Electromagnetic Production of Strangeness

… at the Mainz Microtron (MAMI)

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*Jefferson Lab**

Oct 2o22

** formerly at Mainz University*

Precision Nuclear Physics at Mainz Microtron MAMI

Non-strange physics covered in this conference:

Recent results from the A2 collaboration at MAMI: Paolo Pedroni (INFN-Pavia)

Recent results on Compton scattering at MAMI and on extraction of the proton polarizabilities: Edoardo Mornacchi (U Mainz)

Studying Laws of Nature with Polarisation Observable: Mikhail Bashkanov (U York)

Quasi-free Photoproduction of $\pi^0\pi^\pm$ off Unpolarized and Polarized Deuterons: Sebastian Lutterer (U Basel)

Helicity Dependence for Single π^0 Photoproduction from the Deuteron: Philippe Martel (U Mainz)

- Strangeness photo-production
- Strangeness electro-production
- Hypernuclear decay-pion spectroscopy

Covered in this talk where I had strong personal involvement

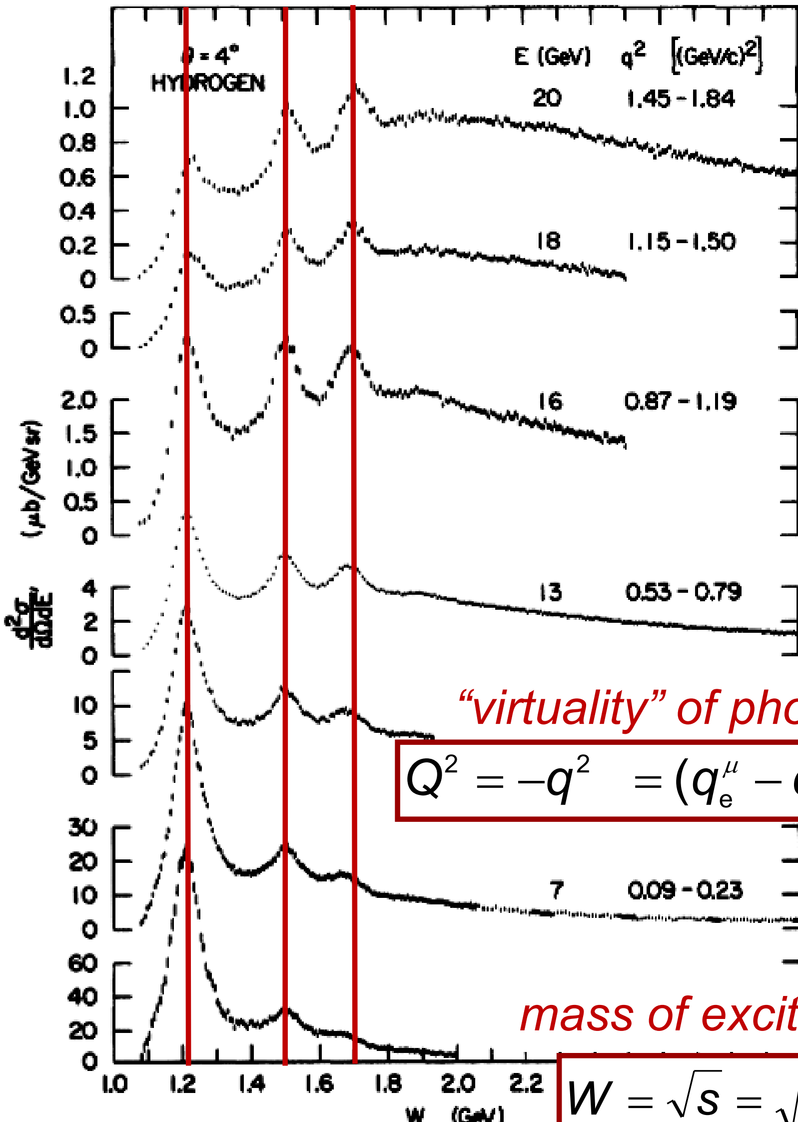
Beyond MAMI:

- New energy recovering superconducting accelerator MESA
- New research buildings: Center for Fundamental Physics

Physics at MESA: Sören Schlimme (U Mainz), 10/21/22, 10:10 AM, Plenary

Excitations off the Proton

[Stein et al., Phys. Rev. D 12 (1975)]



"virtuality" of photon:

$$Q^2 = -q^2 = (q^\mu_e - q^\mu_{e'})^2$$

mass of excited proton:

$$W = \sqrt{s} = \sqrt{(q^\mu + p^\mu_{target})^2}$$

The proton's excitation spectrum reflects its complexity where our knowledge is incomplete

Meson photo- and electro-production:

- Excitation spectrum / quantum nos.
  - → Symmetries
  - → Couplings
  - → Degrees-of-freedom
- Polarization observables
  - → Separation into structure fcts.
  - → Many additional observables
- Selective and exclusive reactions
  - → Sub-dominant resonances
  - → Production mechanisms
- Transitions amplt. and Q^2 evolutions
  - → Structure vs. distance scale

Strangeness Electro-Production off the Nucleon

Interest in strangeness channels:

– Contributing N* resonances in comparison to the πN channel

– Forward peaking due to K^+, K*(892), and K_1(1270) in t-channel

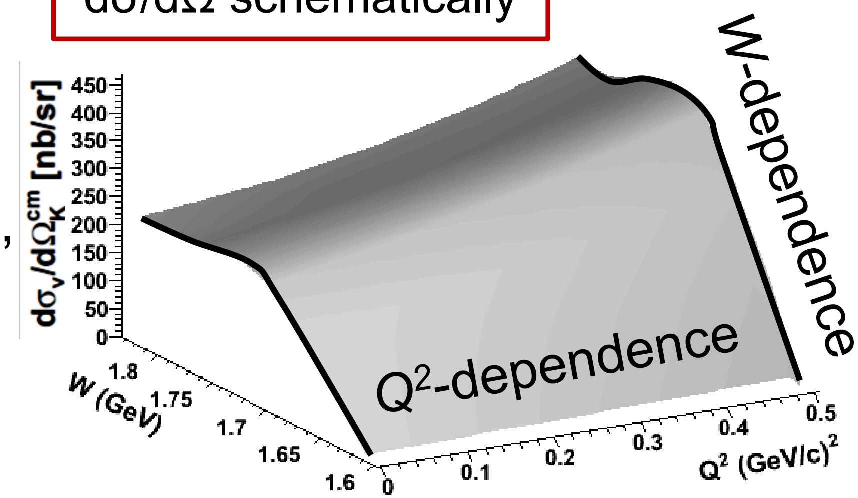
– Interferences between resonances

– Isospin structure:
KΛ final states sensitive to N*, while
KΣ final states sensitive to N* and Δ*

– Strong longitudinal response?

[G. Niculescu et al., Phys. Rev. Lett. **81(9)**, 1805 (1998)]
[R.M. Mohring et al., Phys. Rev. C **67**, 055205 (2003)]

dσ/dΩ schematically



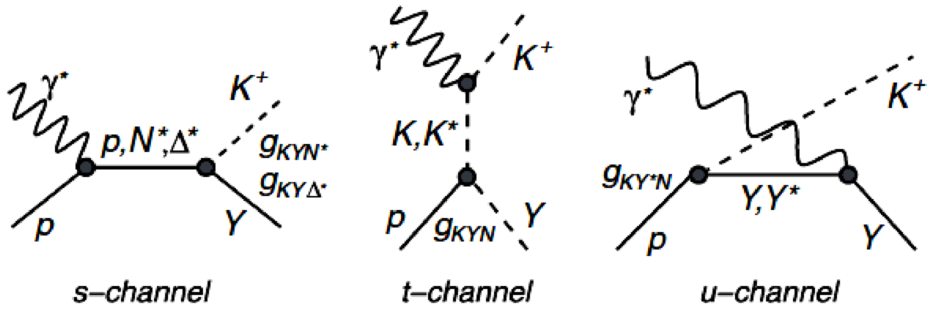
In 3rd resonance region
no dominant resonance

P_{13}(1720) and S_{11}(1650) at $W \sim 1.75$ GeV

L_{IJ} (mass)
L = $K\Lambda$ angular momentum state
I = isospin of resonance x 2
J = total spin of resonance x 2

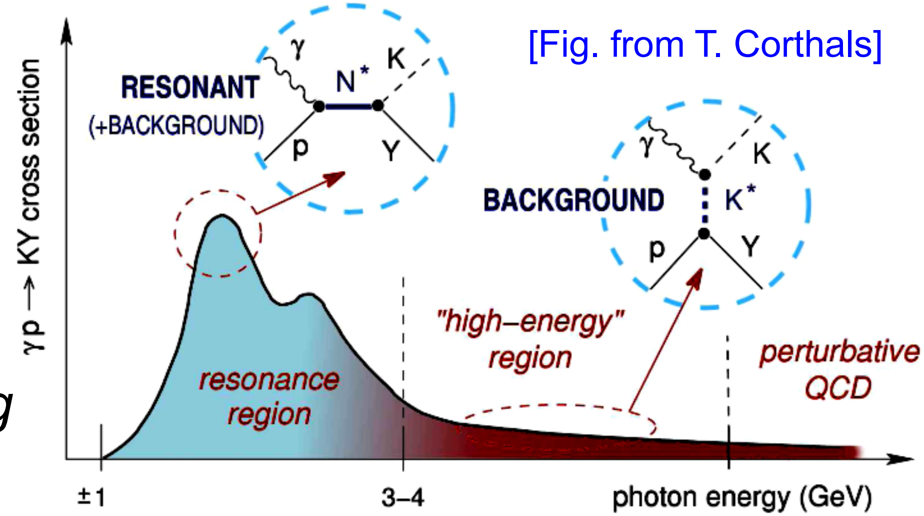
Strangeness electro-production at Q^2 below 1 (GeV/c)^2 offers complementary insight into non-strange excited nucleon states

Effective Lagrangian Models for Strangeness Production



Effective Lagrangian for photon coupling

[Fig. from T. Corthals]



- *Saclay-Lyon A*: No hadronic form-factors, SU(3), crossing symmetry,
  Nucleon (spin 1/2 and 3/2) and hyperon resonances
  Extended Born terms (p, Λ, Σ, K), K*(890), K_1(1270)
  [T. Mizutani et al., Phys. Rev. C 58, 75 (1998)]
- *Kaon-MAID*: Hadronic form-factors, SU(3), no hyperon resonances,
  Only nucleon (spin 1/2 and 3/2) resonances
  Extended Born terms (p, Λ, Σ, K), K*(890), K_1(1270)
  [T. Mart, C. Bennhold, Phys. Rev. C 61, 012201(R) (2000)]
- *RPR*: Regge model for *t*-channel
  Moderate no. of *s*-channel nucleon resonances
  [T. Corthals, D.G. Ireland, T. Van Cauteren, J. Ryckebusch, Phys. Rev. C 75, 045204 (2007)]

The Mainz Microtron

<u>MAMI-B:</u>

3 Race Track Microtrons

- E_0 = 180 ... 883 MeV
- Energy spread ΔE = 13 keV
- ε_x = 9 µm mrad, ε_y = 0.5 µm mrad
- Beam current max. 100 µA c.w.
- Polarization 85%
- Runtime > 7000 hours / year

