Precision Decay-Pion Spectroscopy of Λ-Hypernuclei at MAMI

Florian Schulz
for the A1 Collaboration at MAMI

Outline

- Hypernuclear physics
- Spectroscopy of hypernuclei
- Measurement of hyperhydrogen at MAMI

Introduction

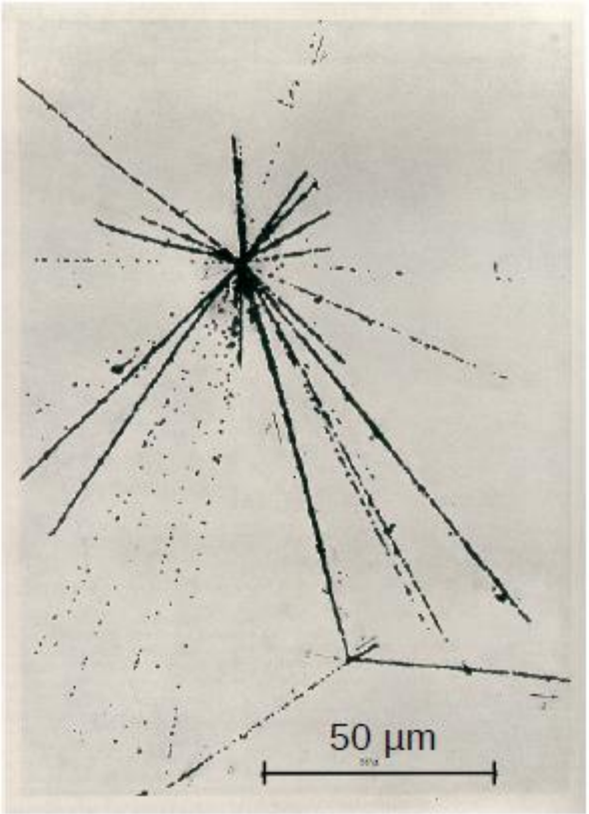
Hypernuclei

Definition

- Bound system of a nucleus and hyperon(s) (Λ, Σ, Ξ, Ω)

Notation

- $^{A}_{Y}Z$ (e.g. $^{4}_{\Lambda}H$)
  Z : charge number
  A : baryon number
  Y : hyperon list

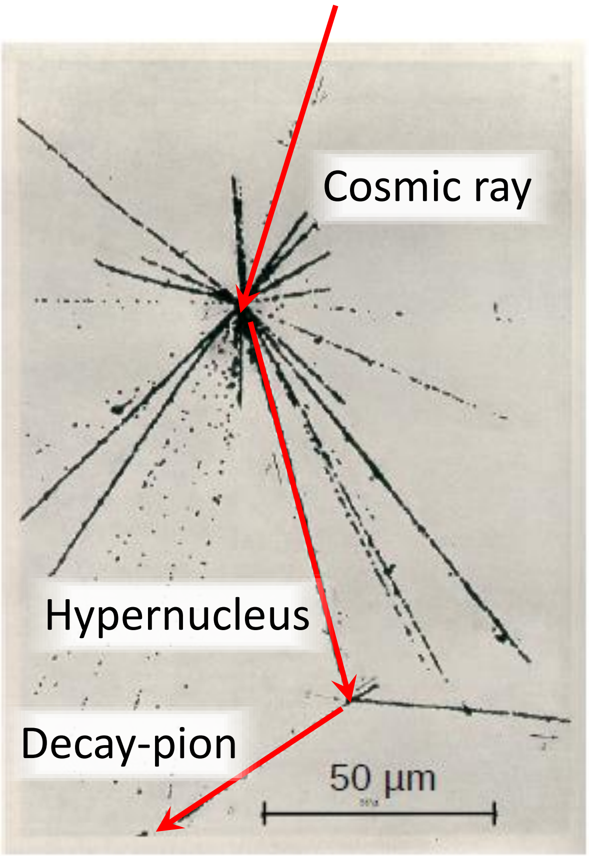


M. Danysz, J. Pniewski: *Delayed disintegration of a heavy nuclear fragment*, I. Philos. Mag. 7, 44:348-350, 1953

Learning from Hypernuclei

Nuclear force

- Nucleon-nucleon (NN) interaction has been extensively studied (NN scattering, spectroscopy)
- Extending to baryon-baryon interaction, including hyperons (Y) is the first step
- NY scattering is very difficult, YY scattering impractical



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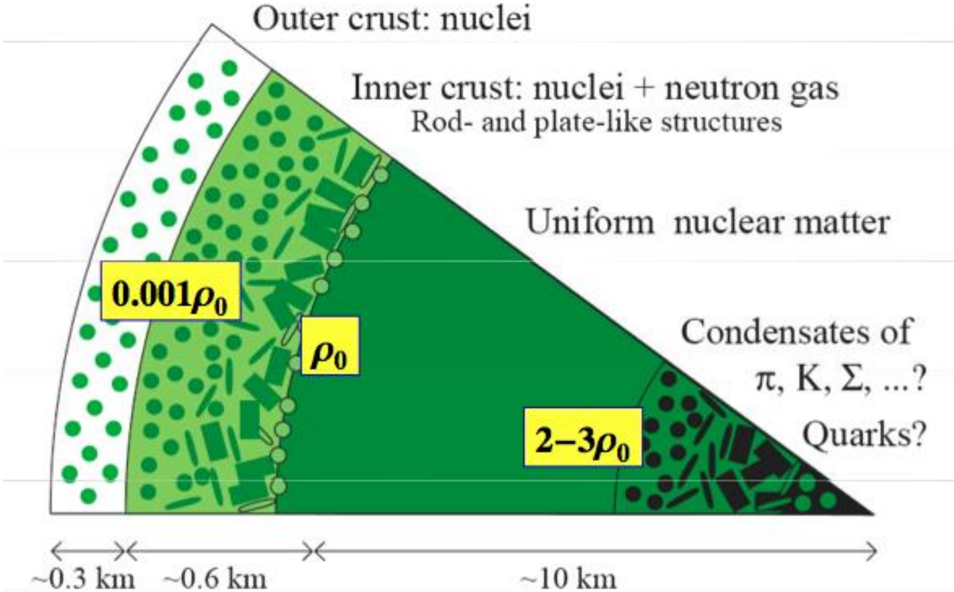
Learning from Hypernuclei

Neutron star structure



- Models including hyperons have difficulties explaining the discovery of neutrons stars with two times the mass of the sun

- will YN & YY interactions solve it?
- or hyperonic three-body forces?
- and what about quark matter?

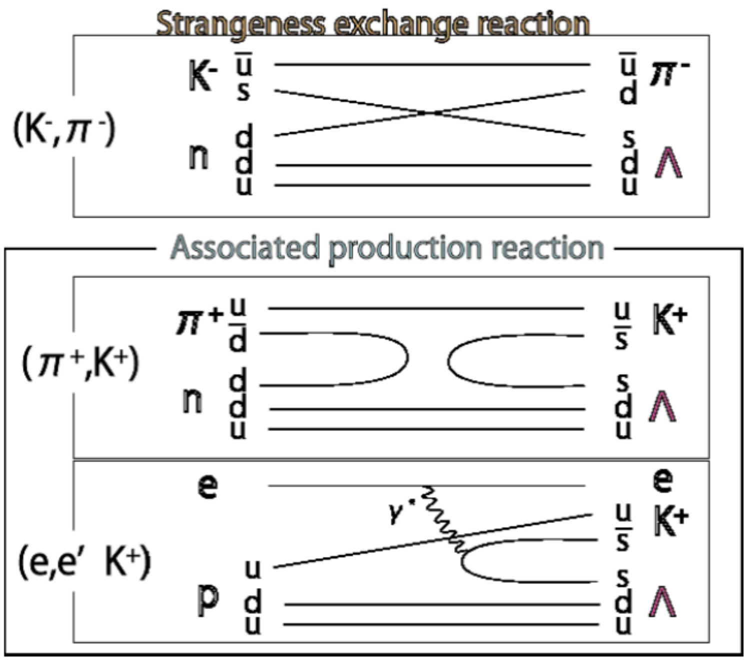
I. Vidaña: *A three hours walk through the physics of neutron stars*,
URL ://rafael.ujf.cas.cz/school14/index.php?location=Presentations

