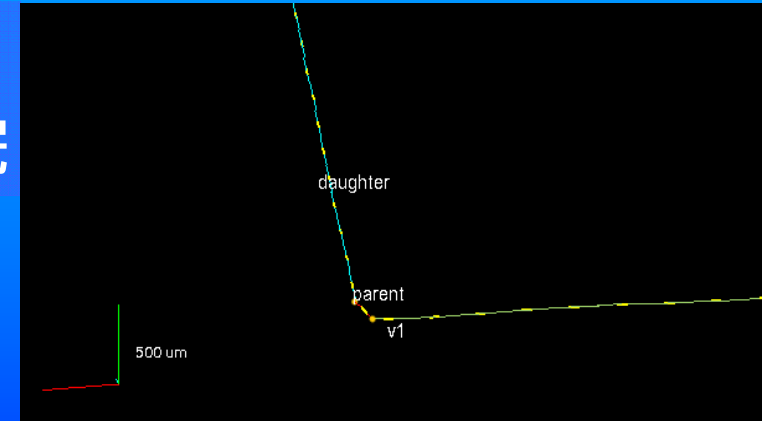
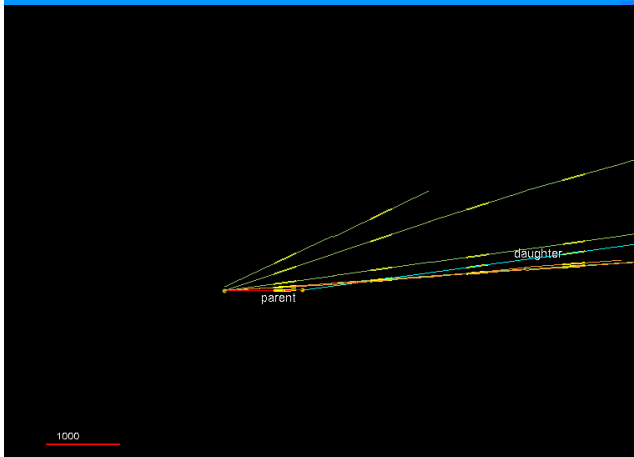


長基線ニュートリノ振動実験OPERAによる タウニュートリノ出現の実証

福田 努

名古屋大学 高等研究院



Outline

- Nuclear Emulsion
- The OPERA experiment
- New Emulsion Experiment

Nuclear Emulsion

原子核乾板

原子核乾板

素粒子など荷電粒子に感度がある特殊な“写真フィルム”

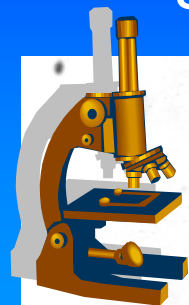
飛跡

$100 \mu\text{m} = 0.1\text{mm}$

サブミクロンの精度を持つ超精密3次元飛跡検出器

Photographic Film technology

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



Microscopic image

Recorded as silver grains along the particle passing through line.

50 μ m

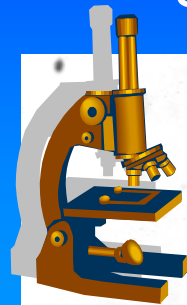
Intrinsic resolution of 0.3 μ m



	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。

Photographic Film technology

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



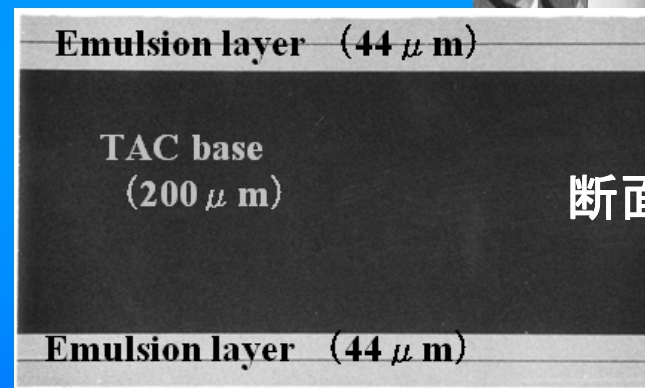
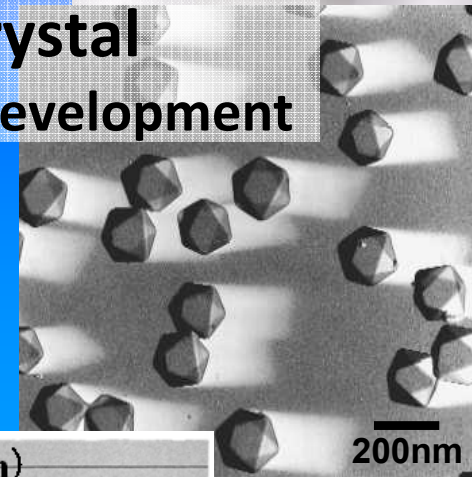
Microscopic image

Recorded as silver grains along the particle passing through line.

50 μ m

Intrinsic resolution of 0.3 μ m

AgBr crystal before development



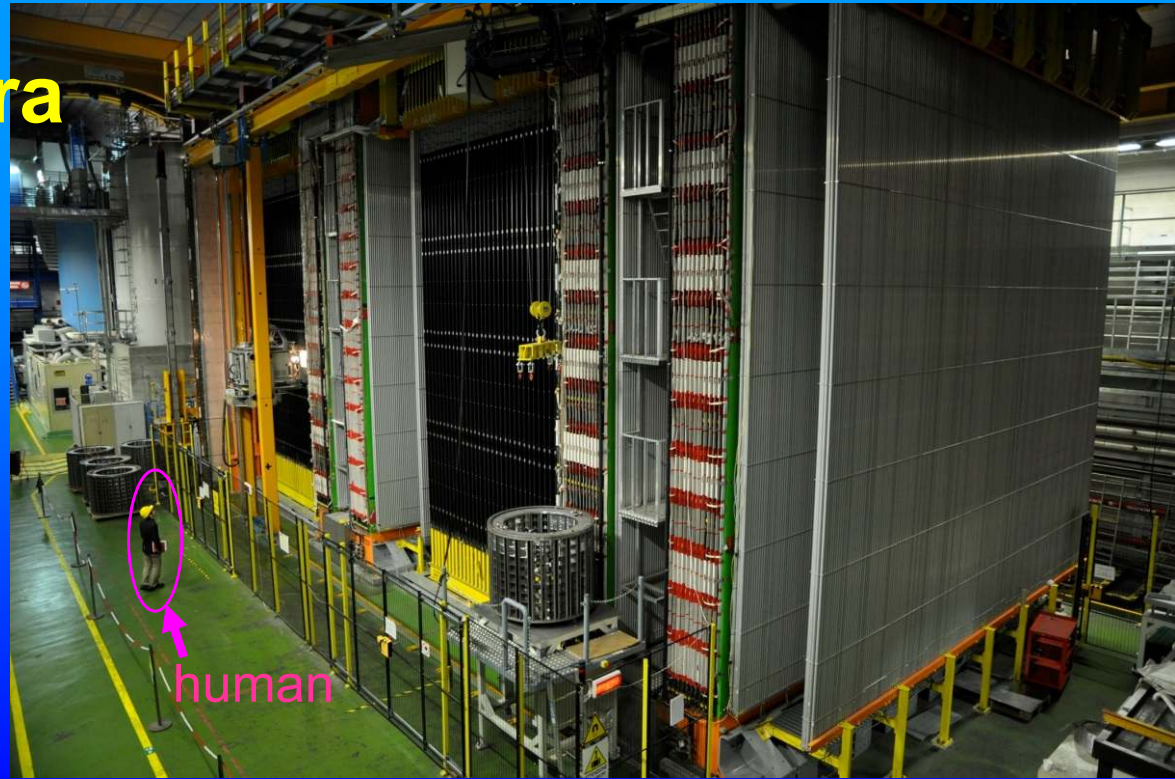
断面図

	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
($\sim 1.6 \times 10^8$ image sensors)



Largest Film Camera
OPERA detector
($\sim 10^{20}$ AgBr crystals)
↑
9000,000 emulsion films



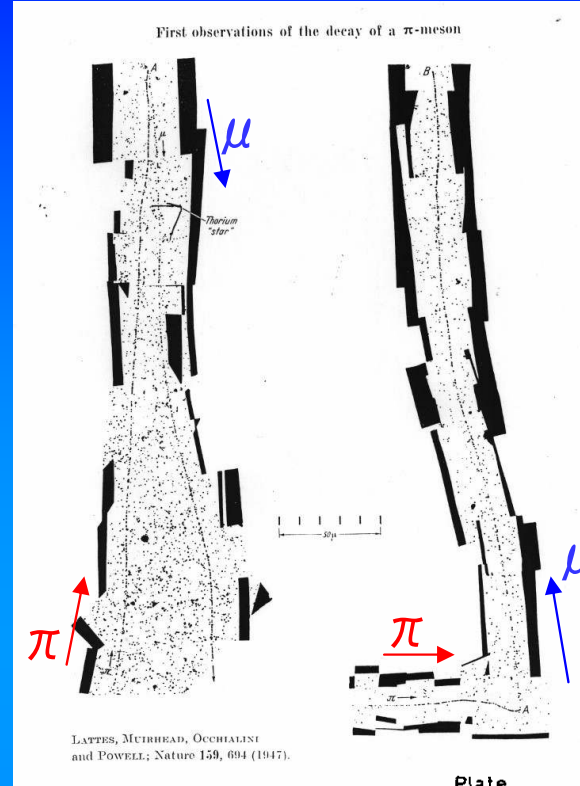
Contribution for fundamental physics... 1947

1896 (A. H. Becquerel)
Discovery of Radioactivity

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

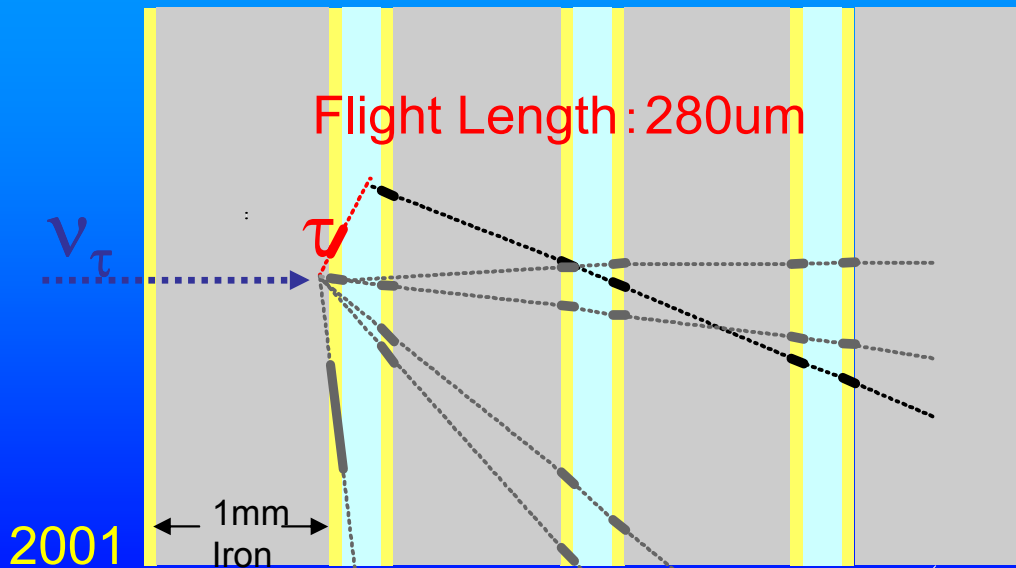
1971 (K. Niu et al.)
Discovery of charm particle
in cosmic-ray

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



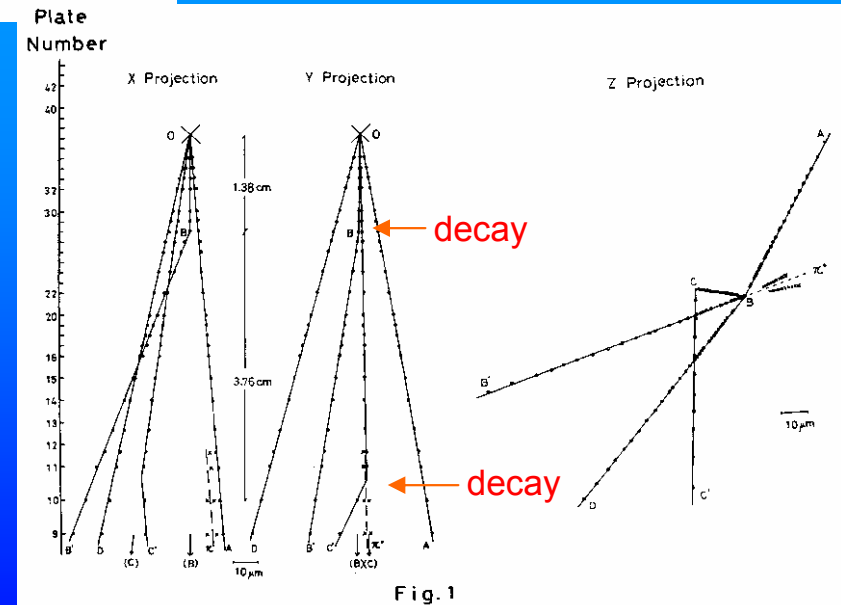
1896

1971



2001

DONUT ν_τ event





OPERA Experiment



OPERA collaboration

11 countries, 26 institutions, 140 physicists



Bari
Bologna
LNF
LNGS
Napoli
Padova
Roma
Salerno



LAPP Annecy
IPHC Strasbourg



INR-RAS Moscow
LPI-RAS Moscow
SINP MSU Moscow
JINR Dubna



Aichi
Toho
Kobe
Nagoya
Nihon



Technion Haifa



LHEP Bern



IHE Brussels



Hamburg



IRB Zagreb



METU Ankara



Jinju

Oscillation Project with Emulsion tRacking Apparatus

- Main goal of OPERA

Verify the $\nu_\mu \rightarrow \nu_\tau$ oscillation at the atmospheric scale in appearance mode (S/N ~ 10).

PMNS (Pontecorvo-Maki-Nakagawa-Sakata) Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric ν , SuperK,
K2K, MINOS, T2K

OPERA

Chooz, Daya Bay, RENO, T2K,
MINOS, NOvA. ...

Solar ν , Borex, SuperK,
SNO, KamLAND, ...

$$\Delta m_{32}^2 = (2.50 \pm 0.04) 10^{-3} \text{ eV}^2$$

$$\theta_{32} = (45.8 \pm 3.2)^\circ$$

$$\theta_{13} = (8.88 \pm 0.39)^\circ$$

PDG 2016

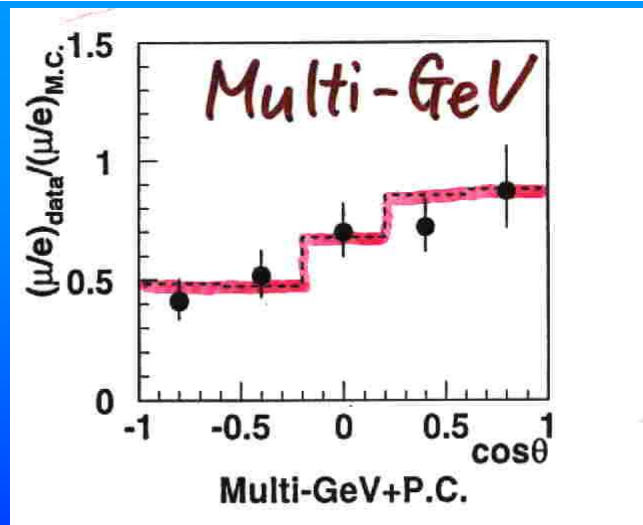
$$\Delta m_{21}^2 = (7.37 \pm 0.16) 10^{-5} \text{ eV}^2$$

$$\theta_{12} = (33.4 \pm 0.85)^\circ$$

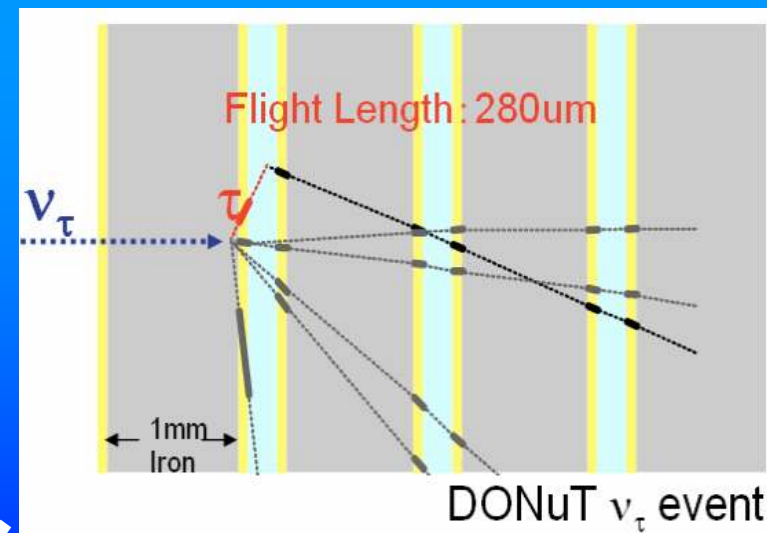
Oscillation Project with Emulsion tRacking Apparatus

- Main goal of OPERA
Verify the $\nu_{\mu} \rightarrow \nu_{\tau}$ oscillation at the atmospheric scale in appearance mode (S/N ~ 10).

Neutrino oscillation (disappearance)
Result from SK in 1998



Direct observation of ν_{τ} events
Result of DONuT in 2001

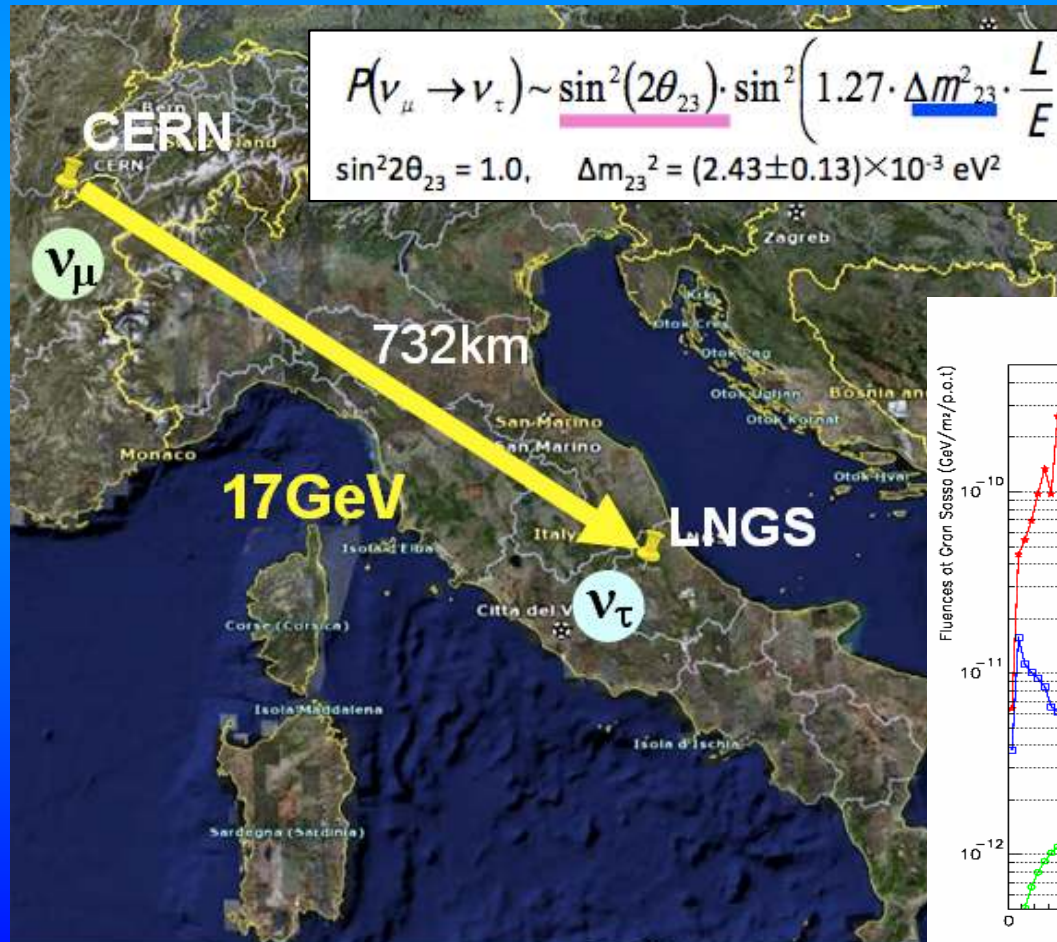


OPERA Start !!

Oscillation Project with Emulsion tRacking Apparatus

Requirements:

- 1) Long baseline
 - 2) High neutrino energy
 - 3) Large target mass
 - 4) High spatial resolution (τ detection capability)
- } CNGS beamline



$$P(\nu_\mu \rightarrow \nu_\tau) \sim \sin^2(2\theta_{23}) \cdot \sin^2\left(1.27 \cdot \frac{\Delta m_{23}^2 \cdot L}{E}\right) \sim 1.77\%$$

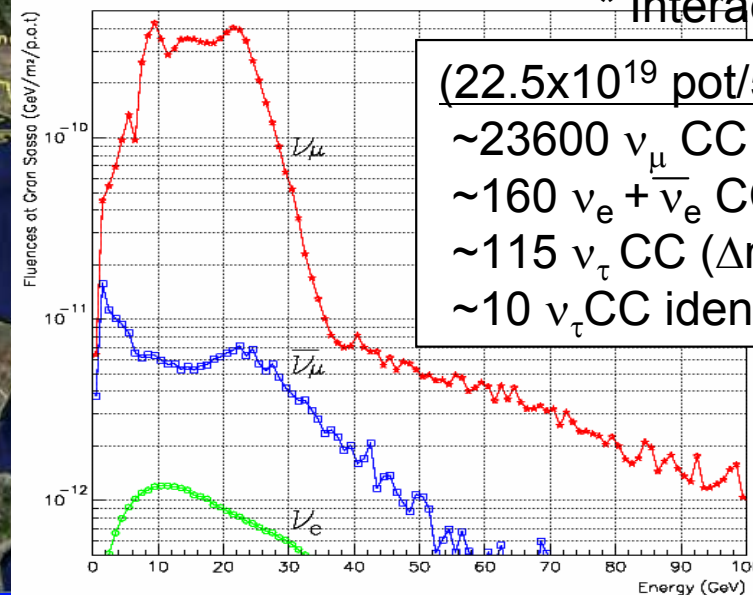
$\sin^2 2\theta_{23} = 1.0, \quad \Delta m_{23}^2 = (2.43 \pm 0.13) \times 10^{-3} \text{ eV}^2$

conventional ν beam

$\langle E_\nu \rangle$ (GeV)	17
$(\nu_e + \bar{\nu}_e) / \nu_\mu$	0.87 %*
$\bar{\nu}_\mu / \nu_\mu$	2.1 %*
ν_τ prompt	Negligible*

* Interaction rate at LNGS

(22.5×10^{19} pot/5years/1.25kton)
 $\sim 23600 \nu_\mu$ CC + NC
 $\sim 160 \nu_e + \bar{\nu}_e$ CC
 $\sim 115 \nu_\tau$ CC ($\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$)
 $\sim 10 \nu_\tau$ CC identified (BG < 1)

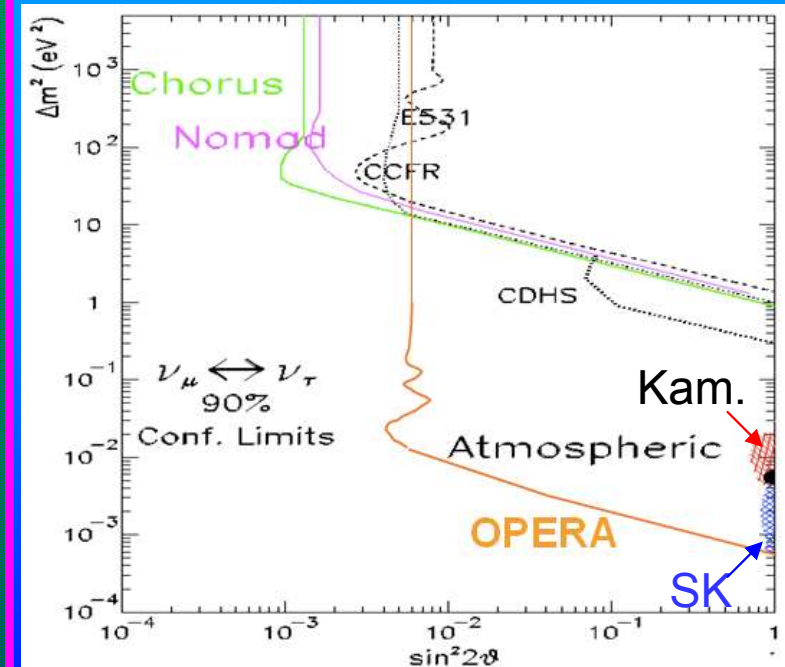


Oscillation Project with Emulsion tRacking Apparatus

- Requirements:
- 1) Long baseline
 - 2) High neutrino energy
 - 3) Large target mass
 - 4) High spatial resolution (τ detection capability)

Long history of neutrino study with nuclear emulsion

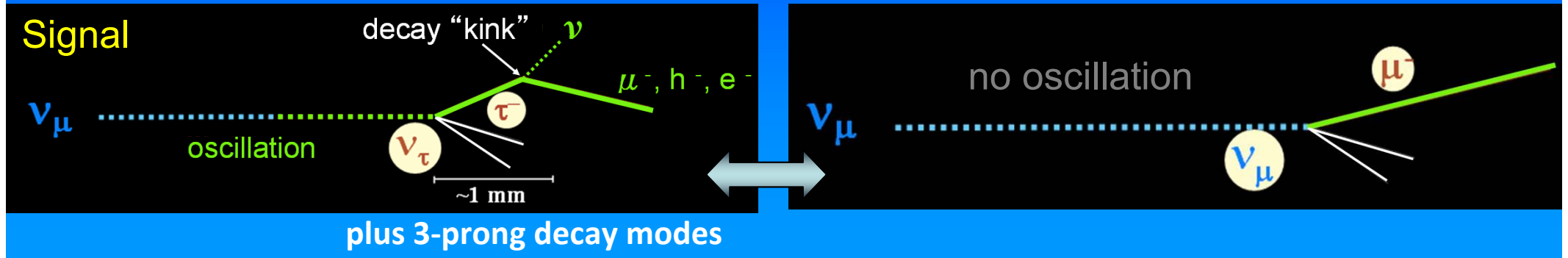
- 1978-1983 Fermilab E531 ~100kg
charm physics, $\nu_\mu \rightarrow \nu_\tau$ oscillation
- 1990-2000 CERN WA95 CHORUS ~1ton
 $\nu_\mu \rightarrow \nu_\tau$ oscillation, charm physics
- 1994-2001 Fermilab E872 DONUT ~1ton
First ν_τ detection
- 2008- CERN CNGS01 OPERA ~1250ton
 $\nu_\mu \rightarrow \nu_\tau$ oscillation



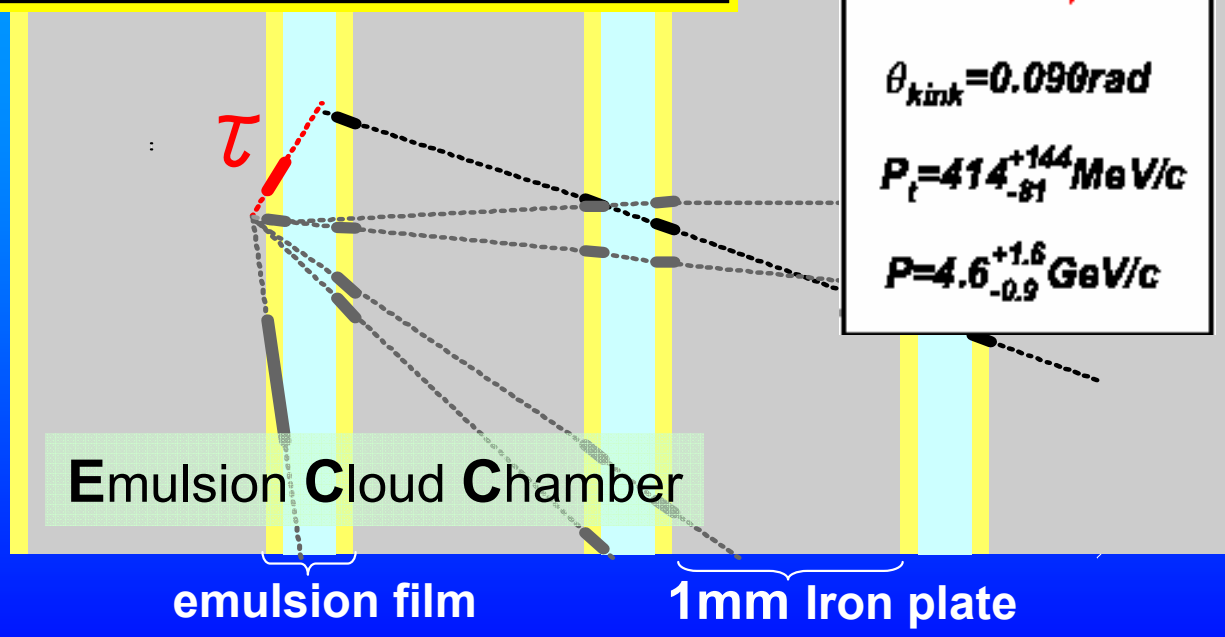
ν_τ detection



Search for τ decay topology on an event by event basis.



ν_τ event by DONUT



Decay mode	BR (%)
$\tau^- \rightarrow \mu^- \nu_\mu \bar{\nu}_\tau$	17.36
$\tau^- \rightarrow e^- \nu_e \bar{\nu}_\tau$	17.85
$\tau^- \rightarrow h^- (n\pi^0) \bar{\nu}_\tau$	49.52
$\tau^- \rightarrow 2h^- h^+ (n\pi^0) \bar{\nu}_\tau$	15.19

➔ Direct observation of ν_τ using emulsion technology
Phys. Lett. B 504 (2001) 218

The OPERA roadmap

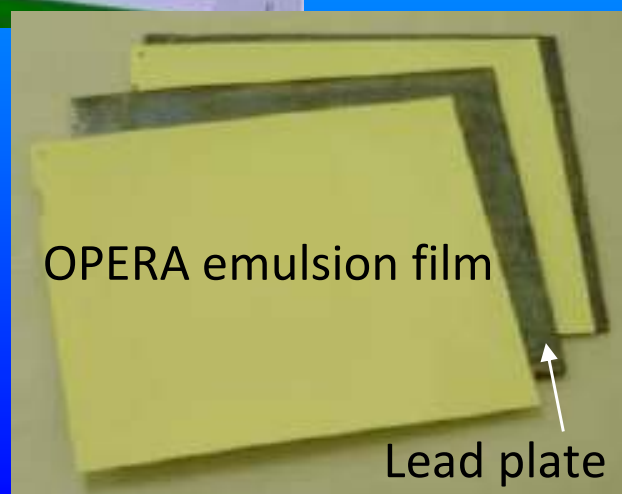
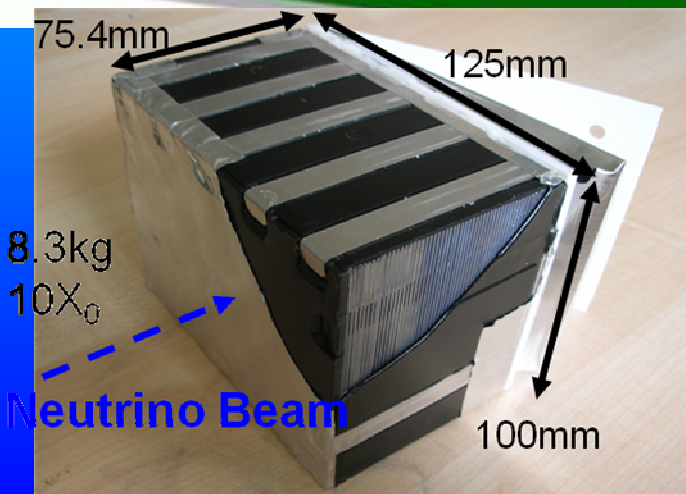
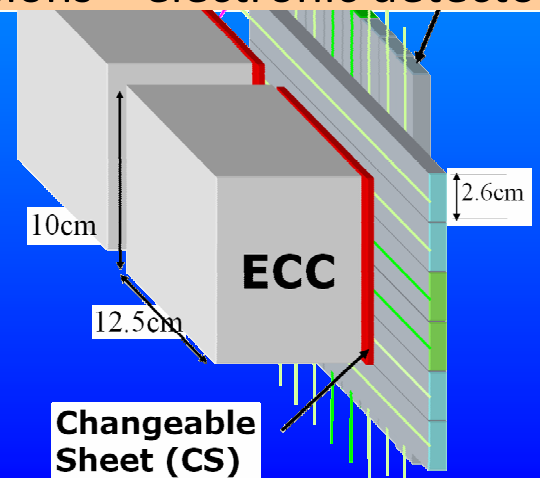


The OPERA detector



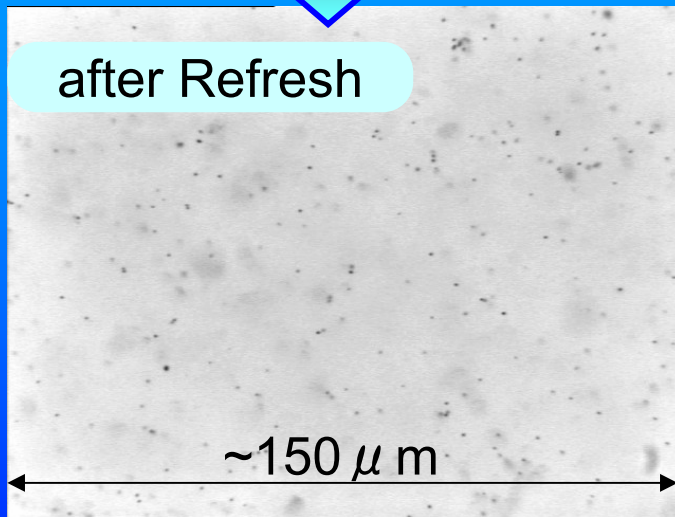
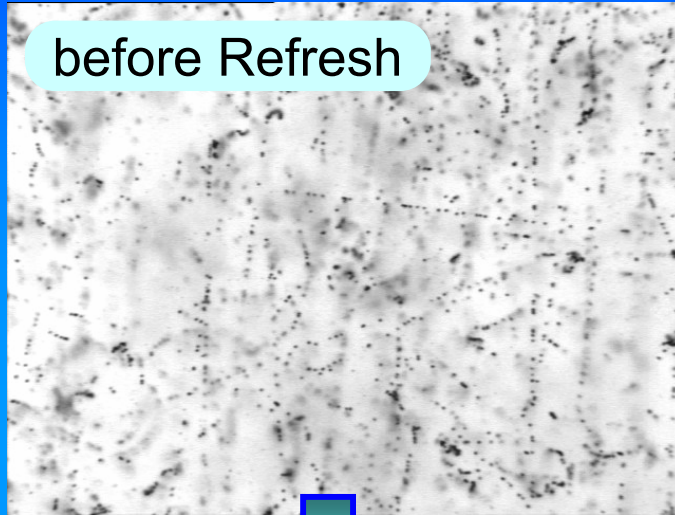
9,000,000 FILMS!!

Hybrid apparatus:
Emulsions + electronic detectors



Refresh

OPERA films are produced in FUJI Co. for several years.



Films from FUJI Co.

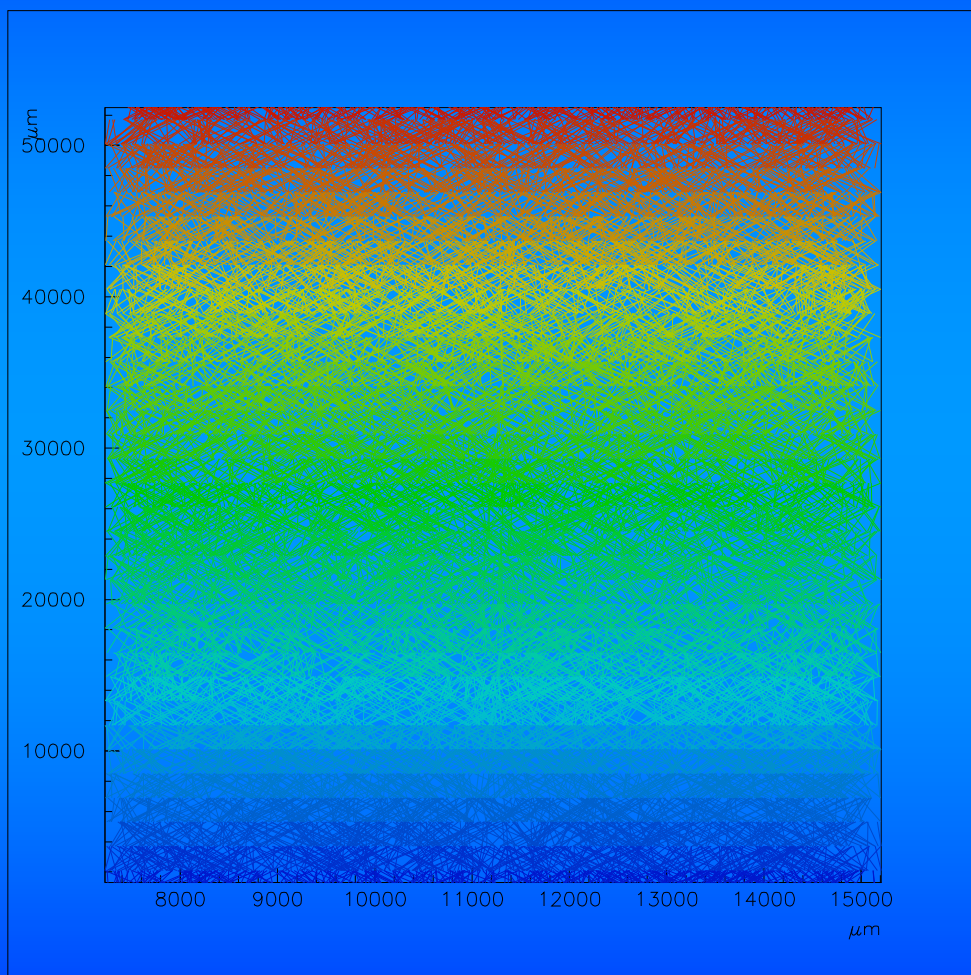
Refresh chamber

30°C, 98%
Noise tracks are deleted
by fading effect.

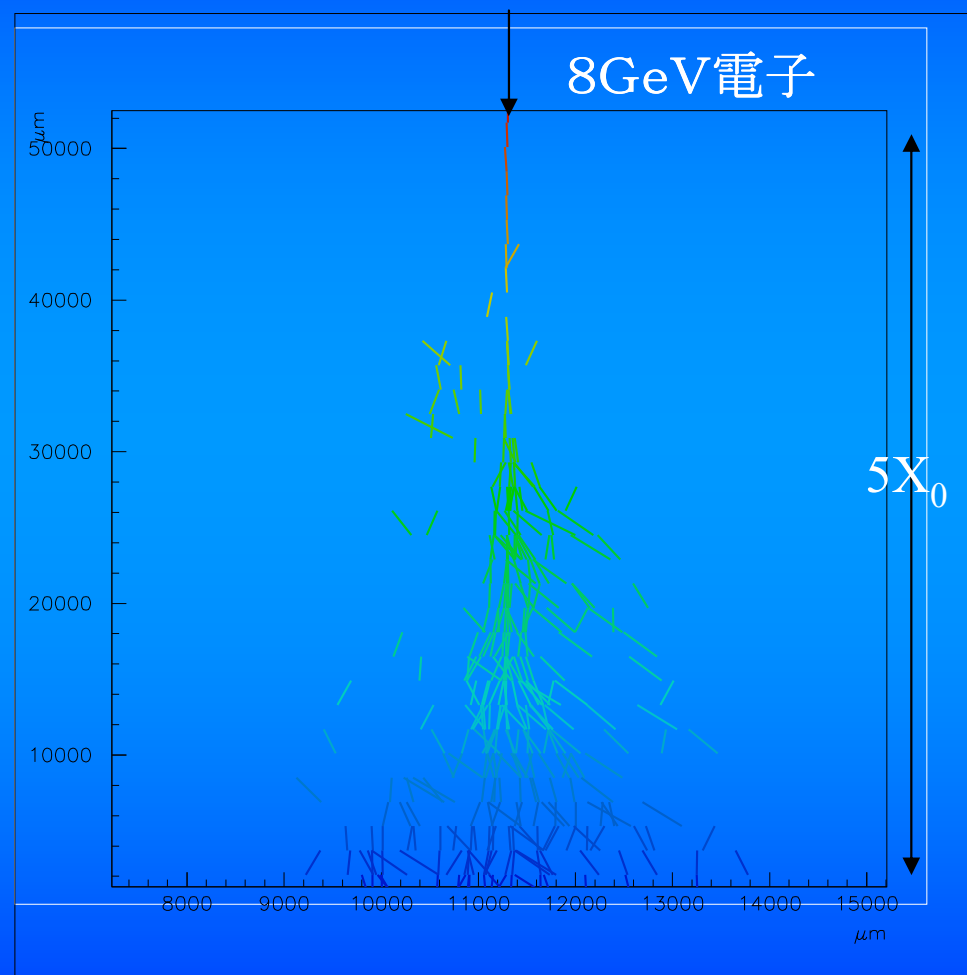


Refresh

No refresh



No refreshed



Electron energy measurement is possible
by shower counting method.

Refresh Facility

Cosmic ray shield

第1計測坑道 rate:1/50(115m.w.e.)

第2計測坑道 rate:1/400(220m.w.e.)

