The Second Generation Hypernuclear Spectroscopy at JLab Hall C (E01-011 experiment)

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for the E01-011 collaboration

PANIC08
Eilat, ISRAEL
11 Nov. 2008

Motivation

➢ Investigate the fine structure of various Λ hypernuclei by the $(e,e'K^+)$ reaction

- $^{12}C(e,e'K^+)^{12}{}_{\Lambda}B$
  - Fine structure of p-shell hypernucleus
  - Mirror-symmetric hypernucleus (vs. $^{12}{}_{\Lambda}C$ @ (π^+,K^+))
- $^{7}Li(e,e'K^+)^{7}{}_{\Lambda}He$
  - Neutron rich hypernucleus
  - ΛN-ΣN coupling
- $^{28}Si(e,e'K^+)^{28}{}_{\Lambda}Al$
  - Single-particle potential
  - First challenge to study beyond the p-shell region

→ New information on ΛN interaction

Second generation hypernuclear spectroscopy @ JLab Hall C (E01-011)

Upgrade of first generation experiment @JLab (E89-009, 2000)

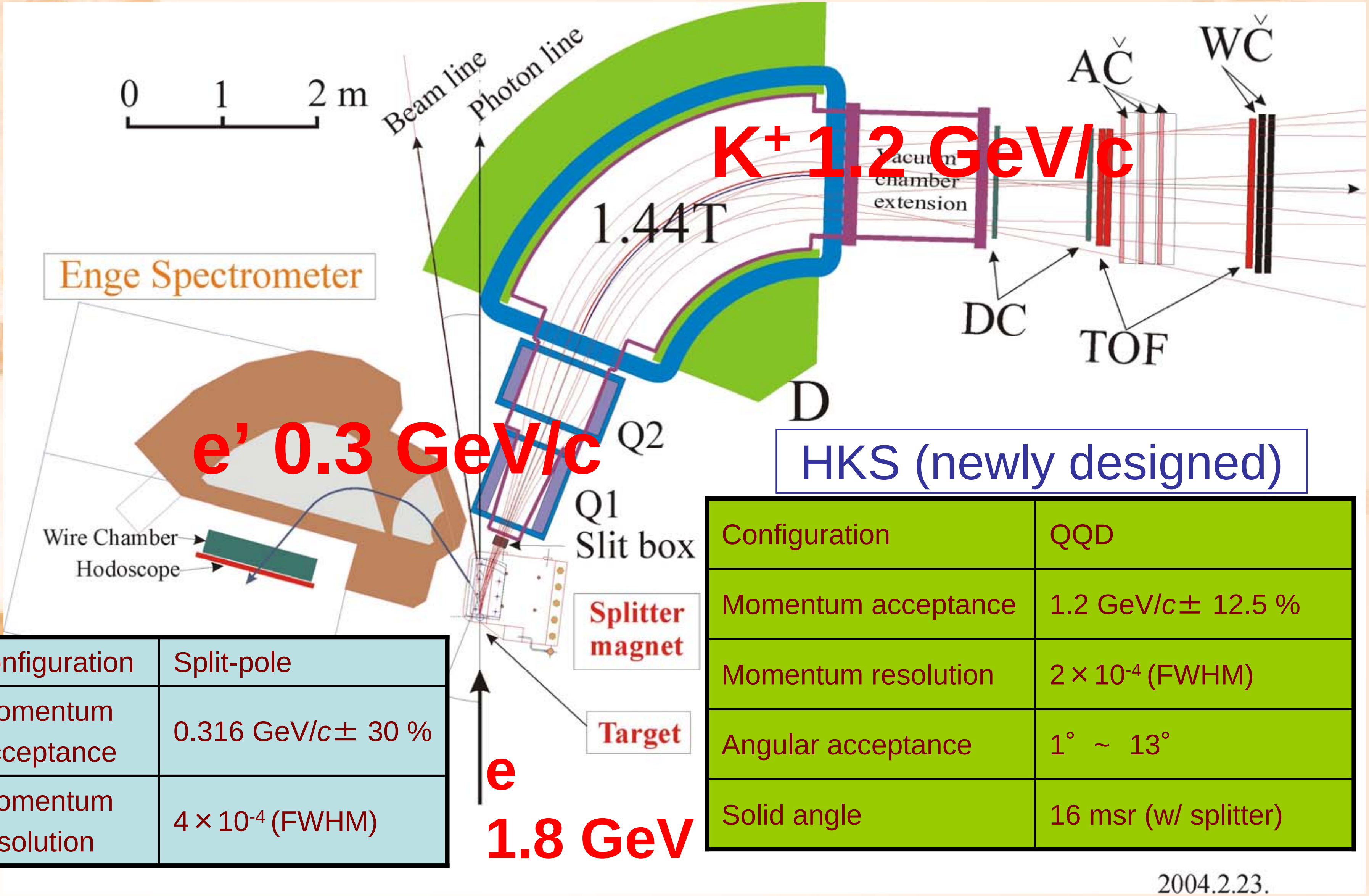
- High-resolution Kaon Spectrometer（HKS）
  - Specialized for hypernuclear spectroscopy
    - Large acceptance
    - Short orbit

➔ < 0.5 **MeV energy resolution w/ high quality primary electron beam from CEBAF@JLab**

- 「Tilt method」 for scattered electron
  - Optimization of detection angle of e’
    - Suppress a huge background from Bremsstraglung and Møller scattering
  - e’ spectrometer vertically tilted by 8 degree

➔**Higher Luminosity w/ better S/N ratio**

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)

Scheme of Data analysis

Particle ID

Select K^+
Time Of Flight, Cherenkov

↓

True coincidence

Select true coincidence event
Coincidence time

↓

Optical matrices

Tune Angular and momentum matrices
Sieve slit run (angle)
Λ,Σ, and $^{12}_{\Lambda}$B g.s. (momentum)

↓

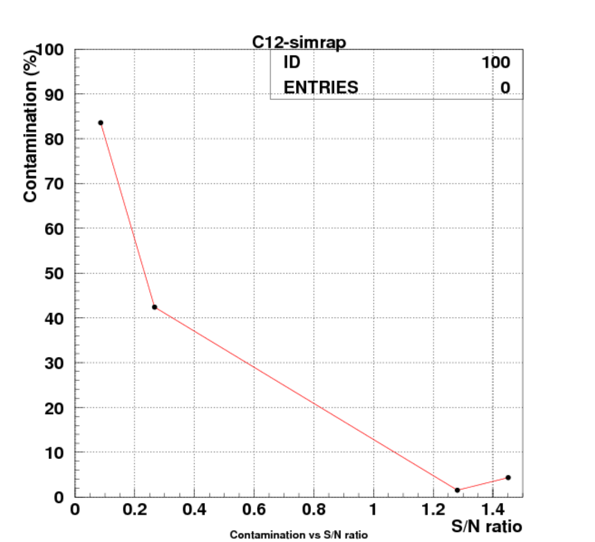
Missing mass

Estimation of systematic errors depend on the tuning procedure

- Blind analysis with simulation data
  - CH_2 data : well-known mass
  - ^{12}C data : binding energies and cross sections were arbitrarily changed and hidden from analyzers
  - Reasonable S/N and statistics
  - Full simulation by GEANT
    - TOSCA field map
    - two-arm coincidence
    - Detector resolution
    - Raster effect
    - Sieve slit data for angle tuning

Blind analysis result

Blind analysis result			Assumed in simulation		
Binding energy [MeV]	Yield [counts]	Contamination [%]	Binding energy [MeV]	Yield [counts]	S/N
11.43 (g.s.)	~491	4.4	11.37 (g.s.)	600	1.45
16.70	~191	83.6	16.31	30	0.09
20.35	~142	42.4	20.31	100	0.27
23.32	~407	1.5	23.37	550	1.28



Systematic error ….
for major peak (S/N > 1),

Accuracy of binding energy ~ 100 keV
cross section ~ 5%

for core excited states(S/N <1),

Accuracy of binding energy ~ 400 keV
cross section ~ 90 %

Efficiencies for cross section estimation

Cross section of the (γ^*, K^+):

$$\overline{\left(\frac{d\sigma}{d\Omega}\right)} = \frac{1}{N_T}\frac{1}{N_\gamma}\sum_{i=1}^{N_K}\frac{1}{\varepsilon_{total}\, d\Omega}$$

N_T : # of target

N_γ: # of V.P.

$d\Omega$: solid angle acceptance of HKS

N_K : yield of Λ, Σ^0, or hypernuclear state

$$\varepsilon_{total} = \varepsilon_{htrk}\cdot\varepsilon_{AC}\cdot\varepsilon_{WC}\cdot\varepsilon_{bk}$$
$$\cdot f_{abs}\cdot f_{decay}\cdot\varepsilon_{etrk}\cdot f_{comp}$$

ε_htrk: ~ 0.96
 HKS tracking efficiency

ε_AC: ~0.96
 AC cut efficiency

ε_WC: ~0.95
 WC cut efficiency

ε_bk: ~0.98
 beta cut efficiency

ε_etrk: ~0.88
 ENGE tracking efficiency

f abs: ~0.82
 Kaon absorption factor

f decay: ~0.35
 Kaon decay factor

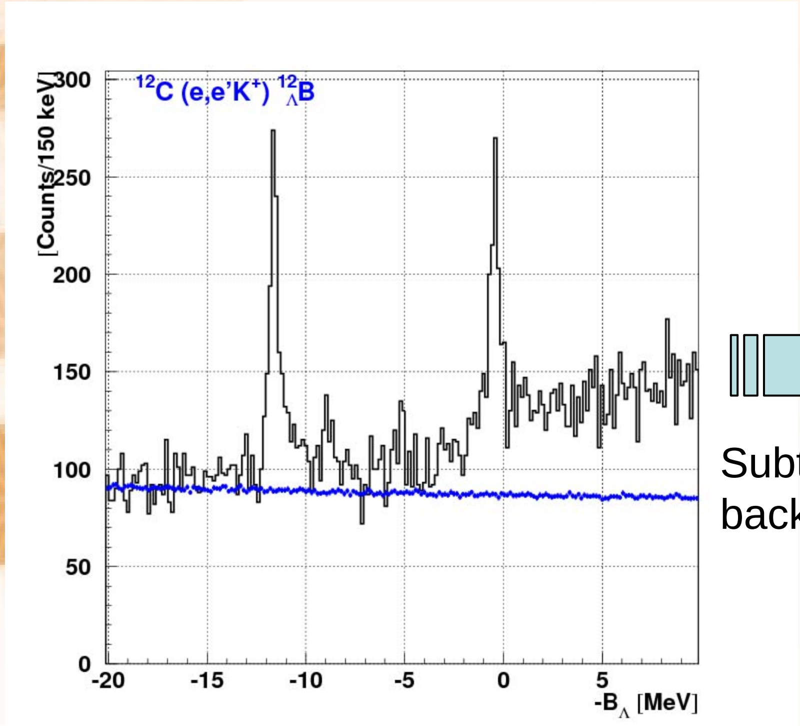
f comp: ~0.97
 Computer dead time factor

