Λ hypernuclear spectroscopy at Jefferson Lab

The 3rd Korea-Japan on Nuclear and Hadron Physics at J-PARC,
at Inha University in Korea

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Contents

- Introduction
  - (e,e'K$^+$) reaction experiment
  - JLab E05-115

- Analysis
  - Energy scale calibration
  - Binding energy systematic error estimation

- Results
  - ^{12}C(e,e'K$^+$)$^{12}_{\Lambda}$B
  - ^{7}Li(e,e'K$^+$)$^{7}_{\Lambda}$He

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- **Introduction**
  - (e,e'K$^+$) reaction experiment
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- Analysis
  - Energy scale calibration
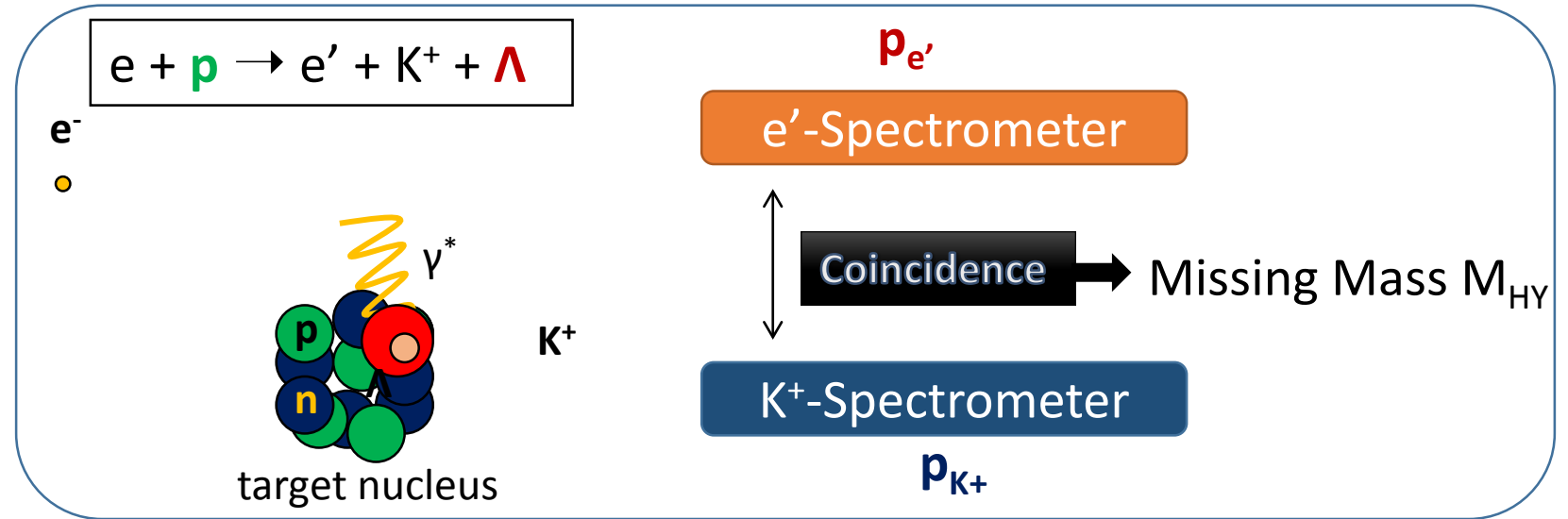 - Binding energy systematic error estimation

- Results
  - $^{12}C(e,e'K^+)^{12}_\Lambda B$
  - $^{7}Li(e,e'K^+)^{7}_\Lambda He$

Spectroscopic experiment by the (e,e'K⁺) reaction

Jefferson Lab
Thomas Jefferson National Accelerator Facility

High intensity (~10^{14} Hz)
Small emittance (2 μm·mrad)
Small energy spread ($\Delta E/E < 10^{-4}$)

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

e^-

γ^*

p
n

target nucleus

K^+

$p_{e'}$

e'-Spectrometer

Coincidence ⟶ Missing Mass M_{HY}

K⁺-Spectrometer

p_{K+}
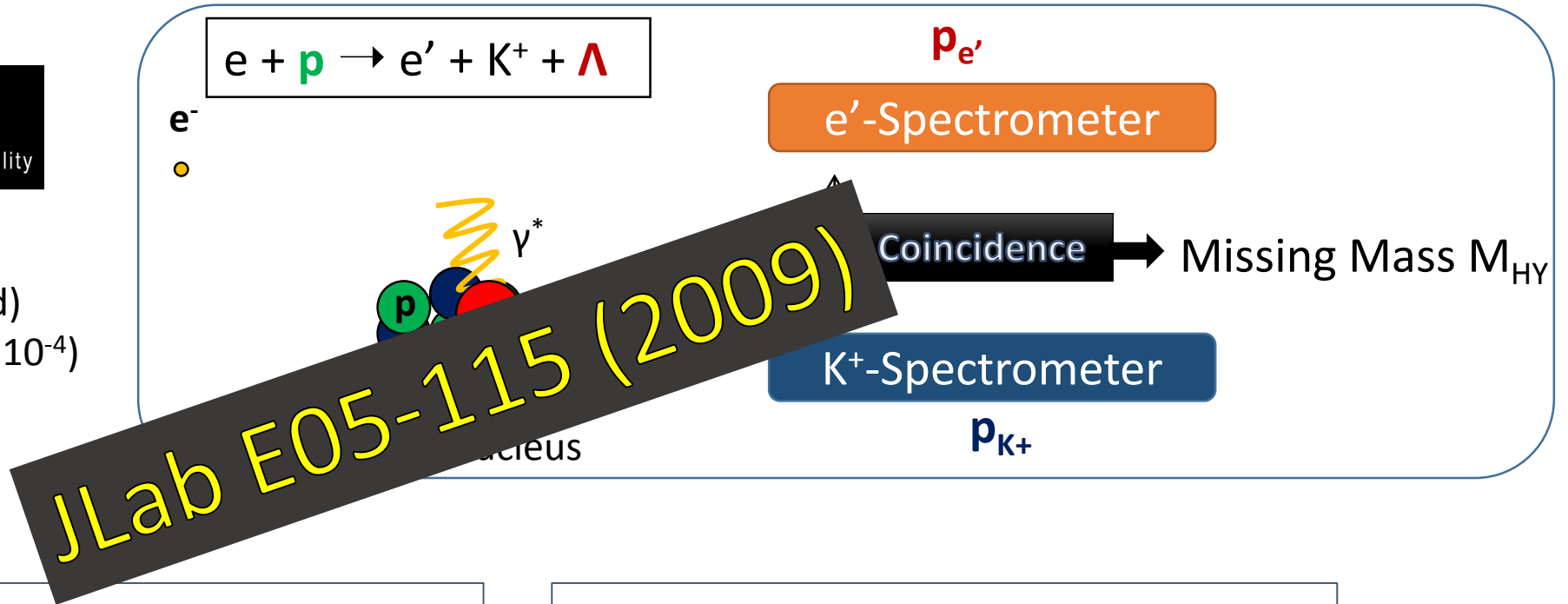
~ 1990's
The (K^-,π^-) , (π^+,K^+) reactions
• Energy resolution ~ a few MeV
• n →Λ

2000~
The (e,e'K⁺) reaction
• Energy resolution **sub-MeV**
• p → Λ

Spectroscopic experiment
by the (e,e'K⁺) reaction

Physics motivation for JLab E05-115

- **$^{7}_{\Lambda}$He**
  - CSB effect in ΛN interaction
  - Λ Glue like role

- **$^{10}_{\Lambda}$Be**
  - CSB effect in ΛN interaction
  - Λ Glue like role
  - Level inversion due to nuclear deformation

- **$^{12}_{\Lambda}$B**
  - Consistency confirmation with old data
  - Finer structures with best resolution

- **$^{52}_{\Lambda}$V** (the first challenge for medium-heavy mass region)
  - Λ single particle potential

Physics motivation for JLab E05-115

- $^{7}_{\Lambda}$He
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- $^{10}_{\Lambda}$Be
  - CSB effect in ΛN interaction
  - Λ Glue like role
  - Level inversion due to nuclear deformation

