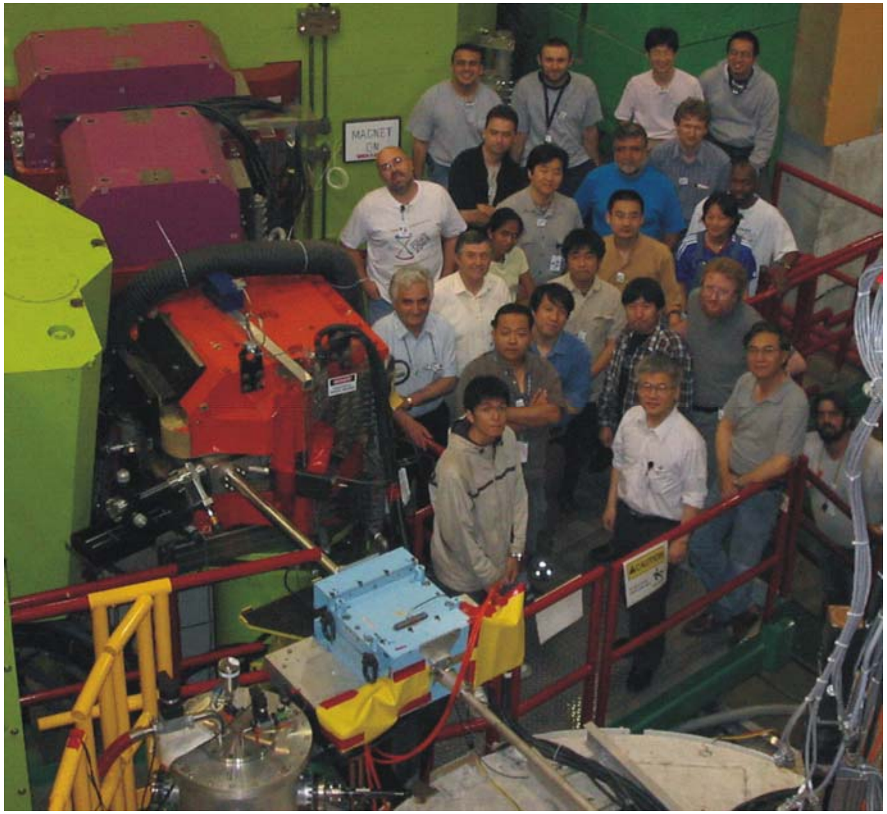
Analysis status of the Λ hypernuclear spectroscopic experiment @ Jlab Hall C (E01-011)



Contents

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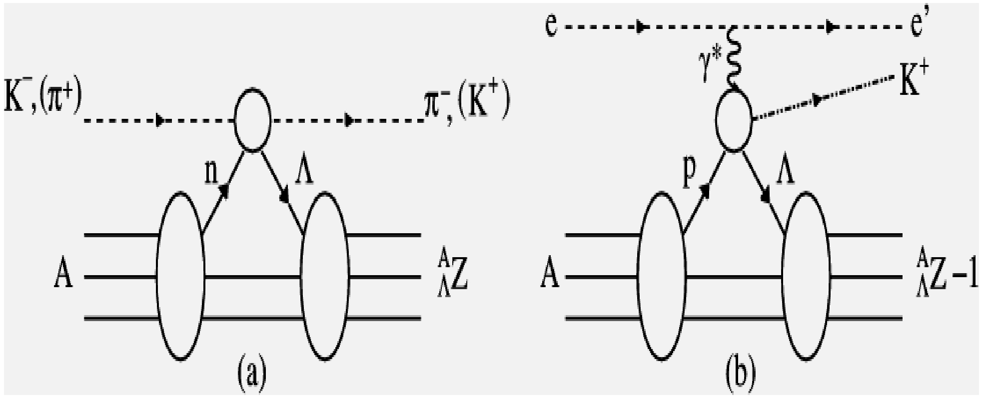
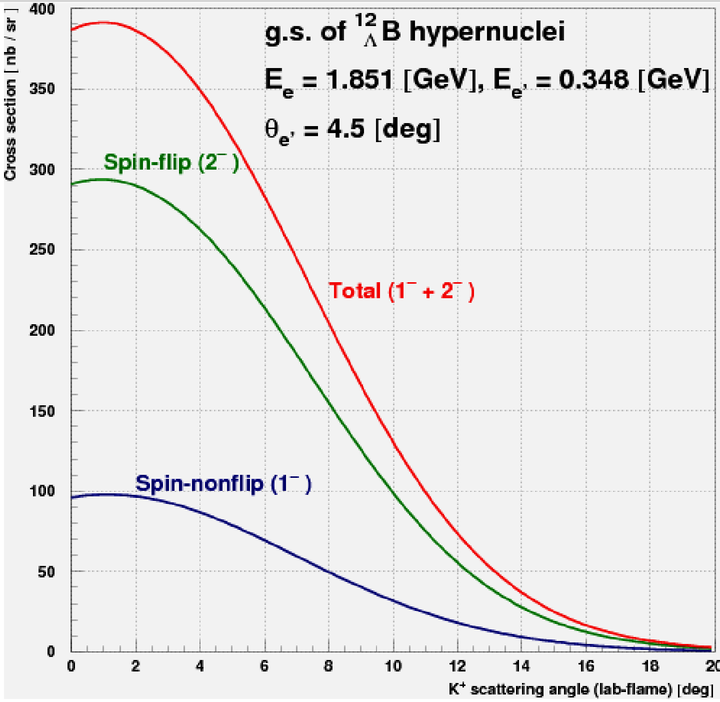
Characteristics of the (e,e'K$^+$) reaction





1) Large momentum transfer

→ generate various kind of states

2) EM production (w/ extremely forward angle detection)

→ large amplitude of spin flip & non-flip states

3) Convert proton to Λ

→ comparison w/ mirror symmetric hypernuclei

4) High quality, primary, continuous electron beam

→ precise spectroscopy

Physics goals of Jlab E01-011

a: Investigate Λ single particle states up to beyond *p*-shell

>> Not only $^{12}C(e,e'K^+)^{12}{}_{\Lambda}B$, also ^{28}Si

b: Observe *p*-shell region of $^{12}{}_{\Lambda}B$ splitting

>> Provide precise information on the spin dependent part of ΛN interaction w/ $^{12}C(e,e'K^+)^{12}{}_{\Lambda}B$ reaction

c: Mirror symmetric Λ hypernuclei, e.g. $^{12}{}_{\Lambda}C$ VS. $^{12}{}_{\Lambda}B$

Historically …

Λ hypernuclear spectroscopy

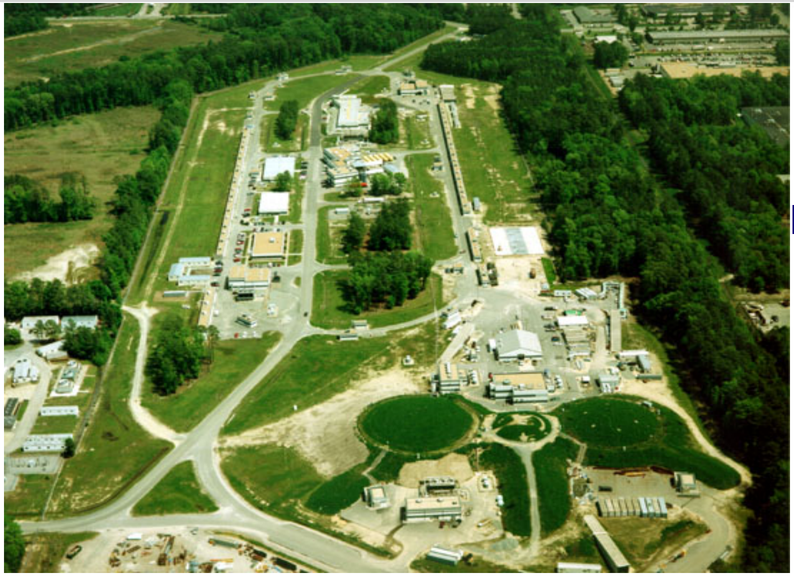
→ well done through (K^-, π^-) & (π^+, K^+) reaction in CERN, BNL and KEK

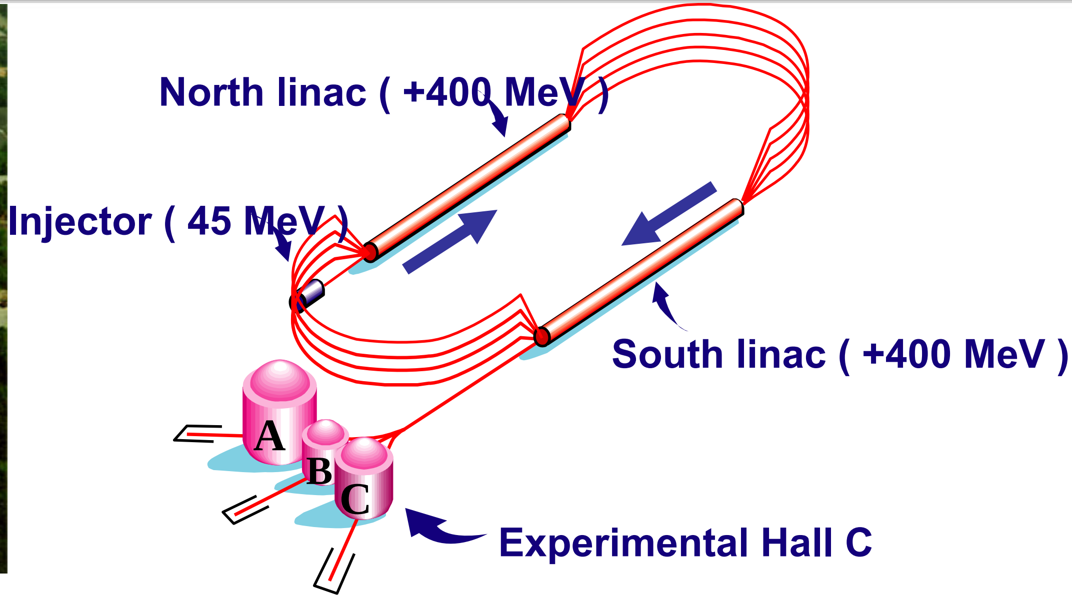
>> Energy resolution was limited (the secondary beam)

$(e,e'K^+)$ reaction? → coincidence measurement required ← CW beam

Jefferson Lab. provides high quality continuous electron beams.

Thomas Jefferson National Accelerator Facility



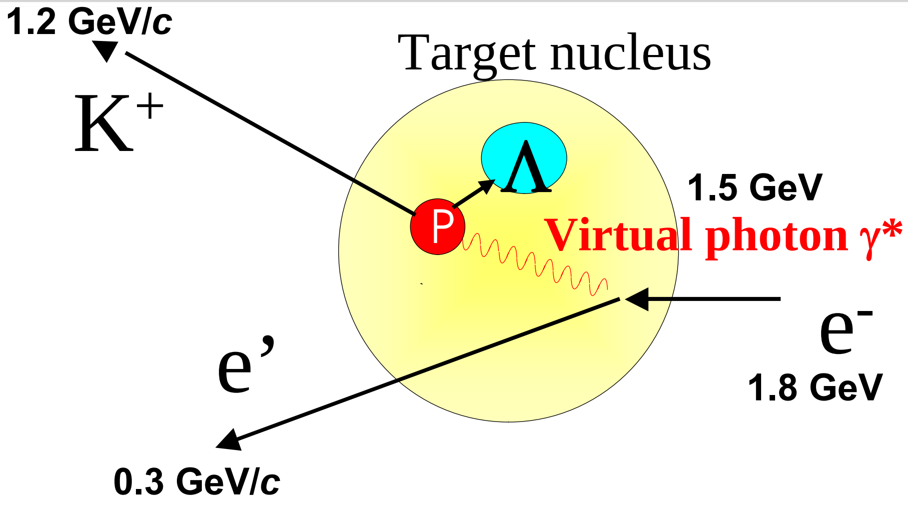


Accelerator spec.

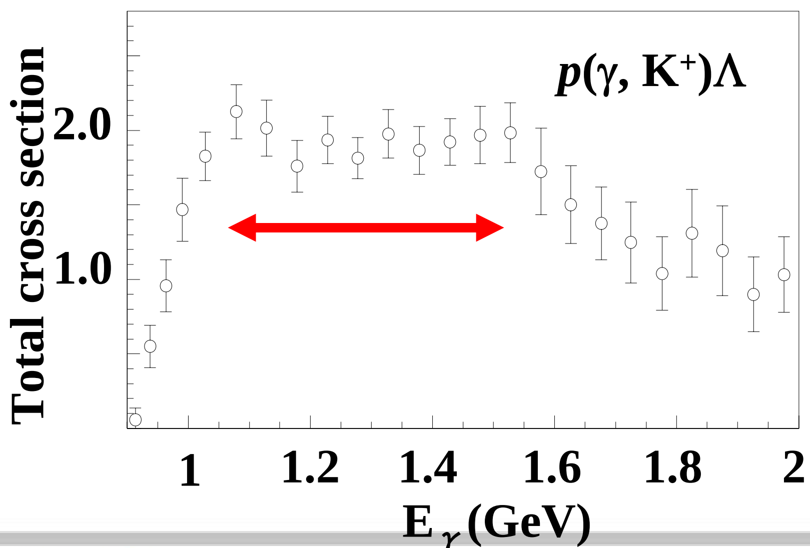
- Duty factor : ~100 % CW beam
- Beam current : < 200 μA
- Maximum energy : 5.5 GeV
- Beam emittance : ~2 × 10^{-9} m･rad
- Energy stability : < 10^{-4}

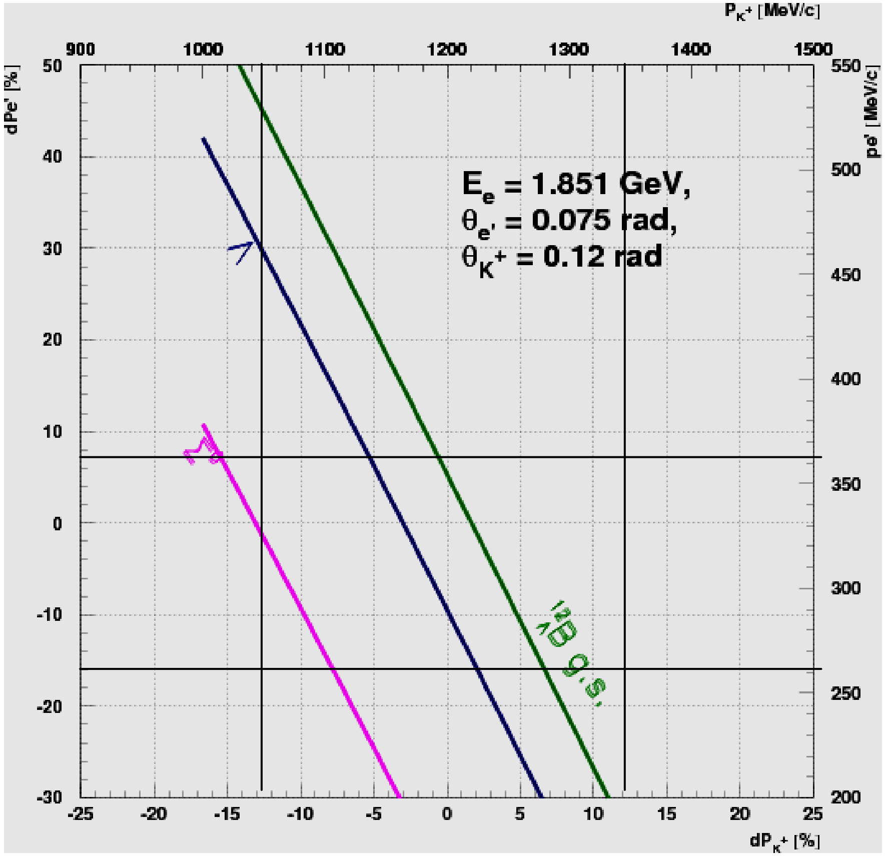
Jlab is a unique facility for (e,e'K^+) experiments

