Neutrino Experiments with Nuclear Emulsion

- OPERA & J-PARC T60 -

福田　努　（東邦大学）

Tsutomu Fukuda (Toho Univ.)

Result from OPERA

Belgium
ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

Italy
Bari
Bologna
LNF Frascati
L'Aquila
LNGS
Naples
Padova
Rome
Salerno

Japan
Aichi edu.
Kobe
Nagoya
Toho
Nihon

Korea
Jinju

Russia
INR RAS Moscow
LPI RAS Moscow
ITEP Moscow
SINP MSU Moscow
JINR Dubna

Switzerland
Bern

Turkey
METU Ankara

PRL 115, 121802 (2015) PHYSICAL REVIEW LETTERS week ending 18 SEPTEMBER 2015

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

N. Agafonova,[1] A. Aleksandrov,[2] A. Anokhina,[3] S. Aoki,[4] A. Ariga,[5] T. Ariga,[5] D. Bender,[6] A. Bertolin,[7] I. Bodnarchuk,[8] C. Bozza,[9] R. Brugnera,[7,10] A. Buonaura,[2,11] S. Buontempo,[2] B. Büttner,[12] M. Chernyavsky,[13] A. Chukanov,[8] L. Consiglio,[2] N. D'Ambrosio,[14] G. De Lellis,[2,11] M. De Serio,[15,16] P. Del Amo Sanchez,[17] A. Di Crescenzo,[2] D. Di Ferdinando,[18] N. Di Marco,[14] S. Dmitrievski,[8] M. Dracos,[19] D. Duchesneau,[17] S. Dusini,[7] T. Dzhatdoev,[3] J. Ebert,[12] A. Ereditato,[5] R. A. Fini,[16] F. Fornari,[18,20] T. Fukuda,[21] G. Galati,[2,11] A. Garfagnini,[7,10] J. Goldberg,[22] Y. Gornushkin,[8] G. Grella,[9] A. M. Guler,[6] C. Gustavino,[23] C. Hagner,[12] T. Hara,[4] H. Hayakawa,[24] A. Hollnagel,[12] B. Hosseini,[2,11] K. Ishiguro,[24] K. Jakovcic,[25] C. Jollet,[19] C. Kamiscioglu,[6] M. Kamiscioglu,[6] J. H. Kim,[26] S. H. Kim,[26,*] N. Kitagawa,[24] B. Klicek,[25] K. Kodama,[27] M. Komatsu,[24] U. Kose,[7,†] I. Kreslo,[5] F. Laudisio,[9] A. Lauria,[2,11] A. Ljubicic,[25] A. Longhin,[28] P. F. Loverre,[23,29] A. Malgin,[1] M. Malenica,[25] G. Mandrioli,[18] T. Matsuo,[21] T. Matsushita,[24] V. Matveev,[1] N. Mauri,[18,20] E. Medinaceli,[7,10] A. Meregaglia,[19] S. Mikado,[30] M. Miyanishi,[24] F. Mizutani,[4] P. Monacelli,[23] M. C. Montesi,[2,11] K. Morishima,[24] M. T. Muciaccia,[15,16] N. Naganawa,[24] T. Naka,[24] M. Nakamura,[24] T. Nakano,[24] Y. Nakatsuka,[24] K. Niwa,[24] S. Ogawa,[21] A. Olchevsky,[8] T. Omura,[24] K. Ozaki,[4] A. Paoloni,[28] L. Paparella,[15,16] B. D. Park,[26,‡] I. G. Park,[26] L. Pasqualini,[18,20] A. Pastore,[15] L. Patrizii,[18] H. Pessard,[17] C. Pistillo,[5] D. Podgrudkov,[3] N. Polukhina,[13] M. Pozzato,[18,20] F. Pupilli,[28] M. Roda,[7,10] T. Roganova,[3] H. Rokujo,[24] G. Rosa,[23,29] O. Ryazhskaya,[1] O. Sato,[24,§] A. Schembri,[14] W. Schmidt-Parzefall,[12] I. Shakirianova,[1] T. Shchedrina,[13,11] A. Sheshukov,[8] H. Shibuya,[21] T. Shiraishi,[24] G. Shoziyoev,[3] S. Simone,[15,16] M. Sioli,[18,20] C. Sirignano,[7,10] G. Sirri,[18] A. Sotnikov,[8] M. Spinetti,[28] L. Stanco,[7] N. Starkov,[13] S. M. Stellacci,[9] M. Stipcevic,[25] P. Strolin,[2,11] S. Takahashi,[4] M. Tenti,[18] F. Terranova,[28,31] V. Tioukov,[2] S. Tufanli,[5,∥] P. Vilain,[32] M. Vladymyrov,[13,¶] L. Votano,[28] J. L. Vuilleumier,[5] G. Wilquet,[32] B. Wonsak,[12] C. S. Yoon,[26] and S. Zemskova[8]

(OPERA Collaboration)

arXiv:1507.01417

PRL **115,** 121802 (2015) PHYSICAL REVIEW LETTERS week ending 18 SEPTEMBER 2015

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The OPERA experiment was designed to search for $\nu_\mu \to \nu_\tau$ oscillations in appearance mode, i.e., by detecting the τ leptons produced in charged current ν_τ interactions. The experiment took data from 2008 to 2012 in the CERN Neutrinos to Gran Sasso beam. The observation of the $\nu_\mu \to \nu_\tau$ appearance, achieved with four candidate events in a subsample of the data, was previously reported. In this Letter, a fifth ν_τ candidate event, found in an enlarged data sample, is described. Together with a further reduction of the expected background, the candidate events detected so far allow us to assess the discovery of $\nu_\mu \to \nu_\tau$ oscillations in appearance mode with a significance larger than 5σ.

5.1σ

DOI: 10.1103/PhysRevLett.115.121802 PACS numbers: 14.60.Pq

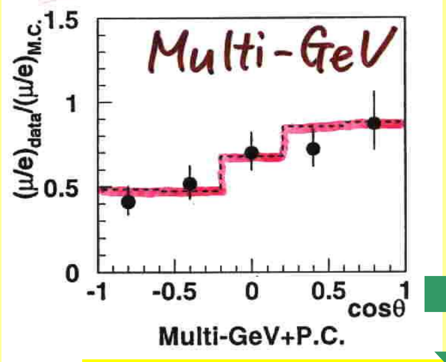
(OPERA Collaboration)

arXiv:1507.01417

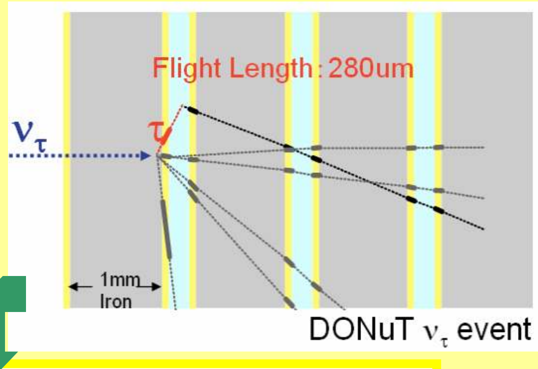
The OPERA experiment

Oscillation Project with Emulsion tRacking Apparatus

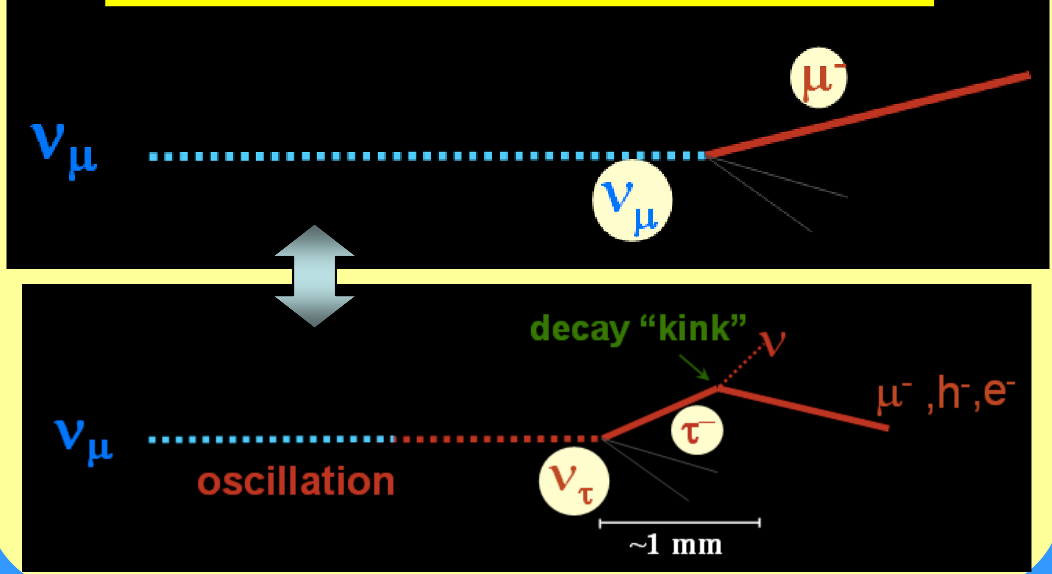
Neutrino oscillation (disappearance)
Result from SK in 1998

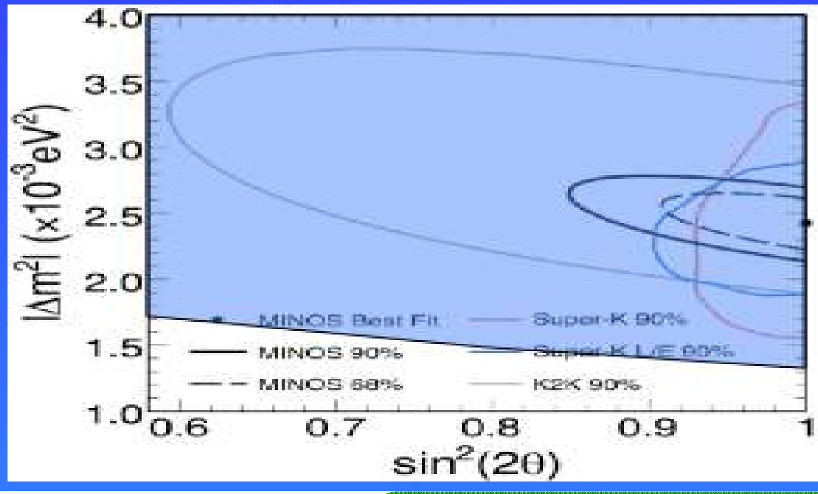


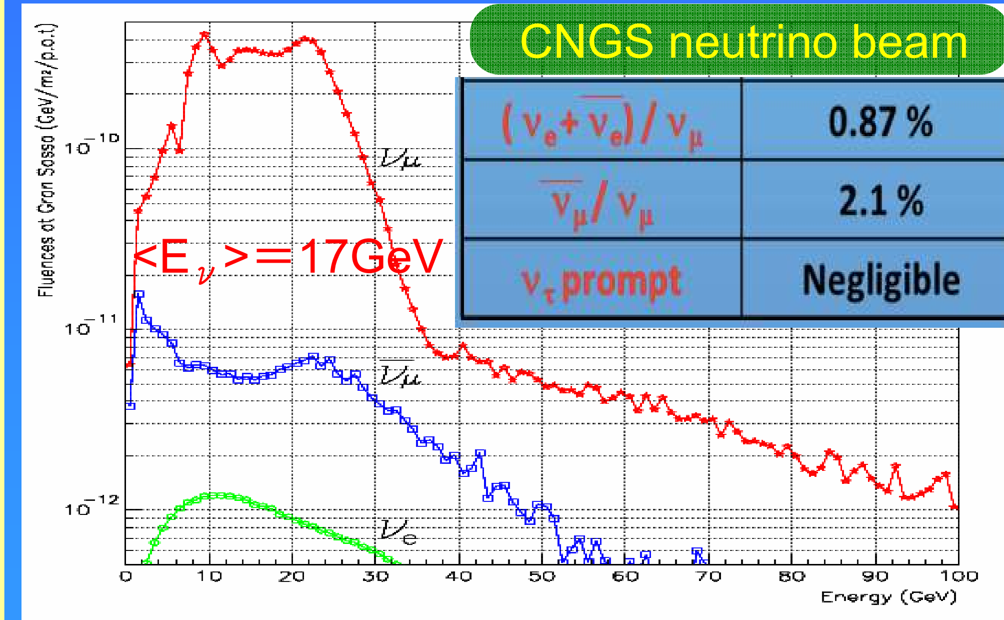
Direct observation of ν_τ events
Result of DONuT in 2001



Verification of neutrino oscillation with ν_τ appearance





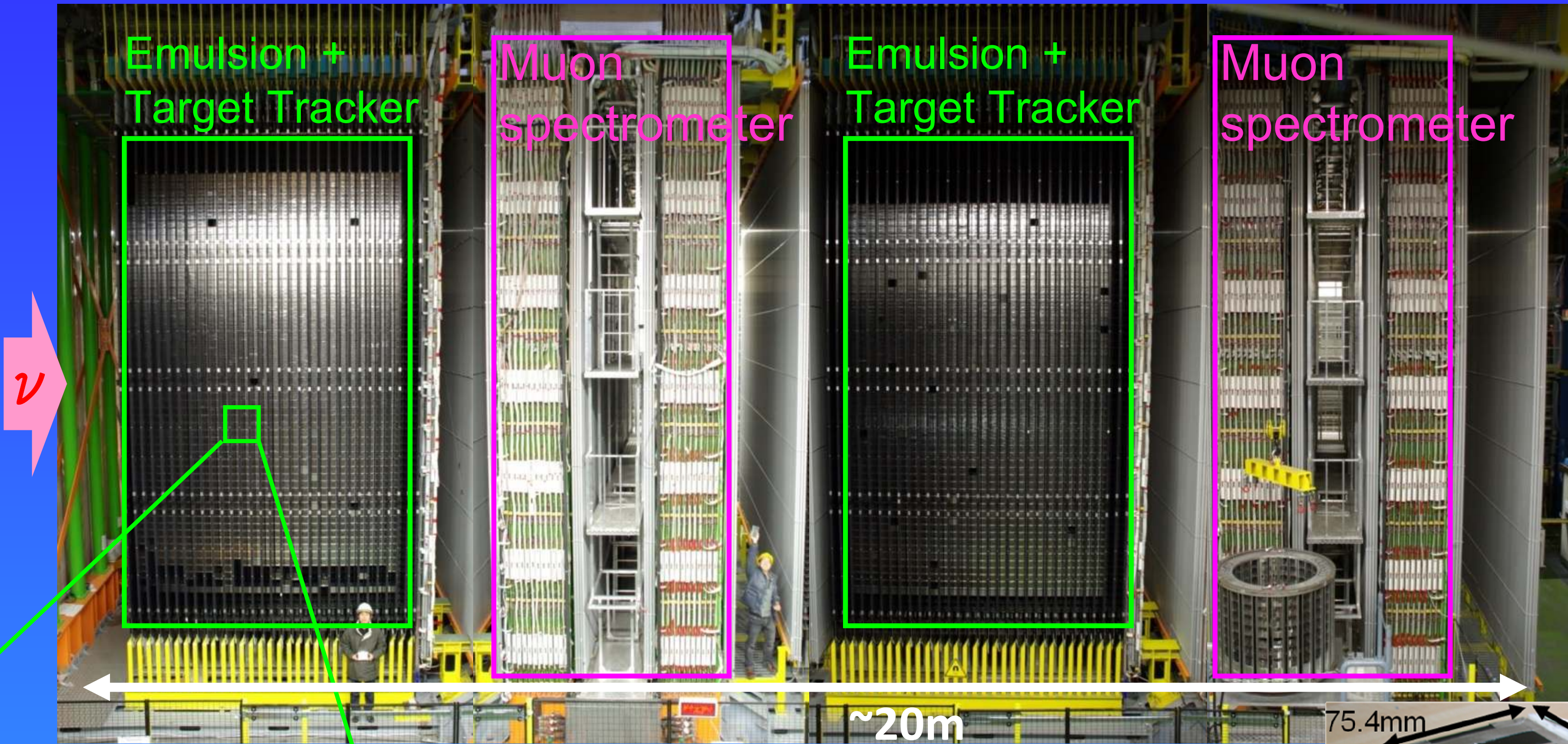


$(\nu_e+\bar{\nu}_e)/\nu_\mu$	0.87 %
$\bar{\nu}_\mu/\nu_\mu$	2.1 %
ν_τ prompt	Negligible

