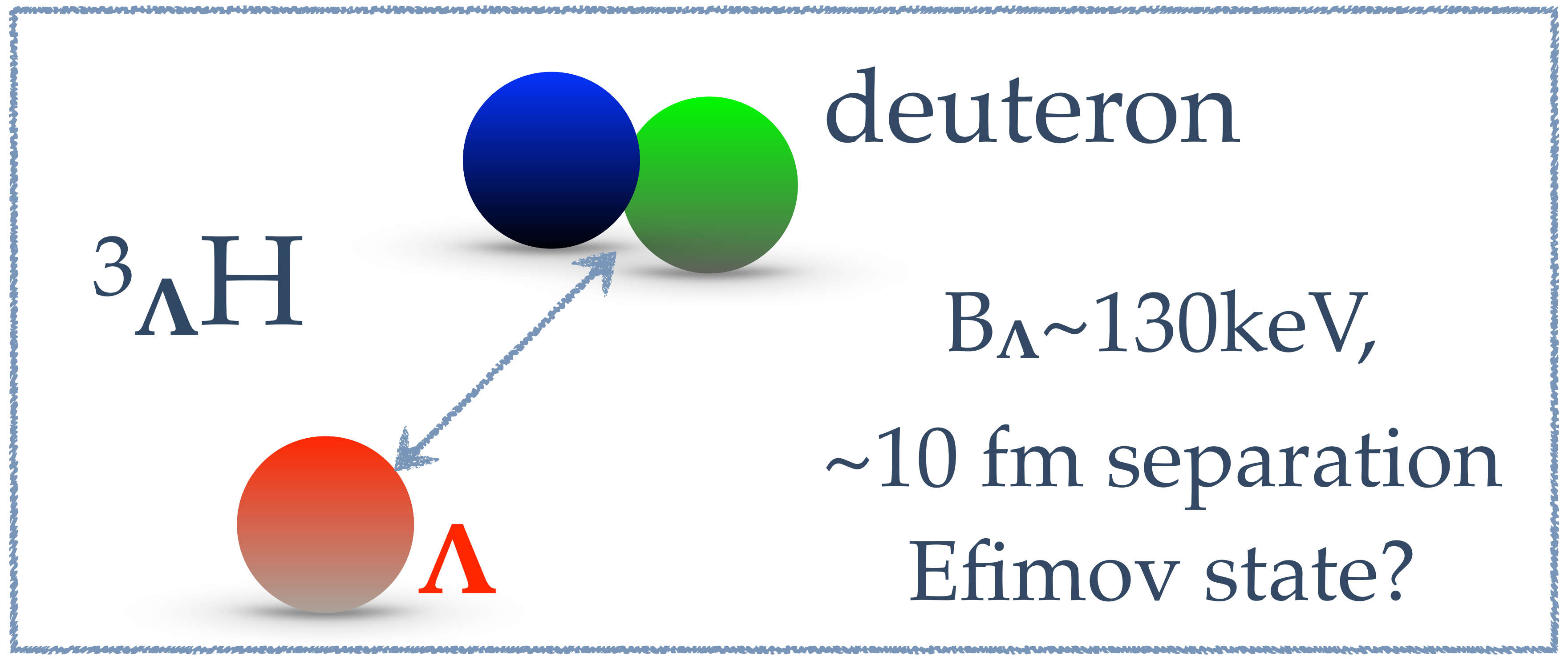
Lifetime measurement of light hypernuclei at J-PARC

Tadashi Hashimoto (JAEA/ASRC)   2023/2/9 @ 第8回クラスター階層領域研究会

Hypertriton

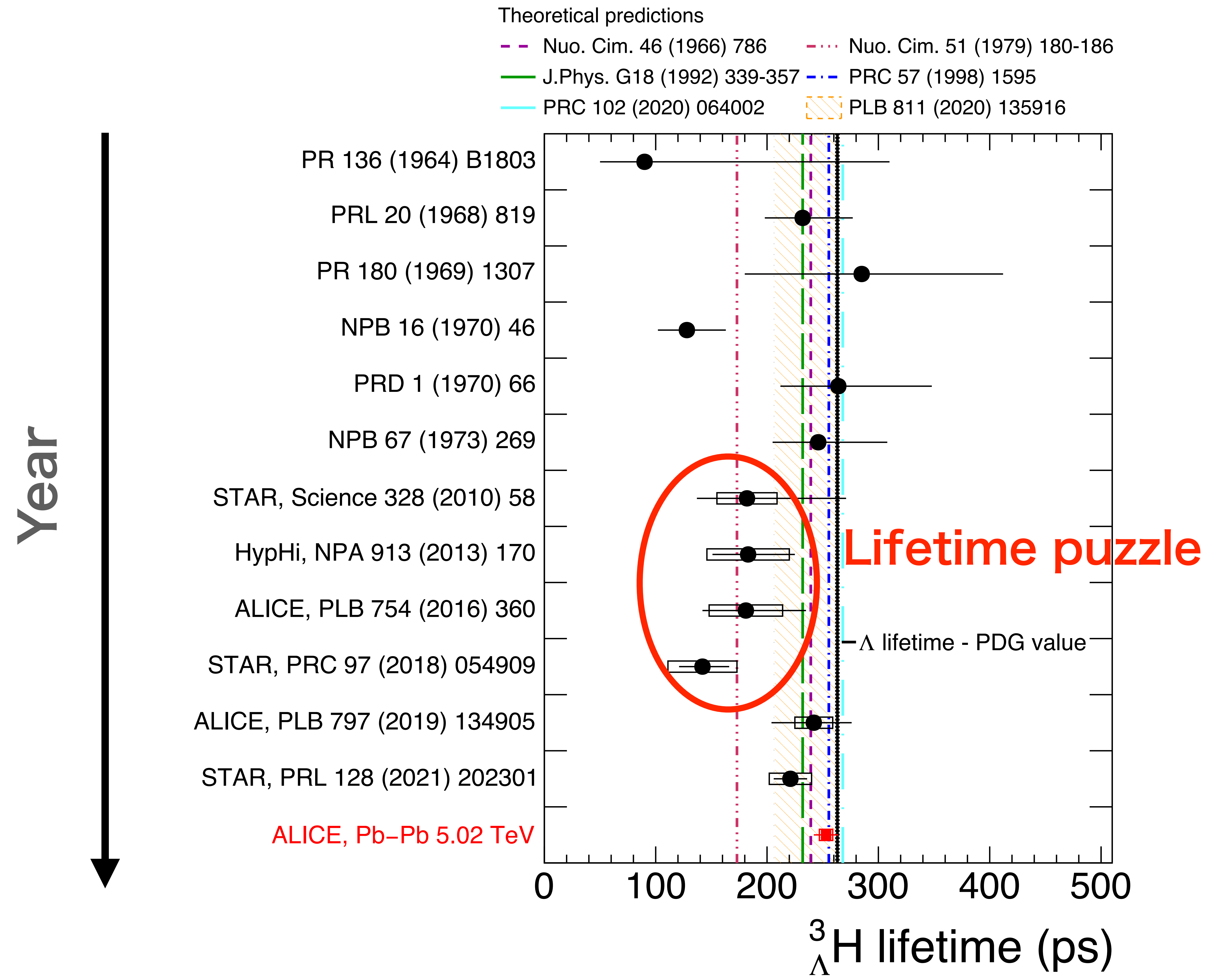
- Lightest hyper nucleus: bench mark for ΛN(ΛNN) interaction models.
- Important input to determine the ΛN spin-singlet strength

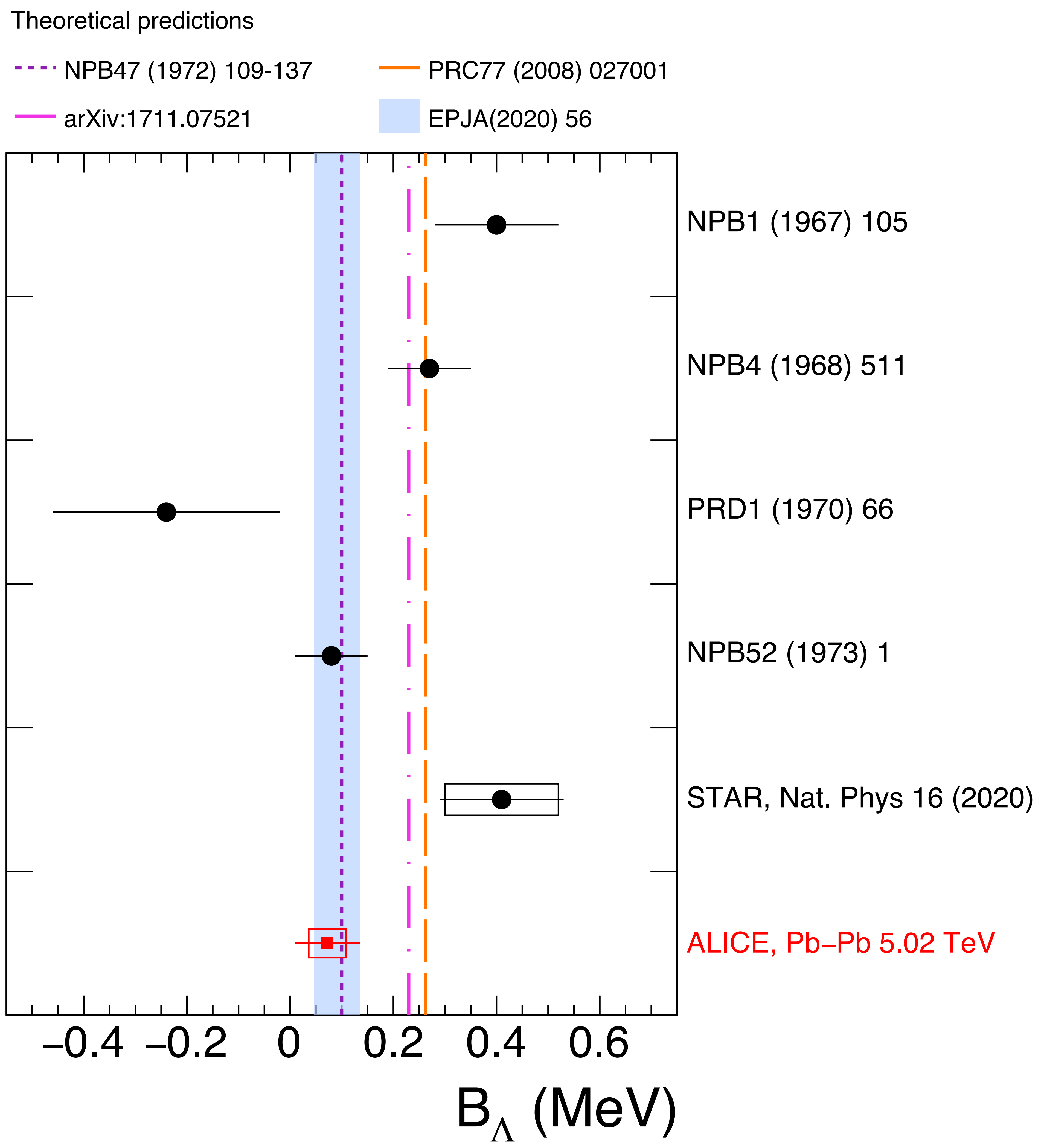


- Small B_{Λ}~130 keV from old emulsion data
  → large spacing between Λ & d
  → lifetime should be simlar to free Λ (263 ps)
  - for example 256 ps by H. Kamada, et al, Phys. Rev. C Nucl. Phys. **57**, 1595 (1998).
- Spin 1/2 determined by the two-body decay ratio R_3 (G. Keyes et al., NPB67, 269, 1973).

