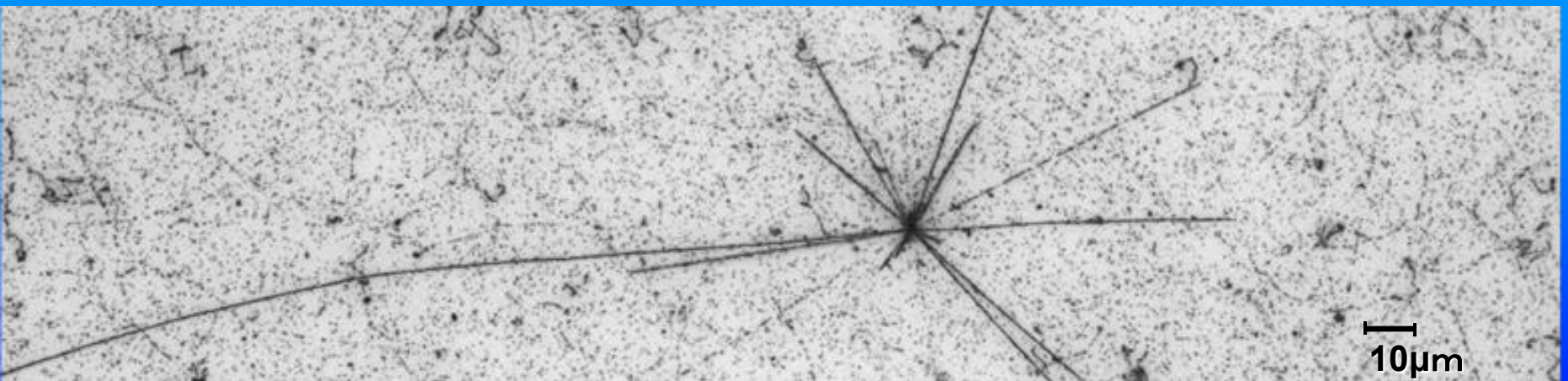


NINJA Experiment :
Neutrino Interaction research with
Nuclear emulsion and J-PARC Accelerator

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



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。

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。

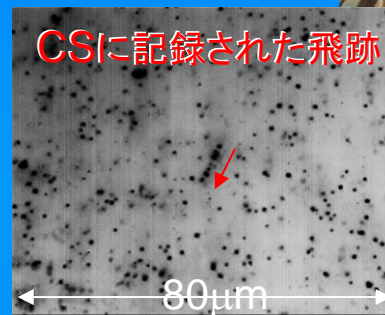
2010年 1st タウニュートリノ反応候補検出。

2012年 2nd タウニュートリノ反応候補検出。

⋮



me

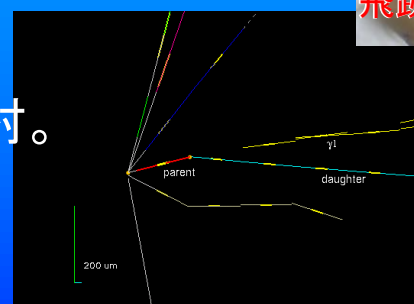


CSIに記録された飛跡

me

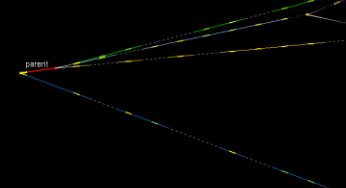


飛跡が見つかった瞬間
2006 9/7



1st ν_τ

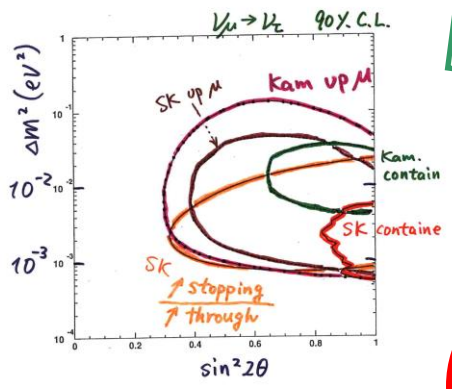
2nd ν_τ



1998

Summary

Evidence for ν_μ oscillations



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

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

4. Conclusions

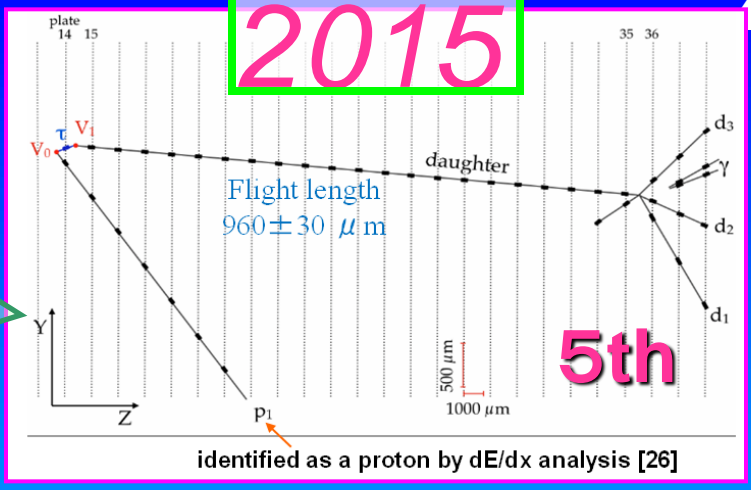
So far both $\nu_\mu \leftrightarrow \nu_\tau$ & $\nu_\mu \leftrightarrow \nu_s$ solutions provide a good fit to atmospheric neutrino anomaly

for $\left\{ \begin{array}{l} 10^{-3} \text{eV}^2 \leq |\Delta m^2| \leq 10^{-2} \text{eV}^2 \\ \sin^2 2\theta \sim 1 \end{array} \right.$

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

done

2015



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. Buonauro,^{2,11} S. Buontempo,² B. Büttner,¹² M. Chernyavsky,¹³ A. Chukanov,⁸ G. De Lellis,^{2,11} M. De Serio,^{15,16} P. Del Amo Sanchez,¹⁷ A. Di Crescenzo,² D. Di S. Dmitrievski,⁸ M. Dracos,¹⁹ D. Duchesneau,¹⁷ S. Dusini,⁷ T. Dzhatdov,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

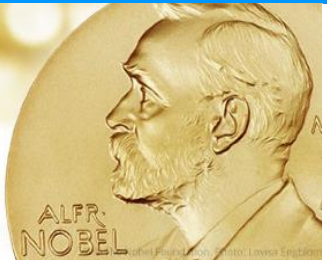
NEUTRINO OSCILLATIONS

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

"For the greatest benefit to mankind"
Alfred Nobel

2015 NOBEL PRIZE IN PHYSICS

Takaaki Kajita
Arthur B. McDonald



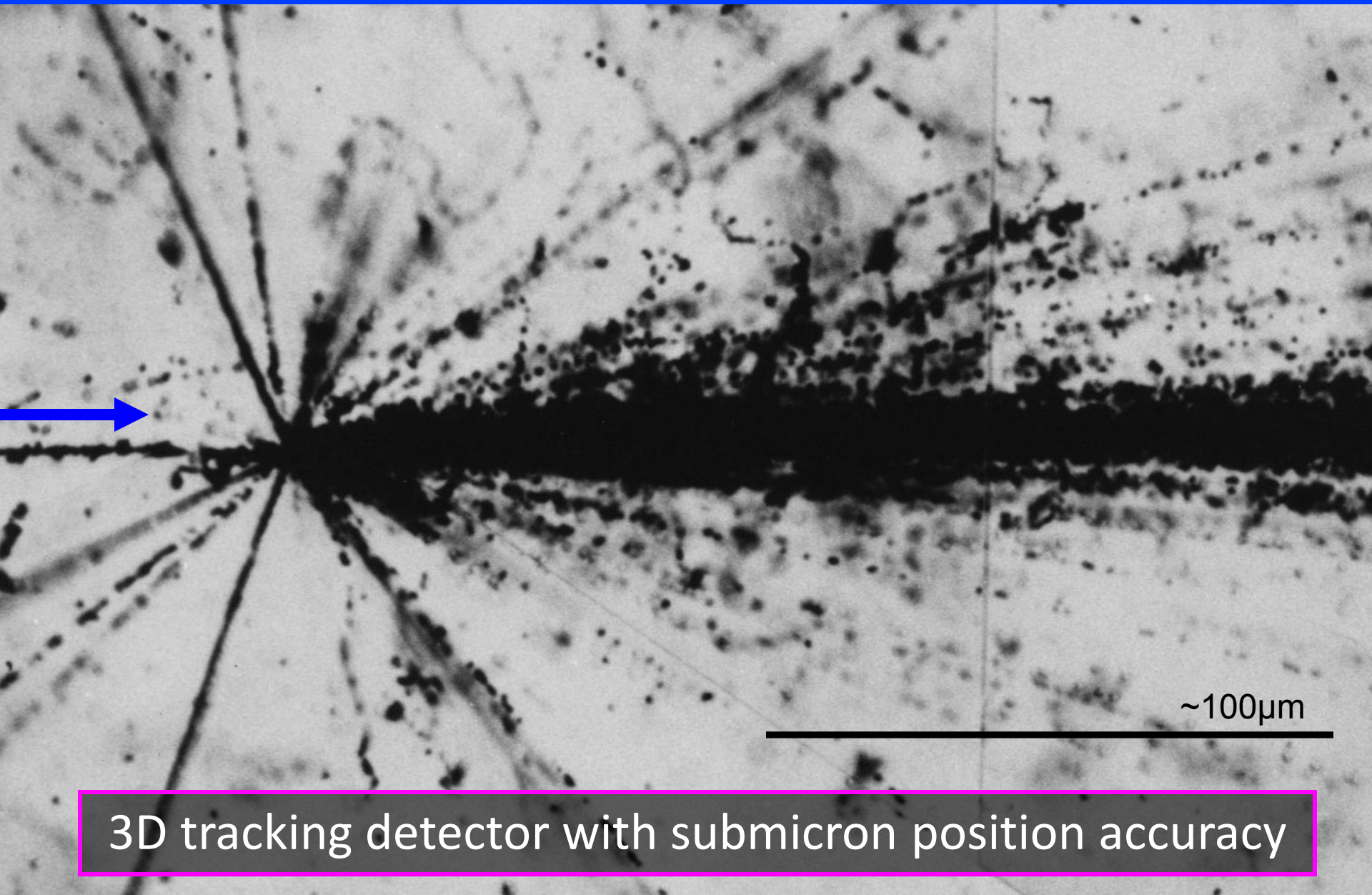
Super-Kamiokande's oscillation results were confirmed by the detectors MACRO [55] and Soudan [56], by the long-baseline accelerator experiments K2K [57], MINOS [58] and T2K [59] and more recently also by the large neutrino telescopes ANTARES [60] and IceCube [61]. Appearance of tau-neutrinos in a muon-neutrino 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

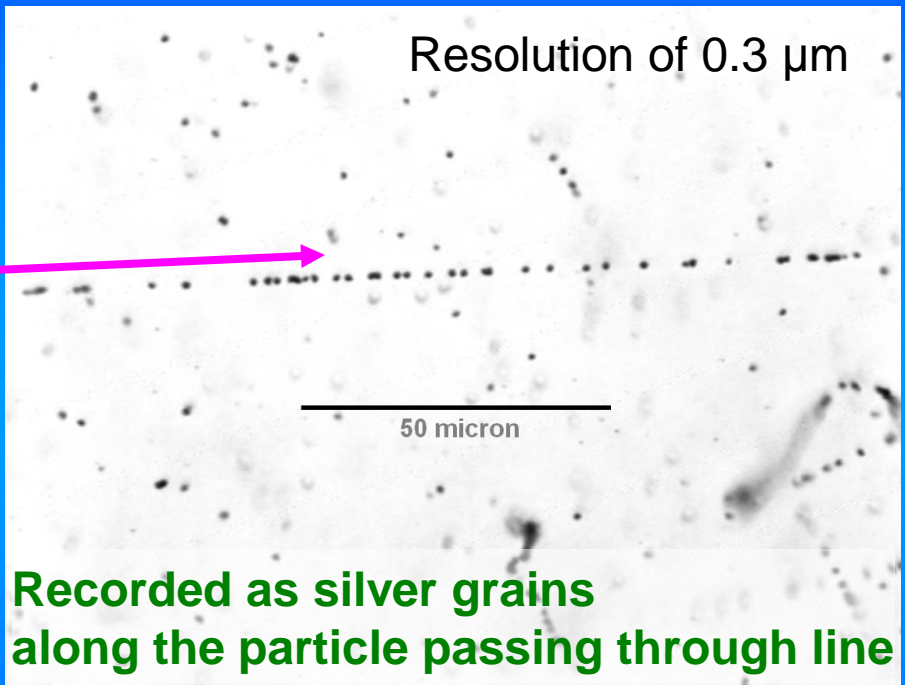
What is Nuclear Emulsion ?



3D tracking detector with submicron position accuracy

Photographic Film technology

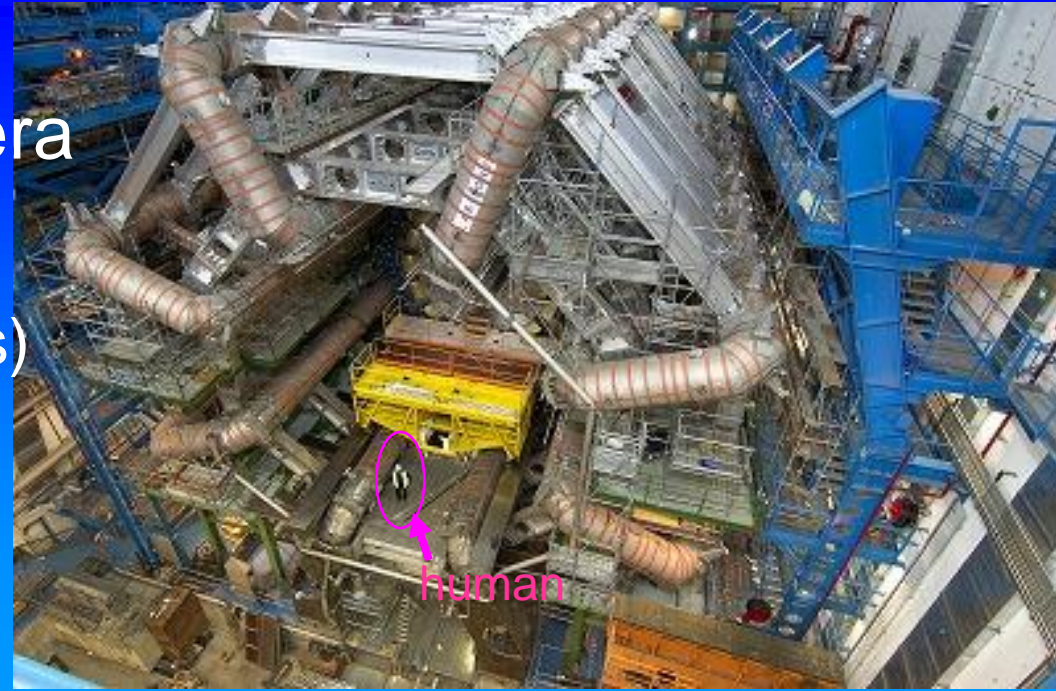
- Nuclear Emulsion is a special photographic film.
- Signal is amplified by chemical process.



	Merit	Image detection
Film camera	High resolution	ハロゲン化銀 (Silver 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 10⁸ image sensors)

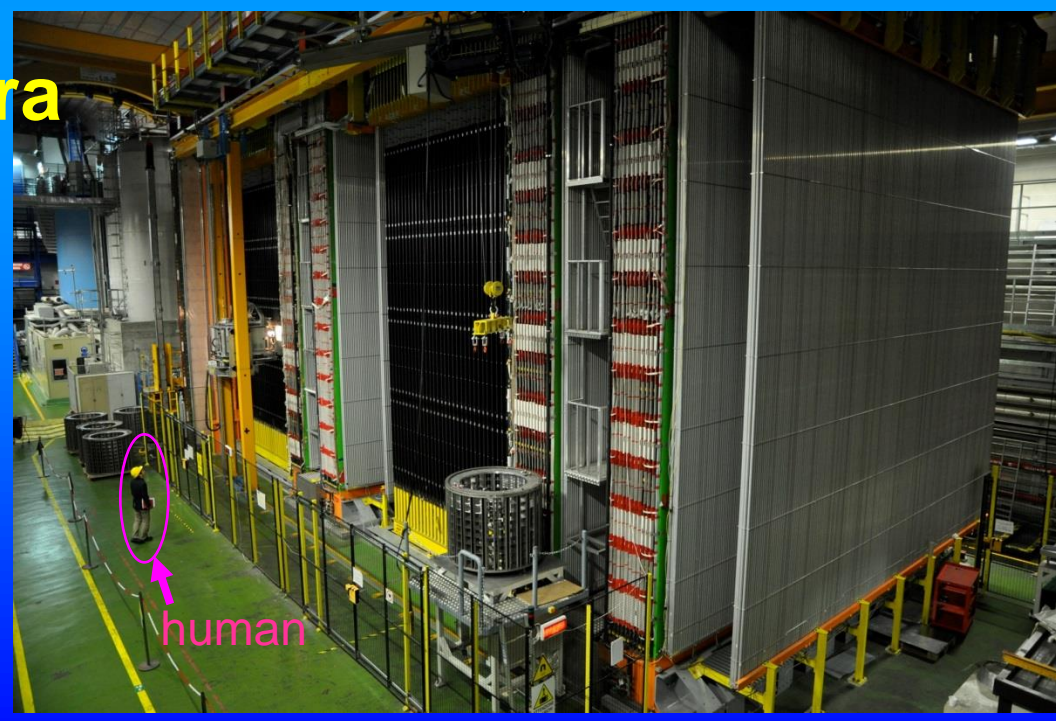


Largest Film Camera

OPERA detector
(~10²⁰ AgBr crystals)



9000,000 emulsion films



Contribution for fundamental physics... 1947



1896

1971

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

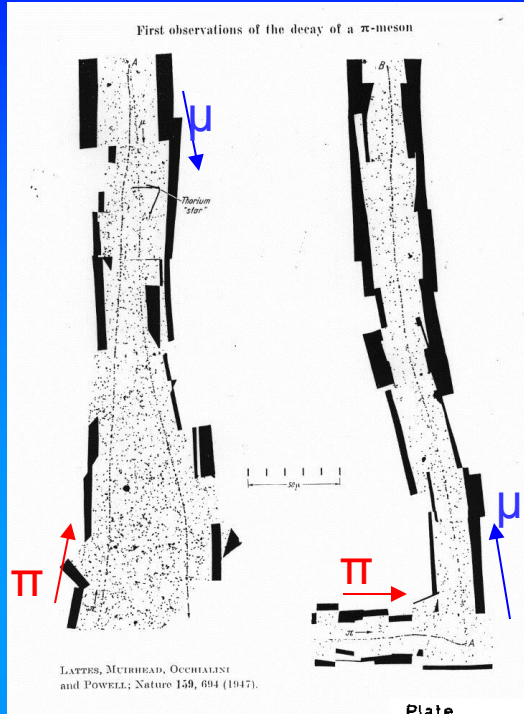
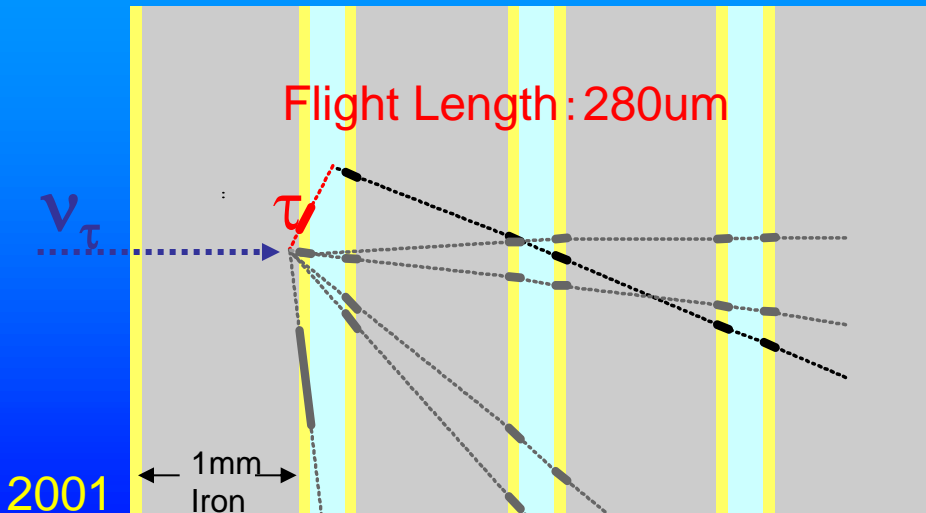
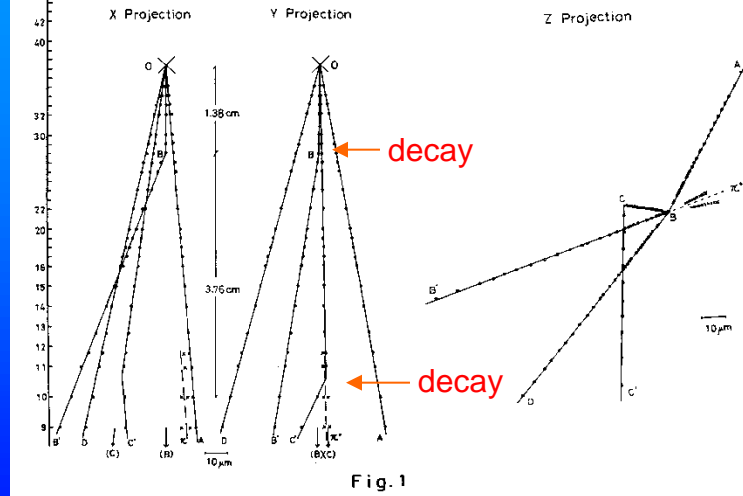


Plate Number

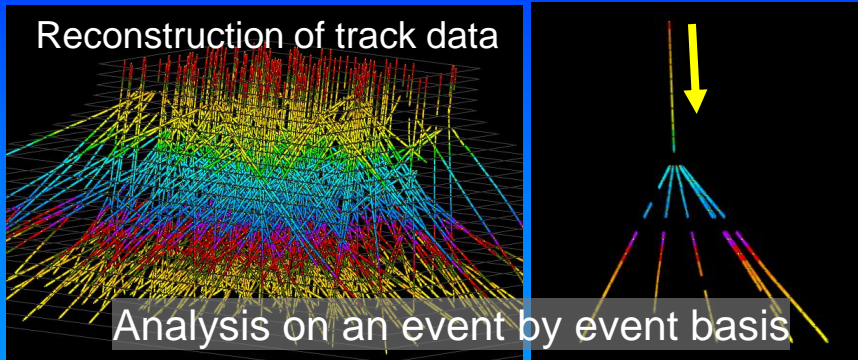


2001

DONUT ν_τ event

Nuclear Emulsion Detector

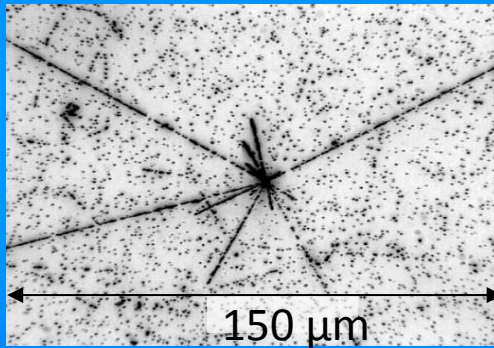
3D reconstruction



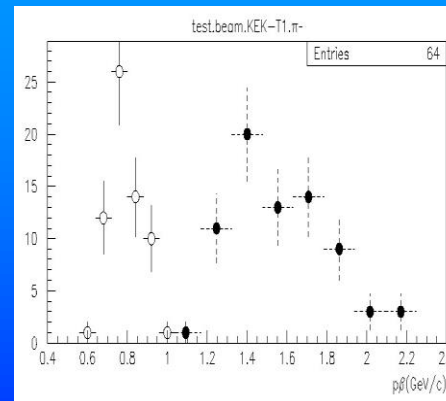
Scalability



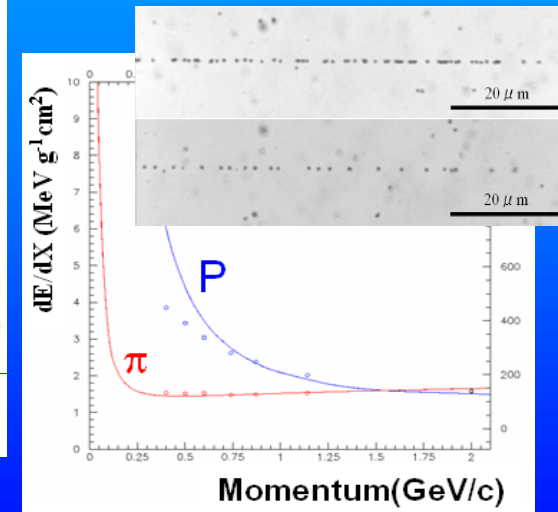
4π detection



Momentum, dE/dx measurement



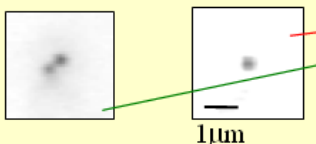
0.8GeV/c π : P = 0.79(GeV/c), dP/P = **11%**
 1.5GeV/c π : P = 1.53(GeV/c), dP/P = **16%**



