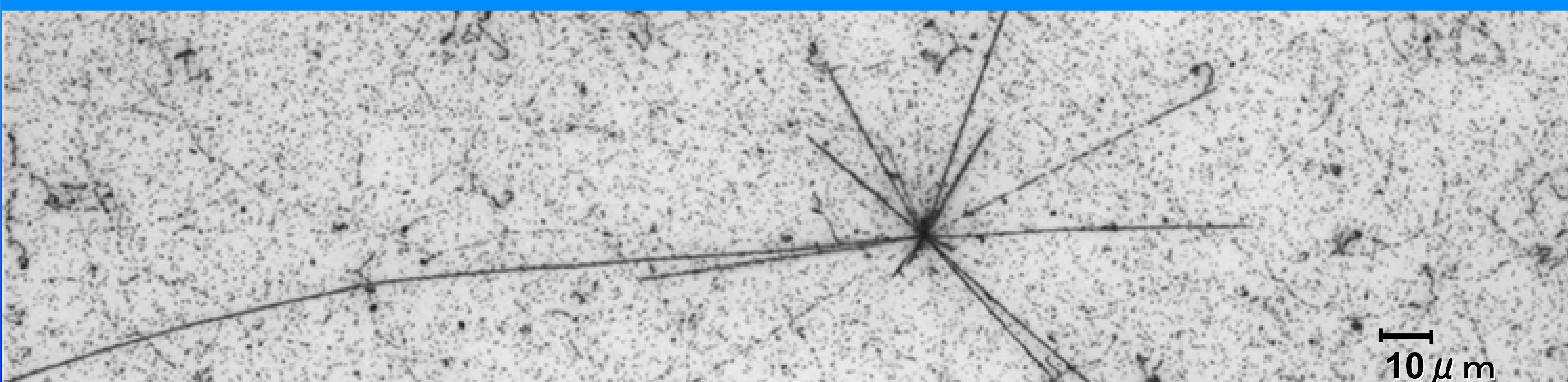
NINJA

# NINJA実験の現況と展望

福田　努（名古屋大学 高等研究院）



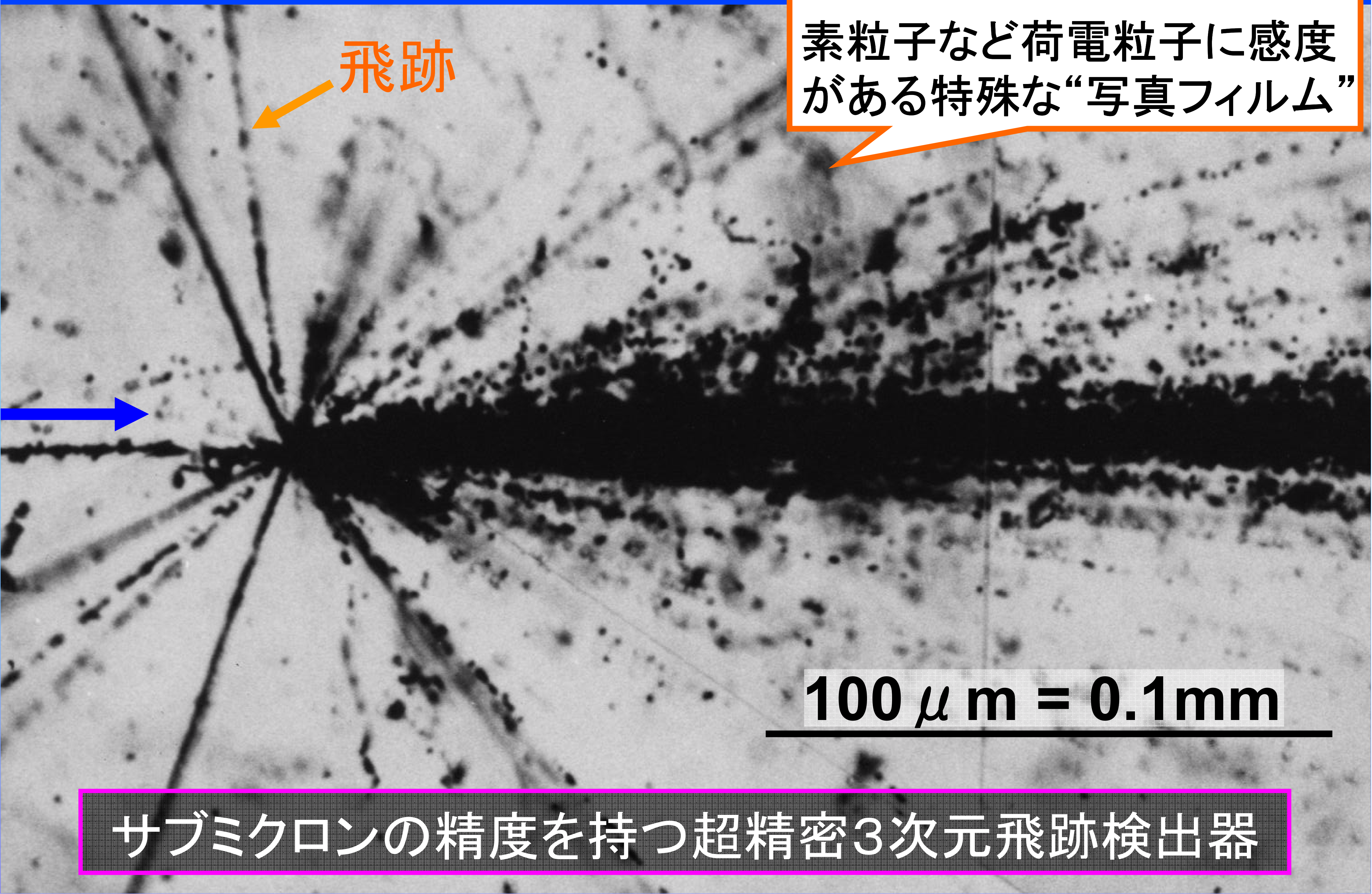

tfukuda@flab.phys.nagoya-u.ac.jp

- Nuclear Emulsion（原子核乾板） 5分
- NINJA Experiment 5分
- Experimental activities with Nuclear Emulsion 5分

# Nuclear Emulsion

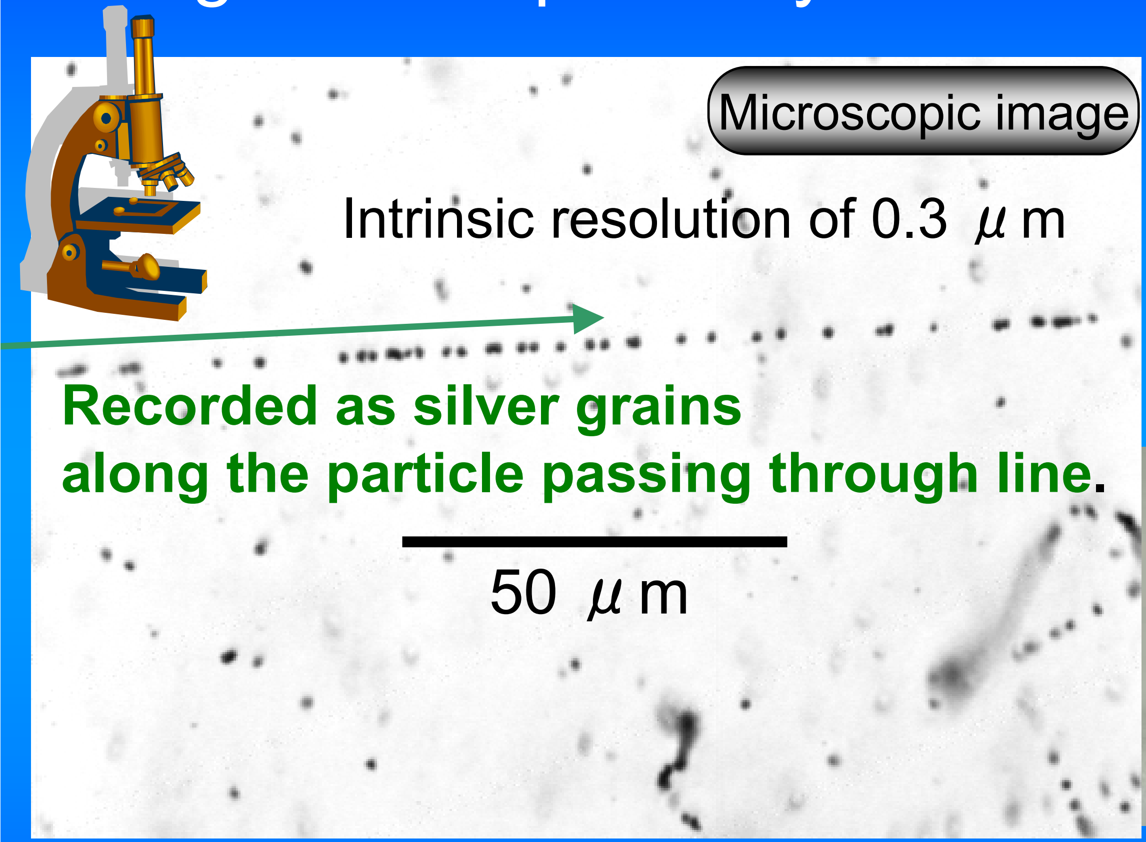

提供：HiggsTan, http://higgstan.com/4koma-emulsion/

# What is Nuclear Emulsion ?

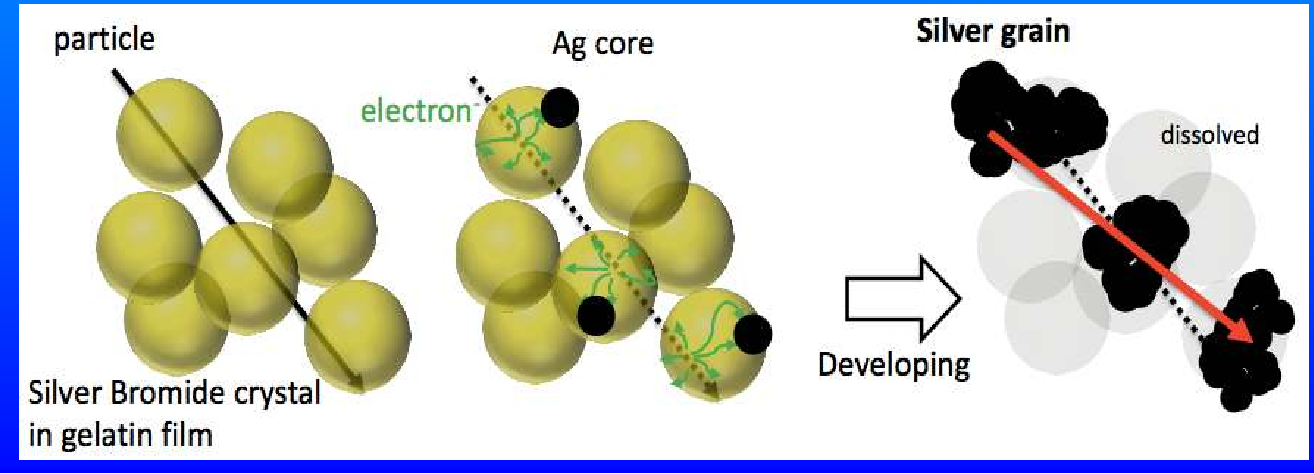


# Photographic Film technology

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



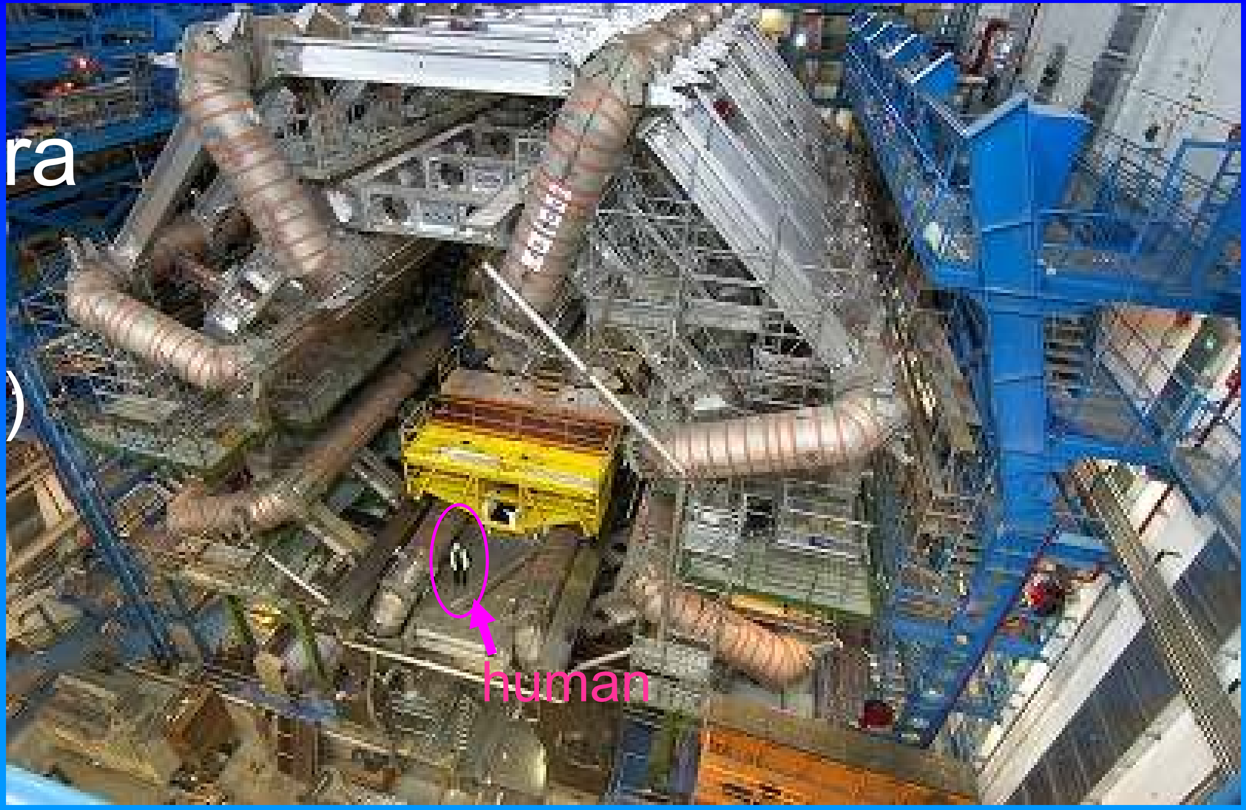



| | Merit |
|---|---|
| Film camera | **High resolution** |
| Digital camera | Real time |

## Largest Digital Camera

ATLAS detector

(~1.6 x $10^8$ image sensors)



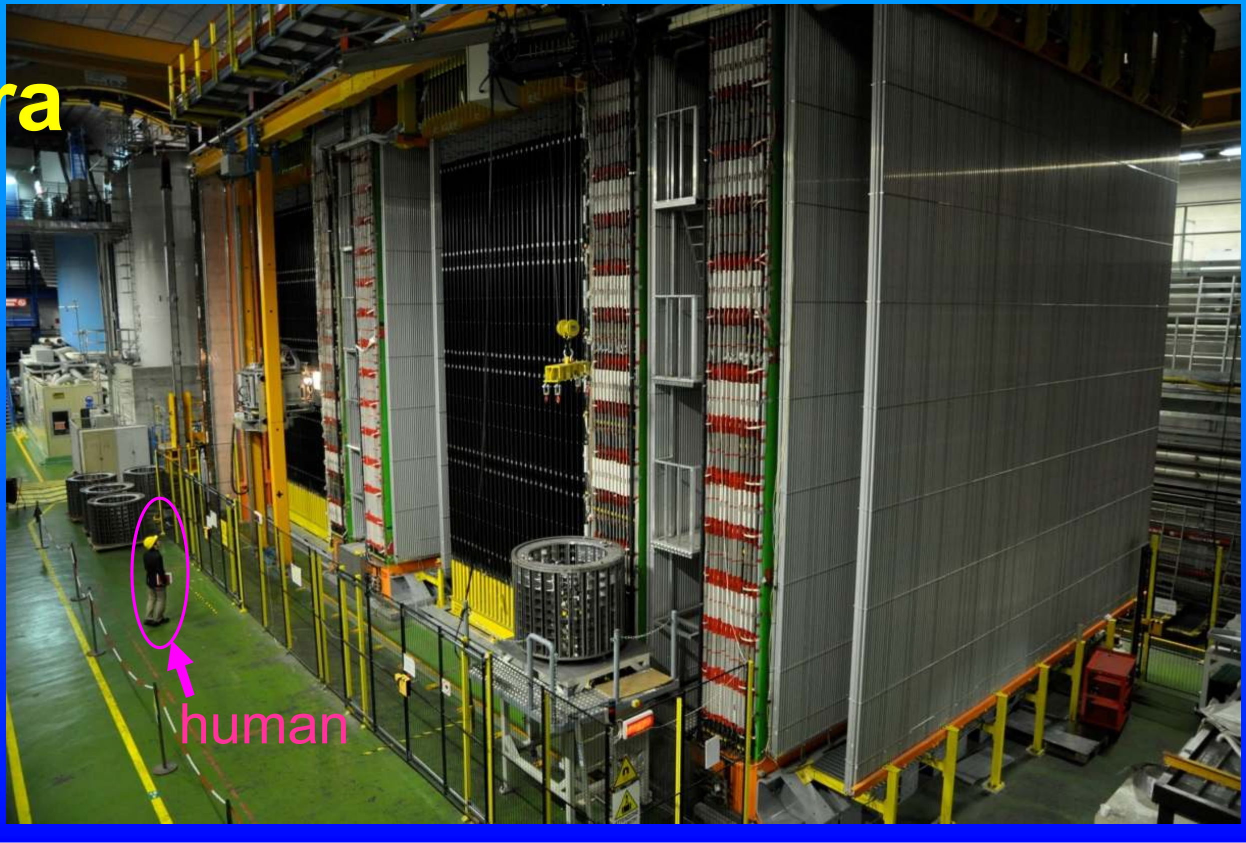

## **Largest Film Camera**

OPERA detector

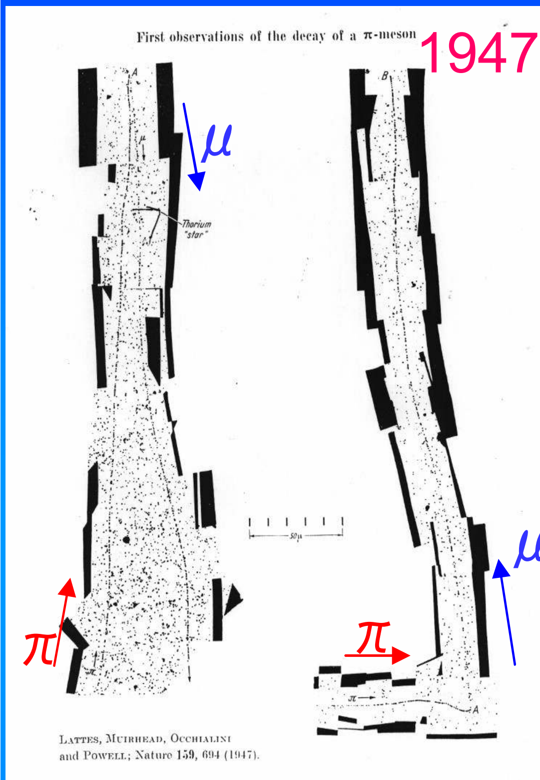
(~$10^{20}$ AgBr crystals)

