Recent Spectroscopic Investigation of Λ-Hypernuclei by the (e,e′K^+) Reaction at JLab Hall C

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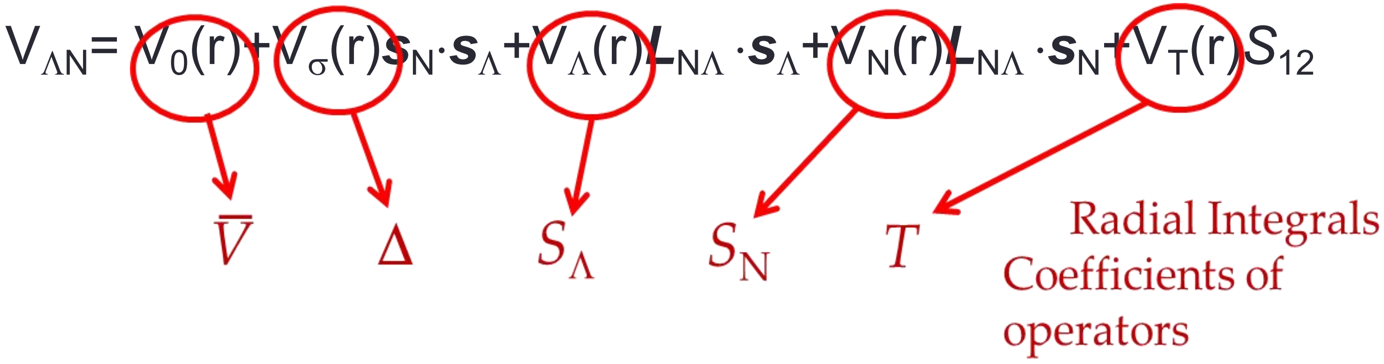
SNP2014

Introduction

Physical Goals:

- To understand YN and YY interactions
- To explore and understand nuclear structure using Λ as a probe
  - **Model the baryonic many body system**
  - **Study the role of Λ in the nuclear medium**

- Shell Model with Λ-N Effective Potential ($p_N s_\Lambda$) for p-shell hypernuclei



$$V_{\Lambda N} = V_0(r) + V_\sigma(r)\,\boldsymbol{s}_N \cdot \boldsymbol{s}_\Lambda + V_\Lambda(r)\,\boldsymbol{L}_{N\Lambda} \cdot \boldsymbol{s}_\Lambda + V_N(r)\,\boldsymbol{L}_{N\Lambda} \cdot \boldsymbol{s}_N + V_T(r)\,S_{12}$$

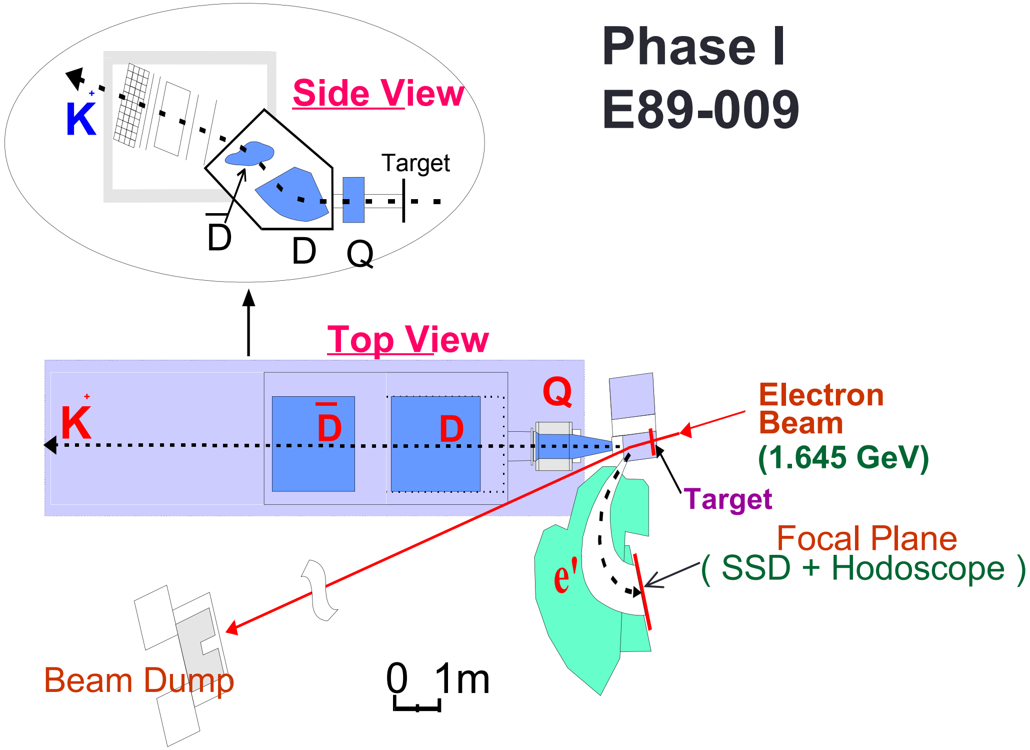
$\bar{V}$ Δ S_Λ S_N T

Radial Integrals Coefficients of operators

Hall C technique in 6GeV program

-common split magnet-

Phase I
E89-009



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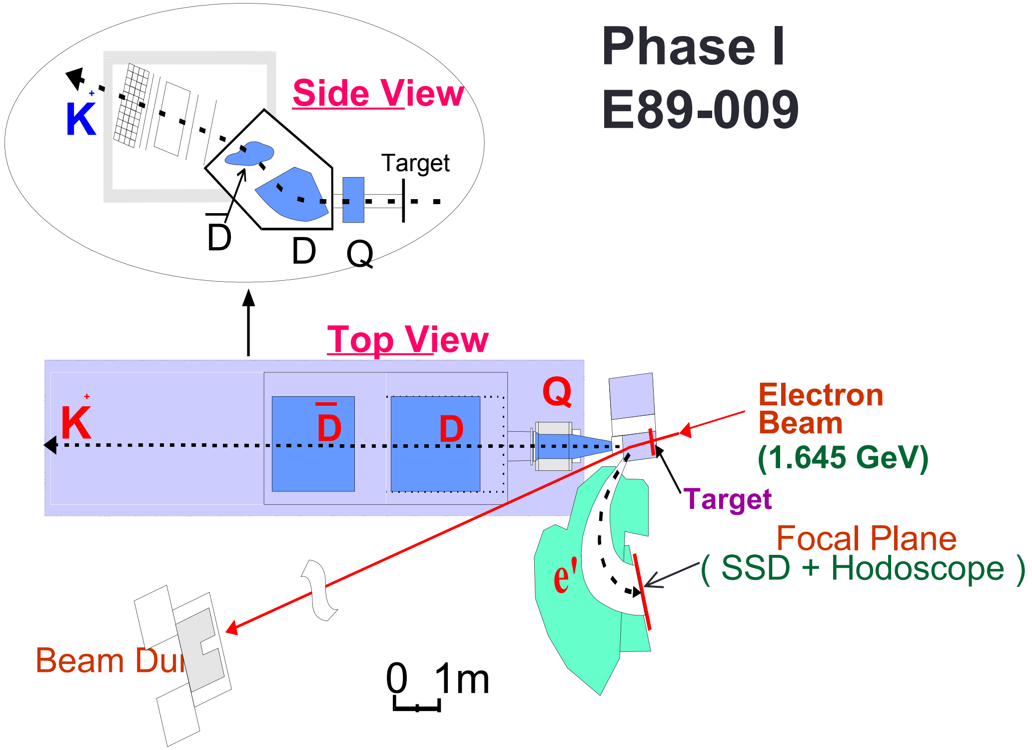

- Zero degree e’ tagging
- High e’ single rate
- Low beam luminosity
- High accidental rate
- Low yield rate
- A first important milestone for hypernuclear physics with electro-production

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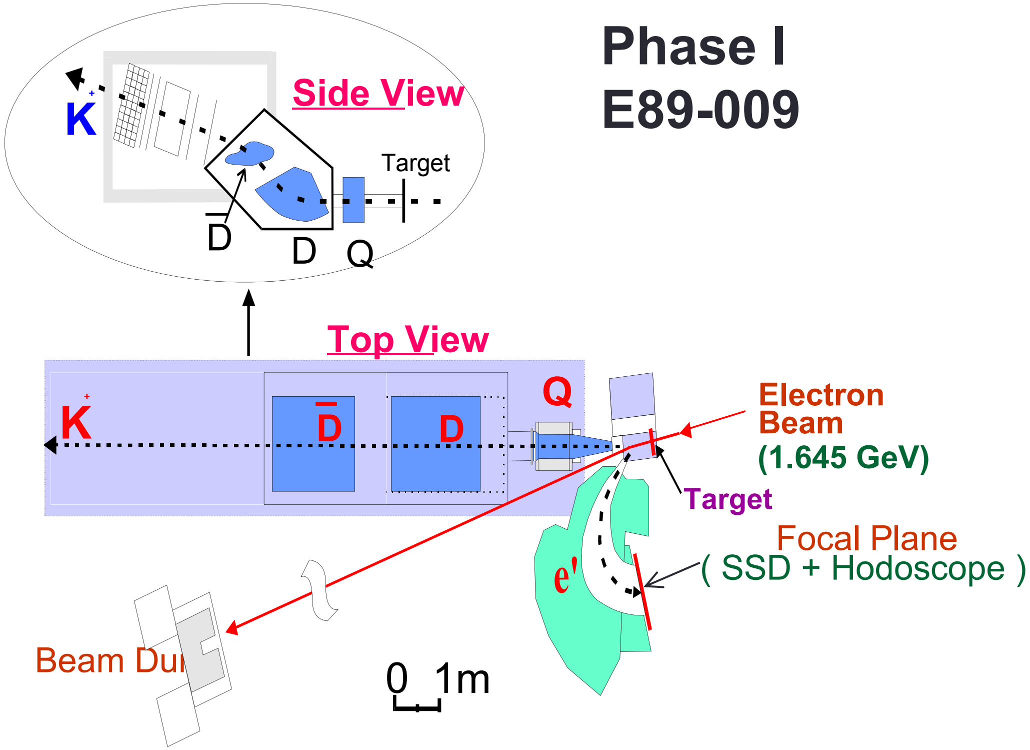

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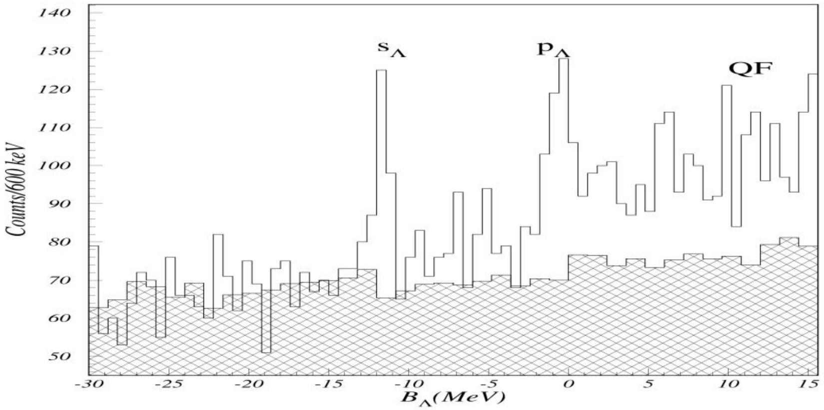

$^{12}_{\Lambda}B$ G.S. peak 920 keV(FWHM}

Hall C technique in 6GeV program

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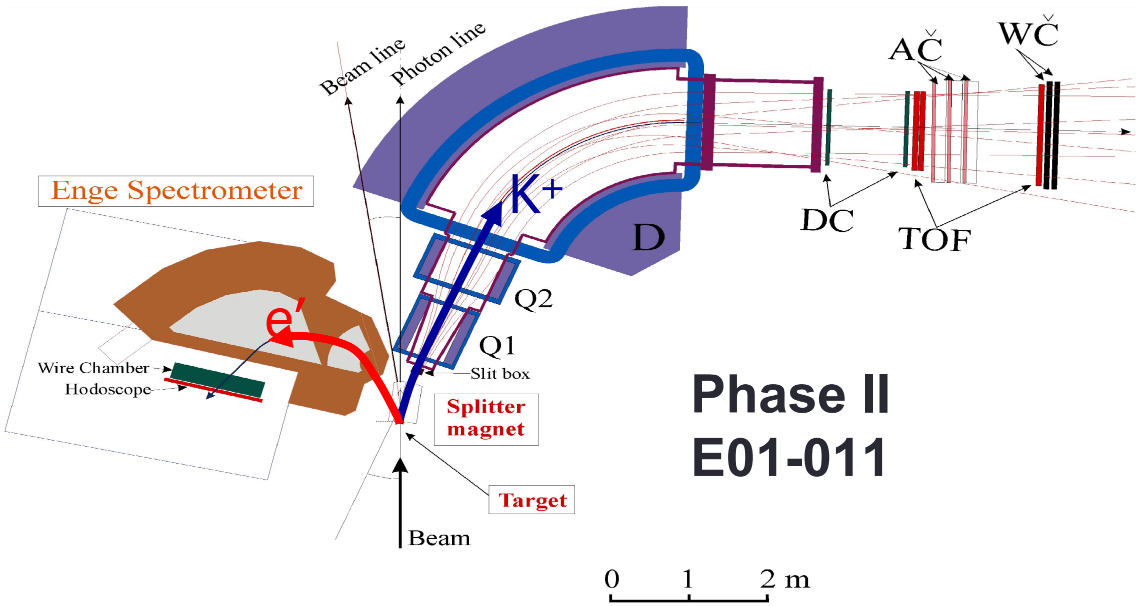
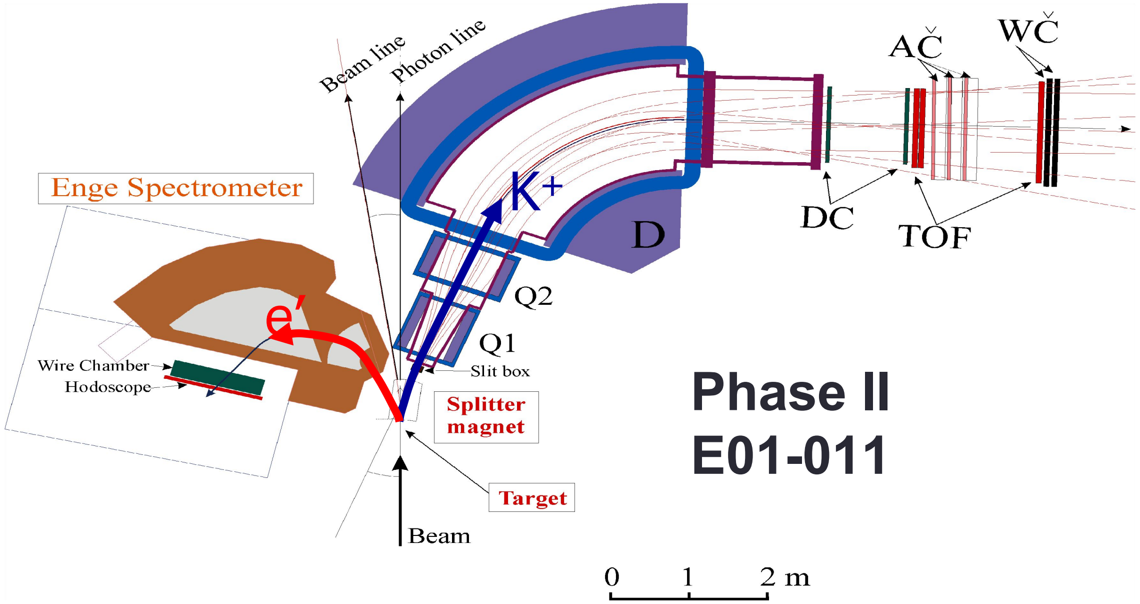