Kinematics

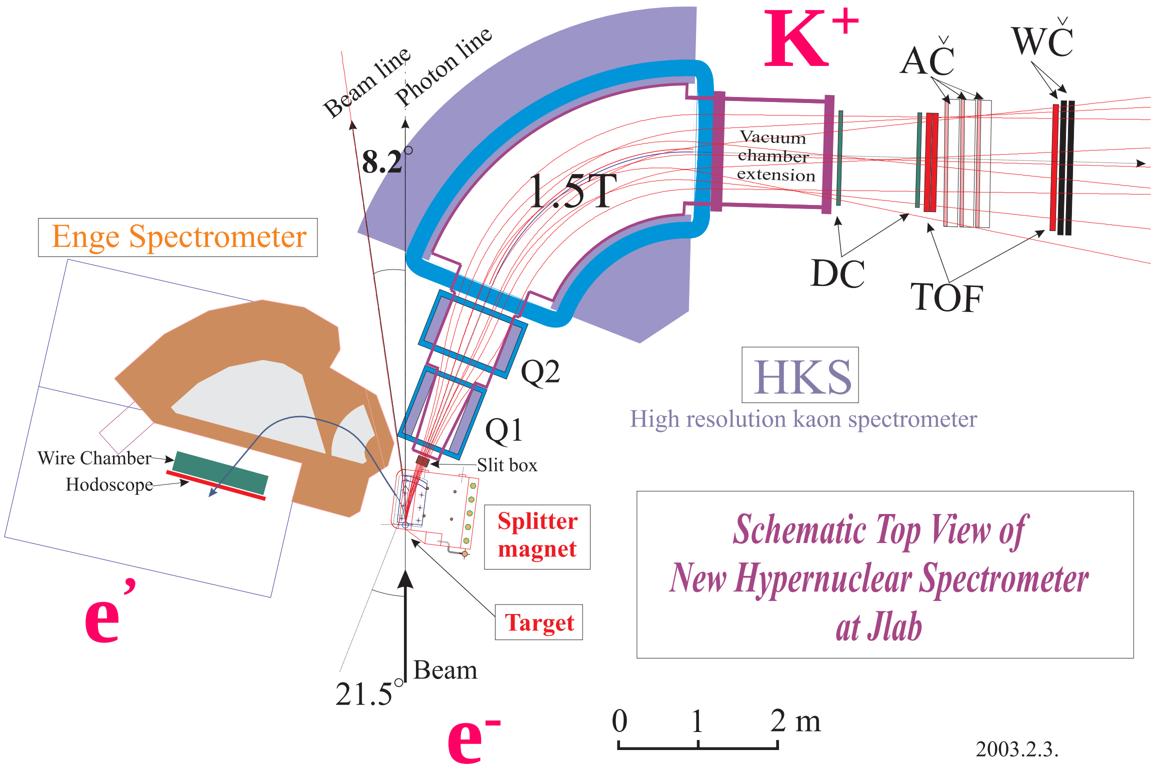


Phys. Lett. B 445, 20 (1998)
M. Q. Tran et al. [SAPHIR, ELSA @ Bonn]





Experimental setup



ENGE

Central momentum	0.3 GeV/c
$\Delta p/p$	5 x 10 $^{-4}$ [FWHM]
Momentum acceptance	±30 %
Tilt angle	7.75°

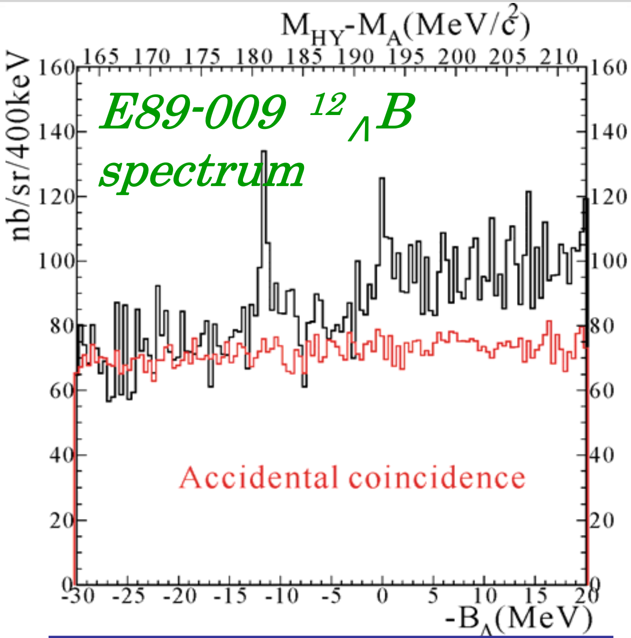
HKS (normal conductive)

Configuration	Q+Q+D
Central momentum	1.2 GeV/c
$\Delta p/p$	2 x 10 $^{-4}$ [FWHM]
Solid angle	16 msr w/ splitter
Flight path	10 m
Momentum acceptance	±12.5 %
Angular acceptance	170 mr (v)
	180 mr (h)
Max. dipole field	1.5 T

Pioneering Λ hypernuclear spectroscopy : Jlab E89-009

E89-009
Beam: 0.66 μA
SOS for K^+ detection :
$\Delta p/p = 5 \times 10^{-4}$ [FWHM]
Solid angle 4 msr(w/ splitter)
Enge for e' detection :
$\Delta p/p = 5 \times 10^{-4}$ [FWHM]

The 1st (e,e'K^+) reaction spectroscopy successfully demonstrated on 2000.



- Net 1 month data
- Energy resolution : 900 keV

Review : 1) small K^+ solid angle, poor energy resolution

→ Upgrade K^+ spectrometer (HKS)

2) Poor S/N ratio due to the Bremsstrahlung associated electrons

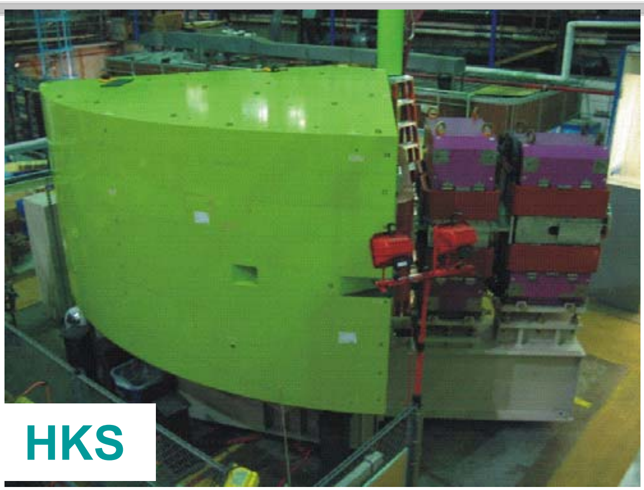
→ Introduce Tilt method for the scattered electron spectrometer

Improvement in the E01-011

1) High resolution Kaon Spectrometer (HKS)

→ Momentum res. : $\Delta p/p = 2 \times 10^{-4}$ [FWHM] *(SOS: 5×10^{-4})*

→ K^+ solid angle : 16 msr w/ splitter *(SOS: 4 msr)*



2)Tilt method for e' arm

Tilt ENGE by ~8 degs upward, shut out Bremsstrahlung, Moller associated electrons. Thus in the case of ^{12}C target…

→ e' detect. rate : ~1 MHz *(E89-009 : ~200 MHz)*

→ Higher beam current : 30 μA *(E89-009 : 0.6 μA)*

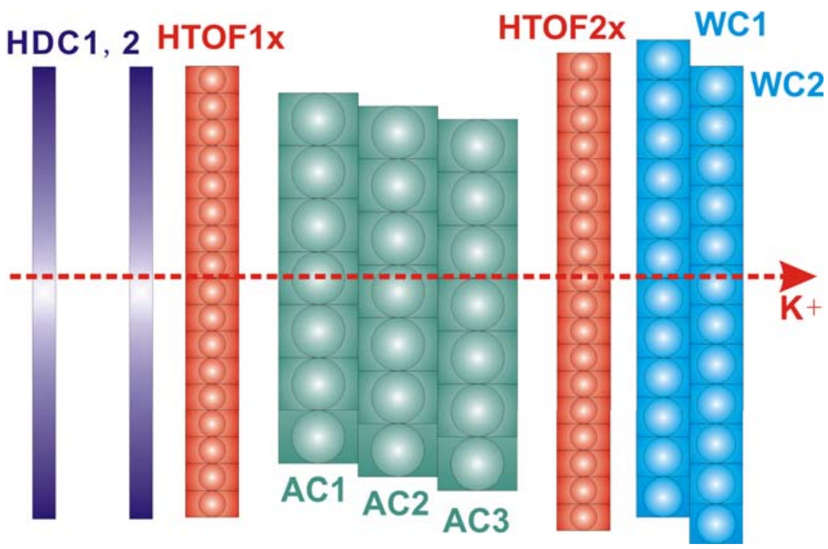
→ Thicker target : 100 mg/cm^2 *(E89-009 : 22 mg/cm^2)*

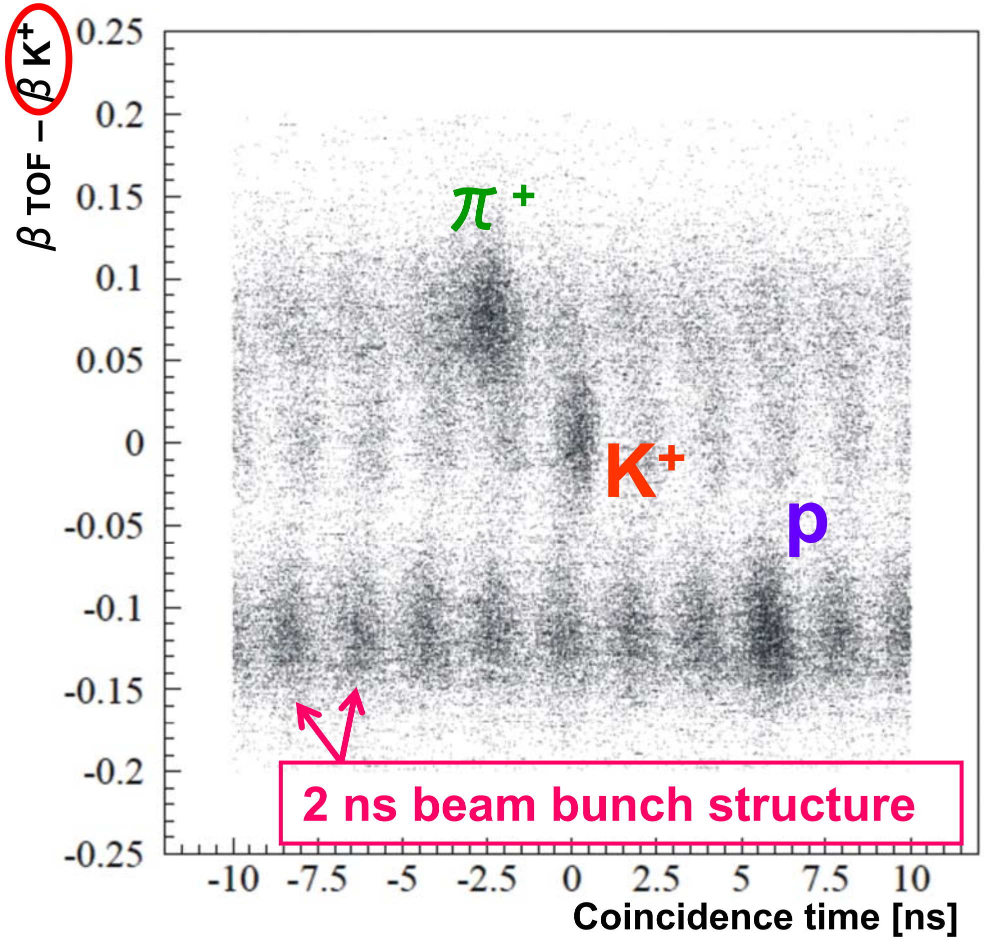
Achieved data taking for higher mass region like ^{28}Si w/ higher resolution

K^+ ID

Trigger: 1X x 2X x WC x $\overline{\mathrm{AC}}$

$$\beta_{K^+} = \frac{p_{trk}}{\sqrt{p_{trk}^{\ 2} + m_{K^+}^{2}}}$$





Rates:

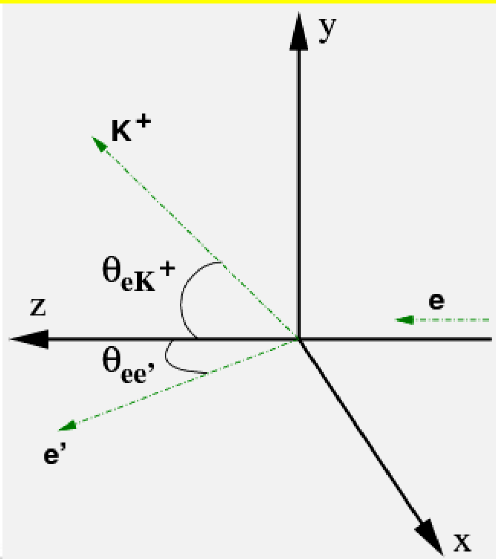
HKS : 12.7 kHz, ENGE : 1.195 MHz, TRIG. : 636 Hz

w/ ^{12}C 100 mg/cm², 26 uA (Comp. dead time < 7%)

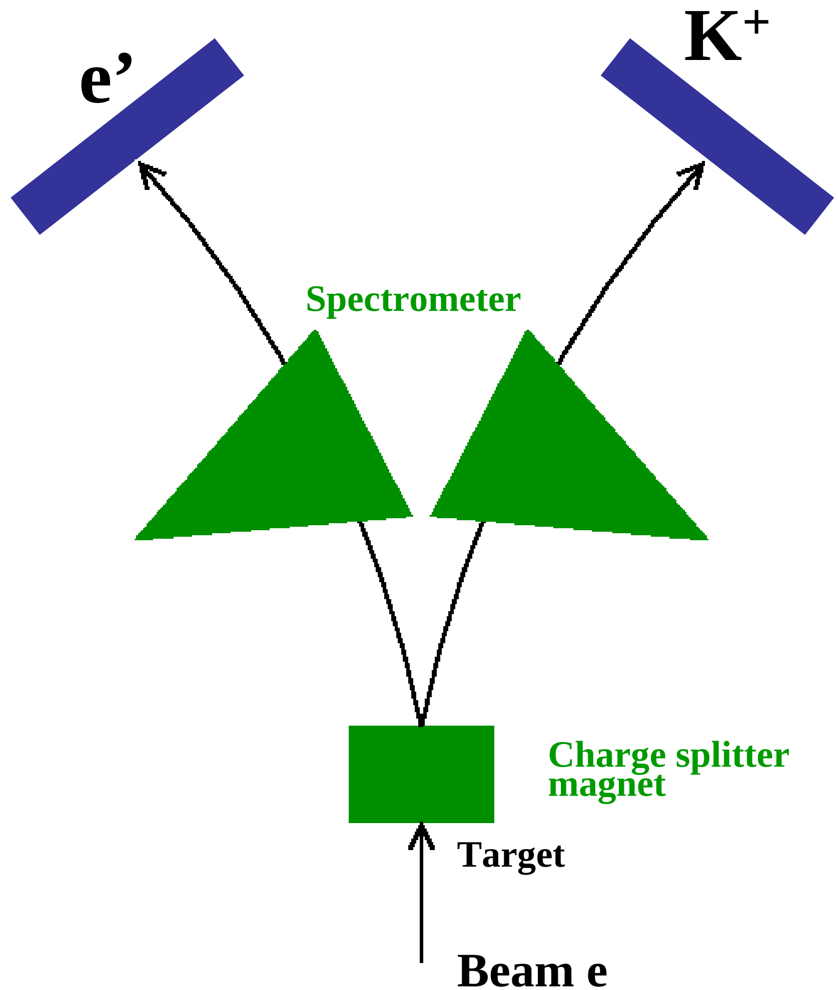
e’ / K$^+$ incident angle (@ target), momentum calibration

$$M_{HY}^2 = (E_e + M_A - E_{K^+} - E_{e'})^2$$
$$- (p_e^2 + p_{e'}^2 + p_{K^+}^2 - 2 p_e p_{e'} \cos\theta_{ee'}$$
$$- 2 p_e p_{K^+} \cos\theta_{eK^+} + 2 p_{e'} p_{K^+} \cos\theta_{e'K^+})$$

$$X_t = \sum_{\alpha+\beta+\gamma+\eta=1}^{6} C(\alpha,\beta,\gamma,\eta) x_f^{\alpha} x'^{\beta}_f y_f^{\gamma} y'^{\eta}_f$$

