(e,e'K^+) hypernuclear spectroscopy with sub-MeV resolution

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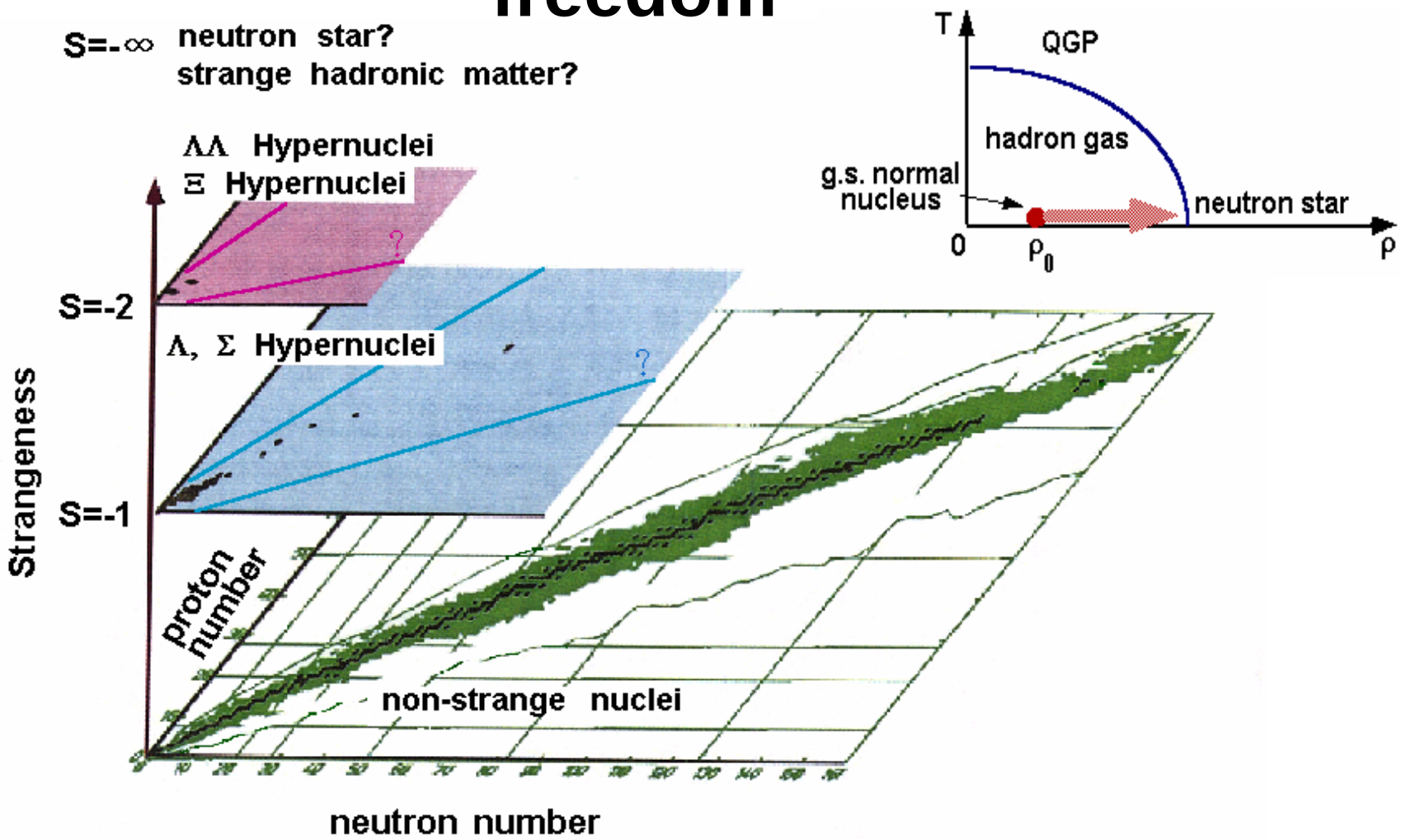
Outline of the talk

1. Introduction to hypernuclear spectroscopy
2. The (e,e'K^+) spectroscopy
3. E89-009 and E01-011 in Hall C
4. Further plan for hypernuclear physics at Jlab with HKS and HES
5. Summary

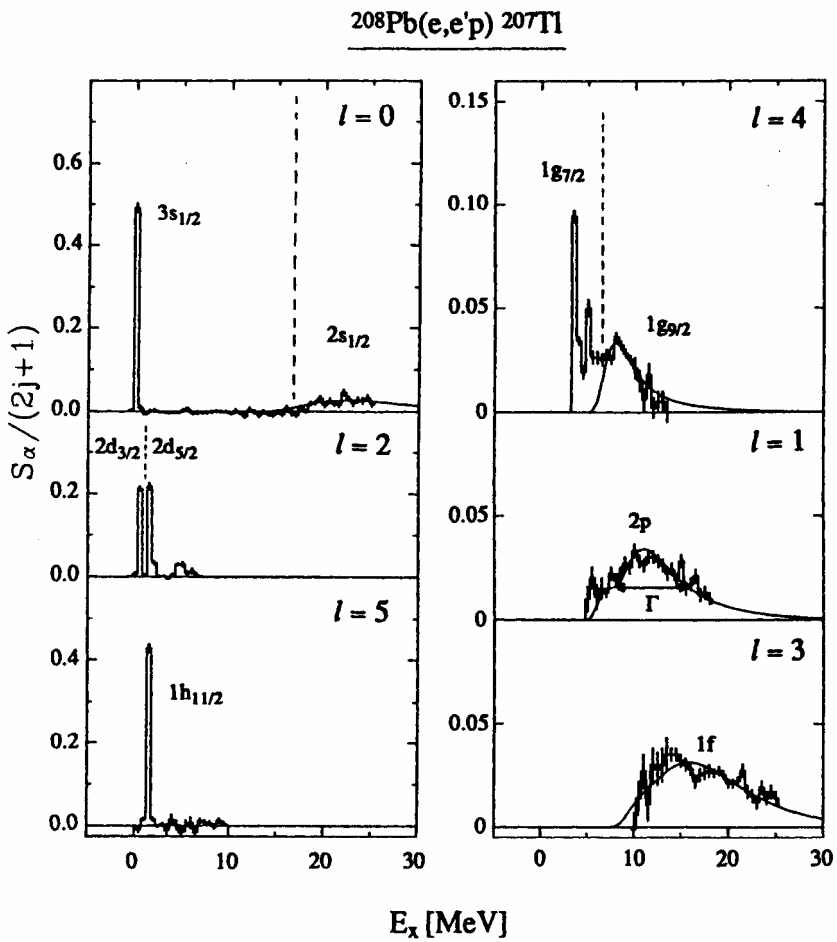
3D Nuclear Chart with a strangeness degree of freedom

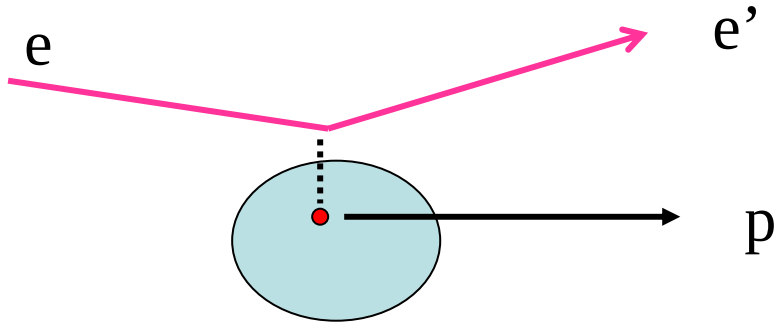


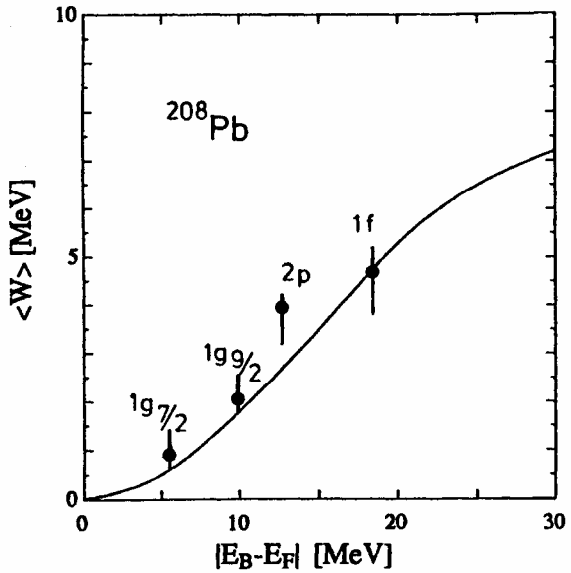
Interests in hypernuclear investigation

- **New degree of freedom**
  - can examine deeply bound states
  - baryon structure in nuclear medium
- **New nuclear structure with strangeness**
  - nucleus with a new quantum number
  - electromagnetic properties
- **Hyperon-nucleon, hyperon-hyperon interaction**
  - Hyperon scattering vs. hypernuclear structure
  - γ-ray spectroscopy plays key role for spin-dependent interactions
  - S=-2 system and beyond
- **Weak interaction in nuclear medium**
  - decay widths, polarization in nonmesonic weak decay

Nucleon single particle orbits







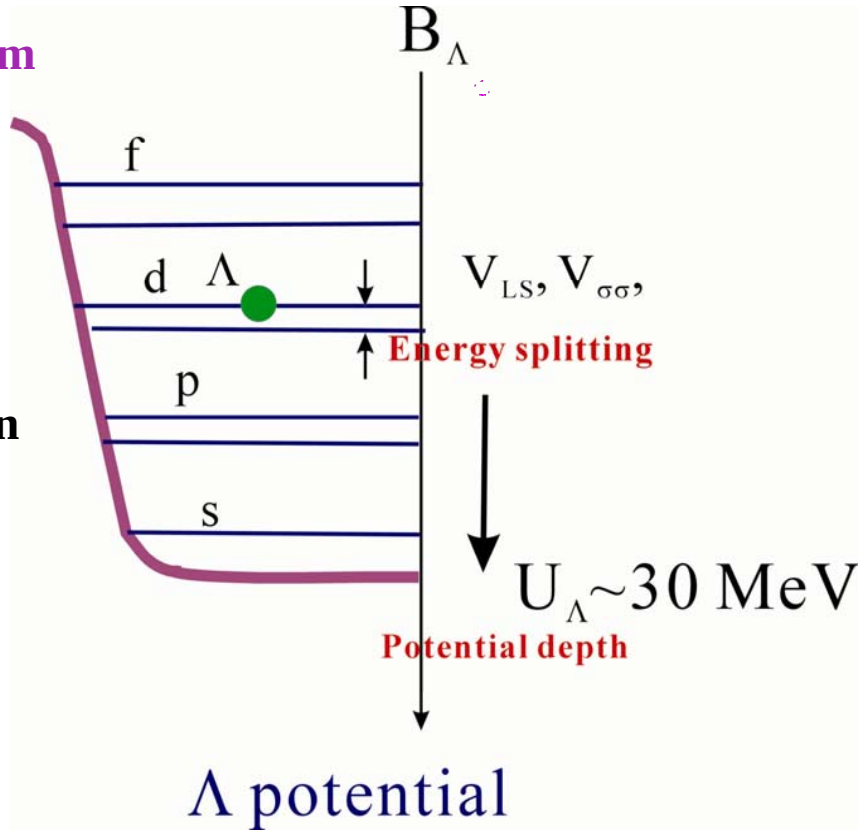
Single particle nature of Λ hypernuclei

Core Nucleus + Λ ⟺ Singly charged atom

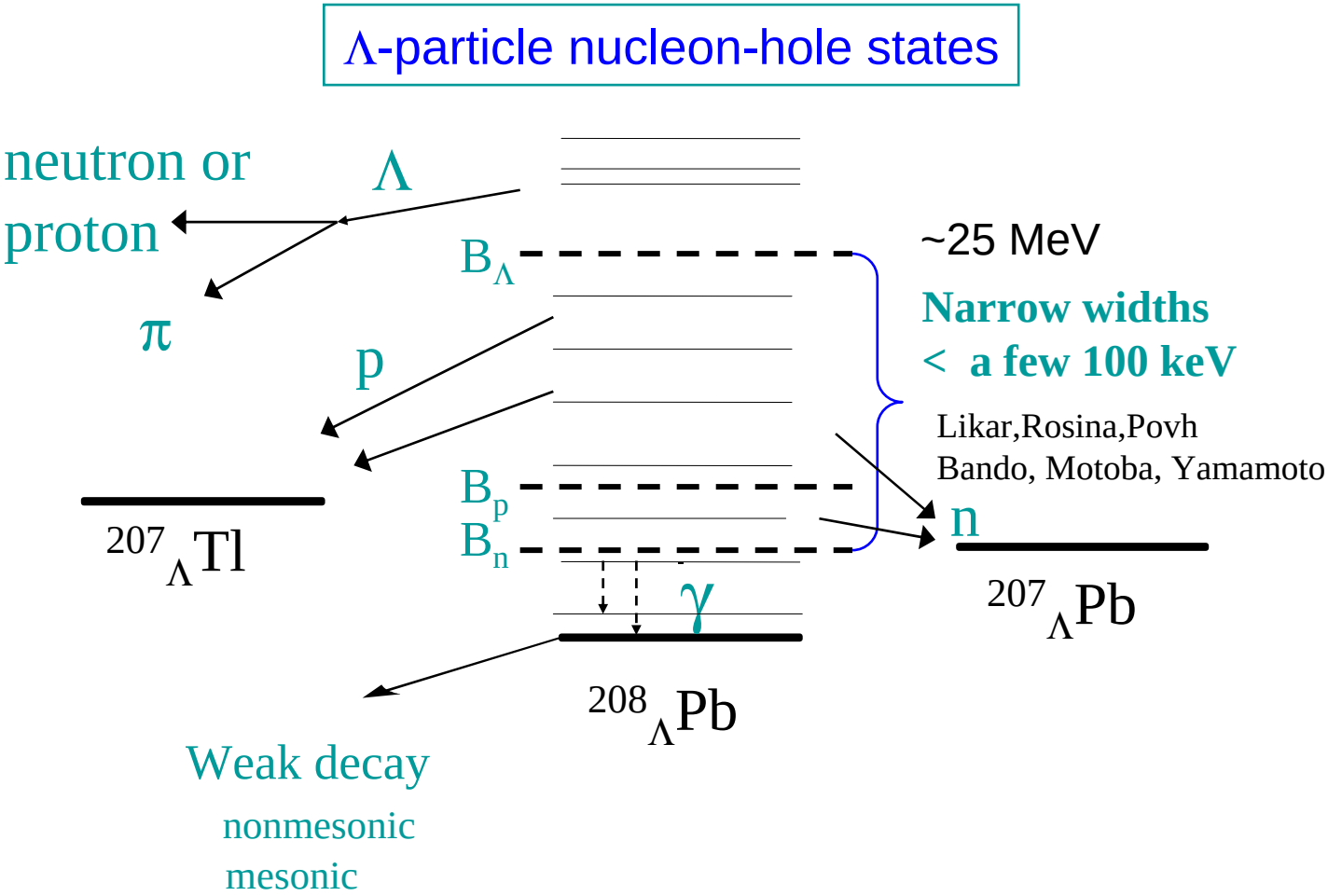
- **Unique structure of hadronic many-body system**
  - **Deeply bound states**
  - **Core excited states**
  - **Glue role of a Λ hyperon**
- **ΛN interaction**
  - **Unified view of baryon-baryon interaction**
  - **Central and spin-dependent ΛN interaction**

Narrow widths of excited states

→ **High precision spectroscopy**



Excited states of Λ hypernuclei



YN, YY Interactions and Hypernuclear Structure

Free YN, YY interaction

Constructed from limited hyperon scattering data

(Meson exchange model: Nijmegen, Julich)

G-matrix calculation

YN, YY effective interaction in finite nuclei

(YN G potential)

$$v_{\Lambda N}(r) = \sum_i (a_i + b_i k_F + c_i k_F^2) \exp(-r^2 / \beta_i^2)$$

Hypernuclear properties, spectroscopic information

from structure calculation (shell model, cluster model…)

Energy levels, Energy splitting, cross sections

Polarizations, weak decay widths

high quality(high resolution & high statistics) spectroscopy plays a significant role

Hypernuclear Hamiltonian

Weaker compared with NN

$$H = H_N^{(Core)} + t_\Lambda + \Sigma V_{\Lambda N}$$

$H_N^{(Core)}$: Core nucleus (Usually hole states)

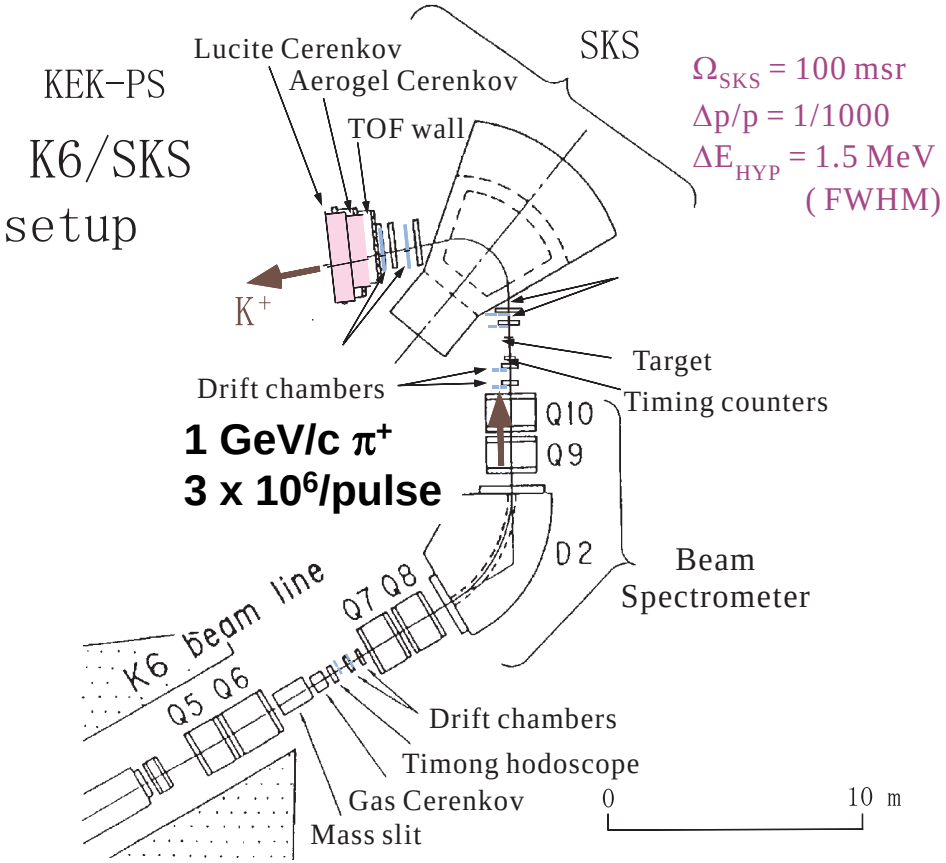
t_Λ : Λ kinetic energy

$V_{\Lambda N}$: effective ΛN interaction
(Nijmegen, Julich ...)

