原子核乾板によるニュートリノ研究

Study of Neutrino with Nuclear Emulsion

福田　努　（東邦大学）

Tsutomu Fukuda (Toho Univ.)

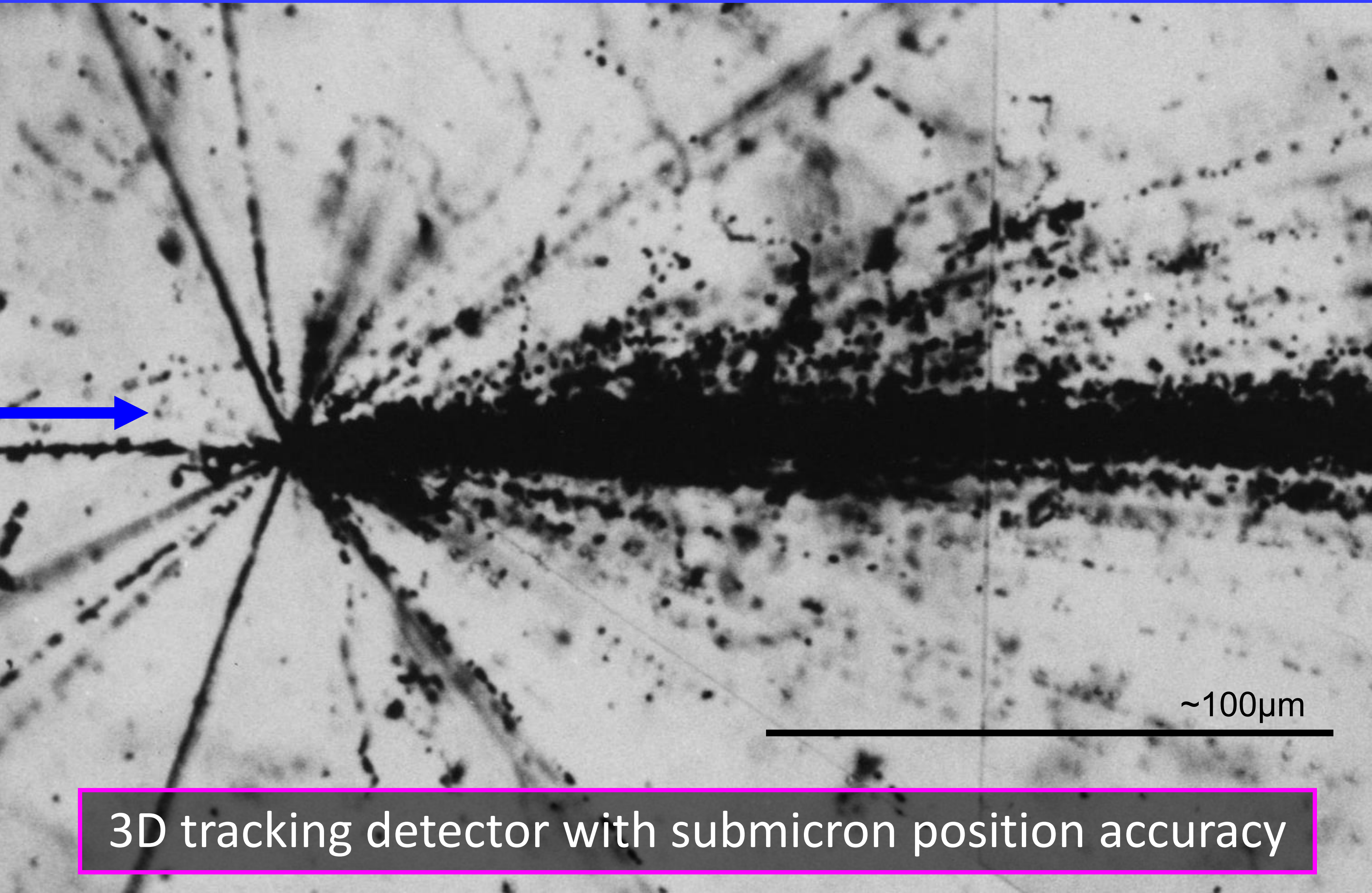
第21回 ICEPPシンポジウム, 2015年2月10日, 白馬村岳美荘

- Nuclear Emulsion
- Result from the OPERA experiment
- New Neutrino Experiment at J-PARC

原子核乾板

Nuclear Emulsion

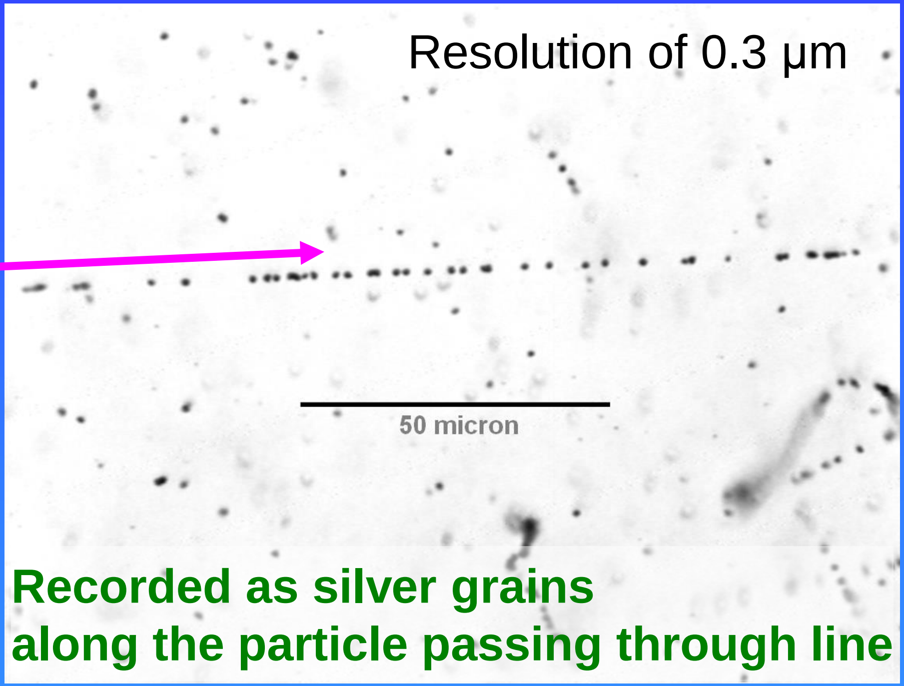
What is Nuclear Emulsion ?



3D tracking detector with submicron position accuracy

Photographic Film technology

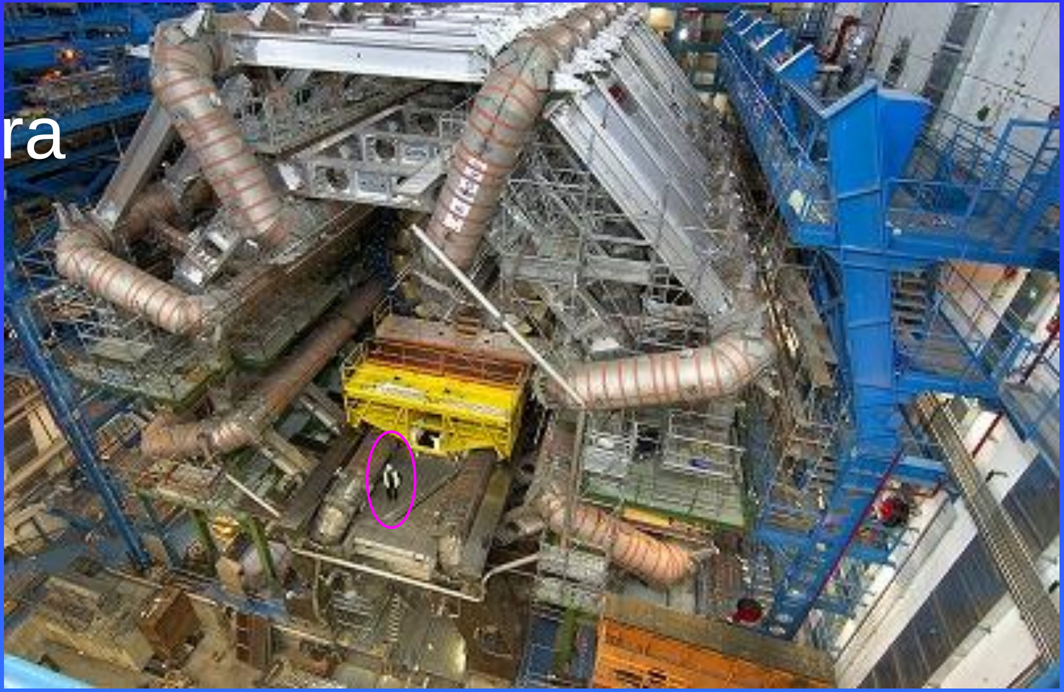
- Nuclear Emulsion is a special photographic film.
- Signal is amplified by chemical process.



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

Largest Digital Camera

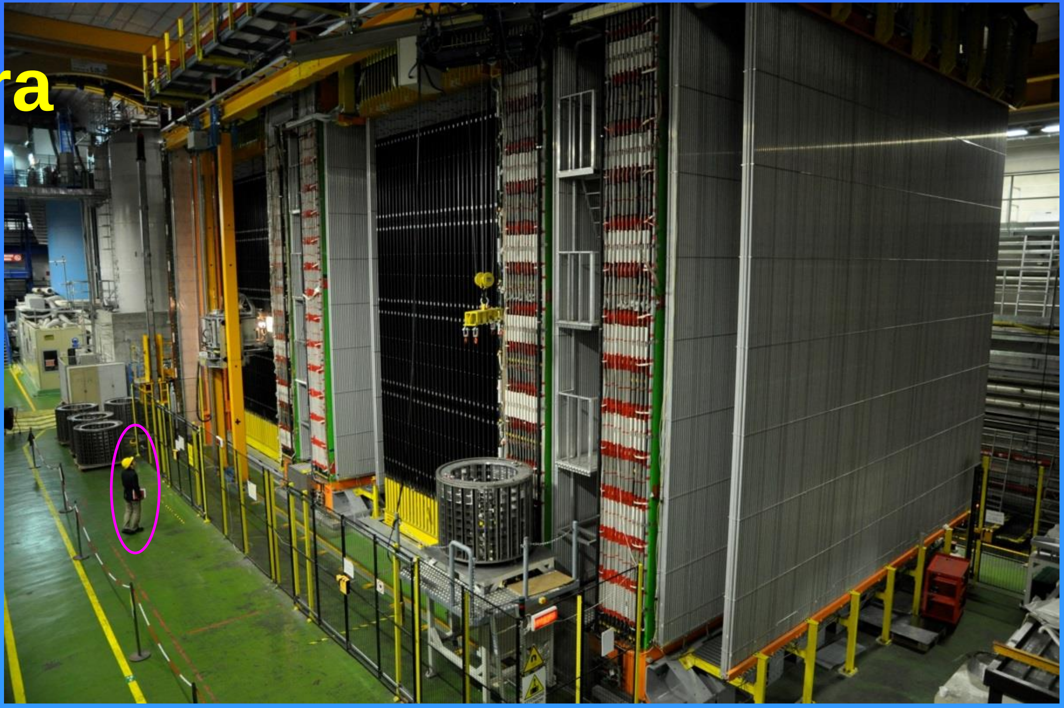
ATLAS detector



Largest Film Camera

OPERA detector

($\sim 10^{20}$ AgBr crystals)



Contribution for fundamental physics

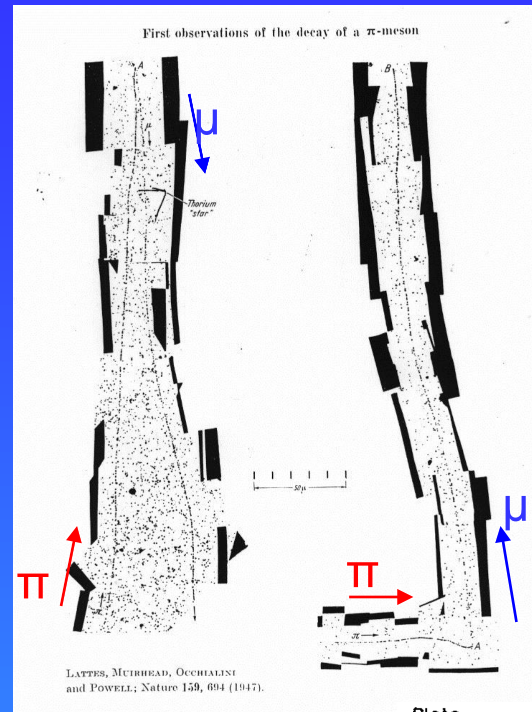
1896 (A. H. Becquerel)
Discovery of Radioactivity

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

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

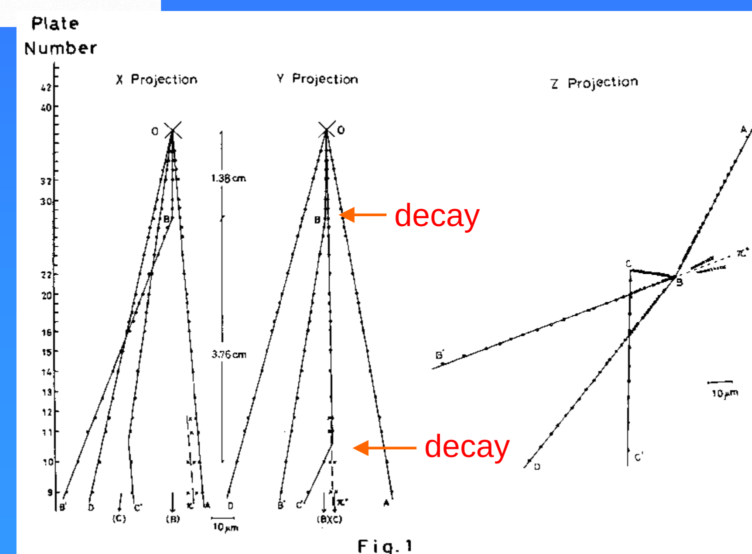
2001 (K.Niwa et al.)
Direct observation of ν_τ

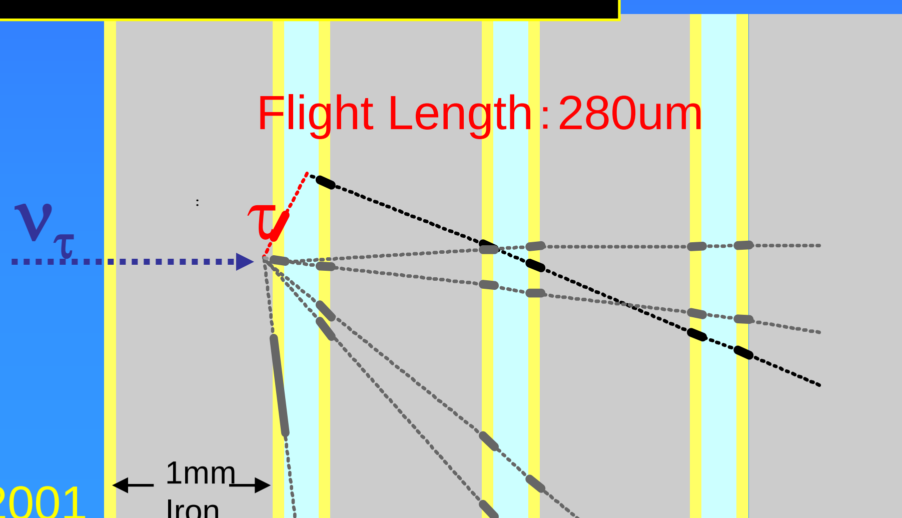
1947



1896

1971





2001

DONuT ν_τ event

Result from OPERA

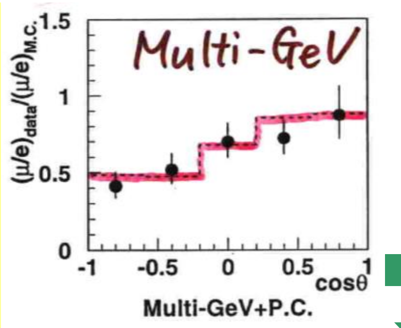
OPERA-CNGS roadmap

The OPERA experiment

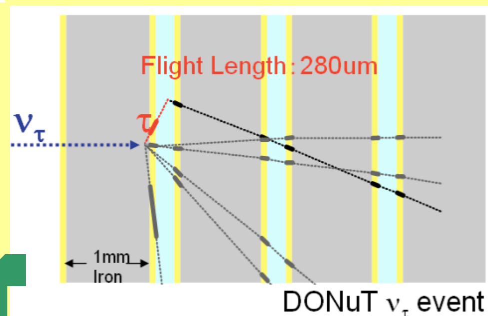
Oscillation **P**roject with **E**mulsion t**R**acking **A**pparatus

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

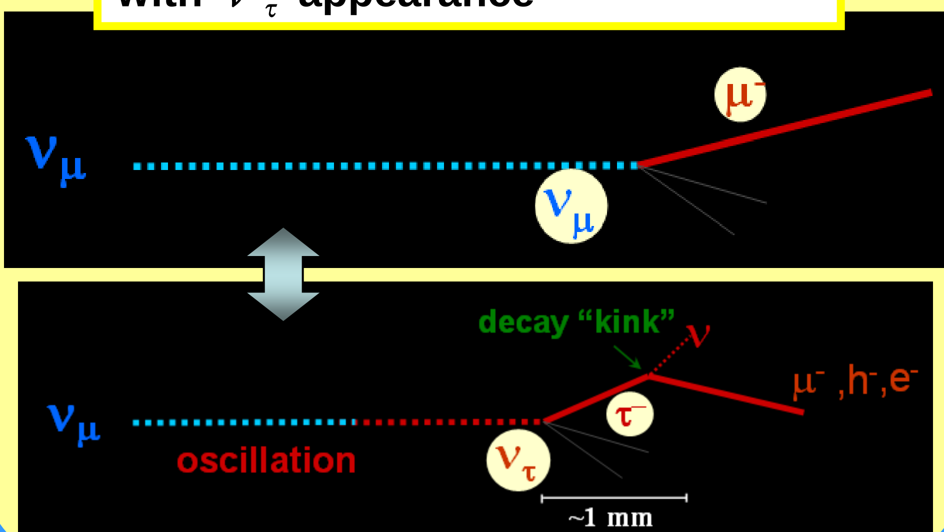
Neutrino oscillation (disappearance)
Result from SK in 1998

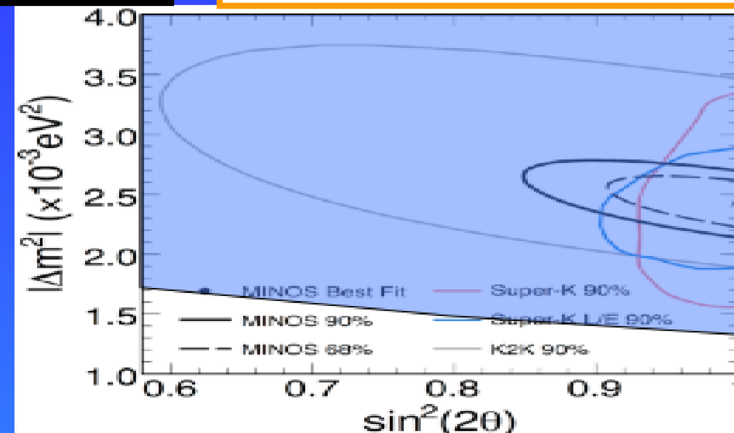


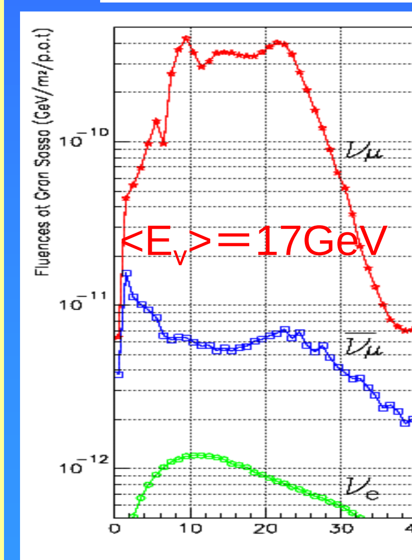
Direct observation of ν_τ events
Result of DONuT in 2001



