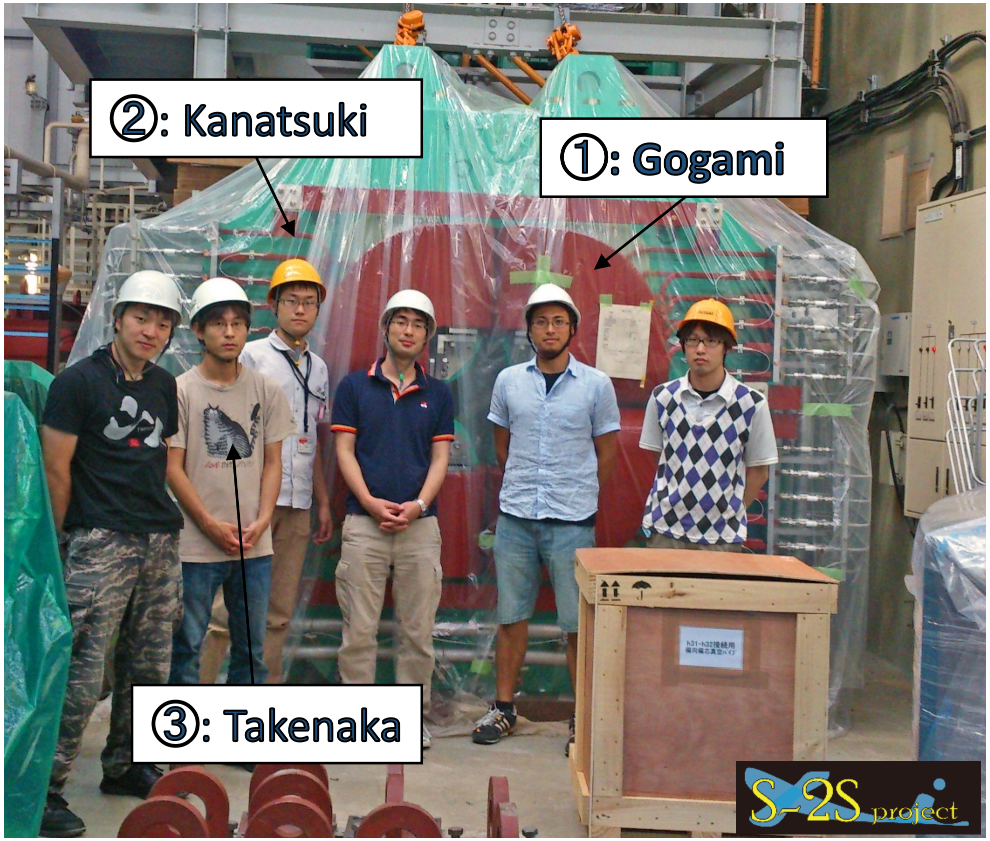
J-PARCにおける
マルチストレンジネス原子核の分光実験

Spectroscopic measurement of multi-strangeness hypernuclei at J-PARC

「ストレンジネスを含む原子核の最近の展開」研究会 @ 熱川
2014/9/26

京都大学大学院理学研究科
後神 利志 (Toshi Gogami)



Contents

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- Previous experiments of Ξ hypernuclei
- Theoretical predictions
- J-PARC E05 experiment

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- **Introduction**
- Previous experiments of Ξ hypernuclei
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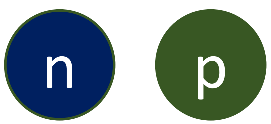
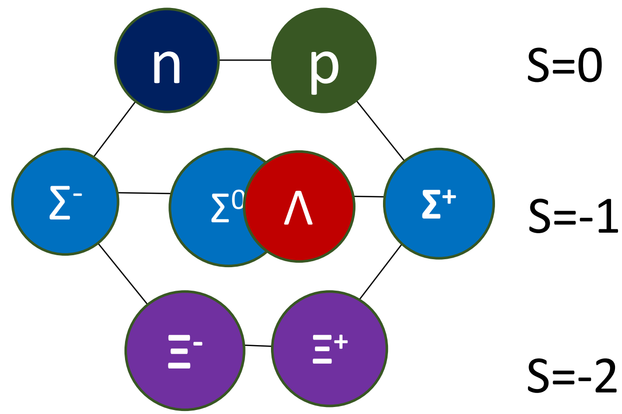
Significance of hypernuclear investigation

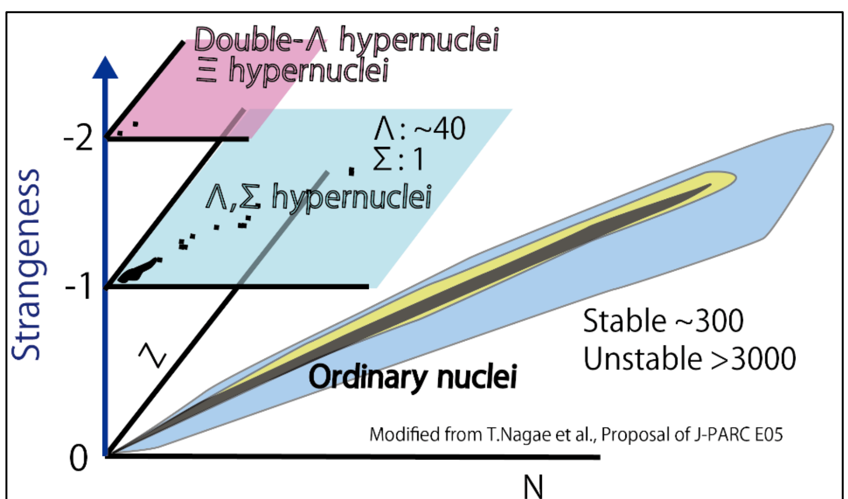
Unified understanding of the strong force (SU(3) symmetry)

Nucleon-nucleon (NN) interaction → Baryon-Baryon (BB) interaction

(Rich data of NN scattering exp.) (Scarce data of YN/YY scattering exp.)







Significance of hyperr

Unified understanding of the

Nucleon-nucleon (NN) interaction →

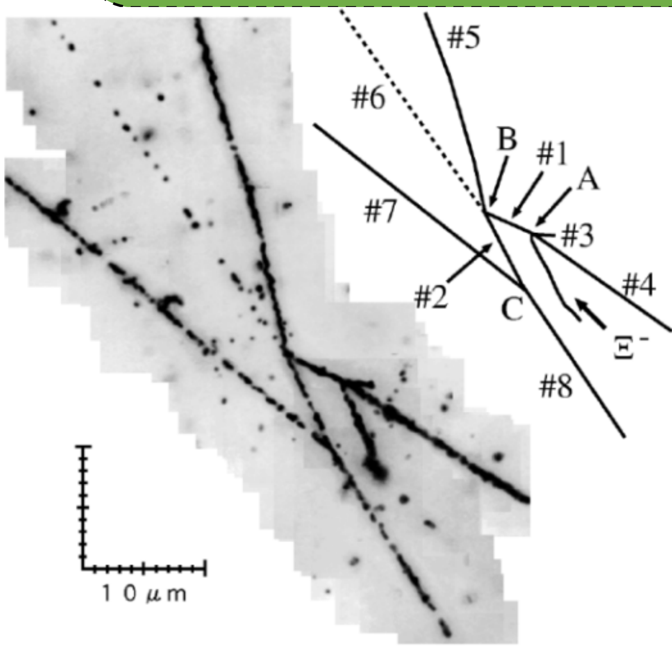
(Rich data of NN scattering exp.)

Almost No information for ΞN interaction

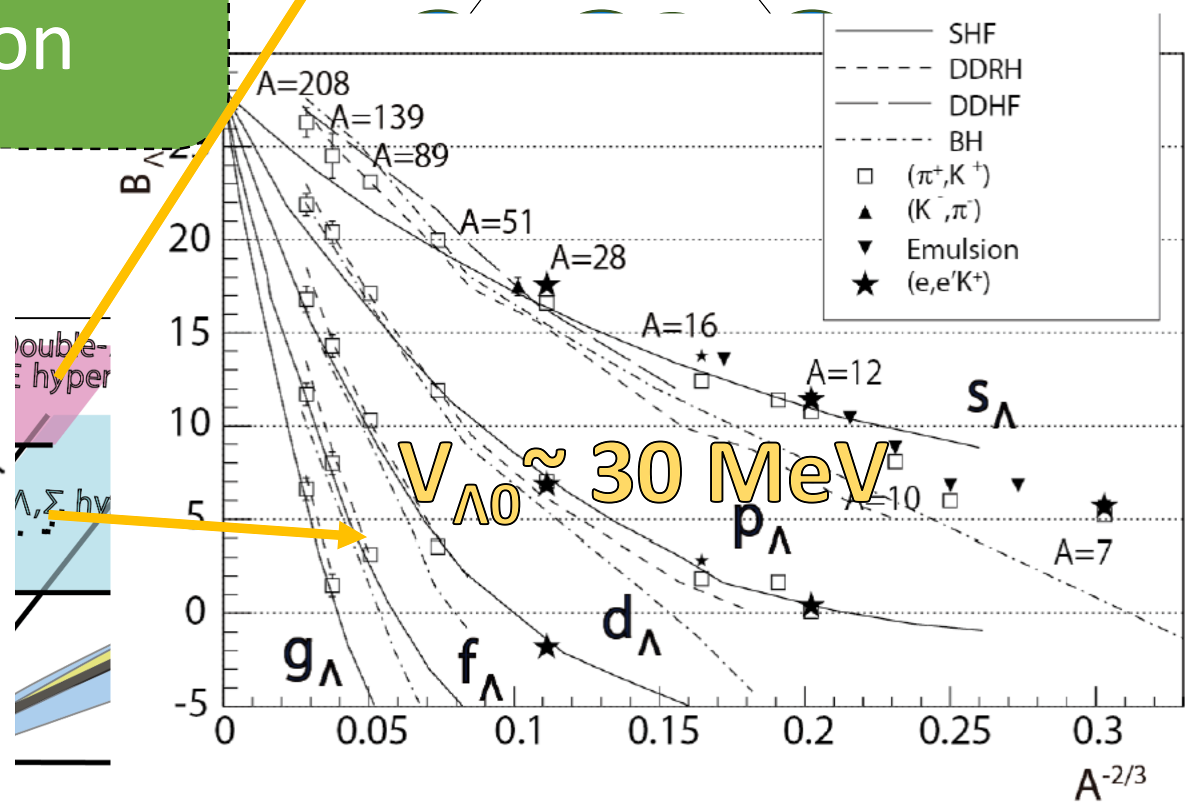
(Scarce data of YN/YY scattering exp.)

n — p S=0

NAGARA
ΛΛ interaction



H. Takahashi et al., PRL 87 (2001) 212502



Significance of hyperr

Almost No information for ΞN interaction

Unified understanding of the

Nucleon-nucleon (NN) interaction →

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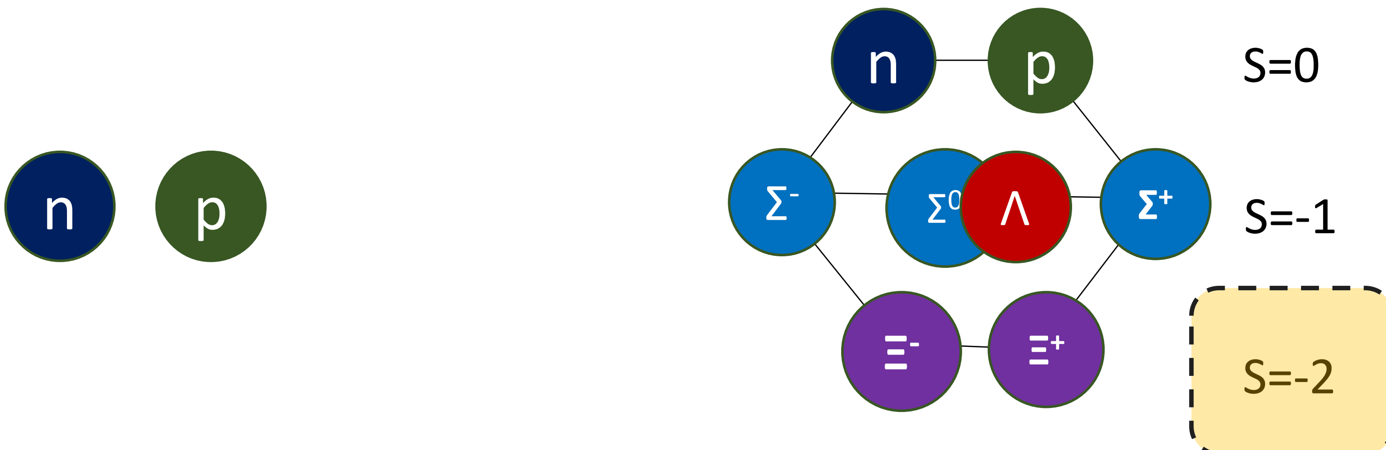
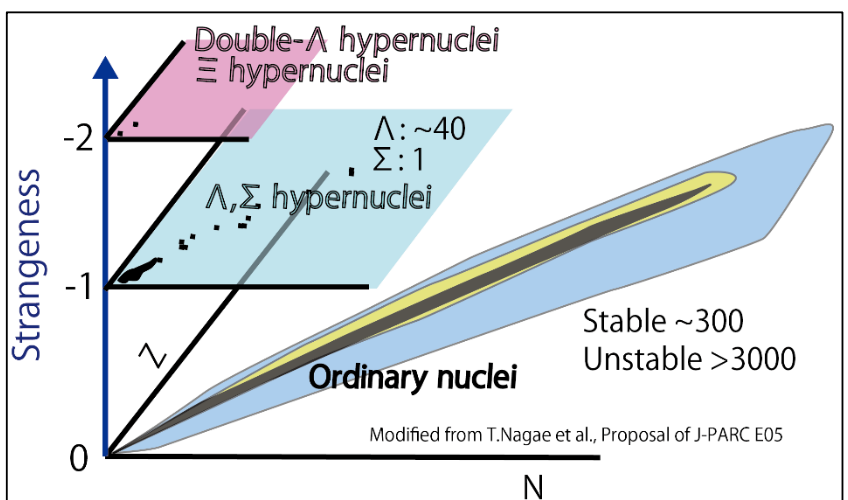


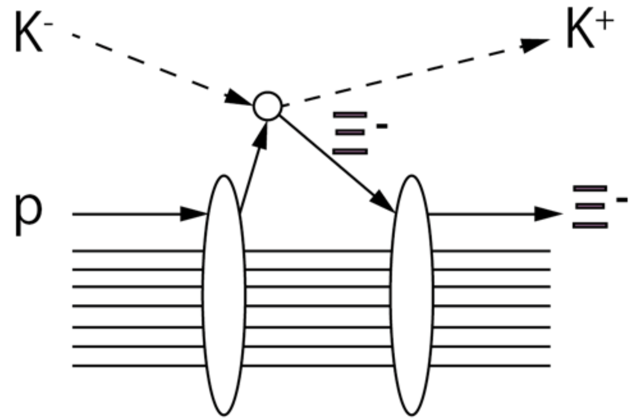
Expansion !!



