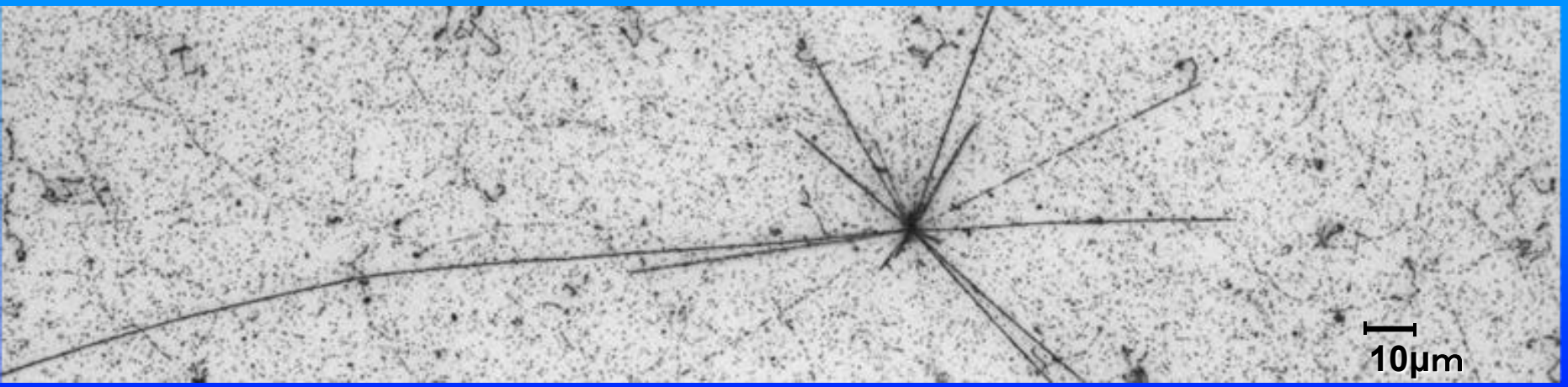
NINJA Experiment :
Neutrino Interaction research with Nuclear emulsion and J-PARC Accelerator

Tsutomu Fukuda（Nagoya Univ.）
on behalf of the NINJA collaboration



J-PARC素粒子原子核セミナー, 23th Feb. 2017@Tokai

Contents

- Introduction
- Nuclear Emulsion Technology
- NINJA Experiment

Profile：福田 努（ふくだ つとむ）

2000年　OPERA実験が正式に承認。

参加

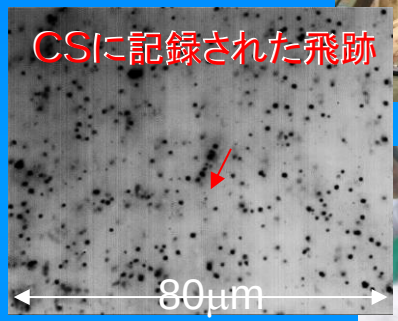
検出器準備

2003年～ OPERAフィルムの大量生産開始。
東濃鉱山地下にてRefresh処理。

me

解析体制準備

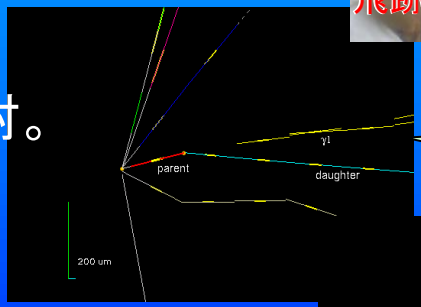
2005年～ KEK, Fermi Labでテスト実験開始。
→ OPERAの解析リハーサルを実施。



ニュートリノビーム照射

2006年　CERNからニュートリノビームのテスト照射。OPERAで初めて原子核乾板上にニュートリノ反応からの飛跡を検出。

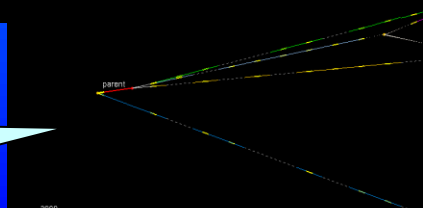
2008年～ 検出器完成。ニュートリノビーム本格照射。
OPERA実験本番開始。



1st ν_τ

2010年　1st タウニュートリノ反応候補検出。

2012年　2nd タウニュートリノ反応候補検出。



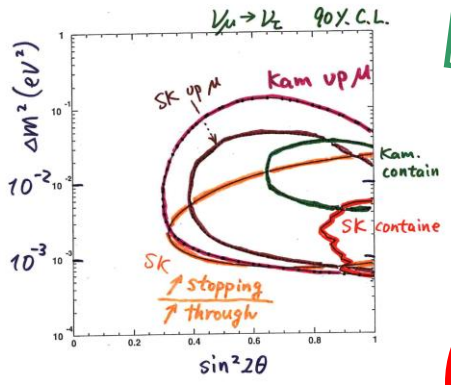
2nd ν_τ

⋮

1998

Summary

Evidence for ν_μ oscillations



- $\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$

($\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$?)

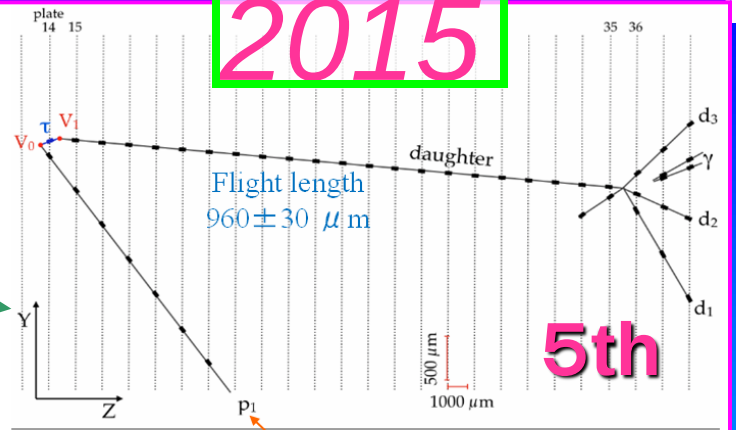
4. Conclusions

So far both $\nu_\mu \leftrightarrow \nu_\tau$ & $\nu_\mu \leftrightarrow \nu_s$ solutions provide a good fit to atmospheric neutrino anomaly for $\begin{cases} 10^{-3} eV^2 \lesssim |\Delta m^2| \lesssim 10^{-2} eV^2 \\ \sin^2 2\theta \sim 1 \end{cases}$.

To be more conclusive, we need more statistics or we have to look for appearance of ν_τ in long baseline experiments.

done

2015



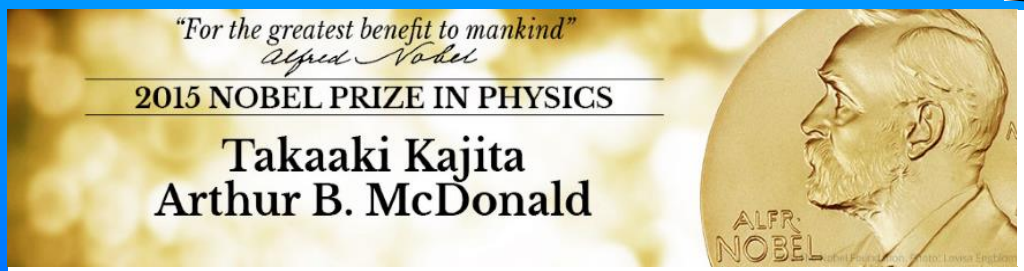
5th

identified as a proton by dE/dx analysis [26]

02 (2015) PHYSICAL REVIEW LETTERS 18 SE

Discovery of τ Neutrino Appearance in the CNGS Neutrino Beam with the OPERA Experiment

A. Aleksandrov,[2] A. Anokhina,[3] S. Aoki,[4] A. Ariga,[5] T. Ariga,[5] D. Bender,[6] A. Bertolin,[7] I. rugnera,[7,10] A. Buonaura,[2,11] S. Buontempo,[2] B. Büttner,[12] M. Chernyavsky,[13] A. Chukanov,[8] [14] G. De Lellis,[2,11] M. De Serio,[15,16] P. Del Amo Sanchez,[17] A. Di Crescenzo,[2] D. Di [14] S. Dmitrievski,[8] M. Dracos,[19] D. Duchesneau,[17] S. Dusini,[7] T. Dzhatdoev,[3] J. Ebert,[12] F. Fornari,[18,20] T. Fukuda,[21] G. Galati,[2,11] A. Garfagnini,[7,10] J. Goldberg,[22] Y. Gornushkin,



Scientific Background on the Nobel Prize in Physics 2015

NEUTRINO OSCILLATIONS

compiled by the Class for Physics of the Royal Swedish Academy of Sciences

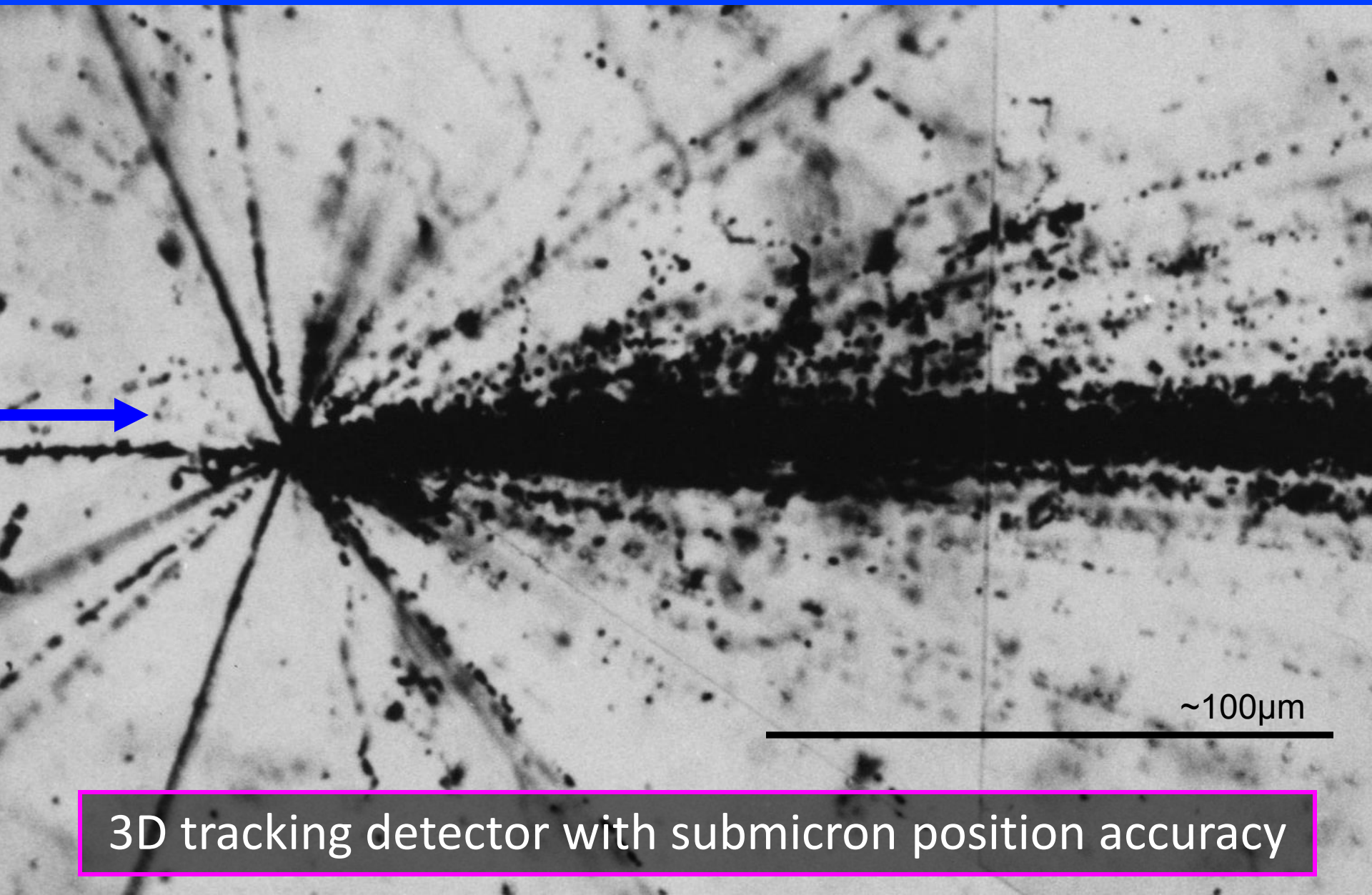
Super-Kamiokande's oscillation results were confirmed by the detectors MACRO [55] and Soudan [56], by the long-baseline accelerator experiments K2K [57], MINOS [58] and T2K [59] and more recently also by the large neutrino telescopes ANTARES [60] and IceCube [61]. Appearance of tau-neutrinos in a muon-neutrino beam has been demonstrated on an event-by-event basis by the OPERA experiment in Gran Sasso, with a neutrino beam from CERN [62].

"発見"から"精密測定"へ

原子核乾板

Nuclear Emulsion

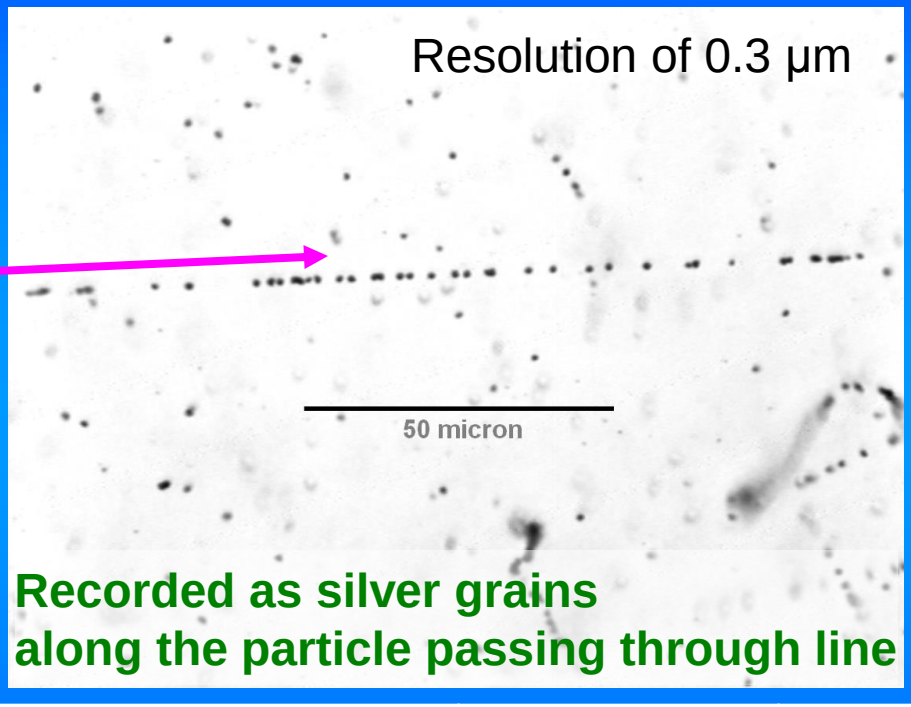
What is Nuclear Emulsion ?



3D tracking detector with submicron position accuracy

Photographic Film technology

- Nuclear Emulsion is a special photographic film.
- Signal is amplified by chemical process.



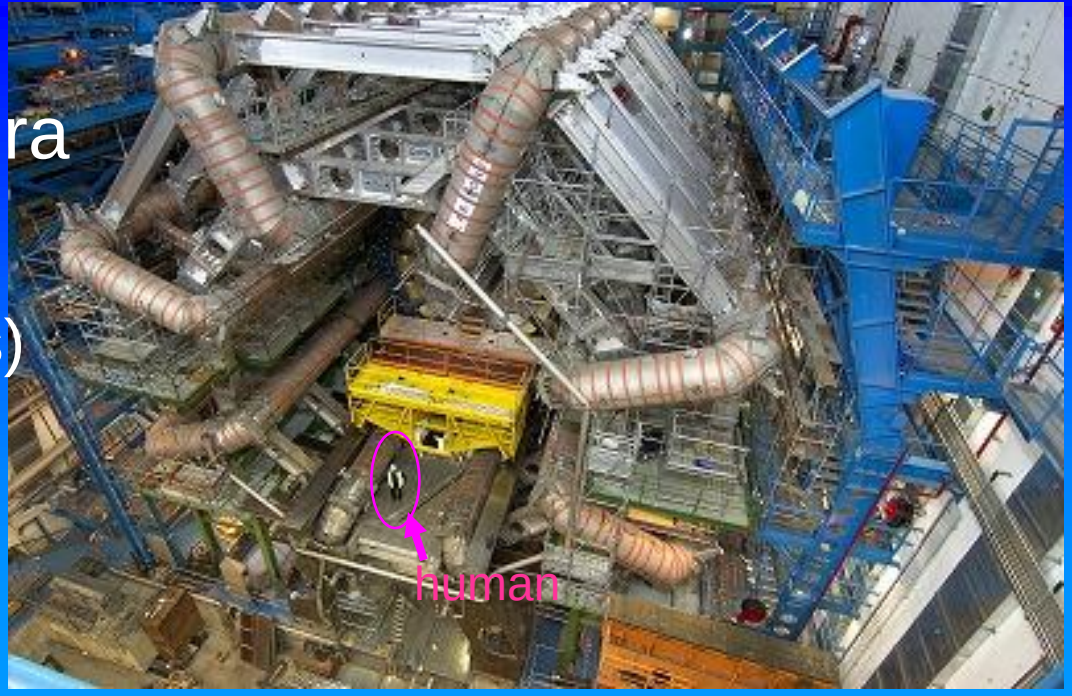
Recorded as silver grains along the particle passing through line

	Merit	Image detection
Film camera	**High resolution**	ハロゲン化銀（Sliver halide） 光のエネルギーが起こす化学変化を利用した光化学反応。
Digital camera	Real time	電荷結合素子（Charged-Coupled Device） 光のエネルギーを電気エネルギーに変換する光電変換。

Largest Digital Camera

ATLAS detector

(~1.6 x 10^8 image sensors)



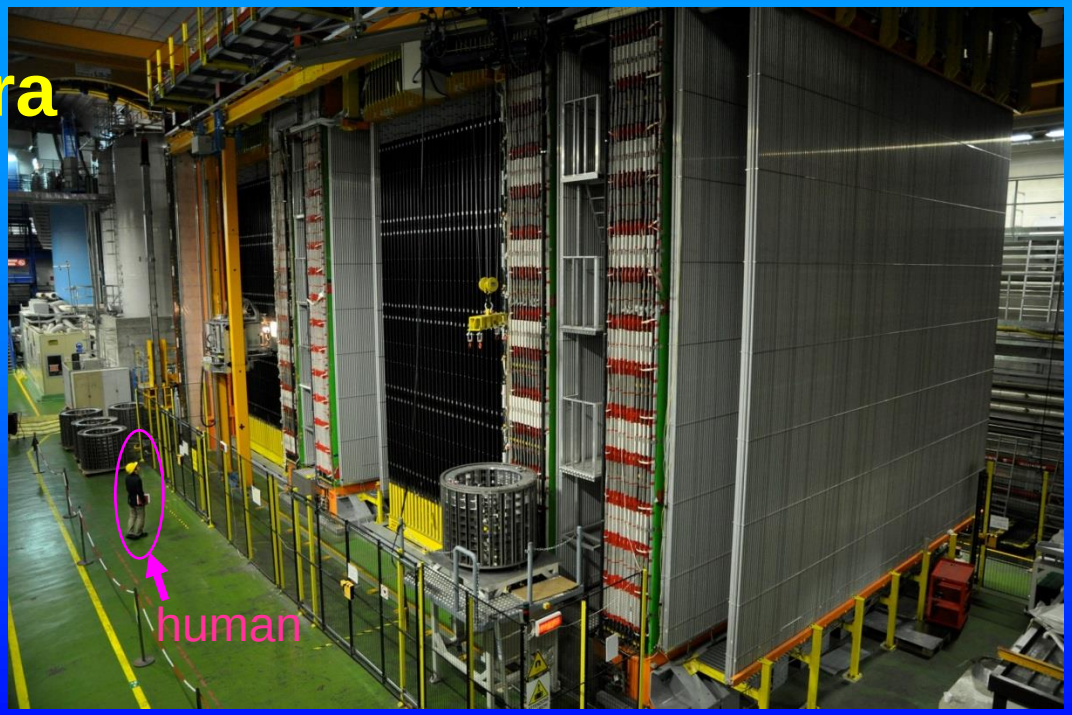
Largest Film Camera

OPERA detector

(~10^{20} AgBr crystals)

↑

9000,000 emulsion films



Contribution for fundamental physics…

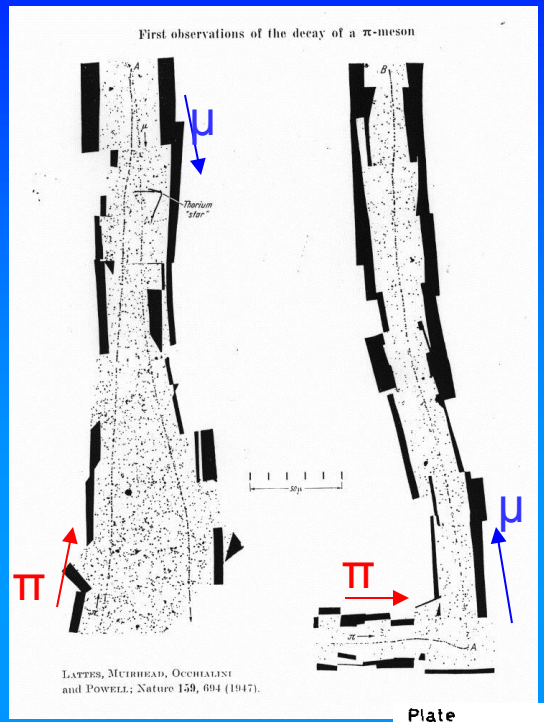
1896 (A. H. Becquerel)
Discovery of Radioactivity

1947 (C. F. Powell et al.)
Discovery of π

1971 (K.Niu et al.)
Discovery of charm particle in cosmic-ray

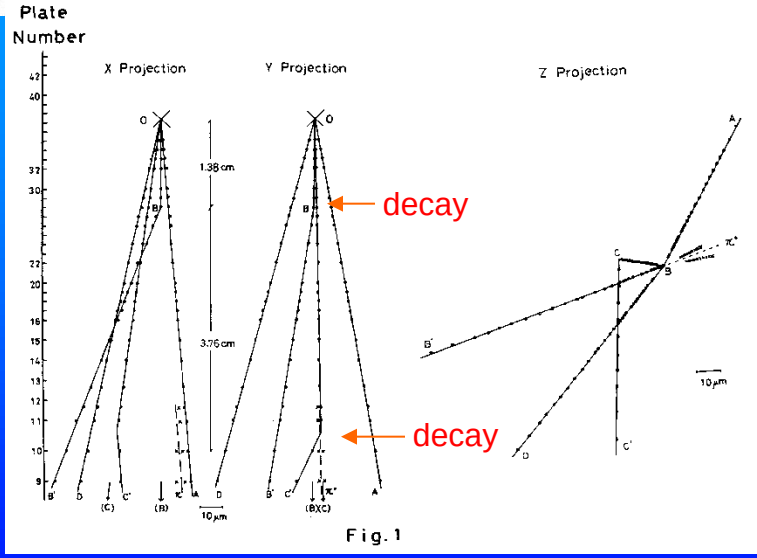
2001 (K.Niwa et al.)
Direct observation of ν_τ

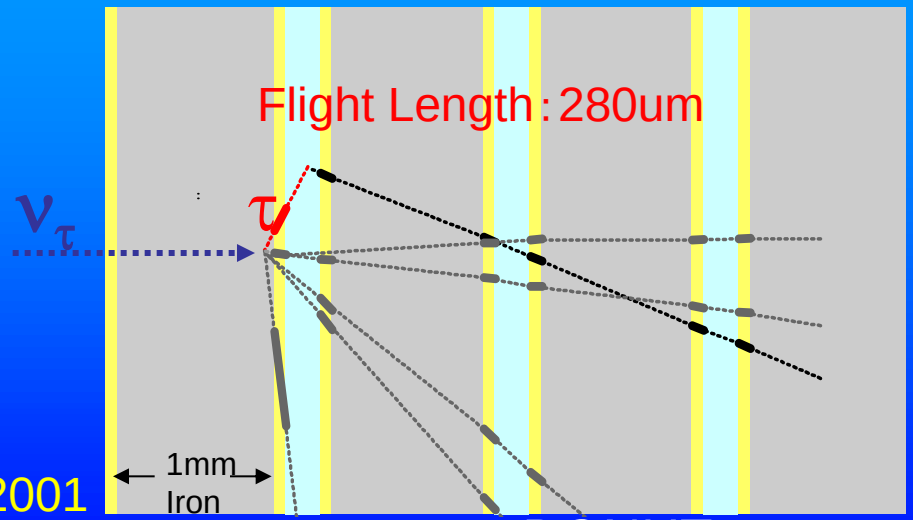
1947



1896

1971



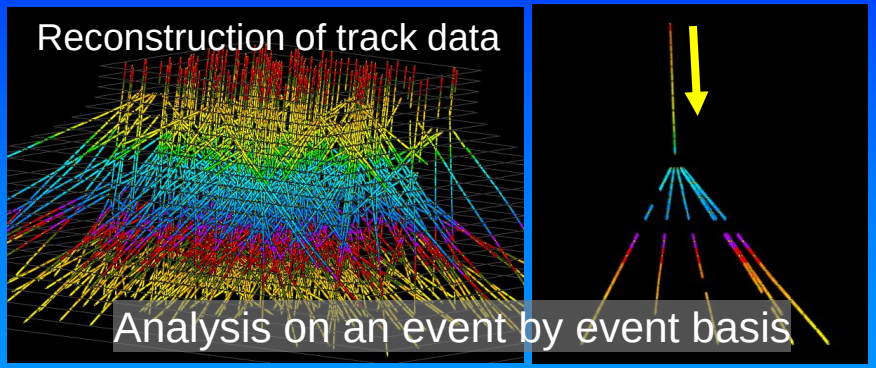


2001

DONUT ν_τ event

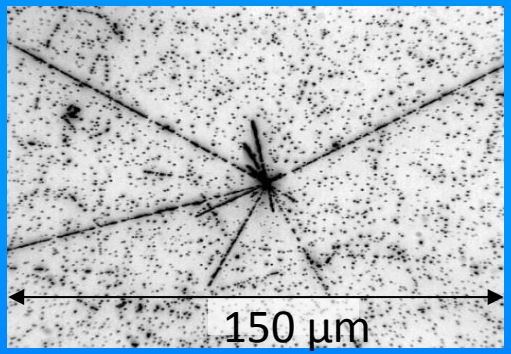
Nuclear Emulsion Detector

3D reconstruction

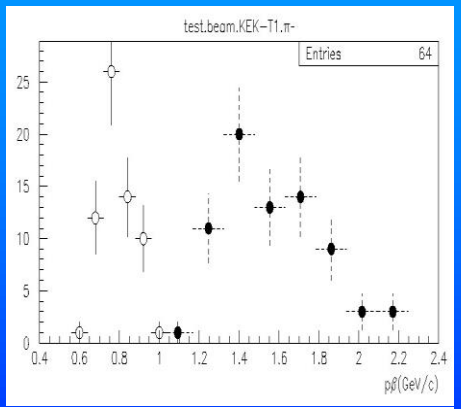


Scalability

4π detection

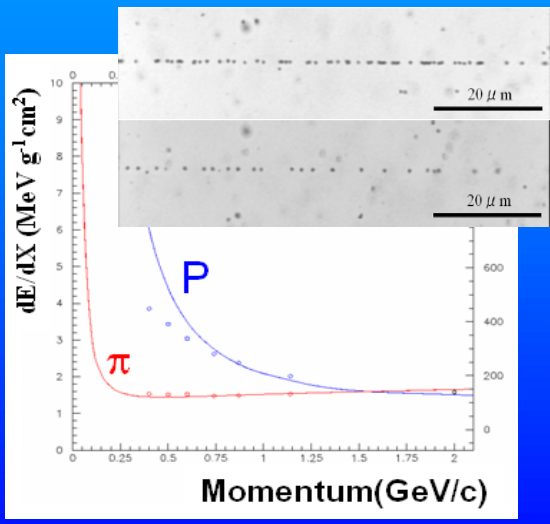


Momentum, dE/dx measurement



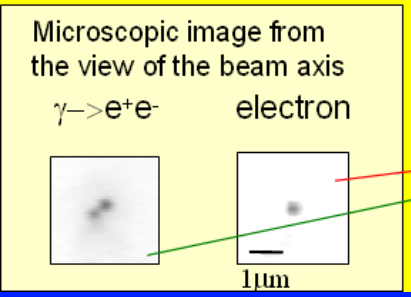
0.8GeV/c π : P =0.79(GeV/c), dP/P =**11**%

