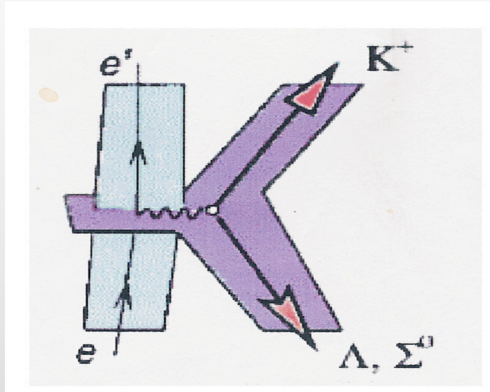
Hypernuclear Spectroscopy by Electron Scattering

- Hypernuclei: A quick introduction
- Electroproduction of hypernuclei
- The experimental Program at Jefferson Lab
  - Overview of the Hall C Setup and Results
  - The Hall A Setup and Results in details
  - Future Program at JLab
- Conclusions



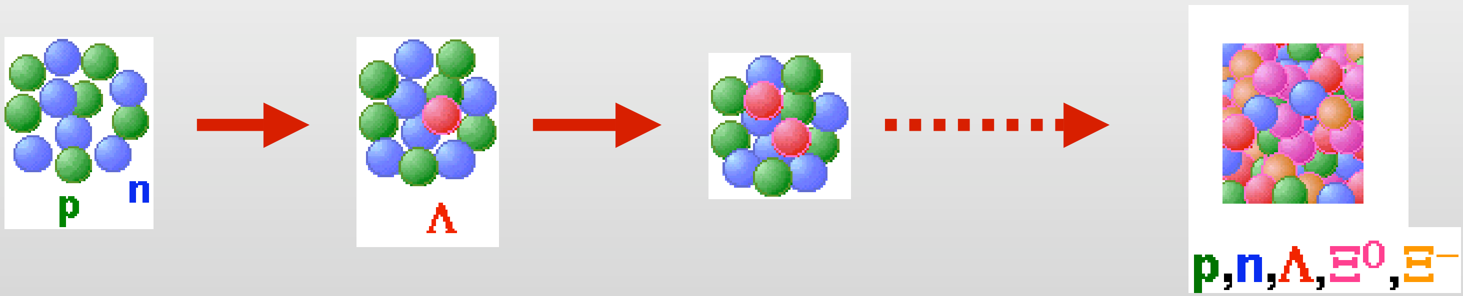
Mauro Iodice
INFN Roma Tre (Italy)

"Electromagnetic Studies of Nuclear Systems" EINN 2007 WORKSHOP
Milos, Greece, September 10 - 2007

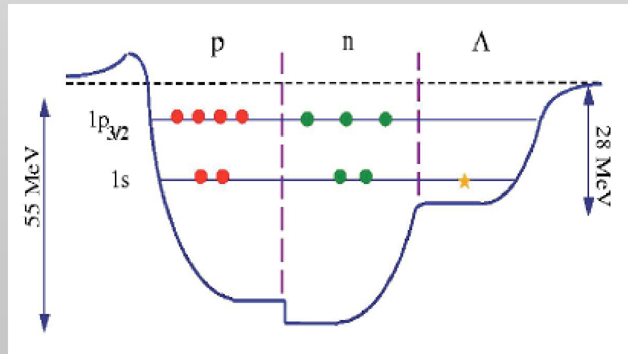
HYPERNUCLEI ...what they are

- **H**ypernuclei are bound states of nucleons with a strange baryon (Lambda hyperon). A hypernucleus is a “laboratory” to study nucleon-hyperon interaction **(Λ-N interaction)**.

- Extension of physics on N-N interaction to system with **S≠0**



- Internal nuclear shell are not Pauli-blocked for hyperons.

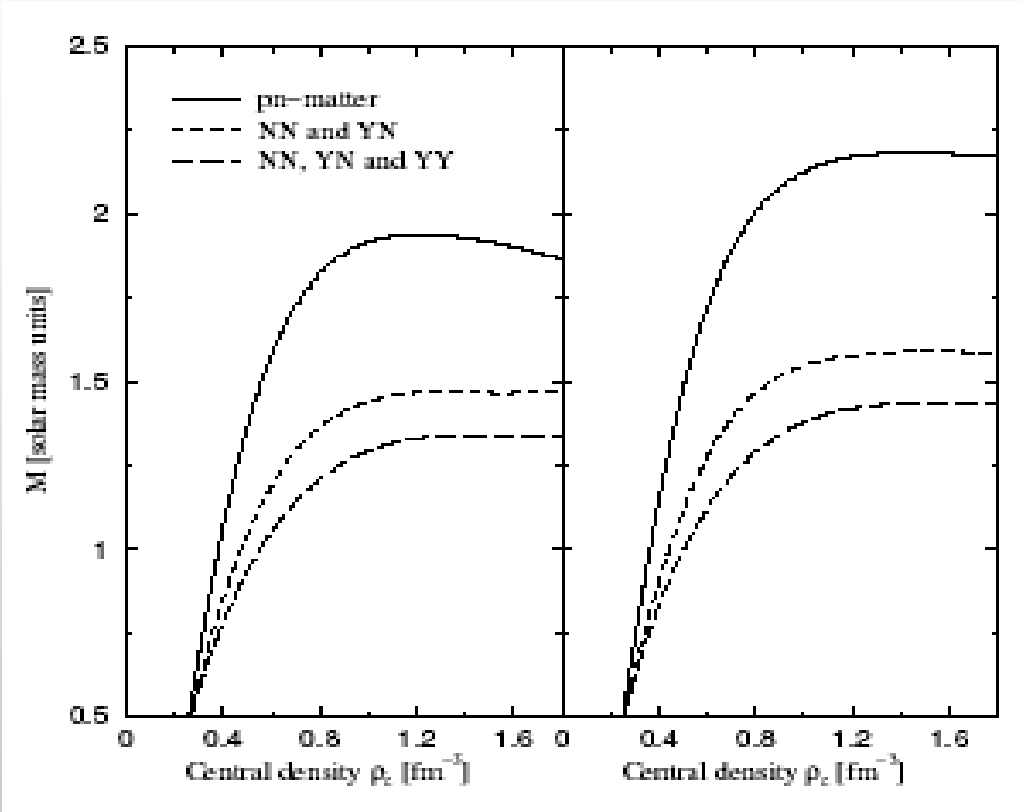


HYPERNUCLEI and ASTROPHYSICS

- **S**trange baryons may appear in neutral β-stable matter through process like:

$$n + e^- \rightarrow \Sigma^- + \nu_e$$

- The presence of strange baryons in neutron stars strongly affect their properties. Example: mass-central density relation for a non-rotating (left) and a rotating (right) star



- The effect strongly depends upon the poorly known interactions of strange baryons

- **More data needed to constrain theoretical models.**

Hypernuclei - historical background - experimental techniques

1953 → 1970 : hypernuclear identification with visualizing techniques emulsions, bubble chambers

1970 → Now : Spectrometers at accelerators:

CERN (up to 1980)

BNL : (K^-, π^-) and (K^+, π^+) production methods

KEK : (K^-, π^-) and (K^+, π^+) production methods

> 2000 : Stopped kaons at DAΦNE (FINUDA) : (K^-_{stop}, π^-)

Elementary reaction on neutron :

$$K^- + n \rightarrow \pi^- + \Lambda$$

$$\pi^+ + n \rightarrow K^+ + \Lambda$$

e.g.

$$^{12}C \rightarrow {}^{12}C_\Lambda$$

> 2000 : **The new electromagnetic way : HYPERNUCLEAR production with ELECTRON BEAM at JLAB**

Elementary reaction on proton :

$$e + p \rightarrow e' + K^+ + \Lambda$$

e.g.

$$^{12}C \rightarrow {}^{12}B_\Lambda$$

Production of MIRROR hypernuclei

Λ: I=0, q=0 $\Rightarrow \Lambda n = \Lambda p$

Spectroscopy of mirror hypernuclei reveal $\Lambda n \neq \Lambda p \Rightarrow \Lambda\Sigma^0$ mixing and ΛN-ΣN coupling

What do we learn from hypernuclear spectroscopy
Hypernuclei and the Λ-N interaction

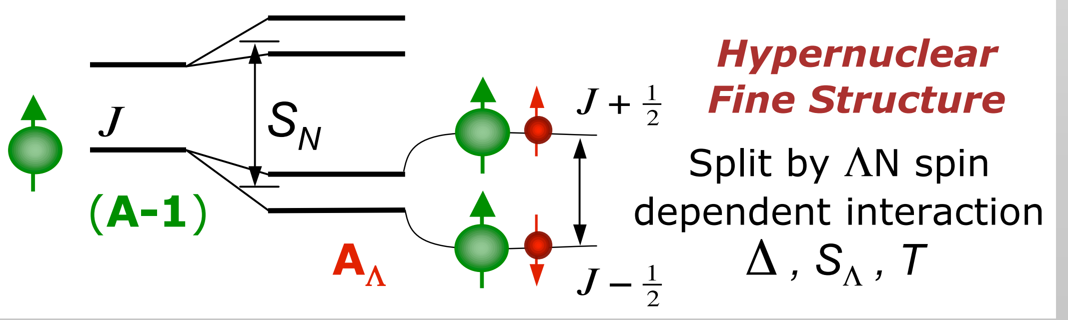
"weak coupling model" J_{A-1} (parent nucleus) $+$ $\Lambda(s-shell)$ (Λ hyperon) $\rightarrow$ $J_{Hyp} = J_{A-1} \pm \frac{1}{2}$ (doublet state)

$$V_{\Lambda N} = V_0(r) + V_\sigma(\mathrm{r})\vec{\mathrm{s}}_\Lambda \cdot \vec{\mathrm{s}}_\mathrm{N} + V_\Lambda(\mathrm{r})\vec{\ell}_{\Lambda N} \cdot \vec{\mathrm{s}}_\Lambda + V_N(\mathrm{r})\vec{\ell}_{\Lambda N} \cdot \vec{\mathrm{s}}_N + V_T(\mathrm{r})\mathrm{S}_{12}$$

V — Δ — S_Λ — S_N — T

Each of the 5 radial integral (V, Δ, S_Λ, S_N, T) can be phenomenologically determined from the low lying level structure of p-shell hypernuclei

Low-lying levels of Λ Hypernuclei



ELECTROproduction of Hypernuclei

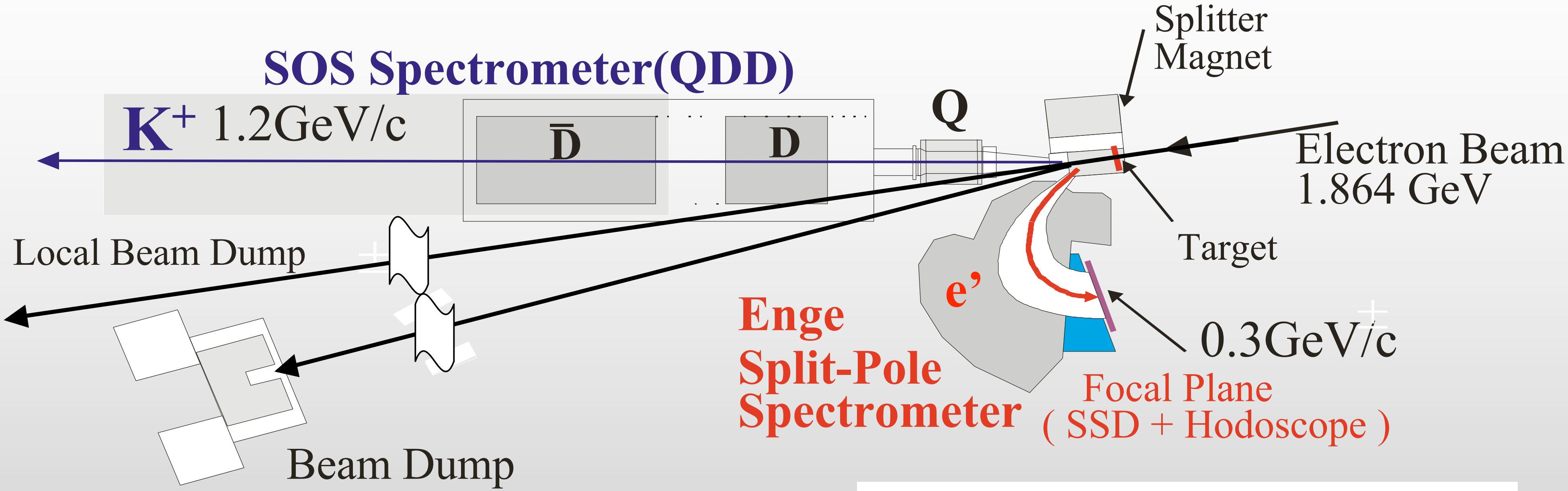
- Hypernuclear physics accesses information on the nature of the force between nucleons and strange baryons, i.e. the **Λ-N interaction**. The nucleus provides a unique laboratory for studying such interaction.

- The characteristics of the **Jefferson Lab. electron beam**, together with those of the experimental equipments, offer a unique opportunity to study hypernuclear spectroscopy via **electromagnetic induced reactions**. **A new experimental approach: alternative to the hadronic induced reactions studied so far.**

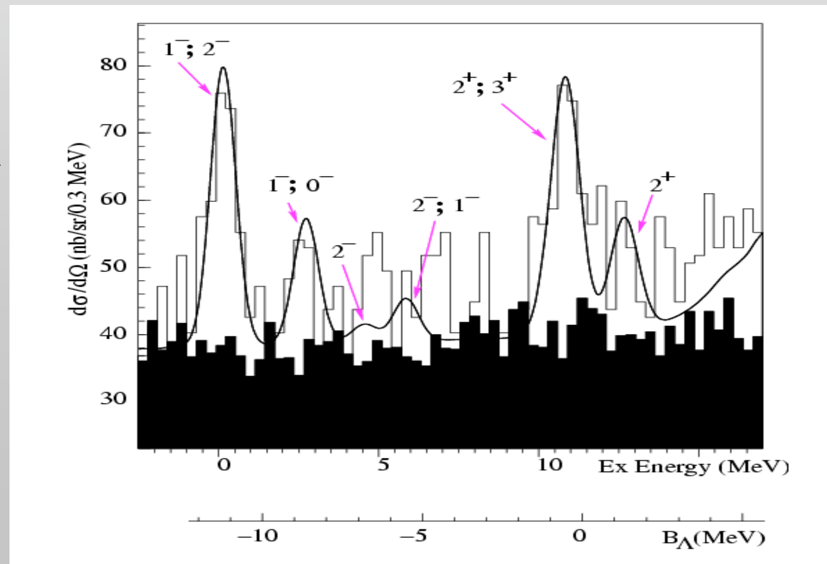
- **The experimental program at Jefferson Lab, in Hall A and in Hall C, has completed its first part of measurements, performing high-resolution hypernuclear spectroscopy on light (p-shell) and medium heavy targets**

- **Different approach:**
  - **Hall C :** Low Luminosity (thin targets low current) Large Acceptance
  - **Hall A :** Small Acceptance - High Luminosity

JLAB Hall C: The First Pioneer Experiment - Jlab **E89-009** - The **HNSS** setup