(K^-,K^+) reaction

The (K^-, K^+) reaction to produce S=-2 nuclei

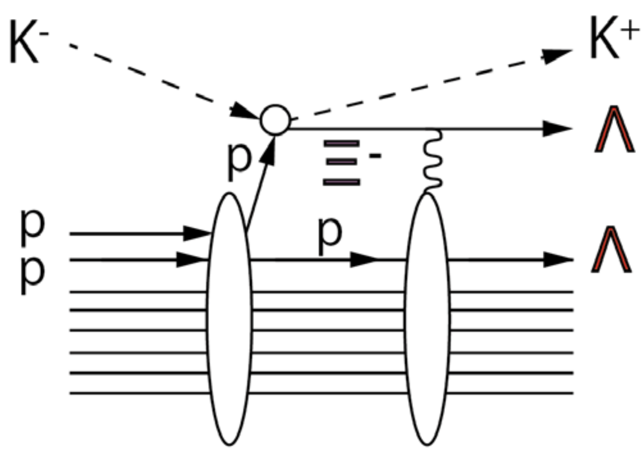
^{A}Z



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

Ξ^- hypernucleus

^{A}Z



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

Double Λ hypernucleus

Contents

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Experimental situations before 1990

Ξ⁻'s binding energy

${}^{8}_{\Xi}$He: 5.9 ± 1.2 MeV[1]

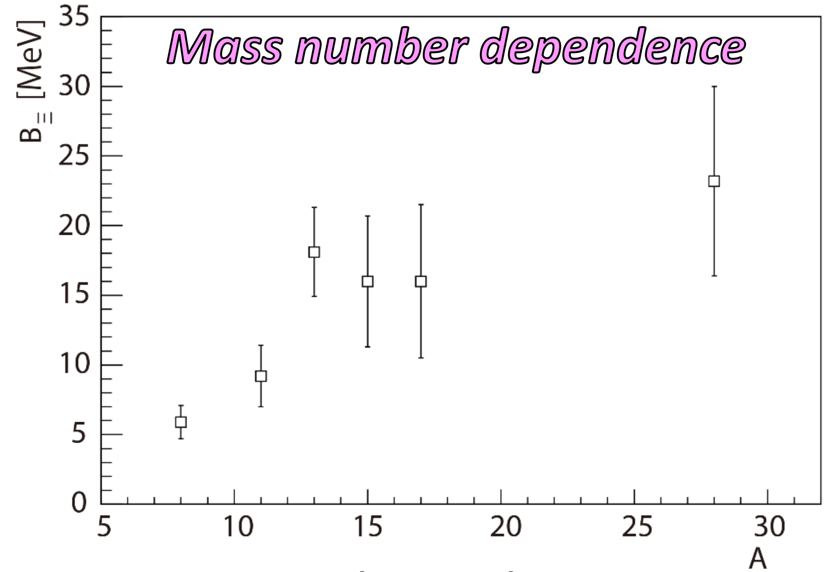
${}^{11}_{\Xi}$B: 9.2 ± 2.2 MeV[2]

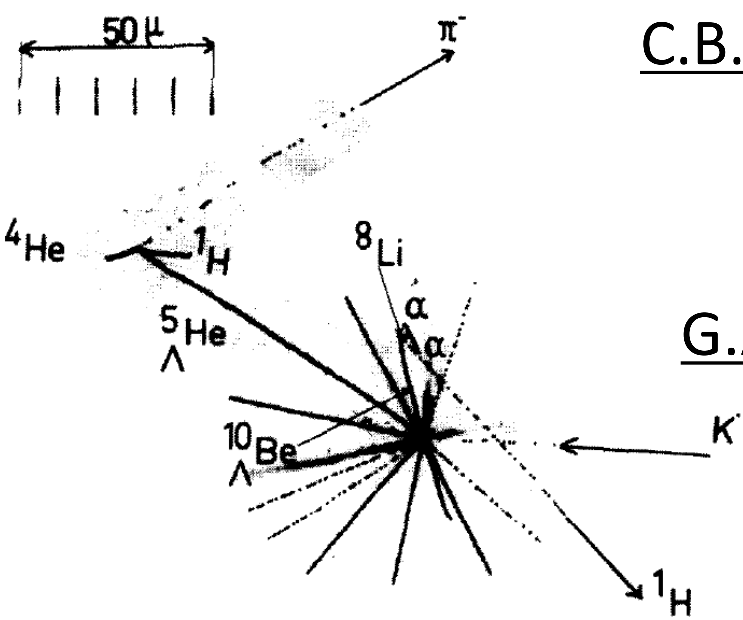
${}^{13}_{\Xi}$C: 18.1 ± 3.2 MeV[3]

${}^{15}_{\Xi}$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]





<u>C.B.Dover and A.Gal (1983)</u>

$$V_{0\Xi} = 24 \pm 4 \text{ MeV } (r_0 = 1.1 \text{ fm})$$
$$V_{0\Xi} = 21 \pm 4 \text{ MeV } (r_0 = 1.25 \text{ fm})$$

<u>G.A.Lalazissis *et al.* (1989)</u>

$$V_{0\Xi} = 22 \text{ MeV}$$

[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*26B(1968)3

Experimental situations before 1990

Ξ⁻'s binding energy

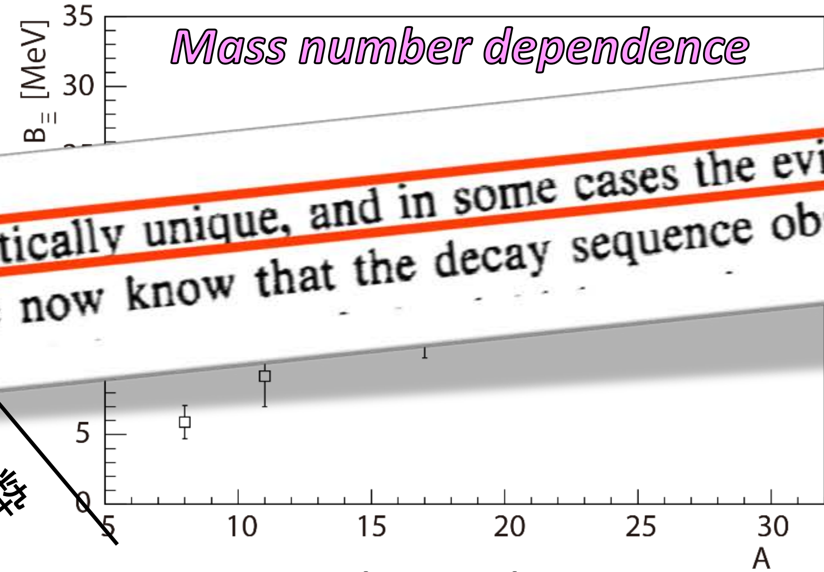
$^{8}_{\Xi}$He: 5.9 ± 1.2 MeV[1]

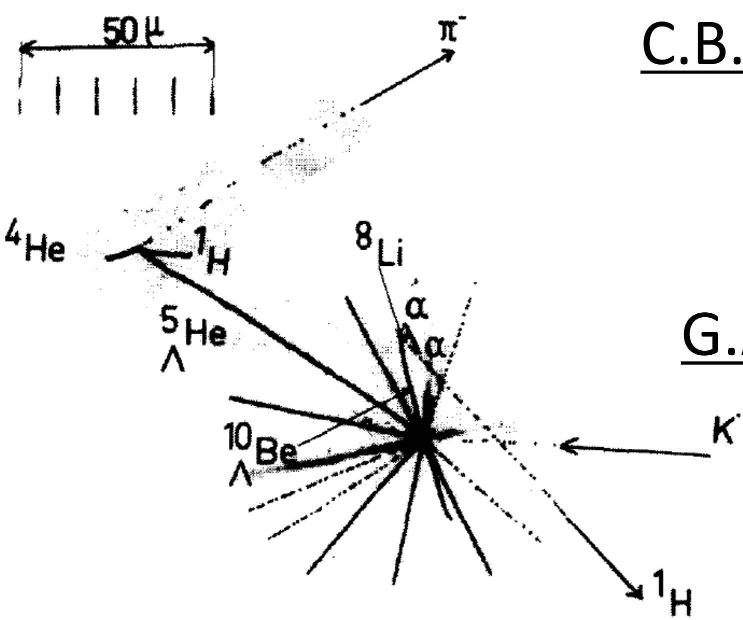
$^{11}_{\Xi}$B: 9.2 ± 2.2 MeV[2]

None of these interpretations is statistically unique, and in some cases the evidence is far from being compelling. Thus, we now know that the decay sequence observed

$_{\Xi}$Al: 23.2 ± 6.8 MeV [4]

抜粋





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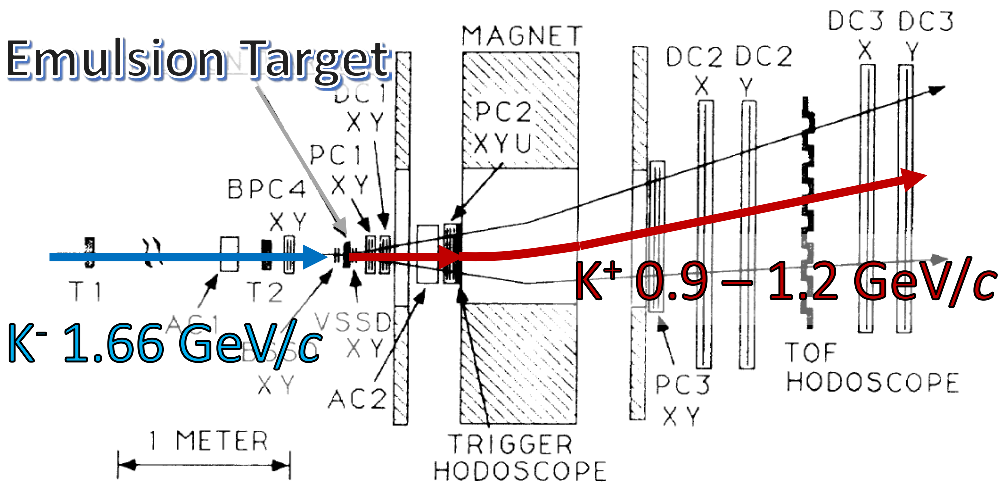
[4]A.Beckdolff *et al.*, *PL*26B(1968)3

Emulsion-counter hybrid experiment (KEK E176)

S.Aoki *et al.*, *PRL***65**(1990)14



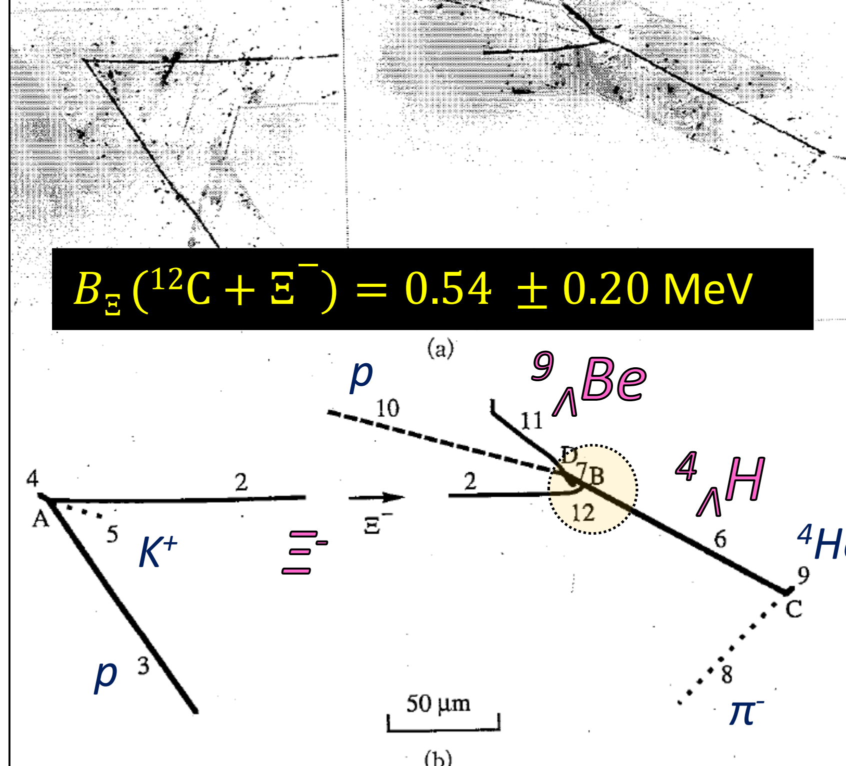
Two events of $^{12}\mathrm{C}+\Xi^-$ bound states

$\Rightarrow$ $V_{0\Xi} = 16$ MeV

Shallower than before !!

YOKOHAMA event

S.Aoki *et al.*, *Progress of Theoretical Physics* **89**(1993)2



$$B_{\Xi}(^{12}\mathrm{C}+\Xi^-) = 0.54 \pm 0.20 \text{ MeV}$$

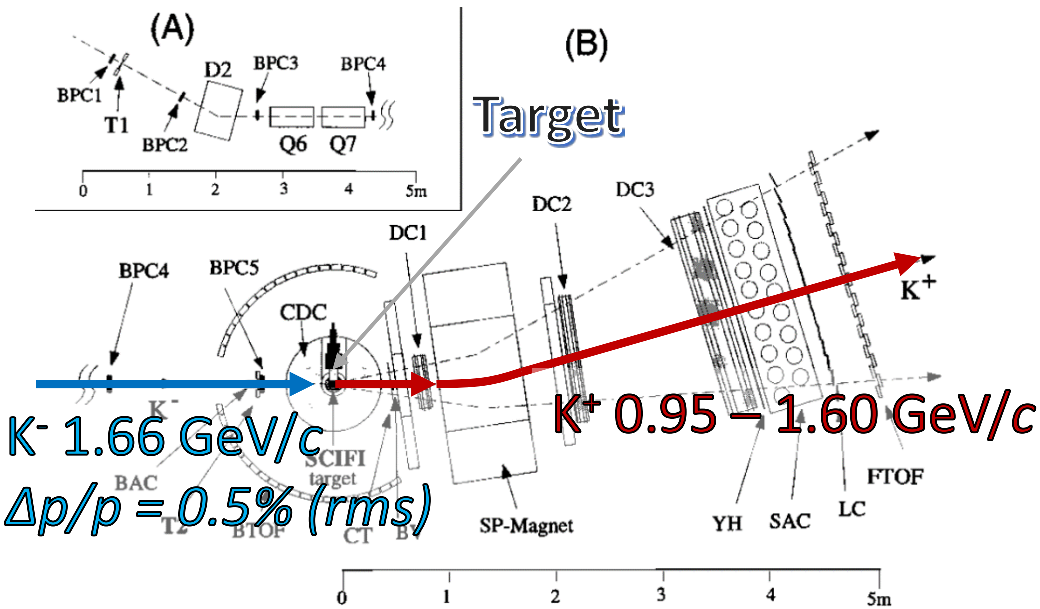
S.Aoki *et al.*, *Physics Letters B* **355**(1995)45-51

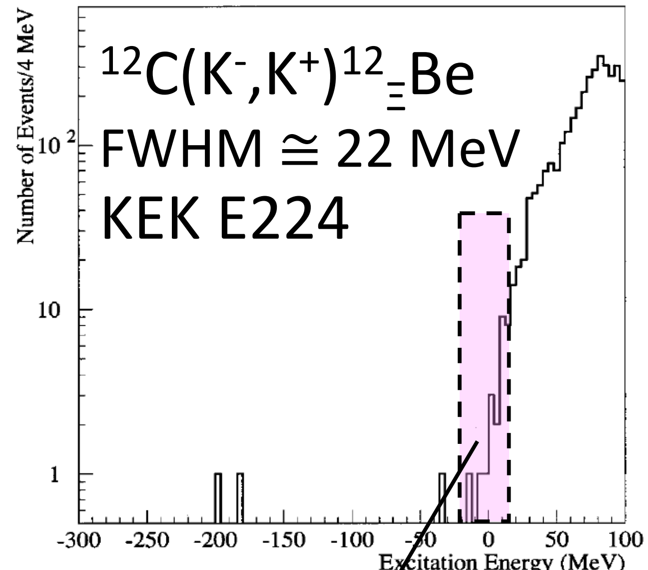
$$B_{\Xi}(^{12}\mathrm{C}+\Xi^-) = 0.62^{+0.18}_{-0.19} \text{ MeV}$$

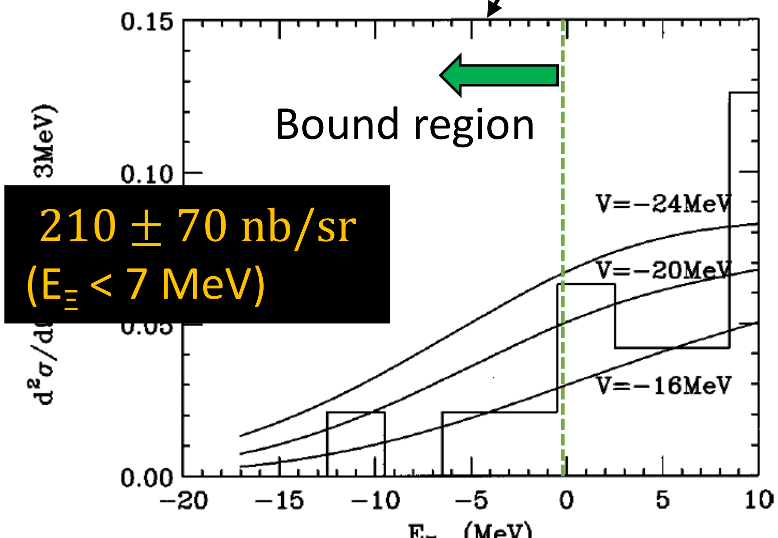
Counter experiment at KEK

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.