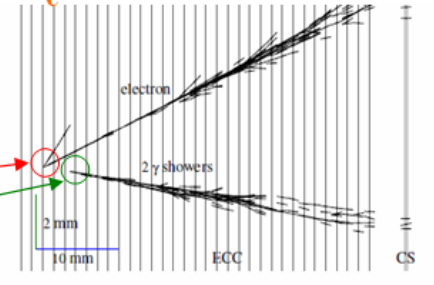
Ultra precise measurement

γ / electron ID

Microscopic image from the view of the beam axis
 $\gamma \rightarrow e^+e^-$ electron

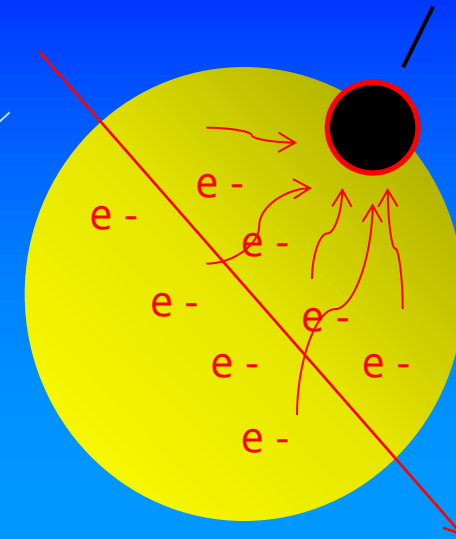
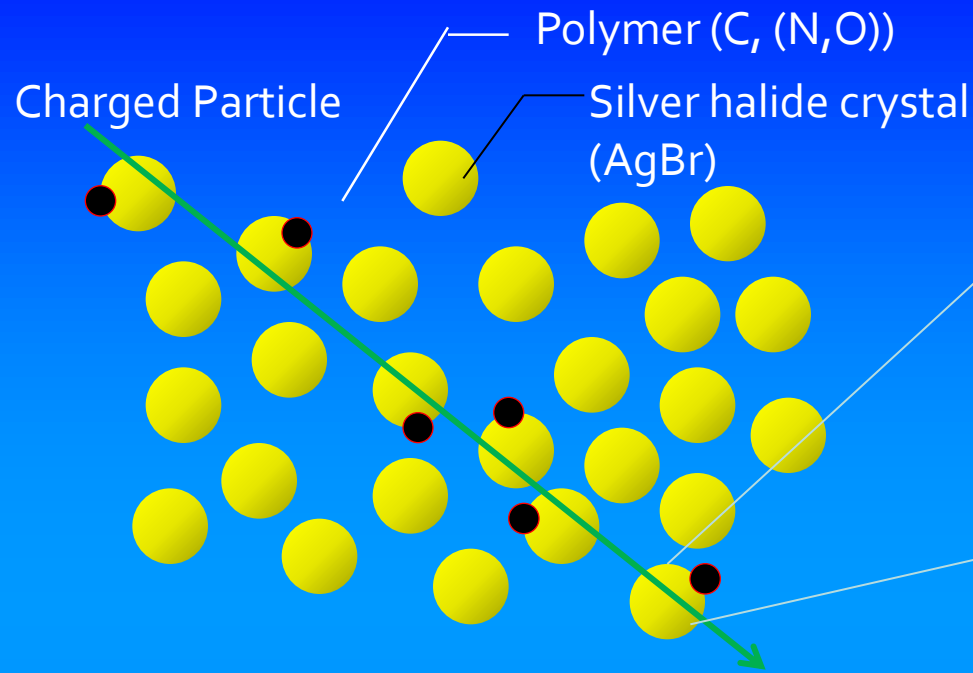


ν_e CC event in OPERA



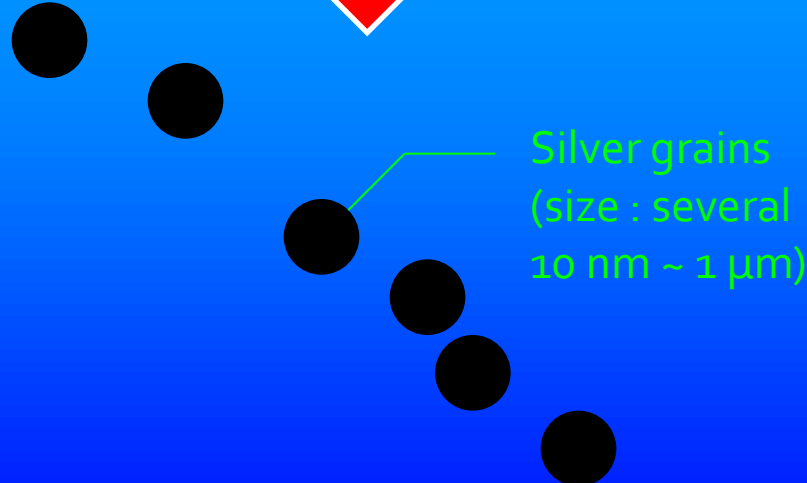
Low BG from ν_μ NC π⁰ production

Nuclear Emulsion Detector

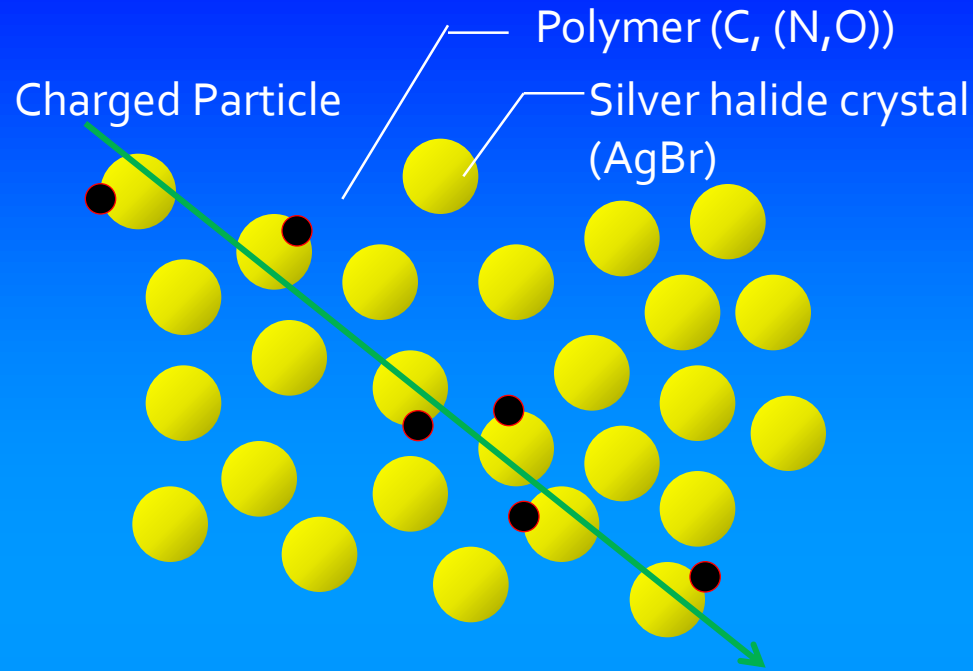


Ionized electrons concentrated on the electron trap to form the latent image specks in a crystal

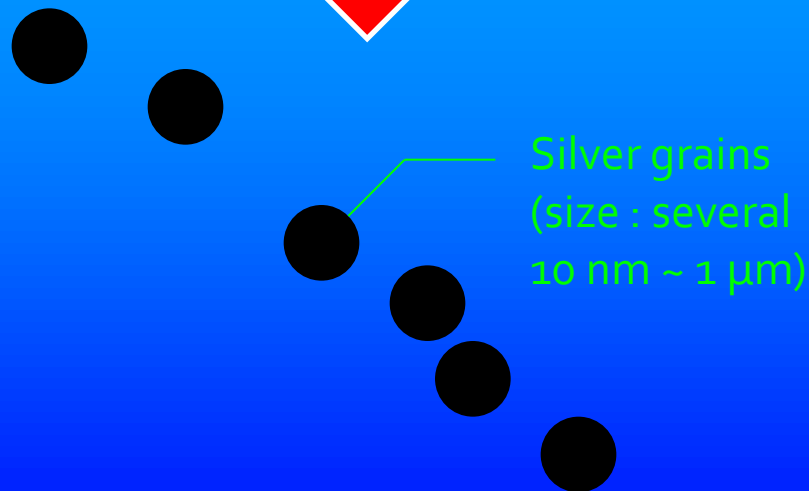
Development treatment



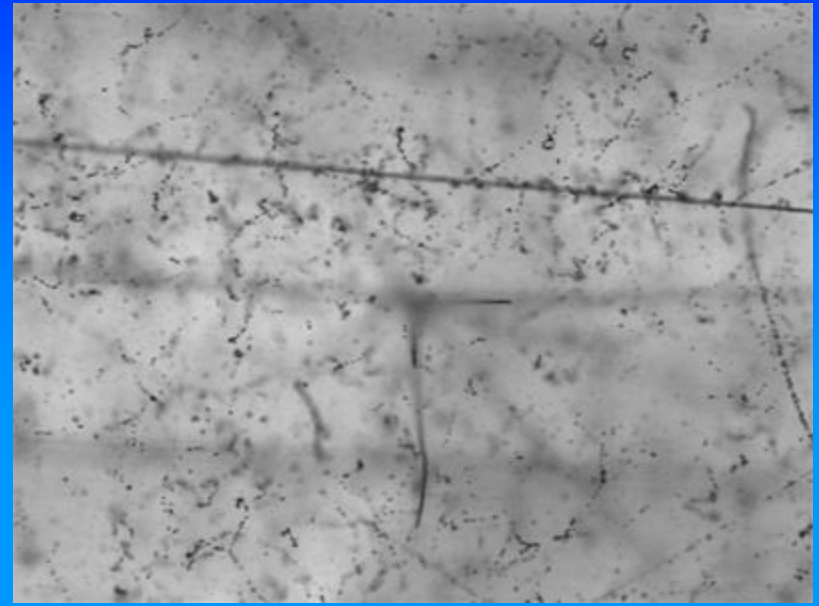
Nuclear Emulsion Detector



Development treatment



Nuclear spallation reaction by heavy ion



100 μm

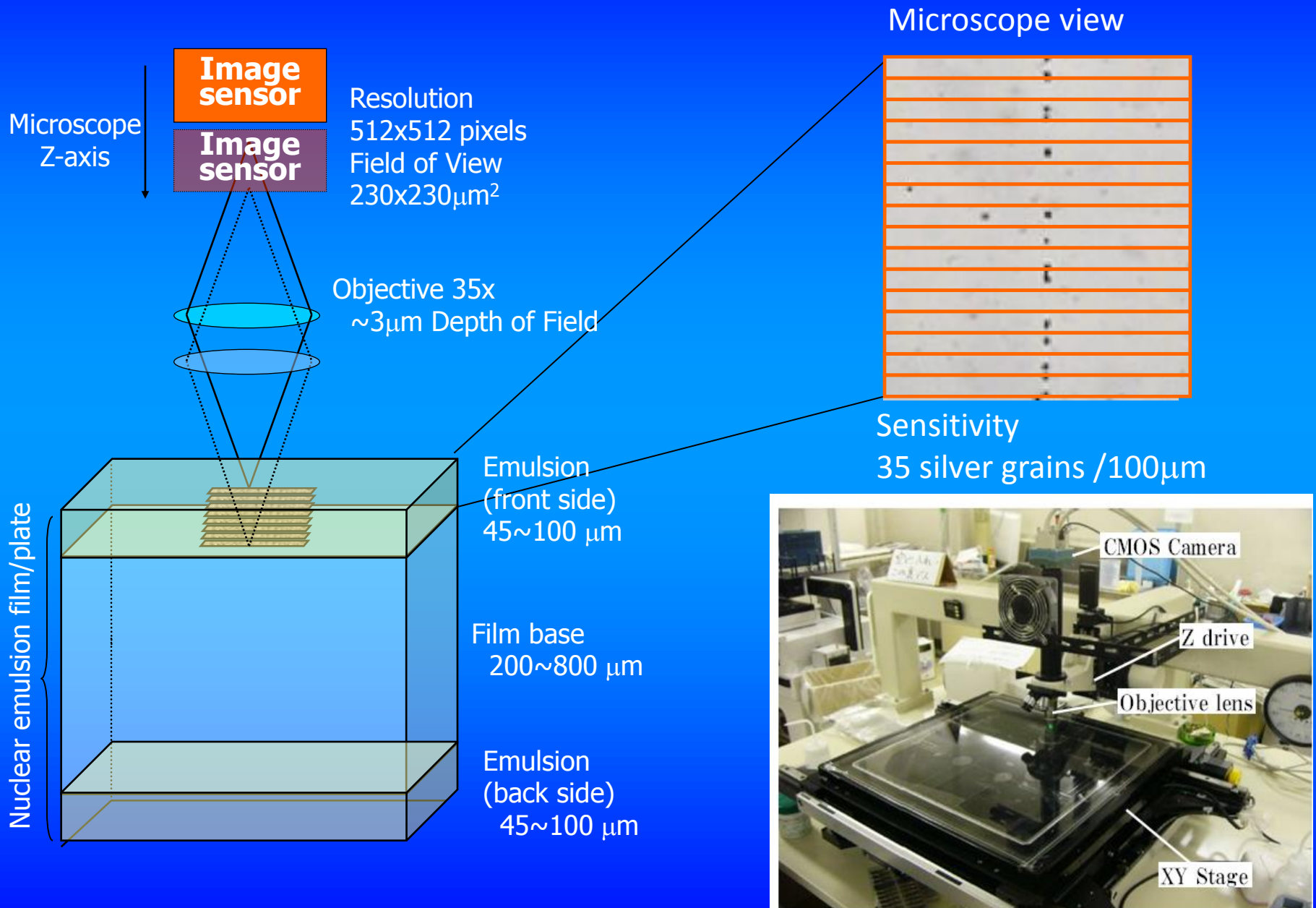
Spatial resolution

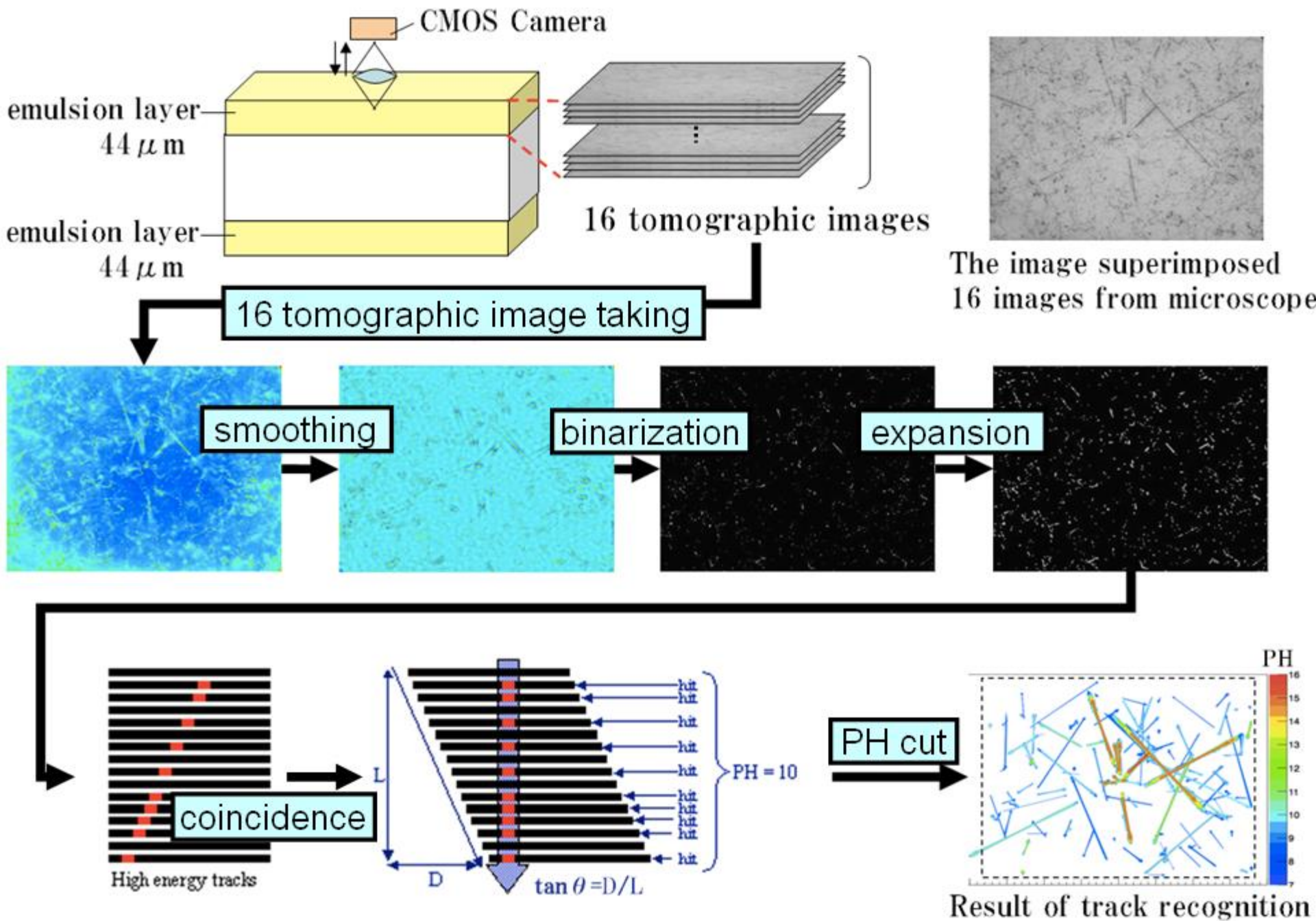
- silver halide crystal size
- number density of silver halide crystal

Sensitivity

- Chemical treatment
- Crystal defect and doping etc.

Readout of tracks in Emulsion





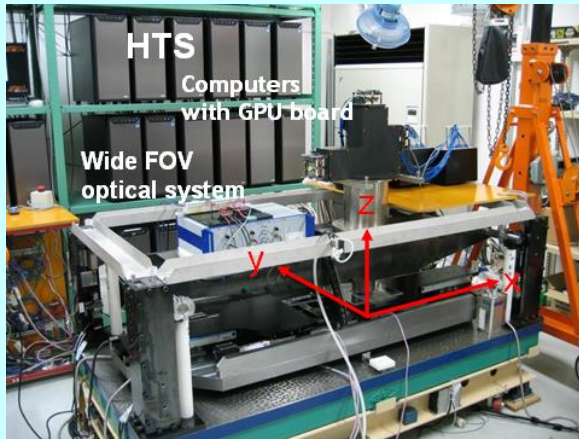
Long history in Neutrino Research

- **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

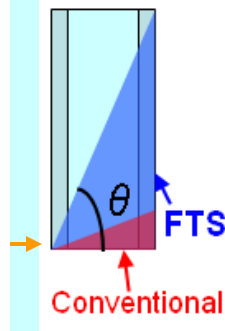
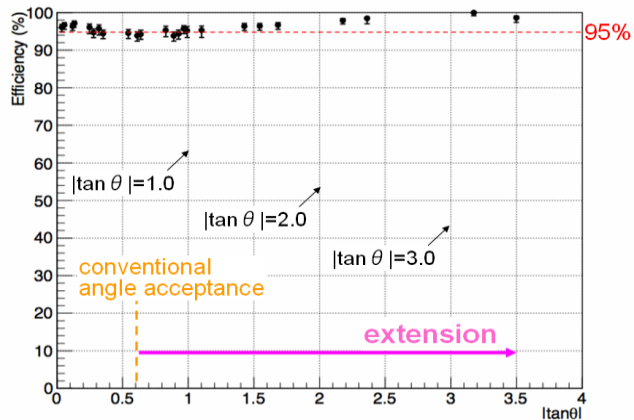
Readout technique

High Speed Scanning



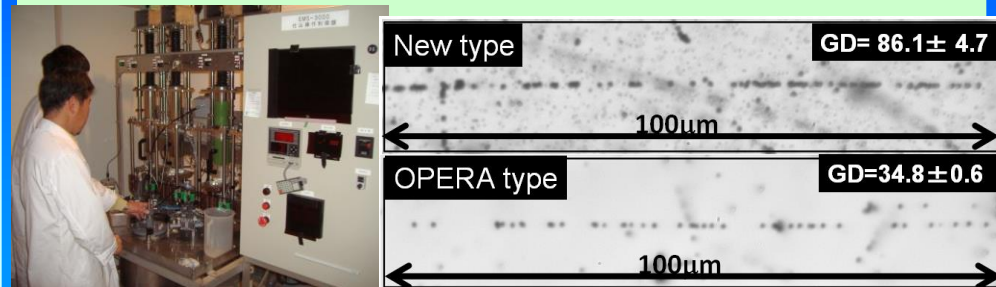
HTS 9,000cm²/h, x100 faster

Large angle tracking technique

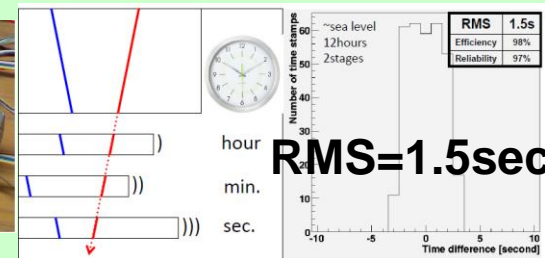
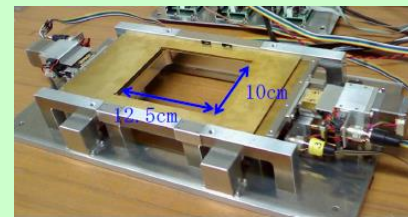


Detector technique

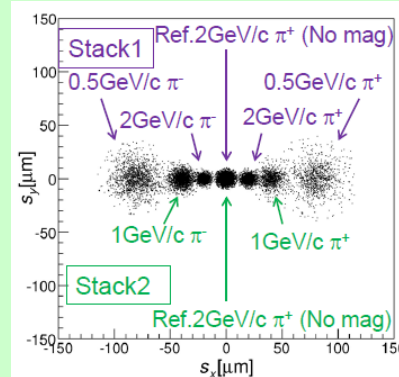
High Sensitive film



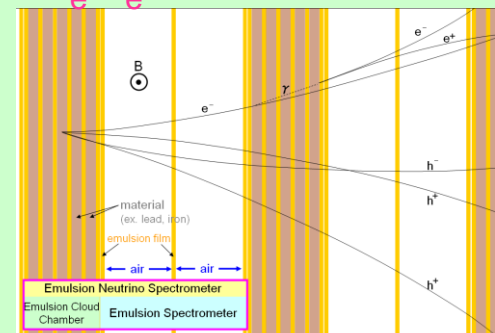
Time resolution



Charge sign ID



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



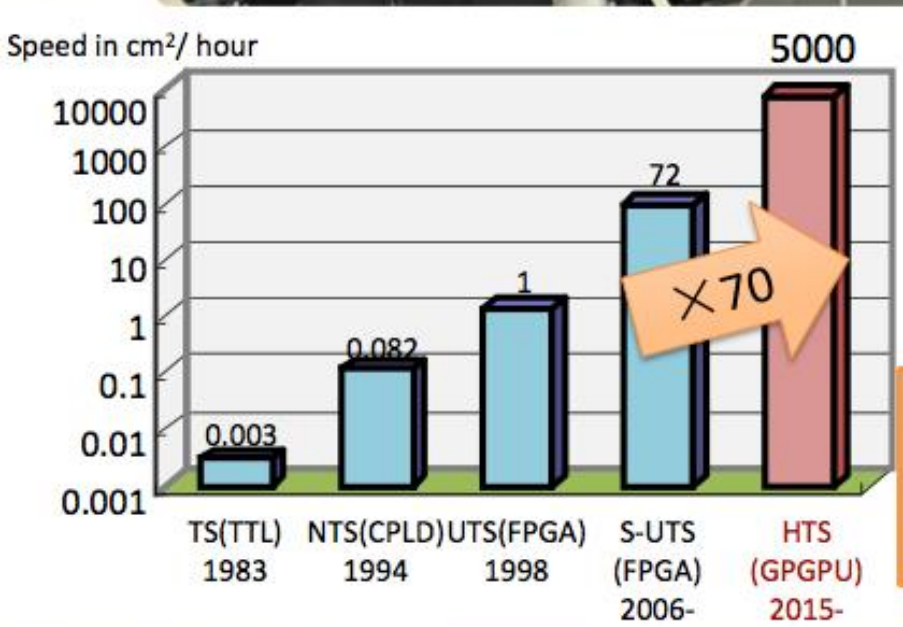
Hyper Track Selector

Processor:
72 GPUs

Camera:
2MP 72 sensors

Objective lens:
FOV 25mm²

Emulsion film
to be scanned .
25x38 cm²
or 25x25cm²
1~1.5 hour



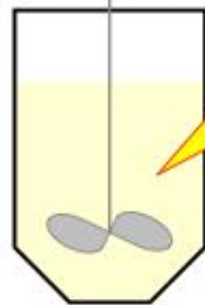
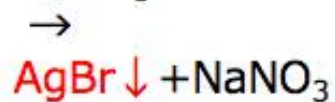
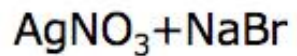
**Scanning time is shared by projects.
In total about 100 m² film area (>1000 films)
were scanned in recent 12 months**



Gel Production Machine at Nagoya Univ.