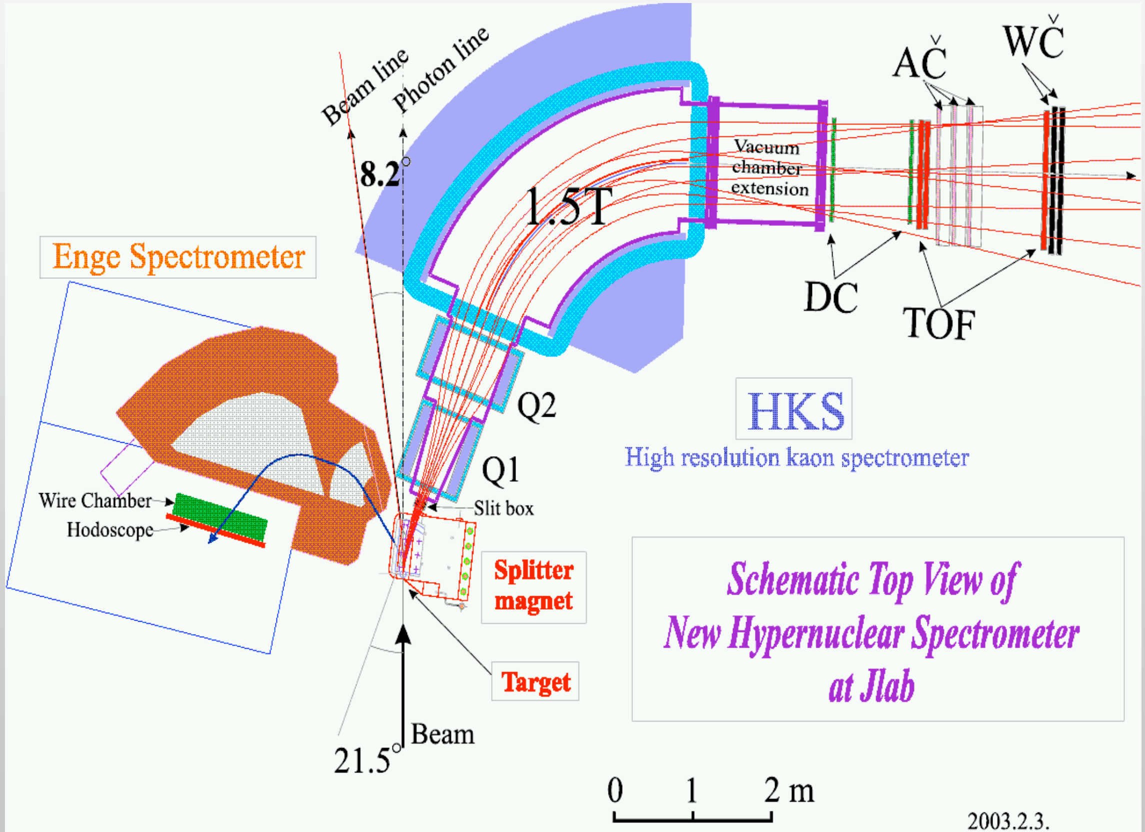


Year 2000: The first generation experiment (E89-009, HNSS) on Carbon Target proved that (e,e'K+) hypernuclear study is possible with high quality electron beam at JLab.



JLAB Hall C Experimental setup - The Second Generation Exp. At Jlab - The **E01-011** setup

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



Two Major Improvements

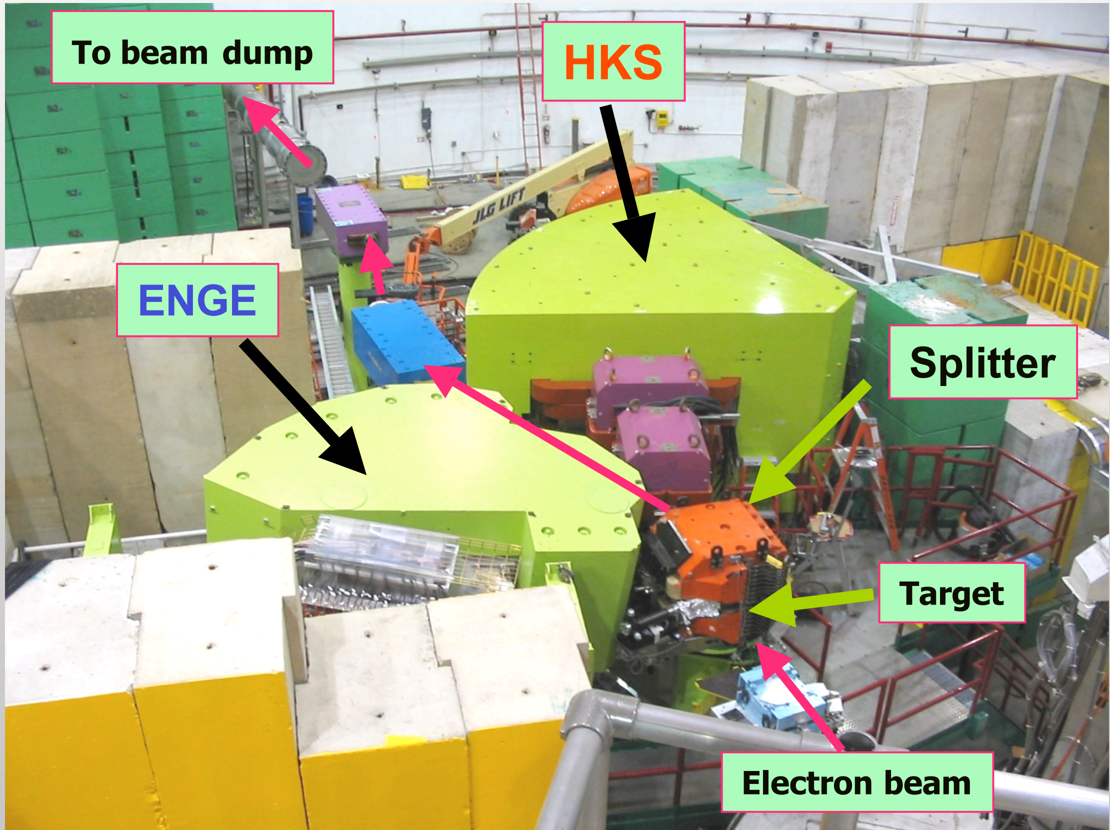
New HKS

Tilt Method

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

JLAB Hall C Experimental setup - The Second Generation Exp. At Jlab - The **E01-011** setup

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



Two Major Improvements

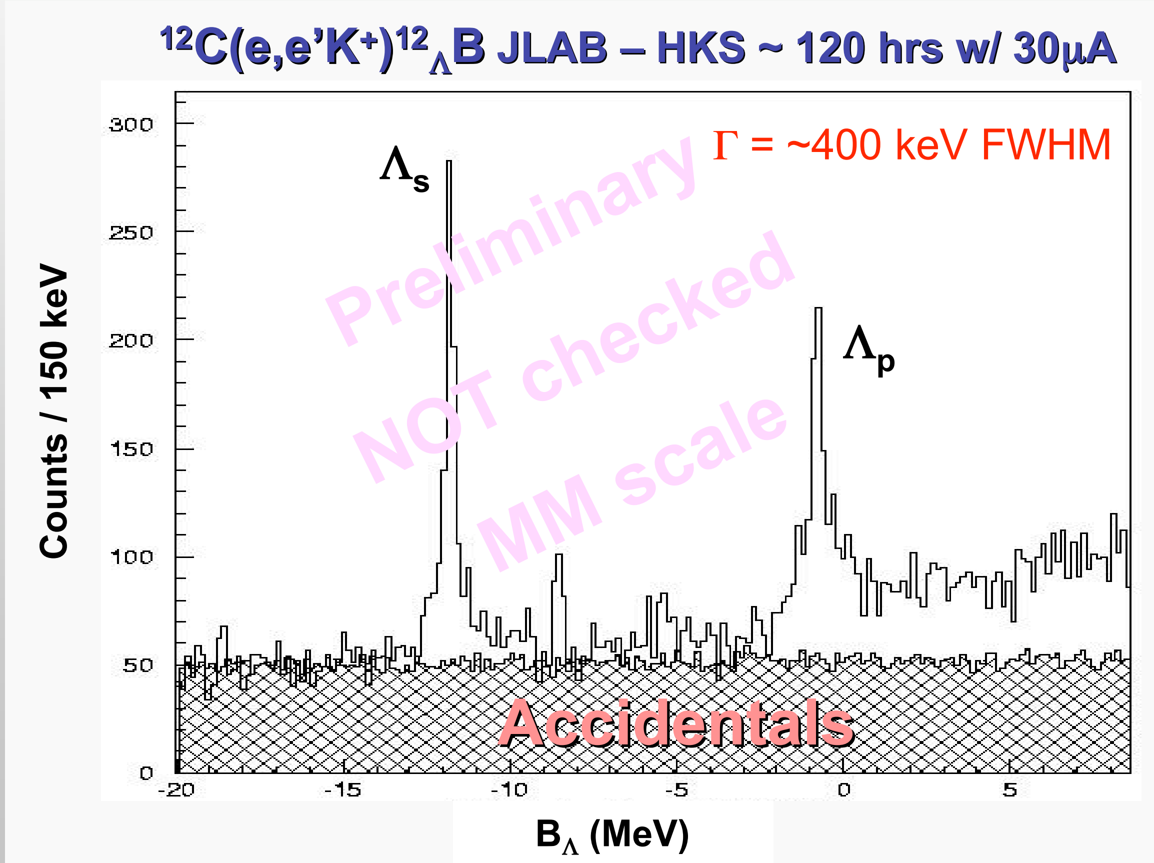
New HKS

Tilt Method

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

JLAB Hall C Experimental setup - The Second Generation Exp. At Jlab - The **E01-011** setup

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



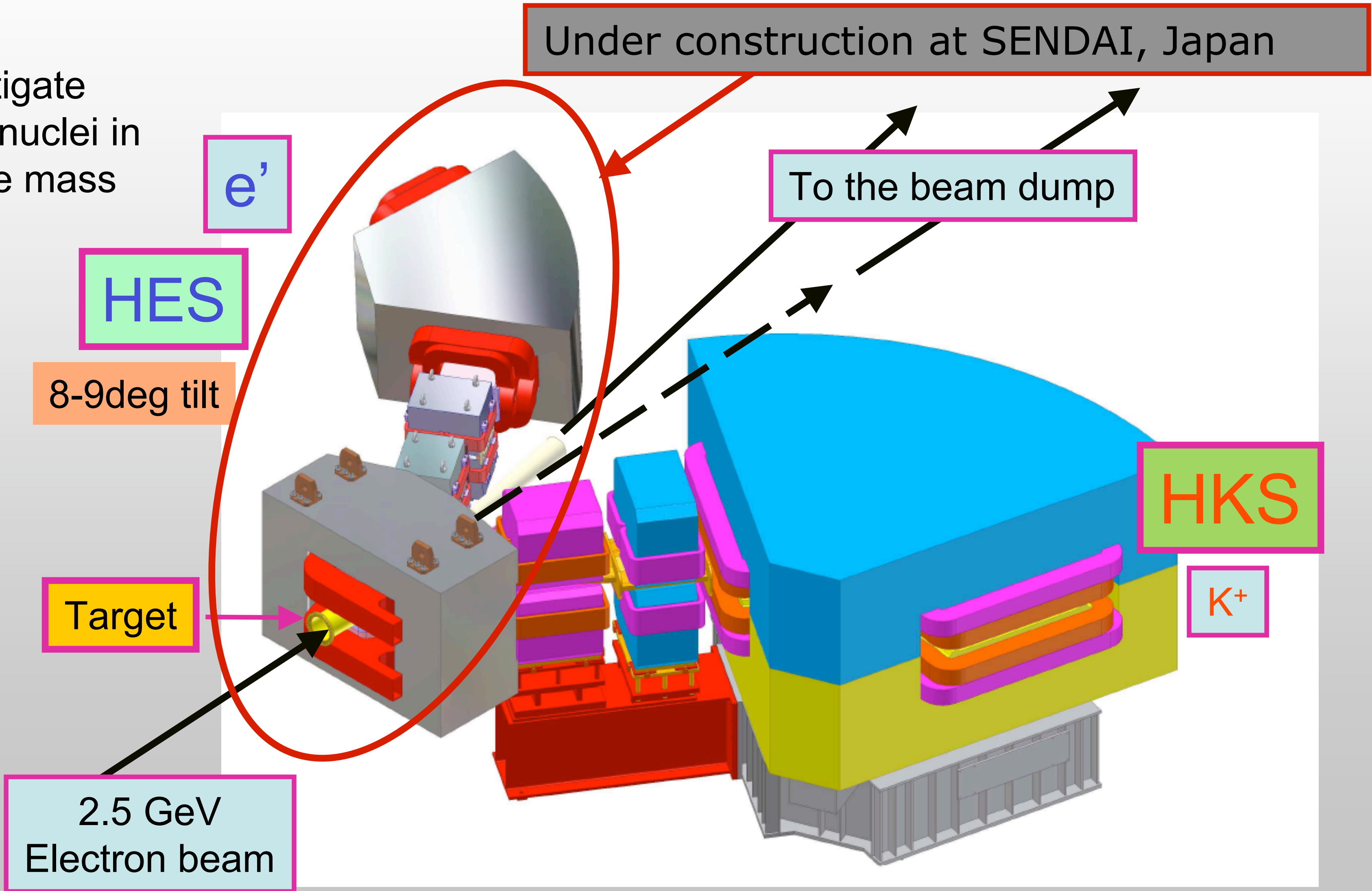
Preliminary Results on

Carbon Target

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

JLAB Hall C Future Experimental setup - The Third Generation Exp. **E05-115**: HKS + HES + New SPL

To investigate hypernuclei in a wide mass range



JLAB Hall A Experiment E94-107

E94107 COLLABORATION

A.Acha, H.Breuer, C.C.Chang, E.Cisbani, F.Cusanno, C.J.DeJager, R. De Leo, R.Feuerbach, S.Frullani, F.Garibaldi*, D.Higinbotham, M.Iodice, L.Lagamba, J.LeRose, P.Markowitz, S.Marrone, R.Michaels, Y.Qiang, B.Reitz, G.M.Urciuoli, B.Wojtsekhowski, and the **Hall A Collaboration**

$^{16}O(e,e'K^+)^{16}{}_{\Lambda}N$

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

$^{9}Be(e,e'K^+)^{9}{}_{\Lambda}Li$

$H(e,e'K^+)\Lambda,\Sigma^0$

E_{beam} = 4.016, 3.777, 3.656 GeV

P_e= 1.80, 1.57, 1.44 GeV/c **P_k= 1.96 GeV/c**

$\theta_e = \theta_K = 6°$

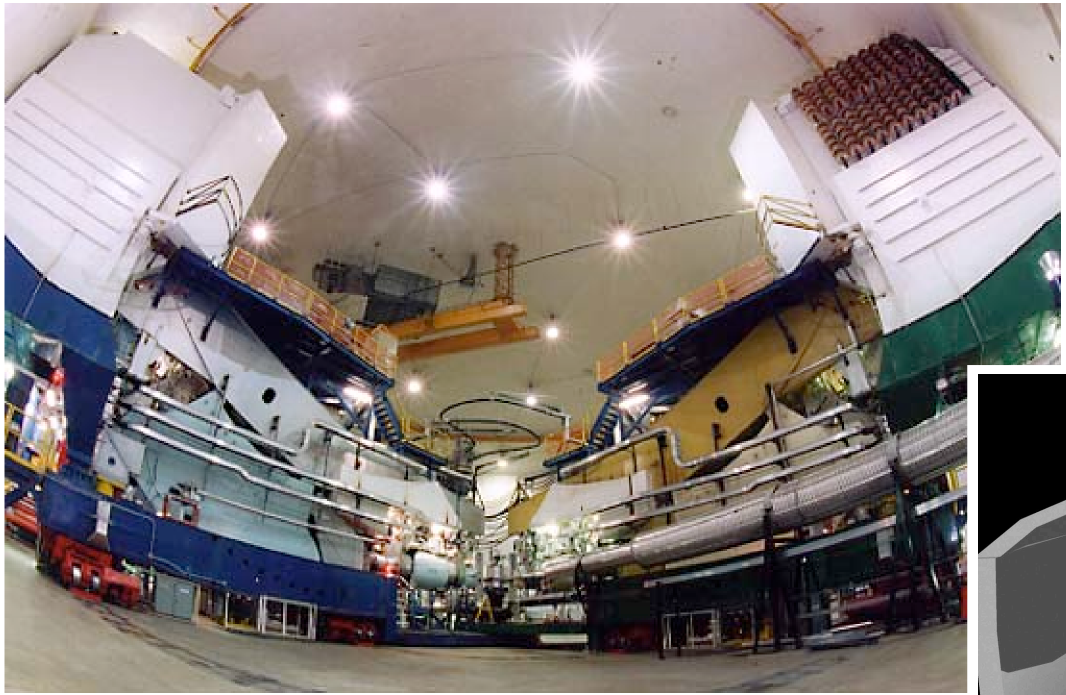
$W \sim 2.2$ GeV $Q^2 \sim 0.07$ (GeV/c)^2