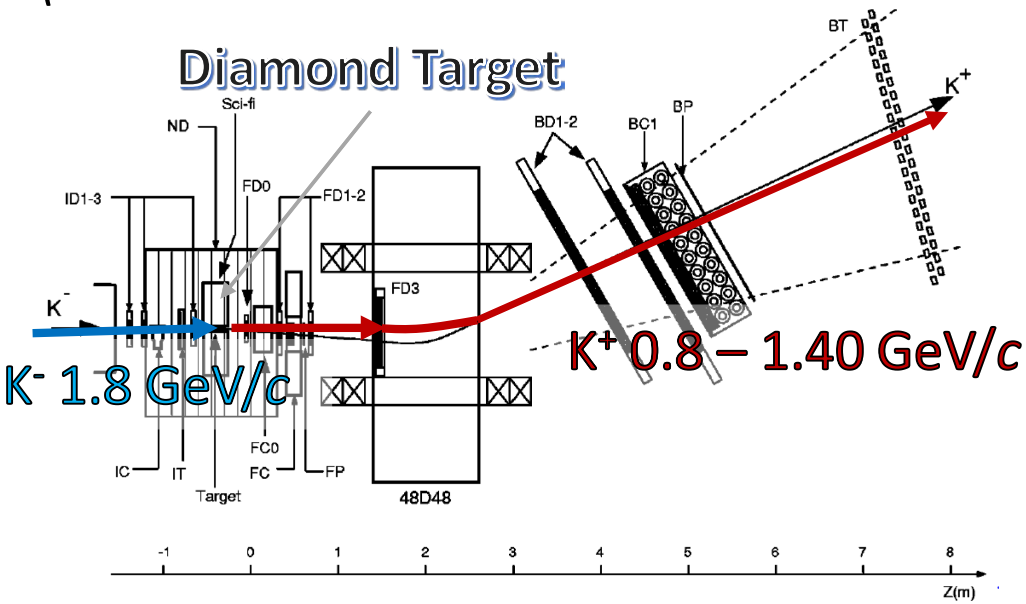
$\Rightarrow$ $V_{0\Xi} < 20$ MeV

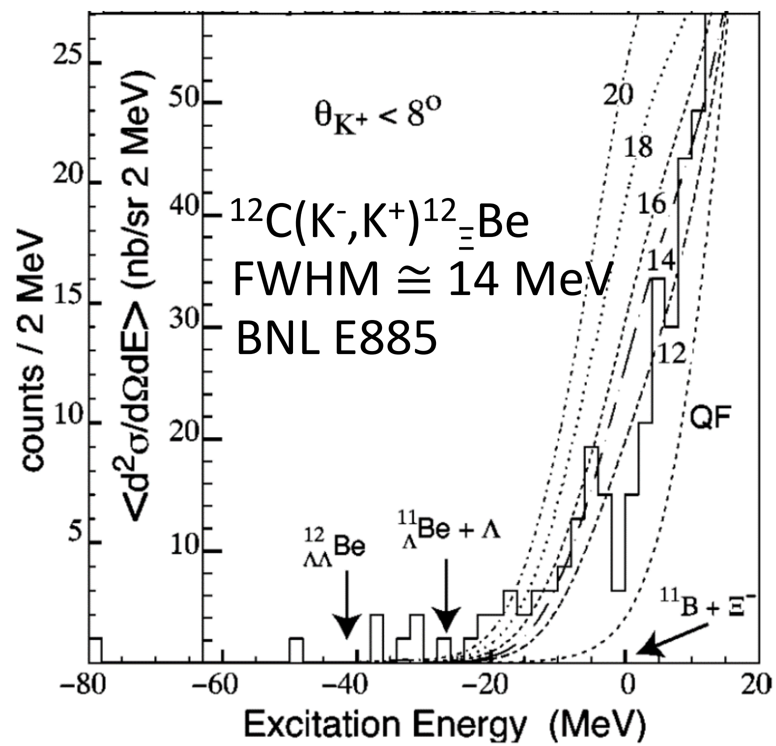
Consistent with KEK E176 !!

Counter experiment at BNL

P.Khaustov *et al.*, *PRC* **61** (2000) 054603

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





	KEK E224	BNL E885
FWHM [MeV]	22	14
	$\times 0.64$	
Sensitivity [/(nb/sr)]	0.05	1.6
	$\times 32$	

89 ± 14 nb/sr $(\theta < 8\ deg)$

42 ± 5 nb/sr $(\theta < 14\ deg)$

$(-20 < E_\Xi < 0$ MeV$)$

→ $V_{0\Xi} \leq 14$ MeV

KISO event (2014)

Overall scanning for old emulsion

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

[1] 仲澤和馬、新学術研究領域「実験と観測で解き明かす中性子星の核物質」第3回研究会

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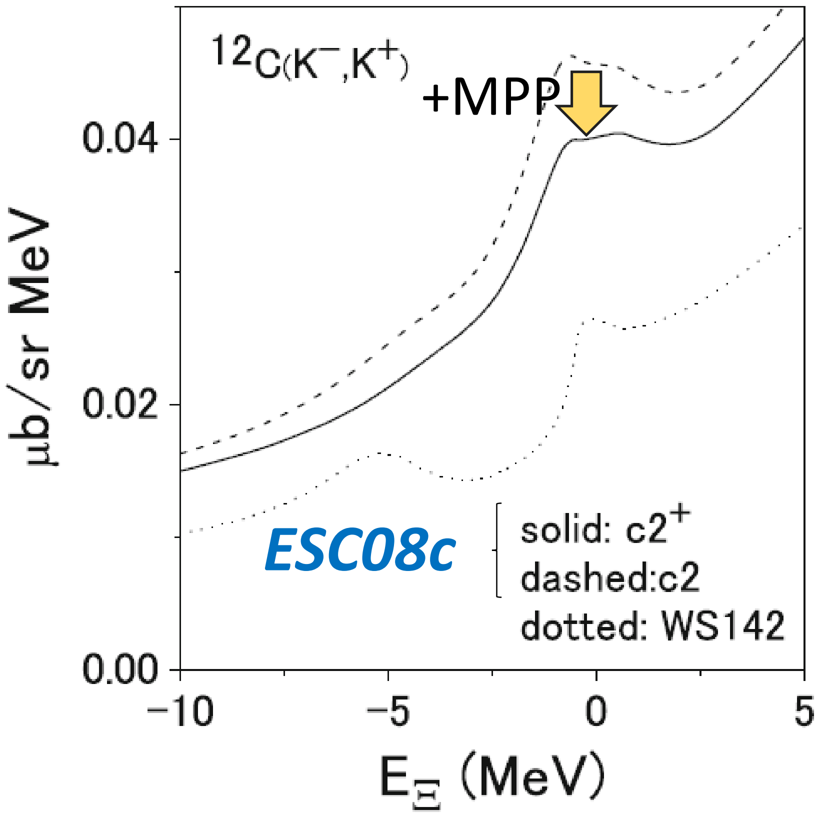
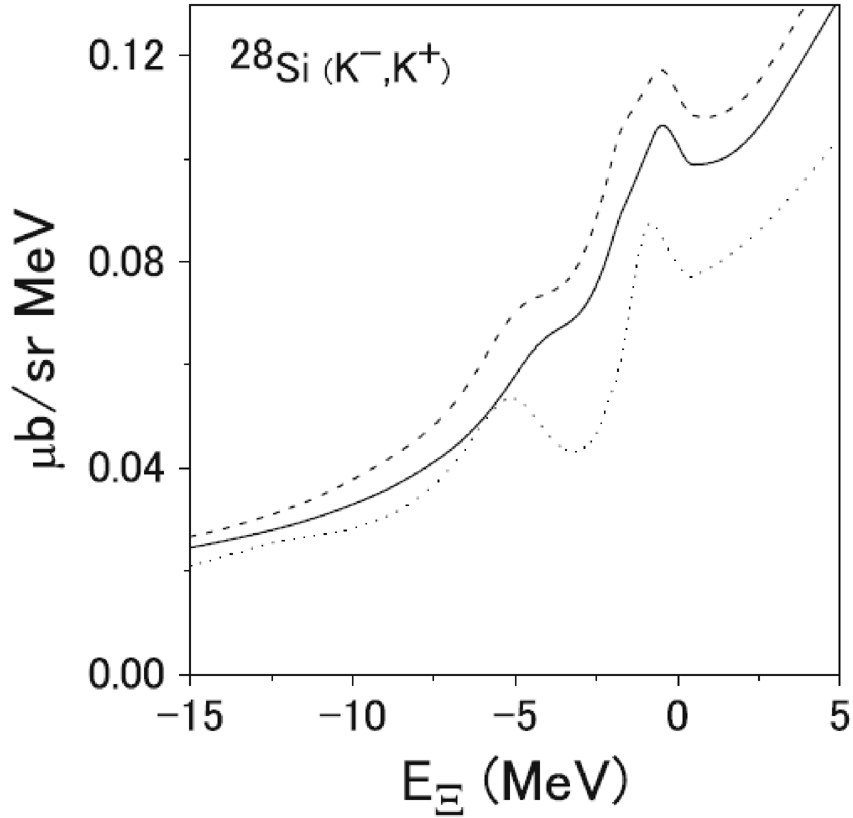
Theoretical calculations/predictions

Y.Yamamoto, E.Hiyama, Th.A.Rijken, *Few-Body Syst.* (2013) **54**:1267-1270

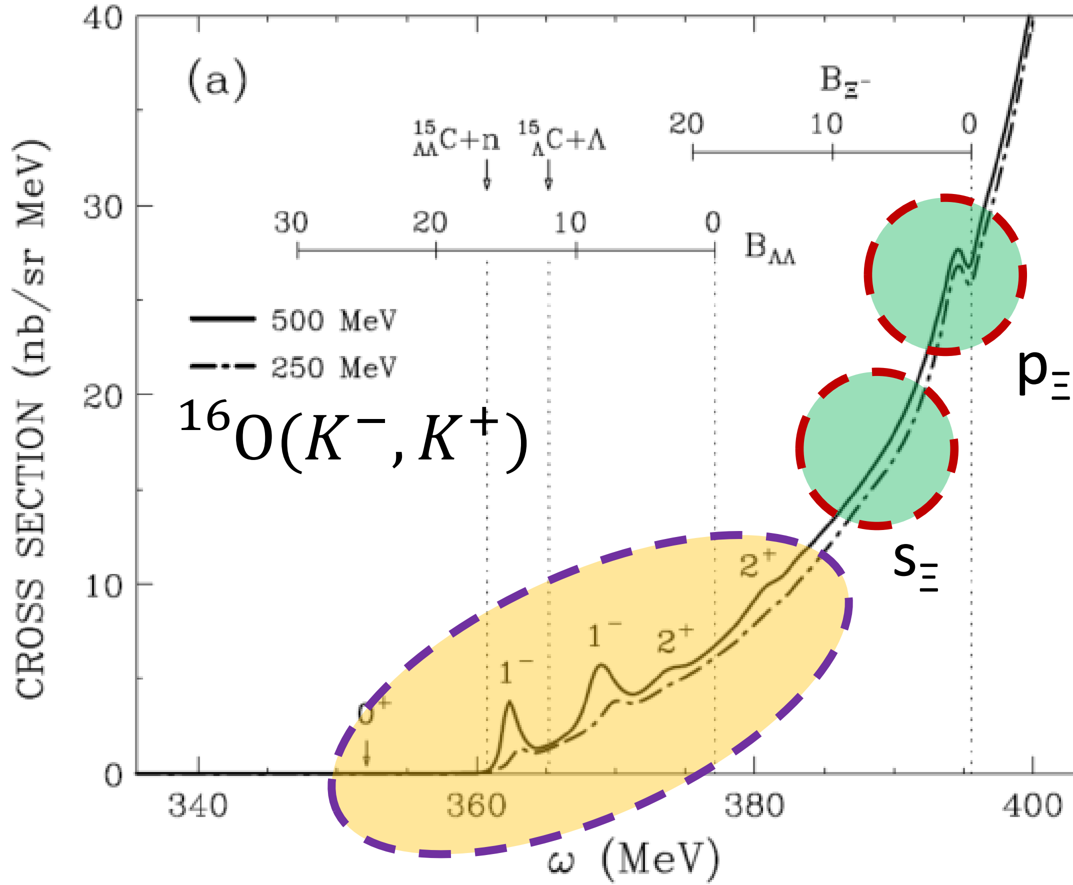




Experimental resolution is assumed to be FWHM = 2 MeV

Theoretical calculations/predictions

T.Harada, Y.Hirabayashi, A.Umeya, *NPA* **914** (2013) 85-90



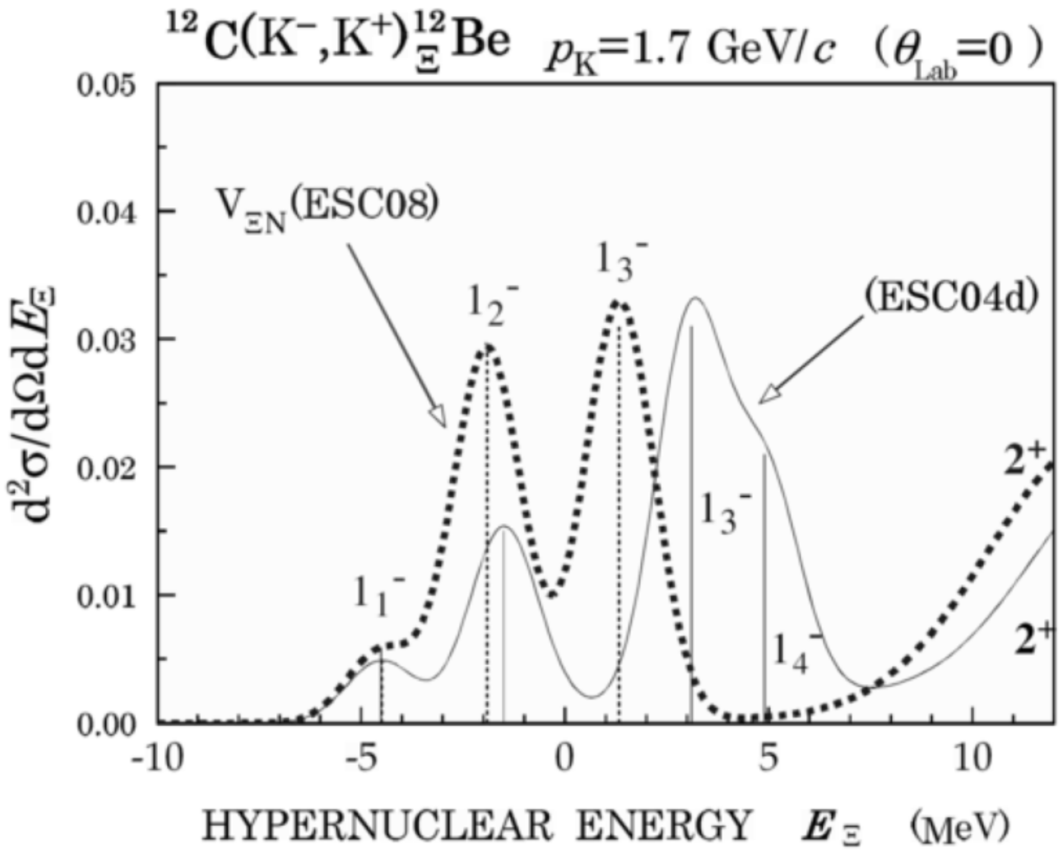
$V_{0\Xi}$ = 14 MeV
Ξp-ΛΛ coupling

1^-

Double Λ hypernuclei

Theoretical calculations/predictions

T.Motoba and S.Sugimoto, *NPA* **835** (2010) 223-230



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J-PARC E05 experiment

GOAL

Confirmation of the existence of $^{11}\mathrm{B} + \Xi^-$ bound state ($^{12}_{\Xi}\mathrm{Be}$)

① Improvement of the energy resolution
←*High momentum spectrometer systems*

② More statistics
←*High intensity K⁻ (J-PARC)*

$^{12}\mathrm{C}(K^-, K^+)^{12}_{\Xi}\mathrm{Be}$

Item \ Experiment	KEK E224	BNL E885	**J-PARC E05**
FWHM [MeV]	22 → ×0.64	14 → ×0.18	**2.5**
Sensitivity [/(nb/sr)]	0.05 → ×32	1.6 → ×1.3	**2.1**

