Observation of Lambpha (${}^{6}_{\Lambda\Lambda}\mathrm{He}$)

- "NAGARA" event -

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KEK-PS E373 collaboration

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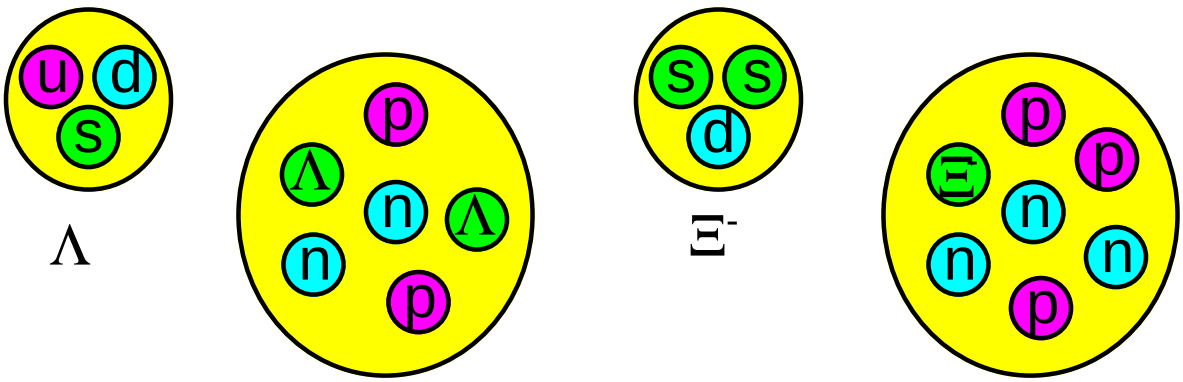
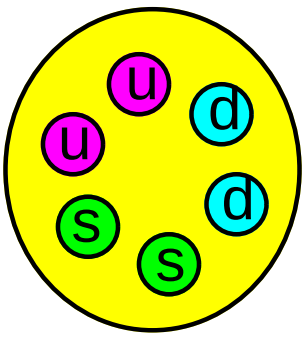
- Event Description
- Event Reconstruction
- Conclusion

KEK-PS E373
Study of Double-Strangeness Nuclei with Hybrid-Emulsion Method

Double-Hypernuclei



H dibaryon



Predicted by R. L. Jaffe
6 quarks in a "bag"
Flavor Singlet
I = 0, $J^{\pi} = 0^{+}$

Λ–Λ interaction ?

$$B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = M({}^{A-2}Z) + 2\,M(\Lambda) - M({}^{A}_{\Lambda\Lambda}Z)$$

$$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) - 2\,B_{\Lambda}({}^{A-1}_{\Lambda}Z)$$

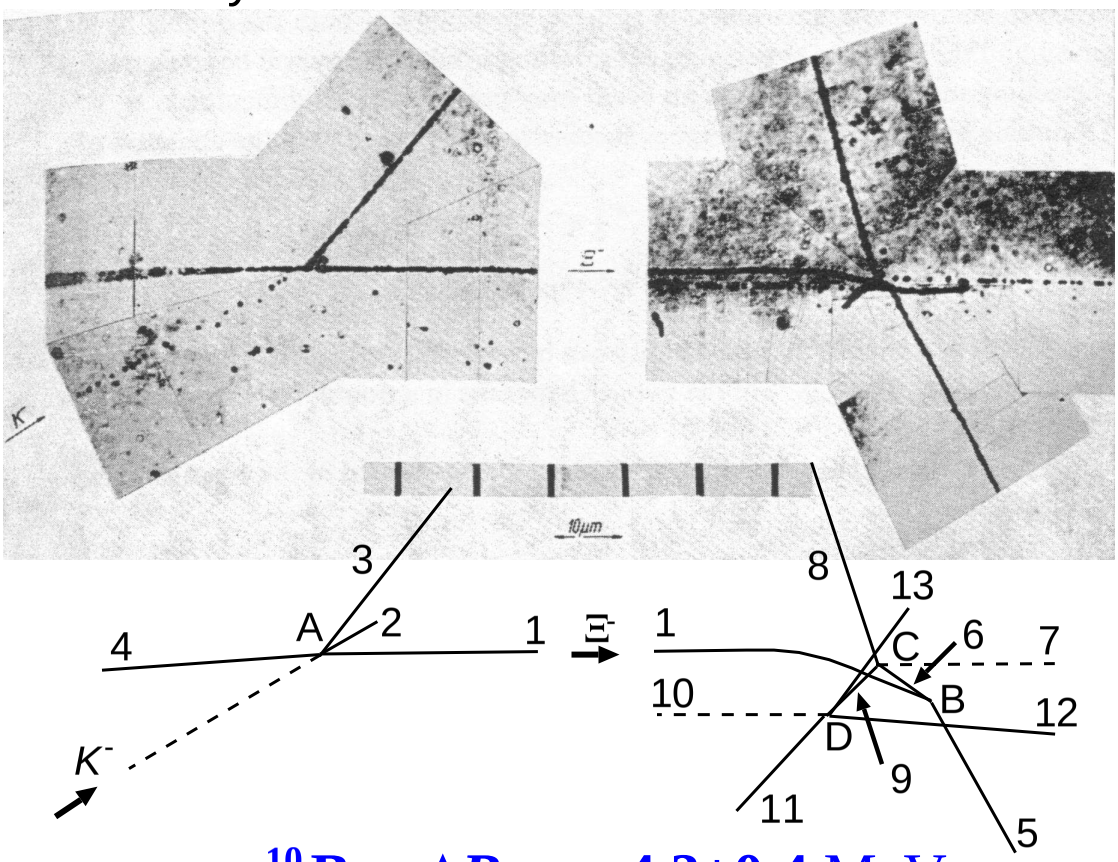
Ξ^-–N interaction ?

