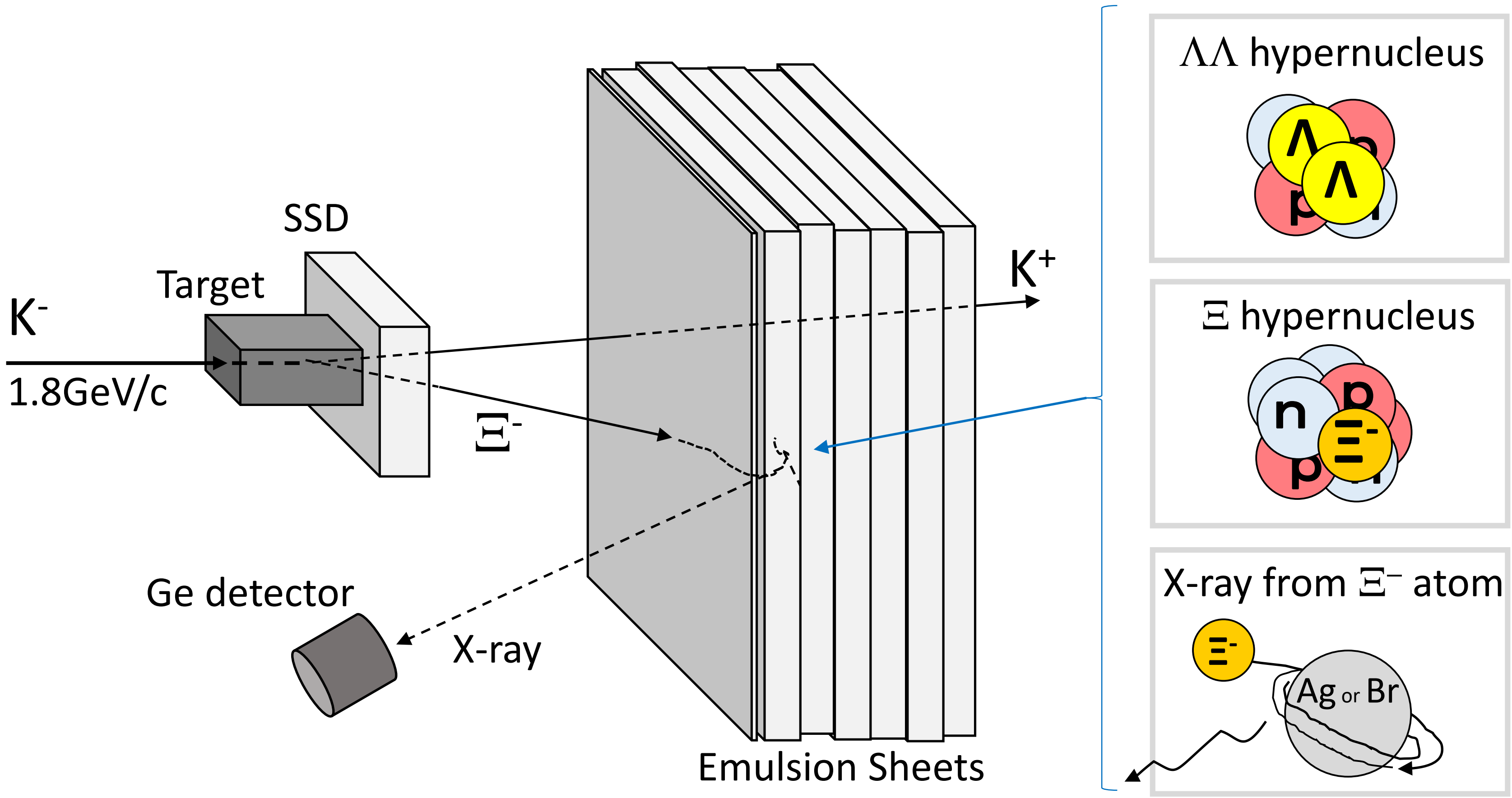
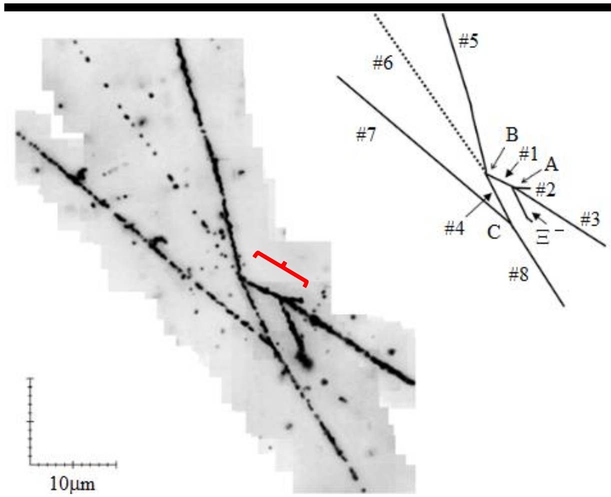
Production of Double-Lambda Hypernuclei at J-PARC



Junya Yoshida (Advanced Science Research Center, JAEA)

On behalf of J-PARC E07 Collaboration

NAGARA, ΛΛ hypernucleus (2001)

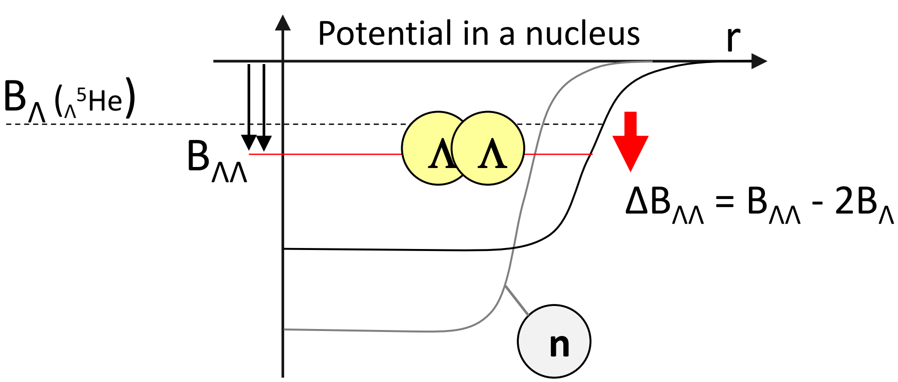


PHYSICAL REVIEW C 88, 014003 (2013)

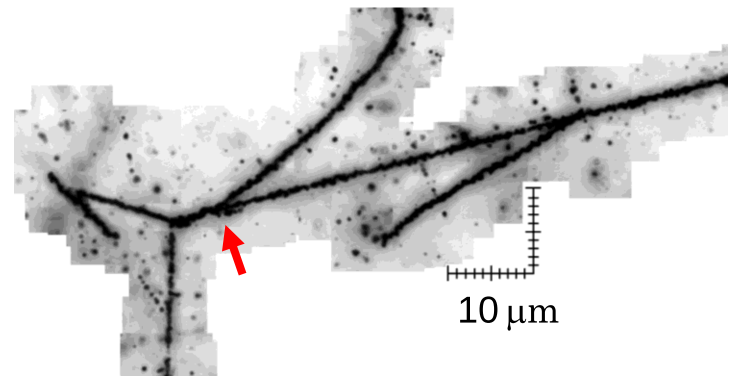
$$\Xi^- + {}^{12}C \rightarrow {}_{\Lambda\Lambda}{}^{6}He + He + t$$

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

$\Delta B_{\Lambda\Lambda}$ = 0.67 +- 0.17 MeV



KISO, Ξ hypernucleus (2013)

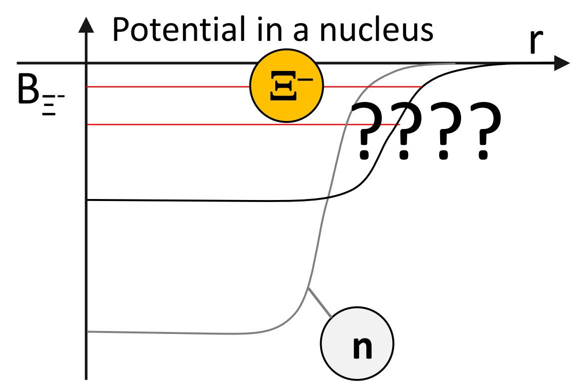


Prog. Theor. Exp. Phys. 2015, 033D02
Annu. Rev. Nucl. Part. Sci. 2018.68.131

$$\Xi^- + {}^{14}N \rightarrow {}^{15}_{\Xi}C \rightarrow {}^{10}_{\Lambda}Be + {}^{5}_{\Lambda}He$$

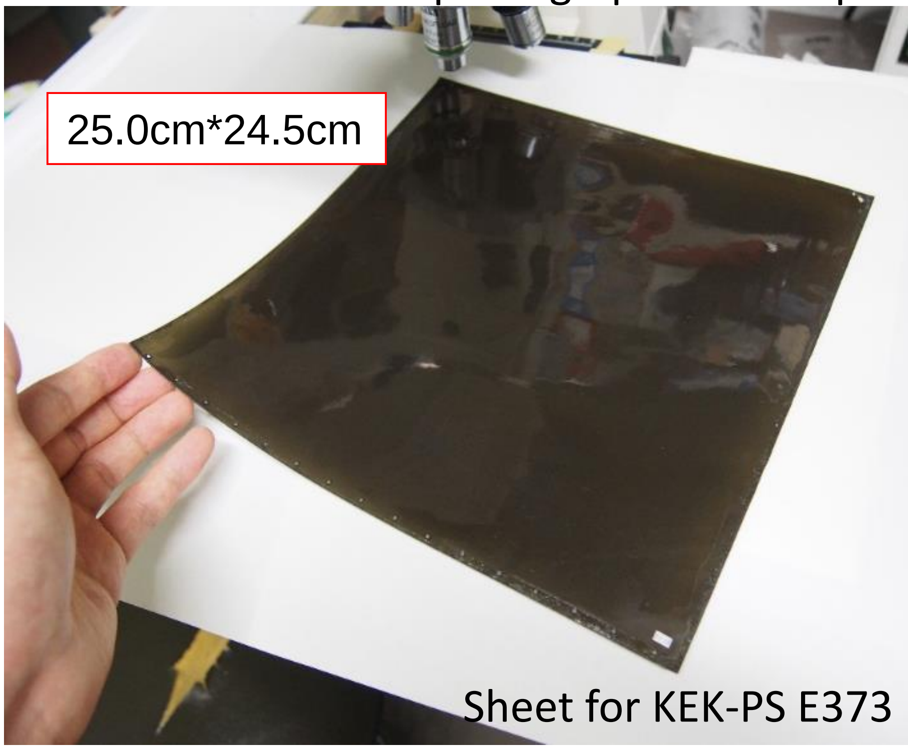
$$(\rightarrow {}^{10}_{\Lambda}Be^* + {}^{5}_{\Lambda}He)$$

B_{Ξ^-} = 1.03 +- 0.18 or 3.87 +- 0.21 MeV

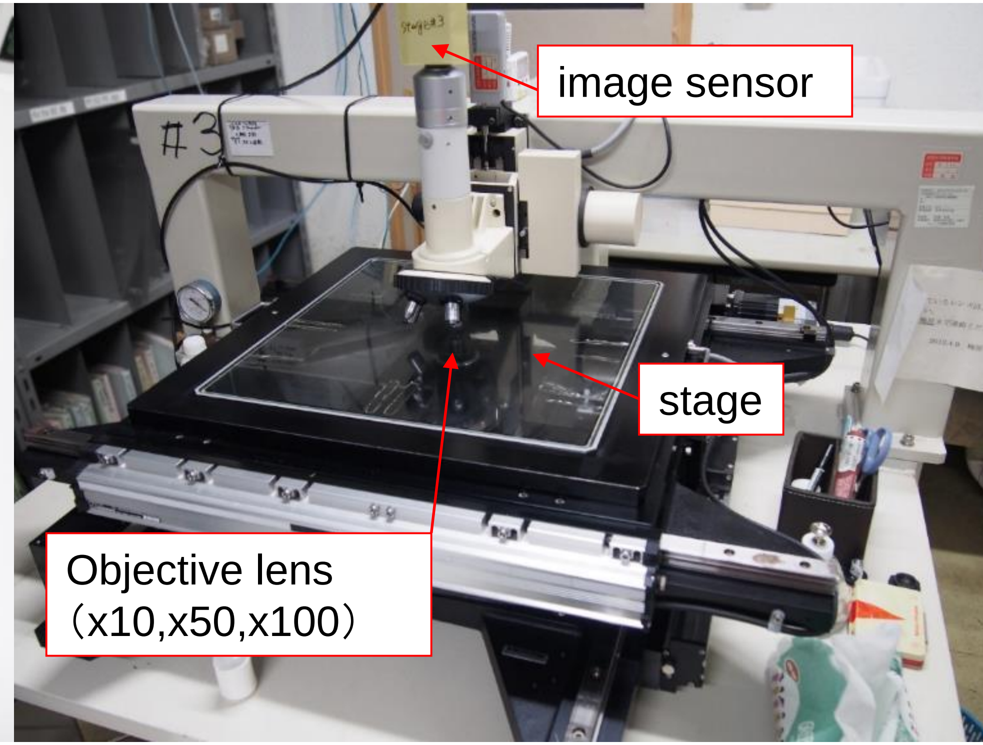


Photographic emulsion sheet for double strangeness nuclei

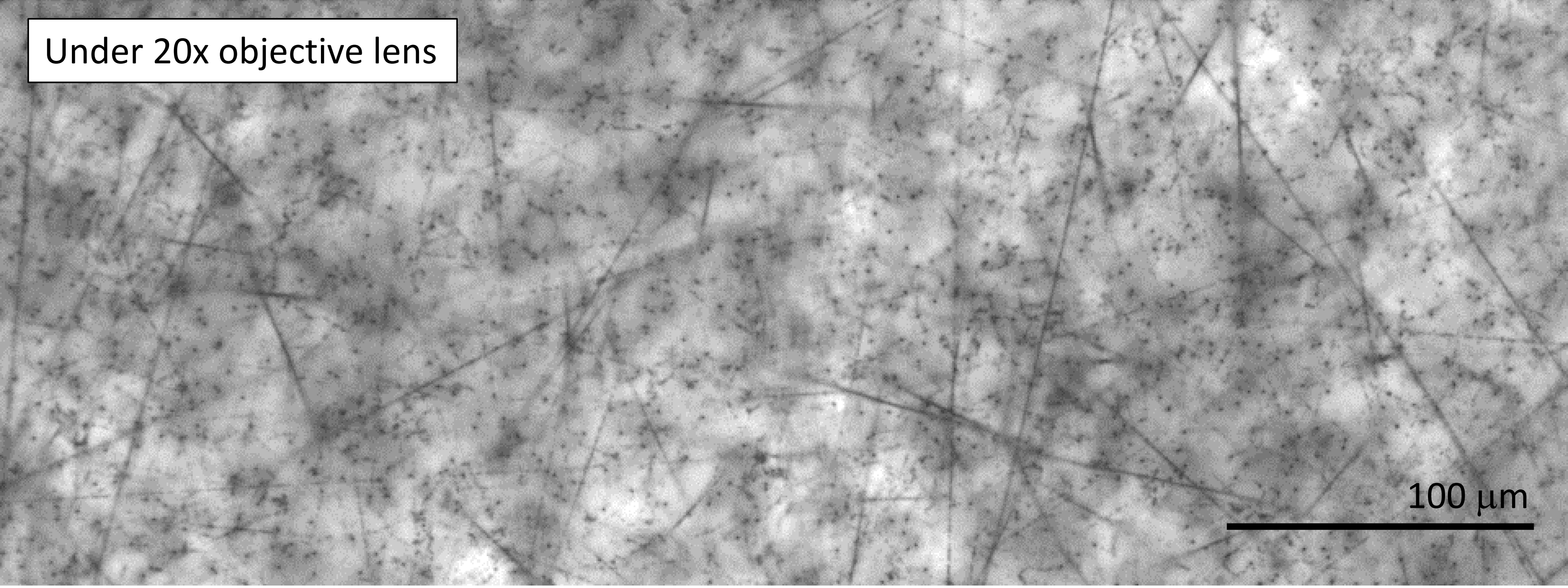
Emulsion sheet after photographic development

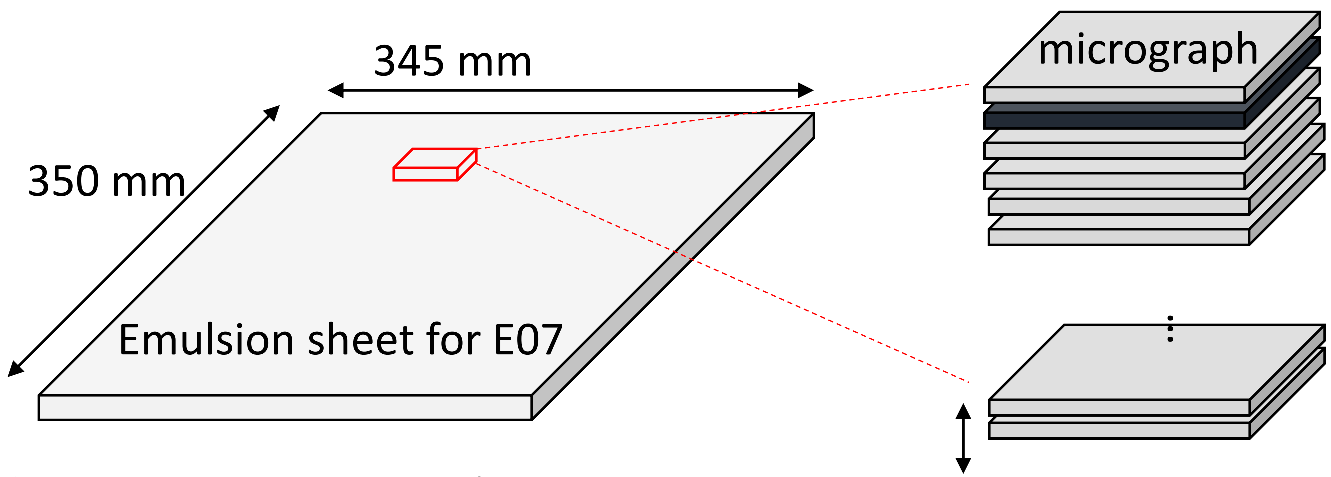


Optical microscope



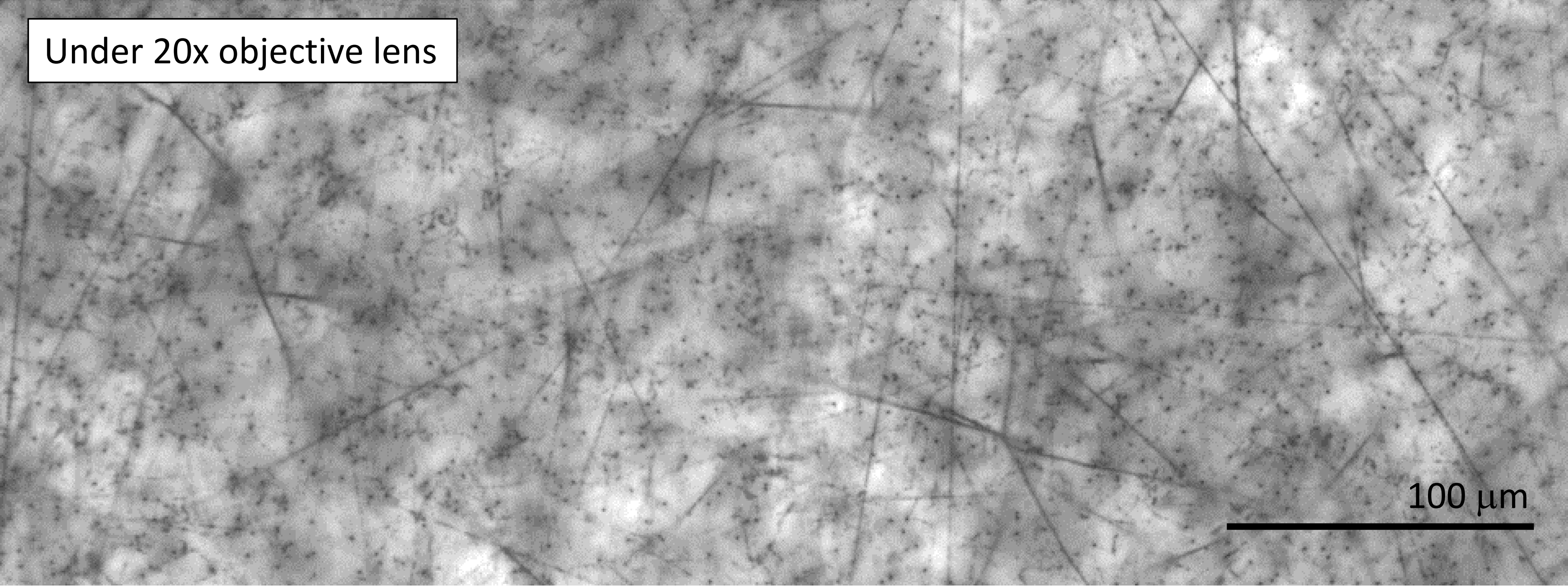
* Thick sheets: Thickness =~1 mm -> ~0.5 mm (after photographic development)
* Optical microscope with computer controlled stage and digital image sensor

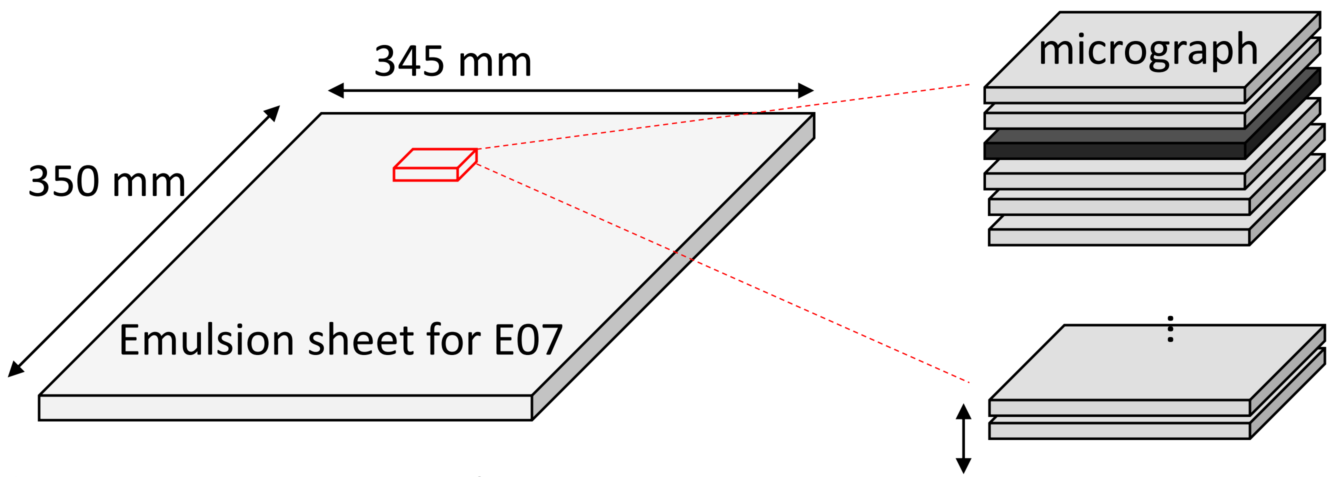




Thickness :1.0 mm→ 0.6 mm after dev.

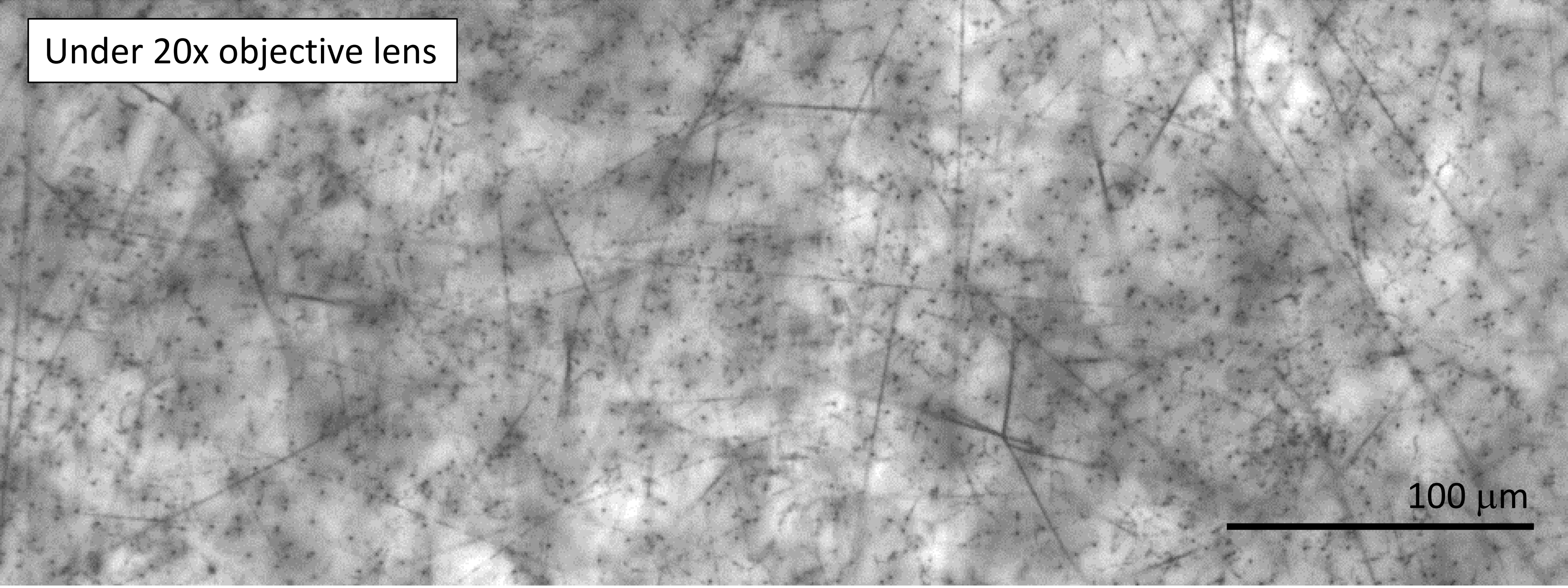
Focal depth: 6 μm, equal to 18 μm before dev.

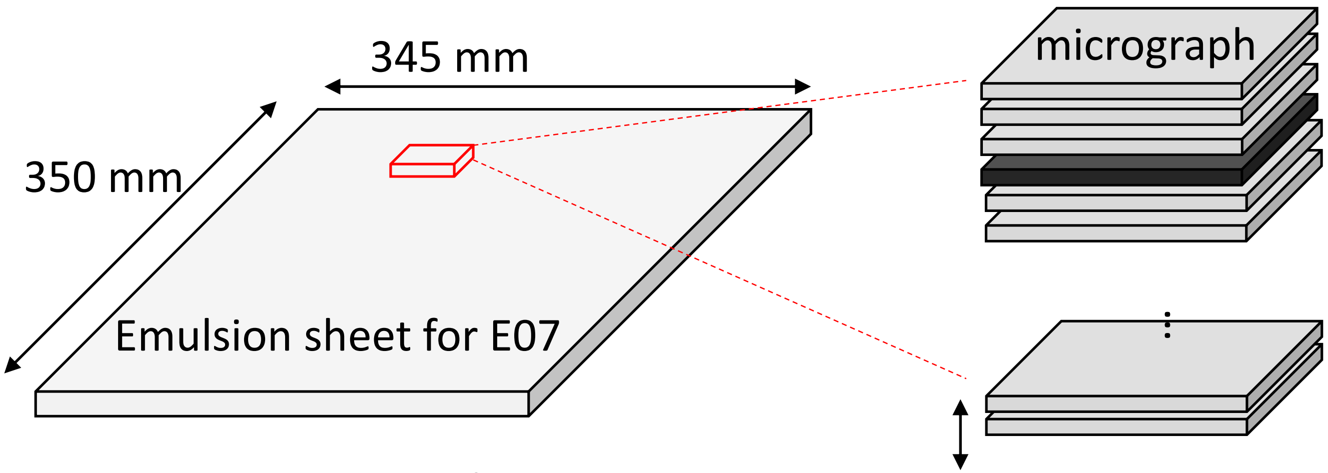




Thickness :1.0 mm→ 0.6 mm after dev.

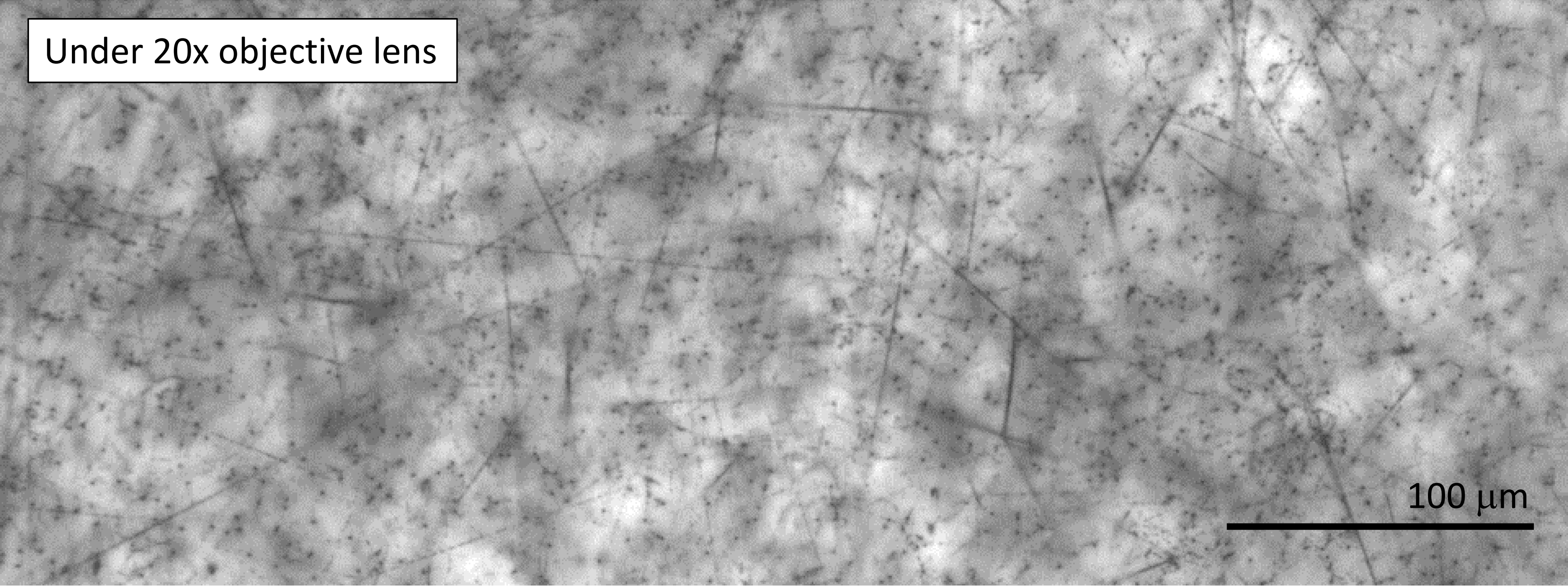
Focal depth: 6 μm, equal to 18 μm before dev.

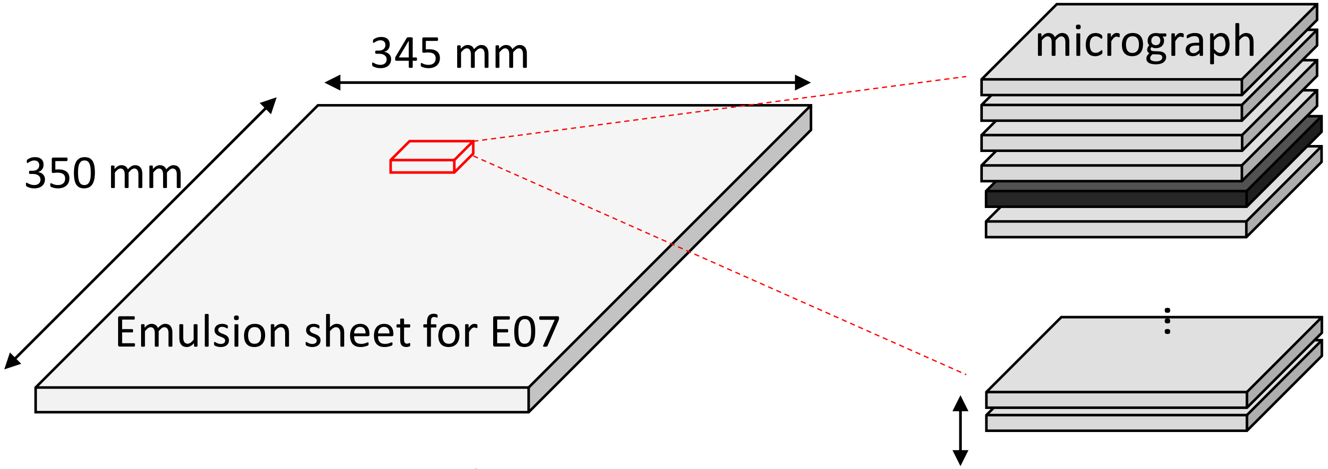




Thickness :1.0 mm→ 0.6 mm after dev.

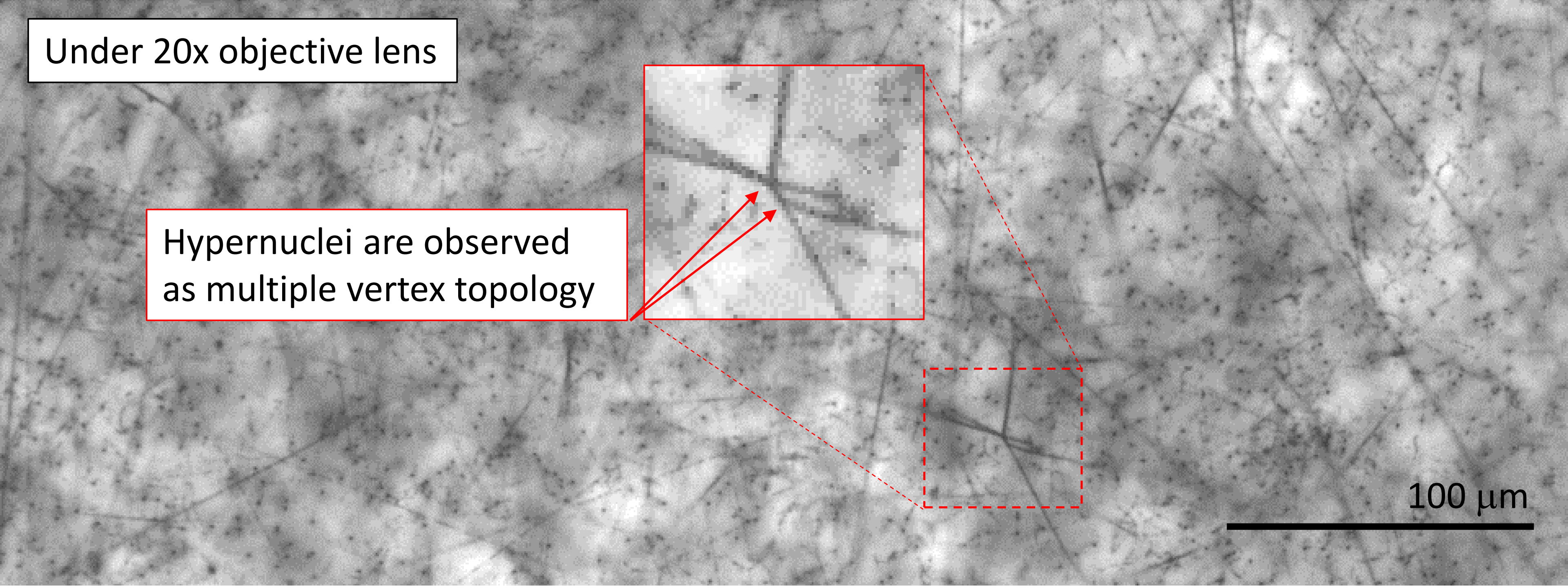
Focal depth: 6 μm, equal to 18 μm before dev.