<u>MAMI-C:</u>

1 Harmonic Double-Sided Microtron

- E_0 up to 1604 MeV

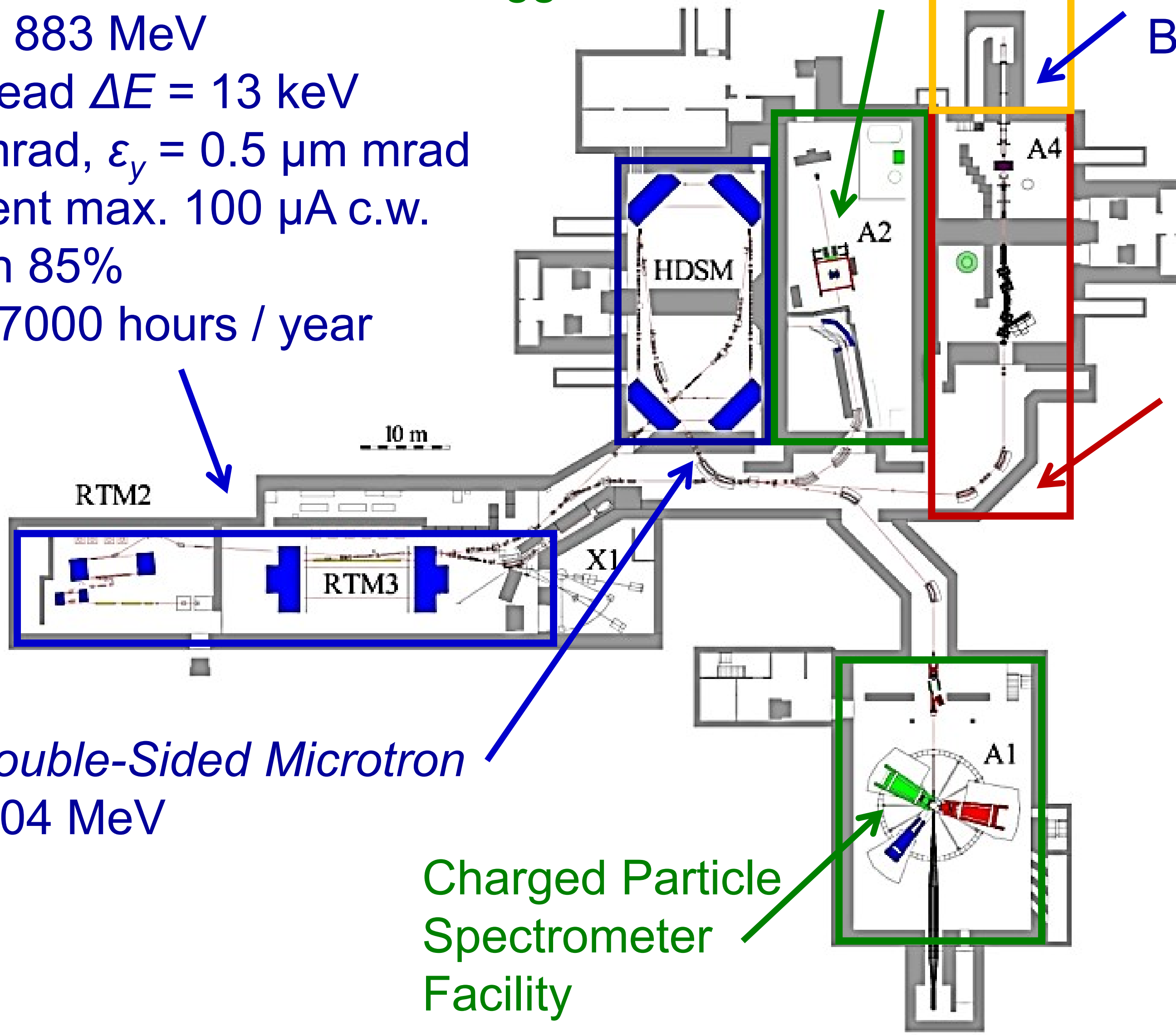
Photon Tagger & 4π Detector

CFP

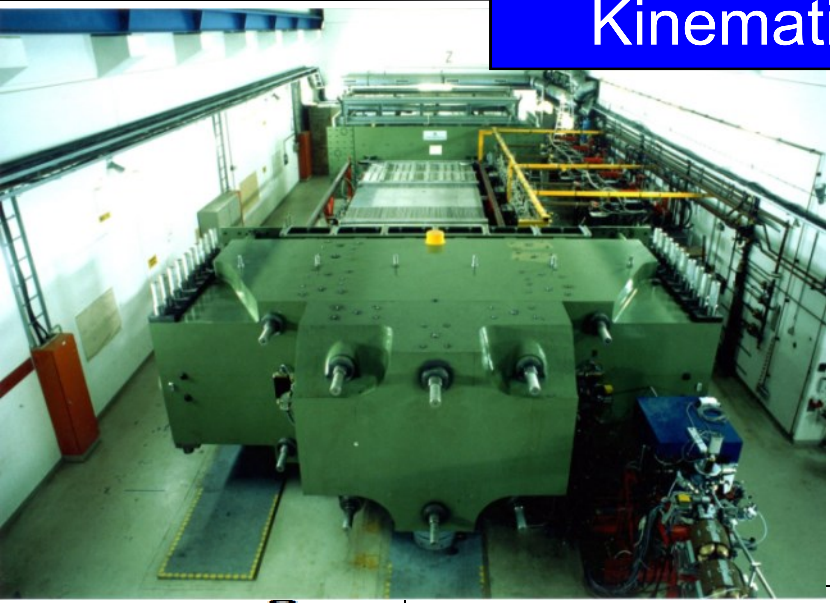
High-Power Beam Dump

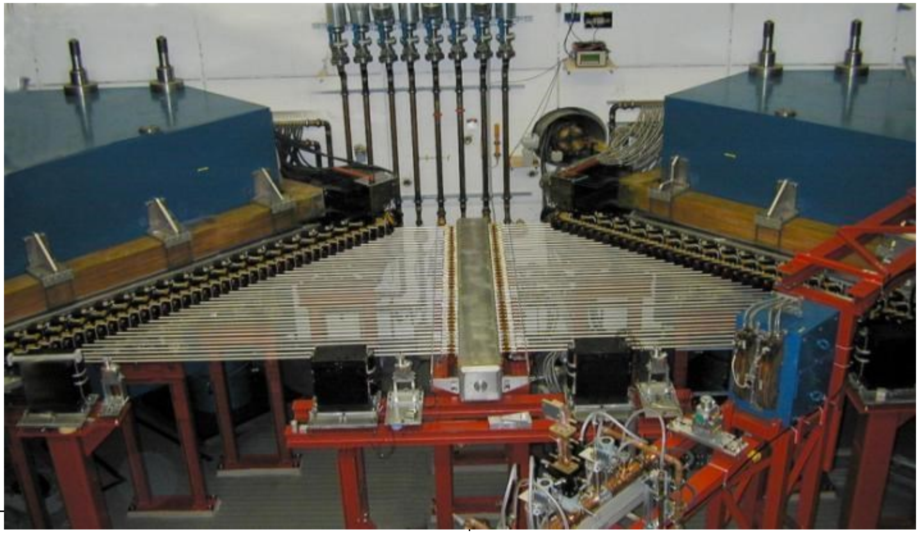
Cleared for MESA

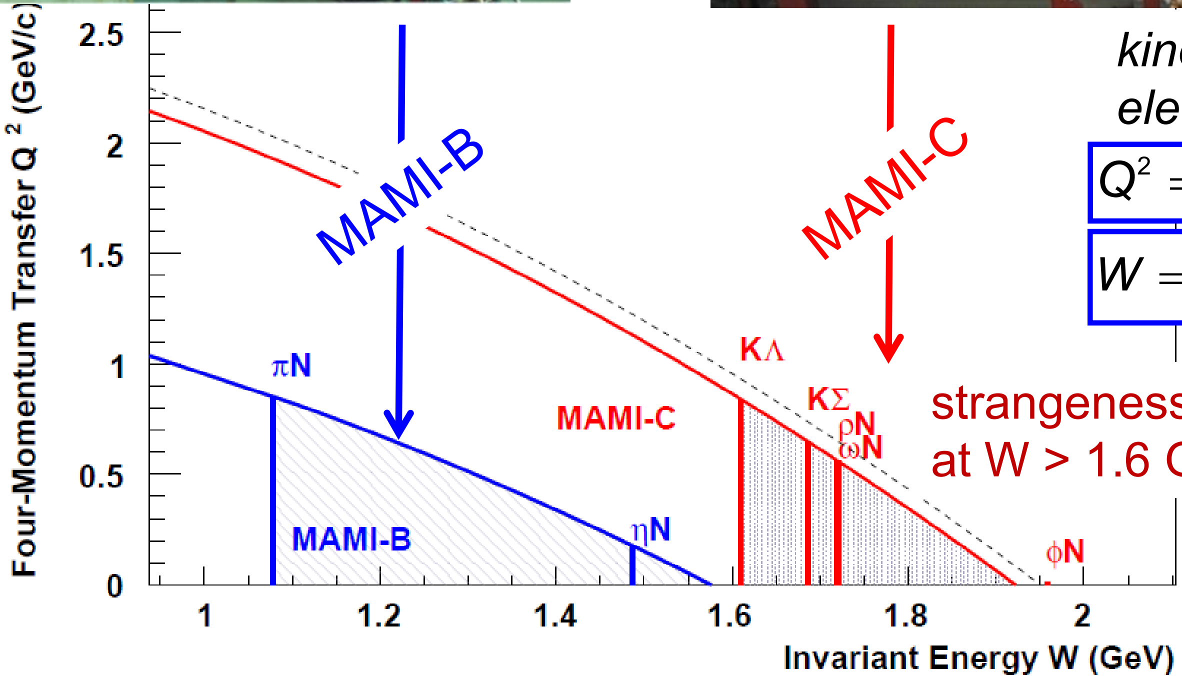
Charged Particle Spectrometer Facility



Kinematic Reach at MAMI







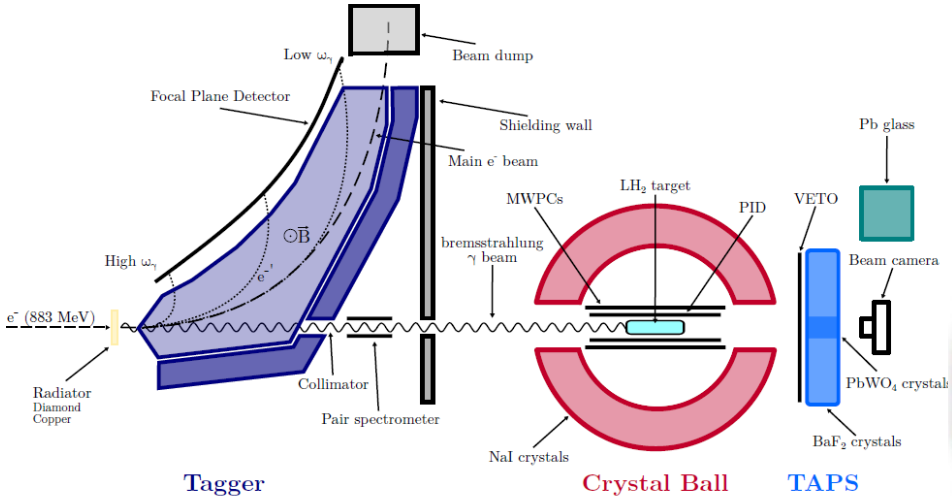
kinematic plane in electro-production:

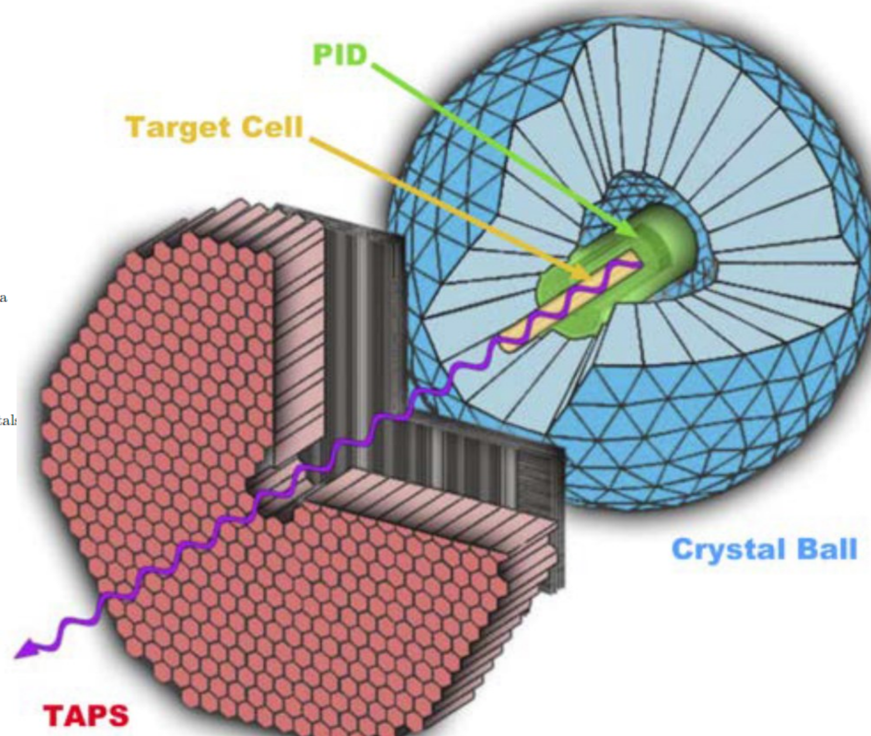
$$Q^2 = -q^2 \quad = (q_e^\mu - q_{e'}^\mu)^2$$

$$W = \sqrt{s} = \sqrt{(q^\mu + p_{target}^\mu)^2}$$

strangeness production at W > 1.6 GeV

Photon Beam Setup at MAMI





$\gamma p \rightarrow K^+\Lambda$ and $\gamma p \rightarrow K^+\Sigma^0$ cross sections

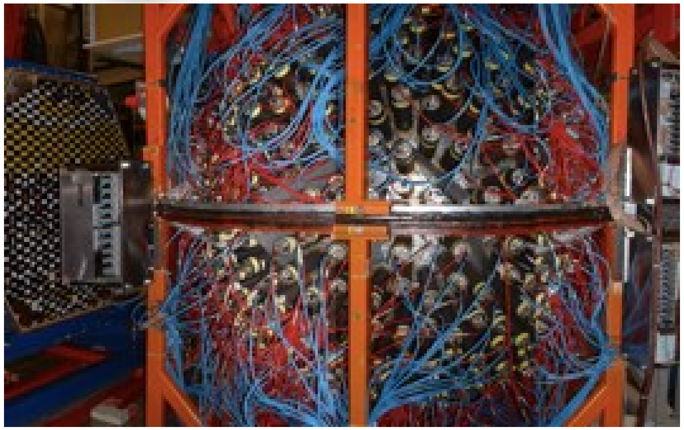
[T. Jude et al. (A2 Collab.), Phys. Lett. B 735, 112 (2014)]

$\gamma p \rightarrow K^0\Sigma^+$ cross sections and
Σ^+ recoil polarization

[P. Aguar-Bartolomé et al. (A2 Collab.), Phys. Rev. C 88, 044601 (2013)]

$\gamma n \rightarrow K^0\Lambda$ and $\gamma n \rightarrow K^0\Sigma^0$ cross sections

[C.S. Akondi et al. (A2 Collab.), Eur. Phys. J.A 55, 11 (2019)]



Magnetic Spectrometer Facility at MAMI

Momentum resolution:

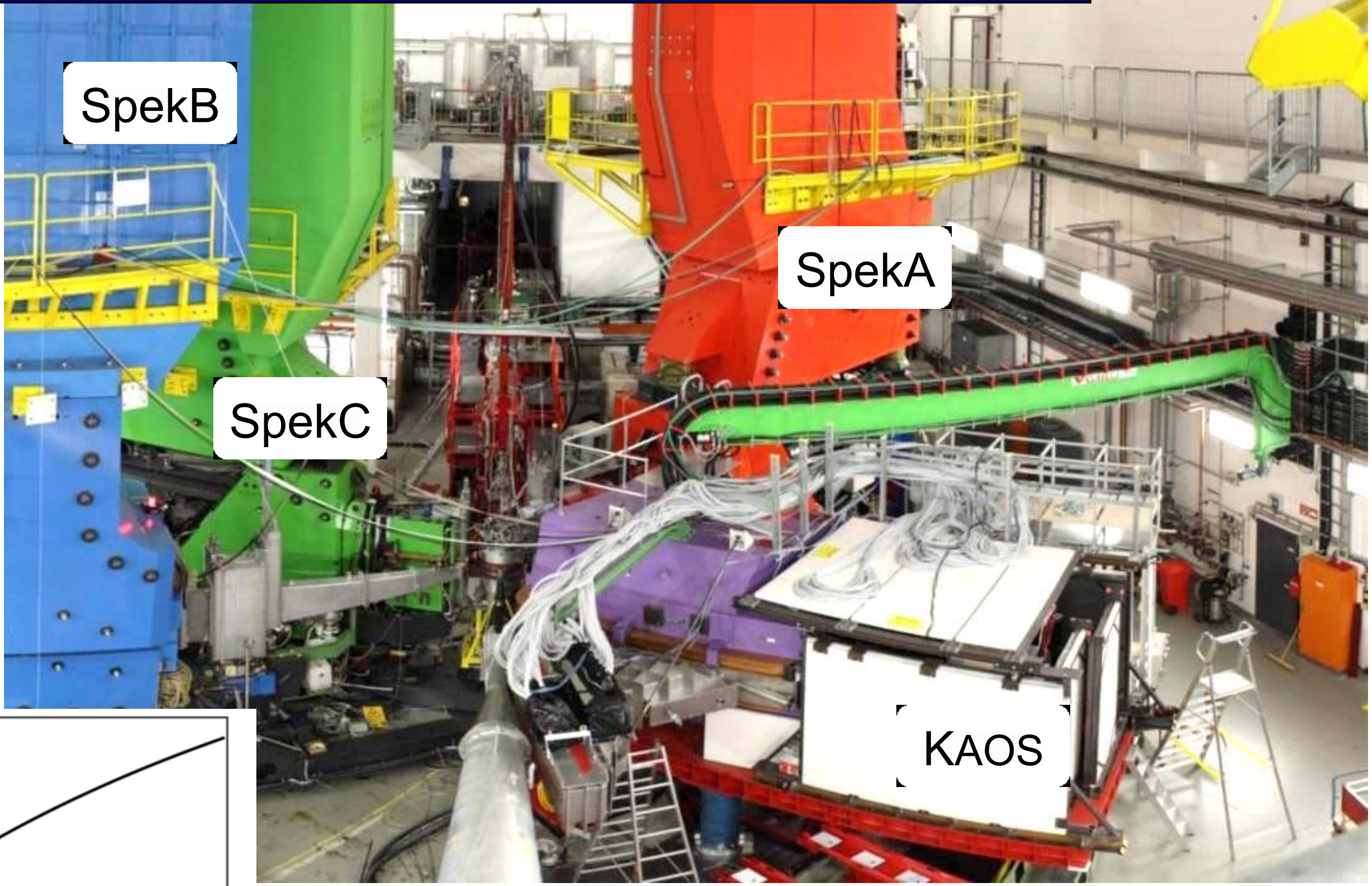
$$\delta p/p < 10^{-4}$$

Momentum acceptance:

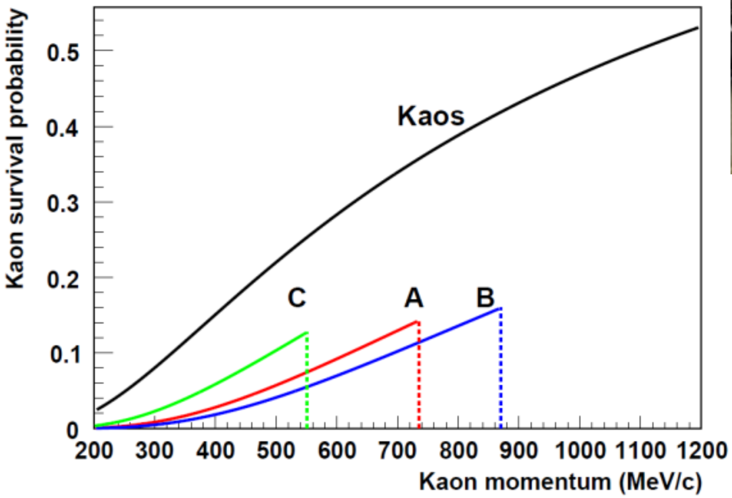
$$\Delta p/p = 20\%$$

Accepted solid angle:

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



Kaon survival probability:



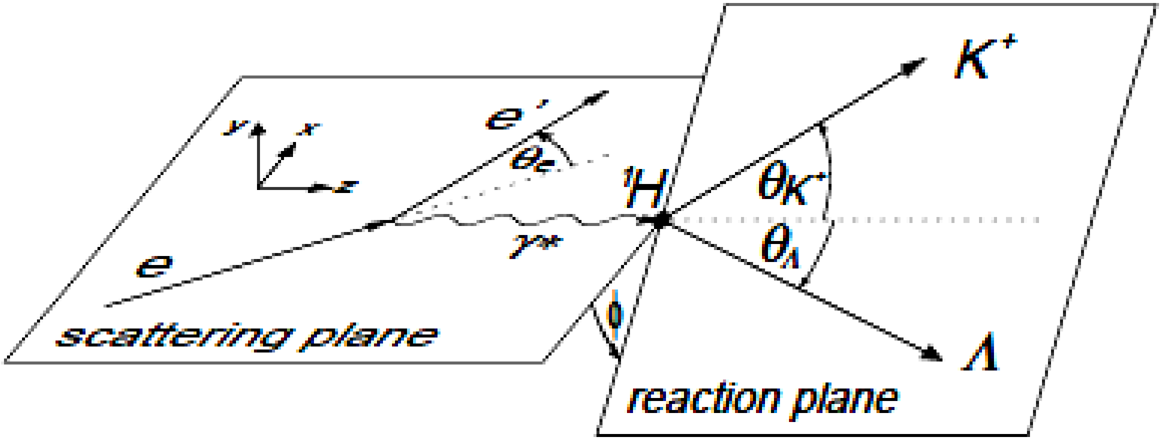
Magnetic focusing spectrometers at MAMI:

- Three high-resolution $\Delta p/p \sim 10^{-4}$ spectrometers
  [K.I. Blomqvist et al., Nucl. Inst. Meth. A 403 (1998)]
- Short-orbit spectrometer (KAOS)
  [P. Achenbach, Eur. Phys. J. ST 198, 307 (2011)]

One-Photon-Exchange Approximation

Five-fold differential cross section separates in **virtual photon flux** and **virtual photoproduction**

$$\frac{d\sigma}{dE'd\Omega_{e'}d\Omega_K^*} = \Gamma \frac{d\sigma}{d\Omega_K^*}$$



$$\frac{d\sigma}{d\Omega_K^*} = \sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT}\cos 2\phi + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi + h\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT'}\sin\phi$$

Degree-of-polarization of photon: $\epsilon = \left(1 + 2\frac{|\vec{q}|^2}{Q^2}\tan^2\theta/2\right)^{-1}$

Helicity of incoming electron: h

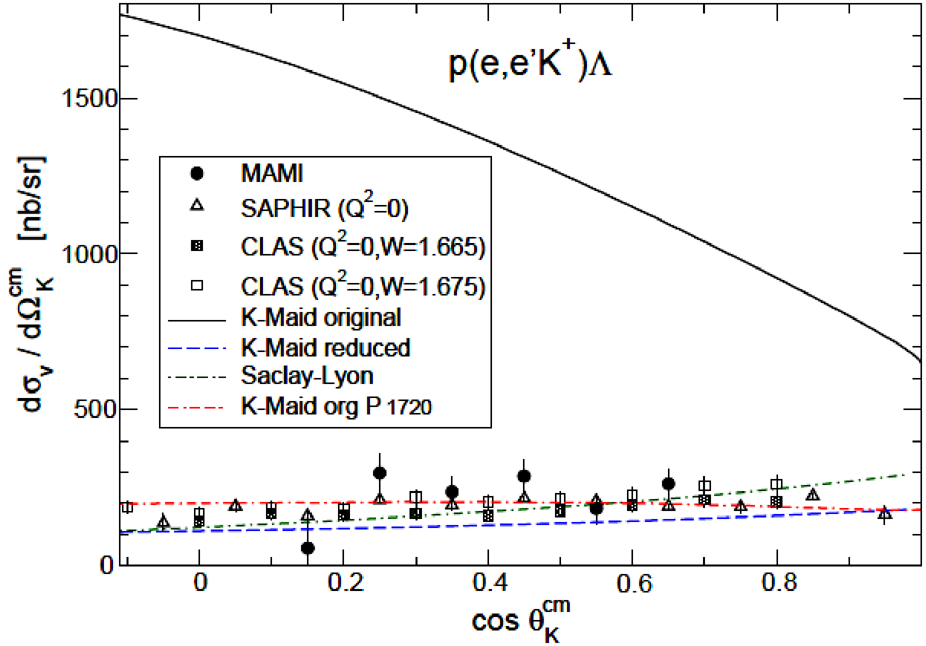
[E. Amaldi, S. Fubini, and G. Furlan, Pion-Electroproduction (1979);
A. Donnachie & G. Shaw, Electromagnetic Interactions of Hadrons (1978)]

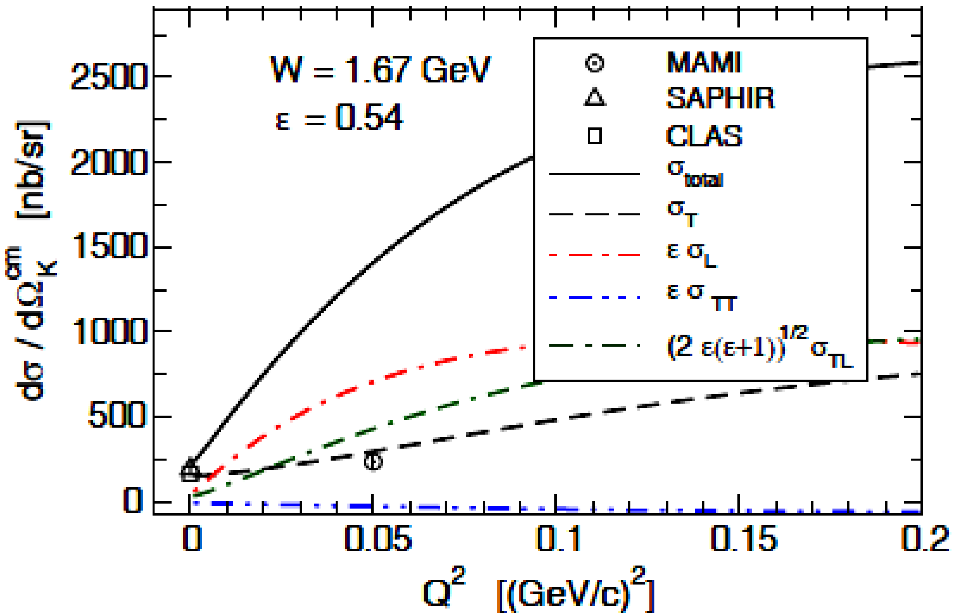
Cross sections for $K\Lambda$ at $Q^2 = 0.050$

$\langle Q^2 \rangle$ $(\mathrm{GeV}/c)^2$	$\langle W \rangle$ GeV	$\langle \epsilon \rangle$ (trans.)	$\langle \omega \rangle$ GeV
0.050	1.670	0.540	1.044

$$\frac{d\sigma}{dE' d\Omega_{e'} d\Omega_K^*} = \Gamma \frac{d\sigma}{d\Omega_K^*}$$

[P. Achenbach *et al.* (A1 Collab.), Eur. Phys. J. A 48 (2012)]





– (Some) available models based on numerous adjustable parameters

– Strong longitudinal couplings → steep increase of dσ/dΩ with Q^2

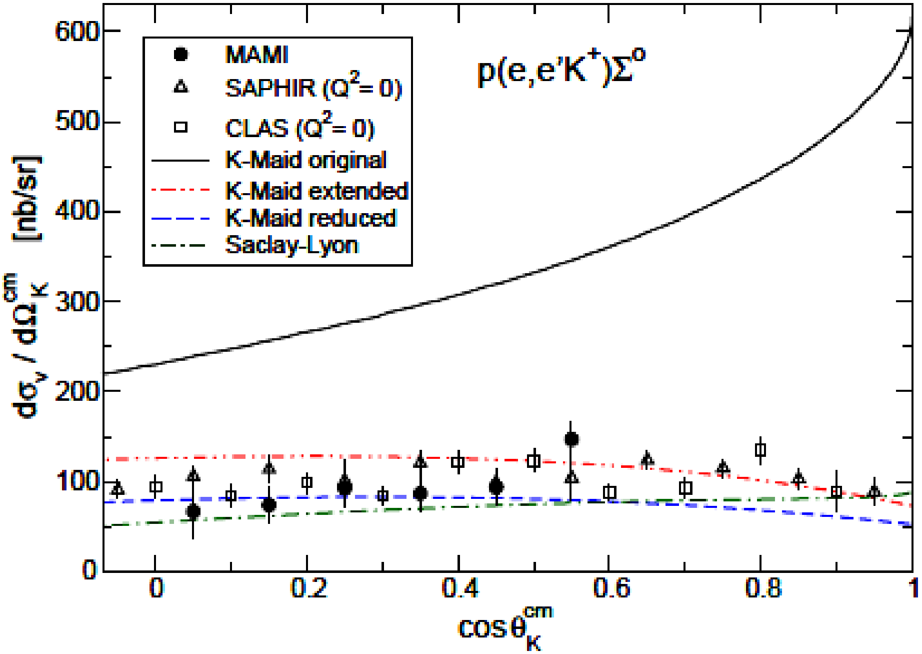
– Strangeness production aids in the construction of theoretical model