Systematic error [%]

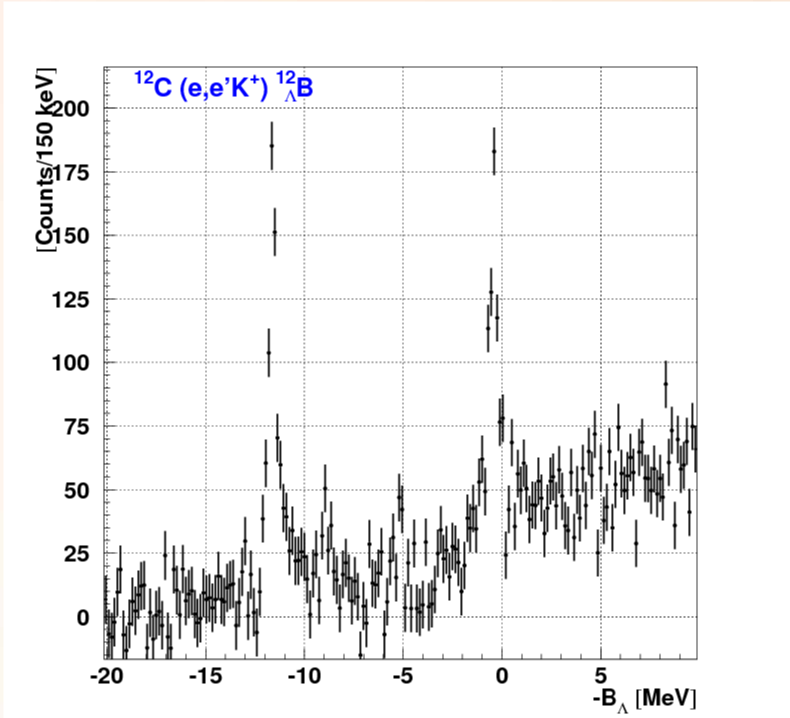
Target	Thickness	N_γ	$d\Omega$	ε_{total}	*Tune (S/N>1)*		Total
7Li	5	**22**	1	3	5		23
12C	2						22
28Si	5						23

Background estimation by mixed event analysis

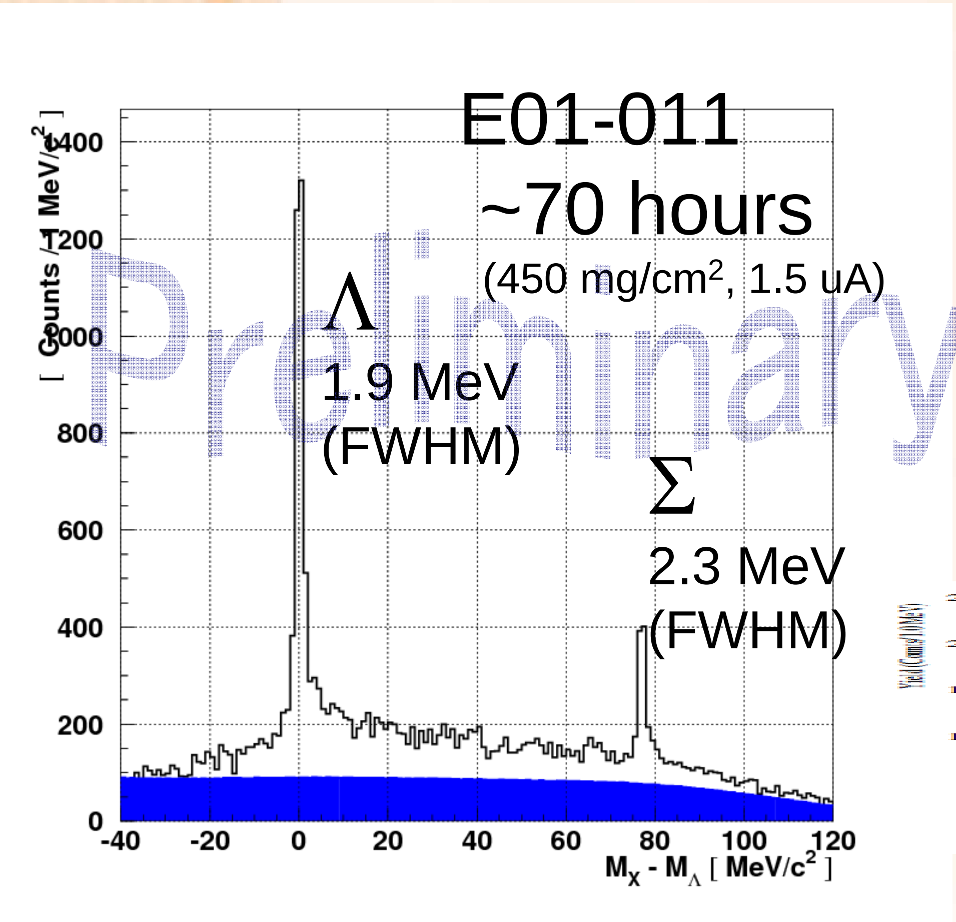
- Background : accidental coincidence between e' and K^+
- Mixed background → random combination of real data (off gate)



Subtract background



Λ and Σ spectra (CH2)

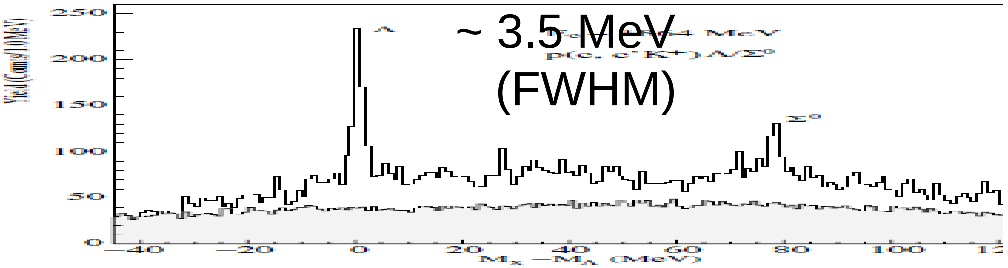


c.f. E89-009, 183 hours

(8.8 mg/cm^2, 0.5 or 1.0 uA)