Phase II
E01-011

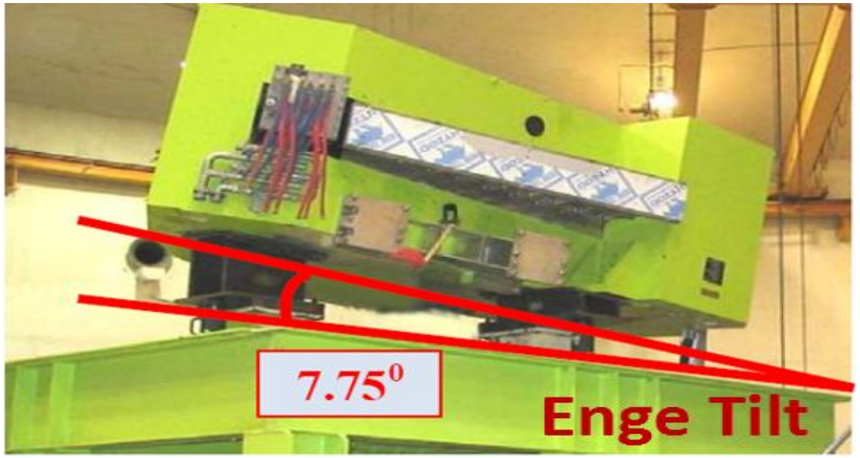
Hall C technique in 6GeV program

-common split magnet-



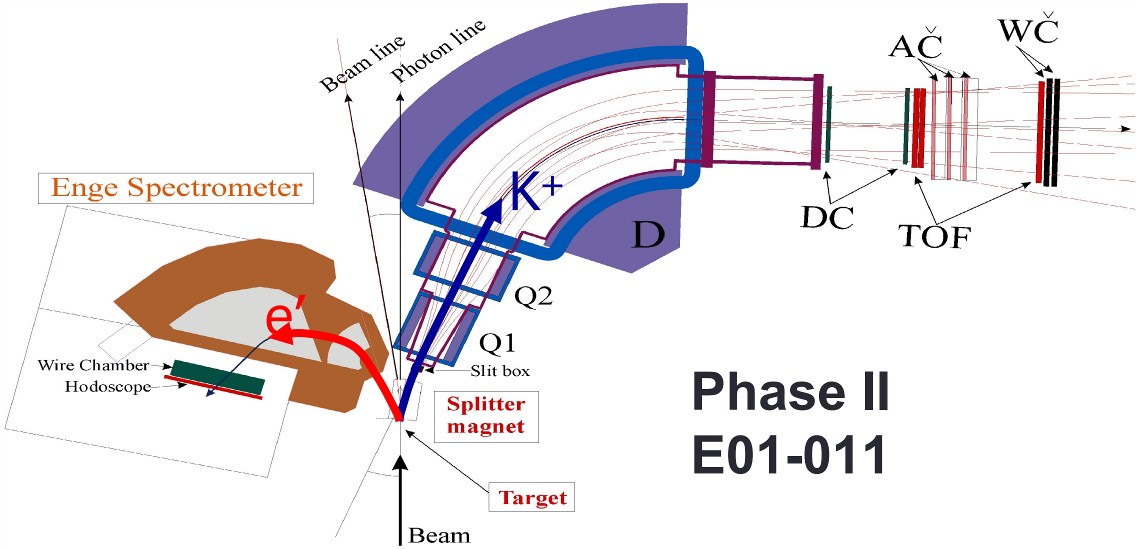
Phase II
E01-011

- ❖ New HKS spectrometer → large ΔΩ
- ❖ Tilted Enge spectrometer → Reduce e' single rate by a factor of 10^{-5}
- ❖ High beam luminosity
- ❖ Accidental rate improves 4 times
- ❖ High yield rate
- ❖ First possible study beyond p-shell



Hall C technique in 6GeV program

-common split magnet-



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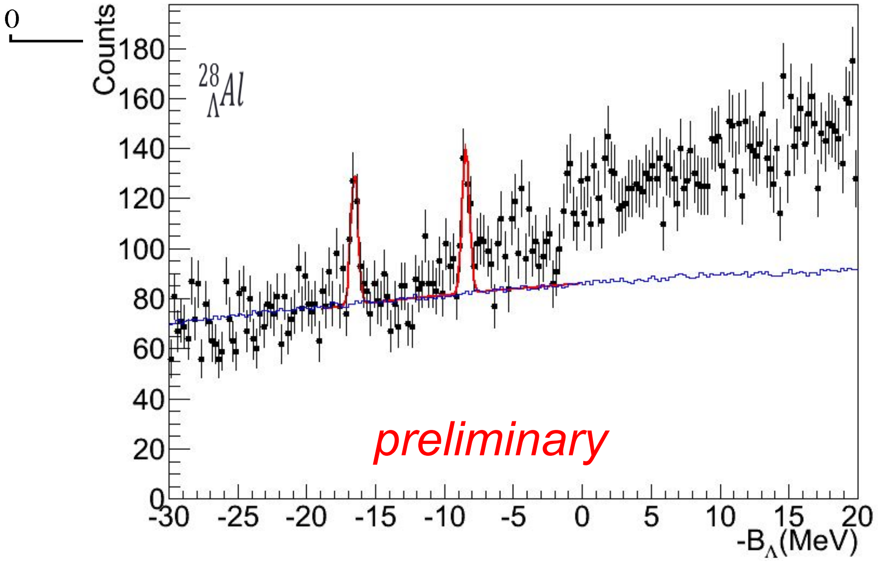

Hall C technique in 6GeV program

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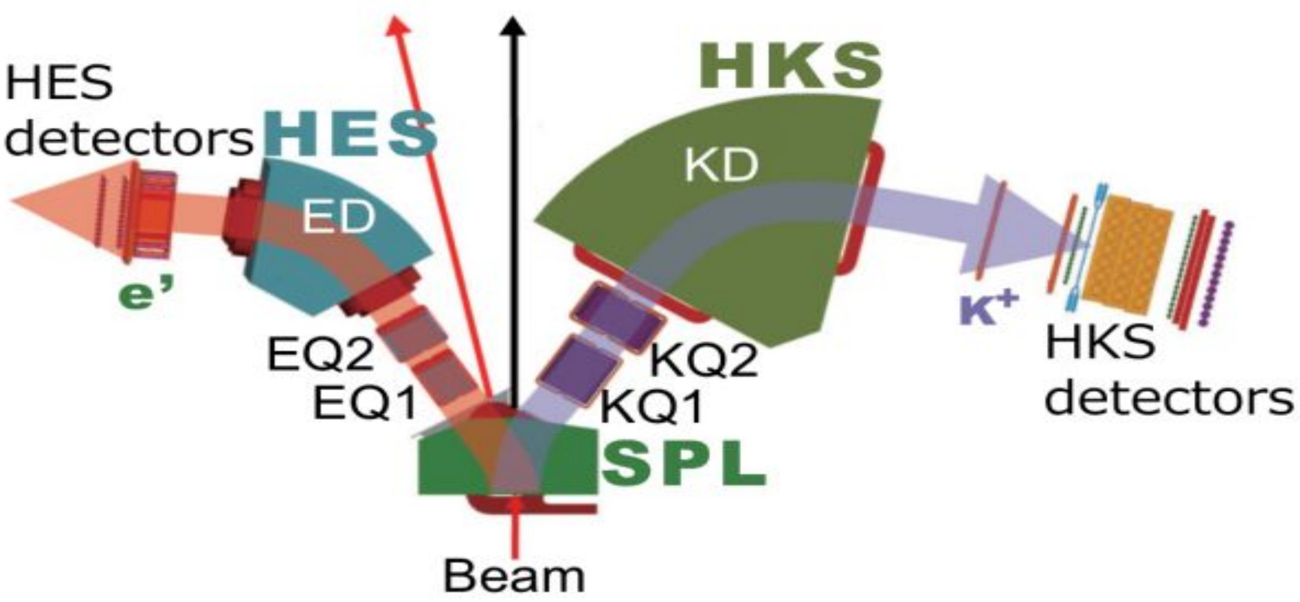

Hall C technique in 6GeV program

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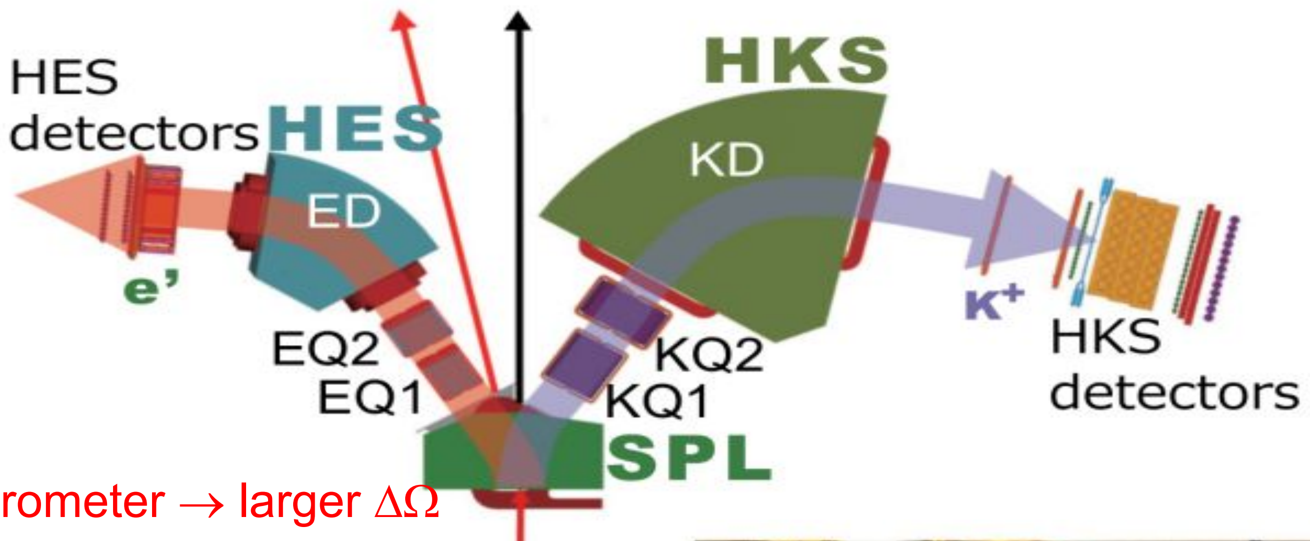
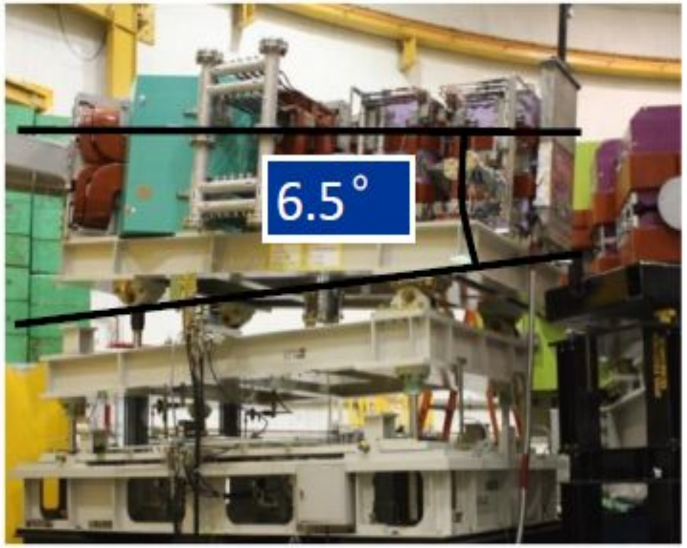


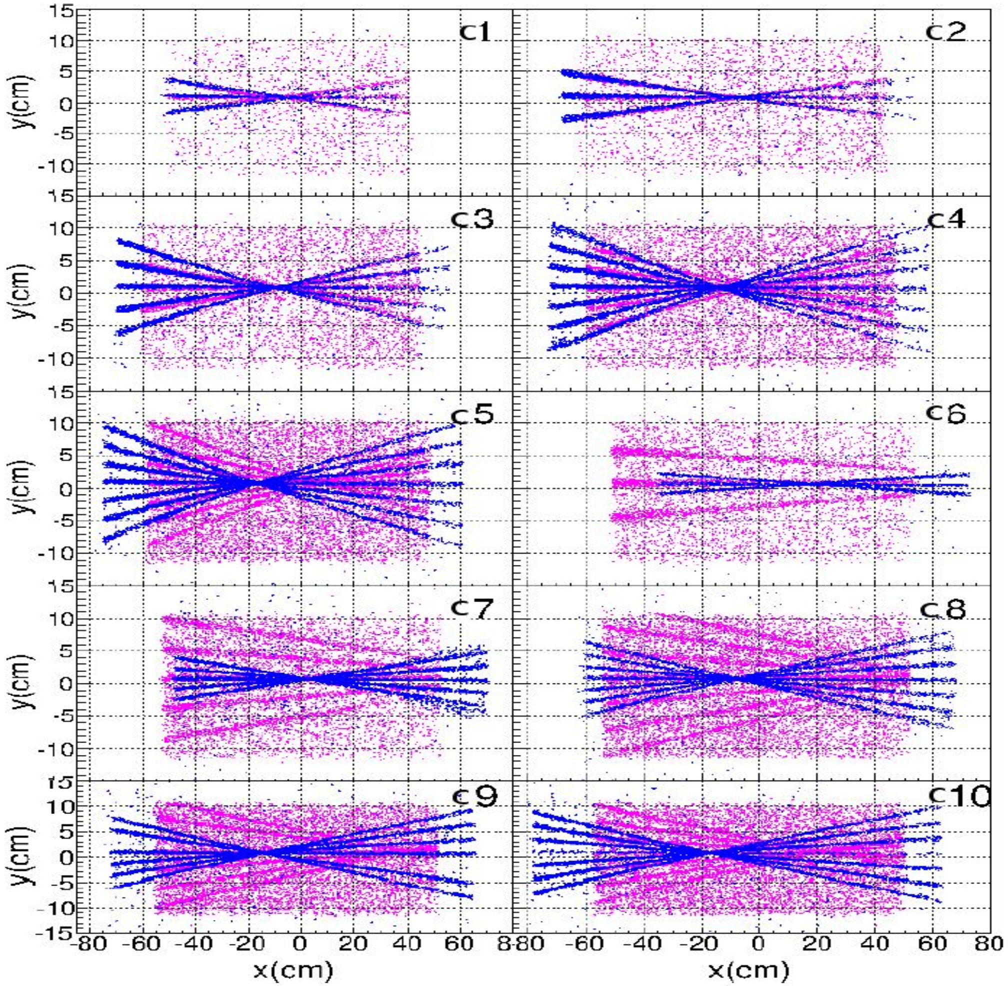
- New HES spectrometer → larger ΔΩ
- Same Tilt Method
- High beam luminosity
- Further improves accidental rate
- Further improves resolution and accuracy
- High yield rate
- First possible study for A > 50