Verification of neutrino oscillation with ν_τ appearance







CNGS neutrino beam

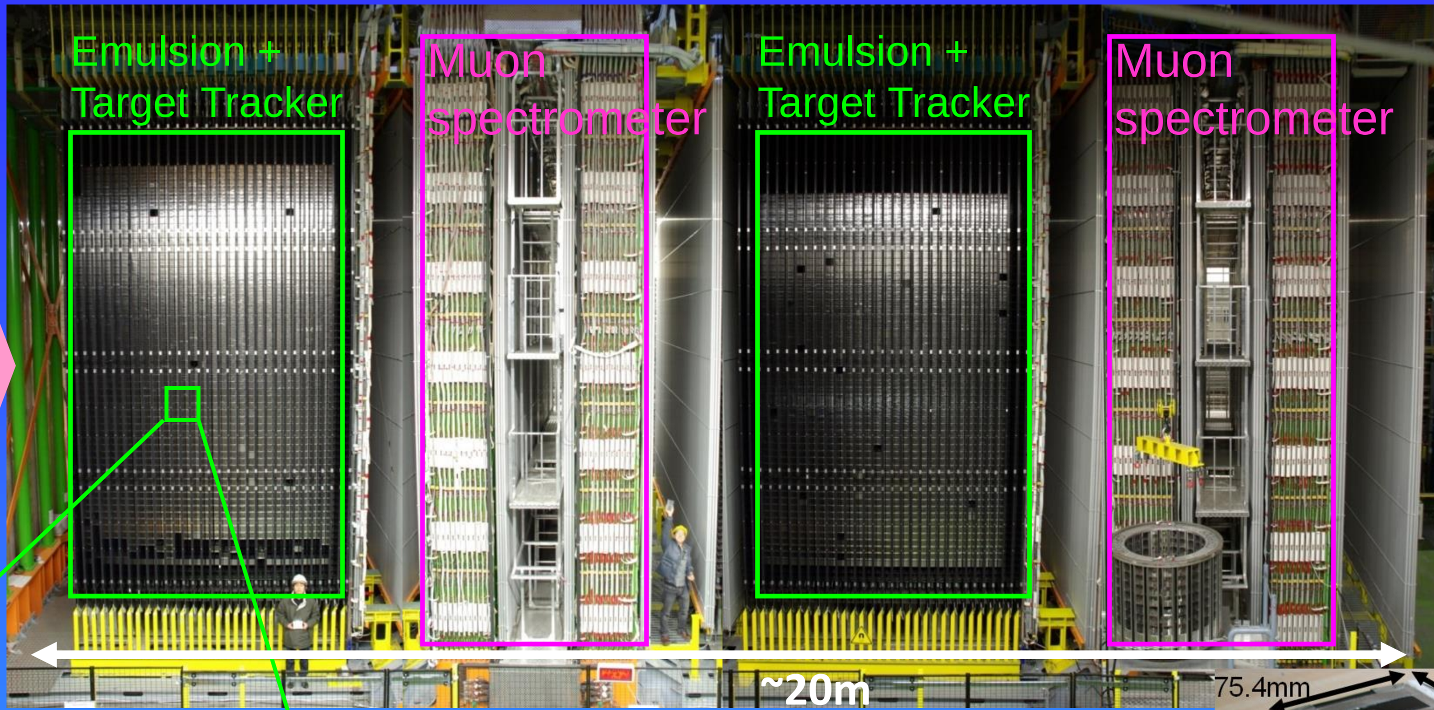
$(\nu_e + \bar{\nu}_e) / \nu_\mu$	0.87 %
$\bar{\nu}_\mu / \nu_\mu$	2.1 %
ν_τ prompt	Negligible

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

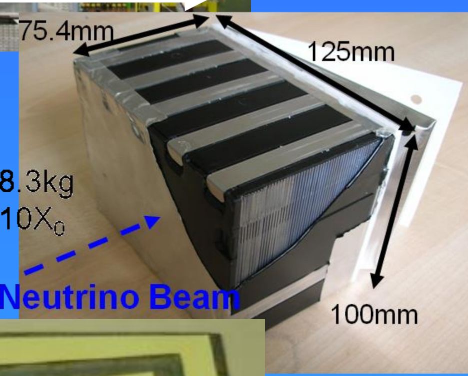
$\sin^2 2\theta_{23} = 1.0$, $\quad \Delta m_{23}^2 = (2.43 \pm 0.13) \times 10^{-3}$ eV^2

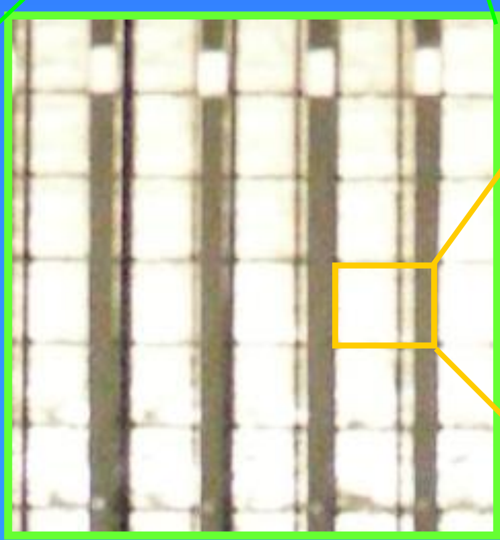
The OPERA Detector

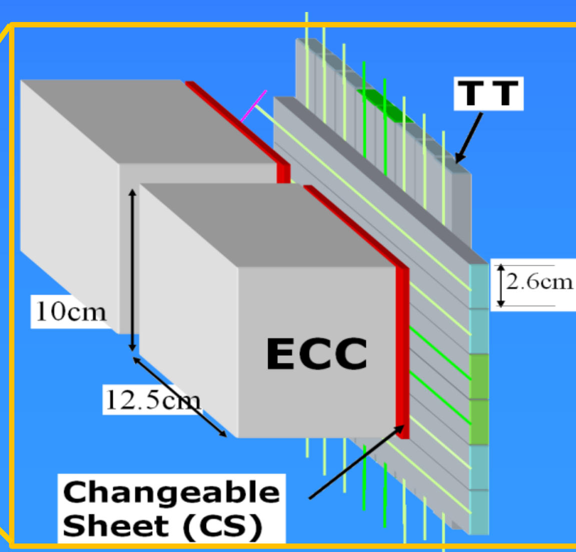
ν

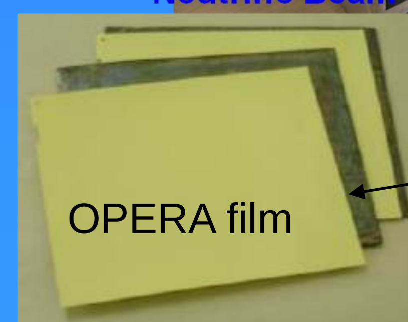


ECC:
~150,000
(1.25kton)



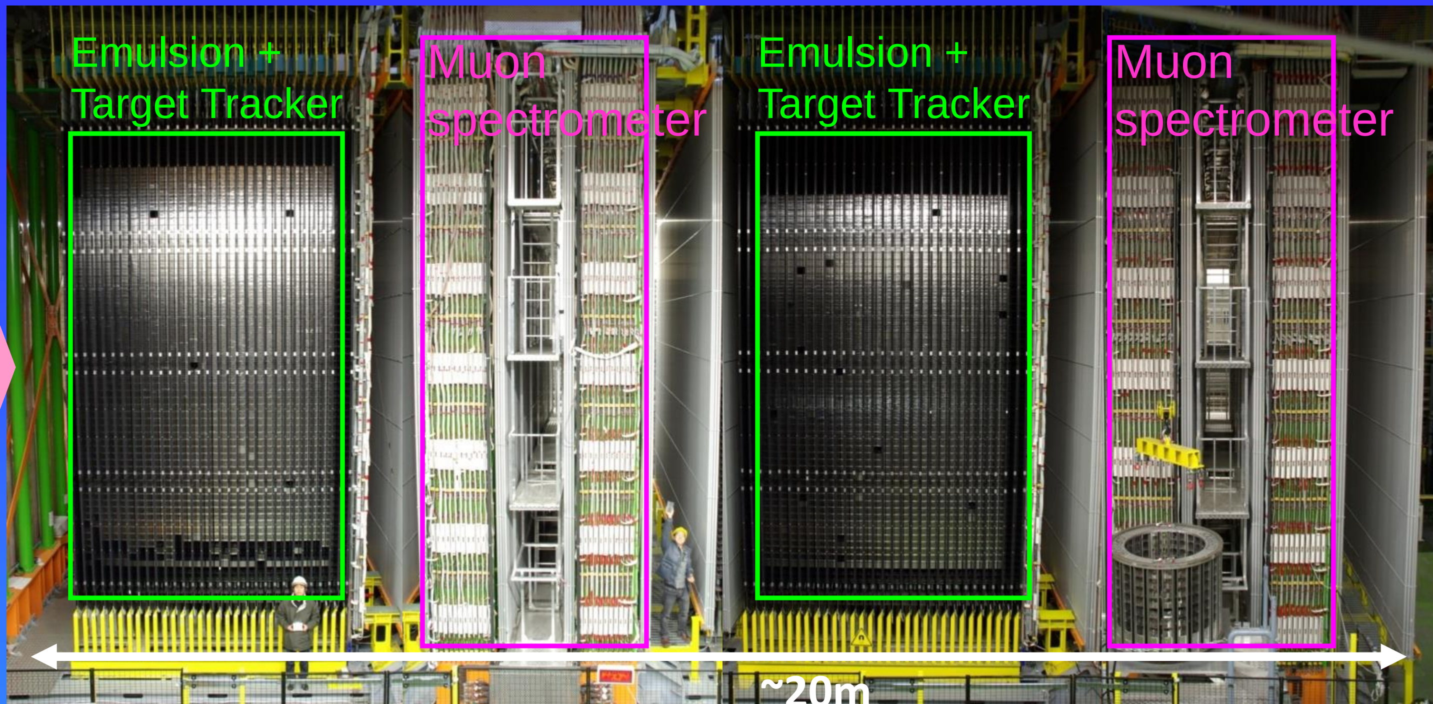


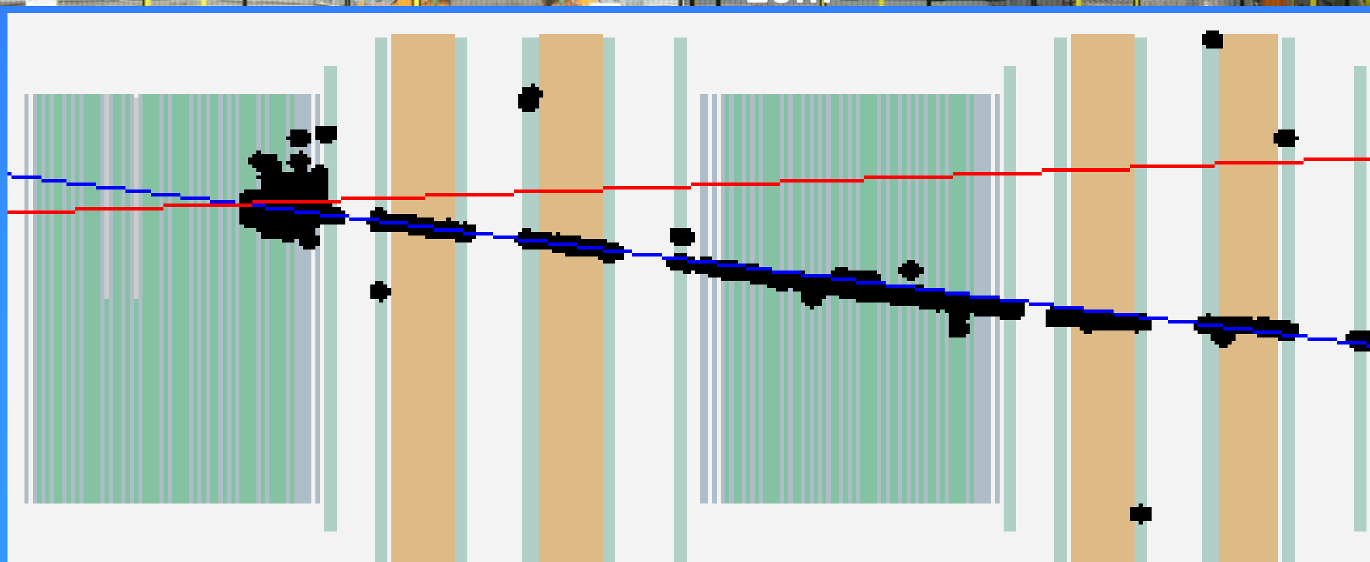




The OPERA Detector

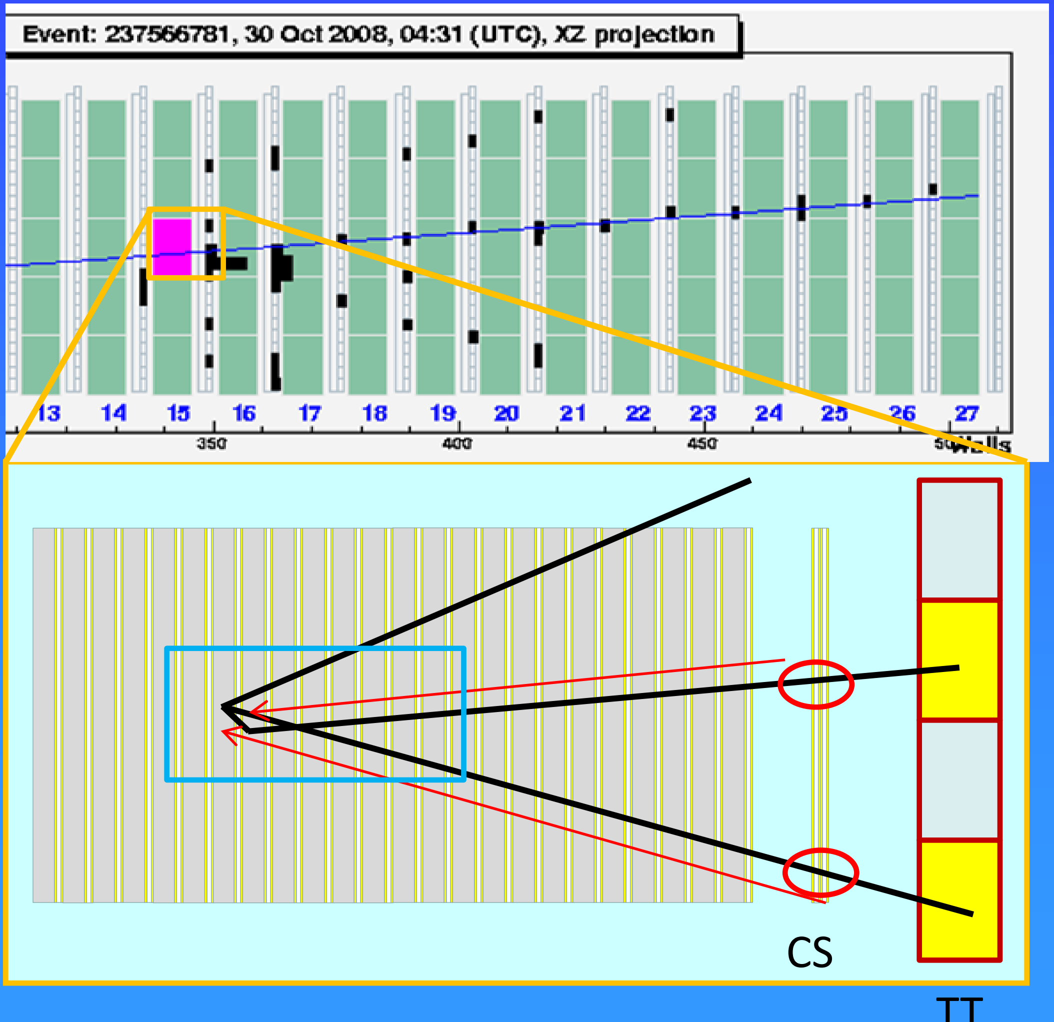
ν

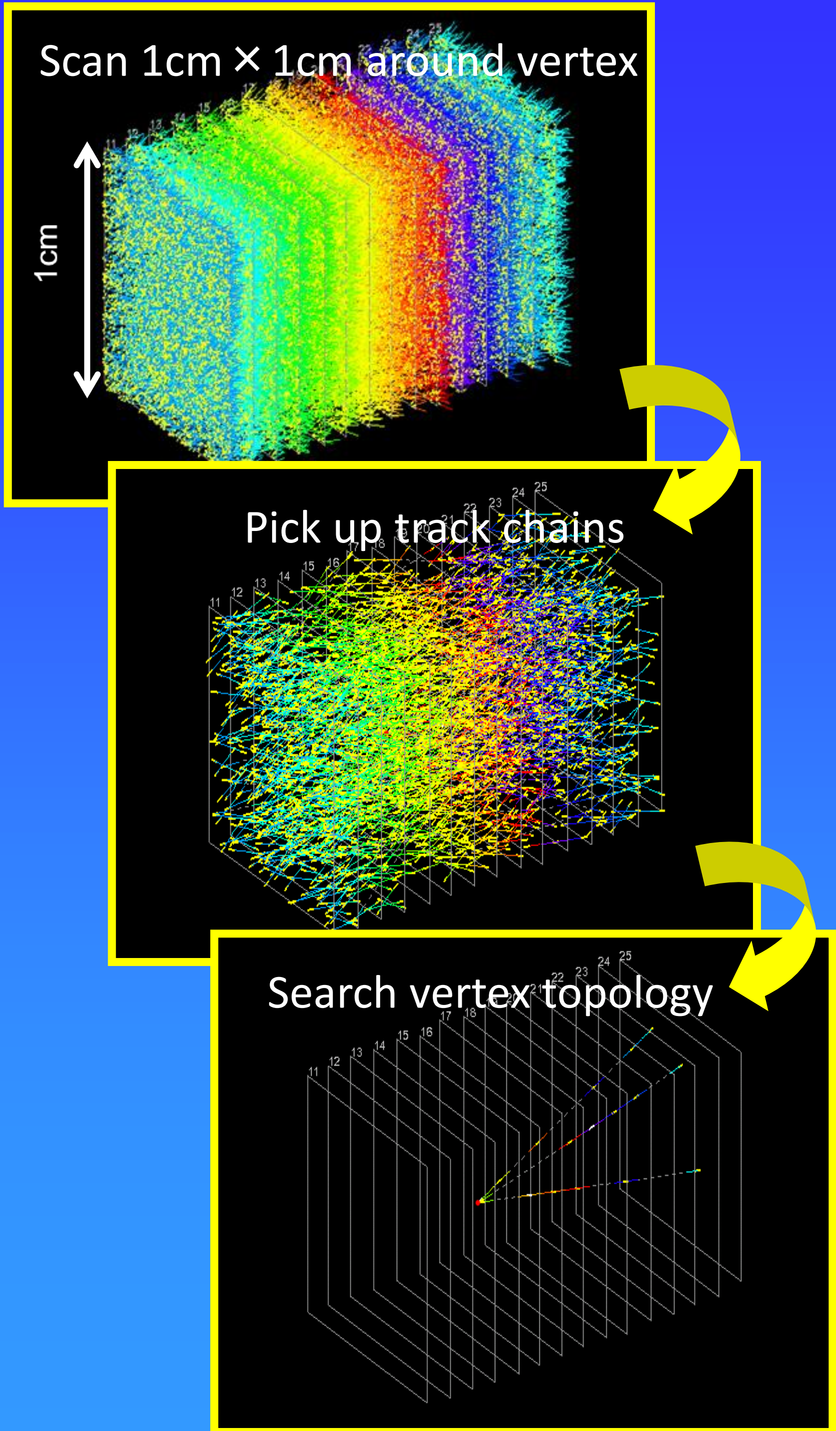




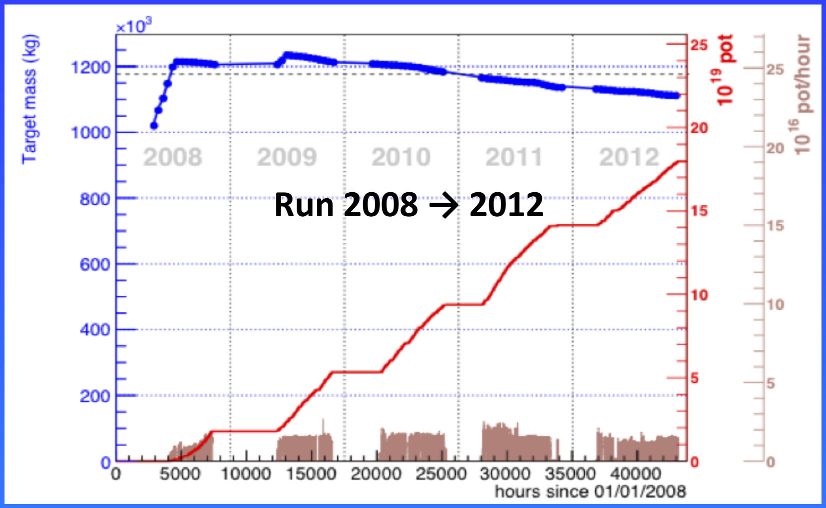
Neutrino event analysis

Scan Back location & Decay search



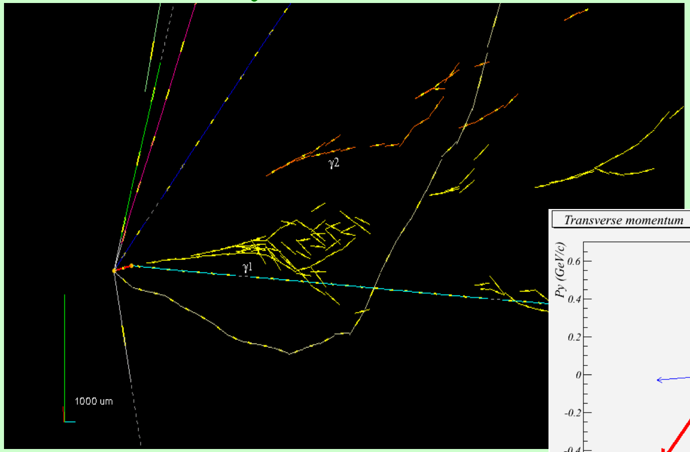


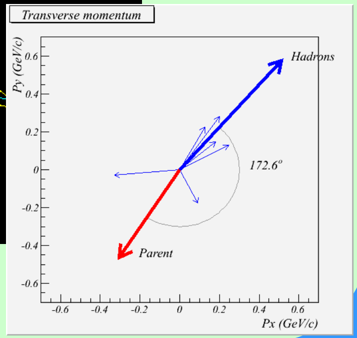
Analysis Status



- Beam: 5year (965days), 17.97×10^{19} p.o.t.
- **80% of proposal.**
- Location & Decay Search:
  6636 neutrino events located .
  6190 events decay search done.