- $^{12}_{\Lambda}$B
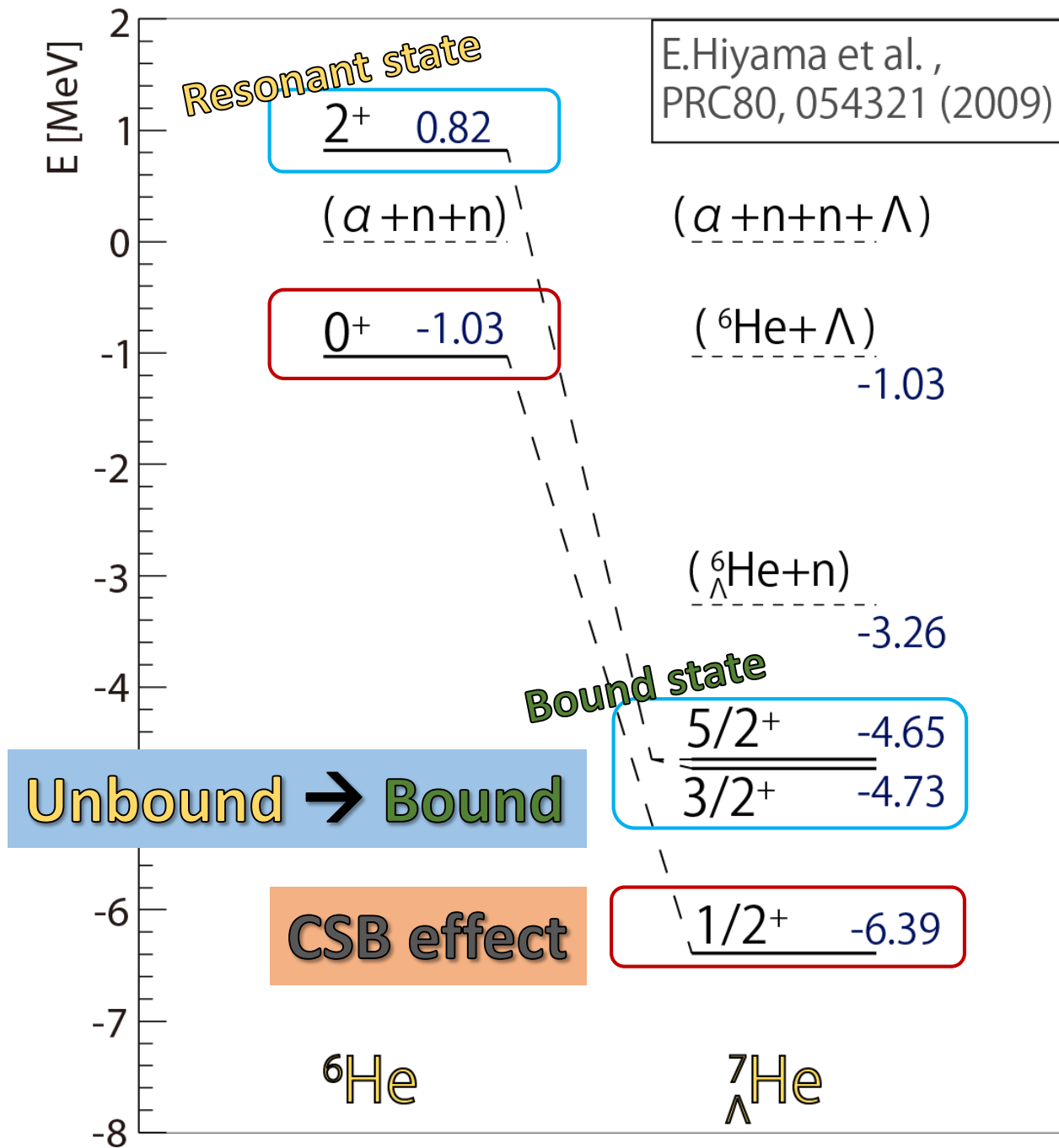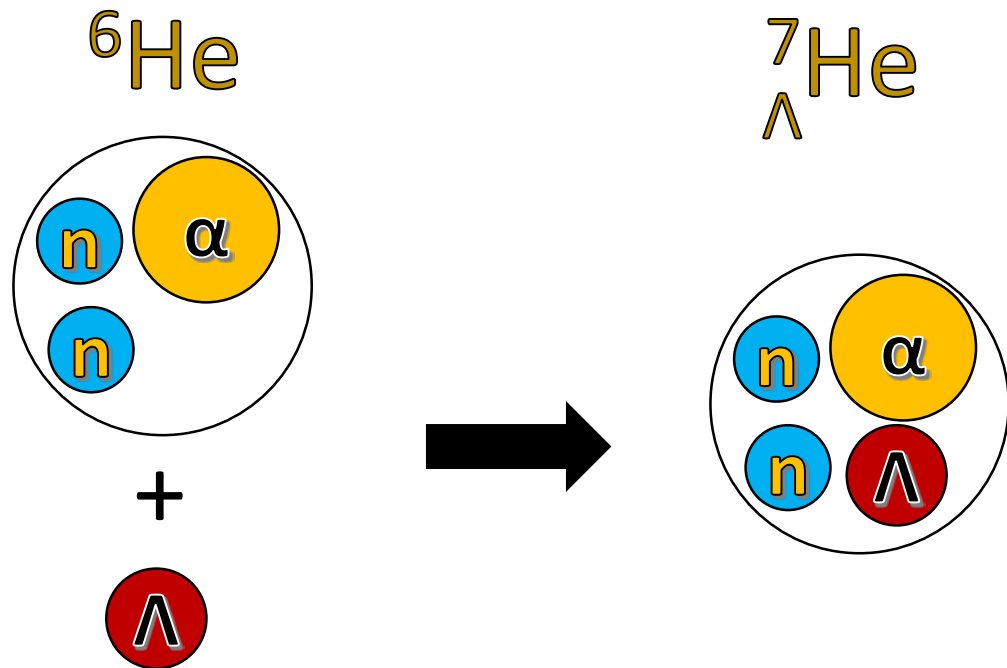 - Consistency confirmation with old data
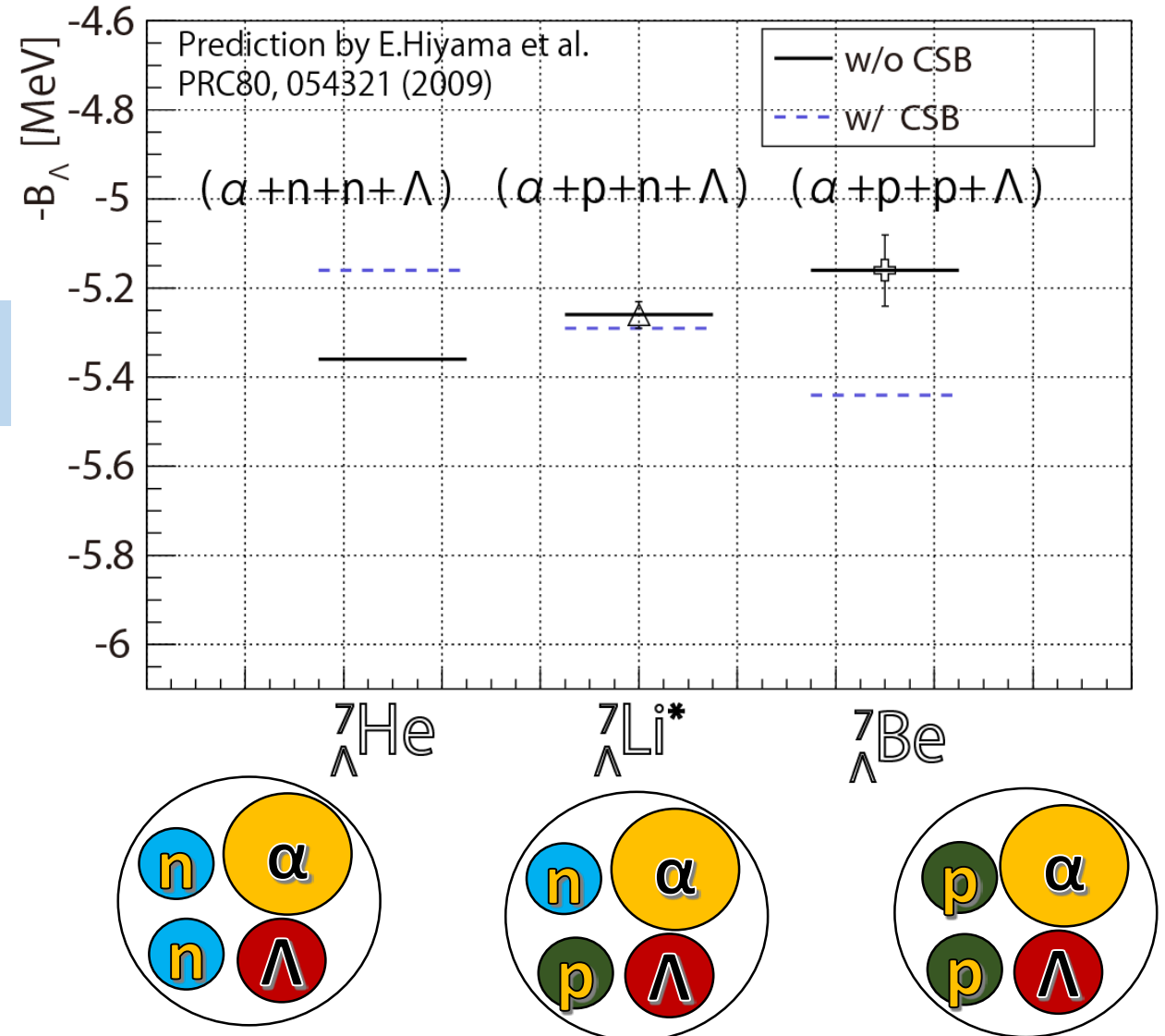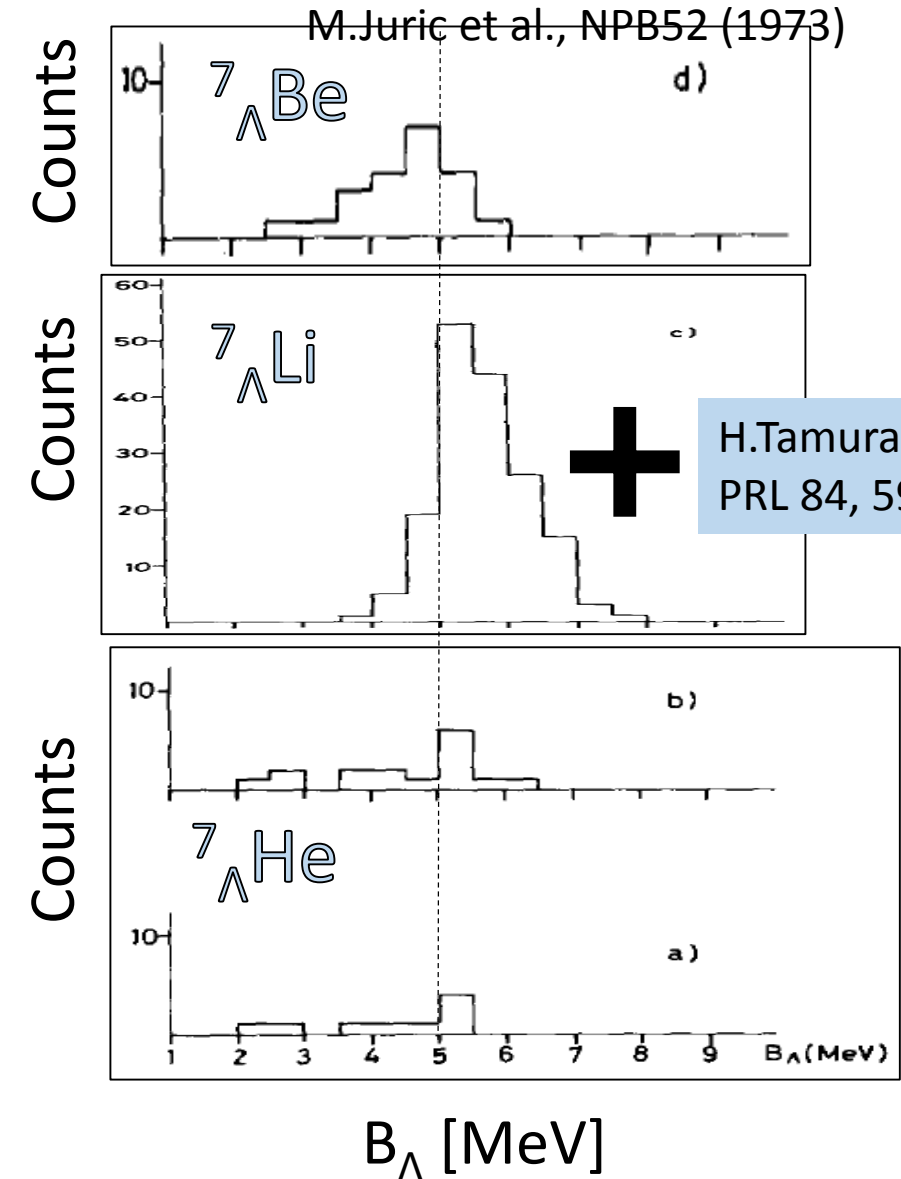 - Finer structures with best resolution

- $^{52}_{\Lambda}$V (the first challenge for medium-heavy mass region)
  - Λ single particle potential

$^{7}_{\Lambda}$He hyprenucleus

^{6}He

$^{7}_{\Lambda}$He

+

Λ

E [MeV]

Resonant state

2^{+} 0.82

(α+n+n)

(α+n+n+Λ)

0^{+} -1.03

(^{6}He+Λ)

-1.03

E.Hiyama et al.,
PRC80, 054321 (2009)

($^{6}_{\Lambda}$He+n)

-3.26

Bound state

5/2^{+} -4.65
3/2^{+} -4.73

Unbound → Bound

CSB effect

1/2^{+} -6.39

^{6}He

$^{7}_{\Lambda}$He

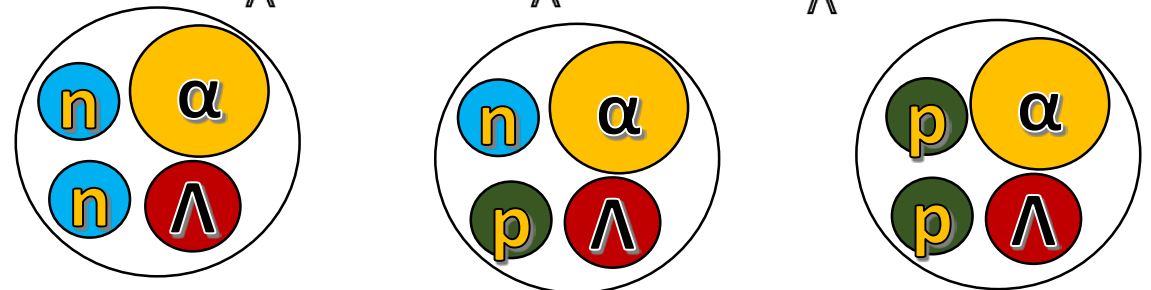# CSB interaction test in A=7 iso-triplet comparison

M.Juric et al., NPB52 (1973)

$^{7}_{\Lambda}$Be

$^{7}_{\Lambda}$Li

$^{7}_{\Lambda}$He

Counts

B$_{\Lambda}$ [MeV]

H.Tamura et al.,
PRL 84, 5963 (2000)

Prediction by E.Hiyama et al.
PRC80, 054321 (2009)

w/o CSB
w/ CSB

$(\alpha+n+n+\Lambda)$ $(\alpha+p+n+\Lambda)$ $(\alpha+p+p+\Lambda)$

-B$_{\Lambda}$ [MeV]

$^{7}_{\Lambda}$He $^{7}_{\Lambda}$Li* $^{7}_{\Lambda}$Be
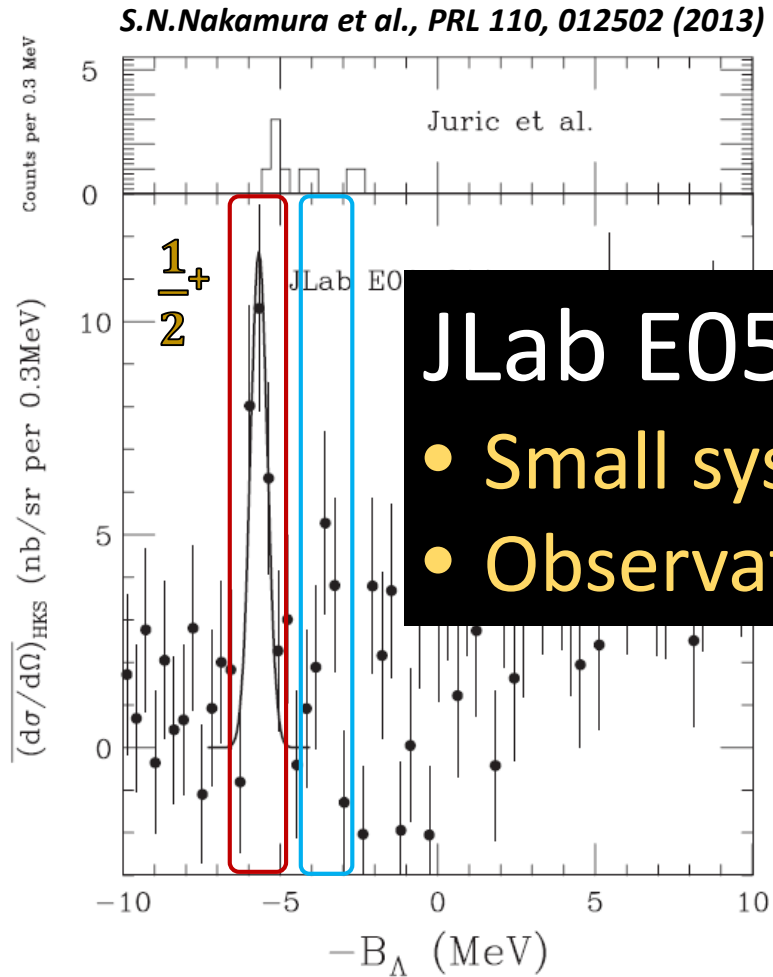
CSB interaction test in A=7 iso-triplet comparison

S.N.Nakamura et al., PRL 110, 012502 (2013)

