

2025年度新博士修士講演会・祝賀会

崩壊パイ中間子分光法 による s殻ラムダハイパー核の 質量測定実験

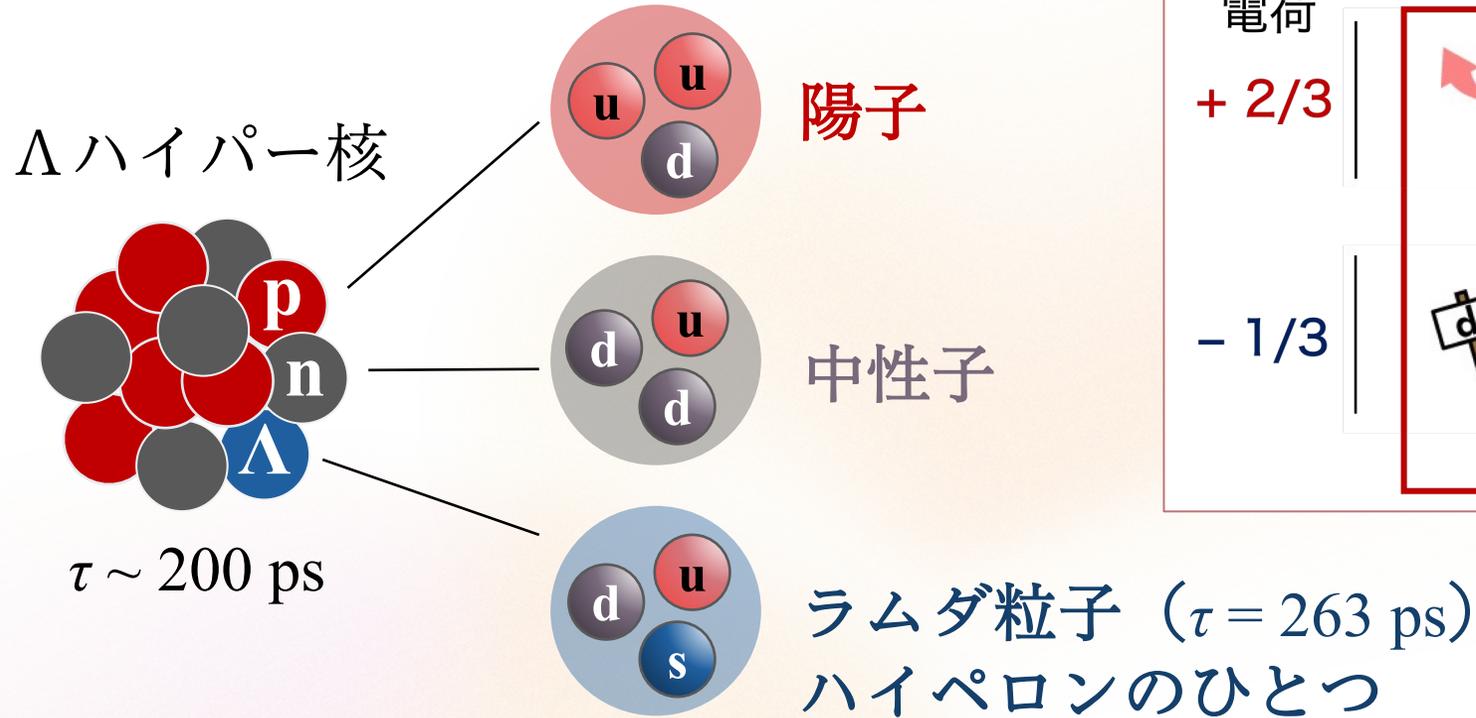
Mass Measurement of s-shell Lambda Hypernuclei
via Decay Pion Spectroscopy

木野 量子 (原子核物理研究室)



Introduction

ハイパー原子核とは



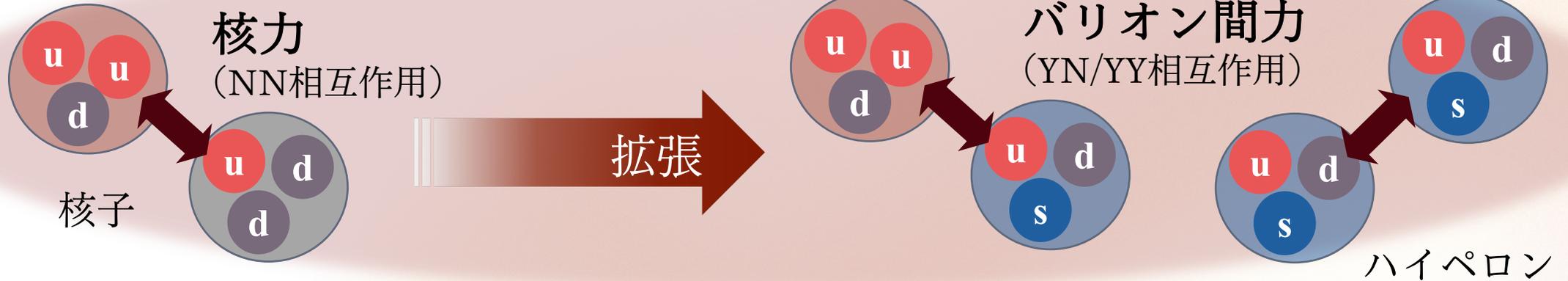
クォーク Quarks		スピン 1/2		
higgstan.com				
電荷	+ 2/3	 up 2.6	 charm ~1270	 top ~170000
	- 1/3	 down 4.9	 strange 104	 bottom ~4200

質量
(MeV/c²)

$${}_{\Lambda}^{12}\text{C} = \text{p 陽子} \times 6\text{個} + \text{n 中性子} \times 5\text{個} + \text{Λ ラムダ粒子} \times 1\text{個}$$

ハイパー原子核の物理

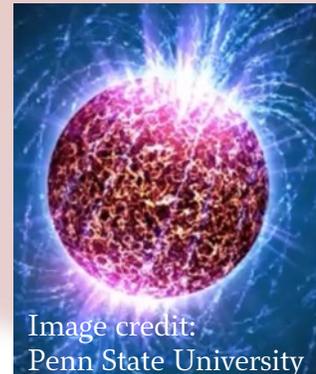
拡張した核力の統一的理解



核構造の理解



重い中性子星の謎

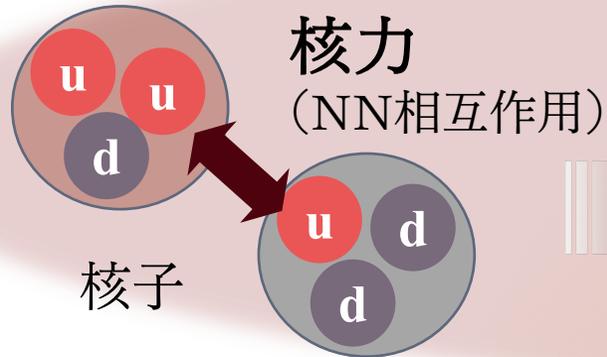


内部にハイペロン出現

ハイパー核
= 中性子星のミニチュア

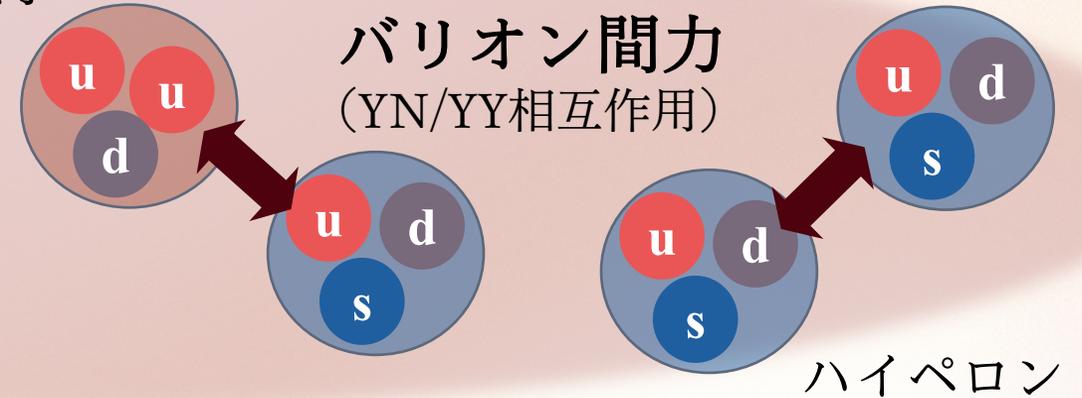
ハイパー原子核の物理

拡張した核力の統一的理解

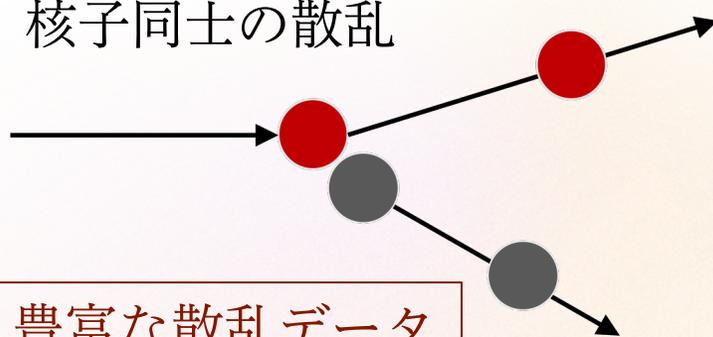


拡張

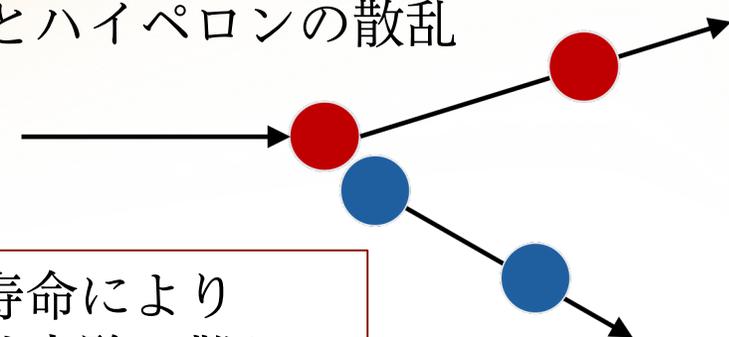
核子



核子同士の散乱



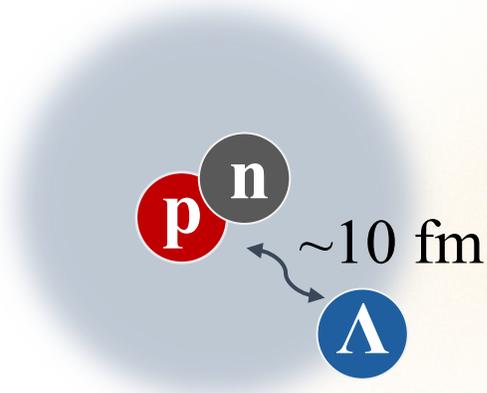
核子とハイペロンの散乱



ハイパートライトン

- [1] M. Juric, Nucl. Phys. B 52, 1 (1973) 1-30.
- [2] H. Kamada *et al.*, PRC 57, 4 (1998)
- [3] STAR Science 328 (2010) 58

${}^3_{\Lambda}\text{H}$ (三重水素 Λ ハイパー核) : **最もシンプル**なラムダハイパー核



S波が支配的
→ B_{Λ} はYN相互作用の
低エネルギーパラメータに敏感

Λ 束縛エネルギー: $B_{\Lambda} \sim 130 \text{ keV}^{[1]}$

$$(B_{\Lambda} = m_{\text{core}} + m_{\Lambda} - m({}^A_{\Lambda}Z))$$

→ RMS半径 $\sim 10 \text{ fm}$

$$\sqrt{\langle r^2 \rangle} \simeq \frac{\hbar}{\sqrt{4\mu B_{\Lambda}}}$$

ハイパートライトン
= ハイパー核物理における
ベンチマーク

ハイパートライトンパズル

- [1] M. Juric, Nucl. Phys. B 52, 1 (1973) 1-30.
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${}^3_{\Lambda}\text{H}$ (三重水素 Λ ハイパー核) : **最もシンプル**なラムダハイパー核



Λ 束縛エネルギー: $B_{\Lambda} \sim 130 \text{ keV}^{[1]}$

寿命: $\sim 150 \text{ ps}^{[3]}$

(典型的な Λ ハイパー核: 200 ps)

