March 18, 2015

S-2Sスペクトロメーターを用いたマルチ・ストレンジネス多体系の精密分光

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- Introduction to S=-2 Systems
  - Double Λ hypernuclei
  - Ξ hypernuclei
- J-PARC E05 experiment
  - Pilot run with SKS
  - S-2S
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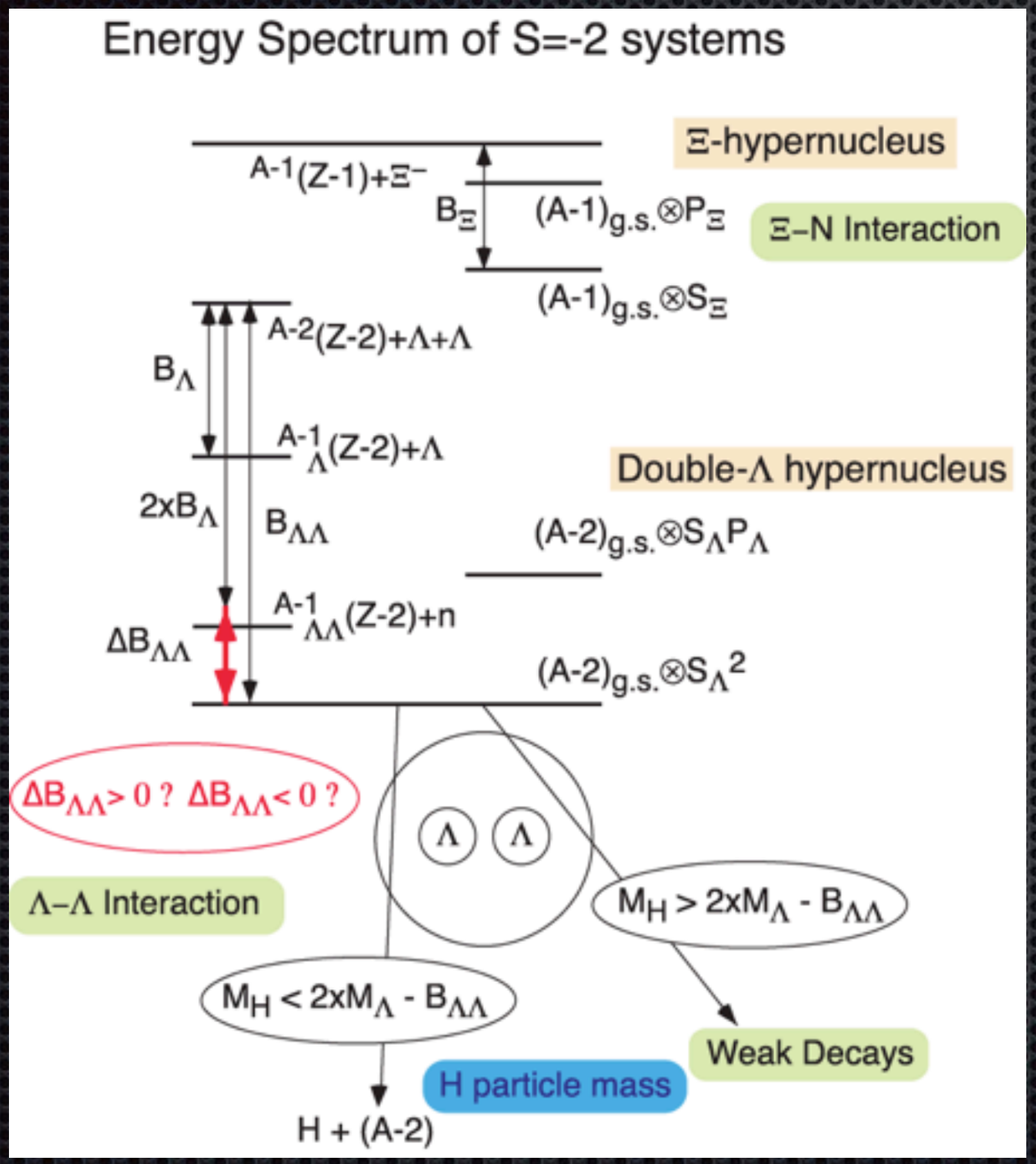
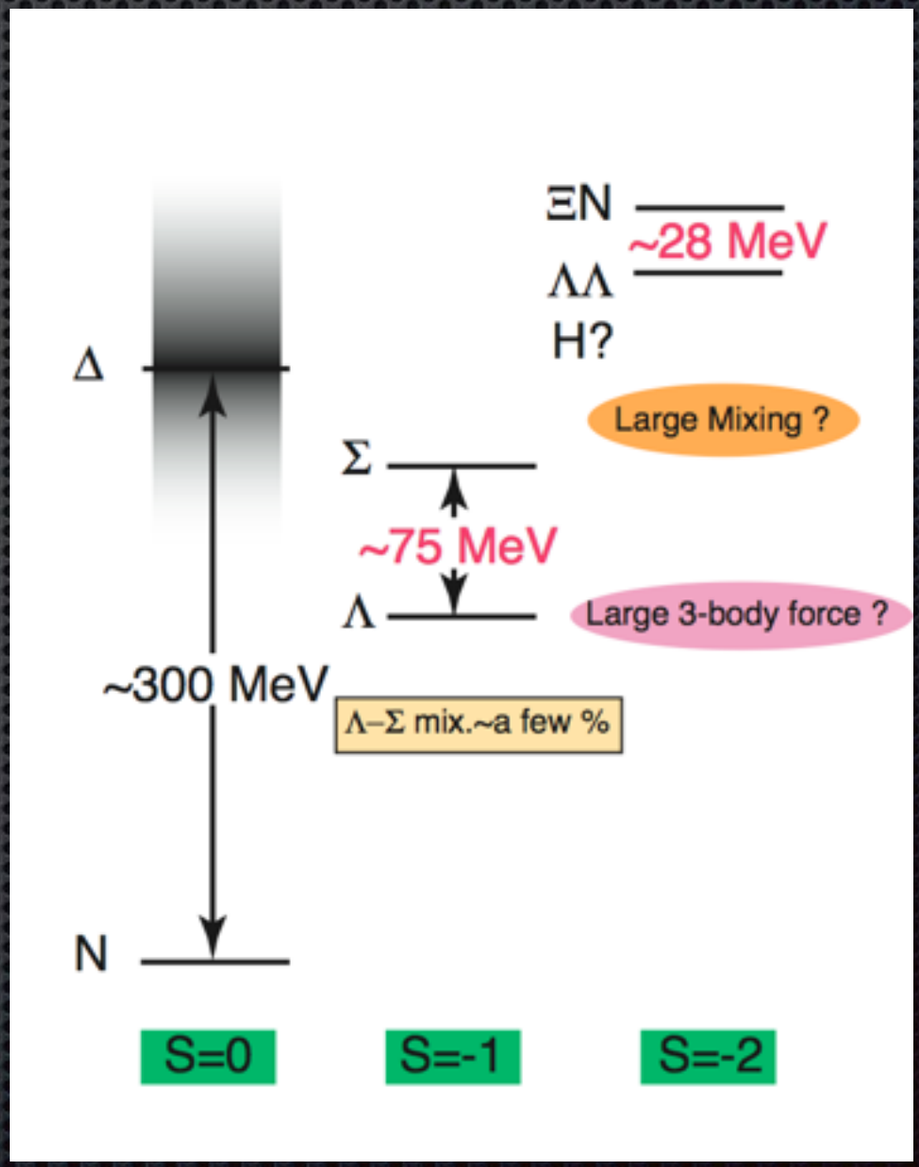
- Summary

S=-2 World


Energy Spectrum of S=-2 systems
Ξ-hypernucleus
A-1(Z-1)+Ξ⁻
BΞ
(A-1)g.s.⊗PΞ
Ξ–N Interaction
(A-1)g.s.⊗SΞ
A-2(Z-2)+Λ+Λ
BΛ
A-1Λ(Z-2)+Λ
Double-Λ hypernucleus
2xBΛ
BΛΛ
(A-2)g.s.⊗SΛPΛ
A-1ΛΛ(Z-2)+n
ΔBΛΛ
(A-2)g.s.⊗SΛ2
ΔBΛΛ> 0 ? ΔBΛΛ< 0 ?
Λ Λ
Λ–Λ Interaction
MH > 2xMΛ - BΛΛ
MH < 2xMΛ - BΛΛ
Weak Decays
H particle mass
H + (A-2)


ΞN
~28 MeV
ΛΛ
H?
Large Mixing ?
Δ
Σ
~75 MeV
Λ
Large 3-body force ?
~300 MeV
Λ–Σ mix.~a few %
N
S=0
S=-1
S=-2

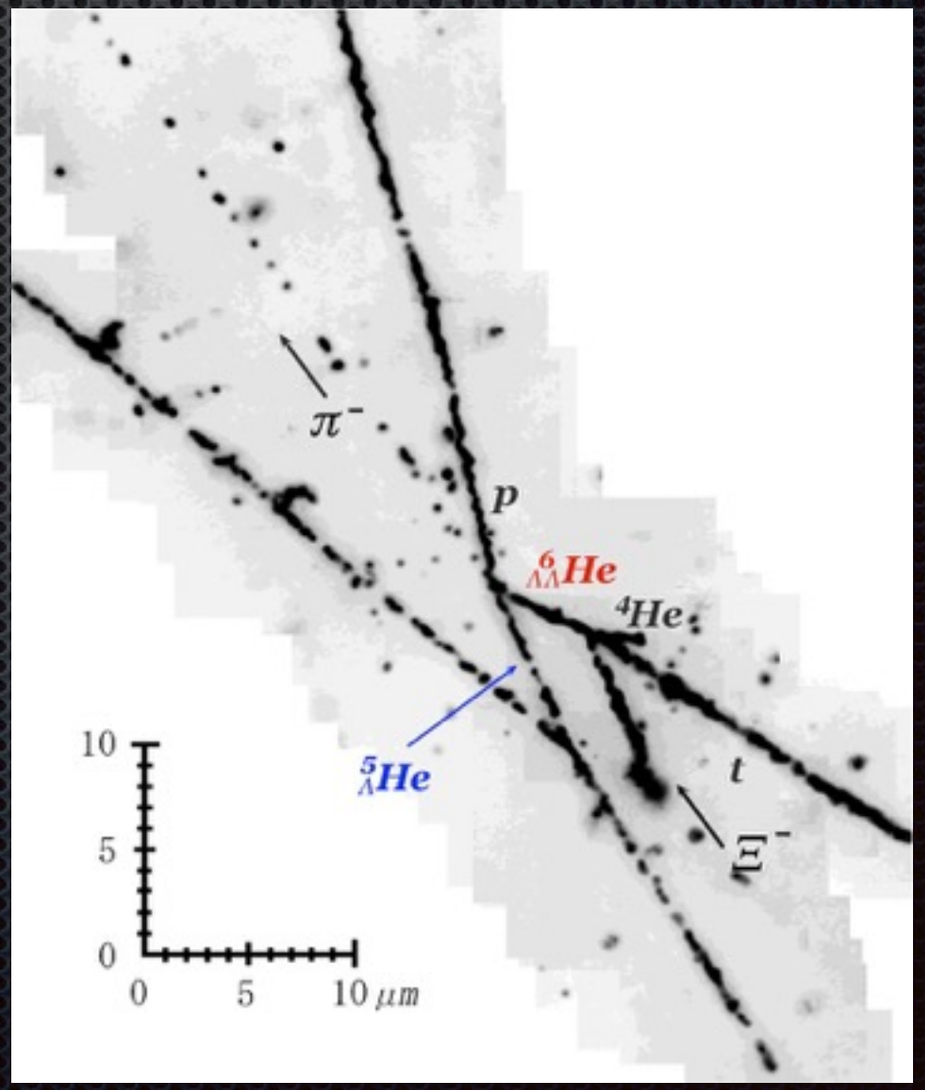
Double-Λ Hypernuclei

- "Nagara" event; ${}^{\Lambda\Lambda}{}^{6}\mathrm{He}$
  - Uniquely identified
  - $\Delta B_{\Lambda\Lambda}$=0.67±0.17 MeV

J.K. Ahn et al., PRC 88 (2013) 014003.

  - smaller than before (~4 MeV)

KEK E373



H. Takahashi et al., PRL87, (2001) 212502.

Double-Λ predicted by Hiyama

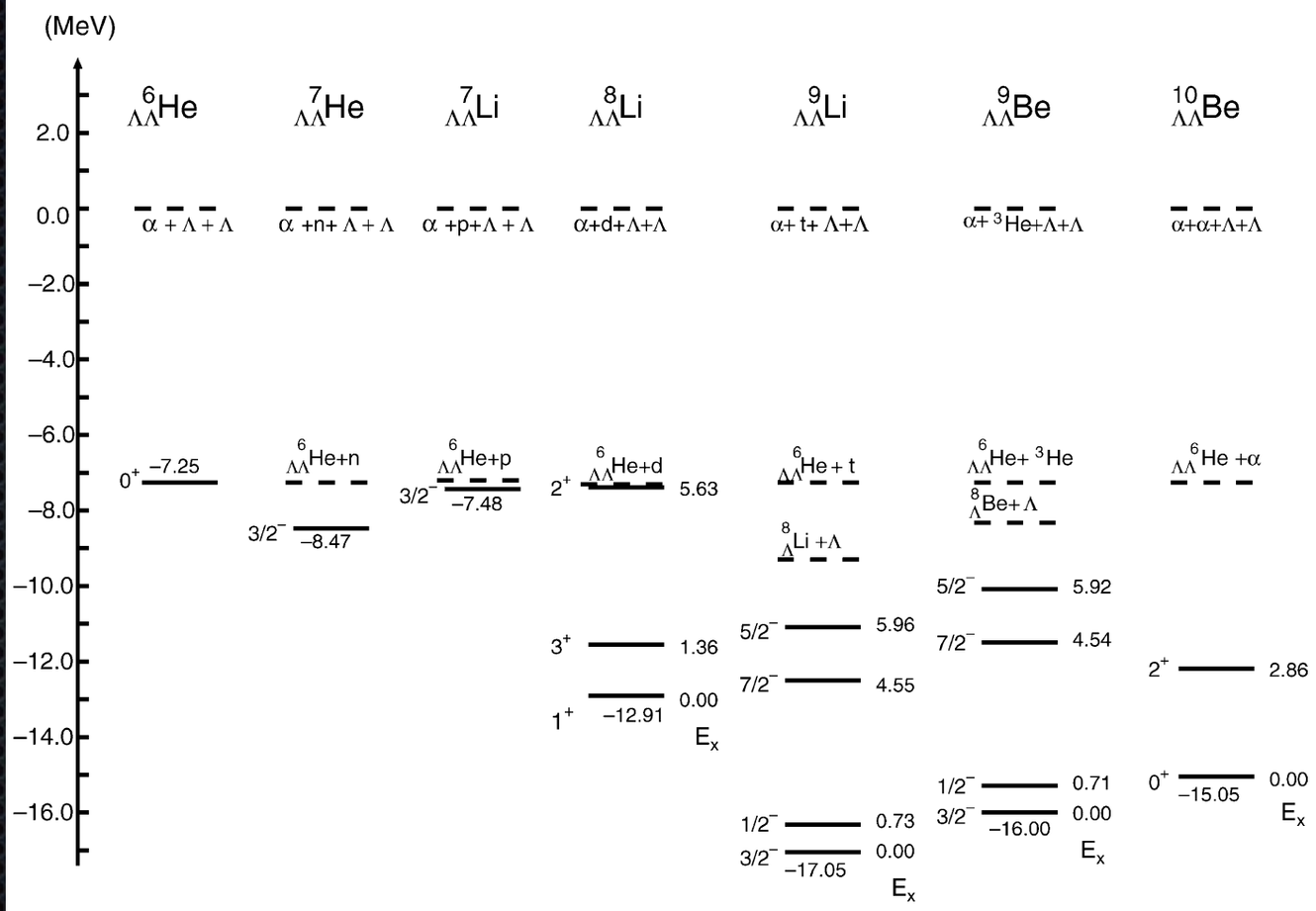


Fig. 3. Calculated energy levels of $A = 7$–10 double Λ hypernuclei.

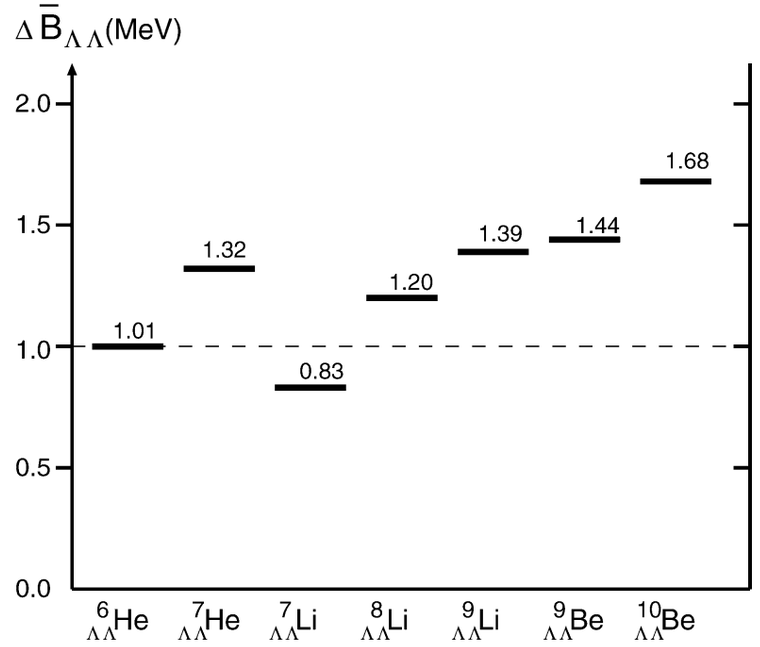
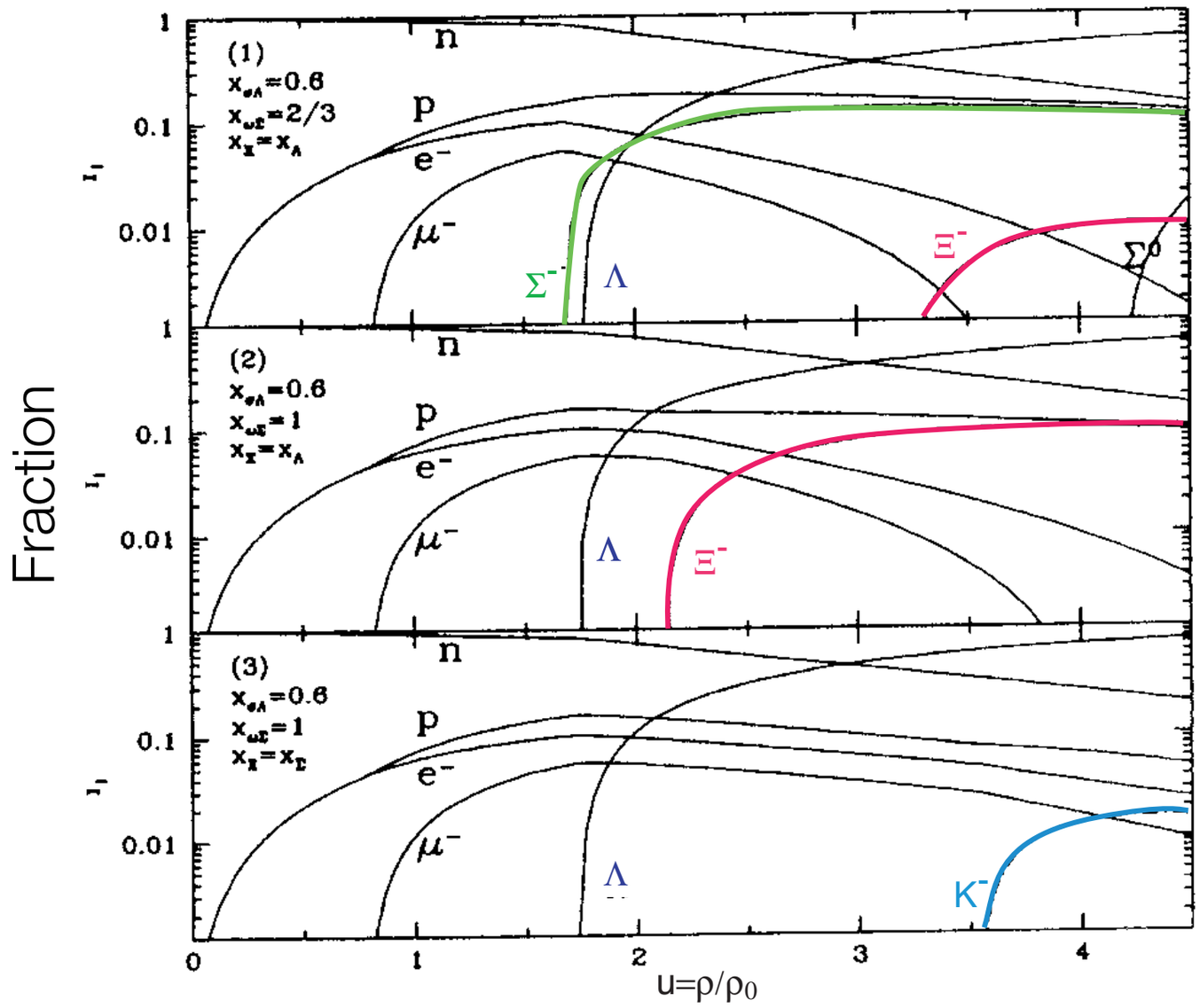


Fig. 4. Calculated values of $\Delta\bar{B}_{\Lambda\Lambda}$.

Ξ-Nucleus potential ?

