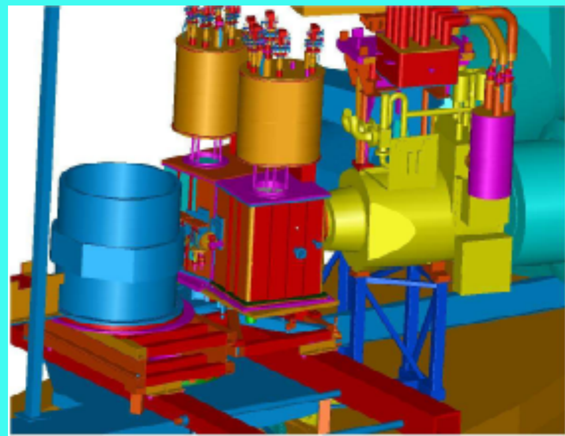
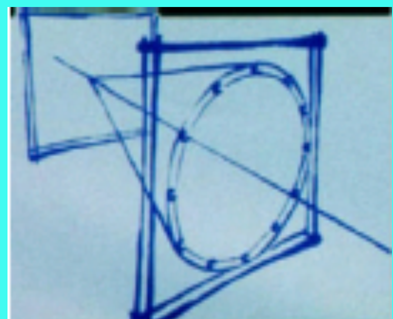
Overview and status of Hall A experiments

F. Garibaldi – Joint SPHERE and JSPS Meeting 2010

- Hypernuclear spectroscopy in Hall A
  - ^{12}C, ^{16}O, ^{9}Be, H
- Next step: angular distribution (elementary reaction)



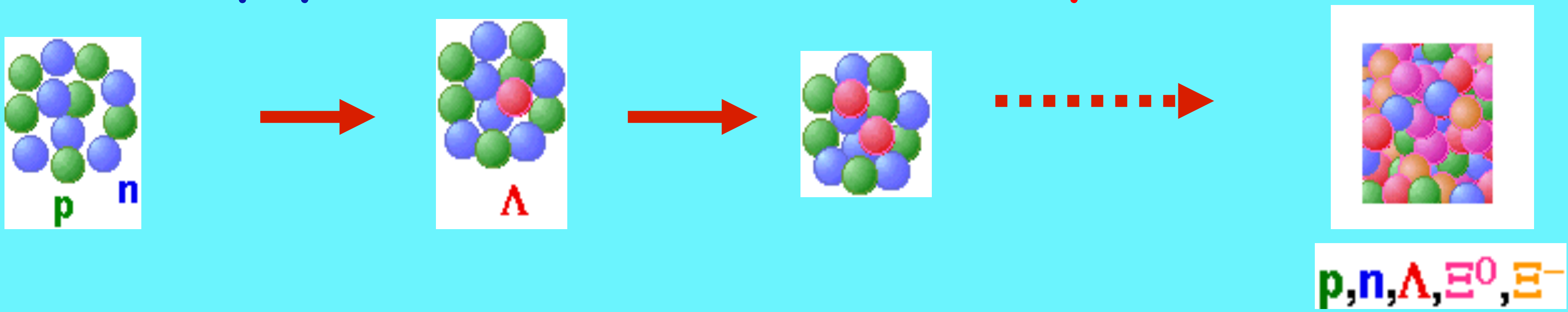
- Experimental issues
  - forward angle (septum magnets)
  - PID
    - TOF
    - aerogel detector
    - RICH



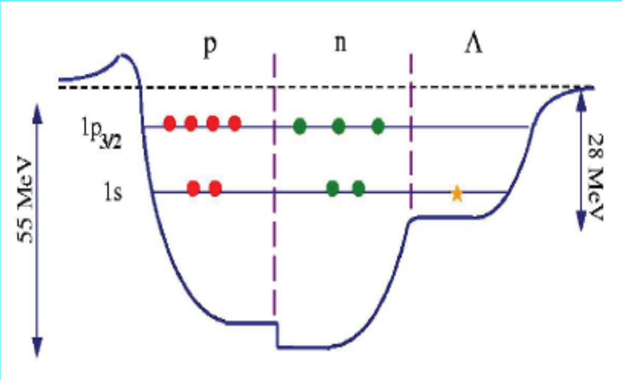
HYPERNUCLEAR PHYSICS

- Hypernuclei are bound states of nucleons with a strange baryon (Λ)

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



- Internal nuclear shell are not Pauli-blocked for hyperons



a "laboratory" to study

↓

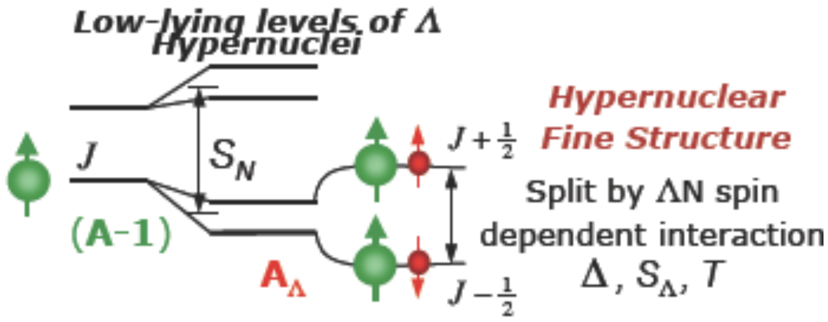
Λ - N interaction

Unique aspects of strangeness many body problems

Spectroscopy of Hypernuclei

hypernuclear data well described by weak coupling model

Λ (s-shell) + J_{A-1} --------> $J=J_{A-1}\pm 1/2$
(Λ hyperon) (parent nucleus) (create *doublet* state)
(J state)

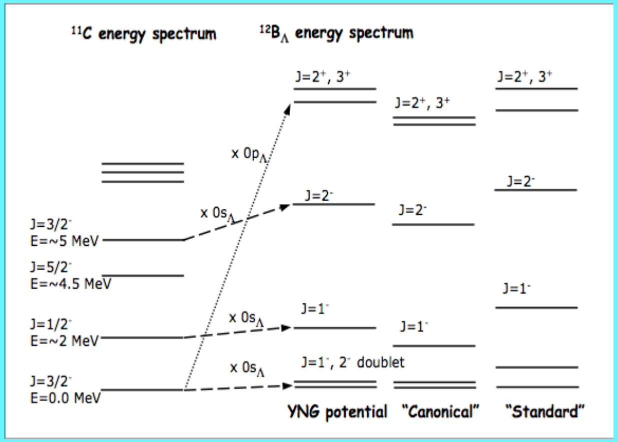


ΛN interaction

V

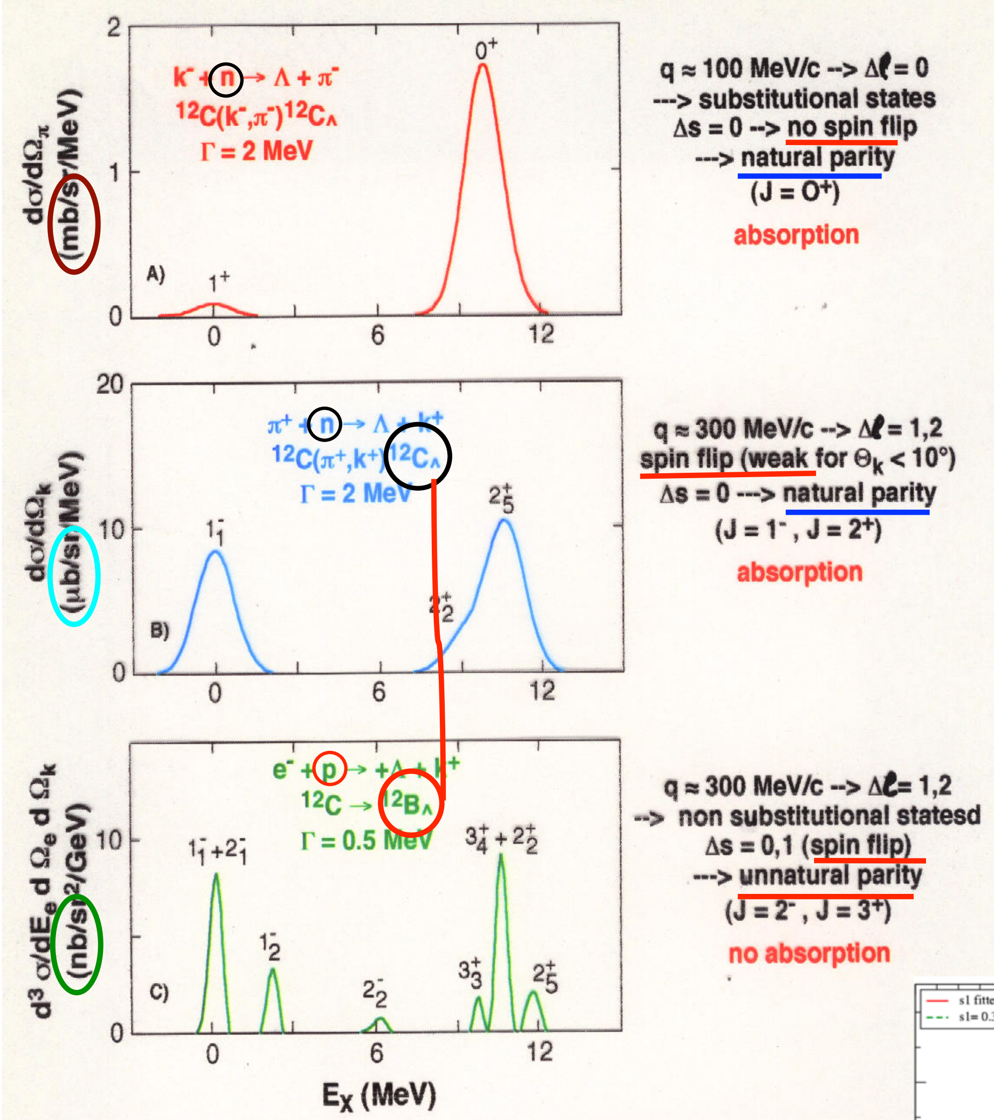
$V_{\Lambda N} = V_0(r)$ central

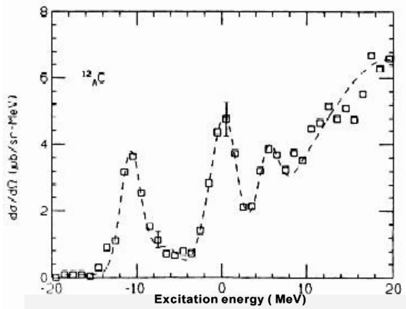
Δ	$+\ V_\sigma(r)\cdot\sigma_N\cdot\sigma_\Lambda$	Δ (spin-spin)
S_Λ	$+\ V_{\sigma 0}(r)\cdot\lambda_{\Lambda N}\cdot\sigma_\Lambda$	σ_Λ (spin-orbit)
S_N	$+\ V_{\sigma 0}(r)\cdot\lambda_{\Lambda N}\cdot\sigma_N$	σ_N (spin-orbit)
T	$+\ V_T(r)\cdot S_{12}$	T (tensor)



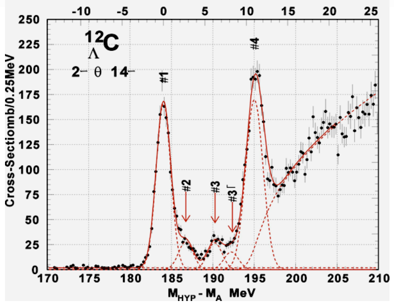
Each of the 5 radial integral (V, Δ, S_Λ, S_N, T) can be phenomenologically determined from the low lying level structure of p-shell hypernuclei

- ✔ most of information is carried out by the spin dependent part
- ✔ doublet splitting determined by Δ, σ_Λ, T



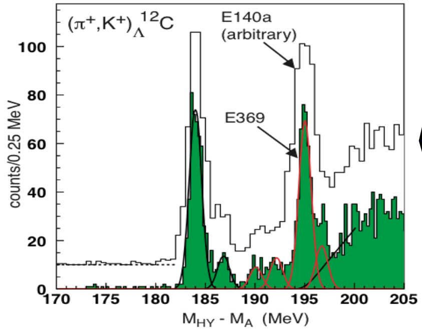


BNL 3 MeV



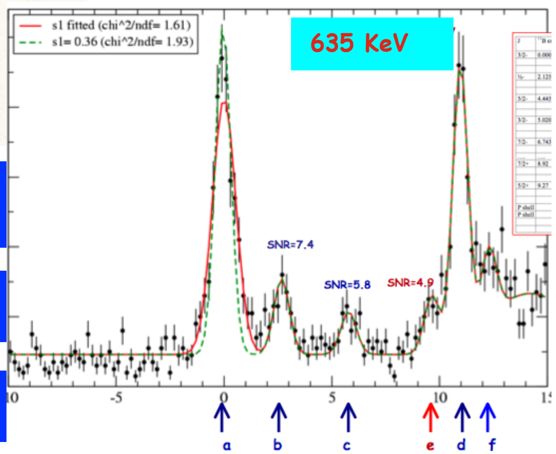
KEK336 2 MeV

Improving energy resolution



~ 1.5 MeV

and



using electromagnetic probe

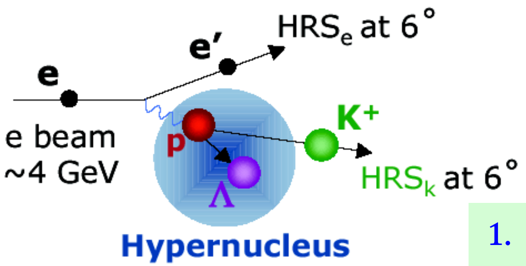
High resolution, high yield, and systematic study is essential

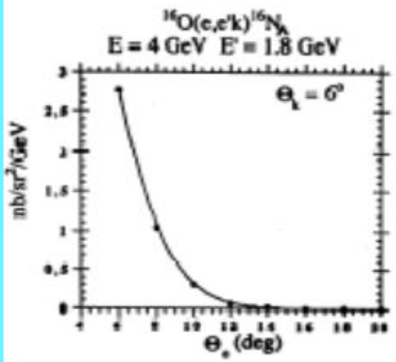
new aspects of hyernuclear structure

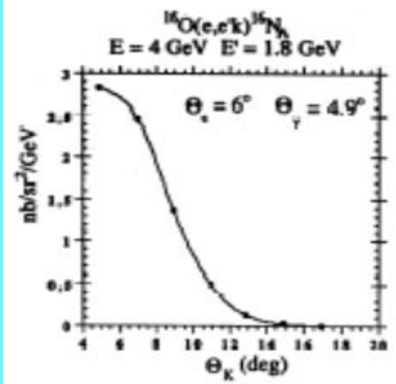
production of mirror hypernuclei

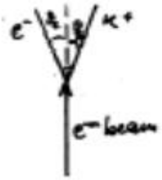
energy resolution ~ 500 KeV

$^{A}Z(e,e'K)^{A}(Z-1)_{\Lambda}$









1. $\Delta E_{beam}/E$: 2.5×10^{-5}
2. $\Delta P/P$: $\sim 10^{-4}$
3. Straggling, energy loss…

~ 500- 600 keV

reasonable counting rates

forward angle

septum magnets

good energy resolution

do not degrade HRS

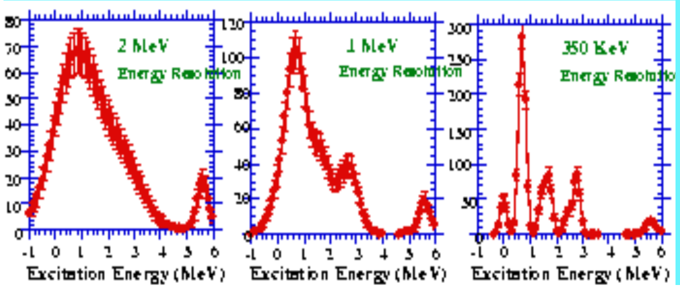
minimize beam energy instability

"background free" spectrum

unambiguous K identification

High P_k/high E_{in} (Kaon survival)

RICH detector



Kaon collaboration

FLORIDA INTERNATIONAL UNIVERSITY

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
and Theorists: Petr Bydzovsky, John Millener, Miloslav Sotona

→ $^{16}O(e,e'K^+)^{16}{}_{\Lambda}N$

→ $^{12}C(e,e'K^+)^{12}{}_{\Lambda}B$

→ $^{9}Be(e,e'K^+)^{9}{}_{\Lambda}Li$

→ $H(e,e'K^+)\Lambda,\Sigma^0$

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/cm²

Counting Rates ~ 0.1 – 10 counts/peak/hour

E-98-108. Electroproduction of Kaons up to Q2=3(GeV/c)2 (P. Markowitz, M. Iodice, S. Frullani, G. Chang spokespersons)

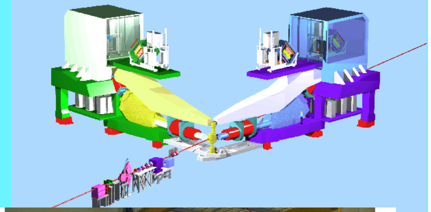
E-07-012. The angular dependence of $^{16}O(e,e'K^+)^{16}N$ and $H(e,e'K^+)\Lambda$ (F. Garibaldi, M.Iodice, J. LeRose, P. Markowitz spokespersons) (run : April-May 2012)

UNIVERSITY OF MARYLAND

HAMPTON UNIVERSITY

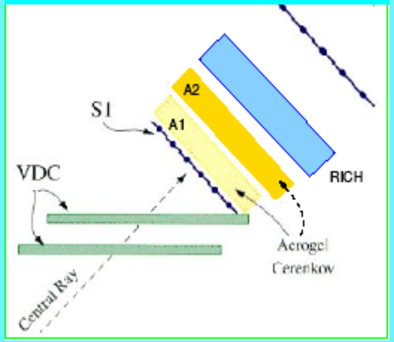
Jefferson Lab Exploring the Nature of Matter

Hall A deector setup

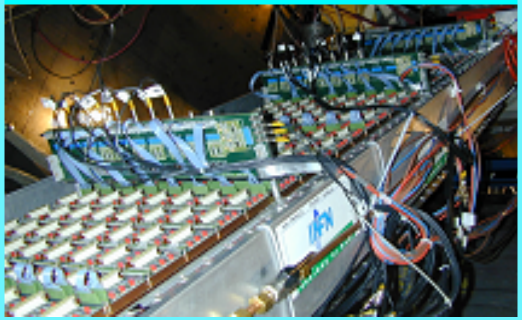


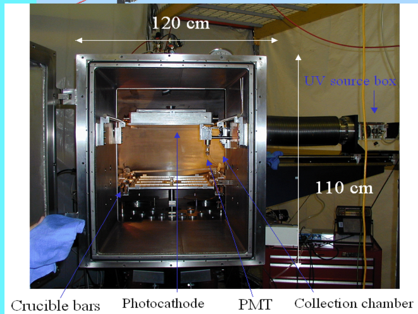
aerogel first generation

hadron arm

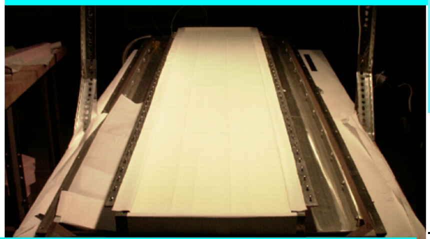


RICH Detector

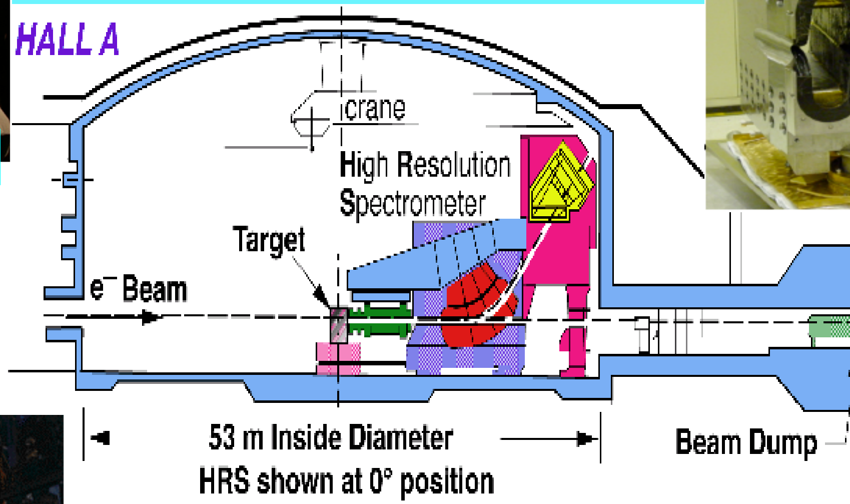


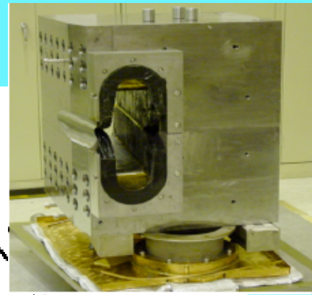


aerogel, cherenkov

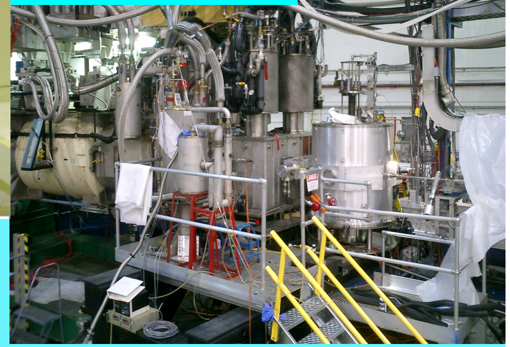


aerogel second generation





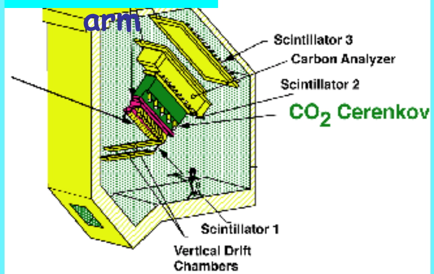
septum magnets



waterfall

gas cherenkov

electron arm



To be added to do the experiment

$^{16}O(e,e'K)^{16}N_\Lambda$ F. Cusanno et al., Phys. Rev. Lett. E052501, 99 (2007)