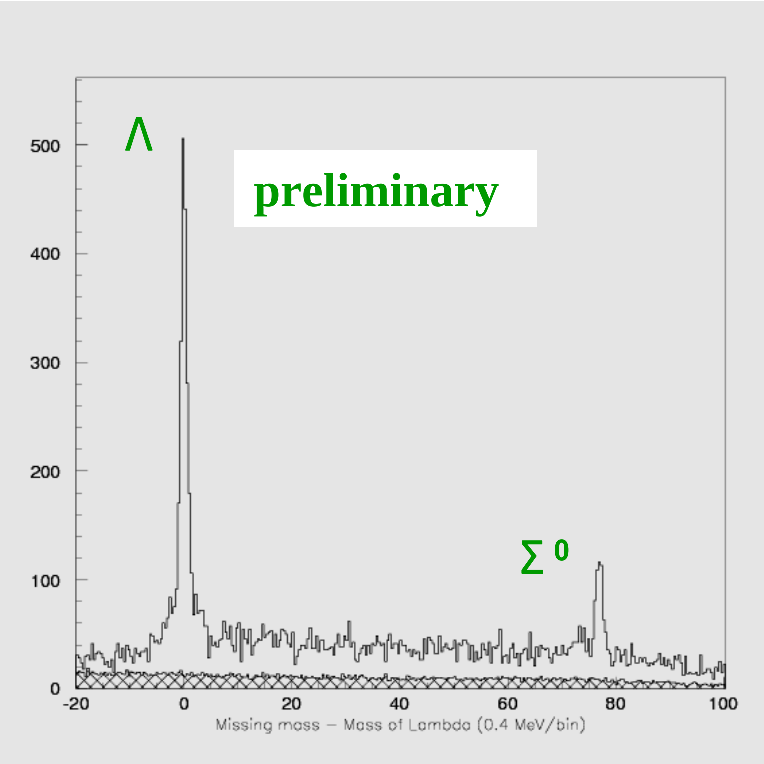


Detect position & angle w/ Drift Chambers



Pe, Pe’, P_{K^+}, θ ee’, θ eK$^+$, θ e’K$^+$

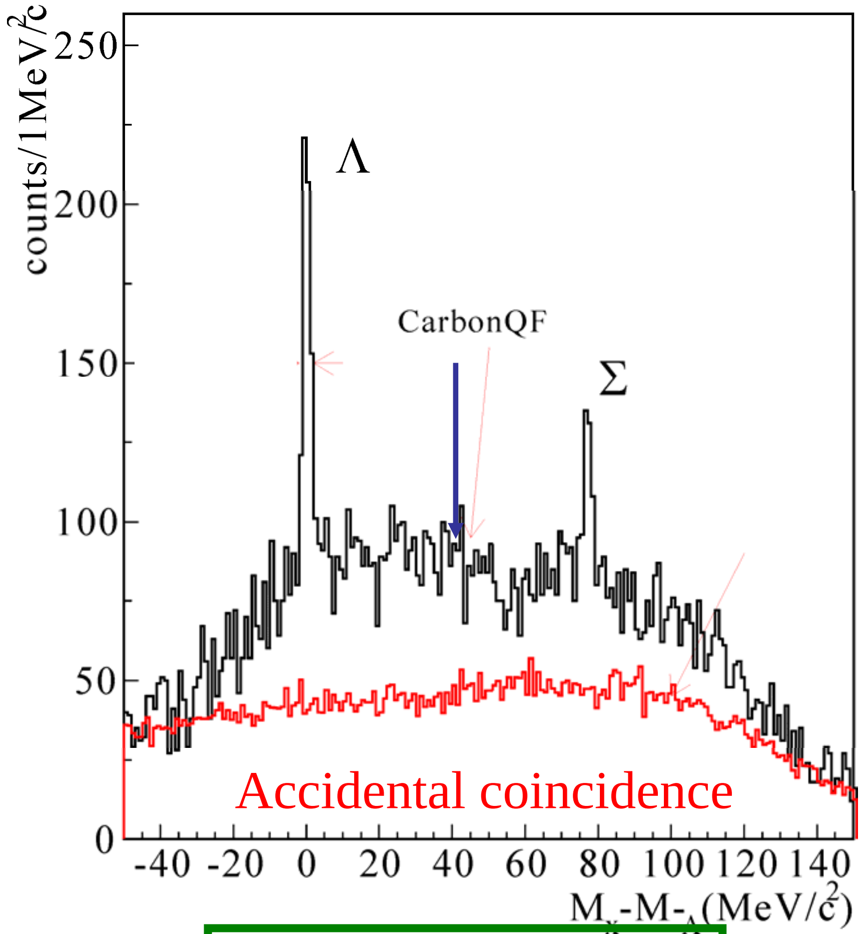
Spectra (preliminary) : p (e,e'K⁺) Λ / Σ ⁰



~70 hrs, 1.5 uA

Γ M_{Λ} = ~1.4 MeV [FWHM]

Γ M_{Σ^0} = ~1.4 MeV [FWHM]

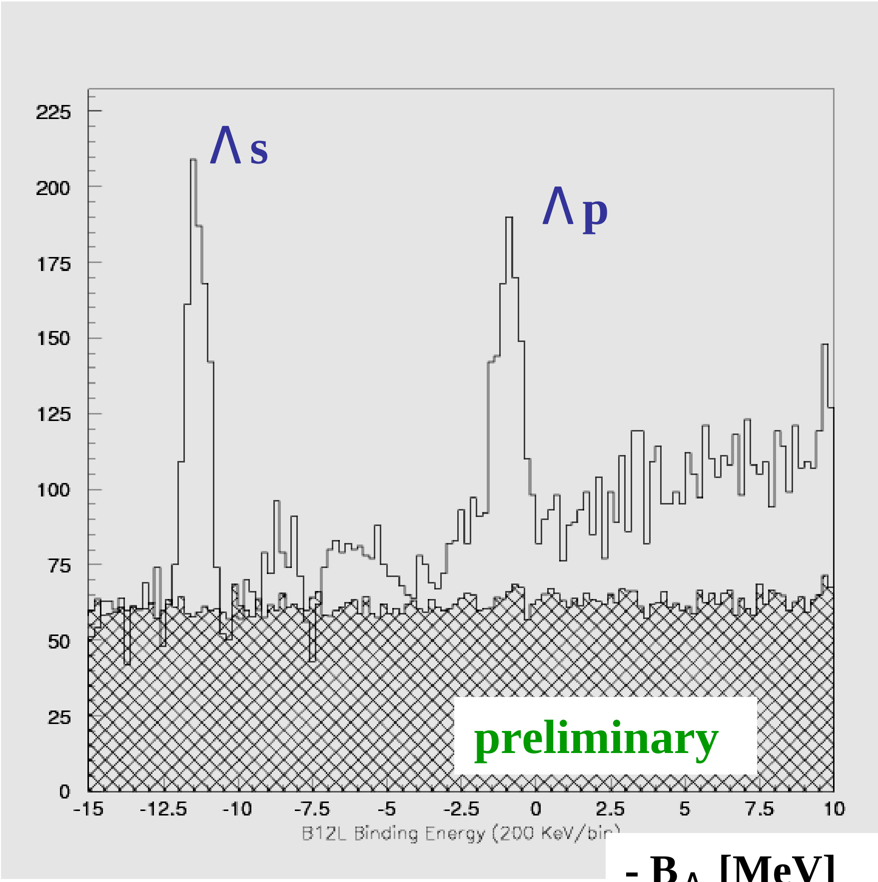


~180 hrs, 0.5/1.0 uA

Γ M_{Λ} = ~1.6 MeV [FWHM]

Γ M_{Σ^0} = ~1.5 MeV [FWHM]

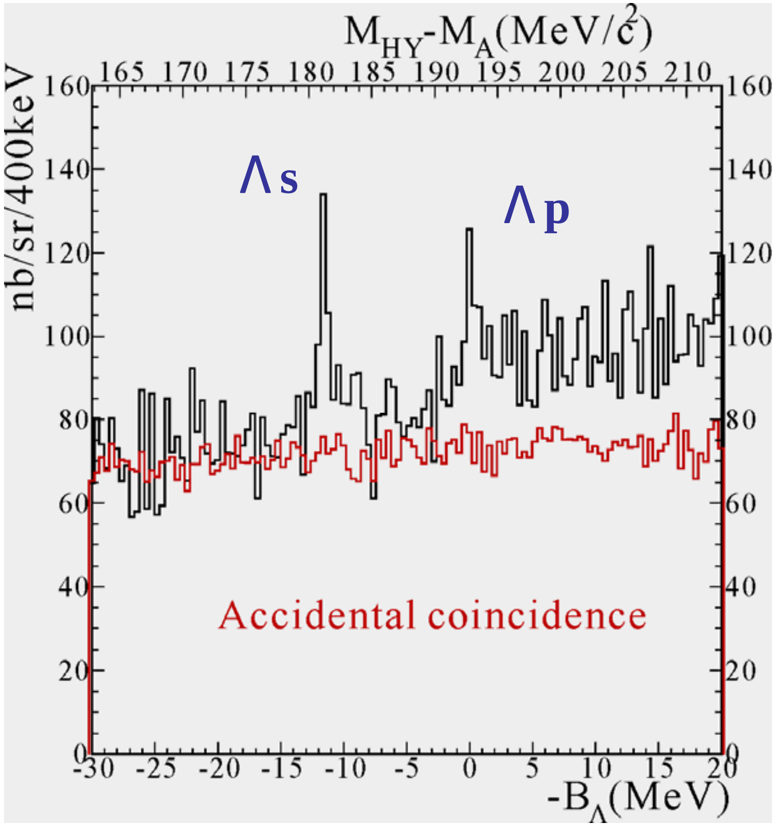
Spectra (preliminary) : $^{12}C\ (e,e'K^+)\ ^{12}{}_{\Lambda}B$



- B_{Λ} [MeV]

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

E89-009 result

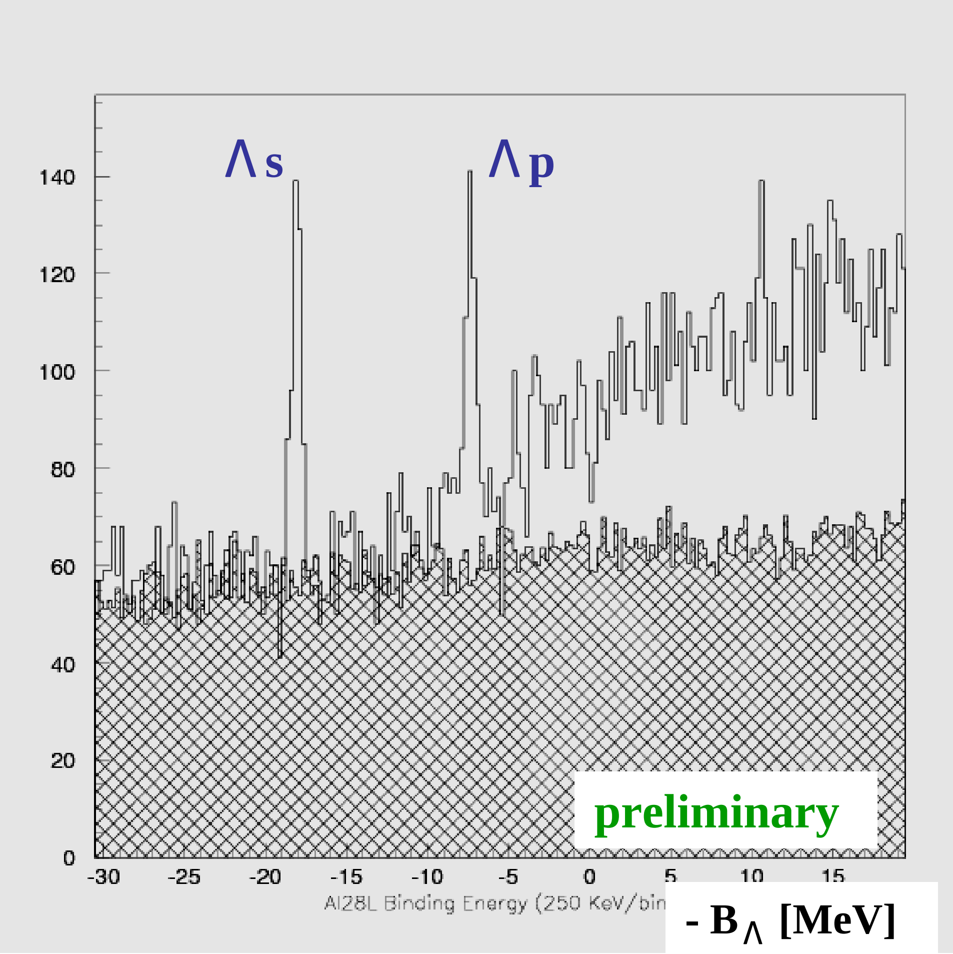


~90 hrs, 30 uA
G.S. (2- / 1-):
Γ = ~670 keV [FWHM]

x ~15 yield, x ~4 S/N achieved

~300 hrs, 0.6 uA
G.S. (2- / 1-):
Γ = ~900 keV [FWHM]

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



~140 hrs, 30 uA

G.S. :
Γ = ~750 keV [FWHM]

Efficiencies

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.

dΩ : solid angle acceptance of HKS

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

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

ε htrk: ~ 0.86
  HKS tracking efficiency

ε trig: ~0.99
  Trigger efficiency

ε AC: ~0.8
  AC cut efficiency

ε WC: ~0.97
  WC cut efficiency

ε bk: ~0.95
  beta cut efficiency

ε etrk: ~0.85
  ENGE tracking efficiency

***f* veto:**
  AC veto factor

***f* abs: ~0.95**
  Kaon absorption factor

***f* decay: ~0.33**
  Kaon decay factor

***f* comp: ~0.93**
  Computer dead time factor

Summary

1) The 2nd generation Spectroscopic experiment for Λ hypernuclei has been completed at Jlab, 2005.

3) $^{28}_{\Lambda}$Al was observed for the 1st time.

   It is a breakthrough for medium mass region.

2) Introduction of the HKS and Tilt method enabled

   high resolution and high statistics data taking.

4) Mass calibration needs further improvement.

5) Efficiencies estimation has been almost done

Backup from here

Characteristics of the (e,e'K+) reaction (2)

Measuring interior structure by mass spectra :

$$M_{HY}^2 = (E_e + M_A - E_{K^+} - E_{e'})^2 - (p_e^2 + p_{e'}^2 + p_{K^+}^2 - 2p_e p_{e'} \cos\theta_{ee'} - 2p_e p_{K^+} \cos\theta_{eK^+} + 2p_{e'} p_{K^+} \cos\theta_{e'K^+})$$

$$X_t = \sum_{\alpha+\beta+\gamma+\eta=1}^{6} C(\alpha,\beta,\gamma,\eta) x_f^{\alpha} x'^{\beta}_f y_f^{\gamma} y'^{\eta}_f$$

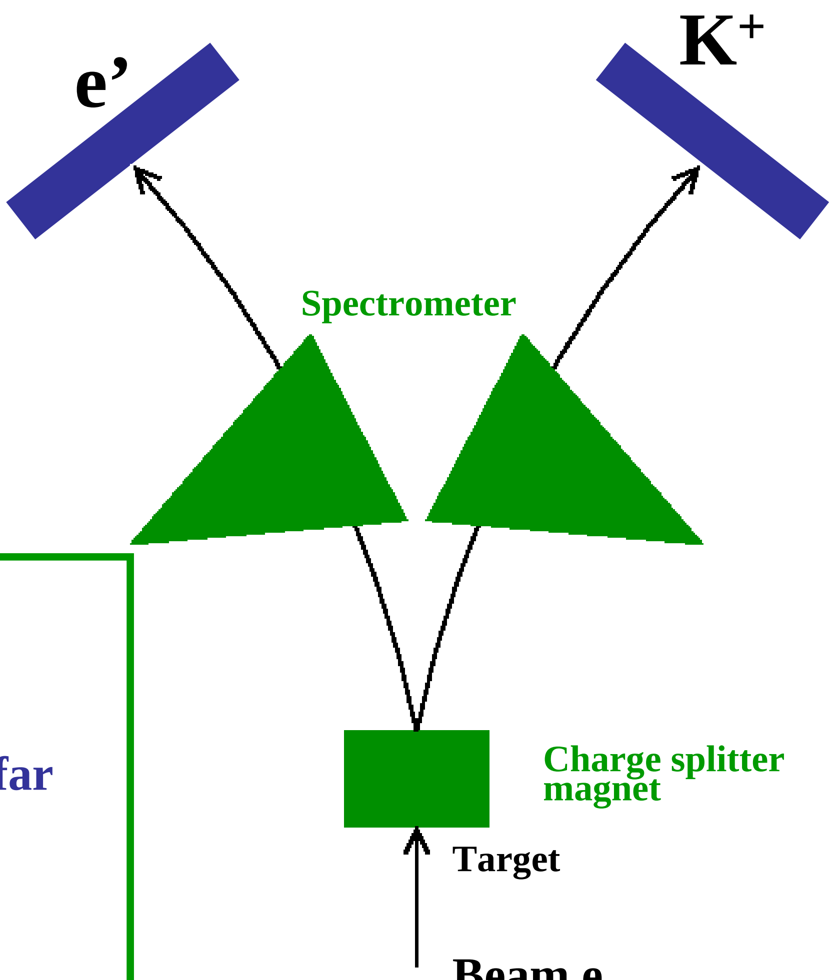
(e,e'K+) spectroscopy : Coincidence experiment