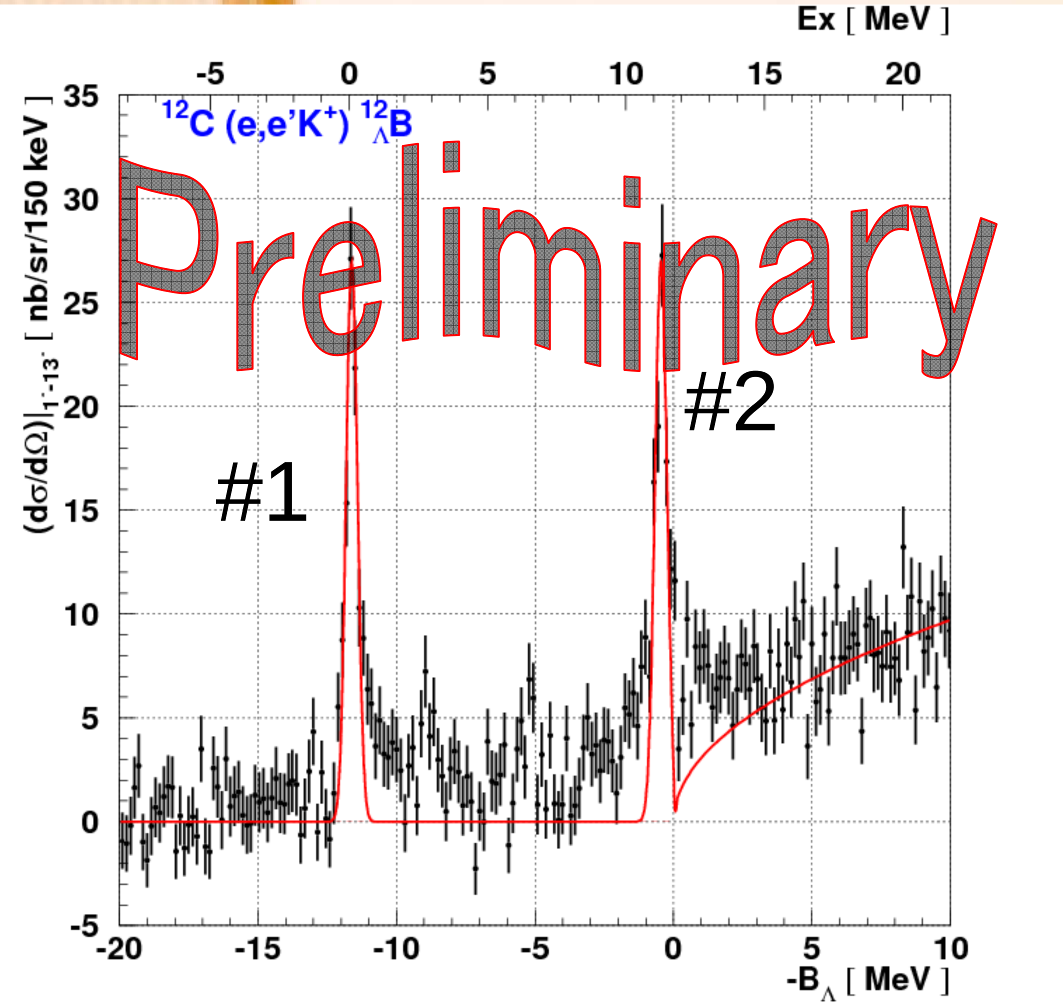
T. Miyoshi *et al*.,

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

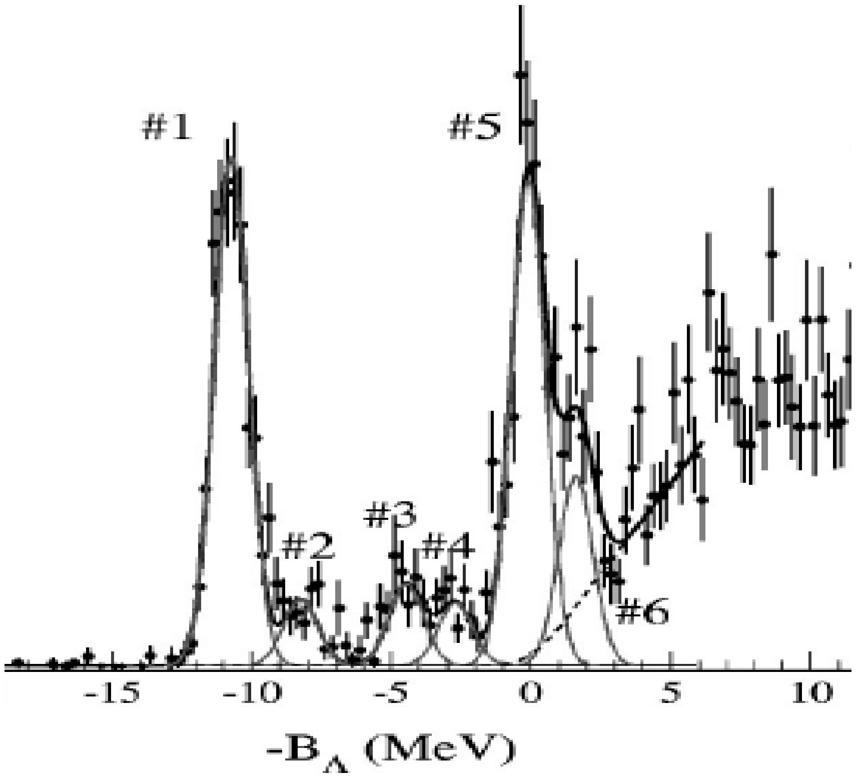


Better resolution and statistics

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



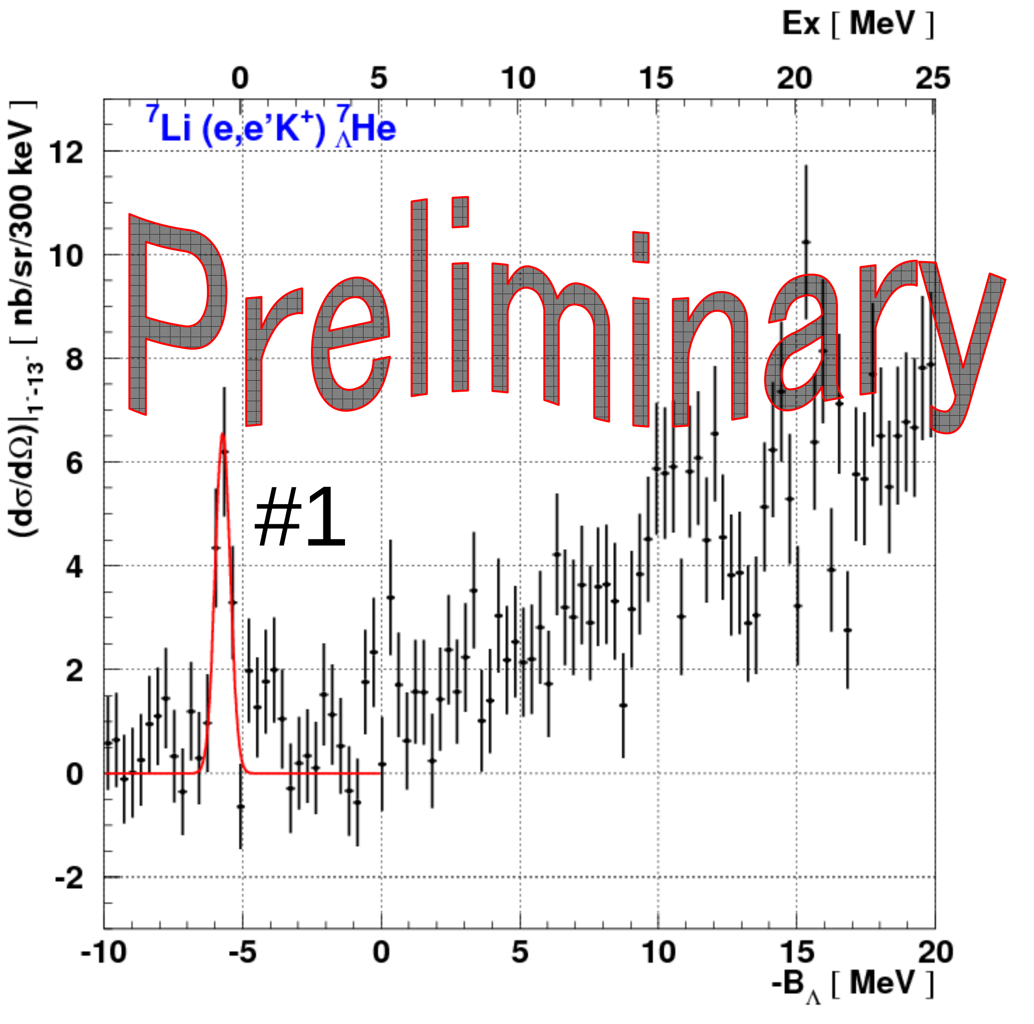
Mirror-symmetric $^{12}{}_{\Lambda}C$ @ (π^+,K^+)
T. Hotchi et al.,
Phys. Rev. C 64(2001) 044302



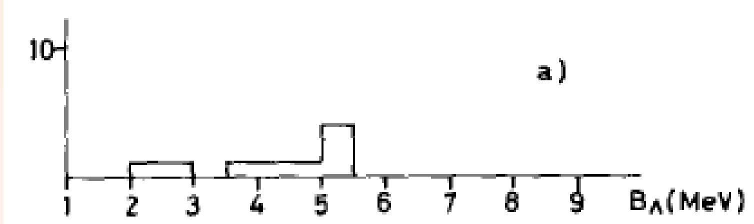
Data taking : ~90 hours w/ 30 μA
Ground State : δ ~ 470 keV (FWHM)

δ ~ 1450 keV (FWHM)

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



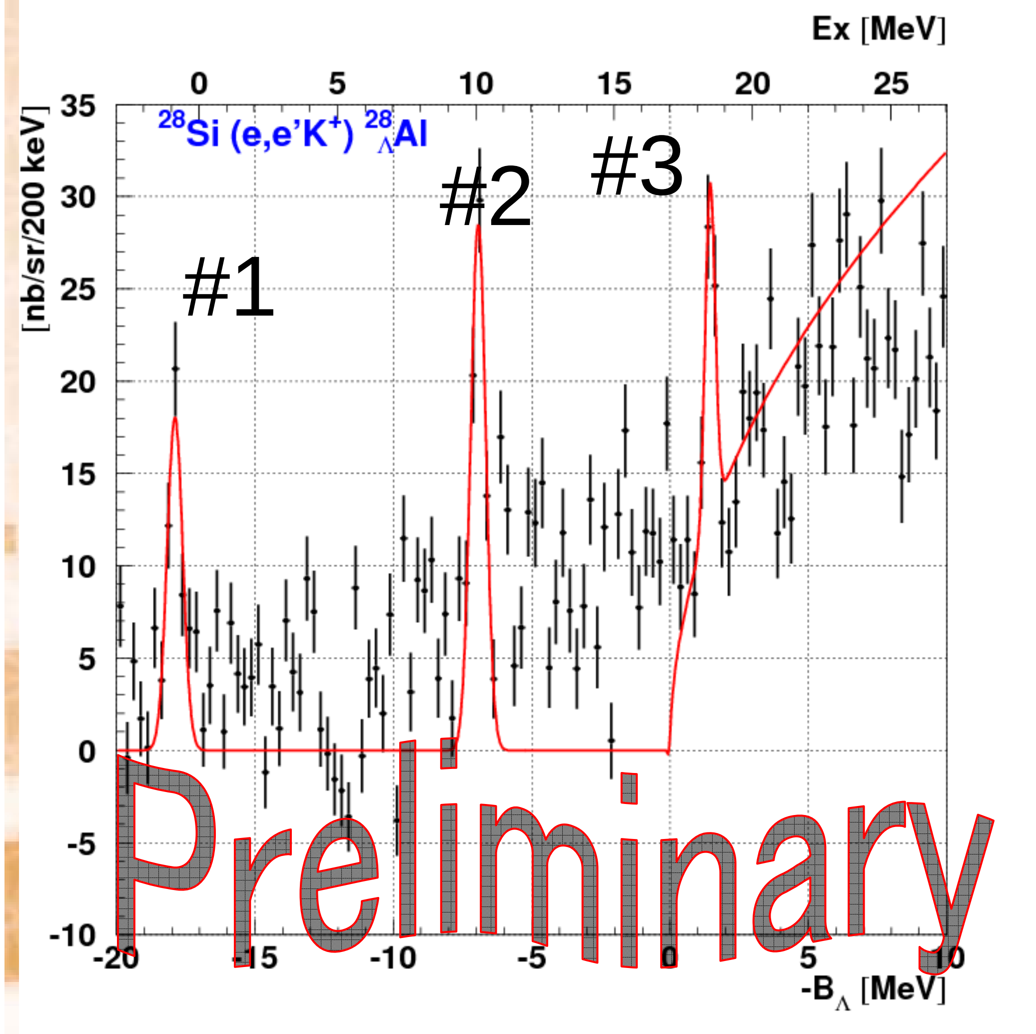
Emulsion data of $^{7}_{\Lambda}He$
M.Jurič et al.,
Nucl. Phs. B52(1973) 1