σ_{sp}= 4.47 nb/(GeV sr^2

σ_{th}= 4.68 nb/(GeV sr^2)

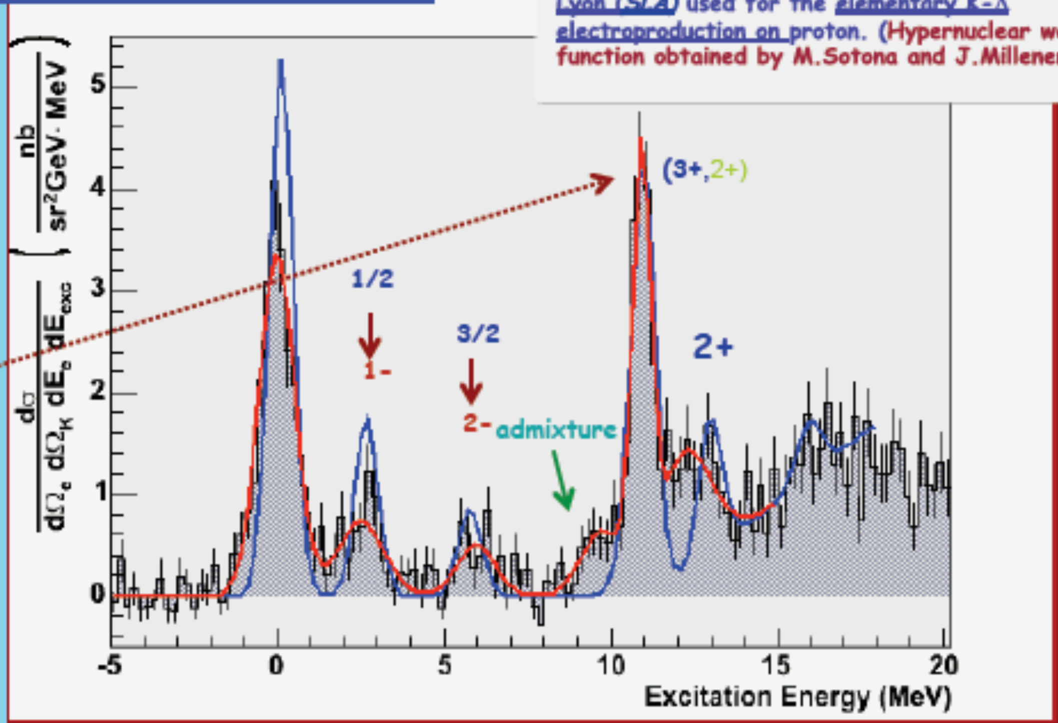
good agreement with theory

E94-107 $^{12}C(e,e'K)^{11}{}_\Lambda B$

TABLE I: Detected levels in the $^{12}C(e,e'K)^{12}B_\Lambda$ Spectrum

Position (MeV)	Width (σ)	SNR	Cross Section (nb/sr^2/GeV)
0.0 ± 0.03	0.53	18.1	4.47 ±0.21(st) ±0.58(sys)
2.52 ± 0.11	0.69	[illegible]	1.26 ±0.11(st) ±0.16(sys)
5.97 ± 0.13	0.55	5.5	0.72 ±0.09(st) ±0.09(sys)
9.76 ± 0.15	0.65	6.7	0.91 ±0.10(st) ±0.12(sys)
10.95 ±0.02	0.27	14.7	2.90 ±0.17(st) ±0.38(sys)
12.22 ±0.11	0.81	10.5	2.42 ±0.16(st) ±0.31(sys)

Red line: Fit to the data
Blue line: *Theoretical* curve: Sagay Saclay-Lyon (SLA) used for the elementary K-Λ electroproduction on proton. (Hypernuclear wave function obtained by M.Sotona and J.Millener)



The energies of the 1/2- and 3/2- levels of the core are raised primarily by the S_N term because the interaction I_N. S_N changes the spacing of the core levels (the magnitude can be changed by changing S_N or changing the p-shell w.f. of the core)

-energy resolution ~ 635 KeV, the best achieved in hypernuclear production experiments

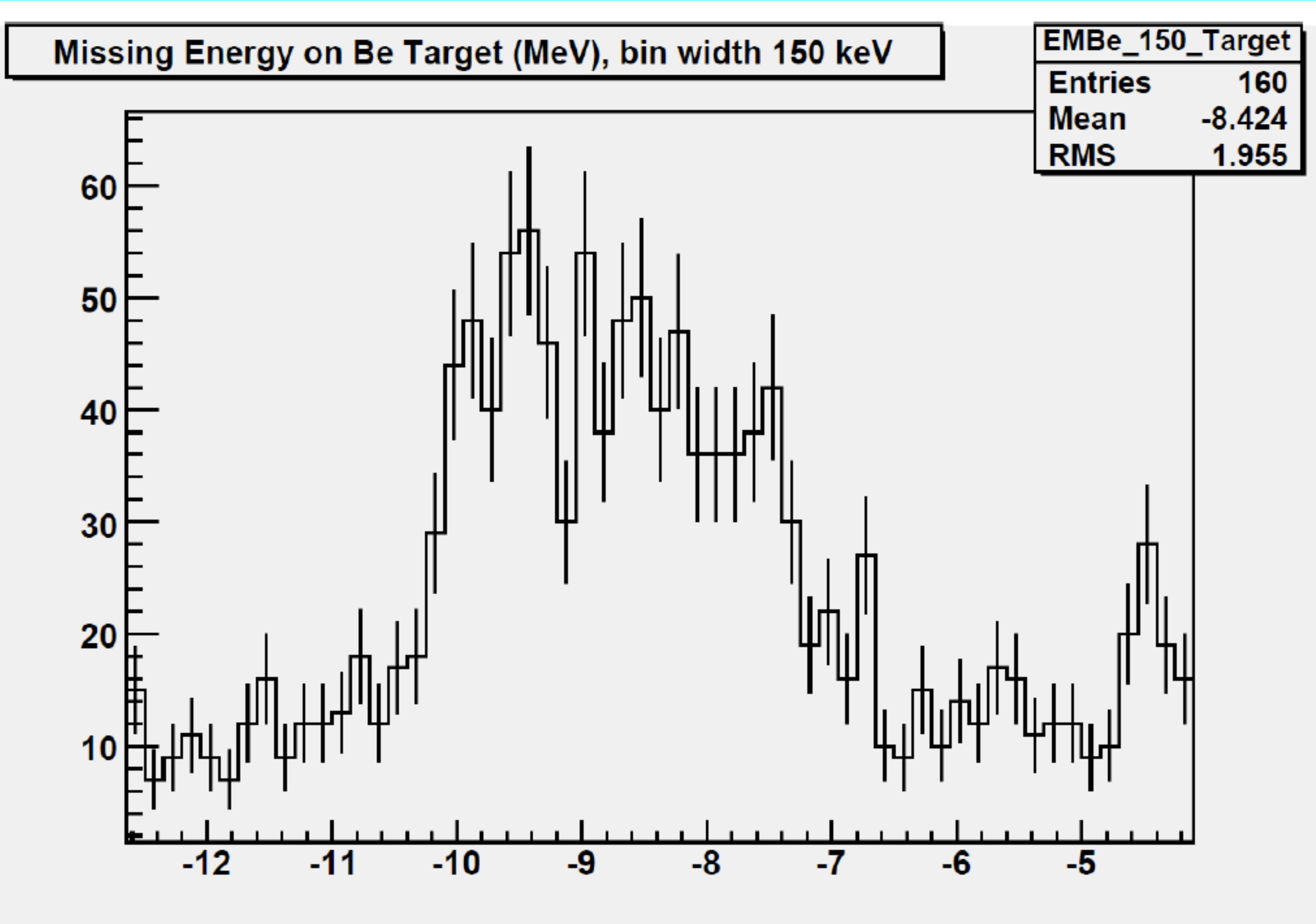
-first clear evidence of excited core states at ~2.5 and 6.5 MeV with high statistical significance

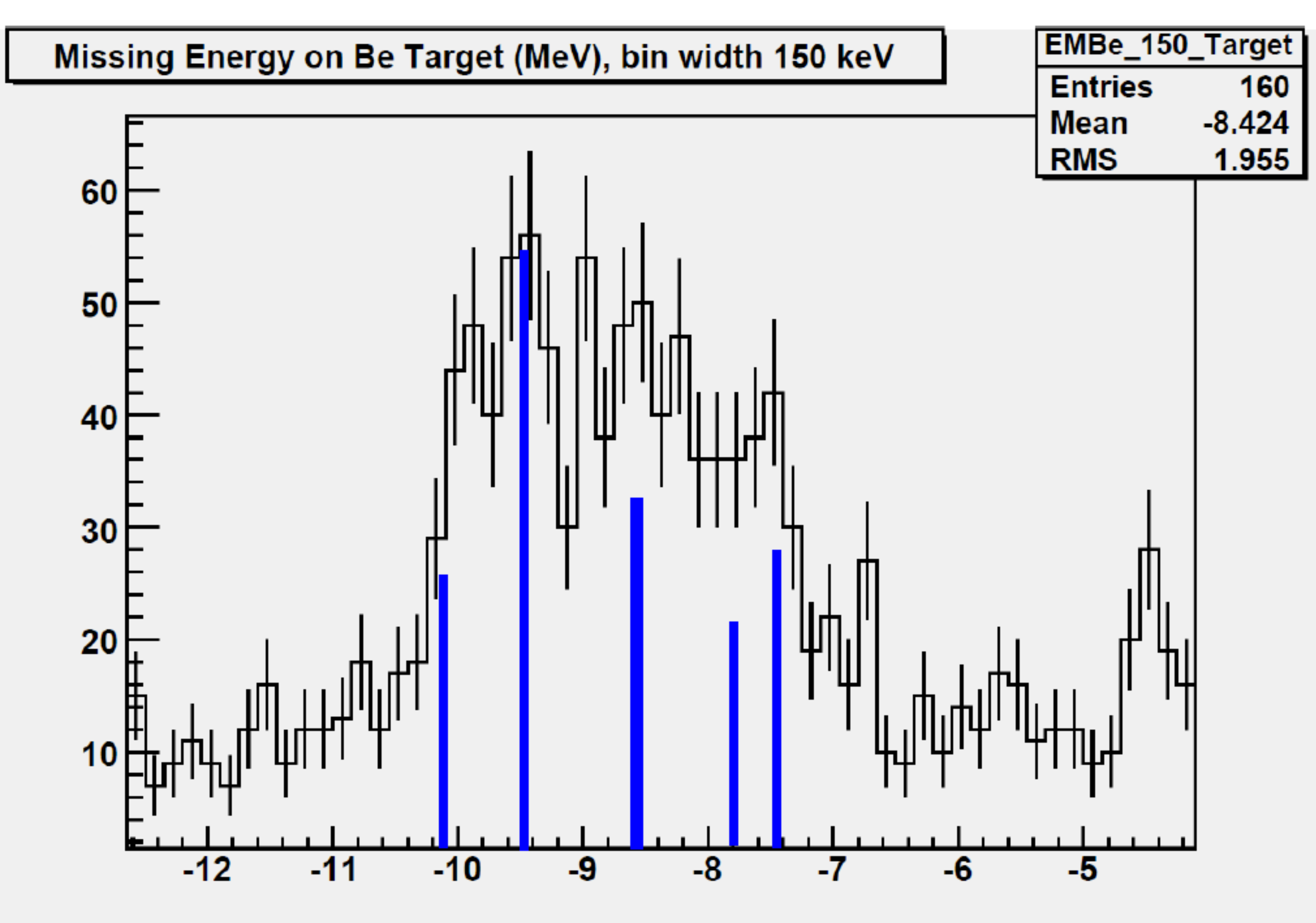
-the width of the strong p_Λ peak and the distribution of strength within several MeV on either side of this peak can put constraints on the hypernuclear structure calculations

-hint for a peak at 9.65 MeV excitation energy (admixture)

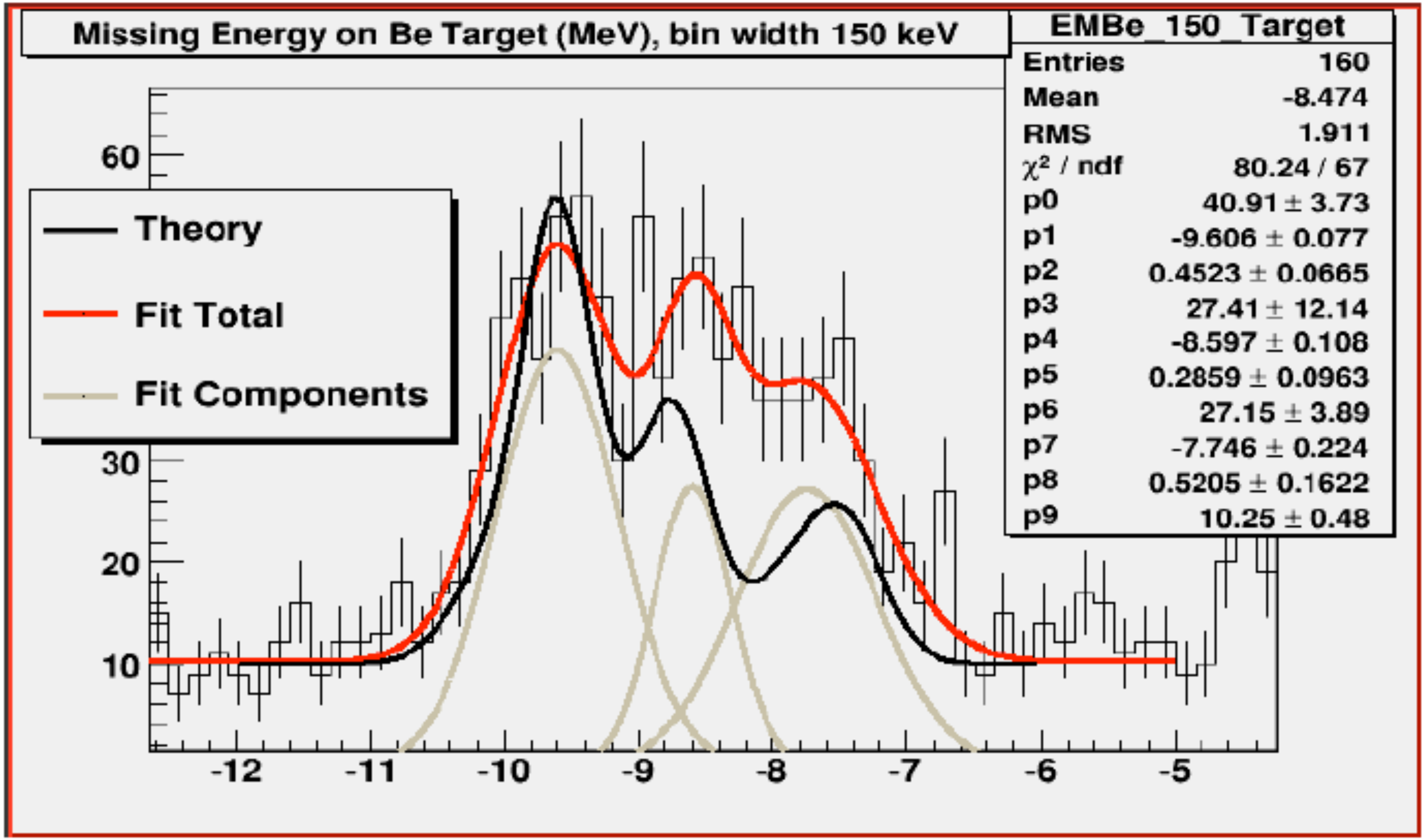
Analysis of the reaction $^9Be(e,e'K)^9Li_\Lambda$

preliminary

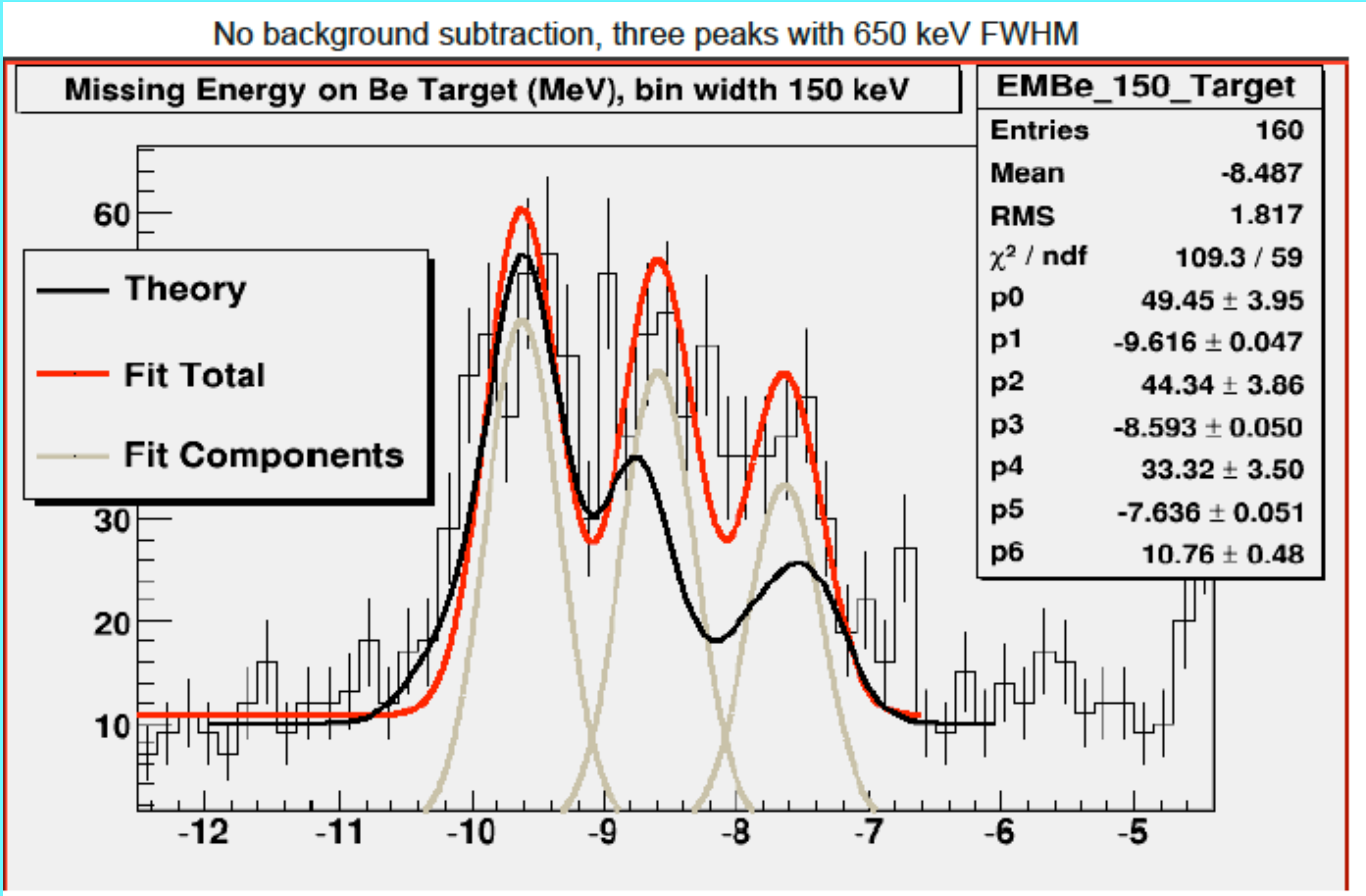



Missing Energy on Be Target (MeV), bin width 150 keV
EMBe_150_Target
Entries 160
Mean -8.424
RMS 1.955
60
50
40
30
20
10
-12
-11
-10
-9
-8
-7
-6
-5