Existence of H dibaryon ?

$$M(H) > 2\,M(\Lambda) - B_{\Lambda\Lambda}$$

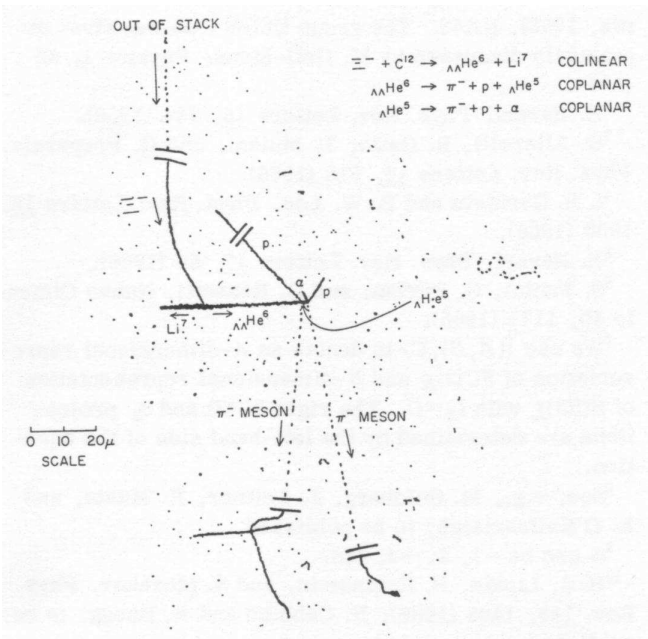
Past Experiments

M. Danysz *et al.*



$^{10}_{\Lambda\Lambda}$**Be** $\Delta B_{\Lambda\Lambda}$ **= 4.3±0.4** MeV

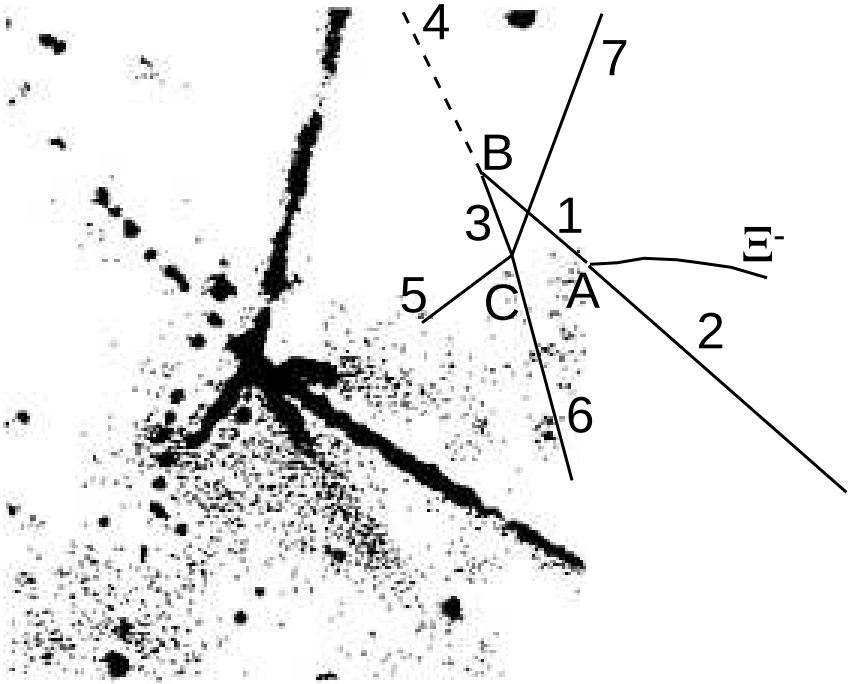
D. J. Prowse



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

$\Delta B_{\Lambda\Lambda}$ **= 4.7±0.5** MeV

KEK-PS E176

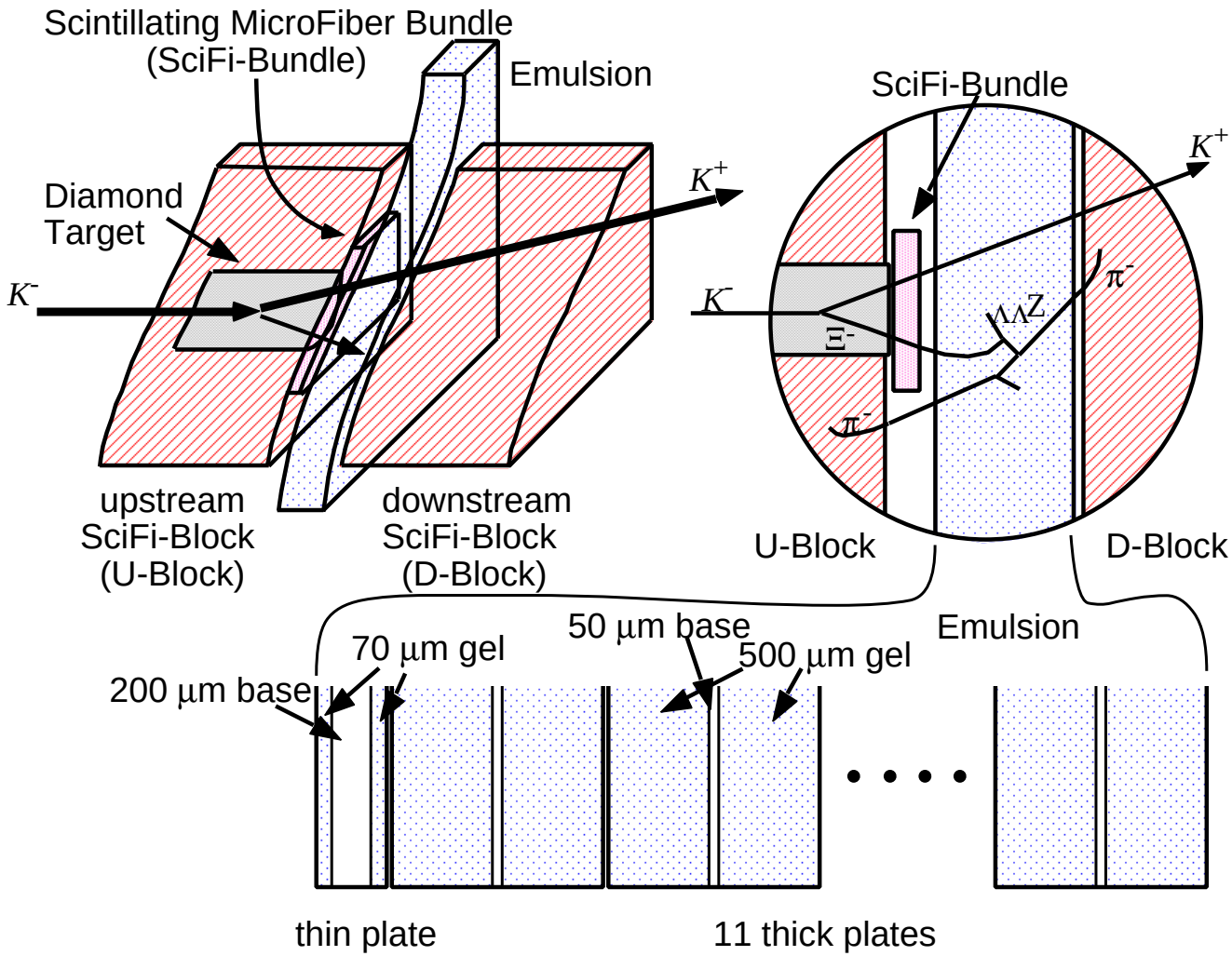