$\rho_0 = 2.8 \cdot 10^{14}$ g/cm^3

Studying Λ-Hypernuclei

Production
- Strangeness exchange
- Strangeness production
  (strong / electromagnetic)

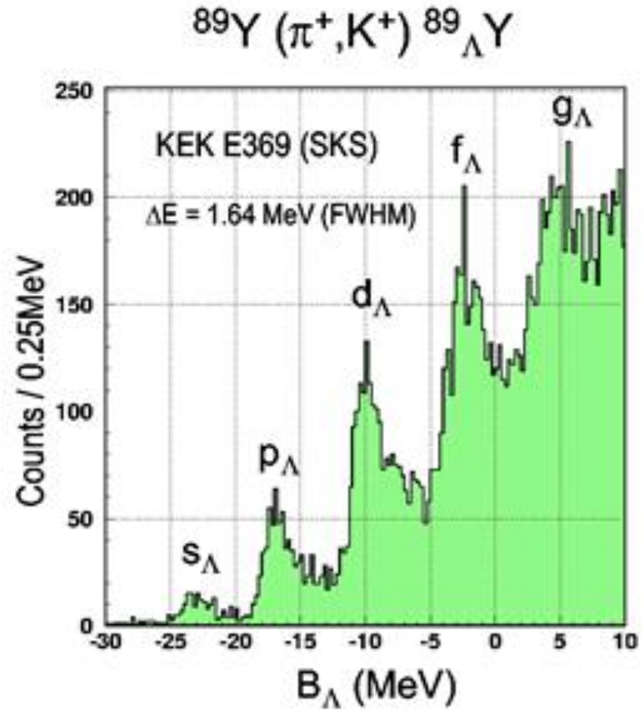
Λ-hypernuclei
- decay by weak interaction (τ ~100ps)
- ➢ narrow width allows spectroscopy



T. Gogami: *Spectroscopic research of Λ hypernuclei up to medium-heavy mass region with the (e,e'K⁺) reaction*, Ph.D. thesis, Tohoku University, 2014

Spectroscopy of Λ-Hypernuclei

Missing mass spectroscopy
- Measuring four-momenta
- Stable target nuclei
- Resolution 1.5 MeV – 500 keV

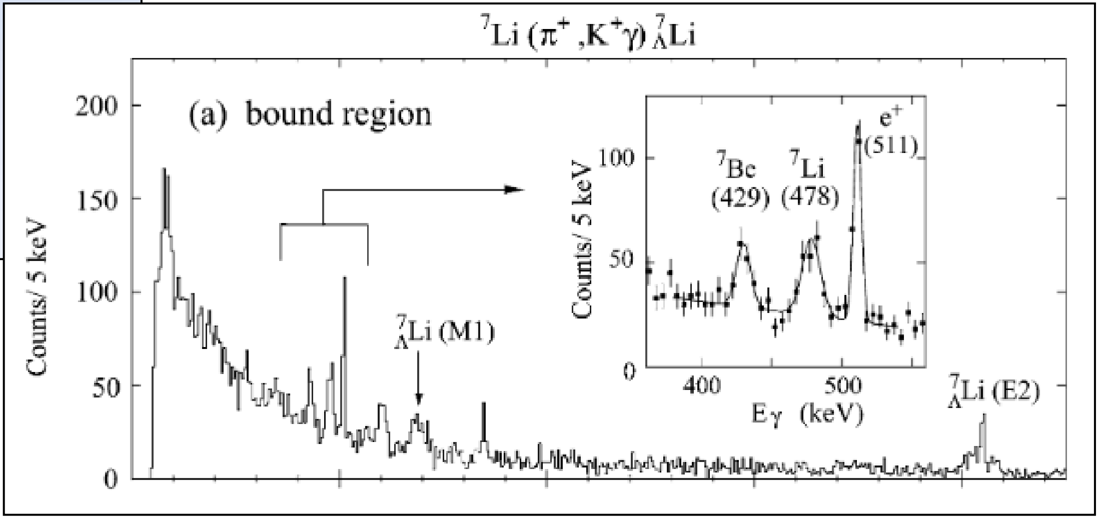


- no pauli blocking for Λ
- probes deep inside the nucleus

Spectroscopy of Λ-Hypernuclei

Missing mass spectroscopy
- Measuring four-momenta
- Stable target nuclei
- Resolution 1.5 MeV – 500 keV

Gamma ray spectroscopy
- Resolution in range of keV
- Stable target nuclei
- No absolute measurement



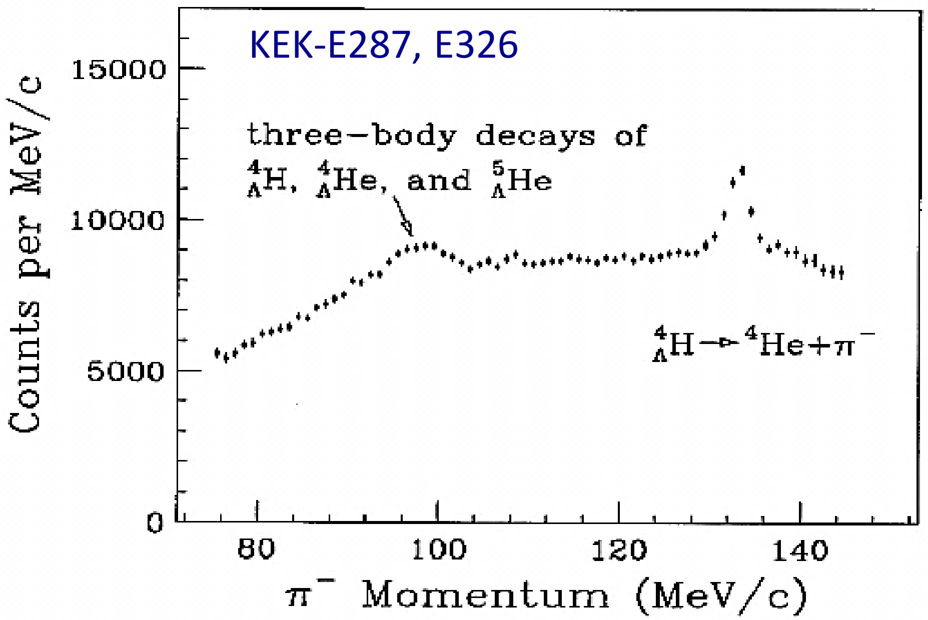
J. Sasao at al.: *$^{7}_{\Lambda}$Li ground-state spin determined by the yield of γ-rays subsequent to weak decay*, Phys. Let. B 579, 258-264, 2004

Spectroscopy of Λ-Hypernuclei

Missing mass spectroscopy
- Measuring four-momenta
- Stable target nuclei
- Resolution 1.5 MeV – 500 keV