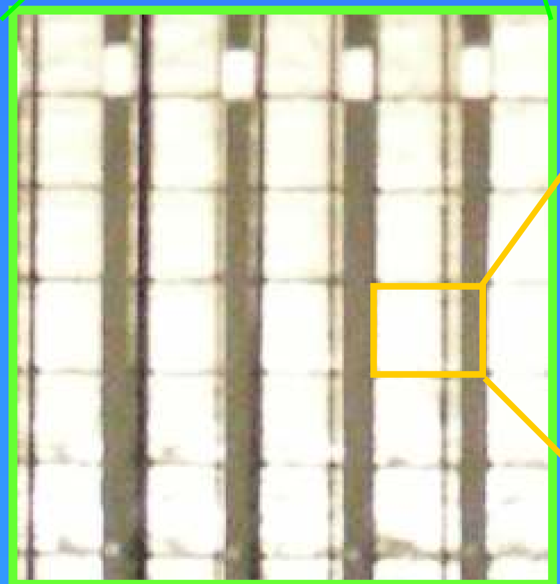
$$P(\nu_\mu \to \nu_\tau) \sim \sin^2(2\theta_{23}) \cdot \sin^2\left(1.27 \cdot \Delta m^2_{23} \cdot \frac{L}{E}\right) \sim 1.7\%$$

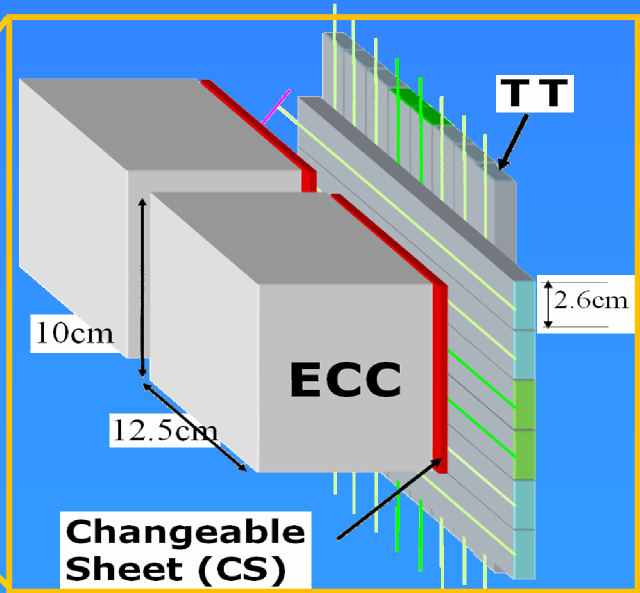
$\sin^2 2\theta_{23} = 1.0$, $\Delta m_{23}^2 = (2.43 \pm 0.13) \times 10^{-3}\ eV^2$

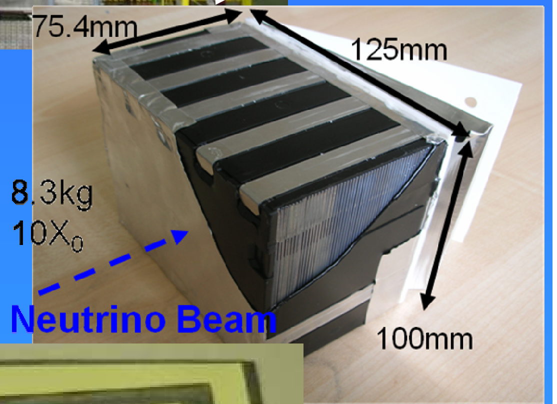
The OPERA Detector

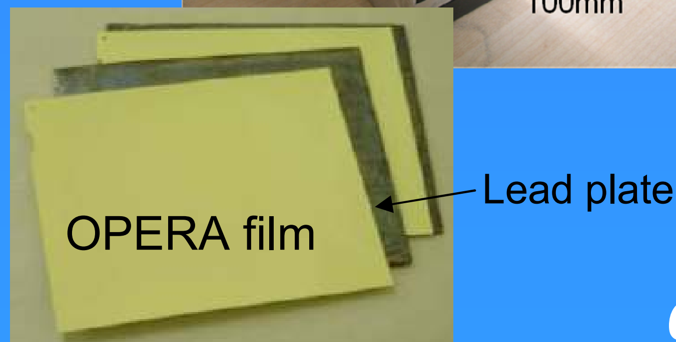


ECC:
~150,000
(1.25kton)