- Chemical Potential:

$$\mu_B = m_B + \frac{k_F^{\,2}}{2m_B} + U(k_F)$$



U Σ <0, U Ξ <0

U Σ >0, U Ξ <0

U Σ >0, U Ξ >0

Experimental situations before 1990

Ξ⁻'s binding energy

$^{8}_{\Xi}$He: 5.9 ± 1.2 MeV[1]

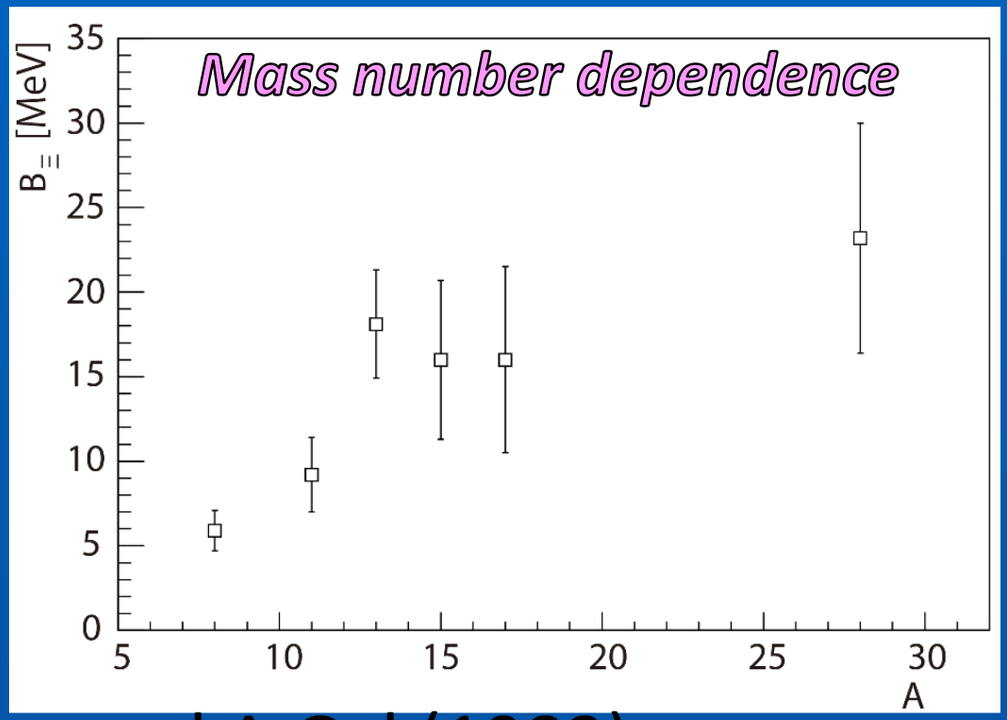
$^{11}_{\Xi}$B: 9.2 ± 2.2 MeV[2]

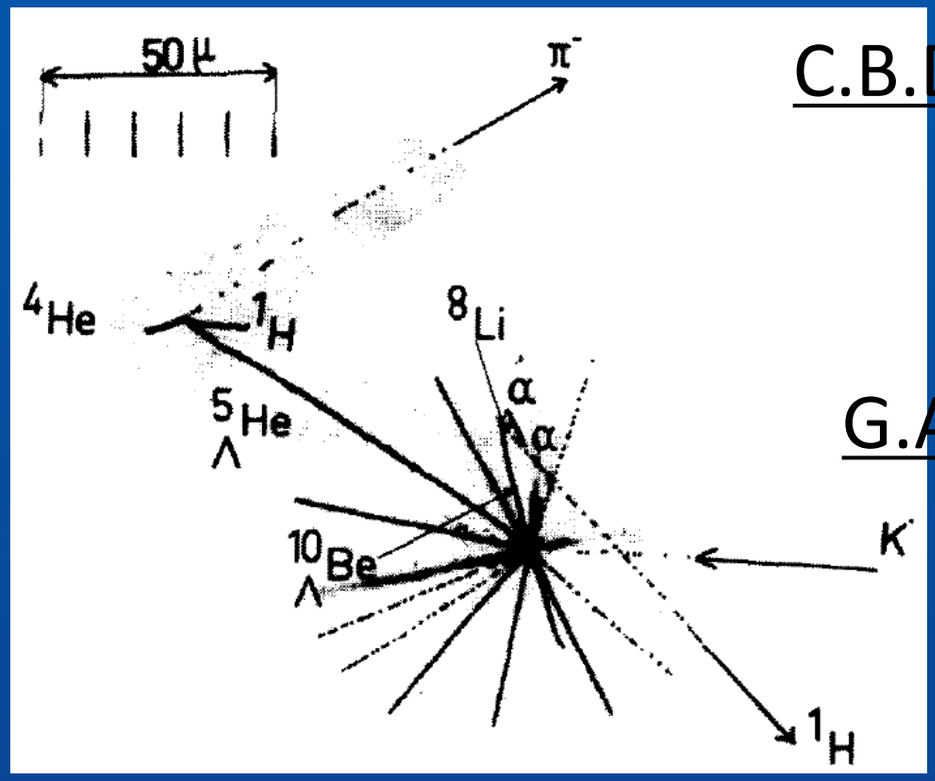
$^{13}_{\Xi}$C: 18.1 ± 3.2 MeV[3]

$^{15}_{\Xi}$C: 16.0 ± 4.7 MeV [4]

$^{17}_{\Xi}$O: 16.0 ± 5.5 MeV[4]

$^{28}_{\Xi}$Al: 23.2 ± 6.8 MeV [4]





C.B.Dover and A.Gal (1983)

$V_{0\Xi} = 24 \pm 4$ MeV ($r_0 = 1.1$ fm)

$V_{0\Xi} = 21 \pm 4$ MeV ($r_0 = 1.25$ fm)

G.A.Lalazissis *et al.* (1989)

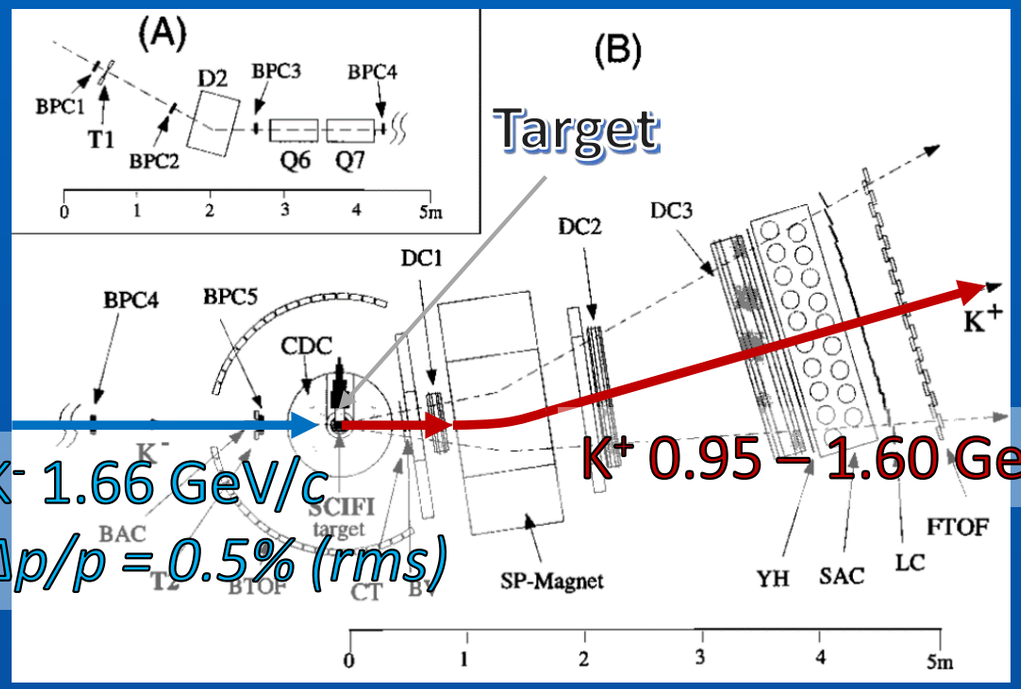
$V_{0\Xi} = 22$ MeV

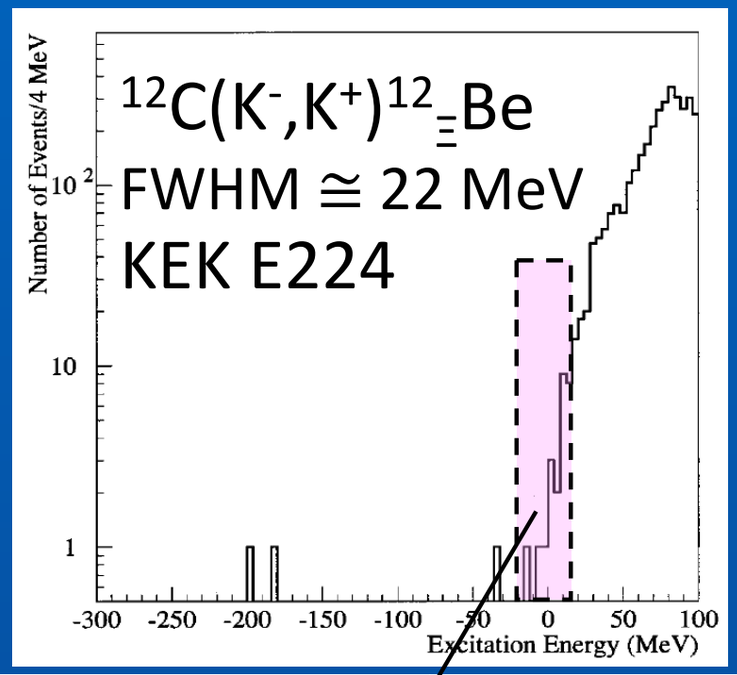
[1]D.H.Wilkinson *et al.*, *PRL* **3** (1959)8
[2]J.Catala *et al.*, *Proc. Int. Conf. on Hypernuclear Physics, Argonne*, Illinois **vol.2**, p.758 (1969)
[3]A.S.Mondal *et al.*, *Nuovo Cimento* **54**A(1979)3
[4]A.Beckdolff *et al.*, *PL***26**B(1968)3

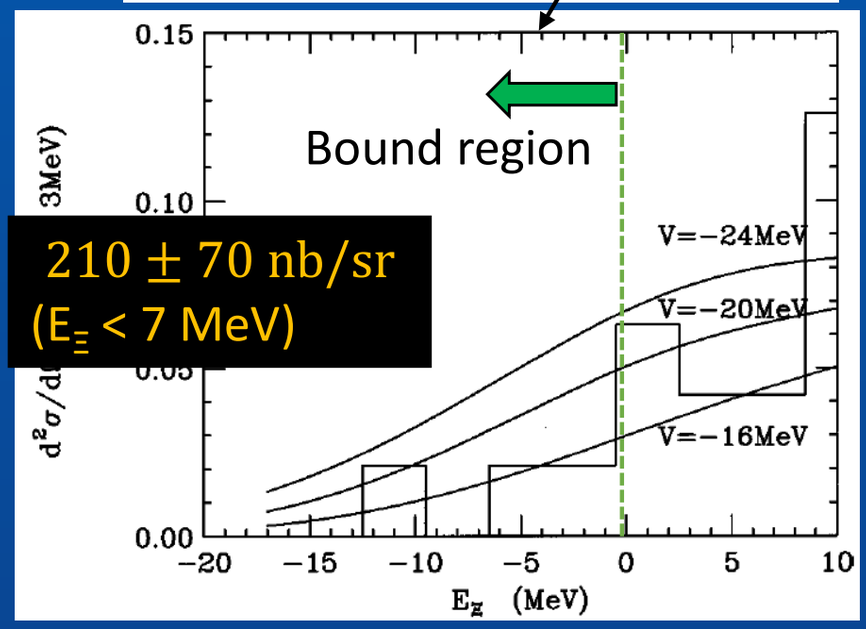
KEK E224

Counter experiment at KEK T.Fukuda *et al.*, *PRC* **58** (1998) 2

*(The **first** direct measurement in the missing mass spectrum.)*







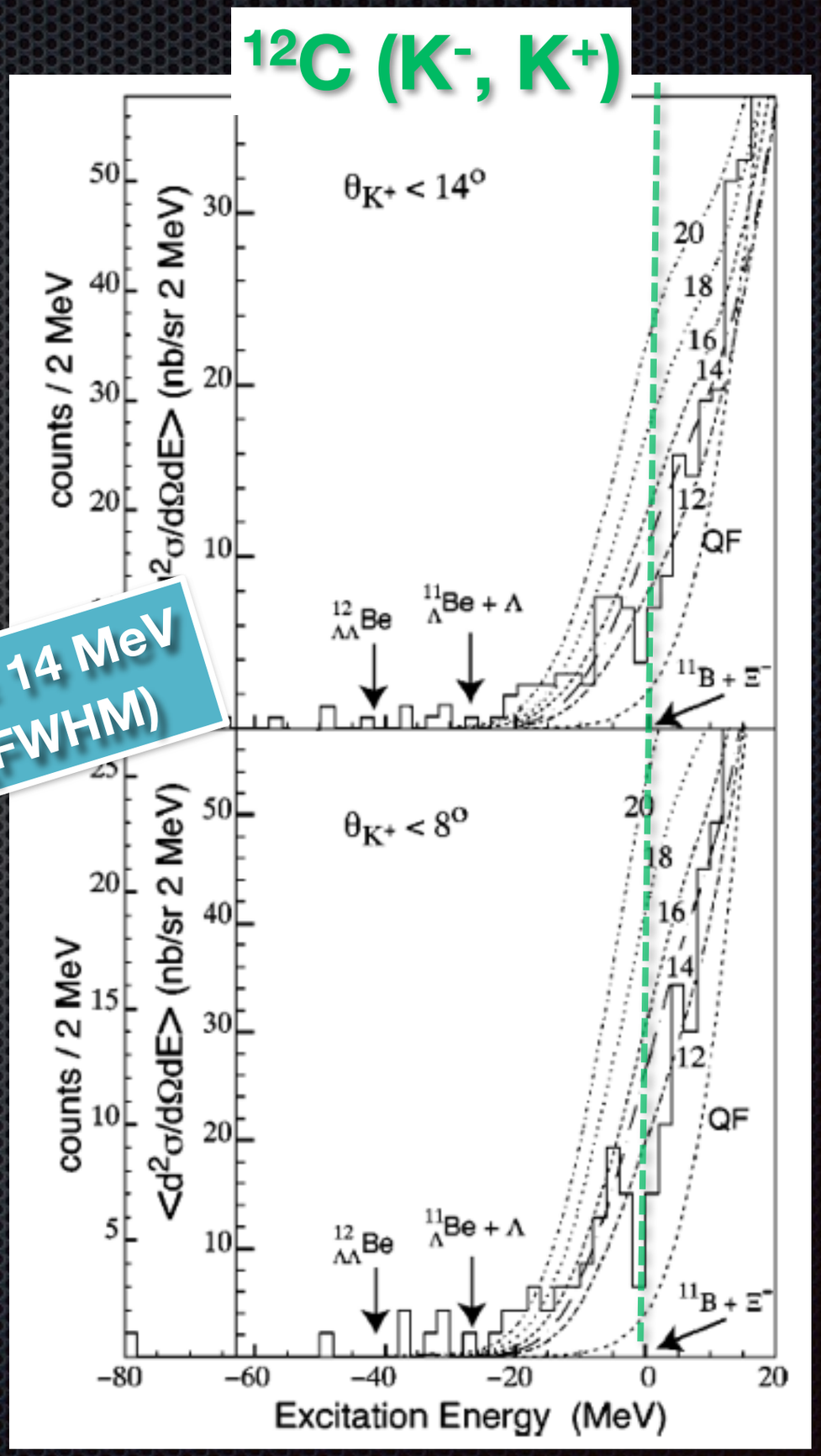
1. Differential cross section (E_{Ξ}<7 MeV) comparison with theory
2. Distribution shape analysis.

→ $V_{0\Xi} < 20$ MeV

Consistent with KEK E176 !!

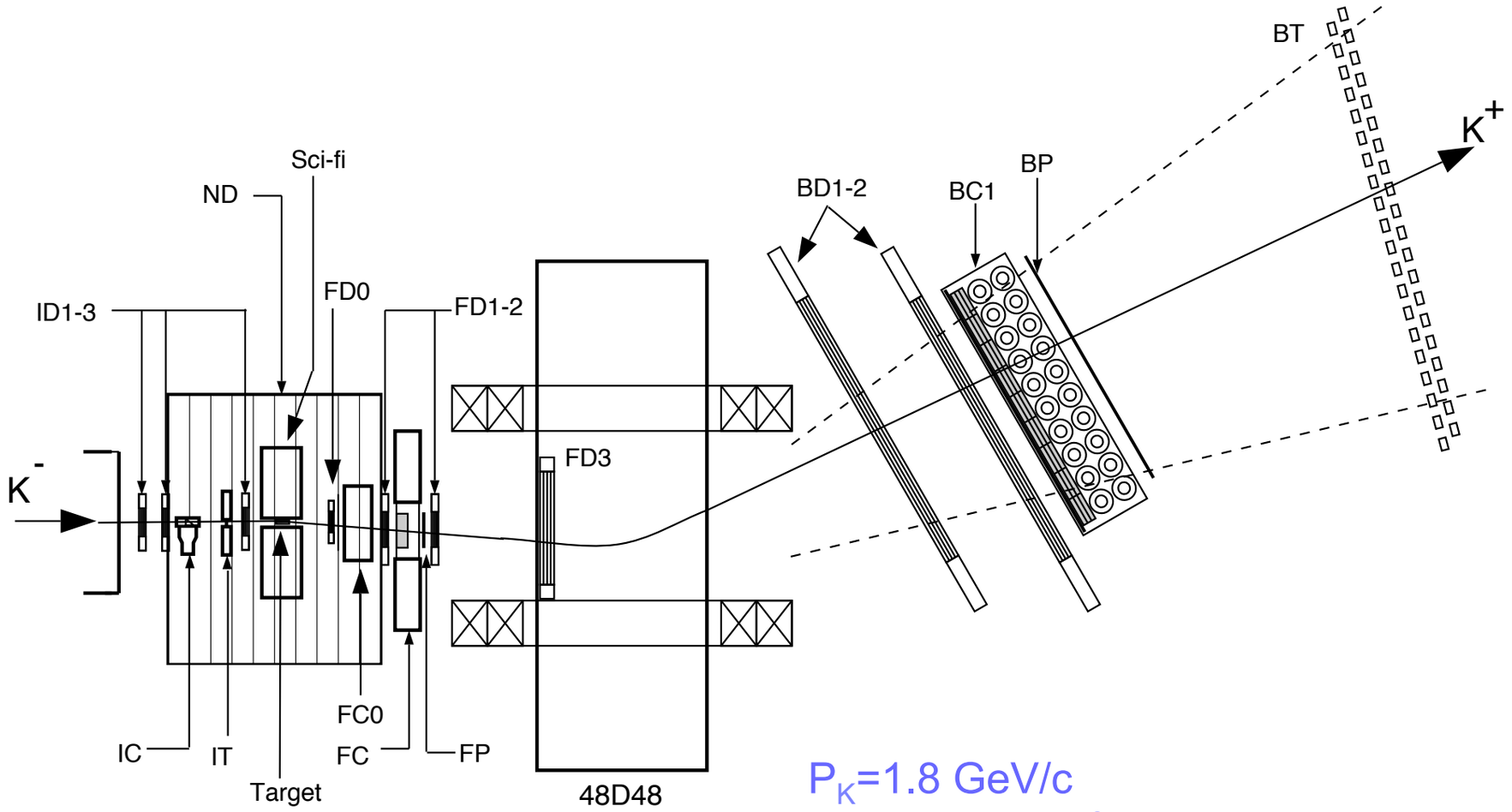
BNL E885

- not clear evidence of Ξ- hypernuclear bound state.
  - because of limited mass resolution
- suggest weakly attractive potential of -14 MeV depth.
  - by shape analysis and counts in bound region, compared with DWIA calc.
- 89±14 nb/sr (<8deg.); 42±5 nb/sr (<14deg.)



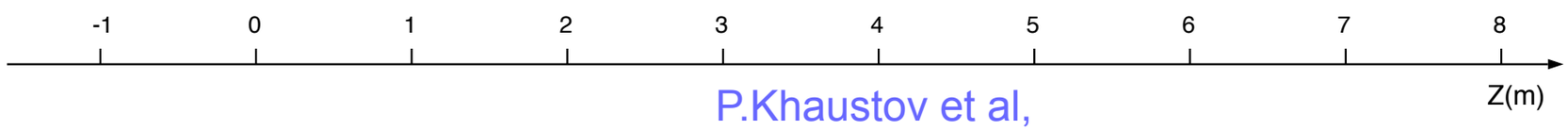
P.Khaustov et al., PRC61(2000)054603

BNL E885



P_K=1.8 GeV/c

ΔM=9.9 MeV/c^2 (FWHM) for $p(K^-,K^+)\Xi^-$



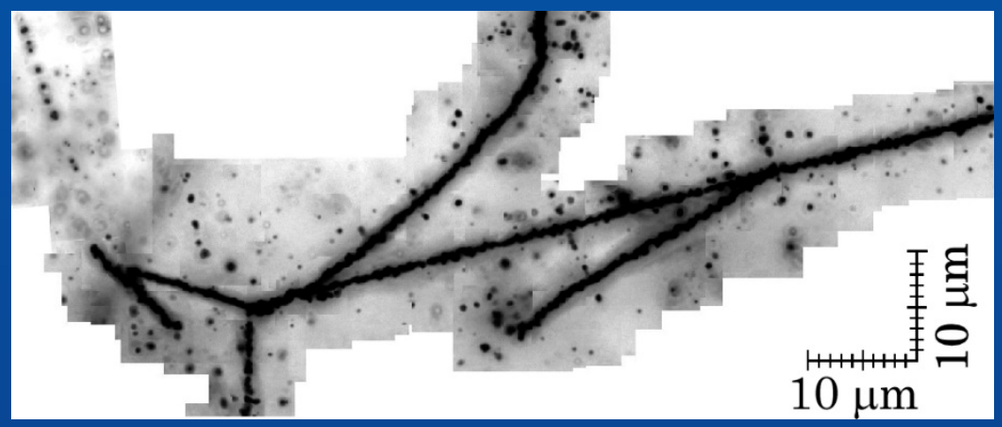
P.Khaustov et al,
PRC61(2000)0546

Kiso Event in E373

- B_{Ξ} = 1.11-4.38 MeV

Overall scanning for old emulsion

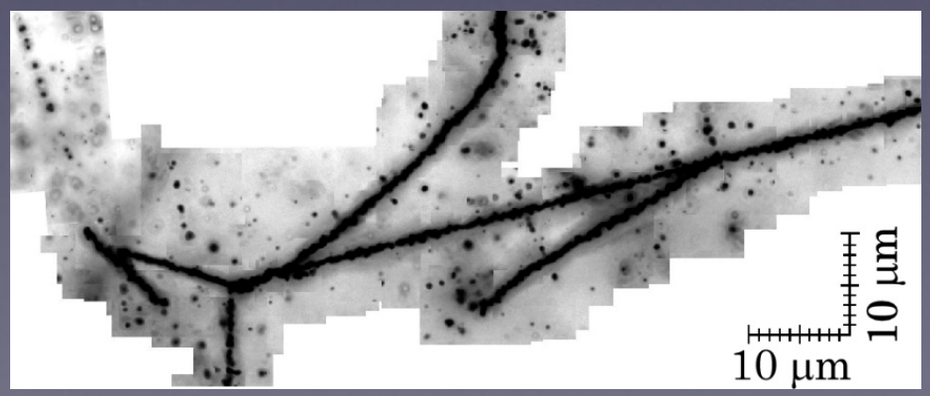
→ $\Xi^- + {}^{14}\mathrm{N} \Rightarrow {}^{10}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He}$ **was uniquely identified[1] !!**