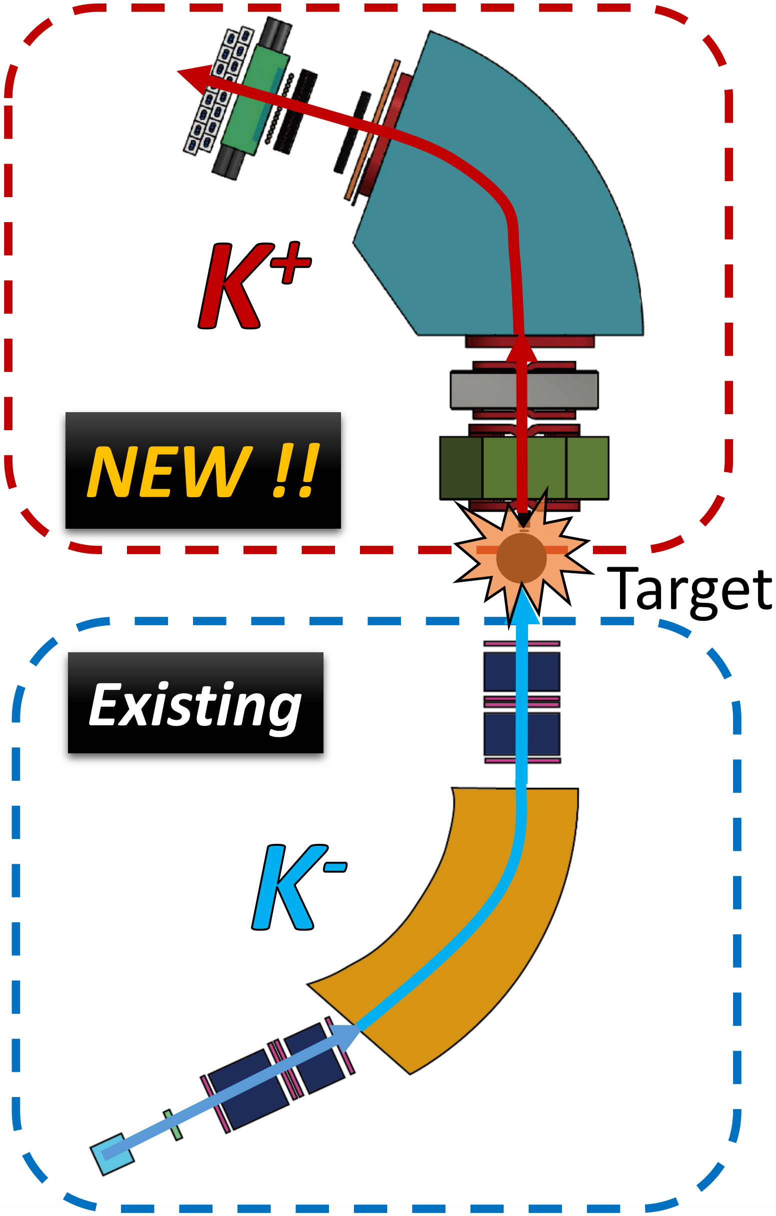
Experimental setup (J-PARC E05) @ K1.8 Beam line

K^+ spectrometer (S-2S)

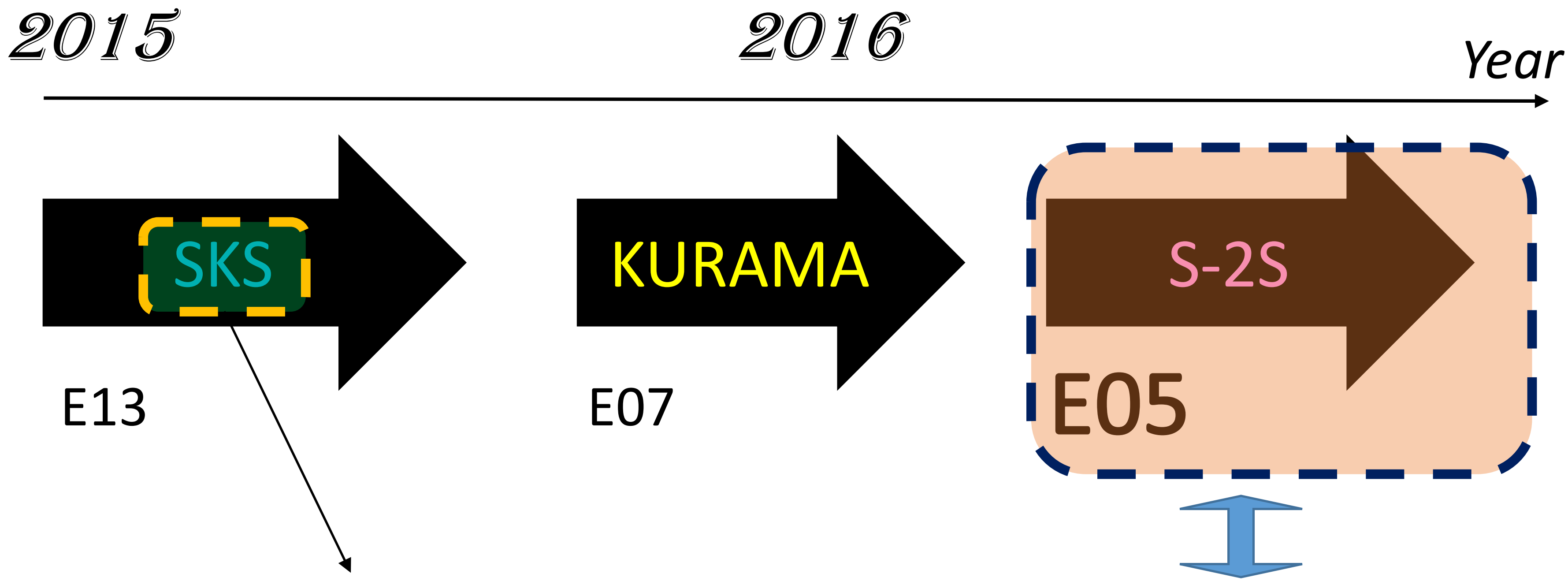
- $p = 1.25 - 1.45$ GeV/c
- $\Delta p/p \approx 5.0 \times 10^{-4}$ (FWHM)
- 55 msr
- $\theta_K = 0.0 - 8.0$ deg

K^- Beam spectrometer

- $p = 1.8$ GeV/c
- $\Delta p/p \approx 10.0 \times 10^{-4}$ (FWHM)
- 1.5×10^6 /spill
- 4 seconds cycle



Rough schedule of experiments in K1.8 Beam line



E05 Phase-0 experiment with SKS(Minus)

→ $^{12}_{\Xi}\mathrm{Be}$ *measuremet with a* CH_2 *target*

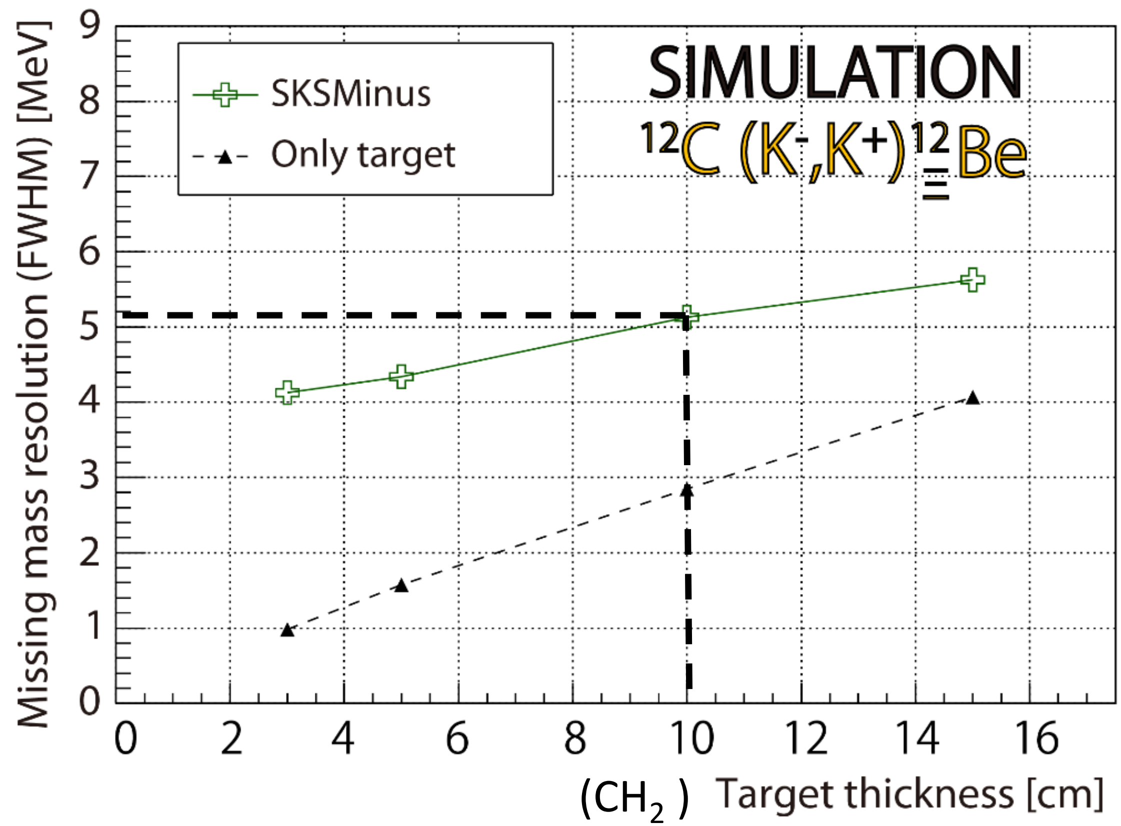
Missing mass resolution with SKSMinus (E05 Phase-0 experiment)

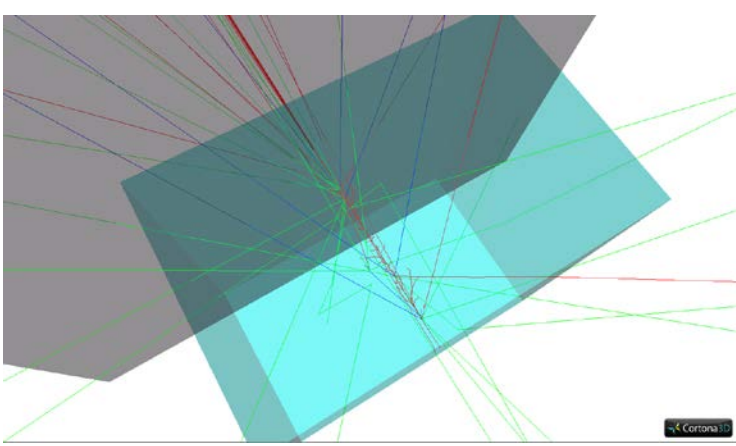
Assumptions

$K^{-}: \frac{\Delta p}{p} = 1.0 \times 10^{-3}$

$K^{+}: \frac{\Delta p}{p} = 2.7 \times 10^{-3}$

$\Delta\vartheta = 2.0$ *mrad*





) MeV with 10 cm* CH_2 target

* 10 cm = 9.3 g/cm^2 for the CH_2 target

Expected yield with SKSMinus (E05 Phase-0 experiment)

Assumptions

- $\Omega = 0.110$ sr (SKSMinus)
- 10 cm (9.3 g/cm^2) CH_2 target
- 4.5×10^5 K^- /spill
- 6 seconds beam cycle
- K^+ survival ratio: 0.6
- Efficiency: 0.7

$$N_t = \frac{9.3 \times 6.022 \times 10^{23}}{14 \times 1.0 \times 10^4} \ [/\mathrm{m}^2]$$

$$N_{\mathrm{beam}} = 4.5 \times 10^5 \times \frac{3600}{6} \times 24 \times 7 \times 4 \ [/\mathrm{month}]$$

$$\varepsilon = 0.6 \times 0.7 \ (\text{Total efficiency})$$

Then, sensitivity is

$$S = 10^{-9} \times 10^{28} \times \Omega \times N_t \times N_{beam} \times \varepsilon$$

$$= 3.35 \ \textbf{[/ (nb/sr) / month].}$$

$$\frac{d\sigma}{d\Omega} = 42 \pm 5 \ \mathrm{nb/sr} \ \cdots (\theta < 14°)^{[1]}$$

140 events [/month] $(-20 < -B_\Xi < 0 \ \mathrm{MeV})$

[1] P.Khaustov *et al.*, *PRC* **61** (2000) 054603

Missing mass resolution and yield comparison

$^{12}\mathrm{C}(K^-, K^+)^{12}_{\Xi}\mathrm{Be}$

Details will be talked by S.Kanatuski

	KEK E224[1]	BNL E885[2]		J-PARC E05 PHASE-0	J-PARC E05 (3 / 5 [g/cm^2])
FWHM [MeV]	22	14		**5**	**2.2 / 2.5**
Sensitivity [/(nb/sr)]	0.05	$\theta < 8°$: 0.47	$\theta < 14°$: 1.6	**3.4**	**1.3 / 2.1**
Cross section [nb/sr]	60 ± 45	89 ± 14	42 ± 5	**42**[2] ($\theta < 14°$)	**89**[2] ($\theta < 8°$)
Yield ($-20 < -B_{\Xi} < 0$ MeV)	3	42	67	**140 [/month]**	**112 / 187 [/month]**
				SKSMinus	***S-2S***

[1] T.Fukuda *et al.*, *PRC* **58** (1998) 2
[2] P.Khaustov *et al.*, *PRC* **61** (2000) 054603

Missing mass resolution and yield comparison

$^{12}C(K^-, K^+)^{12}_{\Xi}Be$

	KEK E224[1]	BNL E885[2]		J-PARC E05 PHASE-0	J-PARC E05 (3 / 5 [g/cm^2])
FWHM [MeV]	22	14		**5**	**2.2 / 2.5**
Sensitivity [/(nb/sr)]	0.05	$\theta < 8°$	$\theta < 14°$	**3.4**	**1.3 / 2.1**
		0.47	1.6		
Cross section [nb/sr]	60 ± 45	89 ± 14	42 ± 5	**42[2]** ($\theta < 14°$)	**89[2]** ($\theta < 8°$)
Yield ($-20 < -B_{\Xi} < 0$ MeV)	3	42	67	**140 (/month)**	**112 / 187 (/month)**

FWHM: $\times 0.36$ (BNL E885 → PHASE-0), $\times 2.0$ (J-PARC E05 → PHASE-0)

Yield: $\times 2$ (BNL E885 → PHASE-0), $\times 0.75$ (J-PARC E05 → PHASE-0)

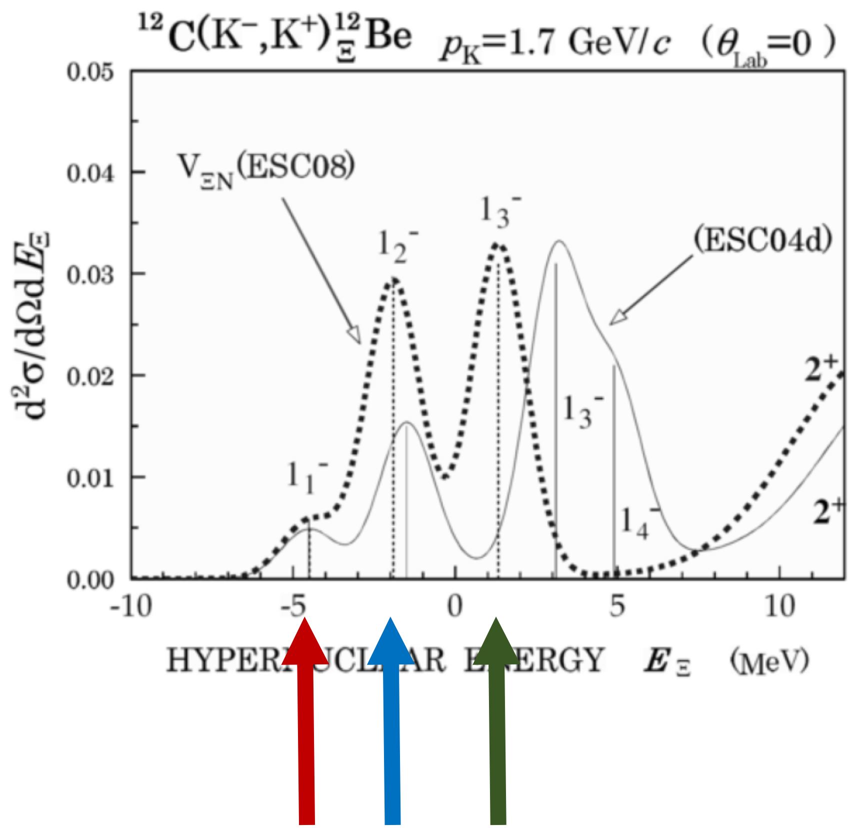
SKSMinus (J-PARC E05 PHASE-0) — S-2S (J-PARC E05)

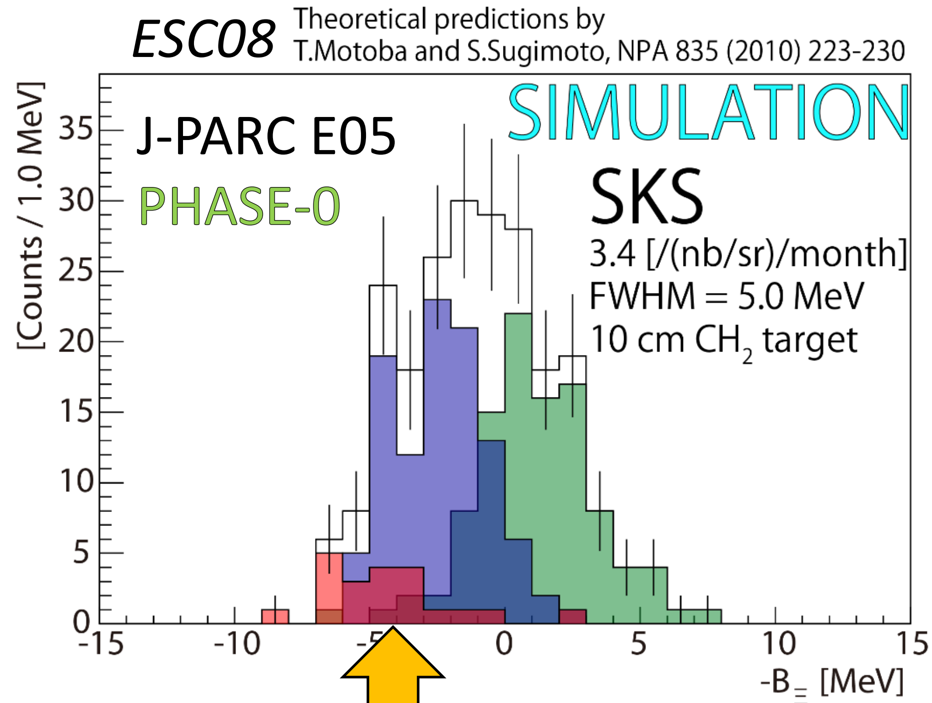
[1] T.Fukuda *et al.*, *PRC* **58** (1998) 2

