High Resolution Λ Hypernuclear Spectroscopy by the (e,e'K+) Reaction at Jlab Hall C

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Outline

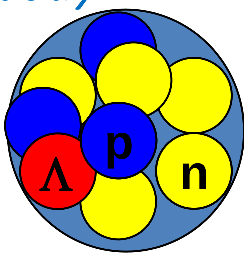
1. Introduction
2. Experimental setup
3. Analysis
4. Results
5. Summary

Introduction

Introduction – *Hypernuclei*

- *A nucleus with one or more nucleons replaced by hyperon, Λ, Σ, …*
- *A Λ-hypernucleus is the nucleus with either a neutron or proton being replaced by a Λ hyperon*
- *Since first hypernucleus found 50 some years ago, hypernuclei have been used as rich laboratory to study YN and YY interactions – Solving many-body problem with Strangeness*

Λ hypernuclei



- New degree of freedom → free from Pauli blocking
  - Baryon structure in nuclear medium
  - Deeply bound nuclear states
  - Long lifetime: *Λ-hypernucleus in ground state* decays only weakly via *$\Lambda \rightarrow \pi N$ or $\Lambda N \rightarrow NN$,* thus mass spectroscopy features with narrow states *(< few 100 keV)*

- Unique structure of hadronic many-body system
  - Nucleus with a new quantum number
  - Core excited states
  - Glueing role of a Λ hyperon

- ΛN interaction
  - Unified view of baryon-baryon interaction in SU(3)
  - Central, spin-dependent … ΛN interaction

Single-particle nature of Λ hypernuclei

Description of a Λ-hypernucleus within two-body frame work –

Nuclear Core (Particle hole) ⊗ Λ (particle)

(Few example states)

(Example of the lowest mass states)

P — $7/2^+$ & $5/2^+$

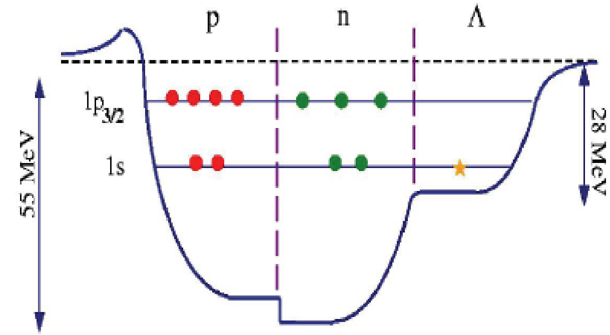
S — $5/2^-$ & $3/2^-$; $1/2^-$; $3/2^-$

^{11}C or ^{11}B **Core**

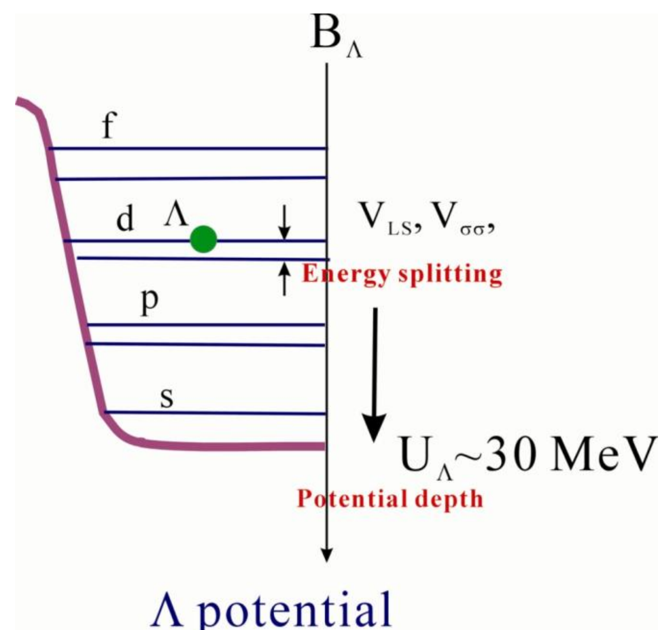
⊗ Λ → **$^{12}{}_{\Lambda}C$ or $^{12}{}_{\Lambda}B$ substitution states**

⊗ Λ → **$^{12}{}_{\Lambda}C$ or $^{12}{}_{\Lambda}B$ core excitations**

⊗ Λ → **$^{12}{}_{\Lambda}C$ or $^{12}{}_{\Lambda}B$ g.s. (deeply bound)**

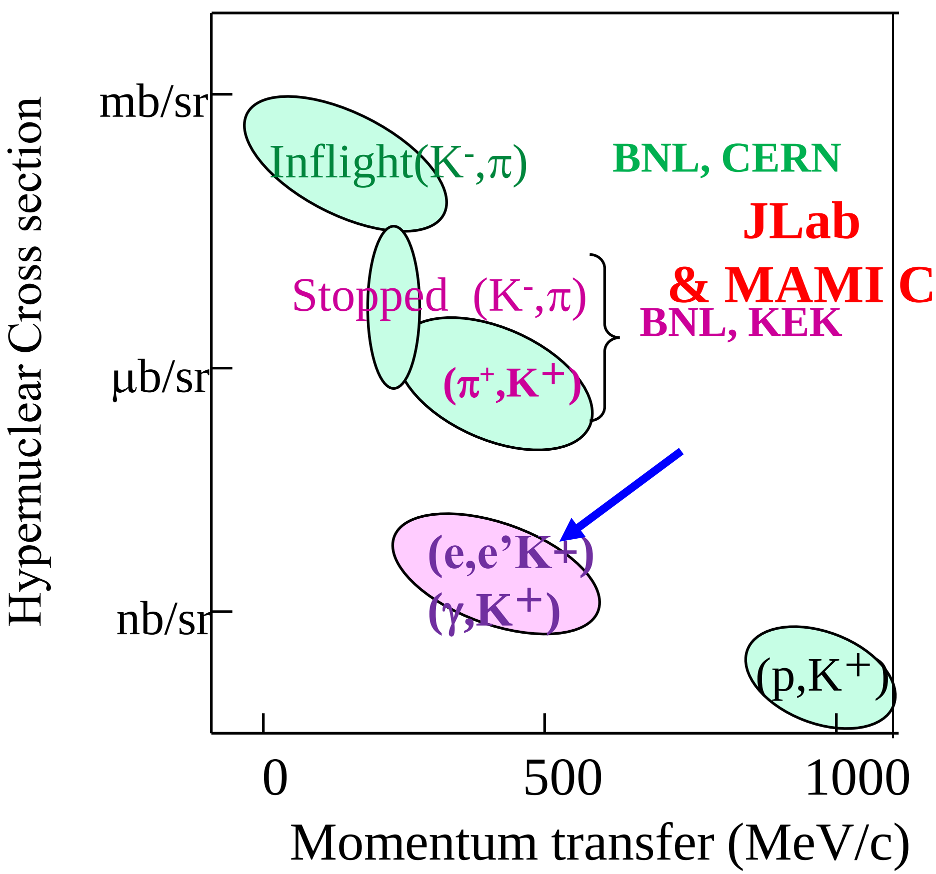


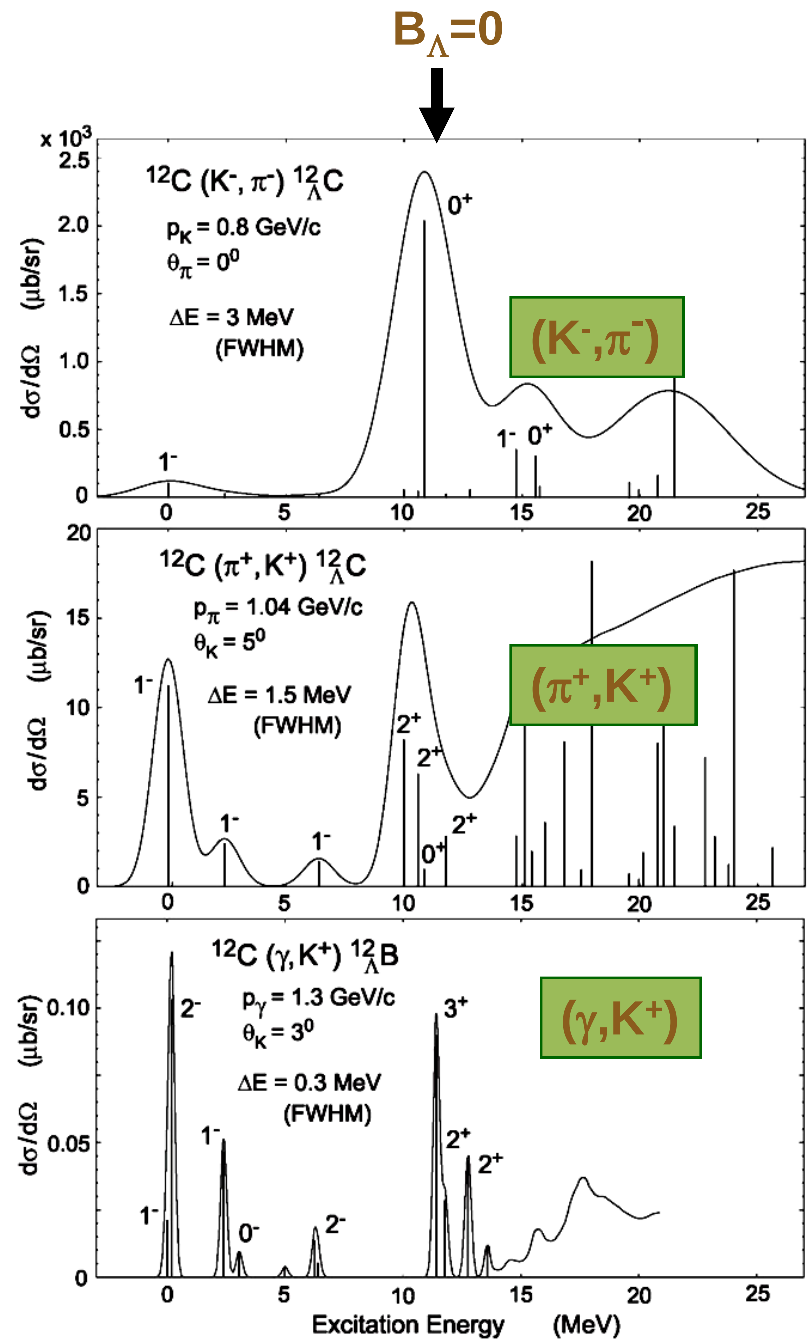
A Λ hyperon in the mean field



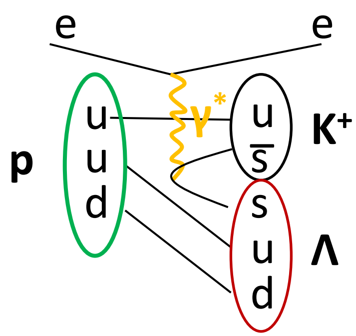
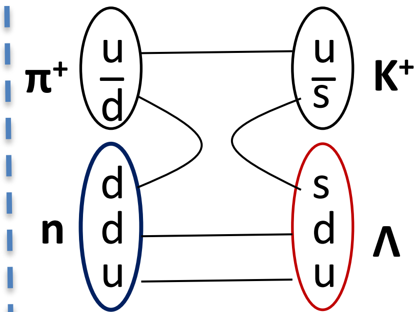
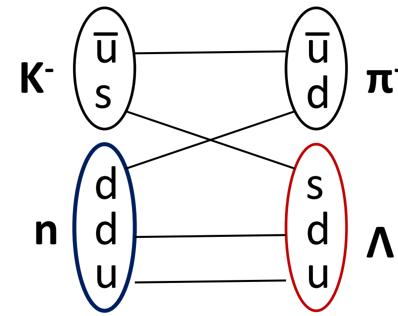
Λ Hypernuclear production

1970s CERN, BNL Counter experiments
with Kaon beam
1980s BNL-AGS, KEK-PS Counter
experiments with K/π
1998 γ-spectroscopy with Hyperball
2000~ (e,e'K+) spectroscopy @ JLab

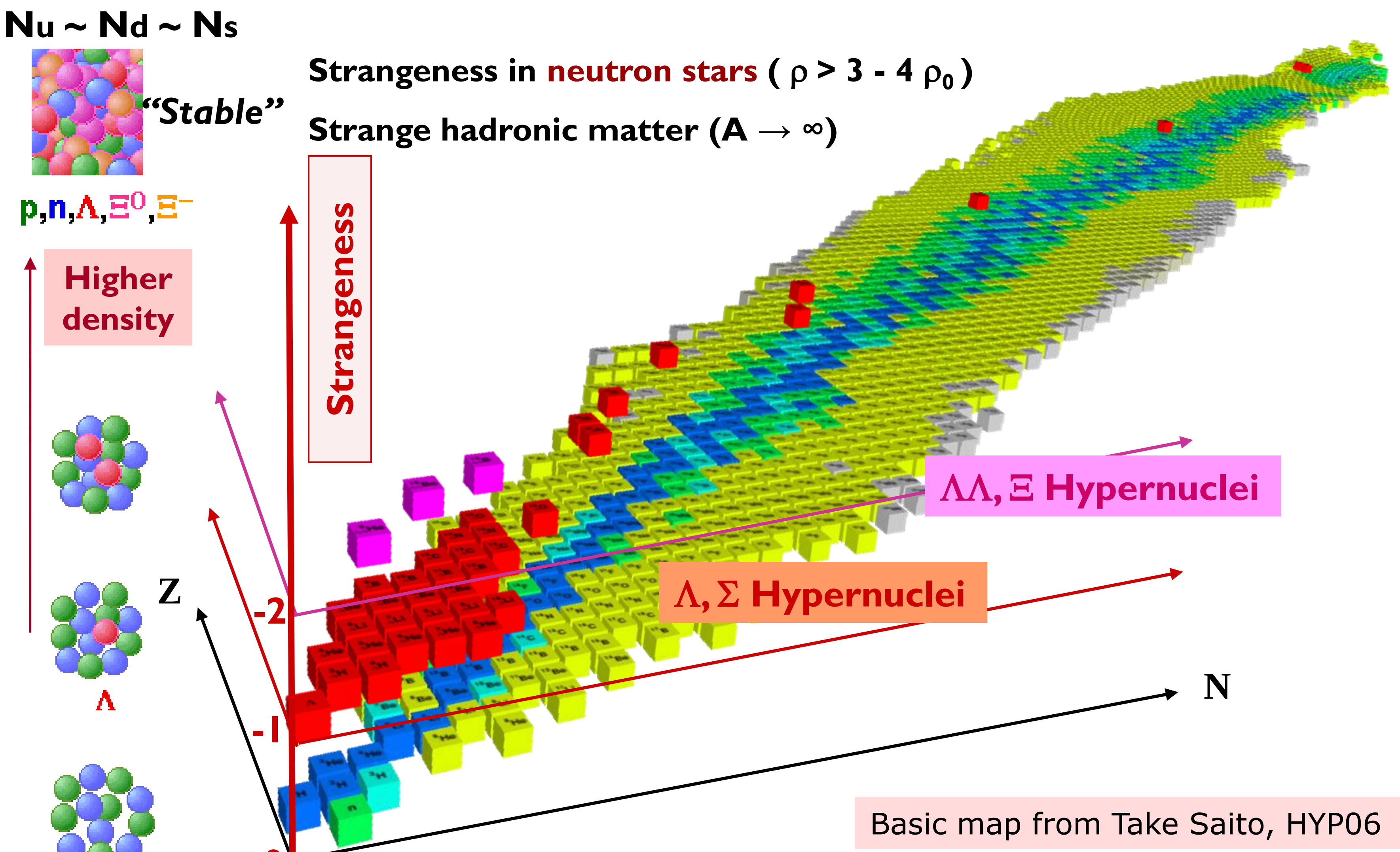




$(e,e'K^+)$ reaction

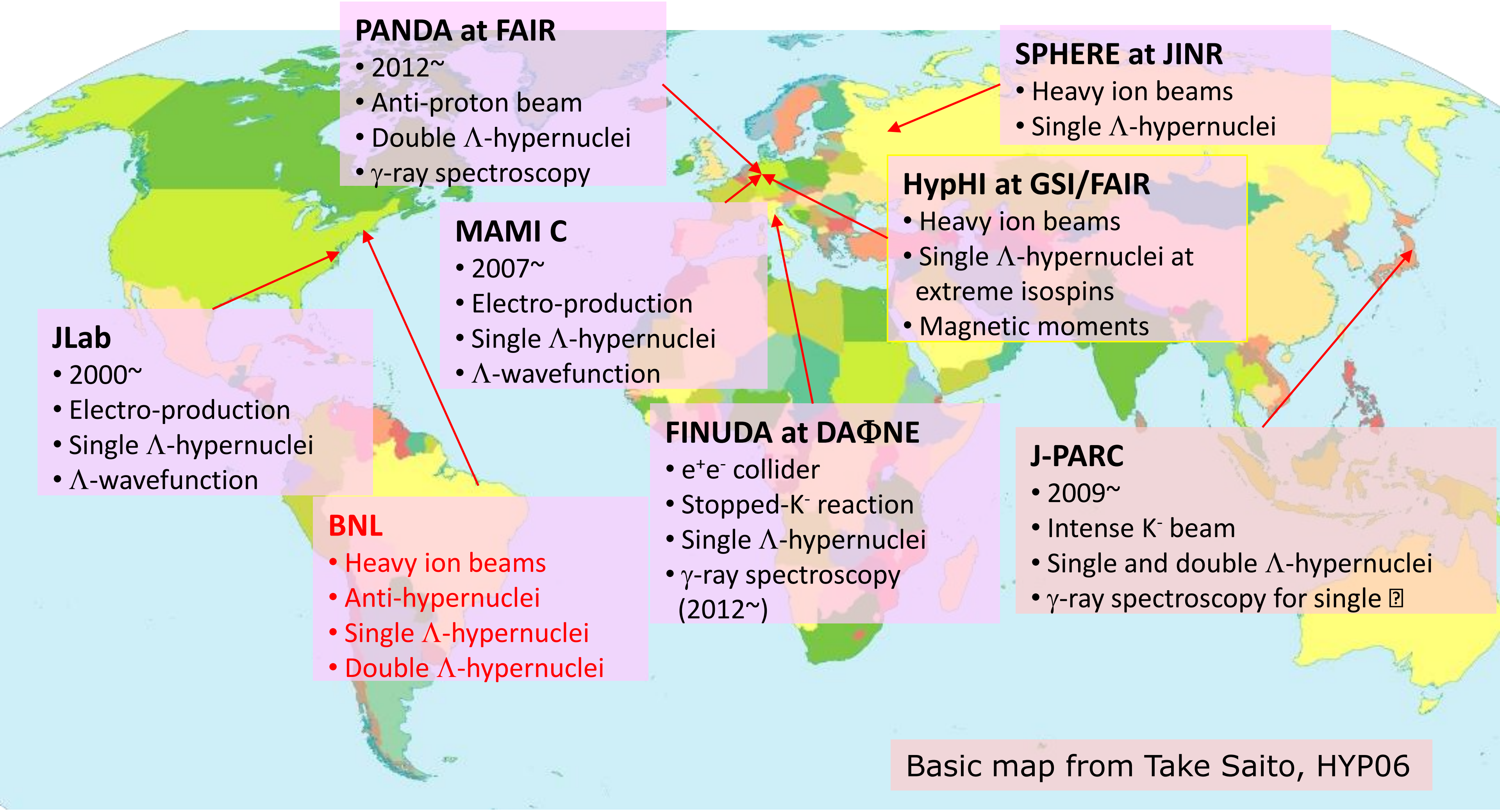
	$(e,e'K^+)$	(π^+, K^+)	(K^-, π^-)
Reaction	$e + p \rightarrow e + K^+ + \Lambda$ 	$\pi^+ + n \rightarrow K^+ + \Lambda$ 	$K^- + n \rightarrow \pi^- + \Lambda$ 
Momentum transfer (p_{beam} = 1.5 [GeV/c])	**~300 [MeV/c]** **Λ can be bounded in deeper orbit**	~300 [MeV/c]	~90 [MeV/c]
Λ's Spin	**flip ≈ non-flip** **Spin dependent structure**	non-flip	non-flip
Λ's from	**proton** **Mirror lambda hypernuclei**	neutron	neutron
Beam	**primary** **High quality , high intensity**	secondary	secondary
Target	**Thin (~100 mg/cm²)** **Isotopically enriched)**	Thick(> a few [g/cm²])	Thick(> a few [g/cm²])
Energy resolution (FWHM)	**≤ 500 [keV]** **Fine structure**	**1 – 3 [MeV]**	**1 – 3 [MeV]**