$^{7}_{\Lambda}$He in JLab E05-115

E.Hiyama et al.,
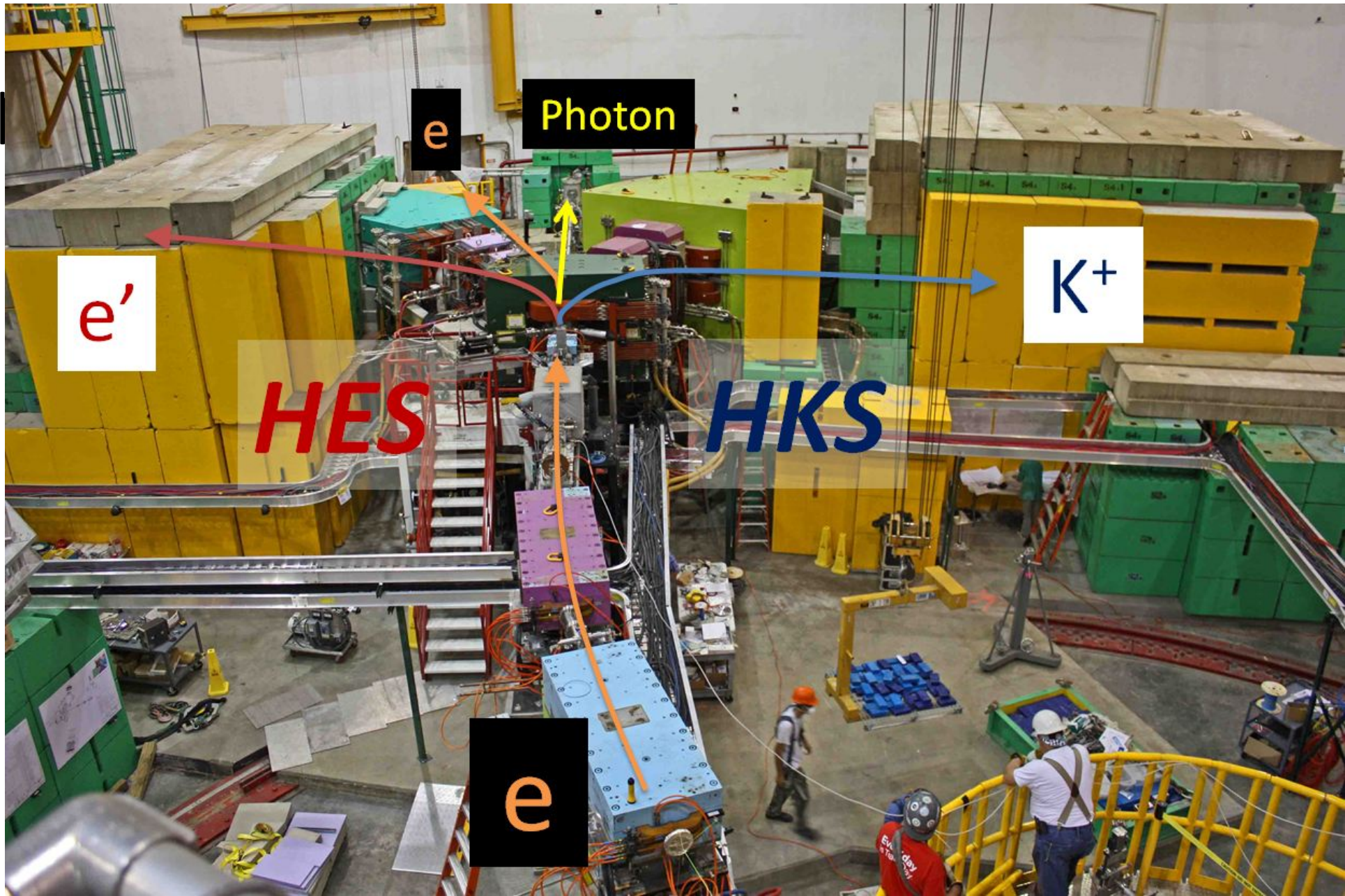PRC80, 054321 (2009)

S.N.Nakamura et al., PRL 110, 012502 (2013)

Resonant state

2^+ 0.82

$(\alpha +n+n)$ $(\alpha +n+n+\Lambda)$

0^+ -1.03 $(^6He+\Lambda)$
-1.03

$(^6_\Lambda He+n)$
-3.26

Bound state

JLab E05-115
- Small systematic error
- Observation of the excited state

$5/2^+$ -4.65
$3/2^+$ -4.73

Unbound → Bound

CSB effect $1/2^+$ -6.39

^6He $^{7}_{\Lambda}He$
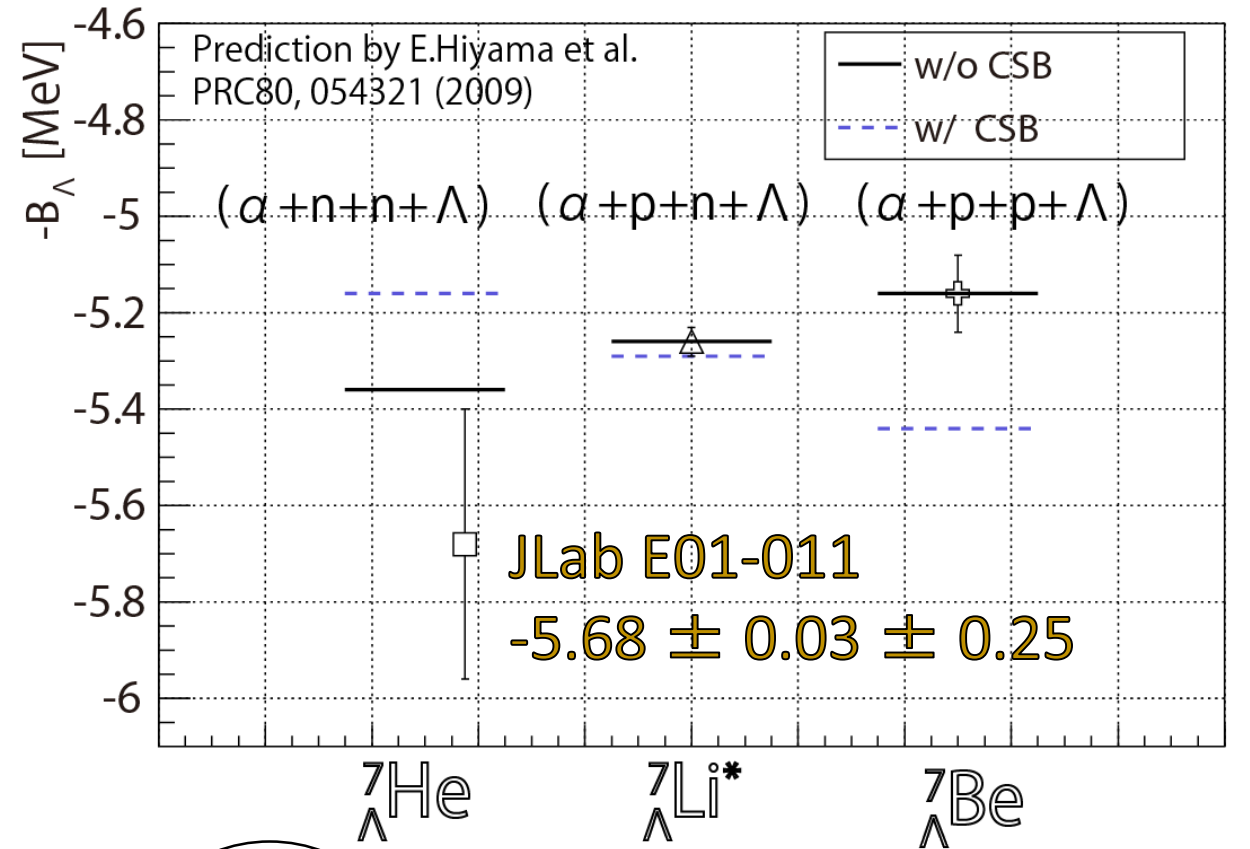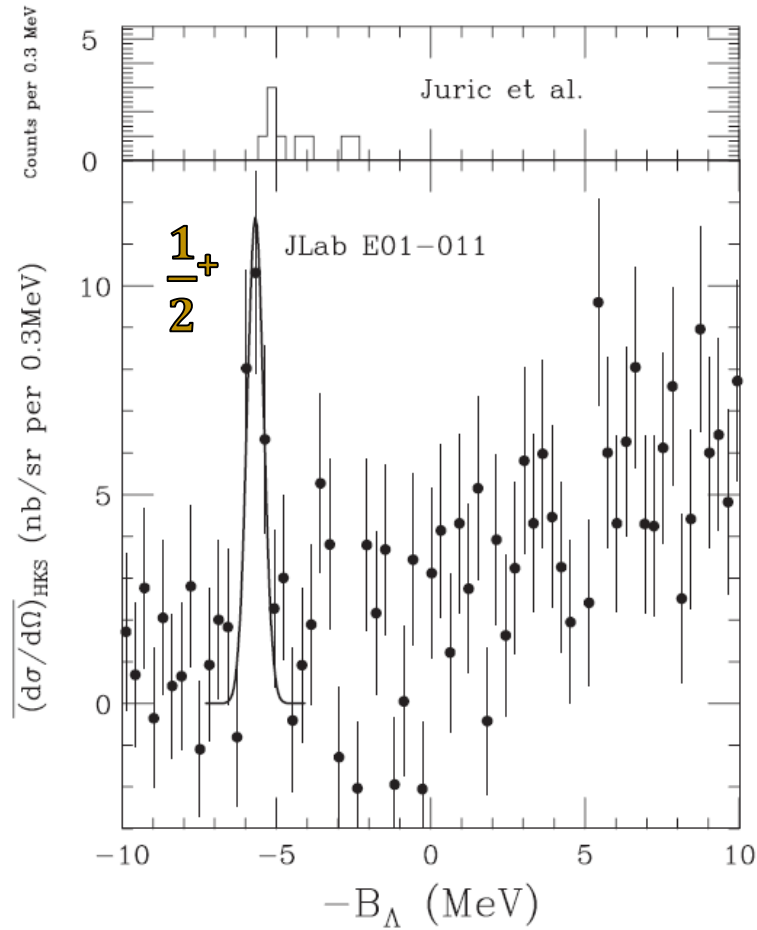
$-B_\Lambda(1/2^+) = -5.68 \pm 0.03 \pm 0.25$

Experimental setup

HES

HKS

e

photon

e'

$\Delta p/p \sim 2 \times 10^{-4}$

$\Delta p/p \sim 2 \times 10^{-4}$

K^+

0.844±0.144 [GeV/c]

ED

KD

$\theta_{e'} = 6.5 \pm 5.0$ [degree]

EQ2

EQ1

KQ2

KQ1

1.20±0.15 [GeV/c]

$\theta_K = 5.7 \pm 4.6$ [degree]

1 [m]

Splitter magnet

Target

Jefferson Lab

2.344 [GeV] electron

Exp

e
Photon

e'

K⁺

HES

HKS

e

Exp
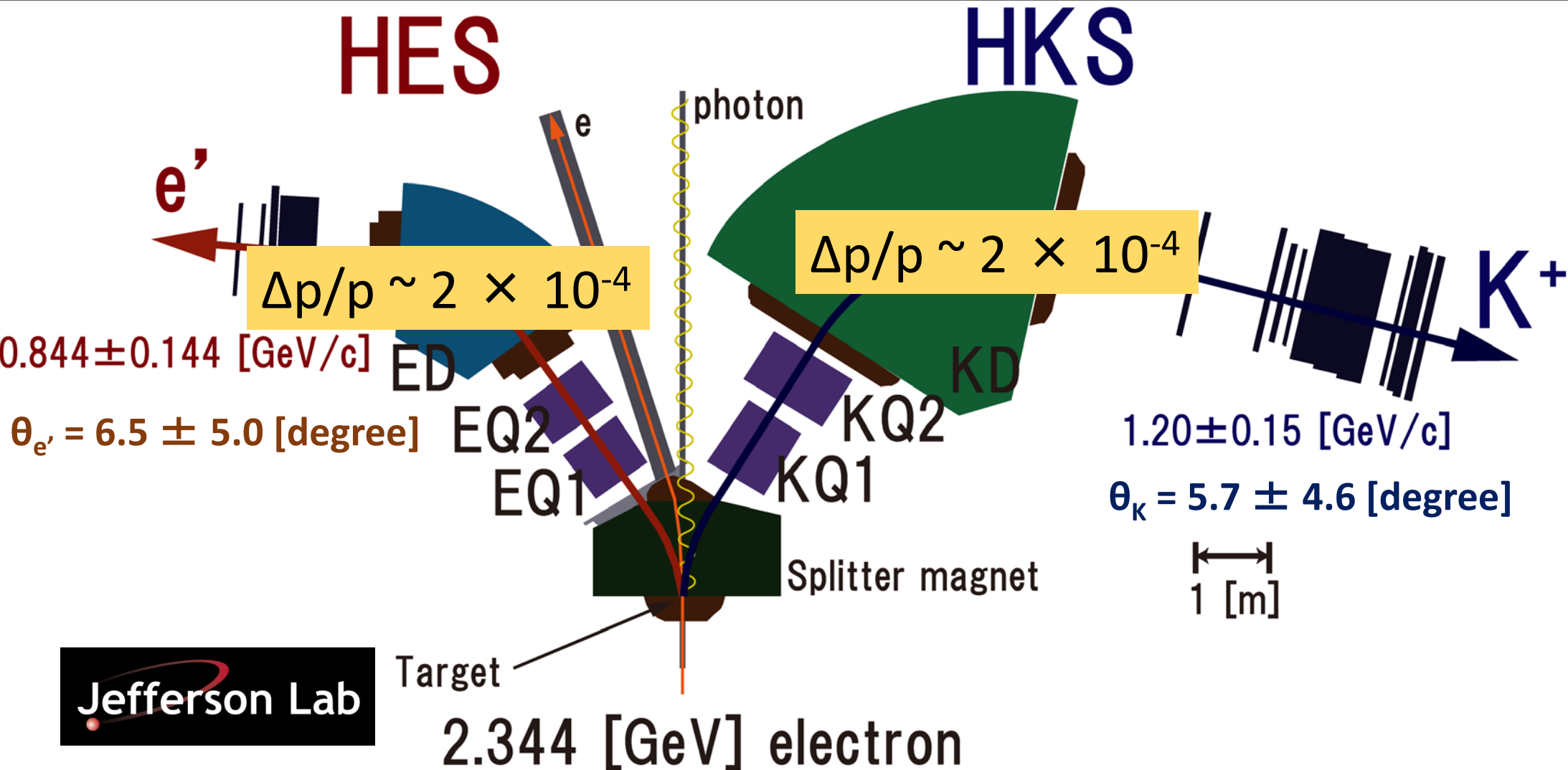
Target ([mg/cm^2])	Hypernucleus Hyperon	Nominal beam current [µA]	Run time [h]	Total incident charge [C] (Number of incident e$^-$)
CH$_2$ (450)	Λ, Σ^0, $^{12}_{\Lambda}$B	2.0	39	0.28 (0.17×10^{19})
H$_2$O (500)	Λ, Σ^0, $^{12}_{\Lambda}$N	2.5	21	0.20 (0.12×10^{19})
^{7}Li (208)	$^7_{\Lambda}$He	35	42	4.84 (3.0×10^{19})
^{9}Be (188)	$^9_{\Lambda}$Li	40	39	5.33 (3.3×10^{19})
^{10}B (56)	$^{10}_{\Lambda}$Be	40	45	6.25 (3.9×10^{19})
^{12}C (88)	$^{12}_{\Lambda}$B	20, 35	55	5.73 (3.6×10^{19})
^{52}Cr (154)	$^{52}_{\Lambda}$V	7.5	230	6.35 (4.0×10^{19})