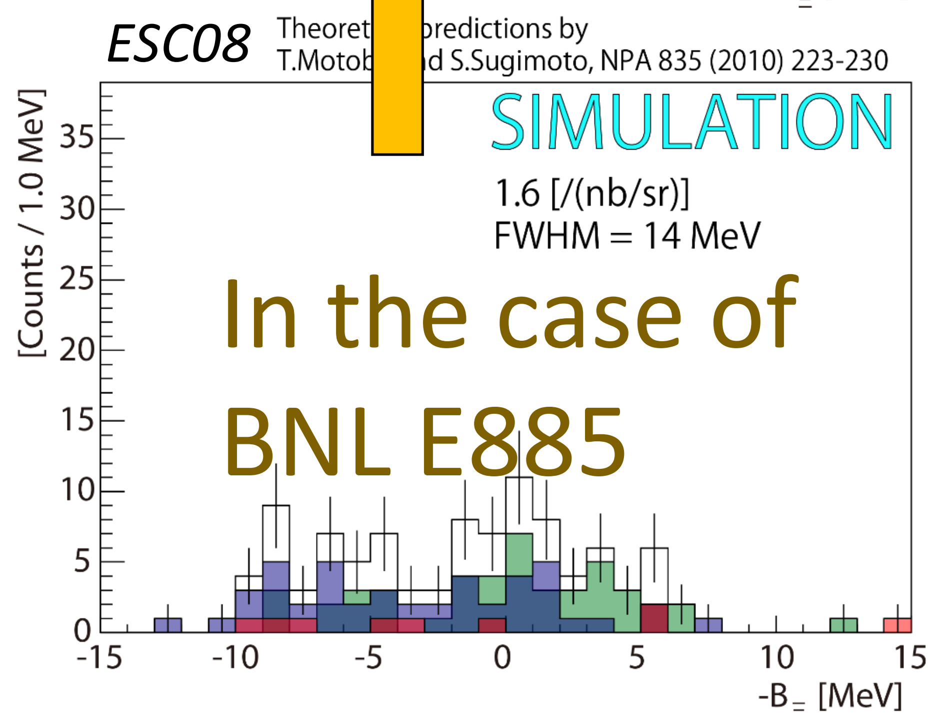
[2] P.Khaustov *et al.*, *PRC* **61** (2000) 054603

Expected spectrum

T.Motoba and S.Sugimoto, *NPA* **835** (2010) 223-230



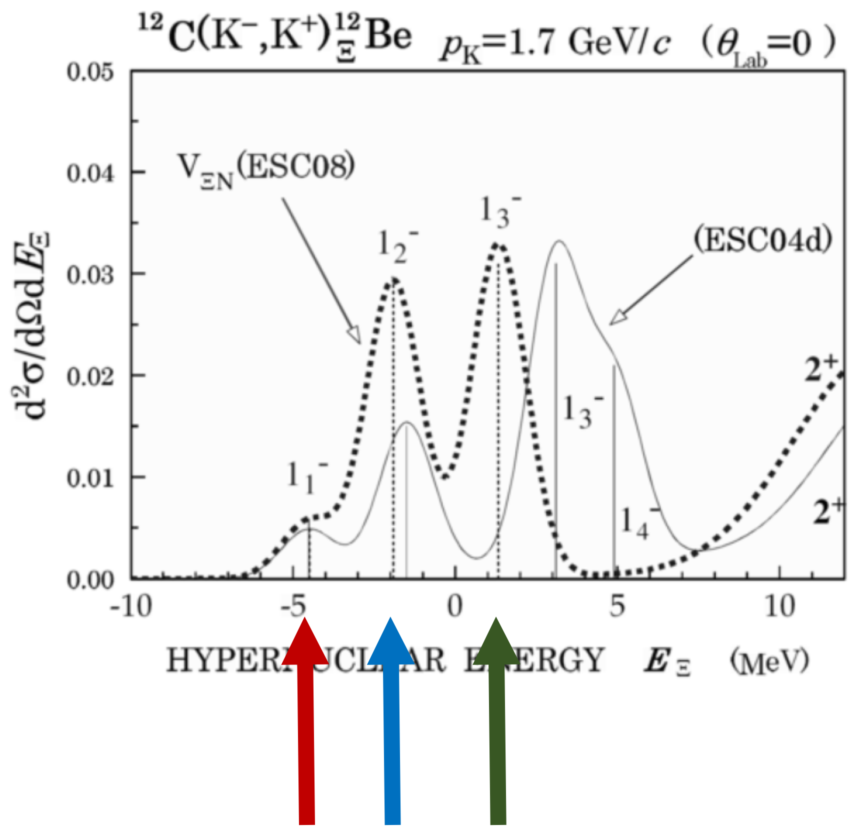


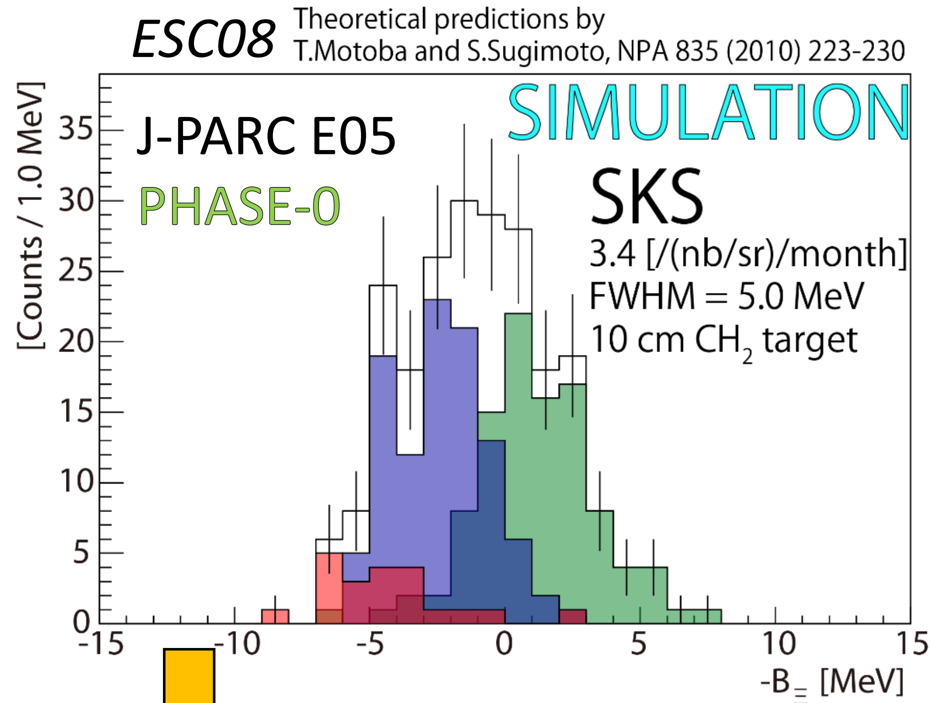


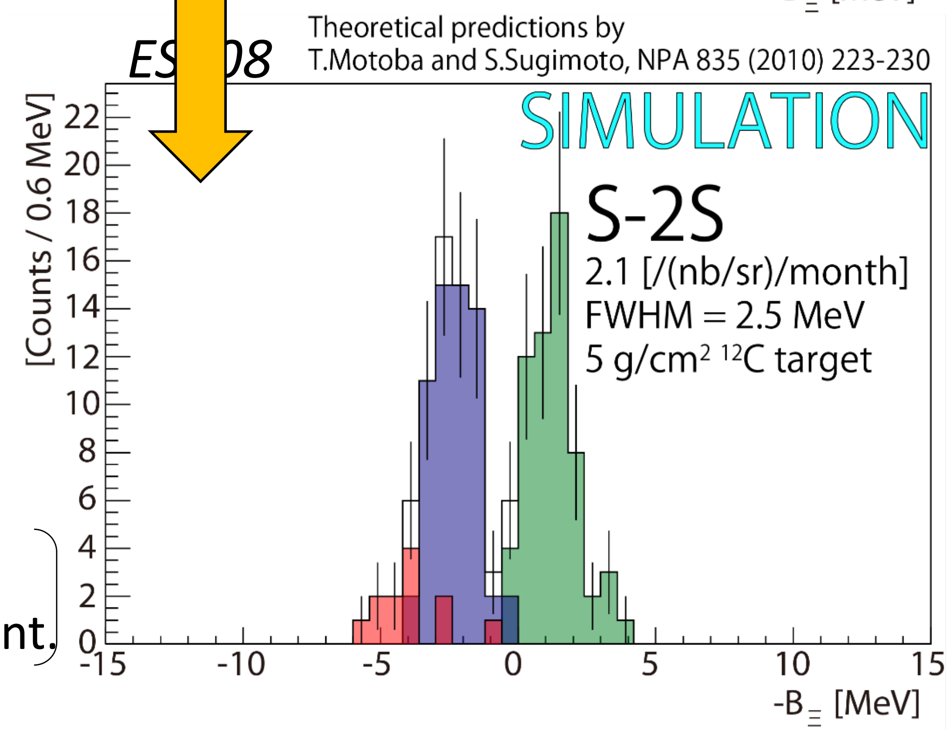
In the simulation,
the conversion width was
not taken into account.

Expected spectrum

T.Motoba and S.Sugimoto, *NPA* **835** (2010) 223-230

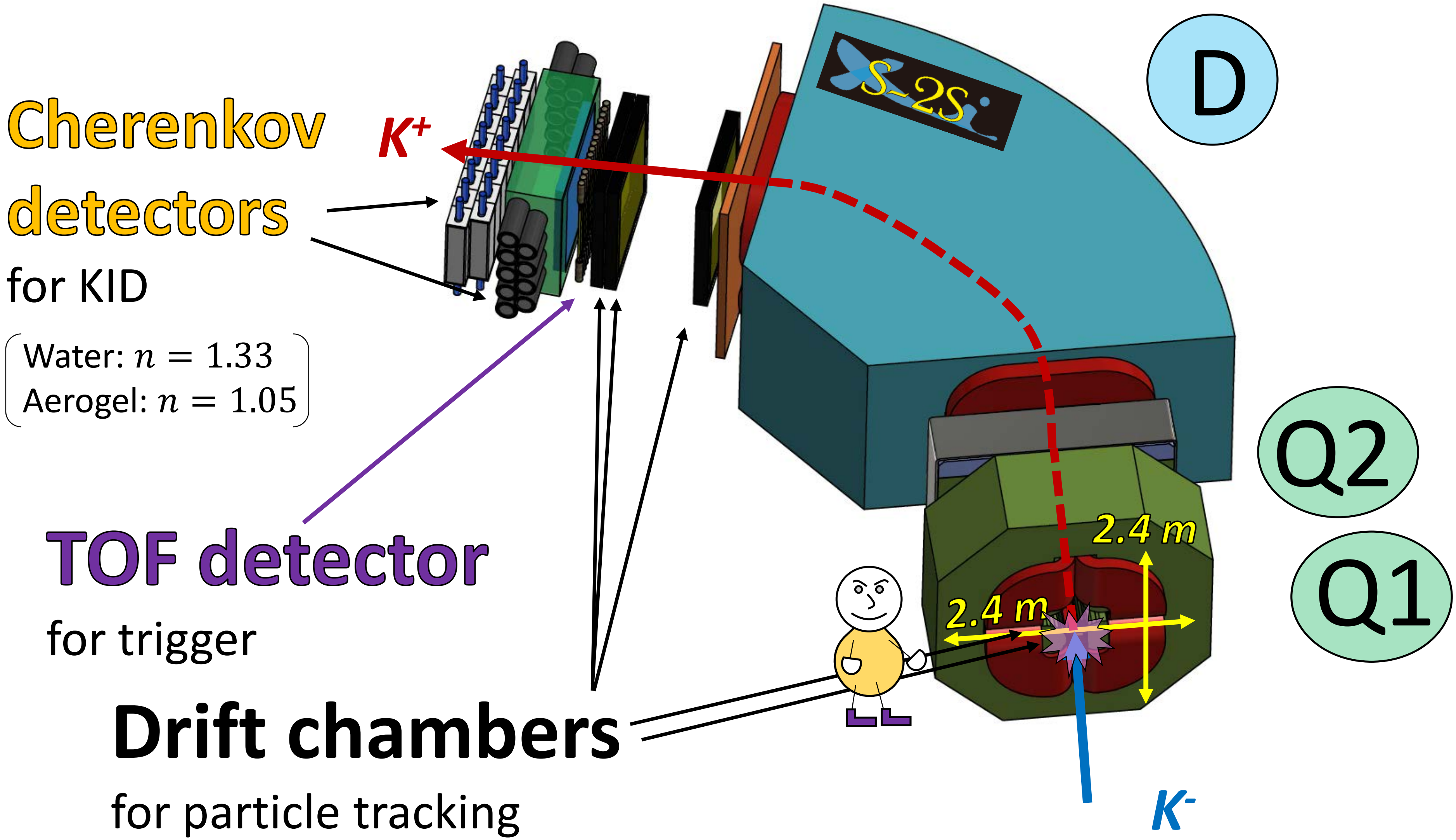






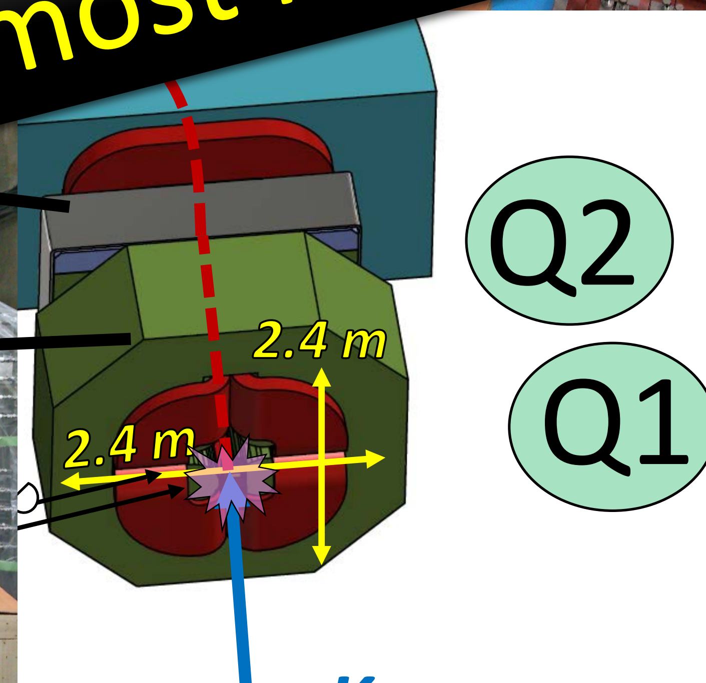
In the simulation,
the ***natural width*** was not taken into account.