World of matter made of u, d, s quarks



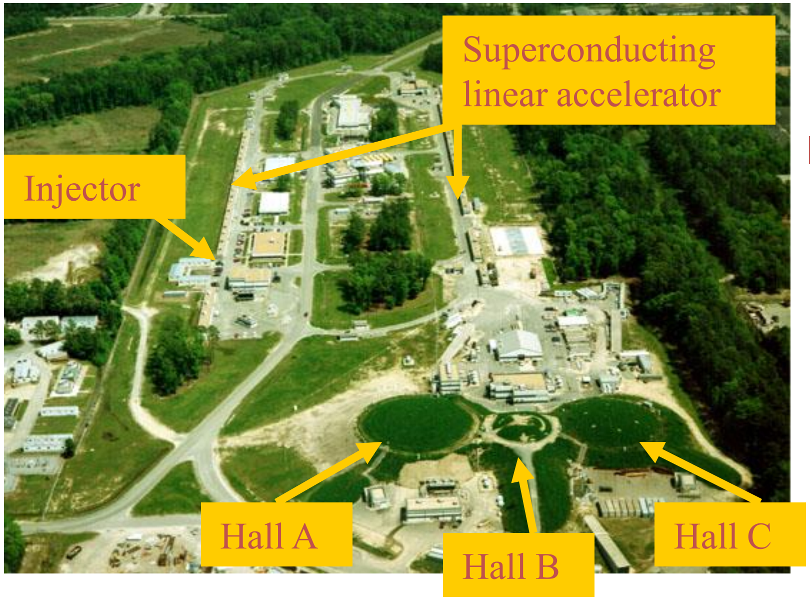
3-dimensional nuclear chart

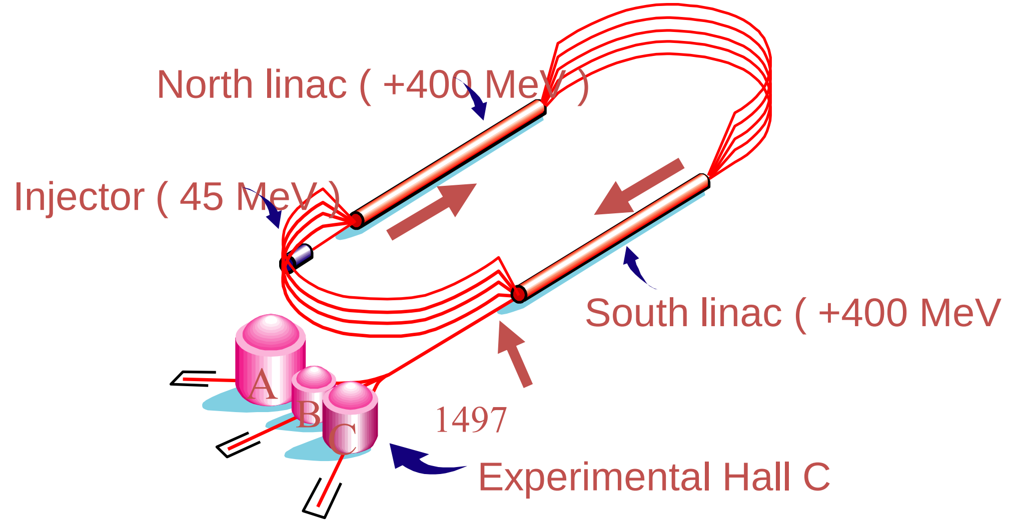
World Hypernucleus Facilities – 2009



Experimental setup

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}

Technical Advantages

100% duty factor (CW beam)

High intensity - Overcome small cross sections to produce hypernuclei in wide mass range

High precision - Highest possible mass spectroscopic precision (resolution & binding energy precision)

Technical Disadvantages

More complicated kinematics – Detect both e' and K^+ at small forward directions

High particle rates – Complicated detector system

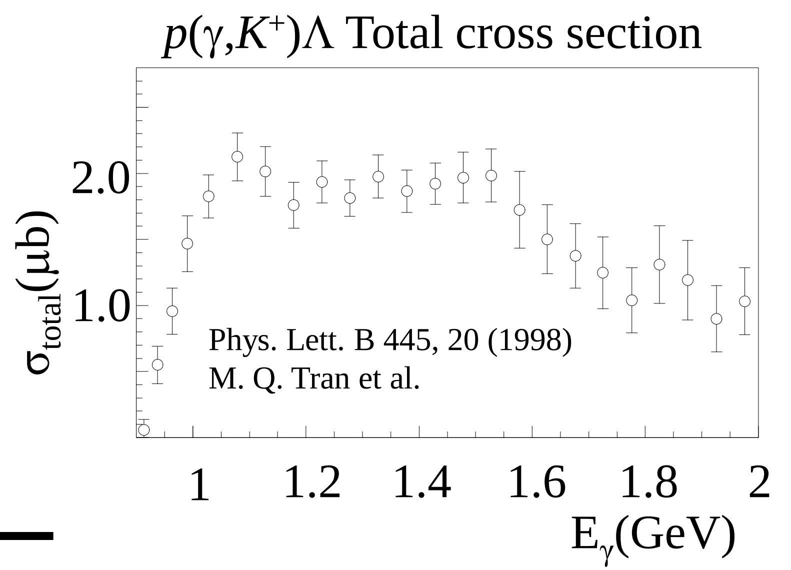
Accidental coincidence background – High electron rates from Bremsstrahlungs and Moller Scattering at small scattering angles

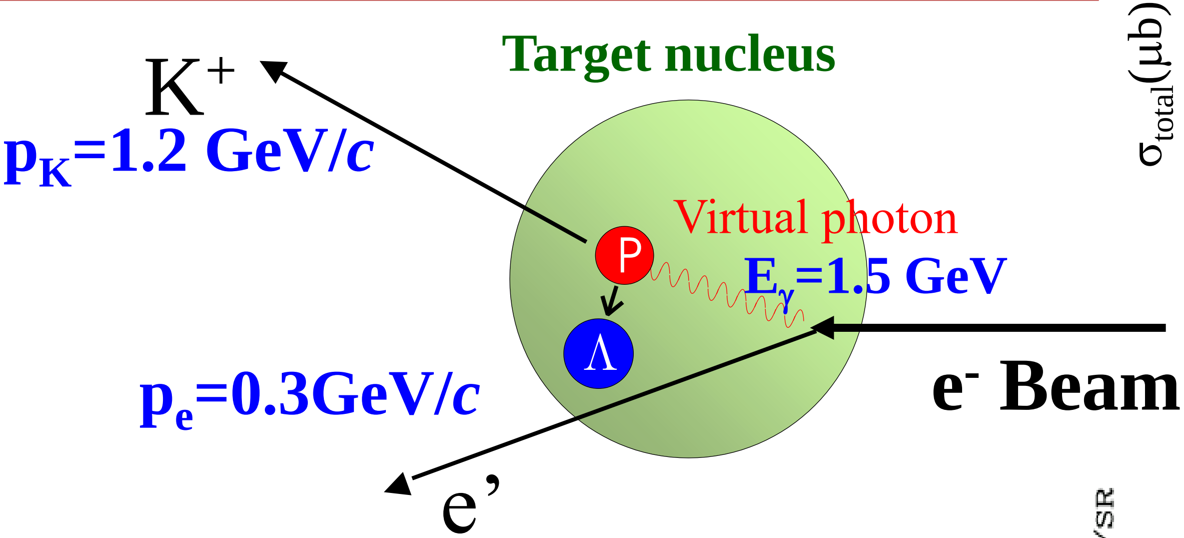
Kinematics of the (e,e'K$^+$) reaction in Hall C

K$^+$ detection

At very forward angle (~ 0 degrees)

Maximum hypernuclear production cross section





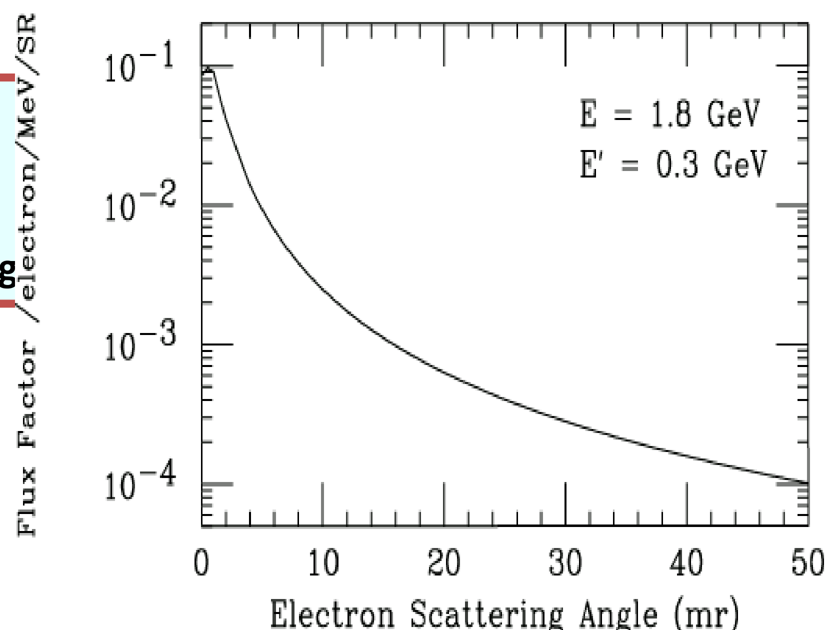
e' detection = tag virtual photon energy and emission angle

At extremely forward angles

Advantage : Large virtual photon flux

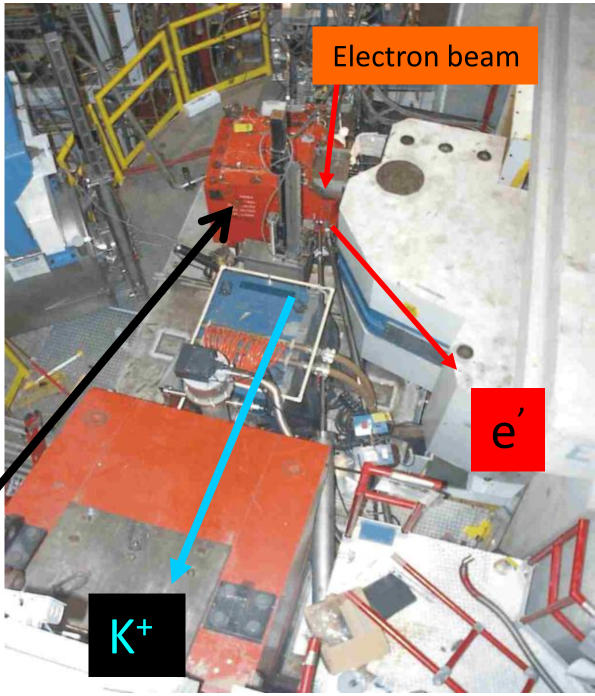
Disadvantage : Huge backgrounds from Bremsstrahlung

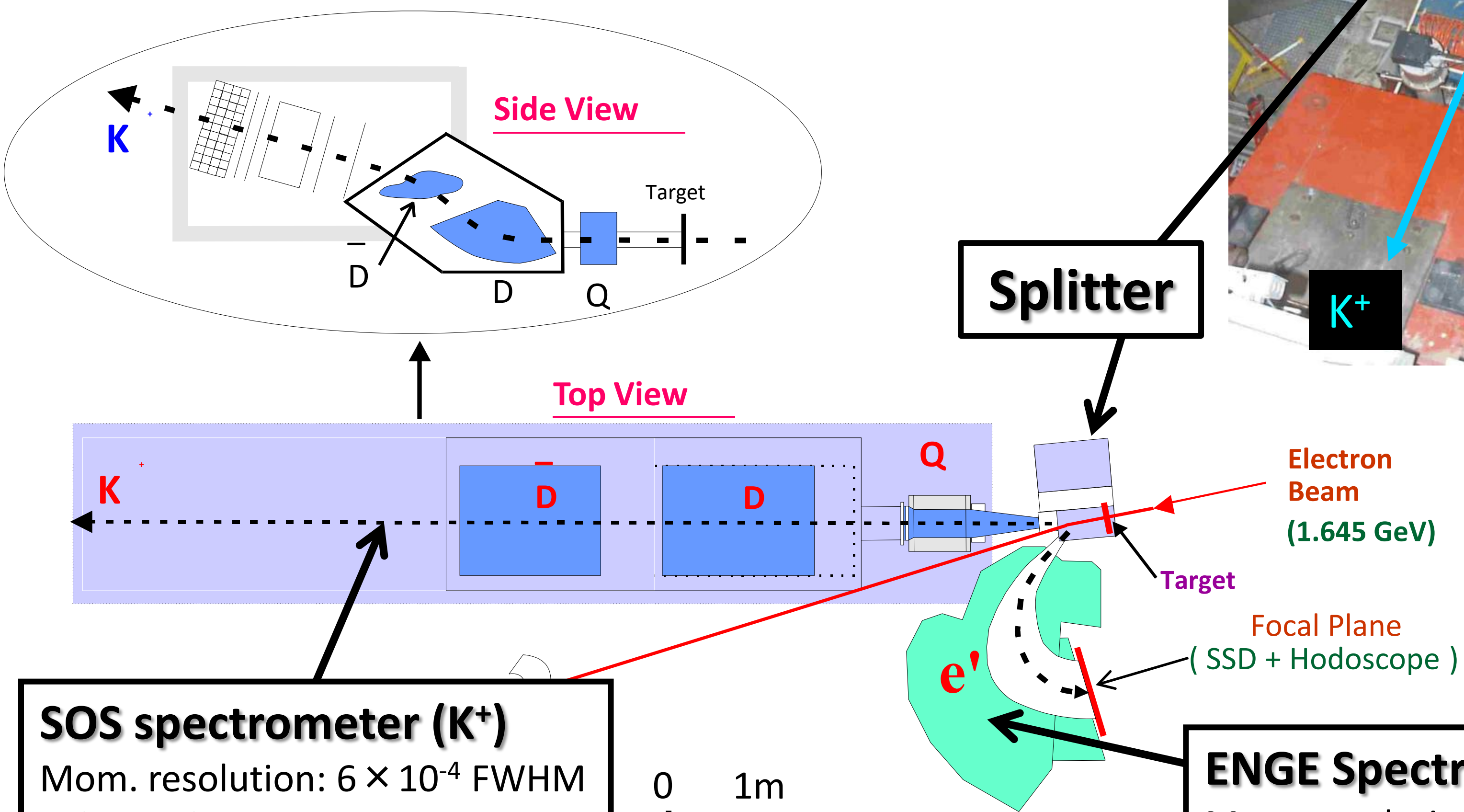
$$\frac{d^5\sigma}{dE'd\Omega'd\Omega_K} = \Gamma \frac{d^2\sigma}{d\Omega_K}$$



Hypernuclear Physics Programs in Hall C

- E89-009 (Phase I, 2000) – Feasibility
- Existing equipment
- Common Splitter – Aims to high yield
- Zero degree tagging on e'





SOS spectrometer (K^+)

Mom. resolution: 6×10^{-4} FWHM

Solid angle acceptance : 5msr

Central angle: 2 degrees

ENGE Spectrometer (e')

Mom. resolution: 5×10^{-4} FWHM

Solid angle acceptance: 1.6msr

The first (e,e'K+) hypernuclear experiment (E89-009, HNSS)

Data taking year 2000

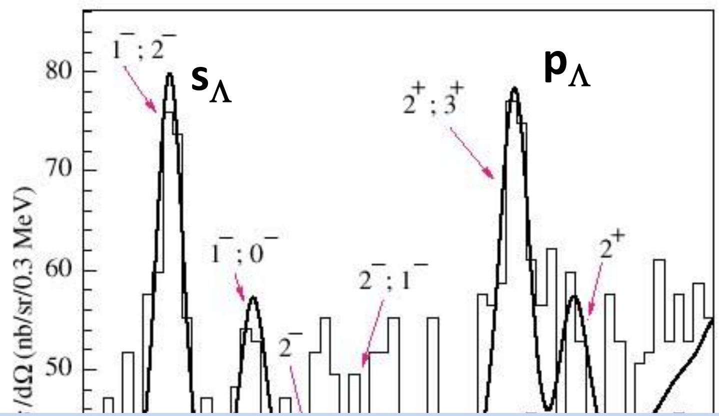
Demonstrated that

the (e,e'K) hypernuclear spectroscopy is possible!

Good energy resolution
<800 keV (FWHM)

Dominant contribution to the resolution: SOS momentum resolution ~600 keV

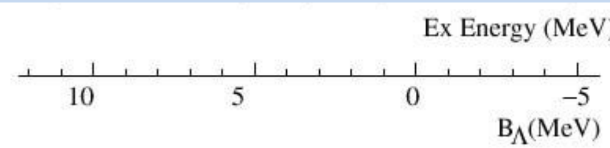
$^{12}C(e,e'K^+)\ ^{12}{}_{\Lambda}B$



First mass spectroscopy on $^{12}{}_{\Lambda}B$ using the (e, e'K+) reaction

T. Miyoshi, et al., Phys. Rev. Lett. Vol.90 , No.23, 232502 (2003)
L. Yuan, et al., Phys. Rev. C, Vol. 73, 044607 (2006)

at that time



PRL 90 (2003) 232502, PRC 73 (2006) 044607

Goals of the 2nd Generation Experiment

Jlab E01-011 (HKS) experiment

High-resolution	3-400 keV (factor of 2 improvement)
High yield rates	> 10 times more yield
Better S/A ratio	> 5 times improvement

Explore hadronic many-body systems with strangeness through the reaction spectroscopy by the $(e,e'K^+)$ reaction

Immediate Physics goals

- $^{12}C(e,eK^+)^{12}{}_{\Lambda}B$
  - demonstrate the mass resolution & hypernuclear yield.
  - core excited states and splitting of the p_{Λ}-state of $^{12}{}_{\Lambda}B$….
  - Mirror symmetric Λ hypernuclei $^{12}{}_{\Lambda}C$ vs. $^{12}{}_{\Lambda}B$
- $^{28}Si(e,e'K^+)^{28}{}_{\Lambda}Al$
  - Prove the $(e,e'K^+)$ spectroscopy is possible for the medium-heavy target possible.
  - precision $^{28}{}_{\Lambda}Al$ hypernuclear structure and *ls* splitting of p-state….

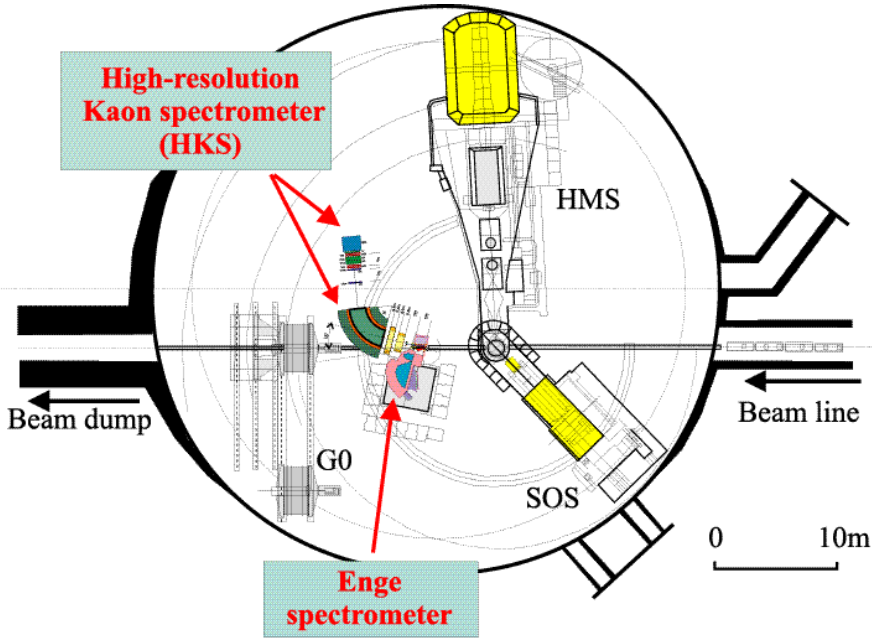
How to improve the E89-009 experiment ?