Experimental status

ALICE arXiv:2209.07360

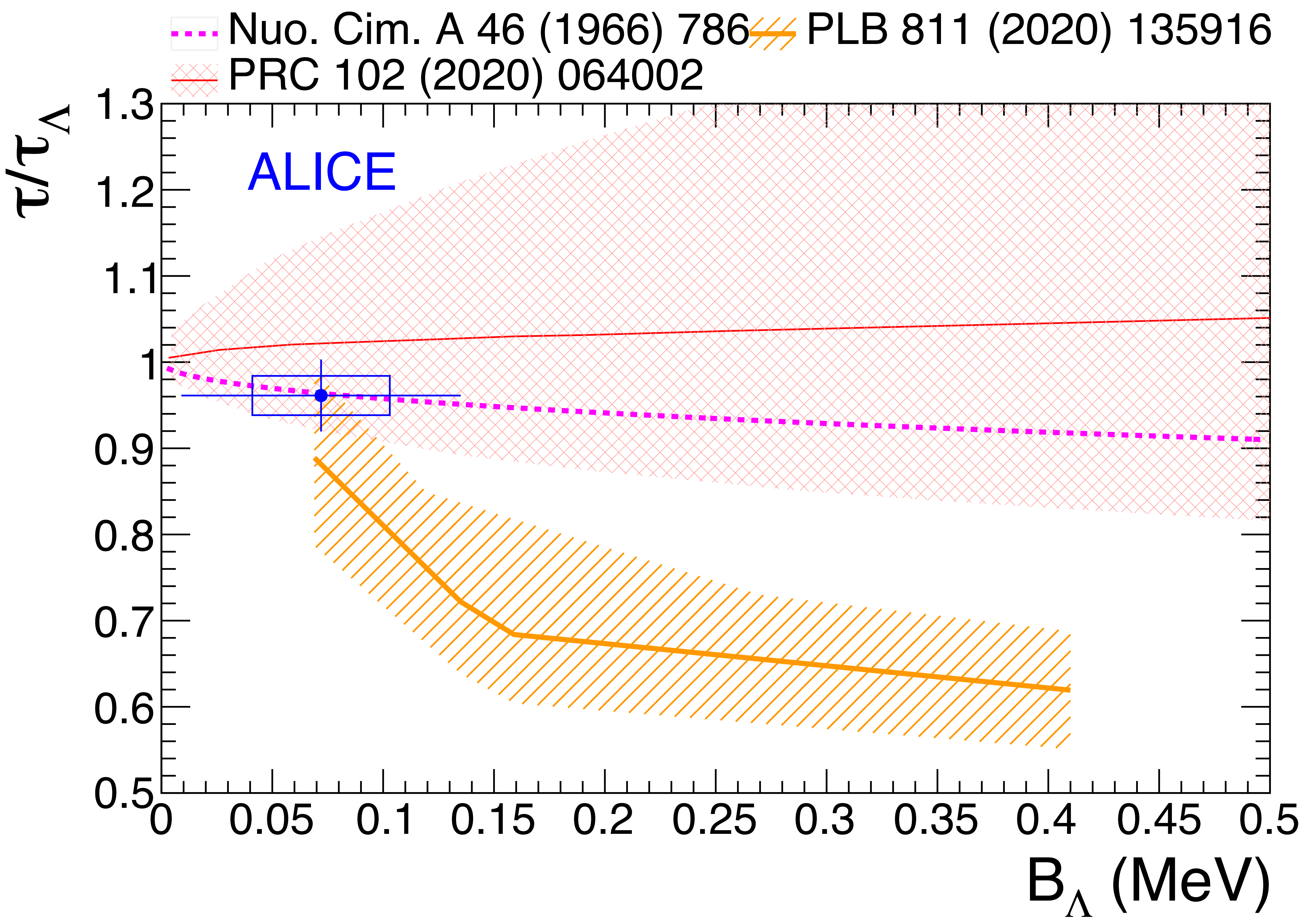




(Part of) Recent progress in theory

- Pion FSI enhance the decay rate 10~20%
  A. Gal, et al, Phys. Lett. B **791**, 48 (2019).
- Σ admixtures reduce the decay rate ~10%
  Strong dependence on B_Λ
  A. Pérez-Obiol, et al, Phys. Lett. B **811**, 135916 (2020).
- Branching ratio depends on B_Λ
  F. Hildenbrand et al., Phys. Rev. C**102**, 064002 (2020).
- etc…

ALICE arXiv:2209.07360



Need precision measurements for Lifetime and B_Λ

Ongoing/Planned experiments

- Heavy ion collision (for lifetime and Binding energy)
  - ALICE Run 3(2021~2024), Run 4 (2027~2030): ~50 times yield expected
  - GSI: FRS+WASA data taking peformed in 2022
- Binding energy measurement
  - MAMI (e, e'K): decay pion spectroscopy. data taking peformed in 2022
  - JLab (e, e'K): C12-19-002
  - J-PARC E07: Emulsion full scan
- Counter experiments for lifetime
  - ELPH: (γ, K+)
  - J-PARC P74: (π-, K^0) at K1.1
  - **J-PARC E73: (K-, π^0) at K1.8BR test data taking peformed in 2020/2021**