Chemical reaction



Injection speed
Mixing speed
Temperature

Crystal size
Crystal shape

chemical

Sensitivity
Stability



200nm

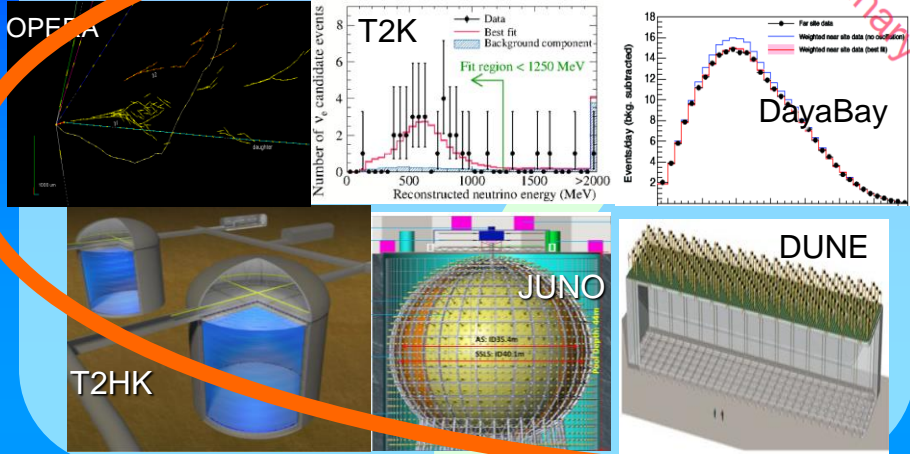
AgBr crystals

NINJA Experiment

Current situation on neutrino physics

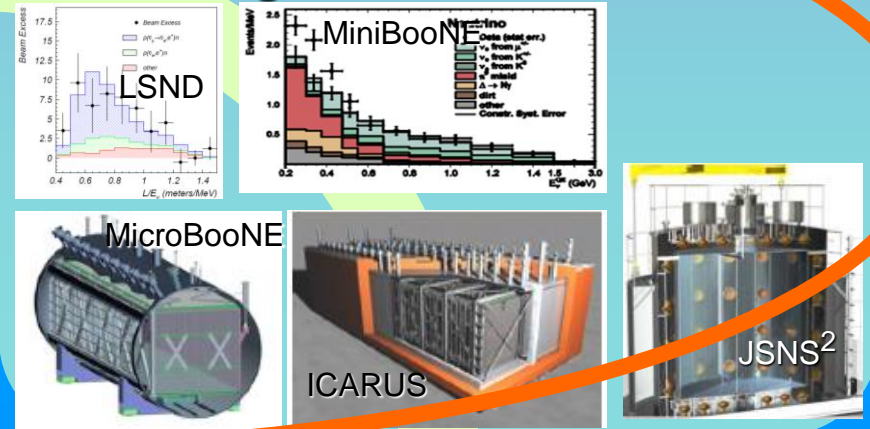
Neutrino oscillation

→ δ_{CP} , mass hierarchy



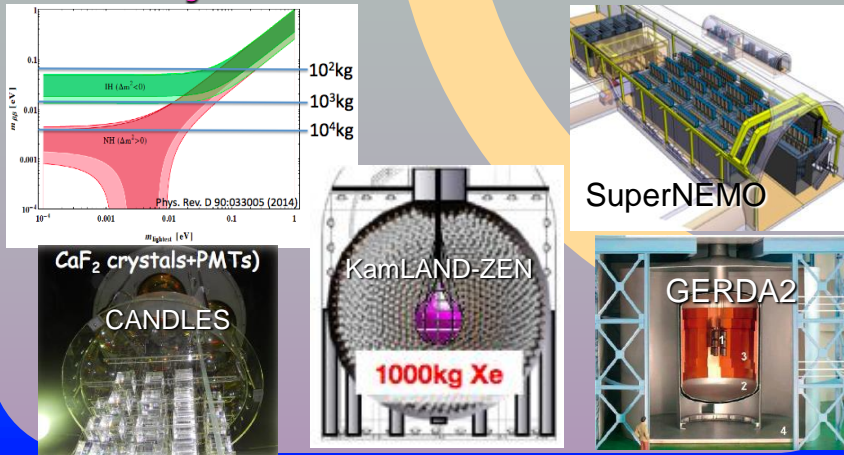
Sterile Neutrinos

→ 4th generation ? Dark matter ?



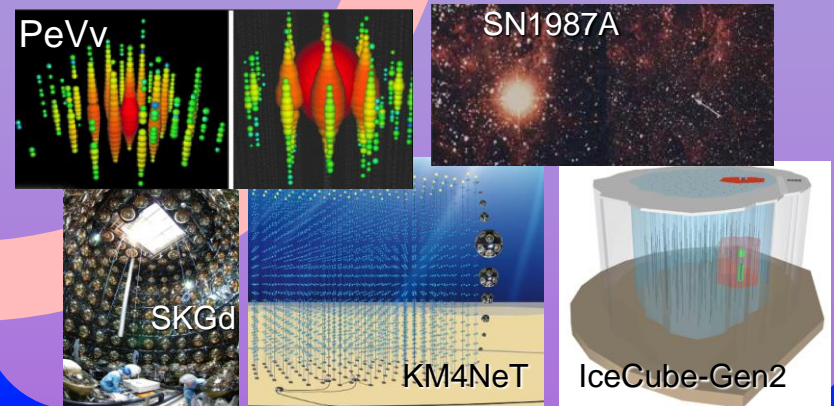
0ν double beta decay

→ majorana / dirac ? m_{ν} mass meas.



Cosmic neutrinos

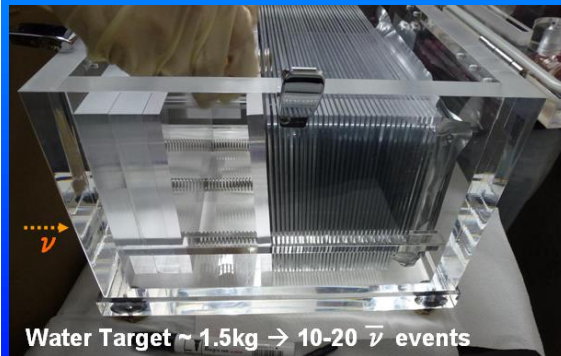
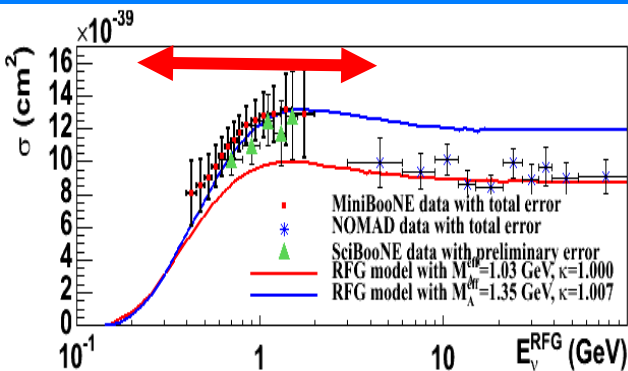
→ Ultra-high energy, Supernova, ...



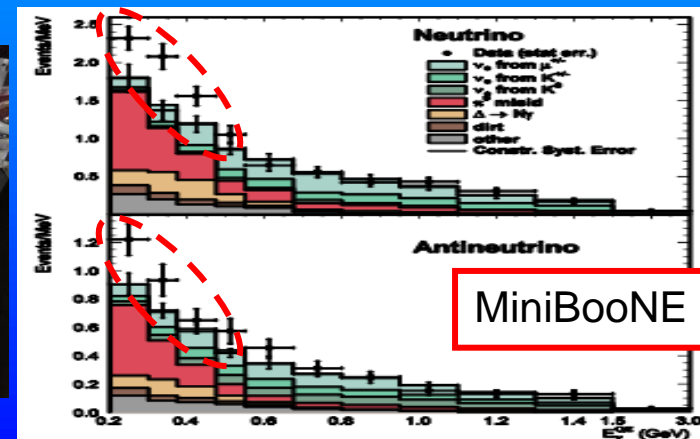
この他にも多くの実験が計画・実施・遂行されている。

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**.



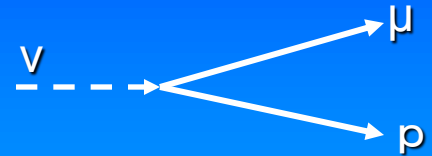
Water Target Emulsion Chamber



Precise measurement of neutrino-nucleus interactions

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

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

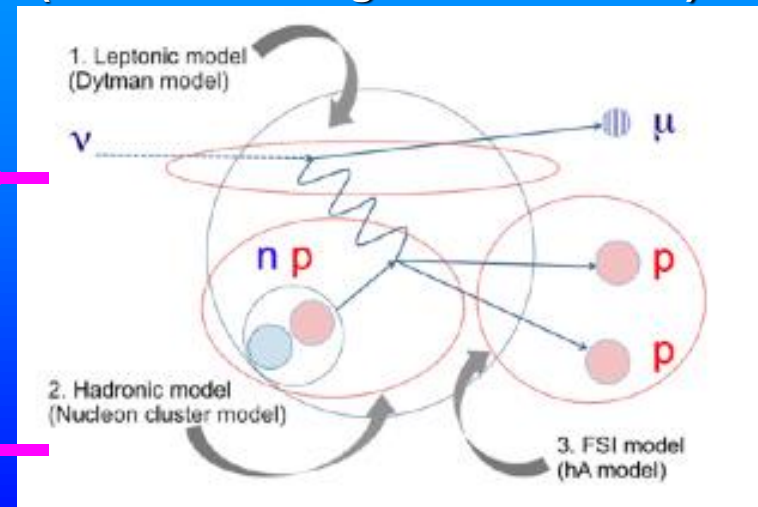


- Other interaction modes contaminate due to final state interaction in nucleon and detector inefficiency.
- Energy can't be reconstructed correctly with these interaction modes.
→ Need precise understanding about neutrino interaction.

uncertainties on predicted events at SK

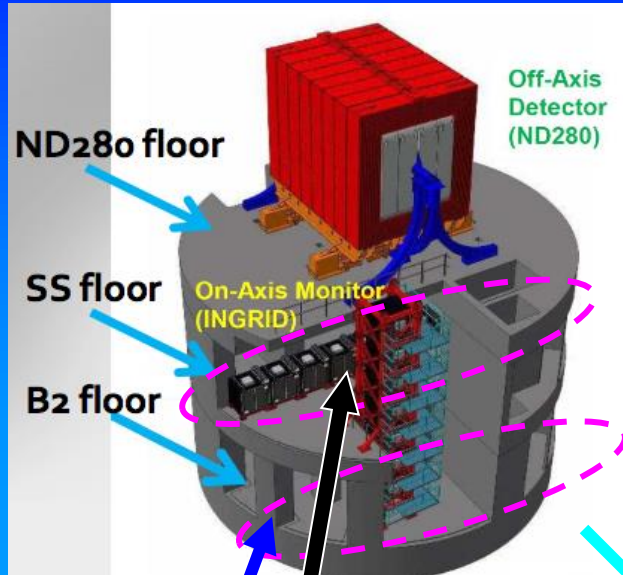
	ν_μ sample 1R $_\mu$ FHC	ν_e sample 1R $_e$ FHC	$\bar{\nu}_\mu$ sample 1R $_\mu$ RHC	$\bar{\nu}_e$ sample 1R $_e$ RHC
ν flux w/o ND280	7,6%	8,9%	7,1%	8,0%
ν flux with ND280	3,6%	3,6%	3,8%	3,8%
ν cross-section w/o ND280	7,7%	7,2%	9,3%	10,1%
ν cross-section with ND280	4,1%	5,1%	4,2%	5,5%
ν flux+cross-section	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 Interaction research with Nuclear emulsion and J-PARC Accelerator



Working group

OPERA

J-PARC

T2K

Experimental site, Neutrino beam

Nihon Univ.

Emulsion development

Univ. Tokyo

T2K near detector

Nagoya Univ.

Film production, Scan

Kyoto Univ.

T2K near detector

Toho Univ.

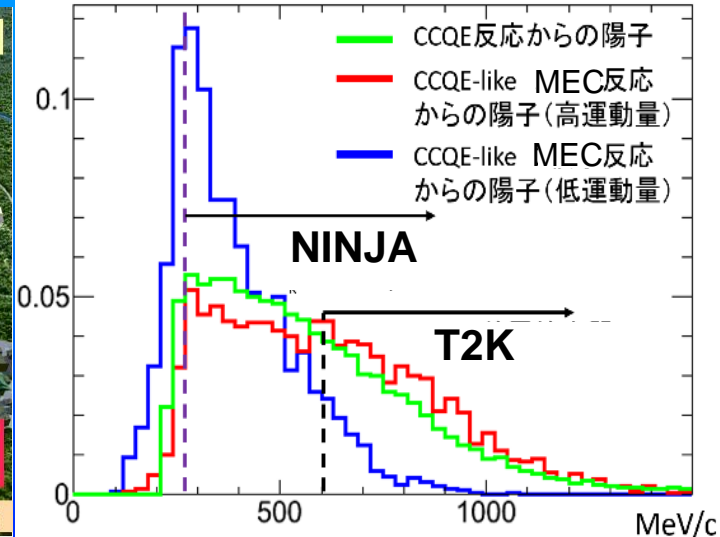
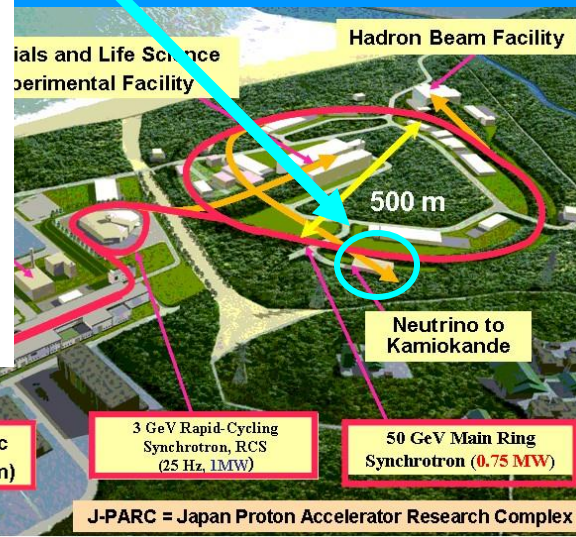
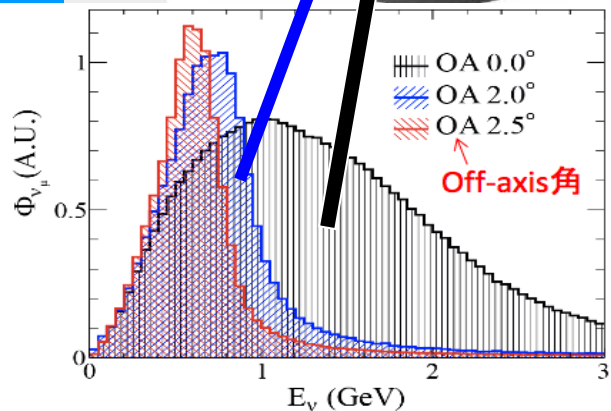
Film production, Scan

Yokohama N Univ.

T2K near detector

Kobe Univ.

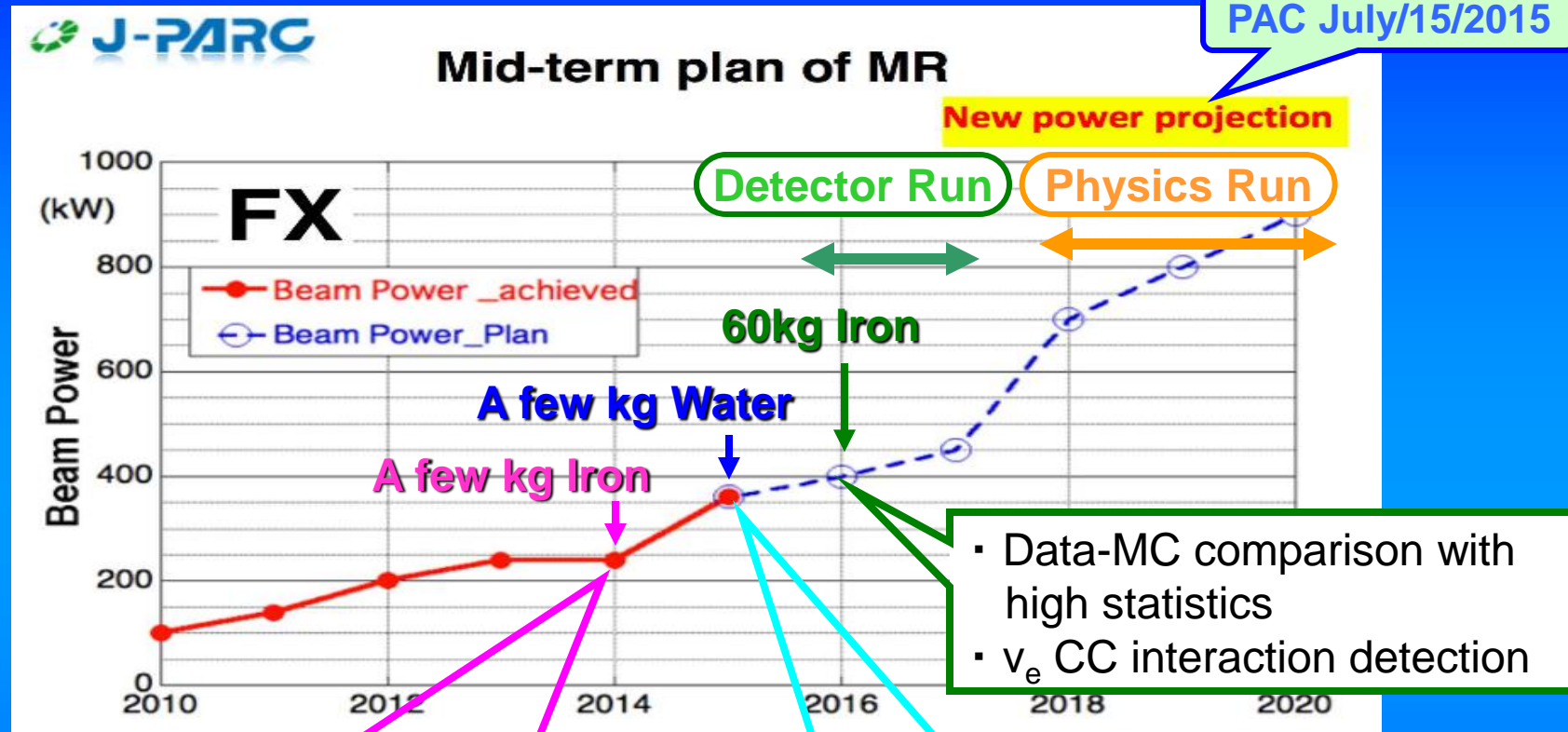
Emulsion Shifter



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

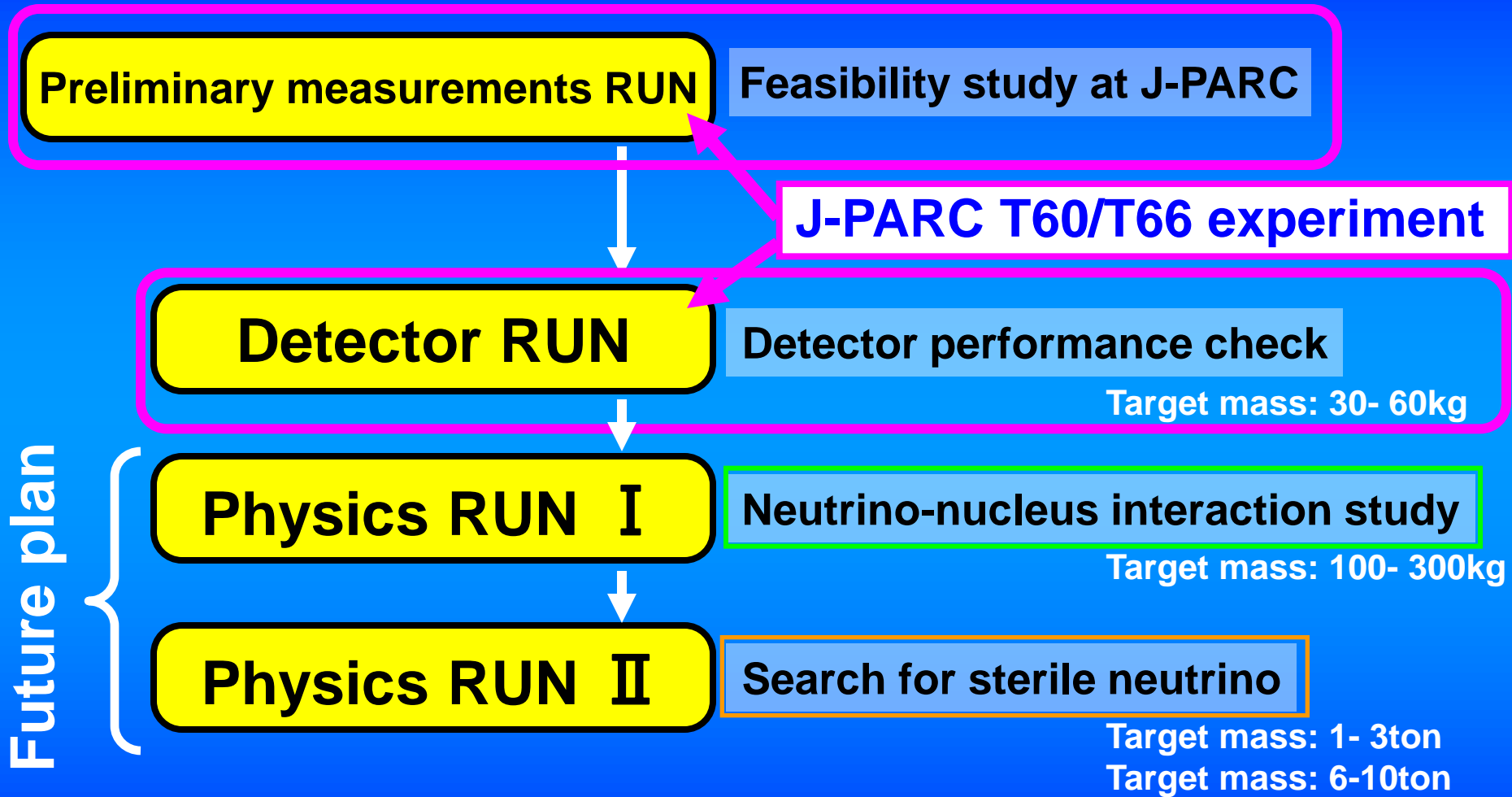


- Emulsion handling @J-PARC
- Demonstration of ν event detection
- Hybrid analysis with T2K near detector

- 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



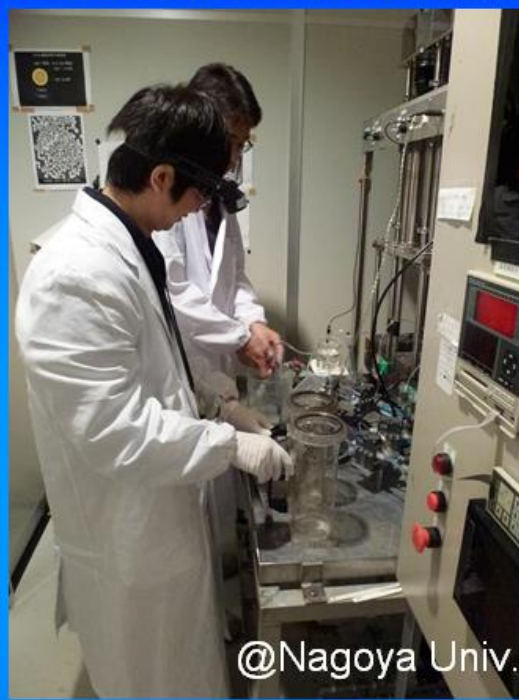
- The aim of T60/T66 is a **feasibility study** and **detector performance check** to make a future plan.
- We will expand the scale of detector gradually, step by step.