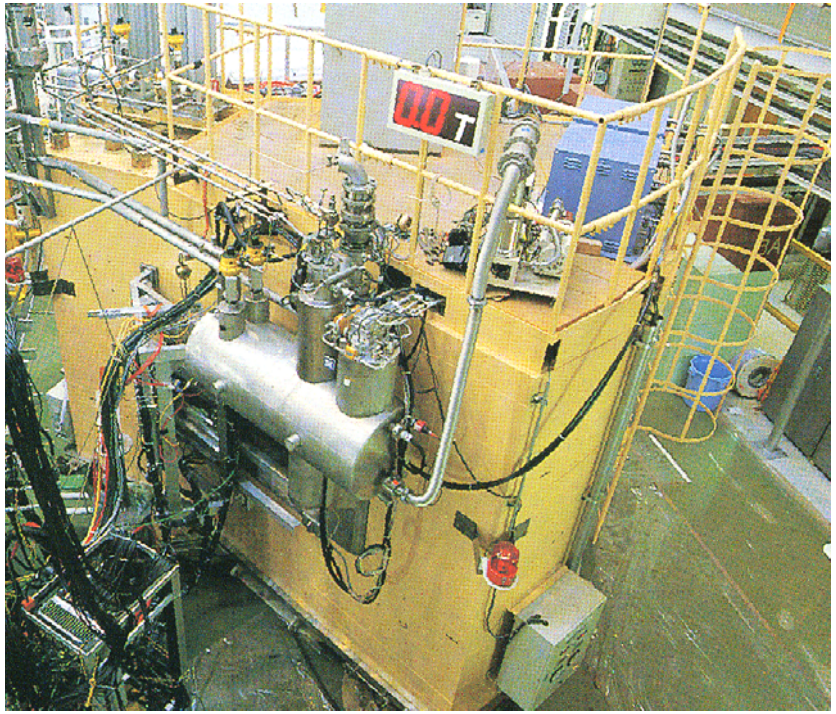
$\mathbf{v}_{\Lambda N}$ weak compared to $\mathbf{v}_{NN}$

Direct comparison of spectroscopic data with structure calculation

The SKS Spectrometer for (π+,K+) reactions at KEK 12 GeV PS

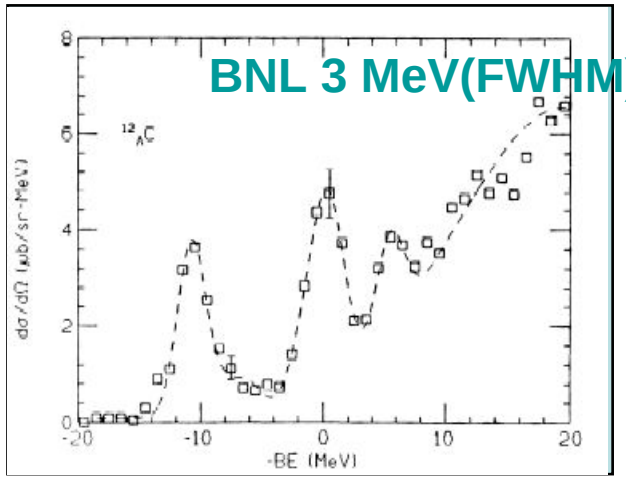


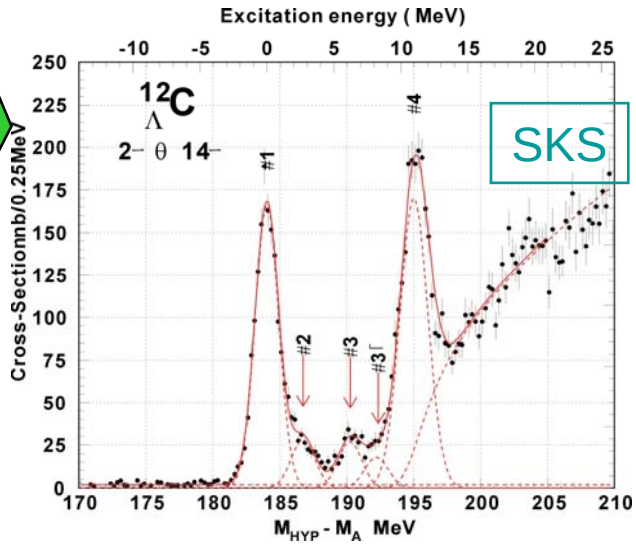
For (π^+,K^+) reaction spectroscopy



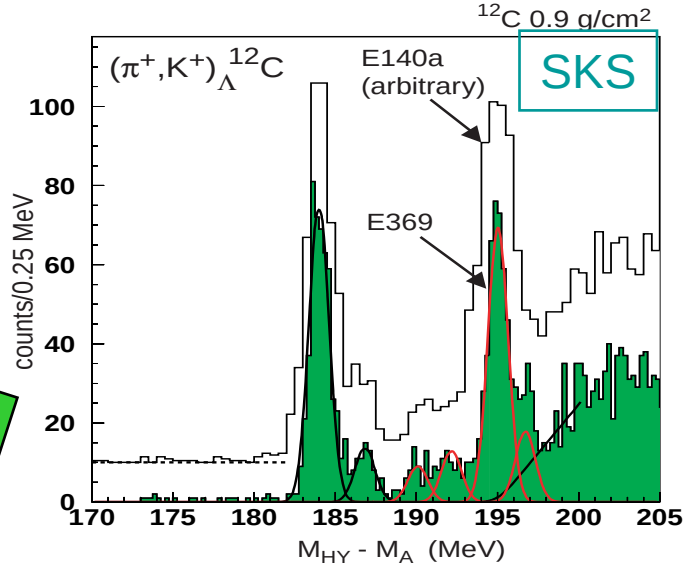
Superconducting Kaon Spectrometer

$^{12}C(\pi^+,K^+)\ ^{12}_{\Lambda}C$ spectra by the SKS spectrometer at KEK 12 GeV PS





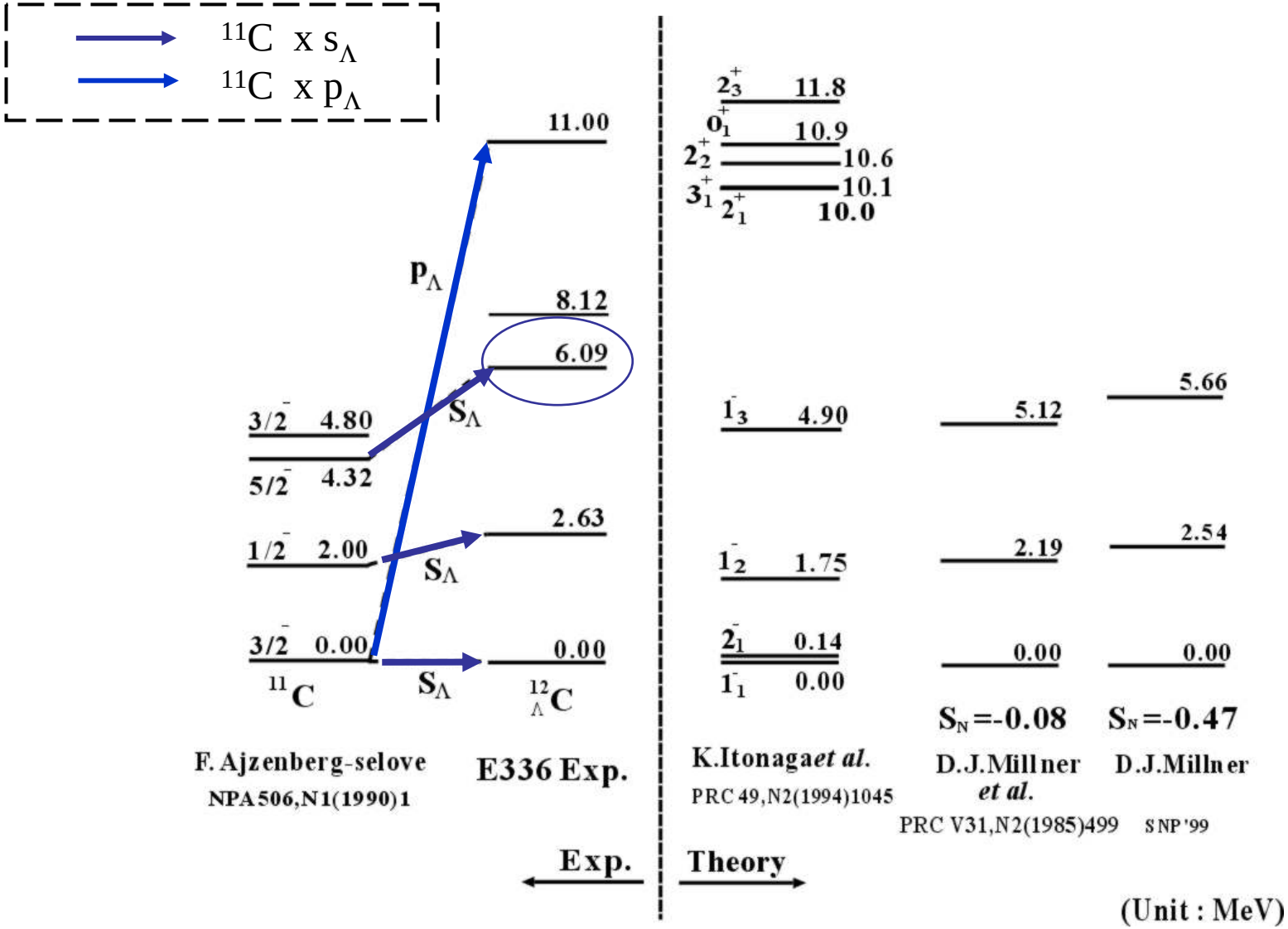
KEK336 2 MeV(FWHM)



KEK E369 1.45 MeV(FWHM)

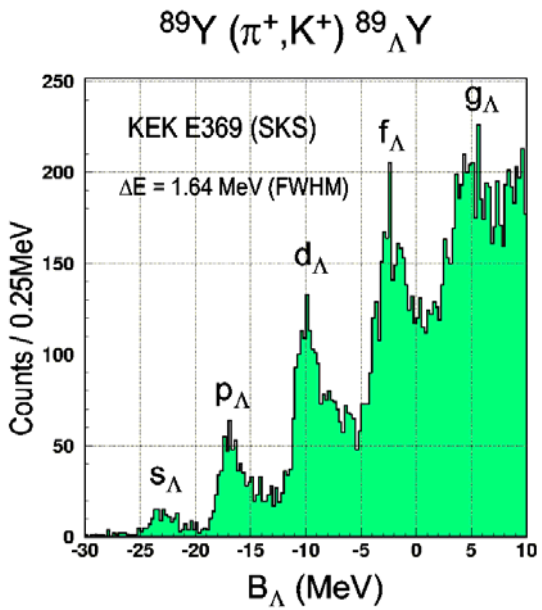
Hypernuclear spectroscopy established

Comparison of $^{12}{}_{\Lambda}C$ energy levels

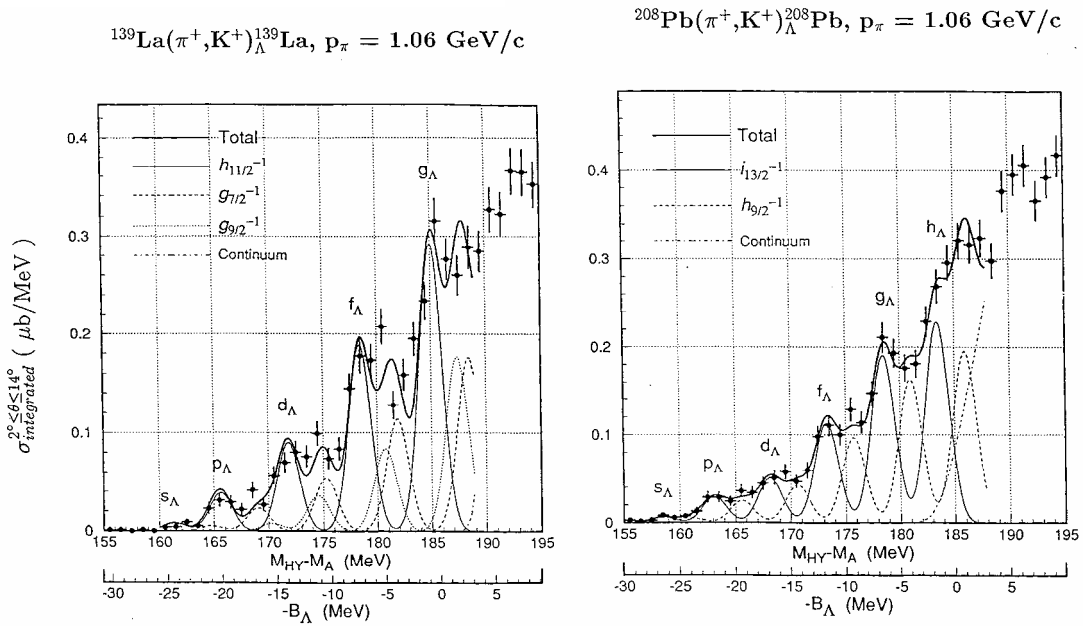


Λ hyperon in heavier nuclei

Λ Single particle states

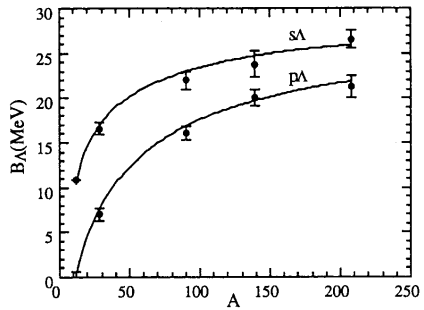


Hotchi et al., PRC 64 (2001) 044302

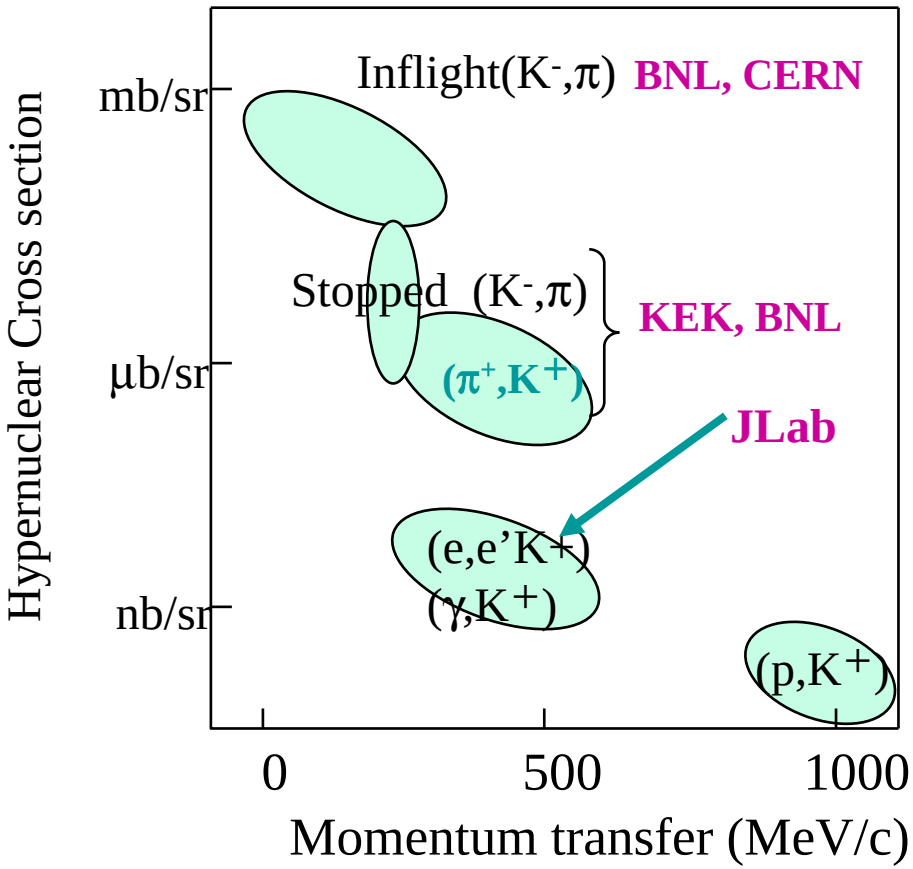


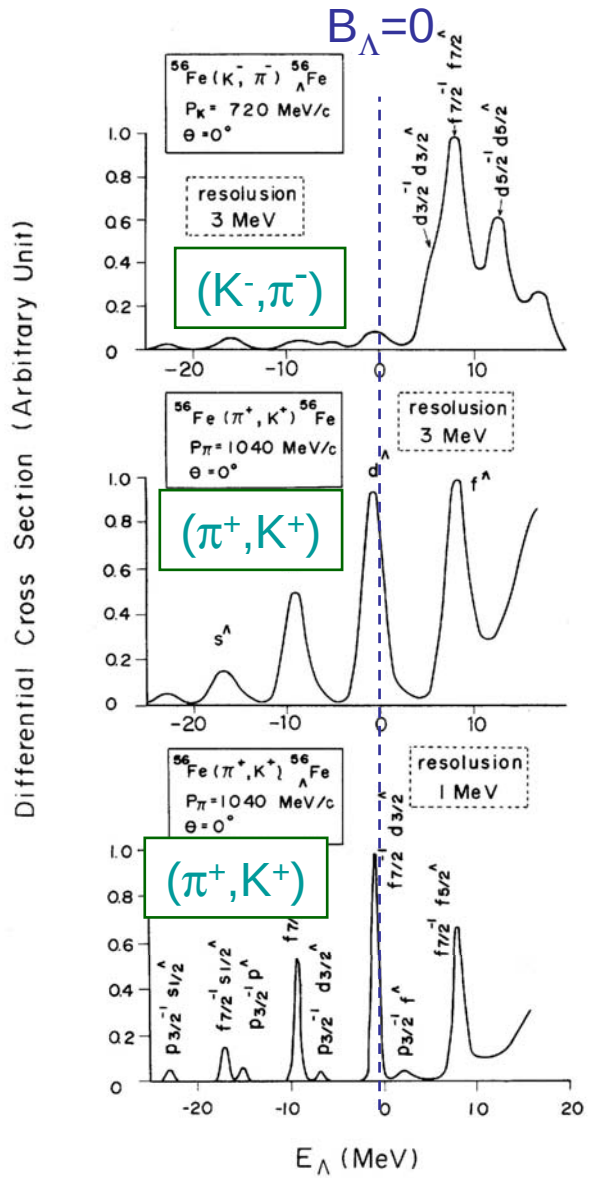
KEK E140a *Hasegawa et. al.. PRC 53 (1996)1210*

Single-particle orbits in nucleus



Λ Hypernuclear production





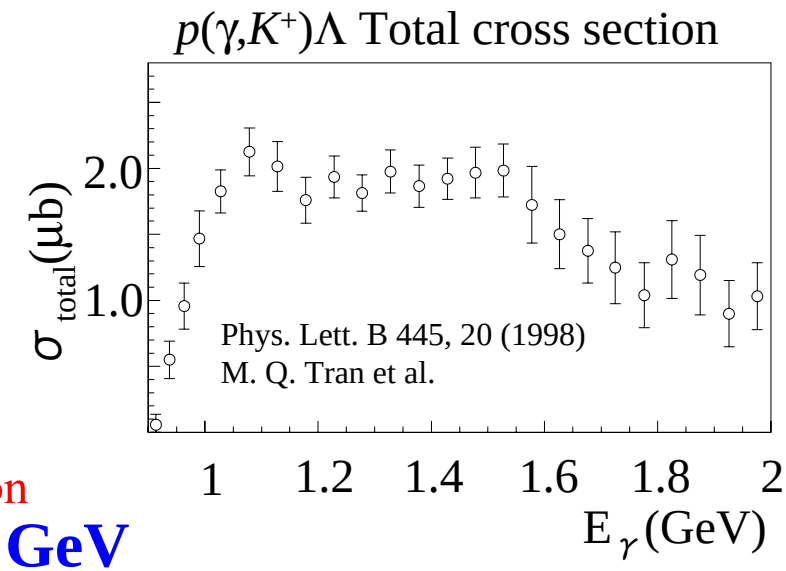
Basic characteristics of (e,e'K^+) spectroscopy

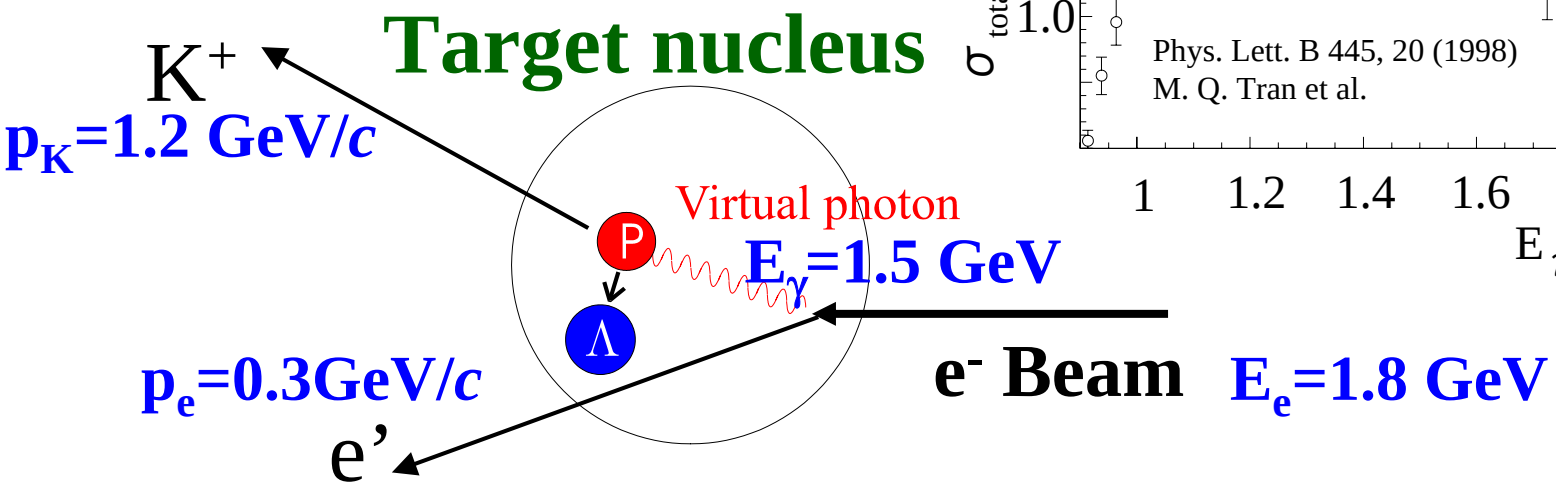
- Proton converted to Λ → Neutron rich Λ hypernuclei
- Large angular momentum transfer → Similarly to (π^+,K^+) reaction
- Spin-flip amplitude → Unnatural parity hypernuclear states
- Sub MeV resolution ← High quality primary beam

- Virtual photon energy
  - Energy dependence of the elementary cross section
- Kaon momentum
  - Resolution & Particle ID
- Beam electron energy
  - Background ?