On the other hand,

1) hard to provide continuous electron beam, so far

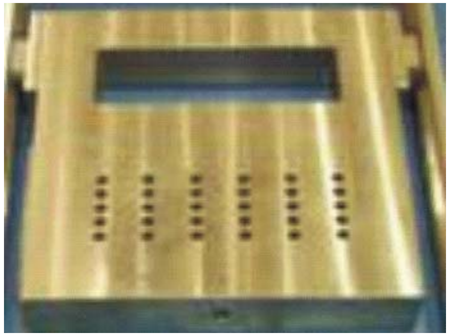
2) hard to ID e'/K+ associated w/ Λ production from huge bunch of accidental samples

Detect position & angle w/ Drift Chambers

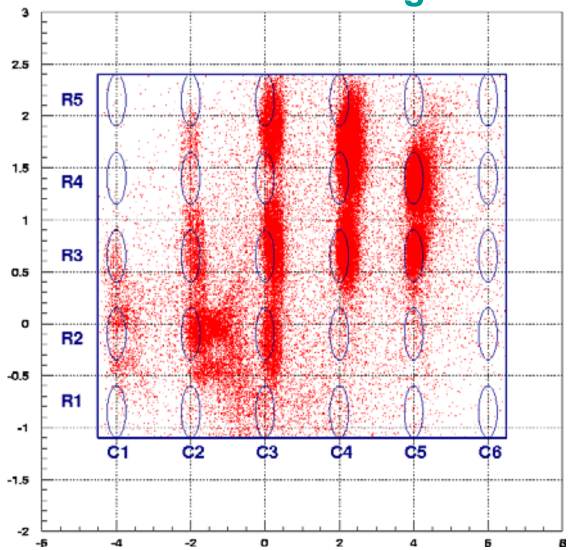


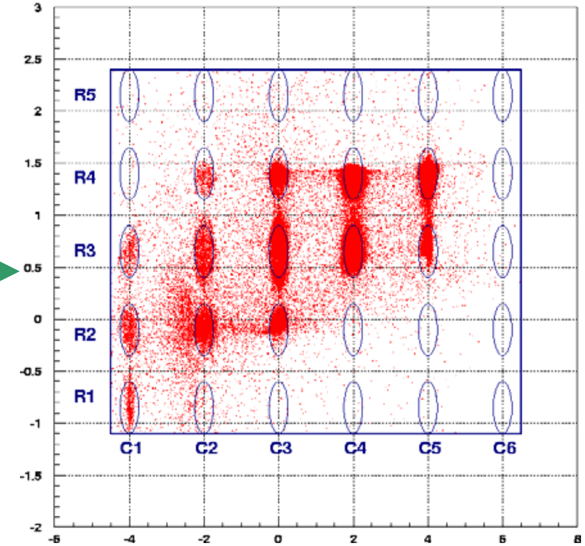
P_e, $P_{e'}$, P_{K^+}, $\theta_{ee'}$, θ_{eK^+}, $\theta_{e'K^+}$

Incident angle calibration (1)

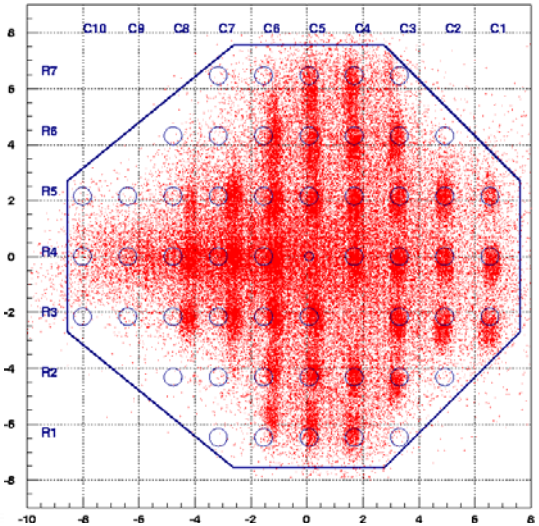


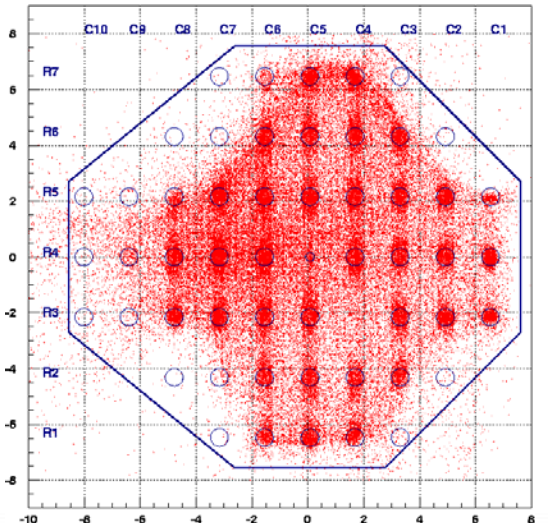
ENGE sieve slit image



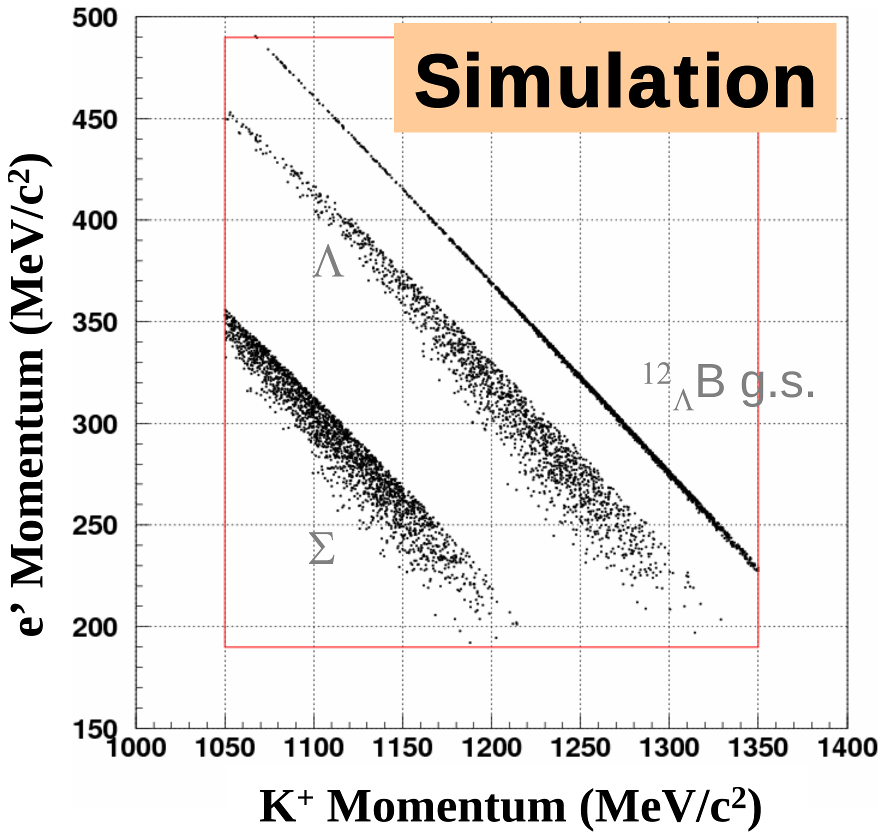


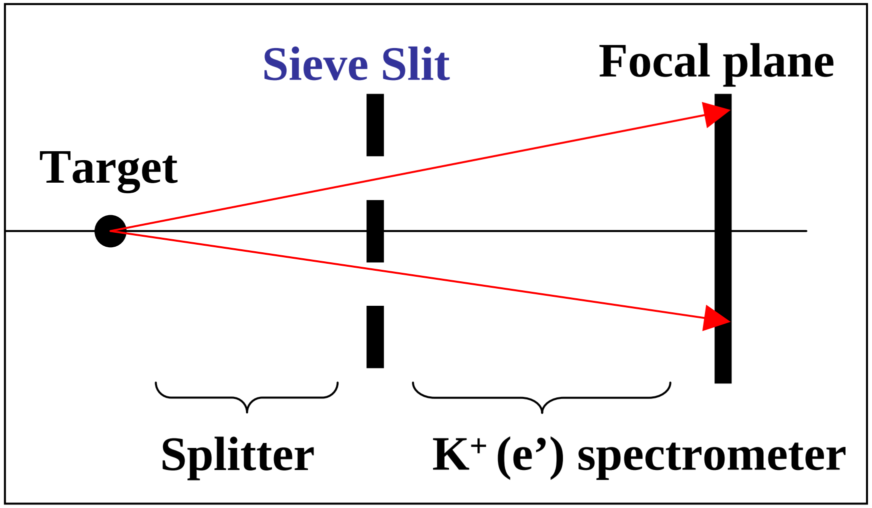
HKS sieve slit image

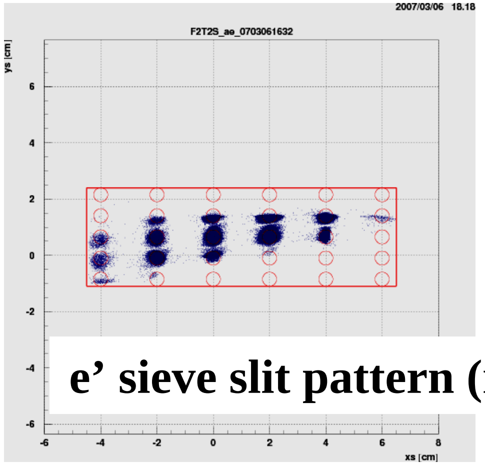




Incident angle calibration (2)





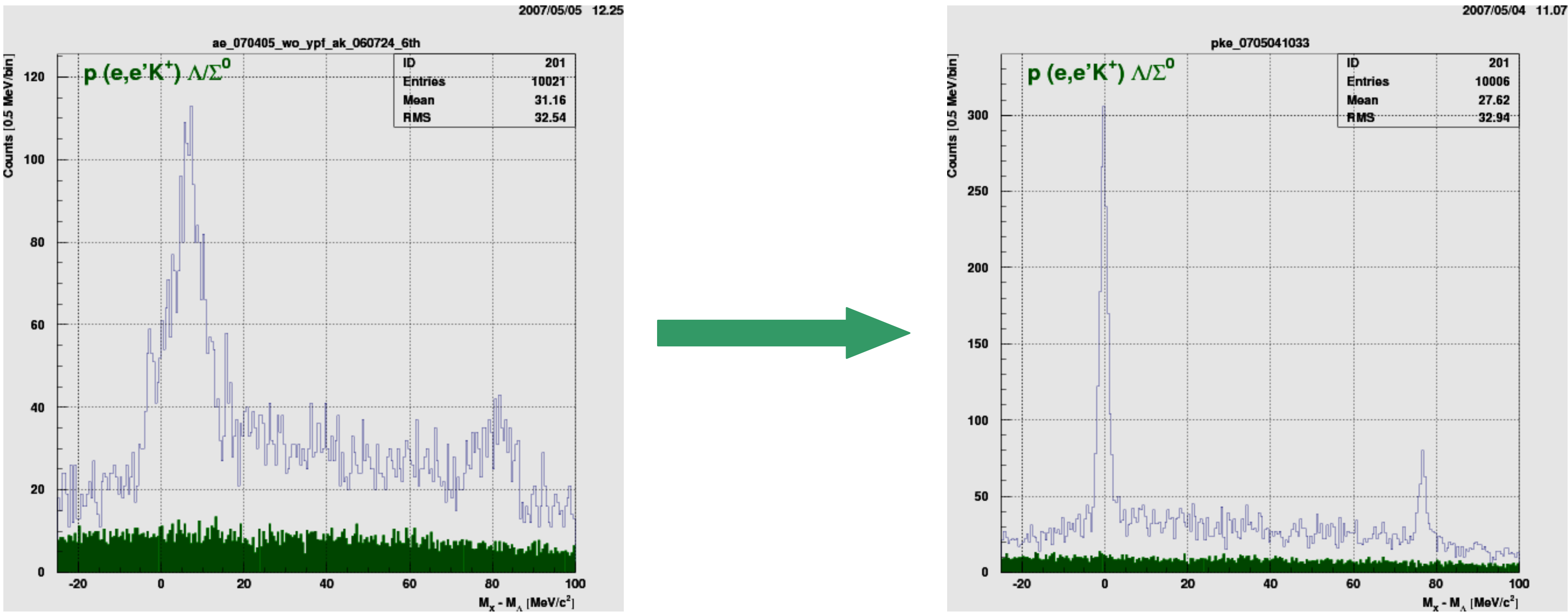


More scattered angle dependence for L and S ($M_{proton} << M_{12C}$)

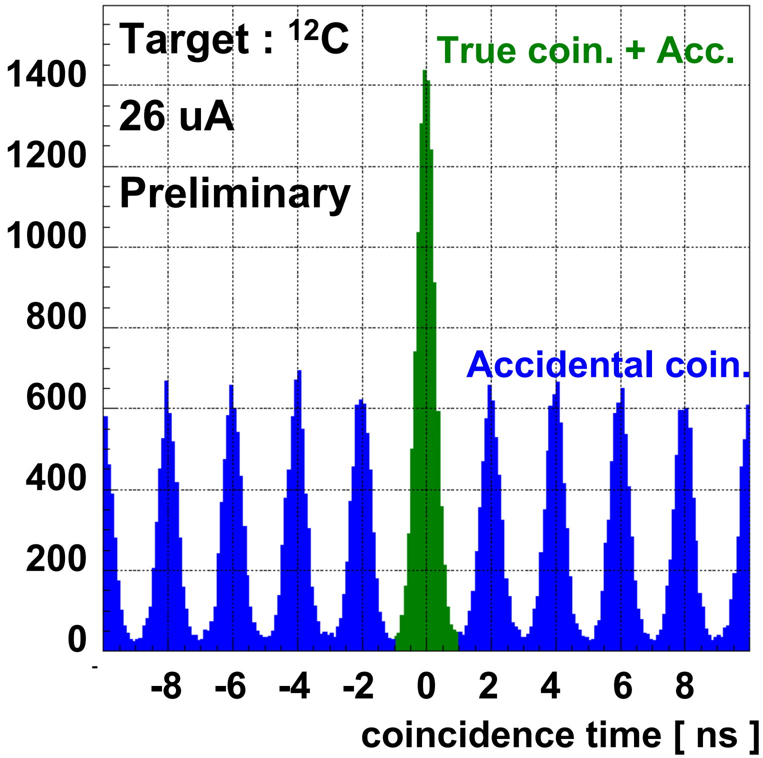
➔ Tune scatted angle by sieve slit data

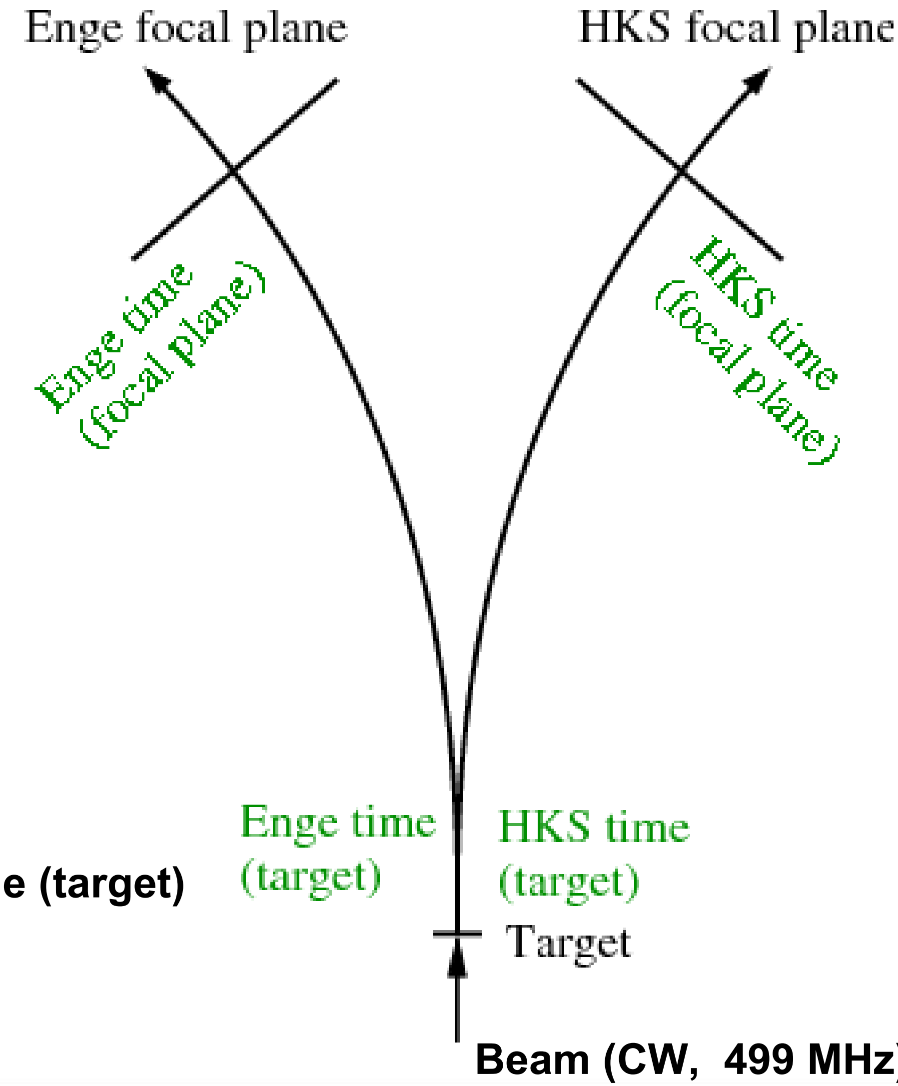
Momentum calibration

Calibrate w/ well known CH_2 (Λ / Σ^0)