“KISO” event

K. Nakazawa et al., KEK E373

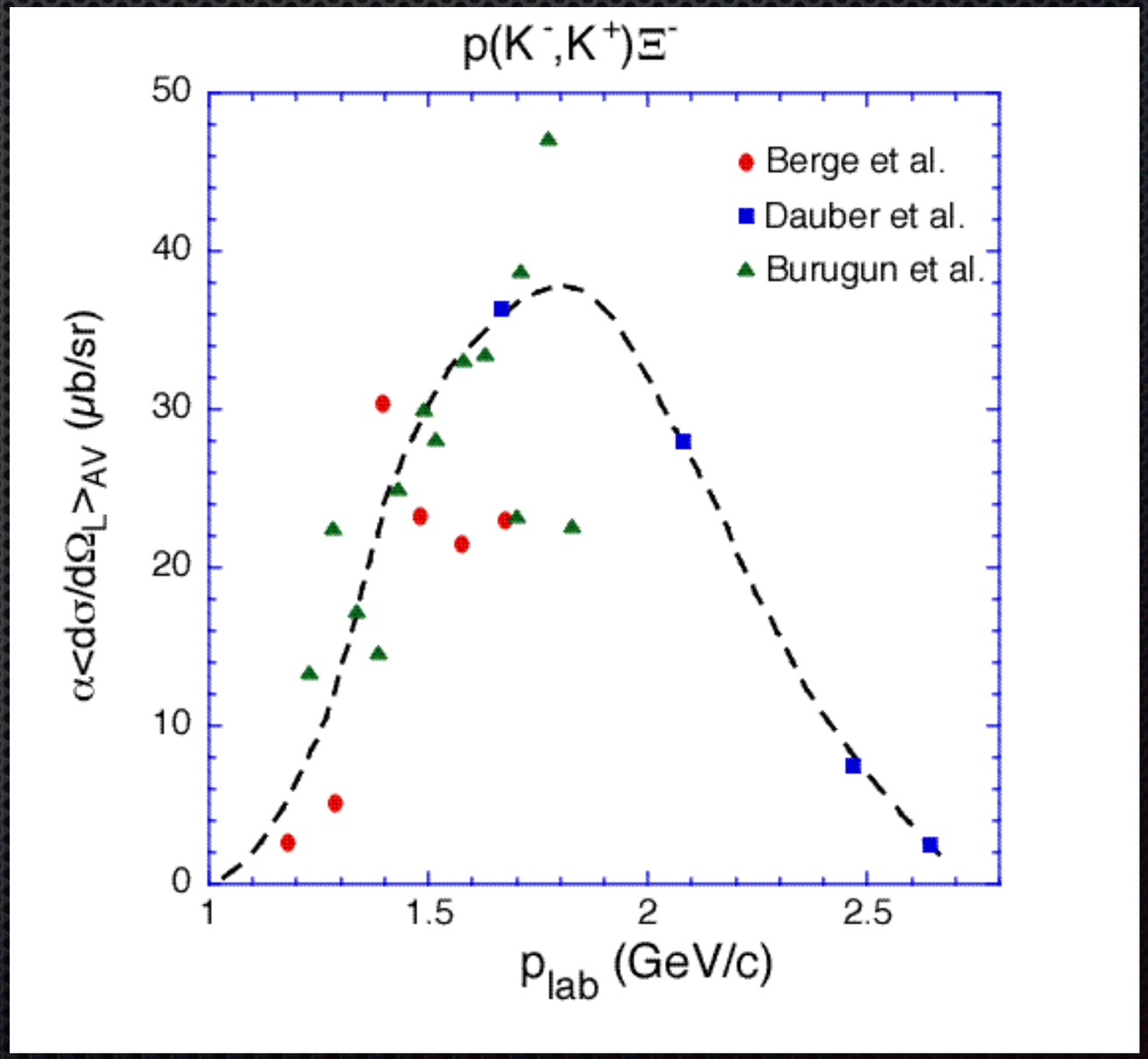
- deeply bound Ξ^--^{14}N system
  - $\Xi^- + {}^{14}\mathrm{N} \rightarrow {}^{10}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He}$
  - $B_{\Xi} = 1.11 \sim 4.38$ MeV $\pm \Gamma/2$
    - Well beyond the atomic binding of 0.17 MeV

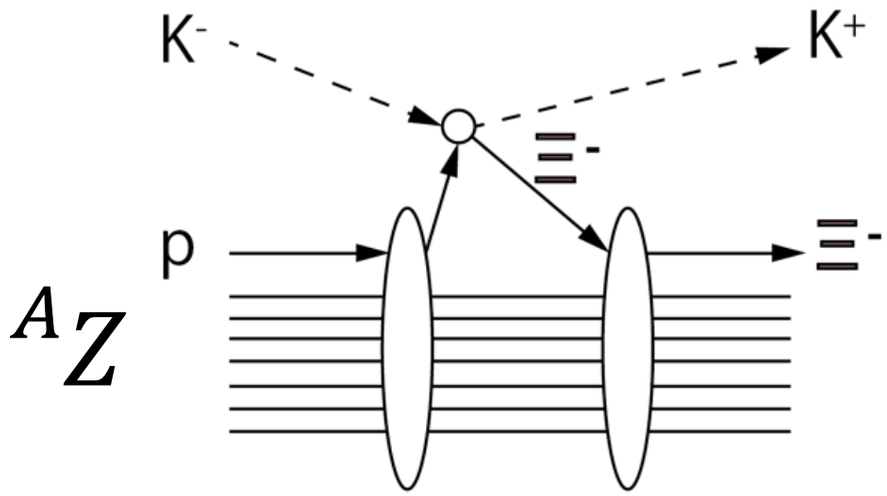


- Ξ hypernuclei do exist !
- Urgency :
  - Measurement of Re($V_Ξ$)
  - $Γ_{ΞN-ΛΛ}$?

Entrance to the S=-2 World

- Doorway Reaction:
  $K^- + p \rightarrow K^+ + \Xi^-$
  at 1.8 GeV/c

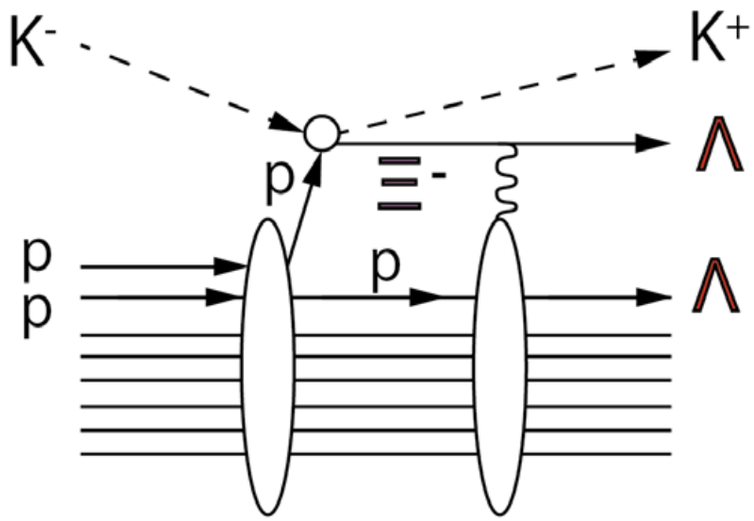




$^{A}_{Z}$

$^{A}_{\Xi\Xi}Z-2$

Ξ⁻ hypernucleus

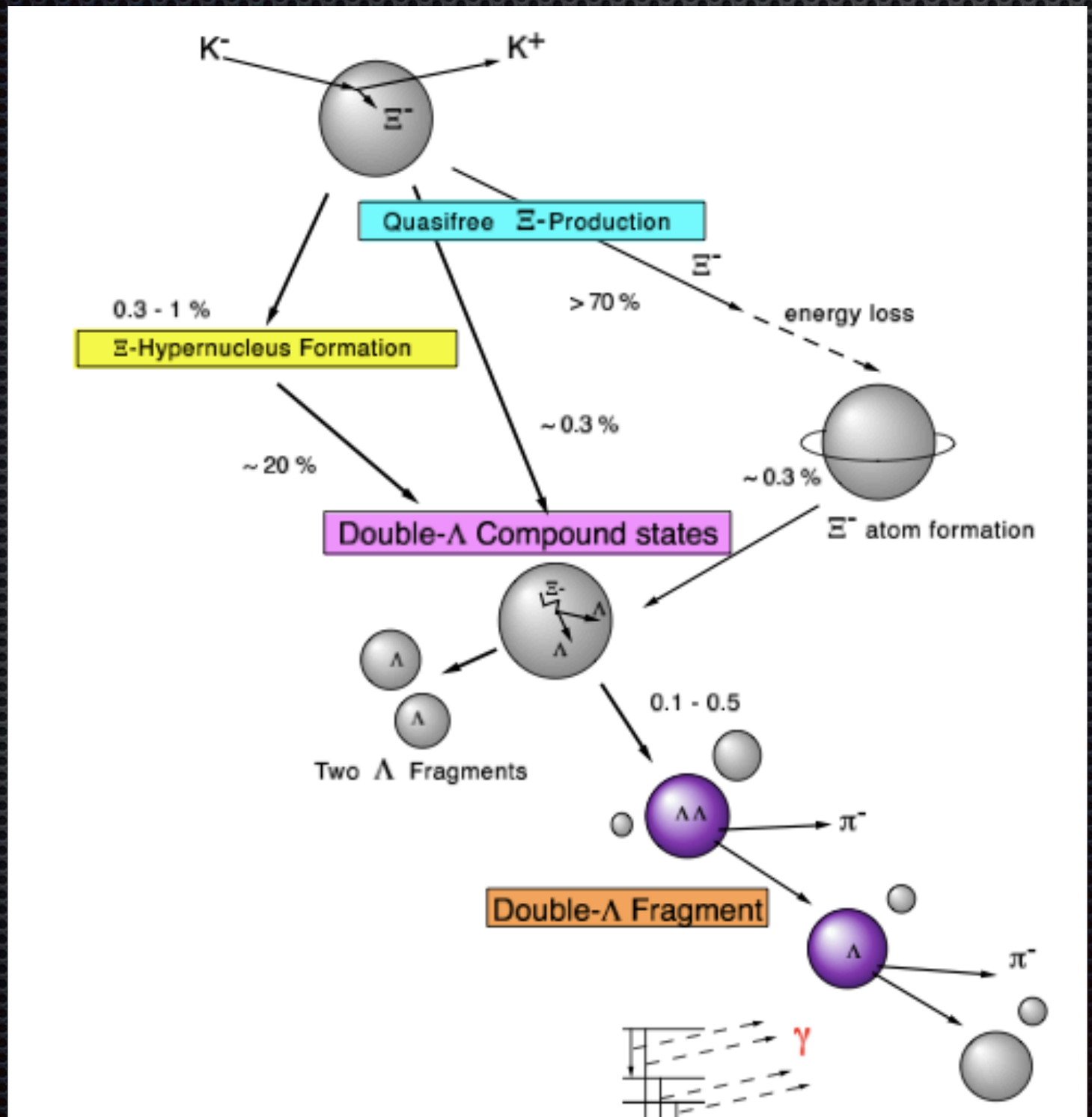


$^{A}_{Z}$

$^{A}_{\Lambda\Lambda}Z-2$

Double Λ hypernucleus

How to produce $S\equiv-2$ hypernuclei ?

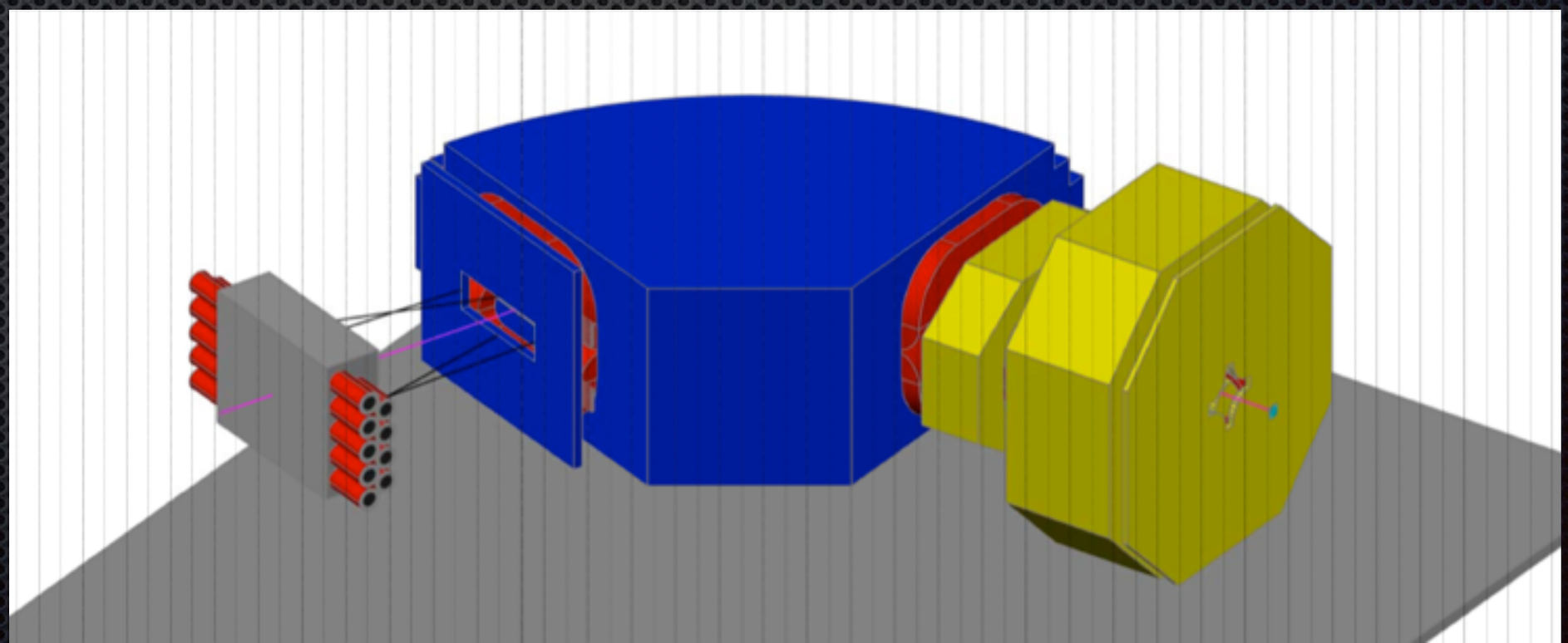


Spectroscopic Study of Ξ-Hypernucleus, $^{12}_{\Xi}$Be, via the ^{12}C(K^-,K^+) Reaction

J-PARC E05
T. Nagae et al.

- Discovery of Ξ-hypernuclei as a peak(s)
- Measurement of Ξ-nucleus potential depth and width of $^{12}_{\Xi}$Be

S=-1 → S=-2 (Multi-Strangeness System)



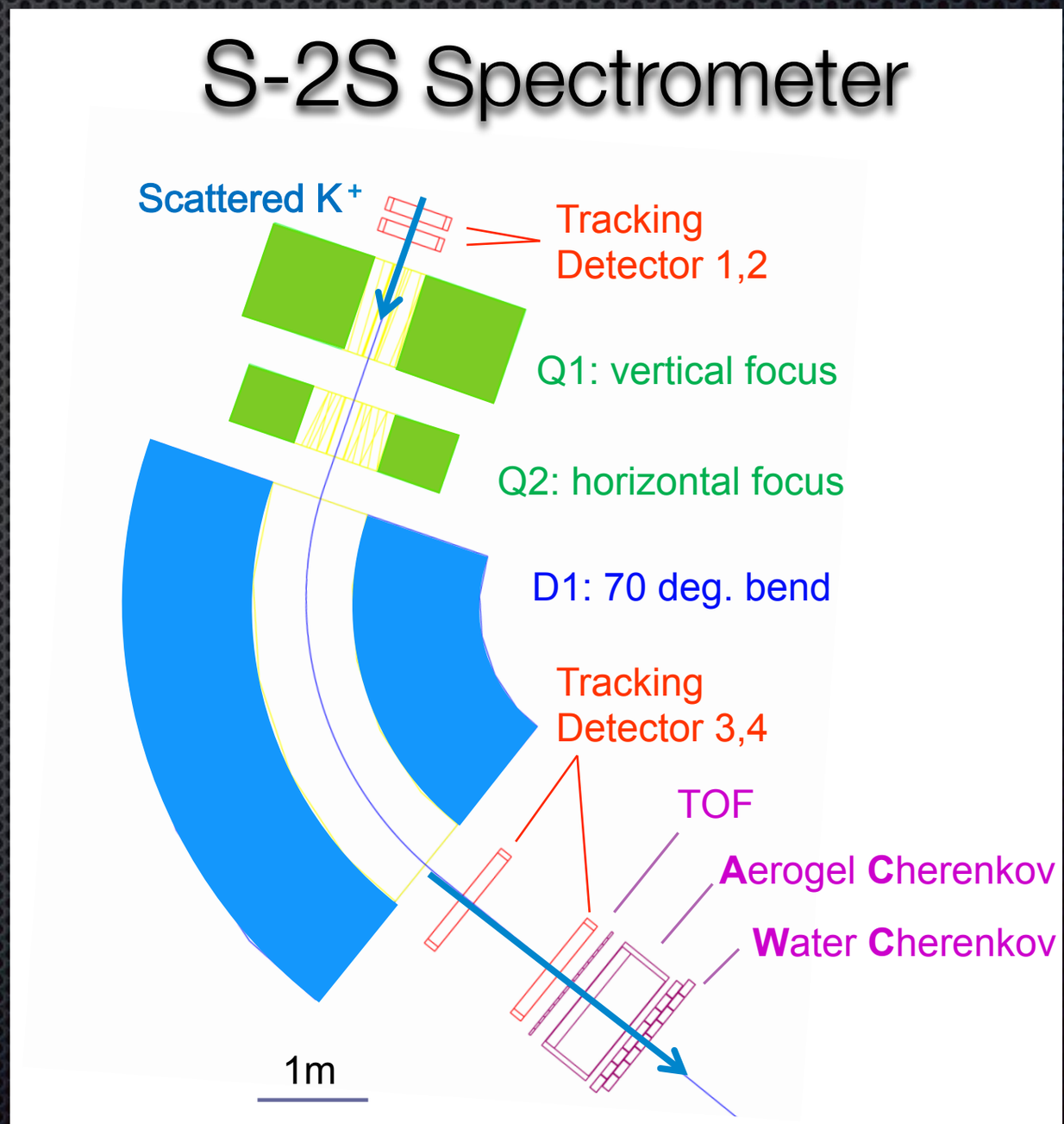
Purpose of E05

- ΞN Interaction: almost no information
  - Attractive of Repulsive ? → Potential depth
  - ΞN→ΛΛ conversion ? →Conversion width
  - Isospin dependence ?

S-2S

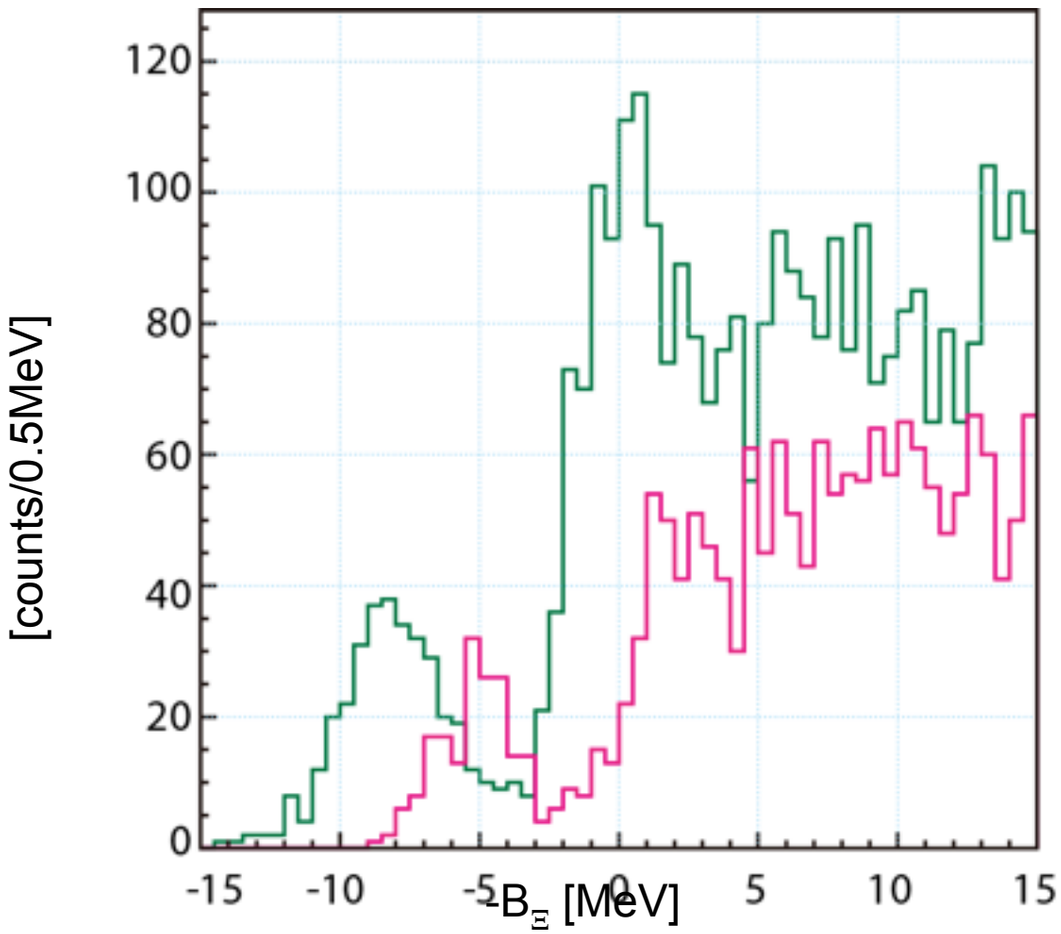
- (K^-,K^+) Spectroscopy @J-PARC
  - $K^-+p \rightarrow K^+ + \Xi^-$ @~1.8 GeV/c
- S-2S: (2010-2015)
  - Acceptance~60 msr
  - $\Delta p/p < 5\times10^{-4}$(FWHM)
  - ΔE=1.5 MeV

	Acceptance $\Delta\Omega$ (msr)	Energy Resolution ΔE (MeV)
BNL	19	14
SKS+	25	3
S-2S	60	1.5



Expected $^{12}_{\Xi}$Be Spectrum

$\Delta E_{meas.}$ = 3 MeV_{FWHM}



V_{Ξ}= -20MeV

V_{Ξ}= -14MeV

U_{Ξ} in Recent Nijmegen Models

Table 3. $U_{\Xi}(\rho_0)$ and partial wave contributions. Conversion width Γ_{Ξ}.