1.5GeV/c π : P =1.53(GeV/c), dP/P =**16**%

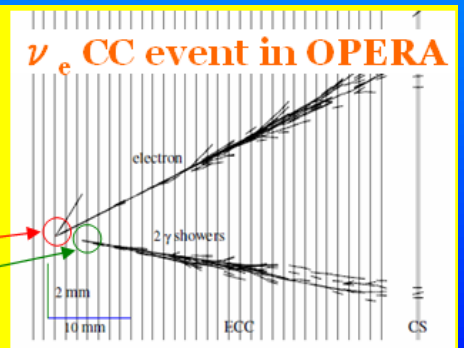


Ultra precise measurement

γ / electron ID

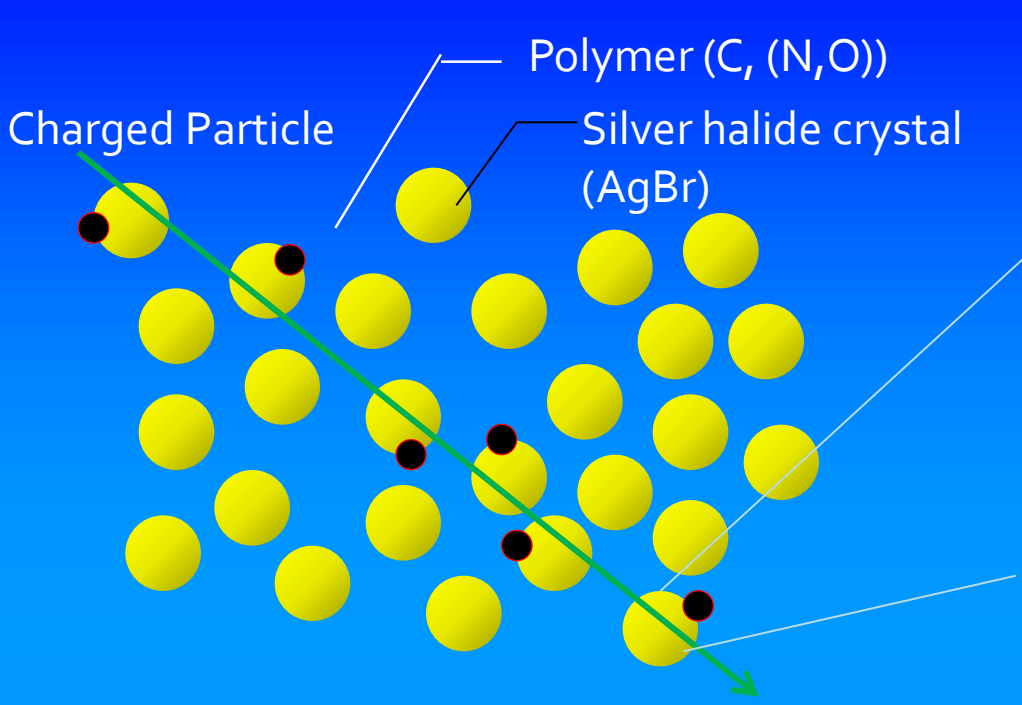


ν_e CC event in OPERA

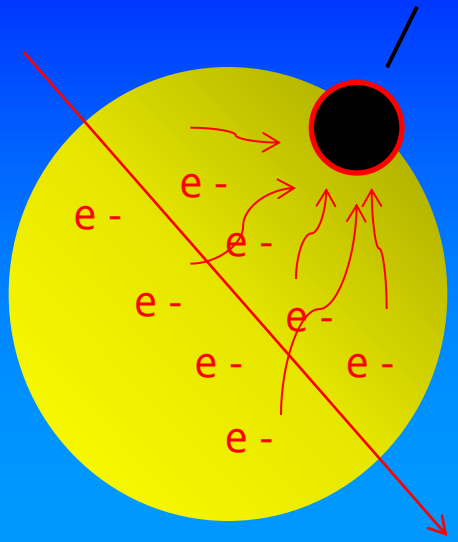


Low BG from ν_μ NC π^0 production

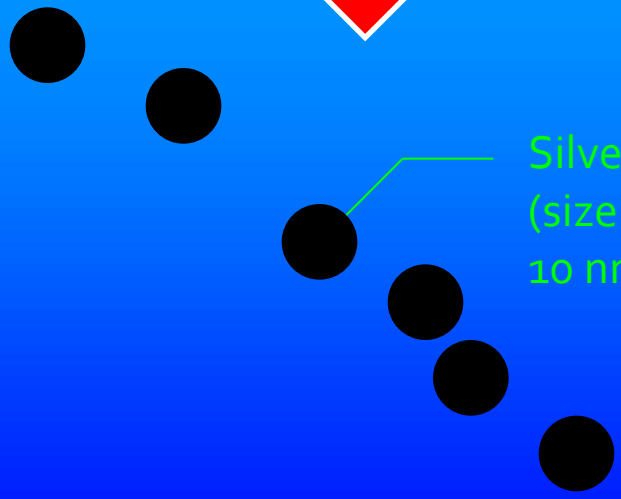
Nuclear Emulsion Detector



$Ag^{+} + e^{-} \rightarrow Ag_1 \cdot \cdot \cdot Ag_n$

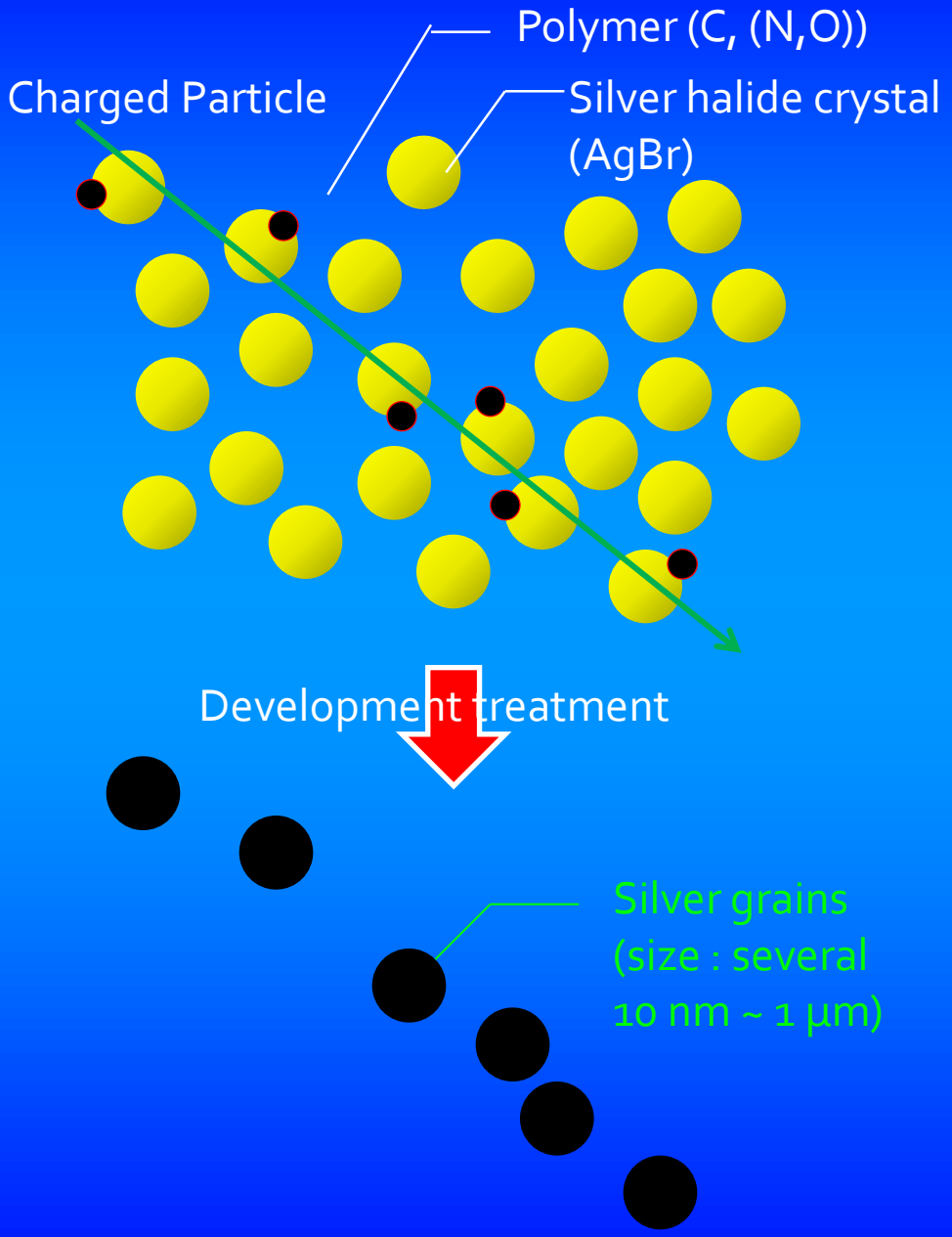


Development treatment

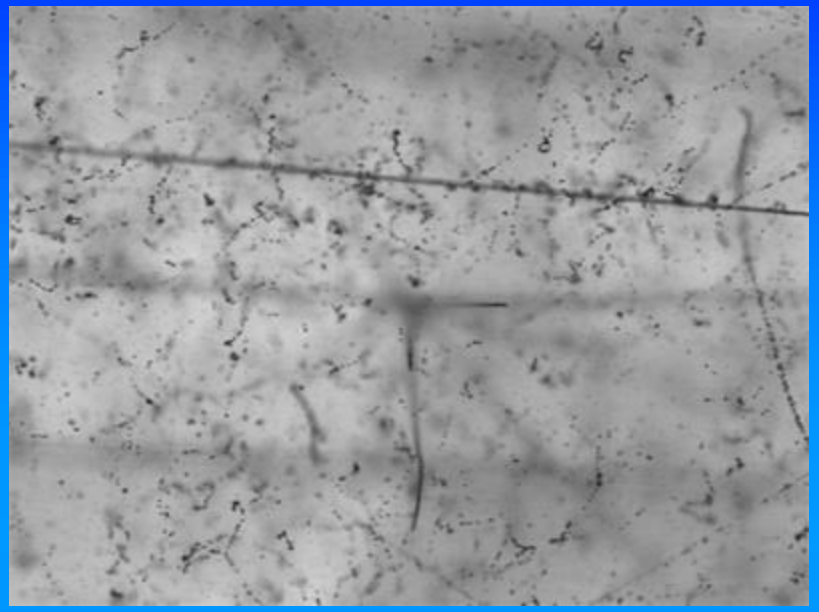


Ionized electrons concentrated on the electron trap to form the latent image specks in a crystal

Nuclear Emulsion Detector



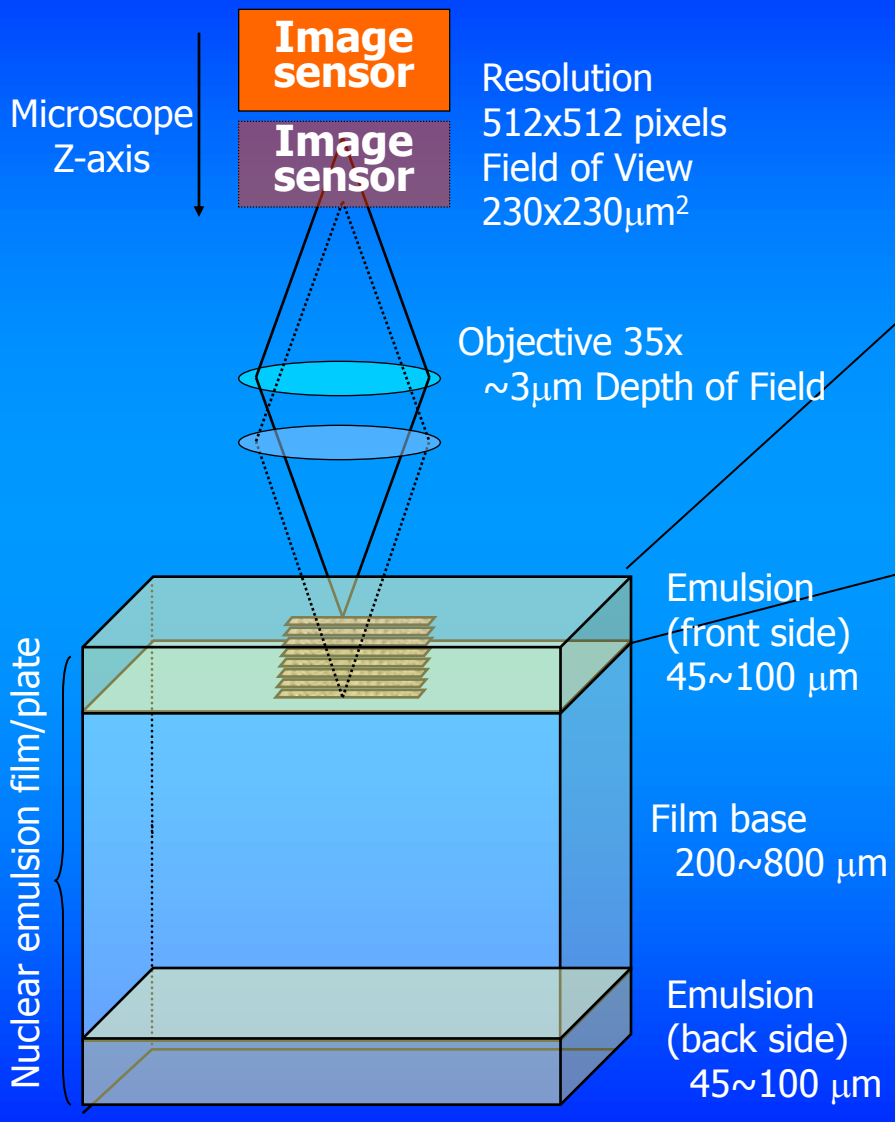
Nuclear spallation reaction by heavy ion



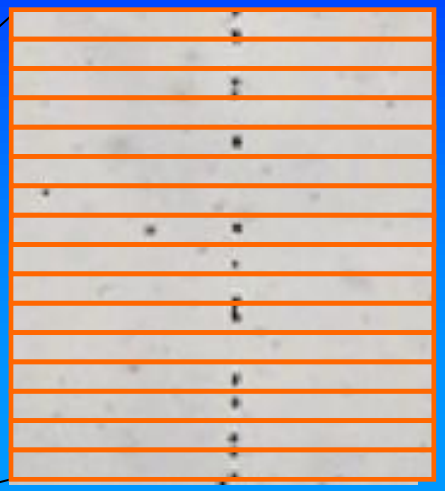
Spatial resolution
- silver halide crystal size
- number density of silver halide crystal

Sensitivity
- Chemical treatment
- Crystal defect and doping etc.

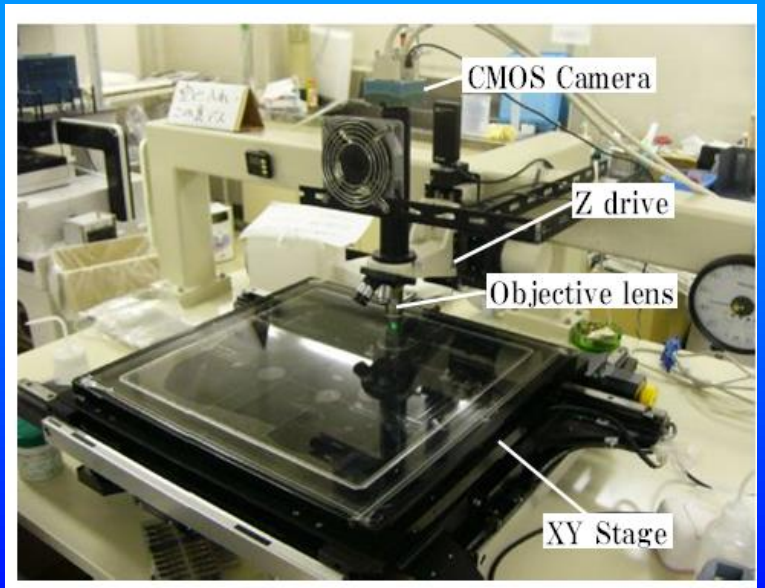
Readout of tracks in Emulsion

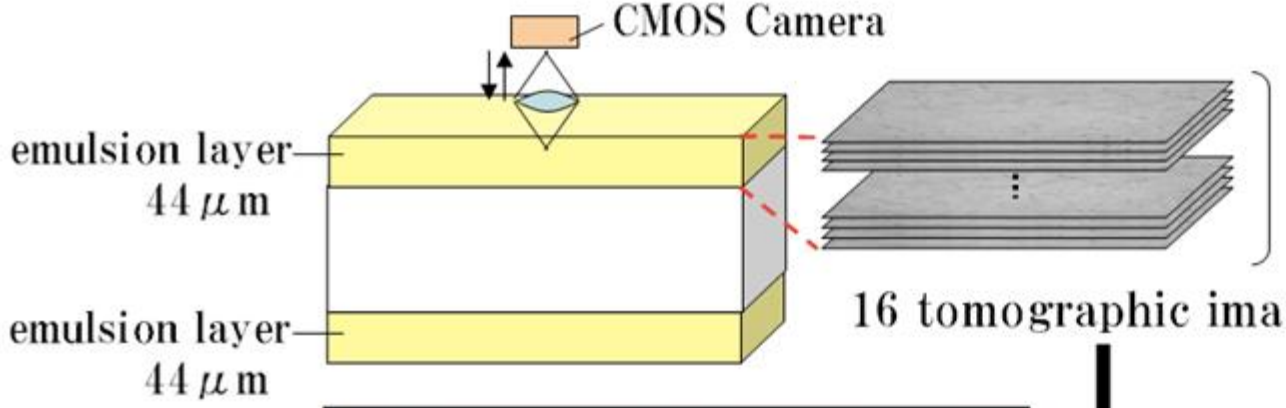


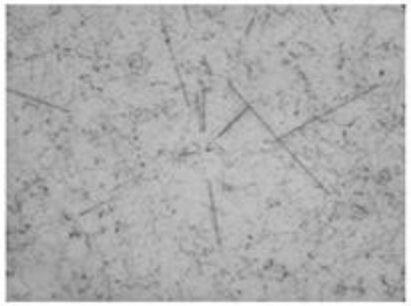
Microscope view



Sensitivity
35 silver grains /100μm

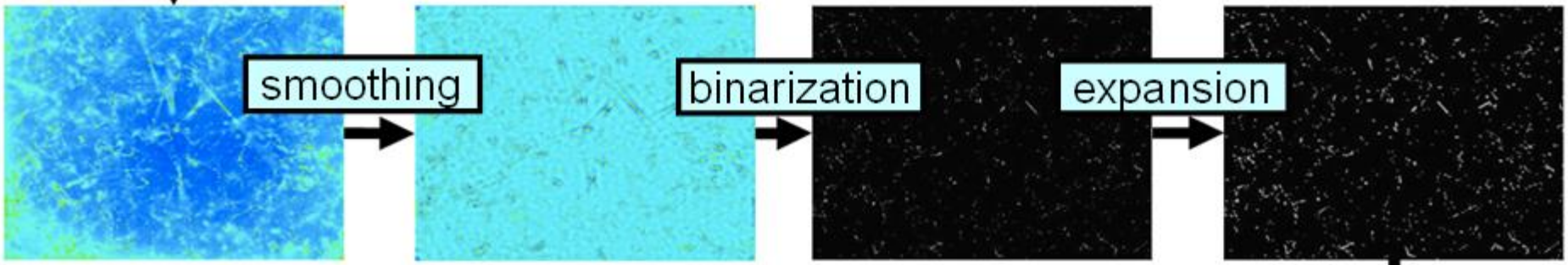


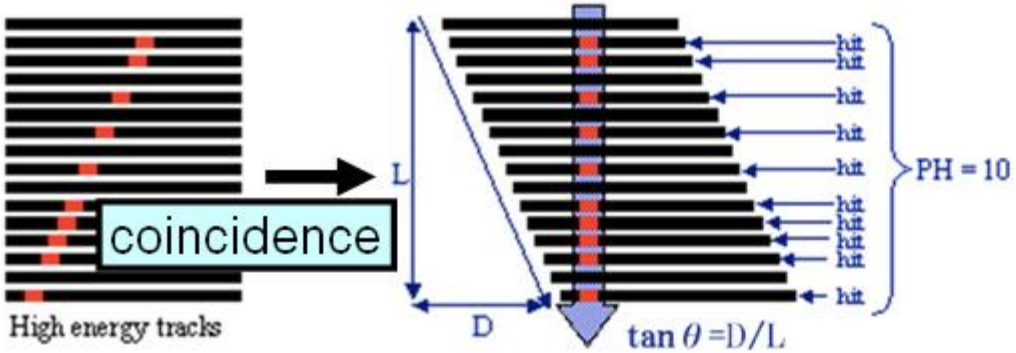




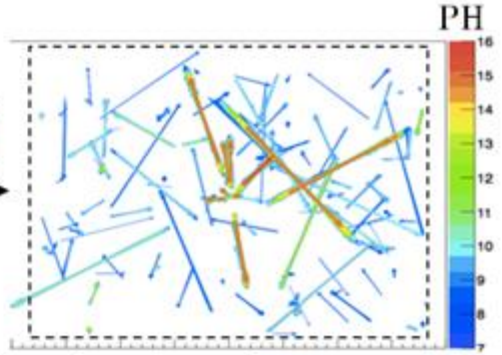
The image superimposed
16 images from microscope

16 tomographic image taking





PH cut



Result of track recognition

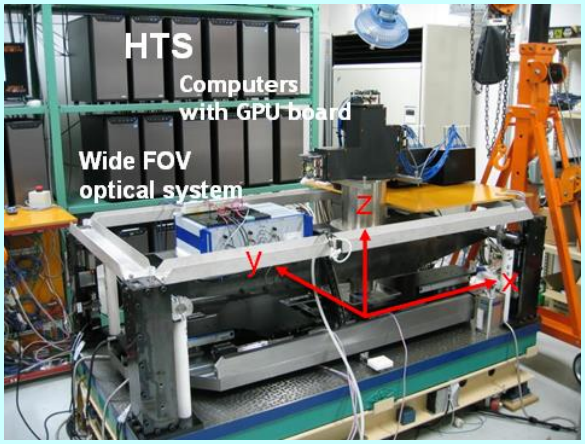
Long history in Neutrino Research

- **1978-1983 Fermilab E531** ~ 100kg
  charm physics, $\nu_\mu \rightarrow \nu_\tau$ oscillation <20GeV>
- **1994-2000 CERN WA95 CHORUS** ~ 1 ton
  $\nu_\mu \rightarrow \nu_\tau$ oscillation, charm physics <27GeV>
- **1997-2001 Fermilab E872 DONuT** ~ 1 ton
  first ν_τ direct observation <80GeV>
- **2008- CERN CNGS01 OPERA** 1250 ton
  $\nu_\mu \rightarrow \nu_\tau$ oscillation <17GeV>