J-PARC E73/T77 experiment

✓ (K^-, π^0) reaction to selectively populate the ground hypernucleus

✓ Lifetime measurement in time domain

(K-, π^0) reaction

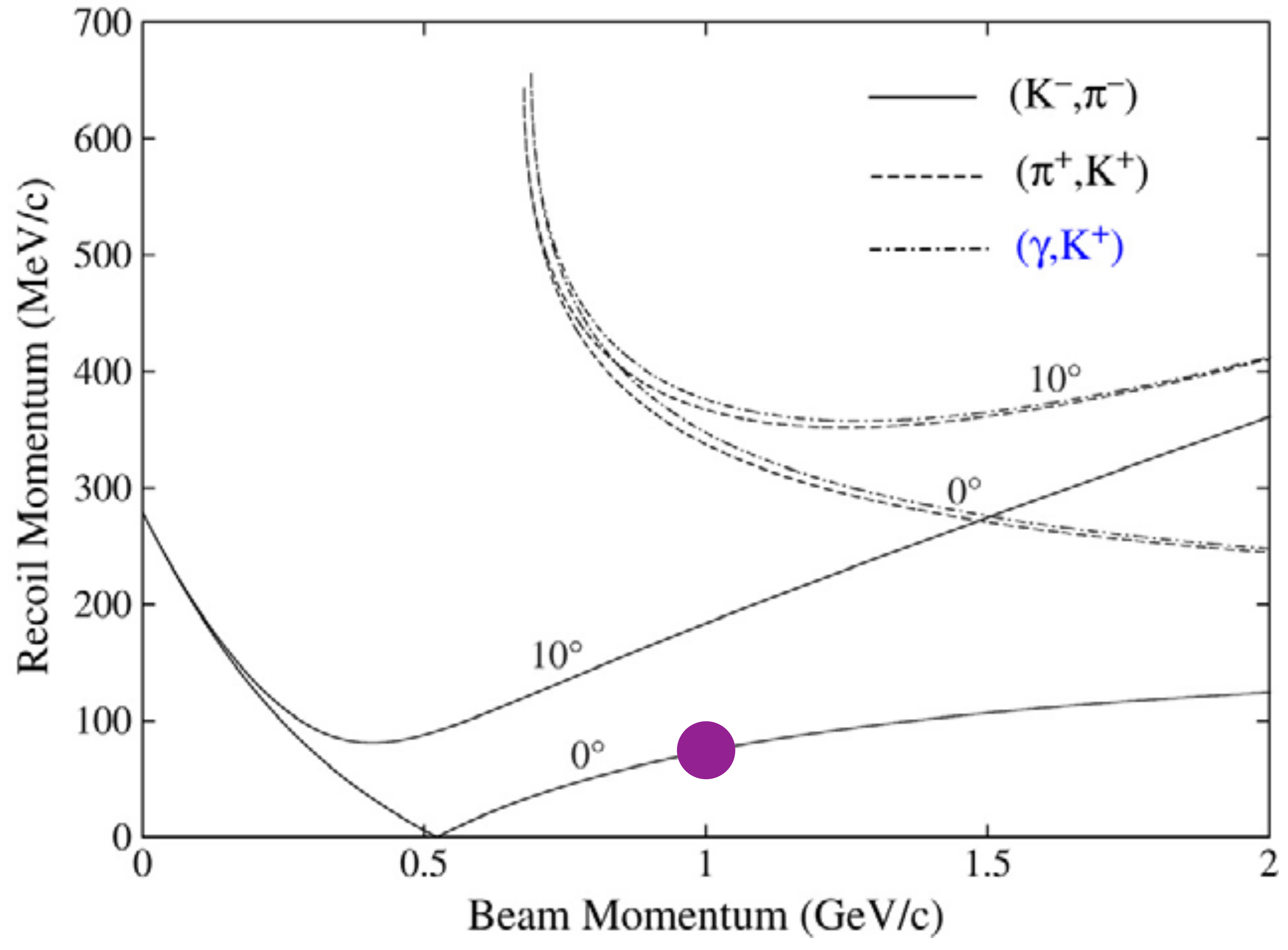
$$K^- + n \to \Lambda + \pi^-$$

widely adopeted with magnetic spectrometers

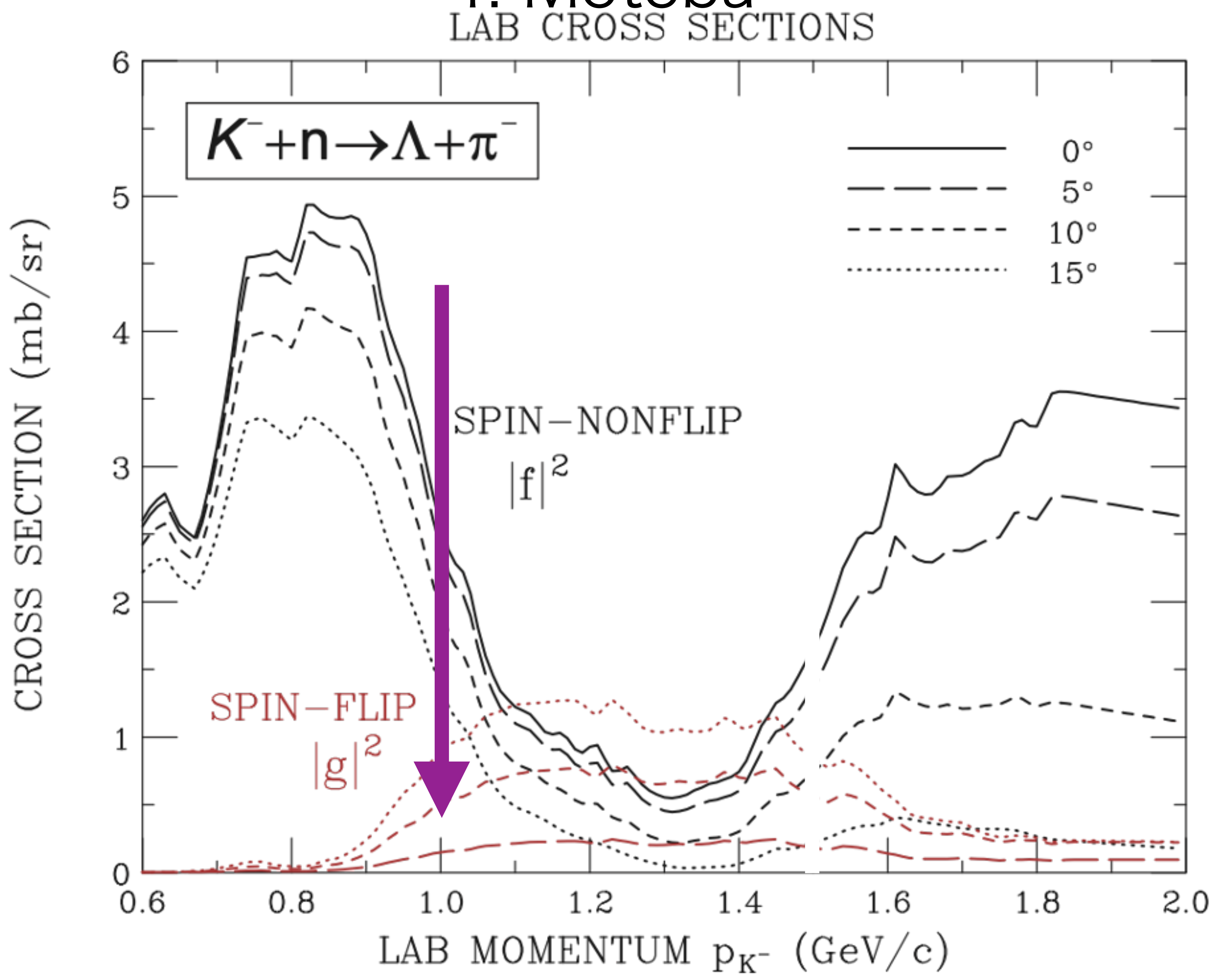
$$K^- + p \to \Lambda + \pi^0$$

difficult to do π^0 spectroscopy

Recoil momentum on Carbon

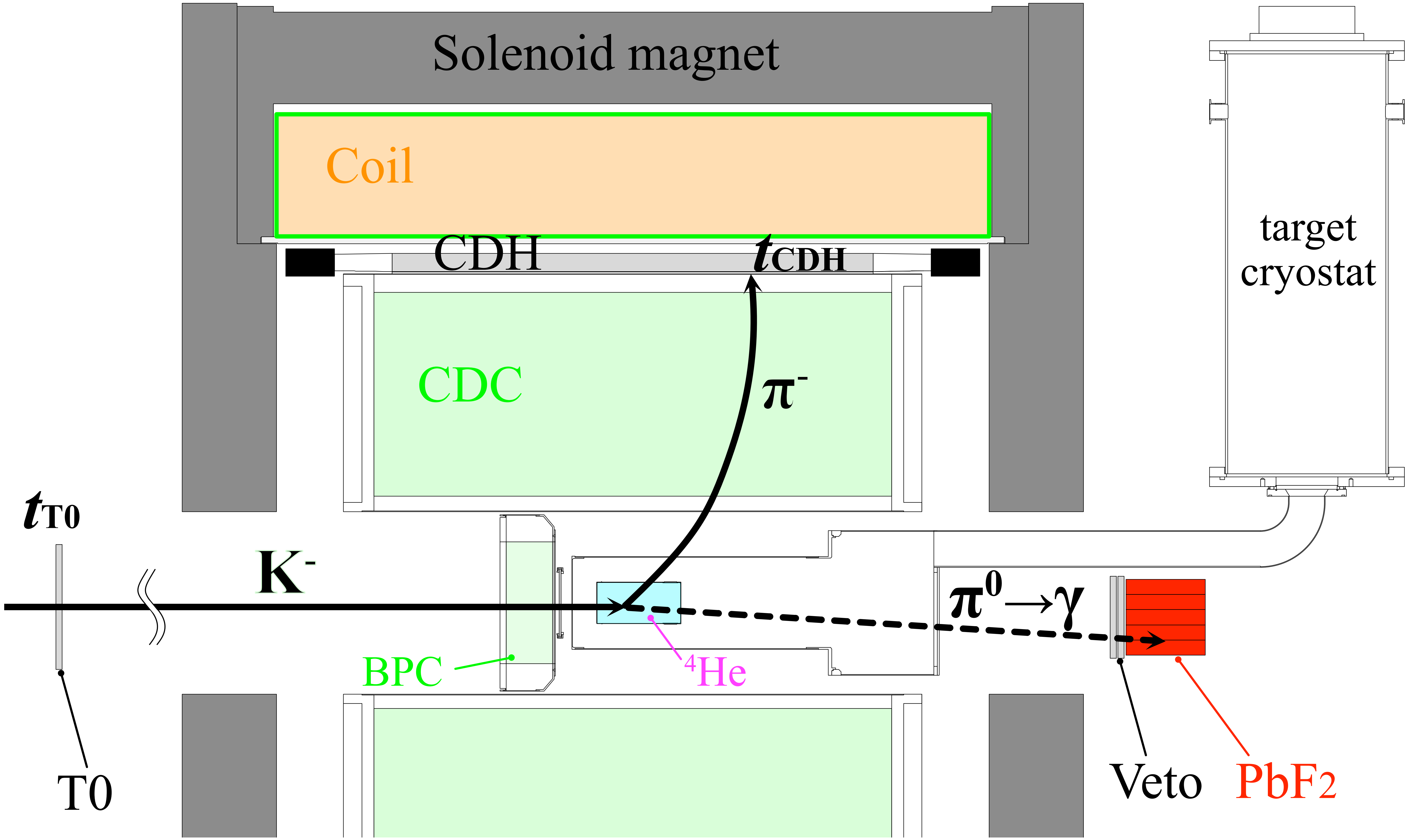


T. Motoba



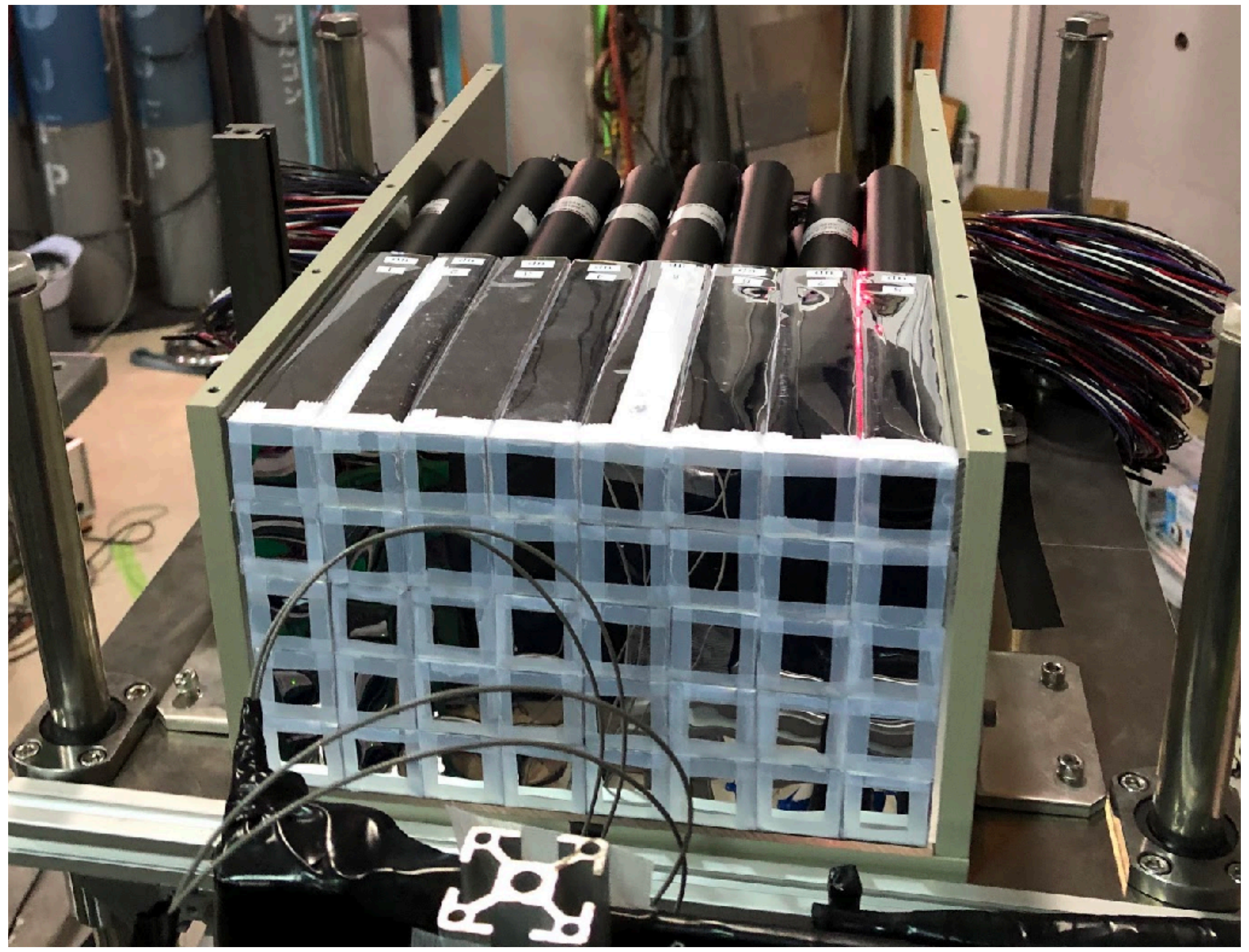
- Convert a proton to a Lambda→ produce neutron-rich hypernucleus
- Low recoil momentum → hypernucleus mostly stops before its decay
- Spin-nonflip reaction is dominant at 1.0 GeV/c or lower
- π^0 spectroscopy is difficult → **high-energy gamma tagging at forward angle**

