JSPS CORE2CORE/SPHERE MEETING

4^{th} Sep 2010

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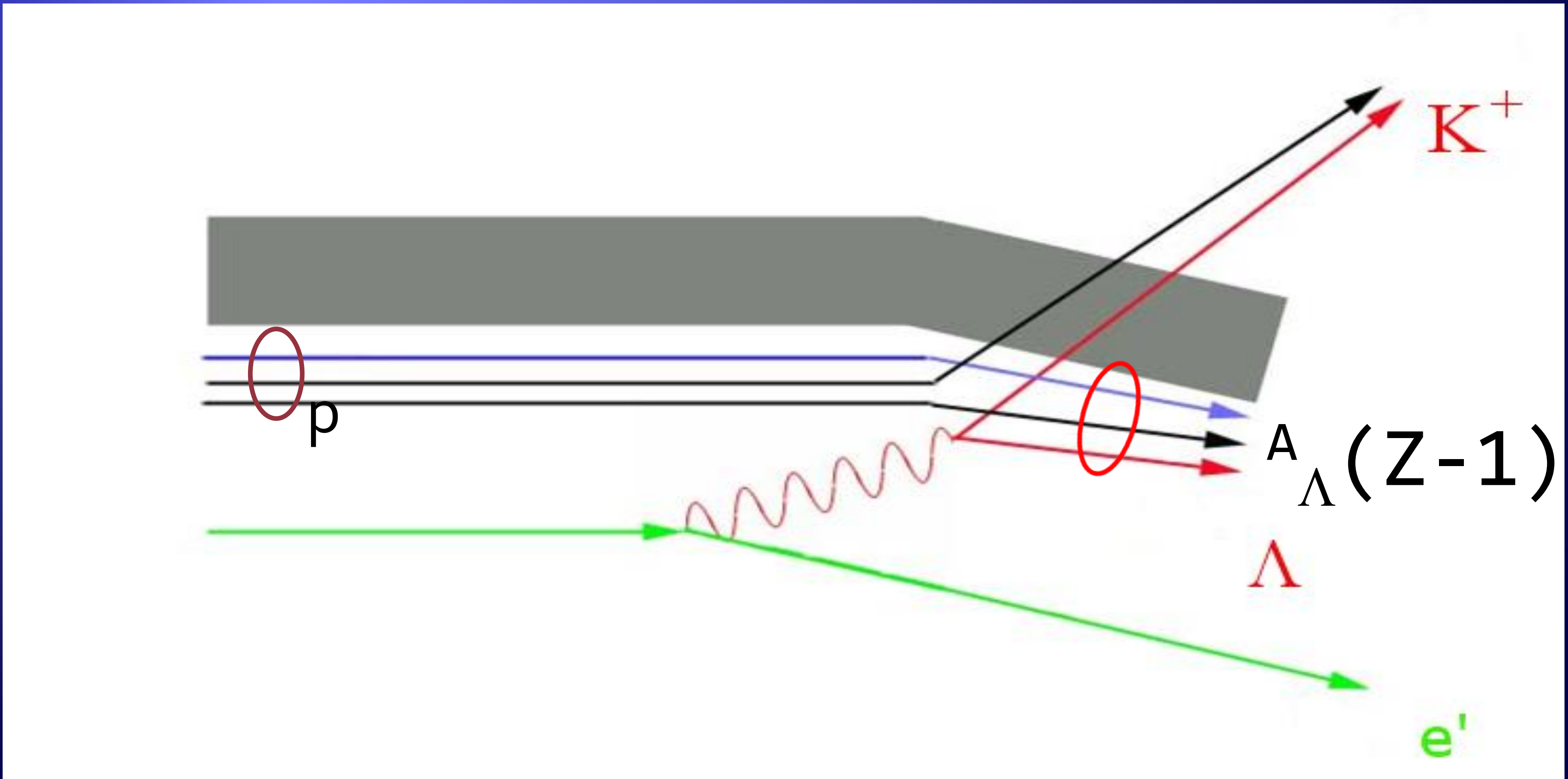
Overview and Status of JLab Hall-C Hypernuclear Experiments

The $^{A}Z(e,e'K^{+})\,^{A}_{\Lambda}(Z\text{-}1)$ reaction for hypernuclear spectroscopy

- (π,K) reaction established hypernuclear reaction spectroscopy
- $(e,e'K)$ has similar features with better resolution



Characteristics of (e,e'K) HY study

- Electromagnetic production
  - Photo/electron strangeness production

- Proton goes to Lambda

- Both spin flip and non-spin flip amplitudes

- High quality primary beam
  - High energy resolution (< 1MeV)
  - Thin enriched target

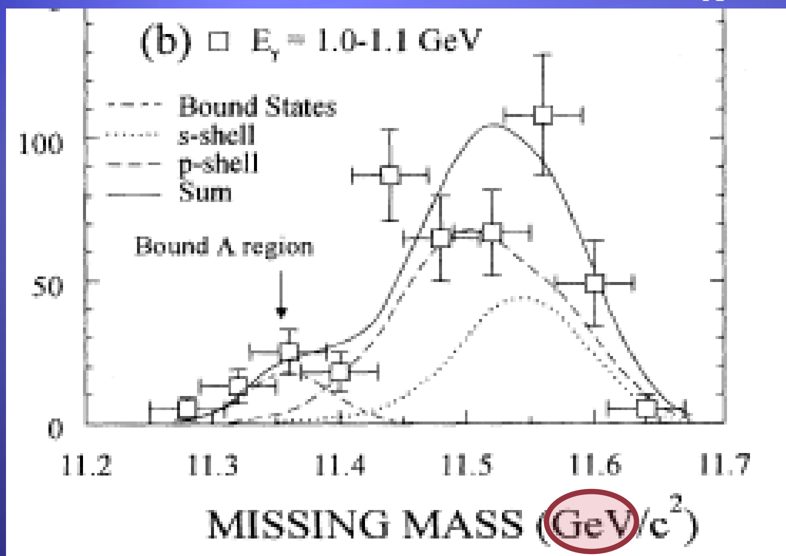
Real photon (γ,K) HY spectroscopy is practically impossible.

Eg. JLab-CLAS Bremsstrahlung tagged photon

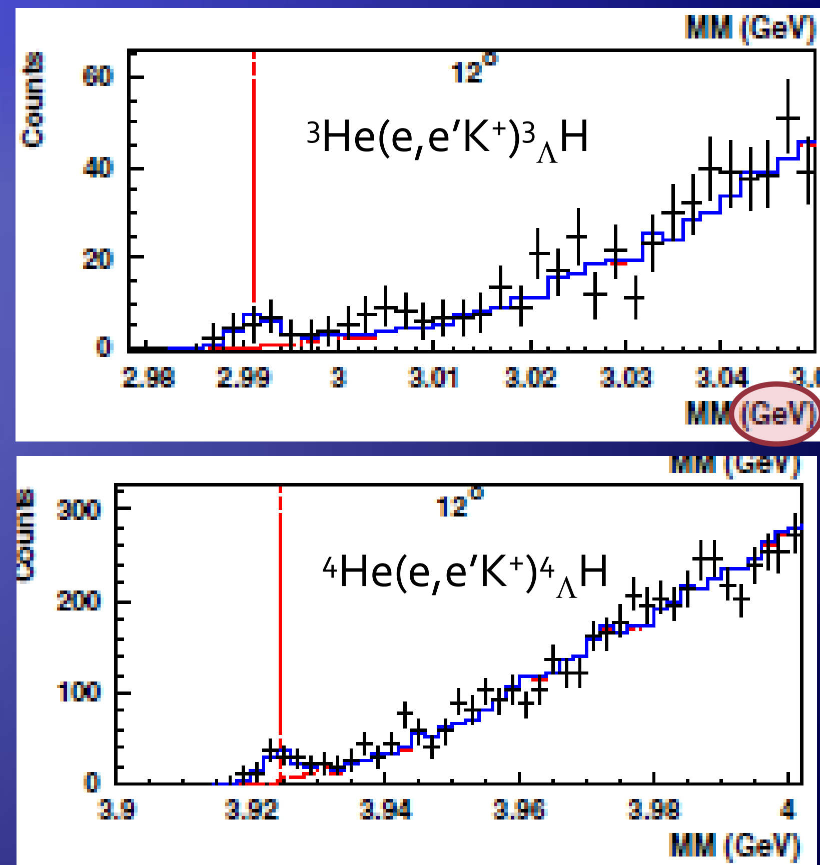
~ 50 MHz, $10^{-3} E_0$ = 2 MeV for 2 GeV

Early works : EM production of Λ Hypernucleus

$^{12}C(\gamma,K^+)^{12}{}_{\Lambda}B$



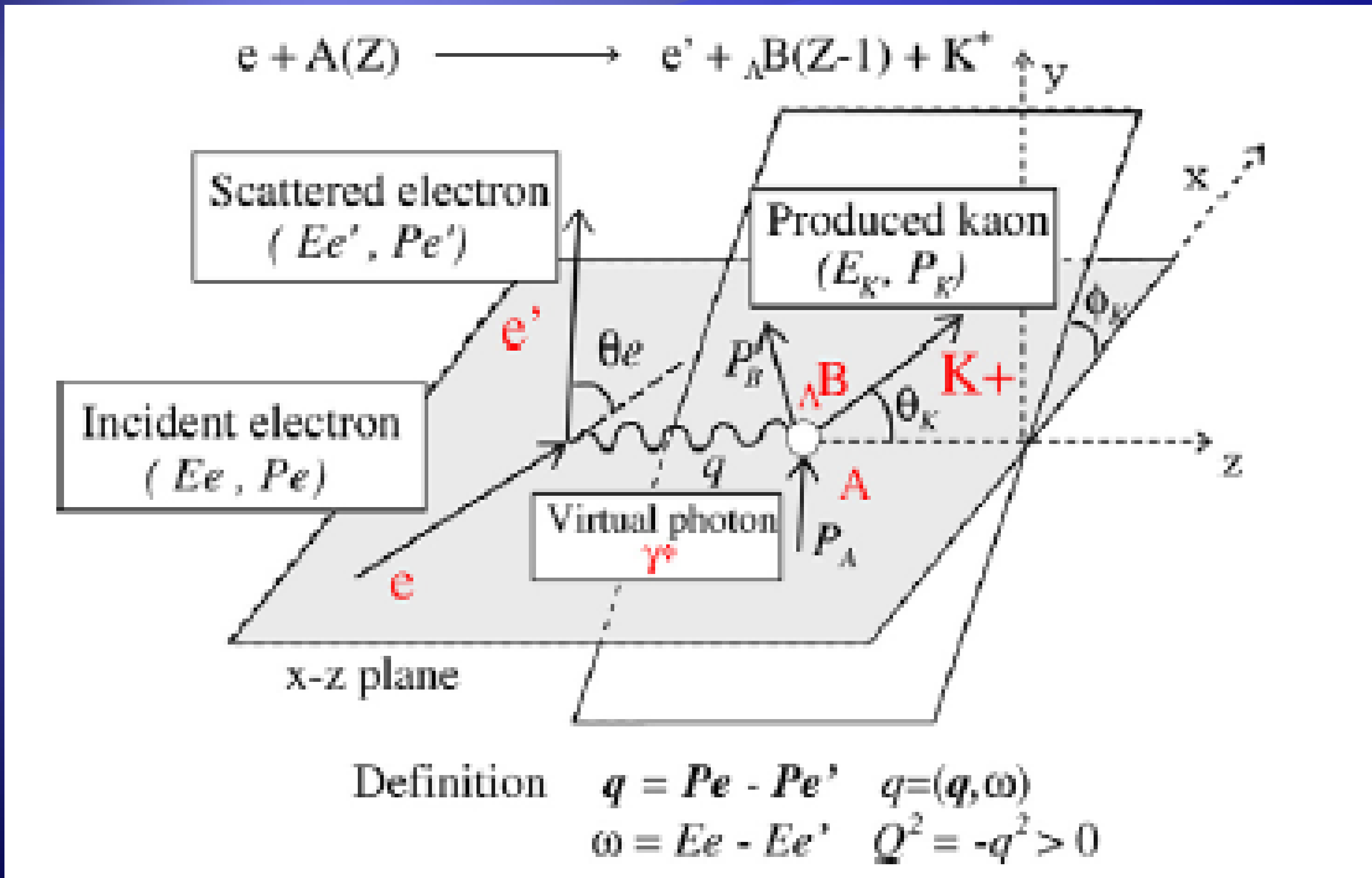
ES132 @INS-TAGX, PRC 52 (1995) 1157.