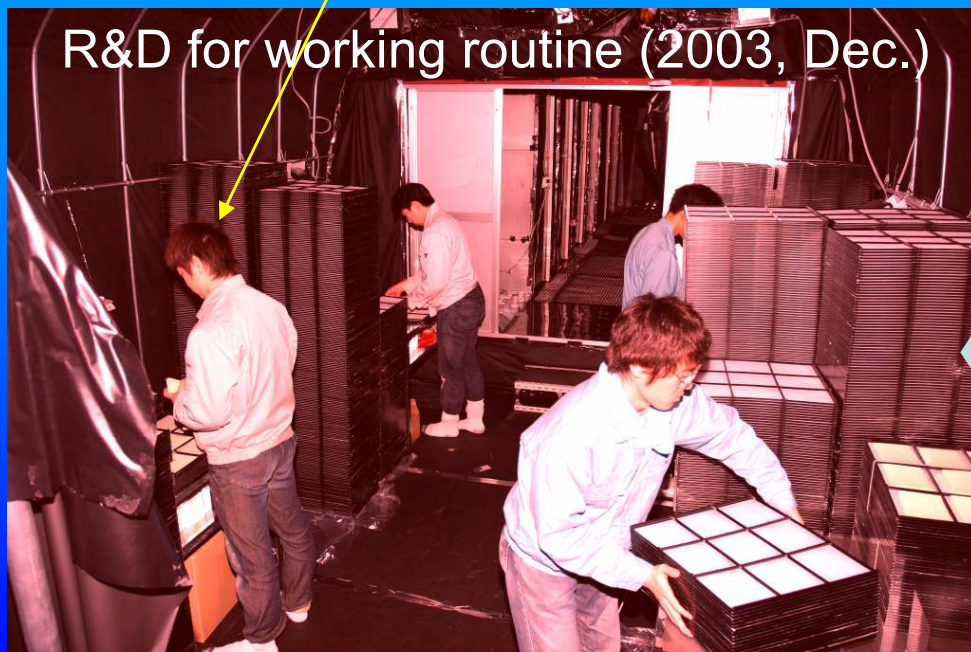
Good access from Nagoya
(~1 hour by car)



Tono mine.



Facility construction(2003, Aug.-Nov.)



Facility construction(2003, Aug.-Nov.)

Refresh facility 完成!



m



R&D for working



**Working by part-time shifter
@First Refresh room, 96m from grand
(2004, Apl.)**



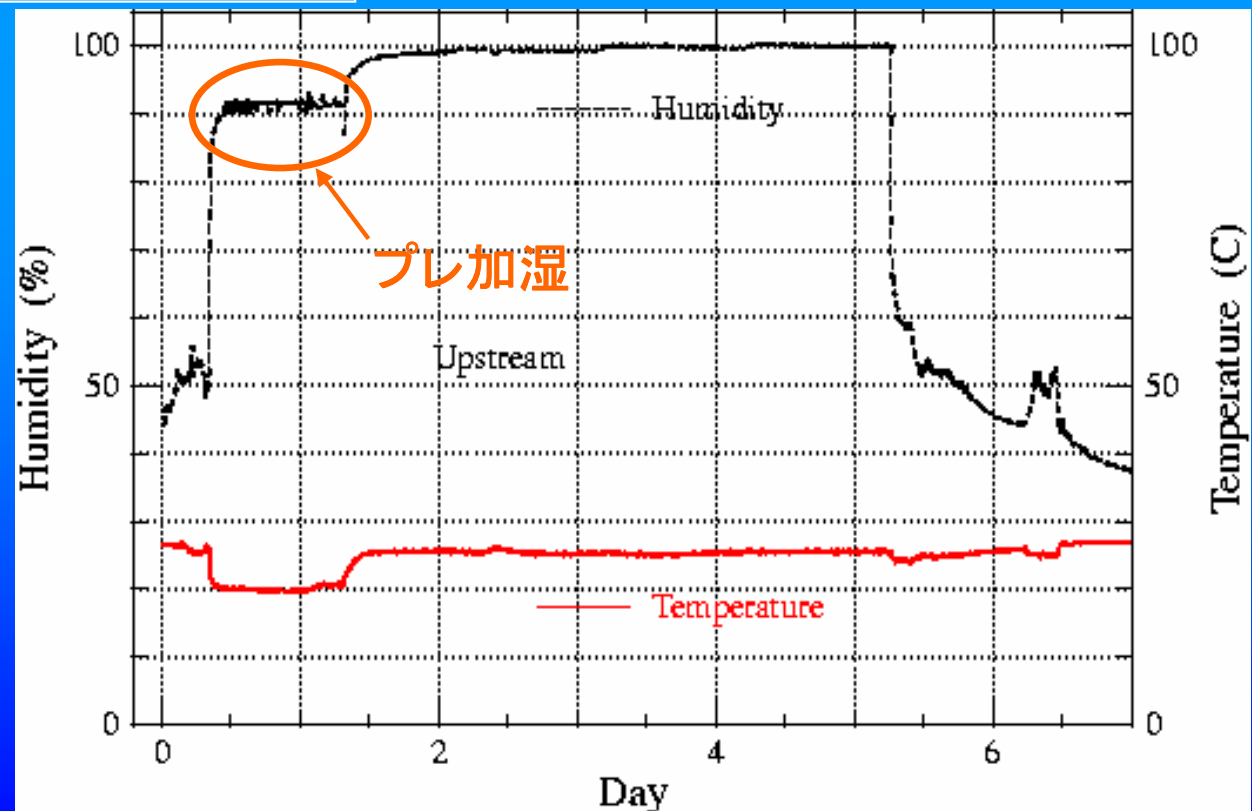
Refresh movie

大量リフレッシュを始めてみると...

- 感度劣化が起こっている...!!

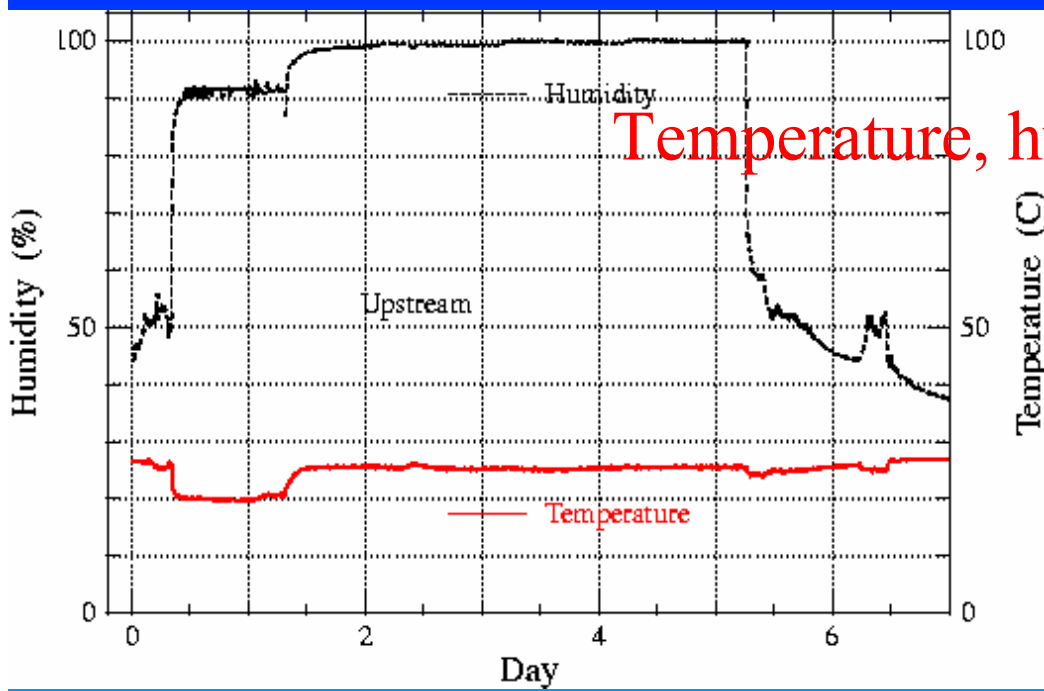
原因を追求したところ、加湿時に原子核乾板自体からガスが放出され、自家中毒によって感度が落ちていることが判明。

容積の異なる袋にフィルムを入れて加速試験

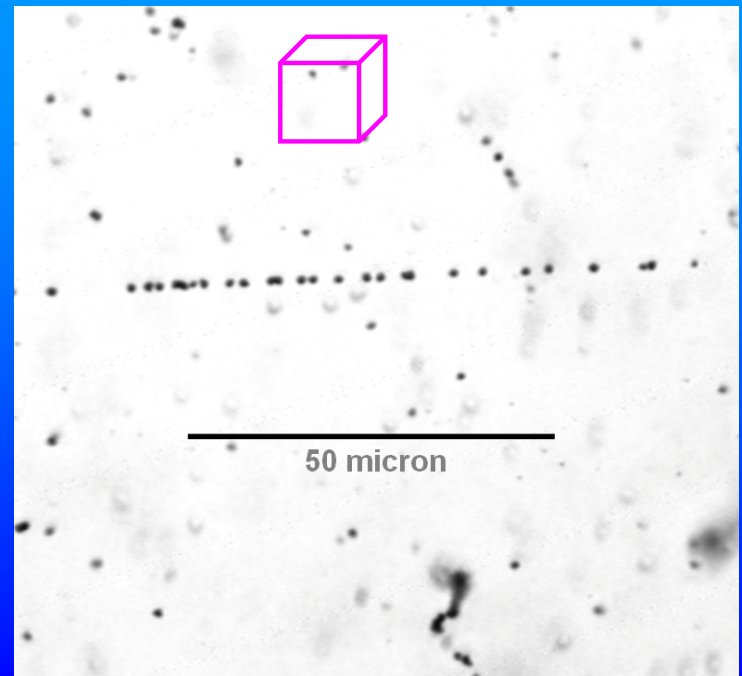
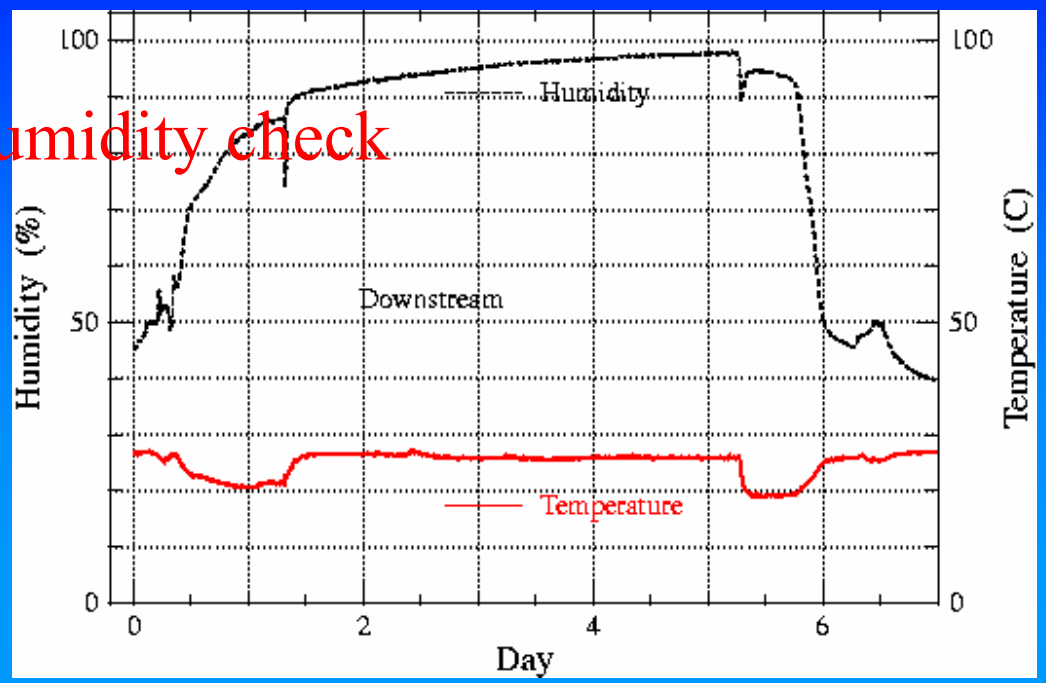


プレ加湿時は排気。
その後、循環系に。

Refreshed film quality check

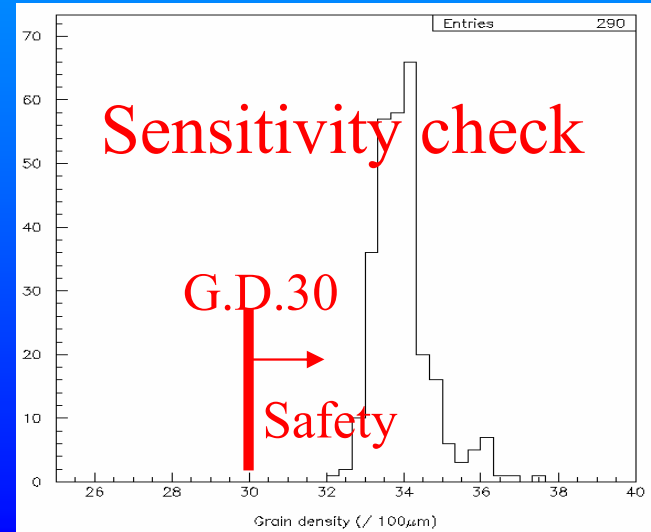


Temperature, humidity check



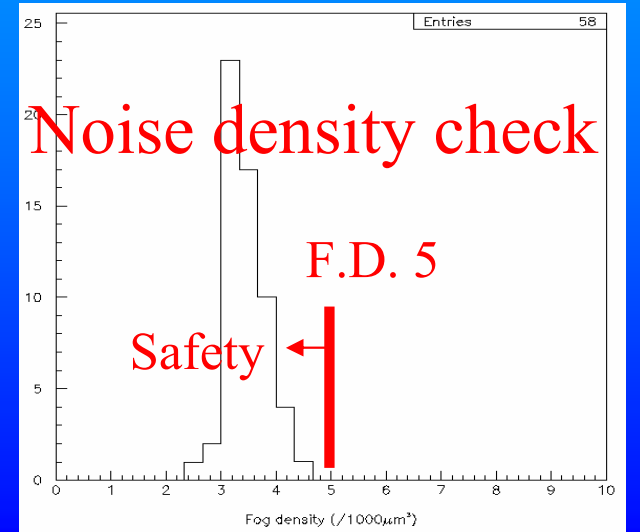
Grain Density

(100 μ mあたりの銀粒子数)

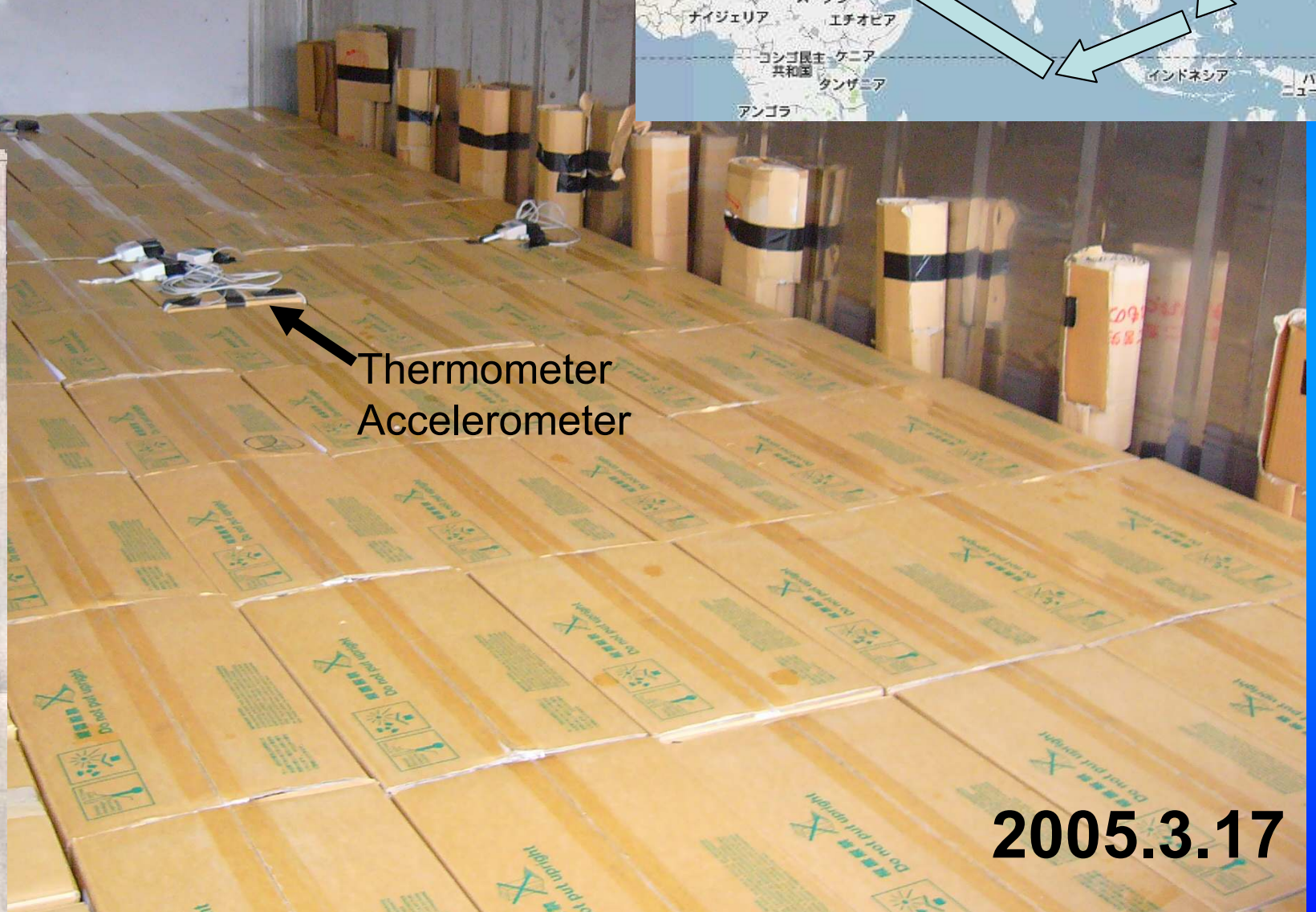


Fog Density

(10³ μ m³あたりの銀粒子数)



2004.Jan.13 Refresh start.
 2005.Mar.17 First shipment
 2007.Apl. 25 Final shipment
 (Total 3322 boxes)



ニュートリノ 実験支える乾板出荷
 主岐 日本と研究の欧州へ

物質を形づくる素粒子ニュートリノに質量があることの確証を得るため、名古屋大学大学院理学研究科の丹羽公雄教授らのグループと欧州の研究機関が、共同で「ニュートリノ振動検証実験OPERA（オペラ）」を行

この実験で使う特殊な写真乾板が、土岐市の核燃料濃縮山の地下坑道で最終処理され、7日に第一便の150万枚がイタリアへ出荷された。

ニュートリノはミューオン、電子、タウの3種類が確認されている。これらが物質を突き抜けて飛ぶ際、別のニュートリノに変身（ニュートリノ振動）することが確認されれば「質量存在」が証明され、ノーベル賞級の成果となる。スーパーカミオカンデ（飛騨市の実験などで研究が進んだが、変身したニュートリノを実際にとらえるため、日欧の共同実験が企画された。

実験は06年6月からの予定。スイスの加速器から飛ばしたニュートリノを約300km離れたイタリアの地下坑道に設置した写真乾板でとらえる。写真乾板は丹羽教授が考案し、富士写真フイルムと共同開発した横12.5cm、縦10cm。

製作過程で浴びた宇宙線の痕跡を消すリフレッティング処理のため東濃鉱山の地下45mと96mの旧坑道を借りて6年続ける実験に必要な乾板1200万枚を処理する。実験に使った乾板は毎日名大に空輸し解析する予定だ。

特選名
 製刀 青江次吉
 十日十日 徳久十四郎

2005.3.17

2004.Jan.13 Refresh start.
 2005.Mar.17 First shipment
 2007.Apl. 25 Final shipment
 (Total 3322 boxes)



ニュートリノ 実験支える乾板出荷
 土岐 日本と研究の欧州へ

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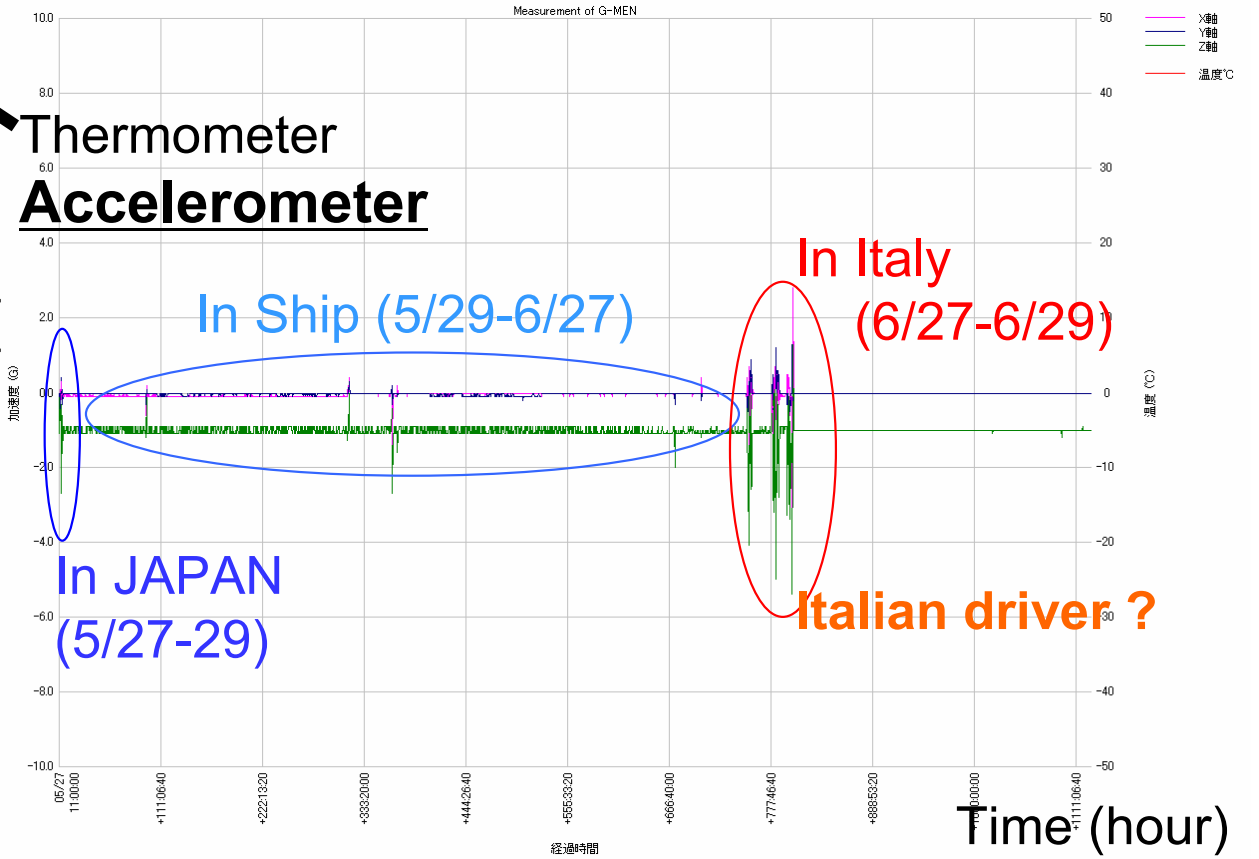
ニュートリノは、電子、タウの3種類が確認されている。これらが物質を突き抜けて飛ぶ際、別のニュートリノに変身（ニュートリノ振動）することが確認され、質量存在が証明された。ノーベル賞級の成果となる。スーパーカミオカンデ（飛騨市の実験などで研究が進んだ）が、変身したニュートリノを実際にとらえるため、日欧の共同実験が企画された。

実験は06年6月からの予定。スイスの加速器から飛ばしたニュートリノを約300km離れたイタリアの地下坑道に設置した検出装置の写真乾板でとらえる。写真乾板は丹羽教授が考案し、半導体写真フィルムと共同開発した横12.5cm、縦10cm。

製作過程で溶びた宇宙線の痕跡を消すリフレクション処理のため東濃鉱山の地下45mと96mの旧坑道を借りて6年続ける実験に必要な乾板1200万枚を処理する。実験に使った乾板は毎日名大に空輸し解析する予定だ。

特選名
 製刀 青江次吉

Thermometer
Accelerometer



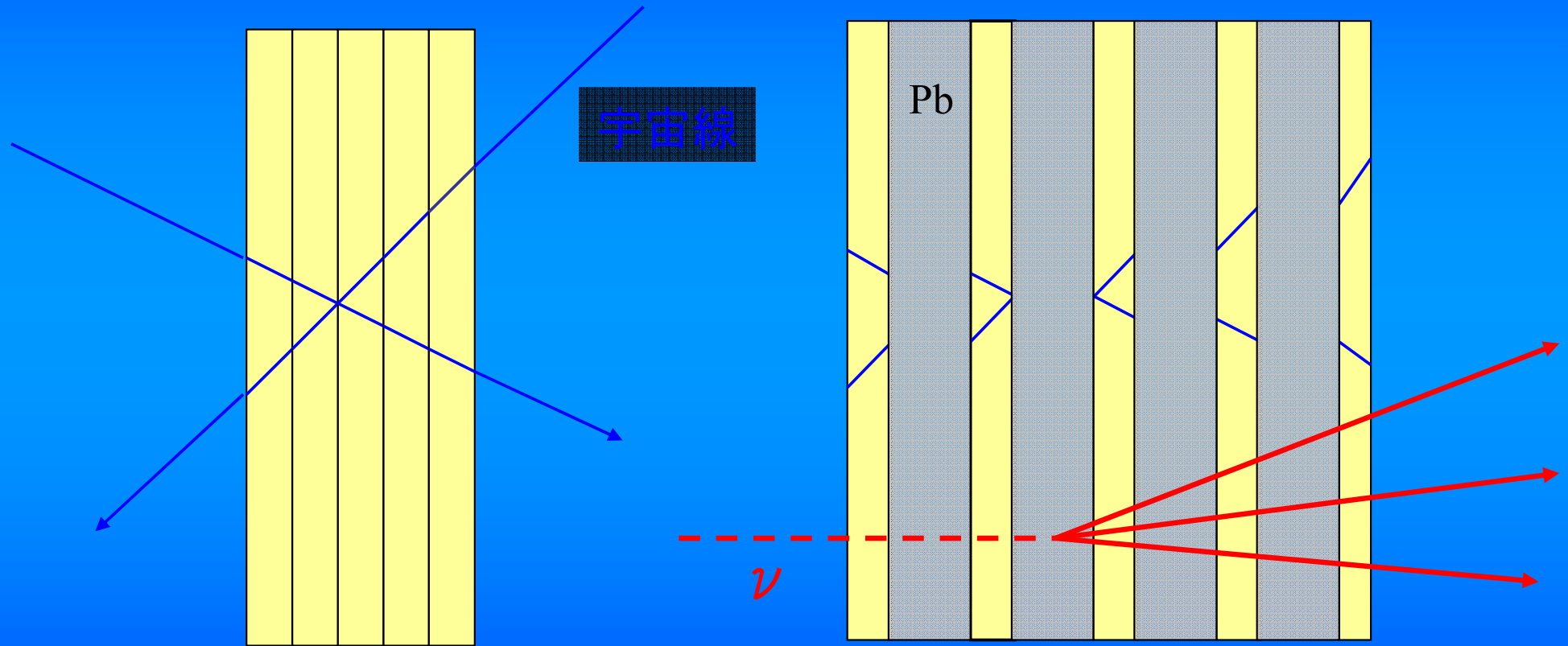
Acceleration (G)

Time (hour)

Filmの輸送 (東濃鉱山 2 GranSasso)

Filmのみ(輸送中)

ECC (ν 照射中)



2種類のアライメントが記録される

Refresh処理後輸送中に入射した宇宙線の排除 (Virtual Refresh)

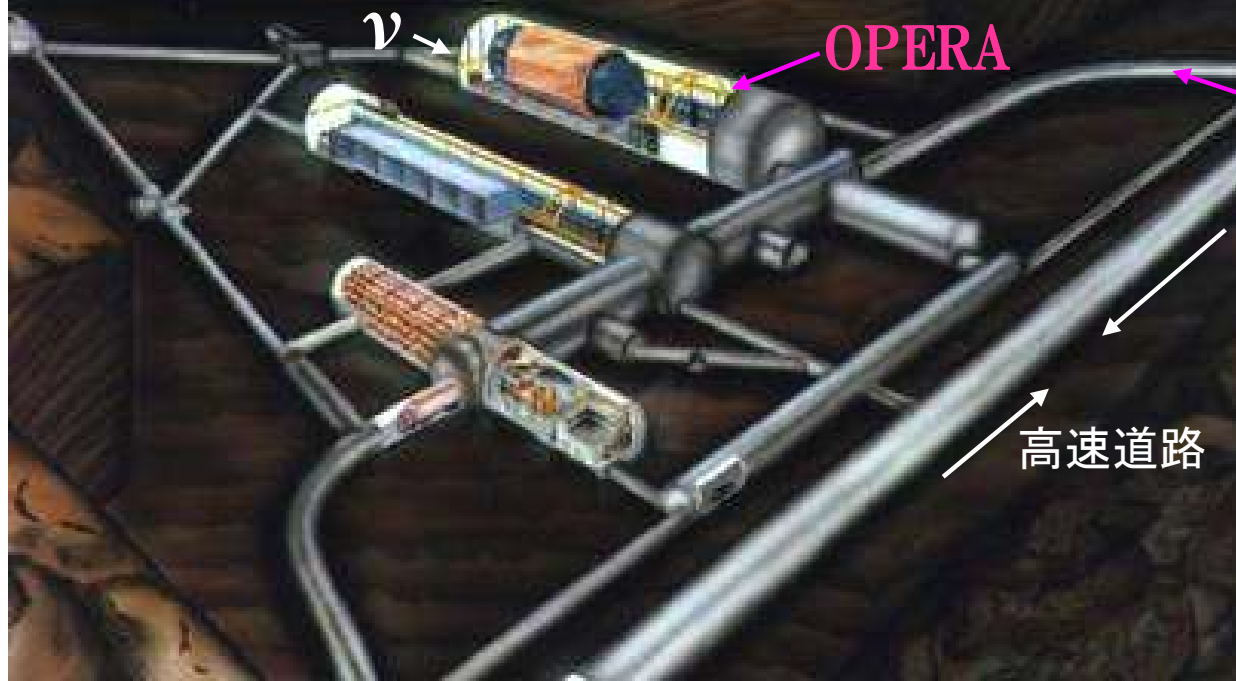
Gran Sasso



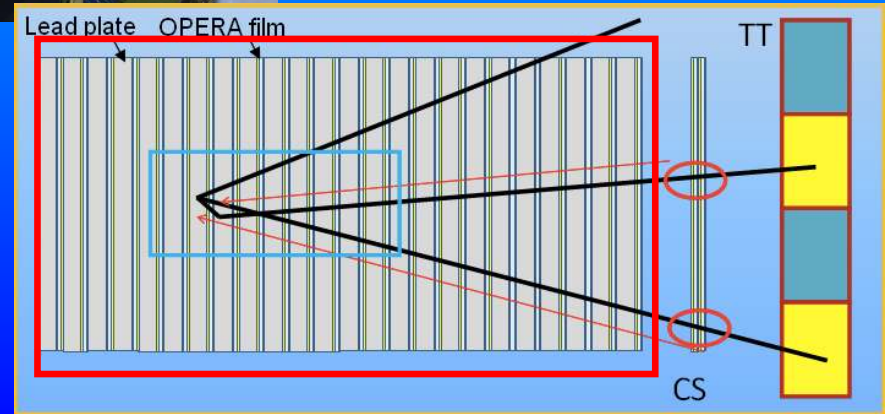
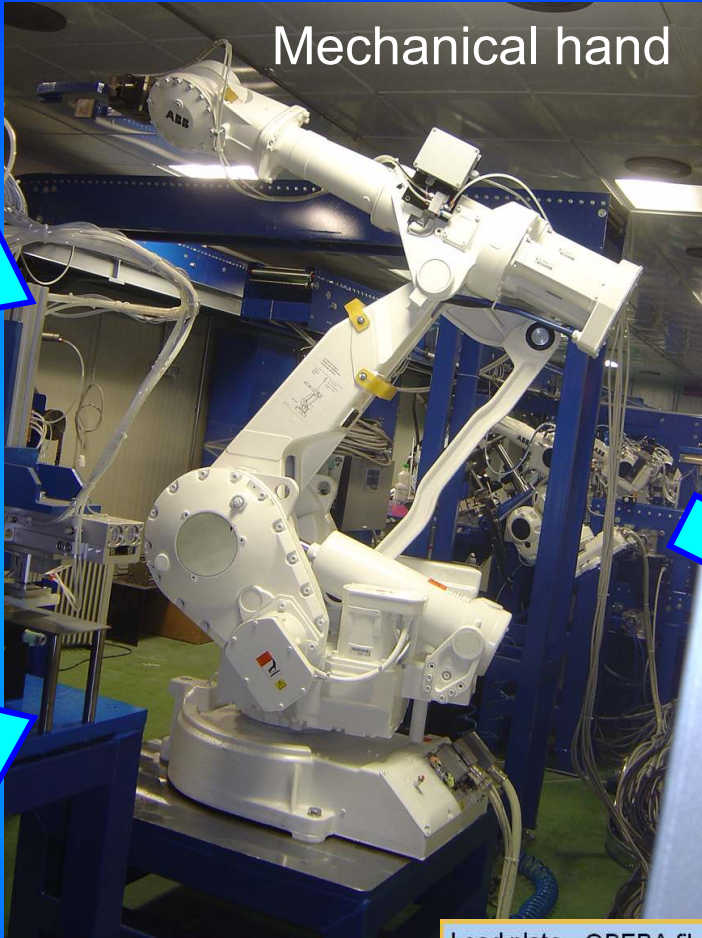
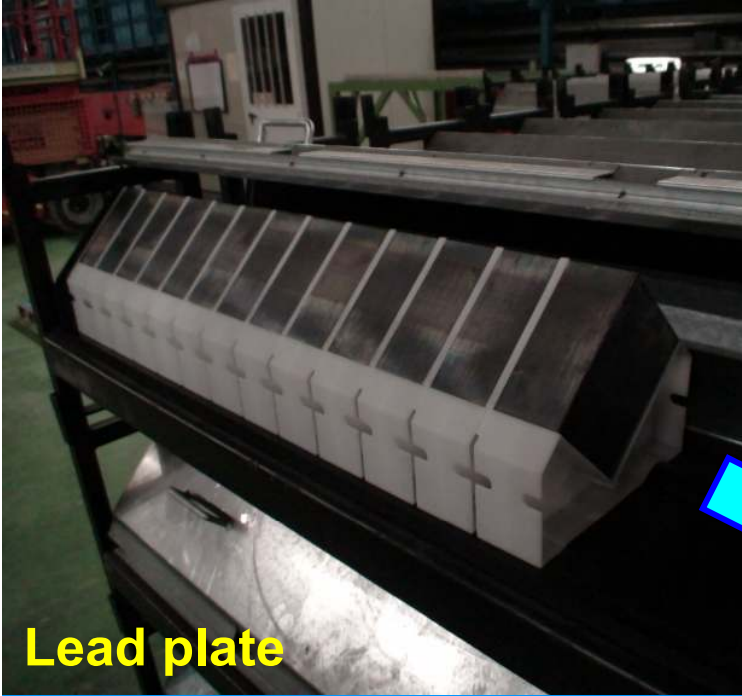
Gran Sasso



Gran Sasso



ECC Production @GS

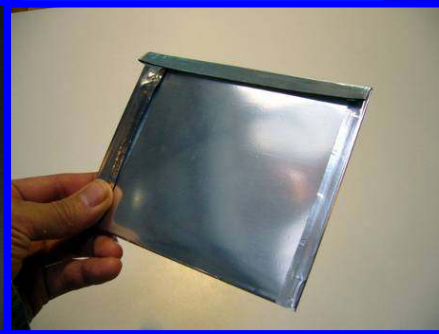


OPERA film



Expert Shifter from JAPAN

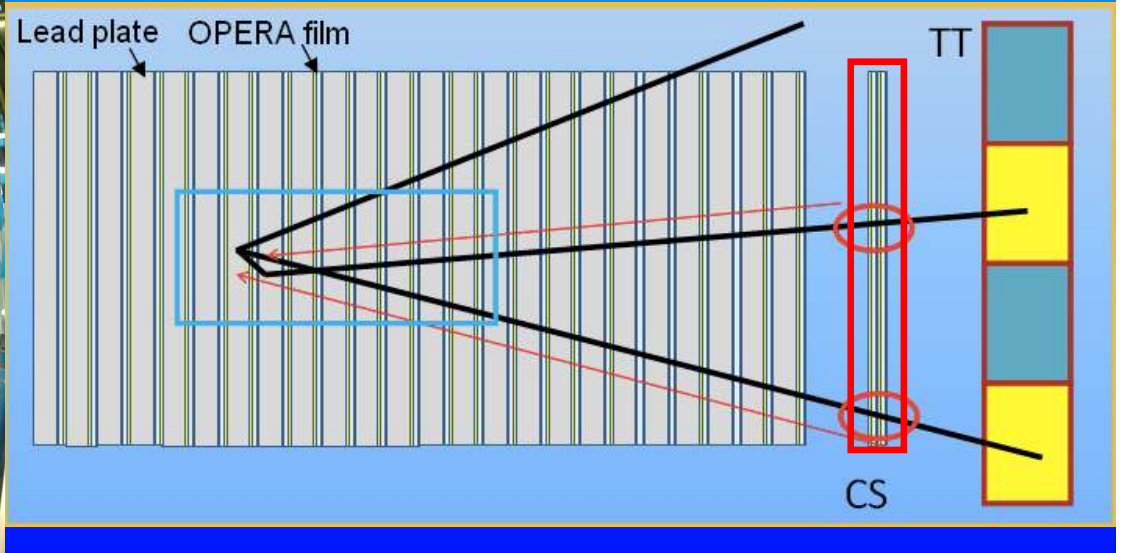
CS Production



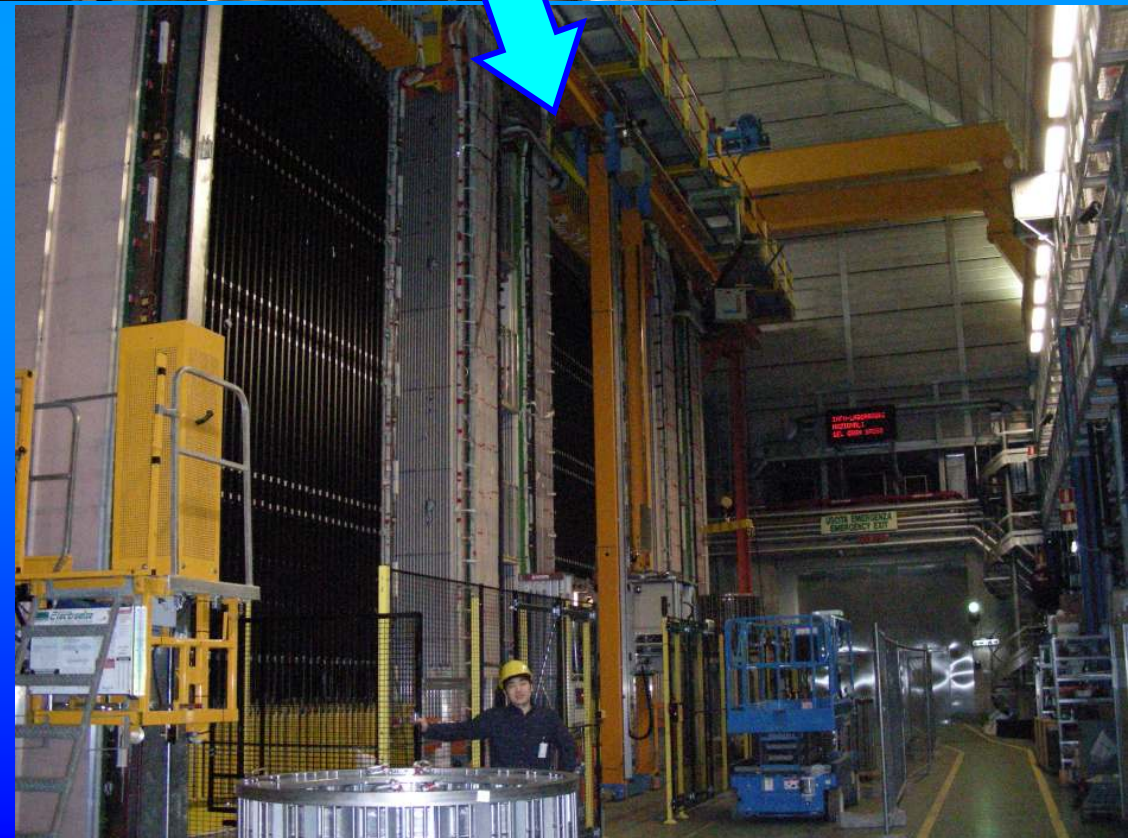
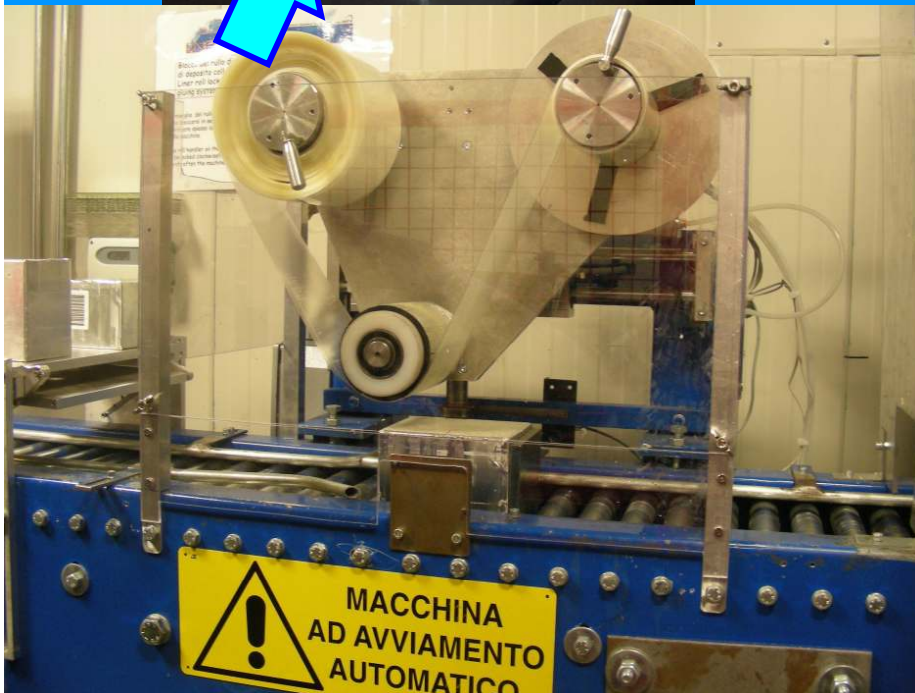
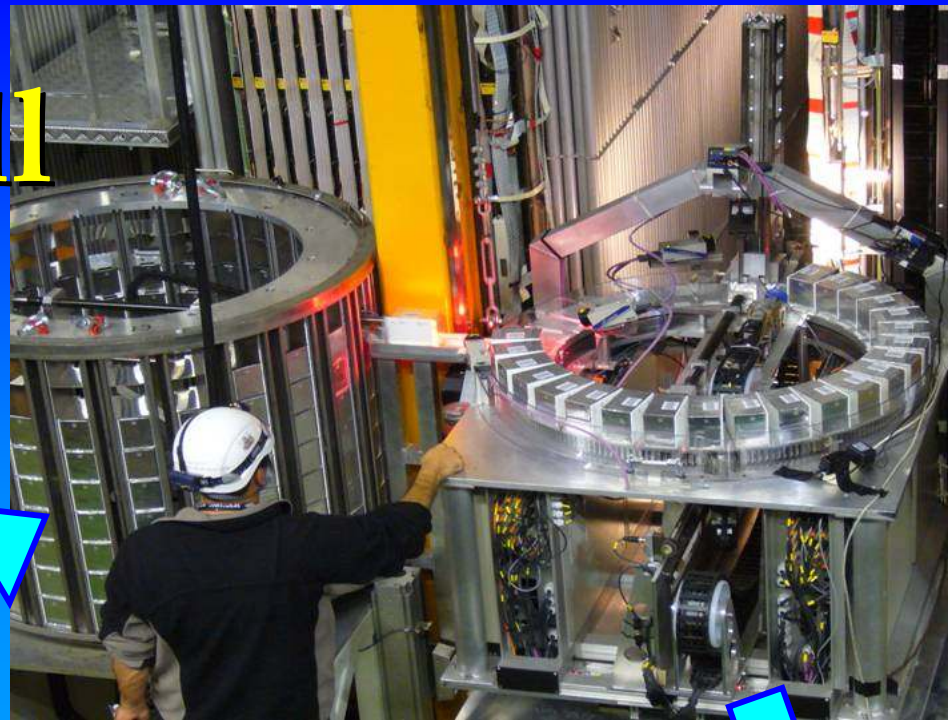
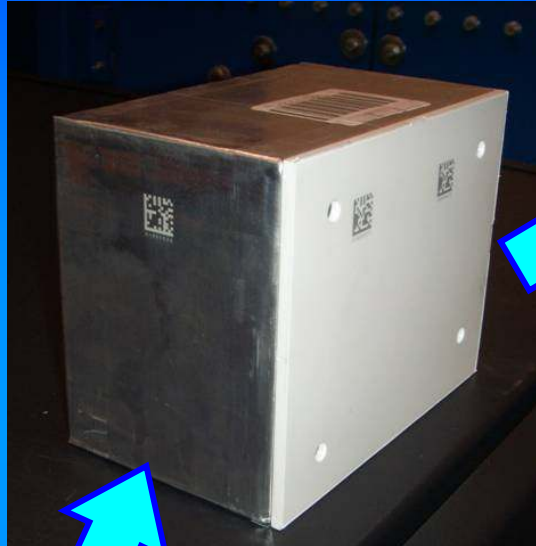
Refresh @ GS!