	T	$^1S_0$	$^3S_1$	$^1P_1$	^3P	U_{Ξ}	Γ_{Ξ}
08a	0	6.0	−1.0	−0.3	−2.1		
	1	8.5	−28.0	0.6	−3.8	−20.2	5.8
08a’	0	5.6	−1.1	−0.3	−2.2		
	1	8.4	−21.5	0.6	−3.9	−14.5	7.0
08b	0	2.4	1.9	−0.6	−2.0		
	1	9.1	−37.8	0.6	−5.4	−31.8	1.2
04d	0	6.4	−19.6	1.1	−2.2		
	1	6.4	−5.0	−1.0	−4.8	−18.7	11.3

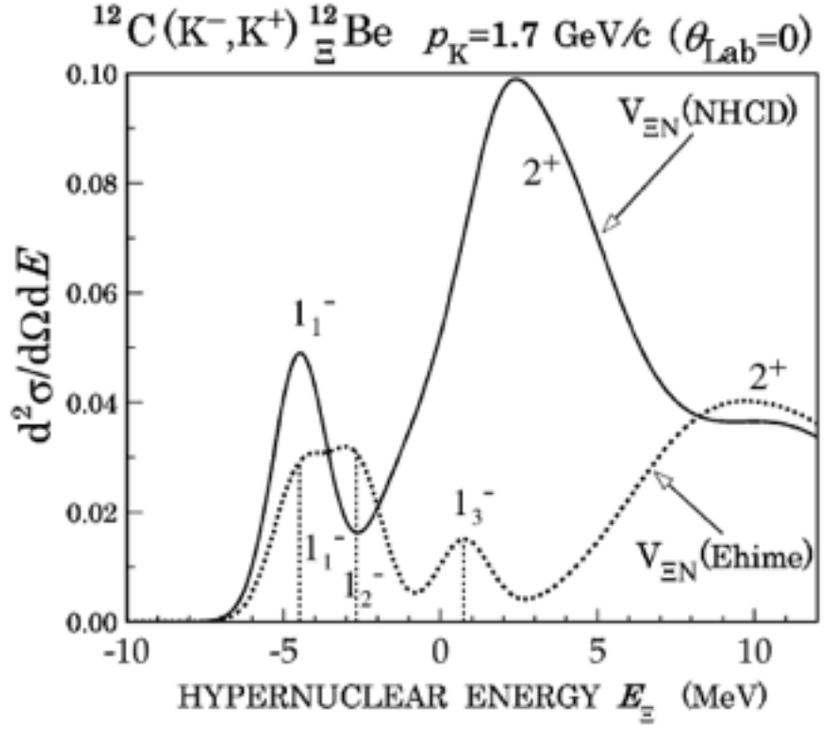


Figure 6: DWIA spectra with NHC-D and Ehime.

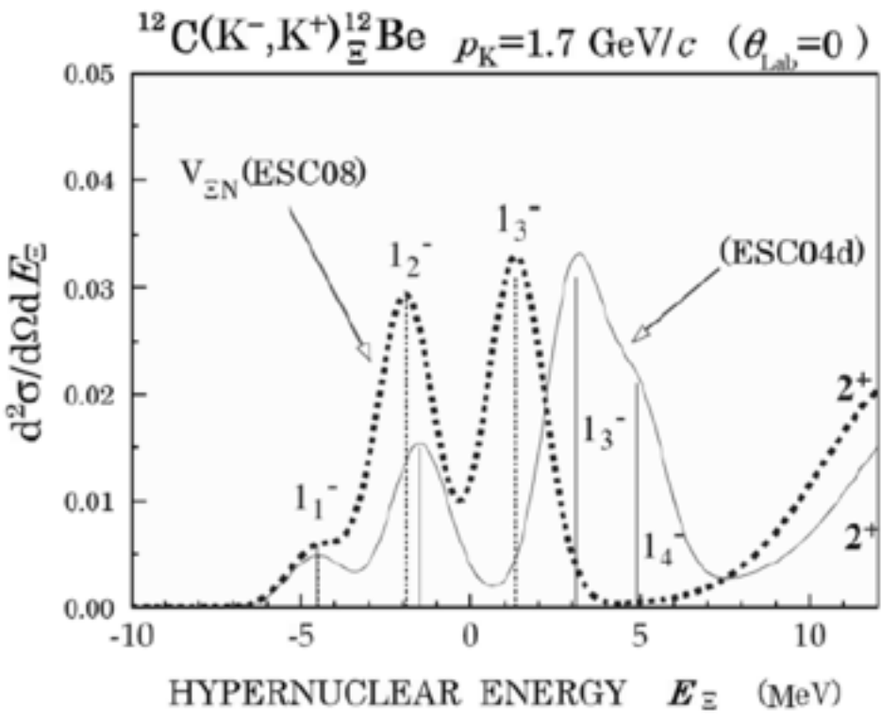
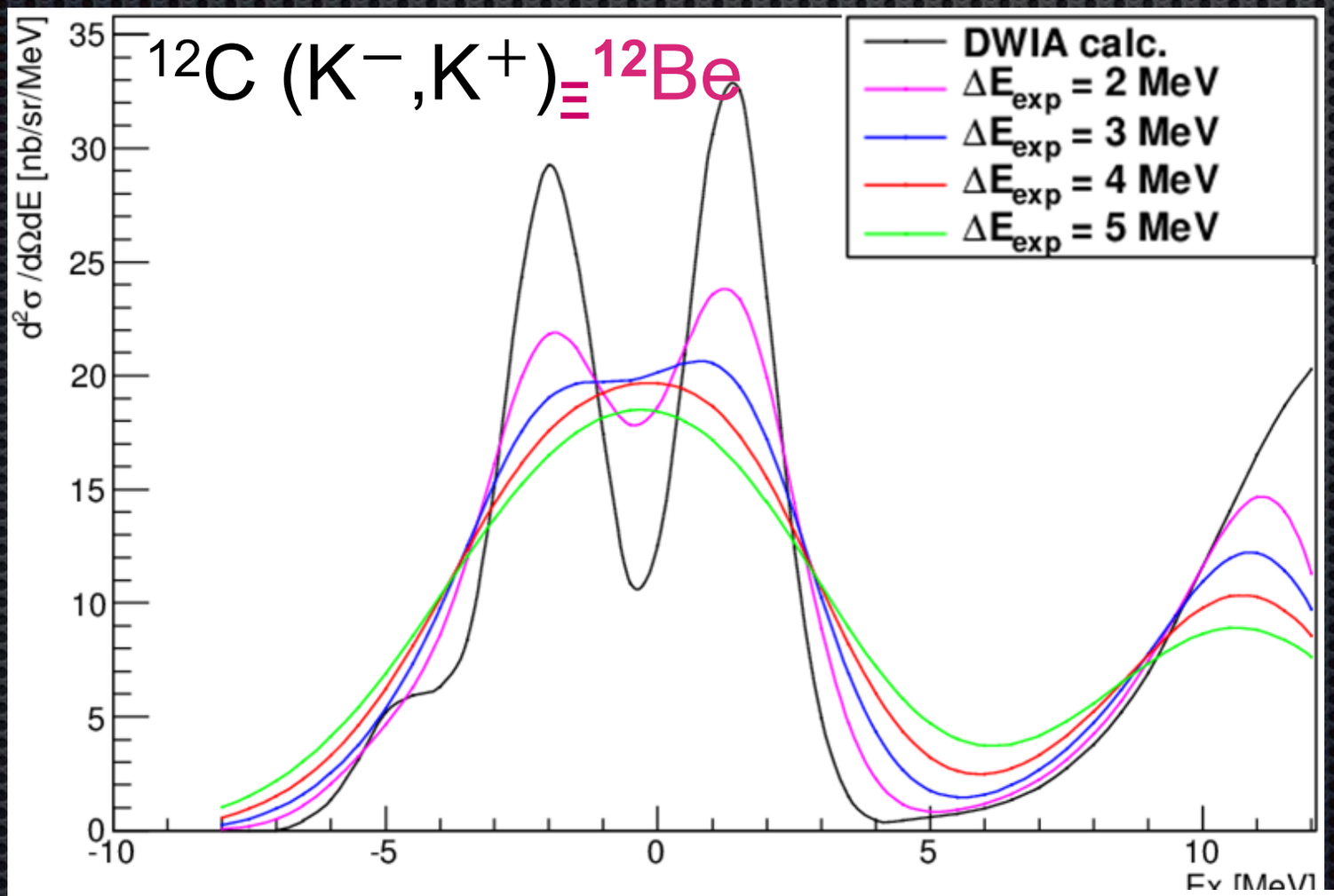


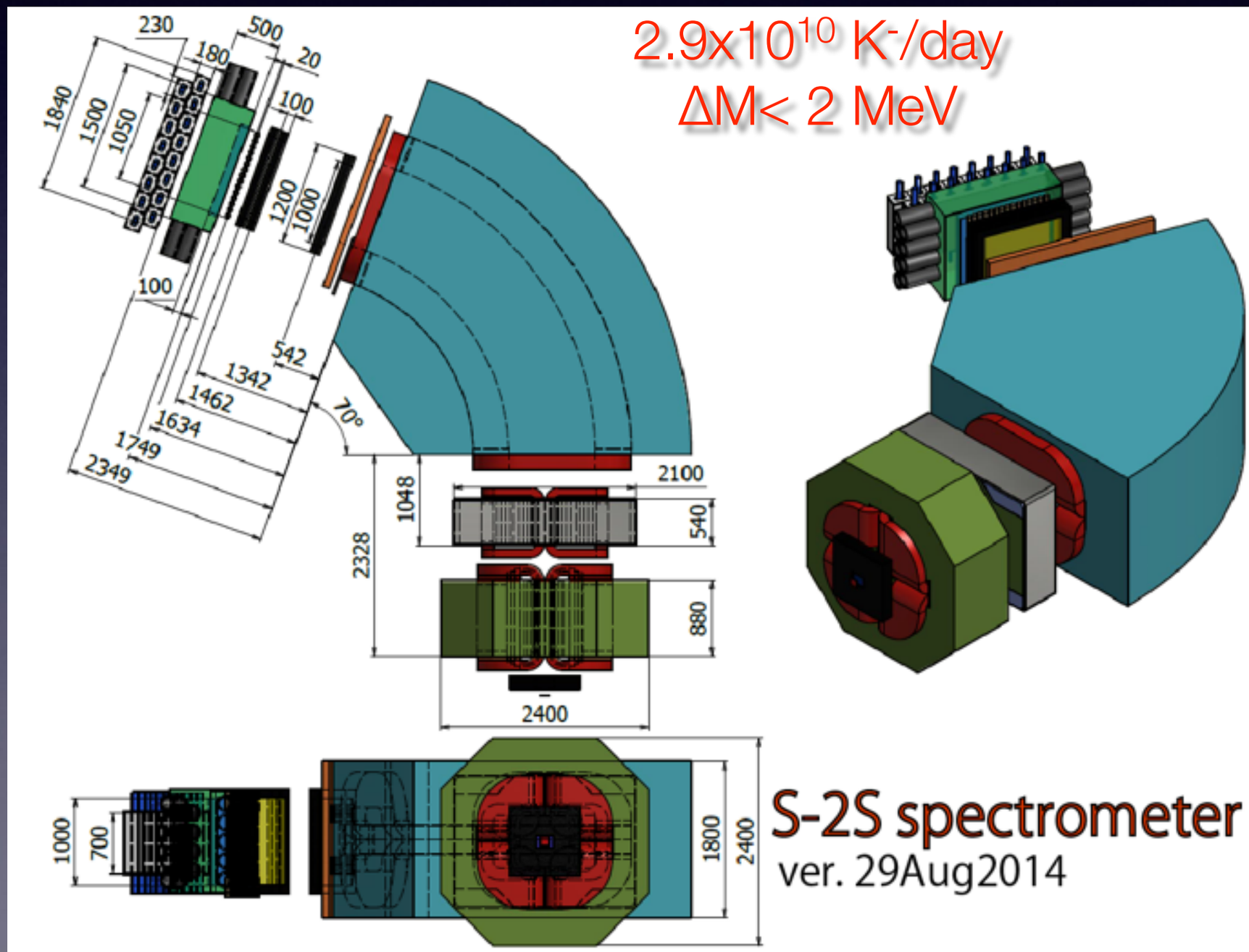
Figure 7: DWIA spectra with ESC04d and ESC08a.



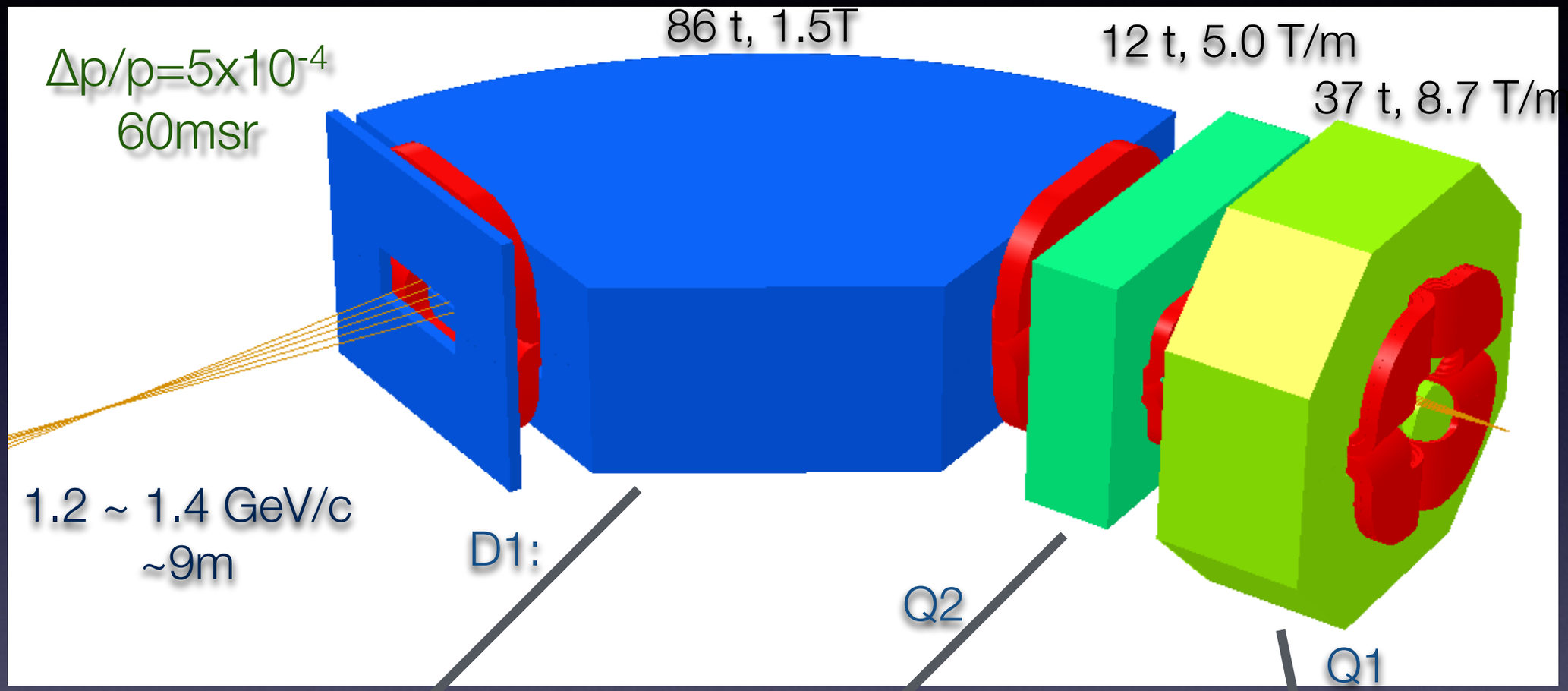
T. Motoba and S. Sugimoto, Nucl. Phys. A 835, 223 (2010)

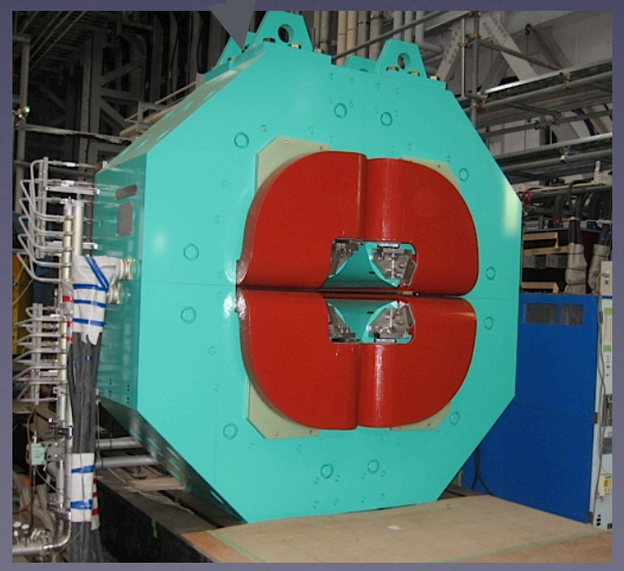
E05 with S-2S

- Grant-In-Aid for Specially promoted research: 2011 – 2015, Total ~$3M
- 60 msr, Δp/p=0.05%
  → ΔM=1.5 MeV
- Construction of S-2S(QQD): ~3 years
  ★Installation in 2016
  ★Data taking in 2017 with > 100 kW !!



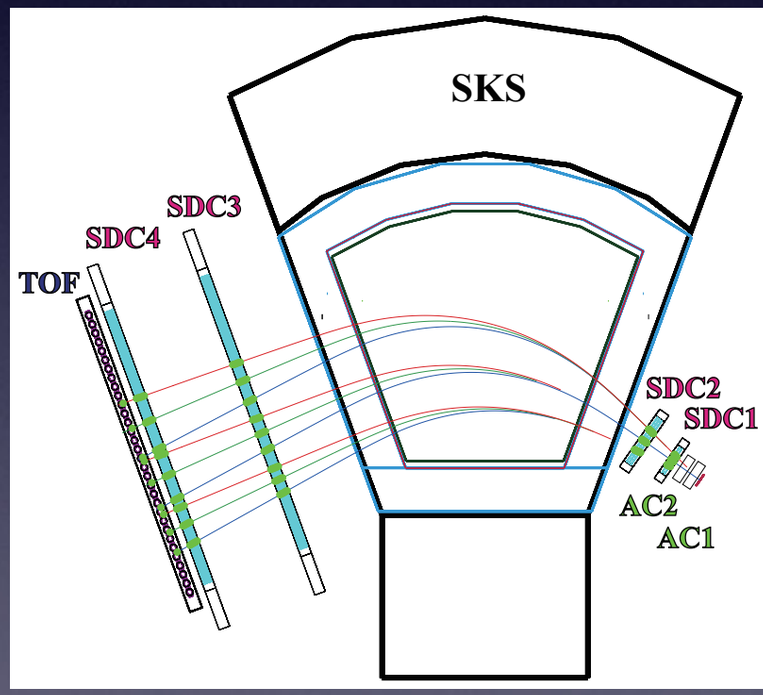
S-2S Construction



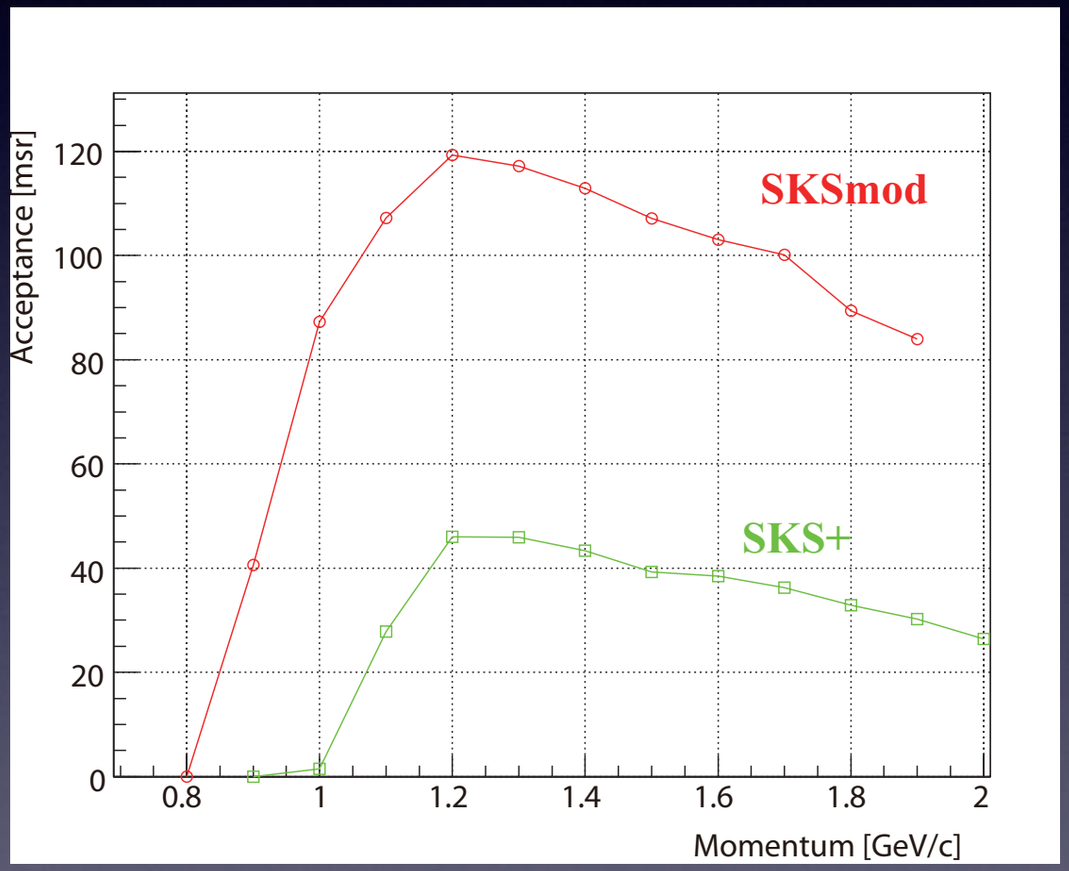


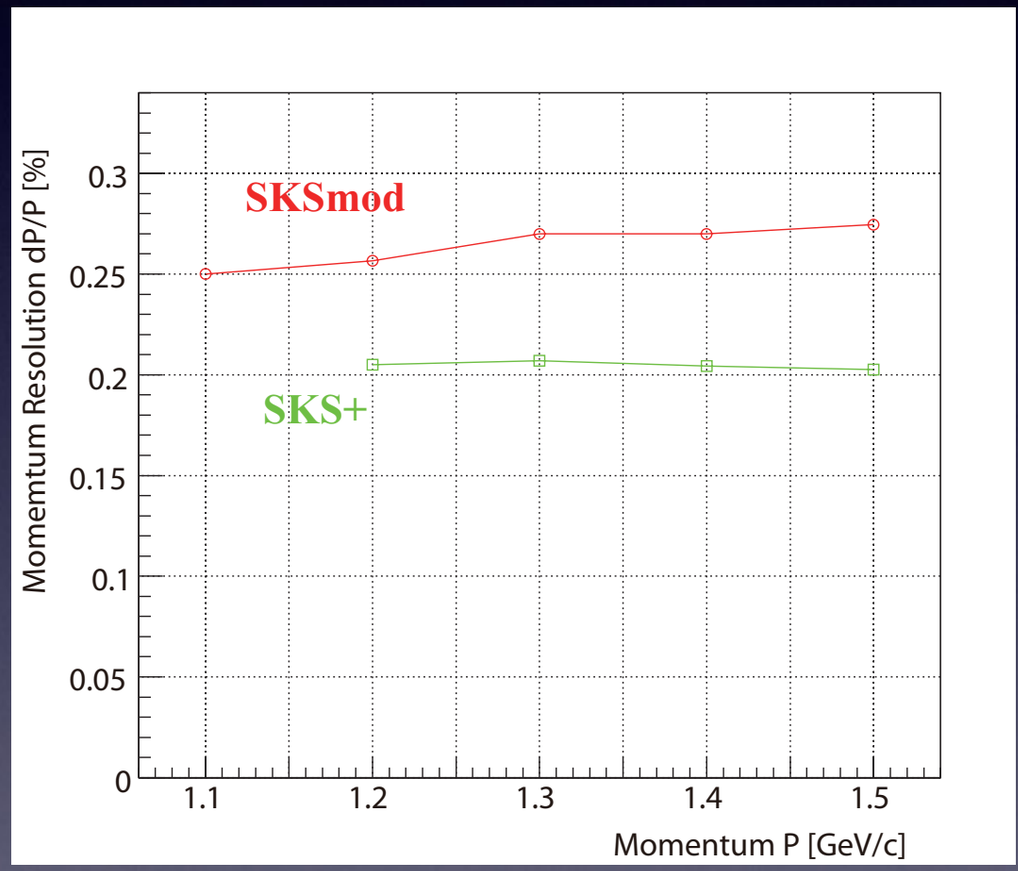
E05 Pilot Run

- K1.8 beam line with SKS (E13 setup')
  - Two AC's(p, π^+) at the entrance of SKS
  - $CH_2(K^-,K^+)$ 9.3g/cm^2 → ΔM=5 MeV$_{FWHM}$
- Two weeks of beam time
  - Detector tuning — 1 day
  - $p(K^-,K^+)\Xi^-$@1.5-1.9 GeV/c — 2 days
  - $^{12}C(K^-,K^+)$ — >10 days