$^{10}_{\Lambda\Lambda}$**Be** $\Delta B_{\Lambda\Lambda}$ **= -4.9±0.7** MeV

or

$^{13}_{\Lambda\Lambda}$**B** $\Delta B_{\Lambda\Lambda}$ **= 4.9±0.7** MeV

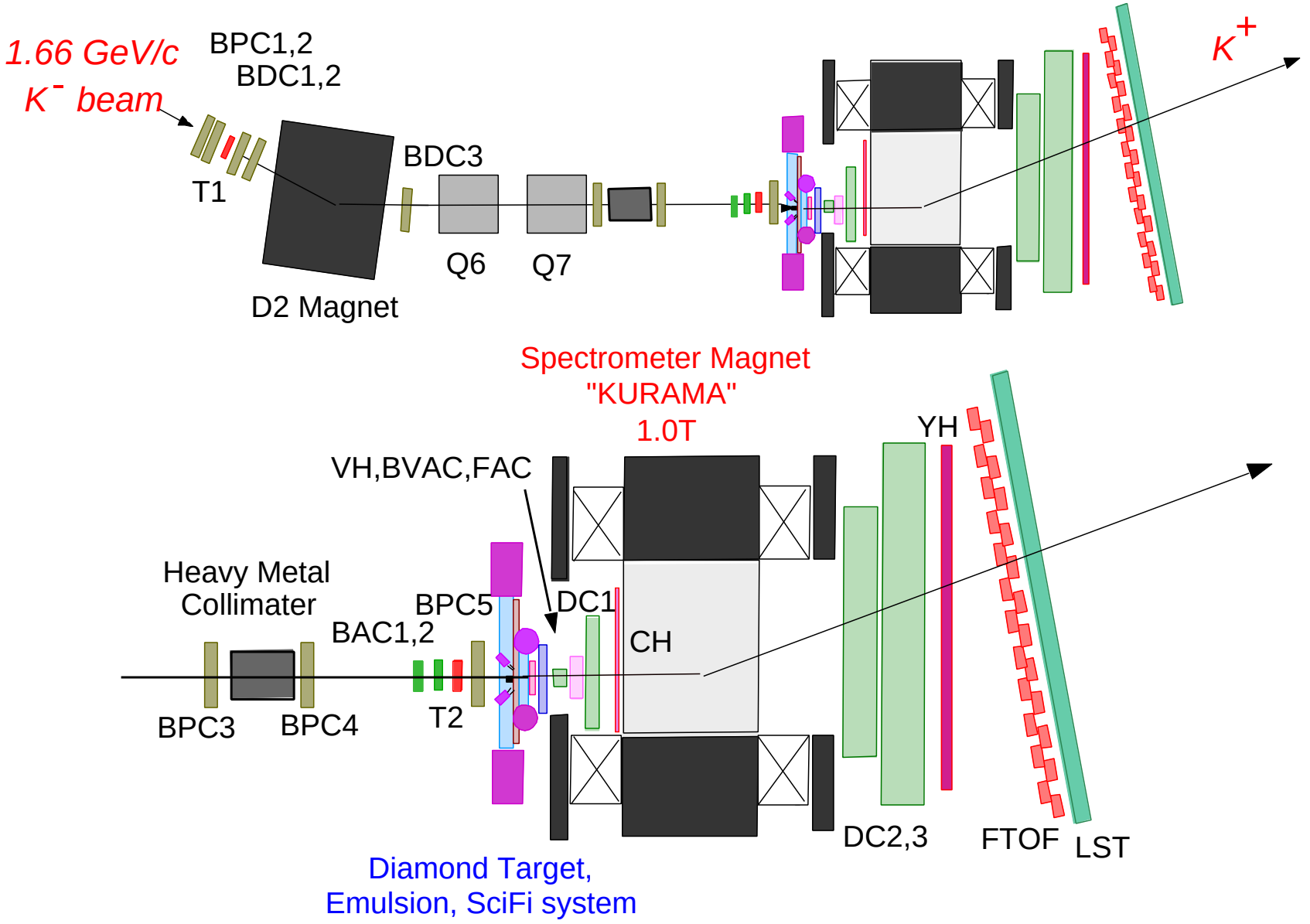
Experimental Procedure



- Ξ^-'s created via the (K^-, K^+) reactions were broght to rest in the emulsion
- The positions and angles of entry of the Ξ^-'s at the emulsion were measured with the SciFi-Bundle detector
- The (K^-, K^+) reactions were tagged by the spectrometer system

