Workshop on J-PARC hadron physics in 2014
10th February 2014

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Hypernucleus experiments at Mainz and JLab

Objectives --- Hypernuclear Physics

A: 1 — 20 — 50 — 200 — 10^{57}

Elementary Process

Strangeness electro-production

Light Hypernuclei (s,p shell)

Extend Nuclear Force to Baryon Interaction

Neutron/Hyperon star,
Strangeness matter
Hyperonization →
Softening of EOS ?

CSB, $\Lambda\Sigma$ coupling in large isospin hypernuclei

Medium - Heavy hypernuclei

Use Λ as a probe to see deep inside of nucleus

Single-particle potential

Distinguishability of a Λ hyperon

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

Production and Decay spectroscopies

Production of Hypernuclei

s-quark exchange
s,sbar pair creation

(K,π) @ J-PARC, DAΦNE

(π,K) @ J-PARC
(e,e'K) @ JLab, MAMI-C
RI /pbar beam @ GSI, FAIR

τ ~ 200 ps

Decay of Hypernuclei

Auger nucleon emission
γ-decay
Weak decay

(e,Kn) possibility discussion

(K,$\pi\gamma$) @ J-PARC

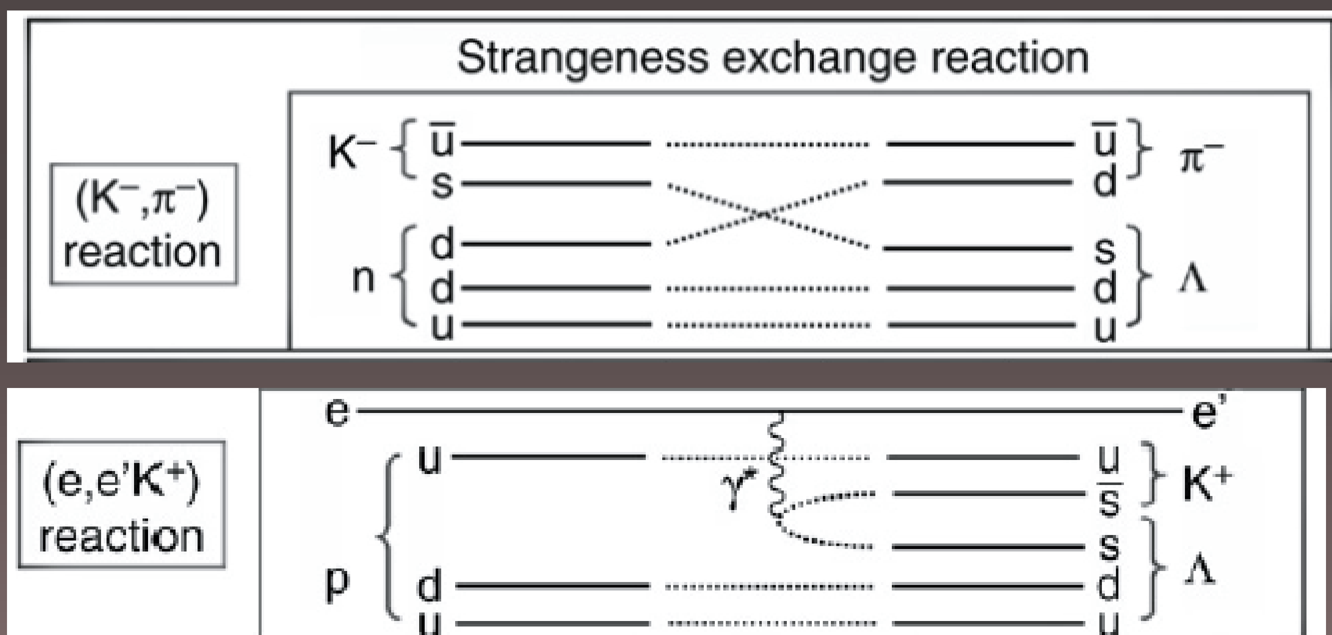
(e,Kπ) @ MAMI-C, JLab

Production of Hypernuclei

s-quark exchange
s,sbar pair creation

(K^-,π^-)

(π^+,K^+), $(e,e'K^+)$



Characteristics of (e,e'K) HY study

- Electromagnetic production
- Convert Proton to Lambda :
  - Mirror to well studied HY by (π,K), (K,π)
  - Absolute energy calibration with Λ and Σ^0 masses
- High quality primary beam
  - High energy resolution (< 1MeV)
  - Thin enriched target

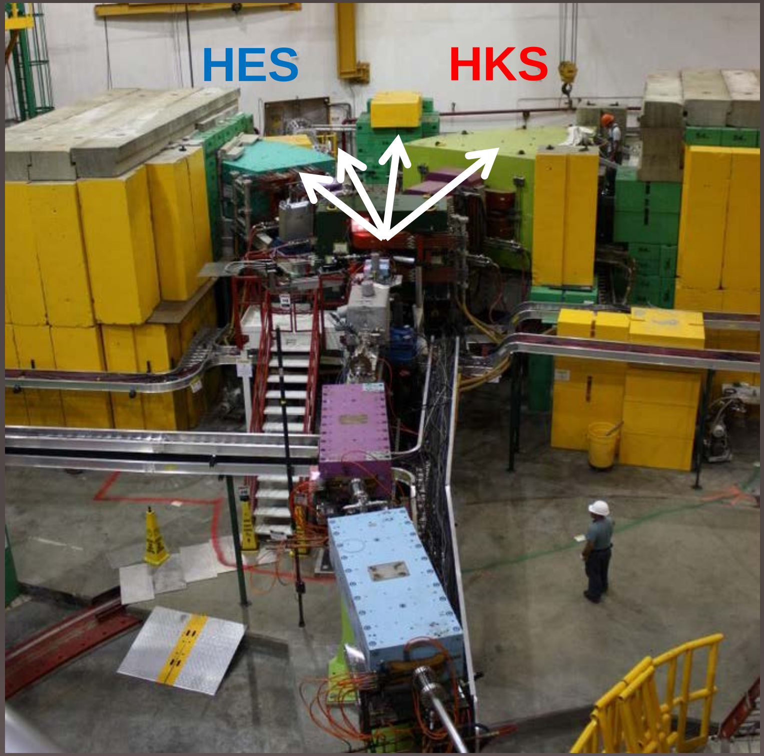
Challenge of (e,e'K) HY Study

- Huge **e' Background** due to
  Bremsstrahlung and **Mϕller** scattering
  Signal/Noise, Detector

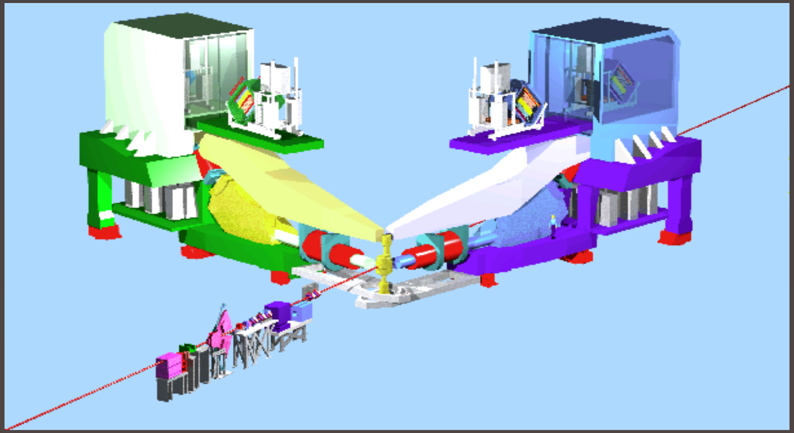
- **Less Hypernuclear Cross Section**
- **Coincidence Measurement** (e', K^+)
  Limited Statistics
  DC beam is necessary

High Quality Electron Beam is Essential !

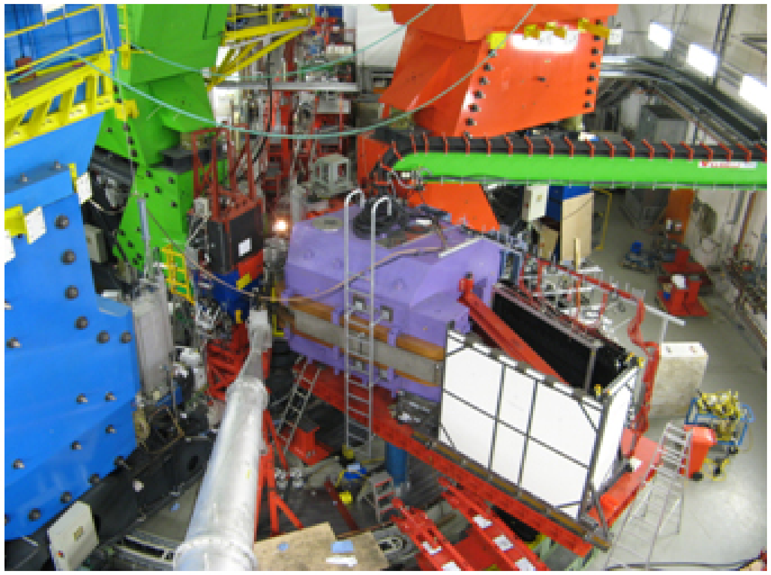
Facilities for (e,e'K$^+$) HY study



JLab Hall-C
HNSS (2000)
HKS (2005)
HKS+HES (2009)



JLab Hall-A HRS+HRS (2004)



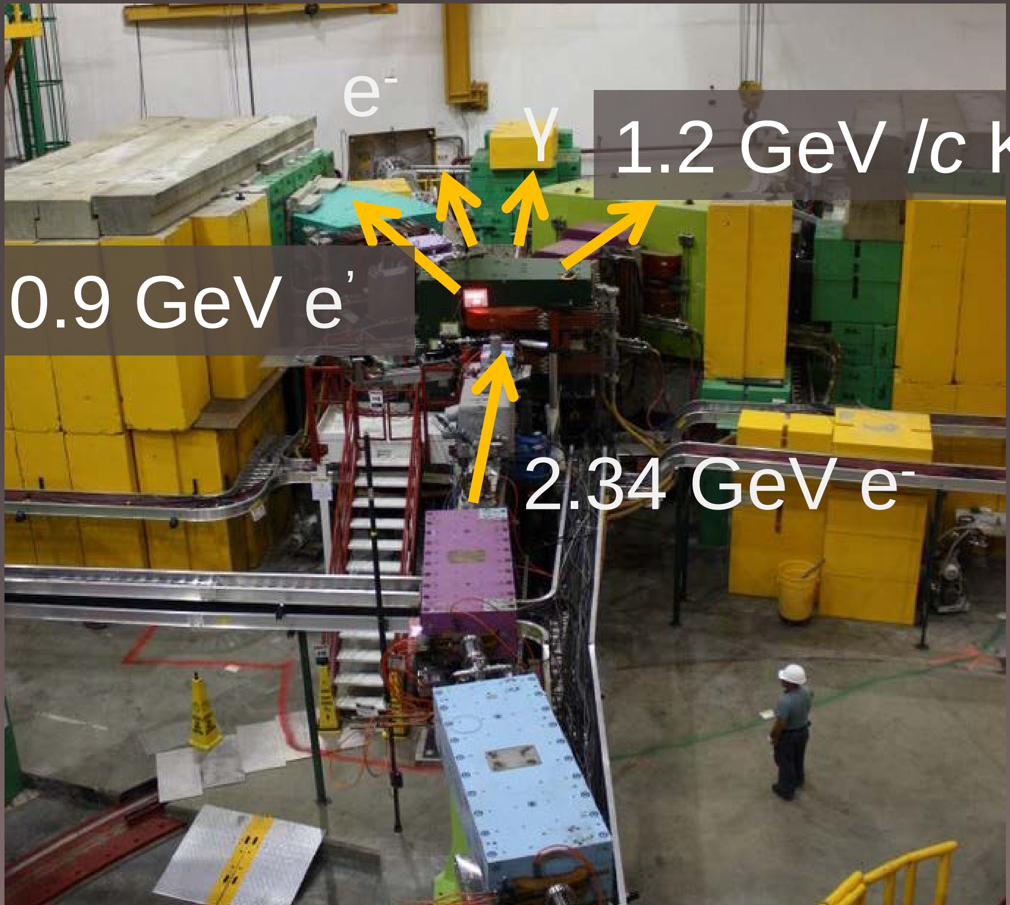
Mainz MAMI-C A1 KaoS (2008-)

(e,e'K) HY study at Jlab Hall C

2000~2009

E89-009, E01-011, E05-115 (Hall C)