- Energy resolution
  - The kaon arm limited hypernuclear mass resolution
- Hypernuclear yield rates
  - High accidental background rate due to Brems electrons
  - Solid angle of the kaon arm (SOS) limited detection efficiency

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

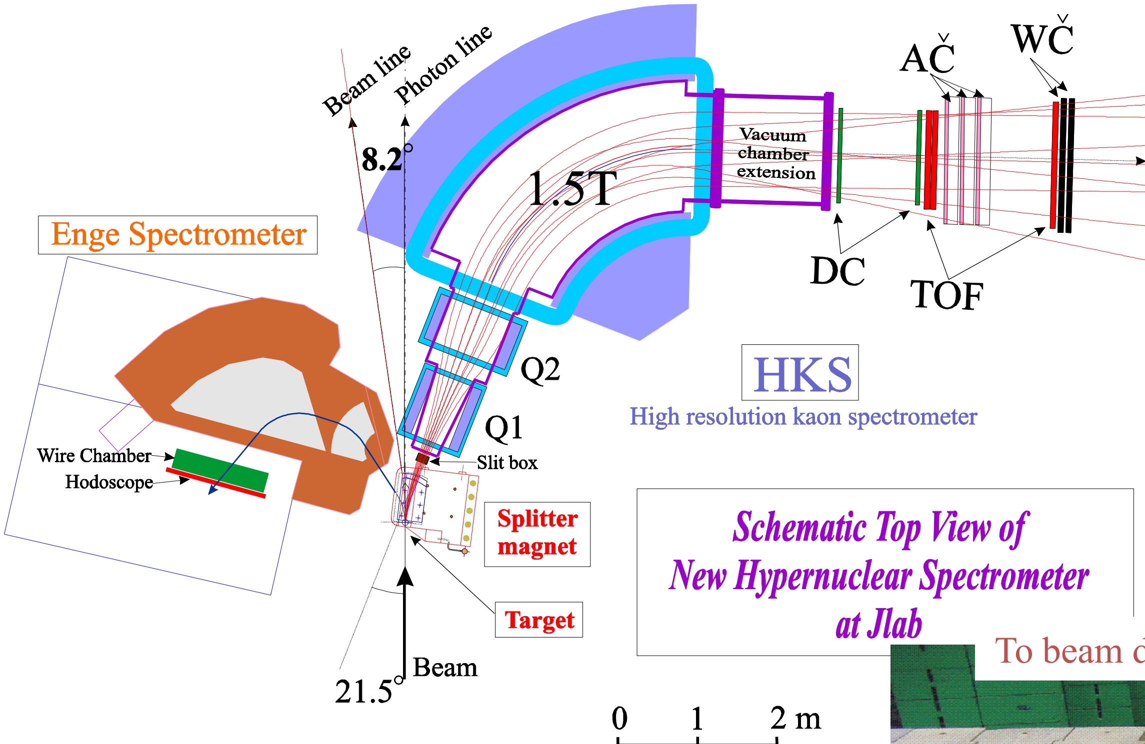
(2) New experimental configuration "Tilt method"

Key Technical Approaches of E01-011



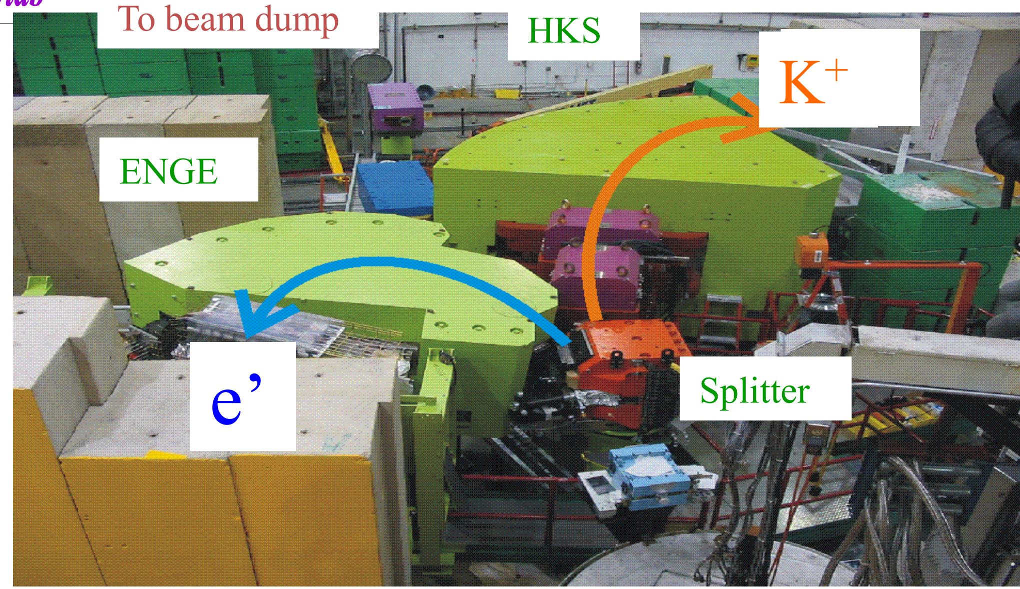
- **Electron arm**
  - Tilt method for the electron arm
    - Suppress Brems electrons by 10^4 times
    - Need higher order terms of the transfer matrix
- **Kaon arm (Replace SOS by HKS)**
  - High Resolution Kaon Spectrometer (HKS)
    - High resolution (2 times) & Large solid angle (3 times)
    - Good particle ID both in the trigger and analysis

Experimental setup



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



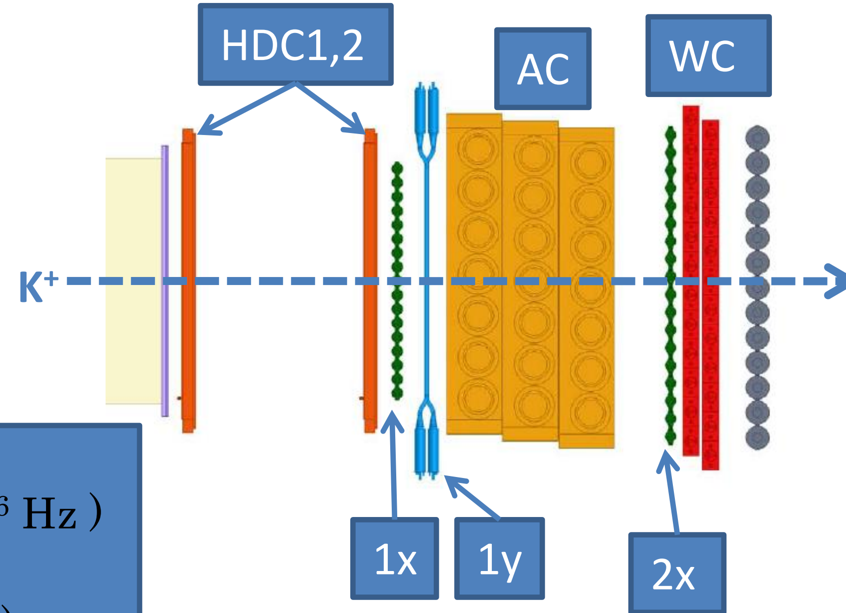
ENGE

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

Detectors

Schematic view of HKS Detectors

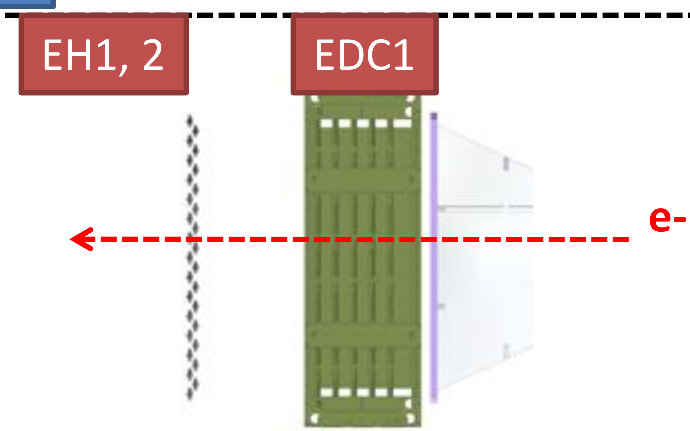
- Drift Chamber … KDC1 + KDC2
- Timing Counter … 1x + 1y + 2x
- Pion rejection … AC
- Proton rejection … WC, LC



- HKS (Kaon trigger) --- 1.2 x 10^4 Hz
  1X x 1Y x 2X x AC x WC （1X x 2X ：1.1 x 10^6 Hz）
  Rejection rate by AC / WC is 1/100
- Enge (e' trigger) --- 1.2 x 10^6 Hz (← 1 x 10^8 Hz)
  Hodoscope 1layer x 2layer
- Coincidence of K and e' --- ~500 Hz
  DAQ dead time ~5%

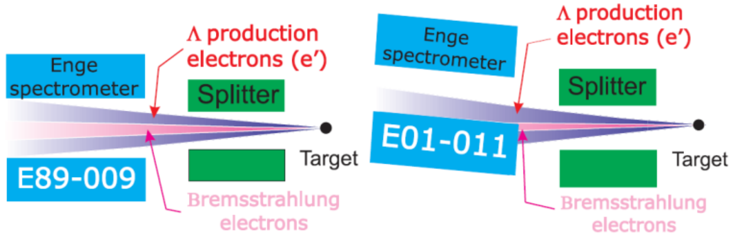
Schematic view of ENGE Detectors

- Drift Chamber … EDC1
- Timing Counter … 1x, 2x, 1y

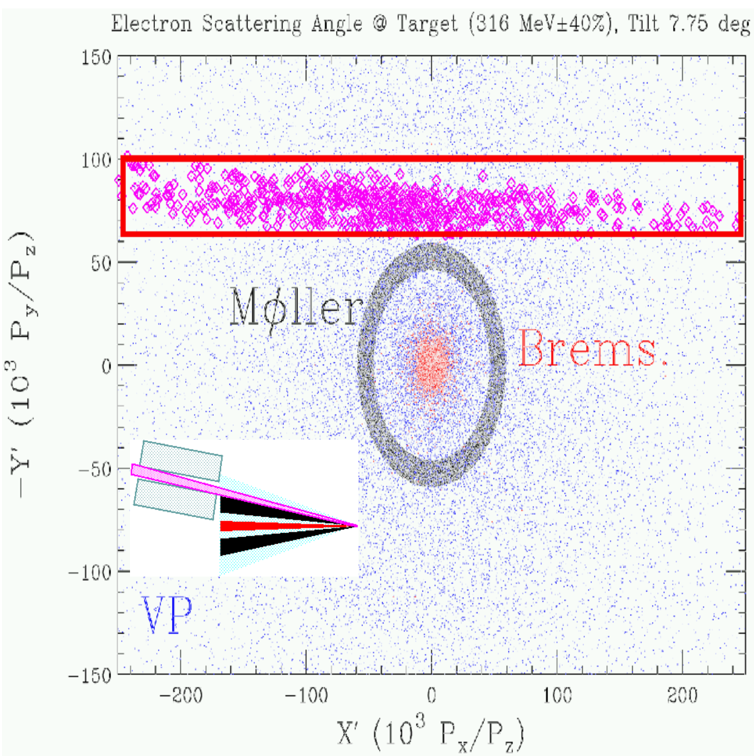


Tilt Method

Tilt e-arm by 7.75 deg. vertically
with respect to splitter & K-arm



(a) Enge configuration used in E89-009. (b) Enge configuration used in E01-001.

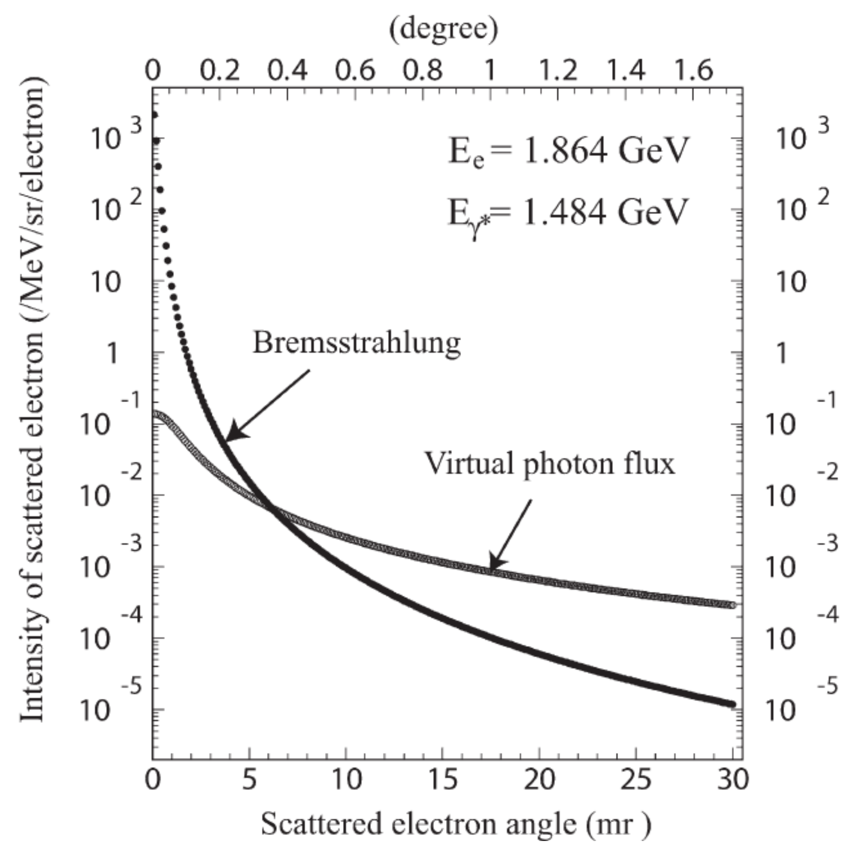


Scattered electrons (0.2 to 0.4 GeV/c)

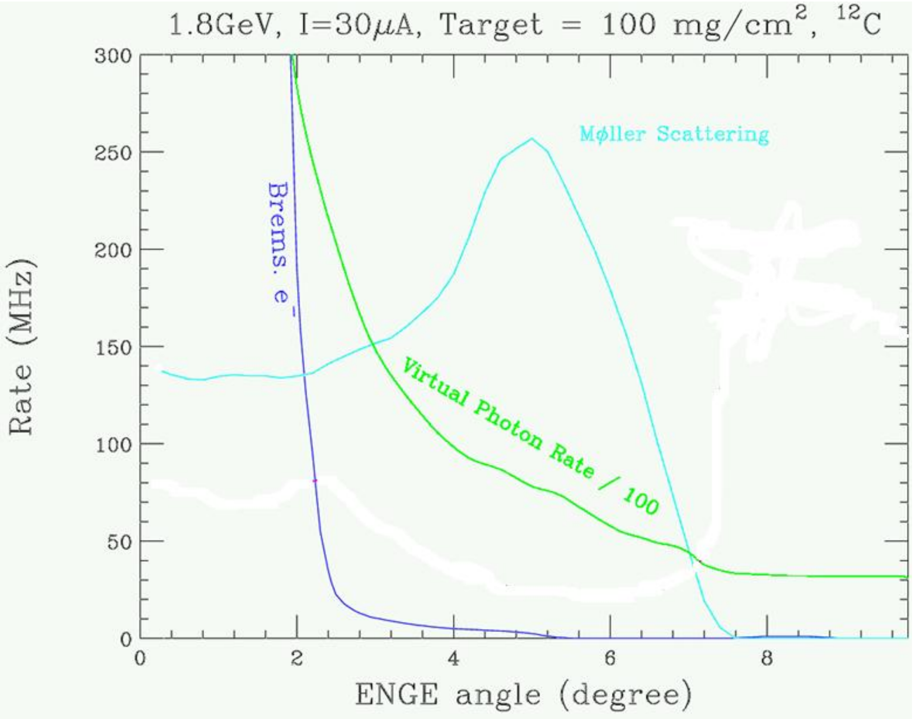
(1)from bremsstrahlung

(2)associate with virtual photons

(3) from Møller scattering



E01-011 setup in JLab Hall C



Tilt e-arm by 7.75 deg. vertically with respect to splitter & K-arm

Singles rate of e-arm

200 MHz → 3 MHz

with

5 times Target thickness

50 times Beam intensity

Compared to E89-009

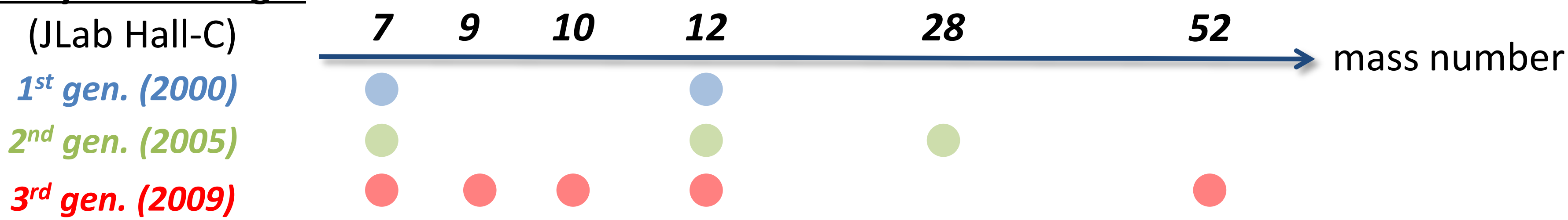
Much better Yield and S/A

Medium-heavy hypernuclei can be studied

Goals of the third Generation Experiment

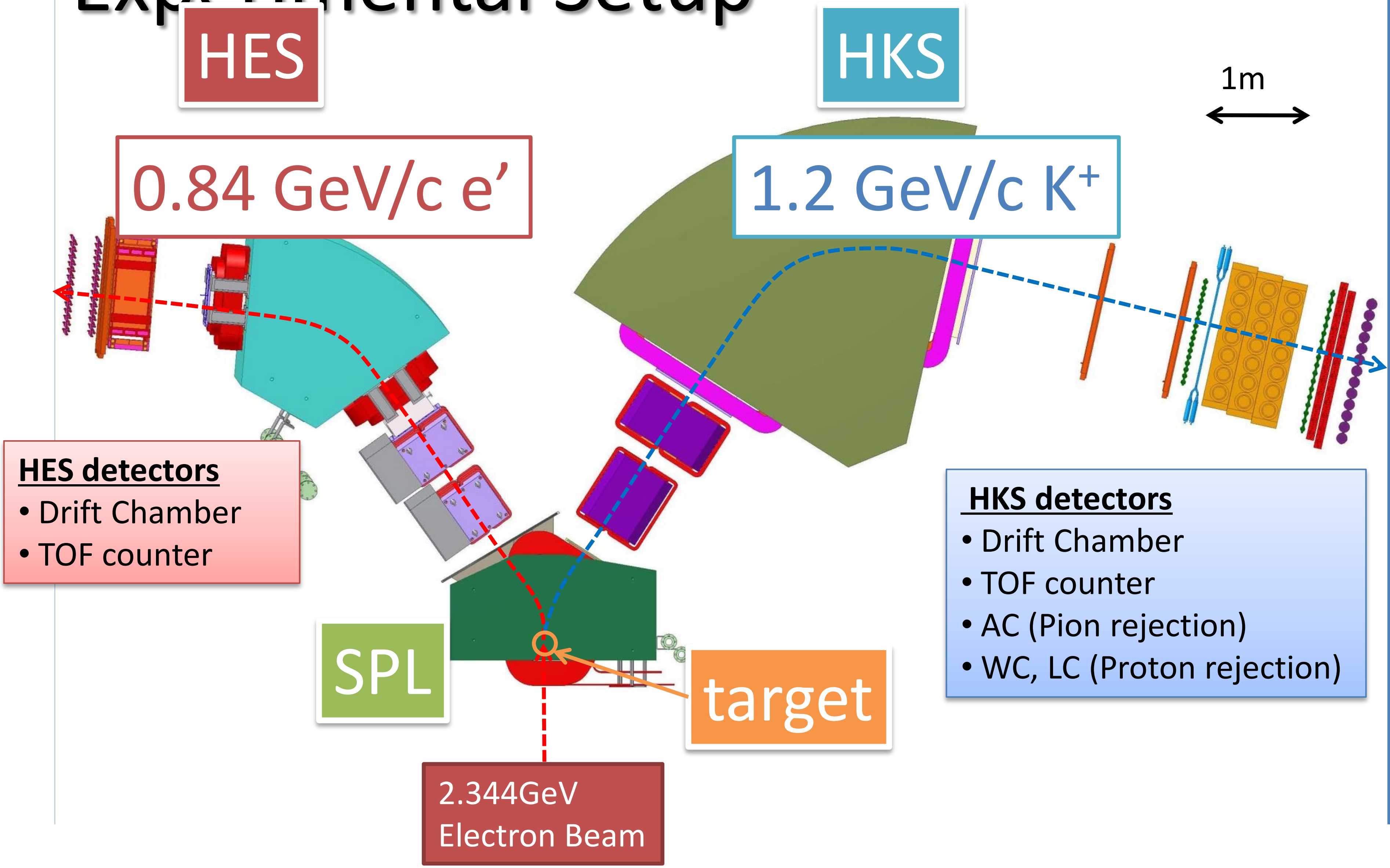
Precise Λ Hypernuclear Spectroscopy in the wide mass region

history of our target



- $^{7}Li(e,e'K^{+})^{7}{}_{\Lambda}He$, $^{10}B(e,e'K^{+})^{10}{}_{\Lambda}Be$, $^{12}C(e,e'K^{+})^{12}{}_{\Lambda}B$
  - Charge Symmetry Breaking (CSB) in ΛN interaction
  - ΛN-ΣN coupling effect
- $^{52}Cr(e,e'K^{+})^{52}{}_{\Lambda}V$
  - A dependence of Λ single particle energies
  - Measurement of fine structure (core configuration mixing, ls splitting…)
- Elementary process : $p(e,e'K^{+})\Lambda/\Sigma^{0}$ or $p(\gamma^{*},K^{+})\Lambda/\Sigma^{0}$
  - Cross section (Q^2 dependency, kaon angle dependency, etc …)

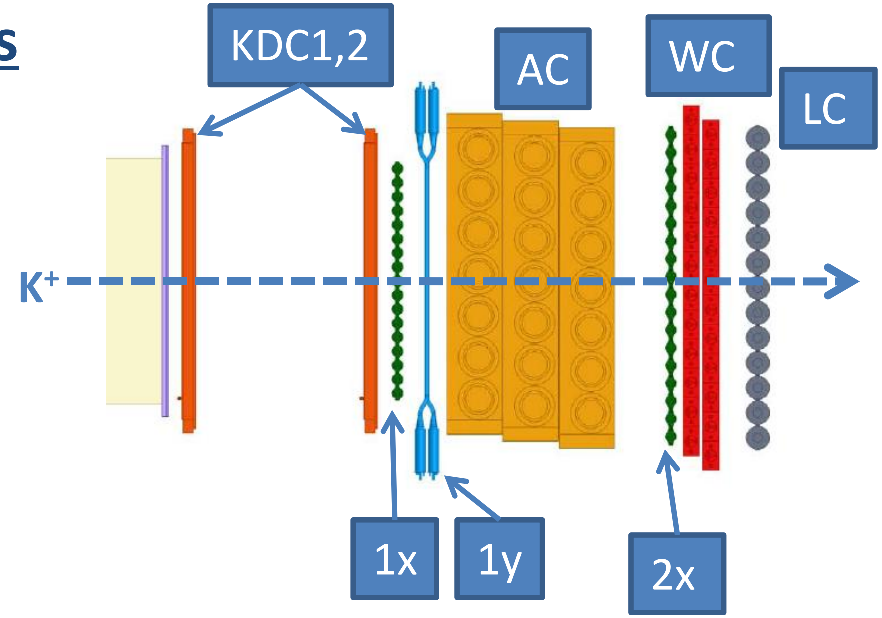
Experimental Setup



Detectors

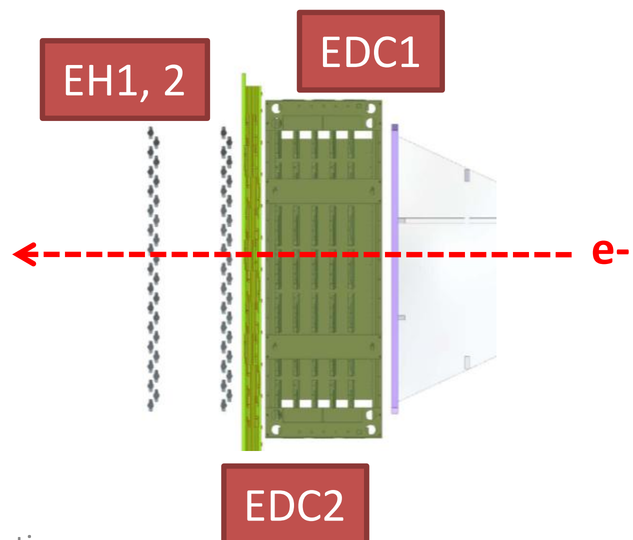
Schematic view of HKS Detectors

- Drift Chamber … KDC1 + KDC2
- Timing Counter … 1x + 1y + 2x
- Pion rejection … AC
- Proton rejection … WC, LC