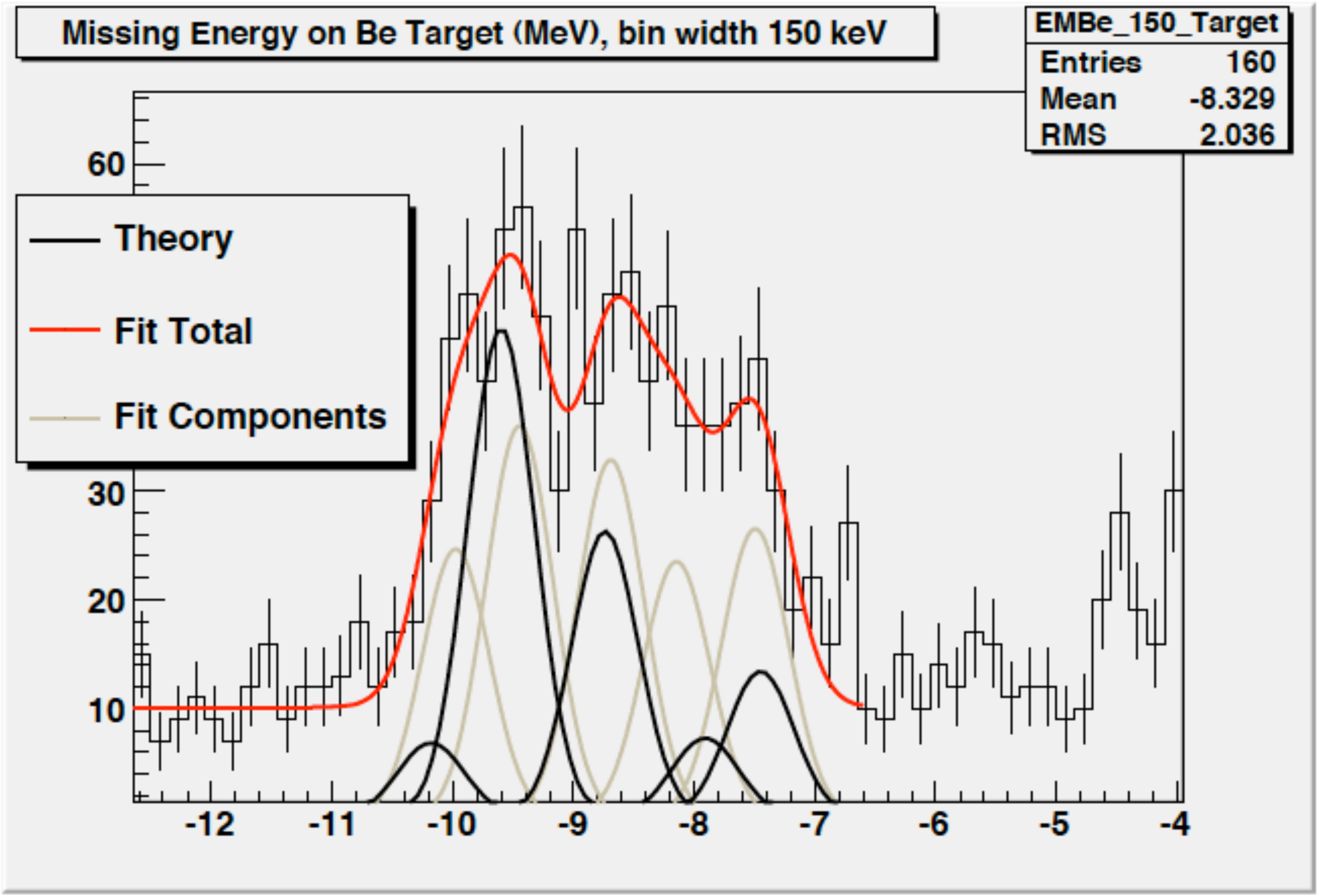
No background subtraction, three peaks with three independent gaussians, extended range of fit



Background fit on the left and right side

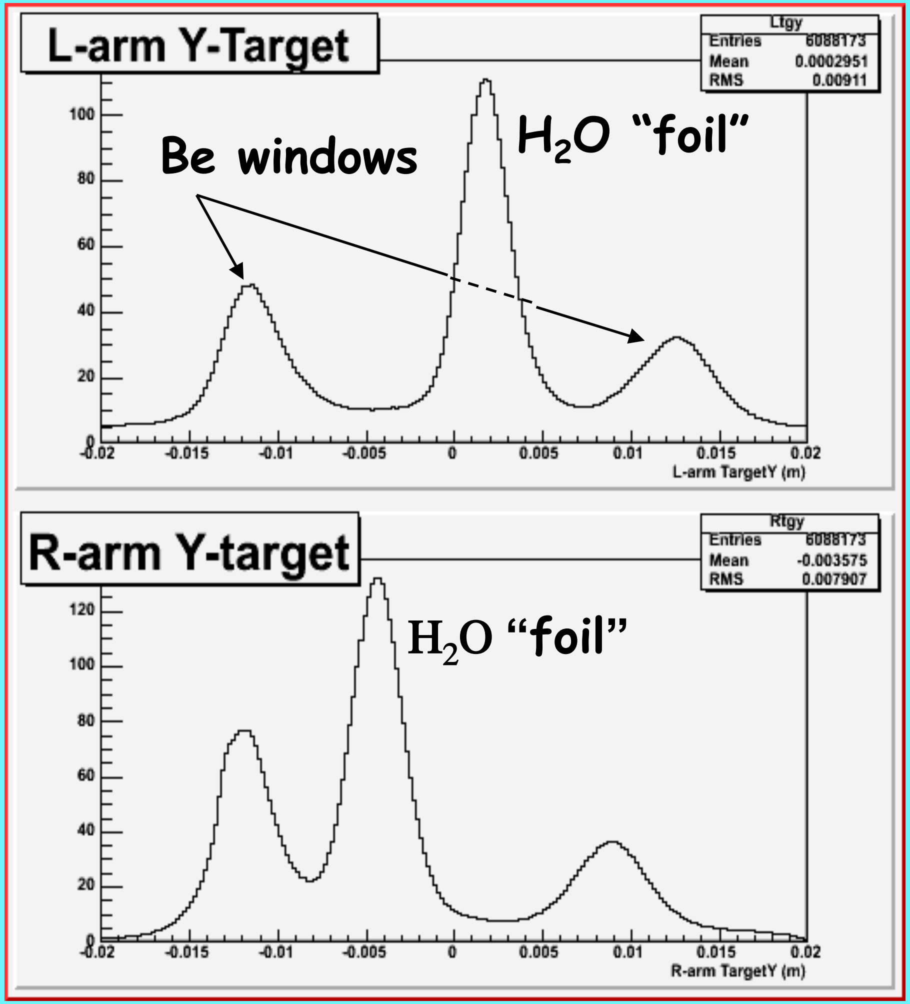


Fit with fixed resolution (form previous experiment)

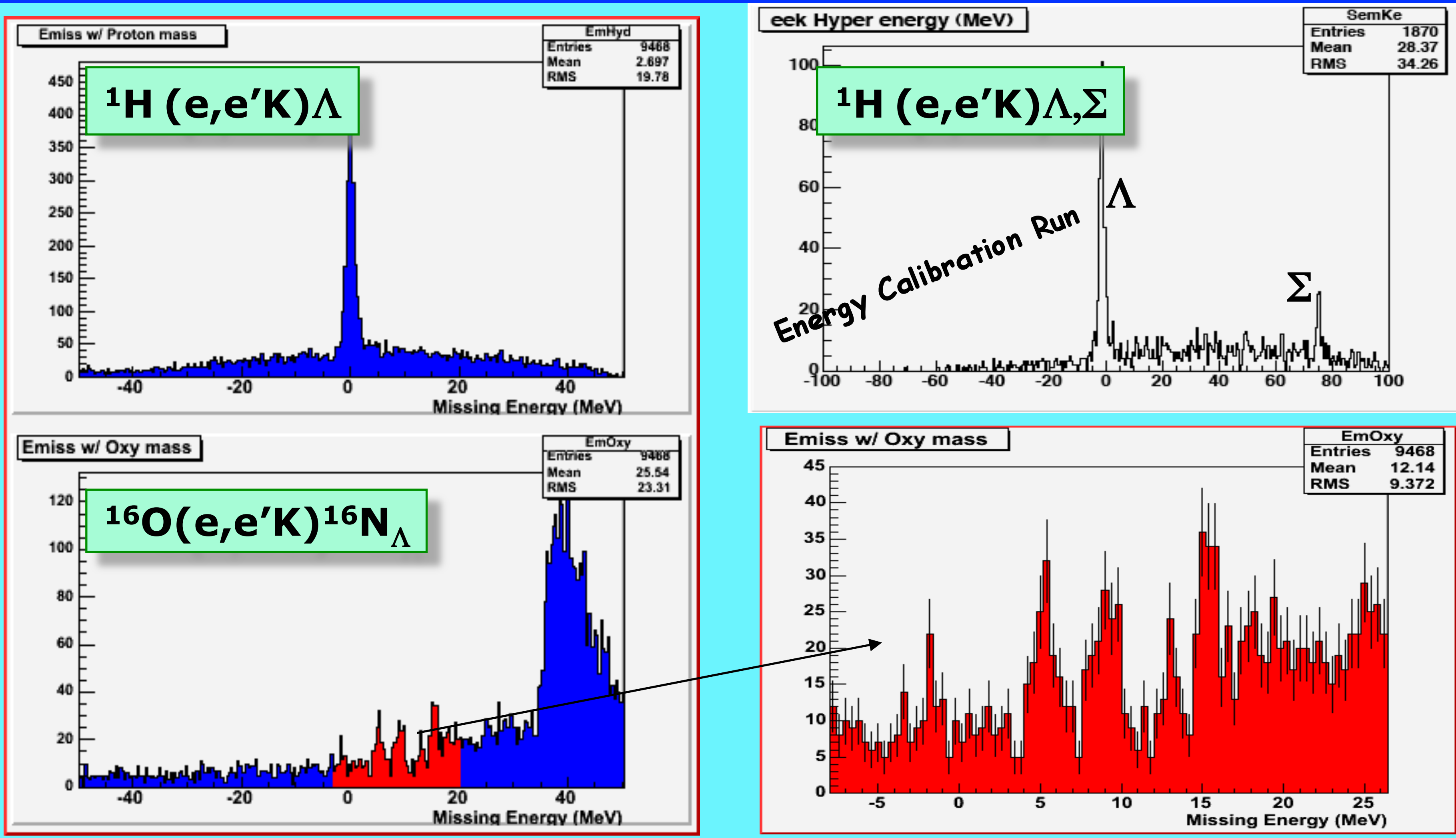


The energy axis is in binding energy calculated from the b. e. of the parent nucleus (Be-9) (how changes the b.e. if you put Lambda instead of p in s shell)

The WATERFALL target: reactions on ^{16}O and ^{1}H nuclei



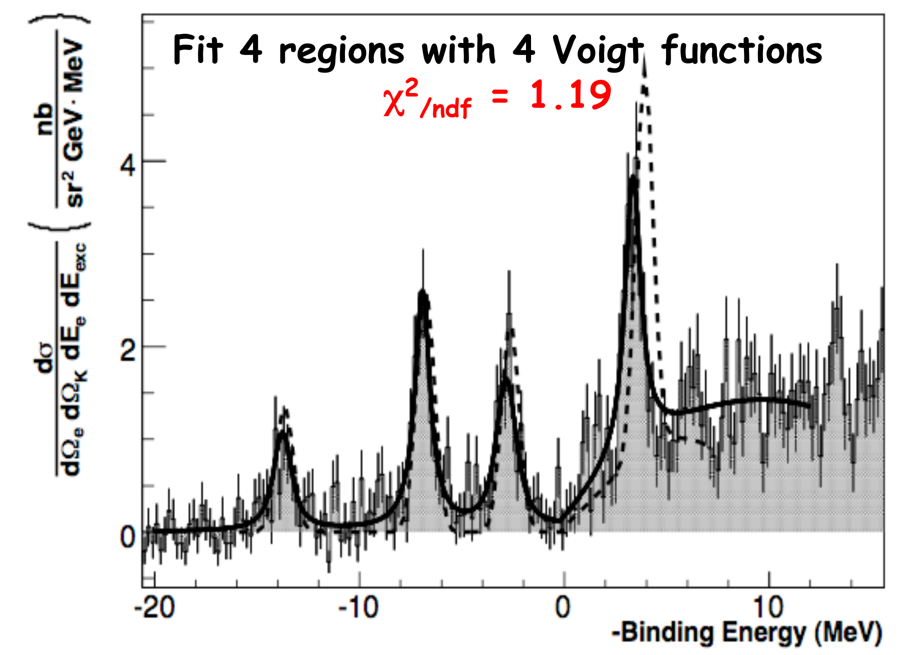
Results on the WATERFALL target - ^{16}O and ^{1}H



- Water thickness from elastic cross section on H
- Precise determination of the particle momenta and beam energy using the Lambda and Sigma peak reconstruction (energy scale calibration)

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

$^{16}O(e,e'K)^{16}N_\Lambda$ F. Cusanno et al. Phys. Rev. Lett. 202501, (2009)



Theoretical model based on :

SLA $p(e,e'K^+)\Lambda$ (elementary process)

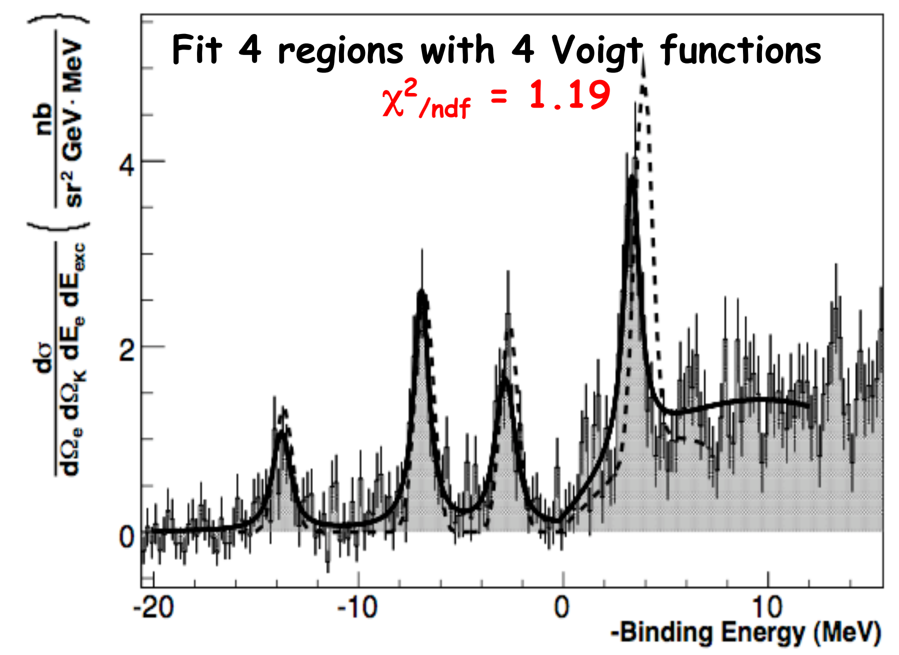
ΛN interaction fixed parameters from KEK and BNL $^{16}{}_\Lambda O$ spectra

- Four peaks reproduced by theory
- The fourth peak (Λ in p state) position disagrees with theory.

This might be an indication of a large spin-orbit term S_Λ

E_x (MeV)	Width (FWHM, MeV)	Cross section ($nb/sr^2/GeV$)	E_x (MeV)	Wave function	J^π	Cross section ($nb/sr^2/GeV$)
0.0/13.76±0.16	1.71	1.45 ± 0.26	0.00	$p_{1/2}^{-1} \otimes s_{1/2\Lambda}$	0^-	0.002
			0.03	$p_{1/2}^{-1} \otimes s_{1/2\Lambda}$	1^-	1.45
6.83 ± 0.06	0.88	3.16 ± 0.35	6.71	$p_{3/2}^{-1} \otimes s_{1/2\Lambda}$	1^-	0.80
			6.93	$p_{3/2}^{-1} \otimes s_{1/2\Lambda}$	2^-	2.11
10.92 ± 0.07	0.99	2.11 ± 0.37	11.00	$p_{1/2}^{-1} \otimes p_{3/2\Lambda}$	2^+	1.82
			11.07	$p_{1/2}^{-1} \otimes p_{1/2\Lambda}$	1^+	0.62
17.10 ± 0.07	1.00	3.44 ± 0.52	17.56	$p_{3/2}^{-1} \otimes p_{1/2\Lambda}$	2^+	2.10
			17.57	$p_{3/2}^{-1} \otimes p_{3/2\Lambda}$	3^+	2.26

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



Binding Energy B_Λ=13.76±0.16 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)

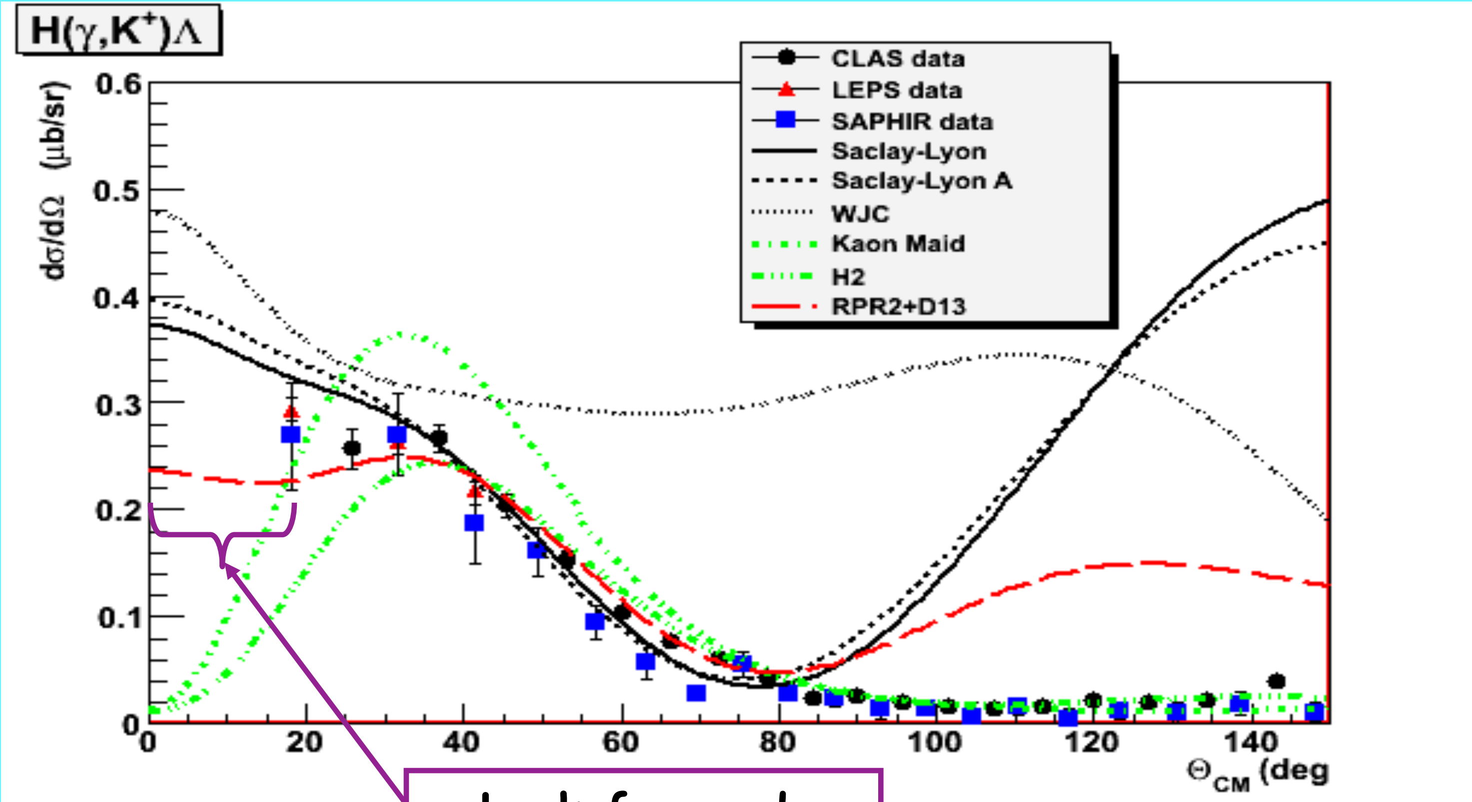
__Within errors__, the binding energy and the excited levels of the mirror hypernuclei $^{16}O_\Lambda$ and $^{16}N_\Lambda$ (this experiment) are in agreement, giving __no strong evidence of charge-dependent effects__