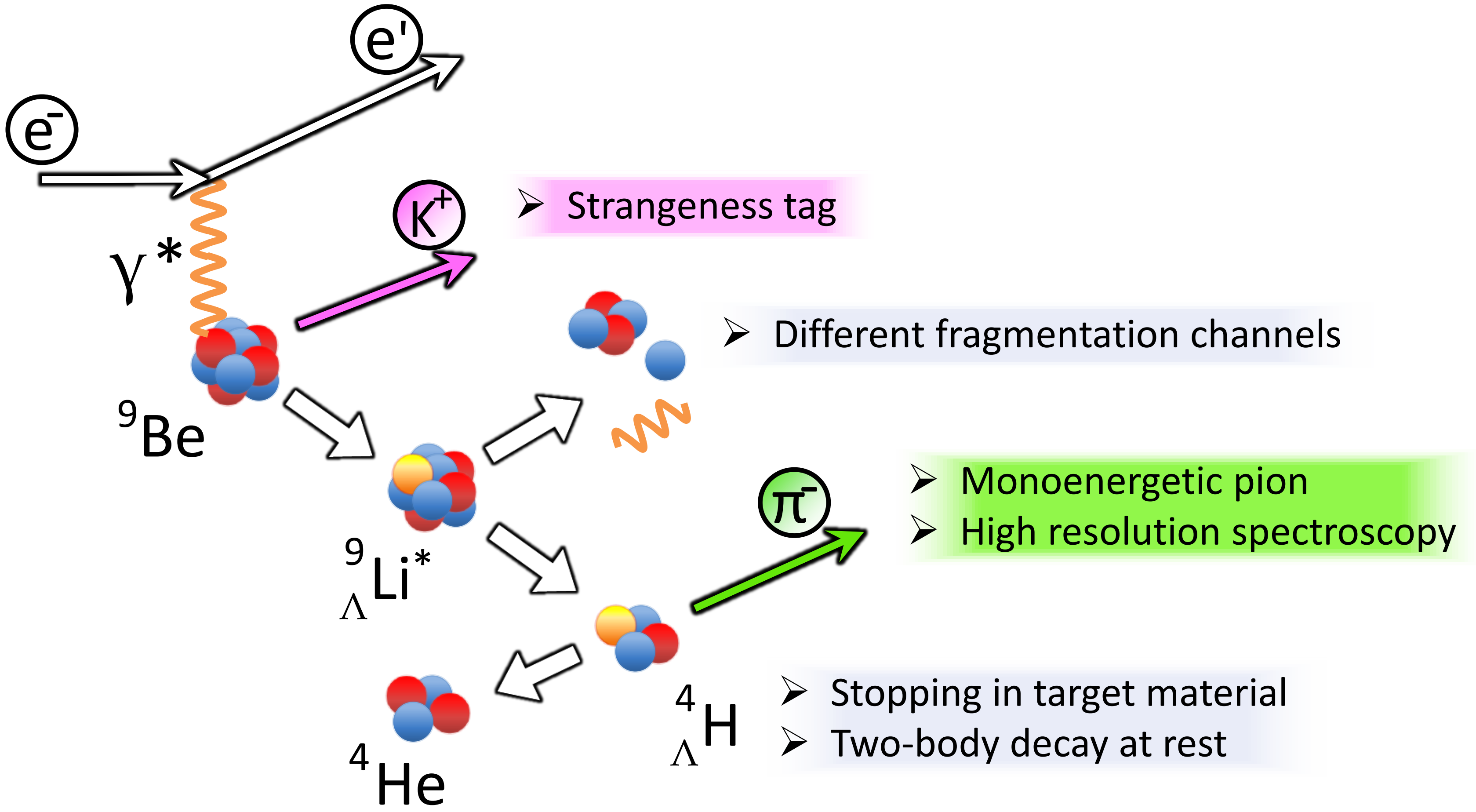
Gamma ray spectroscopy
- Resolution in range of keV
- Stable target nuclei
- No absolute measurement

Decay-pion spectroscopy
- Mesonic two body decays
- Measuring hyperfragments
- Resolution below 100 keV



H. Tamura at al., Phys. Rev. C, 1989

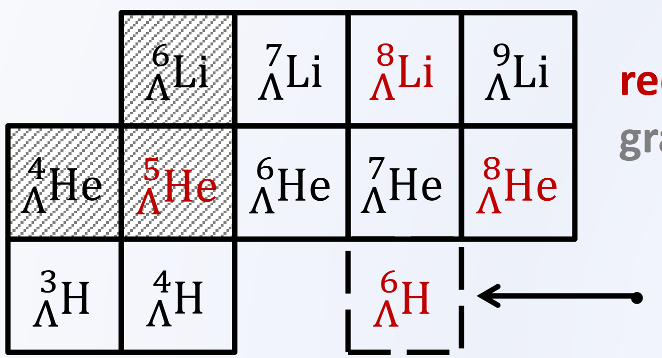
Decay-Pion Spectroscopy of Λ-Hypernuclei



Ground-state masses of Λ-Hypernuclei

$$M_{\mathrm{HYP}} = \sqrt{M_{\mathrm{ncl}}^2 + p_{\pi^-}^2} + \sqrt{M_{\pi^-}^2 + p_{\pi^-}^2}$$

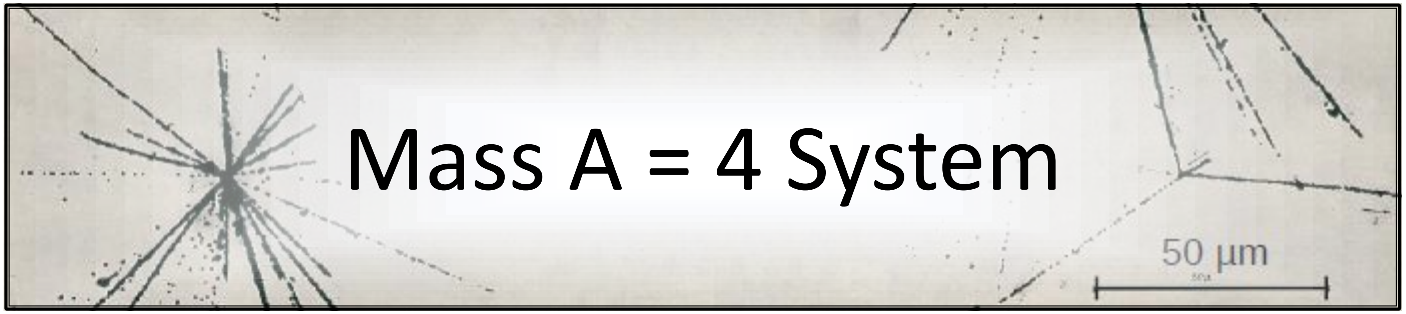
Accessible isotopes with ^{9}Be target



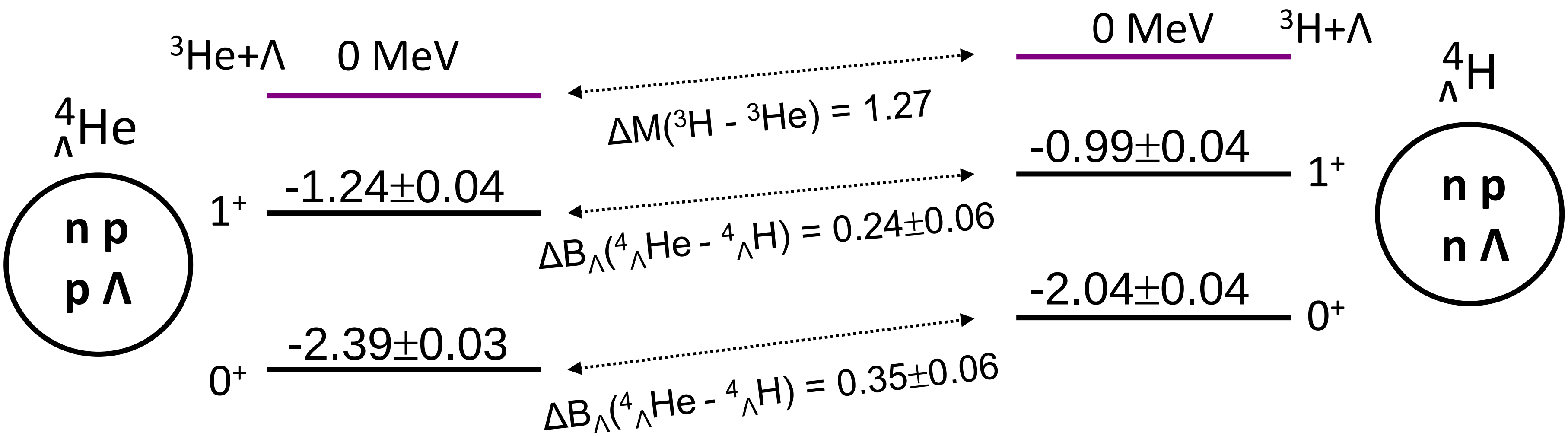
red: inaccessible by MM
gray: no two-body decay