CS facility



Brick install





ECC 150,000 Bricks, 1.25kton target

The OPERA Detector @ Gran Sasso, Italy (1400m underground)

300年に一回の地震に遭遇 ラクイラ地震

2009年4月6日（死亡：300名以上）



激震地：パガニカ

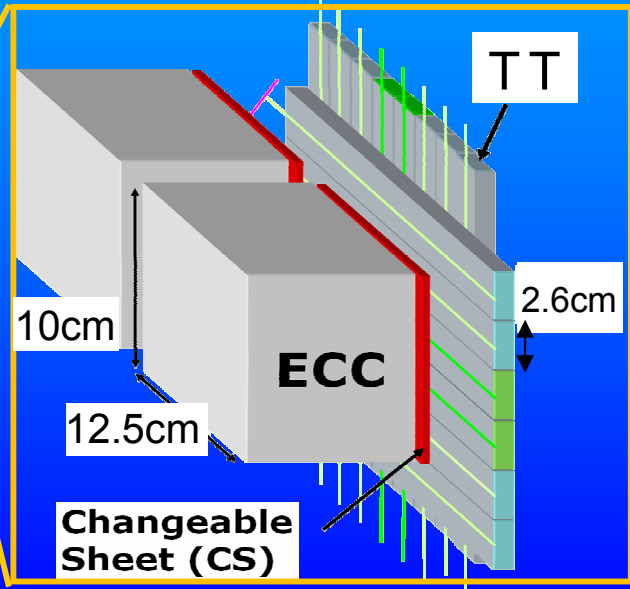
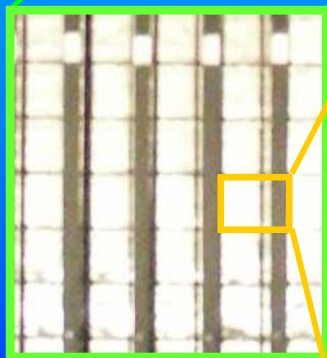
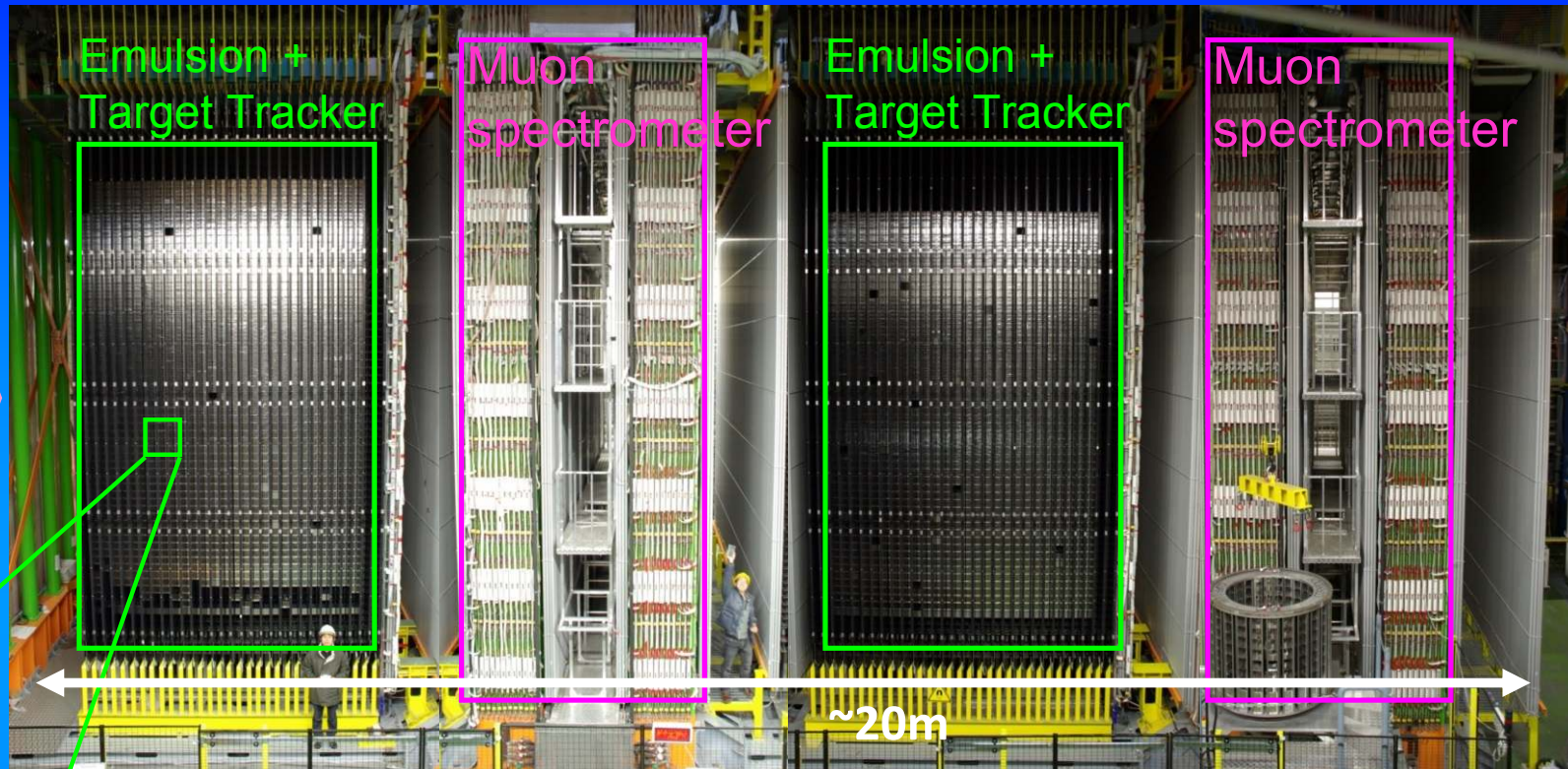
グランサッソーからの距離は約6 km

でも実験を止めずにすんだ

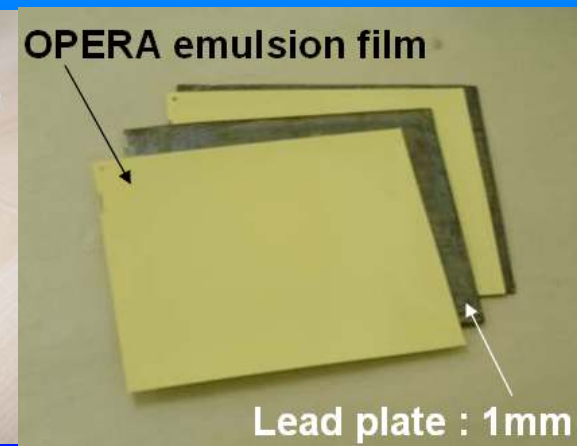
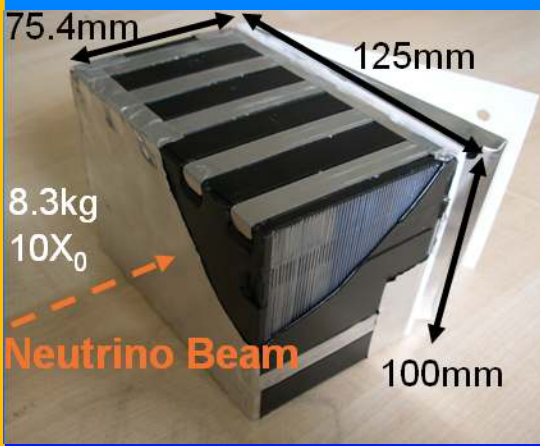
- 幸い検出器に被害なし。実験続行可能。
- 住居に重大被害。立入禁止で住む所を失う!
→アセルジ村のサラさんの好意で無傷の建物に間借り。
- 食料→ ロシアの共同研究者の車で買出し
最悪時：赤十字のキャンプにお世話。

現地：イタリア アセルジ村の皆さんに大変
お世話になりました。大変感謝しています。

The OPERA Detector

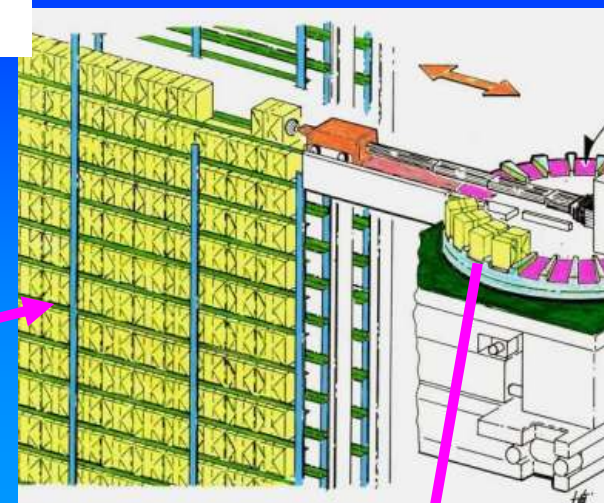
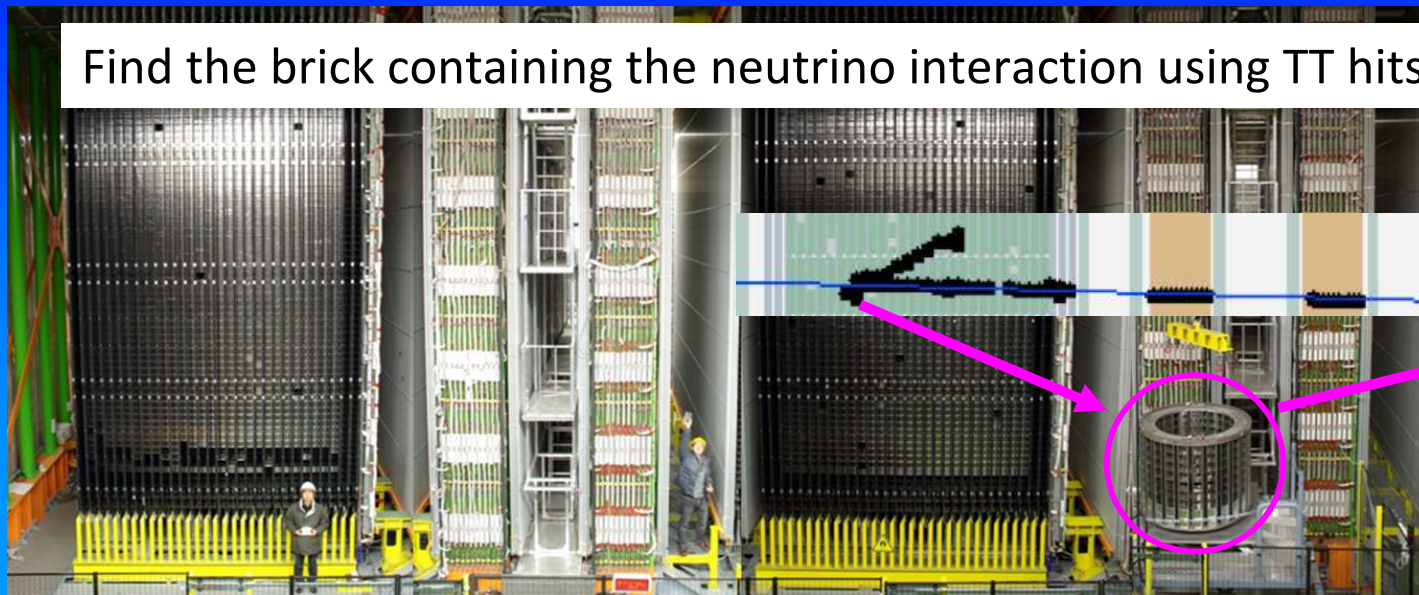


ECC: ~150,000 bricks (1.25 kton)

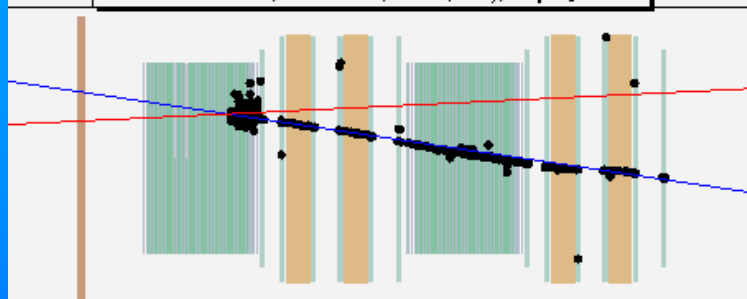


The OPERA detector

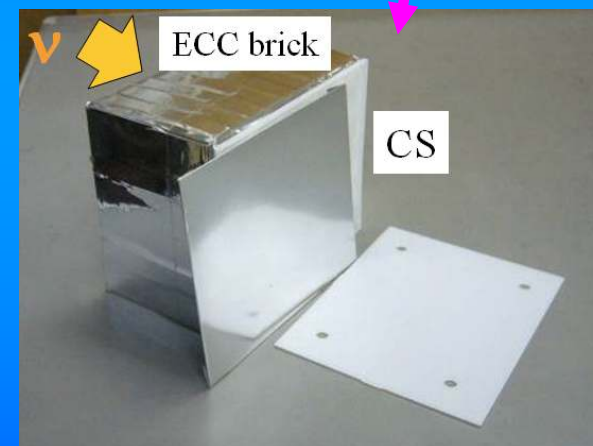
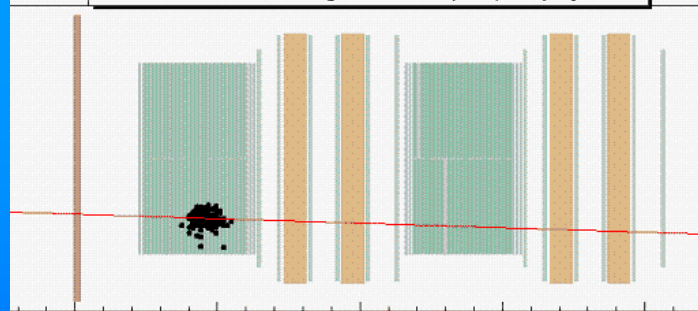
Find the brick containing the neutrino interaction using TT hits



Event: 234213474, 3 Oct 2008, 20:04 (UTC), XZ projection



Event: 226232046, 17 Aug 2008, 08:08 (UTC), XZ projection



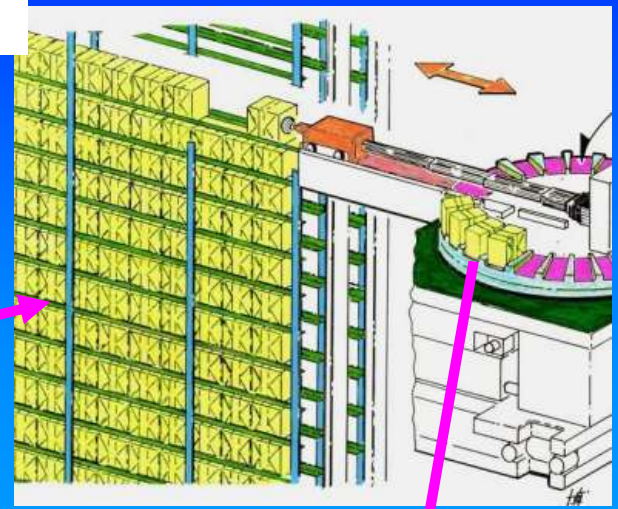
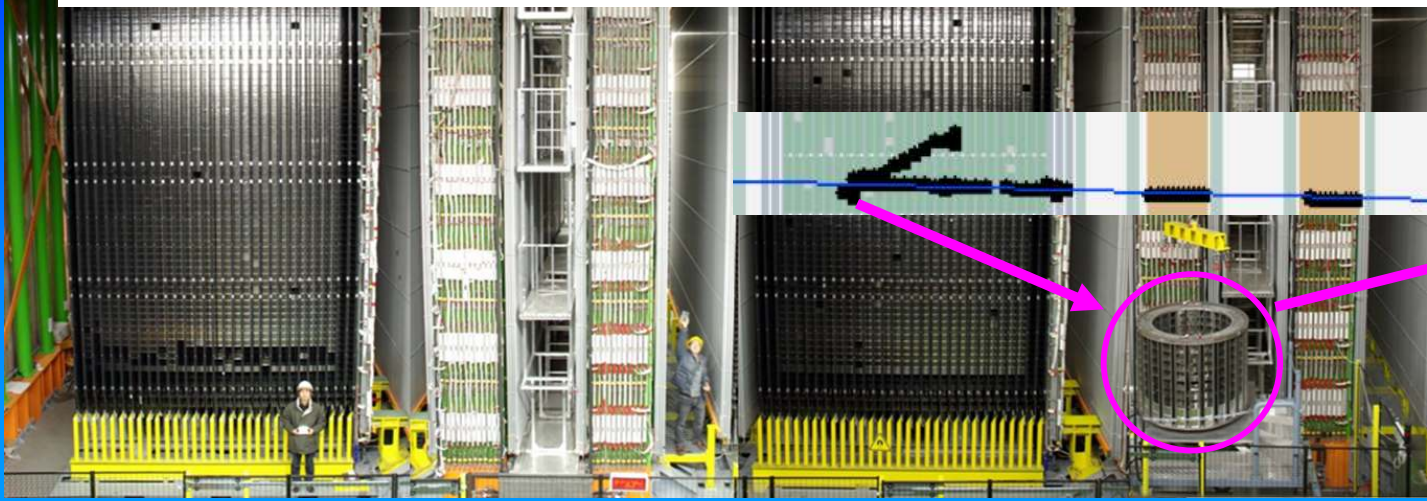
Only CS is analyzed at first.

ν_{μ} CC like event

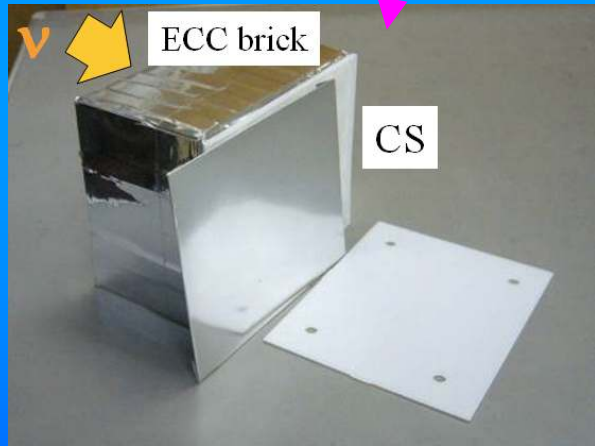
ν_{μ} NC like event

The OPERA detector

Find the brick containing the neutrino interaction using TT hits



検出器から取り出したECC

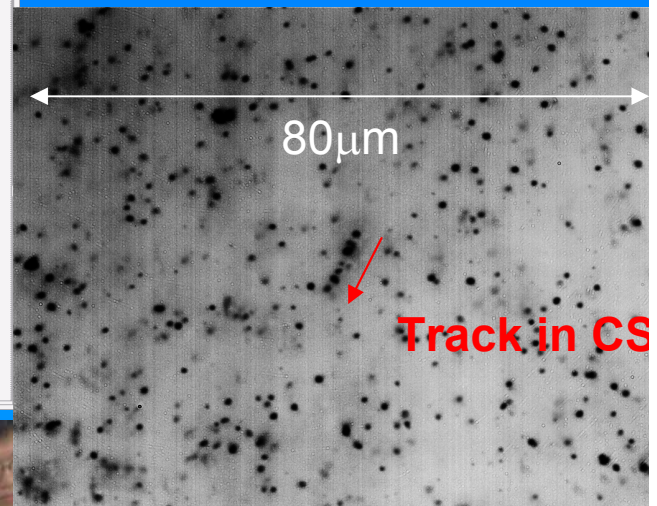
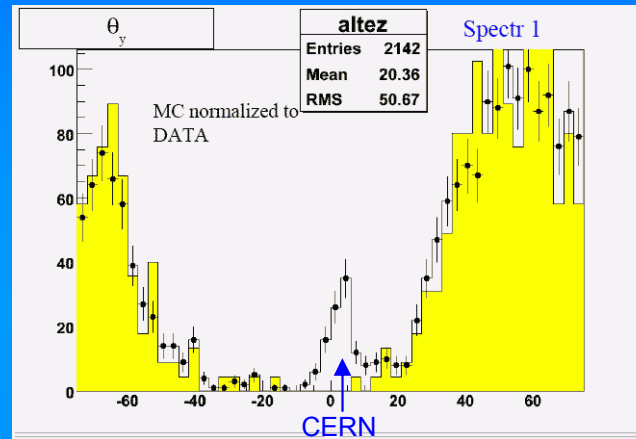
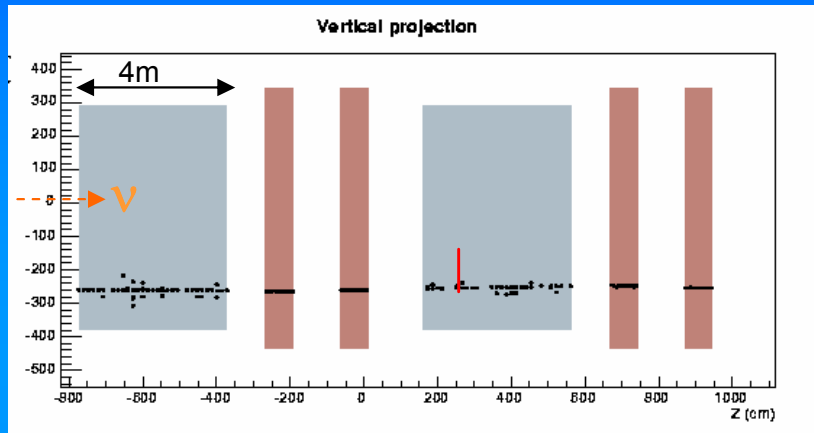


Only CS is analyzed at first.

Commissioning-2006

First observation of a track from CERN in emulsion.

Confirmation of analysis stream from electronic detector to emulsion detector.



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

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放射。イタリア・アペニン山脈地下の

日欧共同実験 名大教授ら「計画通り機能」

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メートル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見える現象をとらえ、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。

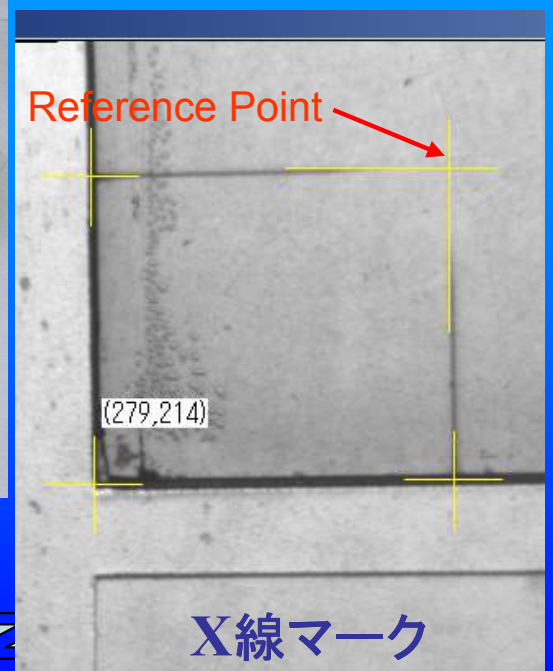
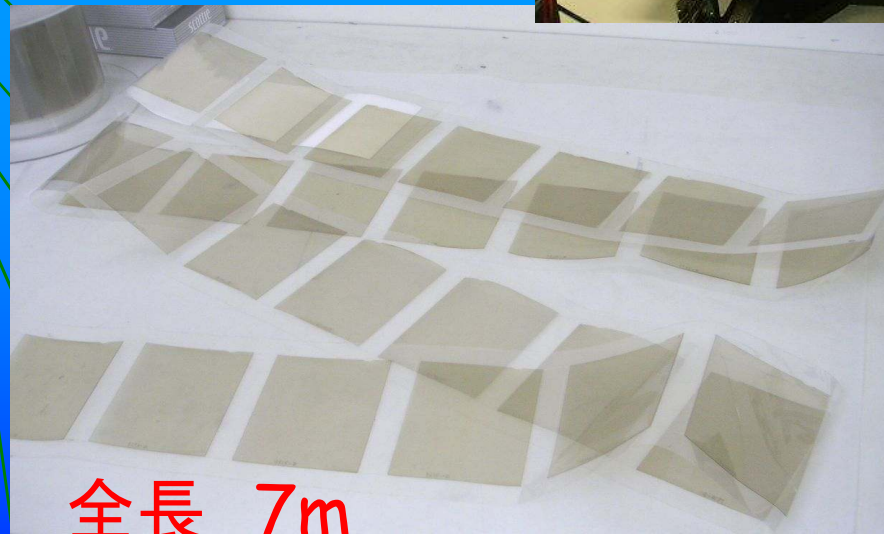
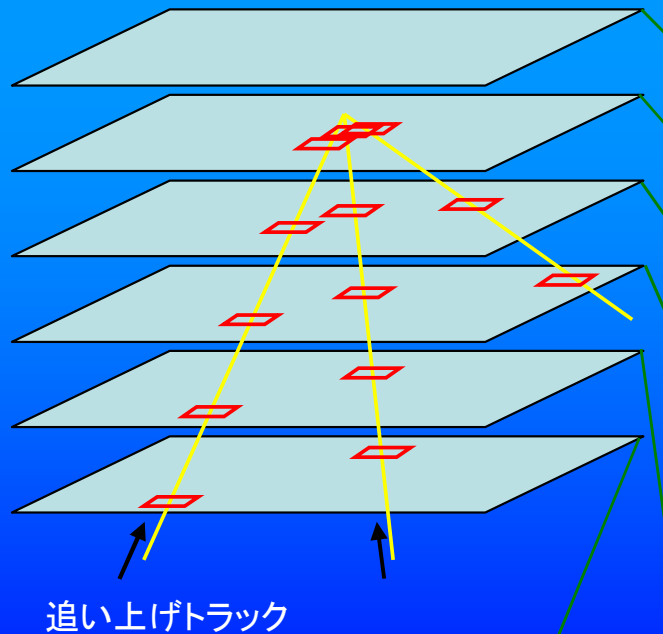


Track is found !

(9/7 19:23)

Plate Changer system の開発

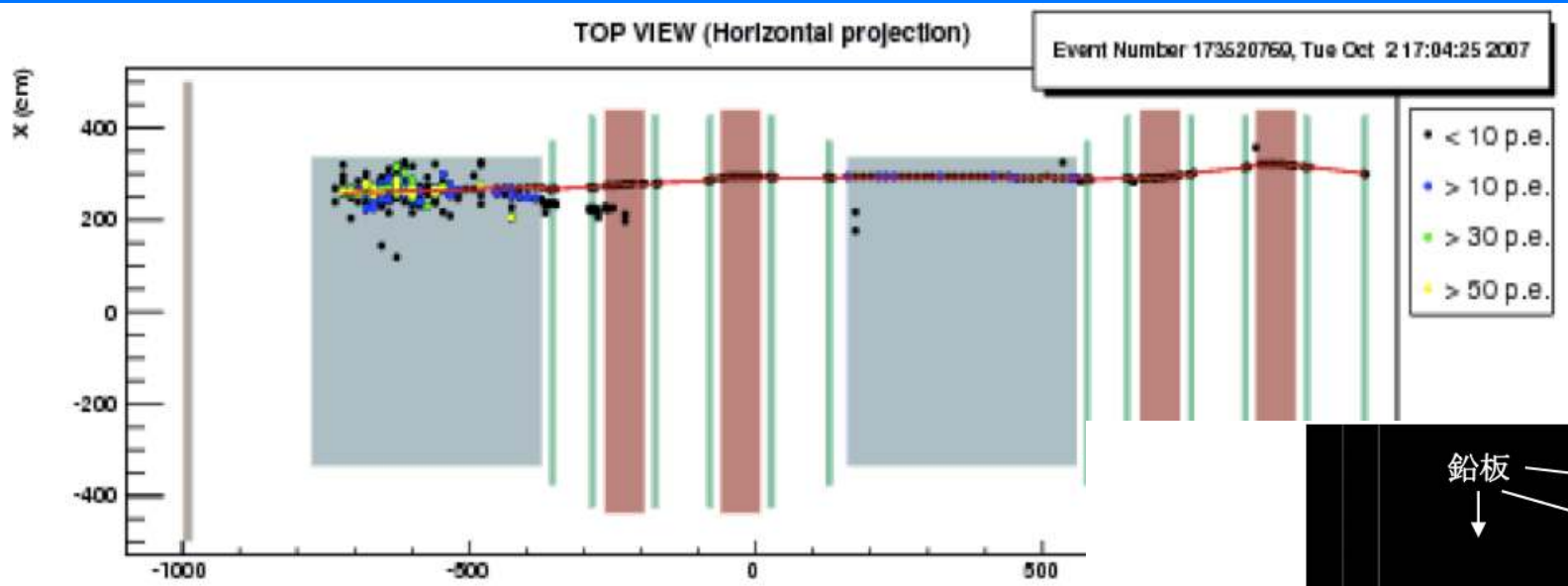
film をSheet に貼り付け、
自動で slide させ、
film の edge にあるX線マークを読みとる
film 交換の時間短縮を達成
(5分 → 10秒)



Commissioning-2007

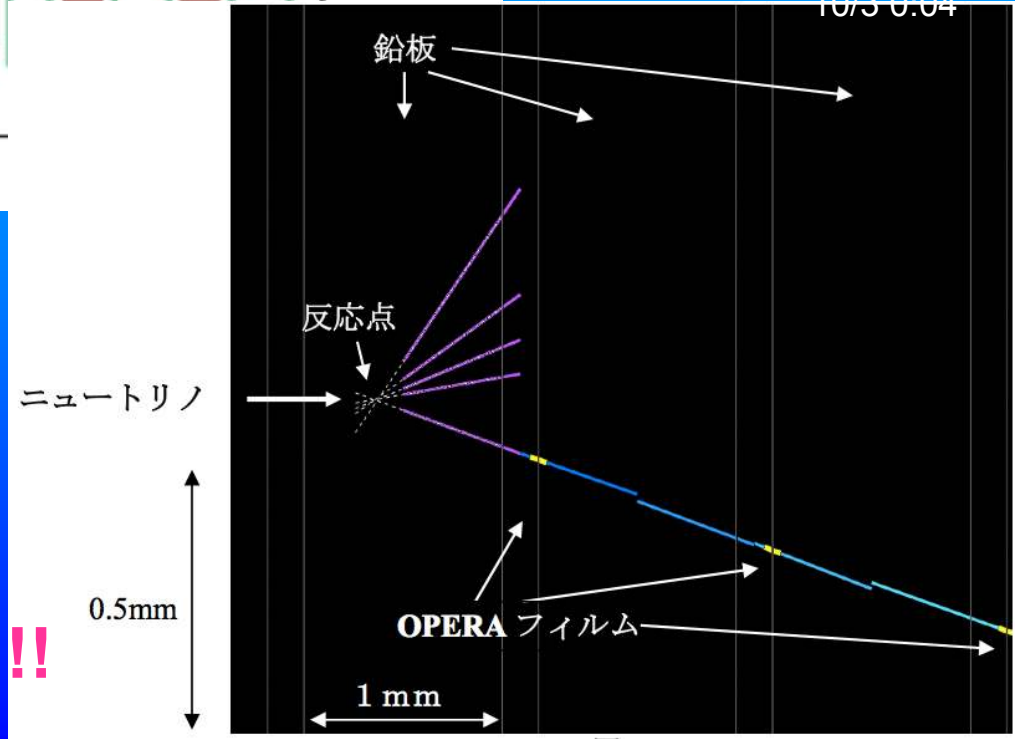
First observation of neutrino events in emulsion.

2007年10月3日



10/3 0:04

Analysis stream was completed !!



Analysis station was moved to Tono mine. from Nagoya Univ. because of Anti-earthquake reinforcement. (2008-2010)

Tono mine again...



OTERA



Opera Team Economical traditional Apartment



We boarded at Japanese temple near Tono.

Real exposure was started from 2008 !

OPERA実験をやり切るために必要なこと

- 大質量の原子核乾板検出器をどうやって作るか。
→ OPERAフィルムの開発(富士フィルム)
鉛ECCの採用、東濃鉱山での大量Refresh...

↑ O.K.

- 大量の原子核乾板のデータを
どうやって解析し切るか？

Neutrino event analysis

- Experimental requirements

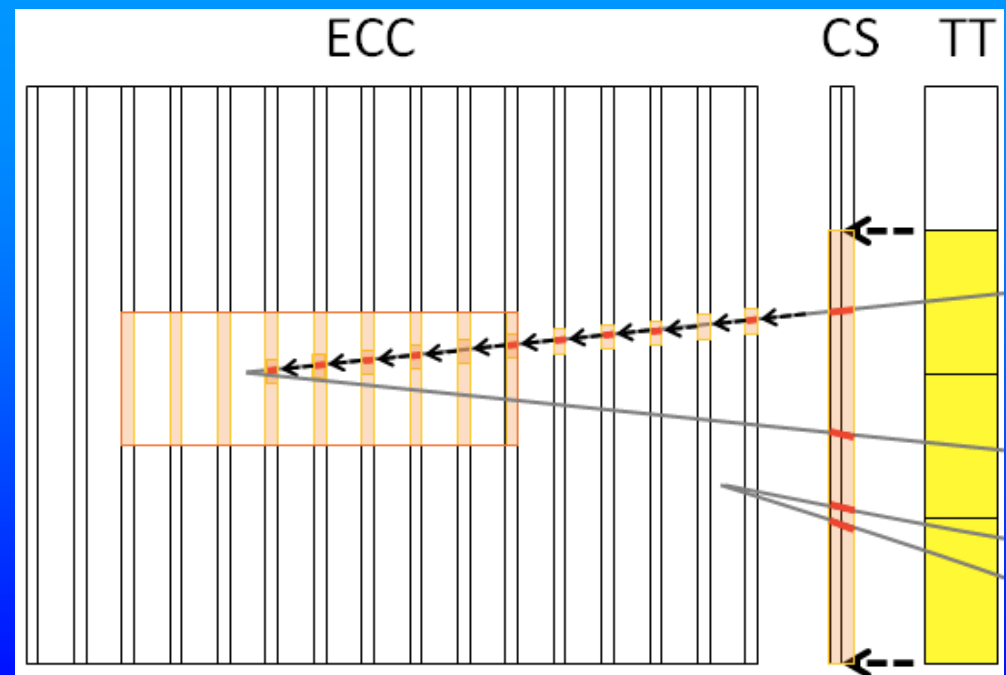
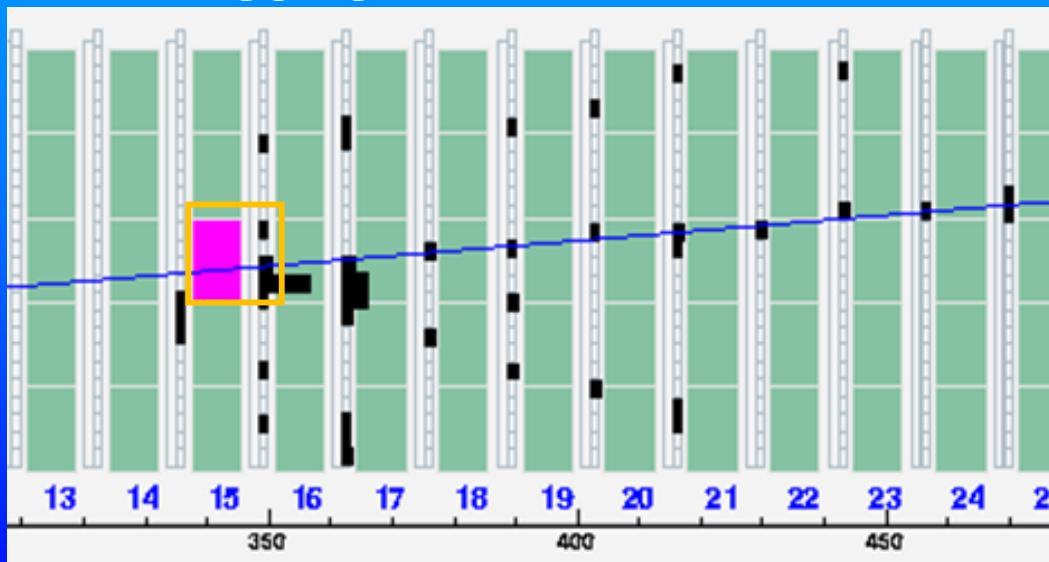
- ✓ Long baseline
- ✓ High neutrino energy → CNGS beamline
- ✓ High spatial resolution (ν_τ detection capability)
- ✓ Large target mass → OPERA detector

Challenge in OPERA



Large amount of emulsion analysis

Brick tagging and Scan back location



Technical breakthrough

High speed scanning
x 20-75

Japanese Scanning System



Scanning speed : 75cm²/h

JINST 5:P04011, (2010)

European Scanning System



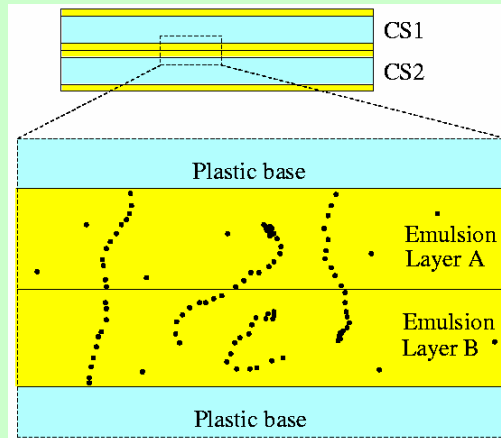
Scanning speed : 20cm²/h

NIM A551 (2005) 261

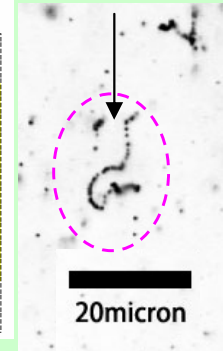
Precision alignment (Compton alignment)

S/N x 10

With noise tracks connected both side of emulsion layer



100keV electron



Alignment accuracy:
 $\sigma = 7.6 \mu m \rightarrow \sigma = 2.0 \mu m$

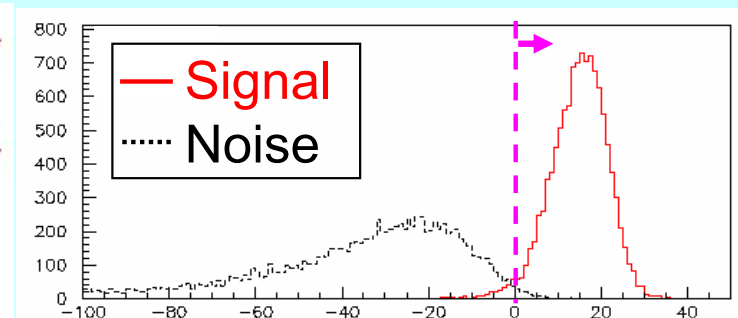
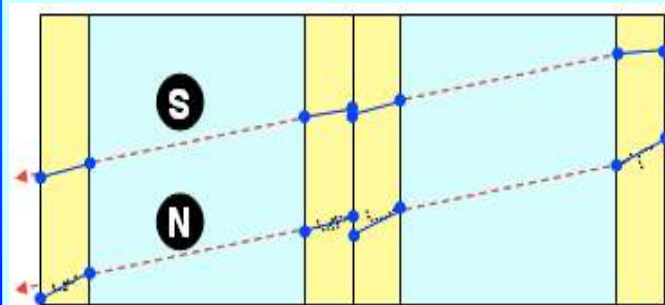
Reduce chance coincidence noises