E91-016 @ JLab-HallC , PRL 93(2004)242501

NEXT STEP: Spectroscopy with mass resolution of sub-MeV

Definition of Kinematic Parameters



Elementary p(γ,K⁺) Λ

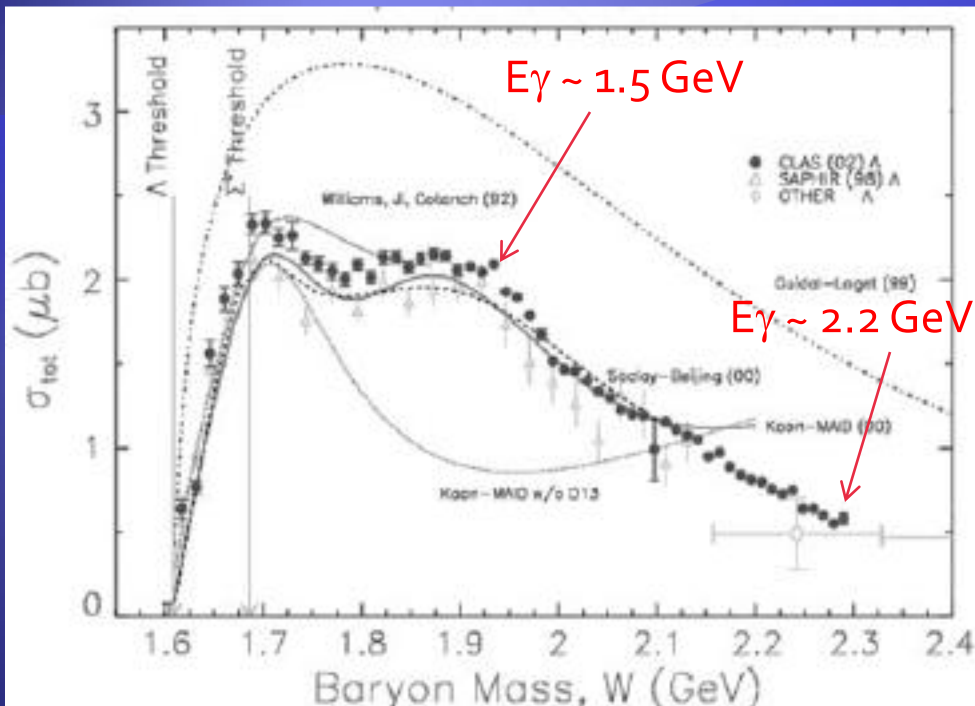


Fig. 2. Total cross-section for Λ-hyperon photoproduction measured at CLAS (solid circles). Data from SAPHIR/Bonn [11] (open triangles) are also shown. The curves are for effective Lagrangian calculations of Bennhold *et al.* as computed by Kaon-MAID [9] (solid), Williams, Ji, and Cotanch [12] (upper dotted), Saghai [13] (dashed), and a Regge-model calculation of Guidal *et al.* [14,15] (dot-dashed). The lower dotted curve illustrates the effect when the $D_{13}(1900)$ resonance in the Kaon-MAID calculation is switched off.

R.A.Schmacher for CLAS

Eur. Phys. J. A **18**, 371–375 (2003)

σ for elementary process

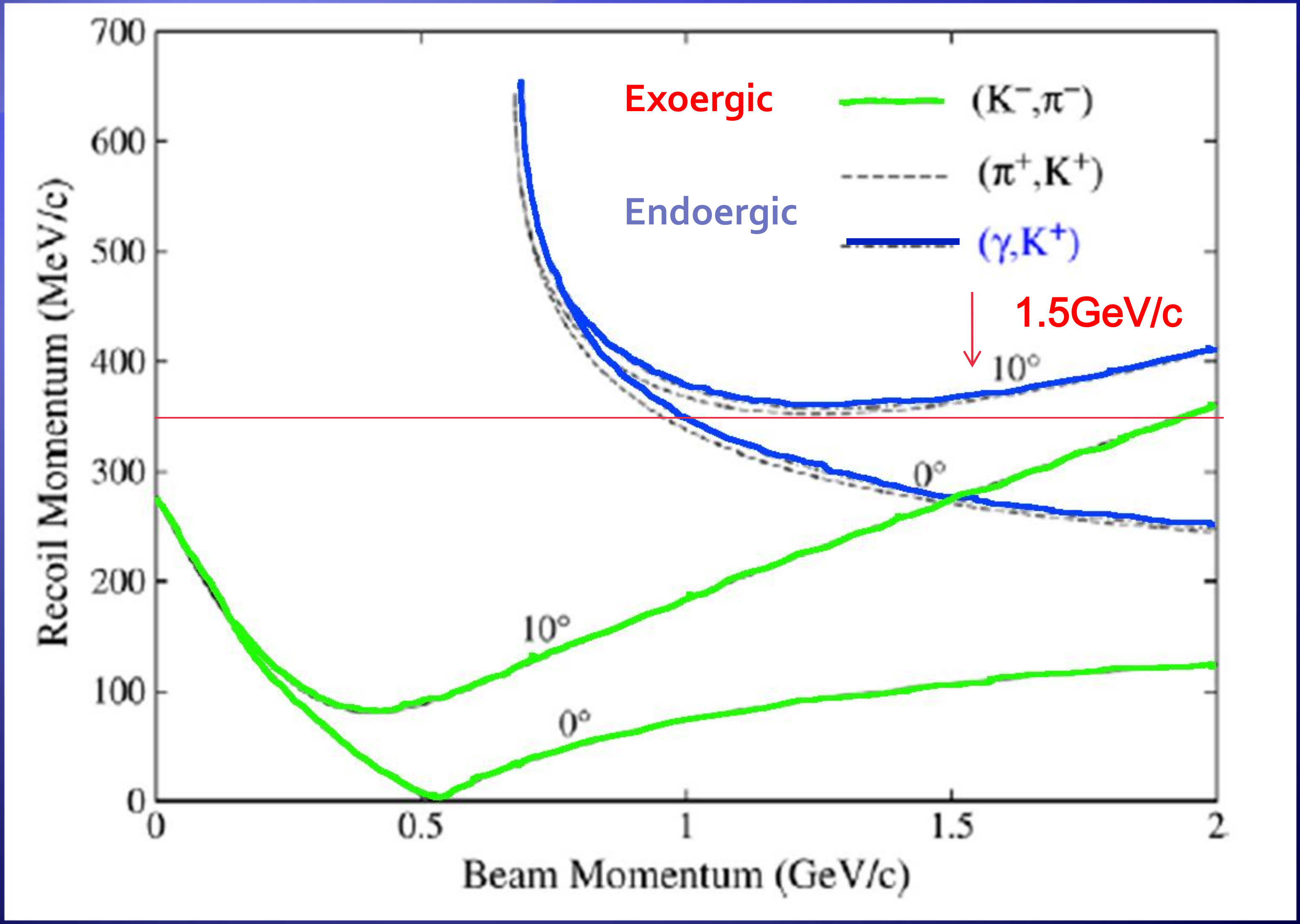
Max. at Eγ ~ 1.5 GeV

Lower Eγ : Close unnecessary reaction channel

Higher Eγ : Smaller K decay loss, Larger Λ trapping rate

Hypernucleus recoil momentum for various reactions

^{12}C target



p(e,e'K)Λ Cross Section

$$\frac{d^3\sigma}{dE_{e'}d\Omega_{e'}d\Omega_K} = \Gamma\left[\frac{d\sigma_T}{d\Omega_K} + \varepsilon_L \frac{d\sigma_L}{d\Omega_K} + \varepsilon \frac{d\sigma_{TT}}{d\Omega_K}\cos(2\phi_K) + \sqrt{2\varepsilon_L(1+\varepsilon)}\frac{d\sigma_{LT}}{d\Omega_K}\cos(\phi_K)\right]$$

$$\Gamma = \frac{\alpha}{2\pi^2}\frac{E'}{E}\frac{E_\gamma}{Q^2}\frac{1}{1-\varepsilon}$$

$$\varepsilon = \left(1 + \frac{2|\mathbf{q}|^2}{Q^2}\tan^2(\theta_e/2)\right)^{-1}$$

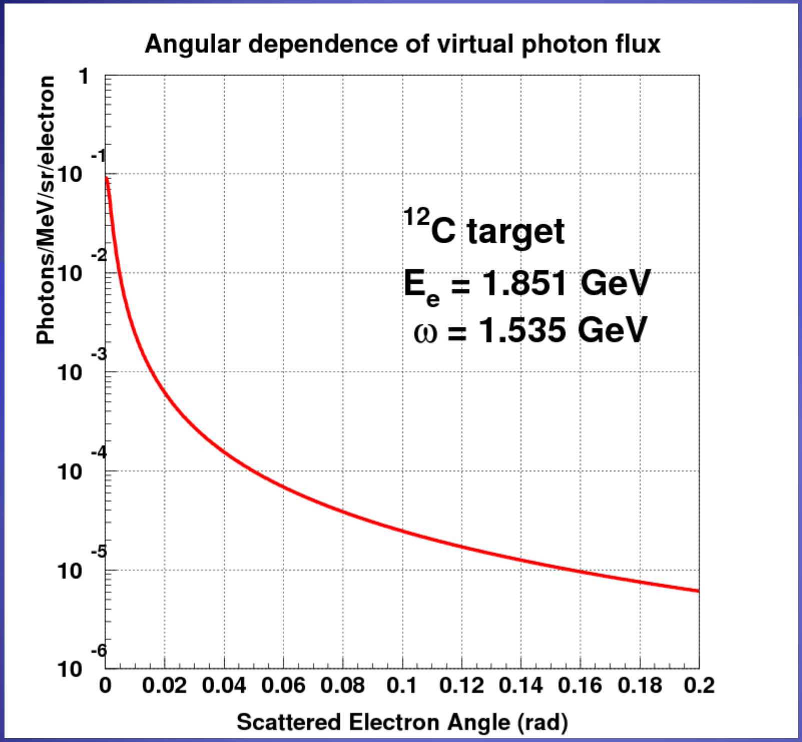
$$\varepsilon_L = \frac{Q^2}{\omega^2}\varepsilon$$

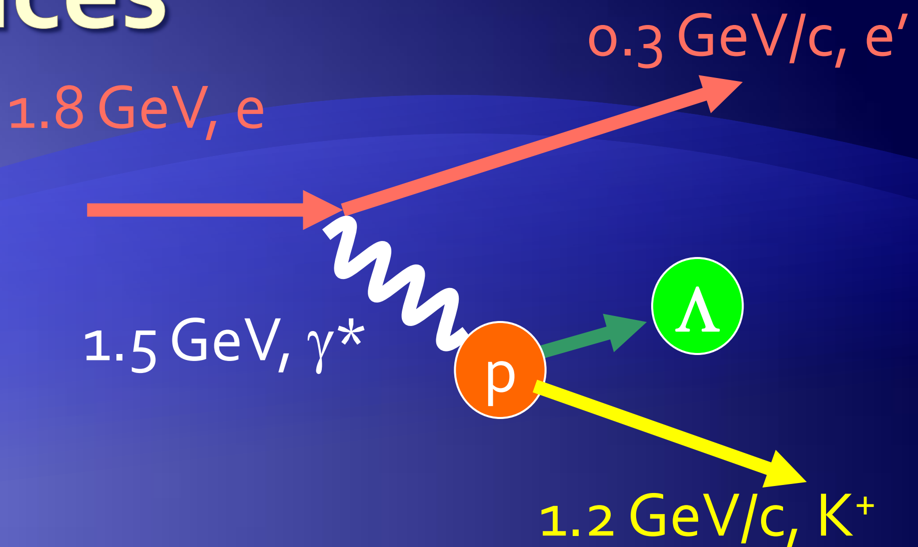
E01-011 : Q^2 ~ 0.01 $(\mathrm{GeV}/c)^2$, θ_e~6.5 deg.
$\varepsilon \sim 0.04$, ε_L~1.7x10^{-4}