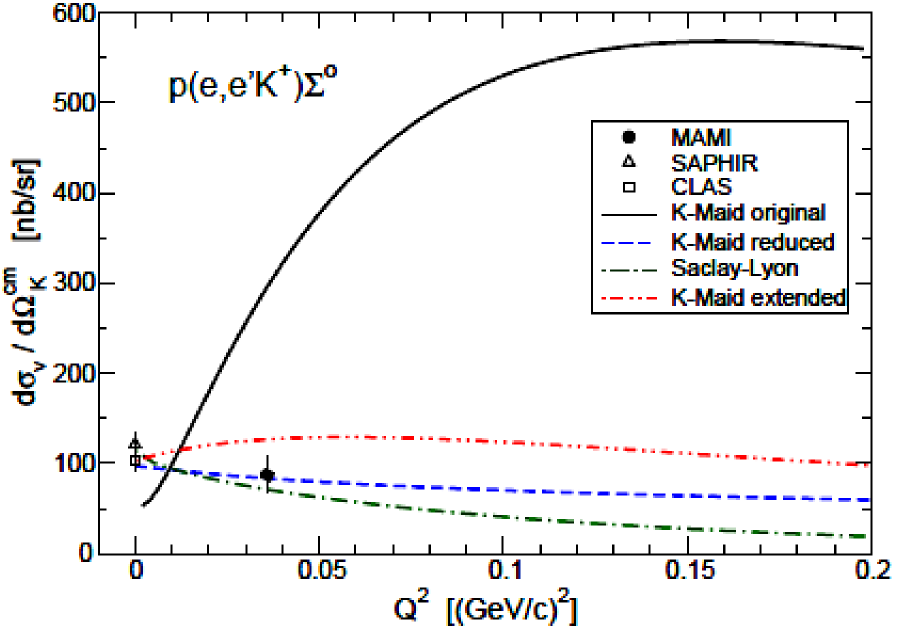
Cross sections for $K\Sigma$ at $Q^2 = 0.036$

$\langle Q^2 \rangle$ $(\text{GeV}/c)^2$	$\langle W \rangle$ GeV	$\langle \epsilon \rangle$ (trans.)	$\langle \omega \rangle$ GeV
0.036	1.750	0.395	1.182

$$\frac{d\sigma}{dE' d\Omega_{e'} d\Omega^*_K} = \Gamma \frac{d\sigma}{d\Omega^*_K}$$

[P. Achenbach *et al.* (A1 Collab.), Eur. Phys. J. A 48 (2012)]





– (Some) available models based on numerous adjustable parameters

– Strong longitudinal couplings → steep increase of dσ/dΩ with Q^2

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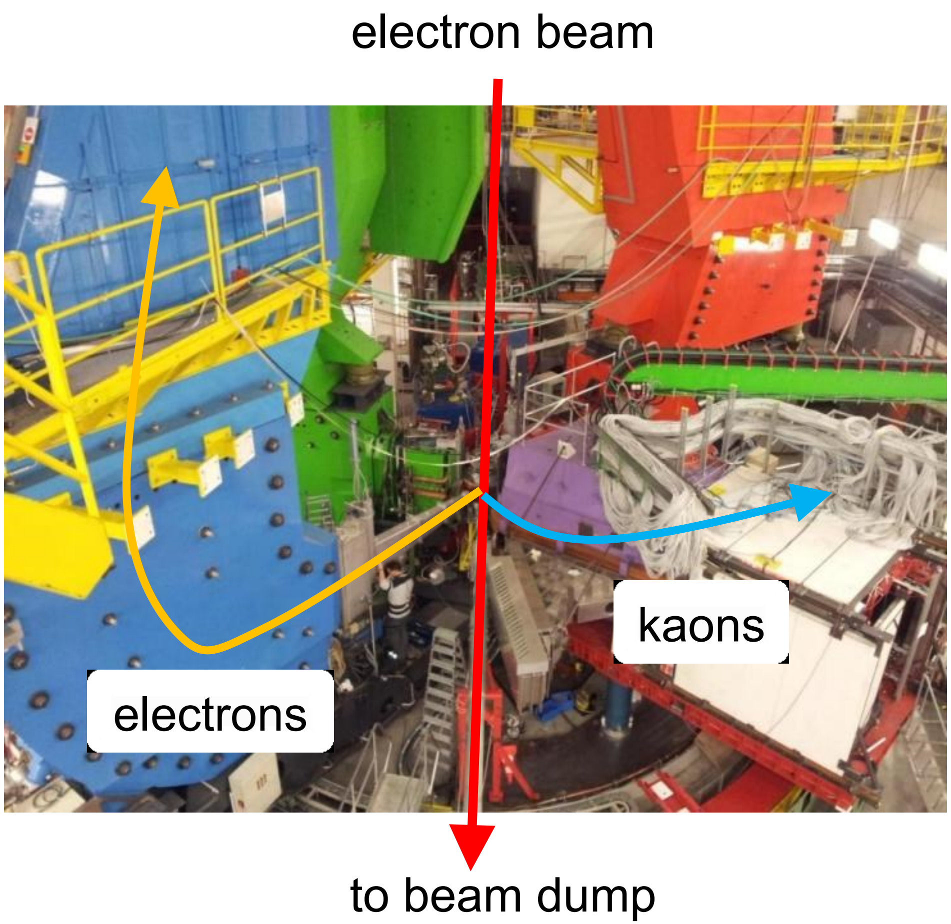
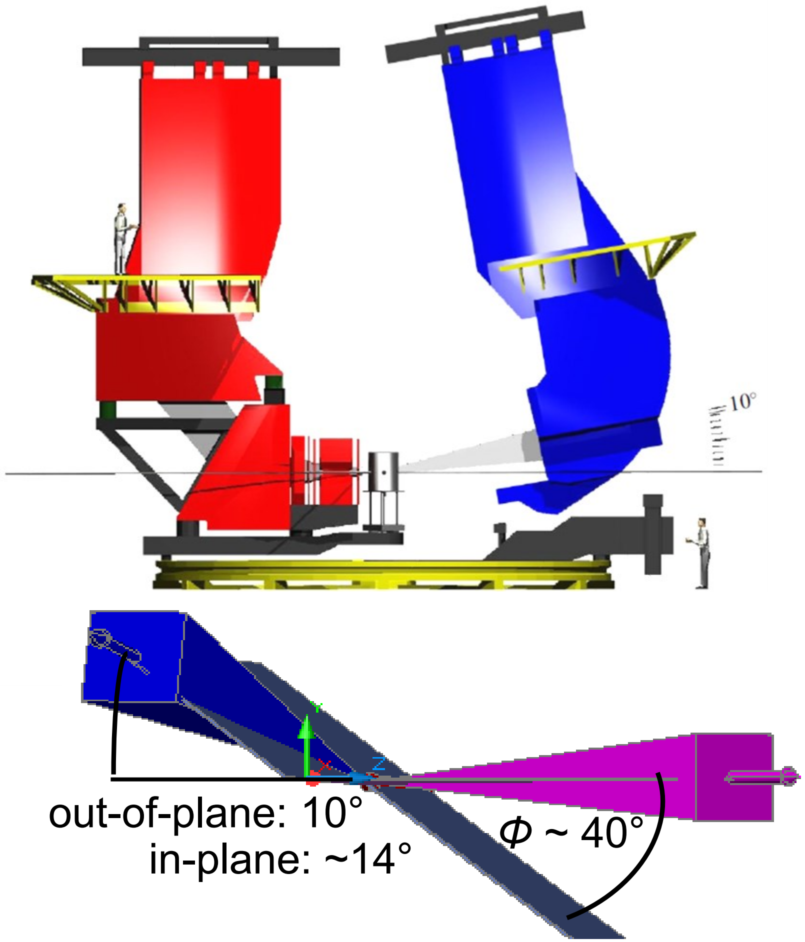
Out-of-Plane Measurements with SpekB



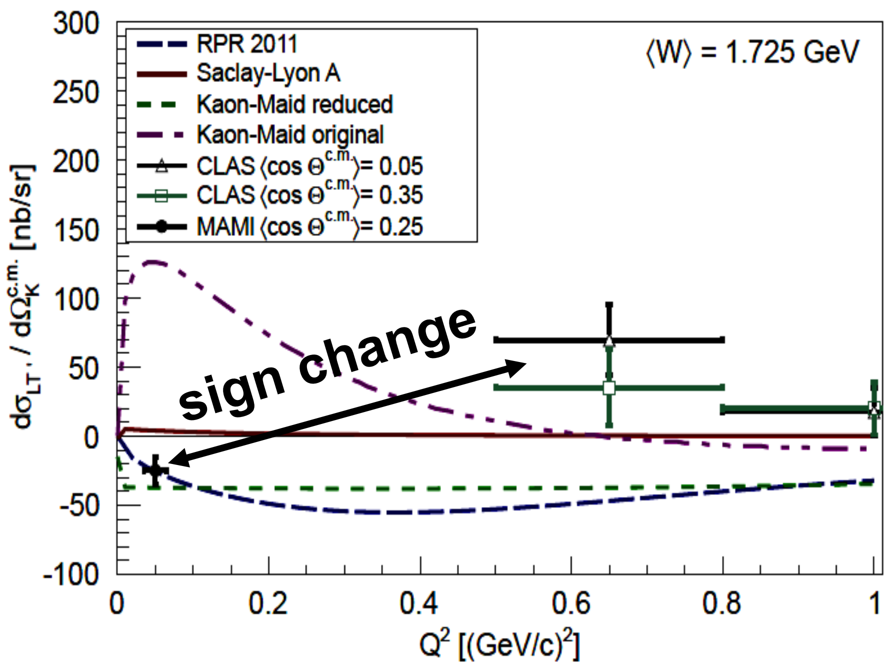


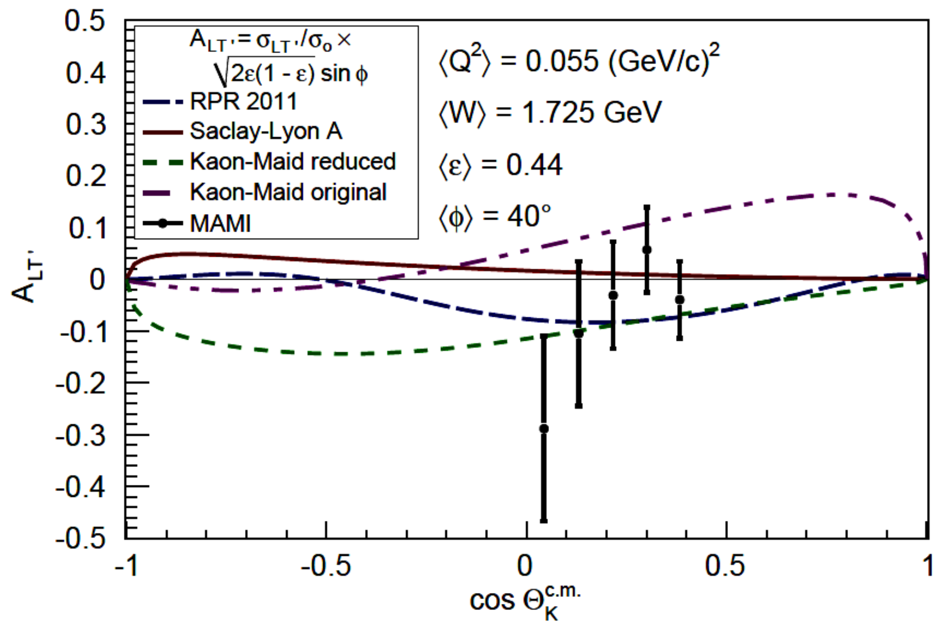
- Electron beam with high degree of polarization
- Out-of-plane capability of Spectrometer B → $\Phi \sim 40°$

Beam Helicity Asymmetries for $K\Lambda$

[P. Achenbach *et al*. (A1 Collab.), Nucl. Phys. A 914 (2013)]

$$A_{LT'} = \frac{\left(\frac{d\sigma}{d\Omega_K^*}\right)^+ - \left(\frac{d\sigma}{d\Omega_K^*}\right)^-}{\left(\frac{d\sigma}{d\Omega_K^*}\right)^+ + \left(\frac{d\sigma}{d\Omega_K^*}\right)^-} = \frac{\sqrt{\epsilon(1-\epsilon)}\sigma_{LT'} \sin\phi}{\sigma_0}$$





- Sensitivity of $\sigma_{LT'}$ to interferences between resonances
- Sign change & angular variation indicates rich resonance structure

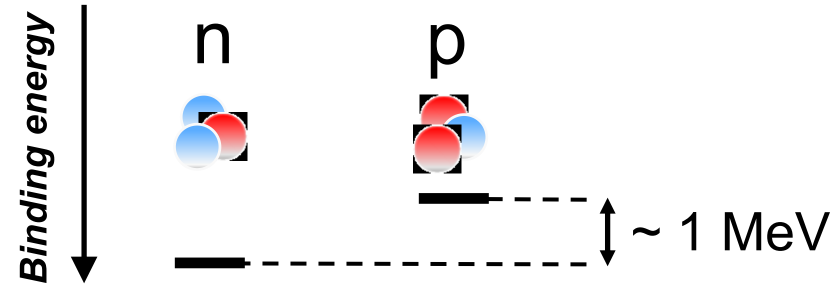
Symmetries in Nuclear Forces

Charge independence: strong force independent of nucleon state

$$(F_{p\text{-}p} = F_{n\text{-}n} = F_{p\text{-}n})$$

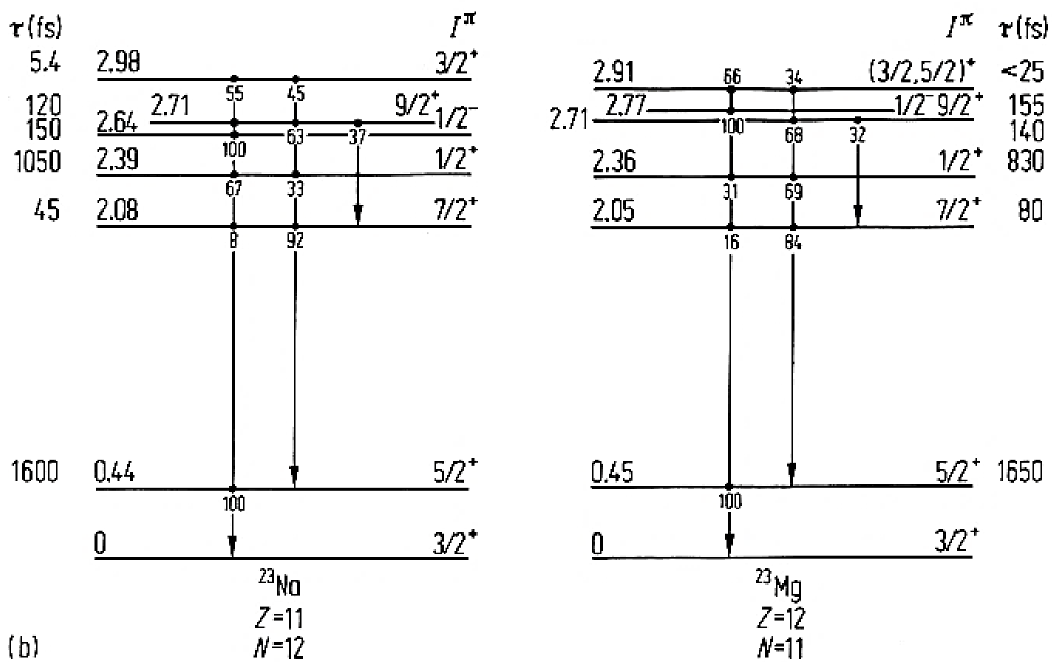
Charge symmetry: strong force independent of nucleon exchange