↑

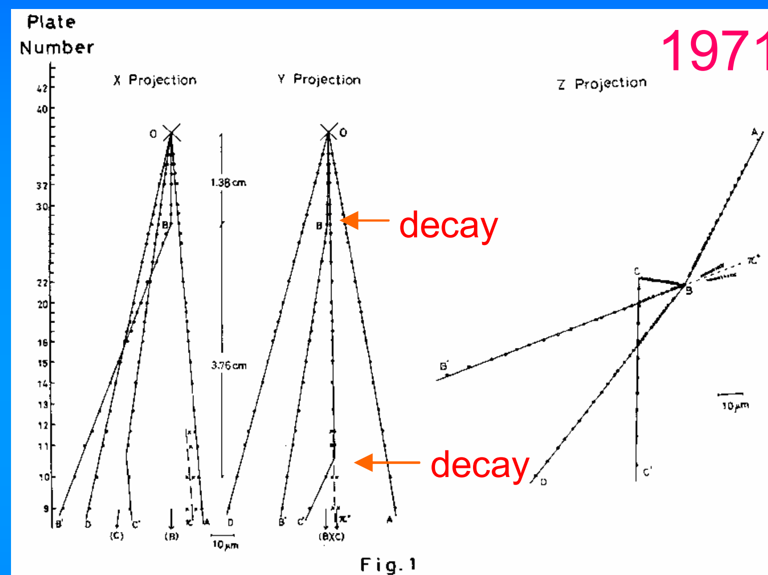
9000,000 emulsion films



# Contribution for fundamental physics…







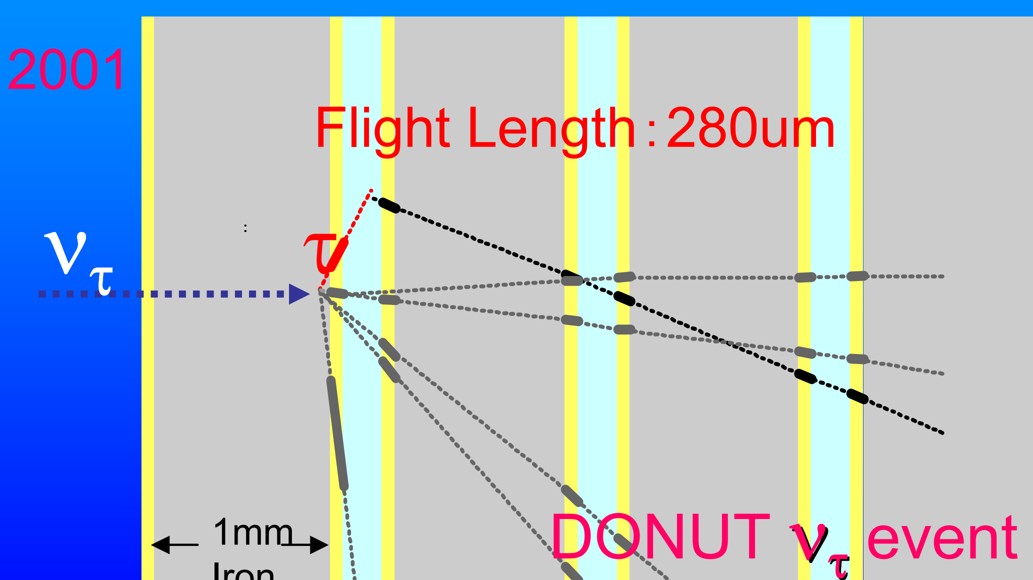

1896 (A. H. Becquerel )
Discovery of Radioactivity

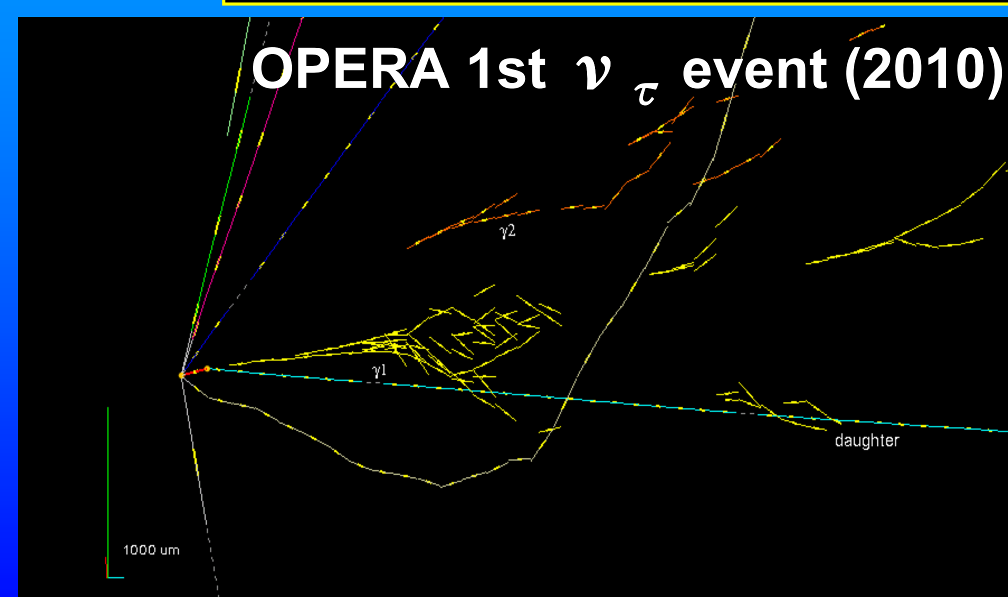
1947 (C. F. Powell et al.)
Discovery of $\pi$

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

2001 (K.Niwa et al.)
Direct observation of $\nu_\tau$

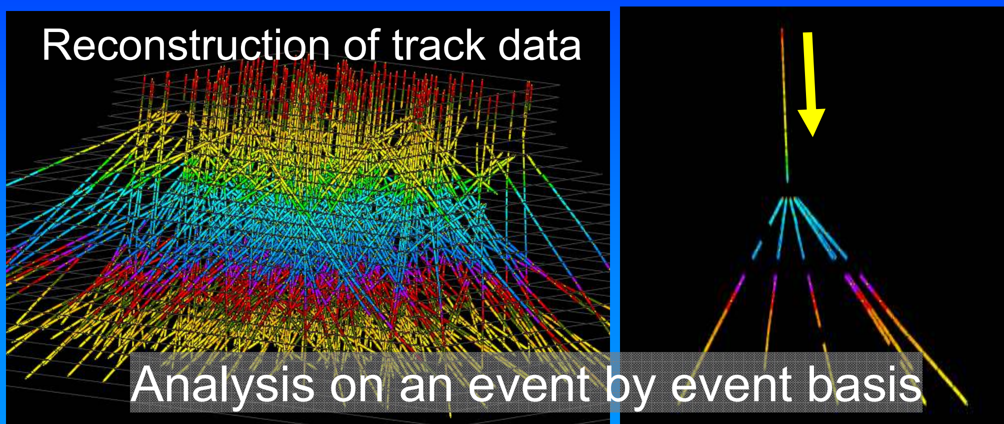
2015 (OPERA)
Direct observation of $\nu_\tau$ Appearance