Virtual but almost real photon

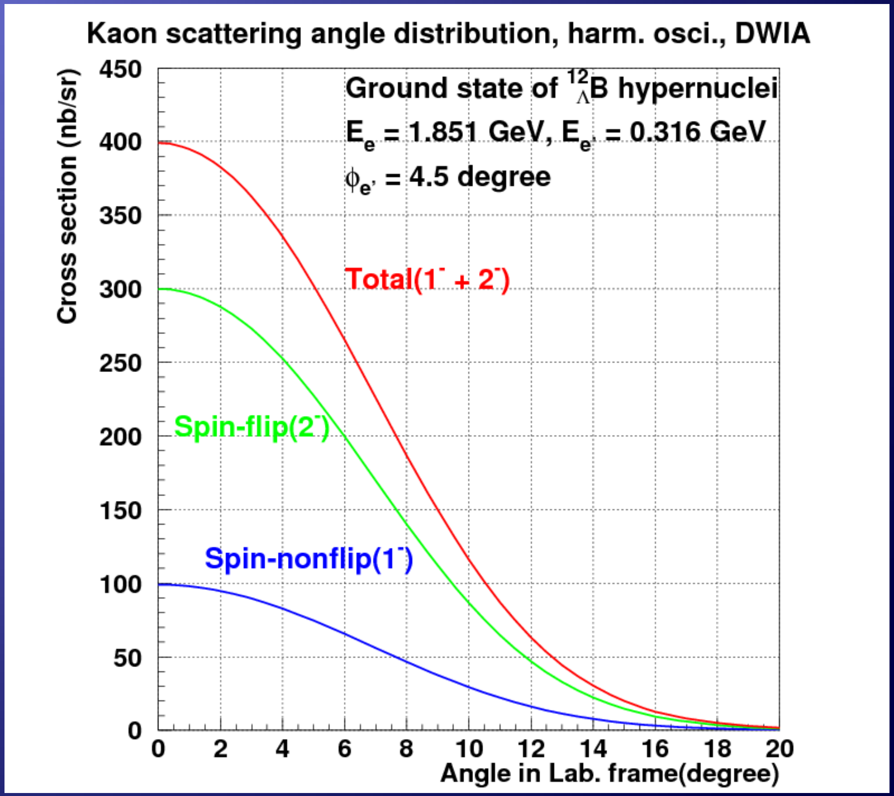
$$\frac{d^3\sigma}{dE_{e'}d\Omega_{e'}d\Omega_K} \sim \Gamma\frac{d\sigma}{d\Omega_K}$$

Angular Dependences





Both of e' & K+ are forward.



Challenge of (e,e'K) HY Study

- Large e' Background due to Bremsstrahlung and Møller scattering

  Signal/Noise, Detector

High Quality Electron Beam is Essential !

- [illegible] Cross Section
- Coincidence Measurement (e', K^+)

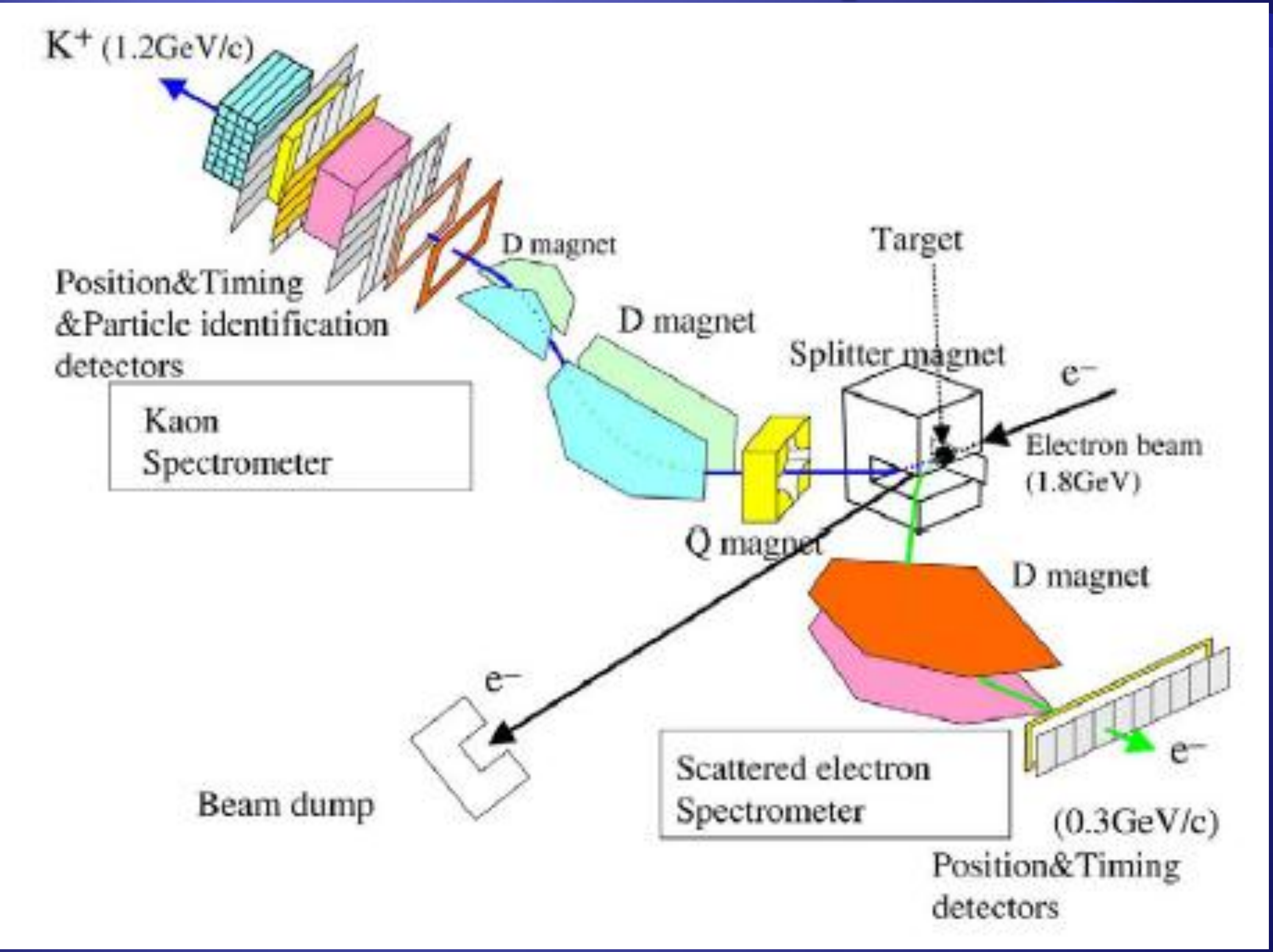
  Limited Statistics, DC beam is necessary

Beam requirements

- Continu
- Electro
- High cu
- Beam s
  - Mome
  - Good

Until upgrade of MAMI-C, CEBAF had been only facility for this program.

First Generation Experiment



SPL + SOS +HMS

E89-009 (HNSS; HyperNuclear Spectrometer System)

Data taking year 2000

The first (e,e'K$^+$) hypernuclear experiment (E89-009, HNSS)

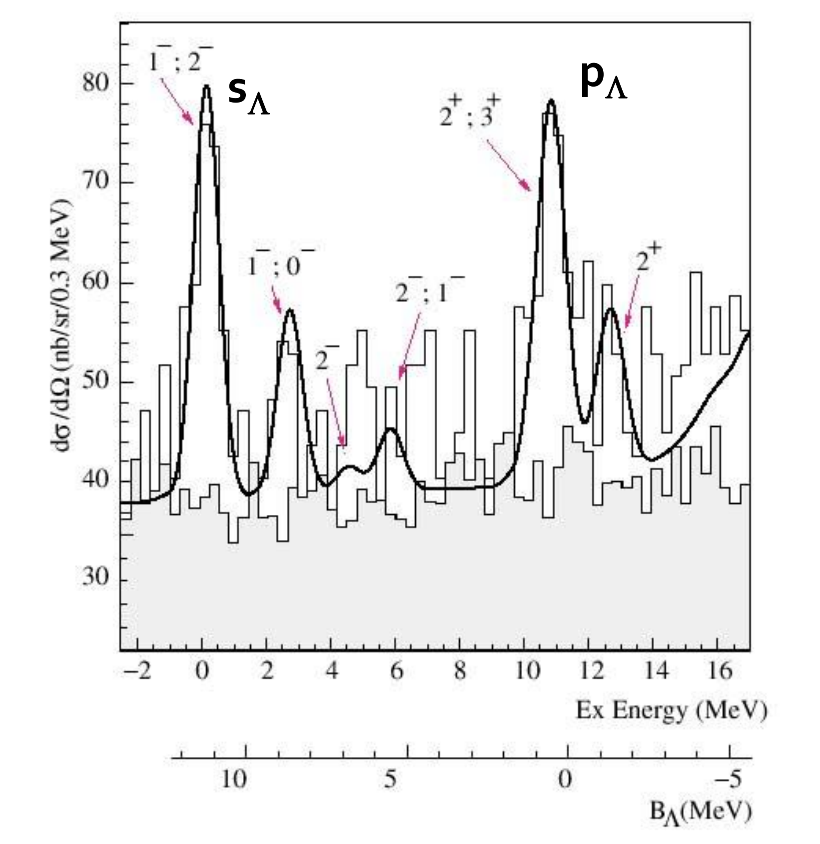
- Demonstrated that

  the (e,e'K) hypernuclear spectroscopy is possible!

Good energy resolution
<800 keV (FWHM)

Best hypernuclear energy resolution achieved by the reaction spectroscopy at that time

$^{12}C(e,e'K^+)\,^{12}_{\Lambda}B$



PRL 90 (2003) 232502, PRC 73 (2006) 044607

Improvement of the E89-009 experiment

- Energy resolution as well as acceptance are limited by the kaon spectrometer (SOS)

$c\tau$ (K^+) ~4m

New Spectrometer

High resolution Kaon Spectrometer (HKS)

Zero degree tagging method to maximize virtual photon flux

Severe background from electrons associated with Bremsstrahlung (200 MHz for e′ arm)