非常に弱い束縛

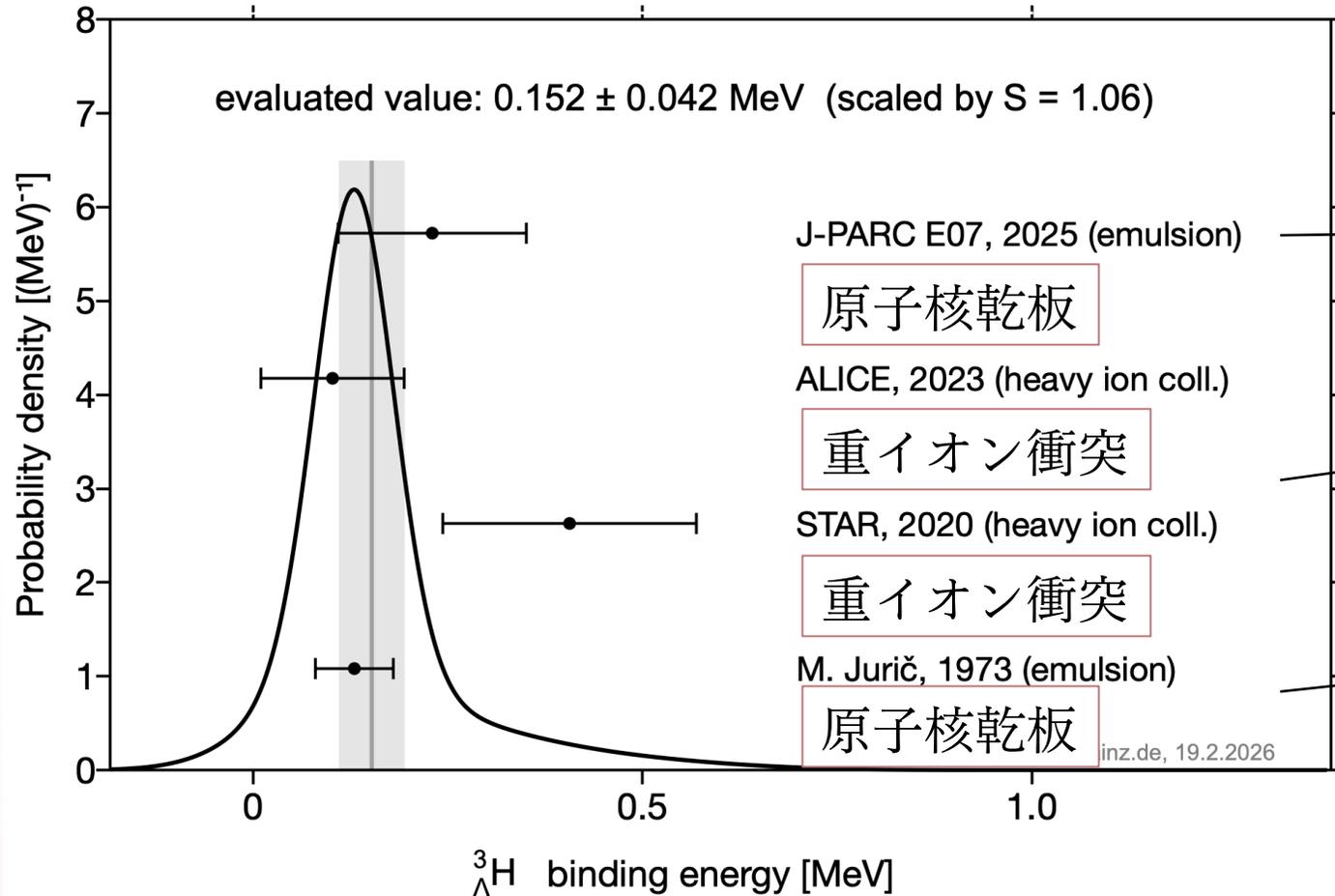
→ 自由空間のラムダ粒子と同程度の寿命?

(Fadeev計算: $\tau = 0.97\tau_{\Lambda} \sim 260 \text{ ps}^{[2]}$)



大きな矛盾!!
小さい B_{Λ} vs 短い寿命 τ

World data of hypertriton B_{Λ}



Hypernuclear database
(<https://hypernuclei.kph.uni-mainz.de/>)

近年系統誤差の評価が改善

重イオン衝突実験同士で
4倍の差

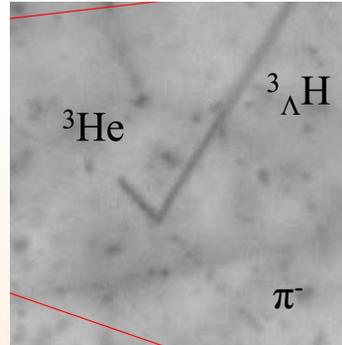
約75%が1970年台までの
原子核乾板データ

“直接”分光実験が重要
→ 「崩壊 π 中間子分光法」

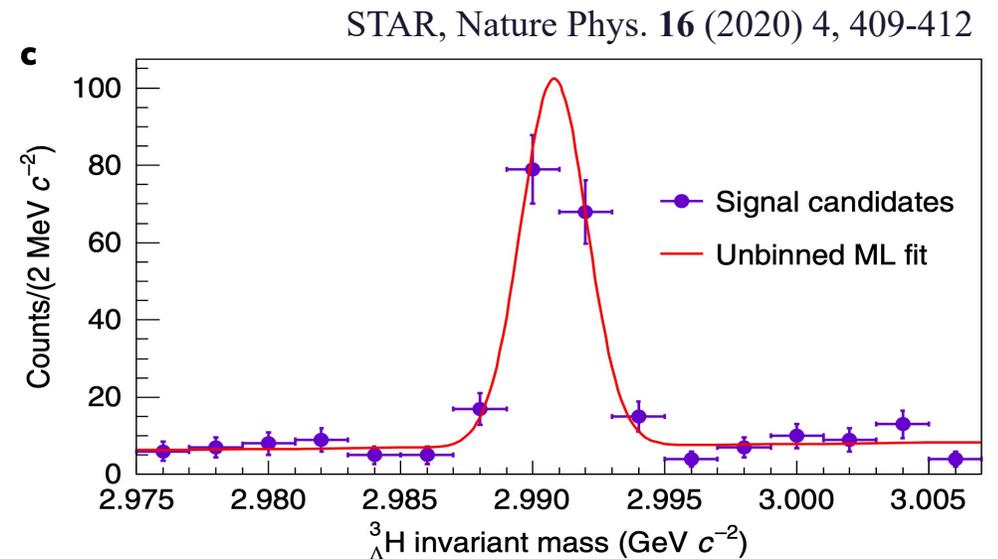
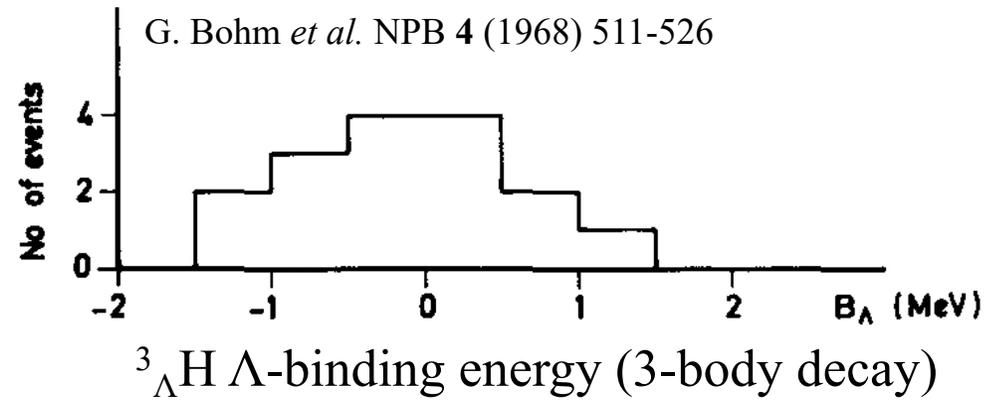
B_Λ の主な測定手法

- 原子核乾板
 - 飛跡の長さ→運動量に変換
 - $\delta B_\Lambda =$ 数10 – 数100 keV
- 重イオン衝突
 - 崩壊粒子→不変質量を再構成
 - $\delta B_\Lambda =$ 数10 – 数100 keV
- $(e, e'K^+)$ 反応質量分光
 - 欠損質量を再構成
 - $\delta B_\Lambda =$ 数10 – 数100 keV

- 崩壊 π 中間子分光法
 - $\delta B_\Lambda < 100$ keV



PTEP 2025, 8 (2025) 083D01

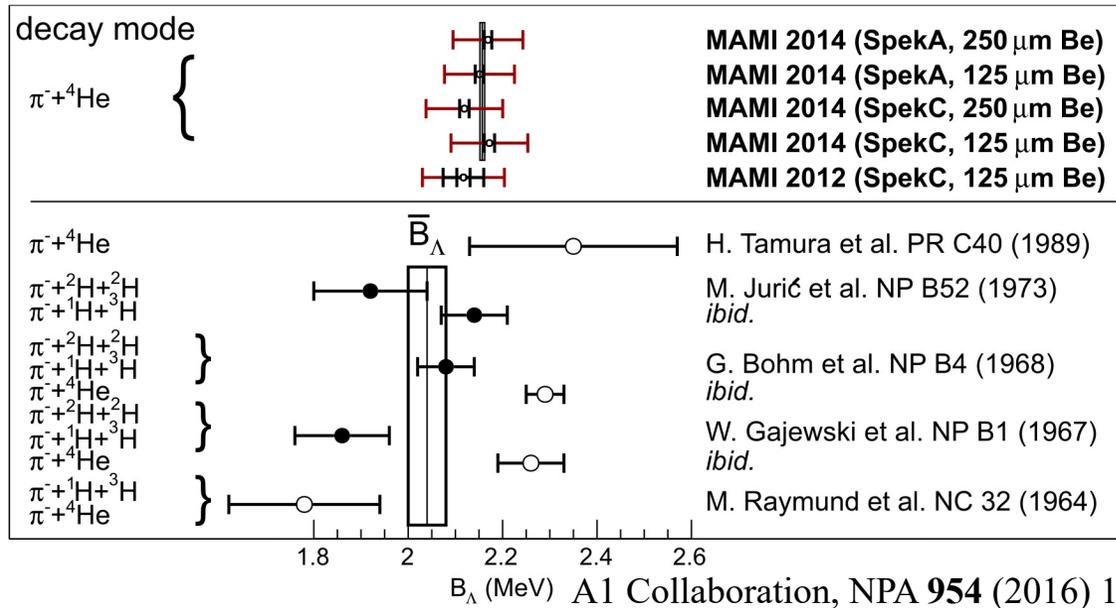


Previous experiment of Decay pion spectroscopy

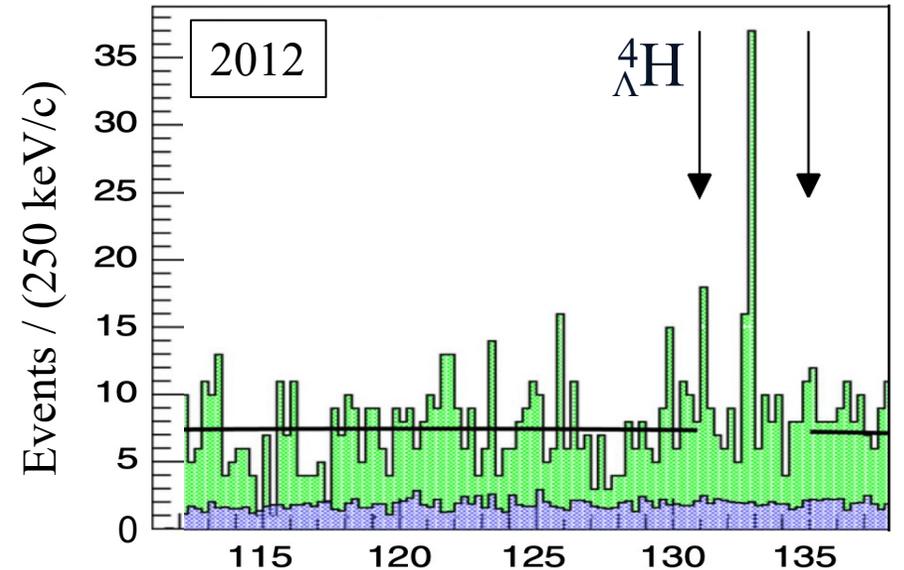
➤ ${}^4_{\Lambda}\text{H}$ の測定結果

$$B_{\Lambda} = 2.12 \pm 0.01 \text{ (stat.)} \pm 0.09 \text{ (syst.) MeV} \quad (2012)$$