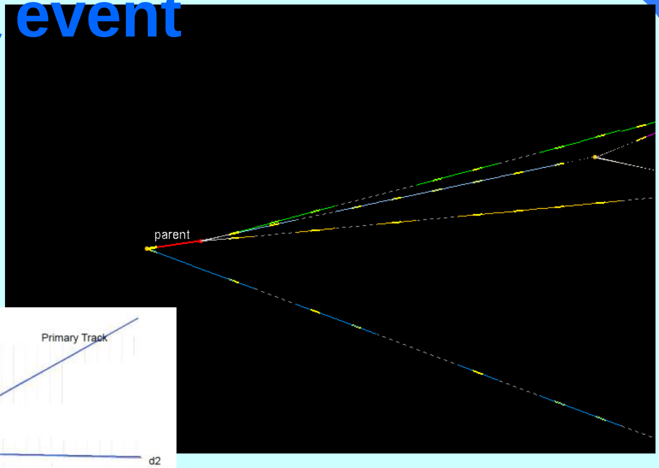
1st ν_τ event $\tau \rightarrow \rho \rightarrow \pi\ \pi^0$

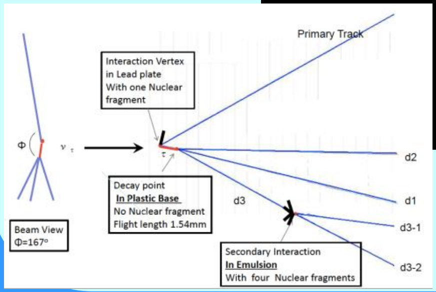




(May 2010)

2nd ν_τ event $\tau \rightarrow 3\pi$



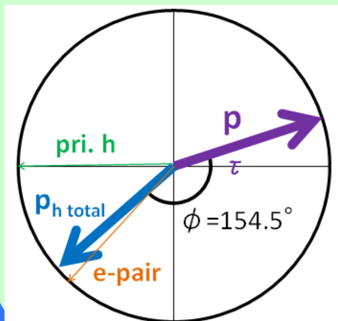


(Jun 2012)

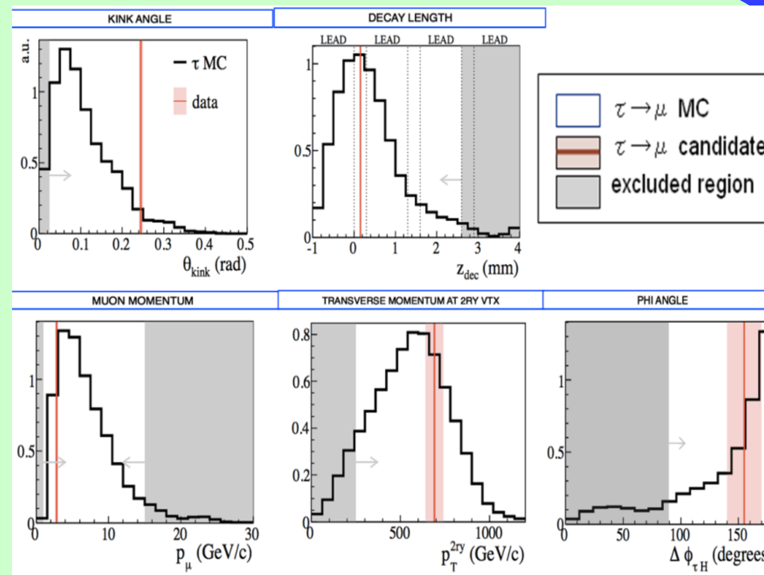
3rd ν_τ candidate events

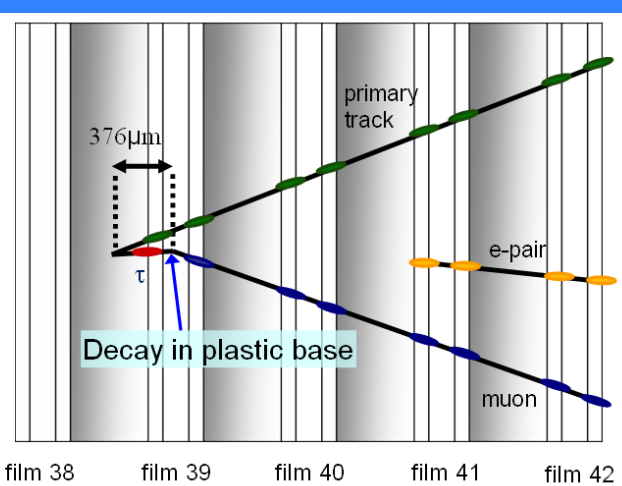
3rd ν_τ event

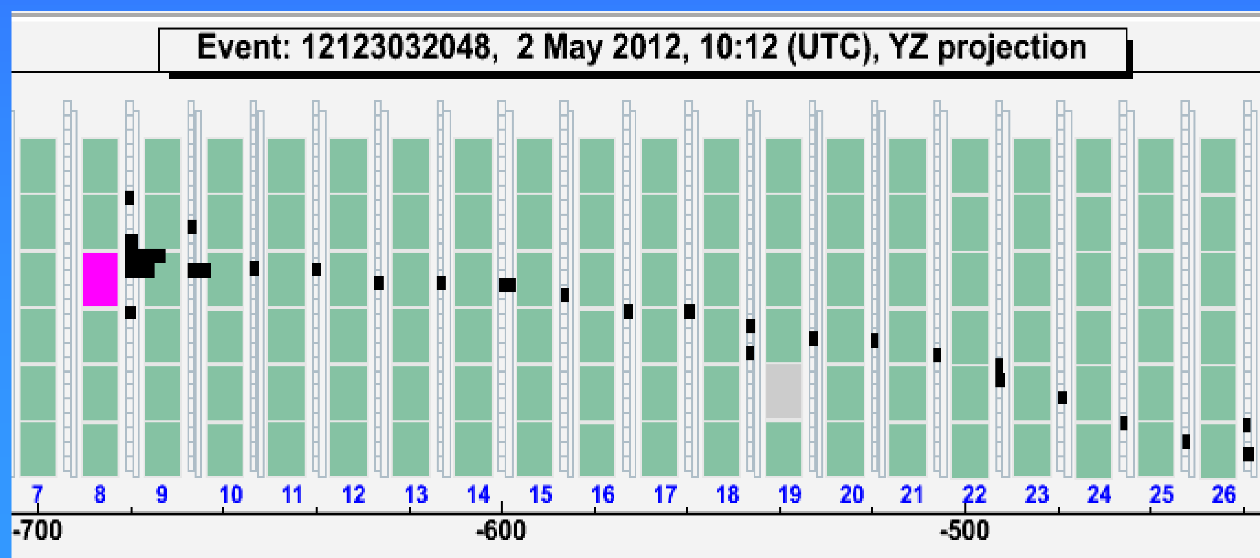
$\tau^- \rightarrow \mu^-$



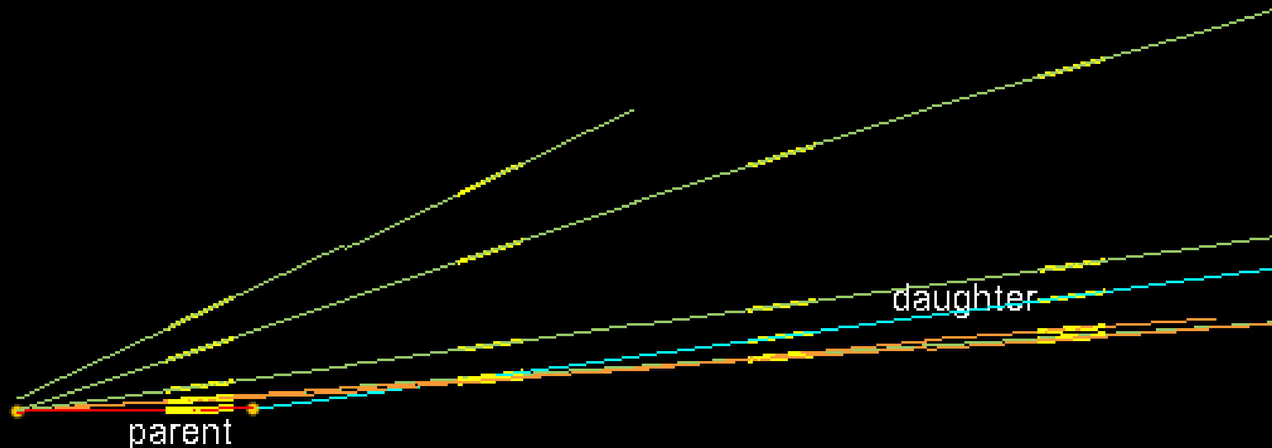
(Mar. 2013)





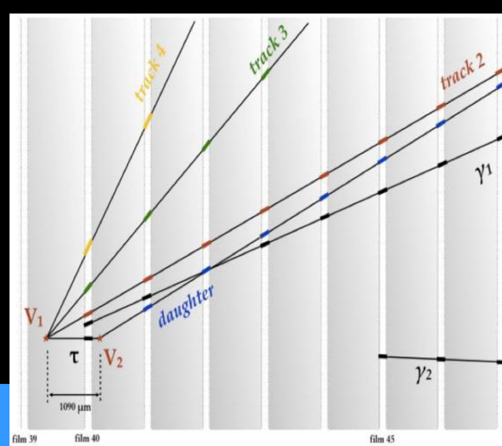


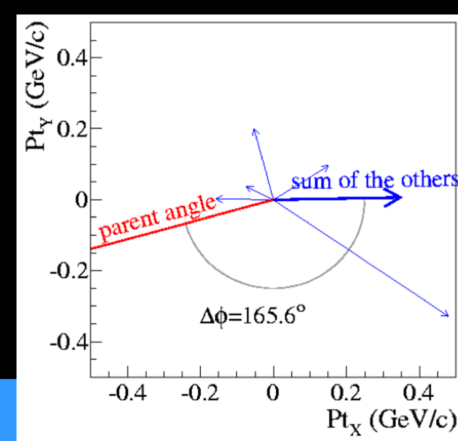
4th ν_τ candidate events



$\tau \rightarrow \pi$

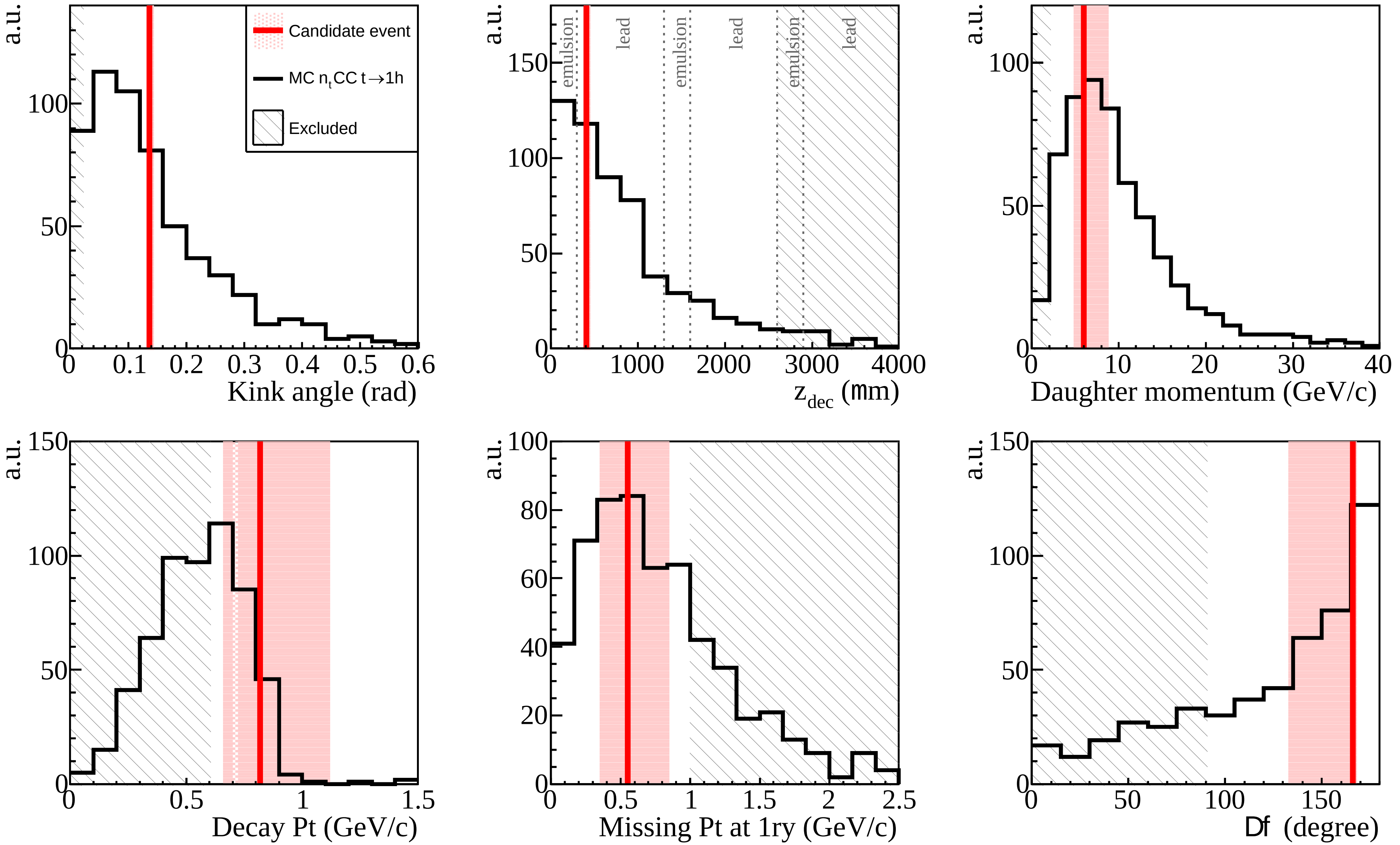
1000





(Mar. 2014)

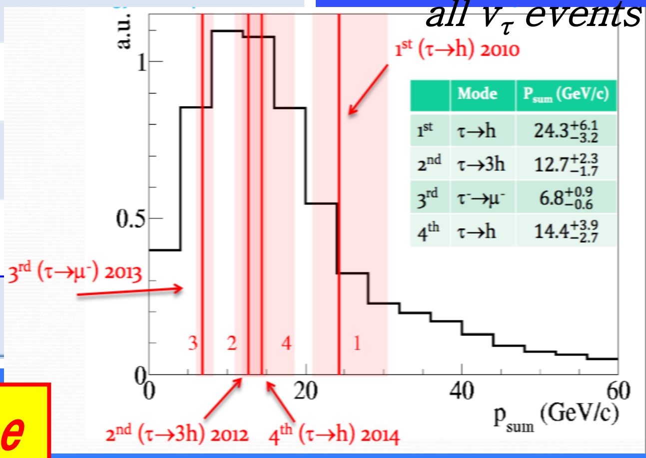
τ→1h decay channel, signal distribution and the values of this event.



Neutrino Oscillation Analysis

Decay channel	Signal expectation	Total background	Observed events
t → h	0.4 ± 0.08	0.033 ± 0.006	2
t → 3h	0.57 ± 0.11	0.155 ± 0.03	1
t → m	0.52 ± 0.1	0.018 ± 0.007	1
t → e	0.61 ± 0.12	0.027 ± 0.005	0
Total	**2.1 ± 0.42**	**0.23 ± 0.04**	**4**

Visible energy of all ν_τ events



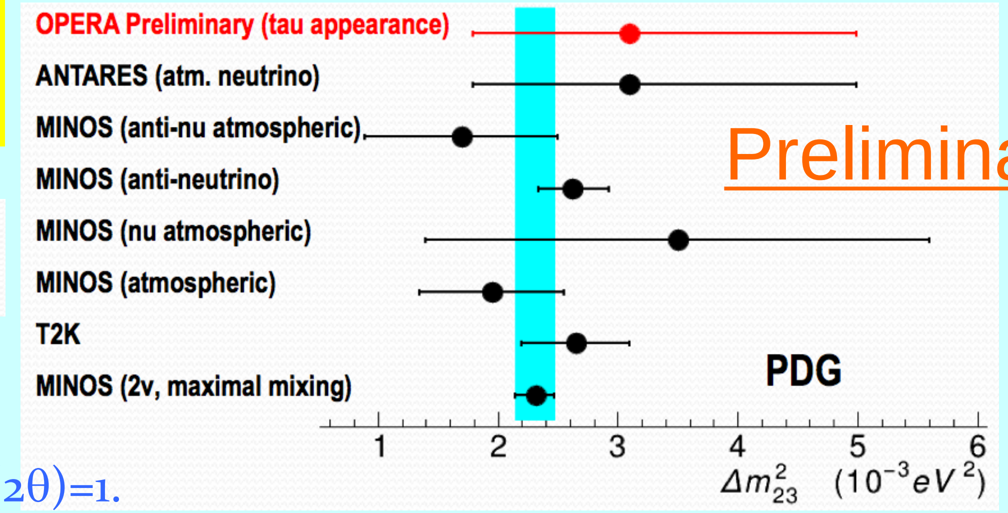
⇨ 4.2σSignificance！

Observation of ν_τ Appearance

First measurement of Δm^2_{32} with ν_τ appearance

$$N_{\nu_\tau} \propto \int \phi(E) sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) \epsilon(E)\sigma(E)dE$$

flux — *detection efficiency* — *cross section*



Preliminary

90% CL intervals assuming sin²(2θ)=1.