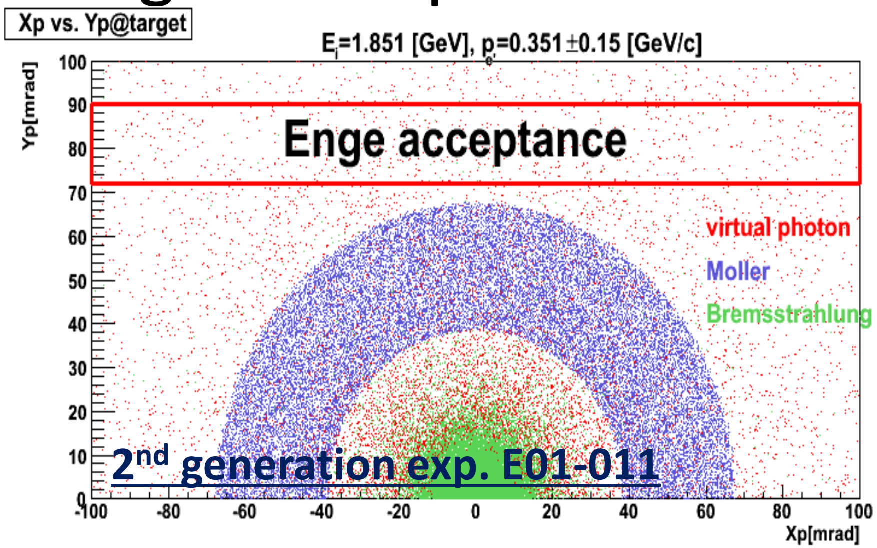


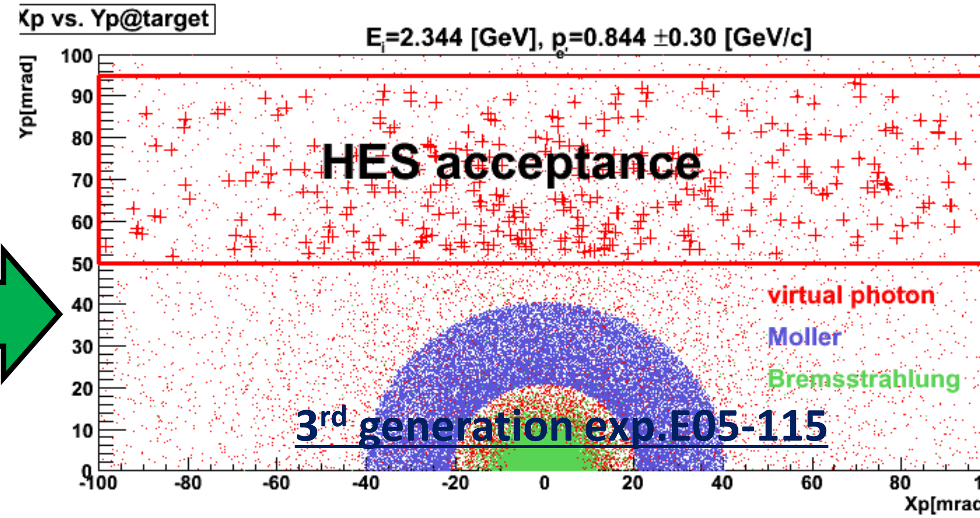
Schematic view of HES Detectors

- Drift Chamber … EDC1 + EDC2
- Timing Counter … 1x + 1y + 2x



Angler acceptance





incident beam energy
1.851 ➔2.344 [GeV]

background gather to forward
➔accept more forward angle

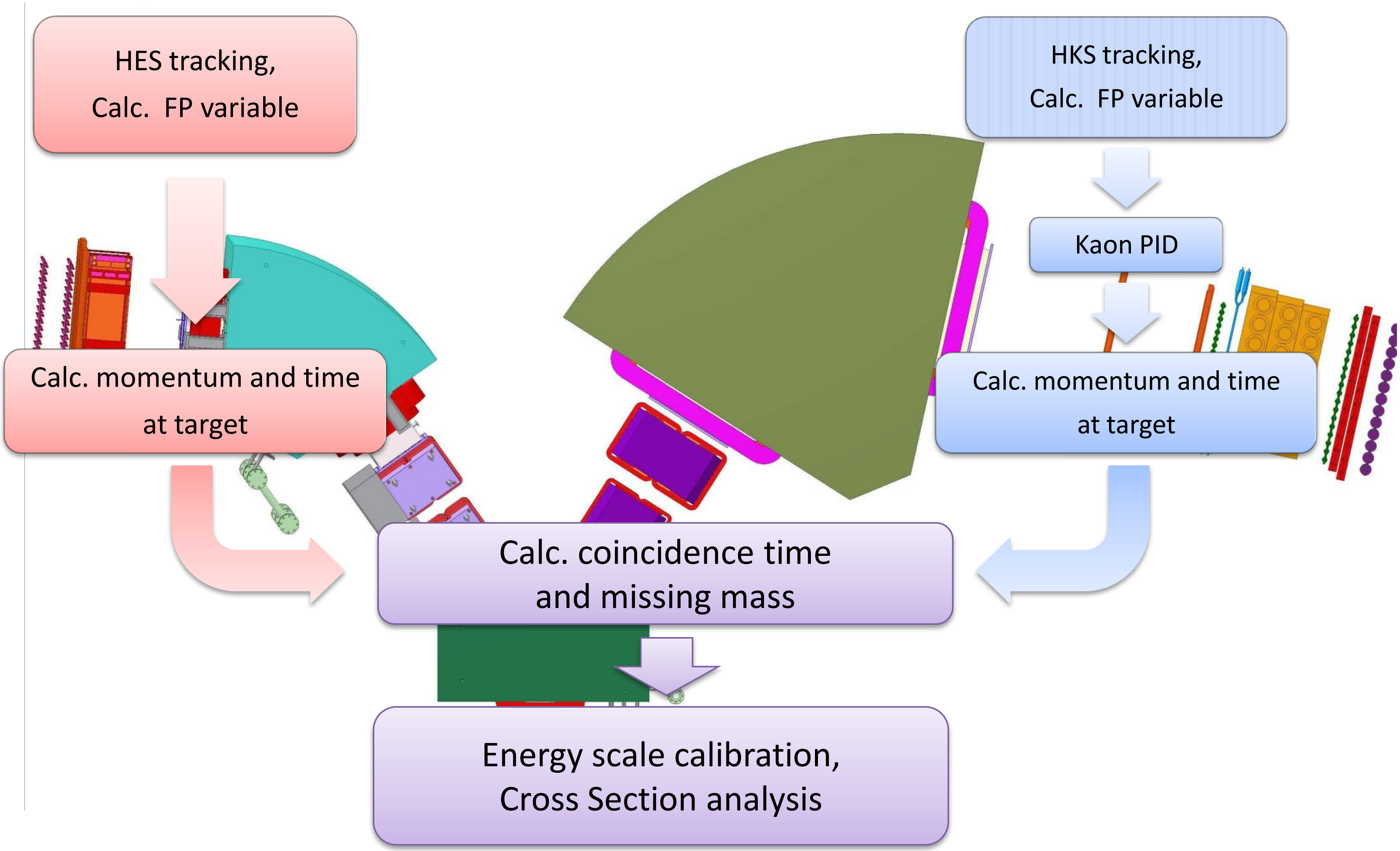
✚

HES has large angle acceptance

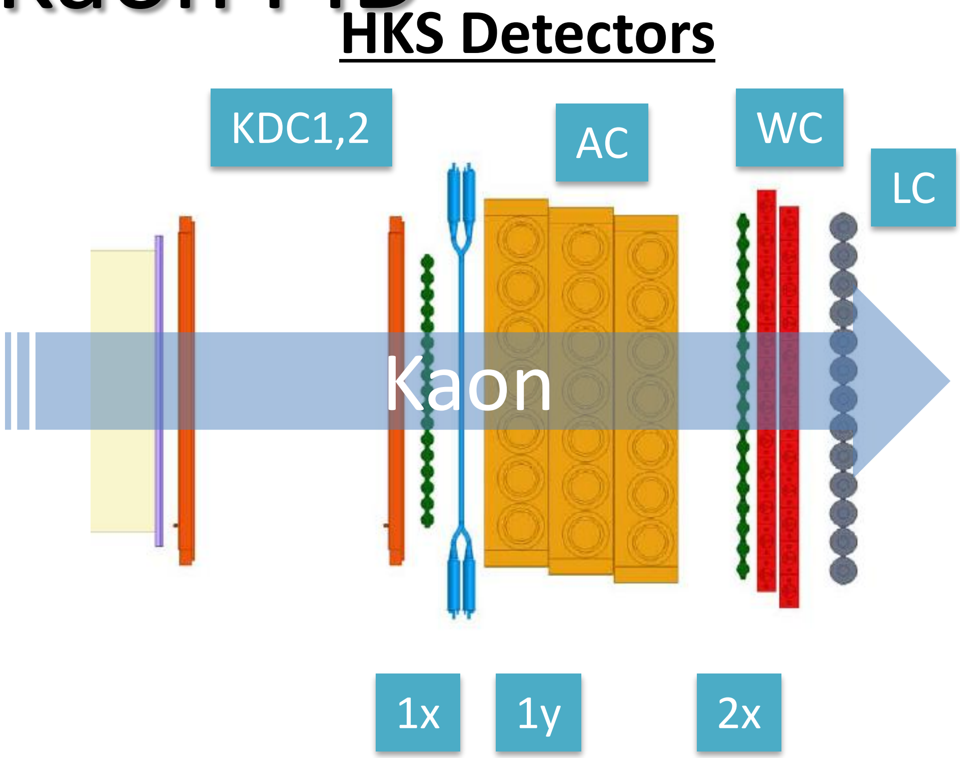
	HES	HKS
Configuration	Q-Q-D（50deg）	Q-Q-D（70deg）
e'/K$^+$ Central Momentum	0.84 GeV/c	1.2 GeV/c
e'/K$^+$ Momentum Acceptance	±0.15 GeV/c	±0.15 GeV/c
e'/K$^+$ Solid Angle	~7msr	~8.5msr
Mom. Resolution (FWHM) [MeV/c]	2.0×10^{-4}	2.0×10^{-4}
Ang. Resolution (FWHM) [mrad]	3	2

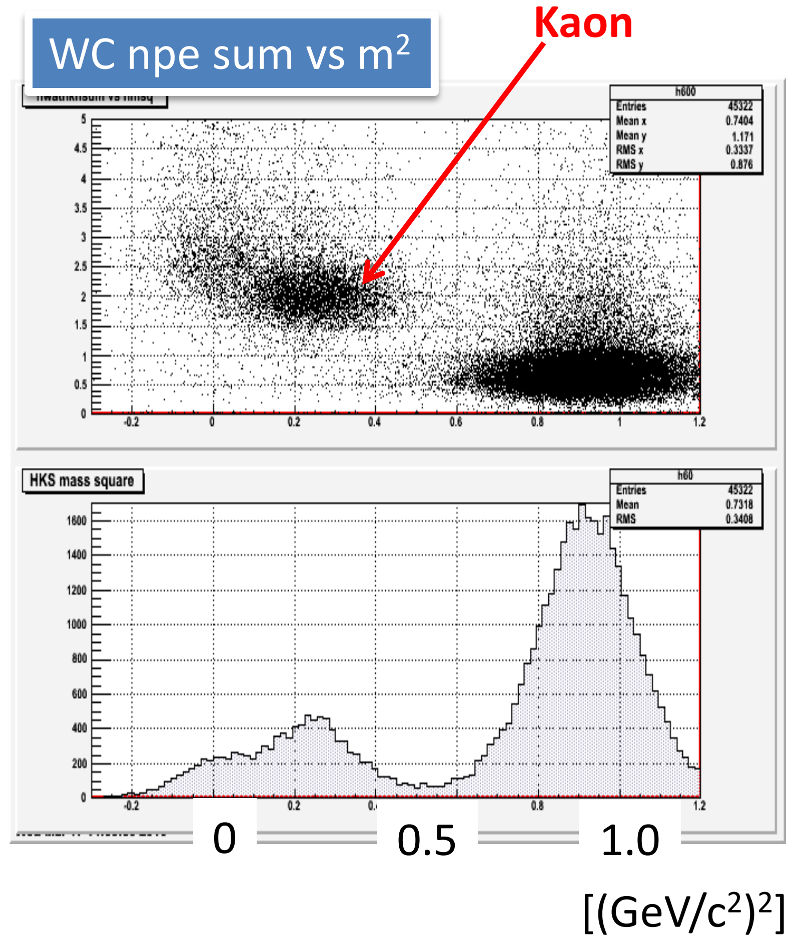
Analysis

Analysis Procedure



Kaon PID



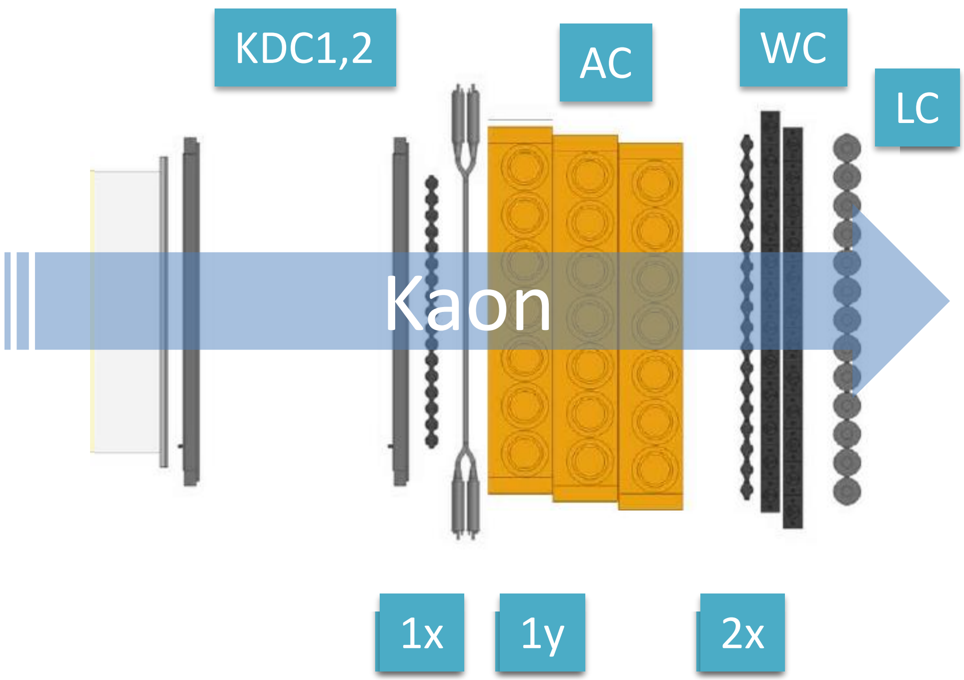


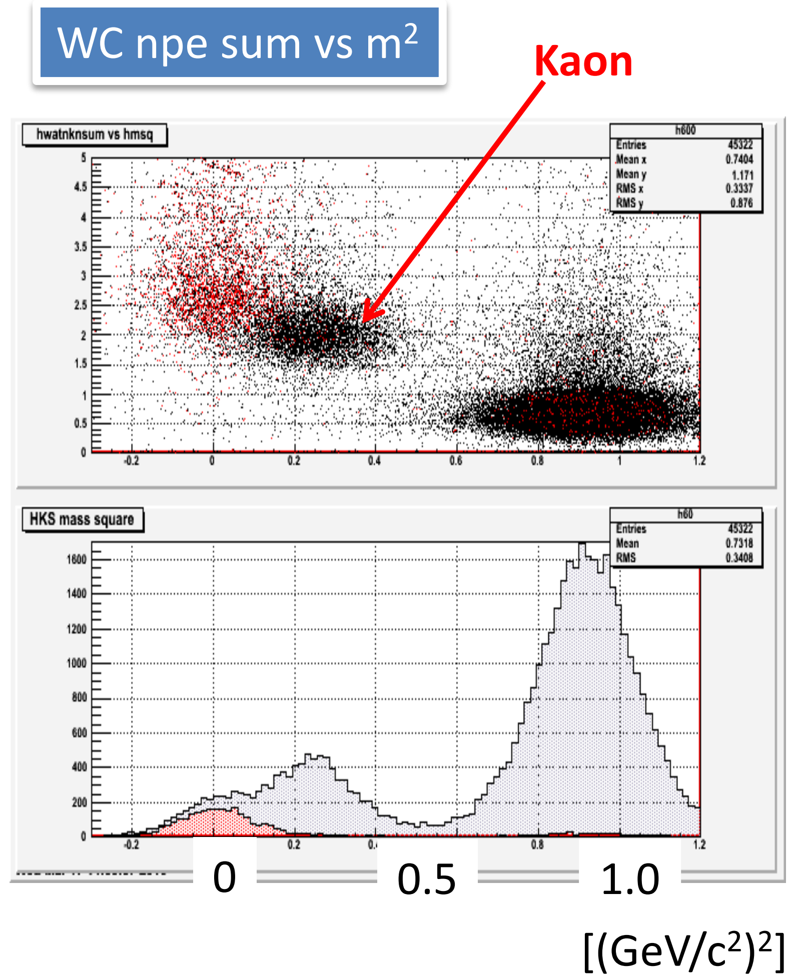
Kaon Cut

1. Reject $\pi^+/e^+/e^-$ using AC npe
2. Reject p using WC npe
3. Select clean K^+ using m^2

Kaon PID

HKS Detectors





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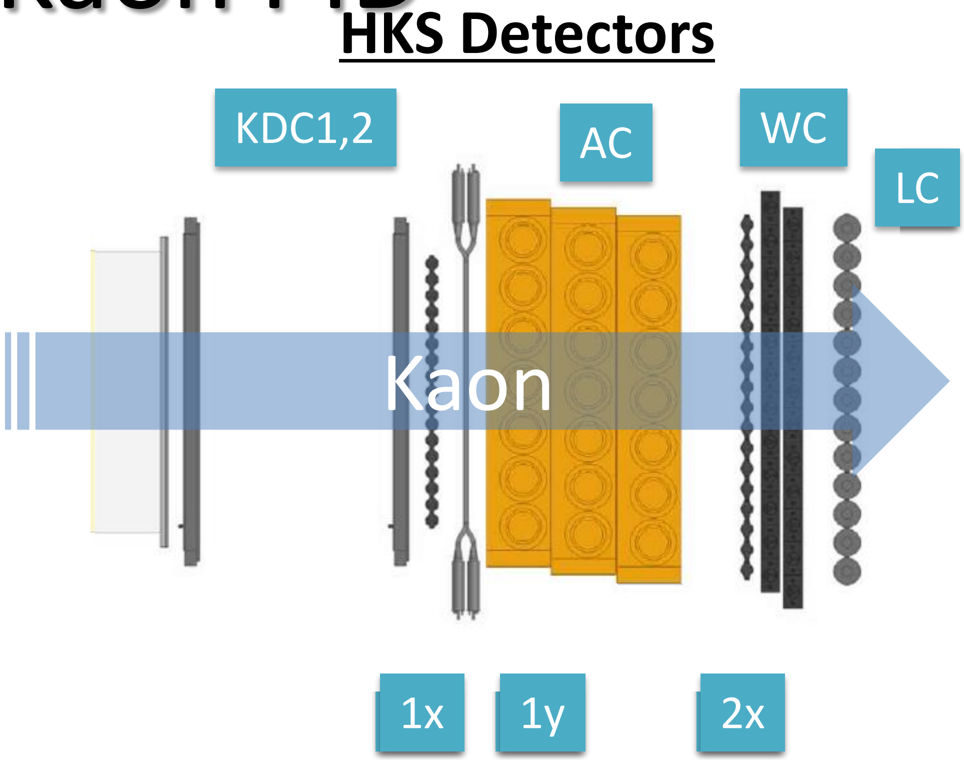