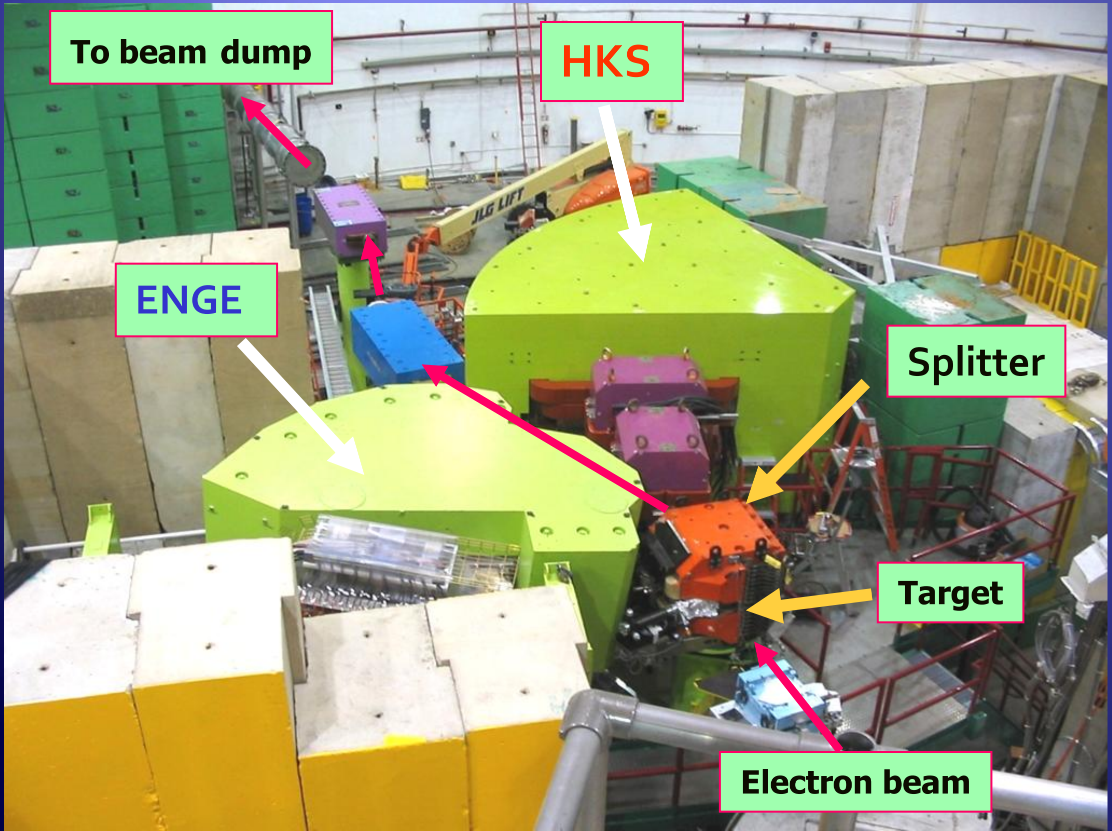
Tilt Method

The 2nd Generation Experiment was approved by Jlab PAC19
E01-011 (Spokesmen: Hashimoto, Tang, Reinhold, Nakamura)

Second Generation Exp. at JLab

2005 E01-011 (Hall C)

First step to midium heavy hypernuclei (^{28}Si, ^{12}C, ^{7}Li)



Two Major Improvements

New HKS

Tilt Method

Beam: 30 μA , 1.8GeV
HKS: $\Delta p/p = 2 \times 10^{-4}$ [FWHM]
Solid angle 16msr(w/ splitter)

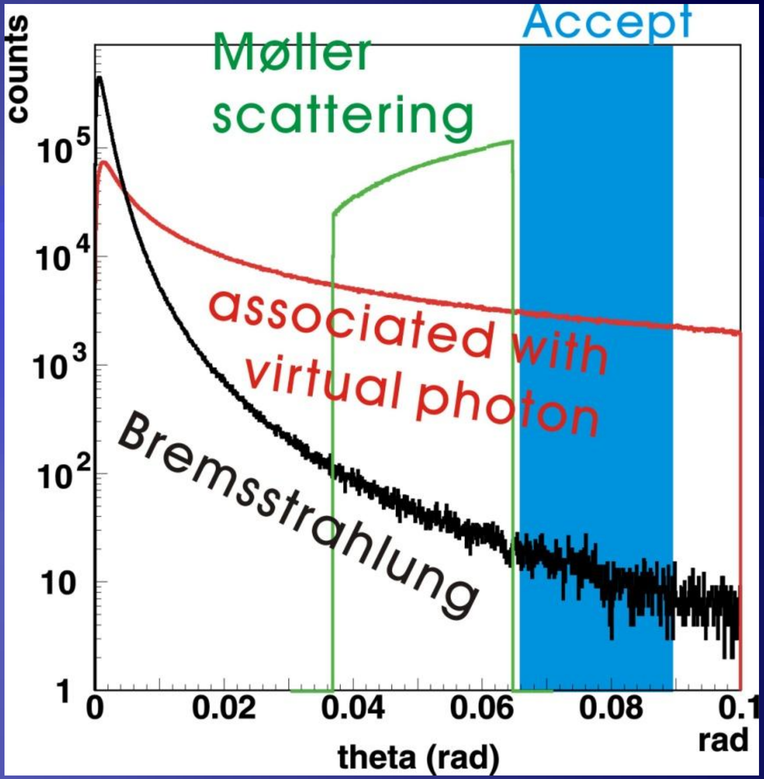
Tilt method

Background electrons

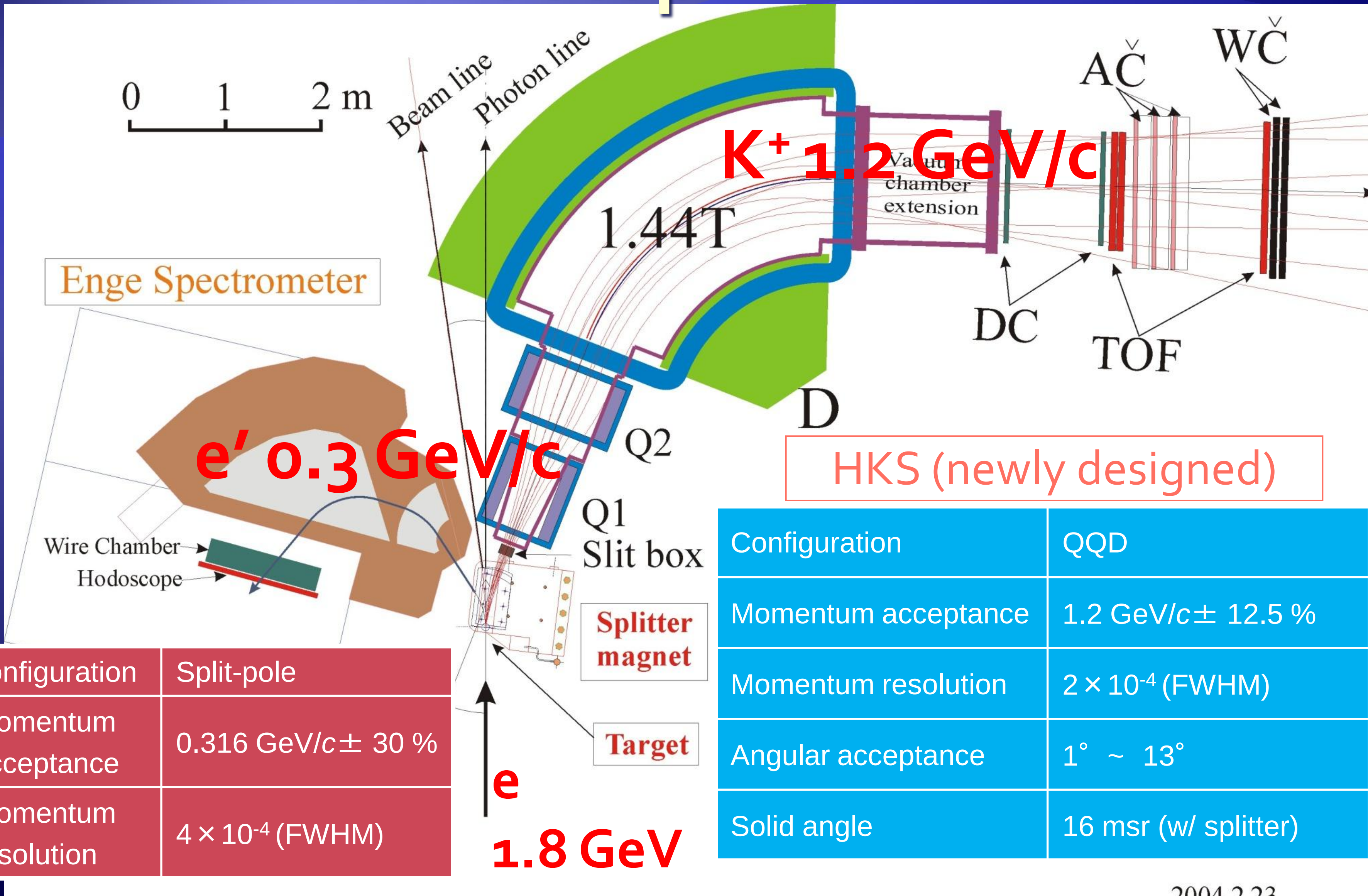
- Bremsstrahlung
  very forward peaked
- Møller scattering
  scattering angle and momentum are correlated

to avoid them

Tilt Enge spectrometer by 8 degree (optimization of e′ detection angle)



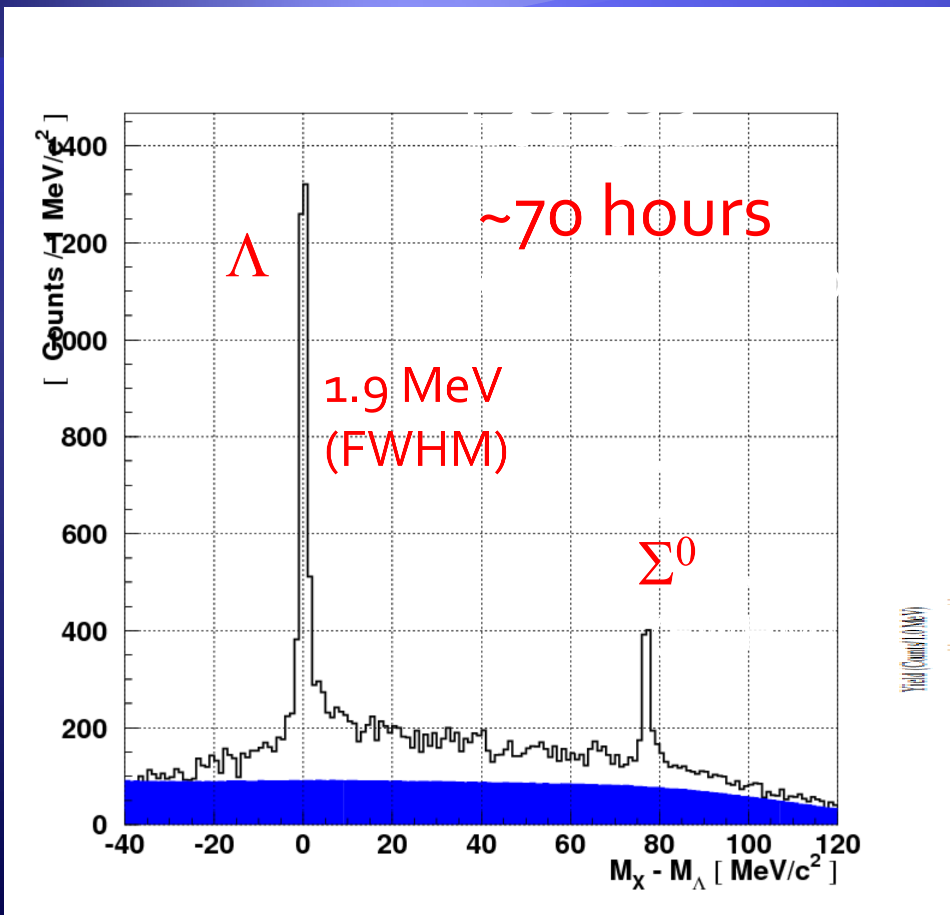
Second Generation Exp.
E01-011 setup



configuration	Split-pole
Momentum acceptance	0.316 GeV/c ± 30 %
Momentum resolution	4×10^{-4} (FWHM)

Configuration	QQD
Momentum acceptance	1.2 GeV/c ± 12.5 %
Momentum resolution	2×10^{-4} (FWHM)
Angular acceptance	1° ~ 13°
Solid angle	16 msr (w/ splitter)

Λ and Σ spectra (CH_2 target)



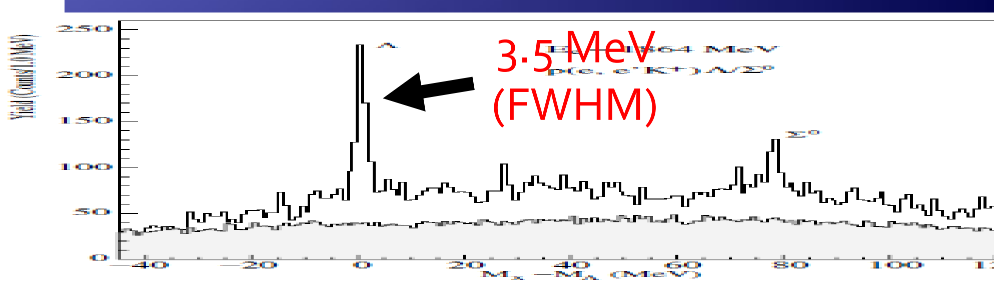
Absolute mass scale calibration

c.f. E89-009, 183 hours

(8.8 mg/cm², 0.5 or 1.0 uA)

T. Miyoshi *et al.*,

Phy. Rev. Lett. **90**, 232502(2003)



Better resolution and statistics

To be published soon.

