Emulsion Neutrino Spectrometer for future neutrino experiments

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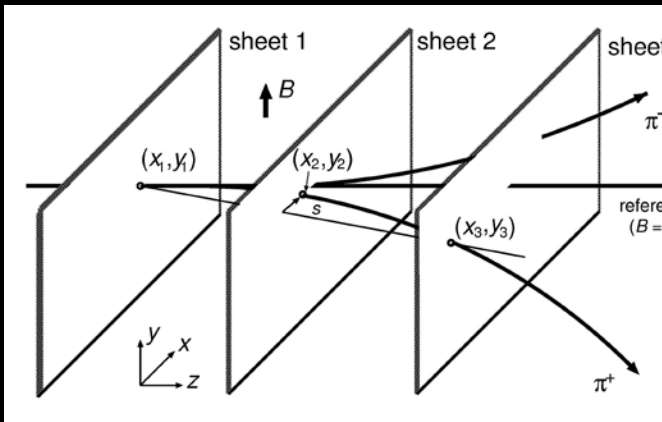
1. Introduction
   Emulsion experiments for neutrino oscillation study
   (E531, CHORUS, DONUT, OPERA)
2. Emulsion Neutrino Spectrometer
3. Results from test beam experiments
4. Practical problems
5. Future prospects

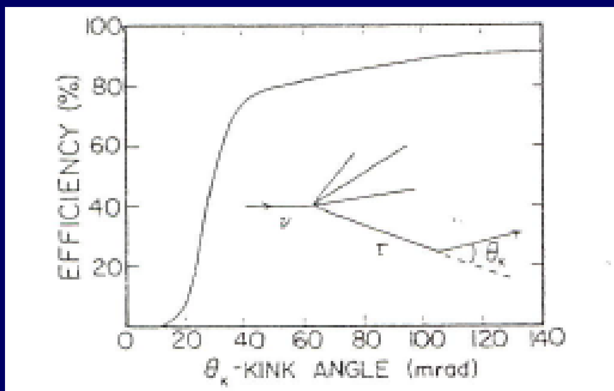


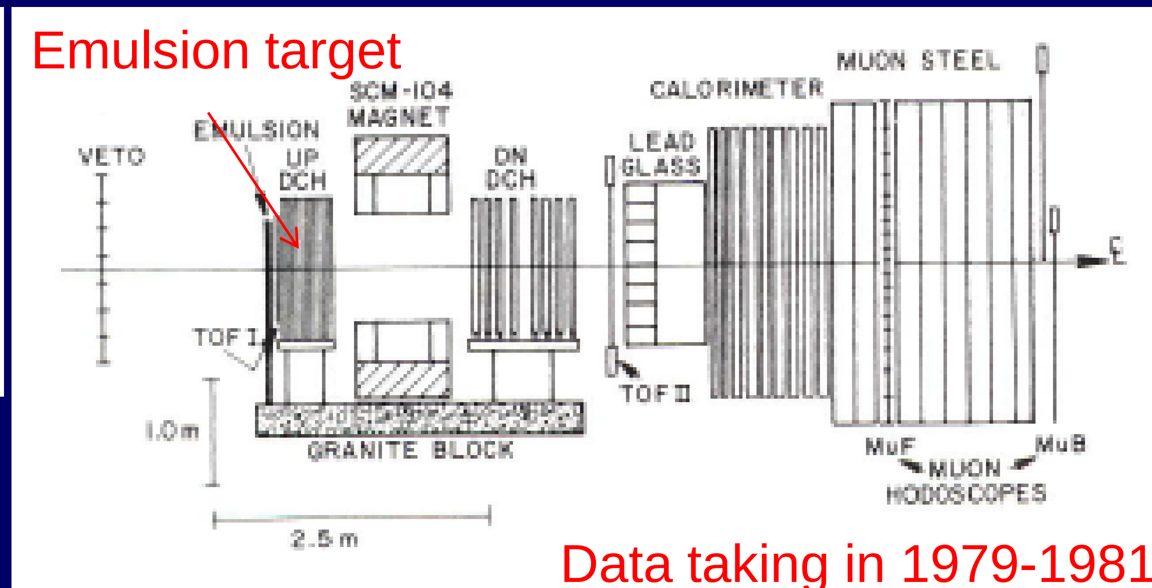
Emulsion experiments for neutrino oscillation

Fermilab E531

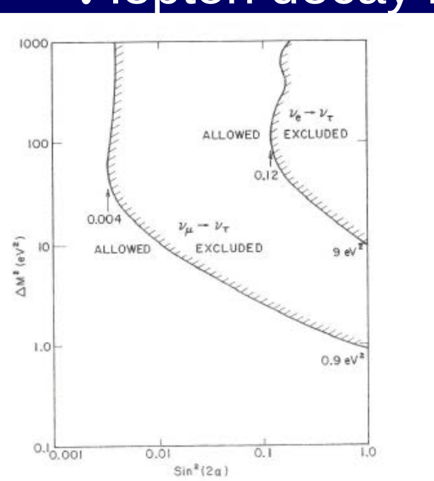
Main purpose: charmed particle lifetimes

It was noticed that emulsion is also suited for detecting τ lepton decay and ν_τ charged current interactions.





τ lepton decay in emulsion



$<E\nu>$=22GeV

L= a few 100m

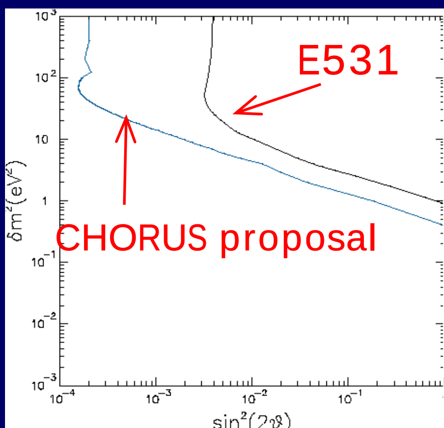
N. Ushida et al.,NIM 224 (1984) 50.

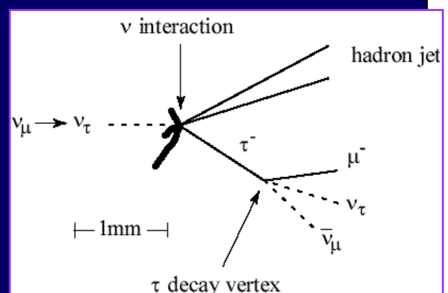
PRL 47 (1981) 1694 and PRL 57 (1986) 2897.

Upper limit of $P(\nu_\mu \rightarrow \nu_\tau)$ was obtained (10^{-3}) based on 1870 ν_μ CC (3886 ν interactions)

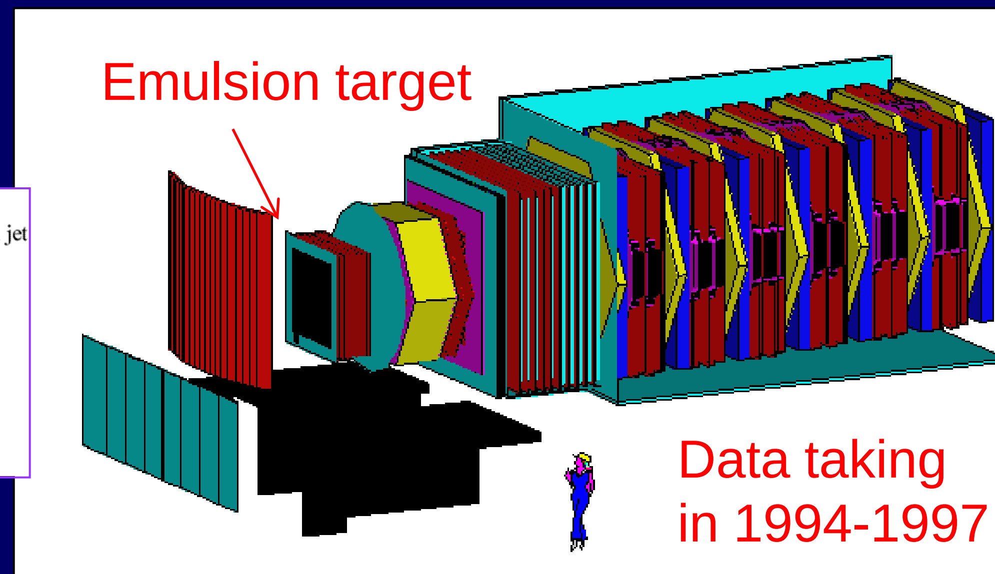
A large-scale search for $\nu_\mu \rightarrow \nu_\tau$ oscillation by direct observation of τ lepton decay in emulsion

CHORUS (CERN Hybrid Oscillation Research ApparatUS)





A ν_τ interaction in emulsion



Search for ν_τ appearance on a "pure" ν_μ beam   <Eν>=27GeV, *L* = a few 100m

High design sensitivity $P(\nu_\mu \rightarrow \nu_\tau)=10^{-4}$ 5.06×10^{19} POT

for $\delta m^2 \approx 1\text{-}10 eV^2$ (relevant for cosmology & DM)

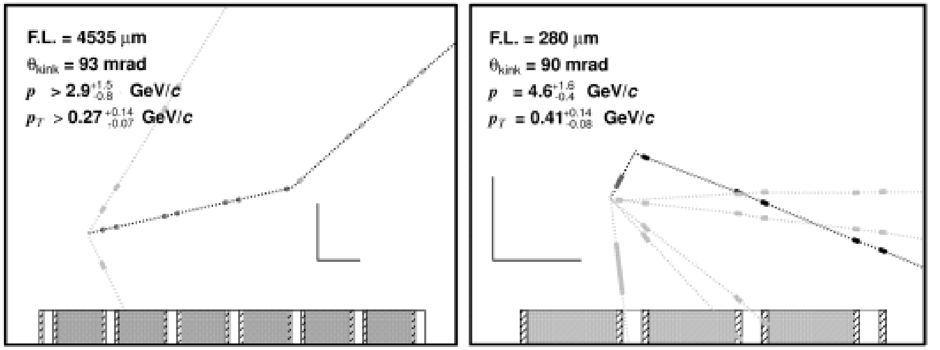
From analysis of 713K(1μ) and 335K(0μ) samples, 143742(1μ) and 23206(0μ) events were located in emulsion. Upper Limit $P(\nu_\mu \rightarrow \nu_\tau) < 2.2 \times 10^{-4}$ obtained.

Phys. Lett. B 497(2001)8., Nucl. Phys. B 793 (2008) 326.

First observation of ν_τ charged current interactions in ECCs of a hybrid experiment

Fermilab E872 DONUT experiment

Data taking in 1997



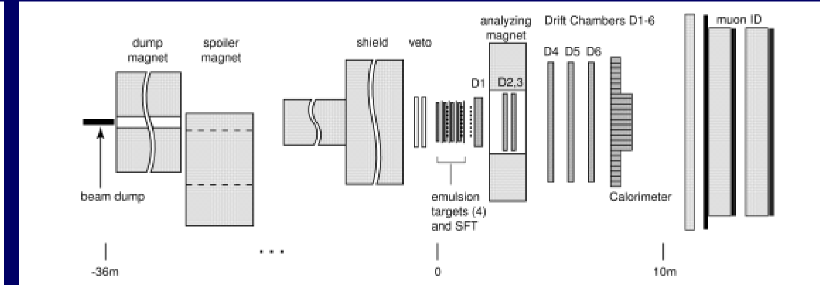
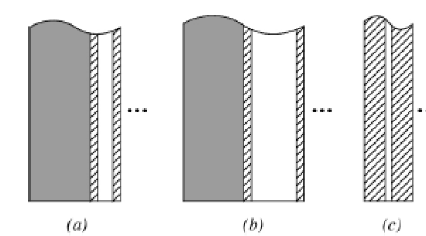
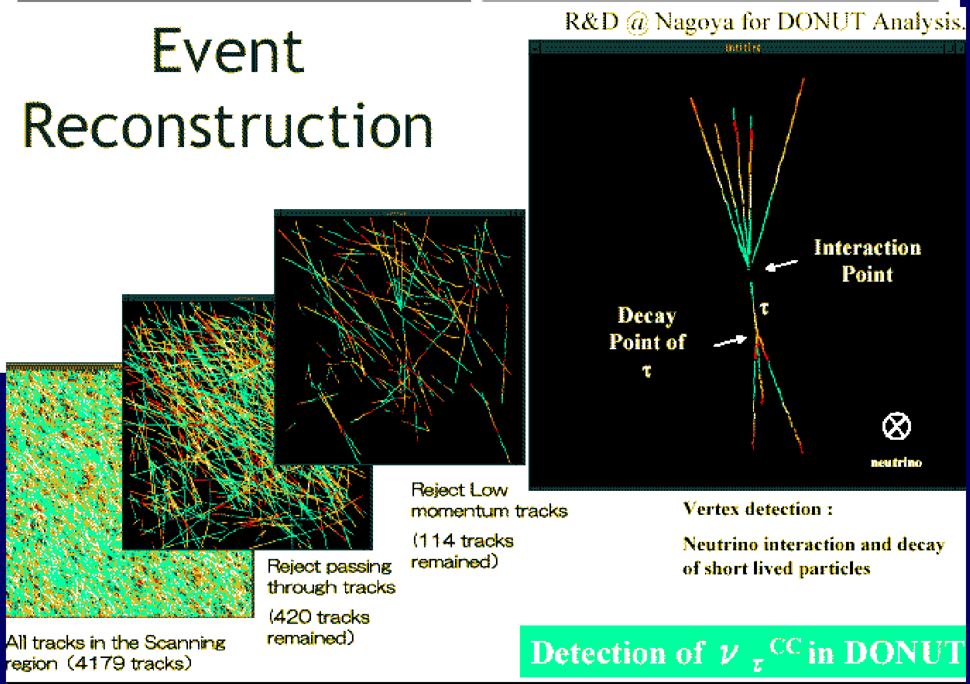


Fig. 1. Experimental beam and spectrometer. At the left, 800 GeV protons were incident on the beam dump, which was 36 m from the first emulsion target. Muon identification was done by range in the system at the right.