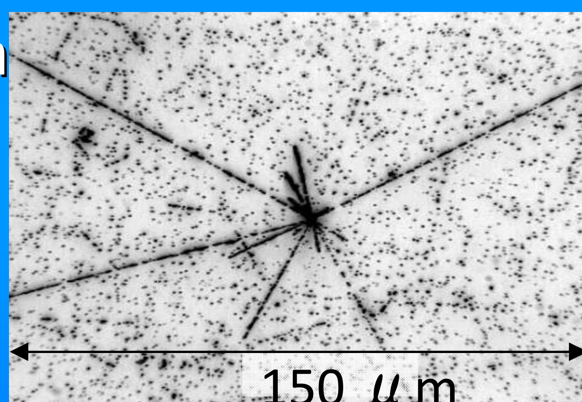
# Nuclear Emulsion Detector

## 3D reconstruction

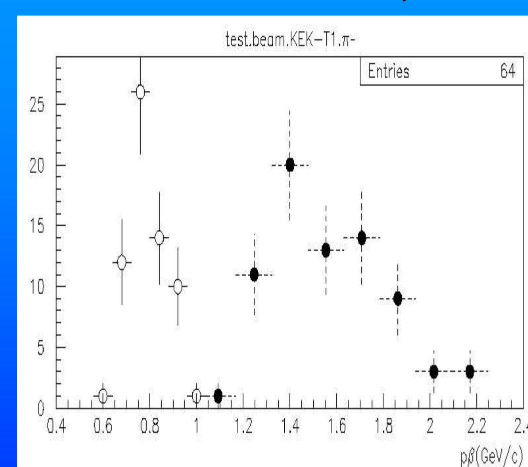



## Scalability


## 4$\pi$ detection

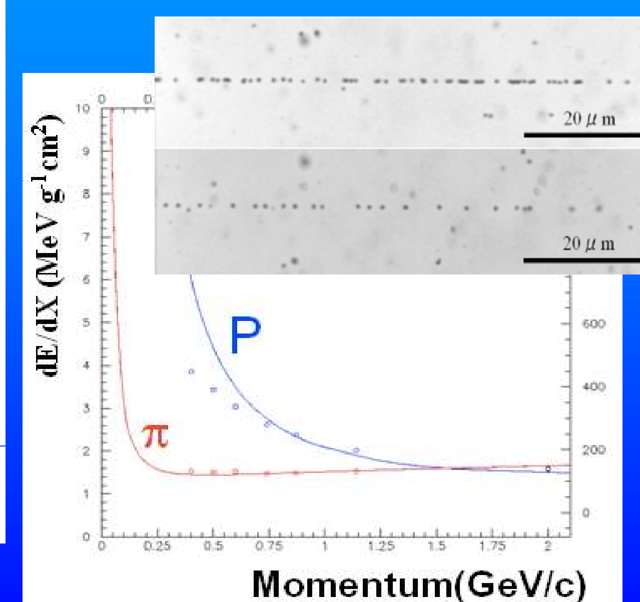



## Momentum, dE/dx measurement

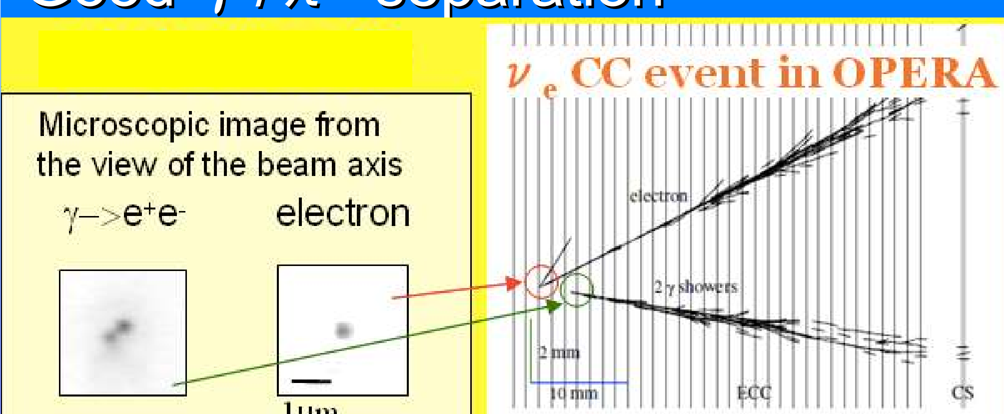



0.8GeV/c $\pi$ : P =0.79(GeV/c), dP/P =**11**%

1.5GeV/c $\pi$ : P =1.53(GeV/c), dP/P =**16**%

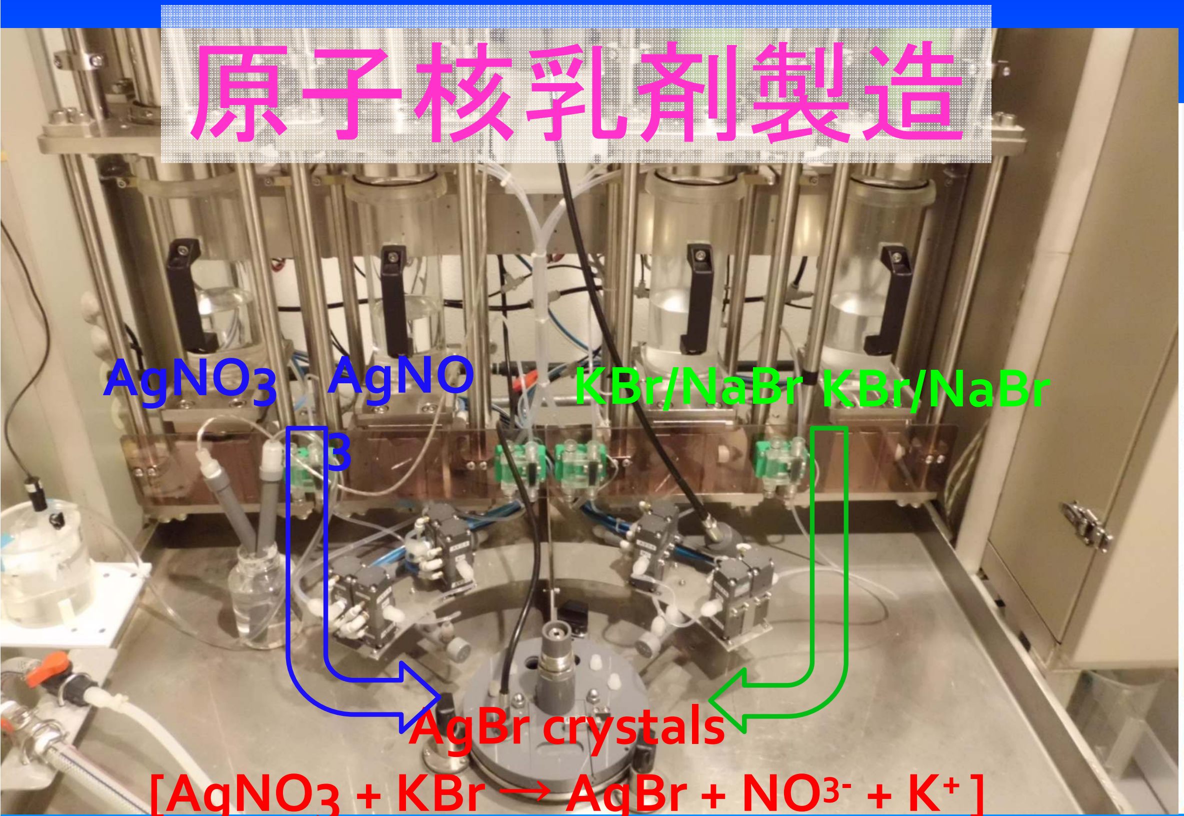


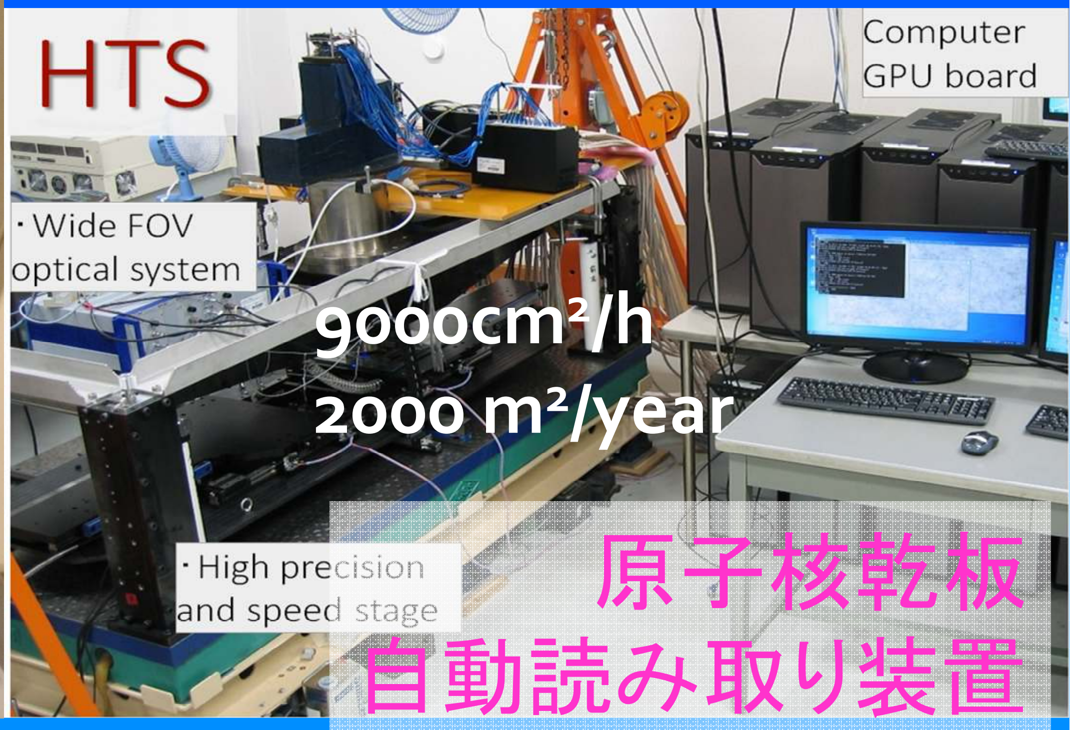

## Good $\gamma / \pi^0$ separation

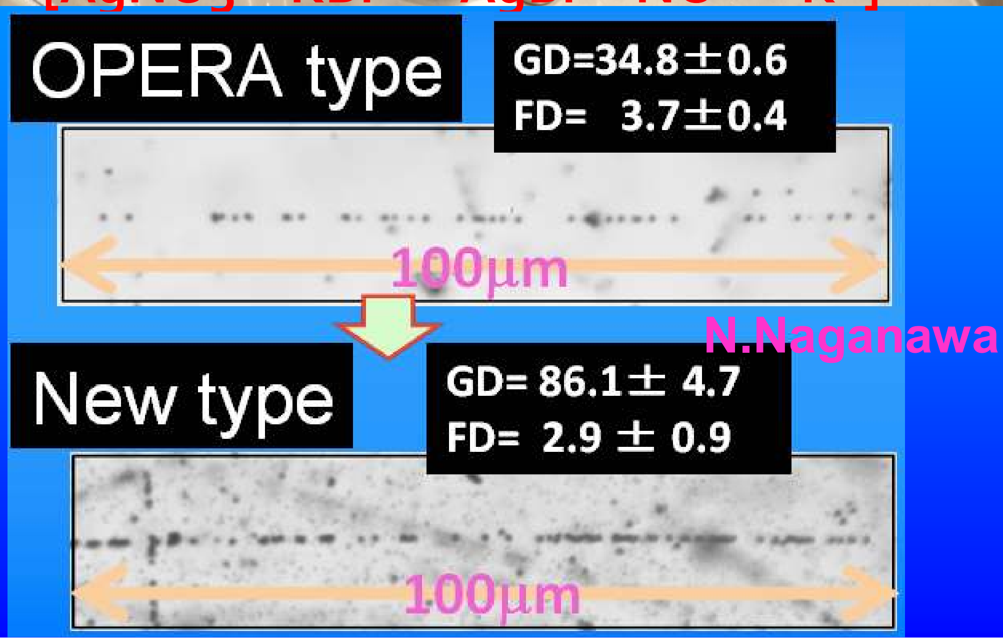


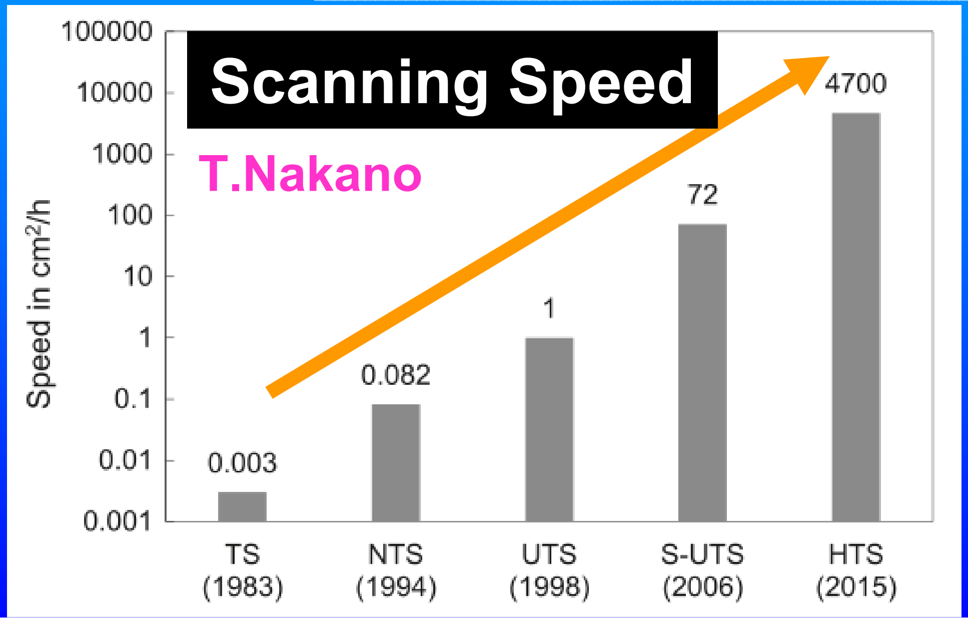

**Low BG from $\nu_\mu$ NC $\pi^0$ production**

# 素粒子実験・応用研究


原子核乳剤製造
AgNO3
AgNO3
KBr/NaBr
KBr/NaBr
AgBr crystals
[AgNO3 + KBr → AgBr + NO3- + K+ ]


HTS
Computer
GPU board
・Wide FOV
optical system
9000cm²/h
2000 m²/year
・High precision
and speed stage
原子核乾板
自動読み取り装置

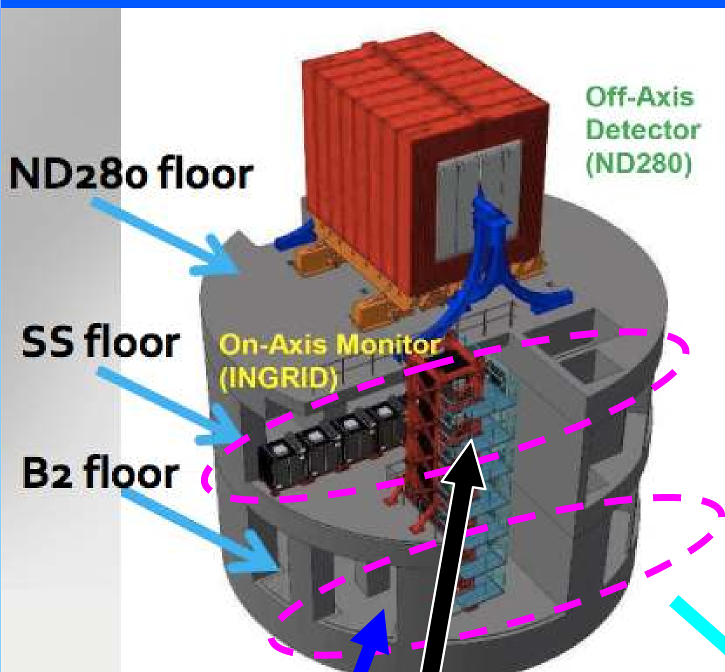

OPERA type
GD=34.8±0.6
FD= 3.7±0.4
100μm
N.Naganawa
New type
GD= 86.1± 4.7
FD= 2.9 ± 0.9
100μm

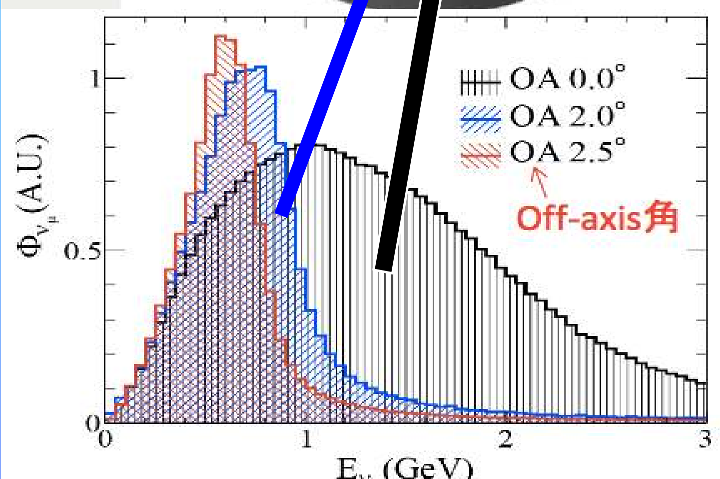

Scanning Speed
T.Nakano
Speed in cm²/h
100000
10000
1000
100
10
1
0.1
0.01
0.001
0.003
0.082
1
72
4700
TS (1983)
NTS (1994)
UTS (1998)
S-UTS (2006)
HTS (2015)

# NINJA Experiment

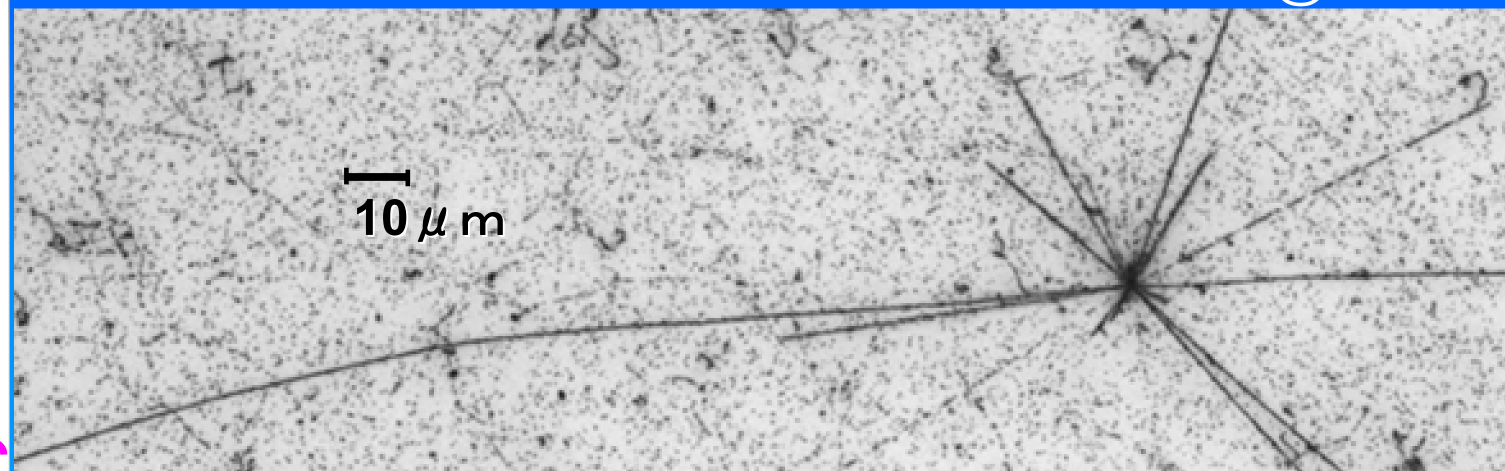
# NINJA Experiment

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

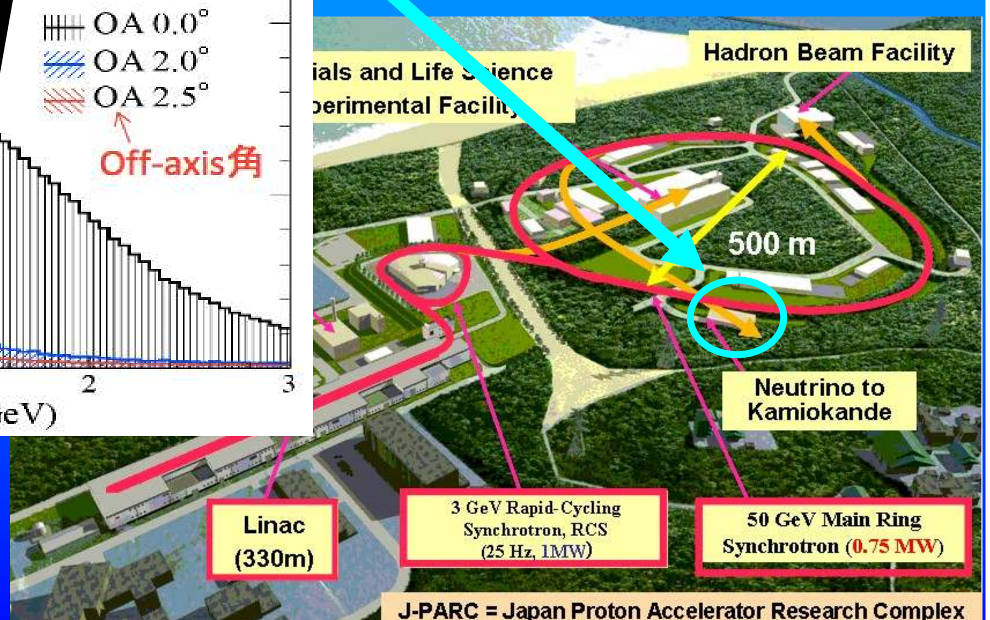


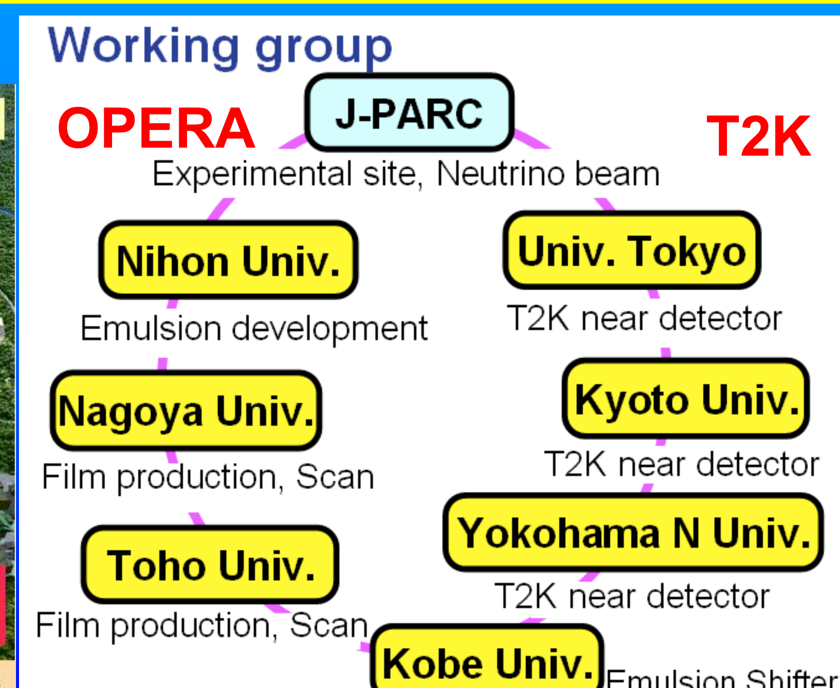




A neutrino interaction in emulsion @J-PARC




**A collaborative project with some member of OPERA and T2K**



# NINJA Collaboration

NINJA

(＊Spokesperson)

*Nihon University*: S. Mikado, Y. Hanaoka
*Nagoya University*: T. Fukuda＊, H. Kawahara, N. Kitagawa, R. Komatani, M.Komatsu, M. Komiyama, K. Morishima, M. Mirishita, M. Nakamura, Y. Nakamura, N. Naganawa, T. Nakano, A. Nishio, H. Rokujo, O. Sato, T. Shiraishi, K. Sugimura, Y. Suzuki, T. Takao
*Toho University*: T. Matsuo, Y. Morimoto, S. Ogawa, H. Oshima, H. Shibuya
*Kobe University*: S. Aoki, K. Kuretsubo, T. Marushima, S. Takahashi
*Yokohama National University*: A. Minamino, D. Yamaguchi
*Kyoto University*: T. Hayashino, A. Hiramoto, A. K. Ichikawa, K. Nakamura, T. Nakaya, I. Sanjana, K. Yasutome
*University of Tokyo*: N. Chikuma, T. Koga, R. Tamura, M. Yokoyama
*ICRR, University of Tokyo*: Y. Hayato

# Physics motivation

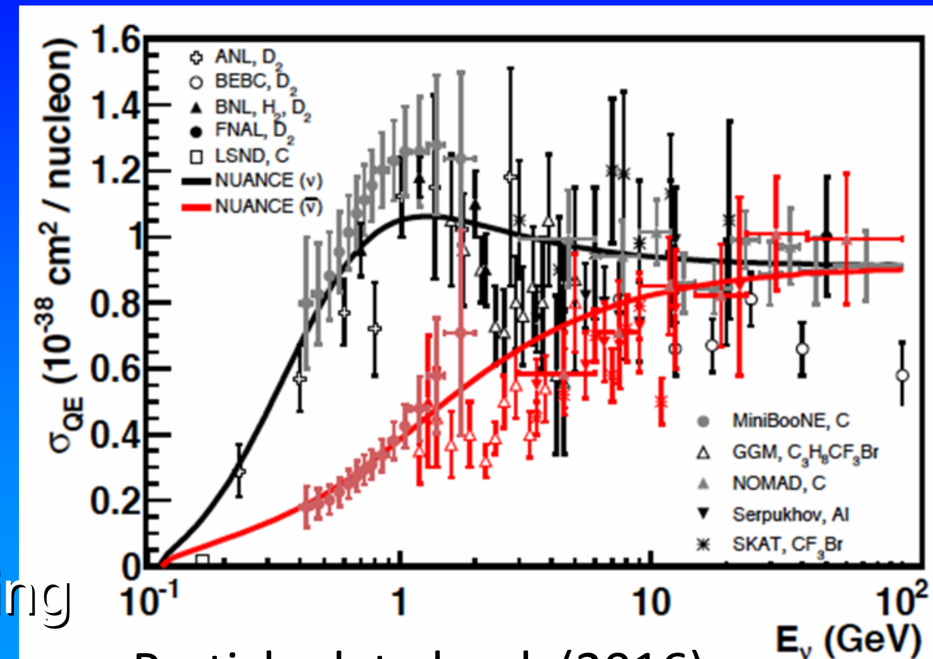
Neutrino interaction
~ Major source of uncertainty in oscillation analysis

| | |
|---|---|
| Total error of 1 ring $\mu$-like sample | ~ 5 % |
| Uncertainty from neutrino interaction and flux | ~ 3 % |
| ( constrained by the near detector data ) | |
| Total error of 1 ring e-like sample ( CCQE-like ) | ~ 6 % |
| Uncertainty from neutrino interaction and flux | ~ 3 % |
| ( constrained by the near detector data ) | |
| Cross-section ratio ( $\nu_\mu$ to $\nu_e$ ) | 2 ~ 3 % |

Need to understand the neutrino-nucleus interaction.
This will reduce the errors from neutrino-nucleus interactions and also, improve the accuracy of the flux measurements with the near detectors.