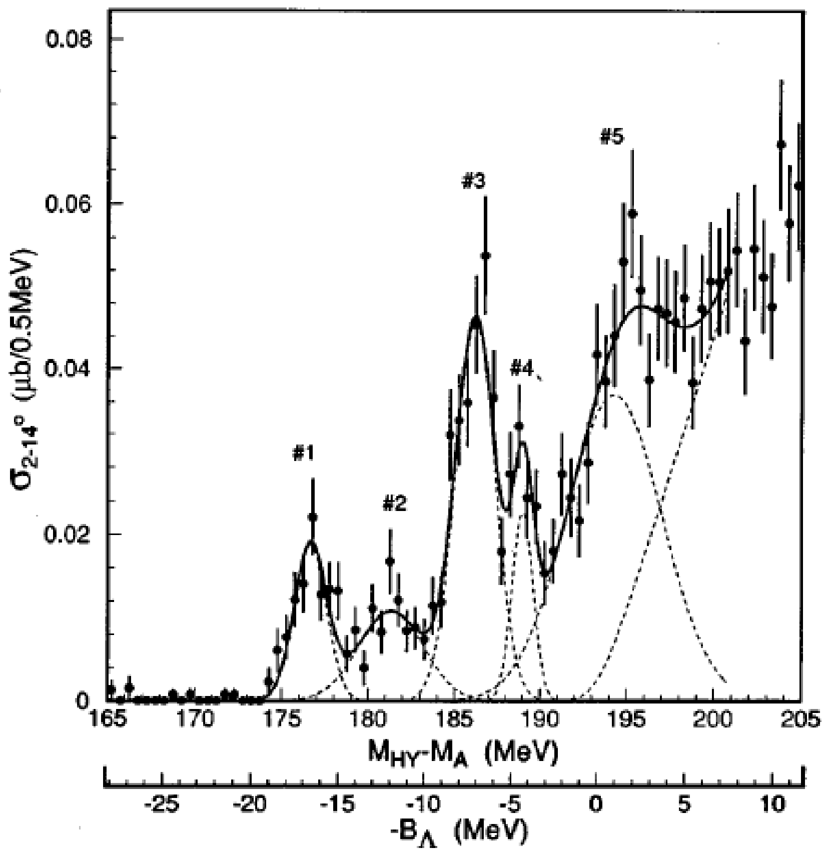
Data taking : ~30 hours w/ 30 μA

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

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



Mirror-symmetric $^{28}{}_{\Lambda}Si$ @ (π^+,K^+)
T. Hasegawa et al.,
Phys. Rev. C 53(1996) 1210



Data taking : ~140 hours w/ 30 μA
Ground State : δ ~ 470 keV (FWHM)

Ground state : δ ~ 2200 keV (FWHM)

Summary

- The second generation Λ hypernuclear spectroscopy by $(e,e'K^+)$ reaction has been carried out successfully at JLab in 2005
- New configurations, **HKS** and **Tilt method**, significantly improved both energy resolution and statistics
- Systematic error depend on tuning procedure was estimated by the blind analysis
- Analysis is in the final stage

- Third generation experiment (JLab E05-115) will be performed in the summer of 2009 w/ new e' spectrometer (**HES**)

To be done

- Further tuning of the spectrometer optics
- More detailed estimation of systematic error by blind analysis

E01-011 Collaboration

- **Tohoku Univ.**
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- **Hampton Univ.**
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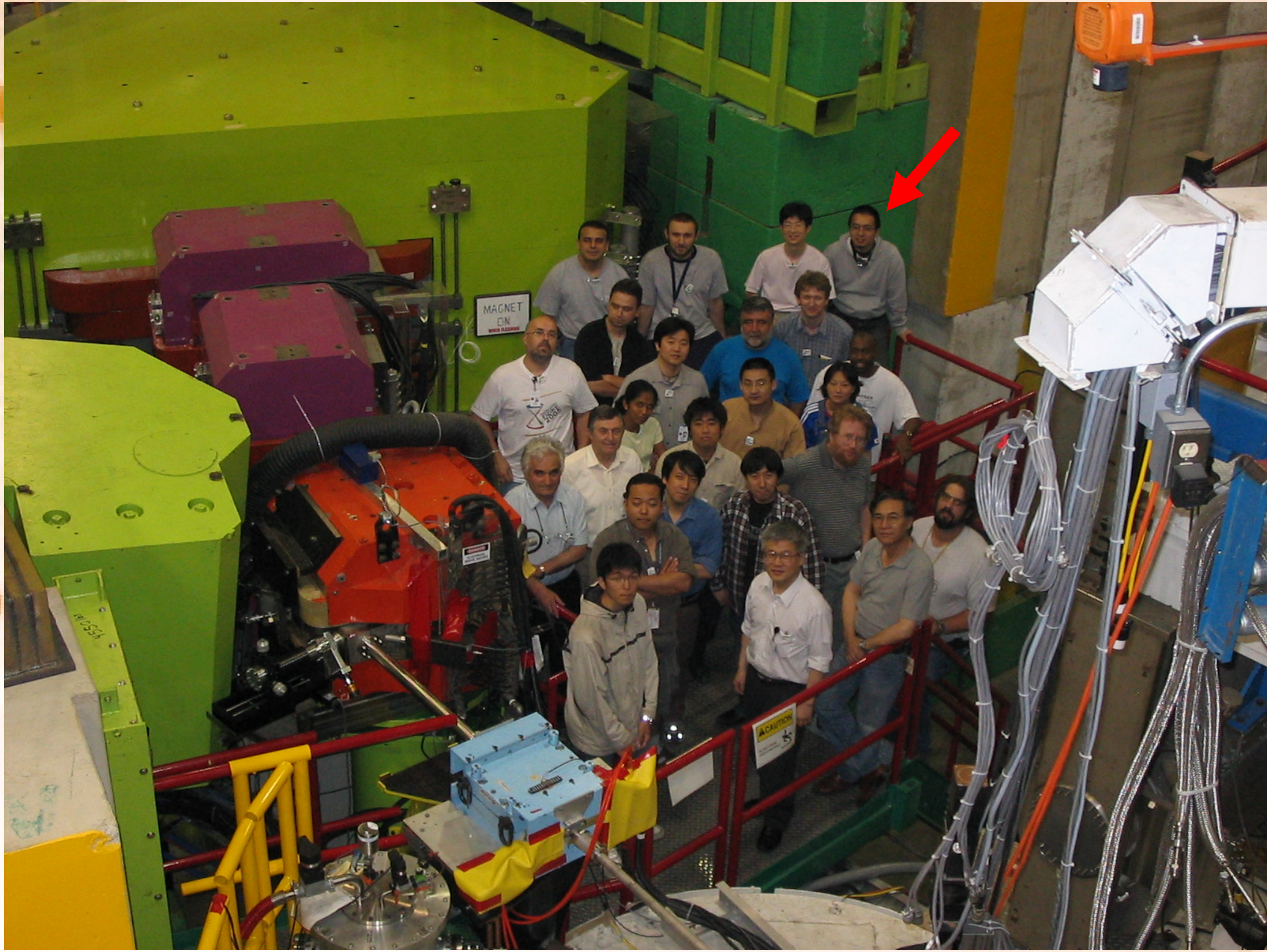
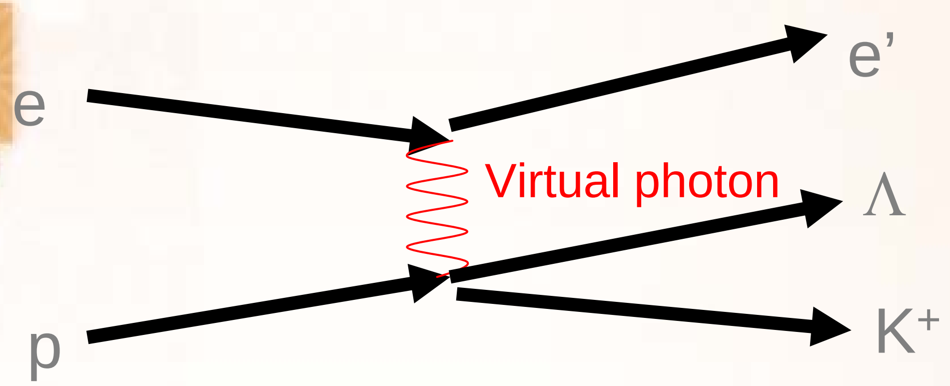
- **Yerevan Physics Institute, Lanzhou Univ., Univ. of Zagreb, North Carolina A&T State Univ., Louisiana Tech Univ., James Madison Univ., Univ. of North Carolina at Wilmington, Duke Univ., Univ. of Maryland, Southern Univ. at New Orleans, California State Univ.**


MAGNET
ON
CAUTION

Λ hypernuclear spectroscopy by the (e,e'K$^+$) reaction

- Large momentum transfer
  → various deeply bound states
- Electromagnetic interaction
  → excite both spin-flip and spin-non-flip state
- Convert proton into Λ
  → neutron rich hypernuclei, mirror hypernuclei
- Primary electron beam
  (smaller emittance than secondary meson beam)
  → better resolution