Beam current : <100 μA Target thickness : ~100 mg/cm^2

Counting Rates ~ **0.1 – 10 counts/peak/hour**

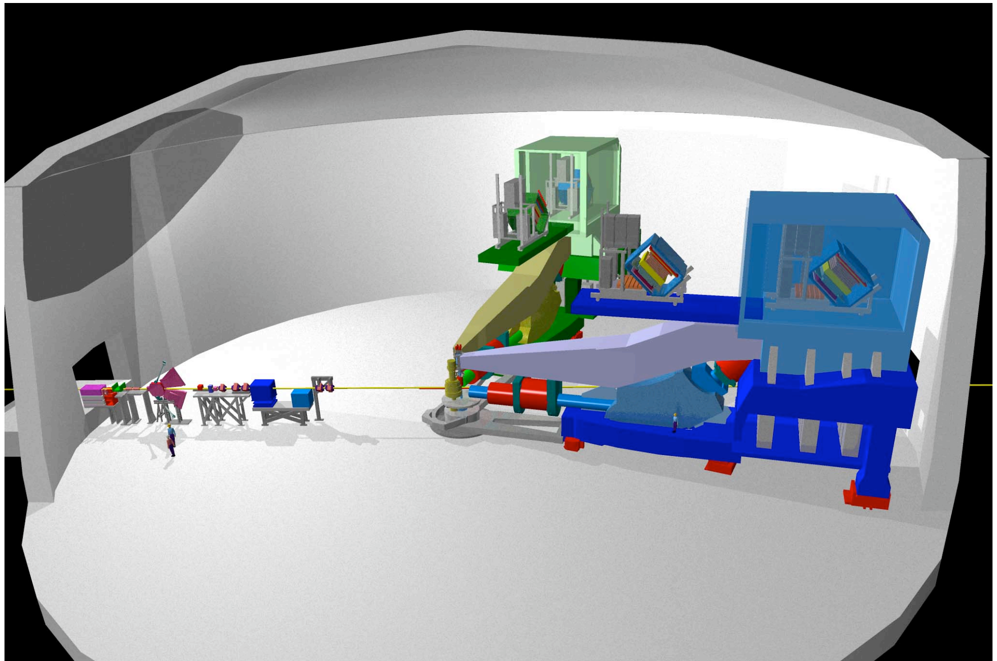
JLAB Hall A Standard Experimental setup

The two High Resolution Spectrometer (HRS) in Hall A @ JLab



HRS – QDQ main characteristics:

Momentum range:	0.3, 4.0 GeV/c
$\Delta p/p$ (FWHM):	**10^{-4}**
Momentum accept.:	± 5 %
Solid angle:	5 – 6 msr
Minimum Angle :	**12.5°**



E94-107 collaboration added:

- **2 superconduction septa**
- **Ring Imaging Cherenkov**

Experimental requirements :

- **D**etection at very forward angle to obtain reasonable counting rate (increase photon flux) → **Septum magnets at 6°**

- Excellent **P**article**ID**entification system for unambiguous *kaon* selection over a large background of *p*, π → **RICH**

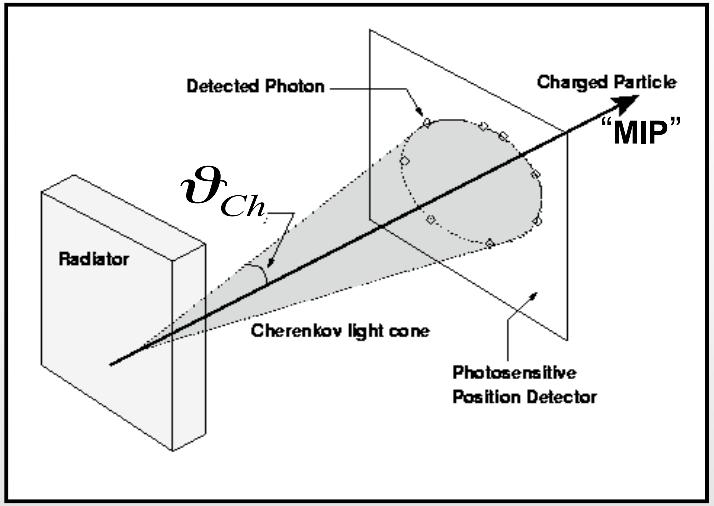
- Accurate monitoring of many parameters over a long period of data taking : Beam energy spread and absolute calibration, spectrometers settings and stability, …

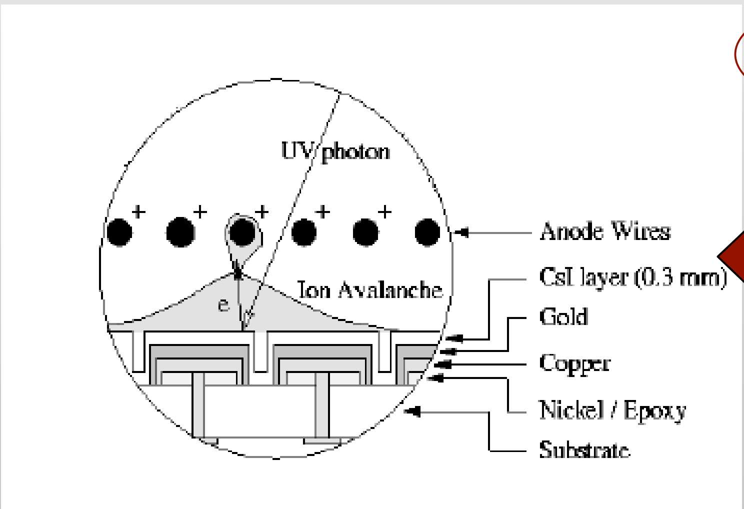
- **E**xcellent energy resolution → Best performance for beam and HRS+Septa with accurate optics calibrations

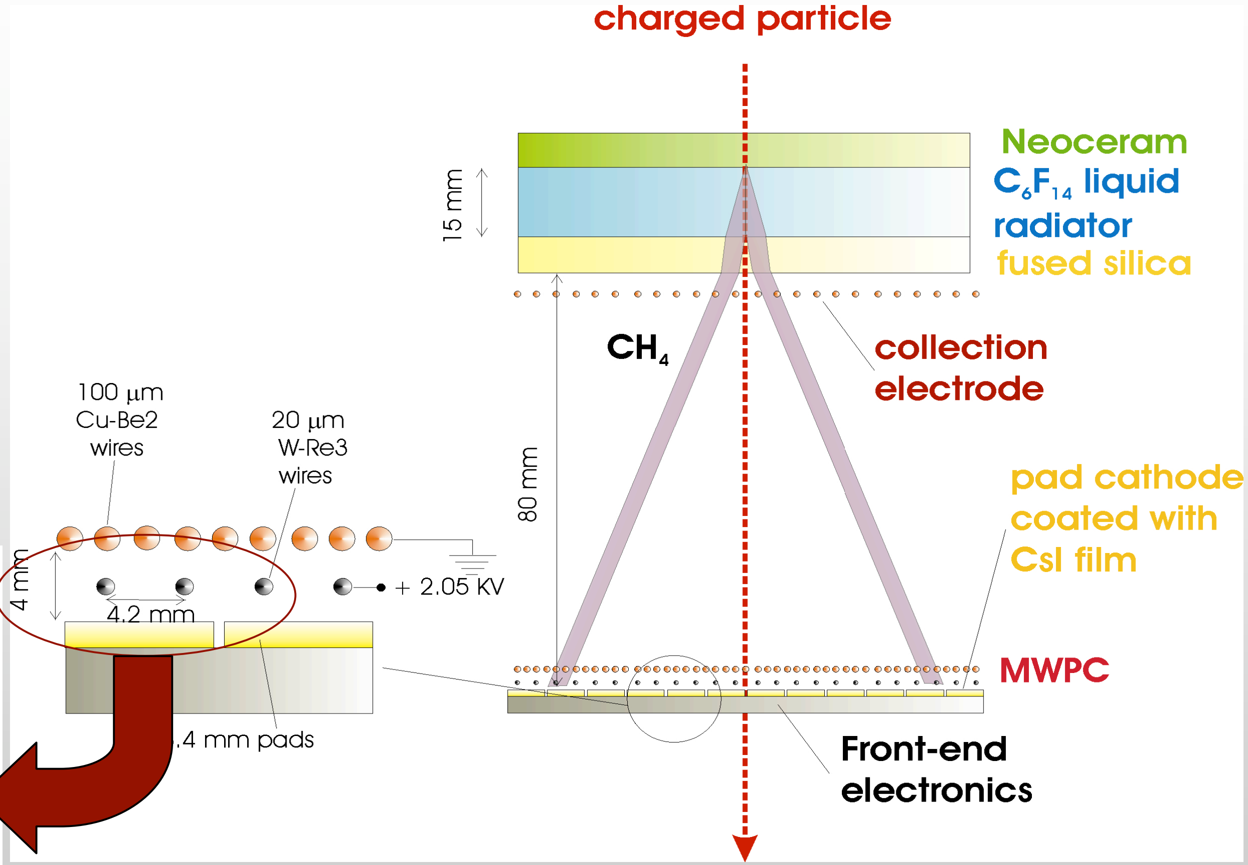
1. $\Delta E_{beam}/E$: 2.5×10^{-5}
2. $\Delta P/P$ (HRS + septum) ~ 10^{-4}
3. Straggling, energy loss…

} Excitation energy resolution **≤ 600 keV**

RICH detector – C_6F_{14}/CsI proximity focusing RICH







Performances:

$N_{p.e.}$ **# of detected photons (p.e.)**
and σ_θ (angular resolution)

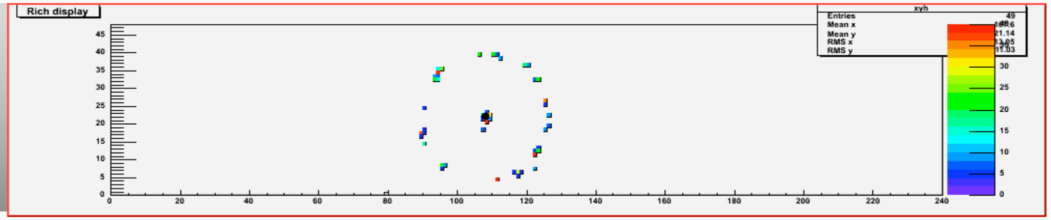
Separation Power

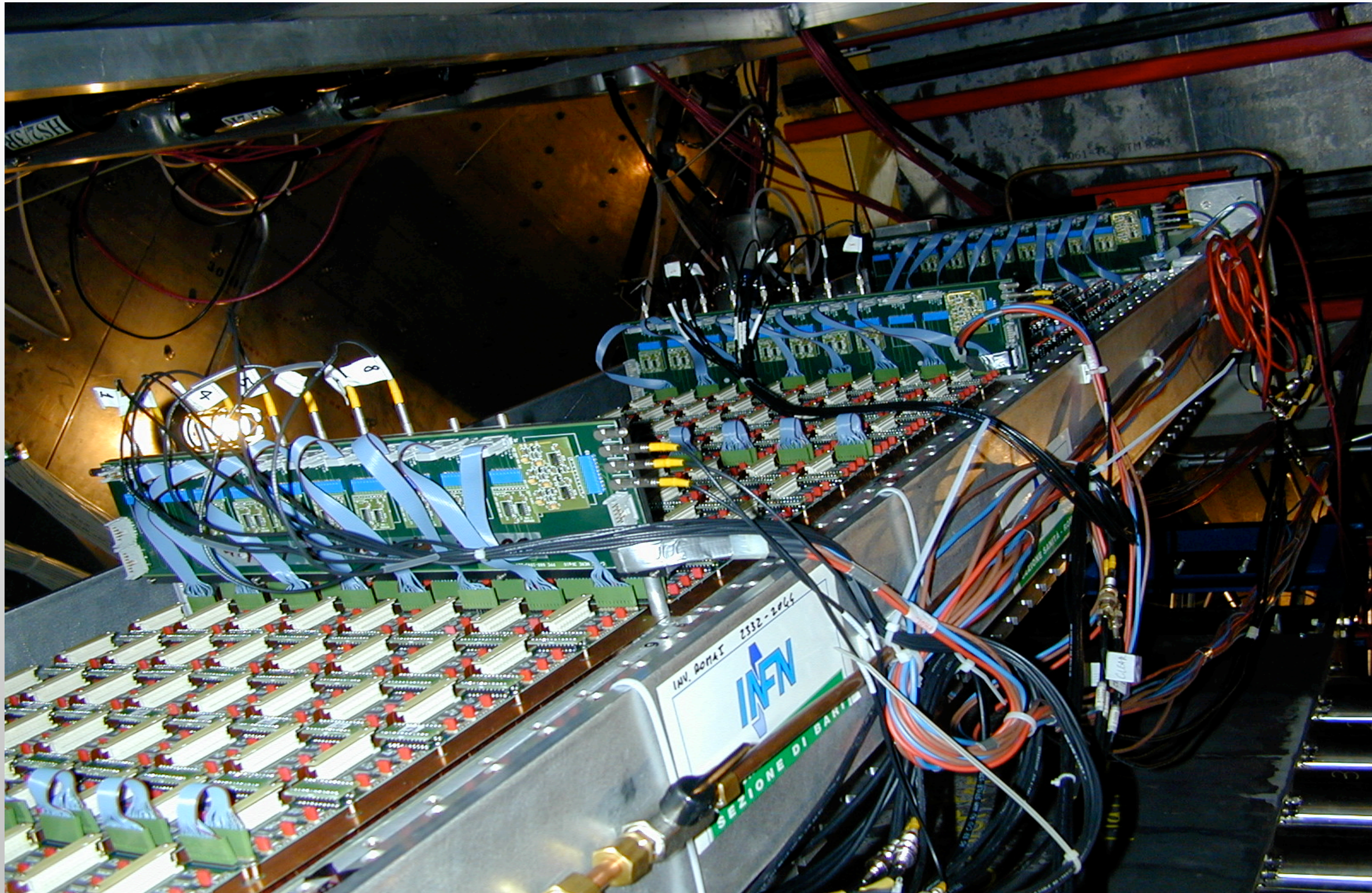
$$\vartheta_2 - \vartheta_1 = n_\sigma \sigma_{\vartheta_c}$$