ECC type target had a repeated structure of 1mm thick stainless steel plates interleaved with emulsion films

K. Kodama et al., PLB 504 (2001) 218.

$9\ \nu_\tau$ observed events 1.5 BG events

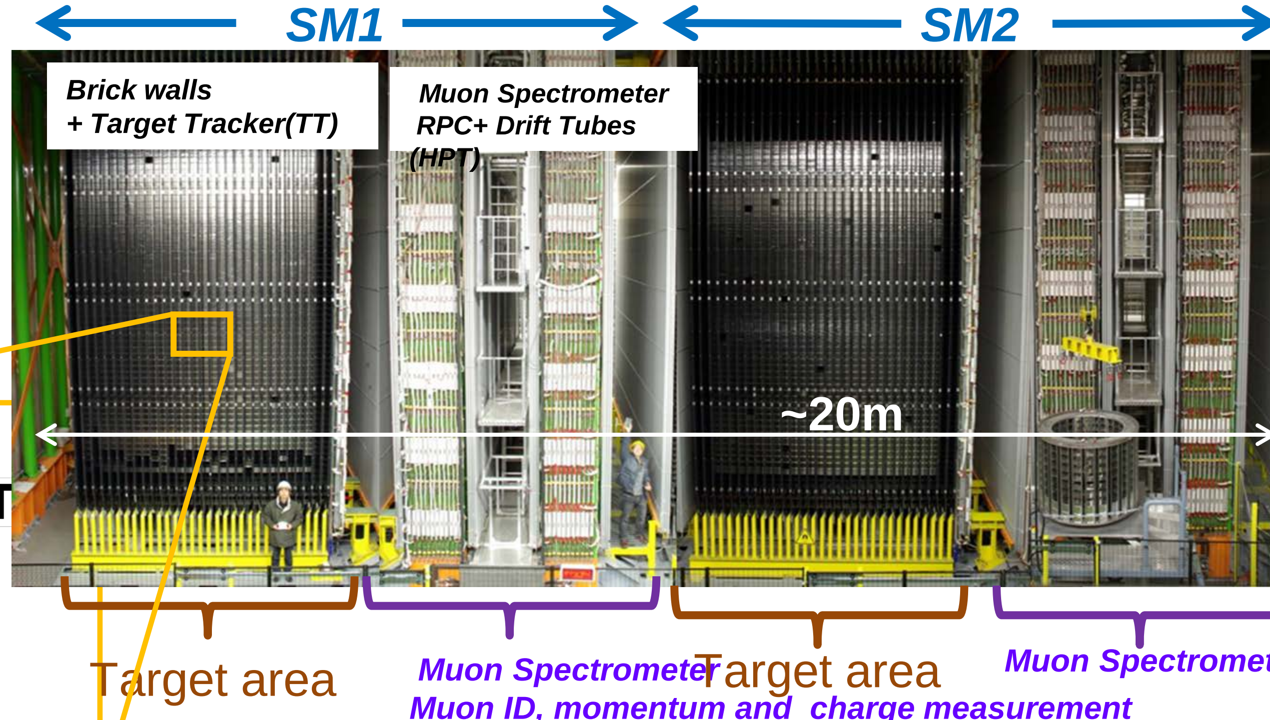
An appearance experiment to search for $\nu_\mu \rightarrow \nu_\tau$ oscillations in the CNGS (OPERA)

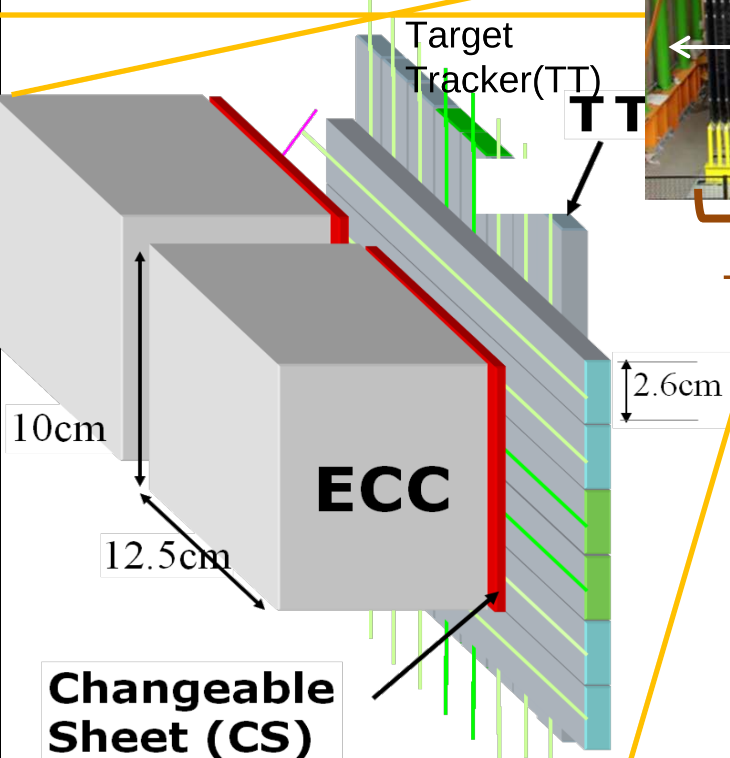
Data taking in 2008-2012

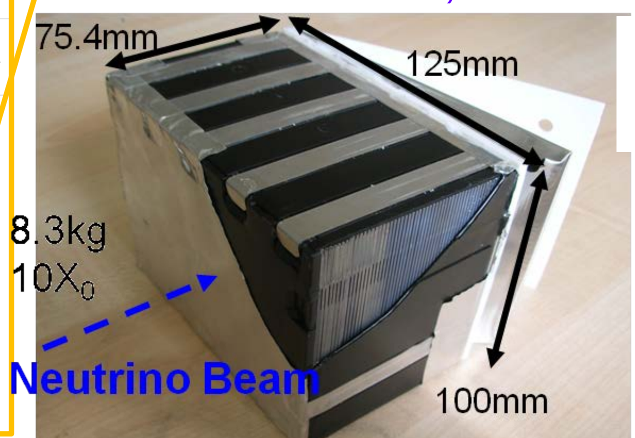
730km

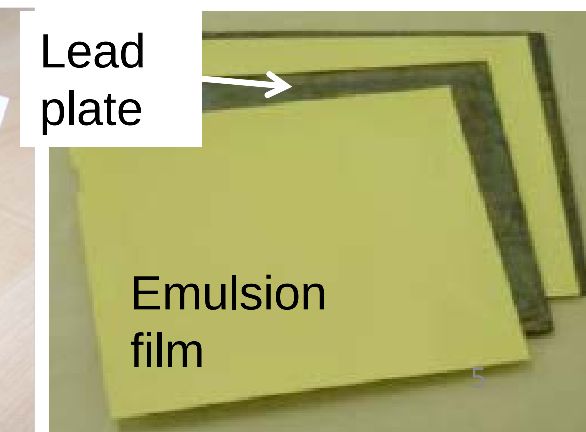
ν_μ beam

Total 1.25 kton, ~150000 ECC bricks



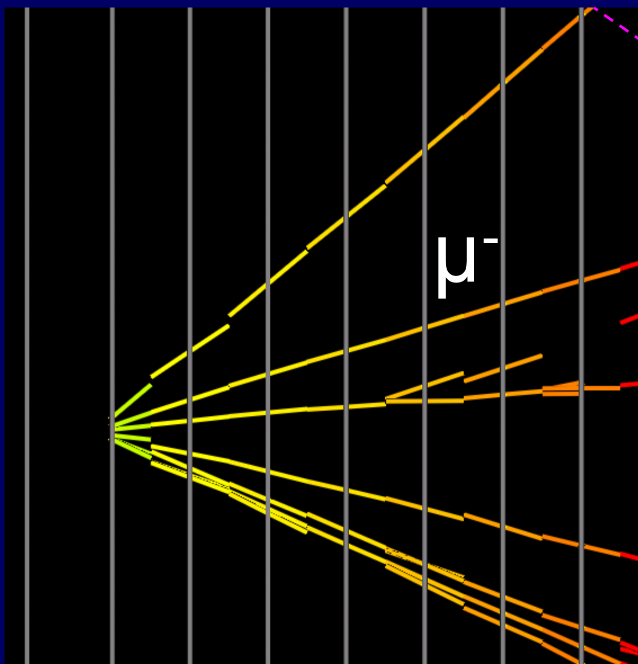




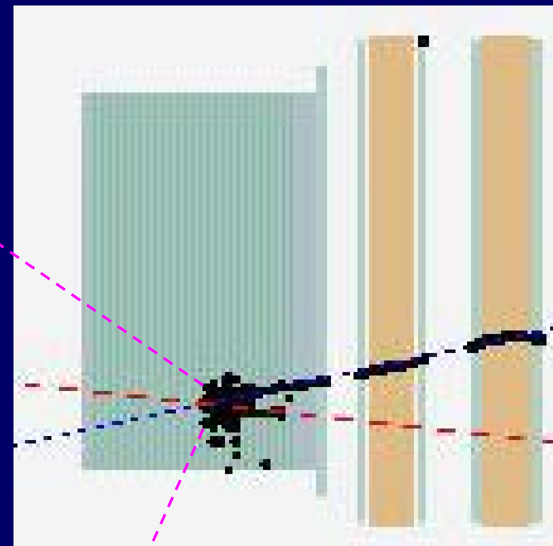


Identification of neutrino interactions in OPERA

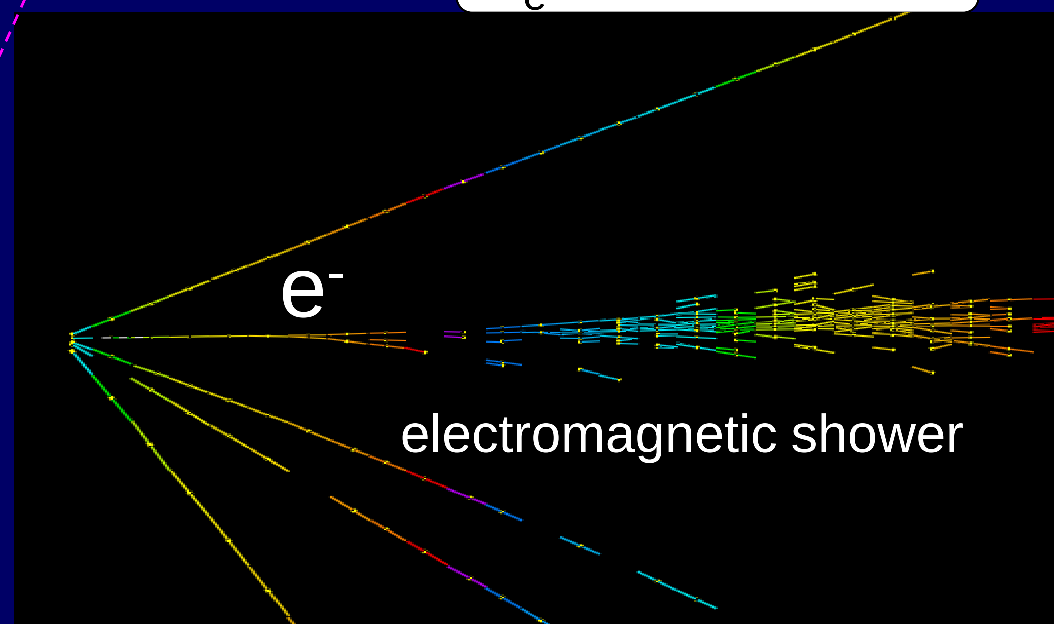
ν_μCC interaction



A muon penetrates several ECC bricks.
(μ1GeV/c：~10ECC→π：~3Interaction length)