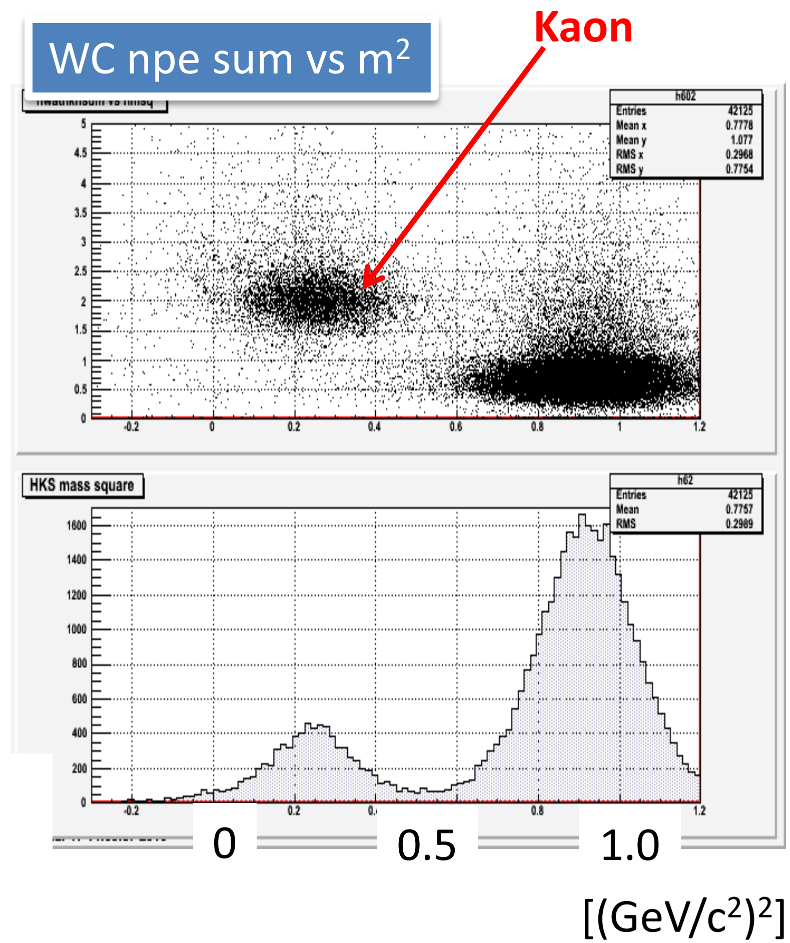

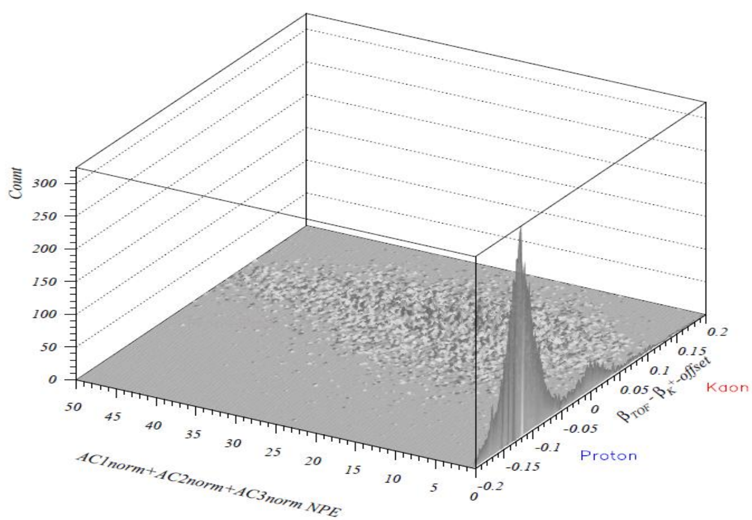

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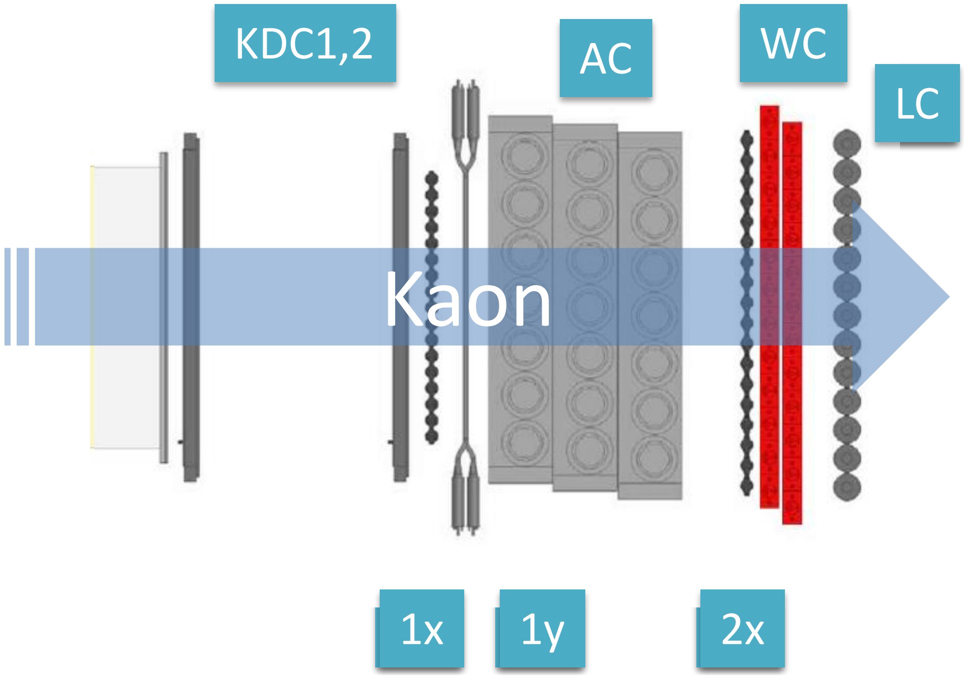

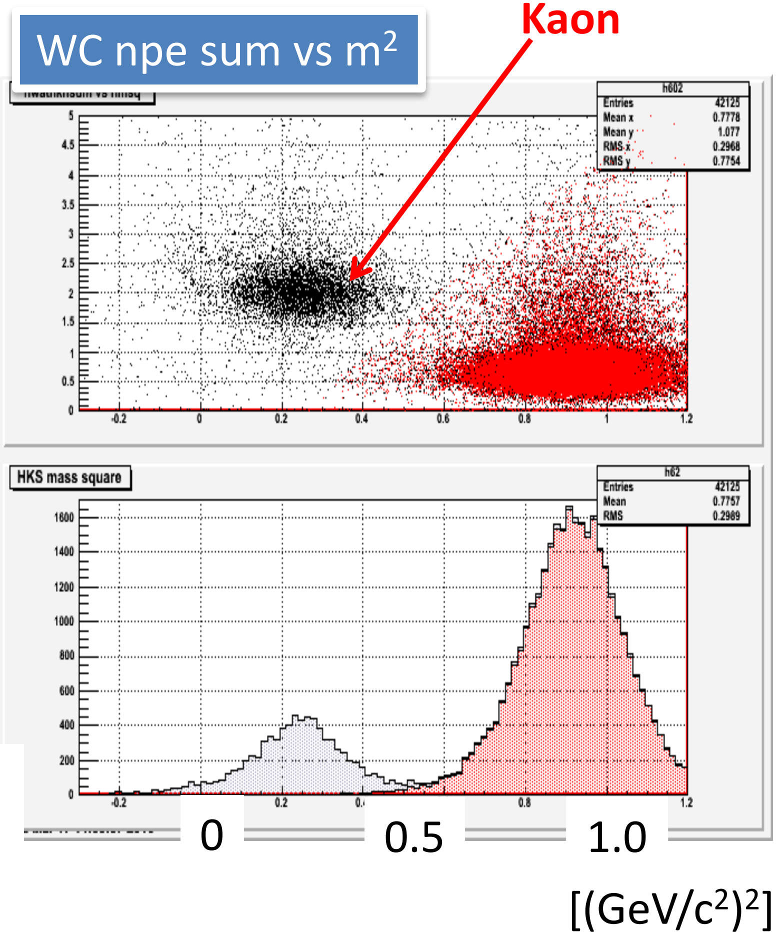

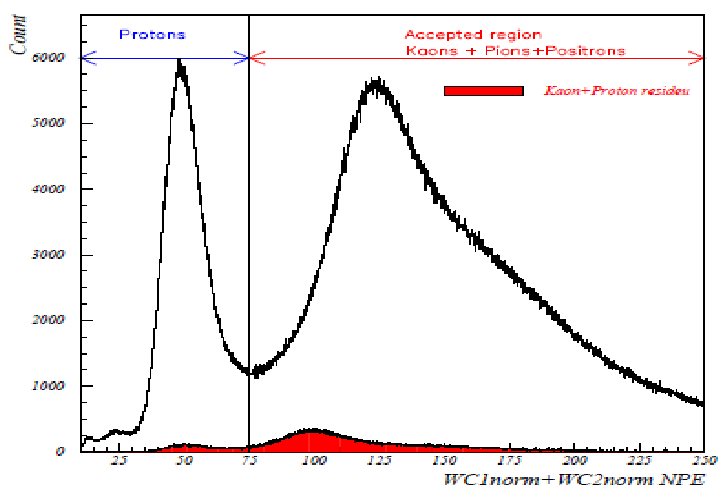

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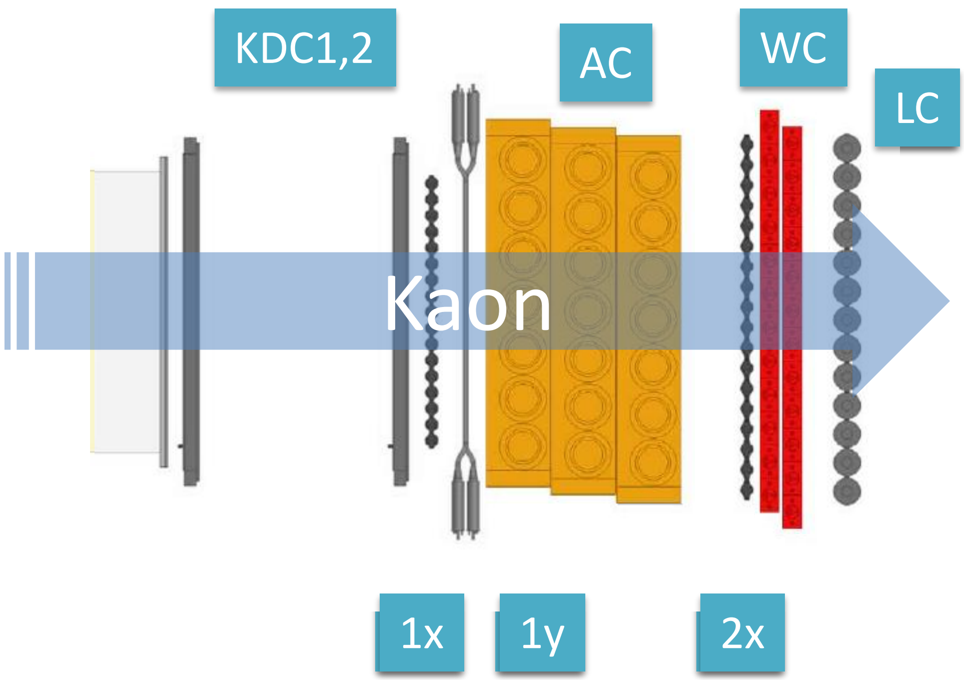
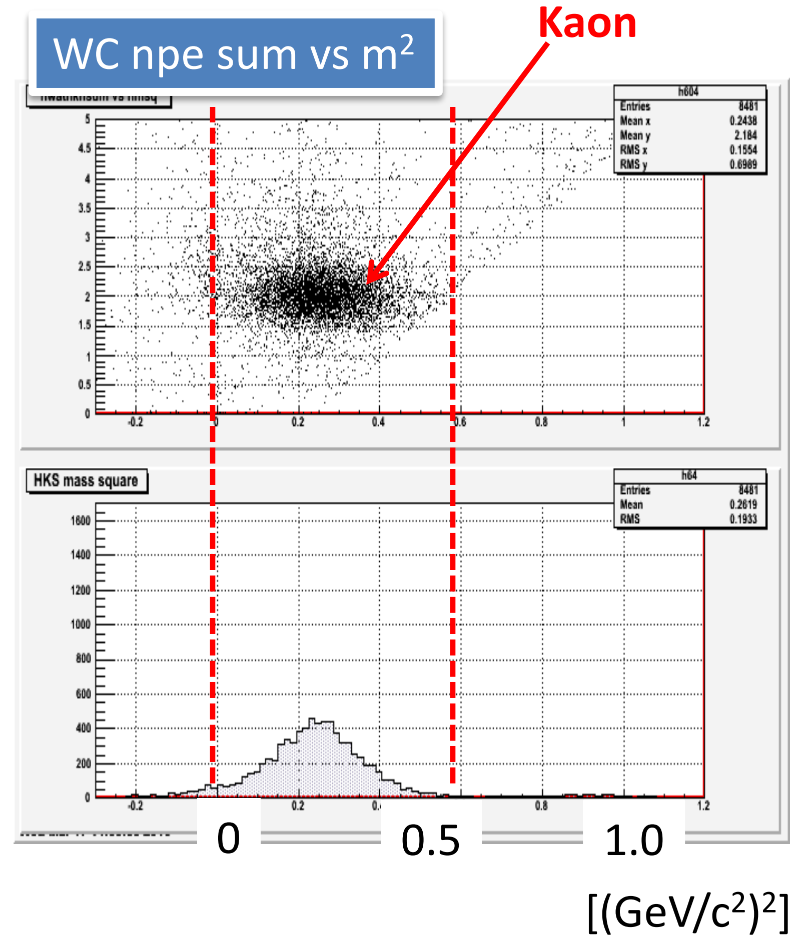
Kaon PID

HKS Detectors





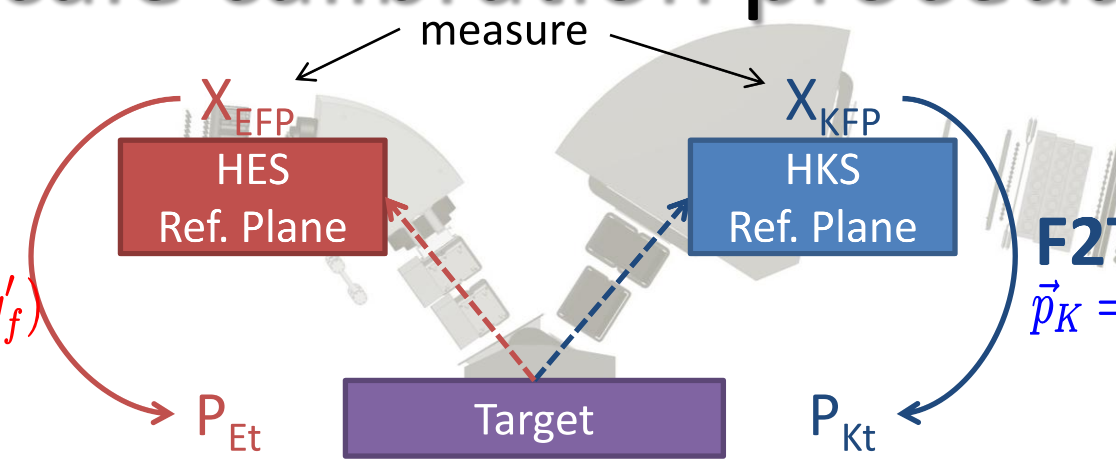
Kaon Cut

1. Reject $\pi^+/e^+/e^-$ using AC npe
2. Reject p using WC npe
3. Select clean K^+ using m^2

Energy scale calibration procedure

F2T function

$\vec{p}_E = f_E(x_f, x'_f, y_f, y'_f)$



F2T function

$\vec{p}_K = f_K(x_f, x'_f, y_f, y'_f)$

Assumption : point source at target

$$f = \sum_{n=0}^{4} \sum_{a_i+b_i+c_i+d_i=n} \alpha_i \cdot (x_f)^{a_i} \cdot (x'_f)^{b_i} \cdot (y_f)^{c_i} \cdot (y'_f)^{d_i}$$

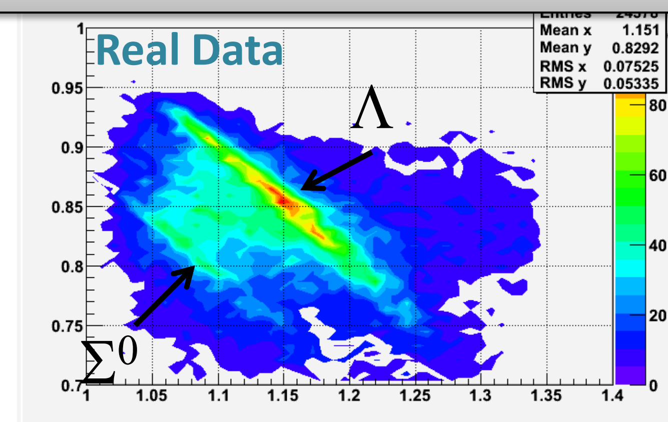
→ Real Data

Calculate from G4, TOSCA field map

→ ***Need to be optimized***

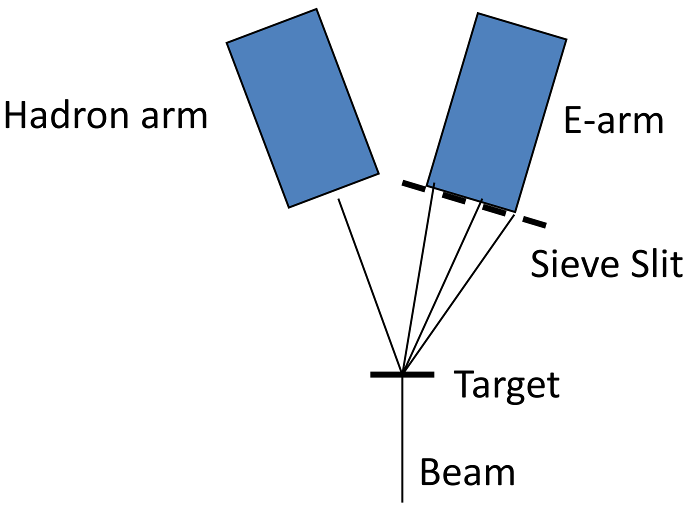
- Λ and Σ^0 peak in proton target run
  - *Momentum calibration*
- Sieve Slit Run
  - *Angle calibration*

HES mom [GeV/c] vs HKS mom [GeV/c]

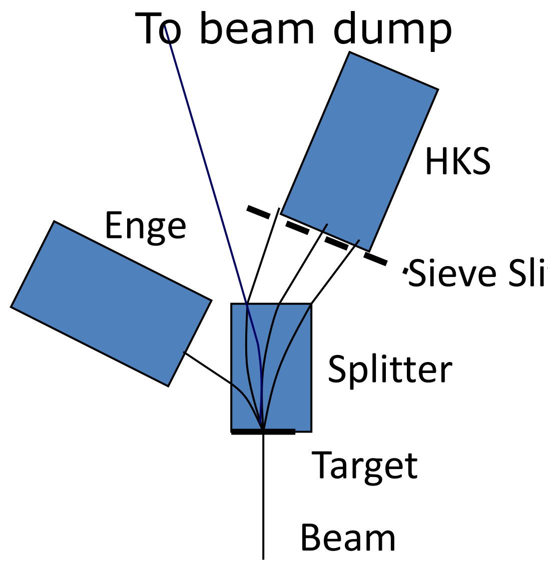


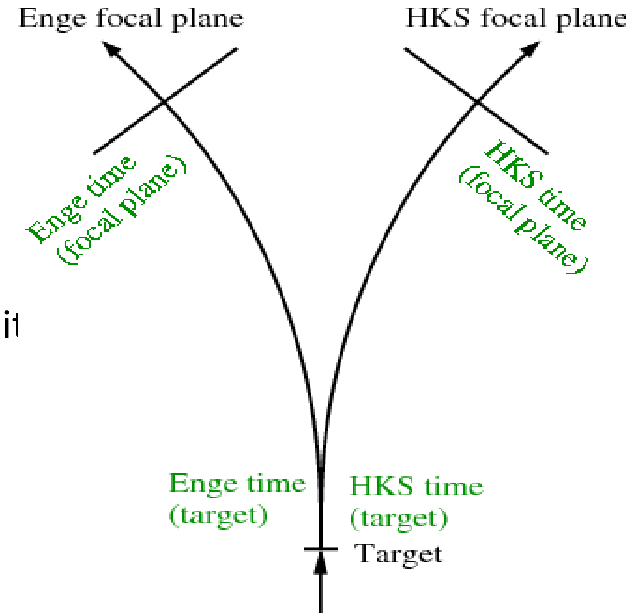
Energy scale calibration procedure

Standard double arm spectrometer



HKS spectrometer system





- Momentum calibration: two arm coupled through Splitter
- Angle calibration: Sieve Slit hole ↔ Scattering angle one to one correspondence destroyed, now also depending on δp and Splitter field

Energy scale calibration procedure

Energy scale calibration … Calibration of momentum vector for HES and HKS

$$M_{HY} = \sqrt{E_{HY}^2 - \vec{p}_{HY}^2}$$
$$= \sqrt{(E_e + E_N - E_K - E_{e'})^2 - (\vec{p_e} - \vec{p_K} - \vec{p_{e'}})^2}.$$

mom. magnitude — mom. vector

	Λ, Σ^0	$^{12}{}_{\Lambda}B$
E_{HY}	~1.1	~11
p_{HY}	~0.4	~0.4 negligible

Geant4 simulation w/ TOSCA field map

- Accuracy = order of 10^{-2}
- Depending on the accuracy of TOSCA model

↓

Sieve Slit calibration

- Accuracy = order of 10^{-3}
- Mainly angle calibration w/ accuracy of <10 mrad

↓

Calibration w/ Λ, Σ^0, $^{12}{}_{\Lambda}B$ gs

- Accuracy = order of 10^{-4}
- Momentum calibration w/ accuracy of a few 100 keV/c
- Linearity, accuracy check

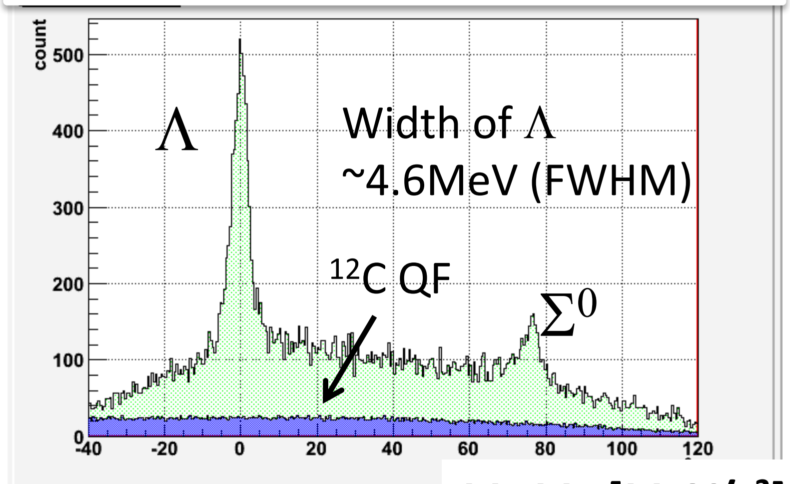
Energy Scale Calibration $-\Lambda$, Σ^0 peak-

$$\chi^2 = w_\Lambda \sum (M_X - M_\Lambda)^2/\sigma_\Lambda^2 + w_{\Sigma^0} \sum (M_X - M_{\Sigma^0})^2/\sigma_{\Sigma^0}^2 + w_{gs} \sum (M_X - M_{gs})^2/\sigma_{gs}^2$$