Good acceptance and energy resolution





- $\Delta\Omega$=110 msr

ΔE=5 MeV_{FWHM}

Comparison of Spectrometers

	ΔΩ (msr)	ΔE (MeV)
BNL	19	14
SKS’	110	5
S-2S	60	1.5

Background triggers

10^5 K^-/spill, CH_2 9.3 g/cm^2

1. K^- decay in flight (GEANT4)

   - Total 180 ($K^- \to \pi^- \pi^- \pi^+$: 110)

2. Reactions in target (JAM code simulation)

   - Total 300 (p: 230, π^+: 30)

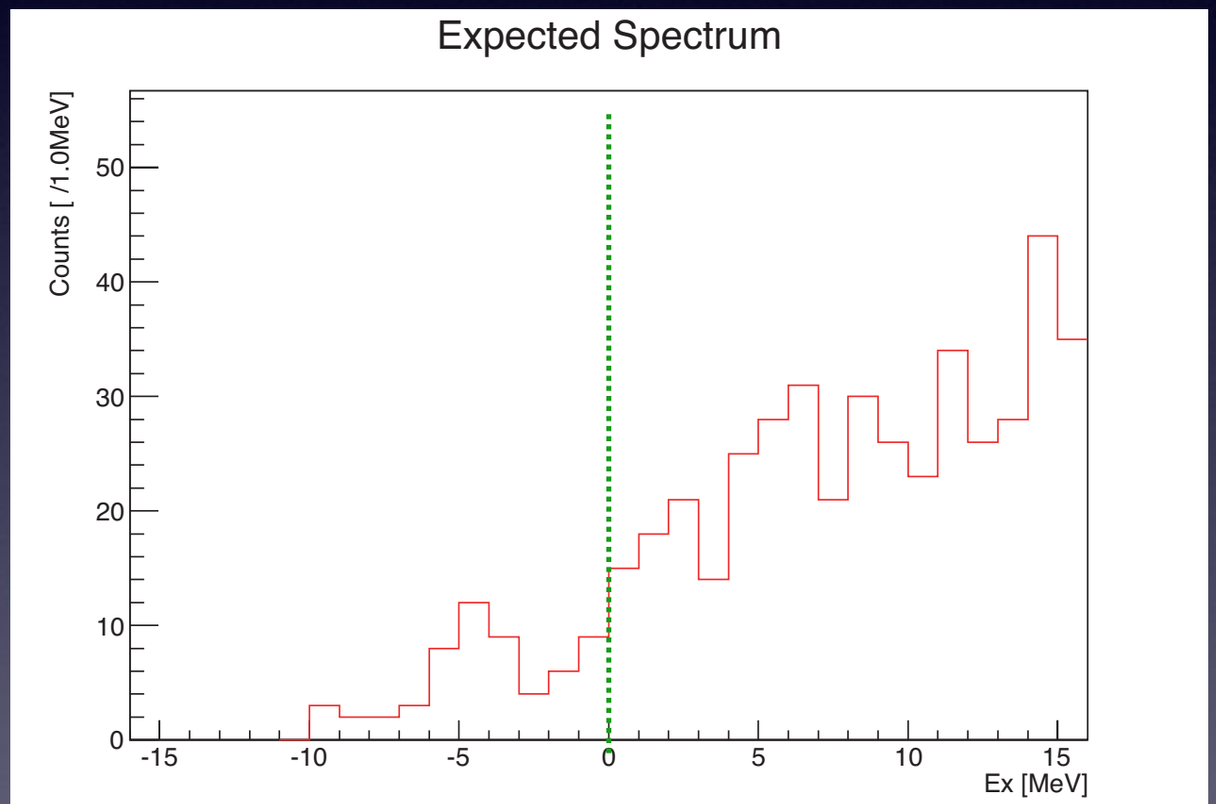
   

   with AC1,2:
   p veto 50%, pion veto 90%

   - Total 160 (p: 115, π^+: 3)

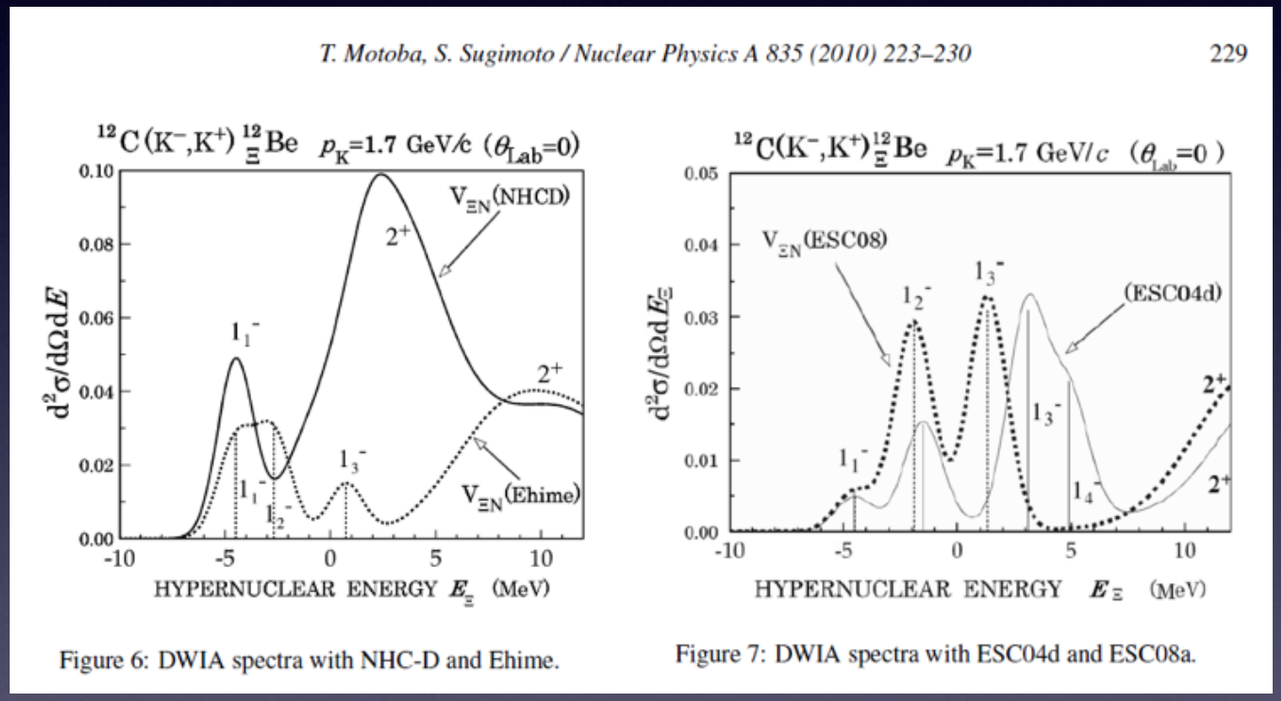
$^{12}C(K^-,K^+)$

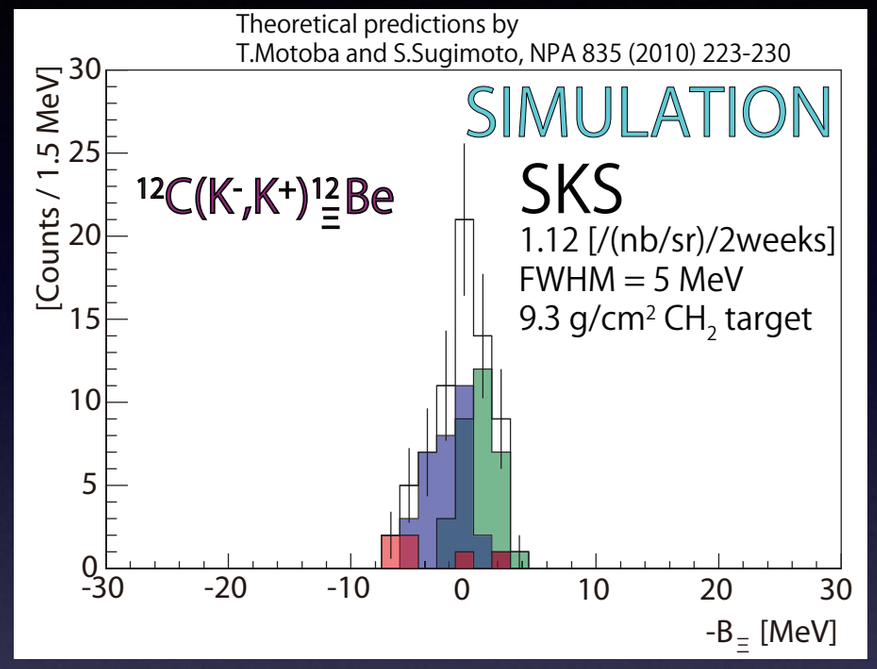
- Woods-Saxon type potential: V=-14 MeV



^{12}C(K$^-$,K$^+$)

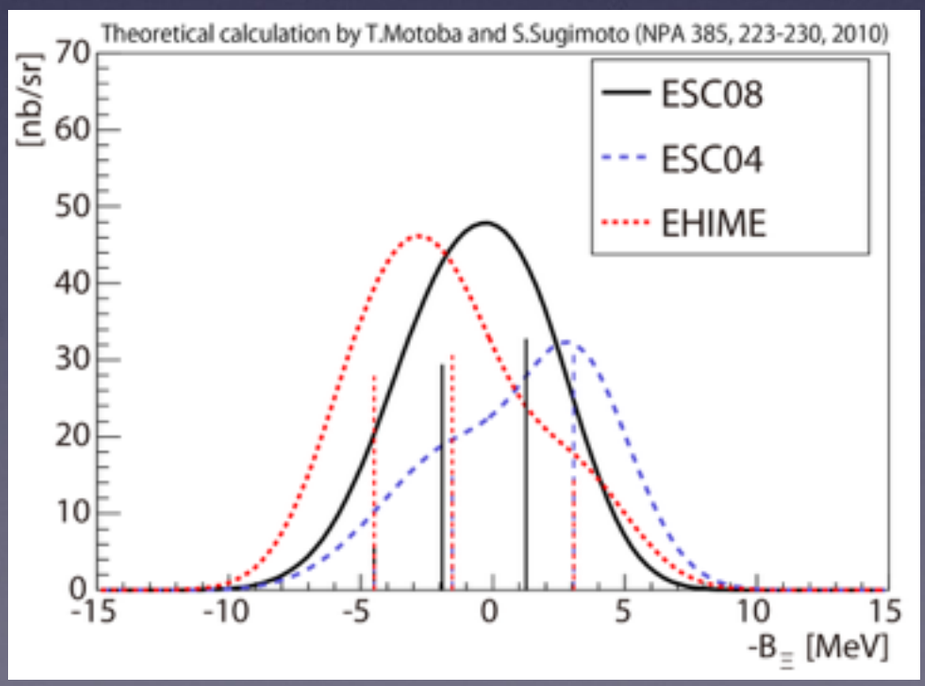
- Theoretical Models
  - ESC08, ESC04, EHIME





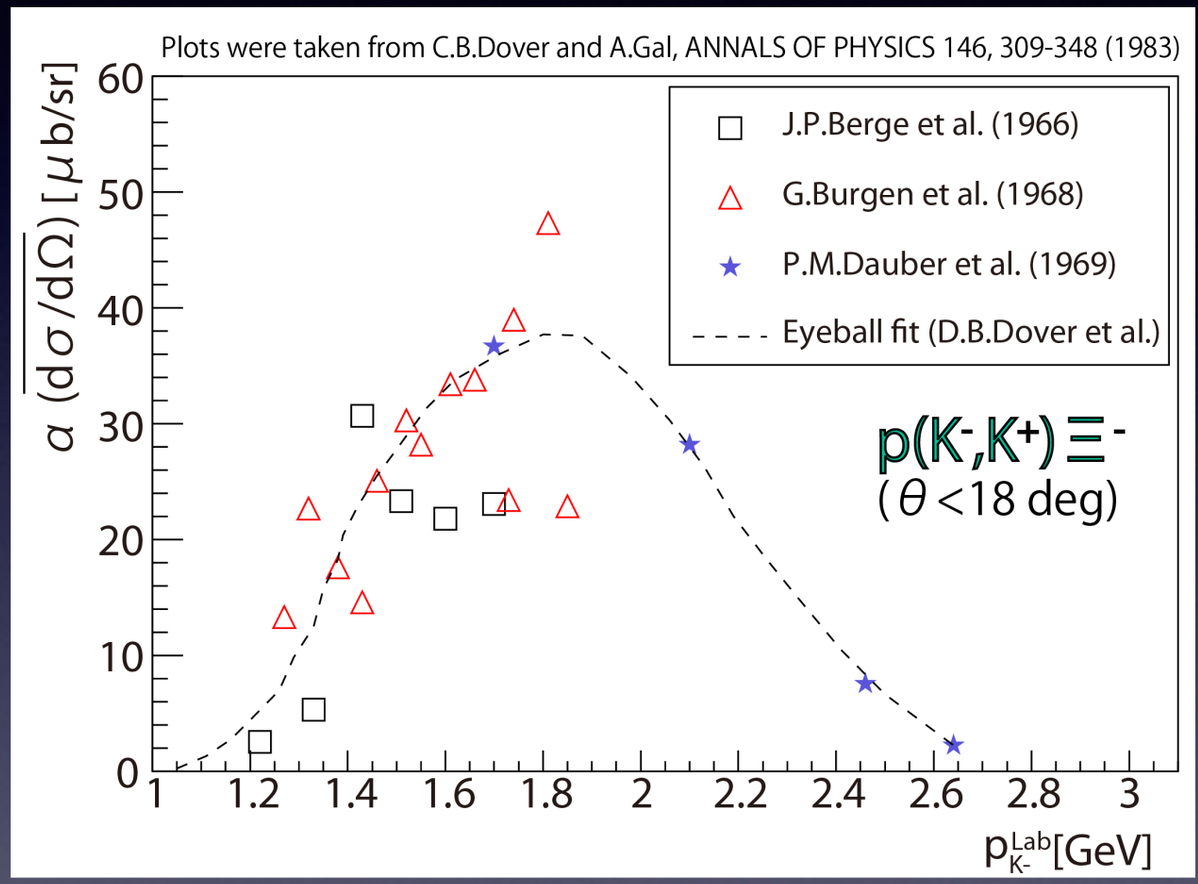
ΔM=5 MeV$_{FWHM}$

~50 events/two weeks



$K^- p \to K^+ \Xi^-$

- Old Data in 60's
  - 10~40 events at forward
- Pilot Run
  - 900-1800 events at Five P_{K^-}



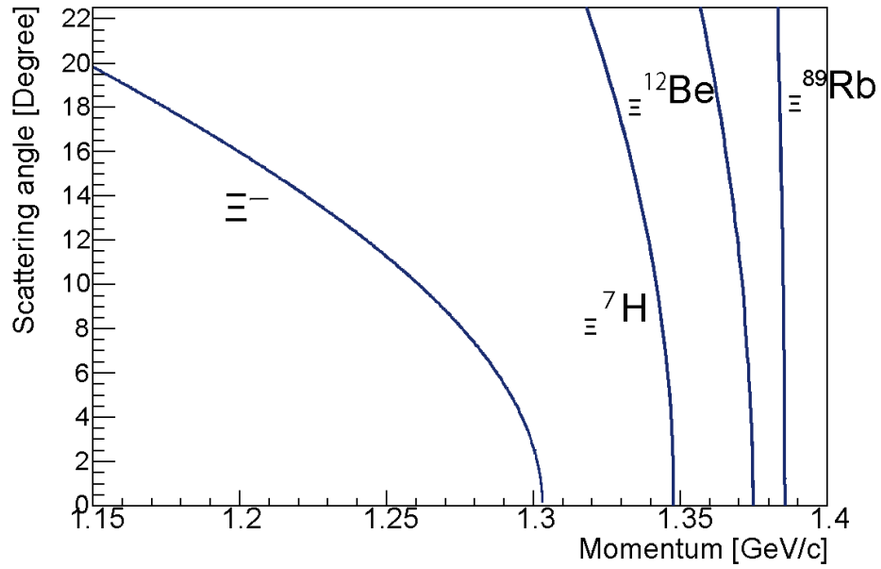
Yield Estimations

- ^{12}C : 3x10^5 K^-/spill, 6s cycle
  - $d\sigma/d\Omega$~42 nb/sr, Ω=0.11 sr
    - → 3.4 /day ~50 /two weeks
- p : $d\sigma/d\Omega$~35 μb/sr
  - →1,800/shift

S-2S

Kinematics of p(K^-,K^+)Ξ

@1.8 GeV/c



K^- ^AZ → $_{\Xi}{}^A(Z\text{-}2)$ K^+

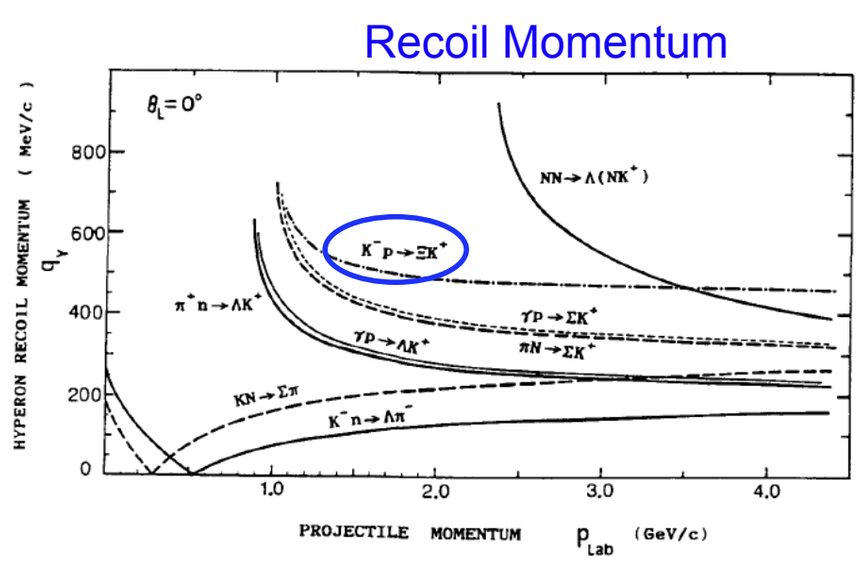


Fig. 2.3. The momentum q_Y transferred to the hyperon Y as a function of the projectile momentum $p_{proj} = p_a$ in the reaction $aN \to Yb$ at $\theta_{b,L} = 0°$.

Missing Mass Resolution

$$M^2 = (E_B + m_T - E_S)^2 - (\vec{p_B} - \vec{p_S})^2$$

$$\Delta M^2 = \left(\frac{\partial M}{\partial p_B}\right)^2 \Delta p_B^2 + \left(\frac{\partial M}{\partial p_S}\right)^2 \Delta p_S^2 + \left(\frac{\partial M}{\partial \theta}\right)^2 \Delta\theta^2 + \Delta E_{\mathrm{strag.}}^2$$

SKS limits ΔMM

Δθ 2mrad [MeV]

	dp/p	Beam	Scat	θ	ΔM
Good!	p_B,p_S 5×10^{-4}	0.84	0.62	0.04	1.0
Current B.L. Performance	p'_B 1×10^{-3}	1.67			1.8
SKSminus	p'_S 3×10^{-3}		3.74		3.8
	p'_B, p'_S	1.67	3.74	0.04	4.1

ΔE_{strag} ← Target thickness

1 MeV ← 3 g/cm^2

2 MeV ← 6 g/cm^2

3 MeV ← 10 g/cm^2

$$\frac{\partial M}{\partial p_B} = \frac{1}{M}[\beta_B(m_T - E_S) + p_S\cos\theta]$$
$$\frac{\partial M}{\partial p_S} = -\frac{1}{M}[\beta_S(m_T + E_B) - p_B\cos\theta]$$
$$\frac{\partial M}{\partial \theta} = -\frac{1}{M}p_B p_S \sin\theta$$

θ=5°
E_{hyp}=0 MeV

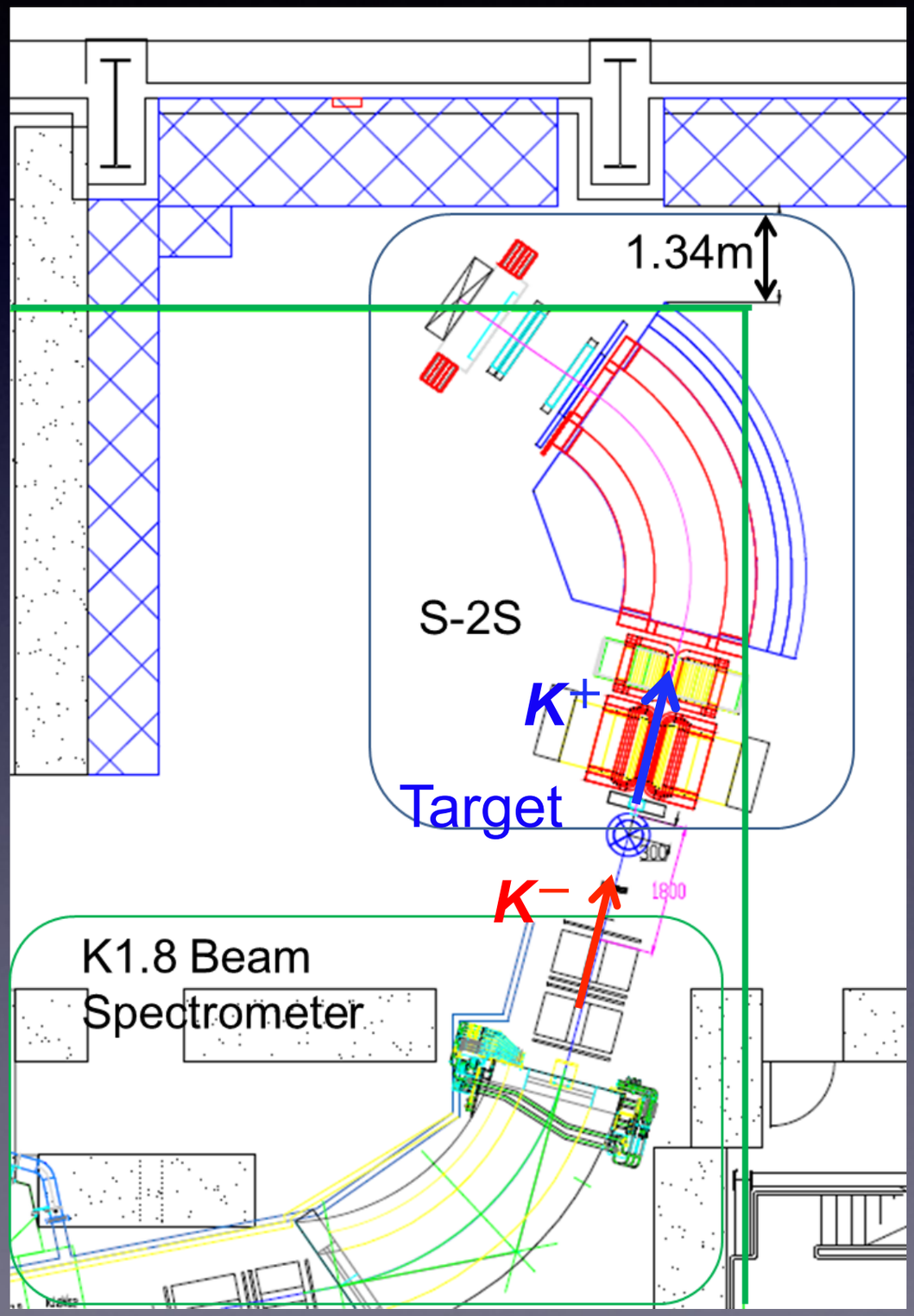
	^{1}H	^{7}Li	^{12}C	^{89}Y
Beam	0.65	0.90	0.93	0.96
Scat	-0.63	-0.88	-0.91	-0.94
Theta	-0.15	-0.03	-0.02	-0.002