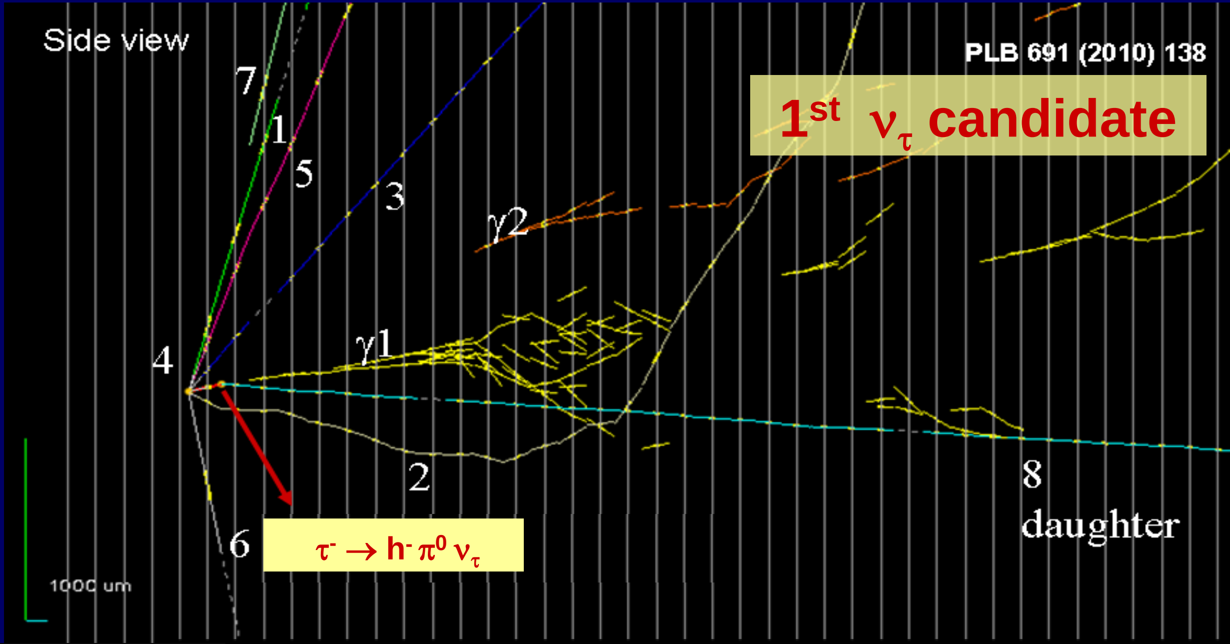


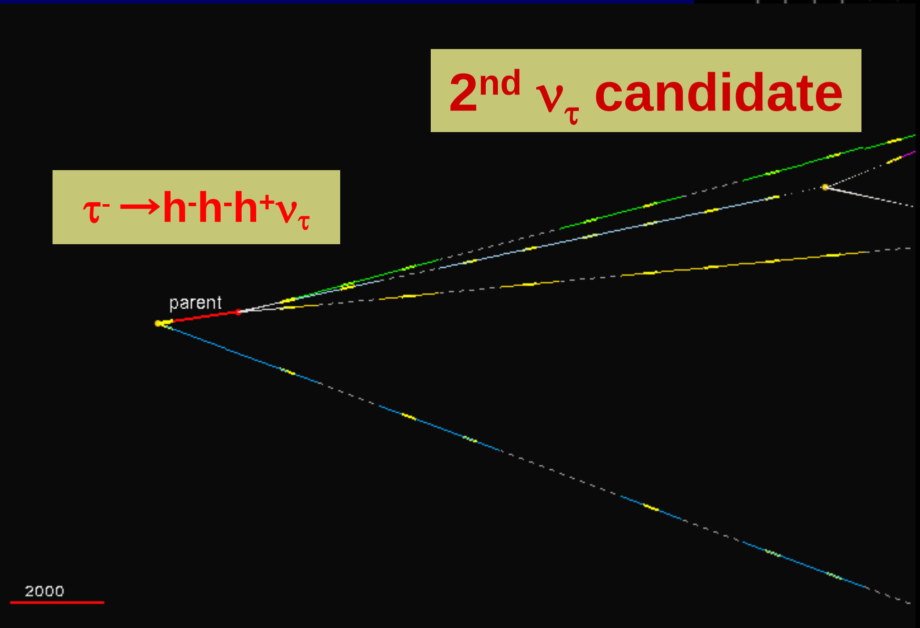
ν_eCC interaction

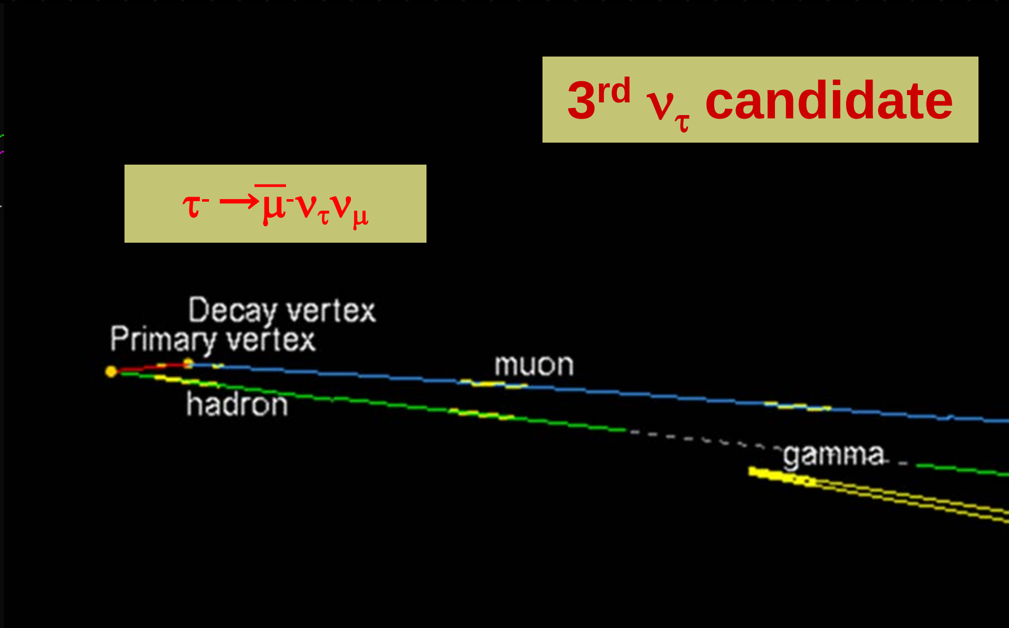


Observed ν_τ candidate events in OPERA

Beam: 5 years (2008-2012)
Total 17.97 x 10^{19} p.o.t.
Analysis:
2008-2009 completed
2010-2012 on going with optimized strategy
To date,
Located 6067
Decay search 4964



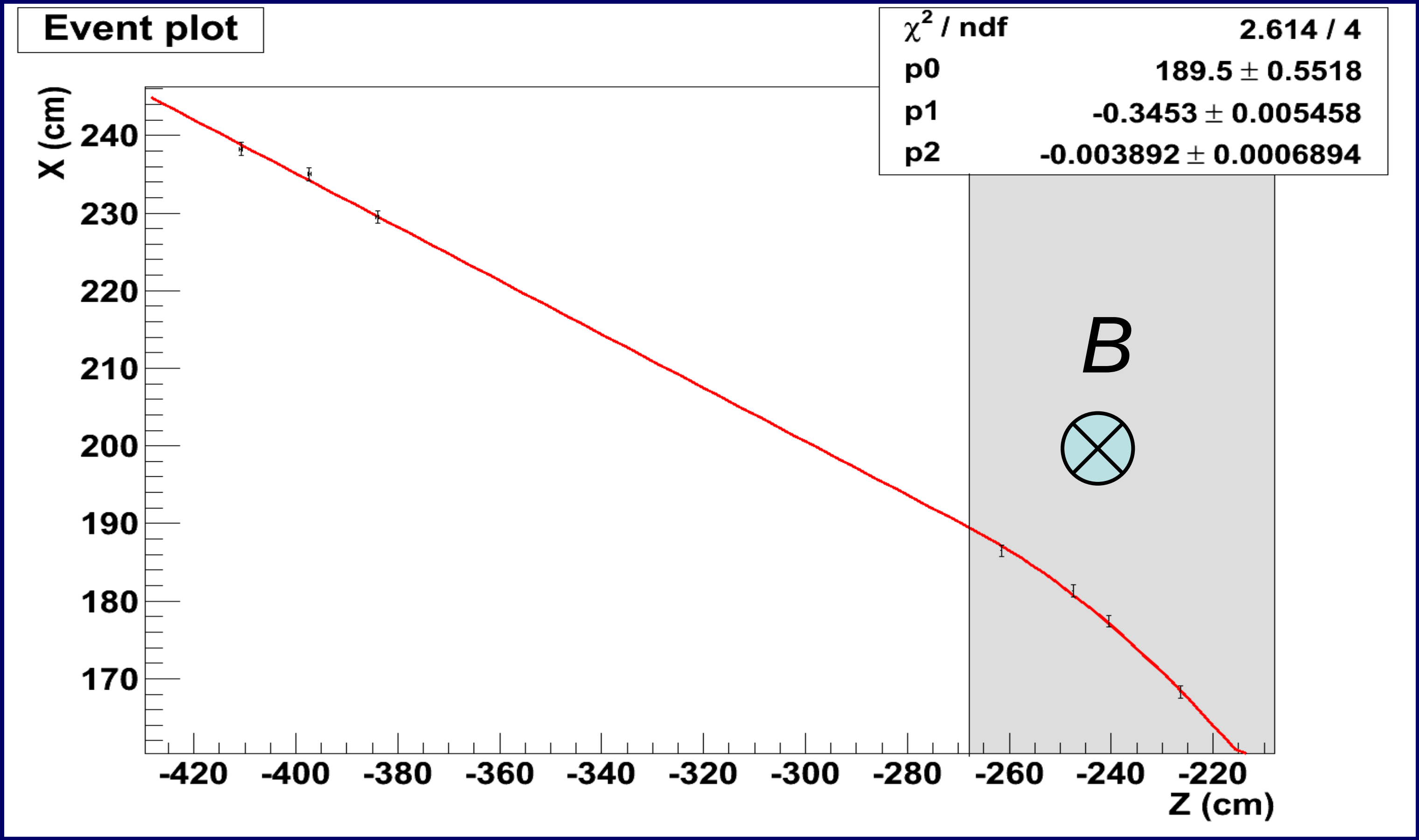




The 3rd candidate event $(\tau \rightarrow \mu \bar{\nu}_\mu \nu_\tau)$ OPERA

The charge sign of the muon

was measured to be negative from its curvature in magnetic field.



The oscillated neutrino is ν_τ (not $\bar{\nu}_\tau$)

Introduction

- Study of neutrino oscillation phenomena has been greatly progressed in recent years.
- For example, discovery of $\nu_\mu \rightarrow \nu_e$ oscillation by T2K
- Measurement of θ_{13} from reactor experiments

- **What is next?** $\rightarrow$ precise measurements of mixing angles, Δm^2
  CP violation δ
- **Let's consider future experiments in the era of precise measurements**
- **Traditional (high intensity) neutrino beams** contain predominantly ν_μ or $\bar{\nu}_\mu$ with a small admixture of ν_e and $\bar{\nu}_e$
- **Muon storage ring (Neutrino Factory)** offers ν_e / $\bar{\nu}_\mu$ and ν_e / $\bar{\nu}_\mu$ beams

Mixture of different flavors or neutrinos/anti-neutrinos

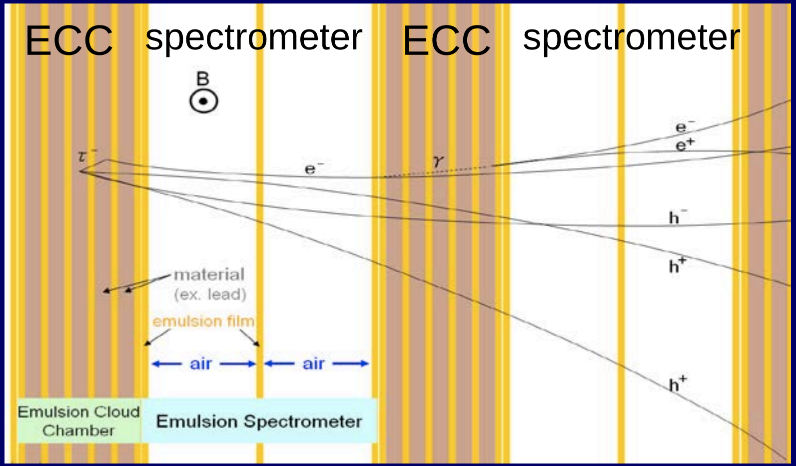
A detector which can identify all the neutrino flavor is strongly required.

The Emulsion Neutrino Spectrometer

- In future neutrino oscillation experiments, it is essential to identify the incident neutrino flavor and also to distinguish neutrino interactions from anti-neutrino interactions.
- Nuclear emulsion detectors can identify the neutrino flavors; ν_e, ν_μ and ν_τ interactions as clearly demonstrated in DONUT and OPERA.
- The Emulsion Neutrino Spectrometer (ENS) will add a new capability to distinguish neutrino interactions from anti-neutrino interactions. It is accomplished by measuring the deflection of the produced lepton in a magnetic field and determining the sign of its charge.
- This talk will report on its conceptual design, performance tests and future prospects.

Conceptual design

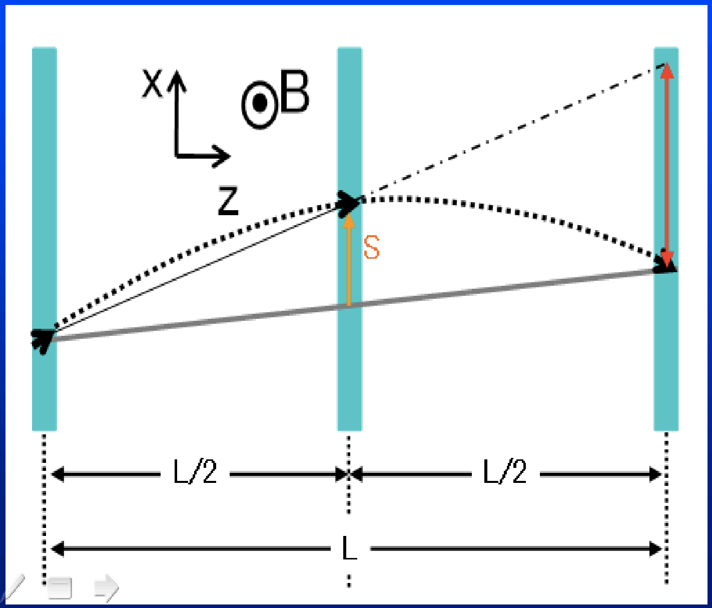
- The Emulsion Neutrino Spectrometer (ENS) is mainly composed of two parts of emulsion detectors.
- One is an Emulsion Cloud Chamber (ECC) to provide a massive target and also to identify secondary particles.
- The other is a spectrometer part to determine the charge sign. Three emulsion films are spaced with each other by a certain distance of less material region and are placed in a magnetic field.



- The sign of the lepton charge from a charged current interaction can be identified in the magnetic field.

The emulsion spectrometer

- The charge sign is determined by measuring the <u>sagitta</u> of charged particles in the spectrometer. The sagitta is defined as the distance between the track position in the middle film and intercept in this film of the straight line joining the track positions in the two external films.



Sagitta s = 0.3 B[T] L^2[m^2]/(8p[GeV/c])

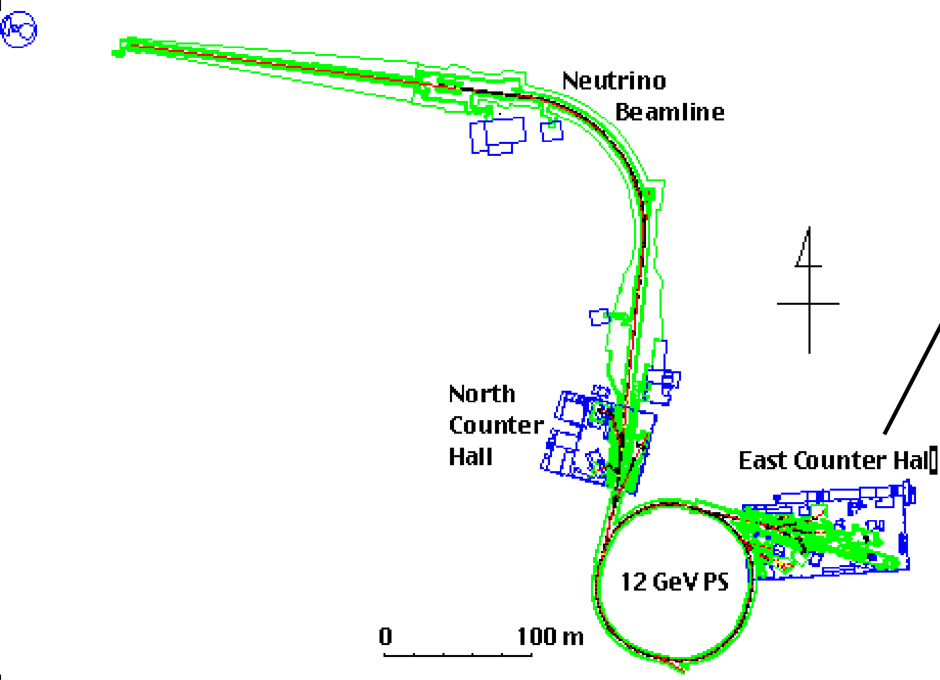
Δp/p ~ 13% @ B =1.057[T], L = 31.679[mm] emulsion plate = OPERA film[3]

