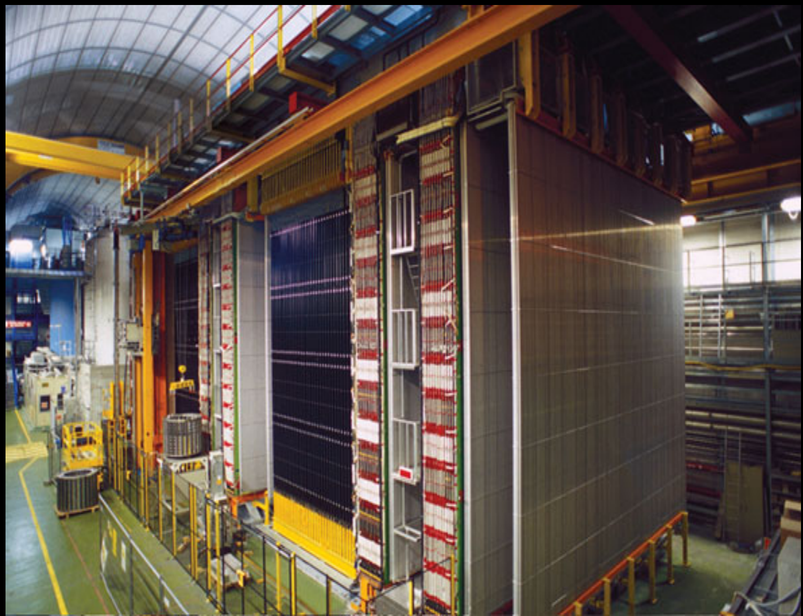
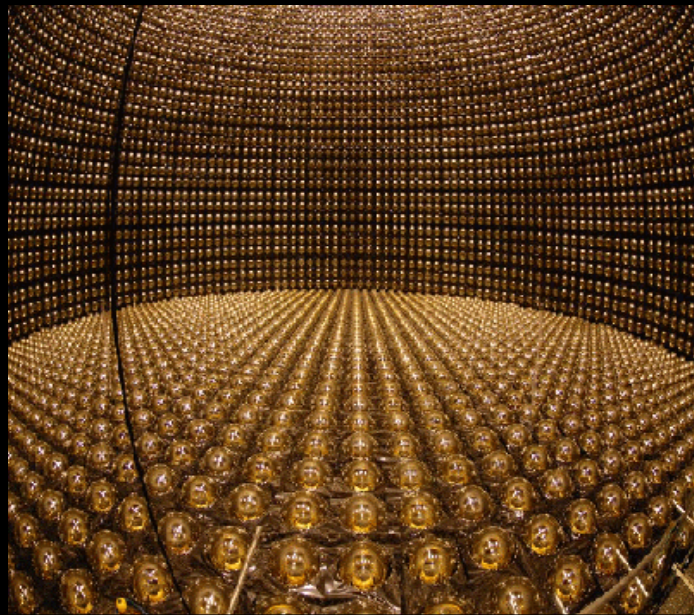
The quest of oscillation appearance: OPERA and T2K





V International Pontecorvo Neutrino Physics School

Antonio Ereditato
University of Bern

Bruno Pontecorvo (Dubna 1984)

PHYSICS: from neutrino mixing to oscillations

3x3 Unitary Mixing Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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 terms **Interference terms** **Solar terms**

$c_{ij} = \cos\theta_{ij},\ s_{ij} = \sin\theta_{ij}$

How to determine the elements of the PMNS matrix

OPERA ↓ **T2K** ↓

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Measured with atm and LBL } \nu} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta} s_{13} & 0 & c_{13} \end{pmatrix}}_{\text{Measured with reactor and LBL } \nu} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Measured with solar, reactor } \nu}$$

Measured with atm and LBL ν — Measured with reactor and LBL ν — Measured with solar, reactor ν

$\theta_{23} \approx \pi/4$ $\theta_{13} \approx \pi/20$ $\theta_{12} \approx \pi/6$