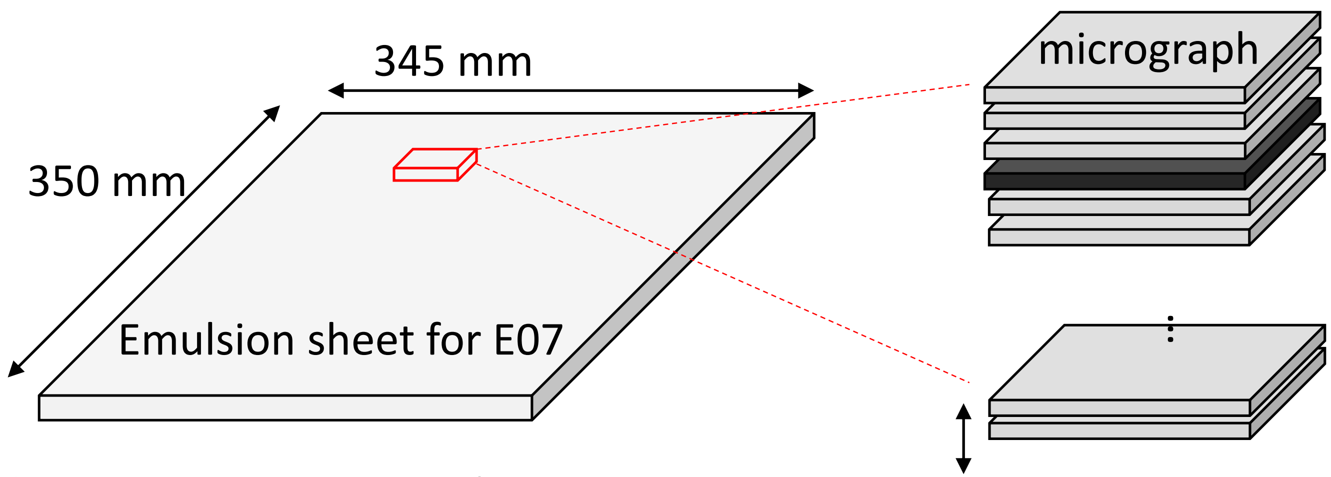




Thickness :1.0 mm→ 0.6 mm after dev.

Focal depth: 6 μm, equal to 18 μm before dev.

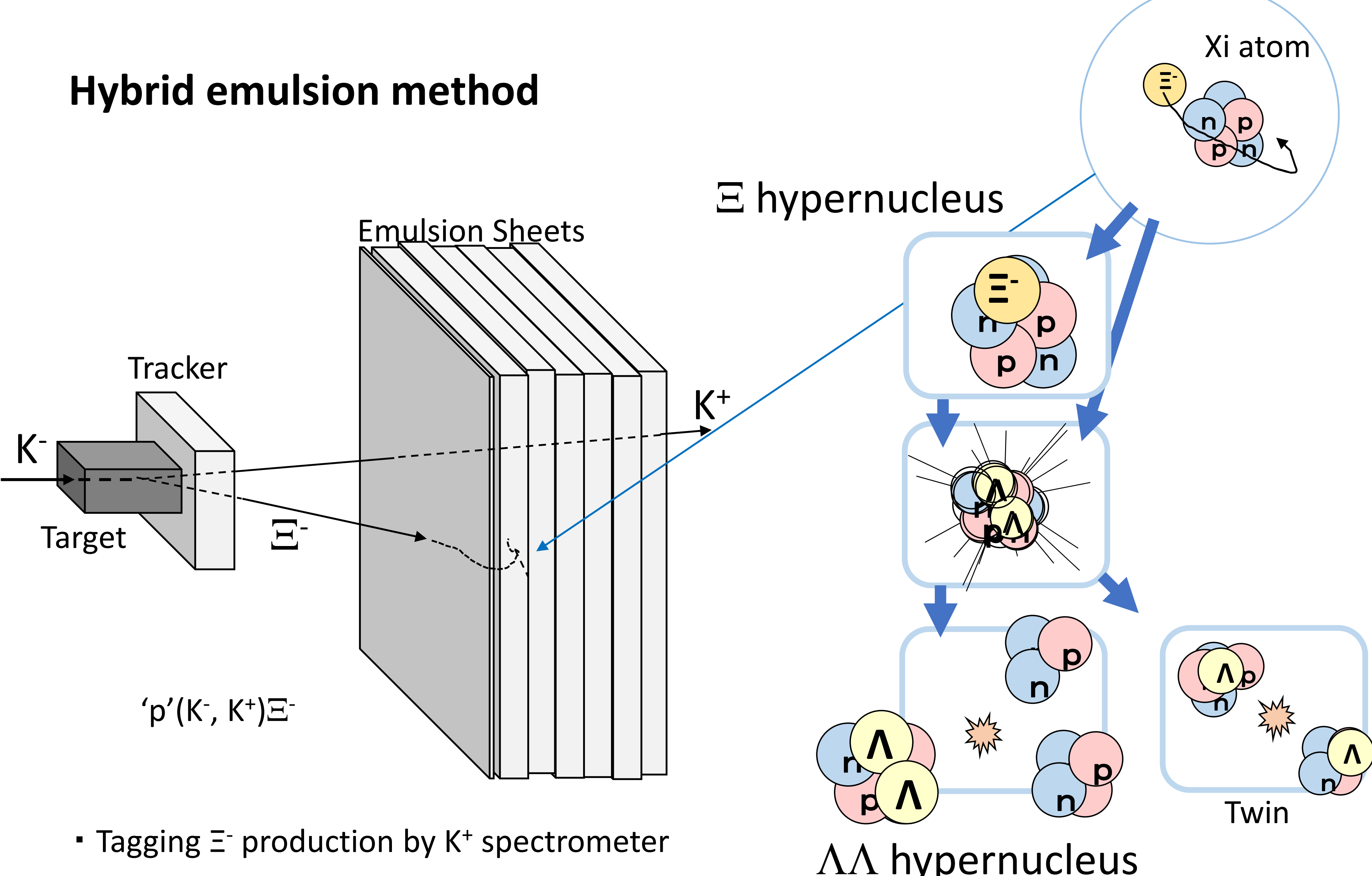




Thickness :1.0 mm→ 0.6 mm after dev.

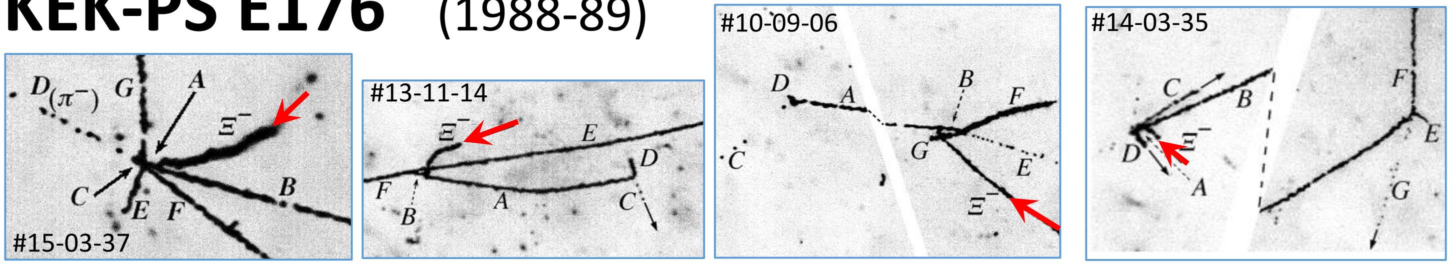
Focal depth: 6 μm, equal to 18 μm before dev.

Hybrid emulsion method



- Tagging Ξ^- production by K^+ spectrometer
- Tracking the Ξ^- with SSD-tracker
- Detecting the Ξ^- track in the 1st emulsion sheet
- Detecting double hypernucleus at the endpoint of Ξ^- track

KEK-PS E176 (1988-89)

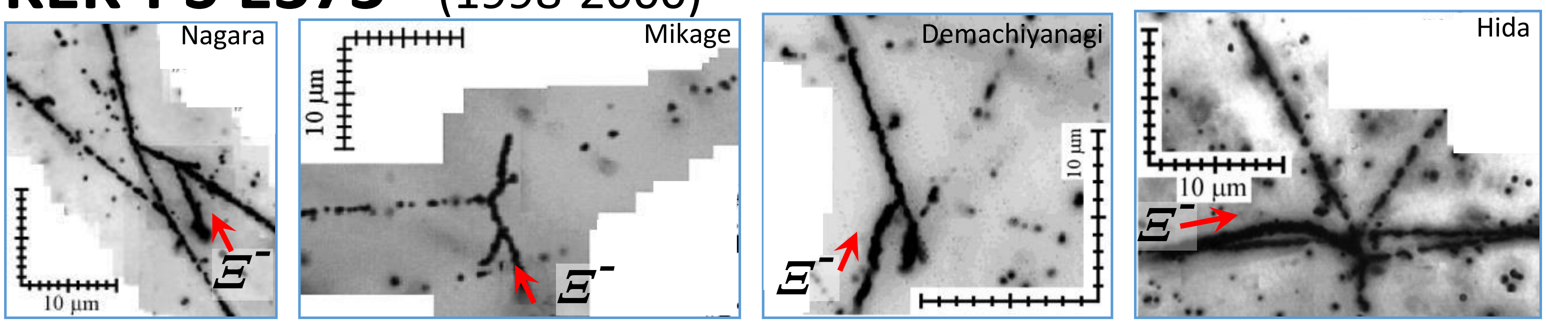


Nuclear Physics A 828 (2009) 191–232

* ~80 Ξ⁻ stop events
* Existence of double Lambda hypernucleus has been confirmed

X10 **statistics**

KEK-PS E373 (1998-2000)



PHYSICAL REVIEW C 88, 014003 (2013)

* At least ~650 Ξ⁻ stop events
* NAGARA, KISO

X10 **statistics**

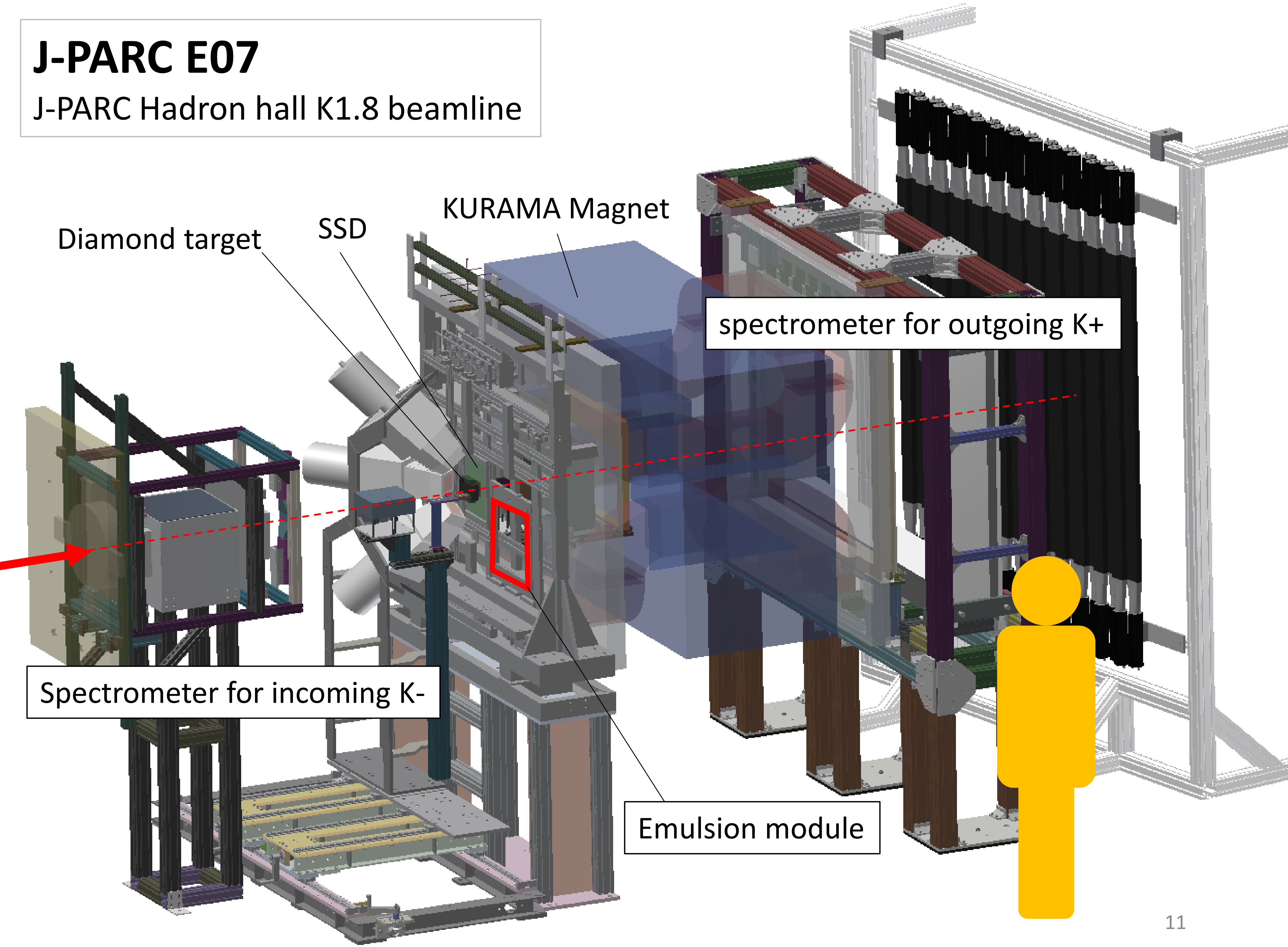
J-PARC E07 (2016-17)

* ~10k Ξ⁻ stop events
* Systematic study of S=-2 system

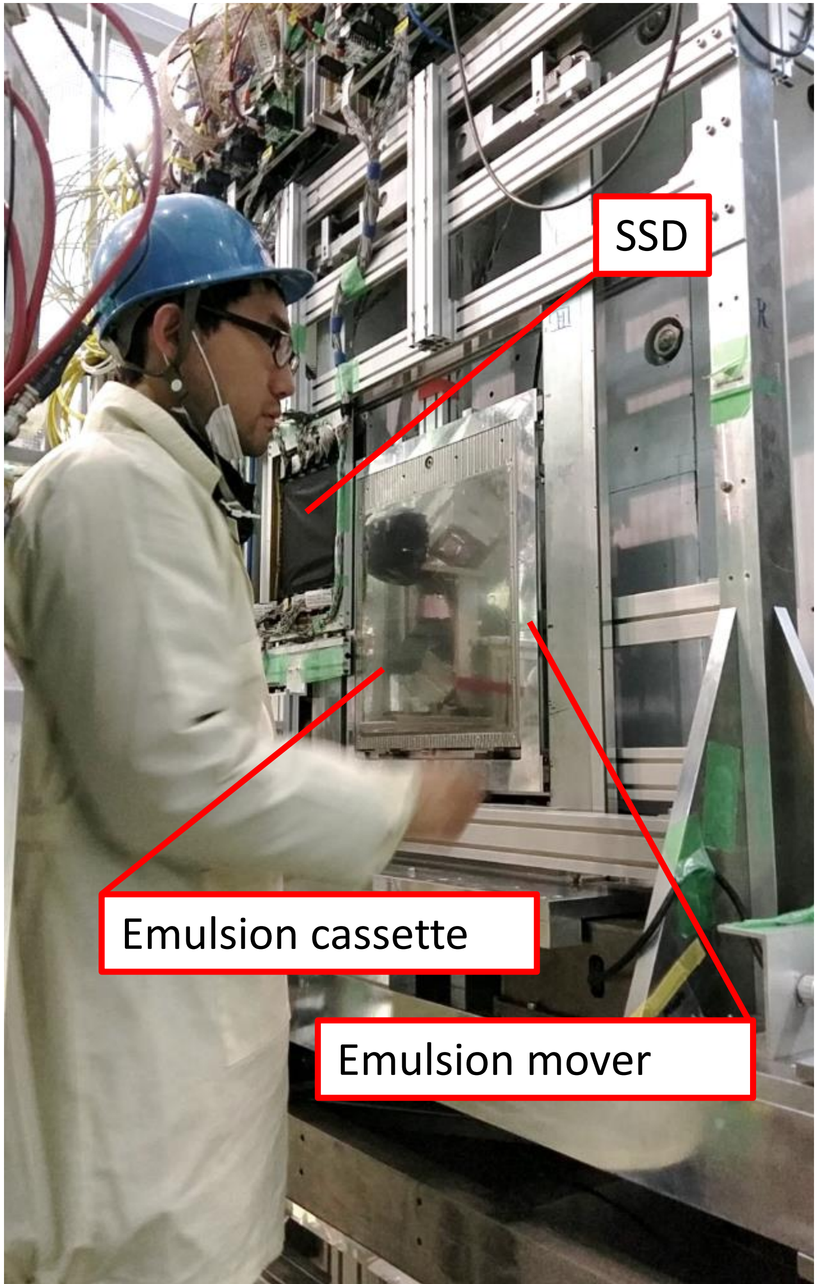
	Emulsion gel	K^- purity	Beam intensity
KEK-PS E373	0.8 tons	25%	$1*10^4$/spill
J-PARC E07	2.1 tons	~85%	$3*10^5$/spill

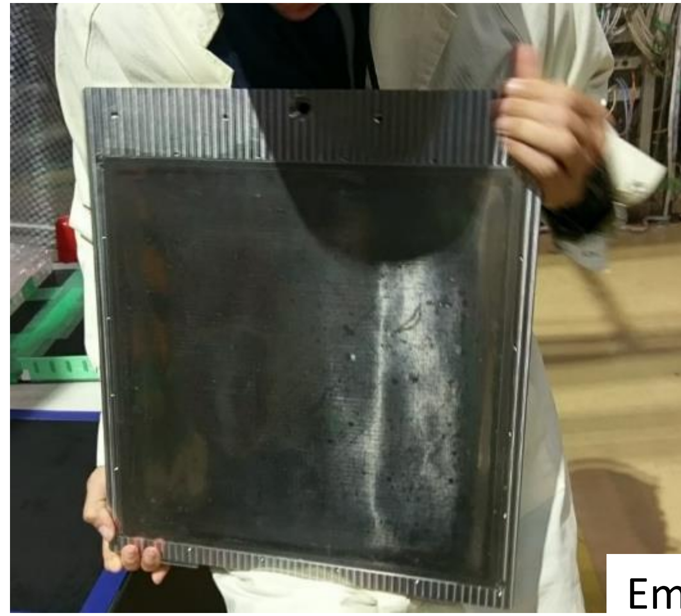
J-PARC E07

J-PARC Hadron hall K1.8 beamline

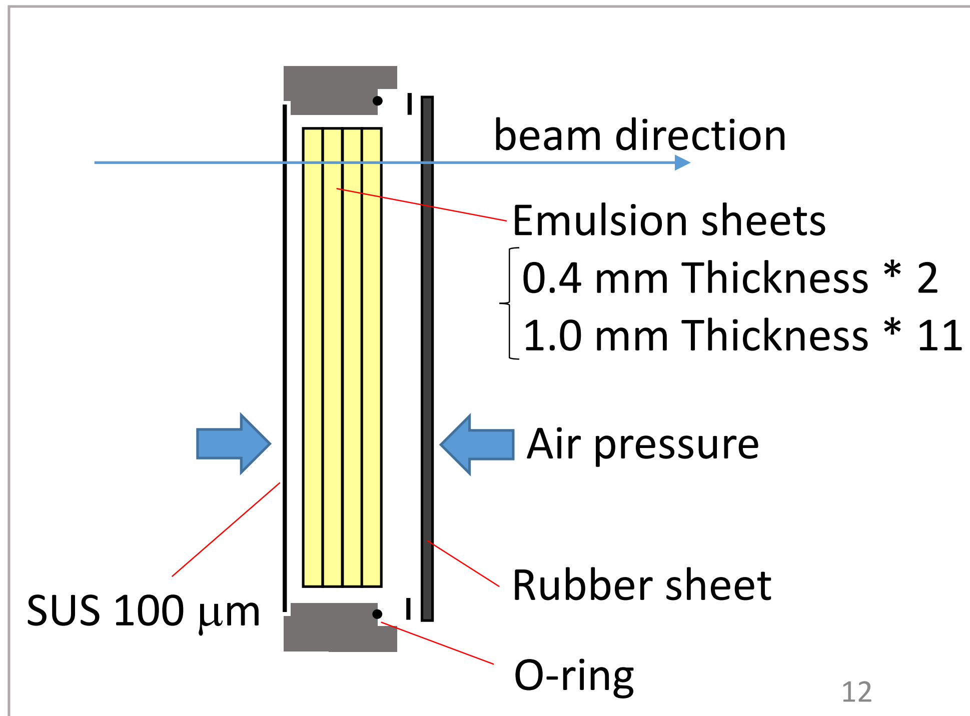


J-PARC Hadron hall K1.8 beamline

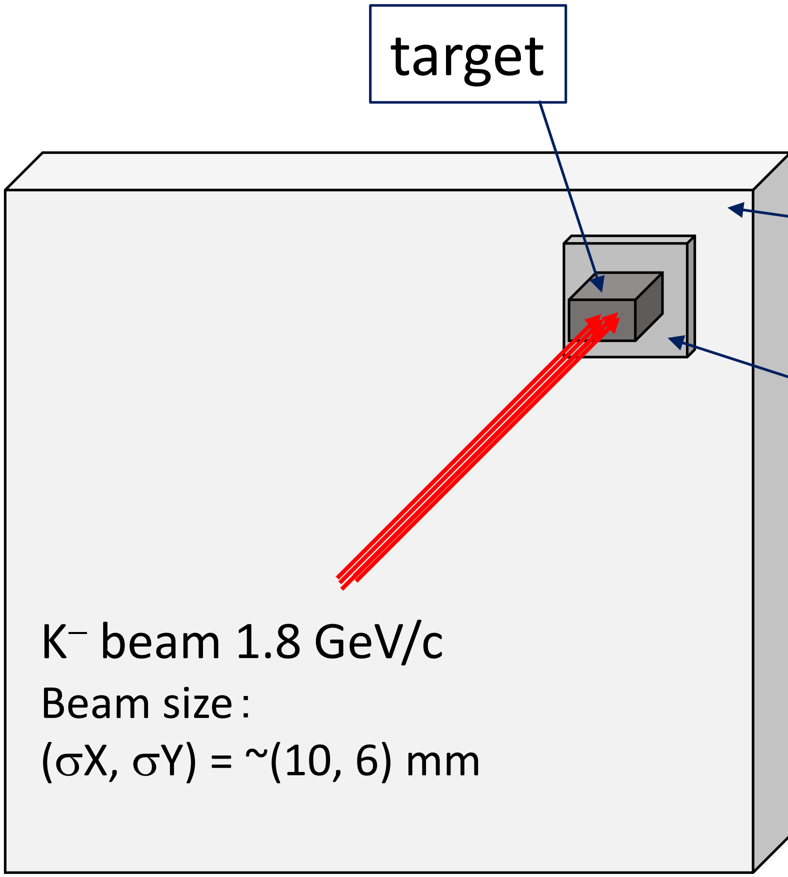


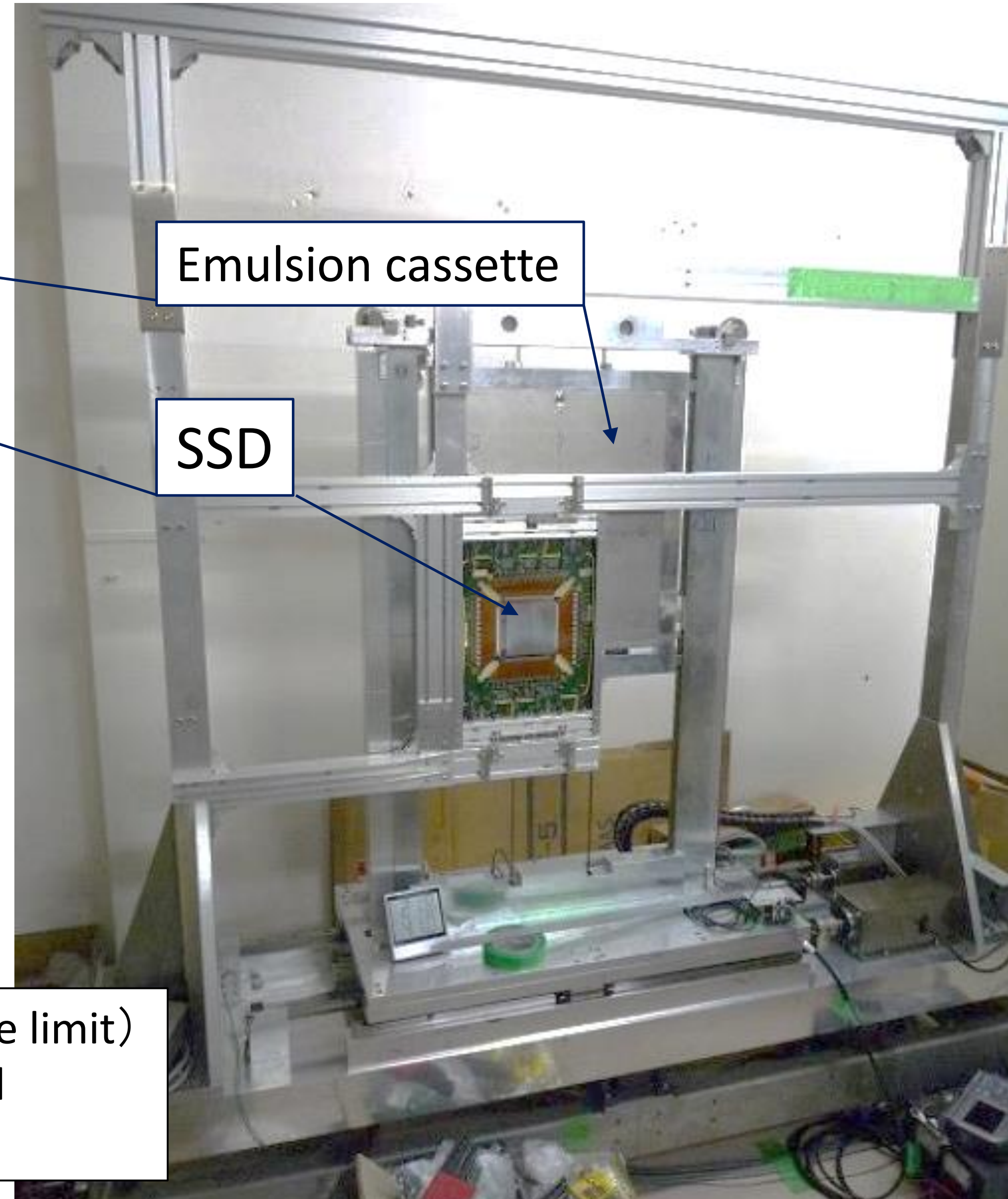


Emulsion cassette



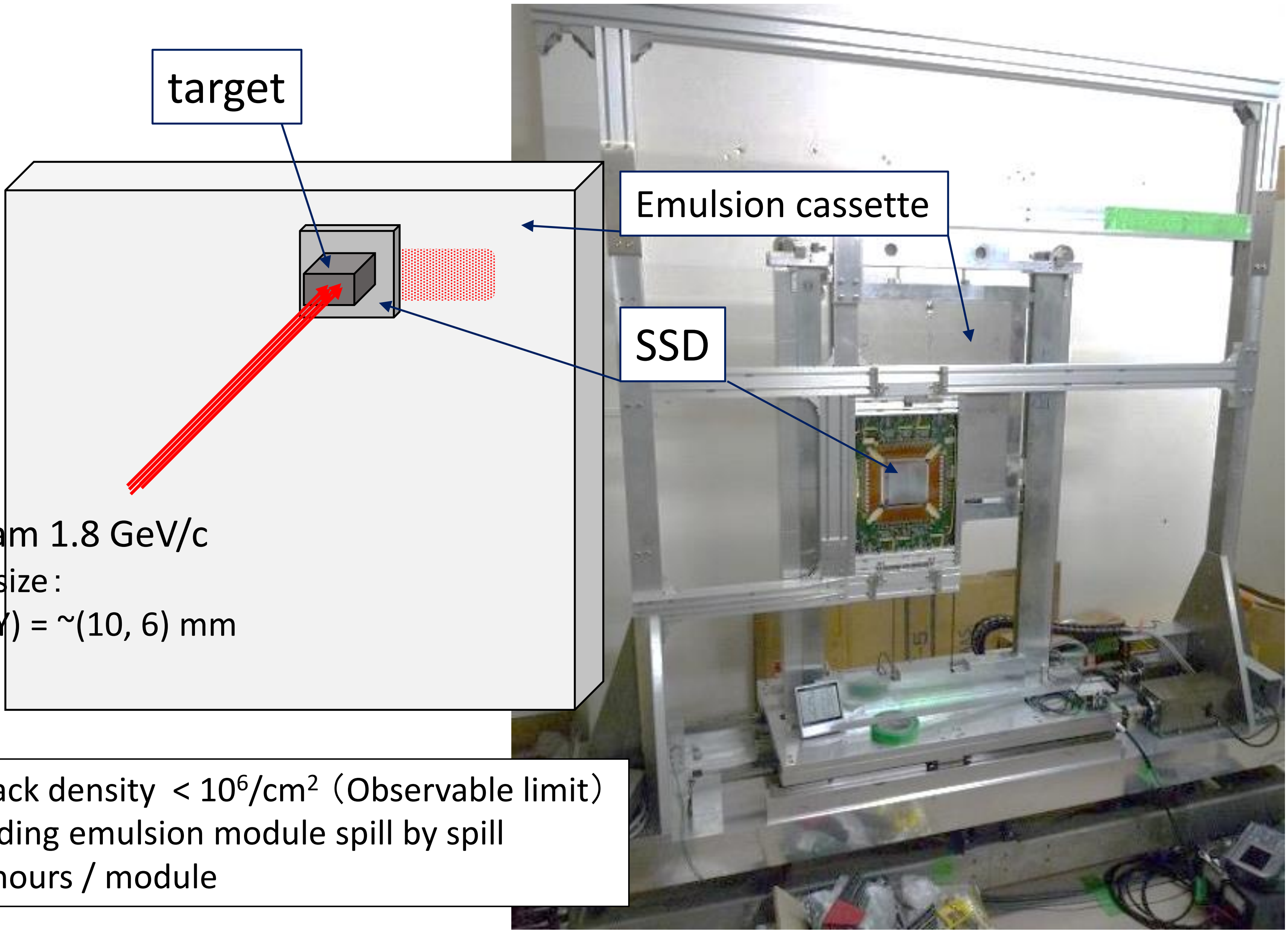
“Emulsion mover” for J-PARC E07





* Track density $< 10^6/cm^2$ (Observable limit)
* Sliding emulsion module spill by spill
* 6 hours / module

"Emulsion mover" for J-PARC E07



K⁻ beam 1.8 GeV/c

Beam size：

(σX, σY) = ~(10, 6) mm

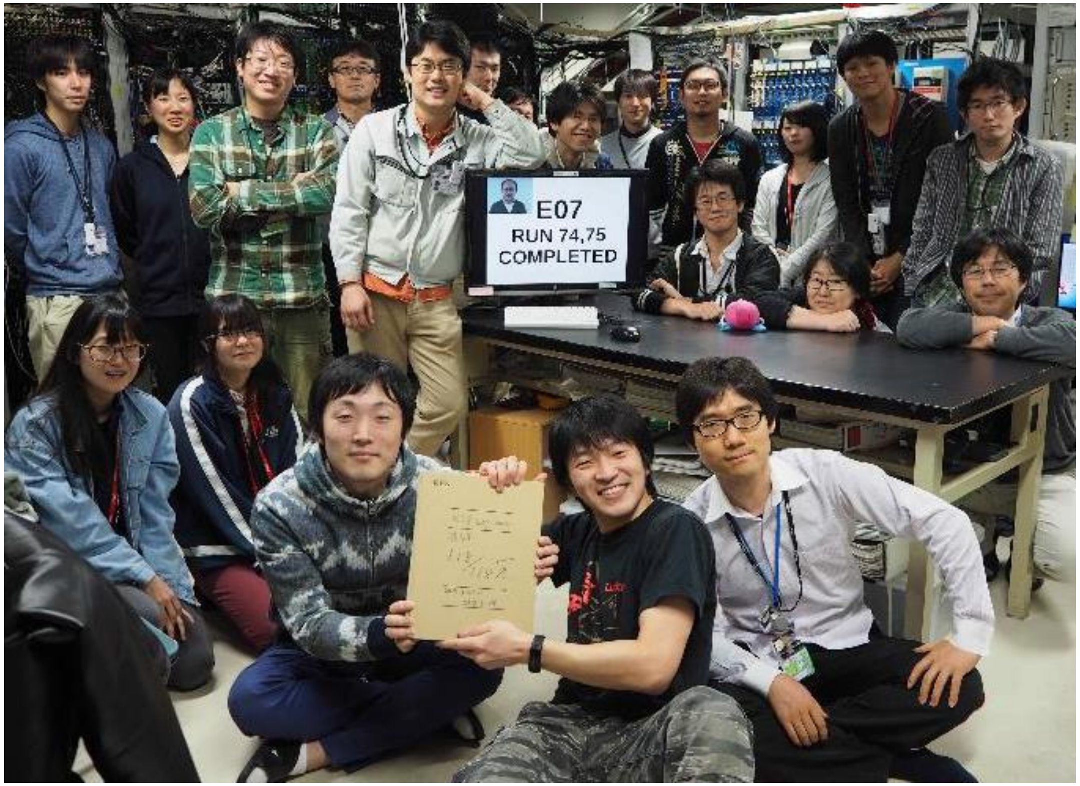
* Track density < 10^6/cm^2 (Observable limit)
* Sliding emulsion module spill by spill
* 6 hours / module