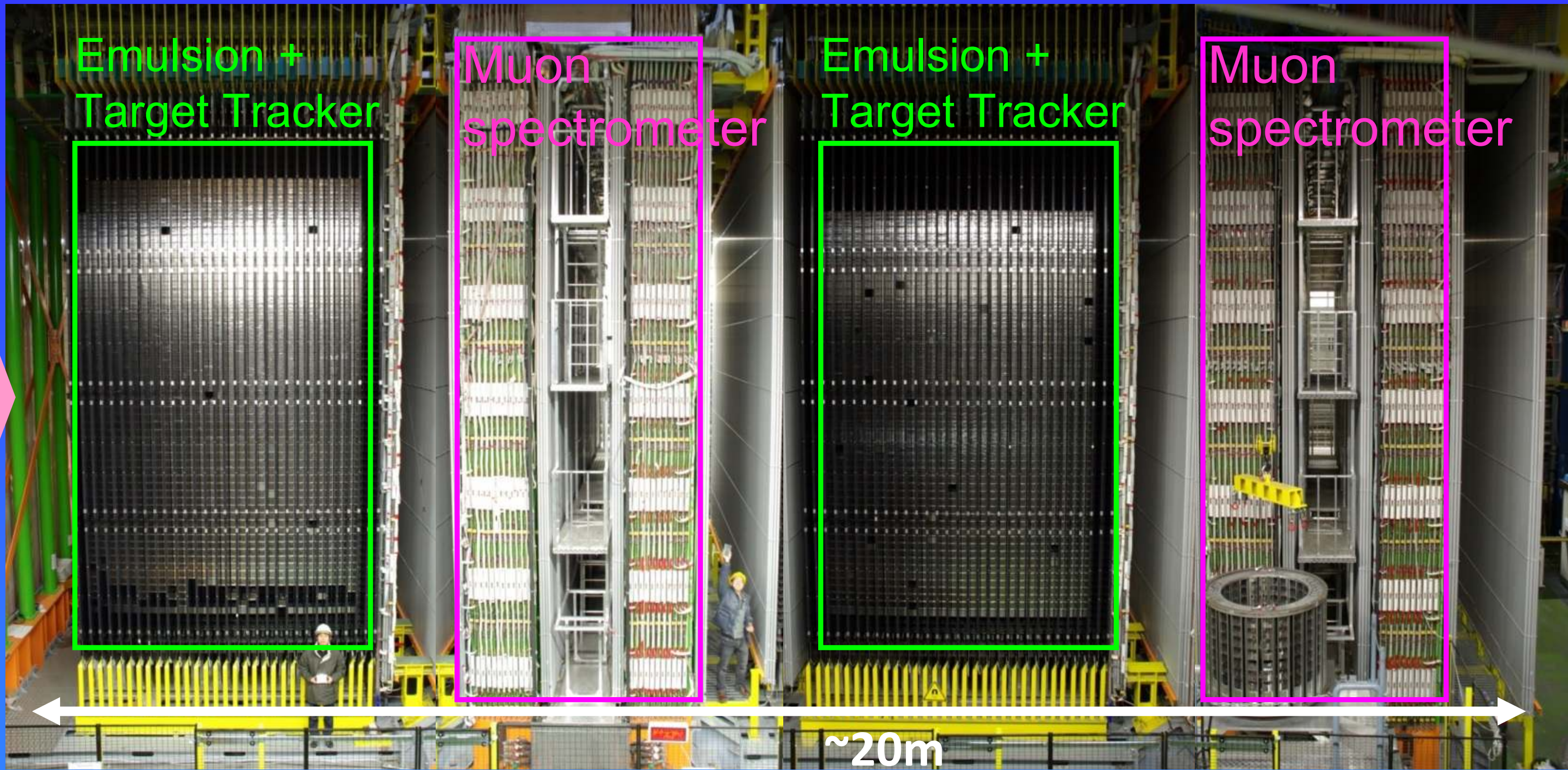




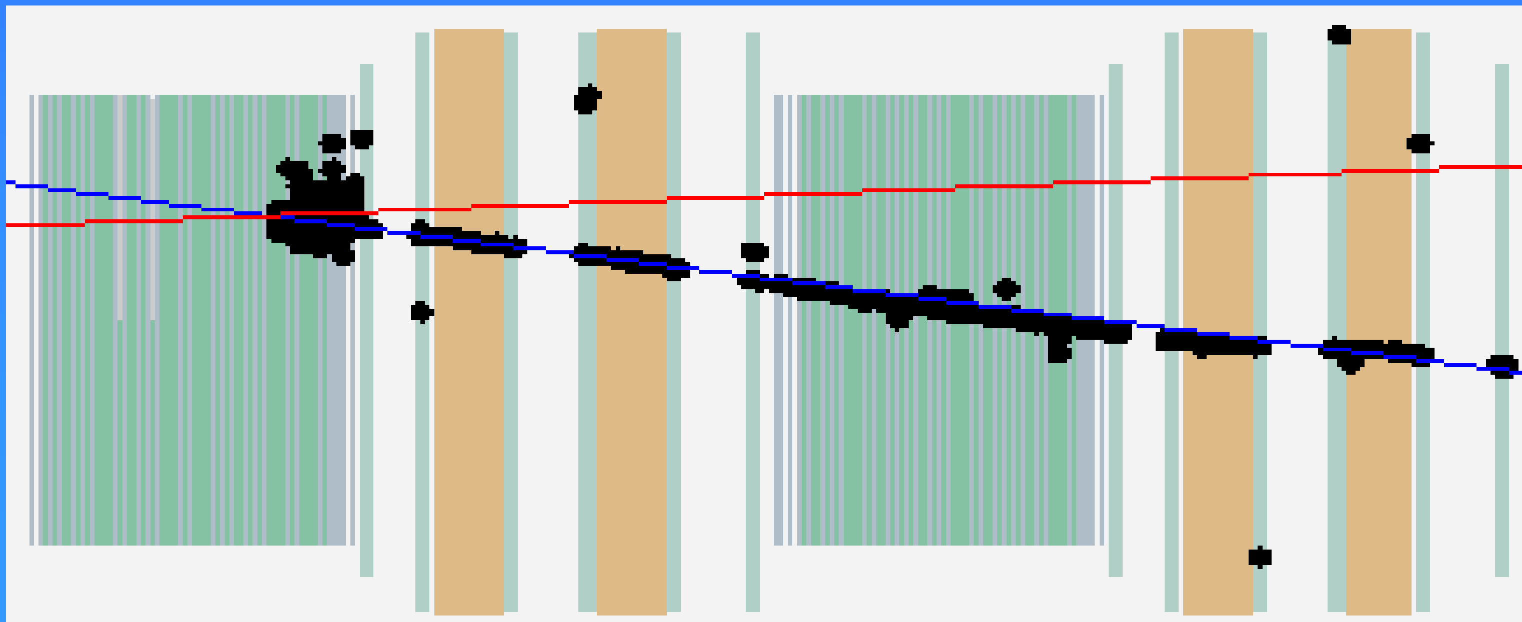


Refresh 900万枚のフィルムのノイズ消し

The OPERA Detector

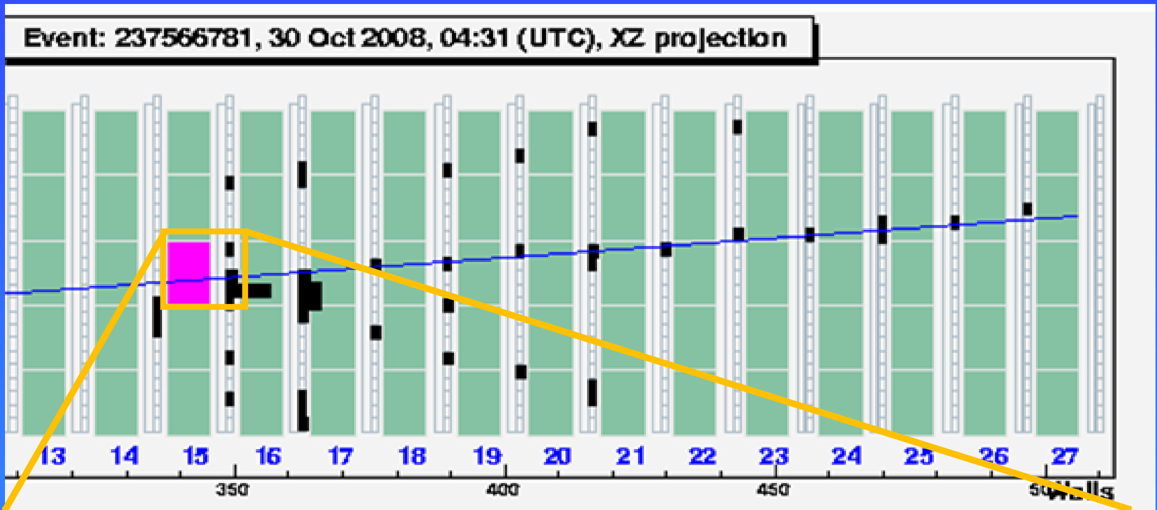


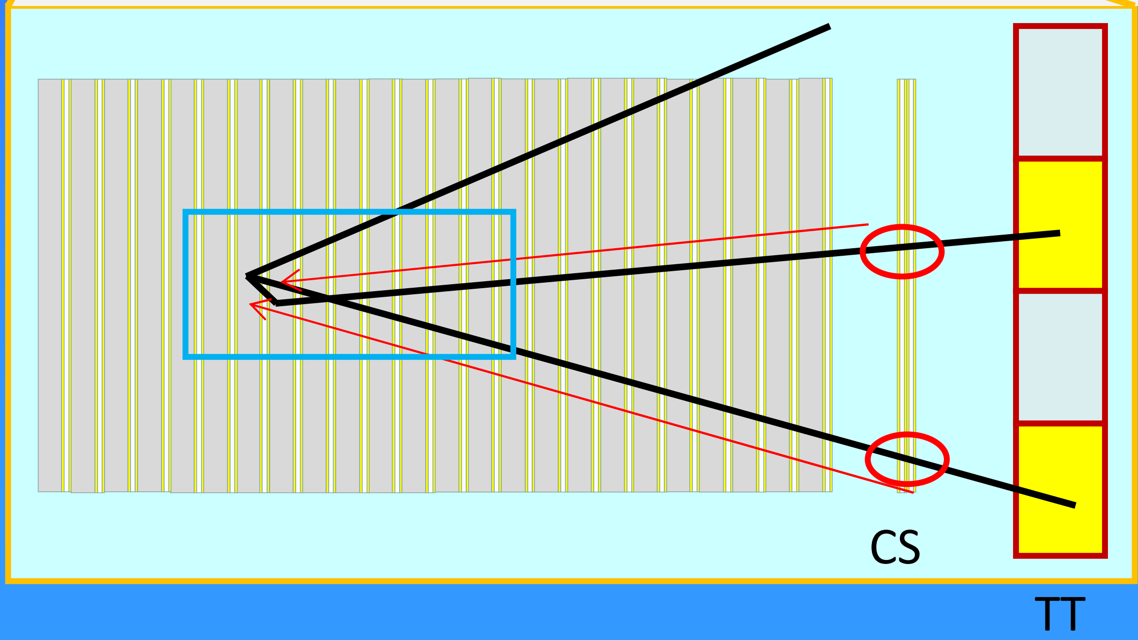
ν

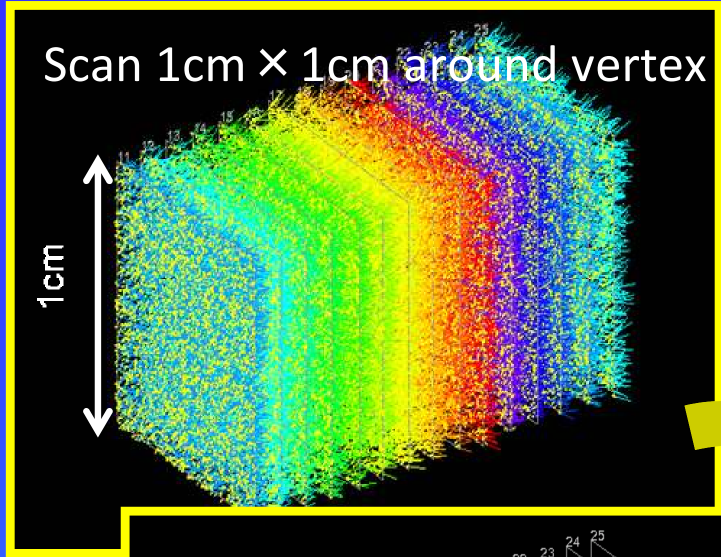


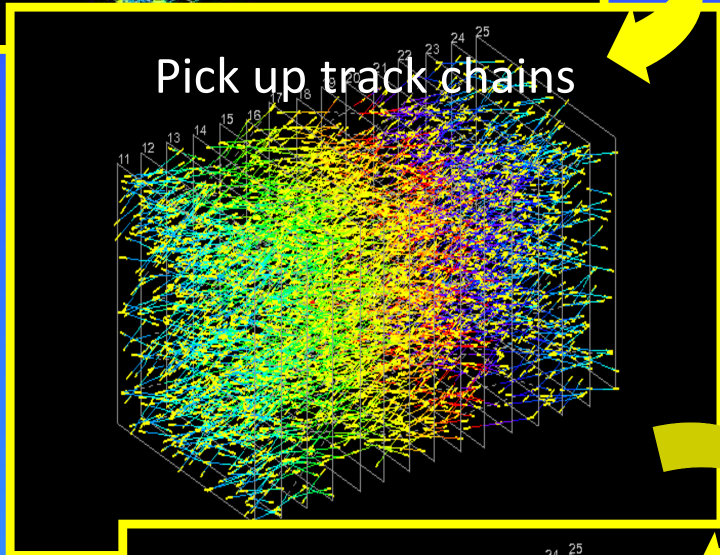
Neutrino event analysis

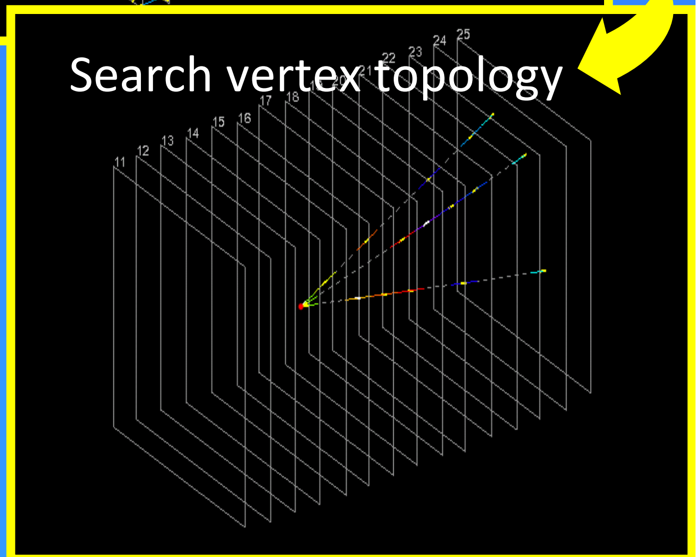
Scan Back location & Decay search







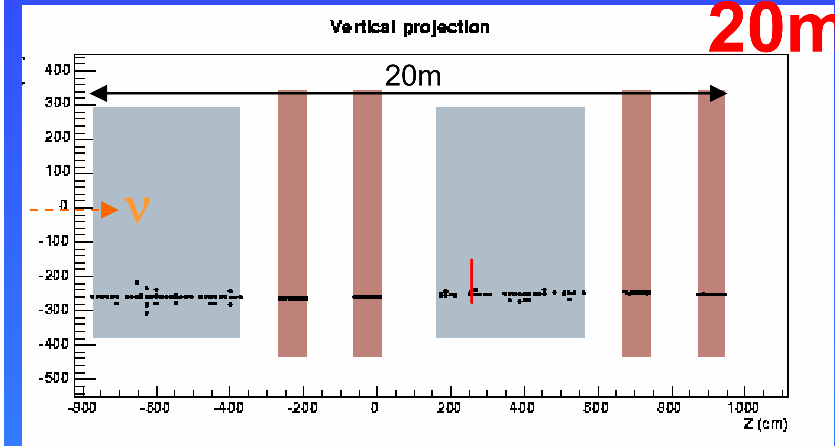


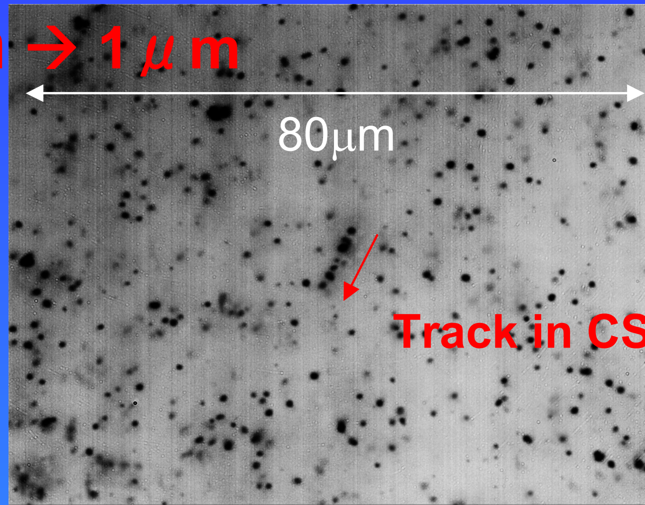


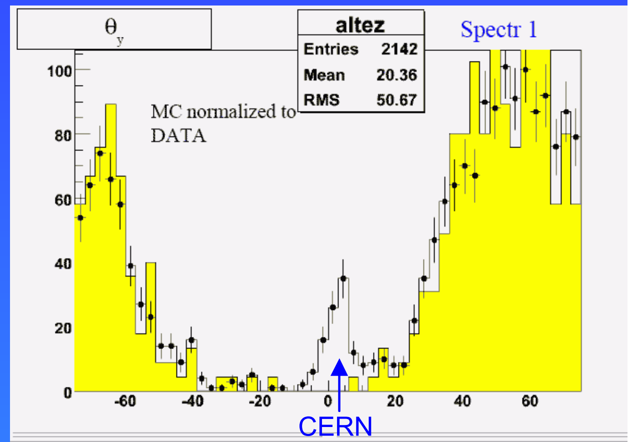
Commissioning-2006

CERNからニュートリノビームをテスト照射。
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。

20m → 1 μm







2006年9月12日（火） 中日新聞朝刊

ニュートリノ

「質量あり」最終確認へ

日欧共同実験 名大教授ら「計画通り機能」

素粒子ニュートリノが質量を持つことの最終確認を目指す国際共同実験OPERA（オペラ）が欧州で始まり、参加する名古屋大の丹羽公雄教授らは十一日、「実験装置が計画通りの機能を発揮していることを確認した」と発表した。実験はスイス・ジュネーブ近郊にある欧州合同原子核研究所（CERN）の加速器からニュートリノを発射。イタリア・アペニン山脈地下のグランサッソ国立研究所に設置した検出器で地下約七百三十キロを飛ぶ間にニュートリノの種類が変わる振動現象を観測する。

振動はニュートリノが質量を持つ証拠だ。東京大宇宙線研究所のスーパーカミオカンデ（岐阜県飛騨市）実験で一九九八年に発見され、ノーベル物理学賞が期待されている。同実験はニュートリノの一部が検出できない別種に変わって減ったようにみえる現象をとらえ、振動を見つけた。オペラ実験は逆に、加速器でできる「ミュー型」という種類のニュートリノが変わって出現する「タウ型」を検出することにより、裏付けを目指す。

実験は十月下旬から本格化する。実験期間の五年間で、二十例程度のタウ型の反応が検出できると予想されている。

track is found !

（9/7 19:23）

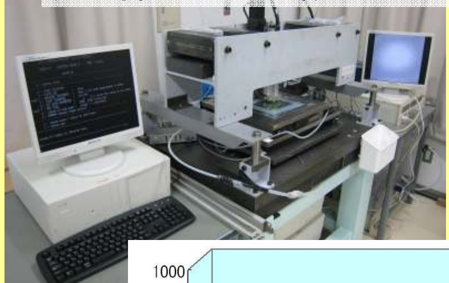
***New J. Phys.* 8 (2006) 303**

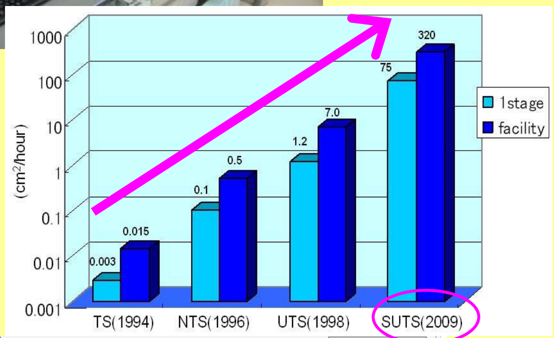
Technical improvements

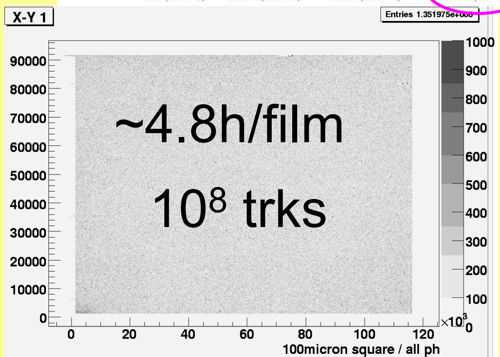
- Challenge in OPERA → 大量のフィルム解析

SUTS
High speed scanning
x 60

流し撮りによる読み取りの高速化



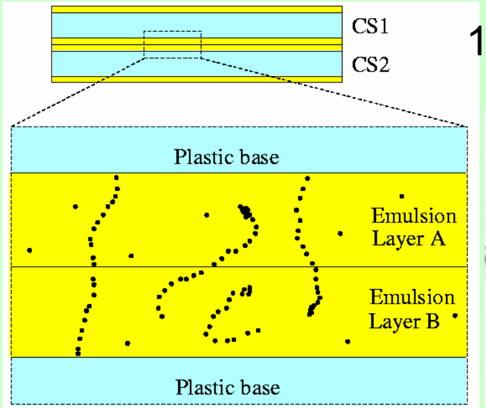


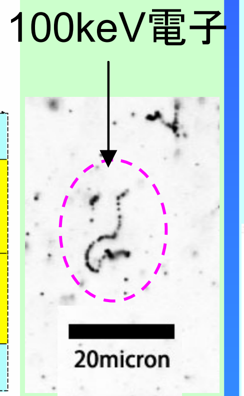


T.Nakano et al., *JINST* 5:P04011 (2010).

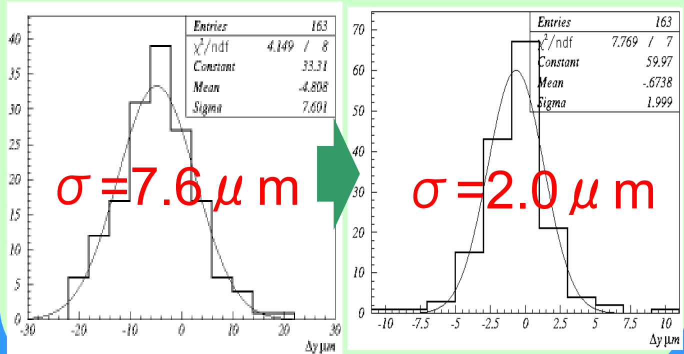
Compton Alignment
Precision alignment
x 10