“glue-like“ behavior, extending drip lines

Mass A = 4 System



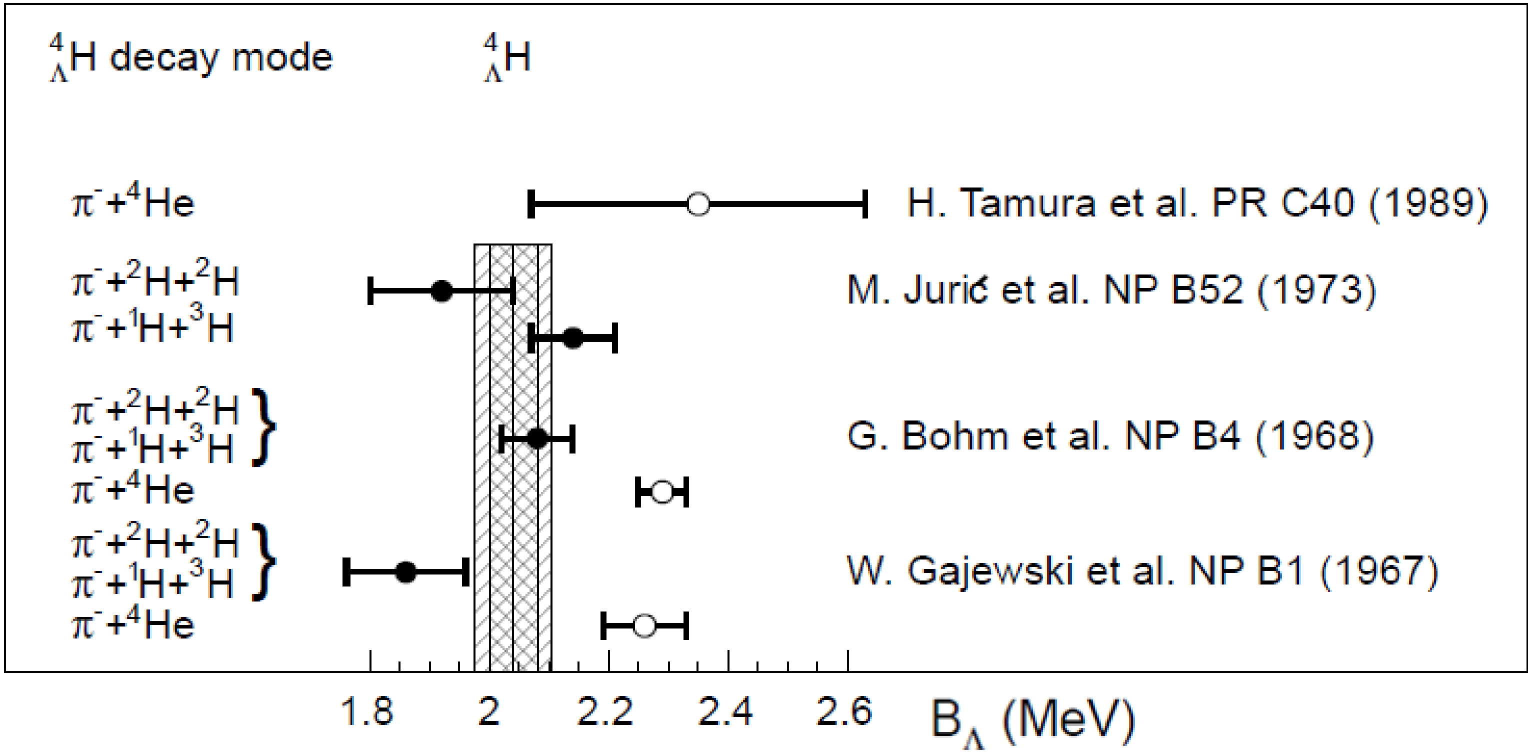
A = 4 Isospin Doublet



- NY interaction can be studied by strange mirror pairs
- Coulomb correction < 50 keV for the $^4{}_\Lambda H$ - $^4{}_\Lambda He$ pair
- The large $\Delta B_\Lambda = 0.35 \pm 0.06$ leads to the interpretation of a strong charge symmetry breaking effect in the ΛN interaction

Experimental data in MeV from [Nuclear Wallet Cards, BNL, 2011]

World data on ${}^{4}_{\Lambda}H$



$${}^{4}_{\Lambda}H \xrightarrow{decay} \pi^{-}+{}^{1}H+{}^{3}H: \quad B = 2.14 \pm 0.07 \text{ MeV}$$

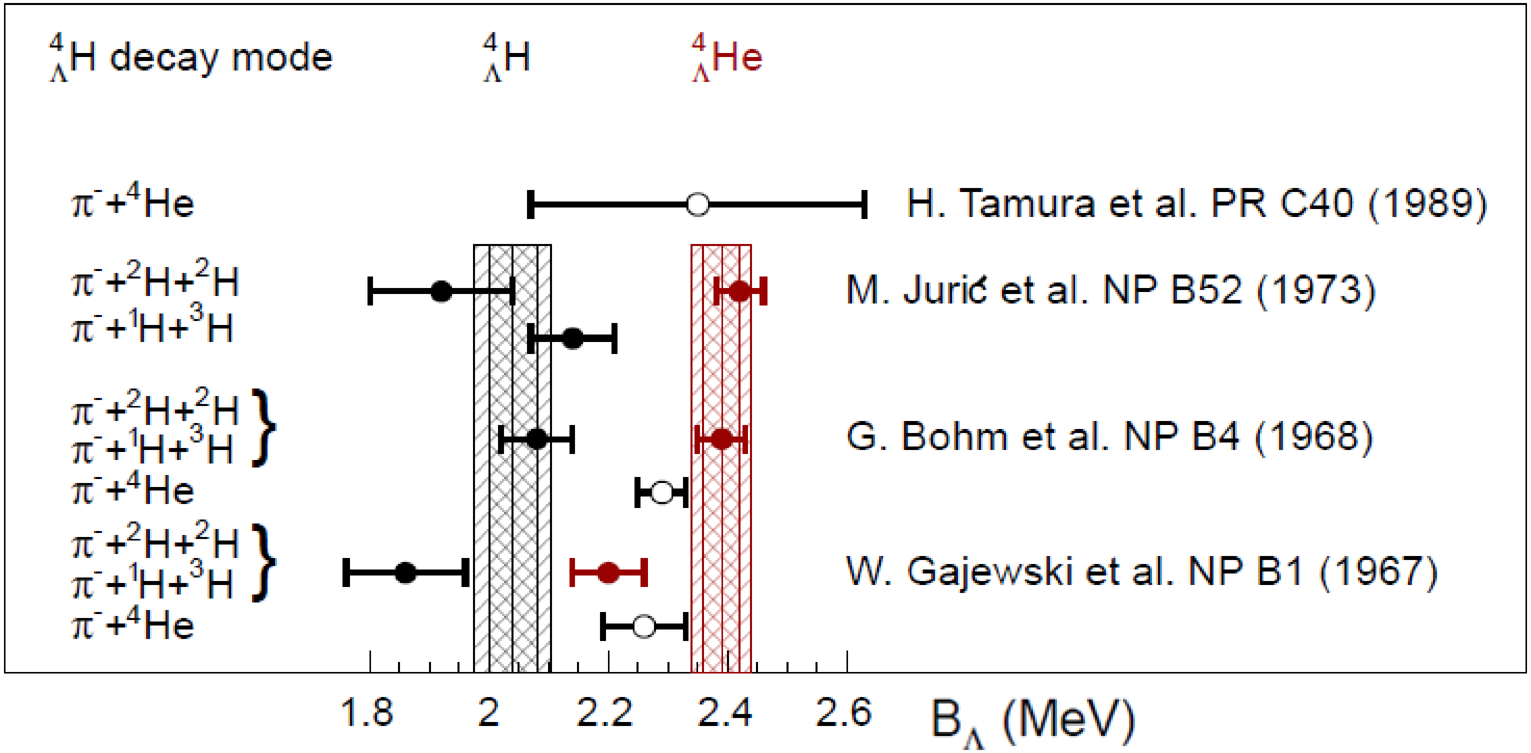
$${}^{4}_{\Lambda}H \xrightarrow{decay} \pi^{-}+{}^{2}H+{}^{2}H: \quad B = 1.92 \pm 0.12 \text{ MeV}$$

0.22 MeV difference

$$\text{Total:} \quad B = 2.08 \pm 0.06 \text{ MeV}$$

[M. Juric et al. NP B52 (1973)]

World data on A = 4 system



$^4_\Lambda\text{He} \xrightarrow{\text{decay}} \pi^- + {}^1\text{H} + {}^3\text{He}$: B = 2.42 ±0.05 MeV