Beam exposure

2016 May-Jun.
KURAMA Commissioning : 5.0 days
Physics : 4.9 days

2017 4/15 - 4/19 (44 kW)
Emulsion exposure : 50 h
calibration : 19 h

2017 5/25 - 6/29 (10 - 37.5 kW)
Emulsion exposure : 23.4 days
calibration : 8.5 h

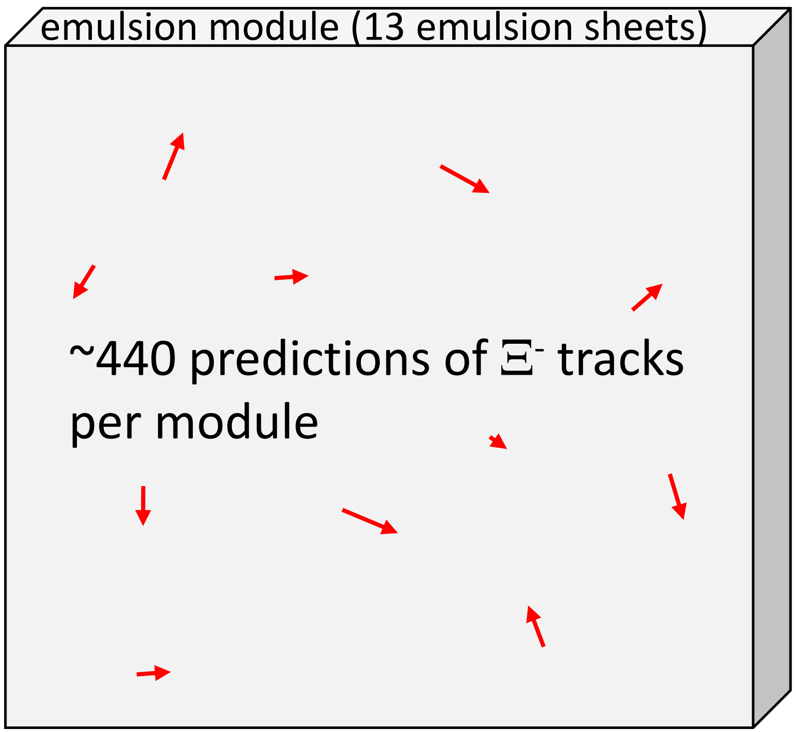


Jul. 1st 2017, Run end photo @K1.8 counting room

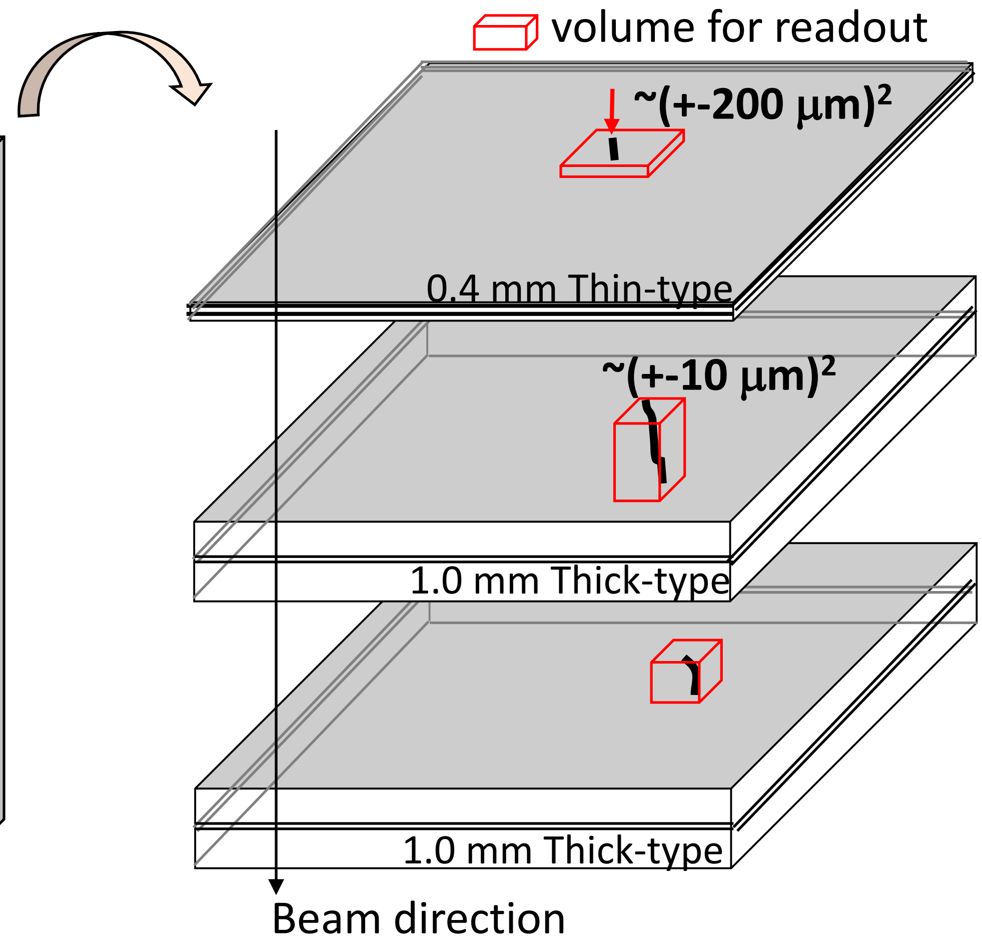
Year	Beam power [kW]	K^- intensity [/spill]	K^- purity	Time [h/mod.]	Integrated K^- [G/mod.]	DAQ Eff.	Emulsion modules
2016	42	260	81%	6.5	0.92	83%	18
2017	44	310	83%	5.6	1.0	84%	8
2017	37.5	280	82%	6.0	1.0	89%	78
2017	10 - 35	120 - 270	50% - 82%	6.5 – 9.0	0.52 – 1.0	89-92%	14

118 emulsion modules * 13 emulsion sheets

Track following for Ξ^- stop event
with dedicated image processing



* Disassembling
* Photographic developing

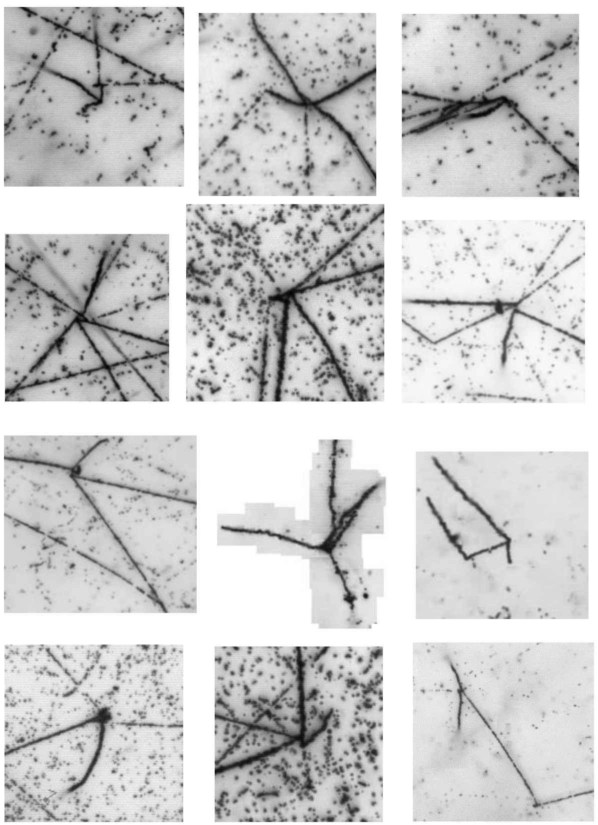


Automated Track Following (Sample Movie)
https://youtu.be/3fiWI5tDx2U

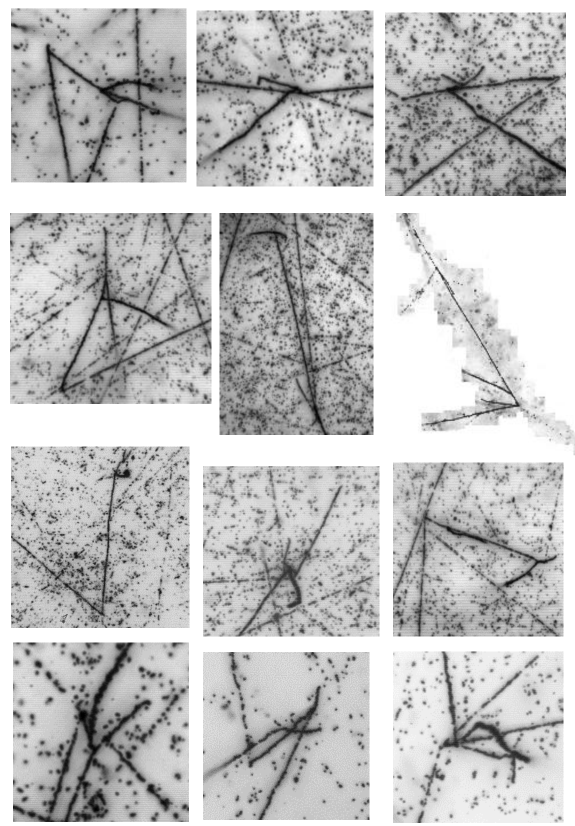
Found event list (2019 Oct.)

	KEK-PS E373	J-PARC E07
Event search	~7 years	1.5 years (2018 Apr. – 2019 Oct.)
S=-2 system	9	31

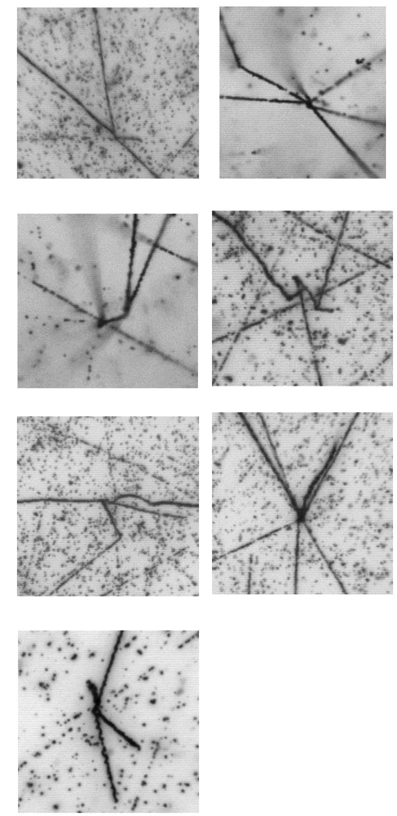
12 double Lambda events



12 twin events



7 others

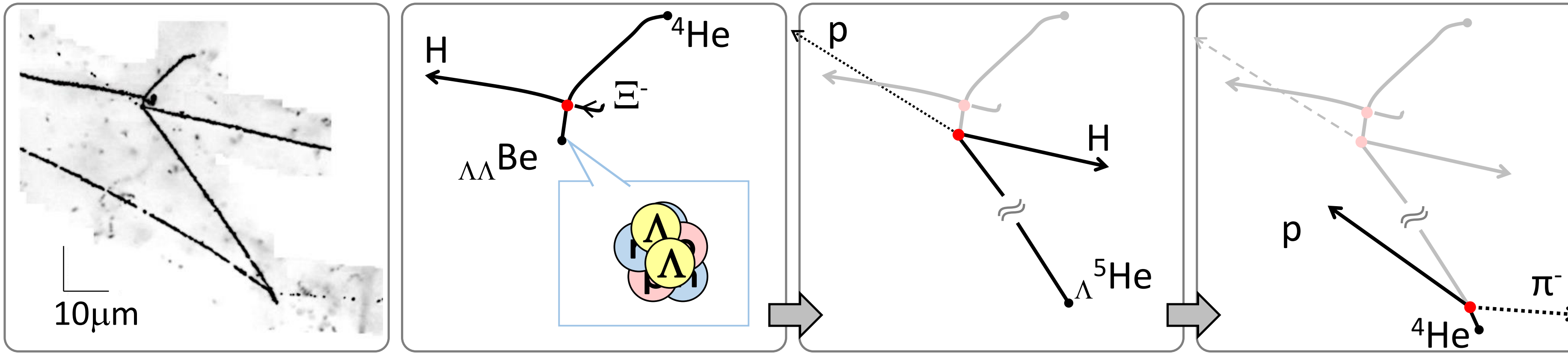


New events are being accumulated successfully and rapidly.

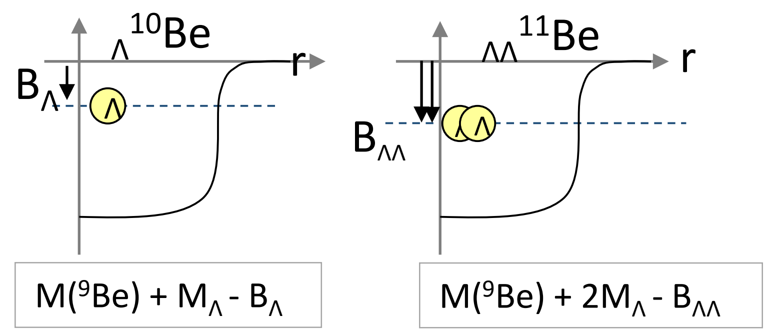
MINO event

Mod#069 pl07
ID : 22381499289376

H. Ekawa et al.,
Prog. Theor. Exp. Phys. 2019, 021D02



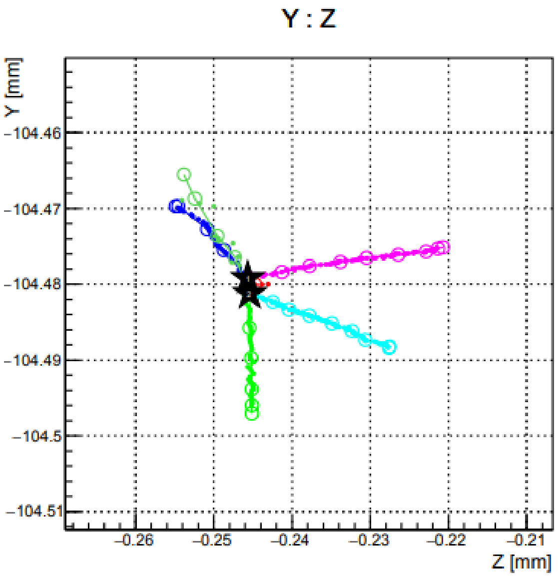
$$^{16}\mathrm{O} + \Xi^- \rightarrow ({}^{10}_{\Lambda\Lambda}\mathrm{Be},\ {}^{11}_{\Lambda\Lambda}\mathrm{Be},\ {}^{12}_{\Lambda\Lambda}\mathrm{Be}) + {}^4\mathrm{He} + (t,\ d,\ p),$$
$$\hookrightarrow {}^5_\Lambda\mathrm{He} + (p, d, t) + p + xn,$$
$$\hookrightarrow {}^4\mathrm{He} + p + \pi^-.$$

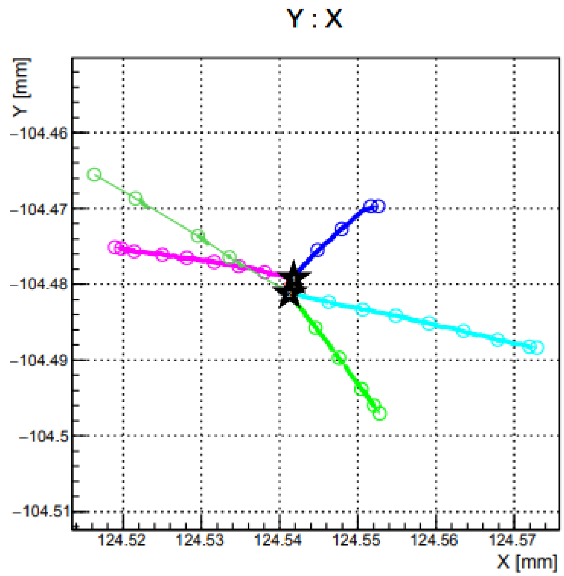


Possible interpretations	$B_{\Lambda\Lambda}$ [MeV]	kinematic fitting χ^2 (DOF=3)
Ξ^- + ^{16}O -> $_{\Lambda\Lambda}{}^{10}$Be + ^{4}He + t	15.05 +- 0.11	11.5
➡ Ξ^- + ^{16}O -> $_{\Lambda\Lambda}{}^{11}$Be + ^{4}He + d	19.07 +- 0.11	7.3
Ξ^- + ^{16}O -> $_{\Lambda\Lambda}{}^{12}$Be* + ^{4}He + p	13.68 +- 0.11 + E_{ex}	11.3

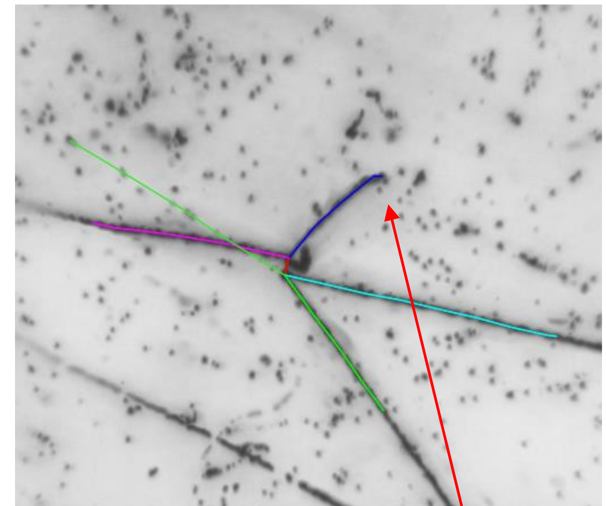
- $_{\Lambda\Lambda}{}^{11}$Be is the most probable in term of kinematic analysis.

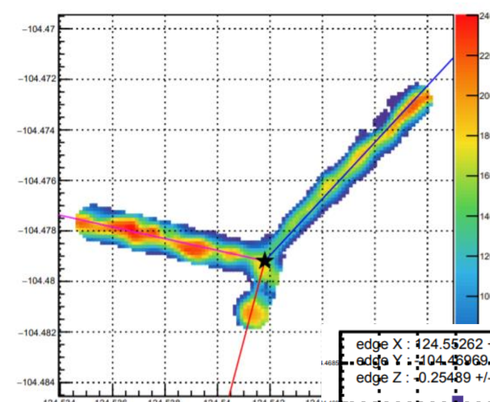
Linear fitting for segmented tracks

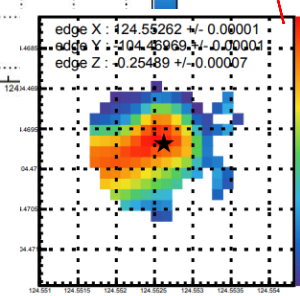




By H. Ekawa







vertex 1 : (124.54180, -104.47919, -0.24566)
vertex 2 : (124.54129, -104.48119, -0.24541)

range 1 : 2.08 +/- 0.21
edge 1 : (124.54129, -104.48119, -0.24541)

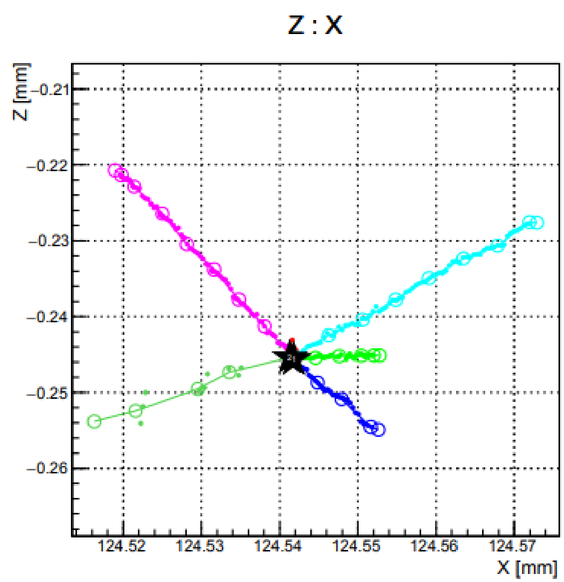
range 2 : 19.59 +/- 0.30
edge 2 : (124.55279, -104.49704, -0.24513)

range 3 : 17.44 +/- 0.18
edge 3 : (124.55262, -104.46969, -0.25489)

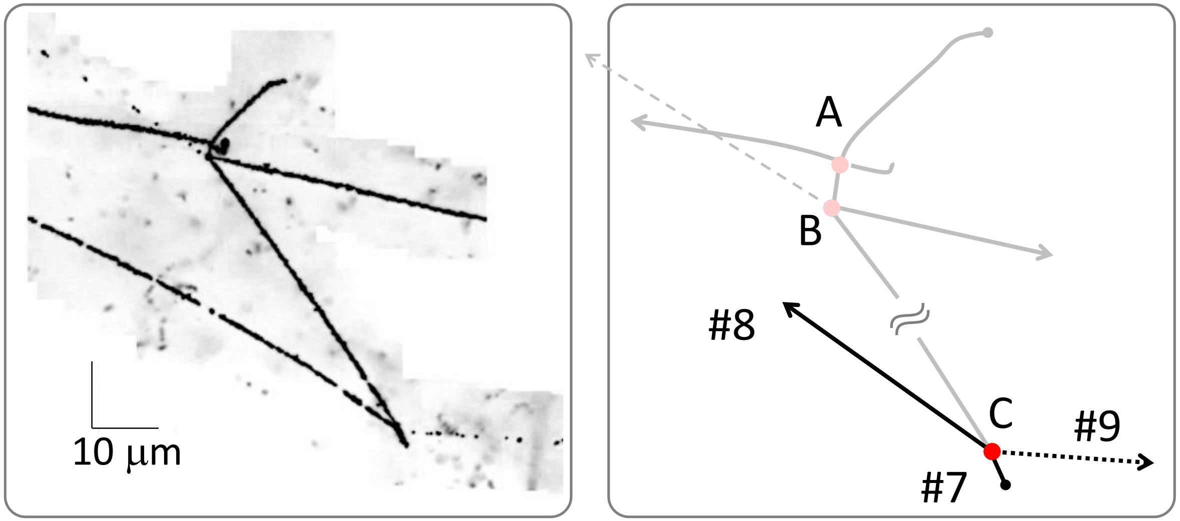
range 4 : 34.15 +/- 0.33
edge 4 : (124.51896, -104.47512, -0.22073)

range 5 : 37.29 +/- 0.32
edge 5 : (124.57291, -104.48835, -0.22764)

range 6 : 30.79 +/- 0.31
edge 6 : (124.51629, -104.46550, -0.25382)



MINO event   vertex-C



Taking all possible combinations of nuclide for the parent and daughter particles.

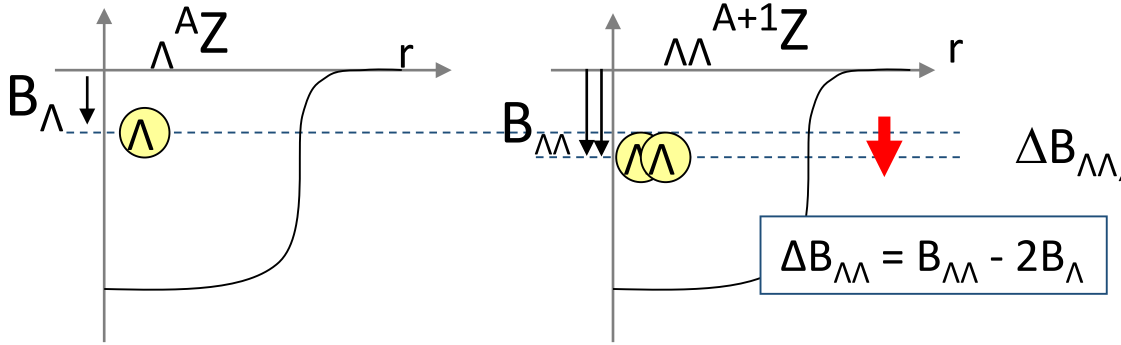
Type	# of case	Example
Daughters without strangeness	65	π^-, p, d, t, ^{3}He, ^{4}H, ^{4}He, … ^{19}B, ^{19}C, ^{19}N, or ^{19}O
Neutral particles	10	n, 2n, 3n, π^0, π^0+n, π^0+2n, Λ, Λ+n, Λ+2n, or none
Single Λ hypernuclei	41	$^3_\Lambda$H, $^4_\Lambda$H, $^4_\Lambda$He, $^5_\Lambda$He, … , $^{17}_\Lambda$N, or $^{18}_\Lambda$N

Table 2. Possible decay modes at vertex C in the case of no neutron emission. Candidates that are accepted by the angular constraint and the conservation of momentum and energy in the 3 σ cut condition are listed. The χ^2 value and the total range of #9 were obtained from the kinematic fitting [11].

Single-Λ hypernucleus (#2)		#7	#8	#9	χ^2	Range (#9) [μm]	Comment
~~$^4_\Lambda$He~~	~~→~~	~~^{3}He~~	~~p~~	~~π^-~~	~~33.1~~	~~16 800~~	rejected
$^5_\Lambda$He	→	^{4}He	p	π^-	5.23	16 270	
~~$^8_\Lambda$Li~~	~~→~~	~~^{6}Li~~	~~d~~	~~π^-~~	~~93.6~~	~~7906~~	rejected
~~$^9_\Lambda$Li~~	~~→~~	~~^{7}Li~~	~~d~~	~~π^-~~	~~105~~	~~10 660~~	rejected

Possible solution

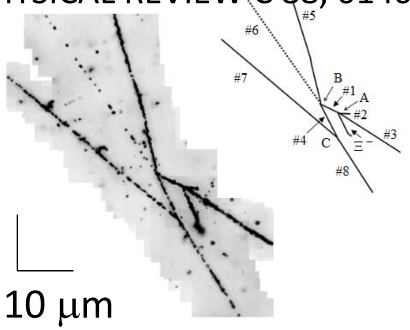
On ΛΛ interaction



$\Delta B_{\Lambda\Lambda}$, An index of ΛΛ interaction

NAGARA Event (2001)

PHYSICAL REVIEW C 88, 014003 (2013)

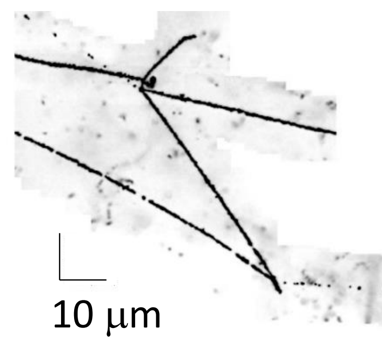


	$\Delta B_{\Lambda\Lambda}$ [MeV]
$_{\Lambda\Lambda}{}^{6}He$	0.67 +- 0.17

where, B_{Ξ^-} = 0.13 MeV

MINO Event (2019)

Prog. Theor. Exp. Phys. 2019, 021D02



	$\Delta B_{\Lambda\Lambda}$ [MeV]
$_{\Lambda\Lambda}{}^{11}Be$	1.87 +- 0.37

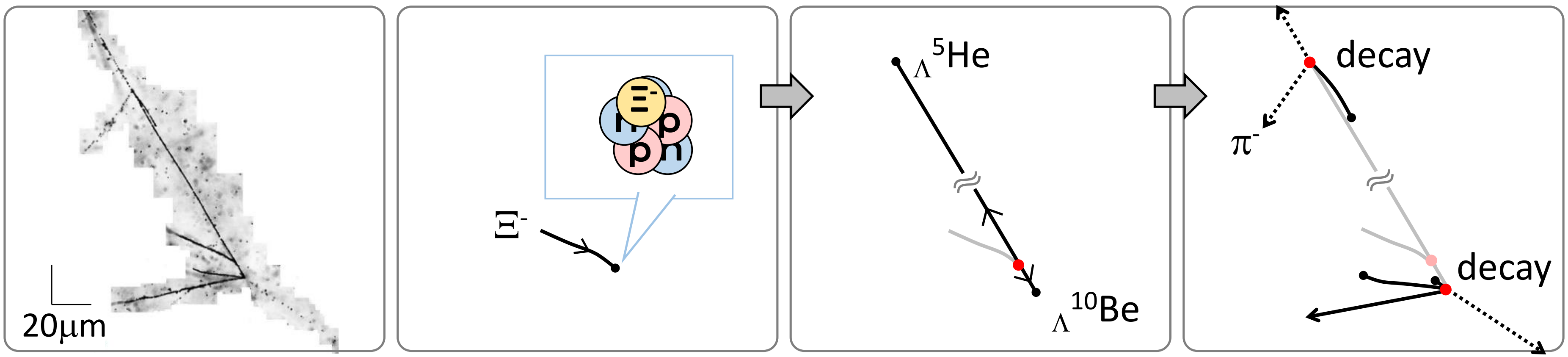
where, B_{Ξ^-} = 0.23 MeV

- ΛΛ interaction is weak attractive force.
- New information on $\Delta B_{\Lambda\Lambda}$ in a different nuclide.

IBUKI event

Mod#047 pl10
ID : 20864938633496

S. H. Hayakawa, Ph.D. Thesis, Osaka Univ. (2019)

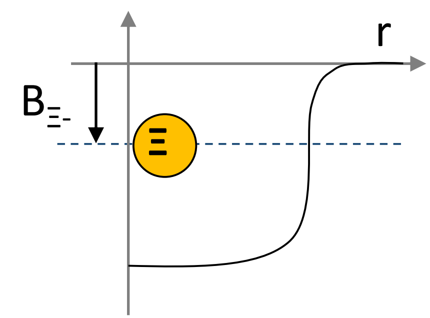


$\Xi^- + {}^{14}N \rightarrow {}_{\Xi}{}^{15}C$

${}_{\Xi}{}^{15}C \rightarrow {}_{\Lambda}{}^{10}Be + {}_{\Lambda}{}^{5}He$

Only ${}_{\Lambda}{}^{10}Be$ is acceptable

${}_{\Lambda}{}^{5}He$ -> 3-prong with π^-
${}_{\Lambda}{}^{10}Be$ -> 4-prong



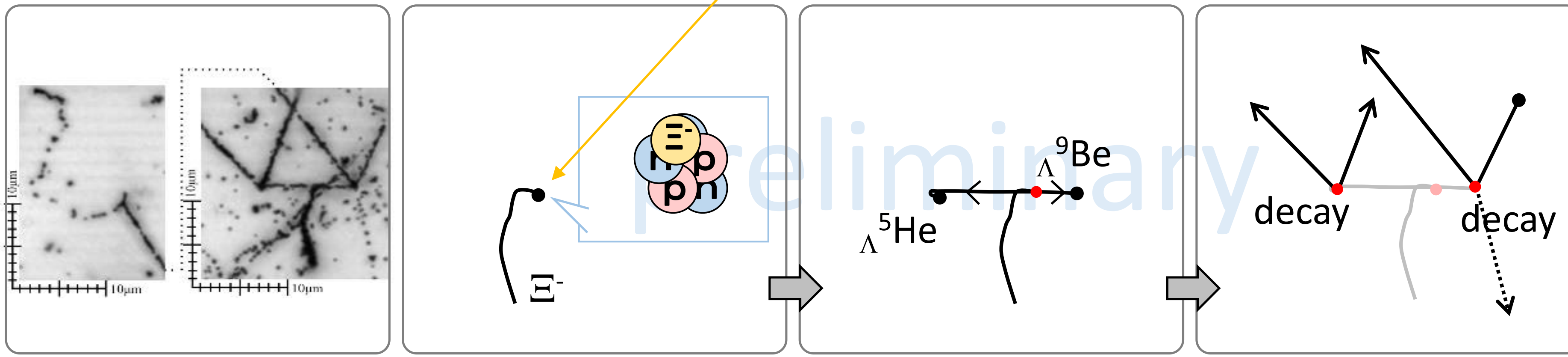
- This event is the 2nd candidate of Ξ hypernucleus.
- The mass and B_{Ξ^-} are determined precisely.

Possible interpretation	B_{Ξ^-} [MeV]	uncertainty of B_{Ξ^-} [MeV]
$\Xi^- + {}^{14}N \rightarrow {}_{\Xi}{}^{15}C \rightarrow {}_{\Lambda}{}^{10}Be + {}_{\Lambda}{}^{5}He$	1.27	0.21

Furthermore, other Ξ hypernucleus candidates have been detected.

