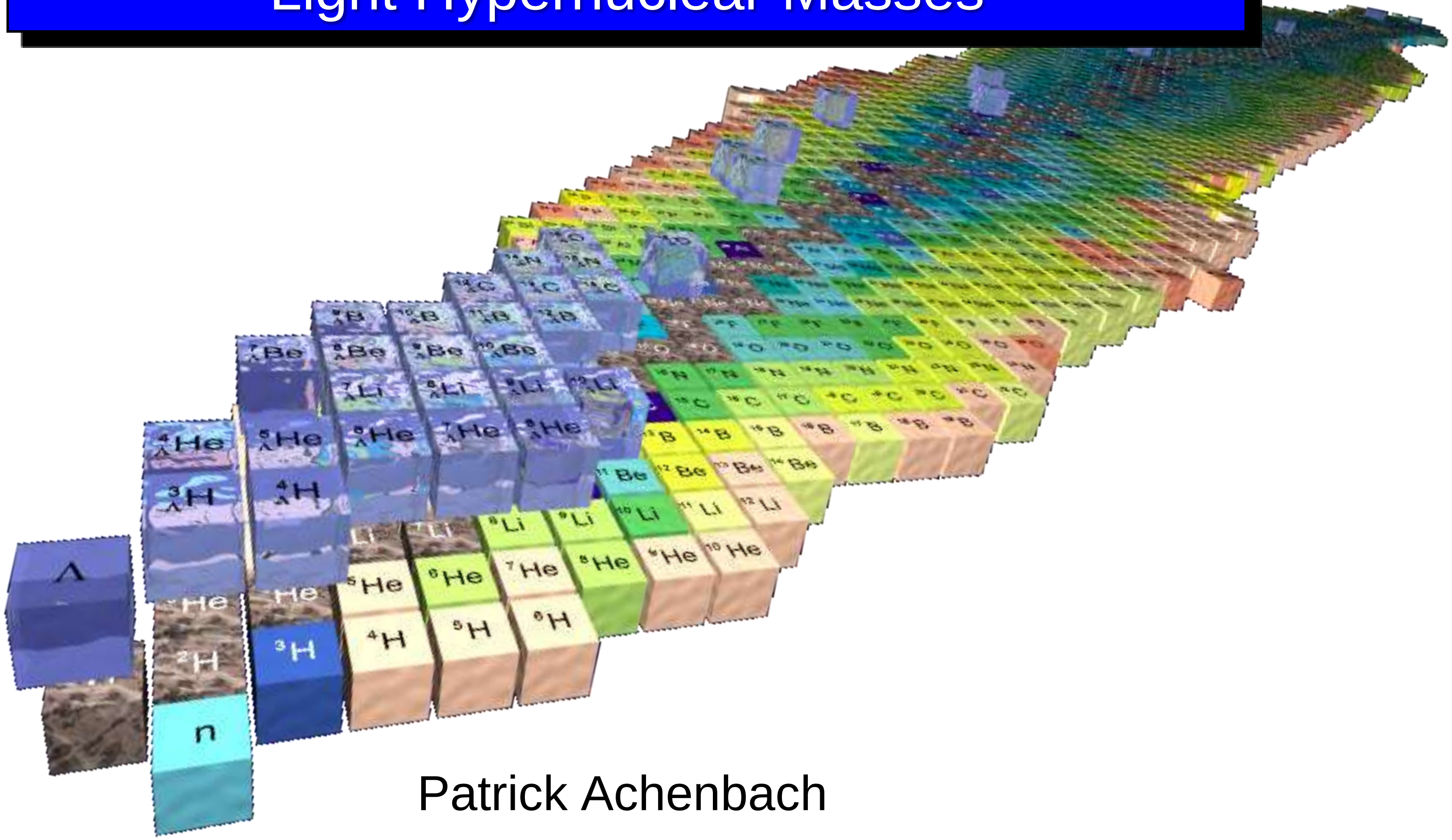
# Precision Spectroscopy of Light Hypernuclear Masses




Patrick Achenbach

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Jan. 2o15

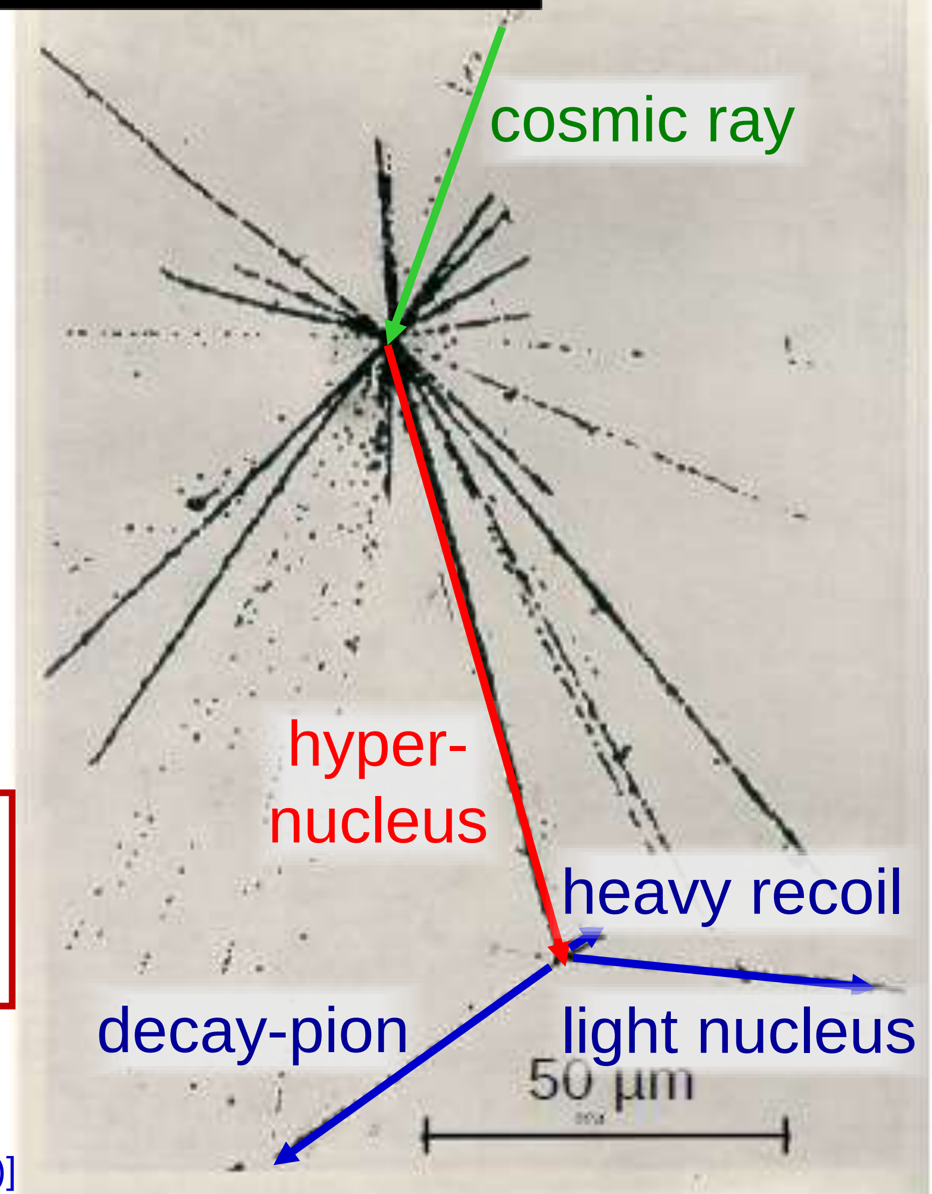
# First observation of a hypernucleus

*Delayed Disintegration of a Heavy Nuclear Fragment: I* *

By M. Danysz and J. Pniewski
Institute of Experimental Physics, University of Warsaw †

“An alternative explanation of the event may be sought in terms of the heavy neutral V-particle […] It is possible that such particles exist not only as free particles, but also in bound states within nuclei.”

- production in nuclear fragmentation
- identification through pionic decay




[M. Danysz & J. Pniewski, Philos. Mag. 7 (44), 348 (1953)]

# List of known hypernuclear masses

| El | A | J(g.s.) | $B_\Lambda$(g.s.) |
|---|---|---|---|
| H | 3 | 1/2+ | 0.13 *5* |
| | 4 | 0+ | 2.04 *4* |
| He | 4 | 0+ | 2.39 *3* |
| | 5 | 1/2+ | 3.12 *2* |
| | 6 | | 4.18 *10* |
| | 8 | | 7.16 *70* |
| Li | 6 | | |
| | 7 | 1/2+[a] | 5.58 *3* |
| | 8 | 1− | 6.80 *3* |
| | 9 | | 8.50 *12* |
| Be | 7 | 1/2+ | 5.16 *8* |
| | 8 | | 6.84 *5* |
| | 9 | 1/2+ | 6.71 *4* |
| | 10 | | 9.11 *22* |
| B | 9 | | 8.29 *18* |
| | 10 | | 8.89 *12* |
| | 11 | | 10.24 *5* |
| | 12 | 1− | 11.37 *6* |
| C | 12 | 1− | 10.80 *18*[b] |
| | 13 | 1/2+ | 11.69 *12* |
| | 14 | | 12.17 *33* |

| El | A | J(g.s.) | $B_\Lambda$(g.s.) |
|---|---|---|---|
| N | 14 | | |
| | 15 | 3/2+[c] | |
| | 16 | | 13.76 *16*[d] |
| O | 16 | 0− | 12.42 *5* |
| | 18 | | |
| Al | 27 | | |
| | 28 | e | |
| Si | 28 | | 16.6 *2* |
| S | 32 | | |
| Ca | 40 | | |
| V | 51 | | 20.0 *2* |
| Fe | 56 | | |
| Y | 89 | | 23.1 *5* |
| La | 139 | | 24.5 *12* |
| Pb | 208 | | 26.3 *8* |
| Bi | 209 | | |

$$-B_\Lambda = M_{HYP} - (M_{Core} + m_\Lambda)$$

poor hypernuclei data compared to ordinary nuclei:

- nuclear structure information for ~ 28 hypernuclides *vs.* 3175 nuclides
- mass error given by error on Λ binding energy of ~ 20-800 keV for hypernuclei *vs.* ε

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

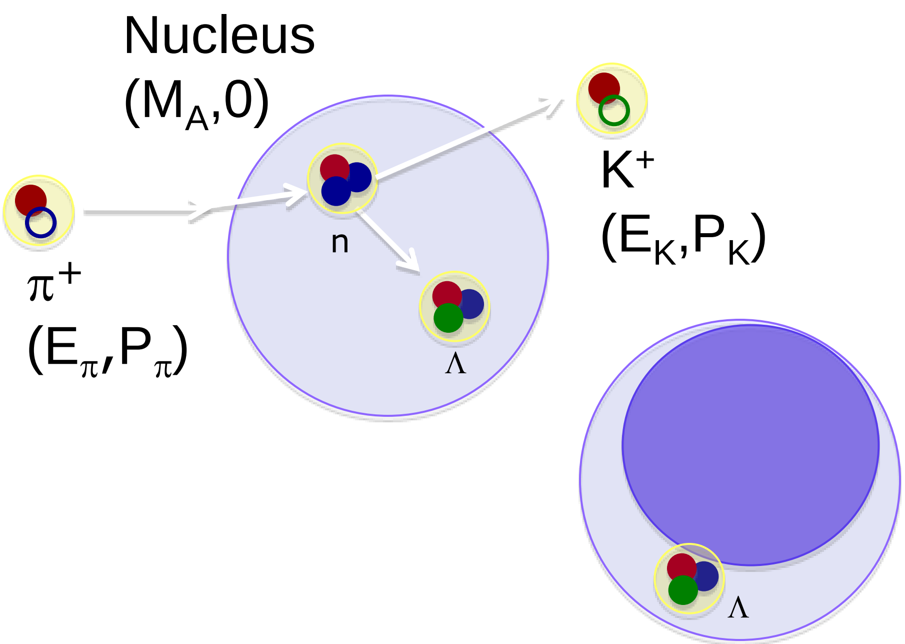
# Medium to heavy hypernuclei A > 14

| El | A | J(g.s.) | $B_\Lambda$(g.s.) |
|---|---|---|---|
| N | 14 | | |
| | 15 | 3/2+[c] | |
| | 16 | | 13.76 *16*[d] |
| O | 16 | 0− | 12.42 *5* |
| | 18 | | |
| Al | 27 | | |
| | 28 | e | |
| Si | 28 | | 16.6 *2* |
| S | 32 | | |
| Ca | 40 | | |
| V | 51 | | 20.0 *2* |
| Fe | 56 | | |
| Y | 89 | | 23.1 *5* |
| La | 139 | | 24.5 *12* |
| Pb | 208 | | 26.3 *8* |
| Bi | 209 | | |

data from counter experiments in ($\pi^+$,$K^+$) or ($K^-$, $\pi^-$) reactions using thick targets ~ 1500-3000 keV mass resolution

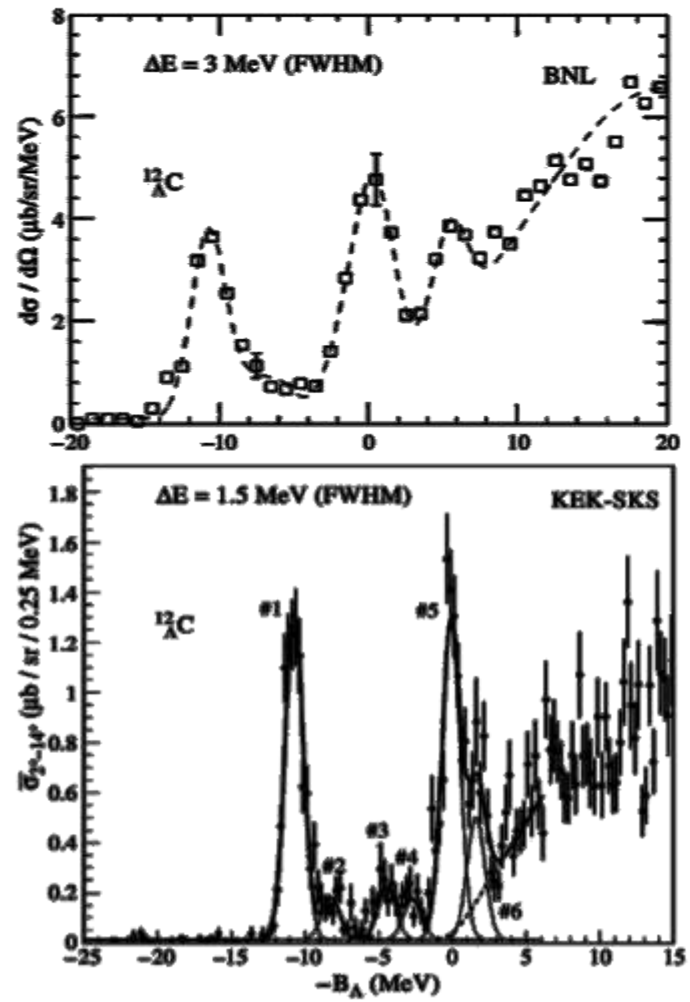
Experimental data in MeV from [Nuclear Wallet Cards, BNL, 2011]

# Production spectroscopy




$$M_{HYP} = \sqrt{(E_\pi + M_A - E_K)^2 - (p_\pi - p_K)^2}$$

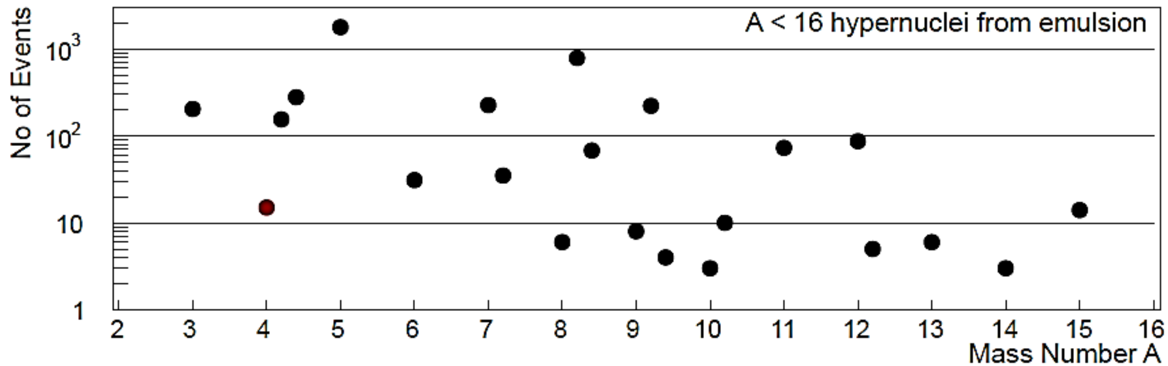
BNL-AGS 3 MeV (FWHM)
[Pile et al., Phys. Rev. Lett. 66 (1991) 2585]




KEK-SKS: 1.5 MeV (FWHM)
[Hotchi et al., Phys. Rev. C 64(2001) 044302]

# Light hypernuclear masses A ≤ 14

| El | A | J(g.s.) | $B_\Lambda$(g.s.) |
|---|---|---|---|
| H | 3 | 1/2+ | 0.13 *5* |
| | 4 | 0+ | 2.04 *4* |
| He | 4 | 0+ | 2.39 *3* |
| | 5 | 1/2+ | 3.12 *2* |
| | 6 | | 4.18 *10* |
| | 8 | | 7.16 *70* |
| Li | 6 | | |
| | 7 | 1/2+[a] | 5.58 *3* |
| | 8 | 1− | 6.80 *3* |
| | 9 | | 8.50 *12* |
| Be | 7 | 1/2+ | 5.16 *8* |
| | 8 | | 6.84 *5* |
| | 9 | 1/2+ | 6.71 *4* |
| | 10 | | 9.11 *22* |
| B | 9 | | 8.29 *18* |
| | 10 | | 8.89 *12* |
| | 11 | | 10.24 *5* |
| | 12 | 1− | 11.37 *6* |
| C | 12 | 1− | 10.80 *18*[b] |
| | 13 | 1/2+ | 11.69 *12* |
| | 14 | | 12.17 *33* |