$$(F_{p\text{-}p} = F_{n\text{-}n})$$



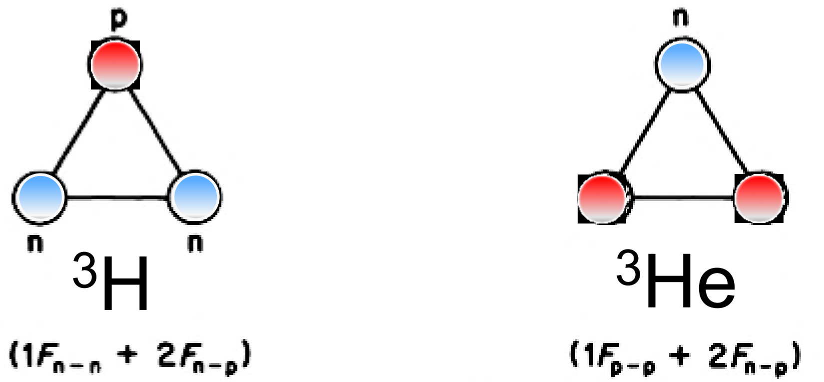
ΔM/M ~ 0.1 %

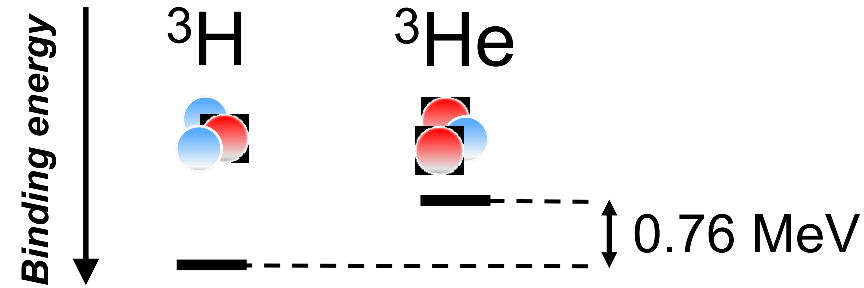
Symmetry in masses, binding energies and level schemes of mirror nuclei, where proton and neutron numbers are exchanged



[Endt & van der Leun, Nucl. Phys. A 310, 67 (1978)]

Charge Symmetry Breaking





$M(^3\mathrm{H}) =$	2808.921	$B(^3\mathrm{H}) =$	8.482
$M(^3\mathrm{He}) =$	2808.391	$B(^3\mathrm{He}) =$	7.718
$\Delta M^3 =$	−0.530	$\Delta B^3 =$	−0.764

… can be studied in mirror nuclei after correcting for Coulomb effects

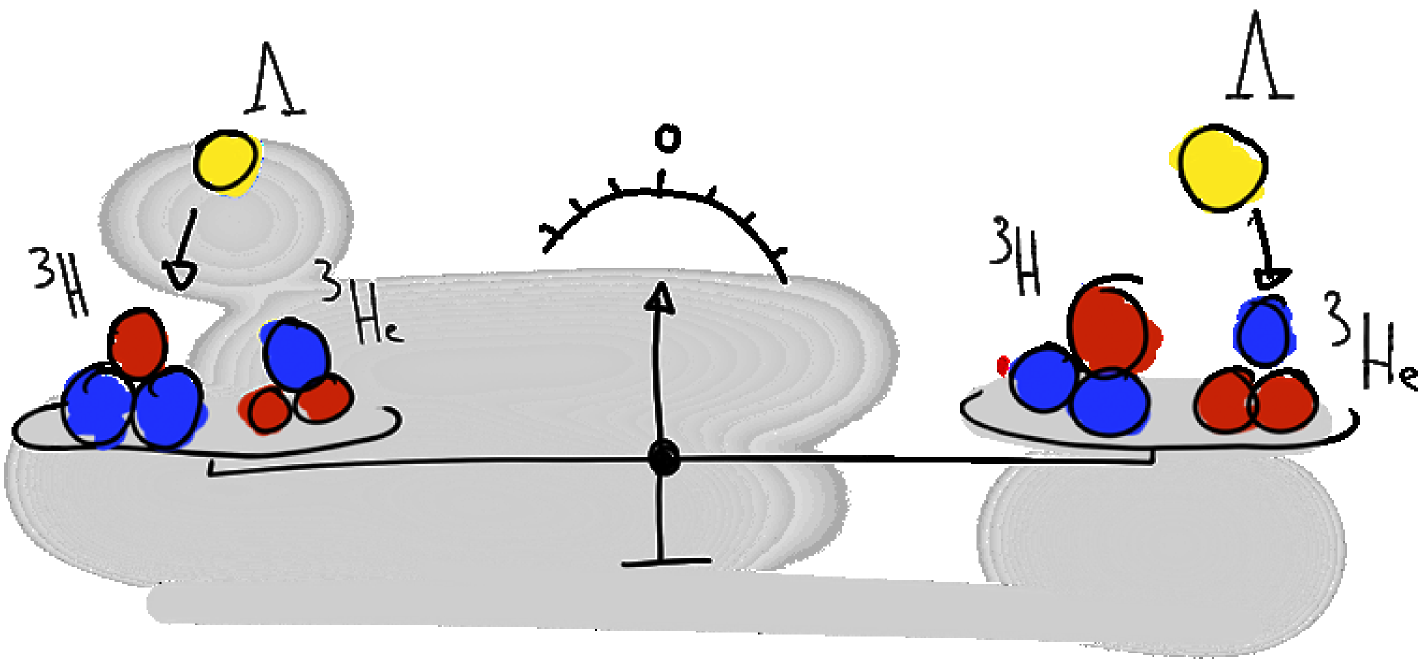
… is dominated by electromagnetic effects

… nuclear part very small, ~ 80 keV in case of ^{3}H - ^{3}He

… is well understood and reproduced by theory using ρ^0-ω mixing

[R. Machleit et al., Phys. Rev. C 63, 034005 (2001)]

Light Hypernuclei as a Testbed for Charge Symmetry



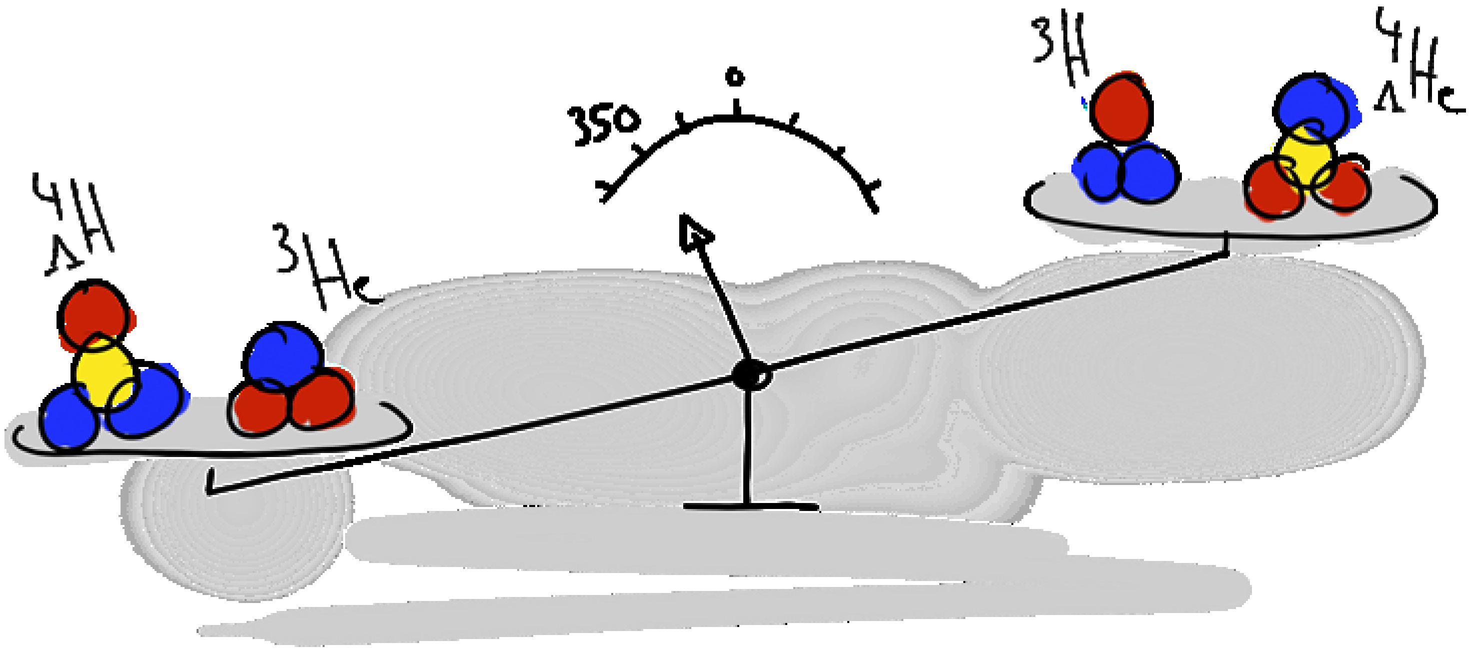
Opportunity to study strong force symmetries with Λ as neutral probe

Λ hyperon has no isospin and no charge:

$$F_{\Lambda\text{-p}} = F_{\Lambda\text{-n}} \rightarrow B_\Lambda\,({}_\Lambda^A Z) = B_\Lambda({}_\Lambda^A Z{+}1)$$

Charge Symmetry Breaking in *A* = *4* System

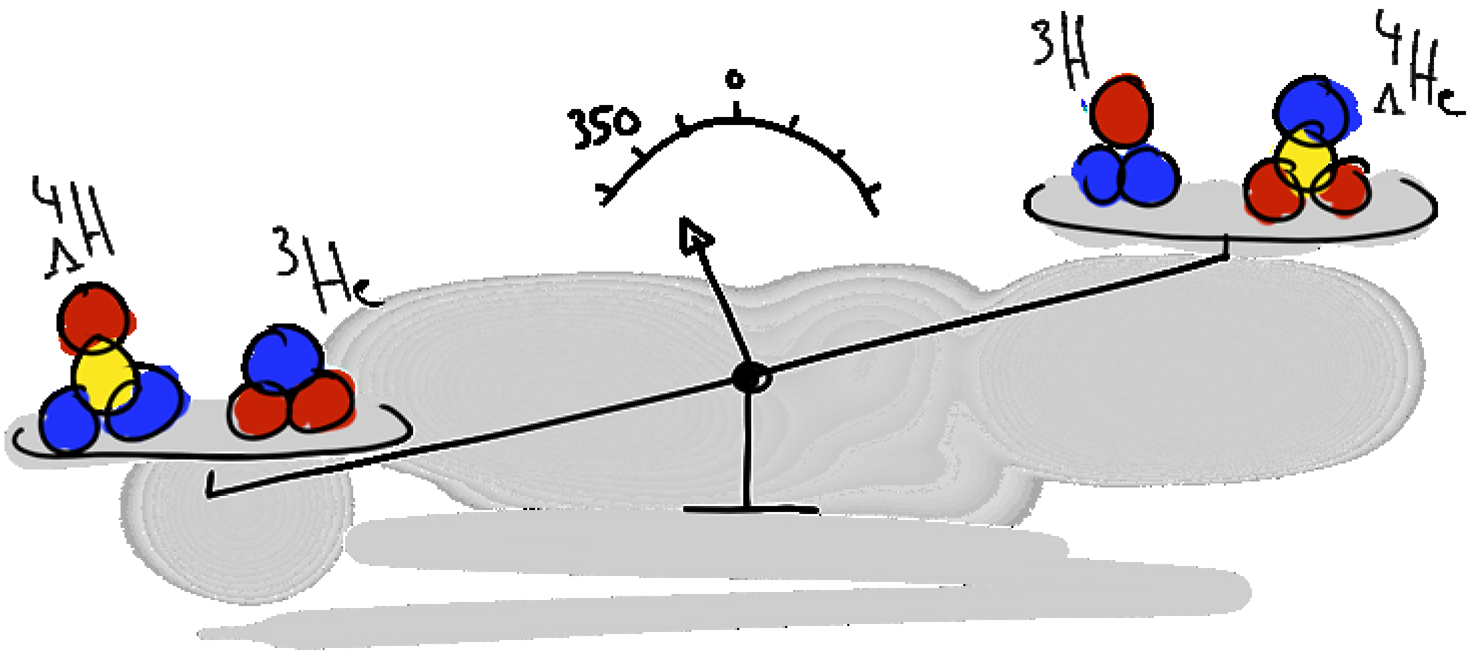
$$-B_\Lambda = M_{HYP} - (M_{Core} + M_\Lambda)$$



$M({}^4_\Lambda\mathrm{H}) =$	3922.56	$B_\Lambda({}^4_\Lambda\mathrm{H}) =$	2.04
$M({}^4_\Lambda\mathrm{He}) =$	3921.68	$B_\Lambda({}^4_\Lambda\mathrm{He}) =$	2.39
$\Delta M^4_\Lambda =$	−0.88	$\Delta B^4_\Lambda =$	0.35