NIM A575 (2007) 466

High S/N discrimination (Track Ranking)

S/N x 100

Likelihood analysis with the linearity and blackness of each tracks



JINST 5:P04009, (2010)

Signal 98%, Noise 1%

Event analysis – Location: CS –

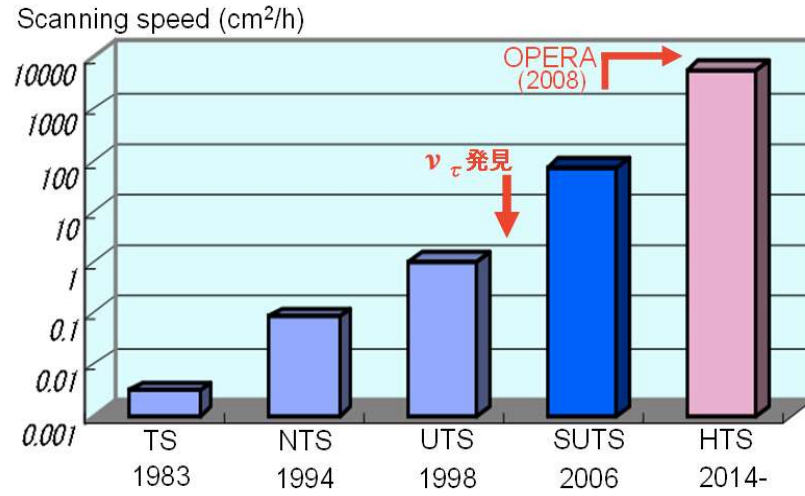
1. Full area CS scan and check tracks to confirm the brick

High speed scanning system

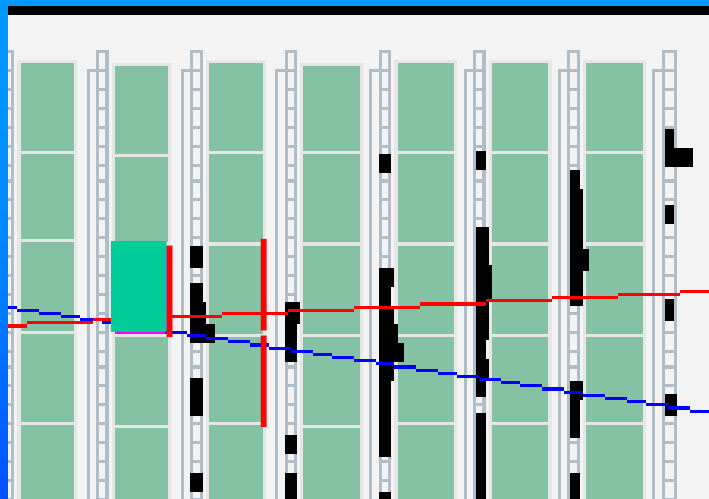
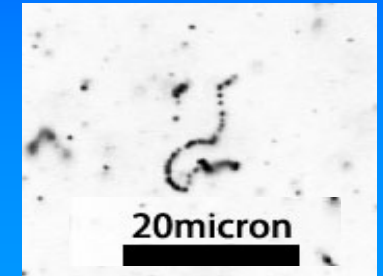
Japanese Scanning System



Scanning speed : 75cm²/h

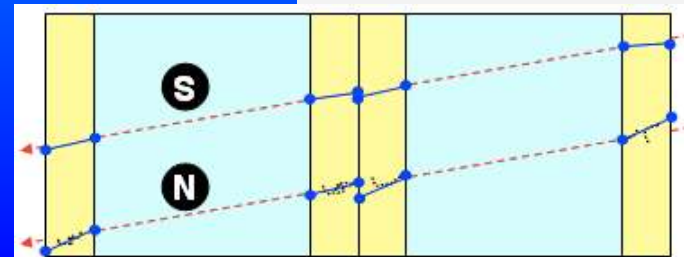
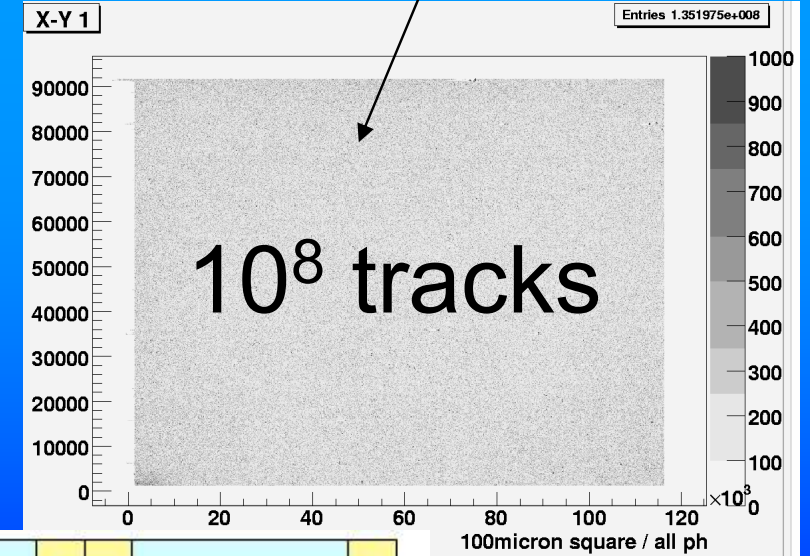
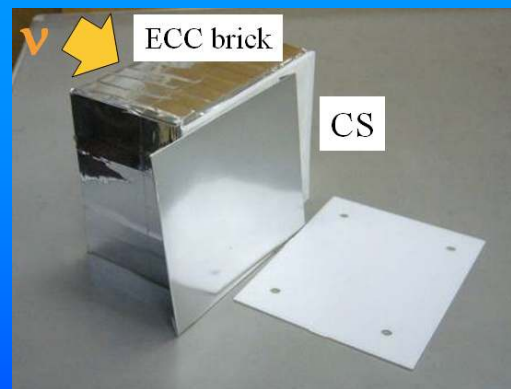


Sub-MeV electrons



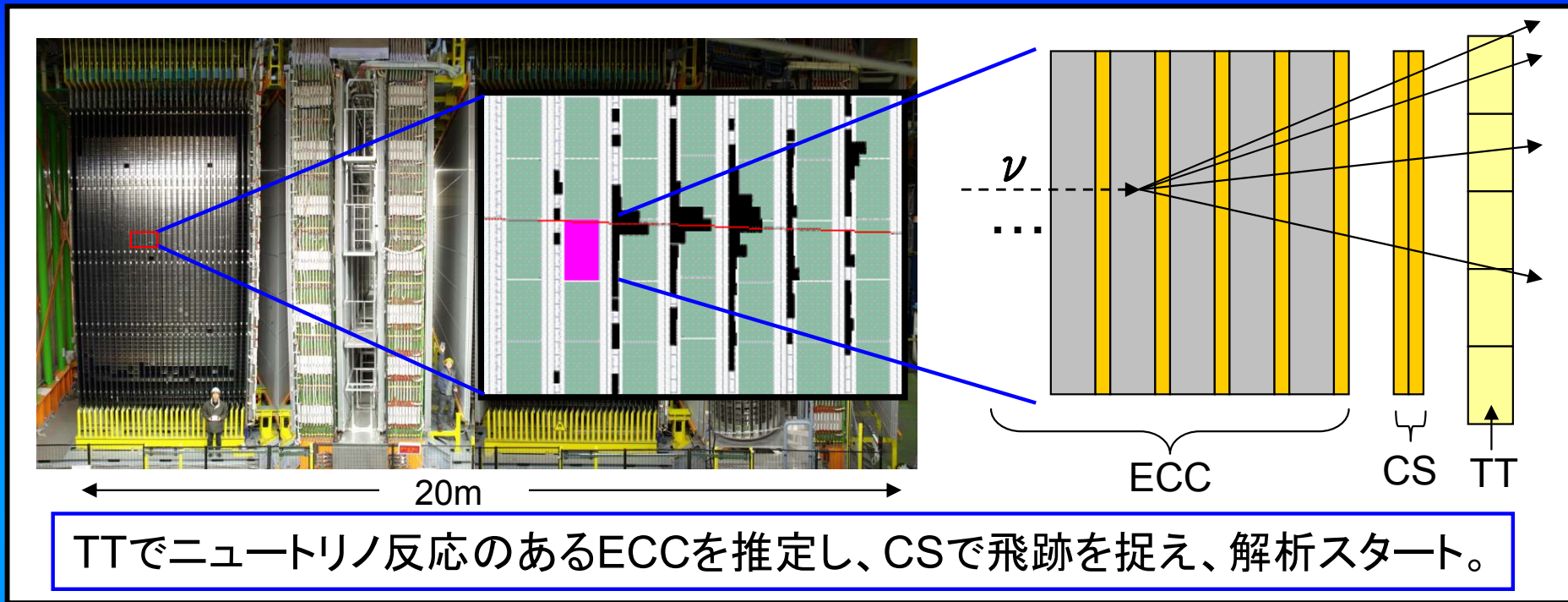
Pick out of High probability CS and CS Scanning

Result



10³ trks

OPERAでの原子核乾板解析



CS解析要求値:

1CSあたり平均400本の肉眼観察 × 15CS/日
→ 約6,000本/日 → 肉眼観察200時間/日

OPERA 5年のRUNで、
200時間/日 × 5年 = **360,000時間**

5人が1日2時間の肉眼観察シフトを行うと、
10時間/日 → 10 × 360日 = 3600時間/年

$360000 / 3600 = 100$

→ OPERAのCS解析に**100年かかる**

現実的な時間内でOPERAの解析を遂行するために
大量の肉眼観察を削減する必要がある。

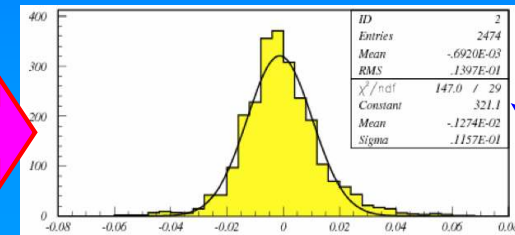
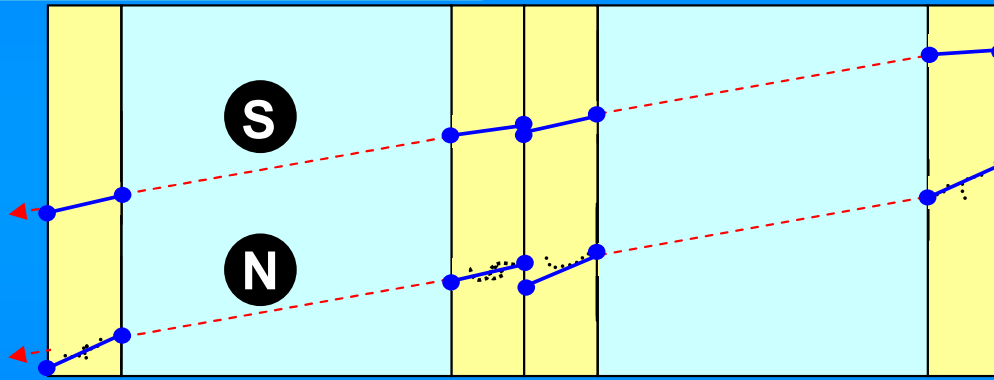
従来の自動飛跡認識処理の『高速化』という技術開発とは質的に異なるアプローチが不可欠

自動飛跡認識アルゴリズムの高精度化

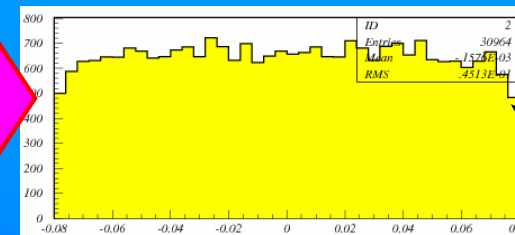
肉眼観察を削減するために、

原子核乾板における自動飛跡認識アルゴリズムの「高精度化」
(高S/N化)

1. 飛跡の直線性に着目

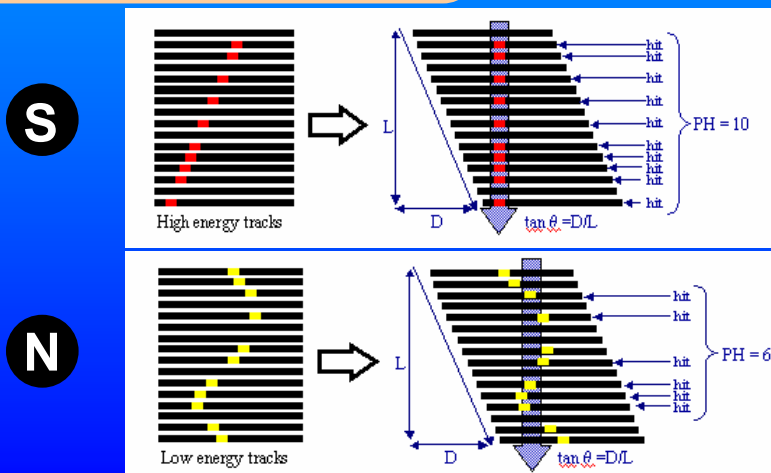


シグナルは、
ガウス分布

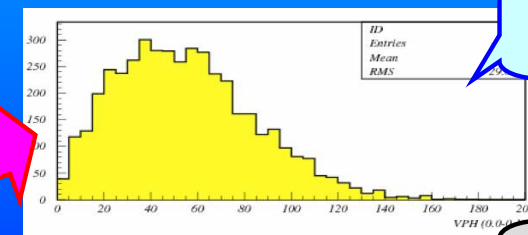


ノイズは、
フラット分布

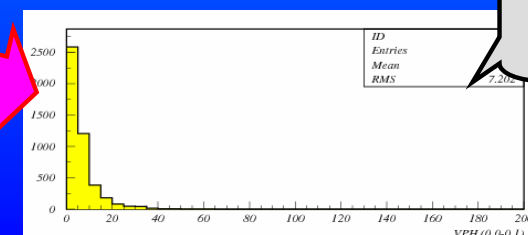
2. 飛跡の濃さに着目



自動読取り装置
で認識したTrack
を構成するpixel数

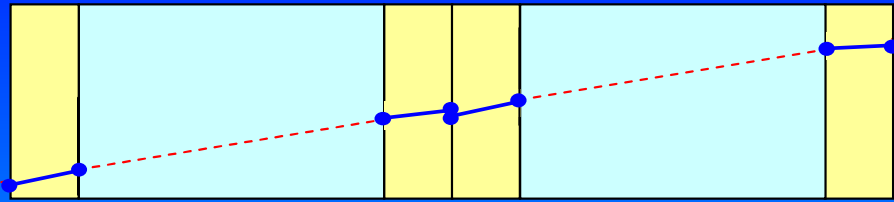


シグナル

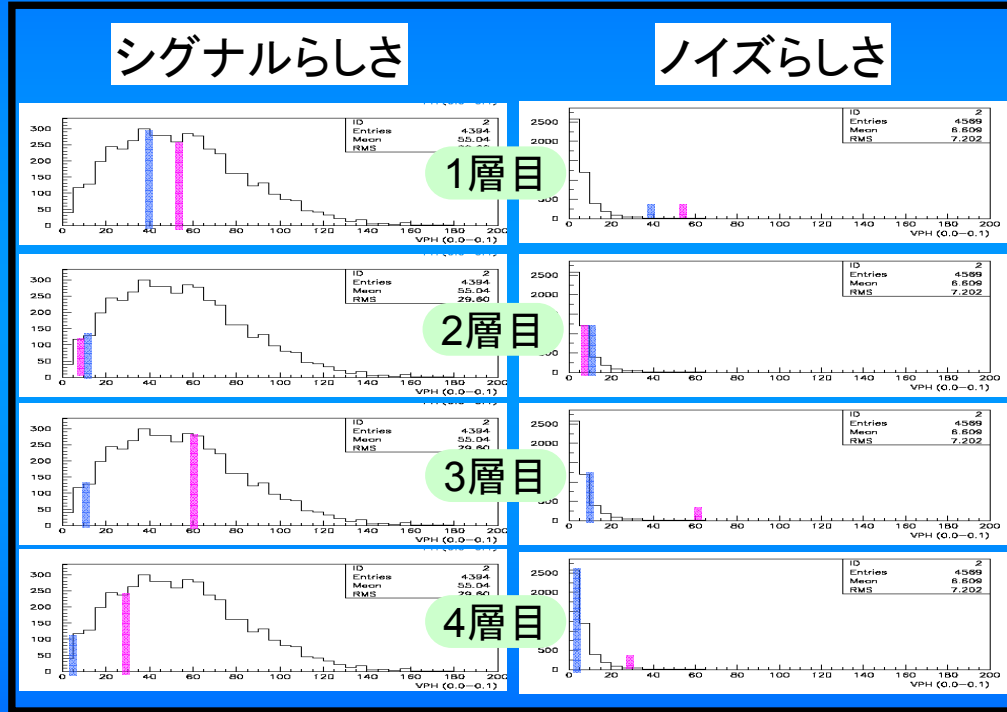


ノイズ

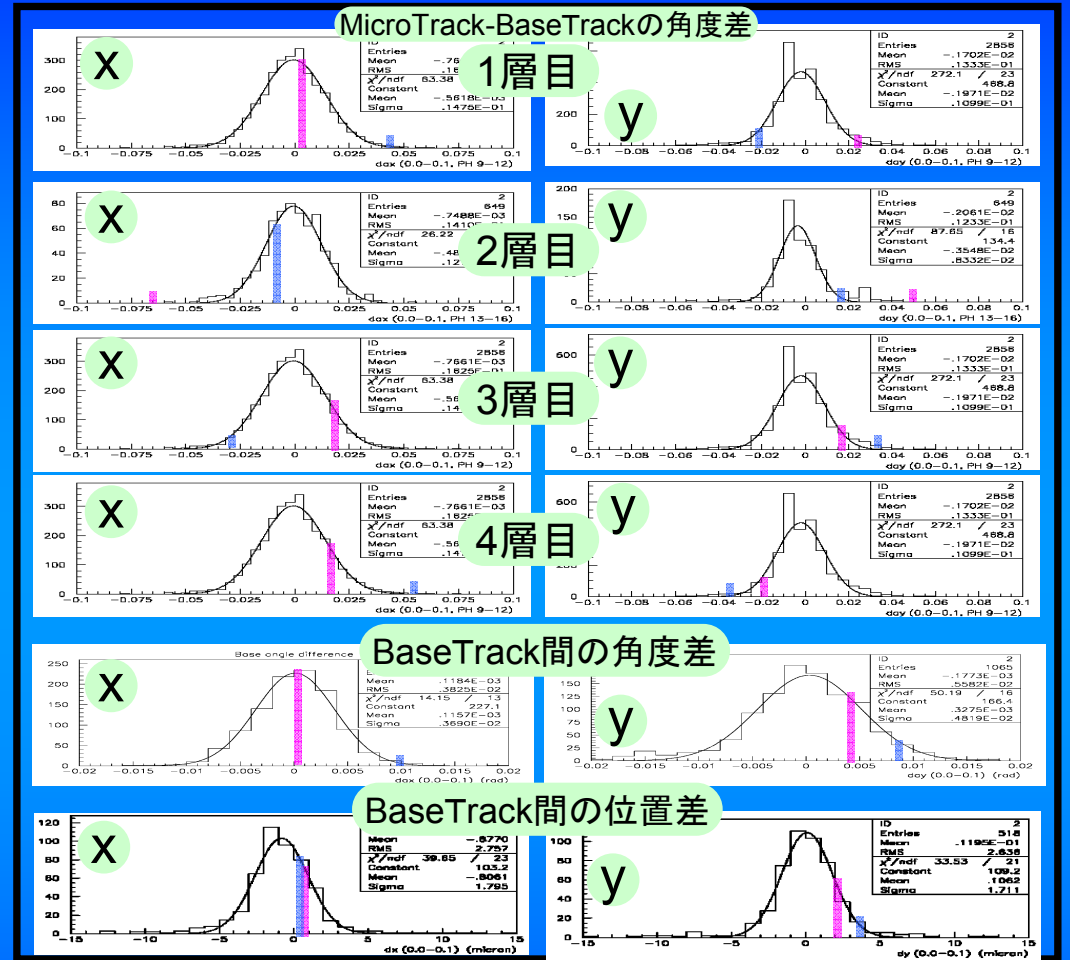
高精度認識アルゴリズムの定式化



濃さ情報: 4パラメータ



直線性: 12パラメータ



シグナルらしさ

$$L^{signal} = \prod_{i=1}^4 P_{VPH_i}^{signal}(\theta) * \prod_{i=1}^8 P_{dA_{micro}_i}^{signal}(\theta, ph) * \prod_{i=1}^2 P_{dA_{base}_i}^{signal}(\theta) * \prod_{i=1}^2 P_{dX_{base}_i}^{signal}(\theta)$$

ノイズらしさ

$$L^{noise} = \prod_{i=1}^4 P_{VPH_i}^{noise}(\theta)$$

最小電離粒子らしさ

Track Ranking Score (R) = $\log \frac{L^{signal}}{L^{noise}}$

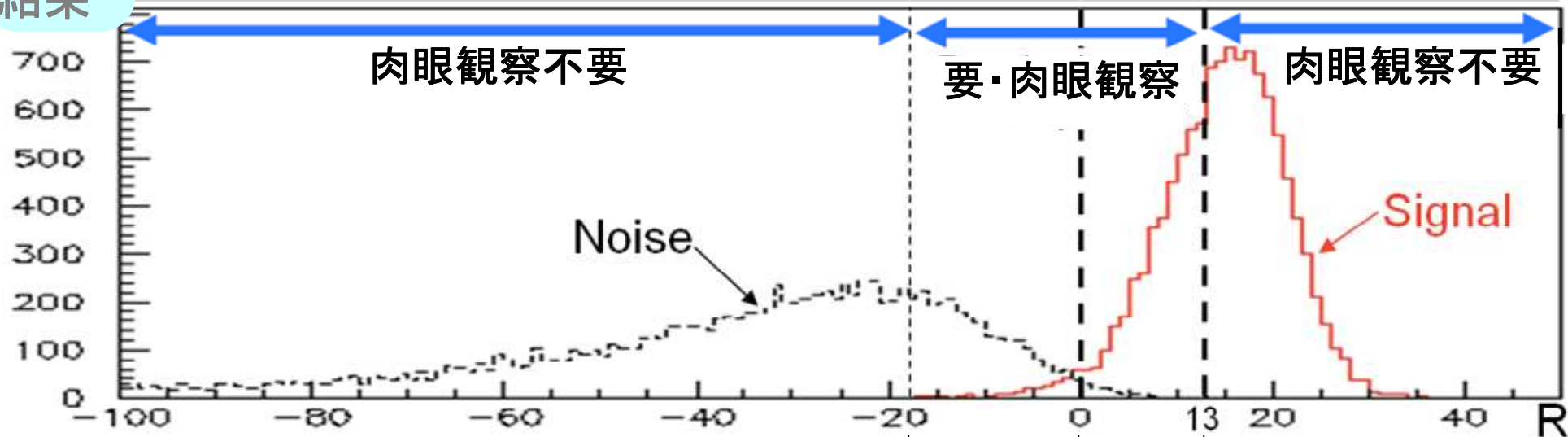
シグナル: 8.7
ノイズ: -8.5

Track Ranking法の性能評価

- 加速器のビームをシグナルサンプル、CSのノイズデータをノイズサンプルとして、**Track Ranking 法**を適用し、両者のとる値を比較した。

T. Fukuda et al., 2010 *JINST* 5 P04009

結果

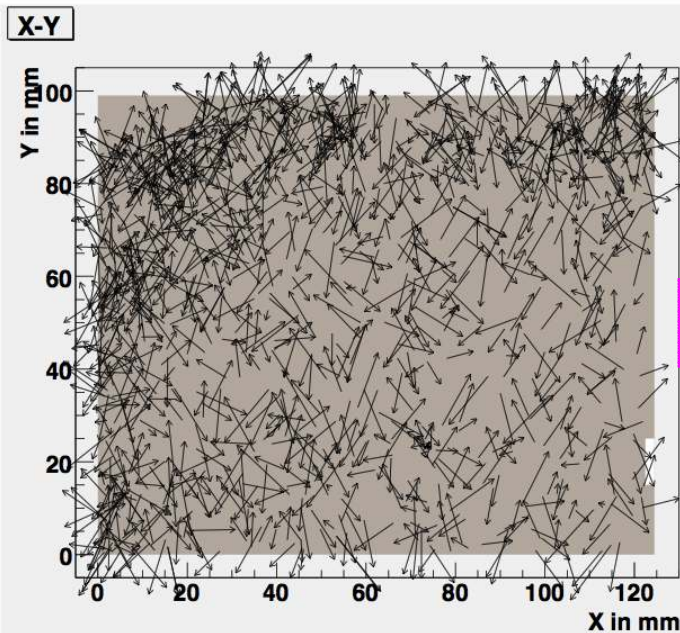


Signal	<0.1%	2%	34%	64%
Noise	77%	22%	1%	<0.1%

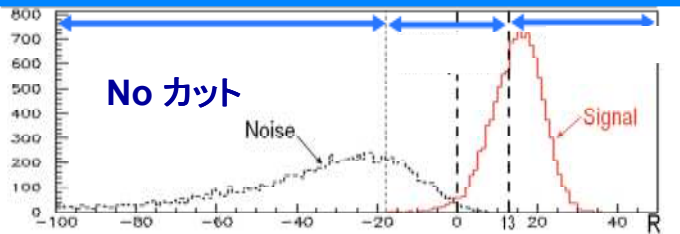
- R>13 は、自動的にシグナルの飛跡であると判定できる。
- 検出効率 : 読み取られたシグナル飛跡のうち、 $(34 + 64) = 98\%$ を保持。
- 肉眼観察量: 自動飛跡読み取り装置から読み取られる飛跡データの99%以上はノイズなので、肉眼観察量は、従来の1/100に抑え込める。

Event analysis – Location: CS –

Track Ranking 適用前



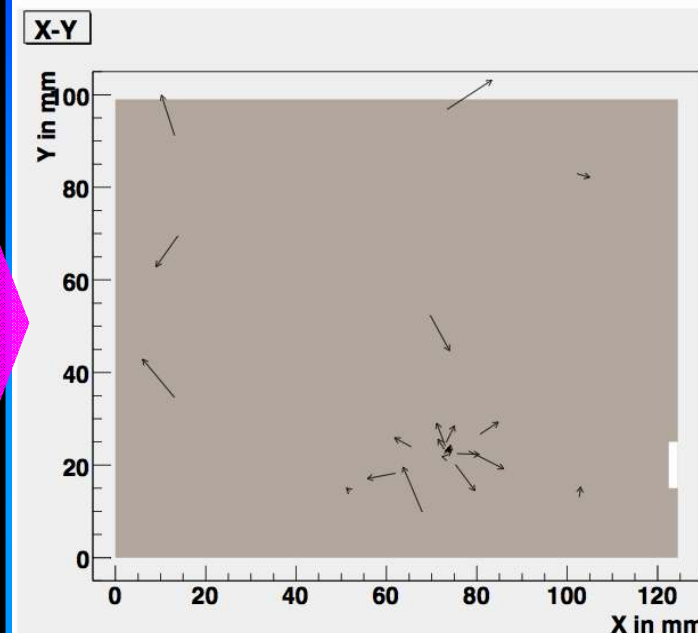
読み取られたTrack数: 1260本



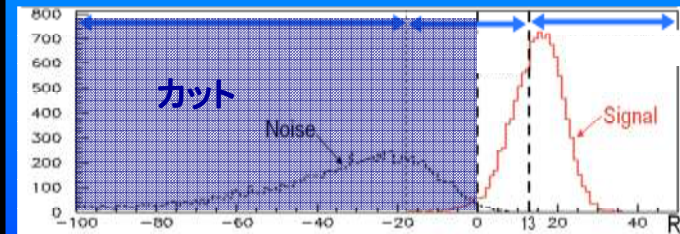
肉眼観察本数: 1260本

肉眼観察時間: 42時間

Track Ranking 適用後

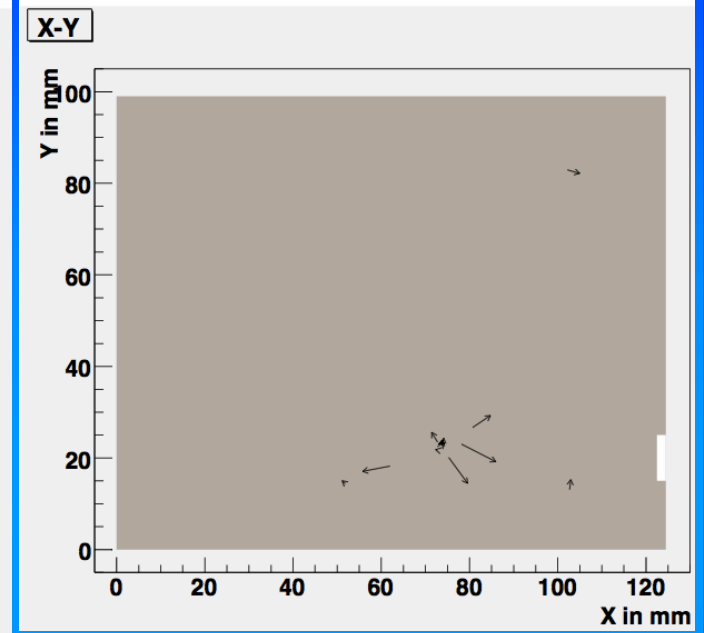


Track Ranking法で選別したTrack数
要・肉眼観察: 10、肉眼観察不要: 14

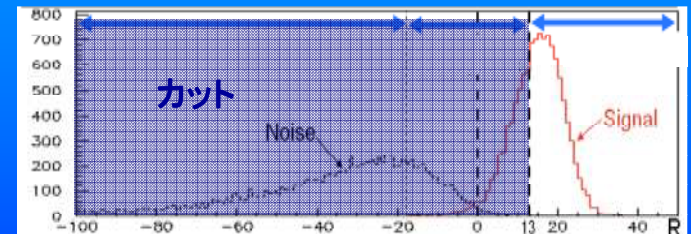


肉眼観察本数: 10本

肉眼観察時間: 20分



Track Ranking法で選別したTrack数
肉眼観察不要: 14



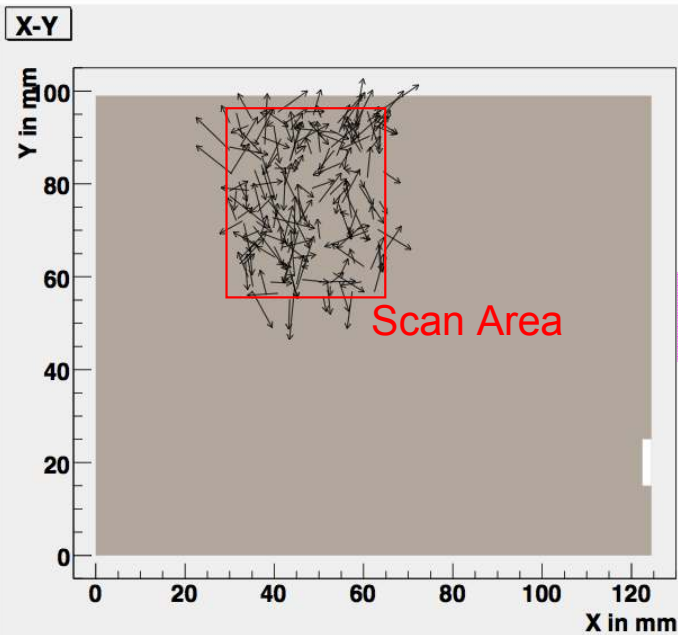
一点に収束するシグナルTrackがある

肉眼観察不要

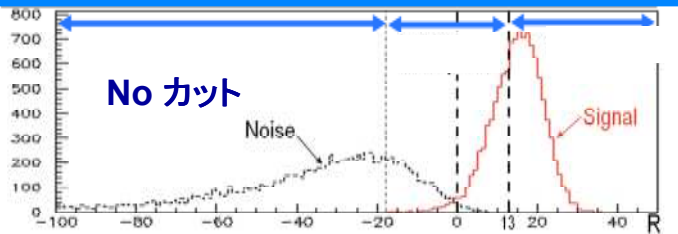
肉眼観察時間: 0秒

Event analysis – Location : CS –

Track Ranking 適用前



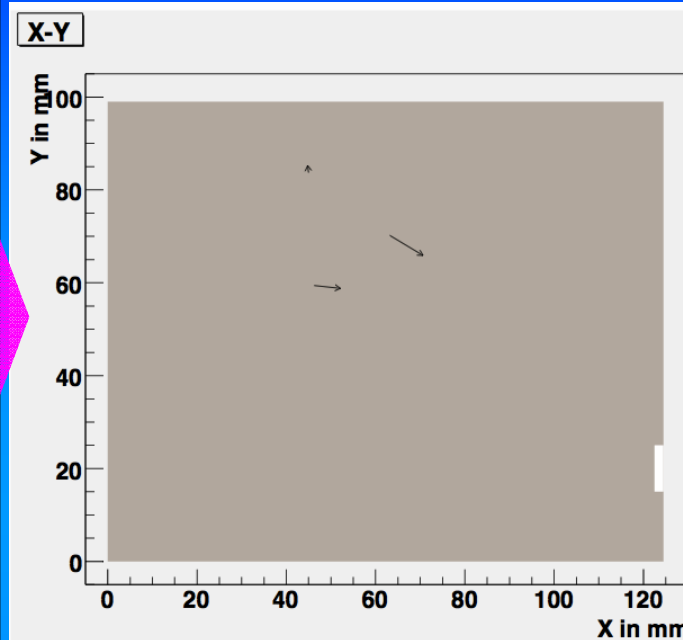
読み取られたTrack数: 194本



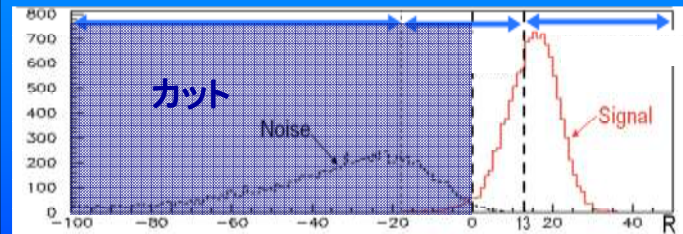
肉眼観察本数: 194本

肉眼観察時間: 6.5時間

Track Ranking 適用後



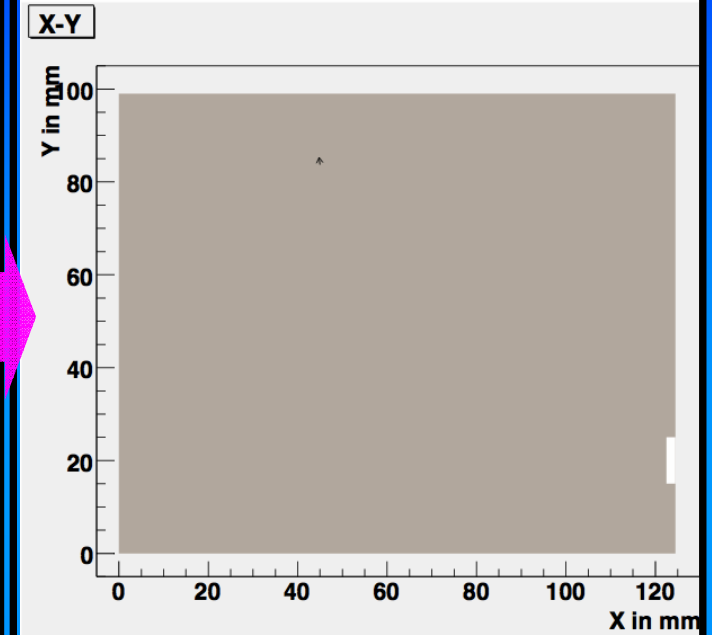
Track Ranking法で選別したTrack数
要・肉眼観察: 3、肉眼観察不要: 0



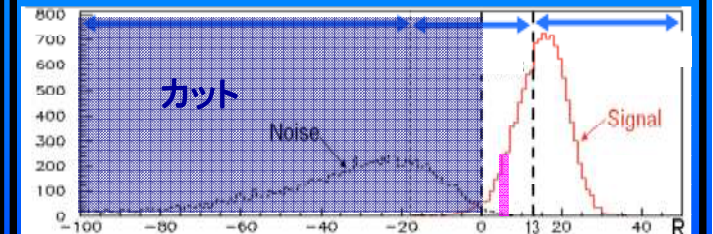
肉眼観察本数: 3本

肉眼観察時間: 6分

肉眼観察後






肉眼観察で確認したTrack数
シグナル: 1、ノイズ: 2



シグナルが1本見つかった

ニュートリノ反応探索スタート

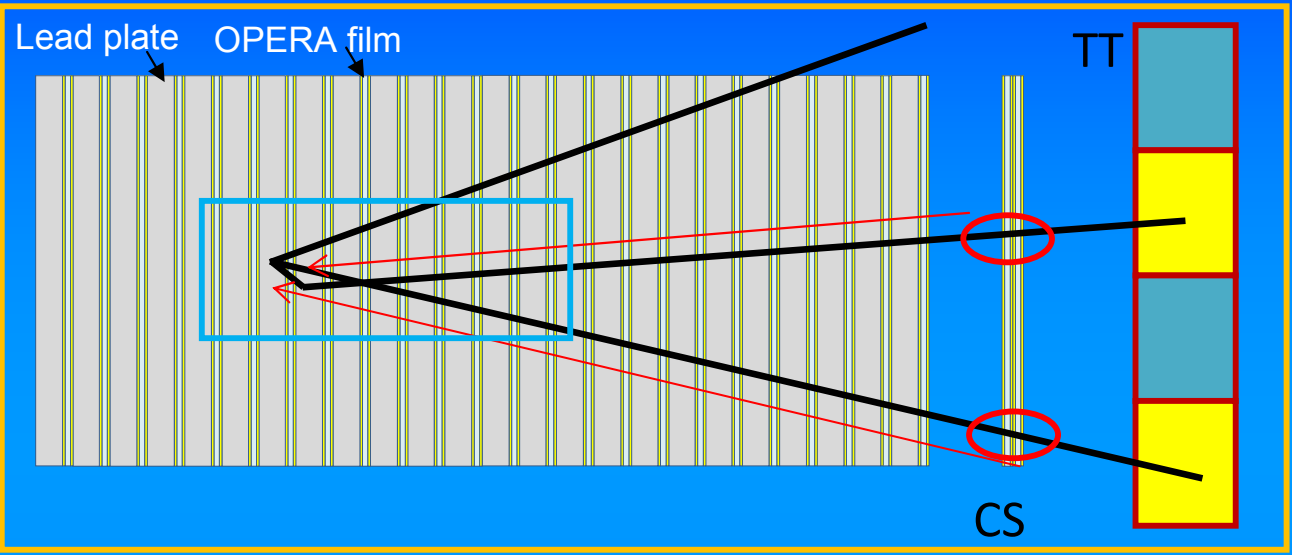
OPERA実験をやり切るために必要なこと

- 大質量の原子核乾板検出器をどうやって作るか。
→ OPERAフィルムの開発(富士フィルム)
鉛ECCの採用、東濃鉍山での大量Refresh...  O.K.
- 大量の原子核乾板の飛跡をどうやって読み出すか。
→ 高速自動飛跡読み取り装置SUTSの開発  O.K.
- 膨大なトラックデータをいかに解析し切るか。
→ 高精度自動飛跡認識アルゴリズムの開発
(Compton Alignment法, Track Ranking法)  O.K.

Event analysis – Location: ECC –



Scan Back Location



Event analysis

→ JP : EU = 50 : 50

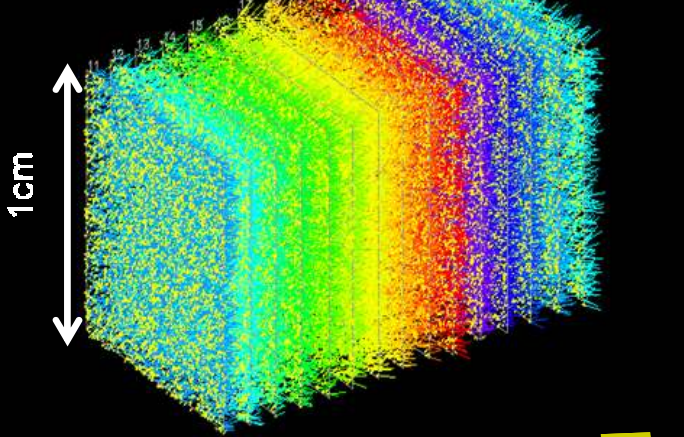


2. Connect tracks found at CS to ECC brick.
3. Follow up tracks to Interaction vertex in the ECC brick.
4. Scan 10 films around interaction vertex.