The (e,e'K$^+$) reaction kinematics of E89-009 & E01-011

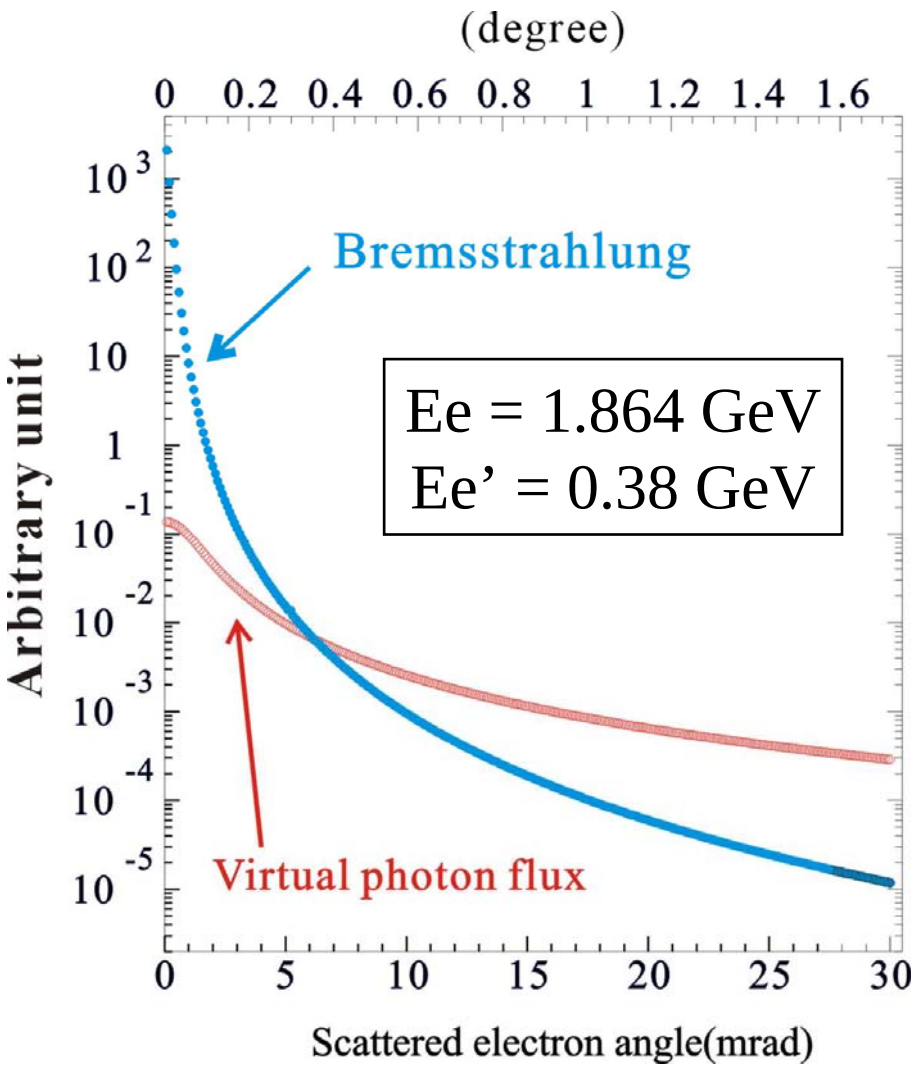
K$^+$ detection
At very forward angle (~ 0 degrees)
Maximum
hypernuclear production cross section

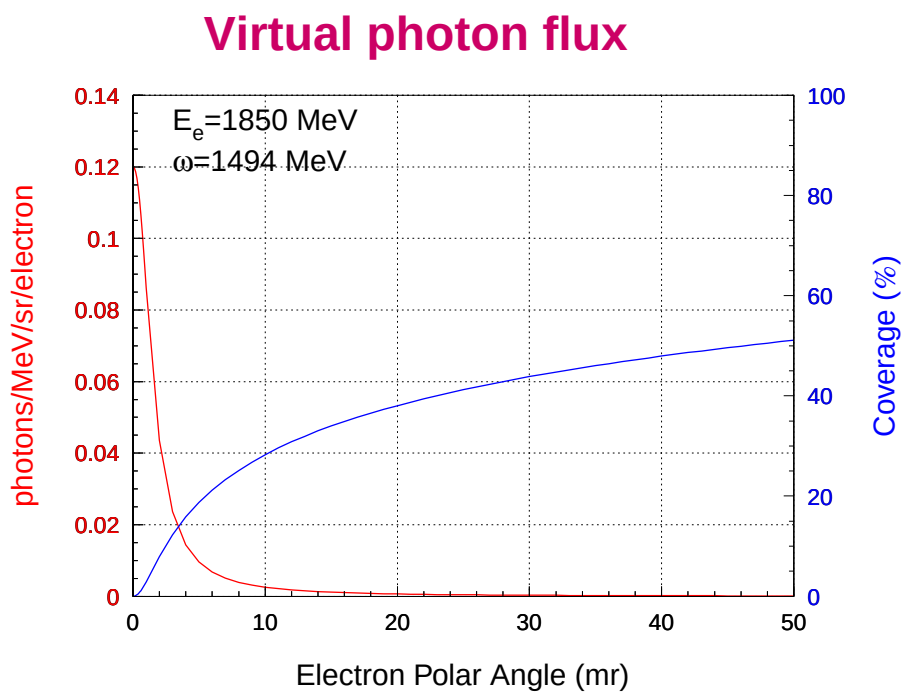




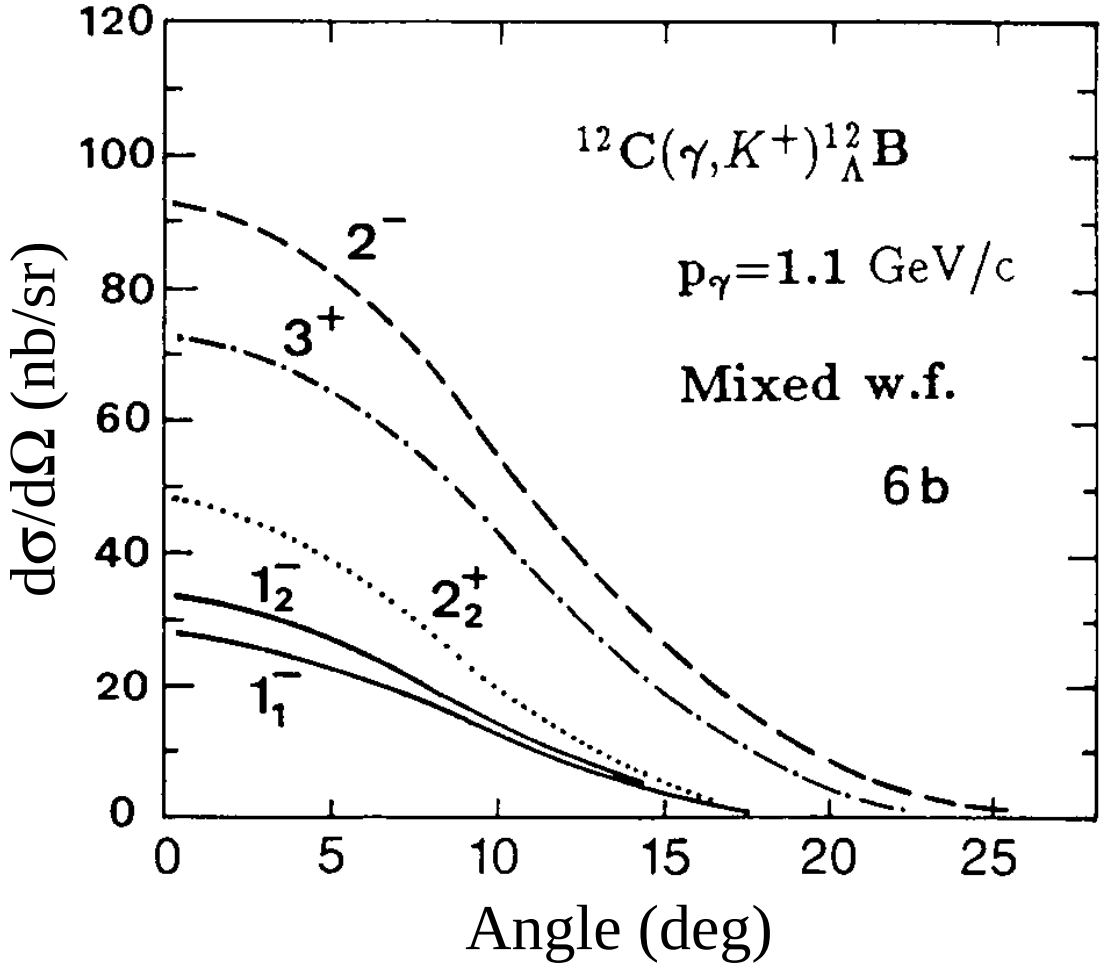
e' detection
At extremely forward angles
Advantage : Large virtual photon flux
Disadvantage : Huge backgrounds from Bremsstrahlung

Angular distribution of electrons associated with virtual and Brems. photons





Kaon Angular Distribution



Calculated
by Sotona's code

E89-009 experiment

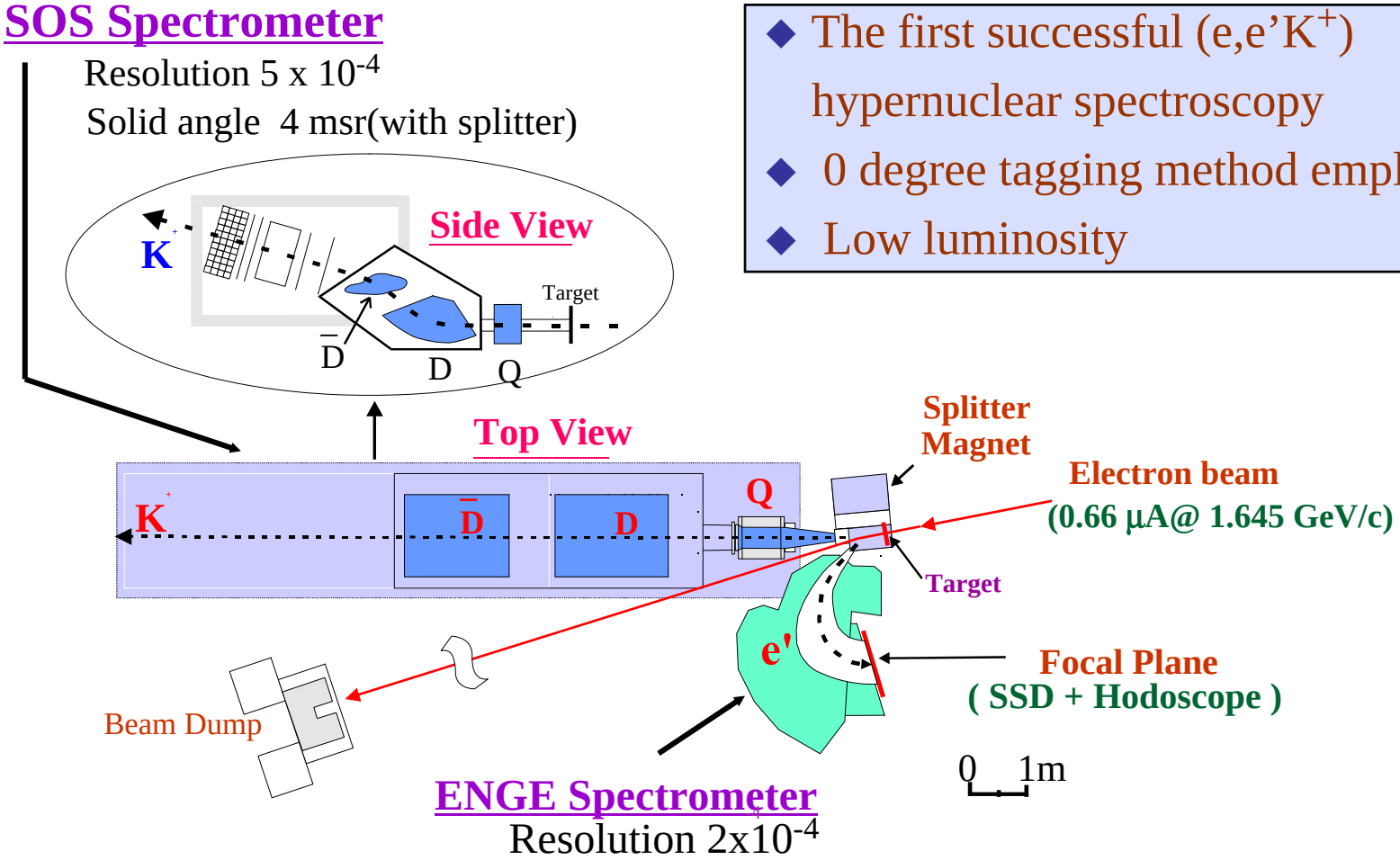
- The first (e,e'K+) experiment
  - In Hall C
  - Electron spectrometer --- Enge split pole
  - Kaon Spectrometer --- SOS (exisiting)
  - 0 degree tagging geometry

E_e = 1.7,1.8 GeV
$\omega = E_\gamma$ = 1.5 GeV
p_K = 1.2 GeV
θ_e = 0 degrees
θ_k = 0-7 degrees

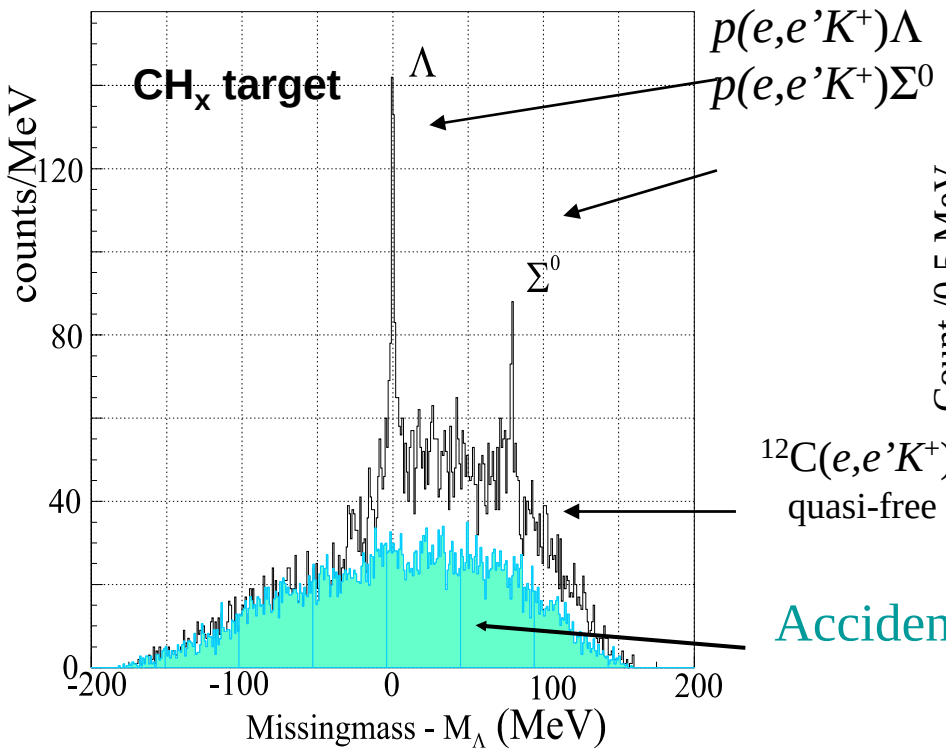
The E89-009 experimental setup

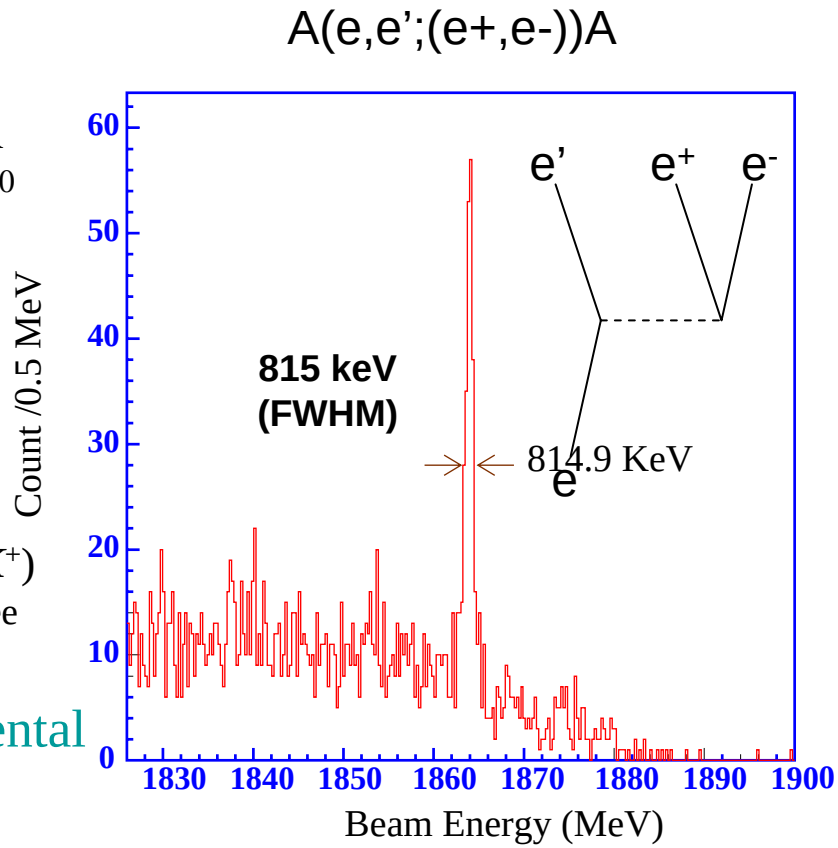
Jlab Hall C HNSS

- The first successful (e,e'K^+) hypernuclear spectroscopy
- 0 degree tagging method employed
- Low luminosity

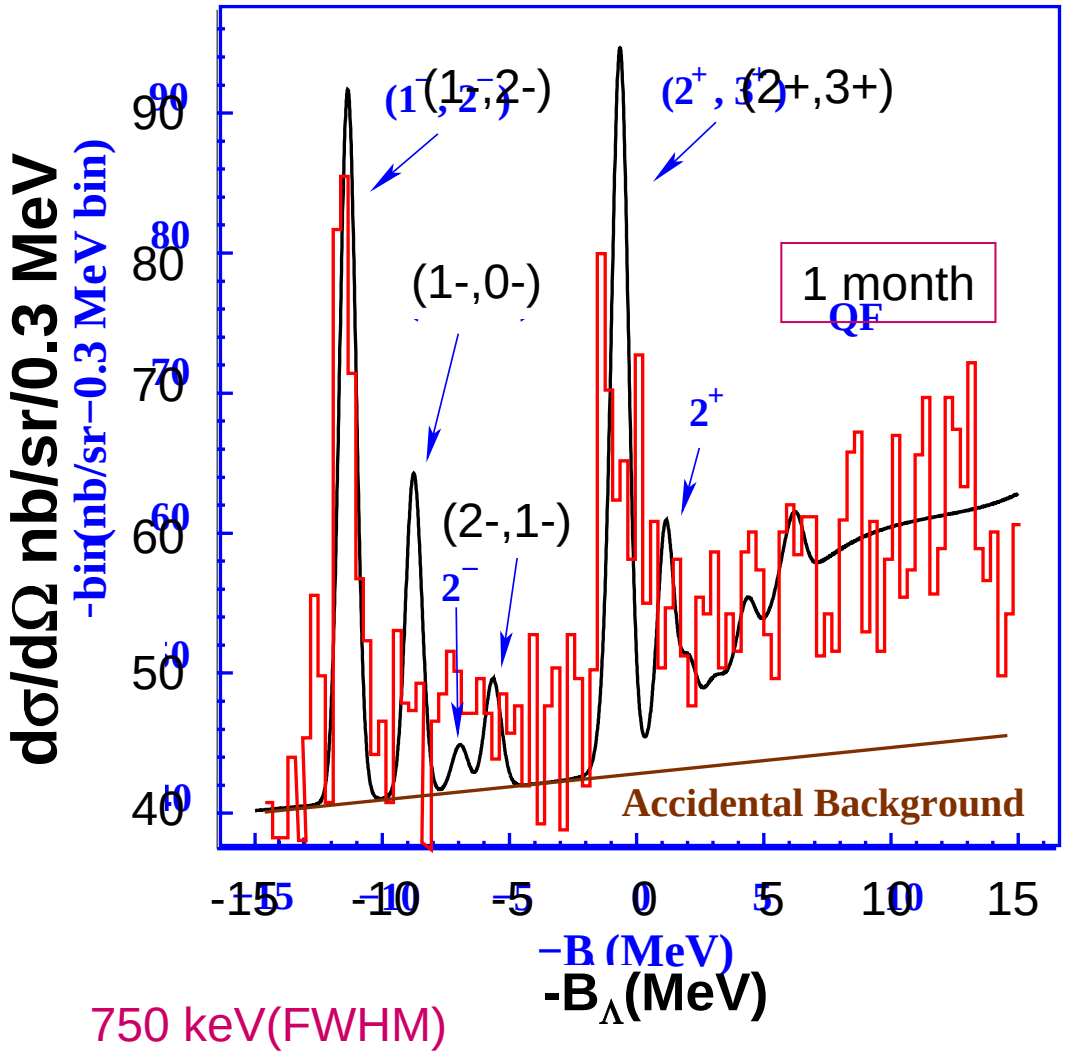


E89-009 calibration





$^{12}{}_{\Lambda}$B spectrum of E89-009



Ground state doublet

Binding energy

B_Λ = 11.4±0.5 MeV

Emulsion data

B_Λ = 11.37 MeV

Cross section

140±17(stat) ±18(sys) nb/sr

Motoba's calculation

J^π	cross section	
1^-	23.4 nb/sr	**138 nb/sr**
2^-	114.5 nb/sr	

E94-107 experiment

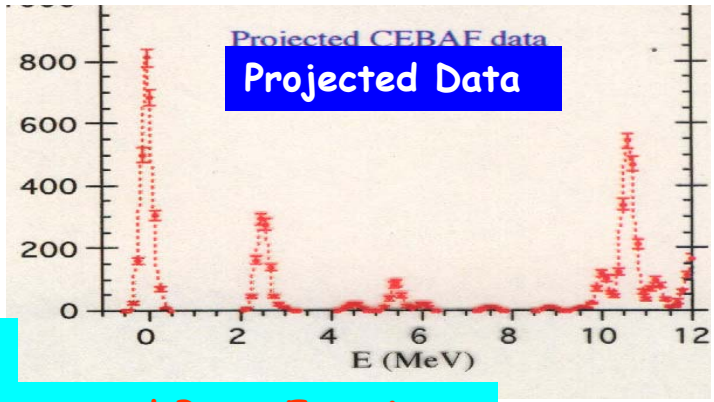
High resolution hypernuclear 1p shell hypernuclear spectroscopy