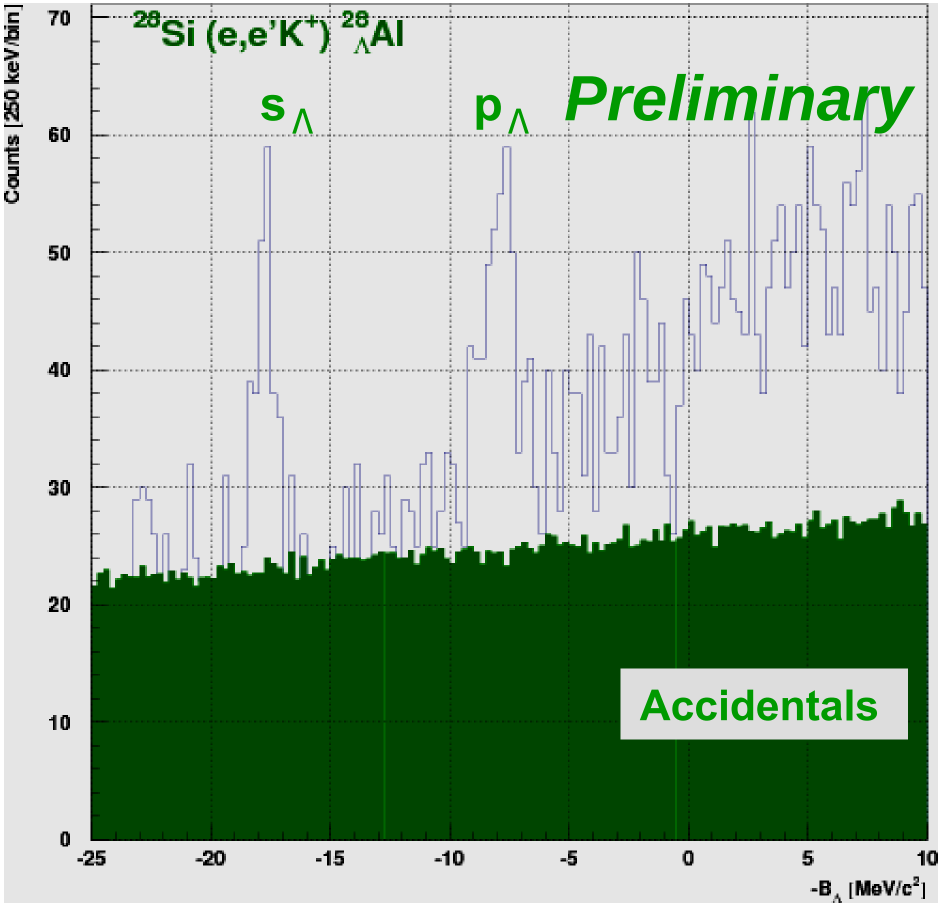
ENGE / HKS coincidence selection





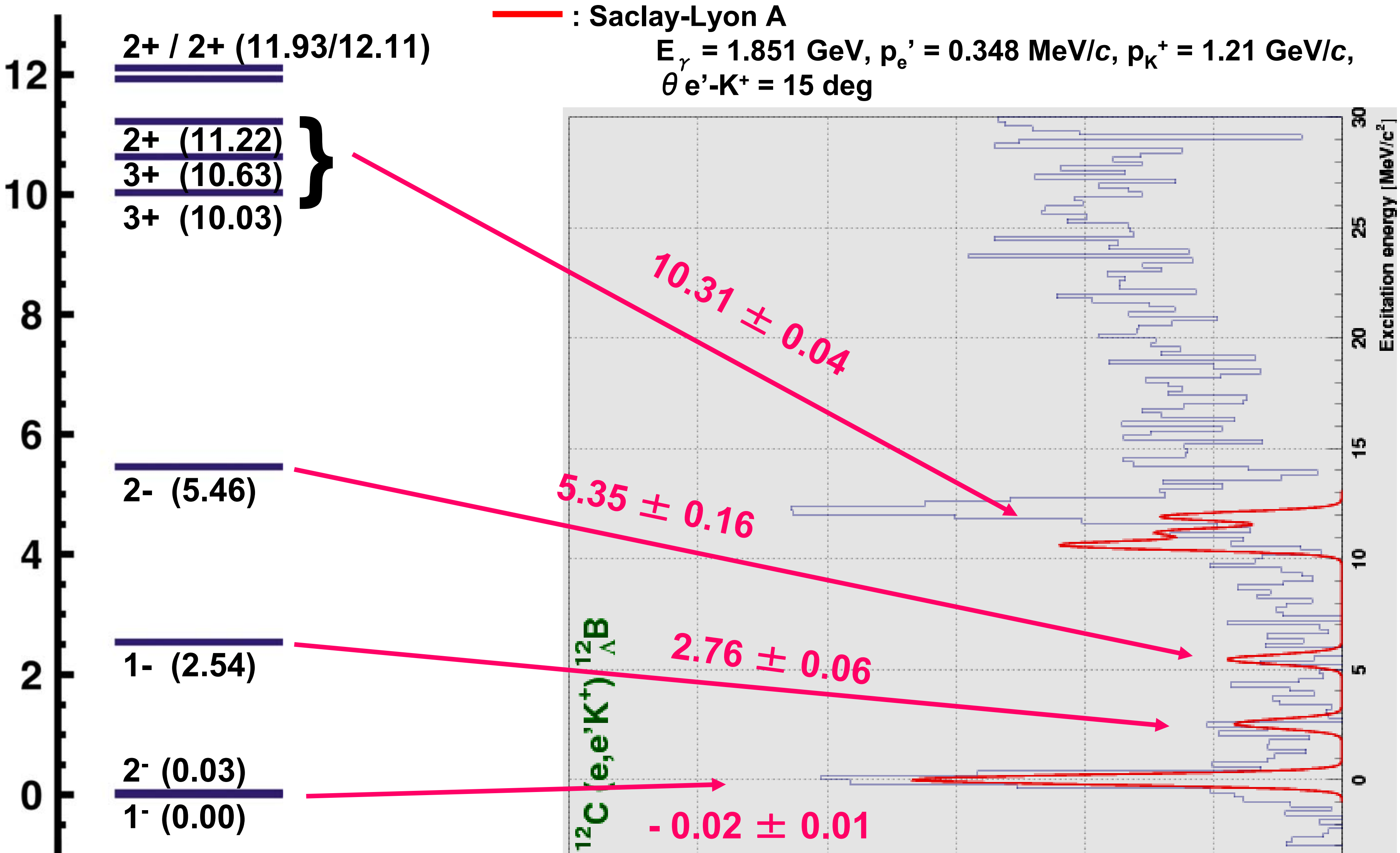
Coincidence time = Enge time (target) – HKS time (target)

Spectra (preliminary)



G.S. :
Γ = 745 keV [FWHM]
$-B_{\Lambda}$ = -17.93 MeV

Comparison with a theoretical model



Sotona's calc. (T. Mizutani, et al., PR C58(1998)75)
SLA

$^{12}{}_{\Lambda}$B : Hall C (upper) V.S. Hall A (lower)

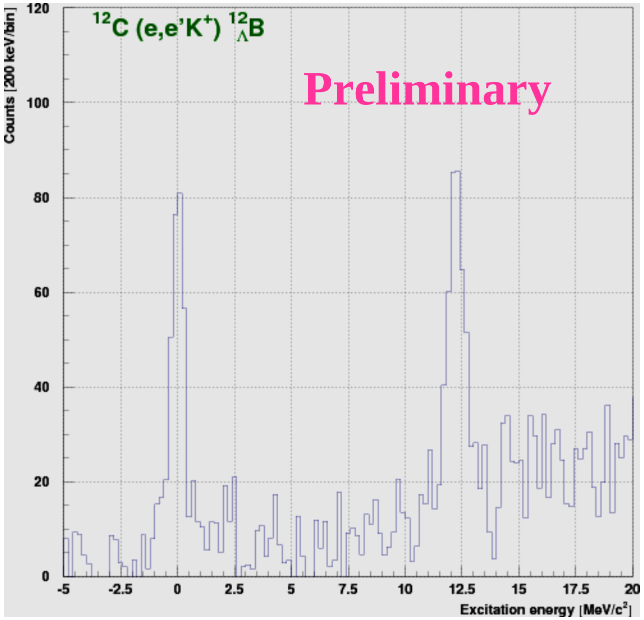
Excitation energy :

12B_L g.s. : 0.0 ± 0.01

12B_L p.s. : 12.280 ± 0.03

Width [FWHM] :

g.s. 0.77 MeV / p.s. 1.62 MeV



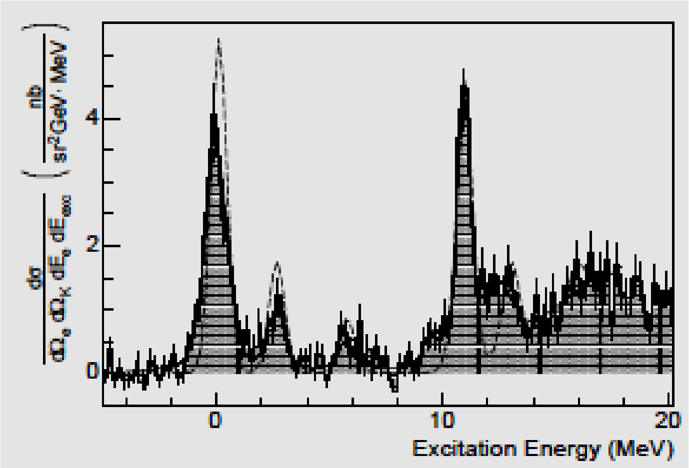
Excitation energy [MeV] :

12B_L g.s. : 0.0 ± 0.03

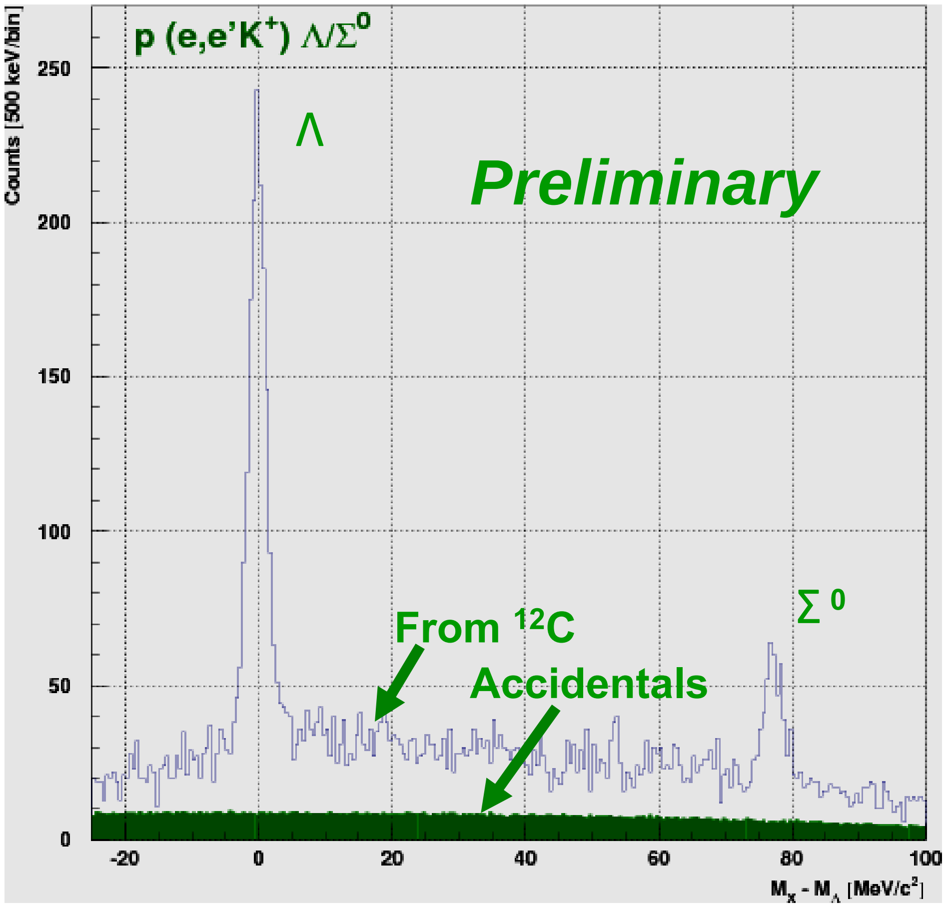
12B_L p.s. : 10.93 ± 0.03

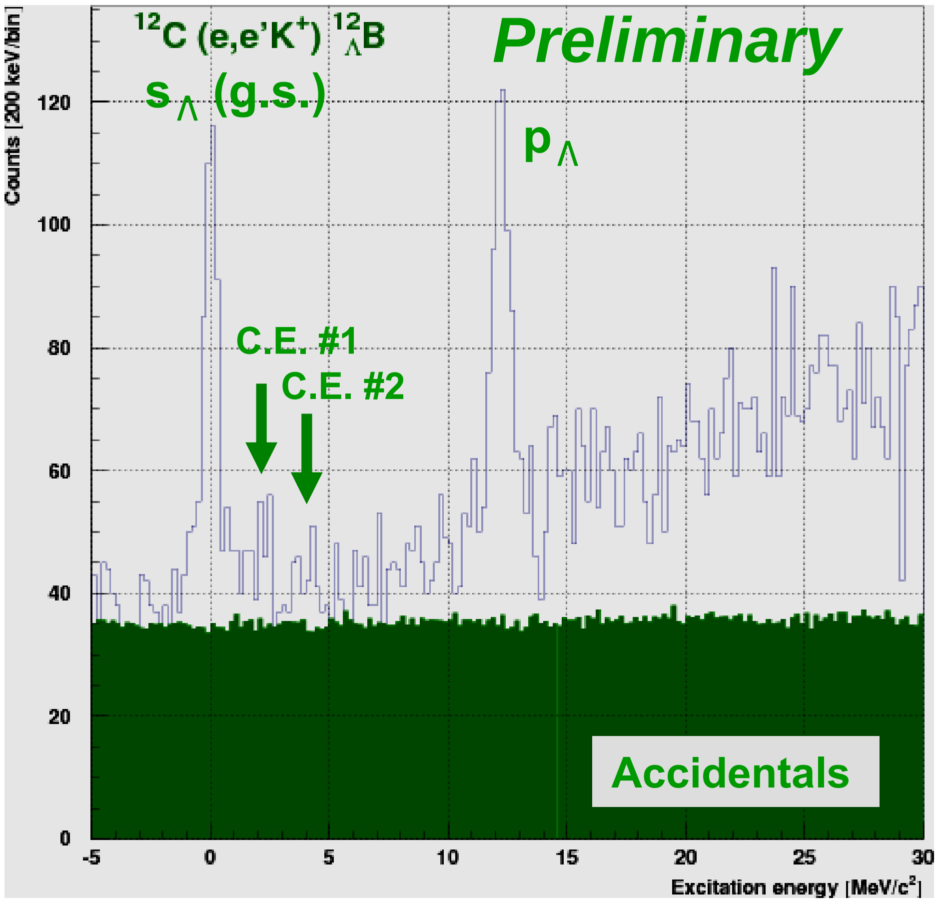
Width [FWHM] :

g.s. 1.15 MeV / p.s. 0.67 MeV



Spectra (preliminary)





ΓM_Λ = 1.43 MeV [FWHM]