Experimental setup

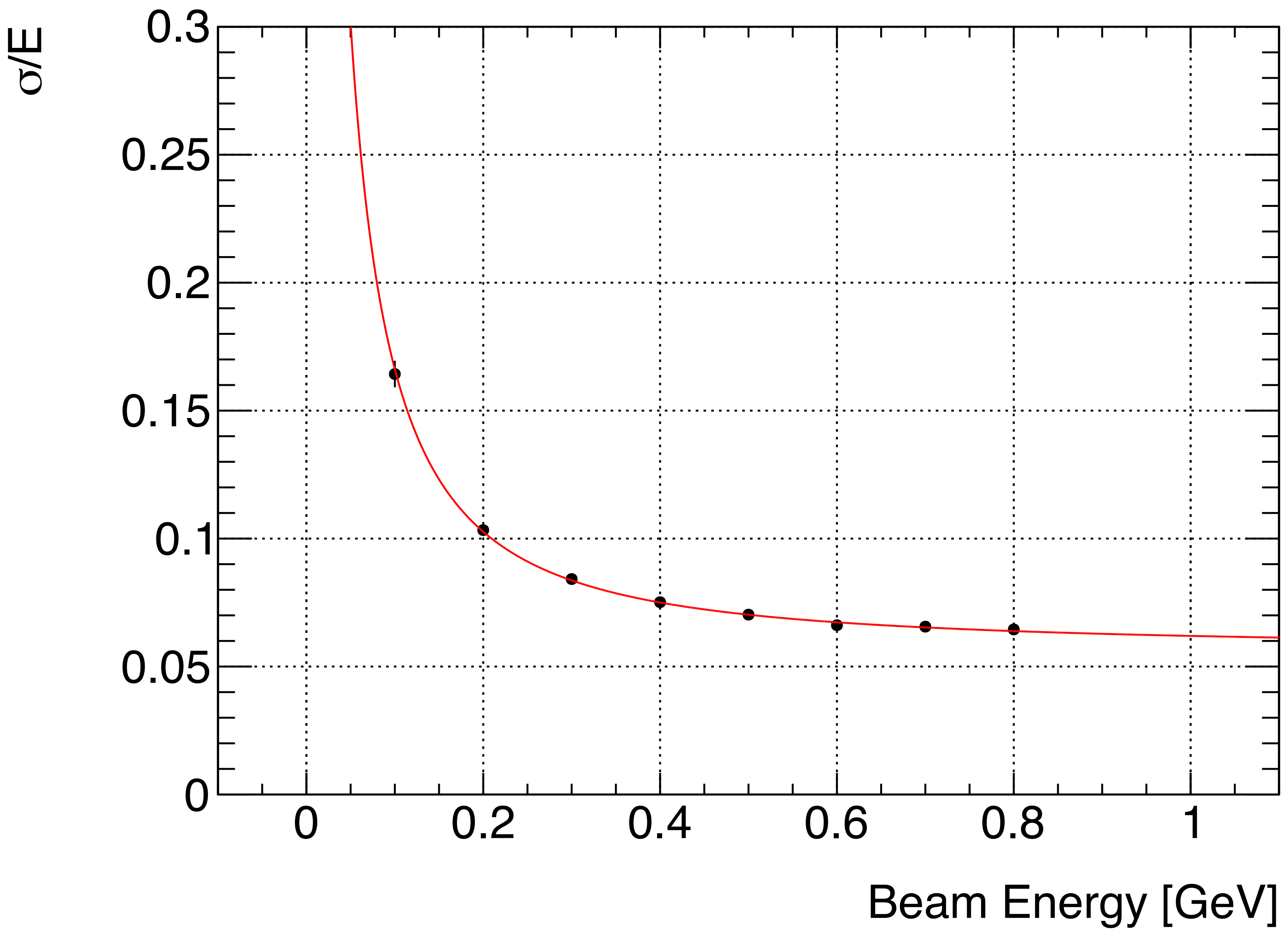


$$t_{decay} = (t_{CDH} - t_{T0}) - t_{CDC}^{calc.} - t_{beam}^{calc.}$$

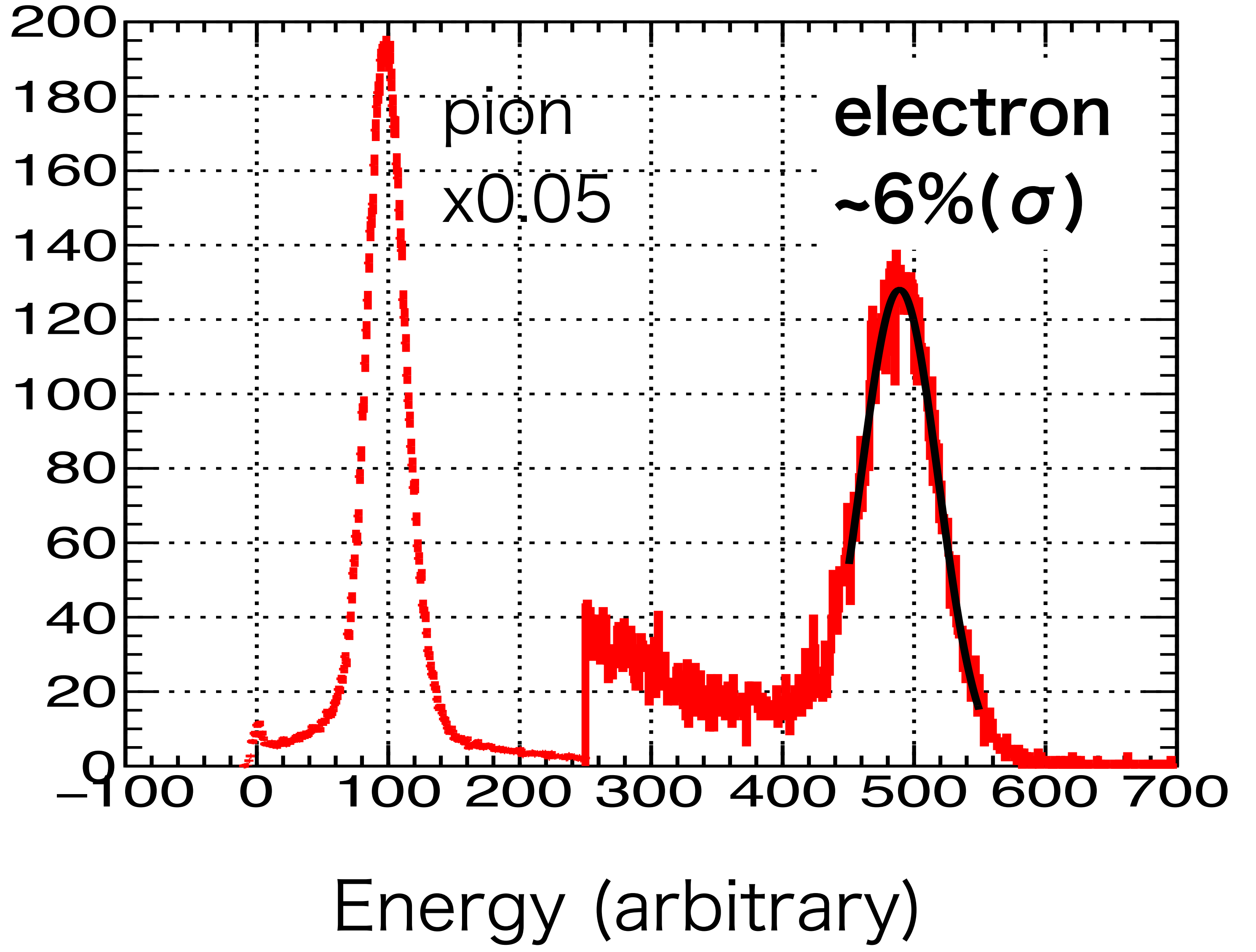
PbF2 EM calorimeter



2019.12: Test experiment @ ELPH using 100~800 MeV e+ beam



Response to 1 GeV/c π-/e- @ J-PARC



- Cherenkov-type, Radiation hard
- 25 x 25 x 140 mm^3
- 40 segment
- 1/4” PMT with Fe magnetic shield

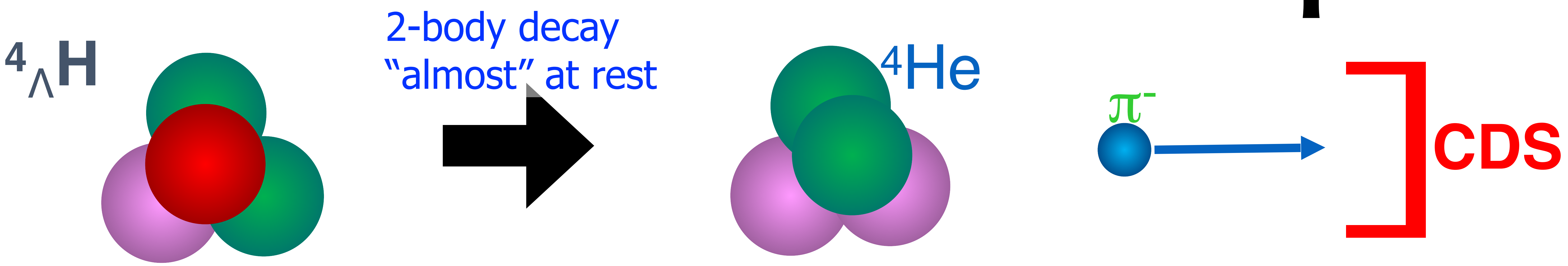
Crystal	Radiation length	Moliere radius	Density	Cost	Resolution	Signal length
PbF_2	0.93 cm	2.22 cm	7.77 g/cm^3	12 USD/cc	5%	2ns

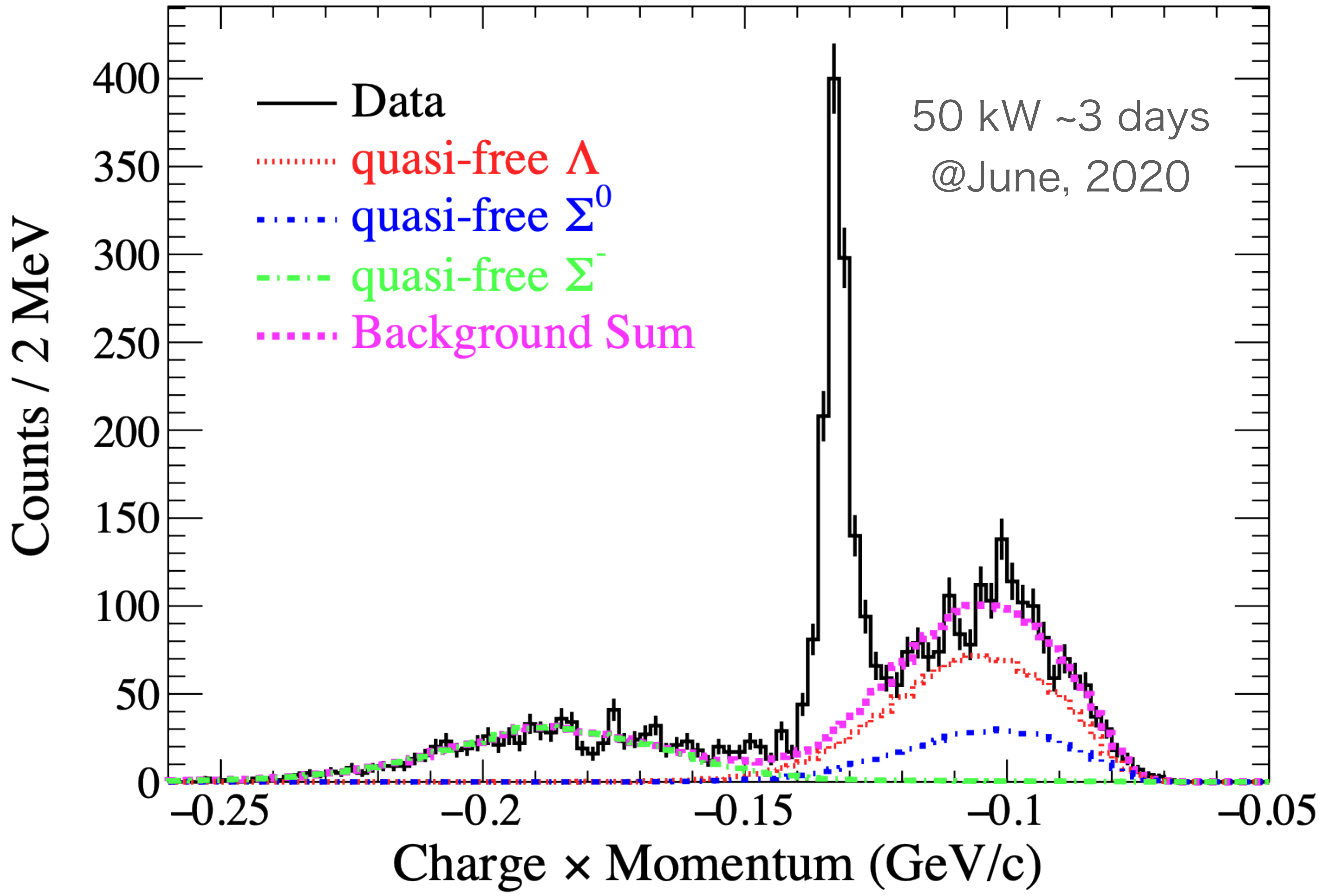
D.F. Anderson, *et al.*, Nucl. Inst. Meth. A290 (1990) 385
P. Achenbach, *et al.*, Nucl. Inst. Meth. A416 (1998) 357

T77/E73@K1.8BR

- ~ 2 x 10^5 K- /spill (~70% on target) @ 50 kW, -1.0 GeV/c
- K/pi ~ 0.4
- ~50 kW @ T77, 2020.6
- ~60 kW @ $E73_{1st}$, 2021.5