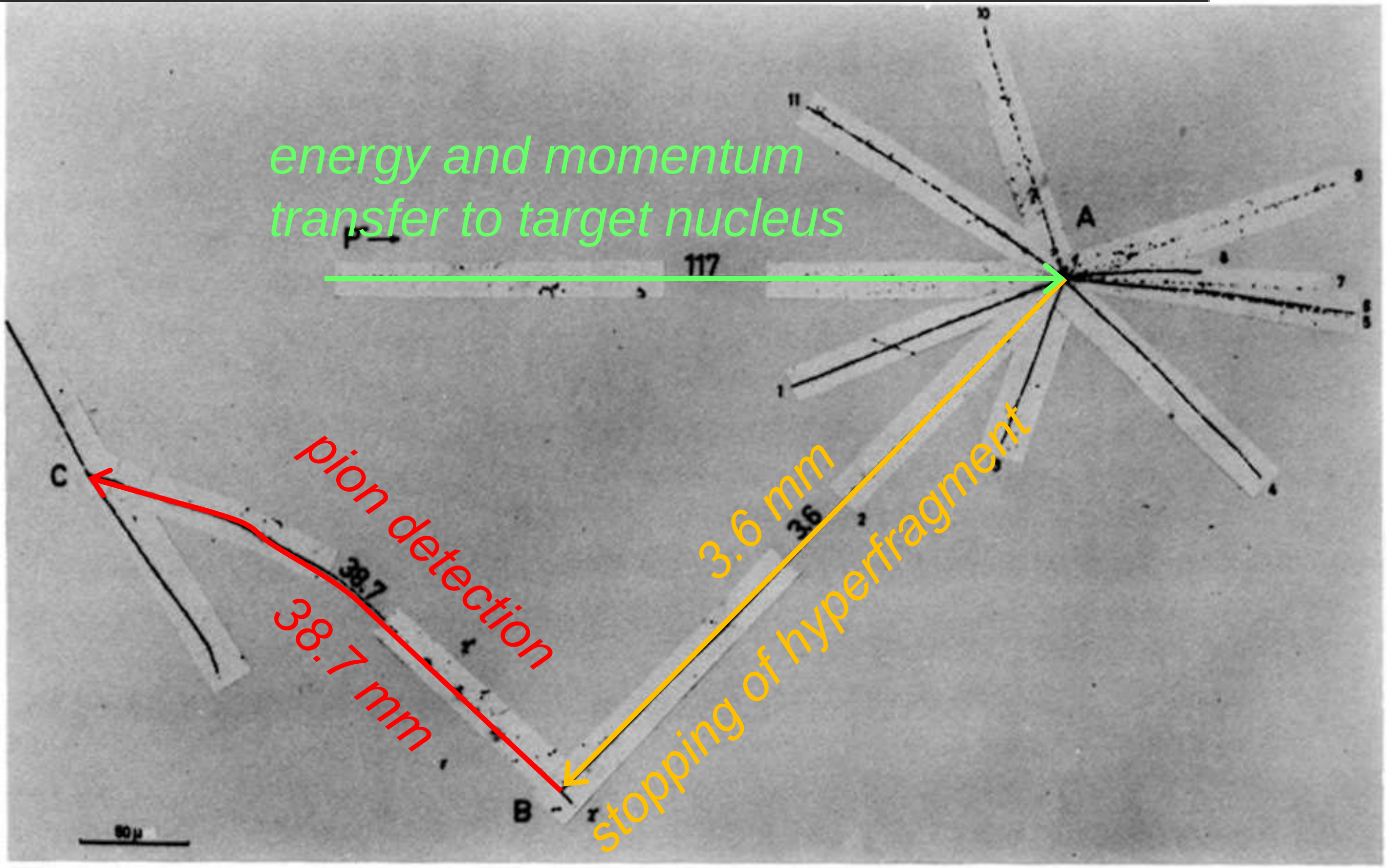

data from emulsion experiments

- often low event counts
- systematic difficulties because of varying emulsion properties
- in addition new data on $^{7}_{\Lambda}$He by HKS (±250 keV) and $^{6}_{\Lambda}$Li and $^{6}_{\Lambda}$H by FINUDA (±1100 keV)

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

# Hypernuclear decay-pion spectroscopy in emulsion

Example for $_{\Lambda}^{4}H$



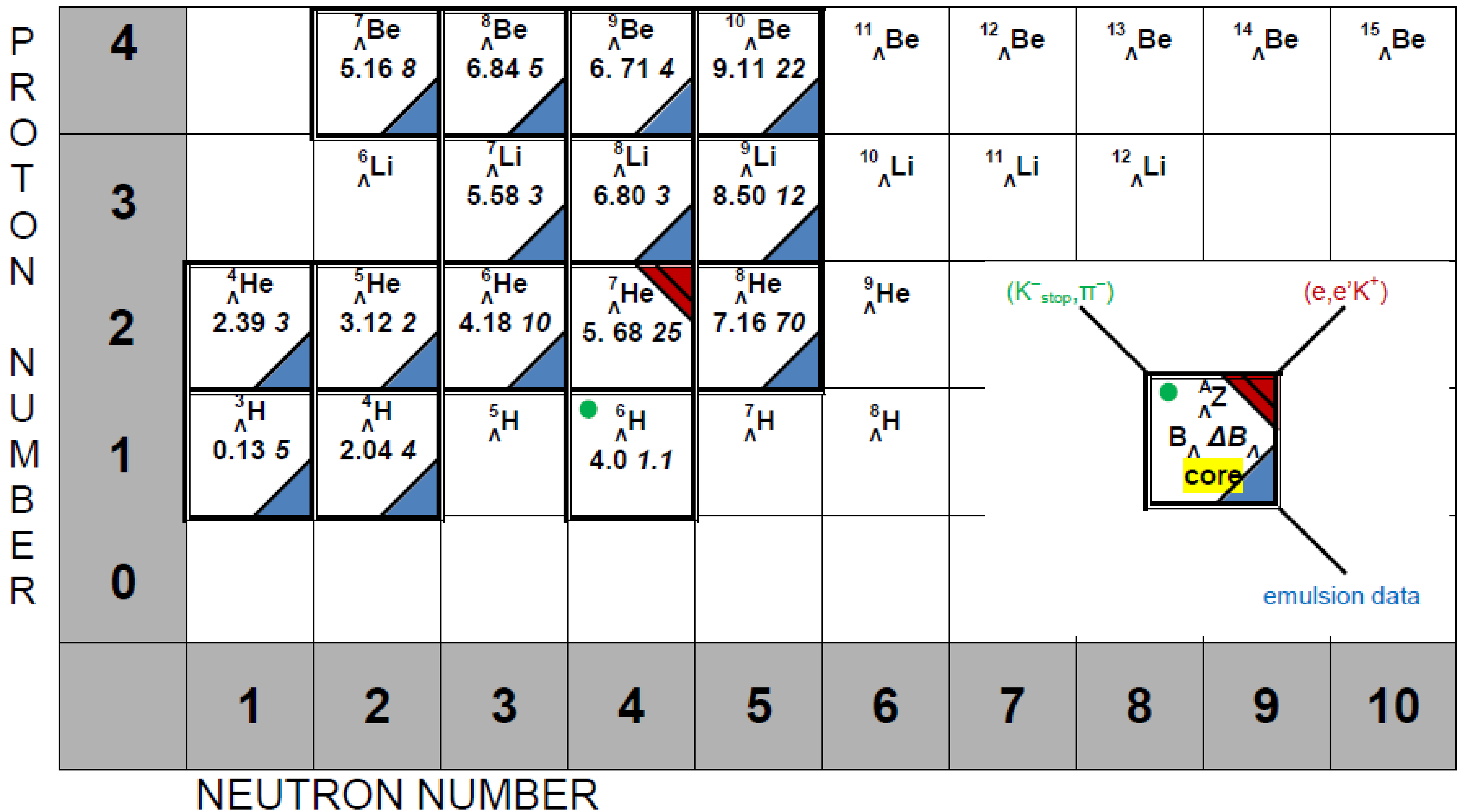

The result is that the event is consistent only with a $_{\Lambda}H^4$ fragment undergoing mesonic two-body decay. The binding energy of the $\Lambda$ in $_{\Lambda}H^4$ is then $B_{\Lambda} = 2.6 \pm 1.0$ Mev, which is consistent also with other measurements of this quantity.[9]

$$_{\Lambda}H^4 \rightarrow He^4 + \pi^- + Q,$$

where $Q = 54.6 \pm 1.0$ Mev.

[A.G. Ekspong et al., Phys. Rev. Lett. 3 (1959) 103]

# Spectroscopy of light hypernuclei



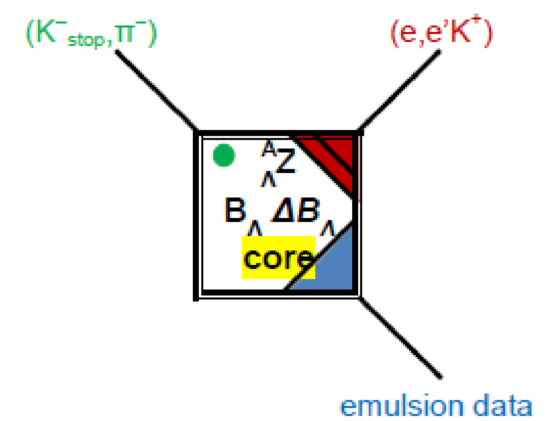
# Spectroscopy of light hypernuclei

superheavy unstable-core hyperisotopes exist because of the stabilizing role of the Λ-hyperon [Dalitz & Levi Setti, NC 30 (1963)]

**unbd** unbound core nucleus

| PROTON NUMBER | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **4** | | $^{7}_{\Lambda}$Be 5.16 *8* unbd | $^{8}_{\Lambda}$Be 6.84 *5* | $^{9}_{\Lambda}$Be 6. 71 *4* unbd | $^{10}_{\Lambda}$Be 9.11 *22* | $^{11}_{\Lambda}$Be | $^{12}_{\Lambda}$Be | $^{13}_{\Lambda}$Be | $^{14}_{\Lambda}$Be unbd | $^{15}_{\Lambda}$Be |
| **3** | | $^{6}_{\Lambda}$Li unbd | $^{7}_{\Lambda}$Li 5.58 *3* | $^{8}_{\Lambda}$Li 6.80 *3* | $^{9}_{\Lambda}$Li 8.50 *12* | $^{10}_{\Lambda}$Li | $^{11}_{\Lambda}$Li unbd | $^{12}_{\Lambda}$Li | | |
| **2** | $^{4}_{\Lambda}$He 2.39 *3* | $^{5}_{\Lambda}$He 3.12 *2* | $^{6}_{\Lambda}$He 4.18 *10* unbd | $^{7}_{\Lambda}$He 5. 68 *25* | $^{8}_{\Lambda}$He 7.16 *70* unbd | $^{9}_{\Lambda}$He | | | | |
| **1** | $^{3}_{\Lambda}$H 0.13 *5* | $^{4}_{\Lambda}$H 2.04 *4* | $^{5}_{\Lambda}$H unbd | $^{6}_{\Lambda}$H 4.0 *1.1* unbd | $^{7}_{\Lambda}$H unbd | $^{8}_{\Lambda}$H unbd | | | | |
| **0** | | | | | | | | | | |
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |

NEUTRON NUMBER



# Spectroscopy of light hypernuclei

undiscovered

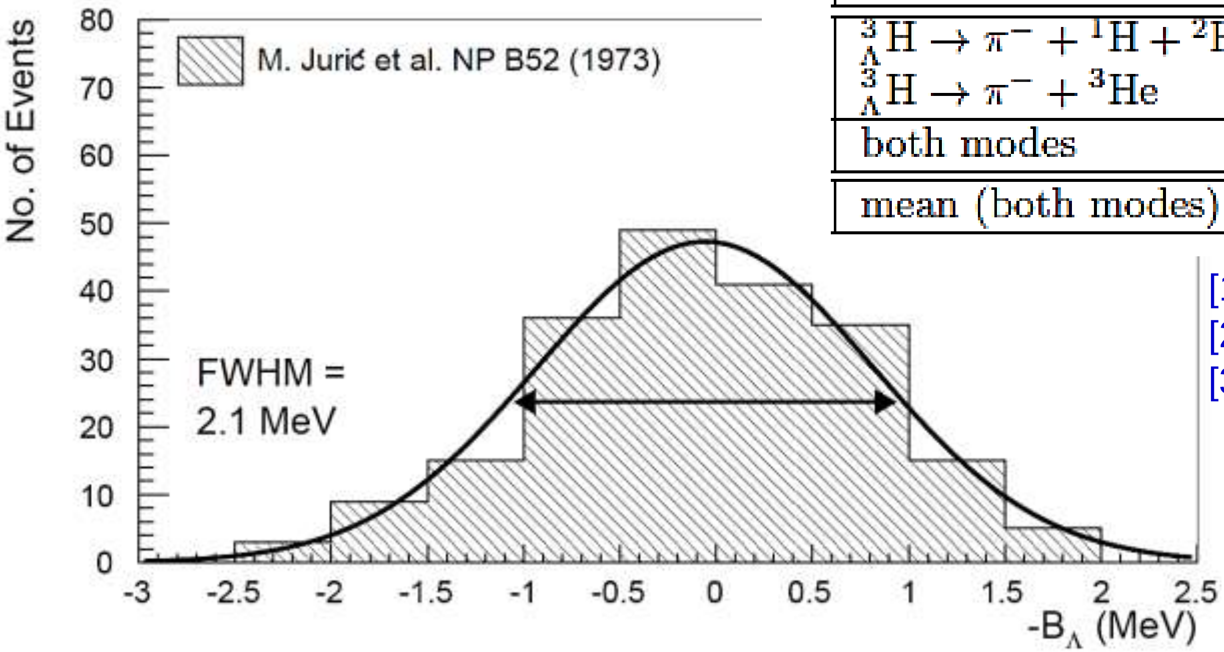
| PROTON NUMBER | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 4 | | ${}^{7}_{\Lambda}$Be 5.16 *8* unbd | ${}^{8}_{\Lambda}$Be 6.84 *5* | ${}^{9}_{\Lambda}$Be 6. 71 *4* unbd | ${}^{10}_{\Lambda}$Be 9.11 *22* | ${}^{11}_{\Lambda}$Be | ${}^{12}_{\Lambda}$Be | ${}^{13}_{\Lambda}$Be | ${}^{14}_{\Lambda}$Be unbd | ${}^{15}_{\Lambda}$Be |
| 3 | | ${}^{6}_{\Lambda}$Li unbd | ${}^{7}_{\Lambda}$Li 5.58 *3* | ${}^{8}_{\Lambda}$Li 6.80 *3* | ${}^{9}_{\Lambda}$Li 8.50 *12* | ${}^{10}_{\Lambda}$Li | ${}^{11}_{\Lambda}$Li unbd | ${}^{12}_{\Lambda}$Li | | |
| 2 | ${}^{4}_{\Lambda}$He 2.39 *3* | ${}^{5}_{\Lambda}$He 3.12 *2* | ${}^{6}_{\Lambda}$He 4.18 *10* unbd | ${}^{7}_{\Lambda}$He 5. 68 *25* | ${}^{8}_{\Lambda}$He 7.16 *70* unbd | ${}^{9}_{\Lambda}$He | | | | |
| 1 | ${}^{3}_{\Lambda}$H 0.13 *5* | ${}^{4}_{\Lambda}$H 2.04 *4* | ${}^{5}_{\Lambda}$H unbd | ${}^{6}_{\Lambda}$H 4.0 *1.1* unbd | ${}^{7}_{\Lambda}$H unbd | ${}^{8}_{\Lambda}$H unbd | | | | |
| 0 | | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

NEUTRON NUMBER

# The mass $A = 3$ System

# World data on $^3_\Lambda$H

| $^3_\Lambda$H decay mode | $N$ | $B_\Lambda$ (MeV) | Ref. |
|---|---|---|---|
| $^3_\Lambda H \to \pi^- + {}^1H + {}^2H$ | 24 | $+0.23 \pm 0.11$ | [1] |
| $^3_\Lambda H \to \pi^- + {}^3He$ | 58 | $+0.06 \pm 0.11$ | [1] |
| both modes | 82 | $+0.15 \pm 0.08$ | [1] |
| $^3_\Lambda H \to \pi^- + {}^1H + {}^2H$ | 16 | $-0.11 \pm 0.13$ | [2] |
| $^3_\Lambda H \to \pi^- + {}^3He$ | 86 | $+0.05 \pm 0.08$ | [2] |
| both modes | 102 | $+0.01 \pm 0.07$ | [2] |
| $^3_\Lambda H \to \pi^- + {}^1H + {}^2H$ | 6 | $+0.33 \pm 0.21$ | [3] |
| $^3_\Lambda H \to \pi^- + {}^3He$ | 26 | $+0.13 \pm 0.15$ | [3] |
| both modes | 32 | $+0.20 \pm 0.12$ | [3] |
| mean (both modes) | 204 | $+0.13 \pm 0.05$ | [1] |

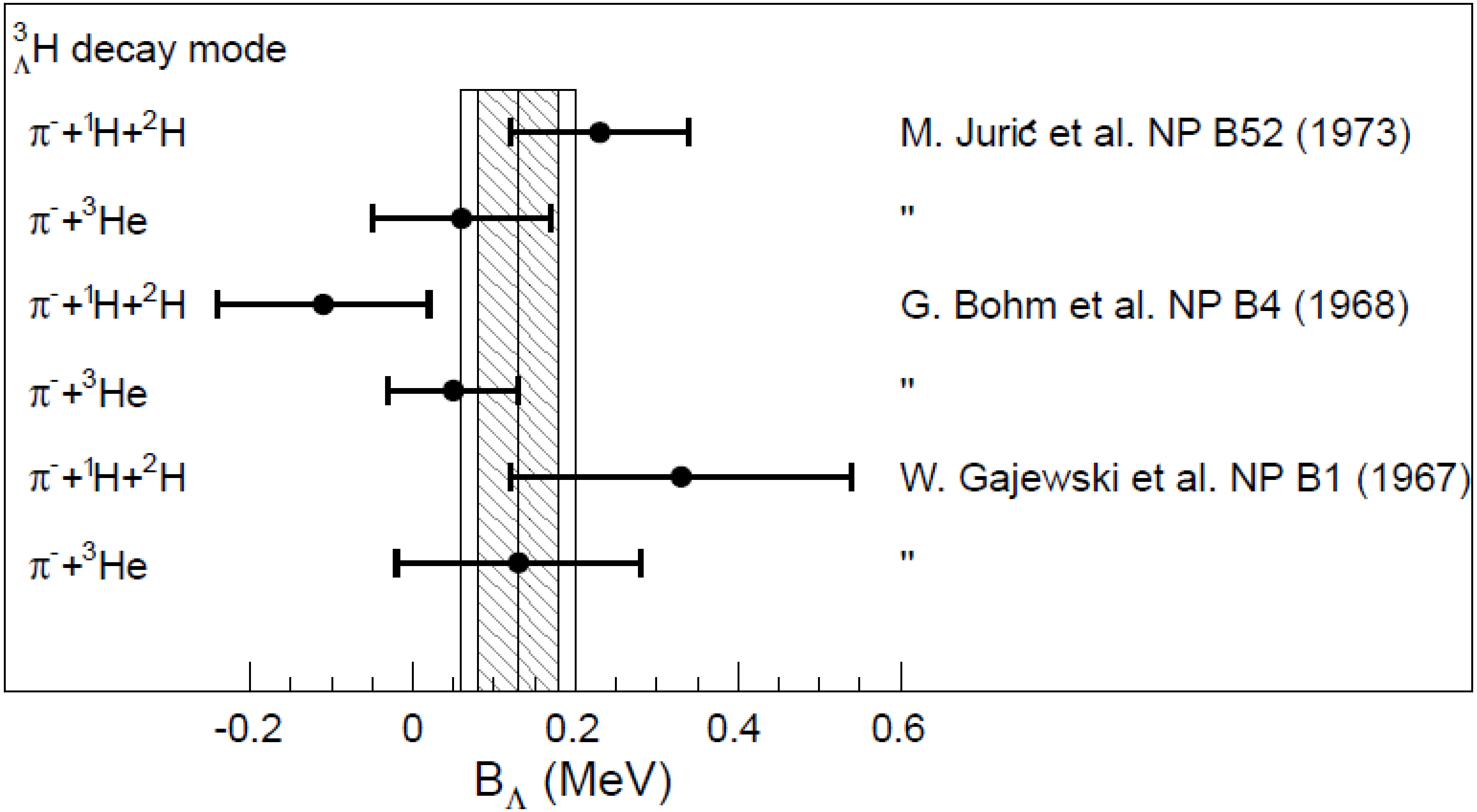




[1] M. Juric et al., NP B52 (1973)
[2] G. Bohm et al. NP B4 (1968)
[3] W. Gajewski et al. NP B1 (1967)