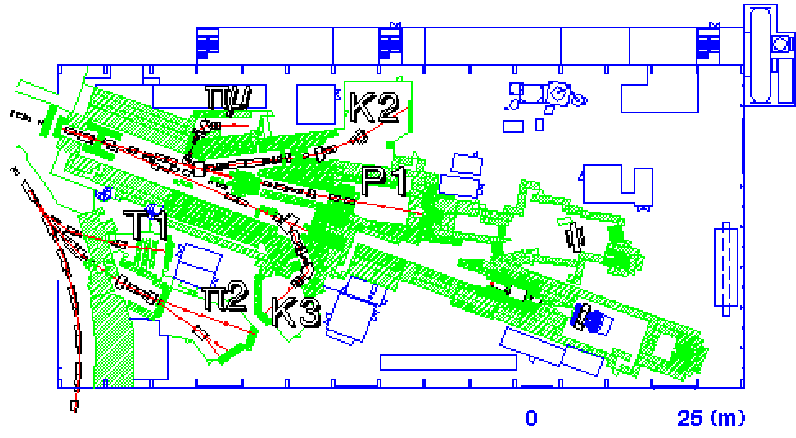
Beam momentum [GeV/c]	Sagitta (expected) [μm]	$\sigma_{Sagitta}$ (expected) [μm]
0.5	79.6	10.6
1.0	39.8	5.2
2.0	19.9	2.6

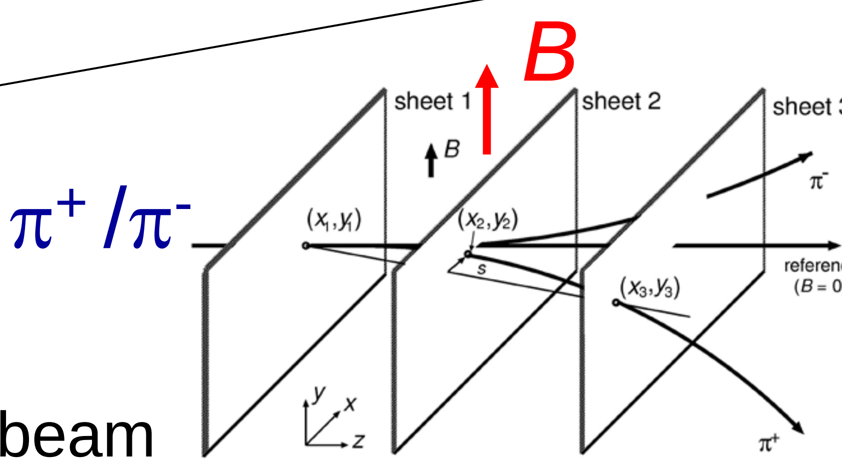
[3] T. Nakamura et al., NIM A 556 (2006) 80, C. Fukushima et al., NIM A 592 (2008) 56.

Test for an emulsion spectrometer was performed.

The beam momentum was set for 0.5, 1.0 and 2.0 GeV/c with the relative spread, $\Delta p/p$ of 5%.



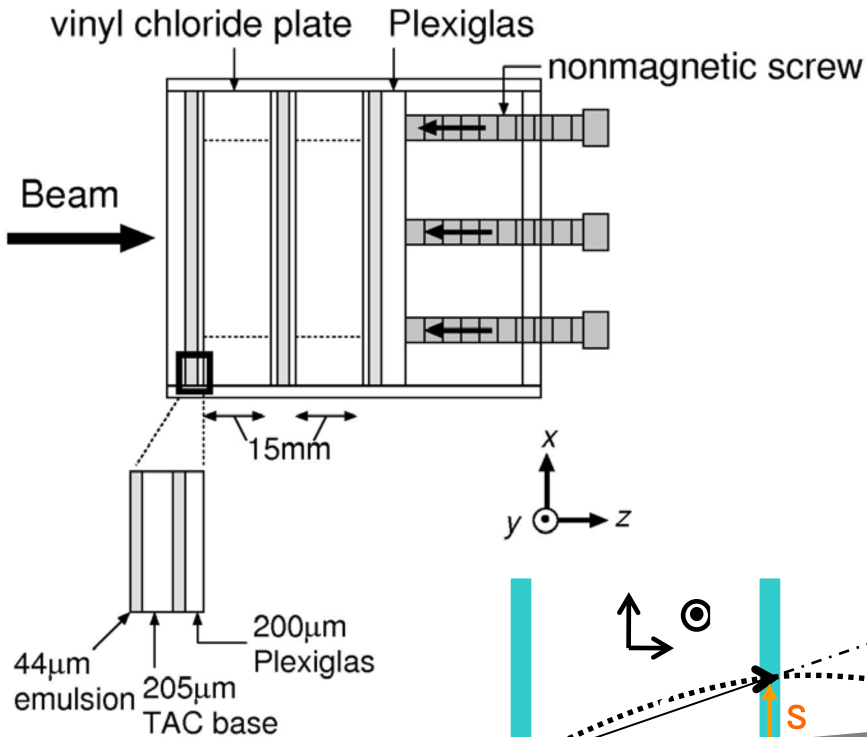


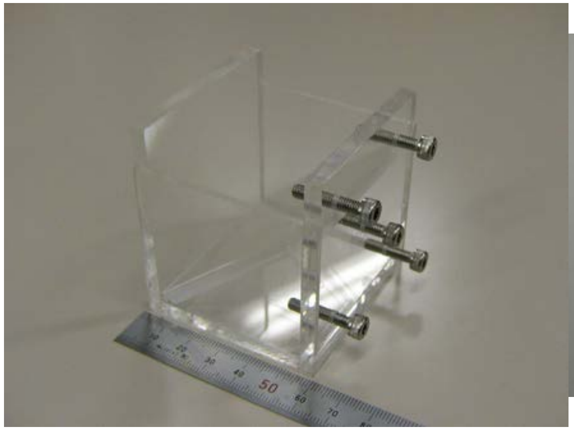


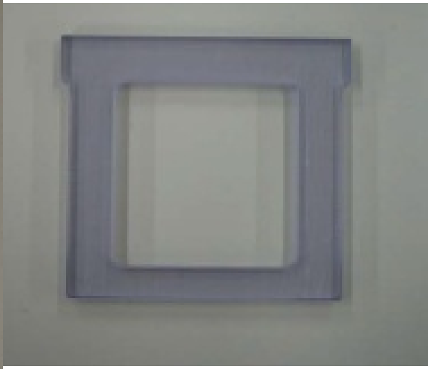
Test Beam Experiment at KEKPS T1 beam

Test Beam Experiment using a thin emulsion spectrometer at KEK PS

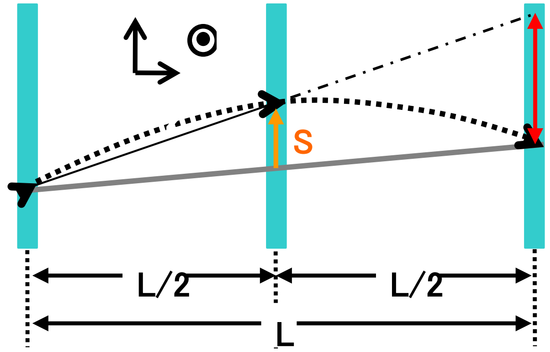
A thin emulsion spectrometer







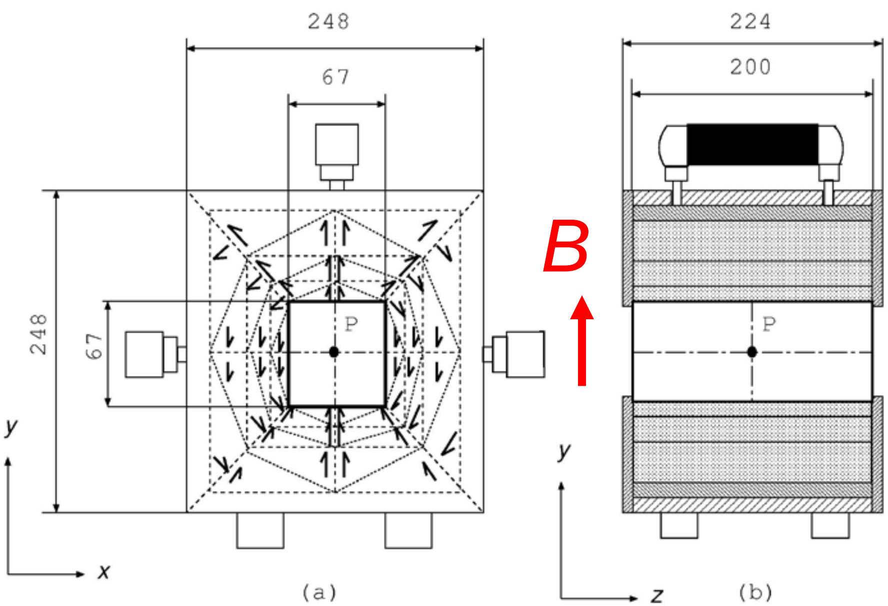
The spacer is a vinyl chloride plate which has a hole of 40mm x 40mm at the center

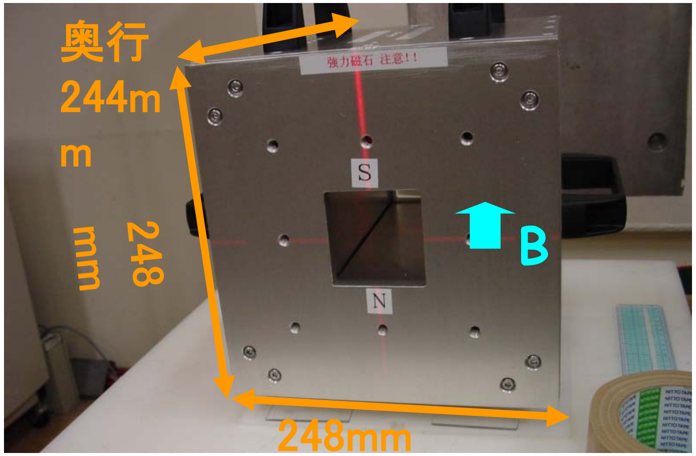


Momentum [GeV/c]	Sagitta [μm]	Spread [μm]
0.5	79.6	10.6
1.0	39.8	5.2
2.0	19.9	2.6

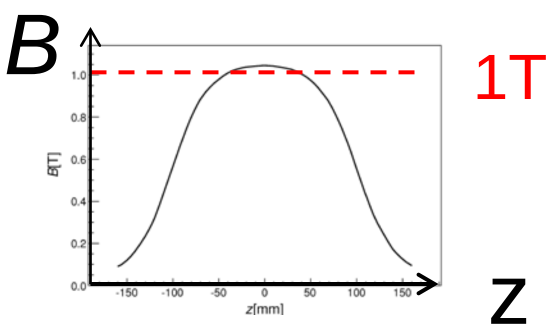
Test Beam Experiment using a thin emulsion spectrometer at KEK PS

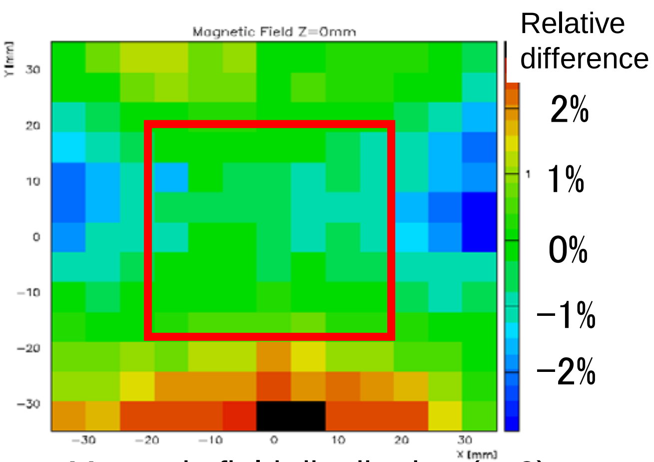
Compact permanent magnet





Halbach-type magnetic circuit

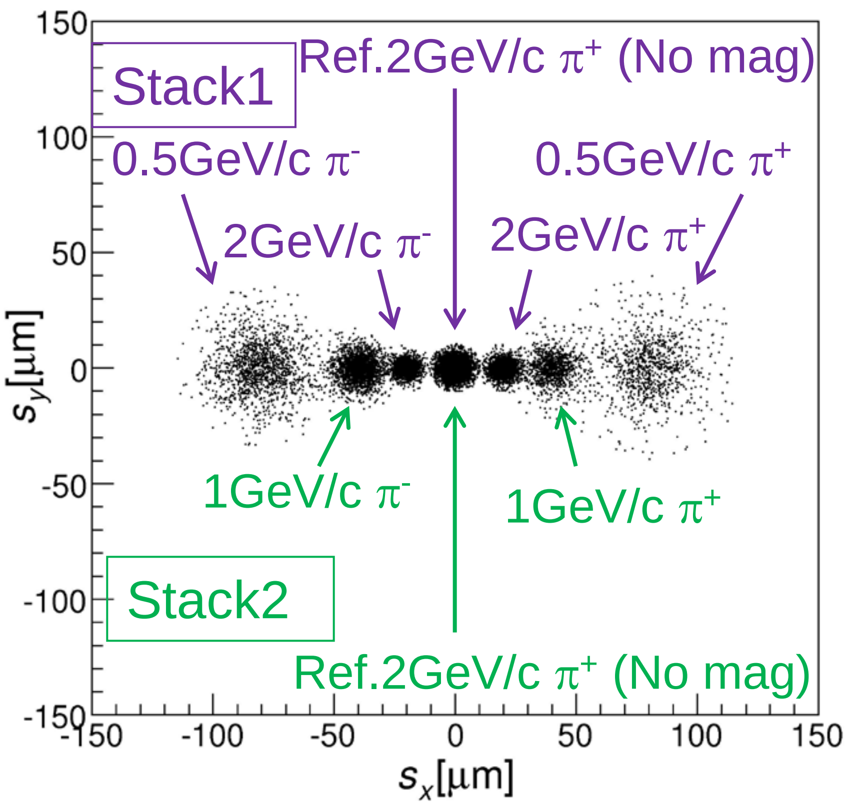




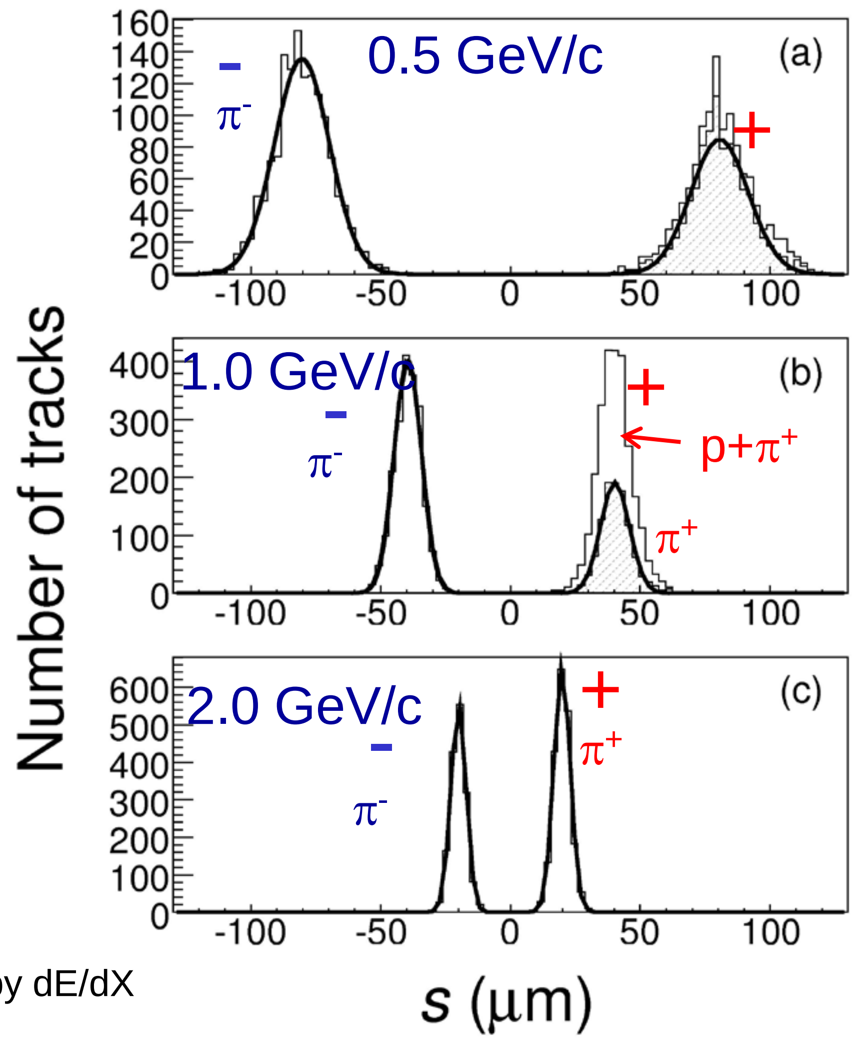
Magnetic field distribution (z=0)