E_x (MeV)	Width (FWHM, MeV)	Cross section ($nb/sr^2/GeV$)	E_x (MeV)	Wave function	J^π	Cross section ($nb/sr^2/GeV$)
0.0/13.76±0.16	1.71	1.45 ± 0.26	0.00	$p_{1/2}^{-1} \otimes s_{1/2\Lambda}$	0^-	0.002
			0.03	$p_{1/2}^{-1} \otimes s_{1/2\Lambda}$	1^-	1.45
6.83 ± 0.06	0.88	3.16 ± 0.35	6.71	$p_{3/2}^{-1} \otimes s_{1/2\Lambda}$	1^-	0.80
			6.93	$p_{3/2}^{-1} \otimes s_{1/2\Lambda}$	2^-	2.11
10.92 ± 0.07	0.99	2.11 ± 0.37	11.00	$p_{1/2}^{-1} \otimes p_{3/2\Lambda}$	2^+	1.82
			11.07	$p_{1/2}^{-1} \otimes p_{1/2\Lambda}$	1^+	0.62
17.10 ± 0.07	1.00	3.44 ± 0.52	17.56	$p_{3/2}^{-1} \otimes p_{1/2\Lambda}$	2^+	2.10
			17.57	$p_{3/2}^{-1} \otimes p_{3/2\Lambda}$	3^+	2.26

H target - The elementary process $^{1}H(e,e'K)\Lambda$

JLab hypernuclear experiments detect K^{+} at small angles & low Q^{2} (close to photon-point)

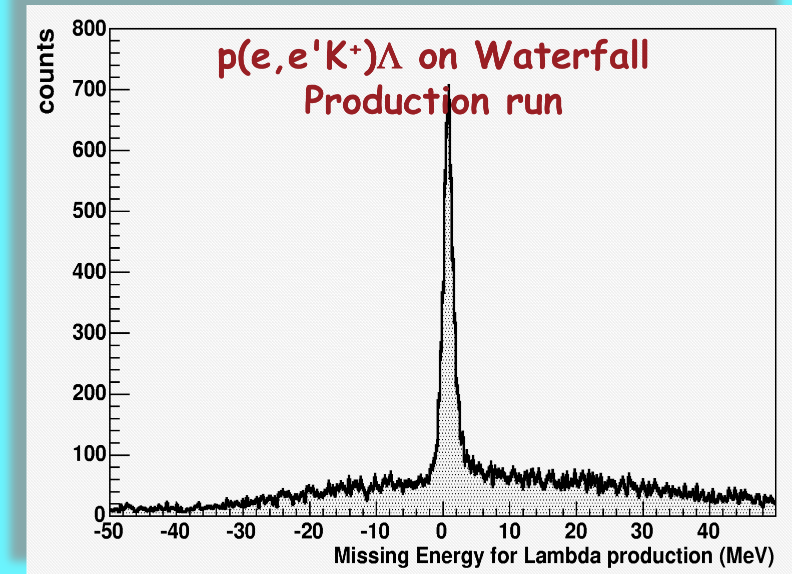
Region not covered existing photo- and electroproduction data CLAS, SAPHIR, and LEPS

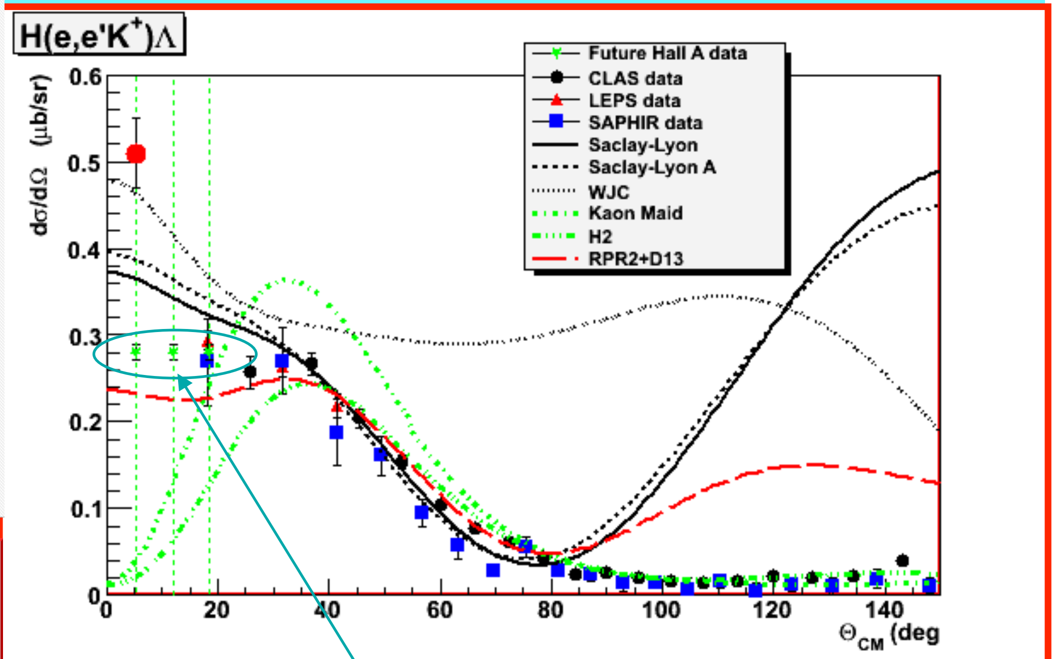


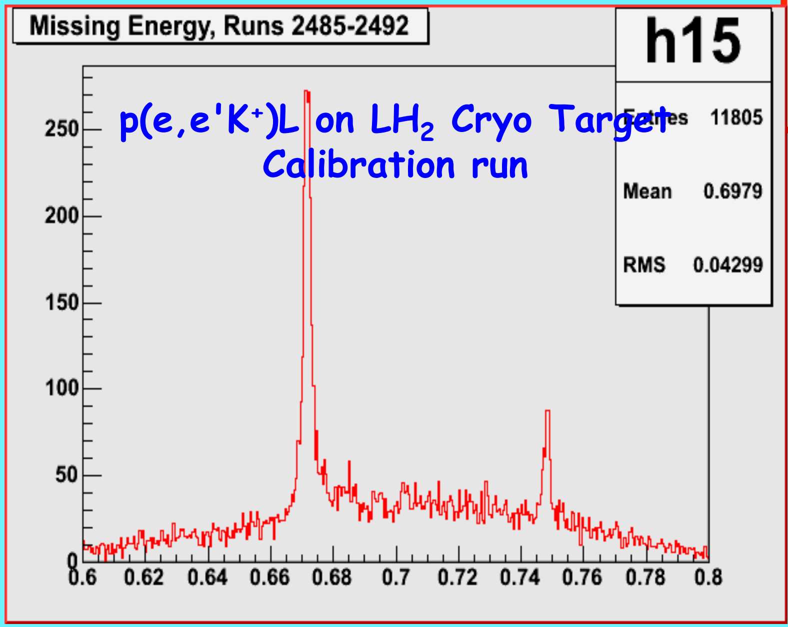
Lack forward angle data

Models differ drastically in this region.
Also makes interpretation of obtained hypernuclear spectra difficult.

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

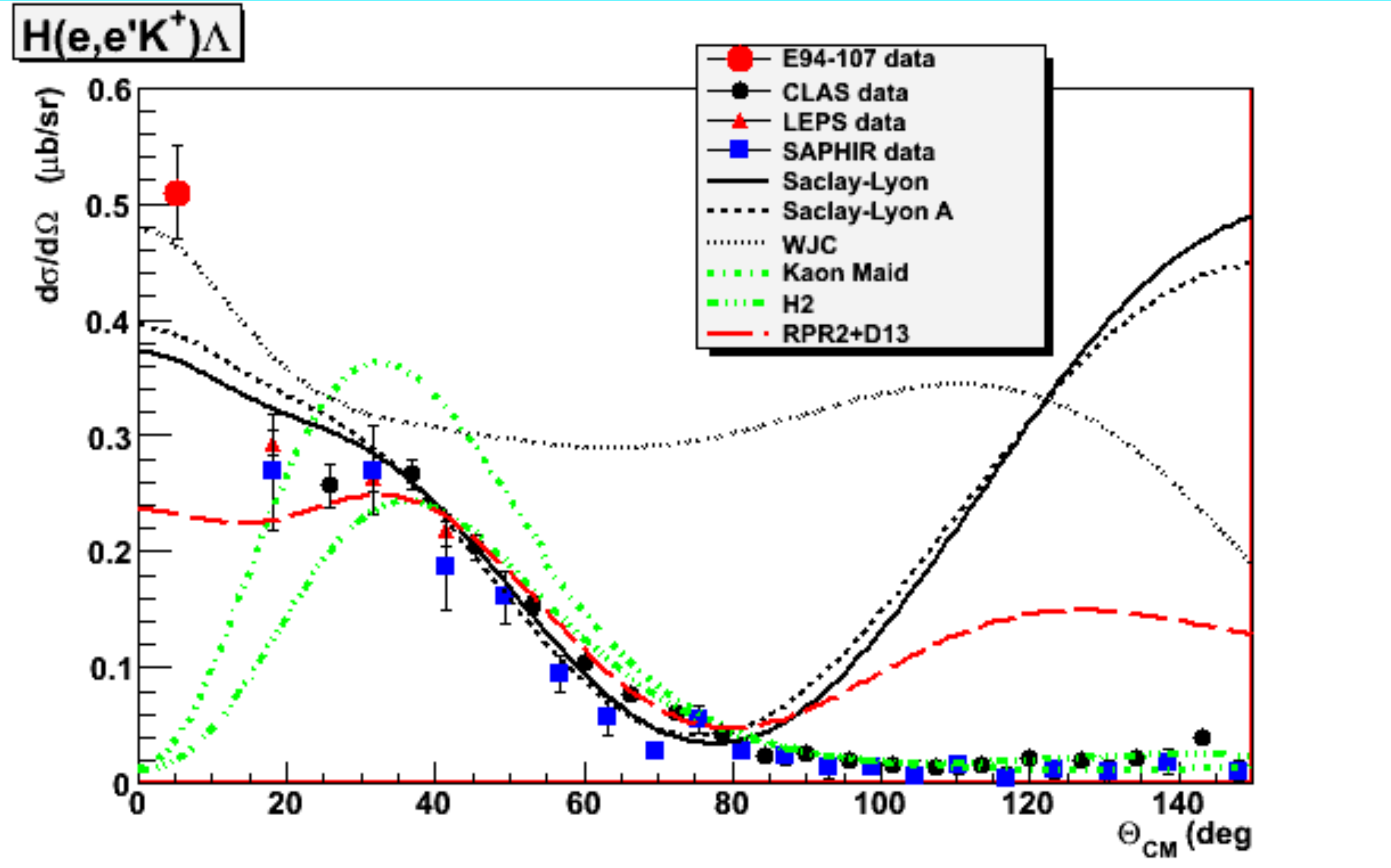






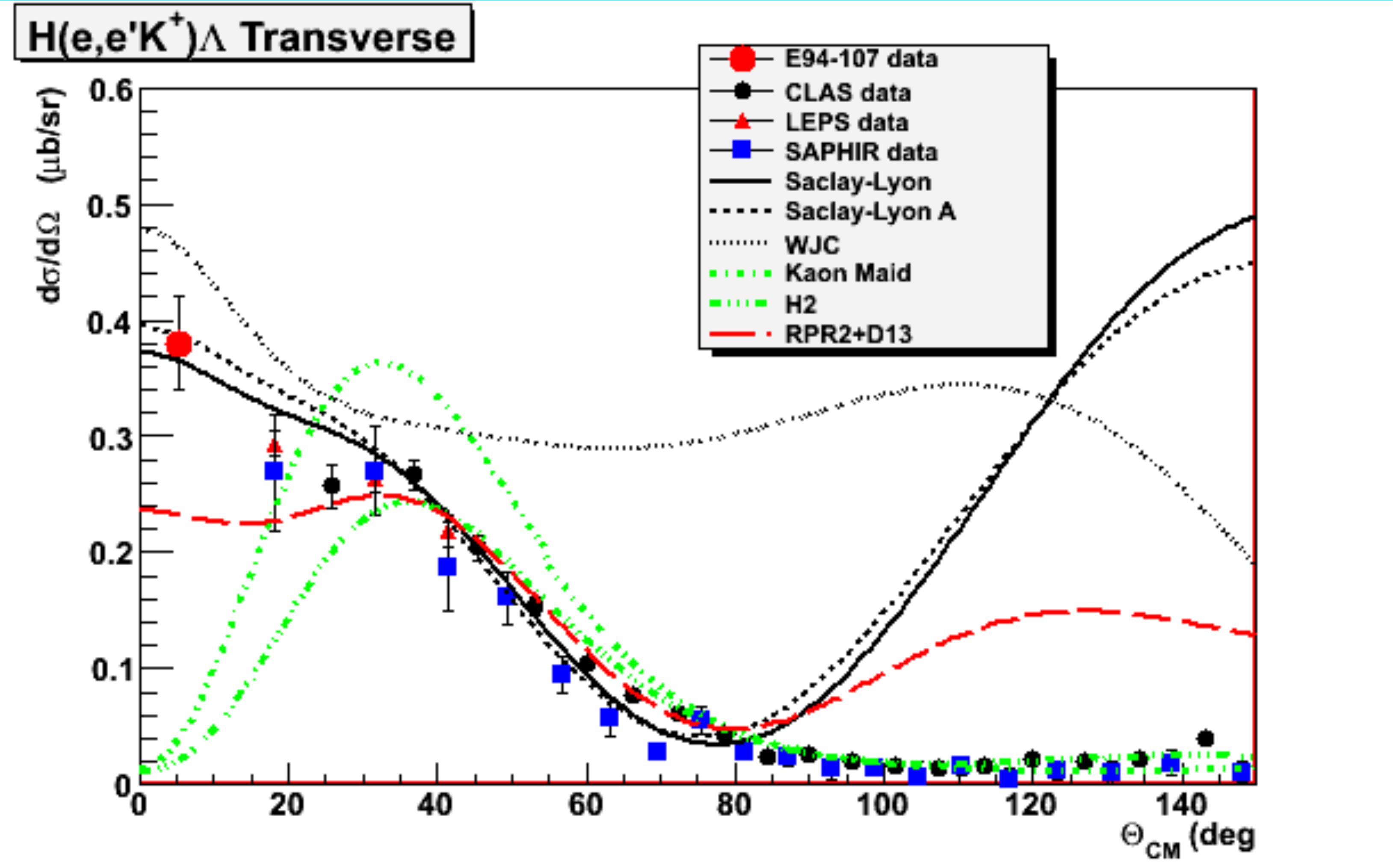
Expected data from E07-012, study the angular dependence of $p(e,e'K)\Lambda$ and $^{16}O(e,e'K)^{16}N_{\Lambda}$ at low Q^2

Results on H target – Angular distribtribution

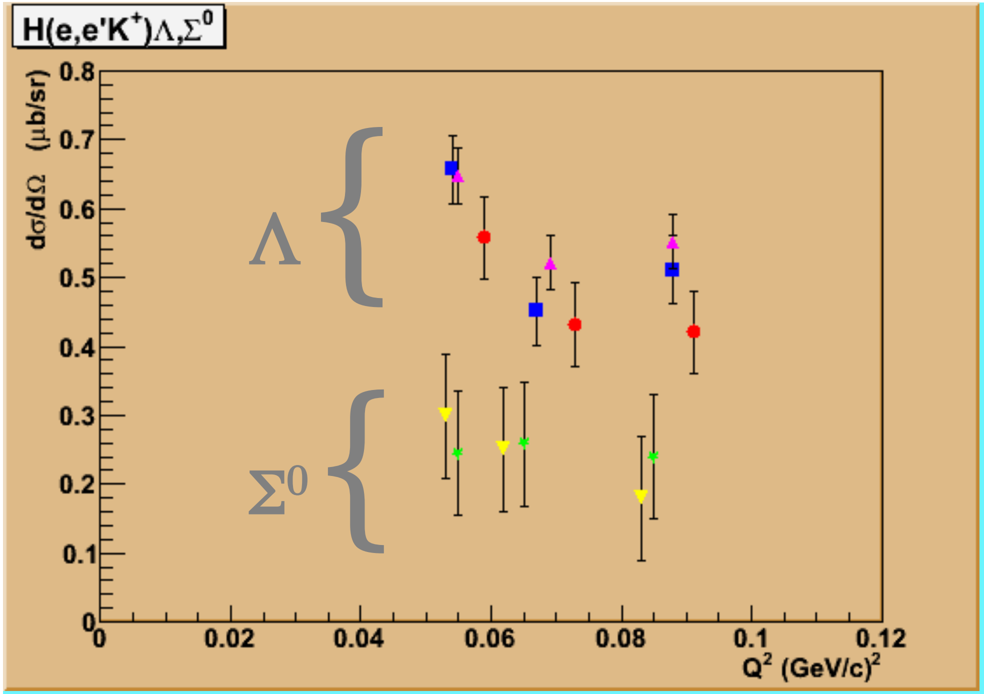


- None of the models is able to describe the data over the entire range
- New data is electroproduction – could longitudinal amplitudes dominate?