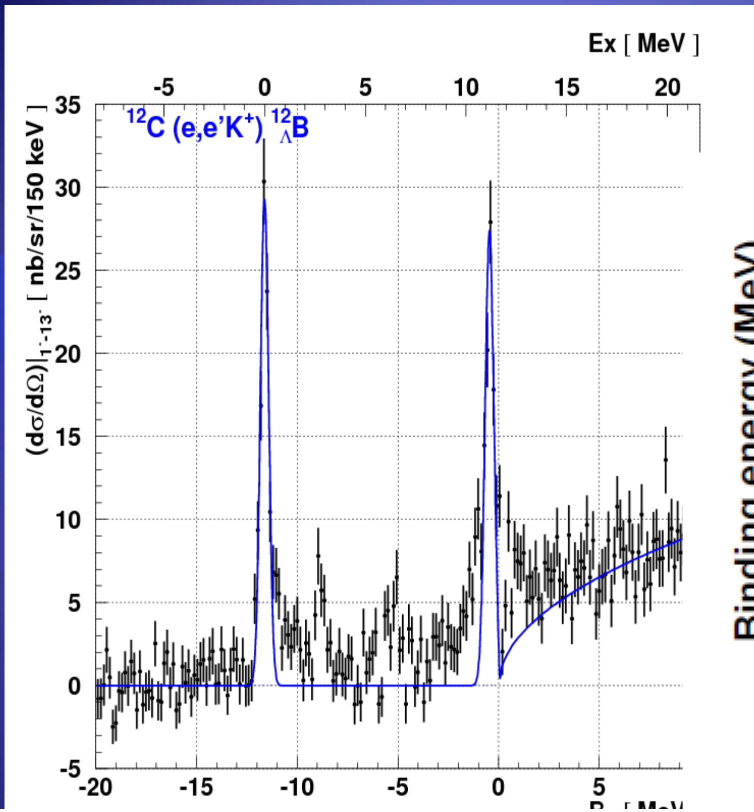
Highlights of E01-011 Results

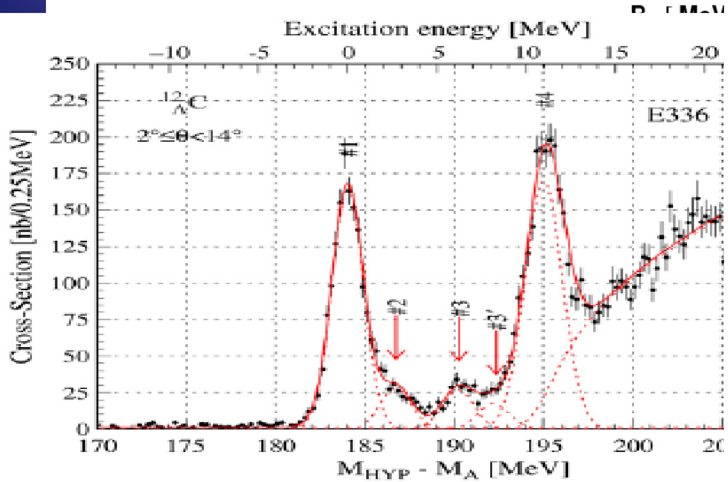
$^{12}_{\Lambda}B$: Reference Spectrum w/ best resolution

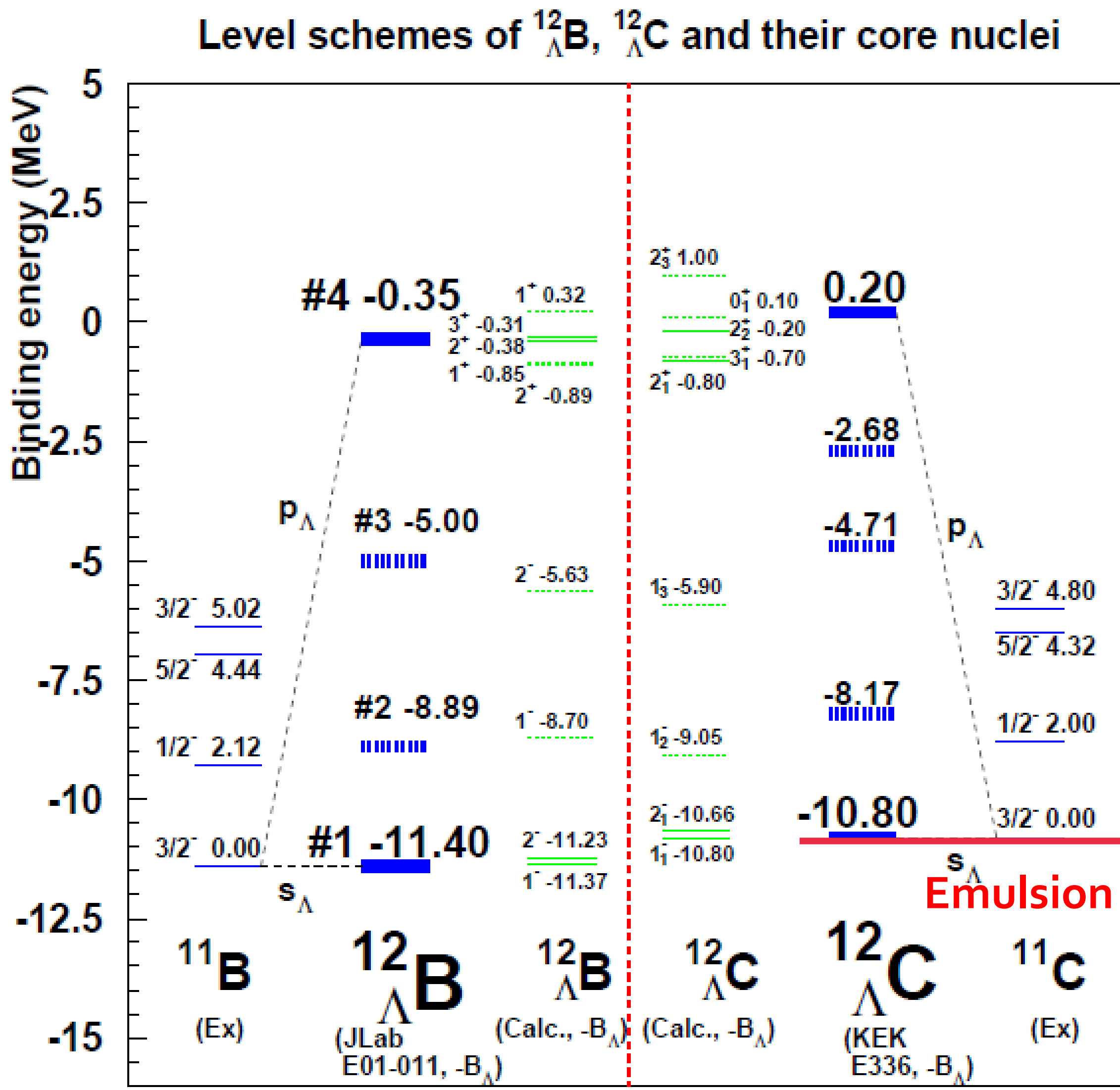
$^{28}_{\Lambda}Al$: First beyond-p shell HY. by (e,e'K)

$^{7}_{\Lambda}He$: First reliable data, CSB effect

$^{12}C(e,e'K^+)^{12}_{\Lambda}B$, $^{12}C(\pi^+,K^+)^{12}_{\Lambda}C$







$^{12}{}_{\Lambda}C$ emulsion data

Nuclear Physics A484 (1988) 520–524

TABLE 1 [a])

Decay mode	Range of the hypernucleus (μm)	B_{Λ} (as $^{12}_{\Lambda}C$) (MeV)	Ref.
1. $^{12}_{\Lambda}C \to \pi^- + {}^{12}N$(g.s.)	—	11.14 ± 0.57	[4]
2. $^{12}_{\Lambda}C \to \pi^- + p + {}^{4}He + {}^{7}Be$	3.0 ± 0.8	10.45 ± 0.33	[3]
3. $^{12}_{\Lambda}C \to \pi^- + p + {}^{11}C$	4.3 ± 0.7	10.50 ± 0.47	[3]
4.	3.5 ± 0.4	10.65 ± 0.33	[1,2]
5.	3.5 ± 0.5	10.85 ± 0.44	[1,2]
6.	3.4 ± 0.5	11.59 ± 0.45	[1,2]
7.	3.2 ± 0.4	15.67 ± 0.50	[1,2]

^{11}C (3/2-) : Ex = 4.8MeV

situation is not the case for π^- mesonic decay modes of $^{12}_{\Lambda}C$: ($\pi^- {}^{12}N$), ($\pi^- p\, {}^{11}C$), ($\pi^- p\, {}^{3}He\, {}^{4}He\, {}^{4}He$) and ($\pi^- p\, {}^{4}He\, {}^{7}Be$). Every one of these decay topologies is easily confused with those of other hypernuclei.

The value obtained for B_{Λ} of $^{12}_{\Lambda}C$, (10.80 ± 0.18) MeV

Statistical errors quoted, systematic errors (~0.04 MeV) reduced by measuring M_{Λ} in same emulsion stack.

Nuclear Physics A547 (1992) 369

$^{12}_{\Lambda}C$	**10.76 ± 0.19**

Statistical error only

Reference for all (π, K) B_{Λ} data:

B_{Λ} ($^{12}{}_{\Lambda}C$g.s.) = 10.76 +-0.19MeV

$^{12}{}_{\Lambda}B$ emulsion data

Nuclear Physics B52 (1973) 1–30.

A NEW DETERMINATION OF THE BINDING-ENERGY VALUES OF THE LIGHT HYPERNUCLEI ($A \leqslant 15$)

(# of events)

$^{12}_{\Lambda}B$	$\pi^- + {}^4He + {}^4He + {}^4He$	61	11.45 ± 0.07

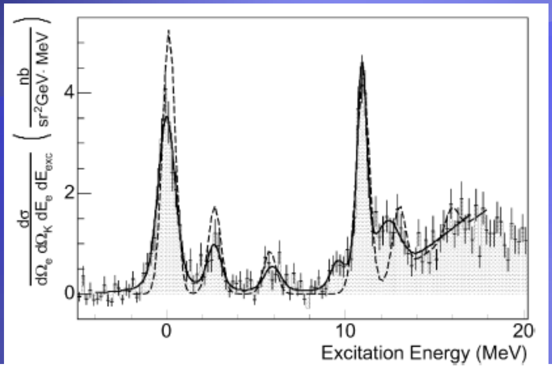
B_{Λ} ($^{12}{}_{\Lambda}$Bg.s.) = 11.45 +-0.07 MeV   Emulsion Result (M.Juric et al.)