Status review of NINJA

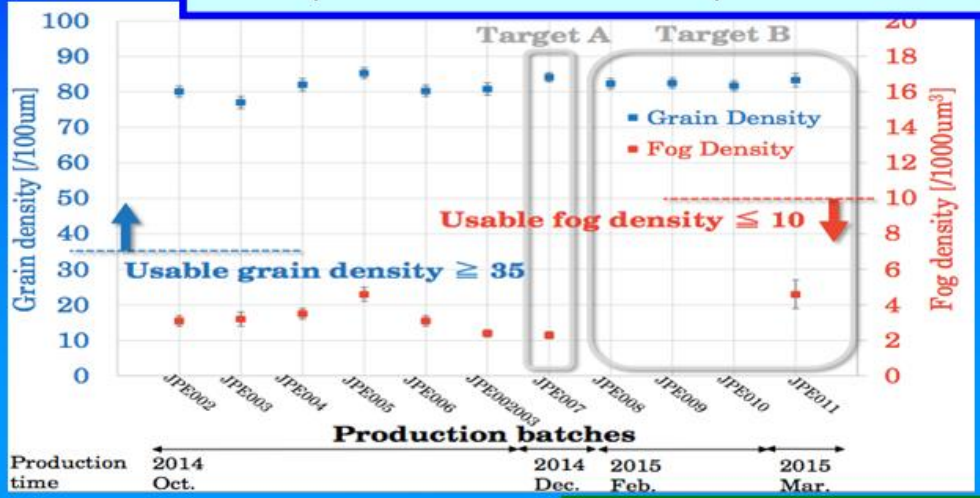
Emulsion gel production in the lab

Nuclear emulsion films were made by ourselves.

Initial performance for each production batch

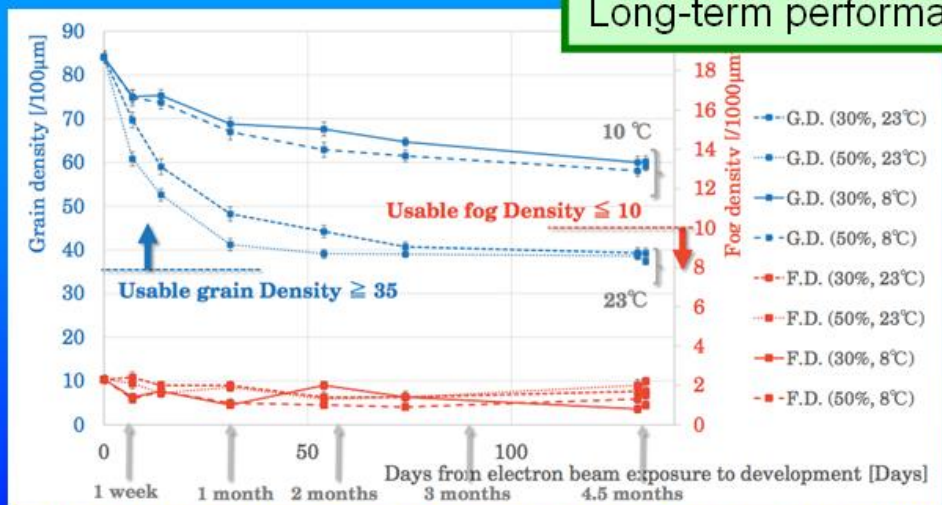
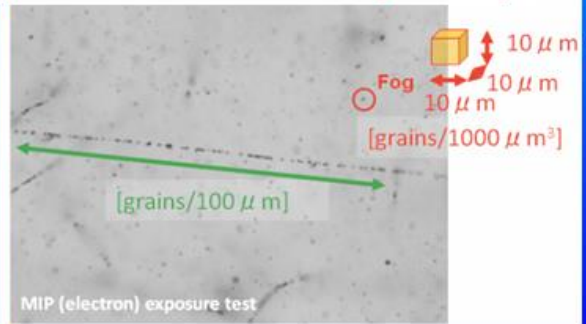


@Nagoya Univ.



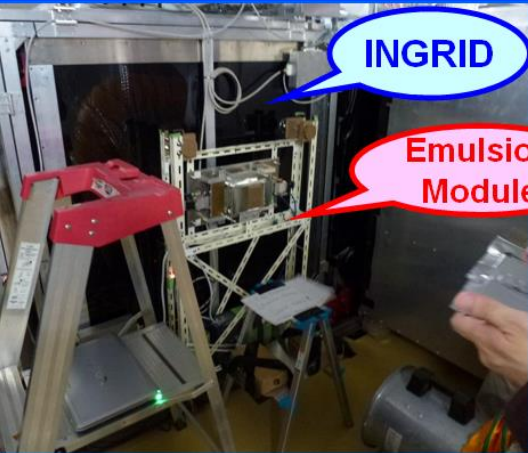
Signal efficiency → Grain density
Isolated random noise → Fog density

Long-term performance

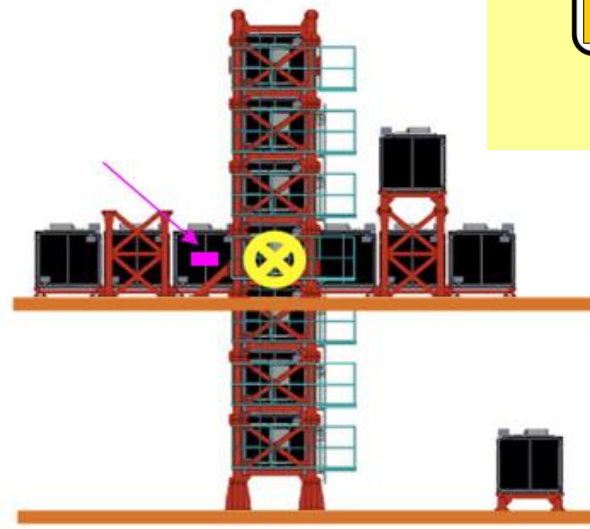
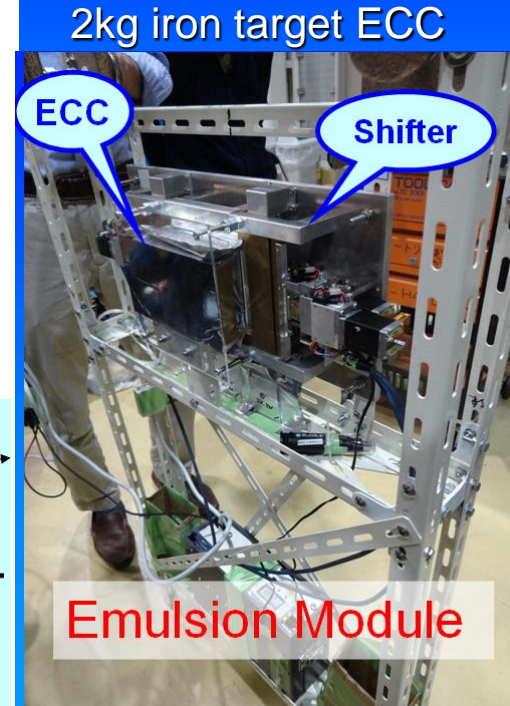
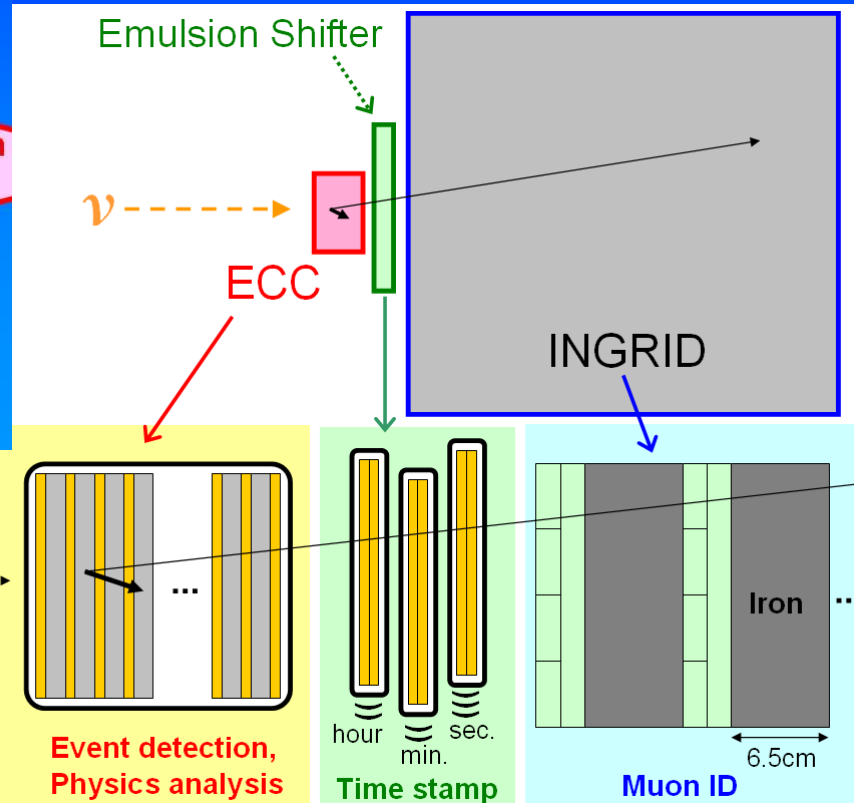


Initial and long-term performance of new emulsion gel is kept at safety level for signal and noise.

Conceptual detector design



SS floor @J-PARC
(Jan. 2015)

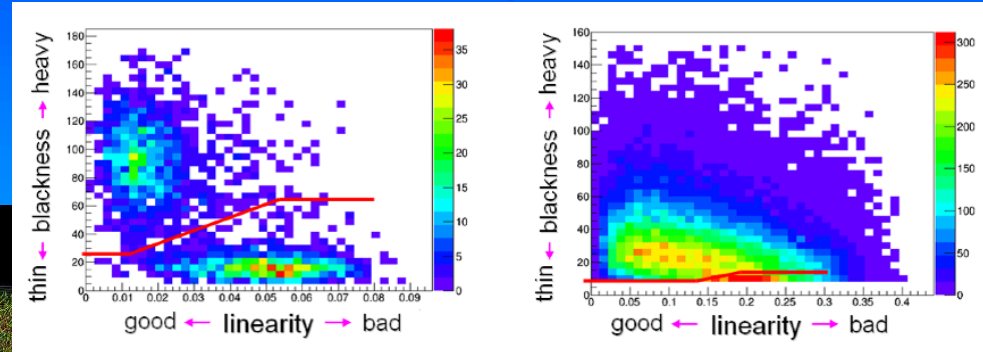


- **Emulsion Cloud Chamber** is a sandwich structure of emulsion films and iron plates.
- Emulsion detector is placed in front of T2K near detector, INGRID.
- Emulsion Shifter is re-used from GRAINE project to give a timing info. to emulsion tracks.
- Muon ID is possible by combined analysis with INGRID.

Reconstructed track data

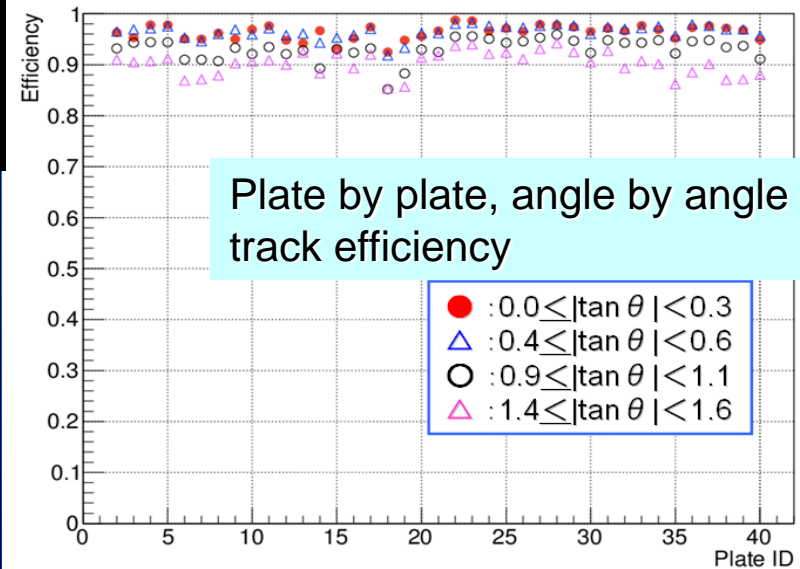
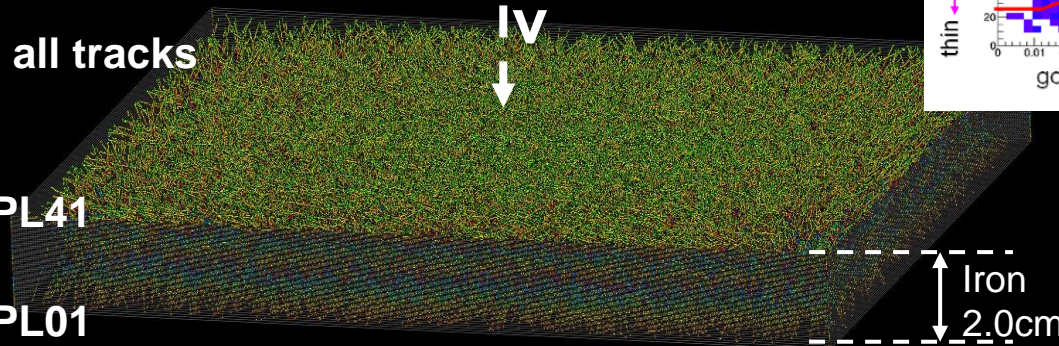
All emulsion films were scanned by HTS. First of all, noise tracks were rejected by evaluating the quality of each tracks. Then tracks were reconstructed.

Track Quality Selection

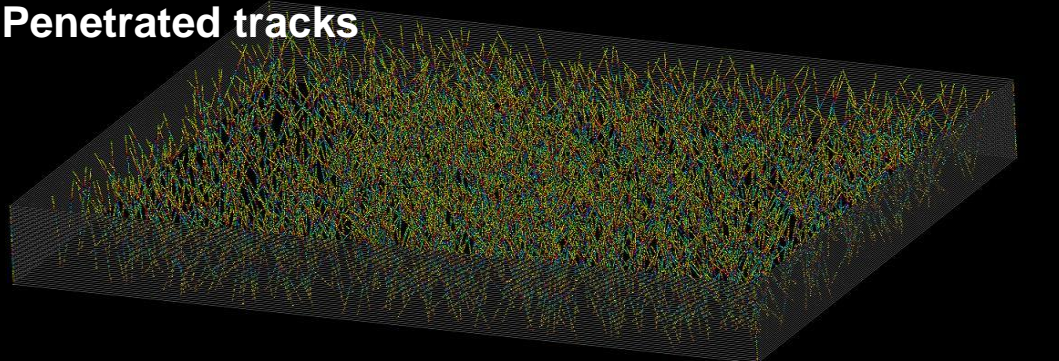


($|\tan\theta| \leq 0.1$)

($1.4 \leq |\tan\theta|$)



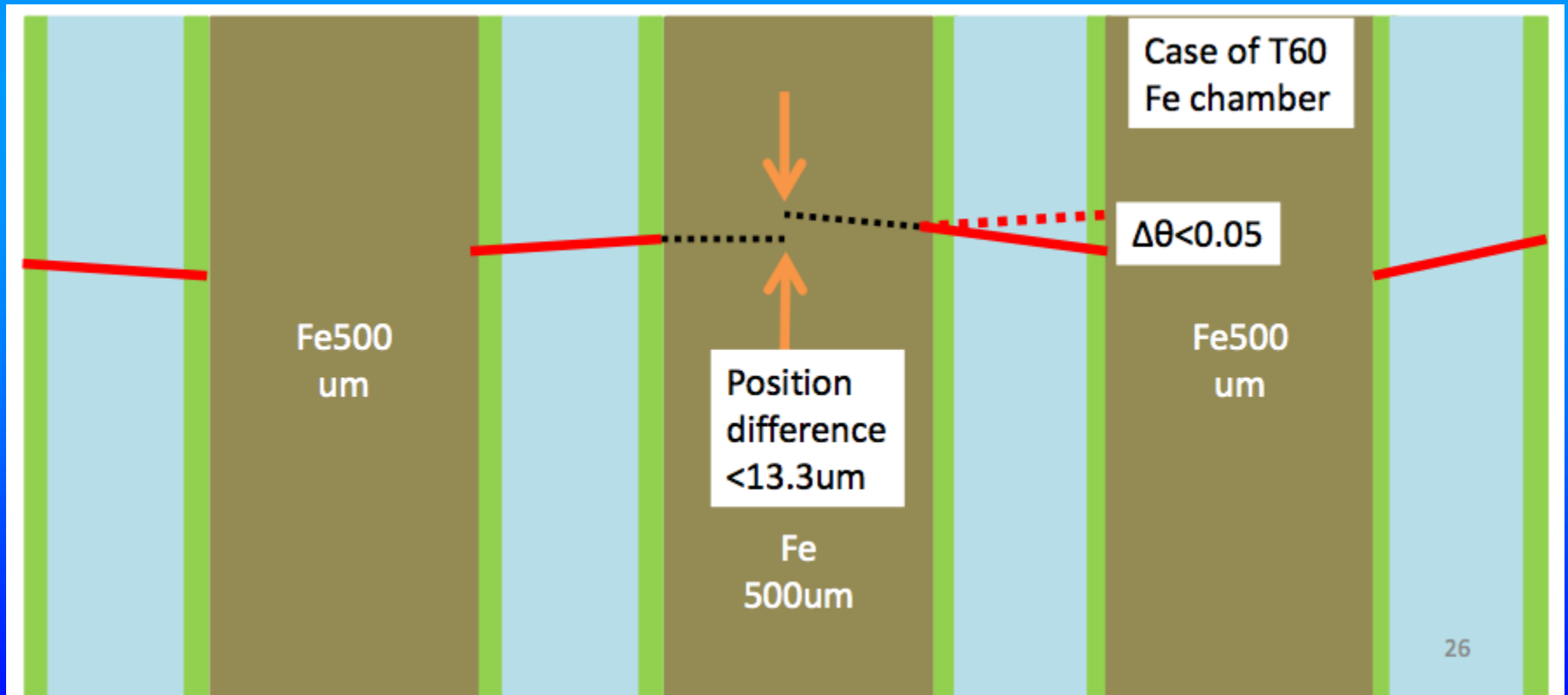
Penetrated tracks



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.

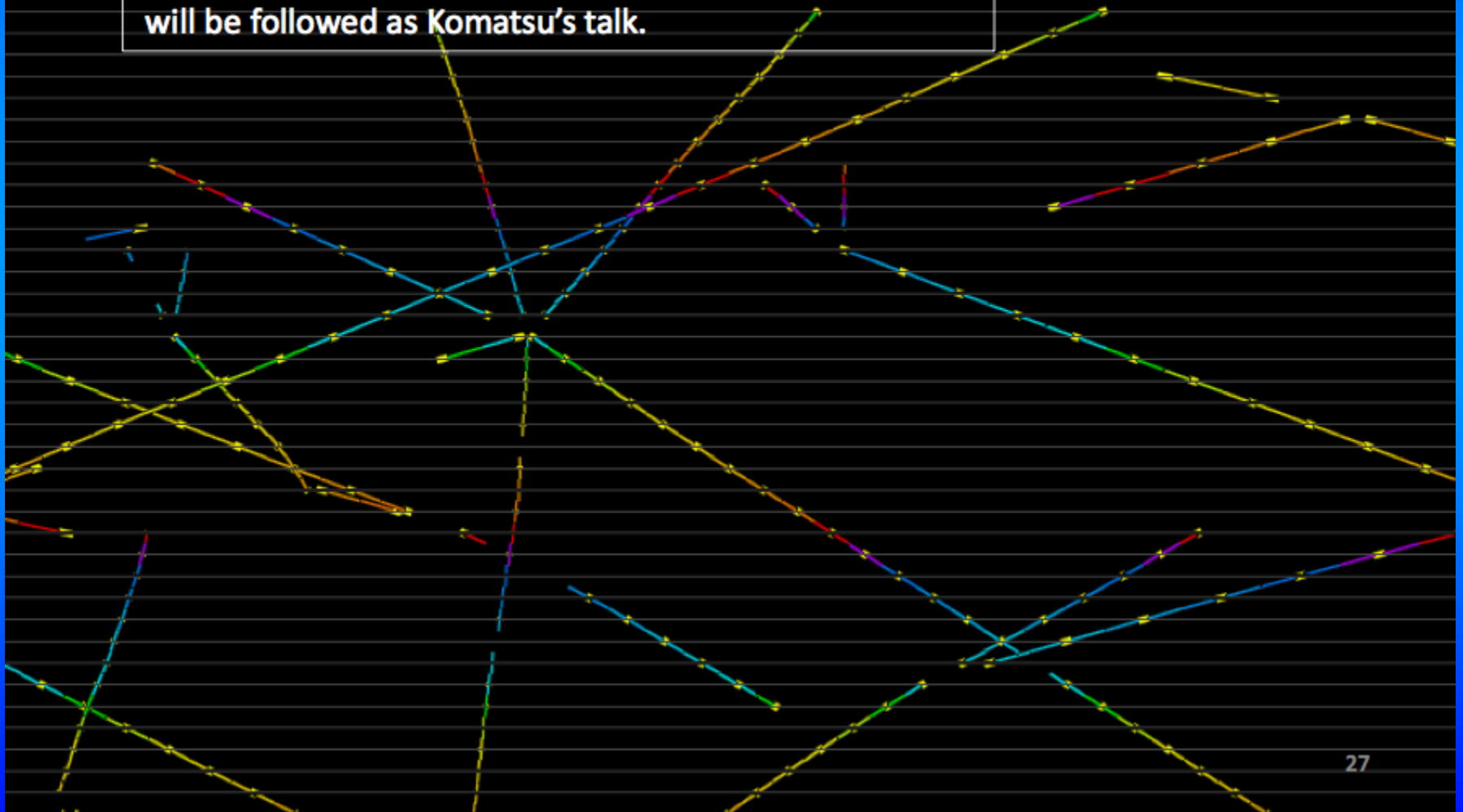


Event analysis sample

Requesting making vertex IP within 20um

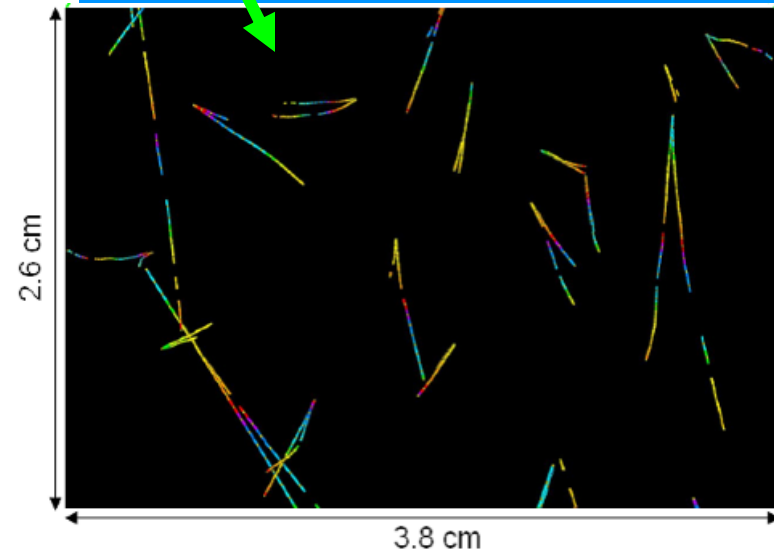
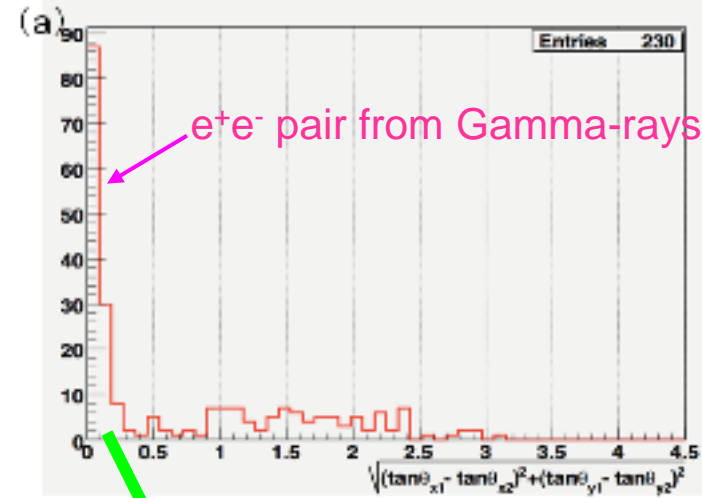
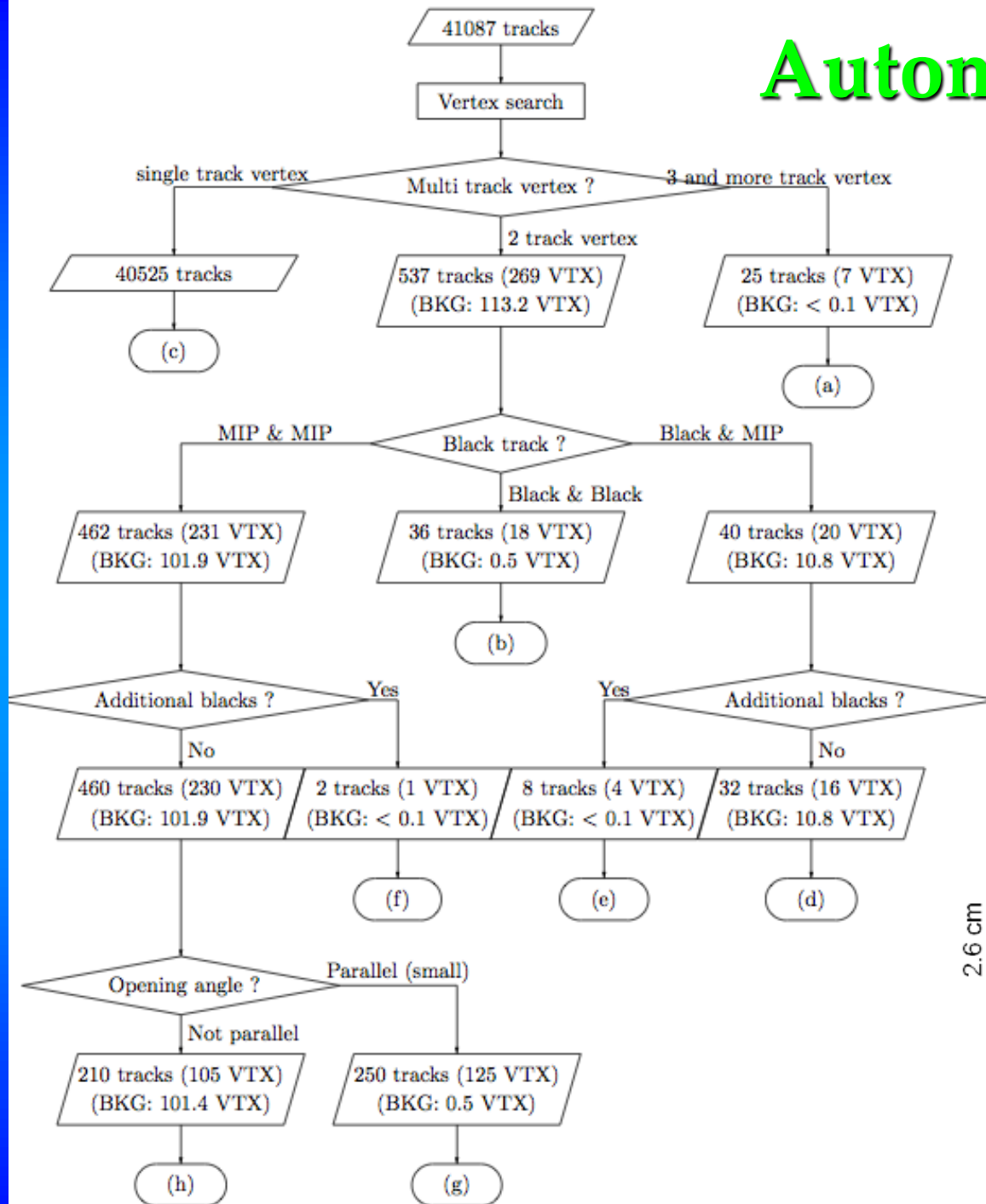
Detailed analysis , momentum measurement particle ID,
will be followed as Komatsu's talk.