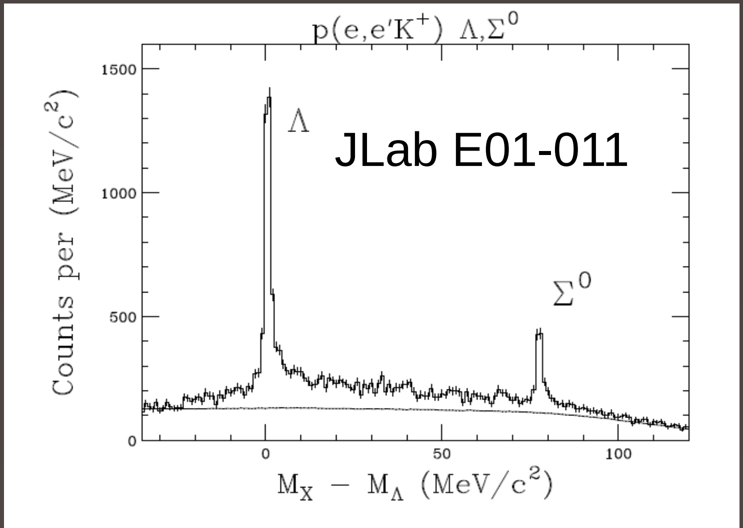
Wide mass range hypernuclear spectroscopy ($^{7}_{\Lambda}He \sim ^{52}_{\Lambda}V$)

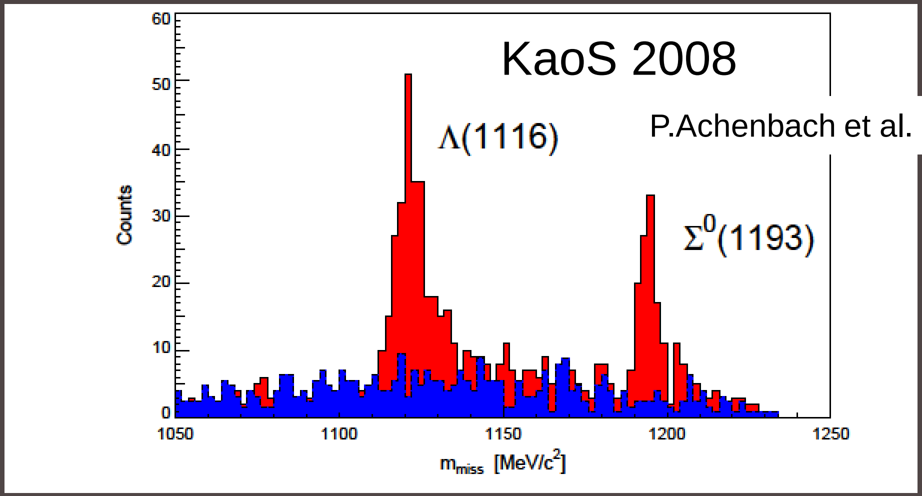


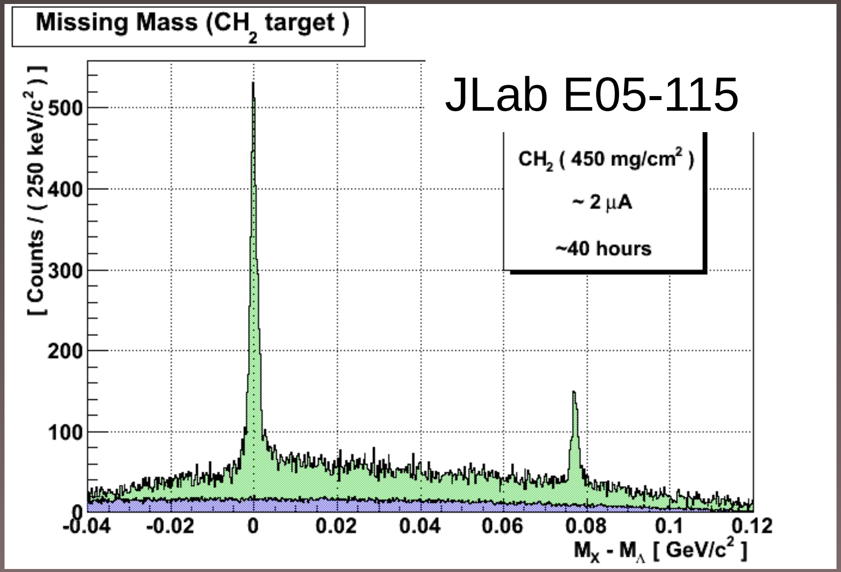
New HKS+HES spectrometers

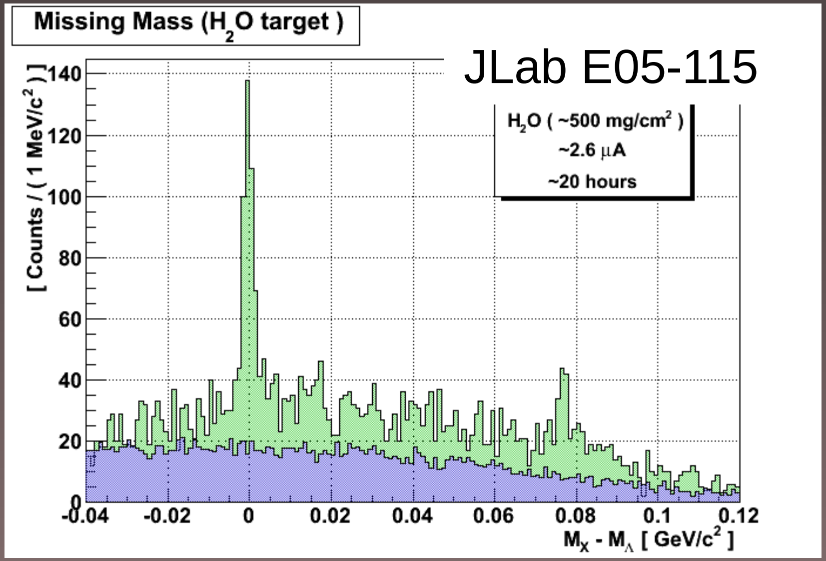
Tilt method suppress electron background by >10000