Will be presented by T. Gogami

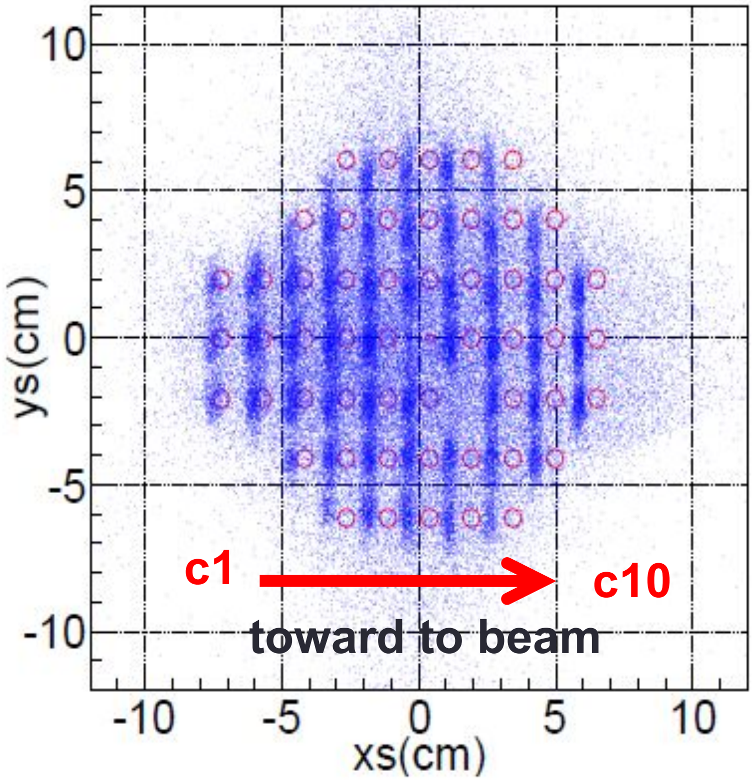


Spectrometer System Calibration

-Forward Optical Tuning-



HKS side



Spectrometer System Calibration

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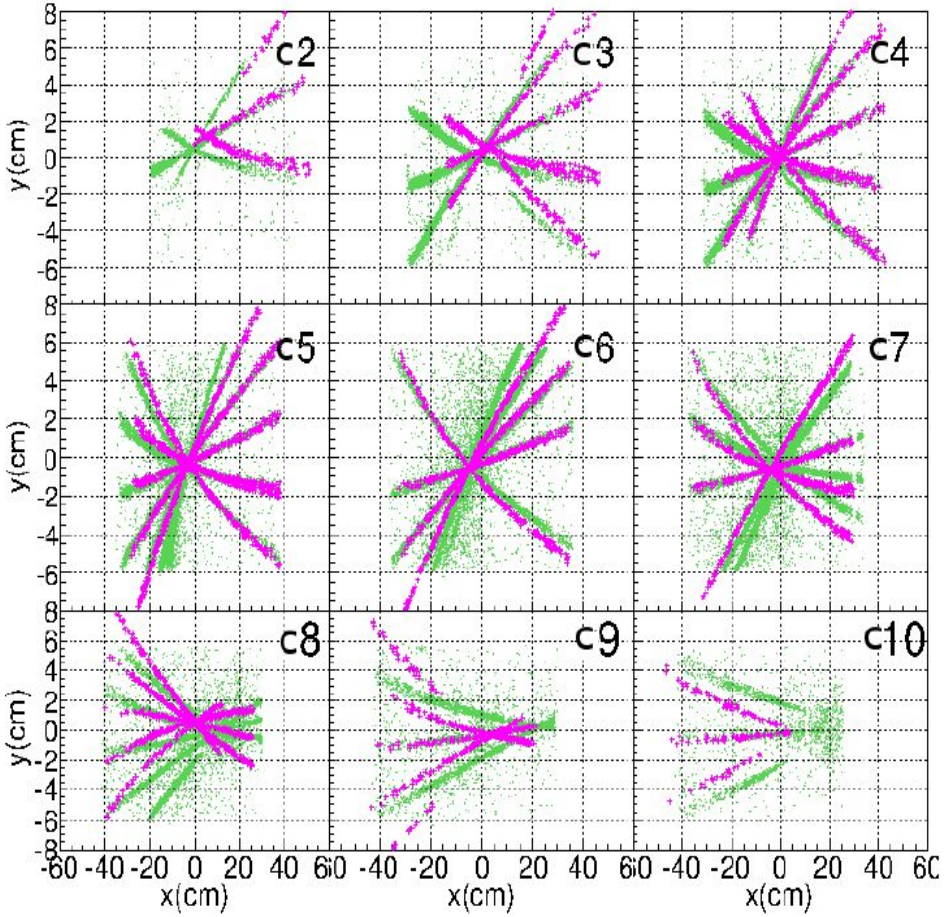
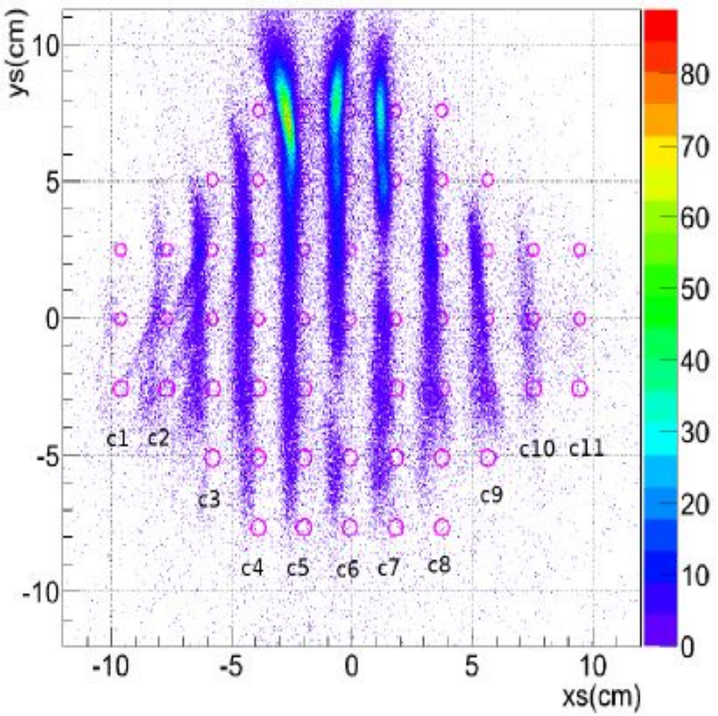


HES side



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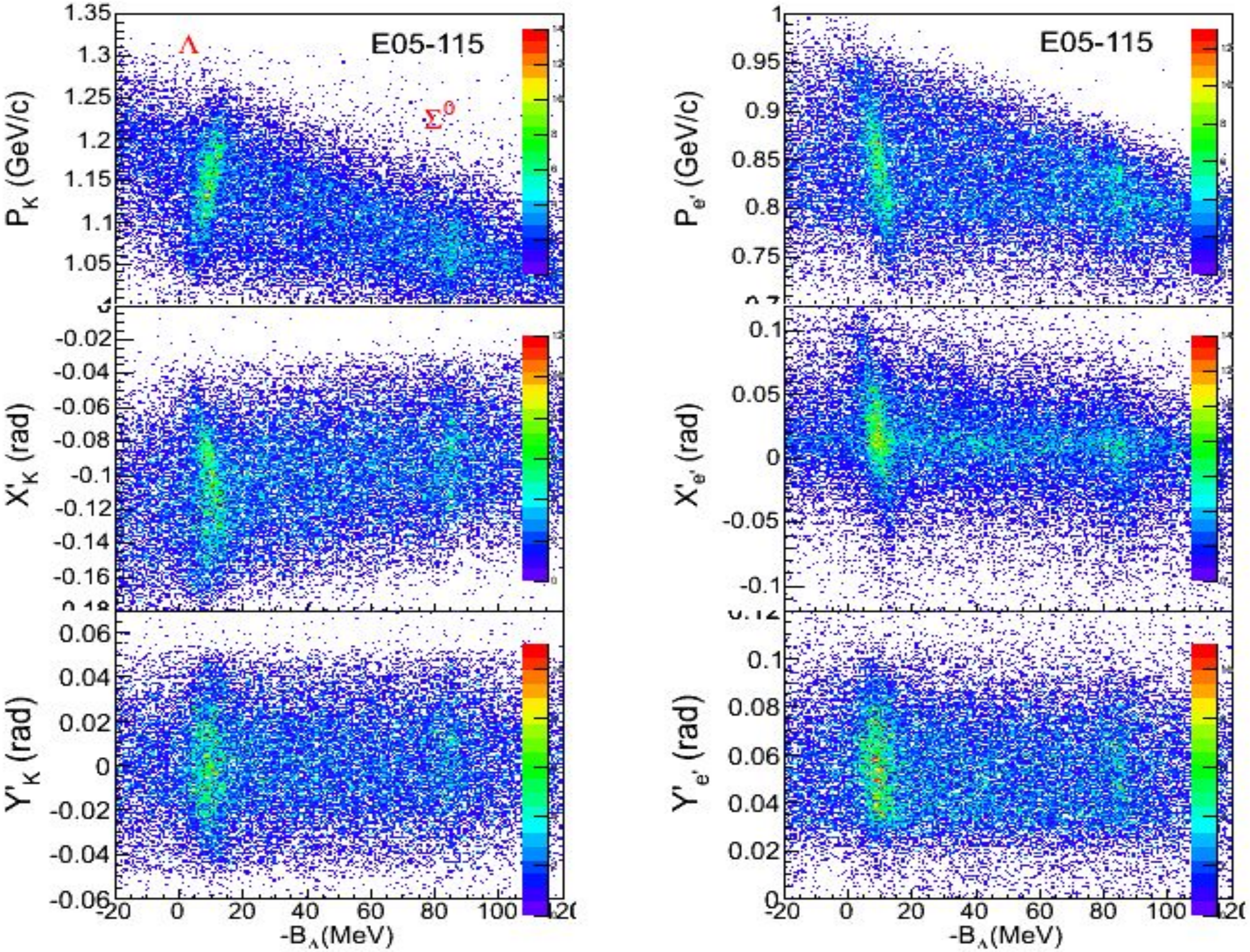
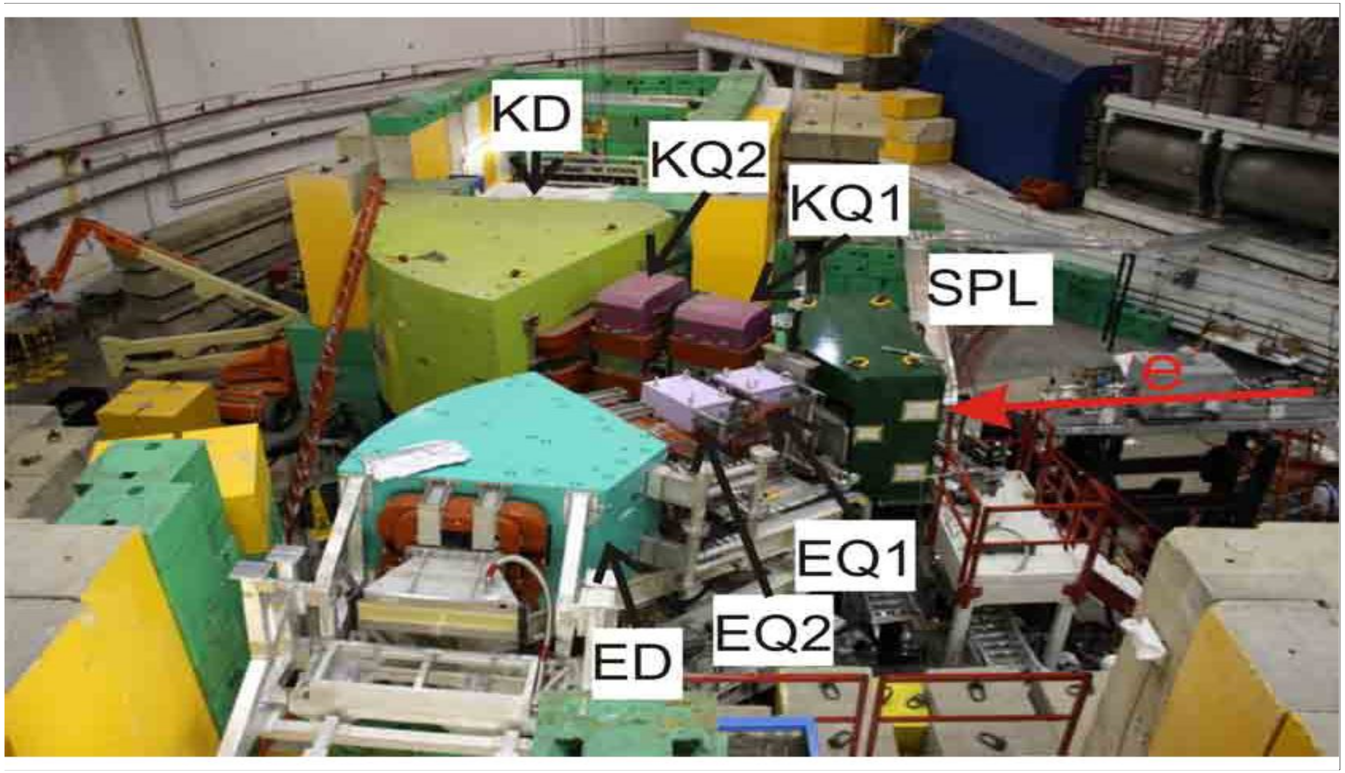
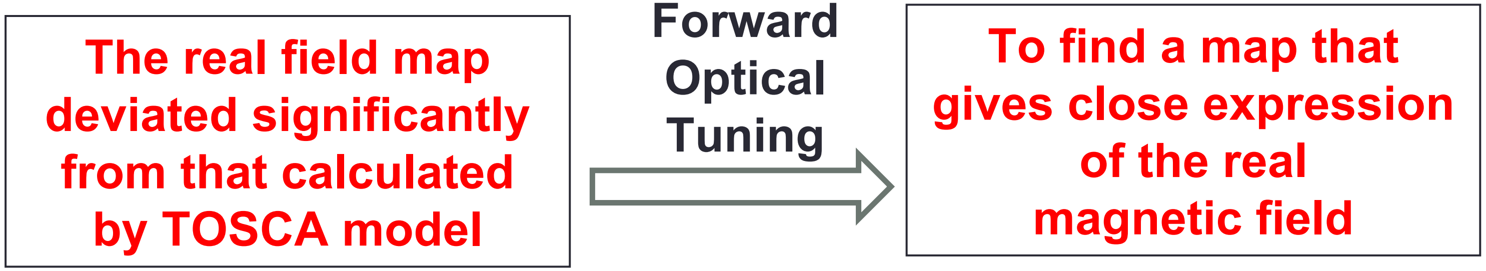


Spectrometer System Calibration
-Forward Optical Tuning-





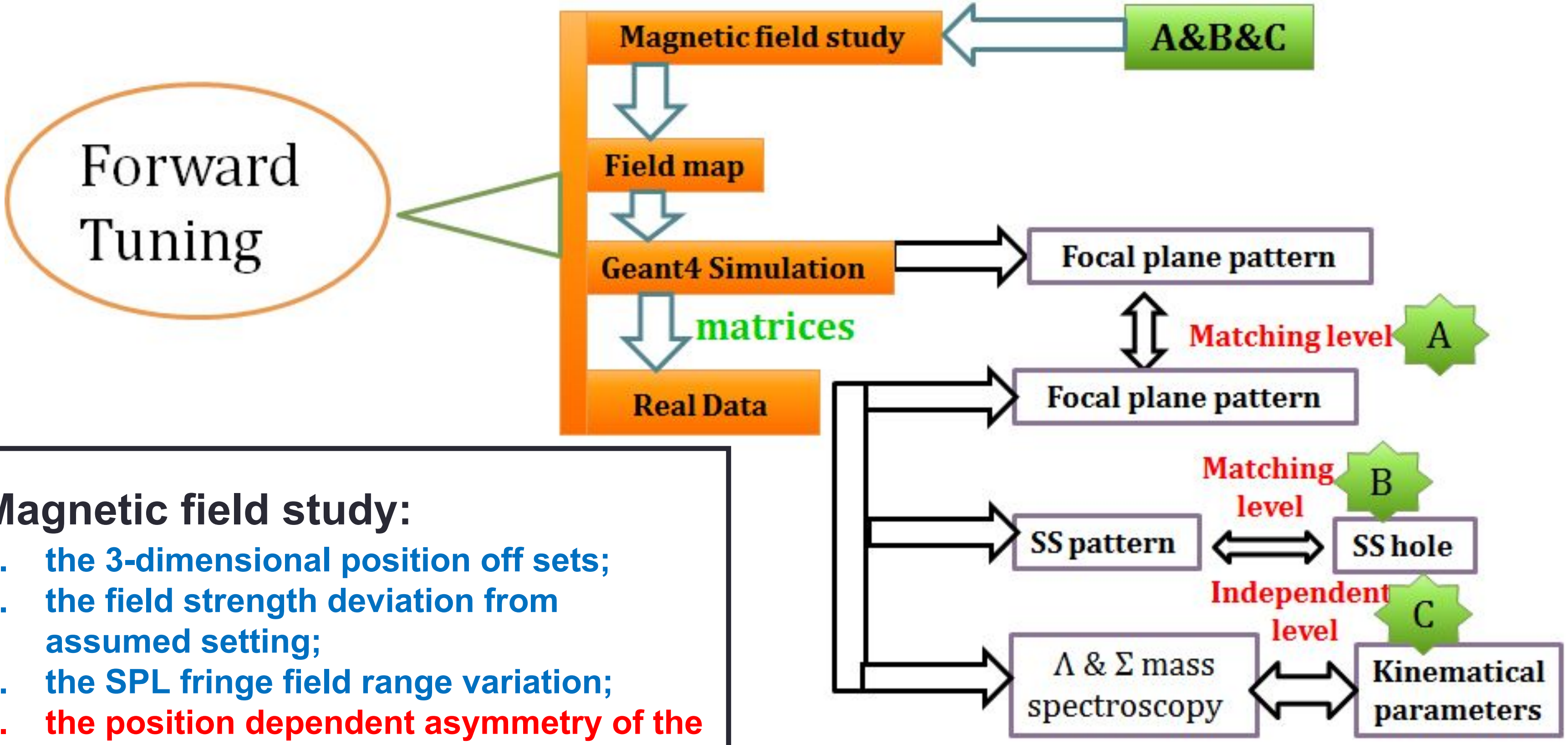
The real field map deviated significantly from that calculated by TOSCA model