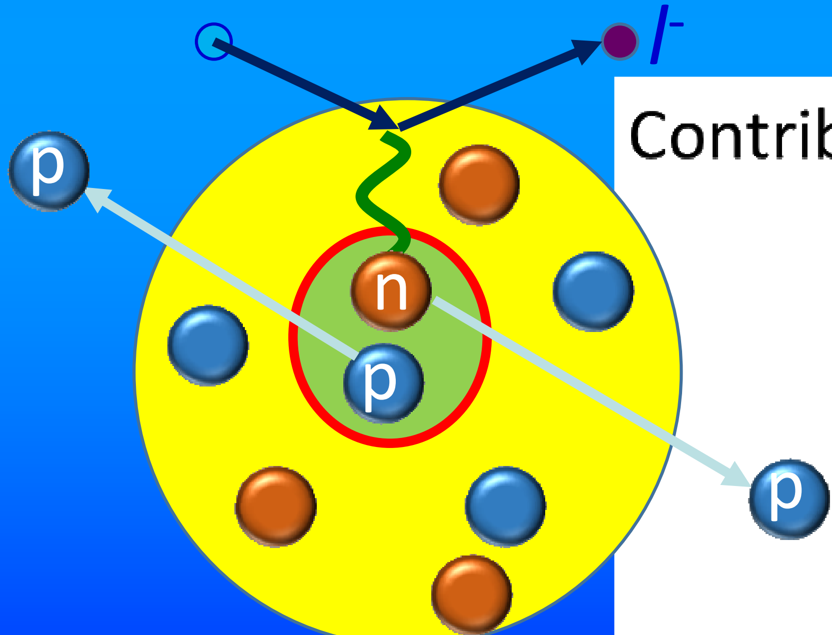
# Current issues

Cross-section of CCQE-like events
Measured value is much larger than the simple model predictions



Particle data book (2016)

Due to the problem in the parameters measured in the old experiments?
Insufficient to consider single nucleon scattering with impulse approximation?



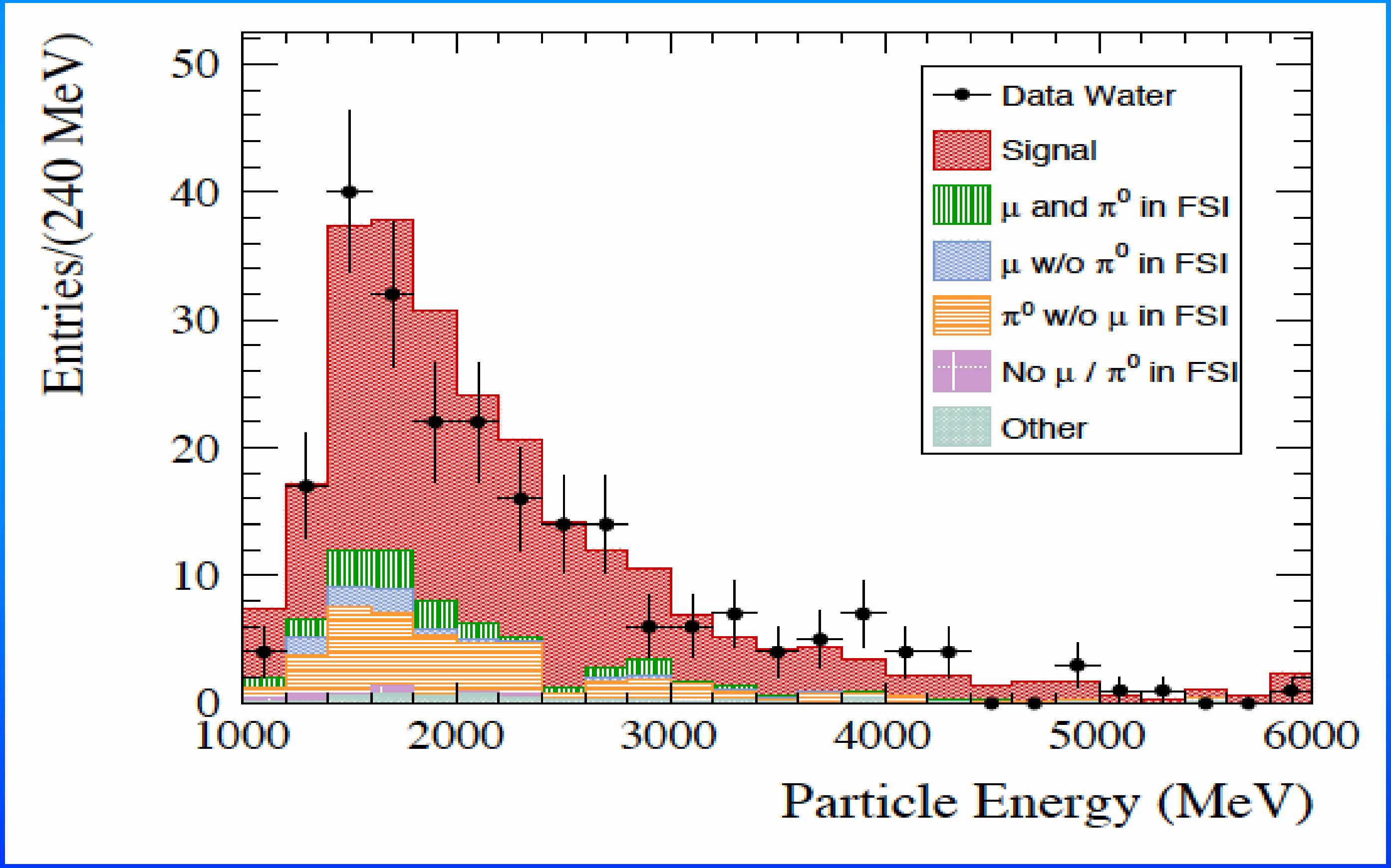

Contribution from 2 nucleon interaction?
Recent experiments did not measure low momentum nucleons.
→ It is not possible to discriminate single nucleon interaction from multi-nucleon interactions.

Interestingly, large suppression is observed in the forward ( small $q^2$ ) region.

# Current issues

Difficulty in measuring $\nu_e$ cross-section
~ rejection of $\pi^0$ contamination

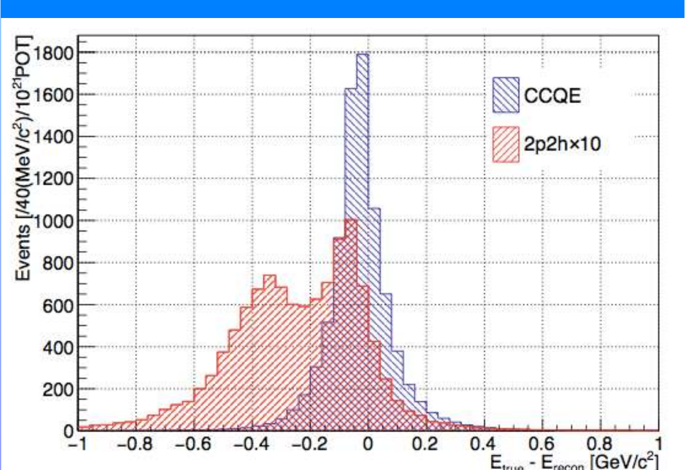
Existing near detector always suffer from contamination from $\pi^0$
It is important to measure low energy electron cross-sections.

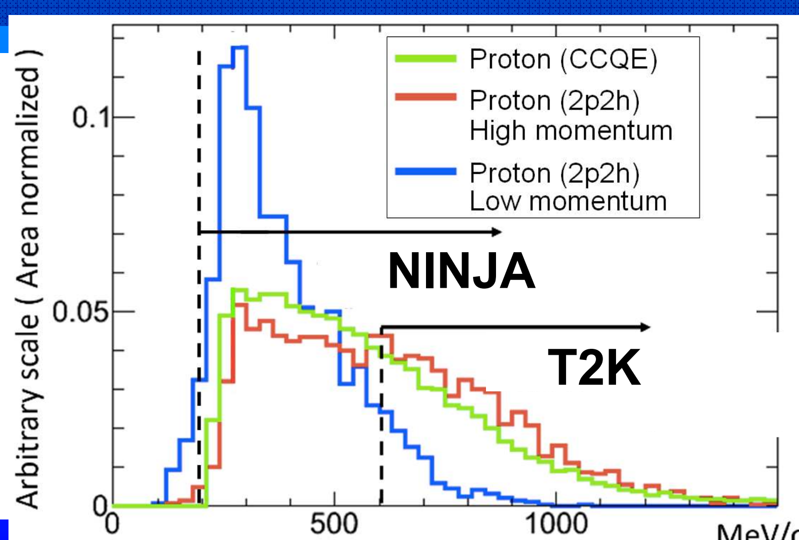


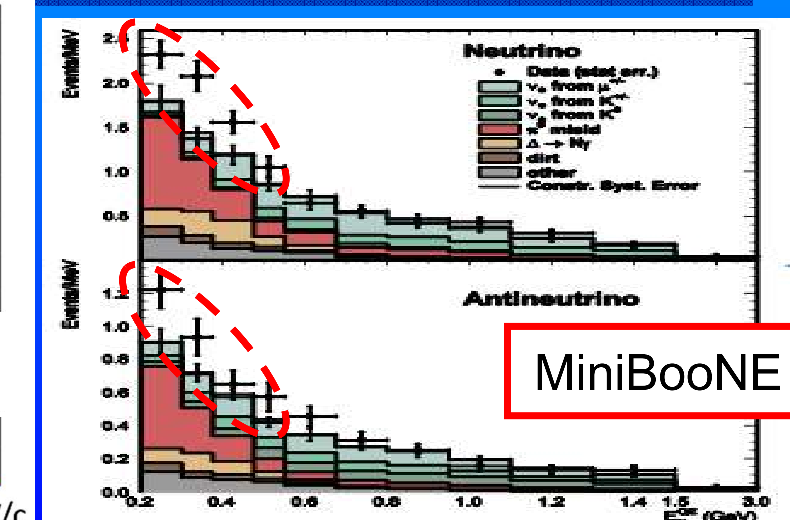

Taken from “Measurement of the electron neutrino charged-current interaction rate on water with the T2K ND280 $\pi$ 0 detector”,
K. Abe et al. (T2K Collaboration) , Phys. Rev. D 91, 112010

# Our approach

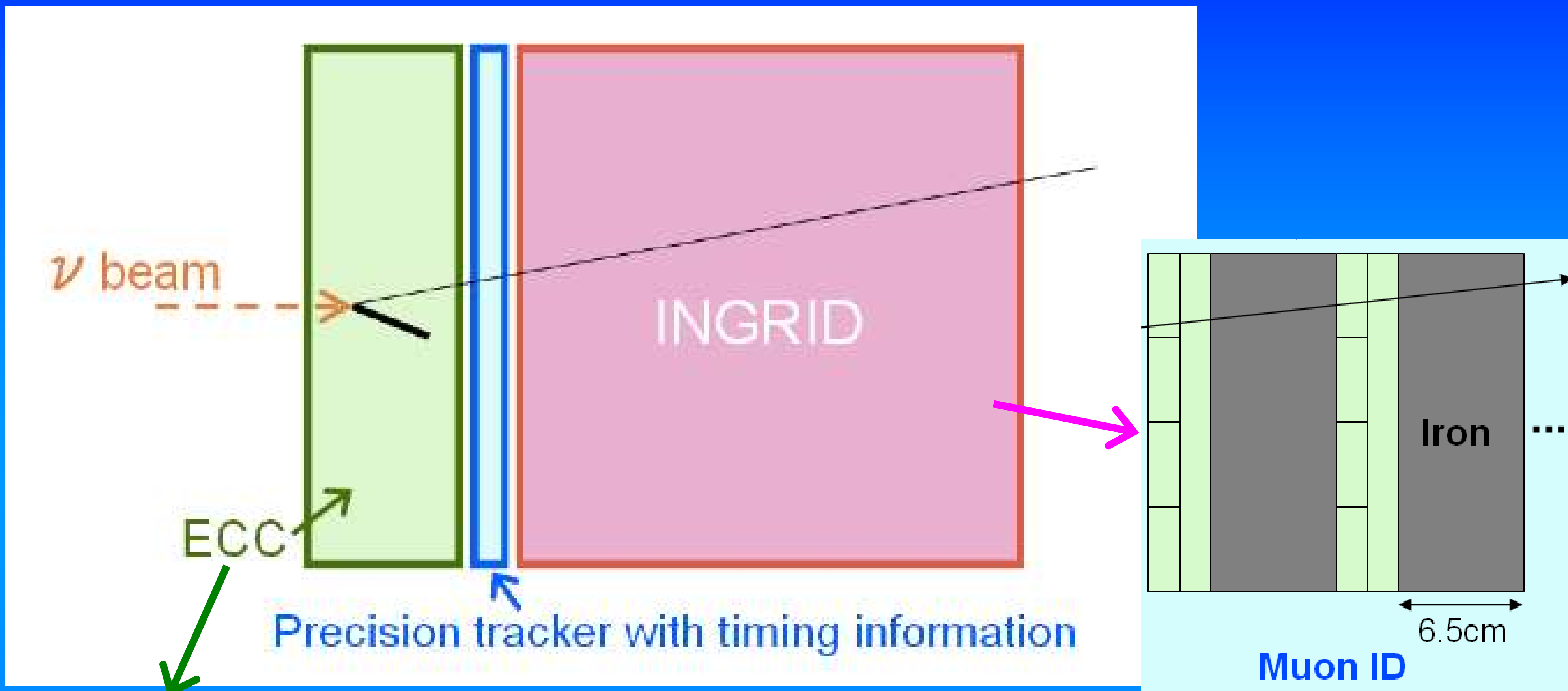
- Precise neutrino-nucleus interaction measurement is important to reduce the systematic uncertainty in future neutrino oscillation experiments.
- We started a new experiment at J-PARC to study low energy neutrino interactions by introducing nuclear emulsion technique.
- The emulsion technique can measure 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 $\nu_e$ cross section and to explore a sterile neutrino.

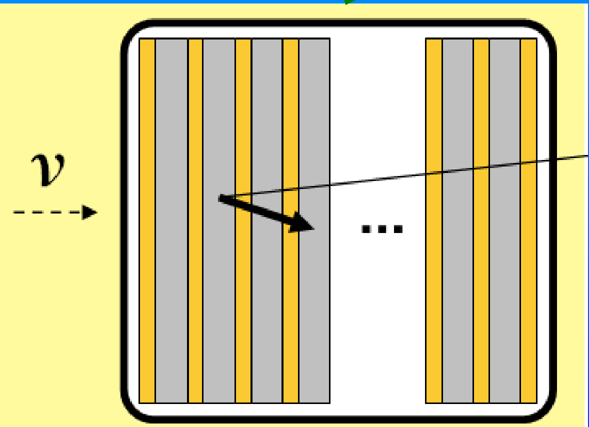


# Conceptual design of the detector




Event detection,
Physics analysis

- **E**mulsion **C**loud **C**hamber (**ECC**) is a sandwich structure of emulsion films and materials.
- ECC is placed in front of T2K near detector, INGRID.
- Precise Tracker is placed between ECC and INGRID to give a timing information to emulsion tracks.
- Muon ID is possible by combined analysis with INGRID.

# NINJA Roadmap

In 2014, plan was proposed and the collaboration started to be established.

