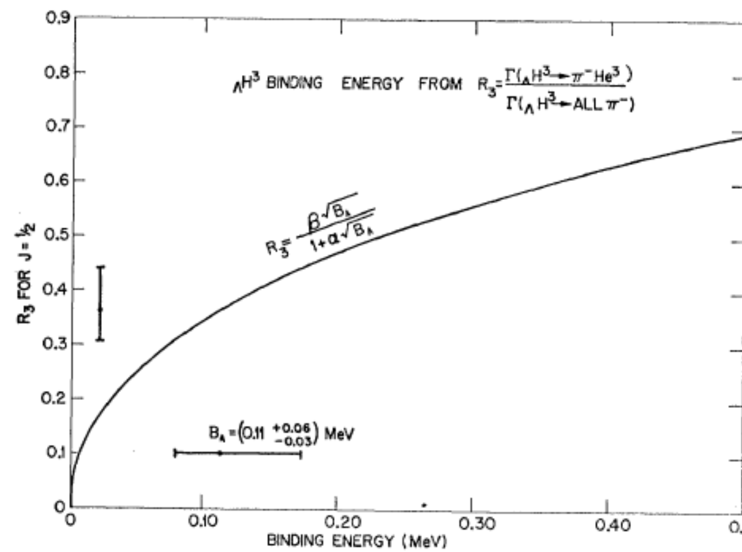


*Fig. is from Phys. Rev. D 1,66 (1970) with $R_3 = 0.36\pm^{0.08}_{0.06}$

**Curve is from Phys. Rev. 113,1604 (1959) with B$_\Lambda$=0.25 MeV, spin 1/2 scenario

Can we measure B_Λ better?

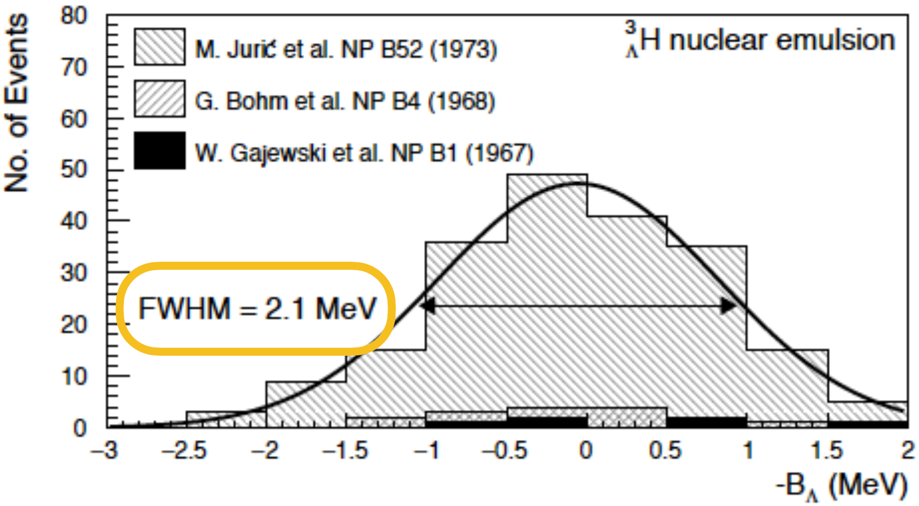
☑ The early data suffers from large statistical uncertainty!

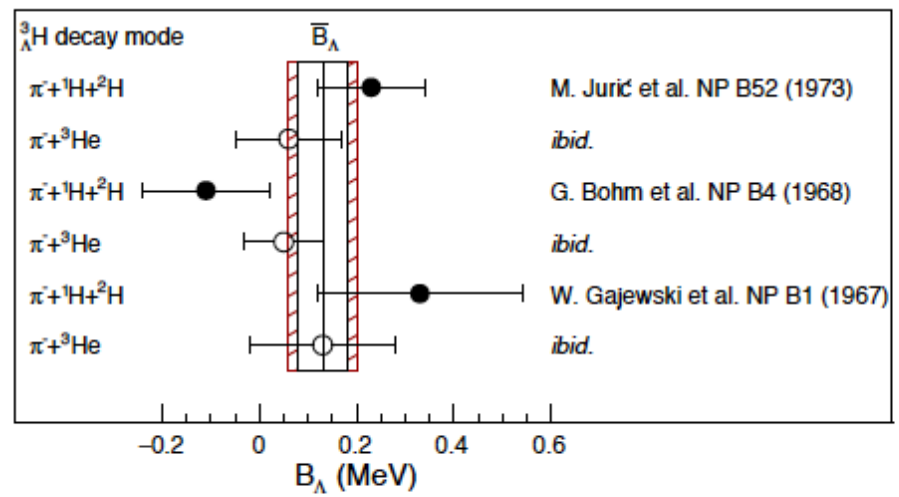
	$B_\Lambda \pm \Delta B_\Lambda$ (MeV)		δB_Λ (MeV)
	Bohm et al.[a]	This work	
${}^{3}_{\Lambda}H$	0.01 ± 0.07	0.15 ± 0.08	0.14 ± 0.11

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

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

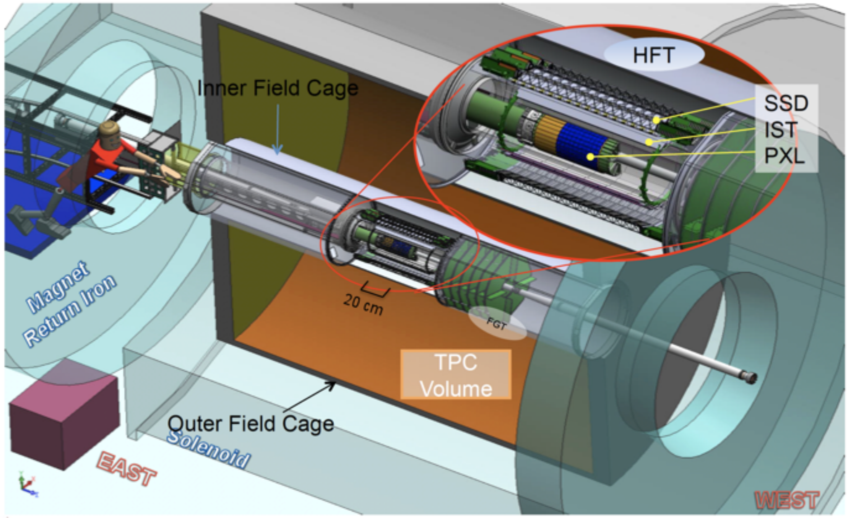
P. Achenbach, PoS (Hadron 2017) 207





"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)