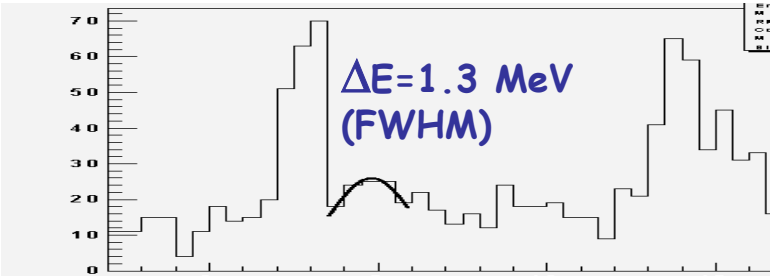
- Hall A
- Septum magnet (Superconducting)
- Electron spectrometer --- HRS (existing)
- Kaon Spectrometer --- HRS (existing)

E_e = 4 GeV
$\omega = E_\gamma$ = 2.2 GeV
p_K = 1.9 GeV
$\theta_e = \theta_k$ = 6 degrees

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

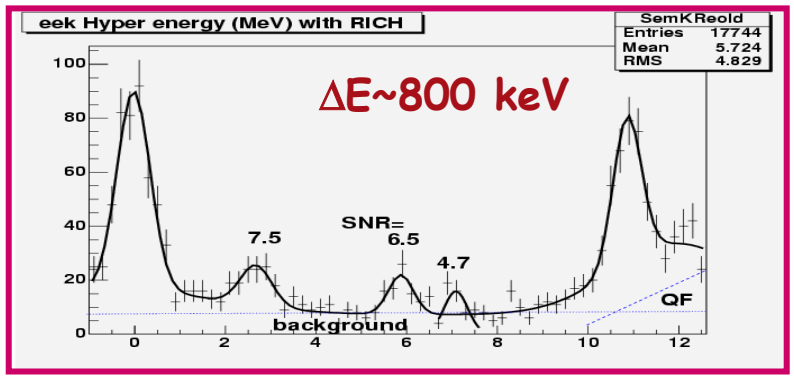
Very Preliminary Data From Garibaldi





"Standard" PID

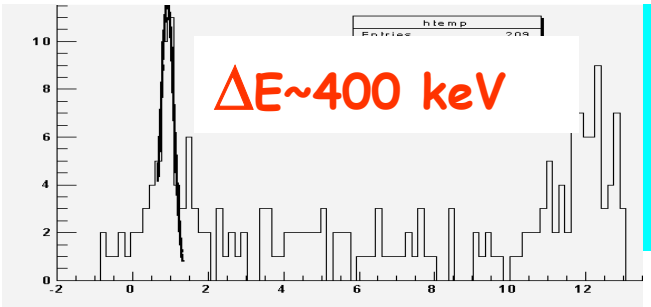
with Multiple Uncorrected Beam Energies



Full statistics with fitted peaks.

Resolution still not fully optimized

Subsets of data appear to have better resolution



Limited statistics

+ cut on Beam x position at 1C12

+ ± 50 keV on relative beam energy

Guarantees beam within specs

→ Beam energy spread and spectrometer resolutions as planned

What limited the E89-009 experiment ?

- Energy resolution
  - The kaon arm limited hypernuclear mass resolution
- Hypernuclear yield rates
  - High accidental background rate due to Brems electrons
  - Kaon spectrometer solid angle limited detection efficiency

(1) A high-resolution large-solid-angle kaon spectrometer

(2) New experimental configuration "Tilt method"

E01-011 design principle

- Optimize the experimental kinematics : Similar to E89-009

  ⇨ Matching the momentum acceptances etc.

- Avoid 0 degree Brems & Moeller associated electrons in ENGE
- Avoid 0 degree positrons in the kaon arm

  ⇨ Tilt method

- Maximize acceptance of the kaon spectrometer
- Realize higher energy resolution(down to a few 100 keV)

  ⇨ High resolution kaon spectrometer

E01-011 experiment

Spectroscopic study of Λ hypernuclei
up to medium-heavy mass region through the (e,e‘K+) reaction

- Hall C
- Electron spectrometer --- Enge split pole
- Kaon Spectrometer --- HKS
- “Tilt method”

E_e = 1.8 GeV
$\omega = E_\gamma$ = 0.3 GeV
p_K = 1.2 GeV
θ_e = 4.5 degrees
θ_k = 1-14 degrees

–The second generation (e,e’K+) experiment

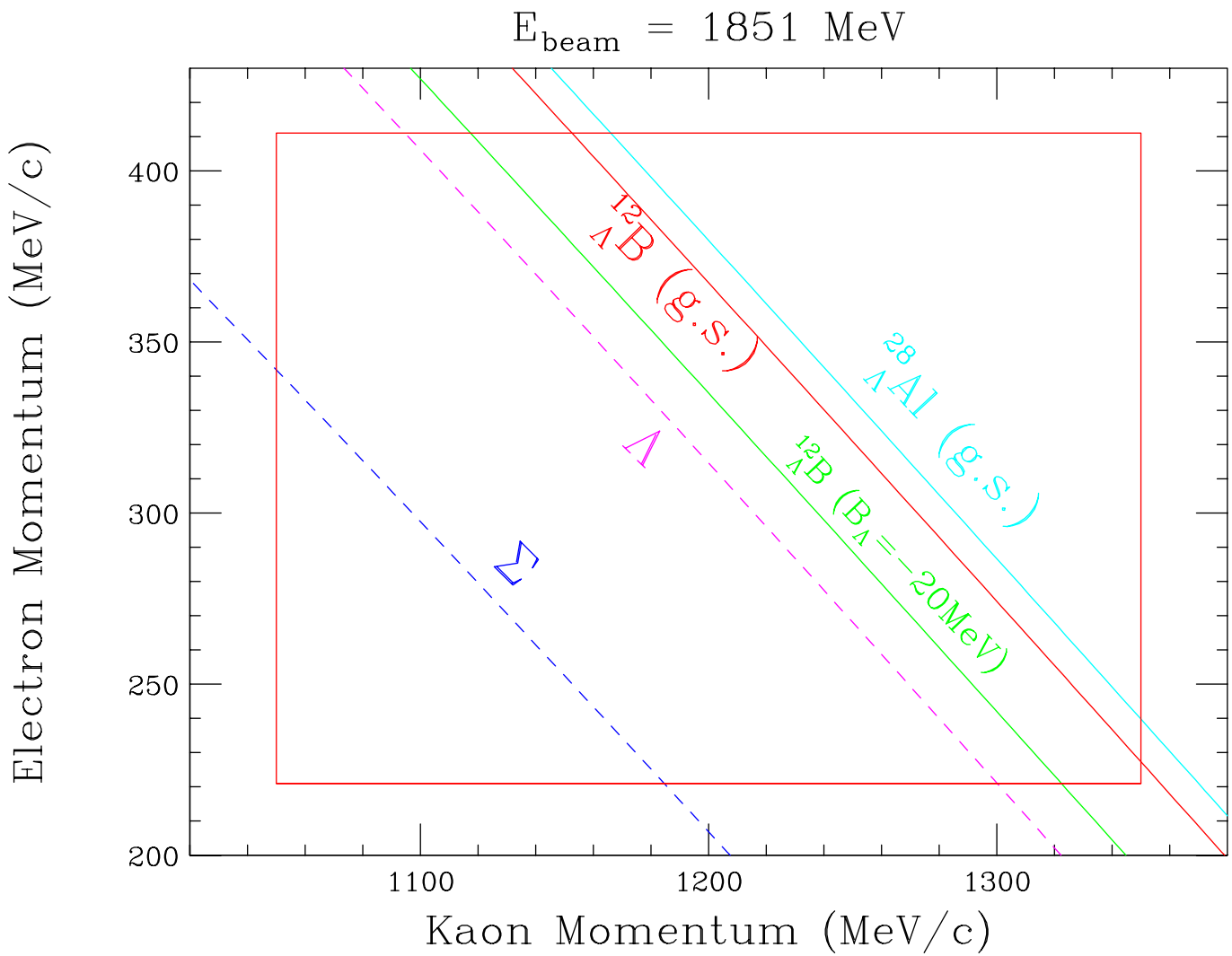
Physics goals of Jlab E01-011

- Hypernuclear structure up to medium-heavy mass region
  - $^{28}{}_{\Lambda}$Si(e,e'K^{+}) $^{28}{}_{\Lambda}$Al reaction and (beyond ^{51}V, ^{89}Y)
- ΛN interaction in the p-shell region
  - ^{12}C(e,e'K^{+})$^{12}{}_{\Lambda}$B reaction
- Mirror symmetric Λ hypernuclei $^{12}{}_{\Lambda}$C vs. $^{12}{}_{\Lambda}$B

High-resolution	3-400 keV
High yield rates	> a few 100/day for $^{12}{}_{\Lambda}$B ground state (comparable to the (π^{+},K^{+}) spectroscopy)

New experiment designed based on the E89-009 experience

Kaon and scattered electron momentum correlation



Tilt Method

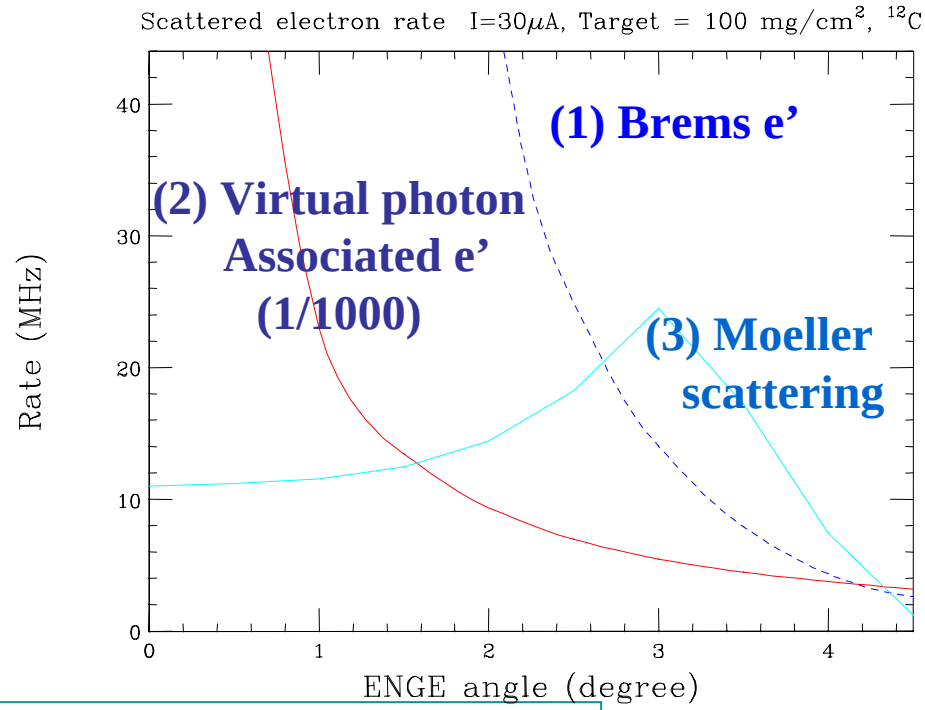
Scattered electrons (0.2 to 0.4 GeV/c)
(1) from bremsstrahlung
(2) associate with virtual photons
(3) from Møller scattering

Tilt e-arm by 4.5 deg. vertically
with respect to the splitter & K-arm

Singles rate of e-arm
100 MHz → < 3 MHz

with
5× Target thickness
50× Beam intensity

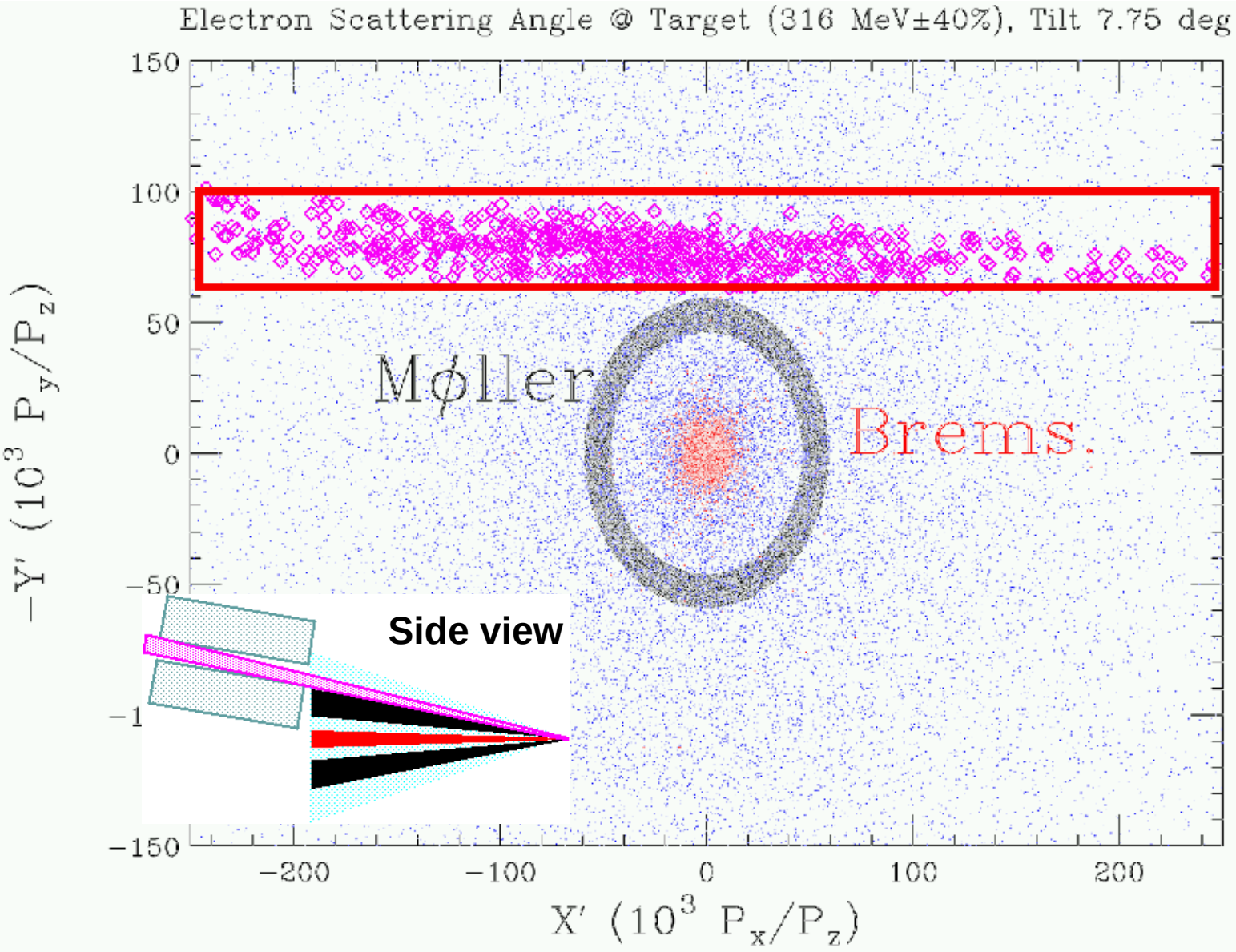
Compared to E89-009



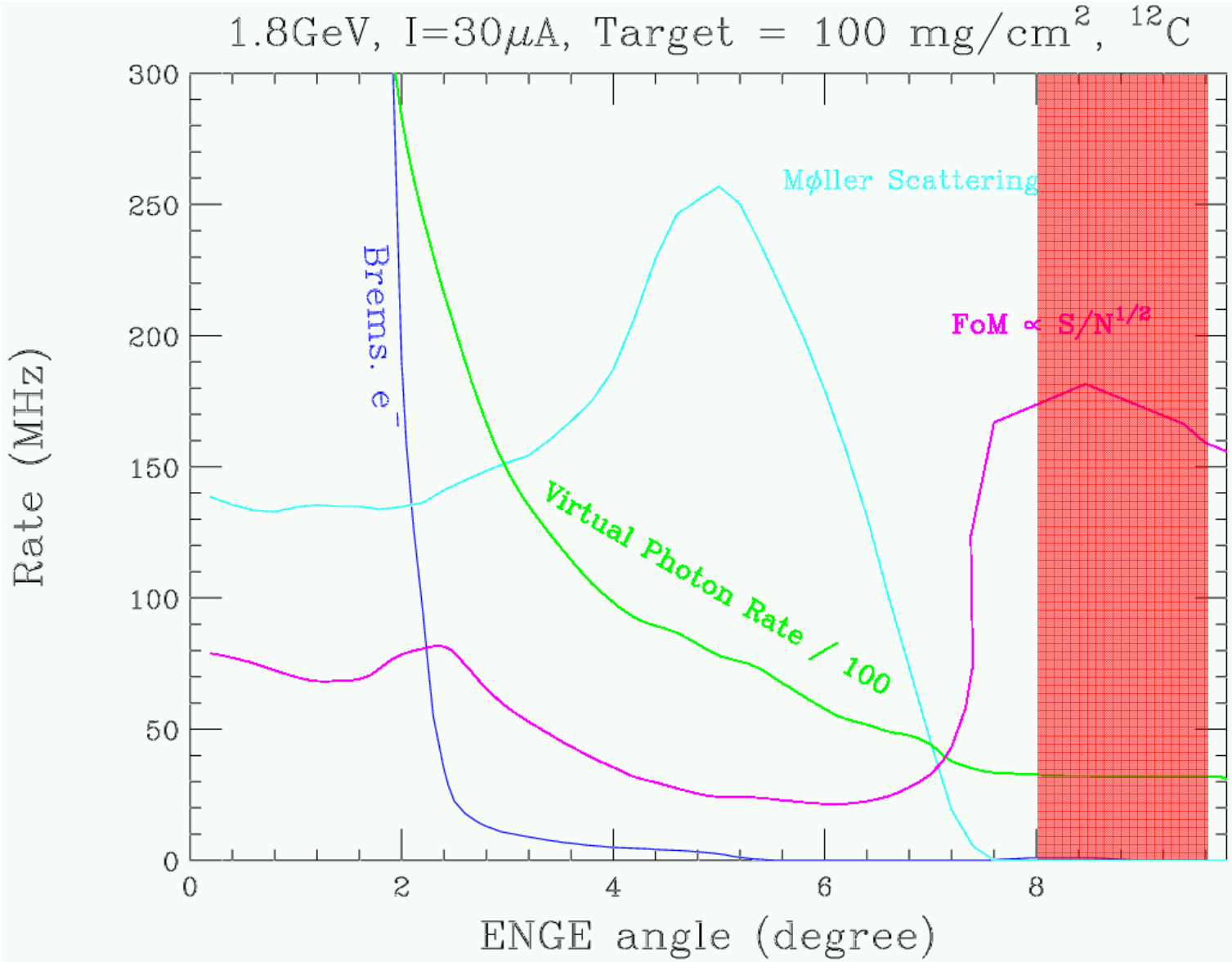
Higher Yield and Better Signal-to-Accidental ratio