T60 Run4 X-proj



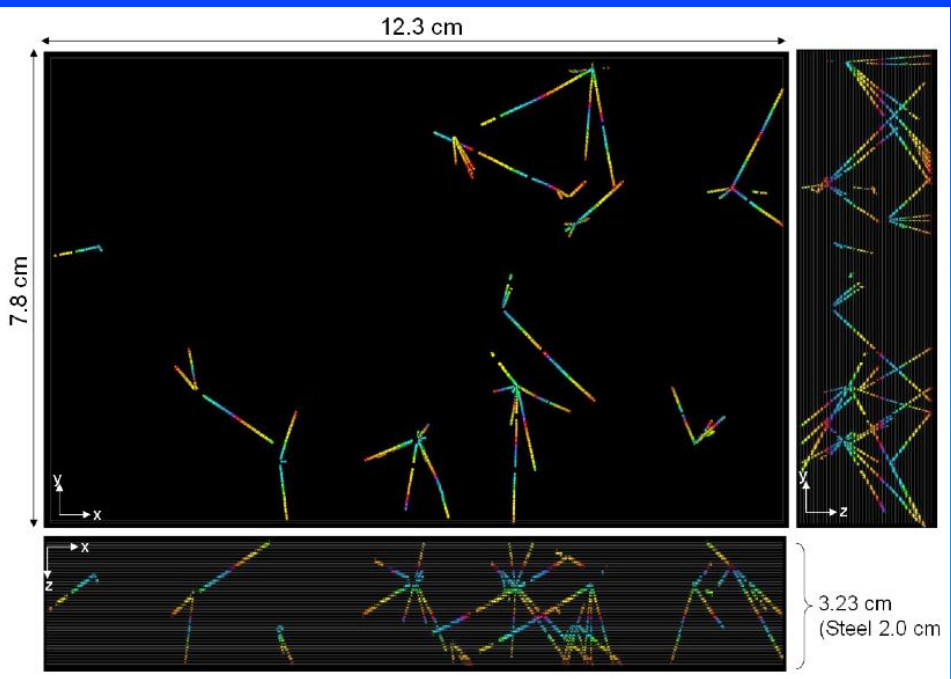
Automatic procedure

Opening angle of 2MIP

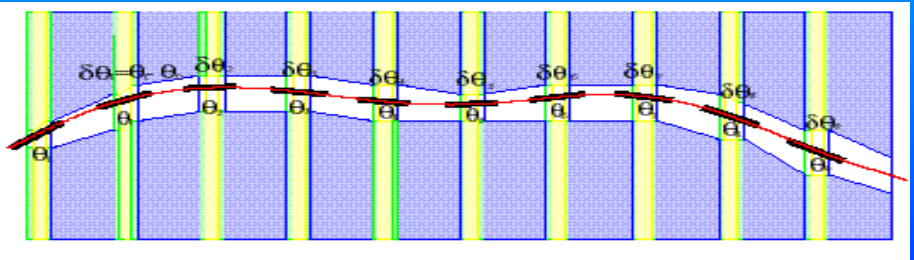


Status review of NINJA

Systematic emulsion analysis

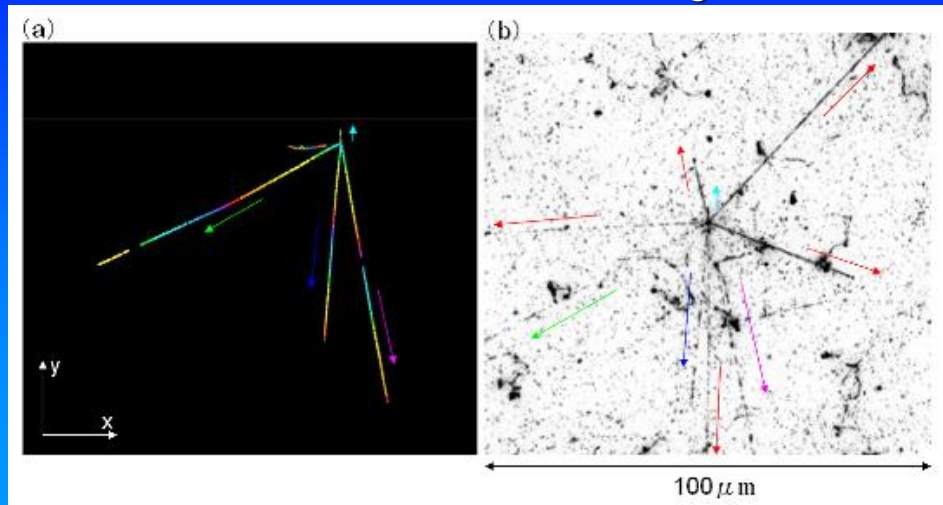


Momentum measurement

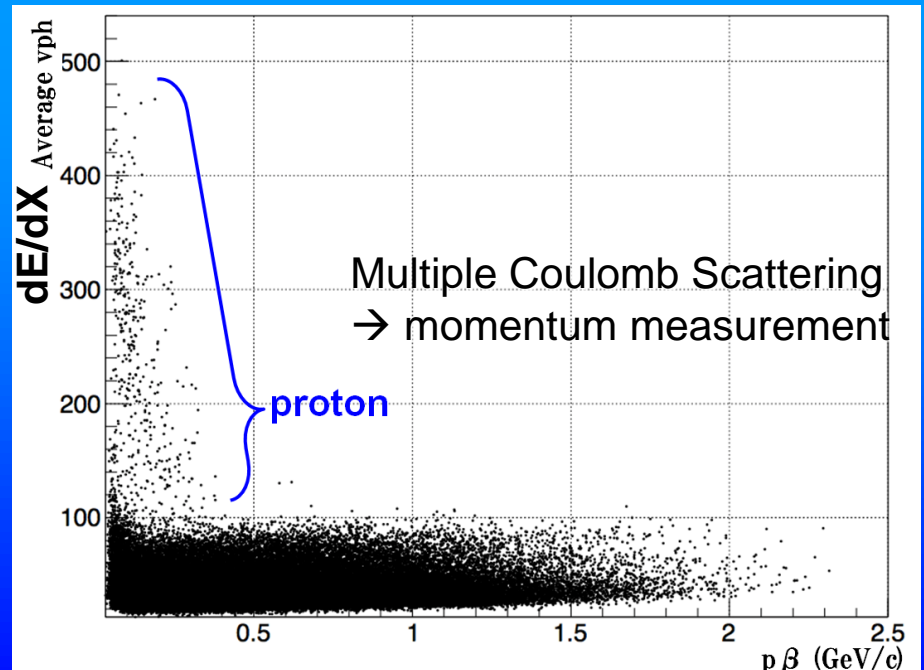


$$\theta_0 = \frac{13.6}{(pc\beta)} \times \sqrt{\frac{x}{X_0}} \times \left[1 + 0.038 \ln\left(\frac{x}{X_0}\right) \right]$$

Interacted in emulsion region

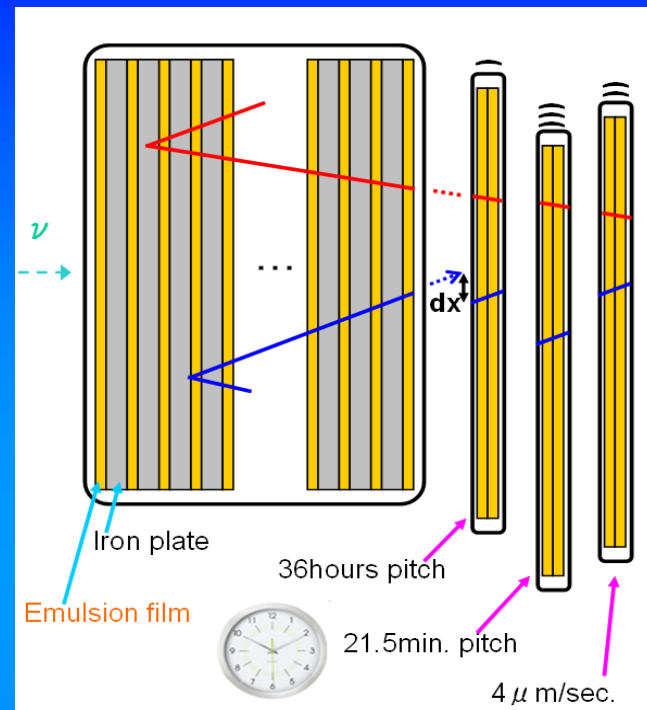


Proton Identification



Status review of NINJA

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

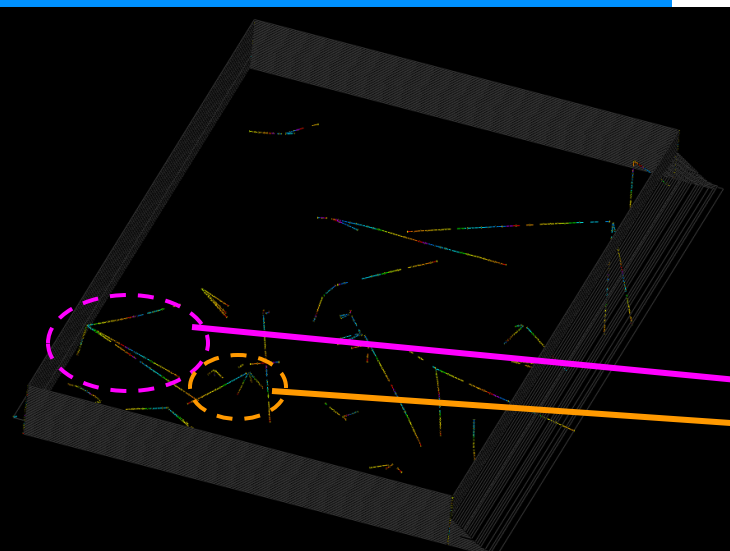
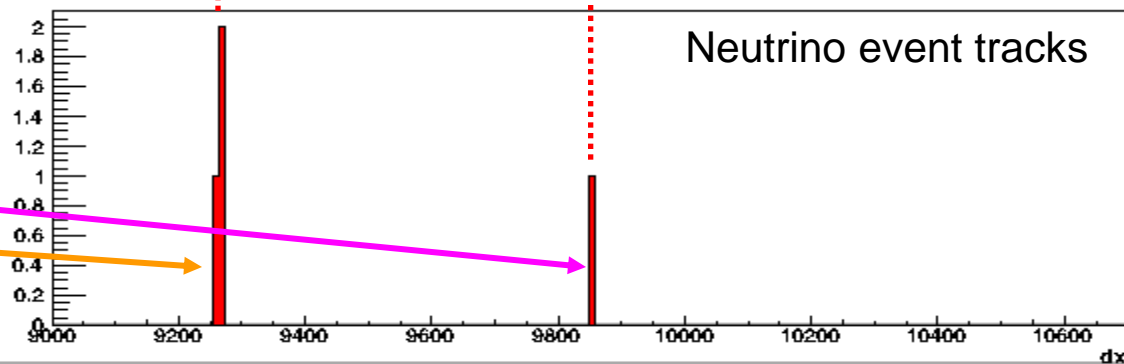
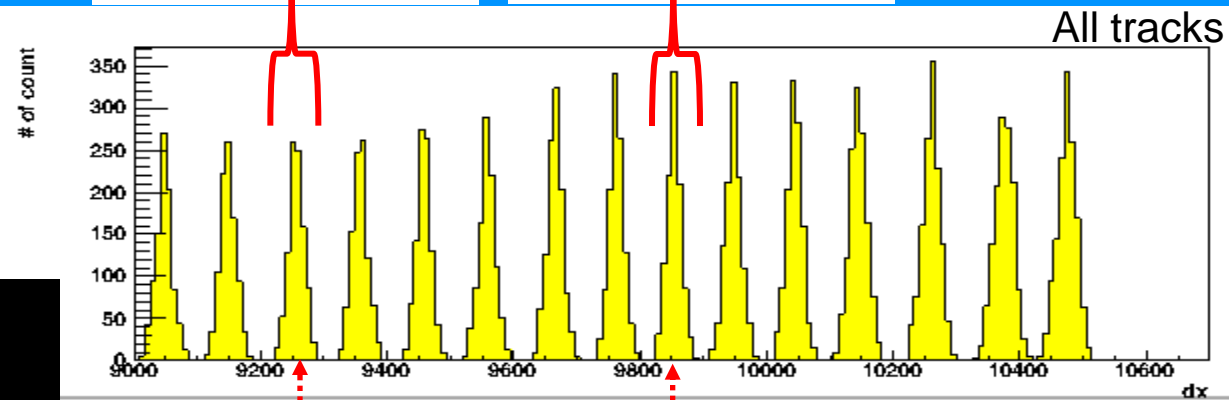
~ Mar.14 14:23:57

Spot 7

Mar.21 2:25:49

~ Mar.23 14:26:12

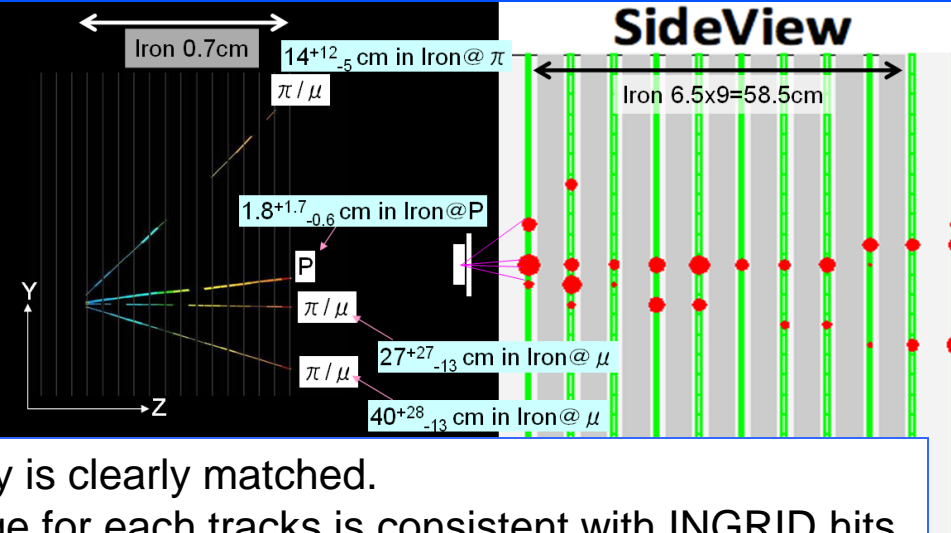
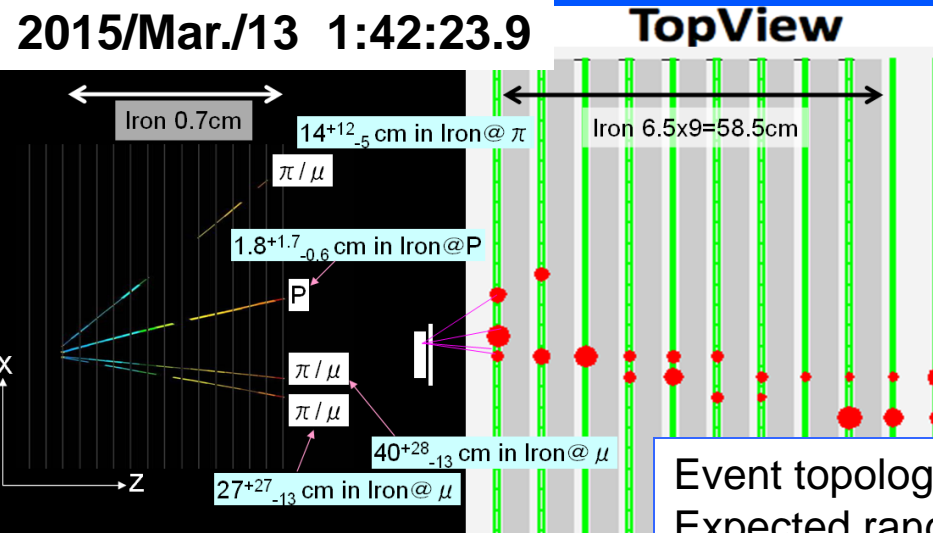
Information from
Top stage



Status review of NINJA

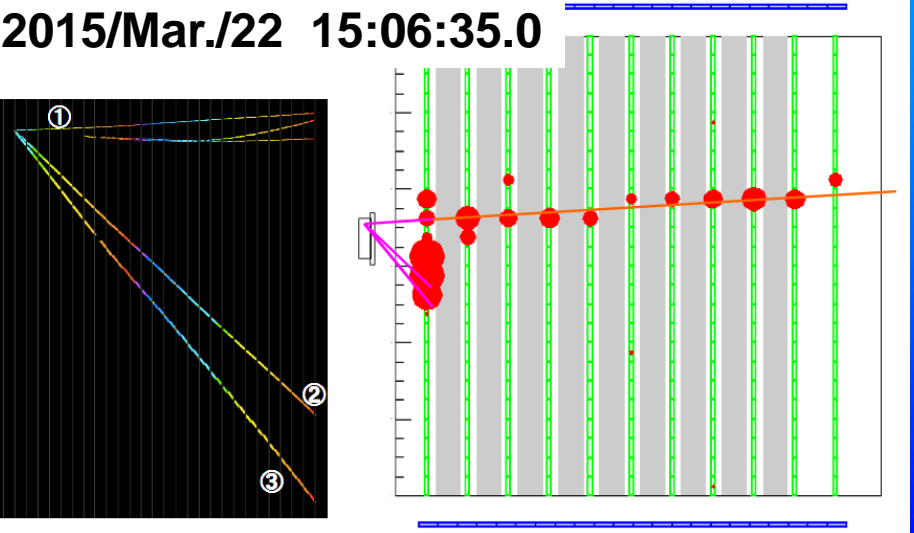
Emulsion-INGRID Hybrid analysis

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

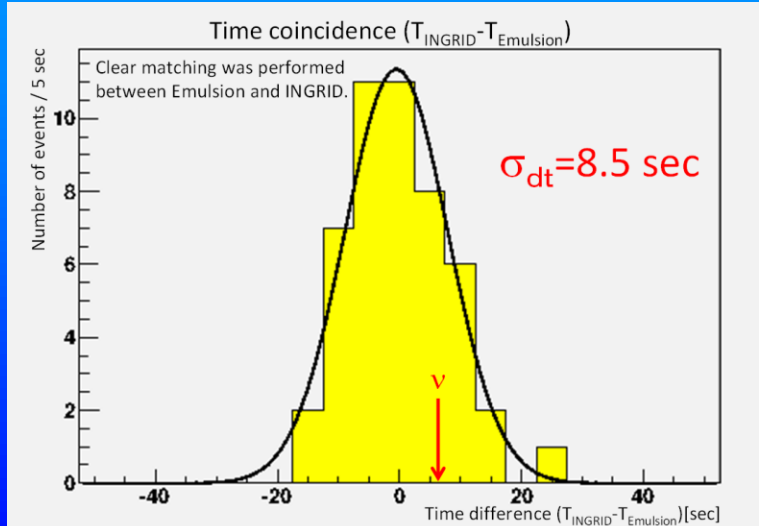


Event topology is clearly matched.
Expected range for each tracks is consistent with INGRID hits.