E373 KINKA

B_{Ξ^-} ~= 5 MeV (${}_{\Lambda}^{9}Be^*$) or 8 MeV (${}_{\Lambda}^{9}Be$)



$\Xi^- + {}^{14}N \rightarrow {}_{\Xi}^{15}C$

${}_{\Xi}^{15}C \rightarrow {}_{\Lambda}^{9}Be + {}_{\Lambda}^{5}He + n$

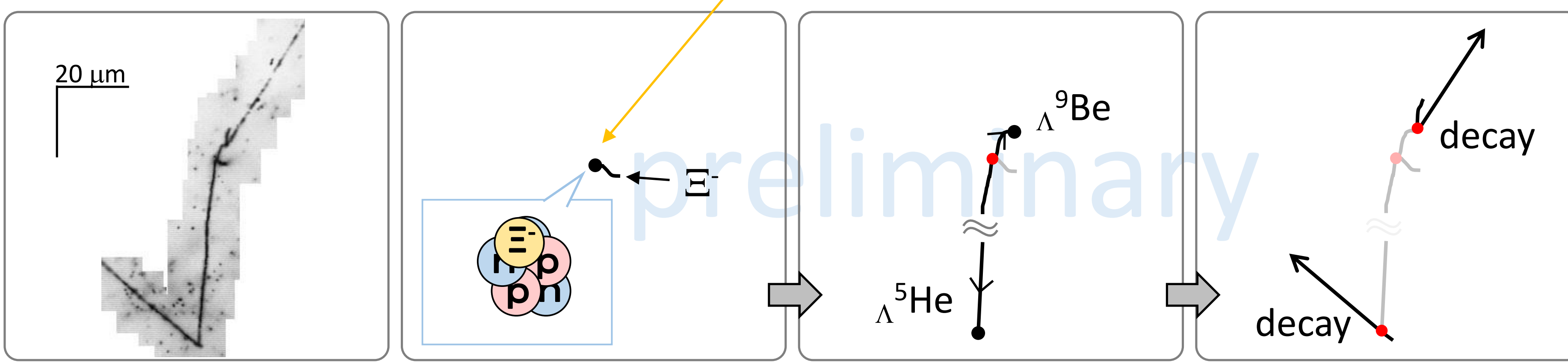
${}_{\Lambda}^{9}Be$ or ${}_{\Lambda}^{9}Be^*$

${}_{\Lambda}^{9}Be$ -> 2-prong
${}_{\Lambda}^{5}He$ -> 2-prong

Twin #007

Mod#043 pl04
ID : 205891673629

B_{Ξ^-} ~= 1.6 MeV



$\Xi^- + {}^{14}N \rightarrow {}_{\Xi}^{15}C$

${}_{\Xi}^{15}C \rightarrow {}_{\Lambda}^{9}Be + {}_{\Lambda}^{5}He + n$

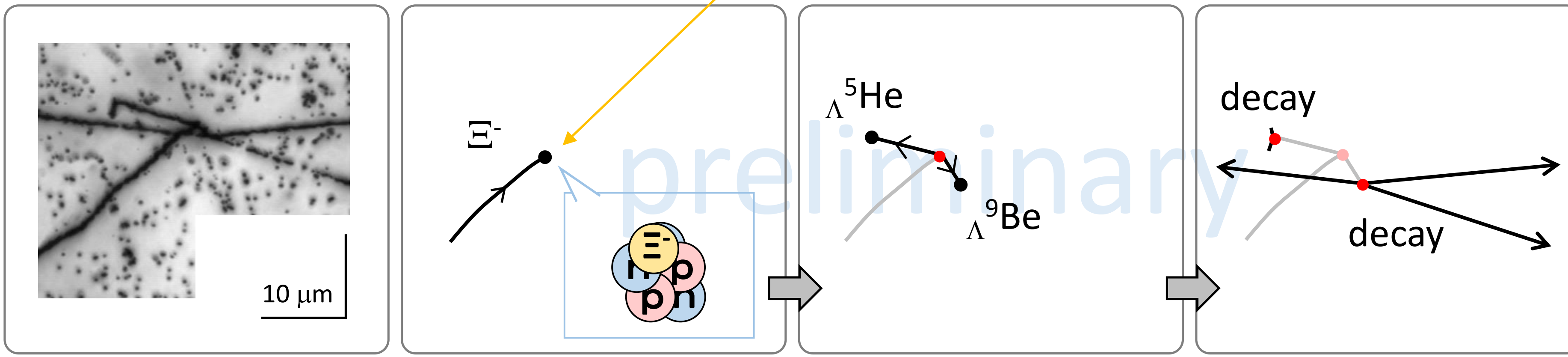
Only ${}_{\Lambda}^{9}Be$ is acceptable

${}_{\Lambda}^{9}Be$ -> 2-prong
${}_{\Lambda}^{5}He$ -> 2-prong

Twin #003

Mod#075 pl07
ID : 22794968788904

B_{Ξ^-} ~= 5 MeV ($_{\Lambda}^{9}Be^*$) or 8 MeV ($_{\Lambda}^{9}Be$)



$\Xi^- + {}^{14}N \rightarrow {}_{\Xi}^{15}C$

${}_{\Xi}^{15}C \rightarrow {}_{\Lambda}^{9}Be + {}_{\Lambda}^{5}He + n$

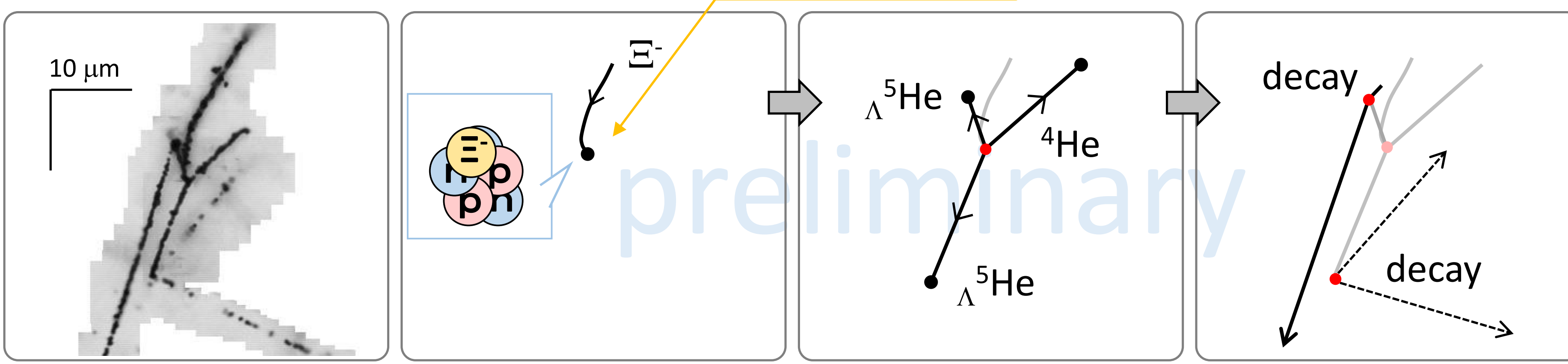
${}_{\Lambda}^{9}Be$ or ${}_{\Lambda}^{9}Be^*$

${}_{\Lambda}^{9}Be$ -> 3-prong
${}_{\Lambda}^{5}He$ -> 2-prong

Twin #010

Mod#019 pl05
ID : 18933242806664

B_{Ξ^-} ~= 6 MeV



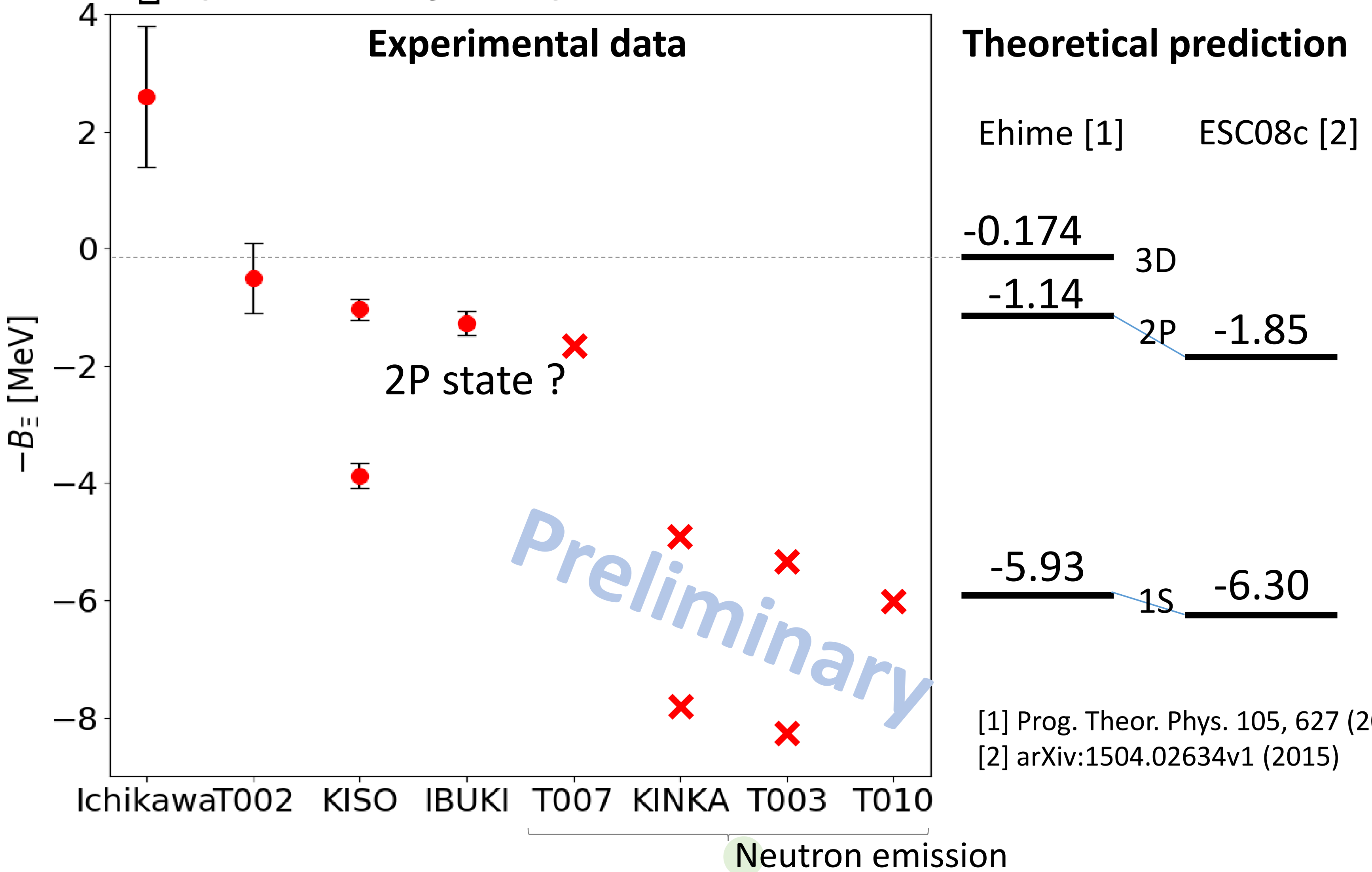
$\Xi^- + {}^{14}N \rightarrow {}_{\Xi}^{15}C$

${}_{\Xi}^{15}C \rightarrow {}_{\Lambda}^{5}He + {}_{\Lambda}^{5}He + {}^{4}He + n$

No excited state

${}_{\Lambda}^{5}He$ -> 2-prong
${}_{\Lambda}^{5}He$ -> 2-prong

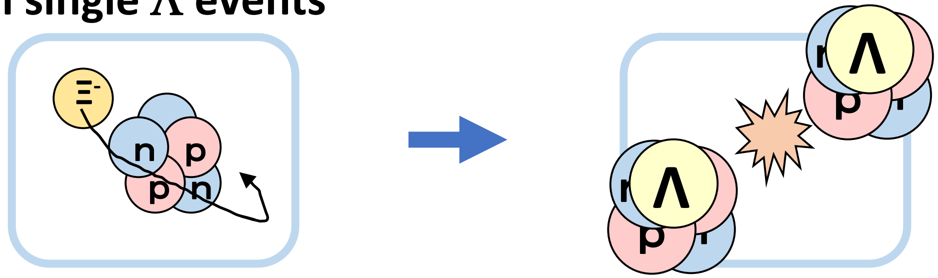
B_{Ξ^-} ($^{14}N + \Xi^-$ System)



[1] Prog. Theor. Phys. 105, 627 (2001)
[2] arXiv:1504.02634v1 (2015)

- **Multiple candidates of Ξ hypernucleus has been detected.**
- The errors for neutron emission case are under validation.
- These events suggest multiple bound states of Ξ^- in the Ξ^- + ^{14}N system.

Nuclides of found twin single Λ events



	Ξ^- Captured by…			Daughter					
	^{12}C	^{14}N	^{16}O	H	He	Li	Be	B	C
E176#10-9-6	●			1			1		
E176#13-11-14	●			1			1		
T008, atomic	●			1	2				
T009, atomic	●				1	1			
T004, atomic			●		1			1	
E373 Ichikawa's		●			3				
T002		●			1		1		
E373 KISO		●			1		1		
T006, IBUKI		●			1		1		
T007		●			1		1		
E373 KINKA		●			1		1		
T003		●			1		1		
T010		●			3				
E176#14-03-35		○	○						
T001									
T005									

Atomic state (E176#10-9-6 – T002)

Ξ hypernuclei (E373 KISO – T010)

preliminary

●: Uniquely identified,
○: Multiple interpretations

Several events are identified as ($\Xi^- + {}^{14}N \rightarrow {}_{\Xi}^{15}C \rightarrow {}_{\Lambda}Be + {}_{\Lambda}He$) although ^{14}N is the most dominant element in emulsion layer.

summary

J-PARC E07 makes a breakthrough in the study of S=-2 system.

New nuclide events and $B_{\Lambda\Lambda}$ and B_{Ξ^-} are being accumulated by event-by-event analysis.

“MINO event” ($_{\Lambda\Lambda}$Be): Prog. Theor. Exp. Phys. 2019, 021D02.
“IBUKI event” ($_{\Xi}{}^{15}$C): Under preparation for publication

Multiple candidates of Ξ hypernucleus have been detected.

The Identification efficiency of “twin” events and the fraction of $\Xi^- + {}^{14}N \rightarrow {}_{\Xi}{}^{15}C$ are high.

The events suggest multiple bound states (2P and 1S state?) of Ξ- in the Ξ^- - ^{14}N.

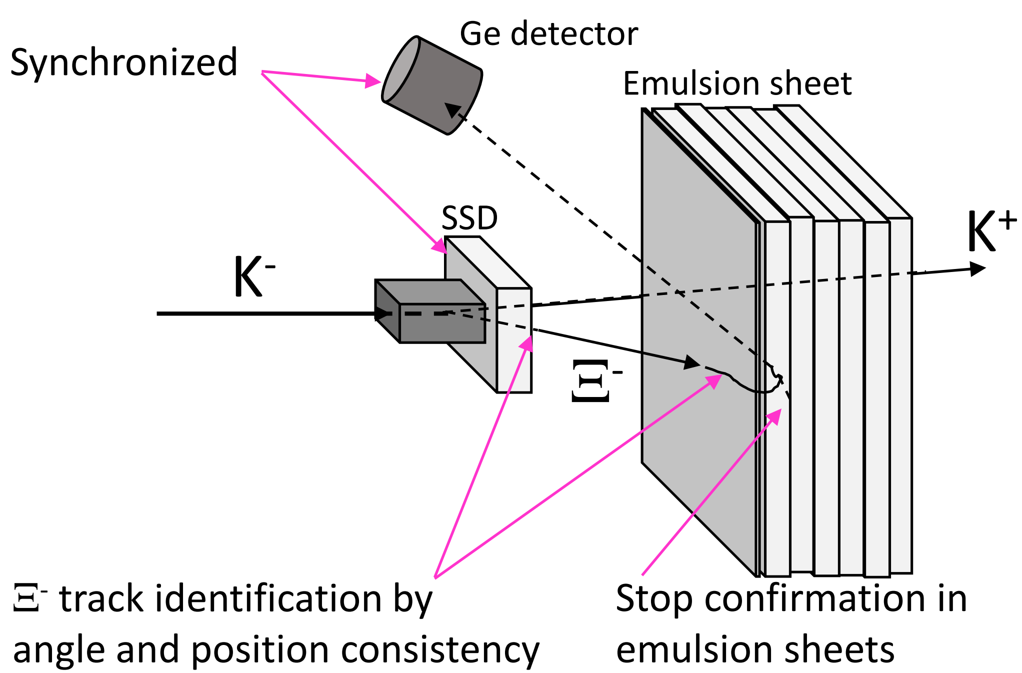
Event hunting is ongoing.

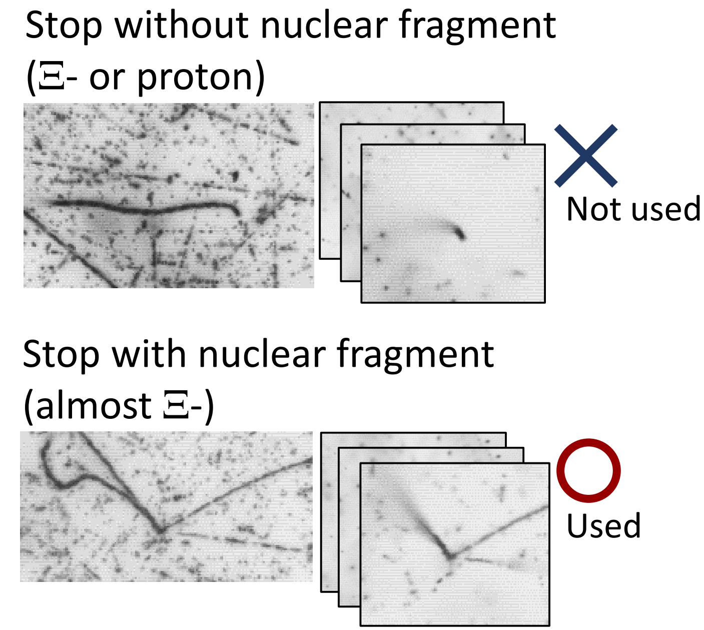
We will detect additional several tens events within a year.

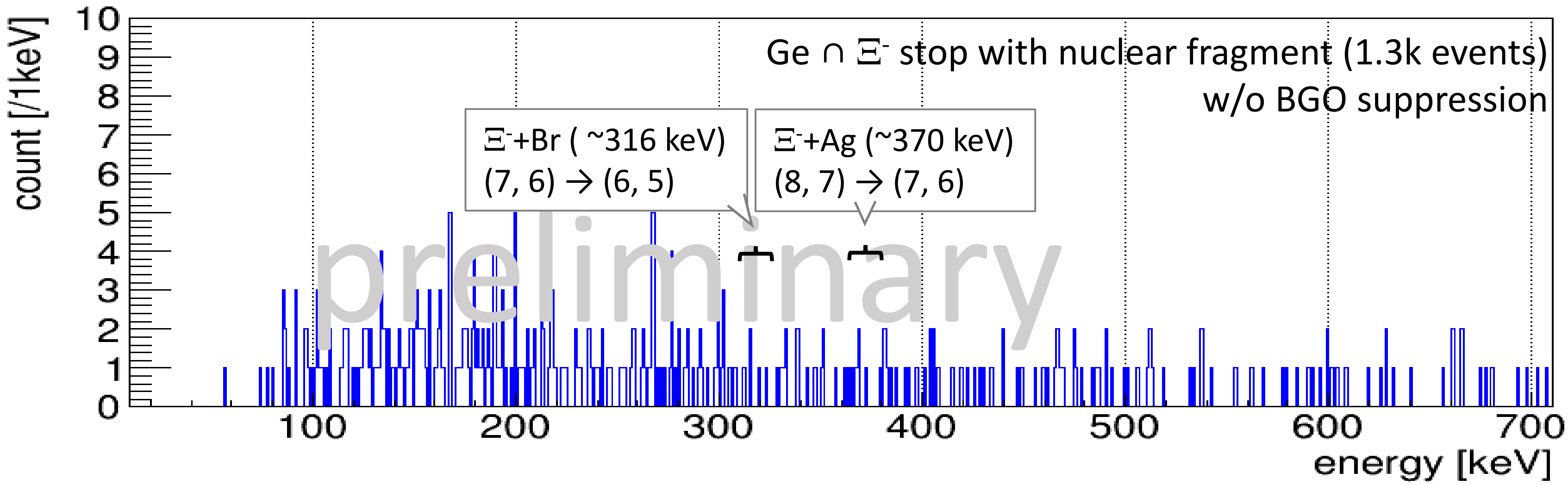
“X-ray measurement from Ξ^- atoms” is ongoing.

X-ray measurement from Ξ^- atom

with Hybrid method combined Ge detector and emulsion







J-PARC E07 Collaboration

Japan	Gifu University JAEA KEK Kyoto University Nagoya University Osaka University RIKEN Tohoku University
Korea	Gyeongsang National University Korea Research Institute of Standards and Science Korea University Seoul National University
China	Chinese Academy of Sciences Institute of High Energy Physics China Shanxi Normal University
Germany	Helmholtz Institute Mainz Johannes Gutenberg-Universität
Myanmar	Lashio University University of Yangon
USA	Ohio University University of New Mexico

6 Countries
24 Institutes
~100 Members

Back up slides:

Physics motivation and design of the experiment.

Number fraction of elements in emulsion layer

FujiFilm ET-7C/7D emulsion

	H	C	N	O	S	Ag	Br	I		SUM
(1) Mass %	1.5	9.3	3.1	6.8	0.2	45.4	33.4	0.3		100.0
(2) A mass	1.0	12.0	14.0	16.0	32.1	107.9	79.9	126.9		
(1) / (2)	1.5	0.8	0.2	0.4	0.0	0.4	0.4	0.0		3.8
Normalized %	39.8	20.6	5.9	11.3	0.2	11.2	11.1	0.1		100.0

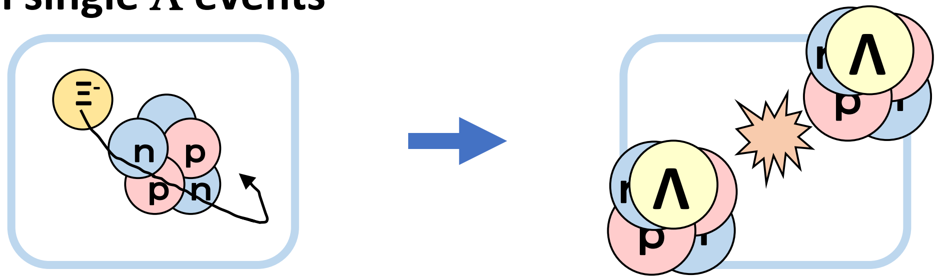
↑

原子数の割合

- 1947年の"Fermi-Teller <Z-law>" によると、AgBr : Gelatin = 0.8 : 0.2
- しかし実際は、何の元素に吸収されるかの比率は、化合物依存が大きい。
- 水素にキャプチャされても、分子を構成する他の元素へ乗り換えが多く発生するらしい
  Ref.; L. I. Ponomarev, Annual Review of Nuclear Science Vol. 23:395-430 (1973)

- R.D. Hill, Suppl. Nuovo Cimento 19 (1961) 83 では、乾板中K^-, μ^- 吸収について、
  理論計算と (仮定が入った) 実験値との比較をしており、
  AgBr吸収 / 全体 = ~ 0.6。

Nuclides of found twin single Λ events



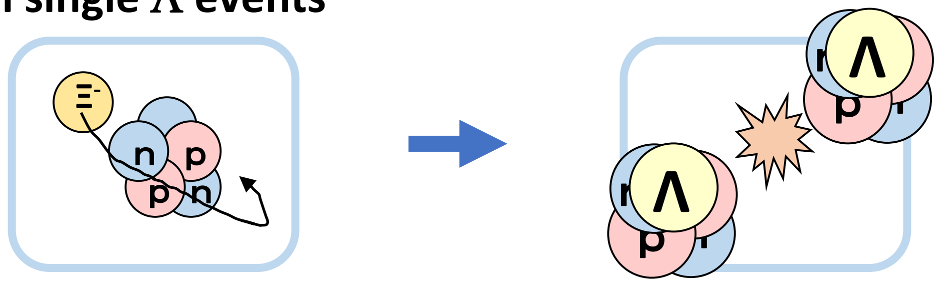
		Ξ^- Captured by…			Daughter					
		^{12}C	^{14}N	^{16}O	H	He	Li	Be	B	C
	E176#10-9-6	●			1			1		
	E176#13-11-14	●			1			1		
	E176#14-03-35		○	○						
E373	E373 Ichikawa's		●			3				
E373	**KISO**		●			1		1		
E373	**KINKA**		●			1		1		
E07	T001									
E07	T002		●			1		1		
E07	T003		●			1		1		
E07	T004, atomic			●		1			1	
E07	T005									
E07	**T006, IBUKI**		●			1		1		
E07	T007		●			1		1		
E07	T008, atomic	●			1	2				
E07	T009, atomic	●				1	1			
E07	T010		●			3				

preliminary

●: Uniquely identified,
○: Multiple interpretations

Many events of ($\Xi^- + {}^{14}N \to {}_{\Xi}{}^{15}C \to {}_{\Lambda}Be + {}_{\Lambda}he$)

Nuclides of found twin single Λ events



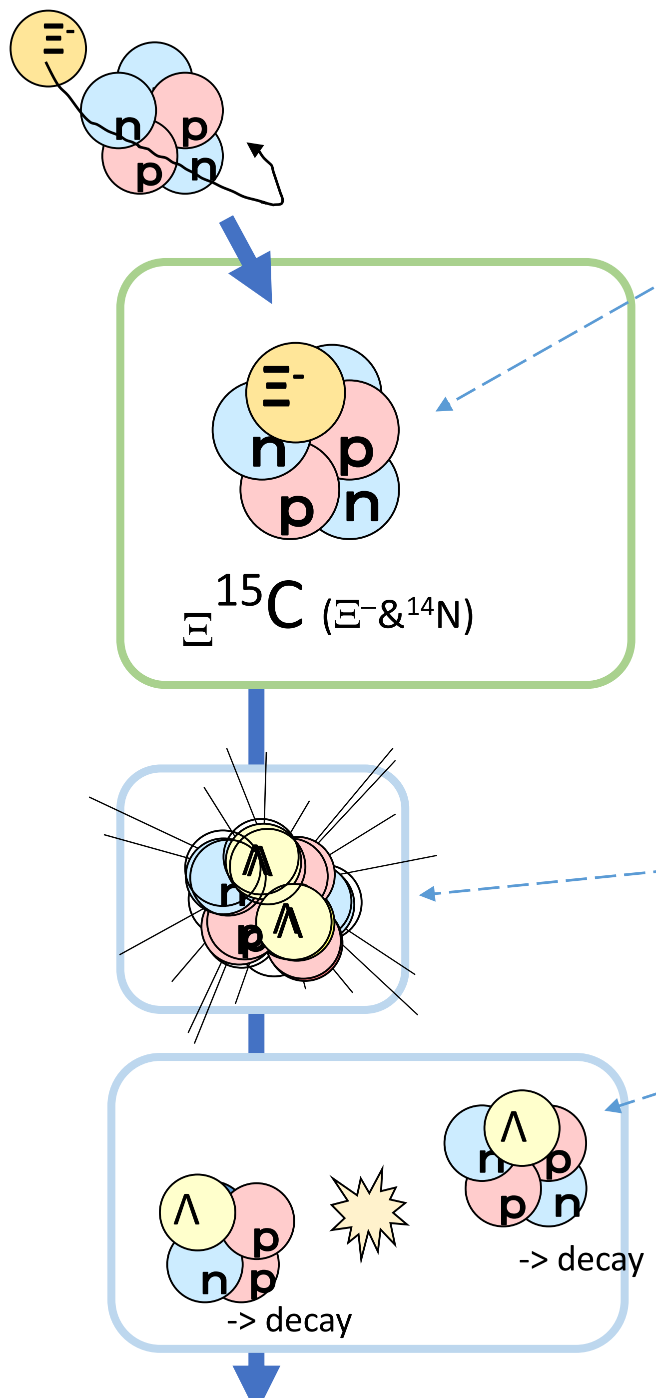
	Ξ^- Captured by…			Daughter					
	^{12}C	^{14}N	^{16}O	H	He	Li	Be	B	C
E176#10-9-6	●			1			1		
E176#13-11-14	●			1			1		
E176#14-03-35		○	○						
E373 Ichikawa's		●			3				
E373 KISO		●			1		1		
E373 KINKA		●			1		1		
T001									
T002		●			1		1		
T003		●			1		1		
T004, atomic			●		1			1	
T005									
T006, IBUKI		●			1		1		
T007		●			1		1		
T008, atomic	●			1	2				
T009, atomic	●				1	1			
T010		●			3				

preliminary

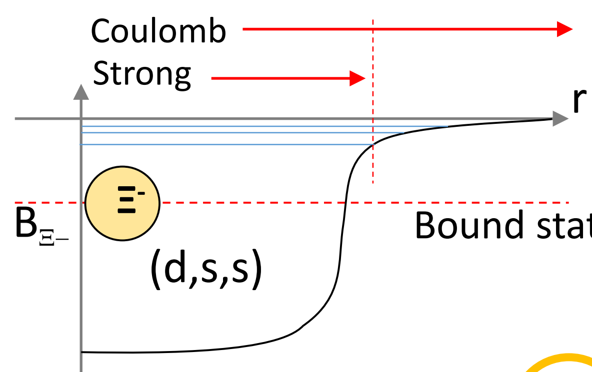
Many events of ($\Xi^- + {}^{14}N \rightarrow {}_{\Xi}{}^{15}C \rightarrow {}_{\Lambda}Be + {}_{\Lambda}he$)

●: Uniquely identified,
○: Multiple interpretations

Ξ hypernuclei detection via "twin Λ hypernuclear event (TLH)"



Ξ Hypernucleus formation (lifetime ~ 10^{-24} s?)



$E_{initial\_state}$ = Mass(^{14}N) + Mass(Ξ^{-}) − B_{Ξ^-}

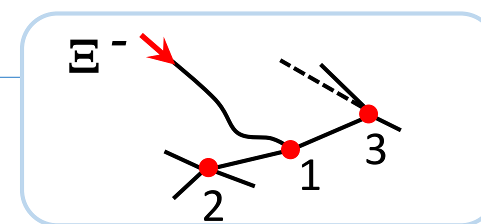
Energy conservation

Decay with strong interaction

p + Ξ^{-} → Λ + Λ + 28 MeV

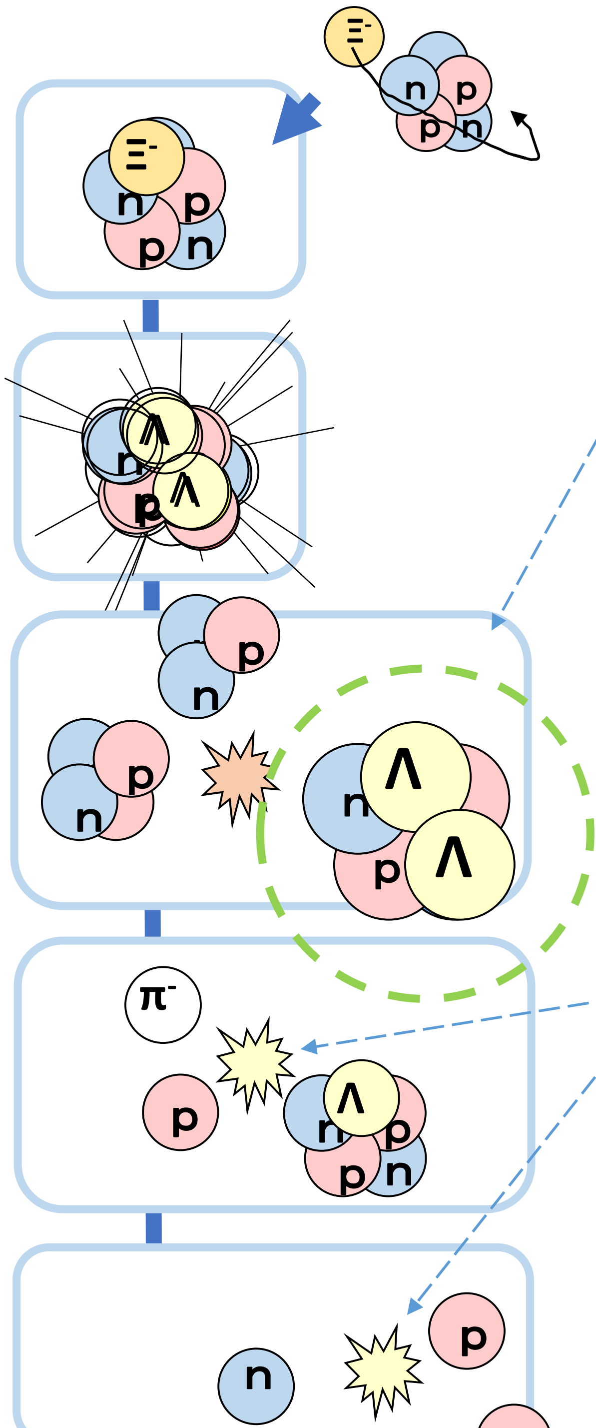
Fragmentation

1) Ξ^{-} stop point
2) decay of the 1st Λ hypernucleus
3) decay of the 2nd Λ hypernucleus



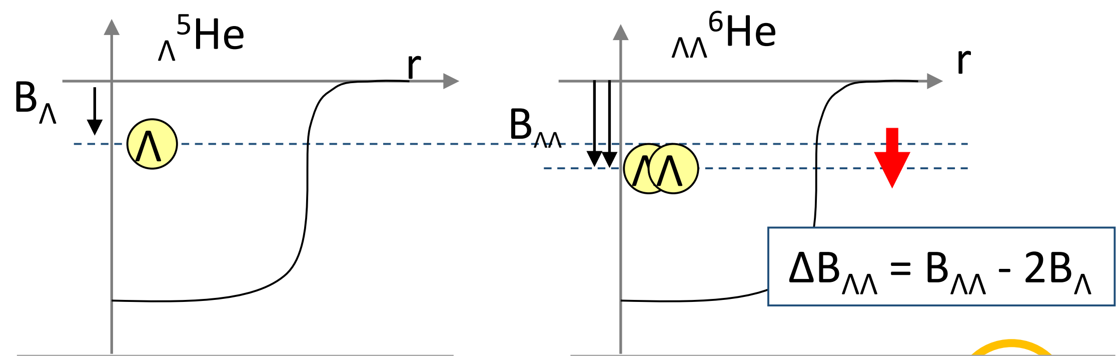
E_{final_state} = SUM(Mass + kinetic energy) for all fragments

ΛΛ hypernuclei (DLH) detection



ΛΛ hypernucleus formation

when both Λ stick to the same nuclear fragment.