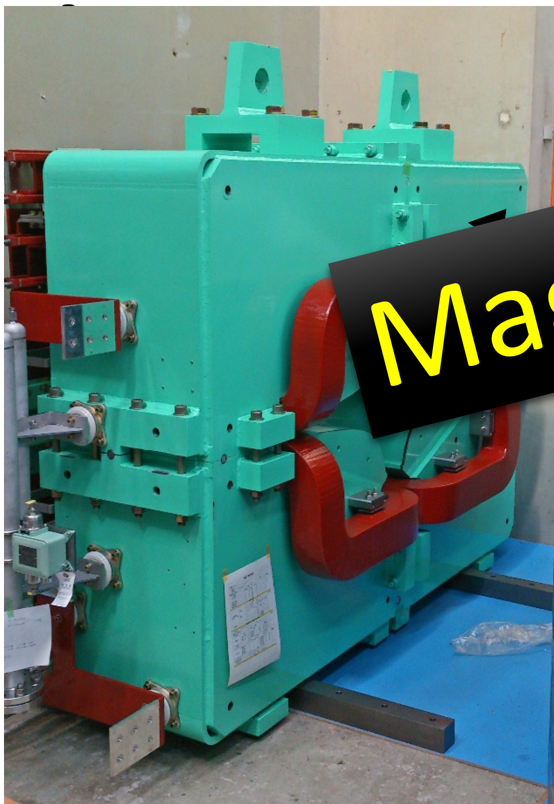
Strangeness -2 Spectrometer (S-2S)



Strangeness -2 Spe

Cherenkov



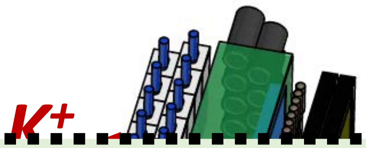


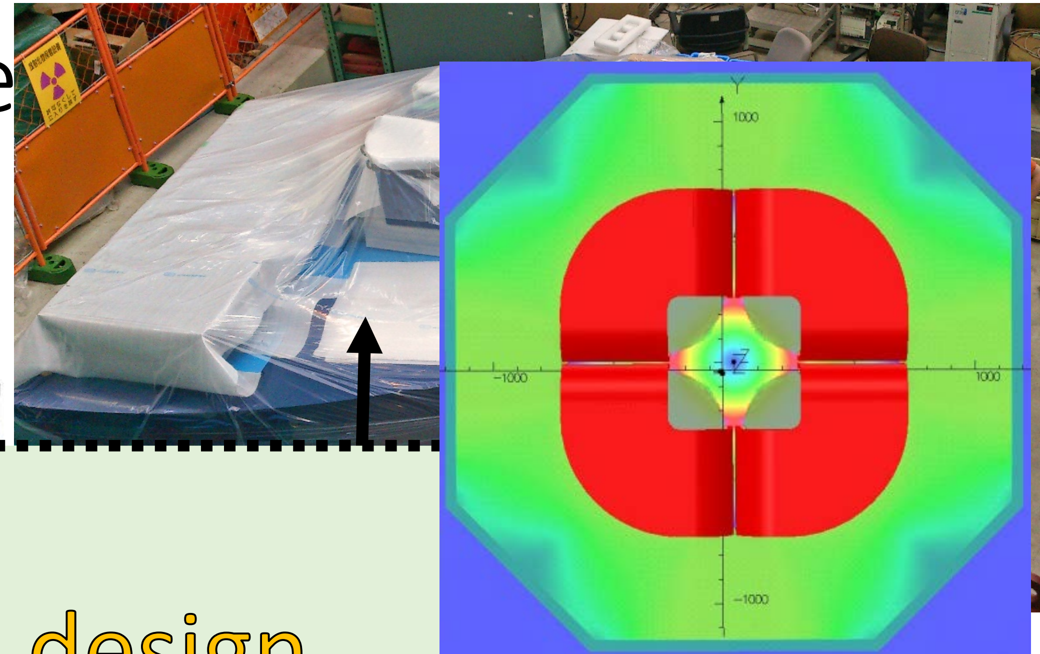
for particle trac

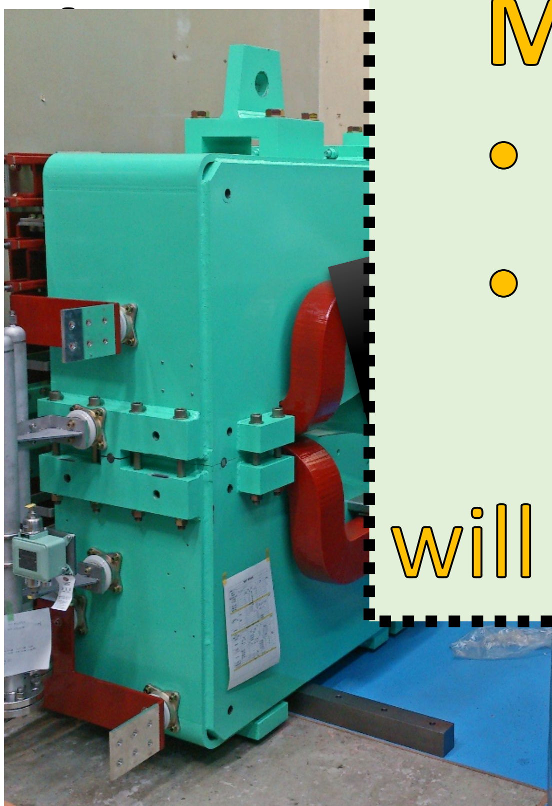
Magnets are almost ready

Strangeness -2 Spe

Cherenkov

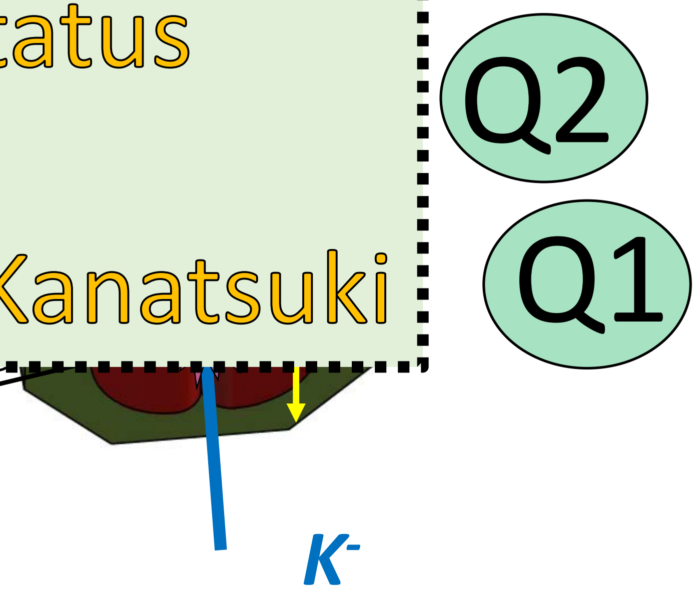






Magnet:
- Optical design
- Construction status

will be given by S. Kanatsuki

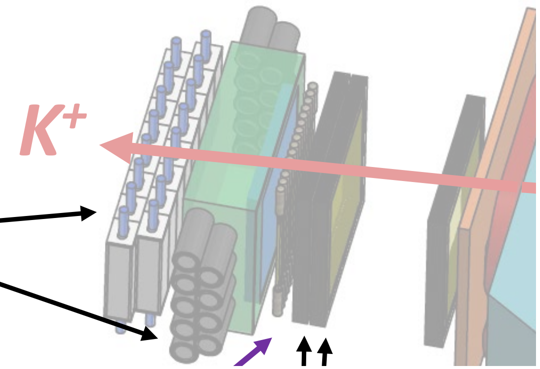


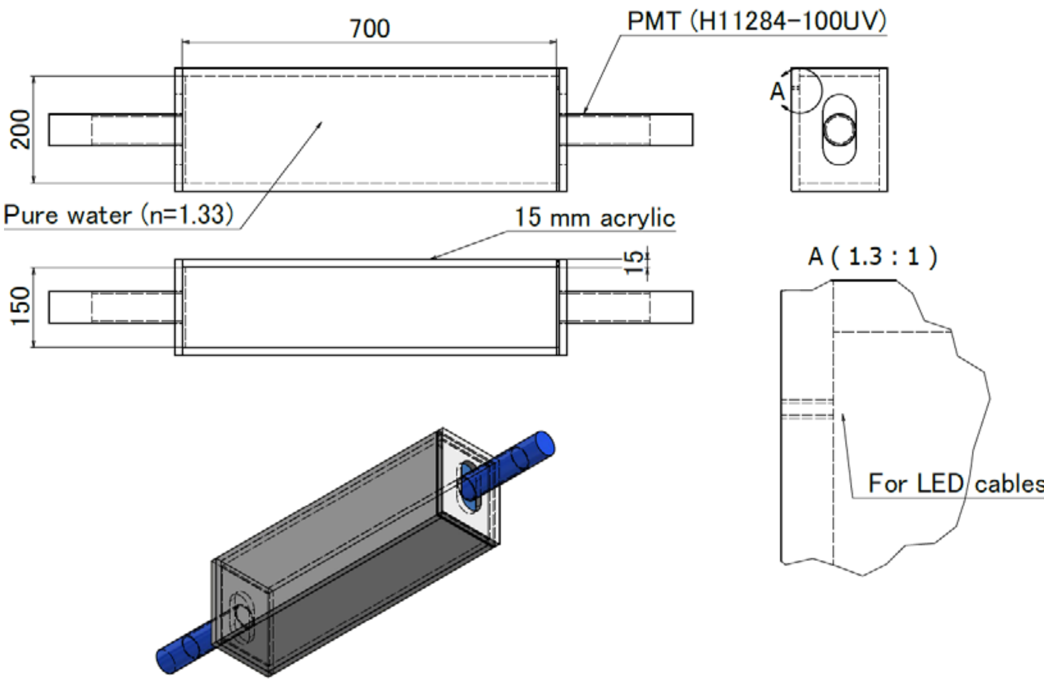
for particle trac

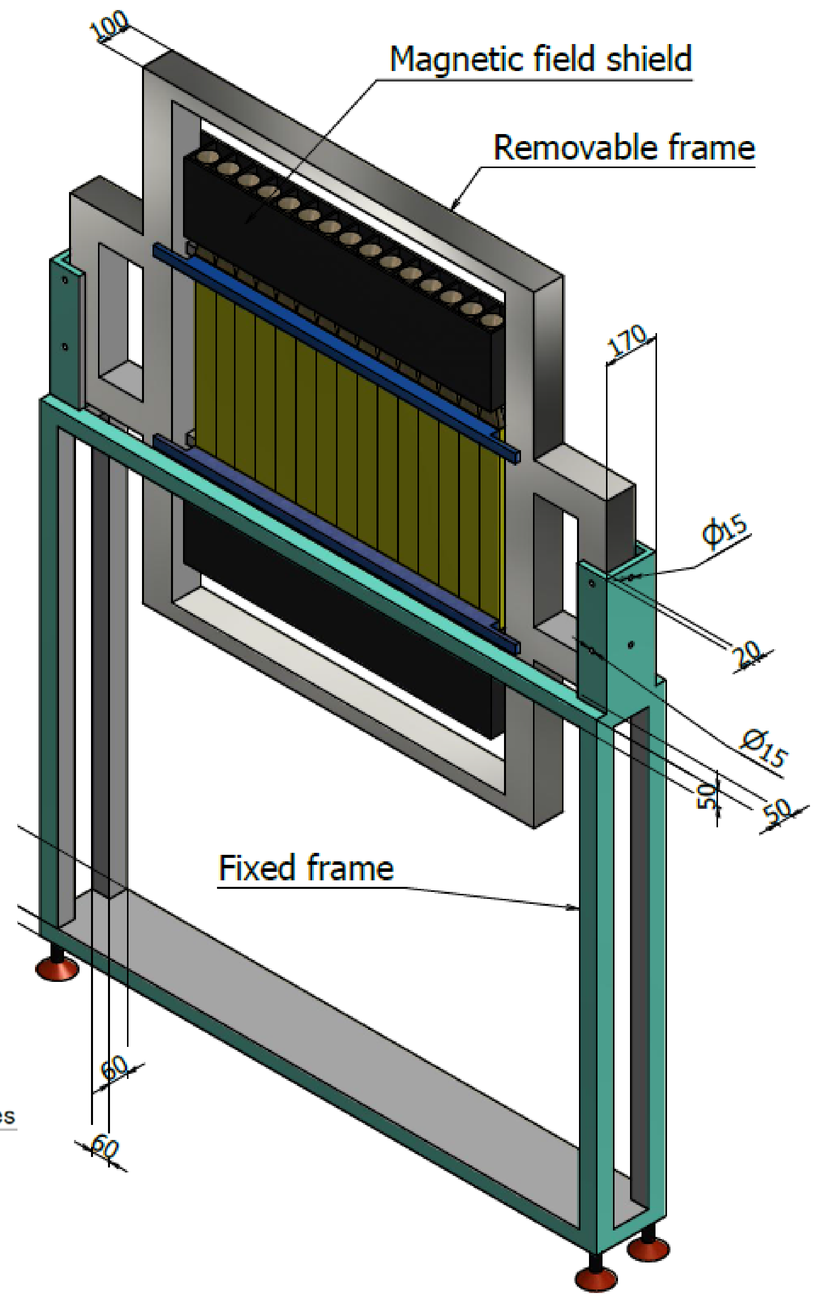
Strangeness -2 Spectrc

Cherenkov detectors

for KID



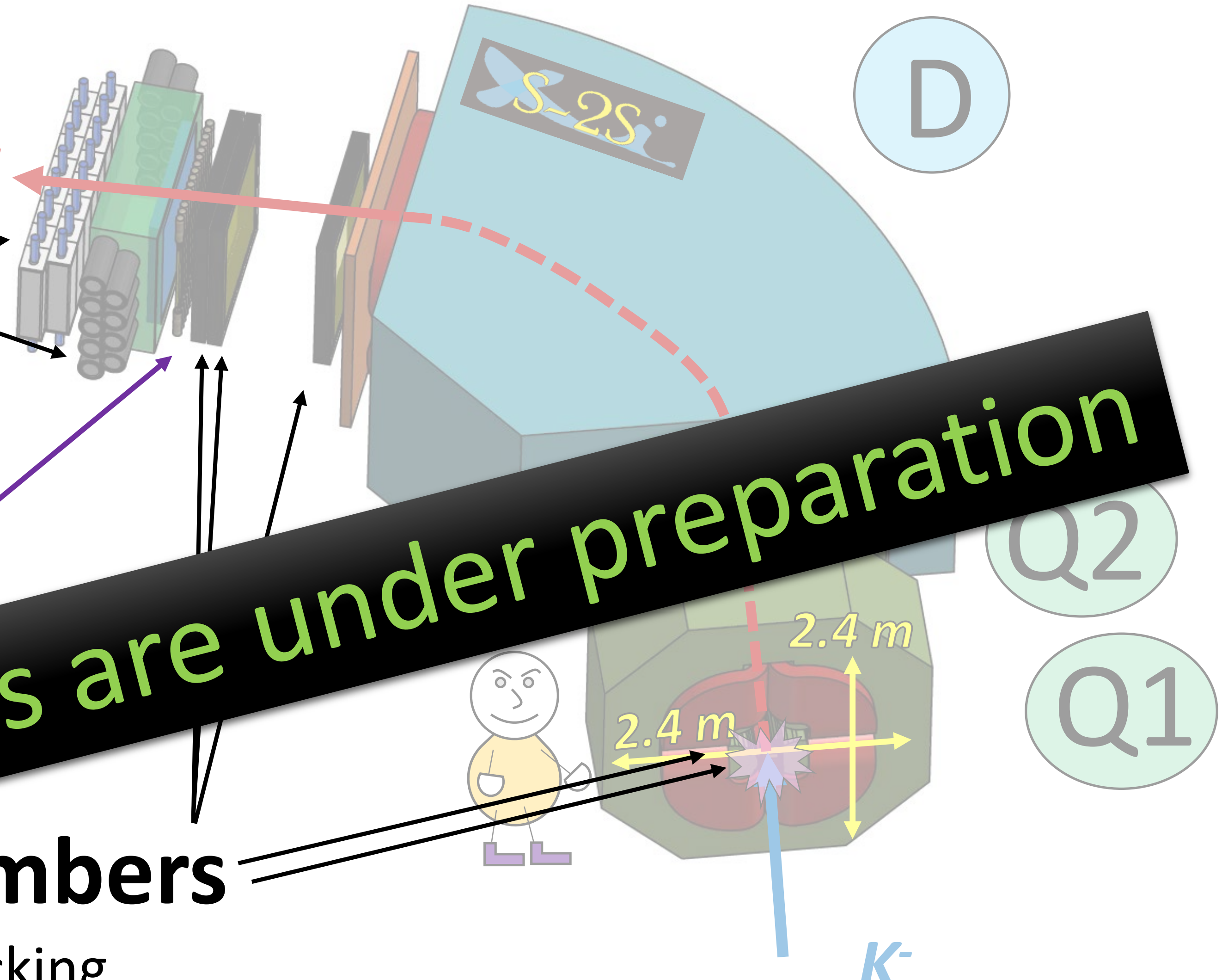




Strangeness -2 Spectrometer (S-2S)