Experimental difficulty

- Huge electron background
- Smaller cross section

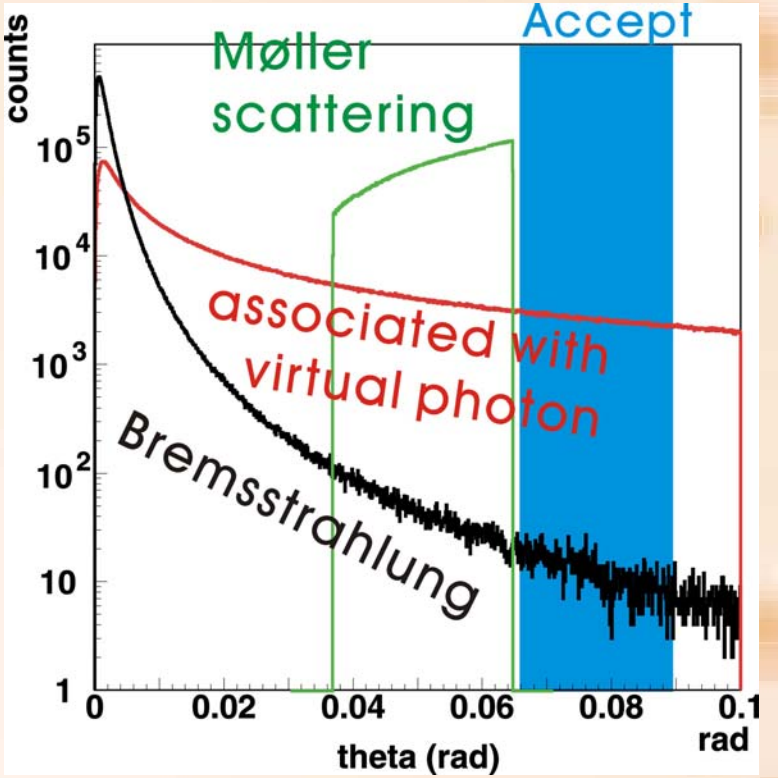
Tilt method

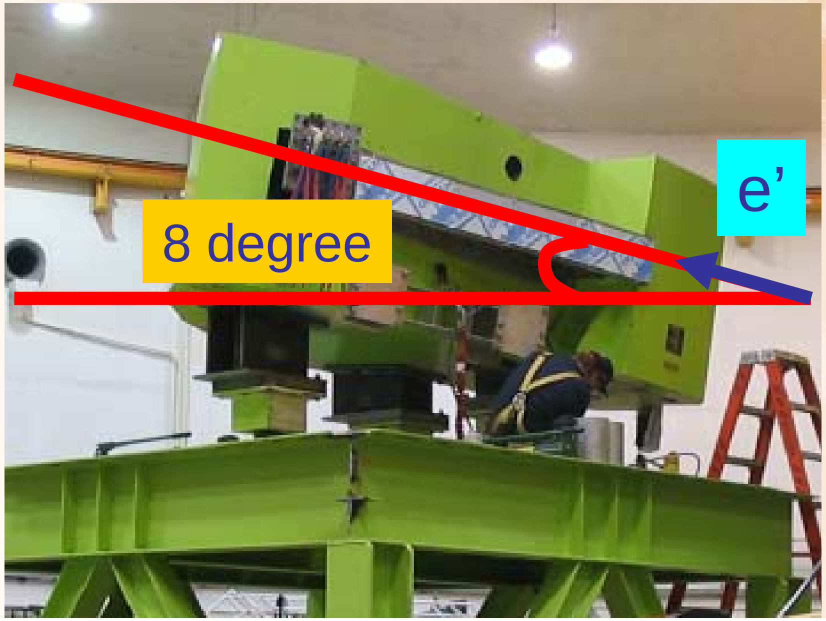
Background electrons

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

to avoid them

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





Trigger singles rate

Trigger rate

Target	Beam current [uA]	HKS single [kHz]	Enge single [kHz]	Coin. [kHz]
$^{12}C(100mg/cm^2)$	30	14.8	1300	0.74
$^{28}Si(65mg/cm^2)$	18	15.3	1600	0.91

c.f. E89-009 : ^{12}C 22mg/cm^2, 0.66uA => 200000 kHz (Enge single)

Luminosity : 200 times higher
Enge singles rate :**100 times lower**

Tilt method worked well

Kinematics comparison

item	E89-009 (Hall C,2000)	E01-011 (Hall C,2005)	E94-107 (Hall A,2004)
Beam energy [GeV]	1.8	1.8	4.0
Virtual photon energy [GeV]	1.5	1.5	2.2
e' momentum acceptance [GeV/c]	0.3±30%	0.3±30%	1.8 ± 5 %
e' detection angle [degree]	0	4.5	6
e' acceptance [msr]	1.6	~2	4.5
K^+ momentum acceptance [GeV/c]	1.2 ±20 %	1.2 ±12.5 %	1.96 ±5 %
K^+ detection angle [degree]	0	7	6
K^+ acceptance [msr]	4	16	4.5
K^+ survival probability [%]	37	33	18

Kinematical condition 1

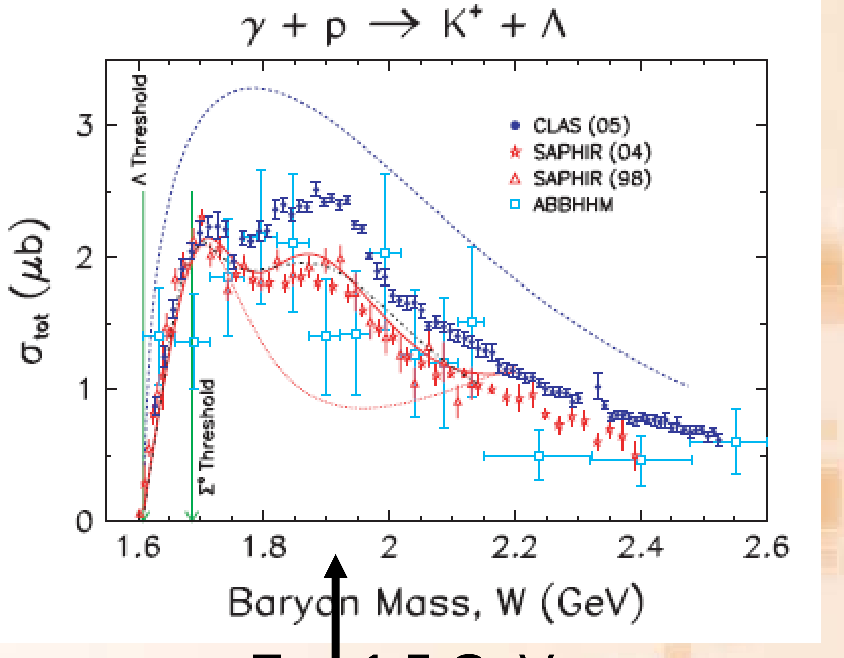
$$\begin{cases} E_{HY} = E_e + M_{tar} - E_{e'} - E_{K+} \\ P_{HY} = P_e - P_{e'} - P_{K+} \end{cases}$$

$E_\gamma = E_e - E_{e'} \sim 1.5$ GeV
Large cross section
$E_{e'} = 0.3$ GeV
ENGE Spectrometer

⇩

$E_e = 1.8$ GeV
$E_{K+} = 1.2$ GeV

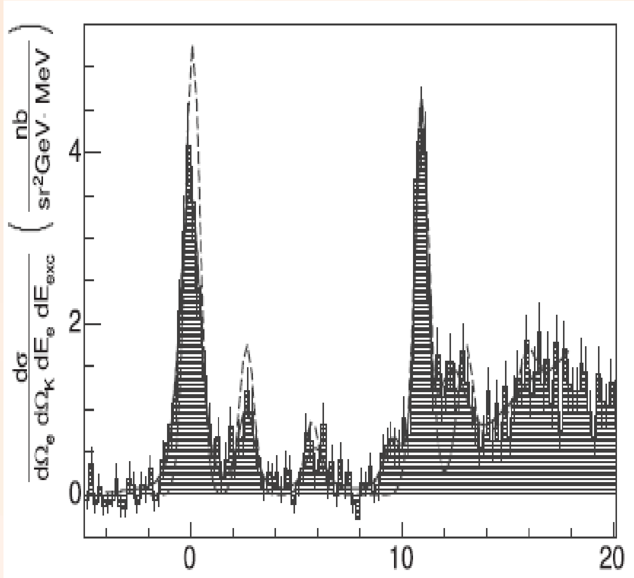
R. Bradford *et al.*,
Phy. Rev. C. **73**, 035202(2006)



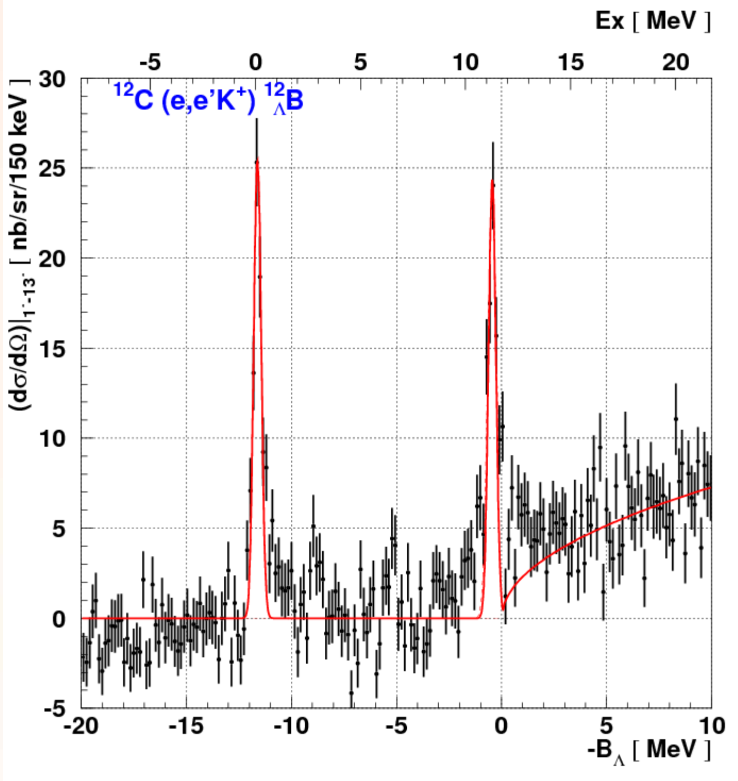
$E_\gamma \sim 1.5$ GeV

Reaction	Threshold(MeV)
$\gamma p \rightarrow K\Lambda$	**911**
$K\Sigma$	**1046**
$K\Lambda(1405)$	1452
$K^*(892)\Lambda$	1679