PTEP

Prog. Theor. Exp. Phys. **2014**, 101C01 (10 pages)
DOI: 10.1093/ptep/ptu132

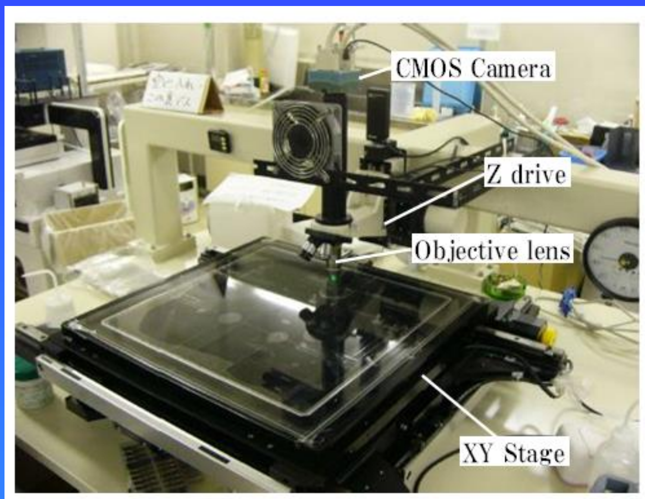
Letter

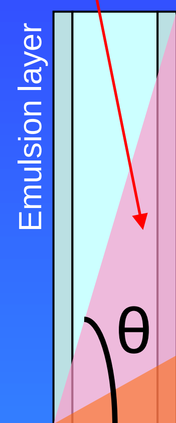
Observation of tau neutrino appearance in the CNGS beam with the OPERA experiment

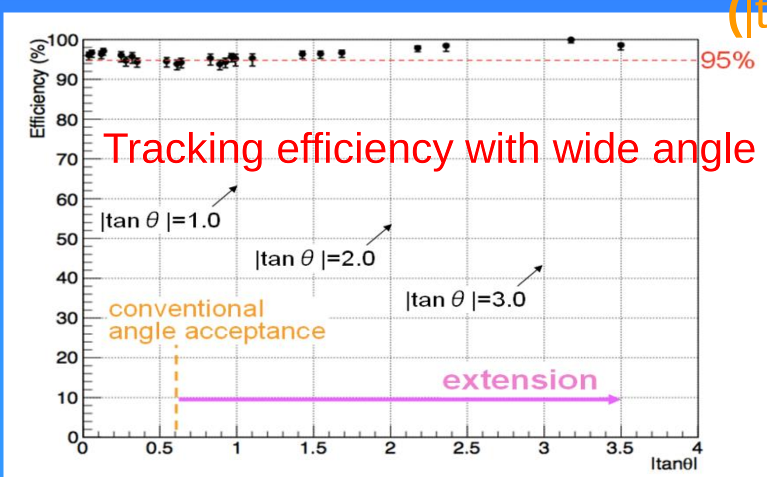
OPERA Collaboration
N. Agafonova[1], A. Aleksandrov[2], A. Anokhina[3], S. Aoki[4], A. Ariga[5], T. Ariga[5,*], T. Asada[6], D. Bender[7], A. Bertolin[8], C. Bozza[9], R. Brugnera[8,10], A. Buonaura[2,11], S. Buontempo[2], B. Büttner[12], M. Chernyavsky[13], A. Chukanov[14], L. Consiglio[2], N. D'Ambrosio[15], G. De Lellis[2,11], M. De Serio[16,17], P. Del Amo Sanchez[18], A. Di Crescenzo[2,11], D. Di Ferdinando[19], N. Di Marco[15], S. Dmitrievski[14], M. Dracos[20], D. Duchesneau[18], S. Dusini[8], T. Dzhatdoev[3], J. Ebert[12], A. Ereditato[5], R. A. Fini[16], T. Fukuda[21], G. Galati[16,17], A. Garfagnini[8,10], G. Giacomelli[19,22,†], C. Goellnitz[12], J. Goldberg[23], Y. Gornushkin[14], G. Grella[9], M. Guler[7], C. Gustavino[24], C. Hagner[12], T. Hara[4], T. Hayakawa[6], A. Hollnagel[12], B. Hosseini[2,11], H. Ishida[21], K. Ishiguro[6], K. Jakovcic[25], C. Jollet[20], C. Kamiscioglu[7,26], M. Kamiscioglu[7], T. Katsuragawa[6], J. Kawada[5], H. Kawahara[6], J. H. Kim[27], S. H. Kim[28], N. Kitagawa[6], B. Klicek[25], K. Kodama[29], M. Komatsu[6], U. Kose[8], I. Kreslo[5], A. Lauria[2,11], J. Lenkeit[12], A. Ljubicic[25], A. Longhin[30], P. Loverre[24,31], M. Malenica[25], A. Malgin[1], G. Mandrioli[19], T. Matsuo[21], V. Matveev[1], N. Mauri[19,22], E. Medinaceli[8,10], A. Meregaglia[20], M. Meyer[12], S. Mikado[32], M. Miyanishi[6], P. Monacelli[24], M. C. Montesi[2,11], K. Morishima[6], M. T. Muciaccia[16,17], N. Naganawa[6], T. Naka[6], M. Nakamura[6], T. Nakano[6], Y. Nakatsuka[6,*], K. Niwa[6], S. Ogawa[21], N. Okateva[13],

Cosmic ray analysis using OPERA detector

Application of large angle tracking technique developed for OPERA BKG study

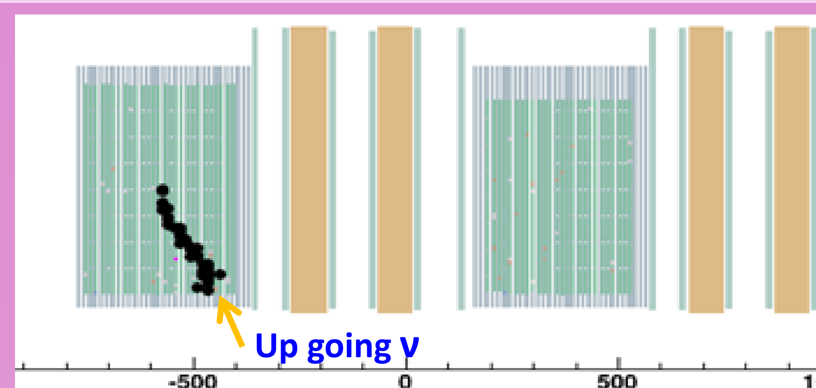




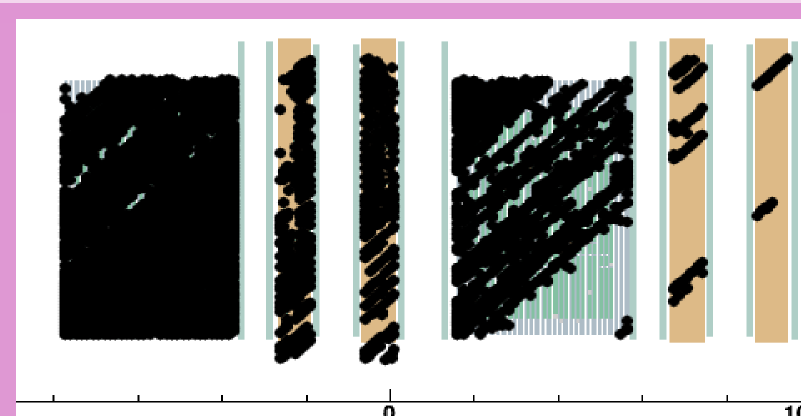


Tracking efficiency with wide angle acceptance

① ν_τ appearance event search in atmospheric neutrino oscillation



② Study of High energy cosmic ray



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

Study of neutrino with Nuclear Emulsion

Target mass

- **1978-1983 Fermilab E531** ~ 100kg

  charm physics, $\nu_\mu \rightarrow \nu_\tau$ oscillation

- **1990-2000 CERN WA95 CHORUS** ~ 1 ton

  $\nu_\mu \rightarrow \nu_\tau$ oscillation, charm physics

- **1994-2001 Fermilab E872 DONUT** ~ 1 ton

  First ν_τ observation

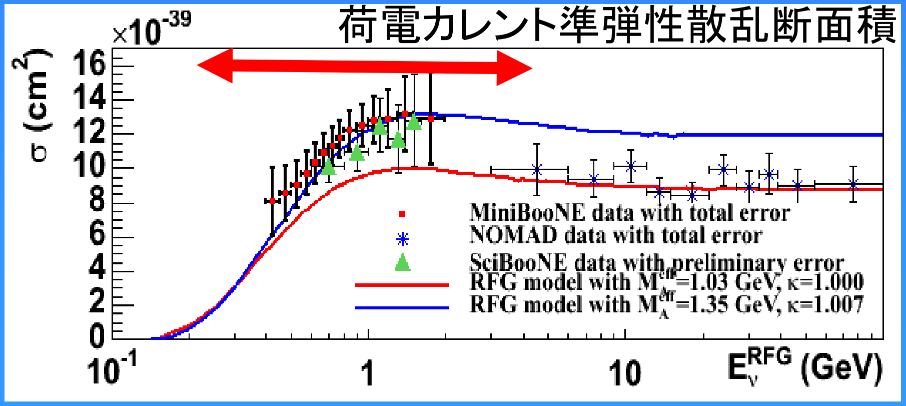
- **2008- CERN CNGS01 OPERA** **1250 ton**

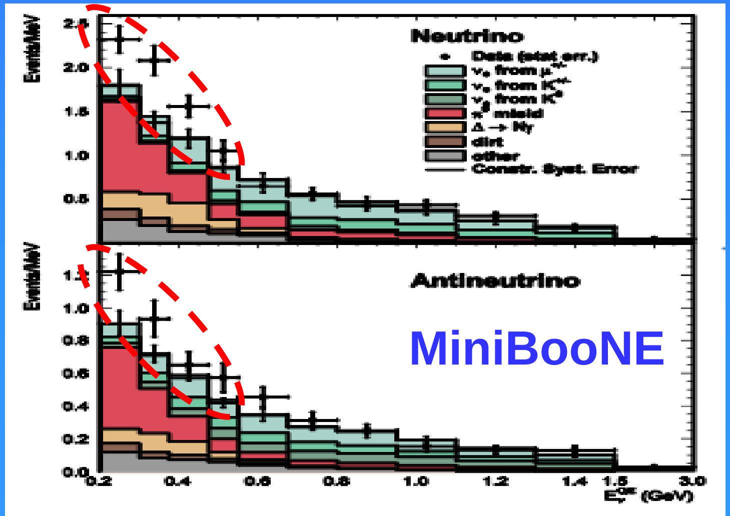
  $\nu_\mu \rightarrow \nu_\tau$ oscillation, $\nu_\mu \rightarrow \nu_e$ oscillation

New Neutrino Experiment at J-PARC

Introduction

- We are planning new experiments at J-PARC to study low energy neutrino interactions by introducing nuclear emulsion technique.
- The emulsion technique can provide good measurements with ultimate position resolution.
- Physics motivation is a detailed (exclusive) study of low energy neutrino – nucleus interactions for a variety of target (H_2O,Fe,C) and
  cross section measurement of low energy ν_e interaction and the exploration of a sterile neutrino.

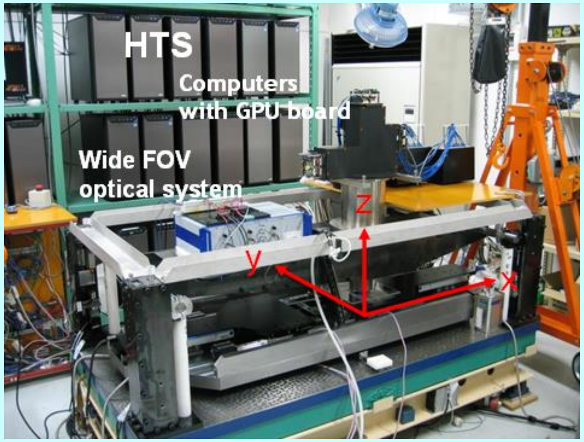




Technical improvement

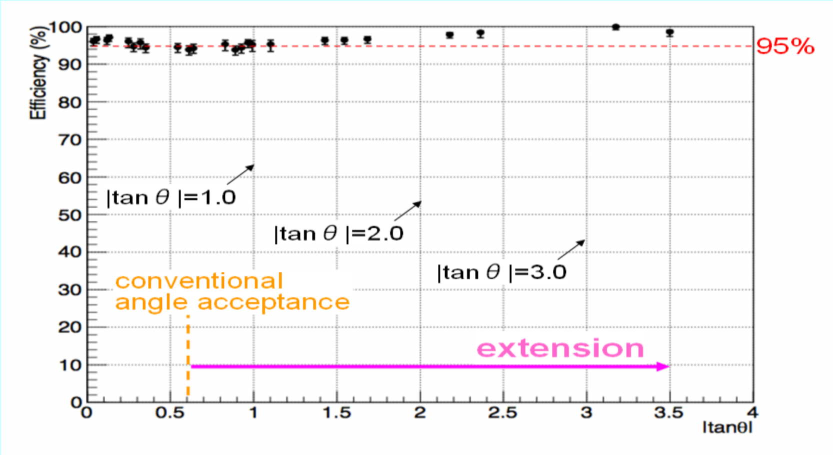
Readout technique

High Speed Scanning



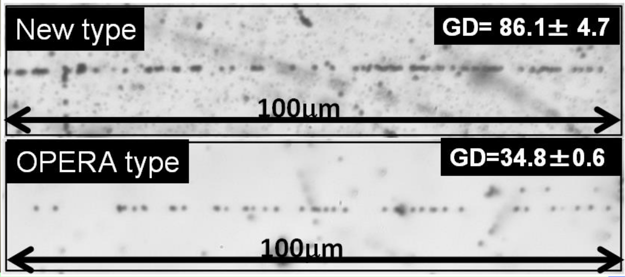
HTS 9,000cm^2/h, x100 faster

Large angle tracking technique

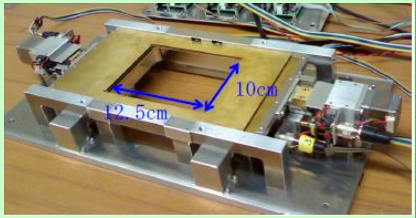


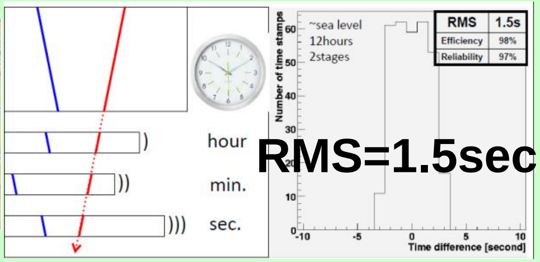
Detector technique

High Sensitive film



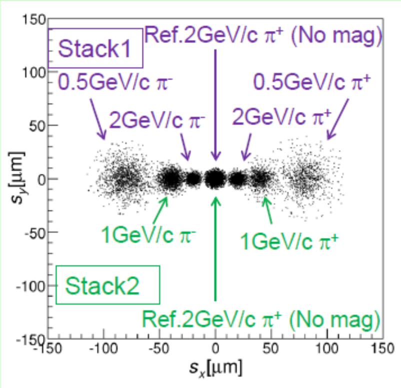
Time resolution



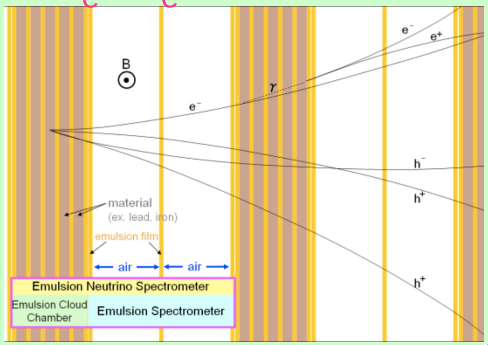


RMS=1.5sec

Charge sign ID

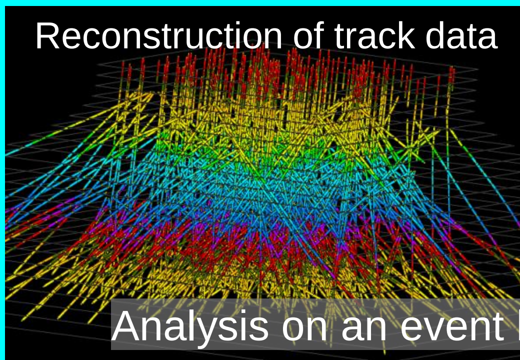


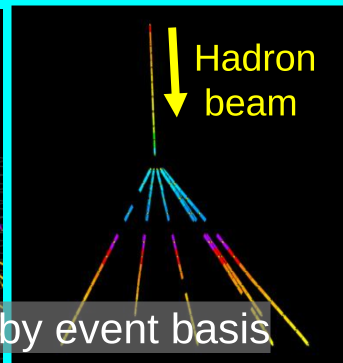
$\nu_e / \overline{\nu}_e$ identification

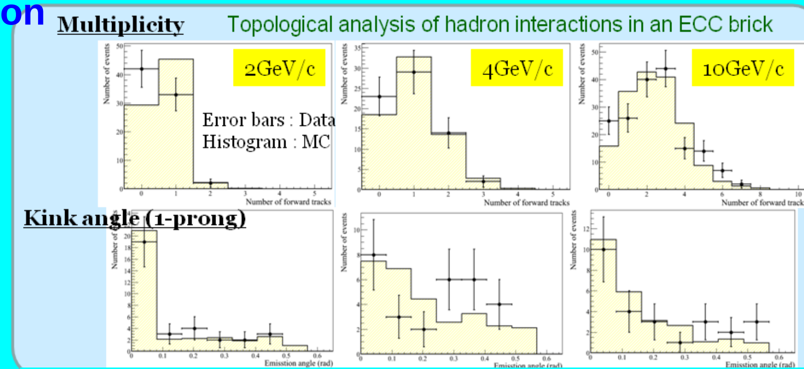


Advantage of Emulsion

Systematic analysis with sub-micron position resolution



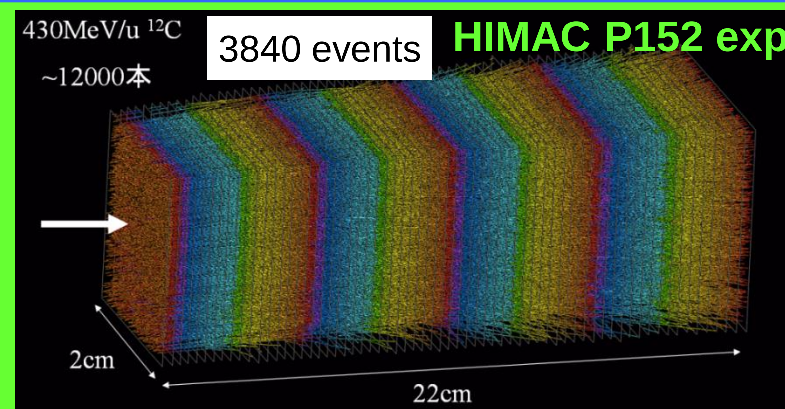




H. Ishida, T. Fukuda et al., *Prog. Theor. Exp. Phys.* 2014, 093C01

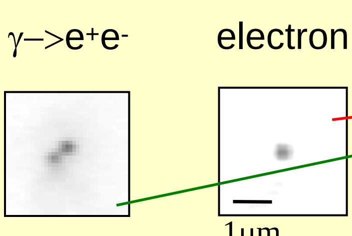
Flexibility for target material

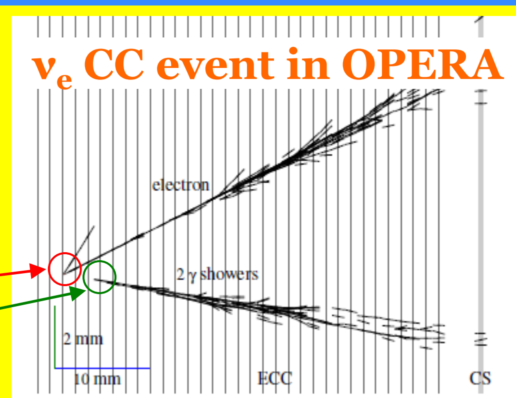
A sandwich structure



γ/ electron ID

Microscopic image from the view of the beam axis





Low background from $\nu_\mu NC\pi^0$ production

Primary electron track is observed as a isolated track, not as a pair of tracks.