Recent technical improvements

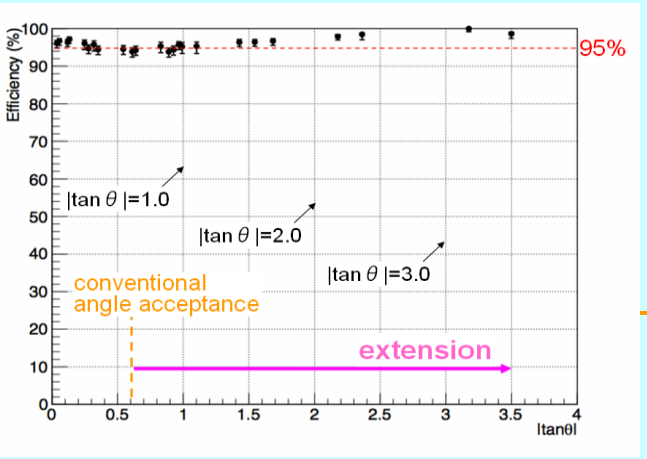
Readout technique

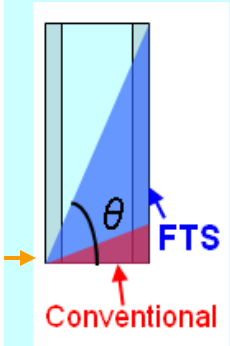
High Speed Scanning



HTS 9,000cm²/h, x100 faster

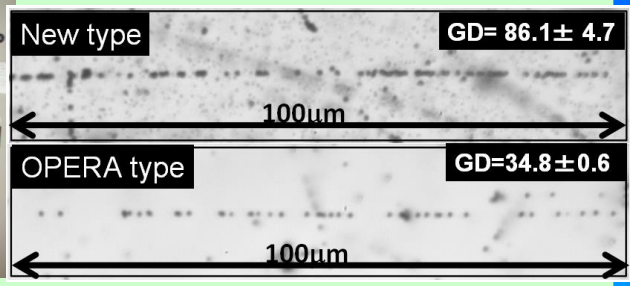
Large angle tracking technique



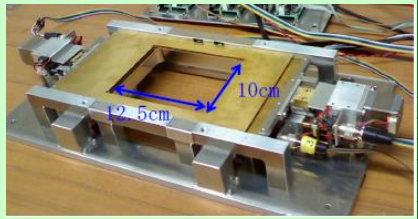


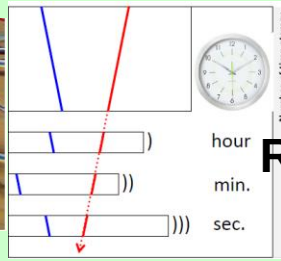
Detector technique

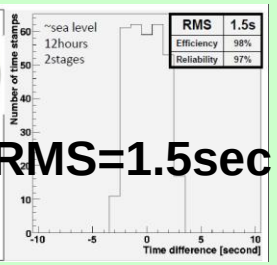
High Sensitive film



Time resolution

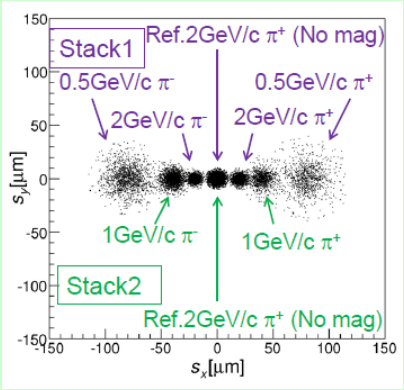




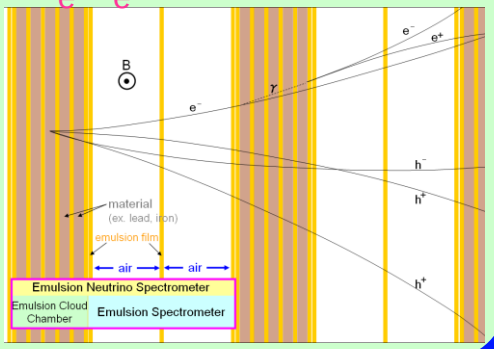


RMS=1.5sec

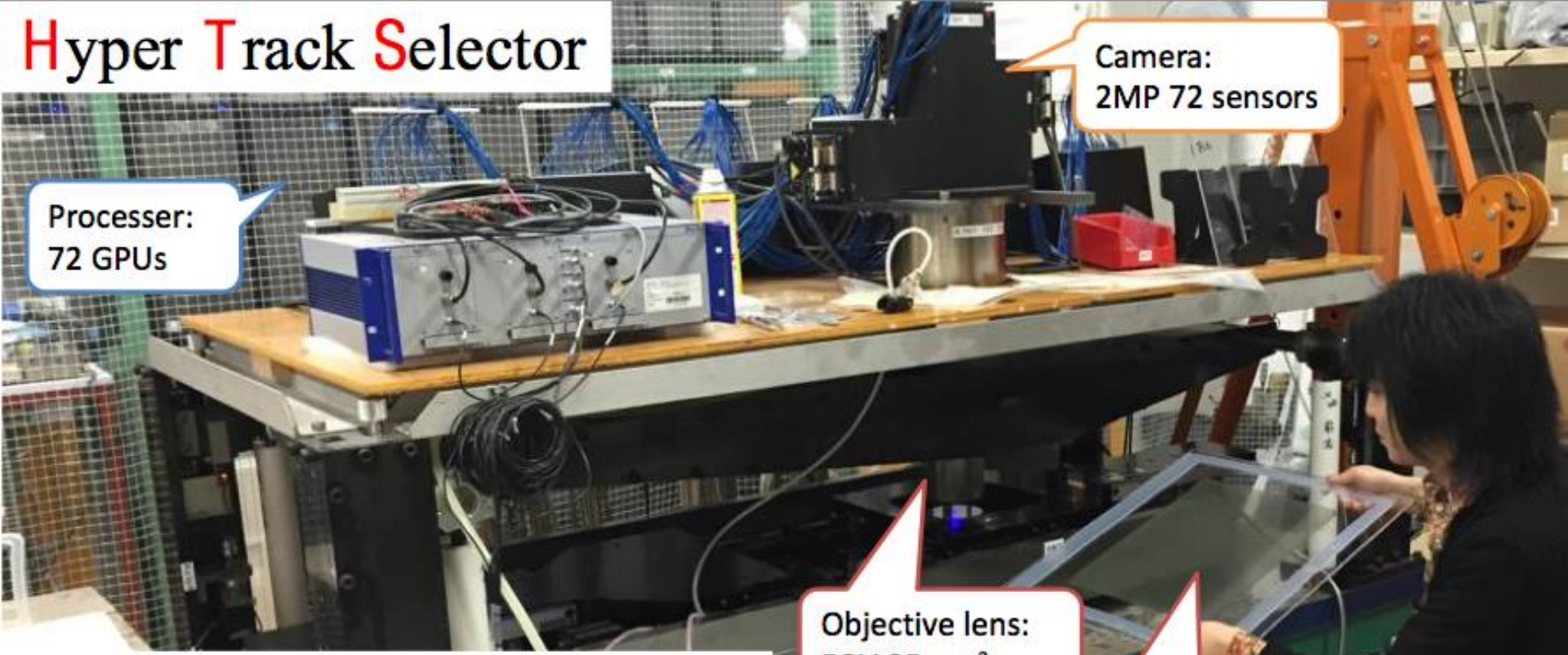
Charge sign ID

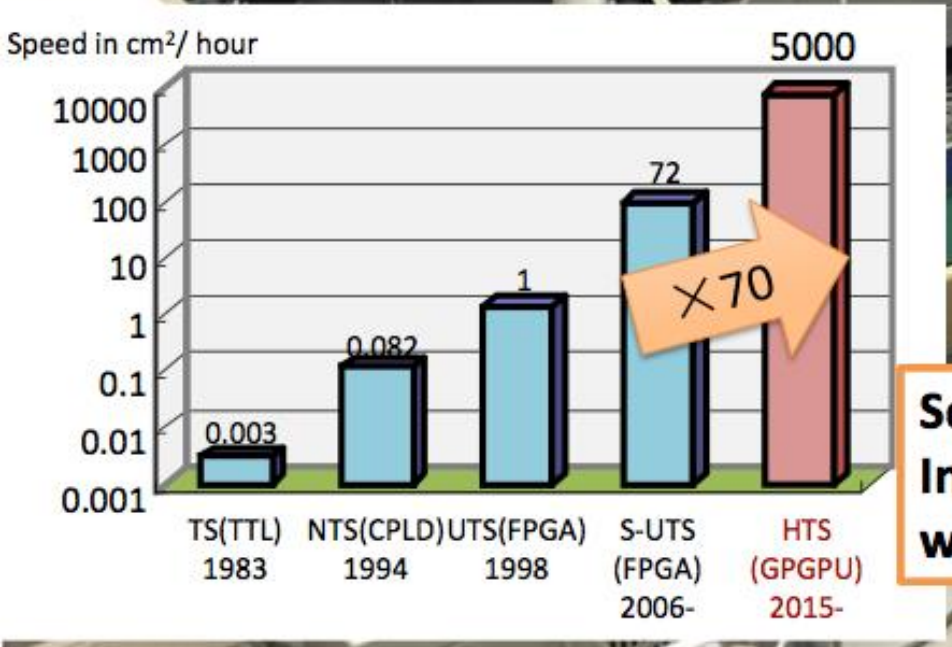


$\nu_e/\bar{\nu}_e$ identification



Hyper Track Selector



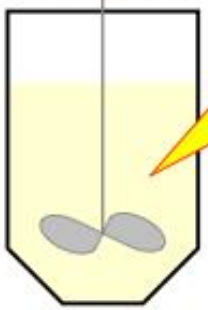


Scanning time is shared by projects.
In total about 100 m² film area (>1000 films) were scanned in recent 12 months

Gel Production Machine at Nagoya Univ.

Chemical reaction

$AgNO_3 + NaBr \rightarrow AgBr\downarrow + NaNO_3$

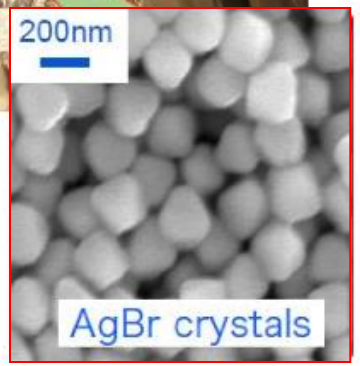


Injection speed
Mixing speed
Temperature

Crystal size
Crystal shape

chemical

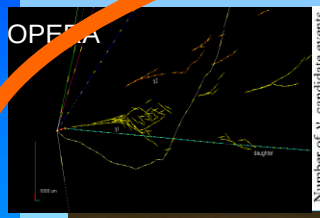
Sensitivity
Stability

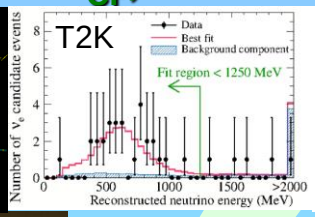


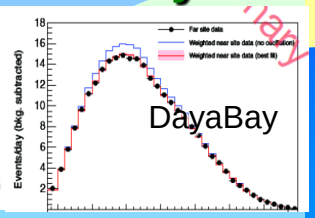
NINJA Experiment

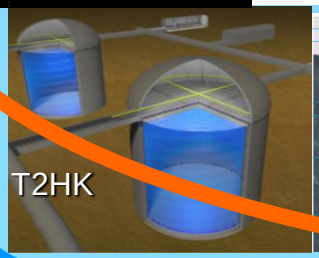
Current situation on neutrino physics

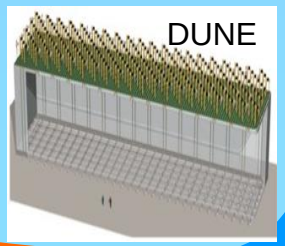
Neutrino oscillation
→ δ_{CP}, mass hierarchy



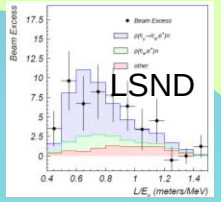


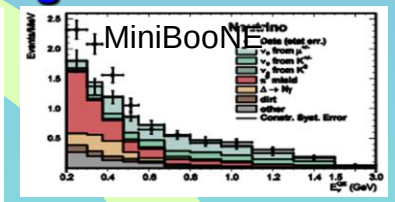


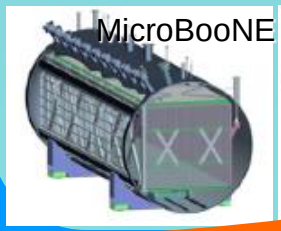


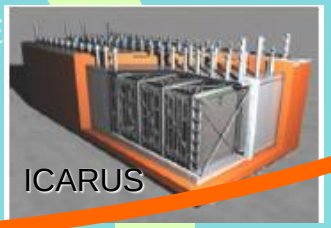


Sterile Neutrinos
→ 4th generation ? Dark matter ?

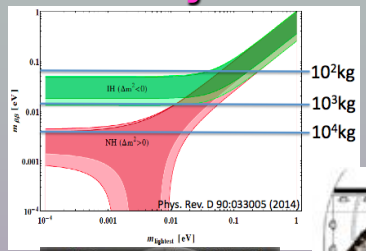


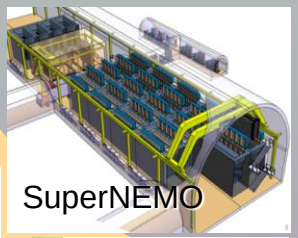


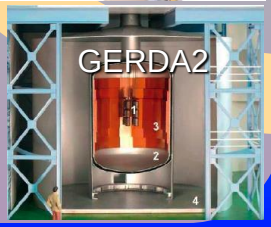




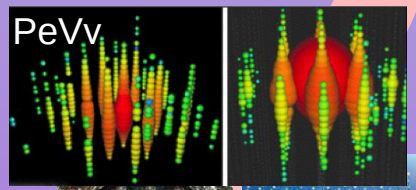
0νdouble beta decay
→ majorana / dirac ? νmass meas.

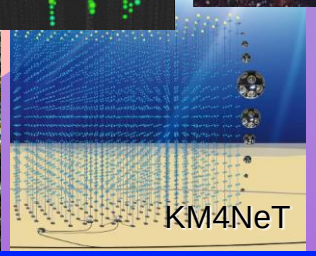


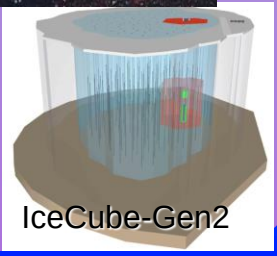




Cosmic neutrinos
→ Ultra-high energy, Supernova,…



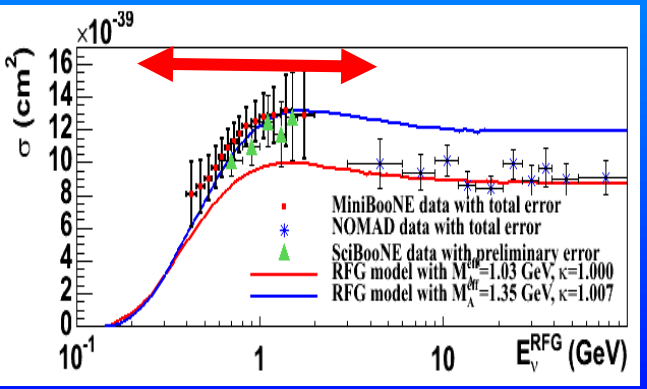


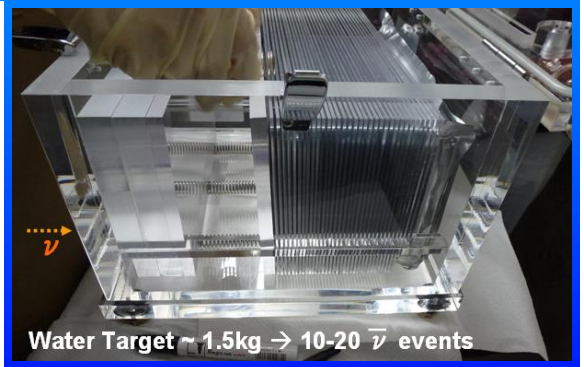


この他にも多くの実験が計画・実施・遂行されている。

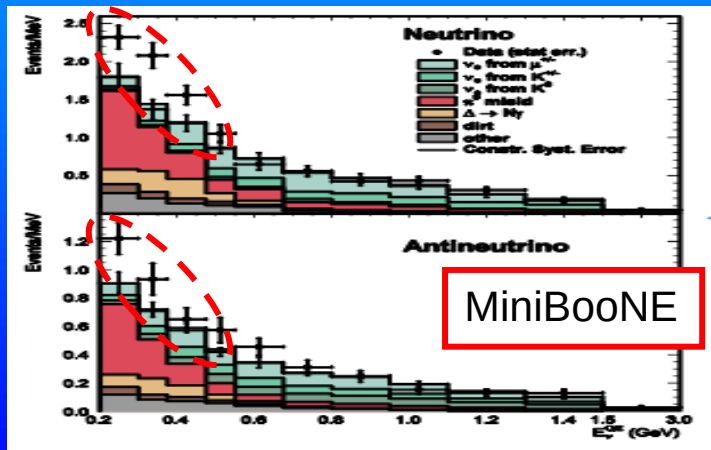
Motivation

- Precise neutrino-nucleus interaction measurement is important to reduce the systematic uncertainty in future neutrino oscillation experiments.
- We started a new experiment at J-PARC to study low energy neutrino interactions by introducing nuclear emulsion technique.
- The emulsion technique can measure all the final state particles with low energy threshold for a variety of targets (H_2O, Fe, C,…).
- Furthermore its ultimate position resolution allow to measure ν_e cross section and to explore of a sterile neutrino.





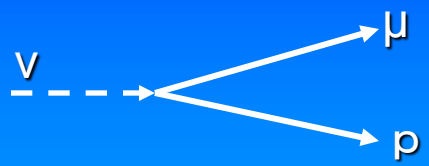
Water Target Emulsion Chamber



Precise measurement of neutrino-nucleus interactions

- CCQE interaction events are used as signal to reconstruct energy in T2K/SK.

$$E_{QE} = \frac{m_p^2 - (m_n - V)^2 - m_\mu^2 + 2(m_n - V)E_\mu}{2((m_n - V) - E_\mu + p_\mu \cos\theta_\mu)}$$

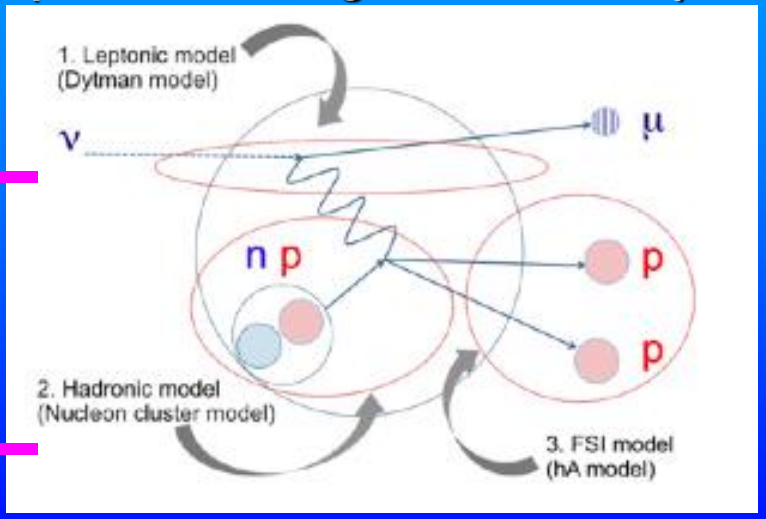


- Other interaction modes contaminate due to final state interaction in nucleon and detector inefficiency.
- Energy can't be reconstructed correctly with these interaction modes.
  → Need precise understanding about neutrino interaction.

uncertainties on predicted events at SK

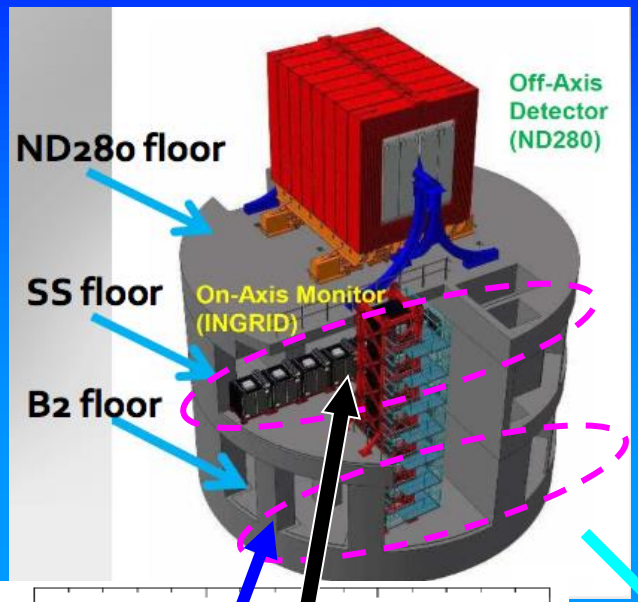
	ν_μ sample 1R$_\mu$ FHC	ν_e sample 1R$_e$ FHC	$\bar{\nu}_\mu$ sample 1R$_\mu$ RHC	$\bar{\nu}_e$ sample 1R$_e$ RHC
ν flux w/o ND280	7,6%	8,9%	7,1%	8,0%
ν flux with ND280	3,6%	3,6%	3,8%	3,8%
ν cross-section w/o ND280	7,7%	7,2%	9,3%	10,1%
ν cross-section with ND280	4,1%	5,1%	4,2%	5,5%
ν flux+cross-section	2,9%	4,2%	3,4%	4,6%
Final or secondary hadron int.	1,5%	2,5%	2,1%	2,5%
Super-K detector	3,9%	2,4%	3,3%	3,1%
Total w/o ND280	12,0%	11,9%	12,5%	13,7%
Total with ND280	**5,0%**	**5,4%**	**5,2%**	**6,2%**

2p-2h interaction in CCQE samples (Meson Exchange Current: MEC)



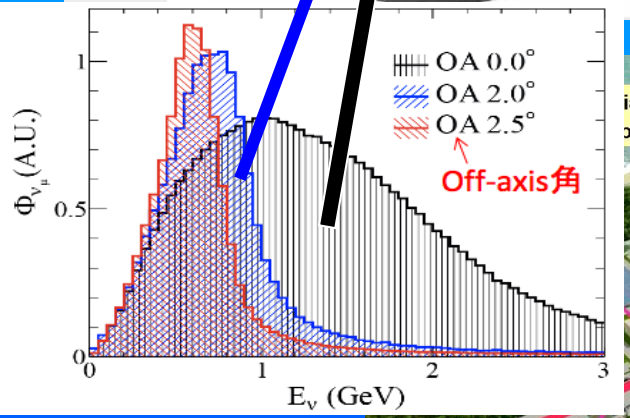
NINJA 実験

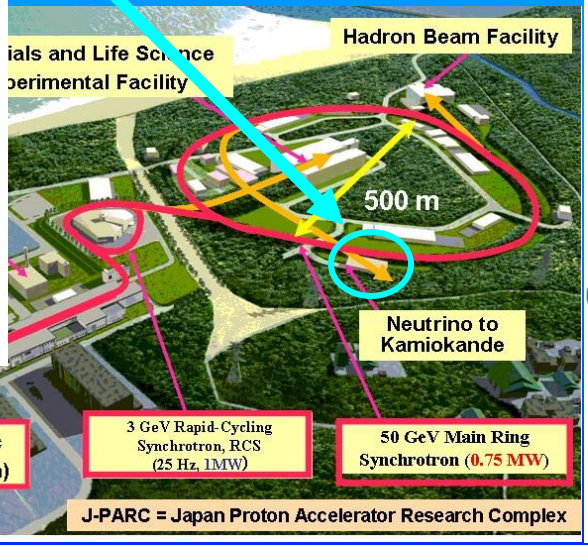
Neutrino **I**nteraction research with **N**uclear emulsion and **J**-PARC **A**ccelerator

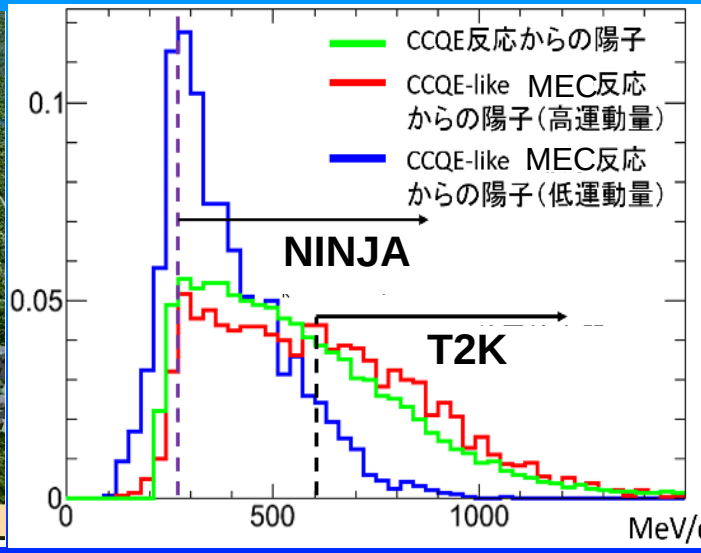


Working group

- **J-PARC** — Experimental site, Neutrino beam
- **OPERA**
  - **Nihon Univ.** — Emulsion development
  - **Nagoya Univ.** — Film production, Scan
  - **Toho Univ.** — Film production, Scan
  - **Kobe Univ.** — Emulsion Shifter
- **T2K**
  - **Univ. Tokyo** — T2K near detector
  - **Kyoto Univ.** — T2K near detector
  - **Yokohama N Univ.** — T2K near detector



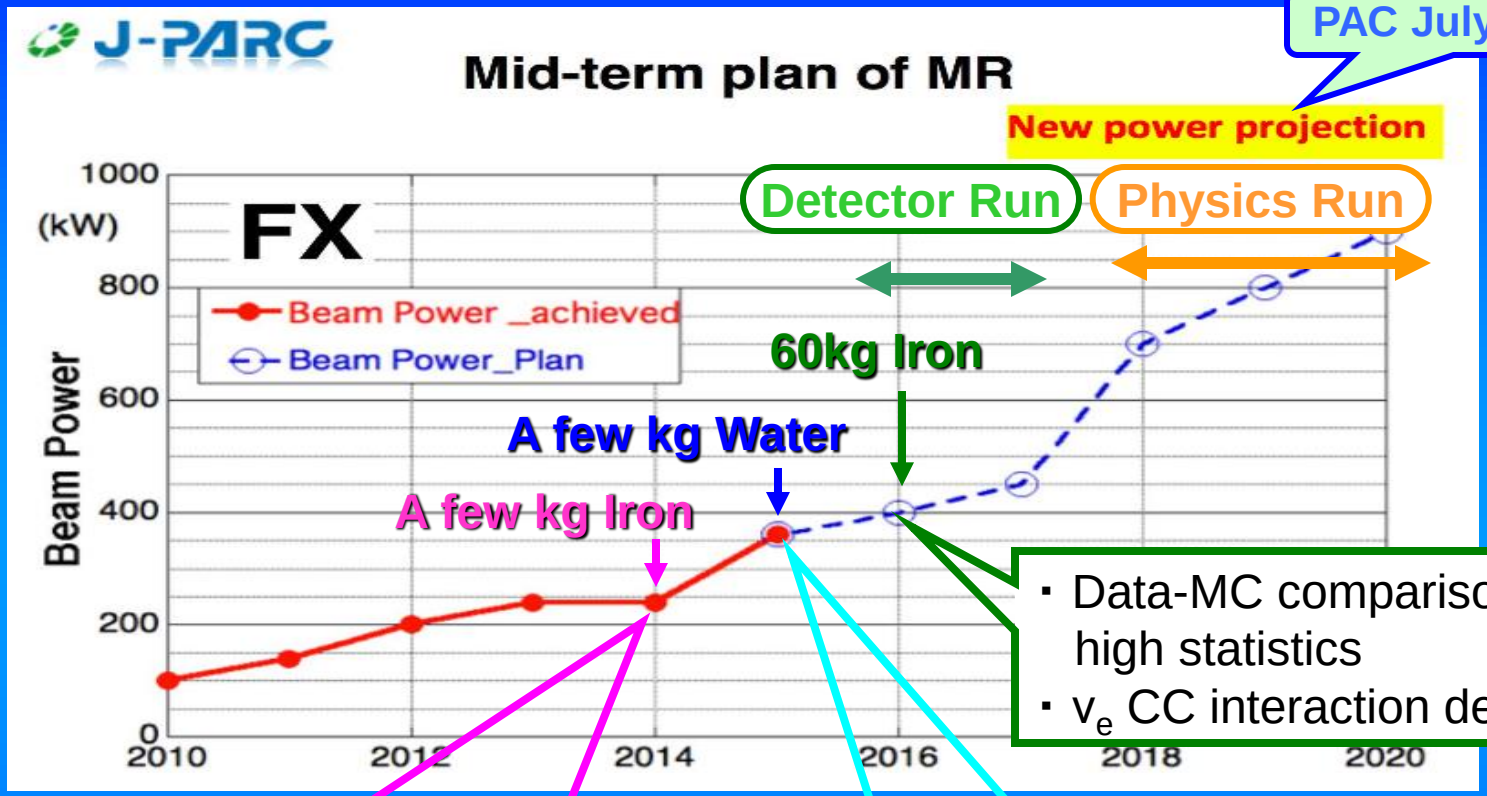




J-PARC

原子核乾板は、MEC反応を測定する**極めて有効な手段** → ニュートリノ反応の精密測定

ν exposure status of NINJA



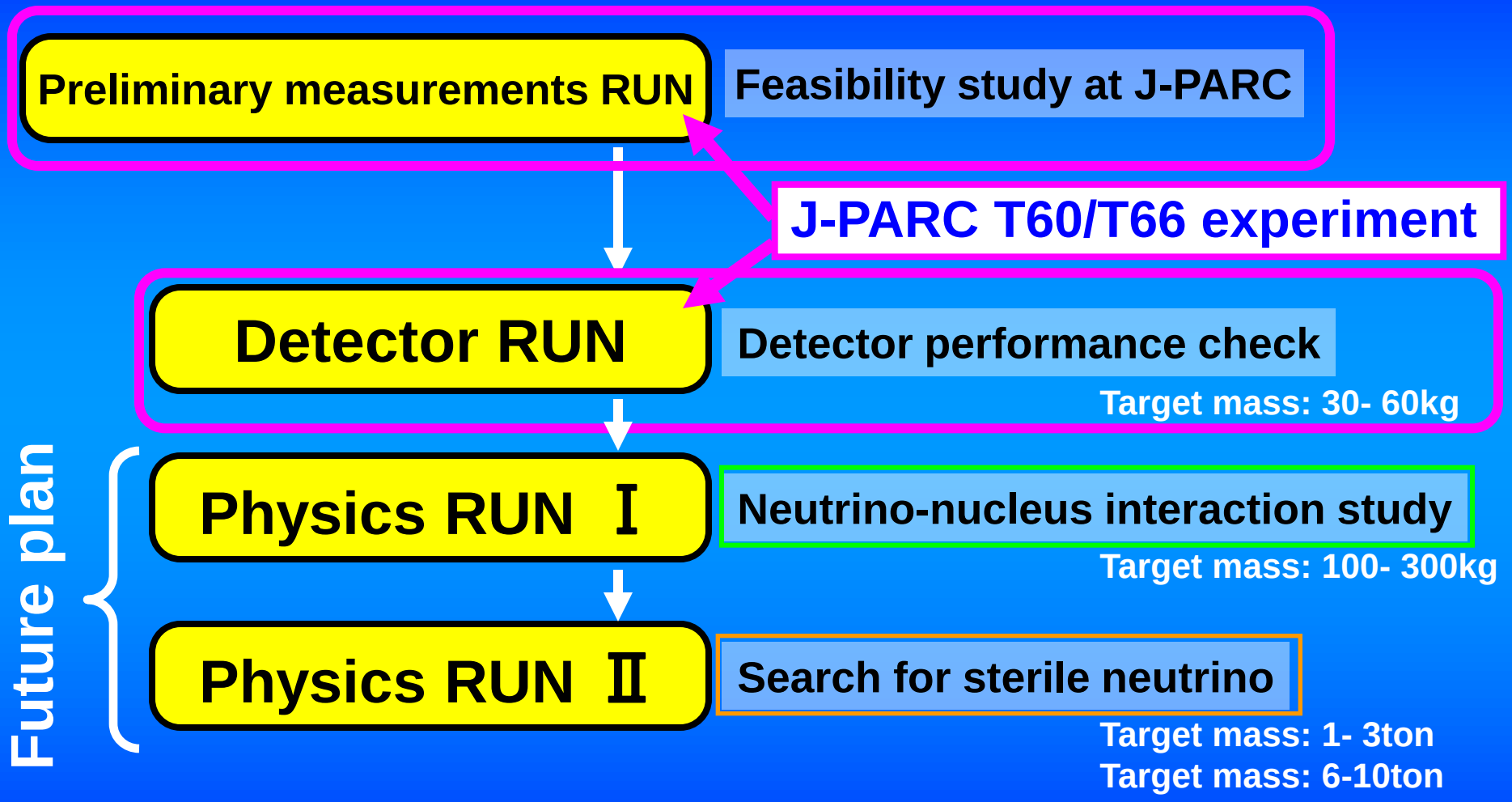
- Data-MC comparison with high statistics
- ν_e CC interaction detection

- Emulsion handling @J-PARC
- Demonstration of ν event detection
- Hybrid analysis with T2K near detector

- ν– Water interaction detection with Emulsion Detector

- We have demonstrated the basic experimental concept at J-PARC site.
- "Detector performance run" was started from last Jan.