環境放射線によるノイズ飛跡を用いてフィルム間の精密アライメント





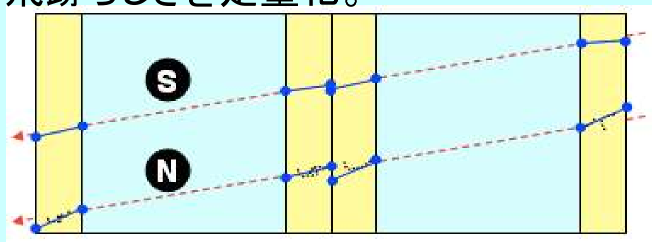
Allowance: 30 μm → 10 μm

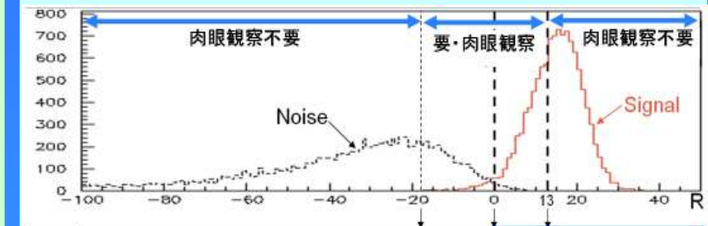


S. Miyamoto et al., *NIM* A 575 (2007) 466.

Track Ranking
High S/N discrimination
x 100

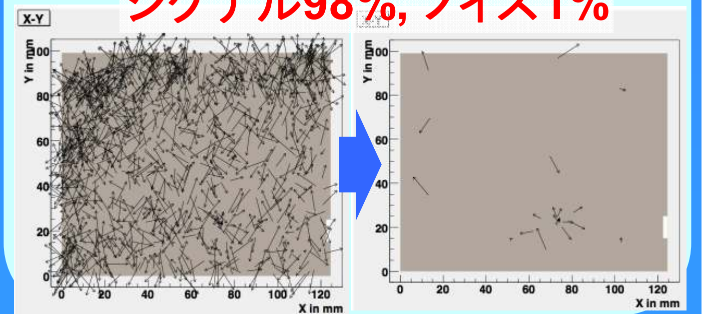
直線性と濃さを総合評価し、シグナル飛跡らしさを定量化。





Signal	<0.1%	2%	34%	64%
Noise	77%	22%	1%	<0.1%

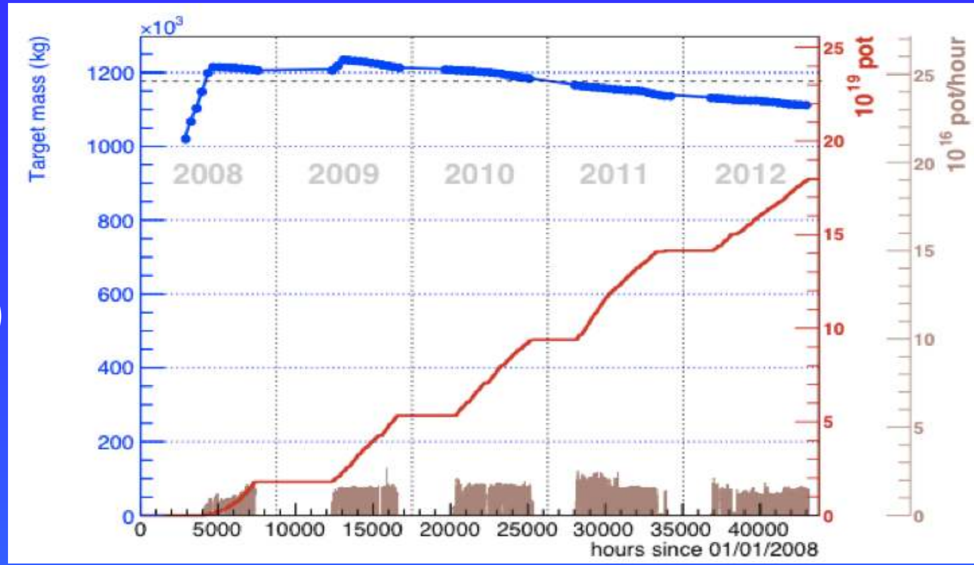
シグナル98%, ノイズ1%

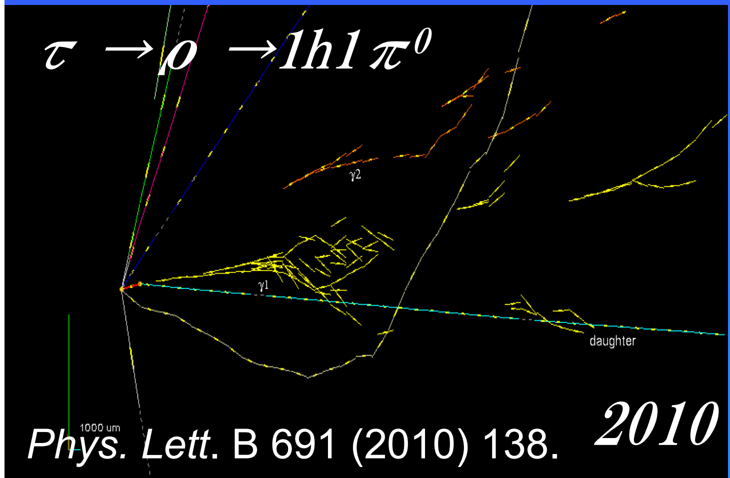


T.Fukuda et al., *JINST* 5:P04009 (2010).

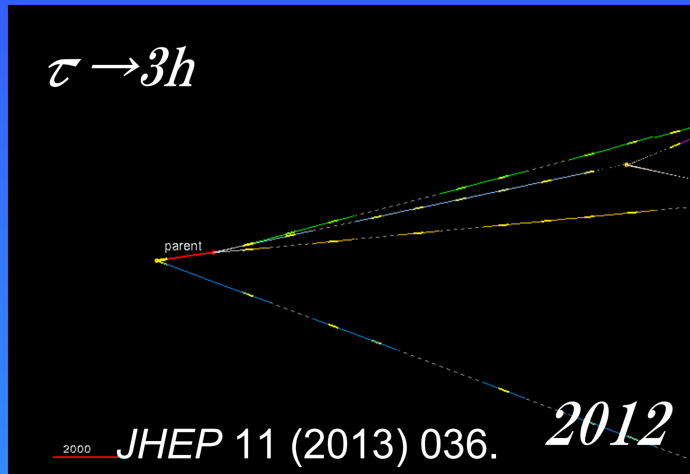
Analysis status

- ν beam : 5year (965days), 17.97 x 10^{19} p.o.t. (80% of proposal)
- 7041 neutrino events located. 6682 events decay searched.

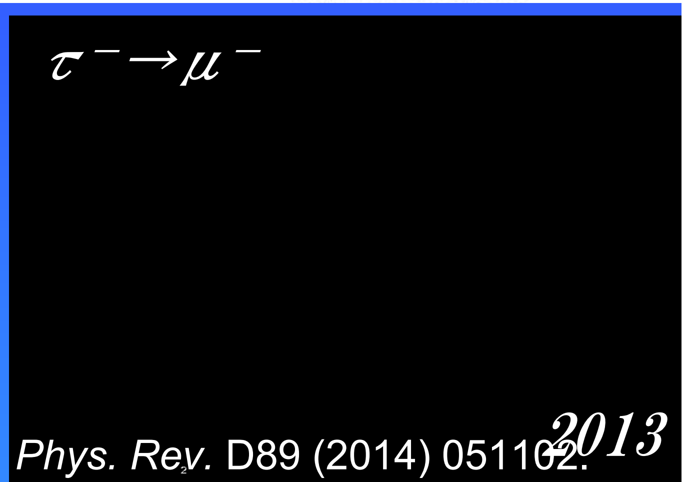




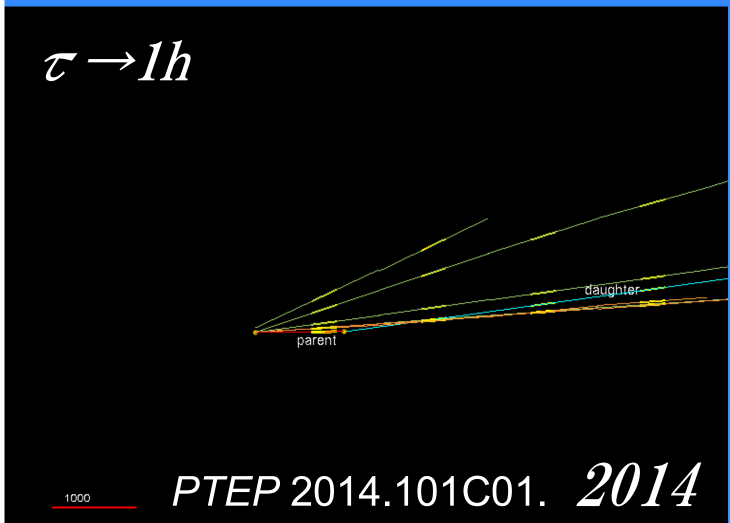
Phys. Lett. B 691 (2010) 138.



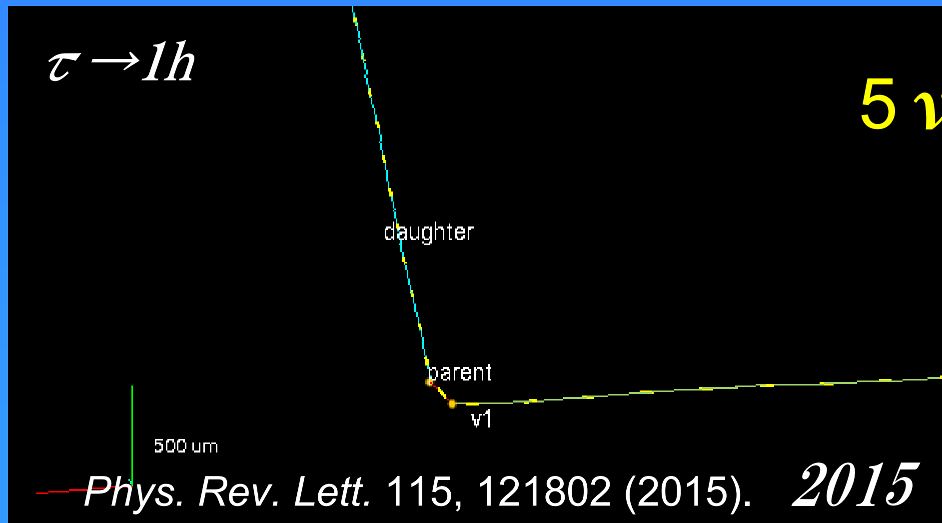
JHEP 11 (2013) 036.



Phys. Rev. D89 (2014) 051102.



PTEP 2014.101C01.



Phys. Rev. Lett. 115, 121802 (2015).

5 ν_τ 反応検出!!

Analysis status

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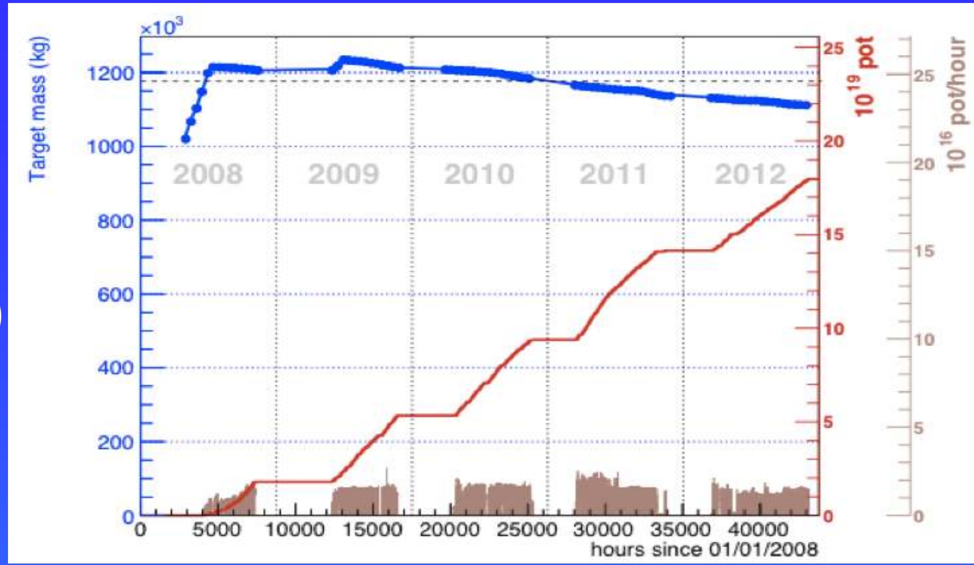
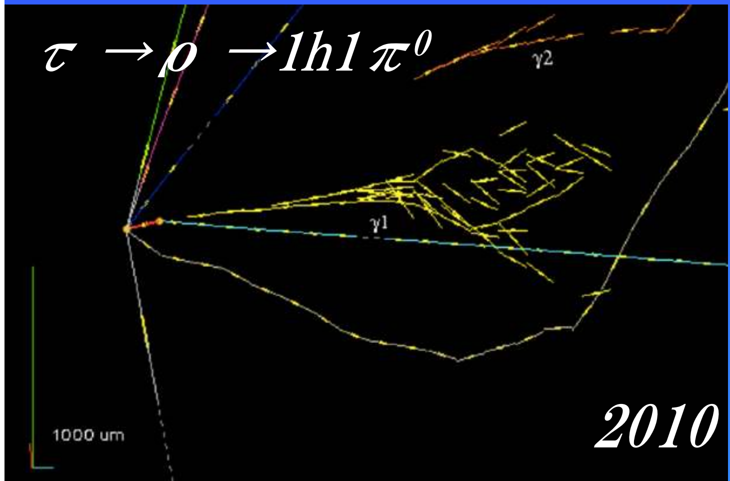
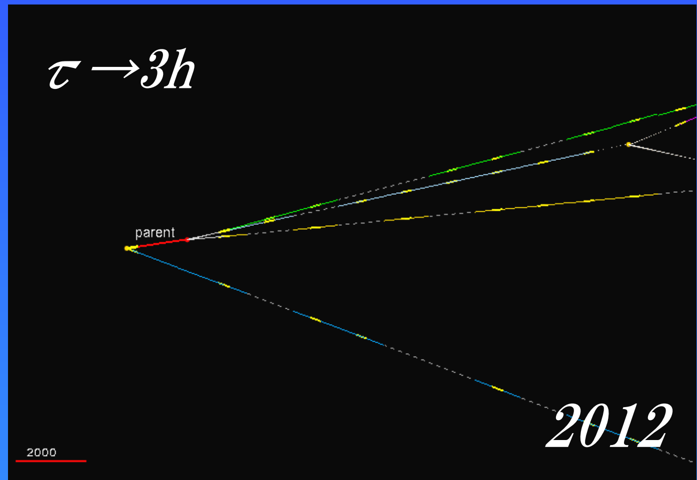
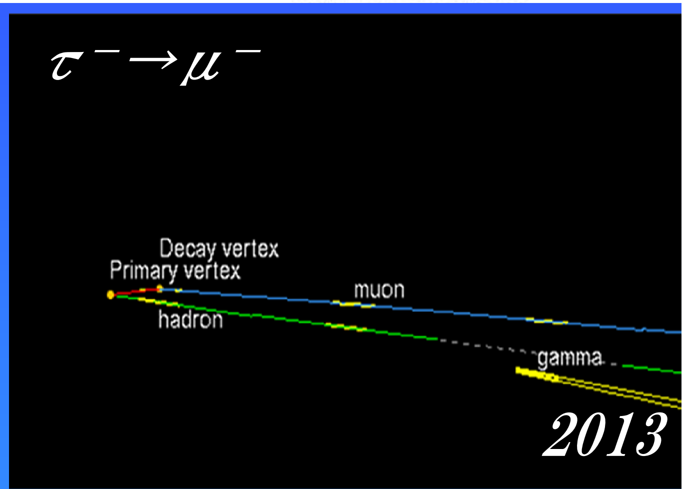
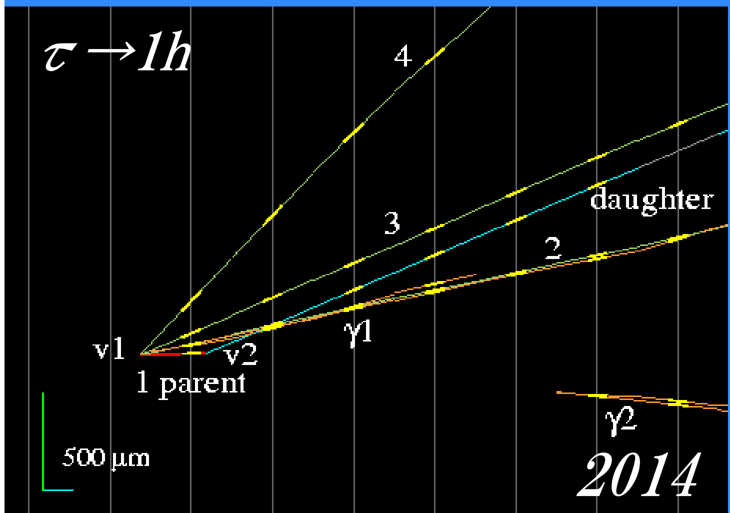
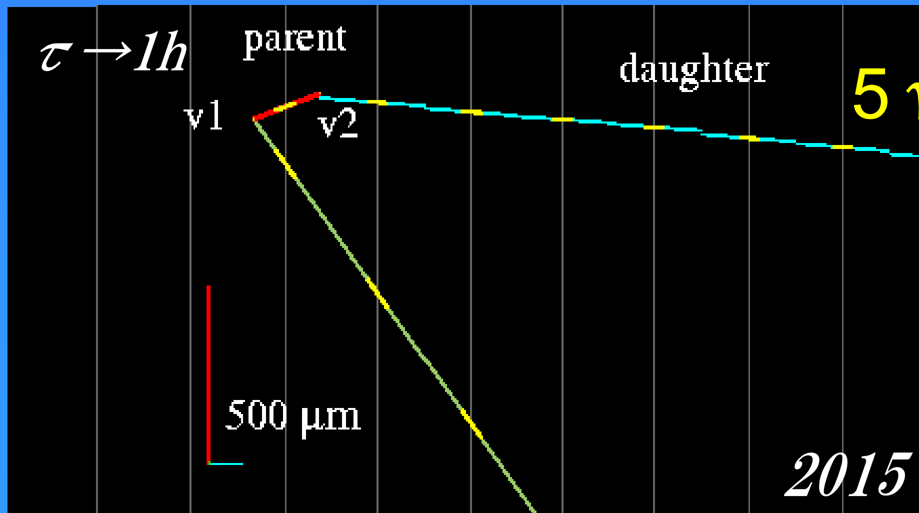