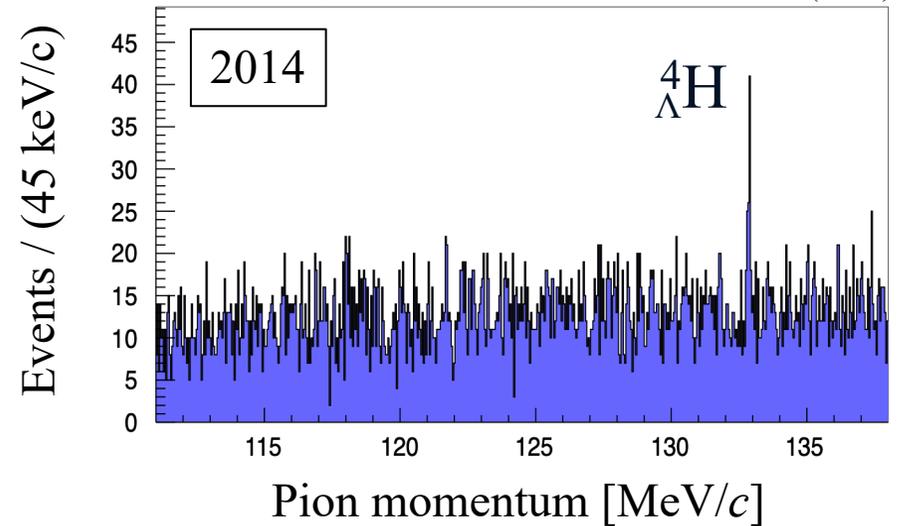
$$B_{\Lambda} = 2.157 \pm 0.005 \text{ (stat.)} \pm 0.077 \text{ (syst.) MeV} \quad (2014)$$



A. Esser, S. Nagao *et al.*, PRL **114** (2015) 232501.



F. Schulz, Doctoral thesis, J.G. Univ. of Mainz (2015)



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$$B_{\Lambda} = 2.157 \pm 0.005 \text{ (stat.)} \pm \mathbf{0.077} \text{ (syst.) MeV} \quad (2014)$$

➤ 二体崩壊における π 運動量:

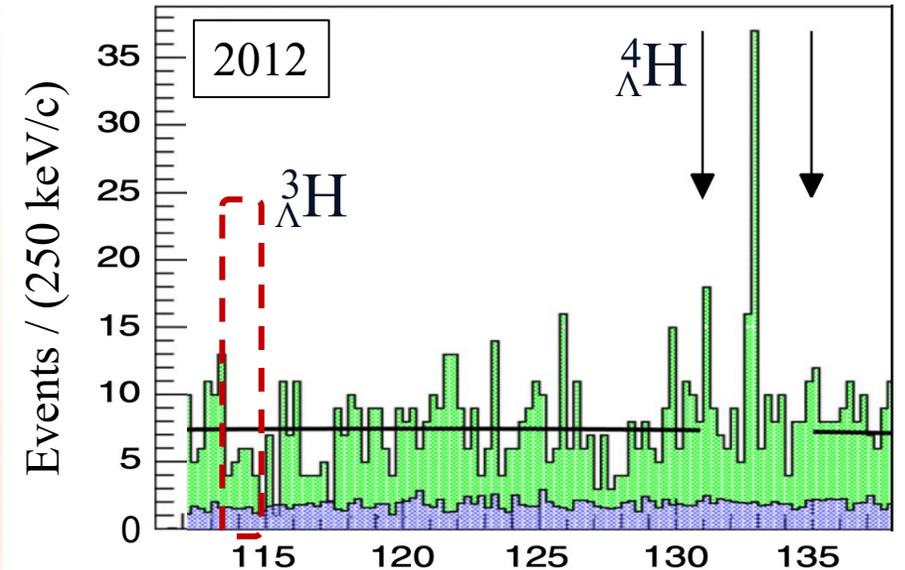
$${}^3_{\Lambda}\text{H} \rightarrow {}^3\text{He} + \pi^{-} @ 114 \text{ MeV}/c$$

$${}^4_{\Lambda}\text{H} \rightarrow {}^4\text{He} + \pi^{-} @ 133 \text{ MeV}/c$$

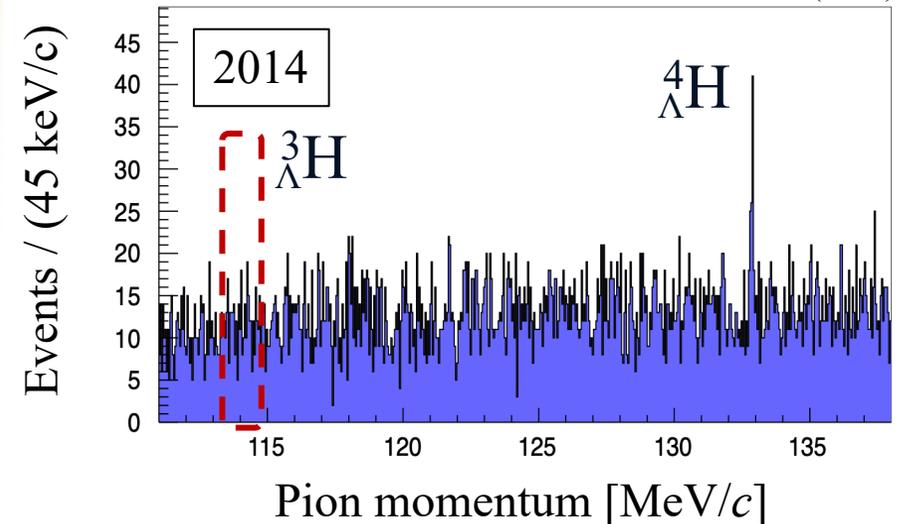
We need to...

- Increase the yield of ${}^3_{\Lambda}\text{H}$
- Suppress systematic errors

A. Esser, S. Nagao *et al.*, PRL **114** (2015) 232501.



F. Schulz, Doctoral thesis, J.G. Univ. of Mainz (2015)



Previous experiment of Decay pion spectroscopy

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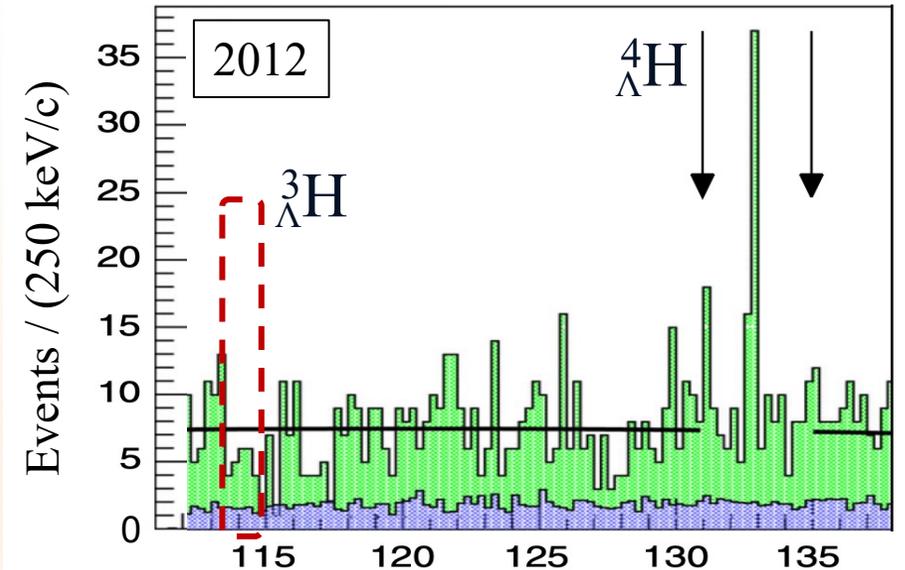
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F. Schulz, Doctoral thesis, J.G. Univ. of Mainz (2015)



New experiment

❑ Increase the yield of ${}^3_{\Lambda}\text{H}$



The new Lithium target system

❑ Suppress systematic errors



High-precision beam energy measurement

Experiment

MAMIにおける弱崩壊 π 中間子分光 = Mainz-Microtron

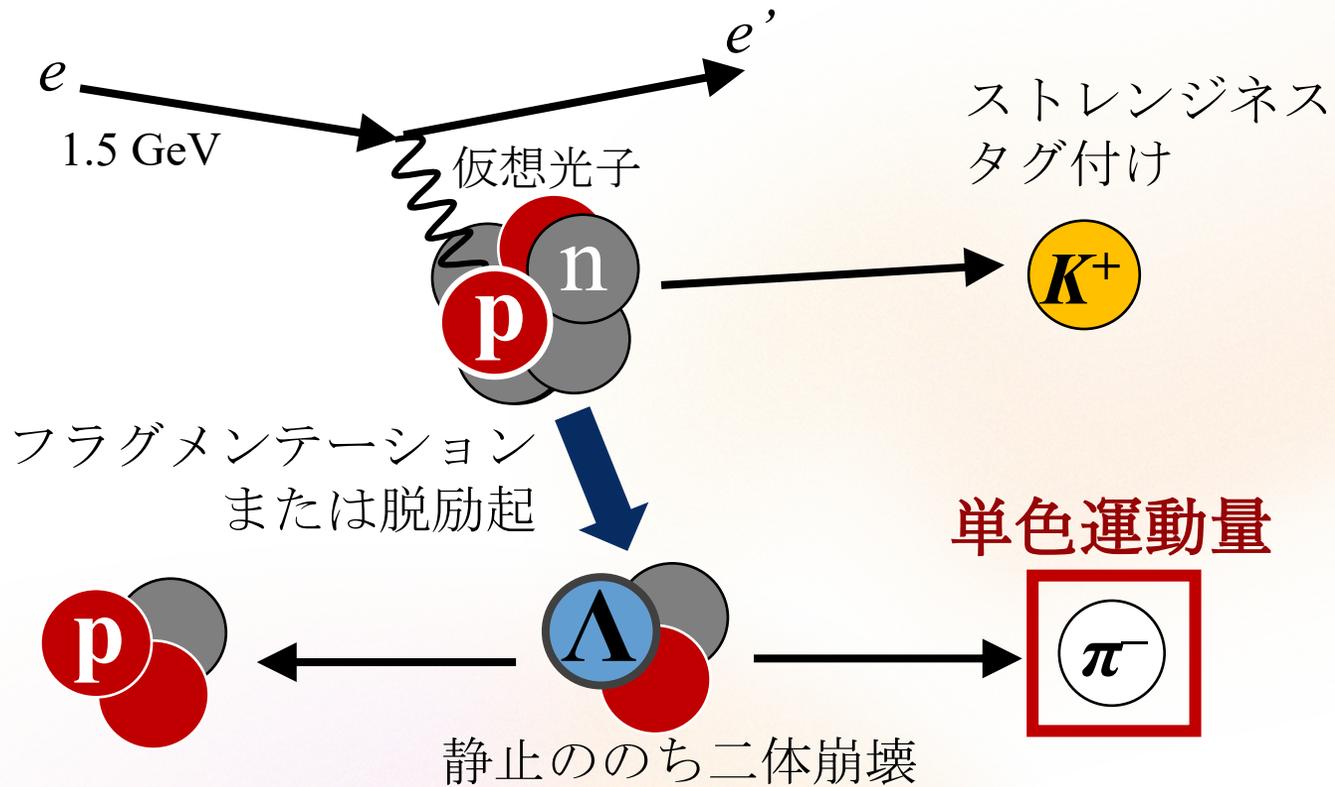
Mainz



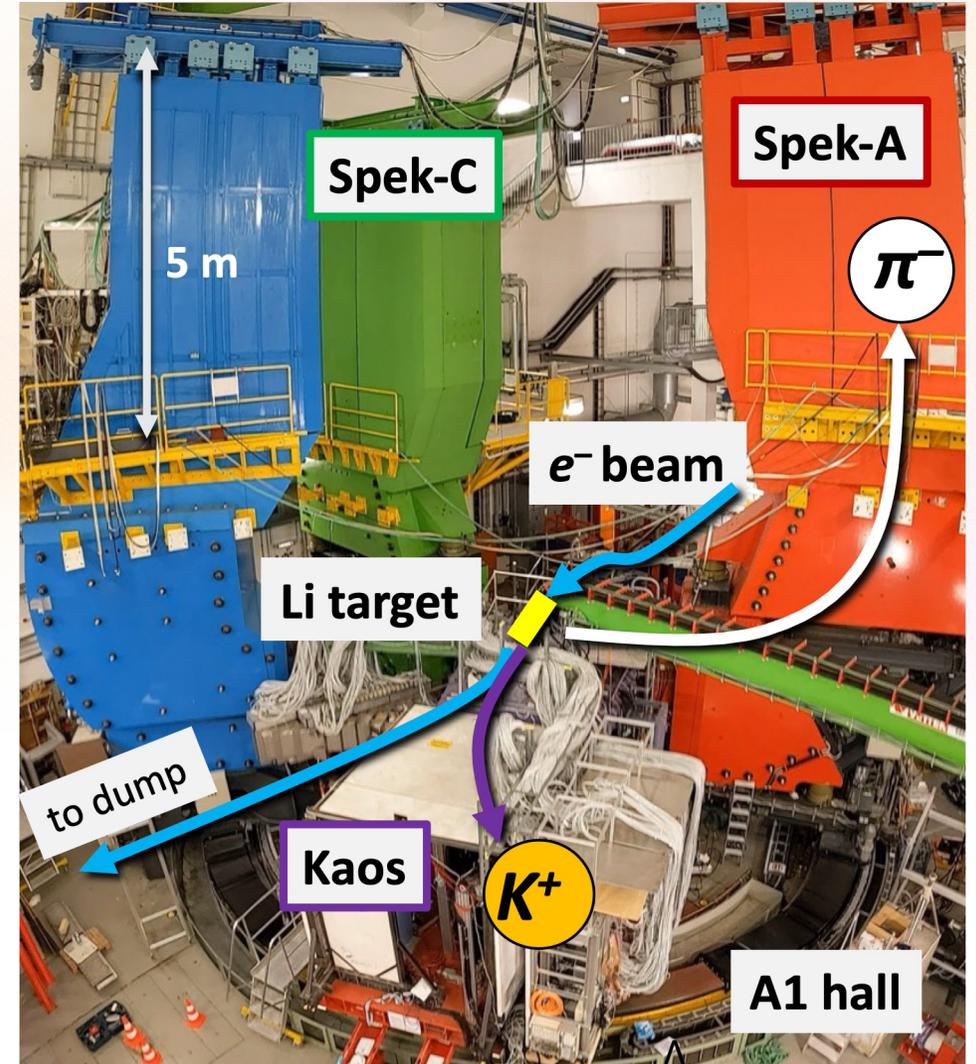
Johannes Gutenberg University, Mainz



Decay pion spectroscopy at MAMI



$$m(\Lambda^A Z) = \sqrt{m(\Lambda^A (Z+1))^2 + p_\pi^2} + \sqrt{m_\pi^2 + p_\pi^2}$$