NINJA Roadmap

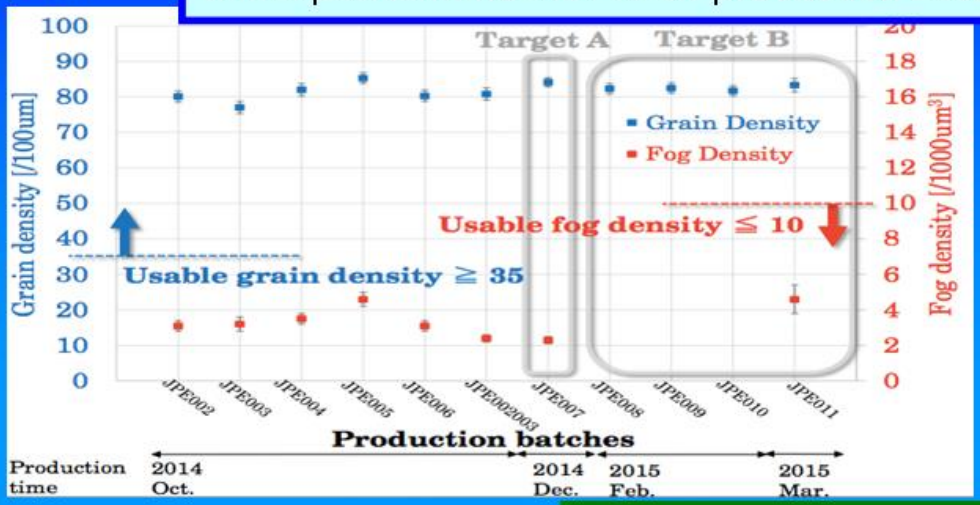


- The aim of T60/T66 is a feasibility study and detector performance check to make a future plan.
- We will expand the scale of detector gradually, step by step.

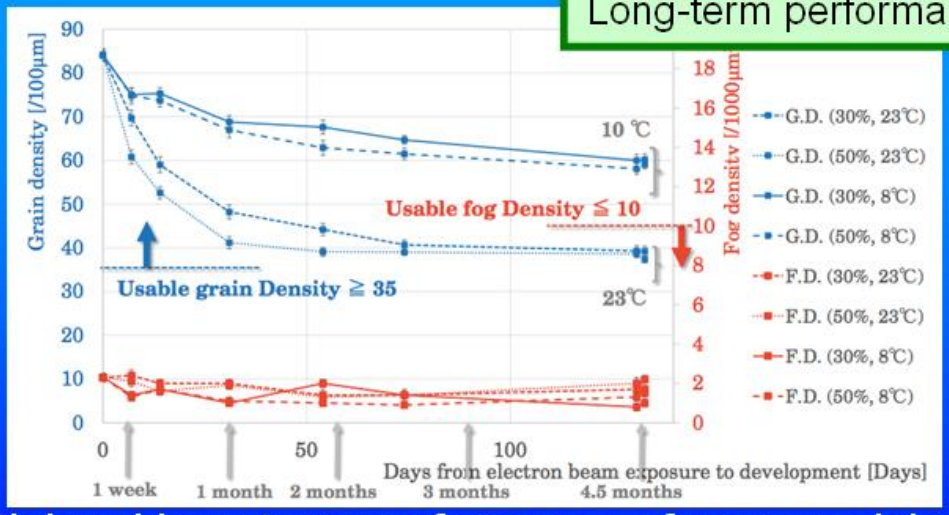
Emulsion gel production in the lab

Nuclear emulsion films were made by ourselves.

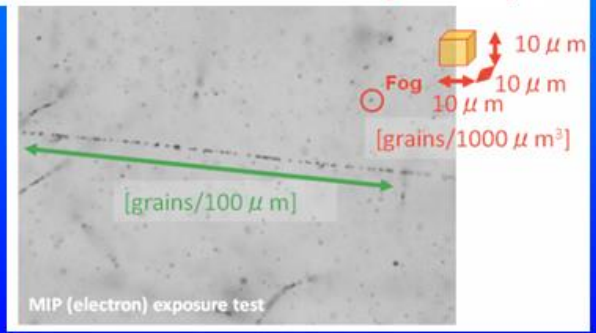
Initial performance for each production batch



Long-term performance

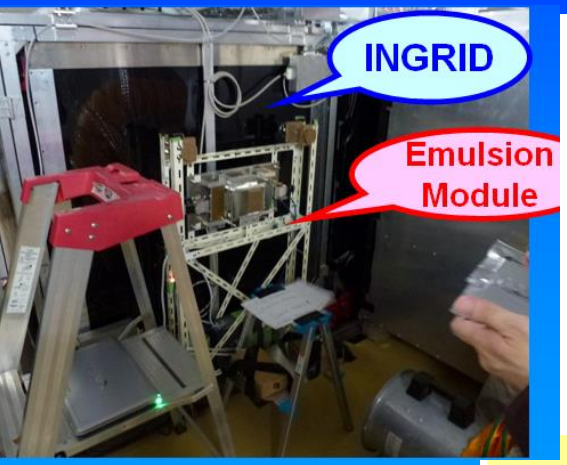


Signal efficiency → Grain density
Isolated random noise → Fog density

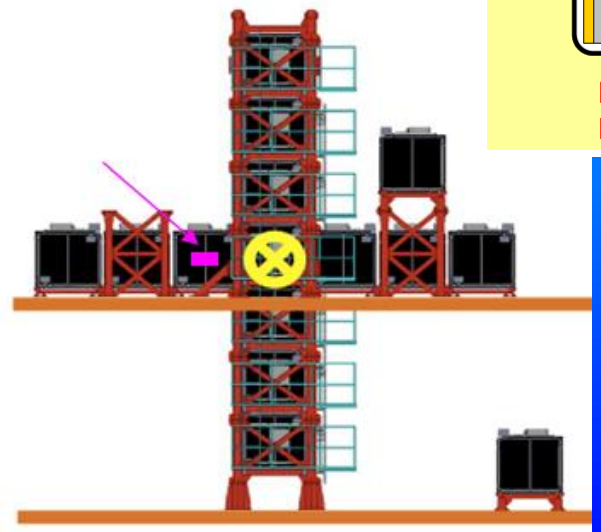


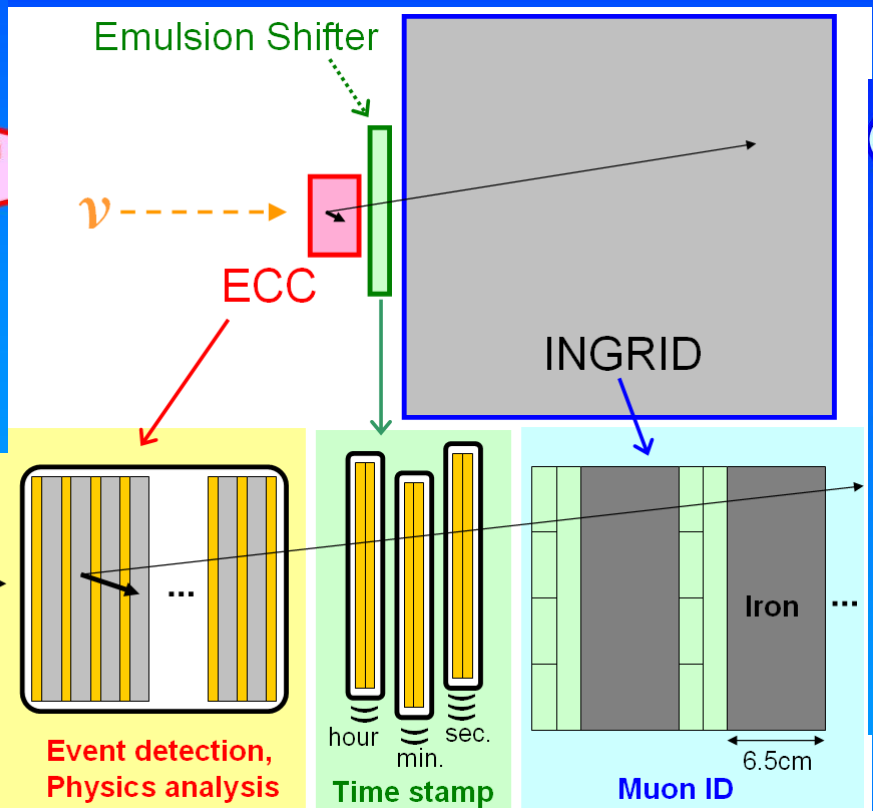
Initial and long-term performance of new emulsion gel is kept at safety level for signal and noise.

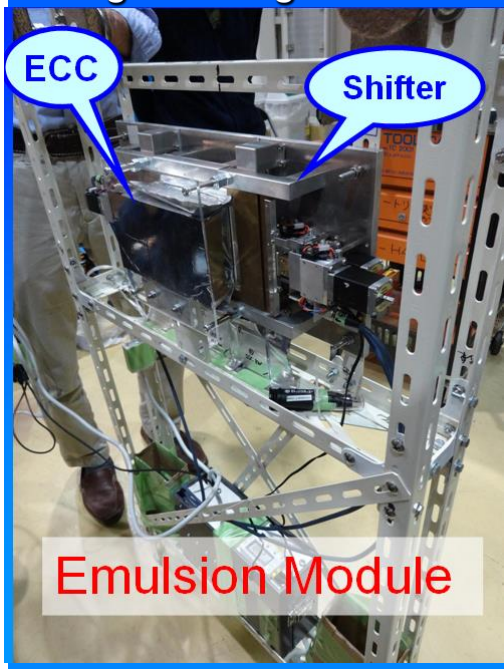
Conceptual detector design



SS floor @J-PARC
(Jan. 2015)



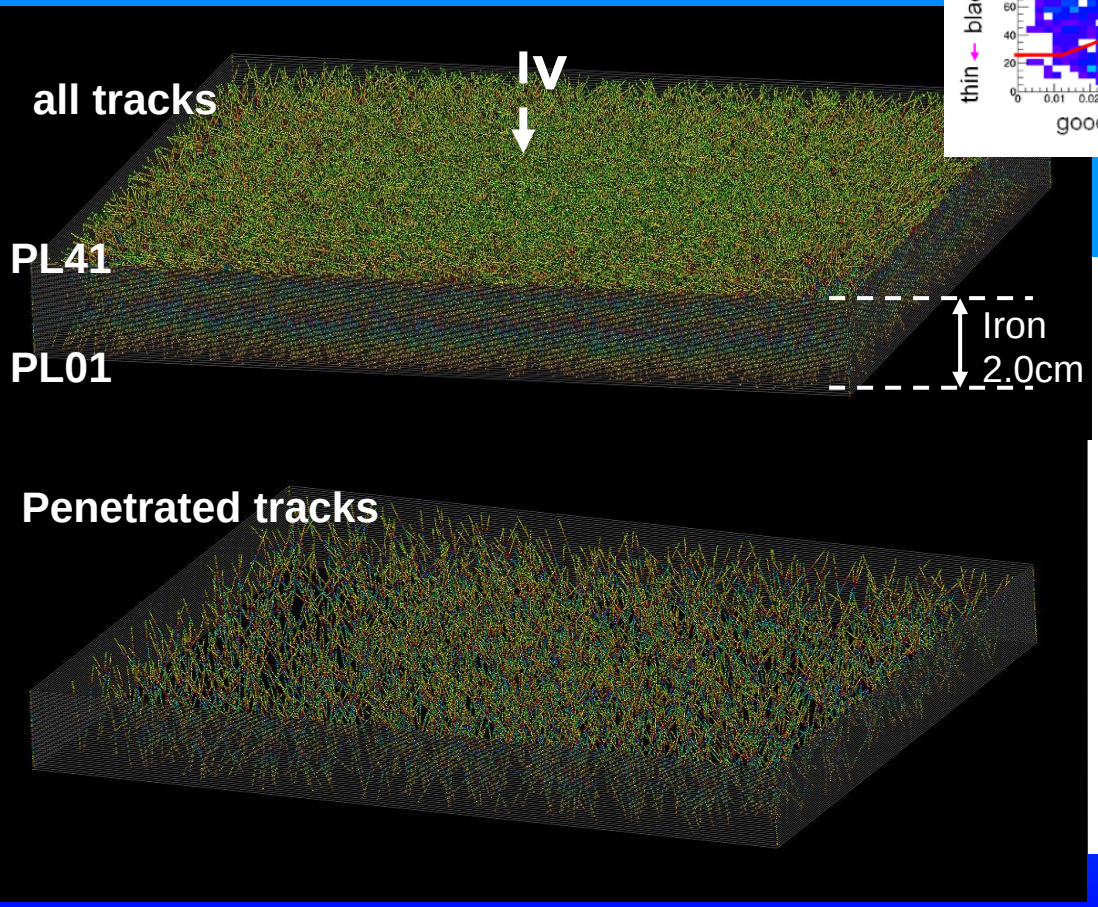




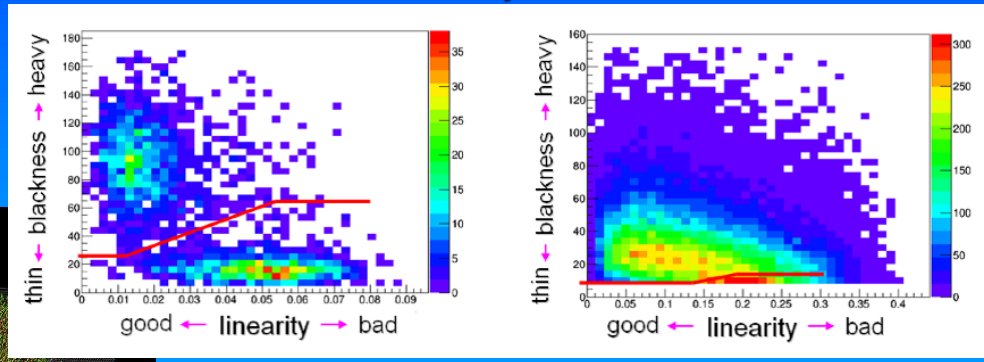
- **E**mulsion **C**loud **C**hamber is a sandwich structure of emulsion films and iron plates.
- Emulsion detector is placed in front of T2K near detector, INGRID.
- Emulsion Shifter is re-used from GRAINE project to give a timing info. to emulsion tracks.
- Muon ID is possible by combined analysis with INGRID.

Reconstructed track data

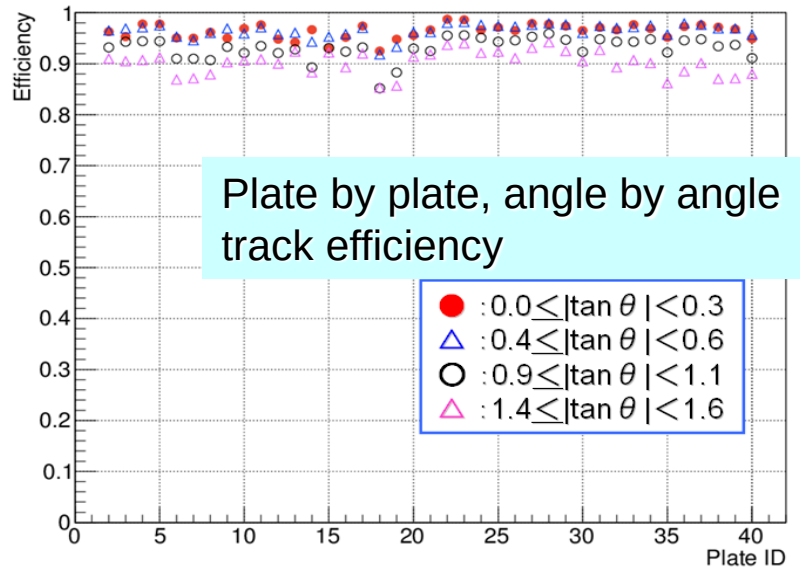
All emulsion films were scanned by HTS.
First of all, noise tracks were rejected by evaluating the quality of each tracks.
Then tracks were reconstructed.



Track Quality Selection



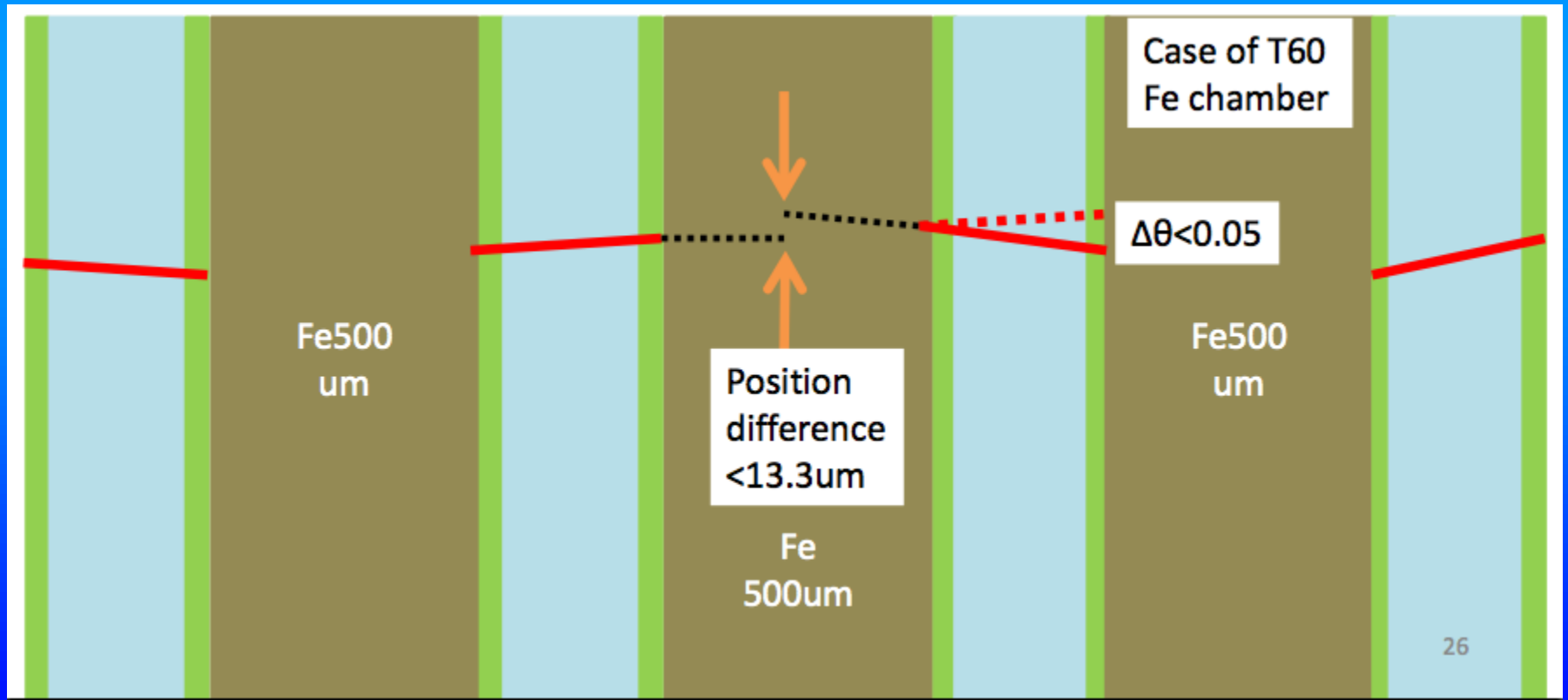
（|tanθ| ≦ 0.1 ）　　（1.4≦ |tanθ| ）



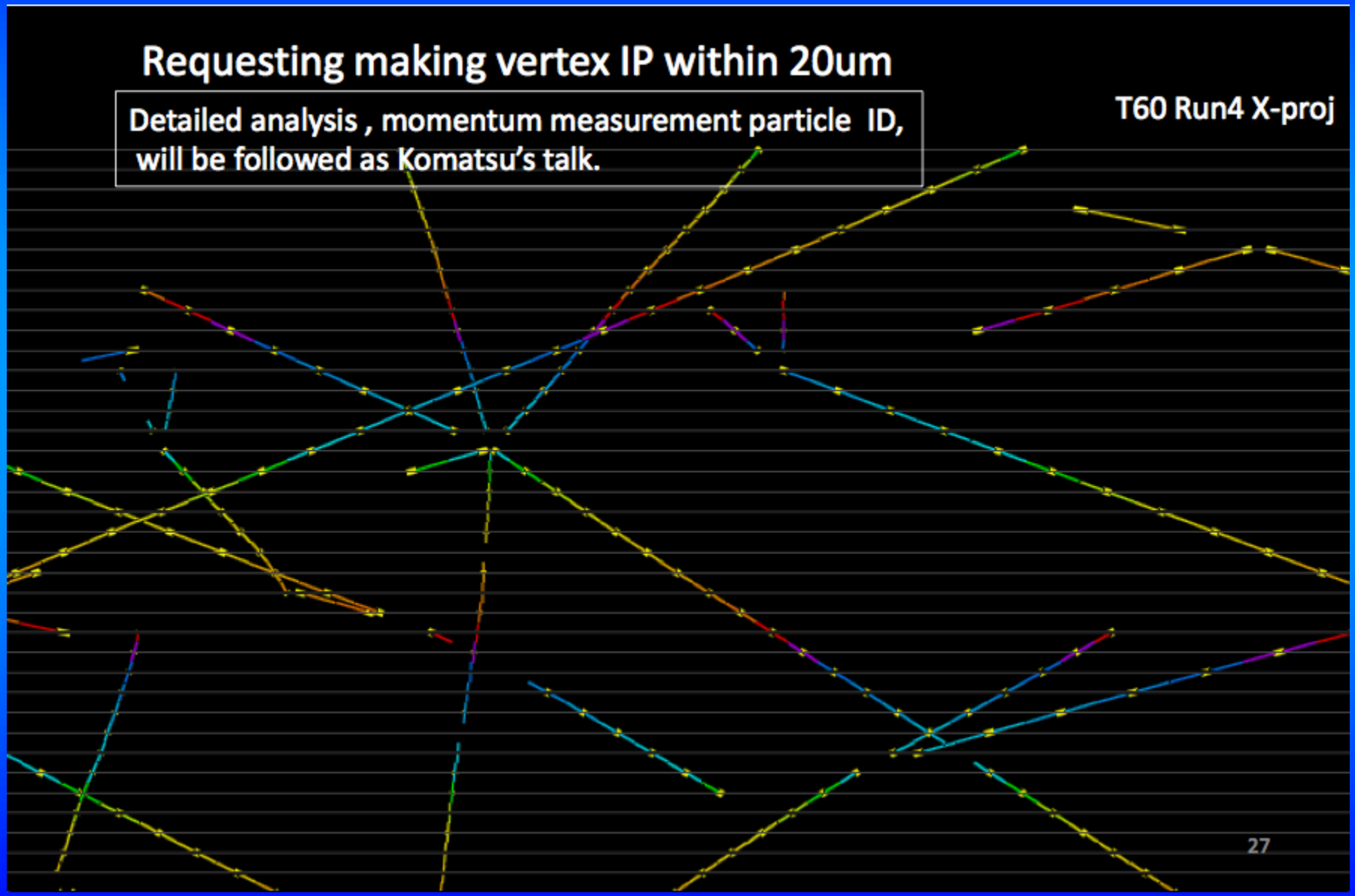
Track reconstruction

- Two base track segments are tried to be connected assuming cut off momentum.
- They are connected if the position and angular difference within the allowance.
  - Position difference between two segments extrapolating at middle place.
  - Angular difference

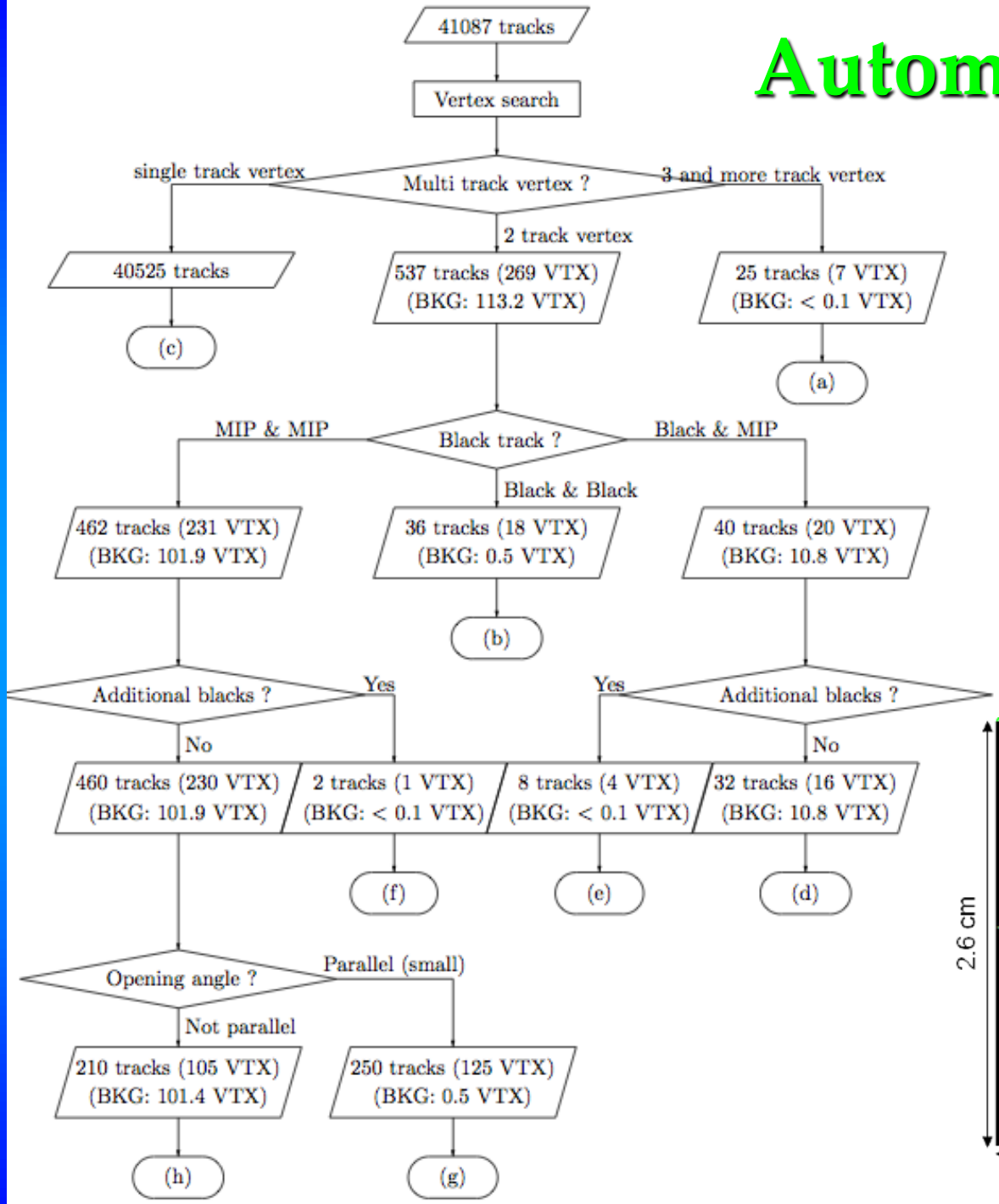
Continue to all possible combination of two tracks → all tracks are reconstructed.