Yield Estimation

	SKSminus	S-2S
Acceptance	110 msr	55 msr
K^+ survival rate	0.6	0.4
Cross section	42 nb/sr (θ<14deg)	89 nb/sr (θ<8deg)
Beam intensity	4.5×10^5 /6s	9×10^5 /4s
Target	9.3 g/cm^2 CH_2	3 g/cm^2 ^{12}C
Yield [/month]	140 events	110 events

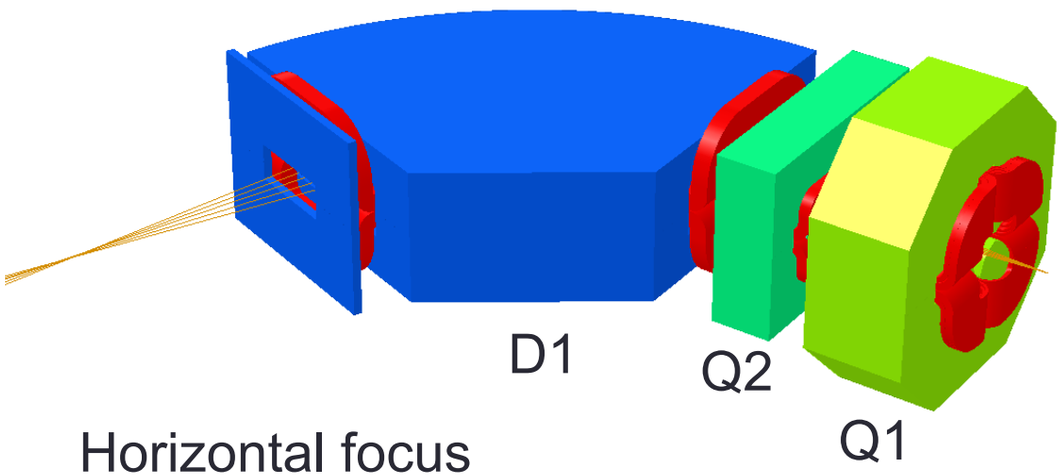
- Notes
  - Efficiency = 0.7
  - Differencial cross section ← result of the BNL-E885 (*Khaustov et al.*)

S-2S @K1.8

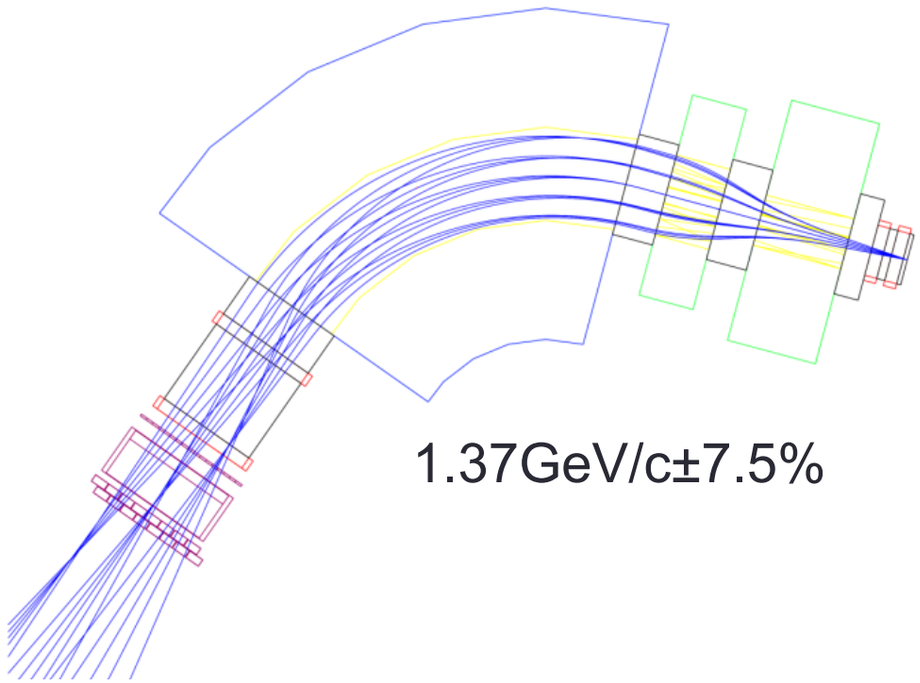


Magnets

- Three normal conducting magnets
- Q1,D1 → Newly constructed
- Q2 → Modification of pole and coil from old magnet



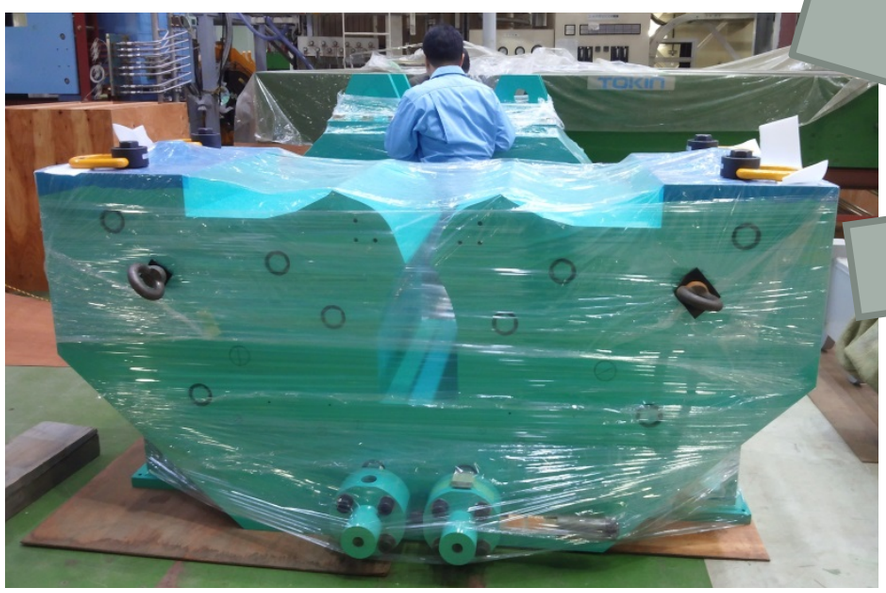
Horizontal focus
～8.5 m @1.37GeV/c



1.37GeV/c±7.5%

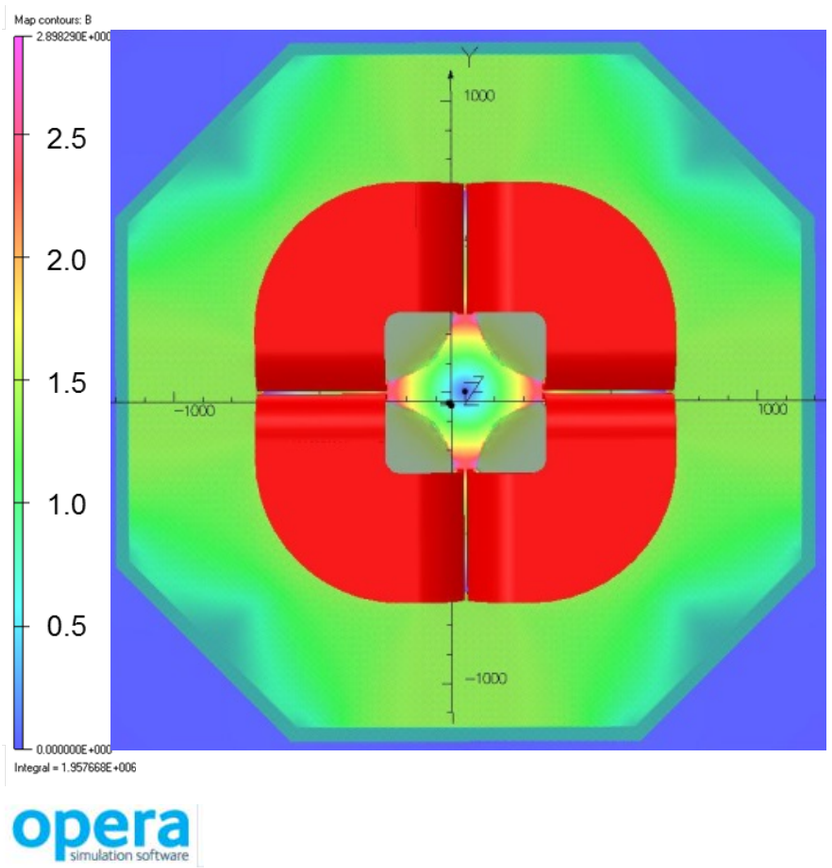
Q1 magnet

- Vertical focus
- 2.4×2.4×0.88 m^3
- Aperture 31 cm
- Total weight 37 ton
- 8.7 T/m

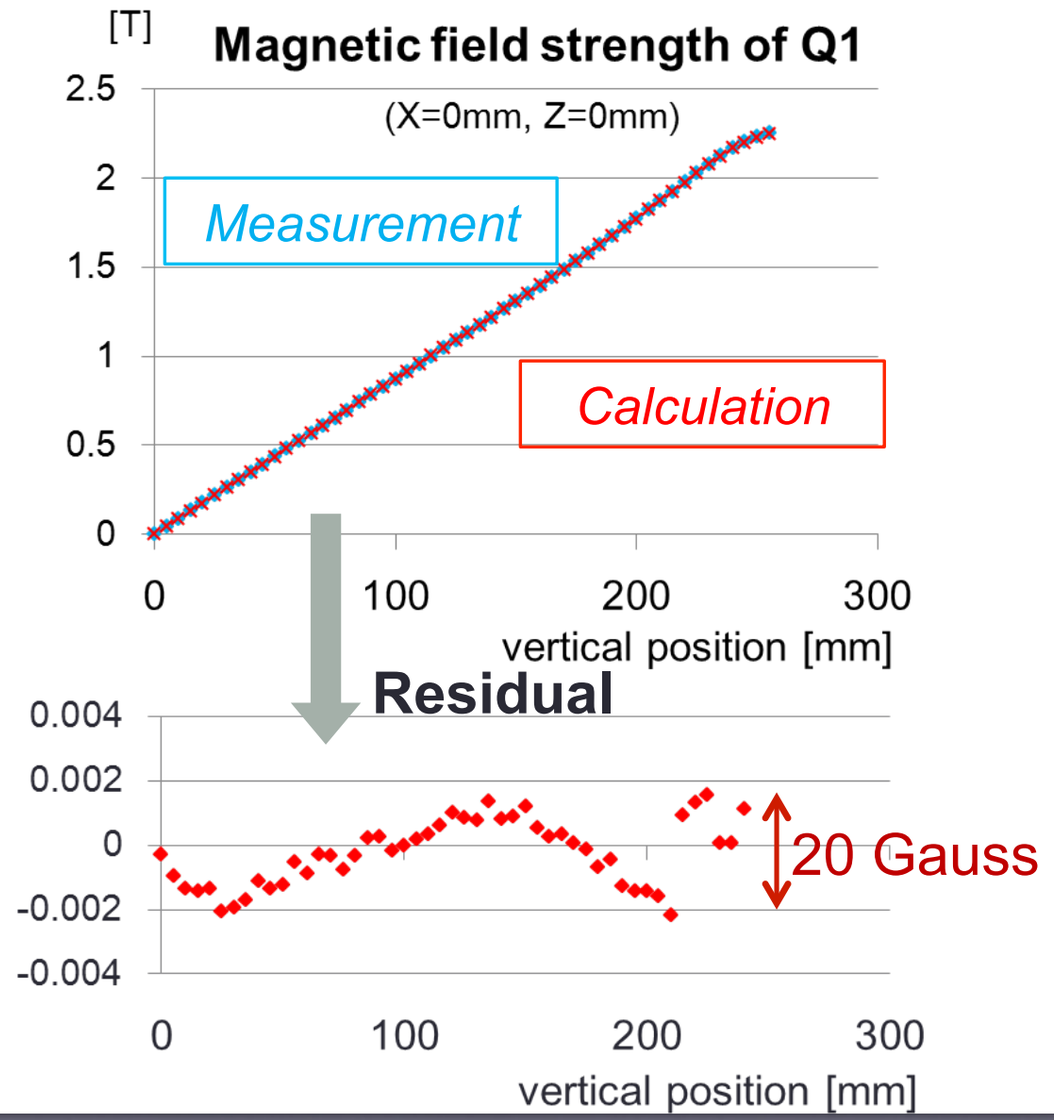


Field Calculation

- 3D electromagnetic analysis with Opera-3d/TOSCA

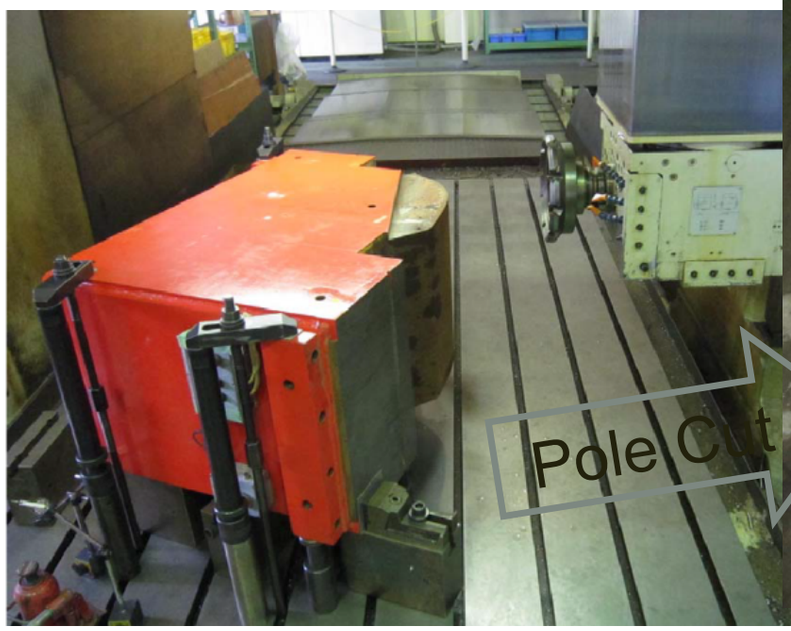


opera simulation software



Q2 magnet

- Horizontal focus
- 2.1×1.54×0.5 m^3
- Aperture 36 cm
- Total weight 12 ton
- 5.0 T/m (measurement)



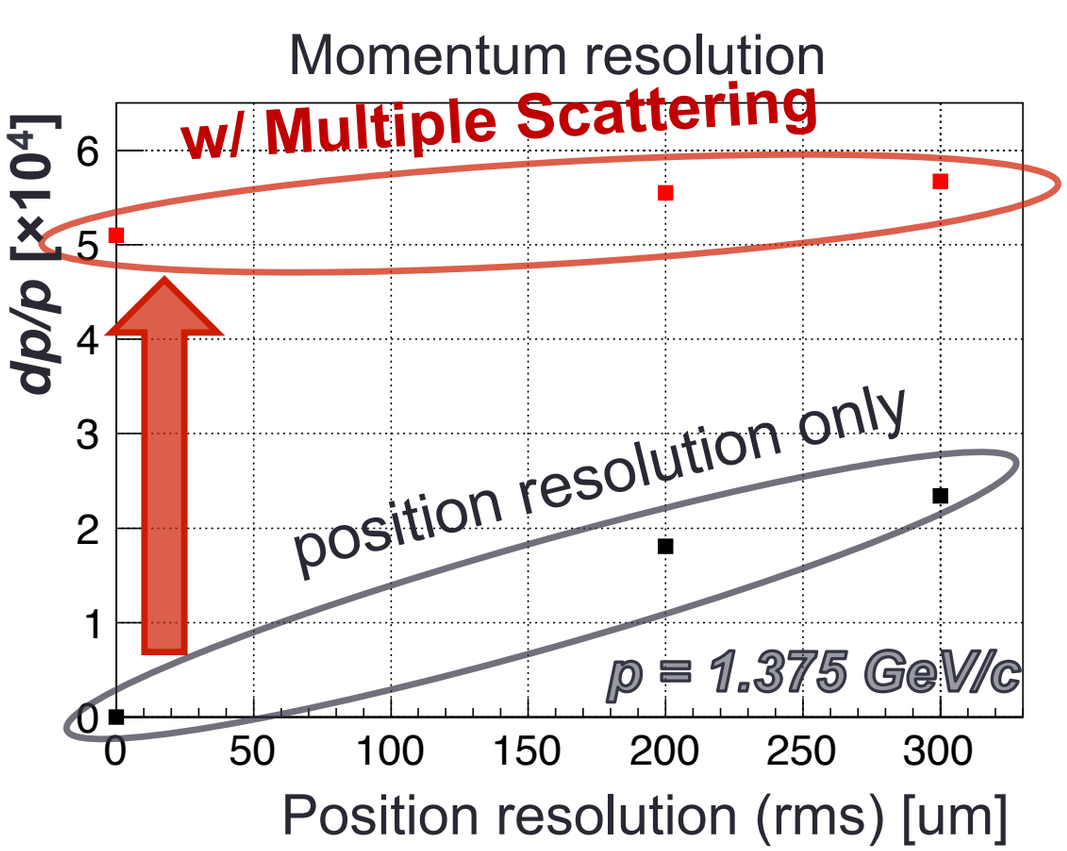
D1 magnet

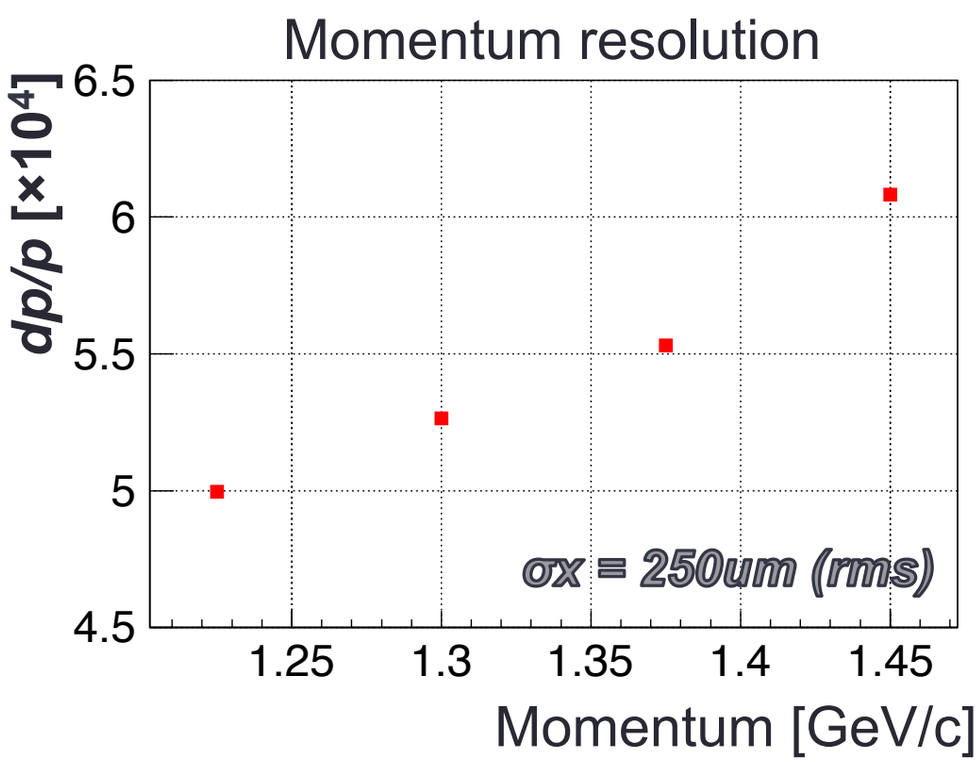
- 1.5 T = 70 deg. bend @1.37 GeV/c
- Gap 80×32 cm^2
- Weight 86 ton