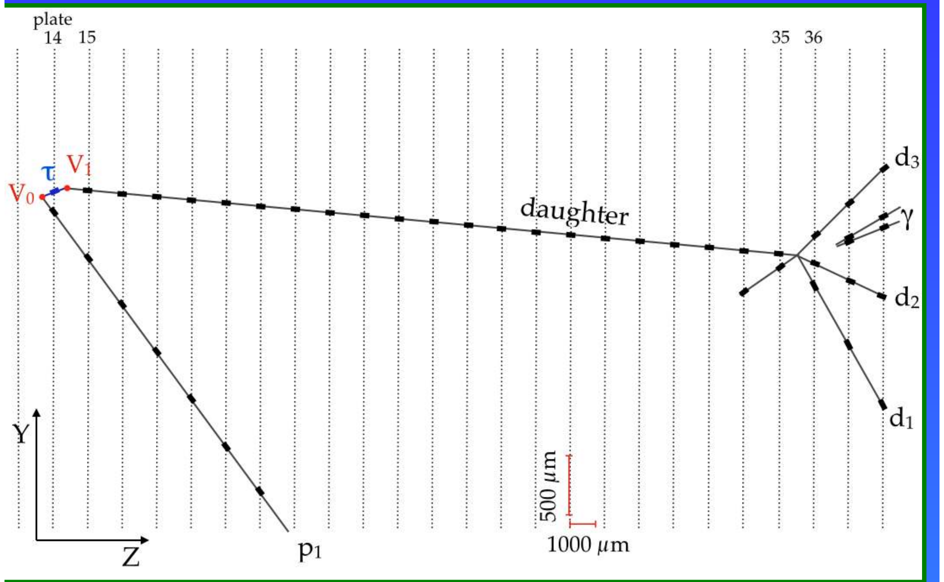


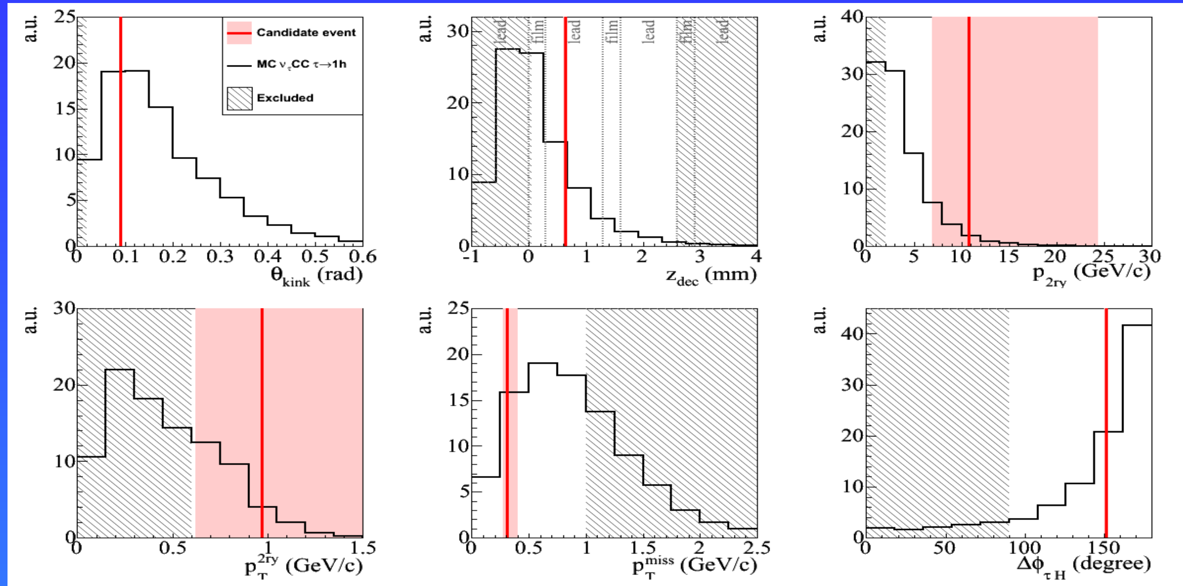


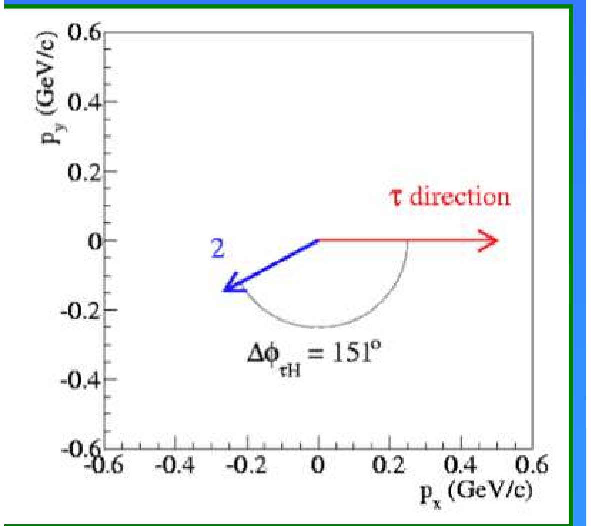


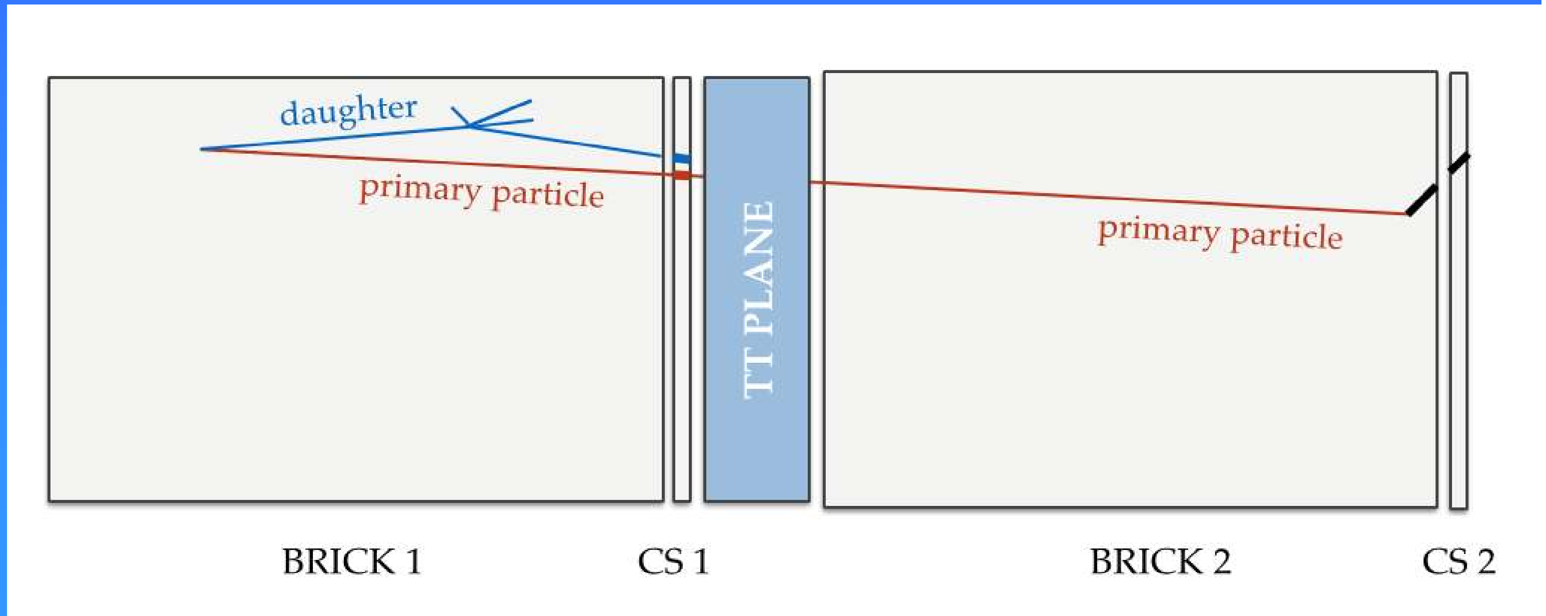
5 ν_τ 反応検出!!

5th ν τ event





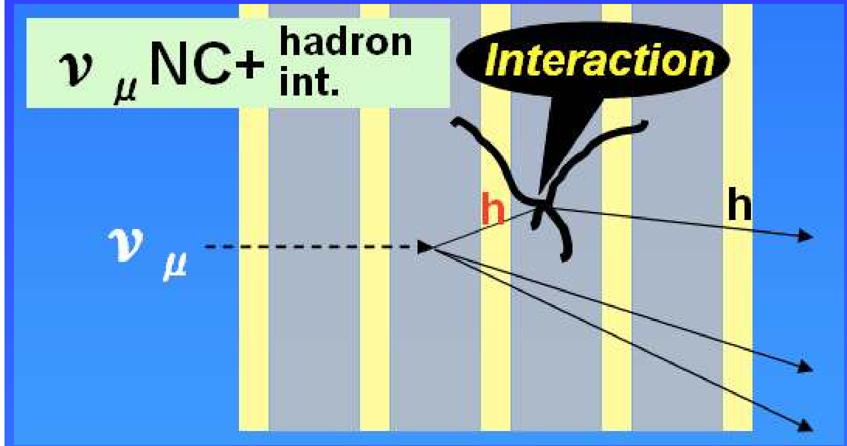


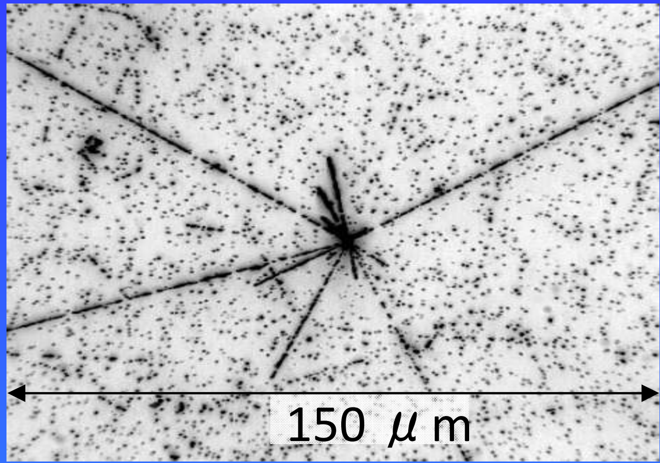


- 全てのTopology, kinematical cut をクリア

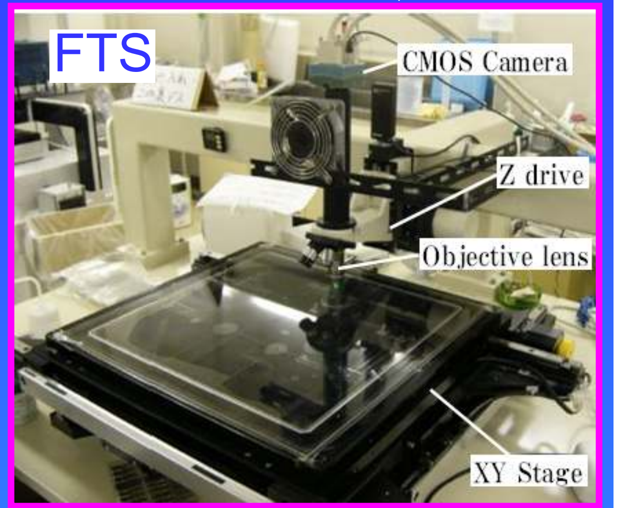
Background reduction

- 核破砕片探索によるハドロンの2次反応バックグラウンドの低減

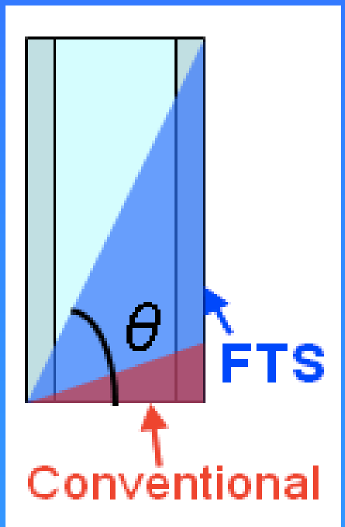


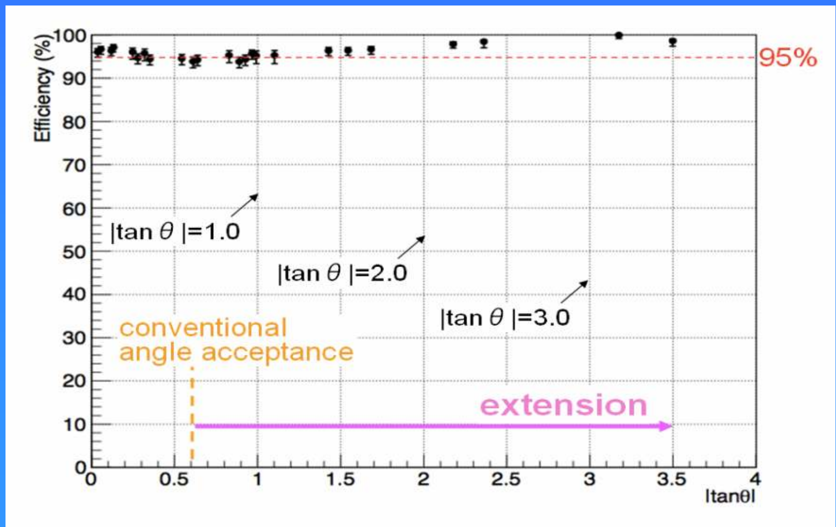


大角度飛跡自動認識装置の開発

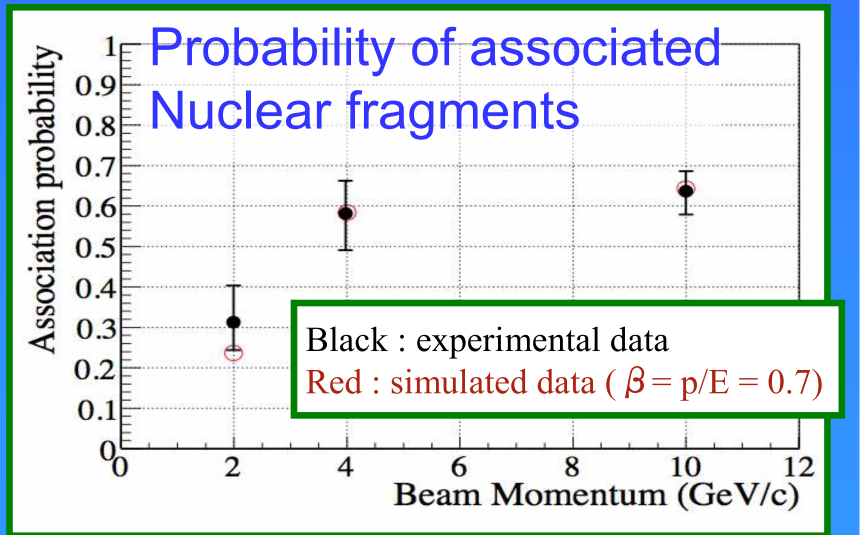


核破砕片があればハドロン2次衝突反応→無ければ崩壊事象





T.Fukuda et al., *JINST* 9:P12017 (2014).