Cherenkov detectors
for KID

Water: $n = 1.33$
Aerogel: $n = 1.05$

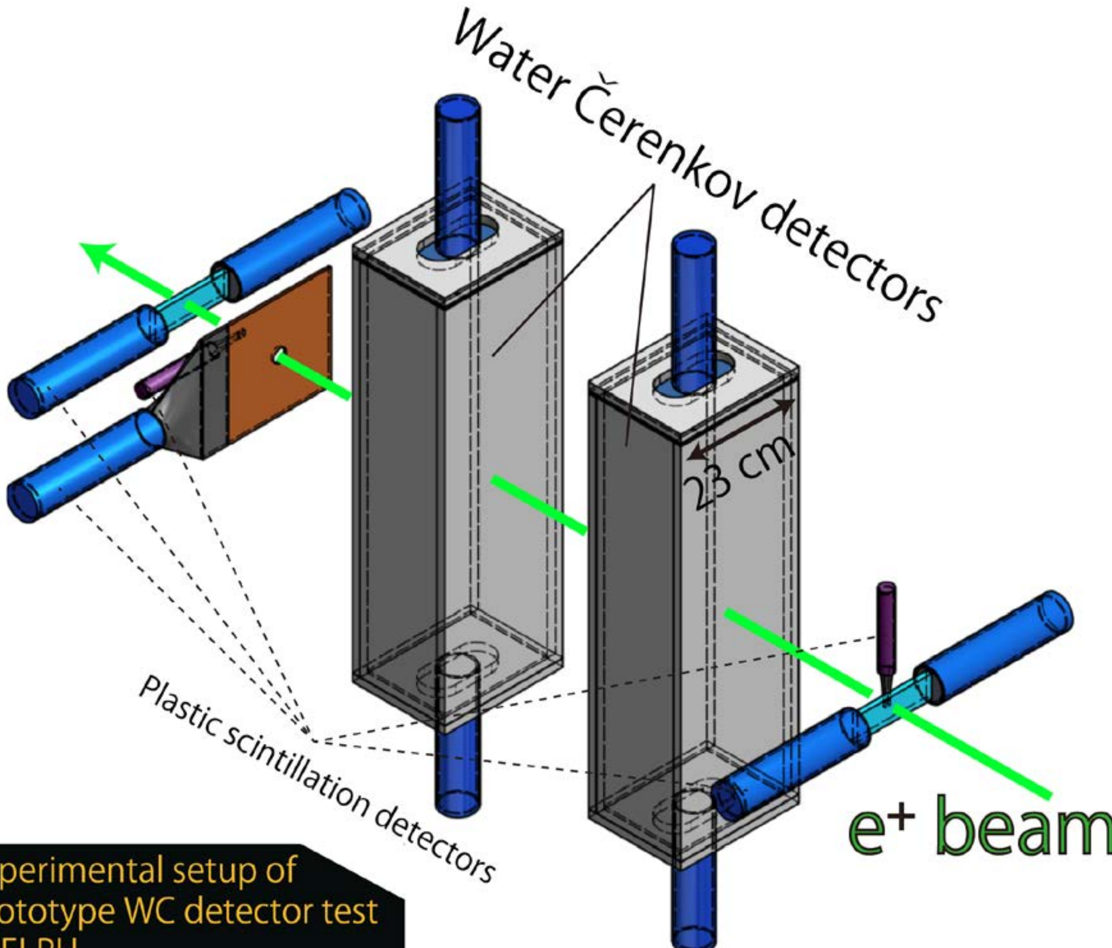


TOF de

Detectors are under preparation

Drift chambers
for particle tracking

NEW Water Cerenkov Detector



Experimental setup of prototype WC detector test at ELPH

WC →

p-K^+ separation

(on-line / off-line)

Prototype test @ ELPH 2014/6/29-30

Details will be given by

K. Takenaka

Summary

J-PARC E05 will be performed
to confirm the existence of $^{11}\mathrm{B} + \Xi^-$ bound state ($^{12}_{\Xi}\mathrm{Be}$).

① FWHM = 5 MeV, yield = 140 [/month] (*PHASE-0*, SKS)

➔ Bound state as a bump structure.

② FWHM = 2.5 MeV, yield = 190 [/month] (S-2S)

➔ Structures would be measured as peaks.

Collaborators of J-PARC E05 experiment

- **Kyoto University, Japan:** Tomofumi Nagae (spokesperson), Hiroyuki Ekawa, Hiroyuki Fujioka, Yudai Ichikawa, Toshiyuki Gogami, Shunsuke Kanatsuki, Megumi Naruki, Kouhei Takenaka
- **KEK, Japan**: Toshiyuki Takahashi, Kanae Aoki, Masaharu Ieiri, Yoshinori Sato, Shin'ya Sawada, Michiko Sekimoto, Hitoshi Takahashi, Akihisa Toyoda
- **JAEA, Japan**: Kenichi Imai, Hitoshi Sugimura
- **Tohoku University, Japan**: Yu Fujii, Takatsugu Ishikawa, Hiroki Kanda, Masashi Kanda, Takeshi Koike, Yue Ma, Kazushige Maeda, Satoshi Nakamura, Hirokazu Tamura, Mifuyu Ukai, Hirohito Yamazaki
- **RIKEN, Japan**: Kenta Itabashi
- **Gifu University, Japan**: Kazuma Nakazawa,
- **Osaka University, Japan**: Shuhei Ajimura, Toshihiko Hiraiwa, Tadafumi Kishimoto, Manabu Moritsu, Hiroyuki Noumi, Atsushi Sakaguchi, Koutarou Shiratori, Tomonori Takahashi Atsushi Tokiyasu, Yu Yosoi
- **JINR Dubna, Russia:** Petr Evtoukhovitch, Vladimir Kalinnikov, W. Kallies, N. Kravchuk, A. Moiseenko, Valentine Samoilov, Zviadi Tsamalaidze, O. Zaimidoroga
- **ITEP, Russia**: A.P. Krutenkova, V.V. Kulikov
- **Seoul National University, Korea:** Kiyoshi Tanida, Ryuta Kiuchi, Kim Mijung
- **Korea University, Korea:** JungKeun Ahn
- **Pusan, Korea:** B.H. Choi
- **CIAE, China:** Y.Y. Fu, C. Li, X. Li, C.Zhou, S.H.Zhou, L.H.Zhu
- **Broohaven National Laboratory:** R.E. Chrien
- **University of New-Mexico:** B. Bassalleck, Yuncheng HAN
- **Florida,International University:** Jeorg Reinhold
- **Hampton University/J-Lab:** L. Tang
- **Torino(Universit), Italy:** B. Luigi, S. Marcello, S. Bufalino
- **Torino(INFN), Italy:** M. Ombretta, E. Botta, M. Agnelllo, A. Feliciello
- **Saha Institute:** Chhanda Samanta
- **BARC, India:** Bidyut Jyoti Roy, Harphool Kumawat

Thank you for your attention !!

http://www-nh.scphys.kyoto-u.ac.jp/Activity/jparc/e05/

Backup

Expected yield with S-2S

Assumptions

- $\Omega = 0.055$ sr
- 3 g/cm^2 ^{12}C target
- 9×10^5 K^- /spill
- 4 seconds beam cycle
- K^+ survival ratio: 0.4
- Efficiency: 0.7

$$N_t = \frac{3.0\times6.022\times10^{23}}{12\times1.0\times10^4} \text{ [/m}^2\text{]}$$

$$N_{\text{beam}} = 9 \times 10^5 \times \frac{3600}{4} \times 24 \times 7 \times 4 \text{ [/month]}$$

$$\varepsilon = 0.6 \times 0.7 \text{ (Total efficiency)}$$

Then, sensitivity is

$$S = 10^{-9} \times 10^{28} \times \Omega \times Nt \times Nbeam \times \varepsilon$$

$$= 1.26 \text{ [/ (nb/sr) / month].}$$

$$\frac{d\sigma}{d\Omega} = 89 \pm 14 \text{ nb/sr} \cdots (\theta < 8^\circ)^{[1]}$$

112 events [/month] $(-20 < -B_\Xi < 0 \text{ MeV})$

[1] P.Khaustov *et al.*, *PRC* **61** (2000) 054603

Missing mass resolutions with ^{12}C target (3, 5 and 8 g/cm^2)

Missing mass resolutions with ^{12}C target (3, 5, 8 g/cm^2)

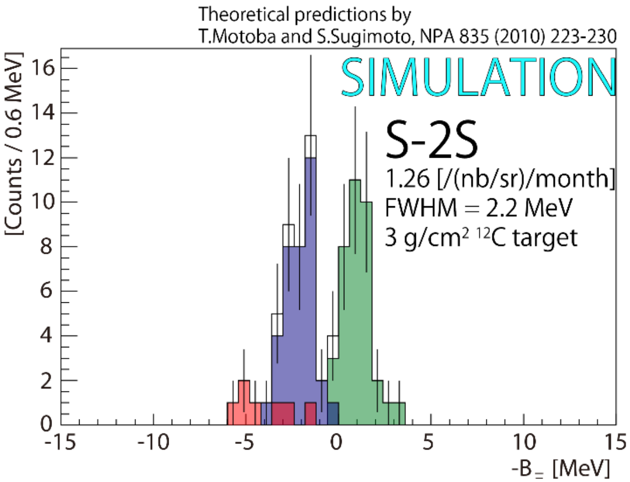
- 3 g/cm^2 ^{12}C
  SKSM: FWHM = 3.99874 +/- 0.0501584 MeV
  S-2S: FWHM = 2.1545 +/- 0.00934945 MeV
- 5 g/cm^2 ^{12}C
  SKSM: FWHM = 4.25089 +/- 0.0613503 MeV
  S-2S: FWHM = 2.49876 +/- 0.0130645 MeV
- 8 g/cm^2 ^{12}C
  SKSM: FWHM = 4.78436 +/- 0.0931848 MeV
  S-2S: FWHM = 3.0576 +/- 0.0240659 MeV

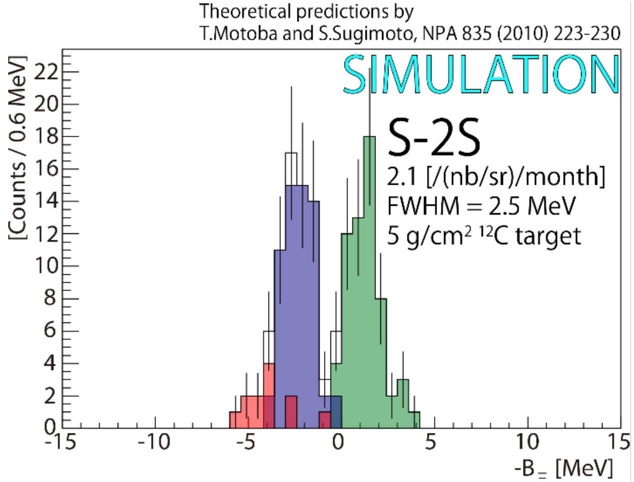
~~~~~~~~~~~~~~~
Fitting range = (-2.5,1.3); //MeV
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

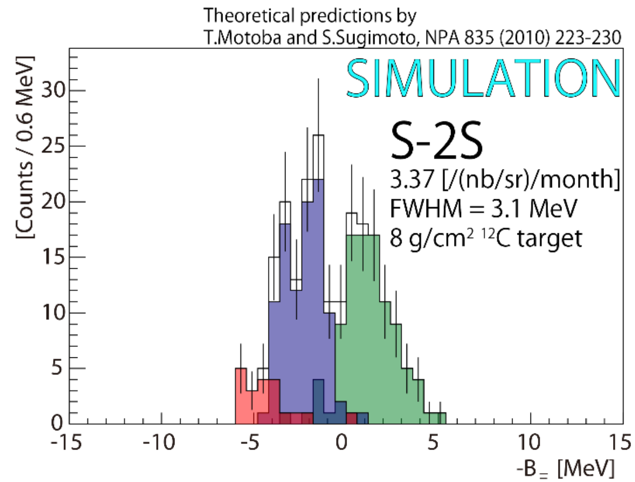
~~~~~~~~~~~~~~~
Assumed Momentum/Angular Resolutions:
dp/p (K- Beam): 10.0E-4
dp/p (S-2S): 5.0E-4
dp/p (SKSM): 27.0E-4
d_theta: 2 mrad
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

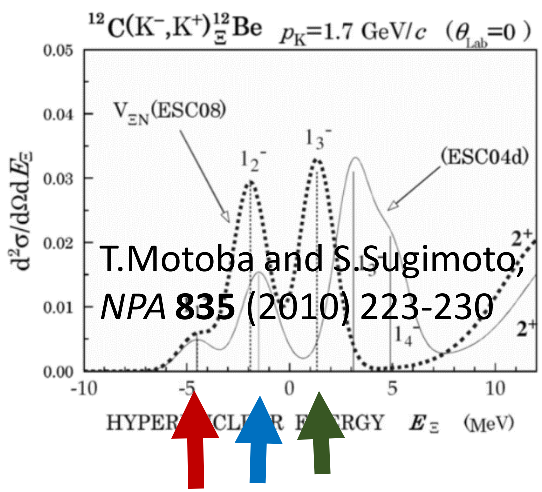
hyperdragon3: /home/dragon/POSI2/analysis/root/elos/
By Toshi Gogami on 22Sep2014

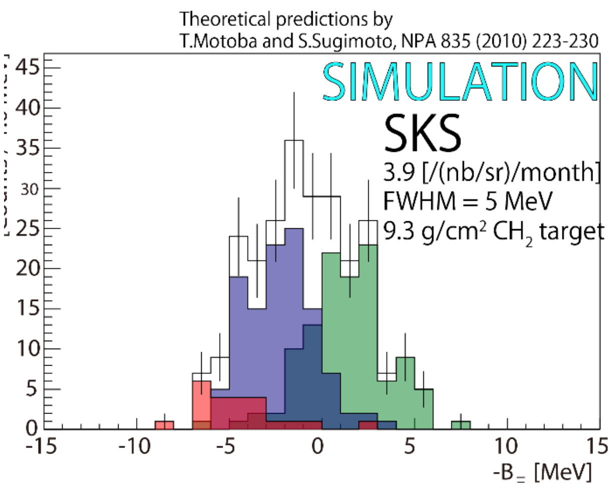
Figures (ESC08)

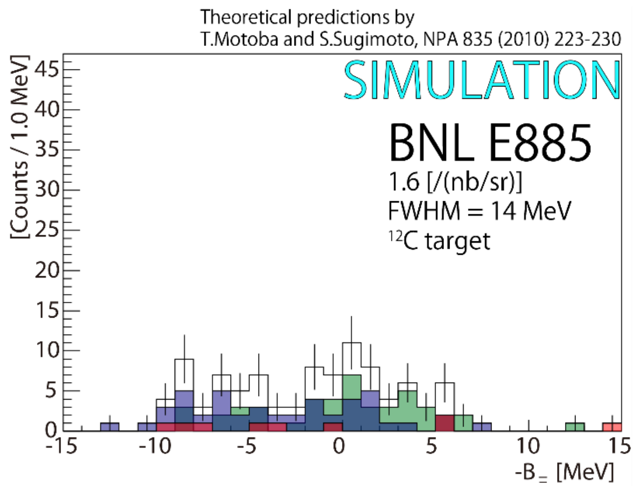












Missing mass resolution

Toshi Gogami

28Aug2014

Assumptions

The natural width was not taken into account.
dE resolution was not considered.
Effect of the inverse transfer matrix is zero.
Assumed resolutions are the following:

K^-: $\frac{\Delta p}{p} = 1.0 \times 10^{-3}$,

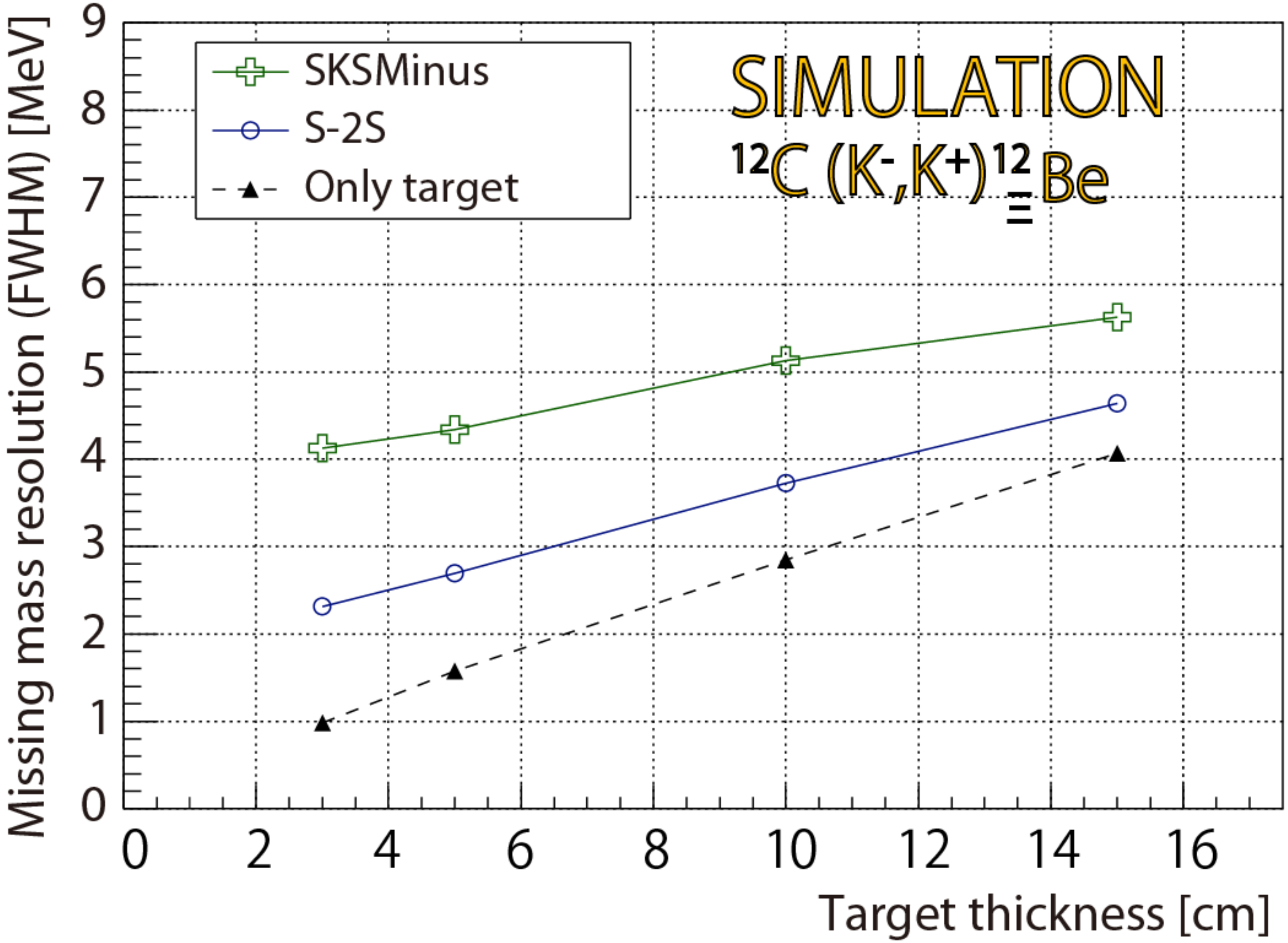
K^+: $\frac{\Delta p}{p} = 5.0 \times 10^{-4}$ (S-2S), 2.7×10^{-3} (SKSMinus),

$\Delta\vartheta = 2.0\ mrad$.