Up to medium-heavy hypernuclei can be studied

Optimization of the tilt angle



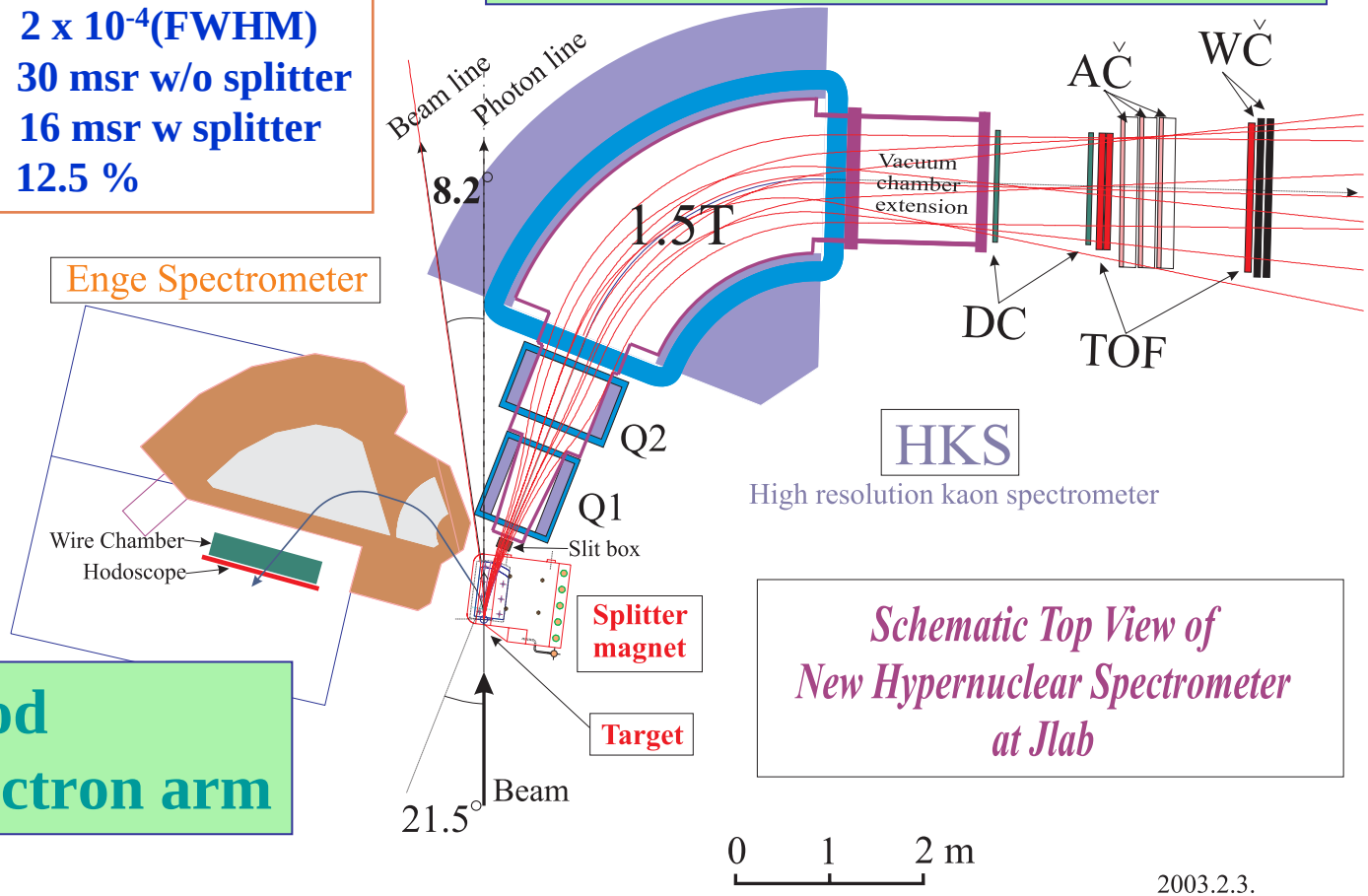
Tilt angle optimization



The HKS spectrometer system

Maximum momentum	**1.2 GeV/c**
Dispersion	**4.7 cm/%**
Momentum resolution	**2 x 10^{-4}(FWHM)**
Solid angle	**30 msr w/o splitter**
	16 msr w splitter
Momentum acceptance	**12.5 %**

High resolution Kaon Spectrometer (HKS)

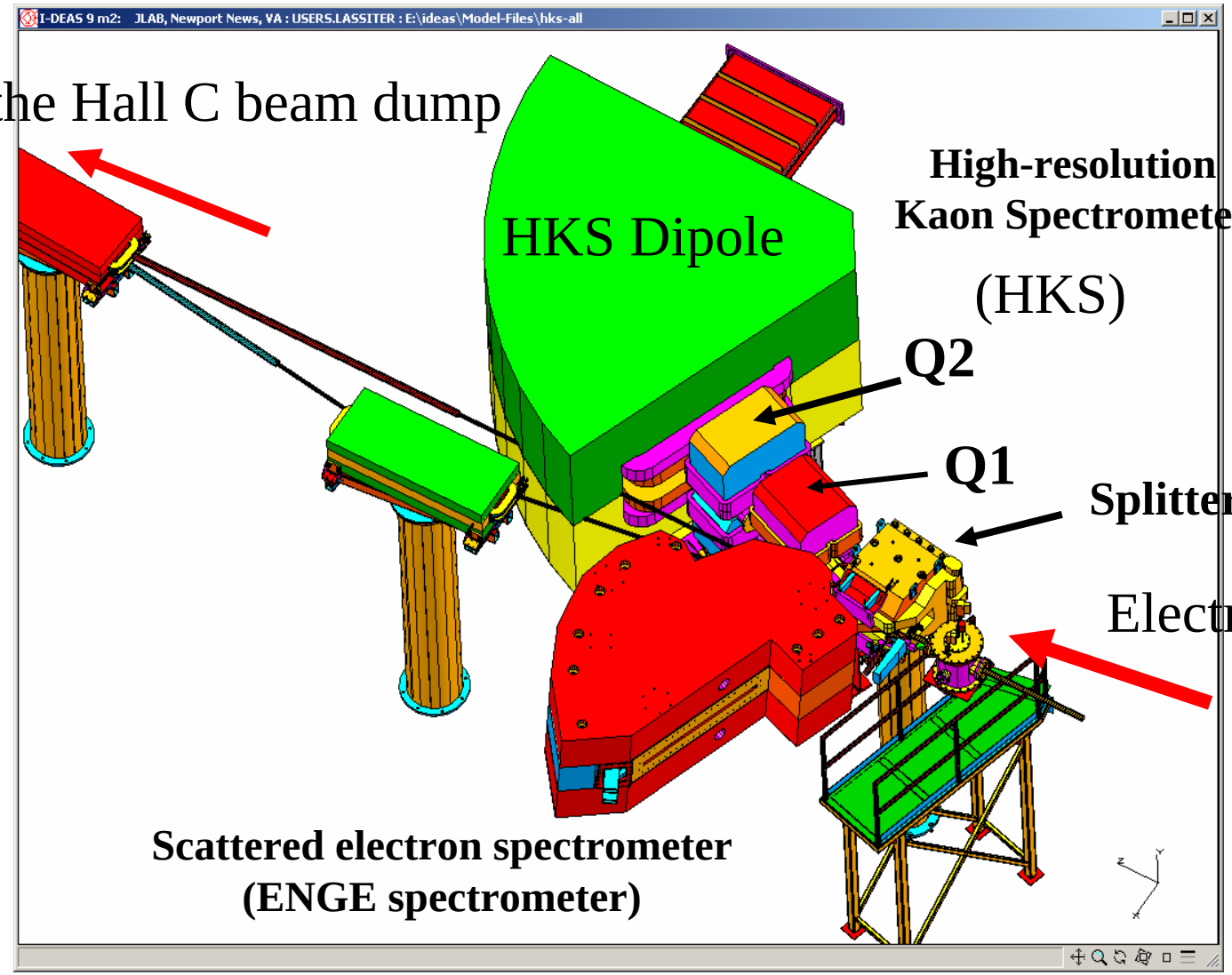


Schematic Top View of New Hypernuclear Spectrometer at Jlab

Tilt method for the electron arm

2003.2.3.

3D CAD Drawing of the E01-011 setup



Expected singles rates

I_e = 30 μA, 100 mg/cm^2

Target	HKS				ENGE	
	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
E89-009 ^{12}C	100	1.4	<1 Hz	0.14	200,000	-
	SOS				ENGE	

Measured values at E89-009 I_e = 0.47 μA, 22 mg/cm^2

Greater hadron rates

High rejection efficiencies against pions and protons are required

Yield comparison of E01-011 and E89-009

Item	E01-011	E89-009	Gain factor
Virtual photon flux per electron($\times 10^{-4}$)	0.2	4	0.05
Target thickness(mg/cm^2)	100	22	4.5
Scattered electron momentum acceptance(MeV/c)	190	120	1.6
Kaon survival rate	0.35	0.4	0.88
Solid angle of K arm	16	5	3.2
Beam current(μA)	30	0.66	45
Estimated yield ($^{12}{}_{\Lambda}B_{gr}$:counts/h)	33	0.9 (measured)	46

Expected hypernuclear production rates in the (e,e'K$^+$) reaction

Hypernuclear production rates

Target	Beam Intensity (μA)	Counts per 100nb/sr/hour	Q-free K+ in HKS(Hz)
^{12}C	30	48	340
^{28}Si	30	21	288
^{51}V	30	11	228

(Target thickness 100 mg/cm^2)

Calculated hypernuclear cross sections

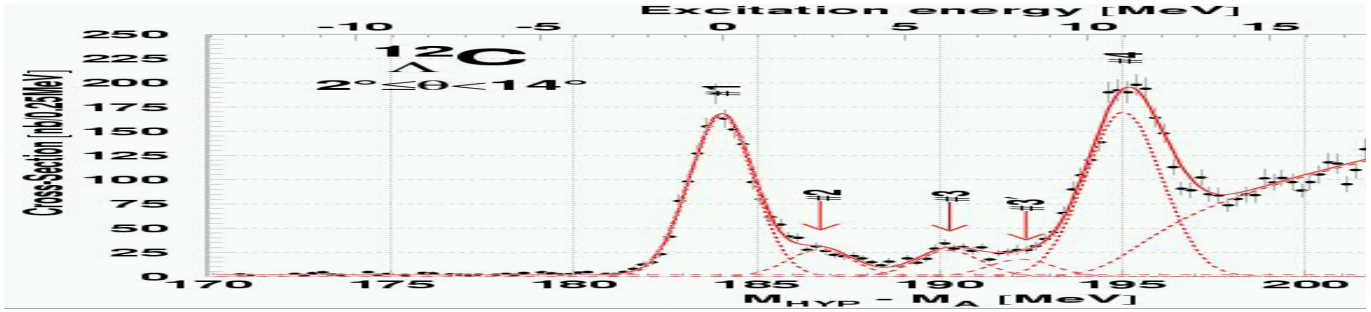
Target	Hypernucleus	Λ orbital	Cross section (nb/sr)
^{12}C	$^{12}{}_{\Lambda}B$	s1/2	112
		p3/2	79
		p1/2	45
^{28}Si	$^{28}{}_{\Lambda}Al$	s1/2	56
		p3/2	95
		p1/2	57
		d5/2	131
		d3/2	111
^{51}V	$^{51}{}_{\Lambda}Ti$	s1/2	18
		p3/2	41
		p1/2	26
		d5/2	52
		d3/2	48
		1s1/2	16
		f7/2	32
		f5/2	38

Expected Energy Resolution

Item	Contribution to the resolution (keV, FWHM)			
Target	^{12}C	^{28}Si	^{51}V	^{89}Y
HKS momentum	230			
Beam momentum	< 180			
Enge momentum	120			
K^+ angle	134	56	32	18
Target thickness	< 180	< 171	< 148	< 138
Overall	**< 390**	**< 360**	**< 350**	**< 345**

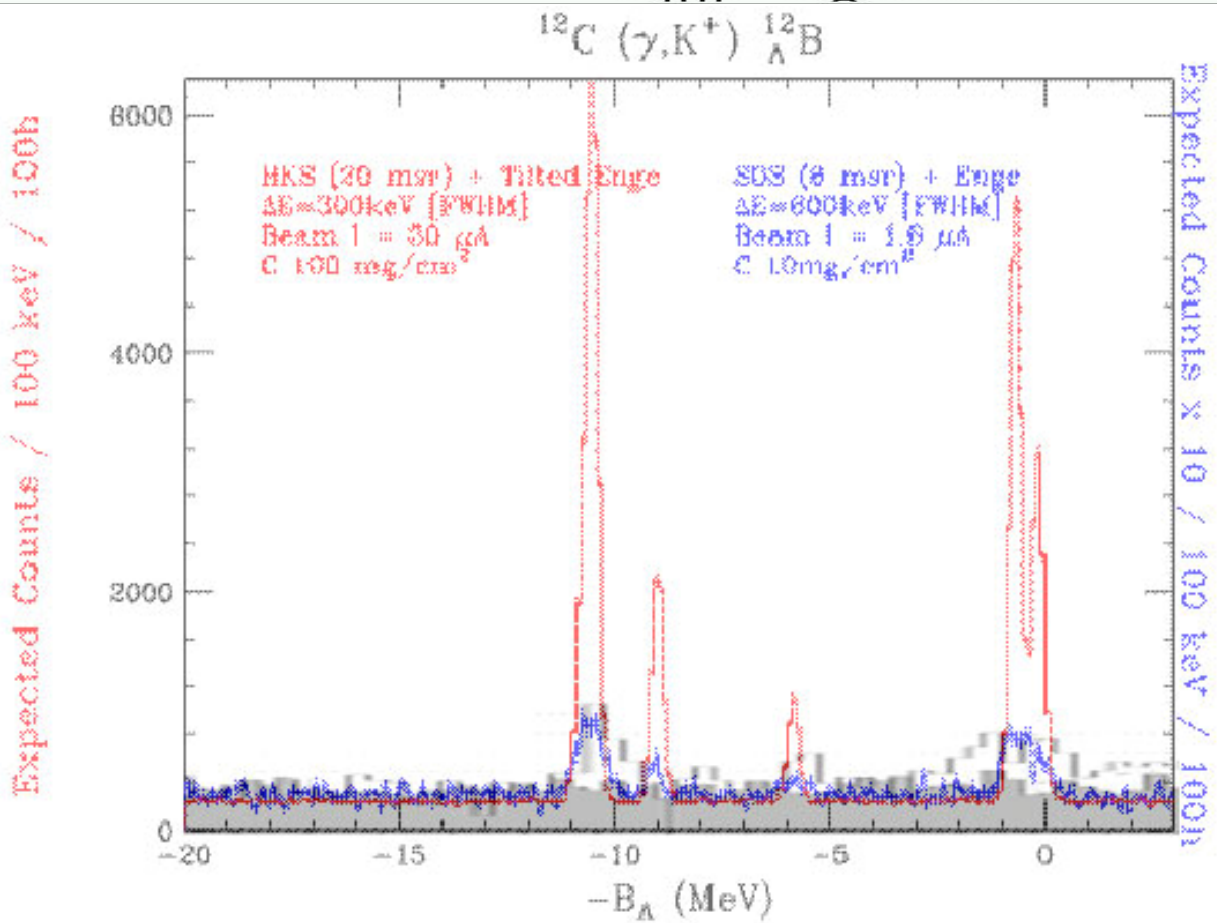
Expected Spectra

KEK-PS E336 :
w/ SKS (π,K) reaction

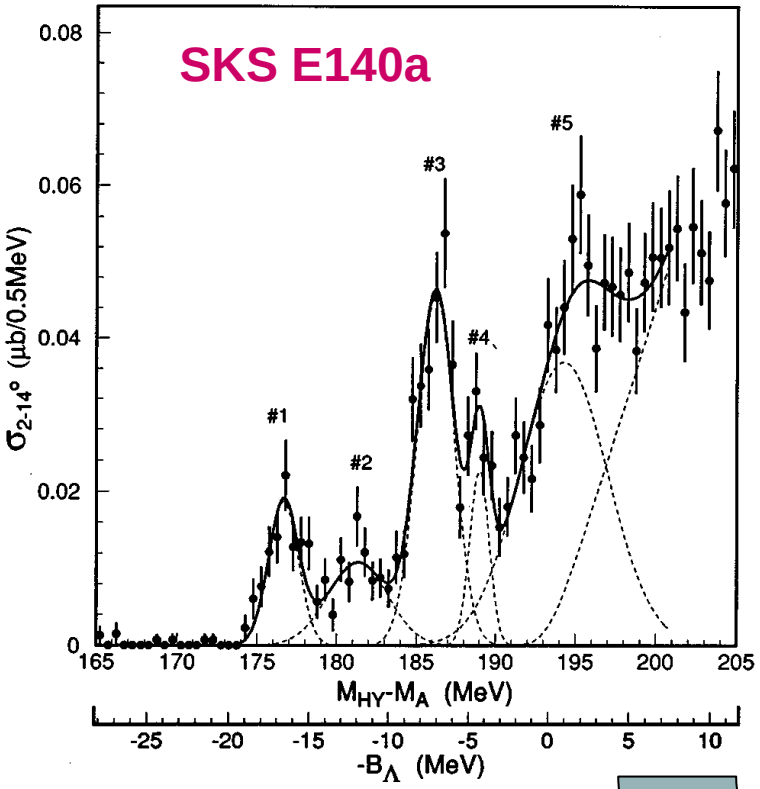


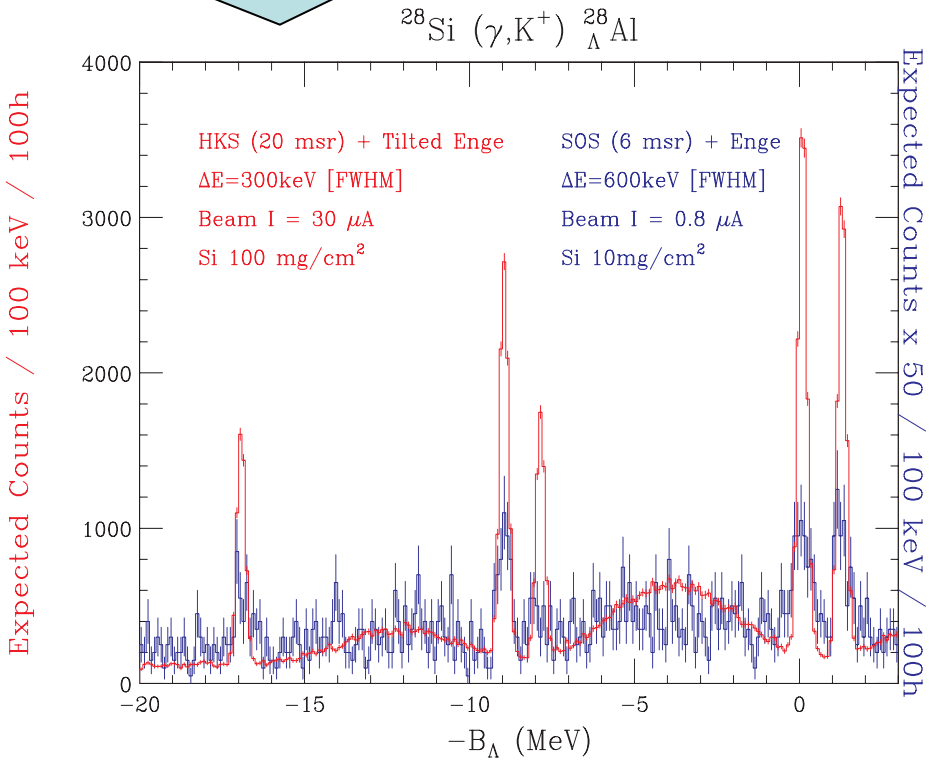
Jlab E01-011 (e,e'K)
with HKS [Expected]

Jlab E89-009 (e,e'K)