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



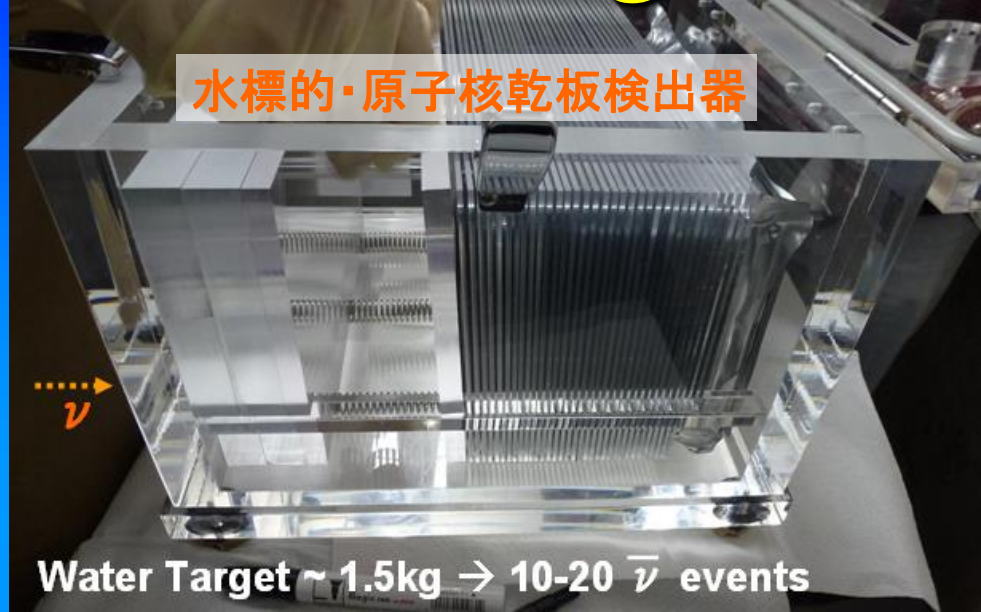
Time resolution for emulsion tracks



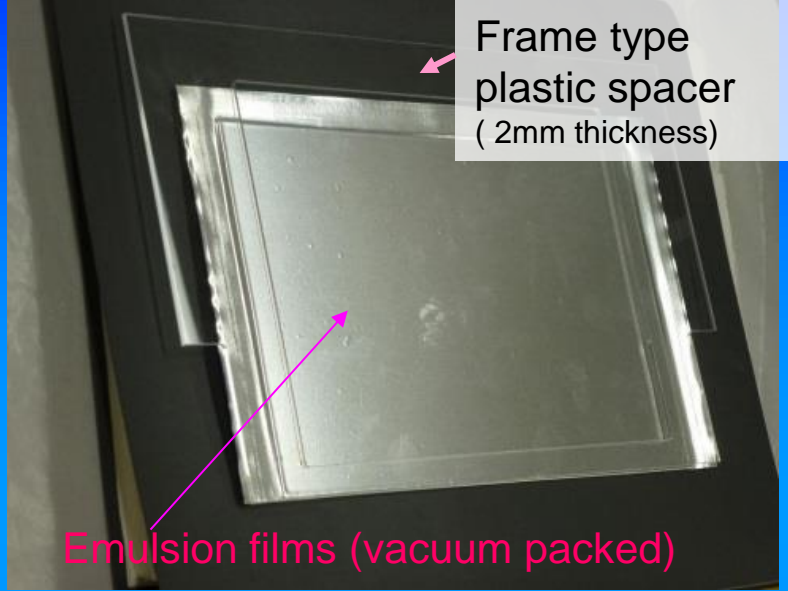
Status review of NINJA

Water target emulsion detector

水標的・原子核乾板検出器

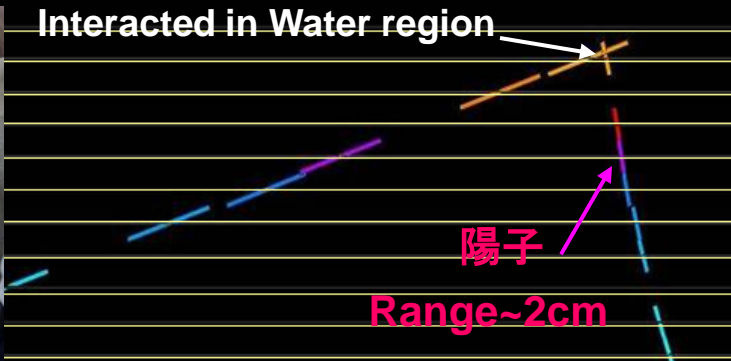


Water Target ~ 1.5kg → 10-20 $\bar{\nu}$ events



Sandwich structure of Emulsion films and Frame type spacers

Pouring water

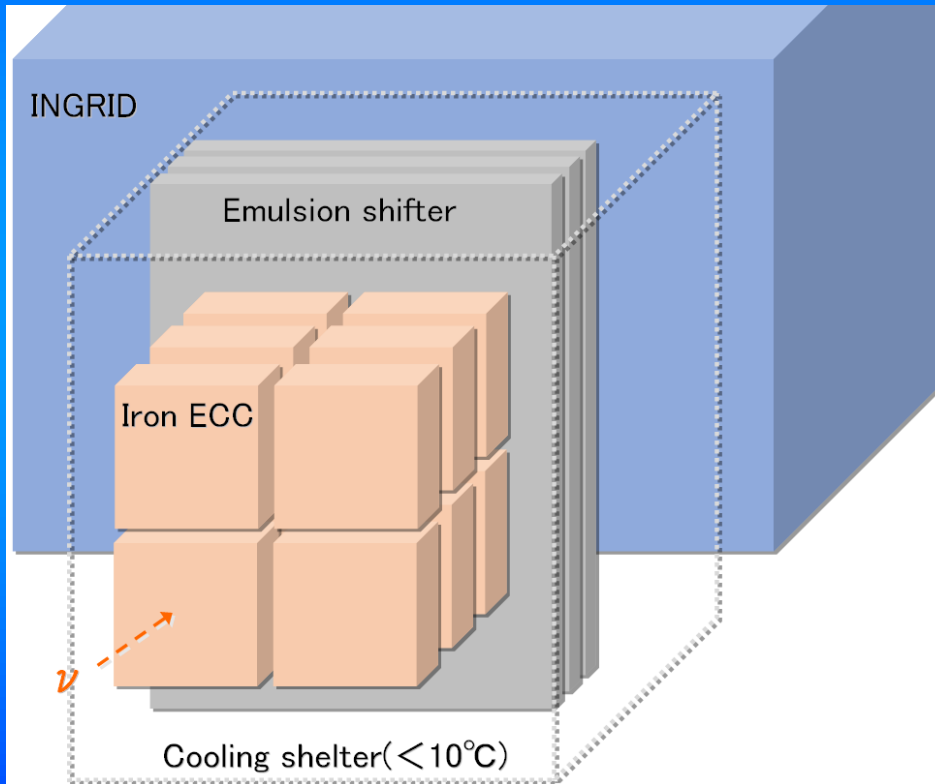


①	$(\tan \theta_x, \tan \theta_y) = (-0.040, 0.845)$	M.I.P
②	$(\tan \theta_x, \tan \theta_y) = (-0.589, -0.074)$	proton
Minimum distance(①-②)=2.4um, depth=620um		

First detection of $\bar{\nu}$ - Water interaction with Emulsion Detector

Detector Run

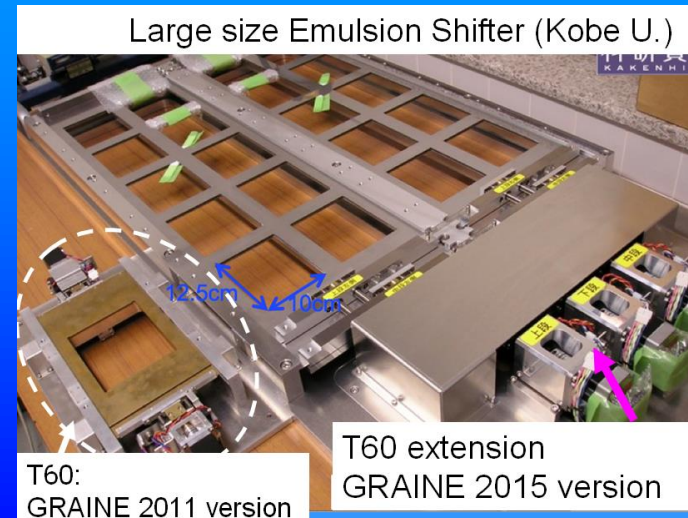
We are starting Detector Run to compare MC with high statistics.

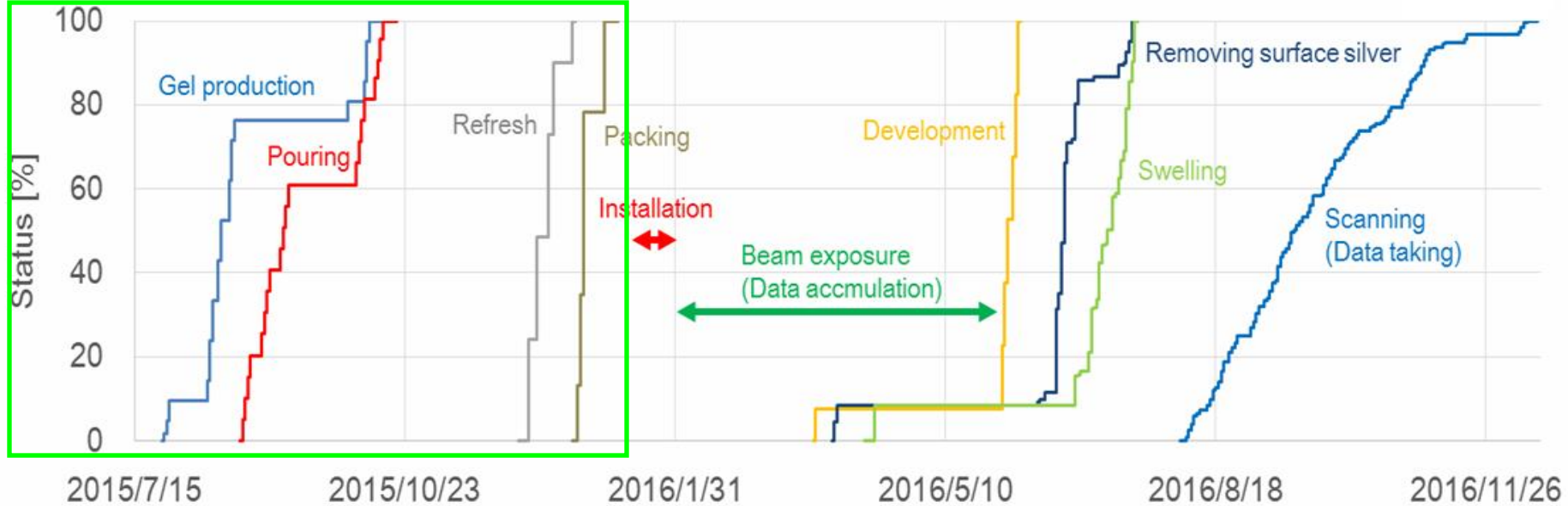


$\bar{\nu}$ exposure : 2016 @SS floor
end of Jan. \rightarrow beam end

- 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)

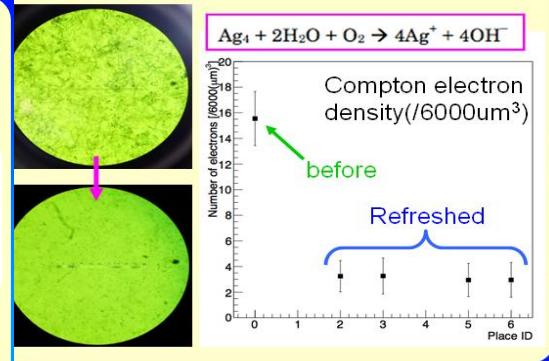
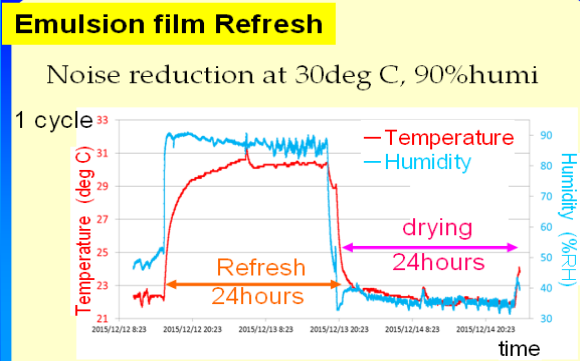
\rightarrow Data – MC comparison with high statistics to check the performance.





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

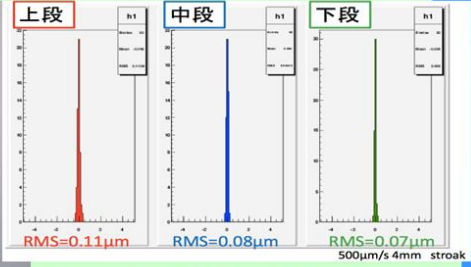
Detector preparation



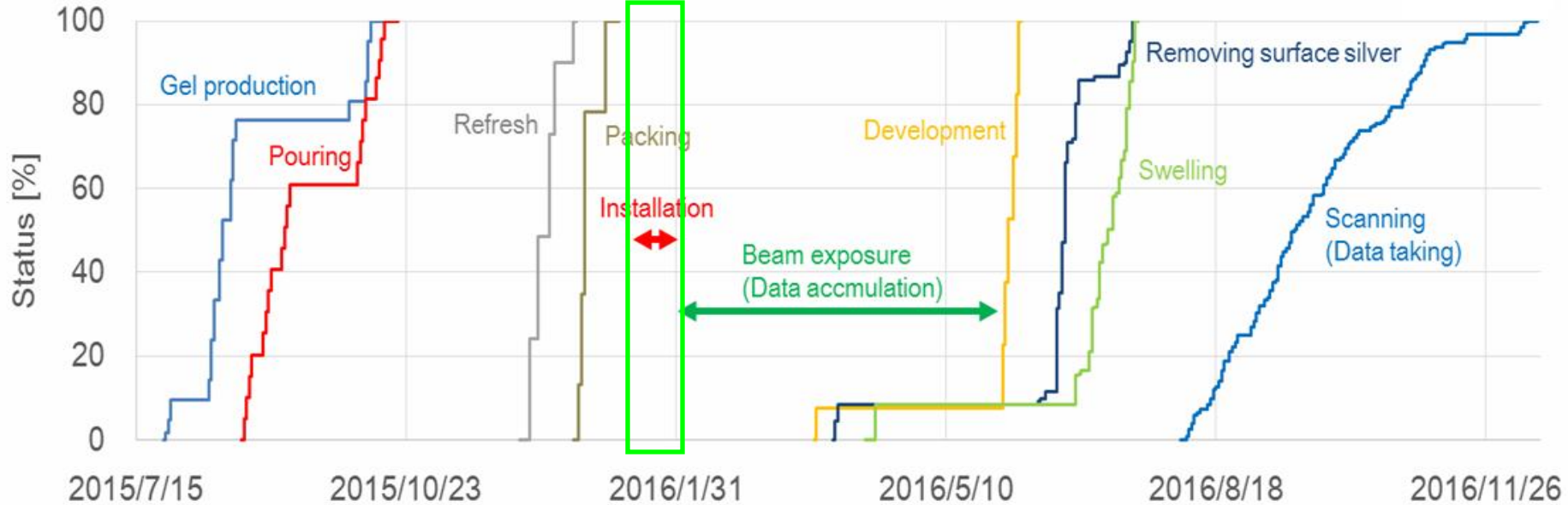
Emulsion film production 2015. July→Oct.
By Toho Univ. & Nihon Univ. member @Nagoya Univ.



Large size Emulsion Shifter
Operation test @Kobe Univ.

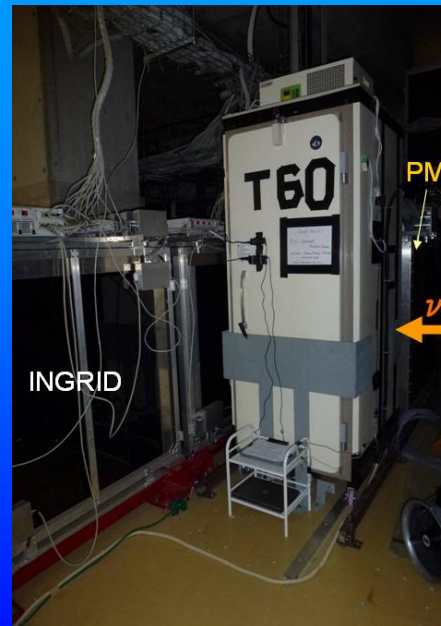
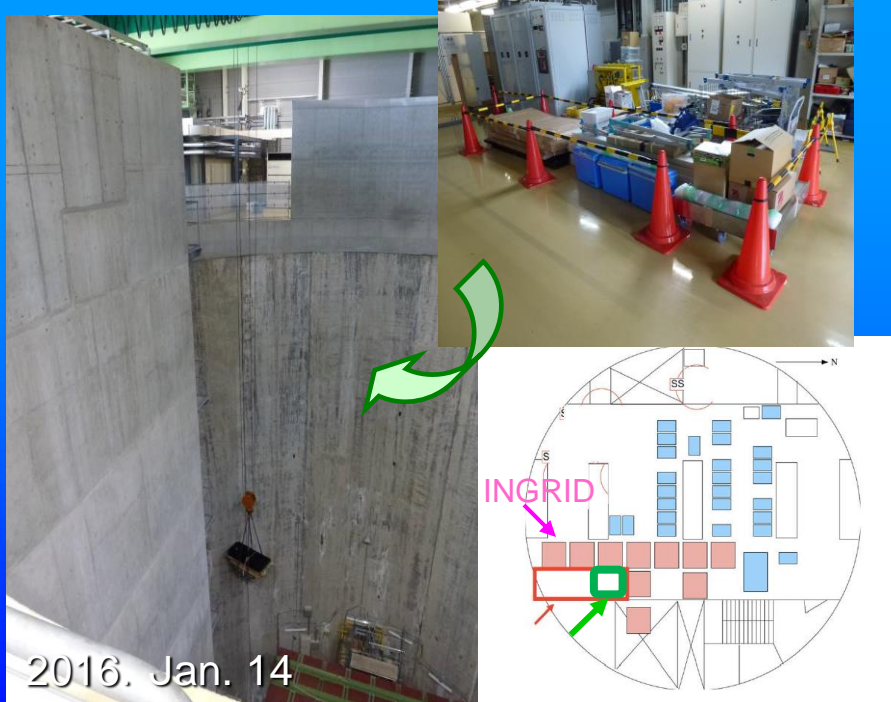


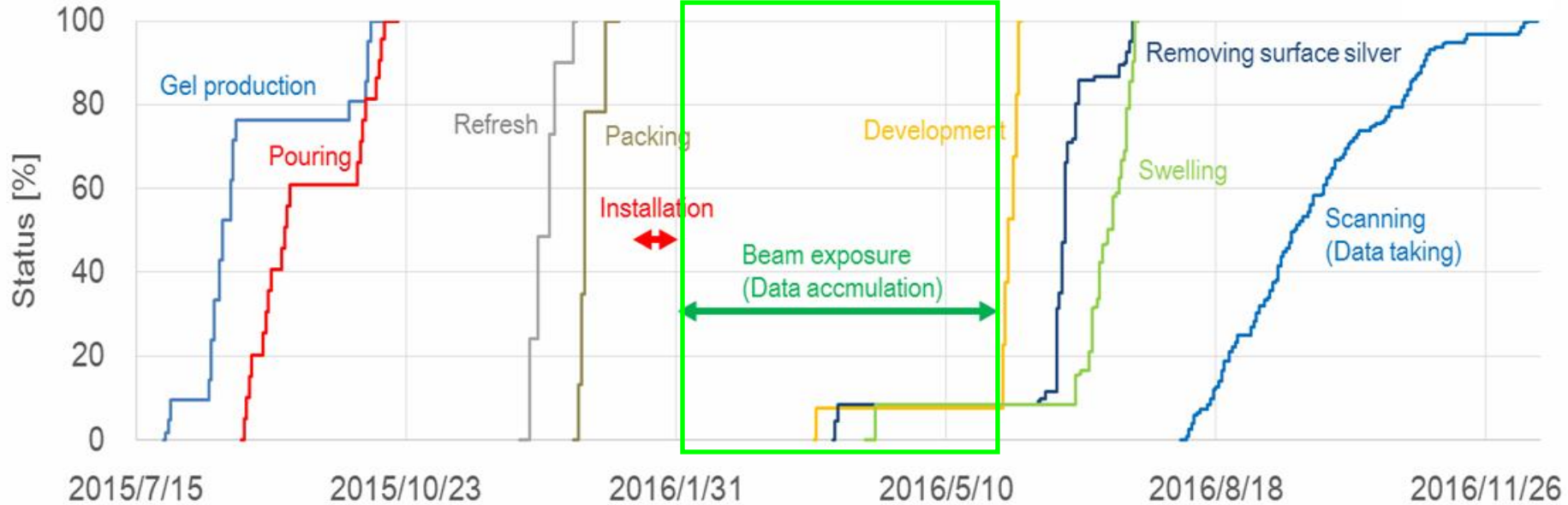
Repeatability for driving in each stage is well below 0.5 μ m.



← Detector construction → ← ν beam exposure → ← Hardware treatment and Scan →

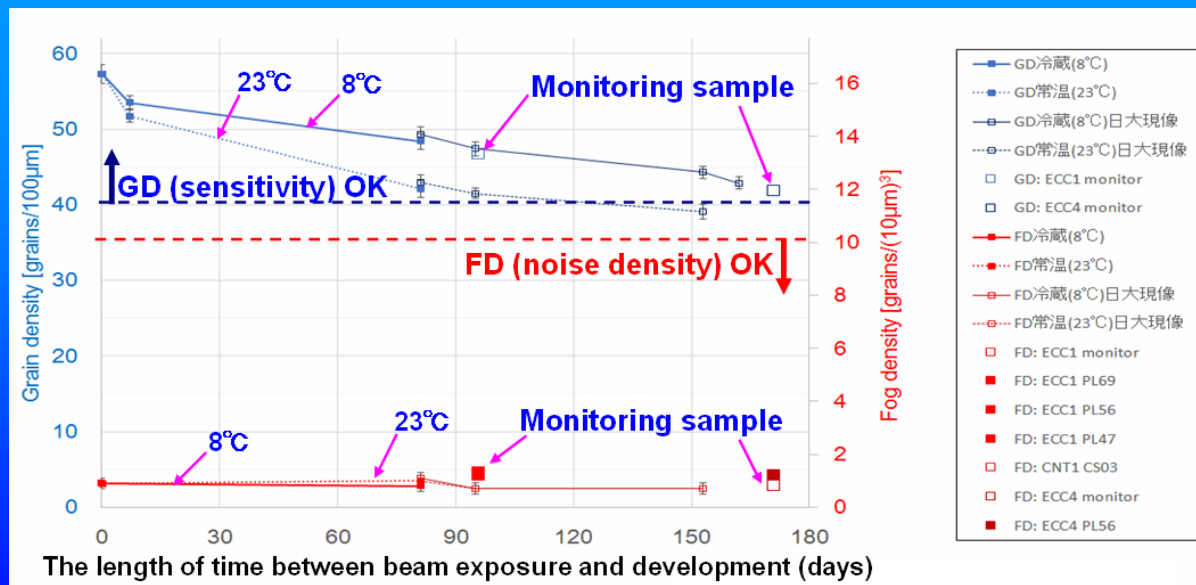
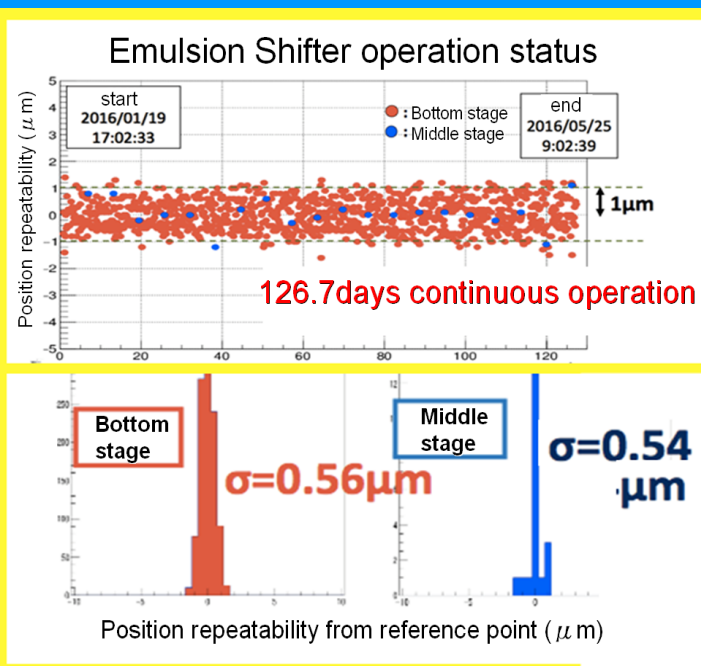
Detector installation

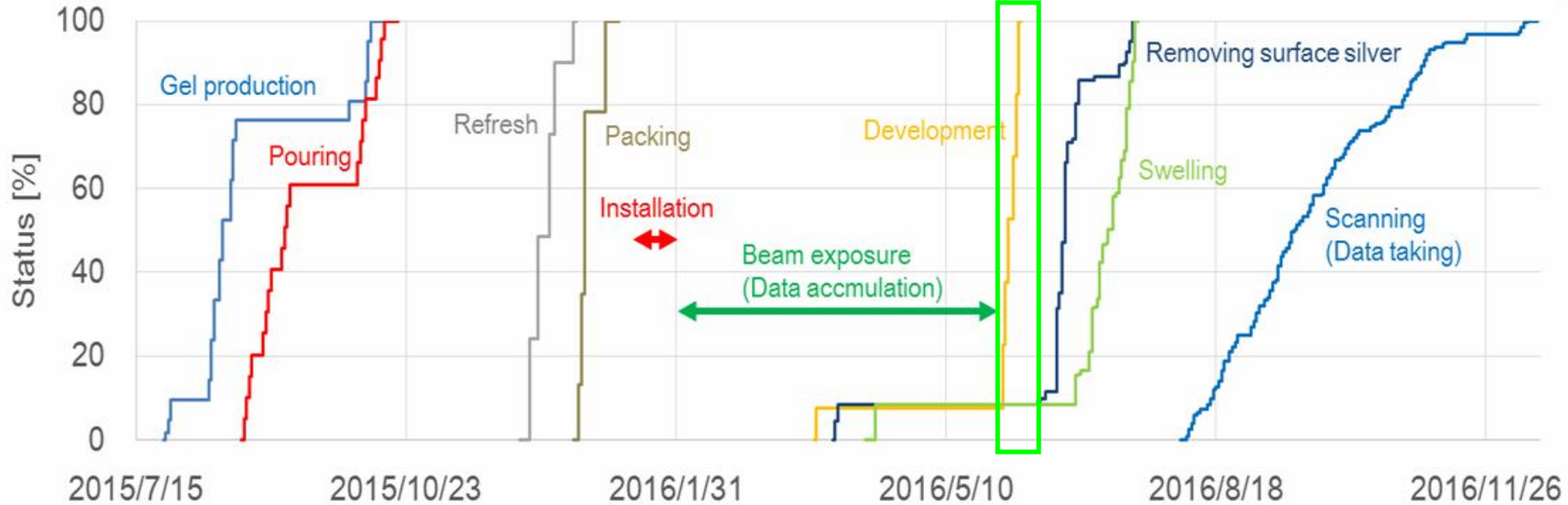




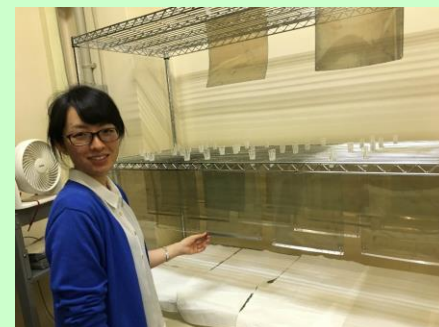
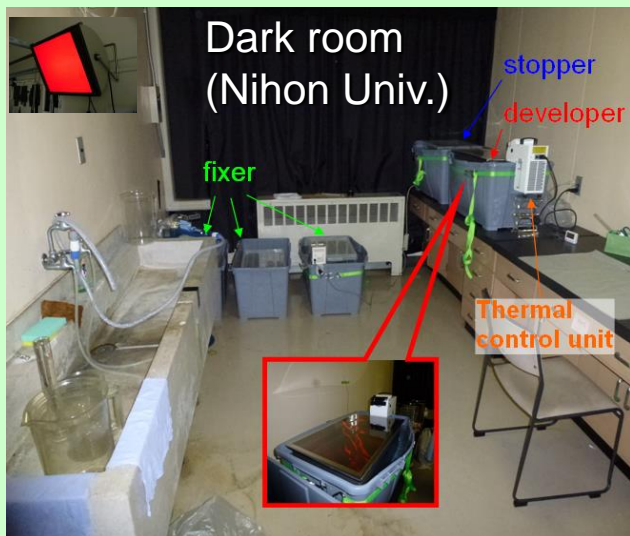
← **Detector construction** ← **$\bar{\nu}$ beam exposure** ← **Hardware treatment and Scanning**