Contents

- Introduction
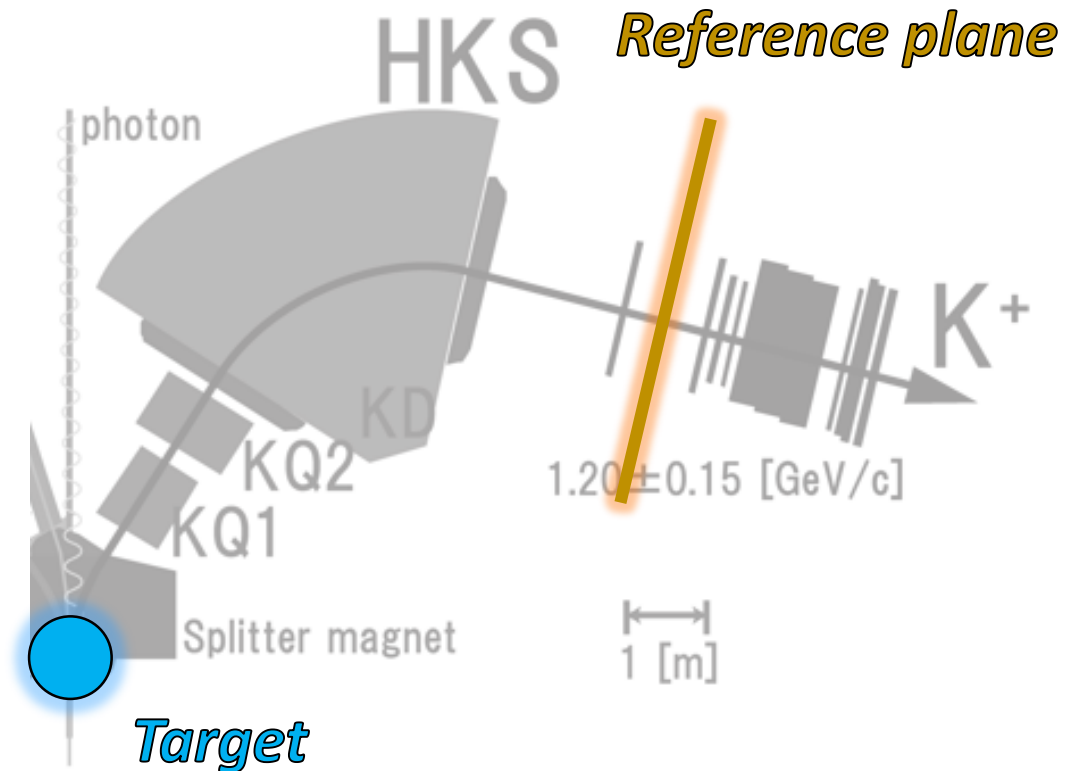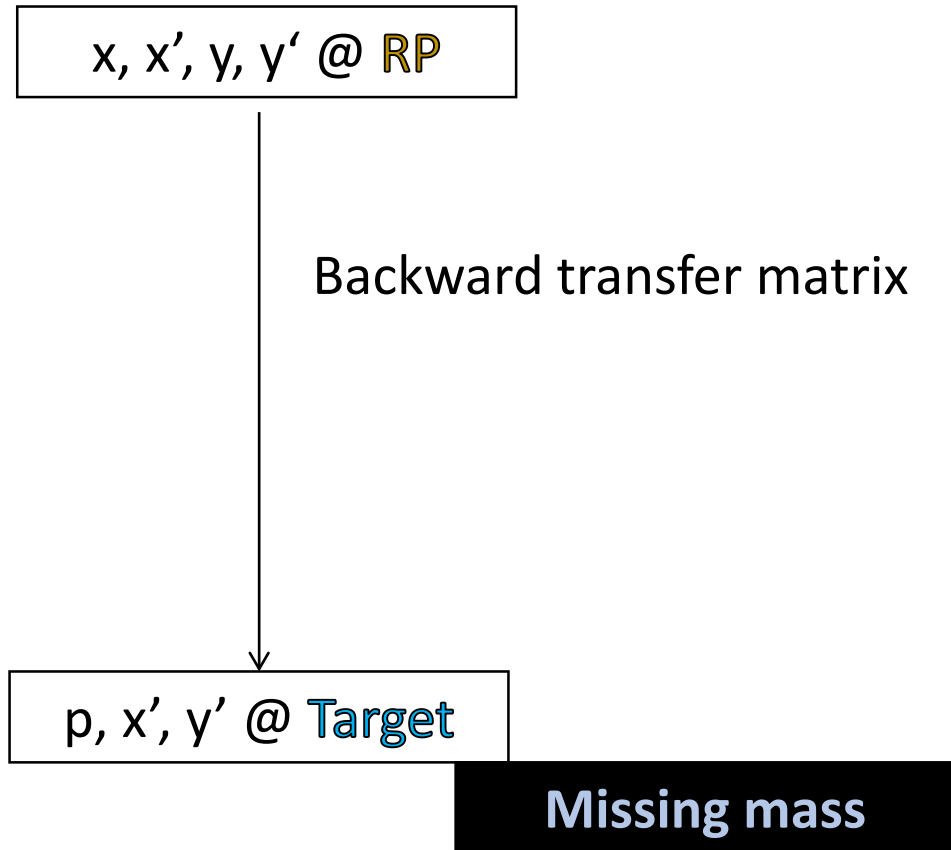 - (e,e'K$^+$) reaction experiment
  - JLab E05-115

- Analysis
  - Energy scale calibration
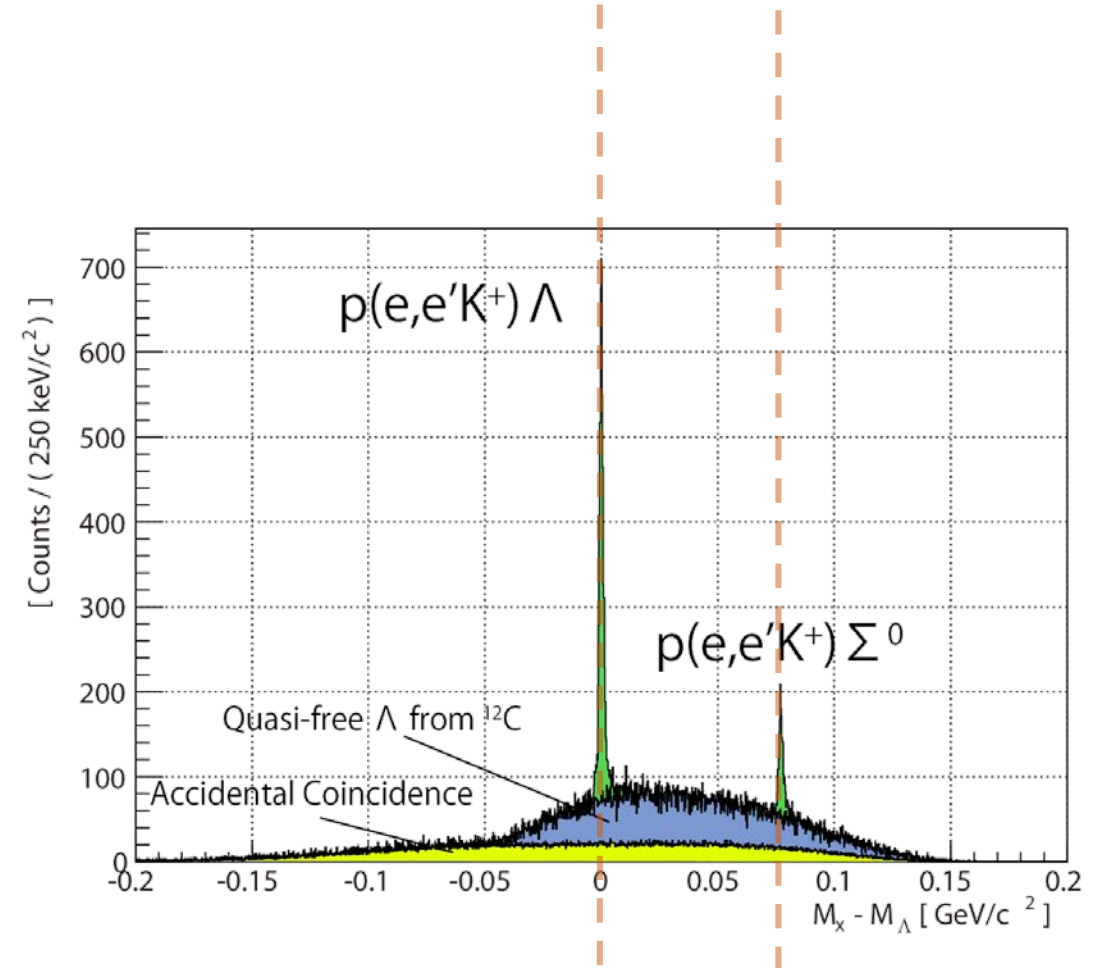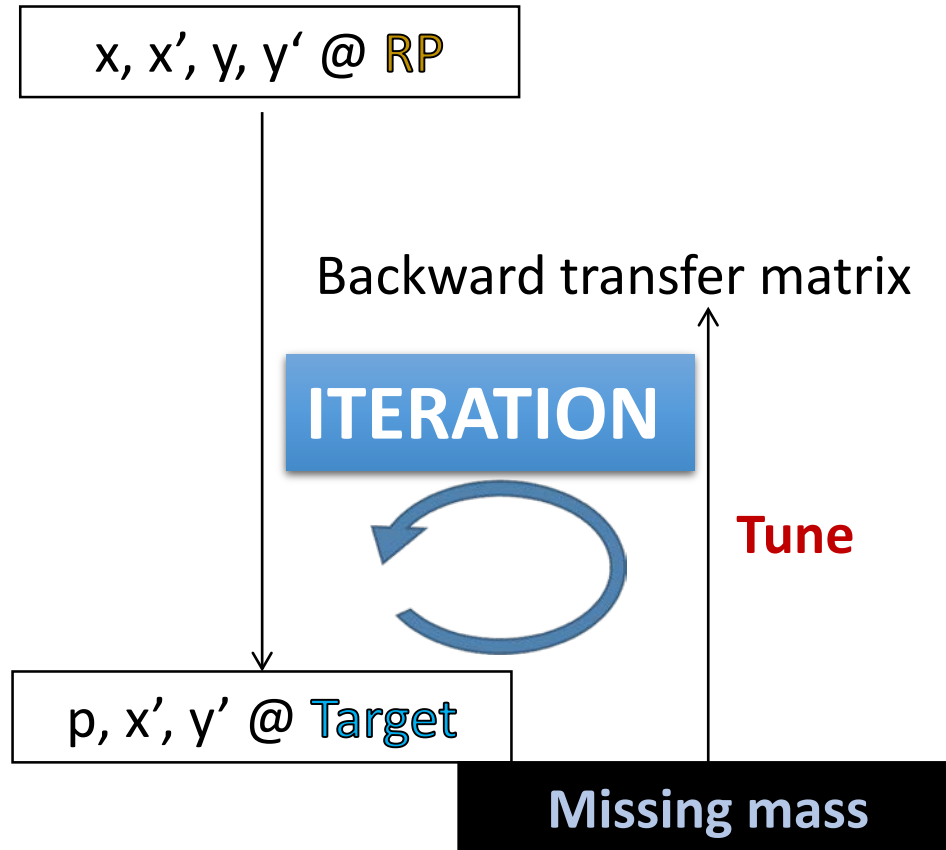 - Binding energy systematic error estimation