Hypertriton: the lightest bound hypernuclear system
about 200 analysed events from emulsion experiments

# World data on $^{3}_{\Lambda}H$

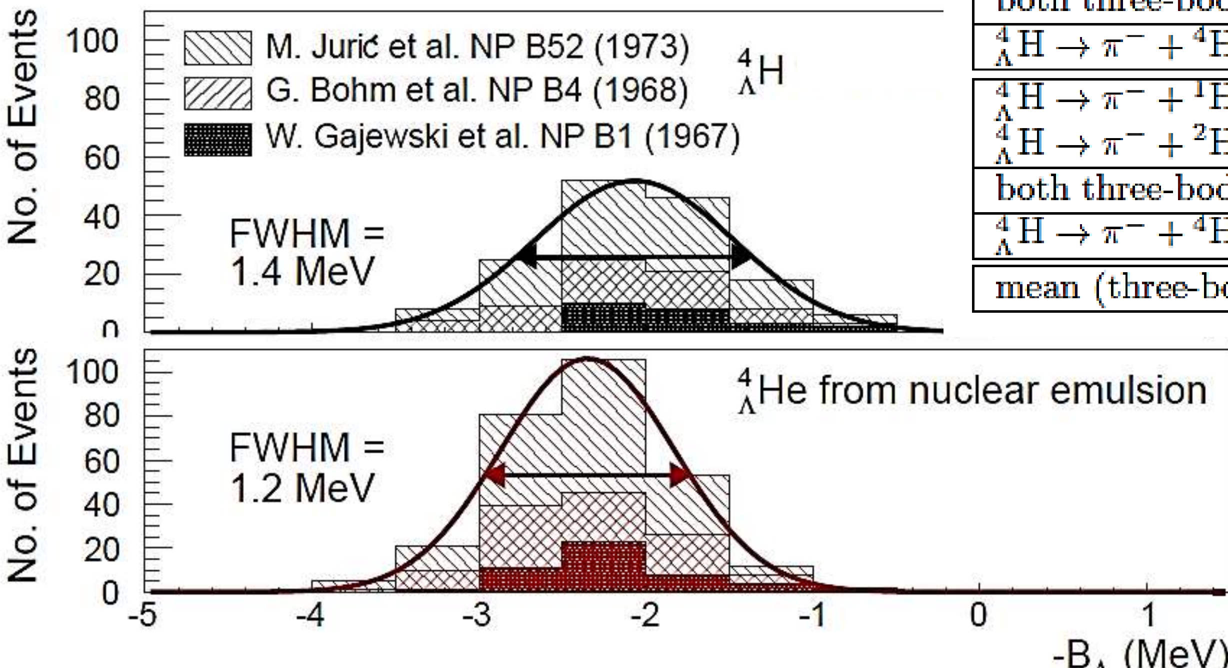



Two-body and three-body decays in agreement

# The mass $A = 4$ System

# World data on *A* = *4* system

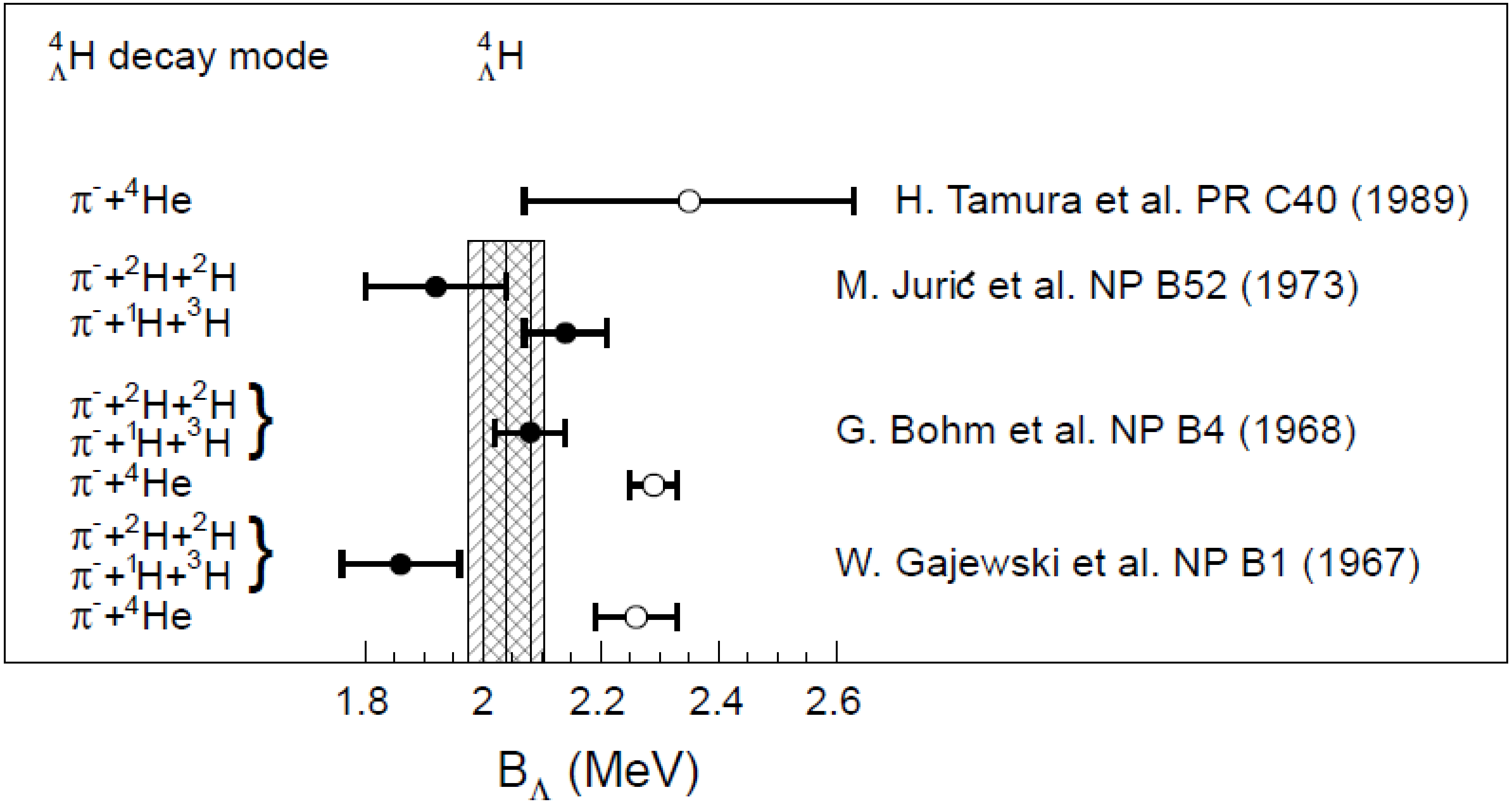
| $^4_\Lambda$H decay mode | $N$ | $B_\Lambda$ (MeV) | Ref. |
|---|---|---|---|
| $^4_\Lambda\mathrm{H} \to \pi^- + {}^1\mathrm{H} + {}^3\mathrm{H}$ | 56 | $+2.14 \pm 0.07$ | [1] |
| $^4_\Lambda\mathrm{H} \to \pi^- + {}^2\mathrm{H} + {}^2\mathrm{H}$ | 11 | $+1.92 \pm 0.12$ | [1] |
| both three-body modes | 67 | $+2.08 \pm 0.06$ | [1] |
| $^4_\Lambda\mathrm{H} \to \pi^- + {}^1\mathrm{H} + {}^3\mathrm{H}$ | 63 | | [2] |
| $^4_\Lambda\mathrm{H} \to \pi^- + {}^2\mathrm{H} + {}^2\mathrm{H}$ | 7 | | [2] |
| both three-body modes | 70 | $+2.08 \pm 0.06$ | [2] |
| $^4_\Lambda\mathrm{H} \to \pi^- + {}^4\mathrm{He}$ | 552 | $+2.29 \pm 0.04$ | [2] |
| $^4_\Lambda\mathrm{H} \to \pi^- + {}^1\mathrm{H} + {}^3\mathrm{H}$ | 21 | | [3] |
| $^4_\Lambda\mathrm{H} \to \pi^- + {}^2\mathrm{H} + {}^2\mathrm{H}$ | 2 | | [3] |
| both three-body modes | 23 | $+1.86 \pm 0.10$ | [3] |
| $^4_\Lambda\mathrm{H} \to \pi^- + {}^4\mathrm{He}$ | 208 | $+2.26 \pm 0.07$ | [3] |
| mean (three-body) | 155 | $+2.04 \pm 0.04$ | [1] |




[1] M. Juric et al., NP B52 (1973)
[2] G. Bohm et al. NP B4 (1968)
[3] W. Gajewski et al. NP B1 (1967)

- Only three-body decay modes used for hyperhydrogen
- 155 events for hyperhydrogen, 279 events for hyperhelium

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

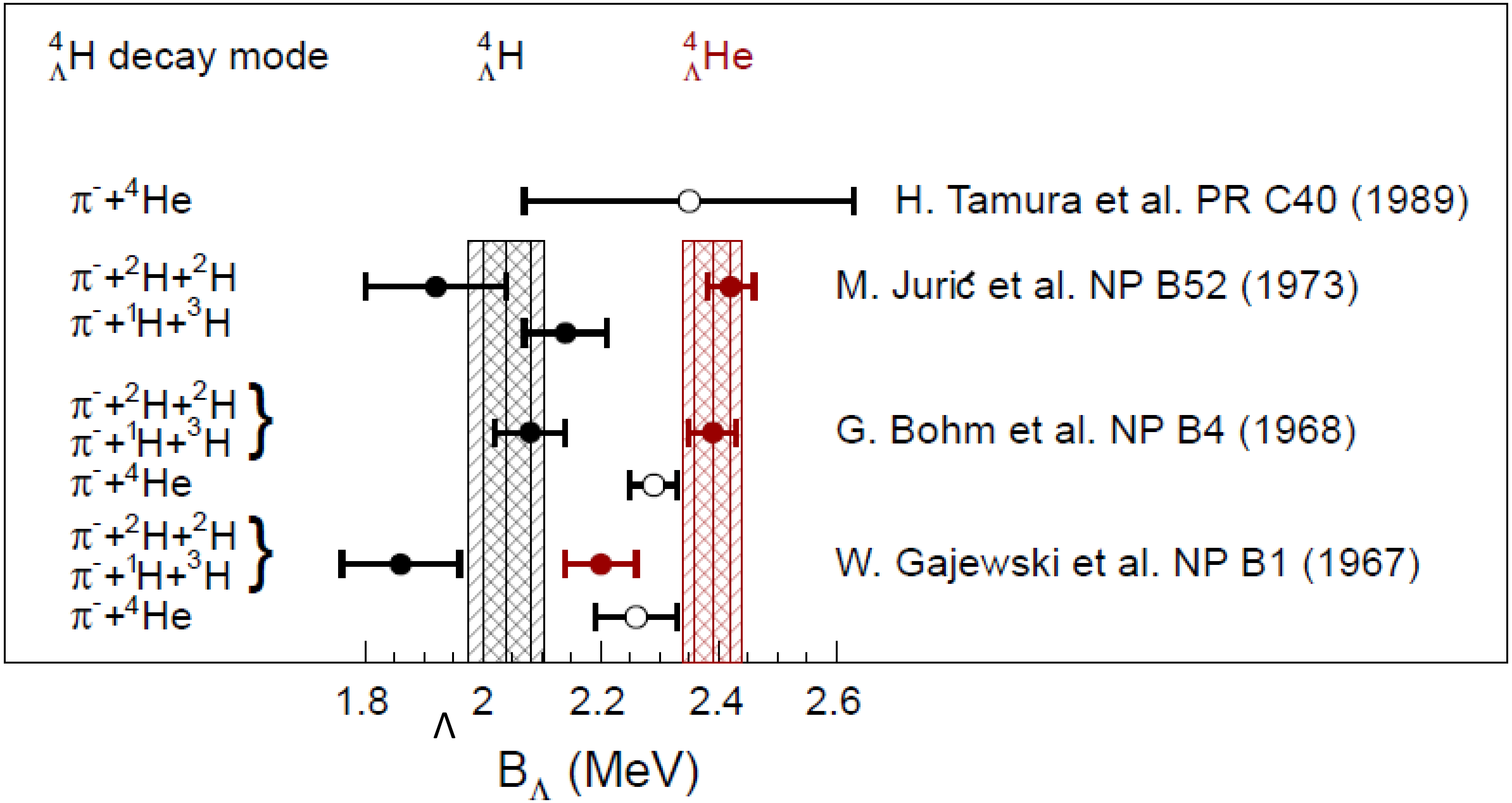



$$\left.\begin{array}{l} {}_{\Lambda}^{4}H \xrightarrow{\text{decay}} \pi^- + {}^1H + {}^3H:\ B = 2.14 \pm 0.07\ \text{MeV} \\ {}_{\Lambda}^{4}H \xrightarrow{\text{decay}} \pi^- + {}^2H + {}^2H:\ B = 1.92 \pm 0.12\ \text{MeV} \end{array}\right\}\ 0.22\ \text{MeV difference}$$

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

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

# World data on $A = 4$ system



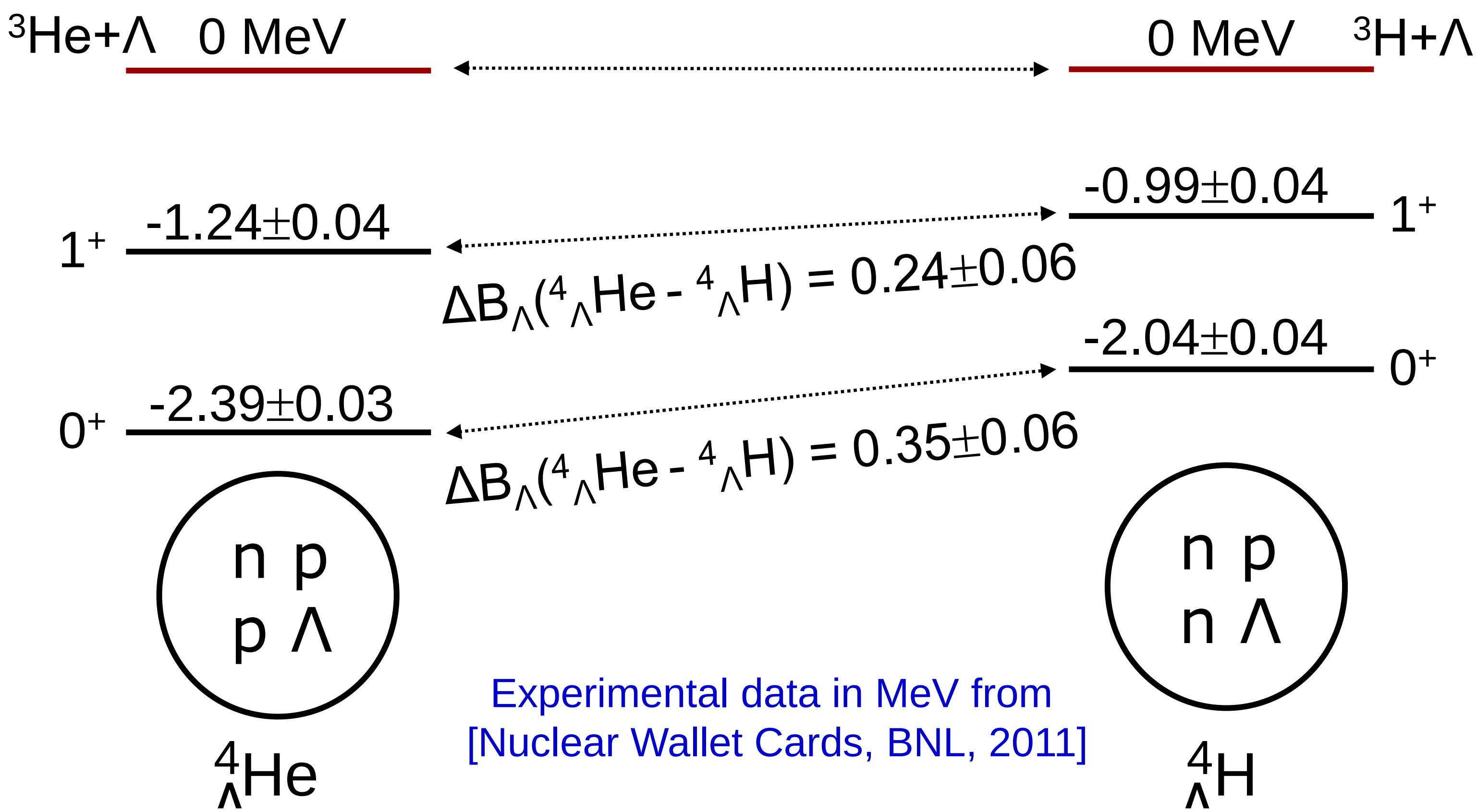

$$^4_\Lambda\text{He} \xrightarrow{\text{decay}} \pi^- + {}^1\text{H} + {}^3\text{He}: B = 2.42 \pm 0.05 \text{ MeV}$$

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

0.02 MeV difference

Total: $B = 2.42 \pm 0.04$ MeV [M. Juric et al. NP B52 (1973)]

# The $A$ = 4 isospin doublet



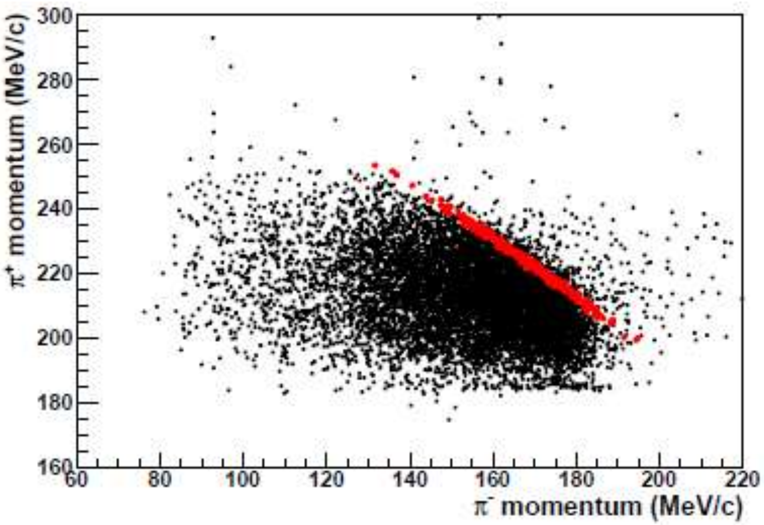

- Nucleon-hyperon interaction can be studied by strange mirror pairs
- Coulomb corrections are < 50 keV for the $^4{}_\Lambda$H - $^4{}_\Lambda$He pair