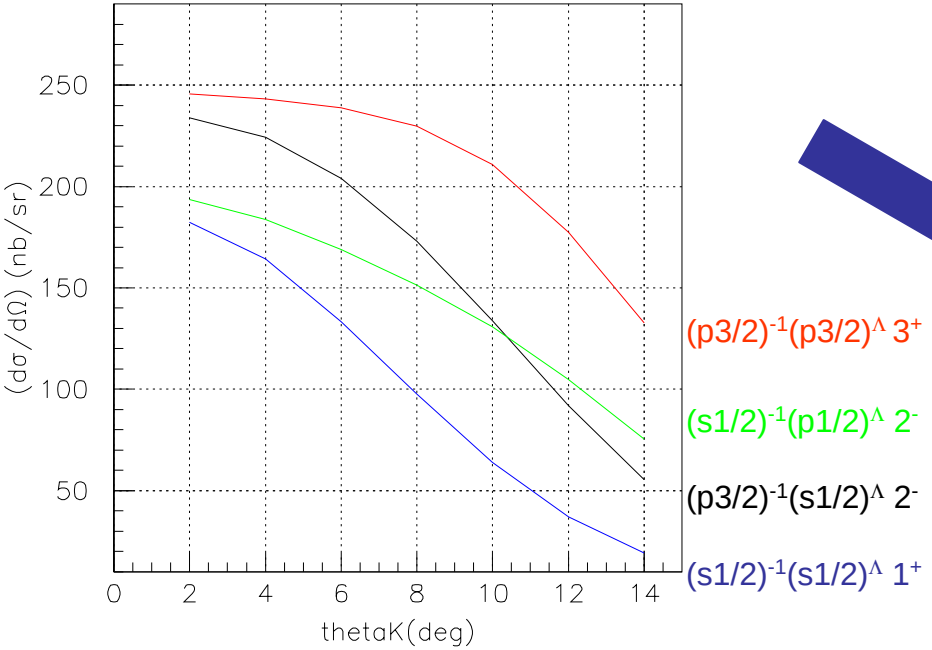
Expected $^{28}{}_{\Lambda}$Al hypernuclear spectra





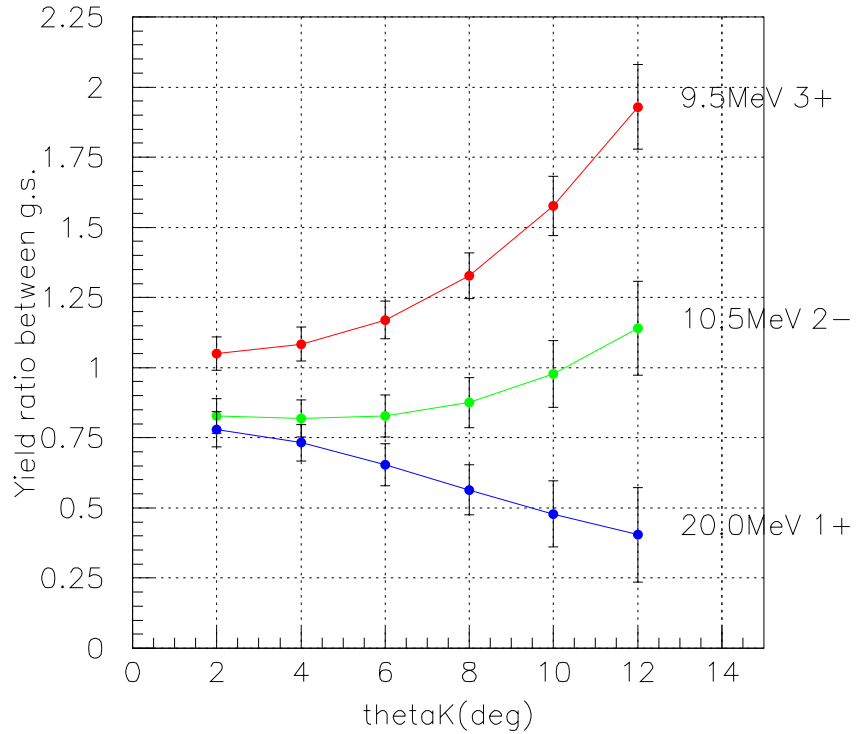
Angular distribution

Angular distribution of $^{12}{}_{\Lambda}B$ states

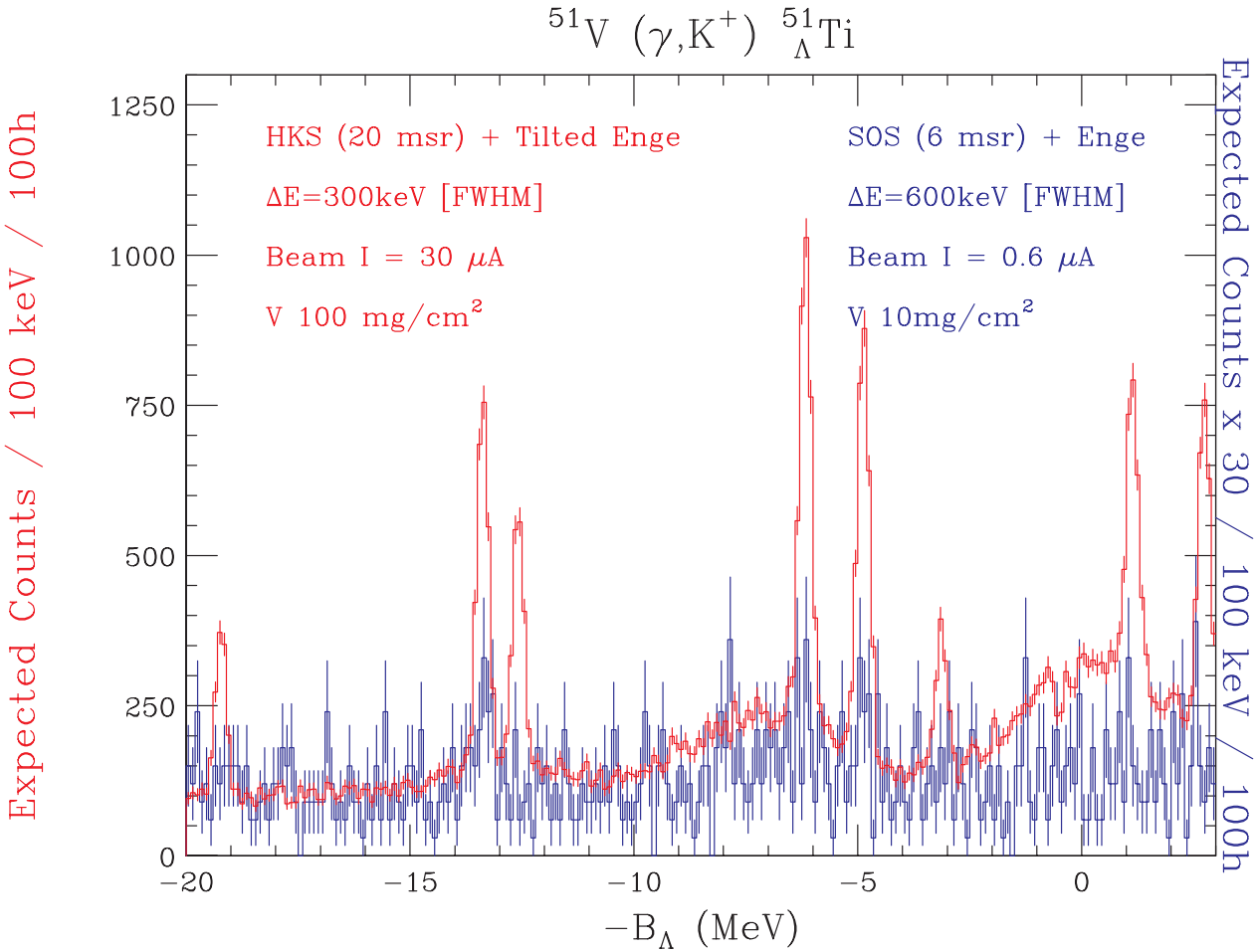


DWIA calculation by a code of M.Sotona

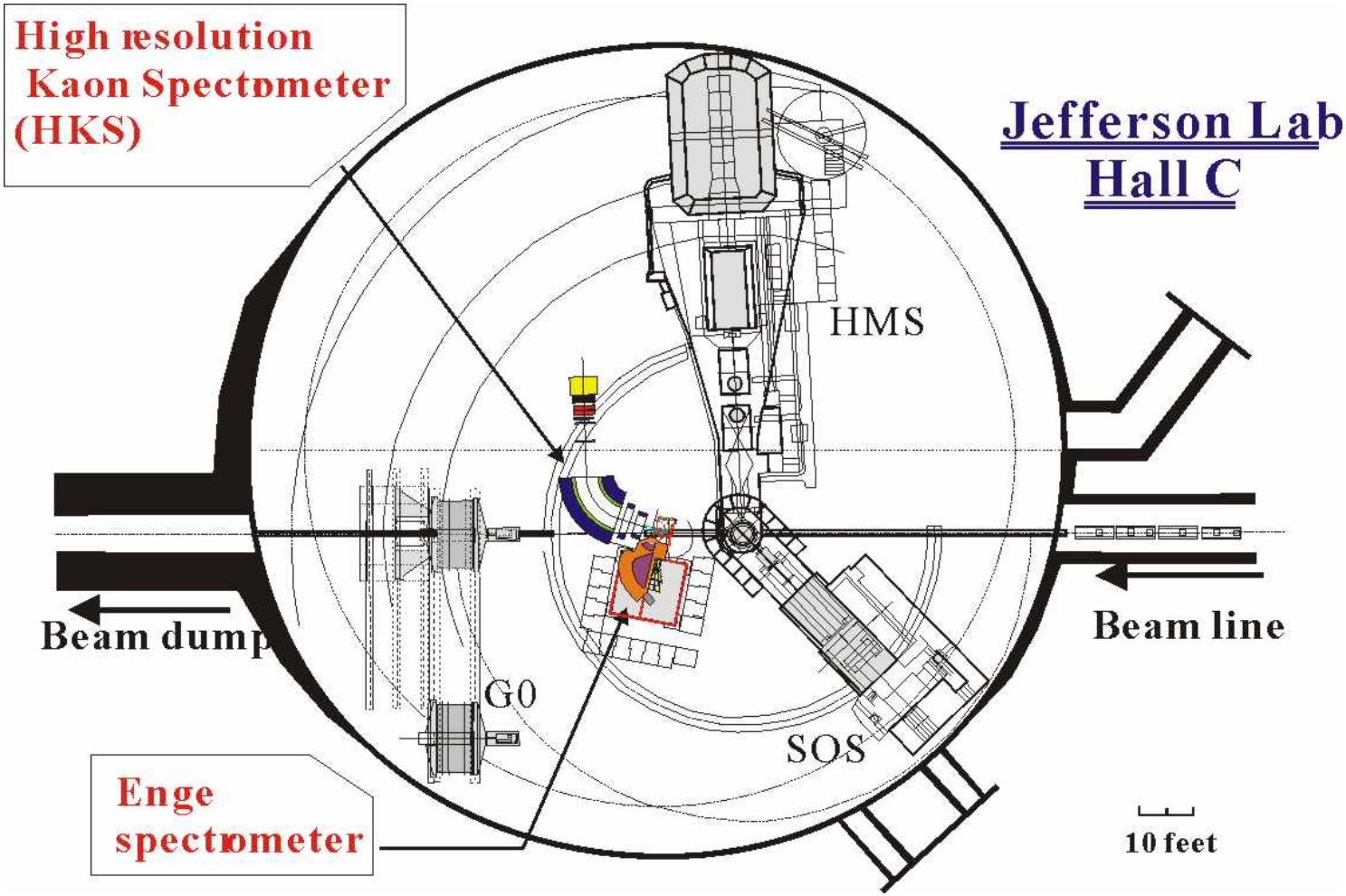
Expected yield ratio between g.s.



Simulated spectrum for $^{51}{}_{\Lambda}V$



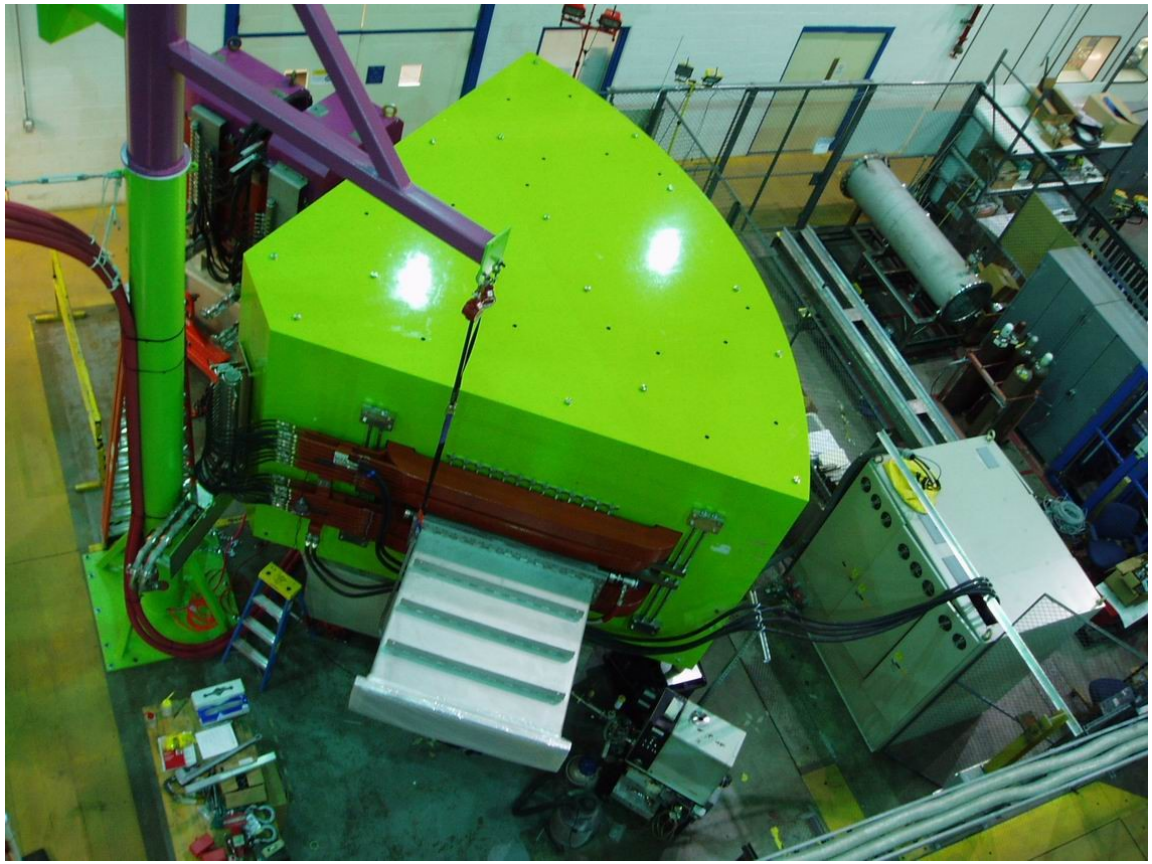
HKS spectrometer system in Hall C



Assembled HKS(QQD)

Delivered to Jlab in November, 2003

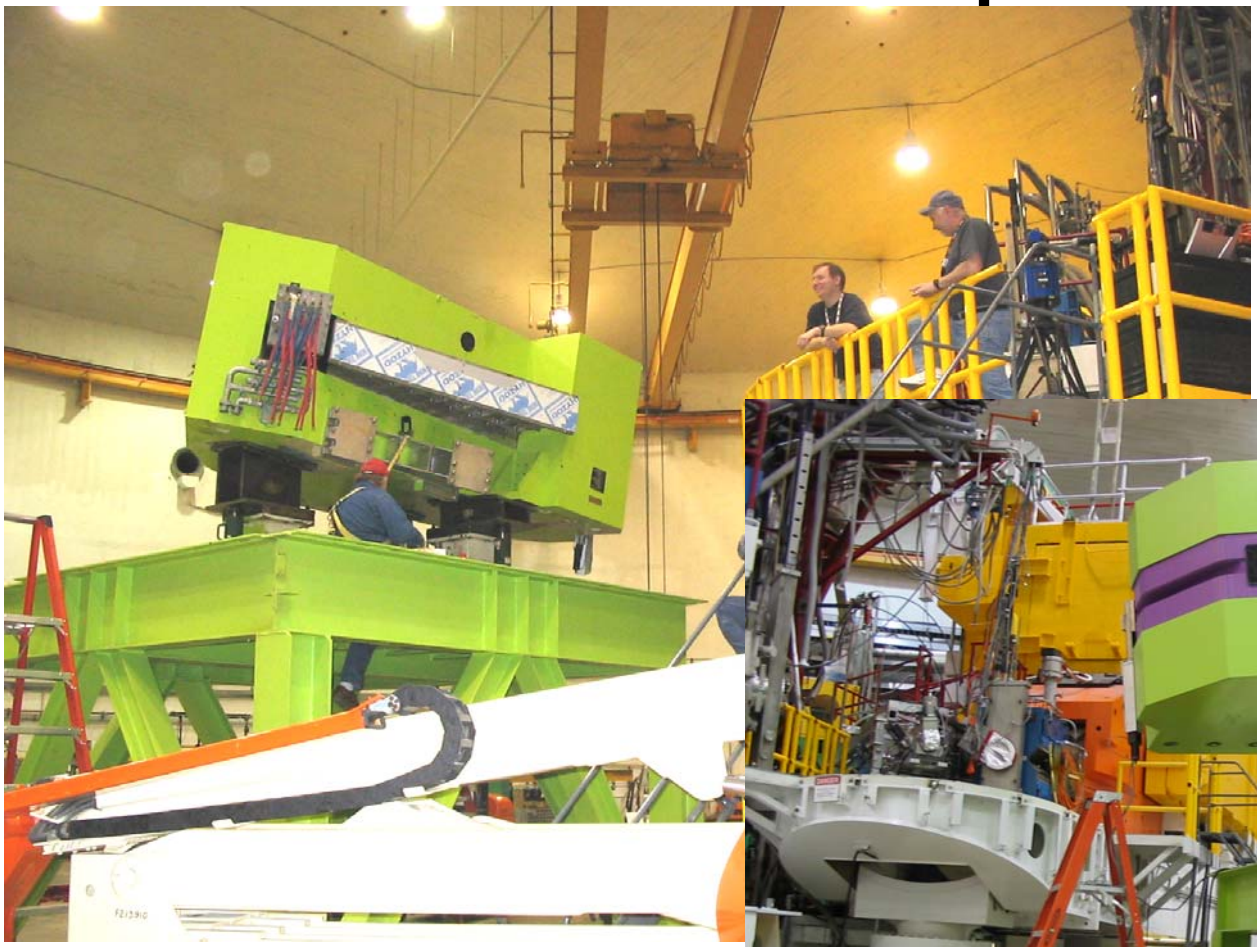
HKS pre-assembled at Jlab

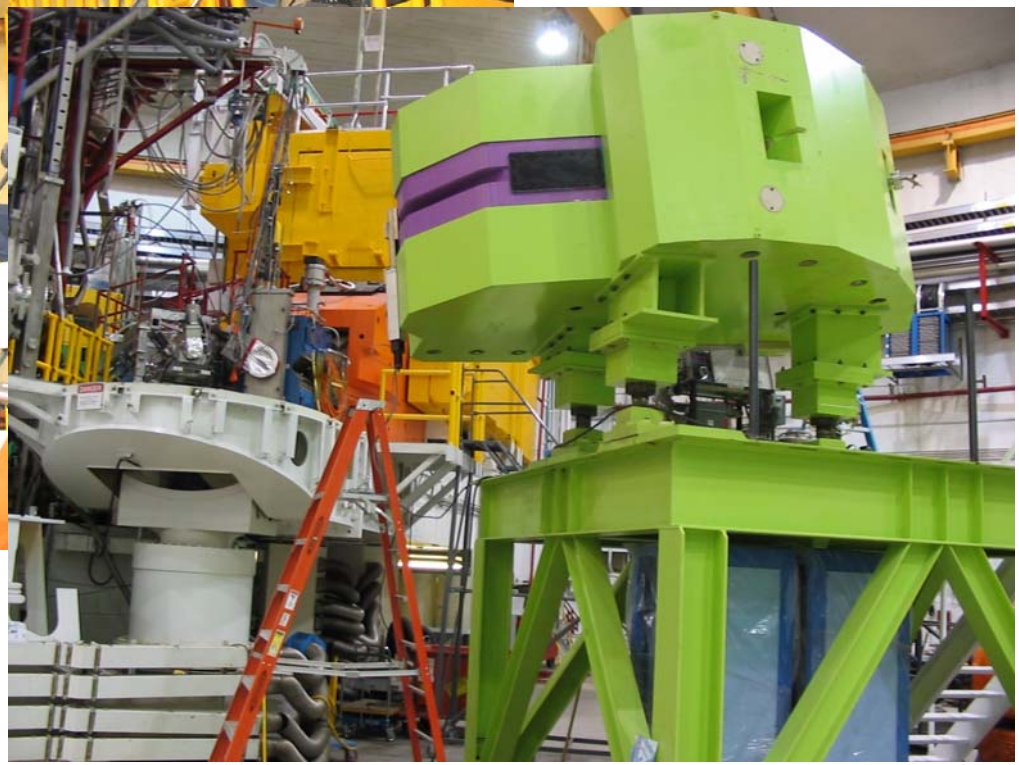


January - June 2005	Installation to Hall C
June 2005	Commissioning
June - August	Data taking