- Results
  - ^{12}C(e,e'K$^+$)$^{12}_\Lambda$B
  - ^{7}Li(e,e'K$^+$)$^{7}_\Lambda$He

Absolute energy scale calibration with Λ and Σ^0

x, x', y, y' @ RP

Backward transfer matrix

p, x', y' @ Target

Missing mass

HKS

Reference plane

photon

K$^+$

KD

KQ2

KQ1

1.20±0.15 [GeV/c]

Splitter magnet

1 [m]

Target

Absolute energy scale calibration with Λ and Σ^0

x, x', y, y' @ RP

Backward transfer matrix

ITERATION

Tune

p, x', y' @ Target

Missing mass

p(e,e'K+) Λ

p(e,e'K+) Σ^0

Quasi-free Λ from ^{12}C

Accidental Coincidence

[Counts / (250 keV/c^2)]

$M_x - M_\Lambda$ [GeV/c^2]

Λ, Σ⁰ comparison
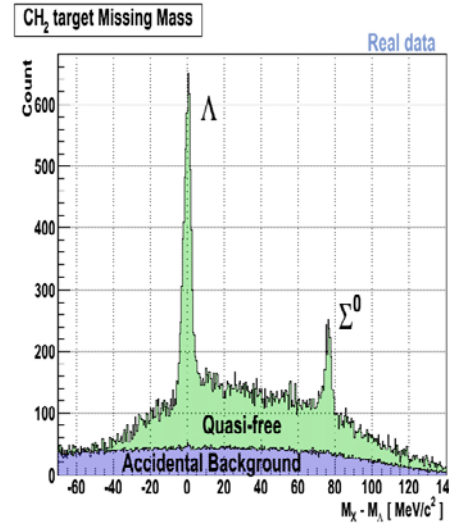
Before
(Δp/p ~ 10⁻³)

After
(Δp/p ~10⁻⁴)
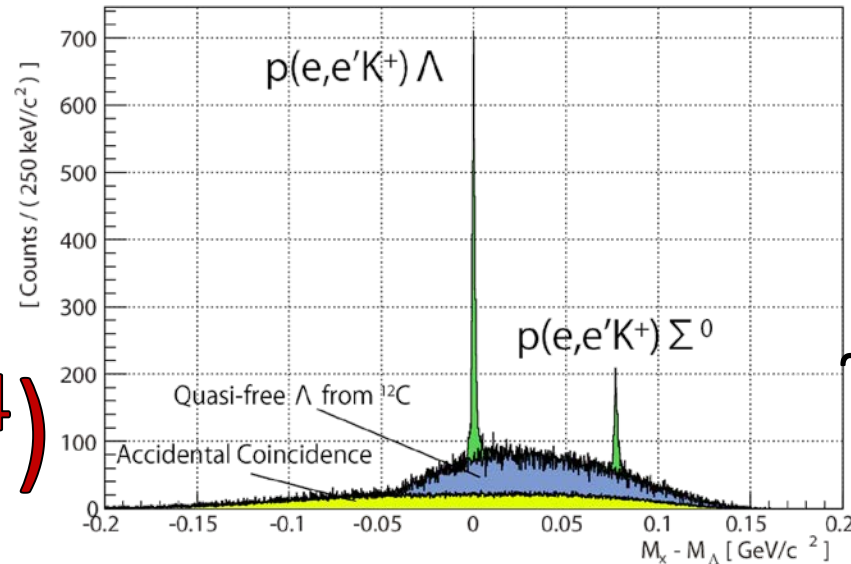
4 MeV (FWHM)

1.6 MeV (FWHM)

~ 0.5 MeV (FWHM) for $^{12}_{\Lambda}$B
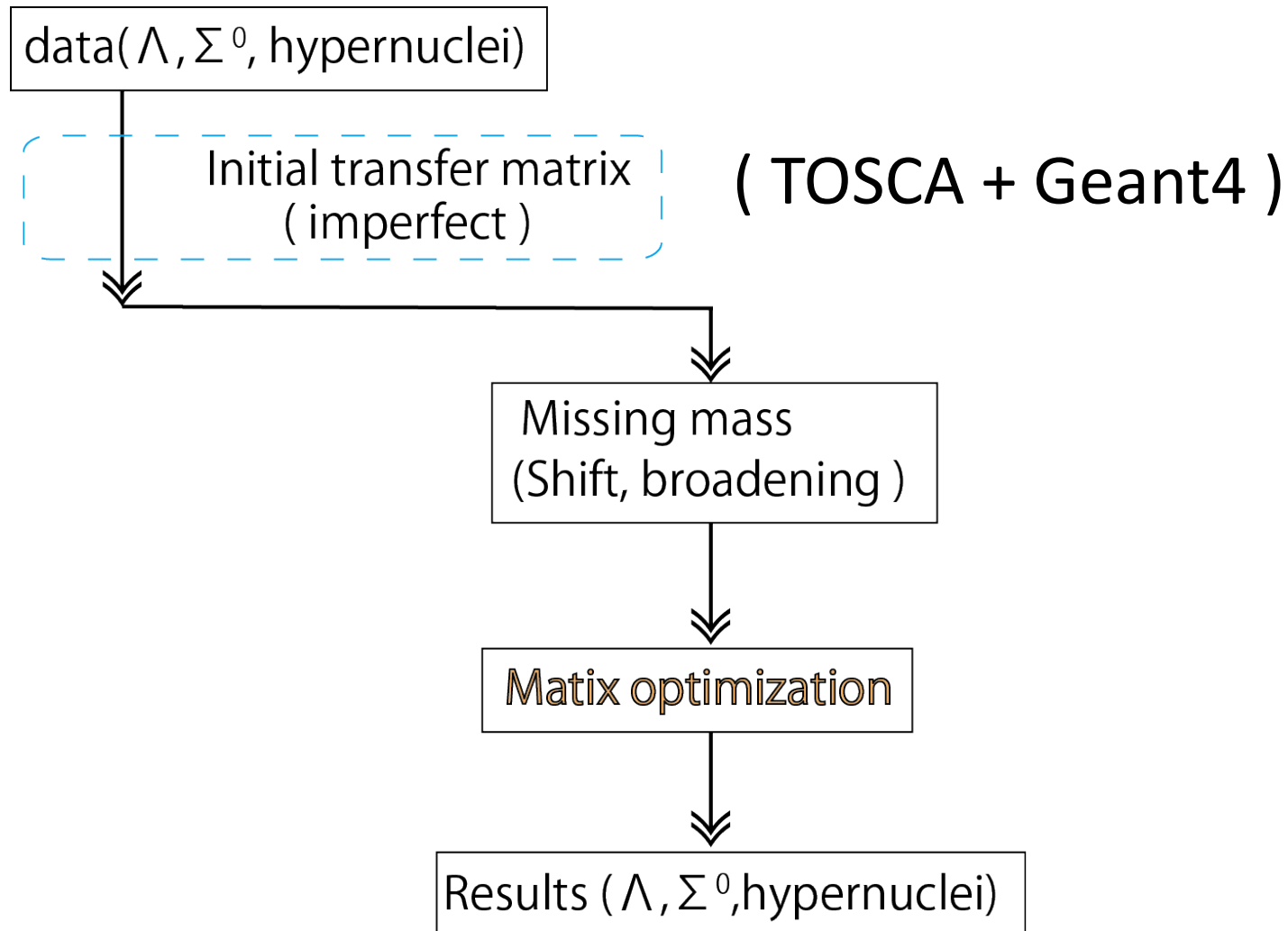
Λ, Σ⁰ comparison

Before
(Δp/p ~ 10⁻³)

4 MeV (FWHM)

How good is the binding energy determined ?
(Systematic error)

1.6 MeV (FWHM)

After
(Δp/p ~10⁻⁴)

~ 0.5 MeV (FWHM) for $^{12}_{\Lambda}B$

Systematic error estimation for binding energy

data(Λ, Σ^0, hypernuclei)

Initial transfer matrix
(imperfect)

(TOSCA + Geant4)

Missing mass
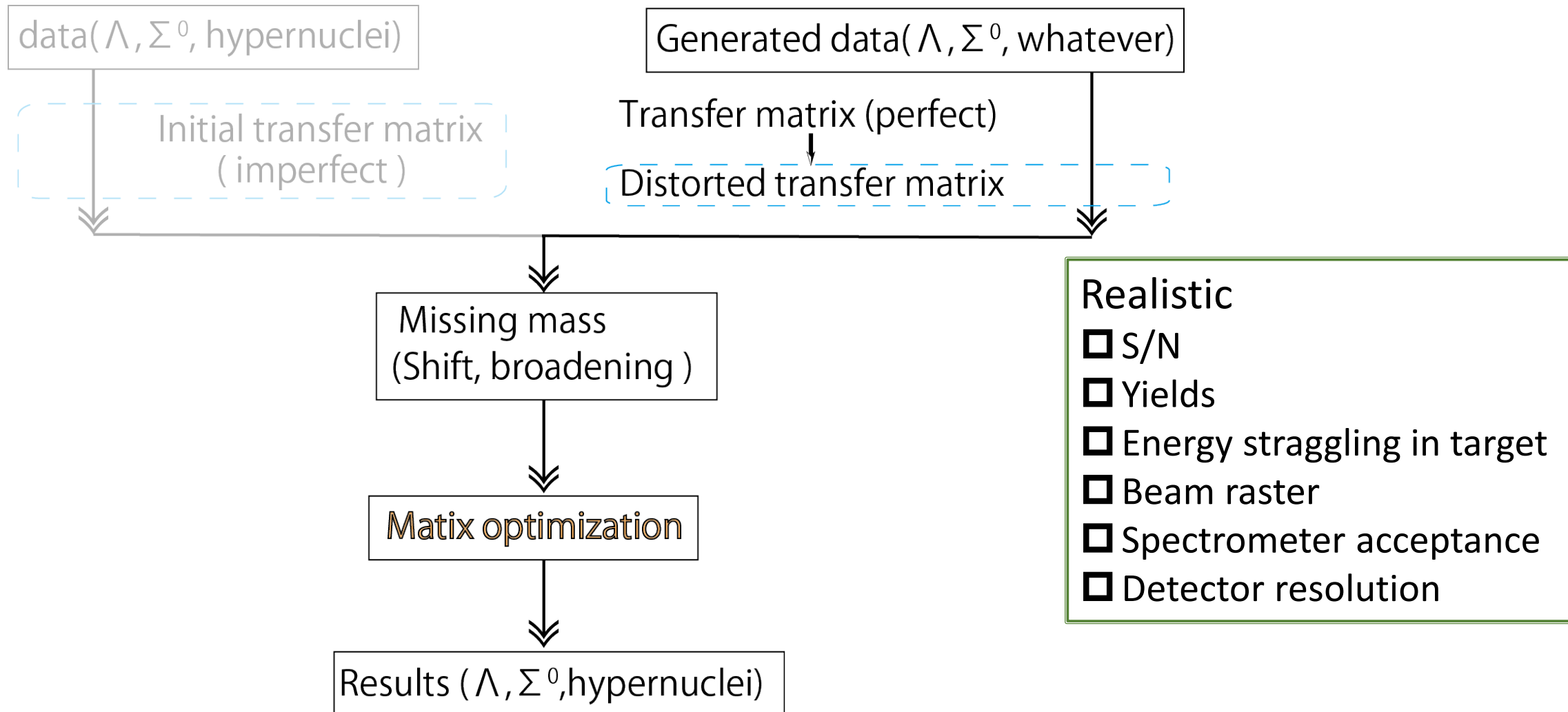(Shift, broadening)