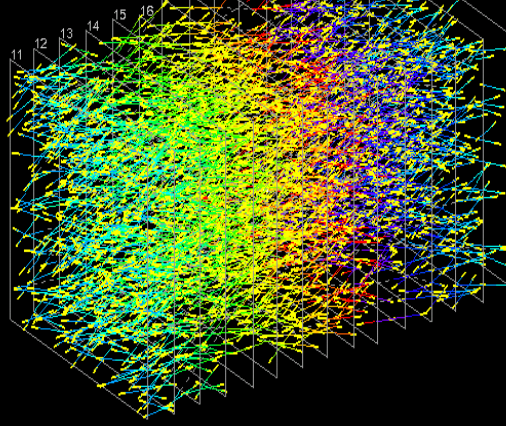


Event analysis – Vertex hunting –

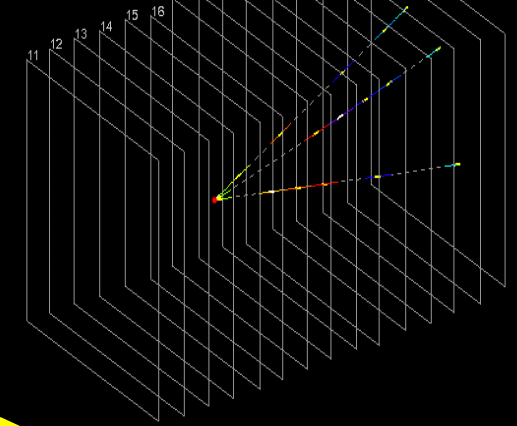
Scan 1cm × 1cm around vertex



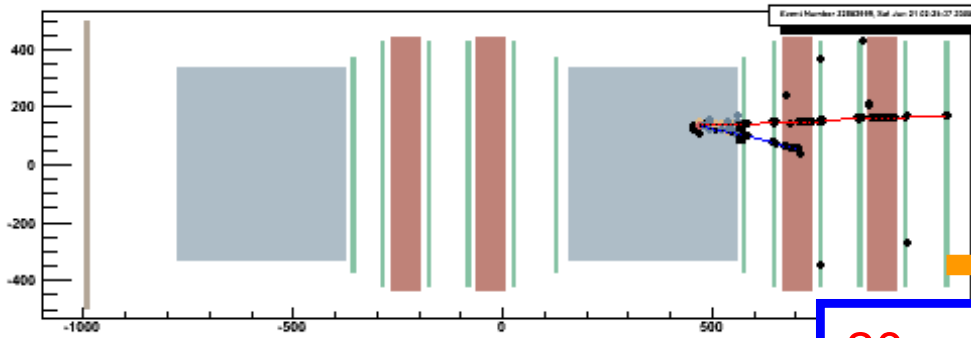
Pick up track chains



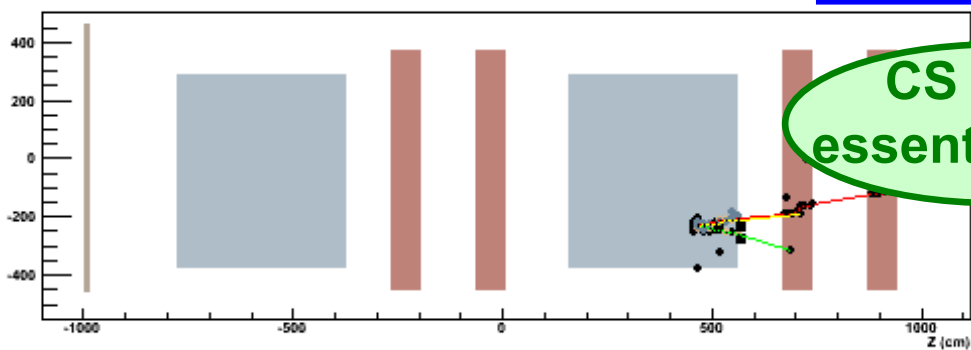
Search vertex topology



TOP VIEW (Horizontal projection)



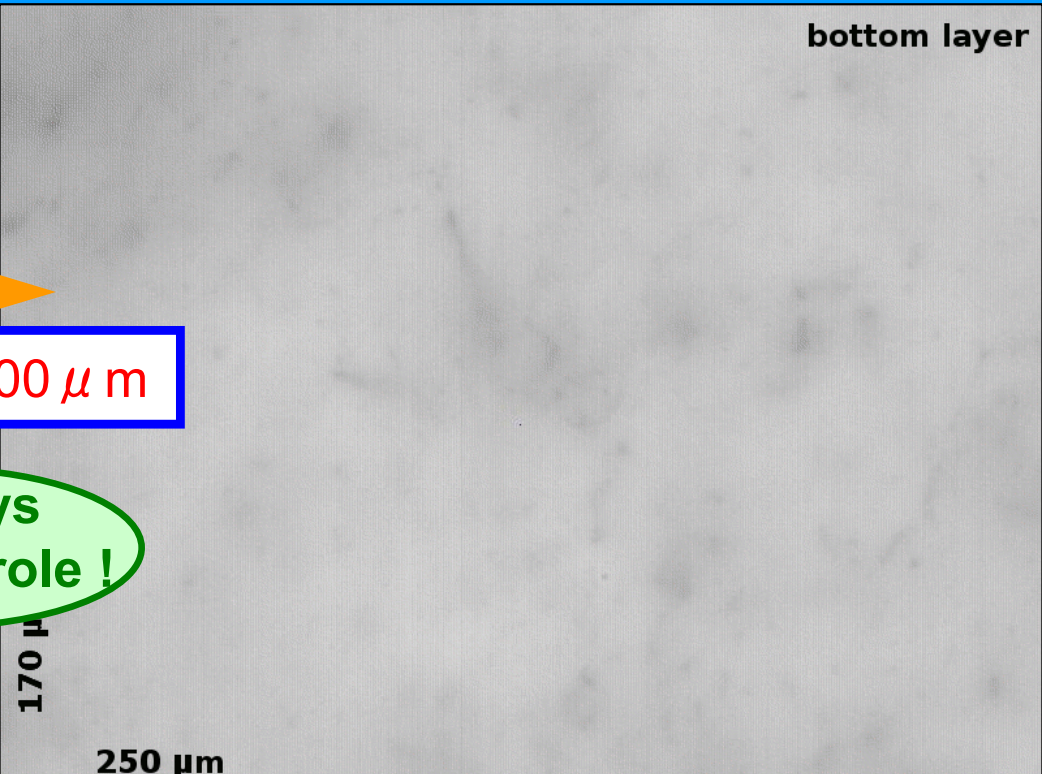
SIDE VIEW (Vertical projection)



20m → 100 μm

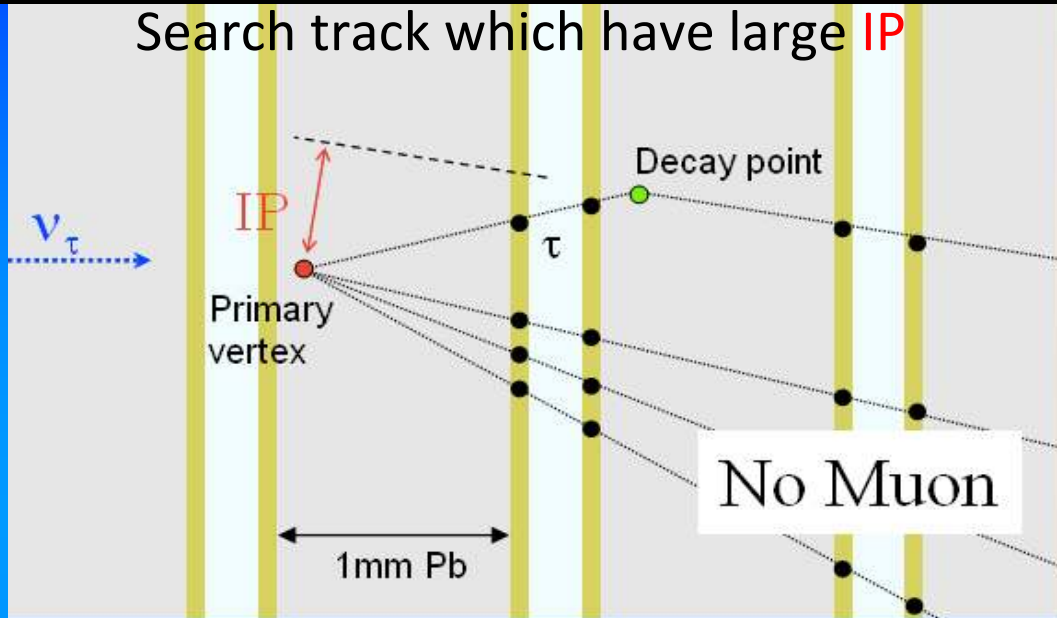
CS plays essential role!

bottom layer

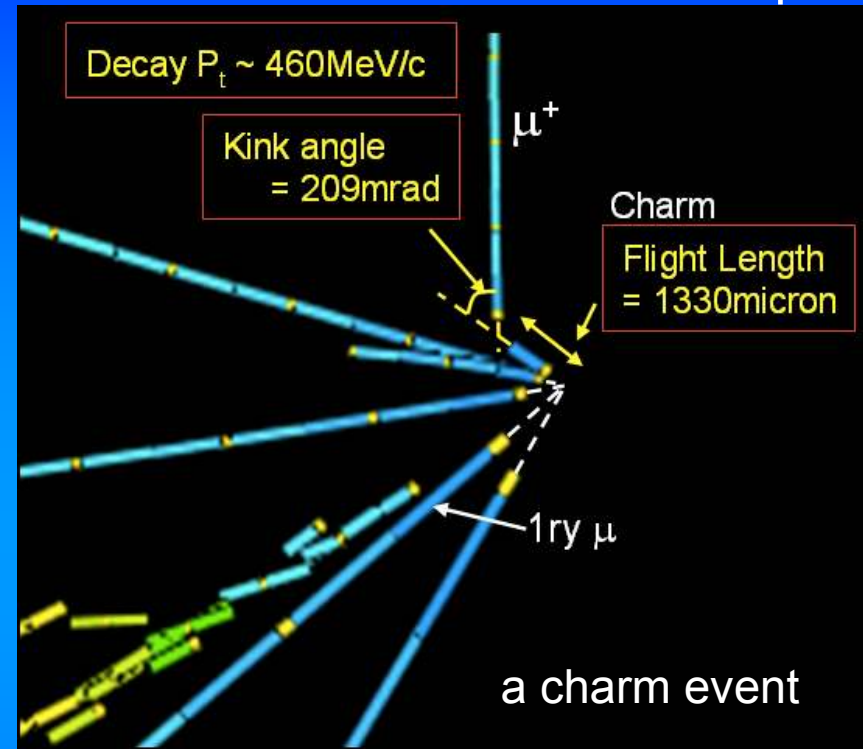


Neutrino event analysis

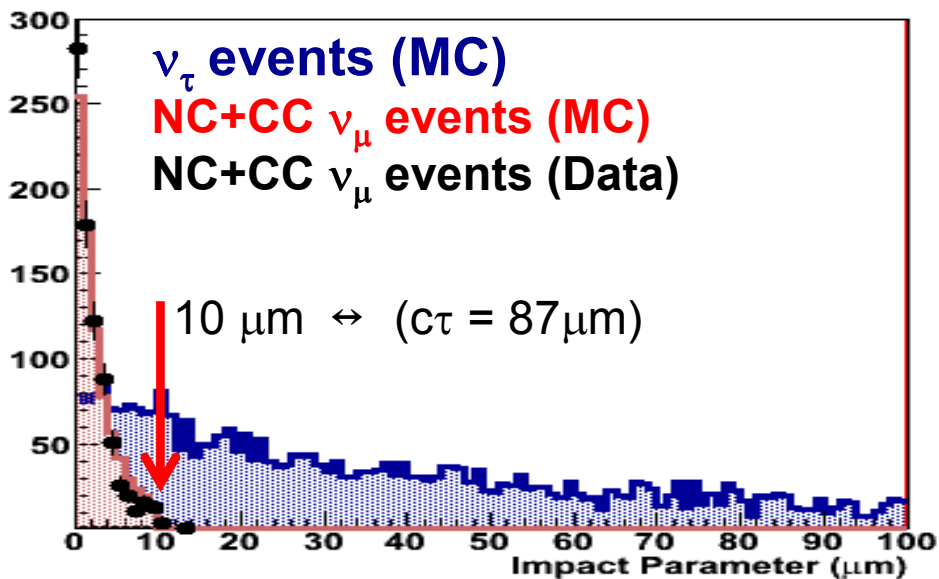
Decay topology search



Charm events as a control sample



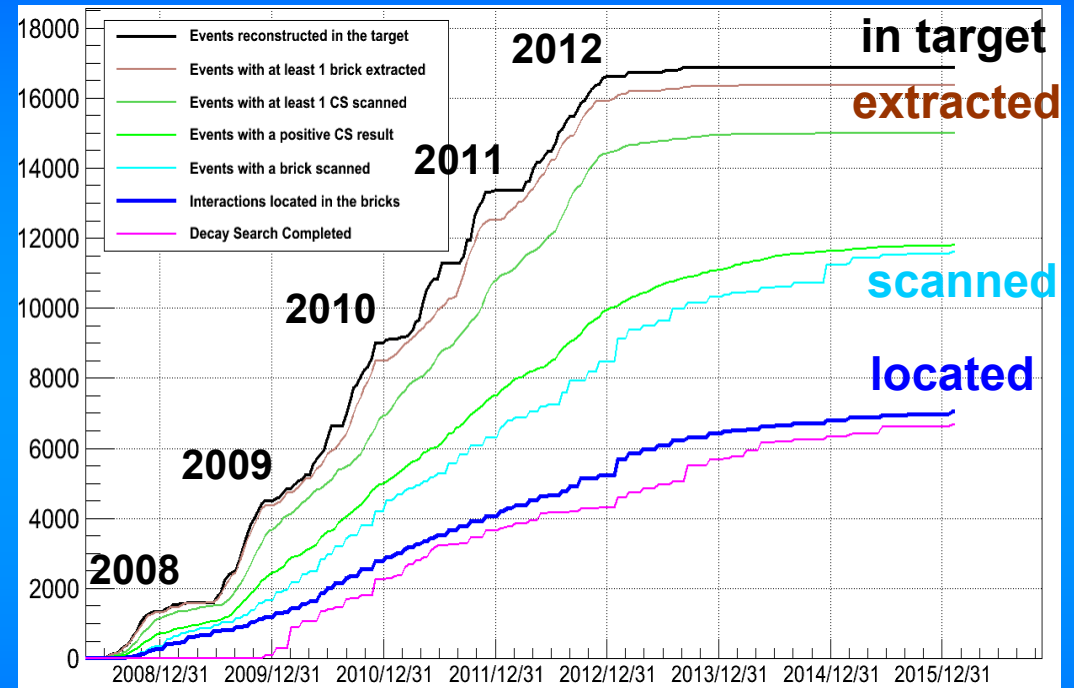
Impact Parameter distribution



Decay topology	Events			Observed
	Expected charm	Expected background	Expected total	
1-prong	21 ± 2	9 ± 3	30 ± 4	19
2-prong	14 ± 1	4 ± 1	18 ± 1	22
3-prong	4 ± 1	1.0 ± 0.3	5 ± 1	5
4-prong	0.9 ± 0.2	–	0.9 ± 0.2	4
Total	40 ± 3	14 ± 3	54 ± 4	50

Data taking

Analysis status

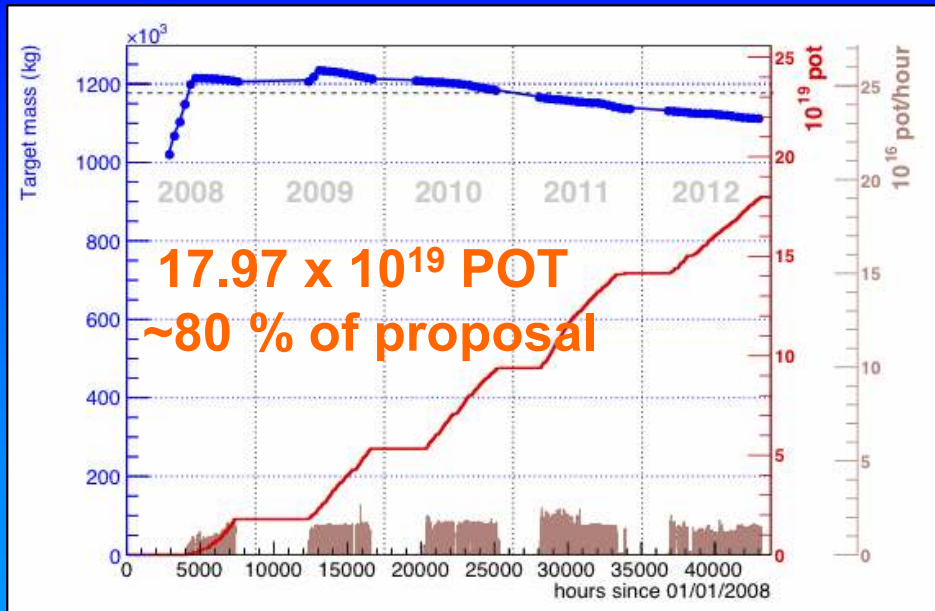


Status

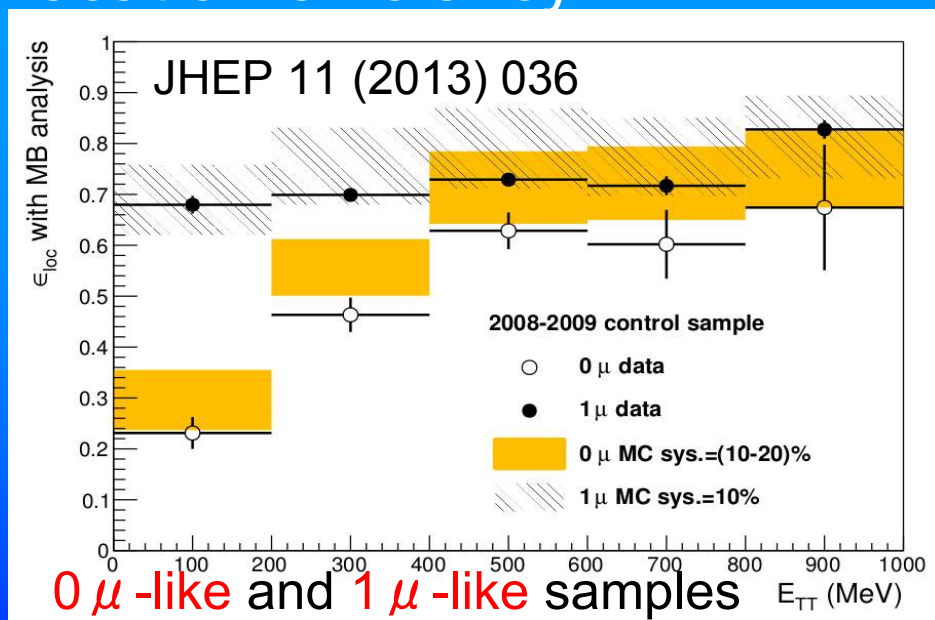
~19600 event registered

~7000 events located

~6700 events fully analyzed



Location efficiency

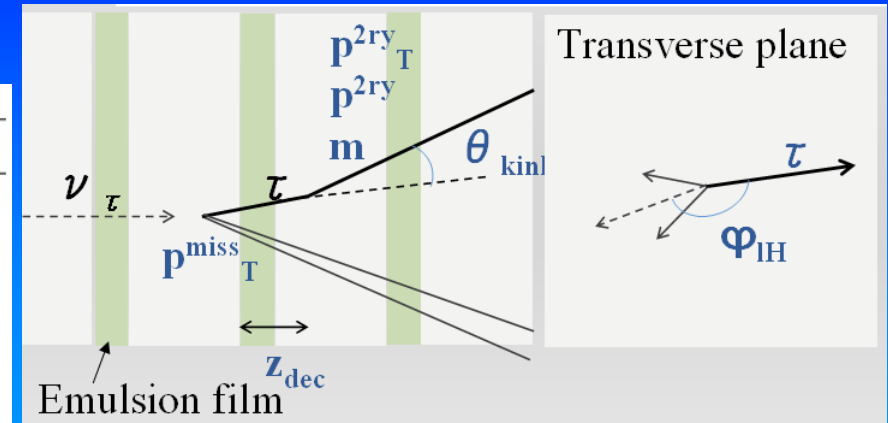


Data-Monte Carlo comparison of the location efficiency as a function of the visible energy in the target scintillators

ν_τ analysis

Kinematical selection

variable	$\tau \rightarrow 1h$	$\tau \rightarrow 3h$	$\tau \rightarrow \mu$	$\tau \rightarrow e$
lepton-tag	No μ or e at the primary vertex			
z_{dec} (μm)	[44, 2600]	< 2600	[44, 2600]	< 2600
p_T^{miss} (GeV/c)	< 1*	< 1*	/	/
ϕ_{lH} (rad)	> $\pi/2^*$	> $\pi/2^*$	/	/
p_T^{2ry} (GeV/c)	> 0.6(0.3)*	/	> 0.25	> 0.1
p^{2ry} (GeV/c)	> 2	> 3	> 1 and < 15	> 1 and < 15
θ_{kink} (mrad)	> 20	< 500	> 20	> 20
m, m_{min} (GeV/c ²)	/	> 0.5 and < 2	/	/



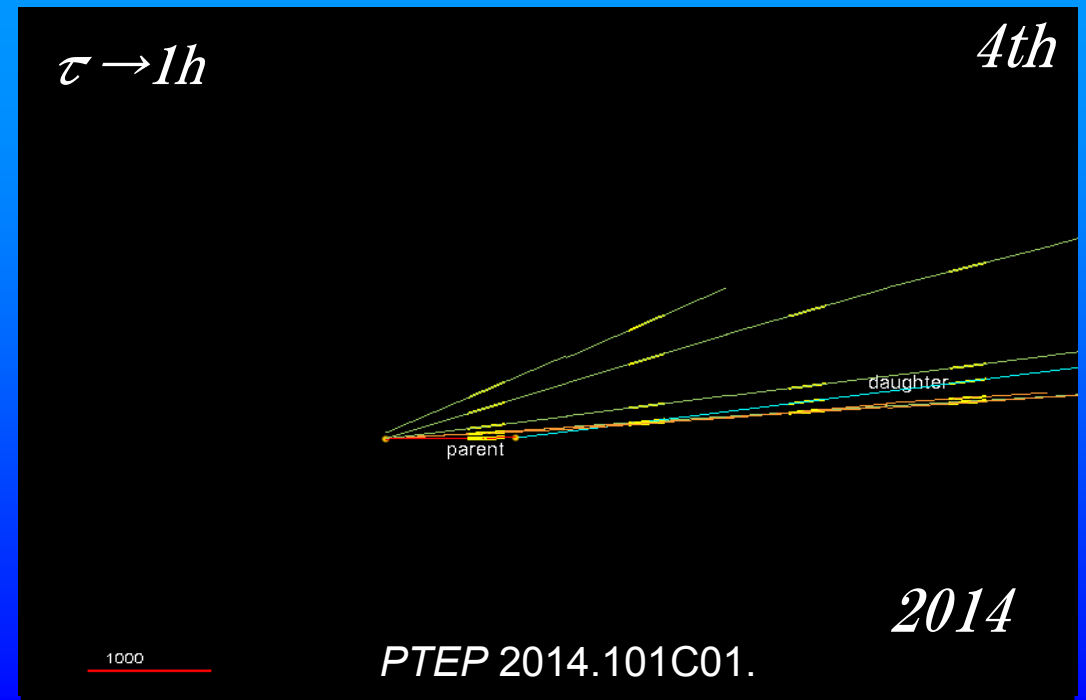
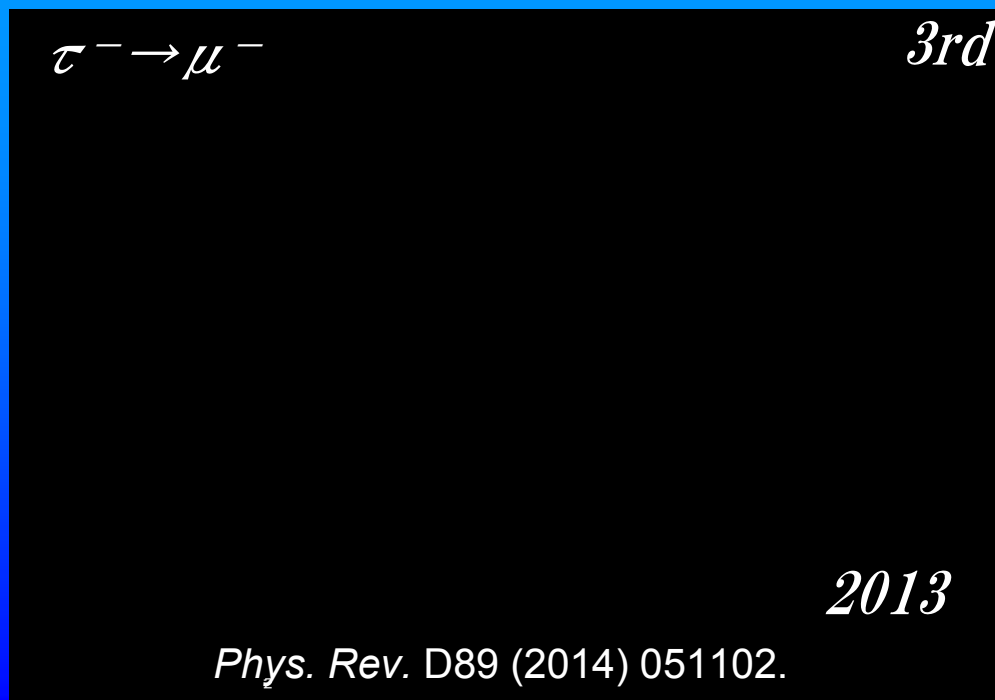
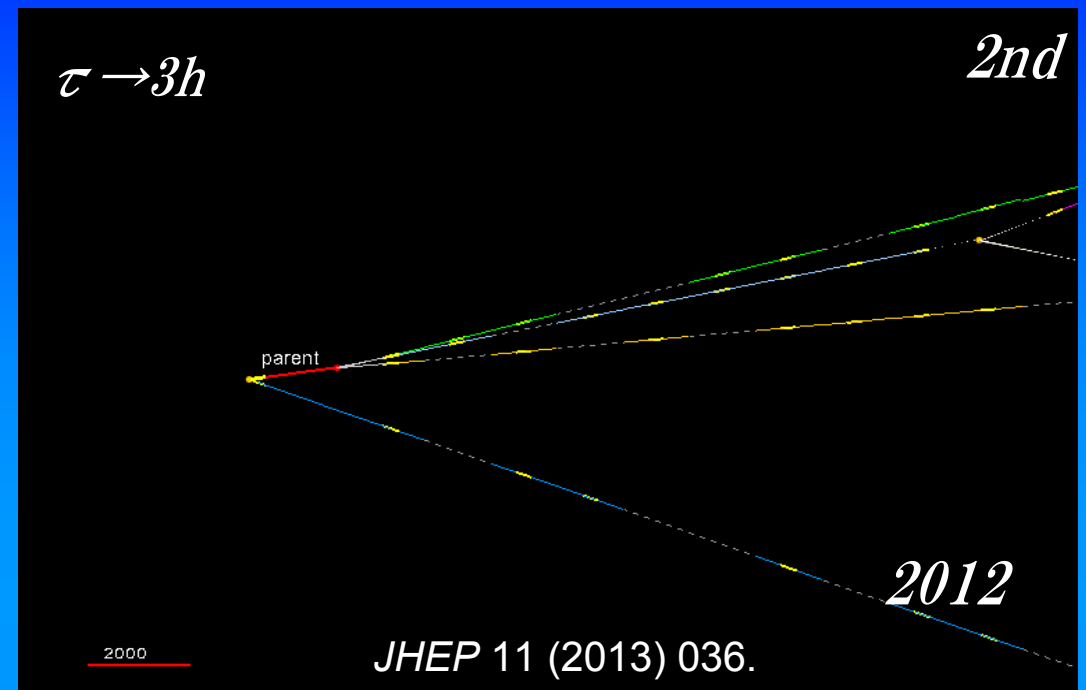
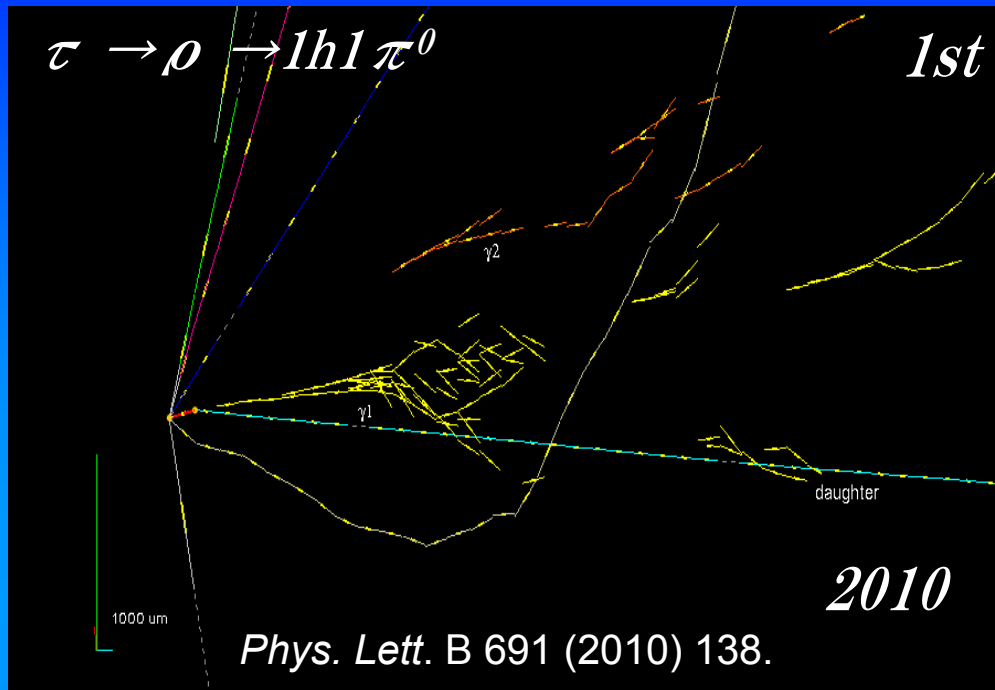
p_T^{miss} : vectorial sum of the transverse momenta of primaries (except the parent) and daughters wrt beam direction
 p_T^{2ry} : transverse momentum of the daughter wrt parent direction

Cuts fixed since the beginning of the experiment

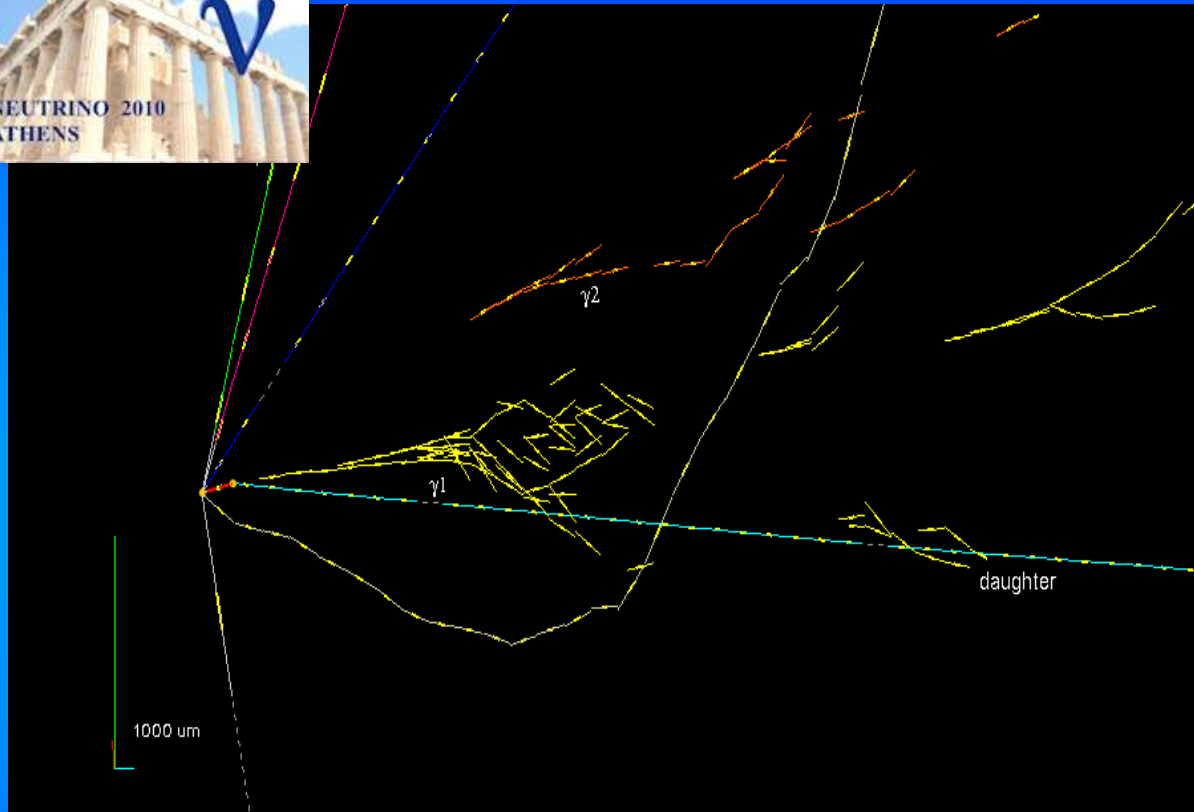
Data sample : The 1st and 2nd most probable bricks for all runs

	2008	2009	2010	2011	2012	Total
p.o.t. (10^{19})	1.74	3.53	4.09	4.75	3.86	17.97
0 μ events	149	253	268	270	204	1144
1 μ events ($p_\mu < 15$ GeV/c)	542	1020	968	966	768	4264
Total events	691	1273	1236	1236	972	5408
Detected ν_τ candidates	-	1	-	1	3	5

ν_τ candidate events



The first ν_τ “appearance” candidate



Event Kinematics

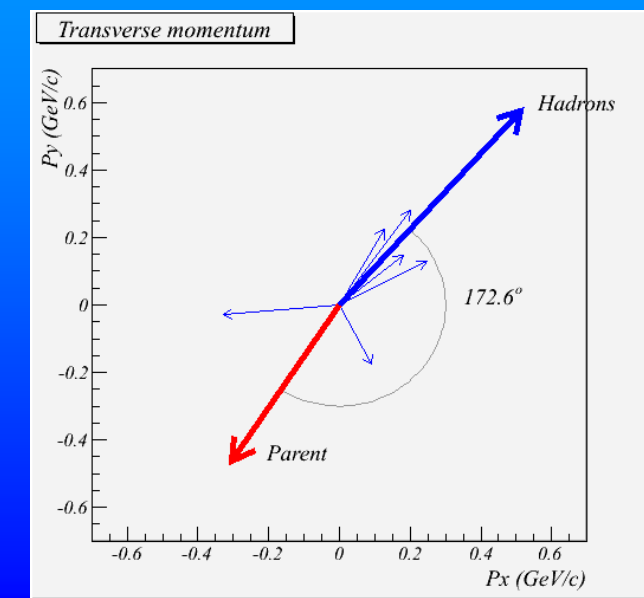
VARIABLE	Measured	Selection criteria
Kink (mrad)	41 ± 2	>20
Decay length (μm)	1335 ± 35	Within 2 lead plates
P daughter (GeV/c)	12^{+6}_{-3}	>2
Pt daughter (MeV/c)	470^{+230}_{-120}	>300 (γ attached)
Missing Pt (MeV/c)	570^{+320}_{-170}	<1000
φ (deg)	173 ± 2	>90

First detection of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode

Reported in [May 2010](#)

Decay channel: $\tau \rightarrow 1h$

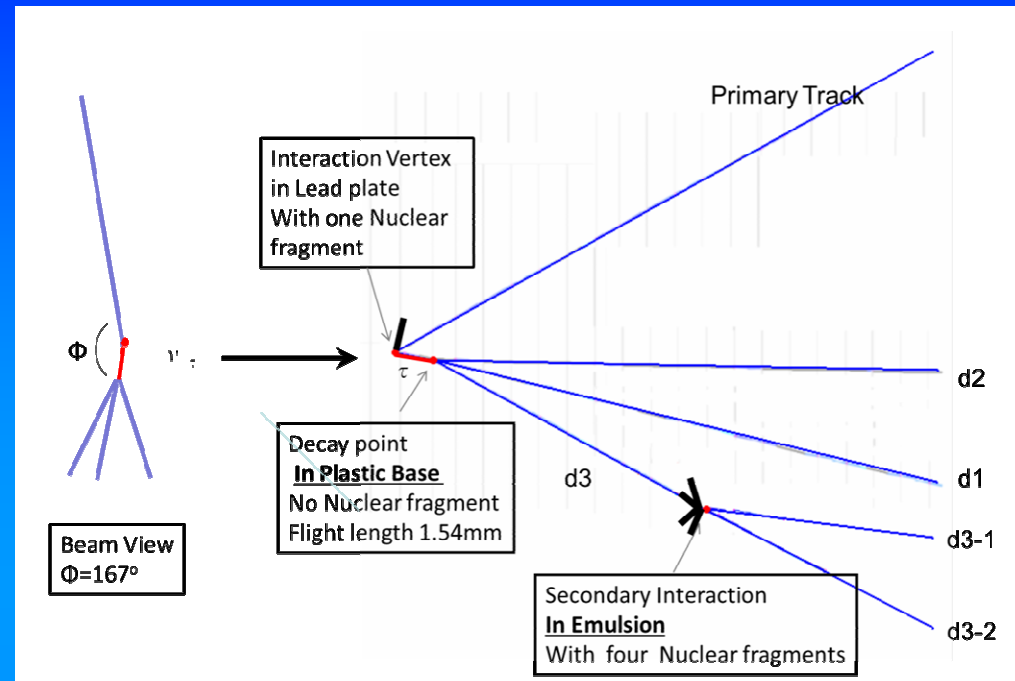
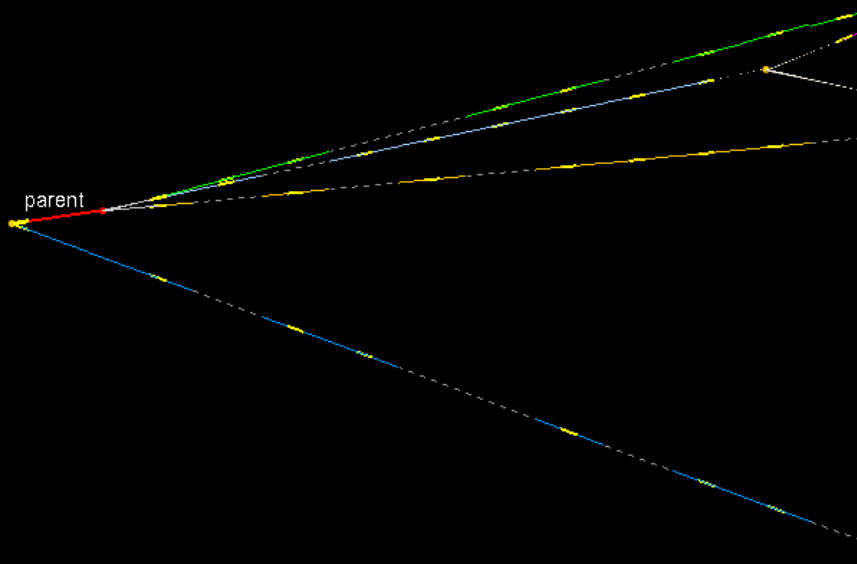
Phys. Lett. B 691 (2010) 138



The 2nd ν_τ candidate

NEUTRINO 2012

June 3-9 2012 Kyoto, Japan



All tracks other than τ were identified as hadrons.
Decay in plastic base.