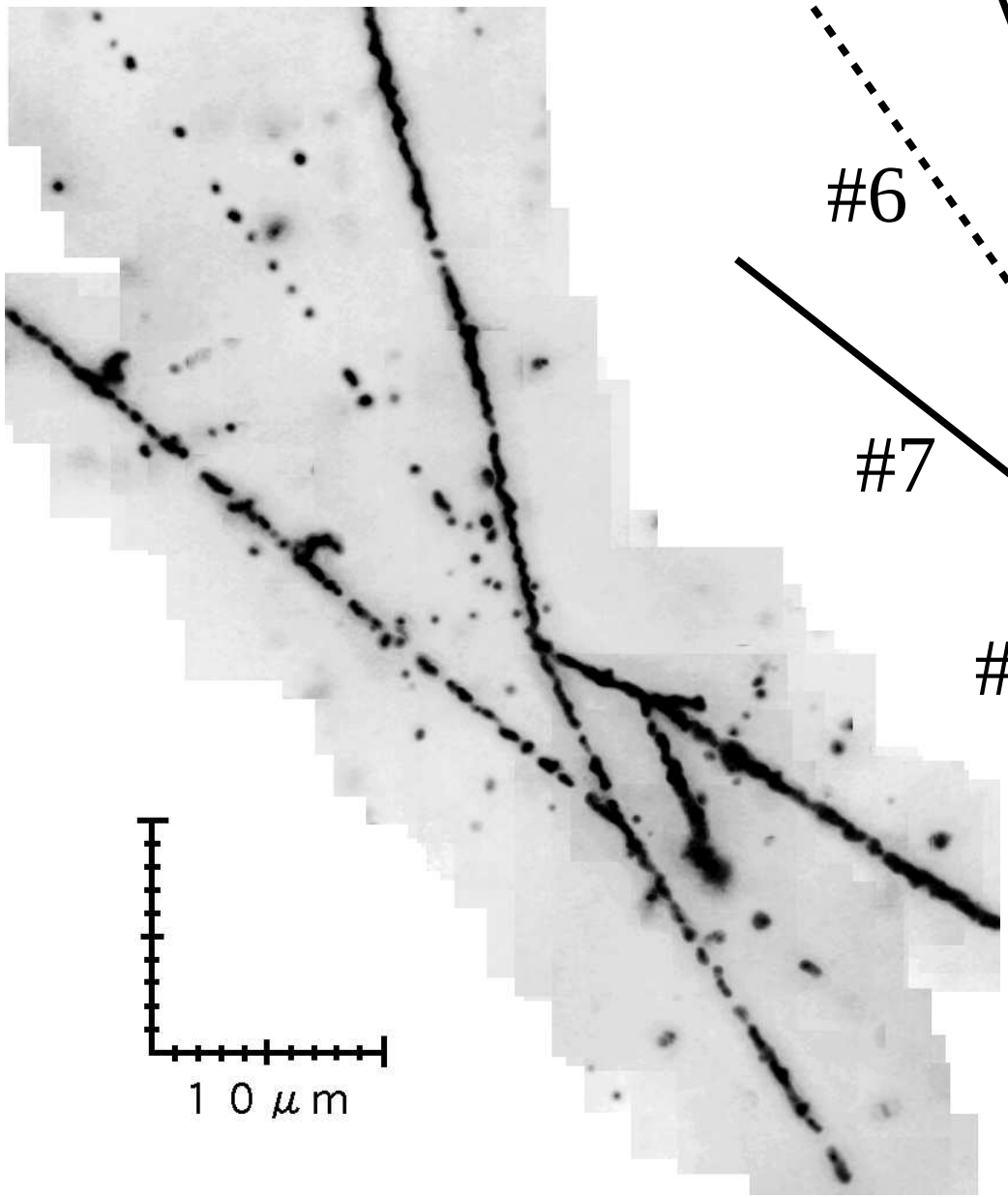
E373 Setup

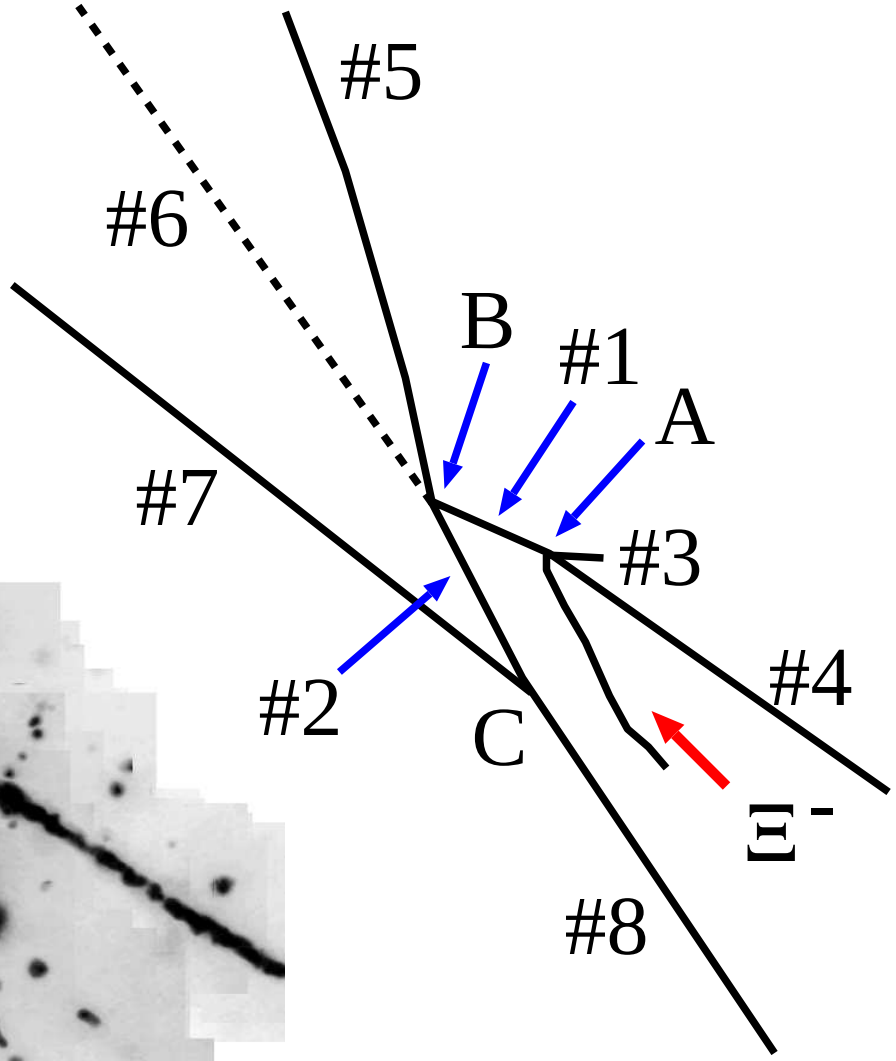
KEK-PS K2 beam line



"NAGARA" Event

found by
Y.S.Iwata (Gifu Univ.)