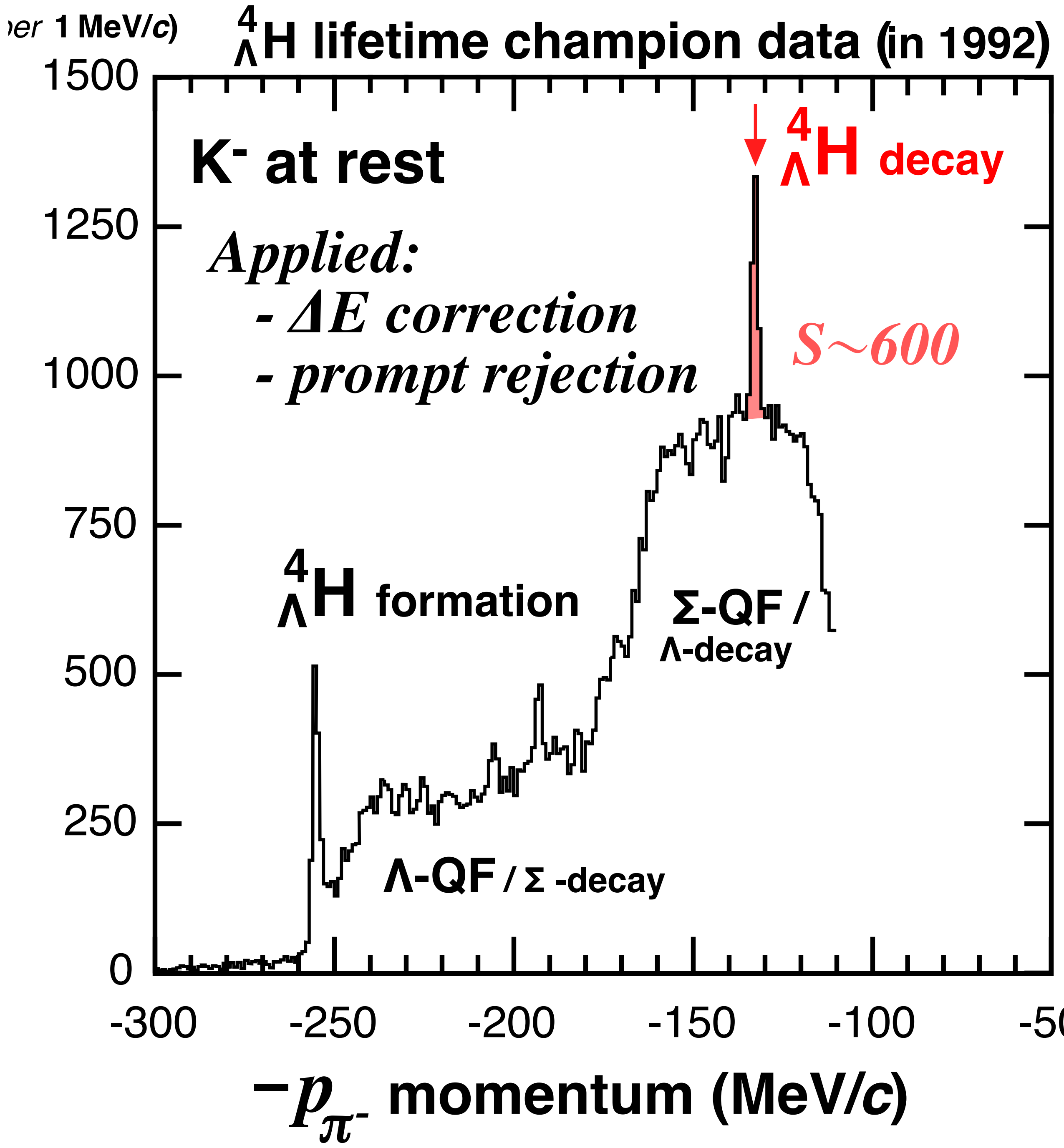
^{4}He data: Pion momentum spectrum





x2 peak count
x10 S/N

H. Outa, Nucl. Phys. A **585**, 109 (1995).



- H4L peak was clearly observed. 1 gamma tagging method is proved for the first time.
- Background is now well understood with quasi-free hyperon processes.

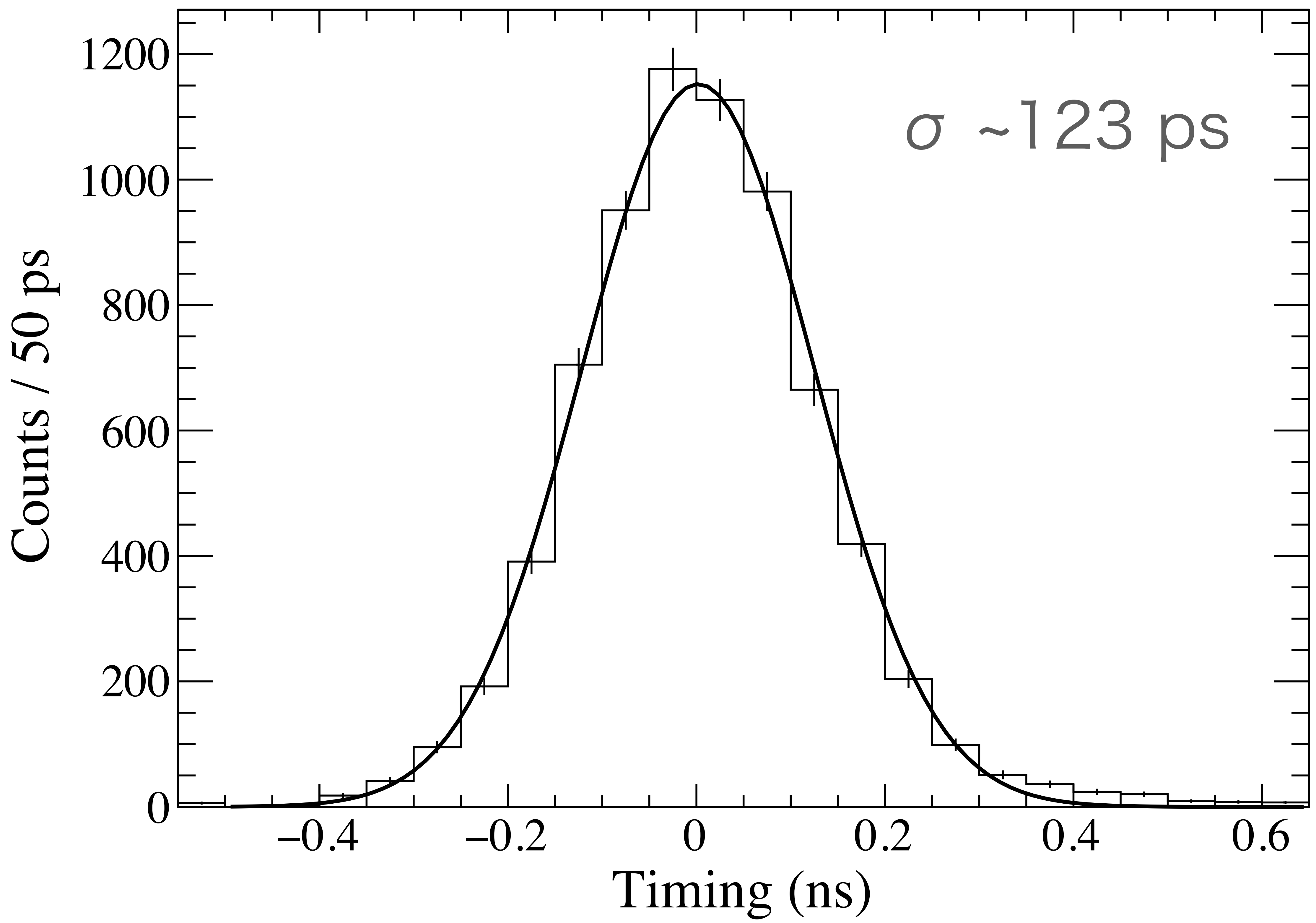
${}^4_\Lambda$H lifetime

arXiv:2302.07443

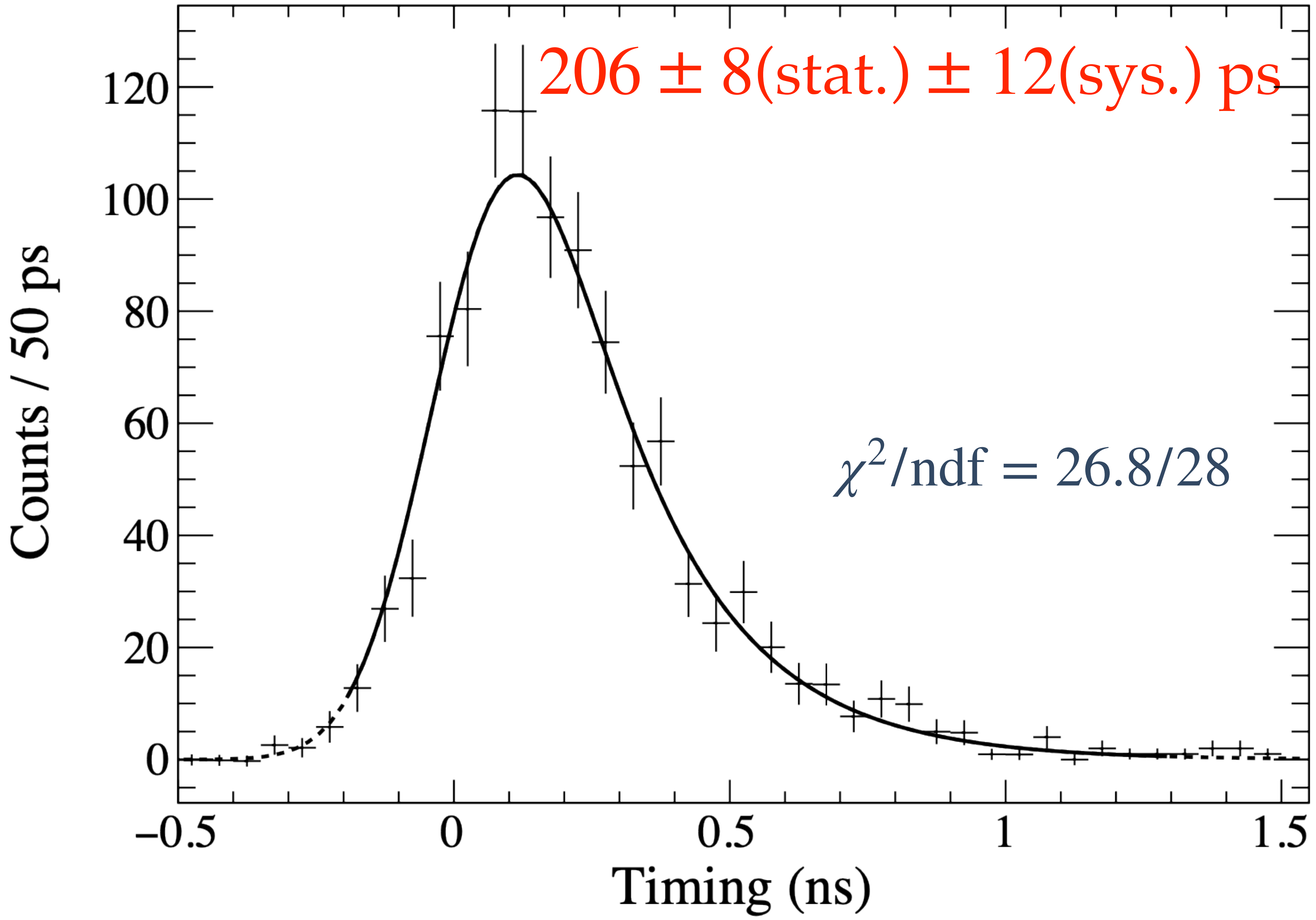
Systematic errors

Contribution	Value
Intrinsic bias of J-PARC T77 approach	±2 ps
Uncertainty from γ selection	±4 ps
Uncertainty of time calibration	±7 ps
Uncertainty of background subtraction	±5 ps
Uncertainty in fitting process	±7 ps
Total (quadratic sum)	±12 ps