Results from the test beam experiment

2D sagitta values of 0.5, 1.0 and 2.0 GeV/c charged particles



Sagitta distributions



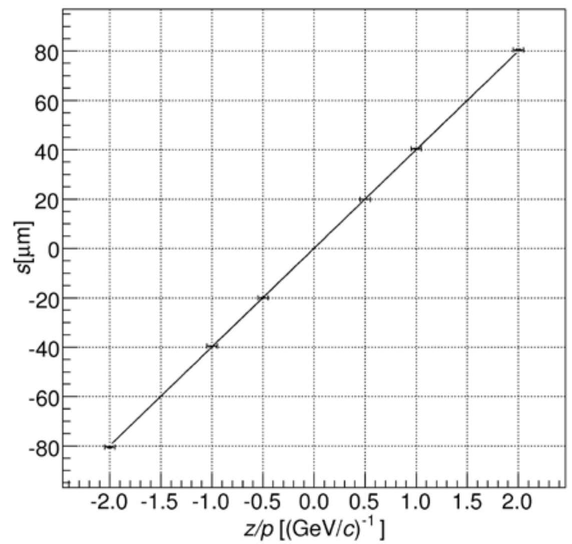
The shaded histograms are for π^+ candidates selected by dE/dX measurements of tracks in emulsion.

Results from the test beam experiment

Test Beam Experiment at KEK PS

p(GeV/c)	0.5		1.0		2.0	
particle	π^+	π^-	π^+	π^-	π^+	π^-
entries	912	1374	1044	2020	2016	1591
s[μm]	80.4	-80.4	40.2	-39.6	19.9	-20.1
σ_s[μm]	10.8	10.6	5.3	5.1	3.0	2.8
σ_s/s[%]	13.4	13.2	13.2	12.9	15.1	13.9
expected s[μm]	79.6	-79.6	39.8	-39.8	19.9	-19.9

Sagitta vs. momentum



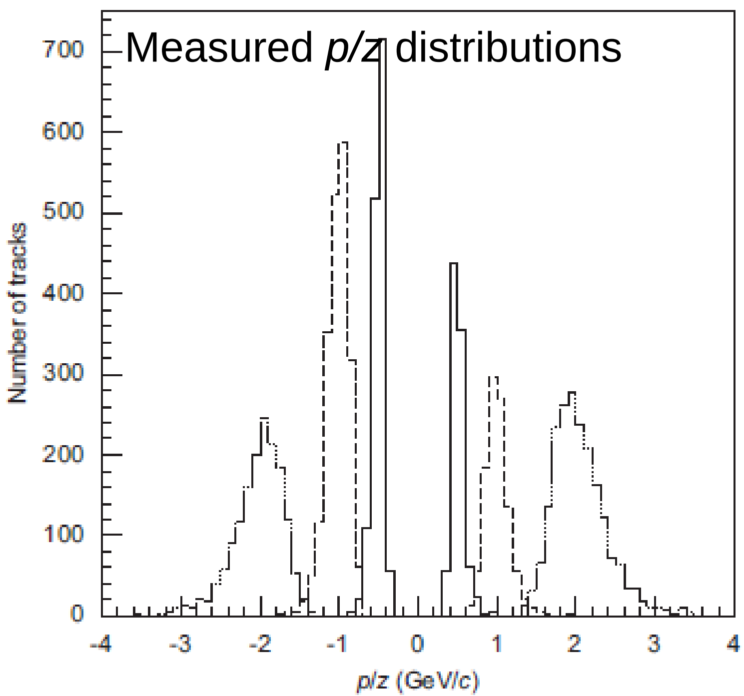
Beam momentum

Results of Gaussian fit, mean and sigma values of sagitta distributions are summarized in the table. They agree well with the expected values.

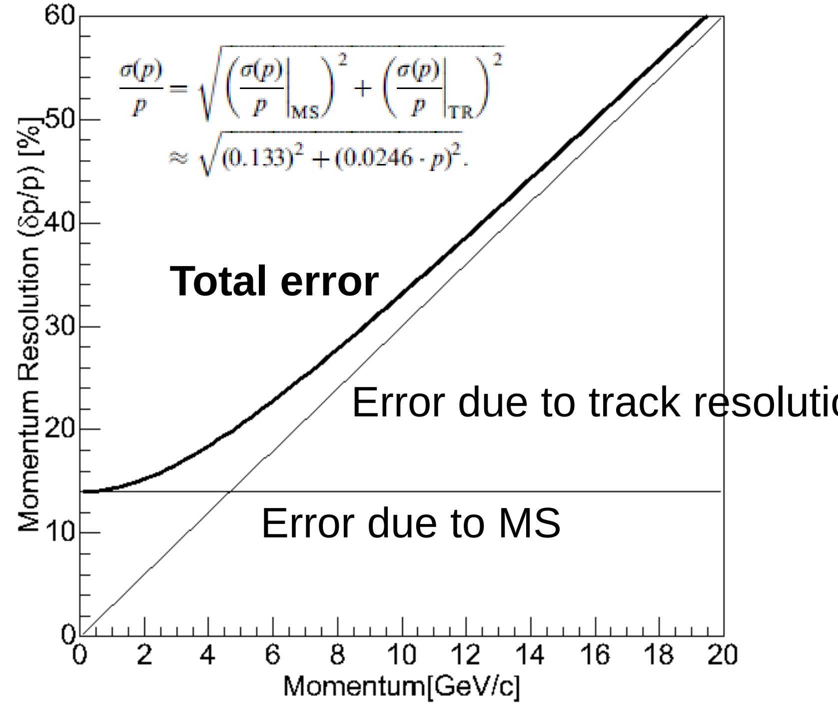
C. Fukushima et al., Nucl. Instr. and Meth. A 592 (2008) 56-62.

Results from the test beam experiment

Test Beam Experiment at KEK PS



Momentum resolution



The momentum resolution of the emulsion spectrometer depends on the errors due to multiple Coulomb scattering and due to the track resolution.

C. Fukushima et al., Nucl. Instr. and Meth. A 592 (2008) 56-62.

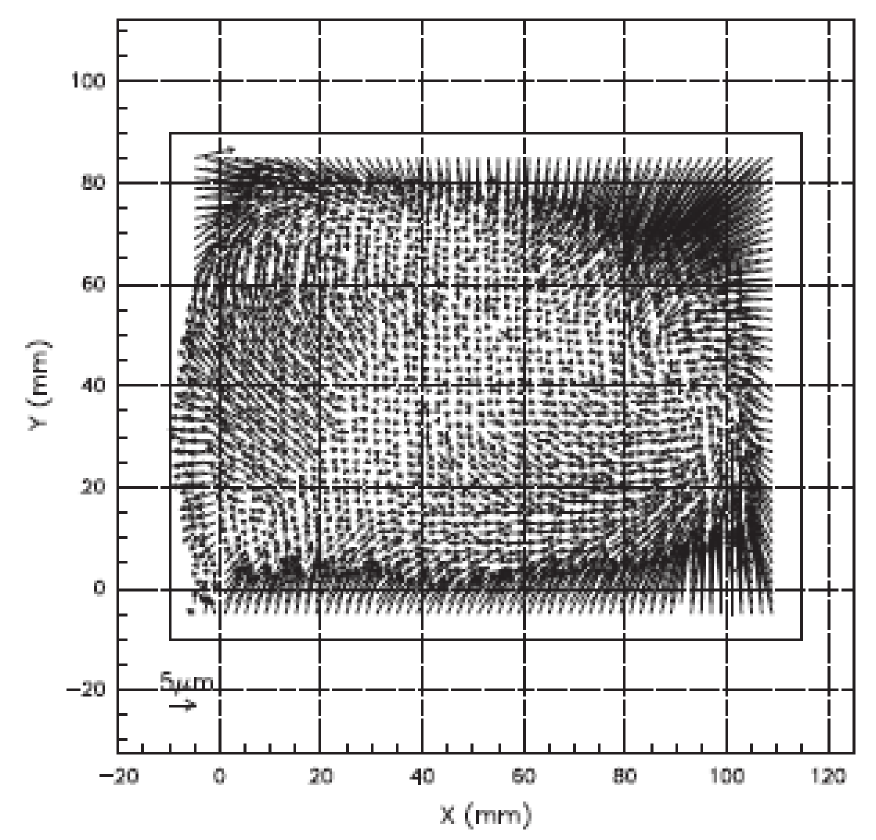
Practical problems found in experiments

1) Deformations in emulsion are produced in the development process, which must be corrected.

2) Slips of emulsion films during the exposure are observed in some cases.
Flatness of emulsion films are not complete.

Practical problem 1 (deformations in emulsion)

- Deformations in emulsion are produced in the development process, which must be corrected.



Film deformation reproduced from the grid mark measurements.

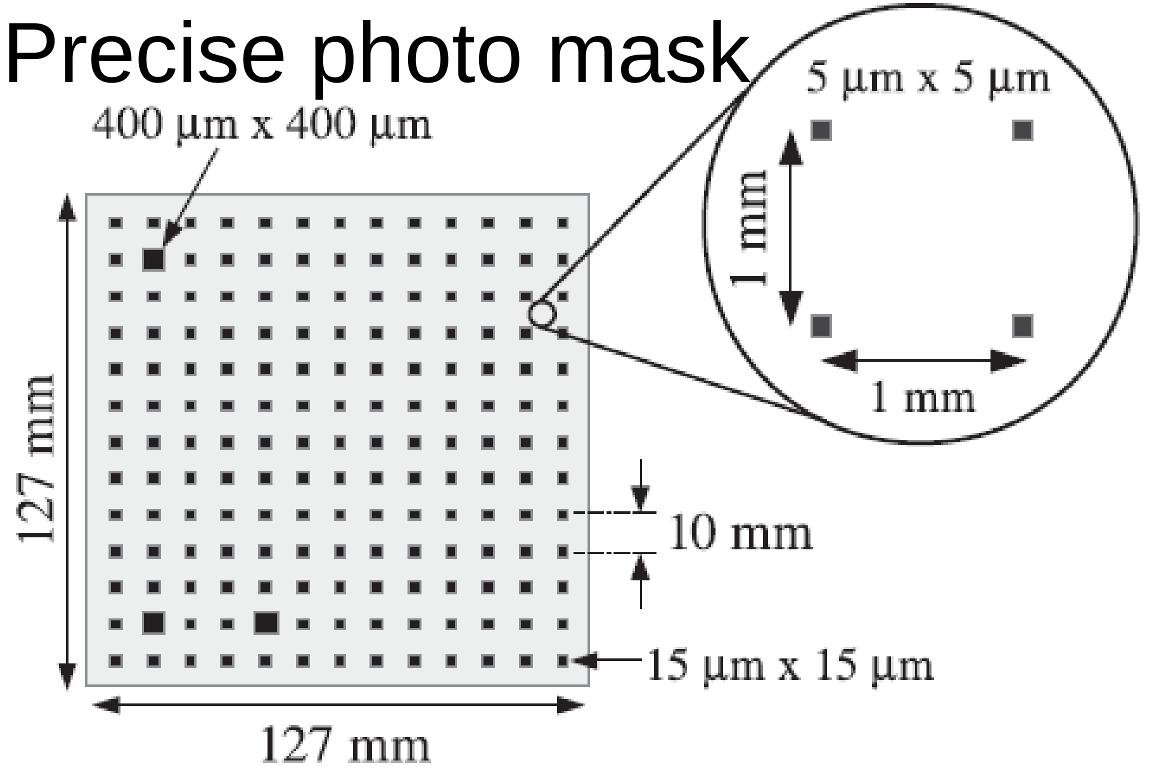
Method of correction

The major part of the deformation in emulsion originates from development process. Typically, these deformations are of the order of 1μm in the center part of the film and 10-20 μm near the edges. By printing on each film before development a set of accurate reference marks, these deformations can be determined by comparing the measured positions of the marks to their nominal ones. By this technique, the whole area of an emulsion film will become a position detector with 1μm accuracy.

Practical problem 1 (deformations in emulsion)

- The photo mask is made of synthetic quartz with a small thermal expansion coefficient of $5.8 \times 10^{-7}\ K^{-1}$.
- Grid marks were printed over a 127mm x127mm area.