The Heavy Flavor Tracker at STAR (HFT)



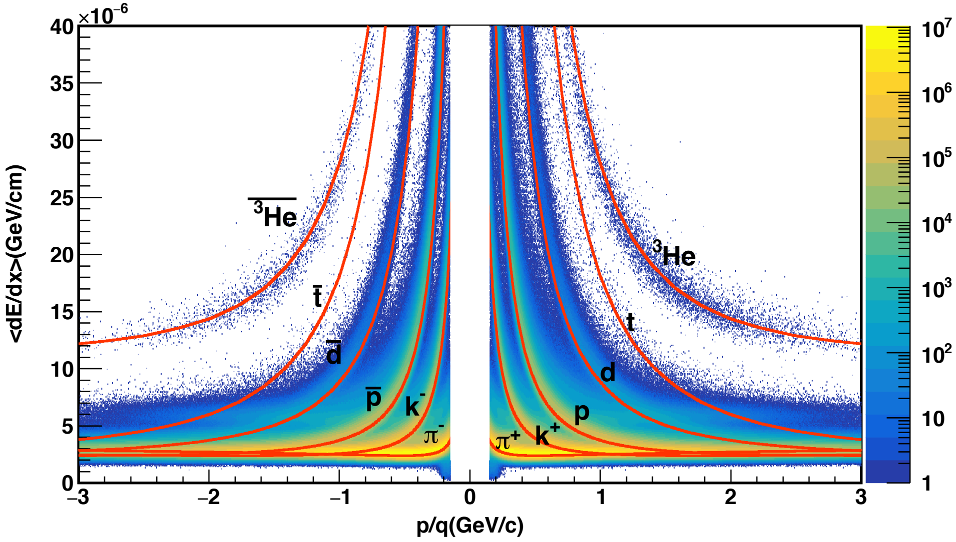
Detector	Radius (cm)	Hit Resolution (R × ϕ) / Z (μm/μm)	Thickness
SSD	22	30/860	1% X_0
IST	14	170/1800	<1.5% X_0
PXL	8	6.2/6.2	0.5% X_0
	2.8	6.2/6.2	0.4% X_0

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

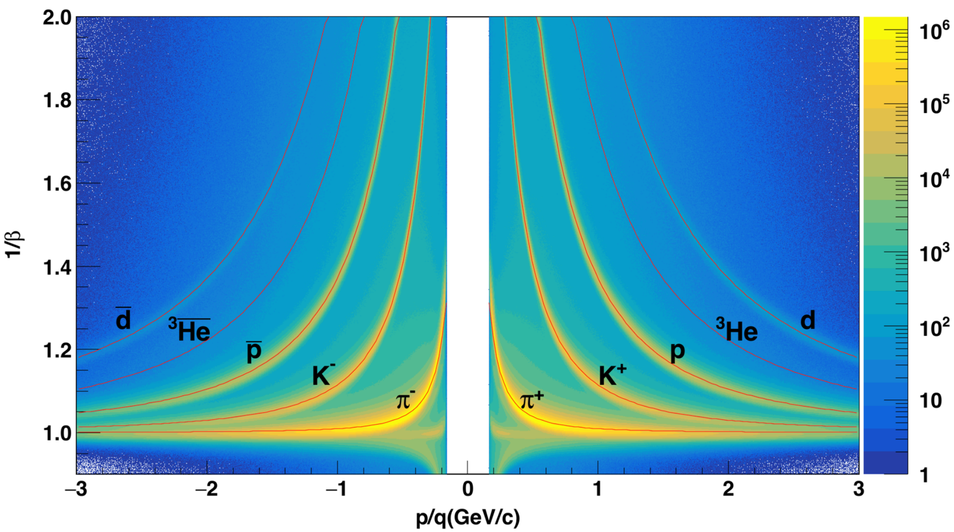
TPC → ~1mm → SSD → ~300μm → IST → ~250μm → PXL → < 30μm → vertex

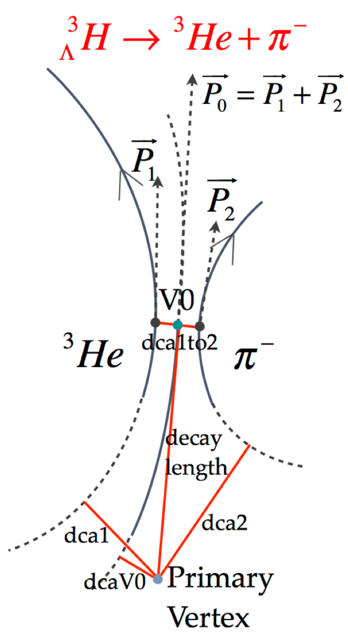
☑ Data : ~1.2 billion Au+Au collision events in 2014, and ~3.4 billion Au+Au collision events in 2016