Magnets in KEK

Momentum Resolution

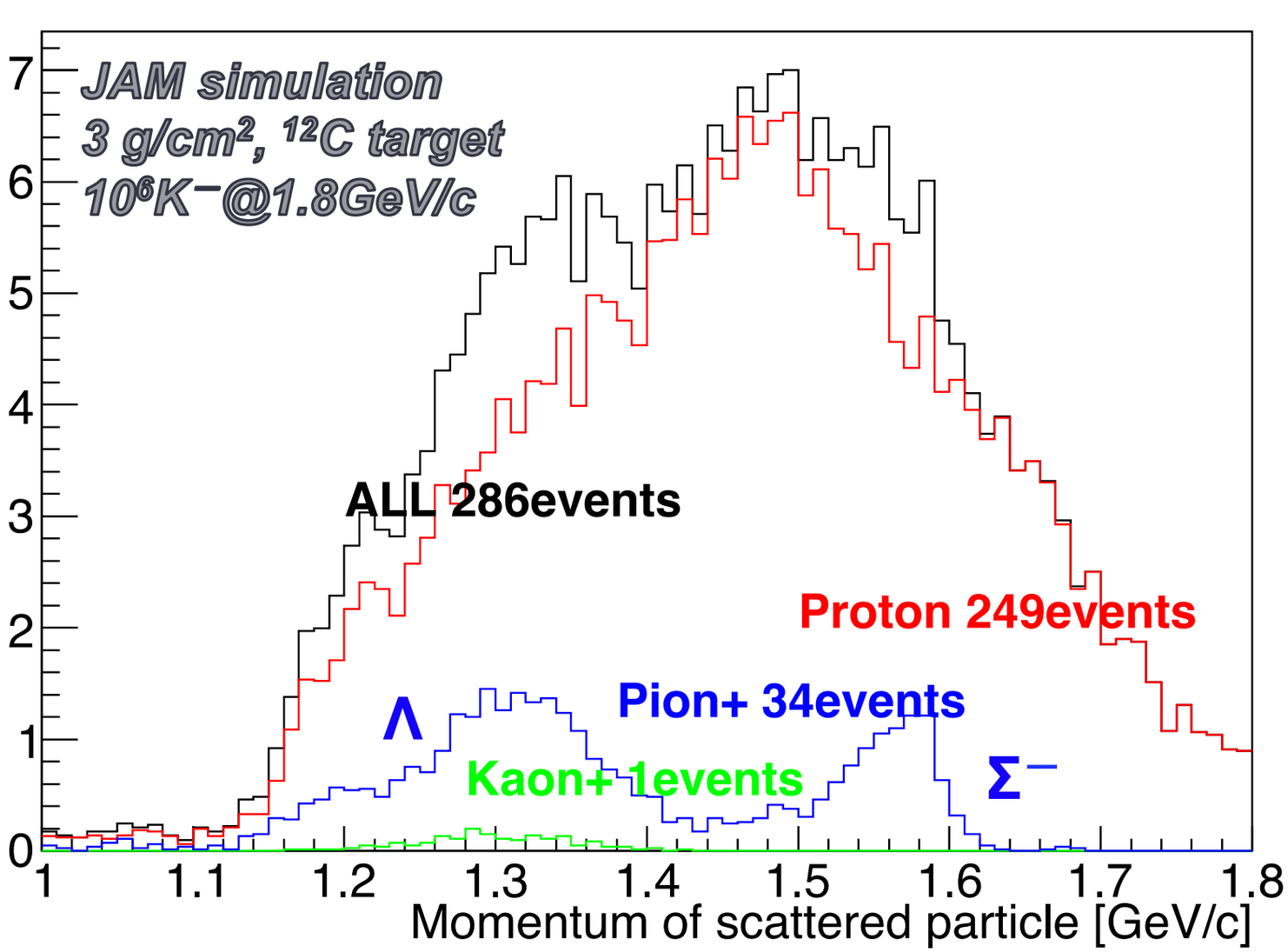
***dp/p* 5～6×10^{-4} (FWHM)**





Magnet condition
Q1,Q2,D1 = 2500A (max)

Background Distributions



Timeline

Ready for installation in JFY2015

		2014.9		2015.4
Magnet				
Q1,Q2	Completed (’13/’14)	Magnet Table		
D1	Yoke only	Coil Mounted		Field measurement /calculation
Drift Chamber				
SDC1	Ready			
SDC2		Design	Production	Performance check
SDC3,4	Almost ready	Design/production PreAmpBoard		
				Repairment on some parts/check
Trigger Counters				
TOF	Materials are ready	Design of support frame		Setup
		Performance check		
AC	Ready			
WC	Prototypes	Performance check		Fabrication
	Test experiments @J-PARC&ELPH	Design actual version		
				Others: HeBag

Physics beyond E05

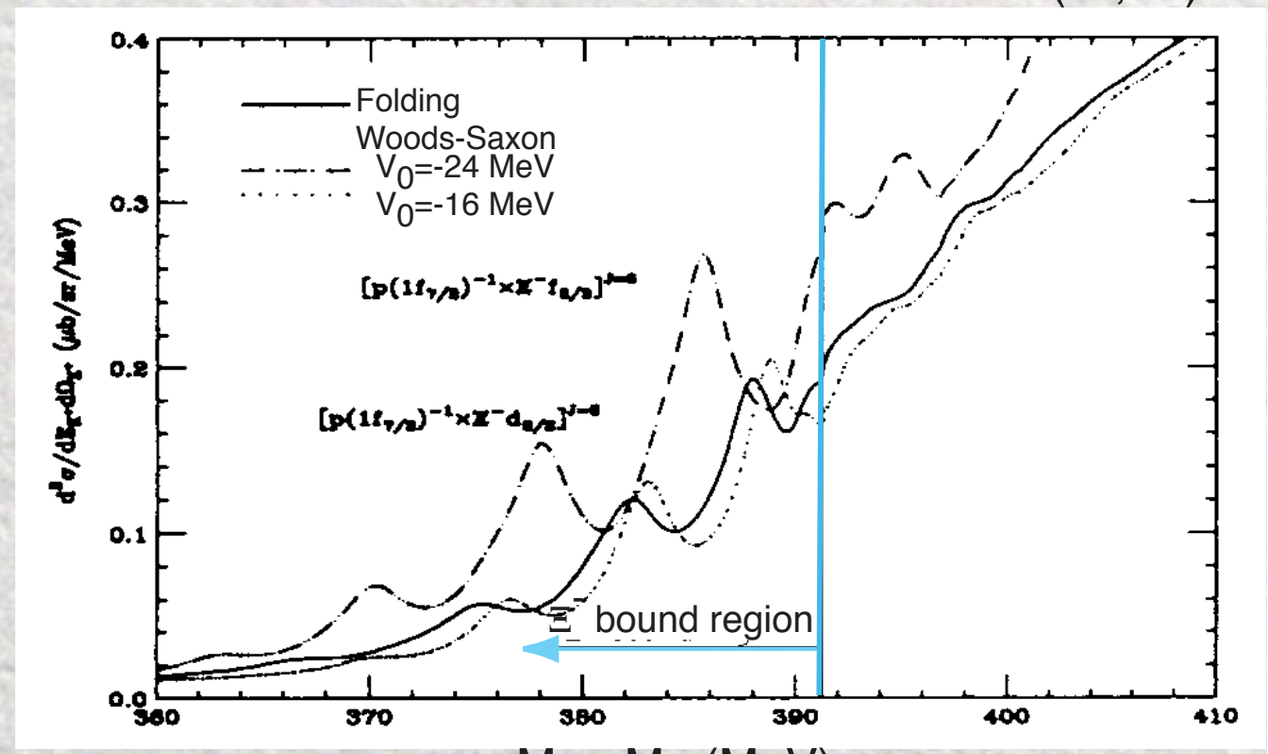
- Spin dependence in light Ξ hypernuclei
  - ^{7}Li(K^{-}, K^{+})$^{7}_{\Xi}$H; annΞ^{-} Lightest Ξ hypernucleus ?
  - ^{10}B(K^{-}, K^{+})$^{10}_{\Xi}$Li; αanΞ^{-}

- Heavy Ξ hypernuclei spectroscopy
  - Coulomb-Assisted bound states ^{89}Y(K^{-}, K^{+})

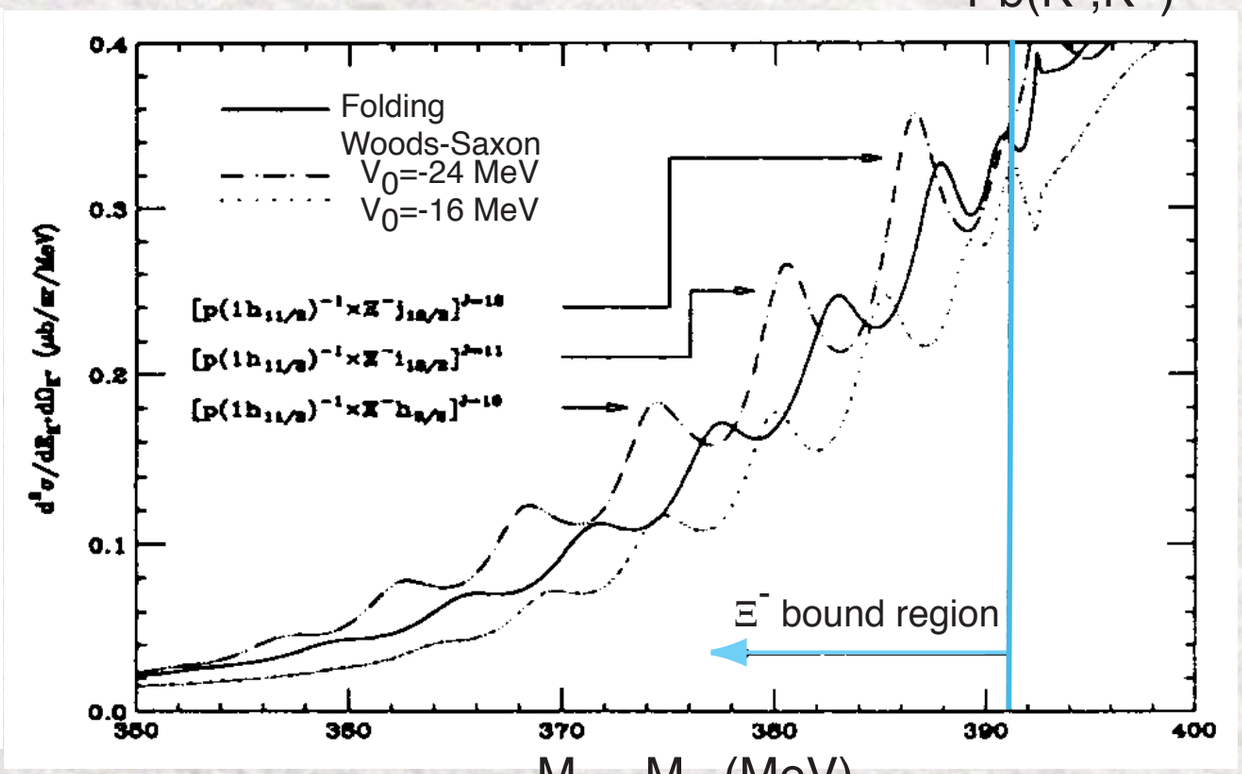
(K^-,K^+) Spectroscopy

- 2 MeV_{FWHM} resolution
- ~6 events/day/MeV for 50 msr, 2g/cm^2-thick Pb
  ~20 days

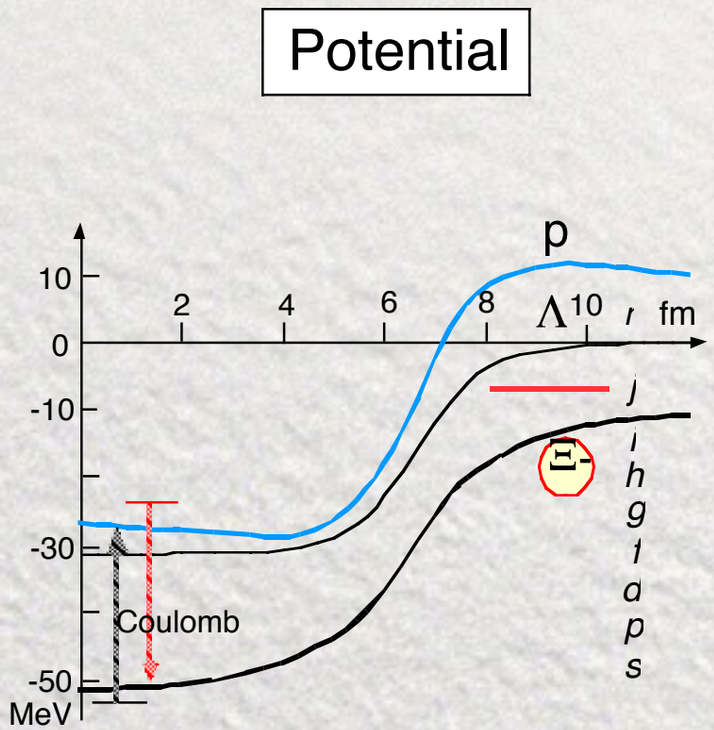
$^{58}Ni(K^-,K^+)$

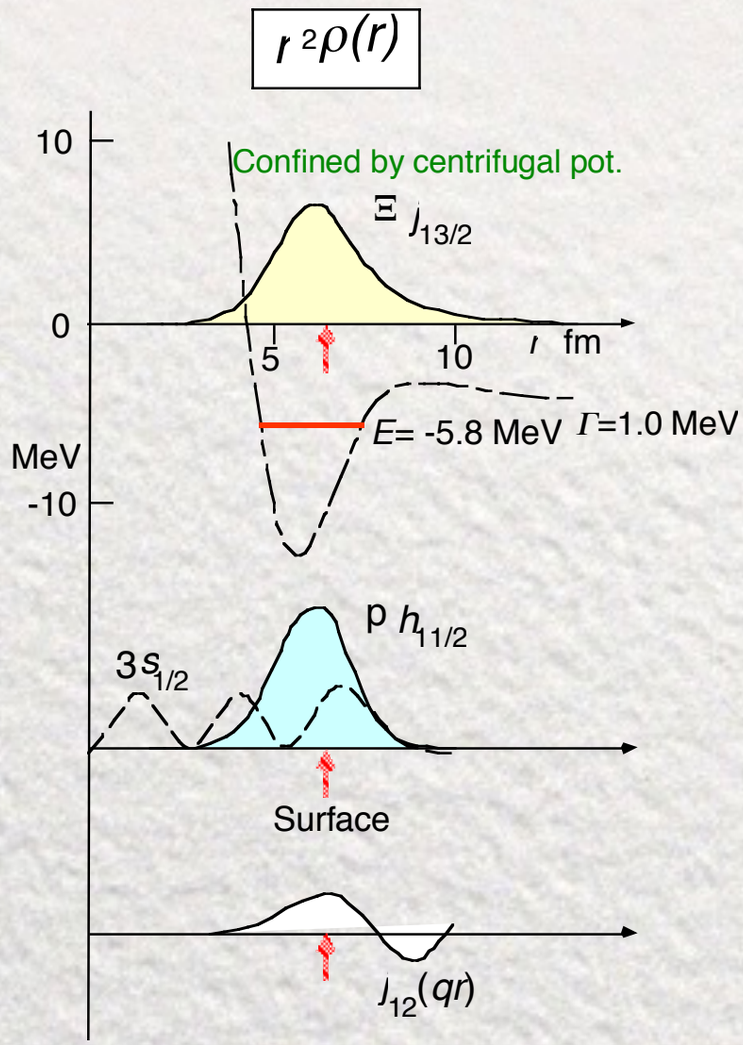


$^{208}Pb(K^-,K^+)$



Unique bound state





Coupling between Ξ hypernuclei and double-Λ hypernuclei

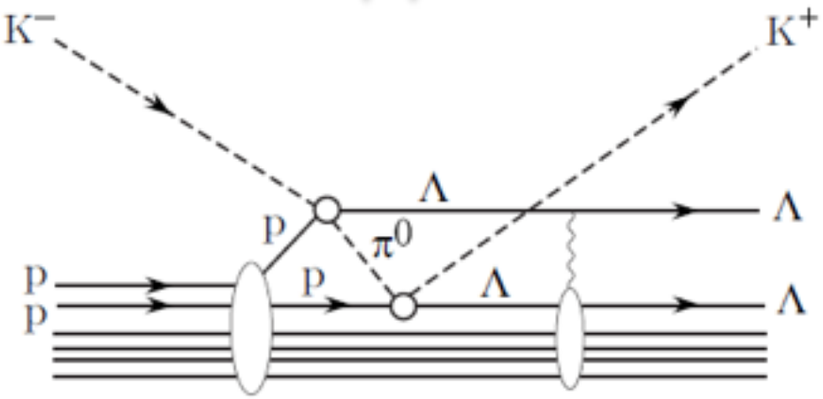
Theoretical Calculation for $^{16}_{\Lambda\Lambda}$C,

via Ξ^- doorways

in the ^{16}O(K$^-$,K$^+$) reaction at 1.8 GeV/c

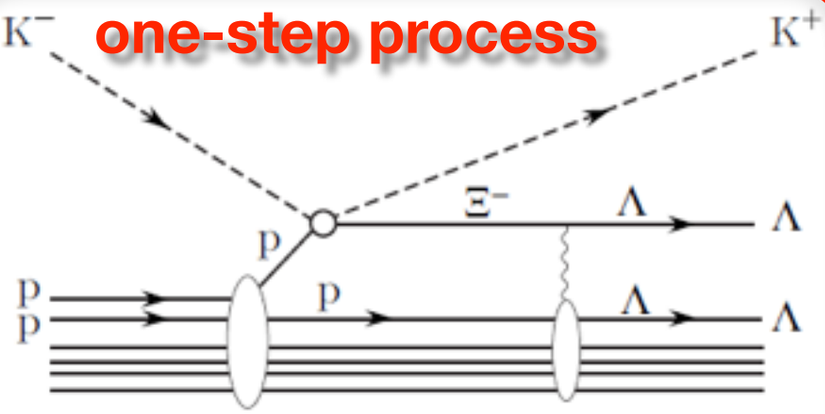
T.Harada, Y.Hirabayashi, A.Umeya,
PLB 690 (2010) 363.

two-step process



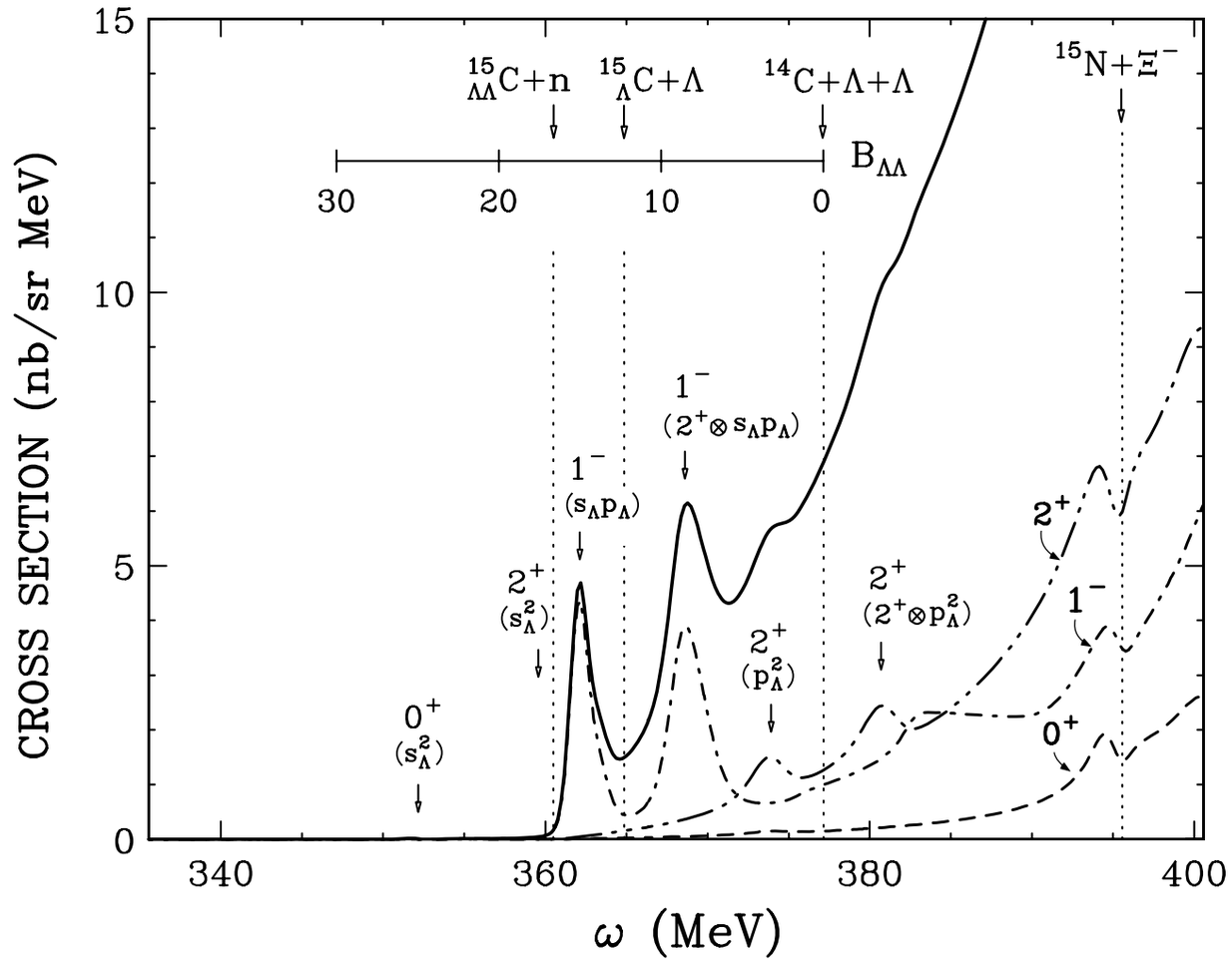
(a)

one-step process



(b)

^{16}O(K$^-$,K$^+$) **7 ~12 nb/sr**



- excited states of double-Λ hyp.
- sensitive to ΞN-ΛΛ coupling strength.