Cherenkov angle resolution

$$\sigma_{\vartheta_c} = \frac{\sigma_\vartheta^{p.e.}}{\sqrt{N_{p.e.}}}$$

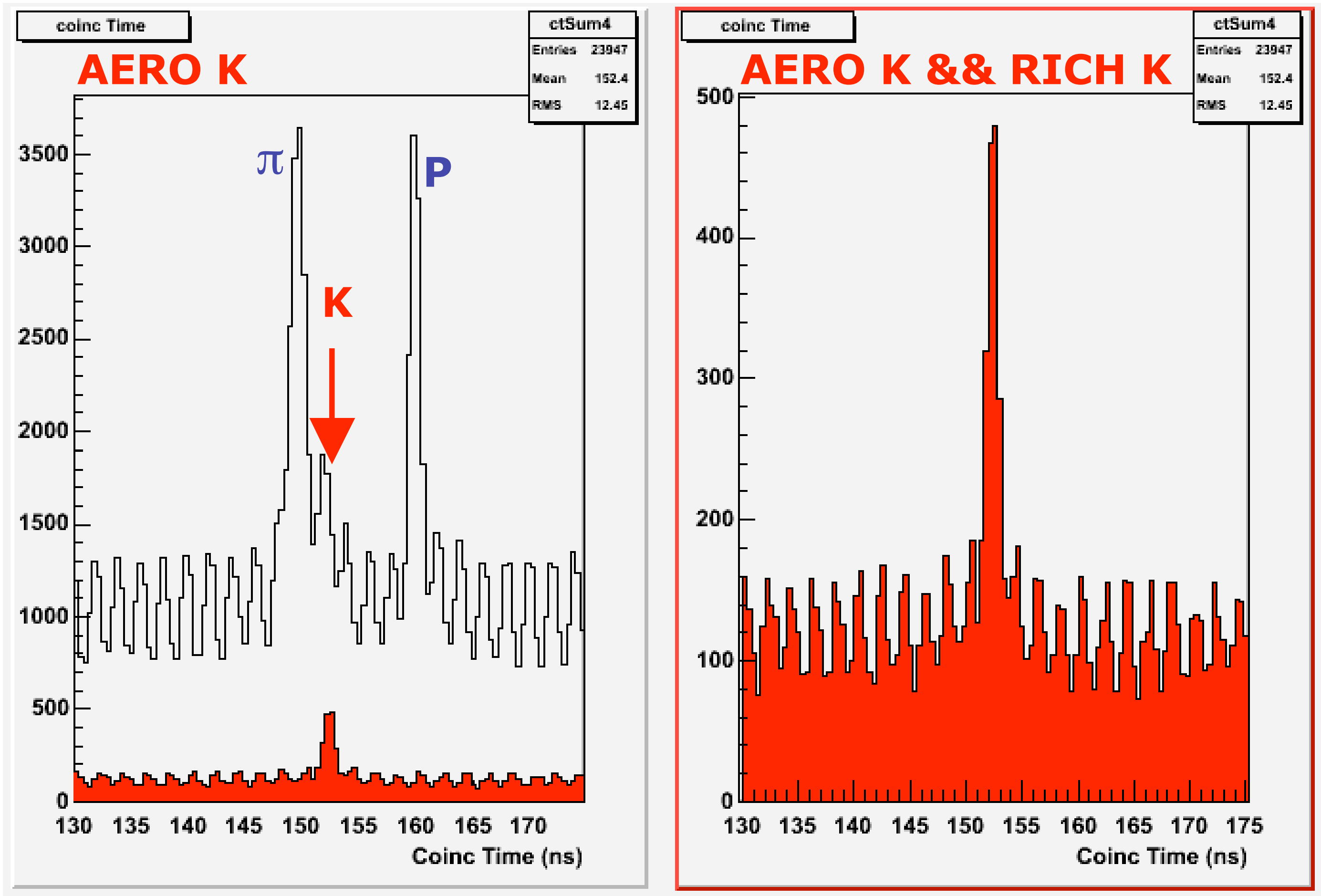
The RICH detector





Rich – PID – Effect of 'Kaon selection':

Coincidence Time selecting kaons on Aerogels and on RICH:



2004

Pion rejection factor ~ 1000

Results on ^{12}C target

Analysis of the reaction $^{12}C(e,e'K)^{12}B_{\Lambda}$

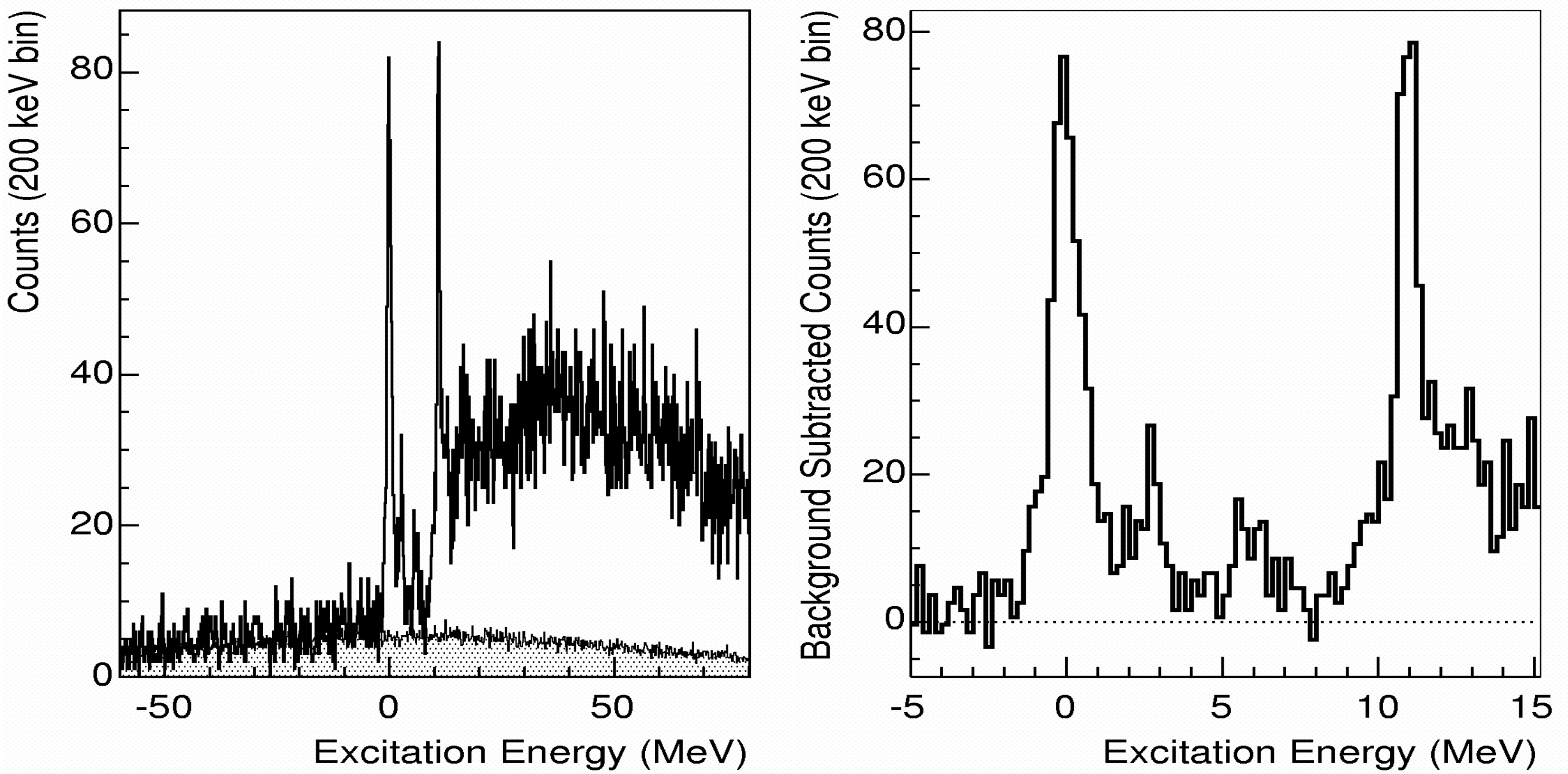
Results published: M.Iodice et al., Phys. Rev. Lett. E052501, 99 (2007).

PHYSICAL REVIEW LETTERS

An experiment measuring electroproduction of hypernuclei has been performed in hall A at Jefferson Lab on a ^{12}C target. In order to increase counting rates and provide unambiguous kaon identification two superconducting septum magnets and a ring imaging Cherenkov detector were added to the hall A standard equipment. An unprecedented energy resolution of less than 700 keV FWHM has been achieved. Thus, the observed $^{12}_{\Lambda}B$ spectrum shows for the first time identifiable strength in the core-excited region between the ground-state *s*-wave Λ peak and the 11 MeV *p*-wave Λ peak.

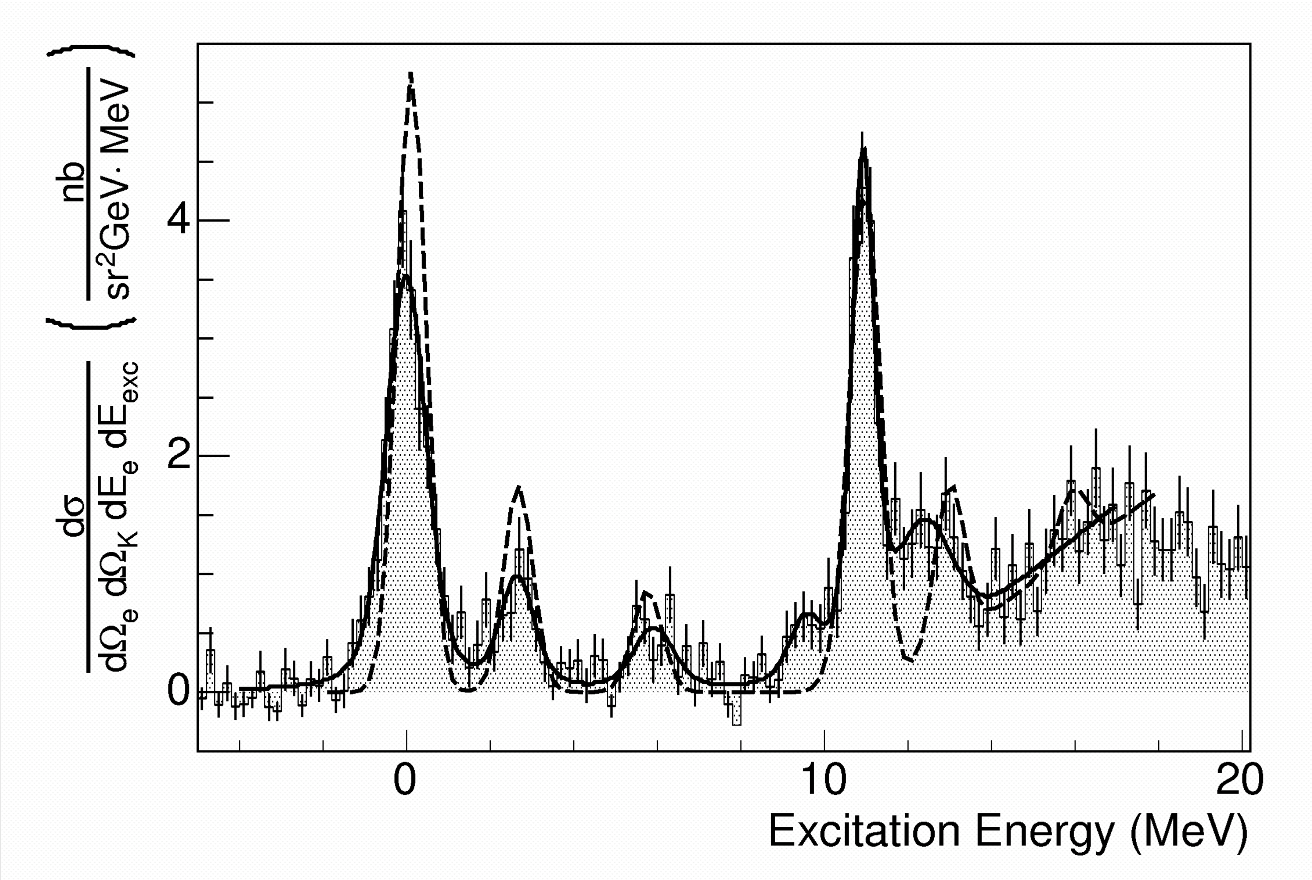
DOI: PACS numbers: 21.80.+a, 21.60.Cs, 25.30.Rw, 27.20.+n

Results on ^{12}C target – Hypernuclear Spectrum of $^{12}B_{\Lambda}$



- BACKGROUND level is very low ⇒ Signal/Noise Ratio is very high
- Clear evidence of core excited peak levels between the grond state and the strongly populated p-Lambda peak at 11 MeV
- Quasi free K-Lambda production dominate the spectrum above 13 MeV

Results on ^{12}C target – Hypernuclear Spectrum of $^{12}B_{\Lambda}$



- Peak Search :
Identified 6 regions with excess counts above background

Position (MeV)	Width (FWHM, MeV)	SNR
0.0 ± 0.03	1.15 ± 0.18	19.7
2.65 ± 0.10	0.95 ± 0.43	7.0
5.92 ± 0.13	1.13 ± 0.29	5.3
9.54 ± 0.16	0.93 ± 0.46	4.4
10.93 ± 0.03	0.67 ± 0.15	20.0
12.36 ± 0.13	1.58 ± 0.29	7.3

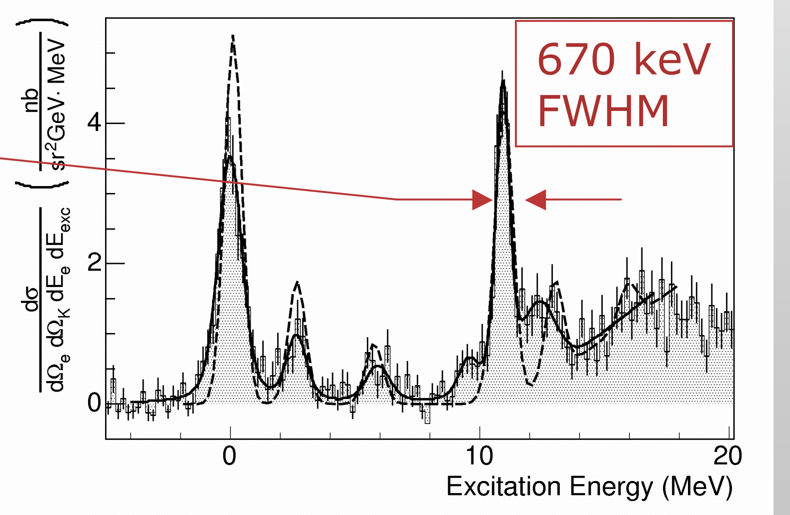
- Fit to the data: Fit 6 regions with 6 Voigt functions (convolution of Gaussian and Lorentzian) ⇒ $\chi^2_{/ndf} = 1.16$
- Theoretical model superimposed curve based on :
  - i) SLA p(e,e′K+)Λ (elementary process)
  - ii) ΛN interaction from $^{7}_{\Lambda}Li$ γ-ray spectra