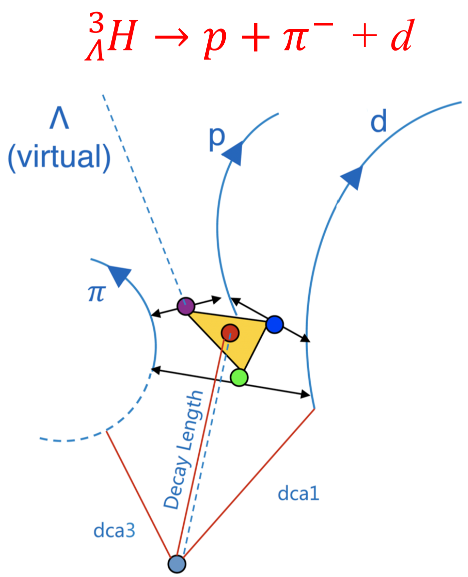
The particle identification in STAR



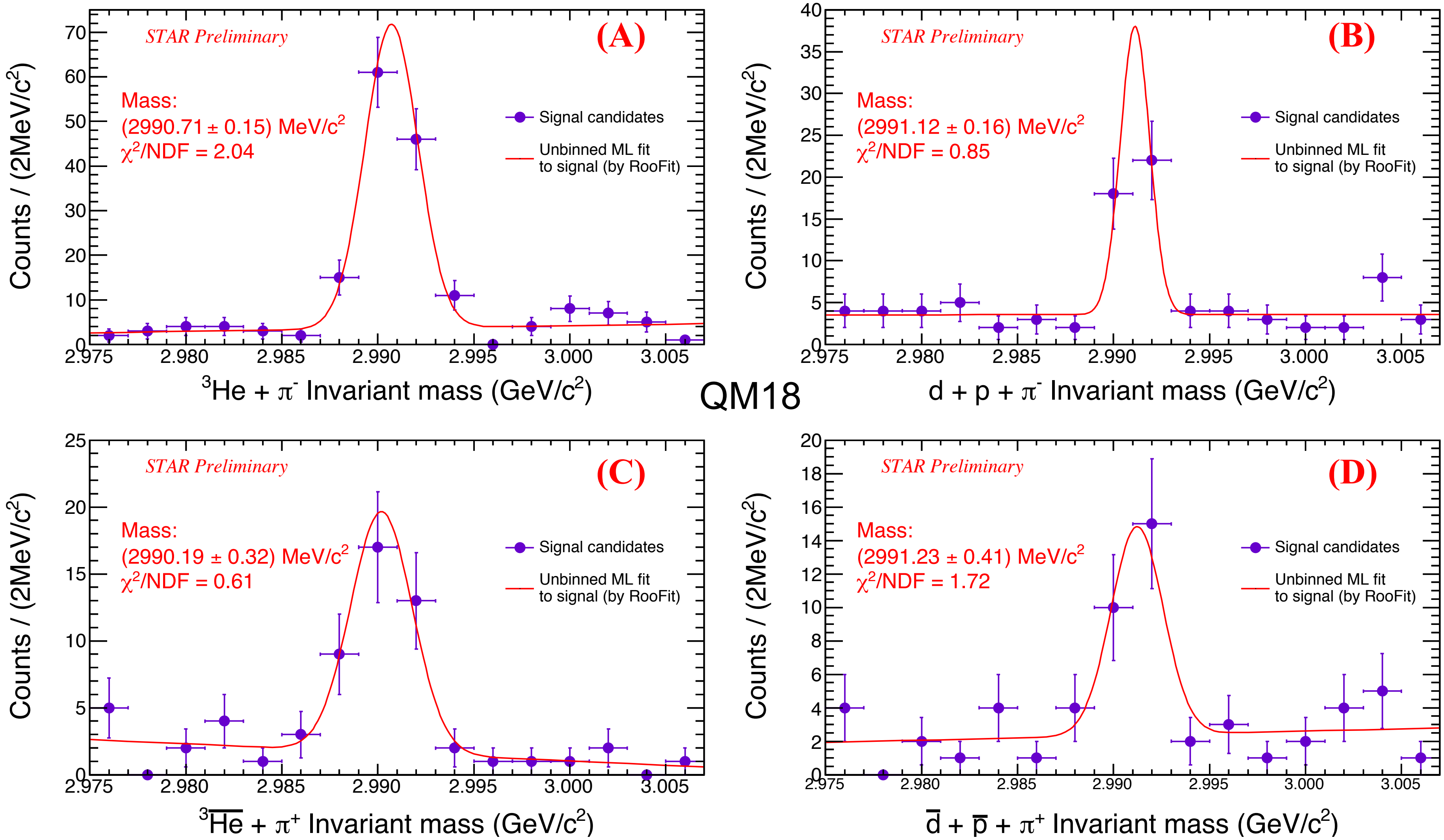
- Clean PID of charge particles from TPC and ToF in STAR
- The topology of hypertriton in STAR detector