$^4_\Lambda\text{He} \xrightarrow{\text{decay}} \pi^- + 2\,{}^1\text{H} + {}^2\text{H}$: B = 2.44 ±0.09 MeV

} 0.02 MeV difference

Total: B = 2.42 ±0.04 MeV

[M. Juric et al. NP B52 (1973)]

Decay-Pion Spectroscopy at MAMI

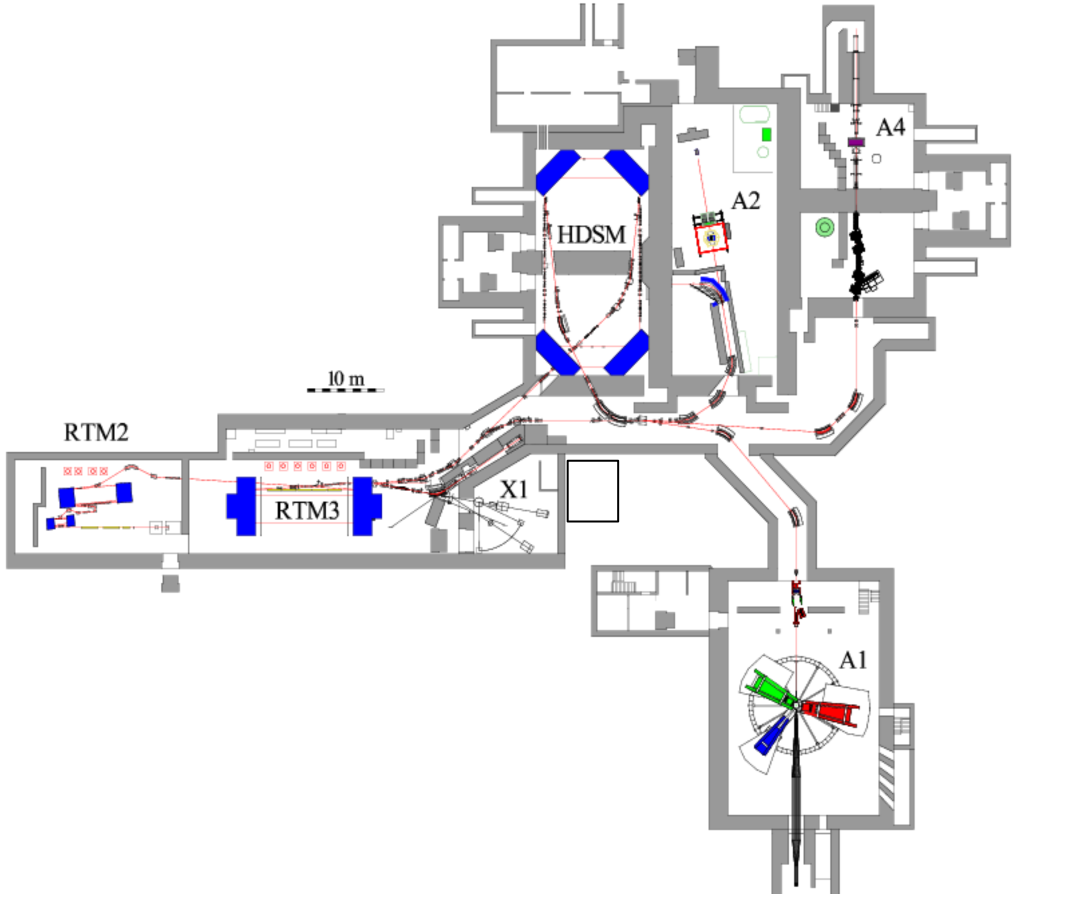
Mainz Microtron

Mainz Microtron

- Continuous wave electron beam
- Maximum beam energy: 1.6 GeV
- Maximum beam current: 100 μA
- Beam polarization > 80 %

Spectrometer facility

- 3 high resolution, $\delta p / p = 10^{-4}$, spectrometers "A/B/C"
- A short orbit spectrometer "Kaos"

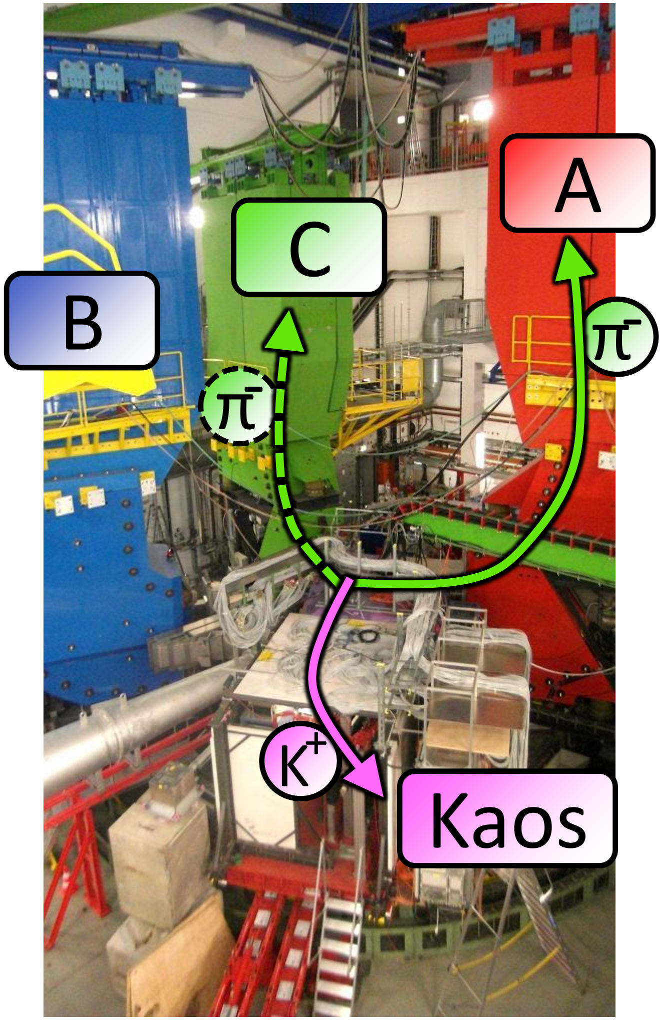


Decay-pion spectroscopy of Λ-hypernuclei

Decay-pion spectroscopy program:
- **2011:** Pioneering run at MAMI
- **2012:** First measurement of $^{4}_{\Lambda}H$
- **2014:** Second measurement campaign

Setup 2012
- Target : ^{9}Be, 22 mg/cm^{2}
- Beam energy : 1.508 GeV
- Beam current : 20 µA

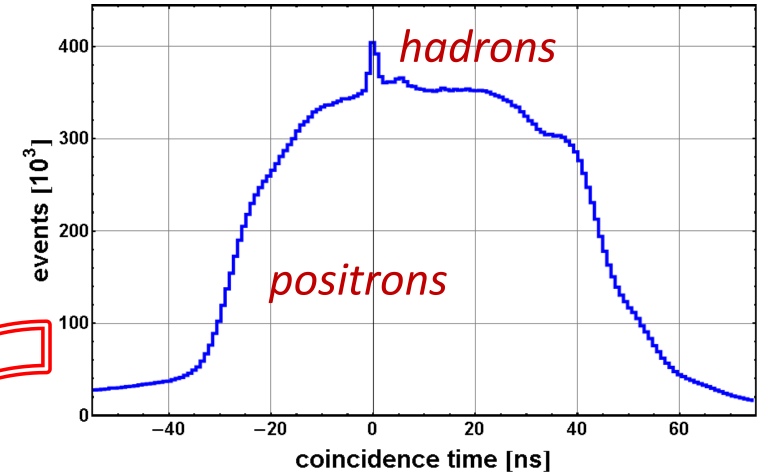
Spectrometer
- A || C : precise π^{-} spectroscopy
- Kaos : K^{+} strangeness tag at 0°