- First idea of Pontecorvo in the late 50’
- Formulation of the formalism: PMNS
- Solar neutrino deficit/puzzle, solar neutrino experiments
- MSW interpretation
- Hints for analogous deficit for atmospheric neutrinos
- Discovery of neutrino oscillations with Super-Kamiokande (atmospheric neutrinos) 1998
- Solution of the solar neutrino puzzle (circa 2002)
- Precision measurement of leading parameters: solar + atmospheric + accelerator + reactor experiments
- Indications of finite (sub-leading) θ_{13} in 2011, discovery of θ_{13} in 2012

- Today, still open questions despite the incredible amount of outstanding results:

mass hierarchy, CP violations, explanation of large mixing angles, direct mass measurements, Dirac vs Majorana, and…

Detection of direct oscillation appearance

Oscillation formulae (3-neutrino scheme)

OPERA

$$\begin{aligned} P(\nu_\mu \to \nu_\tau) \simeq & \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2\Delta_{atm} \\ & - \Delta_{sol}\cos^2\theta_{13}\sin^2 2\theta_{23}(\cos^2\theta_{12} - \sin^2\theta_{13}\sin^2\theta_{12})\sin 2\Delta_{atm} \\ & - \Delta_{sol}\cos\delta\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos 2\theta_{23}\sin 2\Delta_{atm}/2 \\ & + \Delta_{sol}\sin\delta\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\sin^2\Delta_{atm} \end{aligned}$$

T2K

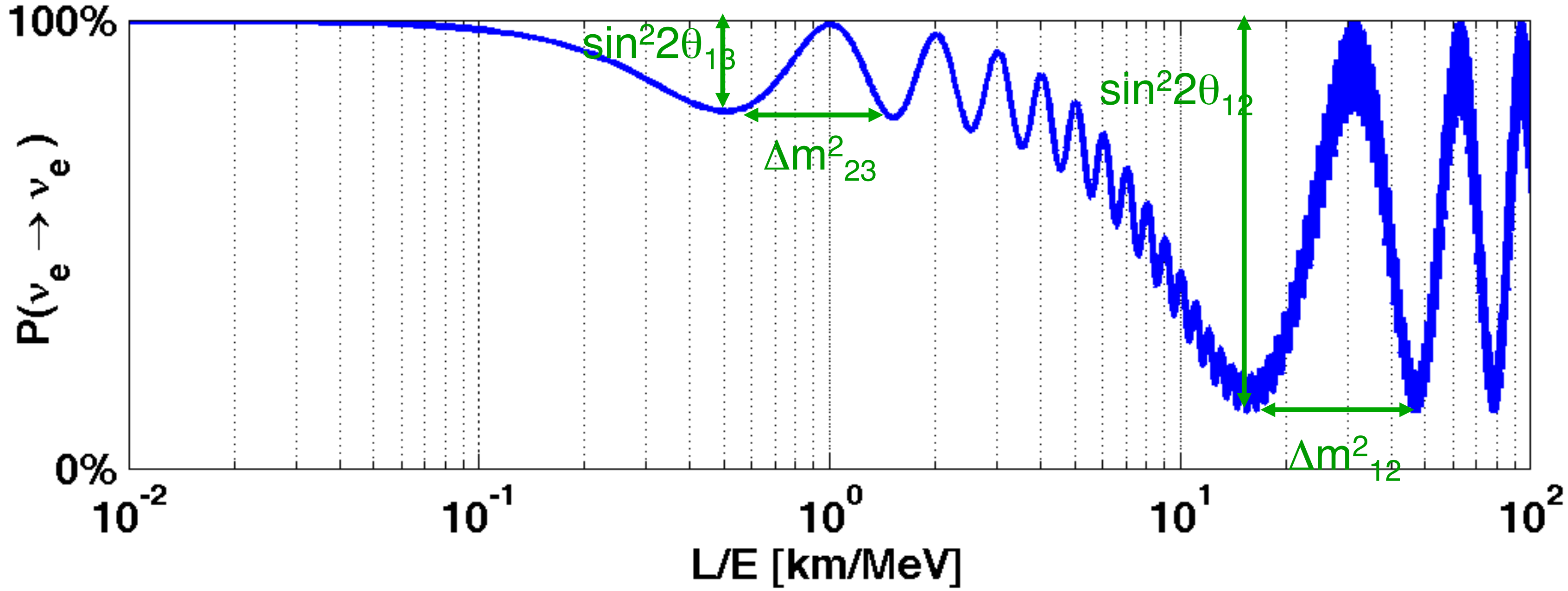
$$\begin{aligned} P(\nu_\mu \to \nu_e) \simeq & \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\Delta_{atm} \\ & - \Delta_{sol}\sin^2\theta_{23}\sin^2\theta_{12}\sin^2 2\theta_{13}\sin 2\Delta_{atm} \\ & + \Delta_{sol}\cos\delta\cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\sin 2\Delta_{atm}/2 \\ & - \Delta_{sol}\sin\delta\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\sin^2\Delta_{atm} \end{aligned}$$