Forward Optical Tuning

To find a map that gives close expression of the real magnetic field

Spectrometer System Calibration

-Forward Optical Tuning-



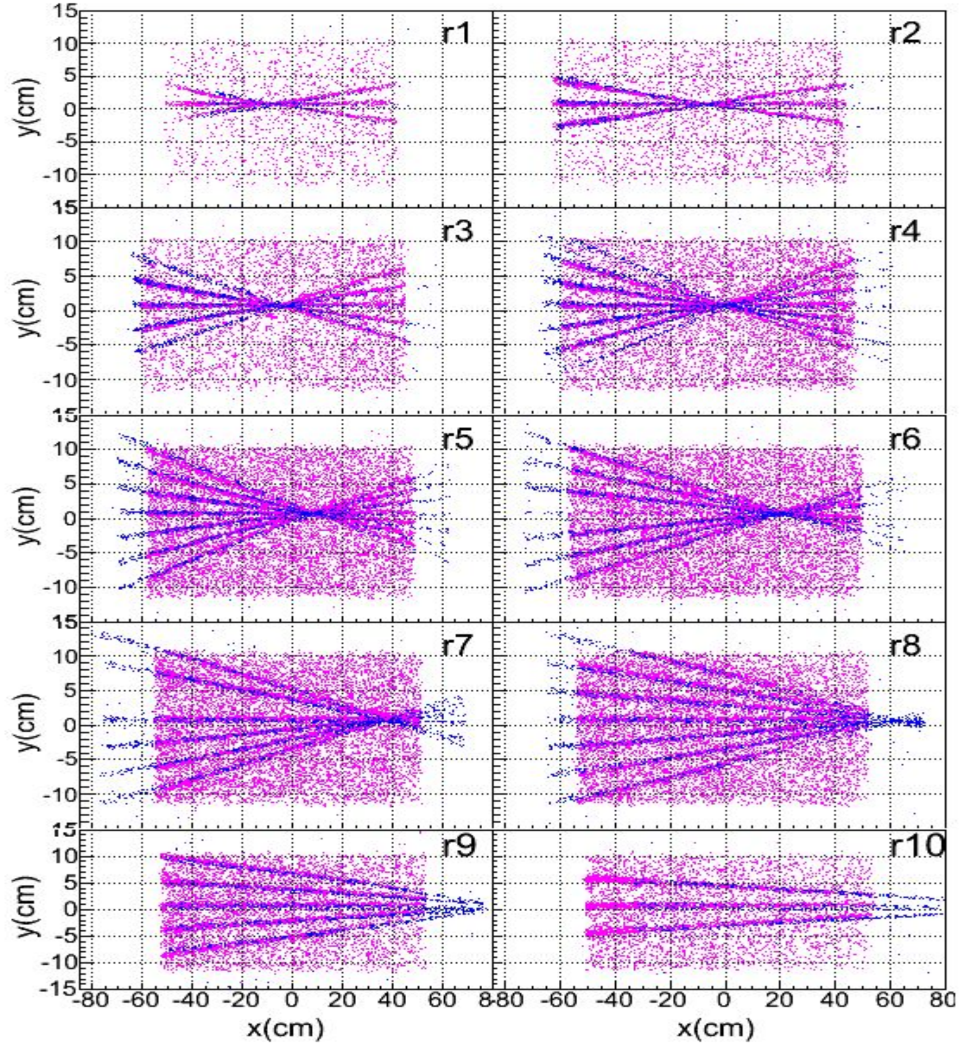
Magnetic field study:

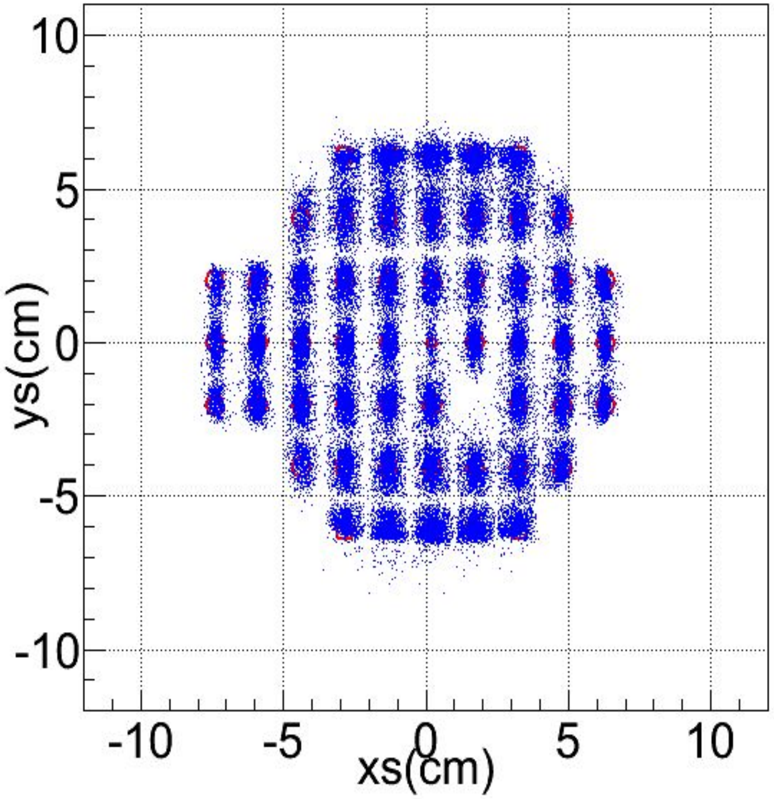
1. the 3-dimensional position off sets;
2. the field strength deviation from assumed setting;
3. the SPL fringe field range variation;
4. the position dependent asymmetry of the field map (symmetry functions)

Each of the above sources was treated as an ingredient and combination of them was made according to the need in meeting all the three criteria.

Spectrometer System Calibration

-Forward Optical Tuning-





Spectrometer System Calibration

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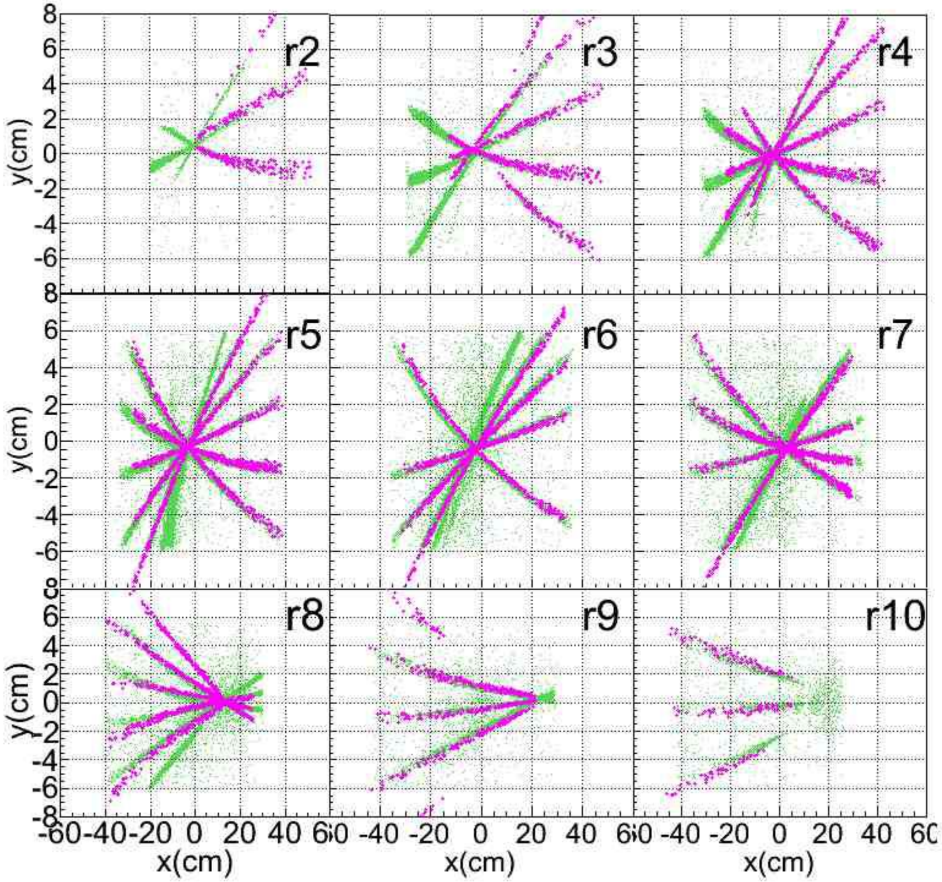

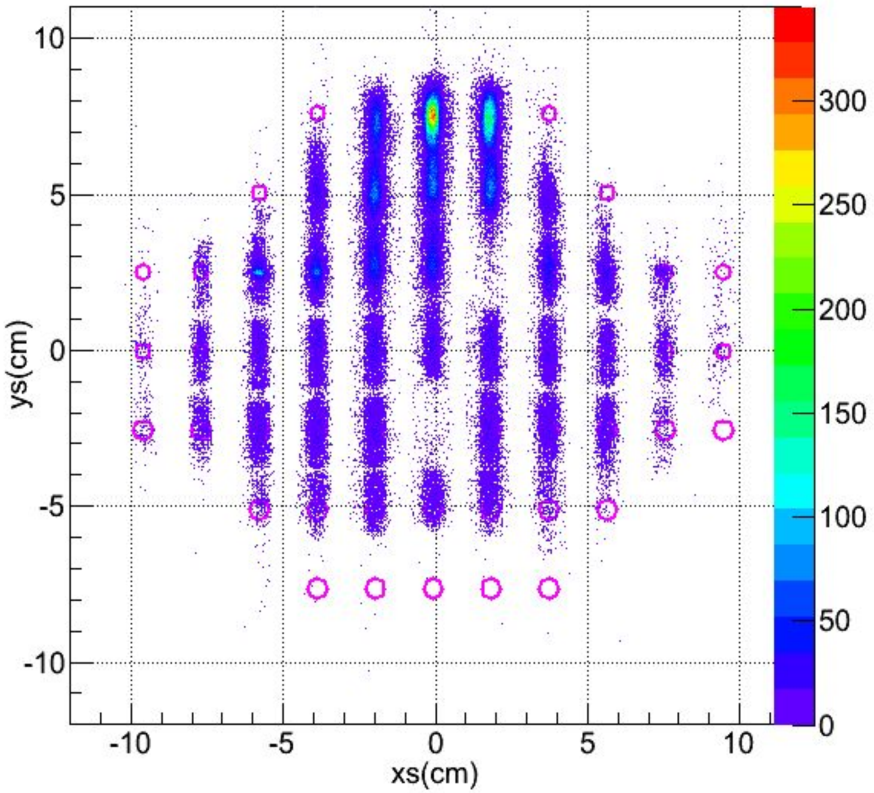

Spectrometer System Calibration

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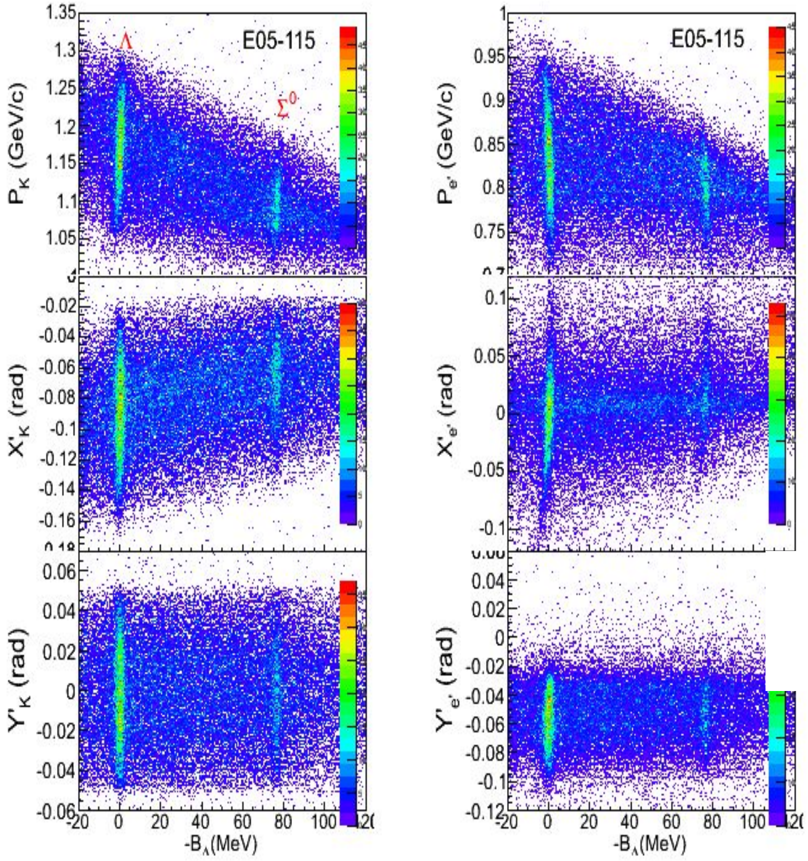
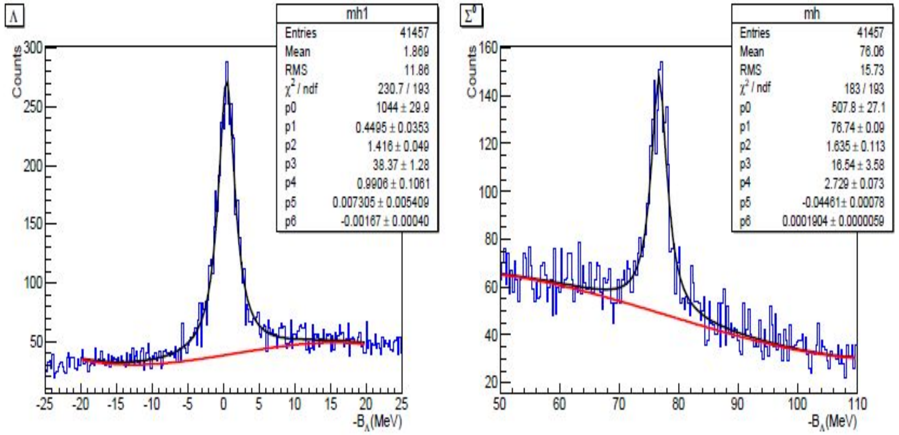




$$F(x) = C(x) + pol3$$

$$C(x) = \frac{1}{\gamma\pi[1 + (\frac{x - x_0}{\gamma})^2]}$$

Cauchy Function

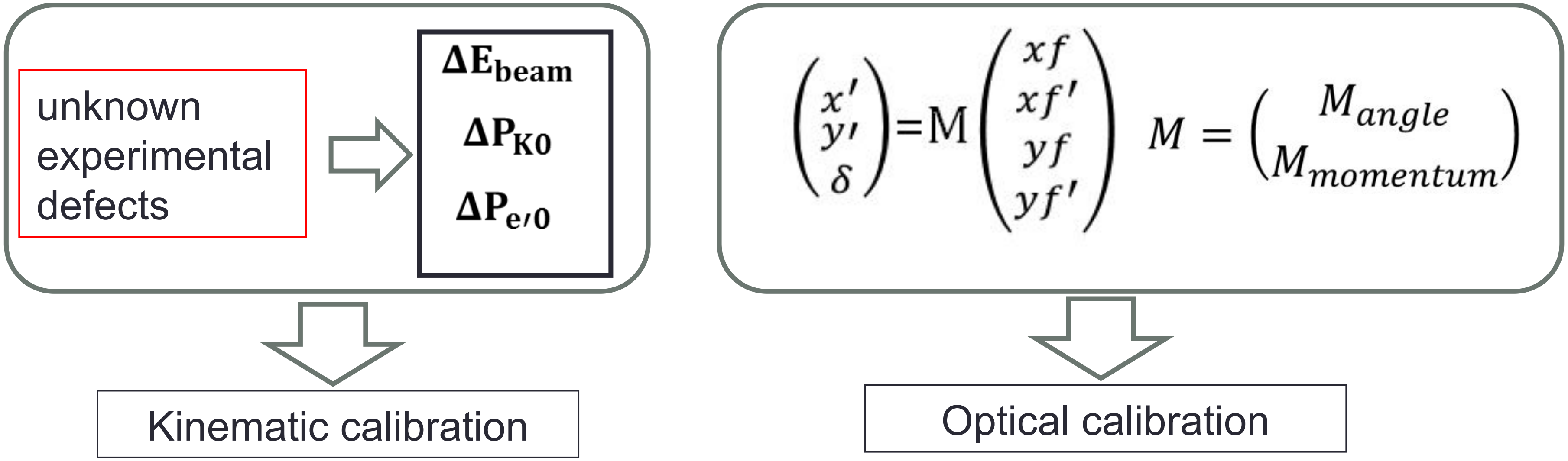
Particle	Mean(MeV)	FWHM(MeV)
Λ	0.450±0.0353	2.832±0.0980
Σ^0	76.740±0.0900	3.270±0.2260