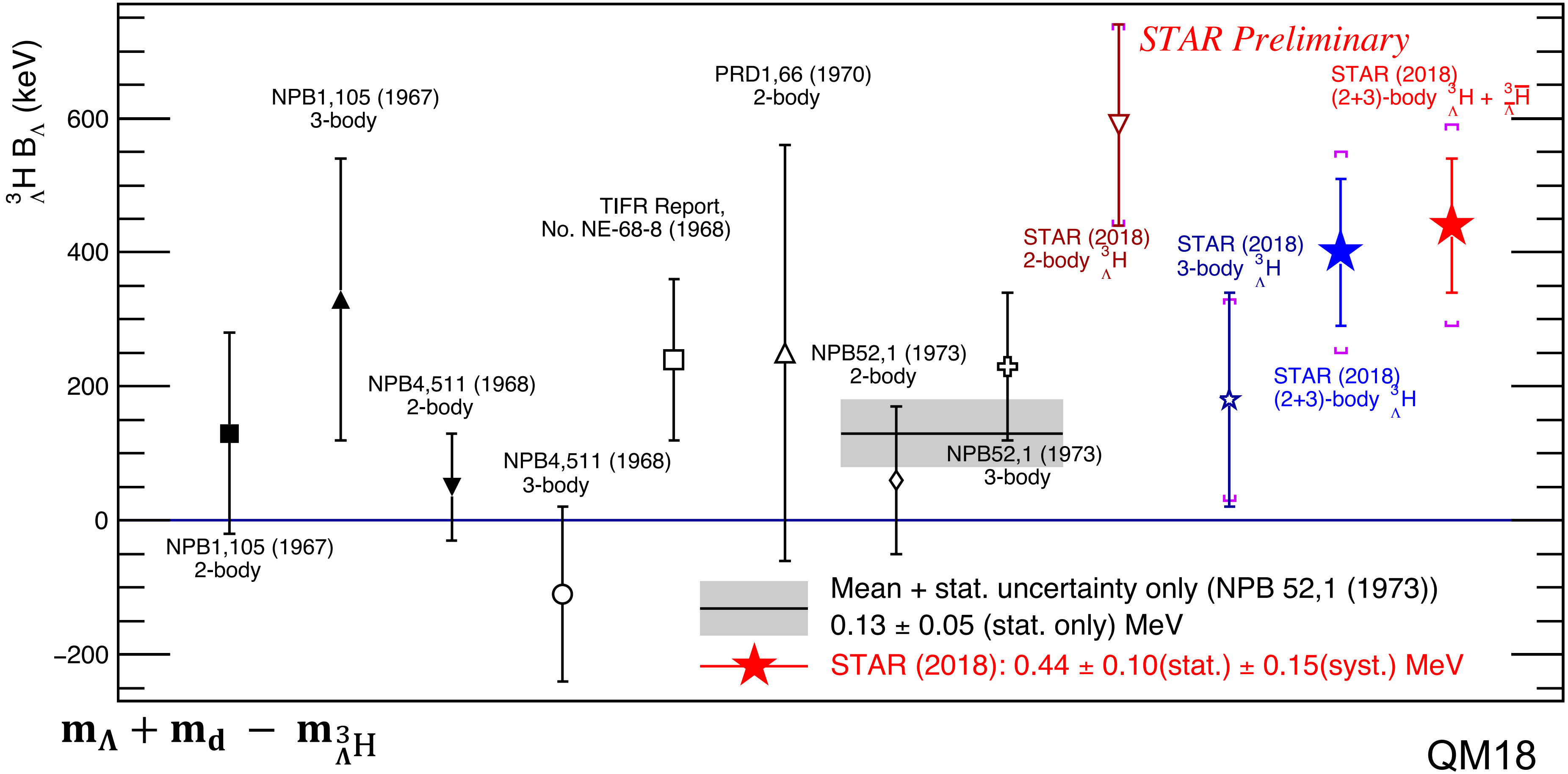


Invariant mass distr. with energy loss correction



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

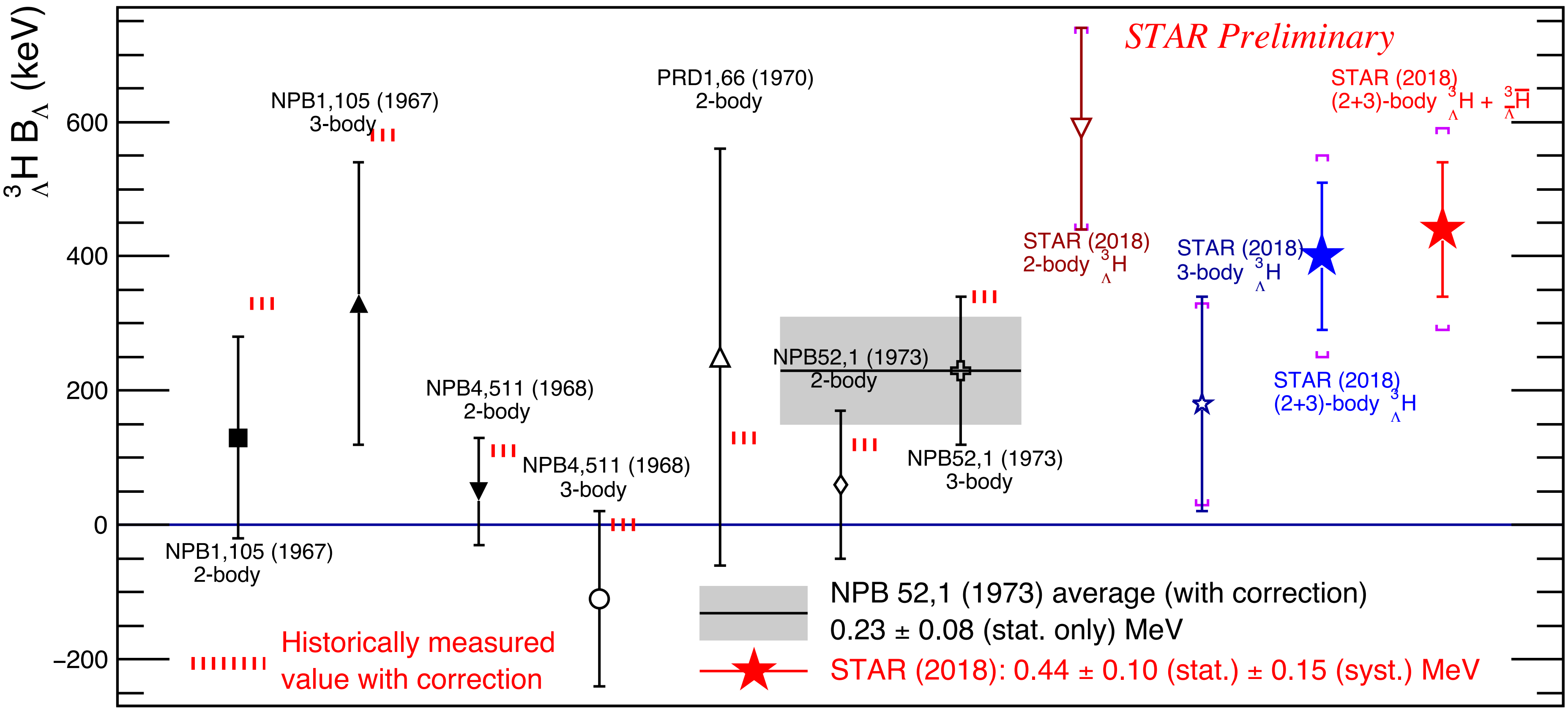
The B_Λ data



QM18

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

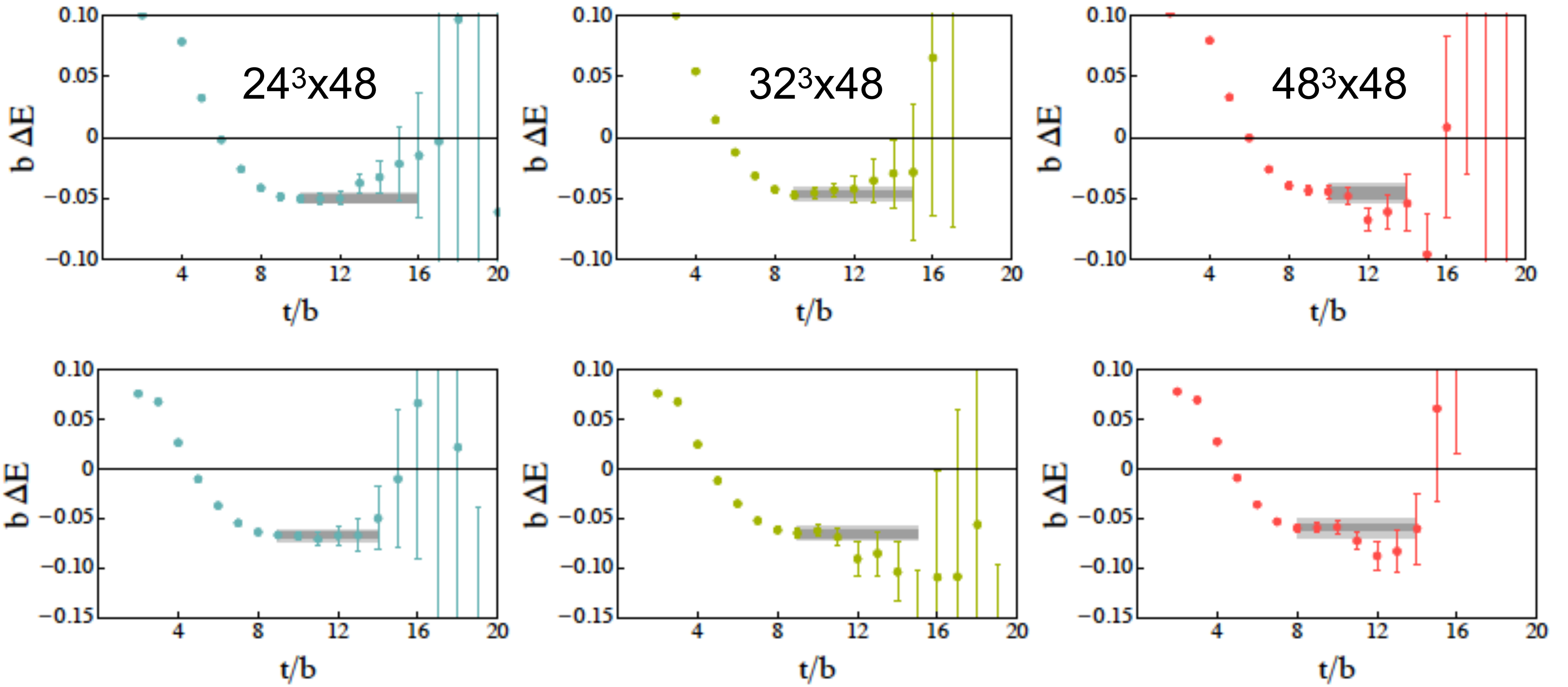
The B_Λ data with re-calibration



QM18