Hall C & Hall A

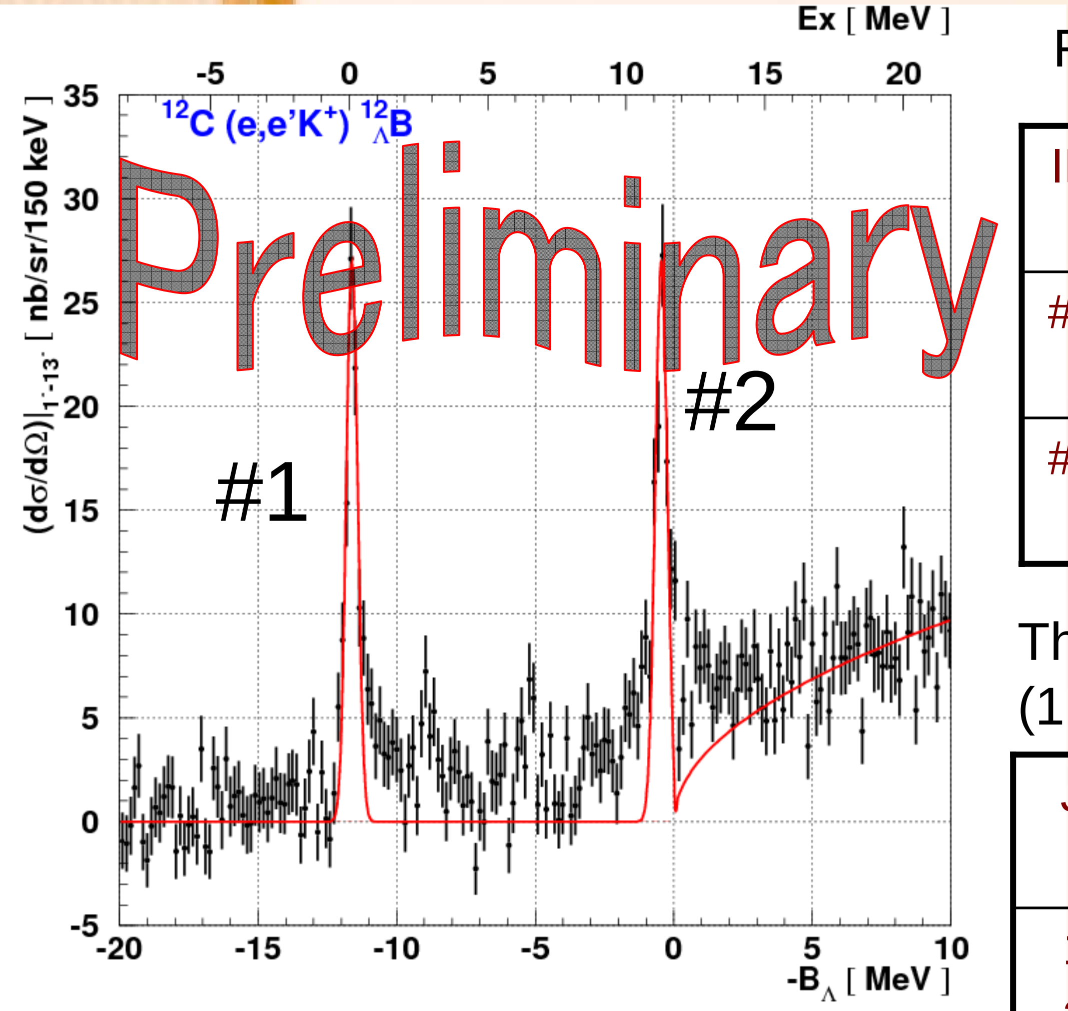


dσ / dΩe dΩK dEe dEexc (nb / sr²GeV· MeV)
0
2
4
0
10
20



Ex [MeV]
-5
0
5
10
15
20
¹²C (e,e'K⁺) ¹²ΛB
(dσ/dΩ)|1°-13° [nb/sr/150 keV]
30
25
20
15
10
5
0
-5
-20
-15
-10
-5
0
5
10
-BΛ [MeV]

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



Data taking : ~90 hours w/ 30 μA

Ground State ($1^-/2^-$) : δ~ 470 keV (FWHM)

Result

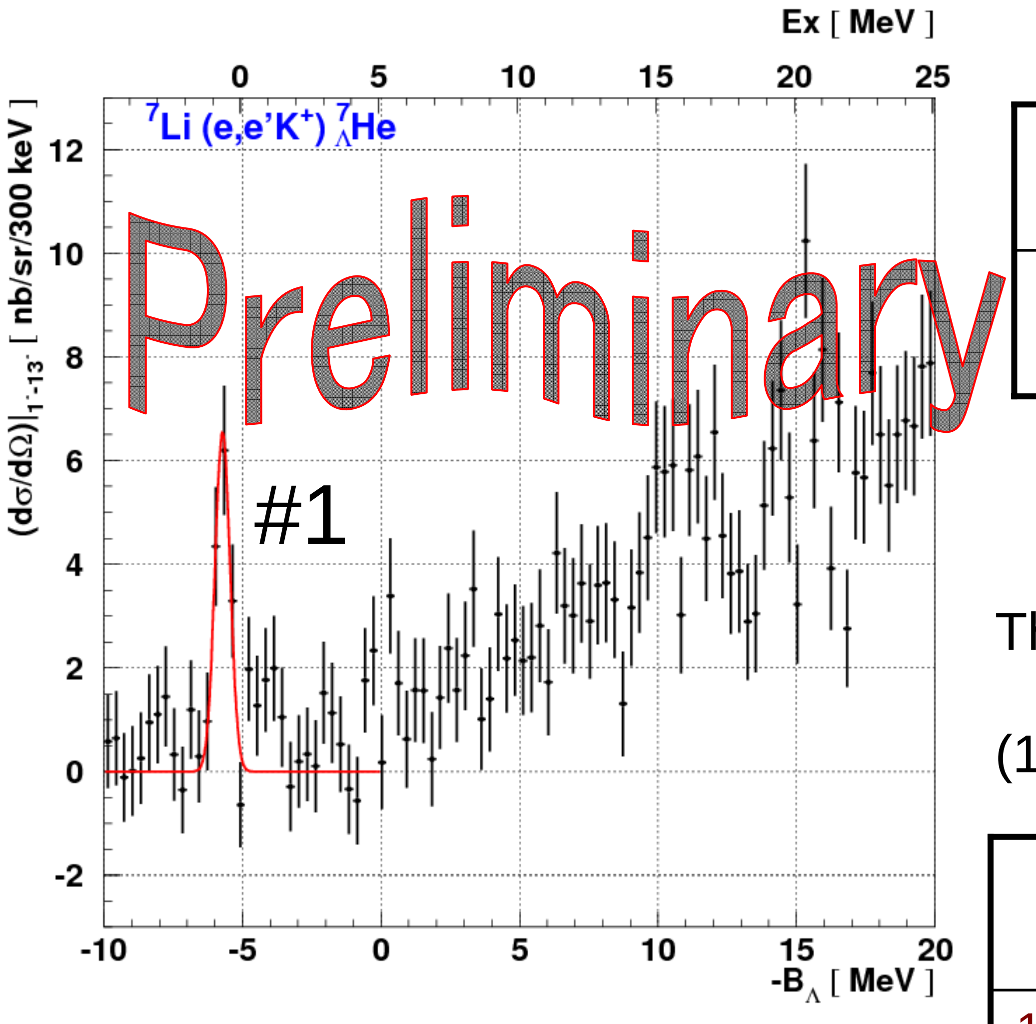
ID	Ex [MeV]	Cross section [nb/sr]
#1	0	89±7 (*stat.*) ±19 (*sys.*)
#2	11.2±0.1 (*stat.*) ±0.1 (*sys.*)	98±7 (*stat.*) ± 22 (*sys.*)

Theory by Sotona *et. al.*

($1.3 < E\gamma < 1.6$ GeV, $1 < \theta_K < 13$ deg.)

J^π	Ex [MeV]	Cross section [nb/sr]		
		SLA	C4	KMAID
1^-	0	19.7	22.8	20.7
2^-	0.14	65.7	82.0	43.0
2^+	10.99	48.3	56.9	38.0
3^+	11.06	75.3	107.3	68.5

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



Data taking : ~30 hours w/ 30 μA

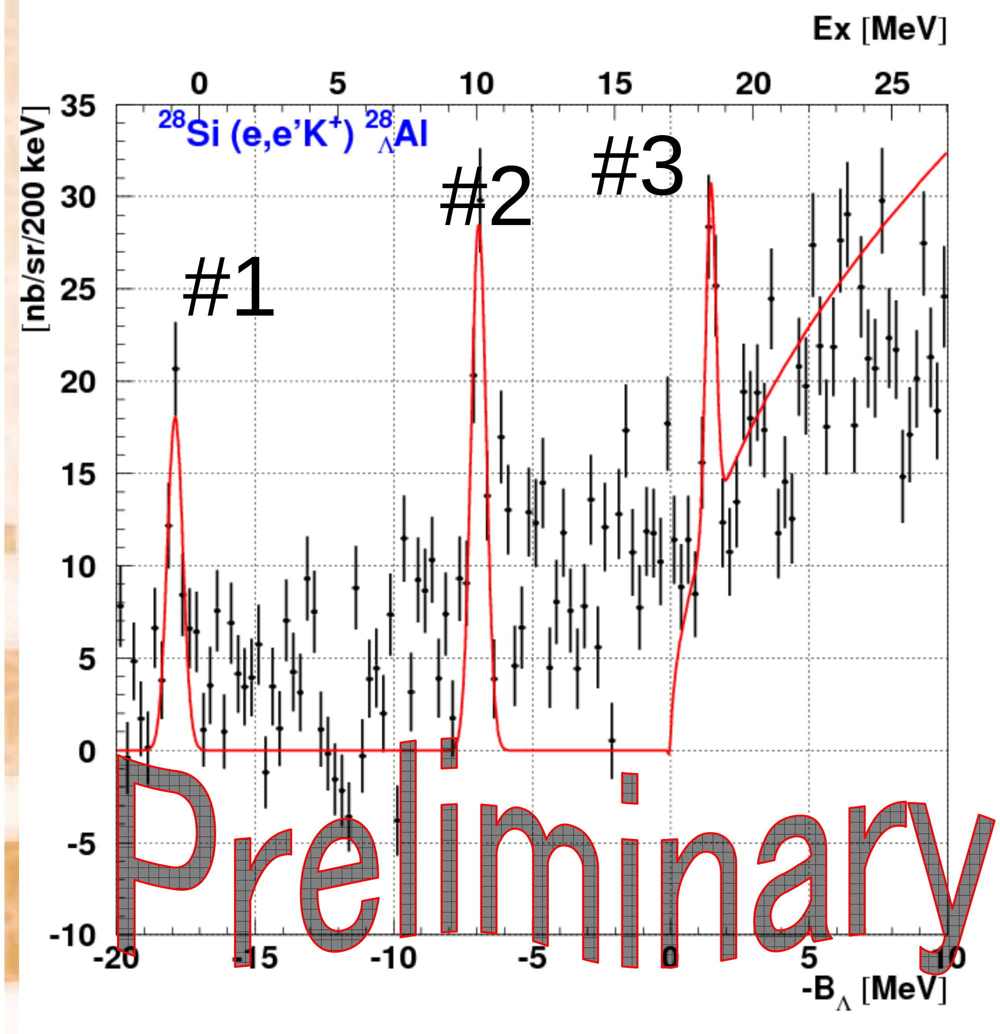
Result

ID	$-B_{\Lambda}$ [MeV]	Cross section [nb/sr]
#1	-5.7±0.2 (*stat.*) ±0.1 (*sys.*)	15±3 (*stat.*) ±3 (*sys.*)

Theory by Sotona *et. al.* (Cross section)
by Hiyama *et. al.* ($-B_{\Lambda}$)
($1.3 < E\gamma < 1.6$ GeV, $1 < \theta_K < 13$ deg.)