Results on ^{12}C target – Hypernuclear Spectrum of $^{12}B_\Lambda$

Experimental data			
Position (MeV)	Width (FWHM, MeV)	SNR	Cross section ($nb/sr^2/GeV$)
0.0 ± 0.03	1.15 ± 0.18	19.7	$4.48 \pm 0.29(stat) \pm 0.63(syst)$
2.65 ± 0.10	0.95 ± 0.43	7.0	$0.75 \pm 0.16(stat) \pm 0.15(syst)$
5.92 ± 0.13	1.13 ± 0.29	5.3	$0.45 \pm 0.13(stat) \pm 0.09(syst)$
9.54 ± 0.16	0.93 ± 0.46	4.4	$0.63 \pm 0.20(stat) \pm 0.13(syst)$
10.93 ± 0.03	0.67 ± 0.15	20.0	$3.42 \pm 0.50(stat) \pm 0.55(syst)$
12.36 ± 0.13	1.58 ± 0.29	7.3	$1.19 \pm 0.36(stat) \pm 0.35(syst)$

Narrowest peak is doublet at 10.93 MeV
⇒ experiment resolution < 700 keV

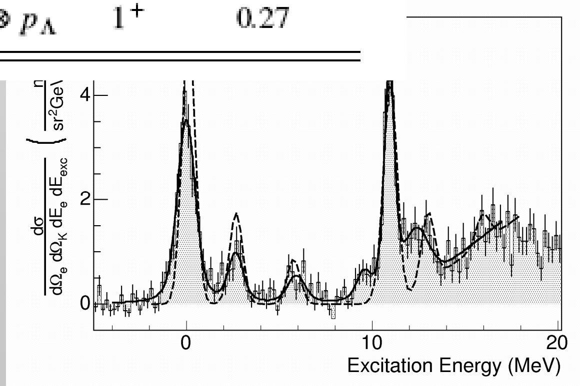
G.S. width is 1150 keV; an unresolved doublet?
What would separation be between two 670 keV peaks? ⇒ ~650 keV
(theory predicts only 140)



Results on ^{12}C target – Hypernuclear Spectrum of $^{12}B_{\Lambda}$

Experimental data				Theoretical prediction			
Position (MeV)	Width (FWHM, MeV)	SNR	Cross section (nb/sr^2/GeV)	E_x (MeV)	Main structure	J^{π}	Cross section (nb/sr^2/GeV)
0.0 ± 0.03	1.15 ± 0.18	19.7	$4.48 \pm 0.29(\text{stat}) \pm 0.63(\text{syst})$	0.0	$^{11}\text{B}(\frac{3}{2}^-; \text{g.s.}) \otimes s_{1/2\Lambda}$	1^-	1.02
				0.14	$^{11}\text{B}(\frac{3}{2}^-; \text{g.s.}) \otimes s_{1/2\Lambda}$	2^-	3.66
2.65 ± 0.10	0.95 ± 0.43	7.0	$0.75 \pm 0.16(\text{stat}) \pm 0.15(\text{syst})$	2.67	$^{11}\text{B}(\frac{1}{2}^-; 2.12) \otimes s_{1/2\Lambda}$	1^-	1.54
5.92 ± 0.13	1.13 ± 0.29	5.3	$0.45 \pm 0.13(\text{stat}) \pm 0.09(\text{syst})$	5.74	$^{11}\text{B}(\frac{3}{2}^-; 5.02) \otimes s_{1/2\Lambda}$	2^-	0.58
				5.85	$^{11}\text{B}(\frac{3}{2}^-; 5.02) \otimes s_{1/2\Lambda}$	1^-	0.18
9.54 ± 0.16	0.93 ± 0.46	4.4	$0.63 \pm 0.20(\text{stat}) \pm 0.13(\text{syst})$	...	...	...	...
10.93 ± 0.03	0.67 ± 0.15	20.0	$3.42 \pm 0.50(\text{stat}) \pm 0.55(\text{syst})$	10.48	$^{11}\text{B}(\frac{3}{2}^-; \text{g.s.}) \otimes p_{3/2\Lambda}$	2^+	0.24
				10.52	$^{11}\text{B}(\frac{3}{2}^-; \text{g.s.}) \otimes p_{\Lambda}$	1^+	0.12
				10.98	$^{11}\text{B}(\frac{3}{2}^-; \text{g.s.}) \otimes p_{1/2\Lambda}$	2^+	1.43
				11.05	$^{11}\text{B}(\frac{3}{2}^-; \text{g.s.}) \otimes p_{3/2\Lambda}$	3^+	2.19
12.36 ± 0.13	1.58 ± 0.29	7.3	$1.19 \pm 0.36(\text{stat}) \pm 0.35(\text{syst})$	12.95	$^{11}\text{B}(\frac{1}{2}^-; 2.12) \otimes p_{3/2\Lambda}$	2^+	0.91
				13.05	$^{11}\text{B}(\frac{1}{2}^-; 2.12) \otimes p_{\Lambda}$	1^+	0.27

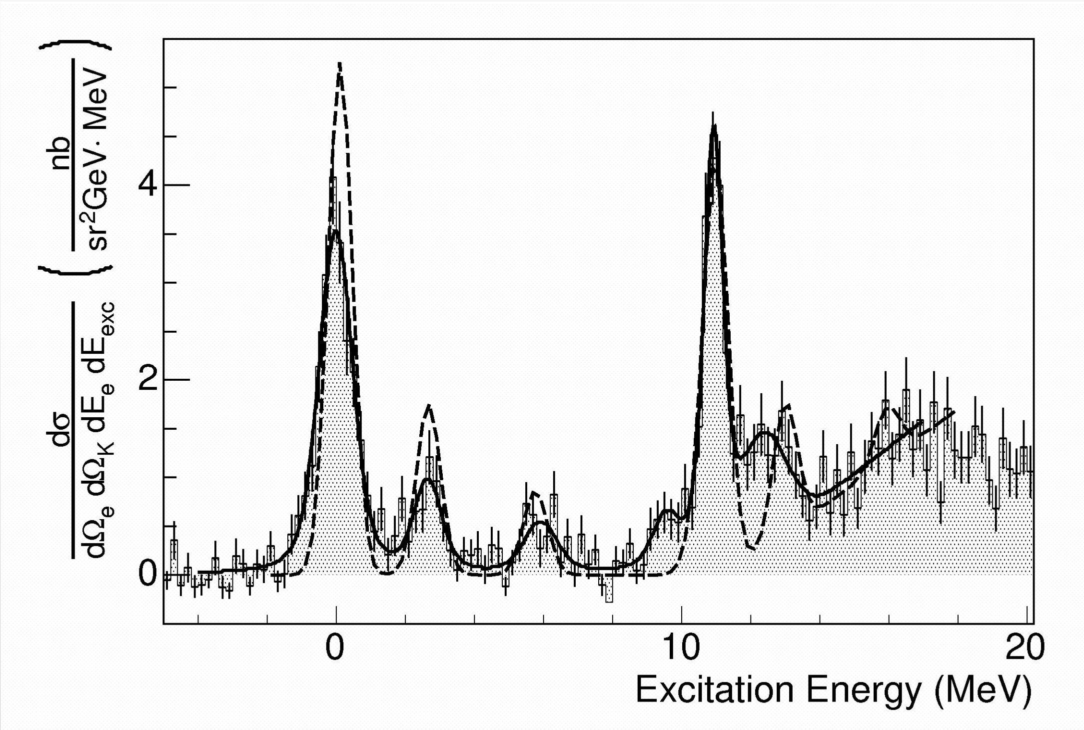
- Measured cross sections in very good agreement with theory

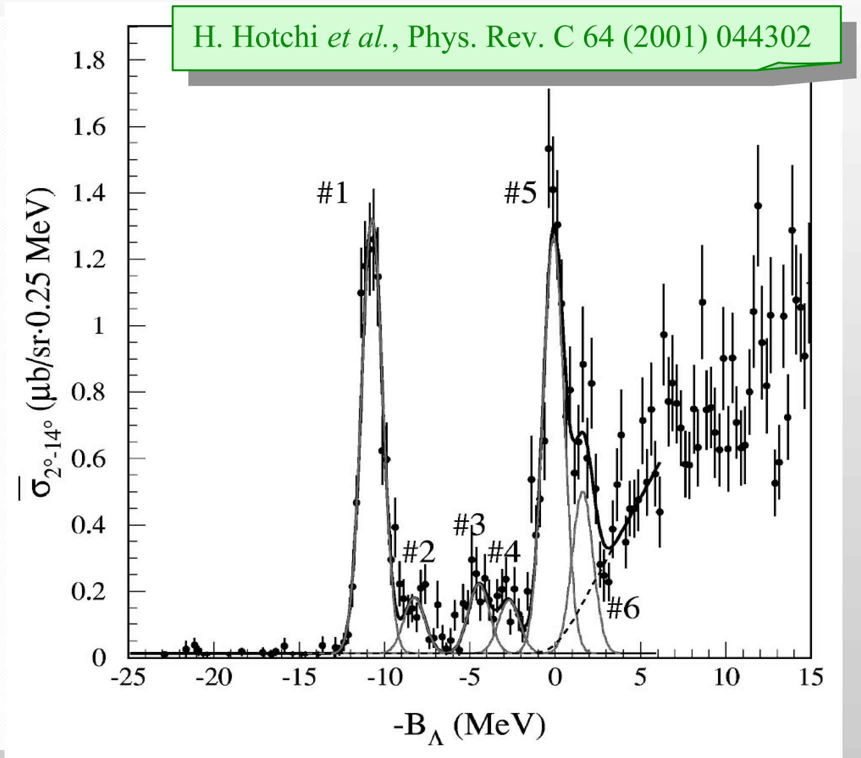


E94-107 **Hall A** Experiment Vs. KEK-E369

$^{12}C(e,e'K)^{12}B_{\Lambda}$

$^{12}C(\pi^{+},K^{+})^{12}C_{\Lambda}$





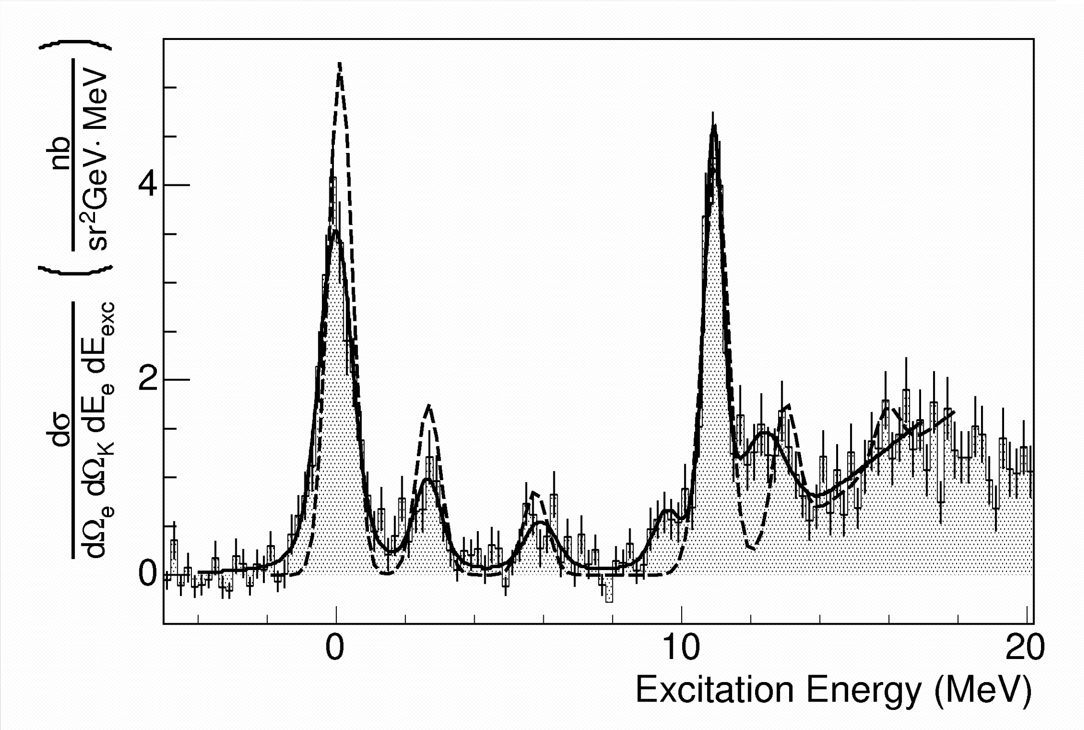
Statistical significance of core excited states:

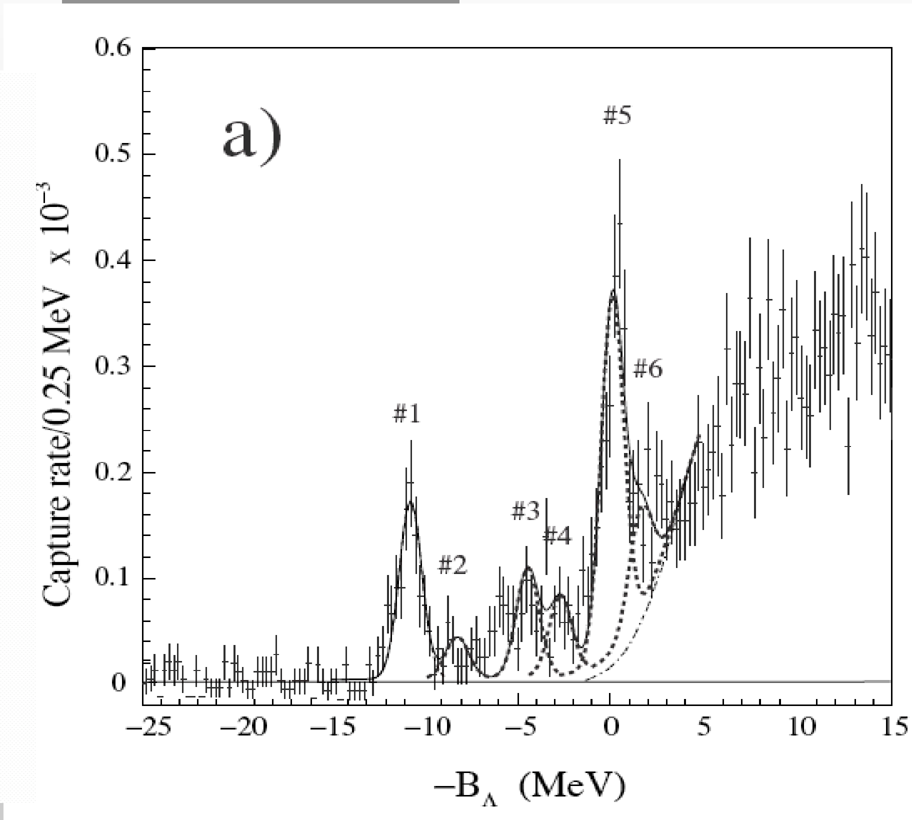
$$\frac{Signal}{\sqrt{Bckgnd}} > 5$$

E94-107 **Hall A** Experiment Vs. **FINUDA** (at DaΦne)