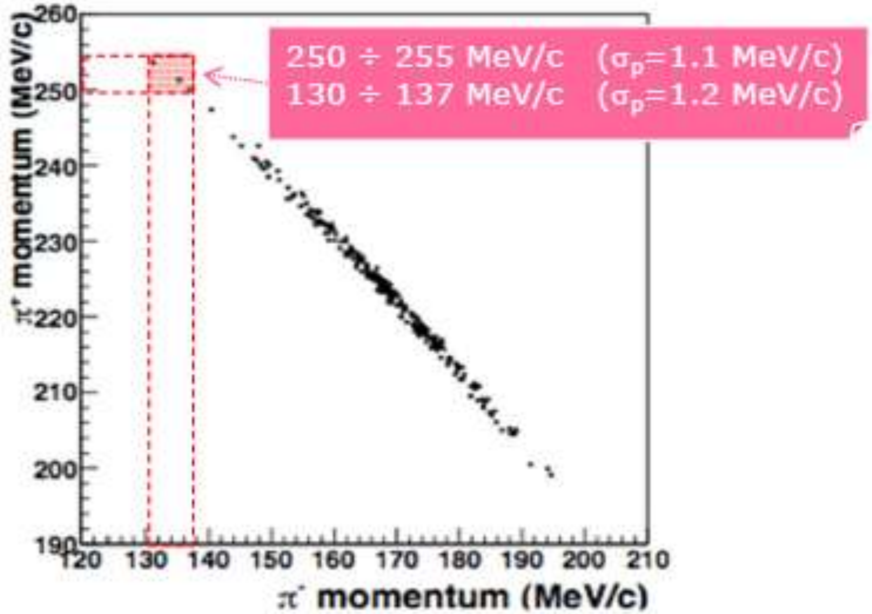
# Modern calculations on *A = 4* system

| Calculation | Interaction | $B_\Lambda(^4_\Lambda H_{gs})$ | $B_\Lambda(^4_\Lambda He_{gs})$ | $\Delta B_\Lambda$ $(^4_\Lambda He - ^4_\Lambda H)$ |
|---|---|---|---|---|
| A. Nogga, H. Kamada and W. Gloeckle, PRL 88, 172501 (2002) | SC97e | 1.47 | 1.54 | 0.07 |
| | SC89 | 2.14 | 1.80 | 0.34 |
| H. Nemura. Y. Akaishi and Y. Suzuki, PRL 89, 142504 (2002) | SC97d | 1.67 | 1.62 | -0.05 |
| | SC97e | 2.06 | 2.02 | -0.04 |
| | SC97f | 2.16 | 2.11 | -0.05 |
| | SC89 | 2.55 | 2.47 | -0.08 |
| E. Hiyama, M. Kamimura, T. Motoba, T. Yamada and Y. Yama PRC 65, 011301 (R) (2001) | AV8 | 2.33 | 2.28 | -0.05 |
| World data average | | 2.04±0.04 | 2.39±0.03 | 0.35±0.06 |

With precise spectroscopy details of *NY*-interaction can be inferred

# Observation of $^6_\Lambda$H by FINUDA




$$K^-_{stop} + {}^6Li \rightarrow {}^6_\Lambda H + \pi^+$$

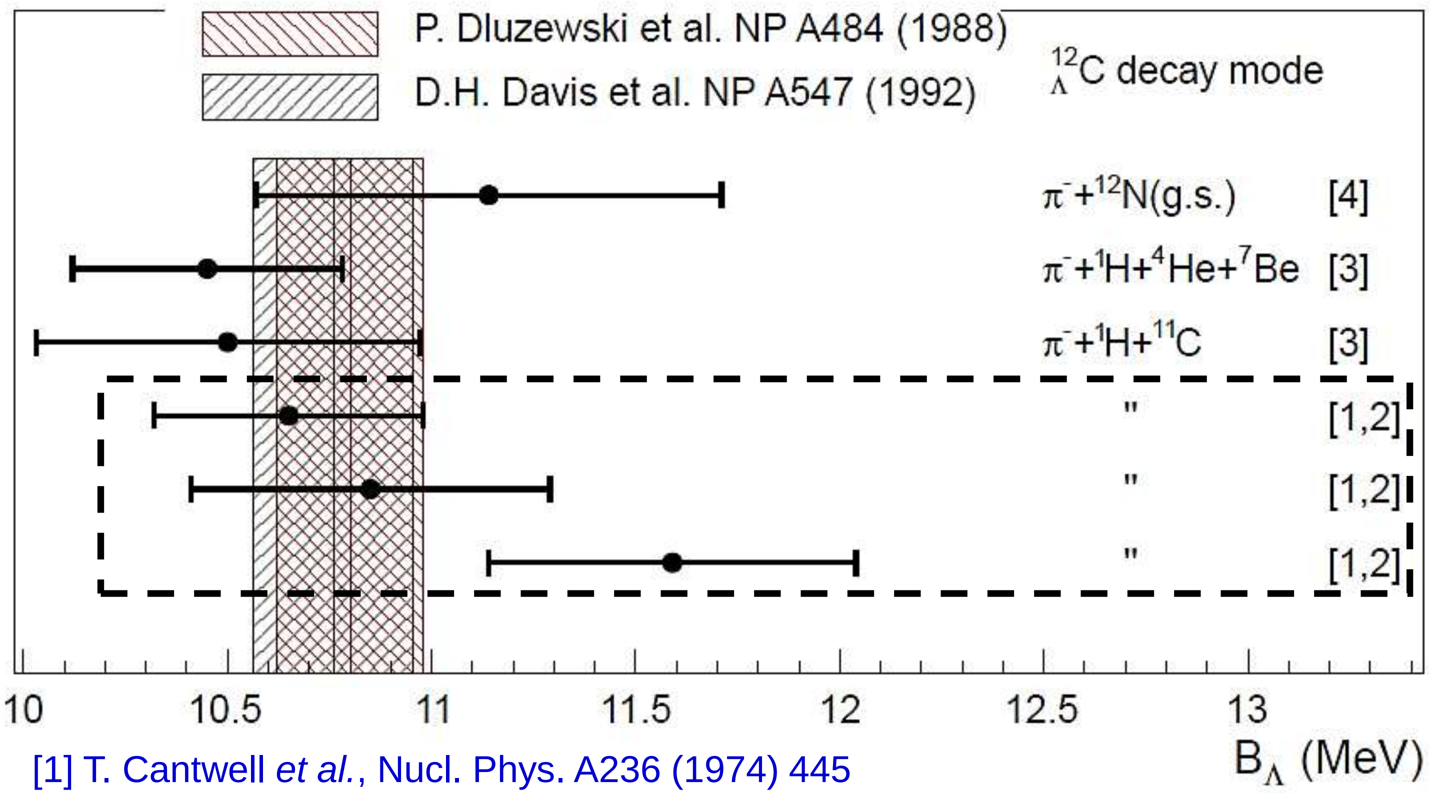
$$^6_\Lambda H \rightarrow {}^6He + \pi^-$$

$(\tau(^6He) \approx 801\ \text{ms})$

| $T_{\text{sum}}$ (MeV) | $p_{\pi^+}$ (MeV/$c$) | $p_{\pi^-}$ (MeV/$c$) | $M(^6_\Lambda\text{H})_{\text{prod.}}$ (MeV) | $M(^6_\Lambda\text{H})_{\text{decay}}$ (MeV) |
|---|---|---|---|---|
| 202.6 ± 1.3 | 251.3 ± 1.1 | 135.1 ± 1.2 | 5802.33 ± 0.96 | 5801.41 ± 0.84 |
| 202.7 ± 1.3 | 250.1 ± 1.1 | 136.9 ± 1.2 | 5803.45 ± 0.96 | 5802.73 ± 0.84 |
| 202.1 ± 1.3 | 253.8 ± 1.1 | 131.2 ± 1.2 | 5799.97 ± 0.96 | 5798.66 ± 0.84 |

[FINUDA, PRL 108, 042501 (2012); arXiv:1203.1954v2 (2012)]

# World data on $^{12}_{\Lambda}C$





[1] T. Cantwell *et al.*, Nucl. Phys. A236 (1974) 445

[2] M. Juric *et al.*, Nucl. Phys. B52 (1973) 1

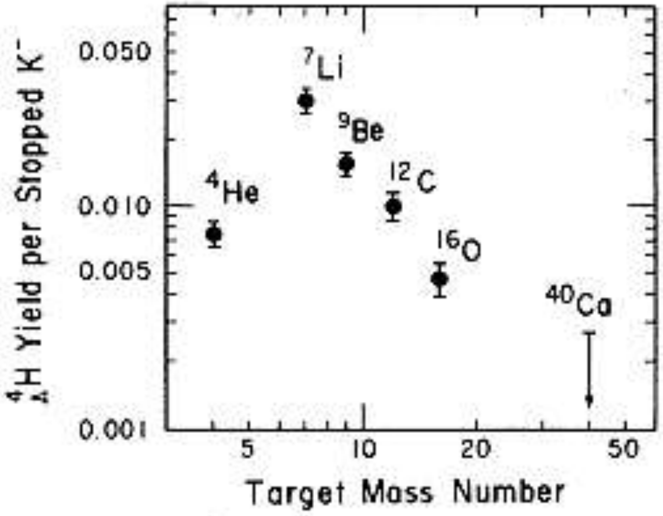
[3] J. Pniewski and D. Zieminska, Proc. of the Seminar on kaon and nucleon interaction and hypernuclei, Zvenigorod (1977) p. 33; Nukleonika 23 (1978) 797; P. Dłuzewski, M.Sc. thesis, University of Warsaw (1977)

[4] S.A. Bunyatov *et al.*, Sov. J. Nucl. Phys. 28 (1978) 222

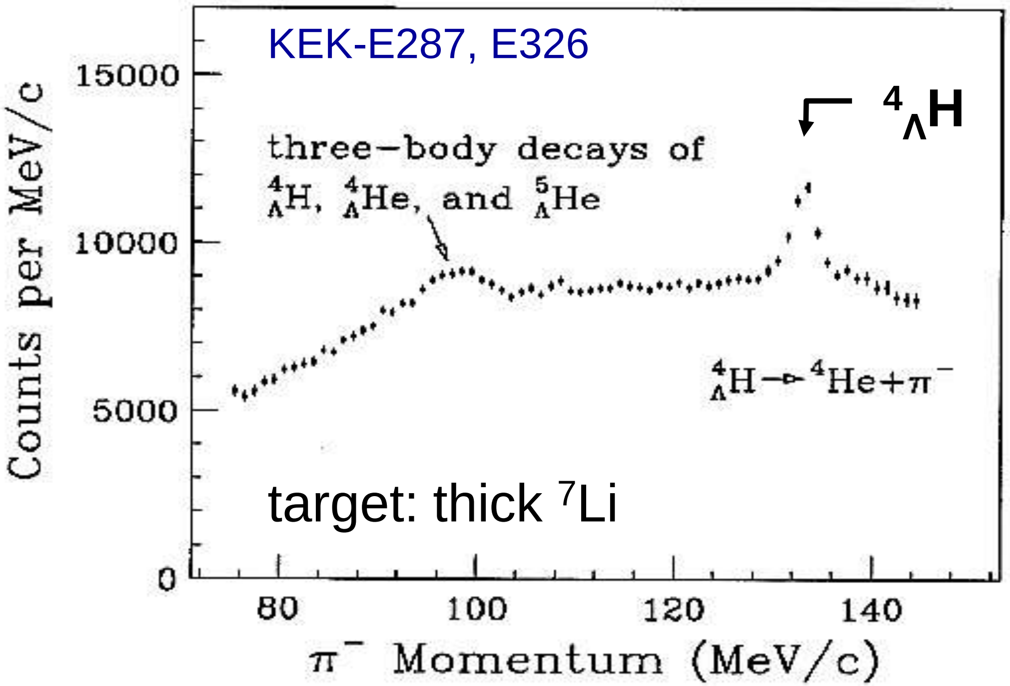

In total only 6 events from 3 different decay modes

# Hyperfragment decay-pion spectroscopy

# Formation of hyperhydrogen on light nuclei



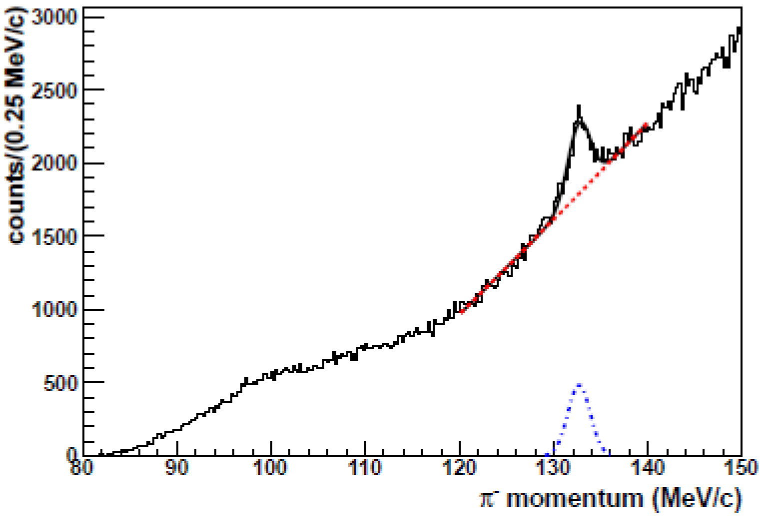

target dependence




- first detection of hyperfragments in a spectrometer
- limited momentum resolution

[H. Tamura et al. Phys. Rev. C 40 (1989)]

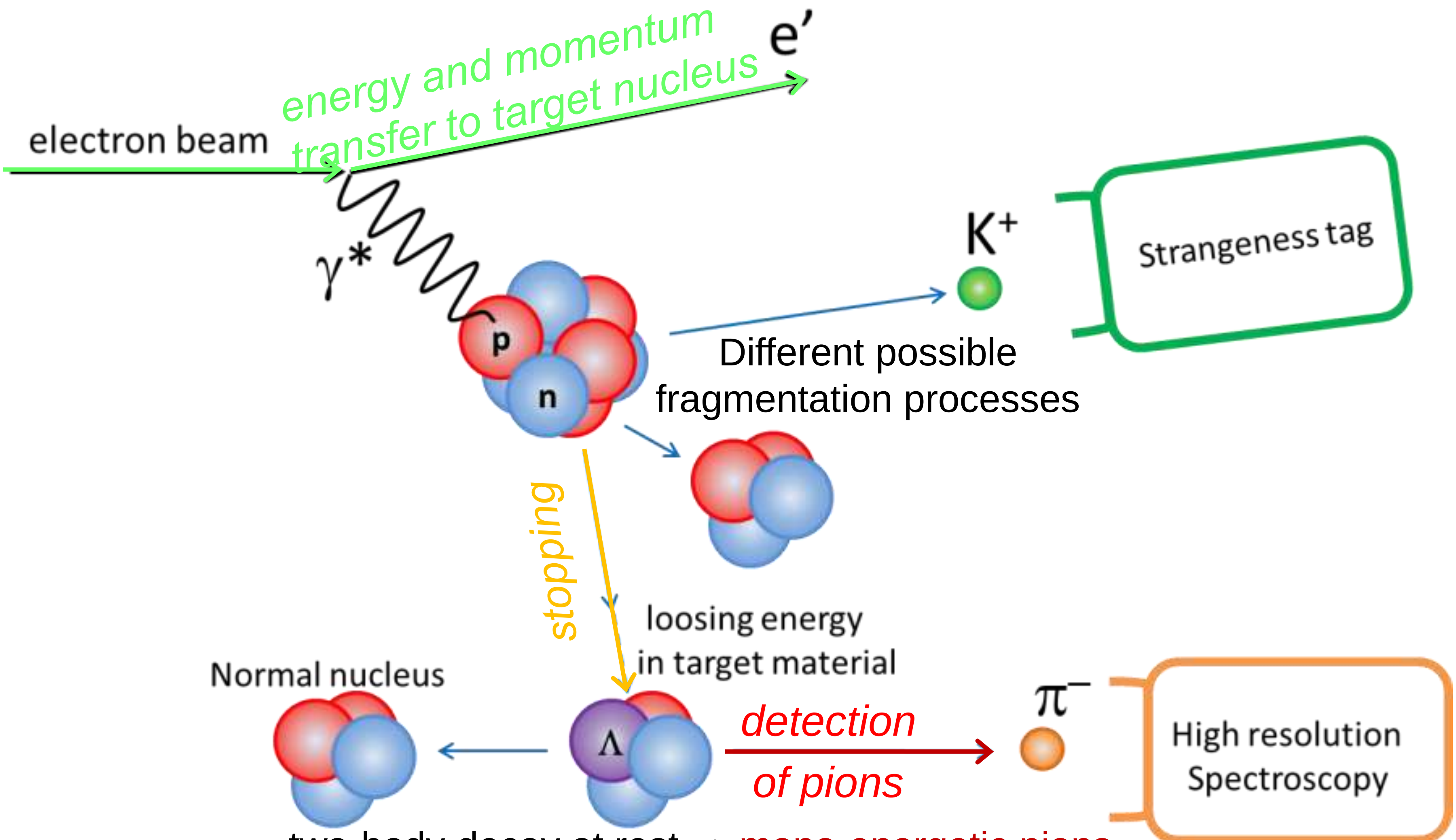
# Observation of $^4_\Lambda$H by FINUDA




gaussian function representing the $^4_\Lambda$H mesonic decay contribution (dot-dashed (blue in the web version) curve); the fit gives a $\chi^2$/ndf = 79.1/74, a mean $\mu_p = (132.6 \pm 0.1)$ MeV/c and a standard deviation $\sigma_p = (1.2 \pm 0.1)$ MeV/c for the gaussian function, directly measuring the experimental resolution. For comparison, $p_{\pi^-} = (132.80 \pm 0.08)$ MeV/c from $B_\Lambda(^4_\Lambda\text{H}) = 2.04 \pm 0.04$ MeV, as determined from emulsion studies [2]; hence the absolute uncertainty is 0.2 MeV/c. and the corresponding systematic uncertainty in the kinetic energy is then $\sigma_{T_{sys}}(\pi^-) = 0.14$ MeV. [FINUDA, arXiv:1203.1954v2 (2012)]

experimental resolution 2.8 MeV/*c* (FWHM)
→ factor 2 worse compared to emulsion
absolute calibration error (133.03 - 132.6) MeV/*c* ~ 400 keV/*c*