New Lithium target design

➤ From Beryllium to Lithium

➤ **Less background** as ${}^9\text{Be}$

No hyper-helium with similar decay pion momenta:

${}^8_{\Lambda}\text{He}$: 116.47 [MeV/c]

(${}^3_{\Lambda}\text{H}$: 114.3 MeV/c)

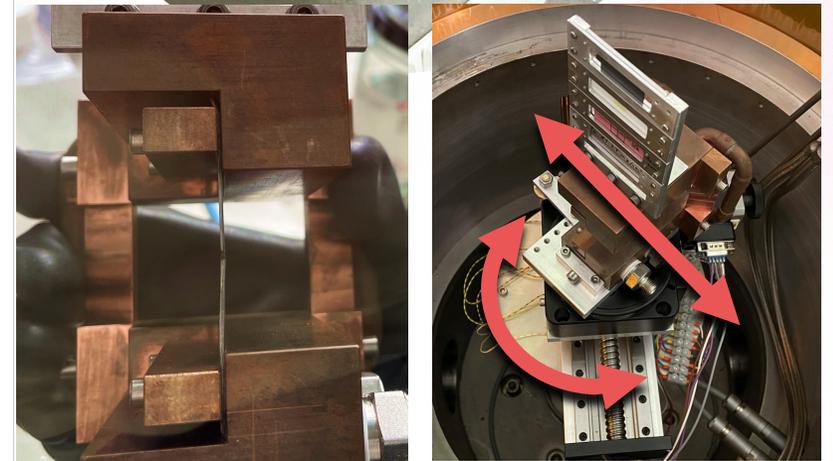
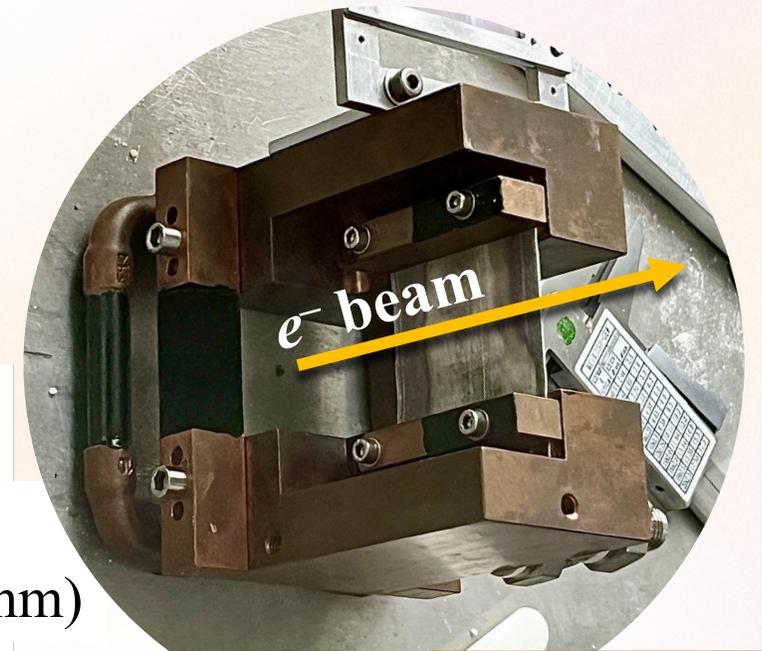
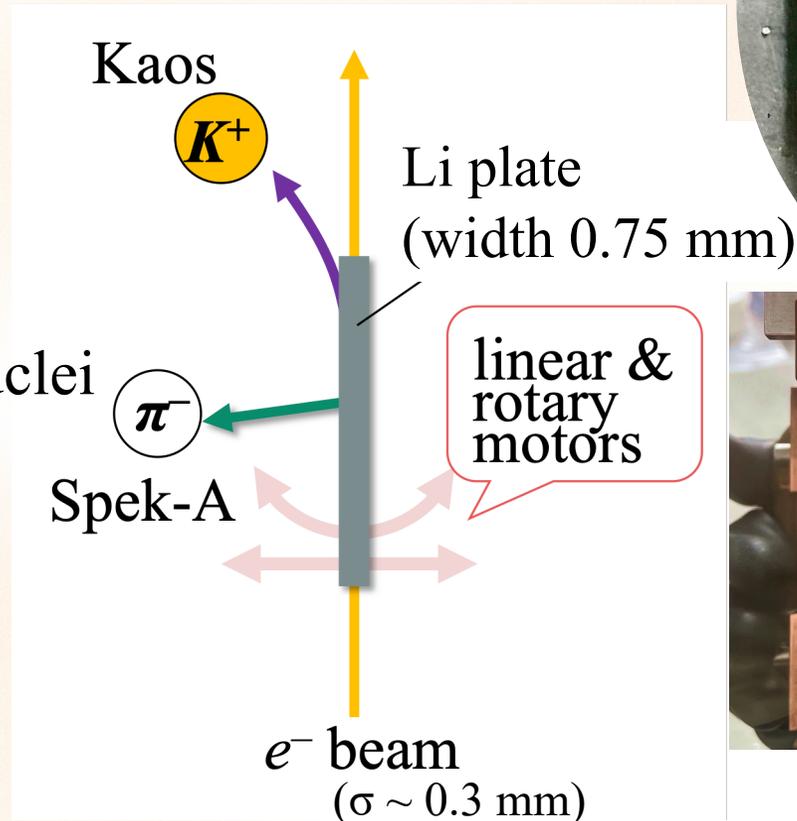
➤ **Maximized rate** of hypernuclei

Beam direction – 45 mm long

${}^9\text{Be}$ 27mg/cm², ~40 μA

↓ ~100 times thicker

${}^7\text{Li}$ **2403** mg/cm², ~1 μA



Spectrometer momentum calibration

Spectrometer momentum calibration
Established elastic electron scattering

➤ Relative resolution: 2×10^{-4}

Momentum difference
(p_m : measured value)

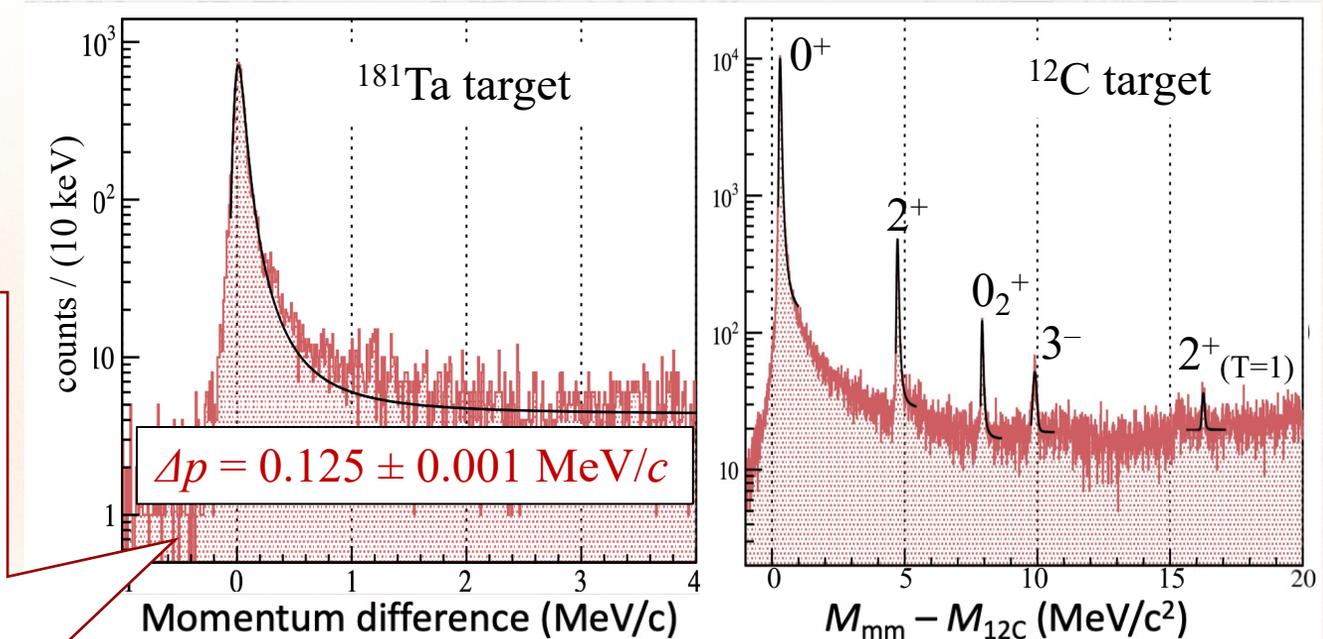
$$= p_{\text{calc}} - p_m$$

$$\approx \frac{E_b}{1 + E_b/M_t(1 - \cos \theta_m)} - p_m \quad (m_e^2 \ll 1)$$

e^- beam energy;
 ± 160 keV uncertainty



systematic error of $B_{\Lambda}({}^4\text{H})$
 $= 77$ keV (2016)



For low energy measurement with high accuracy
($\Delta E/E \sim 18$ keV/195 MeV)