**Pilot RUN** — Feasibility study at J-PARC

**J-PARC T60/T66/T68 experiment**

**Detector RUN** — Detector performance check

Target mass: 1- 60kg

**Physics RUN Ⅰ** — Neutrino-nucleus interaction study

This proposal (P71)

Target mass: 100- 300kg

**Physics RUN Ⅱ** — Search for sterile neutrino

Target mass: 1- 3ton

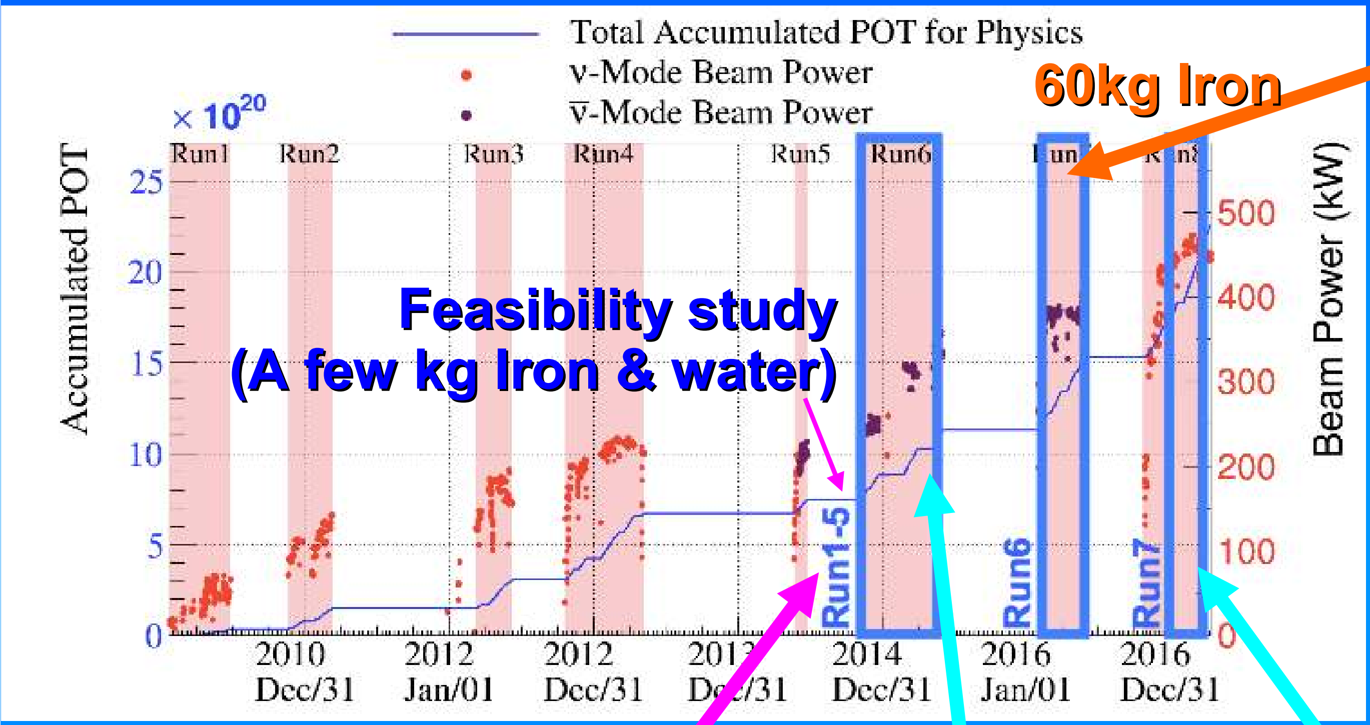
Target mass: 6-10ton

The aim of T60/T66/T68 is a feasibility study and detector performance check.

In this time, we propose the physics run to study neutrino-nucleus interactions.

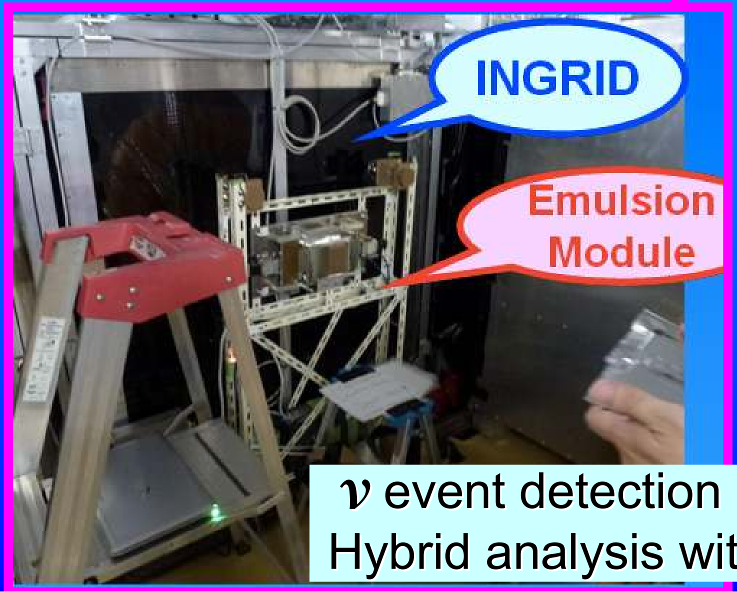
# ν exposure status of NINJA

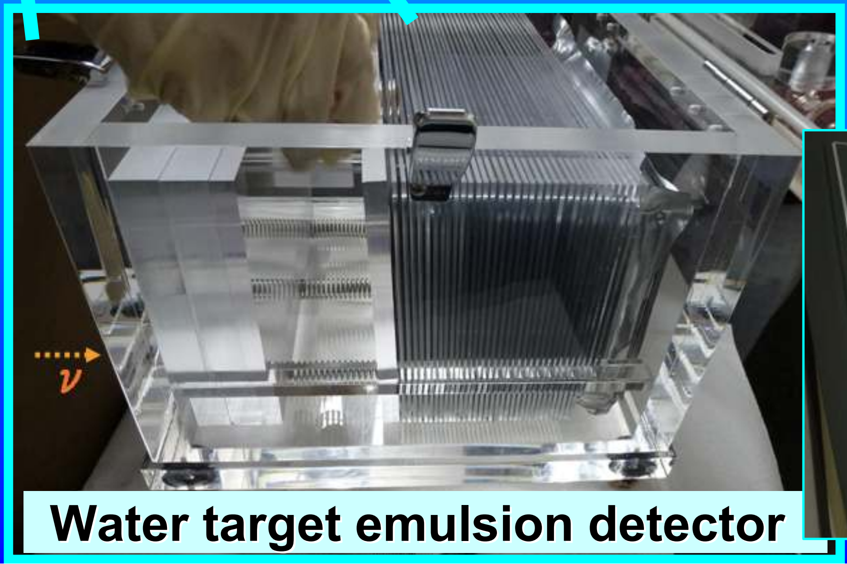
- We have demonstrated the basic experimental concept at J-PARC site.
- "Detector performance run" was started from Jan. 2016.





Analysis is now on progress



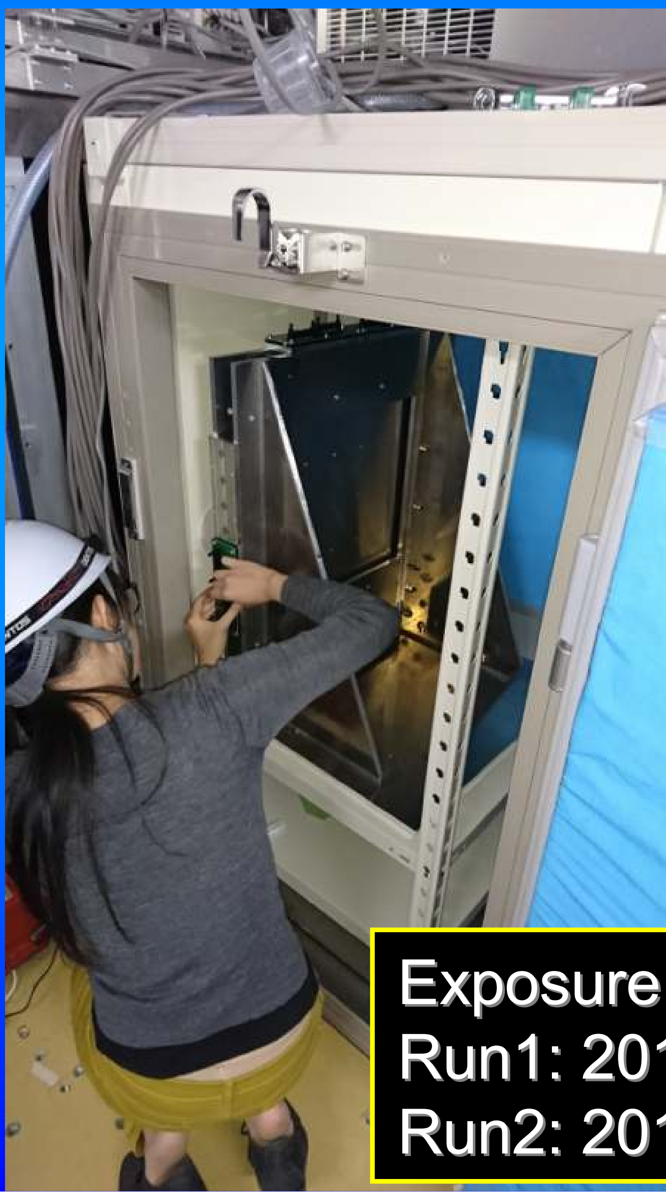



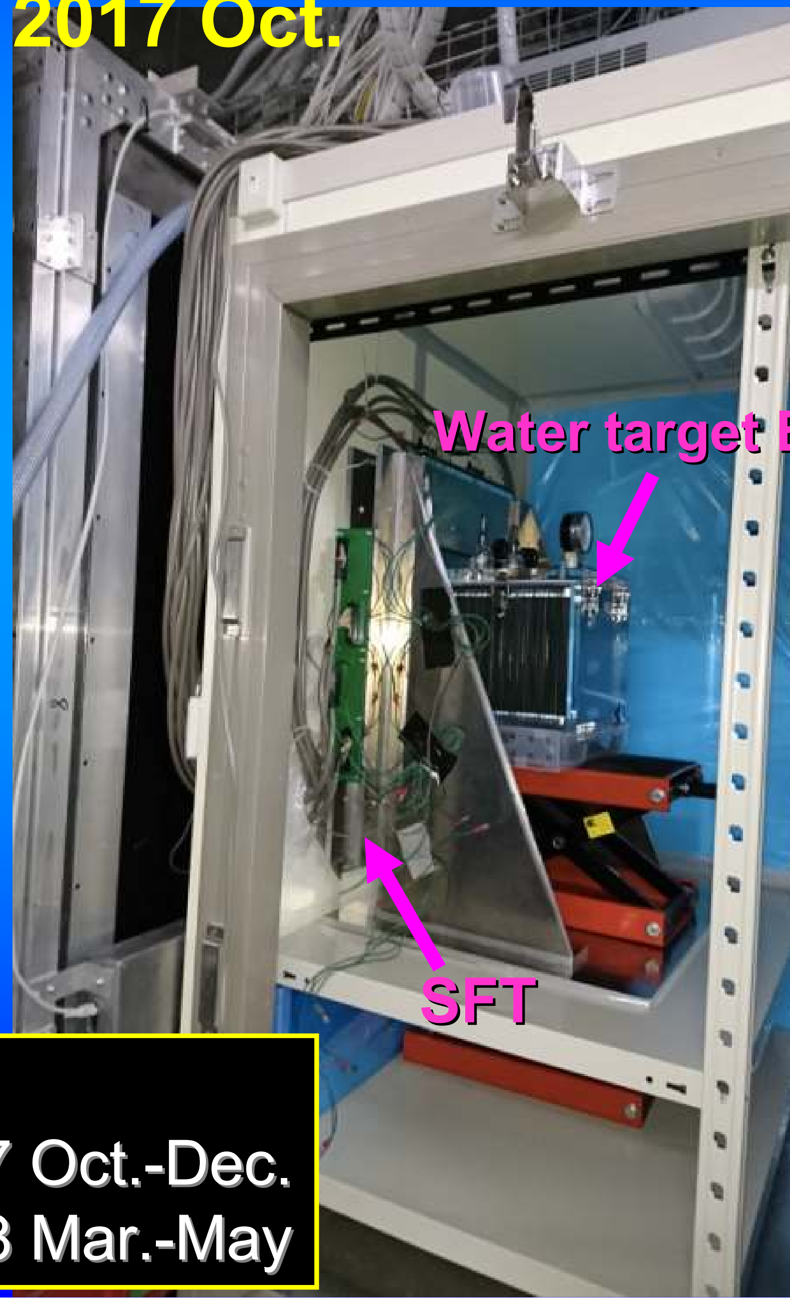

Frame type plastic spacer ( 2mm thickness)

# ν exposure status of NINJA

- We have demonstrated the basic experimental concept at J-PARC site.
- In 2017-2018, Water target detector run is in progress.

**Detector installation：2017 Oct.**



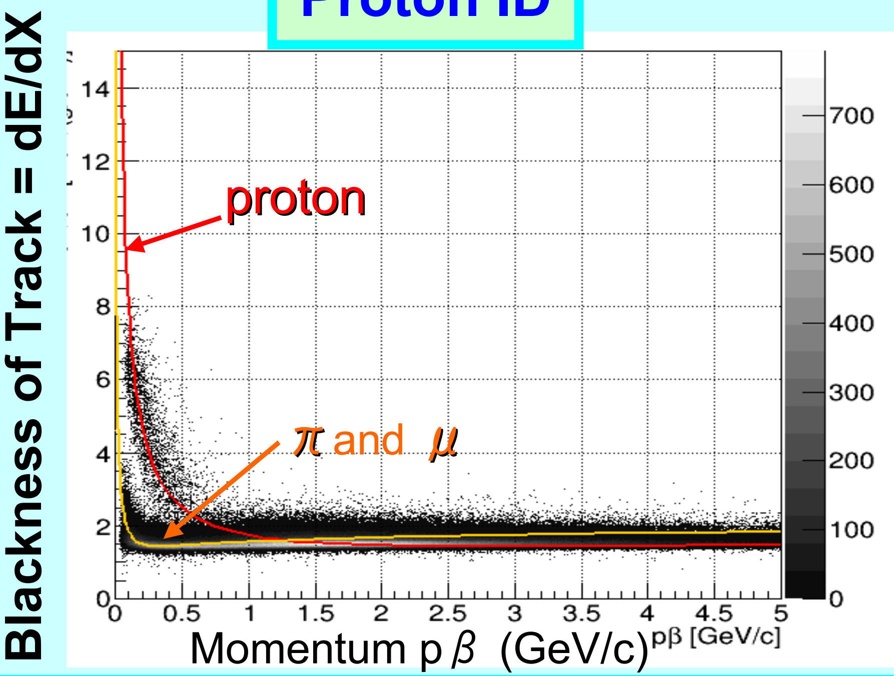




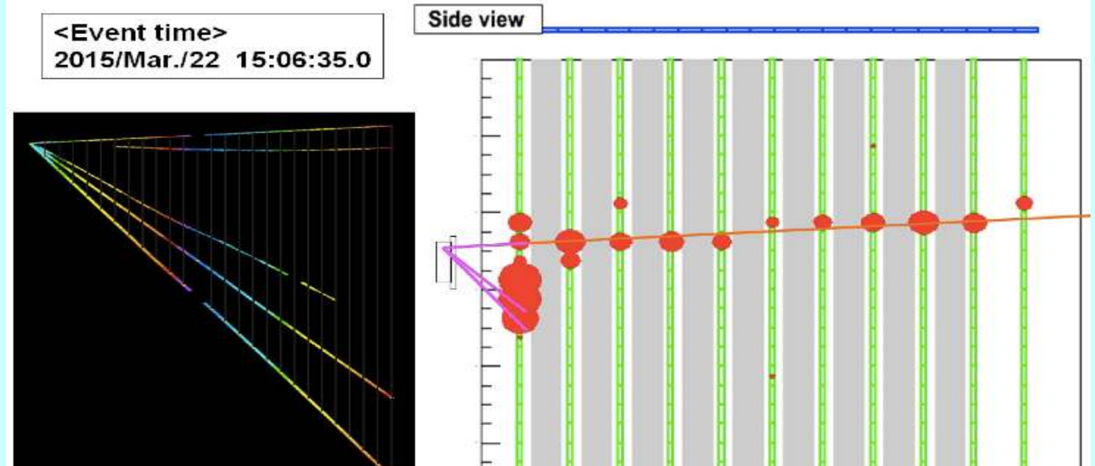
Exposure:
Run1: 2017 Oct.-Dec.
Run2: 2018 Mar.-May

# Analysis status（Iron Target ECC）

## Proton ID

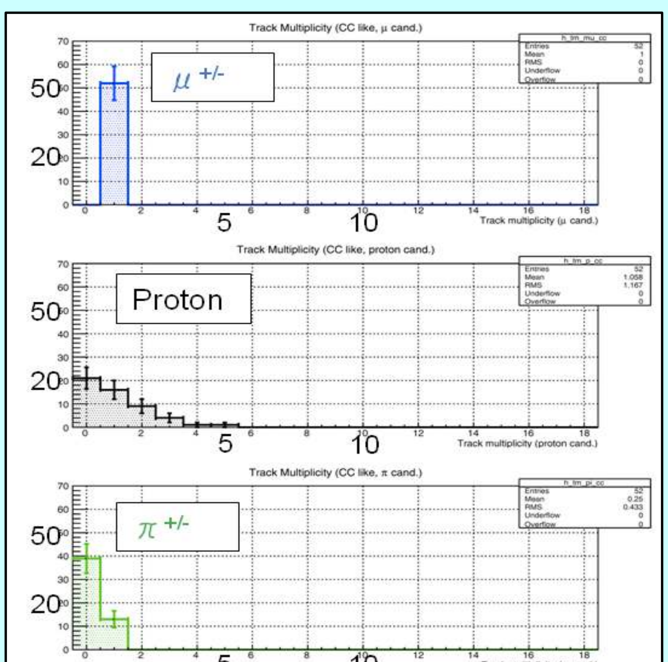



## Muon ID

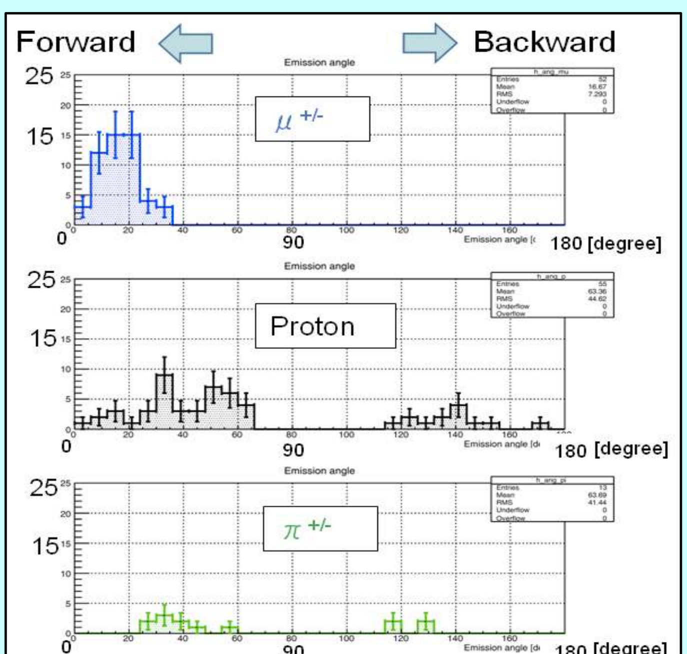



Event topology is matched with timing info. Expected range for each tracks is consistent with INGRID hits.