p(e,e'K$^+$)Λ, Σ^0: Elementary Process

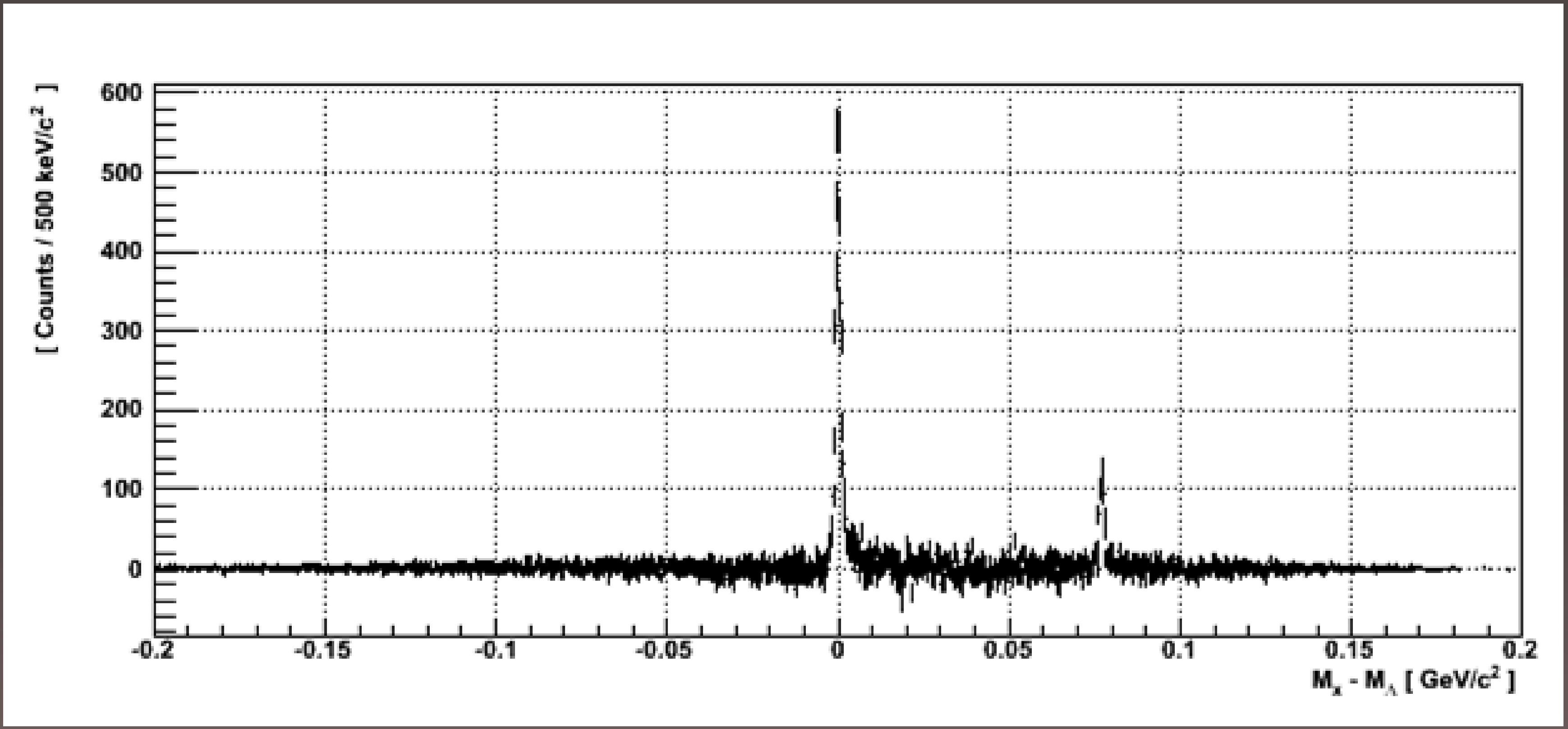




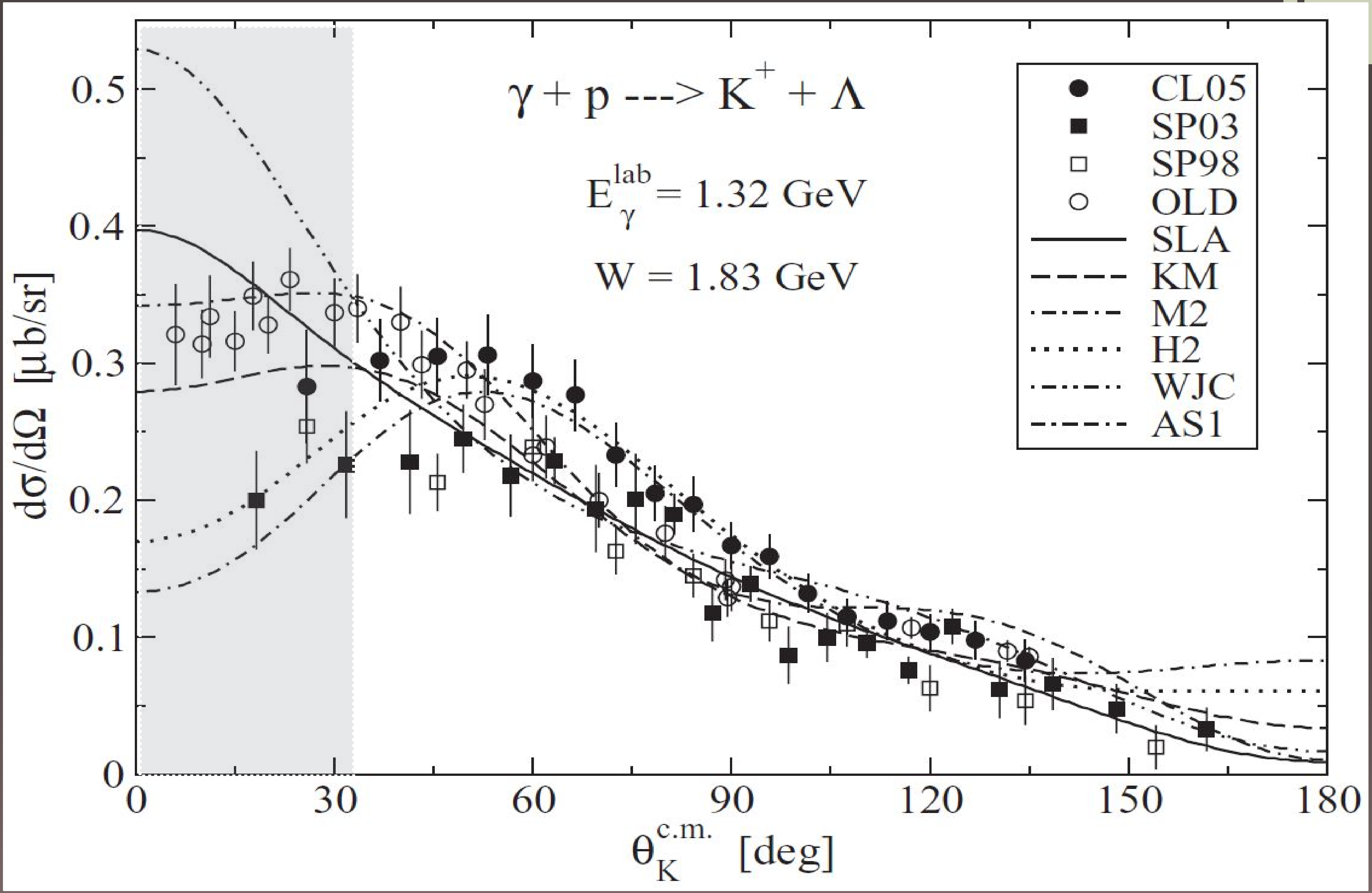




E05-115 $\Lambda \& \Sigma^0$ after BG subtraction

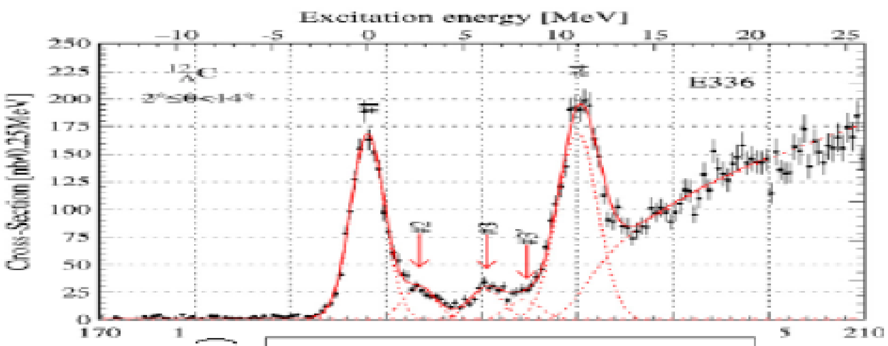


$K^+\Lambda$ production at forward angles



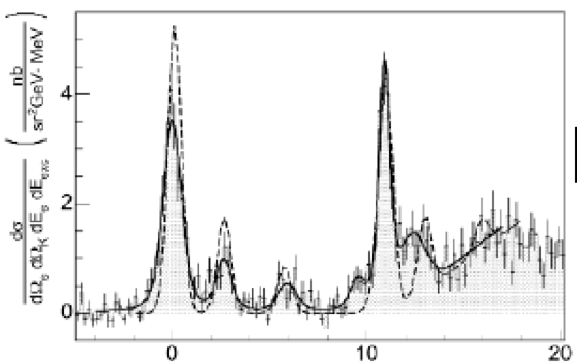
P.Bydzovsky and T.Mart, Phys. Rev. C 76, 065202 (2007)

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



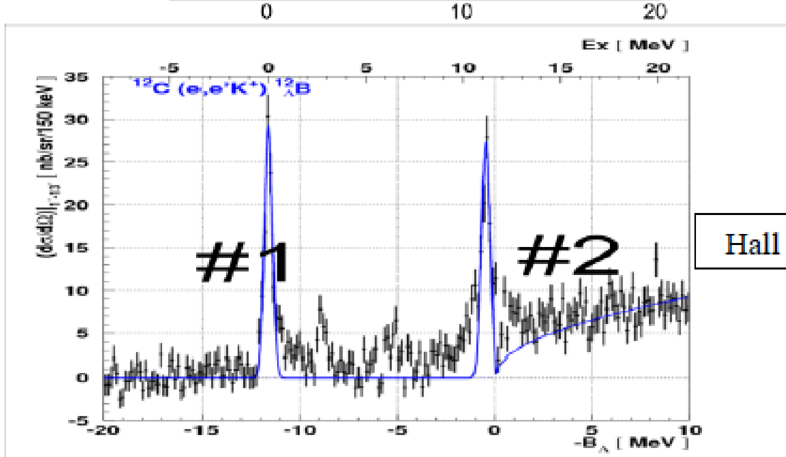
Resolution ~ 2MeV

Excitation energy
(gs energy from emulsion)



Hall A

Resolution ~ 0.65MeV



Hall C

Resolution ~ 0.5MeV

Absolute binding energy

	s_Λ		p_Λ	
Experiment	$Ex(-B_\Lambda)$ [MeV] $\pm$ (stat.) $\pm$ (sys.)	Width [MeV] $\pm$ (stat.)	$Ex(-B_\Lambda)$ [MeV] $\pm$ (stat.) $\pm$ (sys.)	Width [MeV] $\pm$ (stat.)
E01-011	0 ($-11.40 \pm 0.01 \pm 0.14$)	0.61 ± 0.05	$11.05 \pm 0.01 \pm 0.19$ ($-0.41 \pm 0.01 \pm 0.13$)	0.87 ± 0.13
E89-009 [25, 26, 66]	0 (-11.52 ± 0.35)	0.75	(-0.49 ± 0.16)	N/A
E94-107 [64]	0	1.15 ± 0.18	10.93 ± 0.03	0.67 ± 0.15

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

Nuclear Physics B52 (1973) 1–30.

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

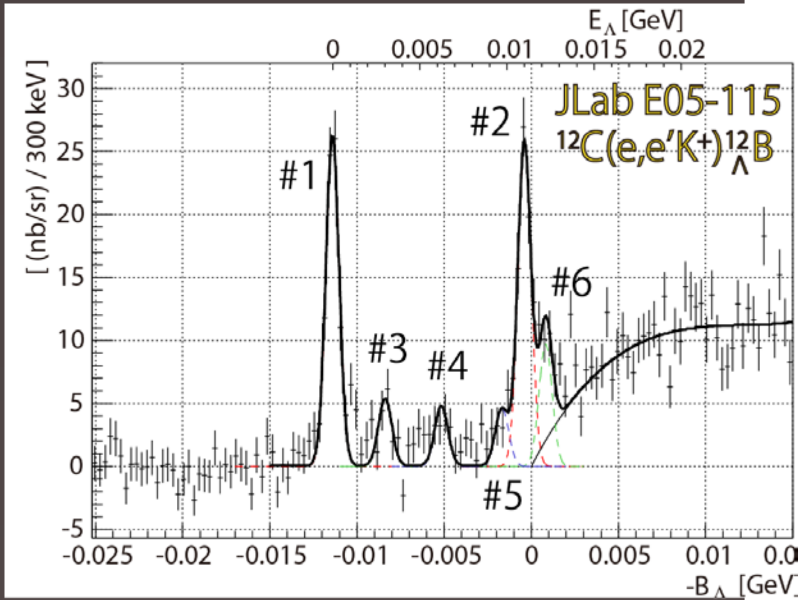
		(# of events)	
$^{12}_{\Lambda}B$	$\pi^- + {}^4He + {}^4He + {}^4He$	61	11.45 ± 0.07

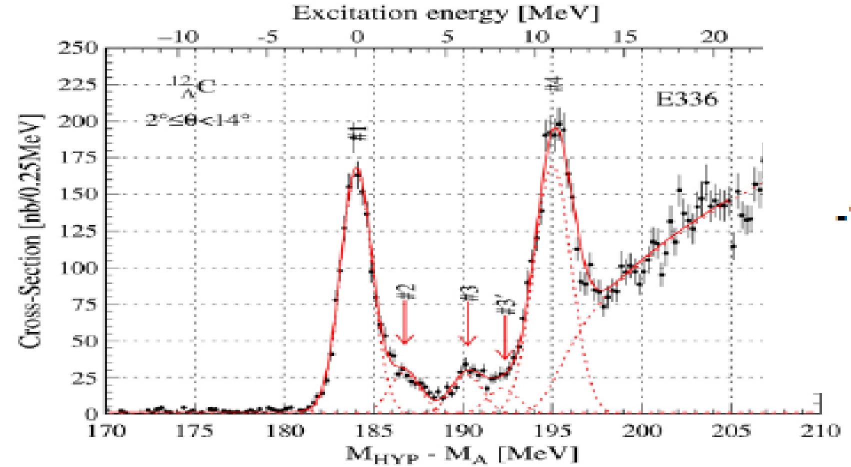
B_Λ ($^{12}{}_{\Lambda}$Bg.s.) = 11.45 +-0.07 MeV Emulsion Result (M.Juric et al.)

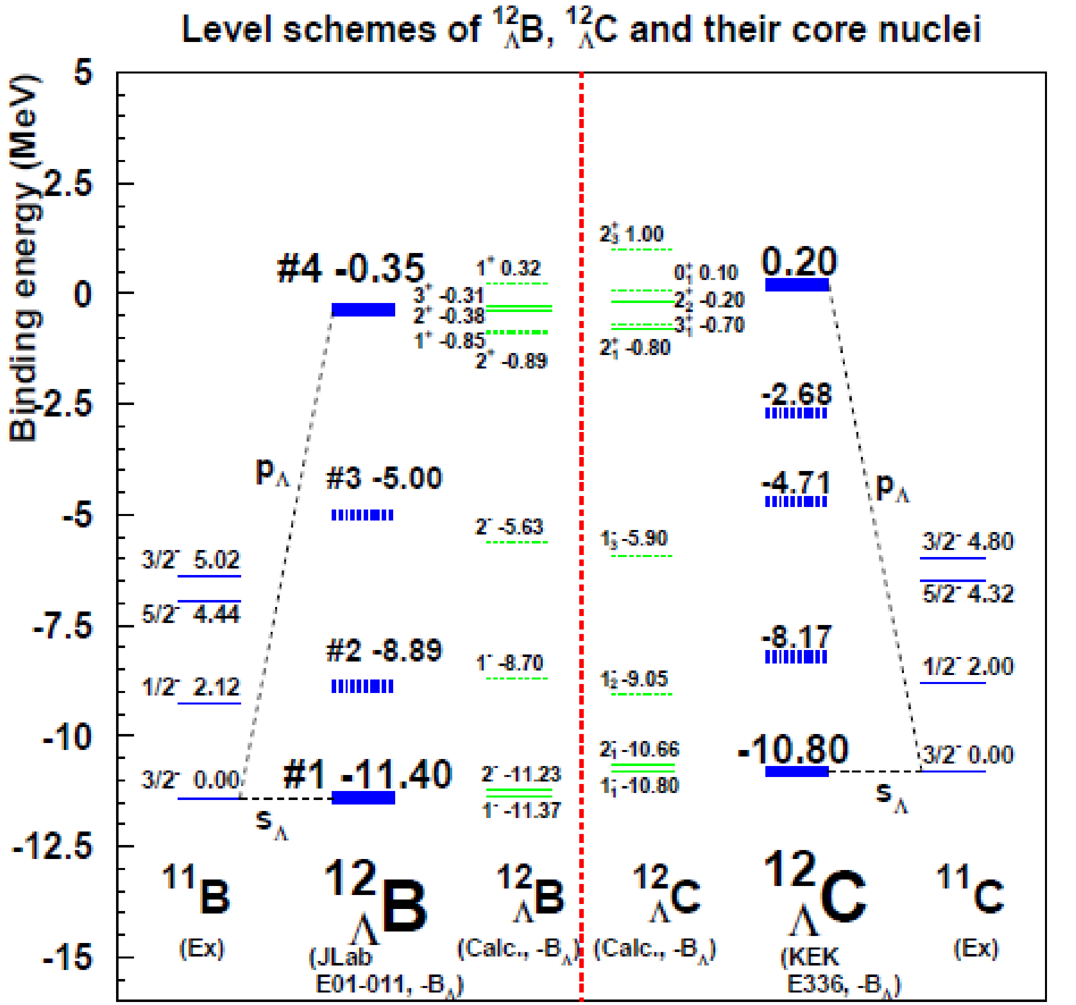
B_Λ ($^{12}{}_{\Lambda}$Bg.s.) = 11.40 +- 0.01 +- 0.14 MeV (E01-011 Preliminary)

Totally independent measurement

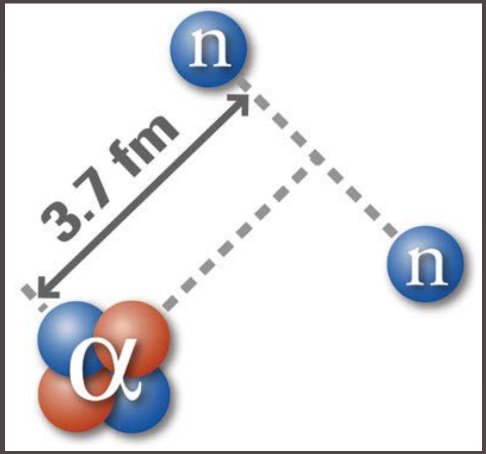
$^{12}C(e,e'K^+)^{12}_{\Lambda}B$, $^{12}C(\pi^+,K^+)^{12}_{\Lambda}C$