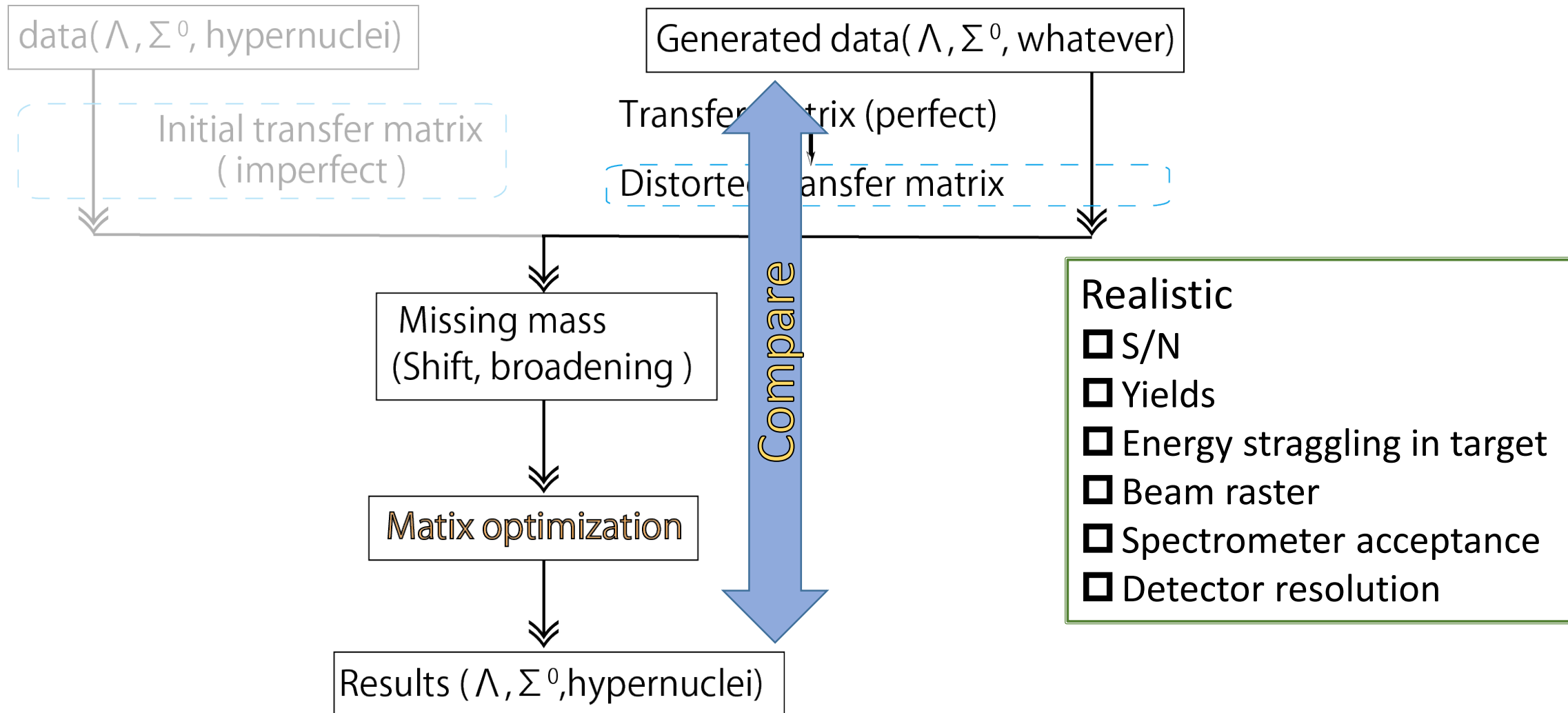Matix optimization
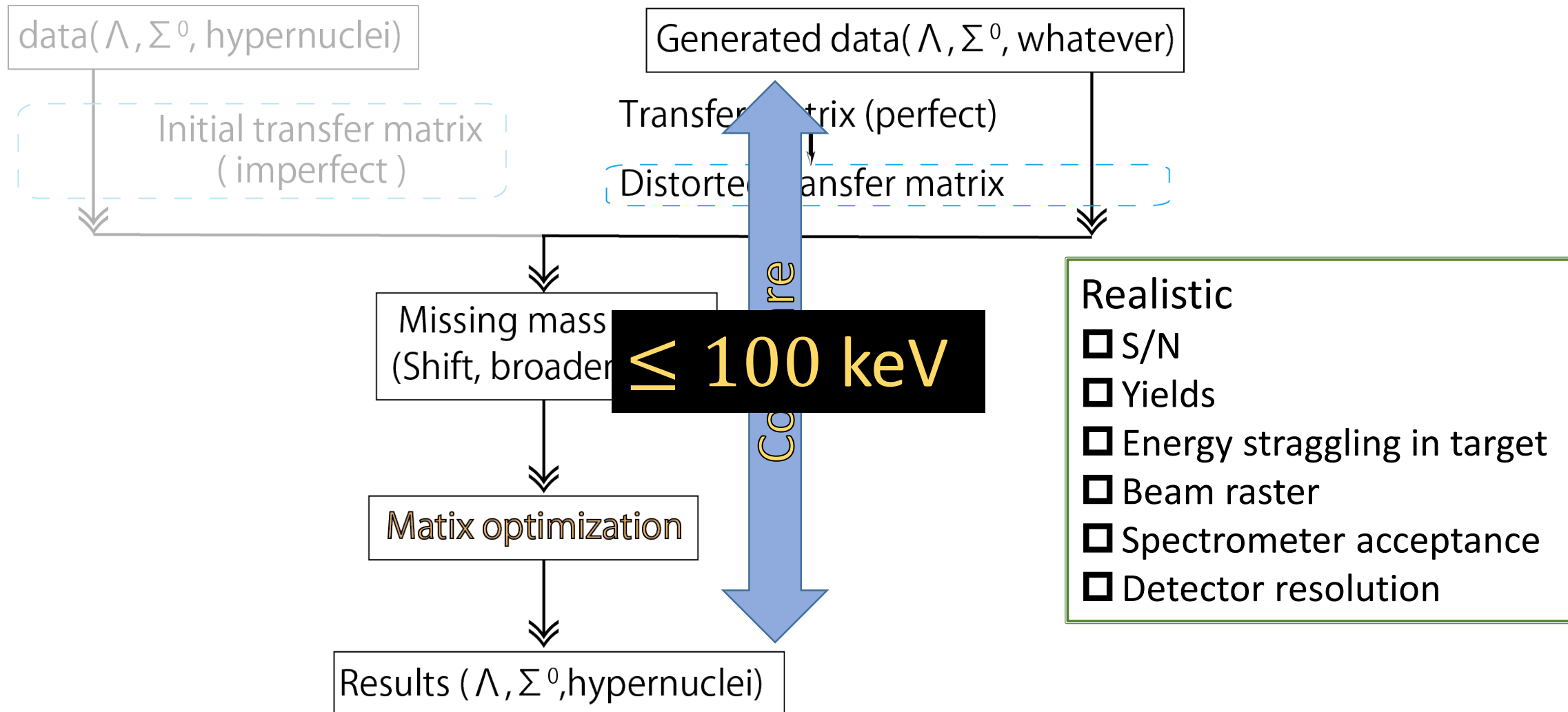
Results (Λ, Σ^0, hypernuclei)

Systematic error estimation for binding energy

Systematic error estimation for binding energy

Systematic error estimation for binding energy

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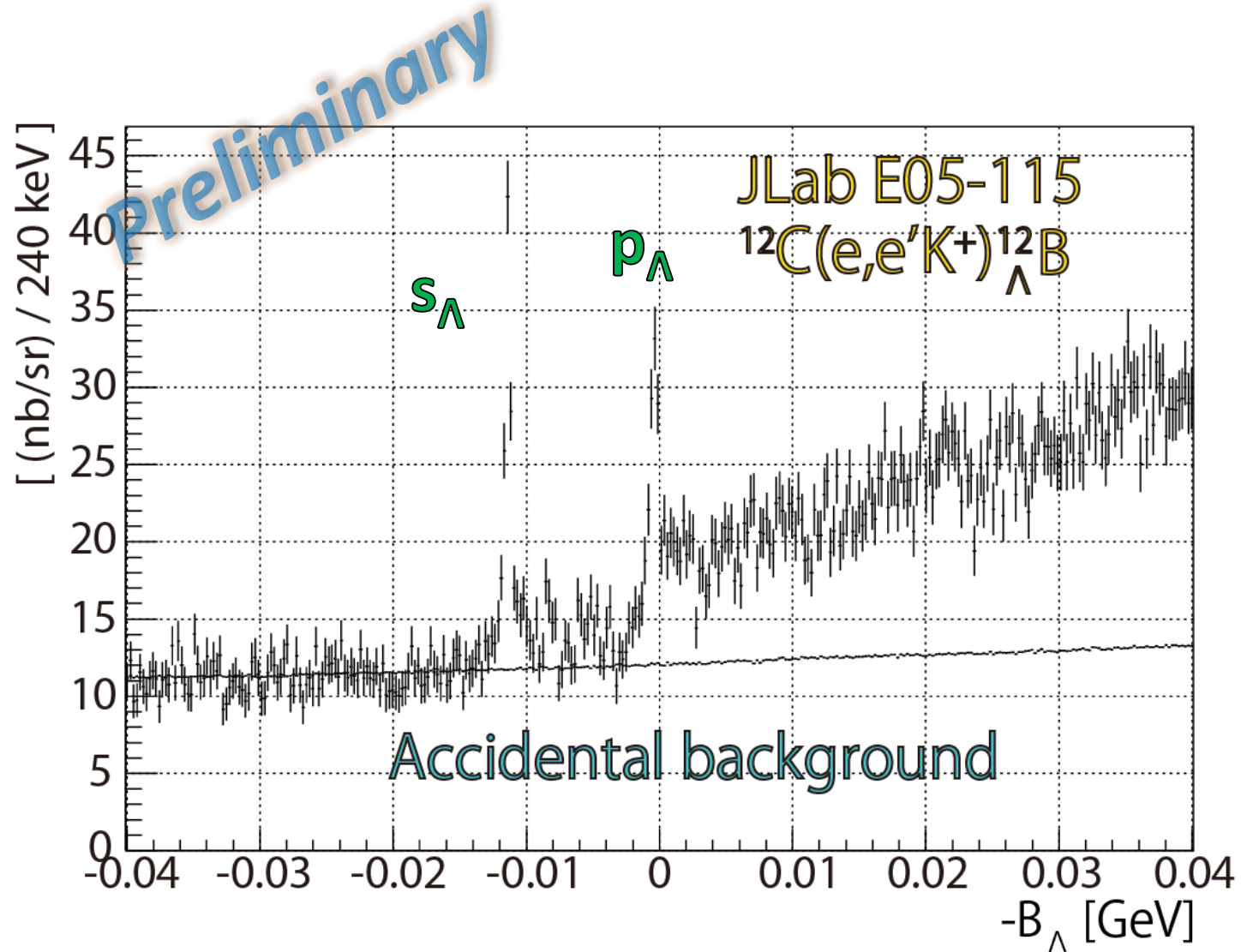 - (e,e'K$^+$) reaction experiment
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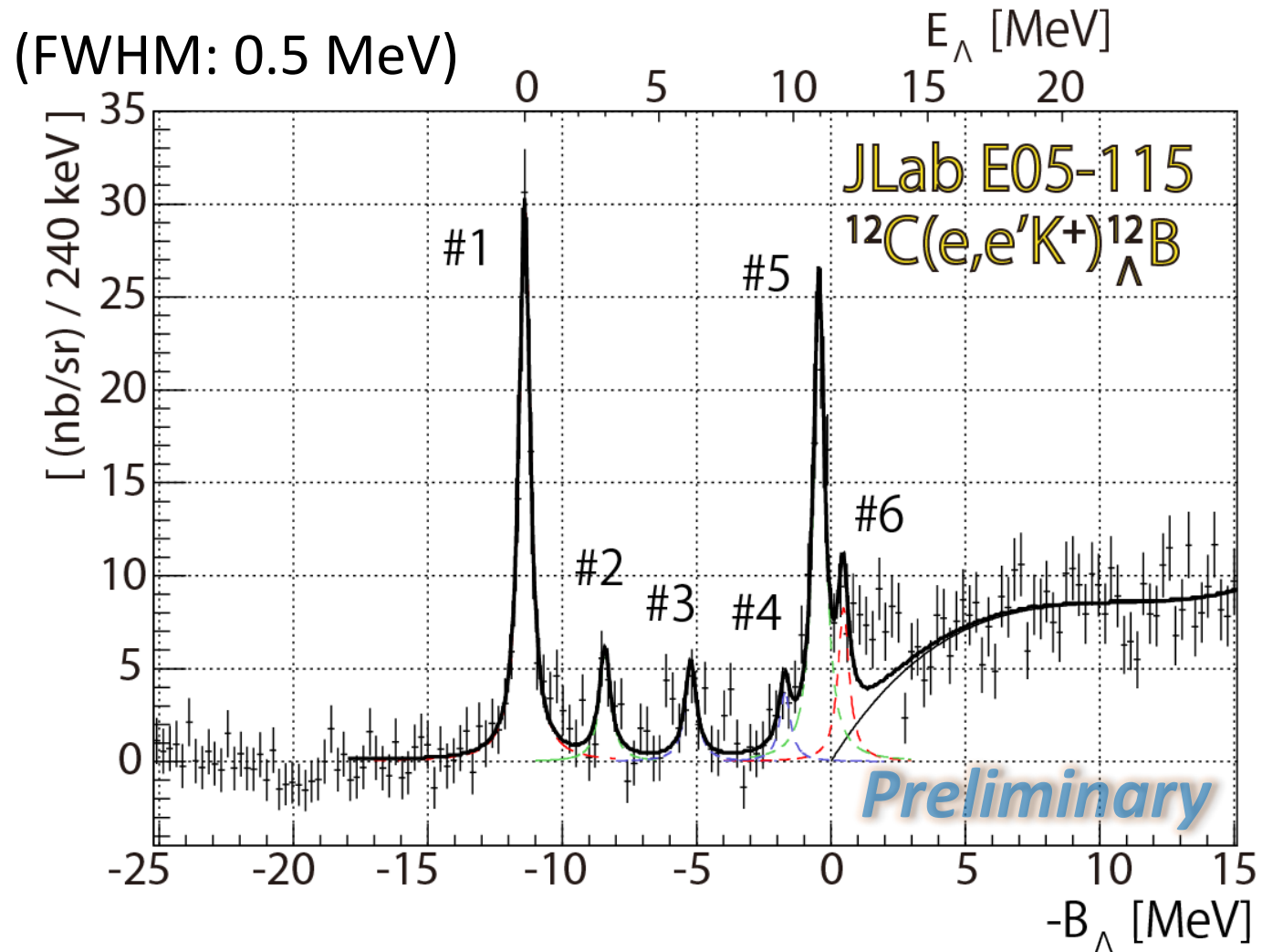 - Binding energy systematic error estimation