(Top View)

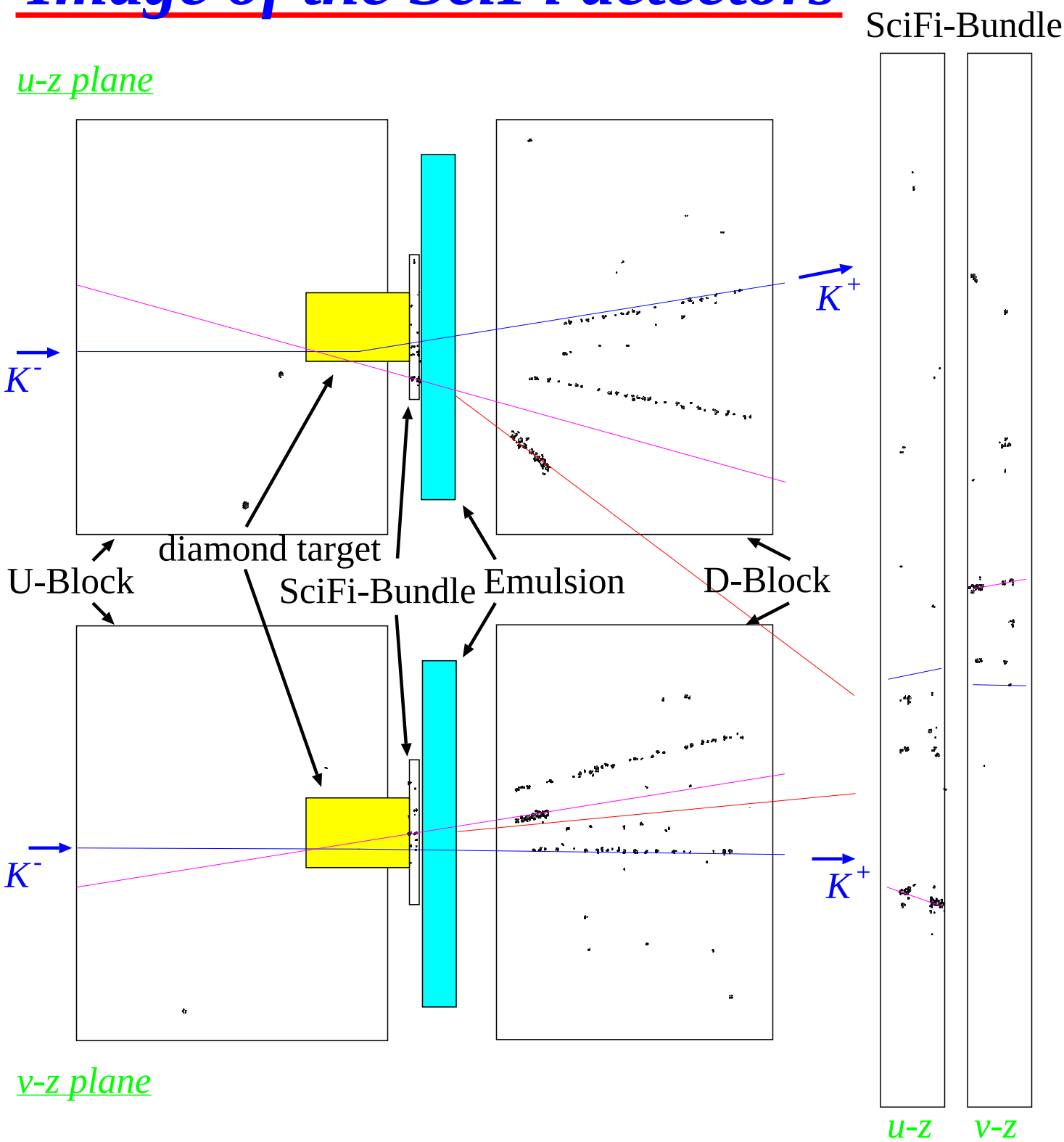
Track Data

track#5, #7 はエマルションで見えている長さのみ

point A, B 共に誤差の範囲内で coplanarity が成立

	Track #	length [μm]	θ [degree]	ϕ [degree]	
point A	#1	8.1 ± 0.3	44.9 ± 2.0	337.5 ± 1.8	double-hypernucleus
	#3	3.2 ± 0.4	57.7 ± 5.2	174.9 ± 2.9	
	#4	88.3 ± 0.5	156.2 ± 0.5	143.0 ± 1.0	
point B	#2	9.1 ± 0.3	77.7 ± 1.6	115.9 ± 0.8	single-hypernucleus
	#5	82.1 ± 0.6	122.8 ± 1.0	284.2 ± 0.7	stopped in base
	#6	13697	81.1 ± 0.8	305.5 ± 0.1	π^-
point C	#7	742.6 ± 0.6	138.5 ± 0.2	322.1 ± 0.3	stopped in D-Block
	#8	5868 ± 20	52.2 ± 1.2	123.7 ± 0.7	scattered before stopping

Image of the SciFi detectors



K⁻, K⁺ tracks measured by the spectrometer system

Ξ⁻ track measured by the SciFi-Bundle detector

extrapolated line using the position and angle informations of track#7 at the bottom of the emulsion stack

π^-/p separation

brightness distribution
near the stopping point in D-Block

π^-の可能性はなし

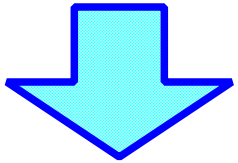
Decay point of Single-hypernucleus (point C)

- mesonic decay の場合

  Q-value が足りない

- non-mesonic decay の場合

  track#7, #8 の片方でも電荷が 2 以上あると
  Q-value が足りない



Λ 核 (track#2) は $_{\Lambda}$He

Decay point of Double-hypernucleus (point B)

娘にΛHeを含むΛΛ核の崩壊モード

$E_{visible}$ 飛程から求めた荷電粒子の運動エネルギーの和
p_{sum} 荷電粒子の運動量の和
E_{total} p_{sum} から求めた中性粒子の運動エネルギーと$E_{visible}$ の和

$$B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = M({}^{A-2}Z) + 2\,M(\Lambda) - M({}^{A}_{\Lambda\Lambda}Z)$$
$$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) - 2\,B_{\Lambda}({}^{A-1}_{\Lambda}Z)$$