Mathematical Spectrometer System Calibration

Purpose: achieve accurate mass spectroscopy with sub-MeV energy resolution

Technique: 2-arm coupled calibration for both kinematics and optics

$$\mathbf{M_{HY0} + \Delta M_{HY} = f\left(E_{beam0} + \Delta E_{beam}\,,\,(P_{Kd0} + \Delta P_{K0})\left(1 + \frac{\delta_K}{100}\right), x'_{tK}, y'_{tK}, (P_{e'd0} + \Delta P_{e'0})\left(1 + \frac{\delta_{e'}}{100}\right), x'_{te'}\,, y'_{te'}\right)}$$



unknown experimental defects

$$\mathbf{\Delta E_{beam}}$$
$$\mathbf{\Delta P_{K0}}$$
$$\mathbf{\Delta P_{e'0}}$$

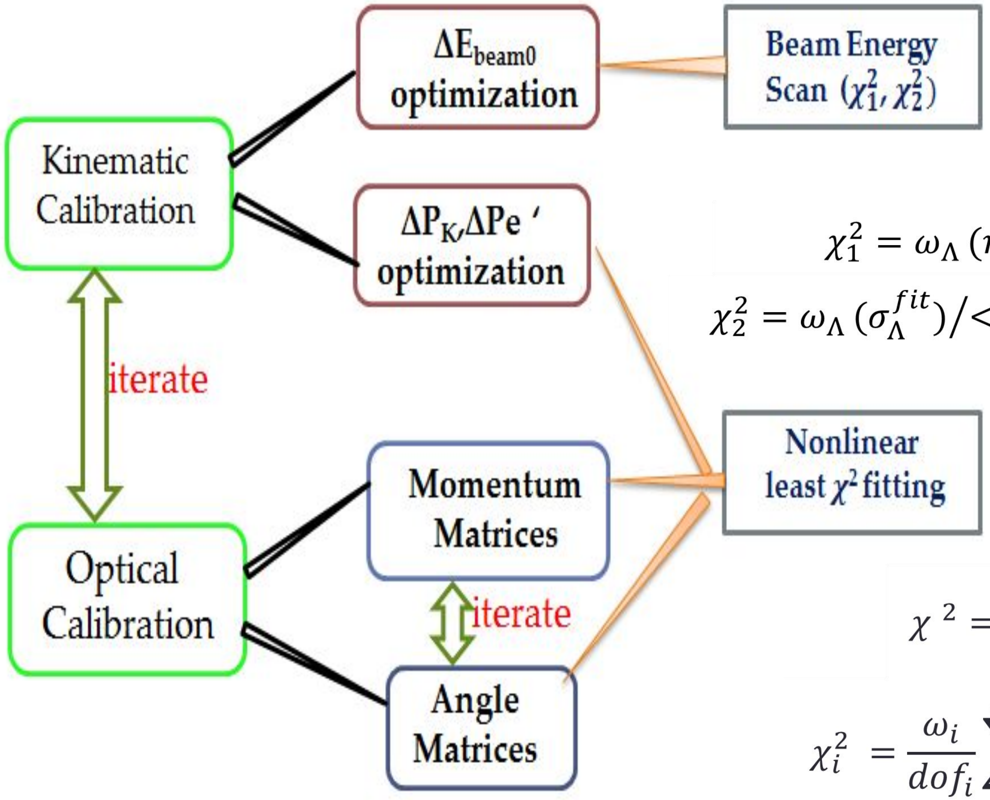
Kinematic calibration

$$\begin{pmatrix} x' \\ y' \\ \delta \end{pmatrix} = \mathrm{M} \begin{pmatrix} xf \\ xf' \\ yf \\ yf' \end{pmatrix} \quad M = \begin{pmatrix} M_{angle} \\ M_{momentum} \end{pmatrix}$$

Optical calibration

Using known masses of Λ, Σ^0 and identified hypernuclear bound states ($^{12}_{\Lambda}$B) for the spectrometer calibration

Mathematical Spectrometer System Calibration



Kinematic Calibration

ΔE_{beam0} optimization

Beam Energy Scan (χ_1^2, χ_2^2)

$\Delta P_K, \Delta Pe$ ' optimization

iterate

Nonlinear least χ^2 fitting

Momentum Matrices

Optical Calibration

iterate

Angle Matrices

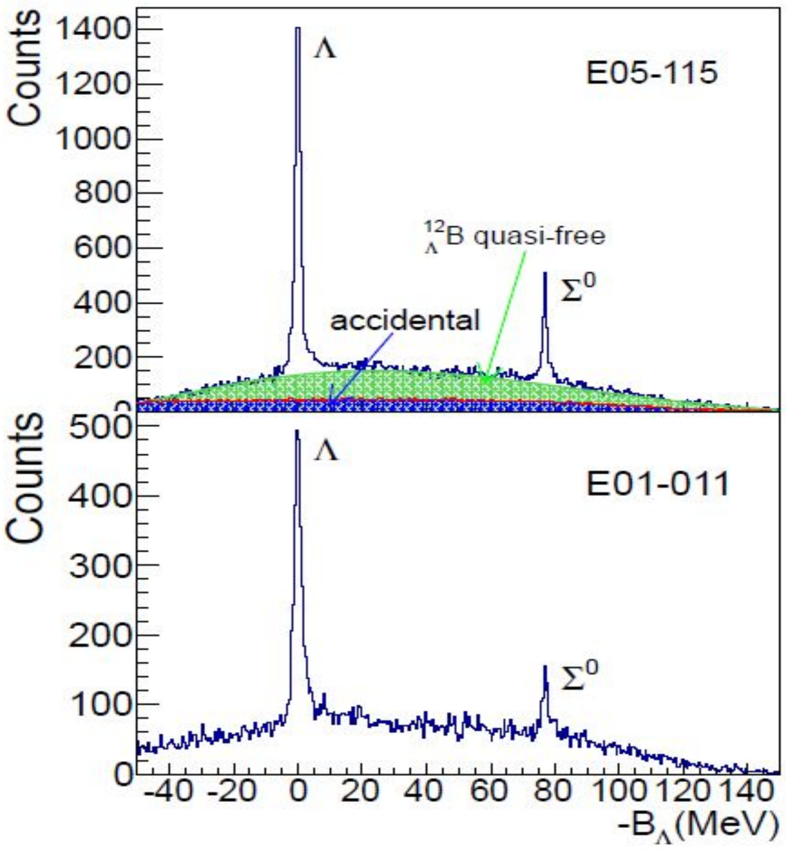
$$\chi_1^2 = \omega_\Lambda \, (m_\Lambda^{fit} - m_\Lambda^0)/\sigma_\Lambda{}^2 + \omega_\Sigma \, (m_\Sigma^{fit} - m_\Sigma^0)/\sigma_\Sigma{}^2$$

$$\chi_2^2 = \omega_\Lambda \, (\sigma_\Lambda^{fit})/<\sigma_\Lambda>^2 + \omega_\Sigma \, (\sigma_\Sigma^{fit})/<\sigma_\Sigma>^2 + \omega_{gs} \, (\sigma_{gs}^{fit})/<\sigma_{gs}>^2$$

$$\chi^2 = \sum \chi_i^2$$

$$\chi_i^2 = \frac{\omega_i}{dof_i} \sum_k^{N_i} (\frac{M_k^{calc} - M^{ref}}{\sigma_k})^2$$

Mathematical Spectrometer System Calibration



mass	mean (MeV)	Width(FWHM) (MeV)
Λ	-0.030±0.015	1.436±0.036
Σ^0	76.940±0.028	1.281±0.070

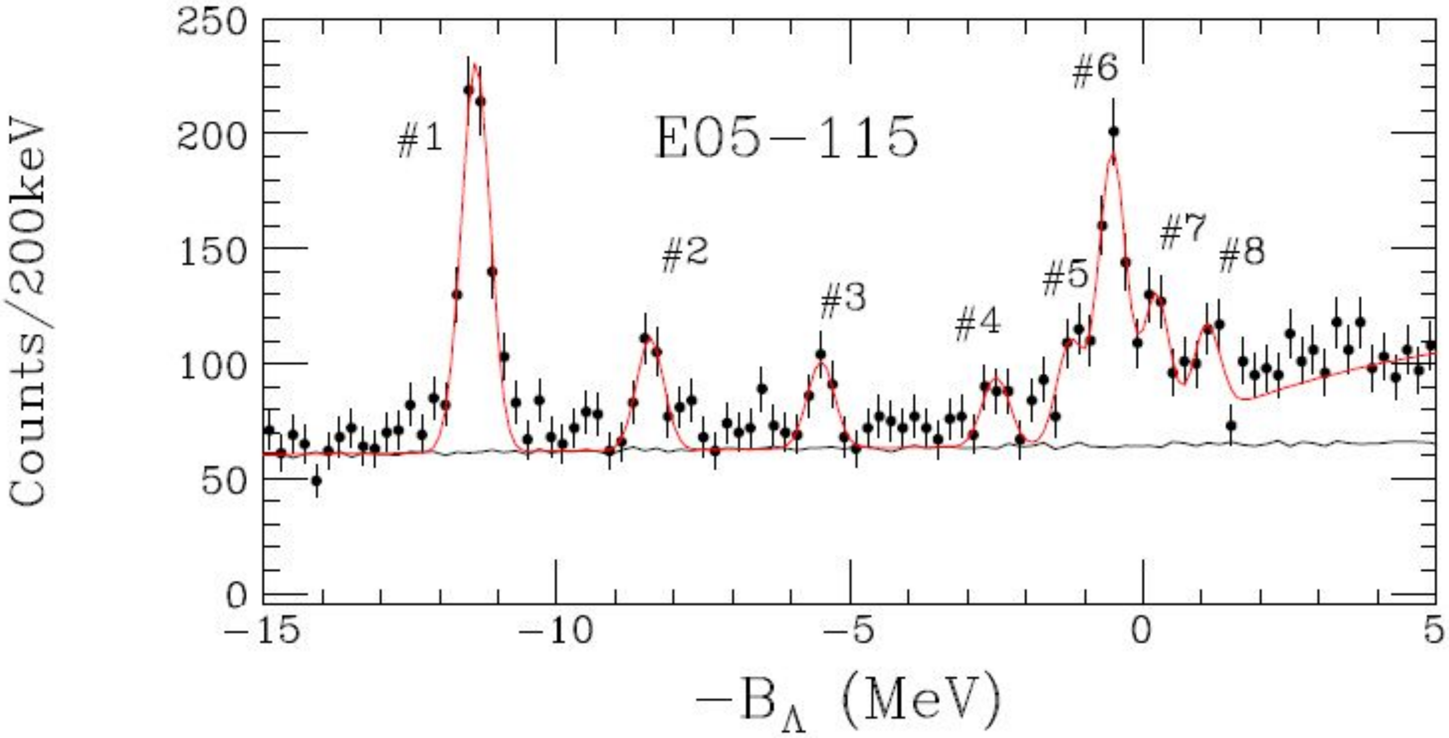
Separation = 76.970±0.031MeV

mass	mean (MeV)	Width(FWHM) (MeV)
Λ	0.014±0.033	1.998±0.085
Σ^0	77.001±0.094	1.946±0.243

Separation = 76.987±0.100MeV

Results and Discussion

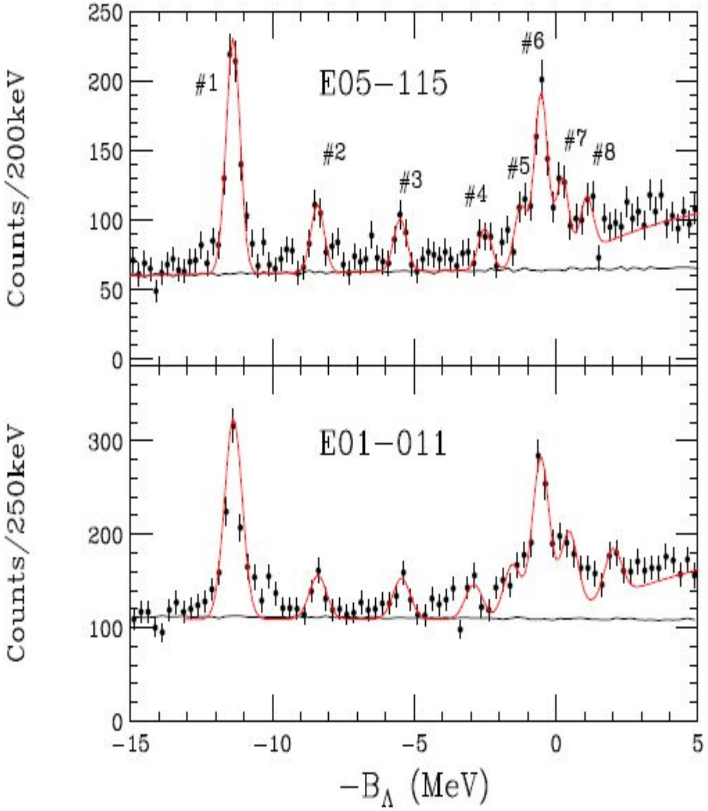
-$^{12}{}_{\Lambda}$B-

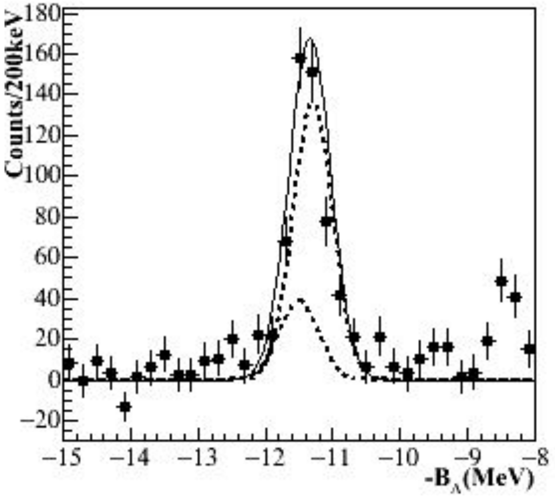


#1 − #4, #7: $\mathbf{s_{\Lambda} \otimes {}^{11}B}$ **core** **#5, 6, 8:** $\mathbf{p_{\Lambda} \otimes {}^{11}B}$ **core**