H. Ishida et al., *PTEP* 2014. 093C01.

大角度飛跡を自動検出できる装置を新たに開発し、実際にハドロン反応の核破砕片付随率を実験で導出。
検出したタウニュートリノ反応に適用し、全てのイベントに核破砕片が付いていないことを確認した。

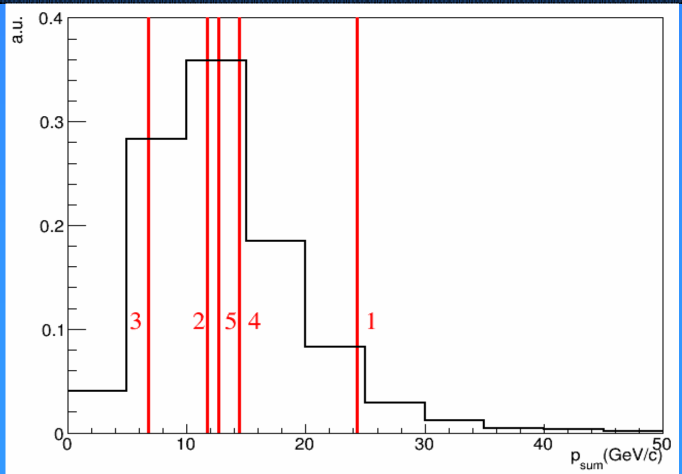
Oscillation analysis

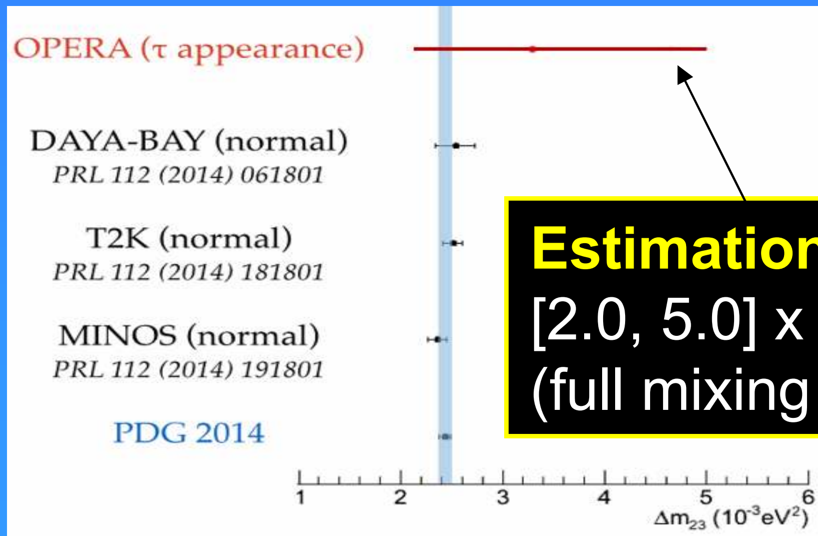
Expected signal and background events for the analyzed data sample

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

- 5 ν_τ events 検出。BG=0.25 events.
  → バックグラウンドで説明できる確率＝1.1 X 10^{-7}
  → **Significance = 5.1 σ, Discovery of ν_τ Appearance !**

Energy distribution of ν_τ events





Estimation of Δm_{23}^2
[2.0, 5.0] x 10^{-3} eV (90% C.L.)
(full mixing を仮定して)

Scientific Background on the Nobel Prize in Physics 2015

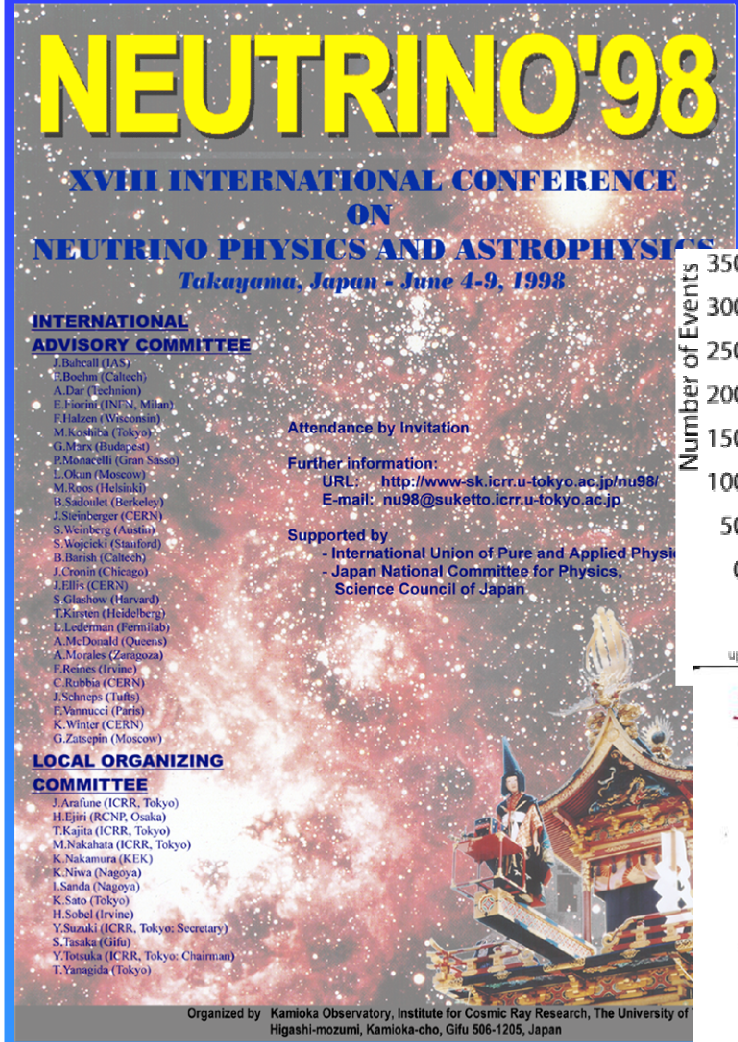
NEUTRINO OSCILLATIONS

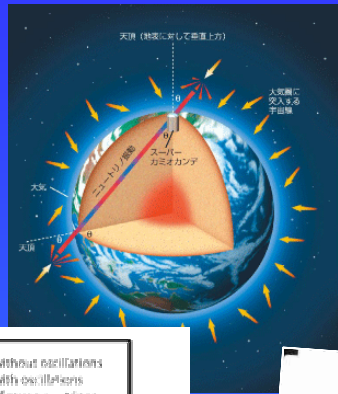
compiled by the Class for Physics of the Royal Swedish Academy of Sciences

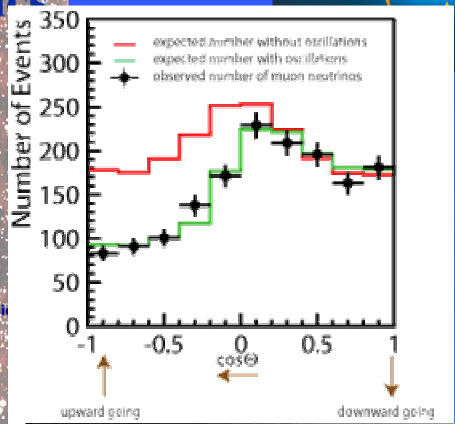
n-

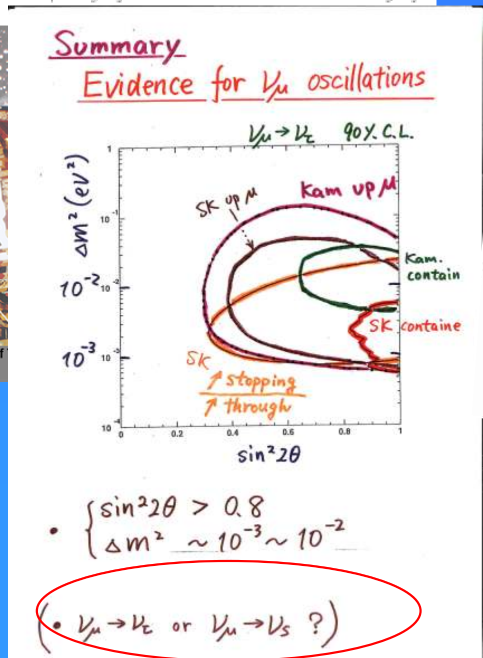
Super-Kamiokande's oscillation results were confirmed by the detectors MACRO [55] and Soudan [56], by the long-baseline accelerator experiments K2K [57], MINOS [58] and T2K [59] and more recently also by the large neutrino telescopes ANTARES [60] and IceCube [61]. Appearance of tau-neutrinos in a muon-neutrino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

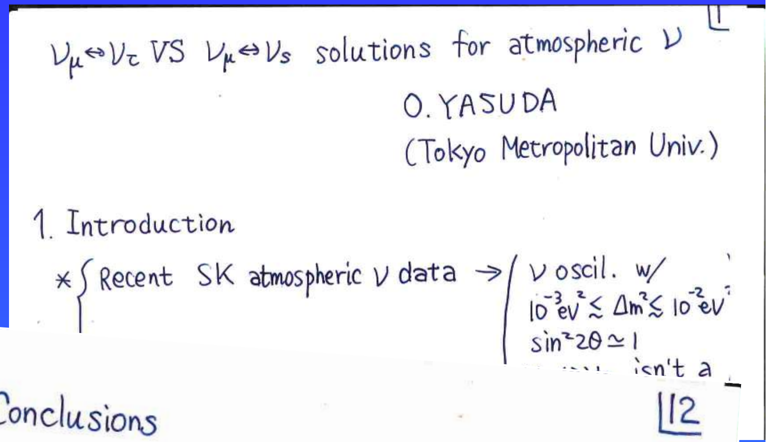
Looking back to XX century…









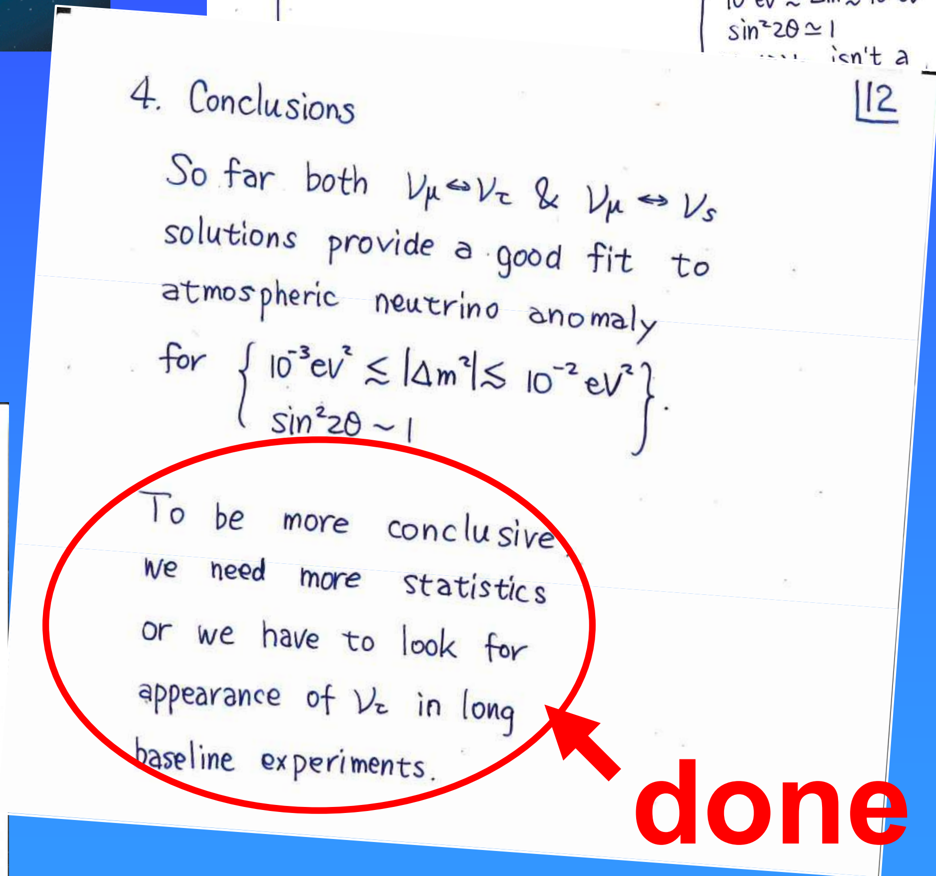


$\nu_\mu \leftrightarrow \nu_\tau$ VS $\nu_\mu \leftrightarrow \nu_s$ solutions for atmospheric ν

O. YASUDA
(Tokyo Metropolitan Univ.)

1. Introduction

* Recent SK atmospheric ν data → ν oscil. w/ $10^{-3} eV^2 \lesssim \Delta m^2 \lesssim 10^{-2} eV^2$, $\sin^2 2\theta \simeq 1$ … isn't a …



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 $\left\{ 10^{-3} eV^2 \lesssim |\Delta m^2| \lesssim 10^{-2} eV^2, \ \sin^2 2\theta \sim 1 \right\}$.

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

done

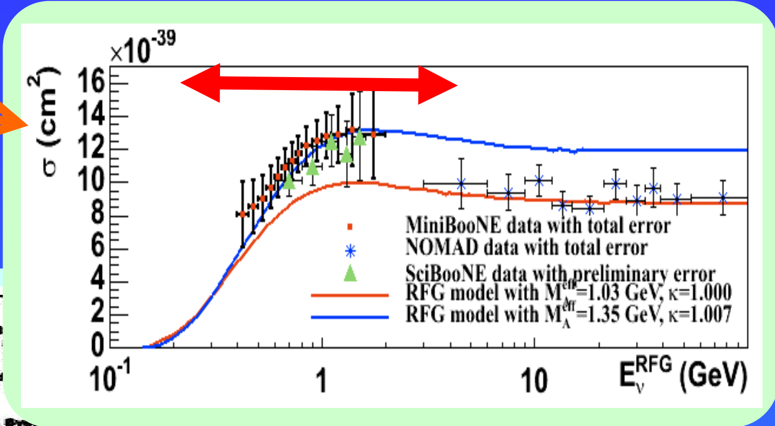
Next step … !!