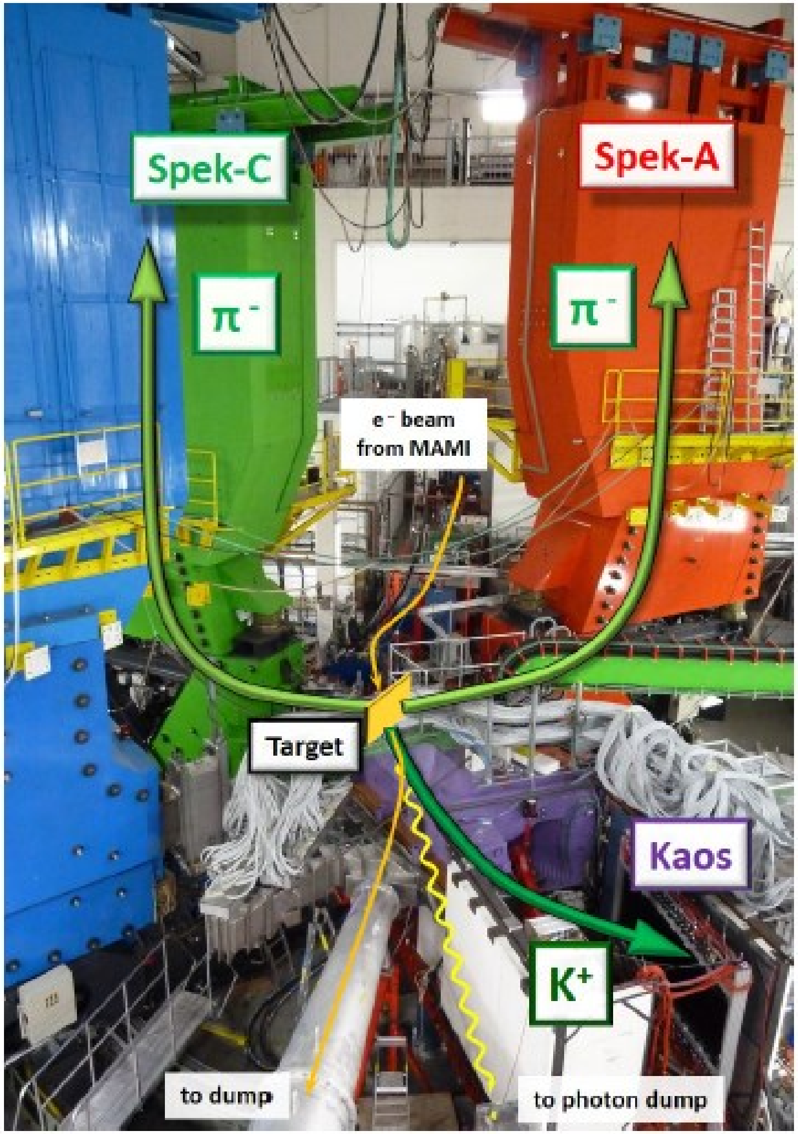
[M. Juric et al., Nucl. Phys. B 52 (1973)]

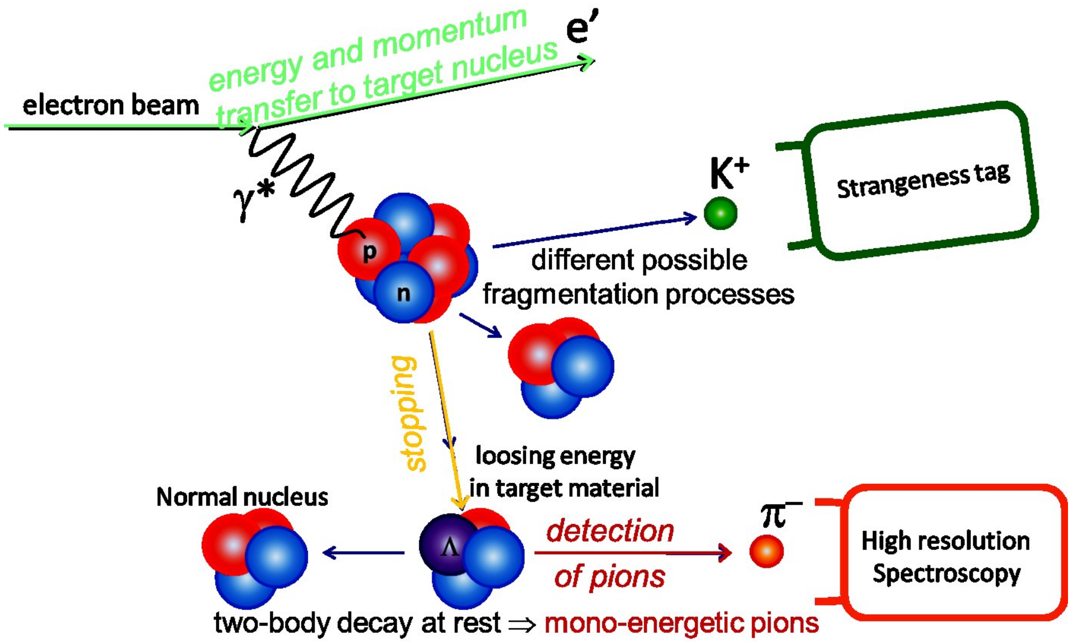
Charge Symmetry Breaking in *A* = *4* System



- $^{4}_{\Lambda}$H – $^{4}_{\Lambda}$He binding energy difference exceptionally large > 300 keV
- CSB about 5 times larger than in ^{3}H – ^{3}He system!
- Why is Λp interaction so much stronger than Λn interaction?

Electron-Induced Hyperfragment Decay-Pion Spectroscopy

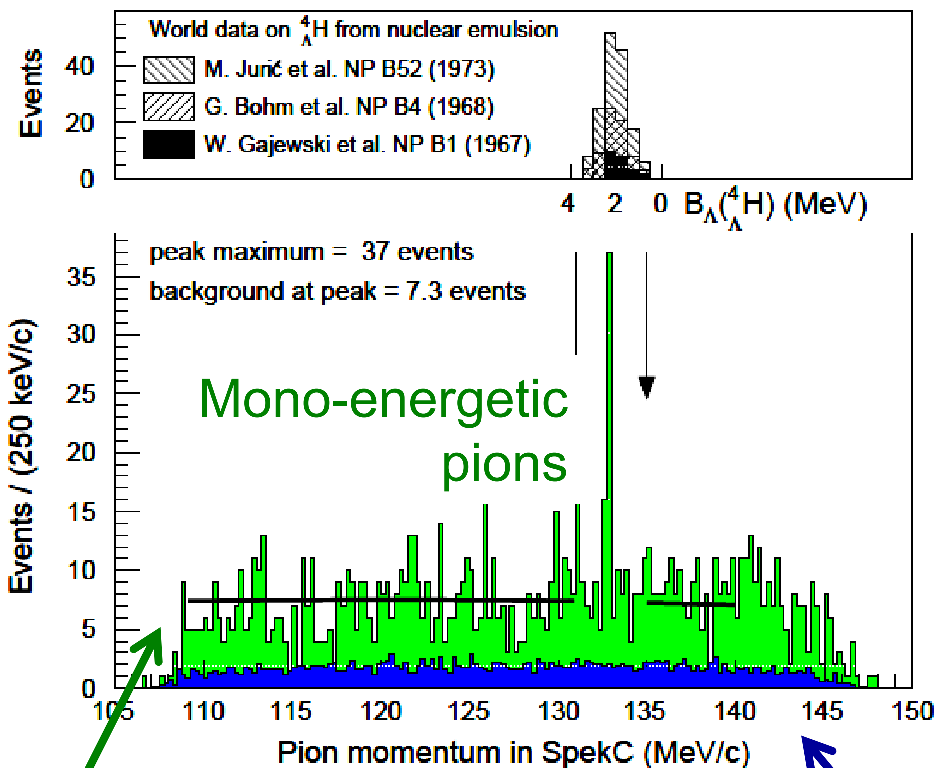




$$M_{\mathrm{HYP}} = \sqrt{M_{\mathrm{ncl}}^2 + p_{\pi^-}^2} + \sqrt{M_{\pi^-}^2 + p_{\pi^-}^2}$$

[Hypernuclear experiments at MAMI in Collaboration with Tohoku University]