E01-011 setup in Hall C

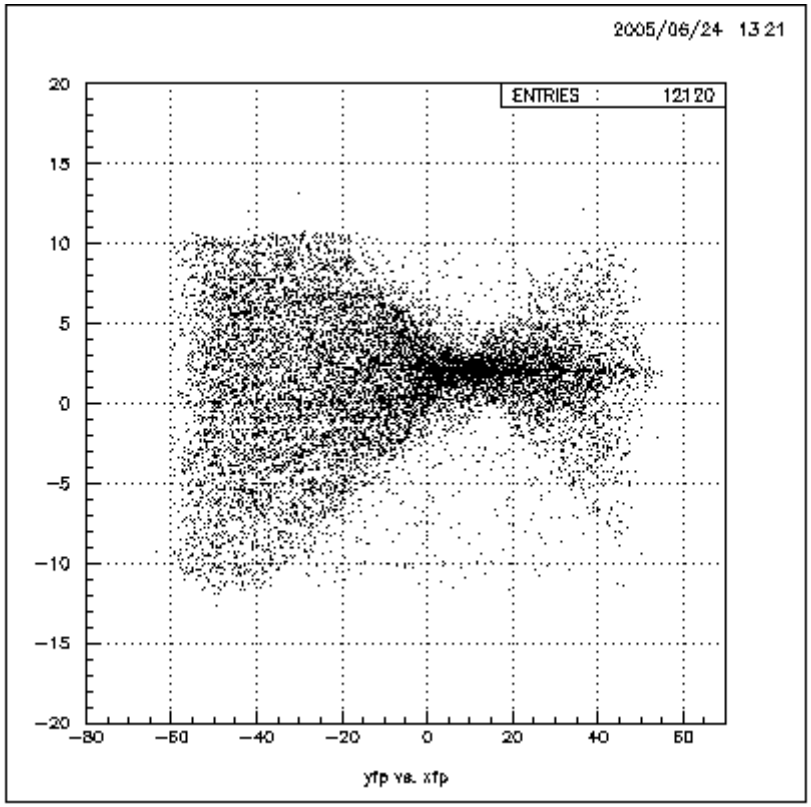
Tilted ENGE spectrometer





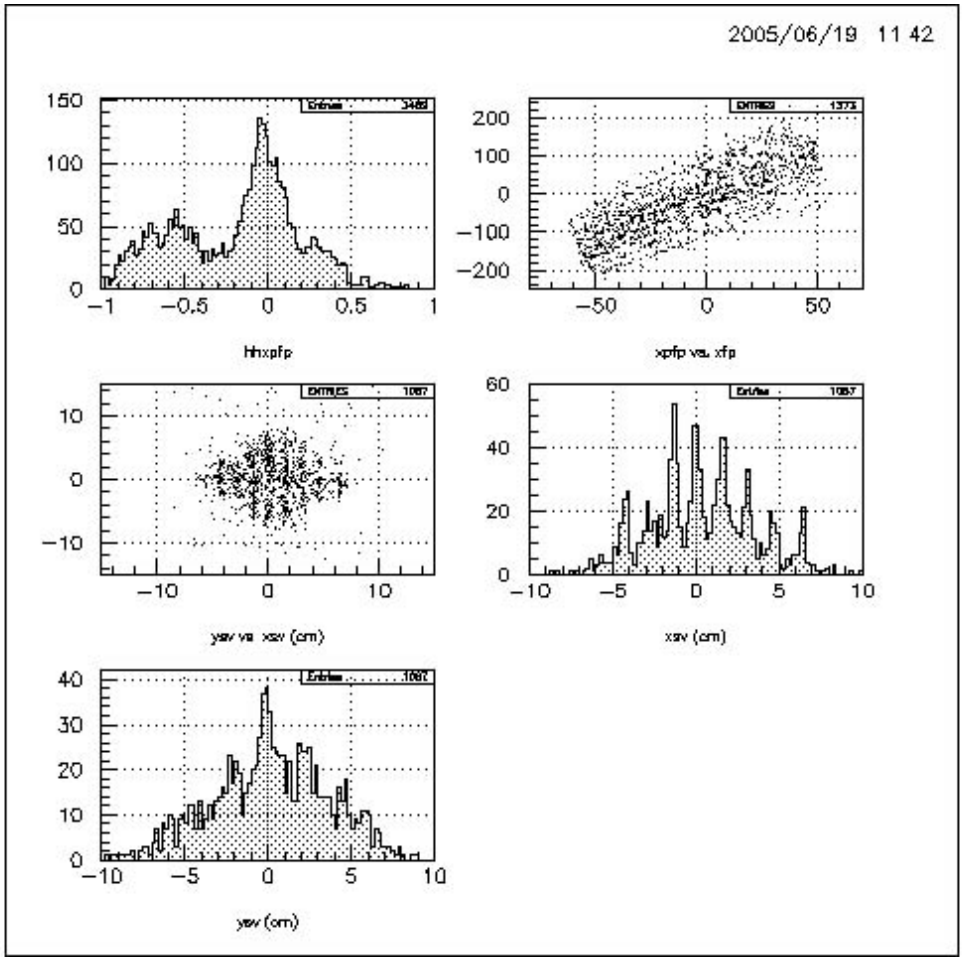
HKS detector package

HKS Optics working



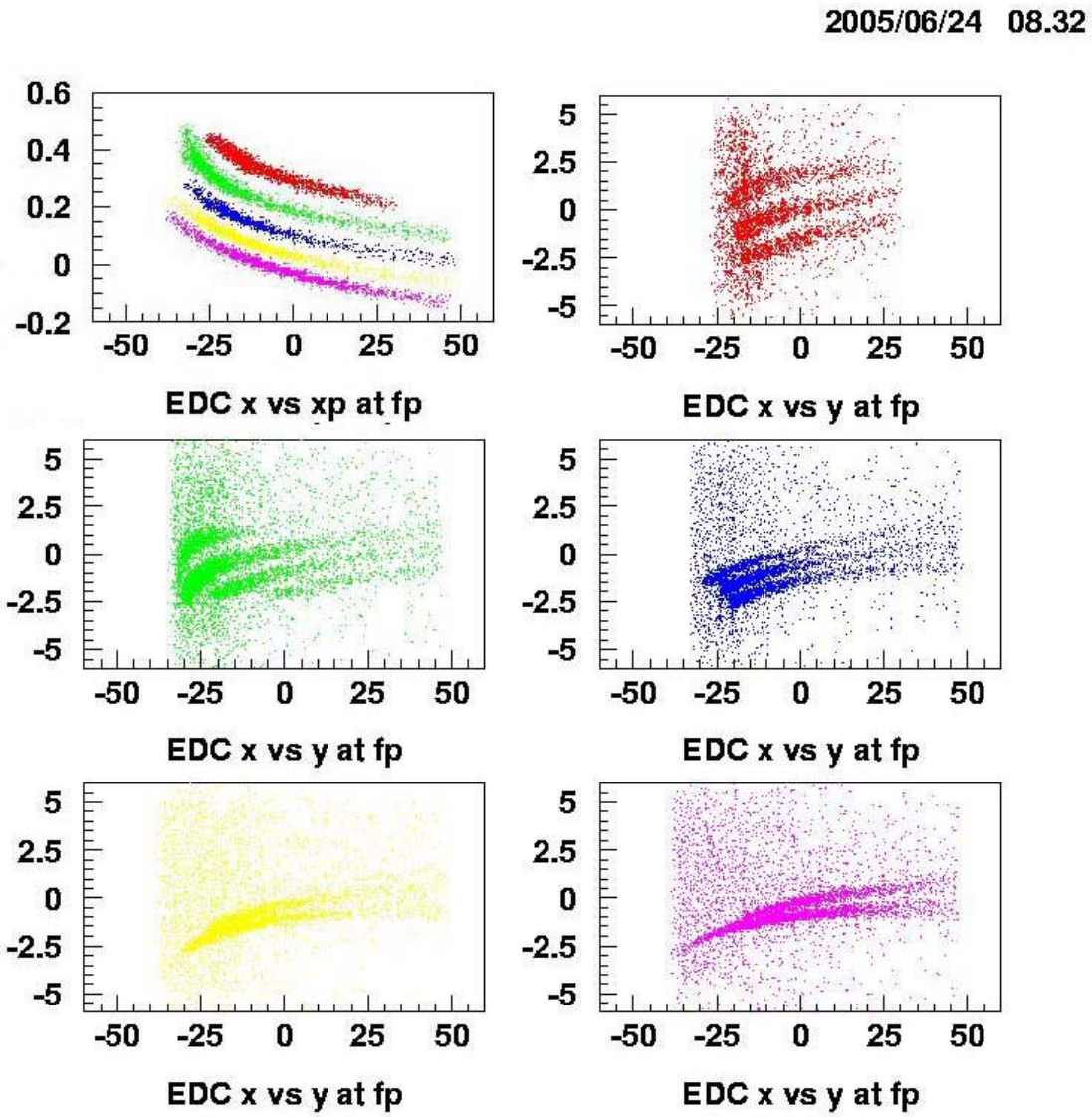
Data taken June, 2005

HKS Sieve split data analysis



Data taken June, 2005

ENGE Sieve Split data analysis



Data taken June, 2005

FUTURE OPTION with 6 GeV, 12 GeV beam

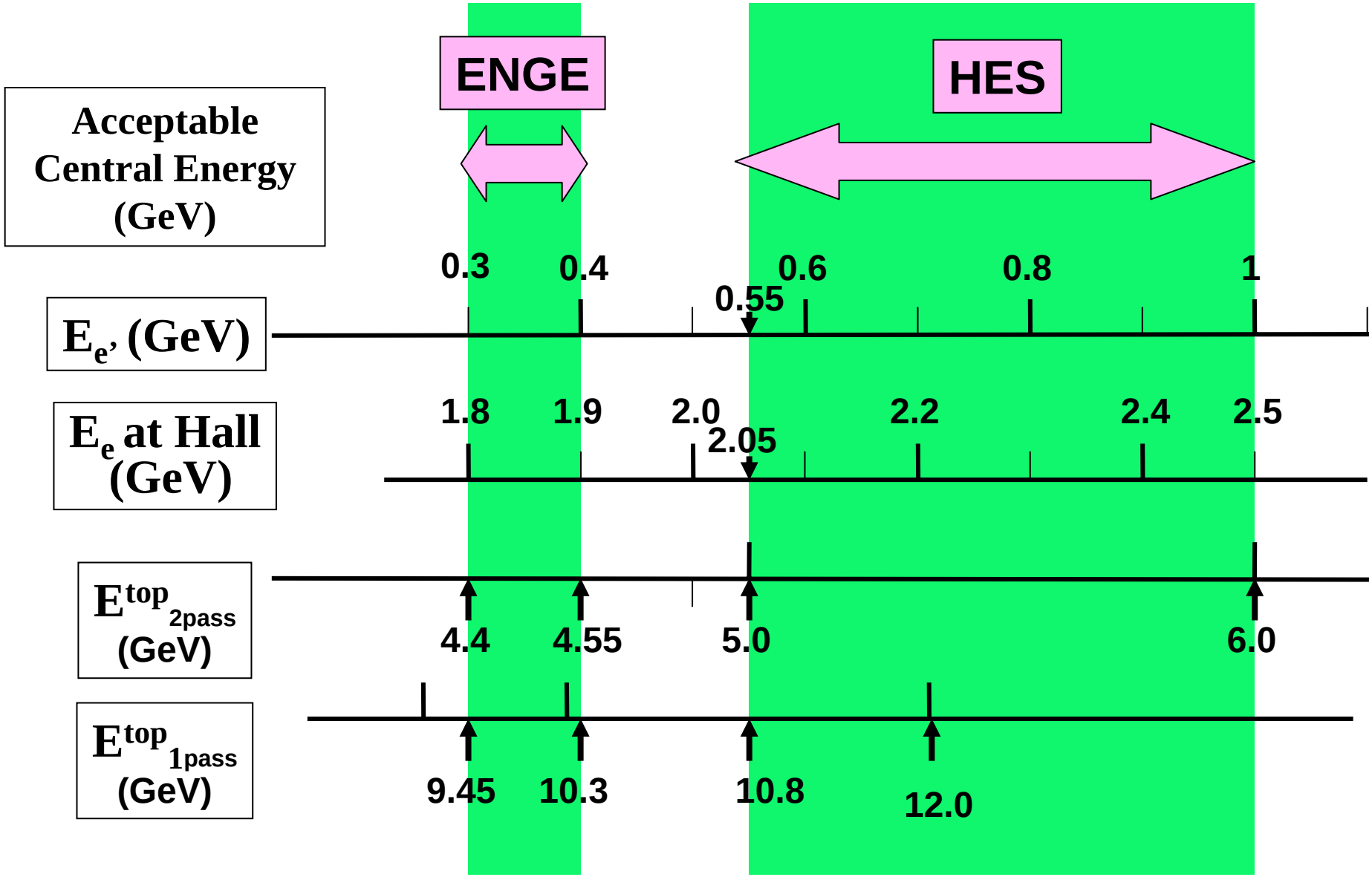
--- widen acceptable beam energy window ---

Table Beam energy and spectrometer

	P_K (GeV/c)	E_{γ^*} (GeV/c)	Ee (GeV/c)	Ee' (GeV/c
E89-009 & E01-011	1.2	1.5	1.8	0.3
E94-107	1.9	2.2	4.0	1.8
Future Option	1.2	1.5	2.4 (6/5*2)	0.9

HKS E_γ dependence 6 GeV

Acceptable energy windows of HKS system with ENGE or HES

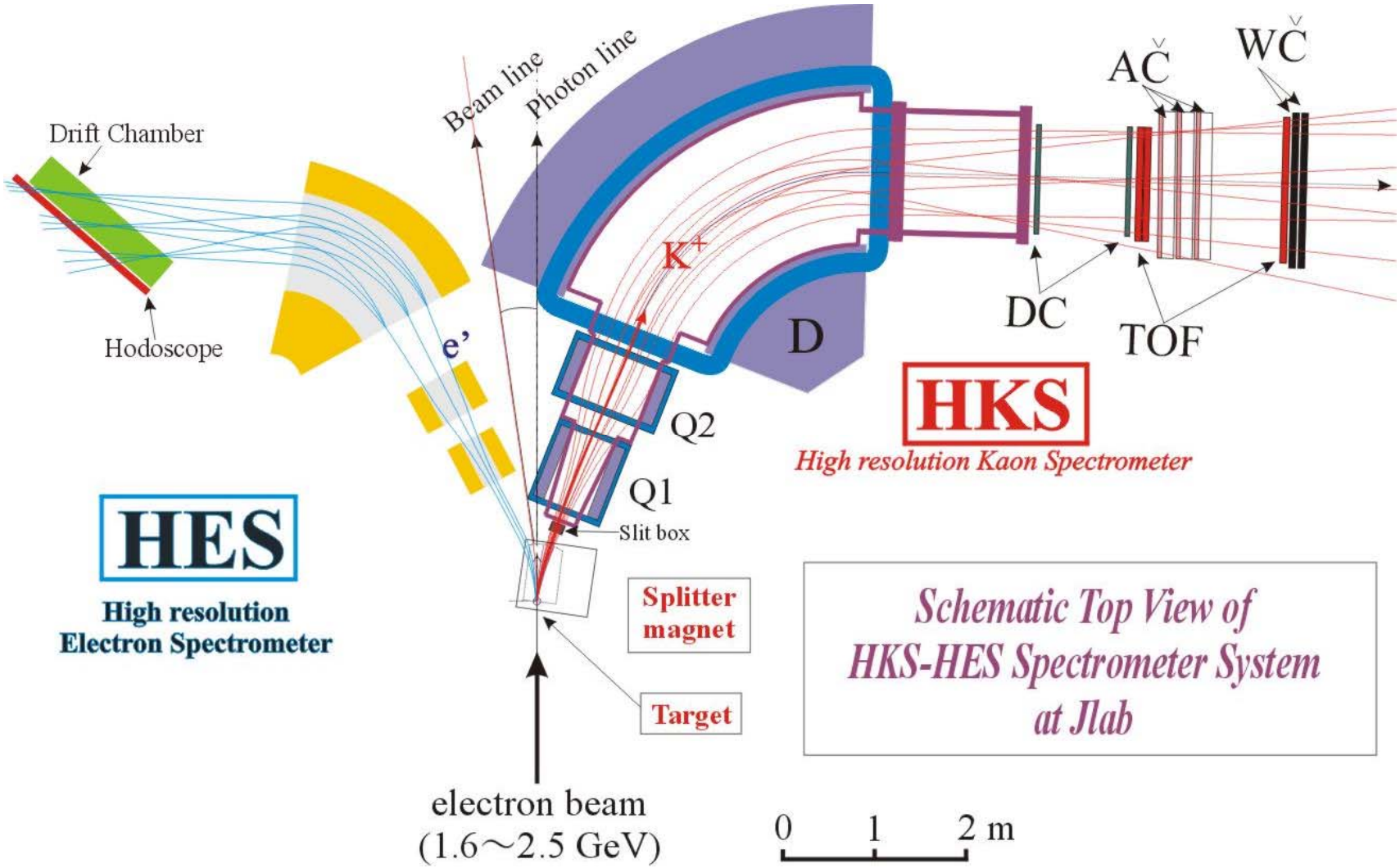


Basic design parameters of HES

- Central momentum
- Tilt angle → smaller due to higher beam energy
  - Virtual photon flux 2-3 times more
- Momentum acceptance should match that of HKS
  - 0.3 GeV independent of the central momentum

Central momentum (GeV/c)	0.55 -1.0
Momentum acceptance (GeV/c)	0.20 GeV/c)
Solid angle (msr; $\Delta\theta_H = \Delta\theta_V$)	3.6
Tilt angle (degrees)	To be optimized(~2-4)

HKS-HES hypernuclear spectrometer system



Present spectrometer design

- Kaons are detected by HKS in the momentum region of 1.05-1.2-1.35 GeV/c
- Beam energy is in the range from

  2.18 GeV/c ---- 12 GeV 1 pass

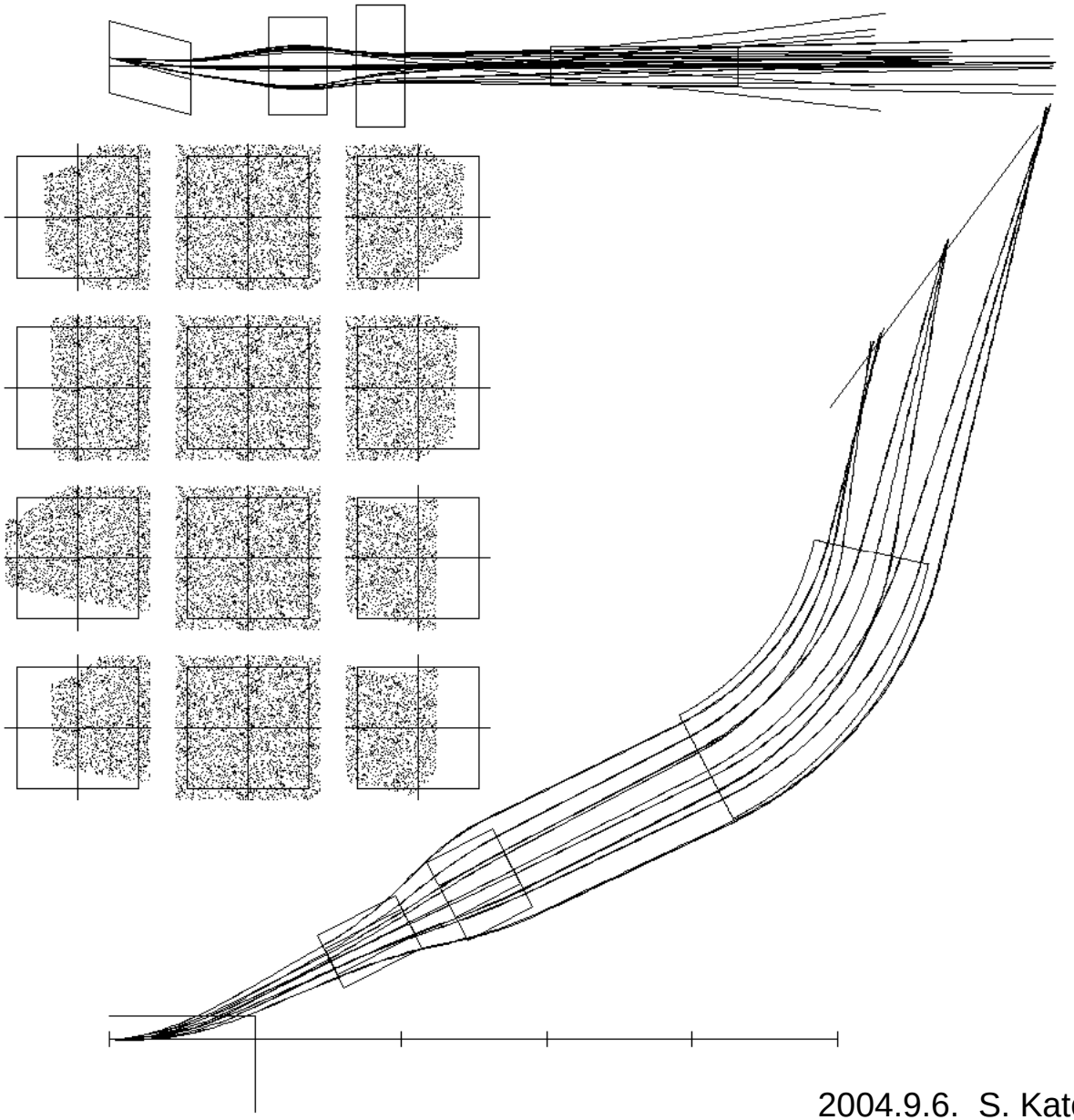
  to 2.4 GeV/c ---- 6 GeV 2 pass
- Optimization of momentum acceptance matching with HKS
- Optics to be optimized as DQQD

HES Parameters

2004.9.14.