Results on H target – Transverse estimate

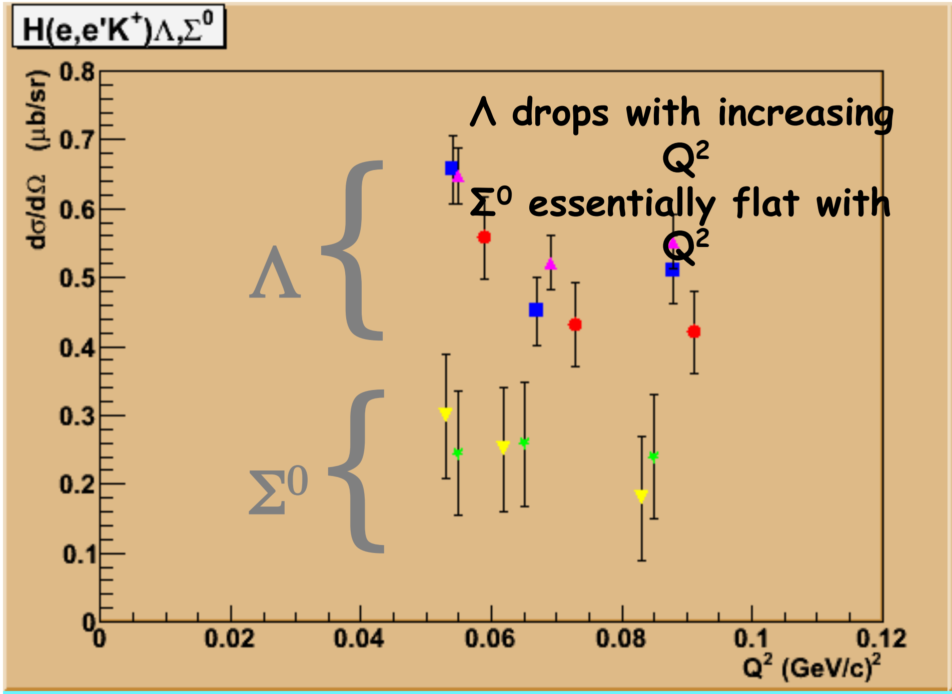


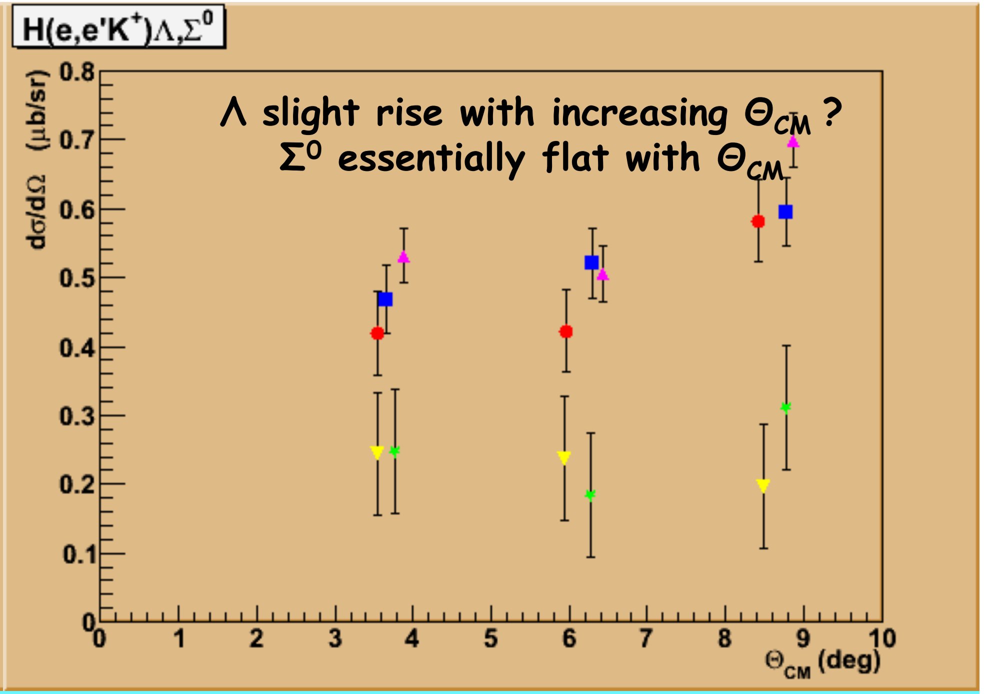
- Estimate of purely transverse amplitudes
- Still greater than most models predict

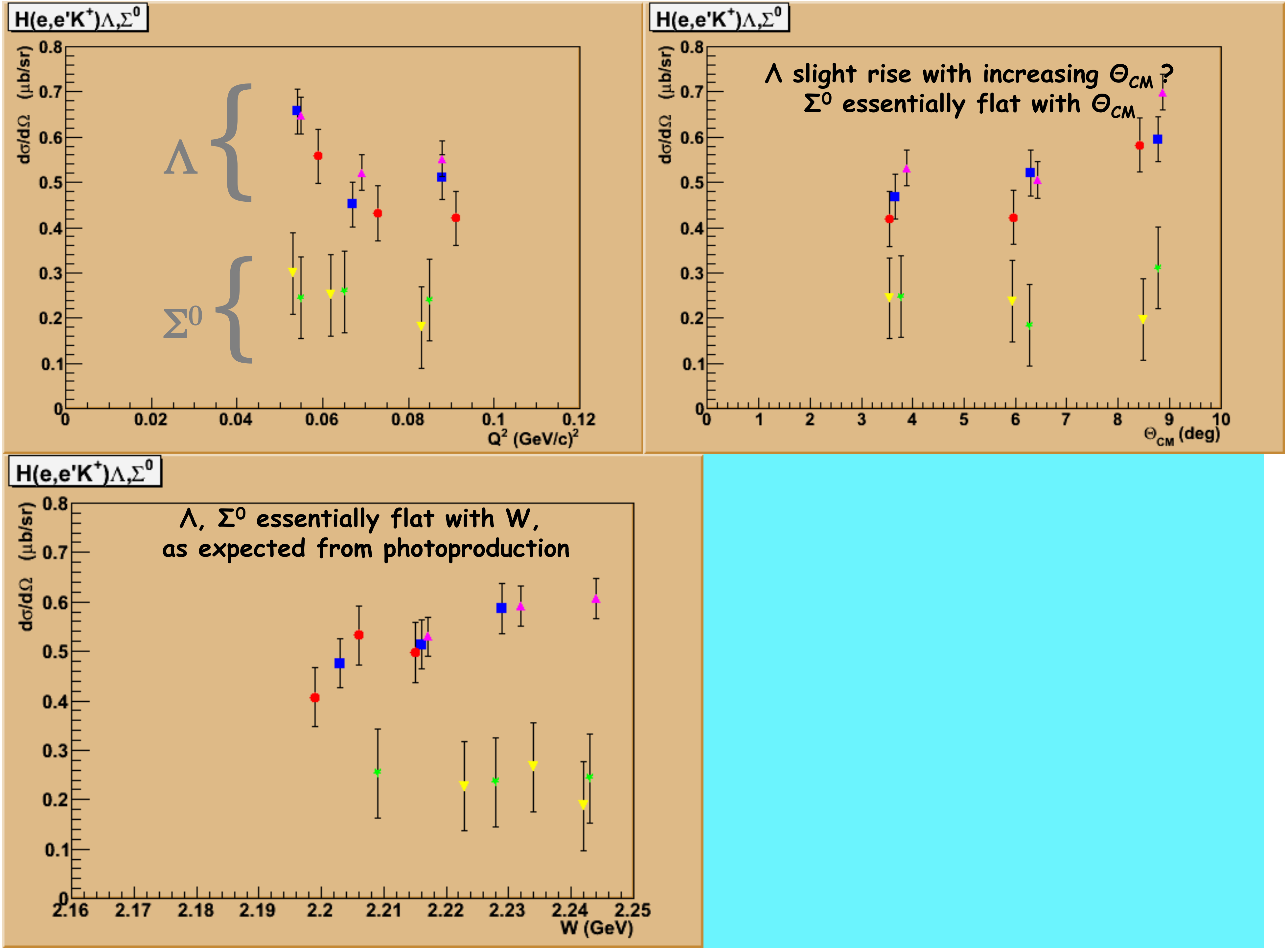


Λ drops with increasing Q^2

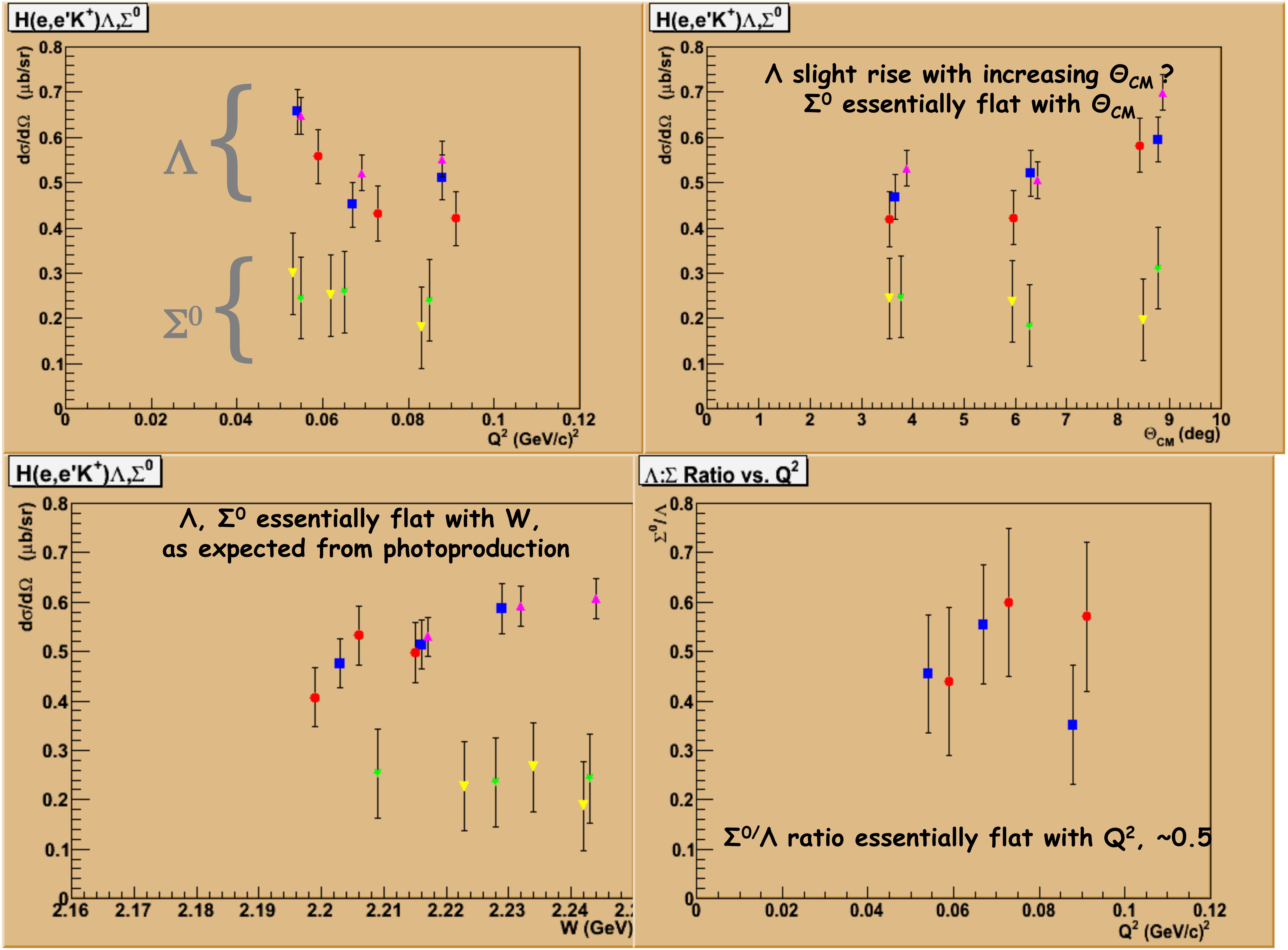
Σ^0 essentially flat with Q^2


H(e,e'K$^+$)Λ,Σ^0
dσ/dΩ (μb/sr)
Λ drops with increasing Q^2
Σ^0 essentially flat with Q^2
Λ
Σ^0
Q^2 (GeV/c)^2


H(e,e'K$^+$)Λ,Σ^0
dσ/dΩ (μb/sr)
Λ slight rise with increasing Θ$_{CM}$?
Σ^0 essentially flat with Θ$_{CM}$
Θ$_{CM}$ (deg)



H(e,e'K+)Λ,Σ0
dσ/dΩ (μb/sr)
Λ
Σ0
Q2 (GeV/c)2
H(e,e'K+)Λ,Σ0
Λ slight rise with increasing ΘCM ?
Σ0 essentially flat with ΘCM
ΘCM (deg)
H(e,e'K+)Λ,Σ0
Λ, Σ0 essentially flat with W,
as expected from photoproduction
W (GeV)



H(e,e'K+)Λ,Σ0
dσ/dΩ (μb/sr)
Q2 (GeV/c)2
Λ
Σ0
H(e,e'K+)Λ,Σ0
Λ slight rise with increasing ΘCM ?
Σ0 essentially flat with ΘCM
ΘCM (deg)
H(e,e'K+)Λ,Σ0
Λ, Σ0 essentially flat with W,
as expected from photoproduction
W (GeV)
Λ:Σ Ratio vs. Q2
Σ0/Λ
Σ0/Λ ratio essentially flat with Q2, ~0.5
Q2 (GeV/c)2

What we learned from hydrogen data

i) the measurement provides the elementary reaction at the same kinematics as the hypernuclear measurement, providing input for hypernuclear calculations

ii) There were no data here before, and the cross section is bigger than some models expected.

iii) This is an unseparated cross section. Longitudinal amplitudes can contribute, but even if we are generous and let sigma_L = 0.5*sigma_T, the transverse cross section is big.

viii) Statistics allows us to bin this data somewhat, and the W behavior is flat. The Q2 dependence falls as expected. It is pretty flat with Theta_CM too but maybe is rising.

v) The Sigma0 also is in the spectra. The behavior is flat with respect to Q2, W, t, and Theta_CM. [Remember Theta_CM is equivalent to t.]

vi) The ratio of Lambda to Sigma0 is ~0.5, less than the 0.6 in photoproduction at 22 degrees, more than the 0.15 that the QHD models predict.

Why?

In this kinematical region models for the K^+- Λ electromagnetic production on protons differ drastically

The interpretation of the hypernuclear spectra is difficult because of the lack of relevant information about the elementary process.

The ratio of the hypernuclear and elementary cross section measured at the same kinematics is almost model independent at very forward kaon scattering angles

↓

The ratio of the hypernuclear and elementary cross section doesn't depend strongly on the electroproducion model and contains direct information on hypercnulear structure and production mechanism

How?

Hall A experimental setup (septum <u>magnets</u>, waterfall <u>target</u>, excellent <u>energy resolution</u> AND <u>Particle Identification</u>) give <u>unique opportunity</u> to measure, <u>simultaneously</u>, **hypernuclear process <u>AND</u> elementary process**

Electroproduction of hypernuclei

$\varepsilon + A \rightarrow \varepsilon' + K^{+} + H$

in DWIA ***(incoming/outgoing particle momenta are ≥ 1 GeV)***

$$\left\langle \psi_H \right| \sum_{i=1}^{Z} \chi_\gamma \chi_K^{*} \boxed{J^\mu(i)} \left| \psi_A \right\rangle$$

- $J^\mu(i)$ – elementary hadron current in lab frame *(frozen-nucleon approx.)*

- χ_γ – virtual-photon wave function *(one-photon approx., no Coulomb distortion)*

- χ_K – distorted kaon w. f. *(eikonal approx. with 1st order optical potential)*

-$\Psi_A(\Psi_H)$ - target nucleus (hypernucleus) nonrelativistic wave functions *(shell model - weak coupling model)*

Angular dependence determined mainly by the momentum transferred to the nucleus (q) via the nucleus - hypernucleus transition form factor (q is a rapidly increasing function of the kaon scattering angle)

The p(e,e'K⁺)Λ electromagnetic X-section

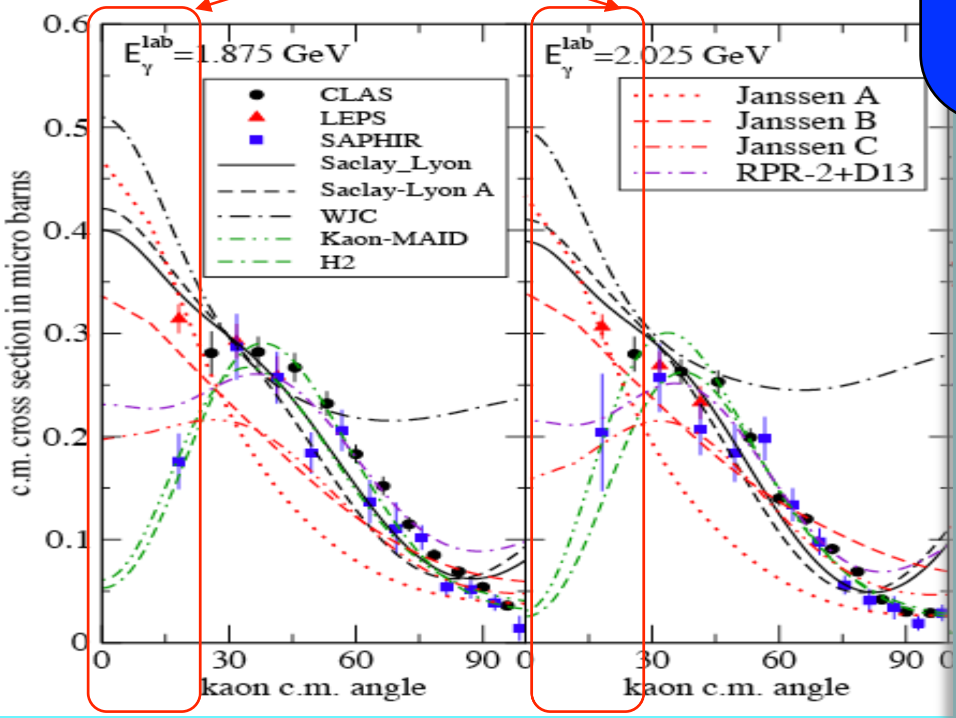
many models on the market which differ just in the choice of the resonances

The theoretical description is poor in the kinematical region relevant for hypernuclear calculations

sharp damping of X-section, connected to the fundamental ingredients of the models, for the hadronic form factors.

two groups of models differing by the treatment of hadronic vertices show LARGE DIFFERENCES

Electro-production model predictions



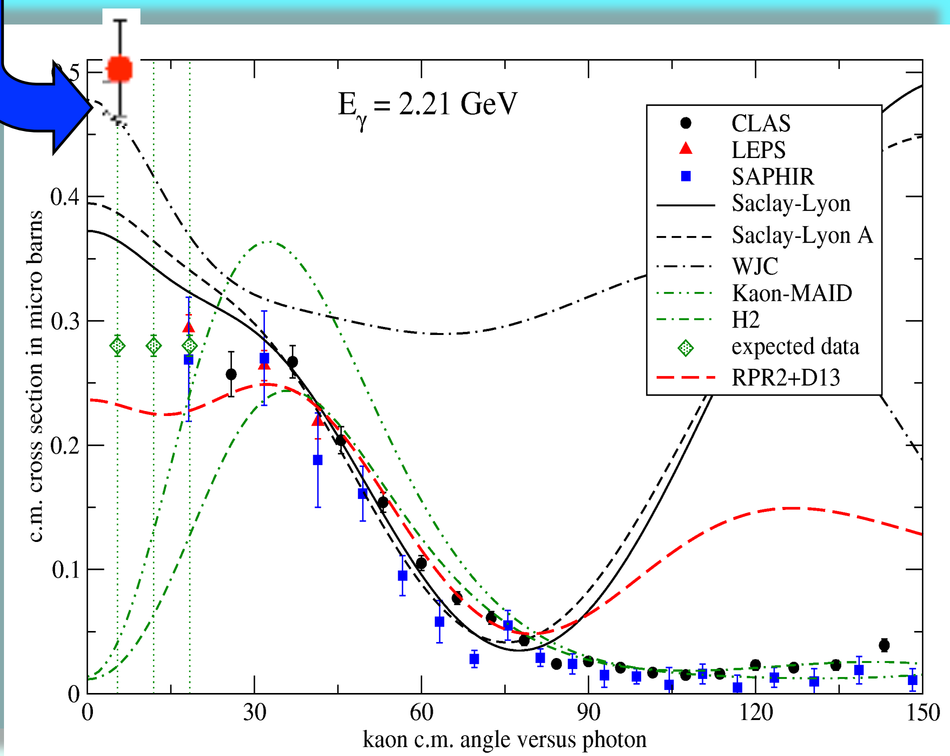


Photo-production existing data and model predictions

TABLE I: Comparison of the spin-independent (f_0) and spin-dependent parts (g_0, g the elementary amplitude is shown for the four models adopted in this paper. The evaluated for two kaon laboratory angles at $E_\gamma^L = 1.3$ GeV. Units of $|f_0|^2$, $|g's|^2$, and Re μb/sr/GeV^4. The laboratory cross sections are in μb/sr.