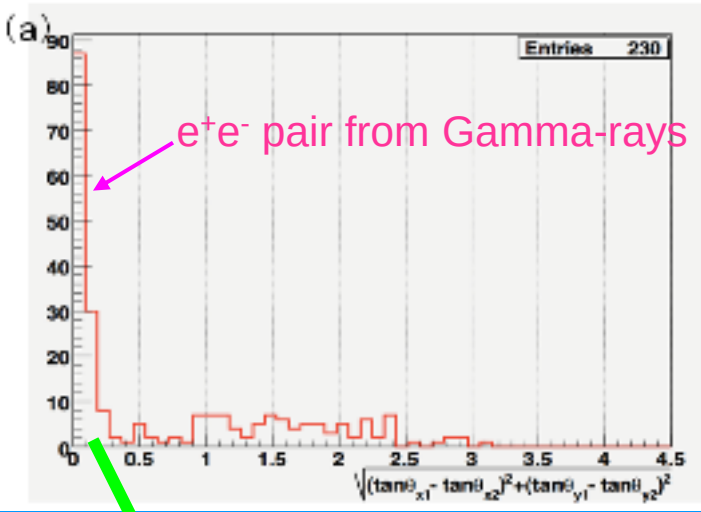
Event analysis sample

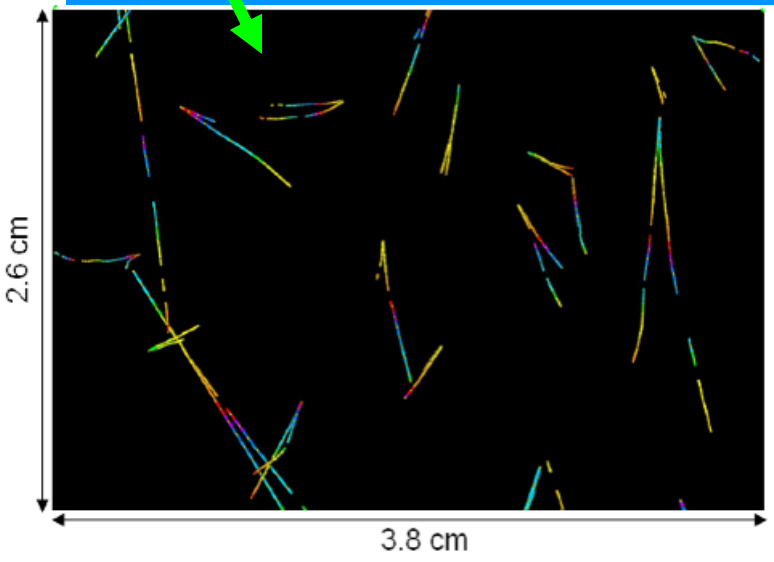


Automatic procedure



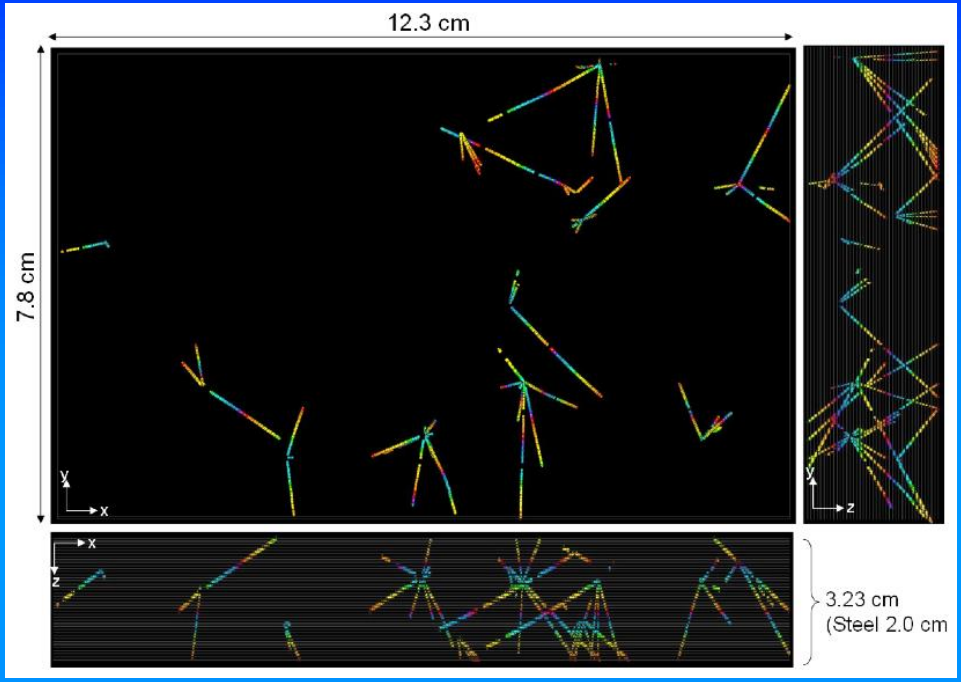
Opening angle of 2MIP



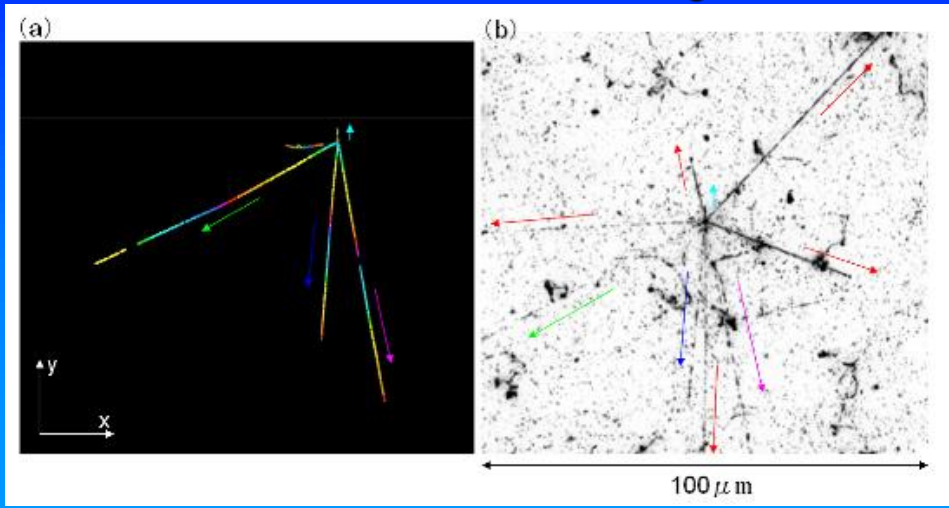


Status review of NINJA

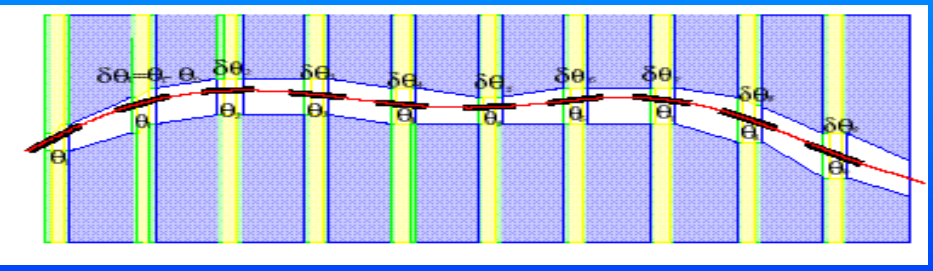
Systematic emulsion analysis



Interacted in emulsion region

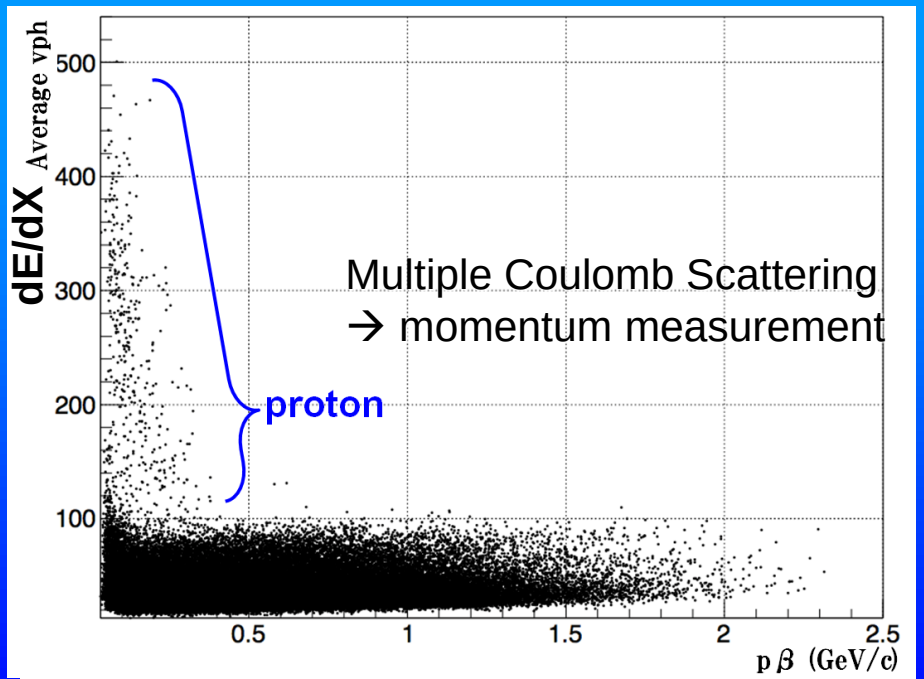


Momentum measurement

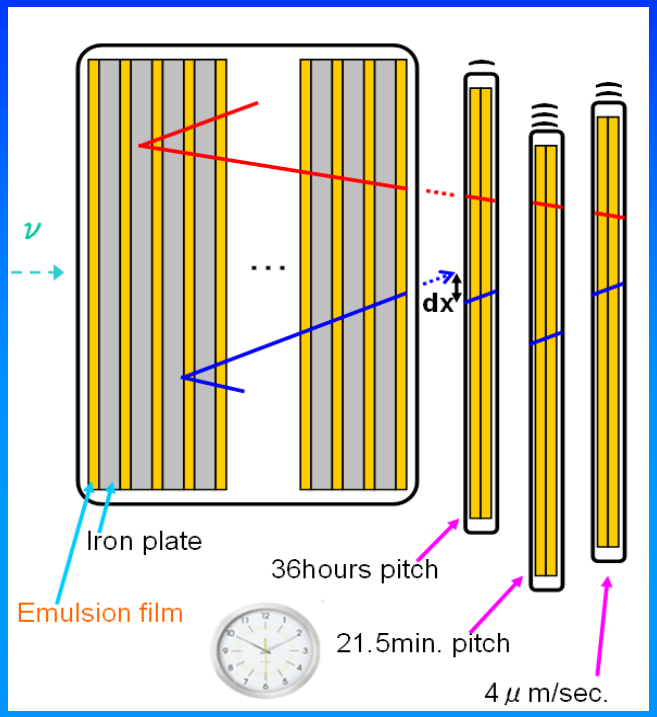


$$\theta_0 = \frac{13.6}{(pc\beta)} \times \sqrt{\frac{x}{X_0}} \times \left[1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right]$$

Proton Identification



Time stamp for ν event with Emulsion Shifter



Emulsion films are set on moving stages controlled by stepping motor.

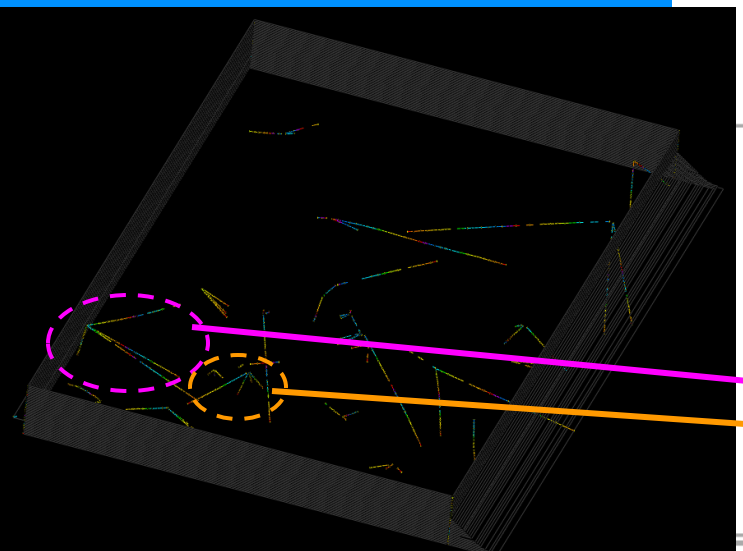
Time stamp is given by coincidence of tracks on each stage.

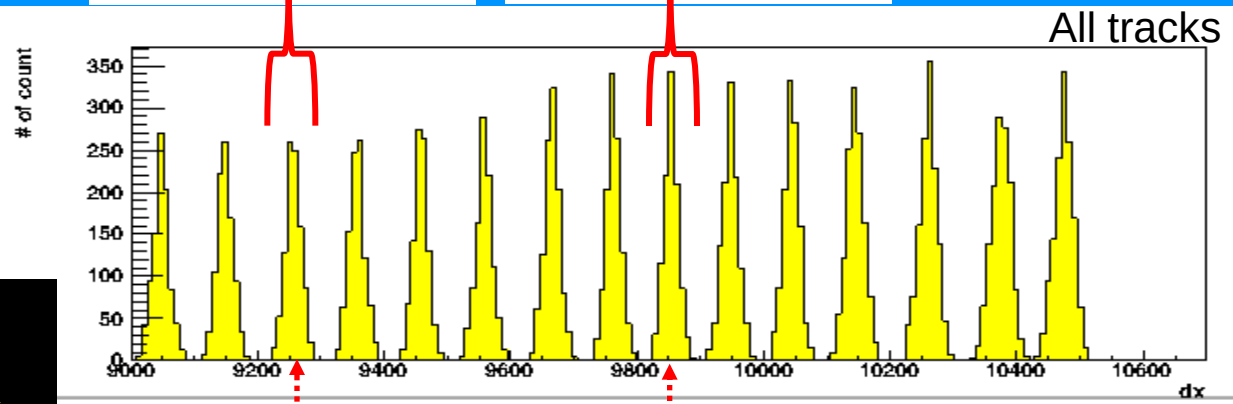
→ Position difference from reference point
= Timing information

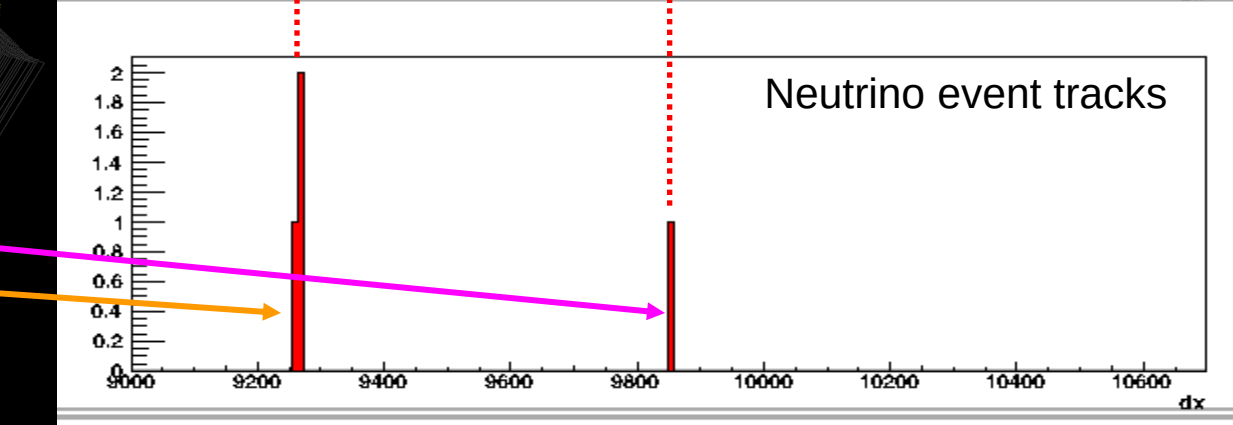
Spot 13
Mar.12 2:23:35
~ Mar.14 14:23:57

Spot 7
Mar.21 2:25:49
~ Mar.23 14:26:12

← Information from Top stage

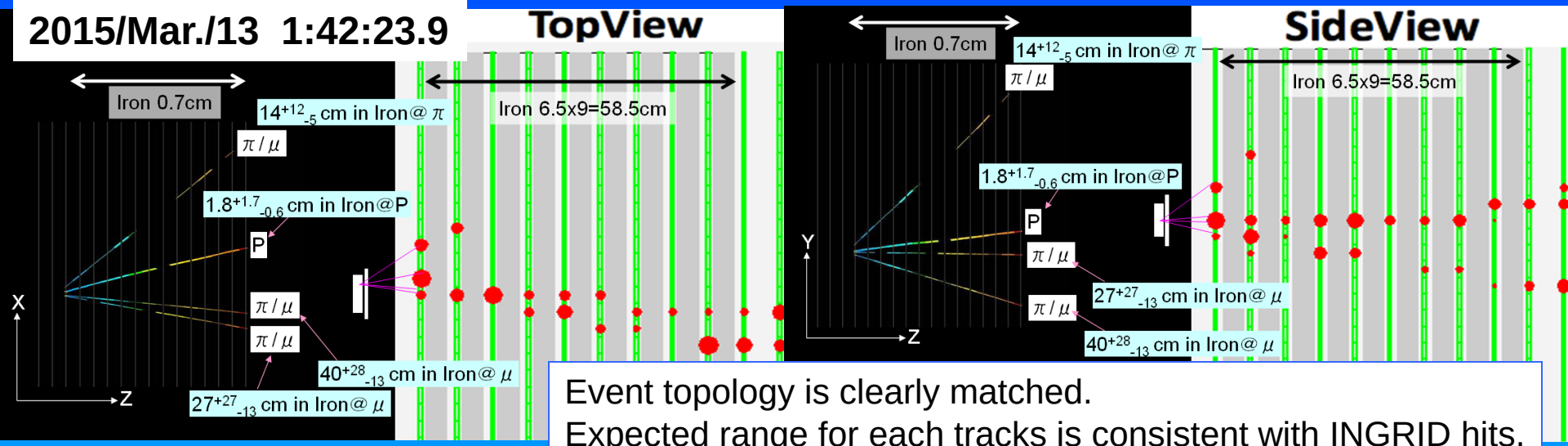






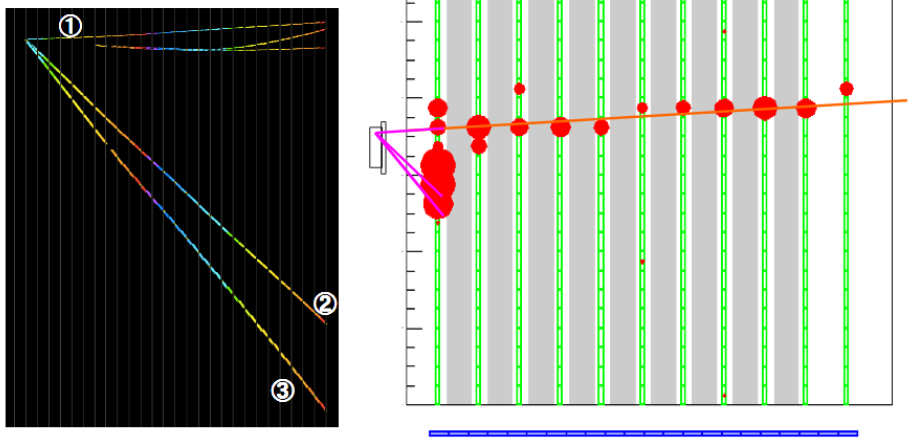
Emulsion-INGRID Hybrid analysis

<Event time>
2015/Mar./13 1:42:23.9

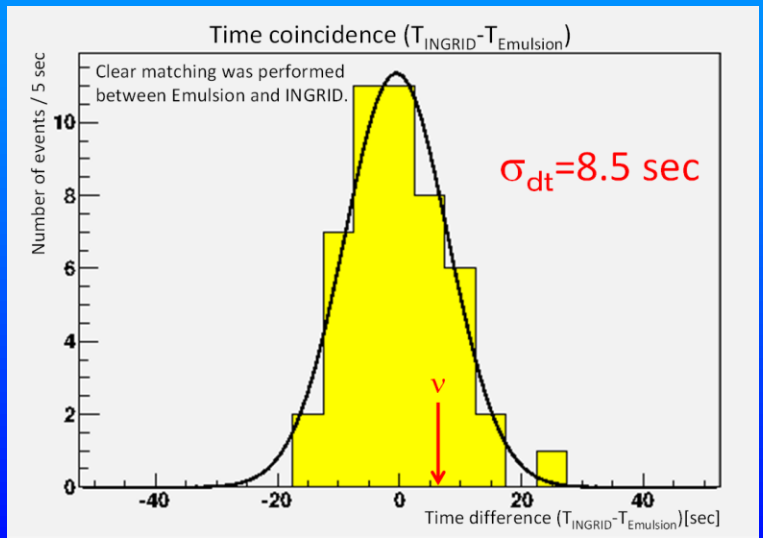


Event topology is clearly matched.
Expected range for each tracks is consistent with INGRID hits.

<Event time>
2015/Mar./22 15:06:35.0

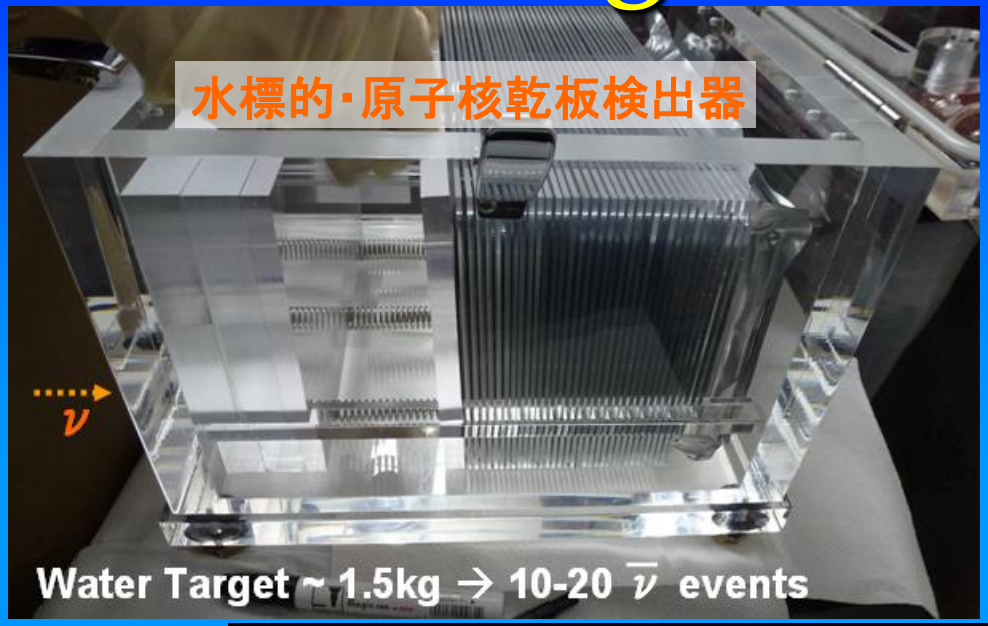


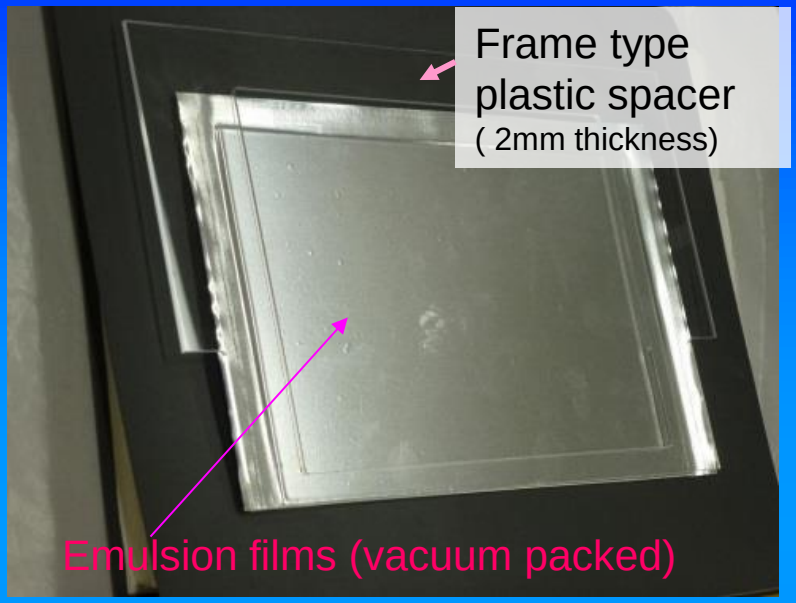
Time resolution for emulsion tracks

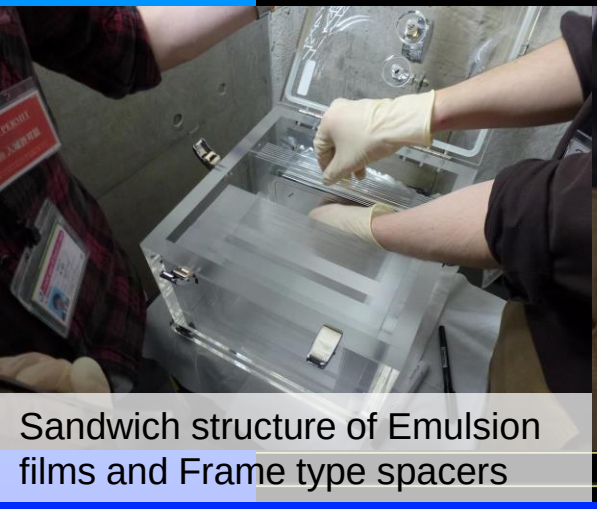


$\bar{\nu}$ exposure in May 2015.