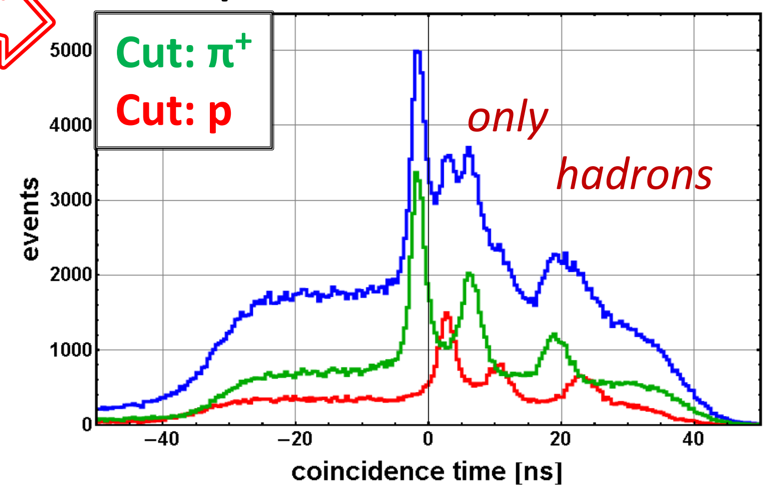
Kaos as dedicated zero-degree tagger

- Suppression of large positron flux with 25 X_0 lead absorber wall

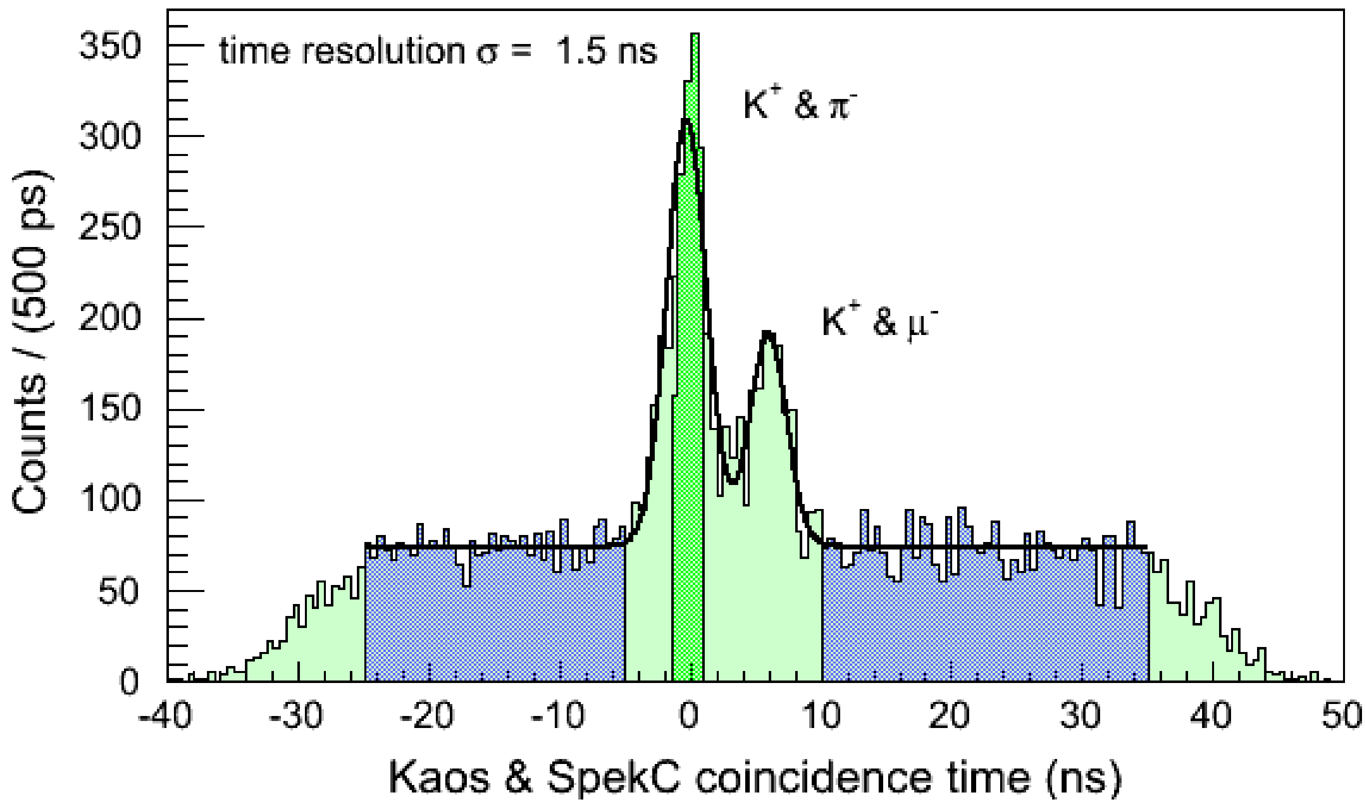
Pinoneering run without absorber



Experiment with absorber

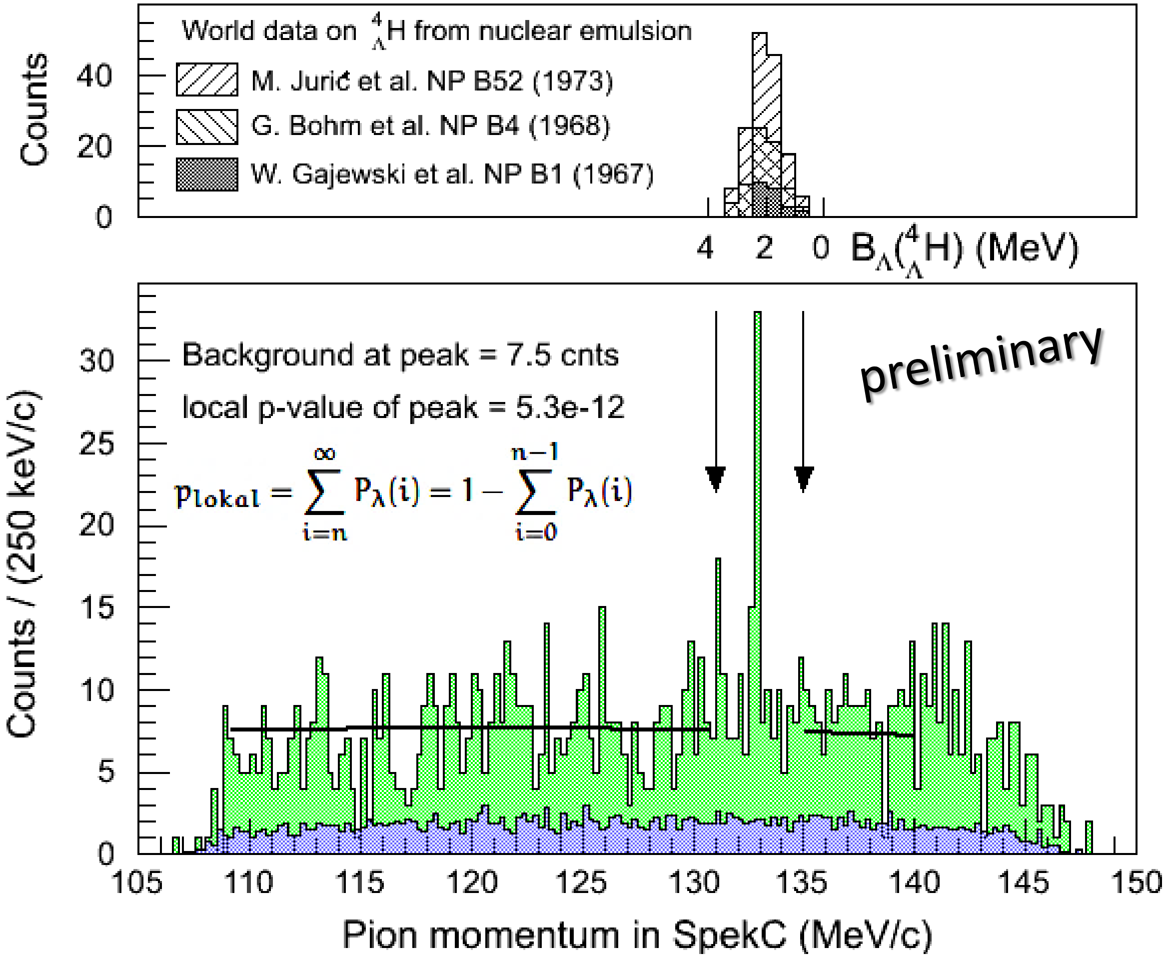


Reaction identification



- established clean tag on strangeness production at zero-degree
- decay-pion detection with Spectrometer A & C ($\delta p/p < 10^{-4}$)
- more than 1000 pion-kaon-coincidences from weak decays of hyperons