# Hyperfragment decay-pion spectroscopy with electron beams

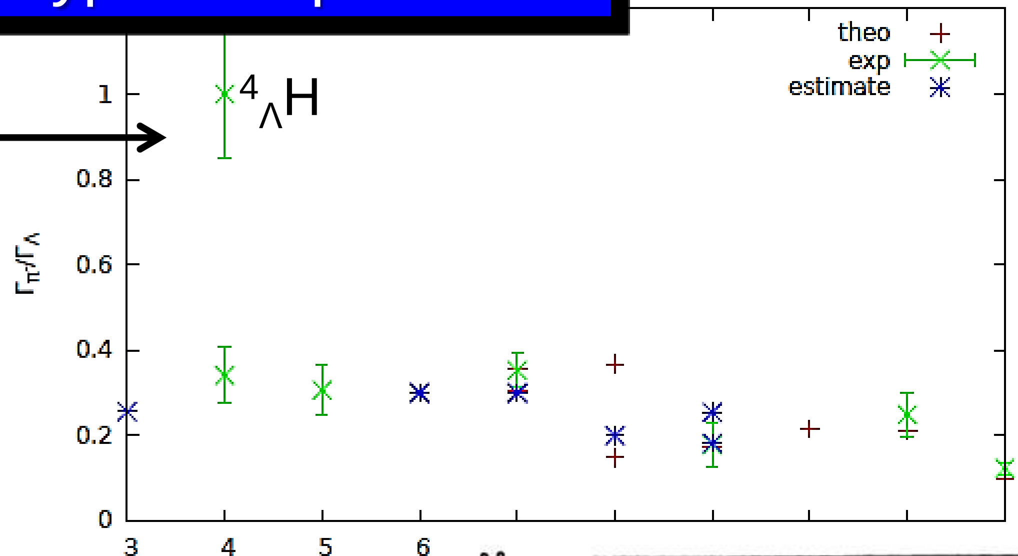



two-body decay at rest ⇒ mono-energetic pions

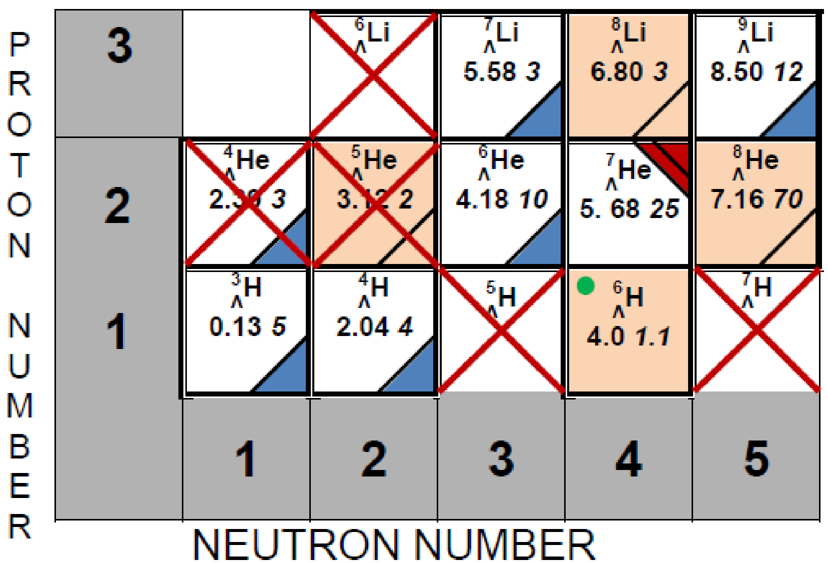
$$M_{\mathrm{HYP}} = \sqrt{M_{\mathrm{ncl}}^2 + p_{\pi^-}^2} + \sqrt{M_{\pi^-}^2 + p_{\pi^-}^2}$$

# Accessible hyperisotopes

highest pionic decay rate →

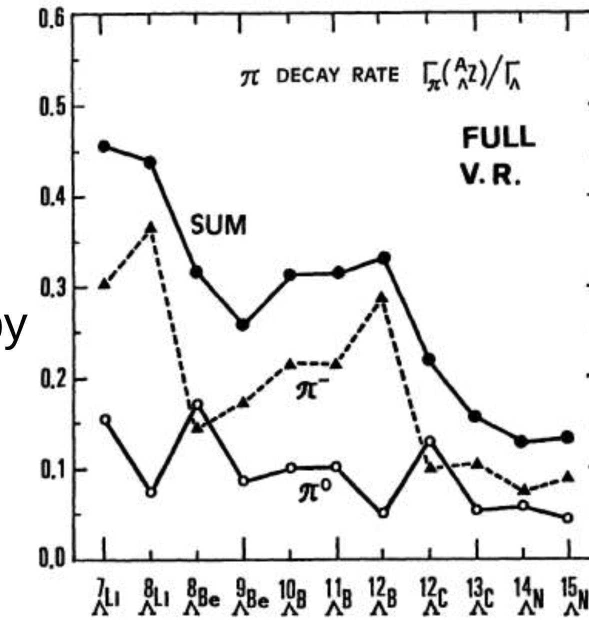



Accessible isotopes with $^9$Be from $^3_\Lambda$H, $^4_\Lambda$H, … to $^9_\Lambda$Li:




no 2-body decay

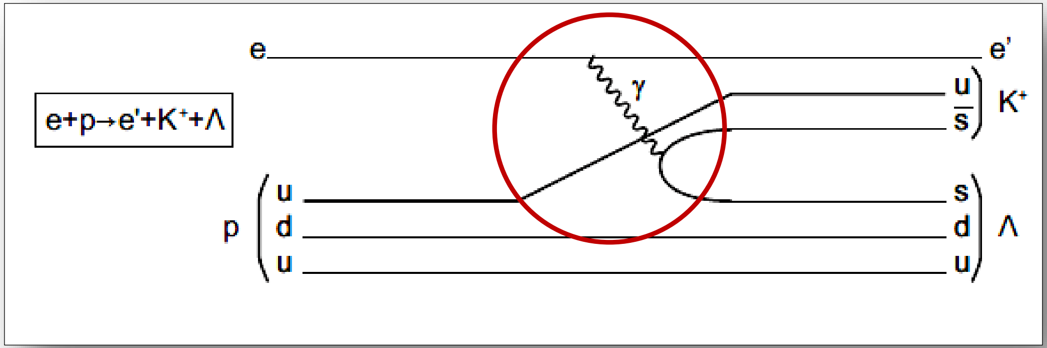
inaccessible by MM spectroscopy




[T. Motoba & K. Itonaga, PTPS 117 (1994)]

# Electroproduction

*hadronic system responds to electromagnetic field produced by scattered electron*




$$E_{CM} = \sqrt{2E_\gamma M_p + M_p^2} = M_\Lambda + M_{K^+} = 1,6\mathrm{GeV}$$

$$\Rightarrow \boxed{E_\gamma = 0,9\mathrm{GeV}}$$

↓

1. CEBAF accelerator at Jefferson Lab (US)
2. MAMI-C accelerator at Mainz University (Germany)

# Experimental challenges

- cross-section for hypernuclei formation
  very small (~100 nb/sr)
  strongly peaked at zero degree electron scattering angle
  falling with increasing kaon angle

- magnetic spectrometers with high resolving powers » 1 m:
  challenge for short-lived particles (kaon lifetime 12,5 ns!)

- forward-scattering region (< 10°) blocked by the exit beam-line

- kaon count rate small compared to background rates

- large rates of Bremsstrahlung and Møller scattering

# Magnetic spectrometer facility at MAMI

Momentum resolution:

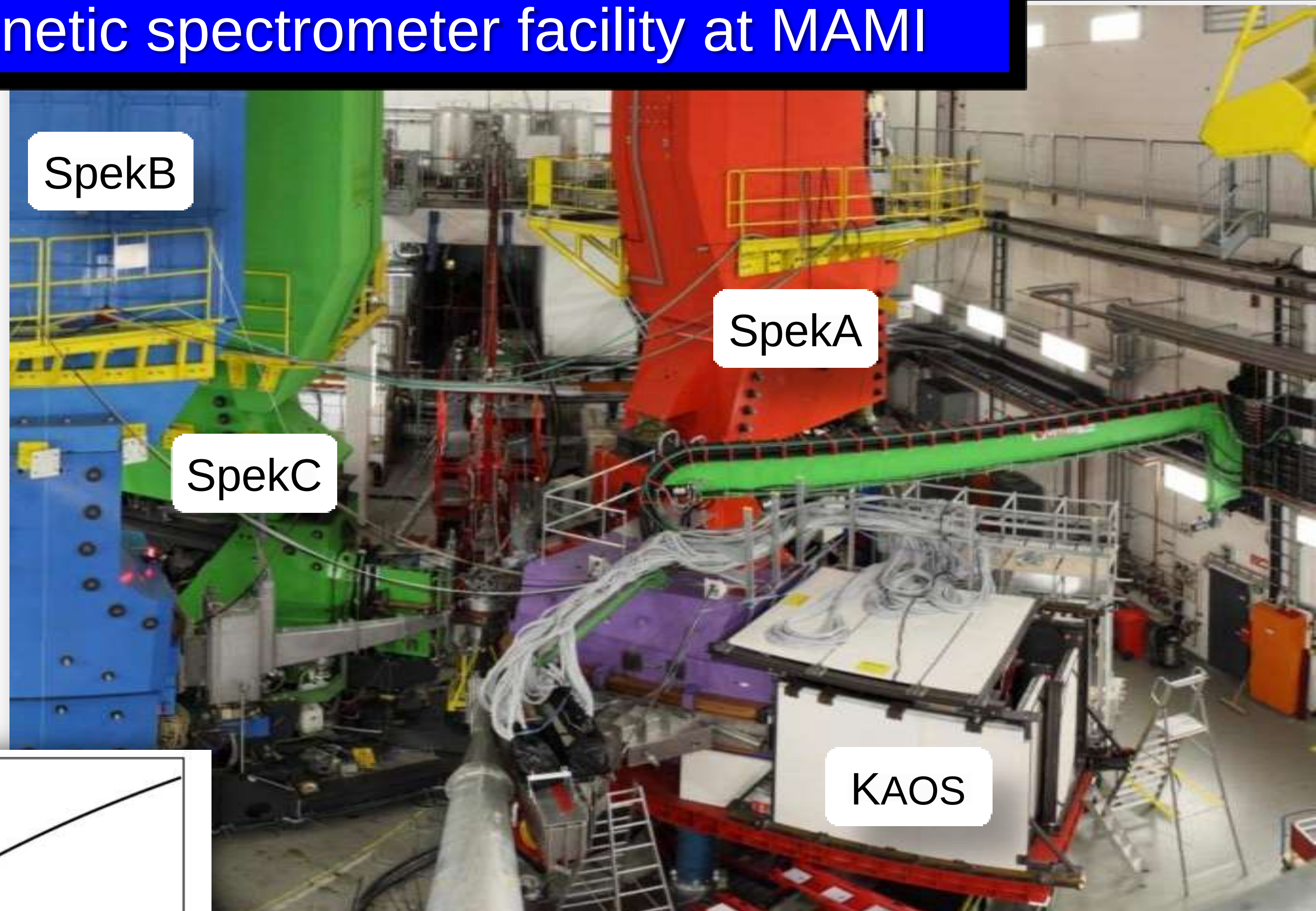
$$\delta p/p < 10^{-4}$$

Momentum acceptance:

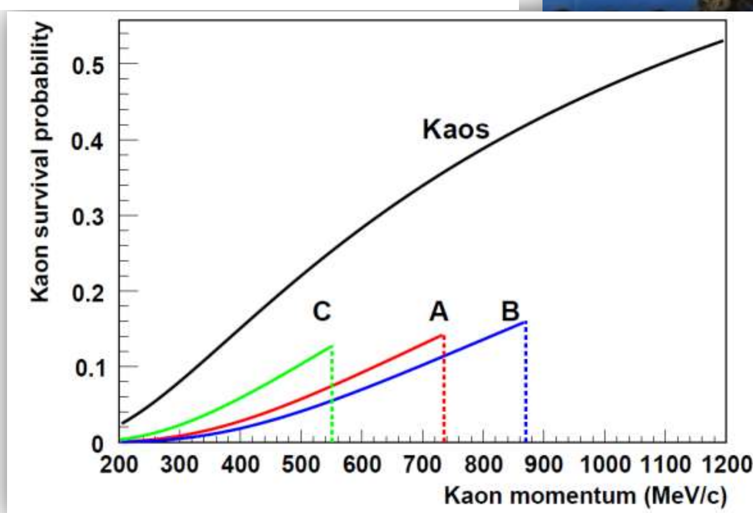
$$\Delta p/p = 20\%$$

Accepted solid angle:

$$\Delta\Omega = 11.5^\circ \times 8.0^\circ = 28\,\mathrm{msr}$$




Kaon survival probability:

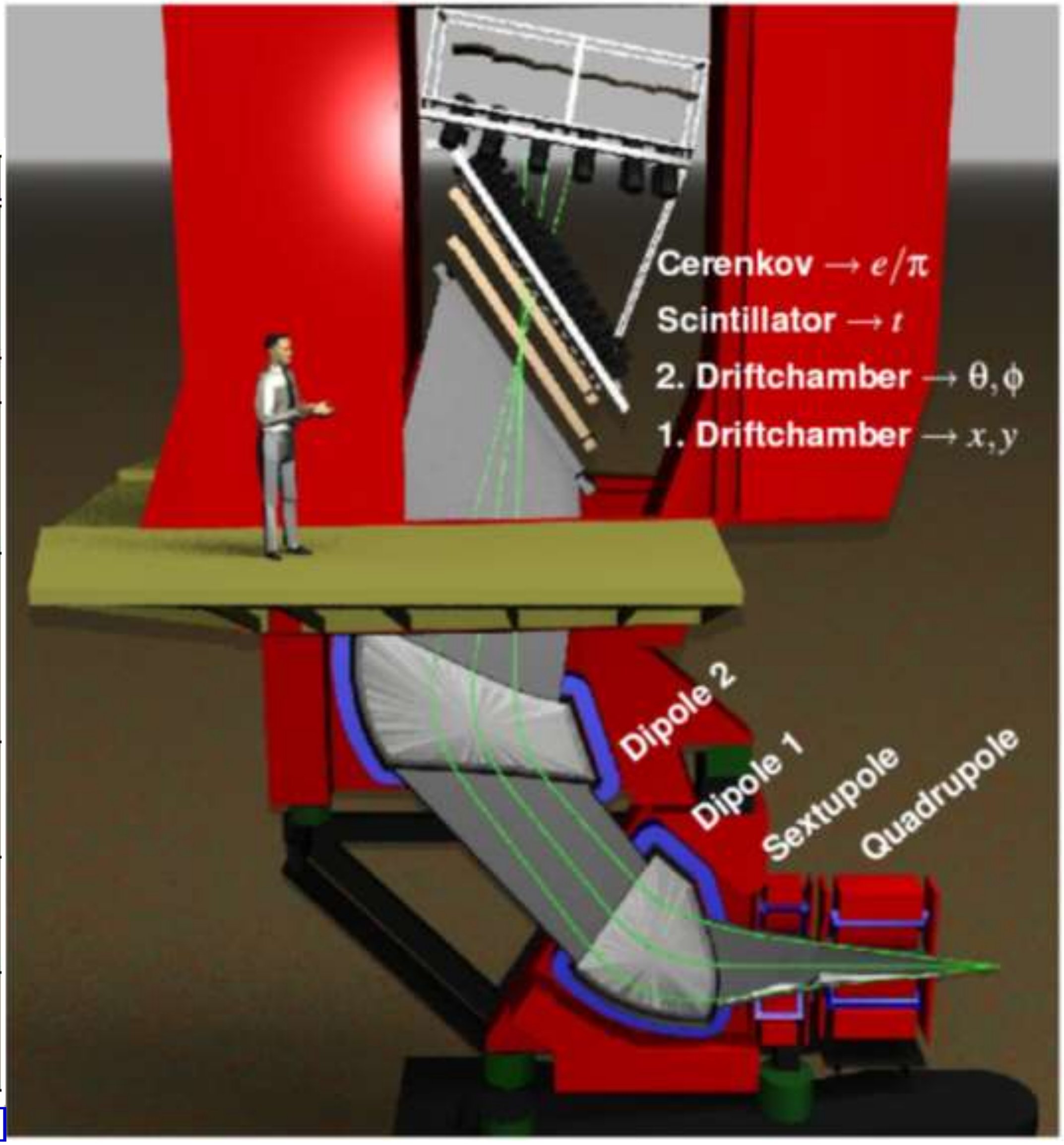



*Magnetic focusing spectrometers at MAMI:*

- 3 high-resolution $\Delta p/p \sim 10^{-4}$ spectrometers (SpekA,B,C)
- 1 short-orbit spectrometer (KAOS, since 2008)

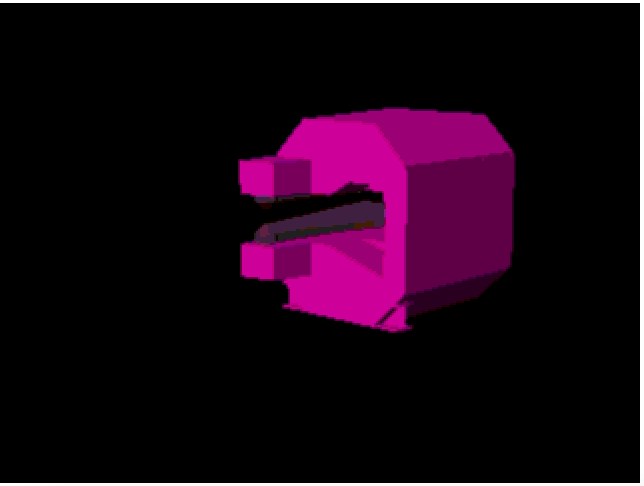
# Magnet Optics for the QSDD Design

| Spectrometer | | A | B | C |
|---|---|---|---|---|
| Configuration | | QSDD | D | QSDD |
| Focussing properties | | | | |
| dispersive plane | | pt →pt | pt →pt | pt →pt |
| nondispersive plane | | \|\| →pt | pt →pt | \|\| →pt |
| Maximum momentum | [MeV/c] | 735 | 870 | 551 |
| Solid angle | [msr] | 28 | 5.6 | 28 |
| Angular range | | | | |
| minimum angle | | 18° | 7° | 18° |
| maximum angle | | 160° | 62° | 160° |
| Momentum acceptance | [%] | 20 | 15 | 25 |
| Angular acceptance | | | | |
| dispersive plane | [mrad] | ±70 | ±70 | ±70 |
| nondispersive plane | [mrad] | ±100 | ±20 | ±100 |
| long-target acceptance | [mm] | 50 | 50 | 50 |
| Angle of focal plane | | 45° | 47° | 45° |
| Length of focal plane | [m] | 1.80 | 1.80 | 1.60 |
| Length of trajectory | [m] | 10.75 | 12.03 | 8.53 |
| Dispersion (central) | [cm/%] | 5.77 | 8.22 | 4.52 |
| Magnigfication (central) | | 0.53 | 0.85 | 0.51 |
| Dispersion / Magnification | [cm/%] | 10.83 | 9.64 | 8.81 |
| Momentum resolution | | $10^{-4}$ | $10^{-4}$ | $10^{-4}$ |
| angular resolution at target | [mrad] | ≤3 | ≤3 | ≤3 |
| position resolution at target | [mm] | 3 – 5 | 1 | 3 – 5 |