Results and Discussion

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





Fitted σ = 231keV for E05-115
Fitted σ = 300keV for E01-011

Fitting range: 1.35MeV

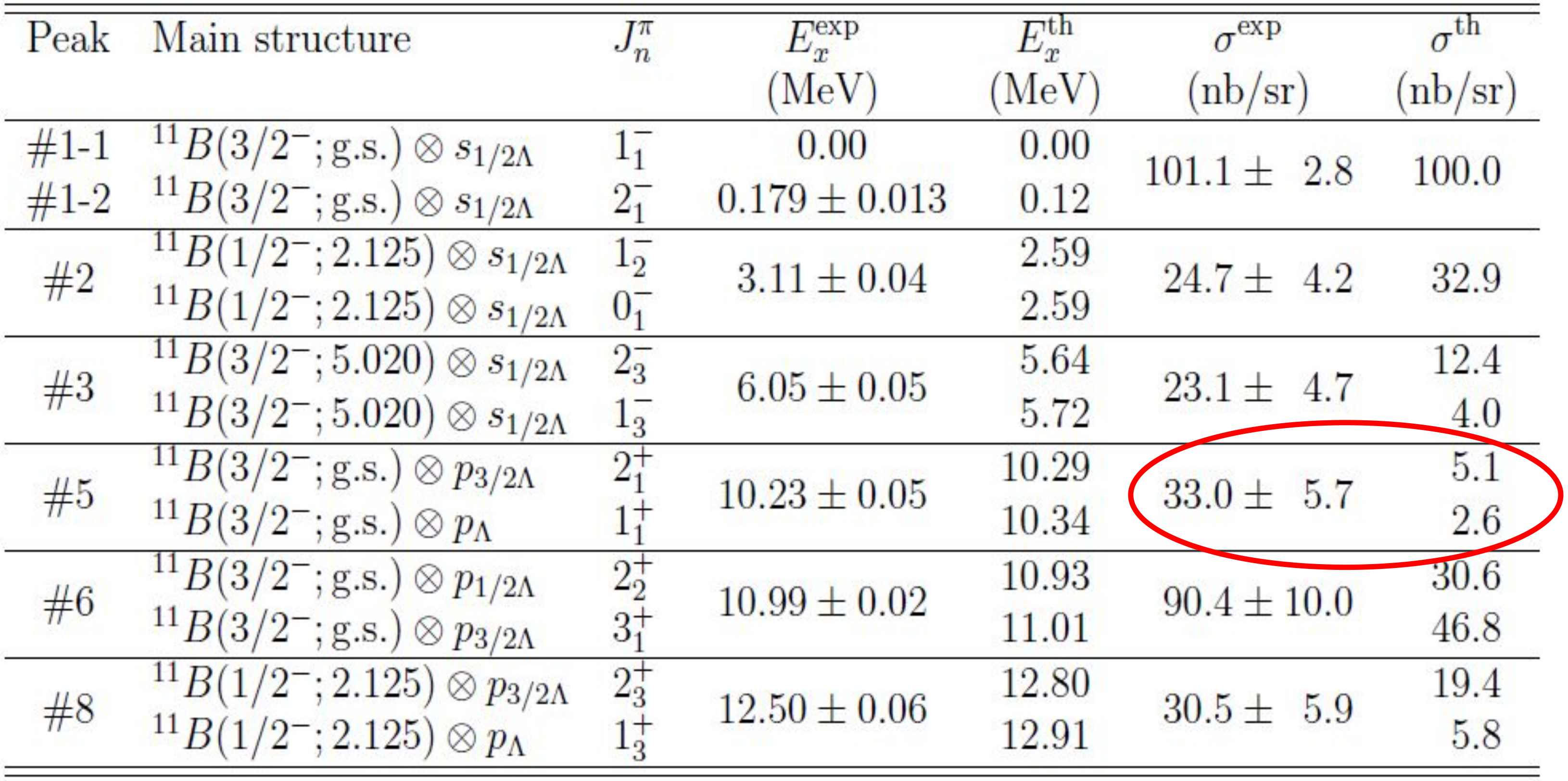
Separation (2^-- 1^-):
E05-115: 181±20keV
E01-011: 176±20keV
Average : 179±20keV
Ratio (2^-/ 1^-)= 3.5

Results and Discussion

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

Quoted uncertainties: statistical

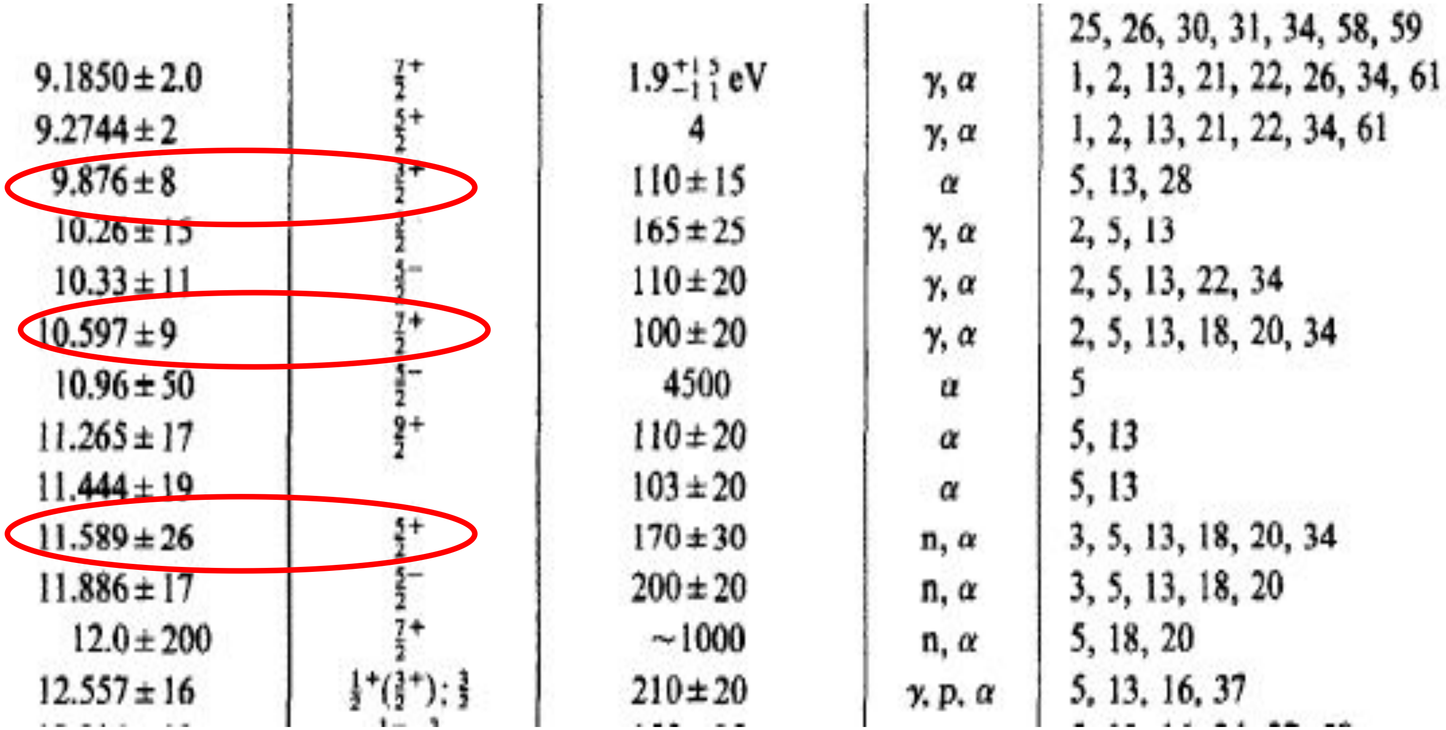
Systematic uncertainties for measured E_x is 0.07MeV



Peak	Main structure	J^π_n	E_x^{exp} (MeV)	E_x^{th} (MeV)	σ^{exp} (nb/sr)	σ^{th} (nb/sr)
#1-1	$^{11}B(3/2^-;\mathrm{g.s.}) \otimes s_{1/2\Lambda}$	1^-_1	0.00	0.00	101.1 ± 2.8	100.0
#1-2	$^{11}B(3/2^-;\mathrm{g.s.}) \otimes s_{1/2\Lambda}$	2^-_1	0.179 ± 0.013	0.12		
#2	$^{11}B(1/2^-;2.125) \otimes s_{1/2\Lambda}$	1^-_2	3.11 ± 0.04	2.59	24.7 ± 4.2	32.9
	$^{11}B(1/2^-;2.125) \otimes s_{1/2\Lambda}$	0^-_1		2.59		
#3	$^{11}B(3/2^-;5.020) \otimes s_{1/2\Lambda}$	2^-_3	6.05 ± 0.05	5.64	23.1 ± 4.7	12.4
	$^{11}B(3/2^-;5.020) \otimes s_{1/2\Lambda}$	1^-_3		5.72		4.0
#5	$^{11}B(3/2^-;\mathrm{g.s.}) \otimes p_{3/2\Lambda}$	2^+_1	10.23 ± 0.05	10.29	33.0 ± 5.7	5.1
	$^{11}B(3/2^-;\mathrm{g.s.}) \otimes p_{\Lambda}$	1^+_1		10.34		2.6
#6	$^{11}B(3/2^-;\mathrm{g.s.}) \otimes p_{1/2\Lambda}$	2^+_2	10.99 ± 0.02	10.93	90.4 ± 10.0	30.6
	$^{11}B(3/2^-;\mathrm{g.s.}) \otimes p_{3/2\Lambda}$	3^+_1		11.01		46.8
#8	$^{11}B(1/2^-;2.125) \otimes p_{3/2\Lambda}$	2^+_3	12.50 ± 0.06	12.80	30.5 ± 5.9	19.4
	$^{11}B(1/2^-;2.125) \otimes p_{\Lambda}$	1^+_3		12.91		5.8

Results and Discussion

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



				25, 26, 30, 31, 34, 58, 59
9.1850±2.0	$\frac{7}{2}^+$	$1.9^{+1.5}_{-1.1}$ eV	γ, α	1, 2, 13, 21, 22, 26, 34, 61
9.2744±2	$\frac{5}{2}^+$	4	γ, α	1, 2, 13, 21, 22, 34, 61
9.876±8	$\frac{3}{2}^+$	110±15	α	5, 13, 28
10.26±15	$\frac{3}{2}$	165±25	γ, α	2, 5, 13
10.33±11	$\frac{5}{2}^-$	110±20	γ, α	2, 5, 13, 22, 34
10.597±9	$\frac{7}{2}^+$	100±20	γ, α	2, 5, 13, 18, 20, 34
10.96±50	$\frac{5}{2}^-$	4500	α	5
11.265±17	$\frac{9}{2}^+$	110±20	α	5, 13
11.444±19		103±20	α	5, 13
11.589±26	$\frac{5}{2}^+$	170±30	n, α	3, 5, 13, 18, 20, 34
11.886±17	$\frac{5}{2}^-$	200±20	n, α	3, 5, 13, 18, 20
12.0±200	$\frac{7}{2}^+$	~1000	n, α	5, 18, 20
12.557±16	$\frac{1}{2}^+(\frac{3}{2}^+); \frac{3}{2}$	210±20	γ, p, α	5, 13, 16, 37

Peak	E_x (MeV)	Structure	^{11}B state	^{11}B E_x (MeV)
#4	**8.85±0.06**	$s^4p^6(sd)\otimes s_{\Lambda}$	**3/2⁺**	**9.88**
Extra #5	**10.23±0.05**	$s^4p^6(sd)\otimes s_{\Lambda}$	**7/2⁺**	**10.60**
#7	**11.75±0.04**	$s^4p^6(sd)\otimes s_{\Lambda}$	**5/2⁺**	**11.60**

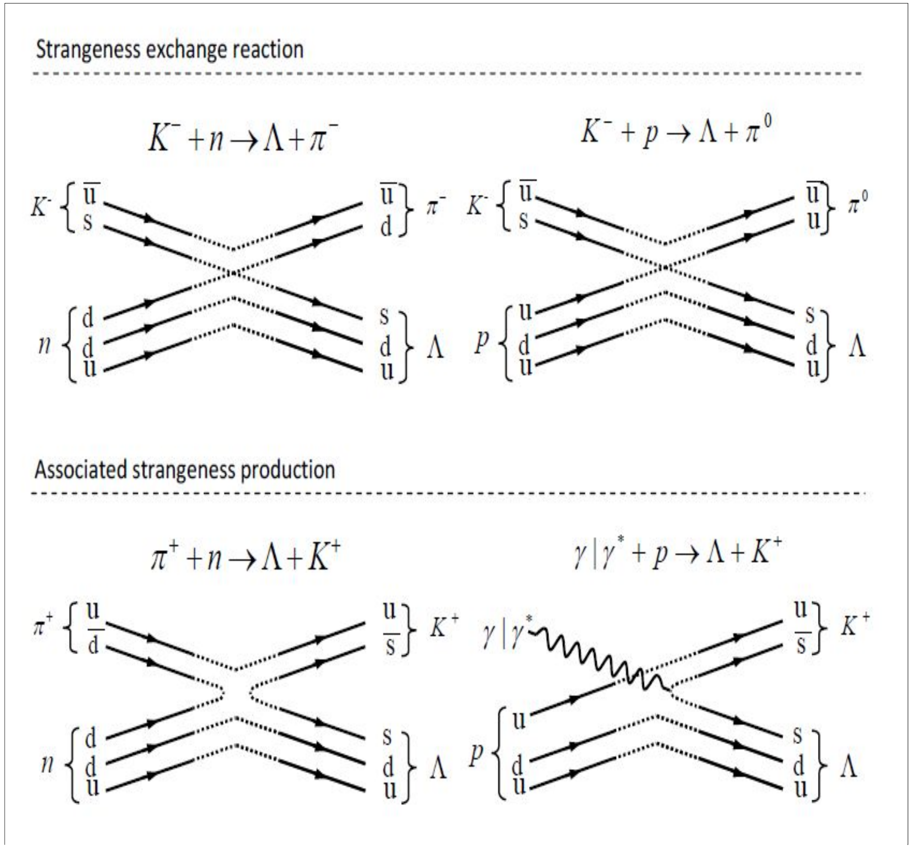
Conclusion

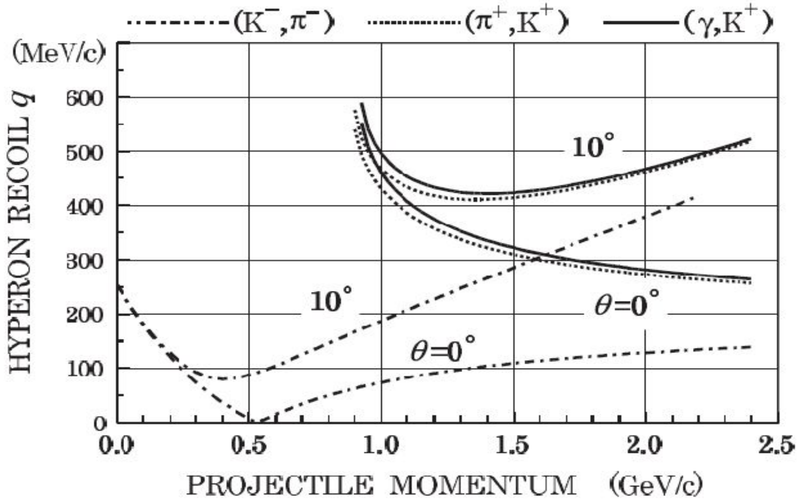
- The unique CEBAF beam has enabled high-precision spectroscopic investigations of hypernuclei for studying the ΛN interaction.
- There is stronger evidence for sd-shell nuclei from spectroscopy of $^{12}{}_{\Lambda}B$
- The key technical improvement for possible future experiments in study spectroscopy of hypernuclei will be the reduction of the accidental background.