CH_2 target data — ^{12}C data

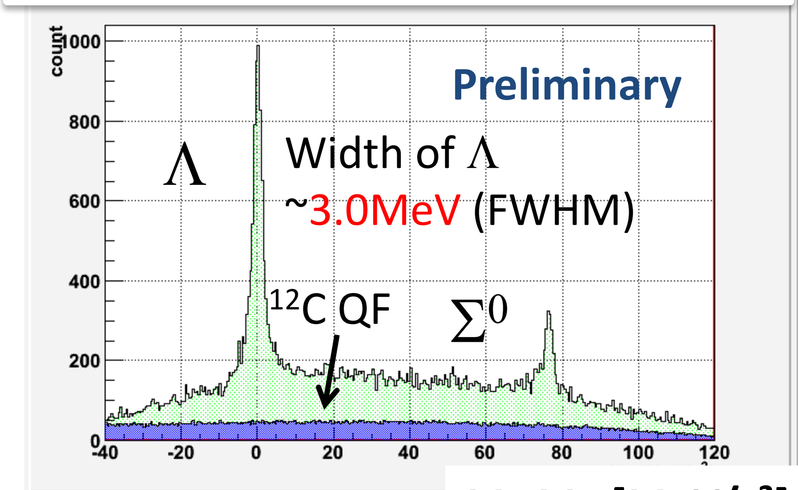
minimize

CH_2 target missing mass w/ initial F2T



M_x-M_Λ [MeV/c^2]

CH_2 target missing mass w/ tuned F2T



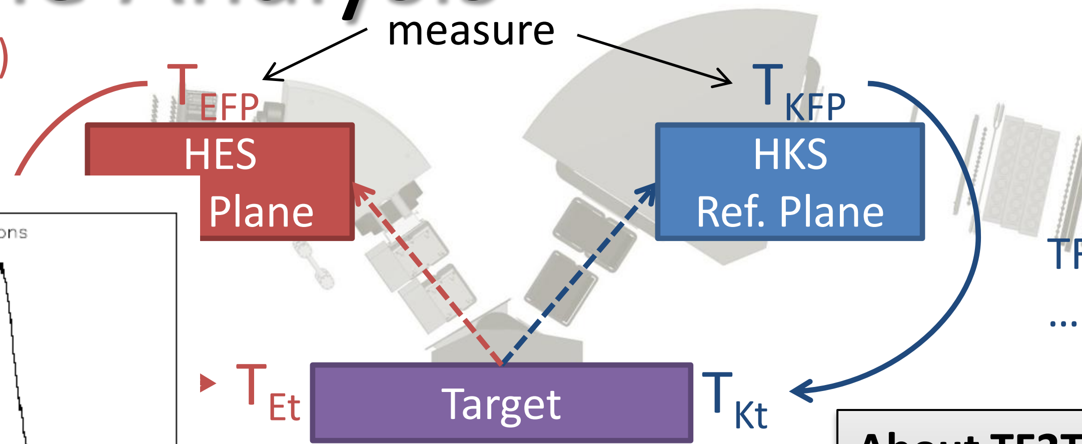
M_x-M_Λ [MeV/c^2]

Design value of mass resolution
hyperon … ~1.2 MeV/c^2 (FWHM)← recoil effect
hypernucleus … ~0.4 MeV/c^2 (FWHM)

analysis is now in progress

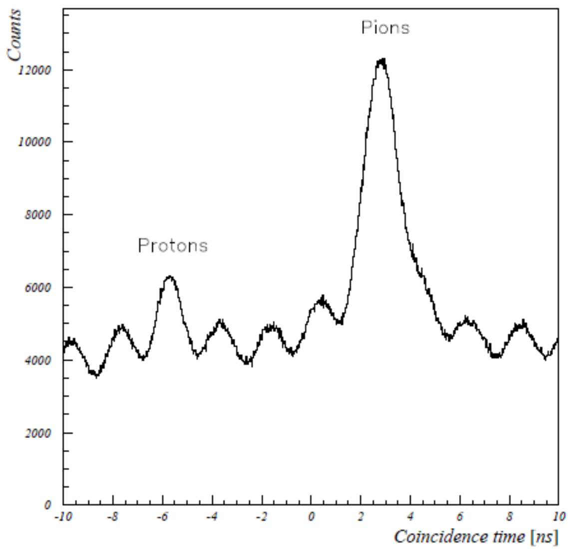
Coin Time Analysis

$TF2T_E(x_f, x'_f, y_f, y'_f)$
… G4 simulation



$TF2T_K(x_f, x'_f, y_f, y'_f)$
… G4 simulation

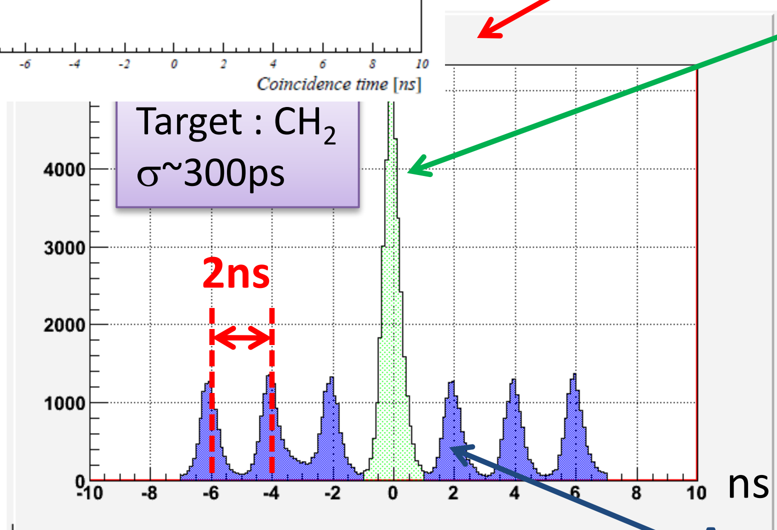
coin time = $T_{Kt} - T_{Et}$

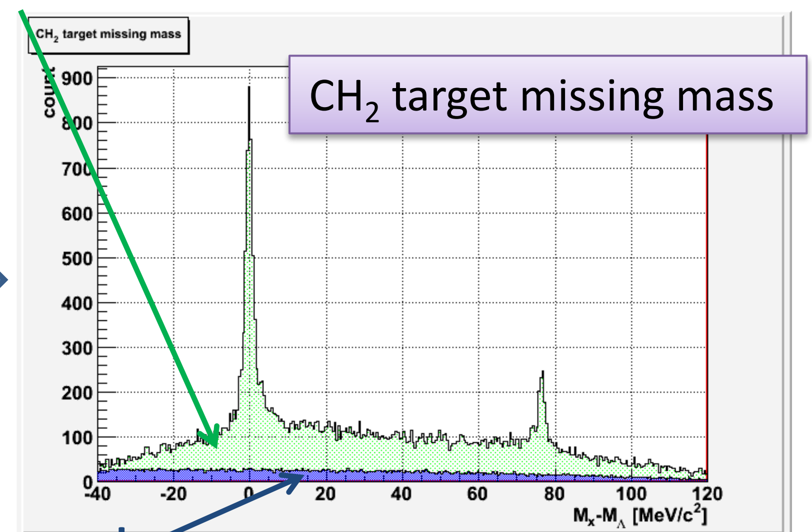


About TF2T

- For path length correction
- 4^{th} polynomial of x_f, x'_f, y_f, y'_f

True coincidence





Acc. Background

Efficiencies for cross section estimation

Cross section of the (γ^*, K^+):

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

N_T : # of target

N_γ: # of V.P.

$d\Omega$: solid angle acceptance of HKS

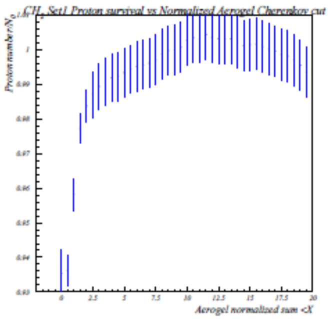
N_K : yield of Λ, Σ^0, or hypernuclear state

$$\varepsilon_{total} = \varepsilon_{Hodo}\cdot\varepsilon_{HTOF1Y}\cdot\varepsilon_{htrk}\cdot\varepsilon_{AC}\cdot\varepsilon_{WC}\cdot\varepsilon_{b}$$
$$\cdot f_{abs}\cdot f_{decay}\cdot\varepsilon_{etrk}\cdot f_{comp}\cdot\varepsilon_{Coin}$$

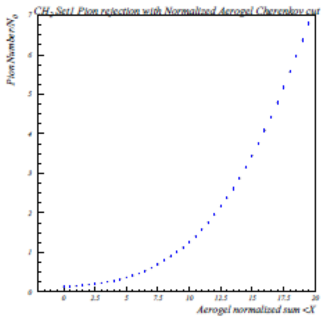
- ε_htrk: ~ 0.96
  HKS tracking efficiency
- ε_AC: ~0.96
  AC cut efficiency
- ε_WC: ~0.95
  WC cut efficiency
- ε_bk: ~0.98
  beta cut efficiency
- ε_etrk: ~0.88
  ENGE tracking efficiency
- *f* abs: ~0.82
  Kaon absorption factor
- *f* decay: ~0.35
  Kaon decay factor
- *f* comp: ~0.97
  Computer dead time factor

Systematic error [%]

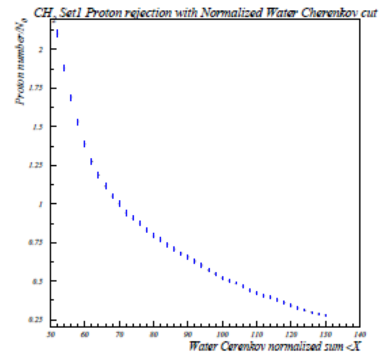
Target	Thickness	N_γ	$d\Omega$	ε_{total}	*Tune (S/N>1)*		Total
7Li	5	22	1	3	5		23
12C	2						22
28Si	5						23



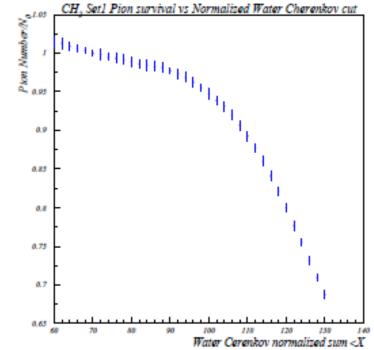
(a) Proton survival



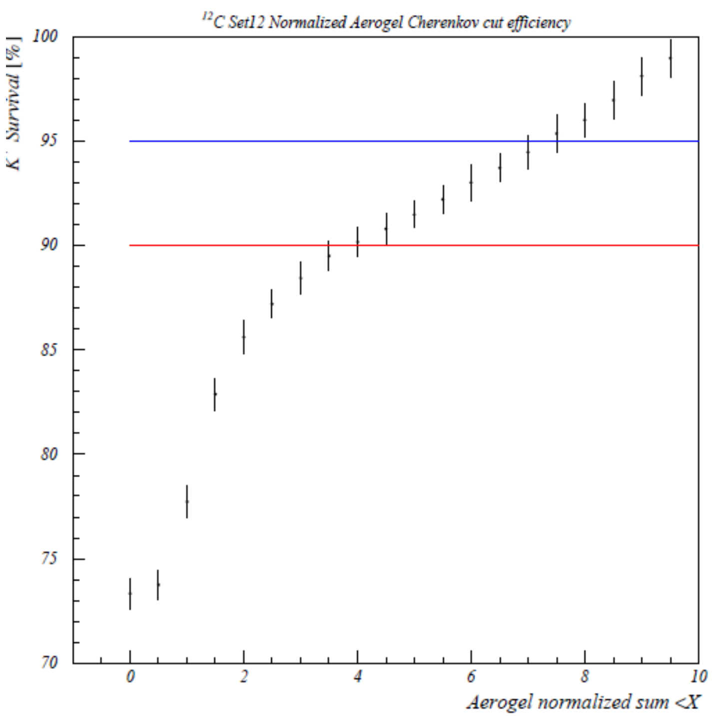
(b) Pion rejection efficiency



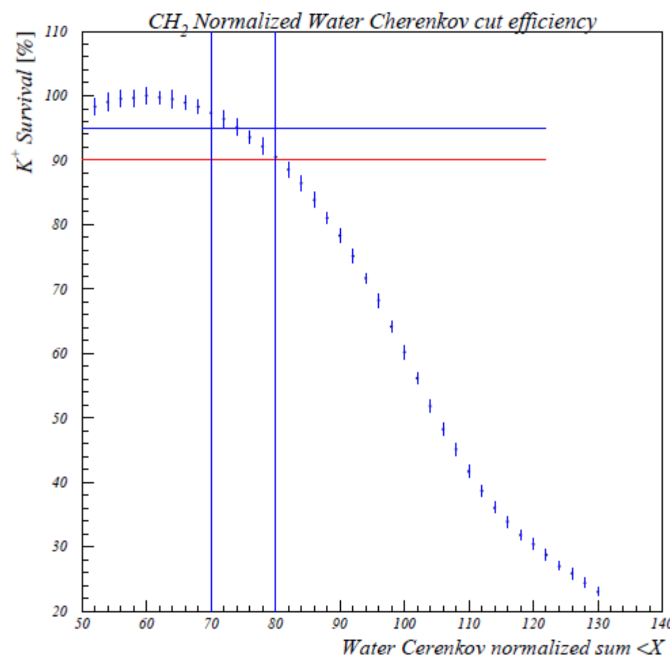
(a) Proton rejection efficiency



(b) Pion survival



(c) Kaon survival efficiency AC



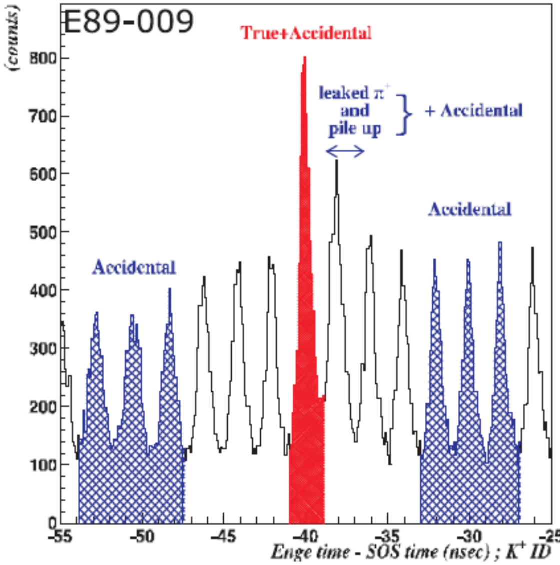
(c) Kaon survival efficiency WC

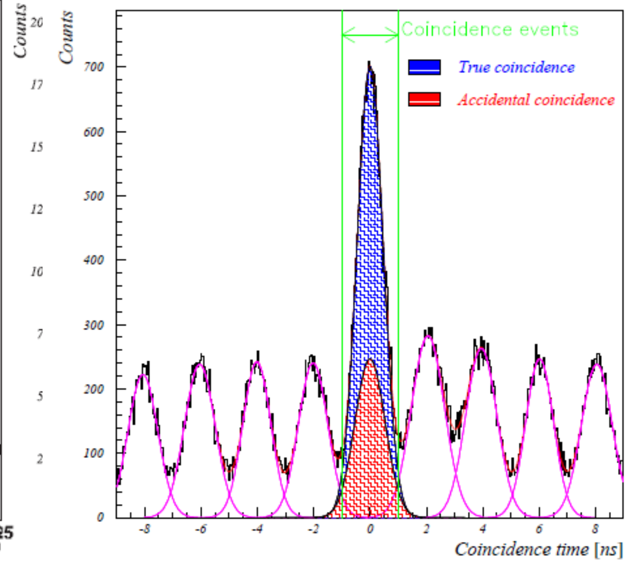
Results

Λ hypernuclei experiment
via (e,e'K+) reaction at JLab Hall-C

	1st generation E89-009 (2000)	2nd generation E01-011 (2005)	3rd generation E05-115 (2009)
configuration	SPL + Enge + SOS existing spectrometers	SPL + Enge + **HKS** +**Tilt method**	new SPL + **HES** + **HKS** + **Tilt method**
beam energy	1.8 [GeV]	1.8 [GeV]	2.344 [GeV]
data	$^{12}_{\Lambda}B$	$^{7}_{\Lambda}He, ^{12}_{\Lambda}B, ^{28}_{\Lambda}Al$	$^{7}_{\Lambda}He, ^{9}_{\Lambda}Li, ^{10}_{\Lambda}Be,$ $^{12}_{\Lambda}B, ^{52}_{\Lambda}V$
resolution (FWHM)	750 [keV]	470 [keV]	400 [keV]
target , thickness intensity	^{12}C, 22 [mg/cm^2] 0.66 [μA] luminosity × 137	^{12}C, 100 [mg/cm^2] 20 [μA]	^{12}C, 112.5 [mg/cm^2] 27 [μA]
yield ($^{12}_{\Lambda}B$ g.s.)	0.36 [/hour]	6.4 [/hour]	30 [/hour]
S/N ($^{12}_{\Lambda}B$ g.s.)	0.6	1.6	analyzing
e' rate	200 [MHz] 1/200	1.0 [MHz]	1.7 [MHz]

E01-011 &E05-115 performance



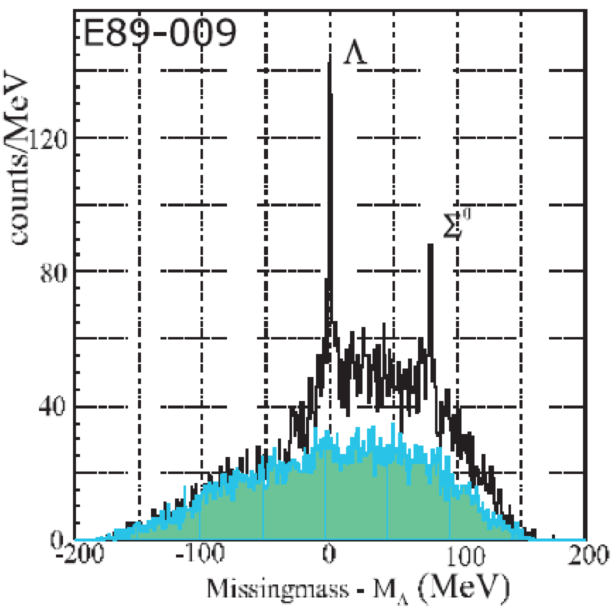


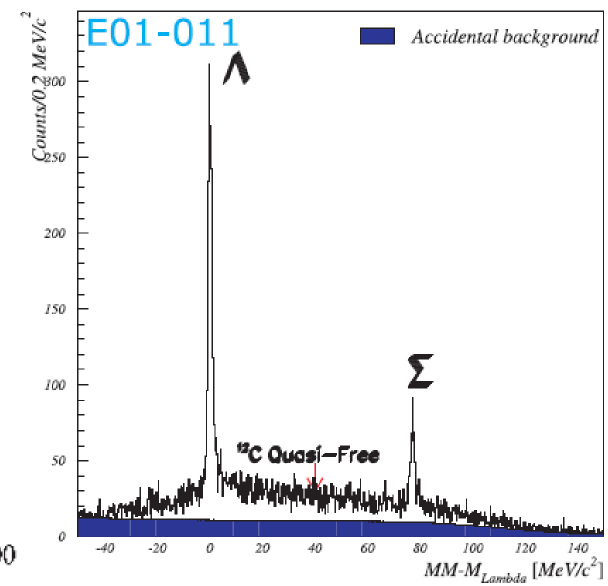
Coincidence time

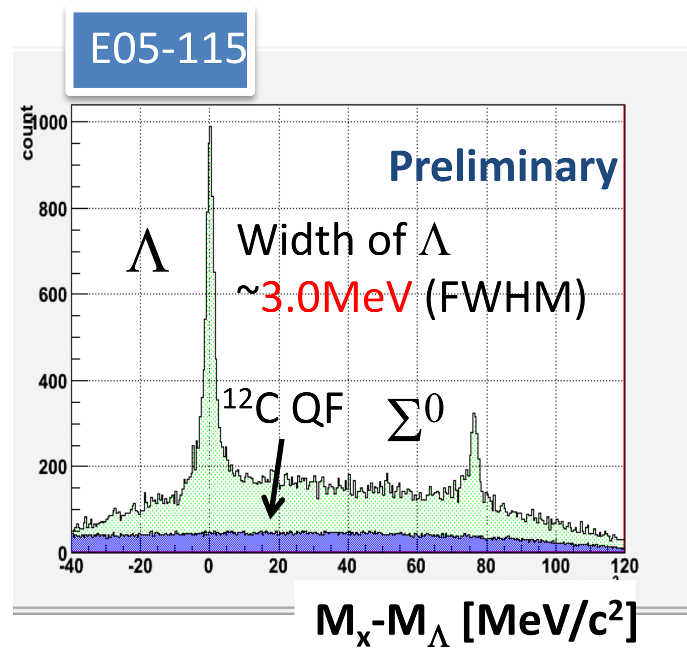
Missing mass spectra
from CH2 target

Energy scale

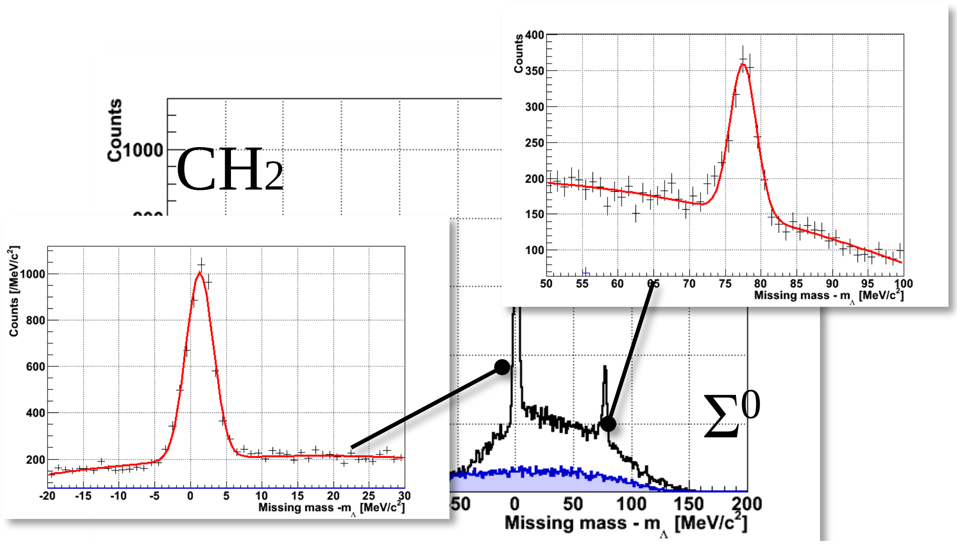
$$B_{\Lambda} = M_{\Lambda} + M_{A} - M_{HY}$$