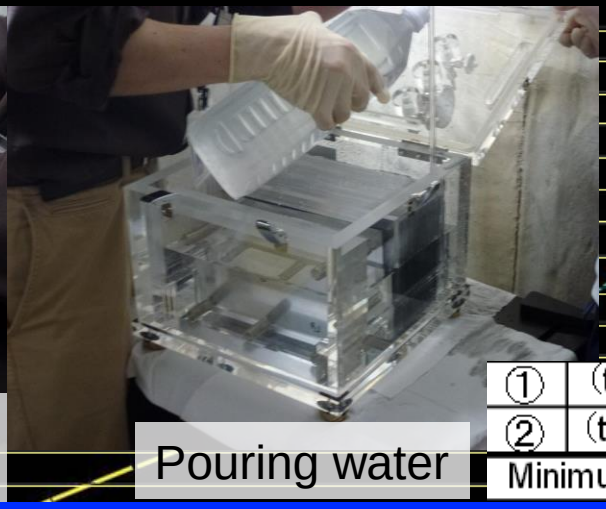
Water target emulsion detector



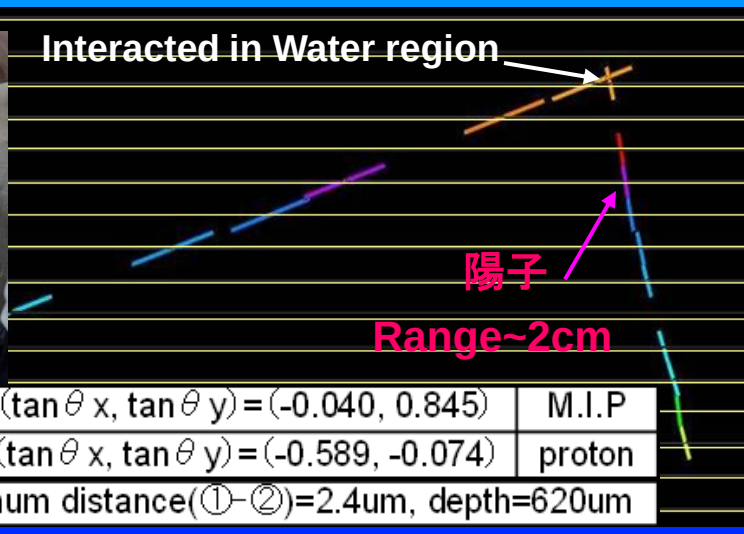




Sandwich structure of Emulsion films and Frame type spacers



Pouring water

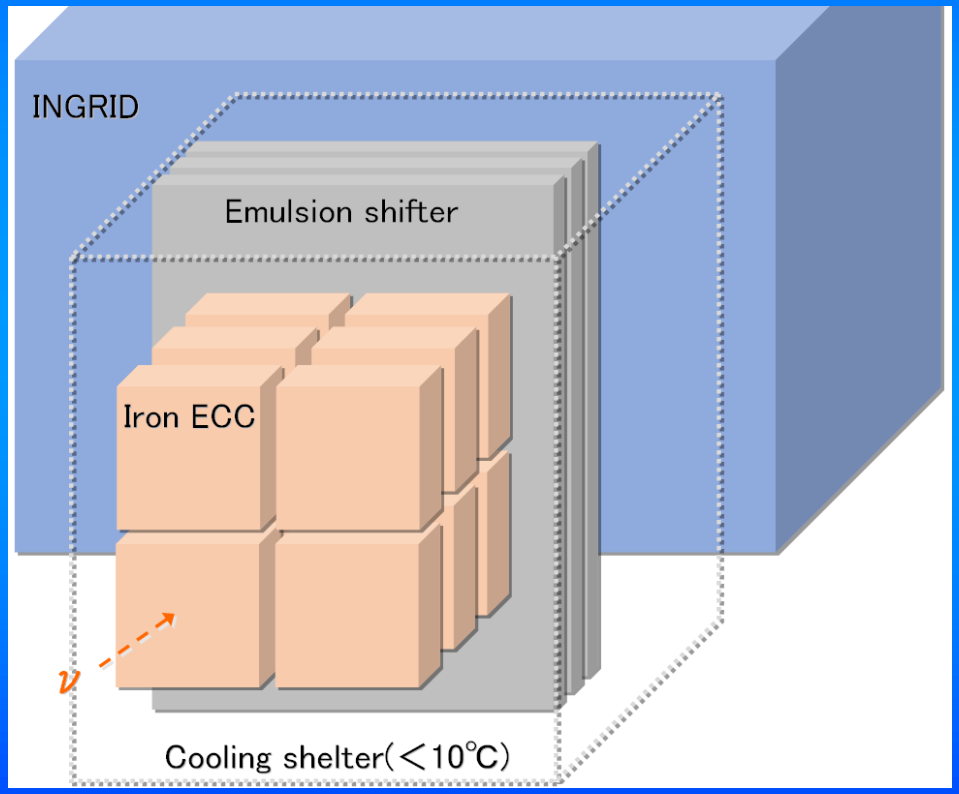


①	(tanθ x, tanθ y)=(-0.040, 0.845)	M.I.P
②	(tanθ x, tanθ y)=(-0.589, -0.074)	proton
Minimum distance(①-②)=2.4um, depth=620um		

First detection of ν - Water interaction with Emulsion Detector

Detector Run

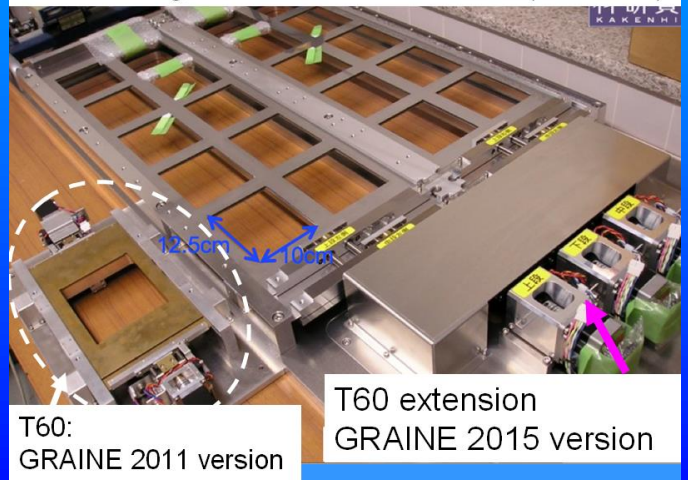
We are starting Detector Run to compare MC with high statistics.

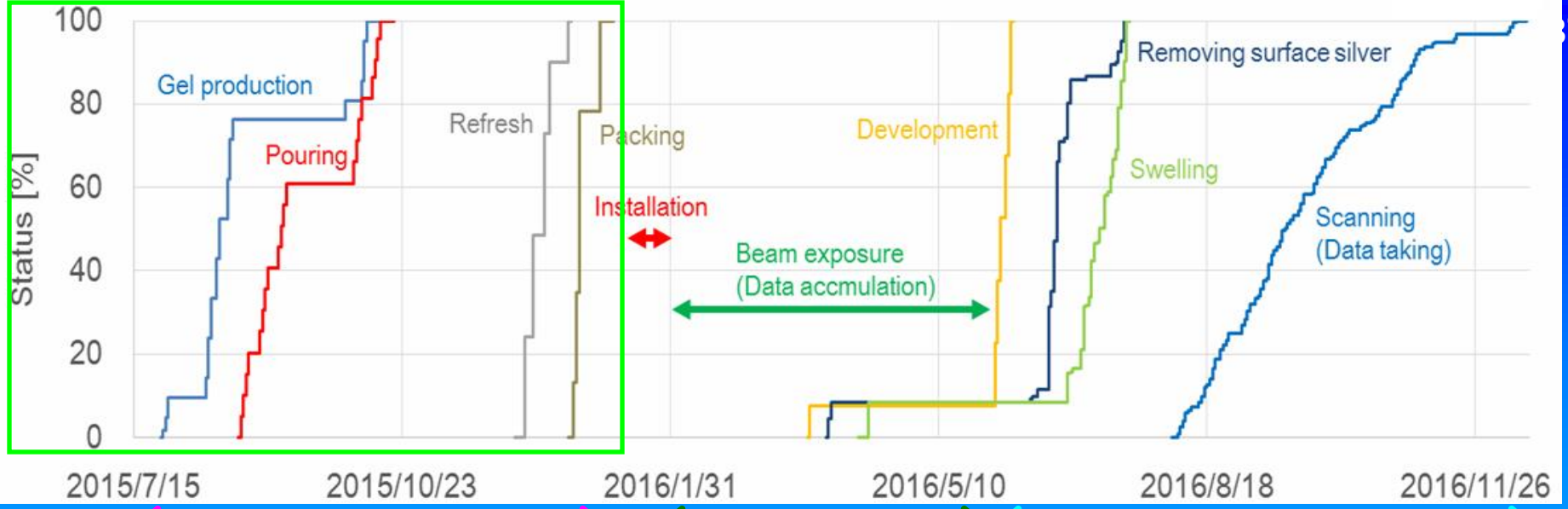


- $\bar{\nu}$ exposure : 2016 @SS floor
  end of Jan. → beam end
- Iron target (total~60kg : 500 μ m seg.)
- High statistics (3-4k $\bar{\nu}_\mu$ events)
- ν_e detection (20-30 $\bar{\nu}_e$ CC events)

→ Data – MC comparison with high statistics to check the performance.

Large size Emulsion Shifter (Kobe U.)





Detector construction

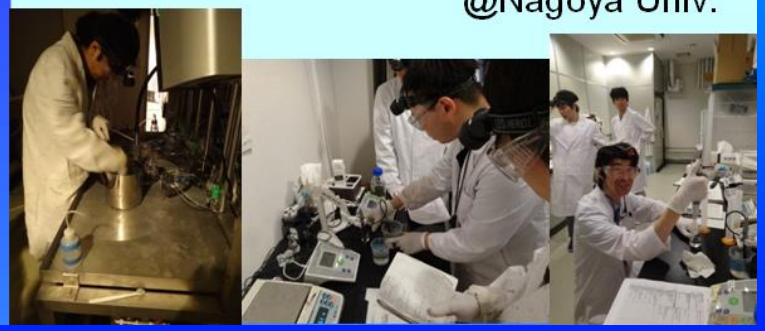
ν beam exposure

Hardware treatment and Scan

Detector preparation

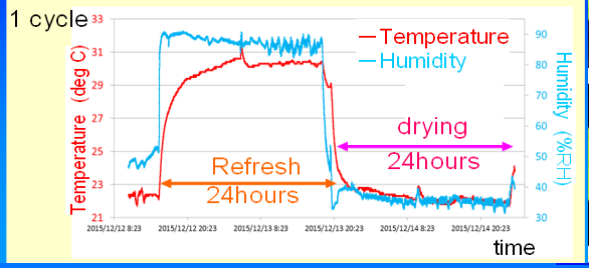
Emulsion film production 2015. July→Oct.

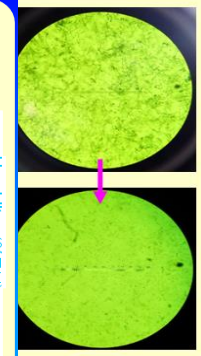
By Toho Univ. & Nihon Univ. member
@Nagoya Univ.



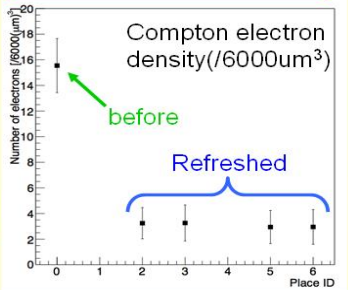
Emulsion film Refresh

Noise reduction at 30deg C, 90%humi



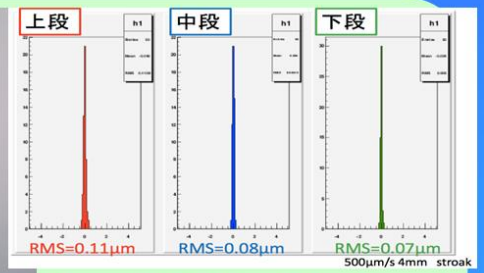


$Ag_4 + 2H_2O + O_2 \rightarrow 4Ag^+ + 4OH^-$

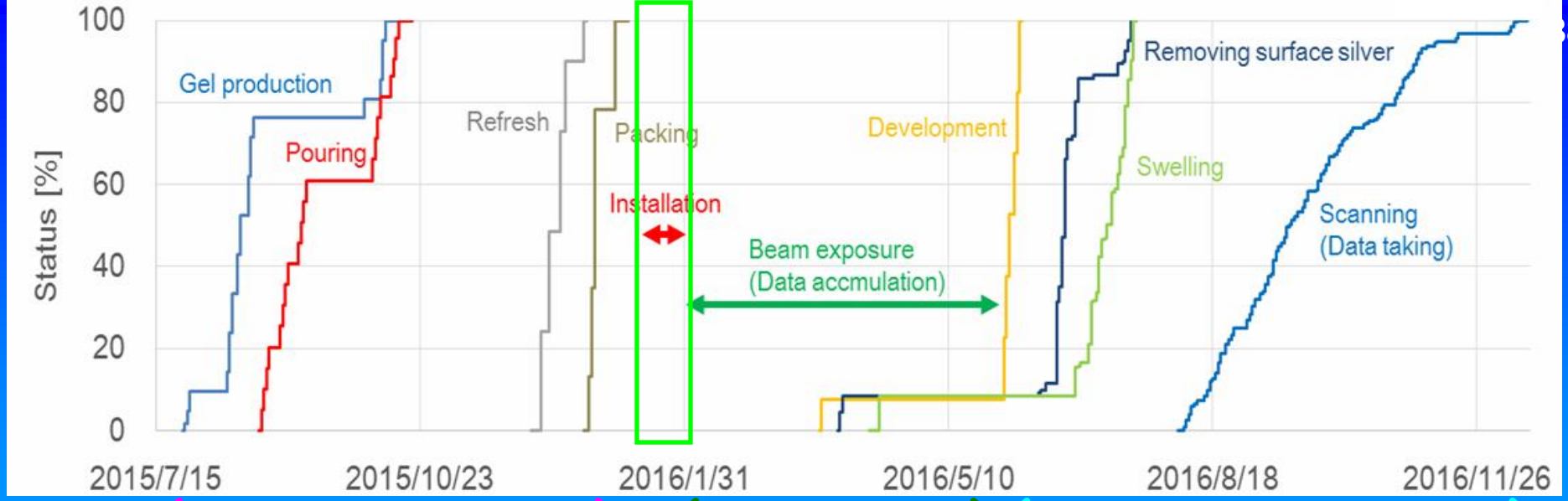


Large size Emulsion Shifter

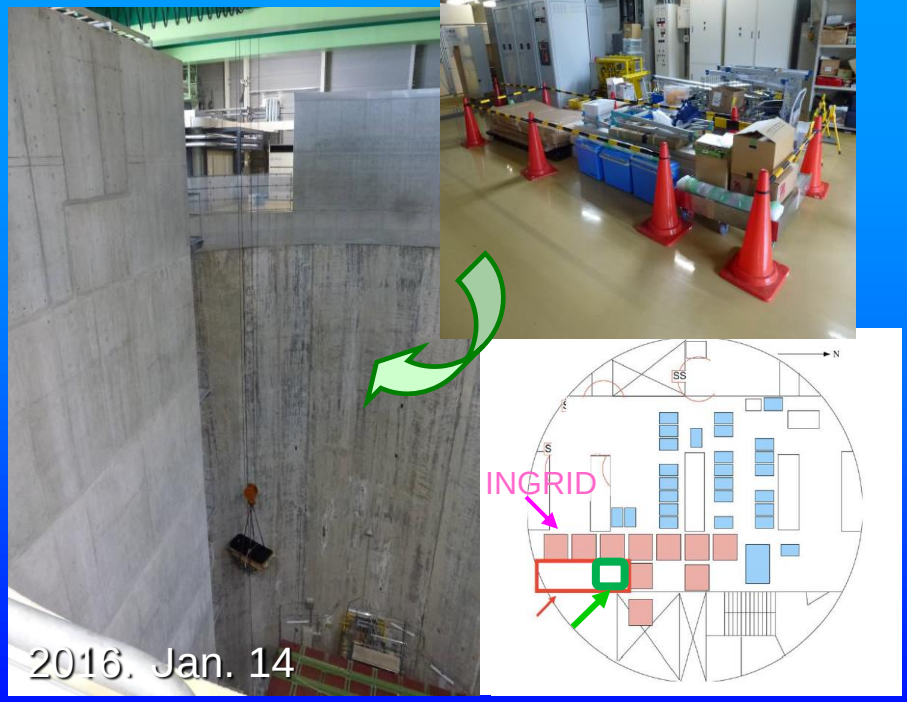
Operation test @Kobe Univ.



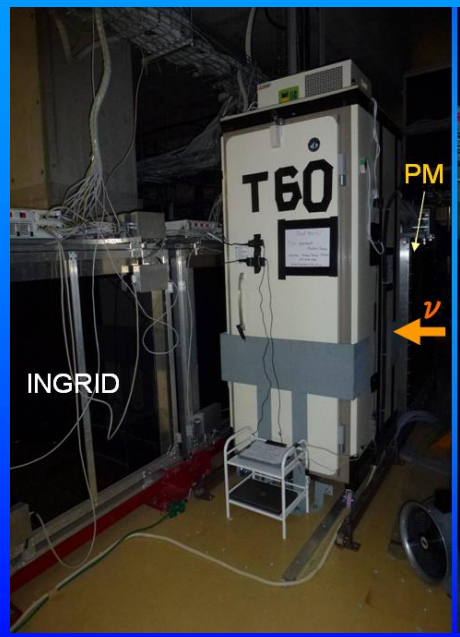
Repeatability for driving in each stage is well below 0.5 μ m.

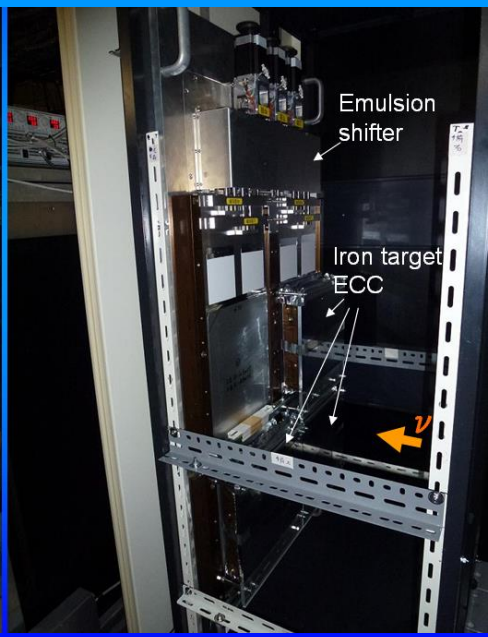


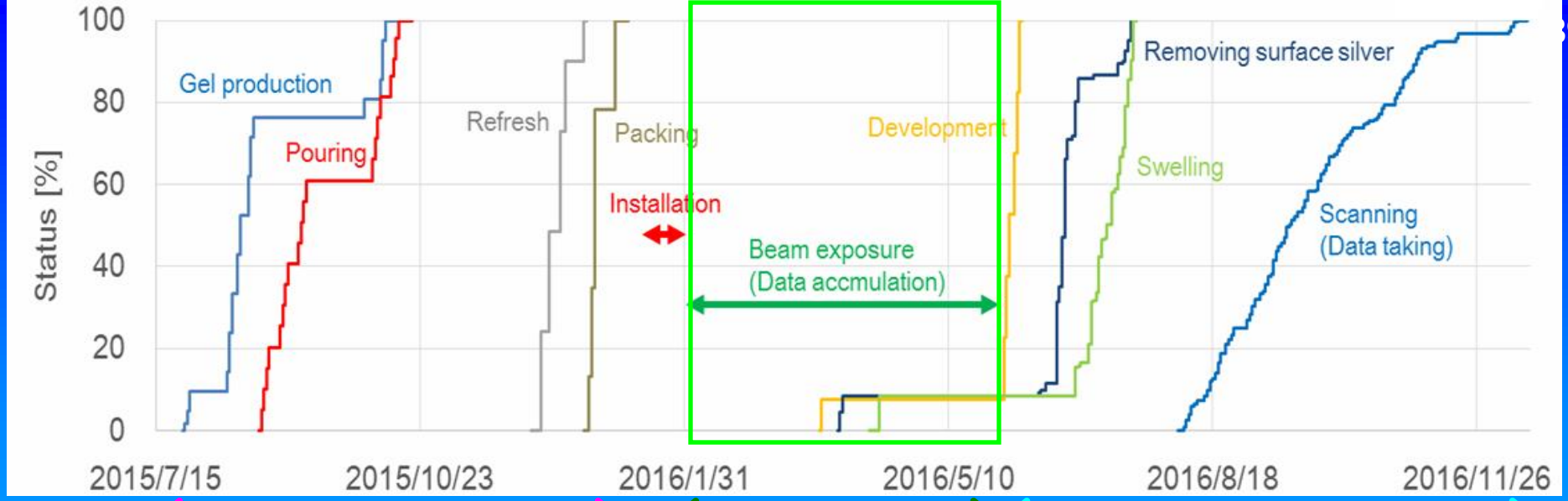
Detector construction | **ν beam exposure** | **Hardware treatment and Scan**



Detector installation

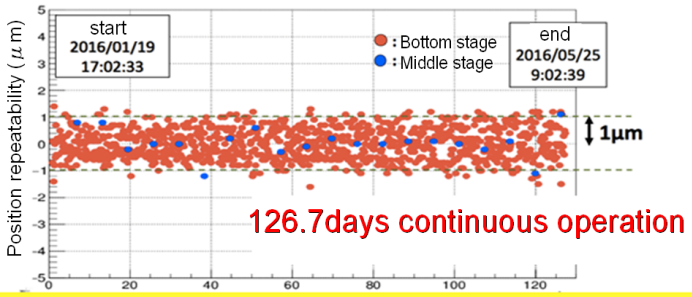


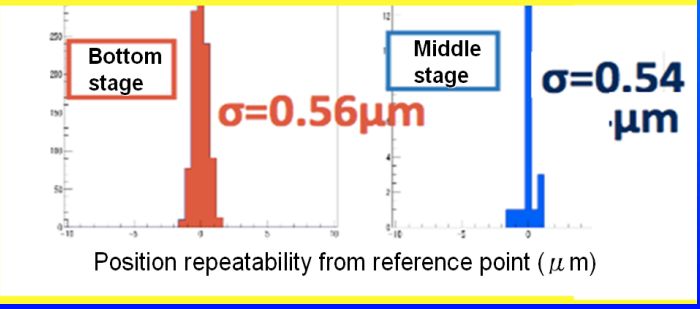




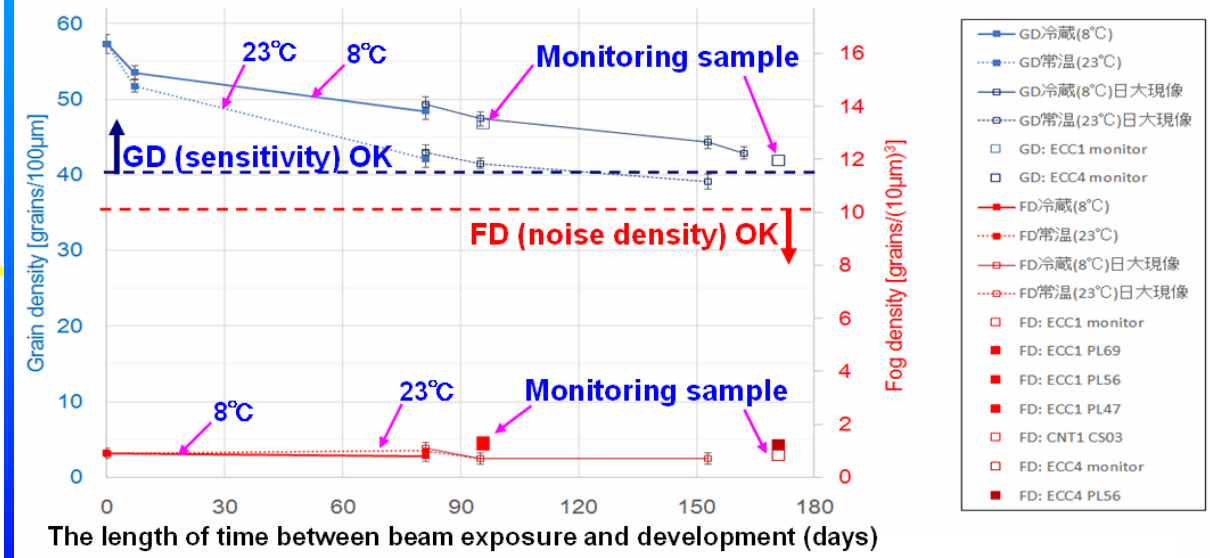
Detector construction | **ν beam exposure** | **Hardware treatment and Scan**