$^{12}C(e,e'K)^{12}B_\Lambda$

$^{12}C(K^-, \pi^-)^{12}C_\Lambda$



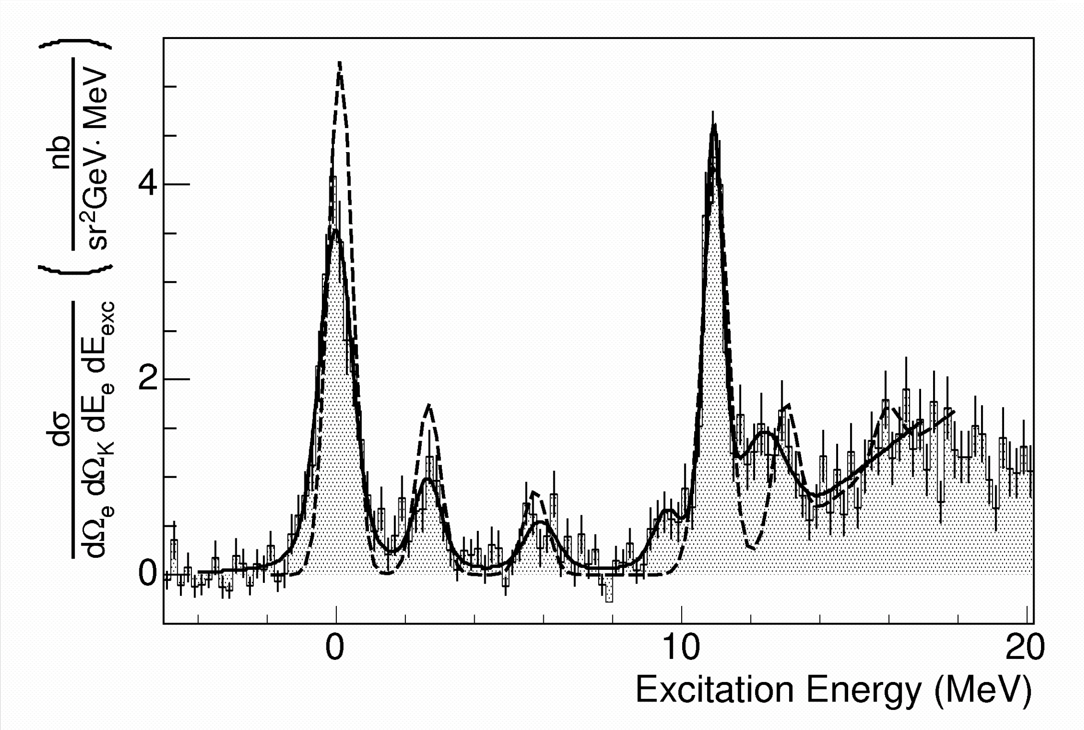


Statistical significance of core excited states:

$$\frac{Signal}{\sqrt{Bckgnd}} > 5$$

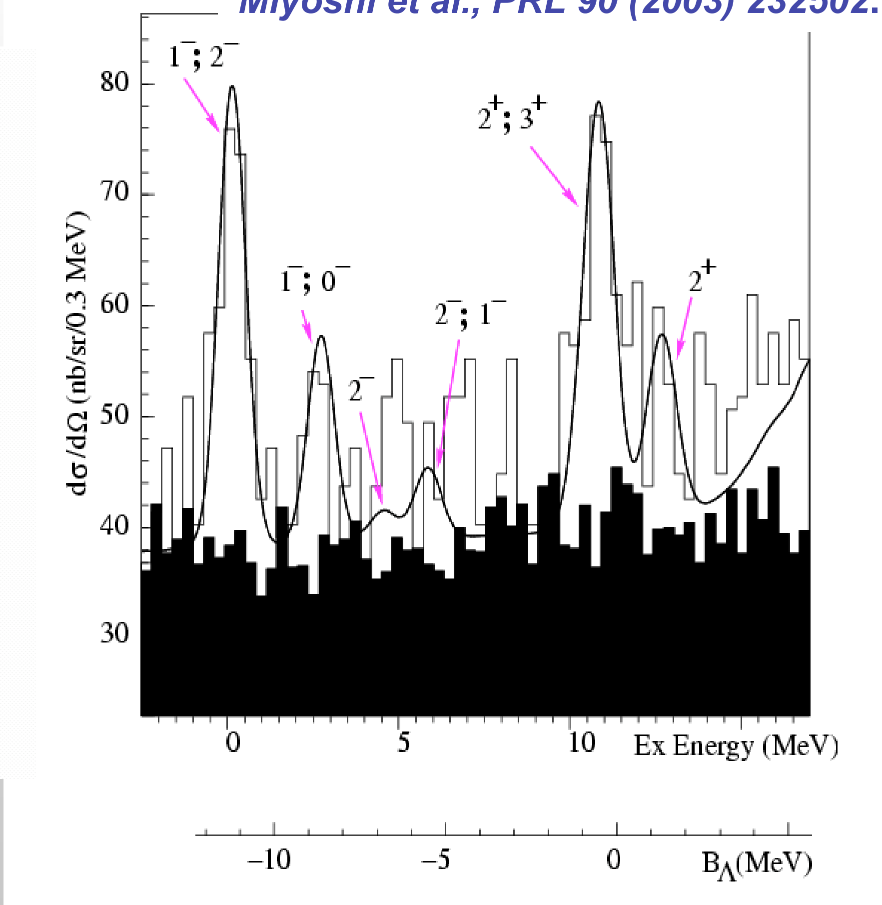
E94-107 Hall A Experiment Vs. HallC E89-009

$^{12}C(e,e'K)^{12}B_{\Lambda}$



$^{12}C(e,e'K)^{12}B_{\Lambda}$

Miyoshi et al., PRL 90 (2003) 232502.



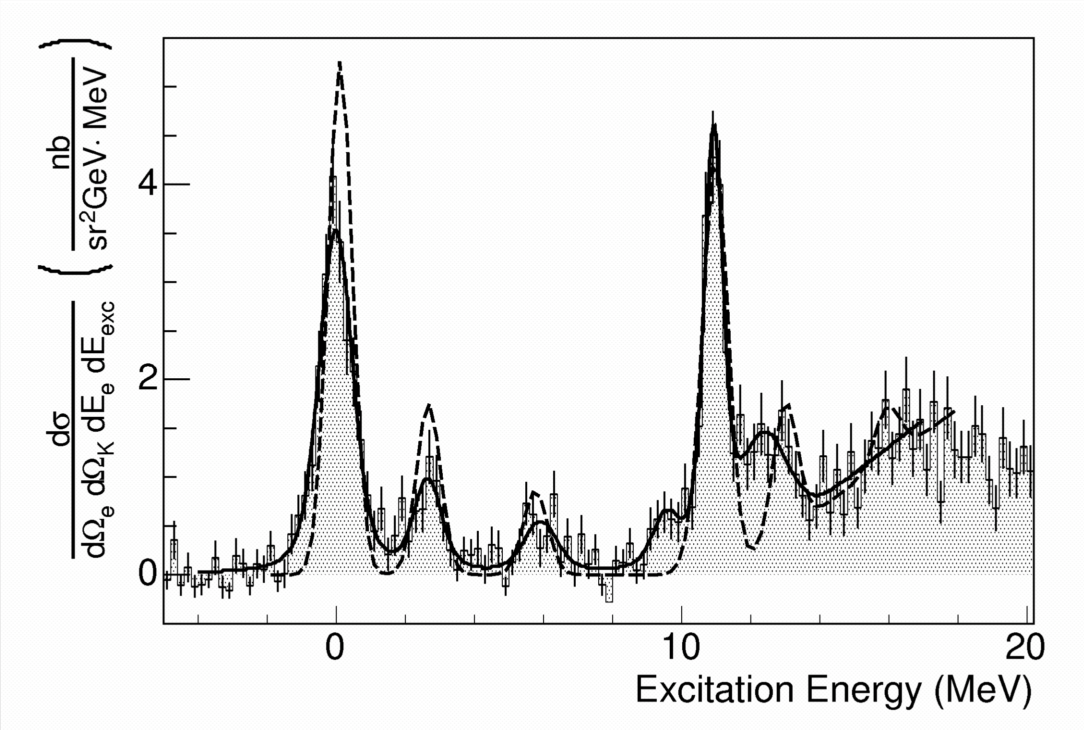
Statistical significance of core excited states:

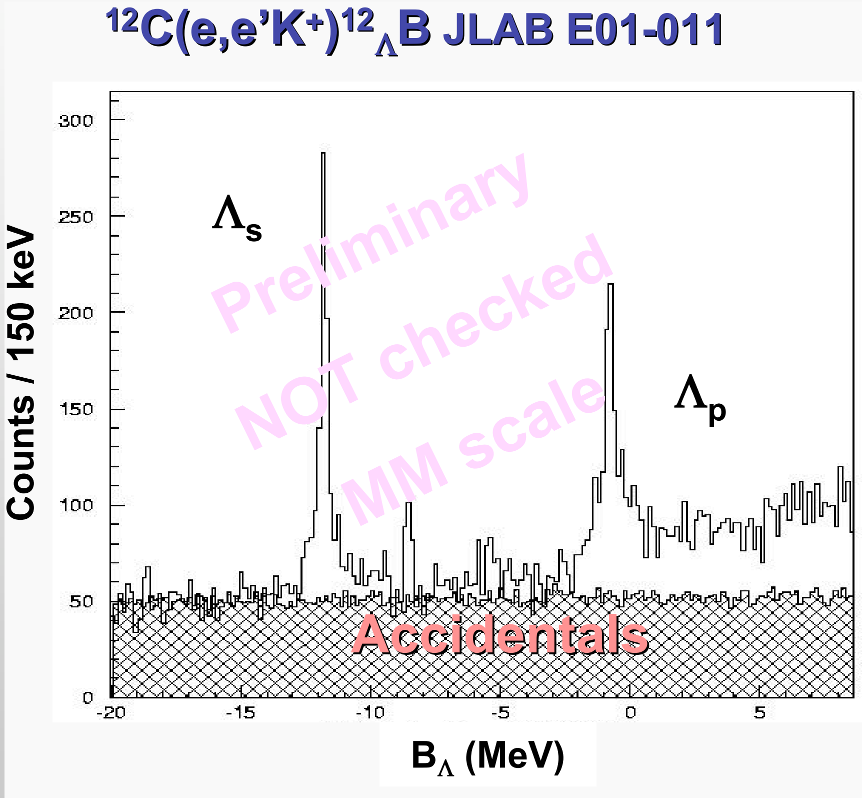
$$\frac{Signal}{\sqrt{Bckgnd}} > 5$$

E94-107 Hall A Experiment Vs. HallC E01-011

$^{12}C(e,e'K)^{12}B_{\Lambda}$

$^{12}C(e,e'K)^{12}B_{\Lambda}$





Statistical significance of core excited states:

$$\frac{Signal}{\sqrt{Bckgnd}} > 5$$

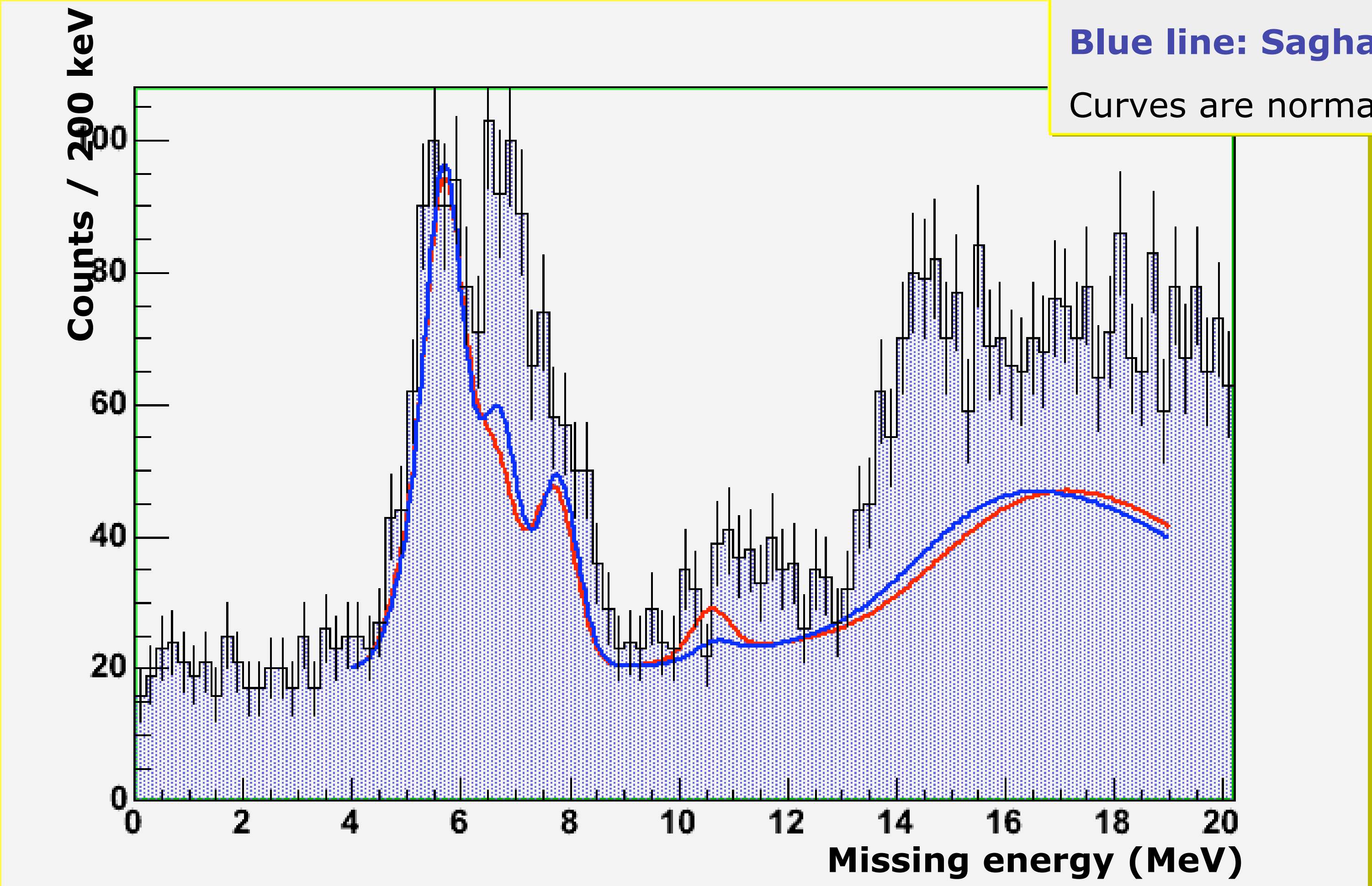
Results from the ^{9}Be target

Analysis of the reaction $^{9}Be(e,e'K)^{9}Li_{\Lambda}$ (very preliminary)

Red line: Benhold-Mart (K MAID)

Blue line: Saghai Saclay-Lyon (SLA)

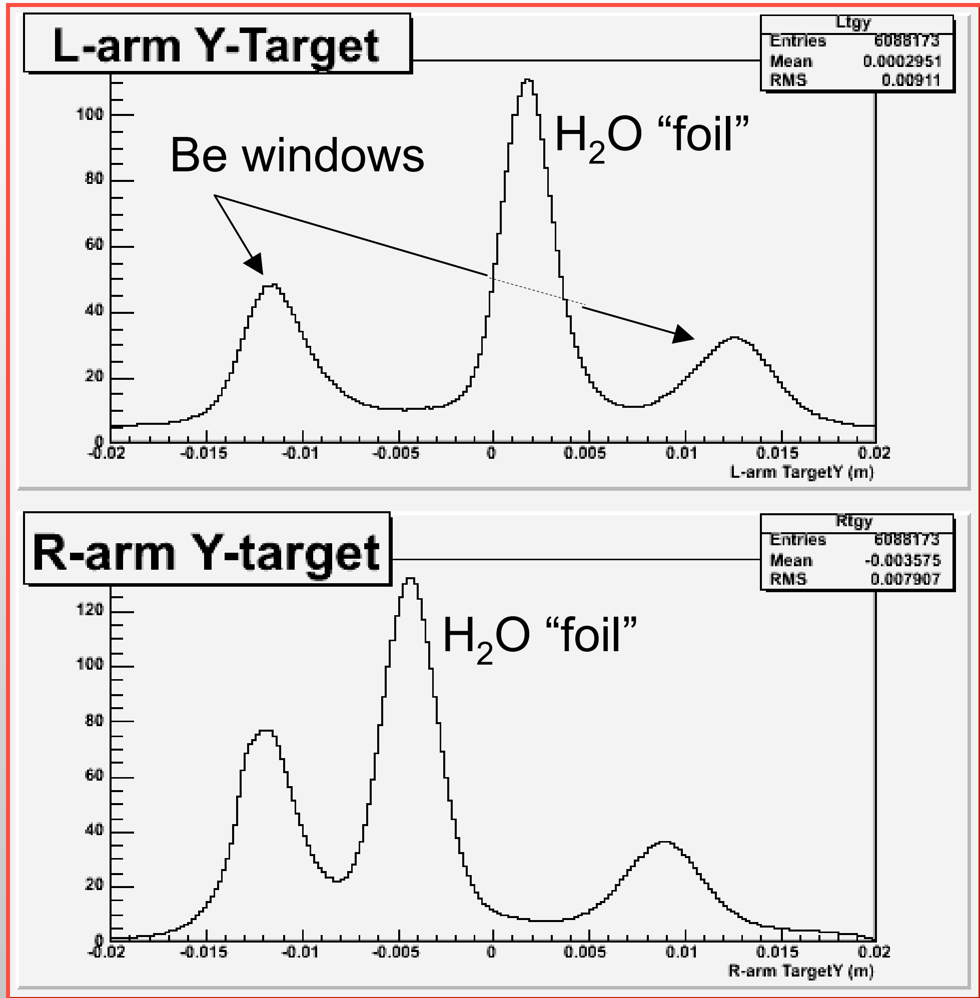
Curves are normalized on g.s. peak.