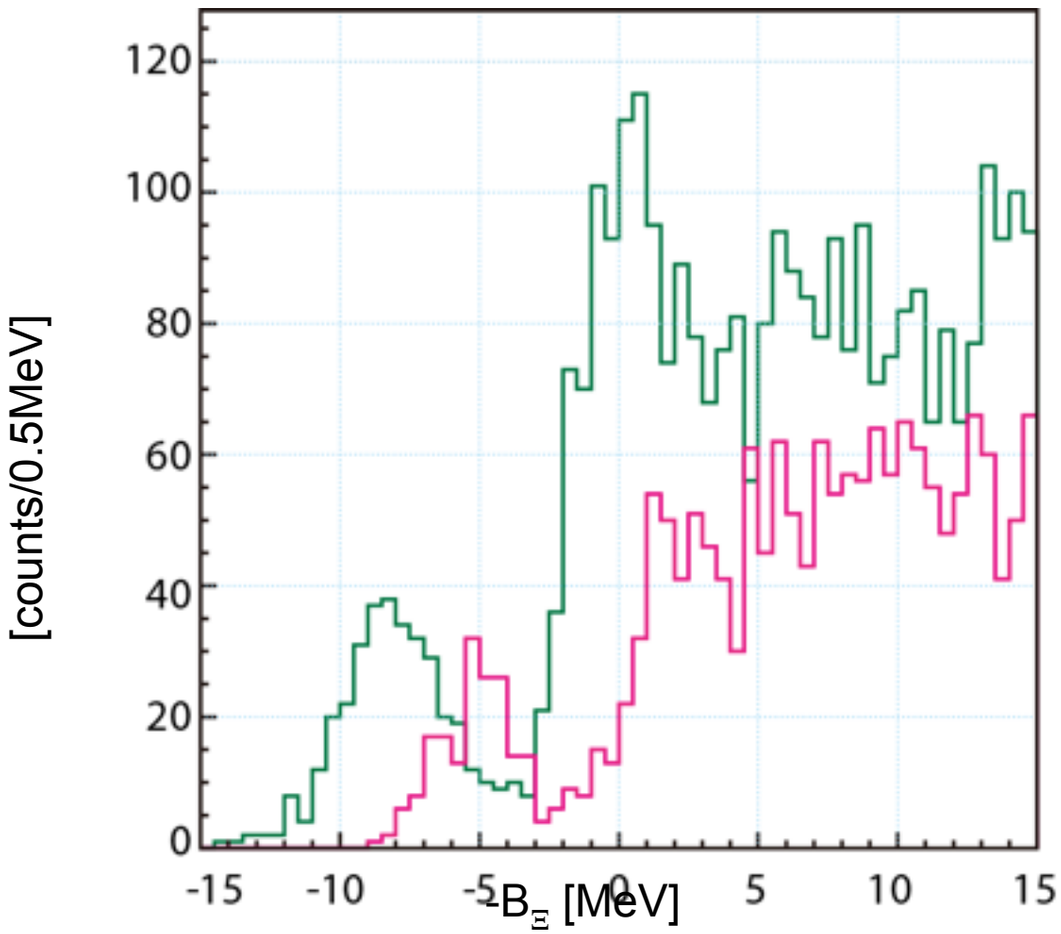
Summary

- S-2S construction is under way.
  - Ready for Installation in JFY2015.
- Pilot run of E05 was proposed for the Fall run in 2015 with SKS.
  - Elementary cross section + $^{12}C(K^-,K^+)$

Backup slides

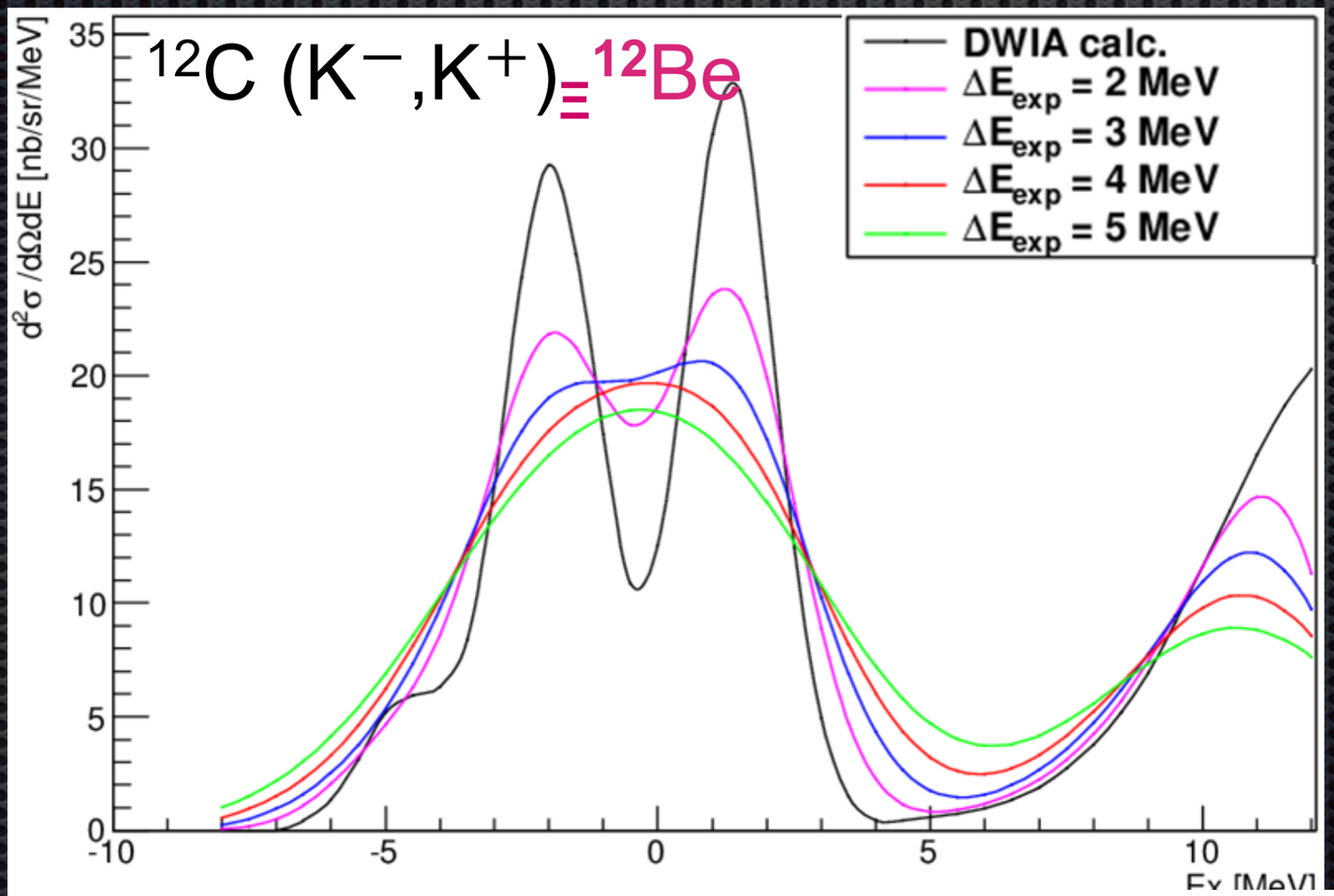
Expected $^{12}_{\Xi}$Be Spectrum

$\Delta E_{meas.}$ = 3 MeV_{FWHM}



V_{Ξ}= -20MeV

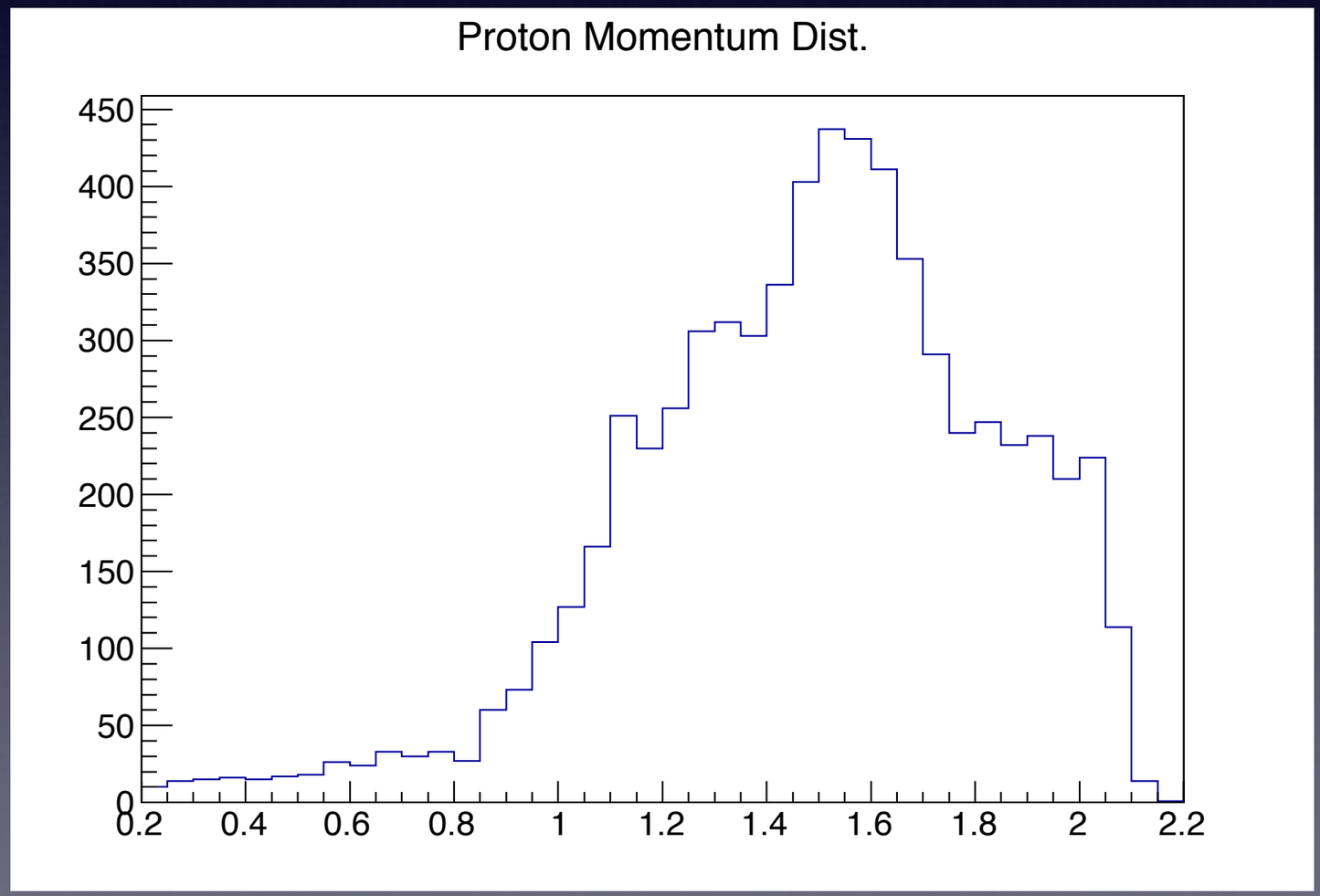
V_{Ξ}= -14MeV



T. Motoba and S. Sugimoto, Nucl. Phys. A 835, 223 (2010)

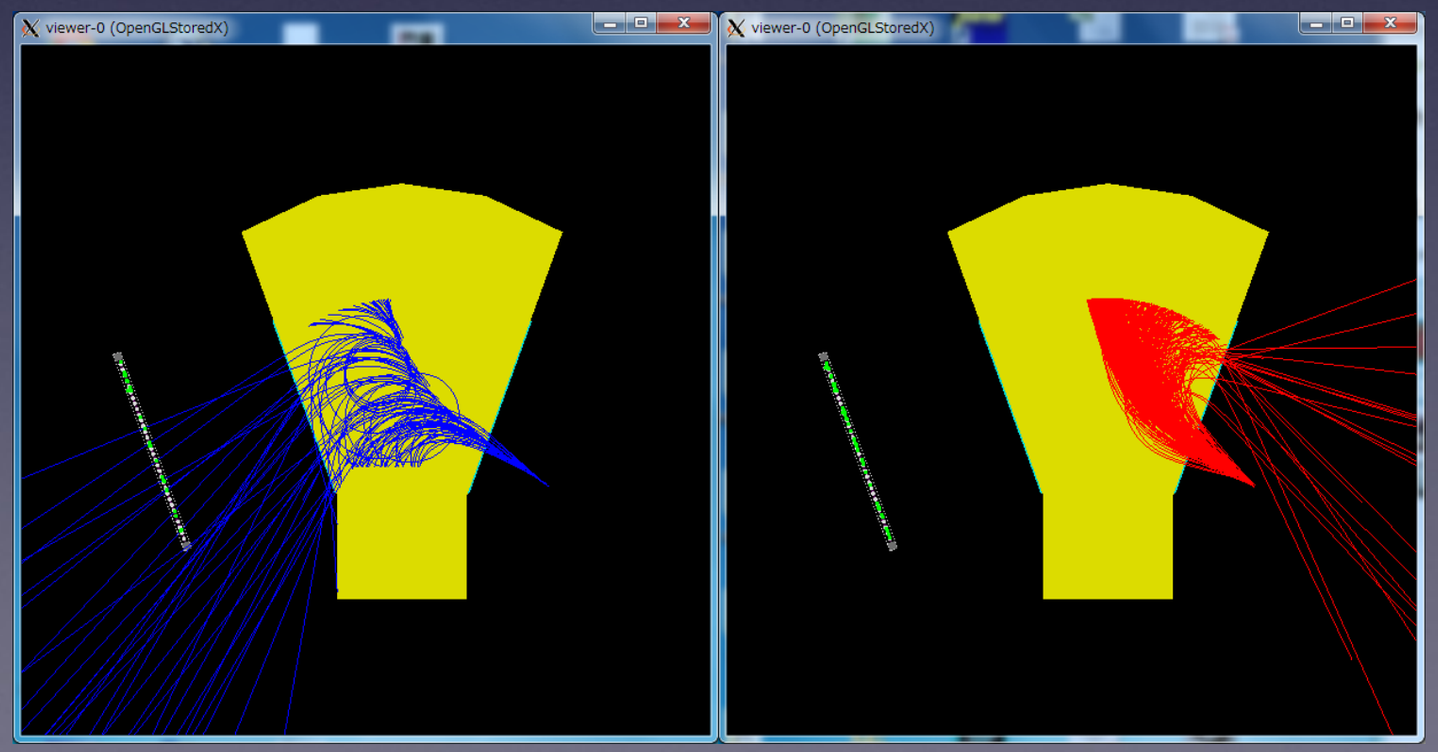
Background Protons

- $K^-p/n \rightarrow pK$, $p\pi K$, hyperon decays

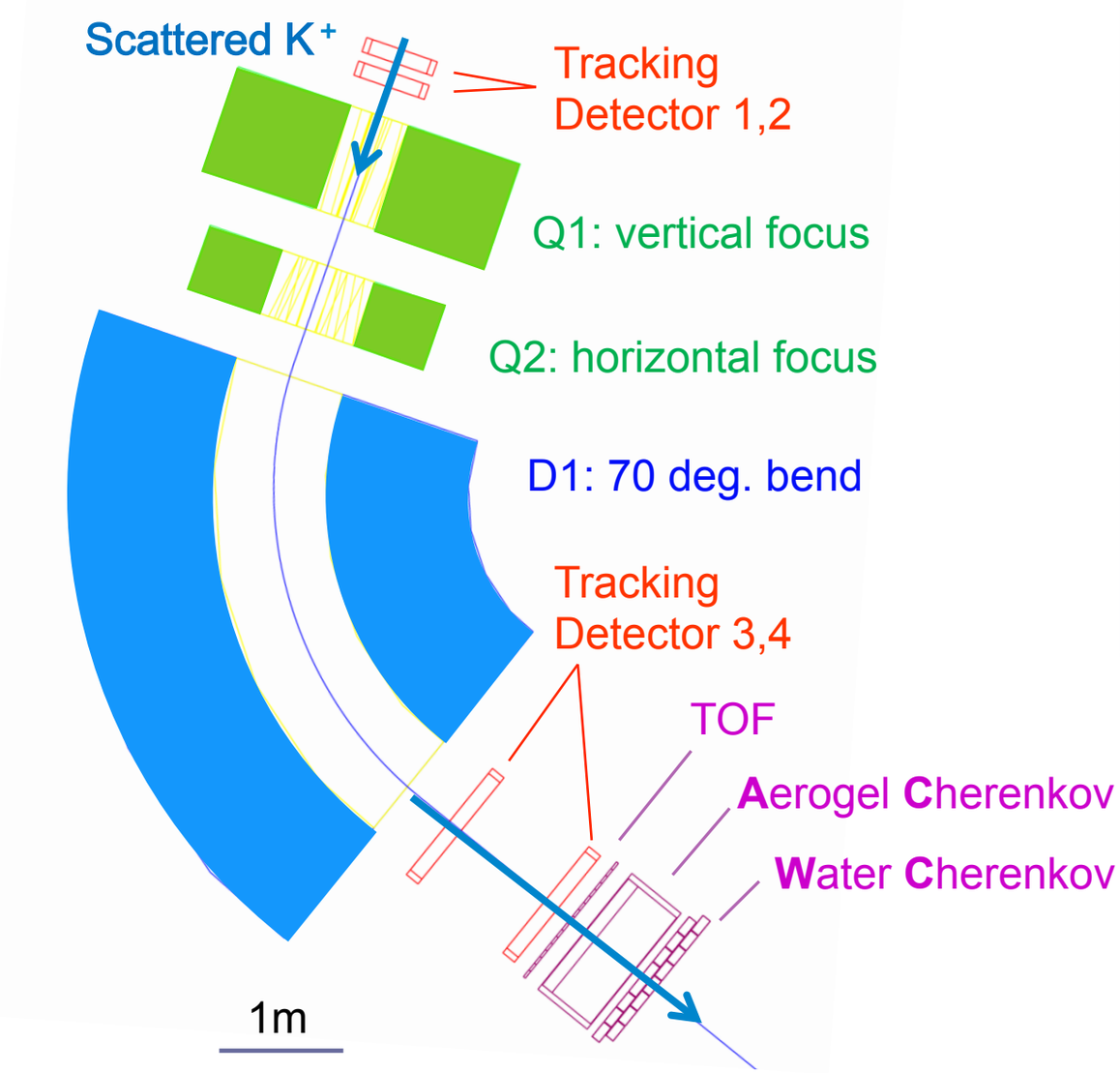


Decay in flight

- K^- decay rate ~20%
  - $K^- \rightarrow \pi^- \pi^- \pi^+$ (5.6%)
  - $\rightarrow \pi^- \pi^0$, $\mu^- \nu$; SKS Yoke



S-2S Spectrometer



U_{Ξ} in Recent Nijmegen Models

Table 3. $U_{\Xi}(\rho_0)$ and partial wave contributions. Conversion width Γ_{Ξ}.

	T	$^1S_0$	$^3S_1$	$^1P_1$	^3P	U_{Ξ}	Γ_{Ξ}
08a	0	6.0	−1.0	−0.3	−2.1		
	1	8.5	−28.0	0.6	−3.8	−20.2	5.8
08a’	0	5.6	−1.1	−0.3	−2.2		
	1	8.4	−21.5	0.6	−3.9	−14.5	7.0
08b	0	2.4	1.9	−0.6	−2.0		
	1	9.1	−37.8	0.6	−5.4	−31.8	1.2
04d	0	6.4	−19.6	1.1	−2.2		
	1	6.4	−5.0	−1.0	−4.8	−18.7	11.3

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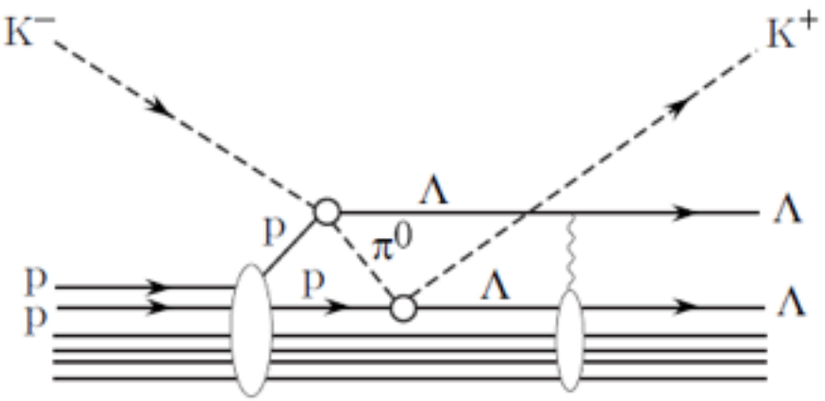
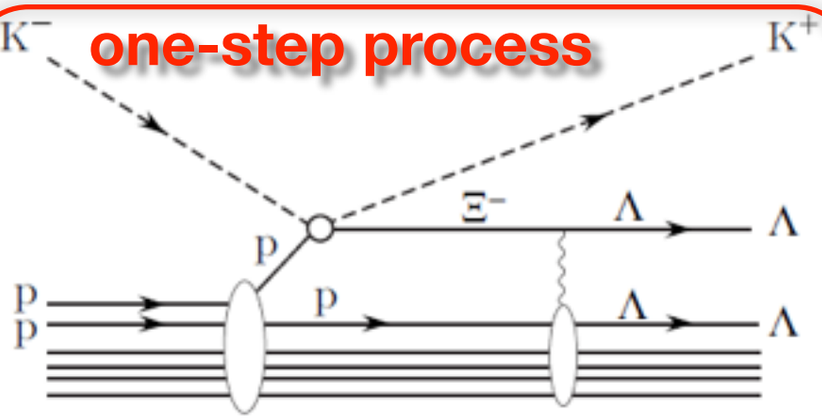


(a)

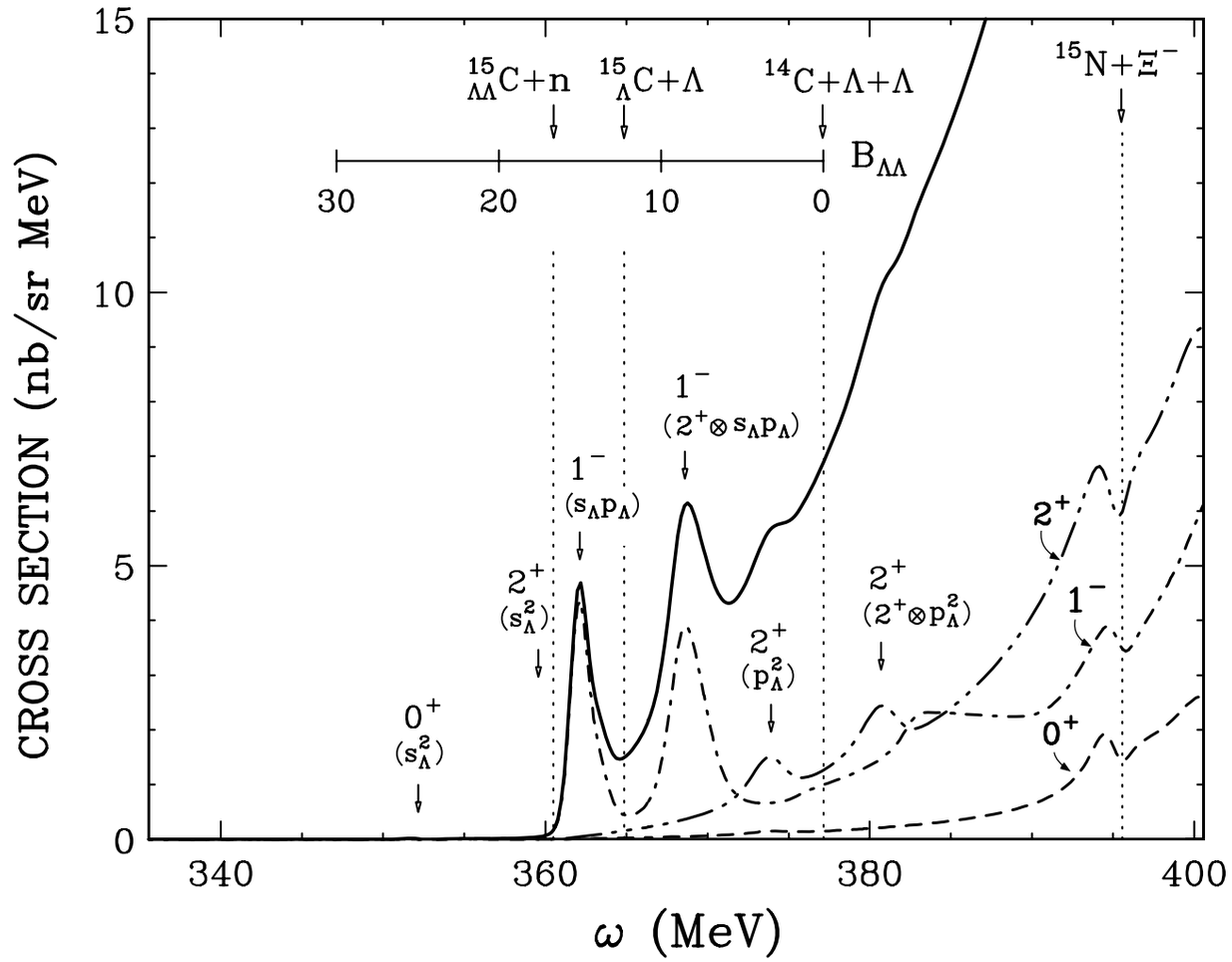
one-step process



(b)

^{16}O(K^-,K^+)

7 ~12 nb/sr



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  - Coulomb-Assisted bound states ^{89}Y(K^-, K^+)