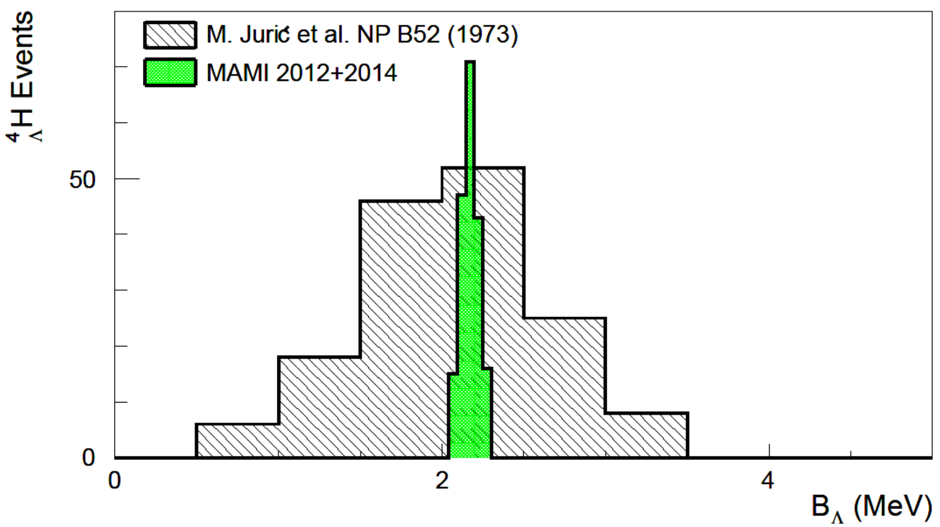
Analysis of Decay-Pion Spectra



Decays of quasi-free produced hyperon

Accidental background reactions

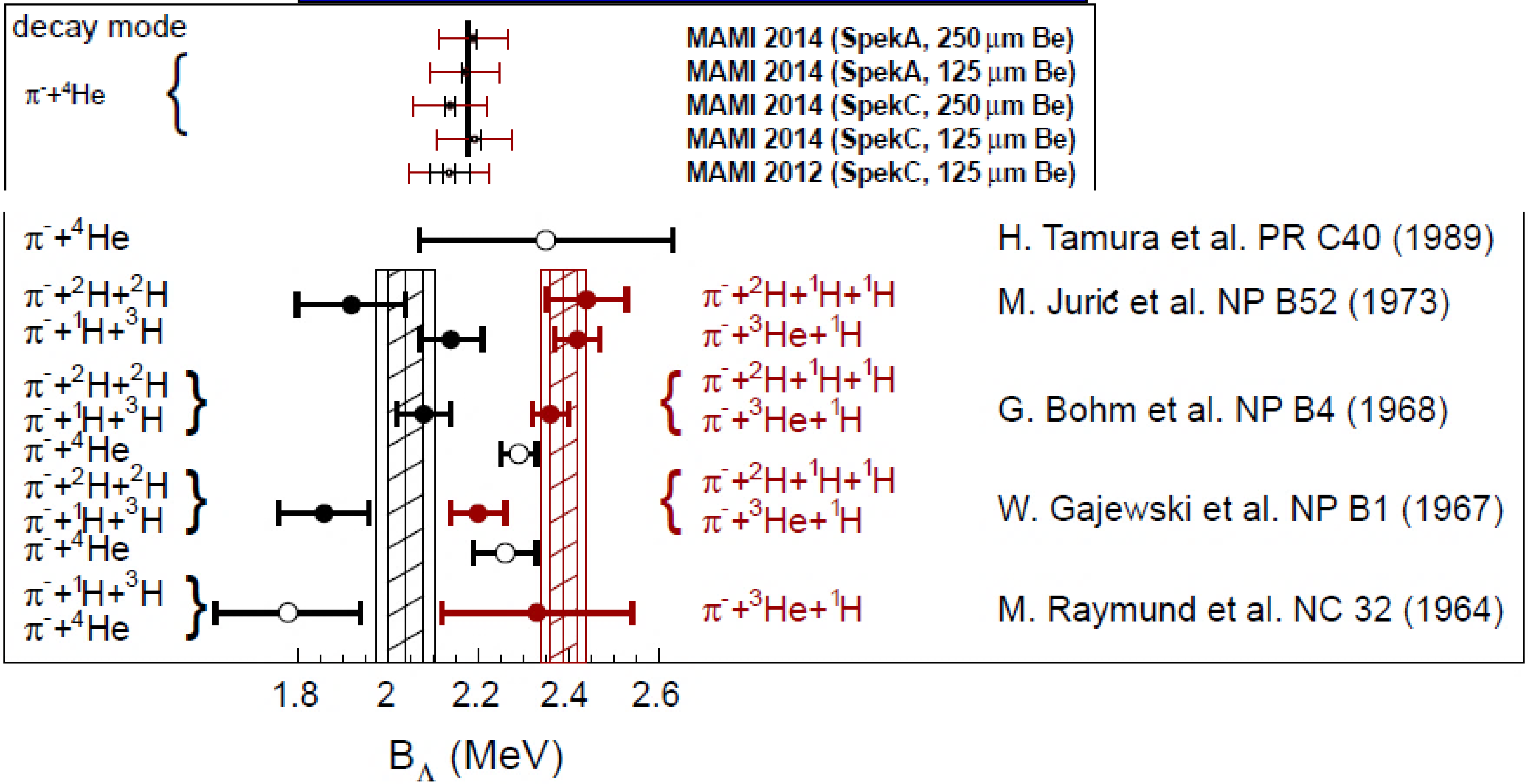
Comparison on binding energy scale



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

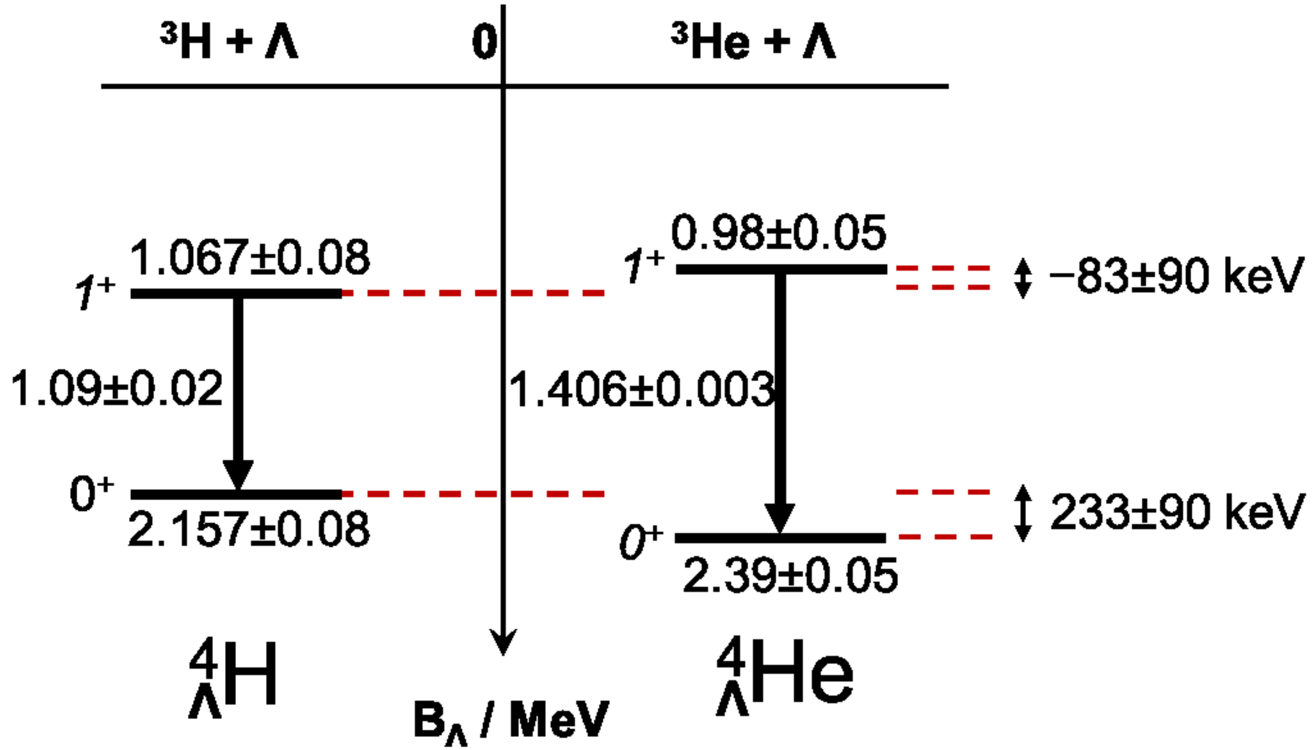
New precision era in hypernuclear physics

World data on $A = 4$ system



	$B_\Lambda(^4_\Lambda H)$	(stat.)	(syst.)	
Emulsion:	2.04	± 0.04	± 0.05 MeV	[M. Juric et al., Nucl. Phys. B 52 (1973)]
MAMI 2012:	2.12	± 0.01	± 0.09 MeV	[A. Esser et al., Phys. Rev. Lett. 114 (2015)]
MAMI 2014:	2.16	± 0.01	± 0.08 MeV	[F. Schulz et al., Nucl. Phys. A (2016)]

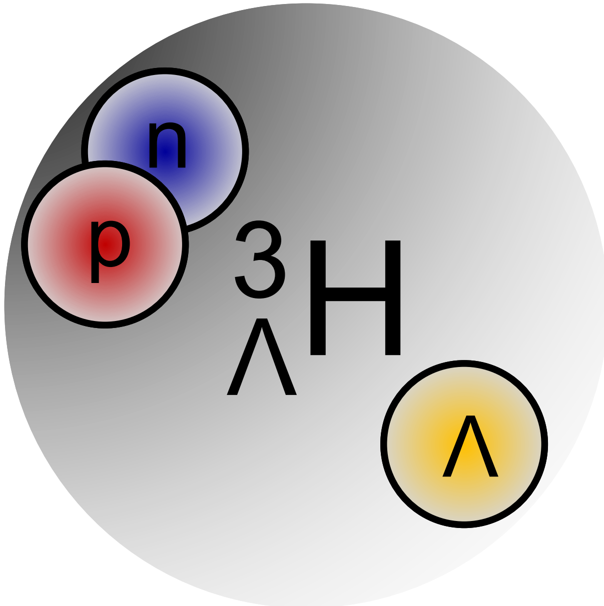
Current knowledge on CSB in the A = 4 system



- CSB is considerably stronger in hyper- than in ordinary nuclei
- CSB in A = 4 system is strongly spin-dependent …
  ...and possibly changing sign between ground and excited states:
  positive CSB for ground state and negative CSB for excited state

A Λ-Hypernuclear Three-Body System

The hypertriton



– Lightest hypernuclear bound state:
$S = -1$, $J^P = ½^+$, $T = 0$

– Simplest system in which Λ particle interacts with nucleons at low energy

– Small Λ separation = binding energy:
B_Λ = 130 ± 50 (stat.) ± 50 (syst.) keV

– Short ranges of NN / ΛN interactions & small total binding energy (B ~2.3 MeV) imply S states and very loose structure

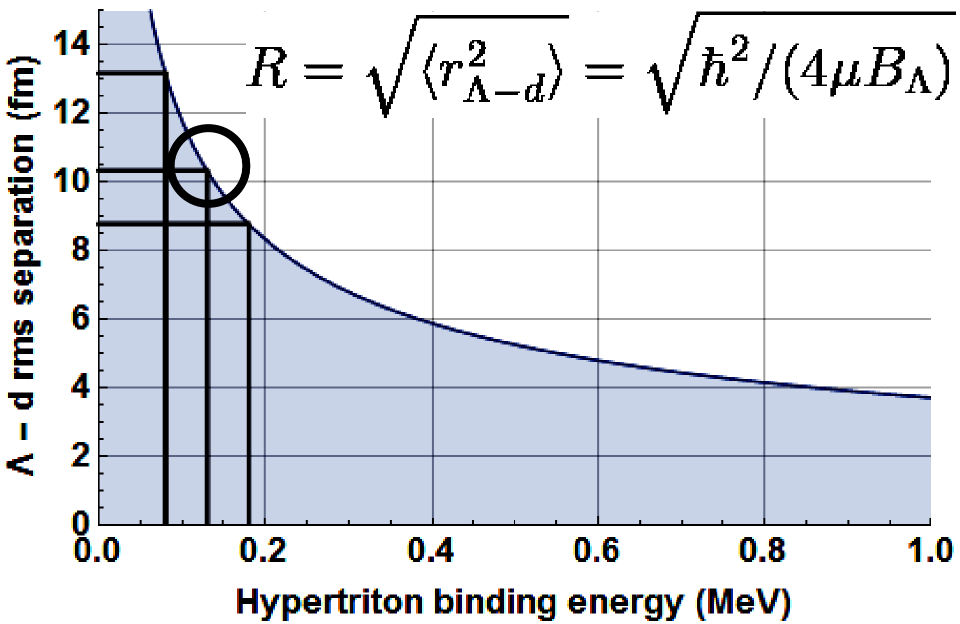
– Mesonic weak decay (MWD) is expected to dominate over non-MWD

How well do we really know the simplest and lightest hypernucleus?

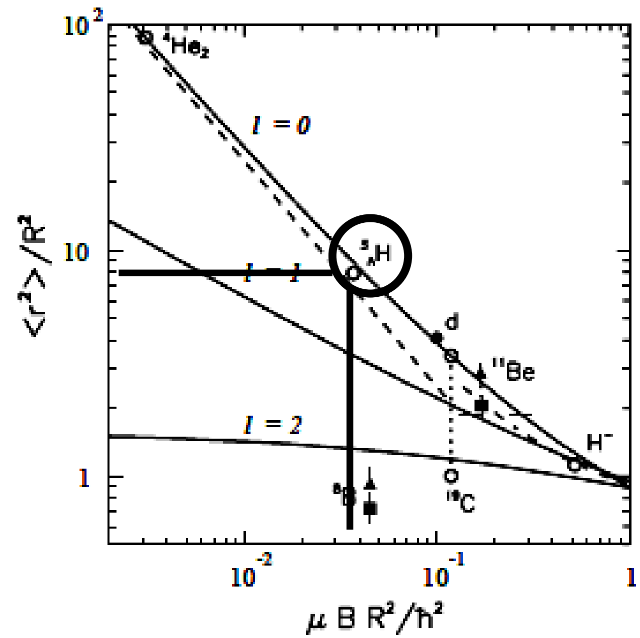
Hypertriton as a Halo System

– Hypertriton has no centrifugal barrier & no Coulomb repulsion

– Universal scaling relation for nuclear systems with small binding



$$R = \sqrt{\langle r^2_{\Lambda-d}\rangle} = \sqrt{\hbar^2/(4\mu B_\Lambda)}$$

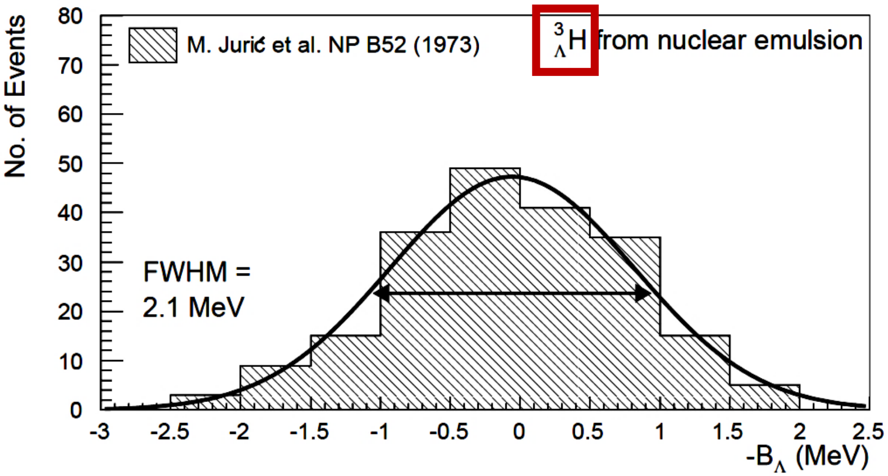


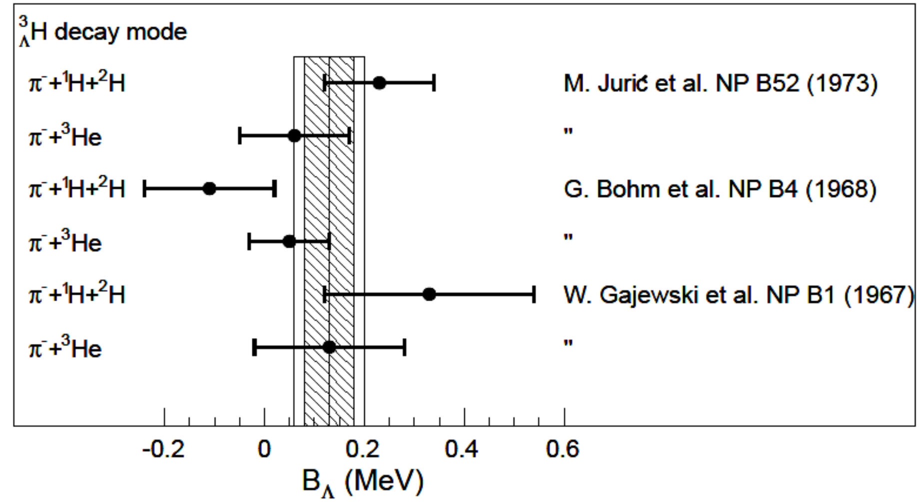
[Riisager et al., Europhys. Lett. 49 (2000)]

– Hypertriton is understood as an effective two-body *dΛ* system

Emulsion Data for $^3_\Lambda H$

Only about 200 analyzed events from 2 decay modes in emulsion:





$$^3_\Lambda H \xrightarrow{decay} \pi^- + ^3He: \quad B_\Lambda = 70 \pm 60 \text{ keV}$$

$$^3_\Lambda H \xrightarrow{decay} \pi^- + ^1H + ^2H: \quad B_\Lambda = 120 \pm 80 \text{ keV}$$