Roadmap

Preliminary measurements RUN — **Feasibility study at J-PARC**

J-PARC T60 experiment

Future plan

Detector RUN — **Detector performance check**

Target mass: 10- 30kg

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

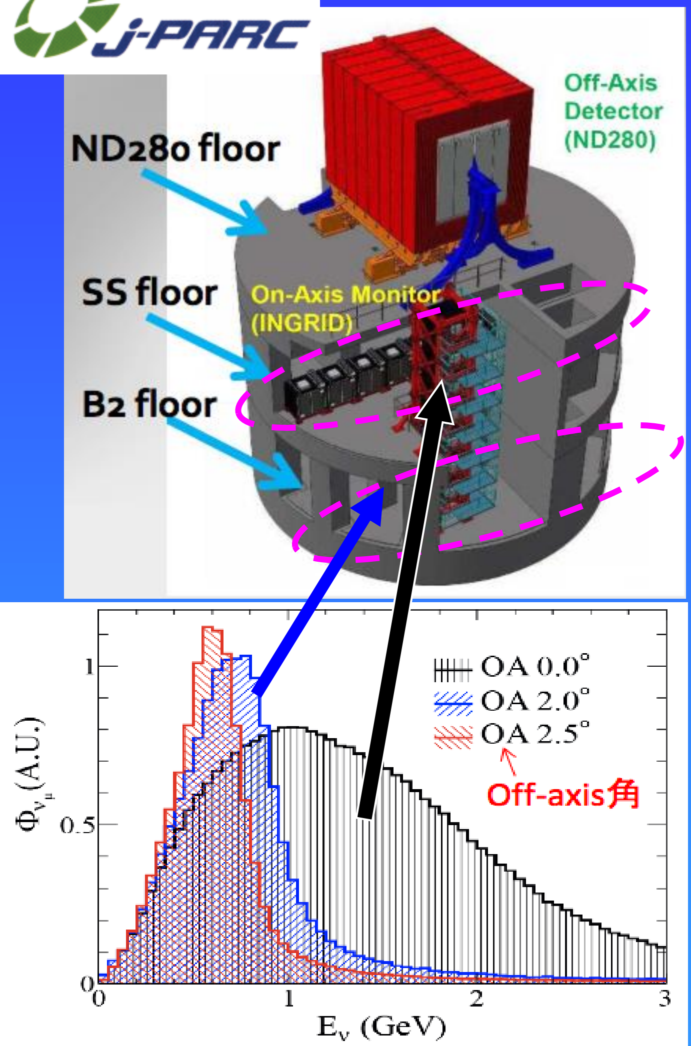
Target mass: 100- 300kg

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

Target mass: 1- 3ton
Target mass: 6-10ton
} depend on sensitivity

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

J-PARC T60 experiment

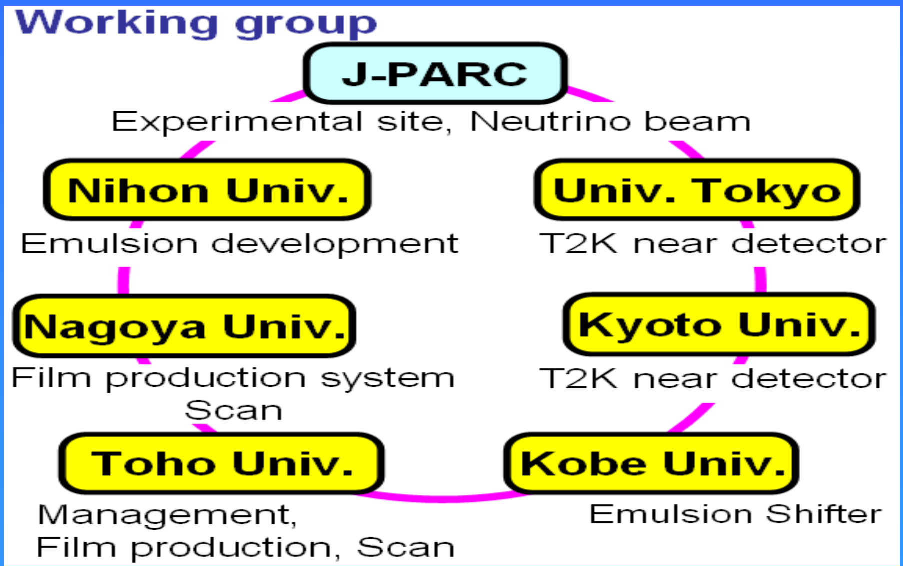


Proposal of an emulsion-based test experiment at J-PARC

Exclusive summary

A test experiment is proposed that equips Emulsion Cloud Chamber as a main detector in order to investigate environmental and beam associated background at the T2K near detector hall in J-PARC, optimal detector structure, and performance of newly developed nuclear emulsion gel. The aim of the experiment is a feasibility study to make a future experimental plan for the study of low energy neutrino-nucleus interactions and the exploration of a sterile neutrino.

- J-PARC PAC endorsed as a test experiment (T60).



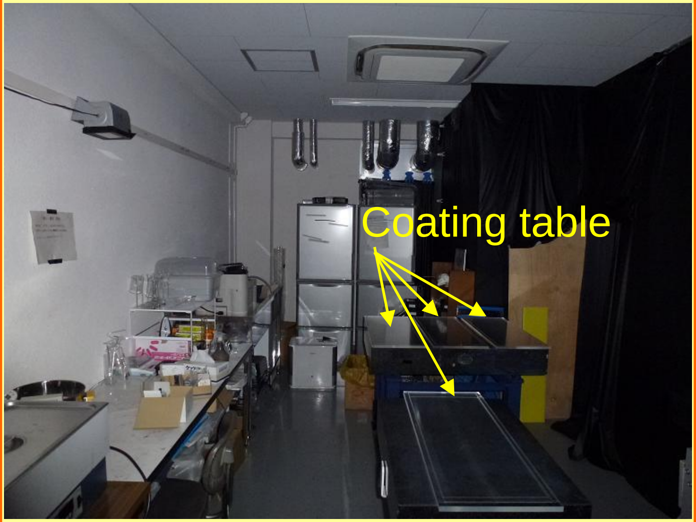
A collaborative project with some member of OPERA and T2K

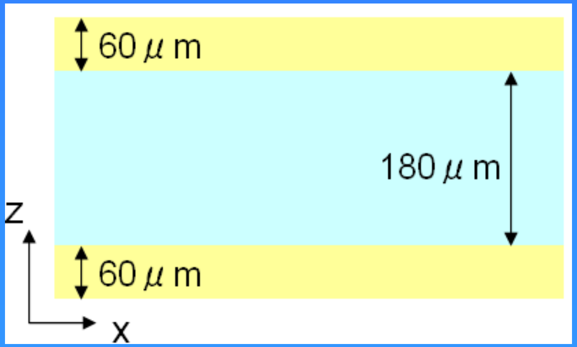
Preparation of emulsion films

Nuclear emulsion gel production system at Nagoya Univ.

6 batch were produced.

Emulsion coating

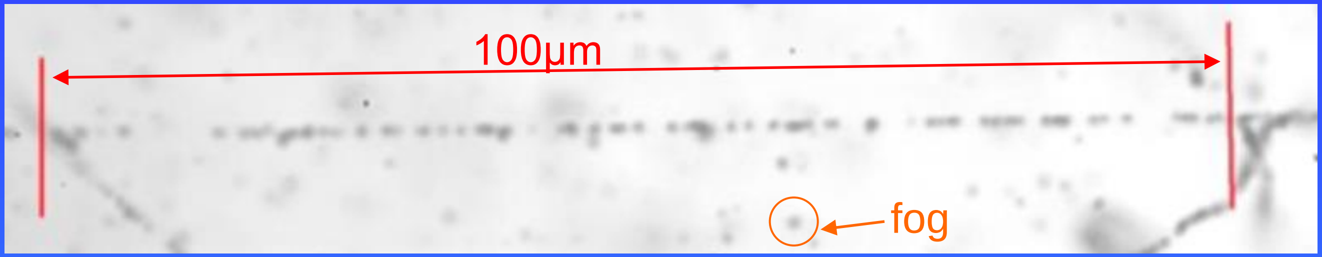


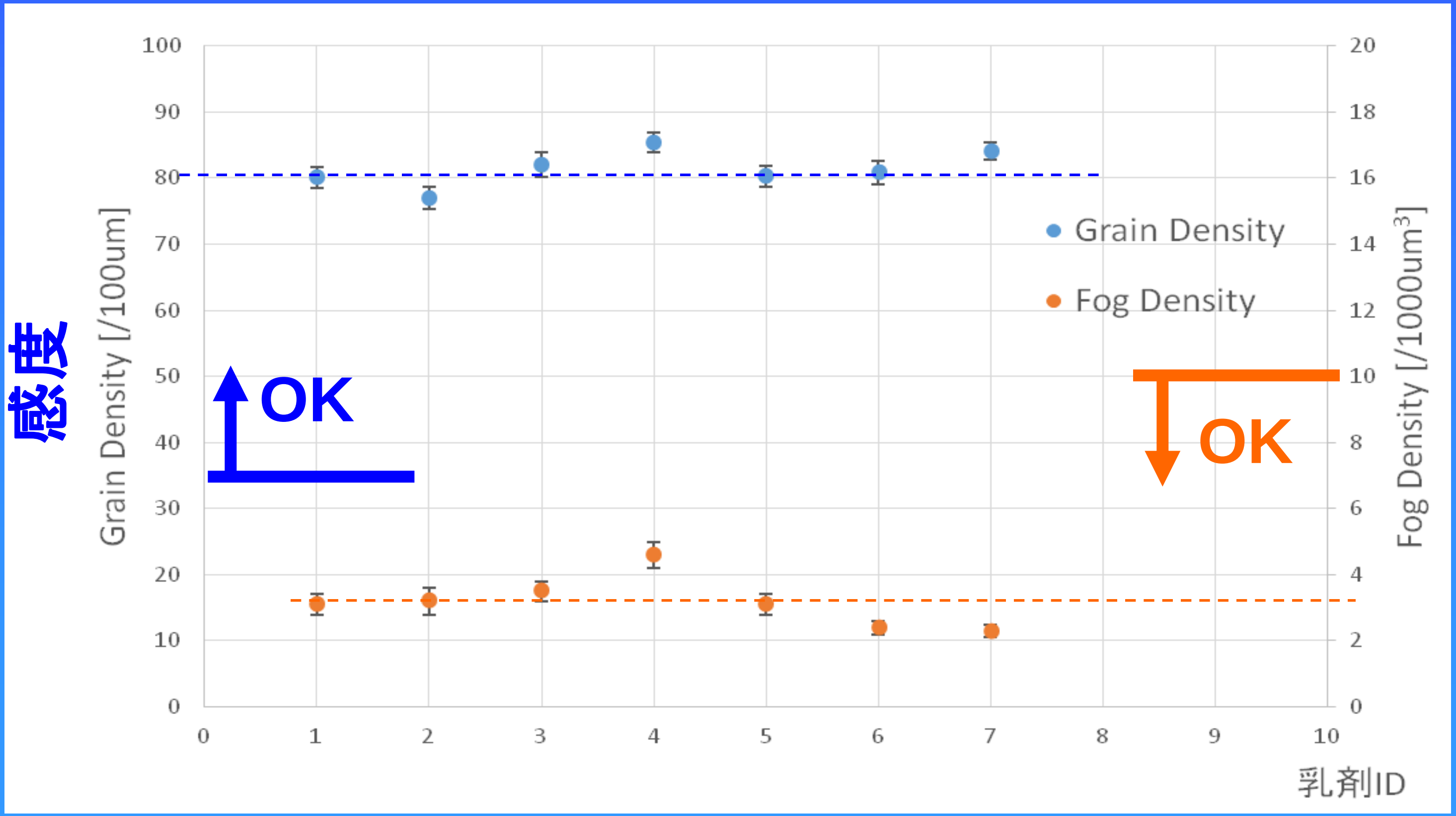


Emulsion coating:
Both sides of plastic base

Nuclear emulsion films for T60

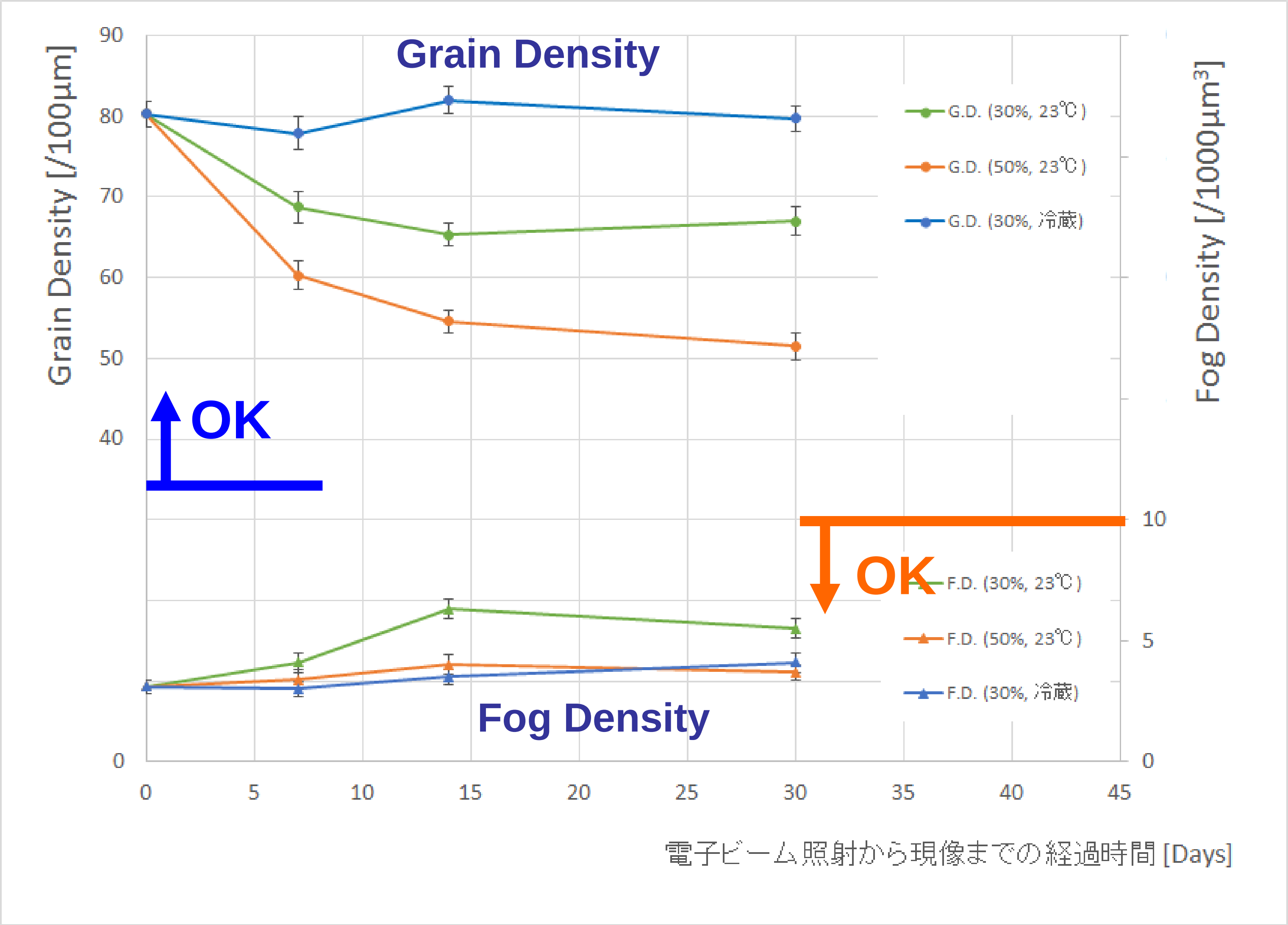
Initial performance：
efficiency and noise density measurement based on grain counting.





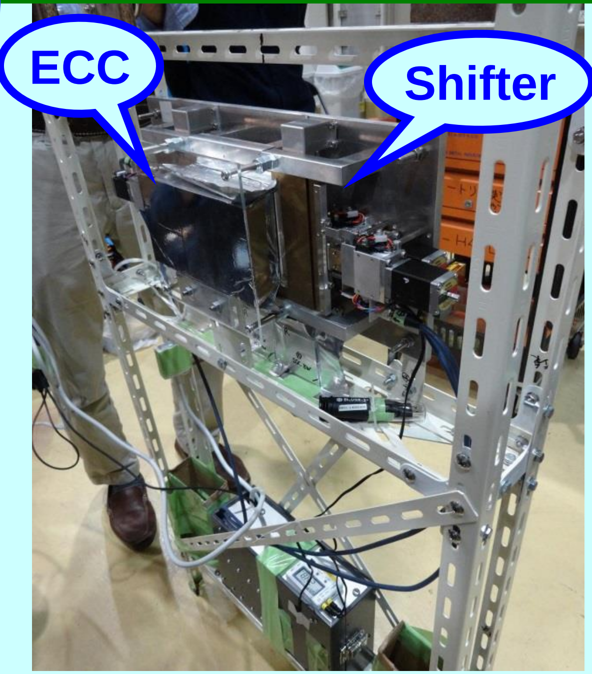
Nuclear emulsion films for T60

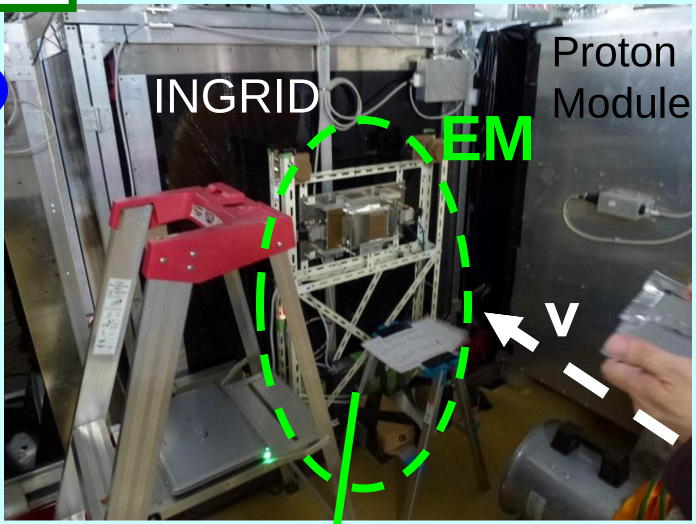
Aging characteristics (fading effect) :
efficiency and noise density measurement based on grain counting.

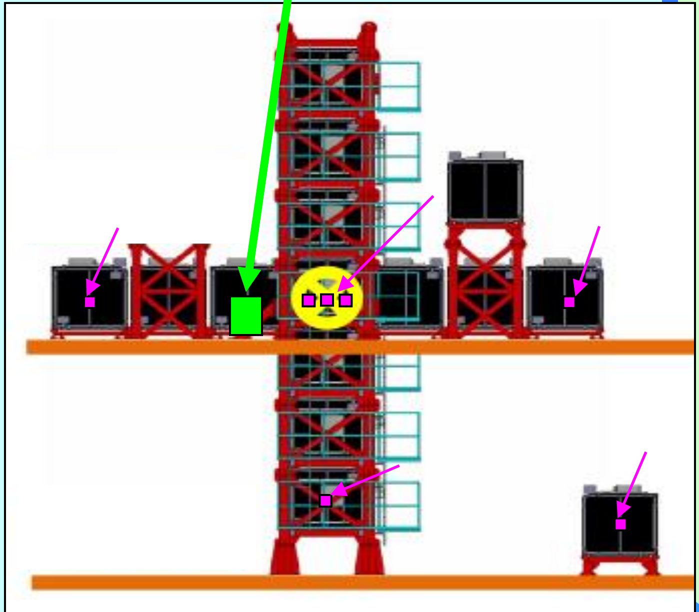


T60 detectors

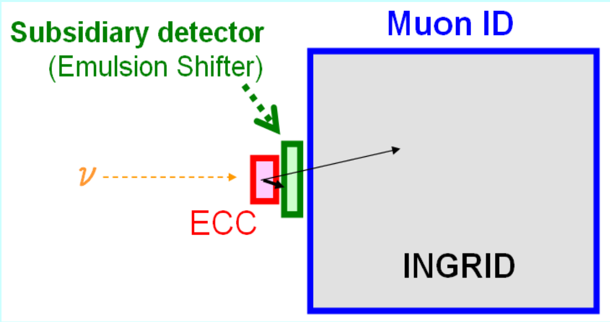
Emulsion Module







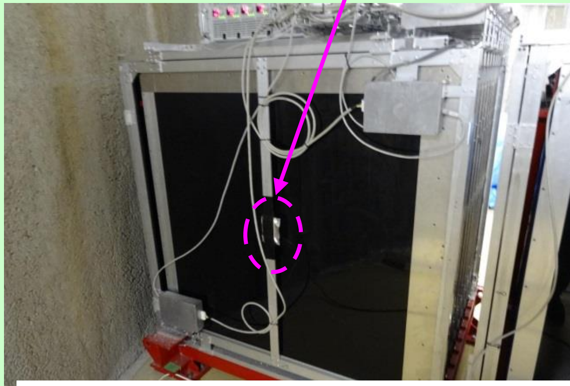
Conceptual design



Track matching between ECC and INGRID by timing information

Monitoring sample

Small films for condition monitoring



Monitoring samples were also placed in front of the INGRIDs.