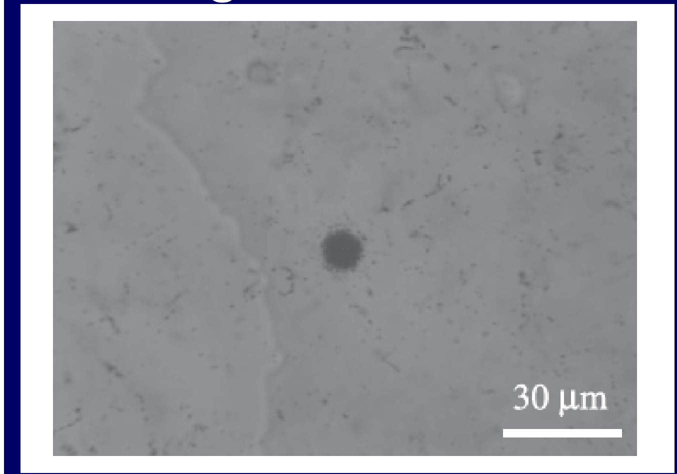
Precise photo mask



Design pattern of grid marks on photo mask.

M. Kimura et al., NIM A 711 (2013) 1.

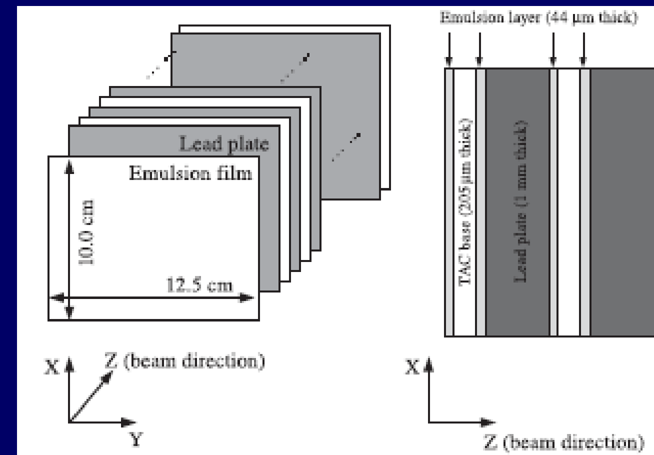
We used a contact printer equipped with a vacuum pump and an electric flash light.



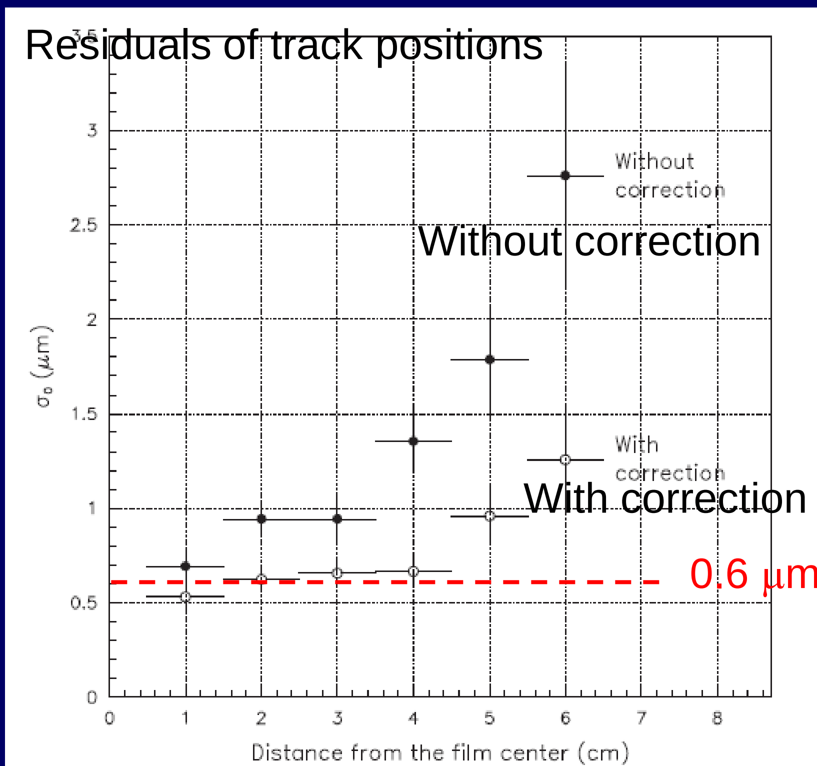
Printed image of a 5µm grid mark.

Practical problem 1 (deformations in emulsion)

- We carried out a muon beam exposure of an ECC brick at CERN SPS T2-H4 beam line.



The ECC brick was exposed to 30, 40, 150 GeV/c muon beams.



Residuals of track positions as a function of distance from the film center.

The deformations in film can be corrected.

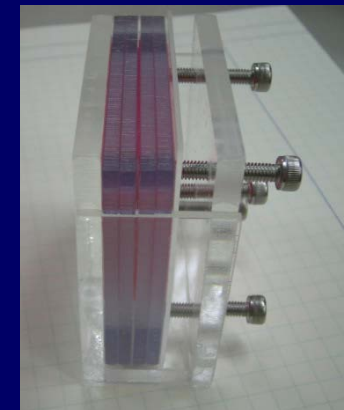
A position measurement accuracy of 0.6 μm is obtained over an area of 5cm x 7cm.

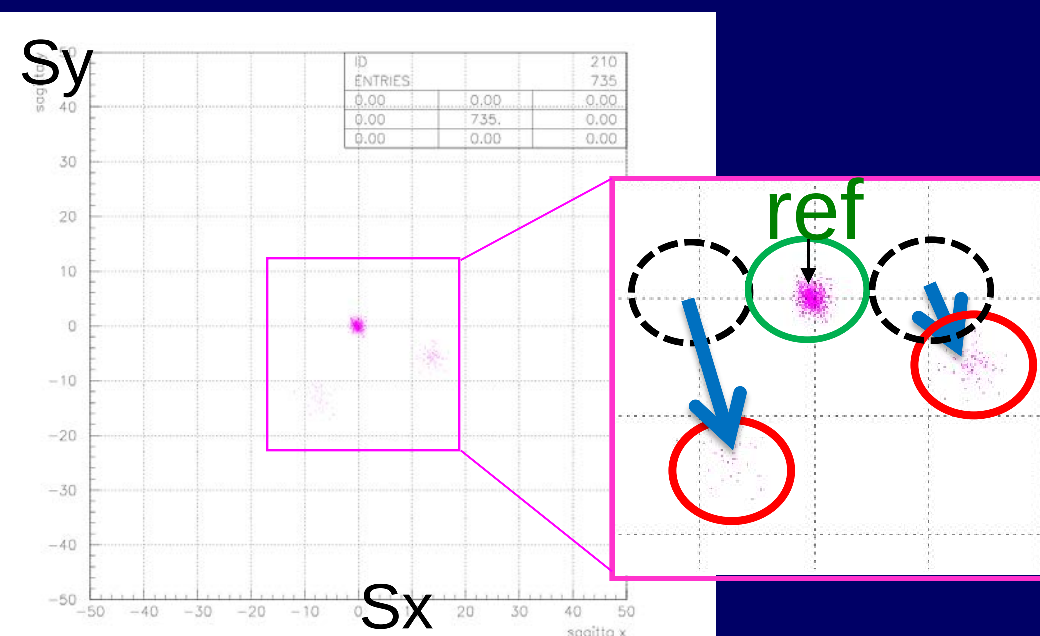
M. Kimura et al., NIM A 711 (2013) 1.

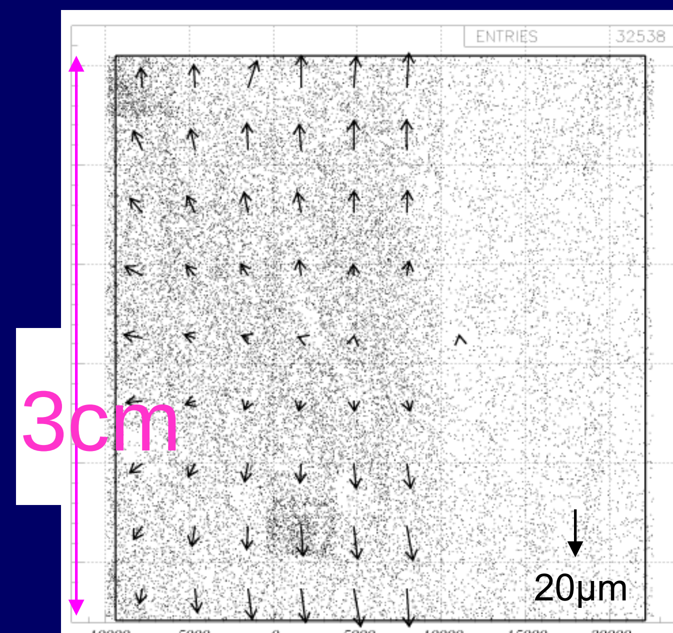
Practical problem 2 (slip and bending)

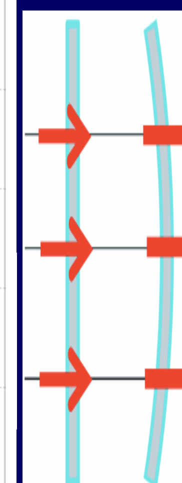
- Slip of emulsion films during the exposure
- Bending of emulsion films

If one tightens the screws strongly, the films bend.
If one tightens the screws weakly, the film slip.



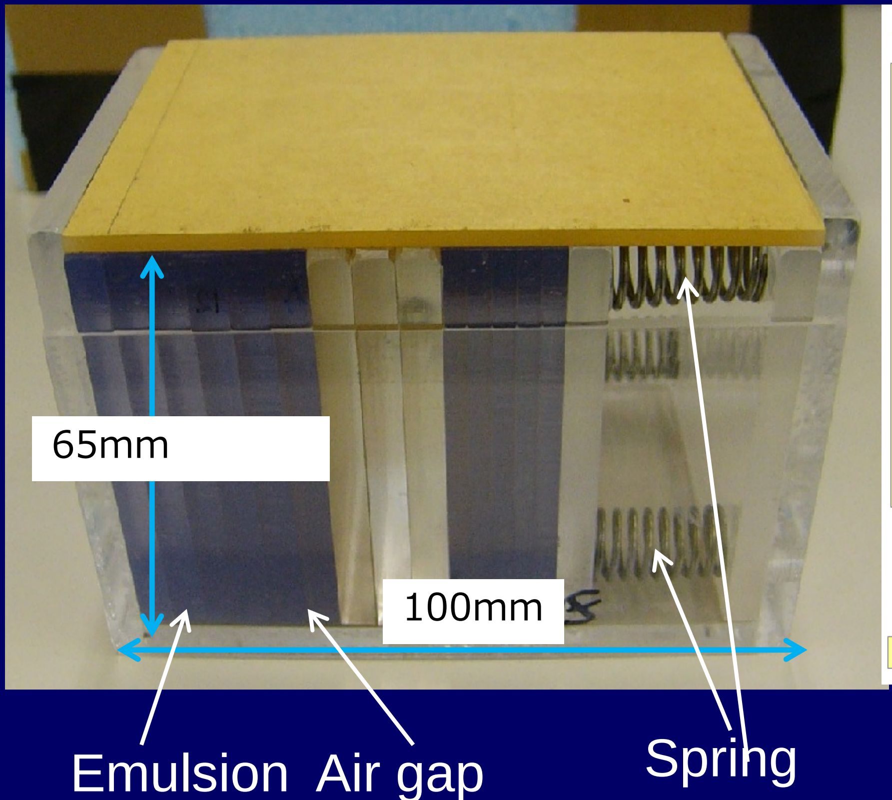


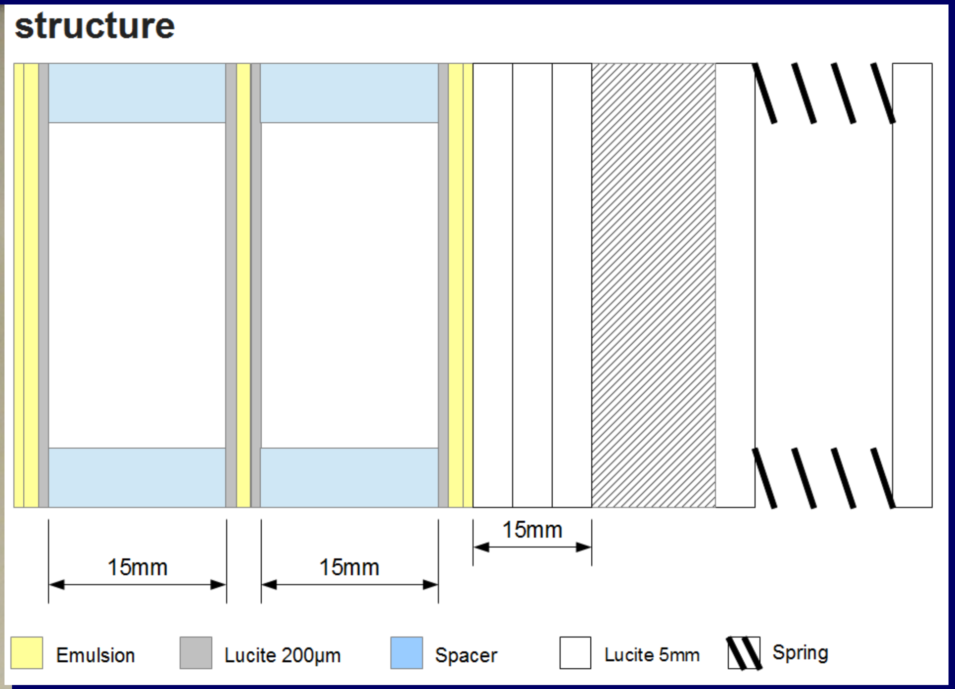




Practical problem 2 (slip and bending)

- A new structure of the emulsion spectrometer were considered.

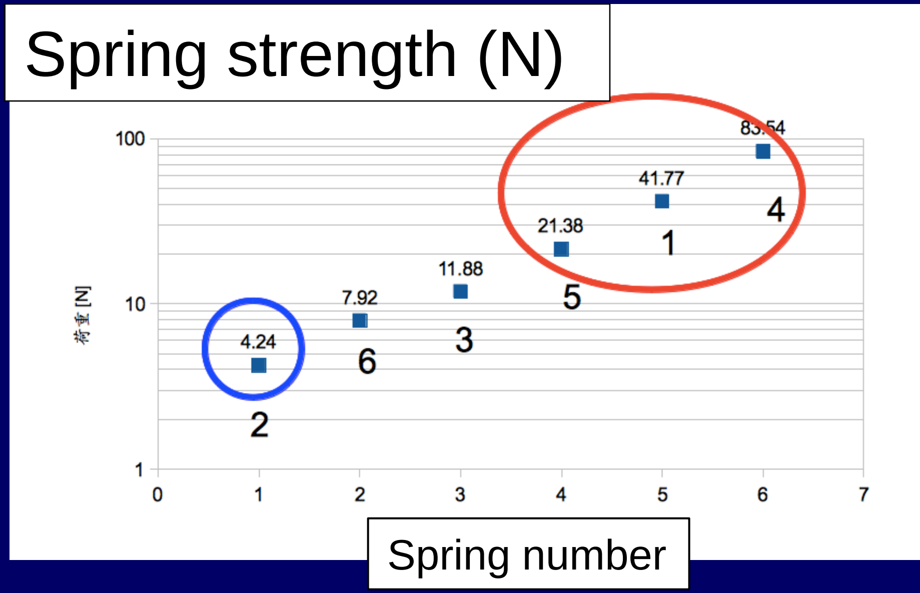




Films and spacers are fixed by springs which give a constant and uniform pressure.