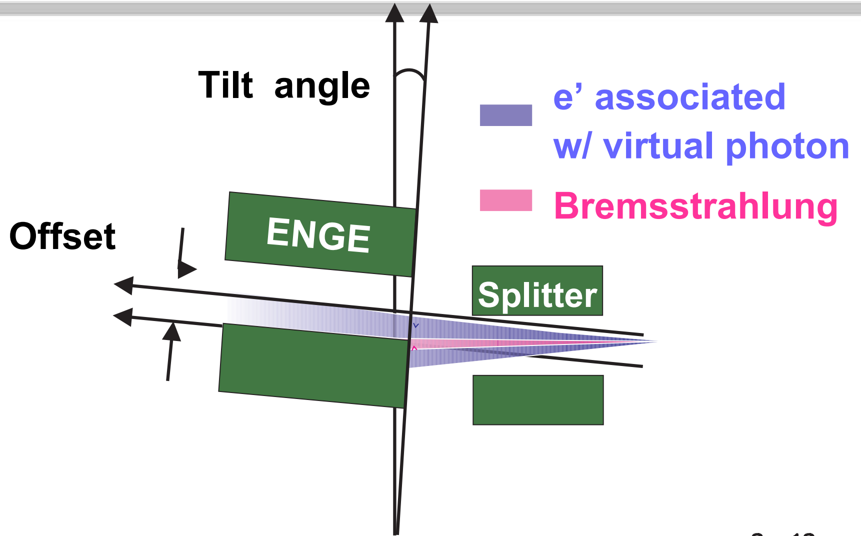
ΓM_{Σ^0} = 1.47 MeV [FWHM]

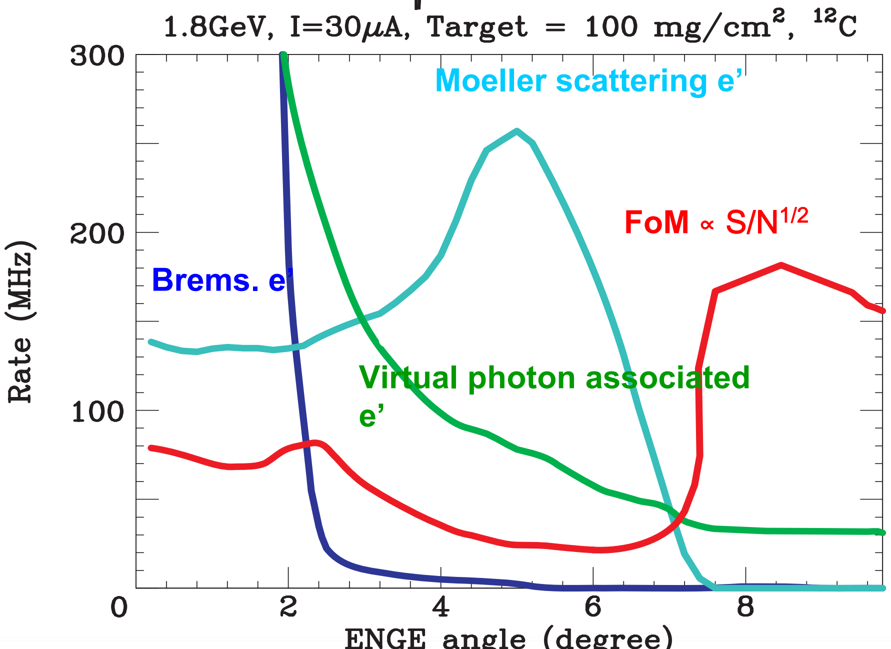
G.S. (2- / 1-):

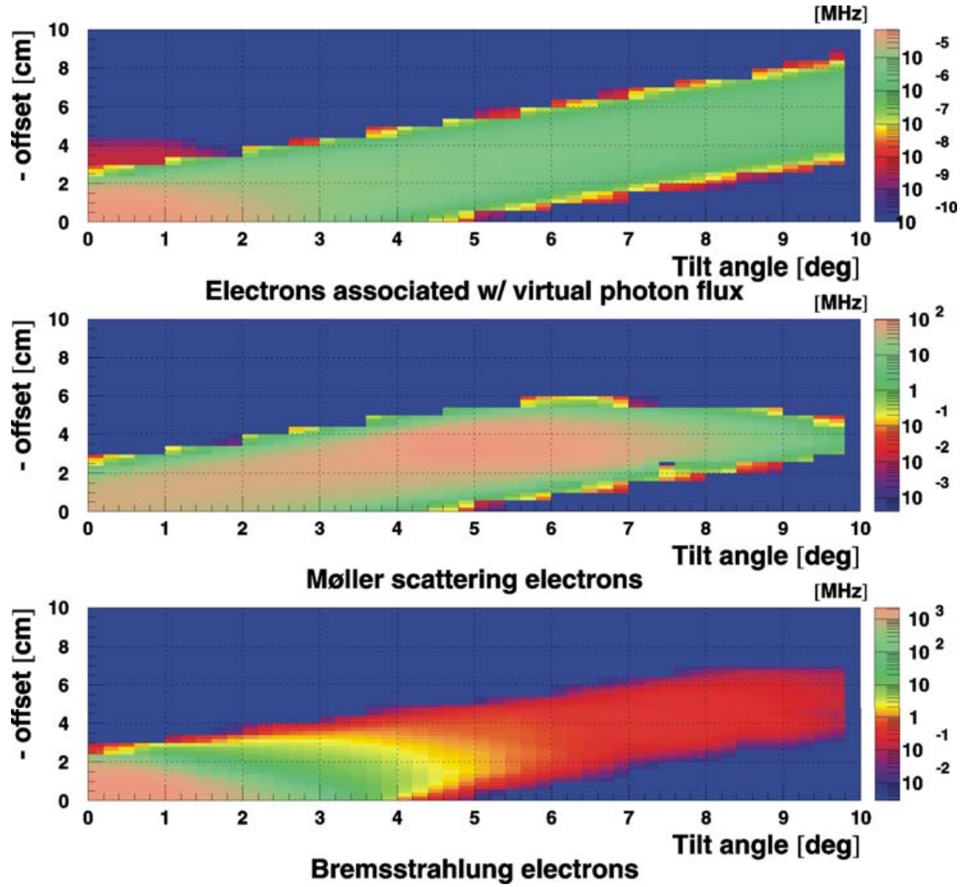
Γ = 775 keV [FWHM]

$-B_\Lambda$ = -11.753 MeV

Tilt method principle





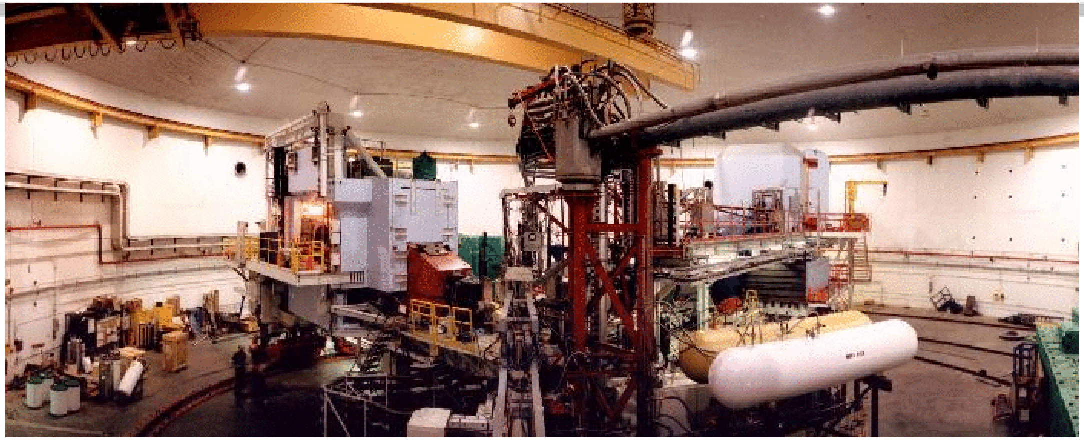


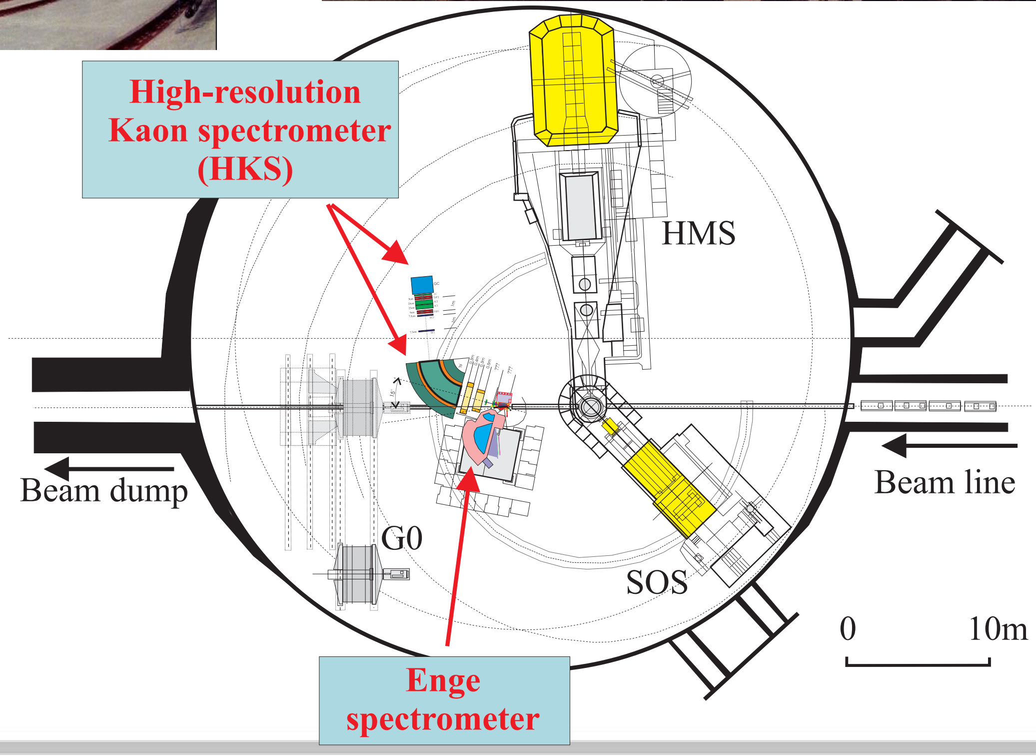
Succeeded to suppress acc. electrons by ~1 MHz

Singles rate comparison : E89-009 VS. E01-011

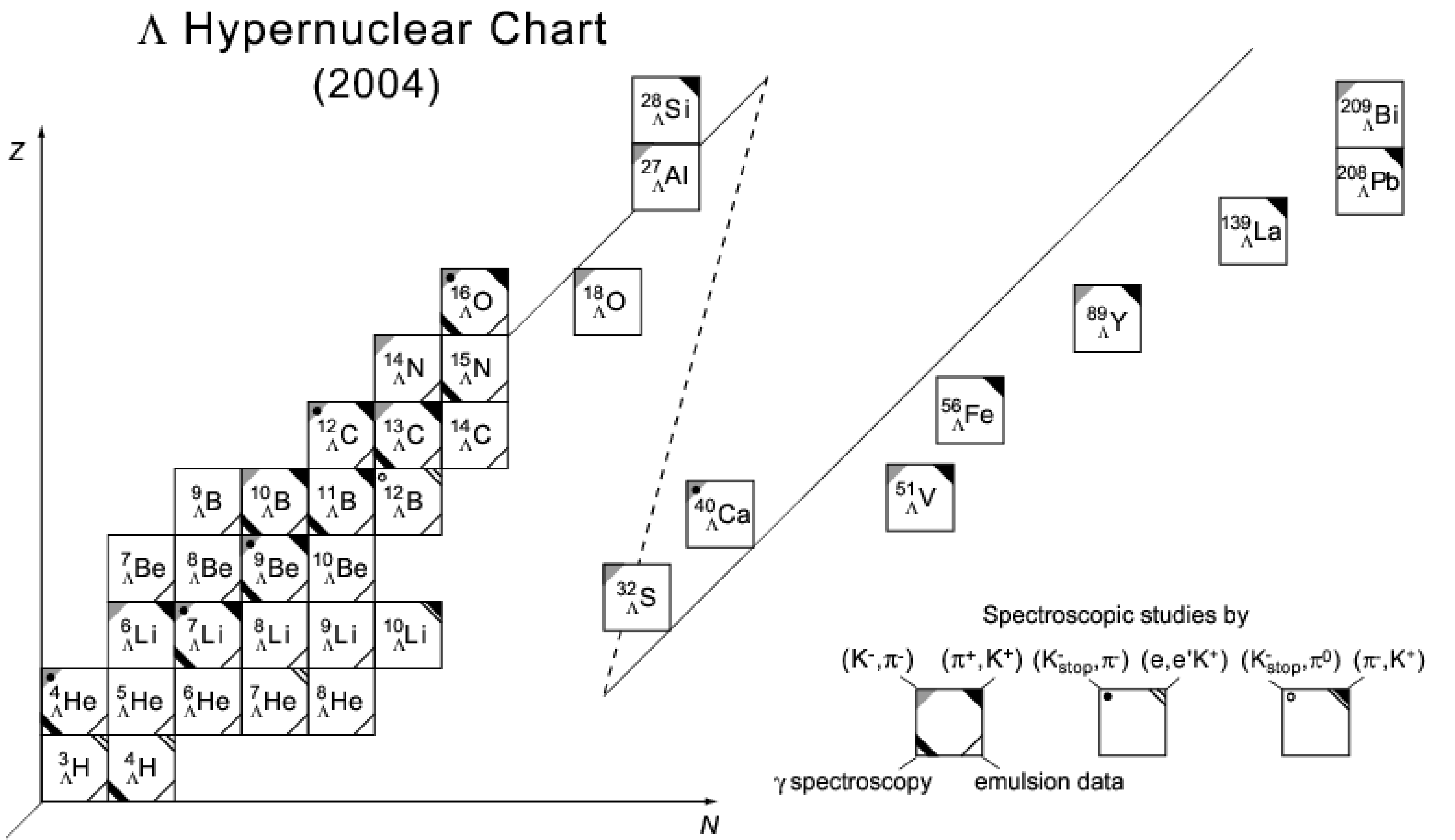
E01-011	Calculated values w/ I_e = 30 μA, 100 mg/cm^2					
	HKS				ENGE	
Target	e^+ (kHz)	π^+ (kHz)	K^+ (kHz)	p (kHz)	e^- (kHz)	π^- (kHz)
^{12}C	---	420	0.38	150	1,000	2.8
^{28}Si	---	420	0.32	130	1,960	2.8
^{51}V	---	410	0.29	120	2,650	3.0
^{12}C	100	1.4	< 1 Hz	0.14	200,000	---
	SOS				ENGE	
E89-009	Measured value w/ I_e = 0.47 μA, 22 mg/cm^2					