Simulation results

		Results [MeV]				Remarks
Target [g/cm^2]		-	-	-	CH_2 (2.79/4.65/9.30/13.95)	
Reaction		$p(K^-,K^+)\Xi$	$^{7}Li(K^-,K^+)^{7}_{\Xi}H$	$^{10}B(K^-,K^+)^{10}_{\Xi}Li$	$^{12}C(K^-,K^+)^{12}_{\Xi}Be$	
Intrinsic Resolution [MeV]	p_{K-}	1.16	1.62	1.66	1.67	Calculations for S-2S
	p_{K+}	-0.38	-0.57	-0.58	-0.59	
	θ_K	-0.35	-0.12	-0.09	-0.07	
	Total	1.27	1.72	1.76	1.77	Quadratic sum
Simulation w/o target (S-2S)		1.29	1.73	1.77	1.78	
Simulation w/o target (SKSMinus)		2	2.9	3	3	
Simulation w/ target (S-2S)					2.3 / 2.7 / 3.7 / 4.6	
Simulation w/ target (SKSMinus)					4.1 / 4.3 / 5.1 / 5.6	
Simulation Only target					1.0 / 1.6 / 2.8 / 4.1	

Simulation results



Each term contribution to the missing mass resolution

Missing mass, M_H

$$M_H^2 = (E_1 + m_t - E_2)^2 - (\vec{p_1} - \vec{p_2})^2$$

$$\begin{cases} \left(\frac{\partial M_H}{\partial p_1}\right)\Delta p_1 = \frac{1}{M_H}\left[\frac{p_1}{E_1}(m_t - E_2) + p_2 \cos\theta\right]\Delta p_1 \\ \left(\frac{\partial M_H}{\partial p_2}\right)\Delta p_2 = \frac{1}{M_H}\left[-\frac{p_2}{E_2}(m_t + E_1) + p_1 \cos\theta\right]\Delta p_2 \\ \left(\frac{\partial M_H}{\partial \theta}\right)\Delta\theta = -\frac{p_1 p_2}{M_H}\sin\theta \cdot \Delta\theta \end{cases}$$

(Missing mass に対する各項の寄与)

Calculated event by event
→ Mean values will be shown in results.

Each term contribution to the missing mass resolution

Missing mass, M_H

$$M_H^2 = (E_1 + m_t - E_2)^2 - (\vec{p_1} - \vec{p_2})^2$$

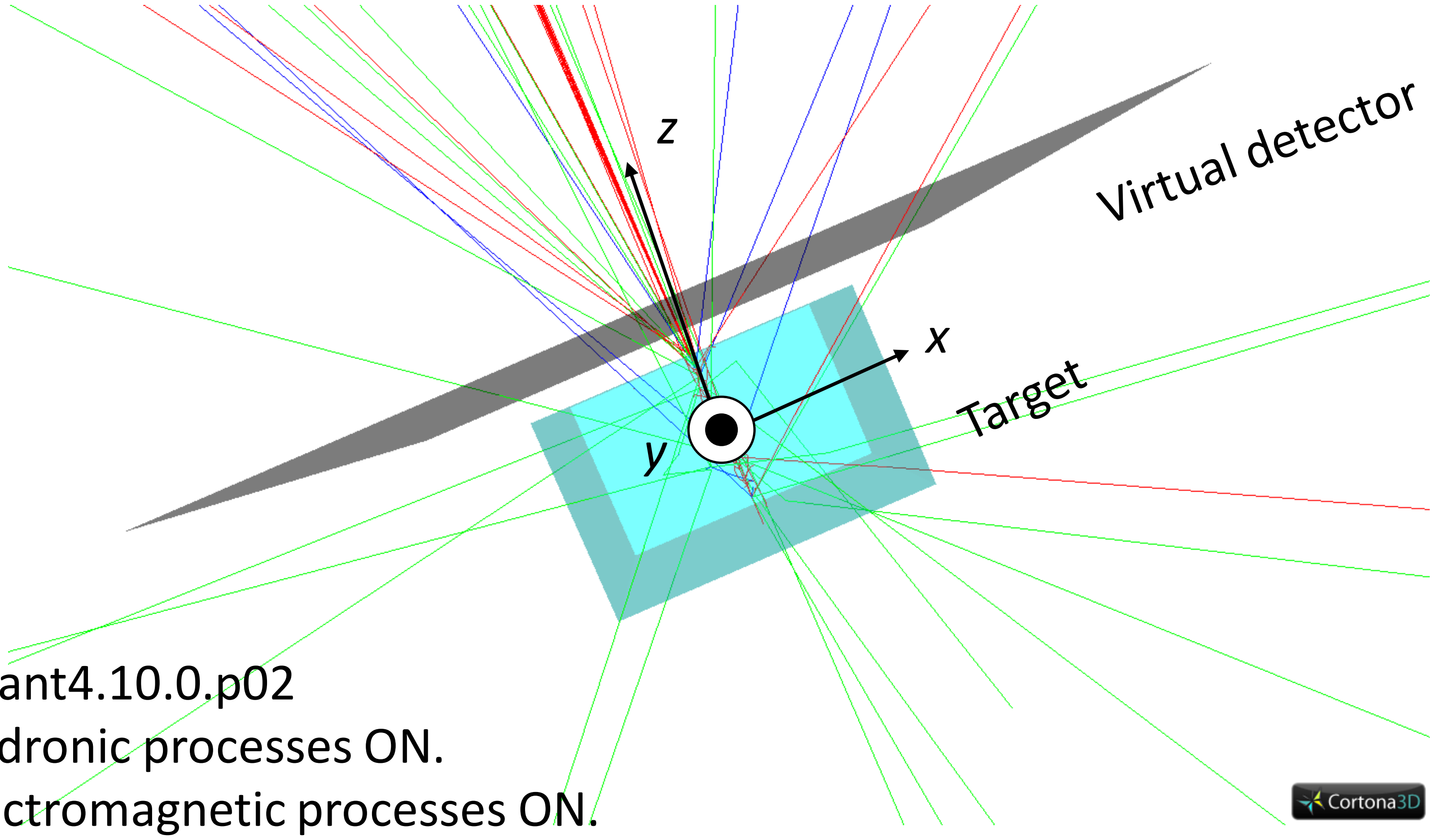
$$\begin{cases} \left(\dfrac{\partial M_H}{\partial p_1}\right)\Delta p_1 = \dfrac{1}{M_H}\left[\dfrac{p_1}{E_1}(m_t - E_2) + p_2 \cos\theta\right]\Delta p_1 \\ \left(\dfrac{\partial M_H}{\partial p_2}\right)\Delta p_2 = \dfrac{1}{M_H}\left[-\dfrac{p_2}{E_2}(m_t + E_1) + p_1 \cos\theta\right]\Delta p_2 \\ \left(\dfrac{\partial M_H}{\partial \theta}\right)\Delta\theta = -\dfrac{p_1 p_2}{M_H}\sin\theta \cdot \Delta\theta \end{cases}$$

(Missing mass に対する各項の寄与)

Calculated event by event

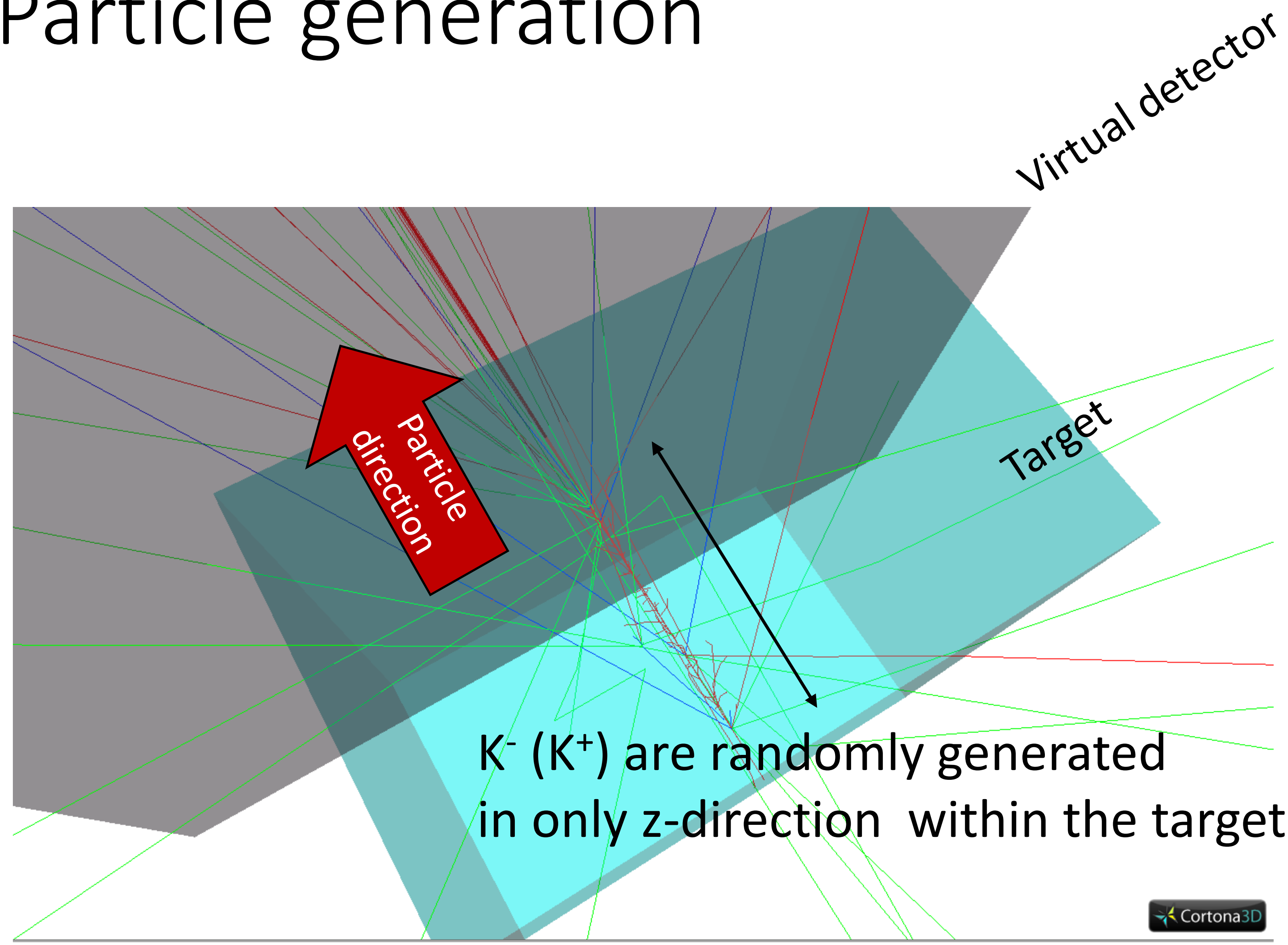
→ Mean values will be shown in results.

Monte Carlo simulation with Geant4



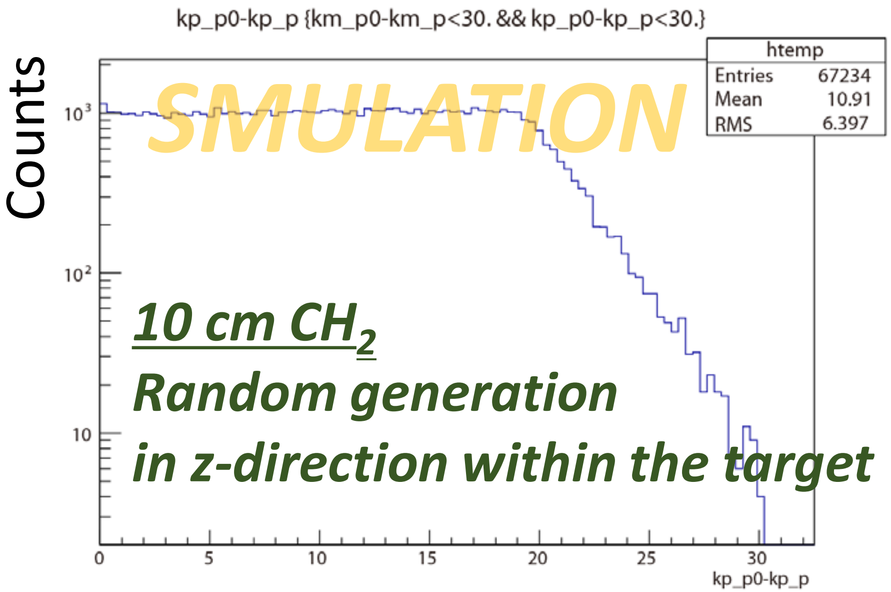
Geant4.10.0.p02
Hadronic processes ON.
Electromagnetic processes ON.

Particle generation

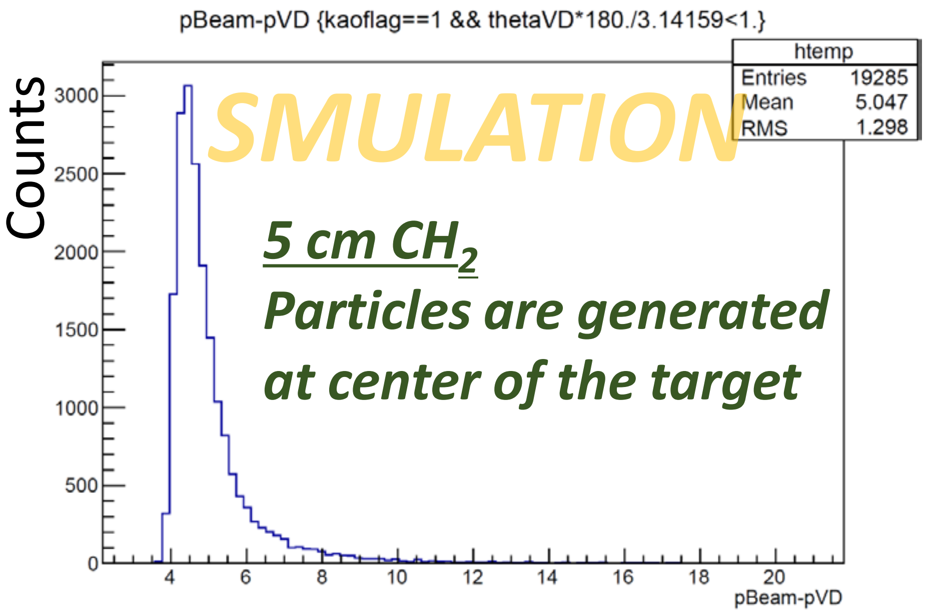


K^- (K^+) are randomly generated in only z-direction within the target

Momentum Loss in Target (Sample figures)



K$^-$ momentum loss in target [MeV]



K$^-$ momentum loss in target [MeV]

Momentum loss correlations between K^- and K^+

Data of 10 cm CH_2 target for all figures.