θ_K^L	Model	$\|f_0\|^2$	$\|g_0\|^2$	$\|g_1\|^2$	$\|g_{-1}\|^2$	Re$(f_0 g_0^*)$	$d\sigma/d\Omega$	Pol(Λ)
	AS1	0.0067	0.374	0.179	0.193	−0.0141	1.91	−0.055
3°	KMAID	0.0149	0.296	0.148	0.148	−0.0642	1.54	−0.212
	C4	0.0002	0.572	0.272	0.281	−0.0063	2.85	−0.019
	SLA	0.0023	0.424	0.211	0.208	−0.0079	2.14	−0.016
	AS1	0.0515	0.352	0.164	0.192	−0.0397	1.84	−0.142
10°	KMAID	0.1205	0.267	0.121	0.129	−0.1793	1.55	−0.575
	C4	0.0010	0.534	0.179	0.204	−0.0179	2.23	−0.066
	SLA	0.0239	0.368	0.175	0.167	−0.0235	1.78	−0.053

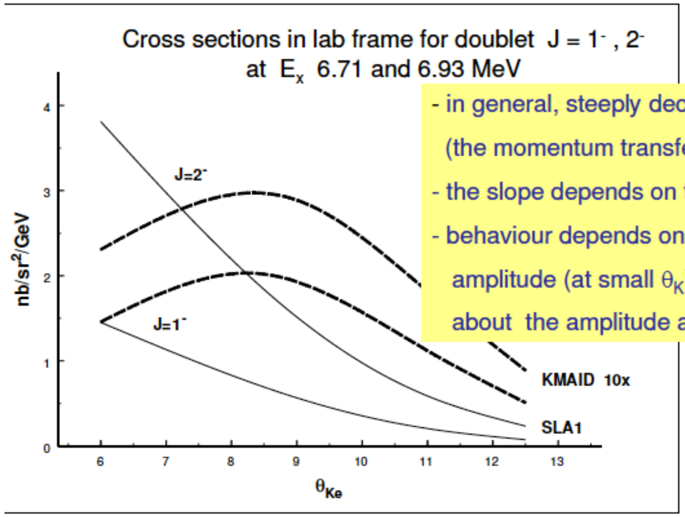
The results differ not only in the magnitude of the X-section (a factor 10) but also in the angular dependence (given by a different spin structure of the elementary amplitudes for smaller energy (1.3 GeV) where the differences are smaller than at 2 GeV

Measuring the angular dependence of the hypernuclear cross section, we may discriminate among models for the elementary process.

the information from the hypernucleus production when the cross sections for productionof various states are measured is reacher than the ordinary elementary cross section

Angular dependence of the cross section

for electroproduction of $^{16}N_\Lambda$ at E_γ= 2.21 GeV and θ_e = 6°



- in general, steeply decreasing dependence (the momentum transfer changes rapidly);
- the slope depends on the spin (J);
- behaviour depends on the elementary amplitude (at small θ_K) – information about the amplitude at small angles.

θ_{Ke} is kaon lab angle with respect to beam

kinematics and counting rates

Incident Electron Energy	3.65 GeV
Virtual photon energy	2.2 GeV
Q^2	0.0789 GeV^2/c^2
Electron scattering angle θ_e	6°
Kaon scattering angle θ_K	8.5°,11.0°
Kaon momentum $\|\vec{p}_K\|$	1.96 GeV/c
Electron momentum	1.45 GeV/c

Table 2: The kinematics of the proposed experiment.

Waterfall Target thicknes = 130 mg/cm^2
Beam current = 100 μA

beam time request

Purpose	Energy	Time
Calibrations	1.6 GeV	2 days
8.5°	3.66 GeV	7 days
11°	3.66 GeV	15 days
Total		24

Angle	Singles (kHz)					Coinc $((h \times MeV)^{-1})$	Accid. $((h \times MeV)^{-1})$
	(e,e')	(e,p)	(e,π^+)	(e,K^+)	(e,π^-)	(e,e'K^+)	(e,e')(e,K^+)
8.5	112	6.6	29	0.7	39	$\sim 0.8 - 2.0$	3.1
11	112	5.2	15.2	0.4	39	$\sim 0.4 - 1.0$	1.7

Table 3: Expected single, accidental, and real coincidence rates of the proposed experiment. Accidentals are f or 3-ns gate in a 1 MeV energy bite.

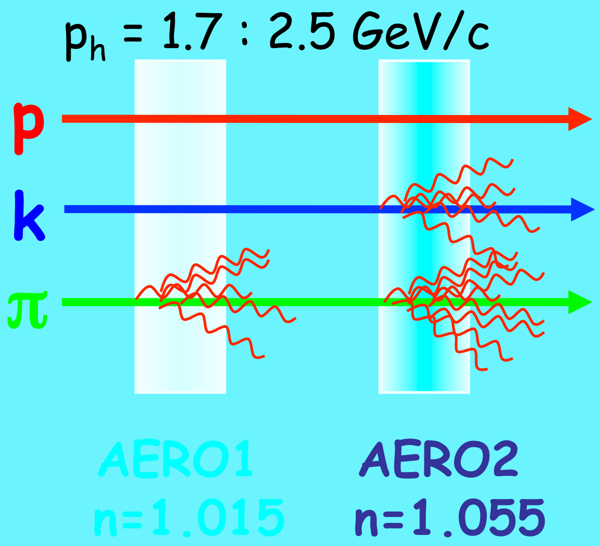
SNR ≥ 6

The PID Challenge

Very forward angle ---> high background of π and p

-TOF and 2 aerogel in not sufficient for unambiguous K identification !

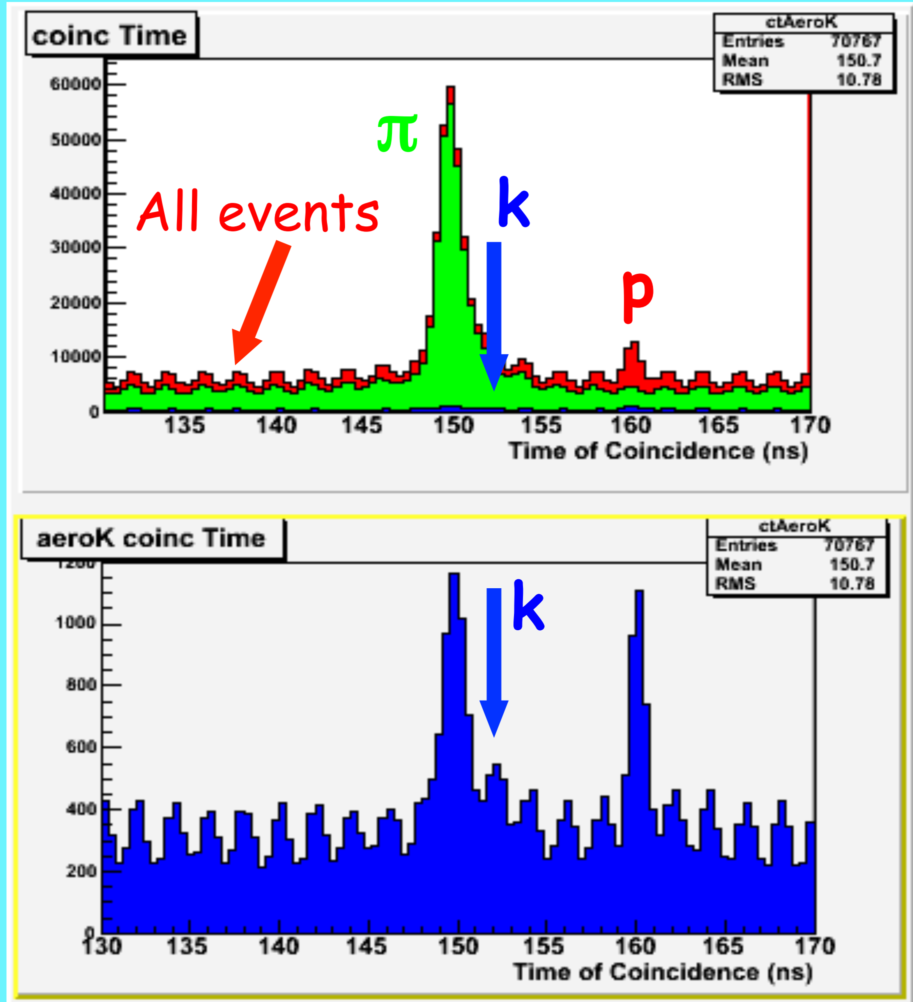
Kaon Identification through Aerogels



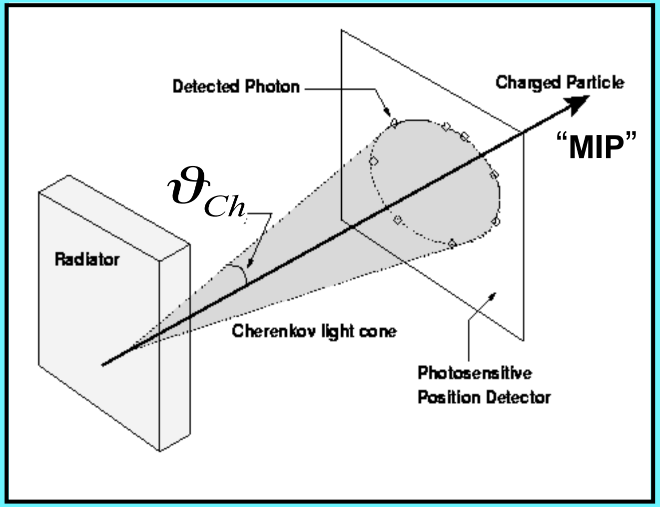
Pions = A1•A2

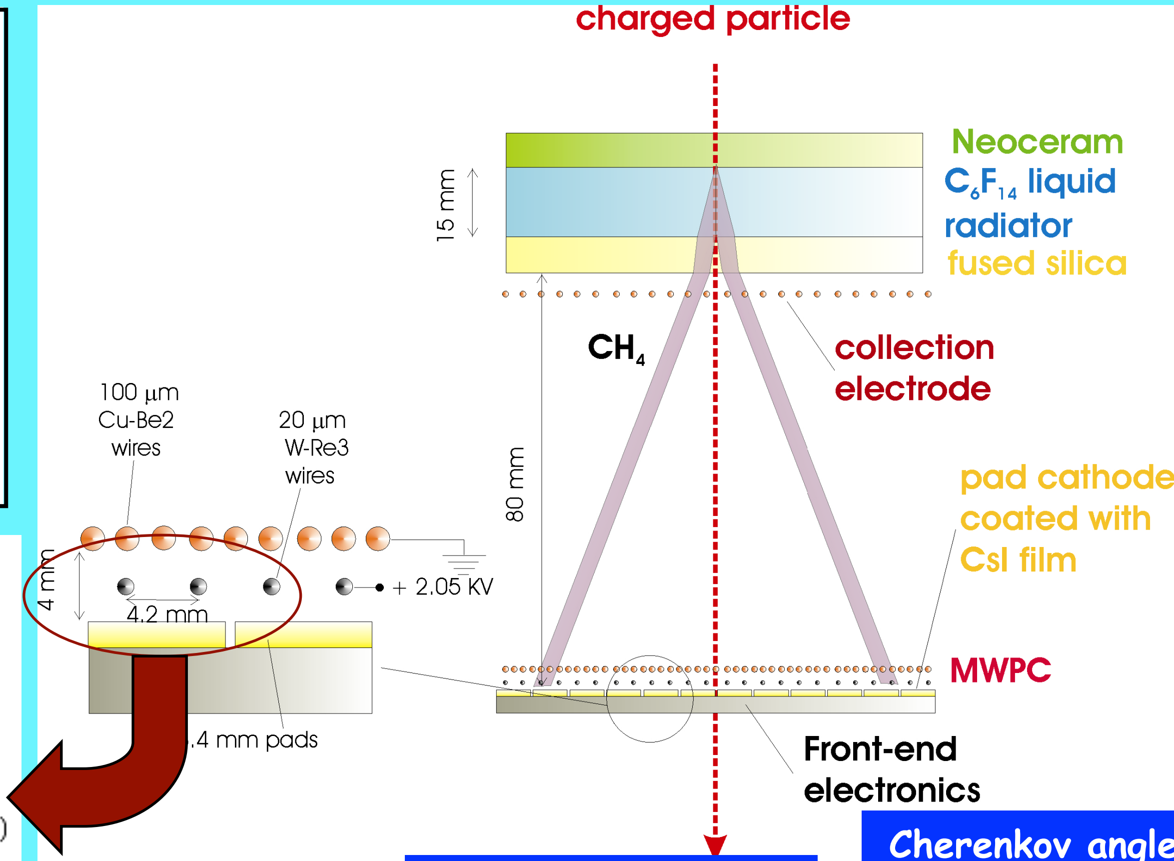
Kaons = $\overline{A1}$•A2

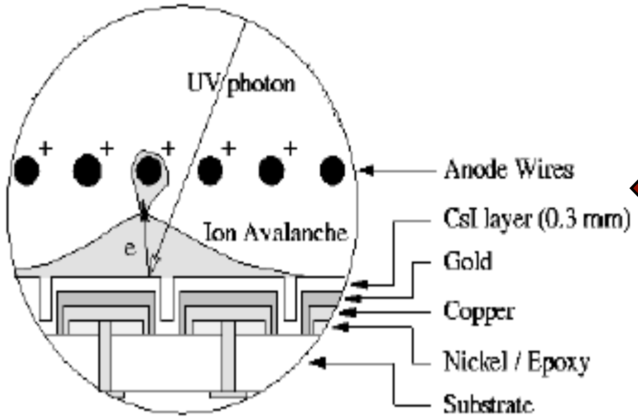
Protons = $\overline{A1}$•$\overline{A2}$



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







Separation Power

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

Cherenkov angle resolution

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

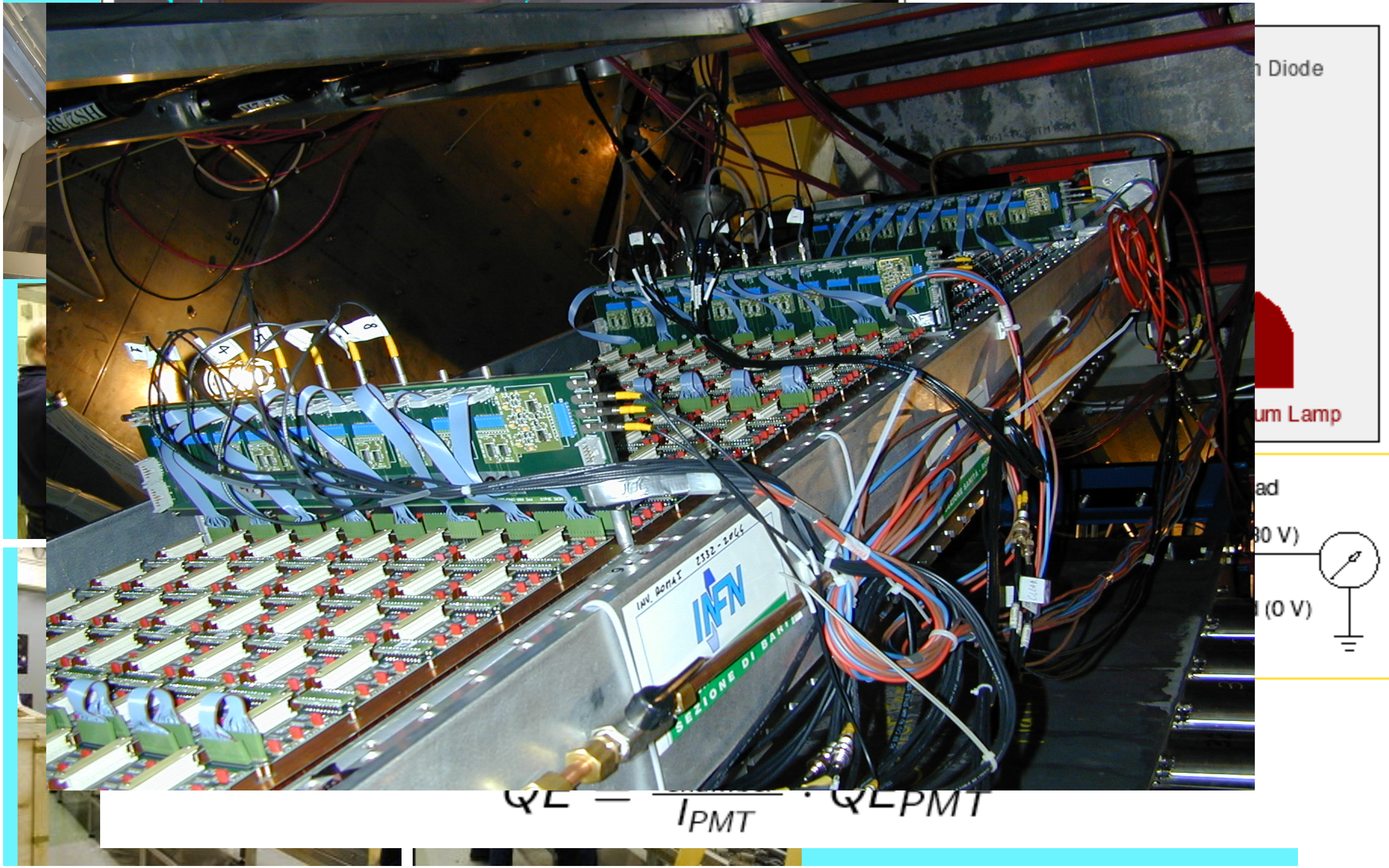
N. of detected photoelectrons

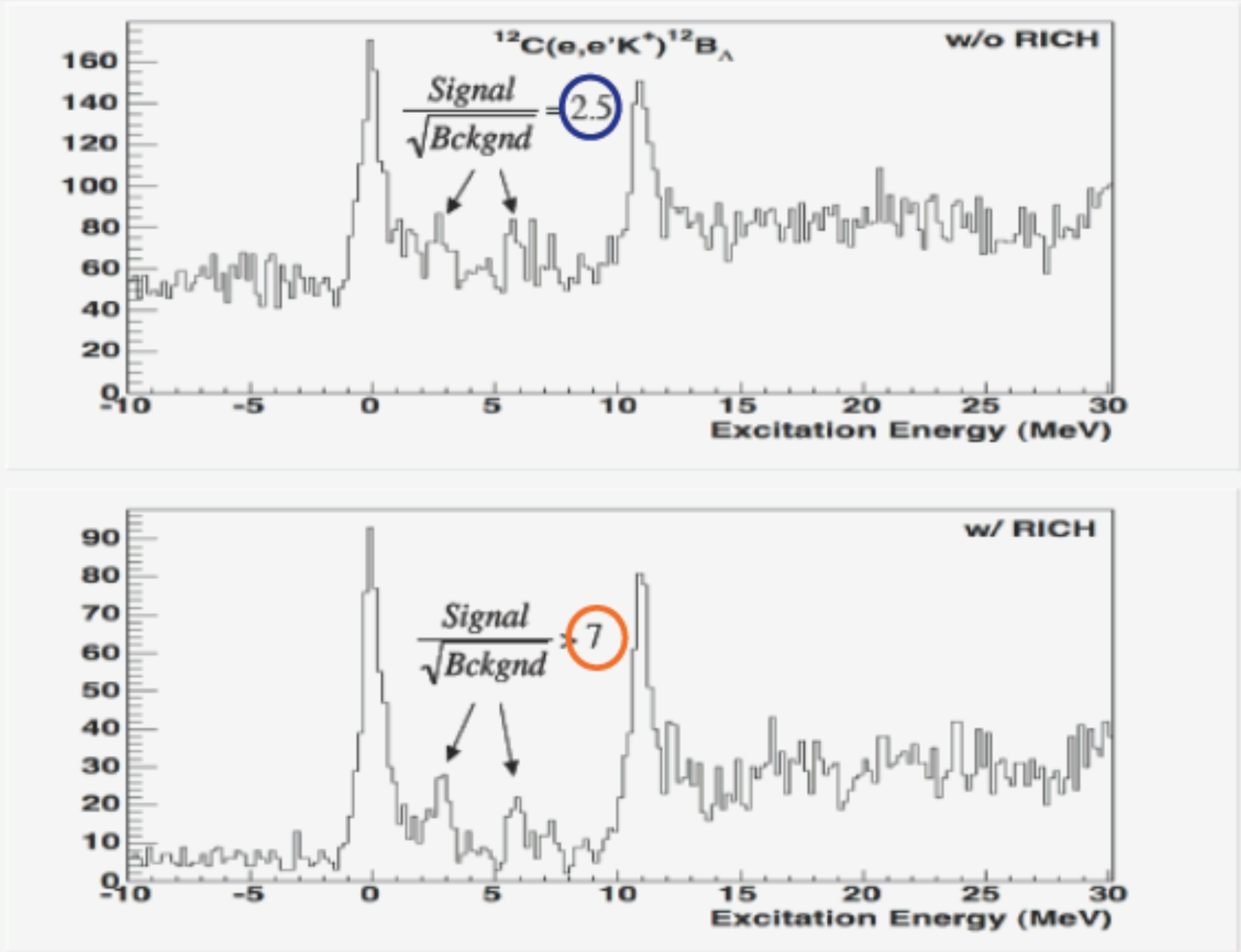
$$N_{p.e.} = 370 L \sin^2 \overline{\vartheta}_c \prod_i \varepsilon_i \Delta E \approx 20 - 50$$

Performances

- $N_{p.e.}$ # of detected photons(p.e.) ← maximize
- and σ_θ (angular resolution) ← minimize

2–axes movement system
3 band filters (160, 185, 220 nm)