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

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

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

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

S_{Λ}

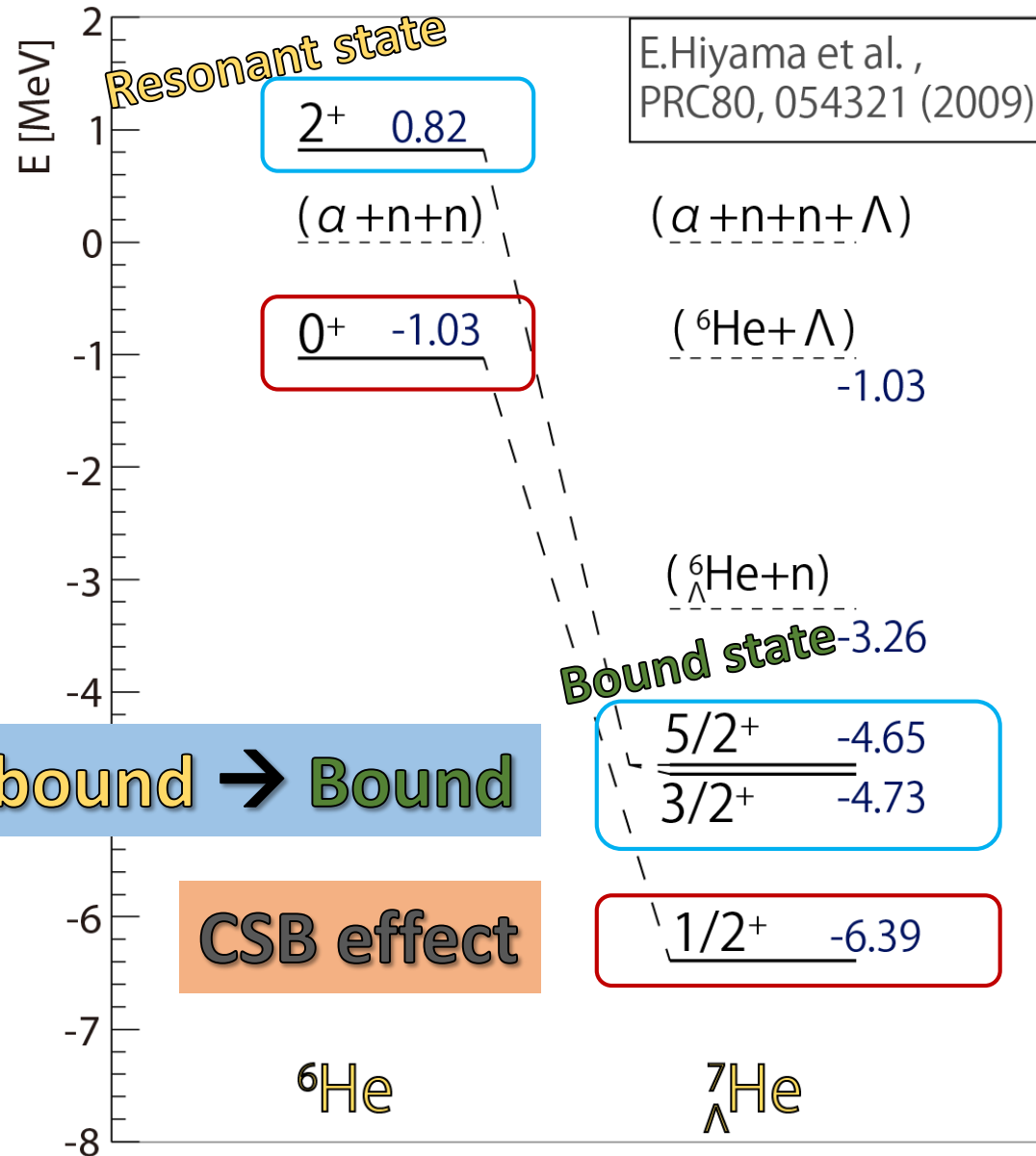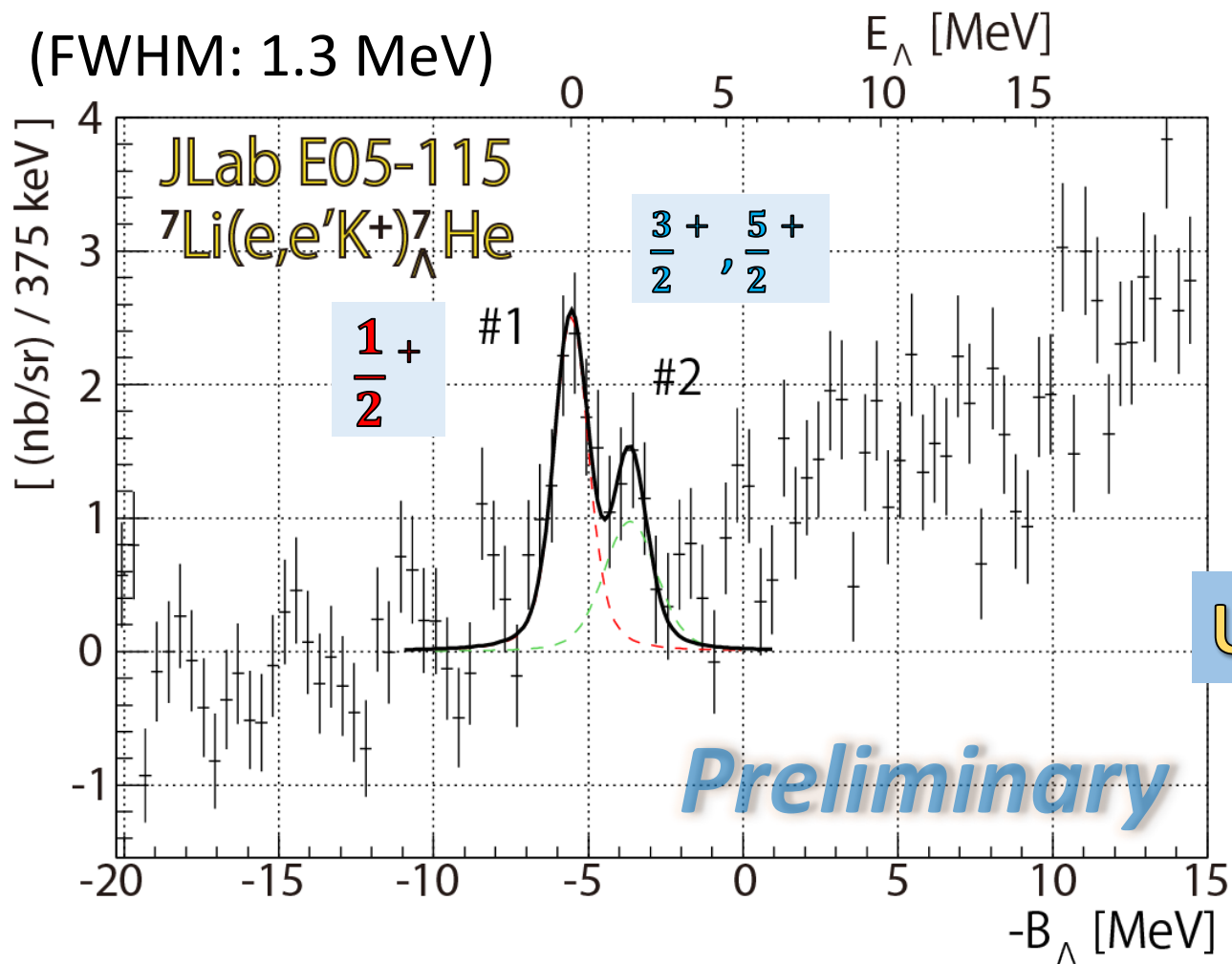| Experiment	$\theta_{\gamma K}^{Lab}$ [degree]	$-B_{\Lambda}$ [MeV]	Cross section [nb/sr]	Extracted value from Motoba-san's prediction
E05-115	6.8	-11.38 $\pm$ 0.02 $\pm$ sys. error	97.8 $\pm$ 3.6 $\pm$ 11.5	75
E01-011	5.8	-11.40 $\pm$ 0.01 $\pm$ 0.04	101 $\pm$ 4.2 (+ 38 − 31)	85
E89-009	0	-11.52 $\pm$ 0.35	140 $\pm$ 17 $\pm$ 18	120
Emulsion		-11.37 $\pm$ 0.06	N/A	-

p_{Λ}

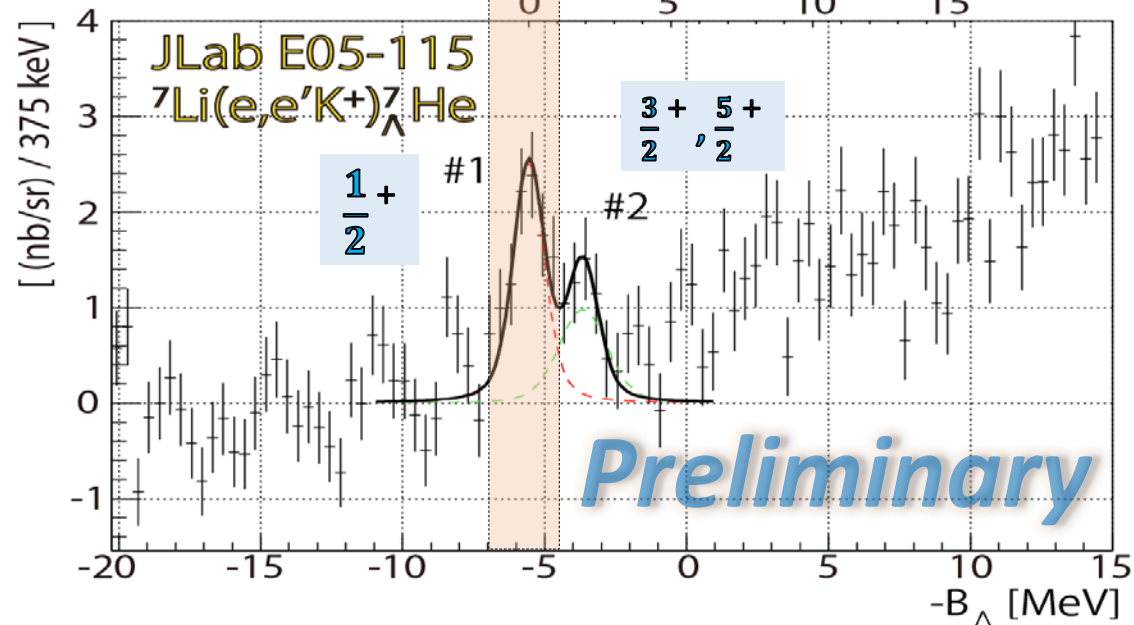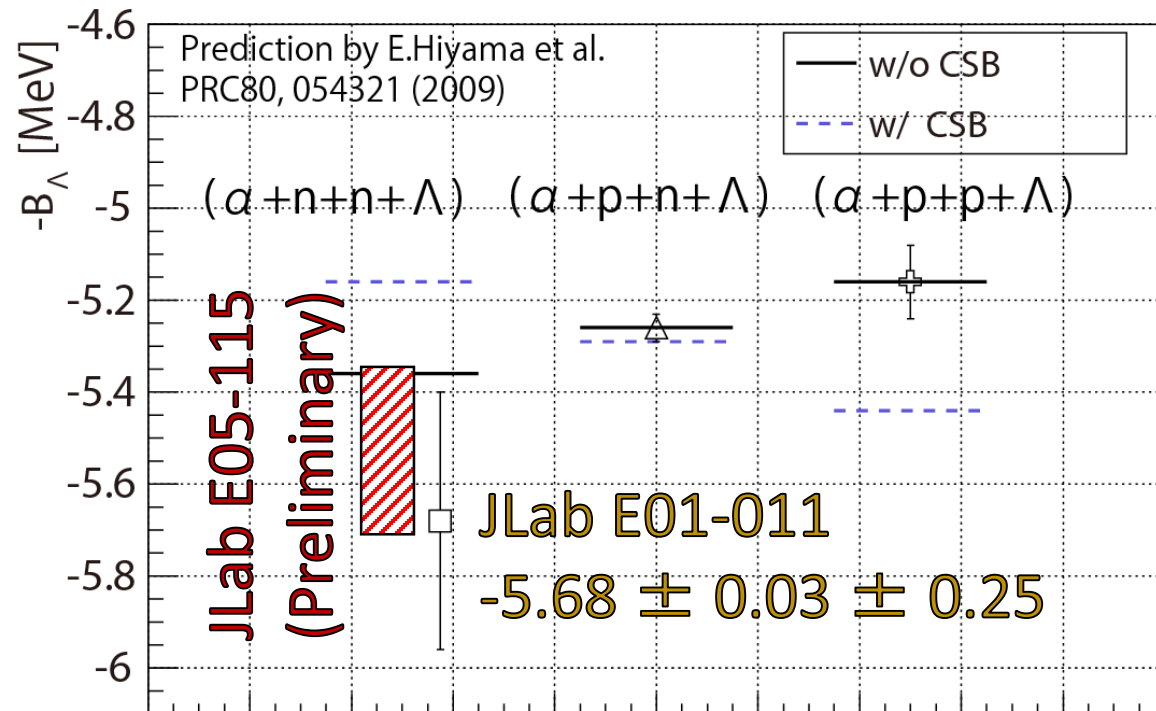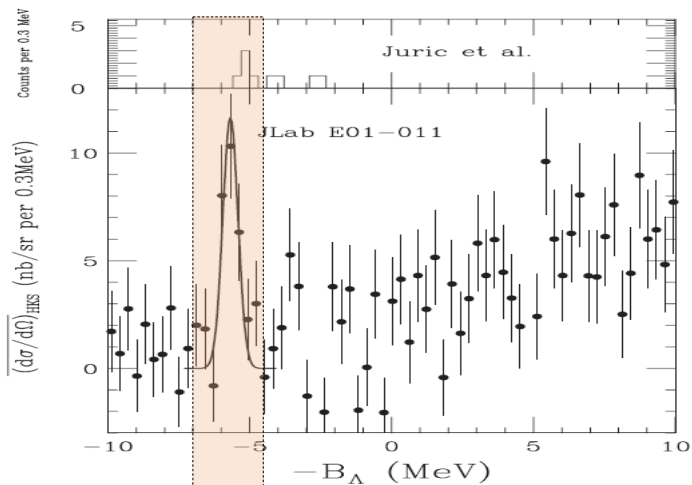| Experiment	$\theta_{\gamma K}^{Lab}$ [degree]	$-B_{\Lambda}$ [MeV]	Cross section [nb/sr]	Extracted value from Motoba-san's prediction
E05-115	6.8	-0.43 $\pm$ 0.03 $\pm$ sys. error	84.1 $\pm$ 3.3 $\pm$ 9.9	85
E01-011	5.8	-0.41 $\pm$ 0.01 $\pm$ 0.13	94 $\pm$ 4.0 $\pm$ 35	96
E89-009		-0.49 $\pm$ 0.16	N/A	-