☑ 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.

Compared to LQCD calculations

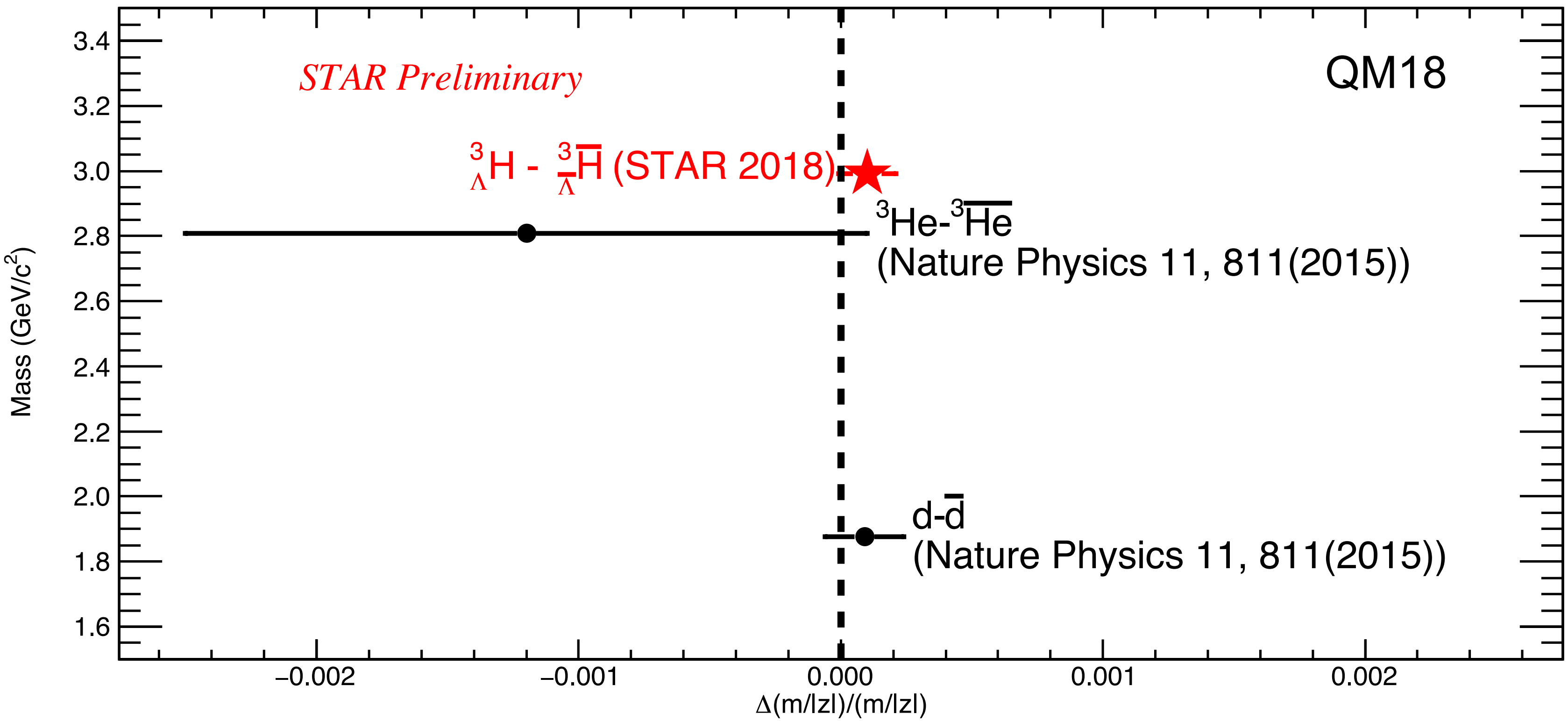


Phys. Rev. D 87, 034506 (2013)

- ☑ NPLQCD calculations, up: the effective baryon mass plots (EMPs) for ^{3}He and HT of spin 1/2; bottom: for HT of spin 3/2 being somewhat more bound than the 1/2 state.
- ☑ AFDMC calculations: -1.2 MeV in 2014, 0.23 MeV in 2018.