$^{12}C(e,e'K^+)^{12}B_\Lambda$
w/o RICH
$\frac{Signal}{\sqrt{Bckgnd}} = 2.5$
160
140
120
100
80
60
40
20
0
-10
-5
0
5
10
15
20
25
30
Excitation Energy (MeV)
w/ RICH
$\frac{Signal}{\sqrt{Bckgnd}} \approx 7$
90
80
70
60
50
40
30
20
10
0
-10
-5
0
5
10
15
20
25
30
Excitation Energy (MeV)

Conclusions

- Experiment E94-107: "systematic" study of p shell light hypernuclei
- The experiment required important modifications on the Hall A apparatus. New experimental equipment showed excellent performance.
- Data on ^{12}C show new information. For the first time significant strength and resolution on the core excited part of the spectrum
- Prediction of the DWIA shell model calculations agree well with the spectra of $^{12}B_{\Lambda}$ and $^{16}N_{\Lambda}$ for Λ in s-state. In the p_{Λ} region more elaborate calculations are needed to fully understand the data
- ^{9}Be preliminary results look promising. Disagreement will stimulate calculation both for elementary reaction and nuclear structure
- The new experiment (angular distribution) is expeted to bring new information on elementary process and hypernuclear structure

Simultaneously measuring the electroproduction cross section on oxygen and hydrogen at a few kaon scattering angles will discriminate between groups of elementary models AND shed new light on problems of hypernuclear physics

Backup slides

PRL 99, 052501 (2007) PHYSICAL REVIEW LETTERS week ending 3 AUGUST 2007

High Resolution Spectroscopy of $^{12}_{\Lambda}B$ by Electroproduction

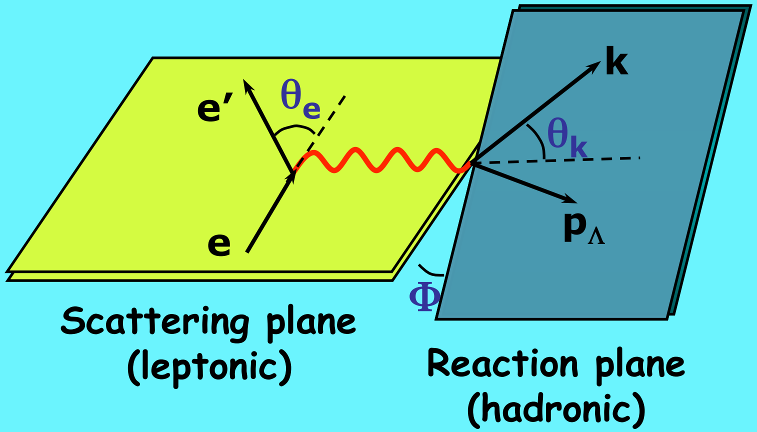
M. Iodice,[1] F. Cusanno,[2] A. Acha,[3] P. Ambrozewicz,[3] K. A. Aniol,[4] P. Baturin,[5] P. Y. Bertin,[6] H. Benaoum,[7] K. I. Blomqvist,[8] W. U. Boeglin,[9] H. Breuer,[9] P. Brindza,[10] P. Bydžovský,[11] A. Camsonne,[6] C. C. Chang,[9] J.-P. Chen,[10] Seonho Choi,[12] E. A. Chudakov,[10] E. Cisbani,[13] S. Colilli,[13] L. Coman,[3] B. J. Craver,[14] G. De Cataldo,[15] C. W. de Jager,[10] R. De Leo,[15] A. P. Deur,[14] C. Ferdi,[6] R. J. Feuerbach,[10] E. Folts,[10] R. Fratoni,[13] S. Frullani,[13] F. Garibaldi,[13] O. Gayou,[16] F. Giulani,[13] J. Gomez,[10] M. Gricia,[13] J. O. Hansen,[10] D. Hayes,[17] D. W. Higinbotham,[10] T. K. Holmstrom,[18] C. E. Hyde,[17,6] H. F. Ibrahim,[17] X. Jiang,[5] L. J. Kaufman,[19] K. Kino,[20] B. Kross,[10] L. Lagamba,[15] J. J. LeRose,[10] R. A. Lindgren,[14] M. Lucentini,[13] D. J. Margaziotis,[4] P. Markowitz,[3] S. Marrone,[15] Z. E. Meziani,[12] K. McCormick,[5] R. W. Michaels,[10] D. J. Millener,[21] T. Miyoshi,[22] B. Moffit,[18] P. A. Monaghan,[16] M. Moteabbed,[3] C. Muñoz Camacho,[23] S. Nanda,[10] E. Nappi,[15] V. V. Nelyubin,[14] B. E. Norum,[14] Y. Okasyasu,[22] K. D. Paschke,[19] C. F. Perdrisat,[18] E. Piasetzky,[24] V. A. Punjabi,[25] Y. Qiang,[16] B. Raue,[3] P. E. Reimer,[26] J. Reinhold,[3] B. Reitz,[10] R. E. Roche,[27] V. M. Rodriguez,[28] A. Saha,[10] F. Santavenere,[13] A. J. Sarty,[29] J. Segal,[10] A. Shahinyan,[30] J. Singh,[14] S. Širca,[31] R. Snyder,[14] P. H. Solvignon,[12] M. Sotona,[11] R. Subedi,[32] V. A. Sulkosky,[18] T. Suzuki,[22] H. Ueno,[33] P. E. Ulmer,[17] G. M. Urciuoli,[2] P. Veneroni,[13] E. Voutier,[34] B. B. Wojtsekhowski,[10] Y. Ye,[35] X. Zheng,[26] S. Zhou,[36] and C. Zorn[10]

PRL 103, 202501 (2009) PHYSICAL REVIEW LETTERS week ending 13 NOVEMBER 2009

High-Resolution Spectroscopy of $^{16}_{\Lambda}N$ by Electroproduction

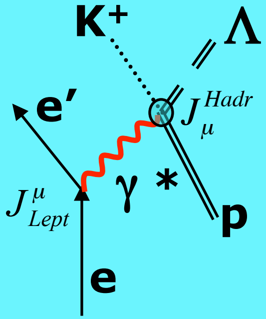
F. Cusanno,[1] G. M. Urciuoli,[1] A. Acha,[2] P. Ambrozewicz,[2] K. A. Aniol,[3] P. Baturin,[4] P. Y. Bertin,[5] H. Benaoum,[6] K. I. Blomqvist,[7] W. U. Boeglin,[2] H. Breuer,[8] P. Brindza,[9] P. Bydžovský,[10] A. Camsonne,[5] C. C. Chang,[8] J.-P. Chen,[9] Seonho Choi,[11] E. A. Chudakov,[9] E. Cisbani,[12] S. Colilli,[12] L. Coman,[2] B. J. Craver,[13] G. De Cataldo,[14] C. W. de Jager,[9] R. De Leo,[14] A. P. Deur,[13] C. Ferdi,[5] R. J. Feuerbach,[9] E. Folts,[9] R. Fratoni,[12] S. Frullani,[12] F. Garibaldi,[12] O. Gayou,[15] F. Giuliani,[12] J. Gomez,[9] M. Gricia,[12] J. O. Hansen,[9] D. Hayes,[16] D. W. Higinbotham,[9] T. K. Holmstrom,[17] C. E. Hyde,[16,5] H. F. Ibrahim,[16] M. Iodice,[18] X. Jiang,[4] L. J. Kaufman,[19] K. Kino,[20] B. Kross,[9] L. Lagamba,[14] J. J. LeRose,[9] R. A. Lindgren,[13] M. Lucentini,[12] D. J. Margaziotis,[3] P. Markowitz,[2] S. Marrone,[14] Z. E. Meziani,[11] K. McCormick,[4] R. W. Michaels,[9] D. J. Millener,[21] T. Miyoshi,[22] B. Moffit,[17] P. A. Monaghan,[15] M. Moteabbed,[2] C. Muñoz Camacho,[23] S. Nanda,[9] E. Nappi,[14] V. V. Nelyubin,[13] B. E. Norum,[13] Y. Okasyasu,[22] K. D. Paschke,[19] C. F. Perdrisat,[17] E. Piasetzky,[24] V. A. Punjabi,[25] Y. Qiang,[15] B. Raue,[2] P. E. Reimer,[26] J. Reinhold,[2] B. Reitz,[9] R. E. Roche,[27] V. M. Rodriguez,[28] A. Saha,[9] F. Santavenere,[12] A. J. Sarty,[29] J. Segal,[9] A. Shahinyan,[30] J. Singh,[13] S. Širca,[31] R. Snyder,[13] P. H. Solvignon,[11] M. Sotona,[10] R. Subedi,[32] V. A. Sulkosky,[17] T. Suzuki,[22] H. Ueno,[33] P. E. Ulmer,[16] P. Veneroni,[12] E. Voutier,[34] B. B. Wojtsekhowski,[9] X. Zheng,[26] and C. Zorn[9]

The p(e,e'K⁺)Λ electromagnetic X-section



$$\frac{d^5\sigma}{dE'\,d\Omega_e d\Omega_K} = \Gamma \frac{d\sigma^{\gamma^*}}{d\Omega_K}\left(\gamma^* + p \rightarrow k + \Lambda\right)$$

$$\frac{d\sigma^{\gamma^*}}{d\Omega_K} = \left[\frac{d\sigma_T}{d\Omega_K} + \varepsilon \frac{d\sigma_L}{d\Omega_K} + \varepsilon\cos 2\Phi \frac{d\sigma_T}{d\Omega_K} + \sqrt{2\varepsilon(\varepsilon+1)}\cos\Phi \frac{d\sigma_{LT}}{d\Omega_K}\right]$$

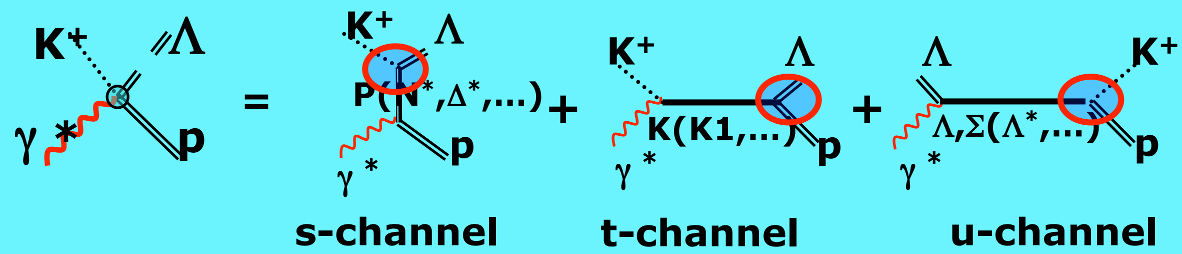


$$J^{Hadr}_{\mu} = \left\langle K^+\Lambda \middle| \hat{J}^{Hadr}_{\mu} \middle| p \right\rangle = \bar{u}(p_\Lambda)\left(\sum_{i=1}^{6} A_i\left(s,t,Q^2\right)\cdot M^i_\mu\right)u(P)$$

At CEBAF energies non-perturbative QCD degrees of freedom have to be taken into account.

- IN PRINCIPLE: the amplitude can be calculated in QCD. IN PRACTICE: semi-phenomenological description Quantum HadronDynamics(QHD), degrees of freedom, nucleon, kaon, resonances.

A diagrammatic semi-phenomenological approach based on hadronic field theories (effective hadronic Lagrangian - QHD) is likely well applicable in the description of the process



The appropriate set of propagators (particles) and coupling constants has to be **established from the data** **and** from **theoretical guidelines** (SU3 broken symmetry)

Missing Energy, Mrecoil, Missing Mass and Hypernuclear excitation Energy :

Reaction: A(e,e'K)X being X eventually the Hypernucleus

$\omega + M_A = E_k + E_X = T_k + m_k + T_X + M_X^*$

$\mathbf{q} = \mathbf{p}_k + \mathbf{P}_X$

Usual definition of Emiss :

$$E_{miss} = \omega - T_K - T_X = m_K + M_X^* - M_A$$

which is computed by :

$$E_{miss} = m_K + M_X^* - M_A = m_K - M_A + \sqrt{(\omega + M_A - E_K)^2 - (\vec{q} - \vec{p}_K)^2}$$

This is the way I define the missing energy which turns out to be the same thing as computed by analyzer. And it is also clear that E_{miss} and the M_x (as referred to as the Recoil Mass) only differ by a constant.

Considering the X system being our Hypernucleus formed by the binding of the Λ hyperon on the Nucleus A with the removal of a proton, we have for the mass M_X :

$$M_X = M_A - m_p + \varepsilon_p + m_\Lambda - \varepsilon_\Lambda$$

where ε_p and ε_Λ are the (positive) binding energies of the proton removed from A and the hyperon bound in the hypernucleus, respectively. Hence for the Missing Energy we will have :

$$E_{miss} = m_K + M_X^* - M_A = m_K + m_\Lambda - m_p + \varepsilon_p - \varepsilon_\Lambda = 671.09\,MeV + \varepsilon_p - \varepsilon_\Lambda \qquad (*)$$

The relevant physics quantities here are: the missing energy Emiss, the recoil mass Mx and the excitation energy $\varepsilon_p - \varepsilon_\Lambda$ all being just translated one with respect to the other.
The same of course is valid for the Missing Mass $M_{miss} = M_X^* - M_A$ having values in the order of $(M_A - m_p + m_\Lambda) - M_A = -m_p + m_\Lambda = 177.4\,MeV$
(to get Mmiss one should also add $(\varepsilon_p - \varepsilon_\Lambda)$)

Let us redefine now the missing energy taking into account the "mass offset" which means by removing $(m_K+m_\Lambda-m_p)$ = 671.09 MeV :

$$E_{miss}=m_K+M^{\Lambda}_X-M_A-(m_K+m_\Lambda-m_p)=M^{\Lambda}_X-M_A-m_\Lambda+m_p$$

Now, for the nuclei 16O, 12C and 9Be the values of the masses can be found on the BNL database, while for the Hypernuclear masses we can rely on the binding energies as measured by emulsion data. These values are here reported:

$$M_{16O}=14895.086 \qquad M^{G.S.}_{16N\Lambda}=15070.941$$
$$M_{12C}=11174.867 \qquad M^{G.S.}_{12B\Lambda}=11356.182$$

$$M_{9Be}=8392.753 \qquad M^{G.S.}_{9Li\Lambda}=8577.867$$

For our definition of missing energy we should get the following values :

$$E_{miss}(^{16}O)=M^{\Lambda}_X-M_A-m_\Lambda+m_p=15070.941-14895.086-1115.683+938.272=-1.556\,MeV$$
$$E_{miss}(^{12}C)=M^{\Lambda}_X-M_A-m_\Lambda+m_p=+3.904\,MeV$$
$$E_{miss}(^{9}Be)=M^{\Lambda}_X-M_A-m_\Lambda+m_p=+7.703\,MeV$$

Cross-Check of Event Selection and Systematics

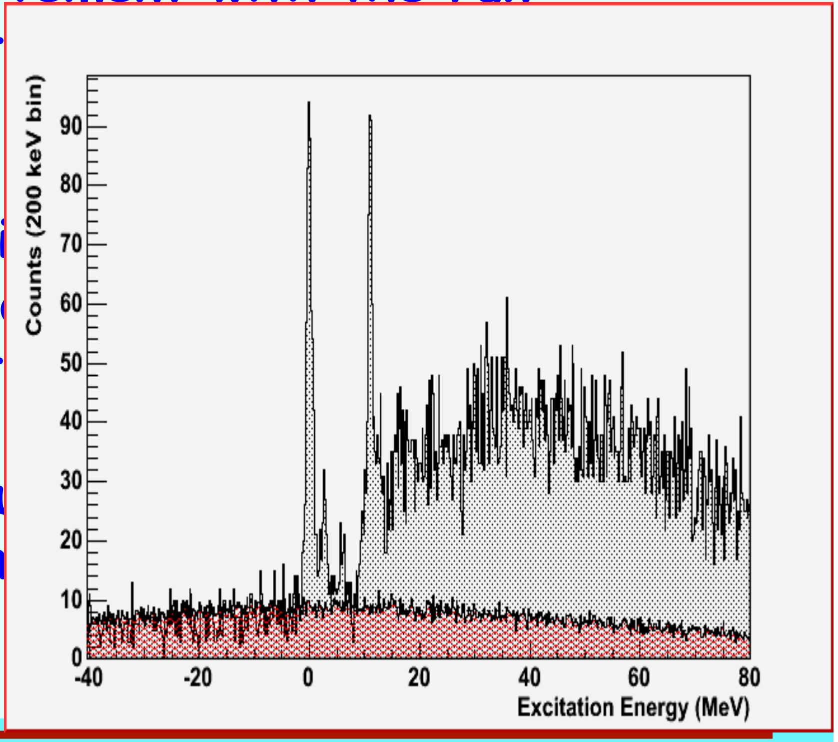
- Preliminary check of the background subtraction (off-CT vs fit at negative Excitation Energy)

- Preliminary check on dependence of missing-mass reconstruction on run-number, day/night, kinematics variables, etc

- Cross-check of quality improvement with the run (event) select

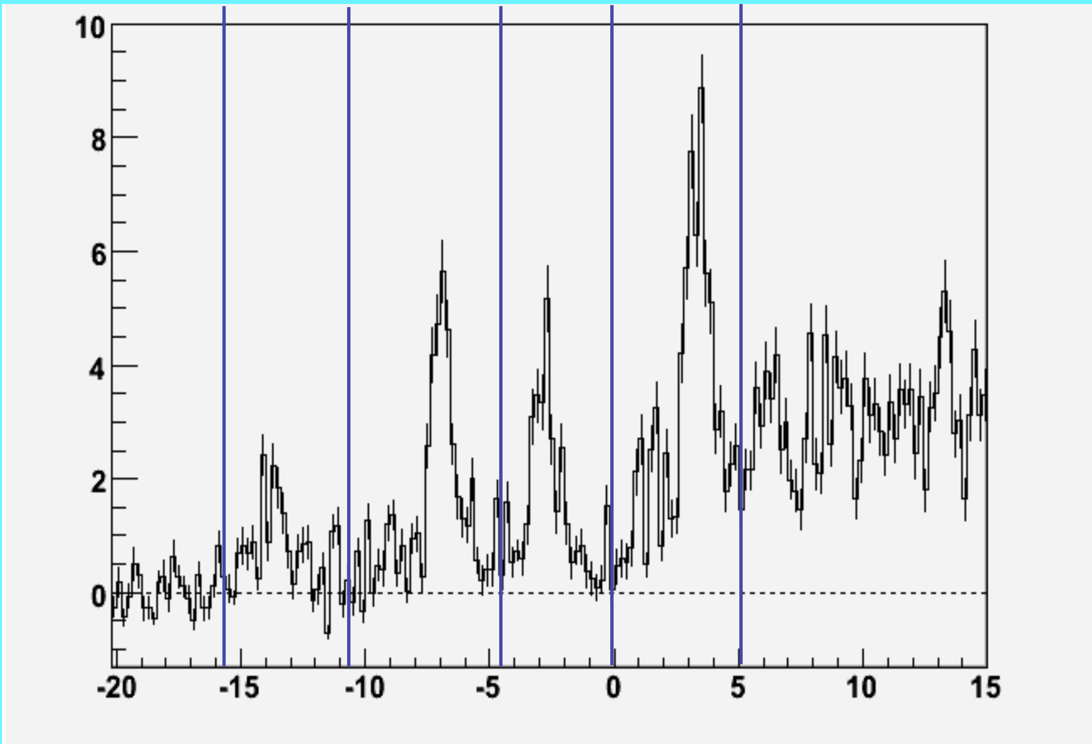
- check (or determination) of from the missing mass: quasi absolute reference (Waterf experiment

- rough check of the absol calculation



Peak Searching

A χ^2-based algorithm is used to detect the individual peaks out of the background fluctuations (Y. Qiang et al, the search of pentaquark partners)