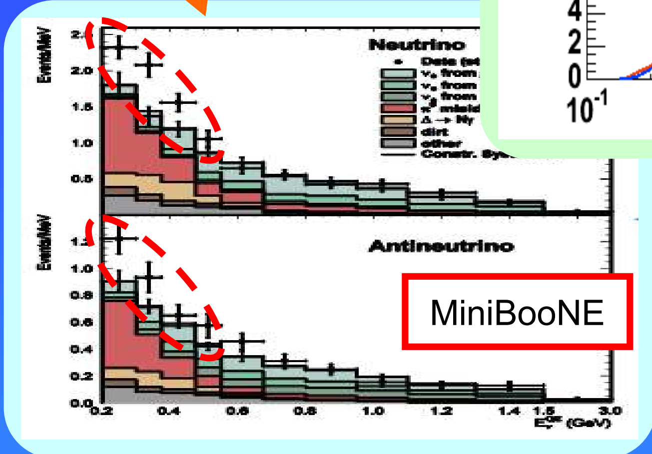
Status of J-PARC T60

J-PARC T60

PI : T. Fukuda (Toho Univ.)
→ tsutomu.fukuda@ph.sci.toho-u.ac.jp

Future Physics goals
- Neutrino Cross Sections
- Sterile neutrinos





New experimental program to study low energy neutrino int. with nuclear emulsion at J-PARC was proposed.
T60 is a first step of this series.

Working group

J-PARC — Experimental site, Neutrino beam

Nihon Univ. — Emulsion development

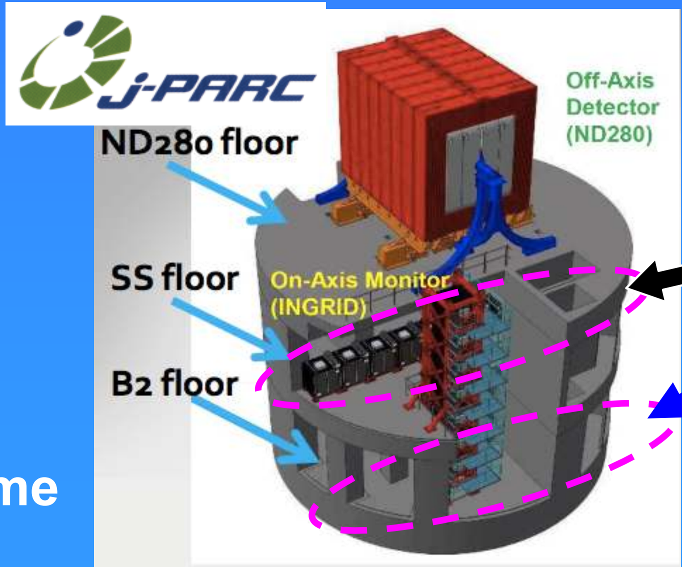
Univ. Tokyo — T2K near detector

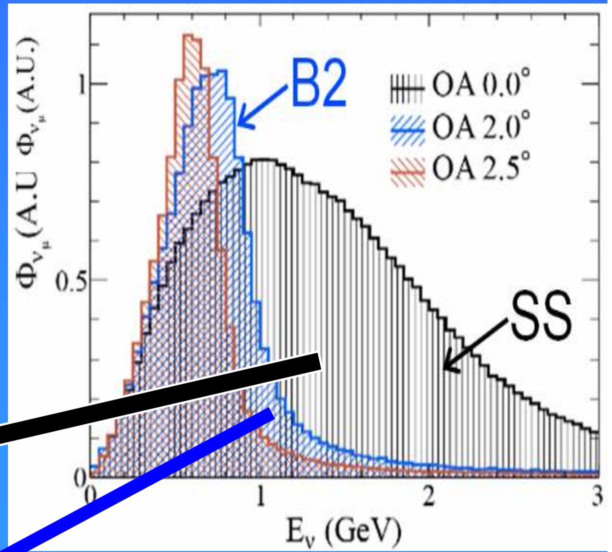
Nagoya Univ. — Film production system, Scan

Kyoto Univ. — T2K near detector

Toho Univ. — Management, Film production, Scan

Kobe Univ. — Emulsion Shifter





A collaborative project with some member of OPERA and T2K

Roadmap

Preliminary measurements RUN — Feasibility study at J-PARC

J-PARC T60 experiment

Detector RUN — Detector performance check
Target mass: 30- 60kg

Future plan

Physics RUN Ⅰ — Neutrino-nucleus interaction study
Target mass: 100- 300kg

Physics RUN Ⅱ — Search for sterile neutrino
Target mass: 1- 3ton
Target mass: 6-10ton