Hyperhydrogen peak search

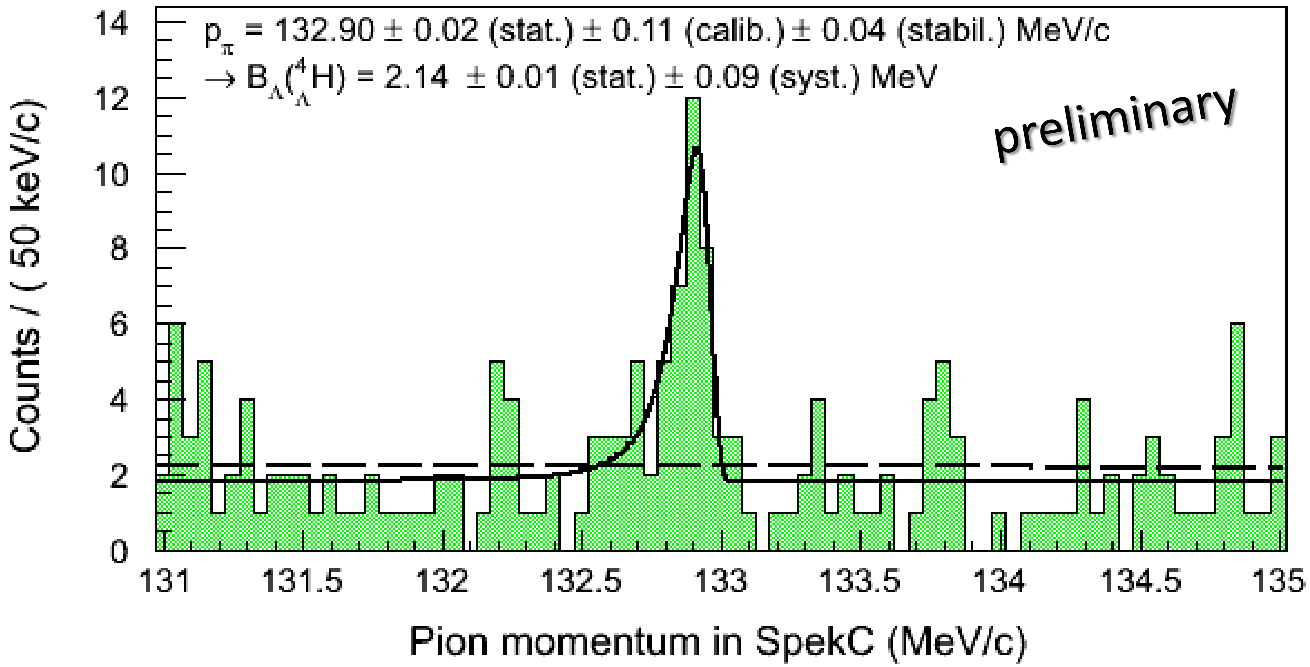


Emulsion data

MAMI data

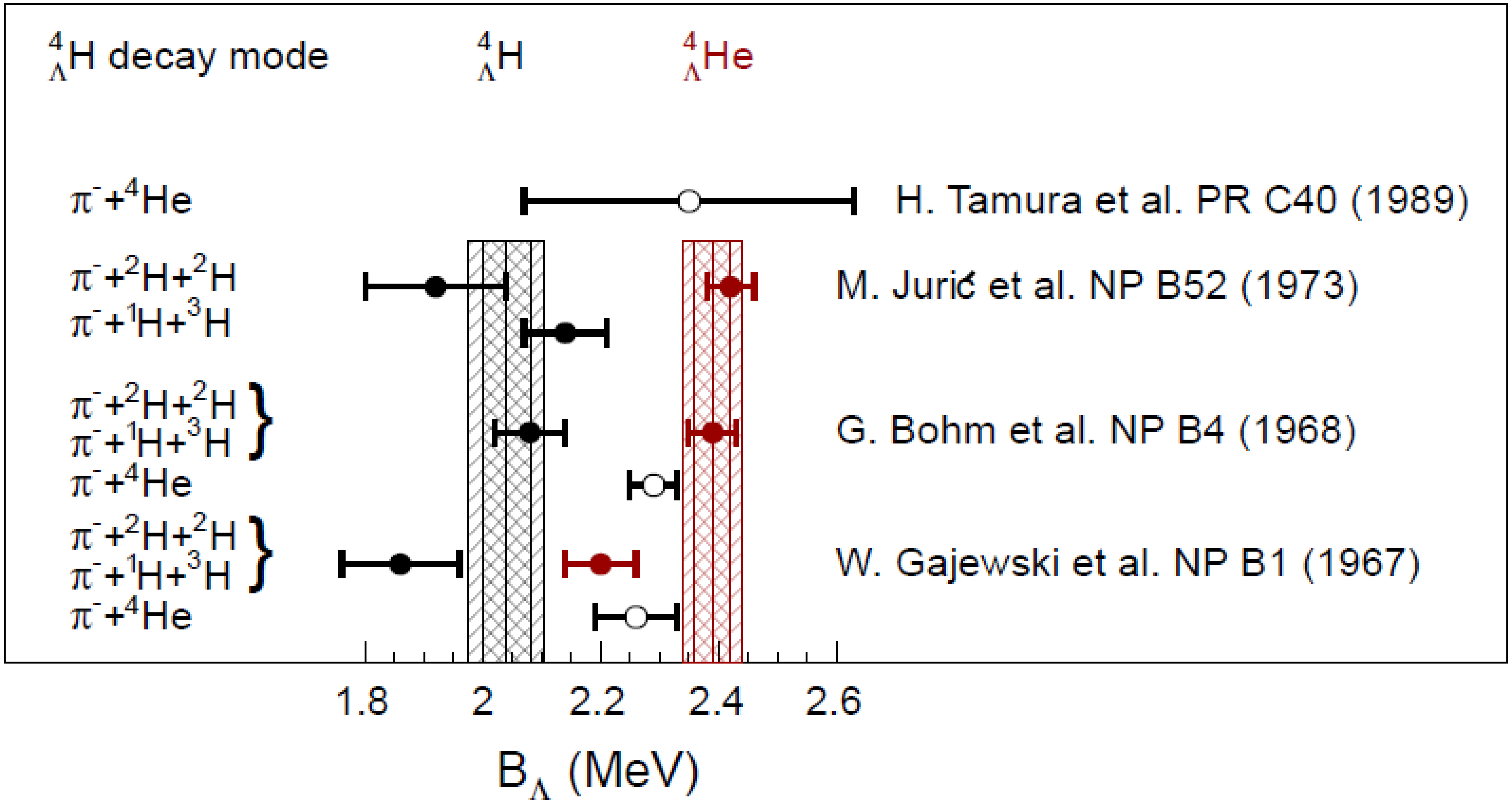
Local excess observed inside the hyperhydrogen search region