double-hyp.	#2	#5	#6		$E_{visible}$ [MeV]	p_{sum} [MeV/c]	E_{total} [MeV]	$B_{\Lambda\Lambda}$ [MeV]	$\Delta B_{\Lambda\Lambda}$ [MeV]
${}^{5}_{\Lambda\Lambda}$He	${}^{4}_{\Lambda}$He	p	π^-		33.1 ± 0.5	11.0 ± 6.4	33.1 ± 0.5	7.1 ± 0.5	2.4 ± 0.5
${}^{6}_{\Lambda\Lambda}$He	${}^{5}_{\Lambda}$He	p	π^-		33.2 ± 0.5	2.1 ± 7.3	34.1 ± 0.6	6.9 ± 0.6	0.6 ± 0.6
${}^{7}_{\Lambda\Lambda}$He	${}^{5}_{\Lambda}$He	p	π^-	$1n$	33.2 ± 0.5	10.9 ± 5.2	> 33.2	< 8.6	< 0.3
${}^{7}_{\Lambda\Lambda}$He	${}^{6}_{\Lambda}$He	p	π^-		33.2 ± 0.5	4.6 ± 7.6	35.7 ± 0.7	6.3 ± 0.7	-2.0 ± 0.7
${}^{8}_{\Lambda\Lambda}$He	${}^{5}_{\Lambda}$He	p	π^-	$2n$	33.2 ± 0.5	10.9 ± 5.2	> 33.2	< 6.8	< -7.2
${}^{8}_{\Lambda\Lambda}$He	${}^{5}_{\Lambda}$He	d	π^-	$1n$	34.1 ± 0.5	36.0 ± 4.9	> 34.8	< 7.4	< -6.6
${}^{8}_{\Lambda\Lambda}$He	${}^{6}_{\Lambda}$He	p	π^-	$1n$	33.2 ± 0.5	26.3 ± 5.6	> 33.6	< 6.6	< -7.4
${}^{8}_{\Lambda\Lambda}$He	${}^{7}_{\Lambda}$He	p	π^-		33.2 ± 0.5	10.0 ± 8.3	37.2 ± 0.8	7.7 ± 0.8	-6.3 ± 0.8
${}^{9}_{\Lambda\Lambda}$He	${}^{5}_{\Lambda}$He	p	π^-	$3n$	33.2 ± 0.5	10.9 ± 5.2	> 33.2	< 7.2	< -7.1
${}^{9}_{\Lambda\Lambda}$He	${}^{5}_{\Lambda}$He	d	π^-	$2n$	34.1 ± 0.5	36.0 ± 4.9	> 34.4	< 8.2	< -6.1
${}^{9}_{\Lambda\Lambda}$He	${}^{5}_{\Lambda}$He	t	π^-	$1n$	34.7 ± 0.5	74.9 ± 5.0	> 37.7	< 11.2	< -3.1
${}^{9}_{\Lambda\Lambda}$He	${}^{6}_{\Lambda}$He	p	π^-	$2n$	33.2 ± 0.5	26.3 ± 5.6	> 33.4	< 7.2	< -7.1
${}^{9}_{\Lambda\Lambda}$He	${}^{6}_{\Lambda}$He	d	π^-	$1n$	34.1 ± 0.5	21.2 ± 5.4	> 34.4	< 8.4	< -5.9
${}^{9}_{\Lambda\Lambda}$He	${}^{7}_{\Lambda}$He	p	π^-	$1n$	33.2 ± 0.5	40.1 ± 6.3	> 34.1	< 11.2	< -3.1
${}^{9}_{\Lambda\Lambda}$He	${}^{7}_{\Lambda}$He	d	π^-		34.1 ± 0.5	12.8 ± 7.9	34.1 ± 0.5	13.4 ± 0.5	-0.9 ± 0.5
${}^{9}_{\Lambda\Lambda}$He	${}^{8}_{\Lambda}$He	p	π^-		33.2 ± 0.5	14.9 ± 9.0	38.6 ± 0.8	6.4 ± 0.8	-7.9 ± 0.8

($\Delta B_{\Lambda\Lambda} > -20$ MeV)

Production point of Double-hypernucleus (point A)

エマルション中の軽い原子核 (^{12}C, ^{14}N, ^{16}O) にΞ^-が吸収された場合のΛΛ核生成モード

ΛΛ核のエネルギー，運動量は$\Delta B_{\Lambda\Lambda} = 0$ とした時の質量で計算

結果の$B_{\Lambda\Lambda}$，$\Delta B_{\Lambda\Lambda}$ の値は $B_{\Xi^-} = 0$ として計算したもの

$\Delta B_{\Lambda\Lambda}$ の誤差には Ξ^- の質量の誤差やΛ核の binding energy の誤差は入っていない

Target	#1	#3	#4		$E_{visible}$ [MeV]	p_{sum} [MeV/c]	E_{total} [MeV]	$B_{\Lambda\Lambda}$ [MeV]	$\Delta B_{\Lambda\Lambda}$ [MeV]
^{12}C	$^{\ 6}_{\Lambda\Lambda}$He	^{4}He	p	$2n$	6.8 ± 0.2	100.4 ± 8.7	> 9.5	> 16.9	> 10.6
^{12}C	$^{\ 6}_{\Lambda\Lambda}$He	^{4}He	d	$1n$	7.8 ± 0.2	54.1 ± 8.7	9.4 ± 0.5	14.5 ± 0.5	8.2 ± 0.5
^{12}C	$^{\ 6}_{\Lambda\Lambda}$He	^{4}He	t		8.5 ± 0.2	21.2 ± 8.9	8.5 ± 0.2	7.3 ± 0.2	1.1 ± 0.2
^{12}C	$^{\ 7}_{\Lambda\Lambda}$He	^{4}He	p	$1n$	6.8 ± 0.2	111.3 ± 8.9	13.4 ± 1.1	21.6 ± 1.1	13.3 ± 1.1
^{14}N	$^{\ 6}_{\Lambda\Lambda}$He	^{7}Li	p	$1n$	7.2 ± 0.3	125.5 ± 12.8	15.5 ± 1.7	24.4 ± 1.7	18.2 ± 1.7
^{14}N	$^{\ 6}_{\Lambda\Lambda}$He	^{6}Li	d	$1n$	8.2 ± 0.3	82.9 ± 12.2	11.9 ± 1.1	25.8 ± 1.1	19.6 ± 1.1
^{14}N	$^{\ 6}_{\Lambda\Lambda}$He	^{4}He	^{4}He	$1n$	16.6 ± 0.2	136.0 ± 8.8	26.4 ± 1.3	17.9 ± 1.3	11.7 ± 1.3
^{14}N	$^{\ 7}_{\Lambda\Lambda}$Li	^{4}He	t	$1n$	10.1 ± 0.2	72.1 ± 9.5	12.8 ± 0.8	26.2 ± 0.8	17.2 ± 0.8
^{14}N	$^{\ 9}_{\Lambda\Lambda}$Li	p	^{4}He	$1n$	17.4 ± 0.2	98.3 ± 9.1	22.6 ± 1.0	31.5 ± 1.0	17.9 ± 1.0
^{16}O	$^{\ 8}_{\Lambda\Lambda}$Li	^{4}He	^{4}He	$1n$	18.2 ± 0.2	62.6 ± 10.1	20.2 ± 0.7	31.1 ± 0.7	19.9 ± 0.7

($\Delta B_{\Lambda\Lambda} < 20$ MeV)