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

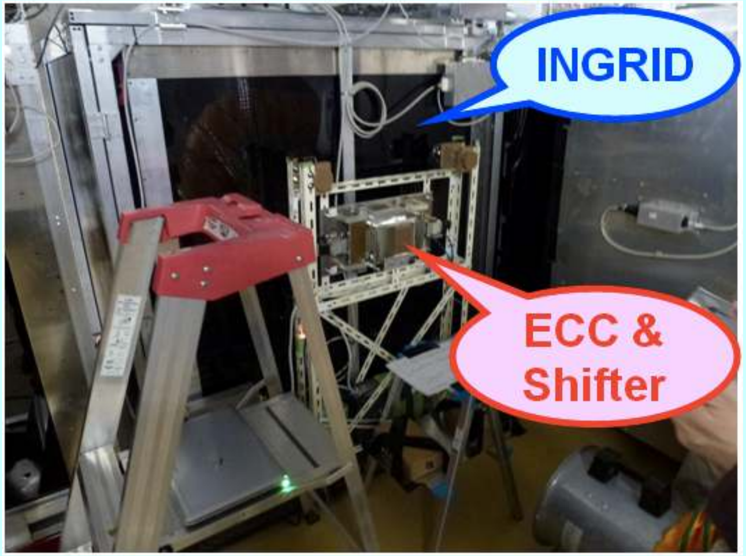
2014. Nov – 2015. Mar

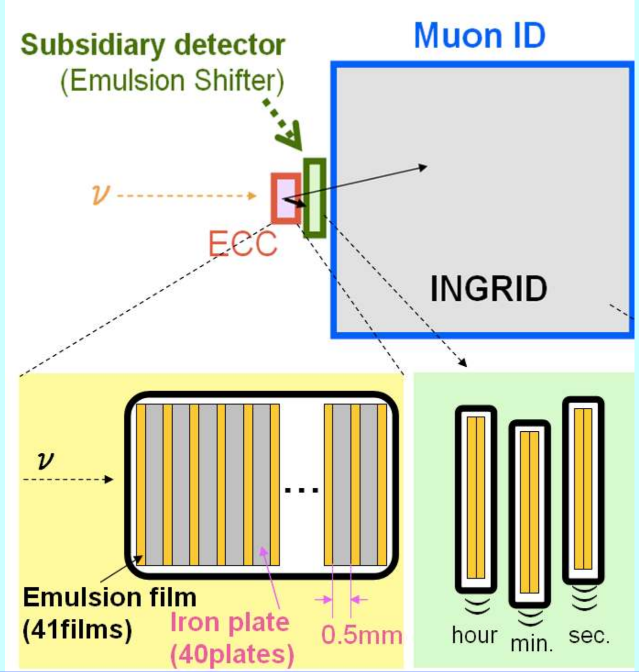
Status of T60

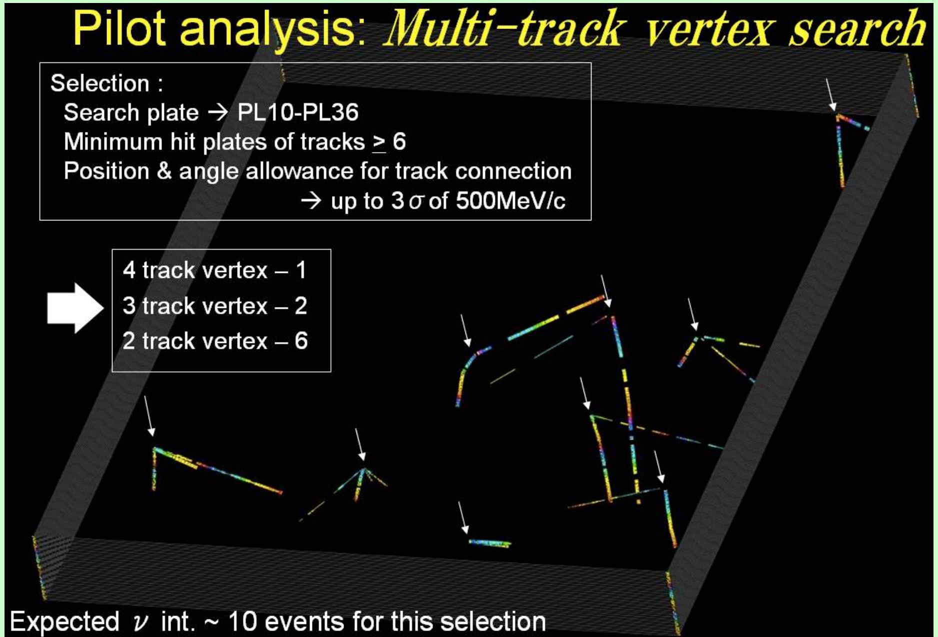
Feasibility study: 2kg Iron target ECC

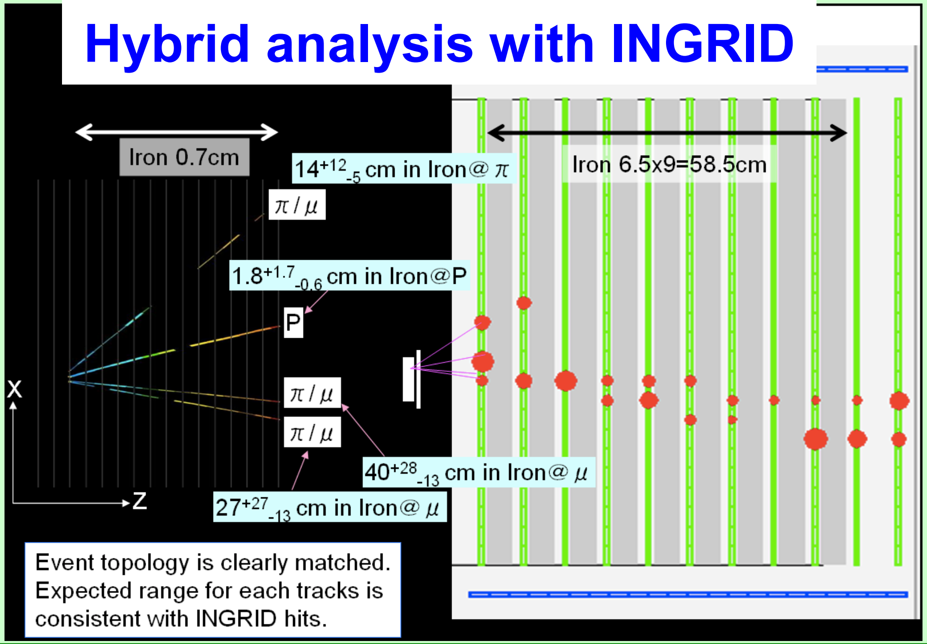
Emulsion film production by ourselves

Installation @J-PARC









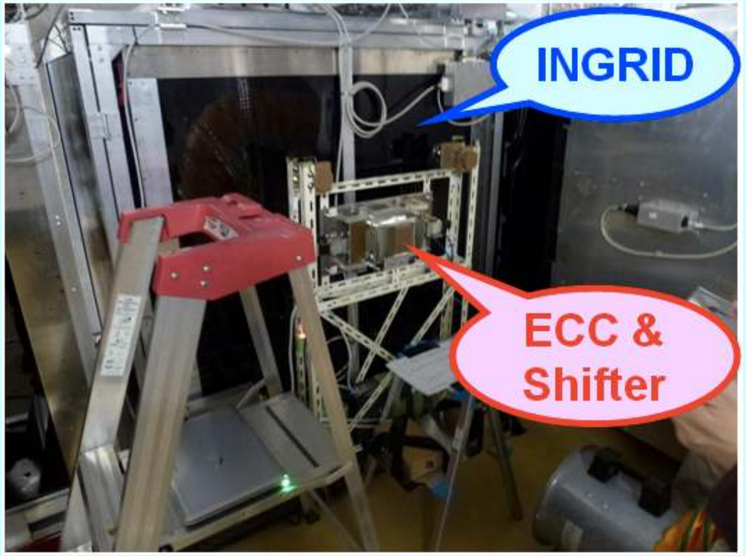
Status of T60

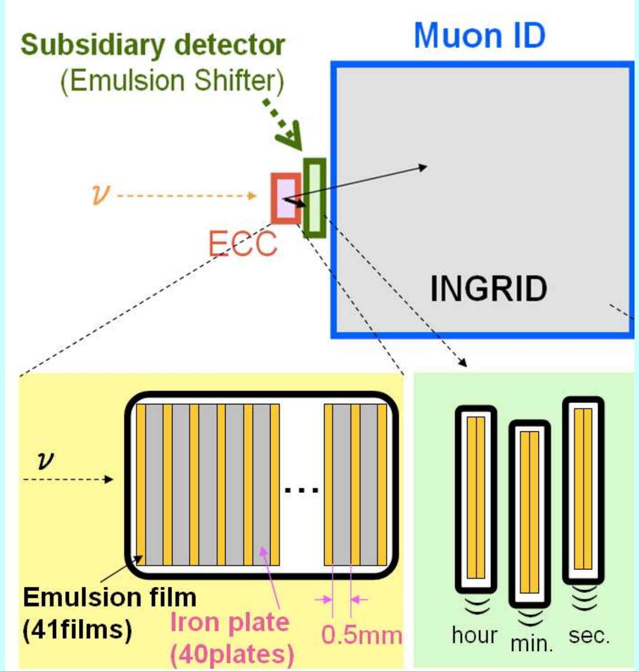
2014. Nov – 2015. Mar

Feasibility study: 2kg Iron target ECC

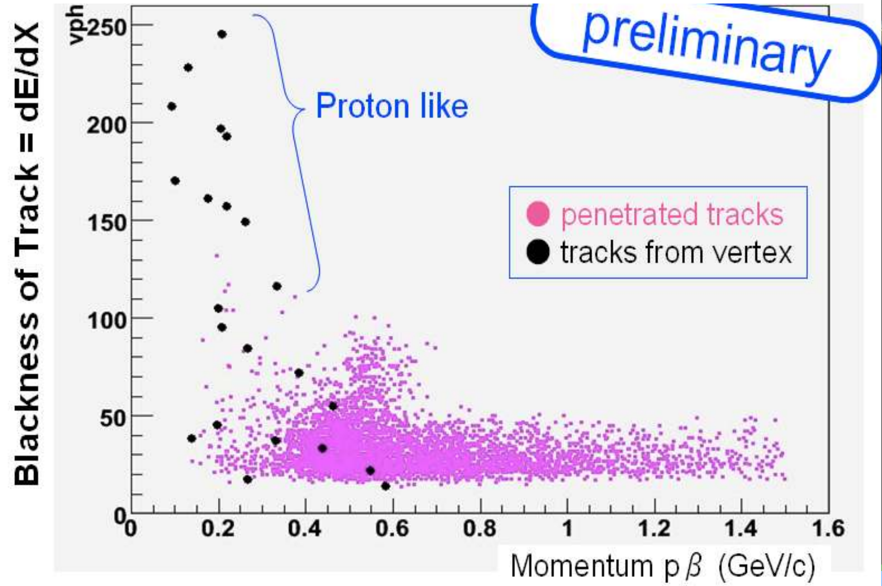
Emulsion film production by ourselves

Installation @J-PARC

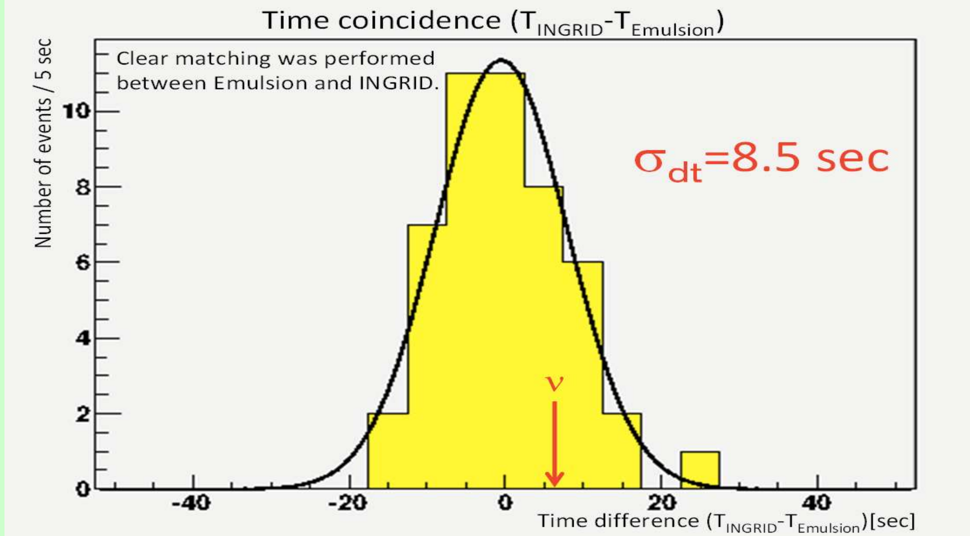




Proton identification



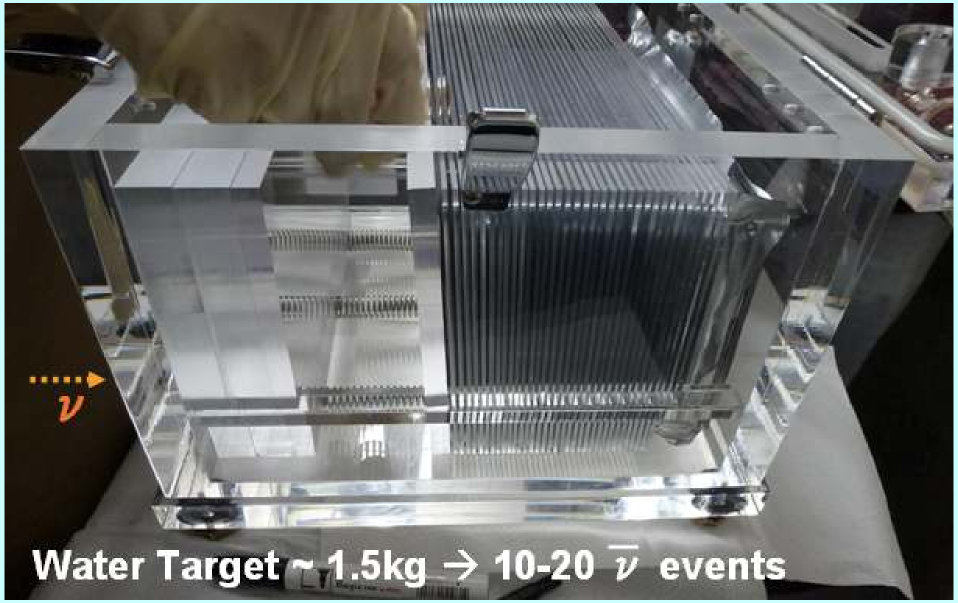
Time resolution

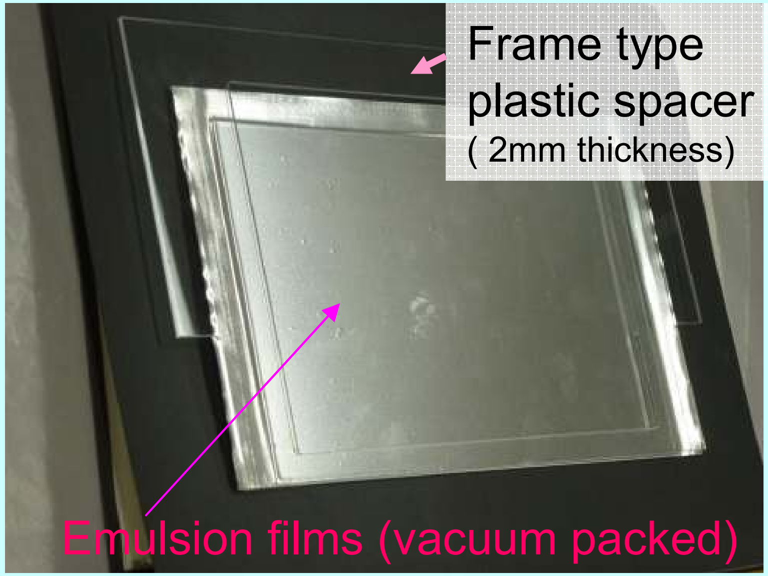


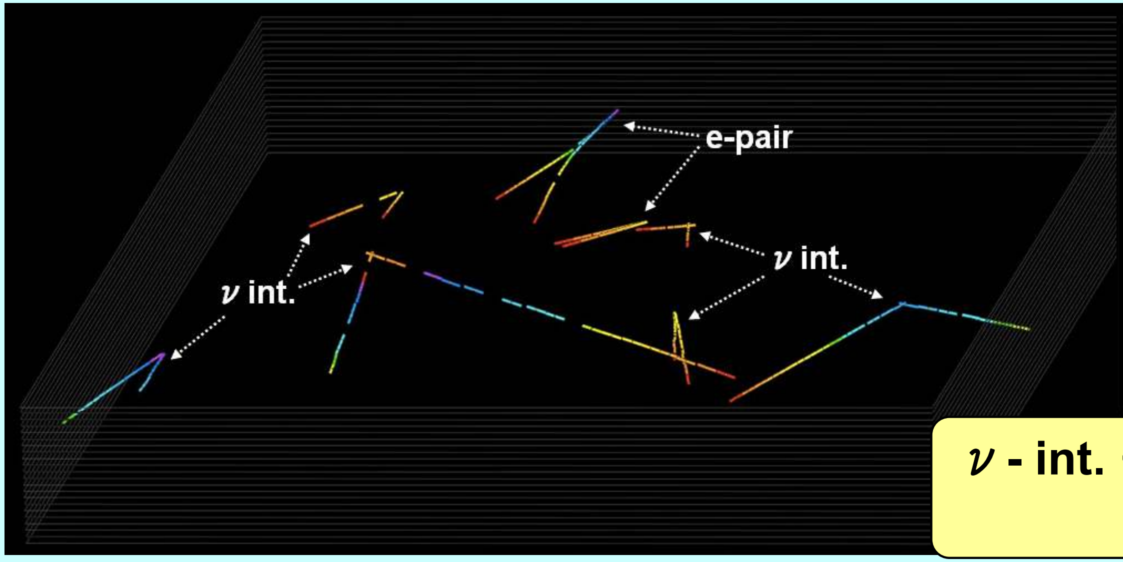
Status of T60

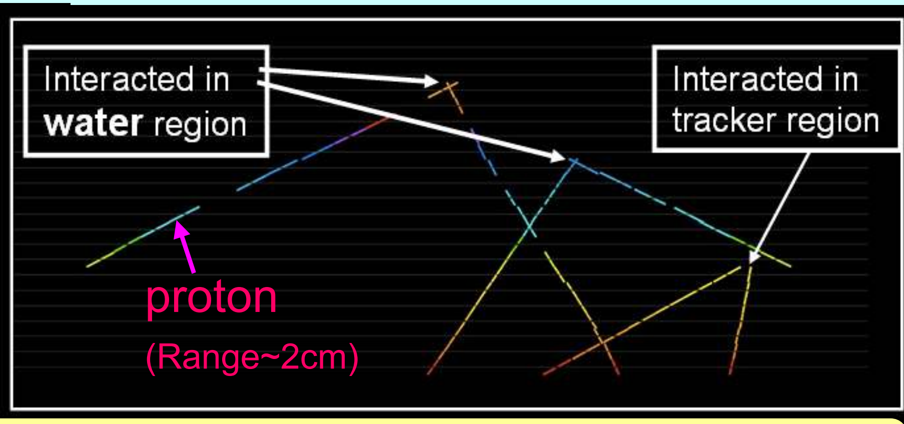
Feasibility study: 1.5kg Water target ECC

Water target emulsion chamber







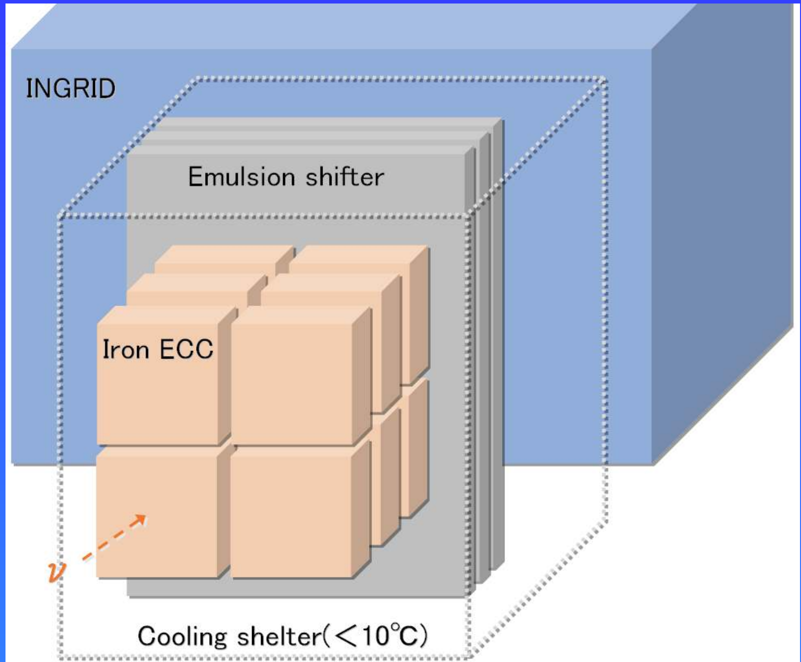


ν - int. → 6 events { Water region : **2** events
Tracker region : 4 events

First observation of ν - Water interactions with Emulsion Detector

Status of T60

Detector Run: 60kg Iron target ECC



- $\overline{\nu}$ exposure : 2016 @SS floor
  end of Jan. → beam end
- Iron target (total~60kg : 500 μ m seg.)
- High statistics (4-6k $\overline{\nu}_{\mu}$ events)
- ν_e detection (30-40 $\overline{\nu}_e$ CC events)

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

Summary

OPERA

- OPERA successfully collected data from 2008 to 2012. A total number of **17.97 x 10^{19} p.o.t.** integrated (~80% of the nominal value).
- **5 ν_τ candidate events** were found with 2.6 signal and 0.25 background events expected in the analyzed sample.
- Significance of the observation is **5.1 σ**

  → **Discovery of ν_τ appearance** in the CNGS beam.

J-PARC

- We are planning neutrino experiments **at J-PARC** to study low energy neutrino - nucleus interactions with nuclear emulsion.
- First of all, we are carrying out a test experiment at J-PARC (**T60**) to check the feasibility and detector performance.
- We demonstrated **neutrino event analysis**, **hybrid analysis** with T2K near detector and detection of **ν-water interactions**.
- We will check the detector performance with high stat. and establish a detailed plan for physics run.

Hadron Production measurements

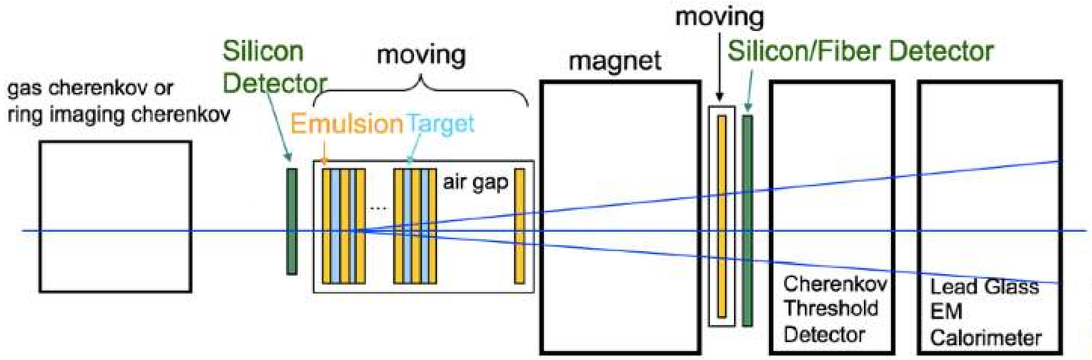
- To reduce uncertainly of neutrino flux (accelerator ν , atmospheric ν)
- Several – 10 GeV/c hadron interactions is studied with nuclear emulsion.
- First, target is Carbon. Then Iron, Aluminum will be performed.

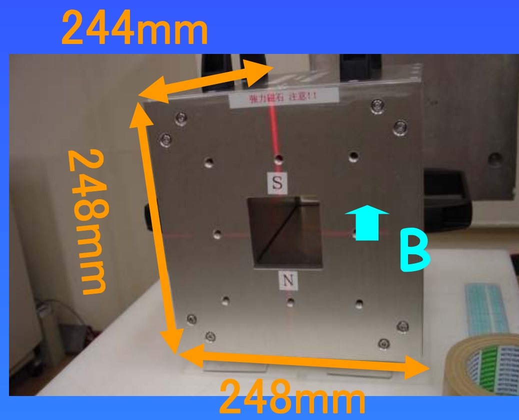
Hybrid Emulsion Detector

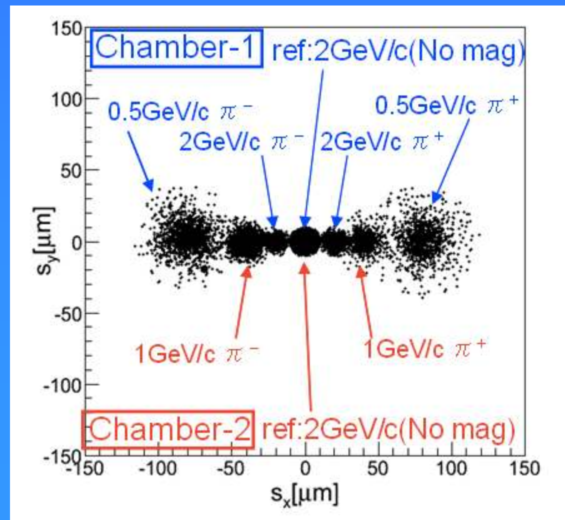
Detector that uses emulsion film tracking is being developed by ICRR, Kavli IPMU, Kyoto U., Toho U. ＋ **KEK, Nagoya U., Kobe U., Nihon U.**

- Minimize material between tracker and target (large systematic effect for HARP)
- Compact size detector can be moved between different beam lines
- Detailed measurements of interaction topologies

Emulsion detector tracks connected to upstream and downstream particle ID detectors by silicon strip or pixel detectors







- We plan to expose hadron beam at Fermilab/CERN in the near future.