(π^-, π^-) data for time-zero alignment



(K^-, π^-) data for H4L production



- Comparable presicion with the latest STAR data $(218 \pm 6(\text{stat.}) \pm 13(\text{sys.}))$

(doi.org/10.1103/PhysRevLett.128.202301)

Precise lifetime measurement of ${}^{4}_{\Lambda}$H hypernucleus using a novel production method★

T. Akaishi[a], H. Asano[b], X. Chen[c], A. Clozza[d], C. Curceanu[d], R. Del Grande[d], C. Guaraldo[d], C. Han[c], T. Hashimoto[e,*], M. Iliescu[d], K. Inoue[a], S. Ishimoto[f], K. Itahashi[b], M. Iwasaki[b], Y. Ma[b,*], M. Miliucci[d], R. Murayama[b], H. Noumi[a], H. Ohnishi[g], S. Okada[i], H. Outa[b], K. Piscicchia[d,j], A. Sakaguchi[a], F. Sakuma[b,*], M. Sato[f], A. Scordo[d], K. Shirotori[a], D. Sirghi[d,h], F. Sirghi[d,h], S. Suzuki[f], K. Tanida[e], T. Toda[a], M. Tokuda[a], T. Yamaga[b], X. Yuan[c], P. Zhang[c], Y. Zhang[c] and H. Zhang[k]

[a] Osaka University, Osaka, 567-0047, Japan
[b] RIKEN, Wako, 351-0198, Japan
[c] Institute of Modern Physics, Lanzhou, 730000, China
[d] Laboratori Nazionali di Frascati dell' INFN, I-0…
[e] Japan Atomic Energy Agency, T…
[f] High Energy …
…gurele, Romania
…tro Studi e Ricerche Enrico Fermi, 00184 Rome, Italy
…000, China

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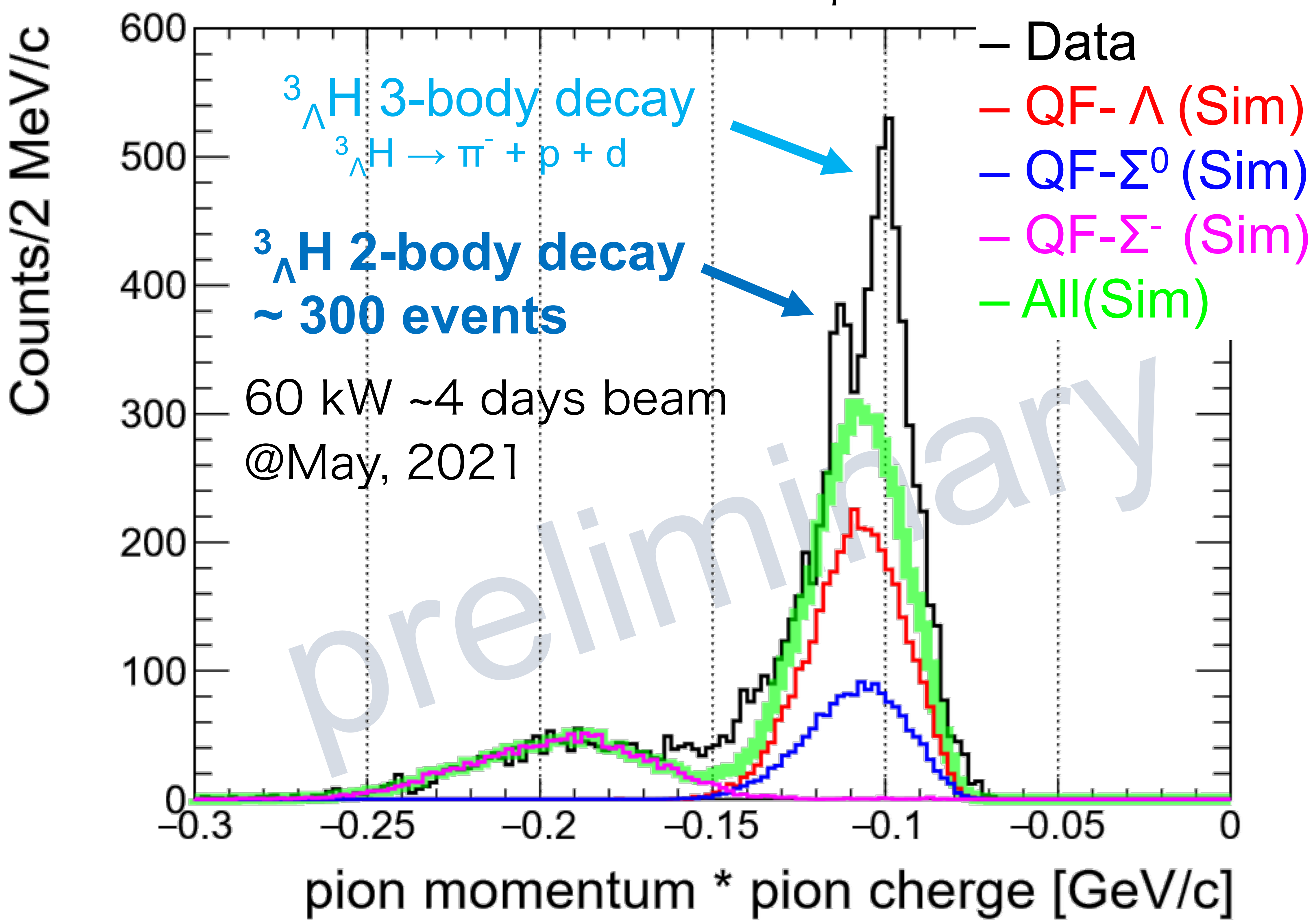
π^0 tagging
hypernuclear weak decay lifetime

ABSTRACT

We present a new measurement of the ${}^{4}_{\Lambda}$H hypernuclear lifetime using a novel production reaction, $K^- + {}^4\text{He} \rightarrow {}^{4}_{\Lambda}\text{H} + \pi^0$, at the J-PARC hadron facility. We demonstrate, for the first time, the effective selection of the hypernuclear bound state using only the γ-ray energy decayed from π^0. This opens the possibility for a systematic study of isospin partner hypernuclei through comparison with data from (K^-, π^-) reaction. As the first application of this method, our result for the ${}^{4}_{\Lambda}$H lifetime, $\tau({}^{4}_{\Lambda}\text{H}) = 206 \pm 8(\text{stat.}) \pm 12(\text{syst.})$ ps, is one of the most precise measurements to date. We are also preparing to measure the lifetime of the hypertriton (${}^{3}_{\Lambda}$H) using the same setup in the near future.

^{3}He test data

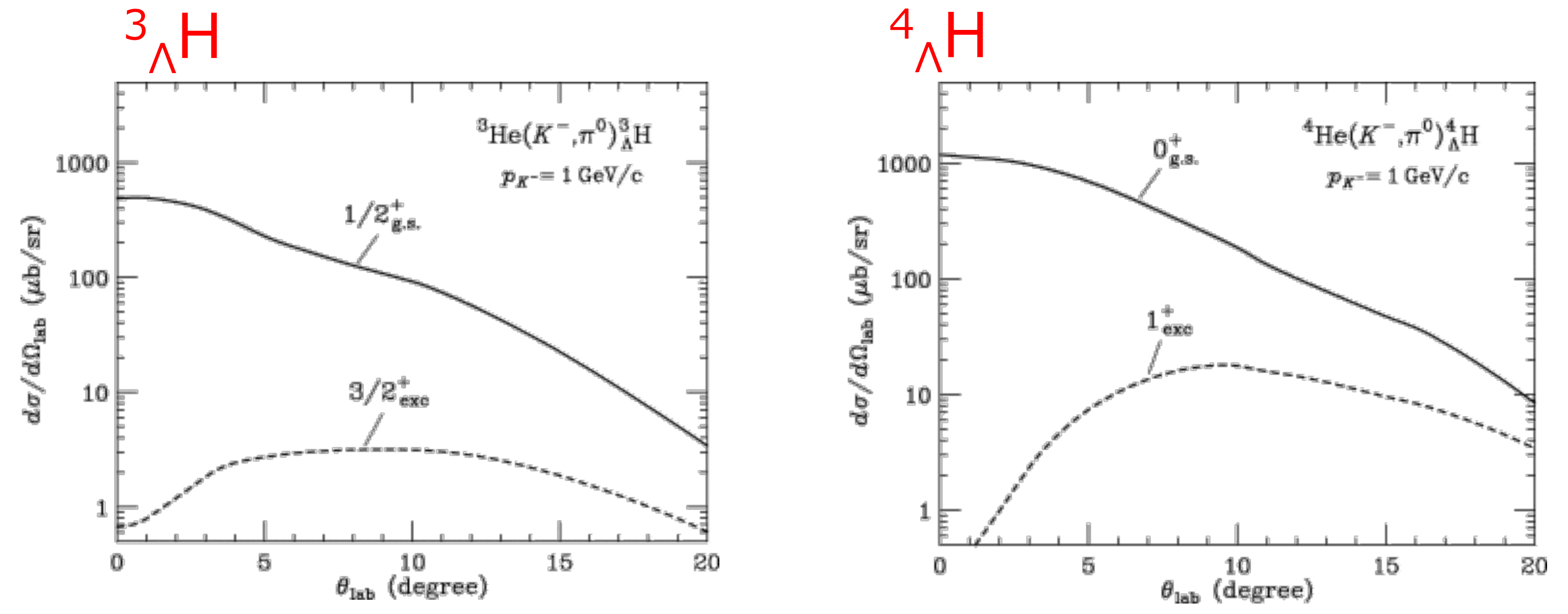
T. Akaishi @ HYP2022 poster session



Ratio of production cross section

- Theoritical calcluaction(DWIA)