Undulator interference method

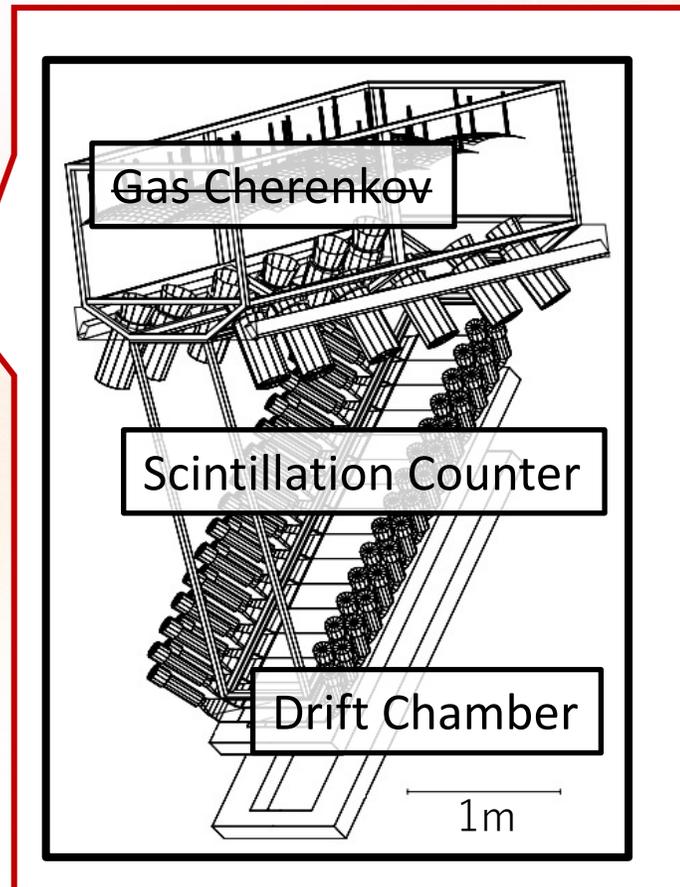
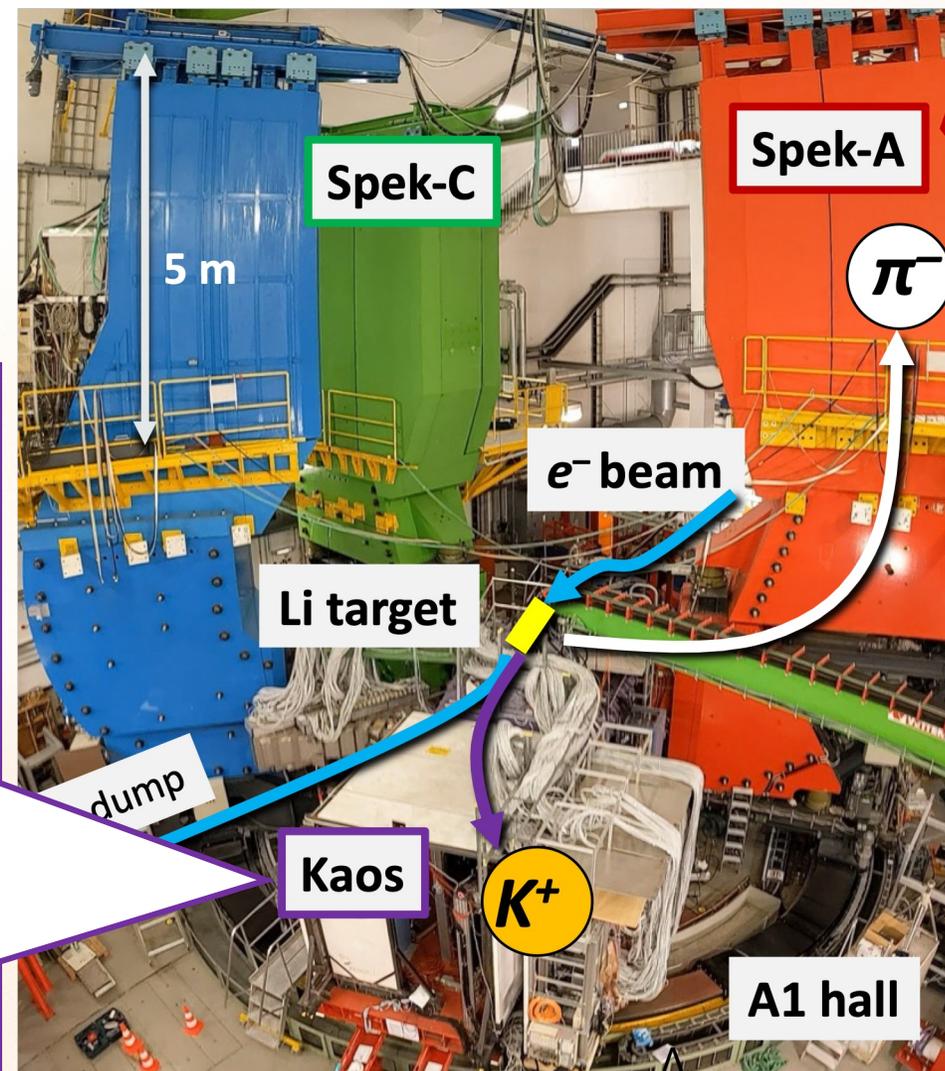
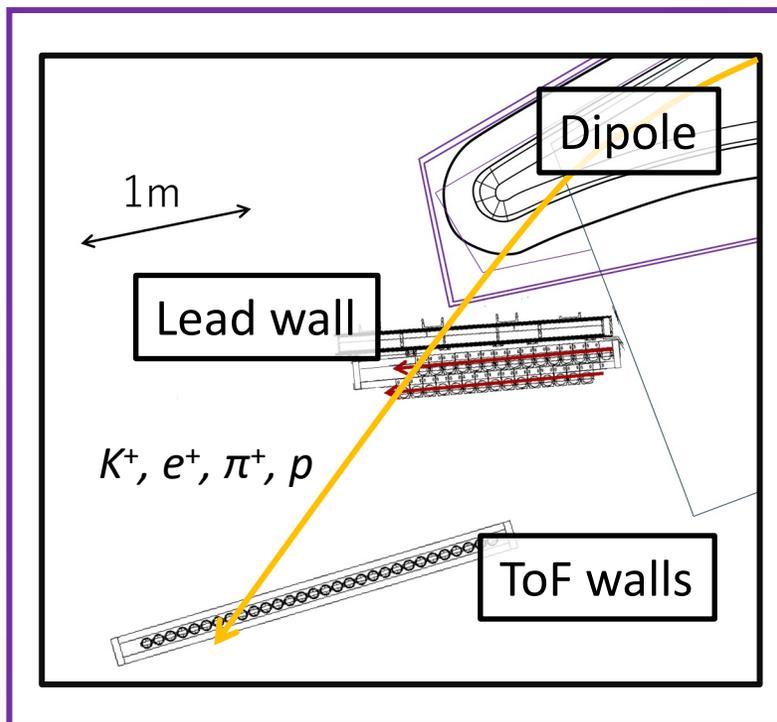
Analysis

Analysis procedure

Kaon tagger

① 粒子識別

→ ストレンジネス
生成イベントを選ぶ



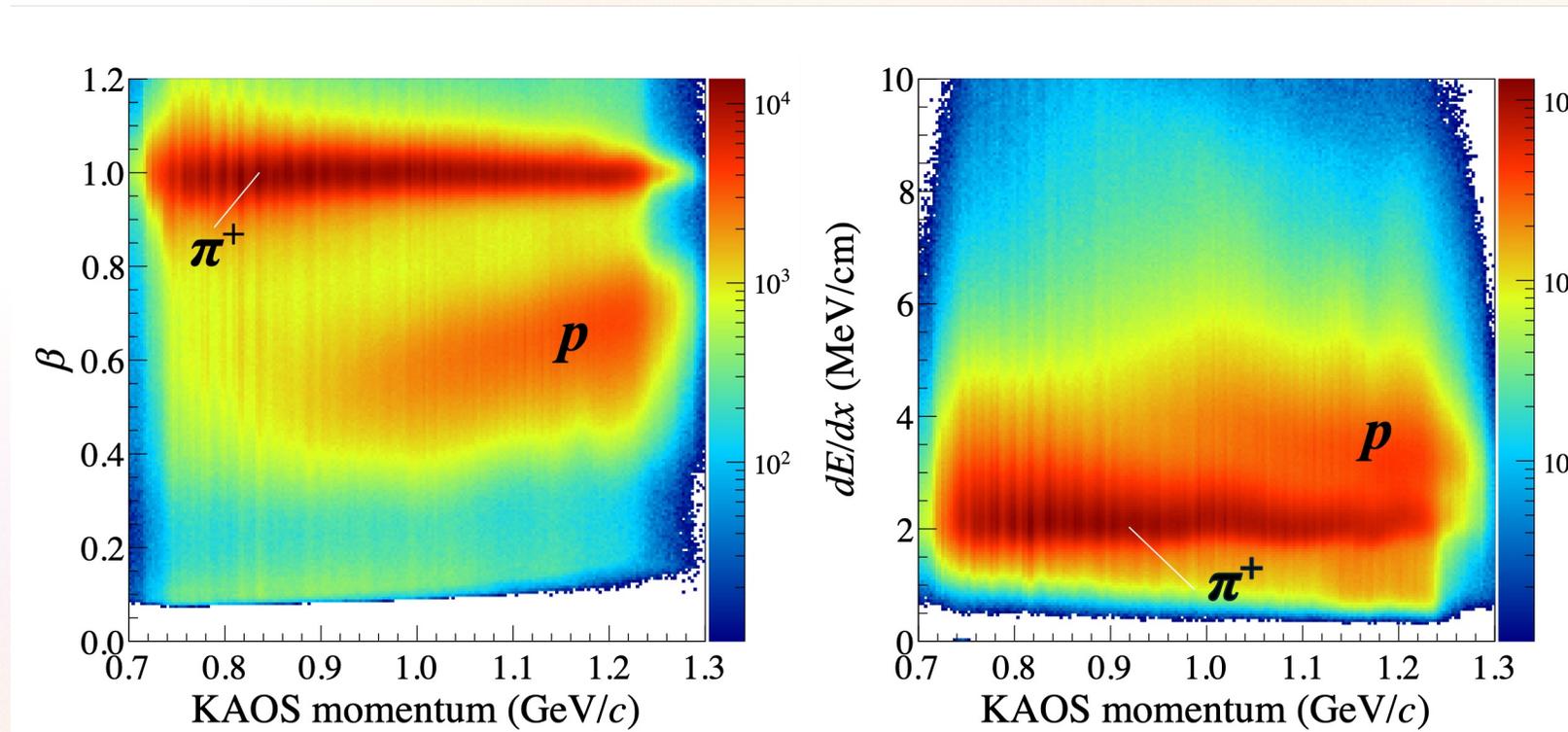
Measuring pion momentum

② 運動量校正

③ ${}^3_{\Lambda}H$ の B_{Λ} を算出

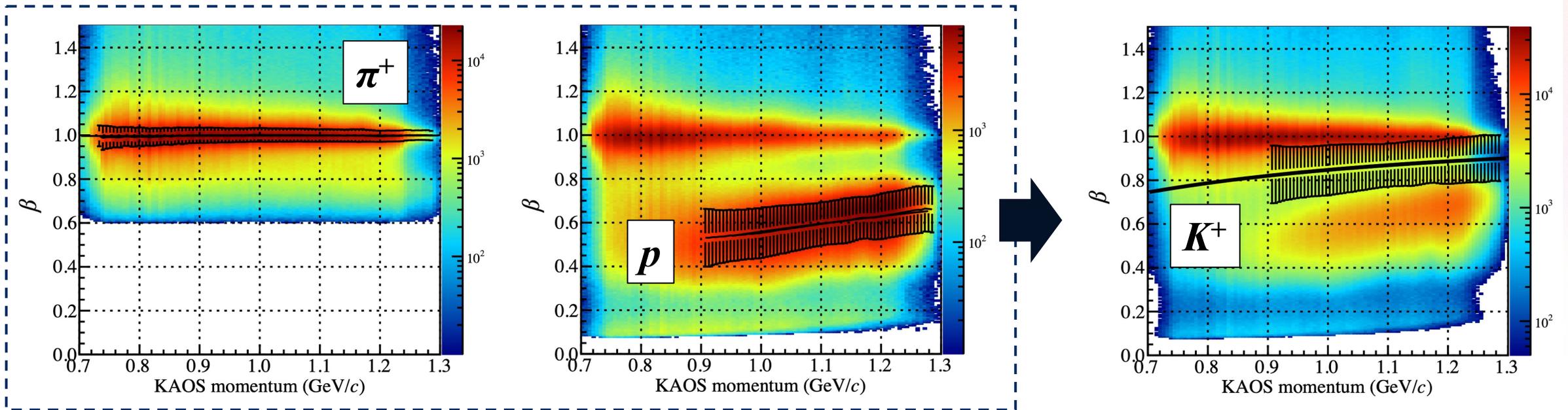
K^+ identification

- π^+ and proton backgrounds are identified using β or dE/dx vs momentum correlation
- K^+ events are selected by relative mass difference from π^+ and proton