Condition of the emulsion film

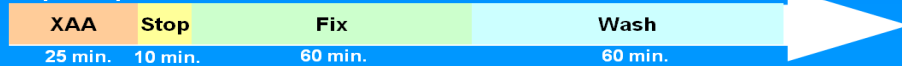


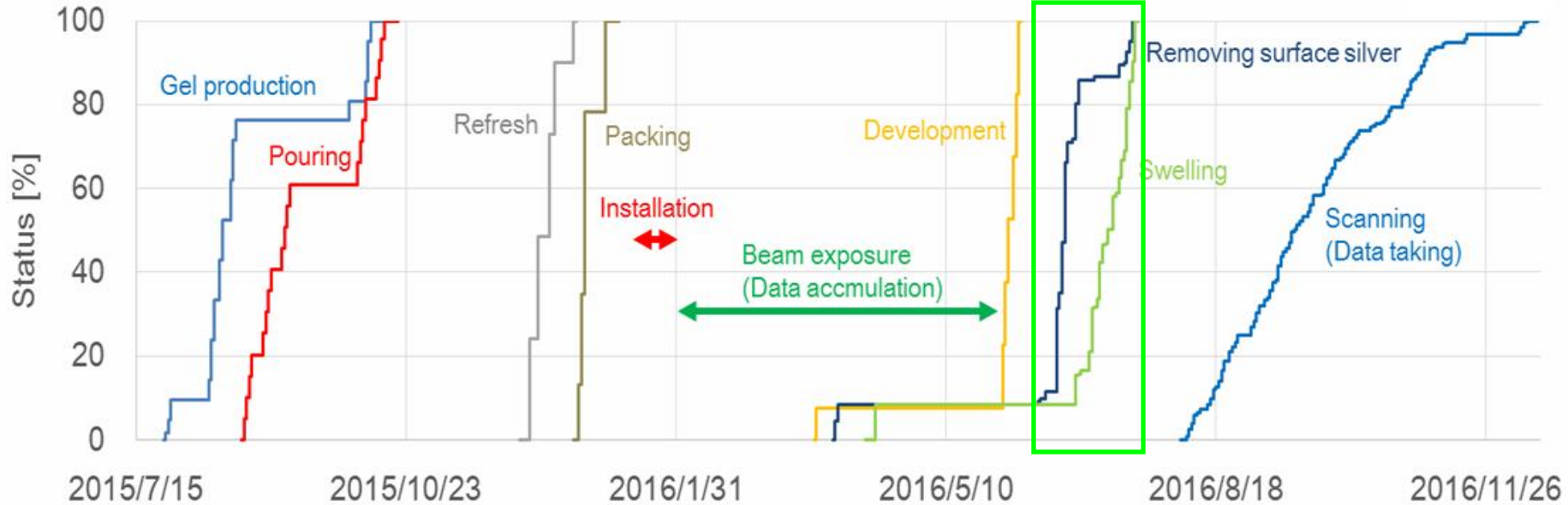


← **Detector construction** ← **ν beam exposure** ← **Hardware treatment and Scan**



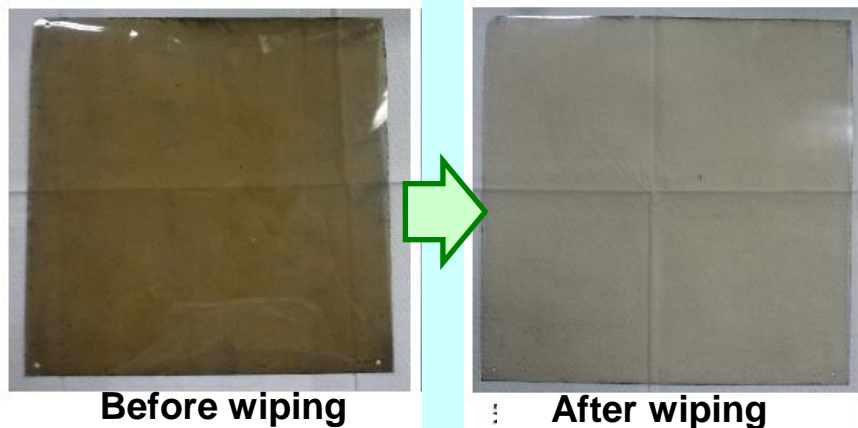
Development process





←→ **Detector construction**
 ←→ **$\bar{\nu}$ beam exposure**
 ←→ **Hardware treatment and Scan**

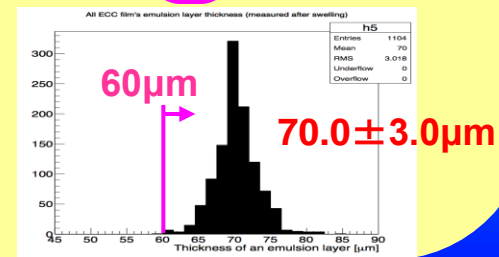
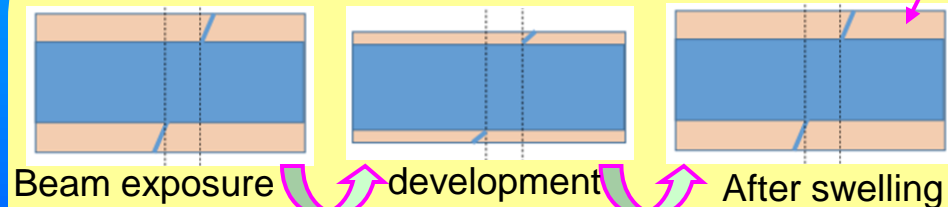
2. Surface silver cleaning

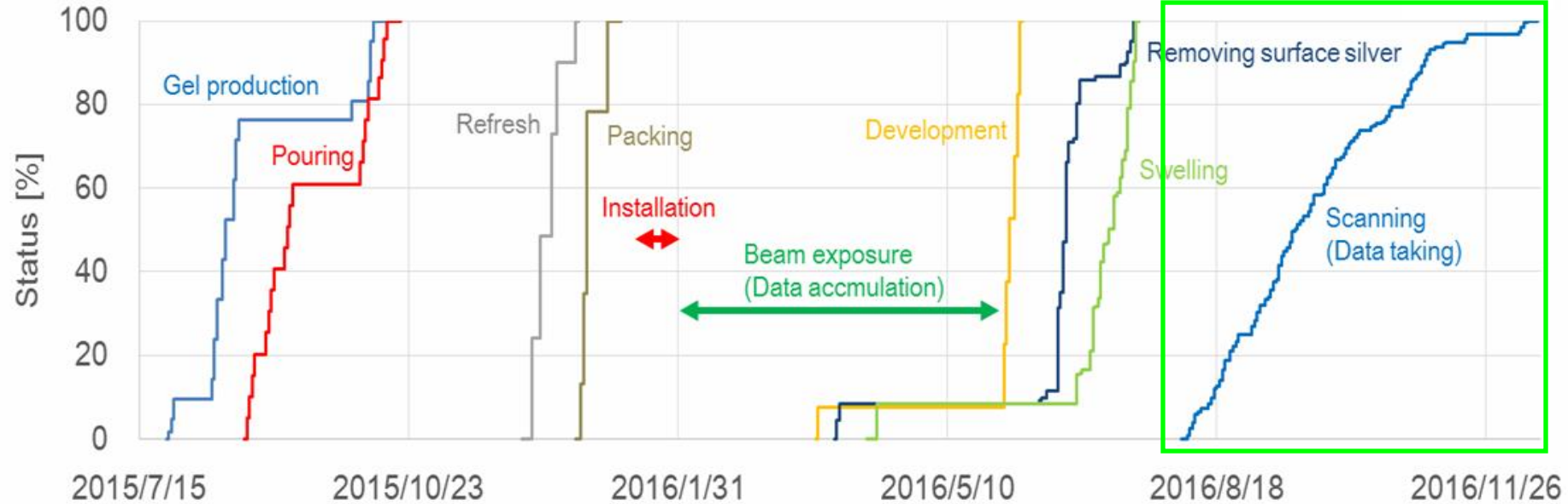


More than 300 films were completed.

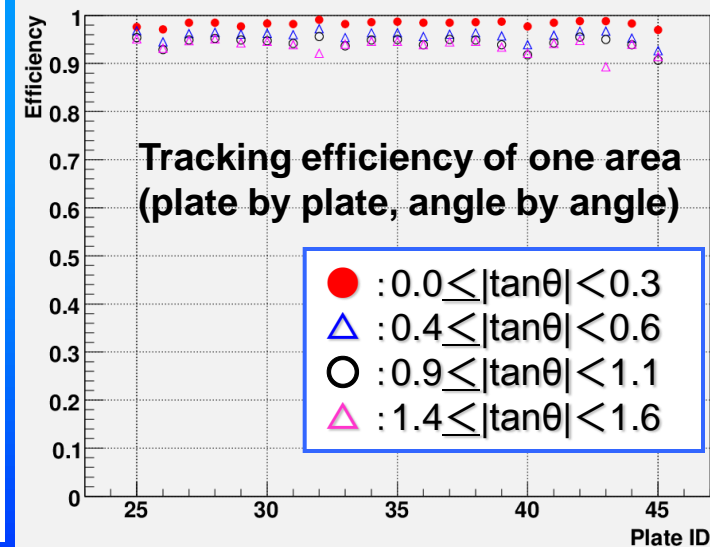
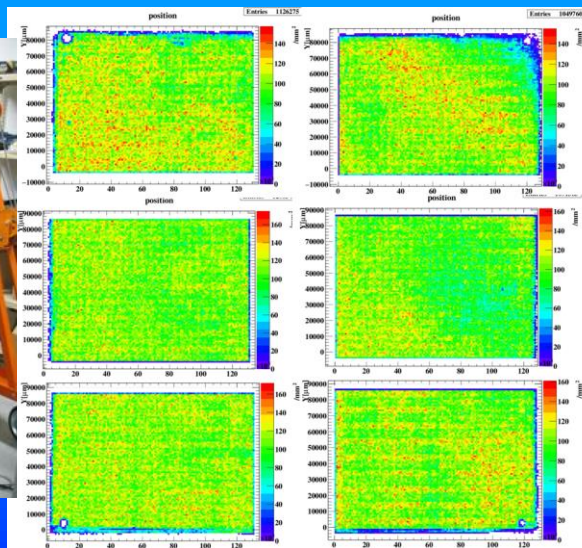
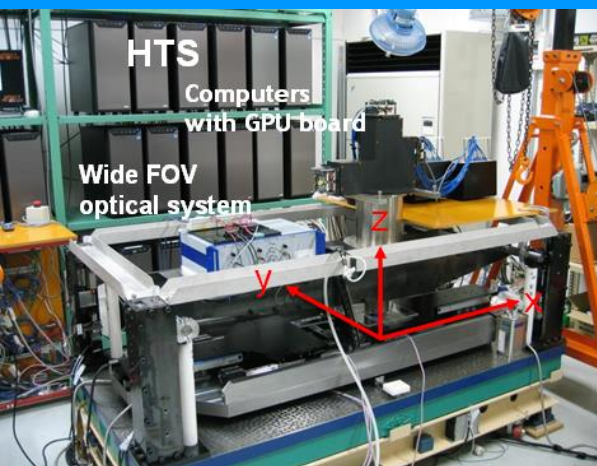
Emulsion swelling

Recovering of emulsion thickness emulsion





← Detector construction → ← ν beam exposure → ← Hardware treatment and Scan →



Data quality check and track reconstruction is under progress.

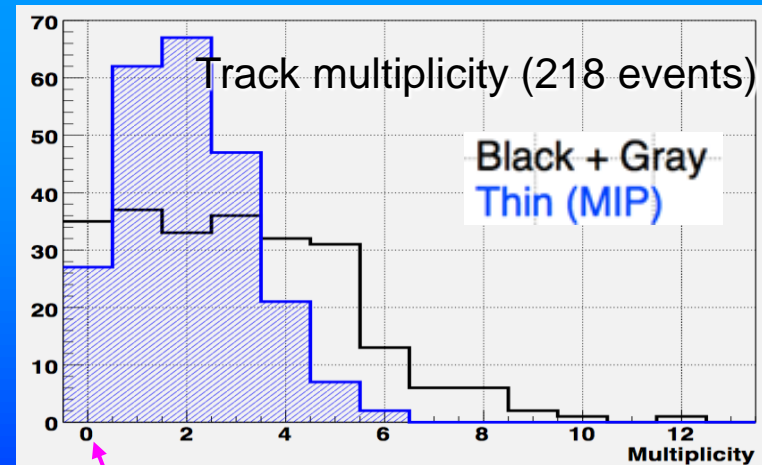
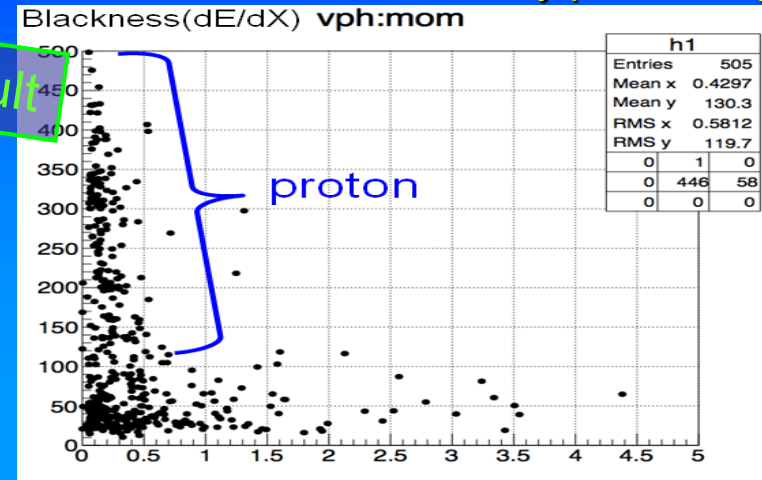
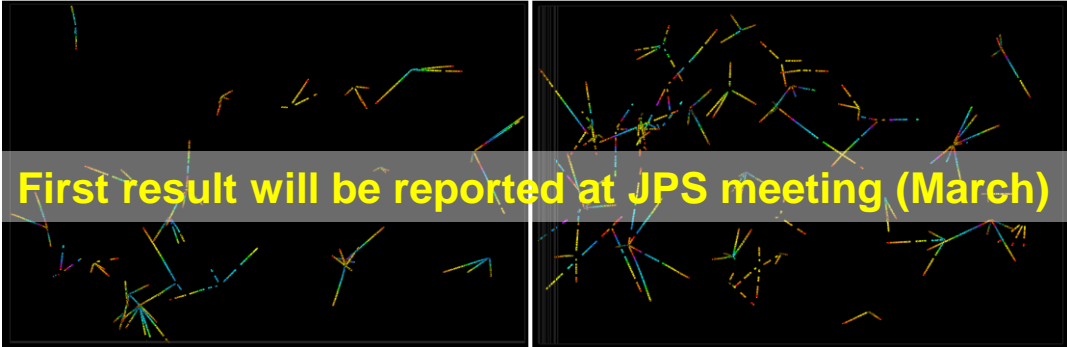
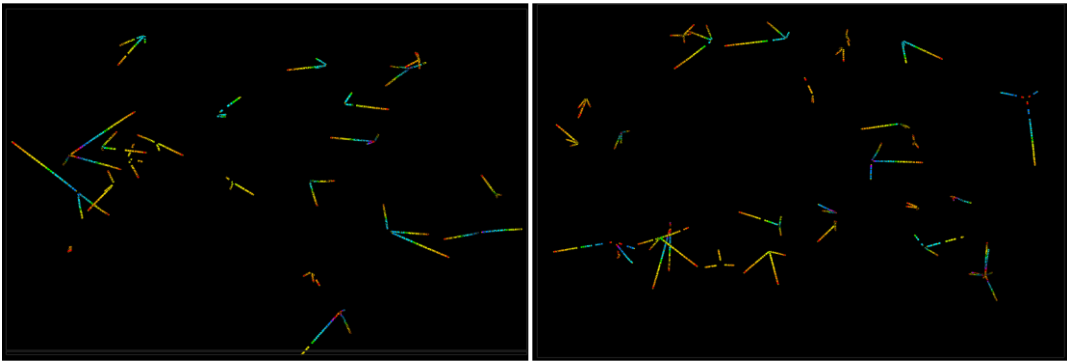
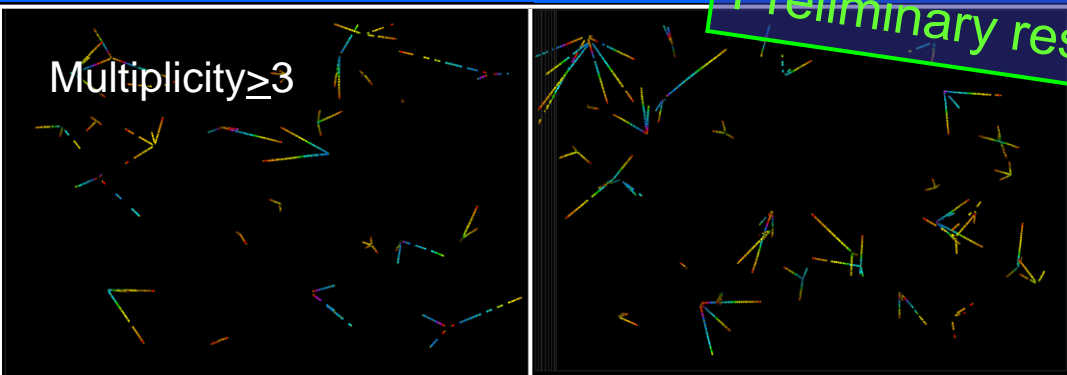
Status review of NINJA

Event analysis is now in progress !

Neutrino event candidates

Very preliminary

Preliminary result



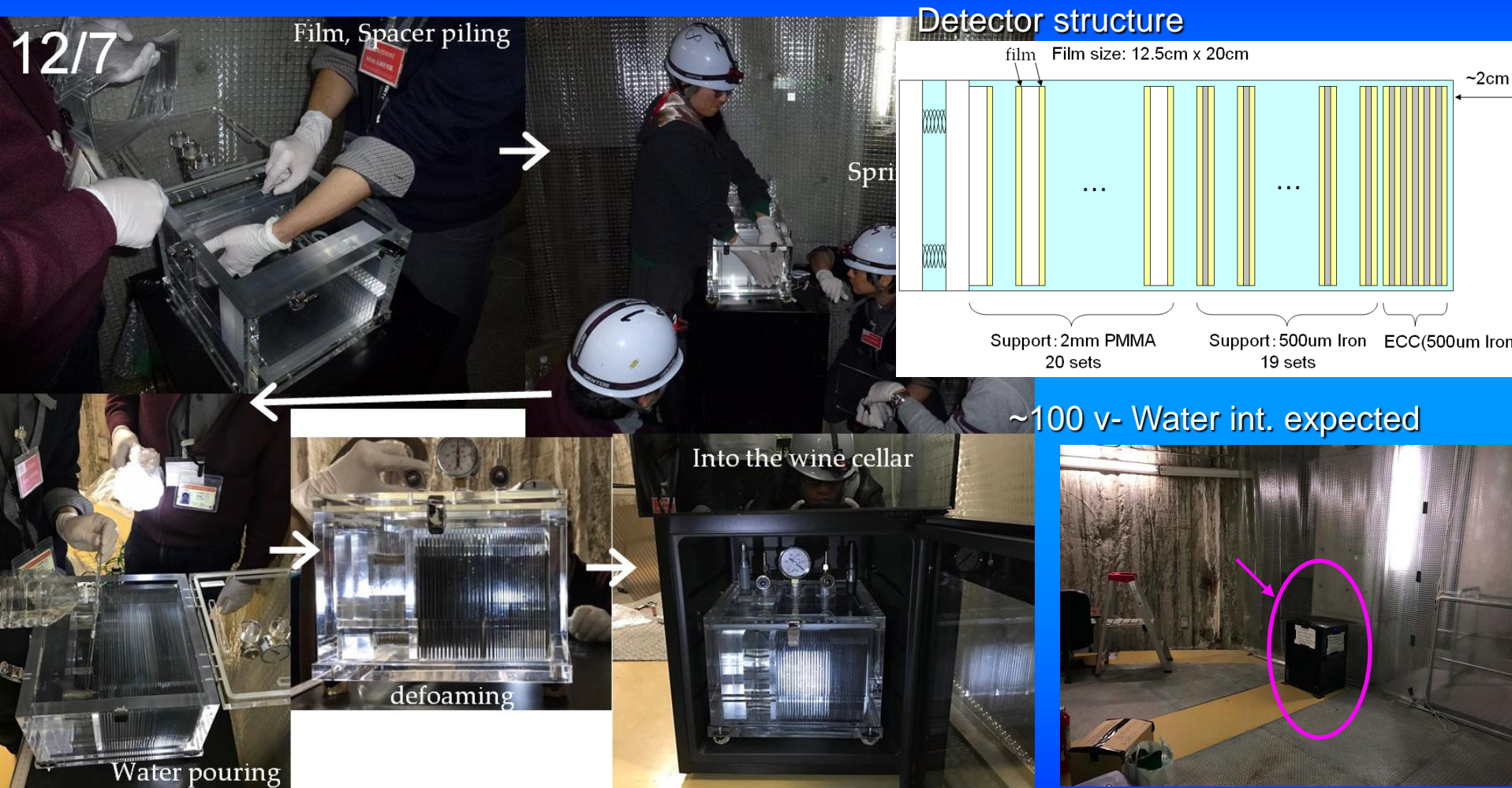
- ~80% of event have proton
- 0 MIP events are detected.
→ neutron interaction ?