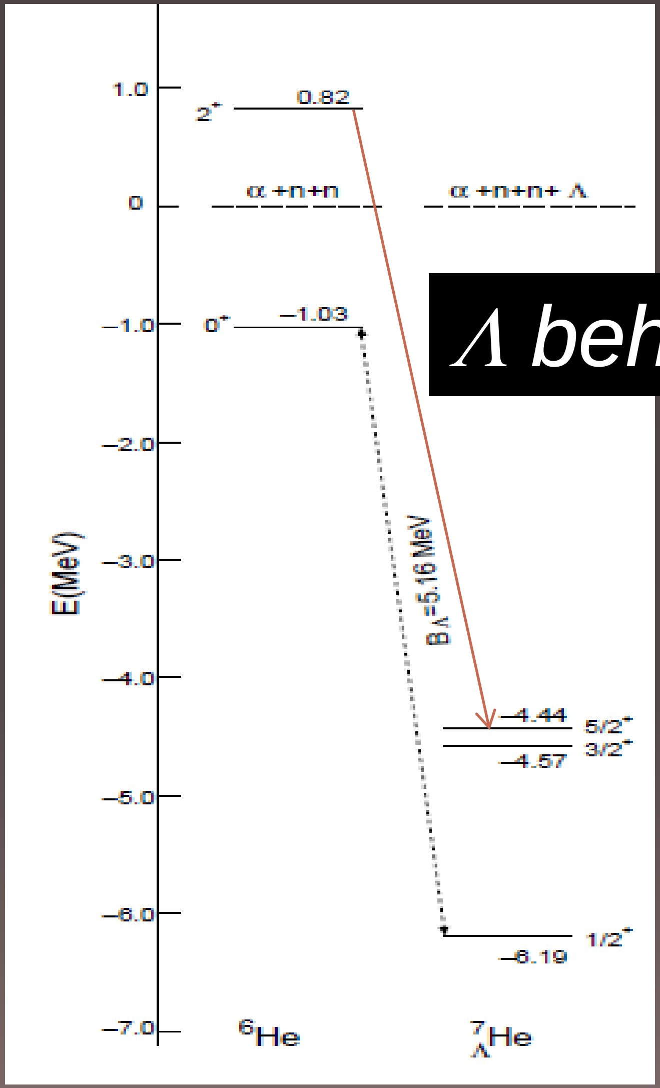




${}^{7}_{\Lambda}\mathrm{He} = {}^{6}\mathrm{He} + \Lambda$



${}^{6}\mathrm{He}$: 2n halo

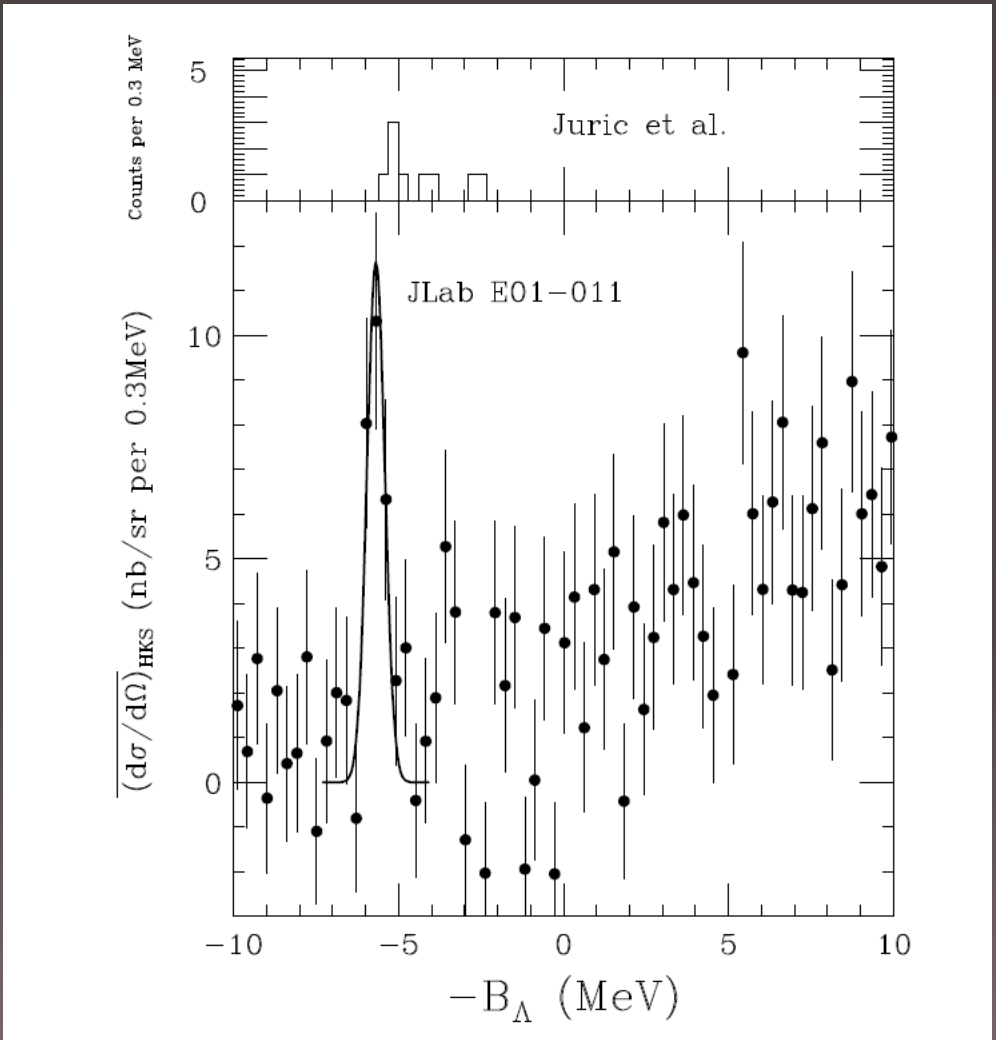


Λ behaves like glue

E.Hiyama et al. PRC 80, 054321 (2009)

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

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



FWHM 0.63 MeV

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

$$-B_\Lambda = -5.68 \pm 0.03(\text{stat.}) \pm 0.25(\text{sys.})\ \text{MeV},$$
$$\overline{\left(\frac{d\sigma}{d\Omega}\right)}_{\text{HKS}} = 26 \pm 5.1(\text{stat.}) \pm 9.9(\text{sys.})\ \text{nb/sr},$$

Last missing information of A=7 hypernuclear iso-triplet

E01-011, *PRL* **110** (2013) 012502.

E01-011(HKS) 90 counts
E05-115(HKS-HES) >500 counts

unbound ^{6}He excited state + Λ = bound $^7_\Lambda$He excited state

B_Λ of light hypermultiplets

$^4_\Lambda$H

$B_\Lambda(^4_\Lambda\mathrm{H}) = 2.04 \pm 0.04\ \mathrm{MeV}$

67 events

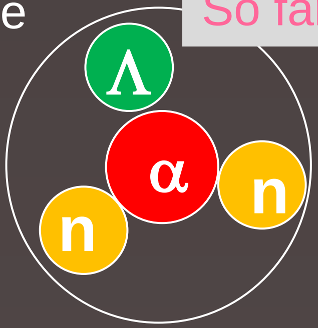
$^4_\Lambda$He

$B_\Lambda(^4_\Lambda\mathrm{He}) = 2.39 \pm 0.03\ \mathrm{MeV}$

98 events

$^7_\Lambda$He

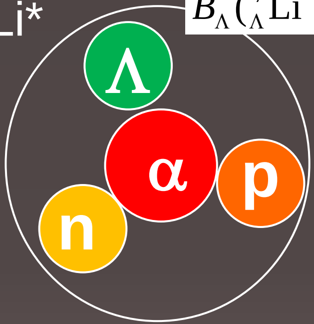
So far NO B_Λ data



$^7_\Lambda$Li*

$B_\Lambda(^7_\Lambda\mathrm{Li}^*) = 5.26 \pm 0.03\ \mathrm{MeV}$

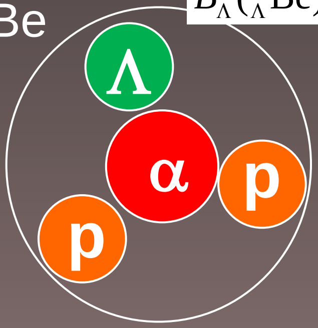
167 events



$^7_\Lambda$Be

$B_\Lambda(^7_\Lambda\mathrm{Be}) = 5.16 \pm 0.08\ \mathrm{MeV}$

15 events



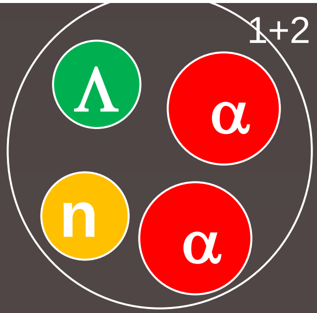
Exp. Data : Emulsion

Nuclear Physics B52 (1973) 1–30.

$^{10}_\Lambda$Be

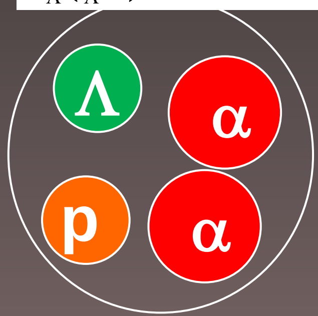
$B_\Lambda(^7_\Lambda\mathrm{Li}^*) = 9.11 \pm 0.22\ \mathrm{MeV}$

1+2 events



$^{10}_\Lambda$B

$B_\Lambda(^{10}_\Lambda\mathrm{B}) = 8.89 \pm 0.12\ \mathrm{MeV}$



10 events

Experimental B_Λ ⇒ Δ_{CSB}

Hiyama *et al.* *PRC80.054321*
PTP 128 (2012) 105.

A=7 Hypernuclear iso-triplet

$B_\Lambda(\text{w/CSB}) = 5.16\ \text{MeV}$

$B_\Lambda(\text{calc}) = 5.36\ \text{MeV}$

$B_\Lambda(^7_\Lambda\text{Li}^*, 1/2^+) = 5.26 \pm 0.03\ \text{MeV}$

$B_\Lambda(\text{calc}) = 5.28\ \text{MeV}$

$B_\Lambda(\text{w/ CSB}) = 5.29\ \text{MeV}$

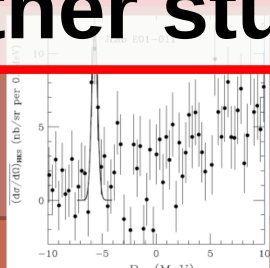
$B_\Lambda(^7_\Lambda\text{Be}, 1/2^+) = 5.16 \pm 0.08\ \text{MeV}$

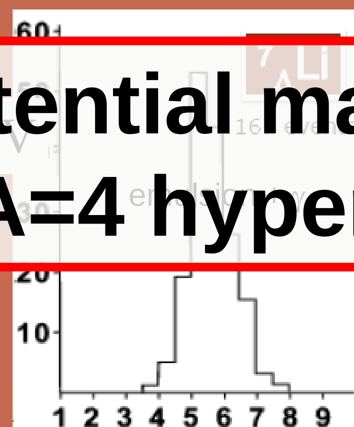
$B_\Lambda(\text{calc}) = 5.21\ \text{MeV}$

$B_\Lambda(\text{w/ CSB}) = 5.44\ \text{MeV}$

Jlab E01-011(HKS)

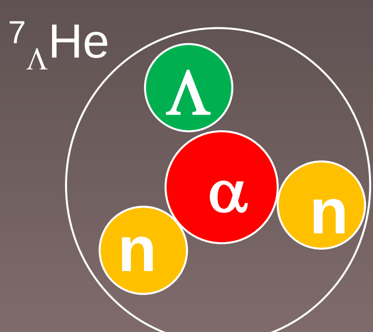
$B_\Lambda(^7_\Lambda\text{He}, 1/2^+) = 5.68 \pm 0.03 \pm 0.25\ \text{MeV}$