Fitting Procedure

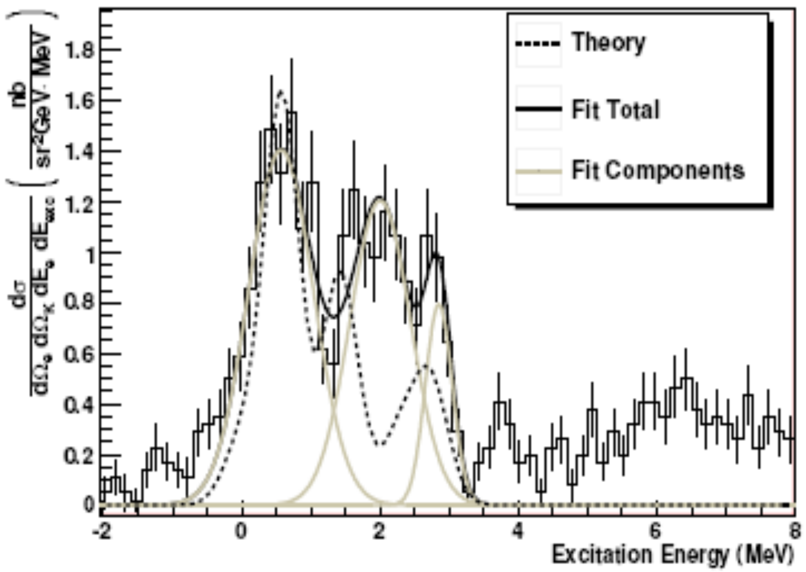
- Assuming the number of peaks according to "the search procedure", individual and global fit with Voigt function is performed (ROOT)

- The leading parameter is c^2

- When peak shape of width is
structure is ver

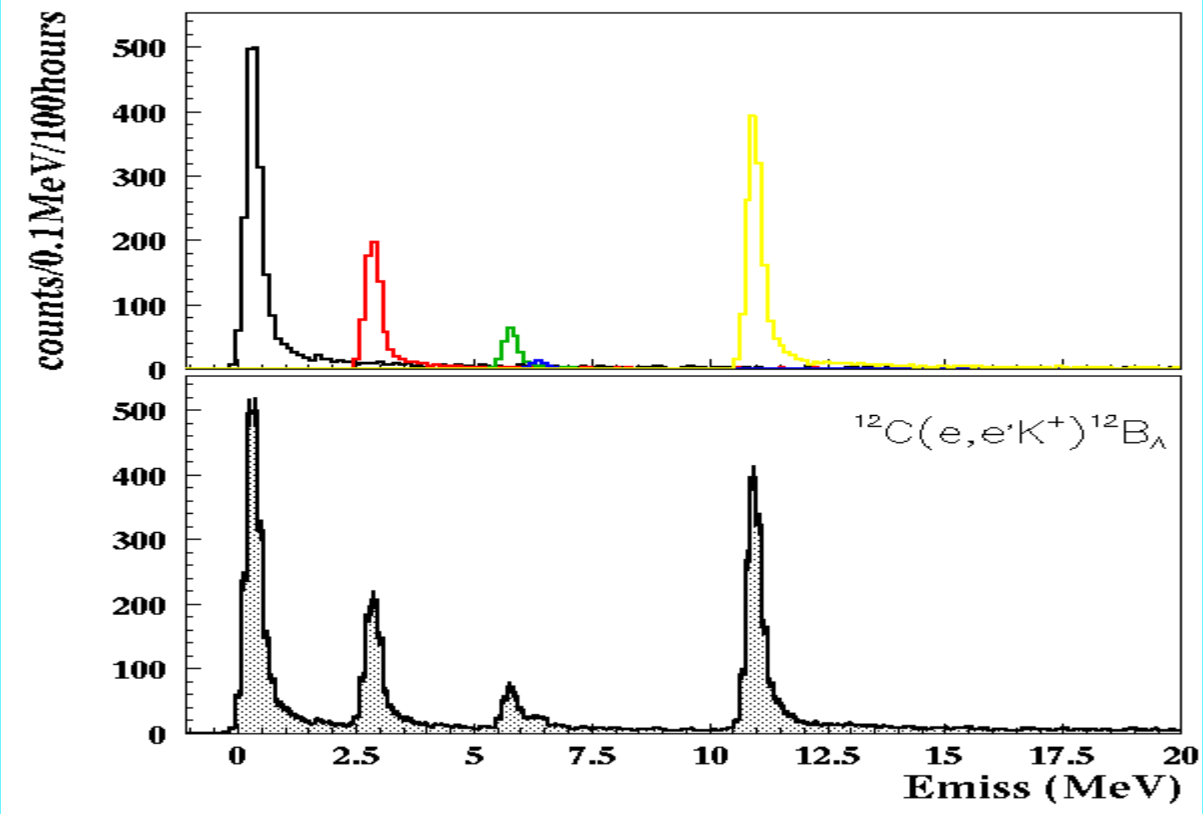
- Fit returns peak position,

- SNR is evaluated (wh

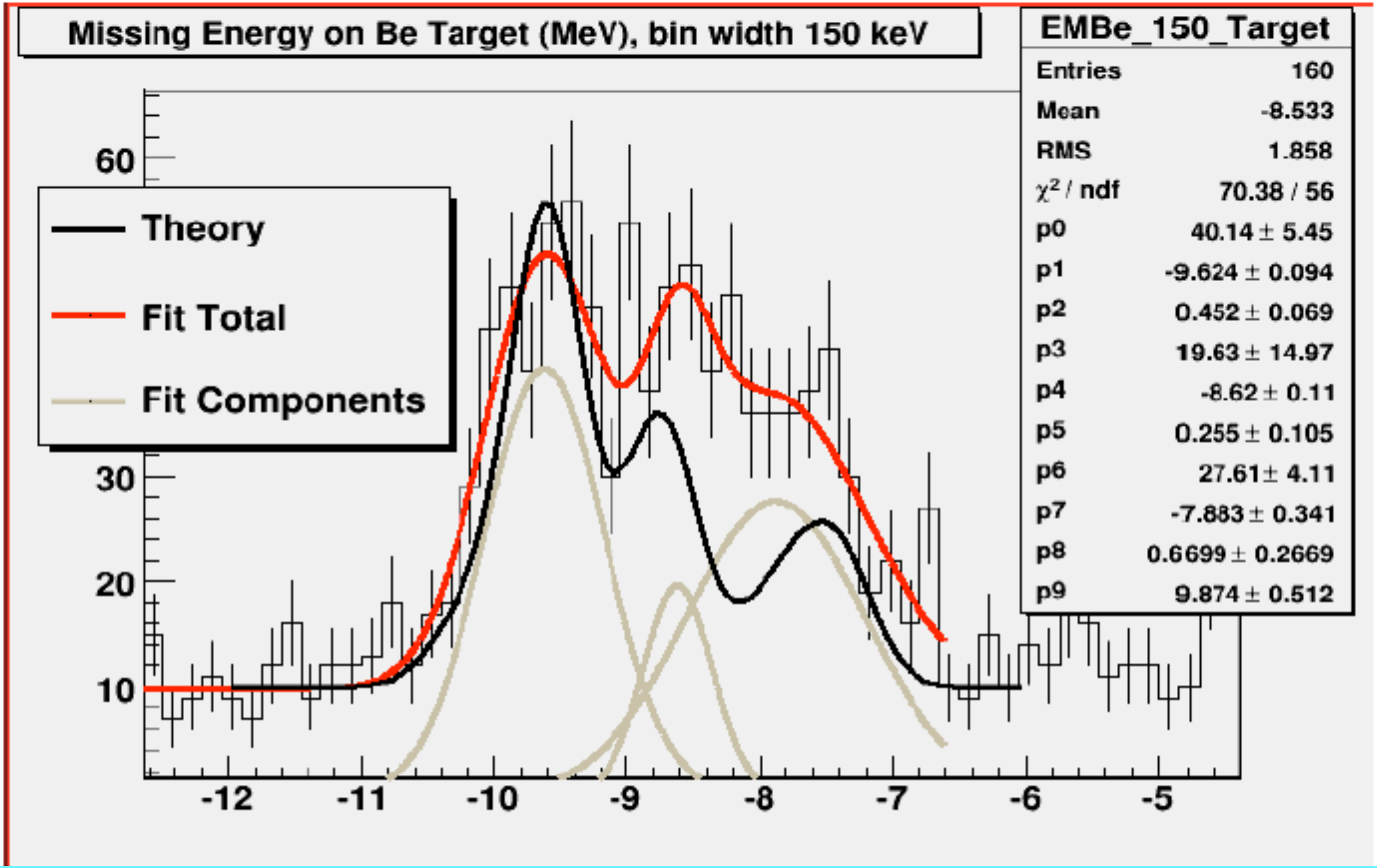


Radiative Corrections

MonteCarlo based iterative procedure is used to take into account of the radiative tail of the peak

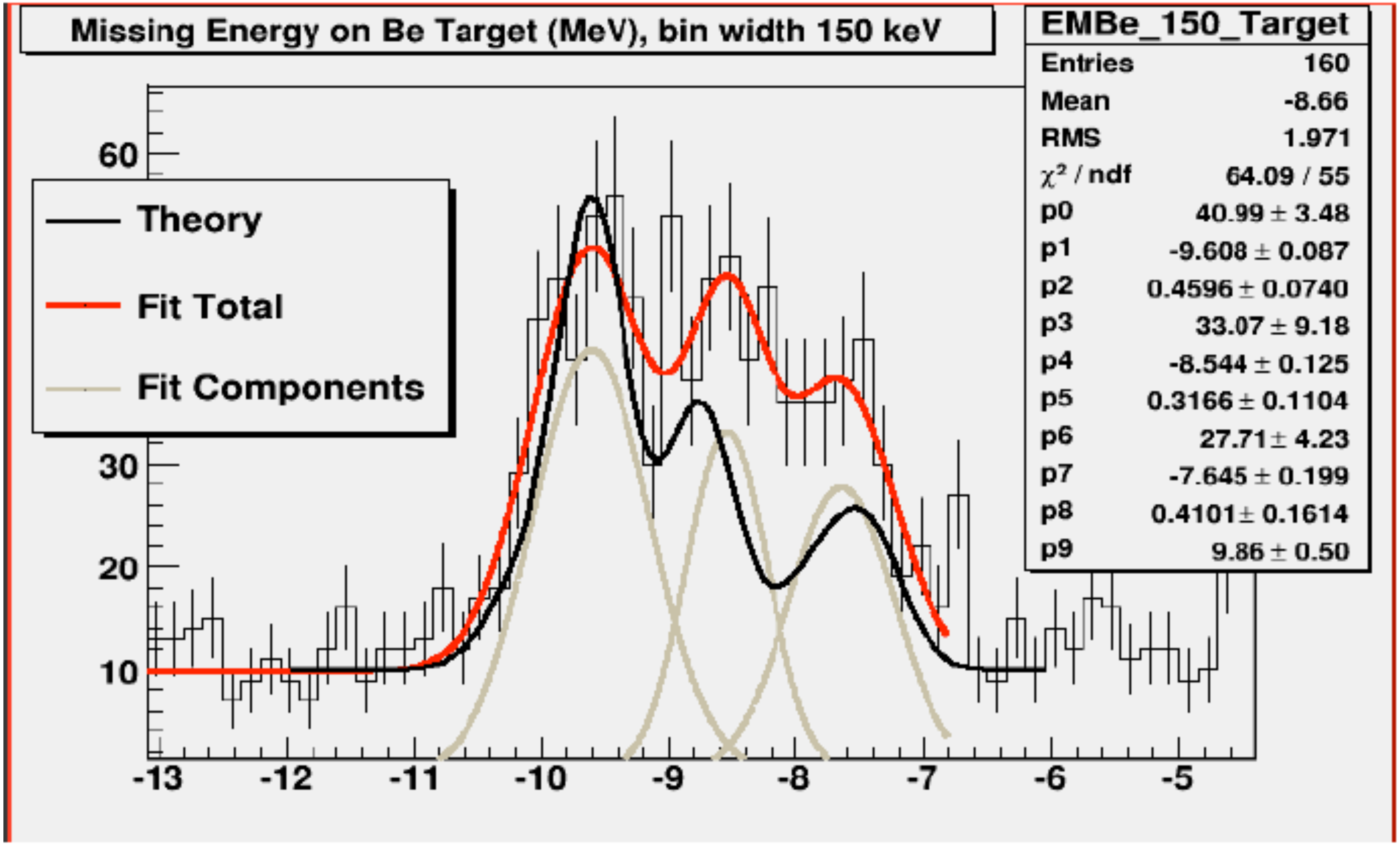


No background subtraction, three peaks with three independent gaussians



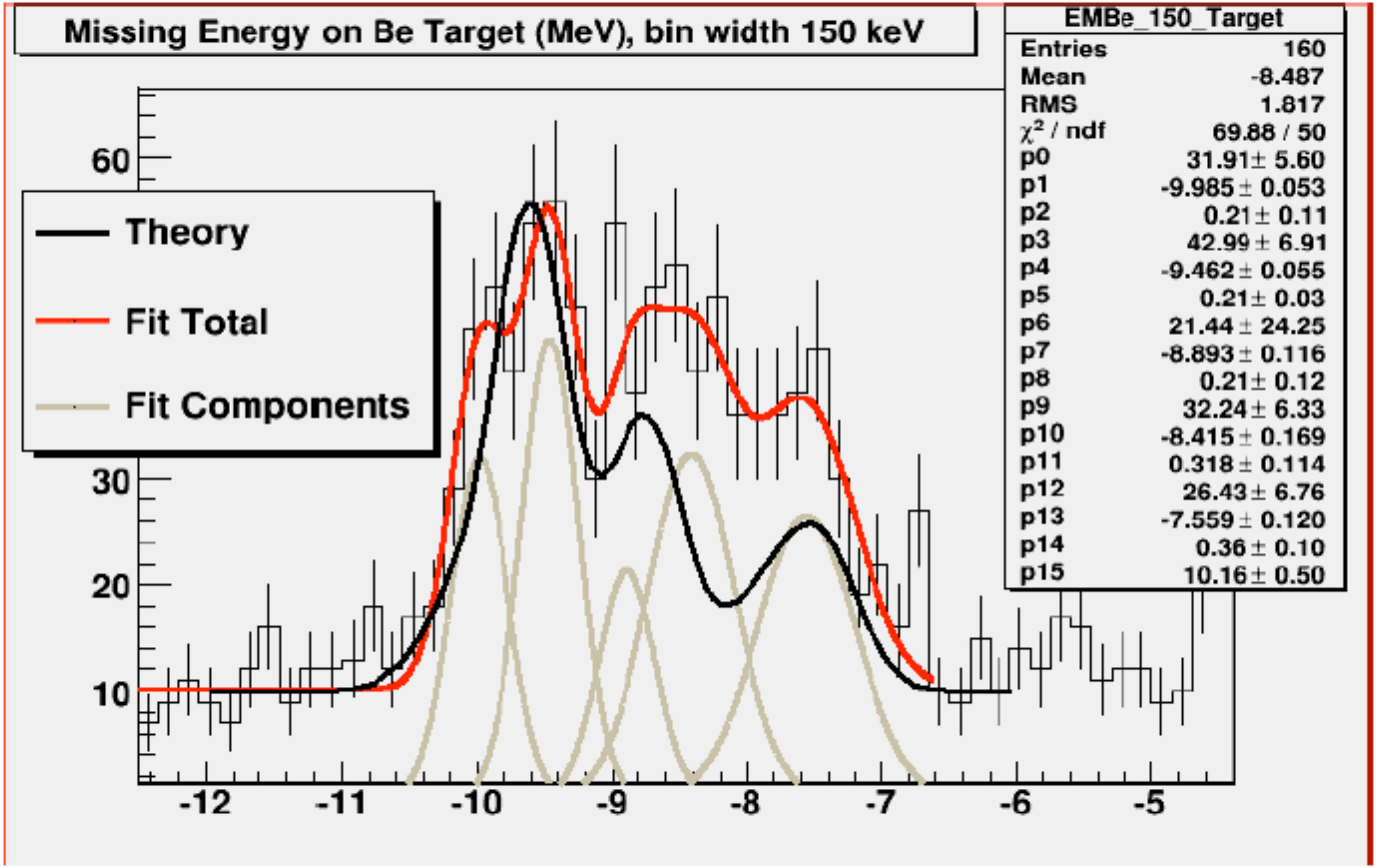
Background fit (5 MeV on the left of the g.s.)

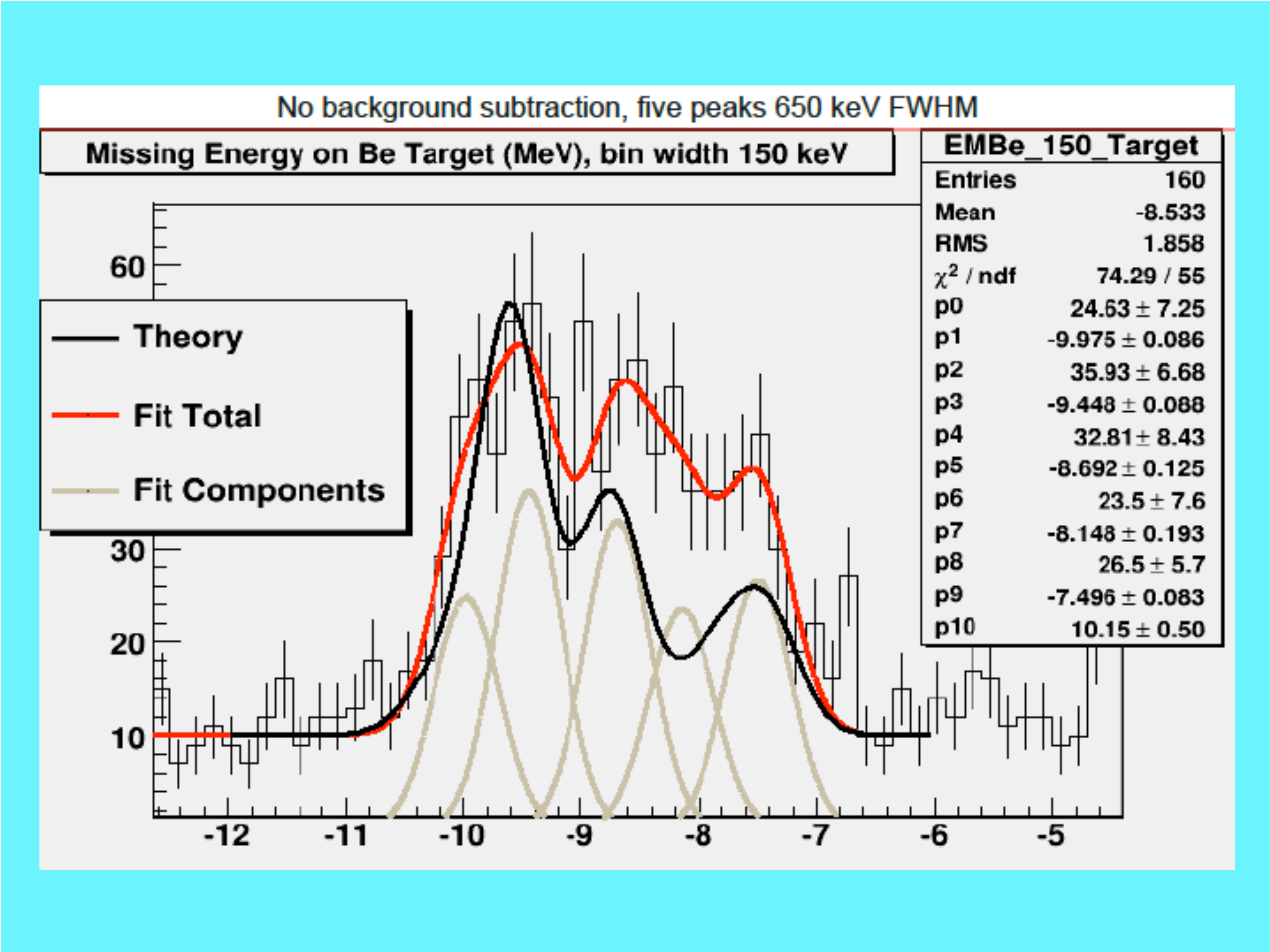
No background subtraction, three peaks with three independent gaussians, restricted range of fit (Guido´s suggestion)



Background fit only on the left

No background subtraction, five peaks with five independent gaussians





No background subtraction, five peaks 650 keV FWHM
Missing Energy on Be Target (MeV), bin width 150 keV
EMBe_150_Target
Entries 160
Mean -8.533
RMS 1.858
χ2 / ndf 74.29 / 55
p0 24.63 ± 7.25
p1 -9.975 ± 0.086
p2 35.93 ± 6.68
p3 -9.448 ± 0.088
p4 32.81 ± 8.43
p5 -8.692 ± 0.125
p6 23.5 ± 7.6
p7 -8.148 ± 0.193
p8 26.5 ± 5.7
p9 -7.496 ± 0.083
p10 10.15 ± 0.50
Theory
Fit Total
Fit Components
60
30
20
10
-12
-11
-10
-9
-8
-7
-6
-5