Future prospects

Preliminary measurements (T60) 2014

↓

Detector Run 2015
(Water & Iron target)

Now we are discussing about some physics targets.
Advices for target physics are very welcome !

Water target:
neutrino – nucleus int. study

Iron target:
Sterile neutrino search

Nano Imaging Tracker target:
first observation
neutrino nucleus coherent scattering

Air + magnetic field:
neutrino beam study, tech. R&D
($\nu_e/\bar{\nu}_e$ separation)

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).
- **4 ν_τ candidate events** were found with 2.1 signal and 0.23 background events expected in the analyzed sample.
- Significance of the observation is **4.2 σ**

→ **Observation 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 carry out a test experiment at J-PARC (**T60**) for the feasibility study.
- We confirmed that the initial quality and the aging characteristics of newly produced emulsion films is kept good sensitivity & low noise.
- We will modify and confirm the details of next run based on the analysis result of T60.

Back up

π 中間子の発見

（湯川中間子）

1935　湯川秀樹
中間子論（核力の担い手として、質量が電子の200~300倍の粒子が存在すべき）

1937　Anderson, Neddermeyer (霧箱)
宇宙線中に新粒子（実はμ粒子）を発見。質量は湯川の予言とおりだが、物質との反応断面積が小さ過ぎる。

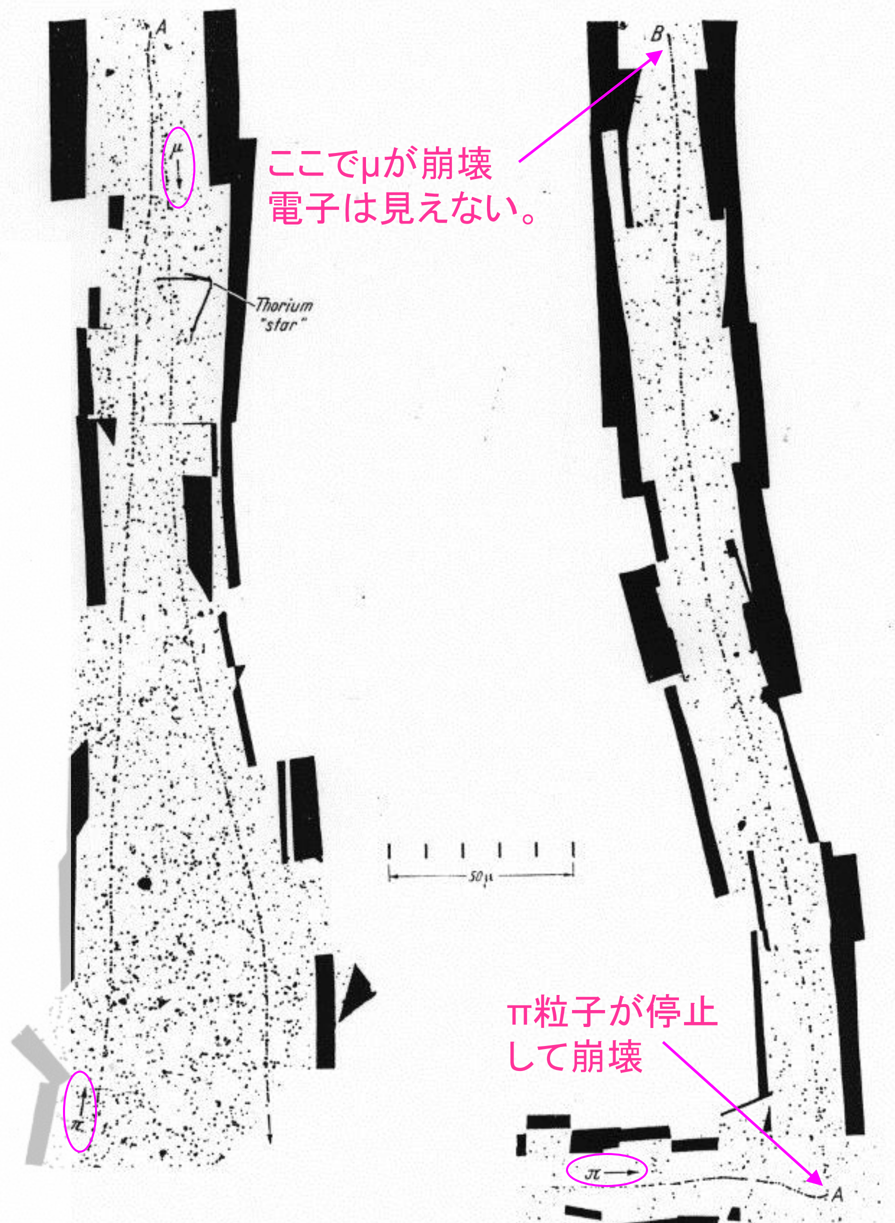
1943　坂田昌一・井上健・谷川安孝
二中間子論（π→μ＋ν）

1945　Coversi ら
μ≠πの実験

1947　Powell ら
上空での宇宙線の中にπ→μ＋νの崩壊現象を発見。

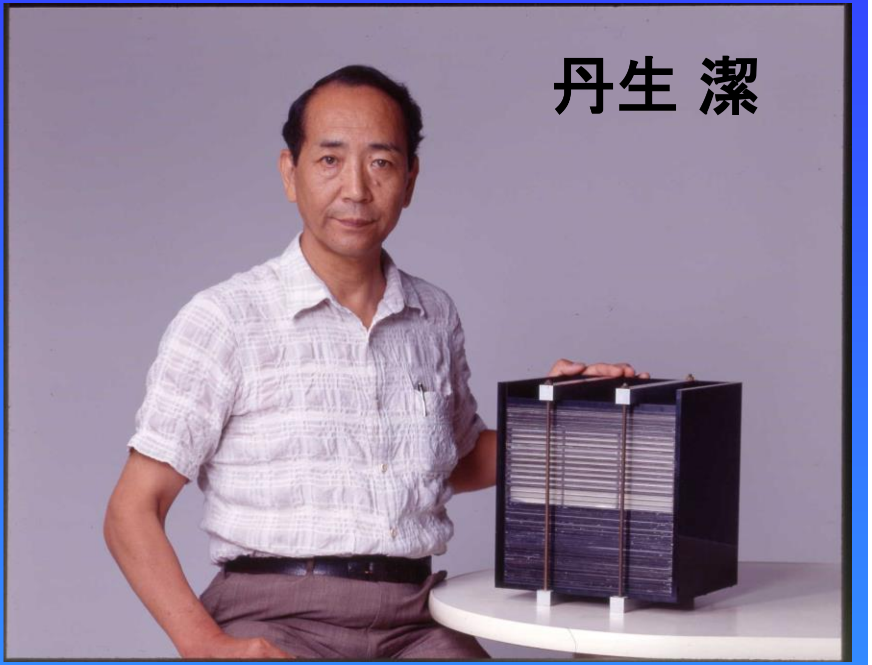
1949　湯川　　　ノーベル賞受賞
1950　Powell　ノーベル賞受賞

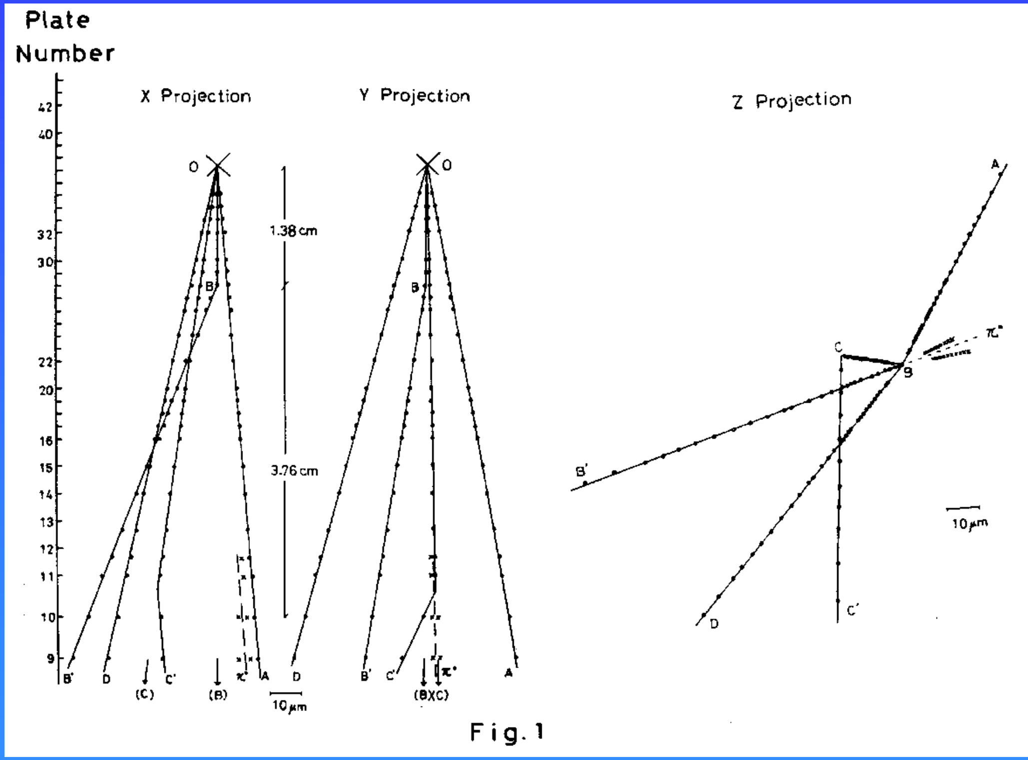
First observations of the decay of a π-meson



Lattes, Muirhead, Occhialini and Powell; Nature 159, 694 (1947).

原子核乾板によるX粒子の発見
（現在のチャーム粒子）



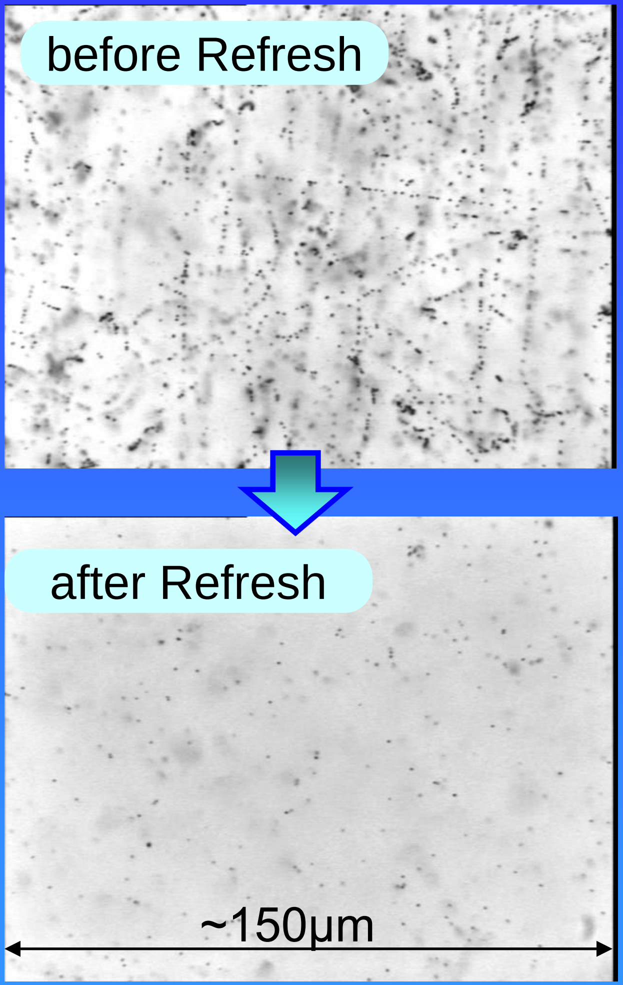


1970年代、欧米→加速器＋泡箱など
日本→宇宙線＋原子核乾板

原子核乾板は解析の非能率さ故に泡箱等にとって変わられていた。日本には大きな加速器がなく、宇宙線を利用していた。

→ **精密ECC技術の開発**
（**E**mulsion **C**loud **C**hamber）

原子核乾板を高温高湿環境(30℃, 98%)に置き、潜像退行を促進
→ 飛跡を消去する



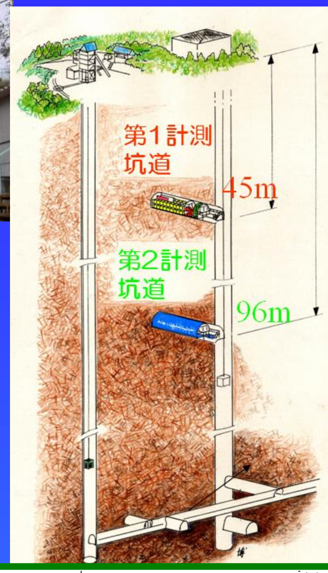
OPERA film は、**<u>Fuji Film ©で製造</u>**される。

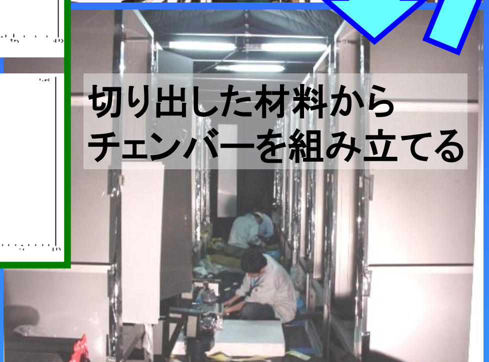
使用枚数

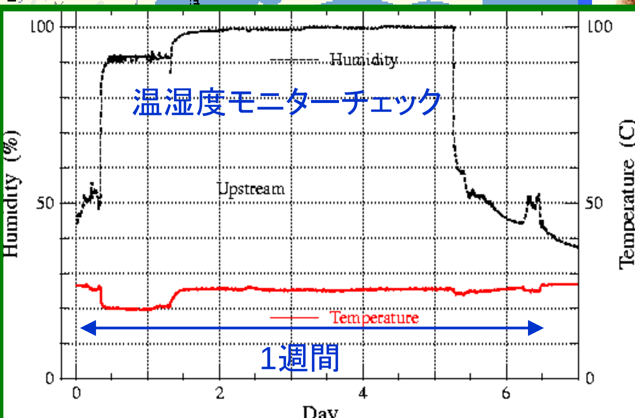
<u>59 films × 150,000 Bricks ~ 9,000,000 films</u>

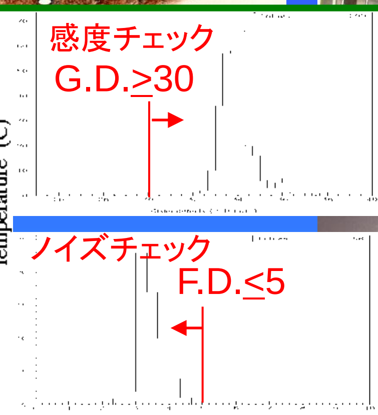
Refresh – 蓄積した飛跡の消去 –

Refresh Facility









Refresh処理済みフィルムをGSに出荷

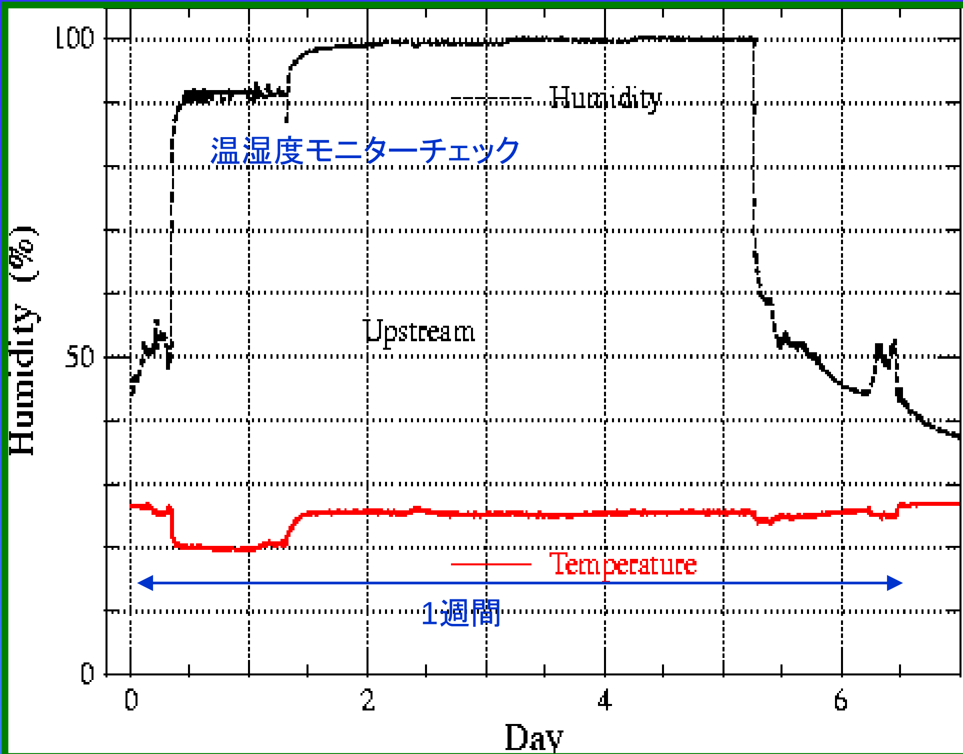
2003.5.26　塗布開始
2004.1.13　リフレッシュ開始
2005.3.17　初出荷
2007.4.25　最終出荷
（全3322箱）