Reported in June 2012

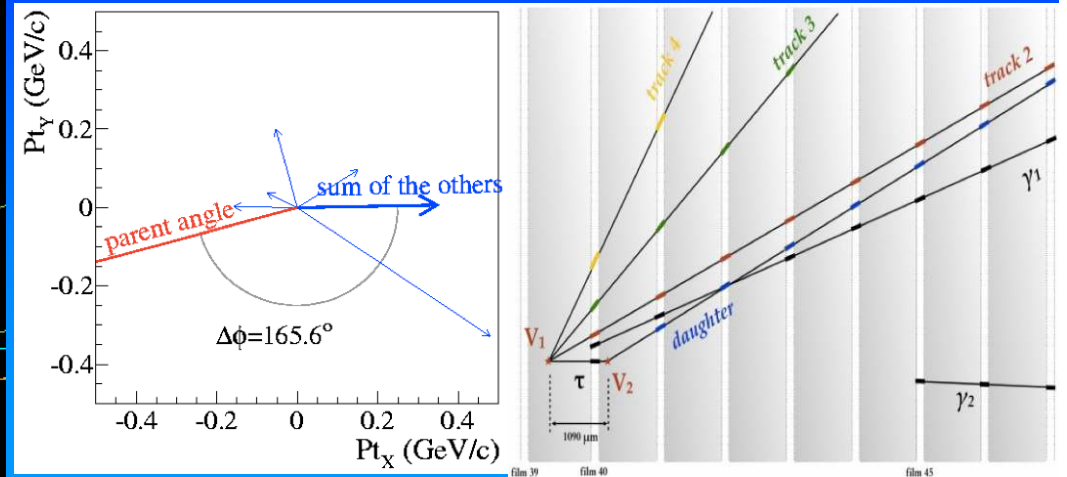
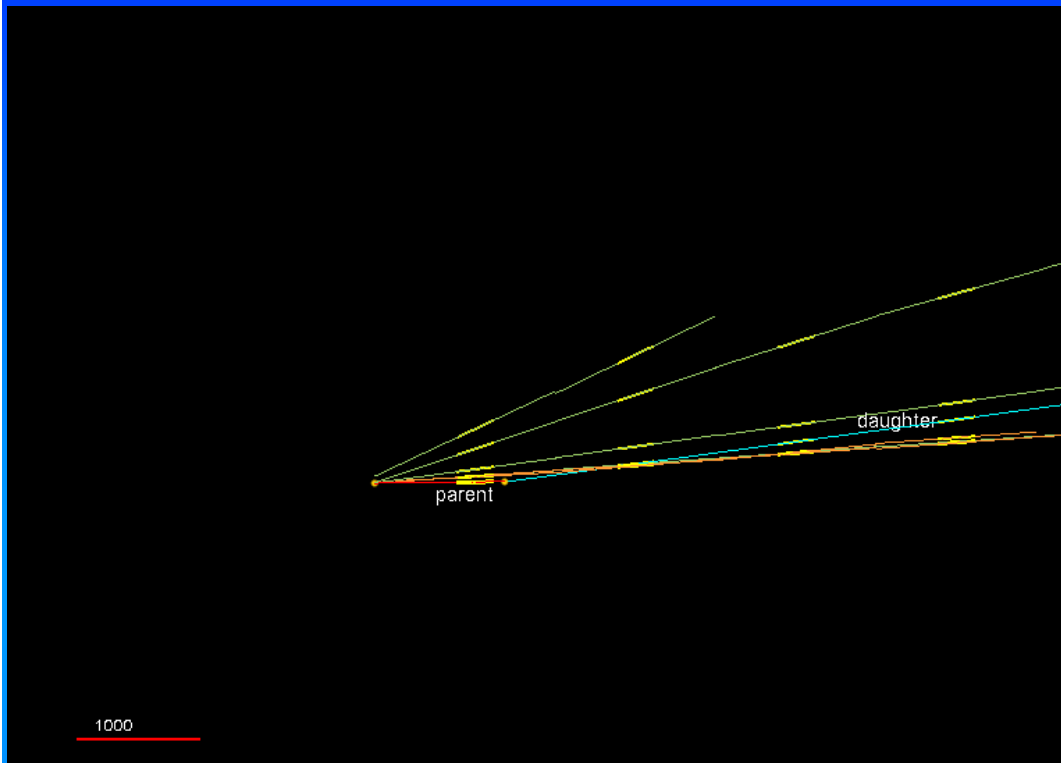
Decay channel: $\tau \rightarrow 3h$

JHEP 11 (2013) 036

Event Kinematics

	Cut	Value	Error
Phi (Tau - Hadron) [degree]	>90	167.8	± 1.1
average kink angle [mrad]	< 500	87.4	± 1.5
Total momentum at 2ry vtx [GeV/c]	> 3.0	8.4	± 1.7
Min Invariant mass [GeV/c ²]	0.5 < < 2.0	0.96	± 0.13
Invariant mass [GeV/c ²]	0.5 < < 2.0	0.80	± 0.12
Transverse Momentum at 1ry vtx [GeV/c]	< 1.0	0.31	± 0.11

The 4th ν_τ candidate

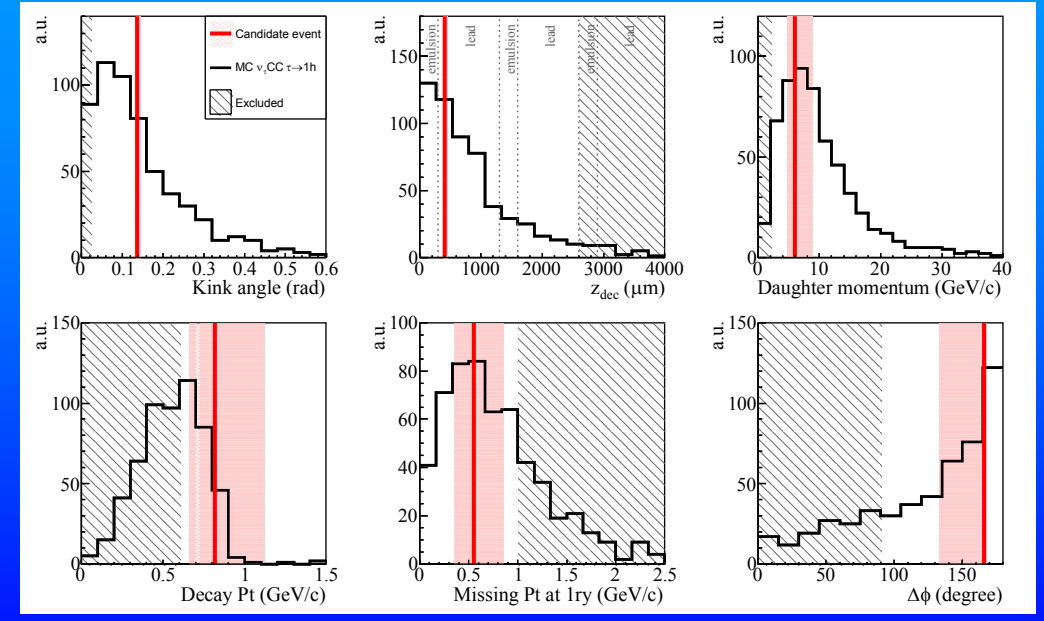


Event Kinematics

Reported in March 2014

Decay channel: $\tau \rightarrow 1h$

Prog. Theor. Exp. Phys. (2014) 101C01



PTEP

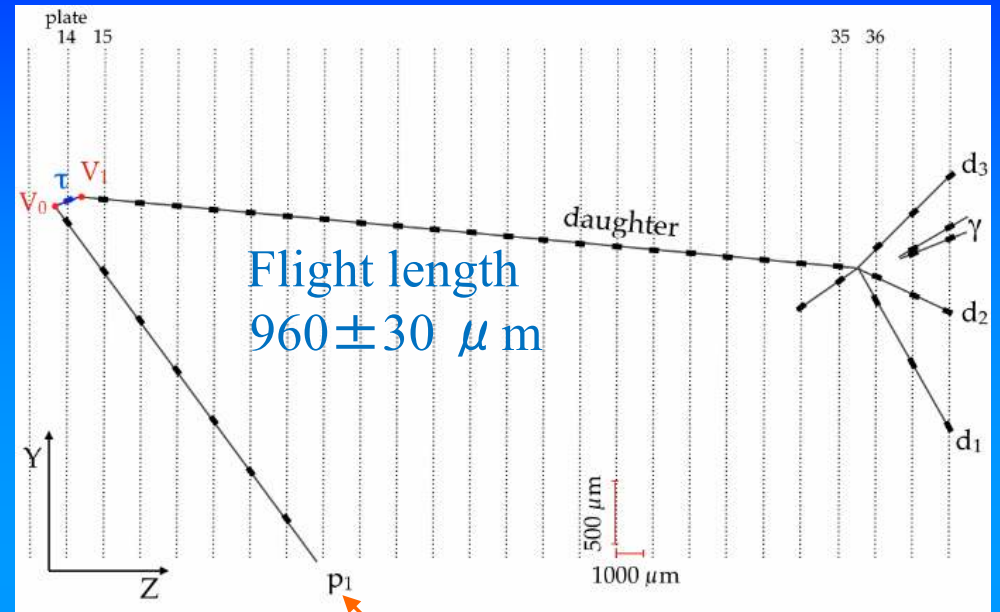
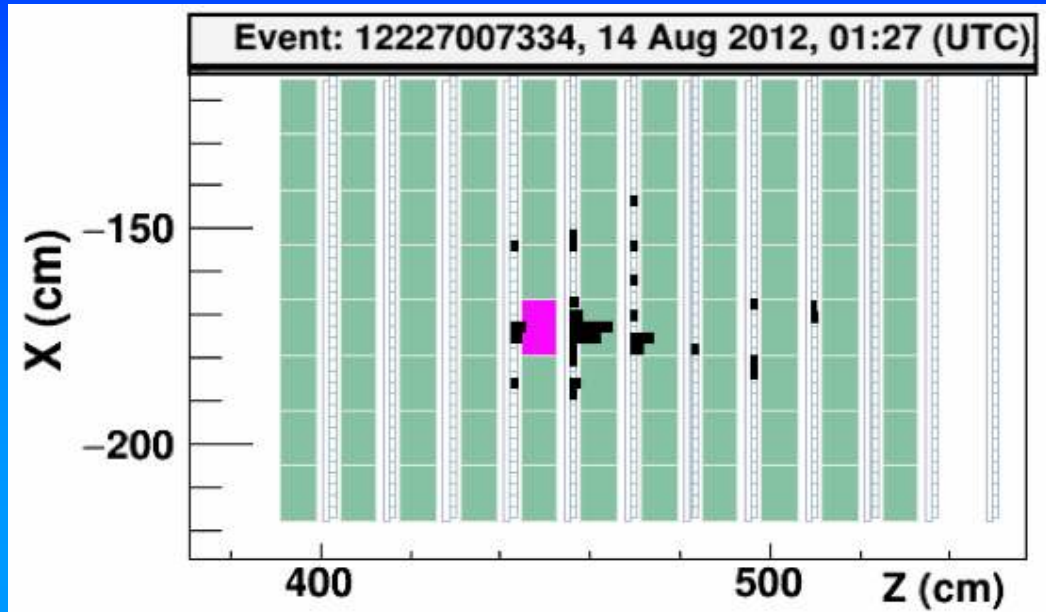
Prog. Theor. Exp. Phys. **2014**, 101C01 (10 pages)
DOI: 10.1093/ptep/ptu132

Letter

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

OPERA Collaboration

The 5th ν_τ event

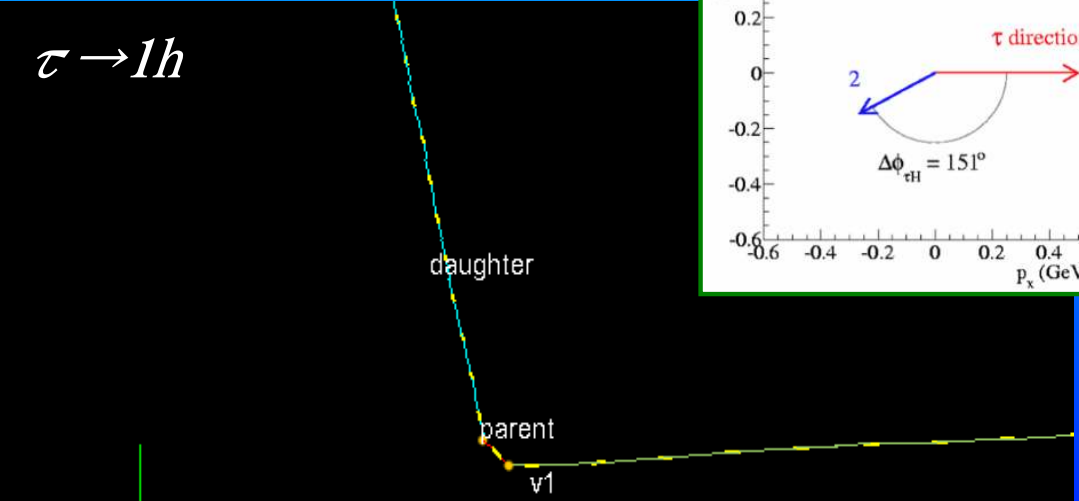
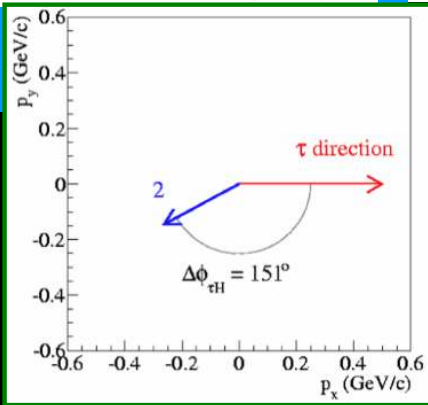


Electronic detectors → No muon

identified as a proton by dE/dx analysis

Kinematical variables

Parameter	Measured value	Selection Criteria
$\Delta\phi_{\tau H}$ ($^\circ$)	151 ± 1	> 90
p_T^{miss} (GeV/c)	0.3 ± 0.1	< 1
θ_{kink} (mrad)	90 ± 2	> 20
z_{dec} (μm)	634 ± 30	[44, 2600]
p_T^{2ry} (GeV/c)	11_{-4}^{+14}	> 2
p_T^{2ry} (GeV/c)	$1.0_{-0.4}^{+1.2}$	> 0.6 (no γ attached)



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

2015

All variables passed the cuts

Background sources

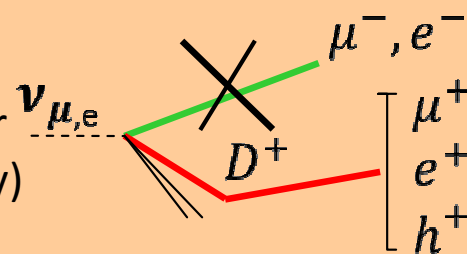
Monte Carlo simulation benchmarked on control samples.

In yellow improvements wrt former analyses

CC with charm production

(all channels)

If primary lepton is not identified and the daughter charge is not (or incorrectly) measured



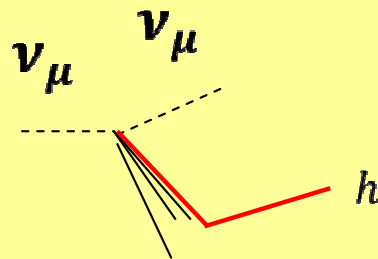
MC tuned on CHORUS data (cross section and fragmentation functions), validated with measured OPERA charm events.

Reduced by "track follow down", procedure and large angle scanning

[Eur.Phys.J. C74 (2014) 2986]

Hadronic interactions

Background for $\tau \rightarrow h$



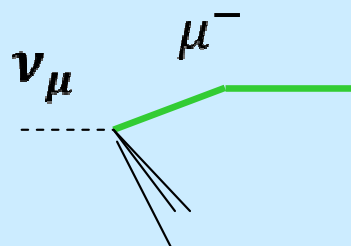
FLUKA + pion test beam data

Reduced by large angle scanning and nuclear fragment search

[PTEP 2014, 093C01 (2014)]

Large angle muon scattering

Background for $\tau \rightarrow \mu$



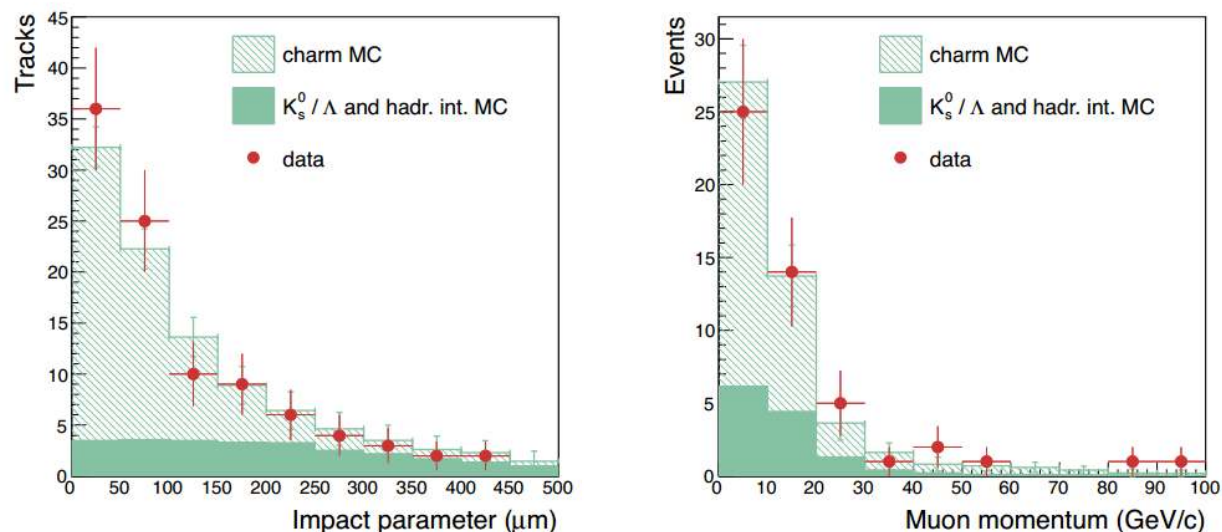
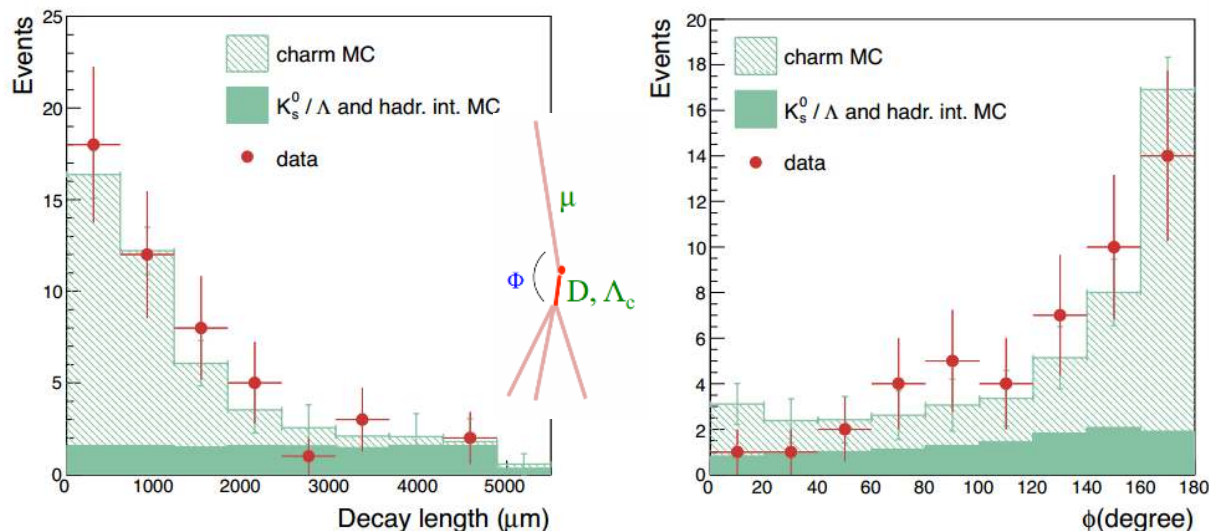
Measurements in the literature (Lead form factor), simulations and dedicated test-beams

[IEEE Transactions on Nuclear Science, vol.62 5]

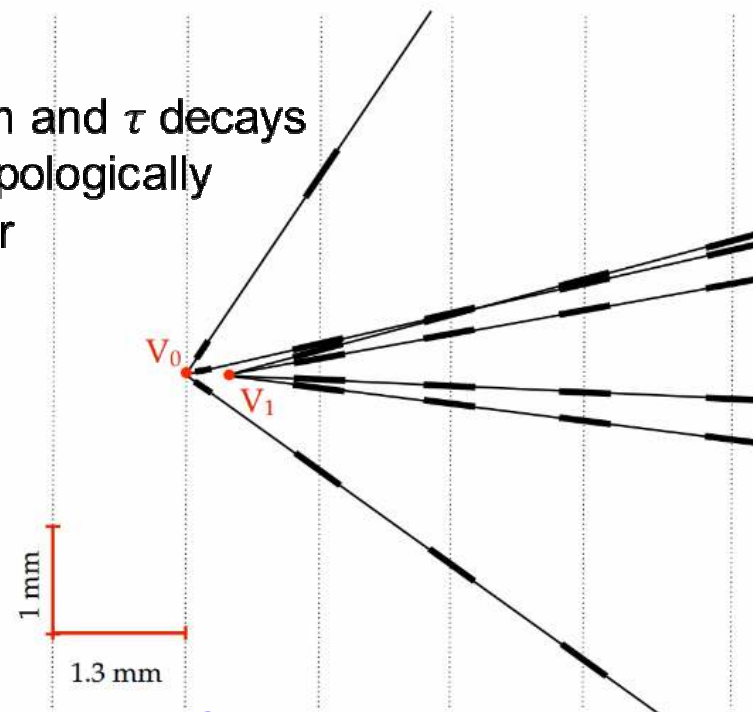
Validation with the CNGS charm events sample

Test for: reconstruction efficiencies, description of kinematical variables, charm background.

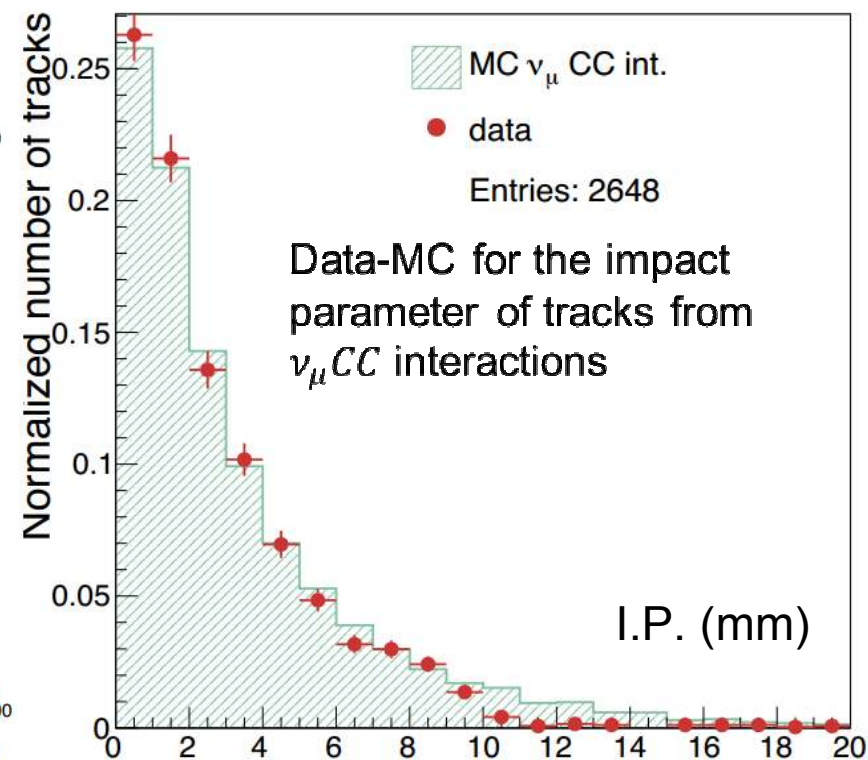
54 ± 4 expected \leftrightarrow 50 observed



Charm and τ decays are topologically Similar



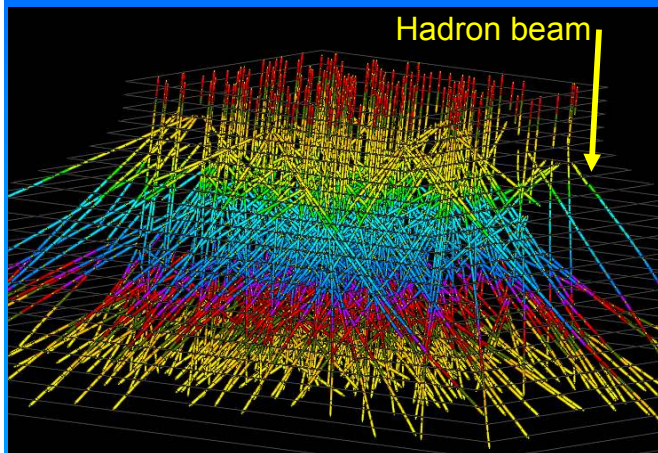
Eur.Phys.J. C74 (2014) 8, 2986



Validation of the hadronic background by test beams

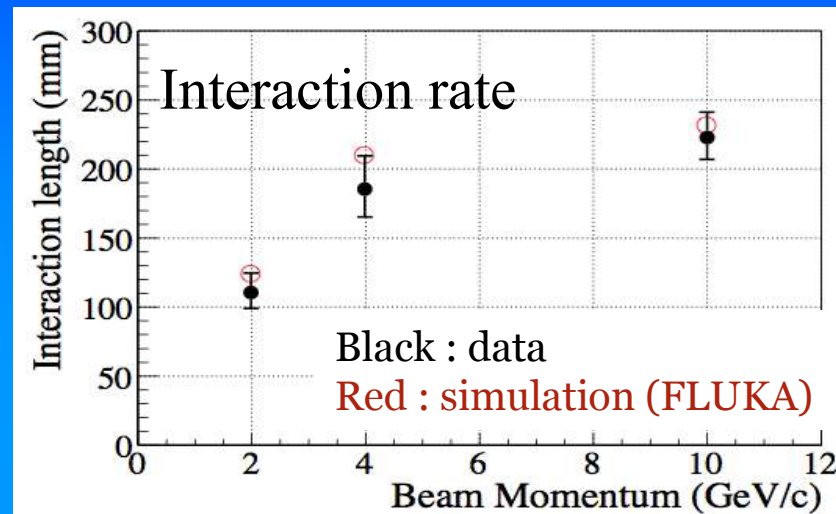
Comparison of large data sample (π^- beam test at CERN) with Fluka simulation

→ check the agreement and estimate the systematic uncertainty



Track length analysed in the brick:

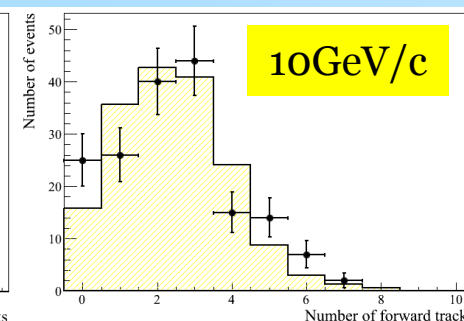
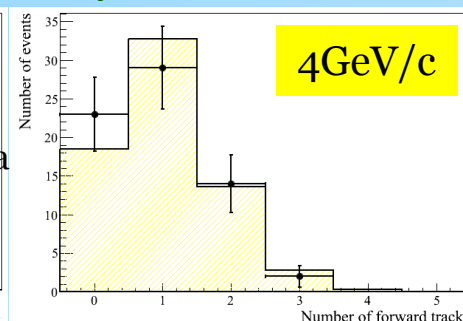
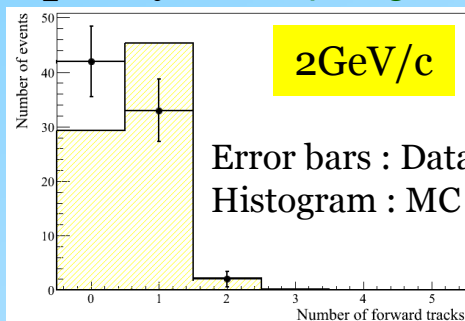
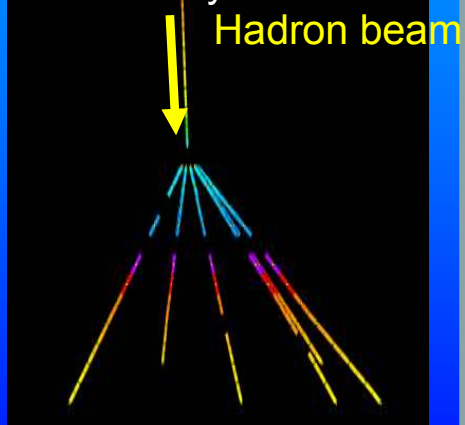
- 2 GeV/c : 8.5 m
- 4 GeV/c : 12.6 m
- 10 GeV/c : 38.5 m



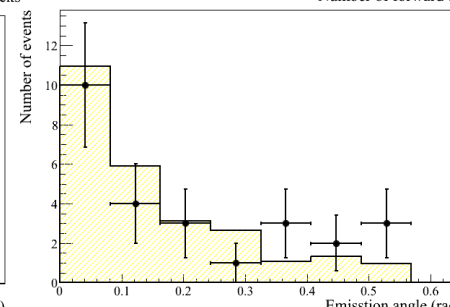
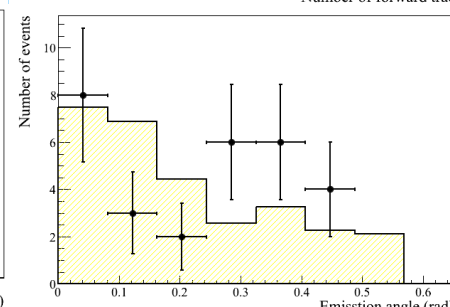
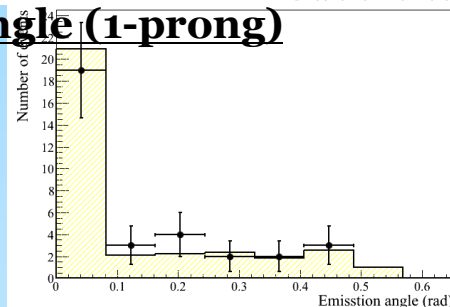
Multiplicity

Topological analysis of hadron interactions in an ECC brick

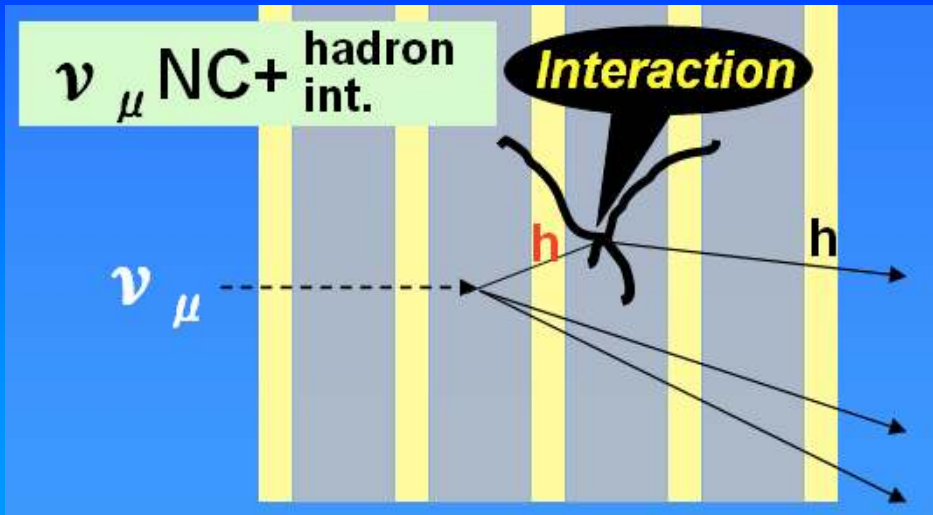
Analysis on an event-by-event basis



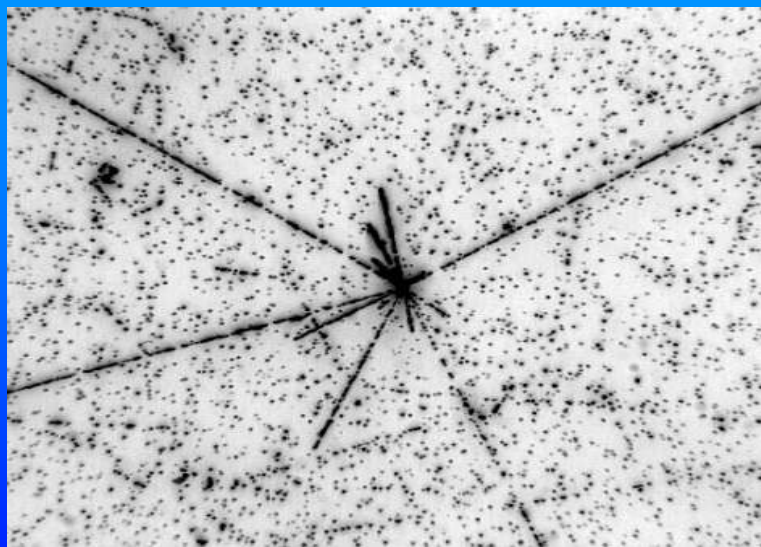
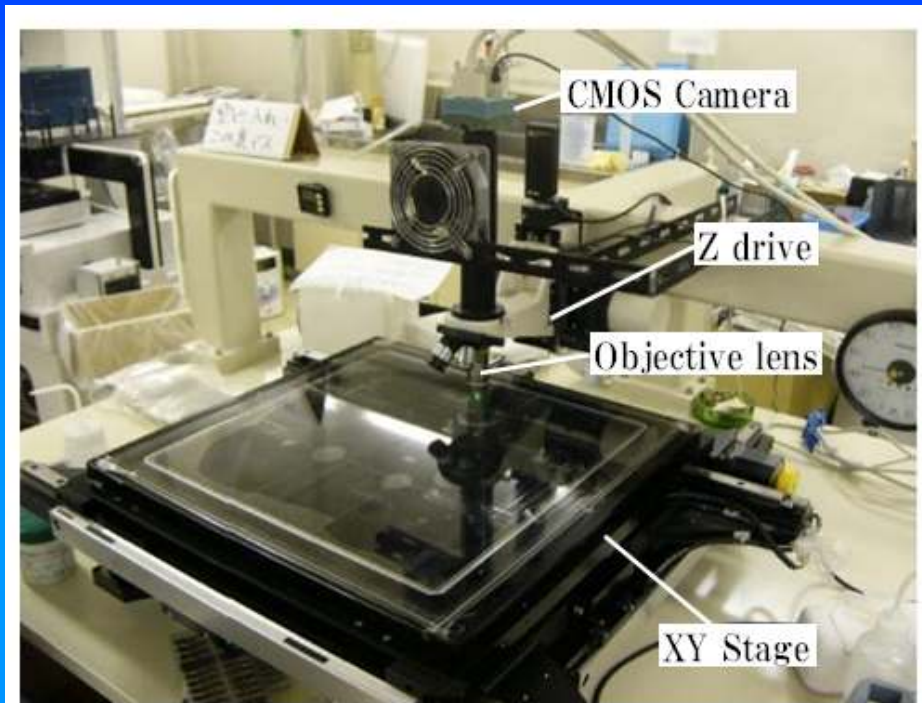
Kink angle (1-prong)



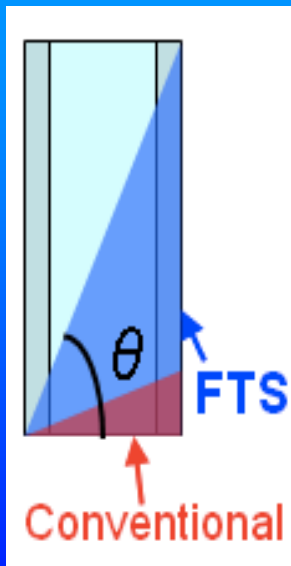
Hadronic background reduction



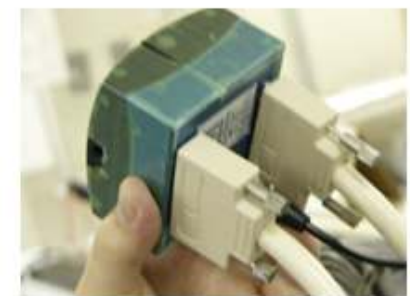
Nuclear fragments:
 a smoking gun for the occurrence of
 an π interaction instead of a decay.



150 μ m

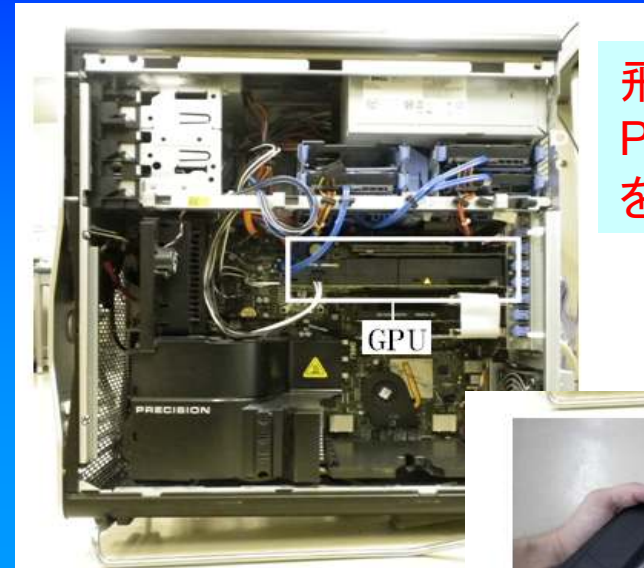
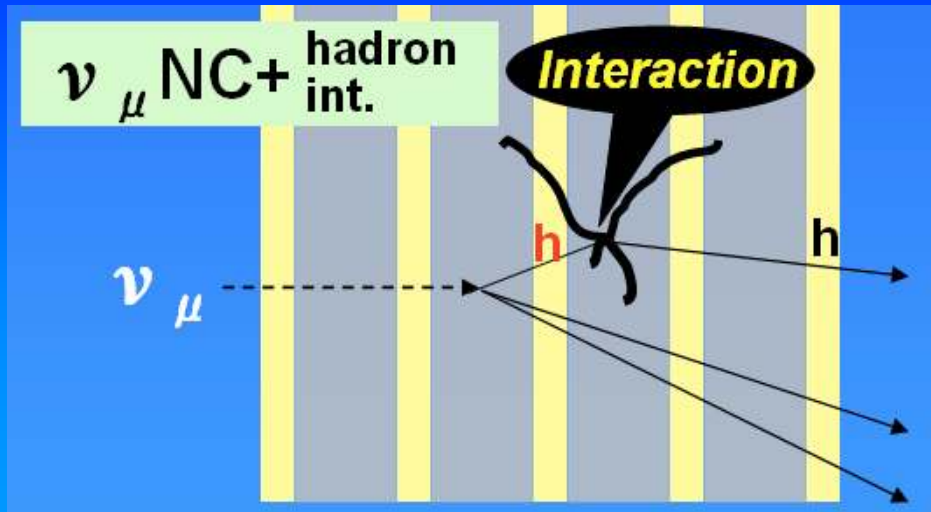


Objective lens
 Nikon CFI Plan x50
 oil immersion lens



CMOS Camera
 Mikrotron
 Eosens MC 1362

Hadronic background reduction



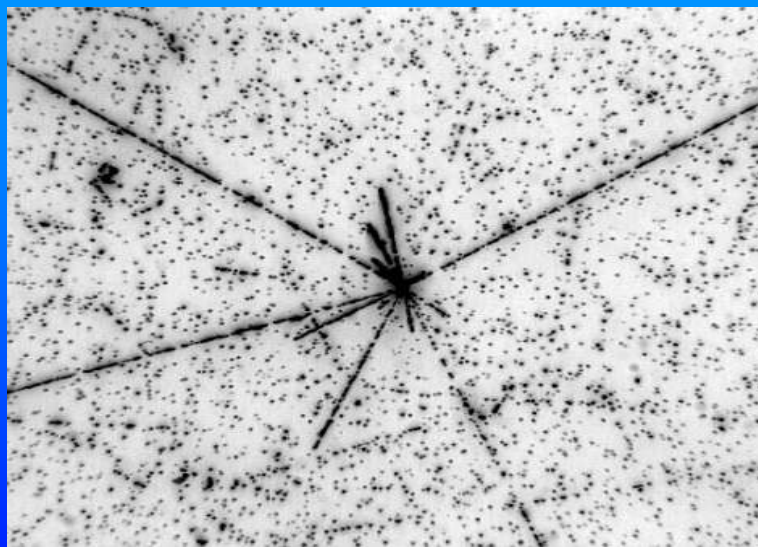
飛跡認識部にGraphics Processing Unit (GPU)を導入。

Nuclear fragments:

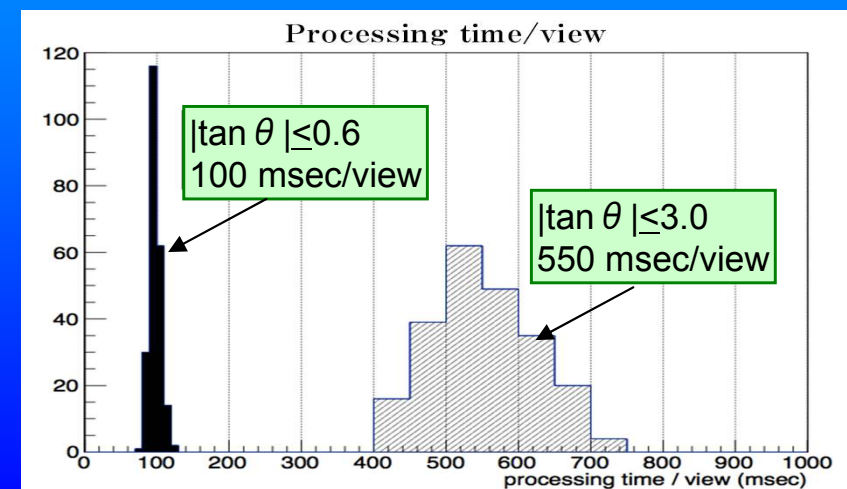
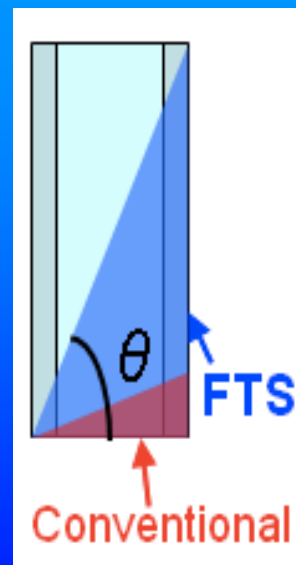
a smoking gun for the occurrence of an π interaction instead of a decay.



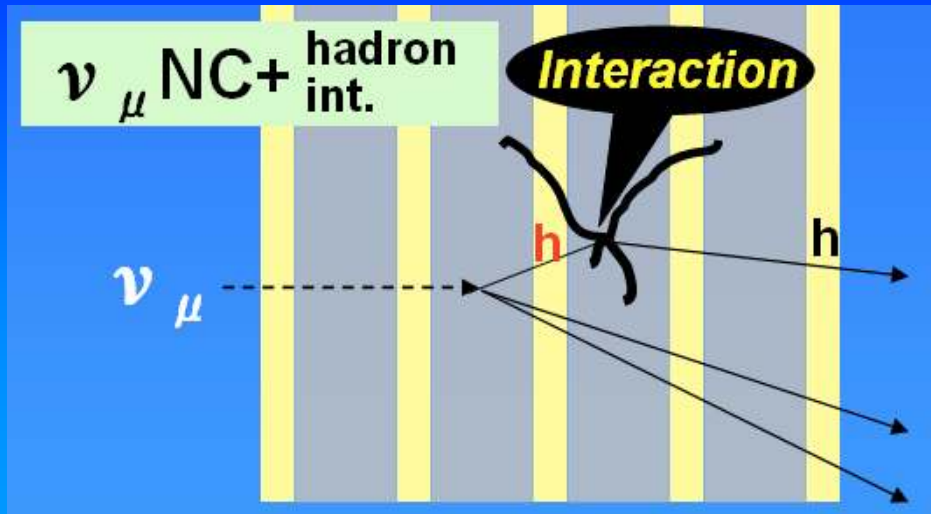
Graphics Processing Unit (GPU)
NVIDIA Tesla C2050



150 μ m

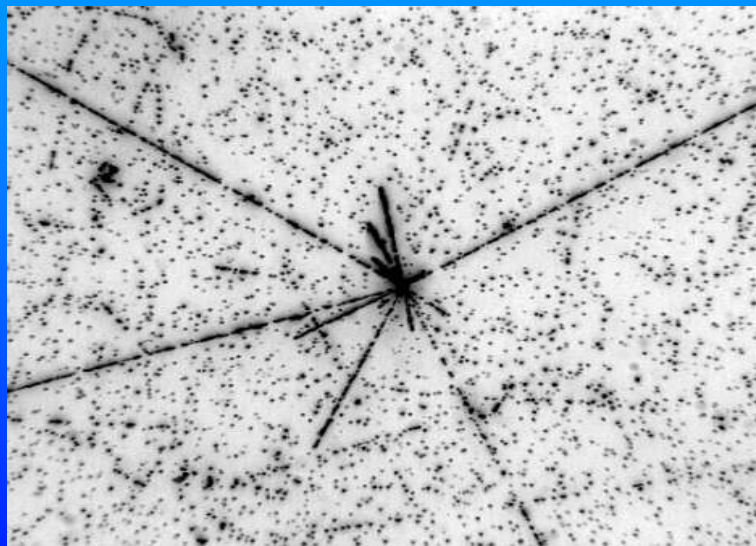


Hadronic background reduction



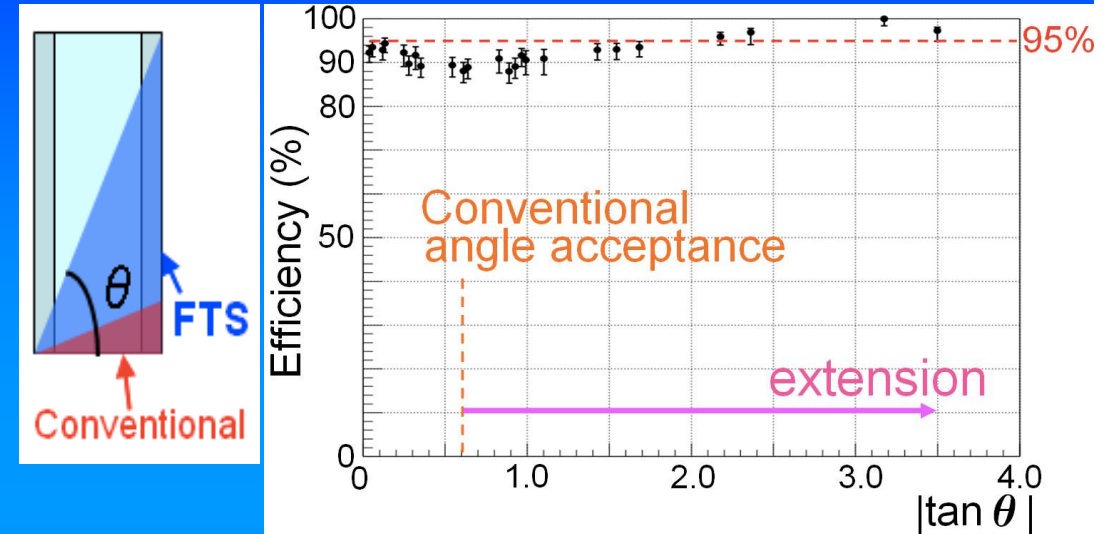
Nuclear fragments:

a smoking gun for the occurrence of an π interaction instead of a decay.