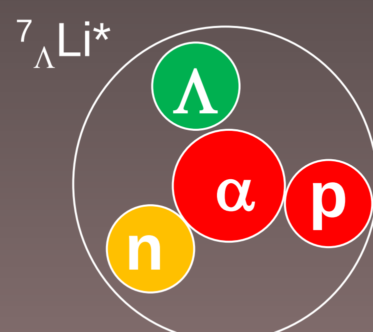


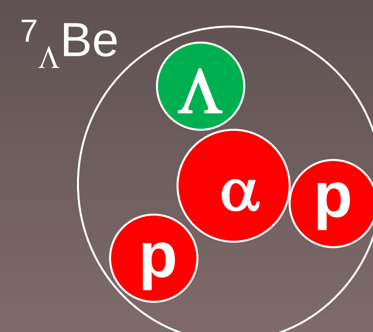


Assumed CSB potential may be too naïve

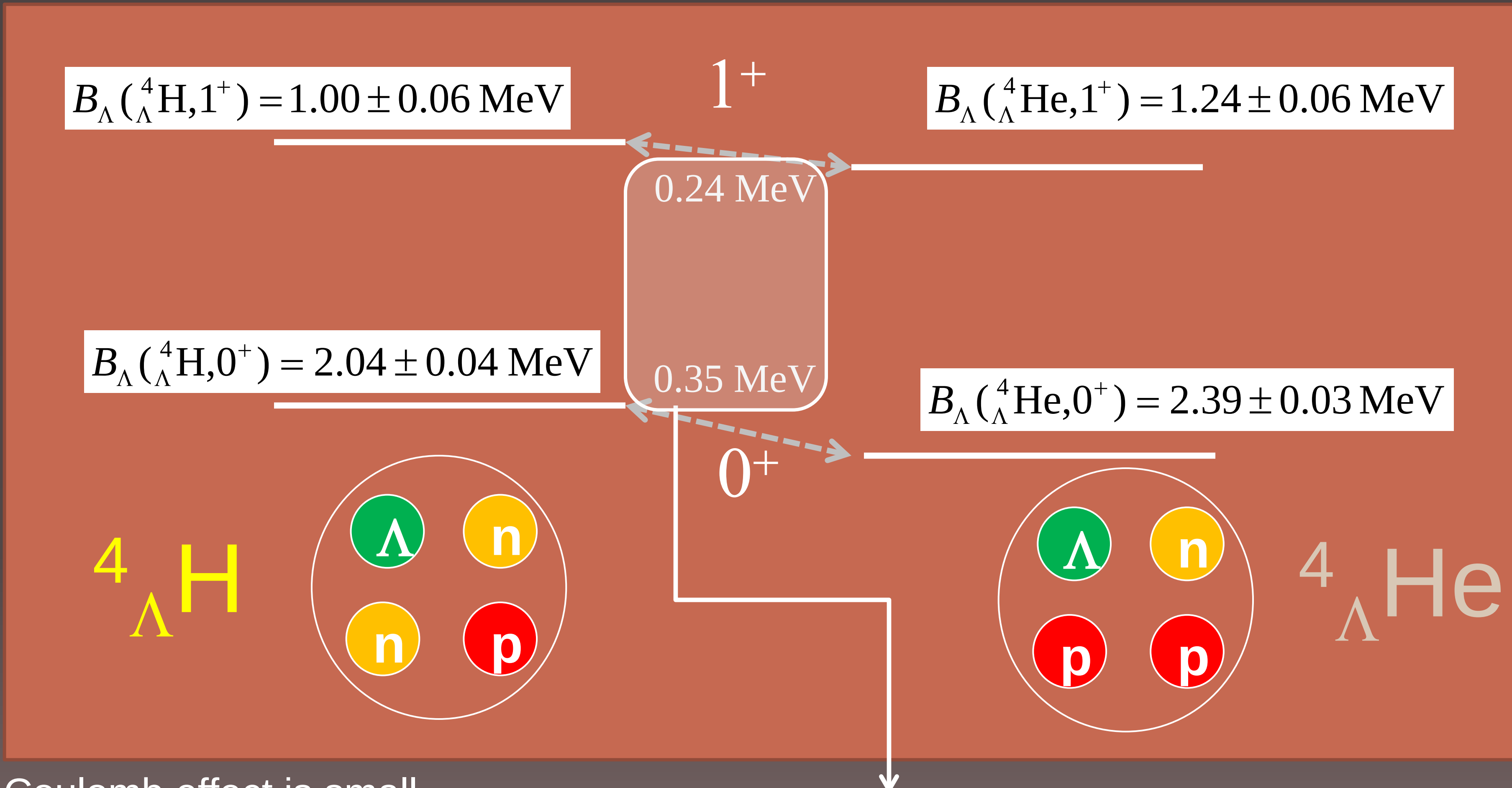
Further study on A=4 hypernuclear systems







Charge Symmetry Breaking Effect of ΛN interaction



Coulomb effect is small.

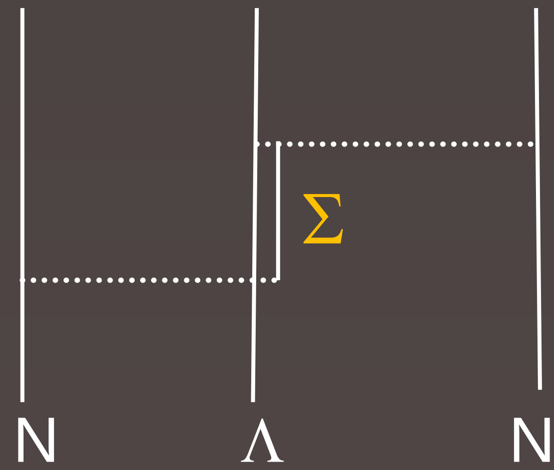
$$-\Delta B_c = 0.050 \pm 0.02 \text{ MeV},$$

$$-\Delta B_c^* = 0.025 \pm 0.015 \text{ MeV}$$

Charge Symmetry Breaking

cf) $B(^3\mathrm{H}) - B(^3\mathrm{He}) - \Delta B_c$ = 764-693 = 71 keV

Possible origins of CSB ΛN int.



ΛΣ mass difference ~ 80 MeV < NΔ mass difference ~ 300MeV

$M(\Sigma^+) < M(\Sigma^0) < M(\Sigma^-)$, $\Delta M(\Sigma^- - \Sigma^+)$~8MeV

Nogga, Kamada, Glockle, PRL 88 (2002) 172501.

~~Consistent understanding of 0^+, 1^+ of ${}^4_\Lambda H$, ${}^4_\Lambda He$~~

Phenomenological potential :

A.R.Bodmer&Q.N.Usmani, PRC 31(1985)1400.

$$V^{CSB} = -\tau_3 T_\pi^2 \frac{1}{8}[(0.568\Delta B_\Lambda + 0.756\Delta B^*_\Lambda) + (0.568\Delta B_\Lambda - 0.756\Delta B^*_\Lambda)\sigma_\Lambda \cdot \sigma_N]$$

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

Nuclear Physics B52 (1973) 1–30.

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

Emulsion Result (M.Juric et al.)

		(# of events)	B_{Λ} (MeV)
$^{4}_{\Lambda}H$	$\pi^- + {}^1H + {}^3H$	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

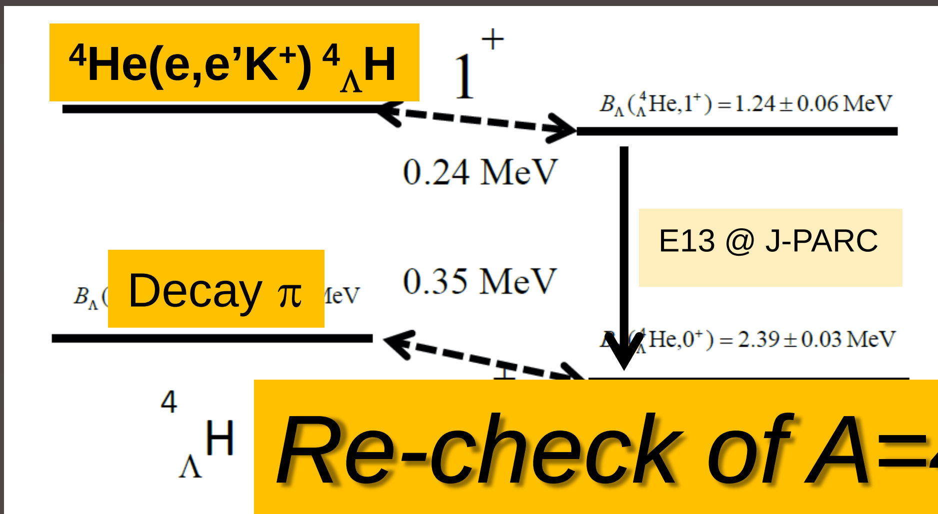
$$2.14 \pm 0.07$$
$$1.92 \pm 0.12$$

Different modes give 0.22 MeV difference

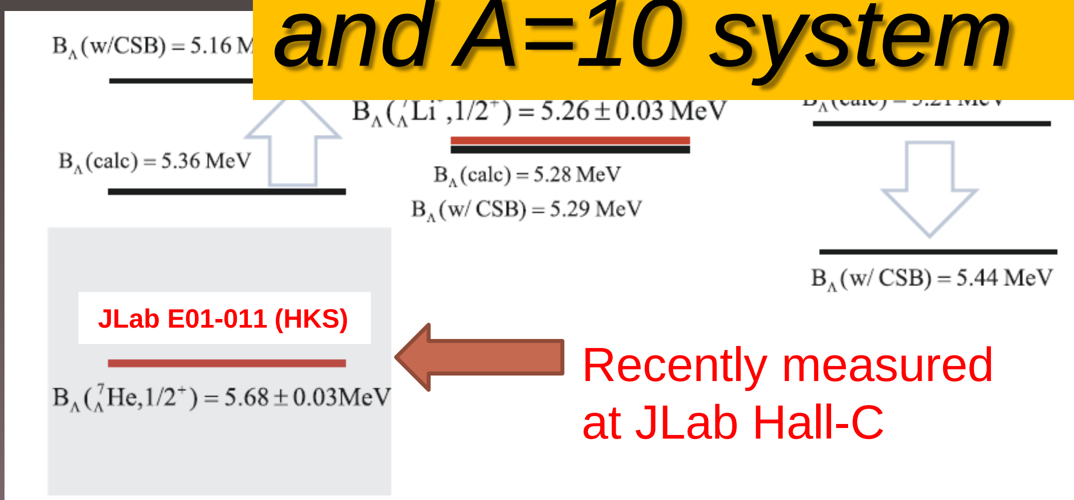
$$\Delta B_{\Lambda}({}^{4}_{\Lambda}\text{He-}{}^{4}_{\Lambda}\text{H},0^{+}) = 0.34 \pm 0.07 \text{ MeV}$$

Few-body physics with strangeness

Charge Symmetry Breaking of ΛN interaction



Re-check of A=4 system and A=10 system



A=4,iso-doublet hypernuclei

Introduced to explain A=4.

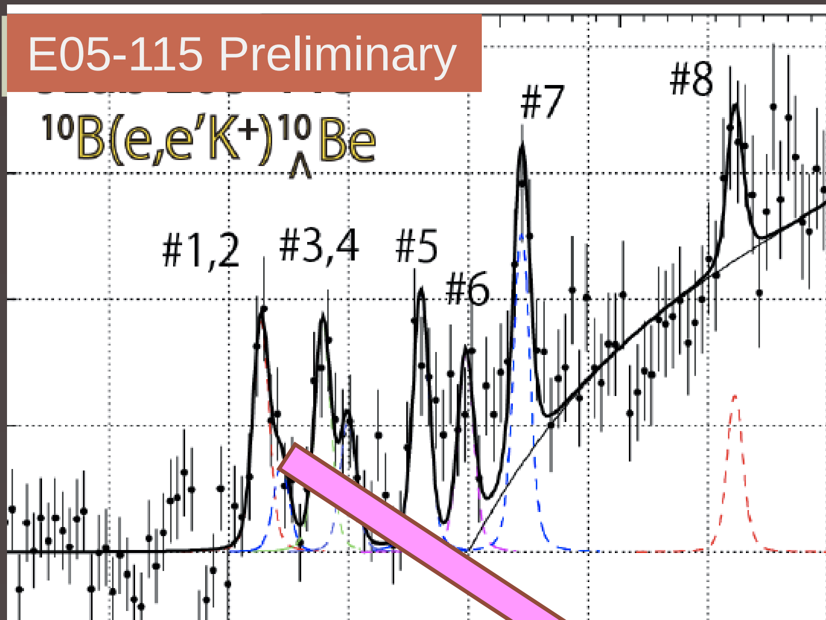
nological CSB potential

NOT necessary for A=7.

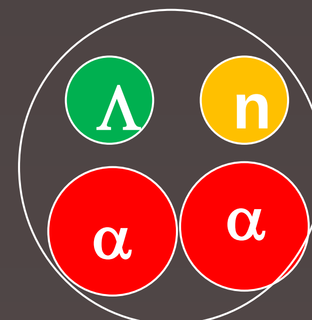
A=7,iso-triplet hypernuclei

A=10,iso-doublet hypernuclei?

$^{10}_{\Lambda}$ ... tant for CSB

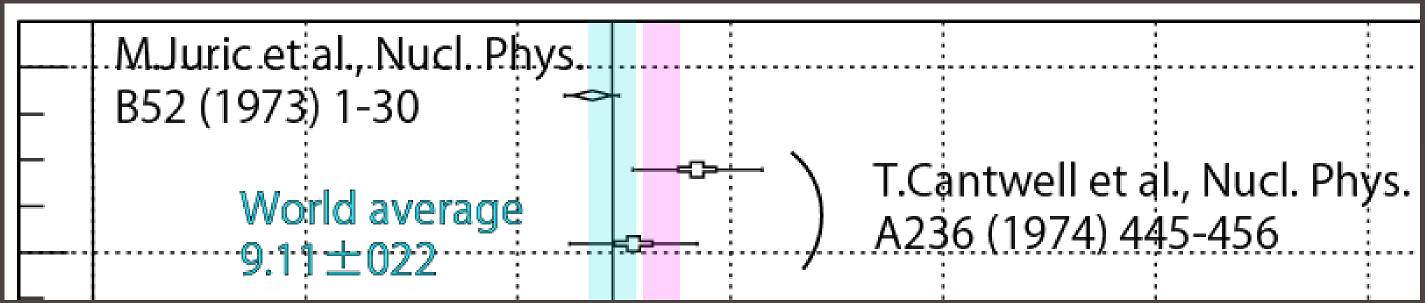


$^{10}_{\Lambda}Be = \alpha + \alpha + n + \Lambda$

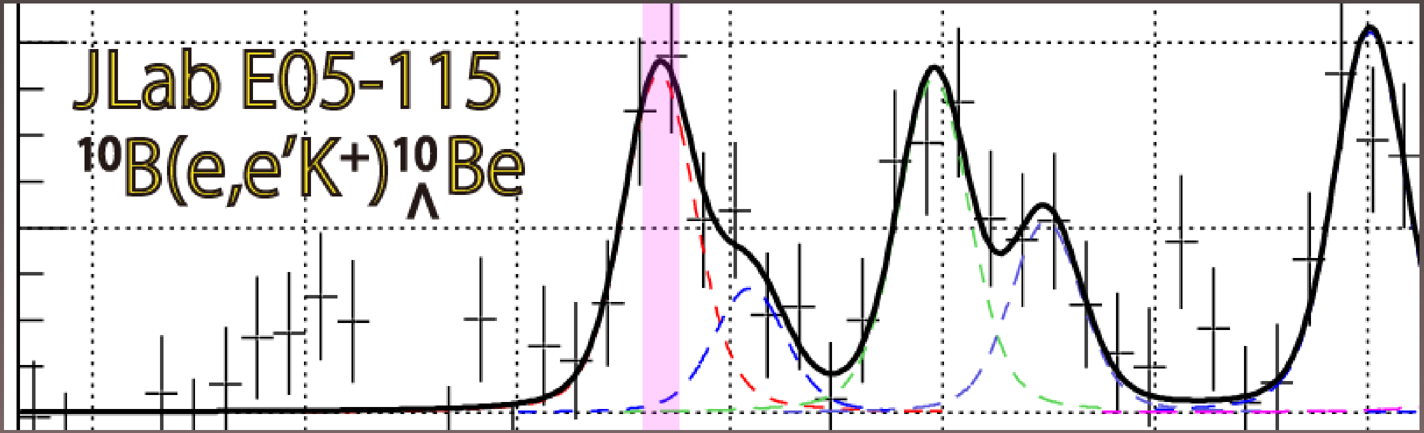


Hiyama , Yamamoto PTP 128 (2012) 10[illegible]