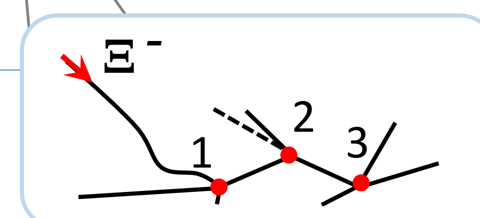


$M({}_{\Lambda}{}^{A}Z) = M({}^{A-1}Z) + M_{\Lambda} - B_{\Lambda}$

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

Sequential decay

1) Ξ^- stop point
2) decay of the ΛΛ hypernucleus
3) decay of Λ hypernucleus



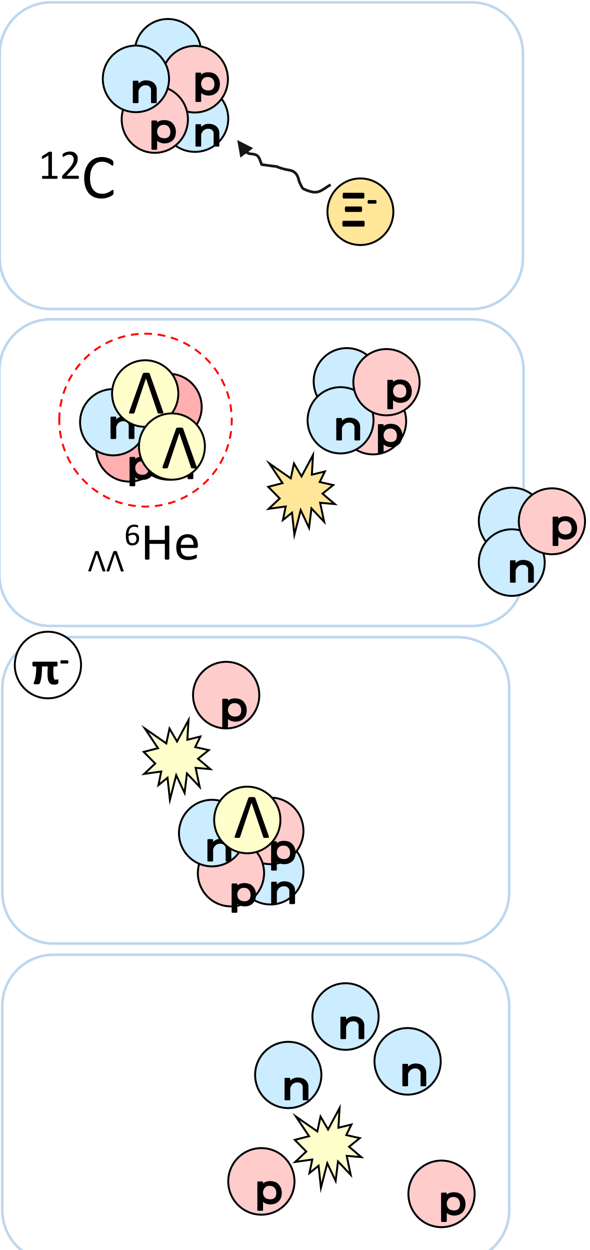
Energy conservation

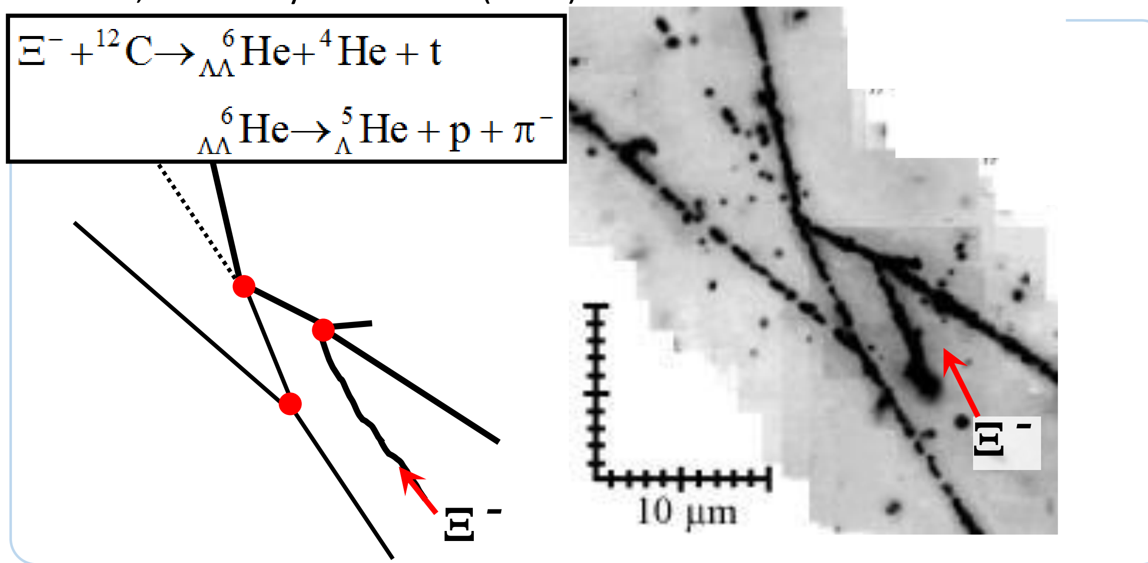
$\text{Mass}(Z) + \text{Mass}(\Xi^-) - B_{\Xi^-} = \text{SUM}(\text{Mass} + \text{kinetic energy})$

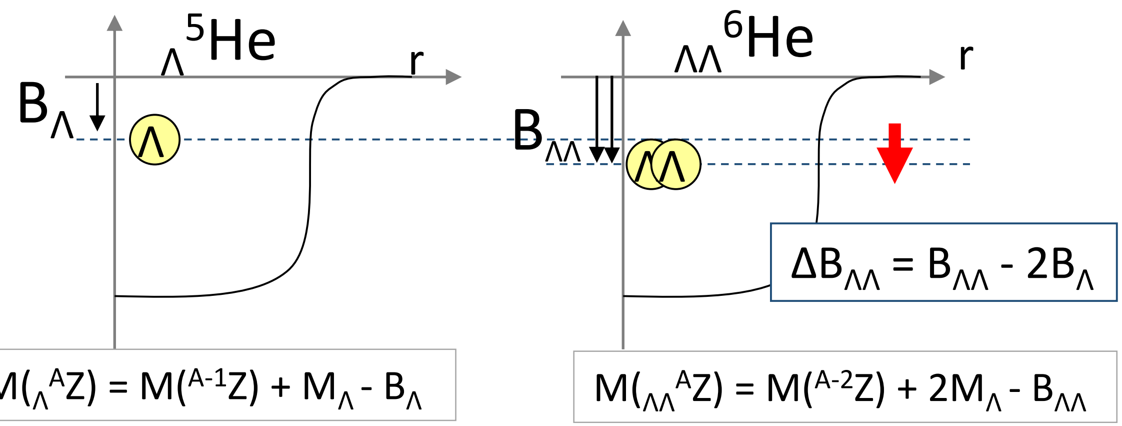
$\text{Mass}(Z) = \text{SUM}(\text{Mass} + \text{kinetic energy})$

Nagara event

H. Takahashi, et.al.: Phys. Rev. Lett. 87 (2001) 212502.
J. K. Ahn, et.al.: Phys. Rev. C 88 (2013) 014003.





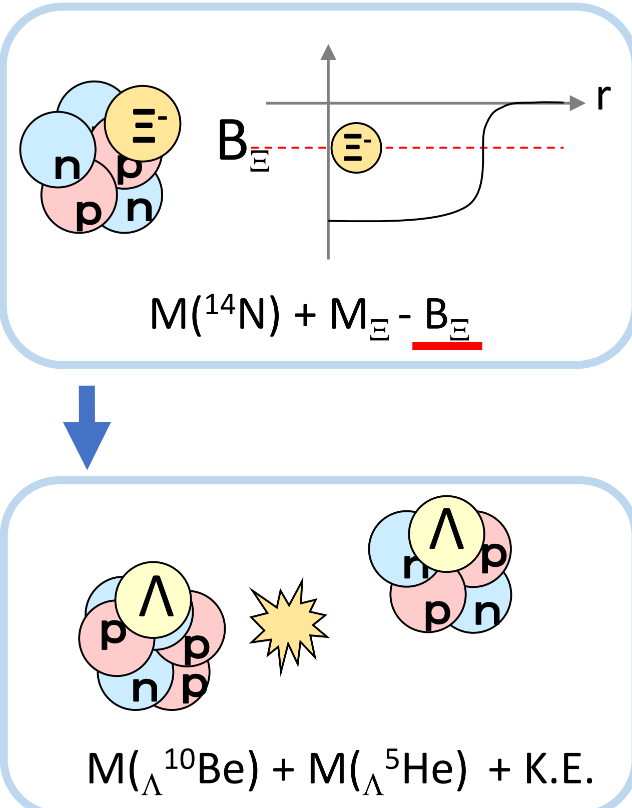


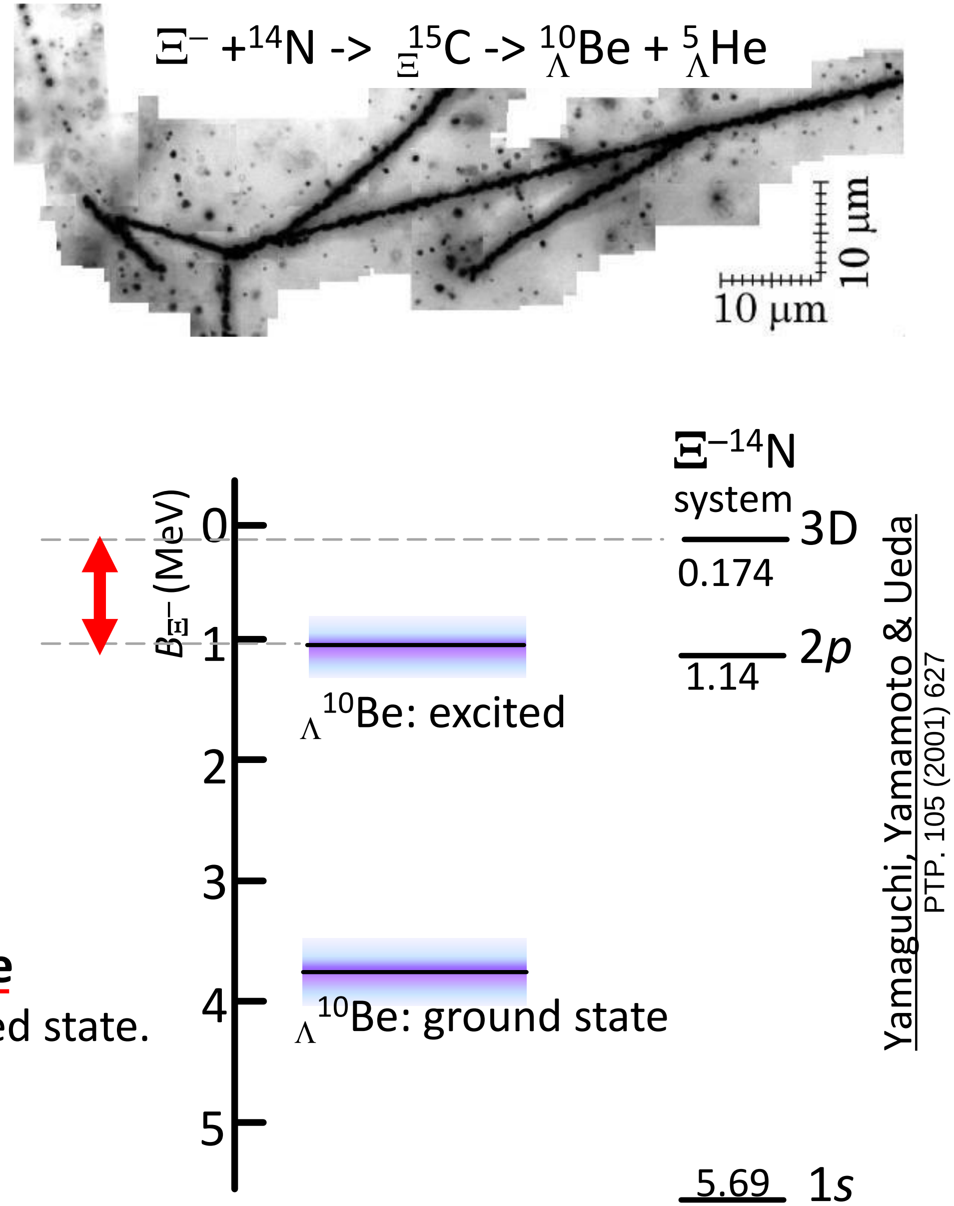
ΛΛ interaction is weekly attractive

$\Delta B_{\Lambda\Lambda}$ = 0.67 +- 0.17 MeV

Where, B_{Ξ^-} = 0.13 MeV

Kiso Event: *PTEP.* (2015) 033D02.





More deep level than the atomic one

even the daughter ${}_\Lambda^{10}Be$ was in any excited state.

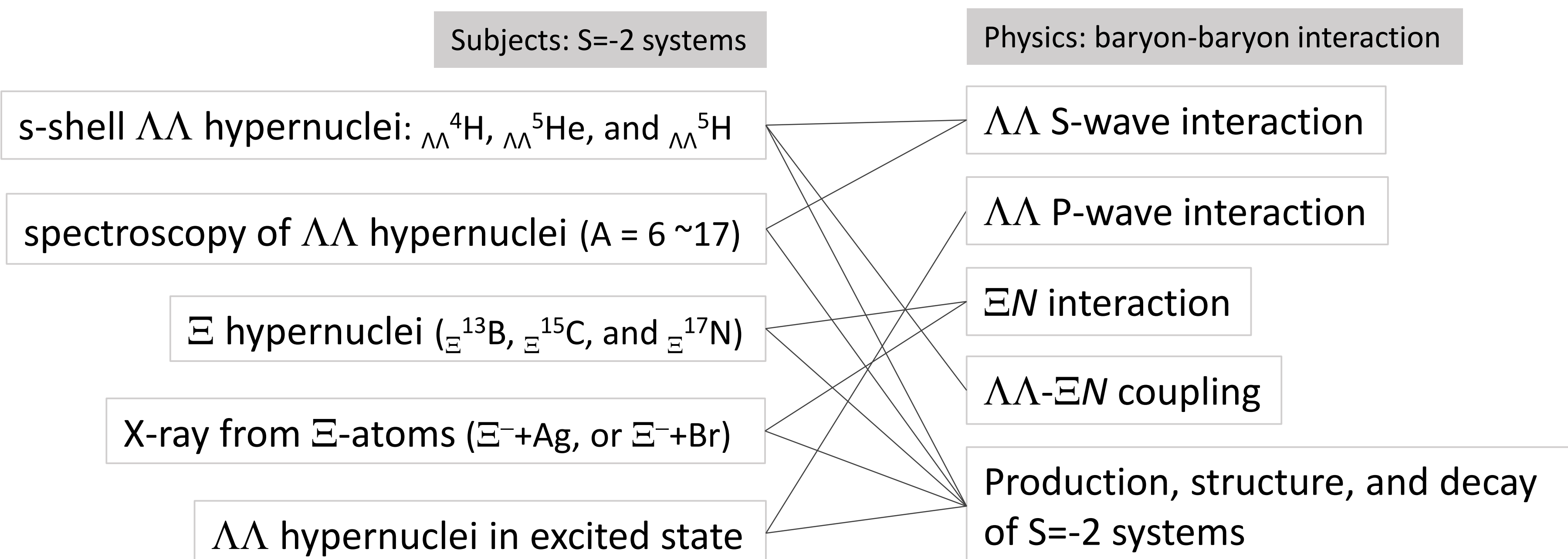
1.03 +- 0.18 or 3.87 +- 0.21 MeV

Annu. Rev. Nucl. Part. Sci. 2018. 68:131–159

Concept: More than 10 times statistics of KEK-PS E373, 10k Ξ^- stop events

	KEK-PS E373	J-PARC E07 (in proposal)
Emulsion gel	0.8 tons	2.1 tons
Purity of K^- beam	25%	~85%
Ξ^- stop yield	~650	10k
S=-2 hypernuclei	9	$\sim 10^2$

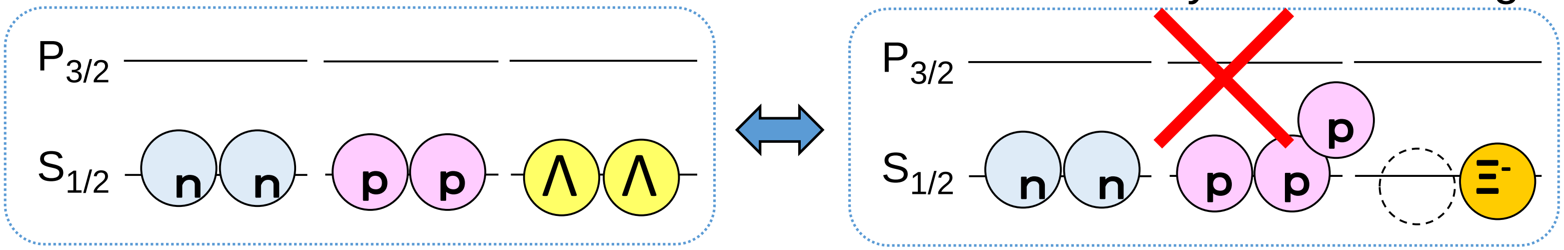
Physics motivations



ΛΛ-Ξ*N* coupling effect

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

Forbidden by Pauli blocking



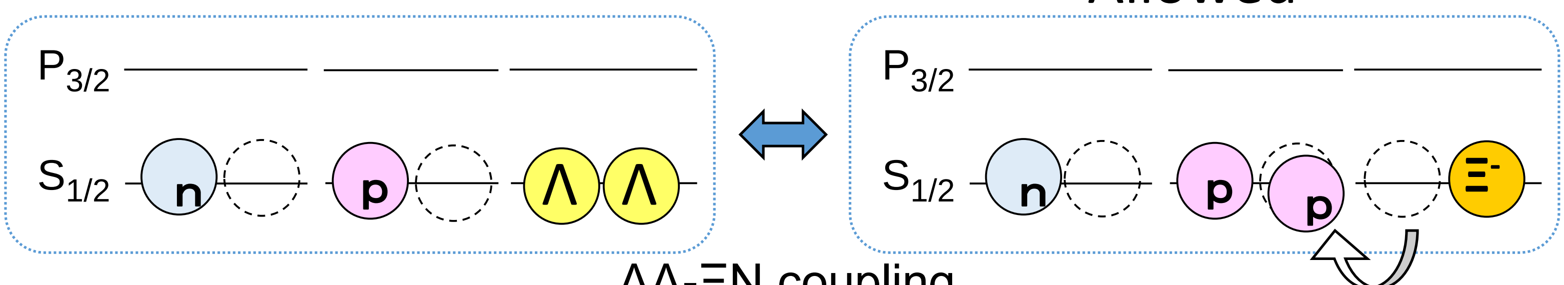
ΛΛ-ΞN coupling

ΛΛ-Ξ*N* coupling effect is small in $^{6}_{\Lambda\Lambda}$He and the p-shell double Λ hypernuclei

- I.R. Afnan and B.F. Gibson, Phys. Rev. C67, 017001 (2003).
- Khin Swe Myint, S. Shinmura and Y. Akaishi, nucl-th/029090.
- T. Yamada and C. Nakamoto, Phys. Rev.C62, 034319 (2000).

$^{4}_{\Lambda\Lambda}$H

Allowed

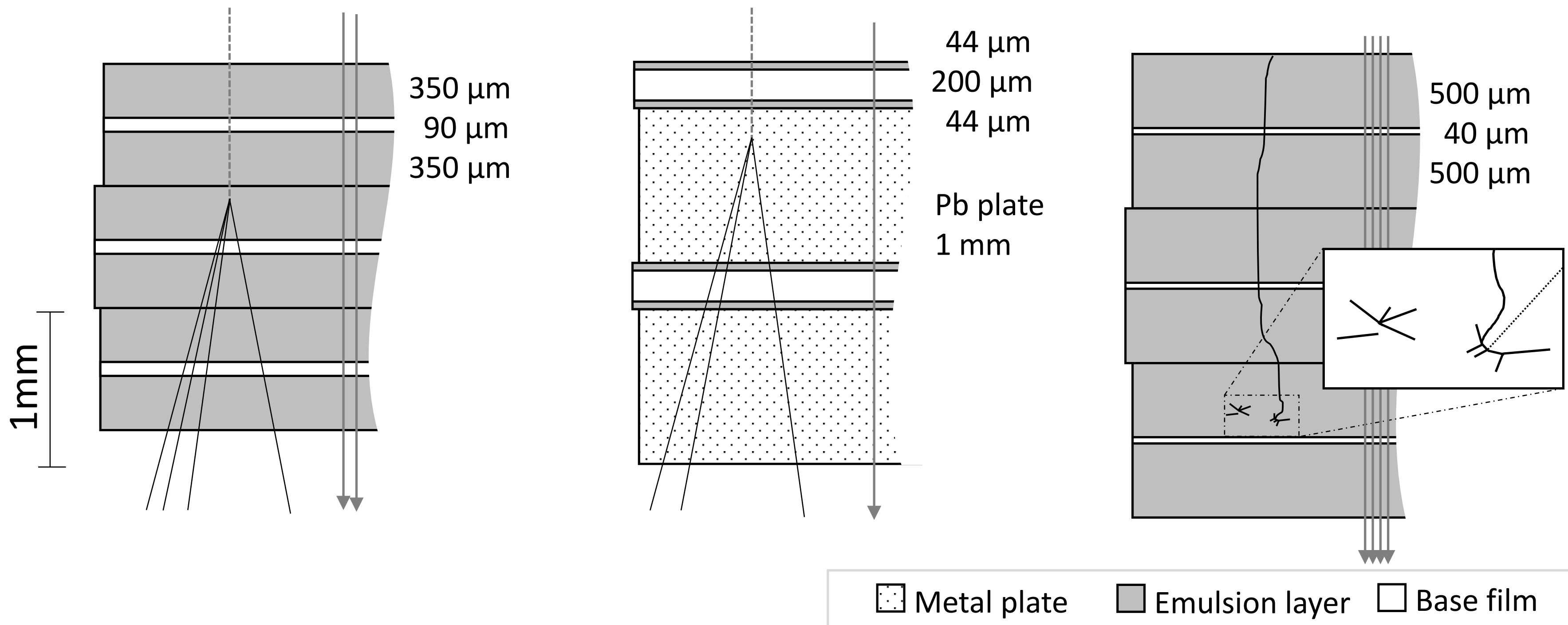


ΛΛ-ΞN coupling

If the strength of ΛΛ-Ξ*N* coupling is enough large, $^{4}_{\Lambda\Lambda}$H can be bound.

Comparison between our and other emulsion experiments

CHORUS | OPERA | J-PARC E07



Track density[/cm2]

CHORUS	OPERA	J-PARC E07
μ^- : 10^4	Cosmic μ for alignment: 10^2	π^- or K^- beam: 10^6
Cosmic μ: 10^4	Compton e: 10^5	2ry particles: 10^5

J. Yoshida et al., N. I. M. A 847 (2017) 86–92

Long walk to J-PARC E07

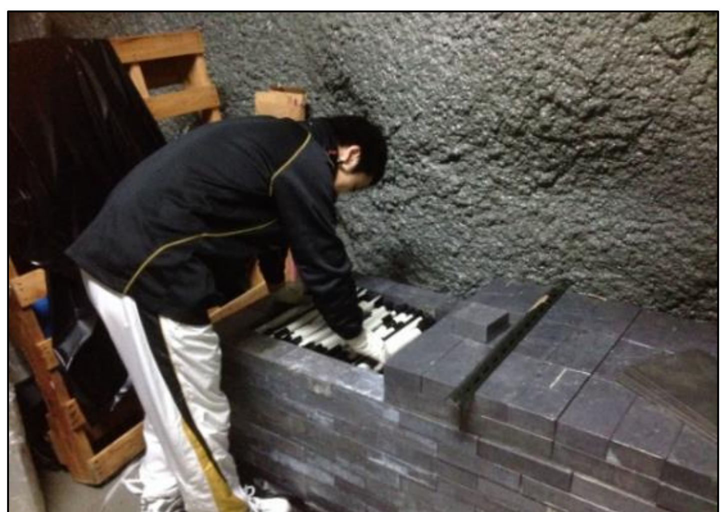
2001	Emulsion experiment BNL E964 was accepted
2006	E964 was cancelled
2007	J-PARC E07 was accepted
2011	Earthquake
2013	Radiation leak accident
2016	1st physics run
2017	2nd physics run

successfully completed

2012-
Emulsion facility in Gifu-Univ.

2013-2014
Emulsion sheet making

2014-2017
Storage in Kamioka mine

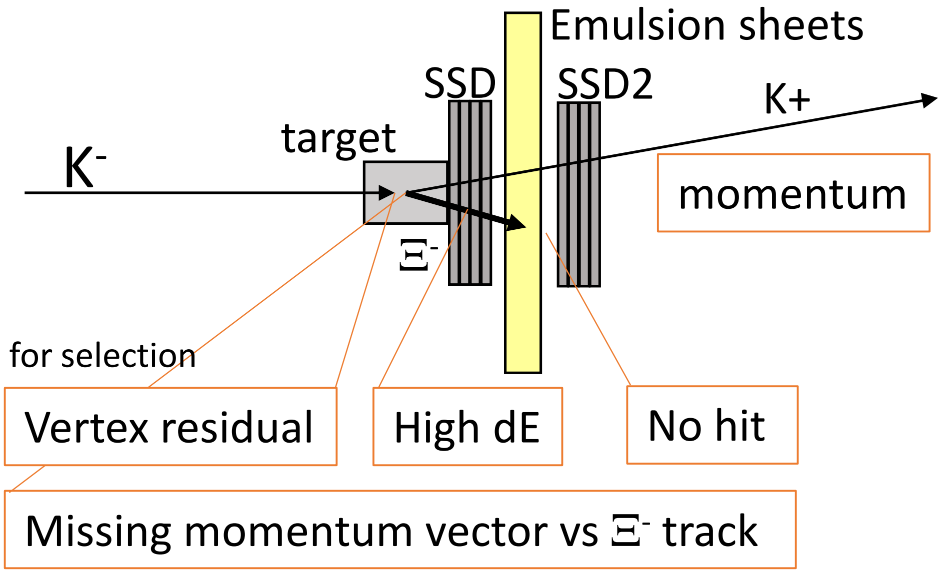


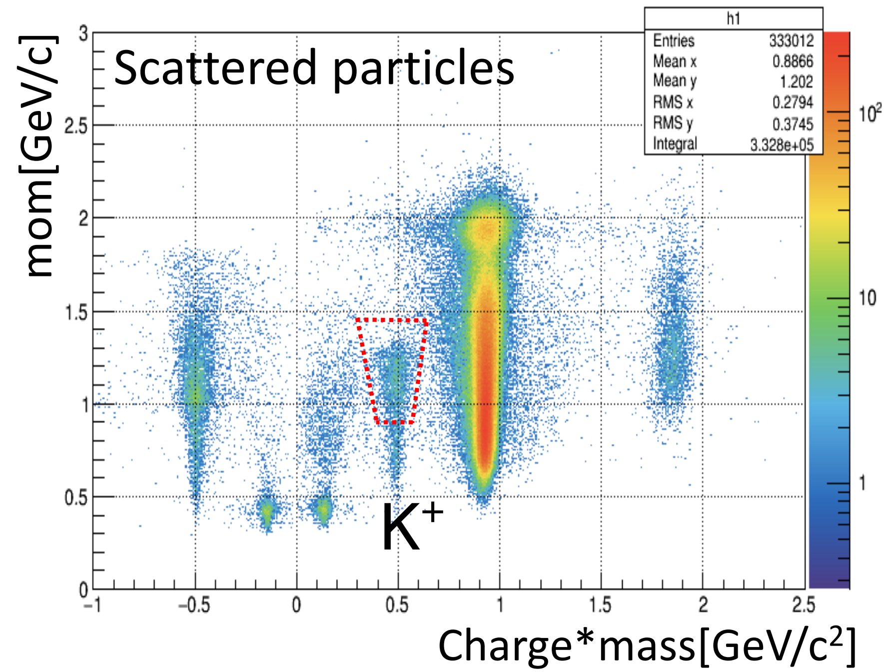
2016-2017
Refreshing

Back up slides:

Event hunting in photographic emulsion sheet

Ξ^- selection from the (K-, K+) reaction by off-line analysis



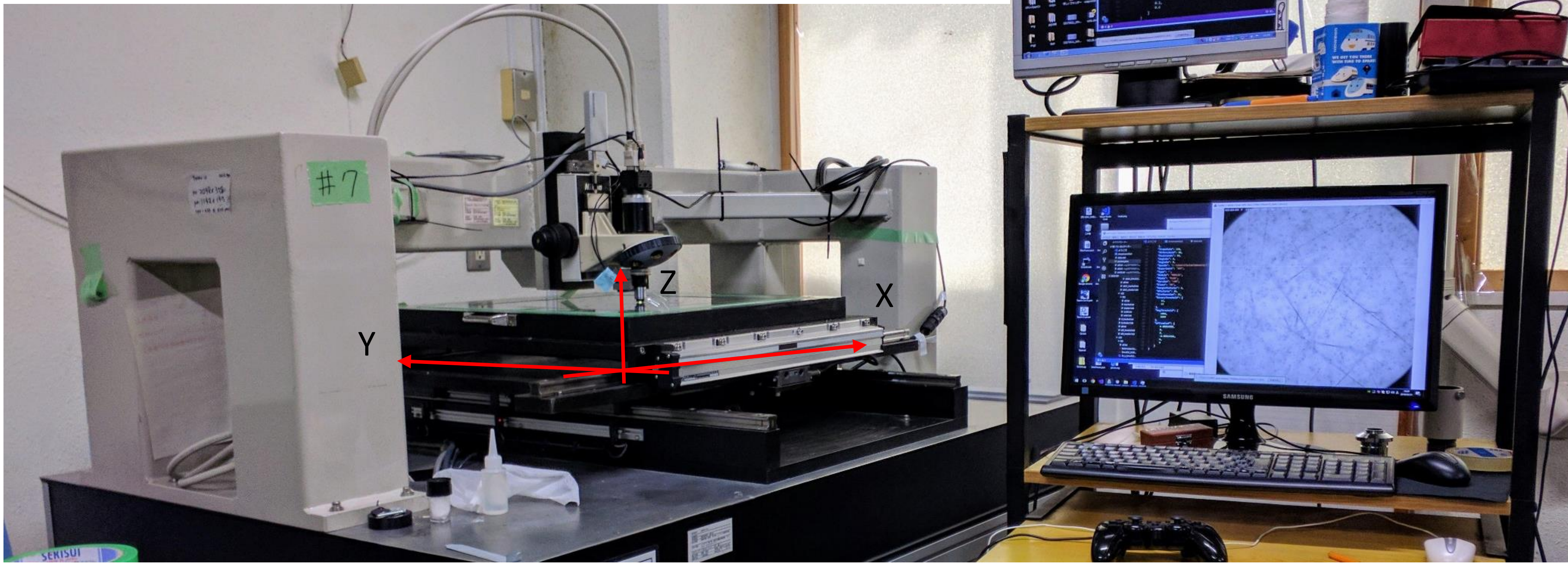


Criteria for Ξ^- track selection

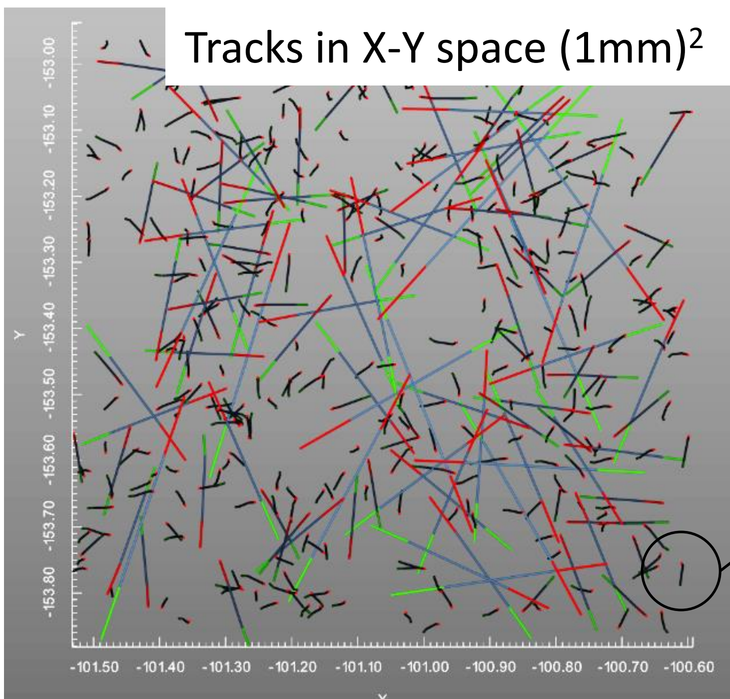
by simulation for 118 modules

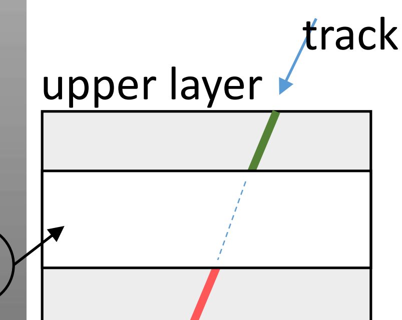
Level	Ξ^- stop	prediction	prediction /mod.	
1	9k	52k	~440	High S/N & stop ratio
2	1k	100k	~850	Realistic selection (+ a few year)
3	1k	~0.7M	6.2k	All Ξ^- stop
4	negligible	~1.9M	16k	All combination