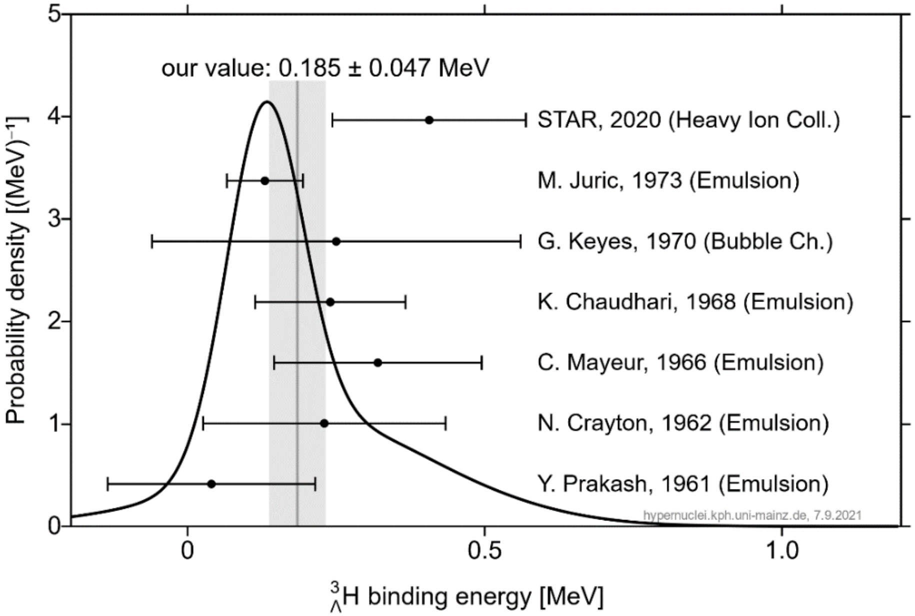
} 50 keV difference

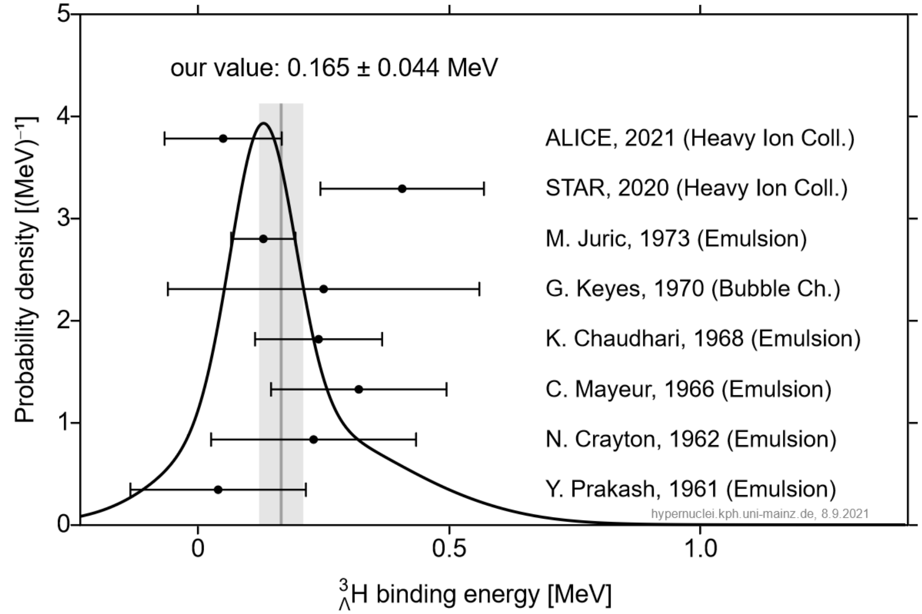
$$\text{Total:} \quad B_\Lambda = 130 \pm 50 \text{ keV}$$

[M. Juric et al., Nucl. Phys. B 52 (1973)]

- For long time only source of binding energy information
- Emulsion data almost consistent with zero
- Data spans over a wide range characterized by a FWHM of 2.1 MeV

Modern Measurements for ${}^{3}_{\Lambda}H$

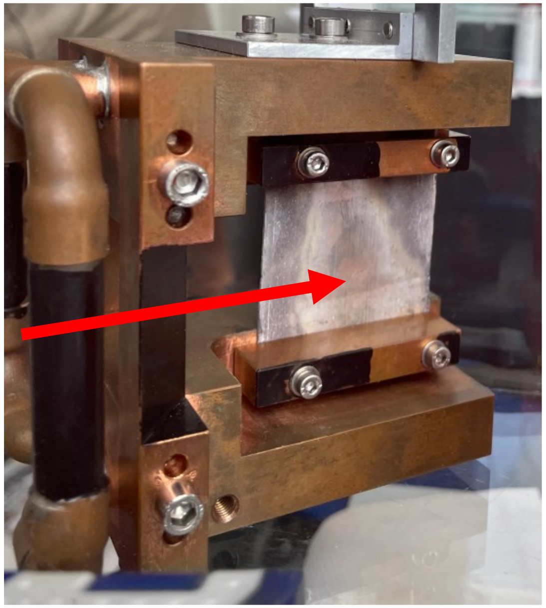




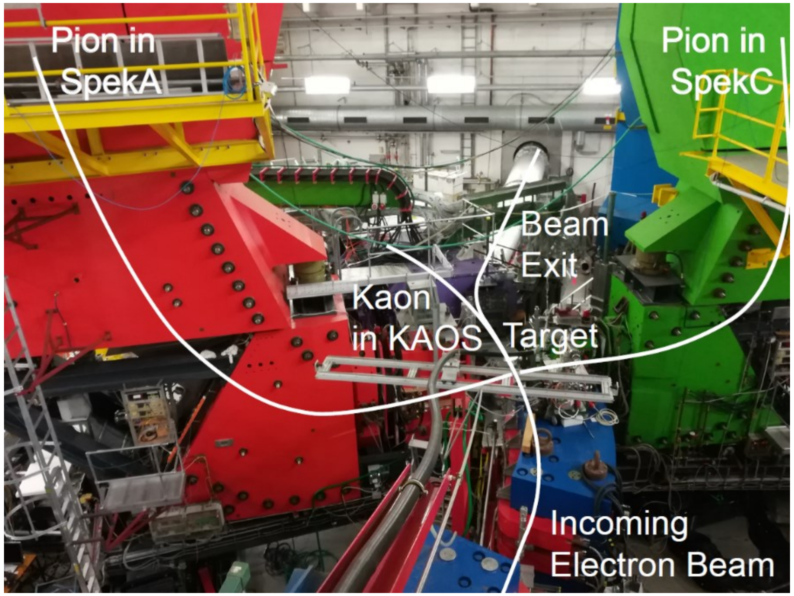
- Latest STAR B_Λ value more than 3 times larger than emulsion value
- Latest ALICE B_Λ value only ½ of emulsion value

$^{3}_{\Lambda}H$ Binding Energy Measurement at MAMI

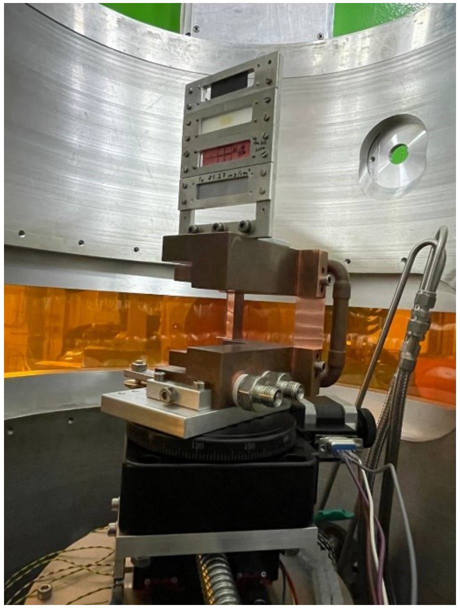
Novel lithium target:



Experimental setup:

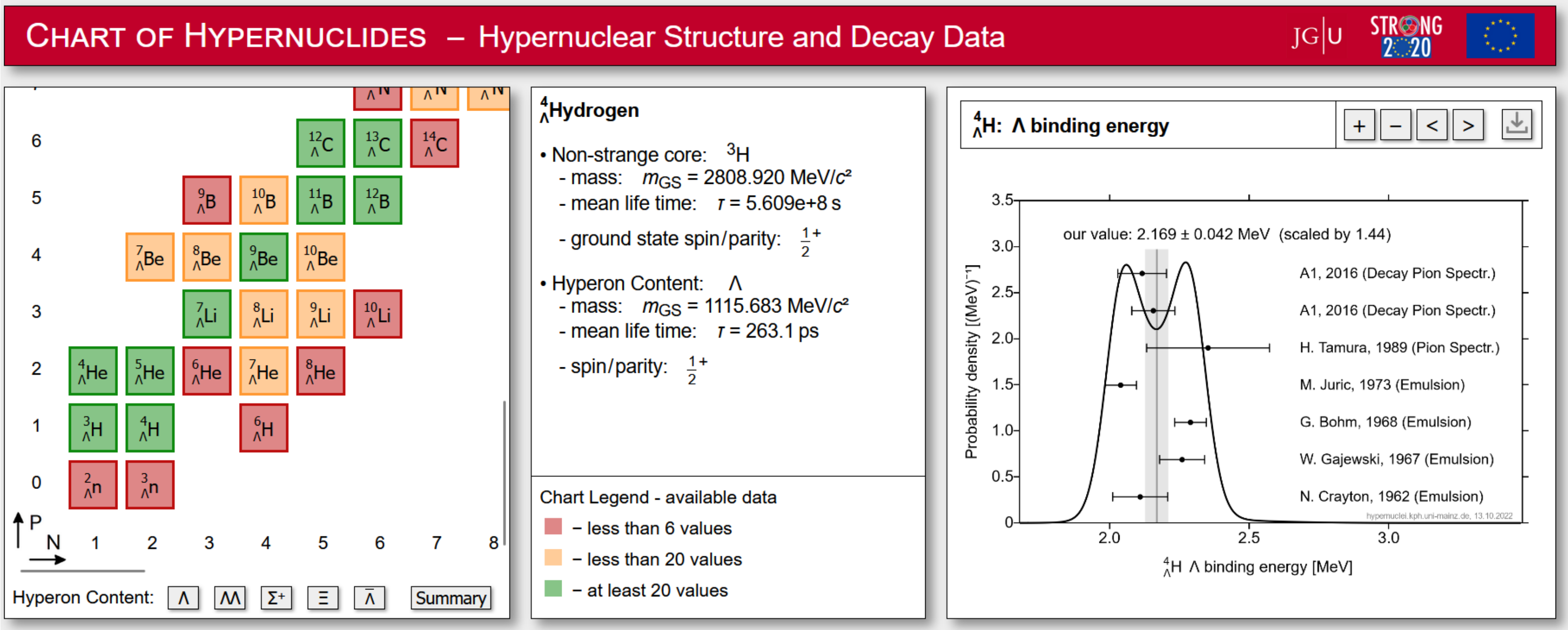


Scattering chamber:



- Higher luminosity & improved positron suppression → more statistics
- 2022 experiment for $^{3}_{\Lambda}H$ and just finished this week!

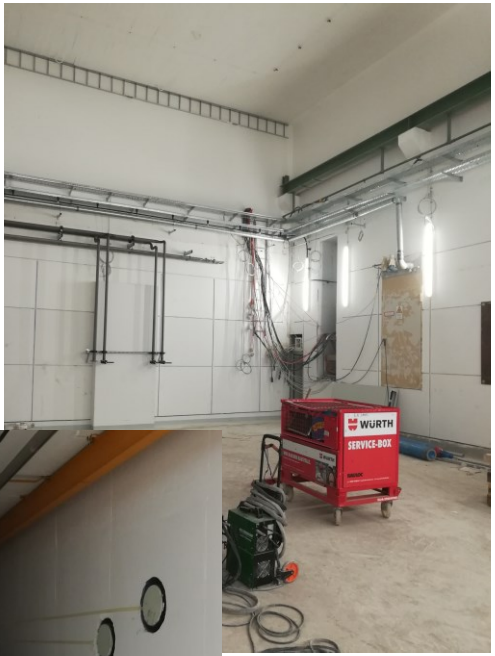
Hypernuclear Database Hosted in Mainz



- Unified approach to collect and combine data
- Consistent treatment of shared systematic and asymmetric errors
- Exclusion of redundant and non-relevant measurements
- Scaling of errors in inconsistent data sets

hypernuclei.kph.uni-mainz.de

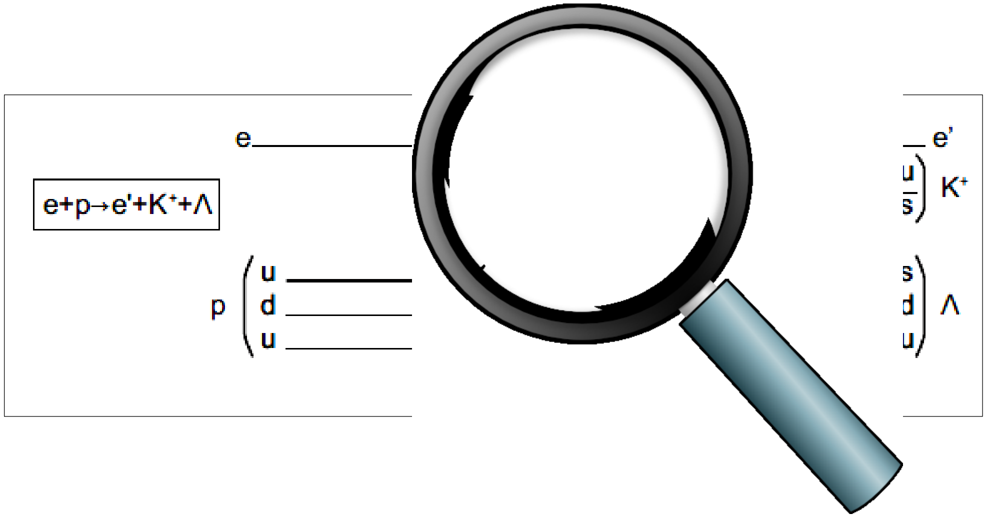
MESA: The Nuclear Physics Future at Mainz

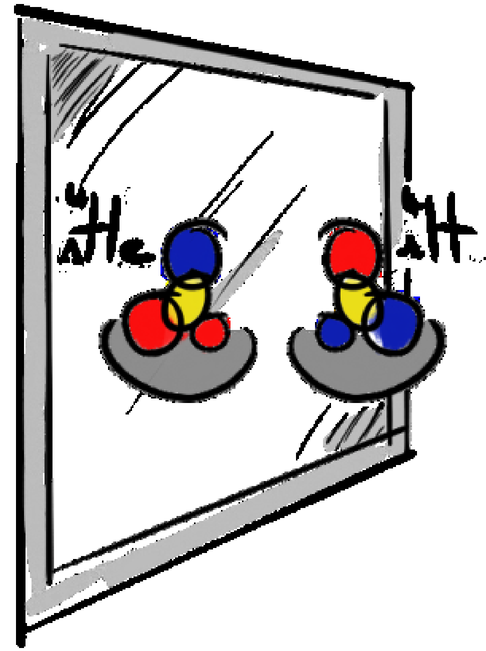


Status as of Summer 2o22:

- Aimed at precision electron scattering & search experiments
- Prestigious Excellence Cluster PRISMA
- Top-level research funding in Germany

A Decade of Precision Strangeness Physics at MAMI





- Elementary strangeness production probed nucleon resonance structure
- High-resolution pion spectroscopy probed nuclear symmetries
- Strangeness program was aligned with activities at PANDA and in Japan
- Hypernuclear experiments triggered creation of a world data base