Phys. Rev. C 89, 014314 (2014), arXiv:1711.07521

Mass difference measurement



☑ ALICE:

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

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

☑ 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

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

- 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

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

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

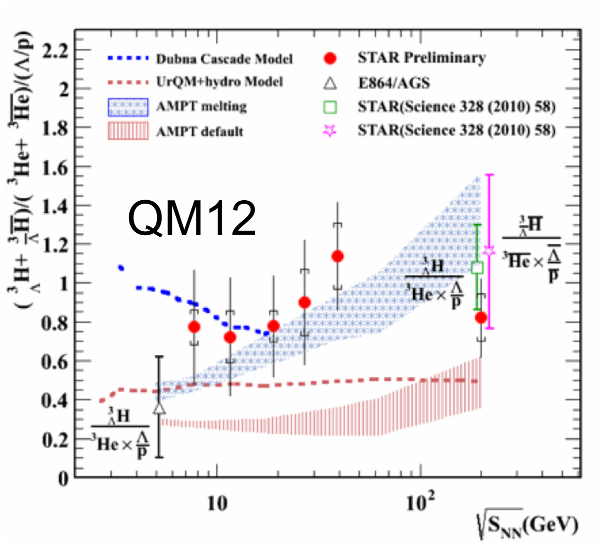
$$B_\Lambda : 0.44 \pm 0.10(stat.) \pm 0.15(syst.)\text{MeV}$$

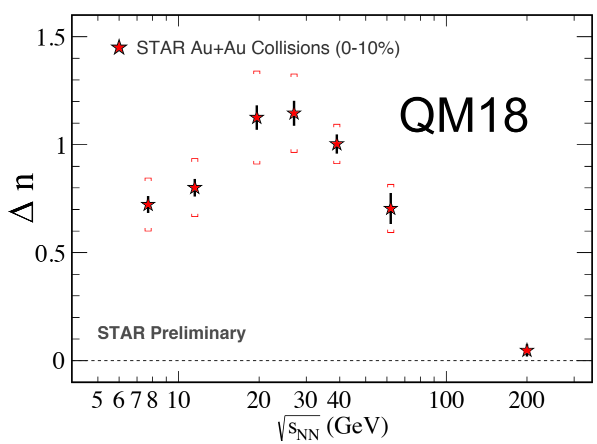
- Mass difference between hypertriton and antihypertriton is estimated

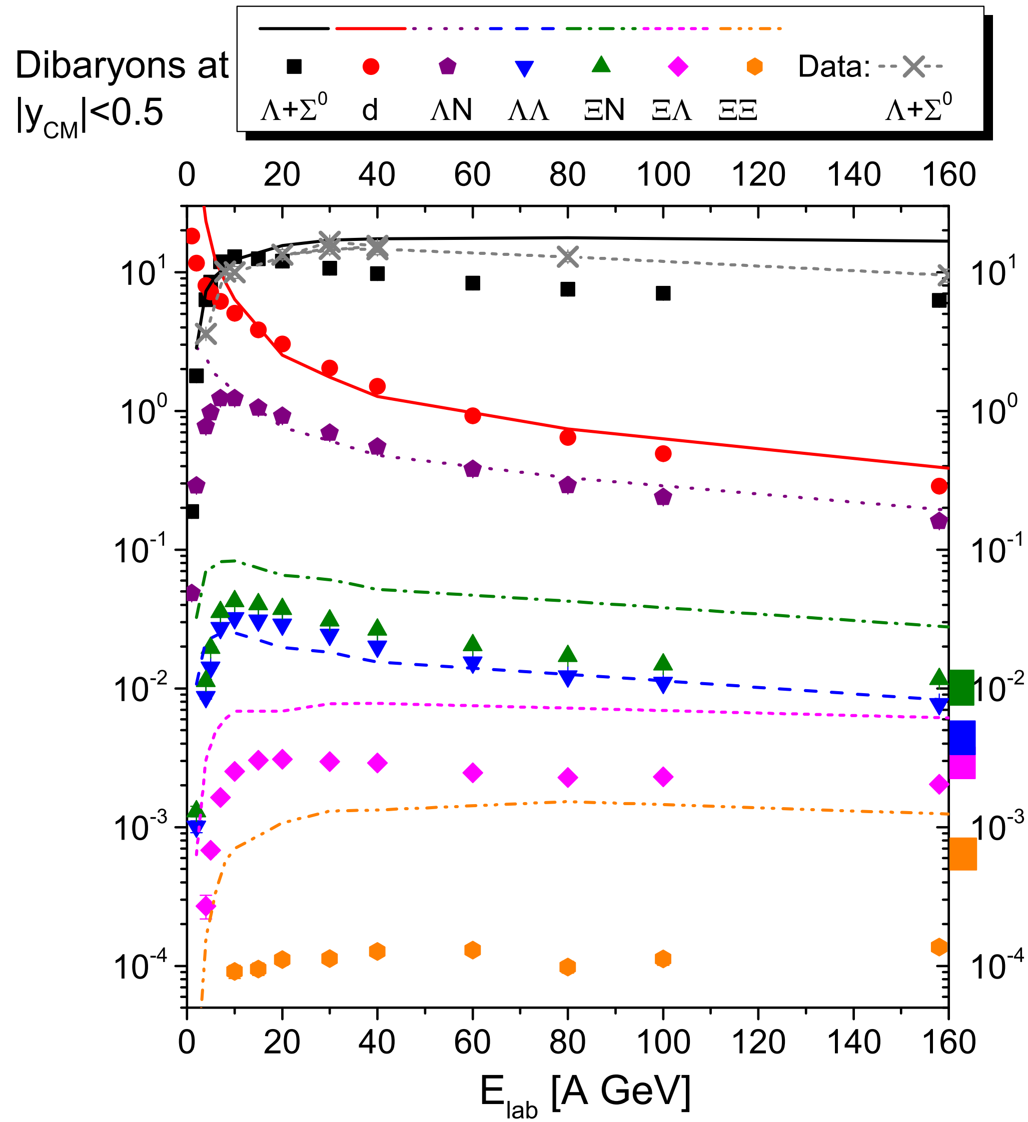
$$\left(\frac{\Delta(m/|z|)}{m/|z|}\right)_{^3_\Lambda H} = (1.0 \pm 0.9(stat.) \pm 0.7(syst.)) \times 10^{-4}$$