	without CSB	with even-state CSB	with even+odd-state CSB	Exp.
$B_\Lambda(^7_\Lambda\mathrm{He})$	5.36	5.16	5.36	5.68 ± 0.03 ± 0.25
$B_\Lambda(^7_\Lambda\mathrm{Li})$	5.28	5.29	[illegible]	5.26 ± 0.03
$B_\Lambda(^7_\Lambda\mathrm{Be})$	5.21	5.44	5.27	5.16±0.08
$B_\Lambda(^{10}_\Lambda\mathrm{Be})$	8.94	8.83	8.96	9.11 ± 0.22
$B_\Lambda(^{10}_\Lambda\mathrm{B})$	8.76	8.85	8.74	8.89 ± 0.12
$\Delta B_\Lambda^{\mathrm{cal}}$	0.18	−0.02	0.22	0.22 ± 0.25

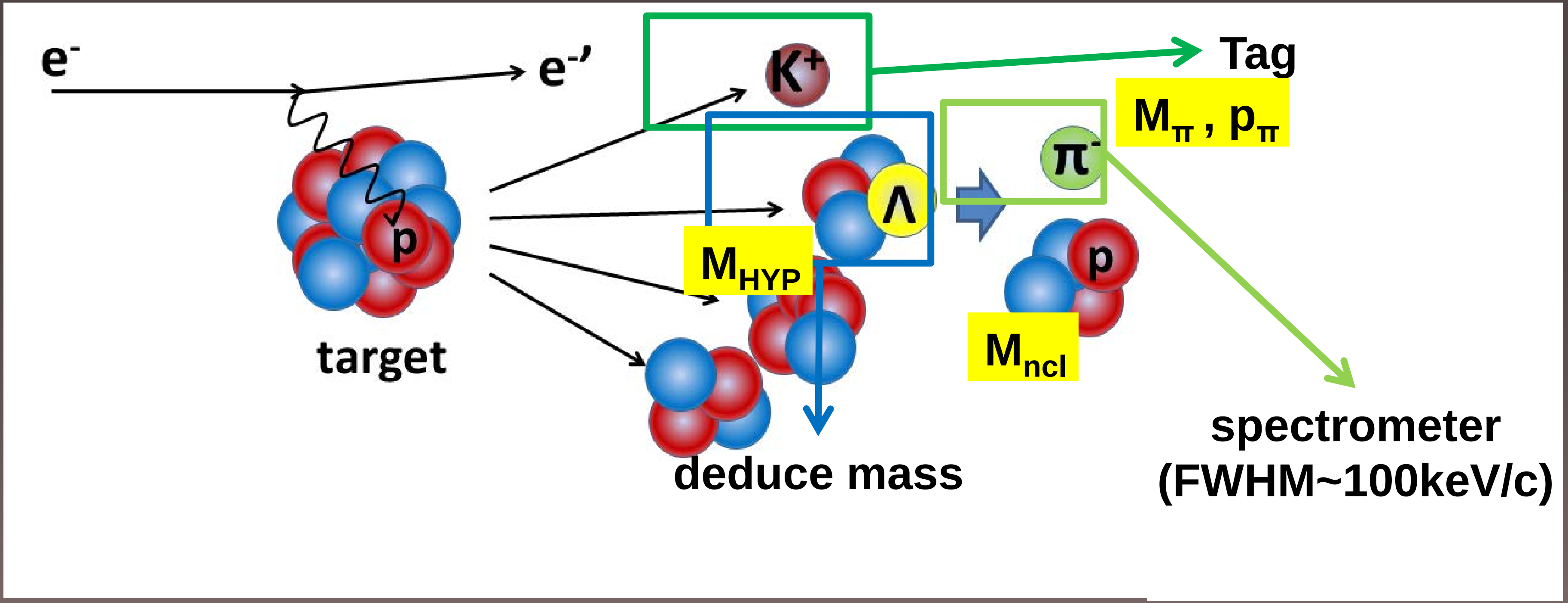


Could be compared with theoretical predictions w/ and w/o CSB.



Decay π Spectroscopy of electro-produced HY (JLab E10-001 and MAMI-C KaoS project)

Study of $^{4}_{\Lambda}H$ ground state



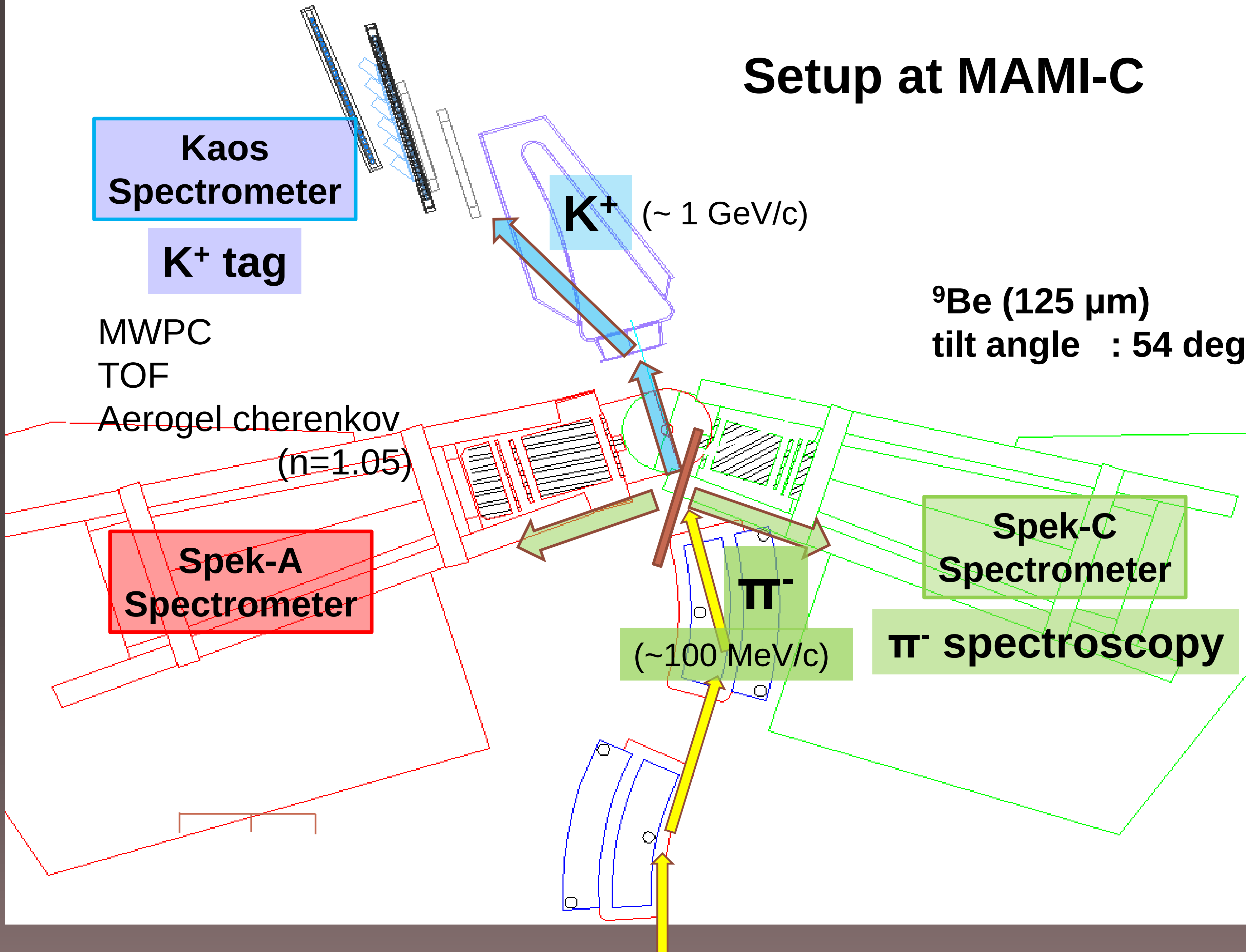
Decay Pion Spectroscopy

- High Resolution (< 150 keV, FWHM):
  Precise determination of B_Λ ($\pm$20keV)
    Suitable for CSB study of light hypernuclei
- Combined with (e,e'K) production:
  Thin target
  Neutron rich light hypernuclei (ΛN-ΣN coupling)
  Neutron drip line limit (such as $^{6}_{\Lambda}H$)
- Formation of quasi-free continuum and fragmentation mechanism

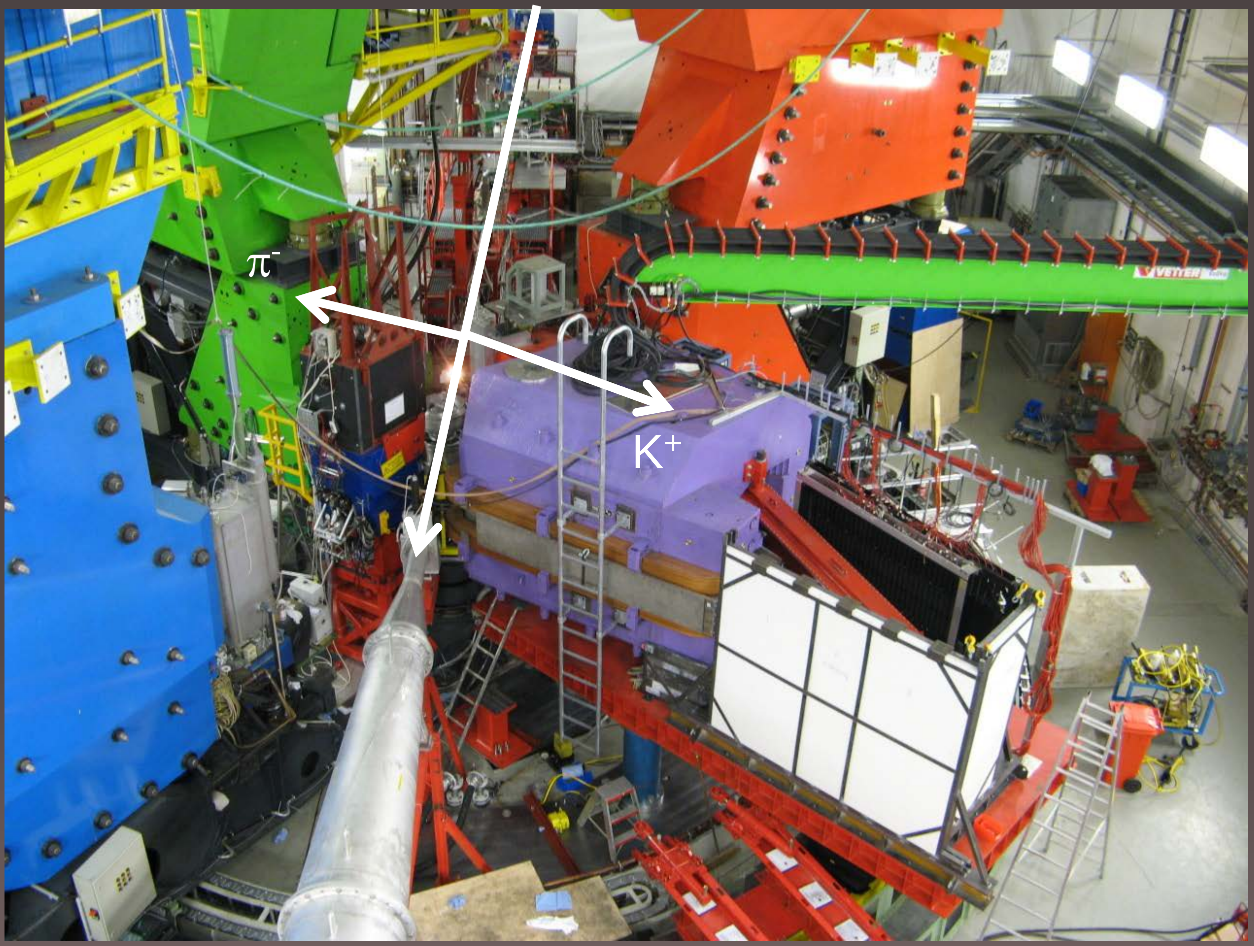
Originally proposed at JLab

Pilot experiments have started at Mainz from 2011.