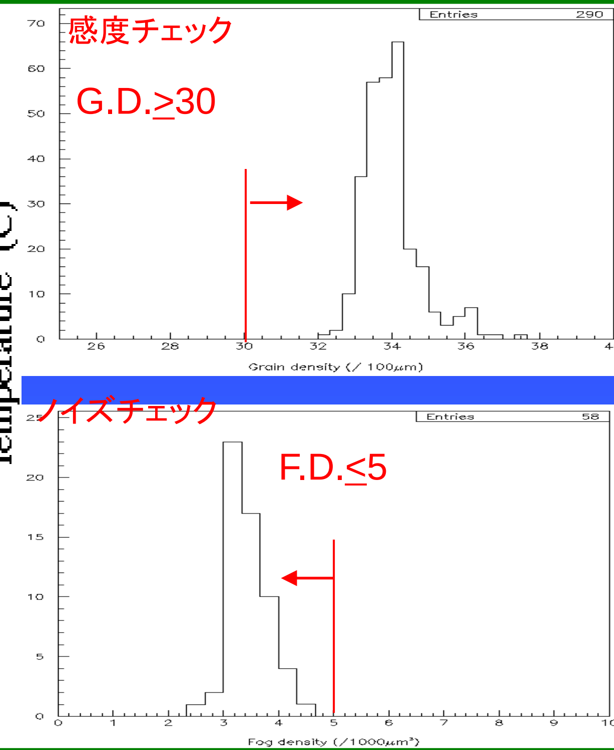

鉱山の地下に、


切り出した材料から
チェンバーを組み立てる


建屋を作り、

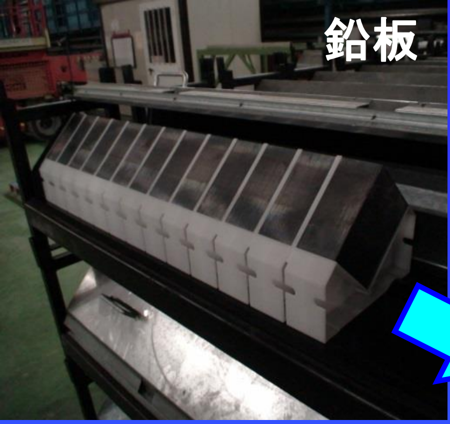

暗室での作業工程を作る

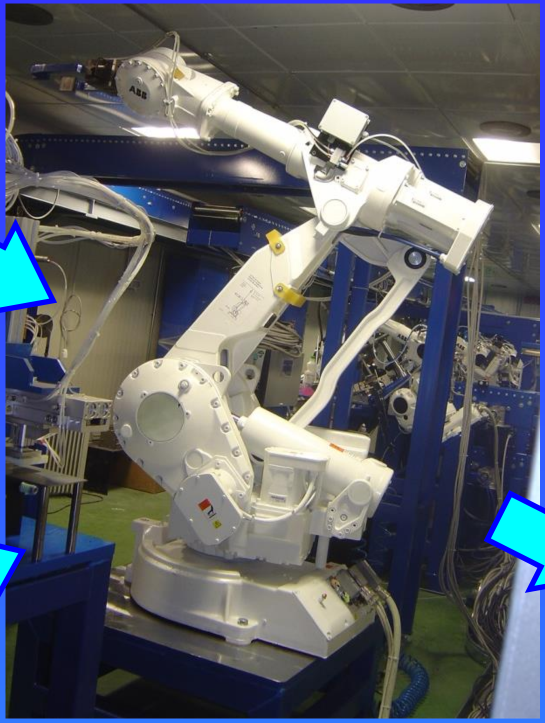


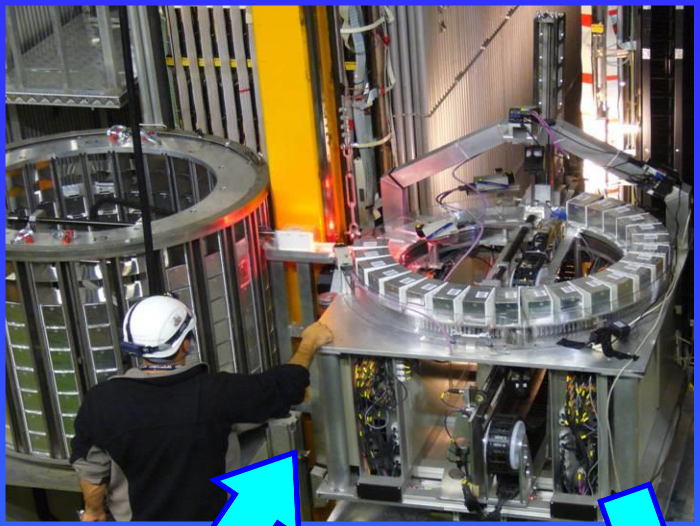


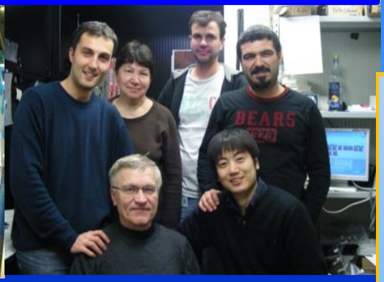
2003.5.26　塗布開始
2004.1.13　リフレッシュ開始
2005.3.17　初出荷
2007.4.25　最終出荷
（全3322箱）

Refresh Facility

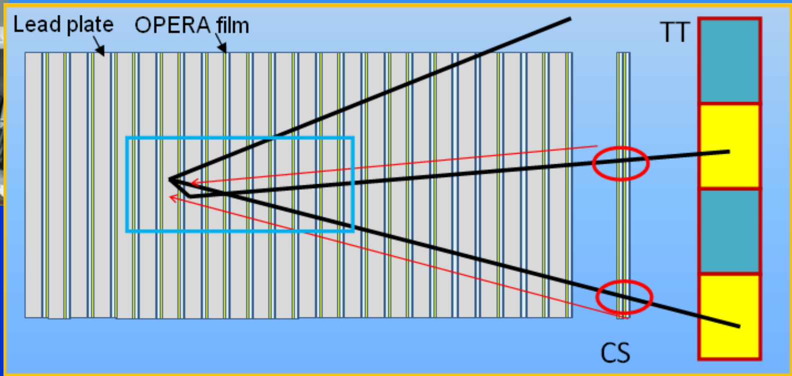








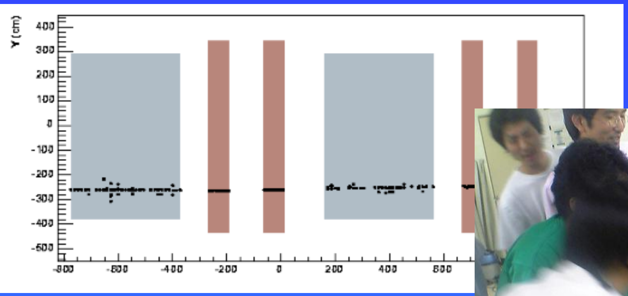
日本から交代でシフトリーダーを派遣



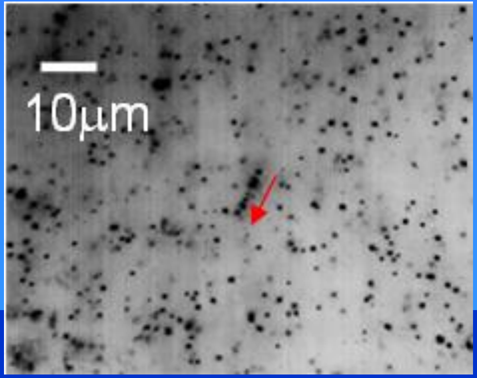
Brick 製造

2006年9月7日

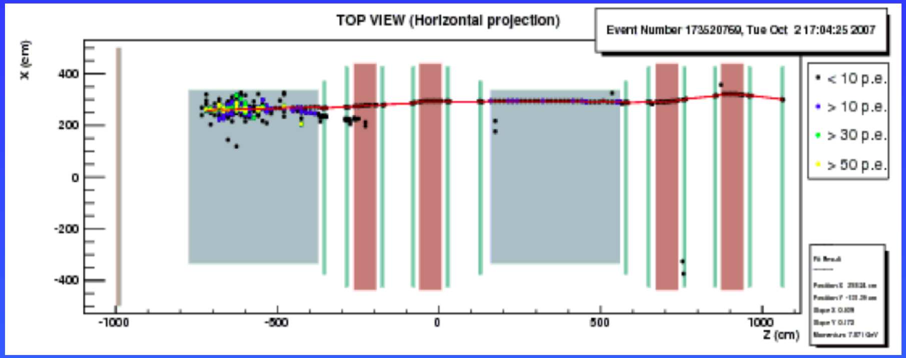
CERNからニュートリノビームのテスト照射。
OPERAで初めて原子核乾板上にニュートリノ反応からの飛跡を検出。

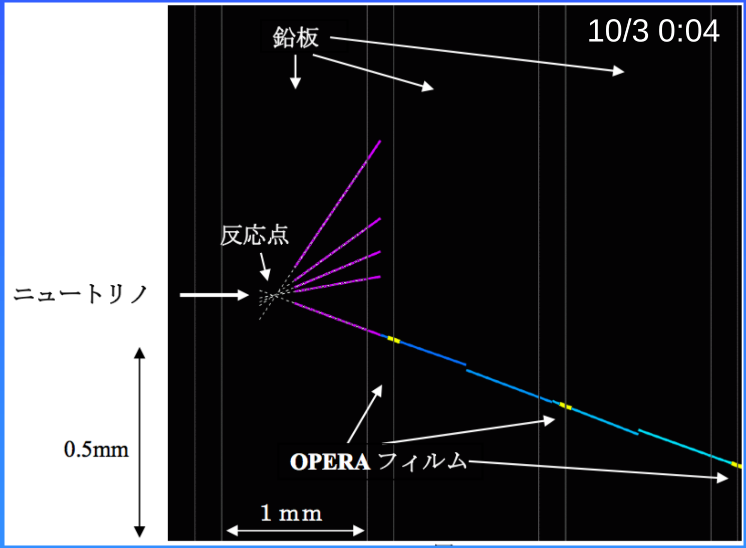


Electronic detector から Emulsion detector への接続を確認。



2007年10月3日





原子核乾板中でニュートリノ反応点を初検出。

Event analysis – ν test run –

大学建物の耐震工事のため、2008年度から
2010年度まで解析室を移転。

鉱山付近のお寺の庫裏に下宿させてもらう。

2008年度より本番開始！

ν_τ のバックグラウンドの研究

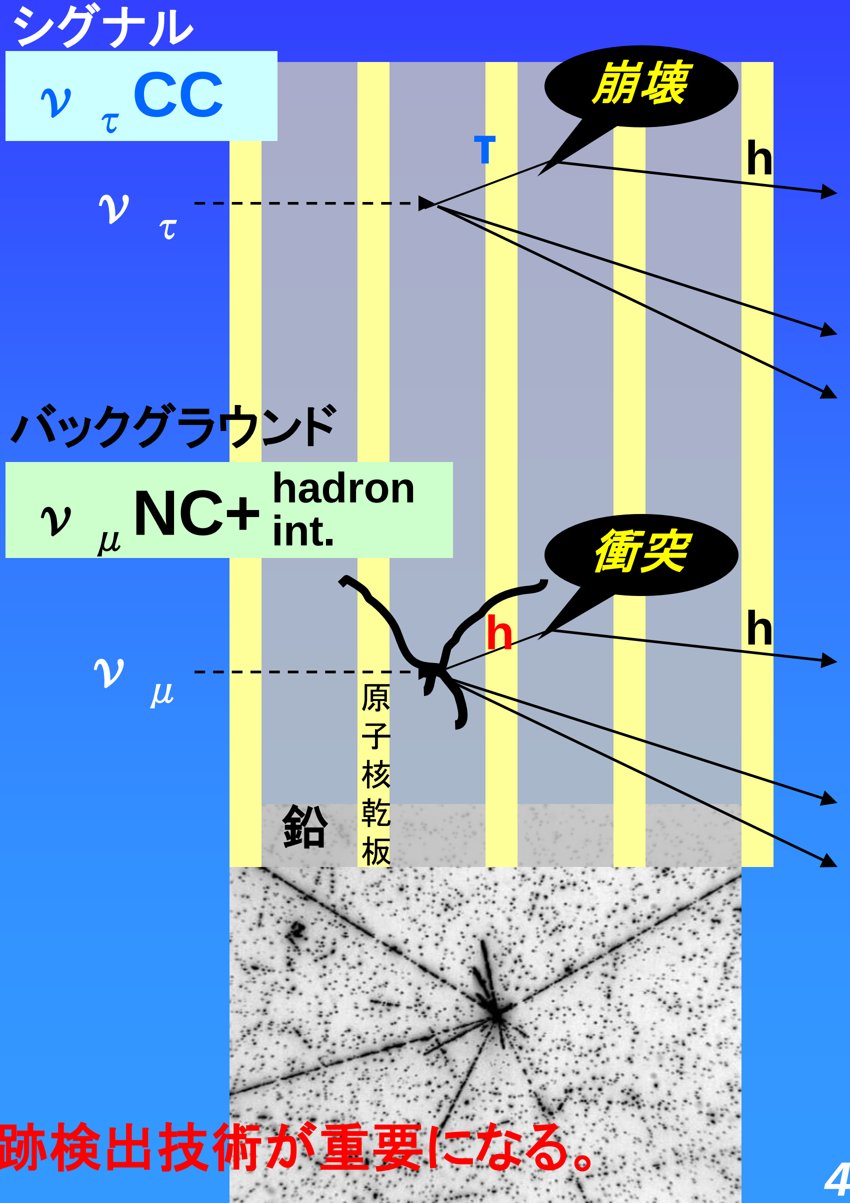
$$\nu_\mu \xrightarrow{\text{oscillation}} \nu_\tau + N \rightarrow \tau^- + X$$

τ粒子の崩壊様式

	Decay mode	BR(%)
3rd	$\tau^- \rightarrow \mu^- \nu_\mu \overline{\nu}_\tau$	17.36
	$\tau^- \rightarrow e^- \nu_e \overline{\nu}_\tau$	17.85
1st 4th	$\tau^- \rightarrow h^- (n\pi^0) \overline{\nu}_\tau$	49.52
2nd	$\tau^- \rightarrow 2h^- h^+ (n\pi^0) \overline{\nu}_\tau$	15.19

(hadron崩壊 2行分: 65%)

・ $\tau \rightarrow$ hadron崩壊に着目。



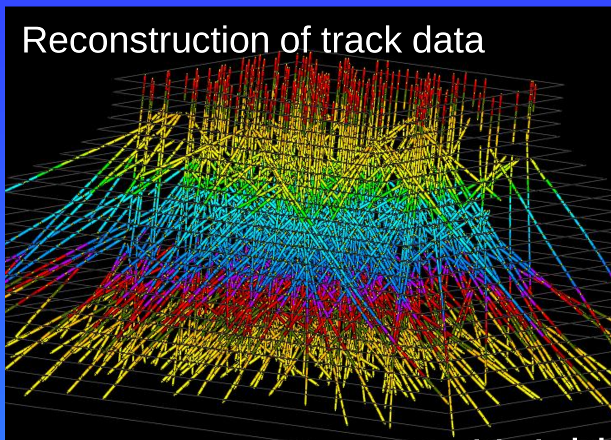
<u>核破砕片の特徴</u>

・電離損失が大きい。

・ほぼ等方的に放出する。 ⇒ **大角度飛跡検出技術が重要になる。**

OPERA型ECCでの
系統的なハドロン反応の解析

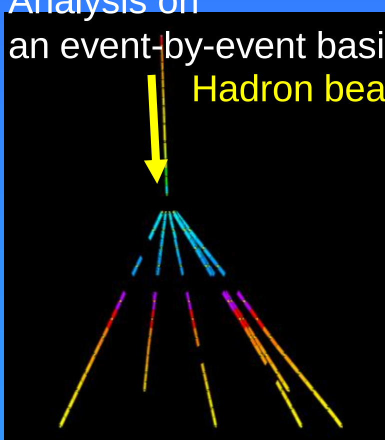
- 2-10GeV/c π^-のEvent by event の詳細な反応解析



	2GeV	4GeV	10GeV
Reconstructed tracks	584 tracks	913 tracks	2205 tracks
Total track length	8.5 m	12.6 m	38.5 m
Interactions	77 events	68 events	173 events

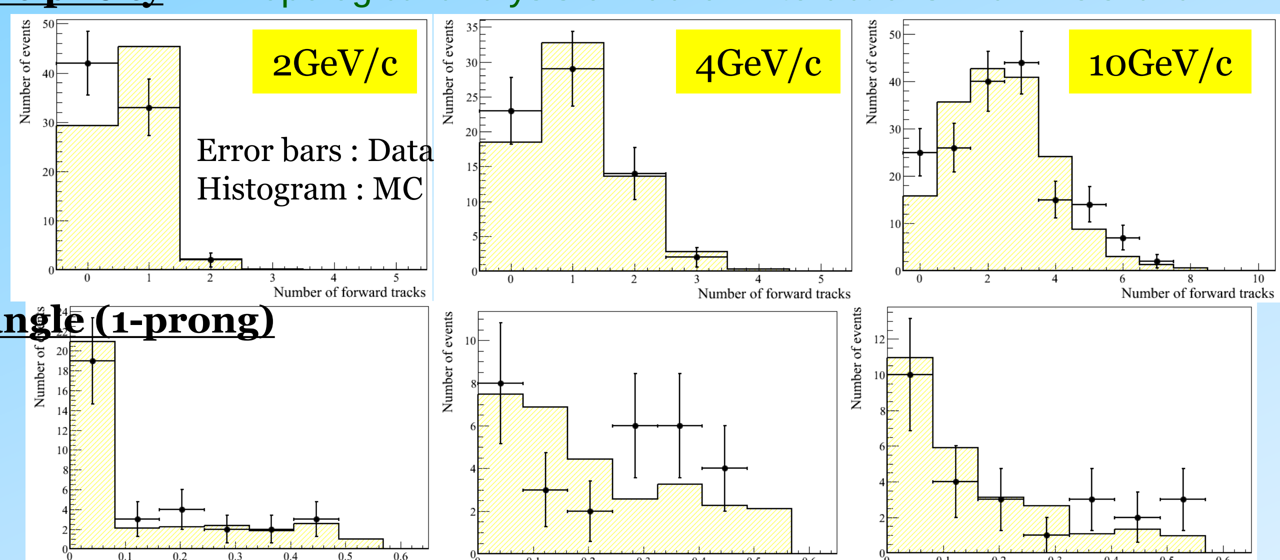
H. Ishida, T. Fukuda et al., *Prog. Theor. Exp. Phys.* 2014, 093C01

Analysis on
an event-by-event basis

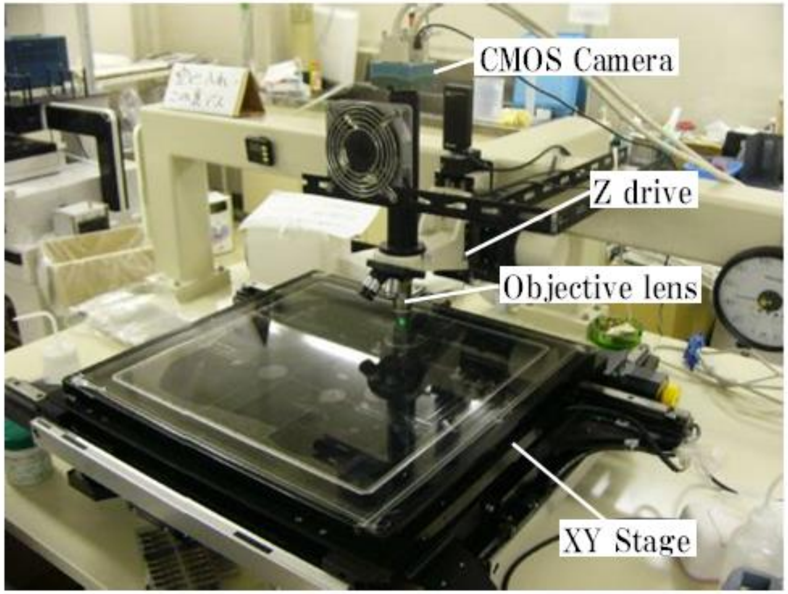


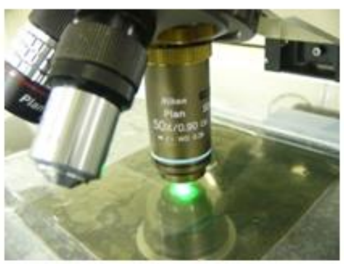
Multiplicity Topological analysis of hadron interactions in an ECC brick

Kink angle (1-prong)