T. Harada and Y. Hirabayashi, Nuclear Physics A 1015 (2021) 122301



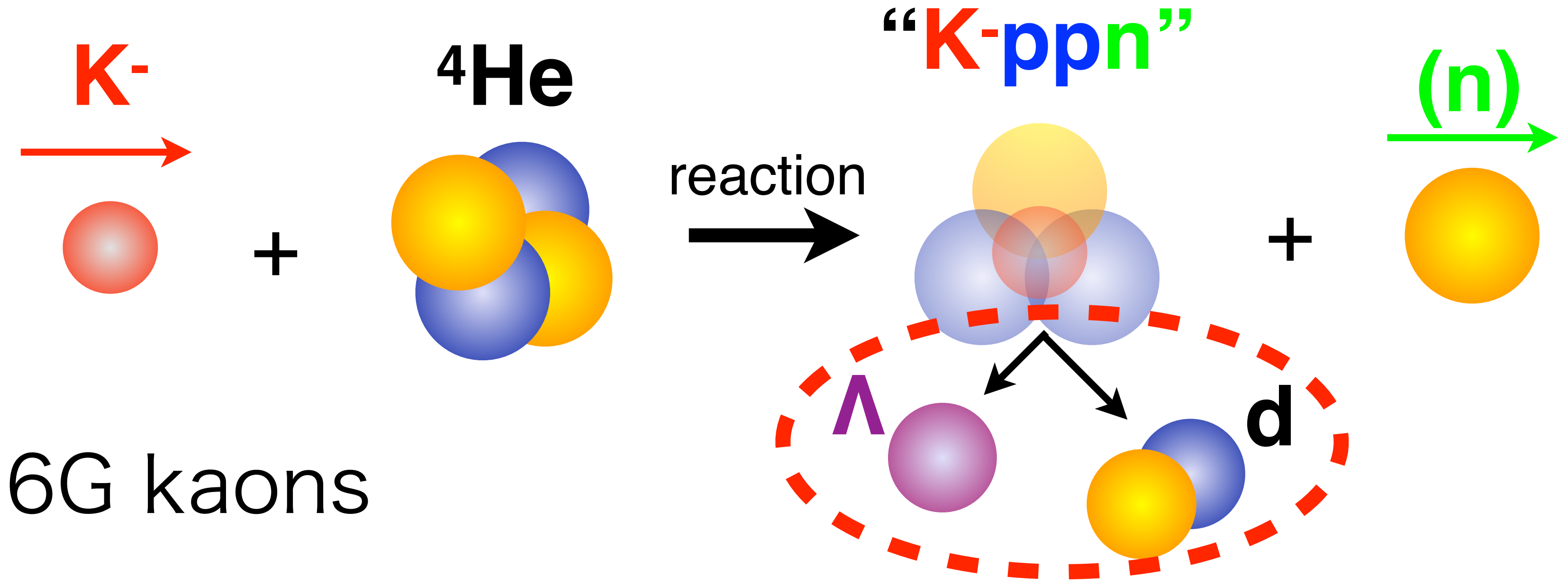
$R = \sigma_{lab}(^{3}_{\Lambda}H)/\sigma_{lab}(^{4}_{\Lambda}H)$

$R \sim 0.3$—0.4 @ $B_{\Lambda}=0.13$ MeV(Emulsion), ~ 0.65 @ $B_{\Lambda}=0.41$ MeV(STAR)

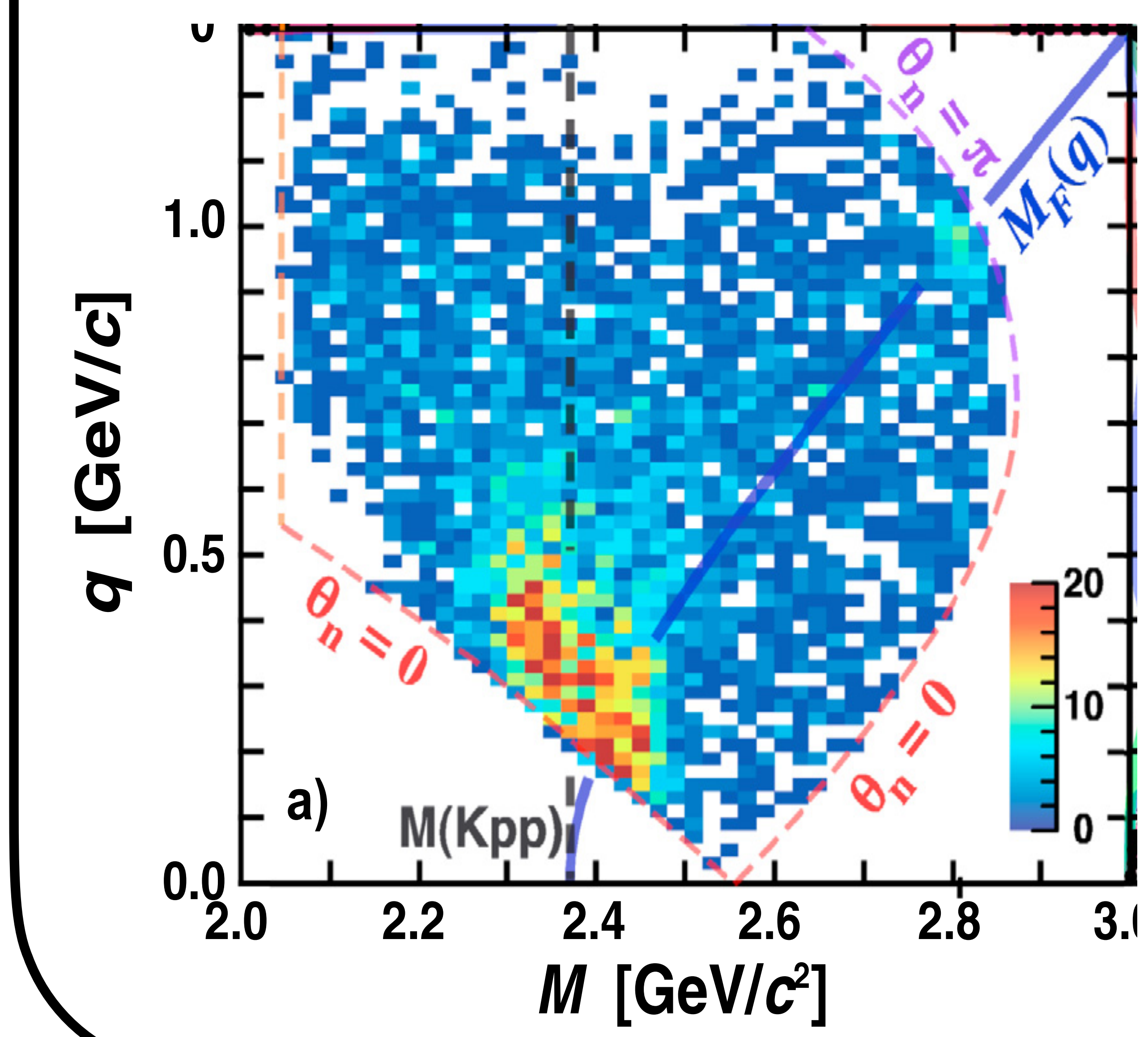
→provides a better understanding of the structure of the $^{3}_{\Lambda}H$ bound states

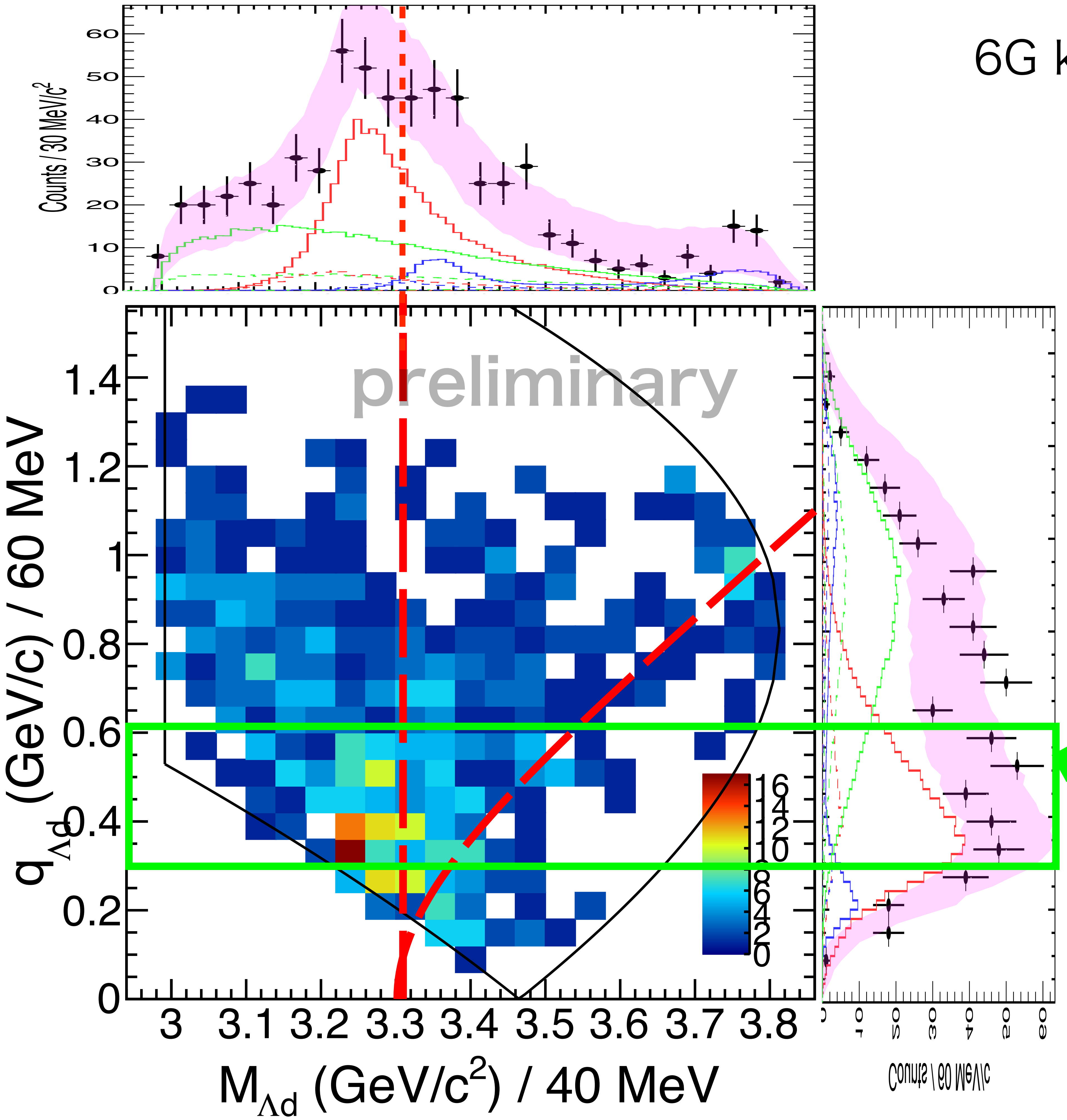
- Successfully observed the peak from 2 body decays.
- $^{3}_{\Lambda}H$ Cross section sensitive to the binding energy of $^{3}_{\Lambda}H$.
- 3-body decays are also observed. could be used for the lifetime evaluation.