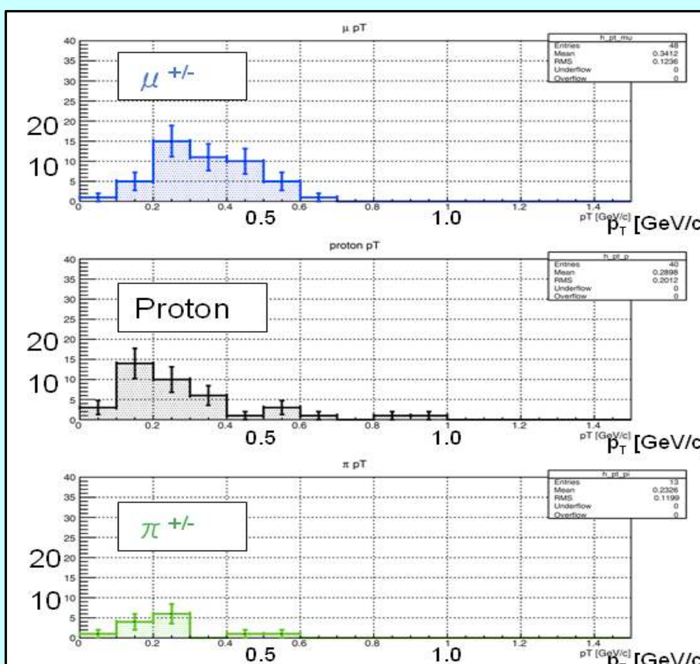
## Track multiplicity (CC like)




## Emission angle




## Transverse momentum



# Physics run Proposal (P71)

We proposed a new experiment (Physics Run) at last J-PARC PAC meeting to study neutrino-water interactions with large statistics.

NINJA

## Proposal for precise measurement of neutrino-water cross-section in NINJA physics run

December 14, 2017


The NINJA Collaboration

S. Aoki[1], N.Chikuma[2], T. Fukuda[3,*], Y. Hanaoka[4], T. Hayashino[5], Y. Hayato[6], A. Hiramoto[5], A. K. Ichikawa[5], H. Kawahara[3], N. Kitagawa[3], T. Koga[2], R. Komatani[3], M. Komatsu[3], M. Komiyama[3], K. Kuretsubo[1], T. Marushima[1], T. Matsuo[7], S. Mikado[4], A. Minamino[8], Y. Morimoto[7], K. Morishima[3], M. Morishita[3], K. Nakamura[5], M. Nakamura[3], Y. Nakamura[3], N. Naganawa[3], T. Nakano[3], T. Nakaya[5], A. Nishio[3], S. Ogawa[7], H. Oshima[7], H. Rokujo[3], I. Sanjana[5], O. Sato[3], H. Shibuya[7], T. Shiraishi[3], K. Sugimura[3], Y. Suzuki[3], S. Takahashi[1], T. Takao[3], R. Tamura[2], D. Yamaguchi[8], K. Yasutome[5] and M. Yokoyama[2]

[1] *Kobe University, Kobe, Japan*
[2] *University of Tokyo, Tokyo, Japan*
[3] *Nagoya University, Nagoya, Japan*
[4] *Nihon University, Narashino, Japan*
[5] *Kyoto University, Kyoto, Japan*
[6] *University of Tokyo, ICRR, Kamioka, Japan*
[7] *Toho University, Funabashi, Japan*
[8] *Yokohama National University, Yokohama, Japan*

* *Spokes person, Email: tfukuda@flab.phys.nagoya-u.ac.jp*



Abstract

We propose a neutrino experiment which aims at measuring neutrino-water cross-sections with nuclear emulsion based detector at J-PARC neutrino beamline. Precise measurement of neutrino-water interactions is important to reduce systematic uncertainties in current and future neutrino oscillation experiments which search for


Goal:

- Validation of the existence of 2p2h reaction
- Cross-section measurement of 2p2h with accuracy of 10%
- Exclusive $\nu_\mu$ and $\nu_e$ cross-section measurement

**25th J-PARC PAC meeting** https://kds.kek.jp/indico/event/26624/

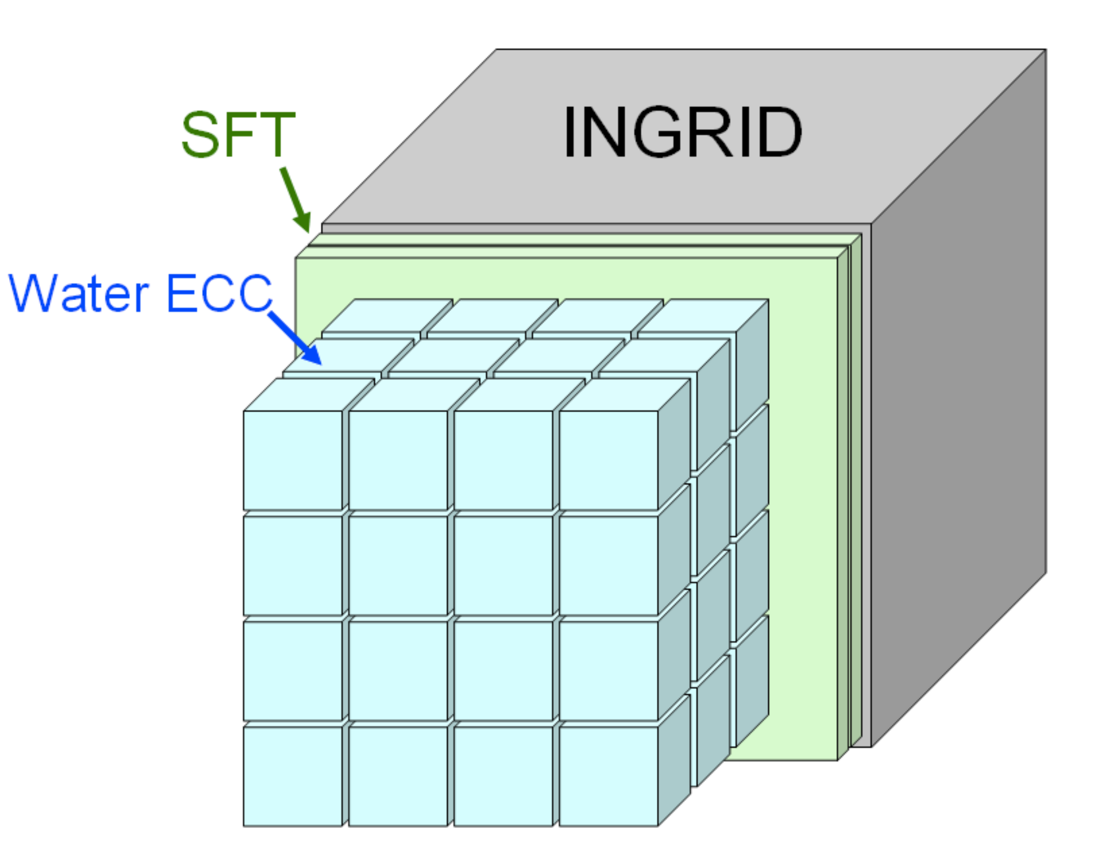
from Monday, January 15, 2018 at **08:00** to Wednesday, January 17, 2018 at **16:00** (Asia/Tokyo)
at **J-PARC Research Building ( 2F Conference room )**

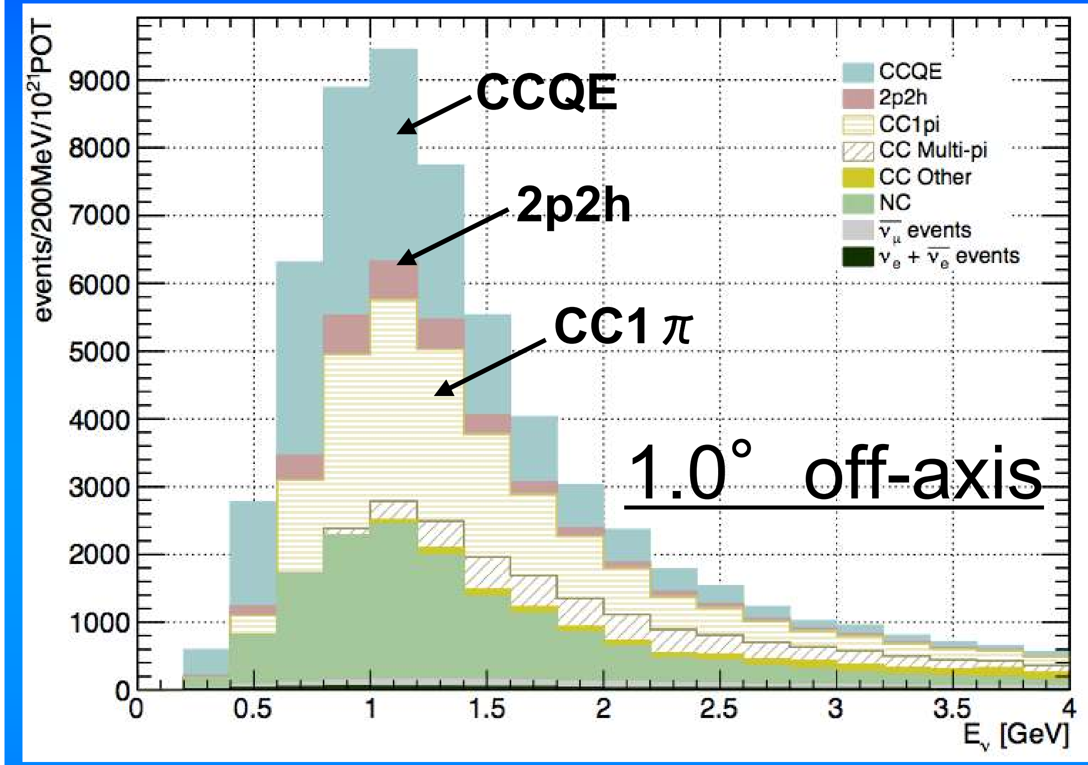
Manage

**Description** All the presentations should include the discussion time of 5 to 10 minutes.

| | |
|---|---|
| 10:50 - 11:10 | Break |
| 11:10 - 11:30 | E61(NuPRISM) *20'*<br>Speaker: Mark Hartz (IPMU)<br>Material: **Slides** |
| 11:30 - 12:00 | P69 (Study of neutrino-nucleus interaction at around 1 GeV) *30'*<br>Speaker: Akihiro Minamino (Yokohama National University)<br>Material: **Slides** |
| 12:00 - 12:30 | P71 (Precise measurement of neutrino-water cross-section) *30'*<br>Speaker: Tsutomu Fukuda (Nagoya University)<br>Material: **Slides** |
| 12:30 - 13:30 | Lunch |
| 13:30 - 14:00 | P70 (Proposal for the next E05 run with the S−2S spectrometer) *30'*<br>Speaker: Tomofumi Nagae (Kyoto University)<br>Material: **Slides** |

# Physics run Proposal (P71)




Expected # of neutrino events
(@200kg water, $1\times10^{21}$POT)

> 1,000 2p2h events@100% eff.
- model dependent
- need to estimate the det. eff.

# Experimental activities with Nuclear Emulsion

# The OPERA Experiment ($\nu_\mu \rightarrow \nu_\tau$)

# $\nu_\tau$ analysis result

Expected signal and background events for the analyzed data sample

| Channel | Expected background | | | | Expected signal | Observed |
|---|---|---|---|---|---|---|
| | Charm | Had. re-interac. | Large $\mu$-scat. | Total | | |
| $\tau \to 1h$ | $0.017 \pm 0.003$ | $0.022 \pm 0.006$ | – | $0.04 \pm 0.01$ | $0.52 \pm 0.10$ | 3 |
| $\tau \to 3h$ | $0.17 \pm 0.03$ | $0.003 \pm 0.001$ | – | $0.17 \pm 0.03$ | $0.73 \pm 0.14$ | 1 |
| $\tau \to \mu$ | $0.004 \pm 0.001$ | – | $0.0002 \pm 0.0001$ | $0.004 \pm 0.001$ | $0.61 \pm 0.12$ | 1 |
| $\tau \to e$ | $0.03 \pm 0.01$ | – | – | $0.03 \pm 0.01$ | $0.78 \pm 0.16$ | 0 |
| Total | $0.22 \pm 0.04$ | $0.02 \pm 0.01$ | $0.0002 \pm 0.0001$ | $0.25 \pm 0.05$ | $2.64 \pm 0.53$ | 5 |

**5 observed events** with **0.25 background**

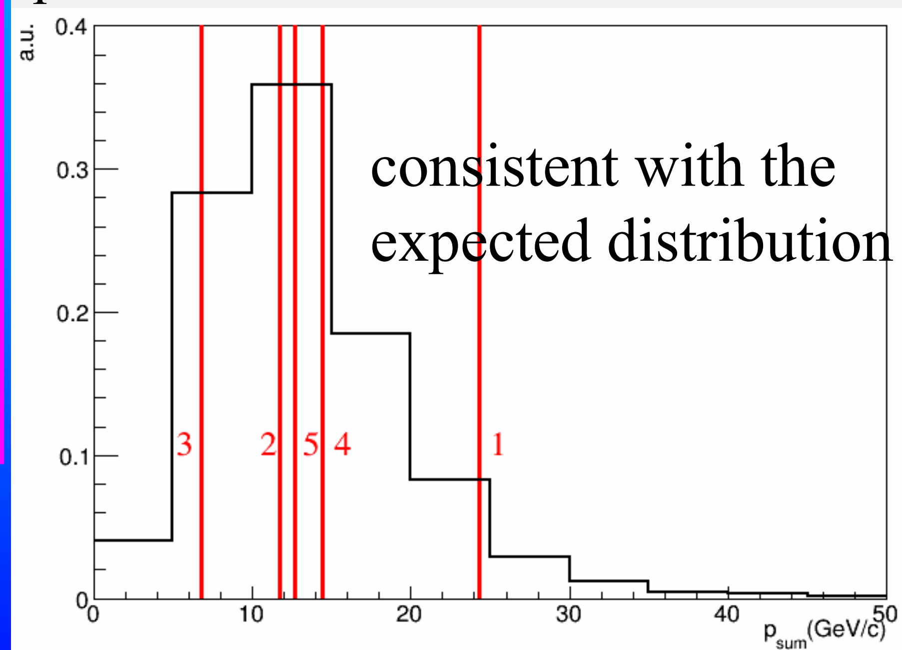
Probability to be explained by background:

$1.1 \times 10^{-7}$ (Fisher, Profile likelihood)

Corresponding to **5.1 $\sigma$** exclusion of the background-only hypothesis

**Discovery of $\nu_\tau$ appearance**

the scalar sum of the momenta of all particles measured in ECC




Estimation of $\Delta m^2_{23}$ (90% C.L.)