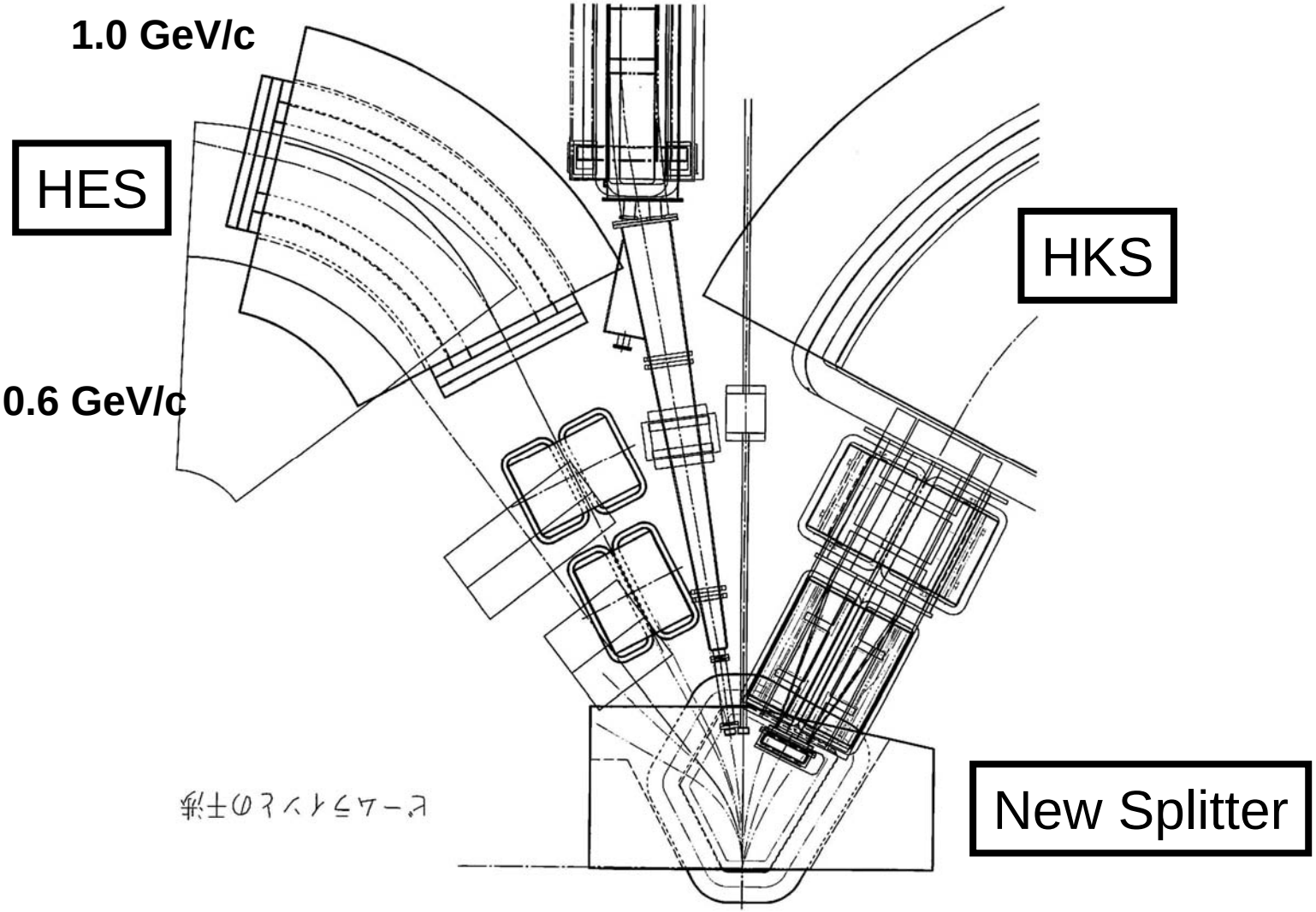
• Splitter		
	Magnetic field	1.9 T
	Full gap	0.15 m
	Length (beam direction)	1 m
• Splitter-Q1		0.8 m
• Q1	Length	0.6 m
	Full gap	0.2 m (Effective full width 0.4 m)
	Yoke full width	0.6 m (including coil)
• Q1-Q2		0.3 cm
• Q2	Length	0.5 cm
	Full gap	0.25 m (Effective full width 0.6 m)
	Yoke full width	0.8 m (including coil)
• Q2 – D		1.5 m
• Dipole		
	Bend	50 degrees
	ρ	2.2 m
	Full gap	0.16 m
	Inner full width	0.8 m

HES optics
1.00 GeV/c

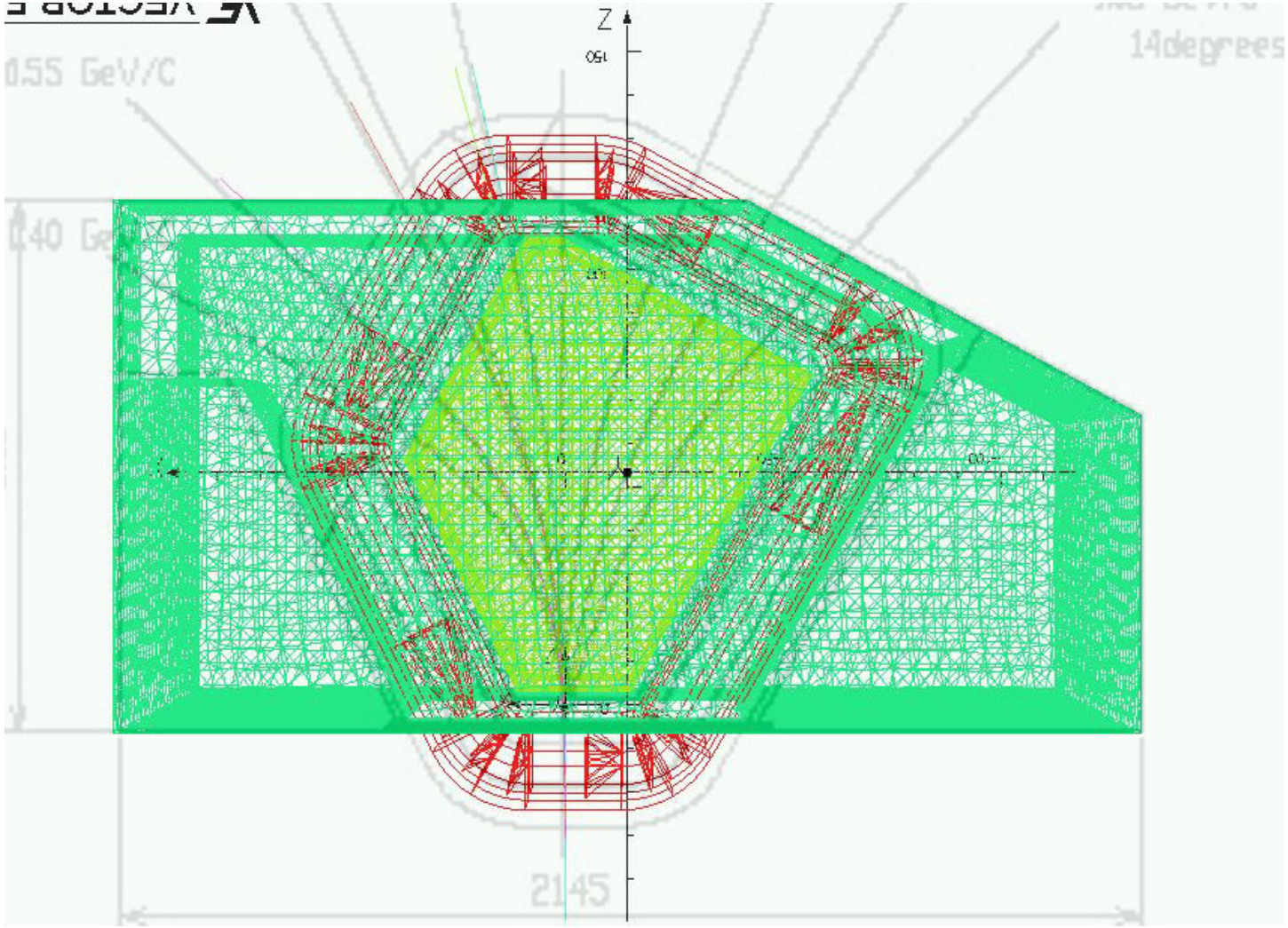


2004.9.6. S. Kato

Splitter, HKS, HES geometry

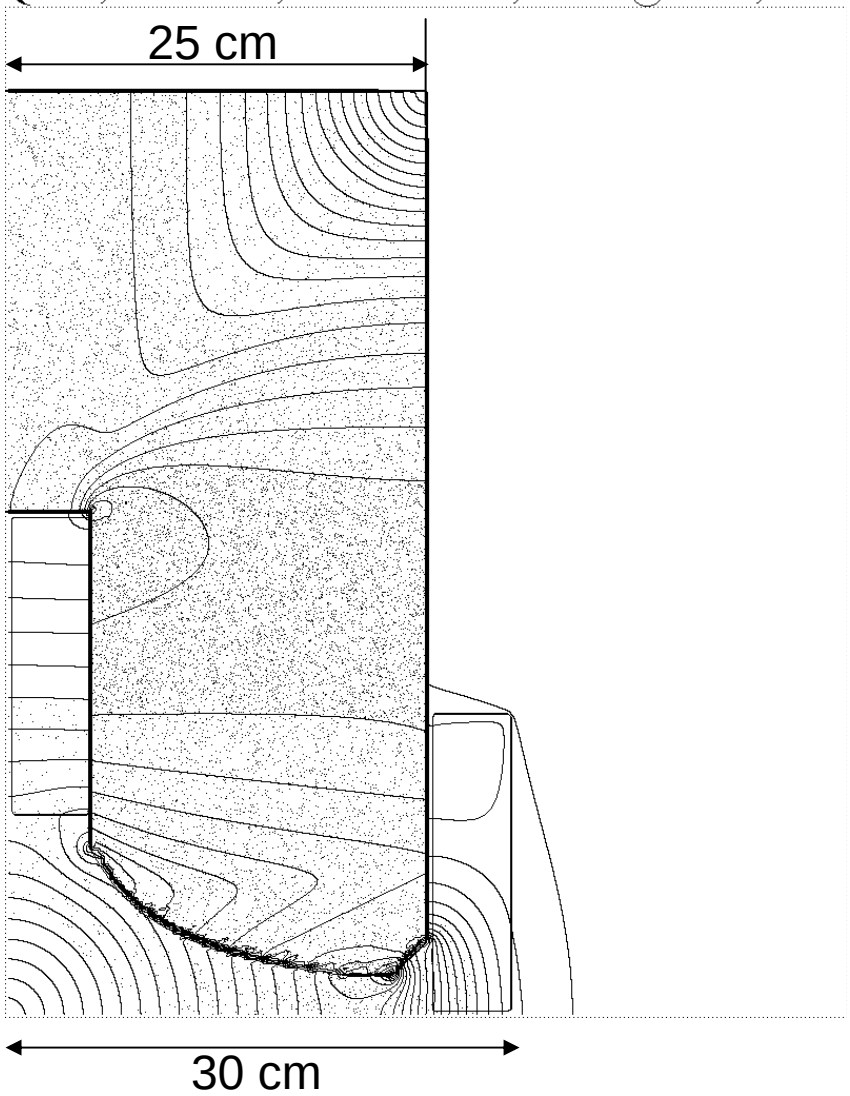


Splitter TOSCA calculation

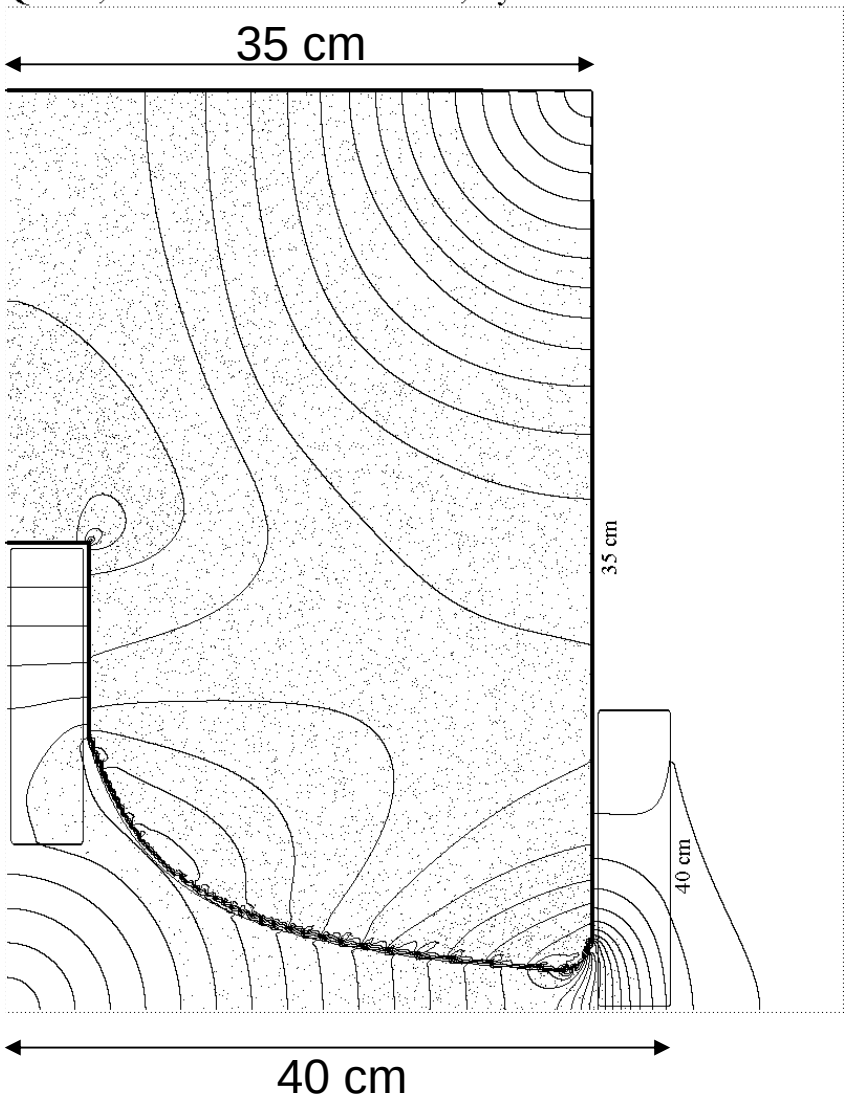


Slim Q1 & Q2

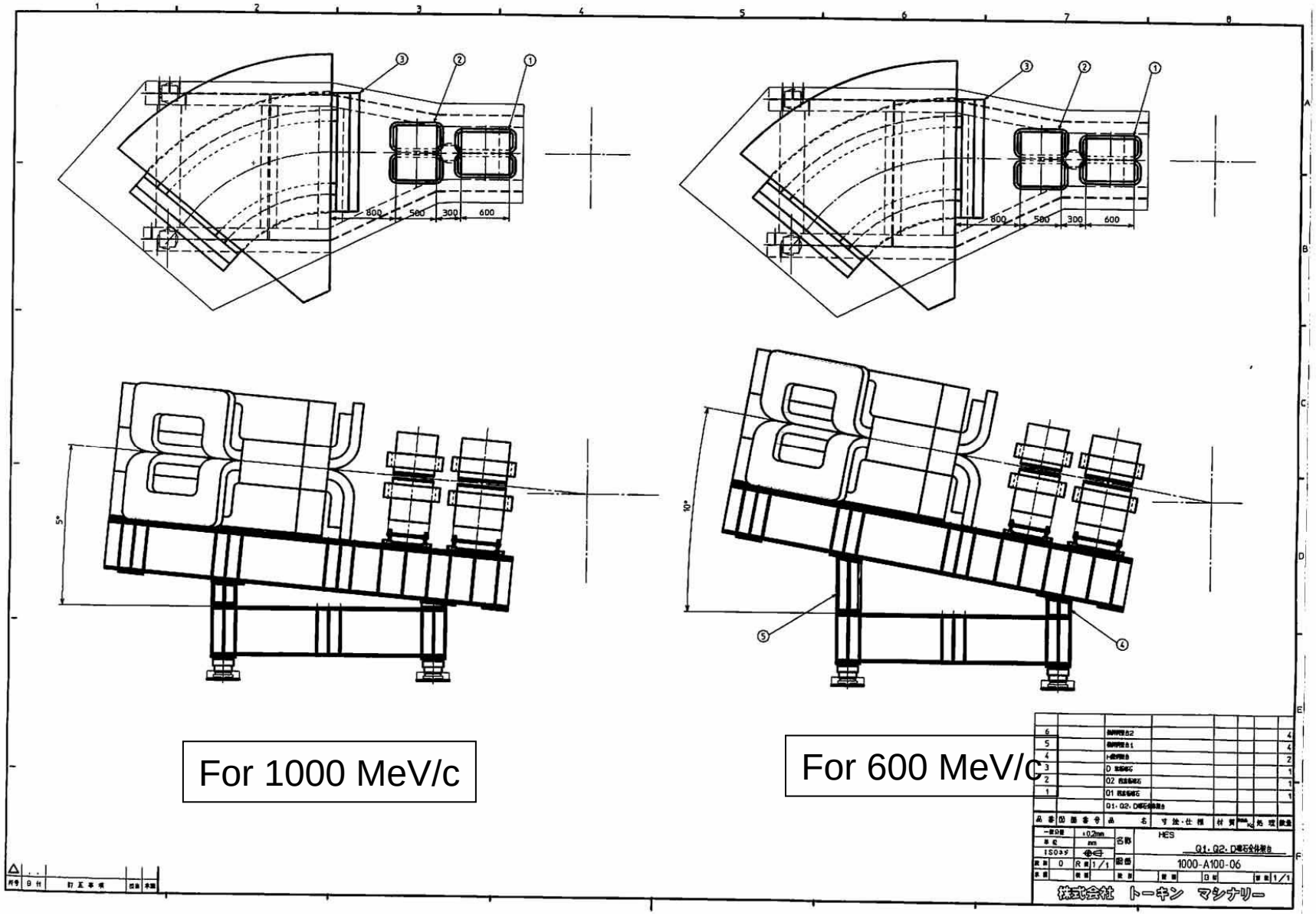
Q20-6, G = 20 cm, slim 8.68 T/m, -4.3% @20 cm, 28 m



Q20-9, 4 A/mm2 G = 25.3 cm, xy=80 cm2 slim 7.34 T/



HES mechanical design



For 1000 MeV/c

For 600 MeV/c

Road map

- E89-009 completed
  - First (e,e'K+) spectroscopy Jlab Hall C
  - ${}^{12}_{\Lambda}$B and (${}^{7}_{\Lambda}$He)
- E97-107 data taking in May, 2004, extra running in June,2005
  - New high-quality (e,e'K+) spectrum on ^{12}C at Hall A
  - ${}^{12}_{\Lambda}$B and ${}^{16}_{\Lambda}$O
- E01-011 run in June-August of 2005
  - Comparable yield with (π+,K+) spectroscopy with a few 100 keV resolution
  - ${}^{12}_{\Lambda}$B, ${}^{28}_{\Lambda}$Al and light hypernuclei (and medium-heavy Λ hypernuclei, ${}^{51}_{\Lambda}$V, ${}^{89}_{\Lambda}$Ti
- High resolution spectroscopy for a wide mass range of Λ hypernuclei with a complete hypernuclear spectrometer system
  - HES-HKS hypernuclear spectrometer system
    - HKS installed in Hall C for E01-011
    - HES under construction and will be shipped to Jlab by the end of 2006.

→wide variety of singles and coincidence experiments by the (e,e'K+) reaction

Complimentary to the spectroscopy with hadronic beams at J-PARC.

Summary

- Precision hypernuclear spectroscopy by the (e,e'K+) reaction plays an essential role in the investigation of hadronic may-body systems that contain "strangeness".
- A high resolution electron spectrometer (HES) is under construction at TOHOKU as a part of the HKS-HES hypernuclear spectrometer system.
- The spectrometer system is designed so that hypernuclear experiments at Jlab in both light and medium-heavy hypernuclei can be conducted with the wide beam energy including 6 GeV and 12 GeV operation and can be installed either in Hall C and Hall A.

HKS-HES
VIRGINIA
HKS-HES