Scanning machine for pl01, scanning time: 2~3hours



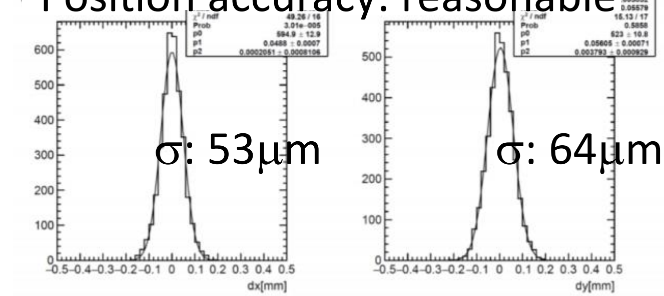
Tracks in X-Y space $(1mm)^2$



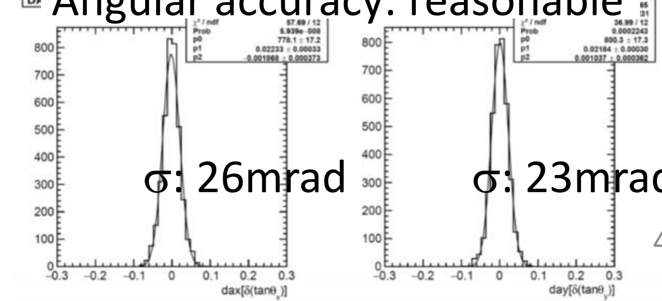


with SSD->pl01 protons

Position accuracy: reasonable

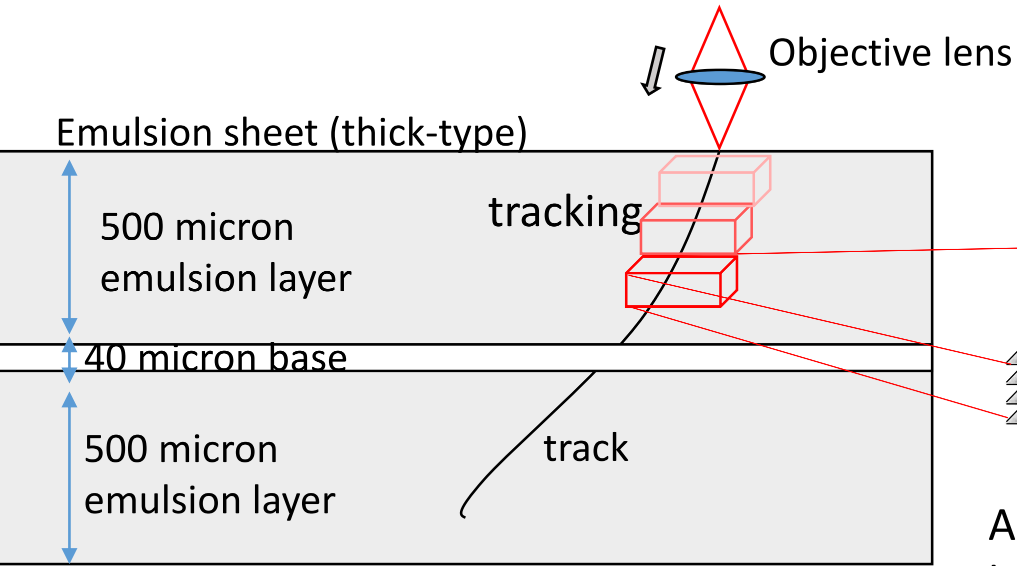


Angular accuracy: reasonable

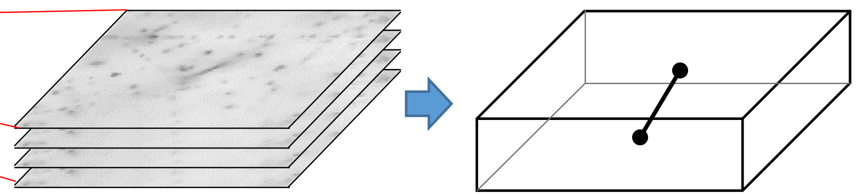


Ξ- tracking in thick-type sheet

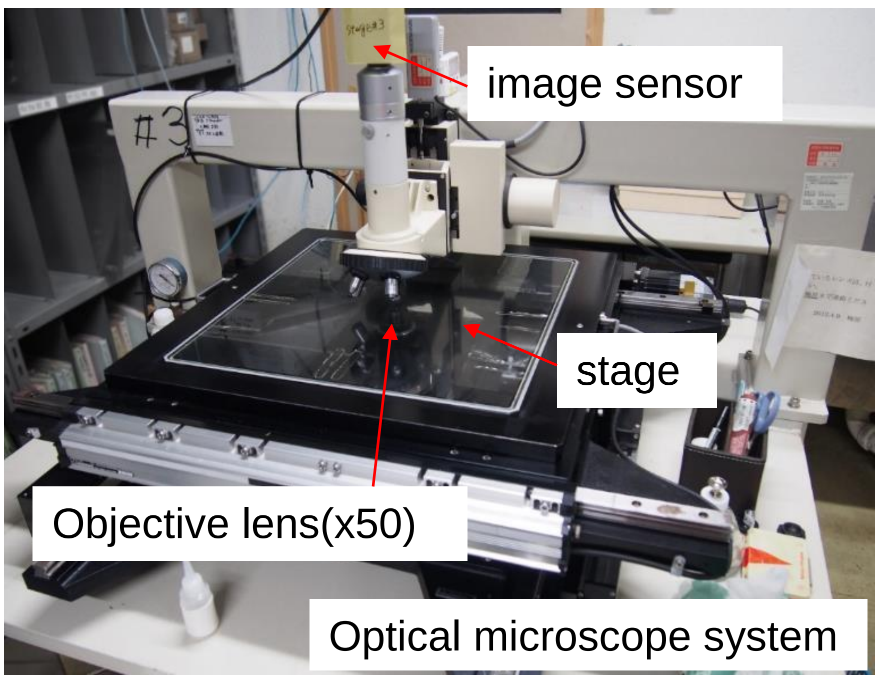
M.K.Soe et al., NIM-A 848 (2017) 66–72

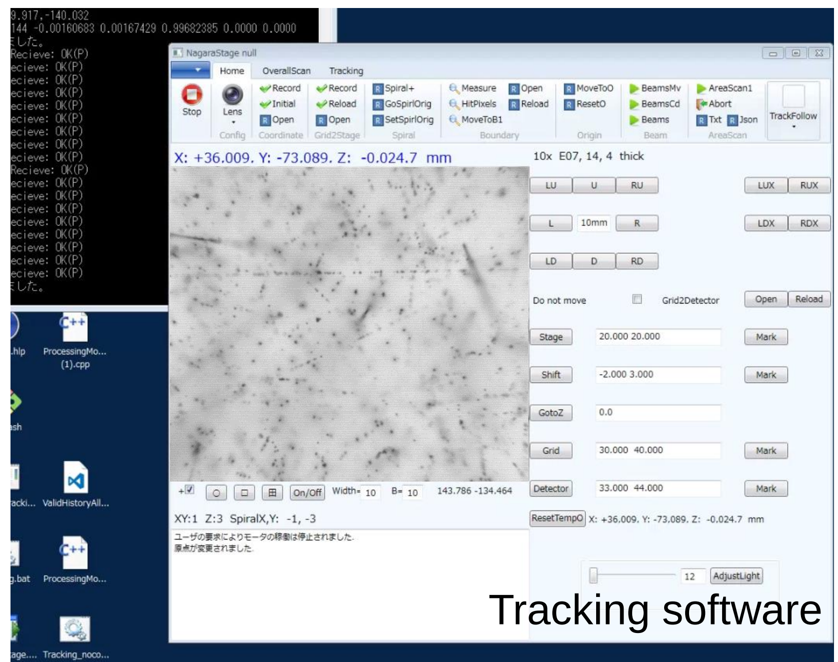


* Tracking with image processing



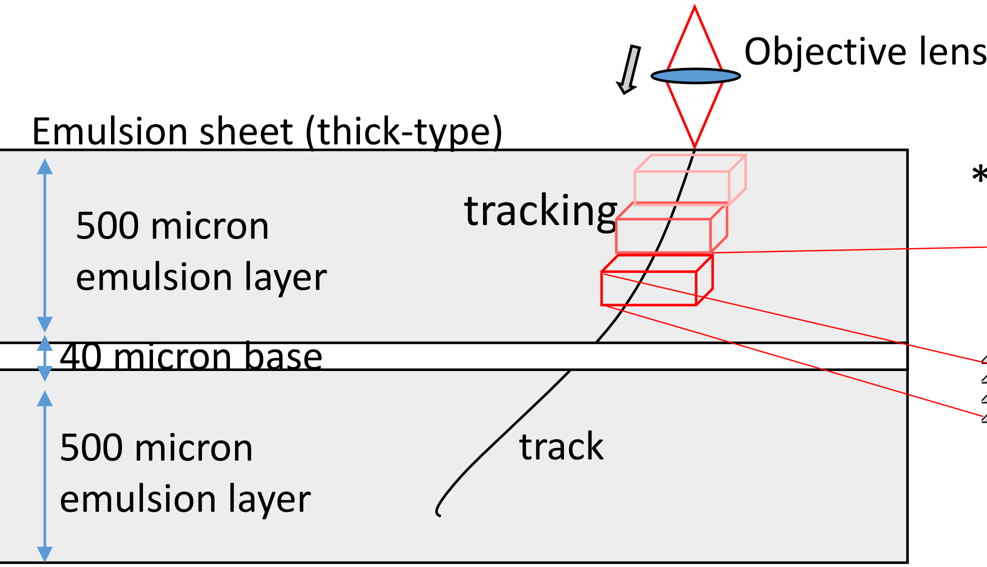
Automated Track Following (Sample Movie)
https://youtu.be/3fiWI5tDx2U



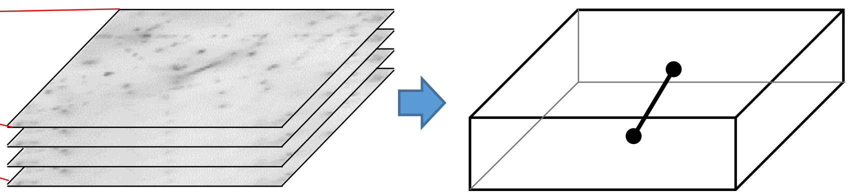


Ξ- tracking in thick-type sheet

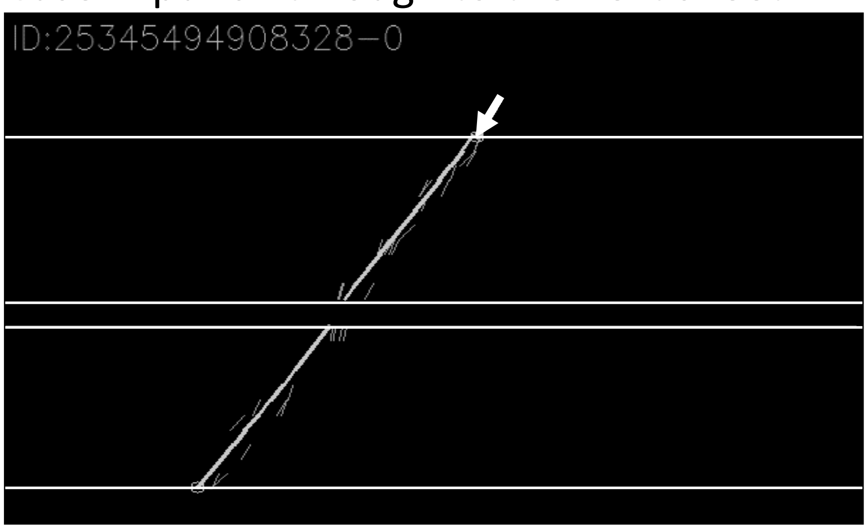
M.K.Soe et al., NIM-A 848 (2017) 66–72



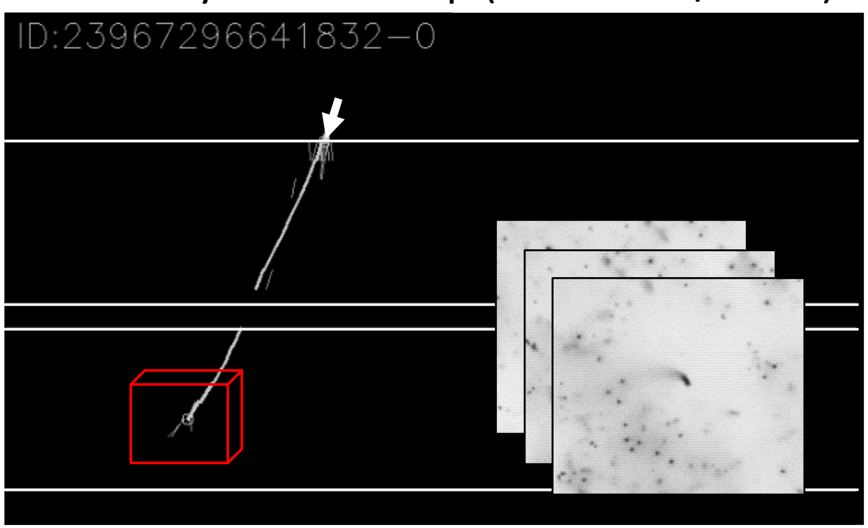
* Tracking with image processing



Case1. punch through to the next sheet



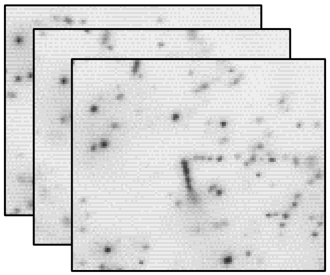
Case2. dizzy track -> stop (~30 tracks/sheet)



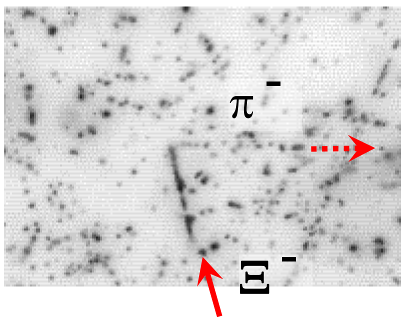
Around stop point -> eye-check

Observation of endpoint

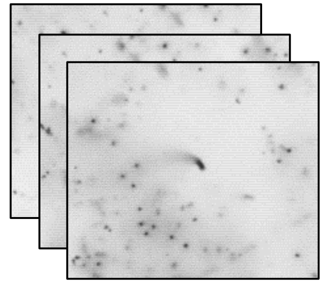
Case1. $\Xi^-\to\Lambda\pi^-$ decay



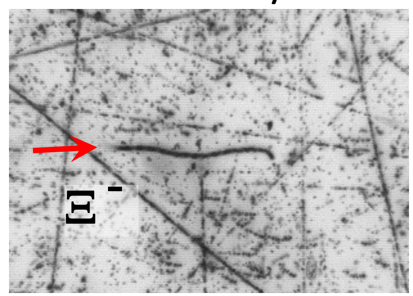
~100 events / mod



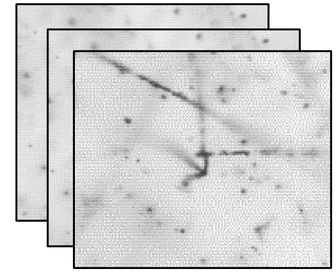
Case2. no visible fragment



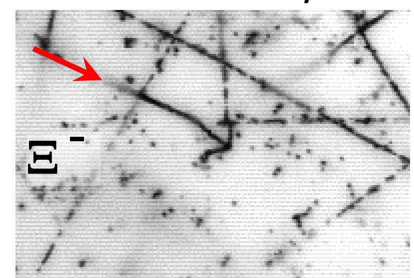
~100 events / mod



Case3. with hyperfragment

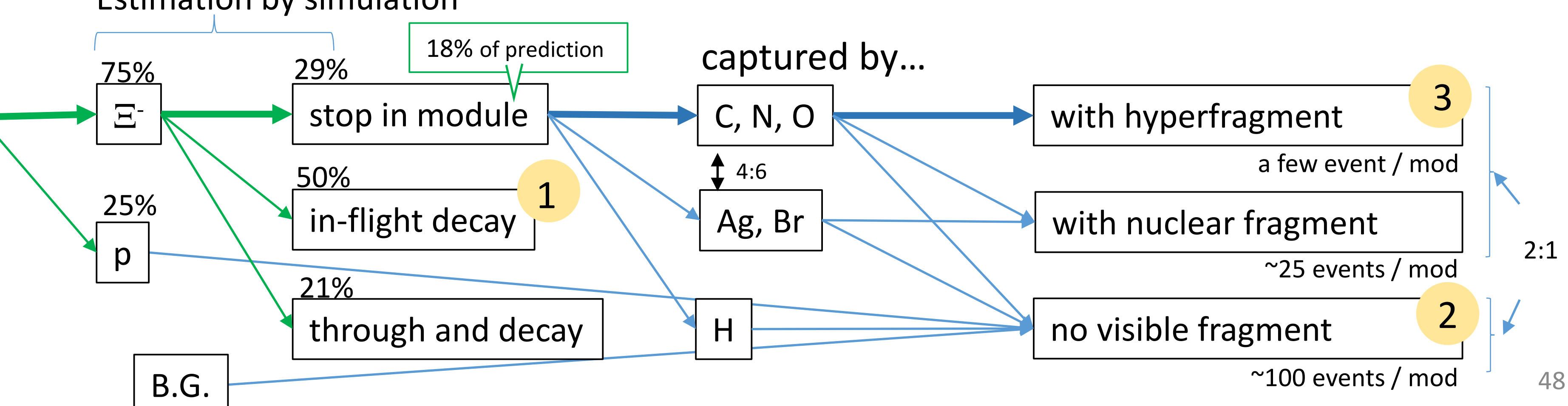


a few events / mod

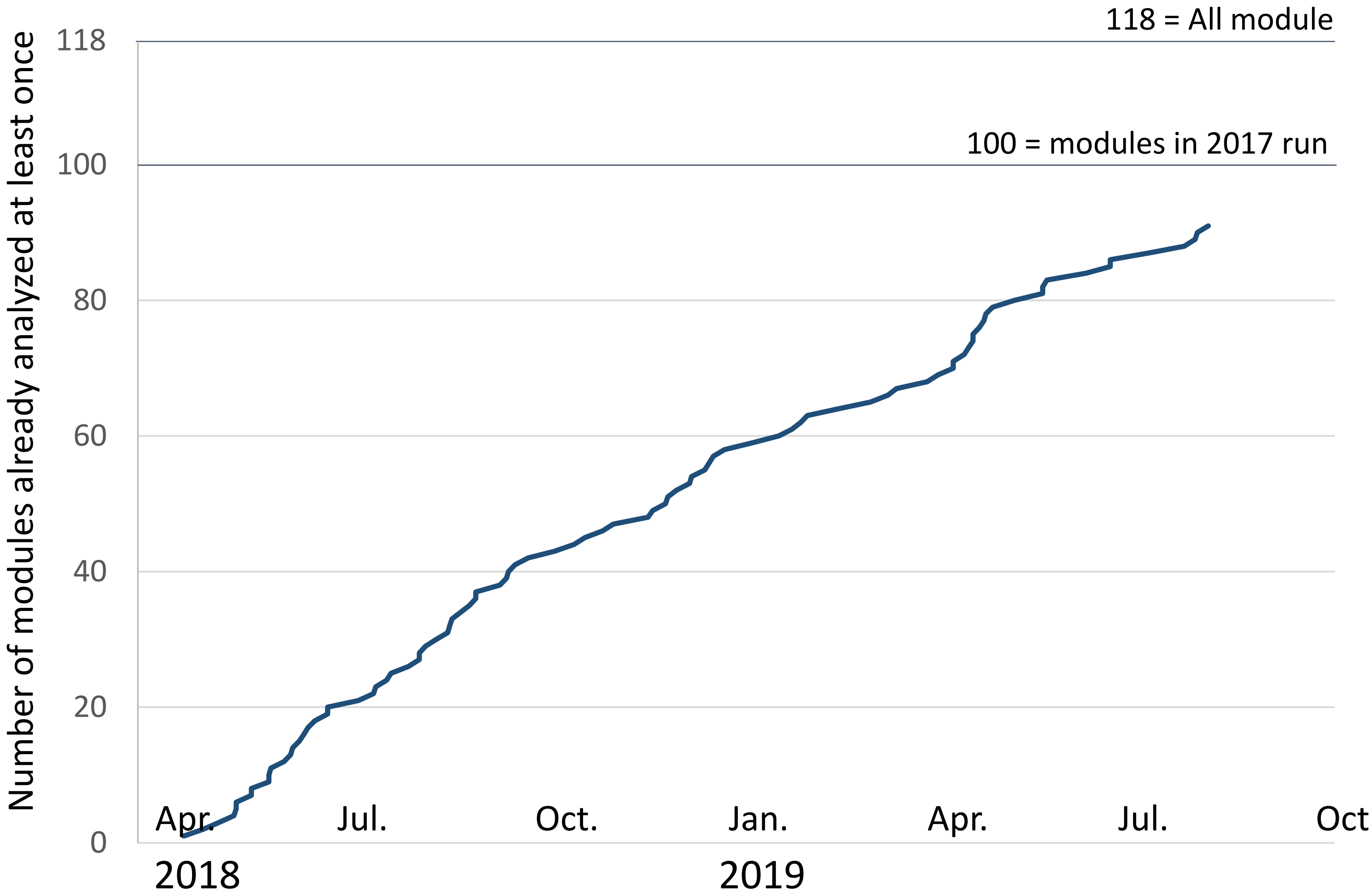


-> detail analysis

Estimation by simulation



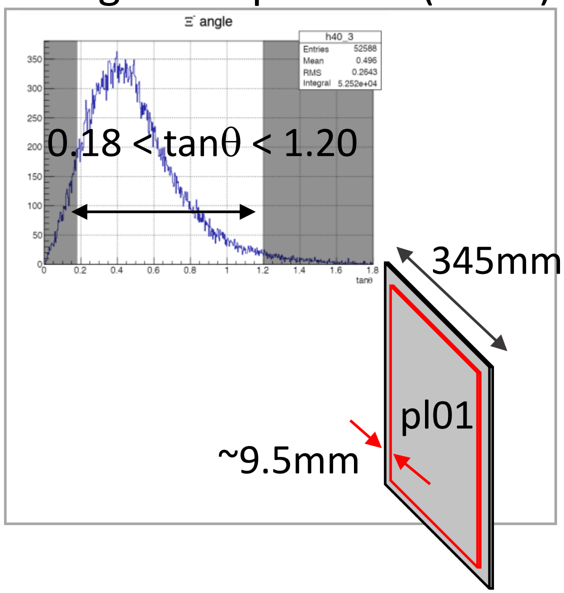
Progress of track following



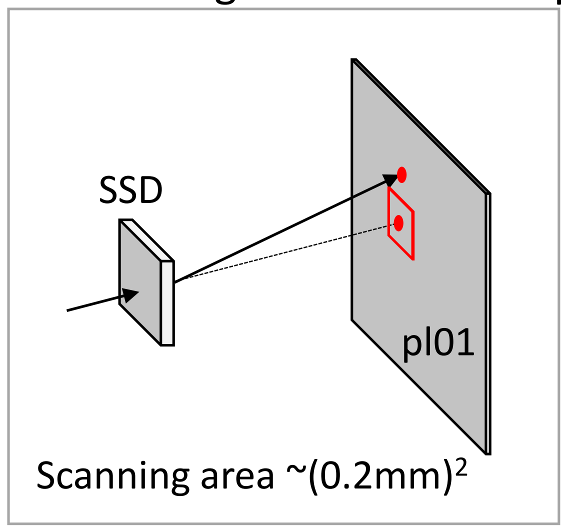
Scanned: 80% of emulsion sheets at least once
Found S=-2 systems: 30 events

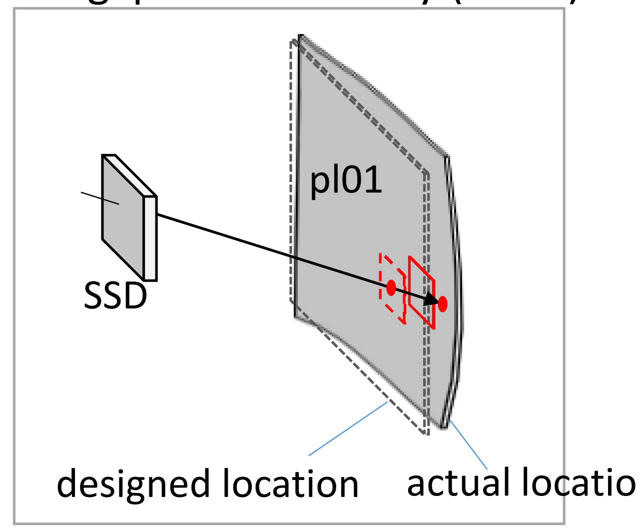
Current event finding efficiency is about 50%
The Inefficiency is due to…

* Angle and position (x80%)



* Scattering in SSD and SSD-pl01 gap un-uniformity (x60%)



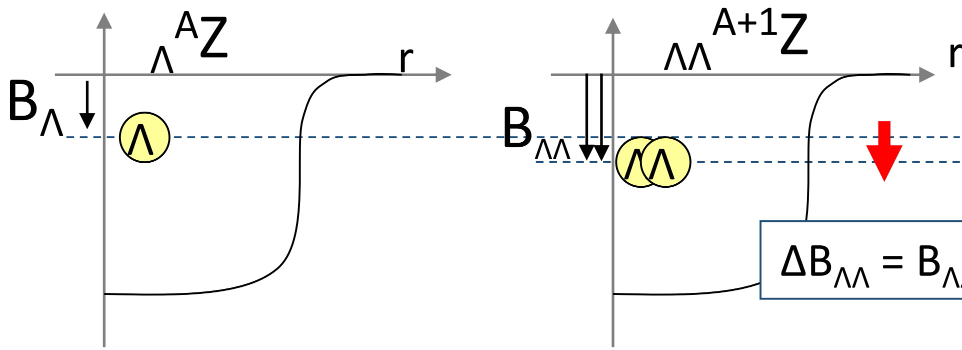


* The correction technique is being developed

Back up slides:

Event by event analysis

On ΛΛ interaction

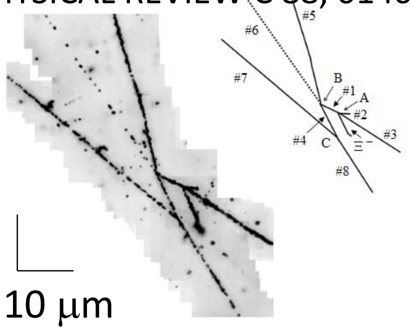


$\Delta B_{\Lambda\Lambda}$, An index of ΛΛ interaction

$\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda} - 2B_{\Lambda}$

NAGARA Event (2001)

PHYSICAL REVIEW C 88, 014003 (2013)

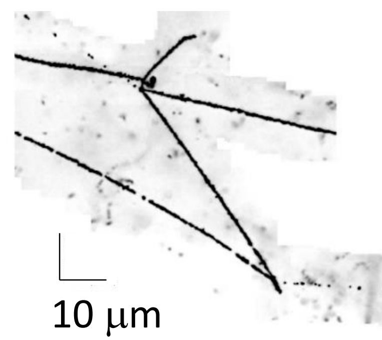


	$\Delta B_{\Lambda\Lambda}$ [MeV]
$_{\Lambda\Lambda}^{6}He$	0.67 +- 0.17

where, B_{Ξ^-} = 0.13 MeV

MINO Event (2019)

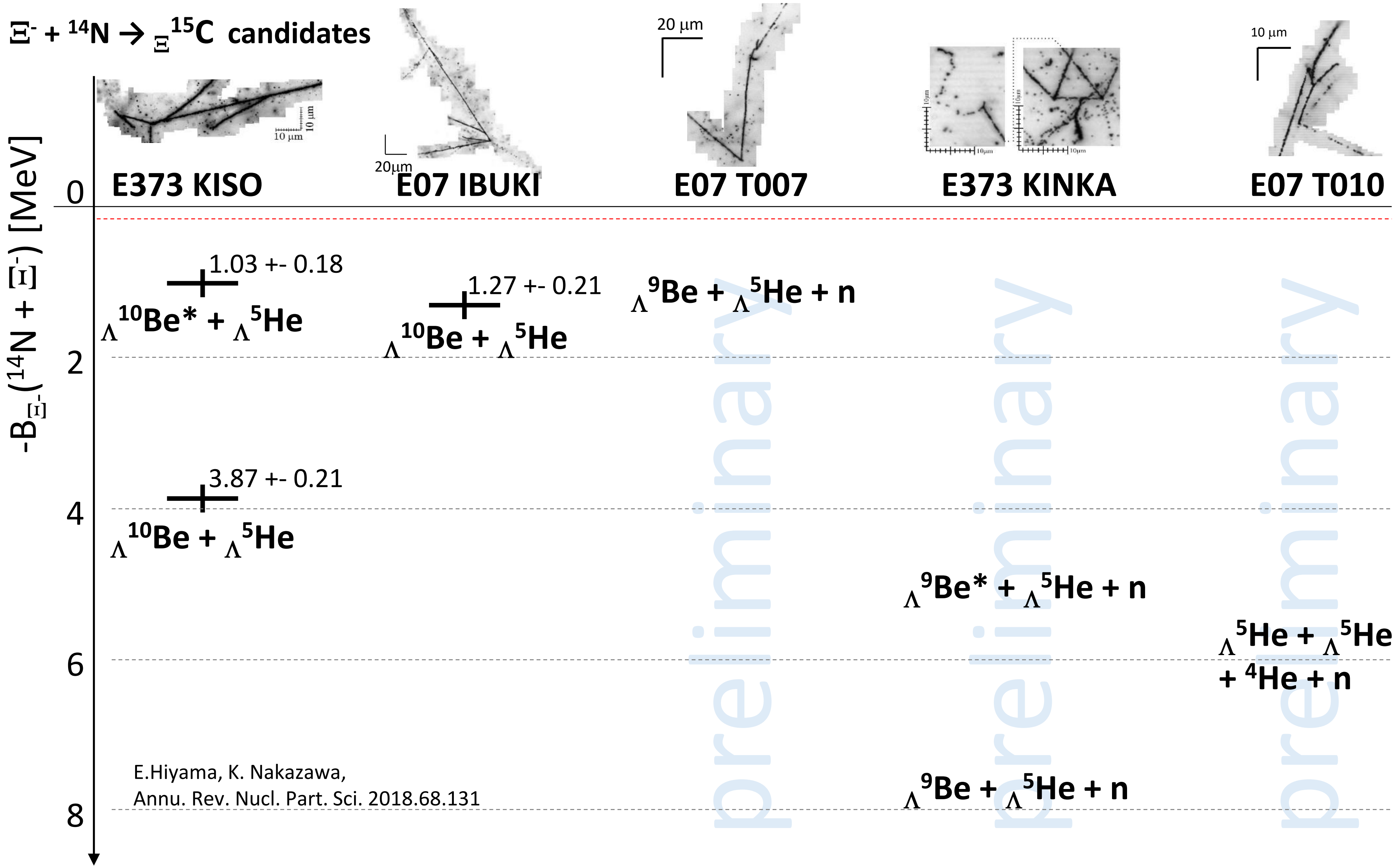
Prog. Theor. Exp. Phys. 2019, 021D02



	$\Delta B_{\Lambda\Lambda}$ [MeV]
$_{\Lambda\Lambda}^{11}Be$	1.87 +- 0.37

where, B_{Ξ^-} = 0.23 MeV

- ΛΛ interaction is weak attractive force.
- New information on ΛΛ interaction in nuclide.

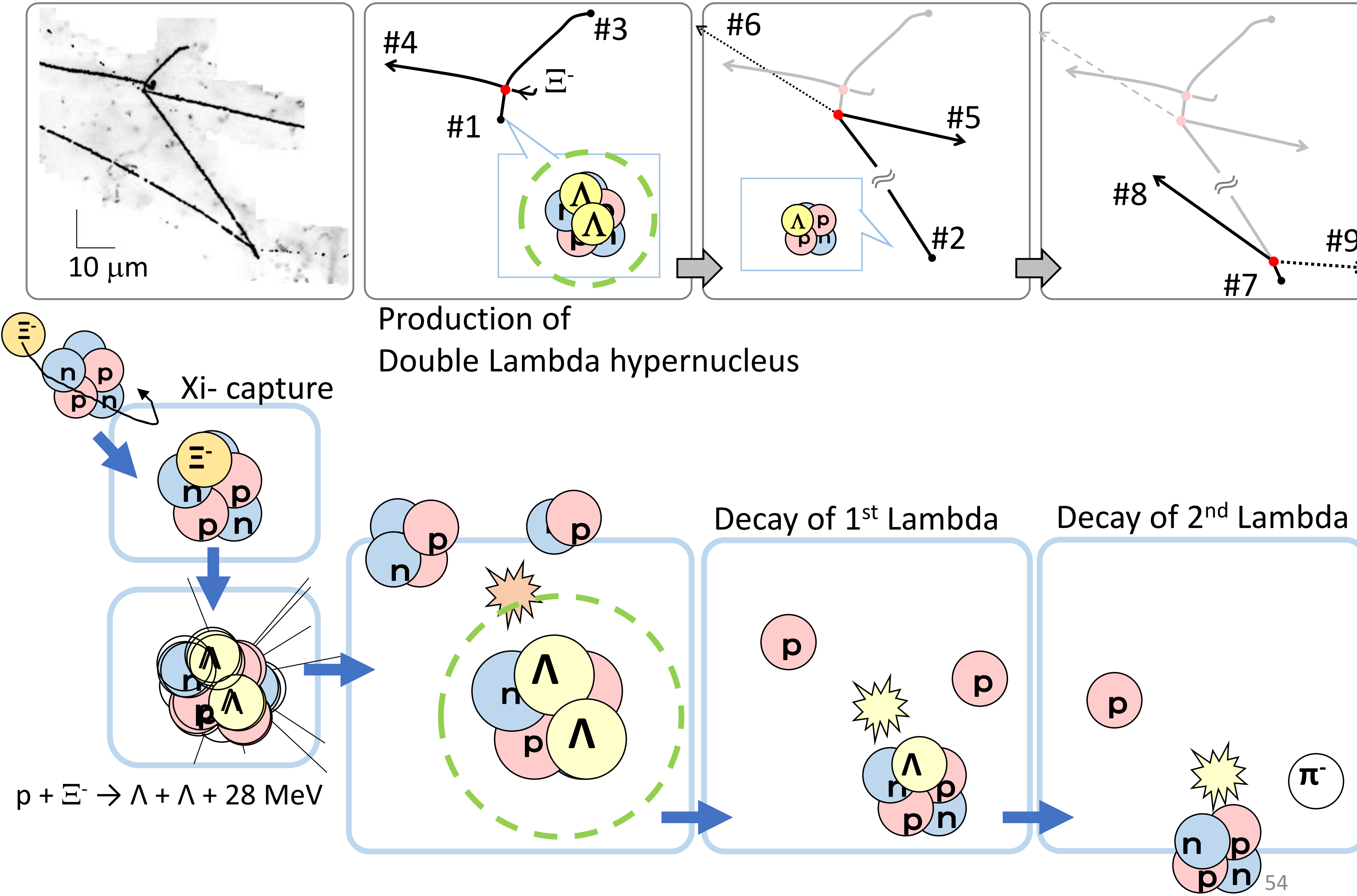


* The red dashed line is 0.174 MeV, 3D atomic state.
* **Multiple candidates of Ξ hypernucleus (B_{Ξ^-} > 3D atomic level) has been found.**
* These events suggest multiple bound states of Ξ^- in the Ξ^- + ^{14}N system.

MINO event

Mod#069 pl07
ID : 22381499289376

H. Ekawa et al.,
Prog. Theor. Exp. Phys. 2019, 021D02

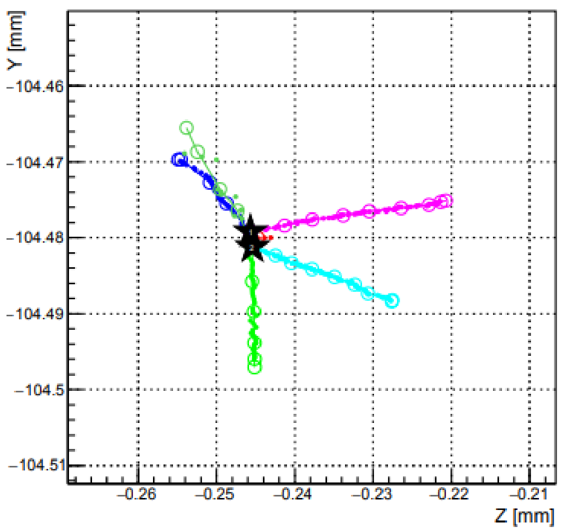


How we identify the nuclides?