Jlab HallC Counting hall

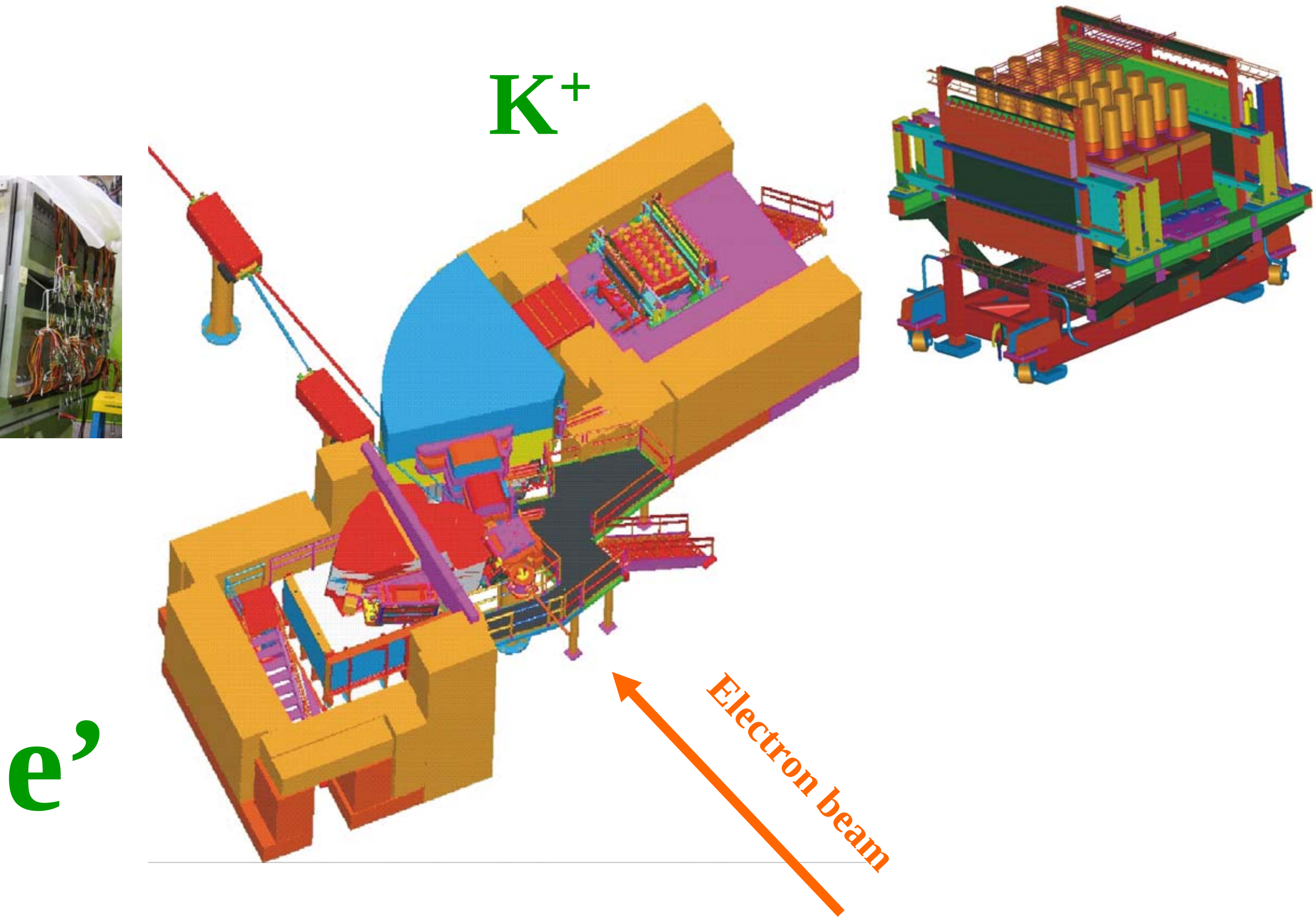




Observed Λ hypernuclear chart

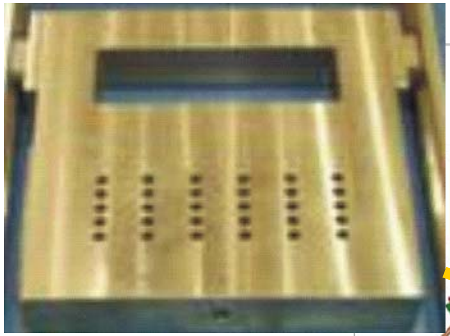


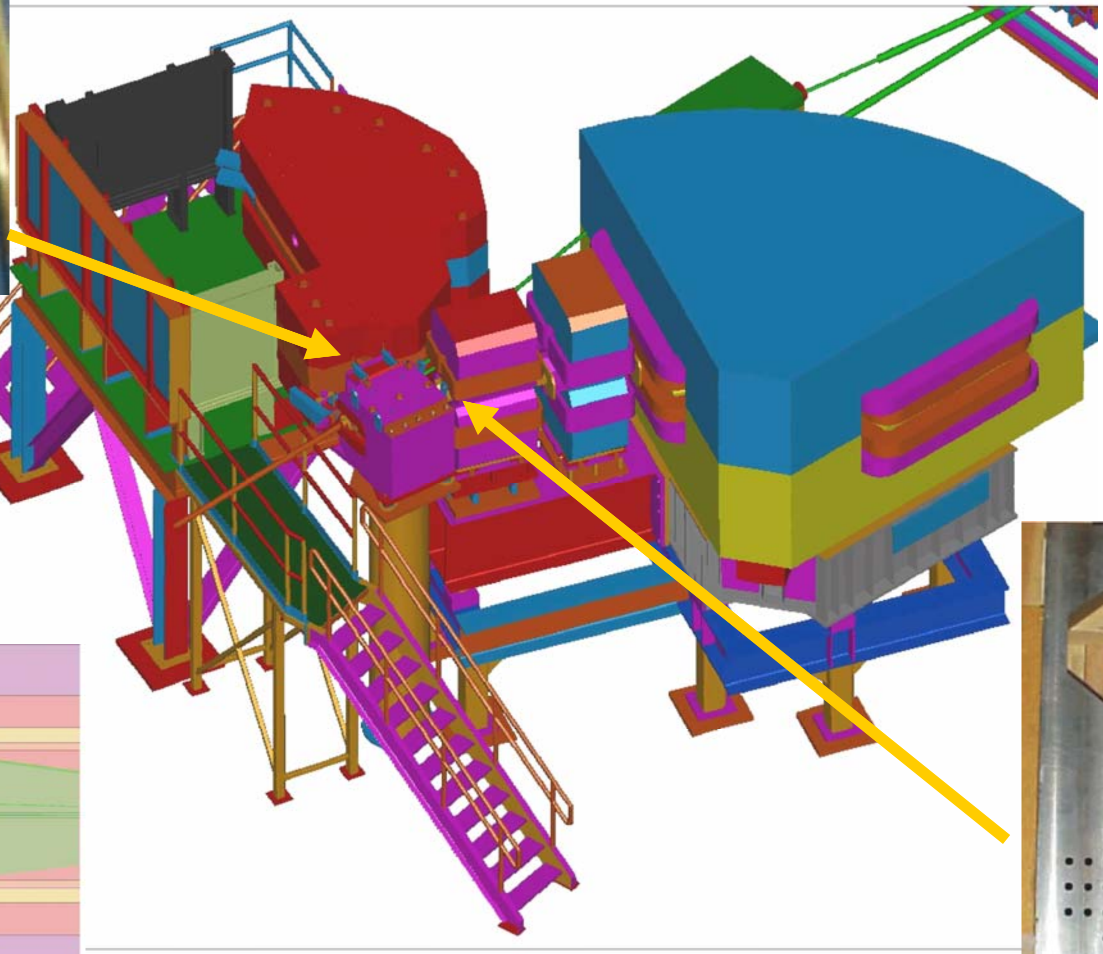
Setup overview

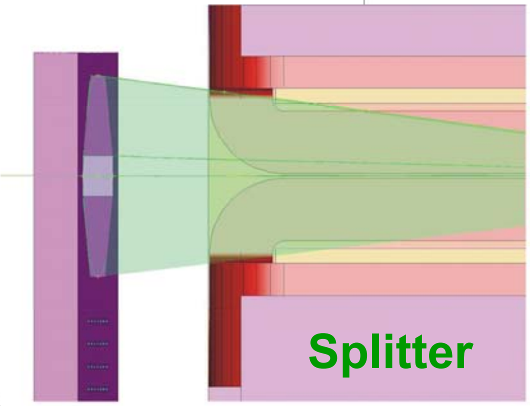


Incident angle calibration (1)

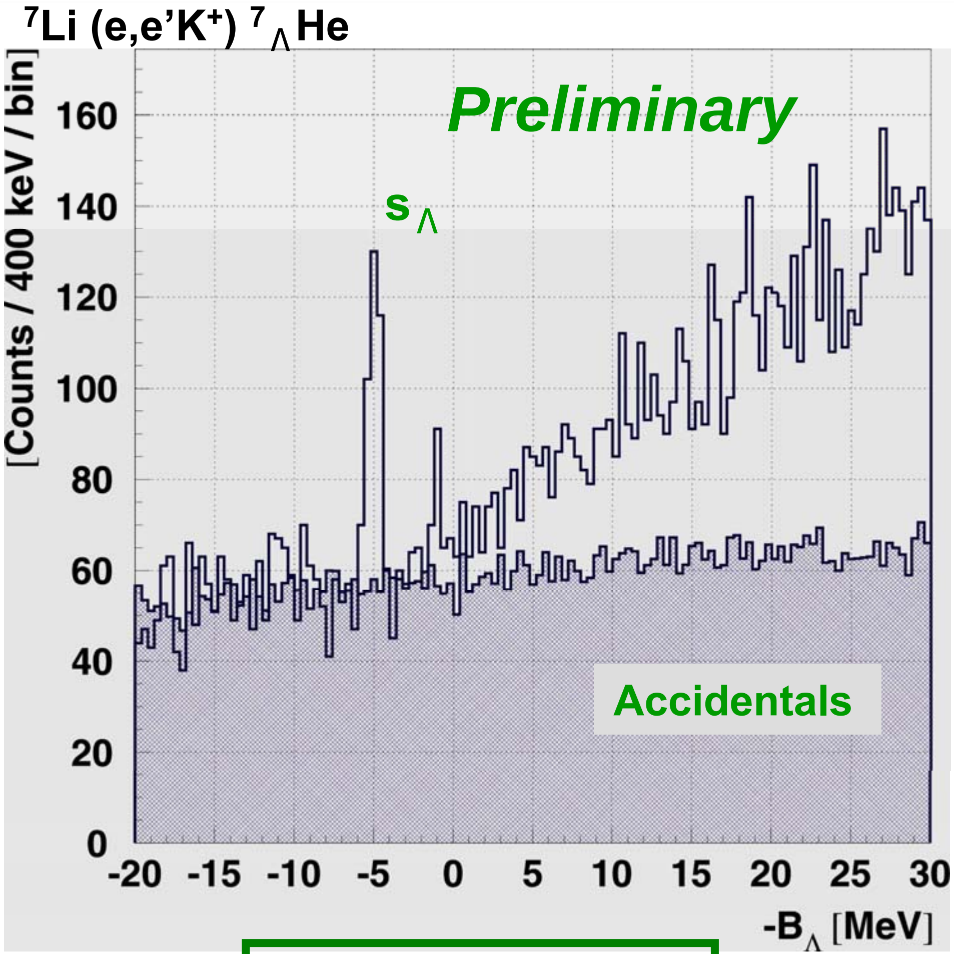
Calibrate incident angle w/ a sieve slit hole



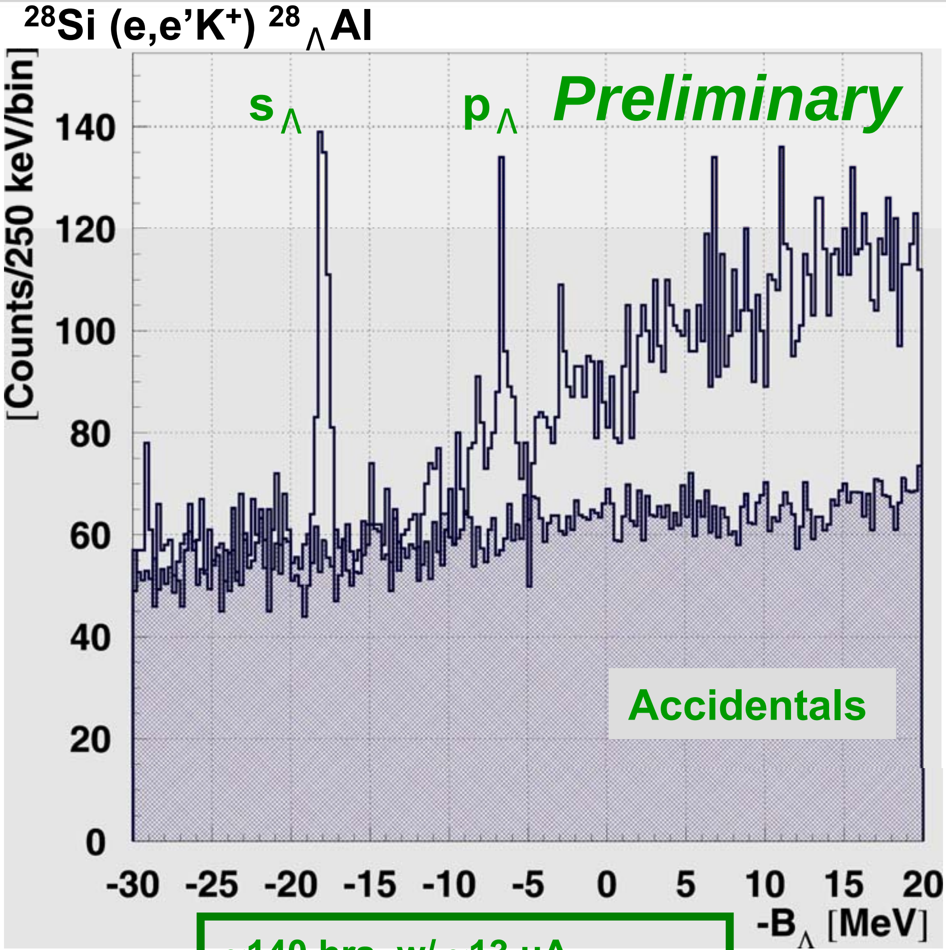




質量スペクトル（暫定結果）

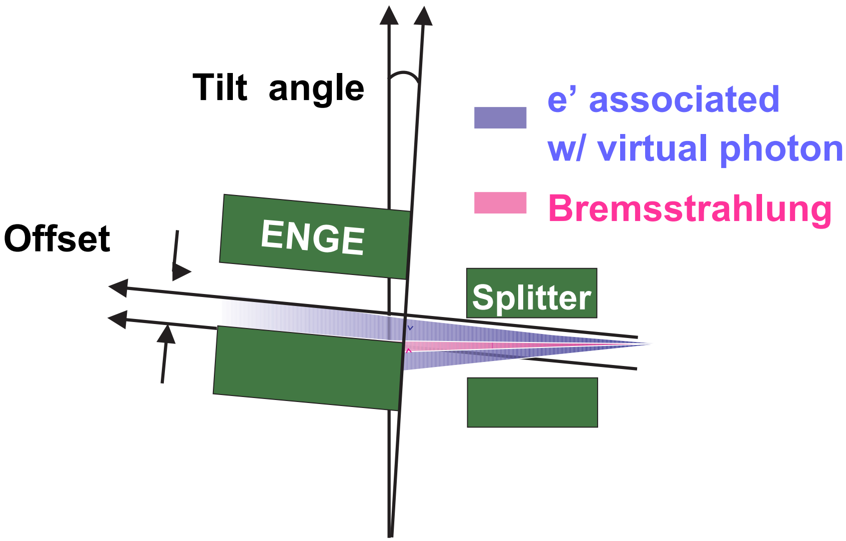


~30 hrs
G.S. :
Γ = 940 keV [FWHM]
$-B_{\Lambda}$ = -5.50 MeV



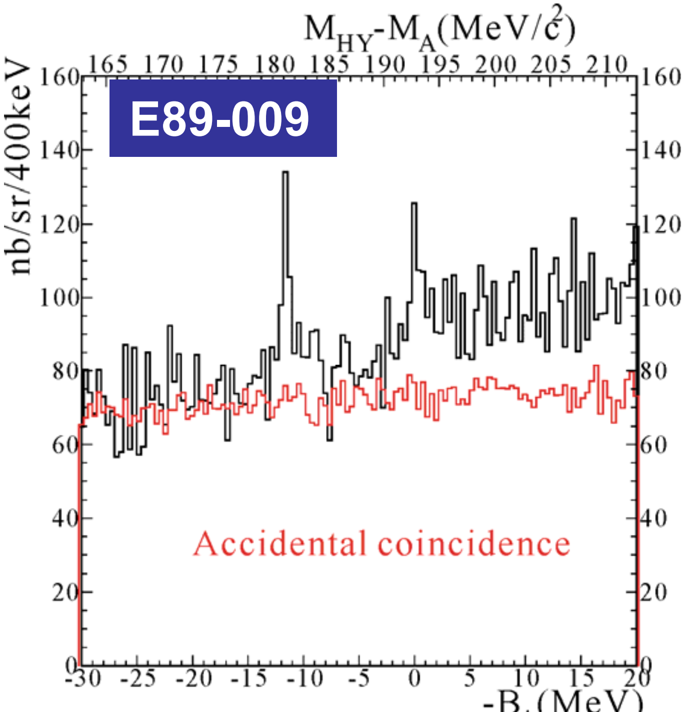
~140 hrs, w/ ~13 uA
G.S. :
Γ = 745 keV [FWHM]
$-B_{\Lambda}$ = -17.93 MeV
Yield = ~ 5/hr (30 uA)