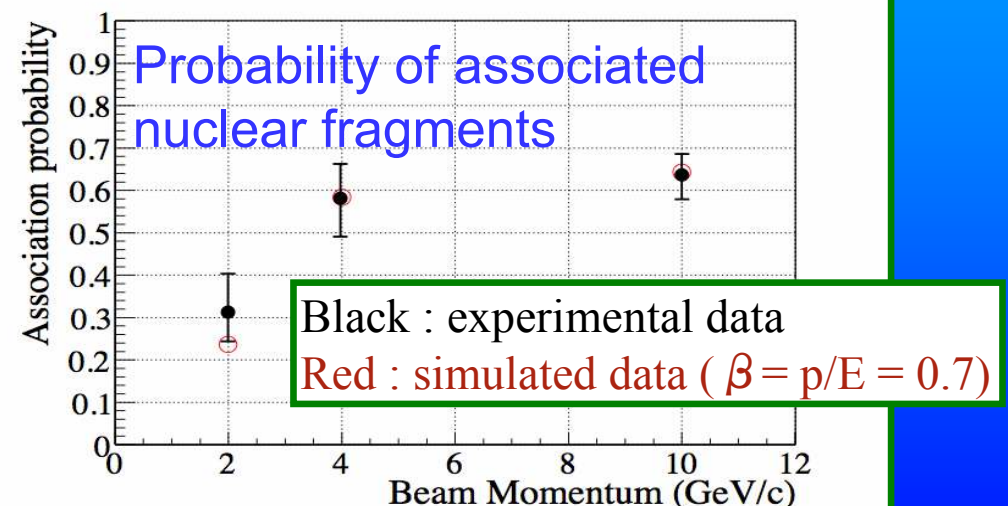
150 μ m

Large angle scanning technique



JINST 8:P01023, (2013), JINST 9:P12017, (2014)

Additional background reduction



PTEP 2014, 093C01 (2014)

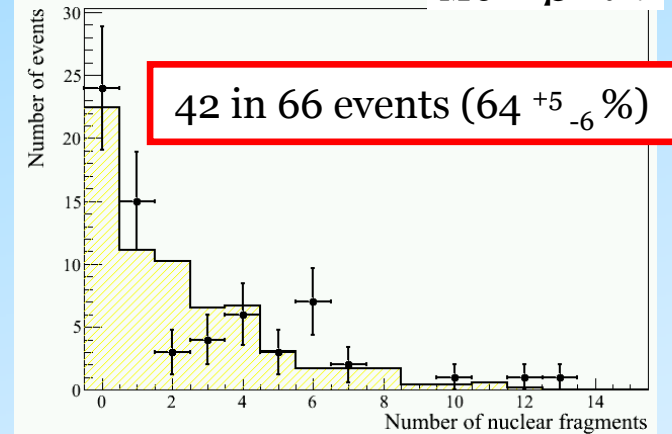
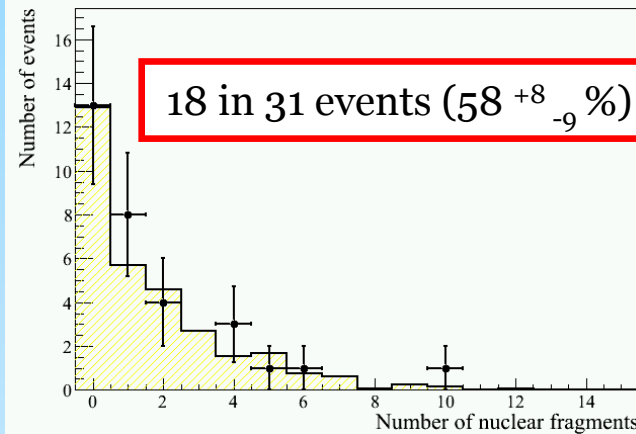
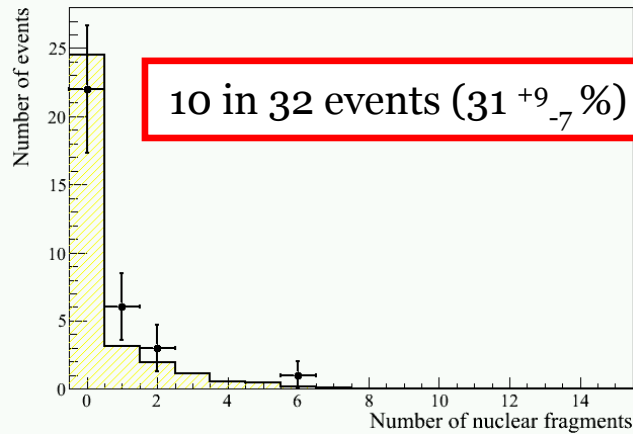
Nuclear fragments in 1 and 3 prong interactions

2GeV/c

4GeV/c

10GeV/c

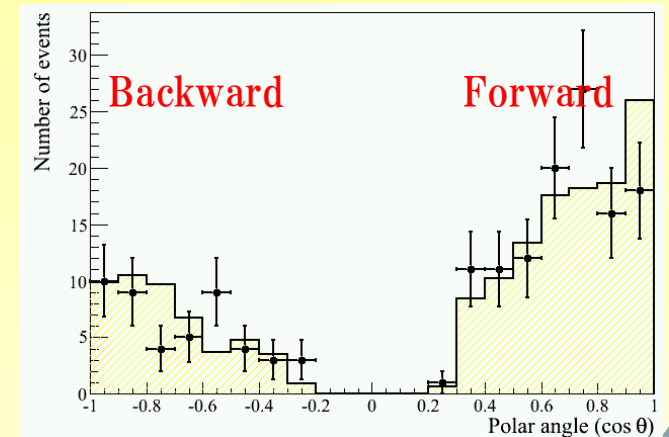
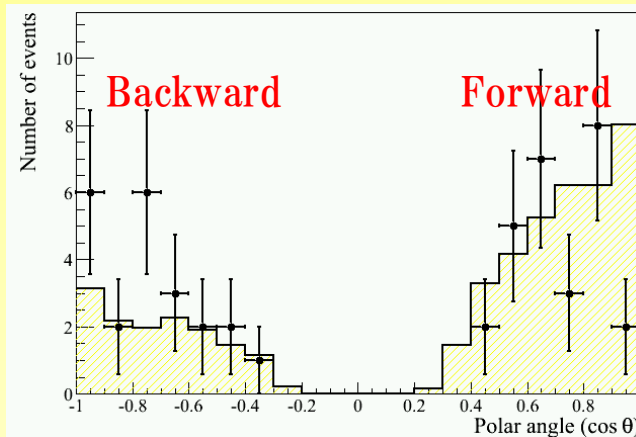
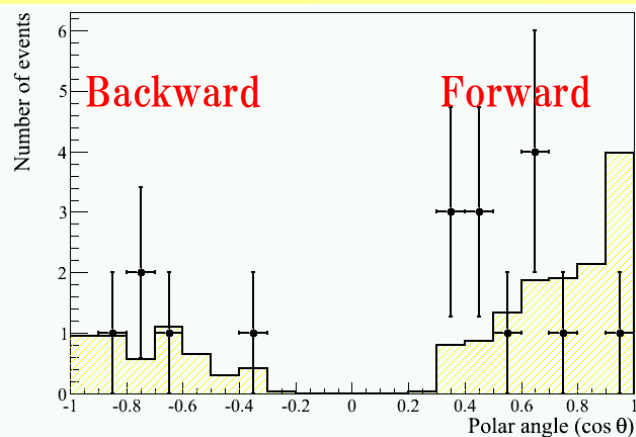
Multiplicity



Error bars : Experimental data
Histogram : Simulated data

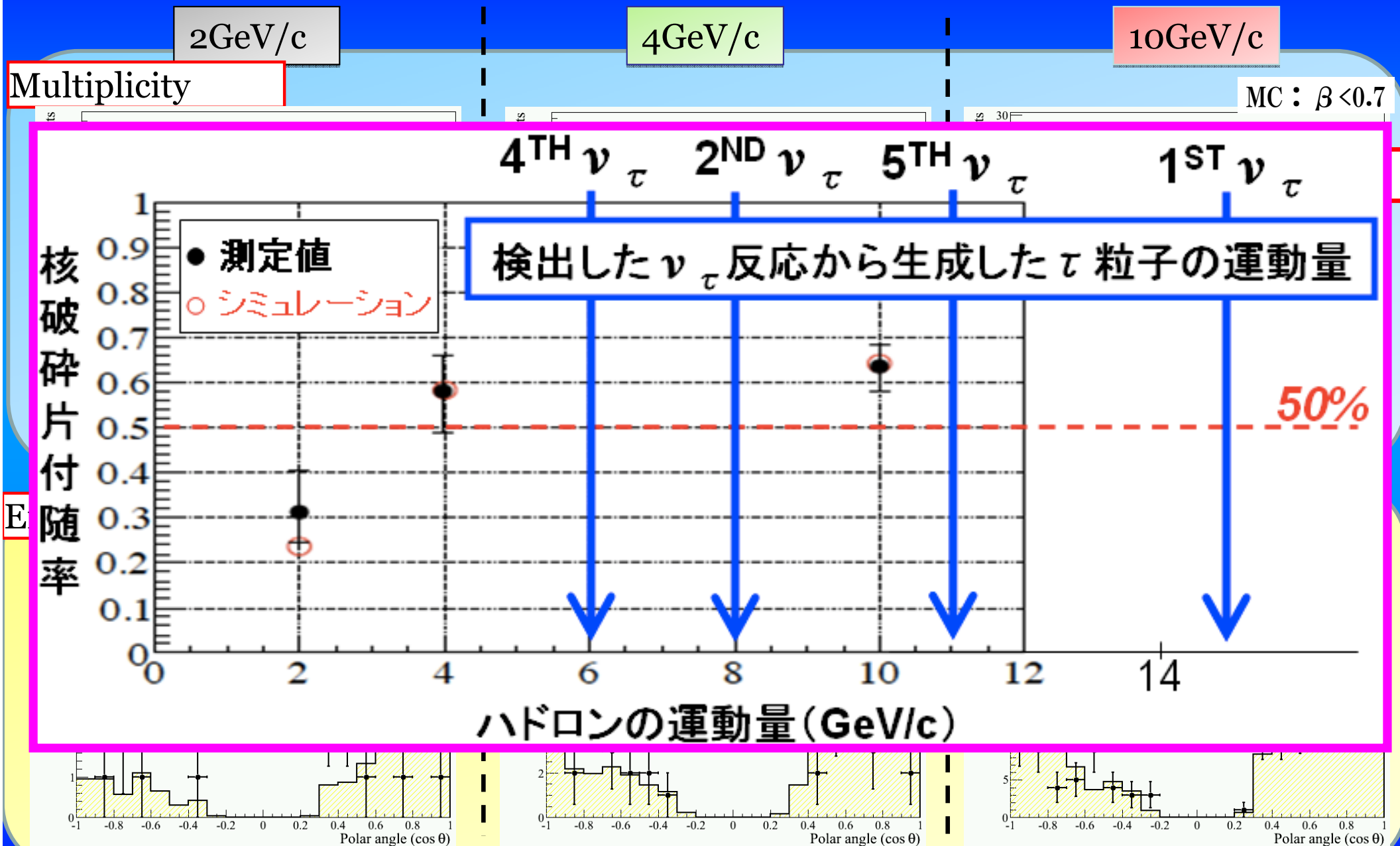
2, 4 GeV/c : $IP < 100 + 0.01dz$
10 GeV/c : $IP < 50 + 0.01dz$

Emission angle ($\cos \theta$)



Agreement with statistical error : Systematic error is 10%.

Nuclear fragments in 1 and 3 prong interactions



Agreement with statistical error : Systematic error is 10%.

ν_τ analysis result

Expected signal and background events for the analyzed data sample

Channel	Expected background				Expected signal	Observed
	Charm	Had. re-interac.	Large μ -scat.	Total		
$\tau \rightarrow 1h$	0.017 ± 0.003	0.022 ± 0.006	—	0.04 ± 0.01	0.52 ± 0.10	3
$\tau \rightarrow 3h$	0.17 ± 0.03	0.003 ± 0.001	—	0.17 ± 0.03	0.73 ± 0.14	1
$\tau \rightarrow \mu$	0.004 ± 0.001	—	0.0002 ± 0.0001	0.004 ± 0.001	0.61 ± 0.12	1
$\tau \rightarrow e$	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 observed events with **0.25 background**

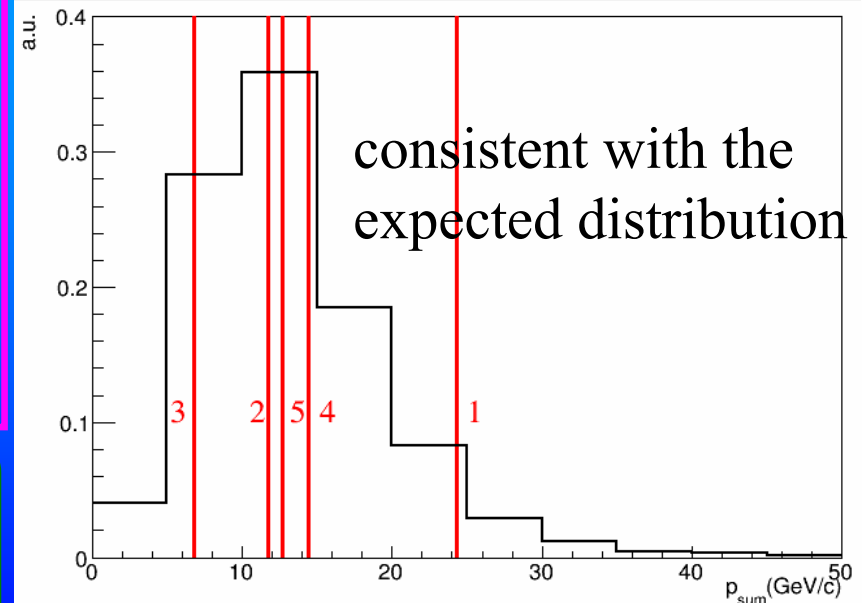
Probability to be explained by background:

1.1×10^{-7} (Fisher, Profile likelihood)

Corresponding to **5.1σ** exclusion
of the background-only hypothesis

Discovery of ν_τ appearance

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



→ Estimation of Δm_{23}^2 (90% C.L.)

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

Δm^2 の精度向上に向けて

- 選別条件を緩めたセレクションを加えることで ν_τ の統計数を増やす。

Golden Selection

variable	$\tau \rightarrow 1h$	$\tau \rightarrow 3h$	$\tau \rightarrow \mu$	$\tau \rightarrow e$
lepton-tag		No μ or e at the primary vertex		
z_{dec} (μm)	[44, 2600]	< 2600	[44, 2600]	< 2600
p_T^{miss} (GeV/c)	< 1*	< 1*	/	/
ϕ_{lH} (rad)	> $\pi/2^*$	> $\pi/2^*$	/	/
p_T^{2ry} (GeV/c)	> 0.6(0.3)*	/	> 0.25	> 0.1
p^{2ry} (GeV/c)	> 2	> 3	> 1 and < 15	> 1 and < 15
θ_{kink} (mrad)	> 20	< 500	> 20	> 20
m, m_{min} (GeV/c ²)	/	> 0.5 and < 2	/	/

Silver Selection

Variable	$\tau \rightarrow 1h$	$\tau \rightarrow 3h$	$\tau \rightarrow \mu$	$\tau \rightarrow e$
z_{dec} (μm)	<2600	<2600	<2600	<2600
p_{2ry}^T (GeV/c)	>0.15	/	>0.1	>0.1
p_{2ry} (GeV/c)	>1	>1	>1	>1
θ_{kink} (rad)	>0.02	>0.02	>0.02	>0.02

(Golden+Silver) のsingle, background

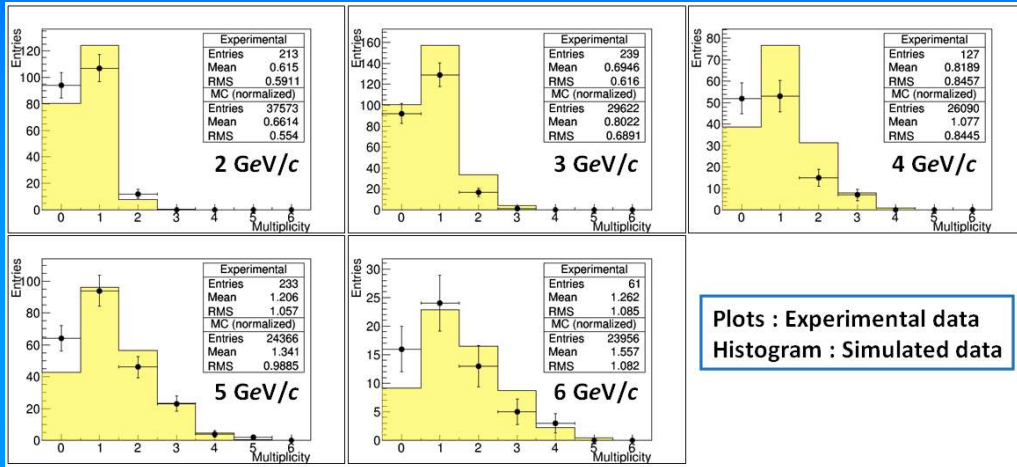
	charm	had reint	las	tot	Expected signal	Observed	
$\tau \rightarrow 1h$	0.0227	0.0238	0.0000	0.0466	0.5734	3	
$\tau \rightarrow \mu$	0.0029	0.0000	0.00021	0.0031	0.5474	1	
$\tau \rightarrow 3h$	0.2049	0.0032	0.0000	0.2081	1.0895	1	
$\tau \rightarrow e$	0.0349	0.0000	0.0000	0.0349	0.7542	0	
新しく増やした選別	$\tau \rightarrow 1h$	0.1321	1.2554	0.0000	1.3875	2.2479	3
	$\tau \rightarrow \mu$	0.0048	0.0000	0.0171	0.0219	0.5436	0
	$\tau \rightarrow 3h$	0.2314	0.0833	0.0000	0.3147	0.6569	2
	$\tau \rightarrow e$	0.0000	0.0000	0.0000	0.0000	0.0423	0
Totale	0.6337	1.3657	0.0173	2.0167	6.4552	10	

BKG: 0.25→2.0, 主にハドロン2次反応が増大。

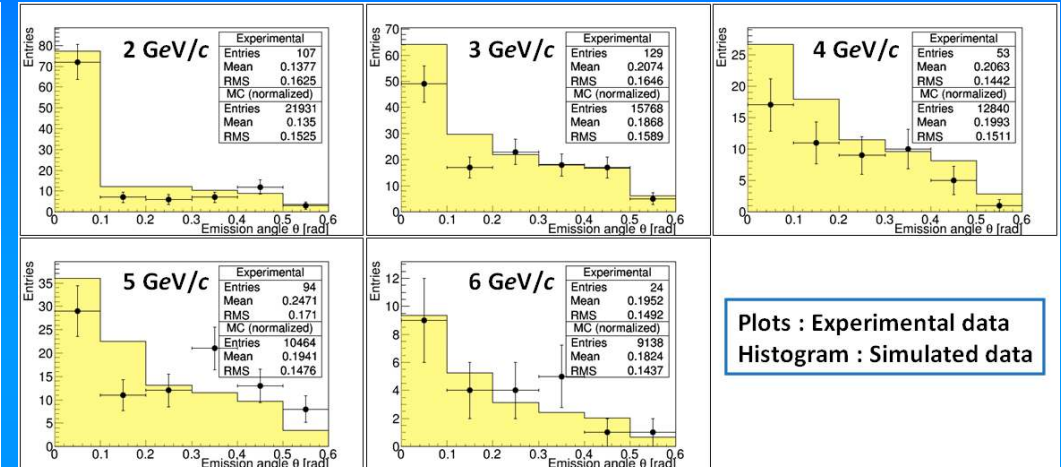
ハドロン反応の精密測定

- 2,3,4,5,6 GeV/c の π -beam を ECC に照射

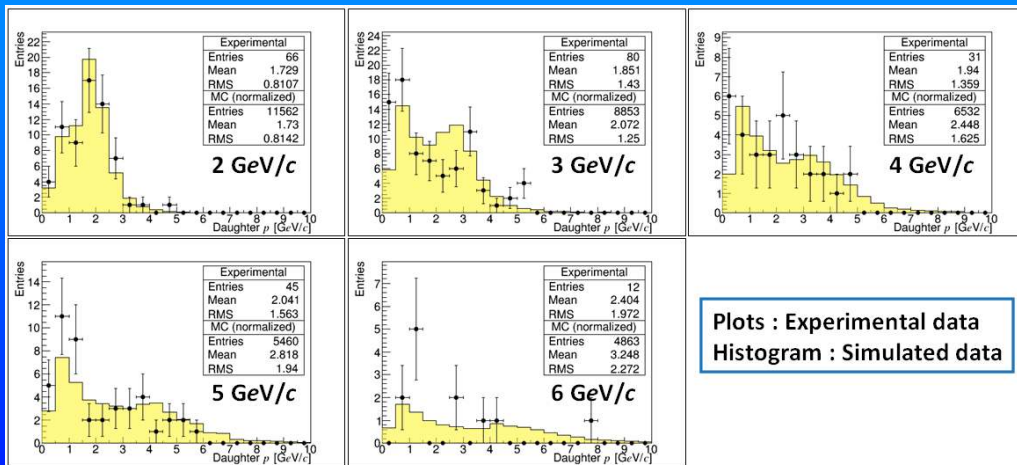
Multiplicity



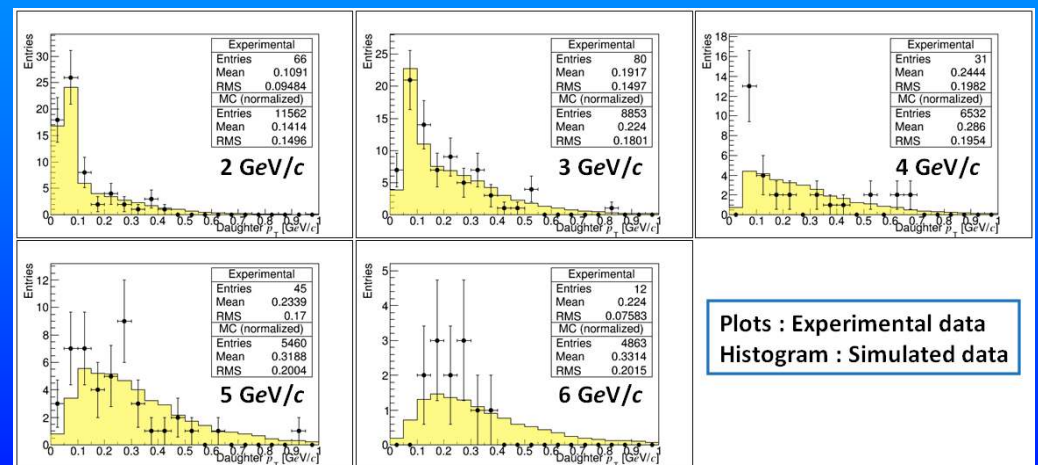
Kink angle (折れ曲がり角度)



Momentum

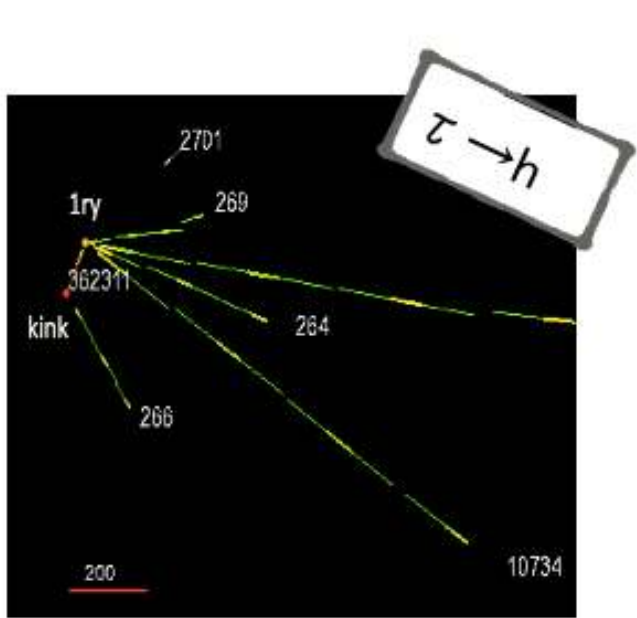


Pt

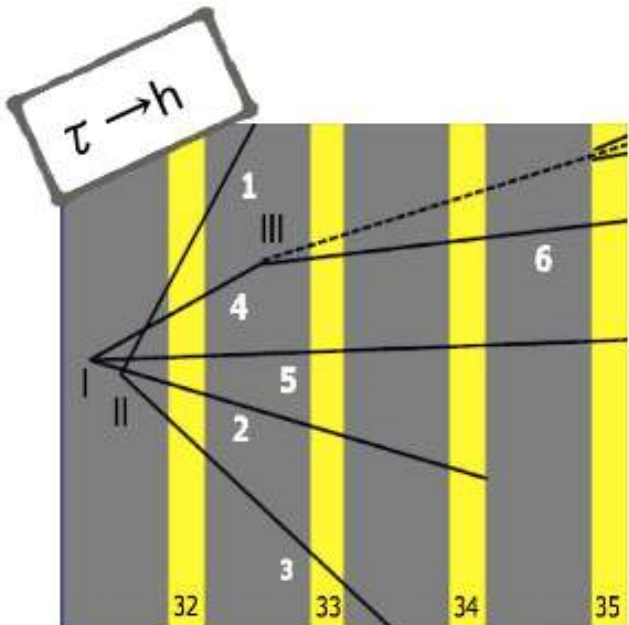


→ シミュレーションとの一致度(シルバーセレクション): 20%

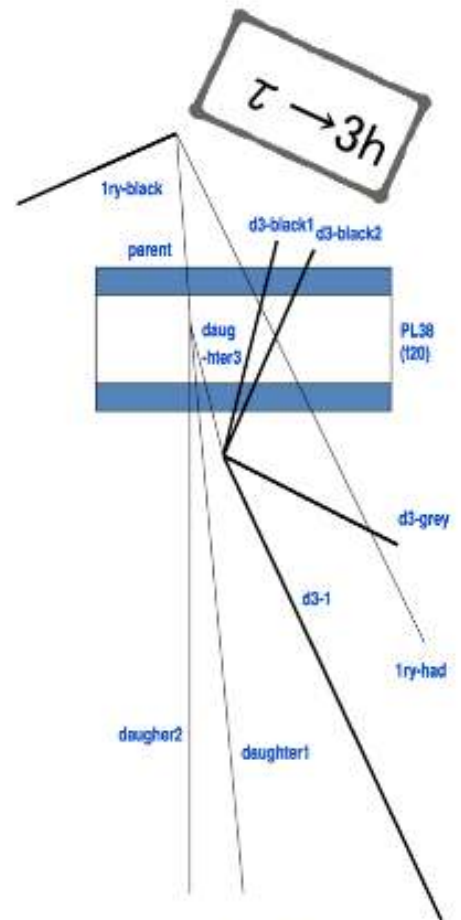
Silver selection で検出された候補



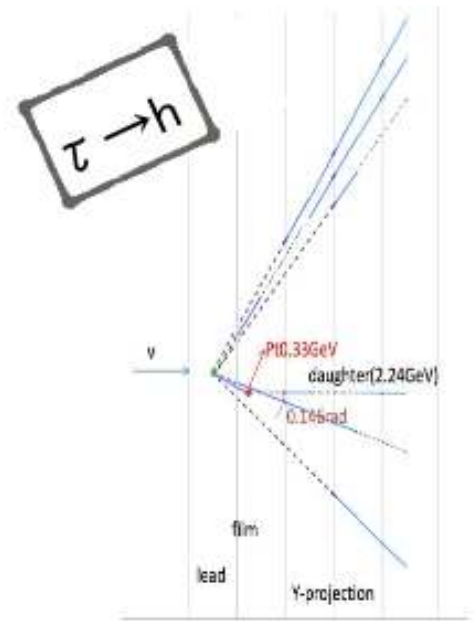
Event 11172035775



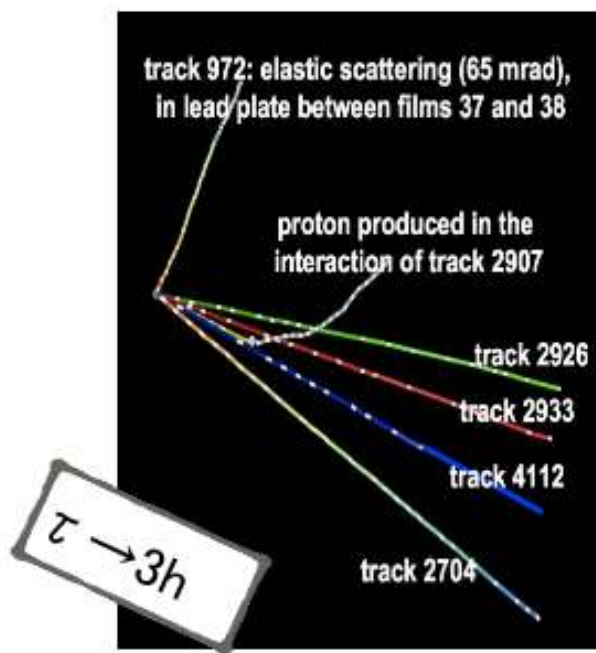
Event 11143018505



Event 11213015702



Event 9190097972



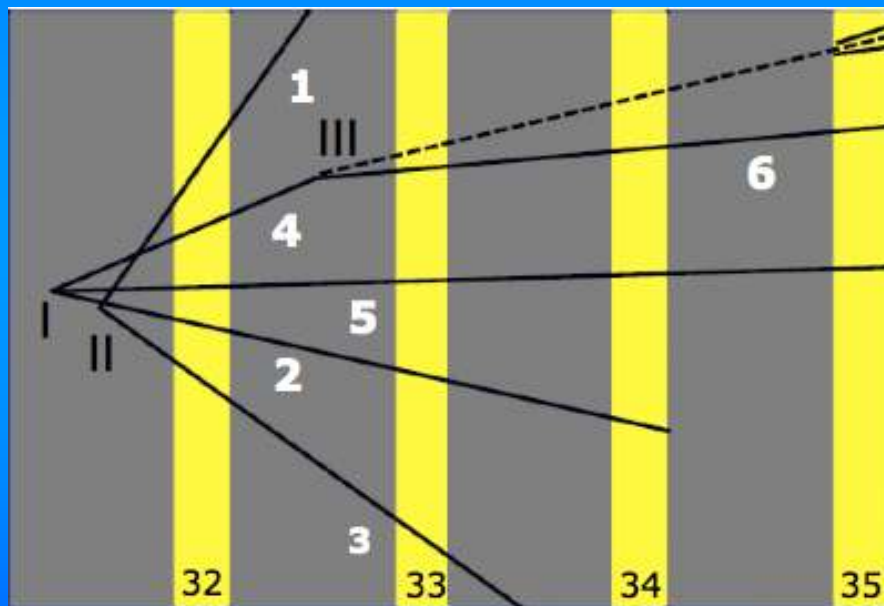
Event 10123059807

Charm 粒子付きタウニュートリノ反応

2個の崩壊バーテックス:

II) 鉛中崩壊 2プロング (F.L. = 103 μm)

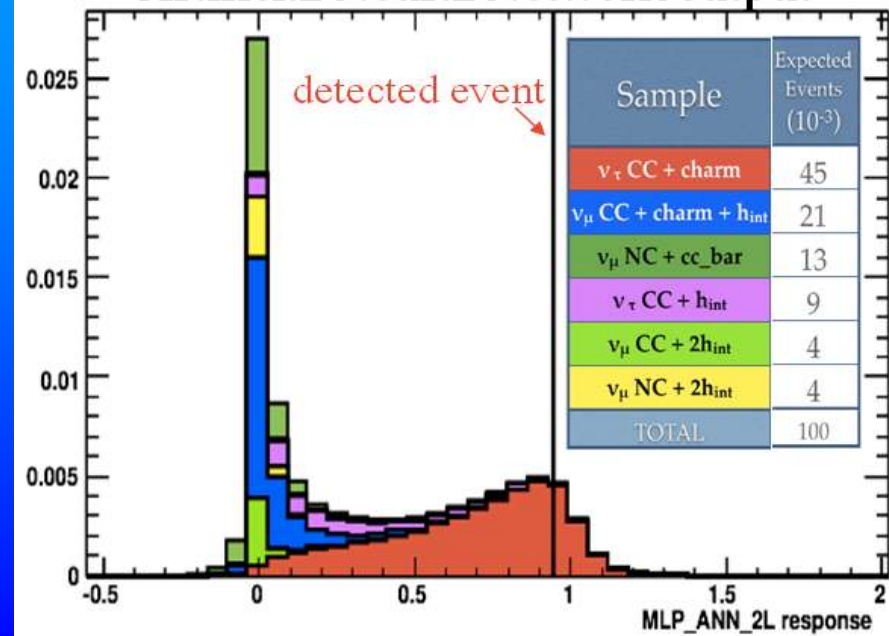
III) 1プロング崩壊(kink) (F.L.= 1174 μm , $\theta_k = 97\text{mrad}$)



Track	θ_x (rad)	θ_y (rad)	One Vertex IP (μm)		
			w.r.t. V_0	Two vertices IP (μm)	
			w.r.t. V_1	w.r.t. V_2	
1	-0.230	-0.275	8.3	36.2	0.1
2	0.121	-0.144	8.8	1.0	6.5
3	0.349	-0.036	4.8	25.9	0.1
4	-0.003	0.088	13.0	1.5	20.4
5	-0.003	-0.025	5.1	2.2	9.6

Vertex ID	Attached track
I (primary)	2, 4, 5
II (secondary)	1, 3
III (kink)	4, 6

Artificial Neural Network output



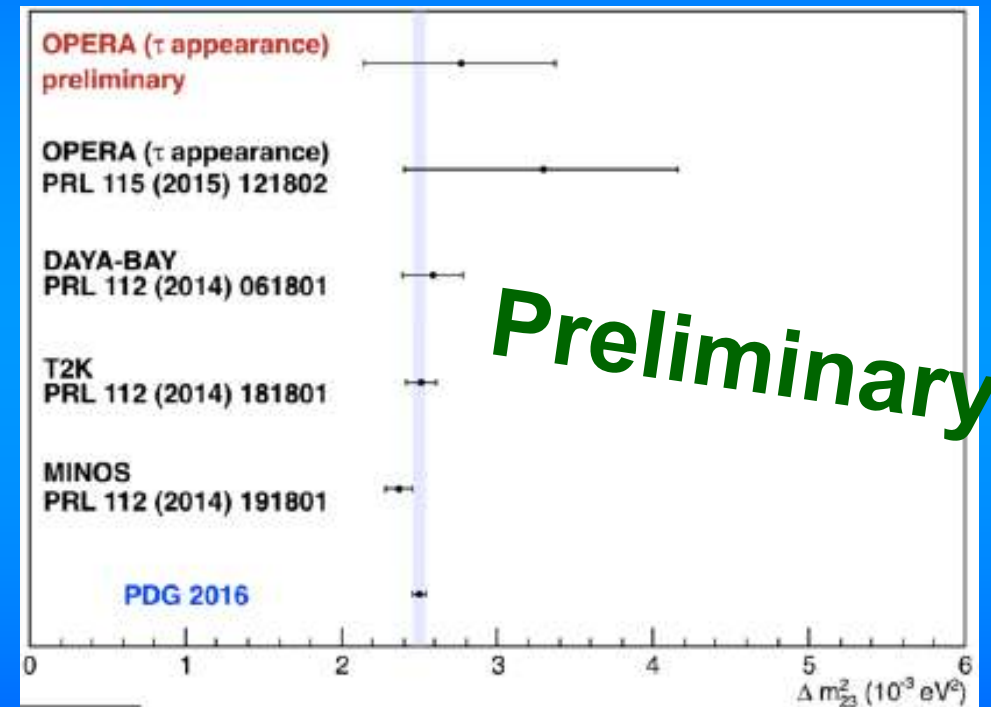
Δm^2 の測定

- 測定値: $10 - 2.0 = 8.0$ の ν_τ
- $N_\tau = N_\mu \times P(\Delta m^2, \sin^2(2\theta)) \times \sigma_\tau \times \varepsilon$, (最大混合を仮定)

Δm^2_{23} を算出(ν_τ 反応断面積はSM)

$\sigma_{\nu_\tau} = \sigma_{\nu_\tau}^{const} EK(E)$			$\sigma_{\nu_\tau}^{const} = 0.67 \cdot 10^{-38} \text{cm}^2 \text{GeV}^{-1}$
Expected Signal	Expected Background	Observed ν_τ	Δm^2_{23} (10^{-3}eV^2)
6.5	2.0	10	$2.8^{+0.6}_{-0.6}$ 68% C.L.

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



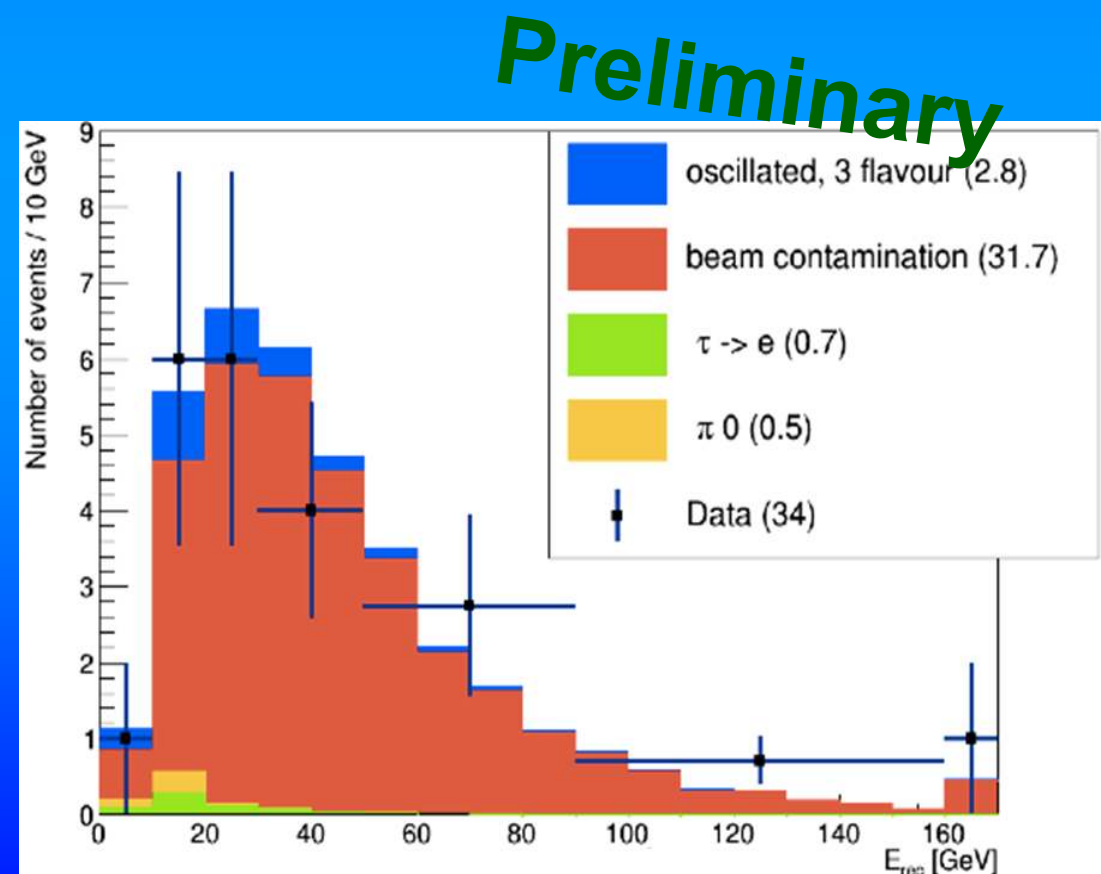
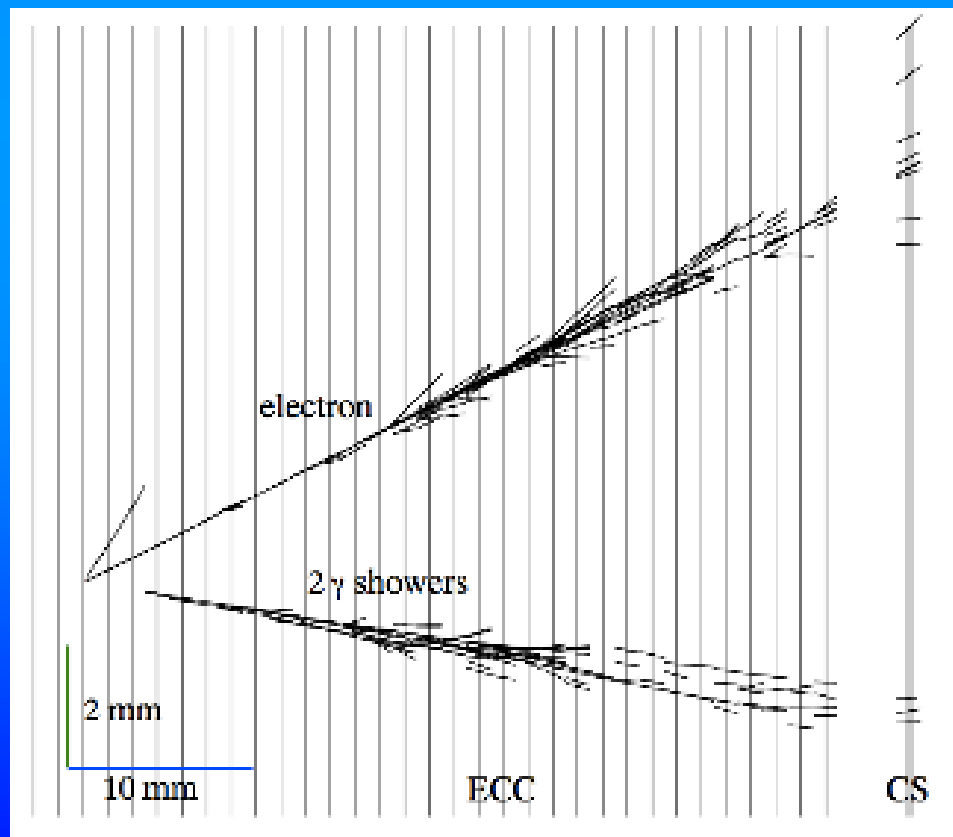
ν_τ 反応断面積を算出(Δm^2_{23} はPDG)

Δm^2_{23} (10^{-3}eV^2)	Expected Signal	Expected Background	Observed ν_τ	$\sigma_{\nu_\tau}^{const}$ ($10^{-38} \text{cm}^2 \text{GeV}^{-1}$)
2.5	6.5	2.0	10	$0.8^{+0.4}_{-0.3}$ 68% C.L.