Setup at MAMI-C

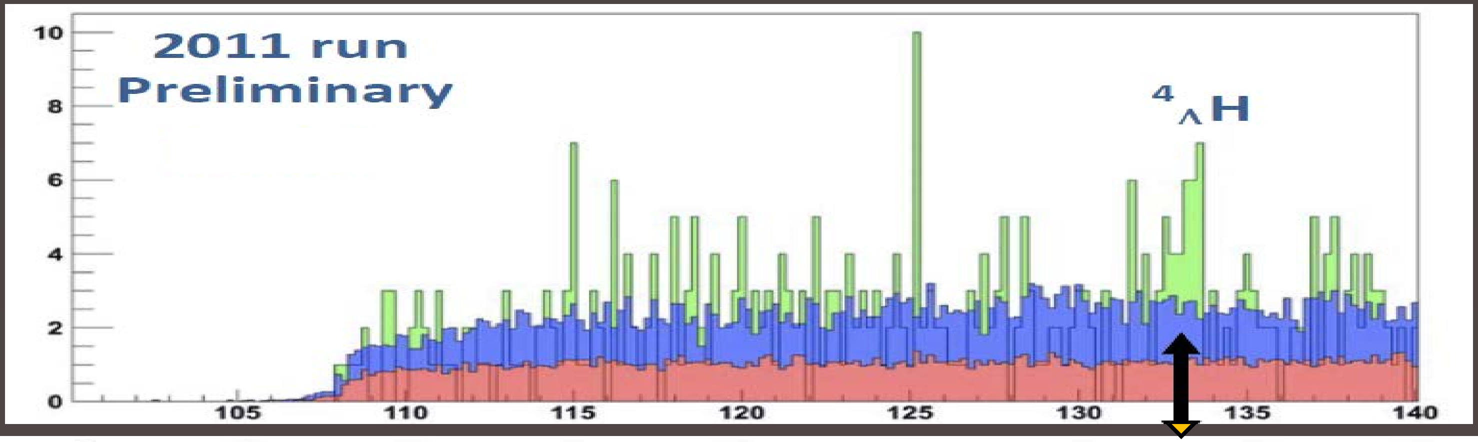


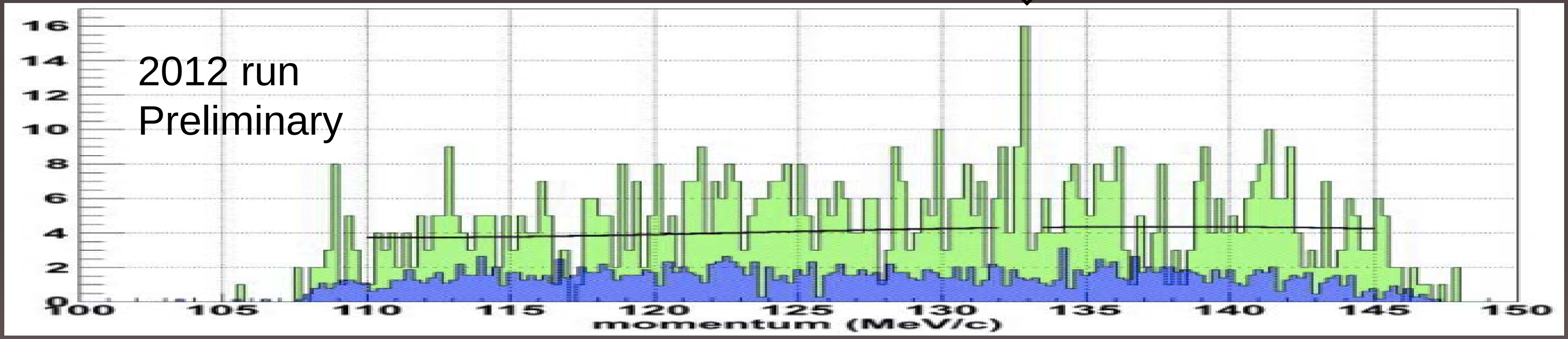
KaoS at MAMI-C (Mainz Univ.)

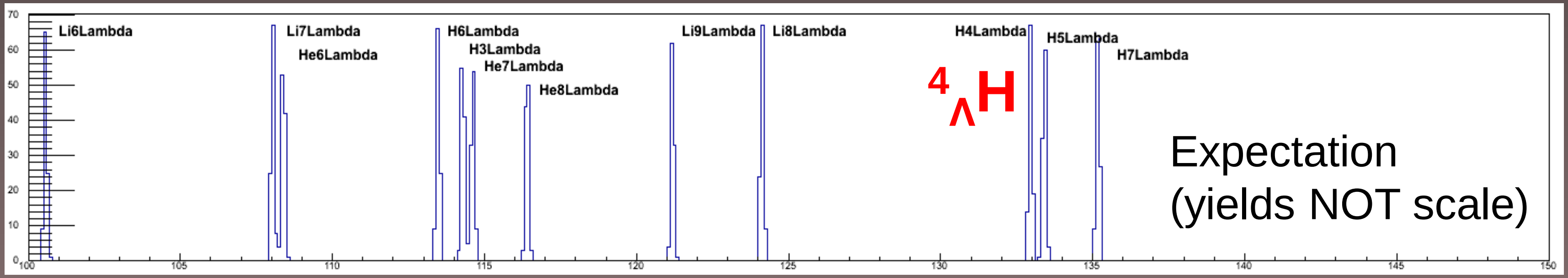


Pilot experiment performed at MAMI-C 2011 &2012

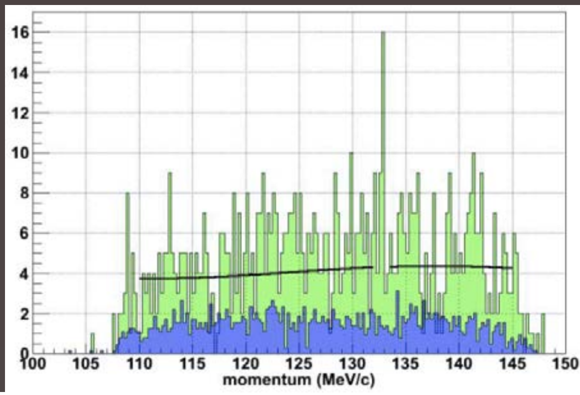
π^- spectrum tagged by K^+

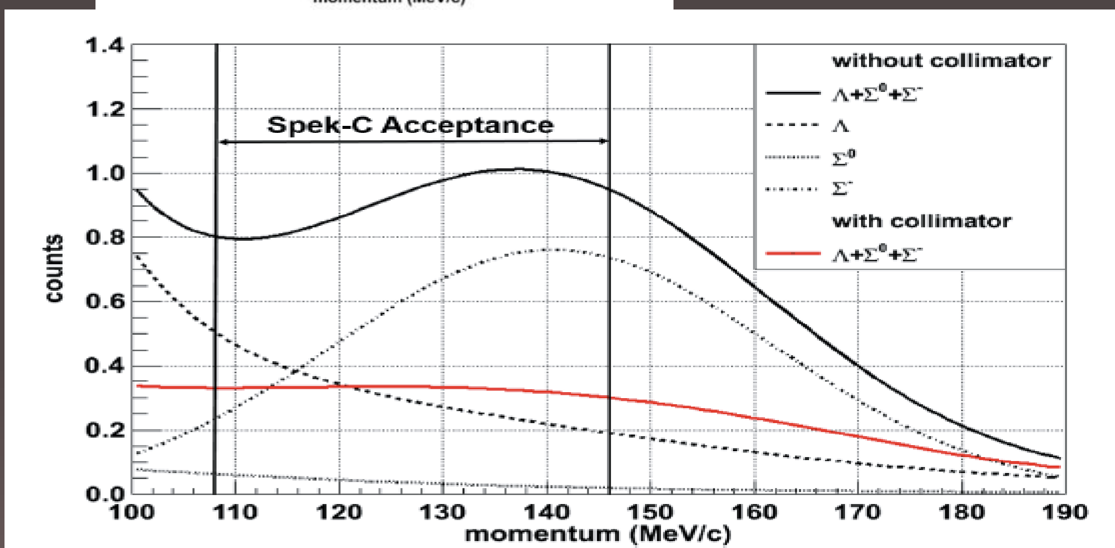




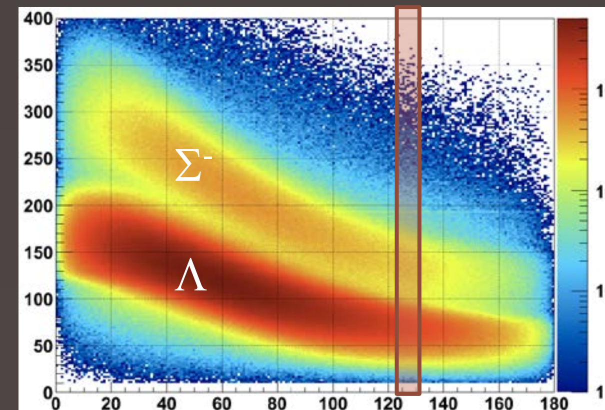


Suppression of background

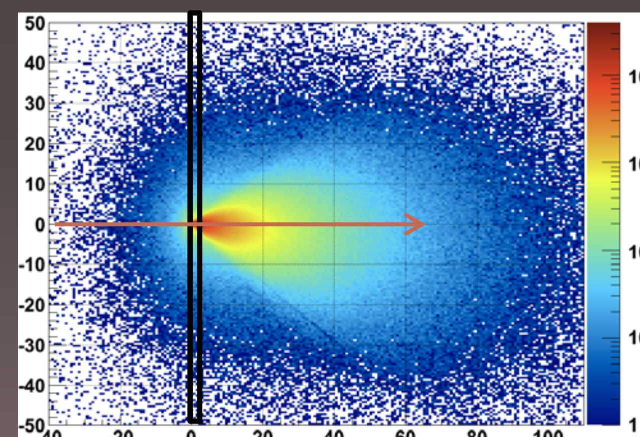




π momentum (MeV/c)



π angle (deg)

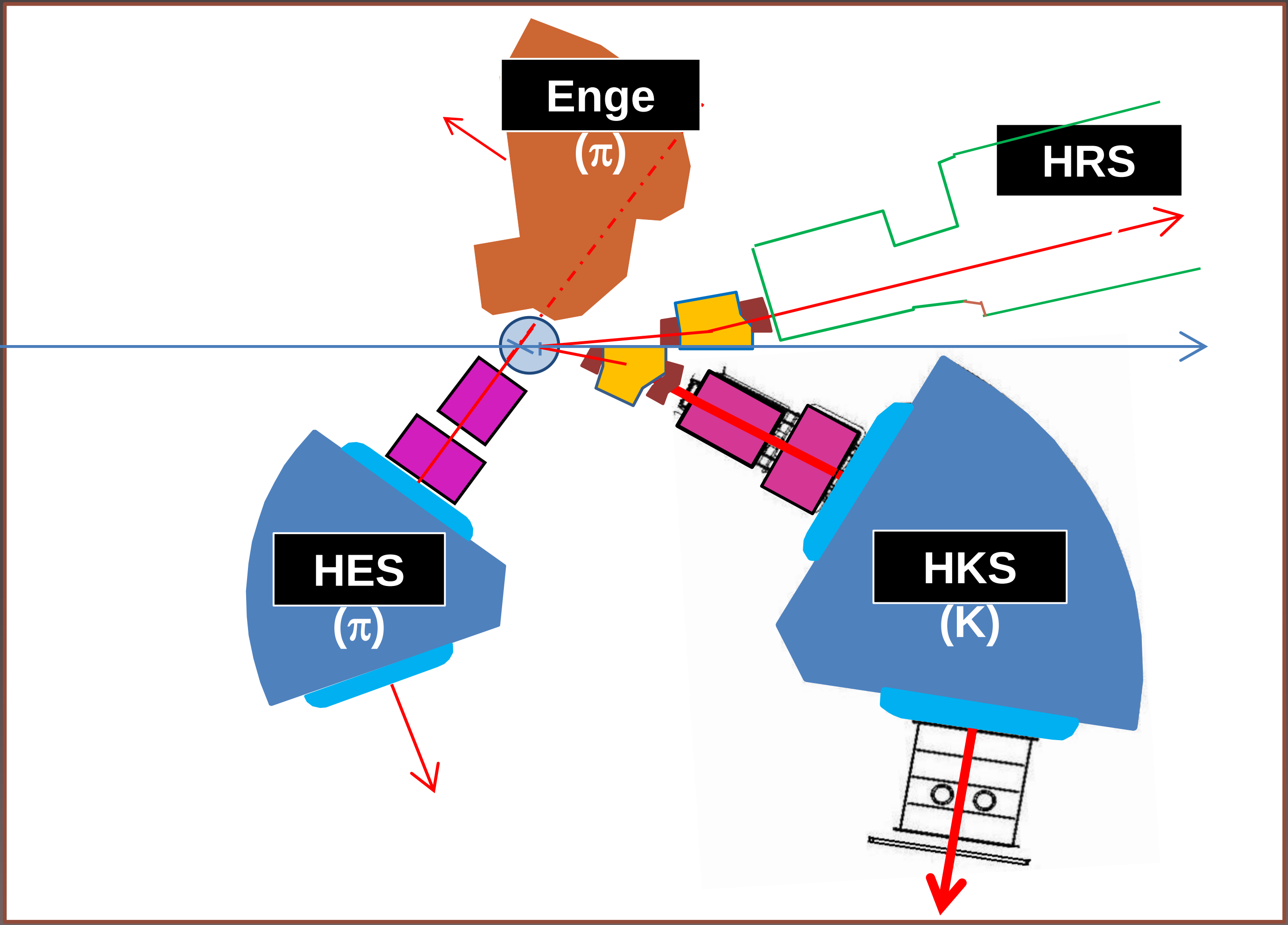


Design of W collimators for summer 2014 run

Z distance from target (mm)