Practical problem 2 (slip and bending)

- To test the new structure emulsion spectrometer,
  we performed a beam exposure at CERN.



Beam: π^- 6.0 GeV/c
Beam density: less than 3 x 10^3 / cm^2
Spring strength: 4, 8, 12, 20, 40, 80 N

We applied two kinds of actions/shocks to the emulsion stack;
1) Insert it into the magnet, 2) drop it on the table from the height of 3cm.

Soft shock Hard shock

Practical problem 2 (slip and bending)

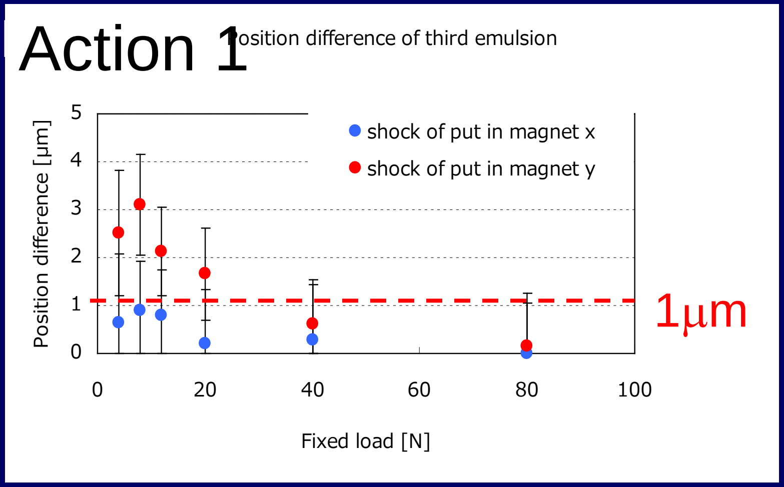
- Beam exposure was performed as follows.
- First, exposure with $\theta = 0.0$ rad for alignment.
- Then action 1) is applied.
- Second, exposure with $\theta = 0.1$ rad
- Action 2) is applied.
- Third, exposure with $\theta = -0.1$ rad
- As we can discriminate three beam tracks from each other, we can separate the effects of action 1) and 2).

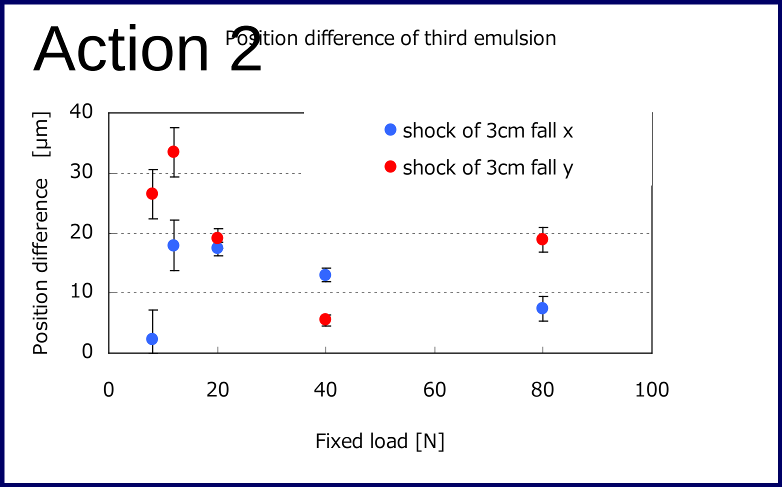
1) Insert it into the magnet. soft shock

2) Drop it from the height of 3cm. Hard shock

- Results from the text beam exposure.
- Good for stack with spring > 40 N

No good stack for action 2

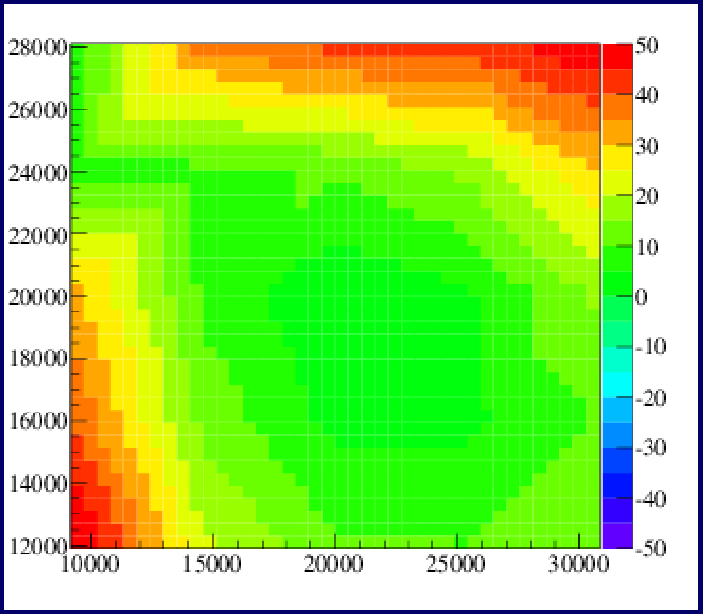




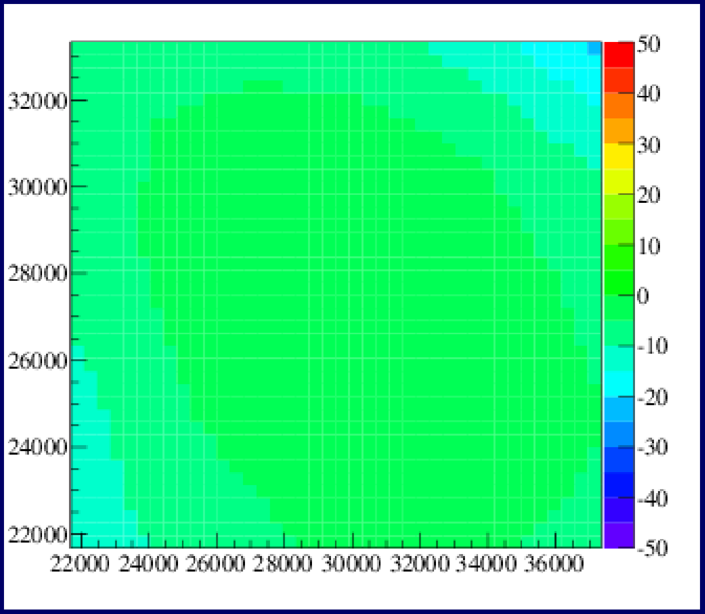
Practical problem 2

- <u>Flatness of films</u>

  is important to use emulsion films as position detectors.



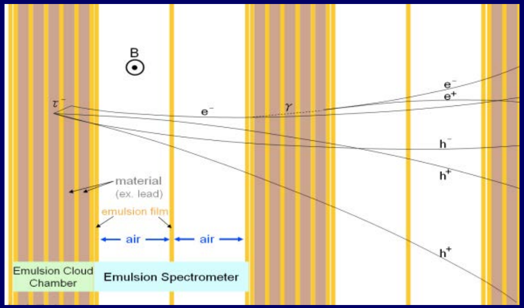
A film in a past experiment



A film in this experiment

Film flatness has been mush improved
by using plastic support and springs which produce uniform pressure.

Conclusions



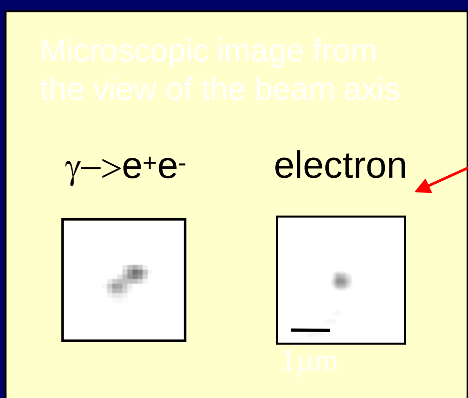
- The emulsion neutrino spectrometer has potential to become one of main detectors in future neutrino experiments.
- Concept and fundamental performances were successfully demonstrated by a test beam experiment.
- At the same time, some technical problems were found.
- By investigating their causes, some solutions have been found and they have been confirmed by test beam experiments.
- It is time to start the next move.

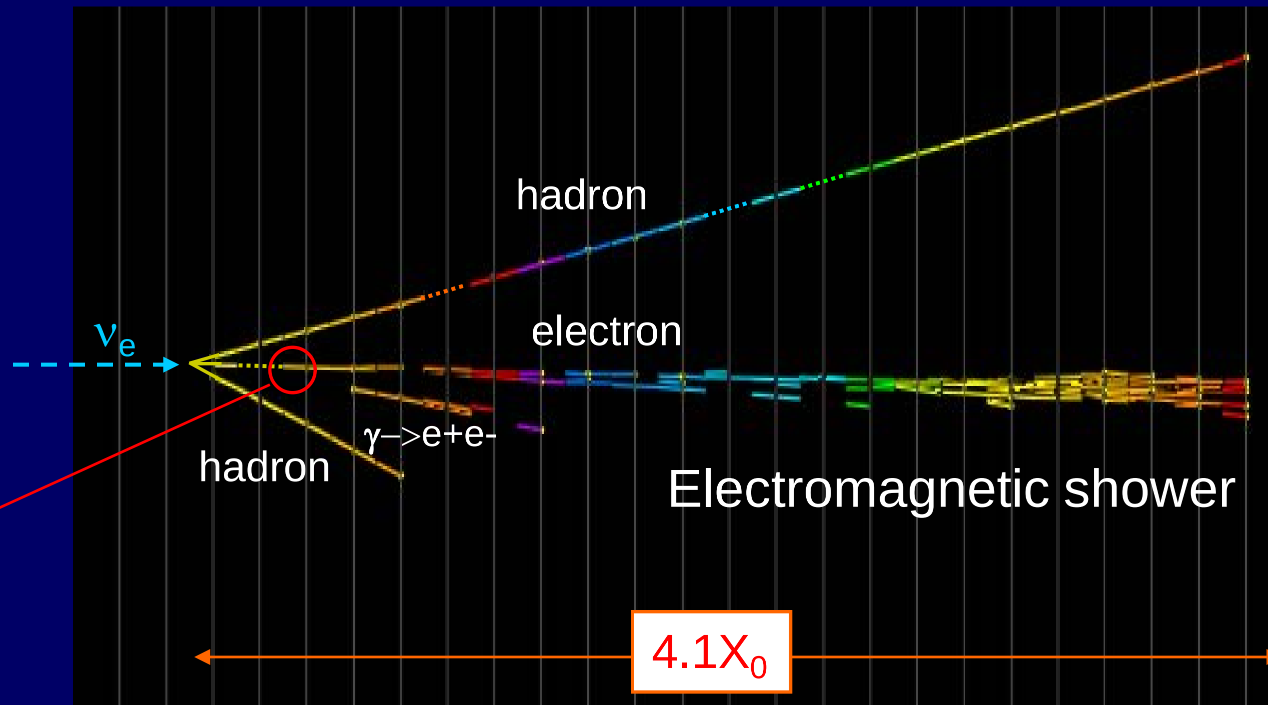
Outlook

- The next subject for the ENS development will be $\nu_e / \bar{\nu}_e$ identification.
- ν_e identification in ECC is being well studied in OPERA. $\nu_e / \bar{\nu}_e$ separation in ENS should be studied.
- Some tests and demonstrations are clearly needed.
- For example, the near detectors hall of J-PARC might be a good place to install the ENS to study low energy neutrino interactions.

Electron Identification in an ECC brick

OPERA





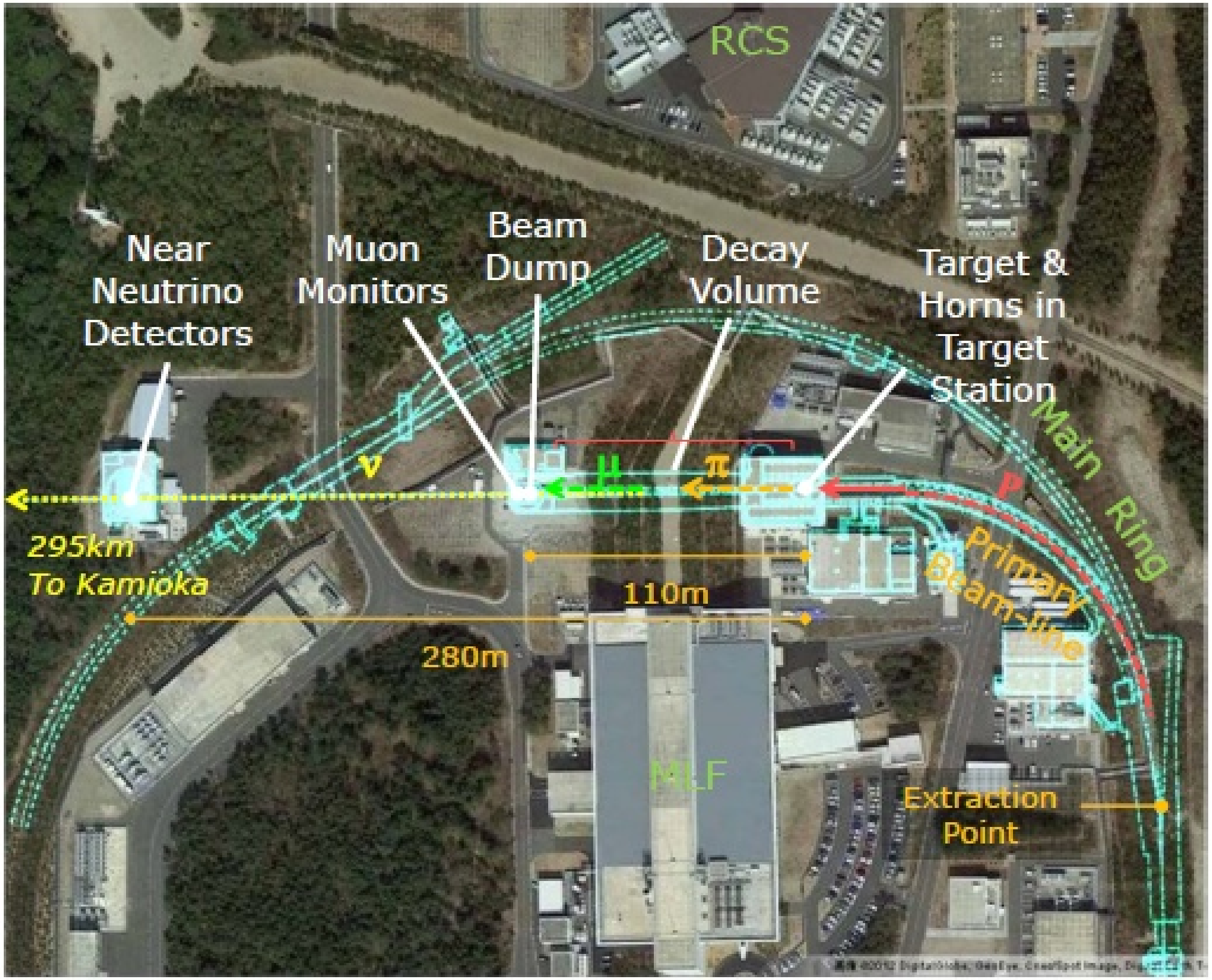
- Primary electron track observed as an isolated track, not as a pair of tracks