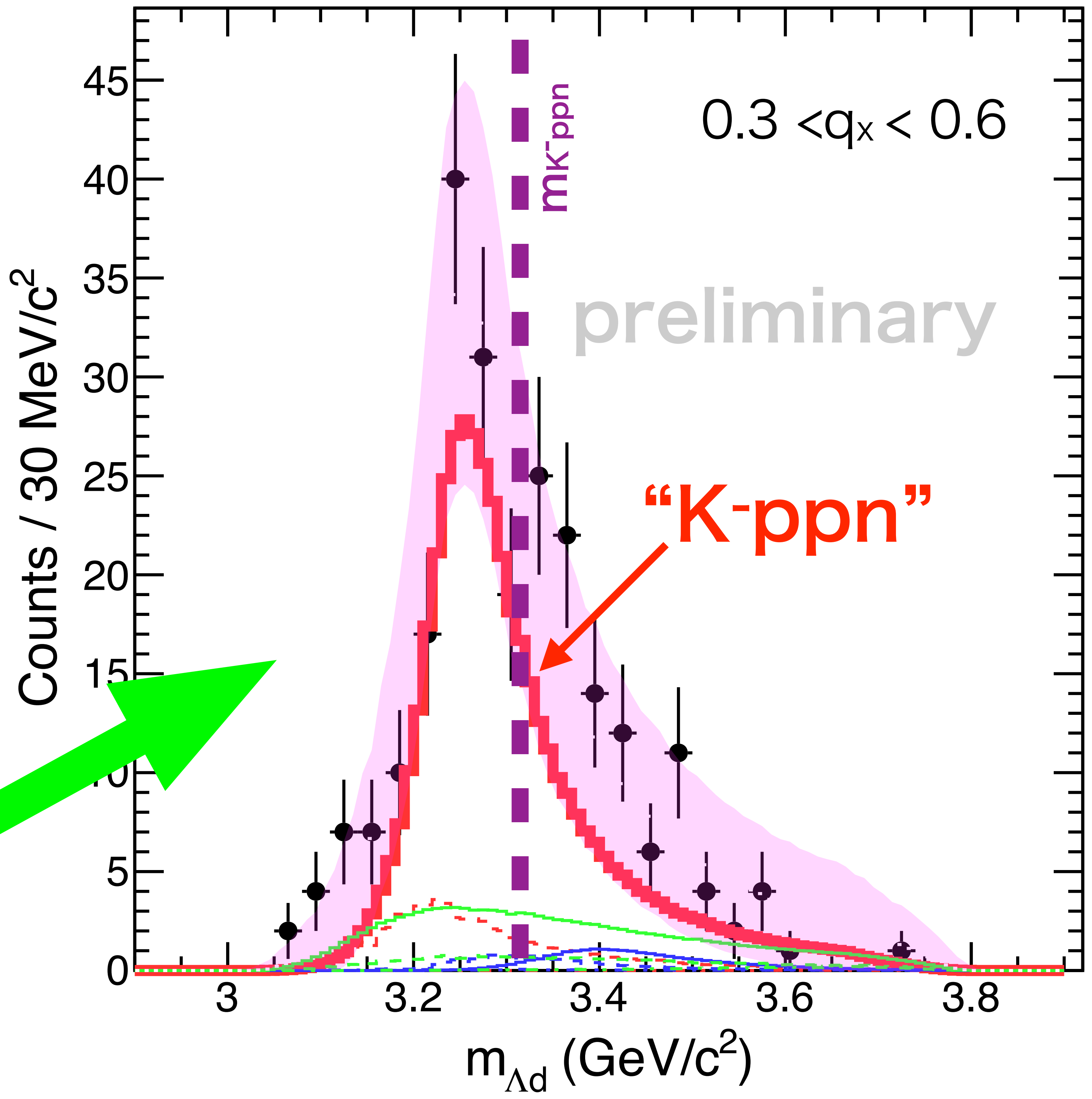
“KbarNNN” in ^{4}He data



Λp system in E15 data
42G kaons
PLB789(2019)620







$B_{\bar{K}NNN} \sim xx \pm 11(\mathrm{stat})$ MeV

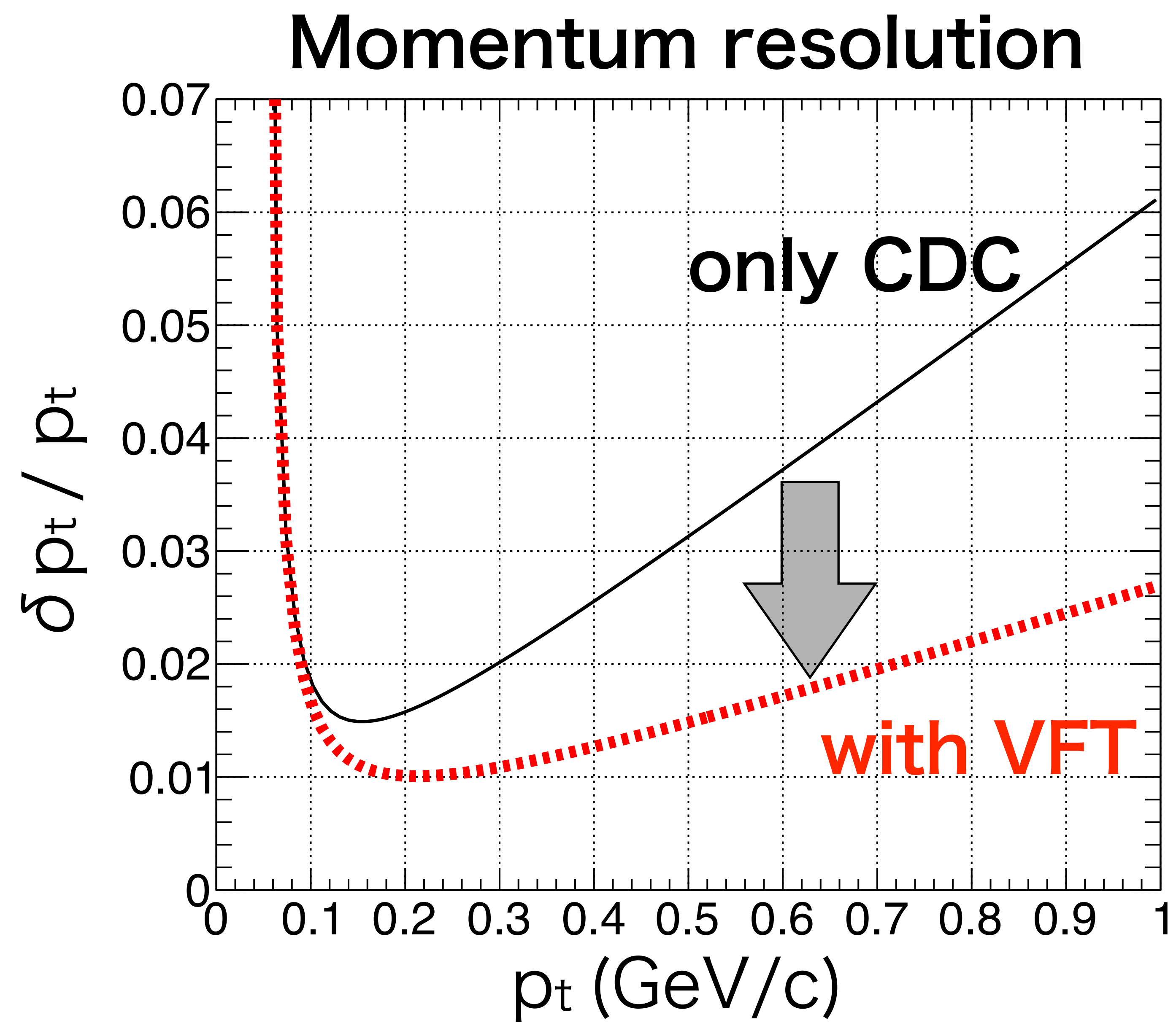
$\Gamma_{\bar{K}NNN} \sim 100$ MeV

$\sigma_{\bar{K}NNN \to \Lambda d} \sim 4\ \mu$b

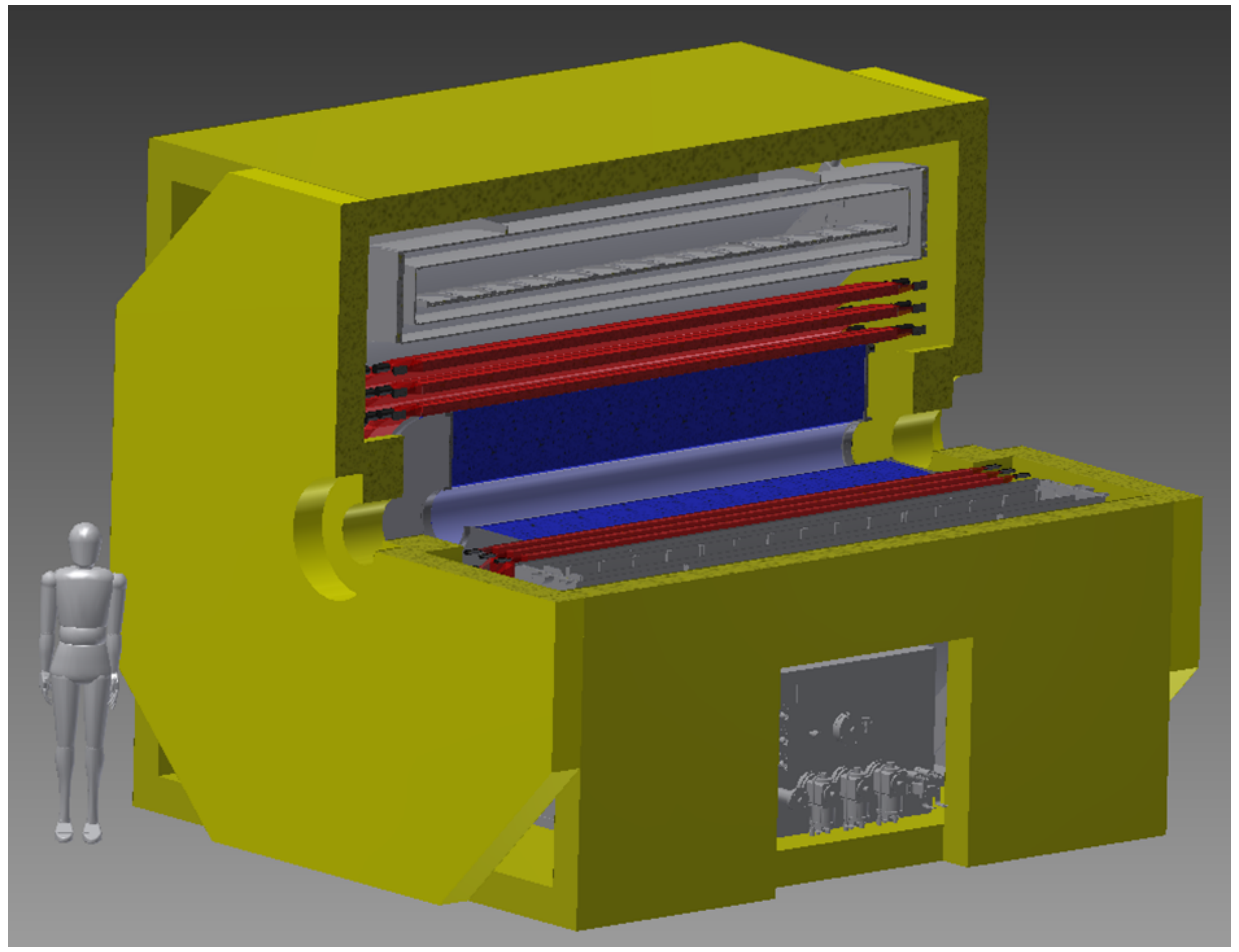
Λd data looks similar to Λp

Status & Outlook

- 2020.6: Feasibility demonstration with Helium-4
  - lifetime paper will appear soon
- 2021.5/6: Cross section measurement with Helium-3
  - Analysis is almost finalized (T. Akaishi Ph.D thesis)
- Now: waiting for the beamtime allocation
  - Lifetime measurement of $^{3}_{\Lambda}\mathrm{H}$ (>1000 events in 25 days) in 2023/24?
  - Vertex detector (VFT) will be installed **using Koubo budget**
    - UU'VV'(45 degrees) spiral 4 layers around the target
    - final assembly is ongoing at the "M-line" company
- 2026~: start experiment with a new solenoid spectrometer



Conceptual design of new CDS



M. Iwasaki (RIKEN) 特別推進 JFY2022—2026

Summary

- Hypertriton provides a benchmark for hypernuclear physics.
- We have explored a new method to investigate the neutron-rich hypernuclei with K^- beam & gamma-ray tagging
  - Lifetime with highest precision and different systematics from HI experiments
    τ ($^4{}_\Lambda$H) : 206 ± 8(stat.) ± 12(syst.) ps → arXiv:2302.07443
  - lifetime of $^3{}_\Lambda$H will be measured in 2023/24: ~20 (stat.), < 20 (syst.) ps
  - Cross section (x Branching ratio) of $^4{}_\Lambda$H, $^3{}_\Lambda$H
- Kaonic nucleus can be studied using the same dataset: "K^{bar}NNN" signals !
- New larger solenoid spectrometer will provide further oppotunities.