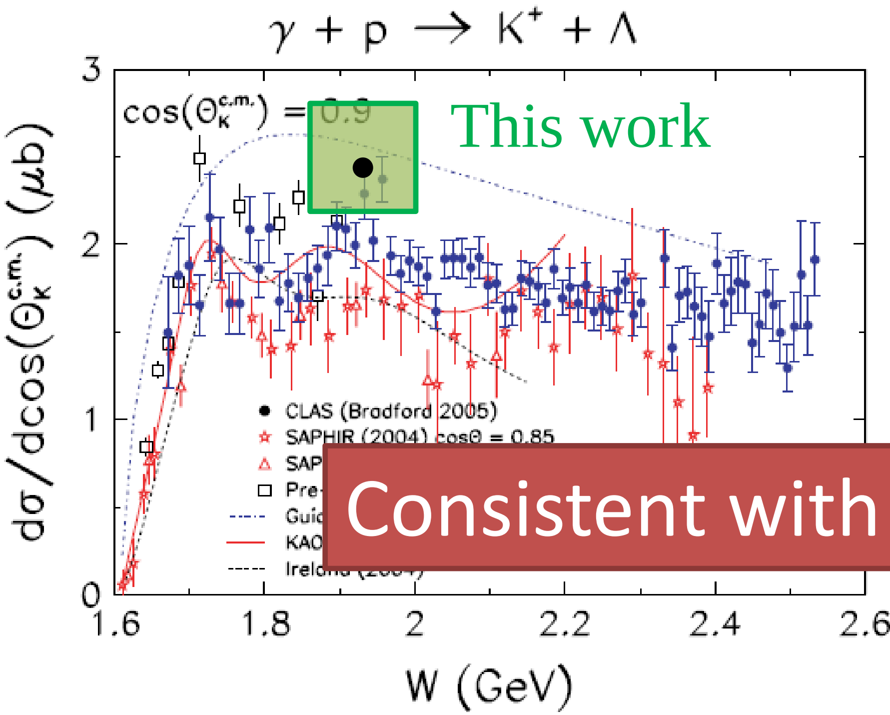


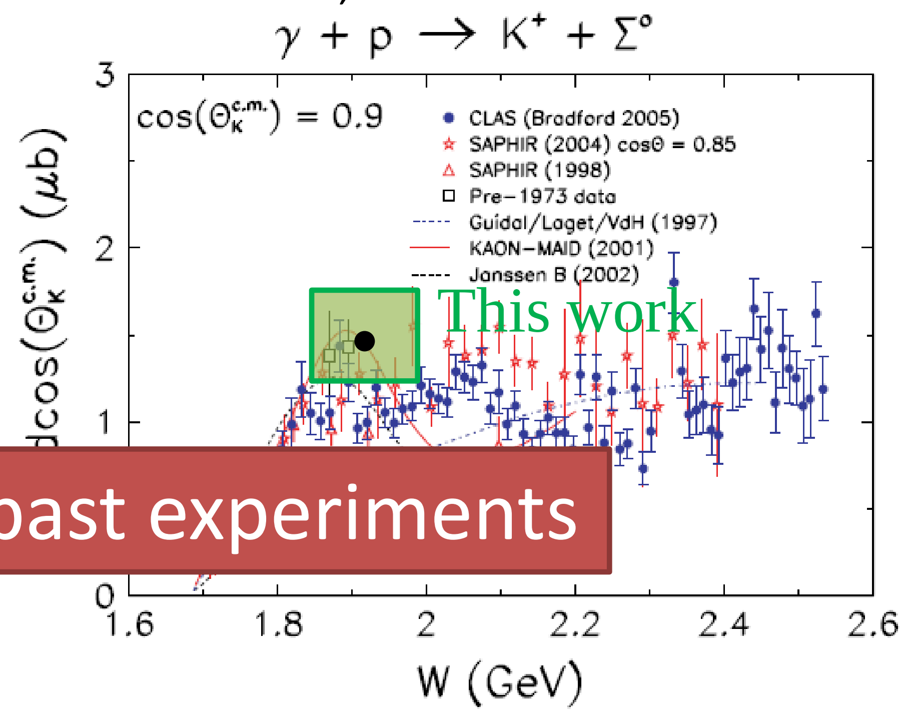
Cross section of Λ and Σ^0



	Cross Section [nb/sr]
Λ	$530 \pm 50(\mathrm{stat})\ ^{+50}_{-20}\ (\mathrm{syst})$
Σ^0	$120 \pm 30(\mathrm{stat})\ ^{+10}_{-10}\ (\mathrm{syst})$

PHYSICAL REVIEW C **73**, 035202 (2006)
R. Bradford, et al.

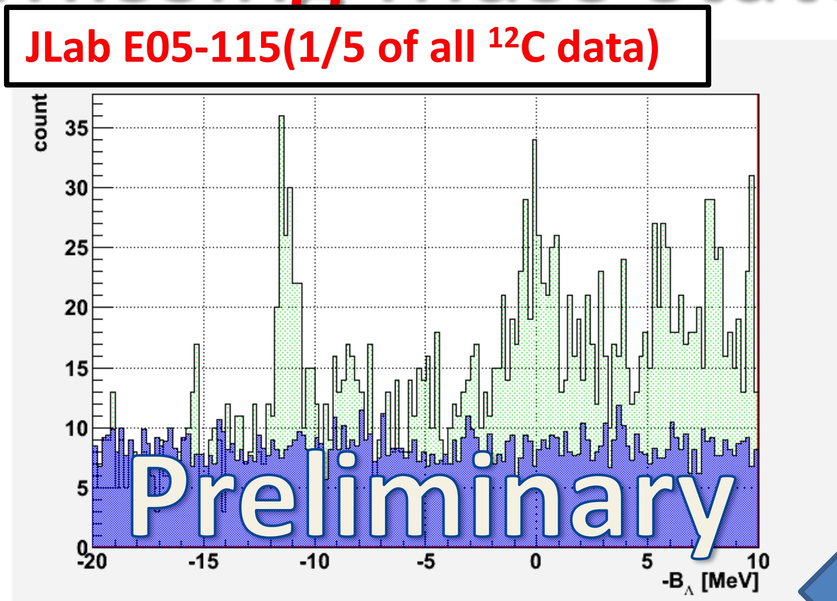


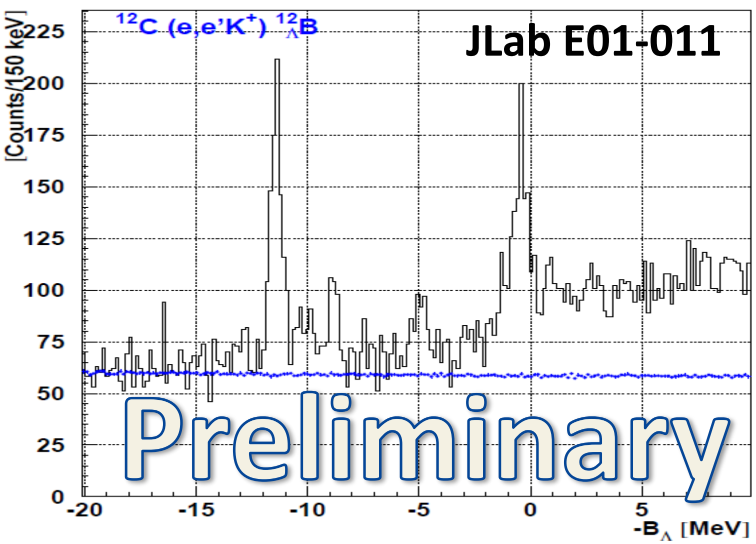


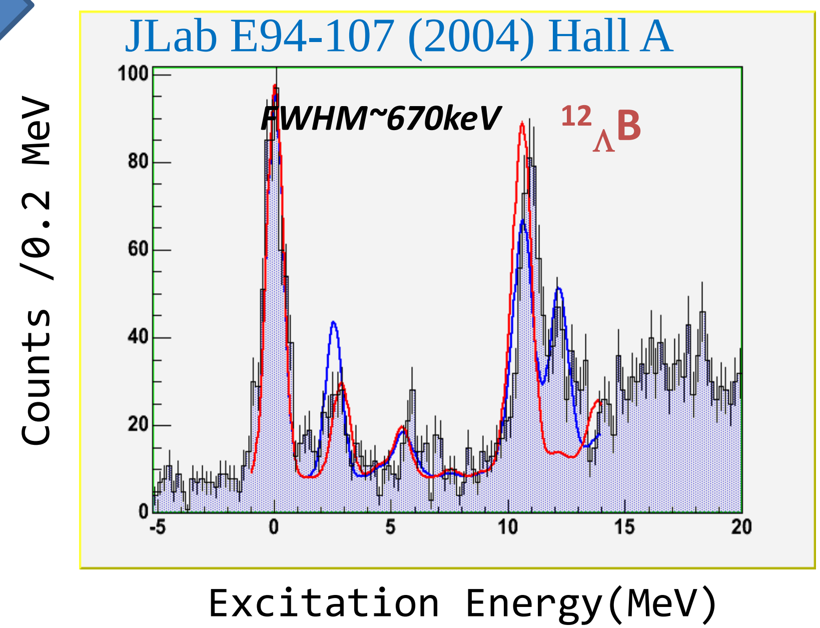
Consistent with past experiments

Missing mass status $^{12}_{\Lambda}B$

Resolution : ~1.0MeV [FWHM]
(preliminary value)
Yield : 27/hour for $^{12}_{\Lambda}B$ gs @ 20uA
(~4 times larger than E01-011)

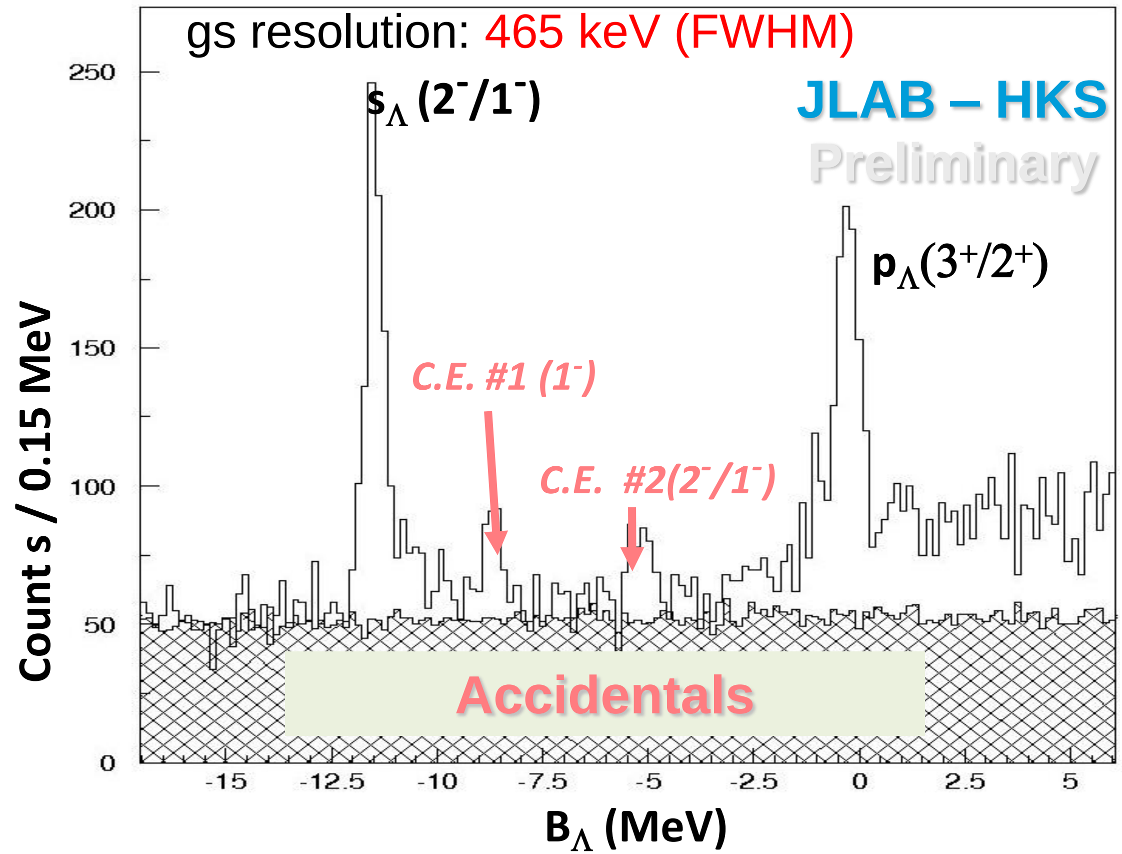


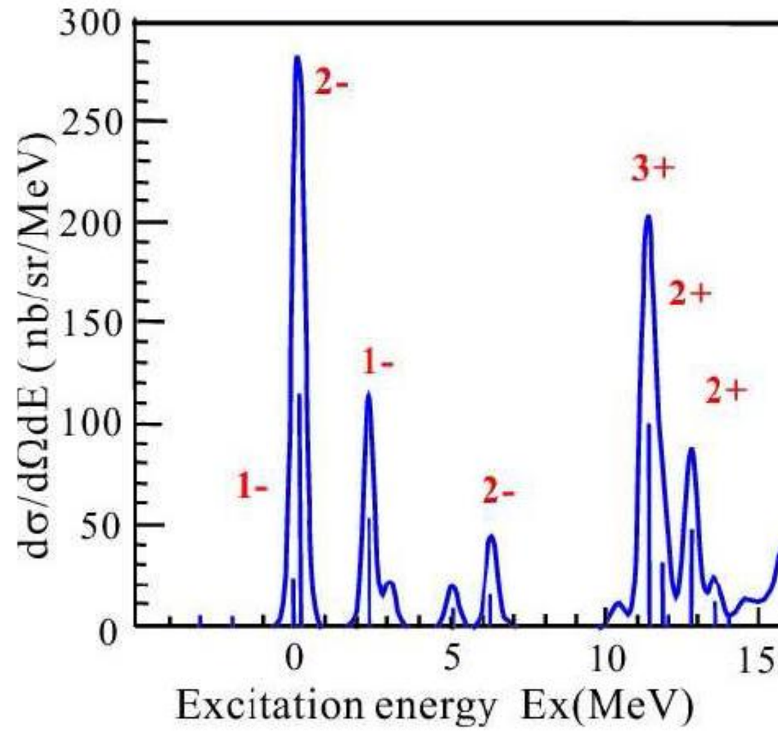


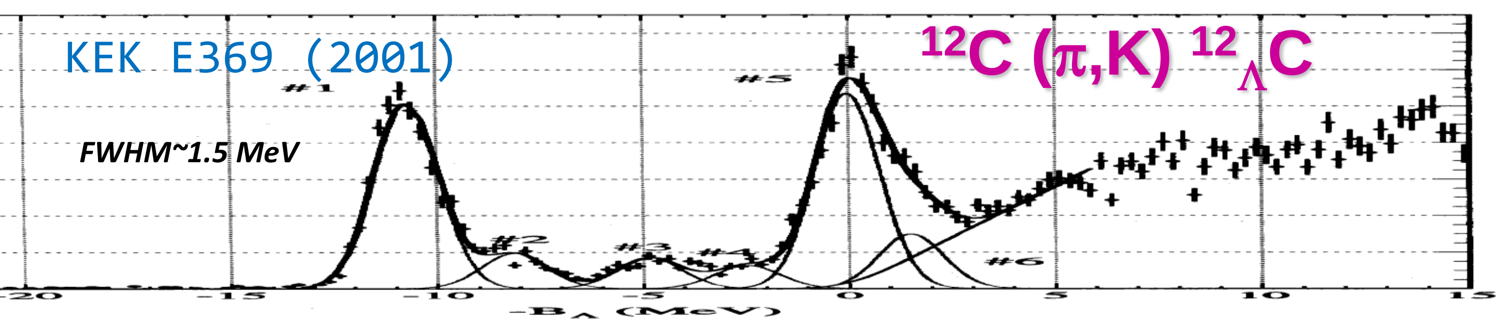


^{12}C (e,e'K) $^{12}_{\Lambda}B$

Comparison to theory and mirror hypernuclei

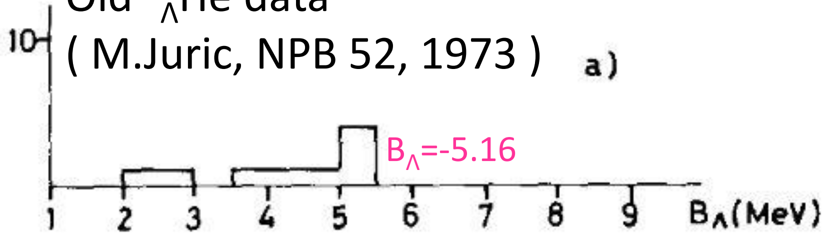






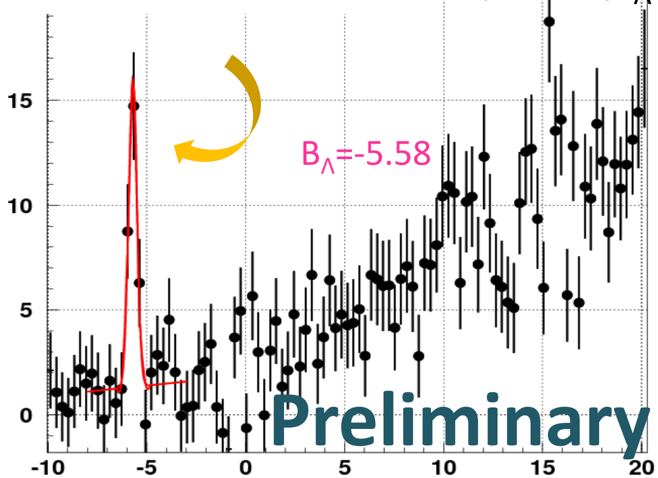
Experimental data of A=7 system

Old $^{7}{}_{\Lambda}$He data
(M.Juric, NPB 52, 1973)



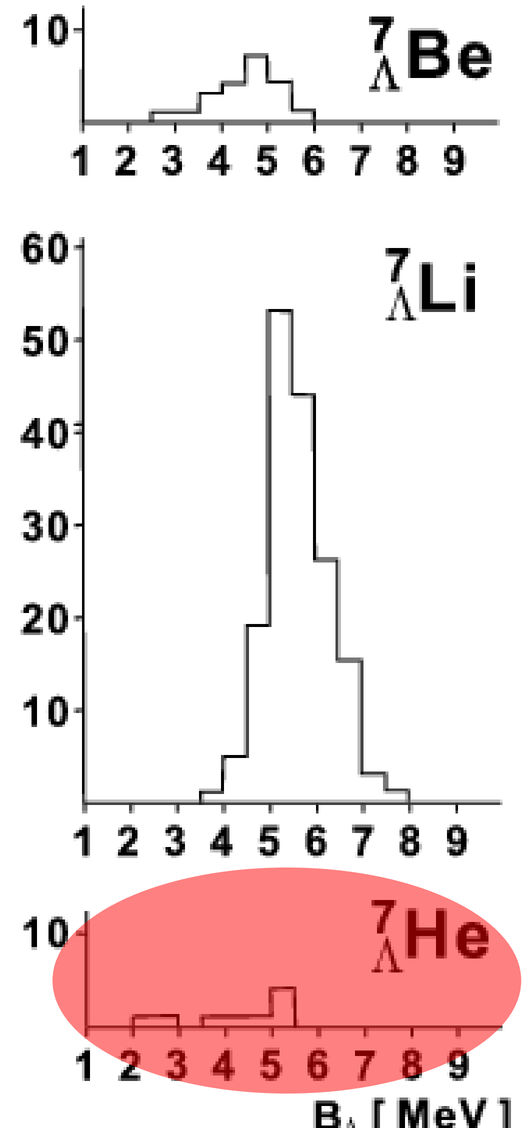
-6.71±0.03 ±0.2 MeV
from α Λ n n

JLab E01-011
^{7}Li(e,e'K^{+})$^{7}{}_{\Lambda}$He



Emulsion data

Nucl. Phys. B52 (1973) 1

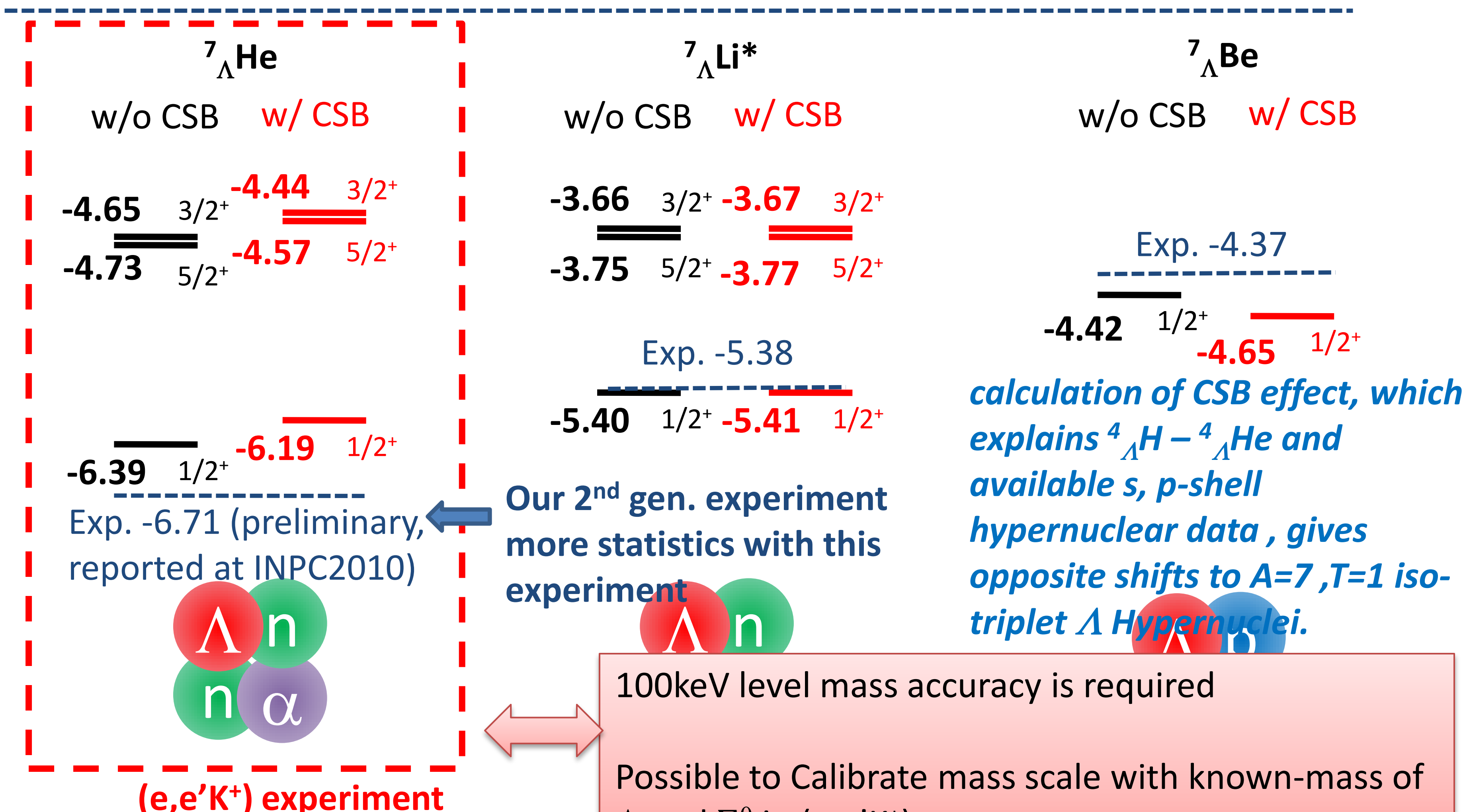


Comparison to theory of A=7 system

Four-body model calculation by E. Hiyama *(PRC 80, 054321 (2009))*

Estimate the CSB potential from ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He data -> apply the potential to the A=7 iso-triplet