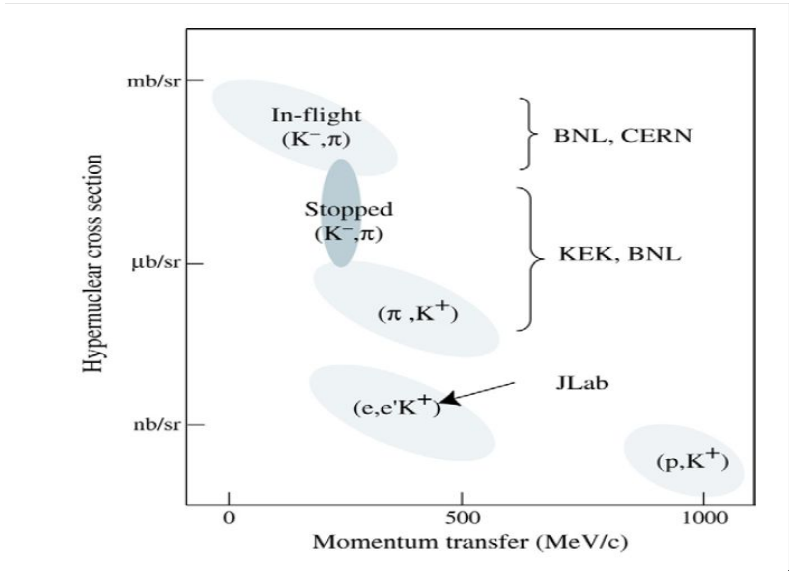
BACKUP

Introduction

-Production of Λ hypernuclei -



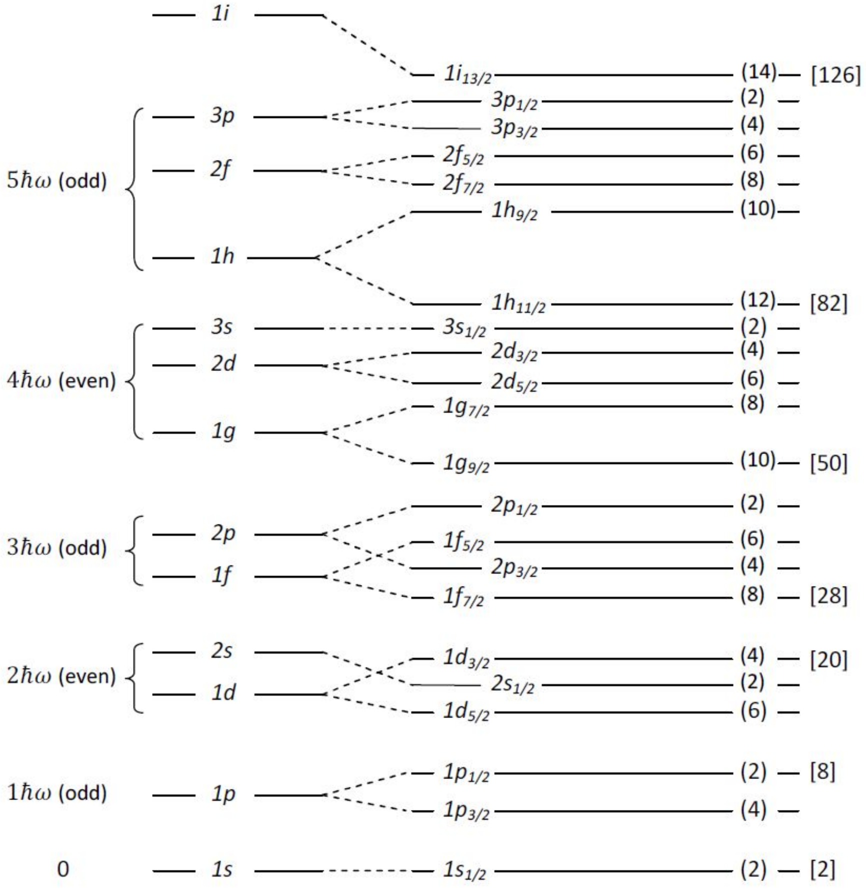




p(e,e'K⁺)Λ : $e \longrightarrow e' + \gamma^*$

$\gamma^* + p \longrightarrow \quad + \Lambda$

Nuclear shell model



3.3 Nuclear states: nuclear spin, parity and excitation energy

Nuclear spin I:

Nucleons (proton, neutron) are Fermions with $s=1/2$

Total angular momentum of the nucleon $j = l + s$ (vector su

Total angular momentum of the nucleus I

$$I = \Sigma_i j_i = \Sigma_i (l_i + s_i)$$

gg-nucleus $I=0$
uu-nucleus $I \neq 0$, but also $I=0$
ug-,gu-nuclei I half integer

Total angular momentum of the atom („hyperfine structure"):

nuclear spin I + electronic shell J = atomic spin F

splitting of atomic J leads to $2I+1$ ($I \leq J$) or $2J+1$ ($J<I$) sublevels

$H_{Hfs} = A\, I \cdot J$ with $E_{Hfs} = A/2\, [F(F+1) - I(I+1) - J(J+1)]$

Parity π (I^π):

symmetry behavior of the wave function under reflection (in space)

$\Pi_{op}\Psi(r) = \Psi(-r) = \pi\,\Psi(r)$ if $\Pi_{op}\,H\,\Pi_{op}^{-1} = H$ with $H\Psi=E\Psi$

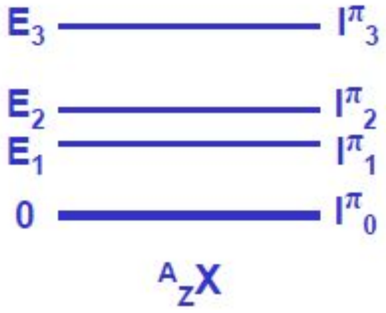
2-fold application = identity operation

therefore: eigenvalues for parity operation +1 or -1.

Parity is a multiplicative quantum number

Parity even (+1): with even orbital angular momentum
Parity odd (-1): with odd orbital angular momentum

characterizing energy levels



Results and Discussion

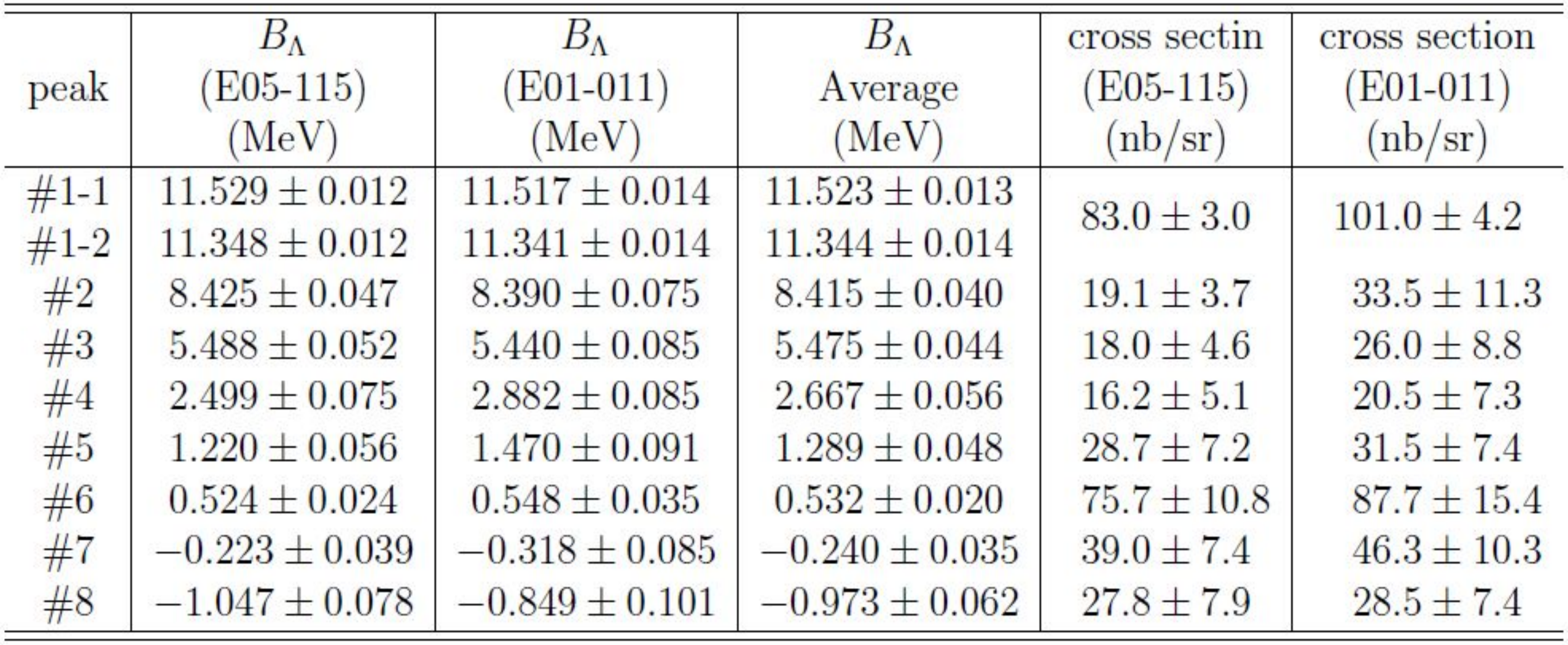
-$^{12}_{\Lambda}$B-

Quoted uncertainties: statistical

Systematic uncertainties for B_{Λ} E05-115: ± 120keV ; E01-011: ± 160keV

Systematic uncertainties for cross section : ± 12%

$\mathrm{E05-115}$: $\theta_{\nu K} = 6.8^{o}$
$\mathrm{E01-011}$: $\theta_{\gamma K} = 5.8^{o}$



peak	B_{Λ} (E05-115) (MeV)	B_{Λ} (E01-011) (MeV)	B_{Λ} Average (MeV)	cross sectin (E05-115) (nb/sr)	cross section (E01-011) (nb/sr)
#1-1	11.529 ± 0.012	11.517 ± 0.014	11.523 ± 0.013	83.0 ± 3.0	101.0 ± 4.2
#1-2	11.348 ± 0.012	11.341 ± 0.014	11.344 ± 0.014		
#2	8.425 ± 0.047	8.390 ± 0.075	8.415 ± 0.040	19.1 ± 3.7	33.5 ± 11.3
#3	5.488 ± 0.052	5.440 ± 0.085	5.475 ± 0.044	18.0 ± 4.6	26.0 ± 8.8
#4	2.499 ± 0.075	2.882 ± 0.085	2.667 ± 0.056	16.2 ± 5.1	20.5 ± 7.3
#5	1.220 ± 0.056	1.470 ± 0.091	1.289 ± 0.048	28.7 ± 7.2	31.5 ± 7.4
#6	0.524 ± 0.024	0.548 ± 0.035	0.532 ± 0.020	75.7 ± 10.8	87.7 ± 15.4
#7	-0.223 ± 0.039	-0.318 ± 0.085	-0.240 ± 0.035	39.0 ± 7.4	46.3 ± 10.3
#8	-1.047 ± 0.078	-0.849 ± 0.101	-0.973 ± 0.062	27.8 ± 7.9	28.5 ± 7.4

2005(E01-011) **2nd Experiment :**

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

- ❖ Newly-constructed **HKS** for K^{+} side
- ❖ Apply **"Tilt Method"** for e' side

2009(E05-115) **3rd Experiment:**

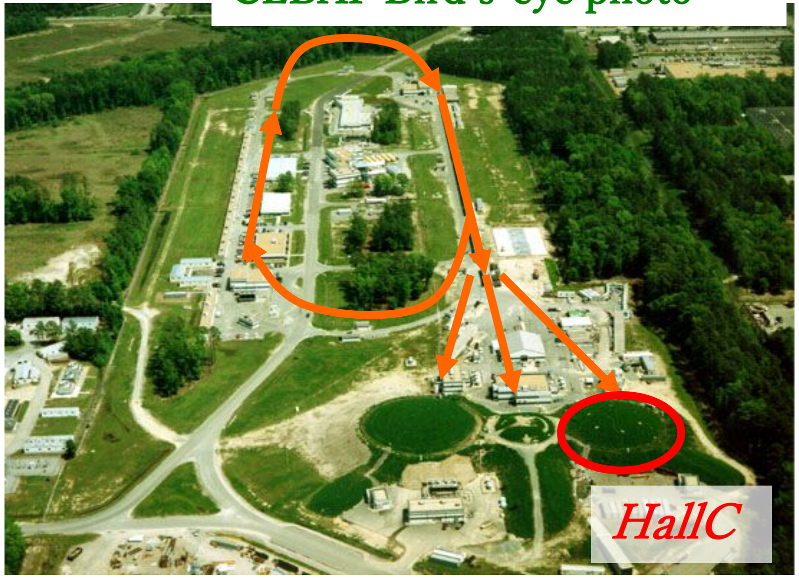
${}^{12}_{☹}\mathrm{B}$, ${}^{7}_{\Lambda}\mathrm{He}$, ${}^{10}_{\Lambda}\mathrm{Be}$, ${}^{9}_{☹}\mathrm{Li}$ and ${}^{52}_{\Lambda}\mathrm{V}$