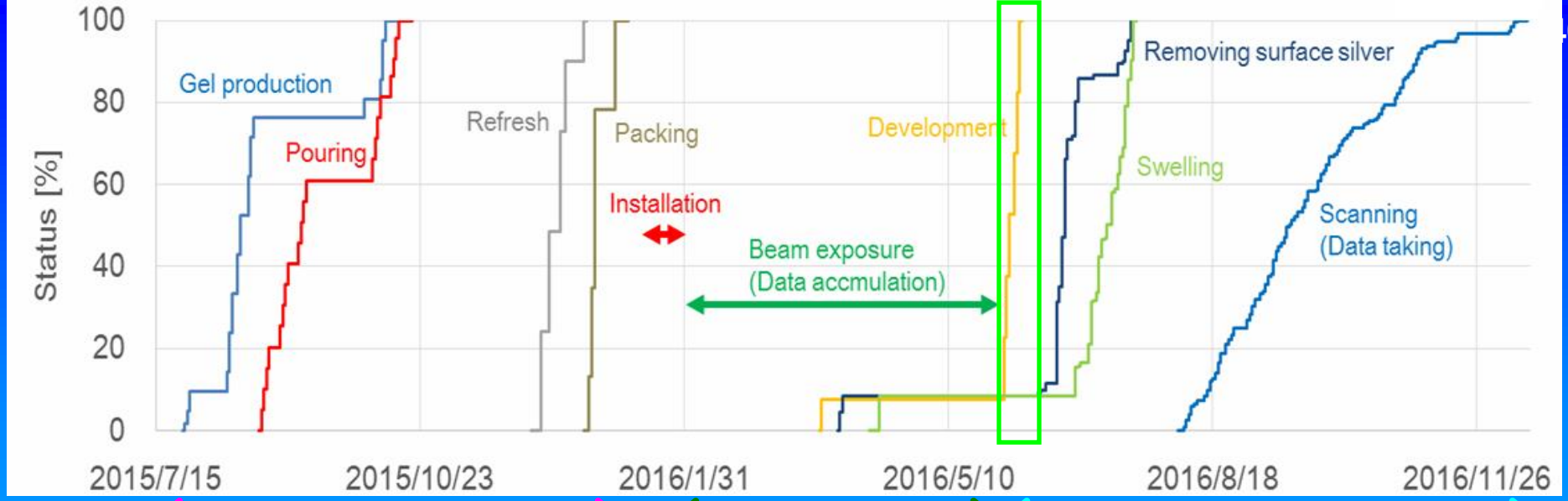
Emulsion Shifter operation status

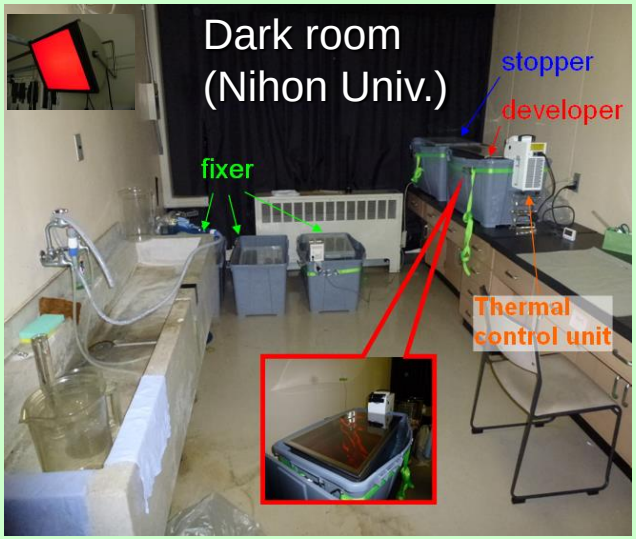


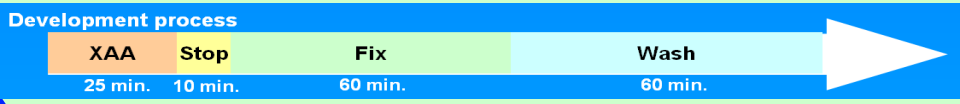


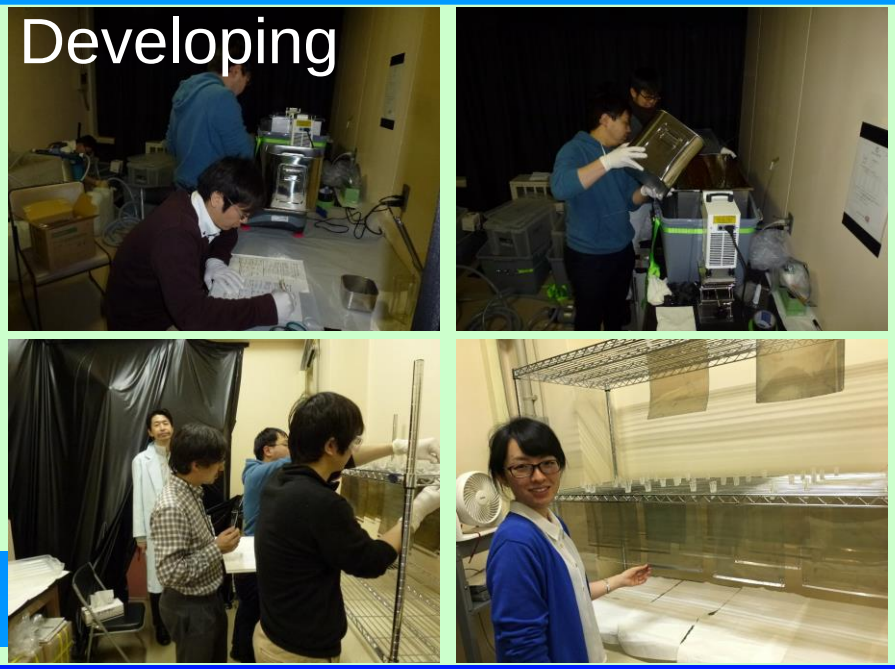
Condition of the emulsion film

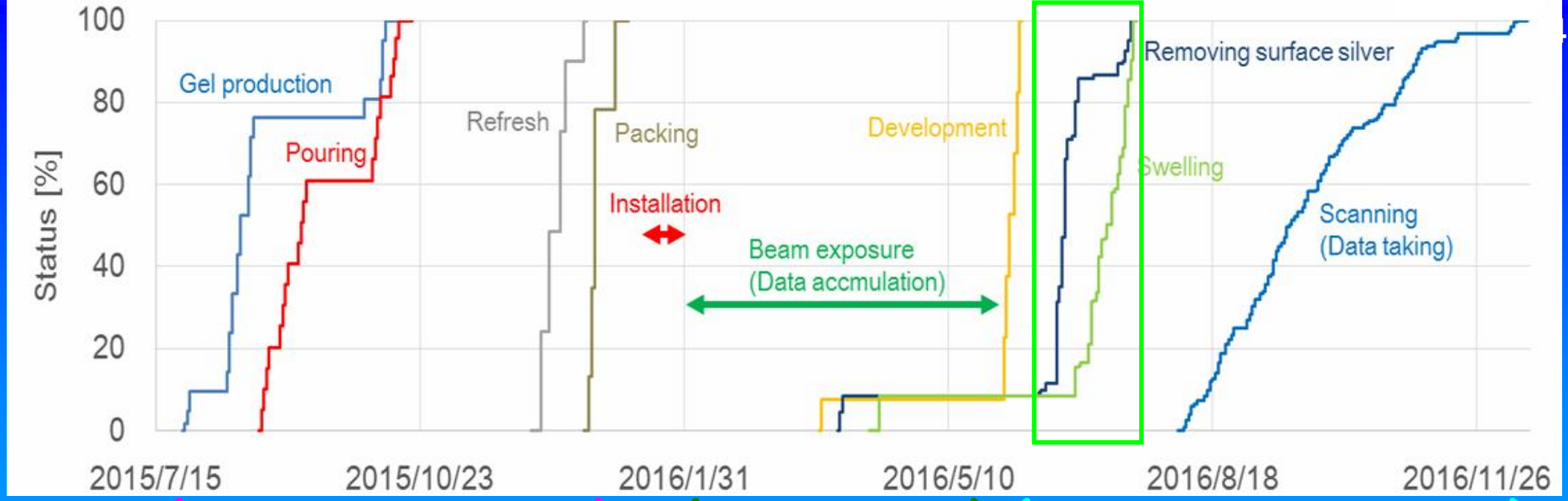



Status [%]
100
80
60
40
20
0
Gel production
Pouring
Refresh
Packing
Installation
Beam exposure
(Data accmulation)
Development
Removing surface silver
Swelling
Scanning
(Data taking)
2015/7/15
2015/10/23
2016/1/31
2016/5/10
2016/8/18
2016/11/26
Detector construction
ν beam exposure
Hardware treatment and Scan

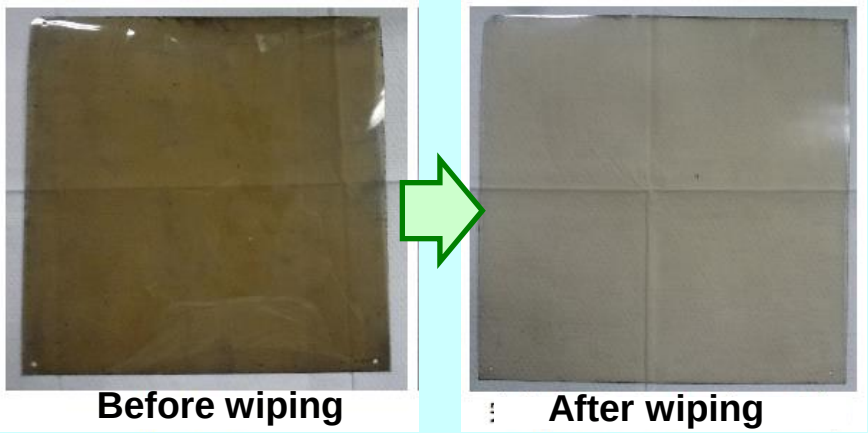

Dark room
(Nihon Univ.)
stopper
developer
fixer
Thermal
control unit


Development process
XAA
Stop
Fix
Wash
25 min.
10 min.
60 min.
60 min.


Developing



2. Surface silver cleaning



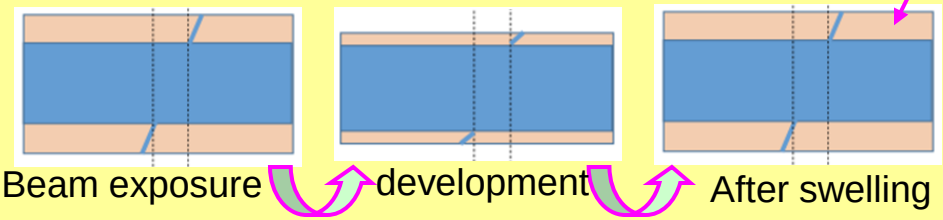
Before wiping

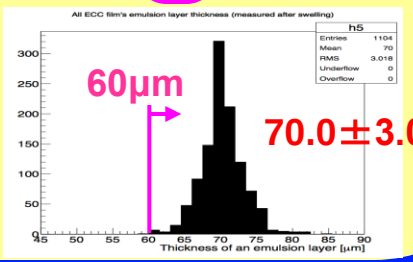
After wiping

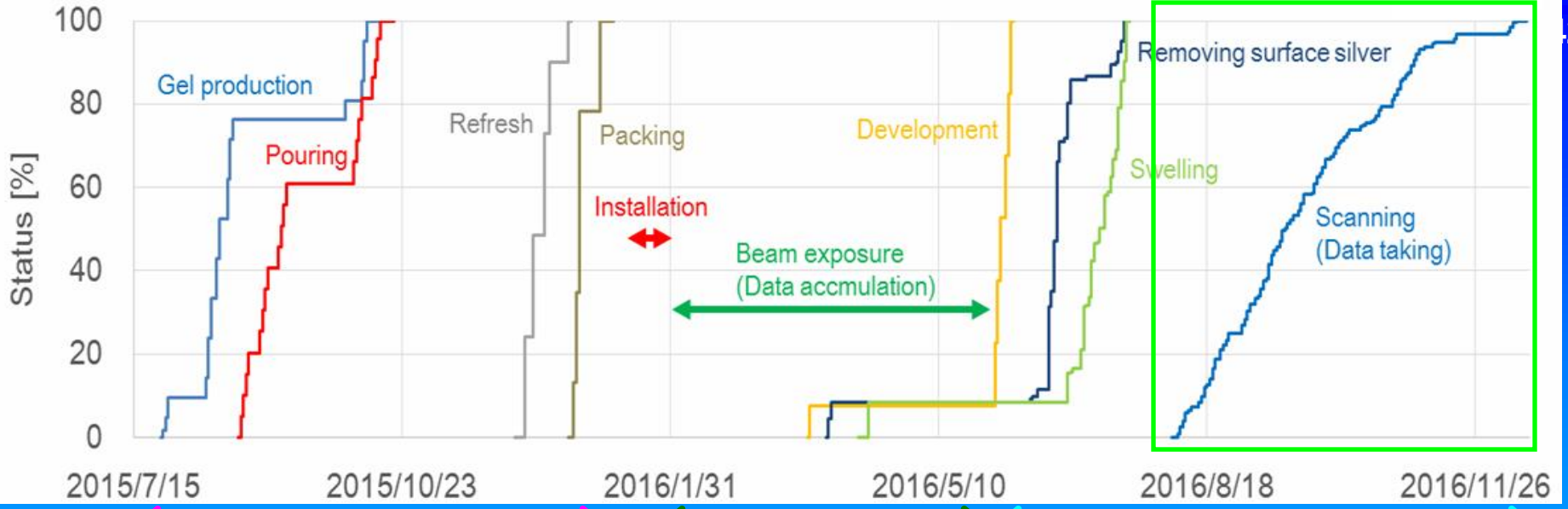
More than 300 films were completed.

Emulsion swelling

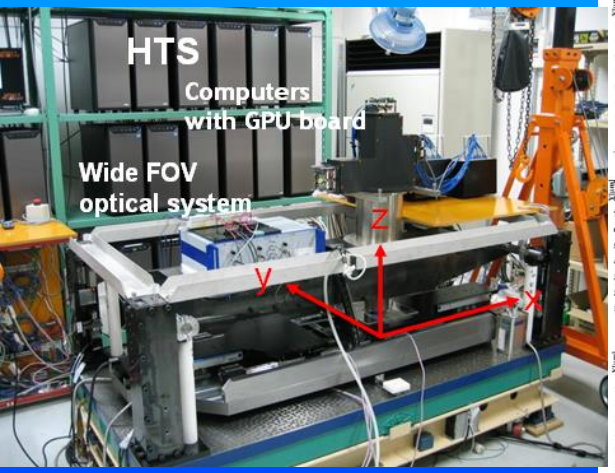
Recovering of emulsion thickness

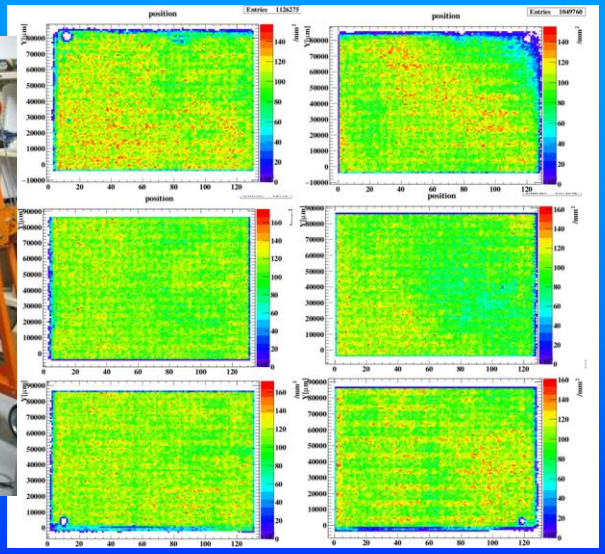


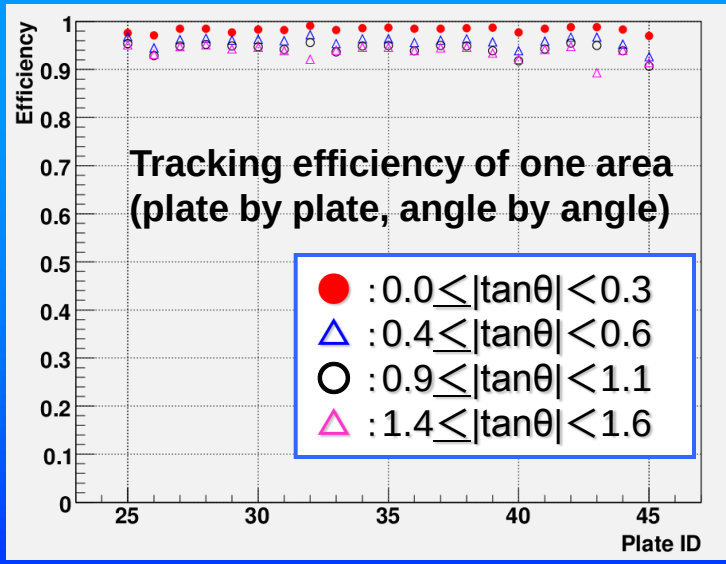




Detector construction | **ν beam exposure** | **Hardware treatment and Scan**







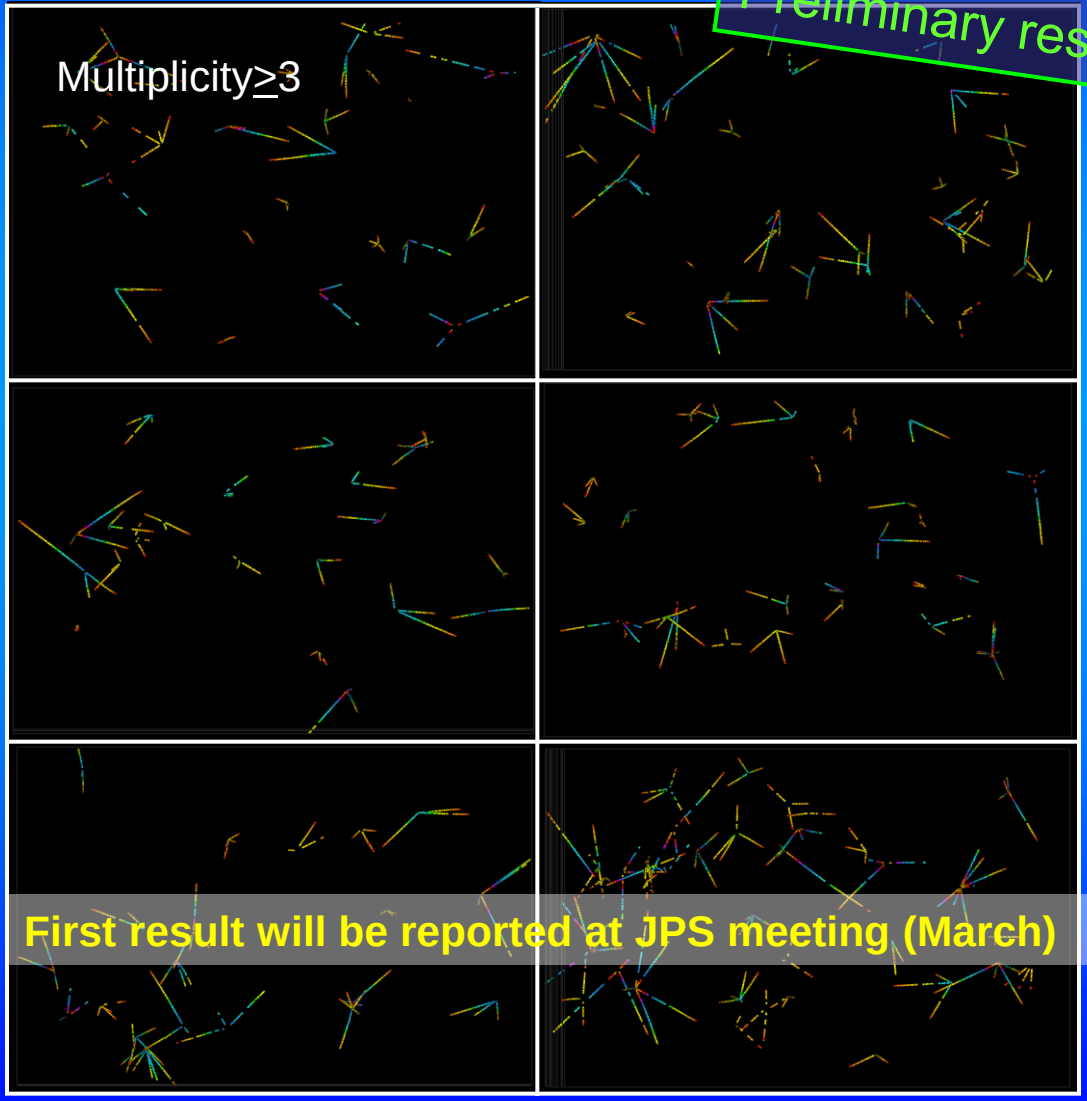
Data quality check and track reconstruction is under progress.

Event analysis is now in progress !

Neutrino event candidates

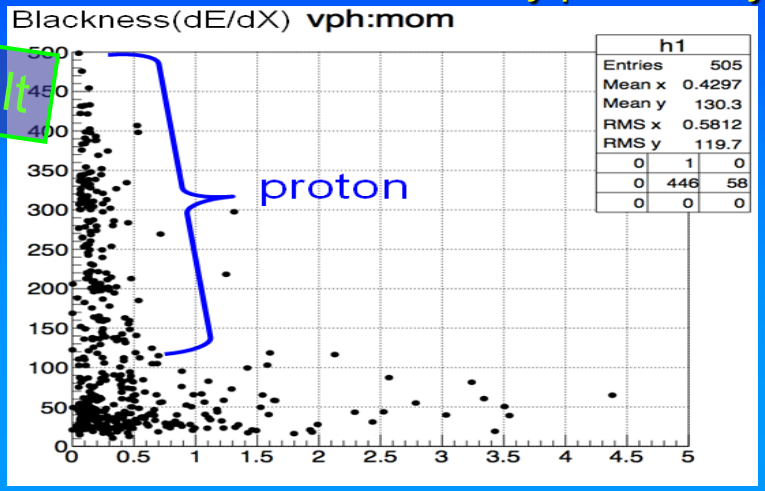
Preliminary result

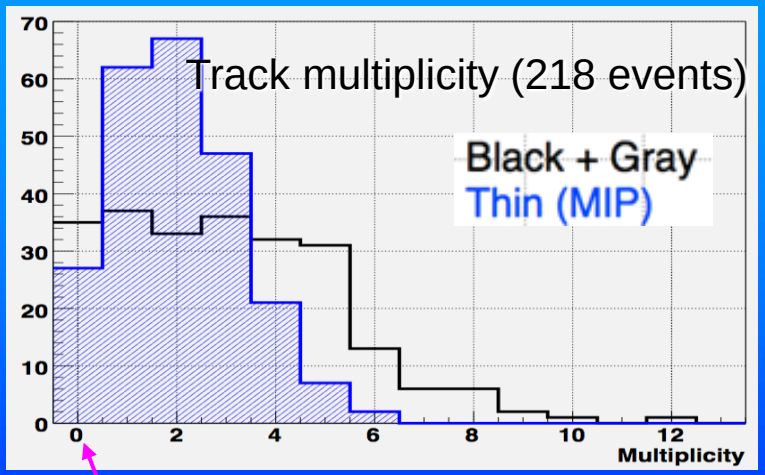
Multiplicity≥3



First result will be reported at JPS meeting (March)

Very preliminary





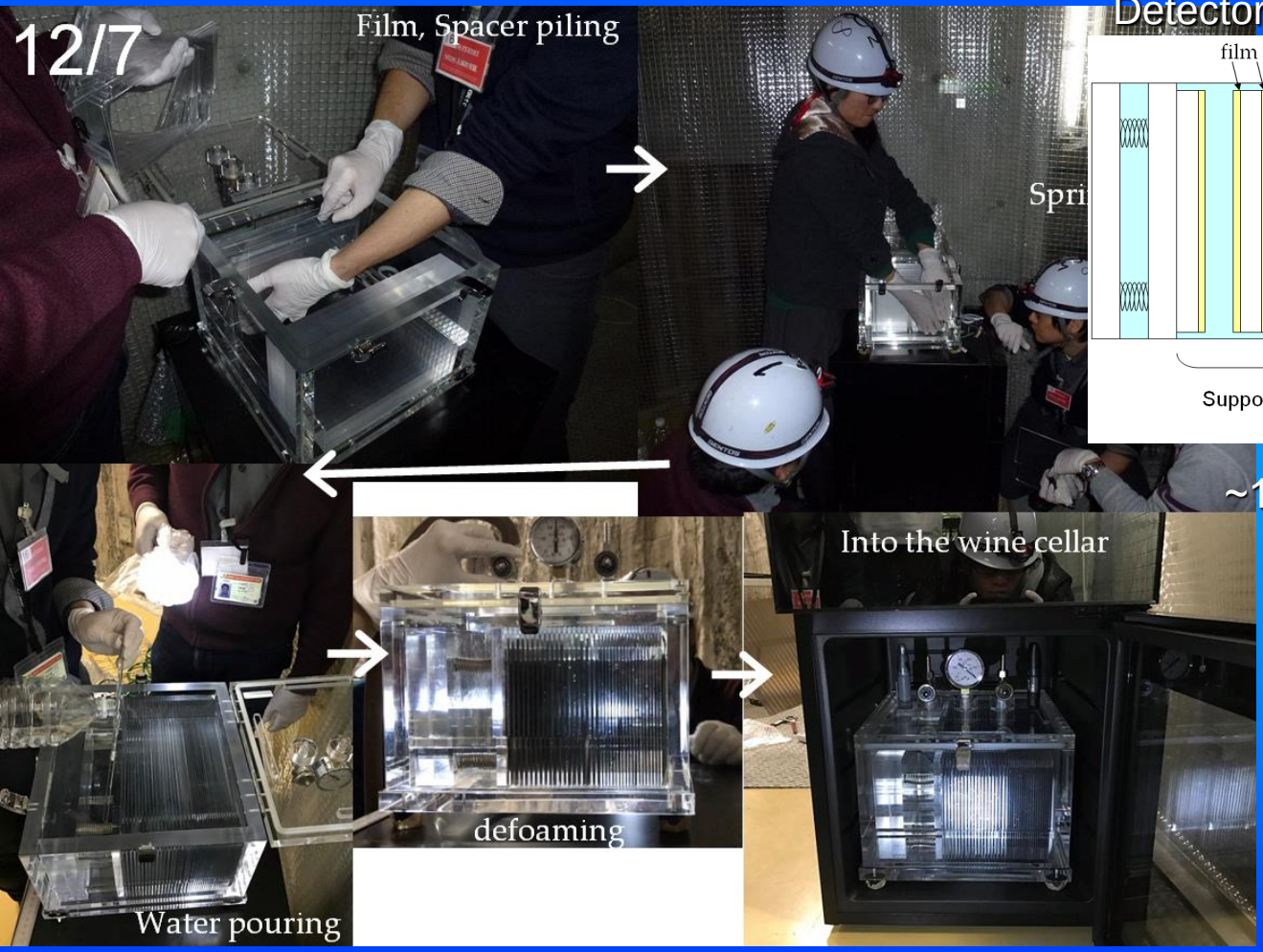
- ~80% of event have proton
- 0 MIP events are detected.
  → neutron interaction ?