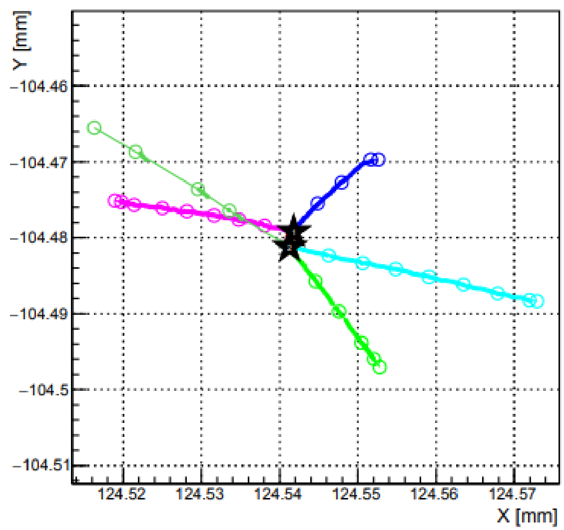
Step1: Measurement of geometrical feature by image processing

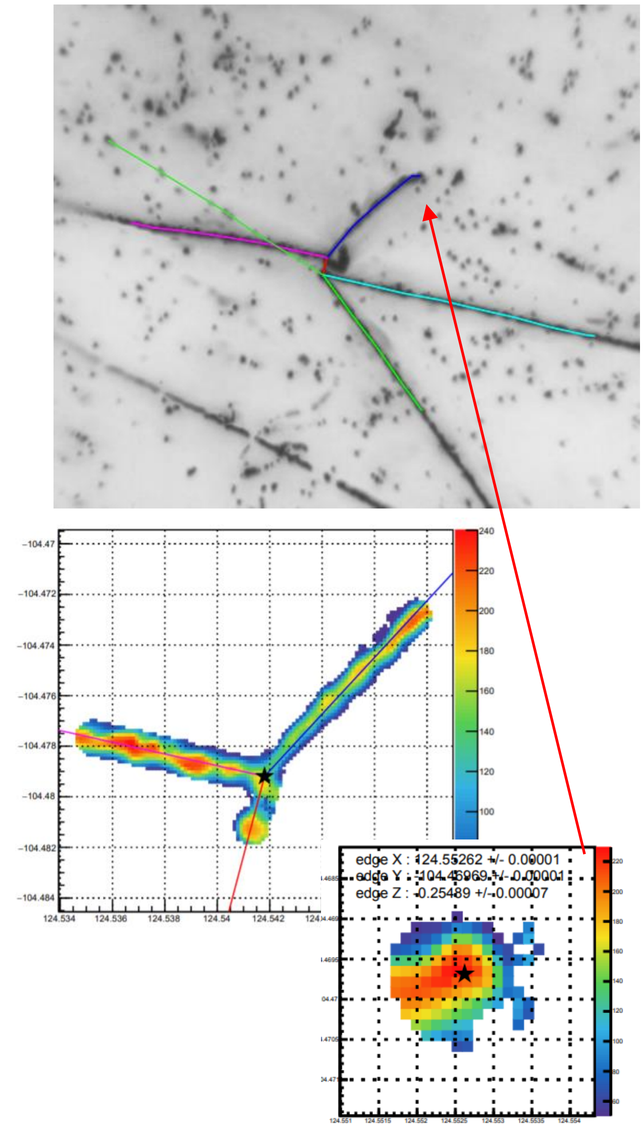
By H. Ekawa

Y : Z



Y : X





vertex 1 : (124.54180, -104.47919, -0.24566)
vertex 2 : (124.54129, -104.48119, -0.24541)

range 1 : 2.08 +/- 0.21
edge 1 : (124.54129, -104.48119, -0.24541)

range 2 : 19.59 +/- 0.30
edge 2 : (124.55279, -104.49704, -0.24513)

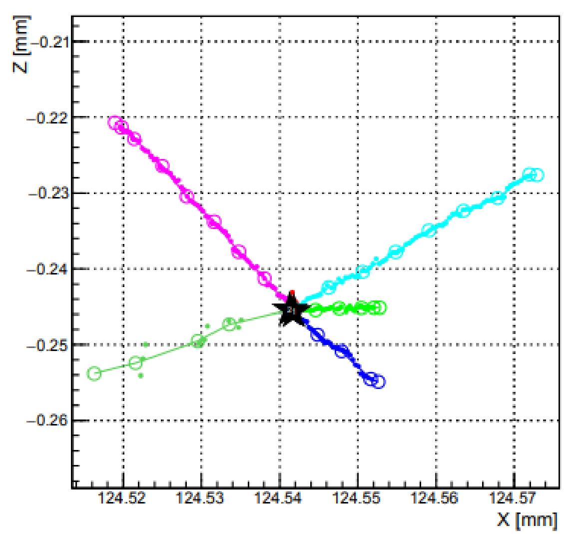
range 3 : 17.44 +/- 0.18
edge 3 : (124.55262, -104.46969, -0.25489)

range 4 : 34.15 +/- 0.33
edge 4 : (124.51896, -104.47512, -0.22073)

range 5 : 37.29 +/- 0.32
edge 5 : (124.57291, -104.48835, -0.22764)

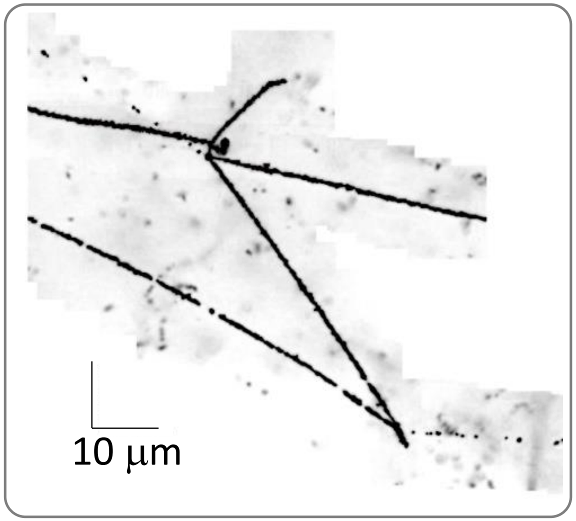
range 6 : 30.79 +/- 0.31
edge 6 : (124.51629, -104.46550, -0.25382)

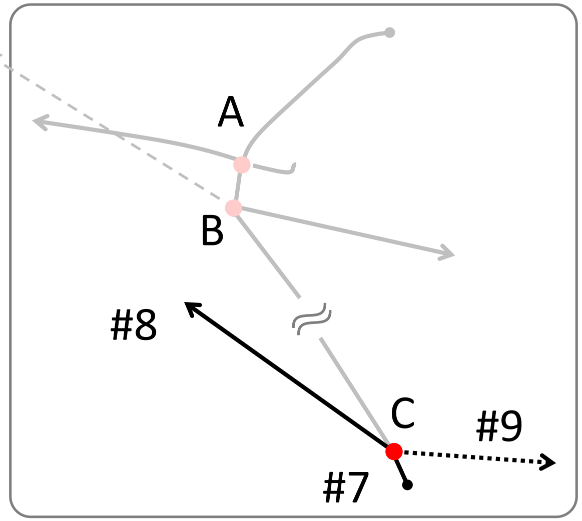
Z : X



How we identify the nuclides?

Step2: Evaluation of kinematic consistency for all possible cases.





Taking all possible combinations of nuclide for the parent and daughter particles.

Type	# of case	Example
Daughters without strangeness	65	π^-, p, d, t, ^{3}He, ^{4}H, ^{4}He, … ^{19}B, ^{19}C, ^{19}N, or ^{19}O
Neutral particles	10	n, 2n, 3n, π^0, π^0+n, π^0+2n, Λ, Λ+n, Λ+2n, or none
Single Λ hypernuclei	41	${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H, ${}^{4}_{\Lambda}$He, ${}^{5}_{\Lambda}$He, … , ${}^{17}_{\Lambda}$N, or ${}^{18}_{\Lambda}$N

Single-Λ hypernucleus (#2)		#7	#8	#9	χ^2	Range (#9) [μm]	Comment
~~${}^{4}_{\Lambda}$He~~	~~$\rightarrow$~~	~~^{3}He~~	~~p~~	~~π^-~~	~~33.1~~	~~16 800~~	~~rejected~~
${}^{5}_{\Lambda}$He	$\rightarrow$	^{4}He	p	π^-	5.23	16 270	
~~${}^{8}_{\Lambda}$Li~~	~~$\rightarrow$~~	~~^{6}Li~~	~~d~~	~~π^-~~	~~93.6~~	~~7906~~	~~rejected~~
~~${}^{9}_{\Lambda}$Li~~	~~$\rightarrow$~~	~~^{7}Li~~	~~d~~	~~π^-~~	~~105~~	~~10 660~~	~~rejected~~

➡ Possible solution.

Blackness of tracks are consistent to the solution.

Nuclides of found double Λ hypernuclei

		Captured by			Daughter					
		^{12}C	^{14}N	^{16}O	H	He	Li	Be	B	C
	Danysz	●						●		
	E176#15-03-37		●						●	
E373	**NAGARA**	●				●				
E373	MIKAGE	○	○			○		○		
E373	DEMACHI-YANAGI	○	○					○	○	
E373	HIDA		○	○				○		
E373	Other 3 events									
E07	D001	○	○				○	○		
E07	D002	○	○	○				○	○	○
E07	D003			●						●
E07	D004			●						●
E07	D005			●						●
E07	D006		○	○					○	○
E07	D007, **MINO**			●				●		
E07	D008									
E07	D009	○	○				○	○		
E07	D010	To be reported soon								
E07	D011	To be reported soon								
E07	D012	To be reported soon								

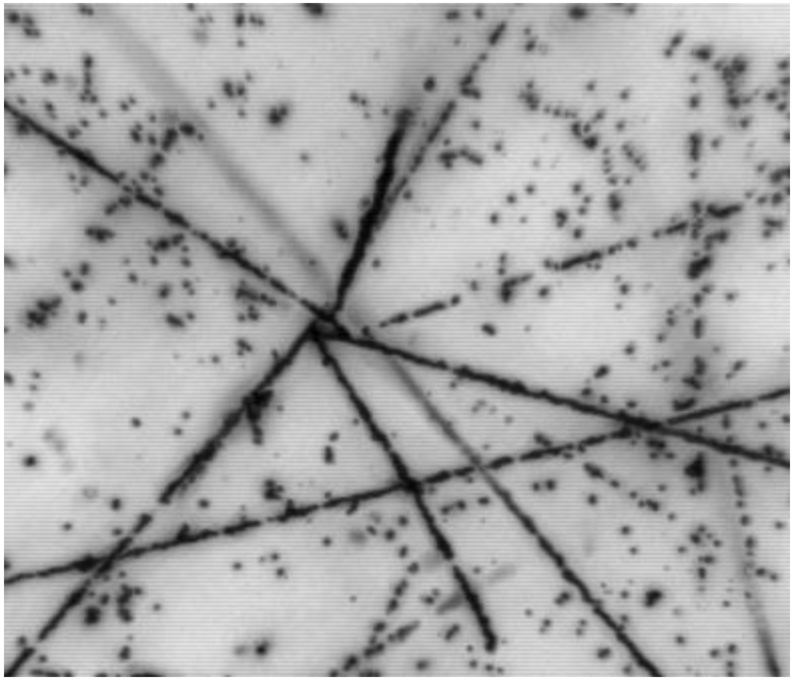
A consistent solution with Nagara

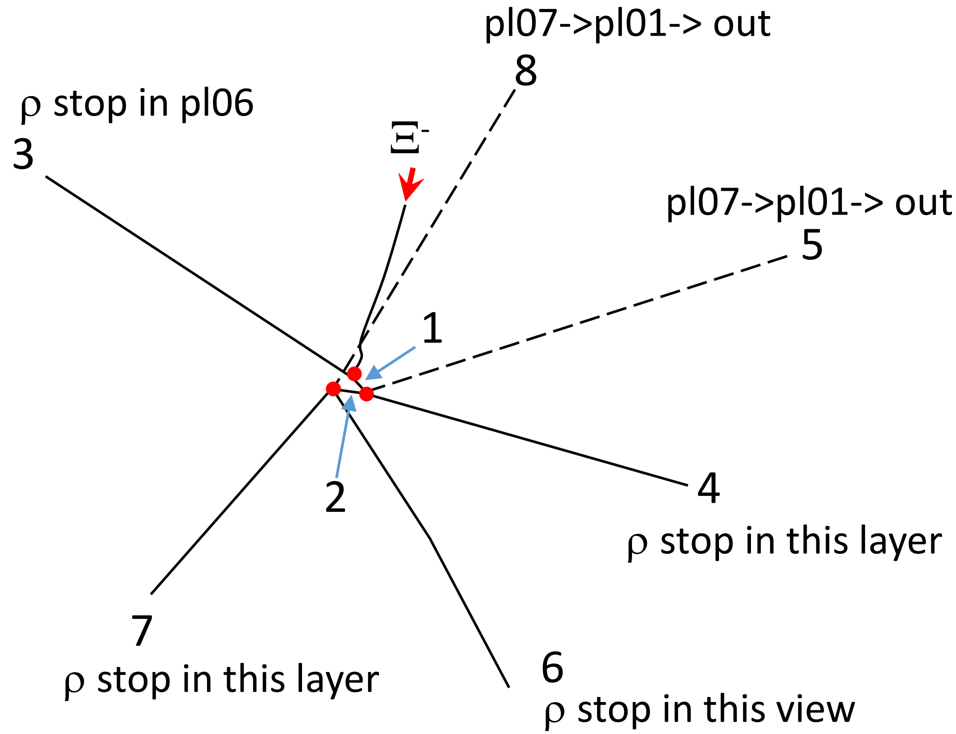
preliminary

●: Uniquely identified, ○: Multiple interpretations

- Statistical analysis with multiple events will provides information on $\Lambda\Lambda$ and ΞN interactions.

Double Λ event (D004)





preliminary result

$\Xi^- \, \& \, {}^{16}O \rightarrow {}_{\Lambda\Lambda}{}^{14}C + p + 2n$

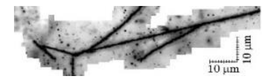
$\Xi^- \, \& \, {}^{16}O \rightarrow {}_{\Lambda\Lambda}{}^{14}C + d + n$

$\Xi^- \, \& \, {}^{16}O \rightarrow {}_{\Lambda\Lambda}{}^{15}C + p + n$

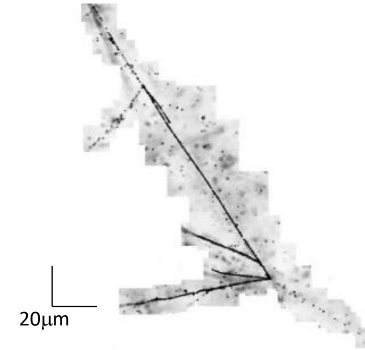
- Possible candidates are 3 listed above.
- The uncertainties of $B_{\Lambda\Lambda}$ of these candidate modes are large (more than 1 MeV)
- Anyway, something ${}_{\Lambda\Lambda}C$ was produced.

$\Xi^{-} + {}^{14}\mathrm{N} \rightarrow {}_{\Lambda}^{10}\mathrm{Be} + {}_{\Lambda}^{5}\mathrm{He}$

The Q-value of this decay mode is the highest among any channel producing "Twin single Λ hypernucleus".



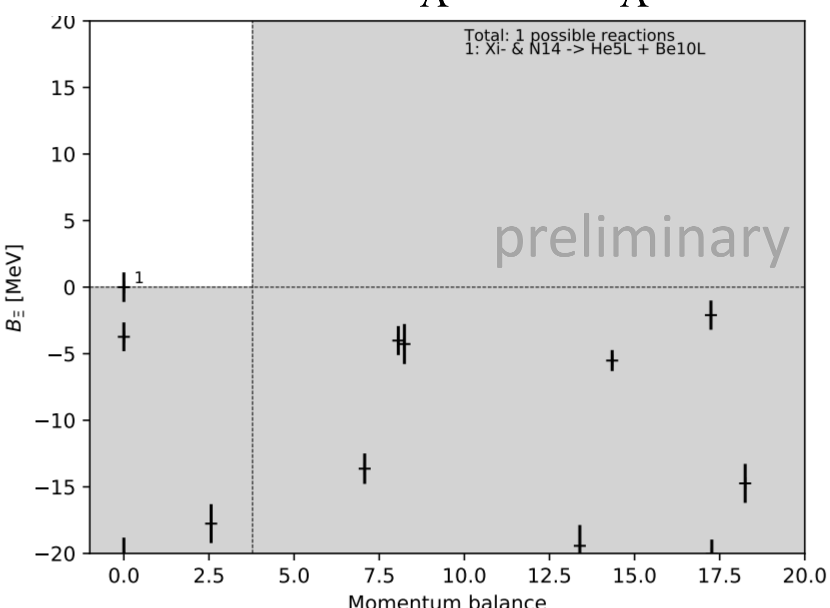
KEK-PS E373 KISO



J-PARC E07 IBUKI

Q-value: 22.1 MeV

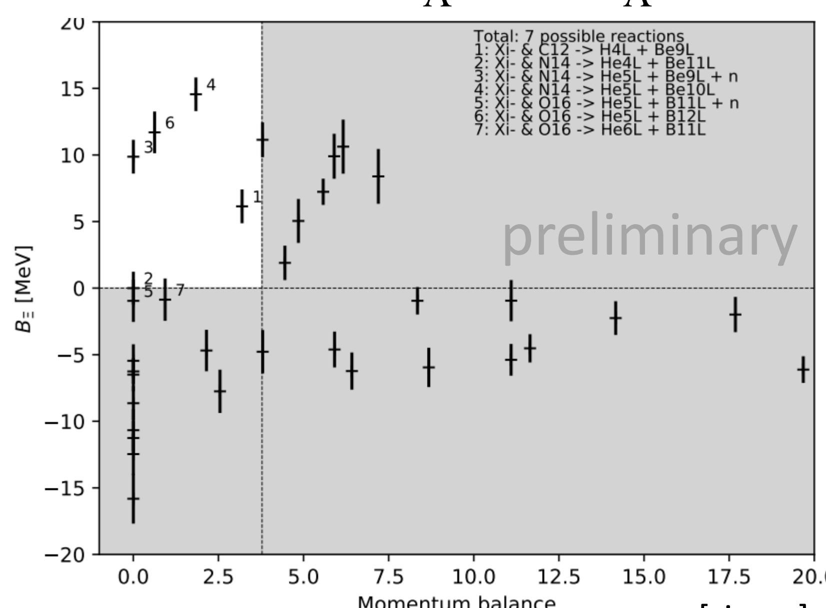
$\Xi^{-} + {}^{14}\mathrm{N} \rightarrow {}_{\Lambda}^{10}\mathrm{Be} + {}_{\Lambda}^{5}\mathrm{He}$



[sigma]

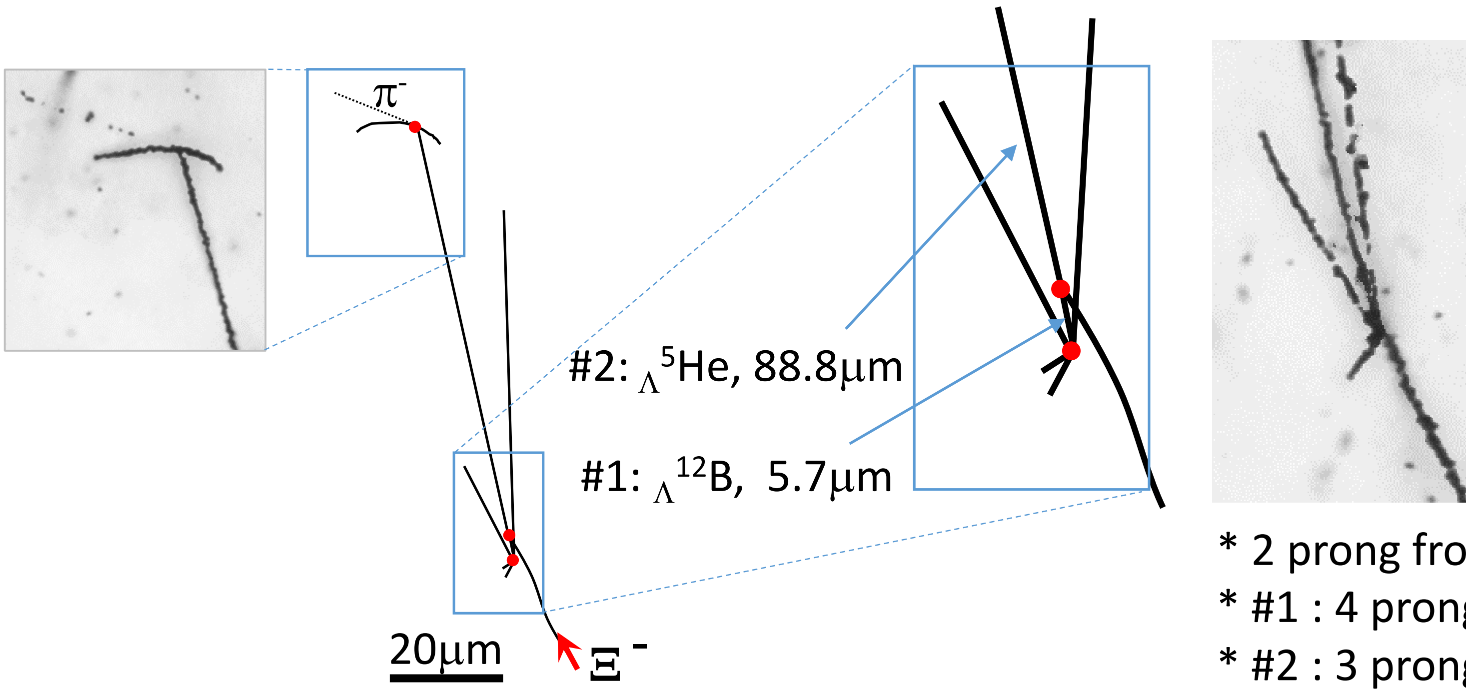
Q-value: 7.3 MeV

$\Xi^{-} + {}^{14}\mathrm{N} \rightarrow {}_{\Lambda}^{11}\mathrm{Be} + {}_{\Lambda}^{4}\mathrm{He}$



[sigma]

A twin single Λ hypernuclear event in mod062 pl11



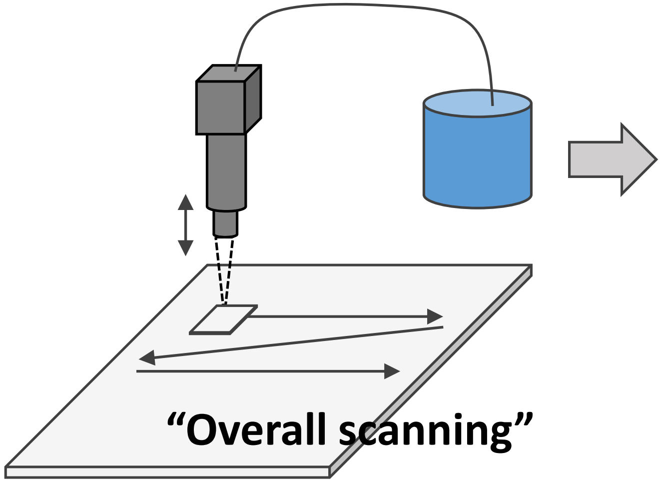
* 2 prong from Ξ^- stop
* #1 : 4 prong
* #2 : 3 prong with π^-

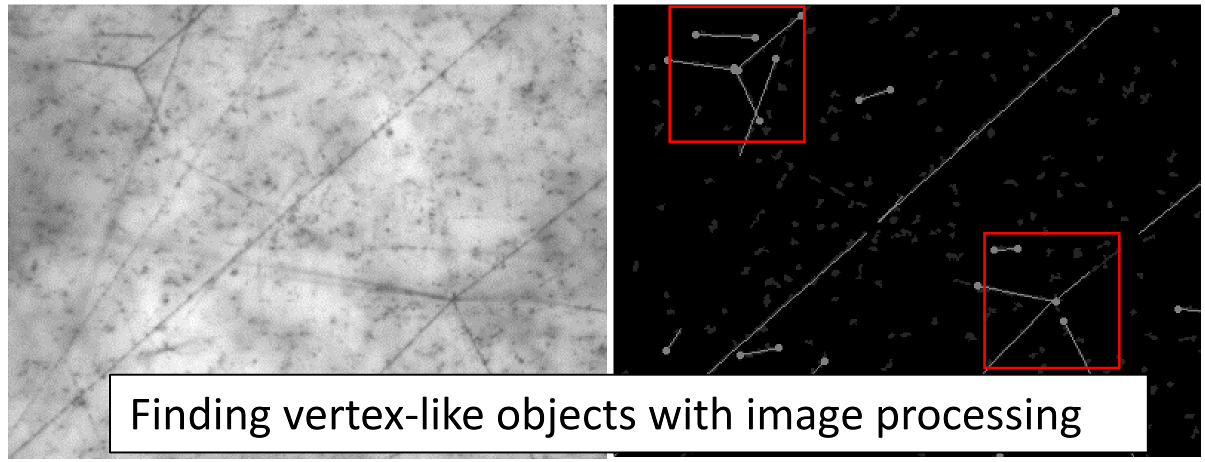
Possible solution:

$\Xi^- + {}^{16}O \rightarrow {}_{\Lambda}^{5}He + {}_{\Lambda}^{12}B$ ($B_{\Xi-}$ = ~0.1 +- 0.1 MeV)

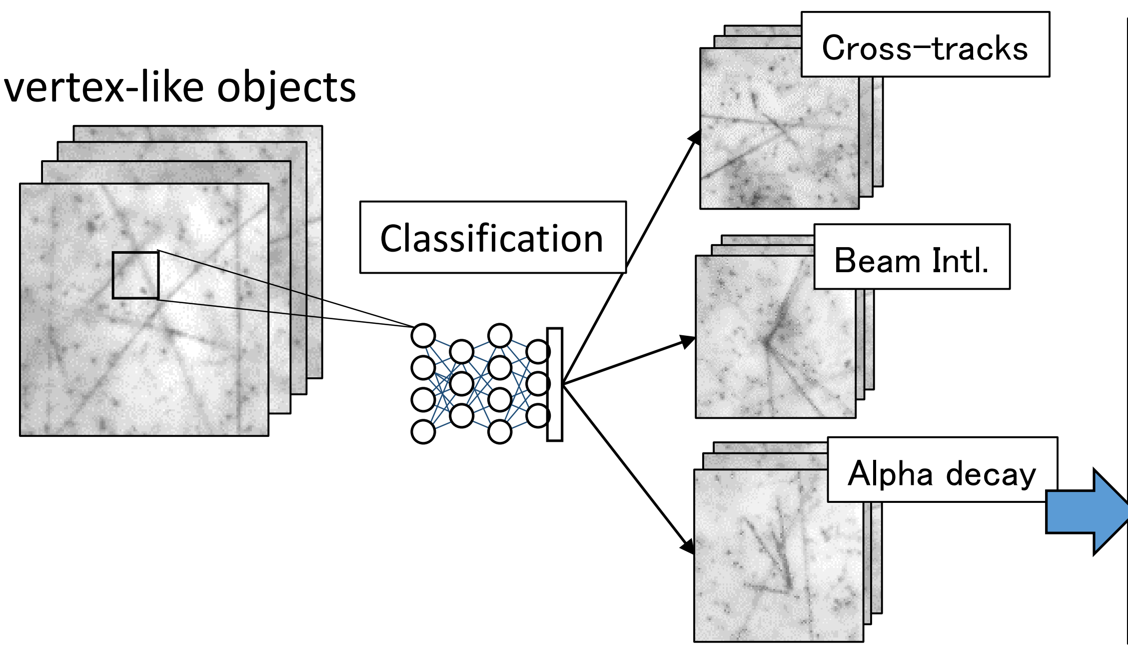
Consistent to atomic bound state, Not a Ξ hypernucleus.

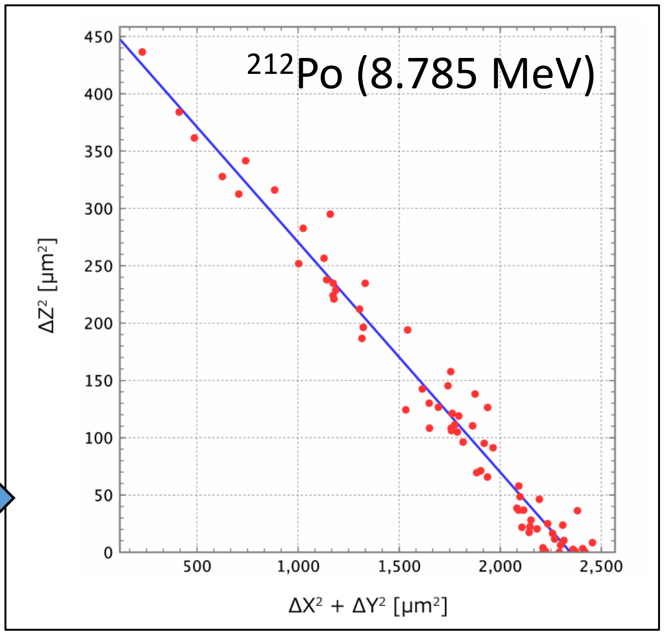
Alpha decay event search by “Vertex-picker”





vertex-like objects



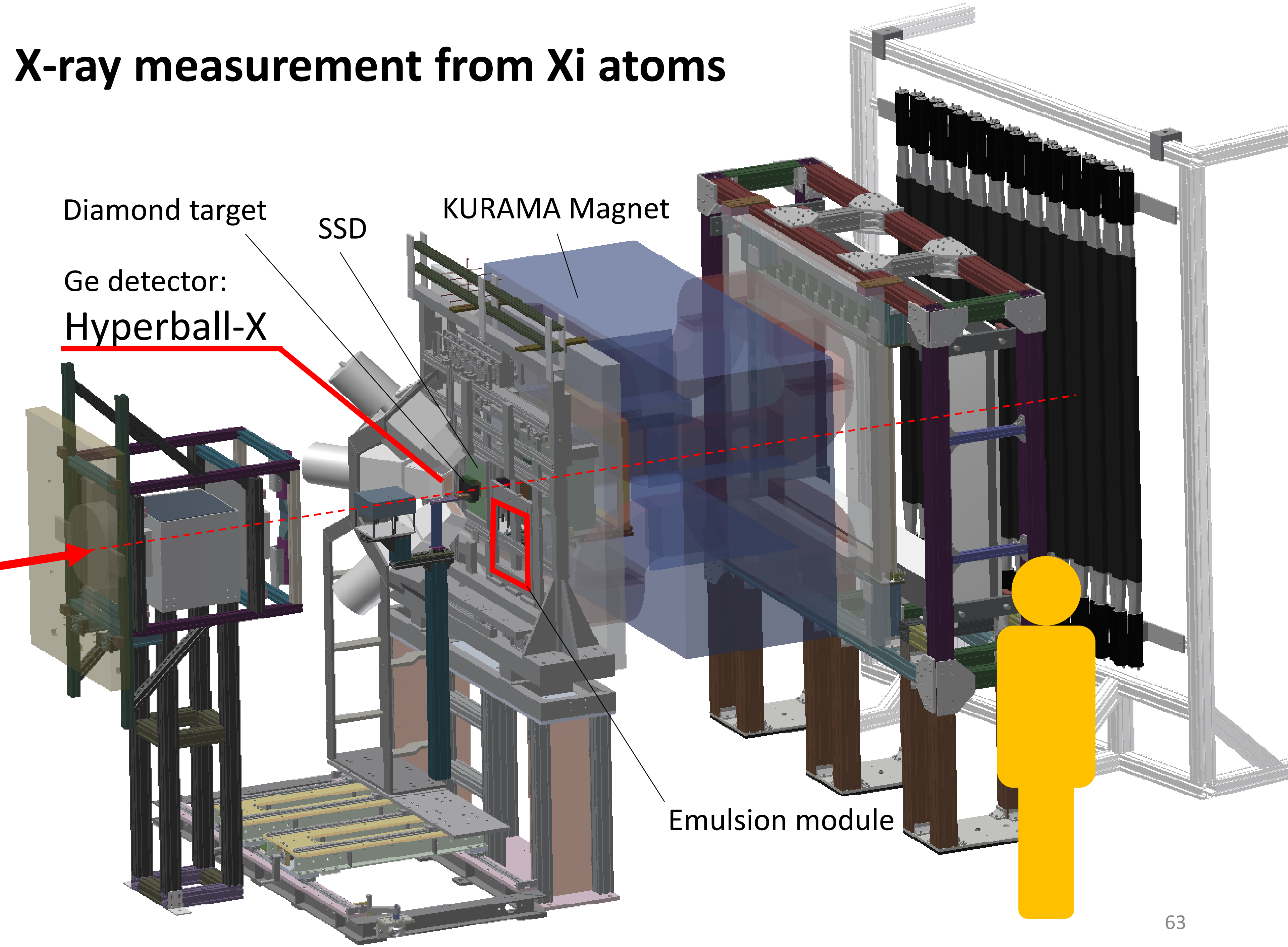


Density and Shrinkage measurement

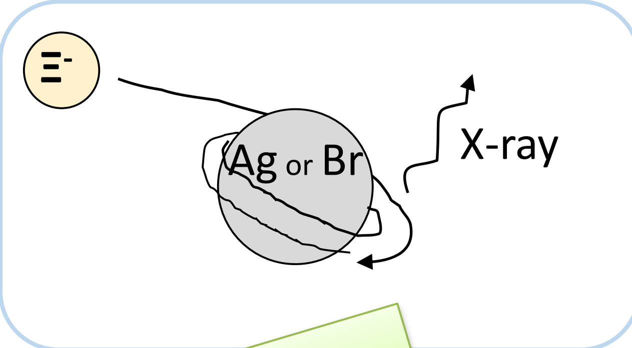
Back up slides:

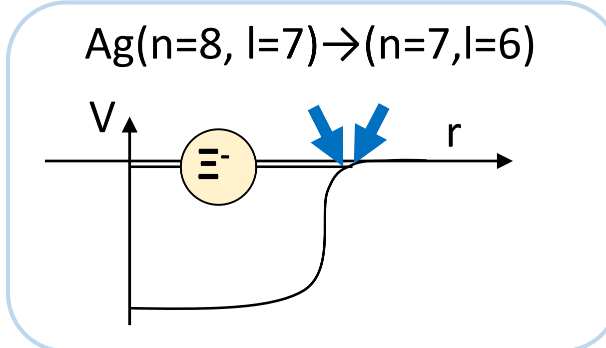
X-ray measurement from Xi atoms by Ge detector

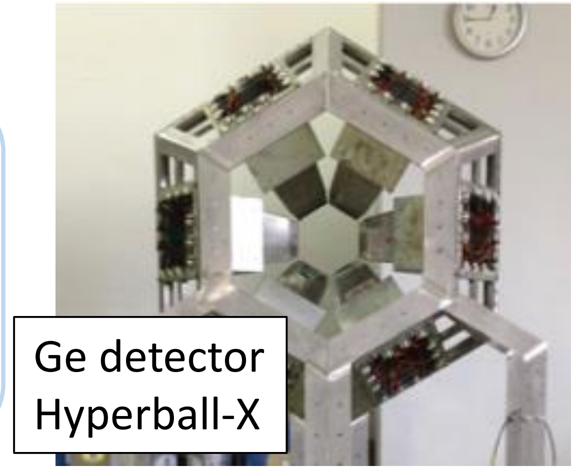
X-ray measurement from Xi atoms

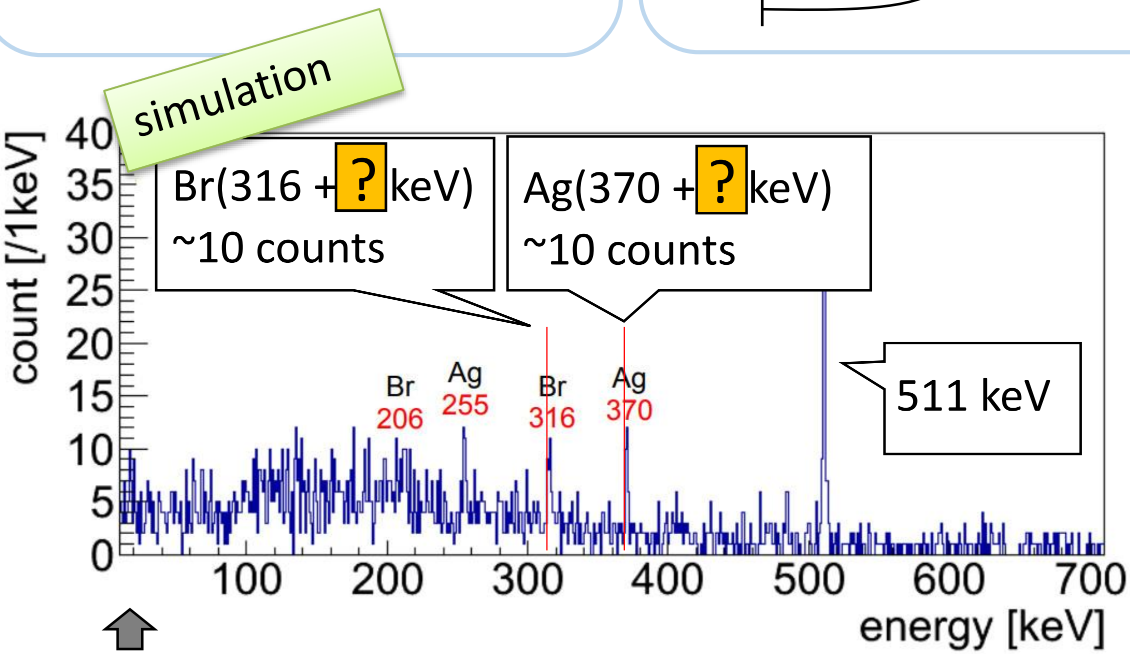


First measurement of X-ray from Ξ-atoms









Z(n,l)	E (keV)	Shift (keV)	Width (keV)
Ag(8,7)→(7,6)			
Case 1	370.45	0.28	0.15
Case 2		3.3	0.79
Br(7,6)→(6,5)			
Case 1	315.5	0.73	0.44
Case 2		5.5	1.74

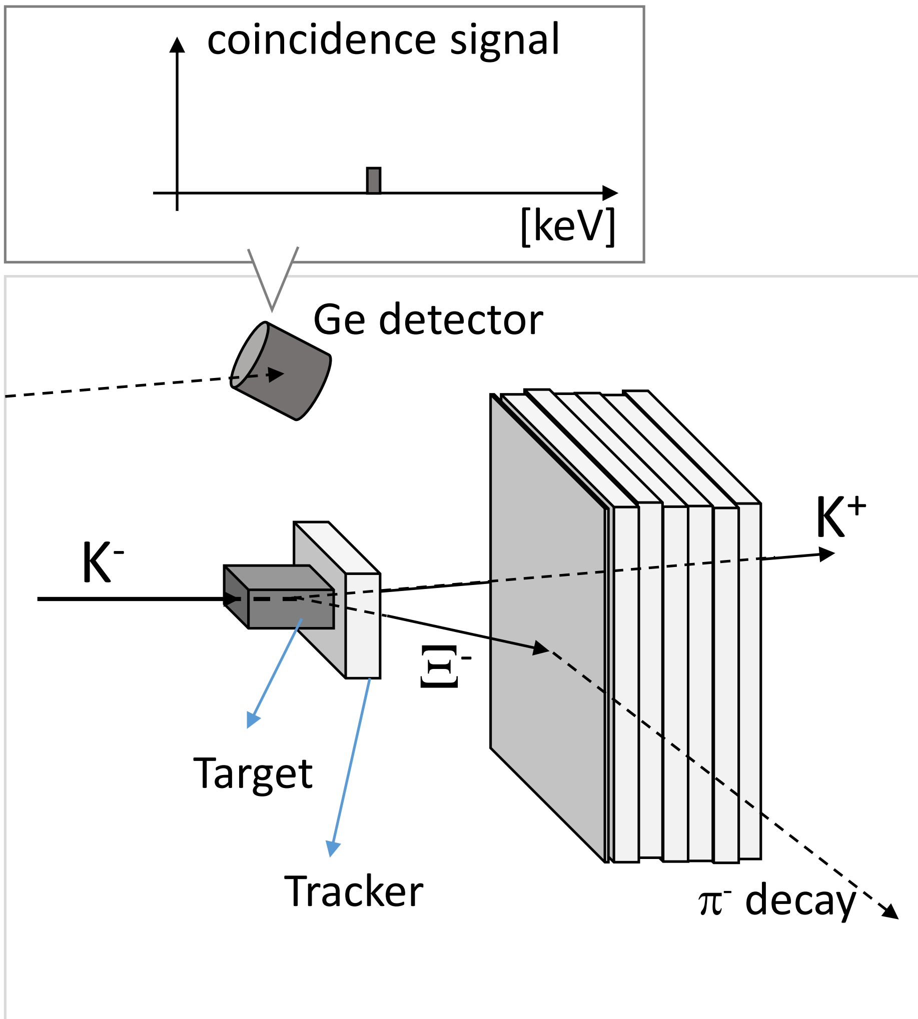
Case 1: assuming potential shape to be the same as the nuclear density ($t\rho$ potential)

Case 2: Nijmegen D model correcting to produce the potential depth of ~ 14 MeV.