Binding energy extraction

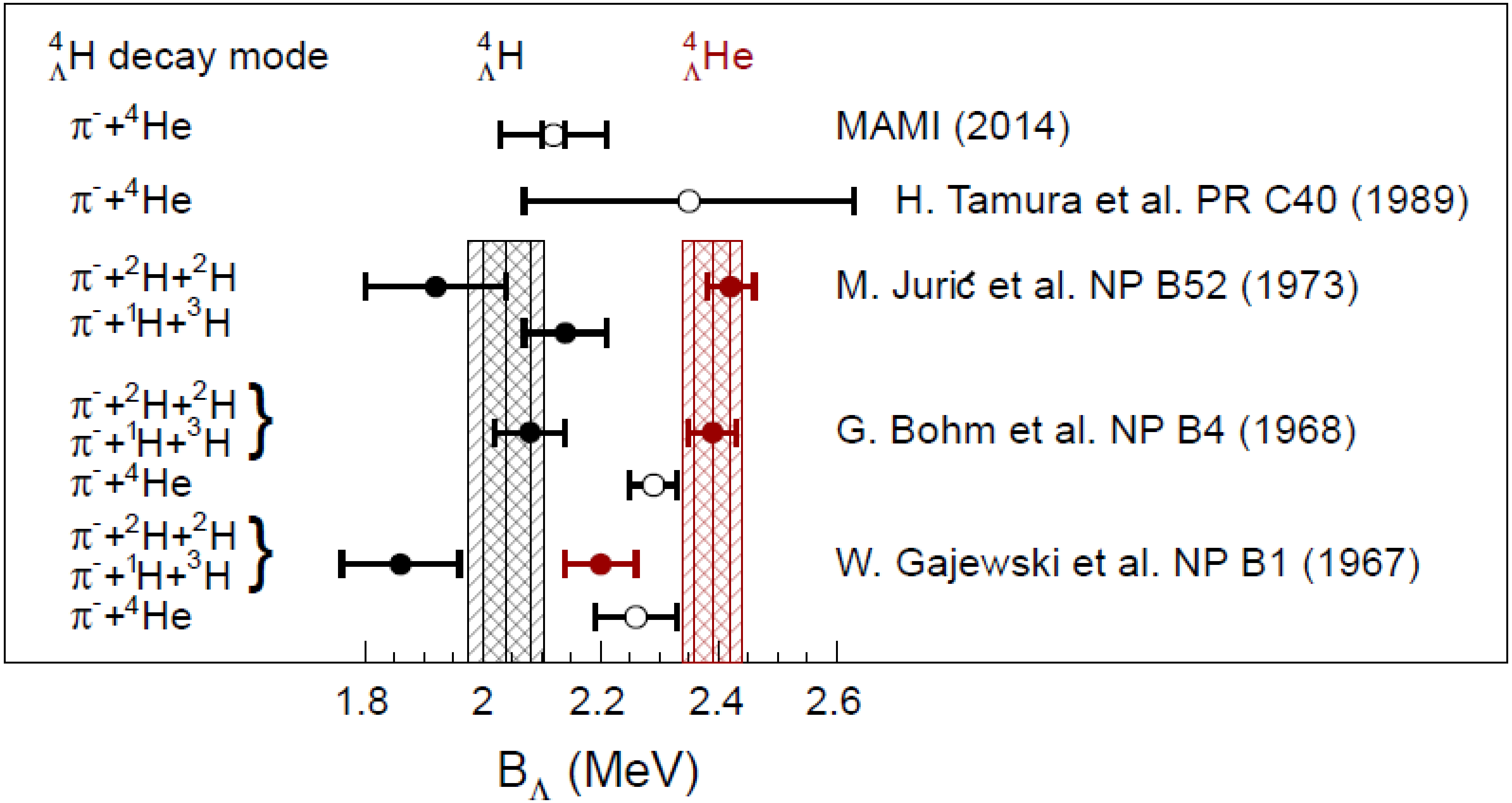


$$M({}^{4}_{\Lambda}\mathrm{H}) = \sqrt{M^2({}^{4}\mathrm{He}) + p_\pi^2} + \sqrt{M_\pi^2 + p_\pi^2} \quad \text{and}$$
$$B_\Lambda = M({}^{3}\mathrm{H}) + M_\Lambda - M({}^{4}_{\Lambda}\mathrm{H}) \quad \text{with c} = 1$$

World data on A = 4 system



World data on A = 4 system

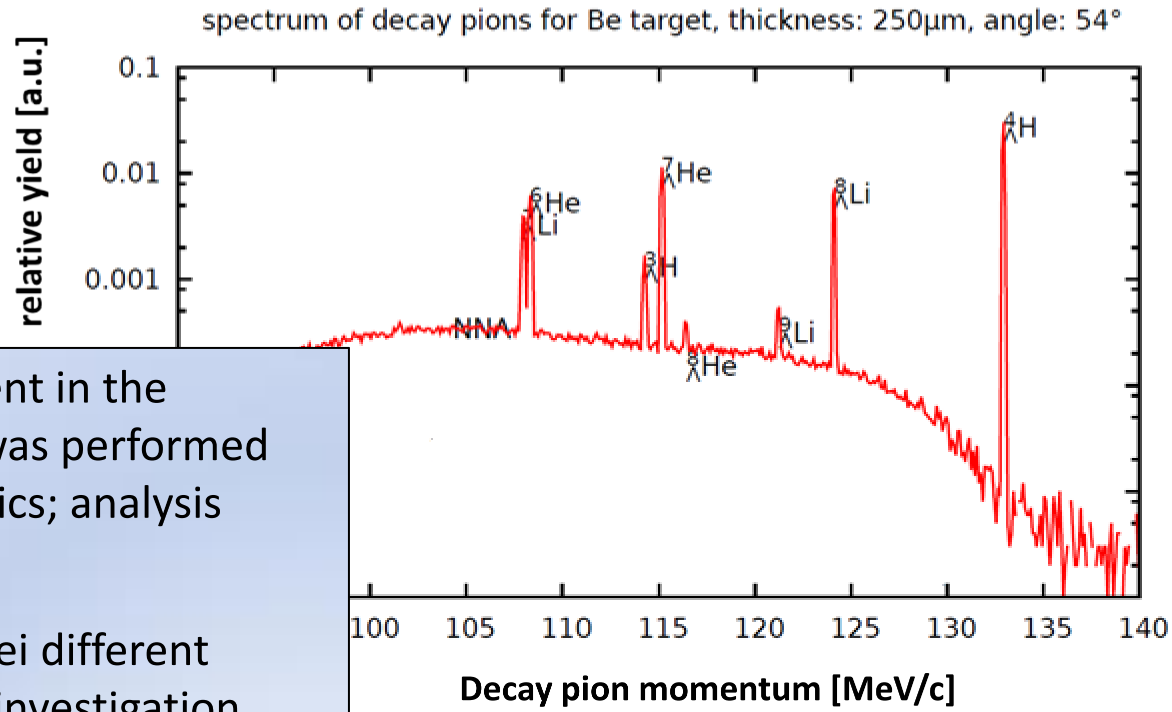


MAMI experiment confirmed Λ binding energy of ${}^4_\Lambda$H:
B_Λ ~ 2.14 ± 0.1 MeV (MAMI 2014 prelim.)

Summary

- Hypernuclei have been studied since the 60's, with applications beyond nuclear physics
- With gamma ray and decay-pion spectroscopy it is now becoming a precision science
- Decay-pion spectroscopy gives access to precise ground state masses of light hypernuclei
- Precise measurements of the A = 4 systems are linked with understanding of the charge symmetry breaking in the ΛN interaction

Outlook



- In 2014 the next experiment in the measurement campaign was performed with 5 times higher statistics; analysis ongoing
- To access other hypernuclei different target material are under investigation
- The dominating systematic error can be reduced afterwards, by improved spectrometer calibration
  → new Ph.D. project

Thank you for your attention

Collaboration list

Institut für Kernphysik, Johannes Gutenberg-Universität, Mainz, Germany:
Patrick Achenbach, Carlos Ayerbe, Ralph Böhm, Michael O. Distler, **Anselm Esser**, Mar Gomez, Alicia Sanchez-Lorente, Harald Merkel, Ulrich Müller, Josef Pochodzalla, Takehiko Saito, Björn Sören Schlimme, Matthias Schoth, **Florian Schulz**, Concettina Sfienti, Adrian Weber
University of Ljubljana and Institut "Josef Stefan", Ljubljana, Slovenia:
Luka Debenjak, Simon Sirca
Department of Physics, University of Zagreb, Croatia:
Damir Bosnar, Ivica Friscic
Department of Physics, Hampton University, VA, USA:
Liguang Tang
Department of Physics, Florida International University, Miami, FL, USA:
Joerg Reinhold
Yerevan Physics Institute, Yerevan, Armenia:
Amur Margaryan
Department of Physics, Tohoku University, Sendai, Japan:
Osamu Hashimoto, Satoshi N. Nakamura, Kyo Tsukada, Toshiyuki Gogami, **Sho Nagao**
GSI, Darmstadt, Germany:
Olga Borodina, Vakkas Bozkurt, Eunhee Kim, Christophe Rappold