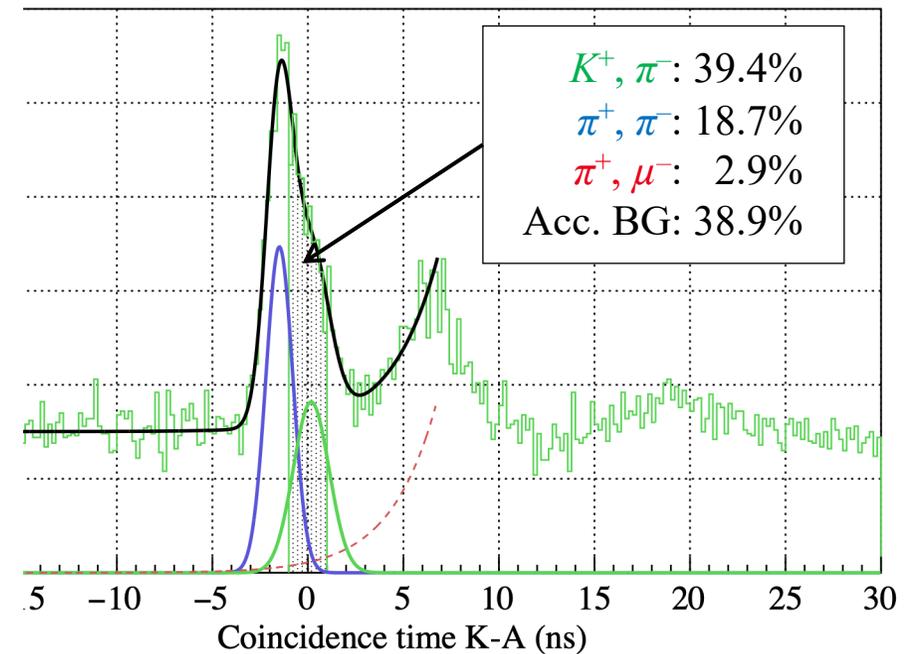
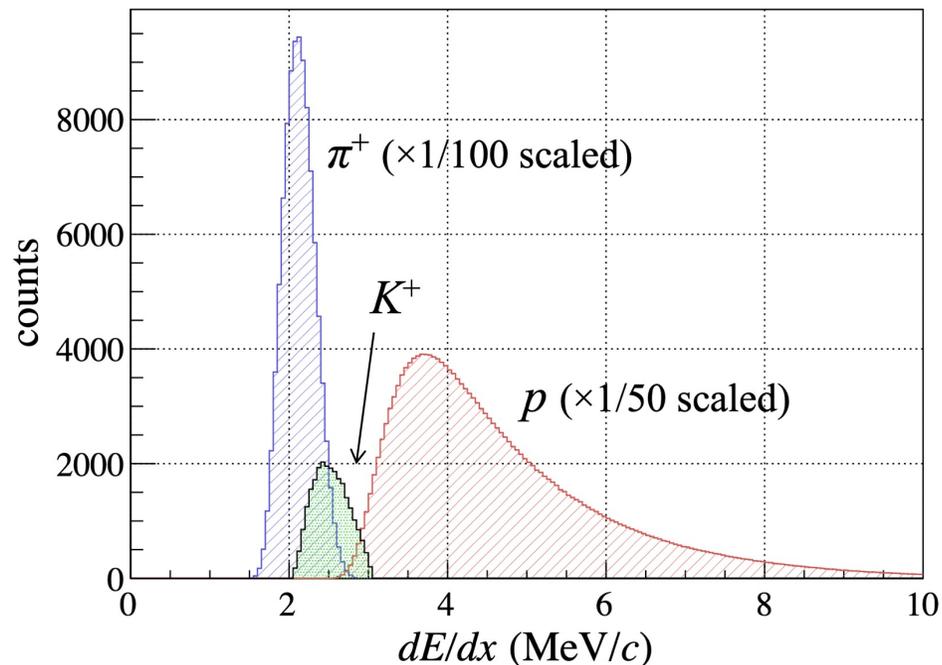
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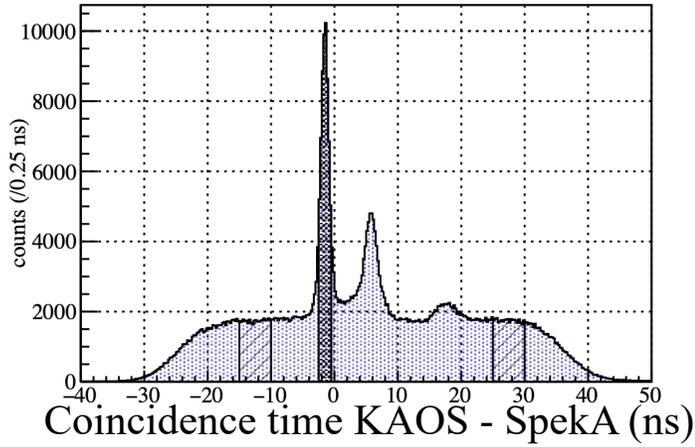
Result of K^+ identification

- Finally, K^+ events are selected under likelihood AND threshold condition for β & dE/dx
- PID purity: (K^+ , π^-) \sim 40%, (π^+ , π^-) \sim 20%, accidental background \sim 40%

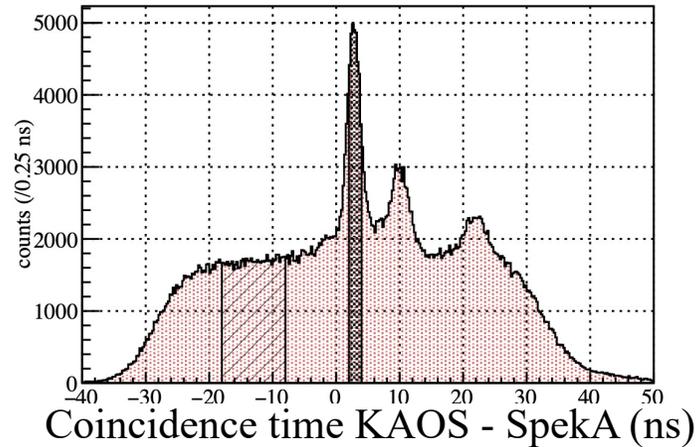


Coincidence time distribution

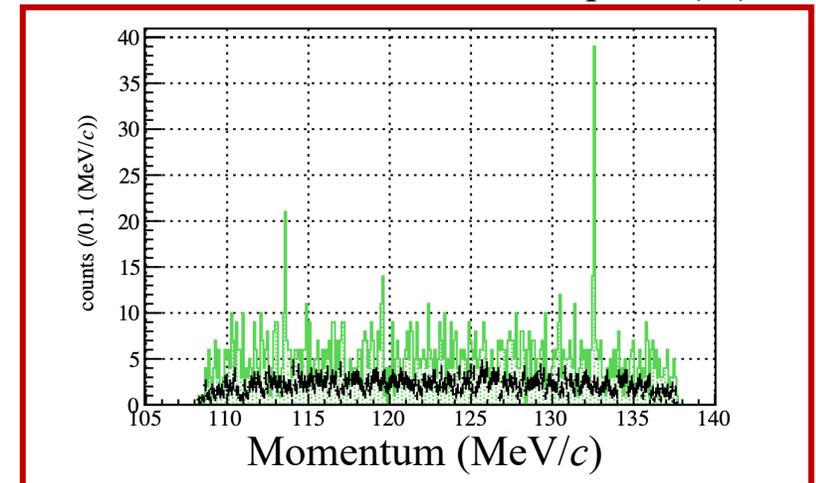
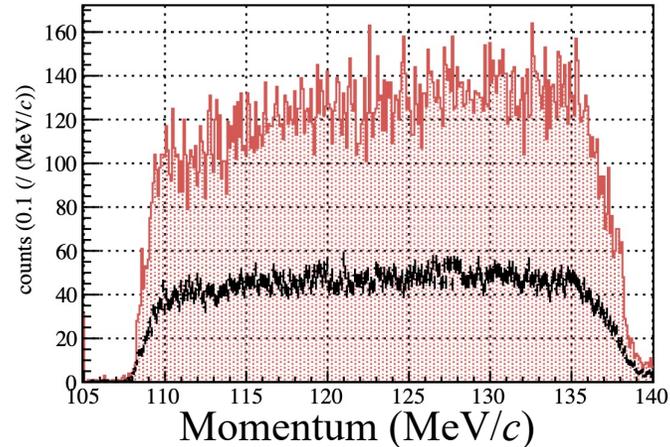
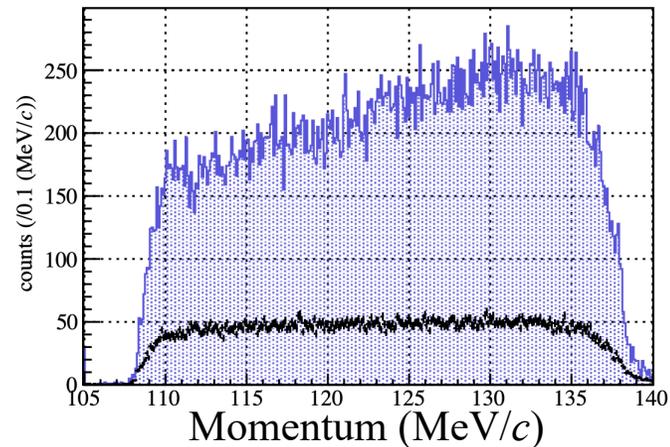
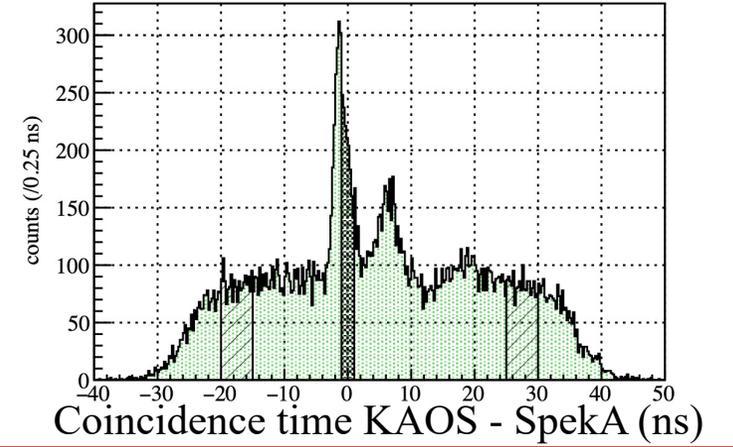
(π^+, π^-) events



(p, π^-) events

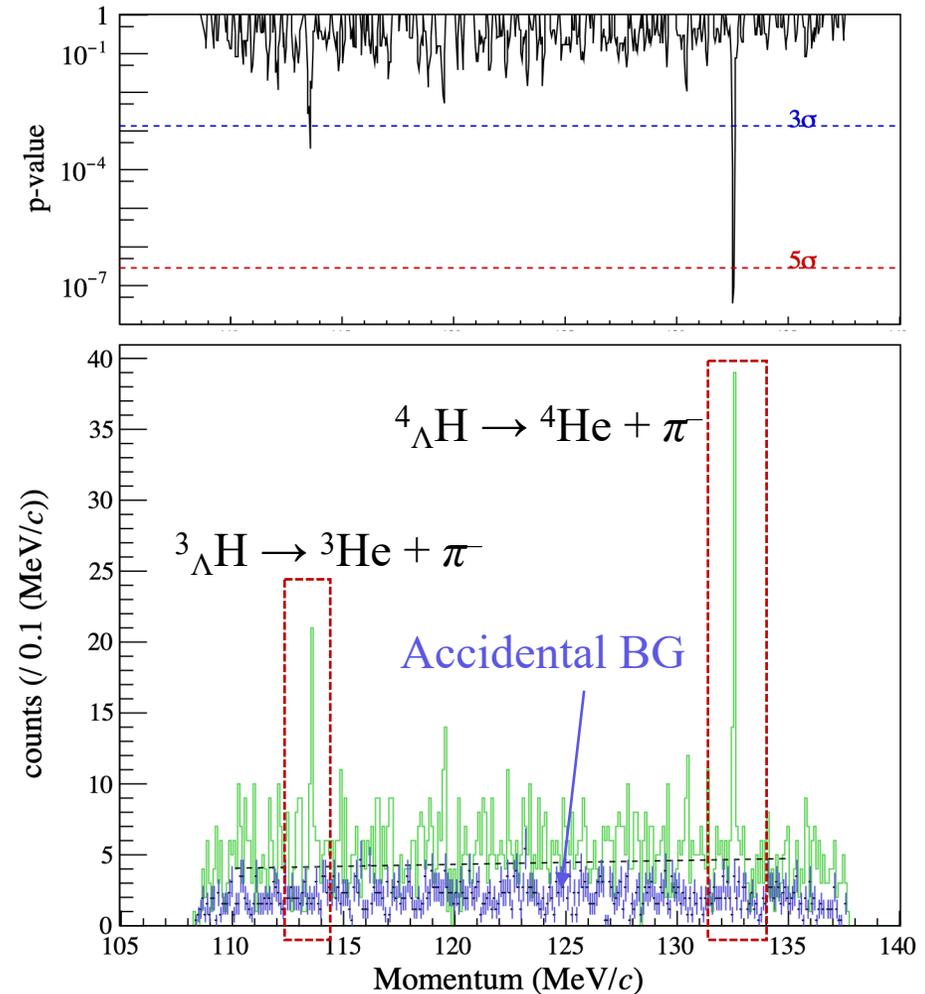


(K^+, π^-) events



Final momentum distribution

- Observed peaks are uniquely identified:
 - ~133 MeV/c for ${}^4_{\Lambda}\text{H}$ decay
 - ~114 MeV/c for ${}^3_{\Lambda}\text{H}$ decay
- p-value was evaluated every 100 keV/c width scanning 40 keV/c steps
- Peak significance: ${}^4_{\Lambda}\text{H} > 5\sigma$, ${}^3_{\Lambda}\text{H} > 3\sigma$