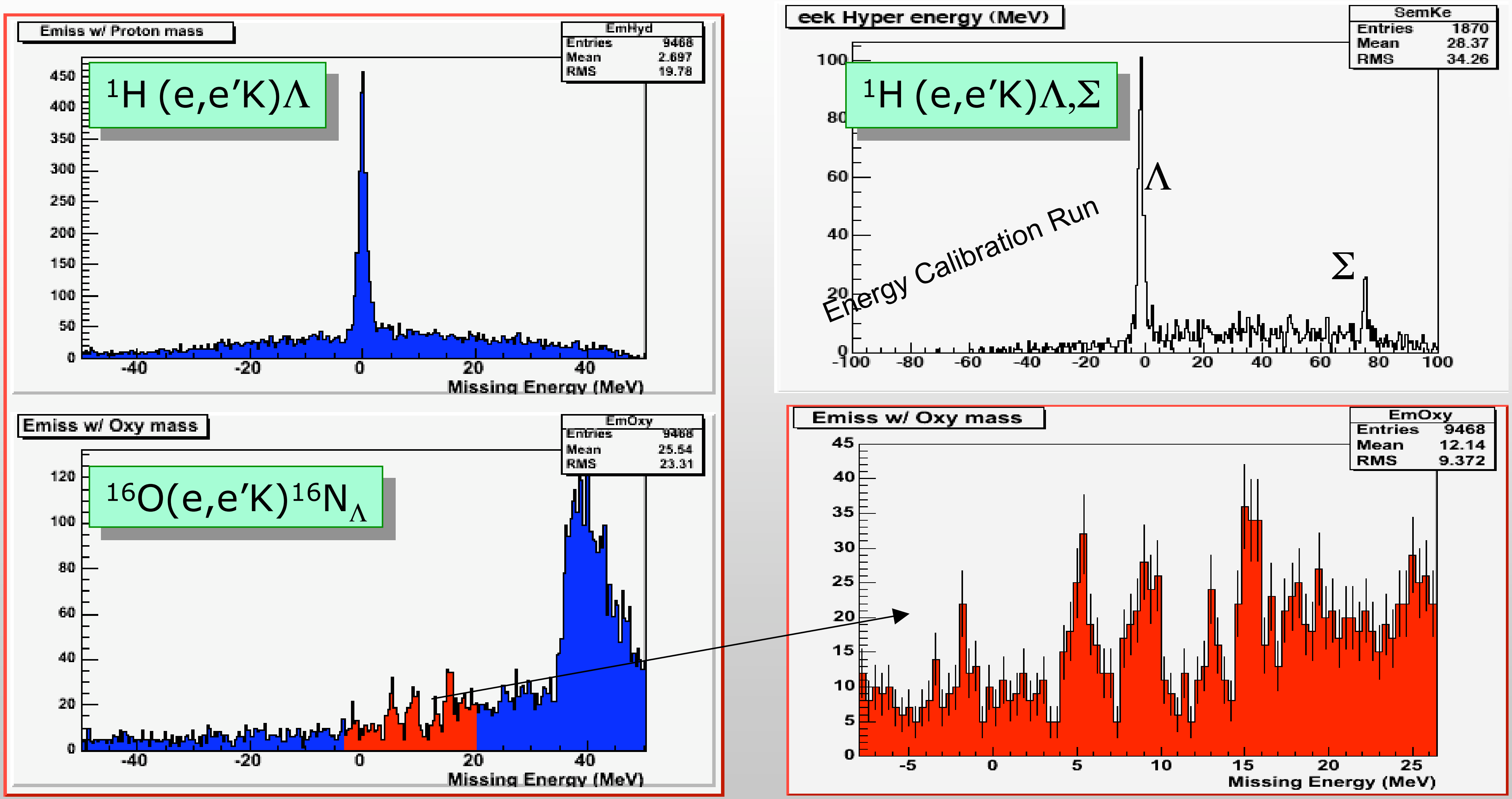
Analysis of the reaction $^{16}\mathbf{O}(e,e'K)^{16}\mathbf{N}_{\Lambda}$

and $^{1}\mathbf{H}(e,e'K)\Lambda$ (elementary reaction)

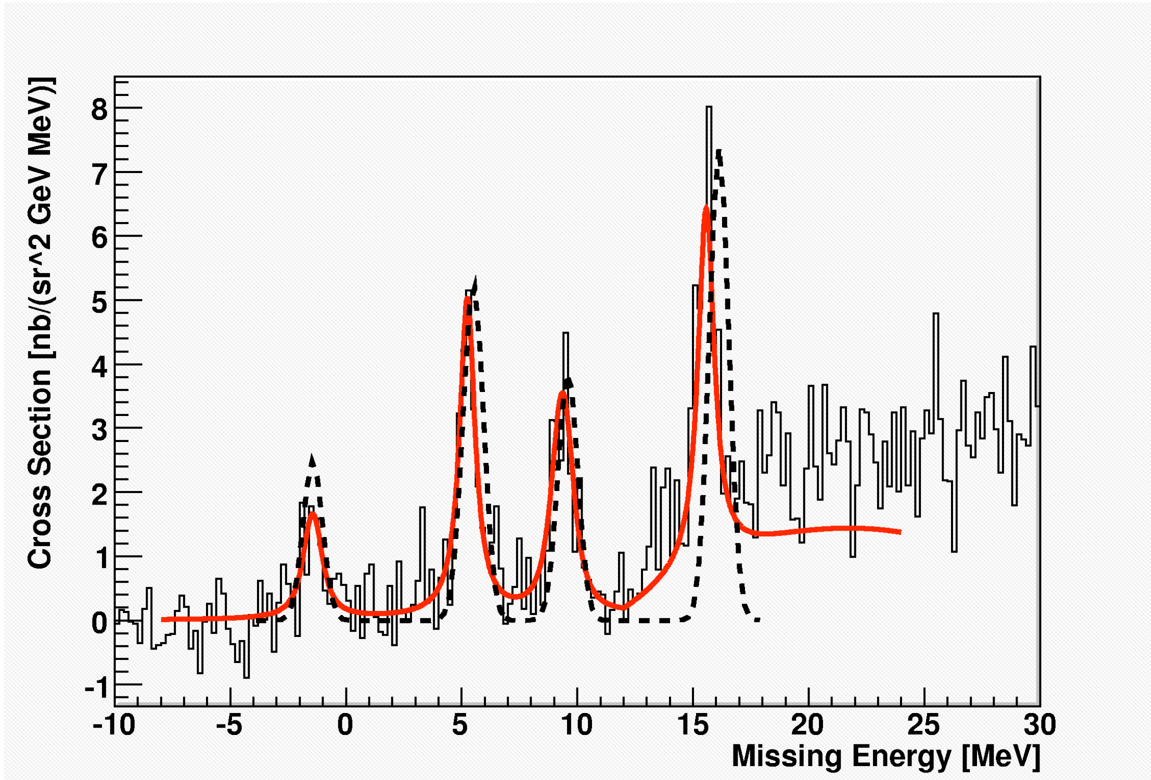
the WATERFALL target: provides ^{16}O and H targets



Preliminary Results on the WATERFALL target - ^{16}O and H spectra



Results on ^{16}O target – Hypernuclear Spectrum of $^{16}N_{\Lambda}$



- Fit to the data: Fit 4 regions with 4 Voigt functions
  $\Rightarrow \chi^2_{/ndf} = 1.19$
- Theoretical model superimposed curve based on :
  - i) SLA p(e,e'K+)Λ (elementary process)
  - ii) ΛN interaction fixed parameters from KEK and BNL $^{16}{}_{\Lambda}$O spectra

- Peak Search :
Identified 4 regions with excess counts above background

E_x/E_Λ (MeV)	Width (FWHM, MeV)
0.0/13.57 ± 0.25	0.992
6.68 ± 0.10	0.800
10.80 ± 0.13	1.125
17.00 ± 0.09	0.851

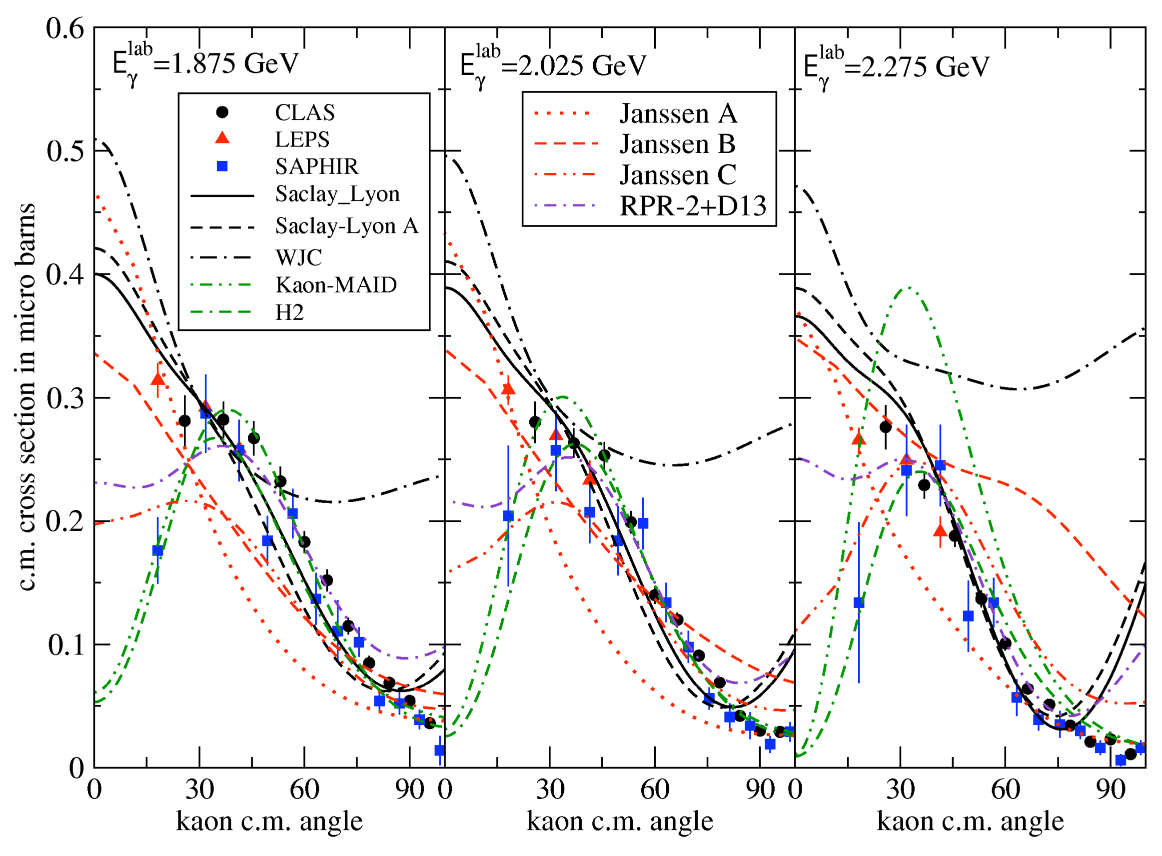
Binding Energy B_{Λ}=13.57±0.25 MeV

Measured for the first time with this level of accuracy (ambiguous interpretation from emulsion data; interaction involving Λ production on *n* more difficult to normalize)

Results on H target – The elementary process $^1H(e,e'K)\Lambda$

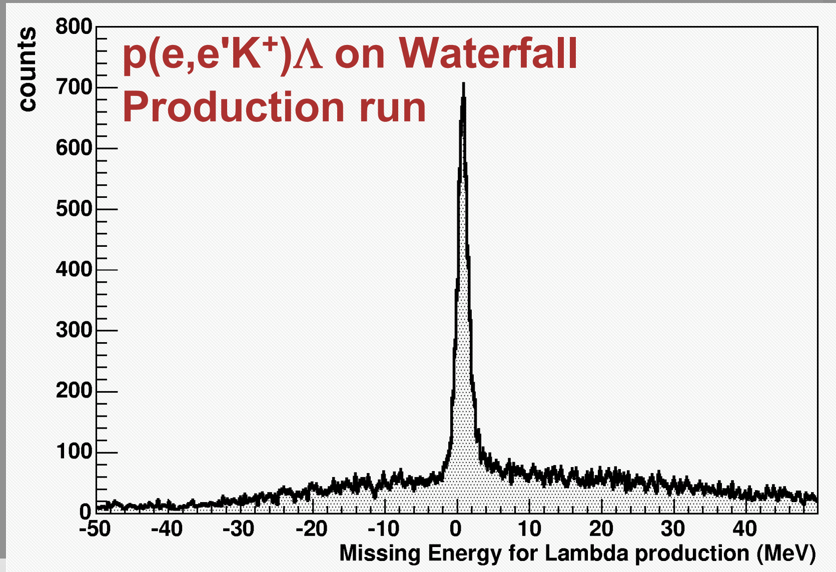
In all Jlab hypernuclear electroproduction experiments the K^+ mesons are detected at very small (few degrees) laboratory scattering angles, at very low Q^2 (close to the photon-point).

This region of kaon scattering angles is not covered, unfortunately, even by recent very precise photo- and electroproduction data on the elementary production process from CLAS, SAPHIR, and LEPS Collaborations.