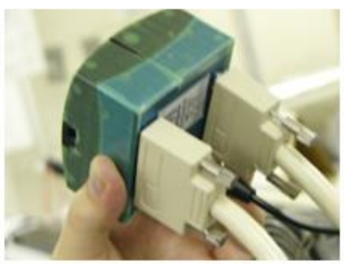


新型原子核乾板自動飛跡認識装置FTSの開発



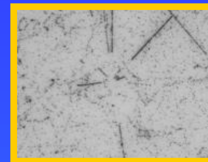


Objective lens
Nikon CFI Plan x50
oil immersion lens



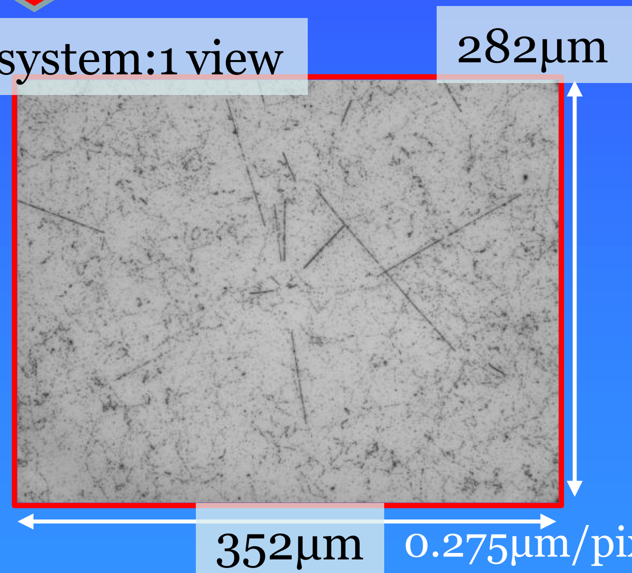
CMOS Camera
Mikrotron
Eosens MC 1362

オリジナル



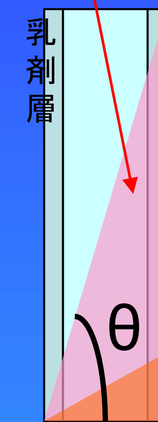
UTS 1 view :
120 μm × 100 μm

New system:1 view



0.275μm/pixel

FTS
(|tanθ|≤3.5)



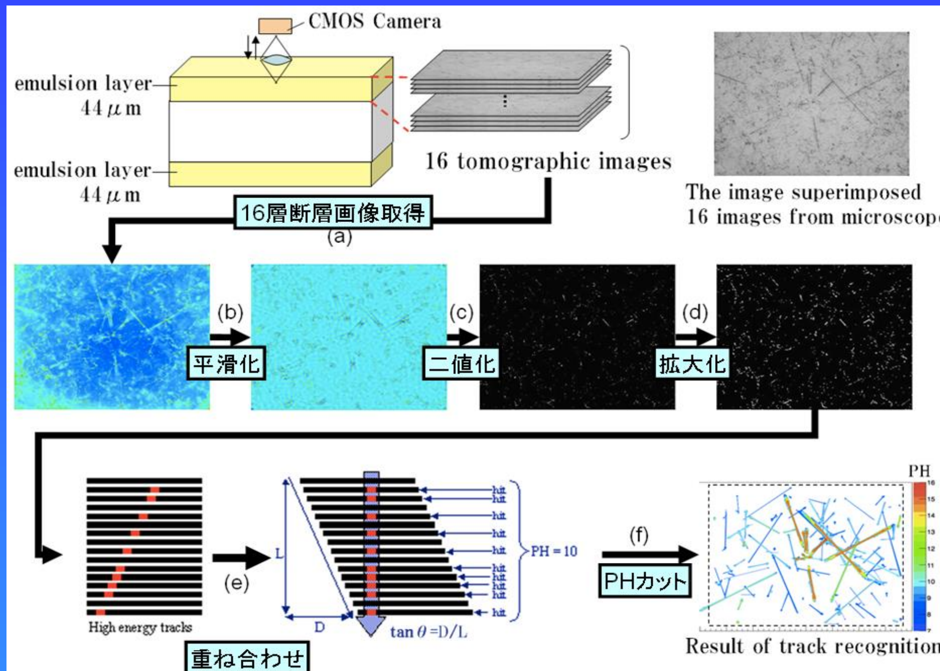
従来
(|tanθ|≤0.6)

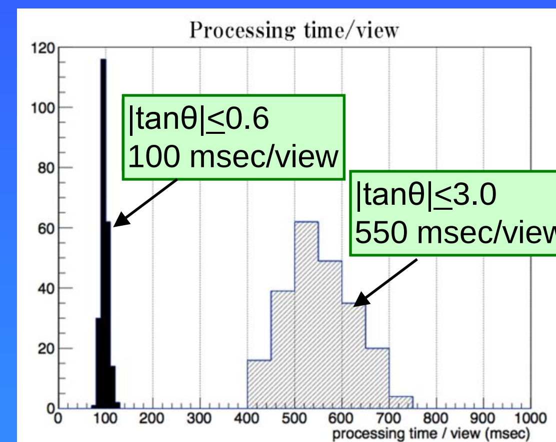
- 大角度飛跡を効率良く検出するために視野の大きなレンズ, カメラを採用した。

Automatic Track recognition using GPU

(T. Fukuda et al., 2013 *JINST* 8 P01023)

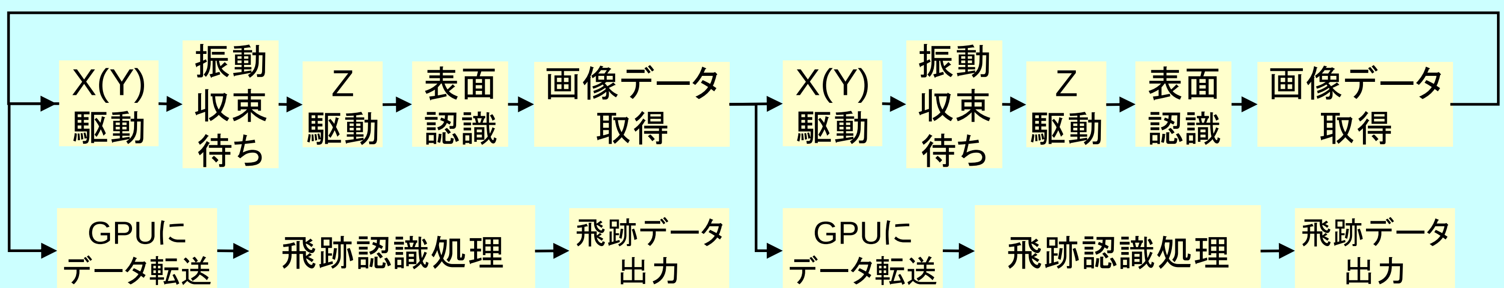
- 自動飛跡認識アルゴリズムは従来のアルゴリズムを踏襲している。
- 自動飛跡認識部にはGraphics Processing Unit (GPU) を採用。



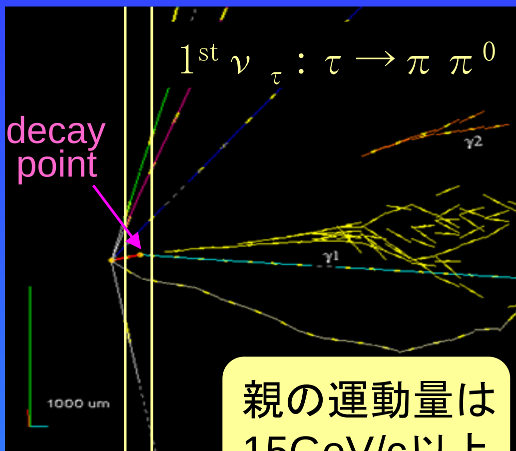


画像処理から飛跡認識までの全てをGPUで処理する自動飛跡読み取り装置を実用化

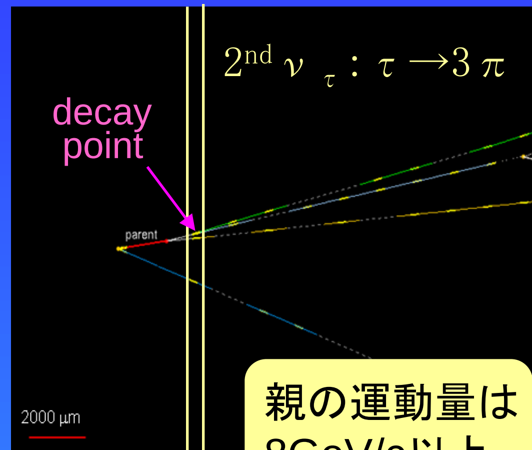
マルチスレッド化による駆動系と飛跡認識系の並列化



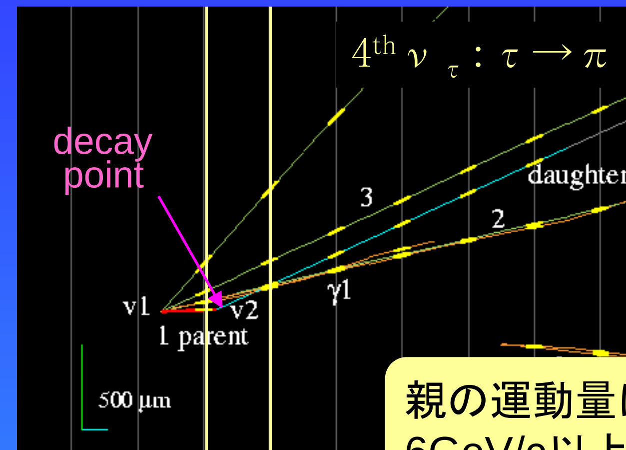
検出したν_τ反応での核破片探索



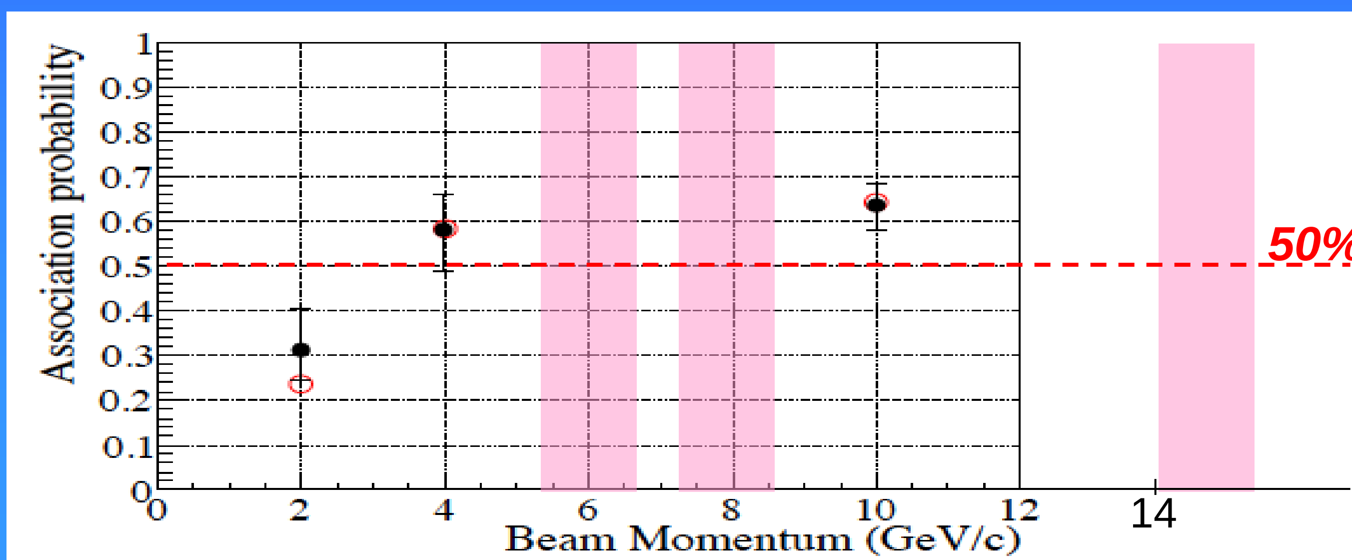
親の運動量は15GeV/c以上



親の運動量は8GeV/c以上



親の運動量は6GeV/c以上



大角度飛跡自動解析

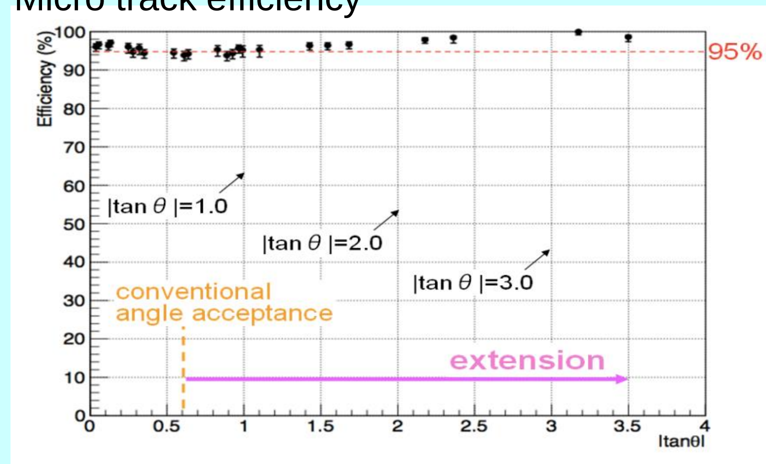
大角度 最小電離粒子飛跡 の自動認識

解析を進める中で、検出効率が高いことに気付いた。
(ここまでの大角度はこれまで検討されてこなかった)

Conventional emulsion gel
(G.D. = 34/100μm)

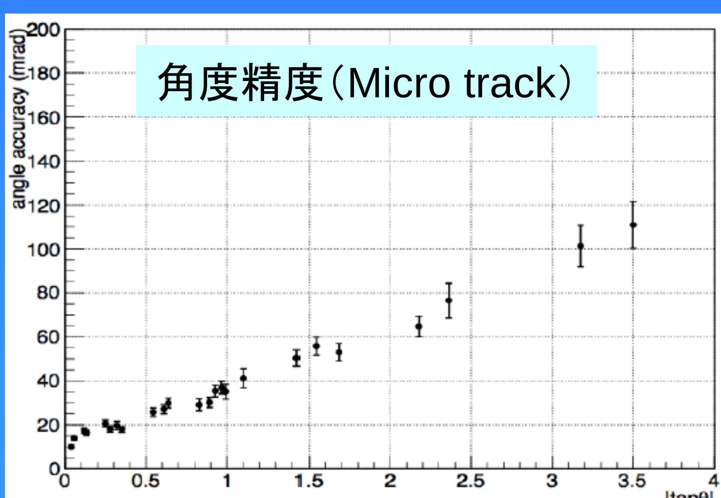
テスト実験
@ CERN

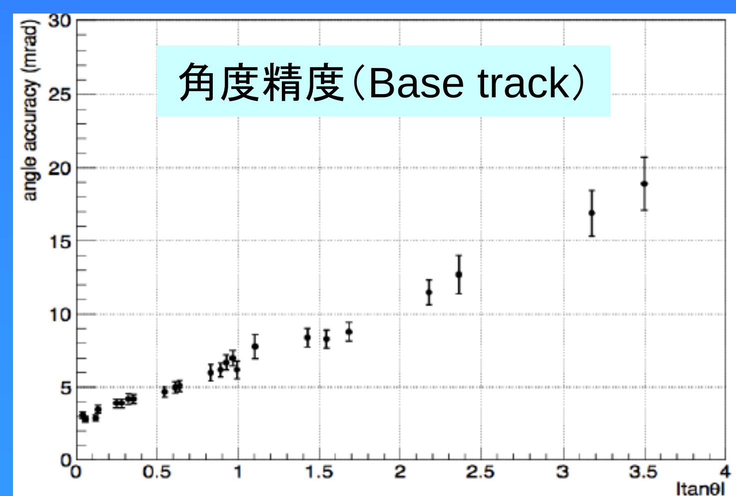
Micro track efficiency



高い検出効率で自動認識できることを実証した。

大角度に渡って自動認識された飛跡の角度精度





$$\tan\theta = \frac{x_2 - x_1}{z_2 - z_1} = \frac{\Delta x}{\Delta z}$$

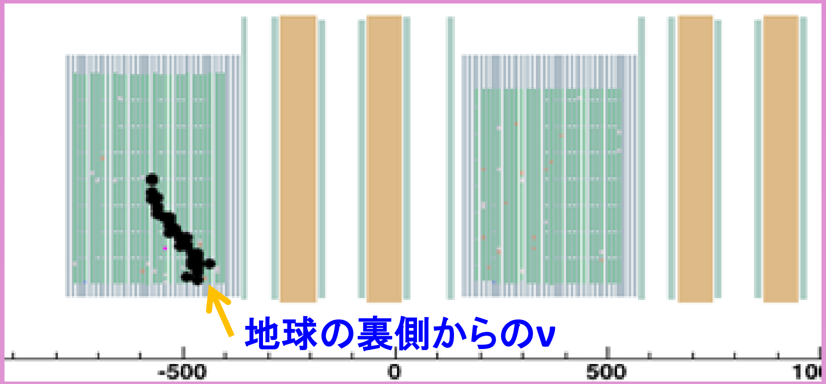
$$\sigma_{\tan\theta}^2 = \frac{2}{\Delta z^2}(\delta x^2 + \delta z^2 \times \tan^2\theta)$$

表面認識の精度
δz=0.8μm

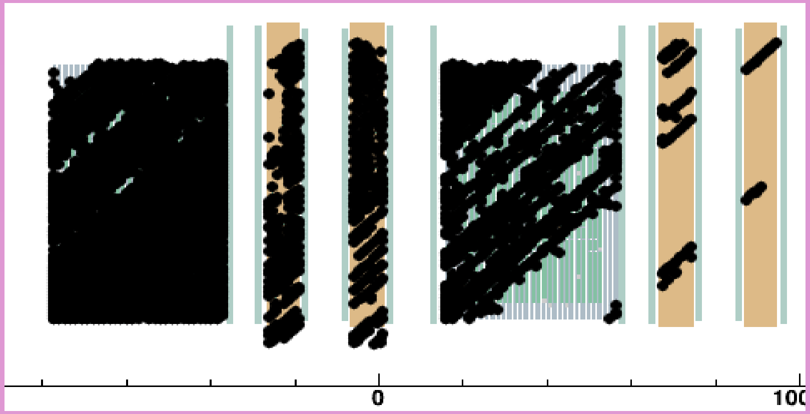
大角度飛跡自動解析の応用

OPERA検出器による宇宙線の解析

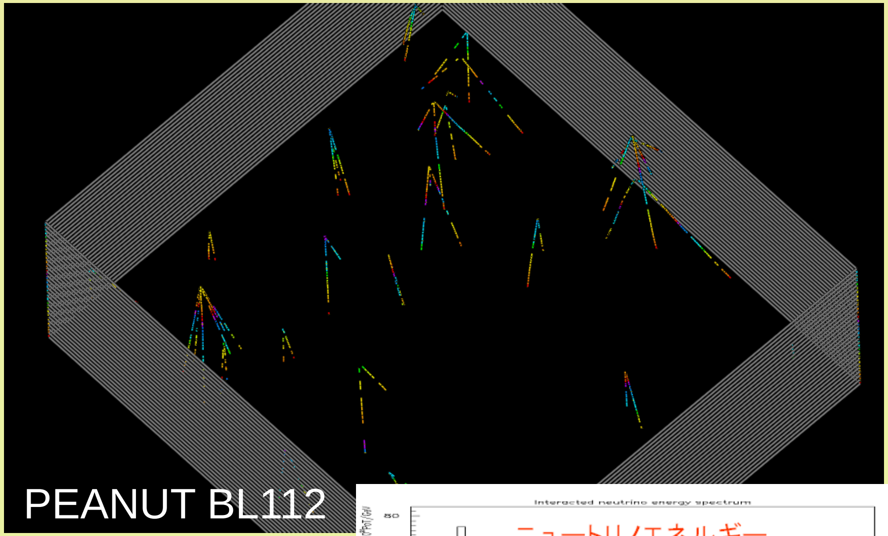
① 大気ニュートリノ振動による
ν_τ出現事象の探索

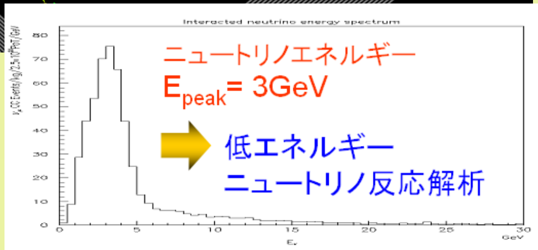


② 高エネルギー宇宙線事象の詳細解析



低エネルギーニュートリノ反応の研究





<u>低エネルギーニュートリノ実験</u>において、

ニュートリノ反応の検出効率、
電子飛跡の検出効率・エネルギー測定精度
の向上が期待できる。

Detector Run (2015)

- We are planning a next exposure for “Detector Run” after summer shut down. (parasitically exposure with T2K (ex. Oct. 2015 ~ Mar. 2016))
- We are considering to set the water target ECC for the detector performance check to study ν–H_2O reaction in low energy region.
- We will submit this proposal to J-PARC PAC before this July.