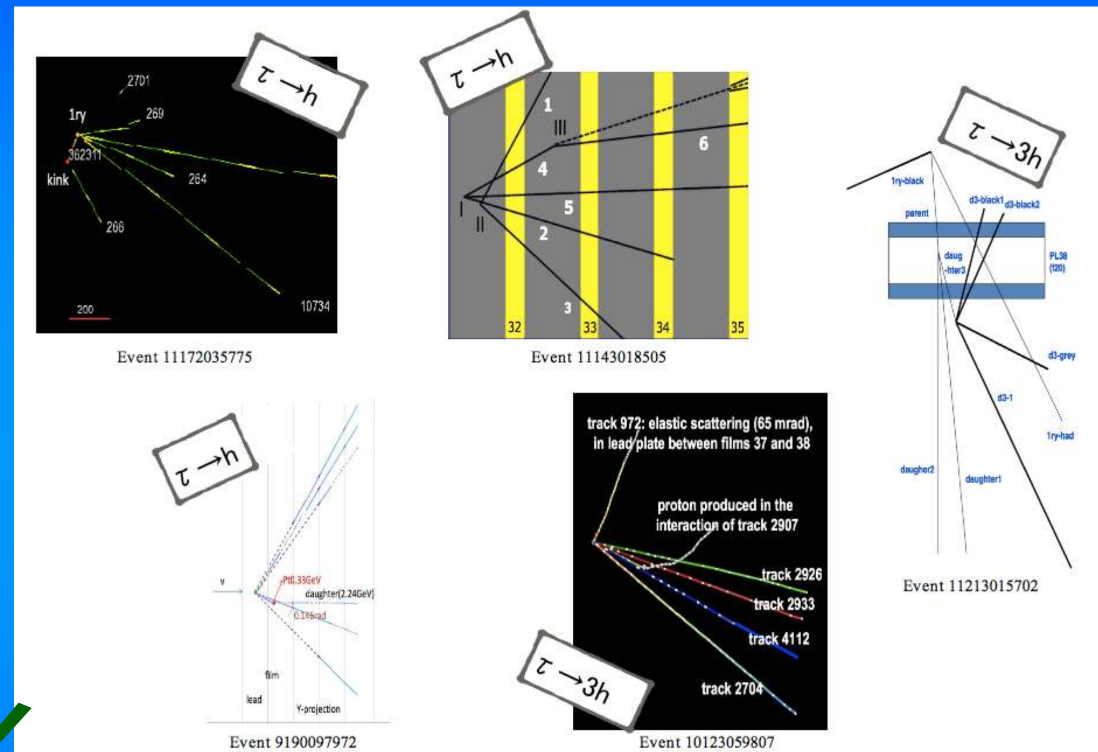
[2.0, 5.0] x $10^{-3}$ $eV^2$ (assuming full mixing)

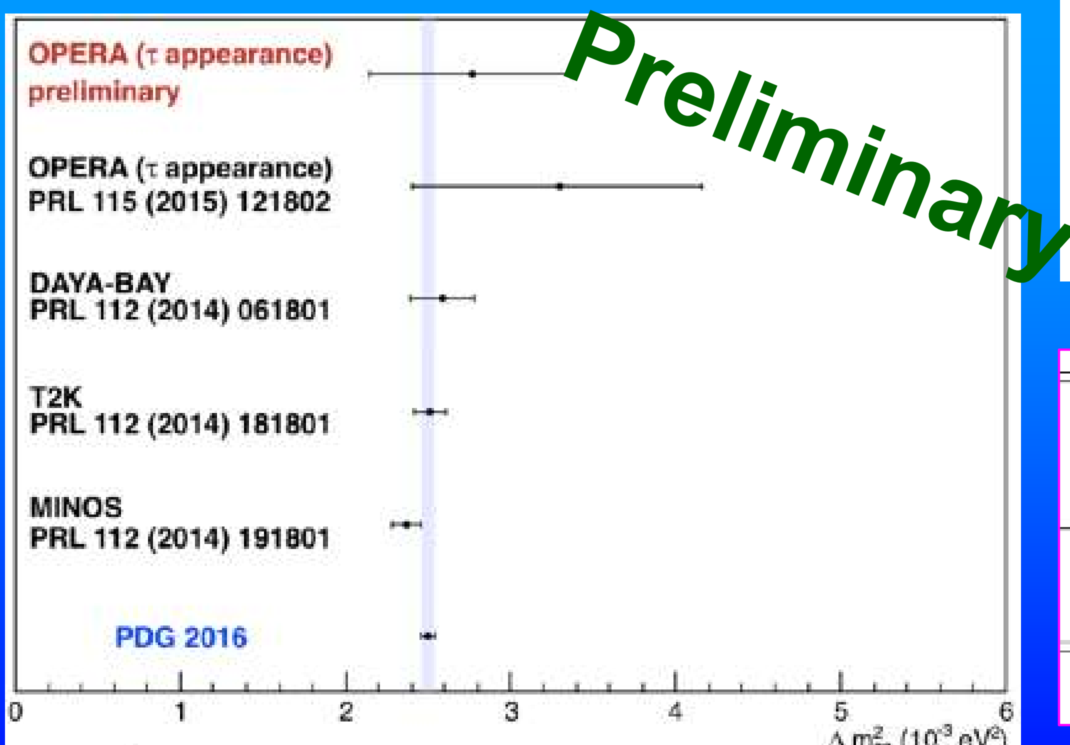
# Improvement of $\Delta m^2$ measurement

- Golden + **Silver** selection

| Variable | $\tau \to 1h$ | $\tau \to 3h$ | $\tau \to \mu$ | $\tau \to e$ |
|---|---|---|---|---|
| $z_{dec}$ $(\mu m)$ | <2600 | <2600 | <2600 | <2600 |
| $p^T_{2ry}$ $(GeV/c)$ | >0.15 | / | >0.1 | >0.1 |
| $p_{2ry}$ $(GeV/c)$ | >1 | >1 | >1 | >1 |
| $\theta_{kink}$ $(rad)$ | >0.02 | >0.02 | >0.02 | >0.02 |

**5 events found (BG:2.0) !**

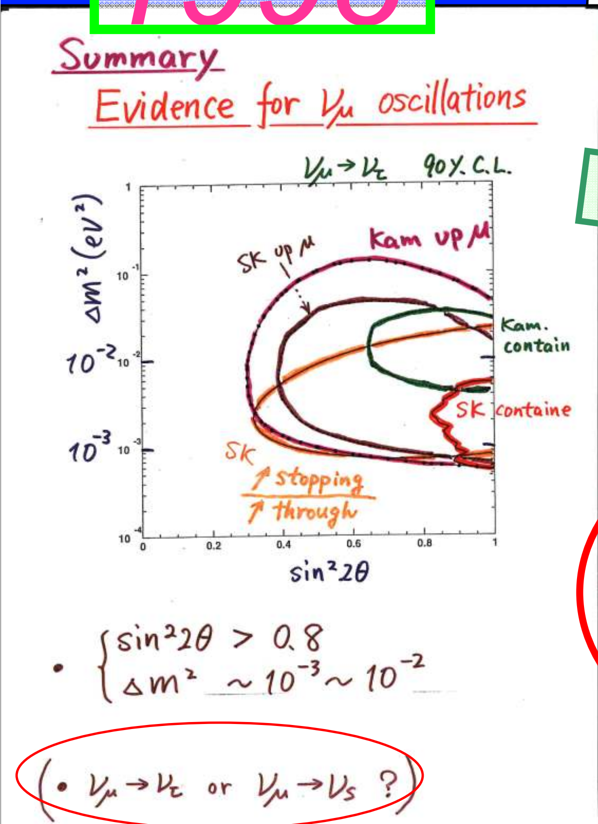



| Expected Signal | Expected Background | Observed $\nu_\tau$ | $\Delta m^2_{23}$ $(10^{-3}\ \mathrm{eV}^2)$ |
|---|---|---|---|
| 6.5 | 2.0 | 10 | $2.8^{+0.6}_{-0.6}$ 68% C.L |

(C.L. evaluated with Feldman-Cousins method)

# 1998



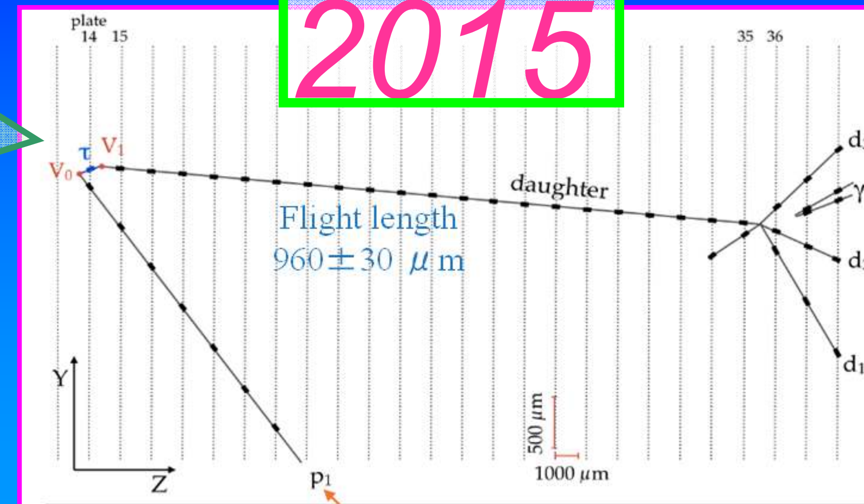

4. Conclusions

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

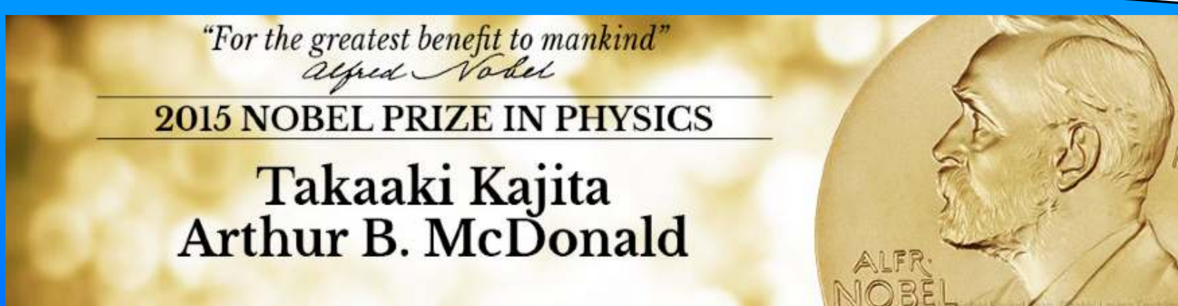
To be more conclusive, we need more statistics or we have to look for appearance of $\nu_\tau$ in long baseline experiments.

**done**

# 2015




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

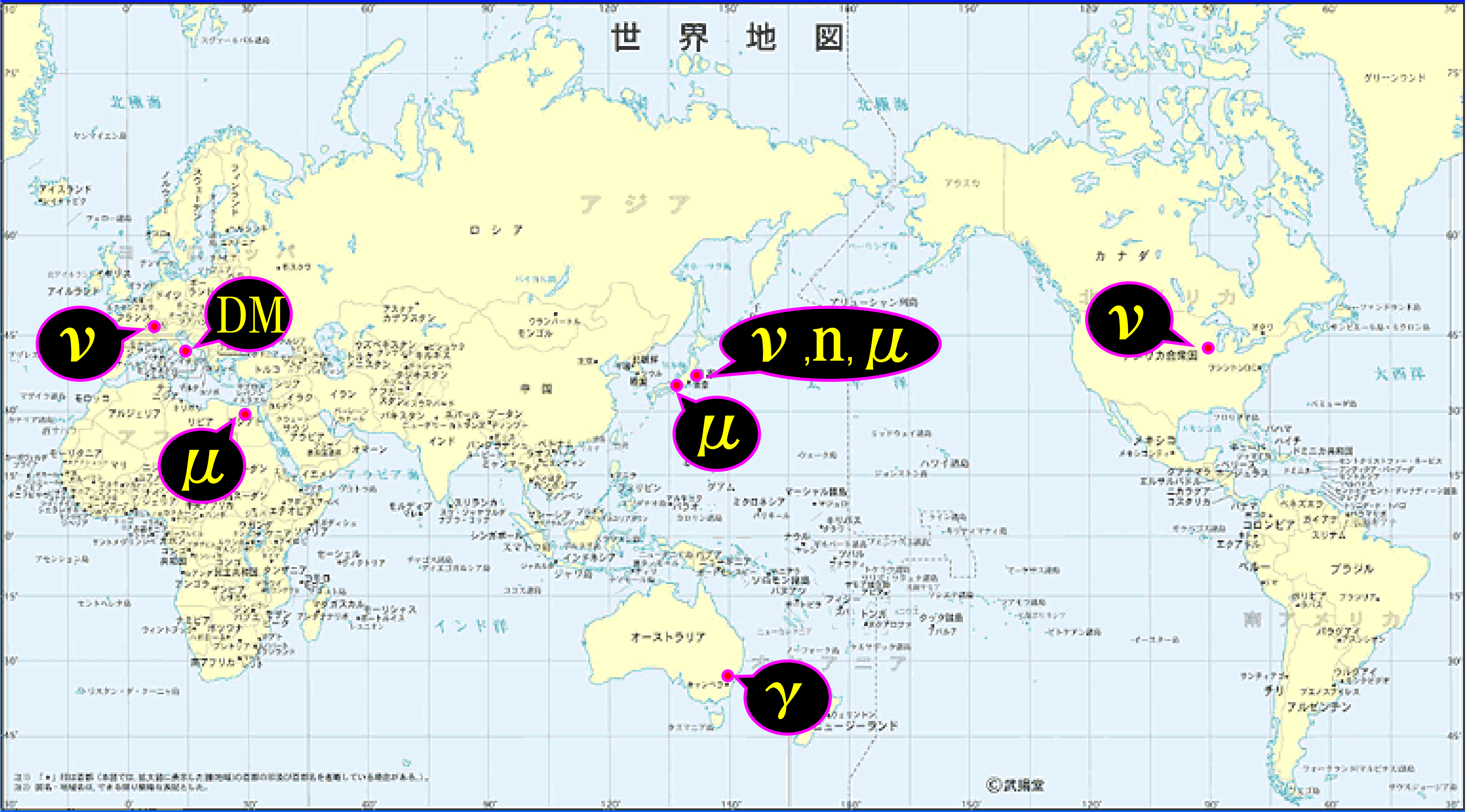



Scientific Background on the Nobel Prize in Physics 2015

NEUTRINO OSCILLATIONS

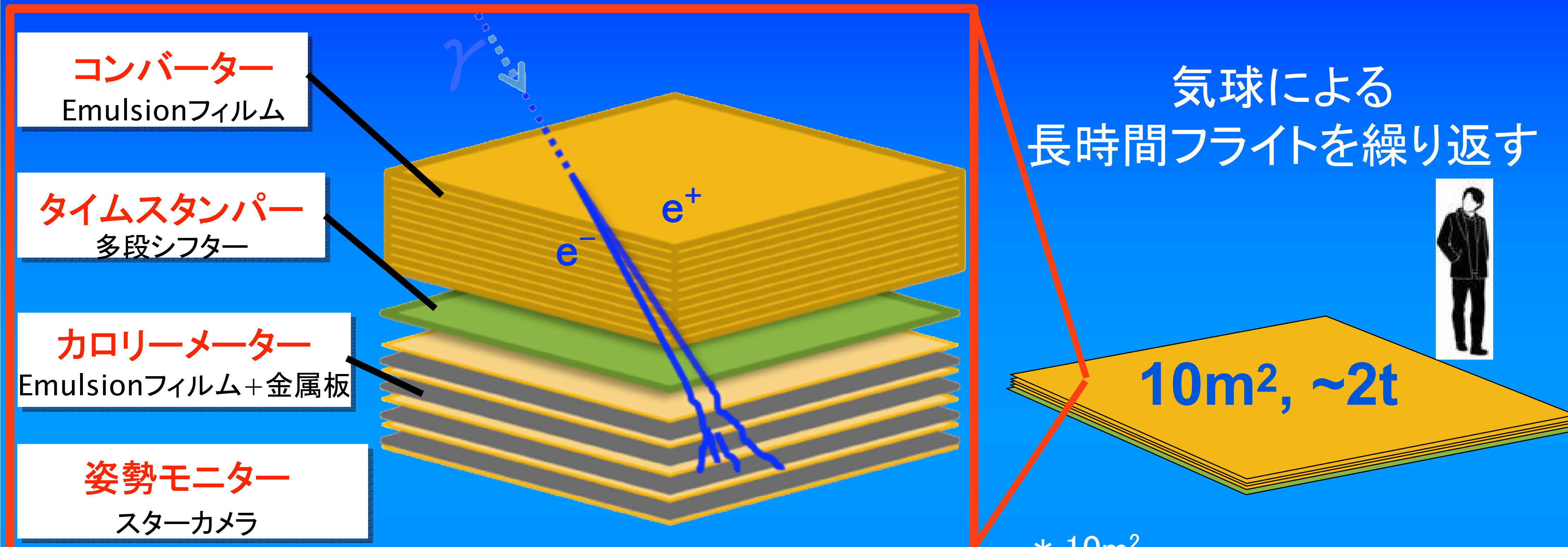
compiled by the Class for Physics of the Royal Swedish Academy of Sciences

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].