Outlook (1)

☑ STAR BES-II and fixed target at 2019 and 2020
- detector upgrades
- hypernuclei @ high baryon density







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

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
  A. Feliciello, HYP2018, USA

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

  S. Nagao, HYP2018, USA

☑ On the mass measurements:

- Decay-pion spectroscopy at MAMI

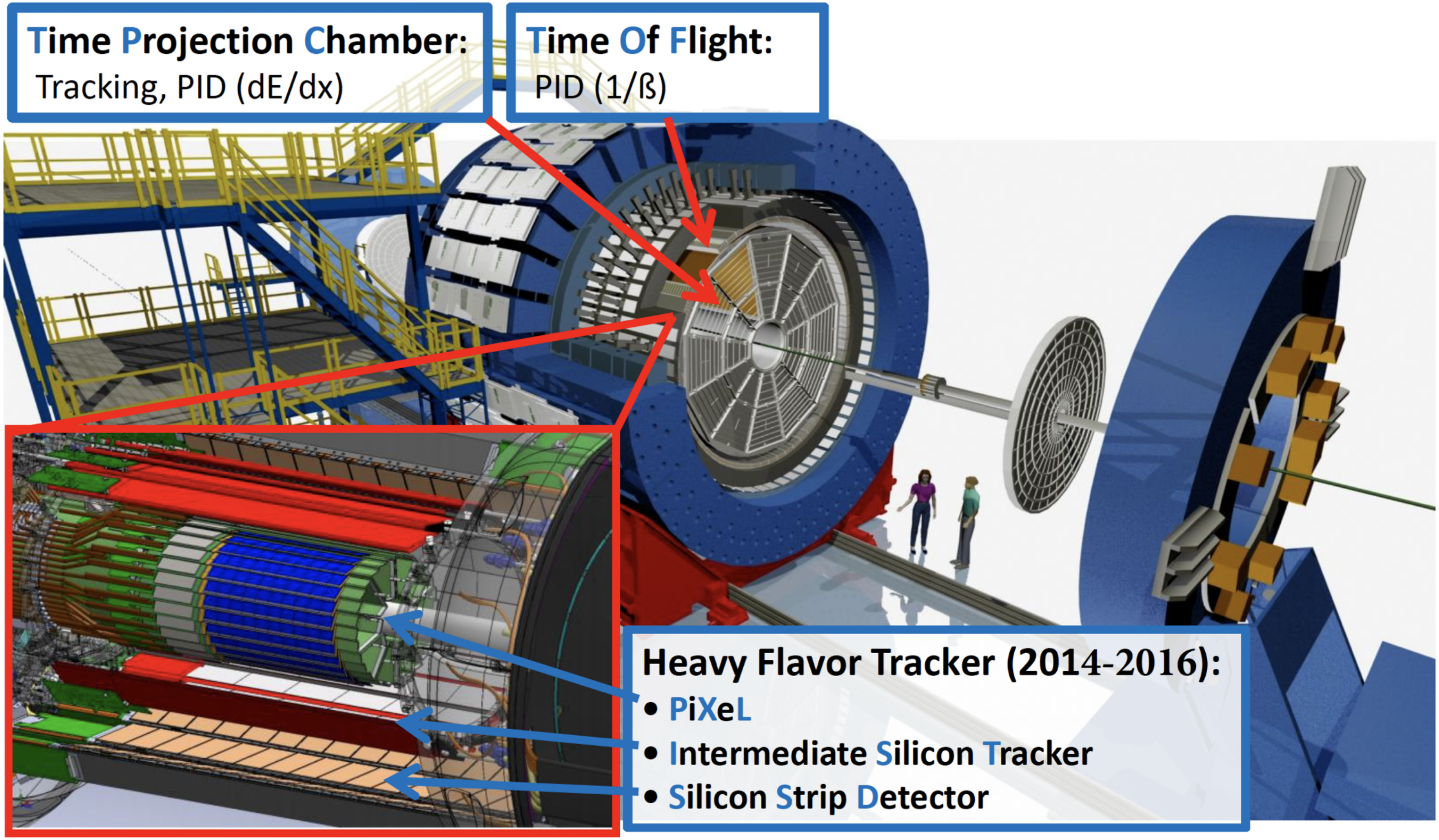
  P. Achenbach, Hadron 2017, Spain

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

  S. Nakamura, HYP2018, USA

Back-up slides

The Solenoidal Tracker at RHIC (STAR)