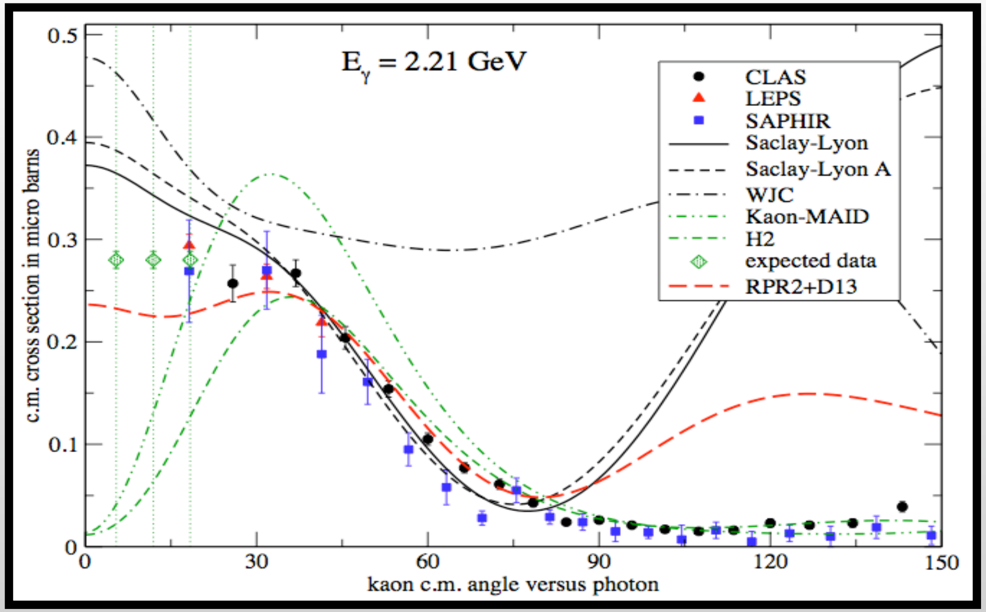


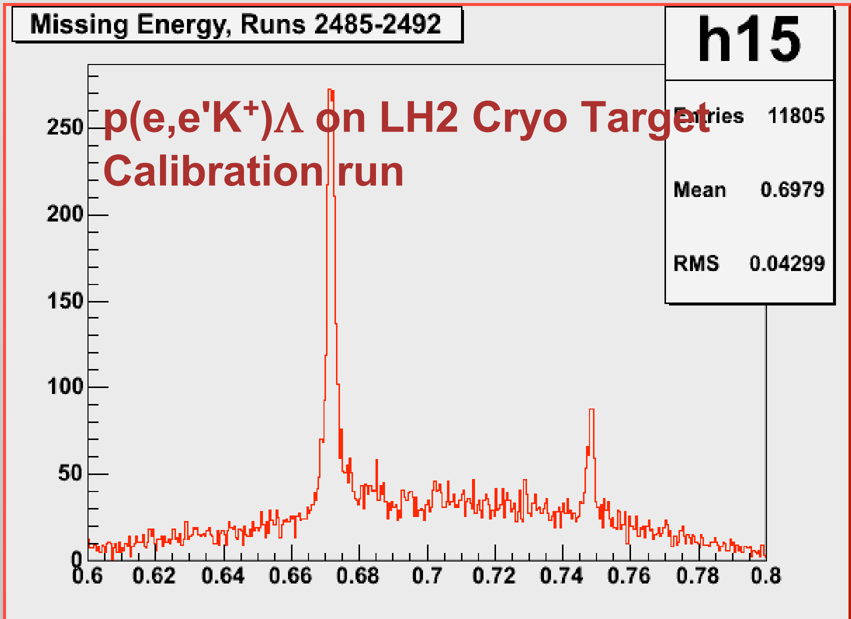
In this kinematic region different models for the K^+-Λ electromagnetic production on protons differ drastically.
This lack of relevant information about the elementary process makes an interpretation of obtained hypernuclear spectra difficult.

Results on H target – The p(e,e'K)Λ Cross Section

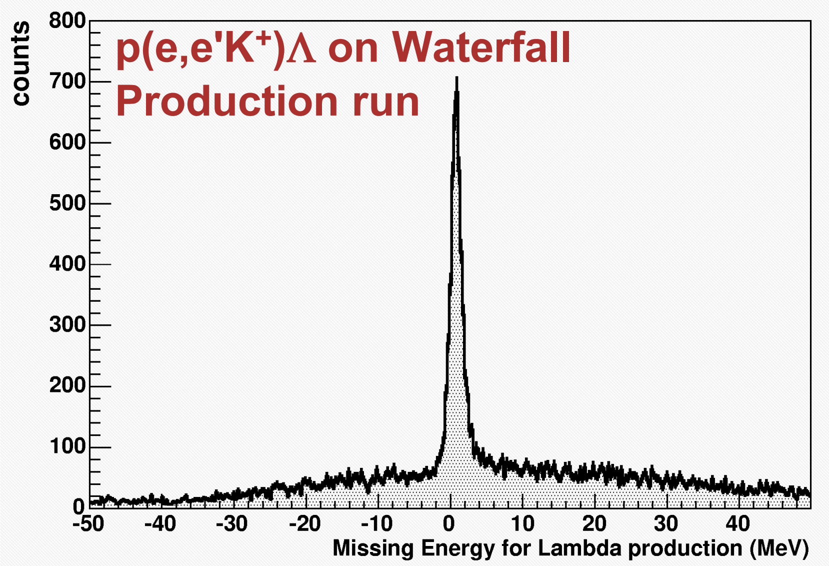


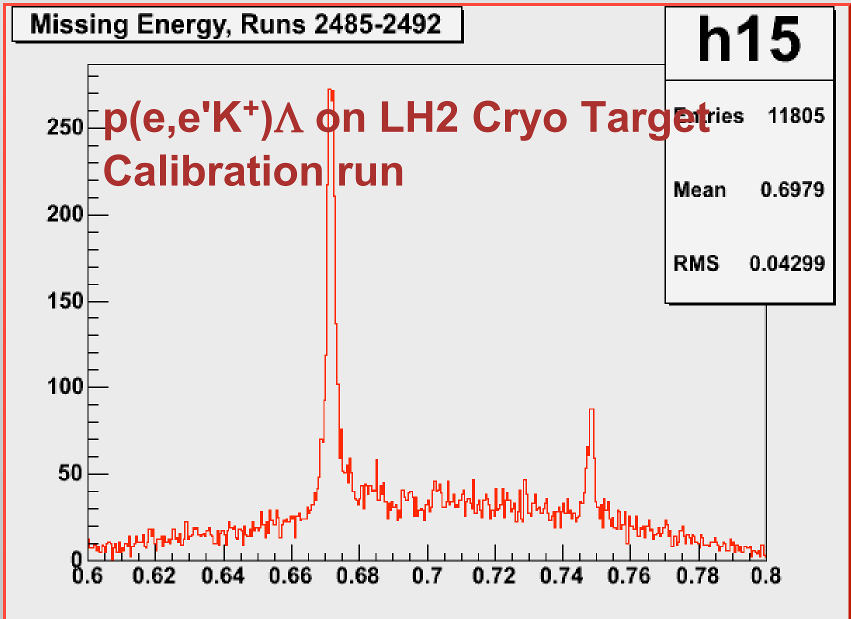
Work on normalizations, acceptances, efficiencies still underway



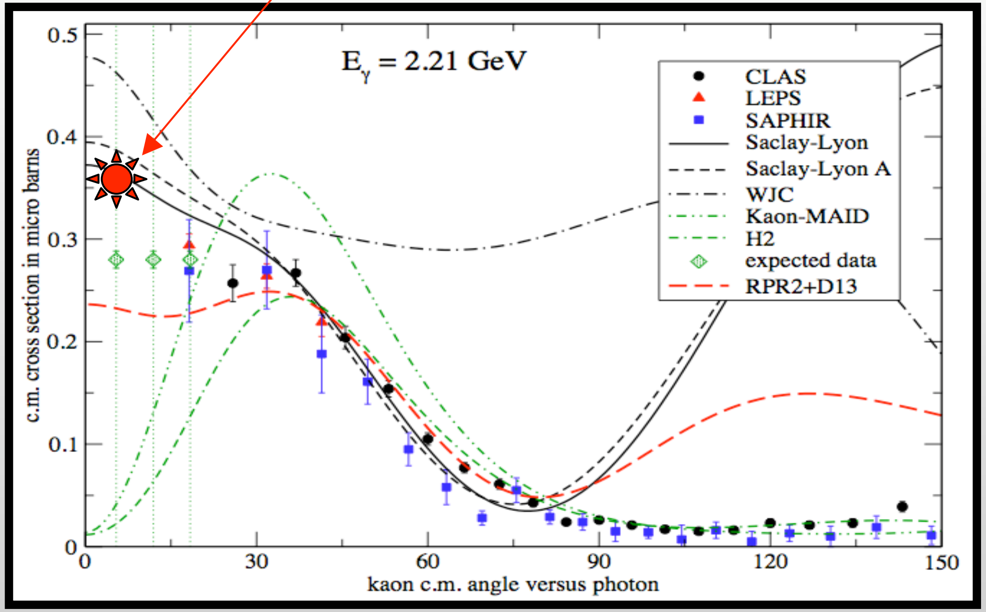


Results on H target – The p(e,e'K)Λ Cross Section



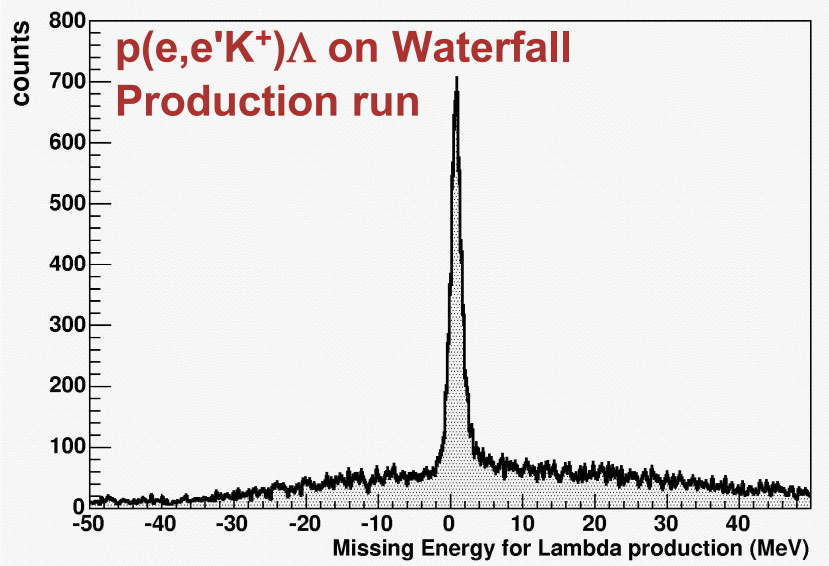


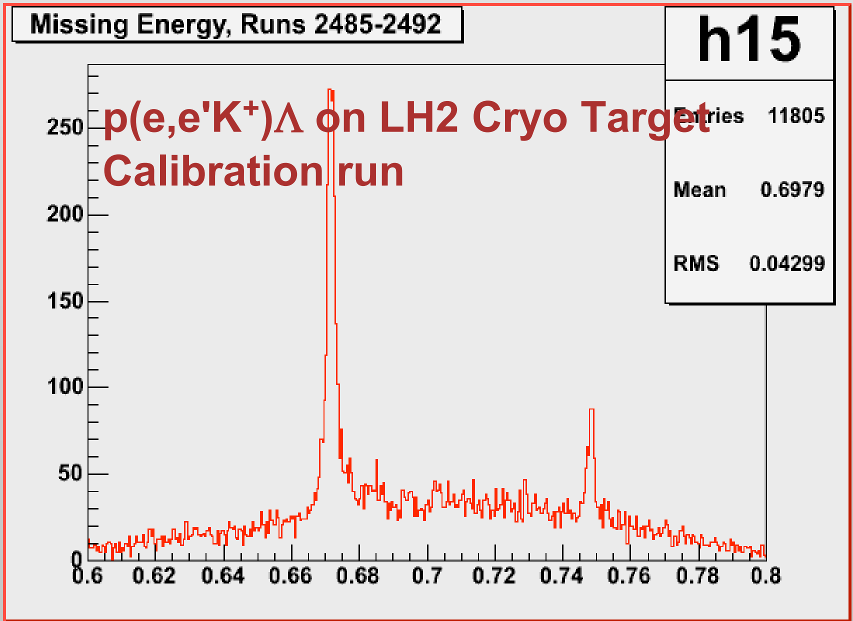
Work on normalizations, acceptances, efficiencies still underway



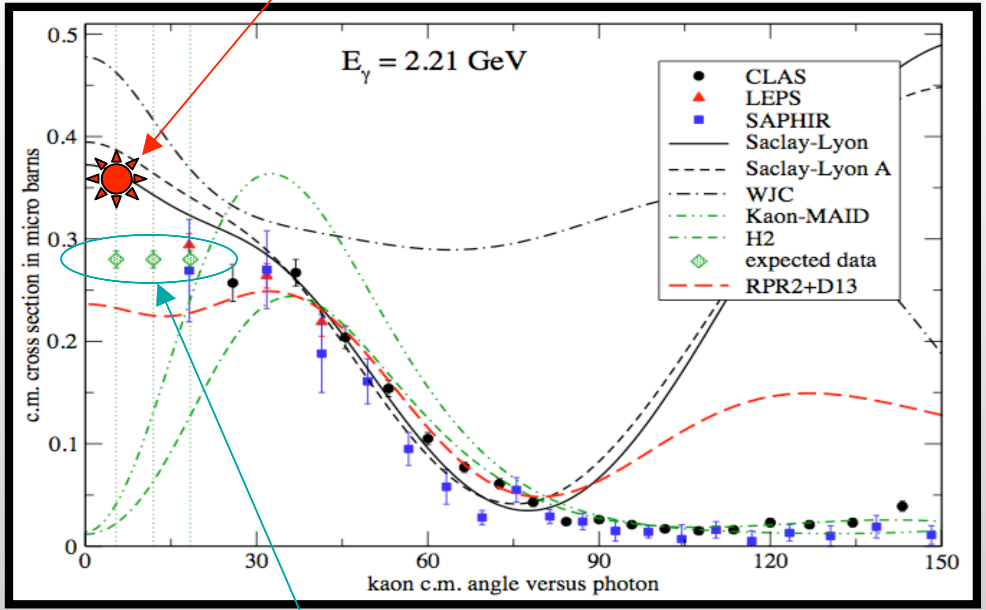
Preliminary results on the p(e,e'K)Λ cross section (consistent between LH_2 and Waterfall target) agree with the Saclay Lyon A Model

Results on H target – The p(e,e'K)Λ Cross Section





Work on normalizations, acceptances, efficiencies still underway



Expected data from the Proposal E07-012 to study the angular dependence of p(e,e'K)Λ and $^{16}O(e,e'K)^{16}N_{\Lambda}$ at Low Q^2 **approved January, 2007**

Conclusions:

- Successful program in Hypernuclear Spectroscopy by Electron Scattering at Jefferson Lab.
- New experimental equipments showed excellent performance.
- High quality data on ^{12}C, ^{7}Li and ^{28}Si (**$^{12}B_{\Lambda}$, $^{7}He_{\Lambda}$ and $^{28}Al_{\Lambda}$** hypernuclei) have been taken in **Hall C**. ^{12}C results published. Analysis in Progress.
- High quality data on ^{12}C, ^{9}Be and ^{16}O targets (**$^{12}B_{\Lambda}$, $^{9}Li_{\Lambda}$ and $^{16}N_{\Lambda}$** hypernuclei) have been taken in **Hall A**. ^{12}C results published. ^{16}O paper in preparation. Analysis in Progress also for the important data on the elementary process $p(e,e'K)\Lambda$
- VERY Promising physics is coming out from Jlab hypernuclear Program
  - ✓ From present data
  - ✓ From APPROVED Experiments