S/N comparison for $^{12}C\ (e,e'K^+)\ ^{12}{}_{\Lambda}B$: E89-009 VS. E01-011

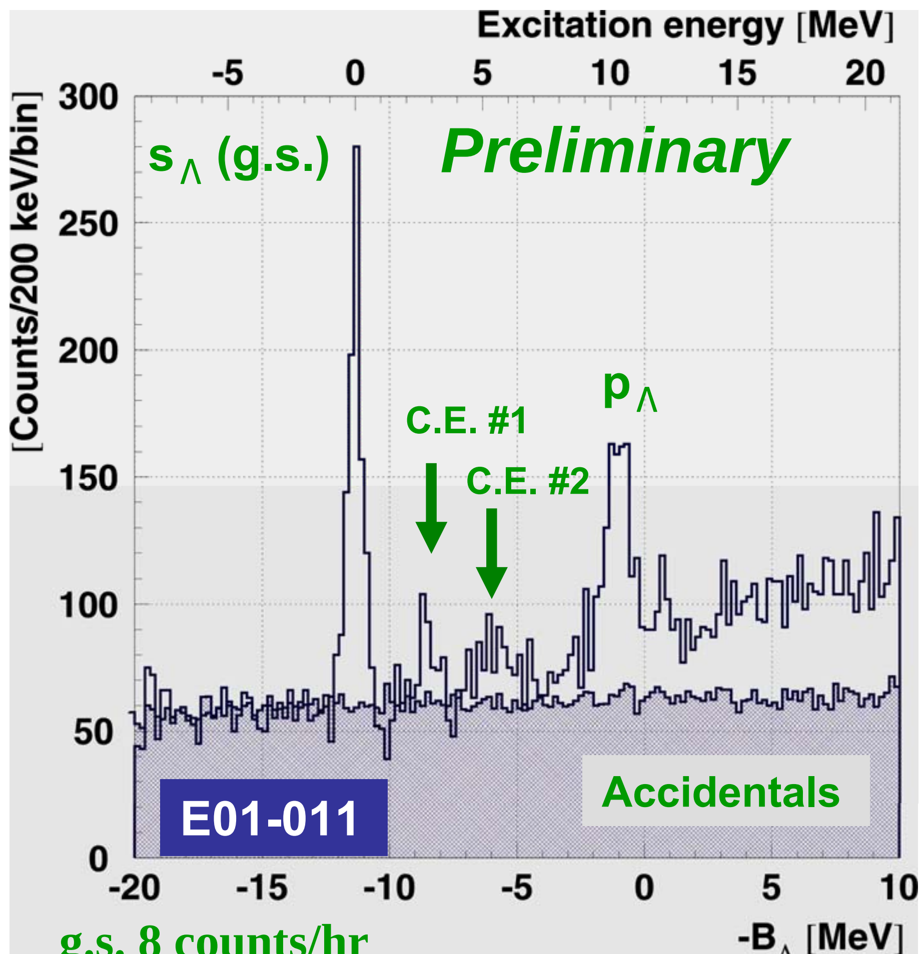


Yield rate : x ~15 S/N : x ~4

improved by Tilt method



g.s. 0.5 counts/hr



g.s. 8 counts/hr

まとめ

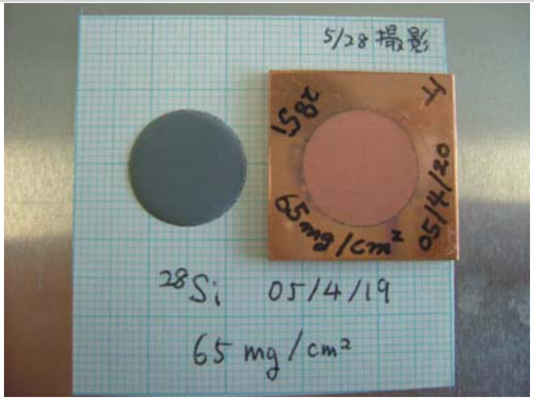
○ 2005 年 6 月より米国 Jlab にて ^{7}Li, ^{9}B, ^{12}C, ^{28}Si 標的に対する (e,e'K^{+}) 反応を用いたΛハイパー核分光実験を行った。

○ ^{7}Li, ^{28}Si 標的については、世界初の観測となる。
特に ^{28}Si については、中重質量領域 (e,e'K+) 反応を用いたハイパー核分光の突破口となった。

○ HKS の導入＋Tilt 法の採用は高分解能・高統計なデータ収集を可能にした。

○ 質量スペクトル導出に対する、光学パラメータの較正は若干改善の余地がある。

Data summary



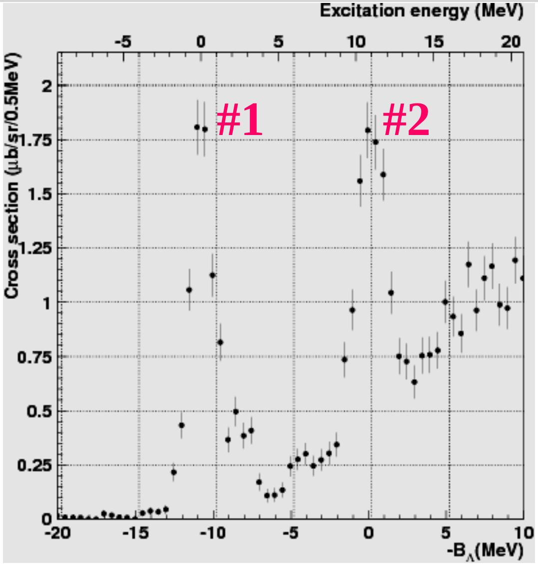
Typical value

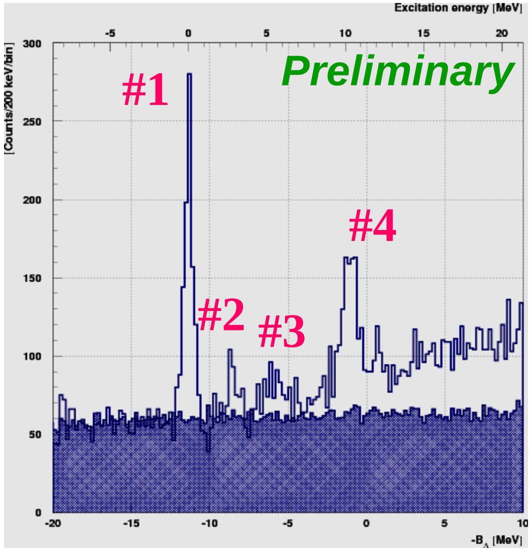
Target	Target thickness [mg/cm^2]	I [μA]	ENGE [MHz]	HKS [kHz]	Trig. [Hz]
CH_2	100	1.5	0.5	2	46
^{7}Li	190	25	1.2	11	850
^{9}Be	190	16	0.9	5	700
^{12}C	100	28	1.2	12	550
^{28}Si	65	13	1.1	7	300
^{51}V	60	14	1.4	8	430
^{89}Y	56	10	1.4	8	420

Beam energy: 1.851 GeV .

K : ~130 Hz w/ ^{12}C, 30 uA

電子線を用いたΛハイパー核分光の特徴





(π^+, K$^+$), (e, e'K$^+$) 反応による鏡映核 (A=12) の束縛エネルギースペクトル比較

^{12}C (π^+, K$^+$) $^{12}{}_\Lambda$C : KEK E140A, ⊿E = 2 MeV [FWHM]

#1 : Ground state : 1$^-$
[^{11}C g.s. ⊗ s_Λ]
#2 : p_Λ state : 2$^+$
[^{11}C g.s. ⊗ p_Λ]

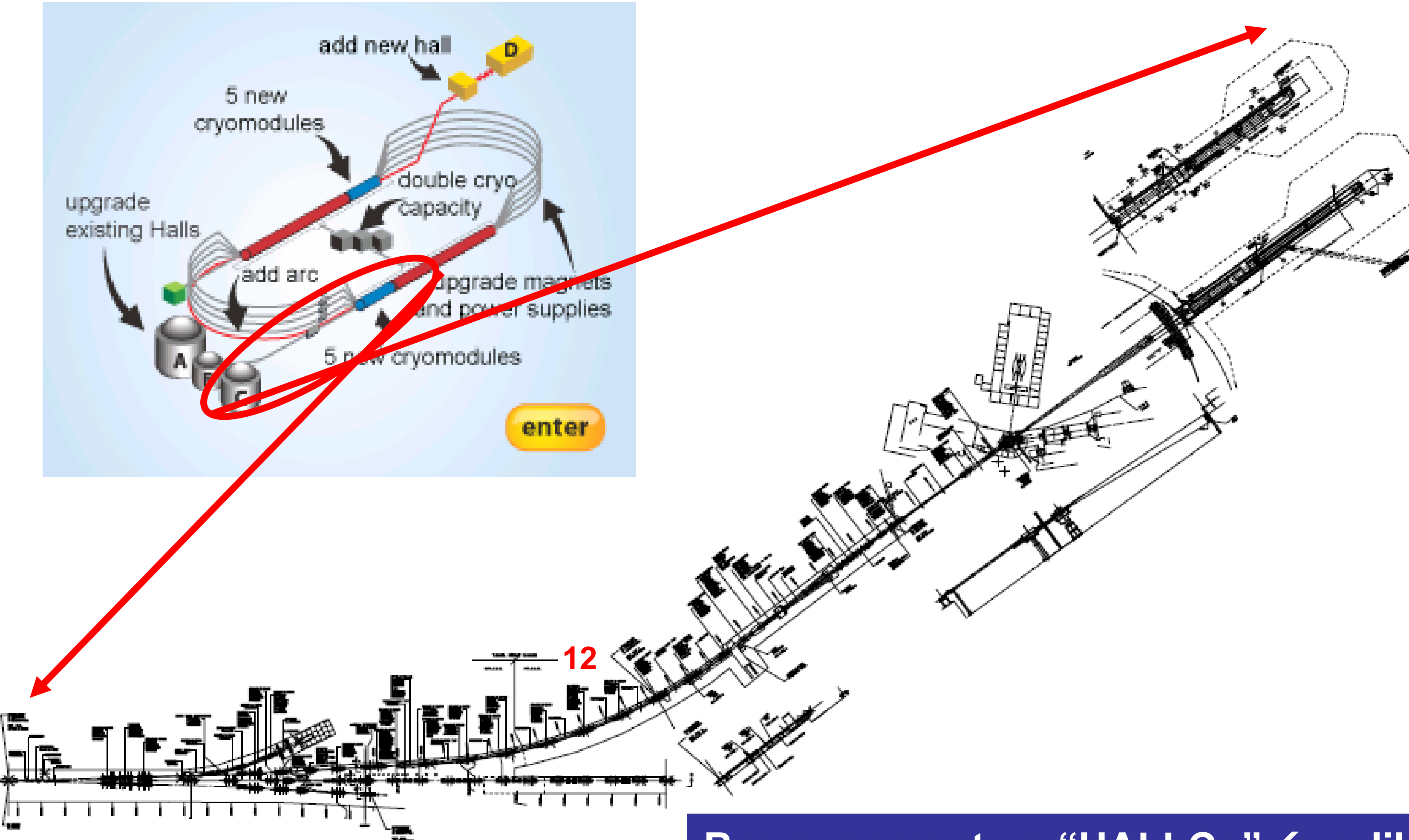
中間子ビームを用いた Λハイパー核分光は、1970 年代より CERN, BNL, KEK などで精力的に行われてきた。一方、ビームサイズ (> 1 cm)、標的厚の制限からエネルギー分解能は数 MeV 程度。

^{12}C (e,e'K$^+$) $^{12}{}_\Lambda$B : Jlab E01-011, ⊿E = ~700 keV [FWHM]

#1 : Ground state doublets : 1$^-$ + 2$^-$
[^{11}B g.s. ⊗ s_Λ]
#2, #3 : Core excited states : 1-, 2-
[^{11}B* ⊗ s_Λ]
#4 : p_Λ states :
[^{11}B g.s. ⊗ $p\Lambda$]

一方、2000 年には Jlab において連続電子線 (ビームサイズ ϕ ~0.1 mm) を用いたΛハイパー核分光実験 (E89-009) が世界で始めて実現し、MeV 以下のエネルギー分解能を実現。

BPMs in switchyard & HallC arc.

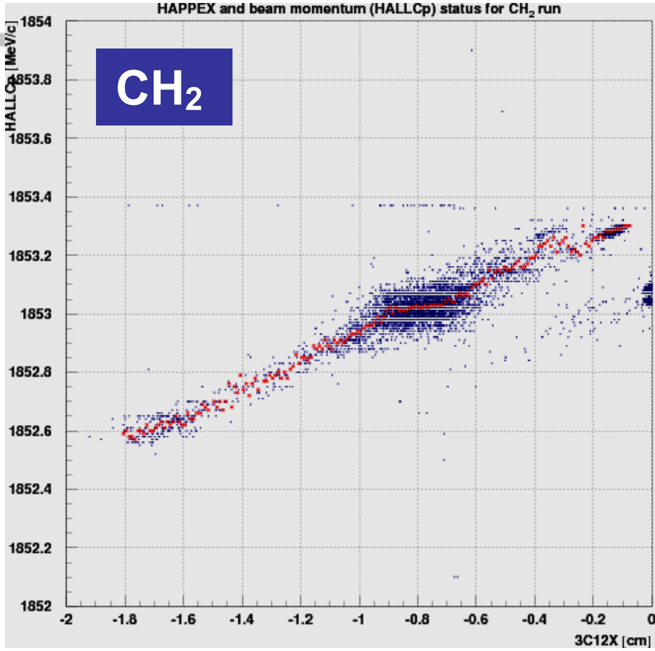


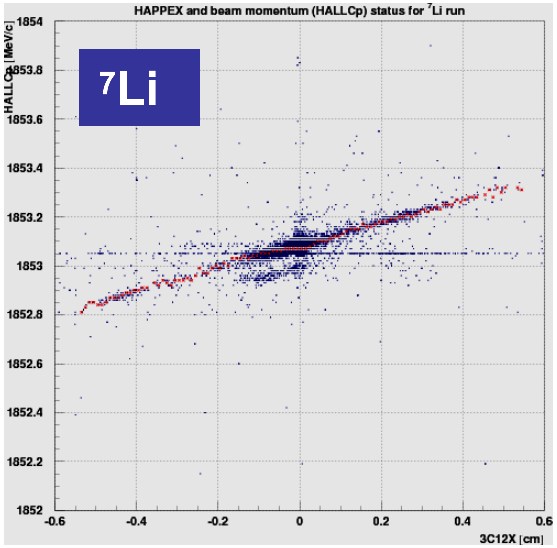
BPMs in EPICS:

IPM3C01
IPM3C02
IPM3C03
IPM3C04
IPM3C05
IPM3C06
IPM3C07
IPM3C07A
IPM3C08
IPM3C10
IPM3C11
IPM3C12
IPM3C14
IPM3C16
IPM3C17
IPM3C17A
IPM3C18
IPM3C19
IPM3C20
IPM3C20A

Beam momentum “HALLCp” ← calibrated w/ a bunch of IPMs

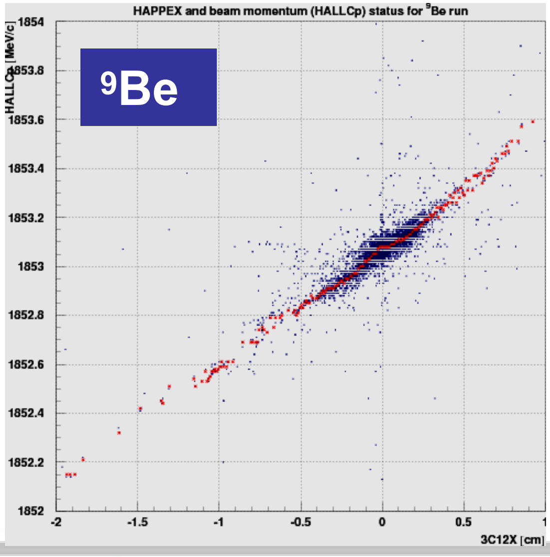
“HALLcp” VS IPM3C12X

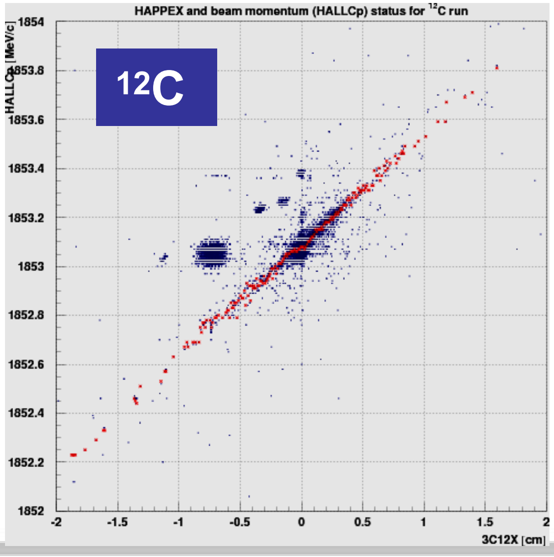


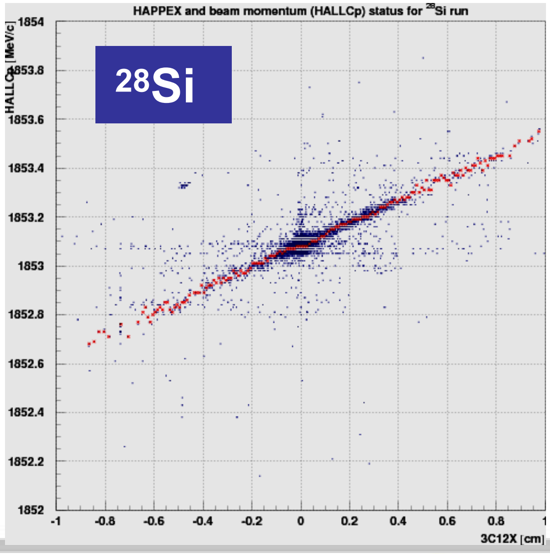


Red:

Centre of mass







Kaon survival rate