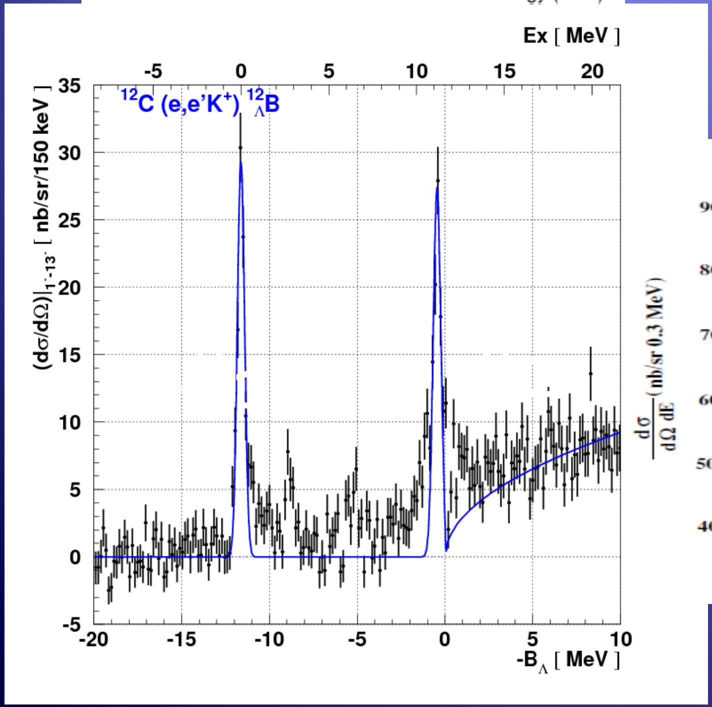
Ref) A=4 System

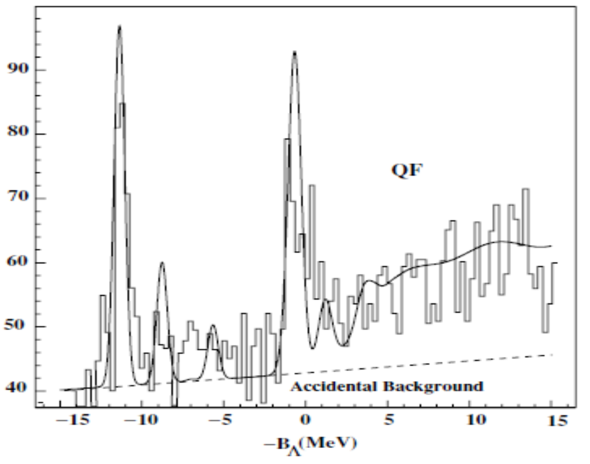
$^4_{\Lambda}H$	$\pi^- + {}^1H + {}^3H$	56	2.14 ± 0.07
	$\pi^- + {}^2H + {}^2H$	11	1.92 ± 0.12
	total	67	2.08 ± 0.06
$^4_{\Lambda}He$	$\pi^- + {}^1H + {}^3He$	83	2.42 ± 0.05
	$\pi^- + {}^1H + {}^1H + {}^2H$	15	2.44 ± 0.09
	total	98	2.42 ± 0.04

Different modes give 0.22 MeV difference
Systematic Error?

$^{12}C(e,e'K^+)^{12}_{\Lambda}B$ @ JLab Hall C & A







Binding energies are consistent with The other (e,e'K) data.

$^{12}{}_{\Lambda}B$ emulsion data

Nuclear Physics B52 (1973) 1–30.

A NEW DETERMINATION OF THE BINDING-ENERGY VALUES OF THE LIGHT HYPERNUCLEI ($A \leqslant 15$)

(# of events)

$^{12}_{\Lambda}B$	$\pi^- + {}^4He + {}^4He + {}^4He$	61	11.45 ± 0.07

B_{Λ} ($^{12}{}_{\Lambda}$Bg.s.) = 11.45 +-0.07 MeV Emulsion Result (M.Juric et al.)

B_{Λ} ($^{12}{}_{\Lambda}$Bg.s.) = 11.40 +-0.01+-0.14MeV Totally Independent Measurement

E01-011 Result (A.Matsumura Ph.D. Thesis)

Ref) A=4 System

Decay π spectroscopy is important

$^{4}_{\Lambda}H$	$\pi^- + {}^1H + {}^3H$	56	2.14 ± 0.07
	$\pi^- + {}^2H + {}^2H$	11	1.92 ± 0.12
	total	67	2.08 ± 0.06
$^{4}_{\Lambda}He$	$\pi^- + {}^1H + {}^3He$	83	2.42 ± 0.05
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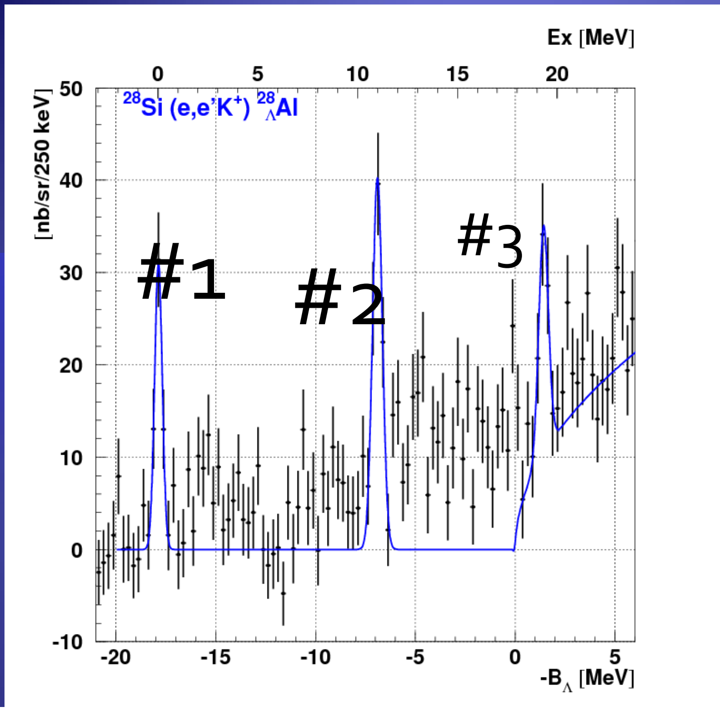
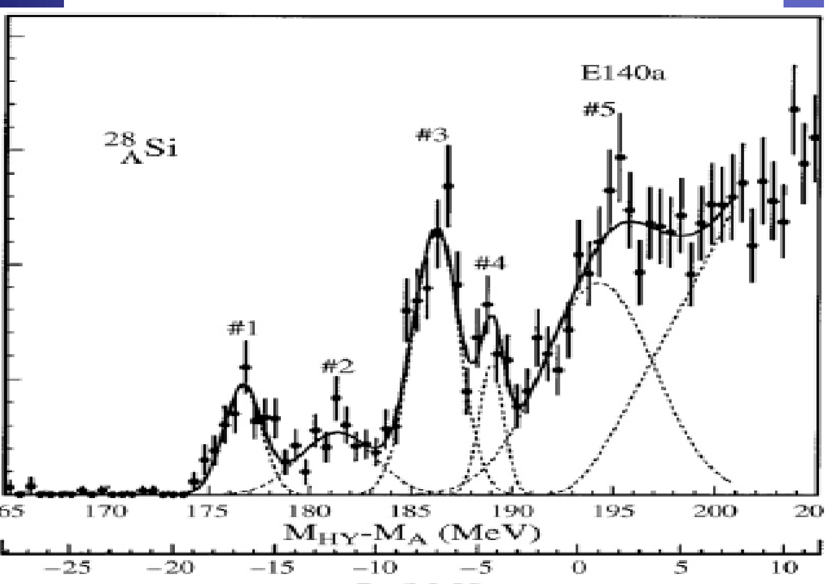
	total	98	2.42 ± 0.04

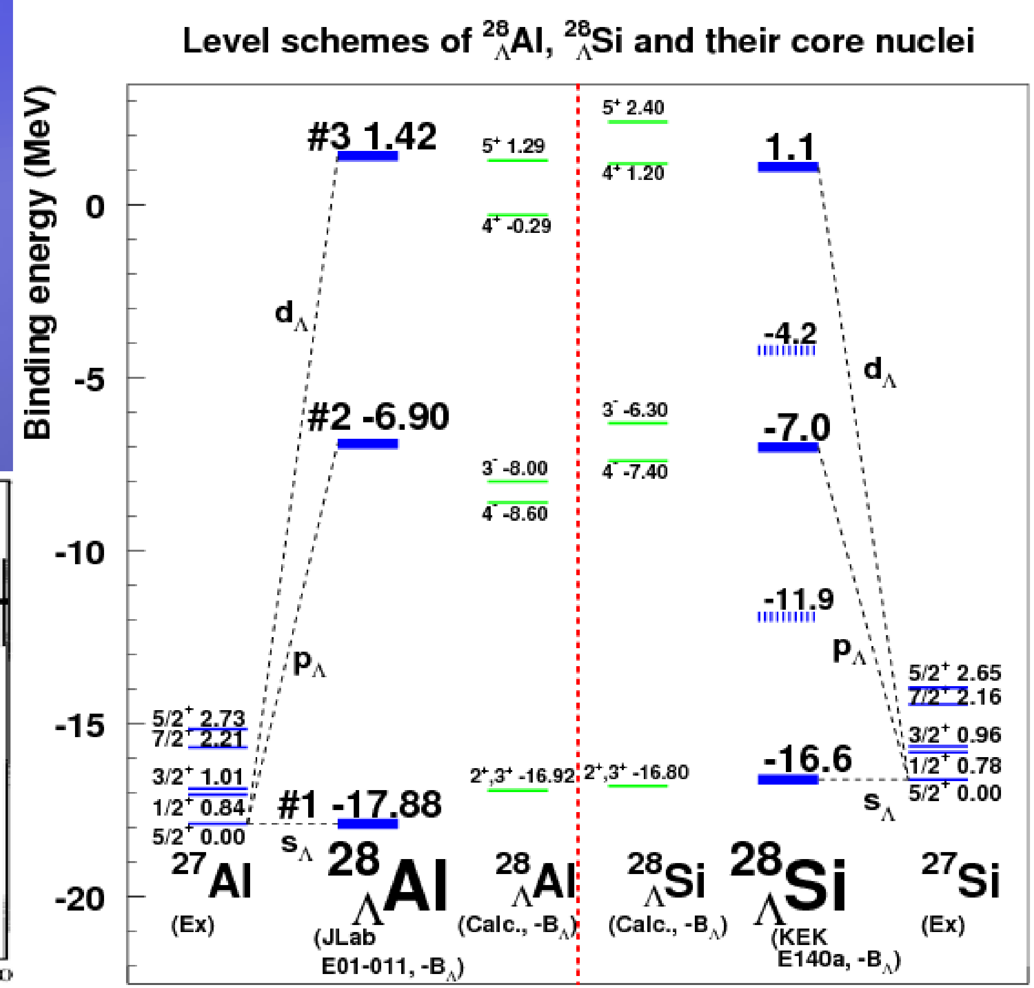
Different modes give 0.22 MeV difference Systematic Error?