- ❖Beam Energy 1.8 ✸2.344 GeV
- ❖Brand-new e' spectrometer, HES

Calibration by the elementary process

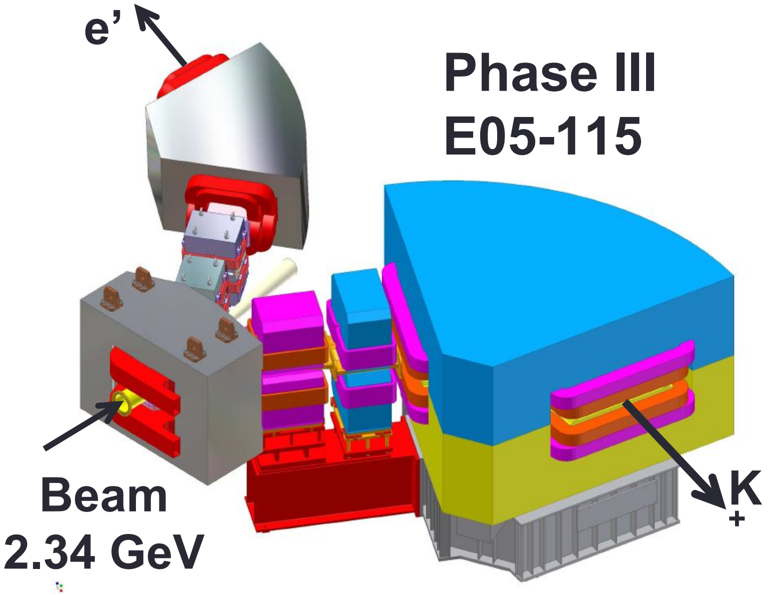
$p(e,e'K^{+})$☹ or 🌢: CH_2

CEBAF Bird's-eye photo

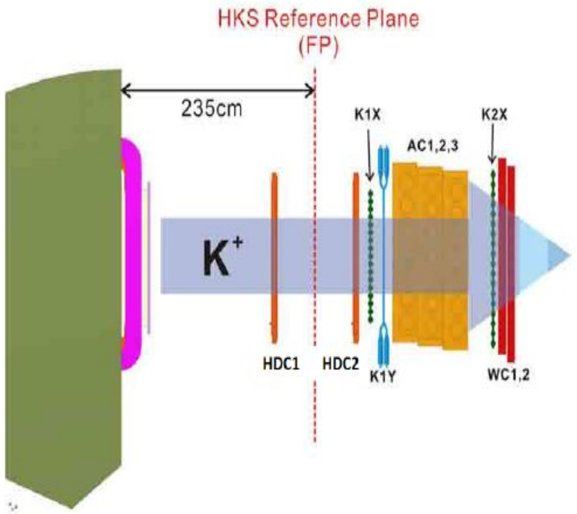


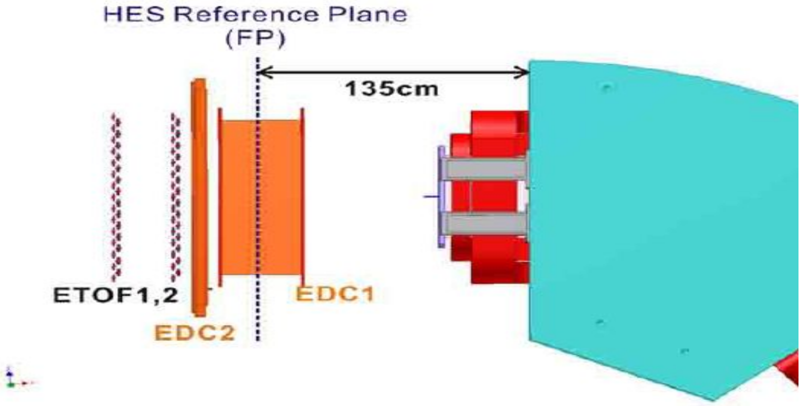
Hall C technique in 6GeV program

-common split magnet-



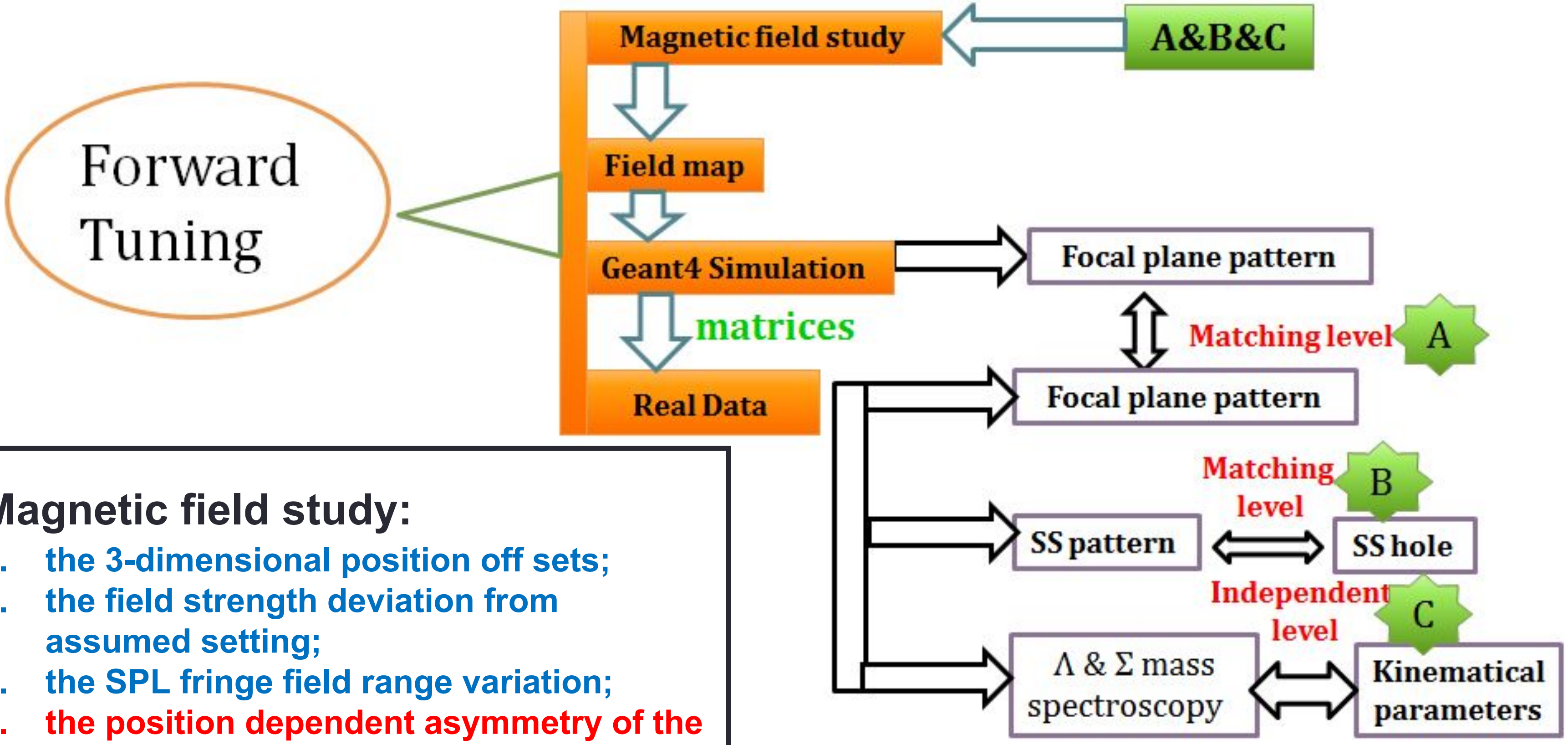
- New HES spectrometer → larger $\Delta\Omega$
- Same Tilt Method
- High beam luminosity
- Further improves accidental rate
- Further improves resolution and accuracy
- High yield rate
- First possible study for A > 50





Spectrometer System Calibration

-Forward Optical Tuning-



Forward Tuning

Magnetic field study ⟸ A&B&C

Field map

Geant4 Simulation ⟹ Focal plane pattern

matrices

Real Data

Focal plane pattern ⇕ Focal plane pattern: Matching level A

SS pattern ⟺ SS hole: Matching level B

Λ & Σ mass spectroscopy ⟺ Kinematical parameters: Independent level C

Magnetic field study:

1. the 3-dimensional position off sets;
2. the field strength deviation from assumed setting;
3. the SPL fringe field range variation;
4. the position dependent asymmetry of the field map (asymmetry functions)

Each of the above sources was treated as an ingredient and combination of them was made according to the need in meeting all the three criteria.

Introduction

Merits of the (e,e'K$^+$) experiment

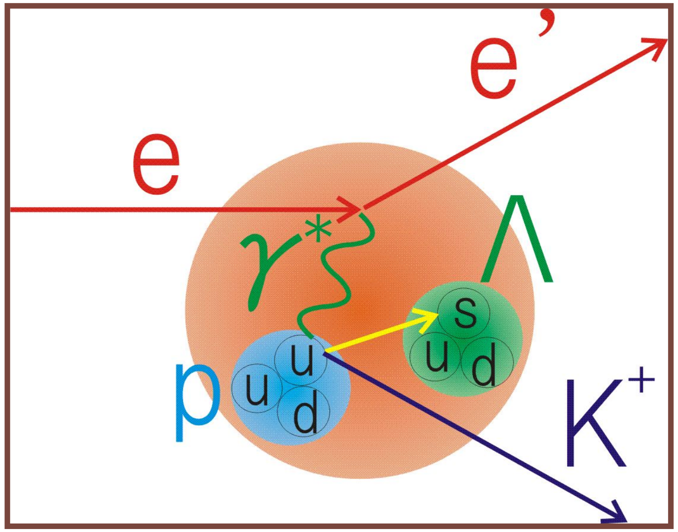
☺ Large momentum transfer

→ Excitation of deeply-bound state

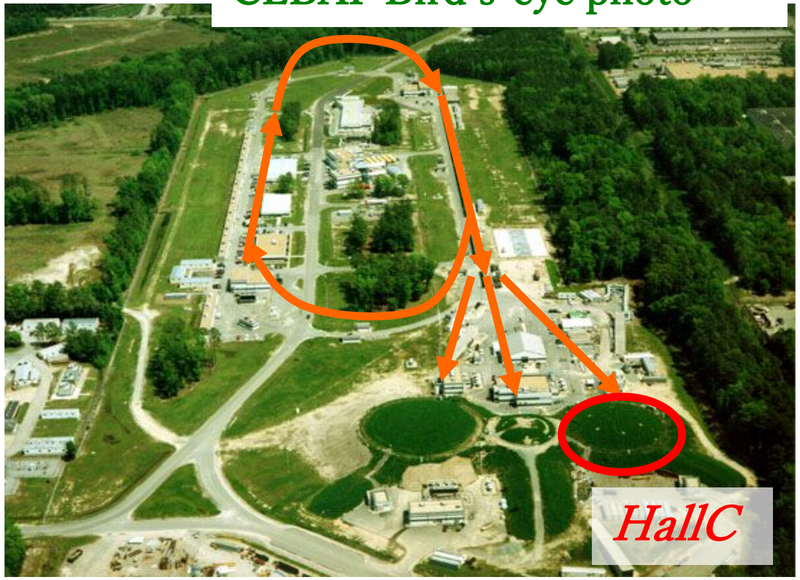
☺ p to Λ reaction → Mirror and Neutron-rich hypernuclei

☺Spin-flip/non-flip production

☺ High Energy Resolution due to CEBAF beam's quality

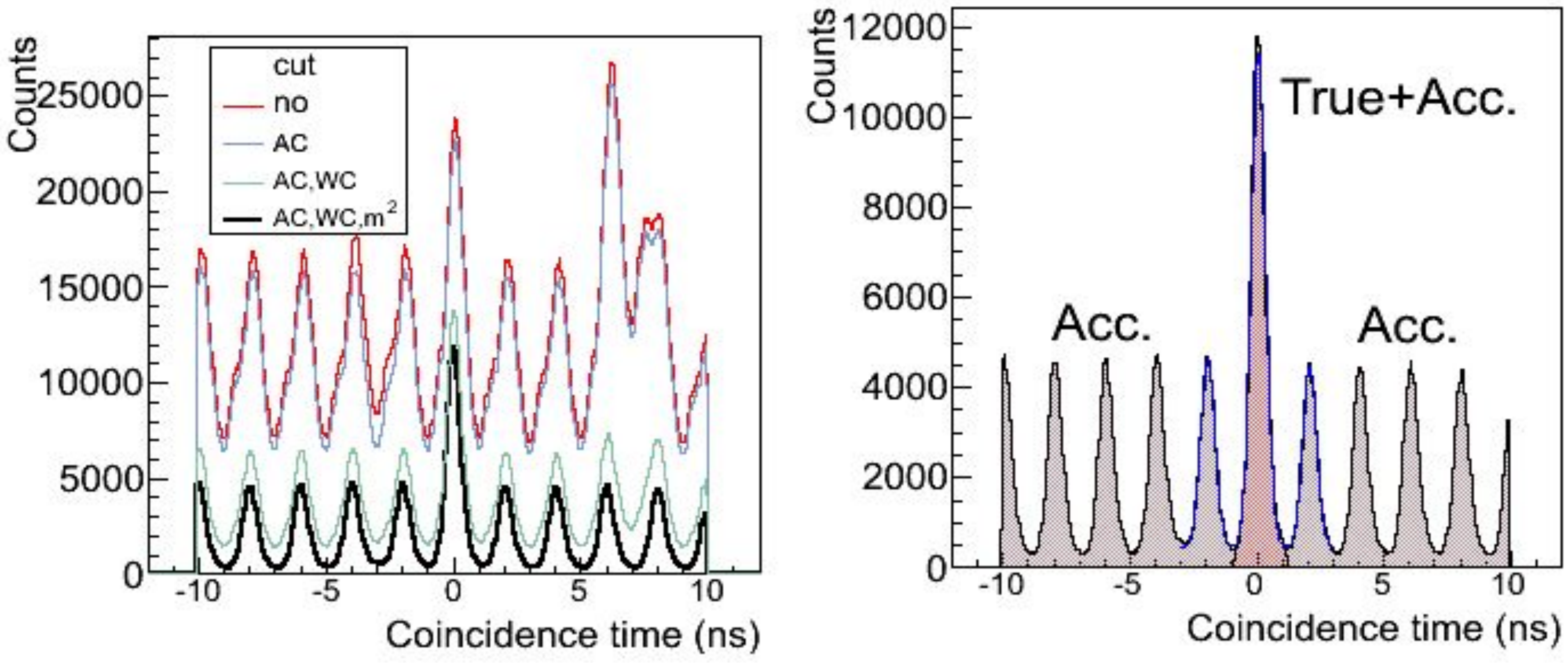


CEBAF Bird's-eye photo



KID and coincidence

Coincidence time: $T_C = T_{HKS} - T_{HES}$



$-1 < T_c < 1$

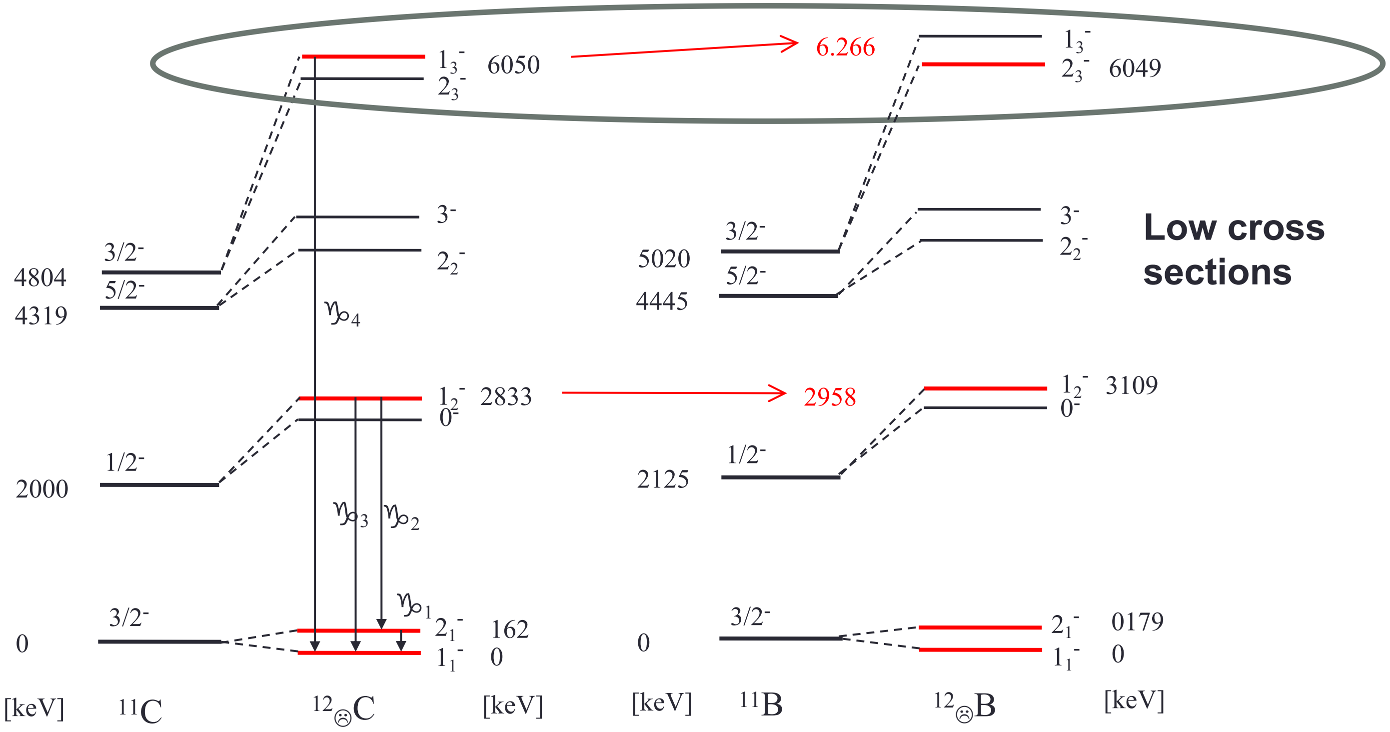
Results and Discussion

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

4th Doublet

2nd Doublet

1st Doublet



#3

Low cross sections

#2

#1

♑ Spectroscopy by KEK-E566

Mass Spectroscopy by HKS

K. Hosomi et al. / Nuclear Physics A 914 (2013) 184–188

4th doublet separation: $\Delta E(1_3^- - 2_3^-) \approx 0.22 \pm 0.06(\mathrm{stat}) \pm 0.07(\mathrm{sys.})$ MeV

Theory prediction: $\Delta E(1_3^- - 2_3^-) = 0.08$