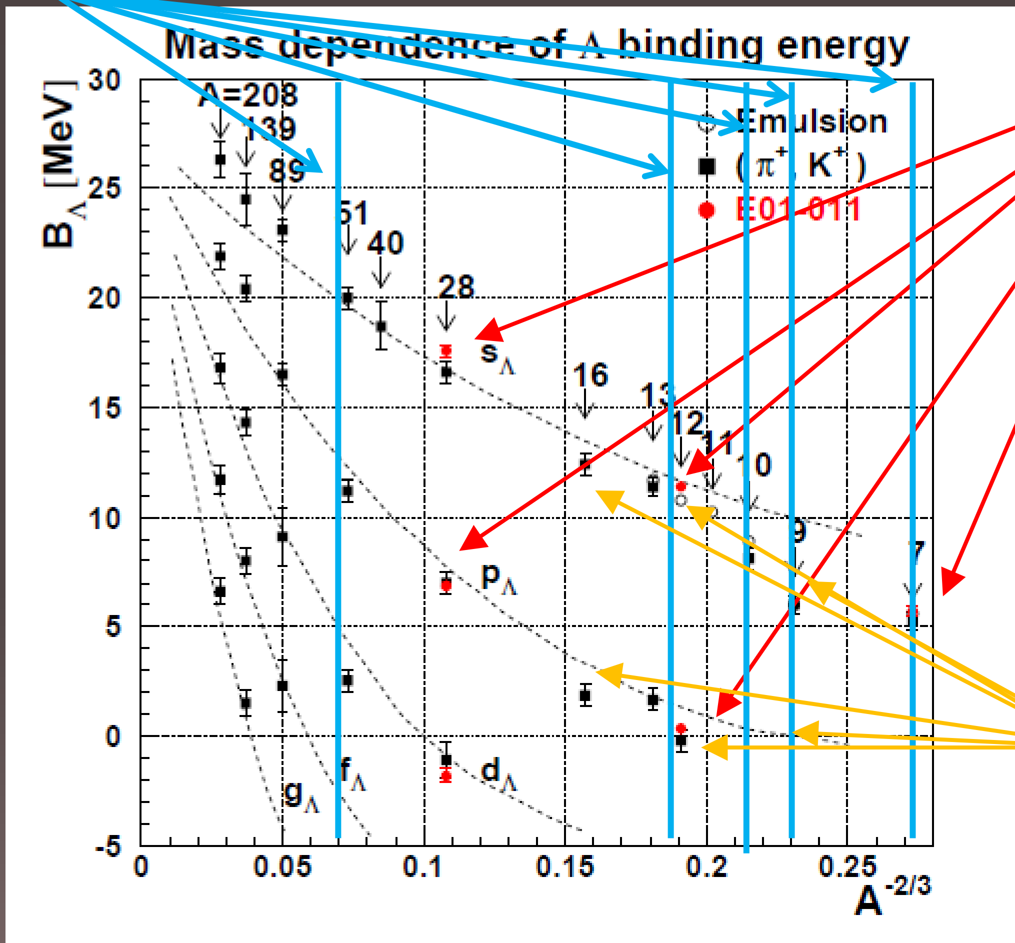
New Experiment at JLab

Beam 4.52 GeV
HKS 1.20 GeV/c
HRS 3.03 GeV (7 deg)
Eγ ~ 1.5 GeV
Q^2 ~ 0.22 $(GeV/c)^2$



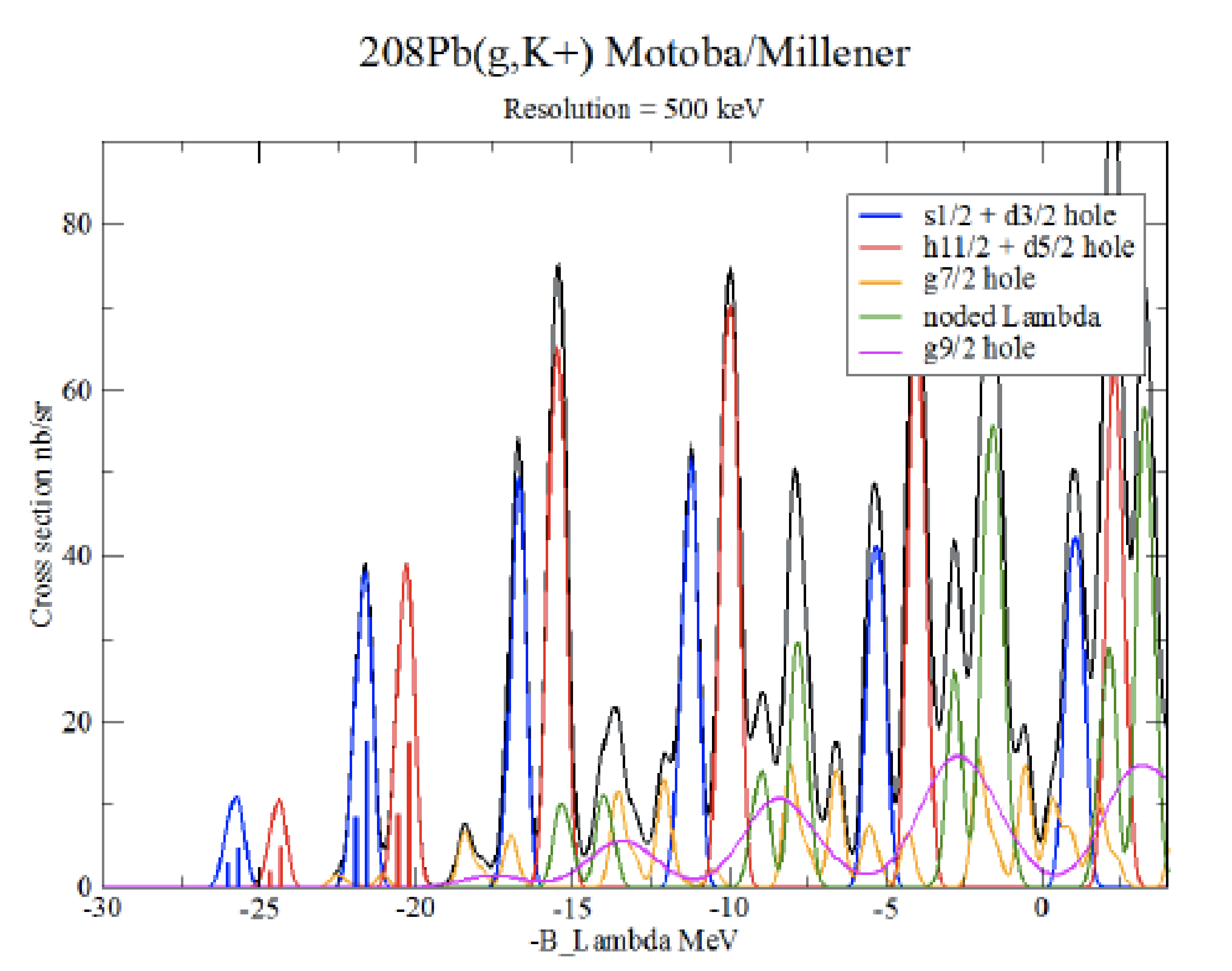
Λ single particle energies

E05-115 (HKS-HES) E01-011(HKS)

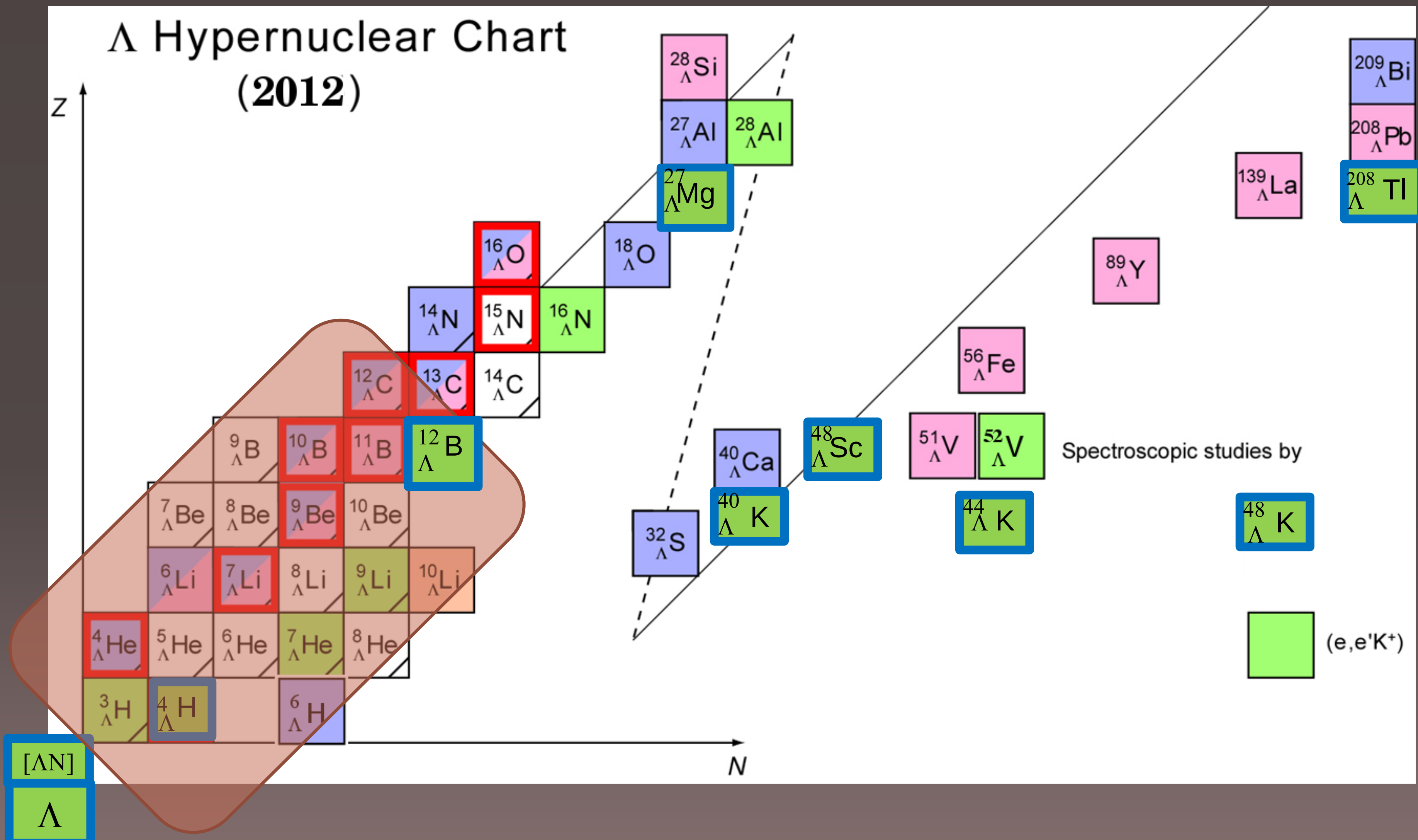


E94-107 (Hall A HY)

^{208}Pb target



Hypernuclear Chart



Summary

- We have been developing large magnetic spectrometers (HKS, HES) and techniques in the last decade at JLab and

  (e,e'K) HY spectroscopy **is** ***now established***.
- Λ electro-production cross section was measure at very small Q^2.
- Binding energy of $^{7}_{\Lambda}He_{gs}$ was determined. Important input for ΛN CSB potential. Data with more statistics and new data $^{10}_{\Lambda}Be_{gs}$ are now analyzed.
- At MAMI-C, decay pion spectroscopy of electro-produced hypernuclei is now on going.

Hypernuclear study with electrons (JLab, Mainz) and with mesons (J-PARC) should progress complimentary in timely manner.