$^{28}Si(e,e'K^+)^{28}_{\Lambda}Al$, $^{28}Si(\pi^+,K^+)^{28}_{\Lambda}Si$

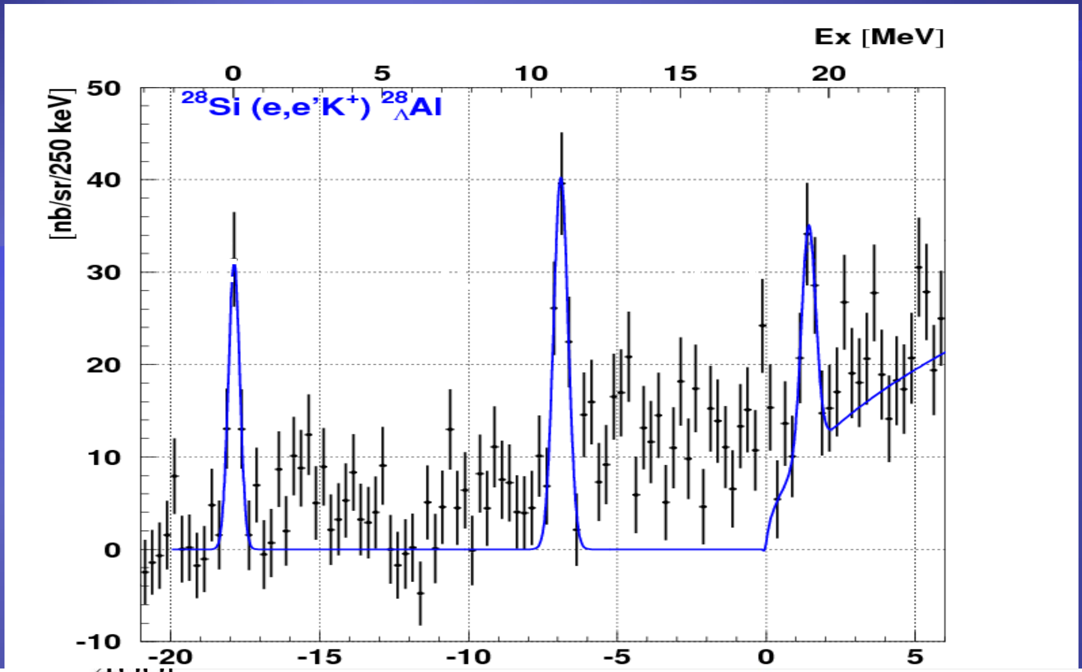


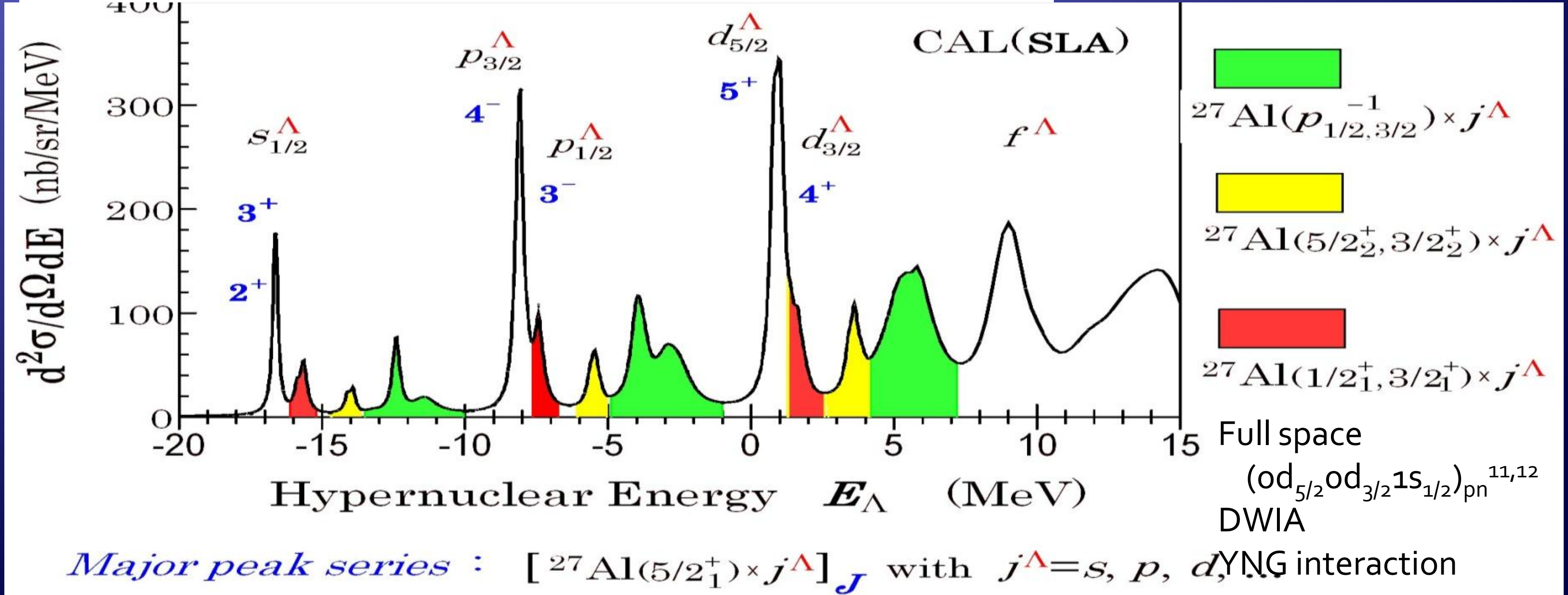
First sd-shell hypernuclear spectroscopy by (e,e'K+)





$^{28}Si(e,e'K^+)^{28}_{\Lambda}Al$ @ JLab Hall C

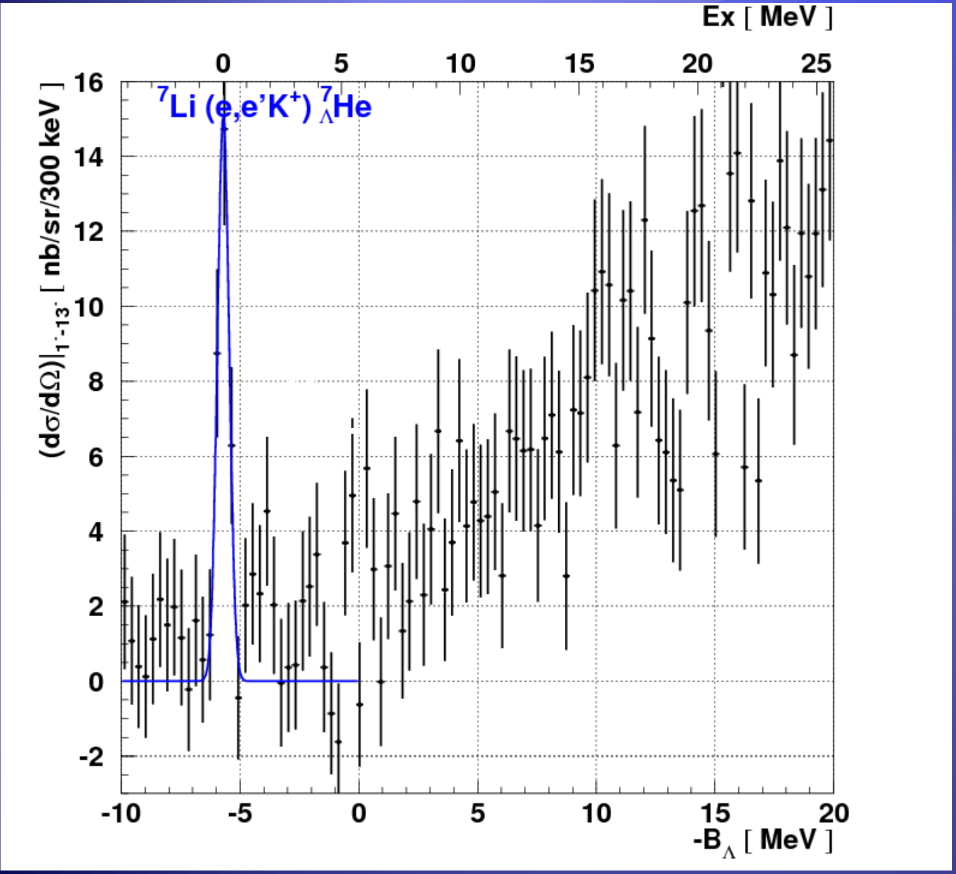




Full space
$(0d_{5/2}0d_{3/2}1s_{1/2})_{pn}$ [11,12]
DWIA
YNG interaction

$^{7}Li(e,e'K^{+})^{7}_{\Lambda}He$

First reliable observation of $^{7}_{\Lambda}He$ w/ good statistics

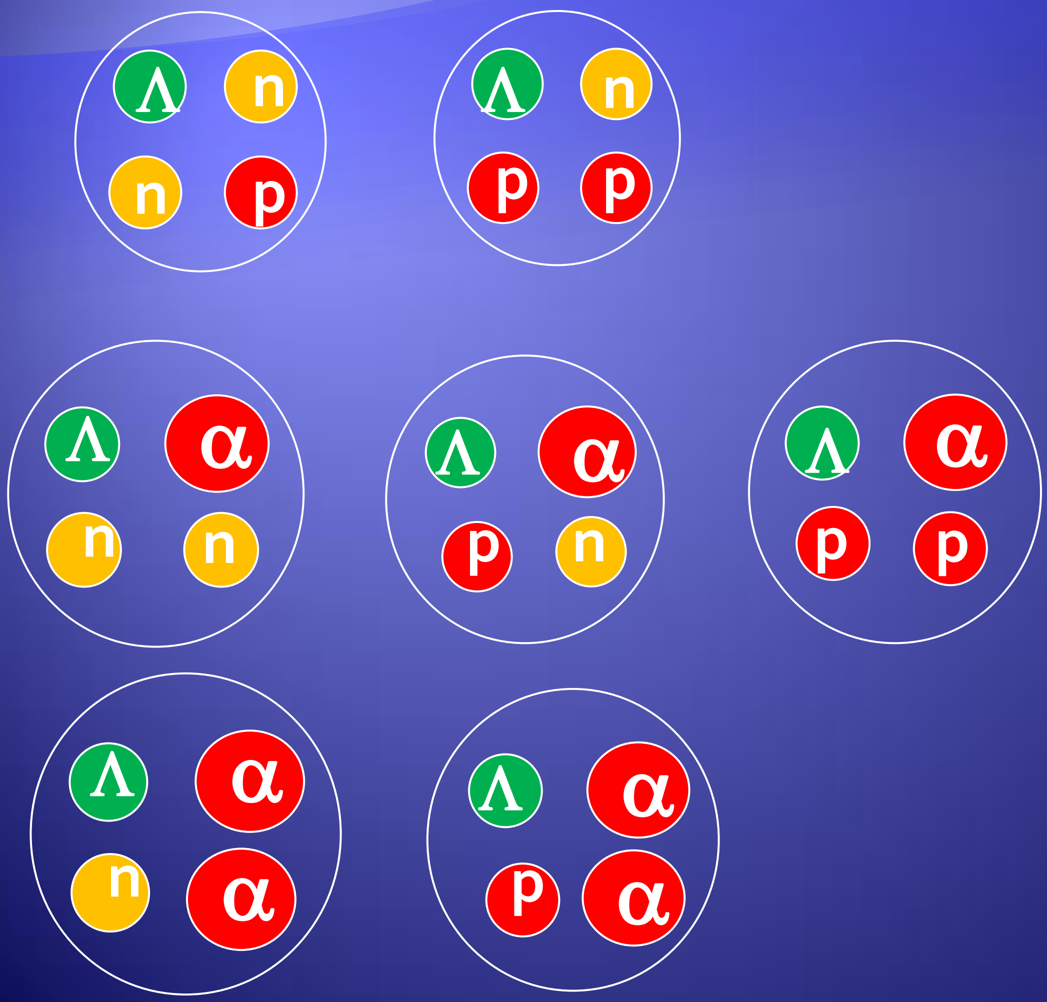


M.Juric et al. NP B52 (1973) 1

Detailed Discussion : Tomorrow

CSB effect by cluster model

Four-body cluster model



A=4, T=1/2 System

${}^{4}_{\Lambda}$H, ${}^{4}_{\Lambda}$He

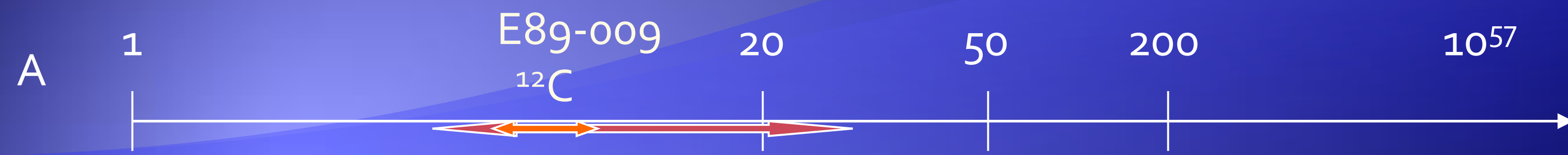
A=7, T=1 iso-triplet

${}^{7}_{\Lambda}$He, ${}^{7}_{\Lambda}$Li*, ${}^{7}_{\Lambda}$Be

A=10, T=1/2 system

${}^{10}_{\Lambda}$Be, ${}^{10}_{\Lambda}$B

Hypernuclei in wide mass range



E01-011

Elementary Process ^{7}Li ^{12}C ^{28}Si

Strangeness electro-production

Light Hypernuclei (s,p shell)

Fine structure

Baryon-baryon interaction in SU(3)

$\Lambda\Sigma$ coupling in large isospin hypernuclei

Cluster structure

Neutron/Hyperon star,

Strangeness matter

Hyperonization →

Softening of EOS ?