Consistency of $\Delta B_{\Lambda\Lambda}$

Target	#1	#3	#4		$\Delta B_{\Lambda\Lambda}$ [MeV]
^{12}C	$^{\ 6}_{\Lambda\Lambda}$He	^{4}He	p	$2n$	> 10.6
^{12}C	$^{\ 6}_{\Lambda\Lambda}$He	^{4}He	d	$1n$	8.2 ± 0.5
^{12}C	$^{\ 6}_{\Lambda\Lambda}$He	^{4}He	t		1.1 ± 0.2
^{12}C	$^{\ 7}_{\Lambda\Lambda}$He	^{4}He	p	$1n$	13.3 ± 1.1
^{14}N	$^{\ 6}_{\Lambda\Lambda}$He	^{7}Li	p	$1n$	18.2 ± 1.7
^{14}N	$^{\ 6}_{\Lambda\Lambda}$He	^{6}Li	d	$1n$	19.6 ± 1.1
^{14}N	$^{\ 6}_{\Lambda\Lambda}$He	^{4}He	^{4}He	$1n$	11.7 ± 1.3
^{14}N	$^{\ 7}_{\Lambda\Lambda}$Li	^{4}He	t	$1n$	17.2 ± 0.8
^{14}N	$^{\ 9}_{\Lambda\Lambda}$Li	p	^{4}He	$1n$	17.9 ± 1.0
^{16}O	$^{\ 8}_{\Lambda\Lambda}$Li	^{4}He	^{4}He	$1n$	19.9 ± 0.7

double-hyp.	#2	#5	#6		$\Delta B_{\Lambda\Lambda}$ [MeV]
$^{\ 5}_{\Lambda\Lambda}$He	$^{\ 4}_{\Lambda}$He	p	π^-		2.4 ± 0.5
$^{\ 6}_{\Lambda\Lambda}$He	$^{\ 5}_{\Lambda}$He	p	π^-		0.6 ± 0.6
$^{\ 7}_{\Lambda\Lambda}$He	$^{\ 5}_{\Lambda}$He	p	π^-	$1n$	< 0.3
$^{\ 7}_{\Lambda\Lambda}$He	$^{\ 6}_{\Lambda}$He	p	π^-		-2.0 ± 0.7
$^{\ 8}_{\Lambda\Lambda}$He	$^{\ 5}_{\Lambda}$He	p	π^-	$2n$	< -7.2
$^{\ 8}_{\Lambda\Lambda}$He	$^{\ 5}_{\Lambda}$He	d	π^-	$1n$	< -6.6
$^{\ 8}_{\Lambda\Lambda}$He	$^{\ 6}_{\Lambda}$He	p	π^-	$1n$	< -7.4
$^{\ 8}_{\Lambda\Lambda}$He	$^{\ 7}_{\Lambda}$He	p	π^-		-6.3 ± 0.8
$^{\ 9}_{\Lambda\Lambda}$He	$^{\ 5}_{\Lambda}$He	p	π^-	$3n$	< -7.1
$^{\ 9}_{\Lambda\Lambda}$He	$^{\ 5}_{\Lambda}$He	d	π^-	$2n$	< -6.1
$^{\ 9}_{\Lambda\Lambda}$He	$^{\ 5}_{\Lambda}$He	t	π^-	$1n$	< -3.1
$^{\ 9}_{\Lambda\Lambda}$He	$^{\ 6}_{\Lambda}$He	p	π^-	$2n$	< -7.1
$^{\ 9}_{\Lambda\Lambda}$He	$^{\ 6}_{\Lambda}$He	d	π^-	$1n$	< -5.9
$^{\ 9}_{\Lambda\Lambda}$He	$^{\ 7}_{\Lambda}$He	p	π^-	$1n$	< -3.1
$^{\ 9}_{\Lambda\Lambda}$He	$^{\ 7}_{\Lambda}$He	d	π^-		-0.9 ± 0.5
$^{\ 9}_{\Lambda\Lambda}$He	$^{\ 8}_{\Lambda}$He	p	π^-		-7.9 ± 0.8

Kinematic Fit

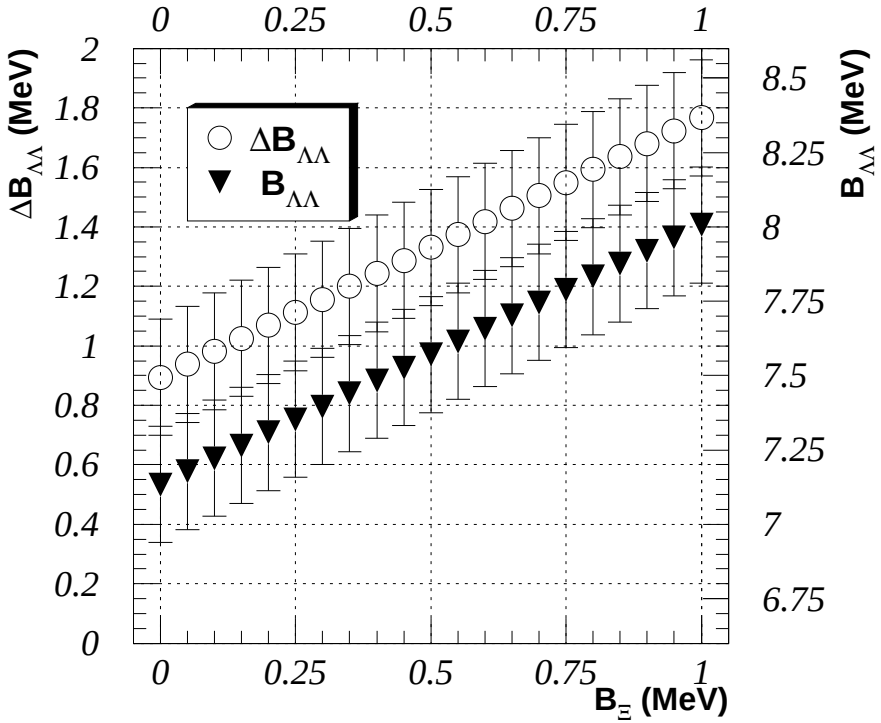
from decay vertex ***B*** :

$$\Delta B_{\Lambda\Lambda} = \mathbf{0.69 \pm 0.54}\ \text{MeV}$$

from production vertex ***A*** :

$$\Delta B_{\Lambda\Lambda} - B_{\Xi^-} = \mathbf{0.92 \pm 0.21}\ \text{MeV}$$

Taking weighted mean
of these values
for several fixed values of
the Ξ^- binding energy B_{Ξ^-}