Examples of neutrino event one by one

Detector Run(T66)

v beam exposure: Dec. 2016- Apr.2017

- R&D for Water target Emulsion detector



大型水標的検出器によるニュートリノ-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

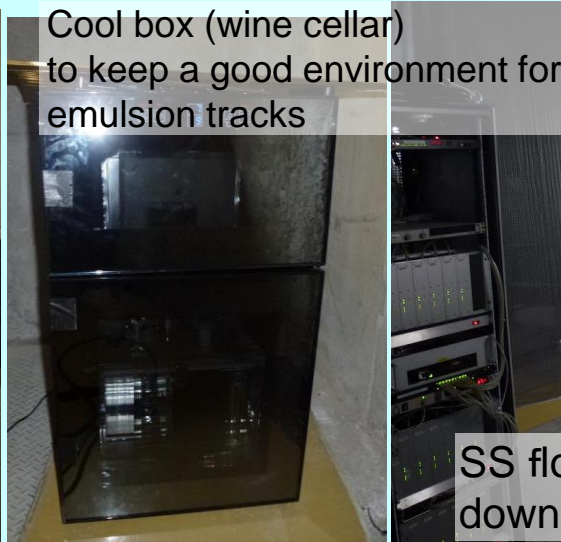
- We are performing a neutrino experiments at J-PARC to study low energy neutrino - nucleus interactions with nuclear emulsion (**NINJA** !).
- We are carrying out a test experiment at J-PARC to check the feasibility and detector performance.
- Beam exposure and film development for the 60kg iron target 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

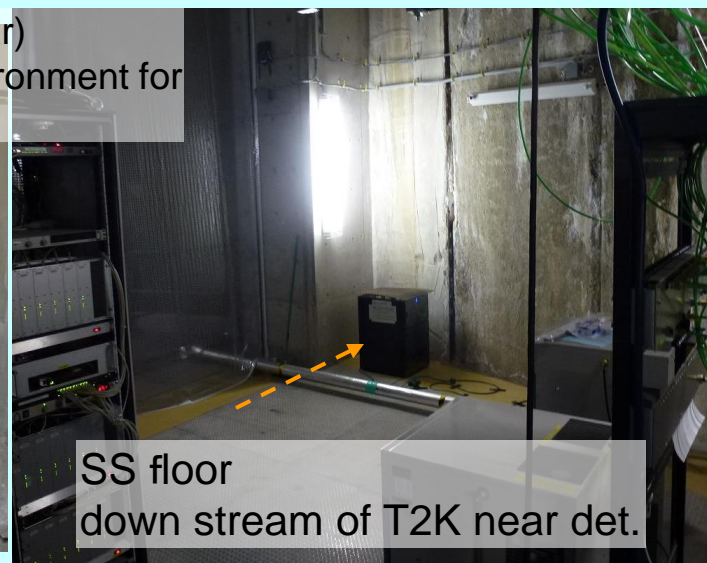
Water target emulsion chamber



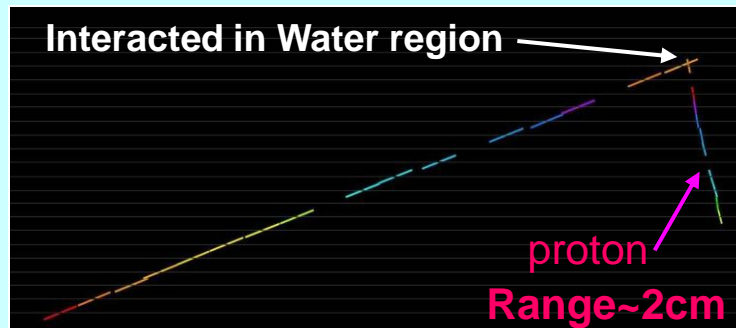
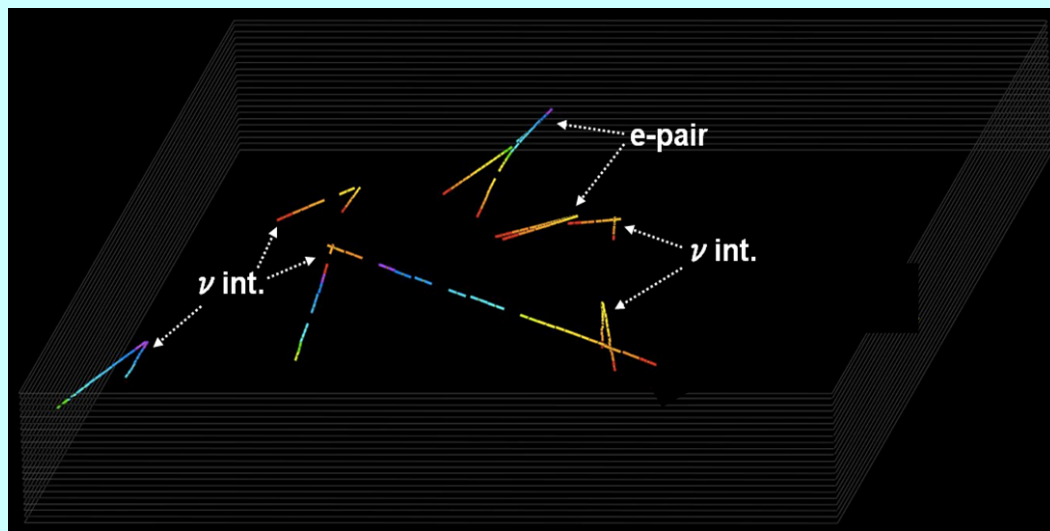
Removal of air bubbles



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



SS floor down stream of T2K near det.



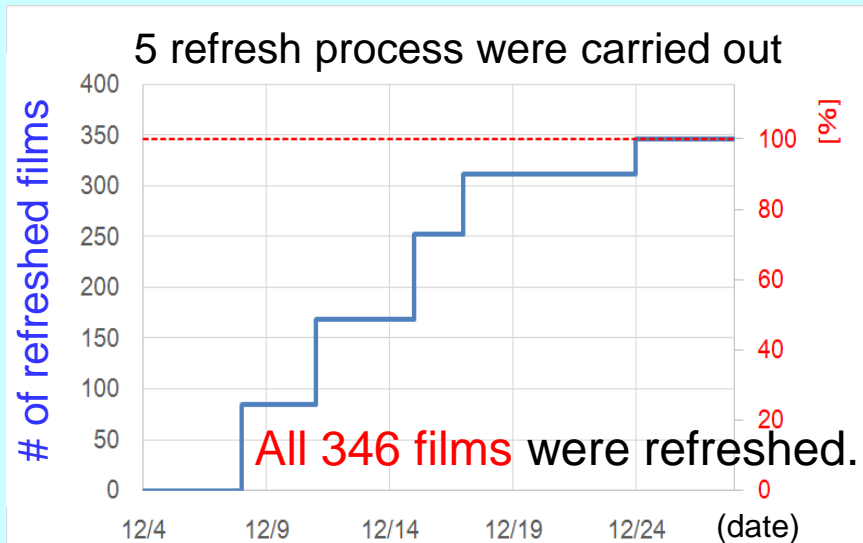
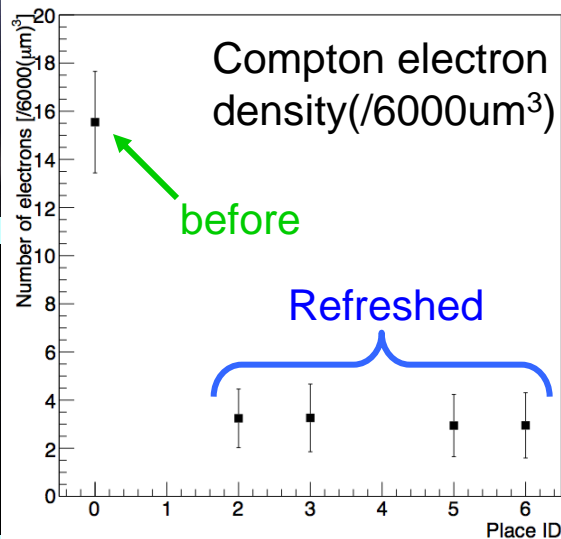
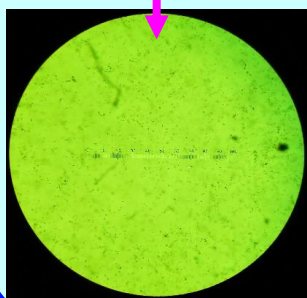
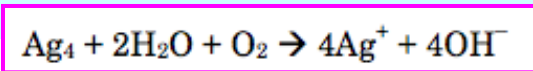
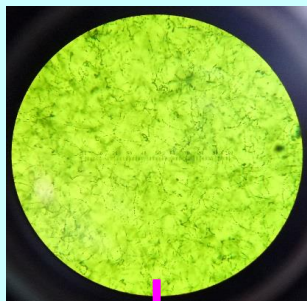
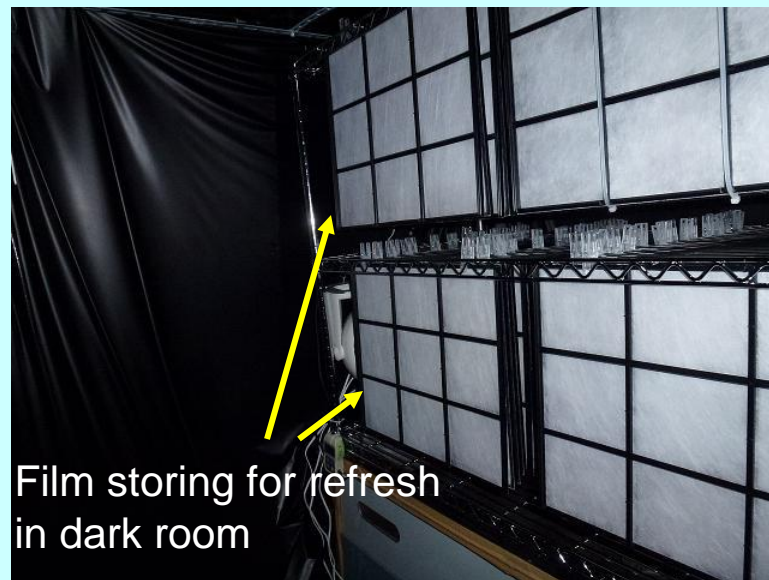
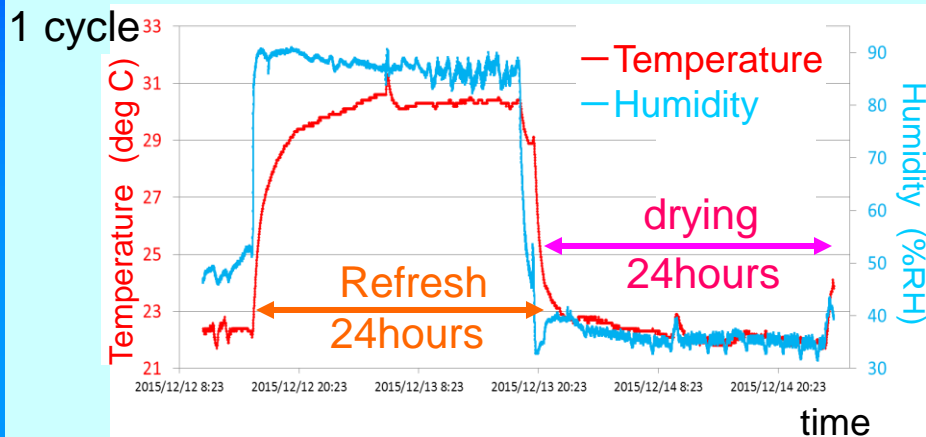
①	$(\tan\theta_x, \tan\theta_y) = (-0.040, 0.845)$	M.I.P
②	$(\tan\theta_x, \tan\theta_y) = (-0.589, -0.074)$	proton
Minimum distance(① - ②)=2.4um, depth=620um		

First detection of ν - Water interaction with Emulsion Detector

Detector preparation

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

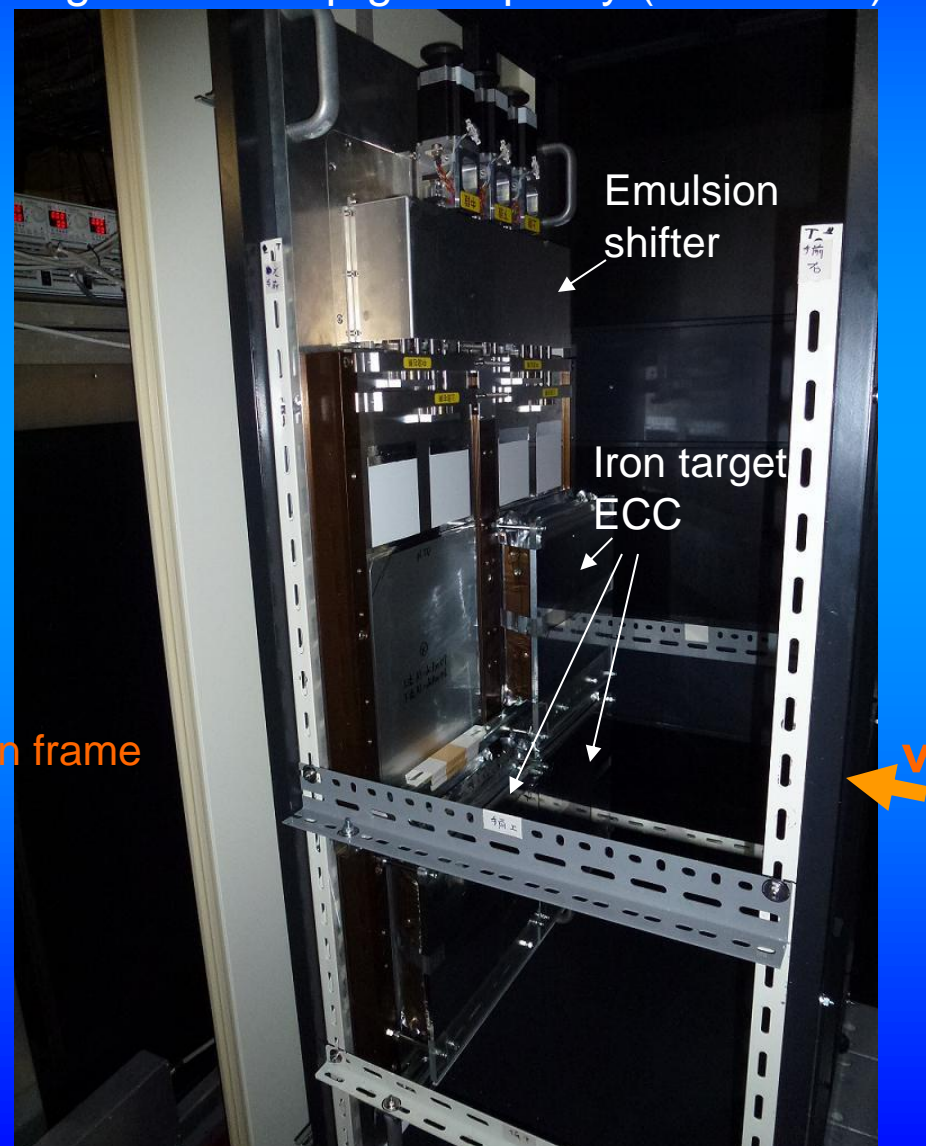
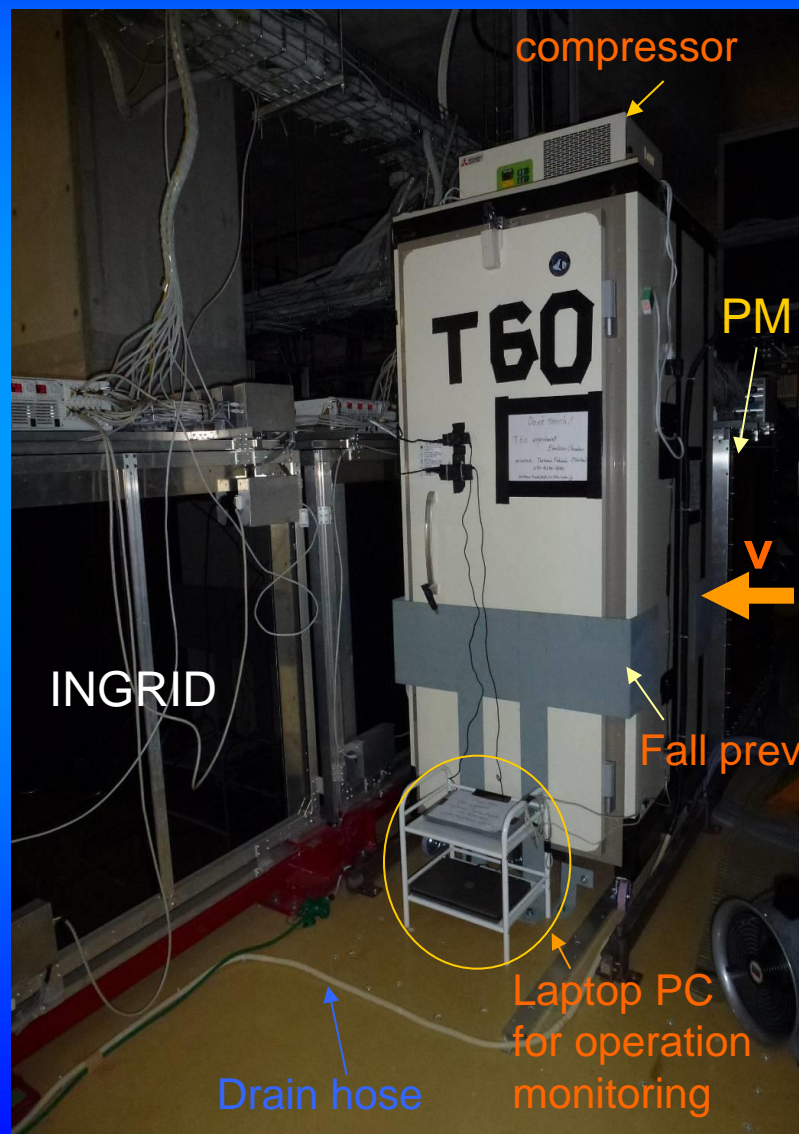
Emulsion film Refresh 2015. Dec @Toho Univ.



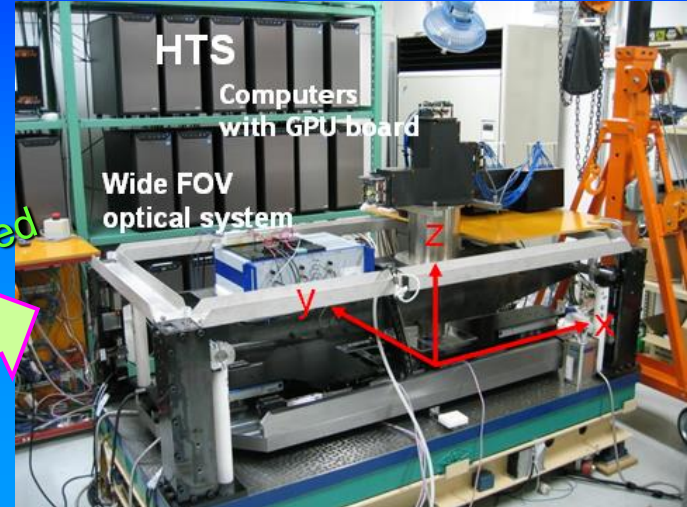
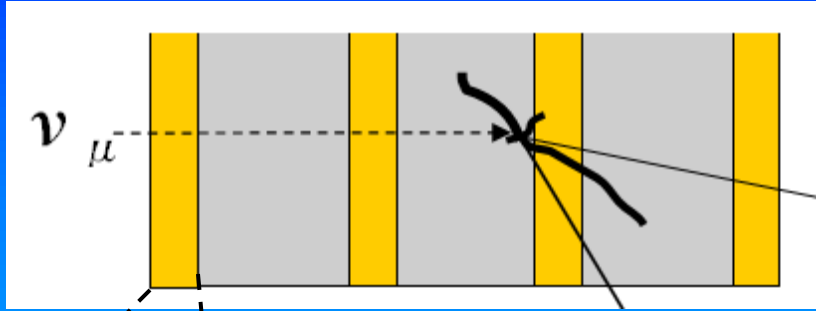
Installation @J-PARC (Jan. 11-20)

Detector was constructed @SS floor.

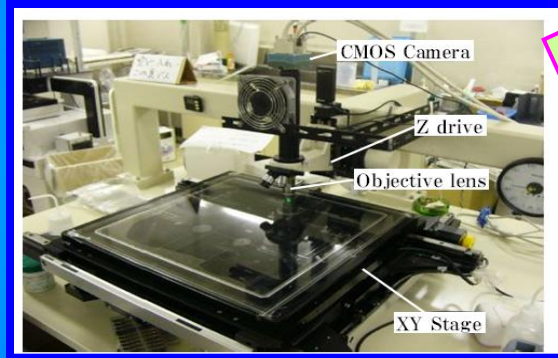
T60 emulsion detector is mounted in cooling box to keep good quality (no refresh).



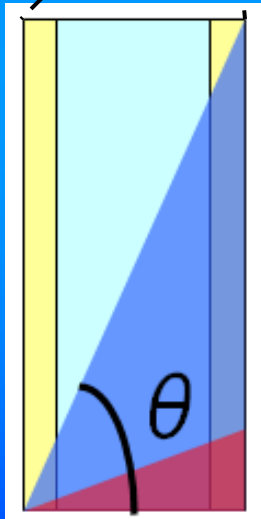
Large angle scanning on HTS



High speed

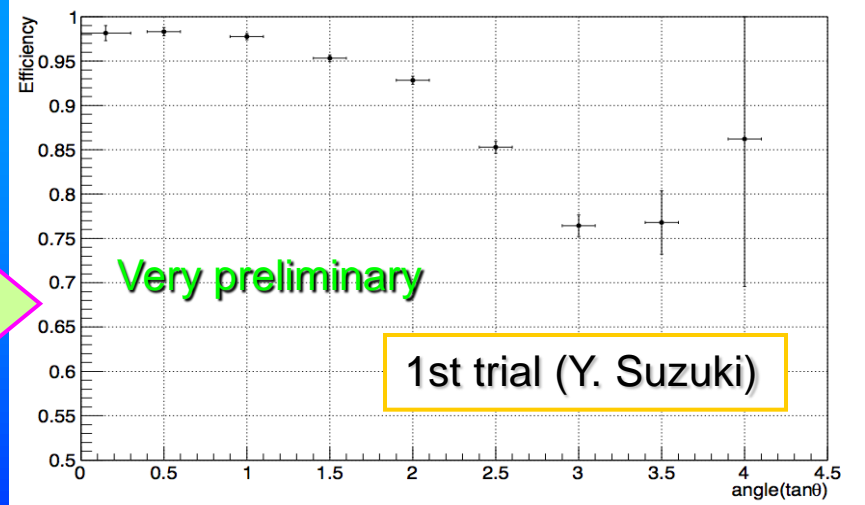
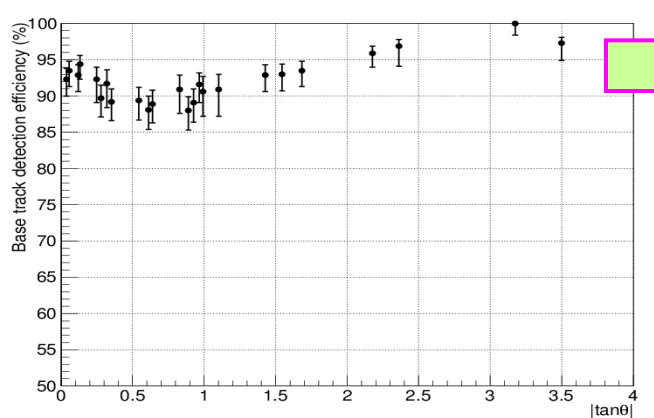


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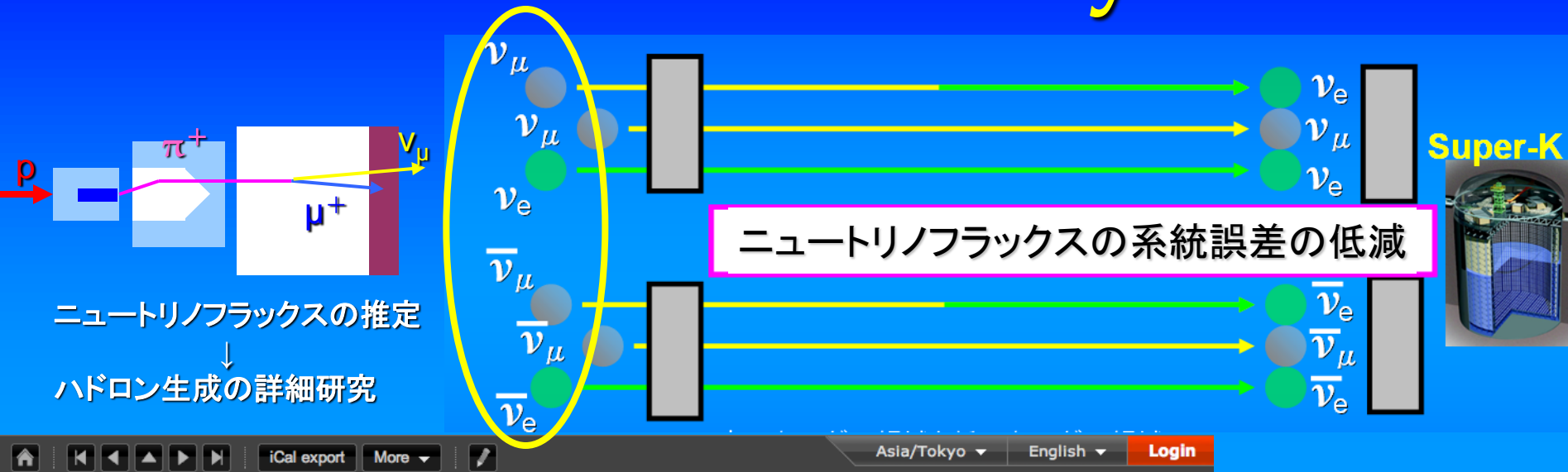
X
Z

$$\frac{X}{Z} = |\tan \theta|$$



We will optimize HTS for LA Scanning

Related activity



Workshop on Hadron Production Measurements with Nuclear Emulsions

3-4 October 2016
Nagoya University
Asia/Tokyo timezone

- Overview
- Scientific Programme
- Timetable
- Contribution List
- Author List
- Registration
- Registration Form
- Accommodation Information