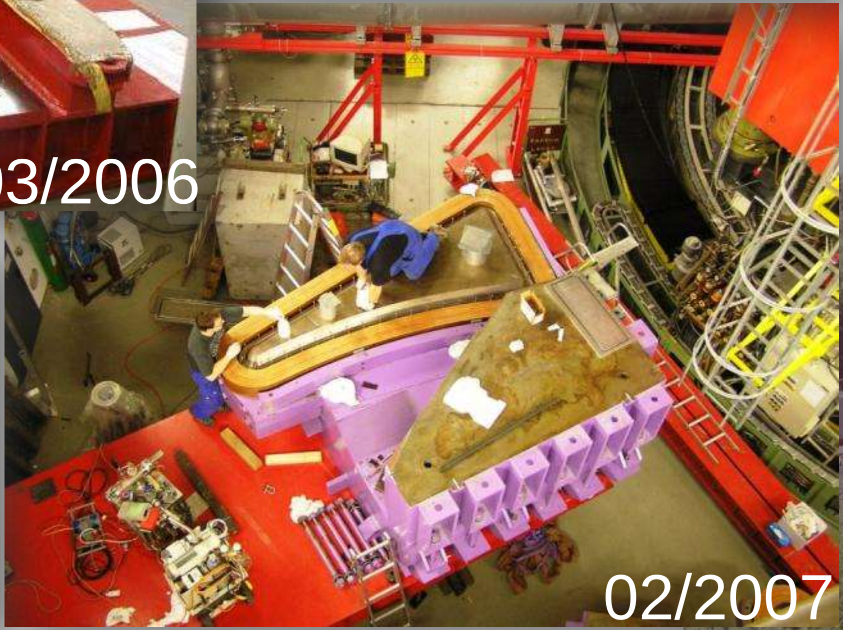



[K.I. Blomqvist et al., Nucl. Inst. Meth. A 403 (1998)]

# Setup of Kaos

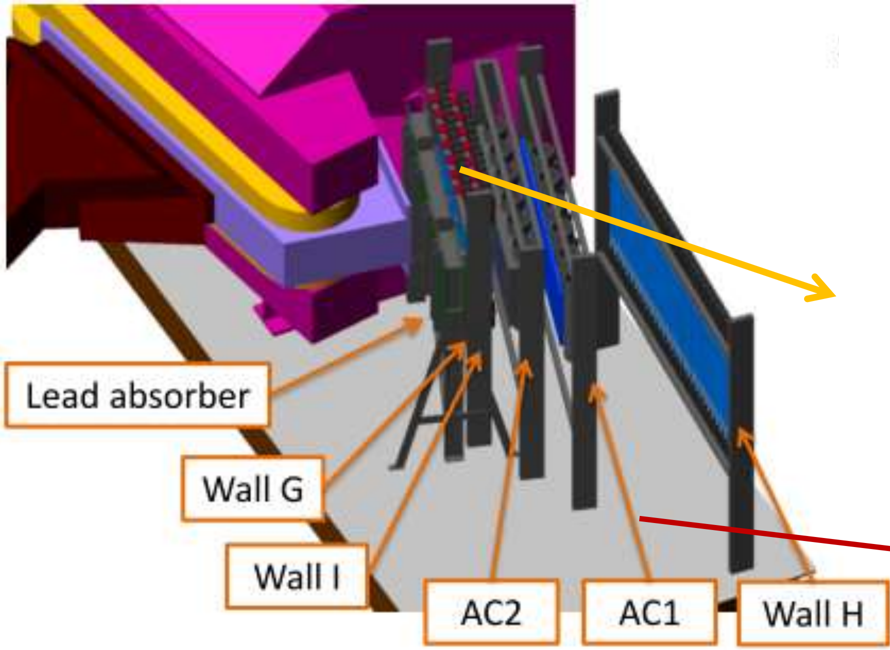


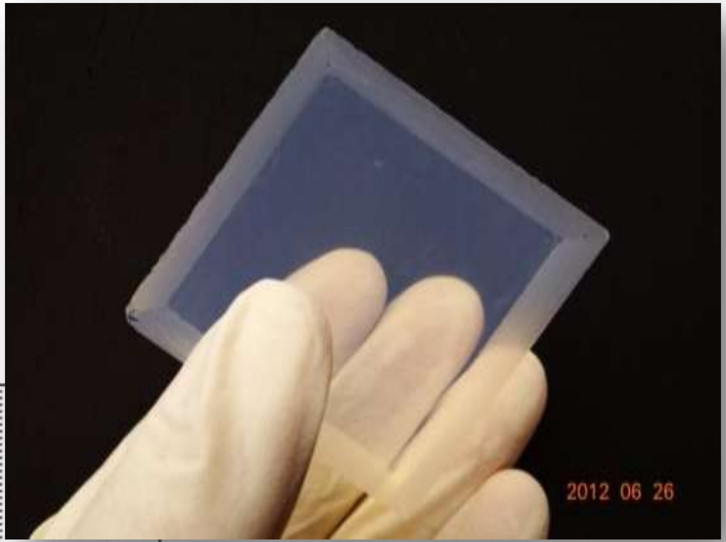


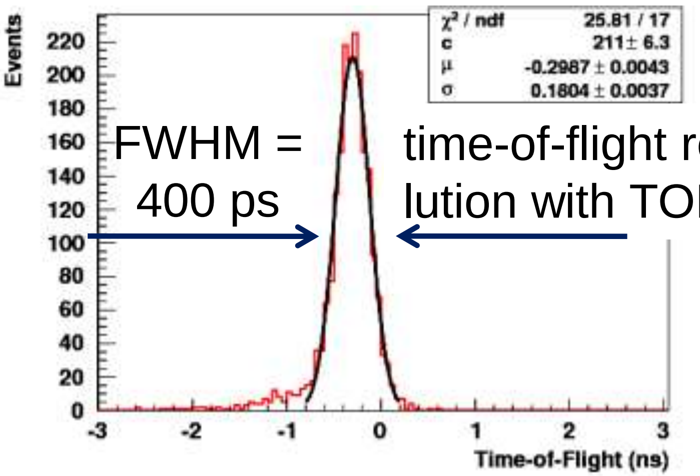




# Particle detection system in KAOS

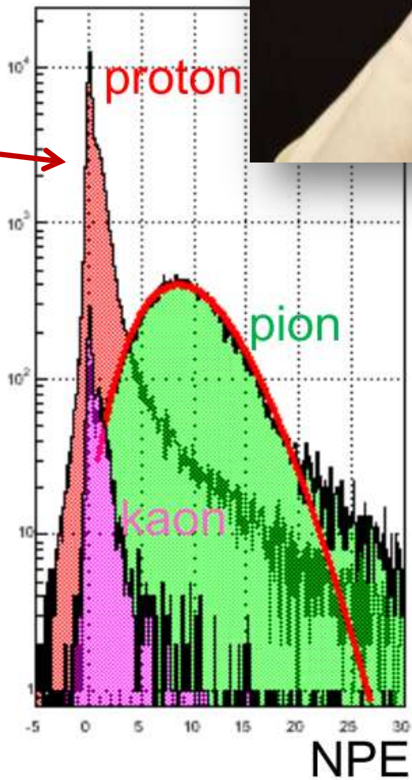


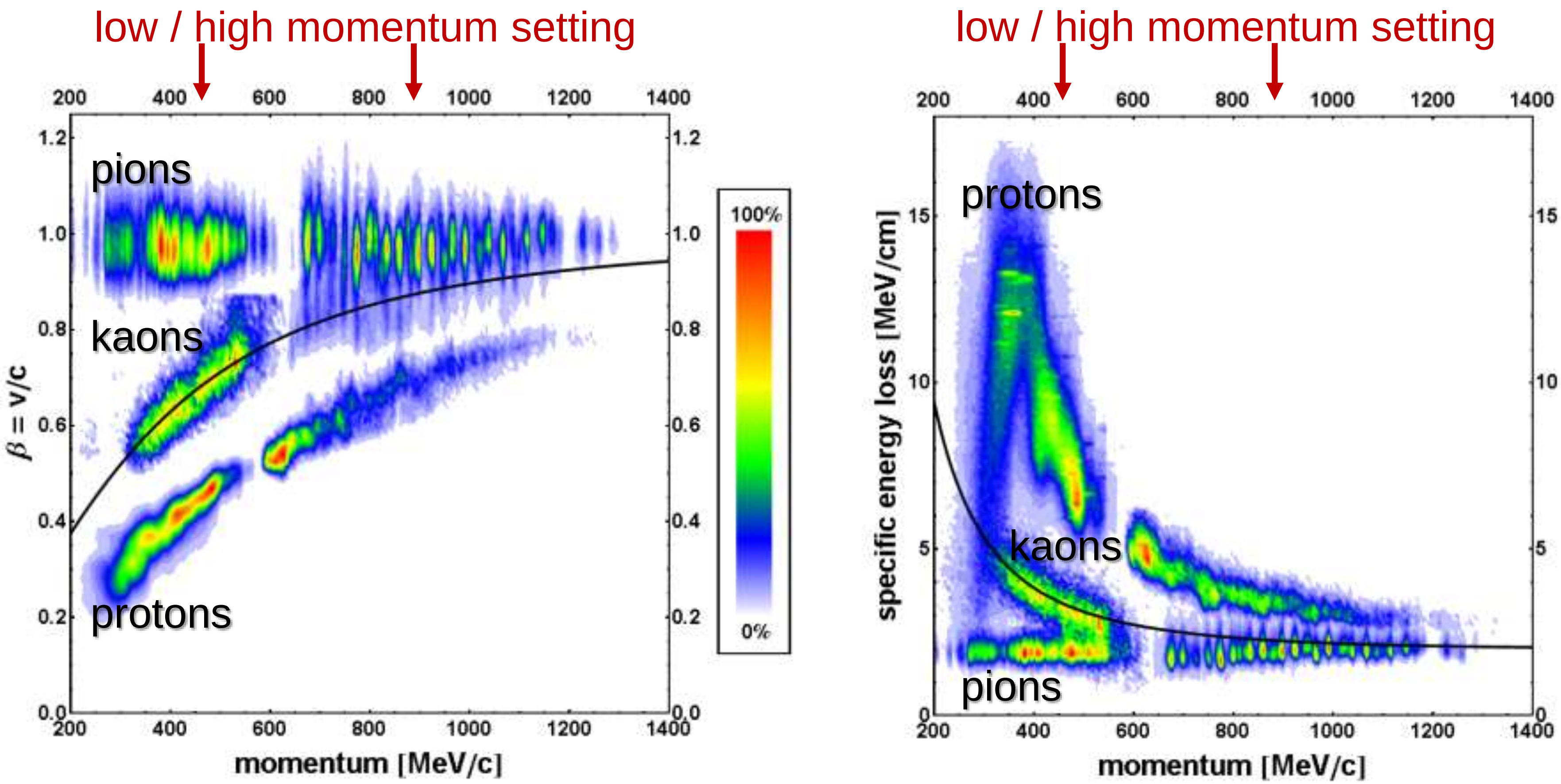

FWHM = 400 ps

time-of-flight resolution with TOF walls




pion detection ε > 95% by aerogel Cherenkov

# Kaon identification using TOF system

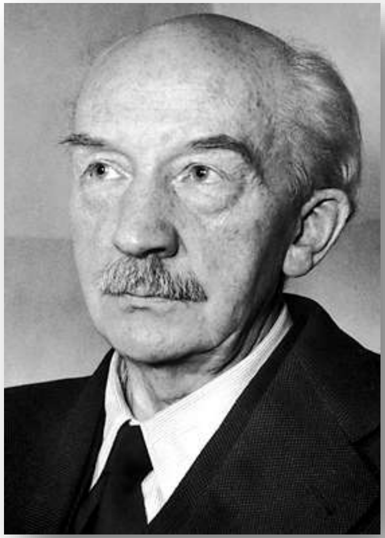



- KAOS can cover 200−1300 MeV/$c$ in only 2 settings
- clean kaon identification at low momenta
- Cherenkov information needed at high momenta

# Reminder: Coincidence Method

Walther Bothe:
The Nobel Prize
in Physics 1954:

"for the coincidence method and his discoveries made therewith"



[W. Bothe & H. Geiger: Zeitschr. f. Phys. 32 (1925) 639]

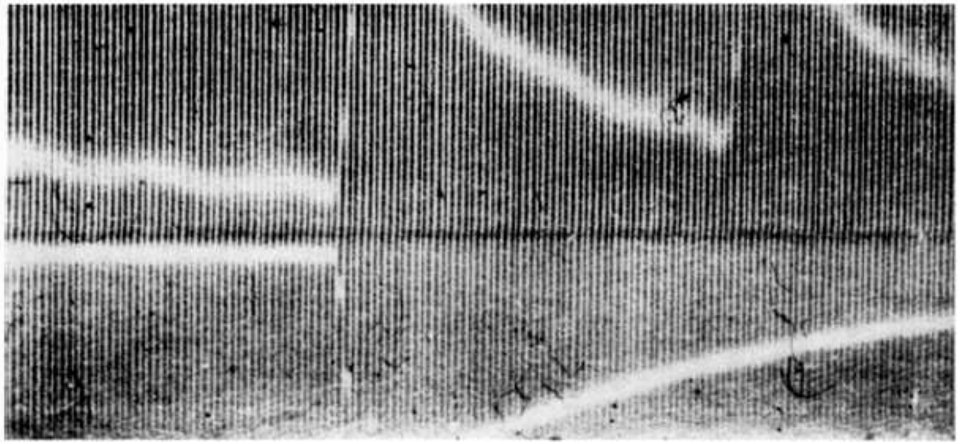


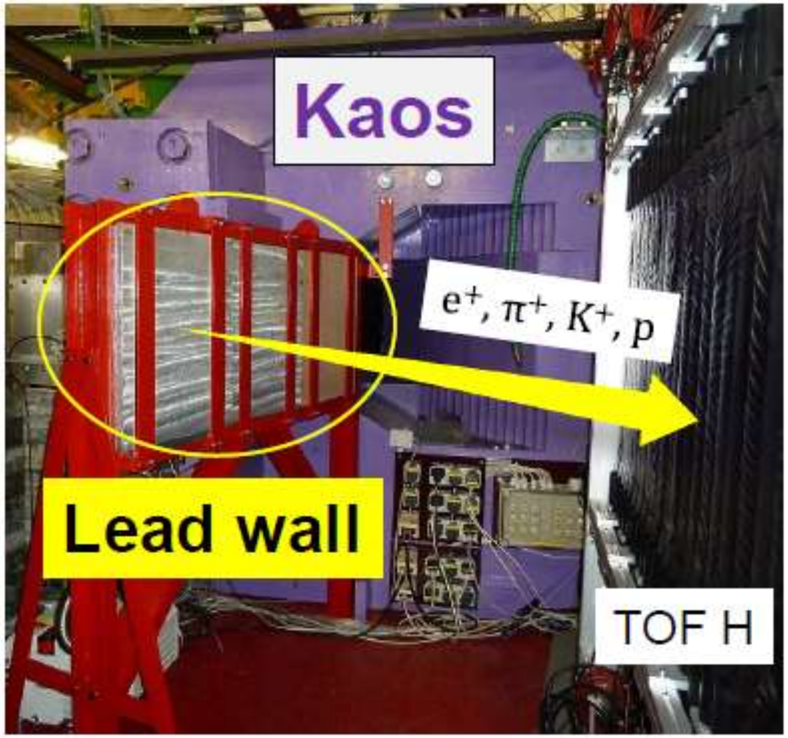

Fig. 7. Beispiel einer Koinzidenz. Streifenabstand $^1/_{1000}$ Sekunde. Oben $e$-Ausschläge, unten $h\nu$-Ausschlag.

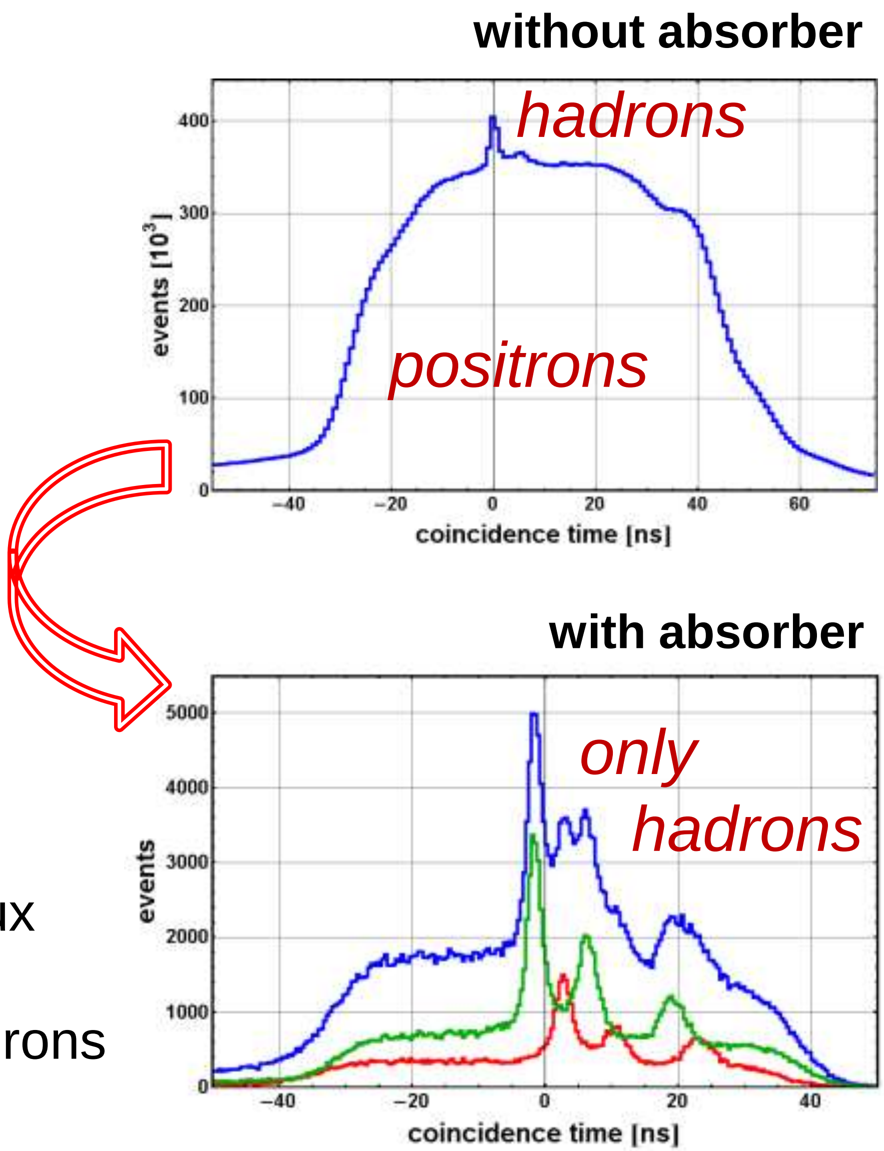
"… we succeeded after a few failures to establish the accuracy of any temporal "coincidence" between the two pointer readings as being $10^{-4}$ sec."

| | | |
|---|---|---|
| Bothe's system: | resolving time | $\delta t = 10^{-4}$ sec = 100 000 ns |
| | DAQ rate | R = 300-500/min ~ 8 Hz |
| modern system: | | $\delta t$ ~ 100 ps |
| | | R ~ kHz-MHz |