Results :

$$B_{\Lambda\Lambda} = \mathbf{7.13 + 0.87\, B_{\Xi^-}\ (\pm 0.19)}\ \text{MeV}$$

$$\Delta B_{\Lambda\Lambda} = \mathbf{0.89 + 0.87\, B_{\Xi^-}\ (\pm 0.20)}\ \text{MeV}$$

Ξ^- *Binding Energy* B_{Ξ^-}

from the production and decay point :

$$B_{\Xi^-} = -0.24 \pm 0.58 \text{ MeV}$$

Theoretical prediction :

Ξ^- capture from an atomic 3D state in ^{12}C is dominant

$$B_{\Xi^-} = 0.13 \text{ MeV}$$

taking this value

$$B_{\Lambda\Lambda} = 7.25 \pm 0.19 \text{ MeV}$$

$$\Delta B_{\Lambda\Lambda} = 1.01 \pm 0.20 \text{ MeV}$$

Conclusion

The nuclide and the decay mode have been identified uniquely:

$$^{12}\mathbf{C} + \Xi^- \longrightarrow {}^{6}_{\Lambda\Lambda}\mathbf{He} + {}^{4}\mathbf{He} + \mathbf{t}$$

$$^{6}_{\Lambda\Lambda}\mathbf{He} \longrightarrow {}^{5}_{\Lambda}\mathbf{He} + \mathbf{p} + \pi^-$$

from the decay point ***B*** :

$$\Delta B_{\Lambda\Lambda} = \mathbf{0.69 \pm 0.54}\ \text{MeV}$$

from the production point ***A*** :

$$\Delta B_{\Lambda\Lambda} - B_{\Xi^-} = \mathbf{0.92 \pm 0.21}\ \text{MeV}$$

Conclusion

Combining the data
from both production and decay vertices :

$$B_{\Lambda\Lambda} = 7.13 + 0.87\, B_{\Xi^-} \ (\pm 0.19) \ \text{MeV}$$

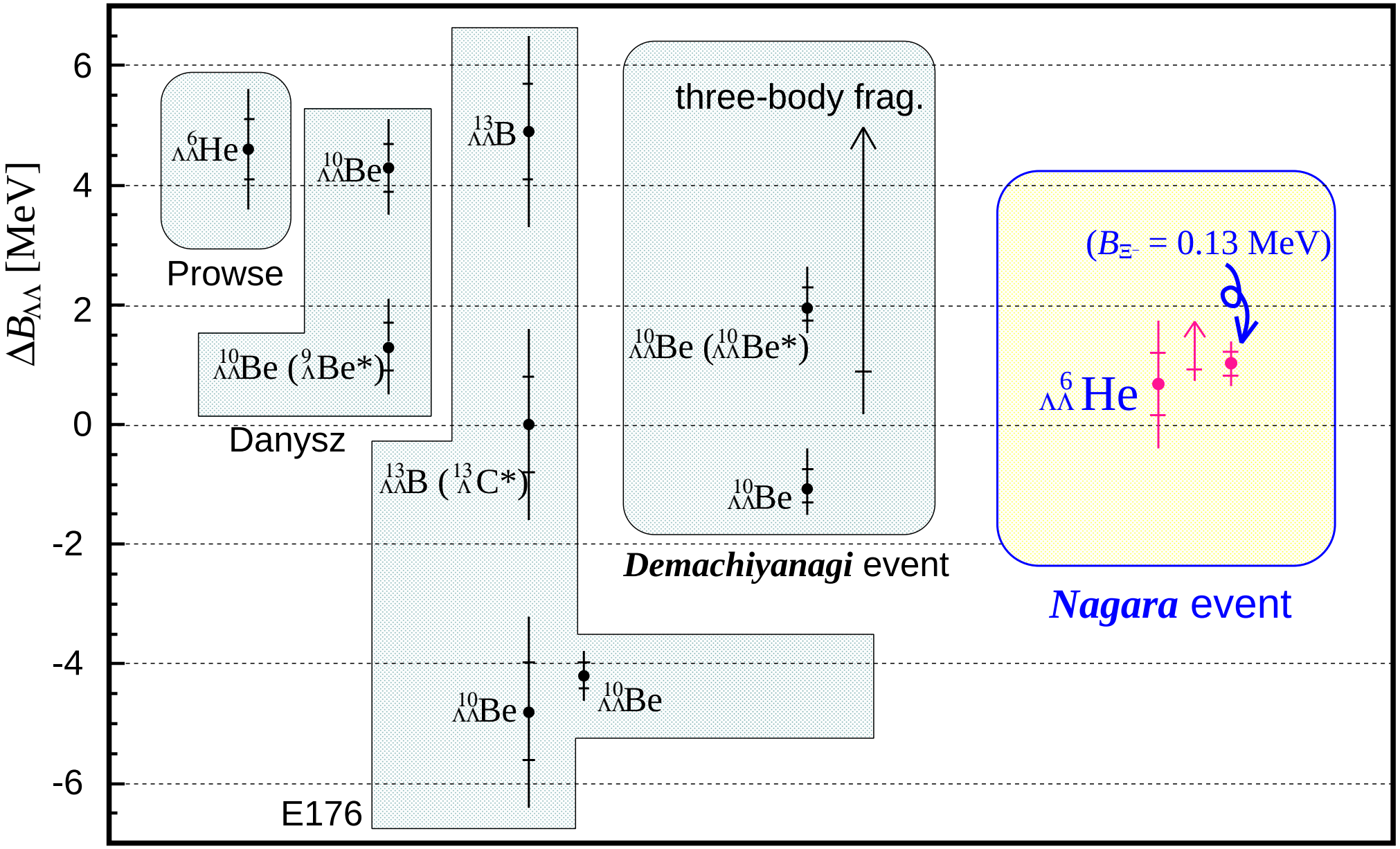
$$\Delta B_{\Lambda\Lambda} = 0.89 + 0.87\, B_{\Xi^-} \ (\pm 0.20) \ \text{MeV}$$

If it is assumed that the Ξ^- hyperon was captured from an atomic 3D state in ^{12}C :

$$B_{\Lambda\Lambda} = 7.25 \pm 0.19 \ \text{MeV}$$

$$\Delta B_{\Lambda\Lambda} = 1.01 \pm 0.20 \ \text{MeV}$$

The lower limit of the mass of the ***H*** dibaryon :

$$M_H > 2223.9 \ \text{MeV} \ (90\% \ \text{C.L.})$$

Comparison with Past Results