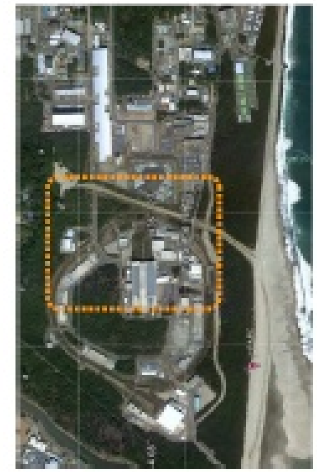
  fine position resolution of nuclear emulsion and fine segmentation (track reconstruction each 1mm lead plate ($0.18X_0$)) in the ECC brick
  –> separate an electron from a $\gamma \to e^+e^-$

- Electromagnetic shower developed in ECC

  –> separate an electron track from that of a pion

Neutrino experimental facility at J-PARC

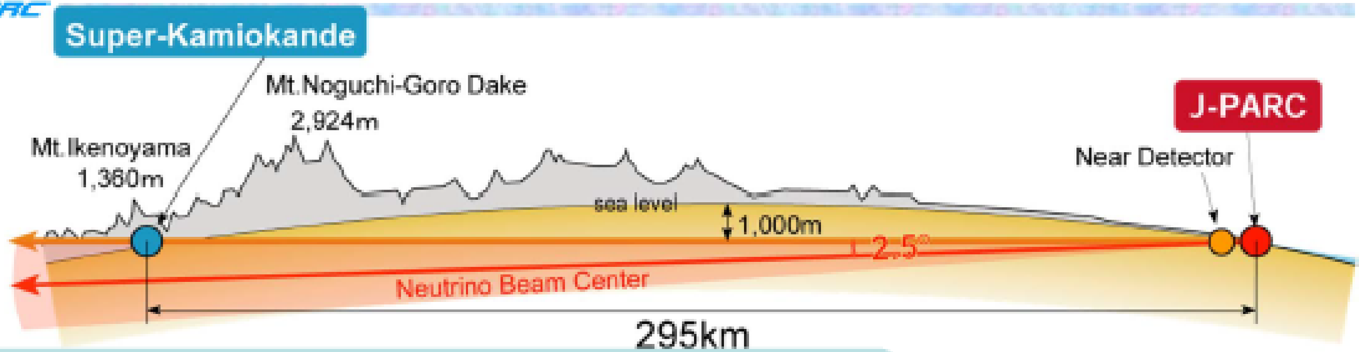


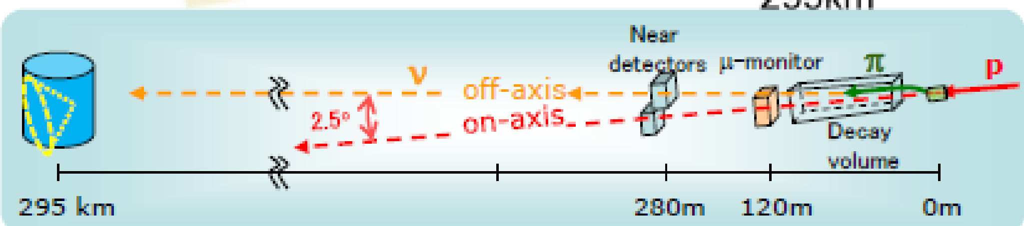


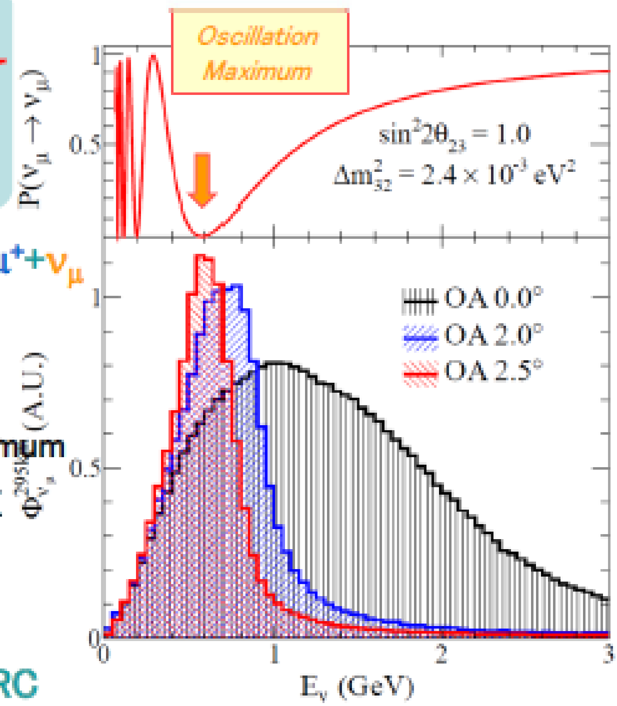
T2K , Y. Yamada 's presentation at JPS meeting 2013.

Near detectors are located at 280 m from the neutrino source.

The T2K experiment (Overview)



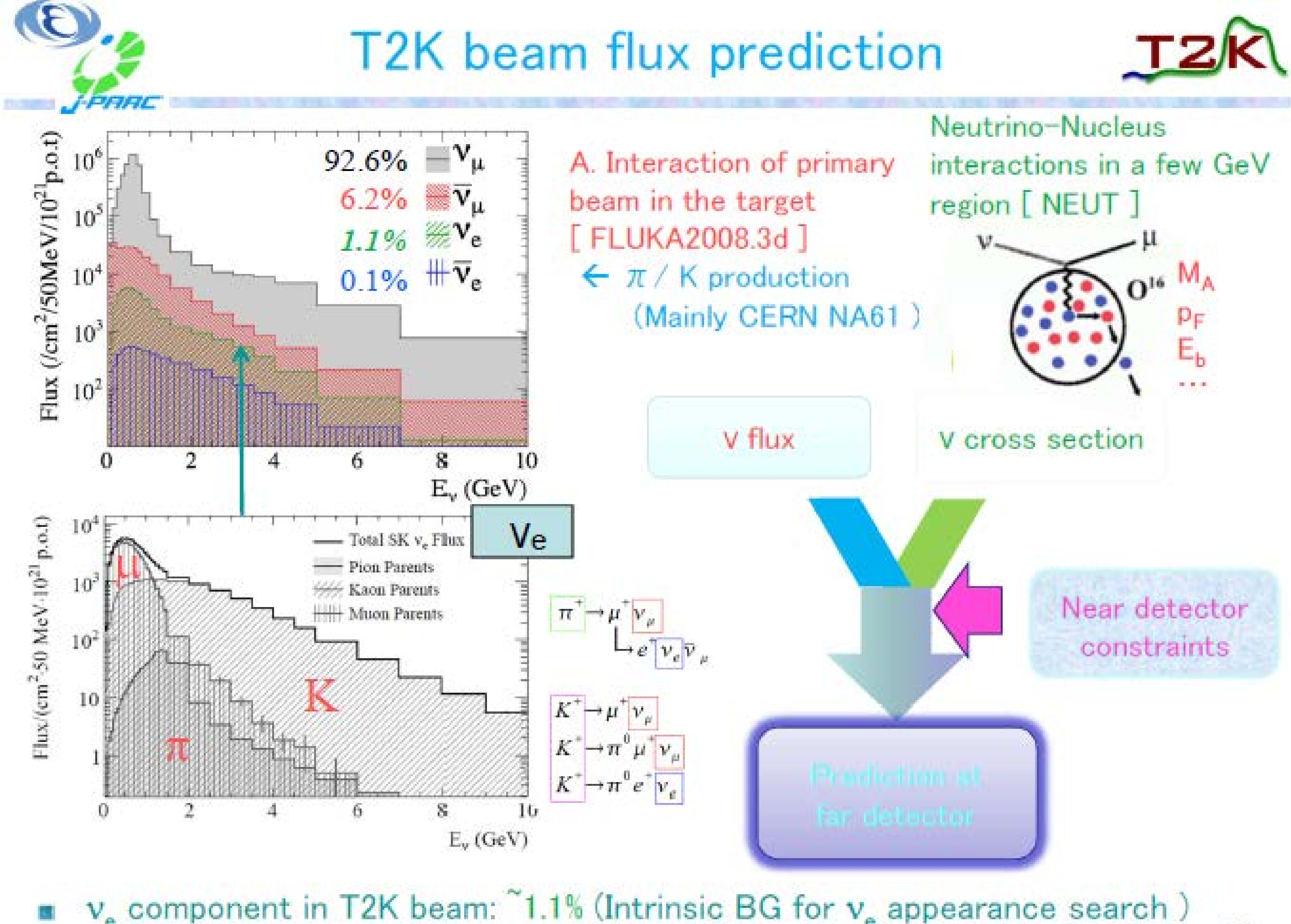




- 30GeV Protons on a graphite target: daughter $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- First application of Off-Axis(OA) beam:
  - Beam is 2.50° off-axis to the far detector direction
  - Low-energy narrow-band beam, peak at oscillation maximum
  - Small high-energy tail: reduce background events in T2K
- Near neutrino detectors @ 280m from target
  - On-Axis (INGRID) detector / Off-Axis (ND280) detector
- Far detector: Super-Kamiokande @ 295km from J-PARC

T2K , Y. Yamada 's presentation at JPS meeting 2013.

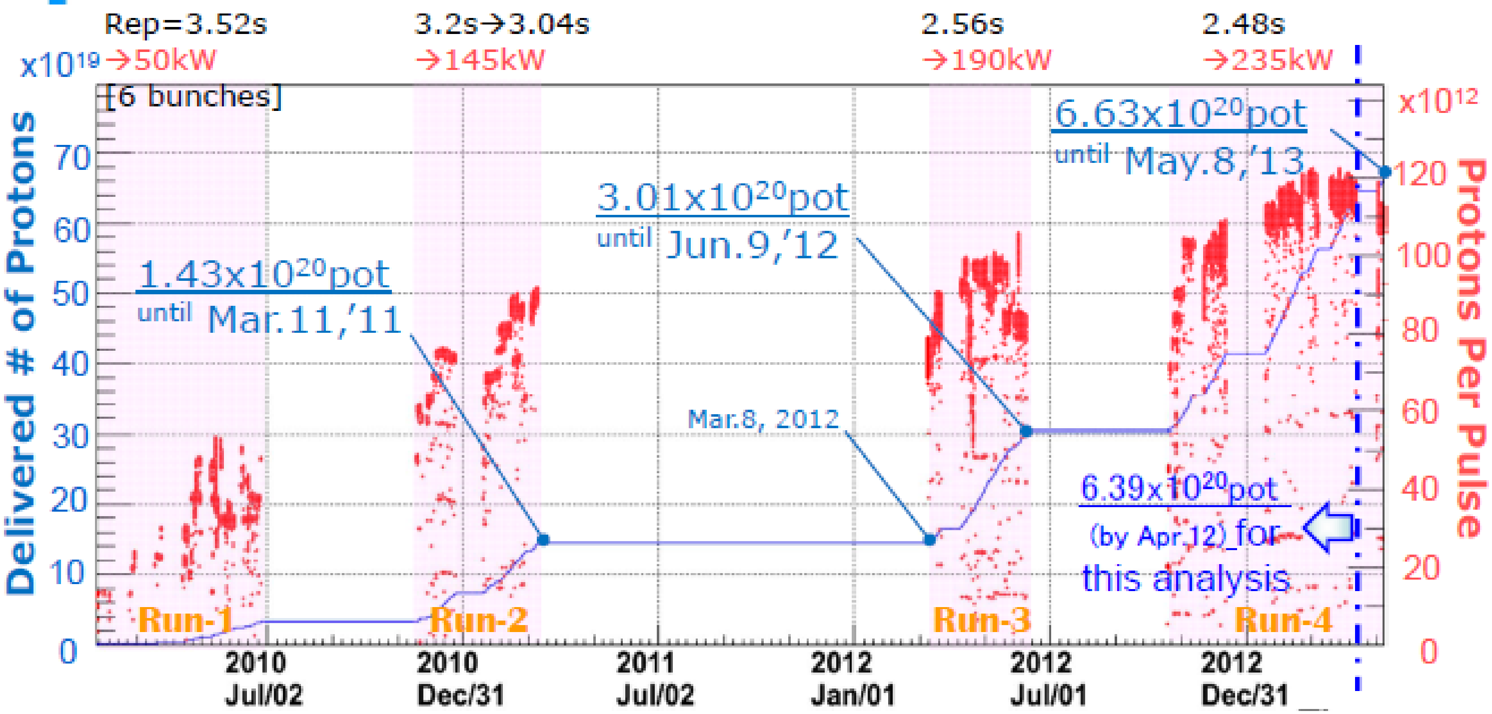
Beam energy peak at around 1 GeV



T2K , Y. Yamada’s presentation at JPS meeting 2013.

1% ν_e, 0.1% $\bar{\nu}_e$ in the ν_μ beam

Delivered POT to neutrino facility



- Stable operation at ~220kW achieved.
  - >1.2x10^14ppp (1.5x10^13x8b) is the *world record* of extracted protons per pulse for synchrotrons.
- Data for today's talk: 6.39x10^20pot (by Apr.12). 6.63x10^20 by May.8.
  - Statistics has been doubled successfully compared to the previous analysis (3.01x10^20pot)

T2K , Y. Yamada's presentation at JPS meeting 2013.

Expected beam:
Beam power : 235kW (2012Oct~) -> 1MW
~3x10^20 pot delivered in 6 months

1×10^{21} /year
170 k events /ton/year
About 10^3 ν_μ events/brick/year
(10 ν_e, 1 $\overline{\nu}_e$ events)

Thank you for your attention!