J^{π}	$-B_{\Lambda}$ [MeV]	Cross section [nb/sr]		
		SLA	C4	KMAID
$1/2^{+}$	-5.56	13.2	16.2	9.7

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



Data taking : ~140 hours w/ 30 μA

Result

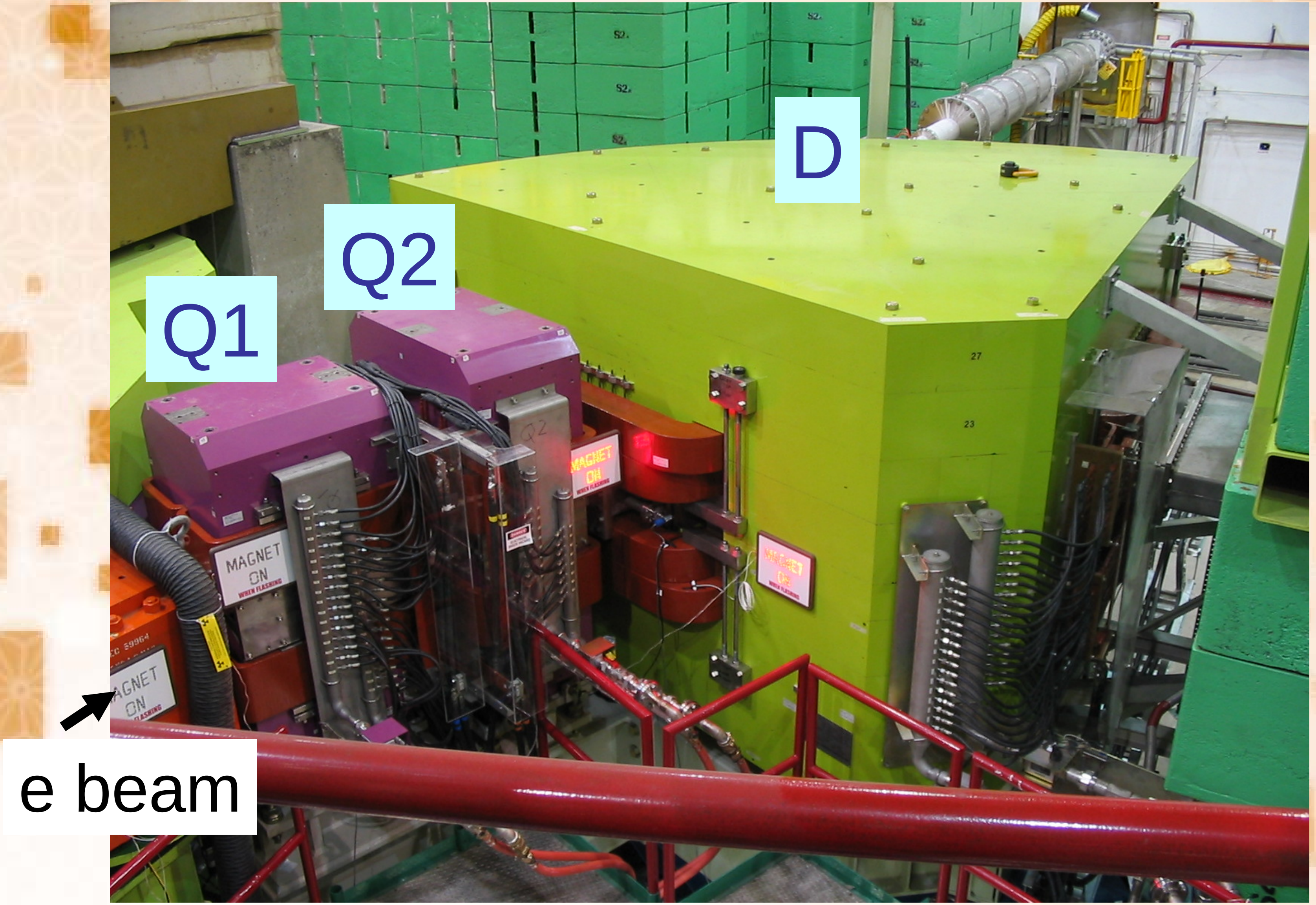
ID	Ex [MeV]	Cross section [nb/sr]
#1	0	51±10 (*stat.*) ±12 (*sys.*)
#2	11.0±0.1 (*stat.*) ±0.1 (*sys.*)	78±13 (*stat.*) ± 18 (*sys.*)
#3	19.3±0.1 (*stat.*) ±0.1 (*sys.*)	33±7 (*stat.*) ± 8 (*sys.*)

Preliminary

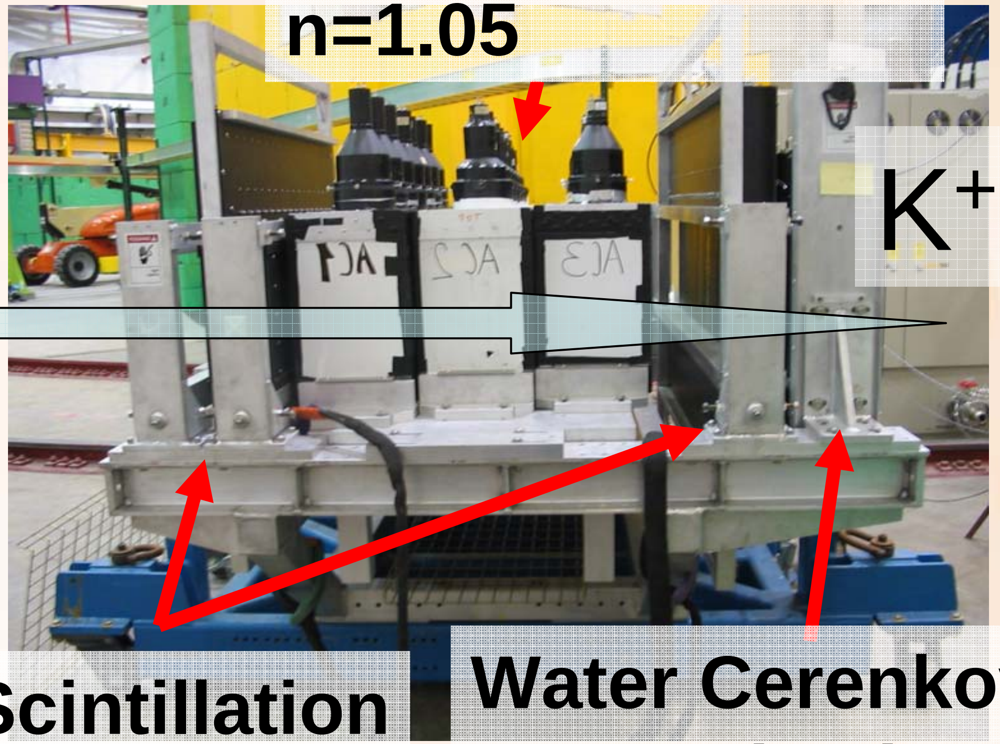
Theory by Sotona *et. al.*
(1.3 < Eγ < 1.6 GeV, 1 < θ_K < 13 deg.)

J^π	Ex [MeV]	Cross section [nb/sr]		
		SLA	C4	KMAID
$2^+,3^+$	0	92.1	112.7	71.76
4^-	9.42	134.9	167.7	117.5
3^-	9.67	91.3	109.1	58.5
4^+	17.6	148.4	184.7	135.1
5^+	17.9	139.1	167.1	89.9