→ 5-6 orders of magnitude improvement

# Kaos spectrometer changed into zero-degree tagger



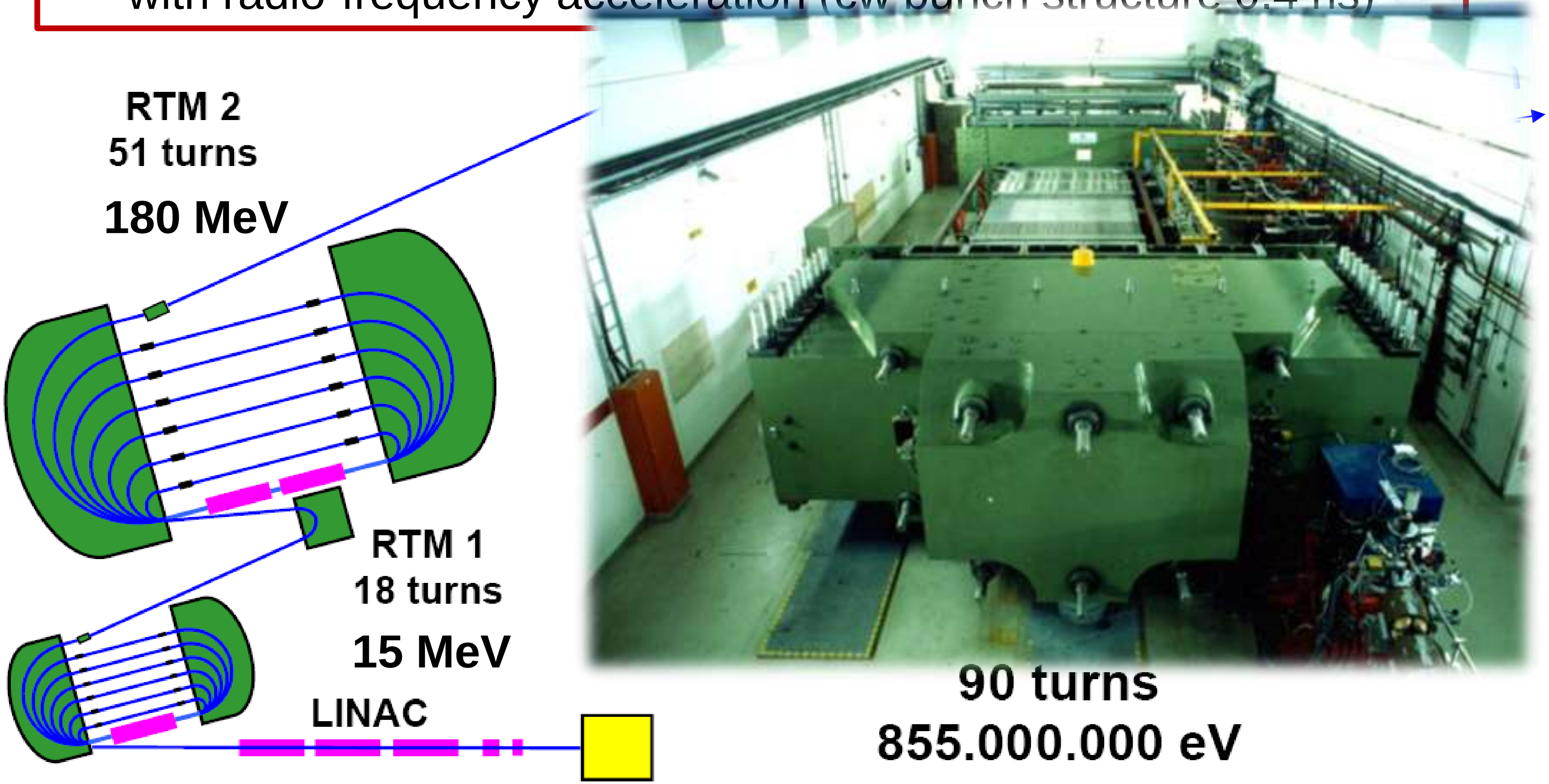




- Suppression of large positron flux with 25 $X_0$ lead absorber wall
- Much cleaner spectra for all hadrons

# Decay-pion spectroscopy results from MAMI

# Race-Track Microtron (RTM)

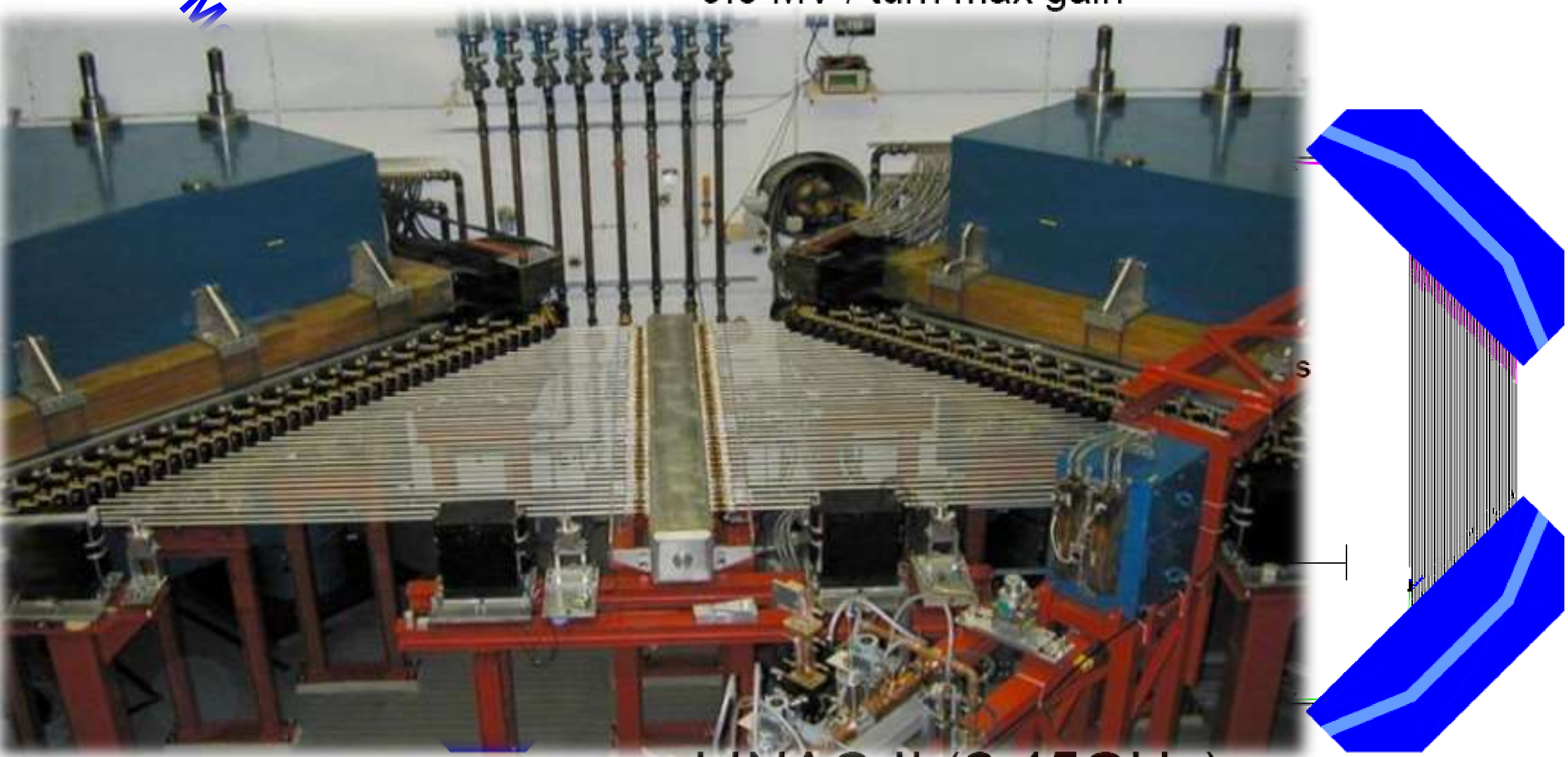
Cascade of 3 RTMs with each 2 magnets + x times the same linac with radio-frequency acceleration (cw bunch structure 0.4 ns)




RTM3: single pass energy gain 7.5 MeV x 90 turns = 675 MeV total energy gain with only 163 kW RF power for 67.5 kW of beam power @100 mA

# Harmonic Double Sided Microtron (HDSM)

9.0 MV / turn max gain



$B_{max}$=1.539 T

LINAC II (2.45GHz)

9.3 MV / turn max gain

[K.-H. Kaiser et al., Nucl. Instr. Meth. A 593 (2008) 159]

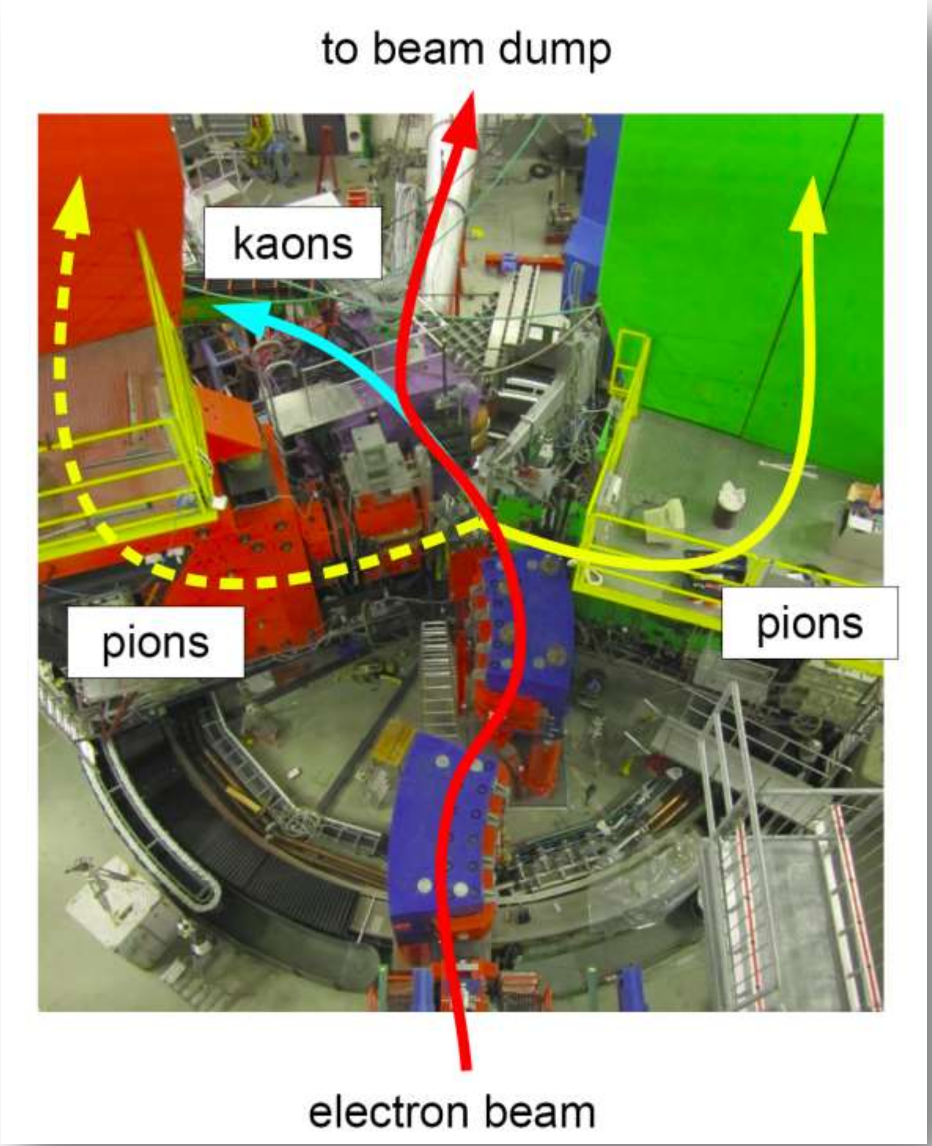
# Experimental realization at MAMI

| **Primary Beam** | |
|---|---|
| Energy | 1.5 GeV |

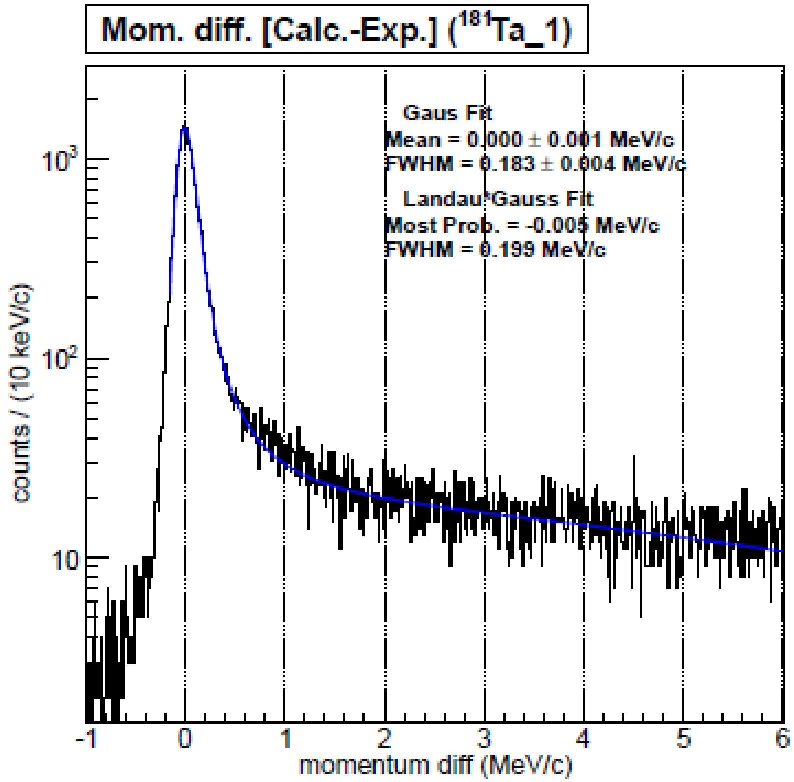
| **Target** | |
|---|---|
| Material | $^{9}$Be |
| Thickness | 125 µm |
| Tilt angle | 54 deg |

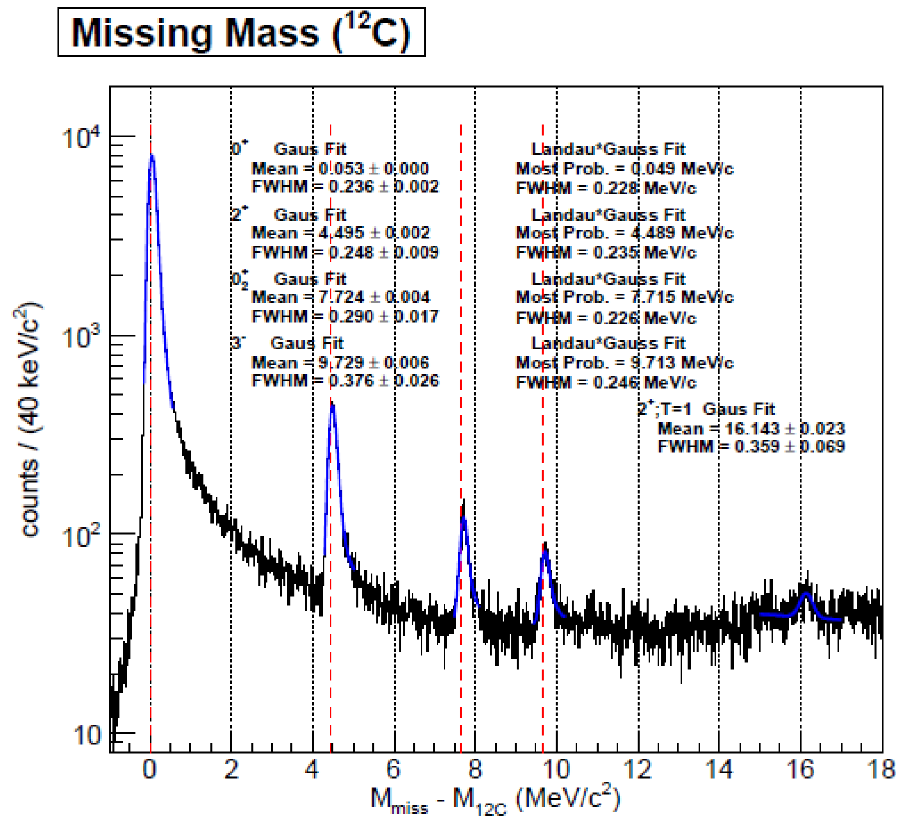
| **Kaos** | |
|---|---|
| Cent. Mom | +900 MeV/c |
| Detector | MWPC, TOF, AC |

| **Spek-A, C** | |
|---|---|
| Cent. Mom | - 115/ -125 MeV/c |
| Detector | DC, TOF, GC |



# Decay pion momentum accuracy

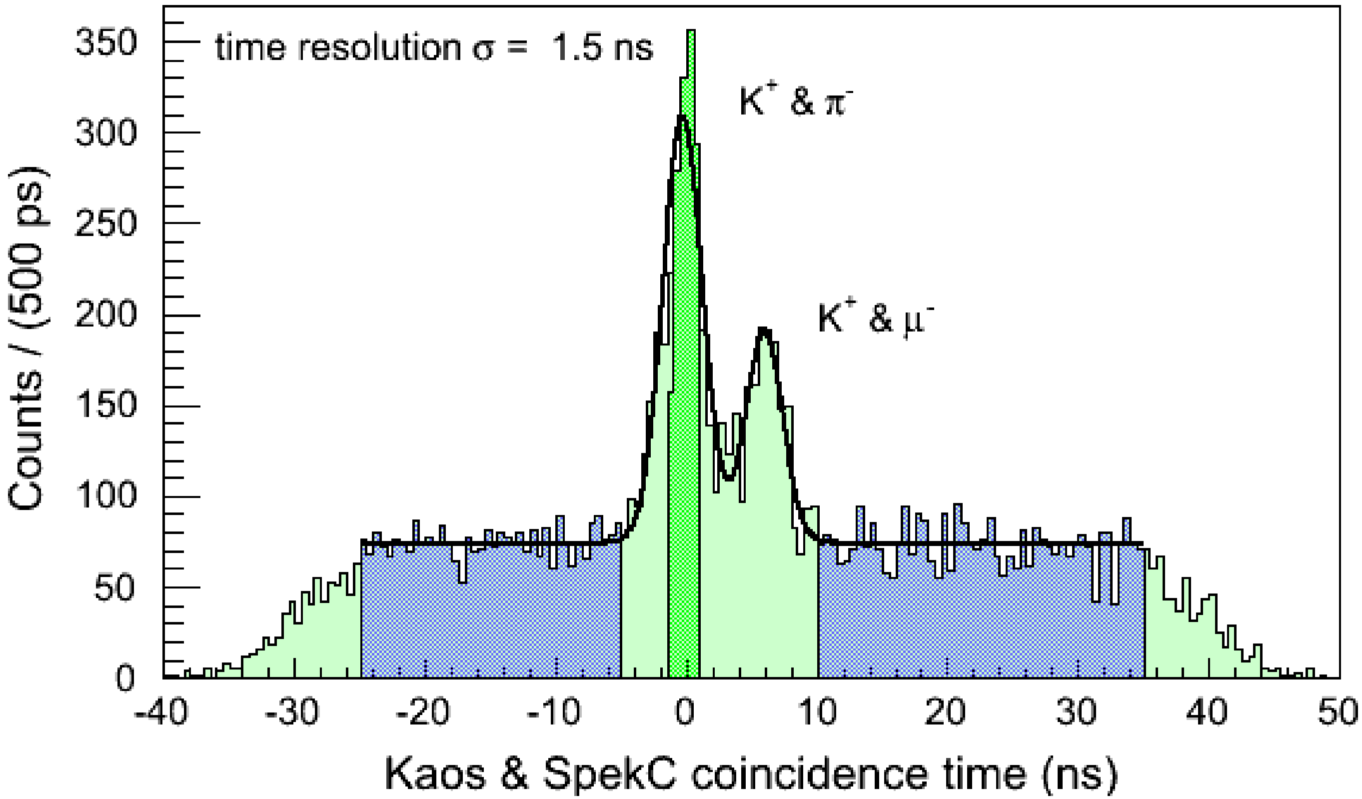



- elastic & inelastic scattering off Ta and C to calibrate spectrometers
- elastic line FWHM of 200 keV/*c* at 200 MeV/*c* momentum
- beam energy measured with absolute accuracy of ± 160 keV