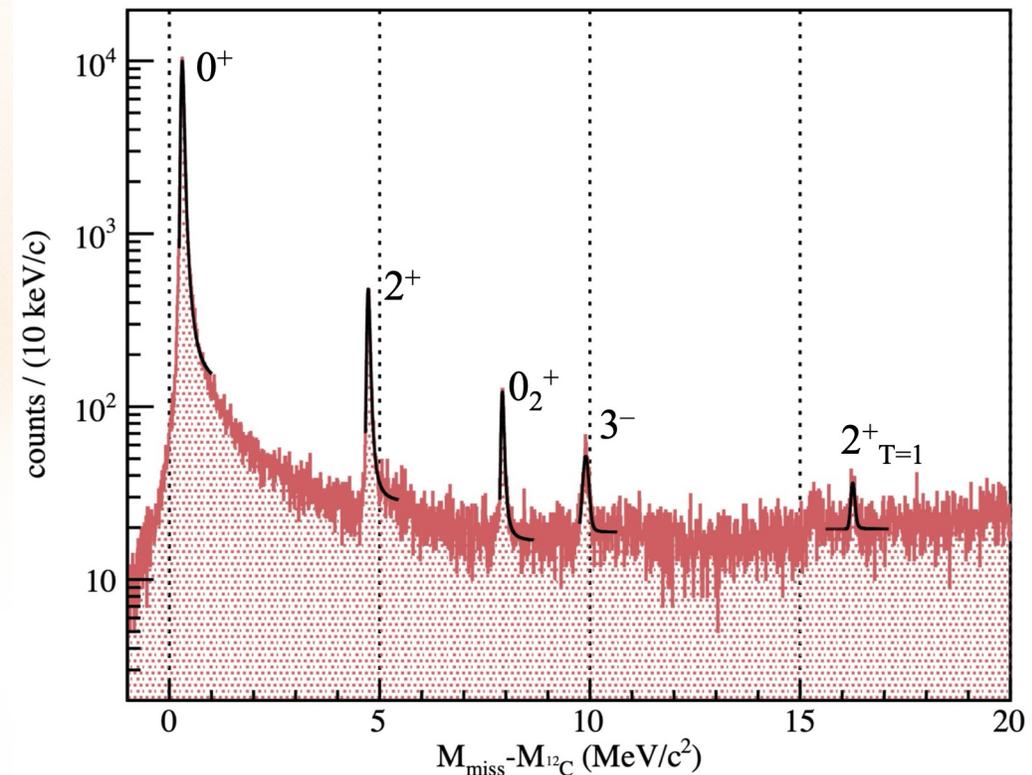


Momentum calibration: linearity

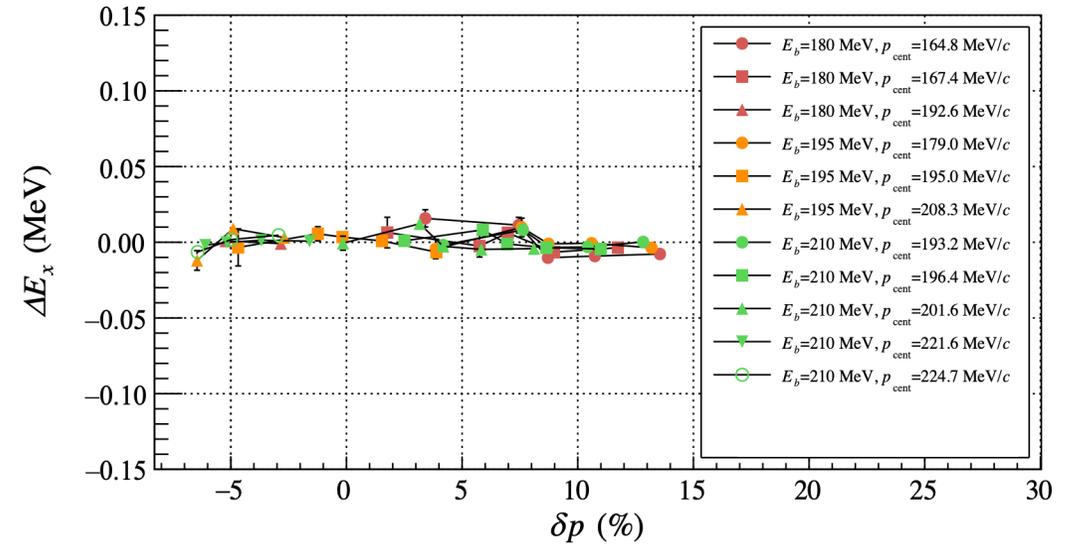
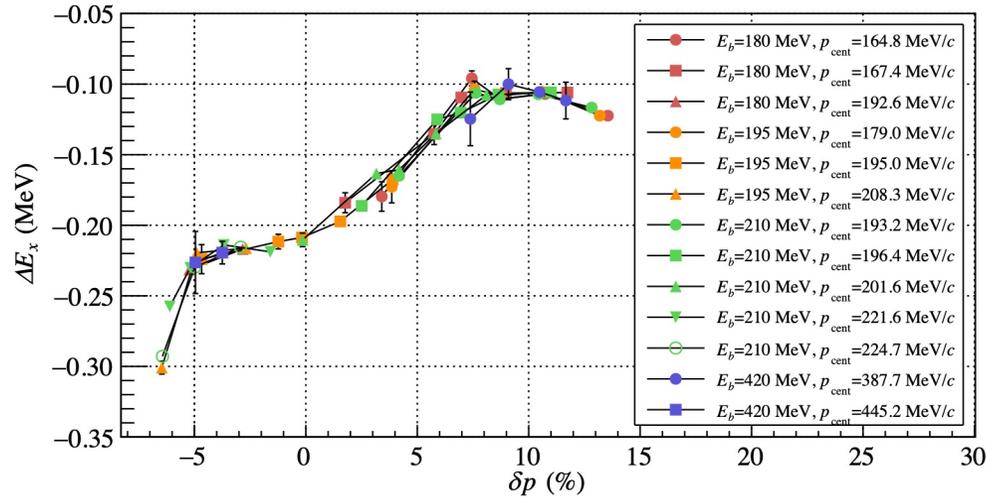
- Elastic scattering with ^{12}C target
- Covering ~ 16 MeV acceptance

- Relative ΔE_x within one data set is not affected by the beam energy input
→ Effective for linearity correction

$$E_x = M_{\text{miss}} - M_{^{12}\text{C}}$$
$$= \sqrt{(E_e + M_{^{12}\text{C}} - E_{e'})^2 - (\vec{p}_e - \vec{p}_{e'})^2} - M_{^{12}\text{C}}$$

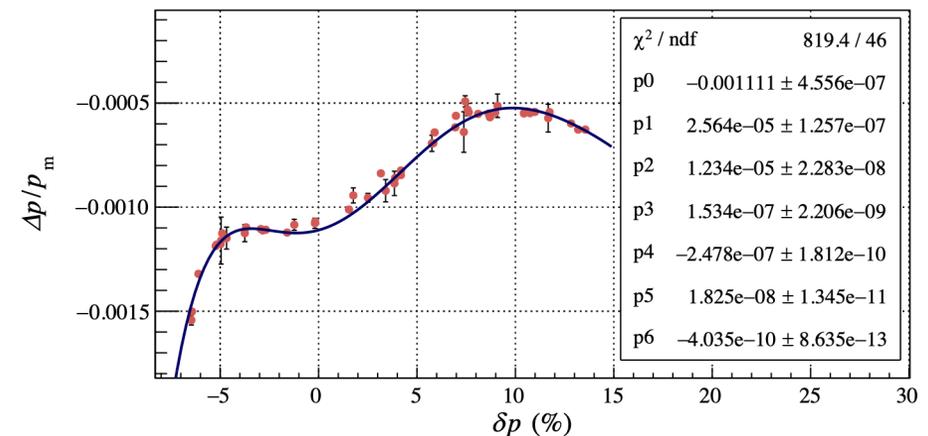


Momentum calibration: linearity



- 6th polynomial correction function
- The correction term was added to the momentum calculation:

$$p'_m = (1 + p_{\text{shift}}) \times p_{\text{central}} \times (1 + \delta p)$$
- Final deviation: $\sigma \sim 2 \text{ keV}/c$



Result

Measured peak structures

${}^3_{\Lambda}\text{H} \rightarrow {}^3\text{He} + \pi^-$ at $\sim 114 \text{ MeV}/c$

${}^4_{\Lambda}\text{H} \rightarrow {}^4\text{He} + \pi^-$ at $\sim 133 \text{ MeV}/c$

First observation of ${}^3_{\Lambda}\text{H}$ with Li target

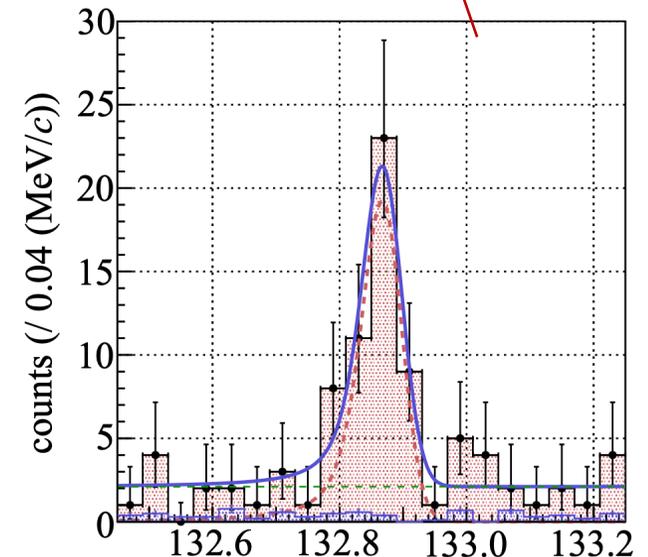
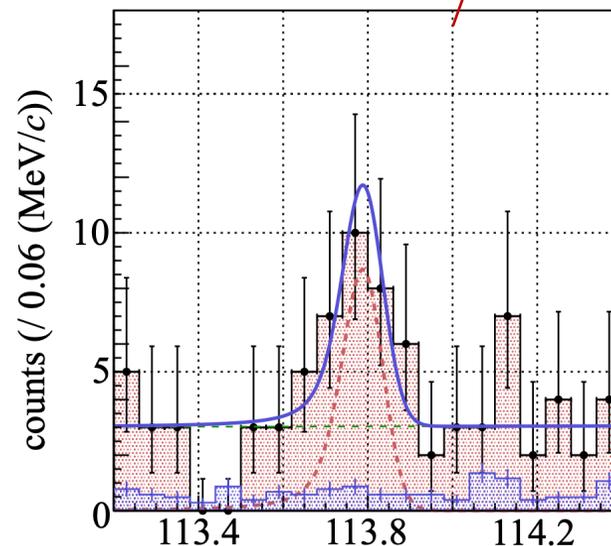
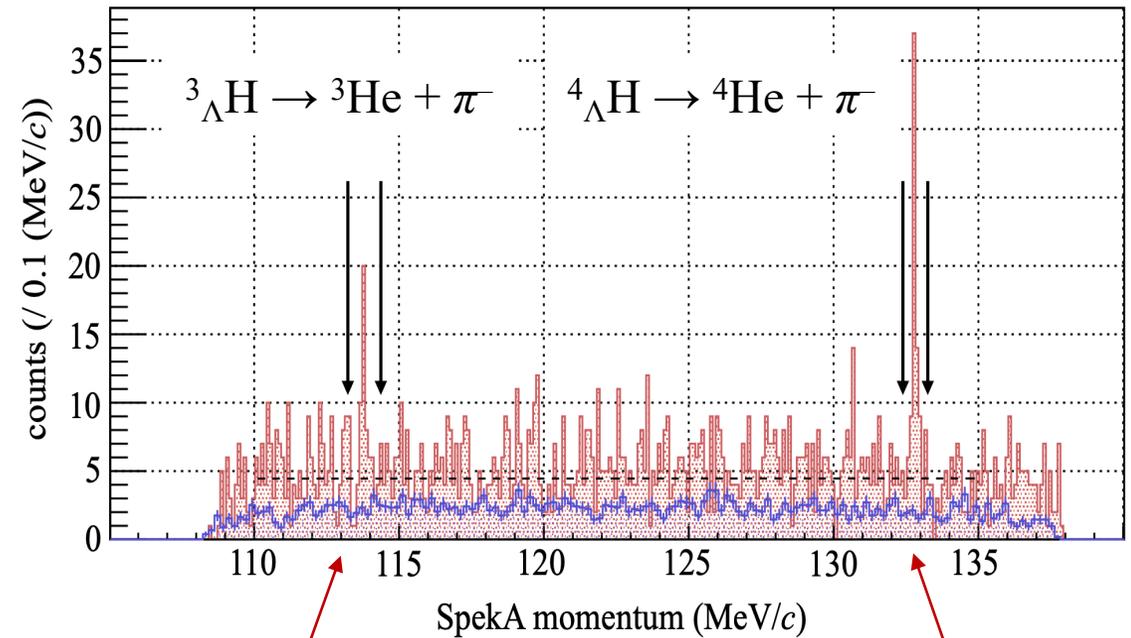
Unbinned fitting