0 MeV : α+Λ+n+n threshold



100keV level mass accuracy is required

Possible to Calibrate mass scale with known-mass of Λ and Σ^0 in (e,e'K$^+$) spectroscopy

Another Physics of $^{7}_{\Lambda}$He

HKS-HES (E05-115)

Unbound neutron halo

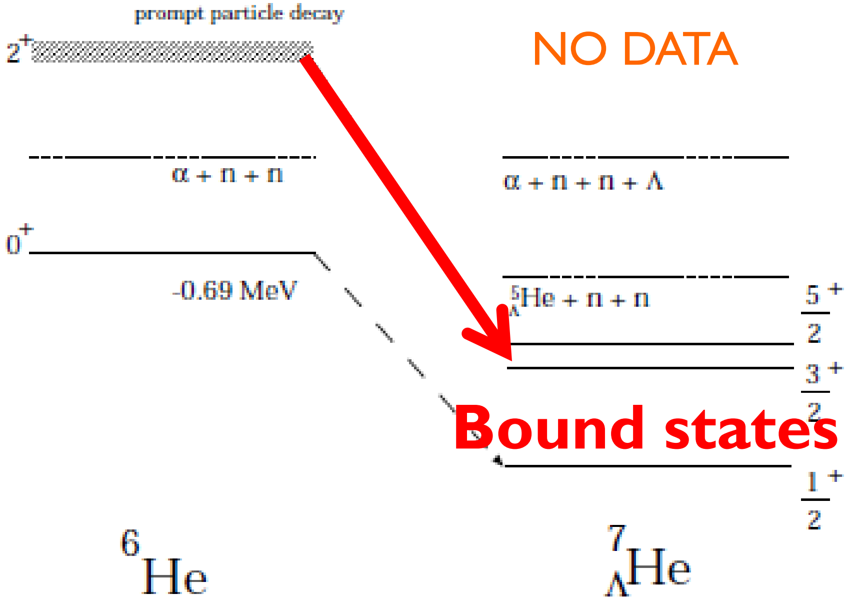
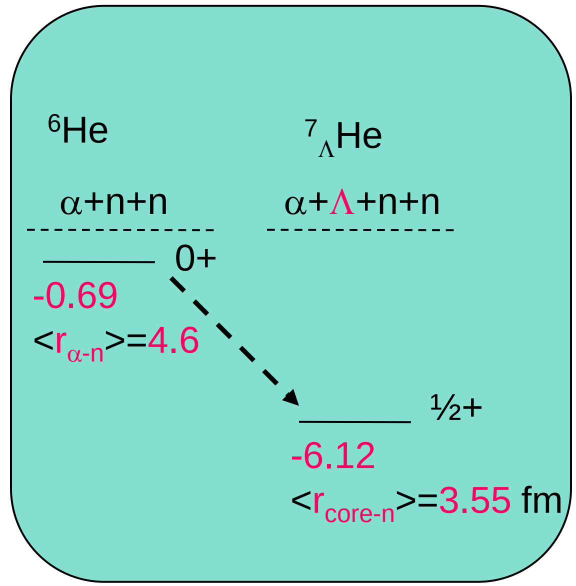
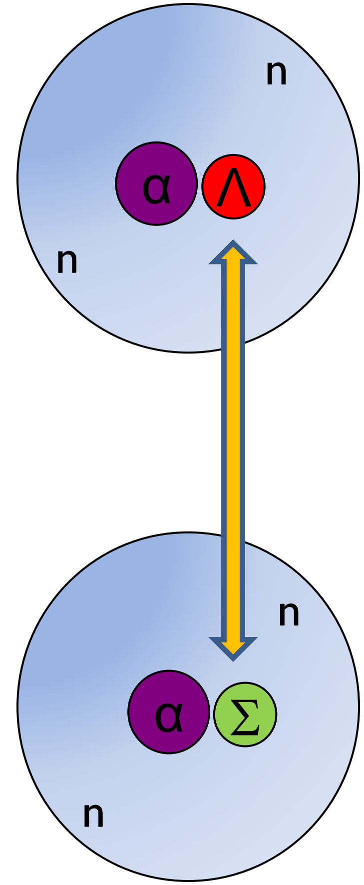


Figure 1: Energy levels for ^{6}He and $^{7}_{\Lambda}$He [7]

- "Gluelike role" of hyperon in $^{7}_{\Lambda}$He

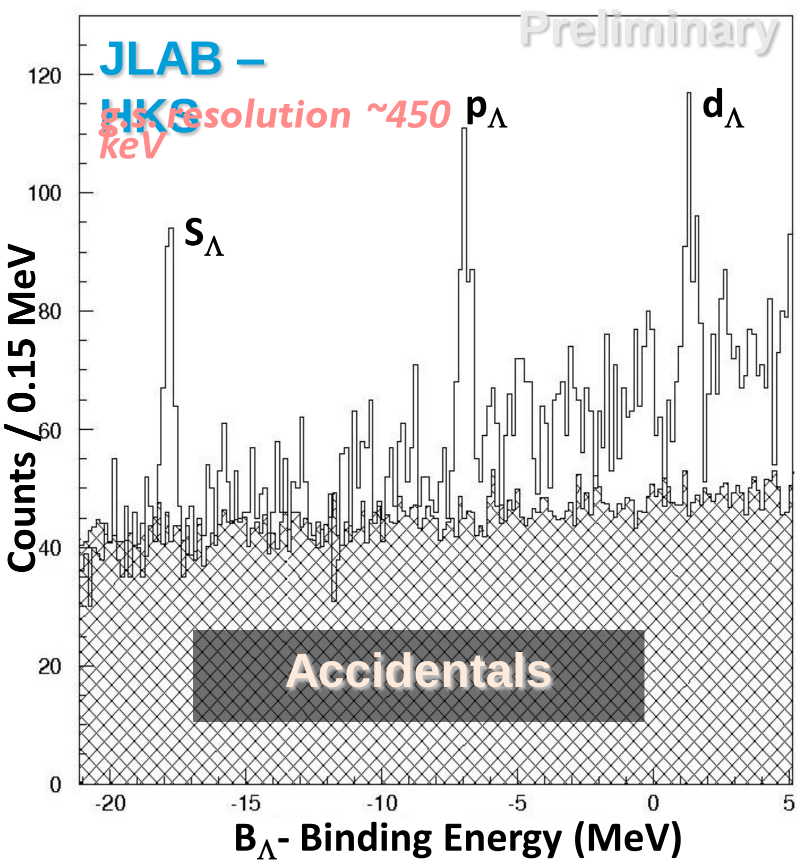


* Hiyama 1997



Direct Observation of Λ's glue-like role

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



First sd-shell hypernuclear spectroscopy by (e,e'K$^+$)

Enriched ^{28}Si target
0.1 g/cm^2
30μA electron beam

Three major peaks

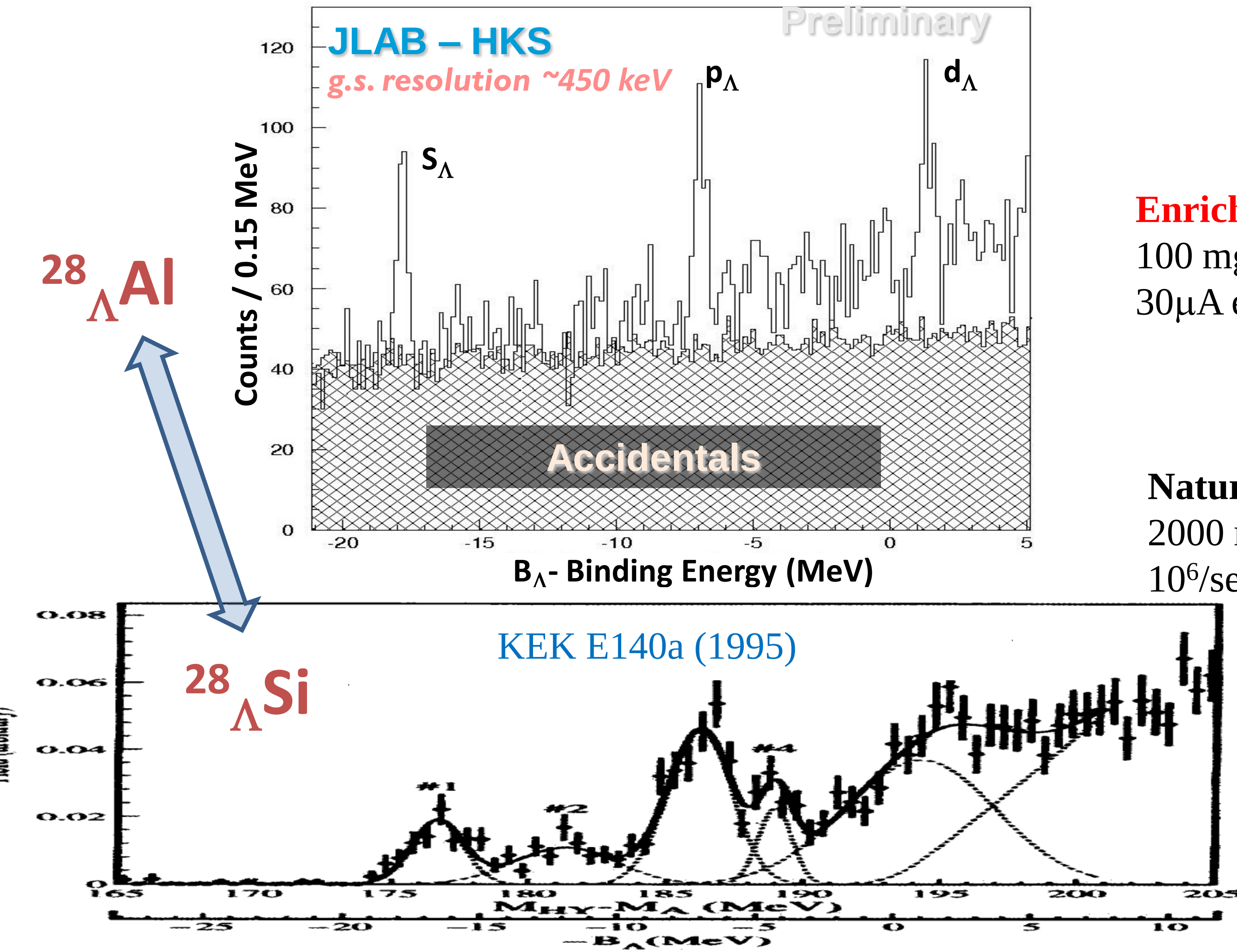
- #1 : $[(d_{5/2})^{-1}_p,(s_{1/2})_\Lambda]$
- #2 : $[(d_{5/2})^{-1}_p,(p_{3/2},p_{1/2})_\Lambda]$
- #3 : $[(d_{5/2})^{-1}_p,(d_{5/2},d_{3/2})_\Lambda]$

Resolution : ~450 keV (FWHM) for g.s.
Data taking : ~30 hours w/ 30 μA

	s-shell	p-shell	d-shell
Counts	157±2	244±4	73±7
Background (3σ)	325±5	513±8	538±12
S/B	0.483±0.009	0.476±0.012	0.138±0.016

^{28}Si(e,e'K$^+$)$^{28}{}_{\Lambda}$Al – First Spectroscopy of $^{28}{}_{\Lambda}$Al

Gateway to hypernuclear spectroscopy in the medium-heavy mass region



Enriched ^{28}Si target
100 mg/cm^2
30μA electron beam

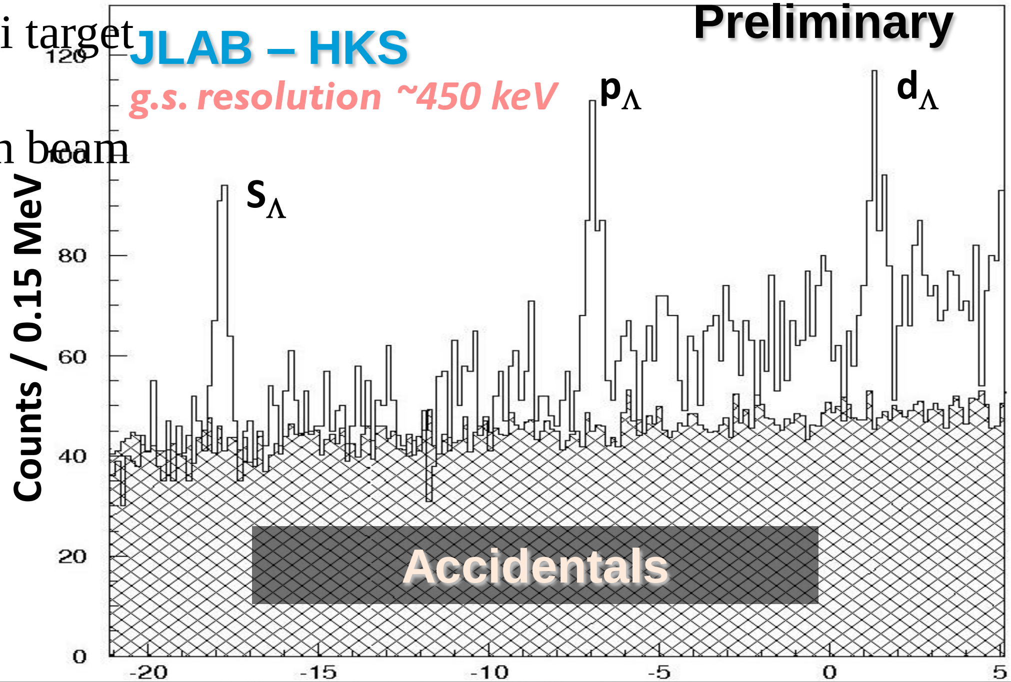
Natural Si target
2000 mg/cm^2
10^6/sec π^+ beam

$^{28}Si(e,e'K^+)^{28}_{\Lambda}Al$ – First Spectroscopy of $^{28}_{\Lambda}Al$

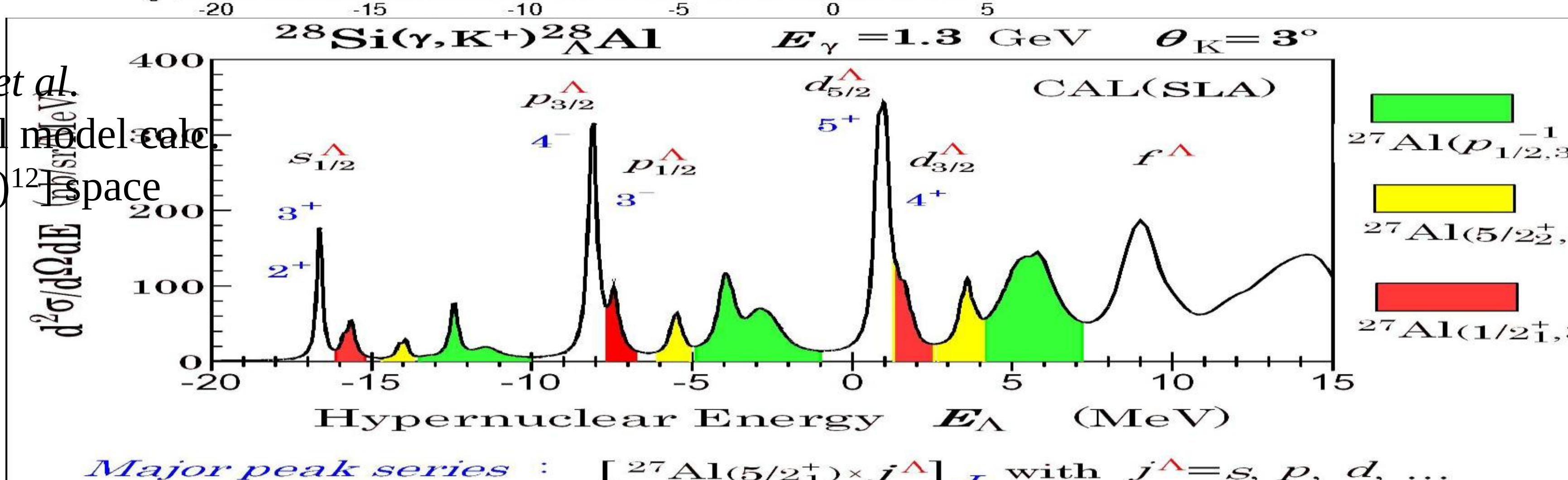
Gateway to hypernuclear spectroscopy in the medium-heavy mass region

Enriched ^{28}Si target
0.1 g/cm^2
30μA electron beam

$^{28}_{\Lambda}Al$



Motoba *et al.*
Full shell model calc.
[$s^4p^{12}(sd)^{12}$] space



Summary

Summary of (e,e'K$^+$) hypernuclear spectroscopy @ JLab-HallC

A: 1 — 10 — 50 →

• Use existing spectrometer

2000 : 1st Gen. Exp.

$^{12}_{\Lambda}$B

Energy resolution ~750keV
✓ World's first (e,e'K) hypernuclear spectroscopy

• Construction of K$^+$ spectrometer (**HKS**)
• Acceptance optimization (**Tilt Method**)

2005 : 2nd Gen. Exp.

$^{7}_{\Lambda}$He, $^{12}_{\Lambda}$B, $^{28}_{\Lambda}$Al

Energy resolution <500keV
✓ HKS and Tilt Method worked fine

• Construction of e' spectrometer (**HES**)
• Construction of New SPL

Final Check of Analysis
Preparing for publication

2009 : 3rd Gen. Exp.

$^{7}_{\Lambda}$He, $^{10}_{\Lambda}$Be, $^{52}_{\Lambda}$V

$^{7}_{\Lambda}$He : CSB, Λ glue-like role
$^{9}_{\Lambda}$Li : p-shell Hy
$^{10}_{\Lambda}$Be : CSB
$^{12}_{\Lambda}$B : Reference data & core excited states
$^{52}_{\Lambda}$V : First mid-heavy HY data, core-config. mixing, ls-force

Summary

- With a high quality electron beam from CEBAF, (e,e'K) hypernuclear spectroscopy was established
- The second gen. exp. E01-011 (HKS) achieved <500keV (FWHM) resolution

$^{12}{}_{\Lambda}B$: s_{Λ} width problem solved

$^{7}{}_{\Lambda}He$: first reliable observation of g.s., CSB

$^{28}{}_{\Lambda}Al$: first observation, doorway to mid-heavy HY

Final Check of Analysis
Preparing for publication

- The third gen. exp. E05-115 (HKS-HES) successfully finished

Λ : Calibration, Elementary Process

$^{7}{}_{\Lambda}He$: CSB, Λ glue-like role

$^{9}{}_{\Lambda}Li$: p-shell Hy

$^{10}{}_{\Lambda}Be$: CSB, Tensor force, Sheds light on $^{10}{}_{\Lambda}B$ problem

$^{12}{}_{\Lambda}B$: Reference data & core excited states

$^{52}{}_{\Lambda}V$: First mid-heavy HY data, core-config. mixing, ls-force

Preparing mass production of 1^{st} condensed data set