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

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

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

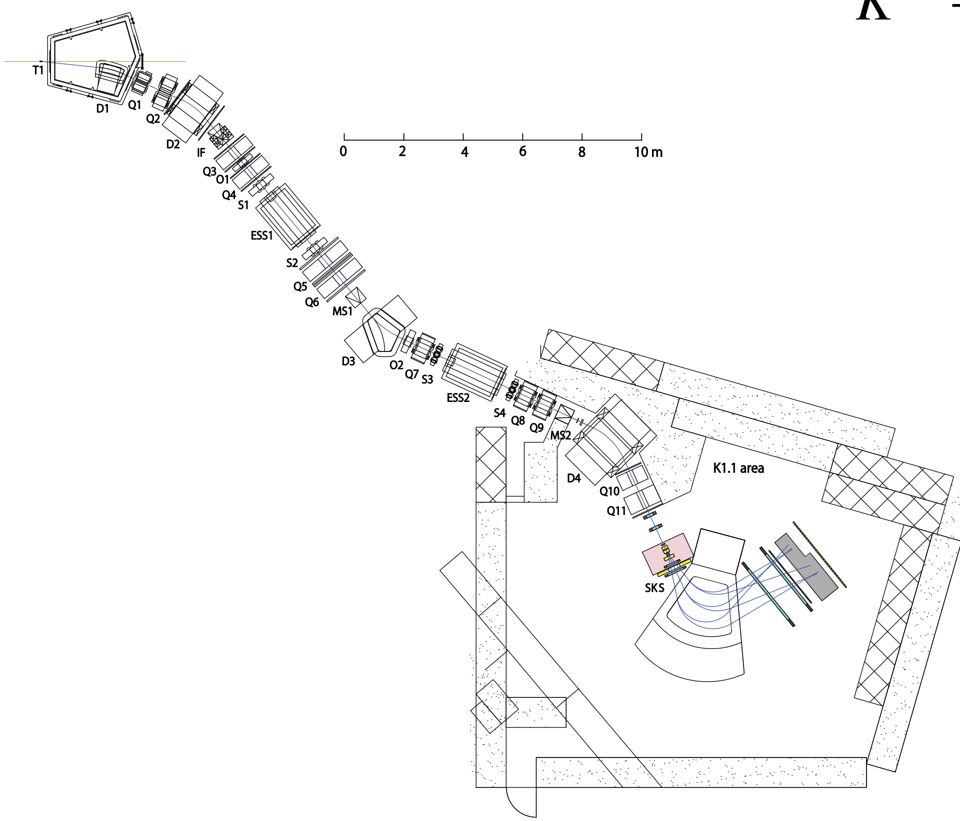
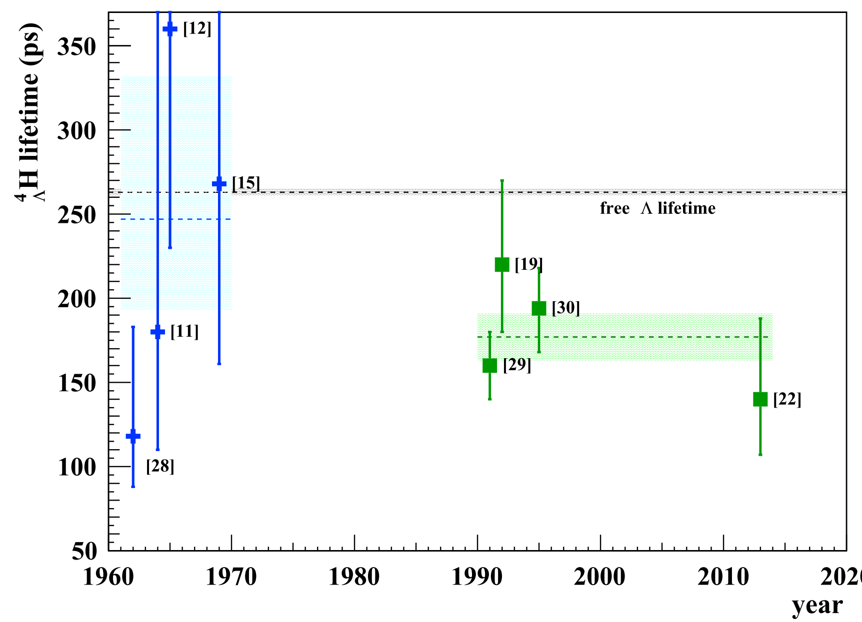
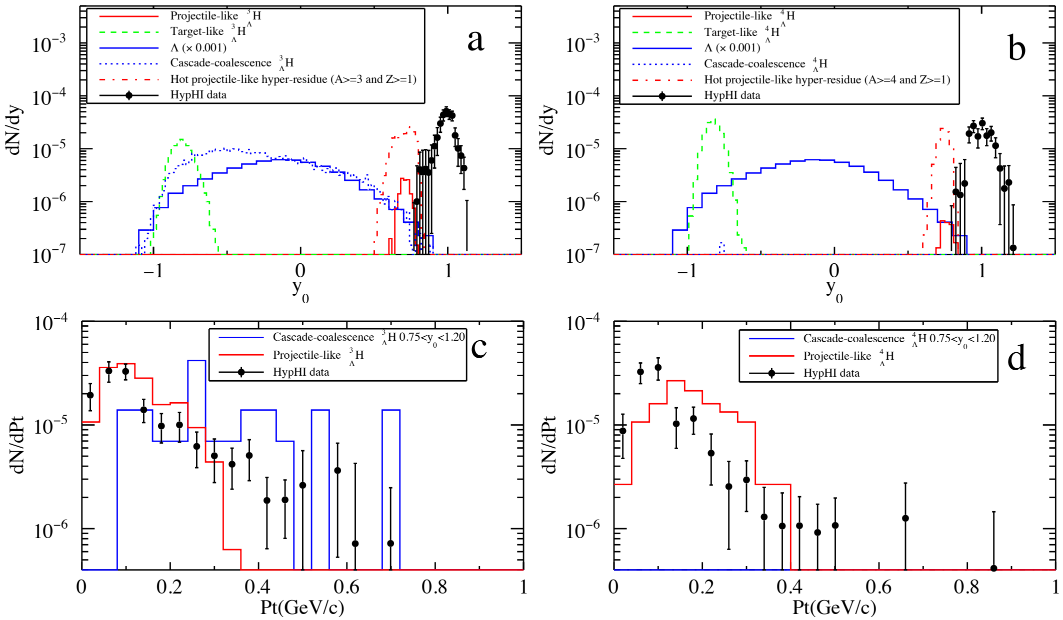


Fig. 4. Layout of the J-PARC K1.1 beam line and K1.1 experimental area. From [46].



Future direction (3)



☑ Light hypernuclei production in peripheral ion collisions

arXiv: 1712.04658