Fitting function: Landau-Gaussian + linear

FWHM: $\sim 100 \text{ keV}/c$

$$p_{\pi^-}({}^3_{\Lambda}\text{H}) = 113.789 \pm 0.020 \text{ MeV}/c$$

(Referenced $p_{\pi^-}({}^4_{\Lambda}\text{H})$ from MAMI2016)



Result

$$B_{\Lambda}(^3_{\Lambda}\text{H}) = 0.523 \pm 0.013 \text{ (stat.)} \pm 0.075 \text{ (syst.) MeV}$$

(Referenced $p_{\pi^-}(^4_{\Lambda}\text{H})$ from MAMI2016)

$^4_{\Lambda}\text{H}$ と $^3_{\Lambda}\text{H}$ の崩壊 π^- 運動量差分 :

$$p_{\pi^-}(^4_{\Lambda}\text{H}) - p_{\pi^-}(^3_{\Lambda}\text{H}) =$$

$$19.078 \pm 0.021 \text{ (stat.)} \pm 0.036 \text{ (syst.) MeV}/c$$

系統誤差

標的内でのエネルギー損失	0.017 MeV
運動量校正 (E_b 以外)	< 0.010 MeV
$p_{\pi^-}(^4_{\Lambda}\text{H})$ MAMI2016のエラー	0.073 MeV

アンジュレータ放射光干渉法解析 : 現在進行中

➡ 最終的な系統誤差 < 30 keV

A. Kasagi *et al.*, PTEP **2025**, 8 (2025) 083D01.

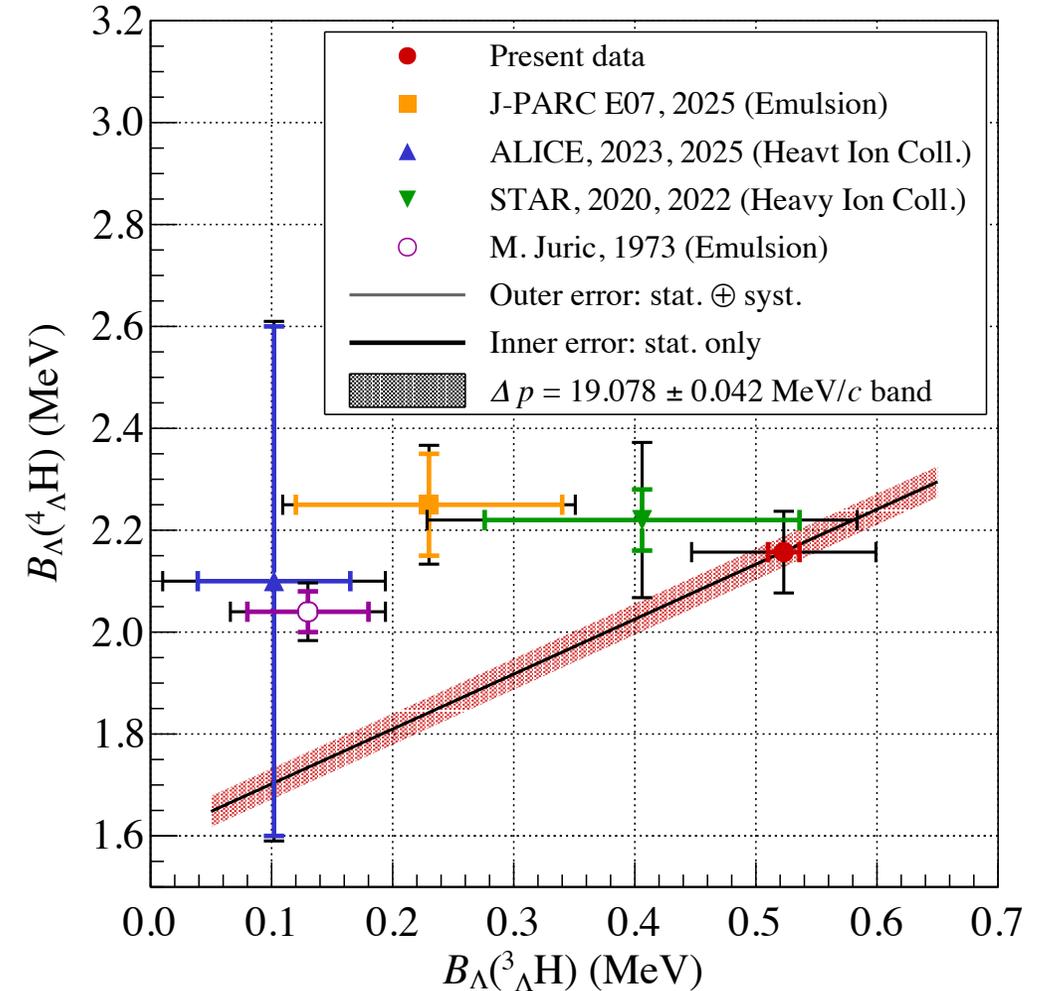
S. Acharya *et al.* (The ALICE Collaboration), PRL **131** (2023) 102302.

S. Acharya *et al.* (The ALICE Collaboration), PRL **134** (2025) 162301.

M. Abdallah *et al.* (The STAR Collaboration), Science **328** (2010) 58.

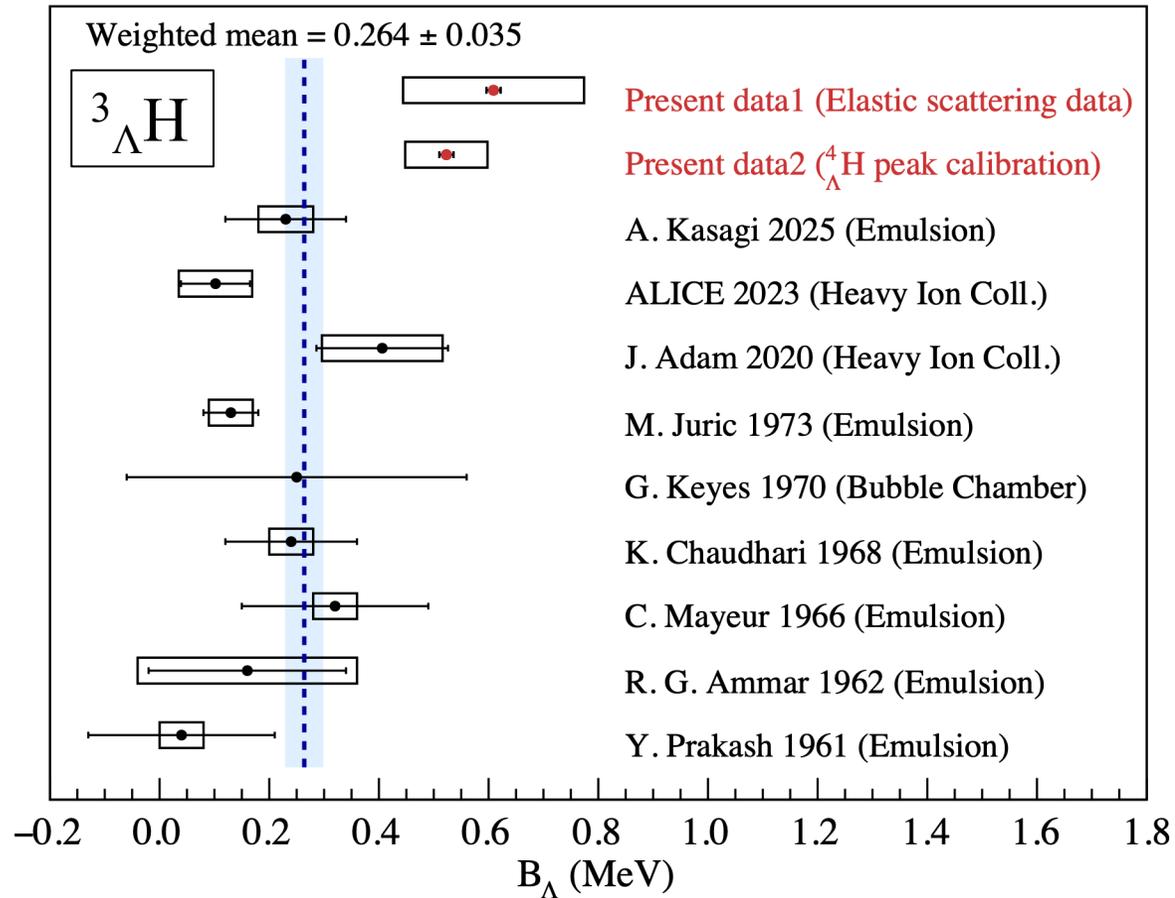
J. Adam *et al.* (The STAR Collaboration), PLB **834** (2022) 137449.

M. Juric, NPB **52**, 1 (1973) 1-30.



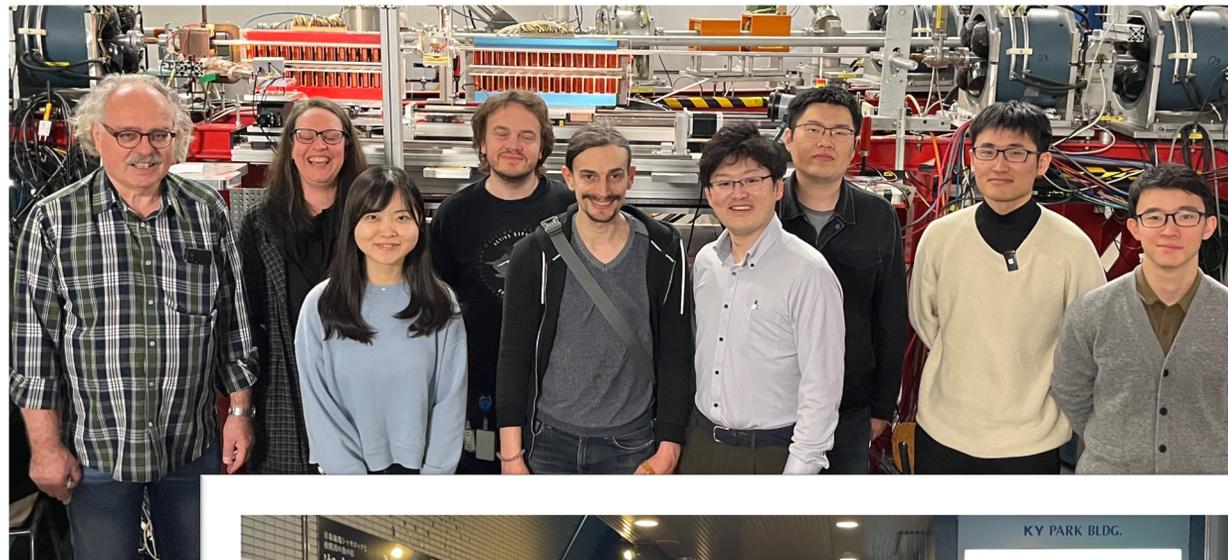
Discussion

今回の結果：これまでの理解 (=130 keV) より有意に大きな値！



- 散乱長は大きくなる？
H. Le, J. Haidenbauer, U. Meißner, A. Nogga, PLB 801 (2020) 135189
- ΛNN 三体力の効果がある可能性
H. Kamada, M. Kohno, K. Miyagawa, PRC 108 (2023) 024004
- 精密少数計算： $\text{nn}\Lambda$ が束縛する可能性
E. Hiyama, S. Ohnishi, B.F. Gibson, and Th.A. Rijken, PRC 89 (2014) 061302
- 短い寿命が説明し得る可能性
A. Pérez-Obiol, D. Gazda, E. Friedman, A. Gal, PLB 811 (2020) 135916

Special thanks



Summary

- 核力の統一的な理解を目指して – ハイパー核物理
- ベンチマーク「ハイパートライトン」の束縛エネルギーを直接分光により測定
 - MAMIにおける崩壊 π 中間子分光法
- 先行研究からのアップデート
 - ${}^7\text{Li}$ 標的によるハイパートライトンの収量アップ
 - 電子弾性散乱 & ${}^{12}\text{C}$ 標的による運動量校正
- 結果
 - $B_{\Lambda}({}^3_{\Lambda}\text{H}) = 0.523 \pm 0.013 \text{ (stat.)} \pm 0.075 \text{ (syst.) MeV}$
 - $p_{\pi^{-}}({}^4_{\Lambda}\text{H}) - p_{\pi^{-}}({}^3_{\Lambda}\text{H}) = 19.078 \pm 0.021 \text{ (stat.)} \pm 0.036 \text{ (syst.) MeV}/c$
- アンジュレータ放射光干渉法による電子エネルギー高精度測定
 - $B_{\Lambda}({}^3_{\Lambda}\text{H})$ 独立に系統誤差 $< 30 \text{ keV}$ で測定可能