Results for ^{7}Li(e,e'K^{+})$^{7}_{\Lambda}$He

(FWHM: 1.3 MeV)

JLab E05-115
^{7}Li(e,e'K^{+})$^{7}_{\Lambda}$He

$\frac{1}{2}^{+}$ #1

$\frac{3}{2}^{+}$, $\frac{5}{2}^{+}$ #2

Preliminary

Resonant state

E.Hiyama et al.,
PRC80, 054321 (2009)

2^{+} 0.82

(α +n+n)   (α +n+n+Λ)

0^{+} -1.03

(^{6}He+Λ)   -1.03

($^{6}_{\Lambda}$He+n)   -3.26

Bound state

$5/2^{+}$ -4.65
$3/2^{+}$ -4.73

Unbound → Bound

CSB effect

$1/2^{+}$ -6.39

^{6}He $^{7}_{\Lambda}$He

Results of $^{7}_{\Lambda}$He

S.N.Nakamura et al., PRL 110, 012502 (2013)

JLab E05-115
^{7}Li(e,e'K^{+})$^{7}_{\Lambda}$He

$\frac{1}{2}^{+}$

$\frac{3}{2}^{+}$, $\frac{5}{2}^{+}$

#1   #2

Preliminary

Prediction by E.Hiyama et al.
PRC80, 054321 (2009)

w/o CSB
w/ CSB

$(\alpha+n+n+\Lambda)$ $(\alpha+p+n+\Lambda)$ $(\alpha+p+p+\Lambda)$

JLab E05-115
(Preliminary)

JLab E01-011
-5.68 ± 0.03 ± 0.25

$^{7}_{\Lambda}$He $^{7}_{\Lambda}$Li* $^{7}_{\Lambda}$Be
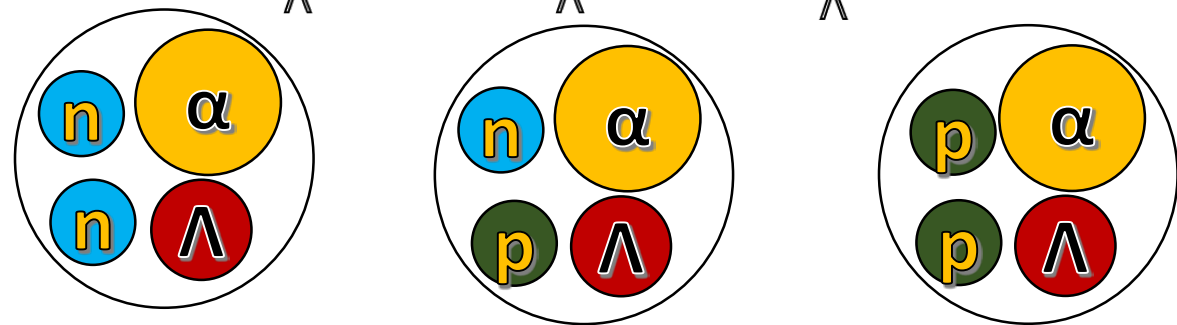
Results of $^{7}_{\Lambda}$He

S.N.Nakamura et al., PRL 110, 012502 (2013)
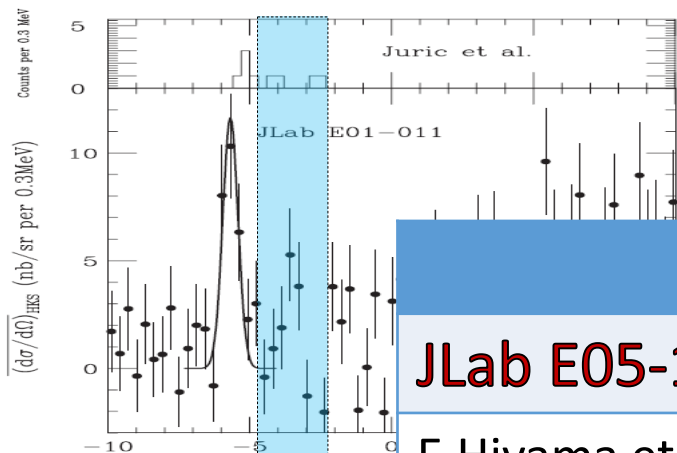
	E_{Λ} (3/2$^+$,5/2$^+$) [MeV]
JLab E05-115	**1.90$\pm$0.2$\pm$ sys. error**
E.Hiyama et al., PRC 80, 054321 (2009)	1.70
M.Sotona et al., PTP 117 (1994)	1.79

E.Hiyama et al., PRC80, 054321 (2009)
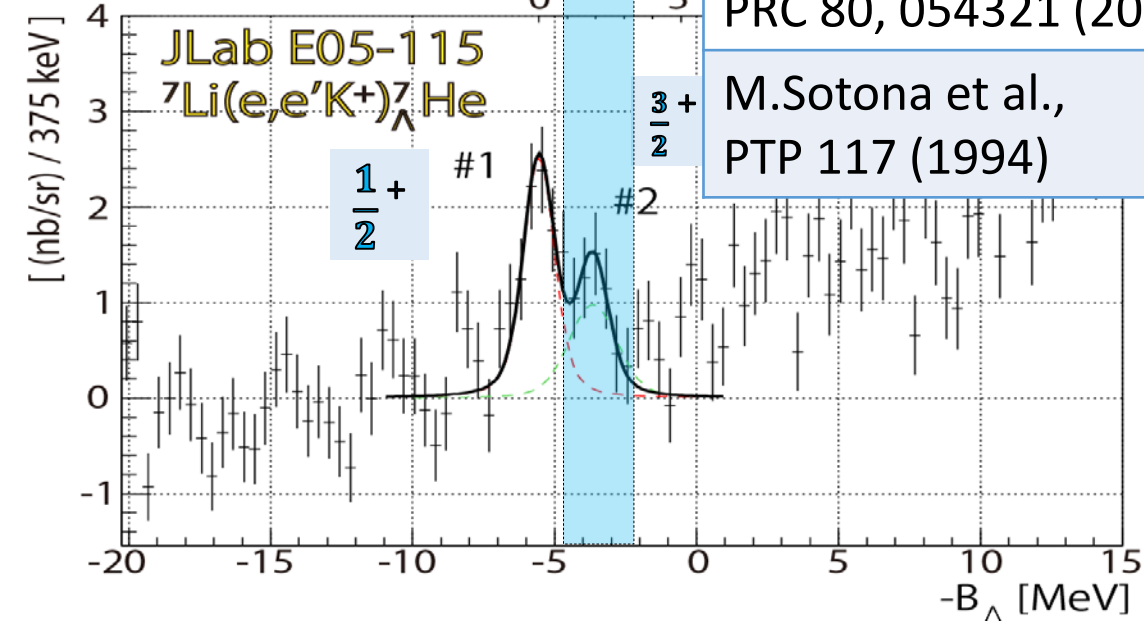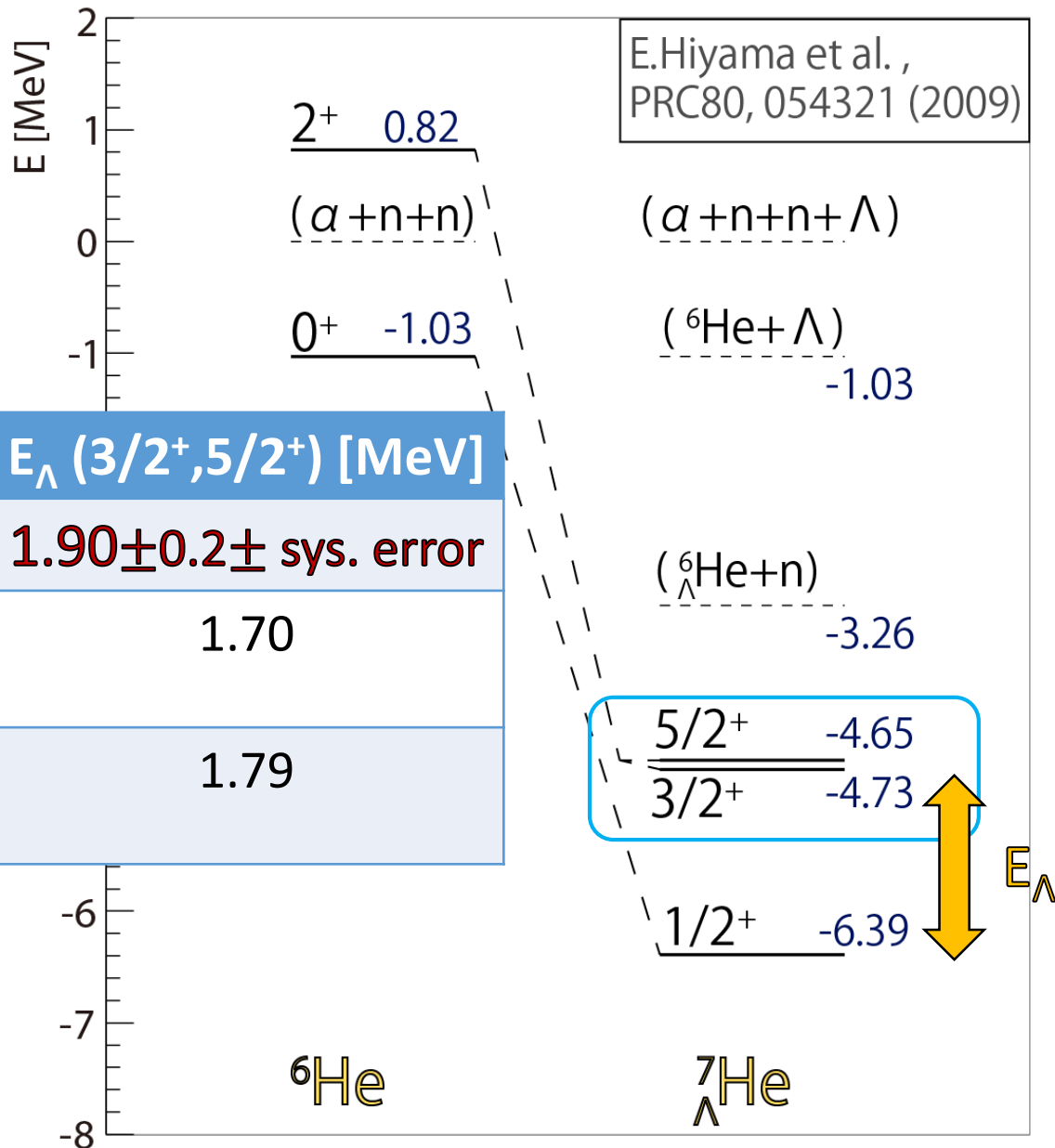
Summary

- ## JLab E05-115 experiment (2009)
  - Λ, Σ^0, $^7_\Lambda$He, $^9_\Lambda$Li, $^{10}_\Lambda$Be, $^{12}_\Lambda$B and $^{52}_\Lambda$V

- ## $^{12}_\Lambda$B
  - Best resolution
  - Consistent with past experiments

- ## $^7_\Lambda$He
  - 1/2+ with small systematic error
  - 2$^+$ (core) $\rightarrow$ 3/2$^+$,5/2$^+$ ($^7_\Lambda$He) was measured

Outlook

- Systematic error
- Fitting to the histogram
- $^{52}_{\Lambda}V$