Examples of neutrino event one by one

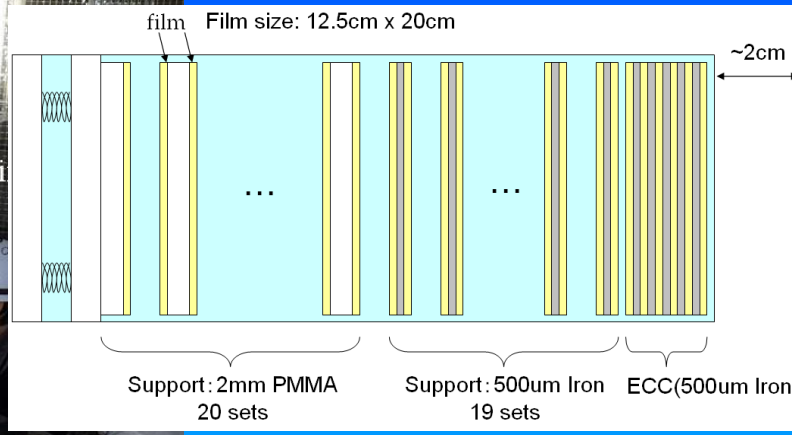
Detector Run(T66)

ν beam exposure : Dec. 2016- Apr.2017

- R&D for Water target Emulsion detector



Detector structure



~100 ν- Water int. expected

大型水標的検出器によるニュートリノー水反応の精密測定に向けて検出器R&Dを継続中
2018年後半に100kg 級の検出器を設置予定。

Summary

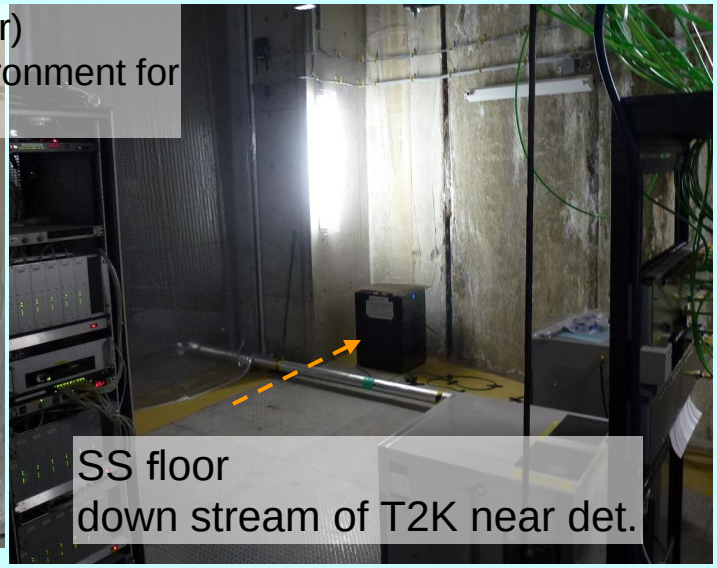
- We are performing a neutrino experiments at J-PARC to study low energy neutrino - nucleus interactions with nuclear emulsion（**NINJA !**）.
- We are carrying out a test experiment at J-PARC to check the feasibility and detector performance.
- Beam exposure and film development for the 60kg iron target ECC was successfully done and the event analysis is now in progress.
- R&D for Water target ECC is performing.
- Now we are discussing about next Physics Run with a large scale water target emulsion detector.

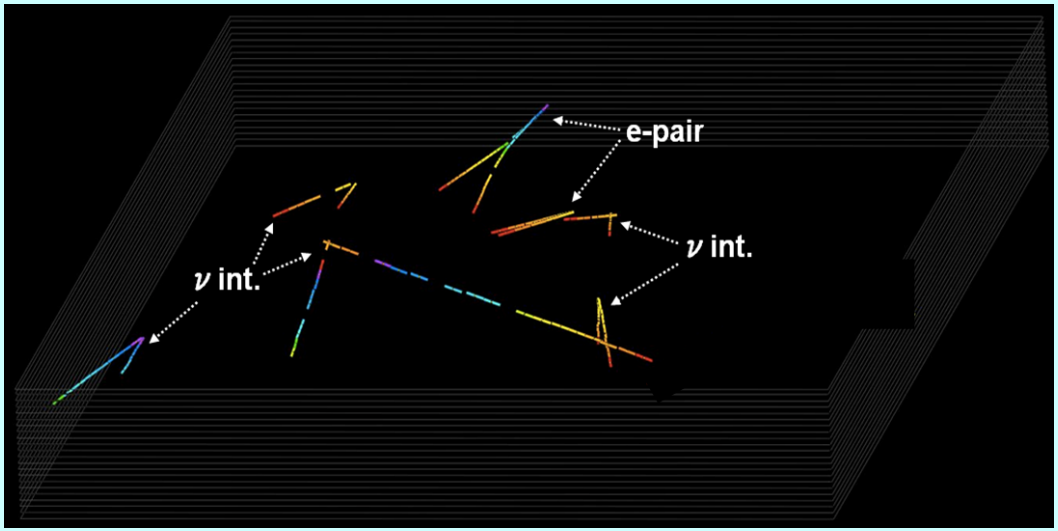
Back up

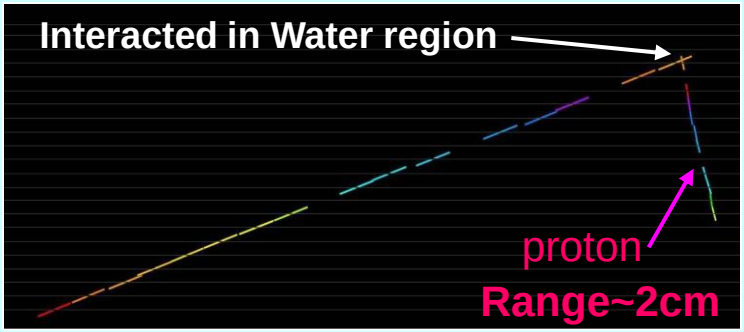
Water target emulsion chamber


Removal of air bubbles


Cool box (wine cellar)
to keep a good environment for
emulsion tracks


SS floor
down stream of T2K near det.





①	(tanθx, tanθy)=(-0.040, 0.845)	M.I.P
②	(tanθx, tanθy)=(-0.589, -0.074)	proton

Minimum distance(① - ②)=2.4um,
depth=620um

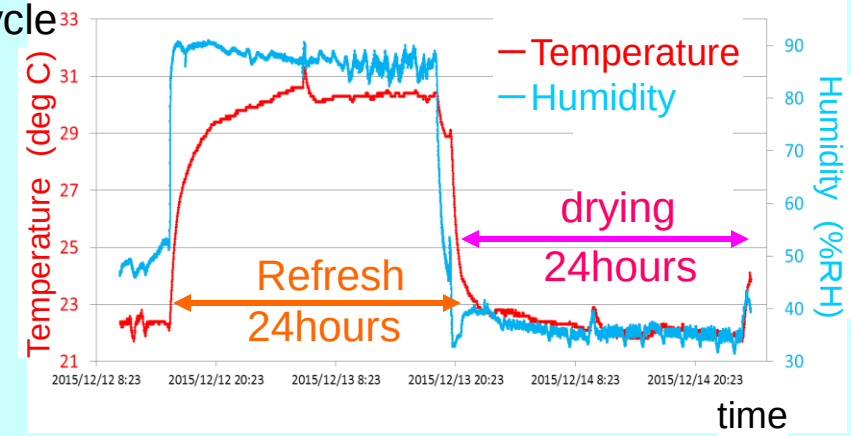
First detection of ν - Water interaction with Emulsion Detector

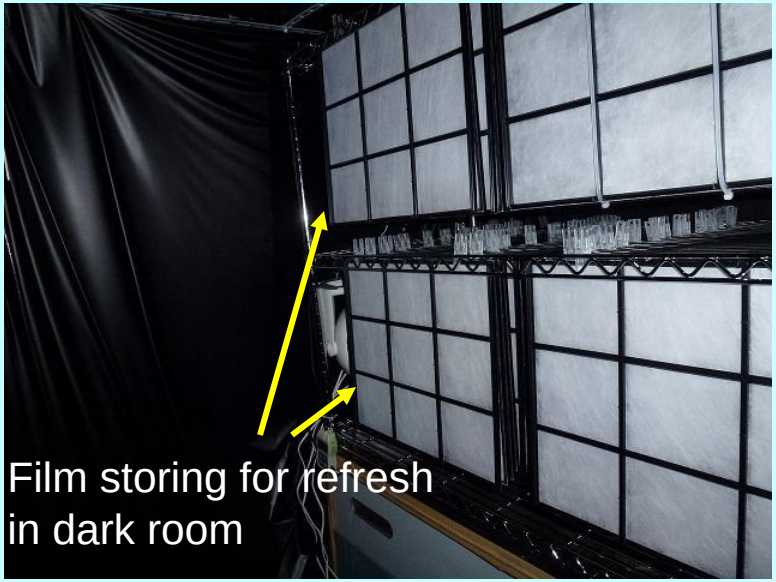
Detector preparation

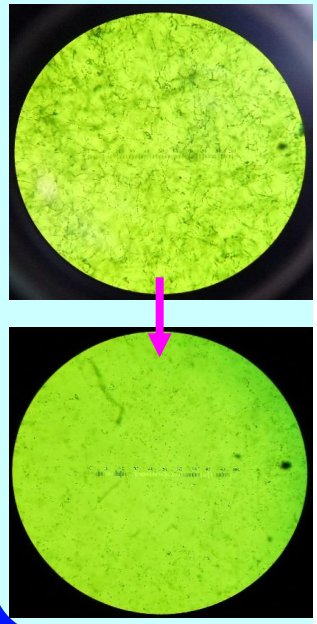
We carried out “Refresh” process to delete noise tracks like OPERA experiment.

Emulsion film Refresh **2015. Dec @Toho Univ.**

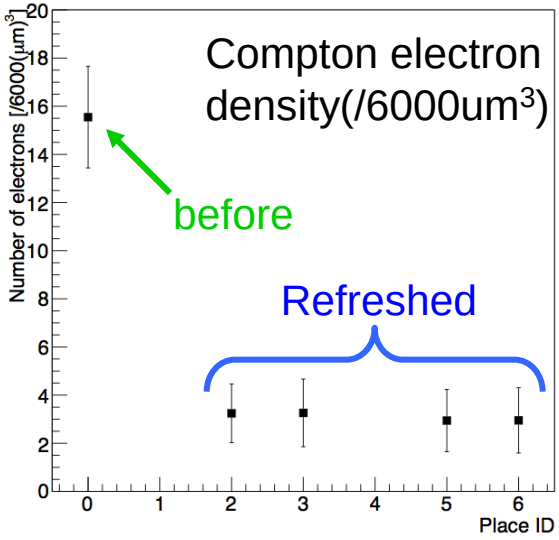
1 cycle

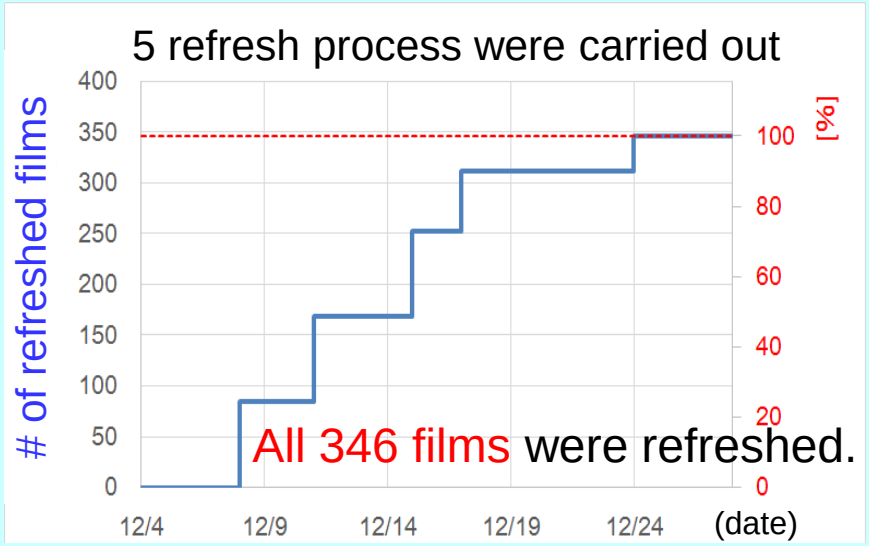






$$Ag_4 + 2H_2O + O_2 \rightarrow 4Ag^+ + 4OH^-$$

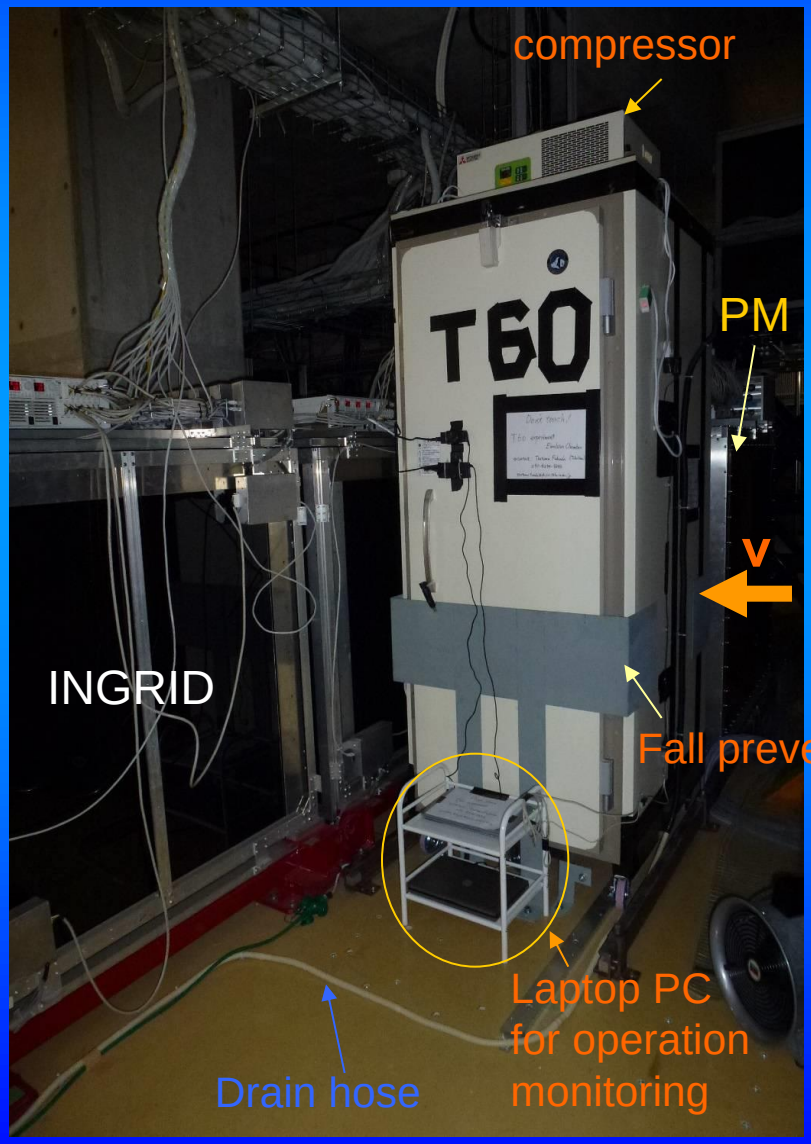


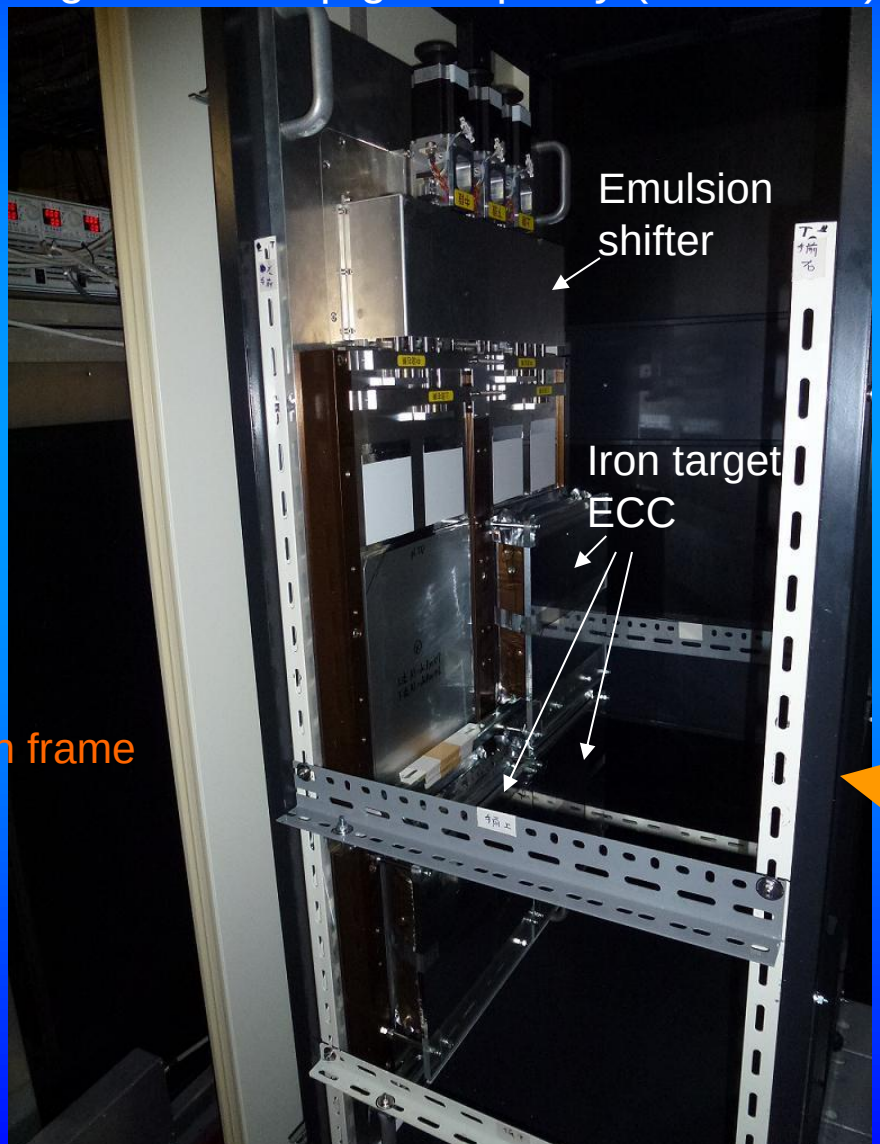


Installation @J-PARC (Jan. 11-20)

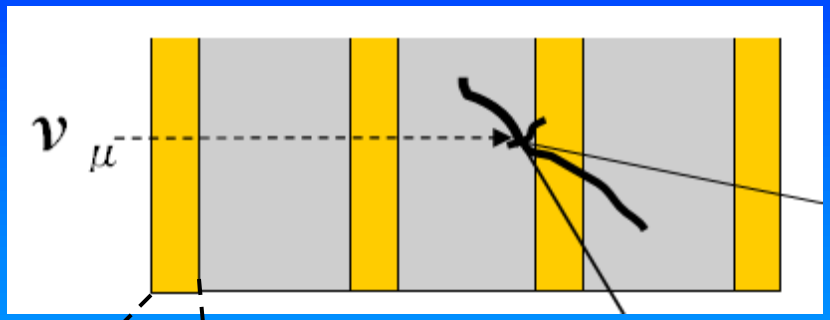
Detector was constructed @SS floor.

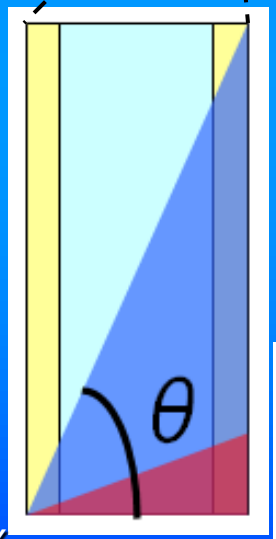
T60 emulsion detector is mounted in cooling box to keep good quality (no refresh).





Large angle scanning on HTS

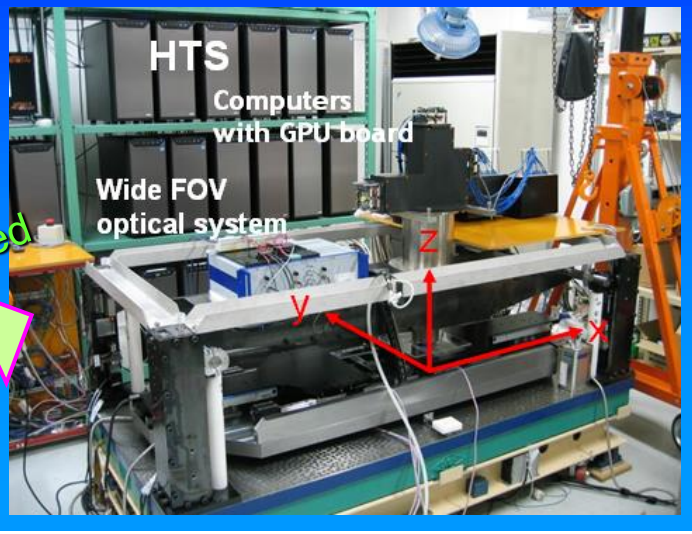


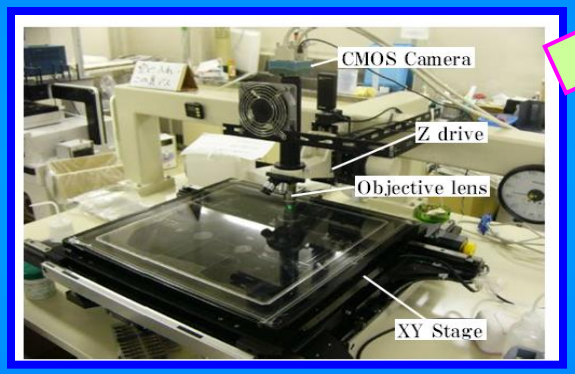


X
Z

$\frac{x}{z} = |\tan\theta|$

High speed





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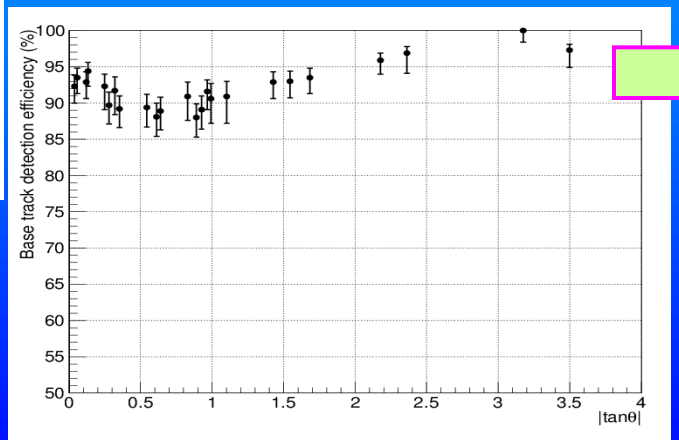
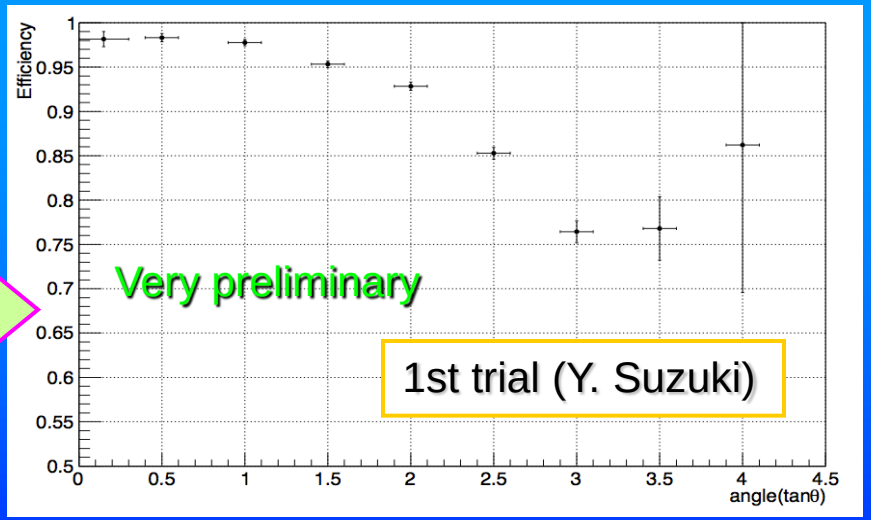
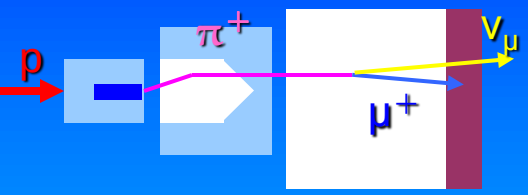


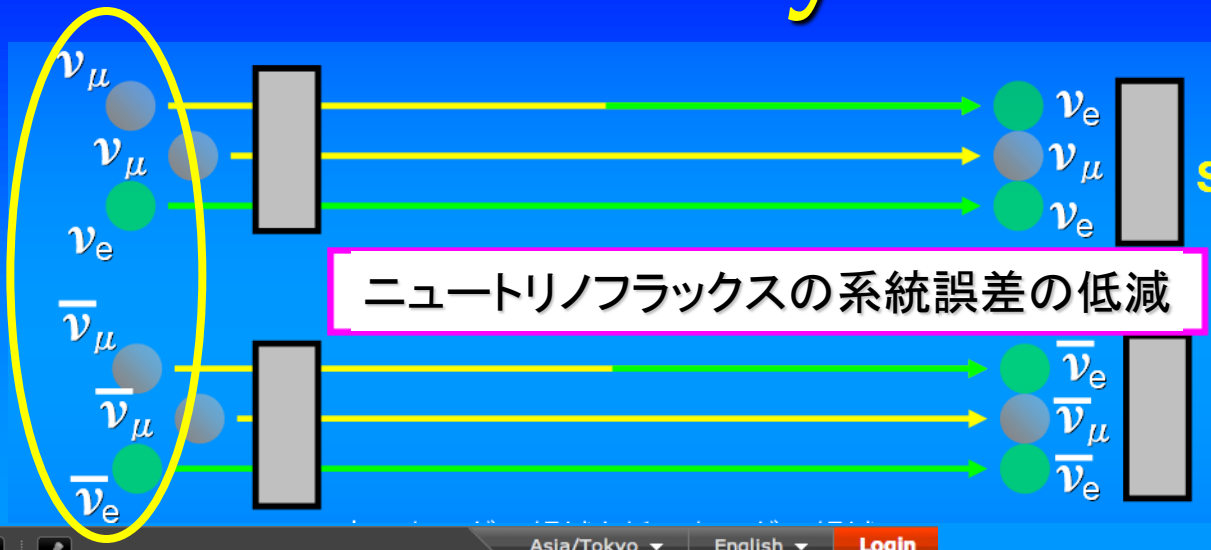


We will optimize HTS for LA Scanning

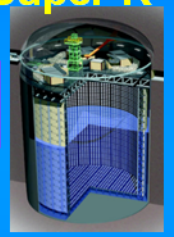
Related activity



ニュートリノフラックスの推定
↓
ハドロン生成の詳細研究



ニュートリノフラックスの系統誤差の低減



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Workshop on Hadron Production Measurements with Nuclear Emulsions

3-4 October 2016
Nagoya University
Asia/Tokyo timezone

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