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

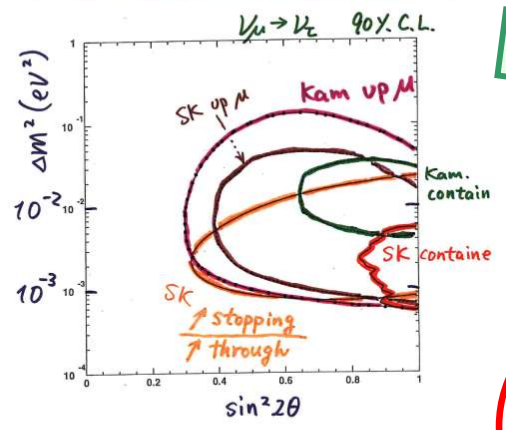
電子ニュートリノへの振動の探索

- μ 付きでない全データ1185反応を解析
- $34 \nu_e$ CC反応を検出 \rightarrow ビーム中の初期混入とコンシステント



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

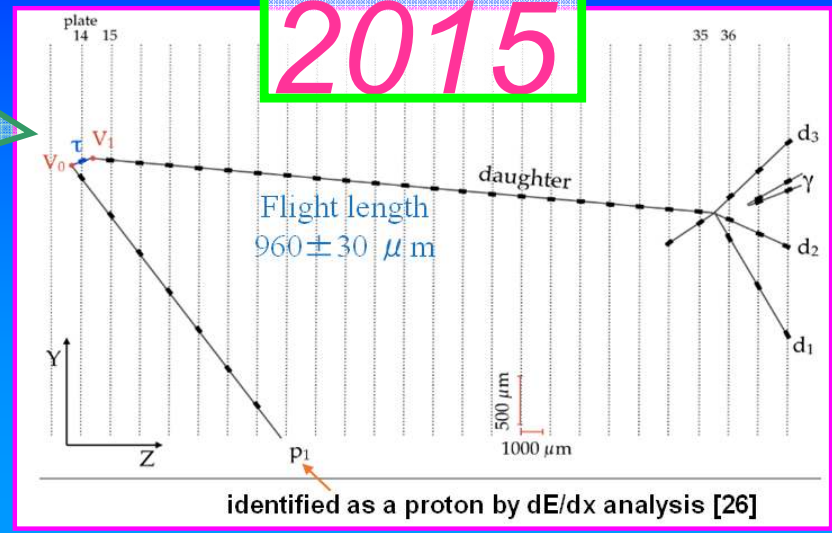
So far both $\nu_\mu \leftrightarrow \nu_\tau$ & $\nu_\mu \leftrightarrow \nu_s$ solutions provide a good fit to atmospheric neutrino anomaly

for $\begin{cases} 10^{-3} eV^2 \lesssim |\Delta m^2| \lesssim 10^{-2} eV^2 \\ \sin^2 2\theta \sim 1 \end{cases}$

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

done

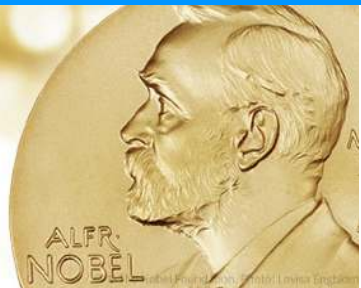
2015



"For the greatest benefit to mankind"
Alfred Nobel

2015 NOBEL PRIZE IN PHYSICS

Takaaki Kajita
Arthur B. McDonald



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].

Conclusions

- 1.8×10^{20} pot by CNGS from 2008 to 2012 (80% of design).
- Analysis technique largely improved and detector successfully measuring ν_e , ν_μ and ν_τ .
- Analysis of extended data sample. Improved background evaluation.
- 5 ν_τ candidate events found with 0.25 background.
- Background-only hypothesis excluded at 5.1σ .
 - **Discovery of ν_τ appearance in the CNGS beam**
- Measurement of $\Delta m_{23}^2 = [2.0-5.0] \times 10^{-3} \text{ eV}^2$.
- Additionally, 3 ν_τ events were found with new selection.
- Measurement of $\Delta m_{23}^2 = 2.8 \pm 0.6 \times 10^{-3} \text{ eV}^2$.

New Emulsion Experiment

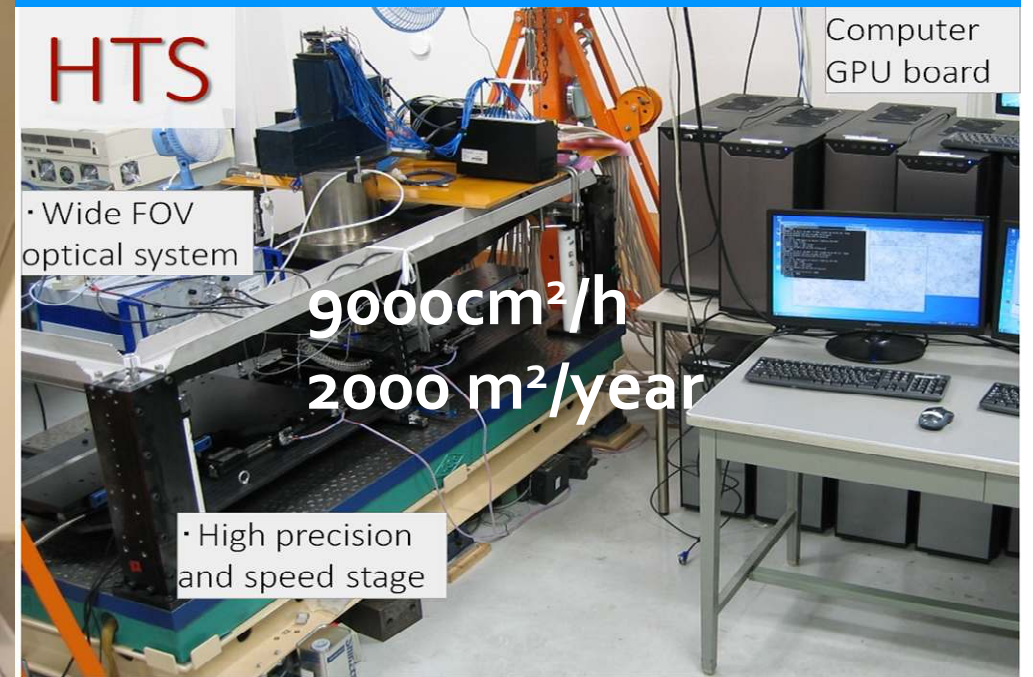
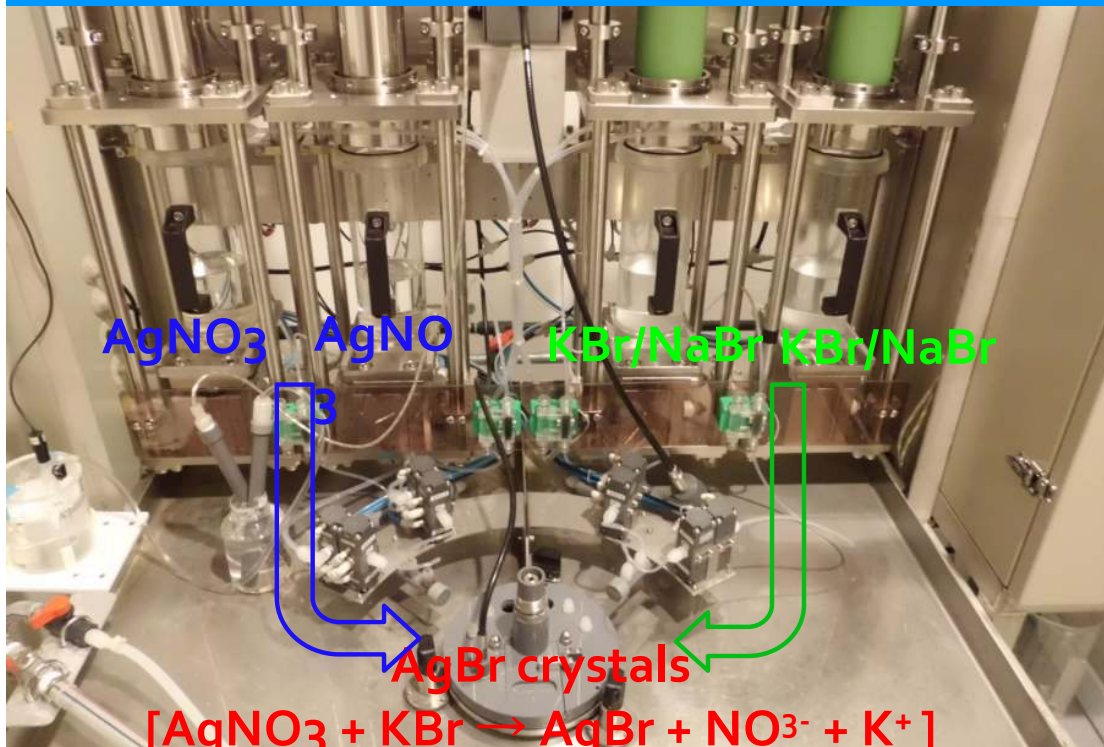
素粒子実験

応用研究

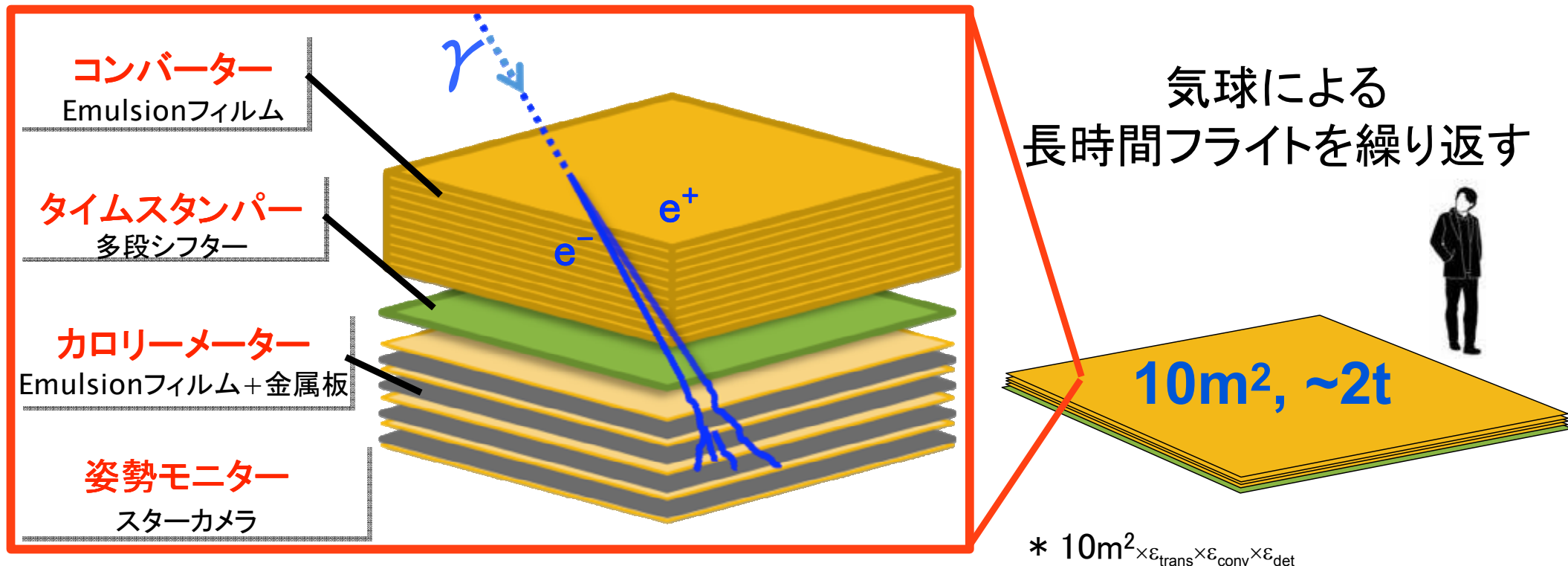
原子核乳剤製造

原子核乾板

自動読み取り装置



気球搭載型エマルジョンガンマ線望遠鏡



	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 *

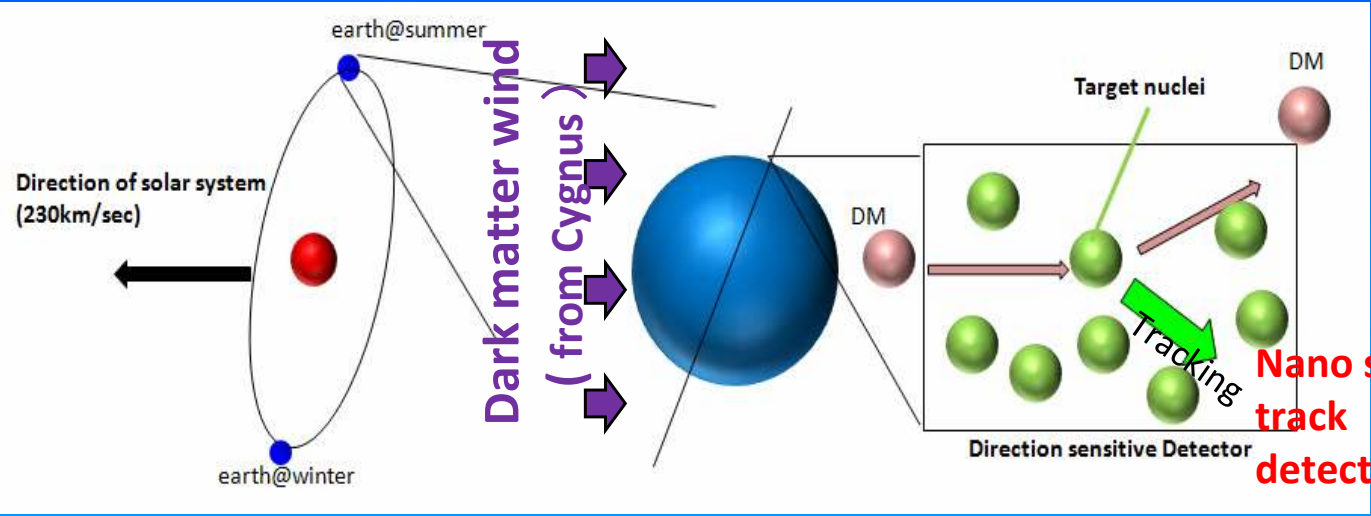
世界最高角度分解能

世界初偏光有感

世界最大口径

Directional dark matter search with scalability

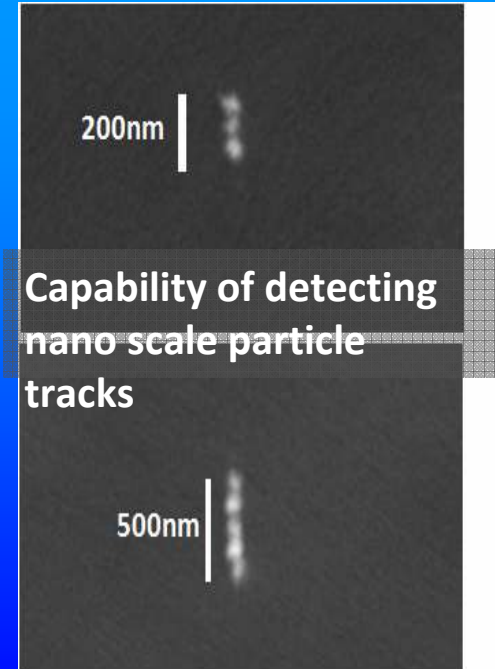
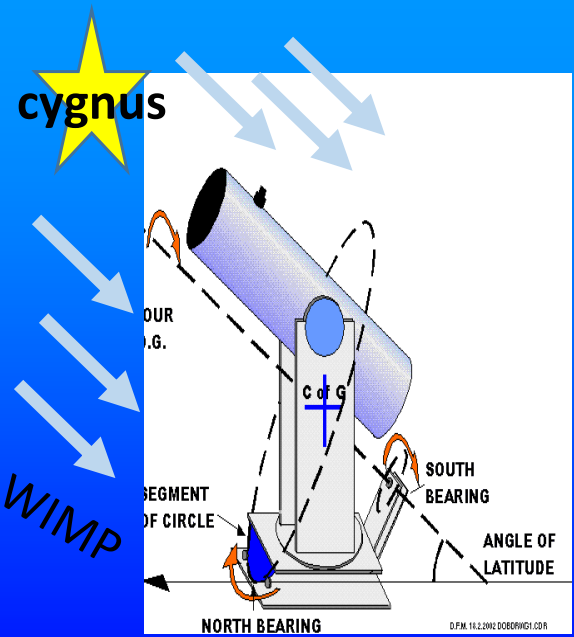
⇒ super-high resolution nuclear emulsion



NEWS: Nuclear Emulsion for WIMPs Search



Proposal submitted to Gran Sasso lab., Italy



Capability of detecting nano scale particle tracks

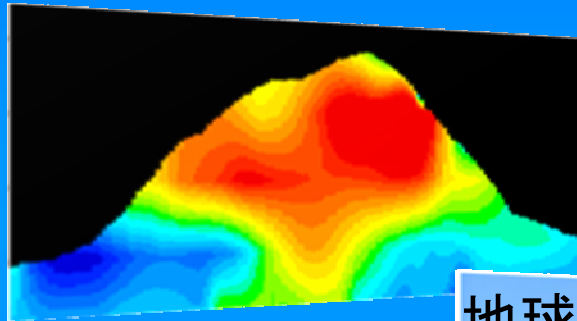
宇宙線ラジオグラフィ

宇宙線ミュ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)

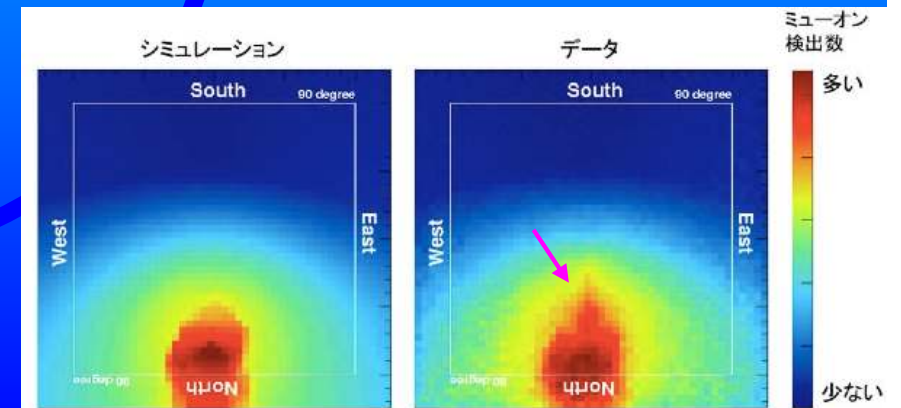


対象

- ・火山
- ・断層
- ・氷河
- ・地下資源



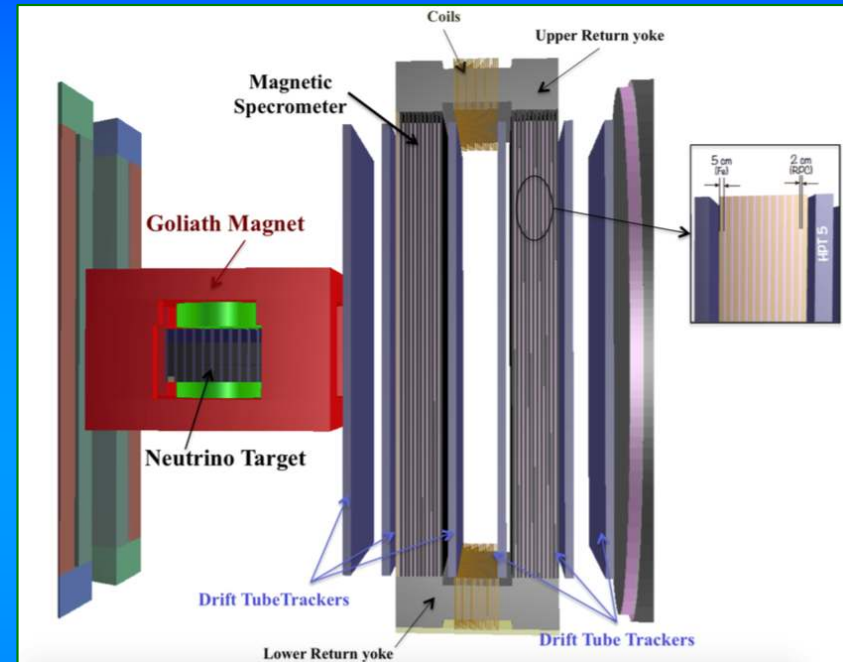
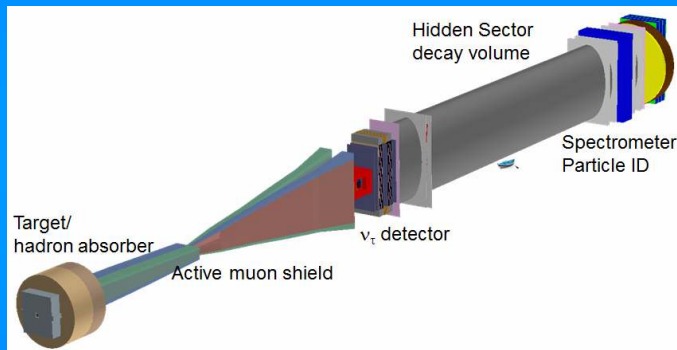
- ・地下空洞調査
- ・ダム of 老朽化調査
- ・鉄筋コンクリート



ν_τ 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.



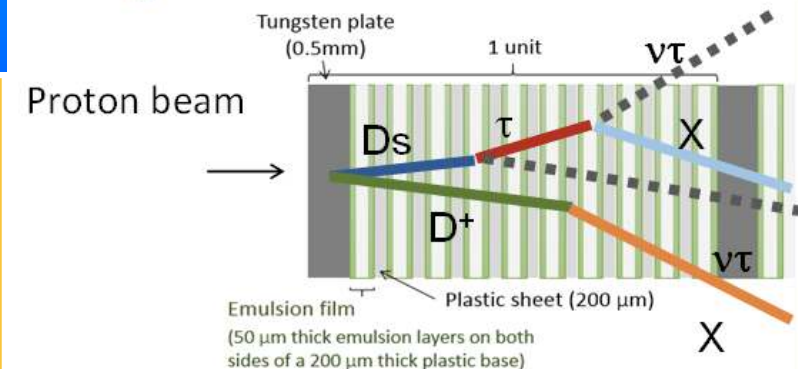
DsTau Project

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

→ Re-evaluation of ν_τ cross section & useful results for future ν_τ experiments

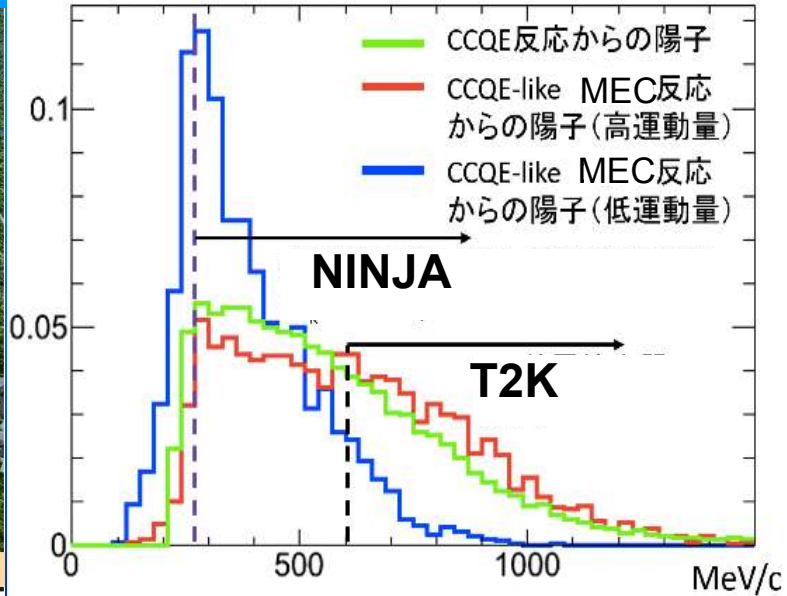
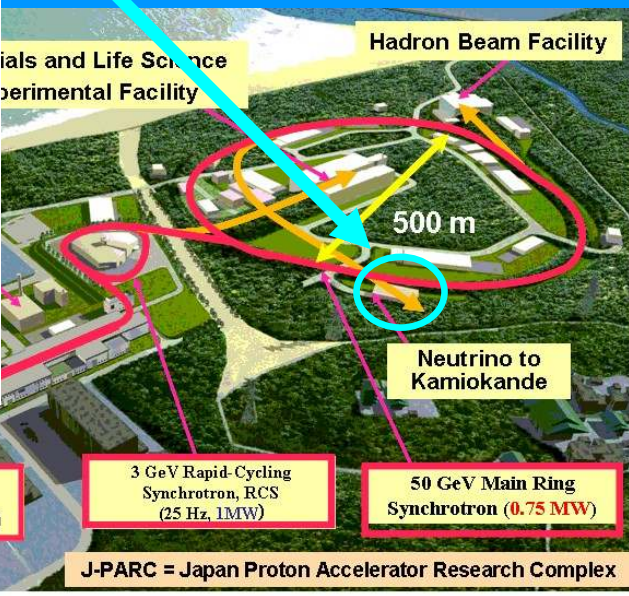
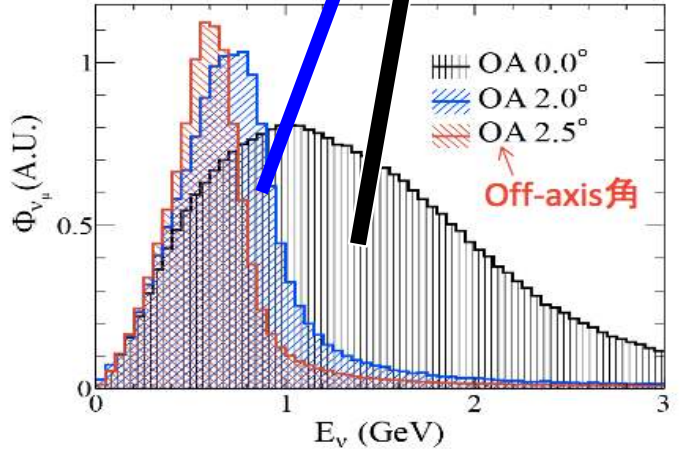
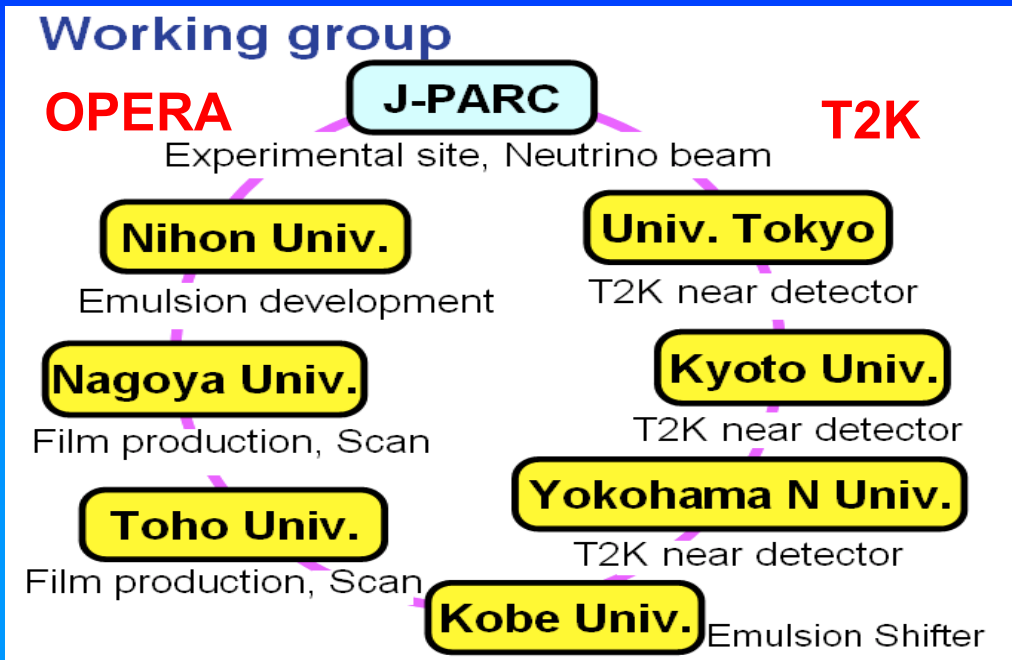
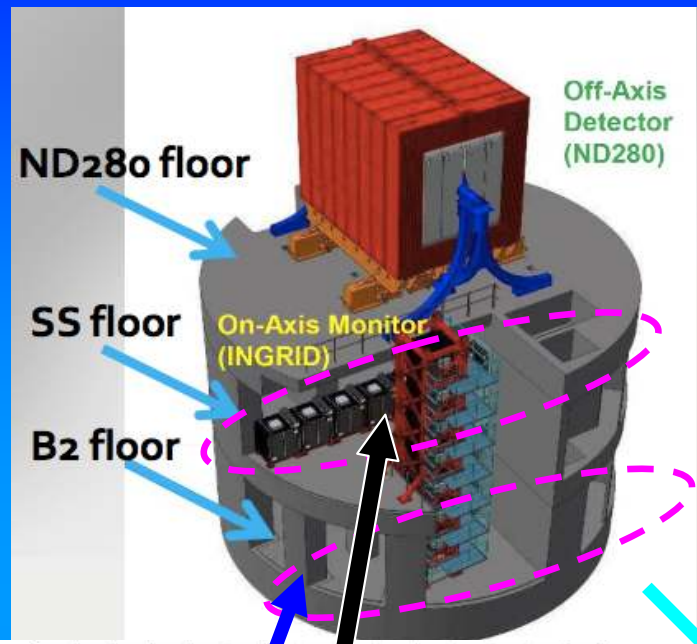
Proton target:

Tungsten foil + emulsion tracker



NINJA 実験

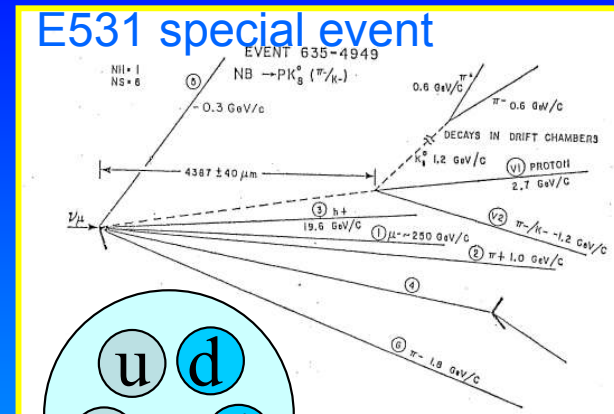
Neutrino Interaction research with Nuclear emulsion and J-PARC Accelerator



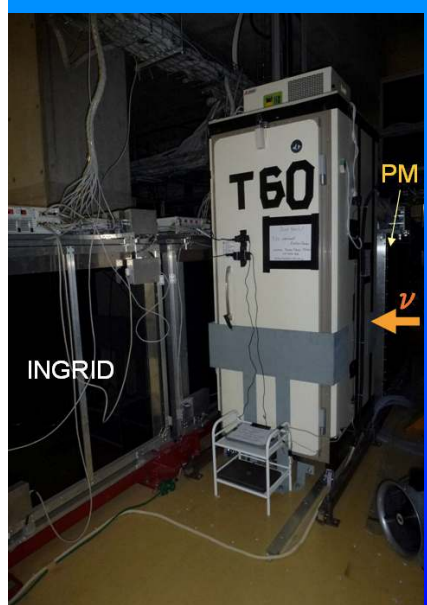
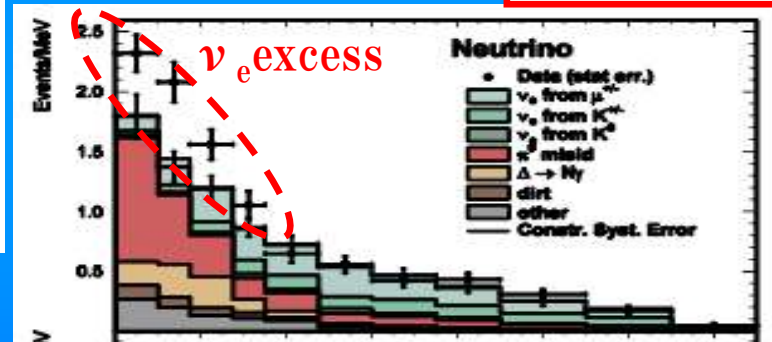
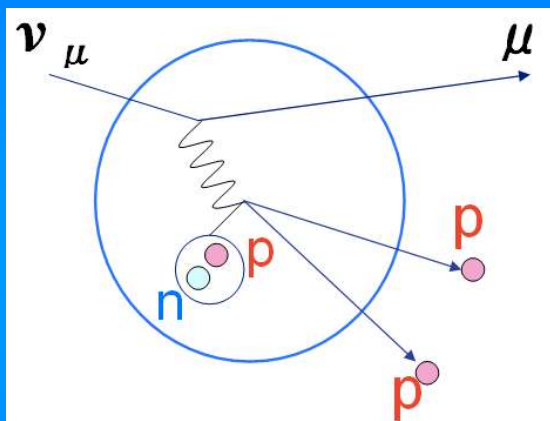
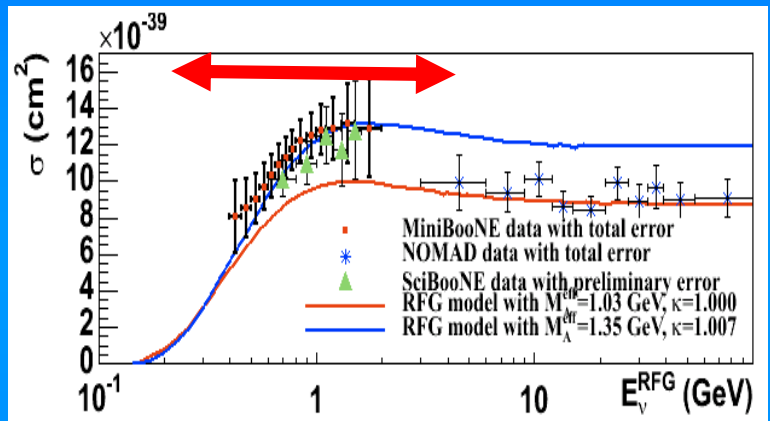
原子核乾板は、MEC反応を測定する極めて有効な手段 → ニュートリノ反応の精密測定

NINJA Experiment

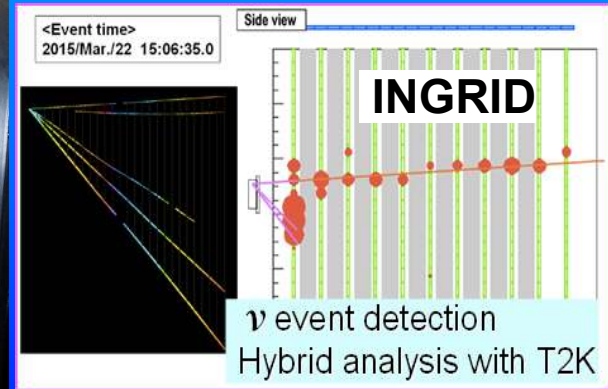
- ・将来のニュートリノセクターにおけるCP対称性の破れの検証を目指し、ニュートリノ-原子核反応断面積の超精密測定を行う。
- ・20年近く正体かわかっていないステライル(不活性)ニュートリノ存在の検証を行う。
- ・チャームペンタクォークやチャーム原子核といったエキゾチックな粒子の探索・測定を行う。



MiniBooNE

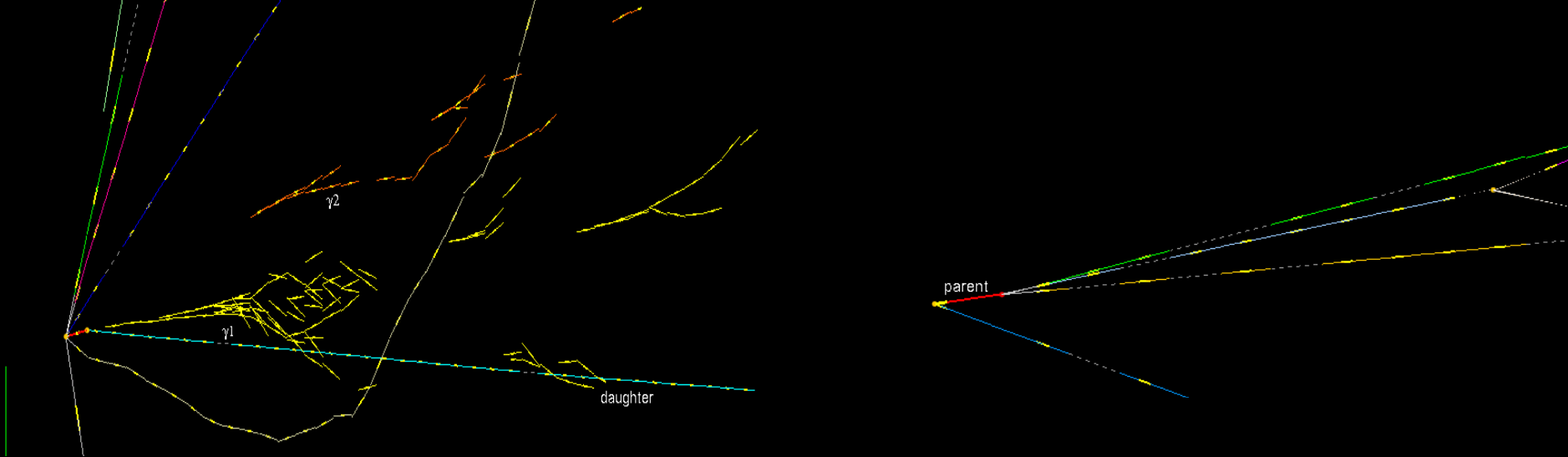


nu beam exposure was finished in the end of May

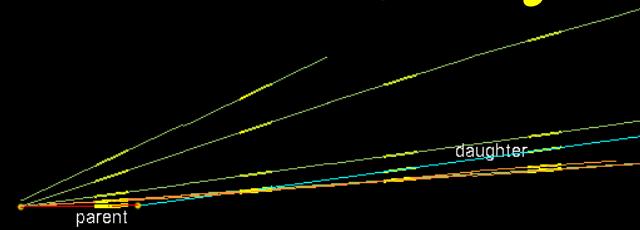


Water Target ~ 1.5kg -> 10-20 nu-bar events

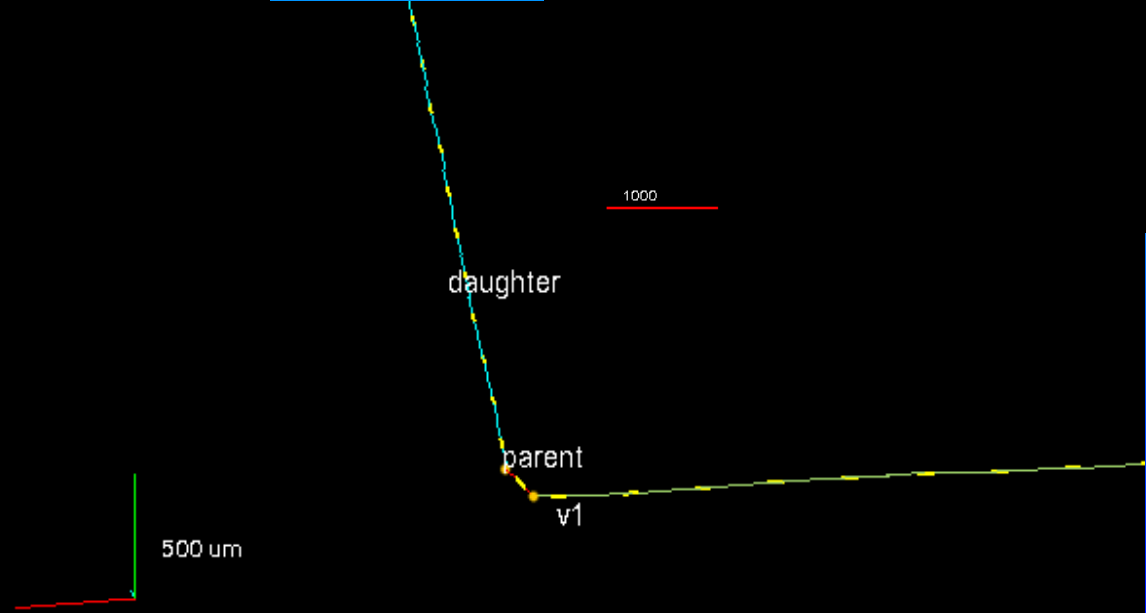
始まったばかりの実験なので、参加者募集中！！



Thank you for your kind attention !



2



Supplements