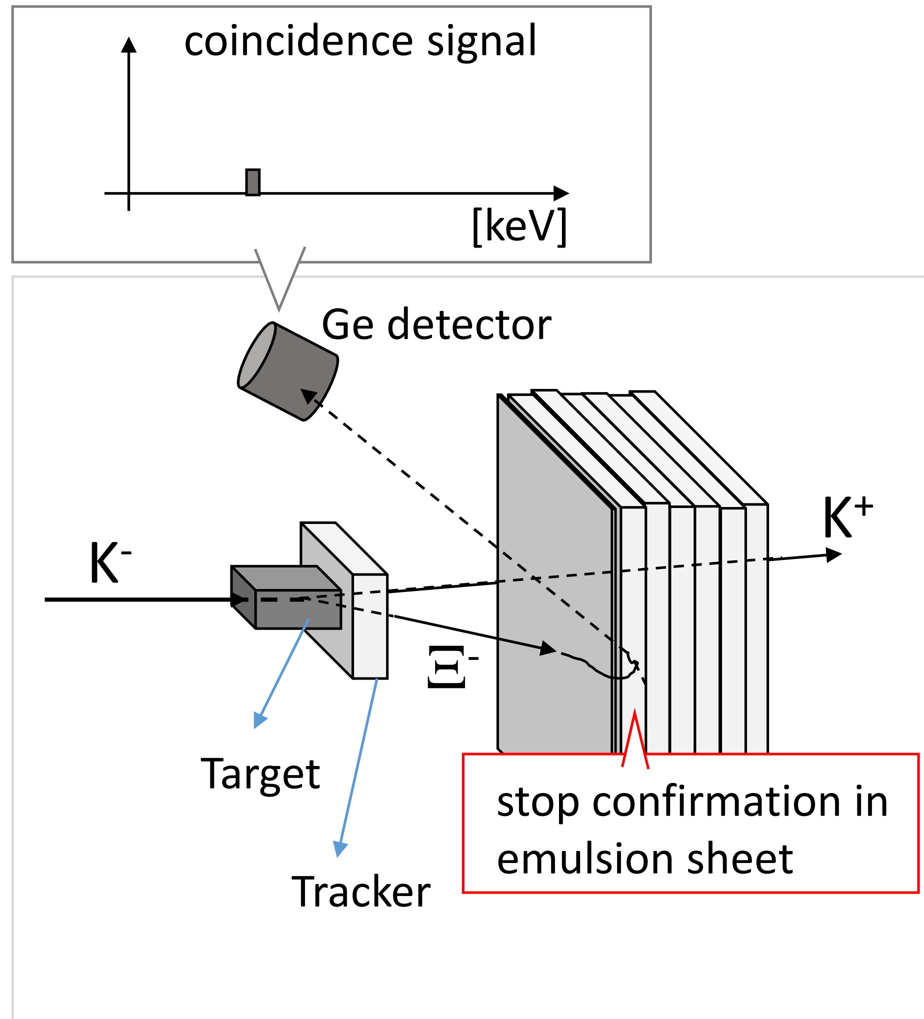
Simulation configuration

* 10^4 Ξ^--stop events in emulsion sheets, with emulsion analysis.
* Energy resolution for Ge : 2keV FWHM
* Statistical accuracy of shift energies : Br(316 keV): 0.4 keV, Ag(370 keV): 0.2 keV
* BGO suppression (gate 20 ns) → 30% BG suppress and 100% signal survival ratio
* P_Ξ = 0.6

Hybrid method : Ge detector and emulsion



Background, to be rejected

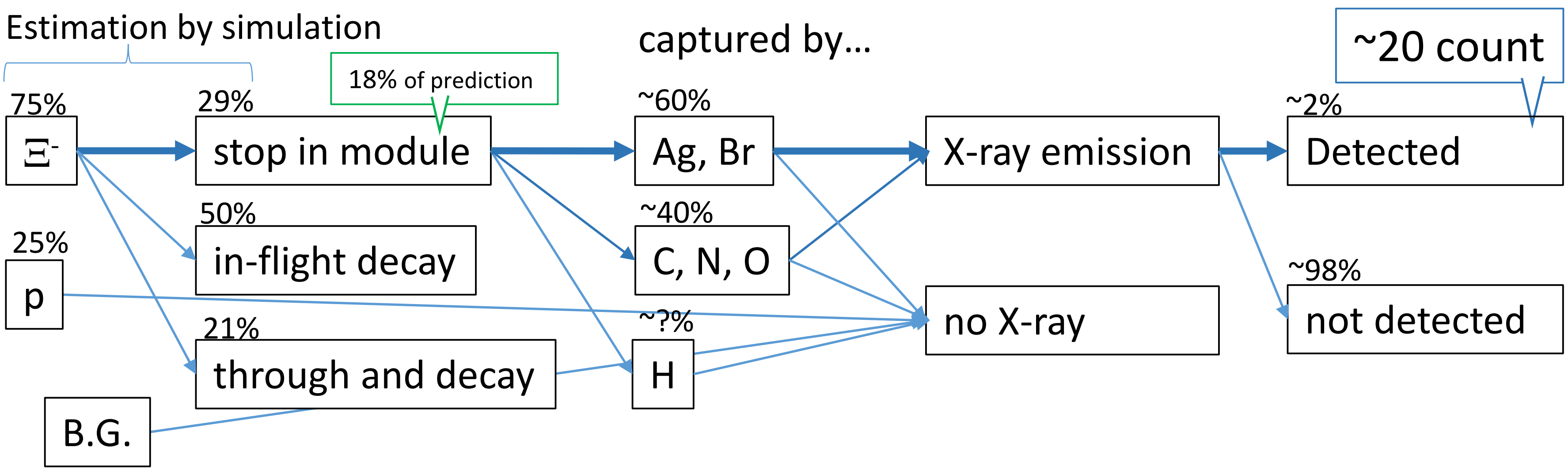


X-ray from Ξ atom

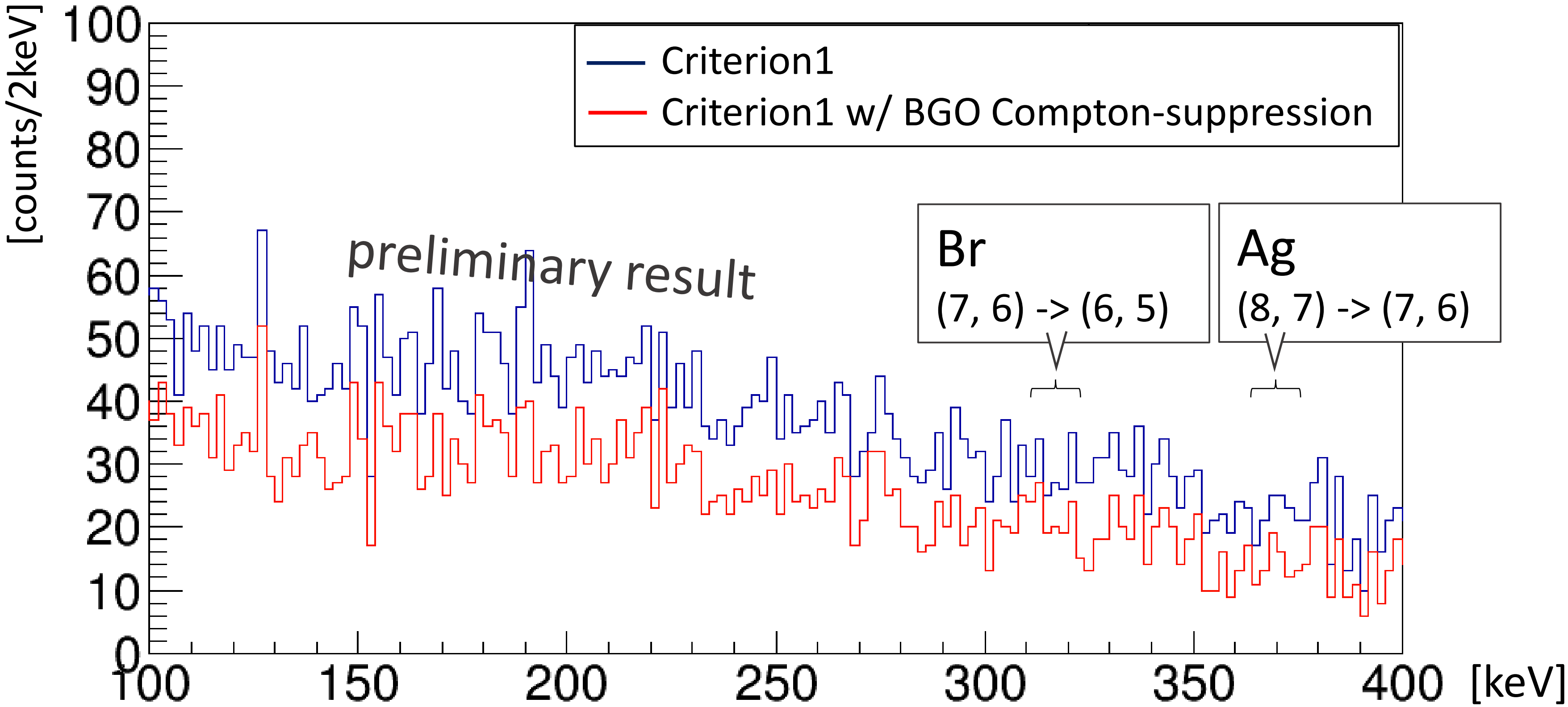
Criteria for Ξ⁻ track selection

by simulation for 118 modules

Level	Ξ⁻ stop	prediction/mod.		
1	9k	~440	High S/N & stop ratio	1st priority
2	1k	~850	Realistic selection	
3	1k	6.2k	All Ξ⁻ stop	
4	negligible	16k	All combination	



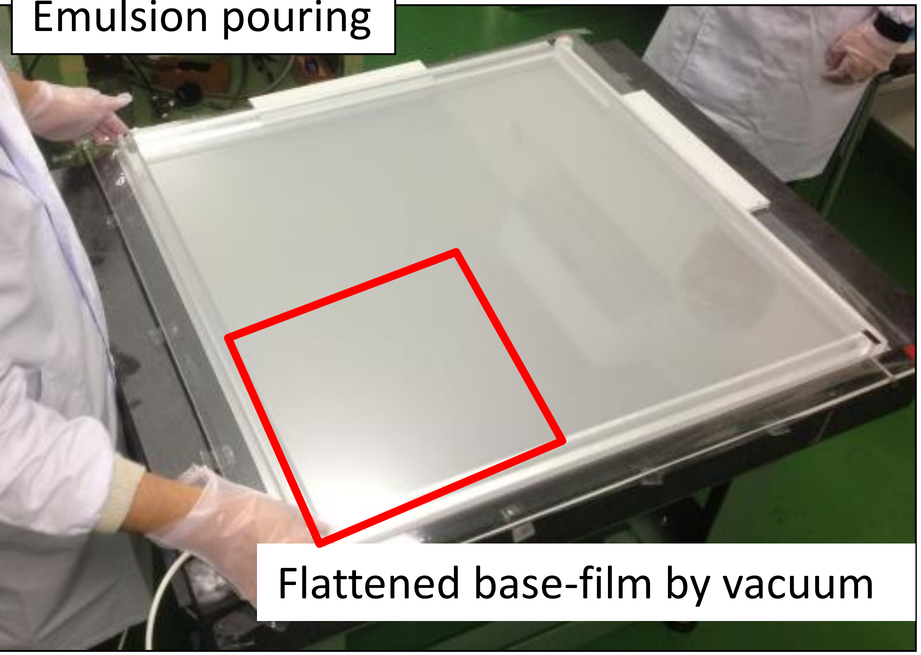
Ge spectra with "1st Criterion" WITHOUT emulsion analysis

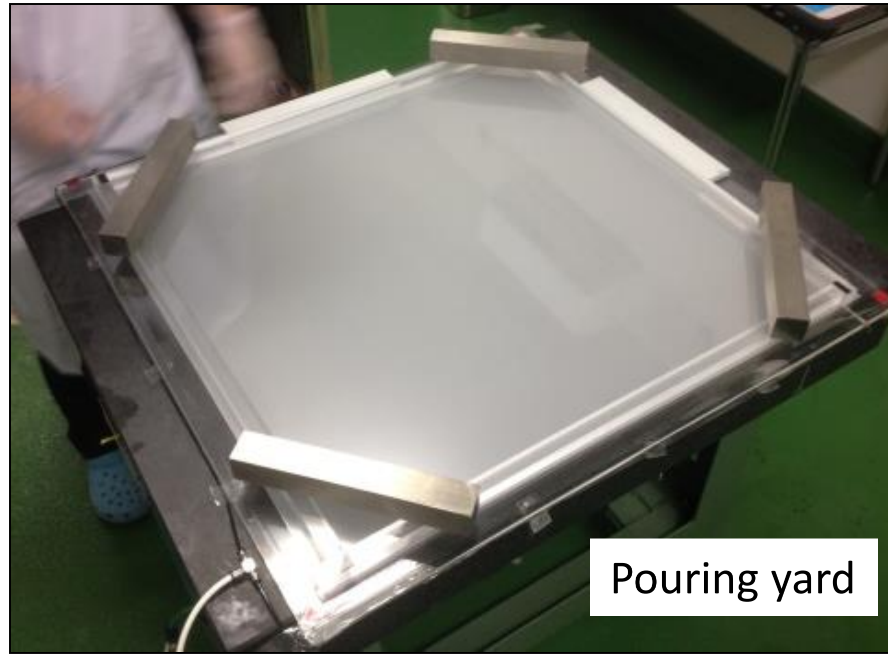


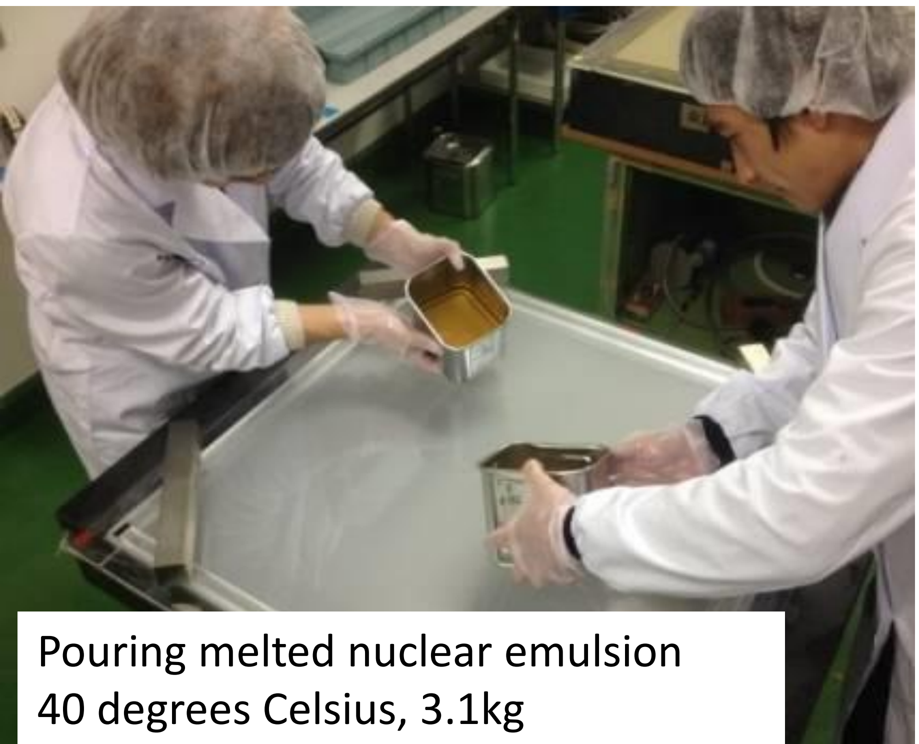
Back up slides:

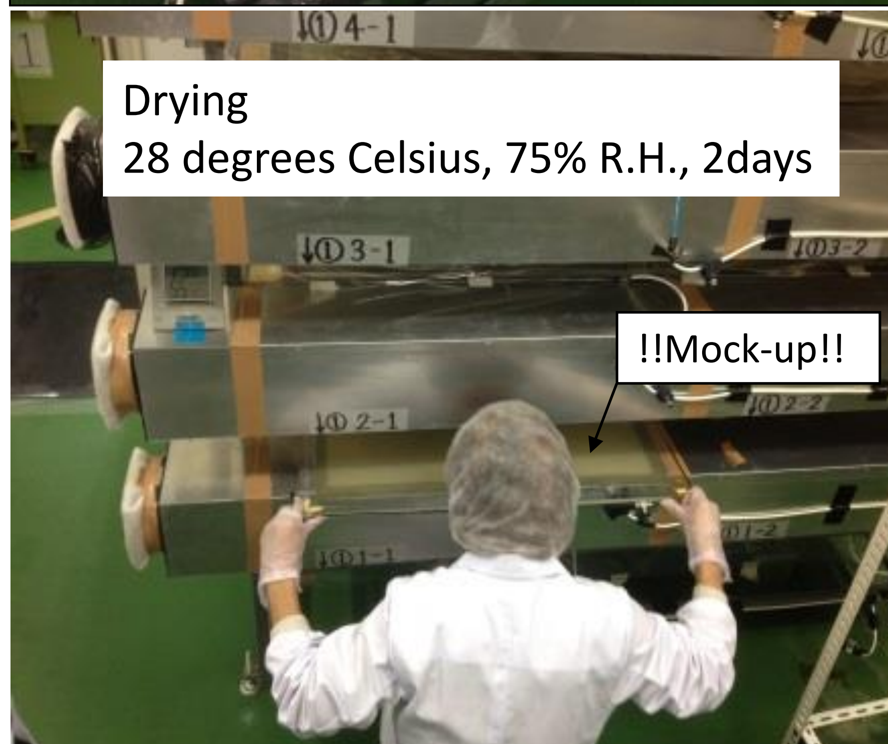
Emulsion sheet handring

Emulsion pouring

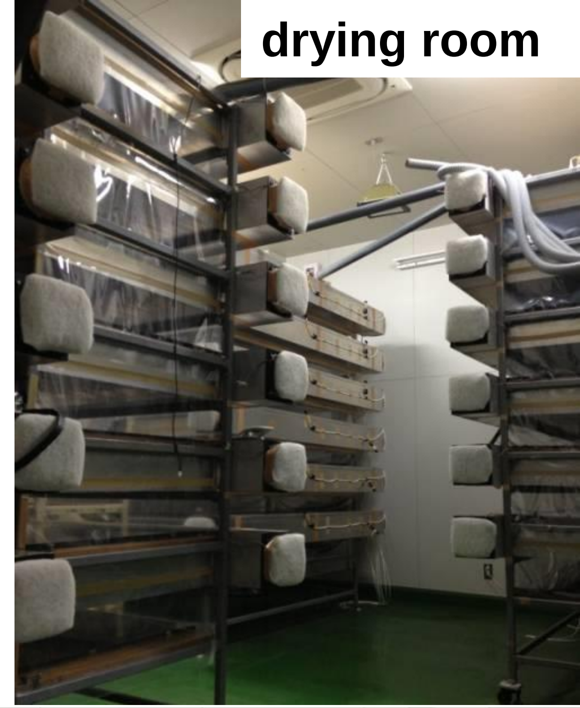




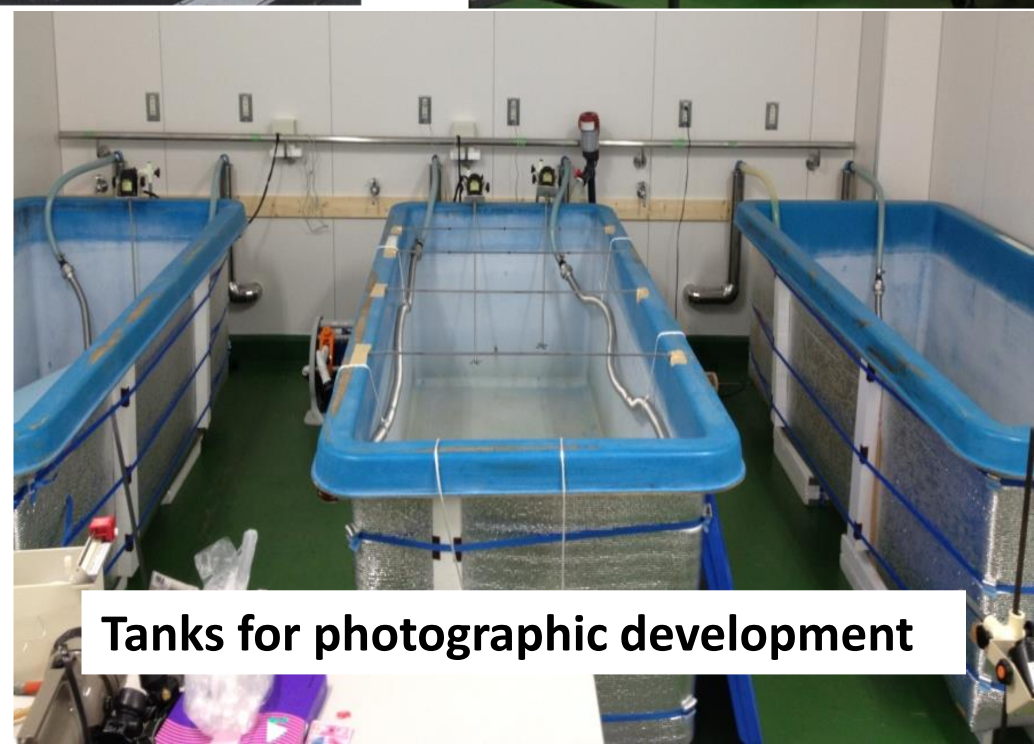




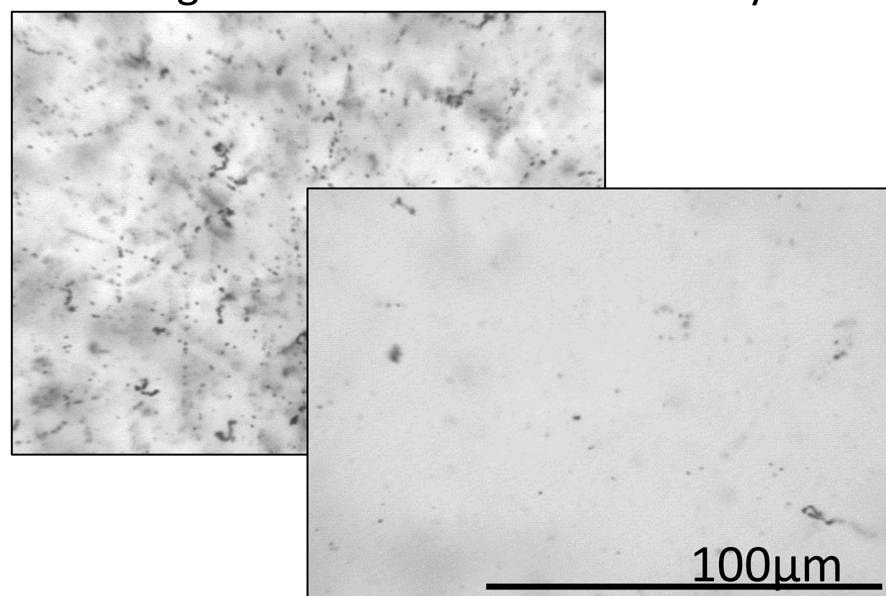

The emulsion facility at Gifu University


drying room


pouring room

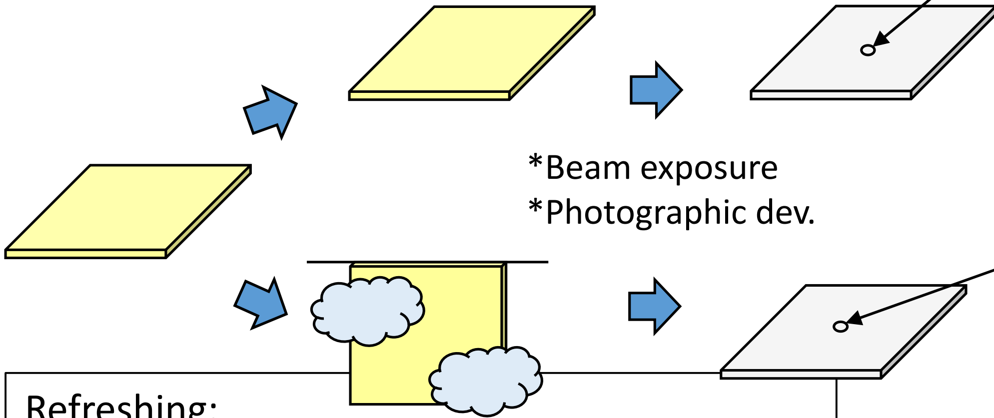

Tanks for photographic development

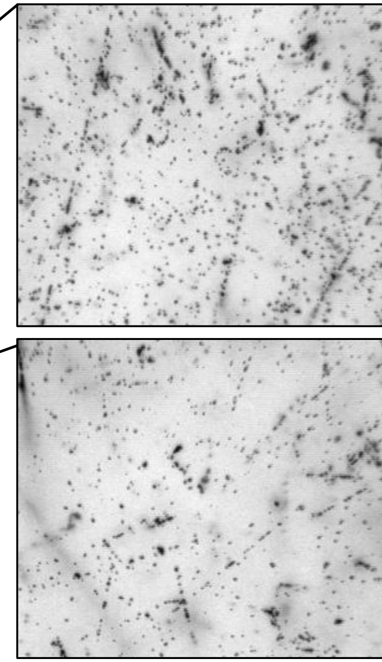
In a refrigerator in Gifu Univ. : ~400days



In Kamioka mine. : ~400days

Refreshing



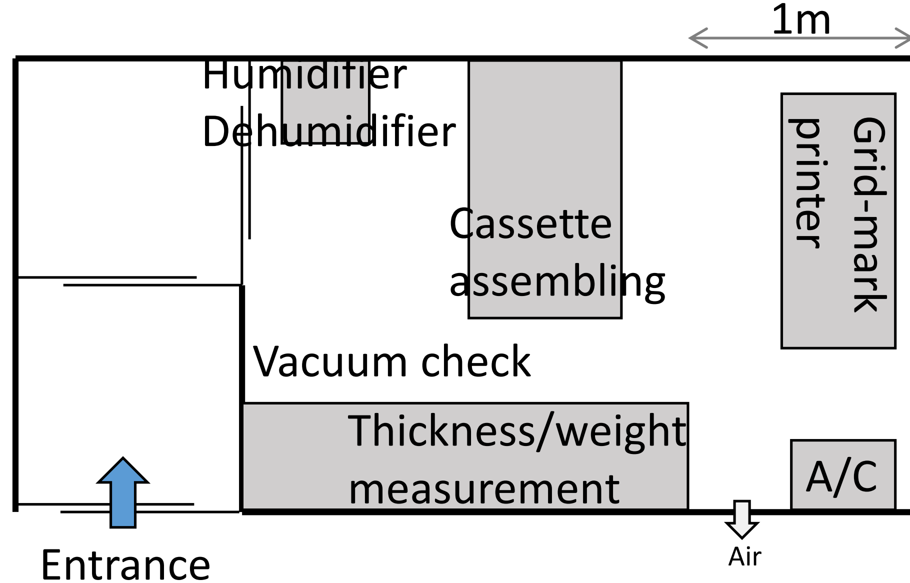


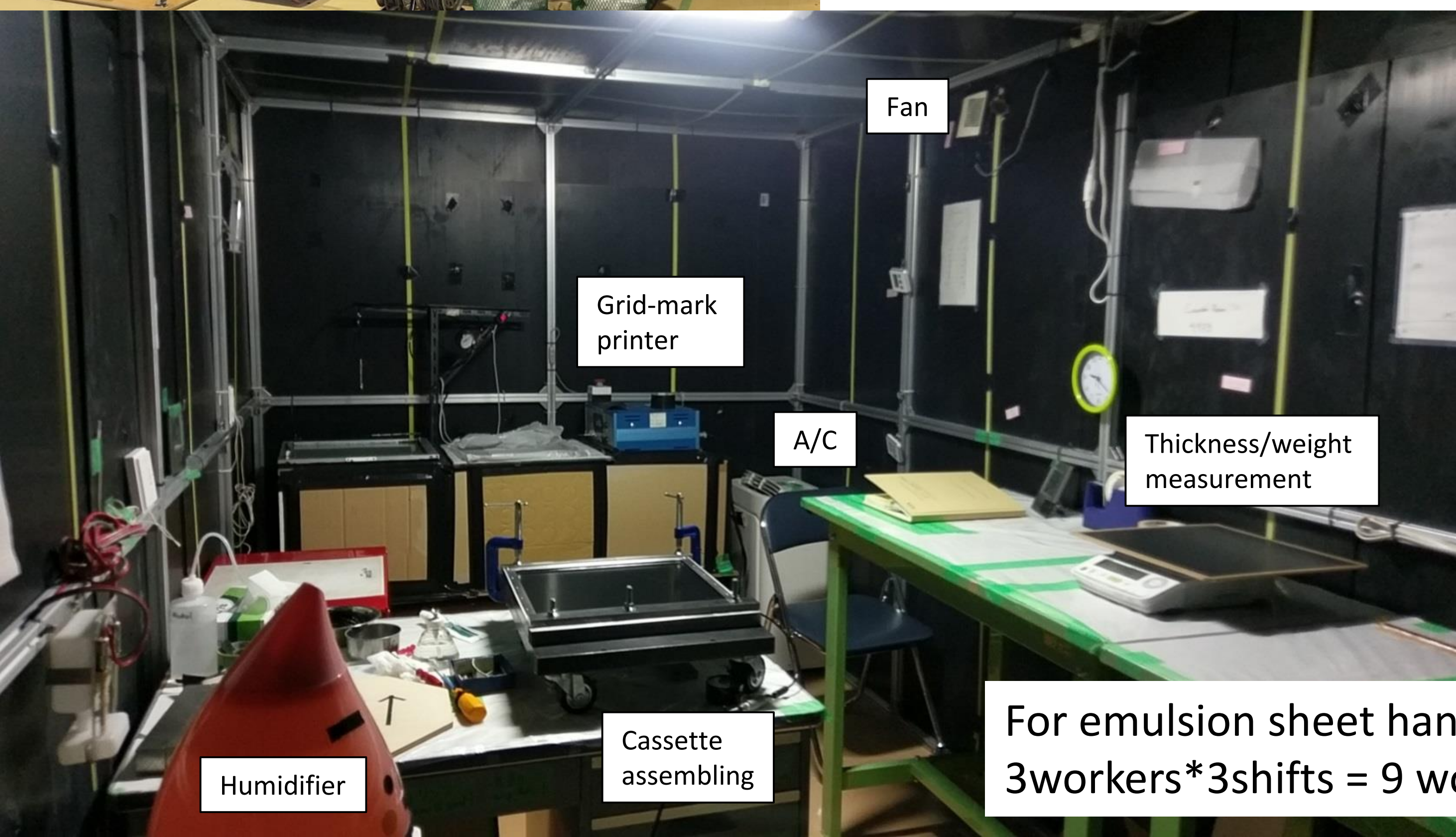
Compton-elec. Tracks / $(100mm)^3$
88.6 +- 3.4
⇩
48.1 +- 2.5

Refreshing:

- 4days in Temp.:25 deg C, Humi.: 90 %
- humidification 2days + 4days + drying 2days
- $4Ag + O_2 + 2H_2O \rightarrow 4Ag^+ + 4OH^-$

Darkroom @ J-PARC Hadron Assembly Bldg.





For emulsion sheet handling
3workers*3shifts = 9 workers/24h