・世界中で原子核乾板実験を展開！

# 気球搭載型エマルションガンマ線望遠鏡




＊ $10m^2 \times \varepsilon_{trans} \times \varepsilon_{conv} \times \varepsilon_{det}$

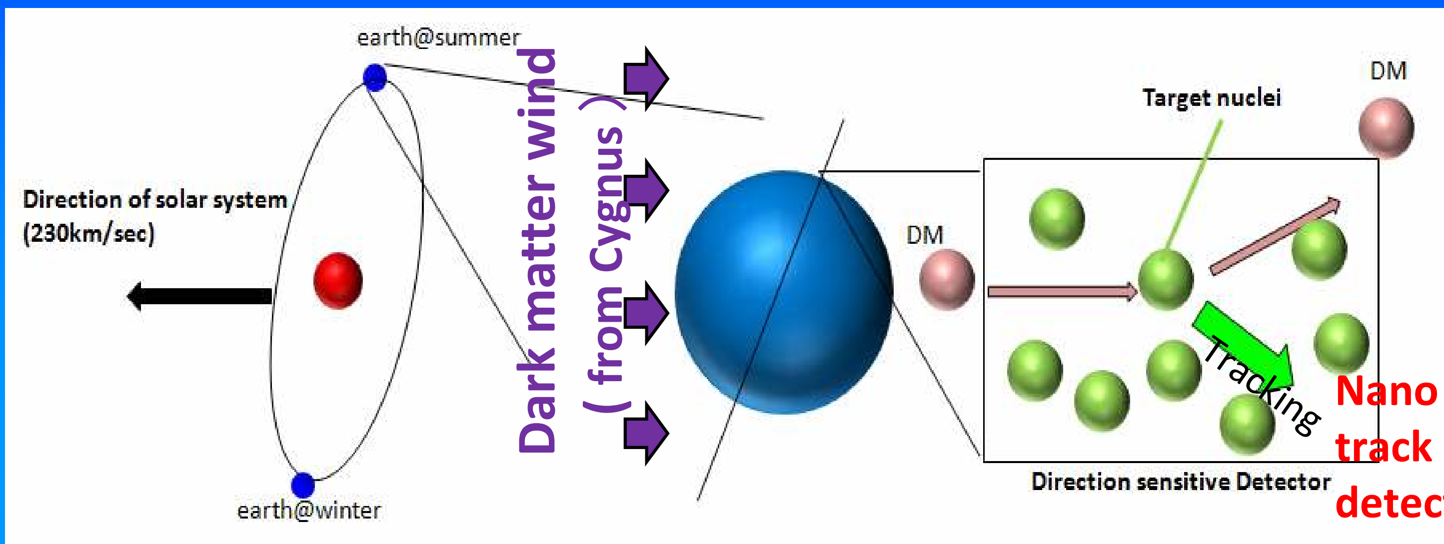
| | Fermi LAT | GRAINE |
|---|---|---|
| 角度分解能 @ 100MeV | 6.0 度 | 6倍 → 1.0 度 |
| 角度分解能 @ 1GeV | 0.90 度 | 9倍 → 0.1 度 |
| 偏光に対する感度 | ― | Yes |
| 有効面積 @ 100MeV | $0.25m^2$ | 8倍 → $2.1m^2$ * |
| 有効面積 @ 1GeV | $0.88m^2$ | 3倍 → $2.8m^2$ * |

最高角度分解能

偏光有感

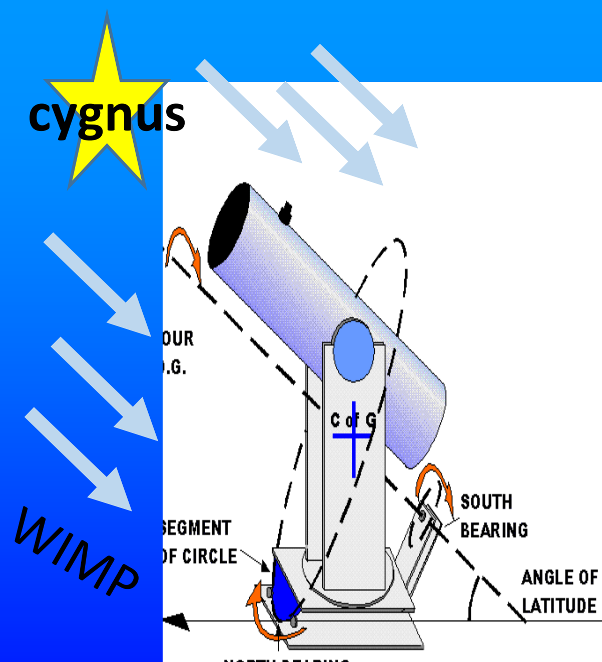
最大口径

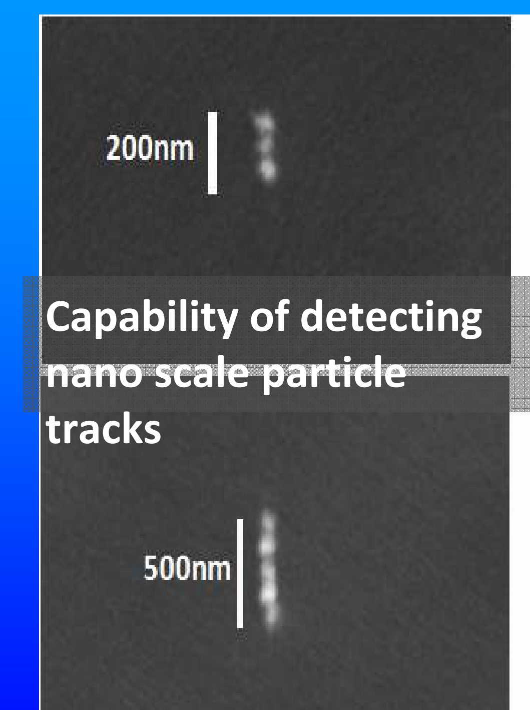
# Directional dark matter search with scalability
## ⇒ super-high resolution nuclear emulsion




Nano scale track detection !!





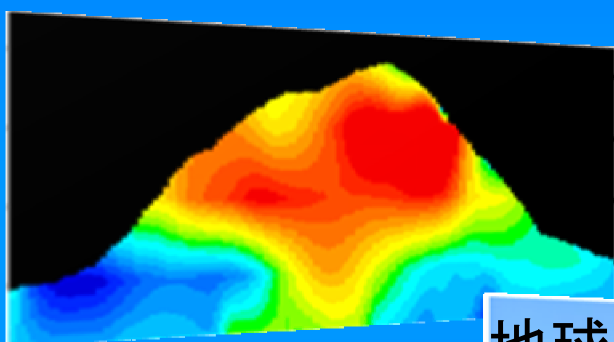



# 宇宙線ラジオグラフィ

宇宙線ミューオンの高い透過性を用いた“大型構造物の内部イメージング”


・原子炉
・溶鉱炉

・ピラミッド
・古墳
・地下遺跡

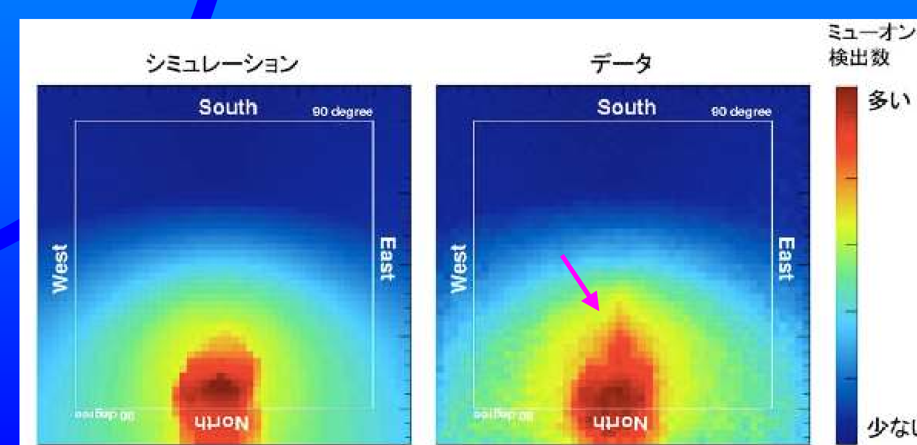


昭和新山（2007）


対象


・火山
・断層
・氷河
・地下資源

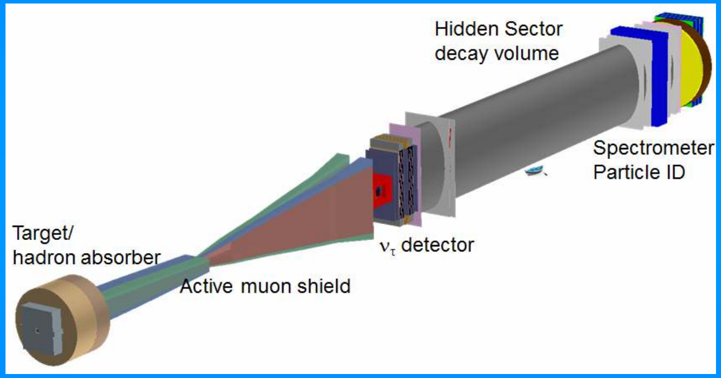

・地下空洞調査
・ダムの老朽化調査
・鉄筋コンクリート

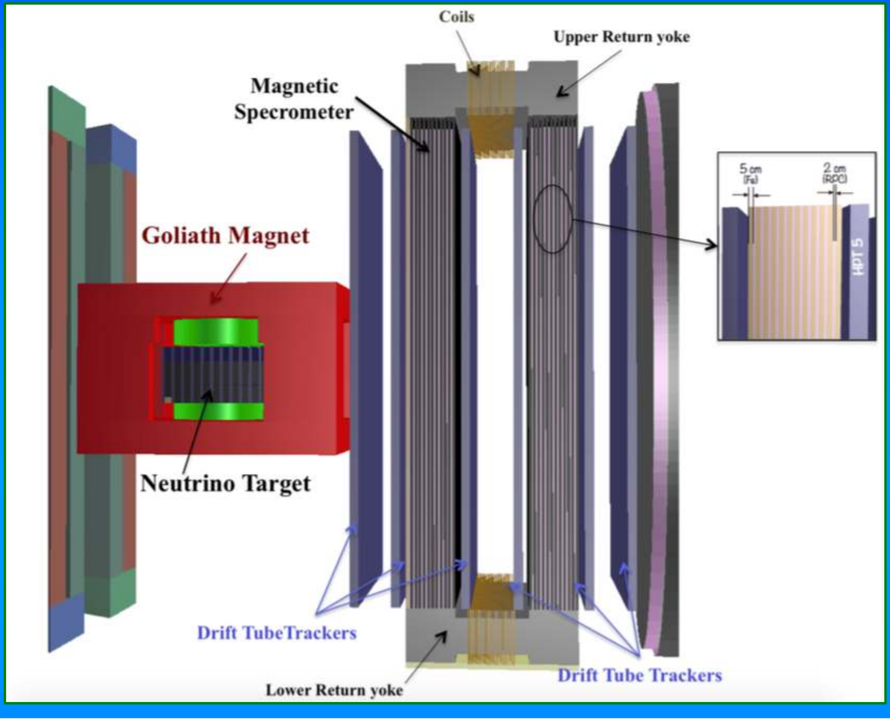


# $\nu_\tau$ Physics

## SHiP Project

- Huge beam bump experiment at SPS from 2026.
- More than 1000 of tau and anti tau neutrino interaction separately using compact emulsion spectrometer.

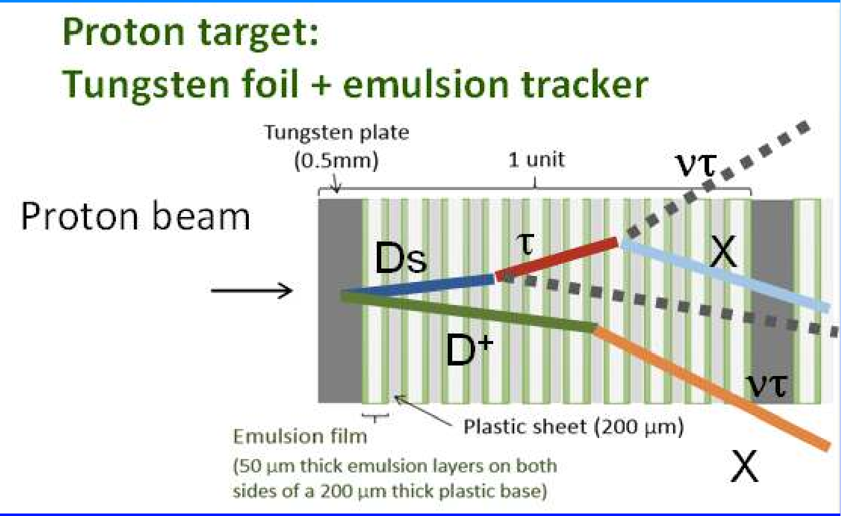


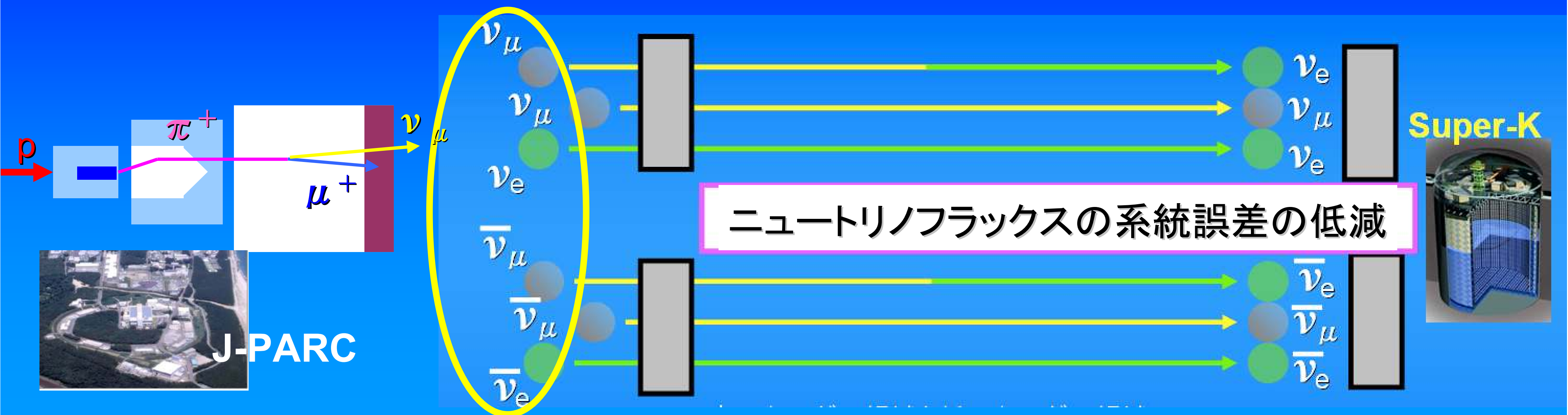

## DsTau Project

- $\nu_\tau$ cross section was measured by DONUT with large uncertainty(~50%) on $\nu_\tau$ flux at beam source.
- The uncertainty reduction on $\nu_\tau$ production cross section is important.
- $D_s \rightarrow \tau \rightarrow X$ precision measurement in high energy proton interactions

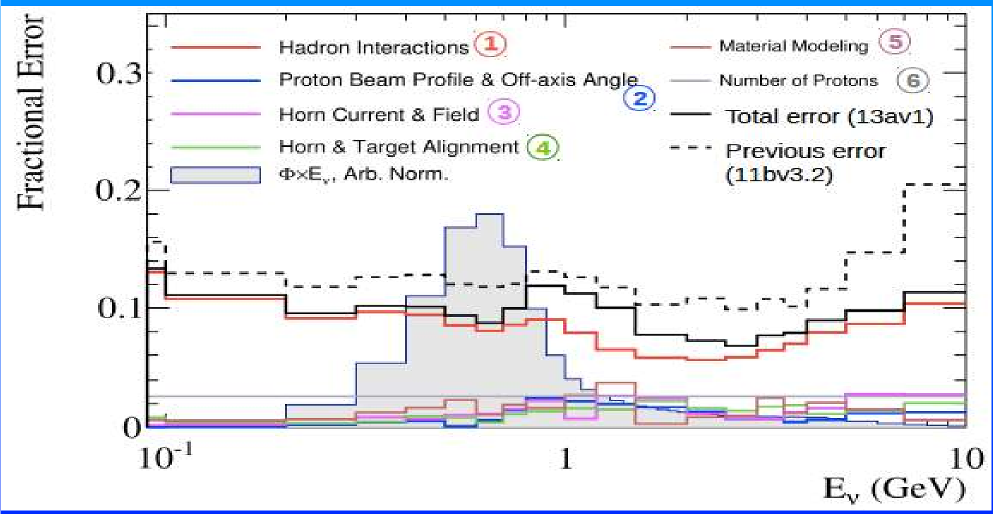
→ Re-evaluation of $\nu_\tau$ cross section & useful results for future $\nu_\tau$ experiments

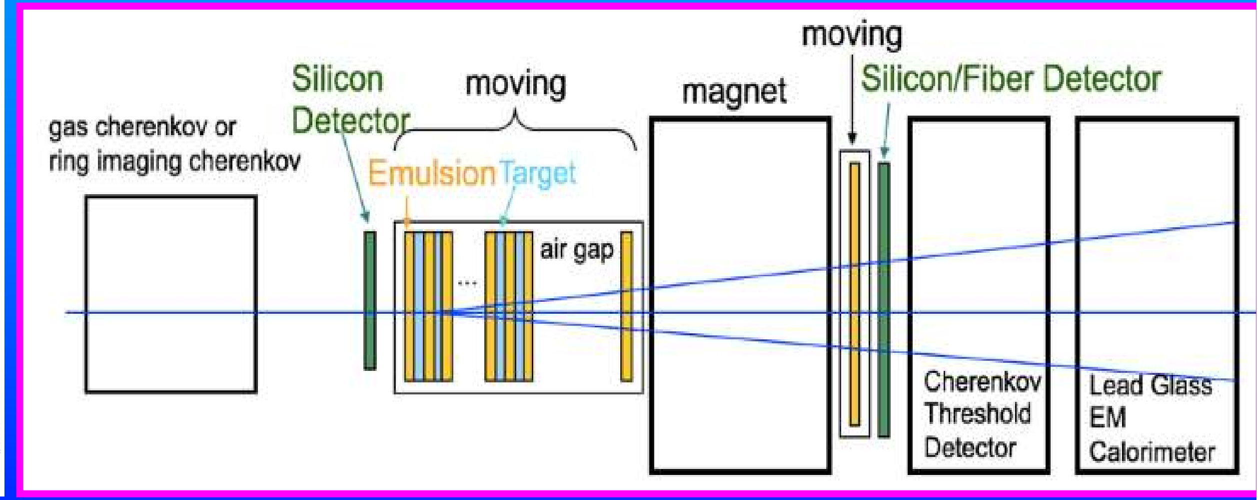


# Hadron production experiment@Fermilab




## Neutrino flux measurement → Hadron production study




・Chiba, Fermilab, ICRR, KEK, Kobe, Nagoya, Toho, TRIUMF

# Summary

- Precise neutrino-water interactions is important for future neutrino oscillation analysis. (Especially, 2p2h and $\nu_e$)
- We are performing a neutrino experiments at J-PARC to study low energy neutrino - nucleus interactions by introducing nuclear emulsion (**NINJA Experiment**).
- We have carried out a test experiment at J-PARC (**T60/T66/T68**) to check the feasibility and detector performance.
- We successfully demonstrated the detector performance and the analysis in the emulsion based detector (Iron, Water ECC).
- we proposed a new neutrino experiment to measure neutrino-water cross-section precisely (Physics Run) to J-PARC PAC.

# Back up