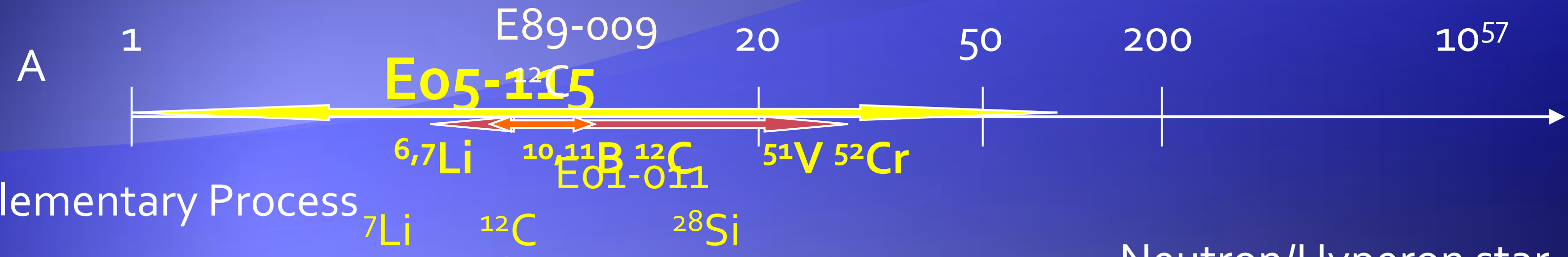
Medium - Heavy hypernuclei

Single-particle potential

Distinguishability of a Λ hyperon

$U_0(r)$, $m_\Lambda{}^*(r)$, $V_{\Lambda NN}$, ...

Hypernuclei in wide mass range



Elementary Process

Strangeness electro-production

Light Hypernuclei (s,p shell)

Fine structure

Baryon-baryon interaction in SU(3)

$\Lambda\Sigma$ coupling in large isospin hypernuclei

Cluster structure

Neutron/Hyperon star,

Strangeness matter

Hyperonization →

Softening of EOS ?

Medium - Heavy hypernuclei

Single-particle potential

Distinguishability of a Λ hyperon

$U_0(r)$, $m_\Lambda^*(r)$, $V_{\Lambda NN}$, ...

3rd Generation Experiment

Third Generation Exp. at JLab

2009 E05-115 (Hall C)

Wide mass range hypernuclear spectroscopy ($^{52}_{\Lambda}V$, $^{12}_{\Lambda}B$, $^{10}_{\Lambda}Be$, $^{9}_{\Lambda}Li$, $^{7}_{\Lambda}He$)

Major Improvements

(10 times more VP tagging)

New HES

best match to HKS

New Calibrations

H_2O cell target

Beam energy scan

Goals of the 3^{rd} Generation Experiment

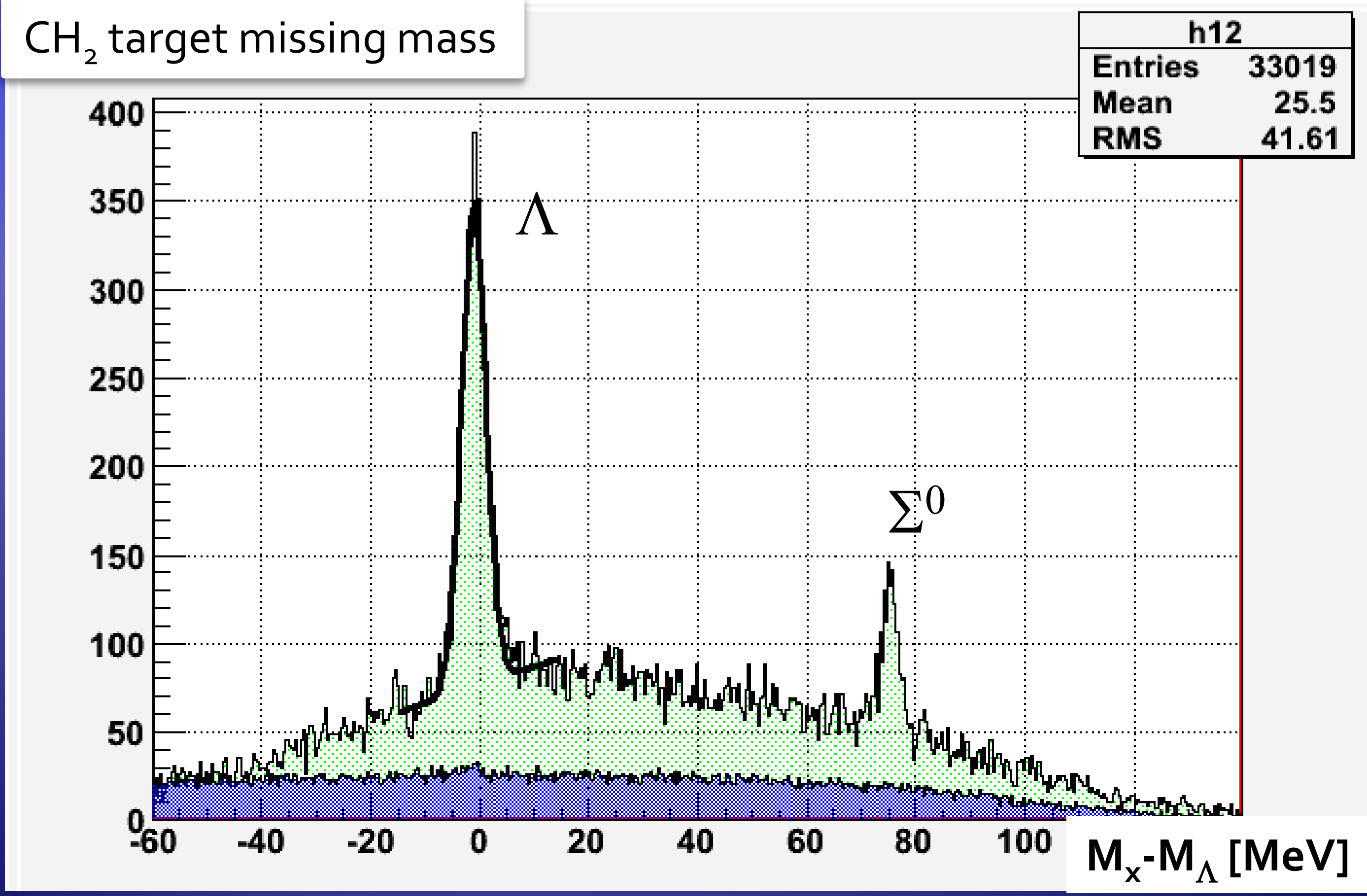
- $^{7}Li(e,e'K^{+})^{7}_{\Lambda}He$, $^{10}B(e,e'K^{+})^{10}_{\Lambda}Be$
  - Cluster model, shell model approach
    - Charge Symmetry Breaking in ΛN interaction
    - ΛN-ΣN coupling effect
- $^{52}Cr(e,e'K^{+})^{52}_{\Lambda}V$
  - Shell model, Mean field theory
    - A dependence of Λ single particle energies
    - Measurement of fine structure (core configuration mixing, ls splitting…)

Missing mass calibration data

Elementary process of
Electromagnetic production of strangeness

$$e + p \to e' + K^+ + \Lambda/\Sigma^0$$

CH$_2$ target missing mass



M_x-M_Λ [MeV]

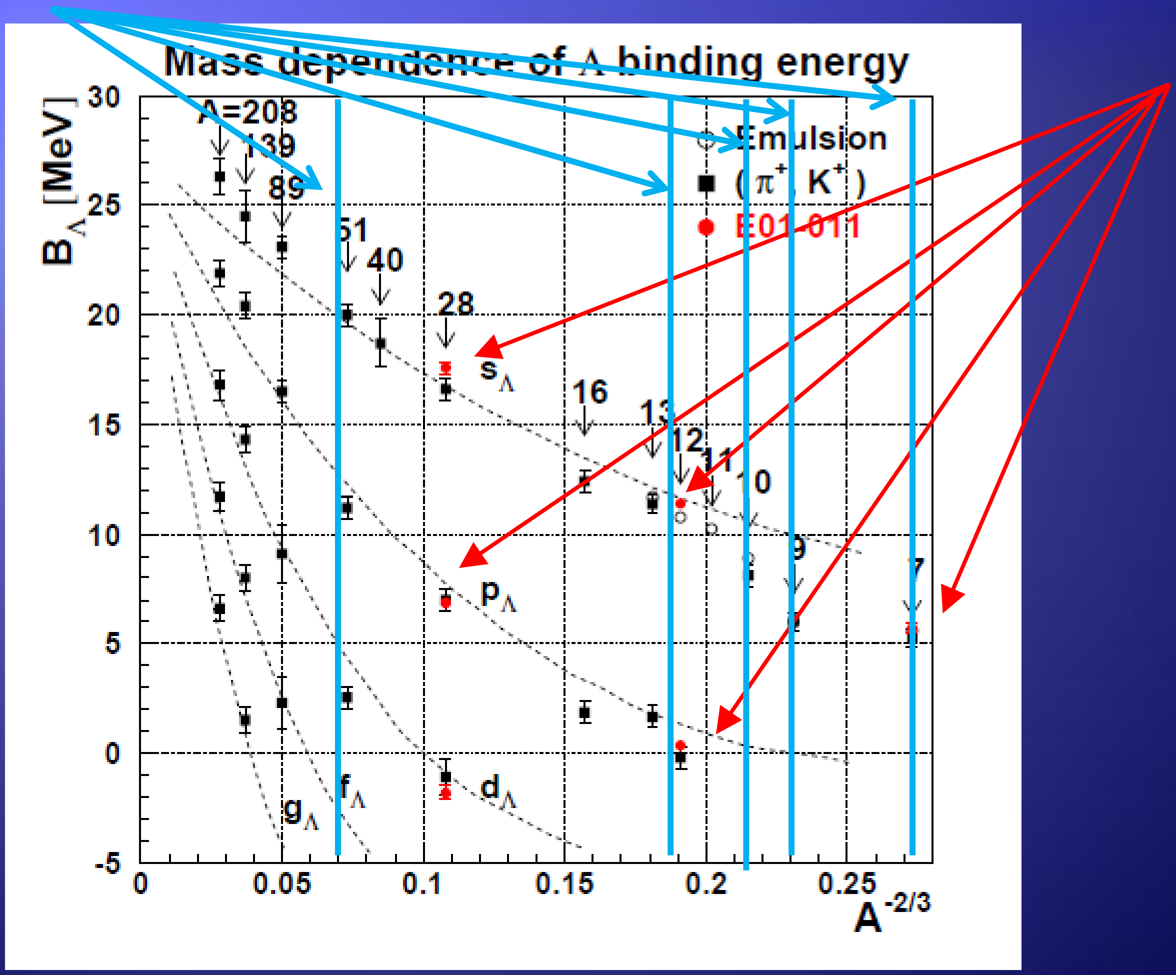
Analysis Status
By Kawama

E05-115 (2009) preliminary

Λ single particle energies

JLab E05-115

JLab E01-011



Summary

- With a high quality electron beam from CEBAF, (e,e'K) hypernuclear spectroscopy was established
- The second gen. exp. E01-011 (HKS) achieved ~500keV (FWHM) resolution

$^{12}_{\Lambda}$B : reference data with the best resolution

$^{7}_{\Lambda}$He : first reliable observation of g.s., CSB

$^{28}_{\Lambda}$Al : first observation, doorway to mid-heavy HY

- The third gen. exp. E05-115 (HKS-HES) successfully finished

Λ, Σ^0 , $^{7}_{\Lambda}$He, $^{9}_{\Lambda}$Li, $^{10}_{\Lambda}$Be, $^{12}_{\Lambda}$B, $^{52}_{\Lambda}$V