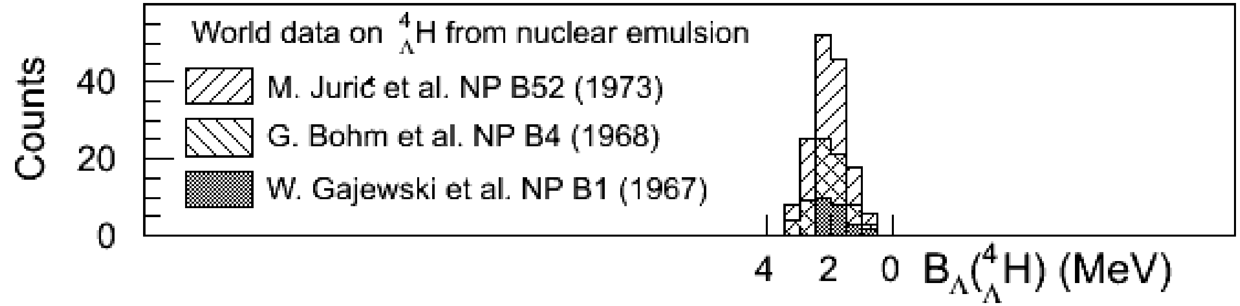
# Reaction identification

with cut on gas Cherenkov signal for electron rejection

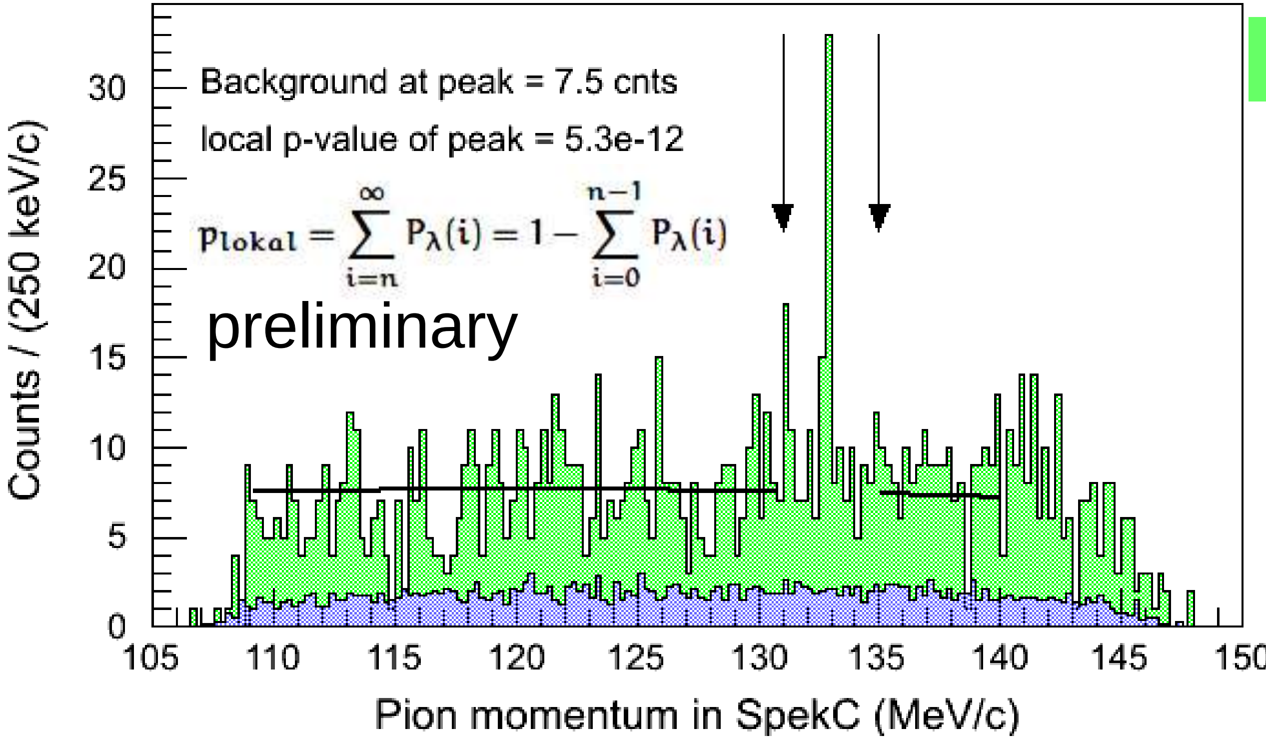



- established clean tag on strangeness production at zero-degree
- decay-pion detection with Spectrometer A & C (dp/p <$10^{-4}$)
- more than 1000 pion-kaon-coincidences from weak decays of hyperons

# Hyperhydrogen peak search



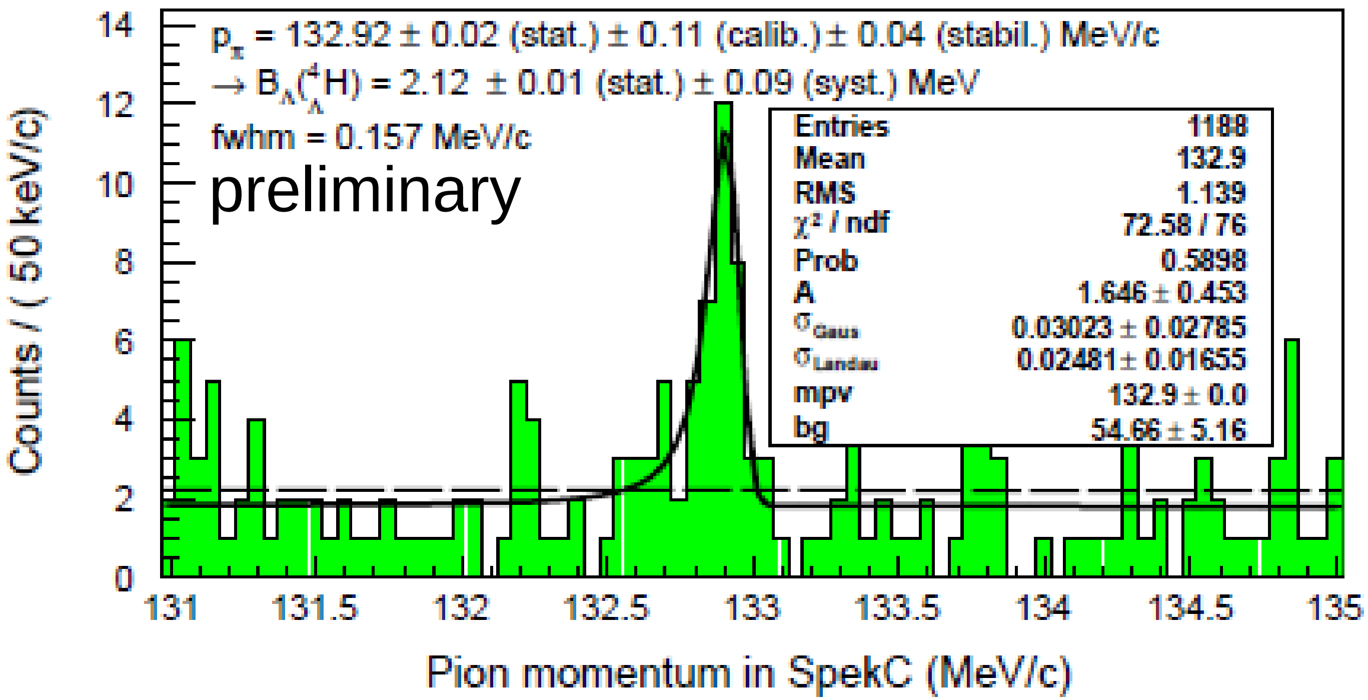

Emulsion data




MAMI data

local excess observed inside the hyperhydrogen search region

# Binding energy extraction



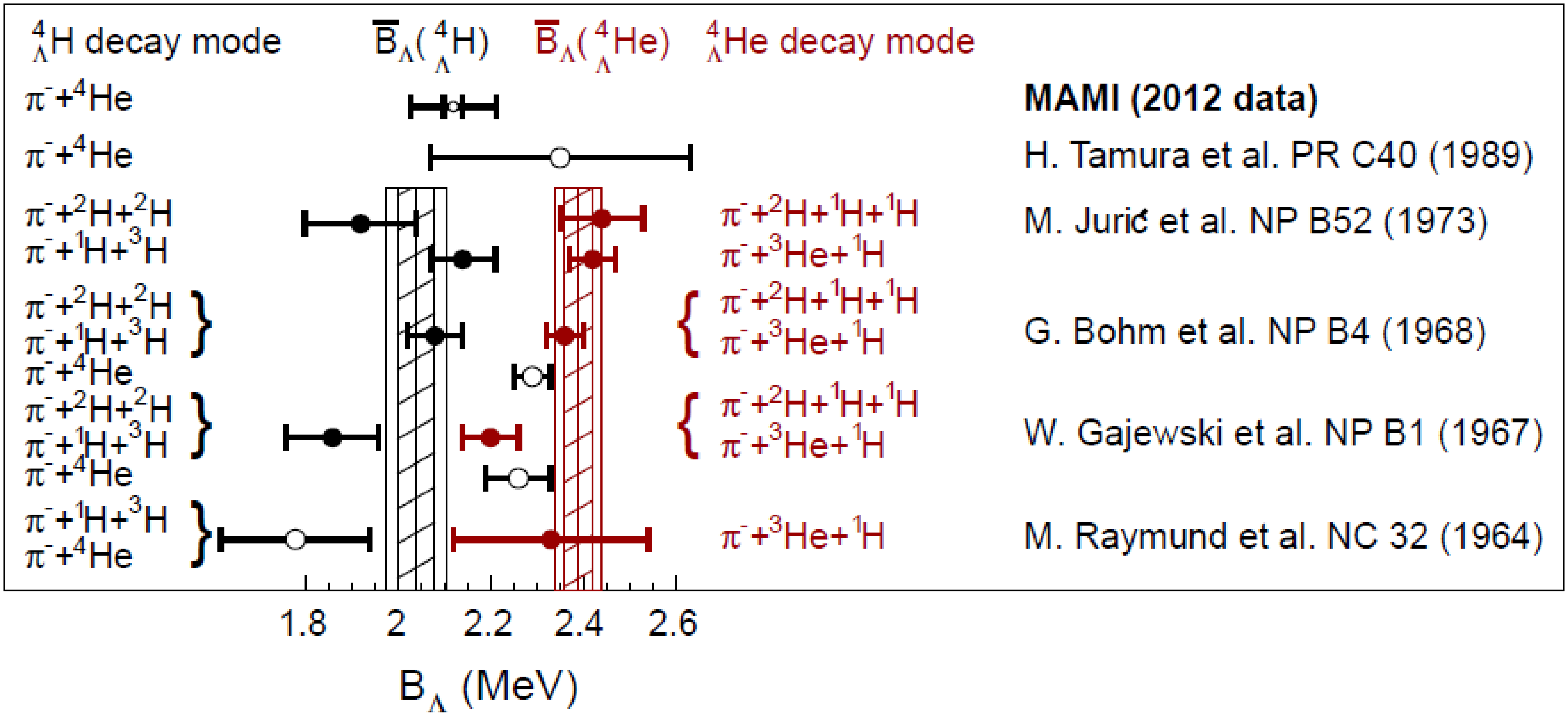

$$M(^4_\Lambda\mathrm{H}) = \sqrt{M^2(^4\mathrm{He}) + p_\pi^2} + \sqrt{M_\pi^2 + p_\pi^2} \quad \text{and}$$

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

$$S = \sqrt{-2\ln\frac{L(BG)}{L(S+BG)}}$$ = 4.7 with binned analysis

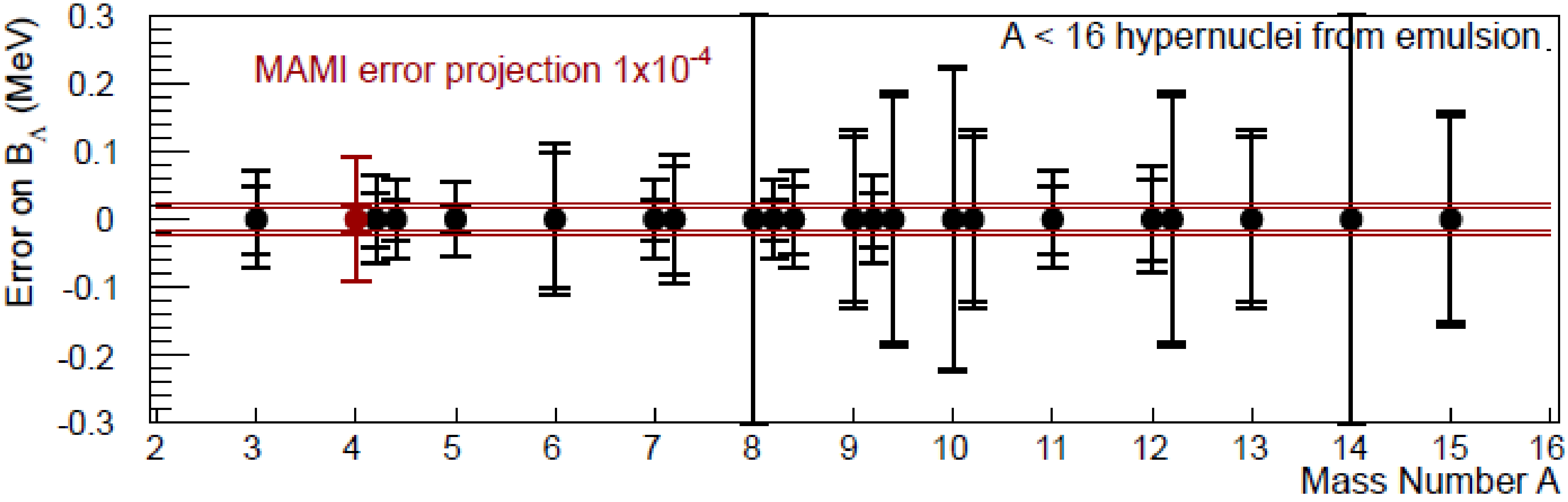
$S$ ~ 4-5 with unbinned analysis

# World data on *A* = *4* system




MAMI experiment confirmed Λ separation energy of $_{\Lambda}^{4}H$:
$B_{\Lambda} \sim 2.12 \pm 0.1$ MeV (MAMI 2014 prelim.)

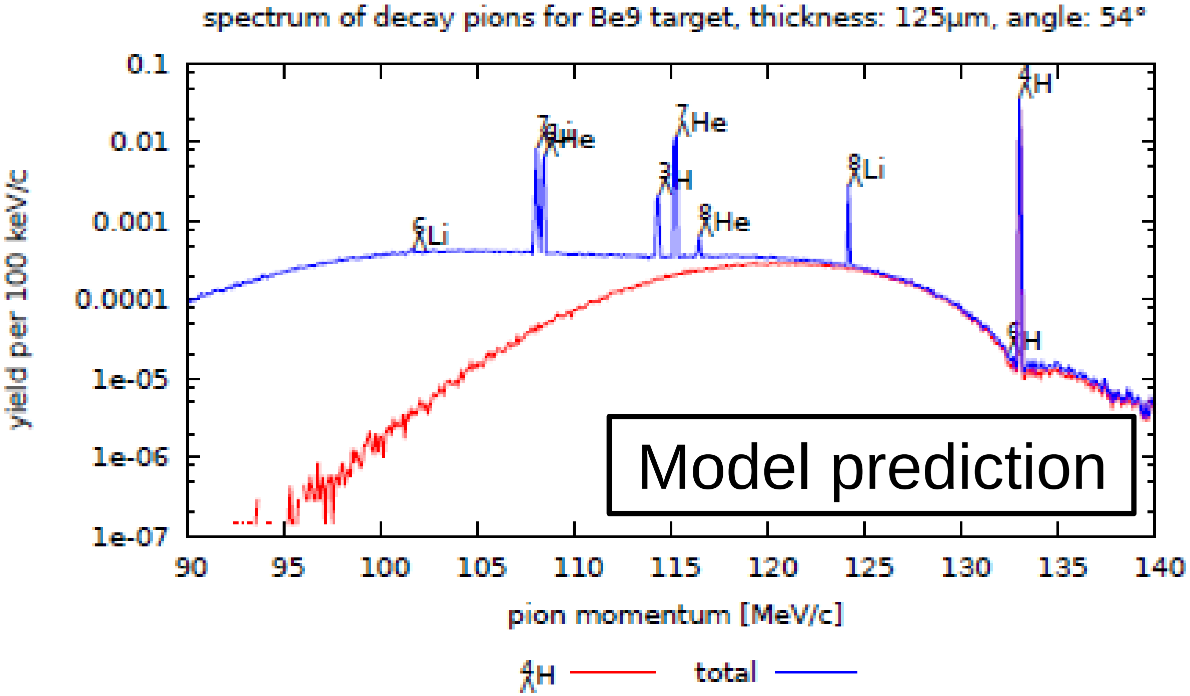
# Comparison of errors




Emulsion: dominated by statistical error

MAMI: dominated (sofar) by systematic error of beam energy

# Continuation of Experiment




| | $P_{decay}$ [MeV/c] | $Y_{stopped}$ |
|---|---|---|
| $^{4}_{\Lambda}$H | 133.028 | 0.34242 |
| $^{7}_{\Lambda}$He | 115.259 | 0.16475 |
| $^{7}_{\Lambda}$Li | 108.108 | 0.07159 |
| $^{6}_{\Lambda}$He | 108.472 | 0.08647 |

- In 2014 next generation experiment performed with 5 x higher statistics
- Different target materials are under investigation
- Dominating systematic error can be reduced by improved calibrations

# Conclusions and prospects

- **Decay-pion spectroscopy it is now becoming a precision science**
- **Decay-pion spectroscopy gives access to ground state masses of light hypernuclei**
- **Precise measurements of the *A = 4* system linked to understanding of charge symmetry breaking in *ΛN* interaction**
- **The accuracy of masses of many light hyperisotopes could be improved by this technique**