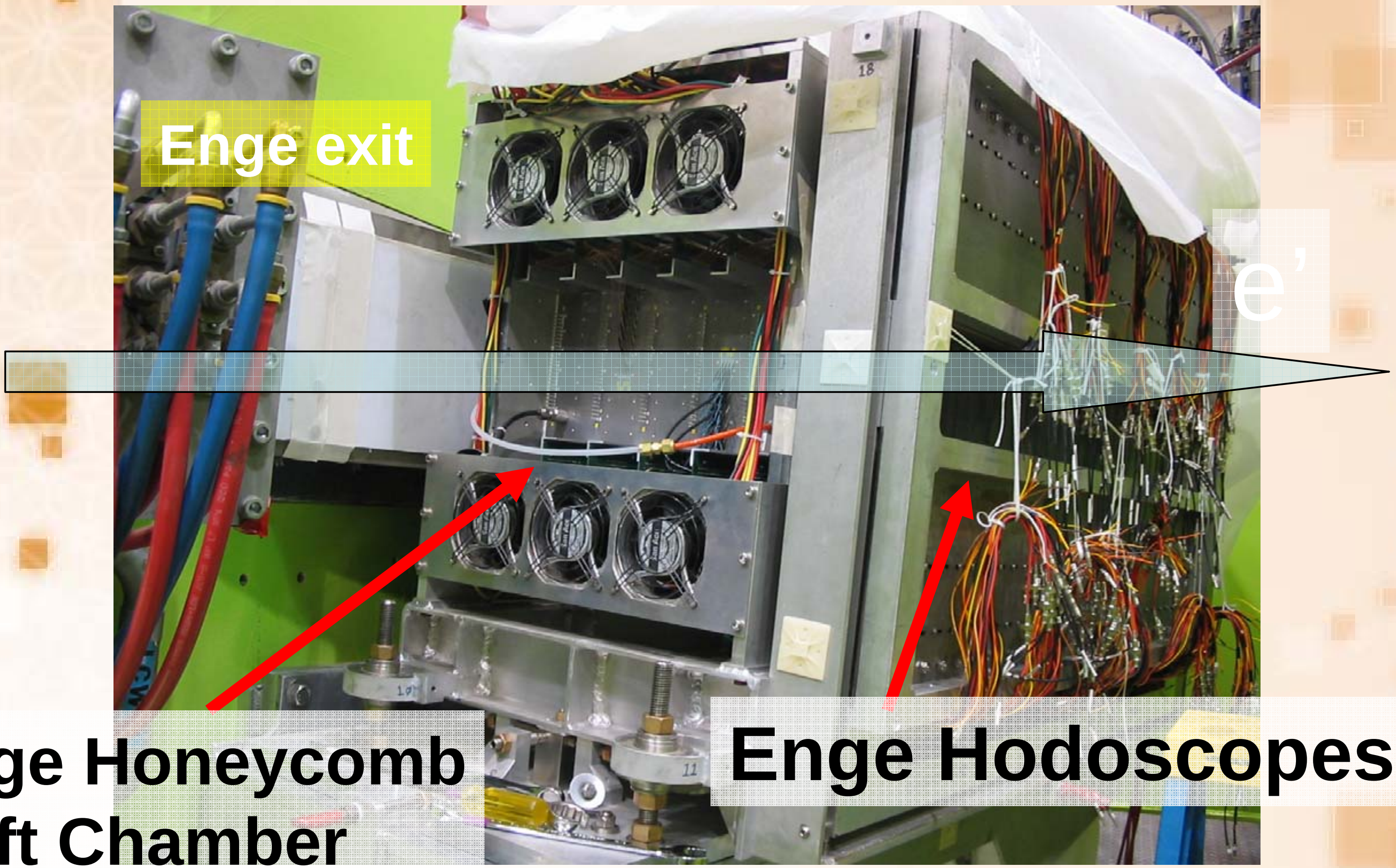
HKS spectrometer



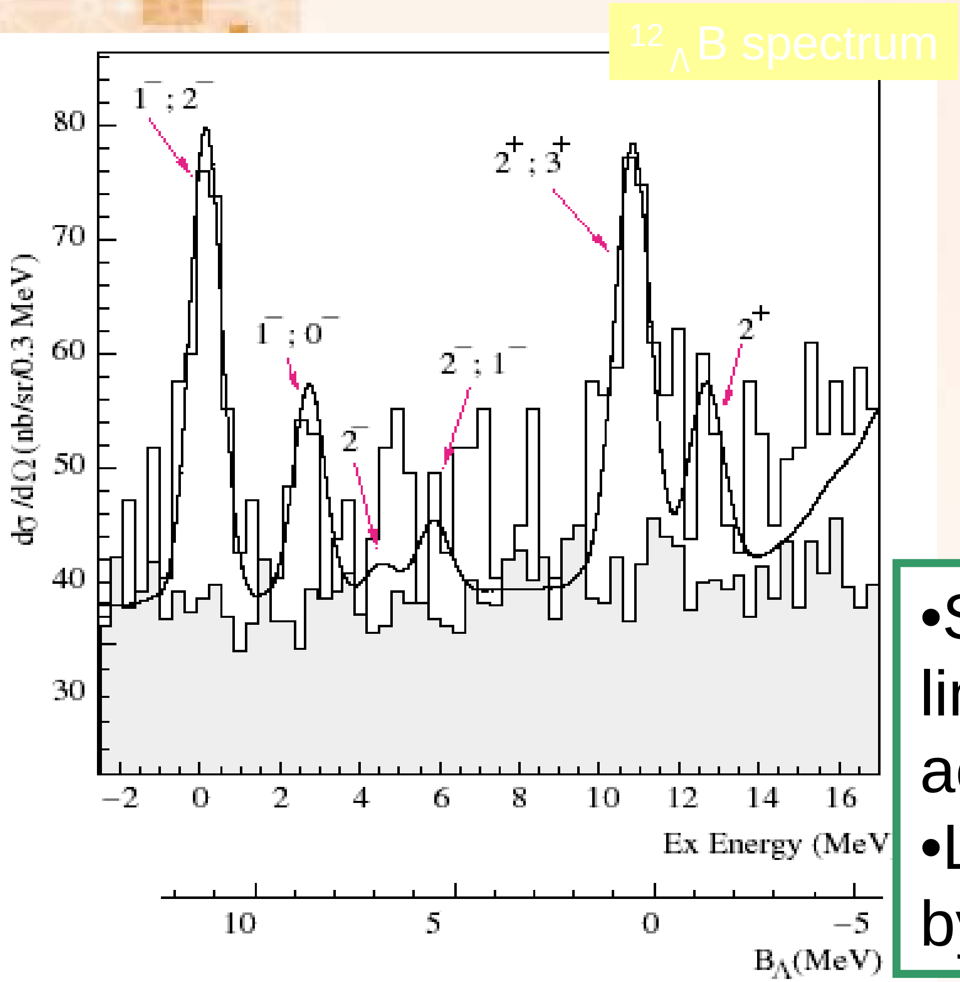
HKS detectors



Enge detectors



First (e,e'K$^+$) hypernuclear spectroscopy JLAB E89-009(2000)



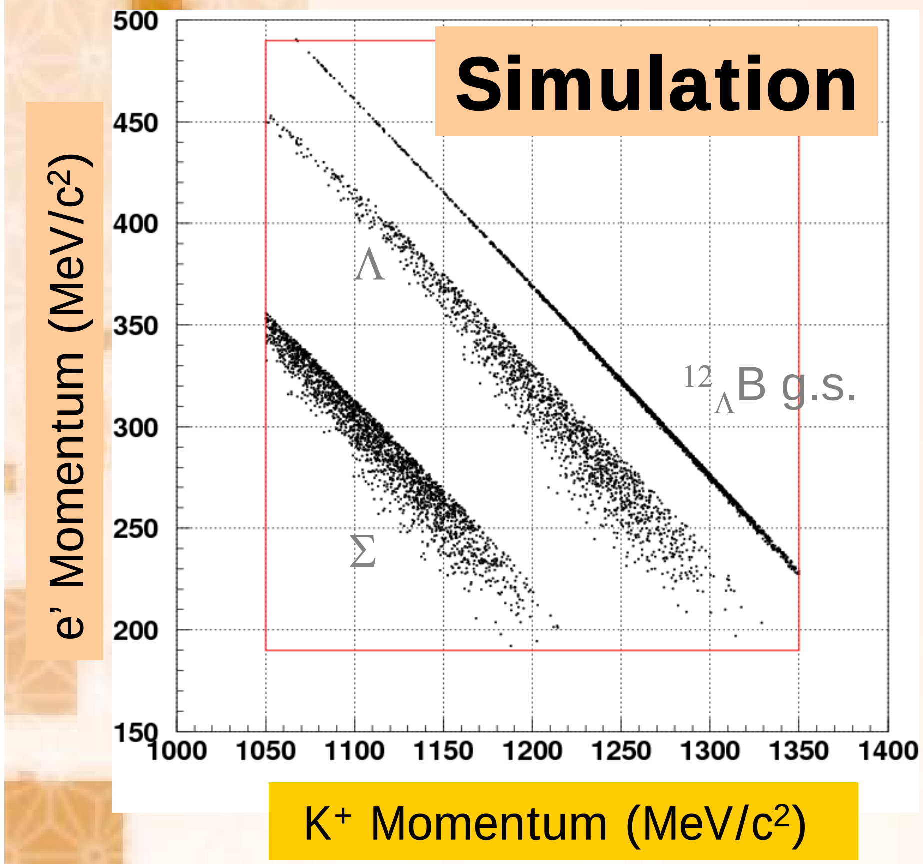
T. Miyoshi *et al*., Phy. Rev. Lett. **90**, 232502(2003)

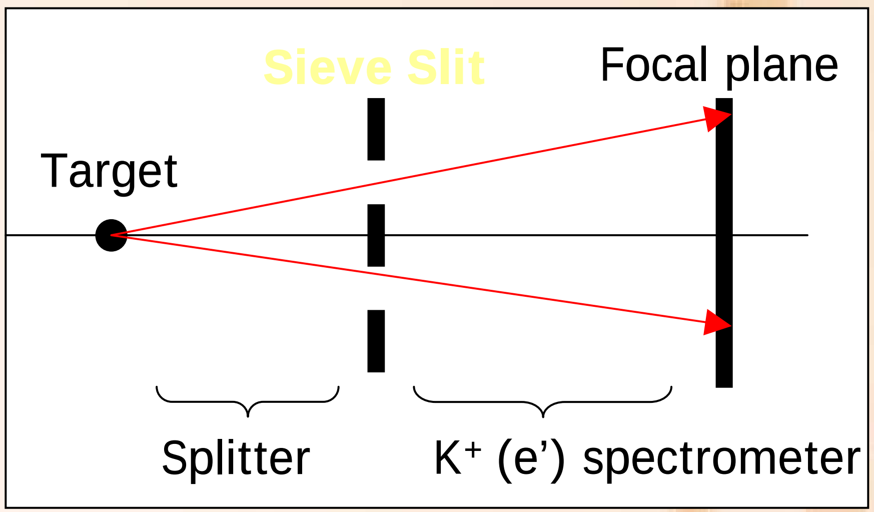
- detected e' by ENGE and K$^+$ by SOS at forward angle

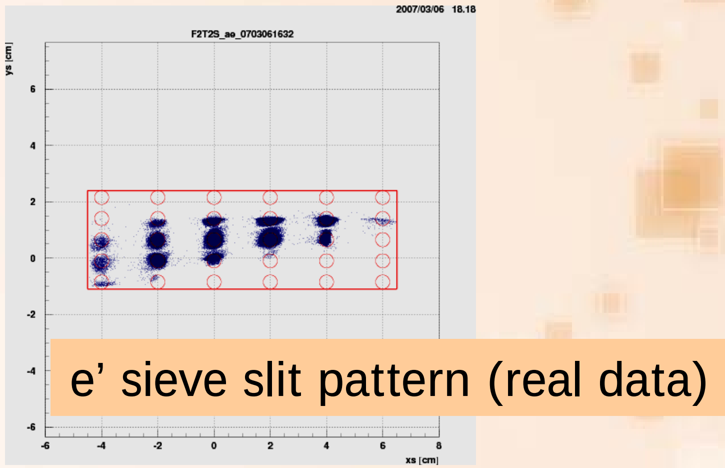
Problems

- SOS(JLAB Hall C equipment) limited resolution and acceptance
- Large amounts of Background by Bremsstrahlung

Angle and momentum calibration







More scattered angle dependence for Λ and Σ (M_{proton} << M_{12C})

➔ Tune scatted angle by sieve slit data