Dominant terms

$$P(\nu_\mu \rightarrow \nu_\tau) \sim \sin^2 2\theta_{23}\cos^4\theta_{13}\sin^2(\Delta m^2_{23}L/4E)$$

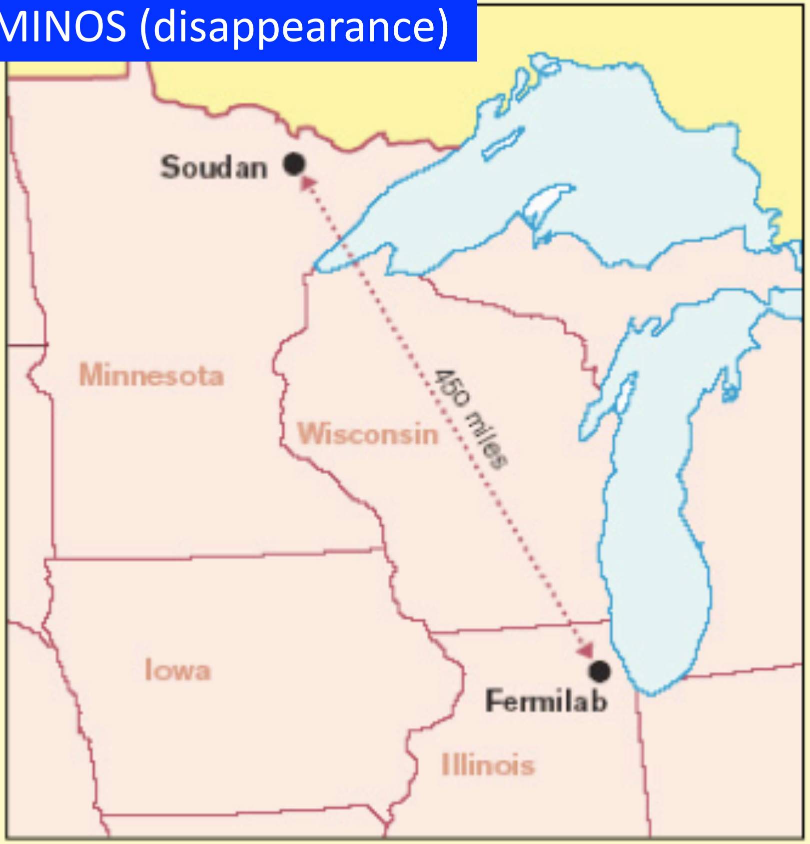
$$P(\nu_\mu \rightarrow \nu_e) \sim \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2(\Delta m^2_{23}L/4E)$$

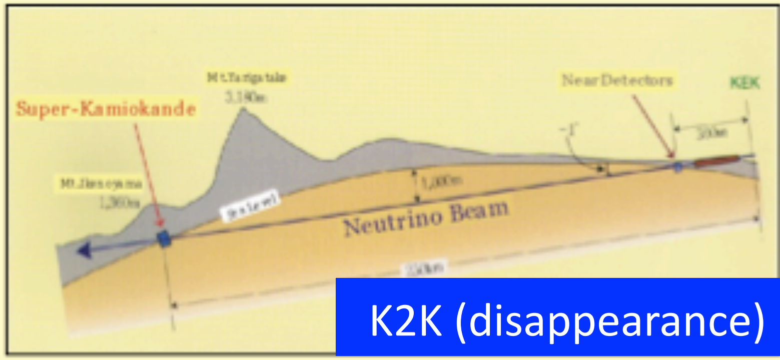
Example: ν_e survival (3-neutrino scheme)



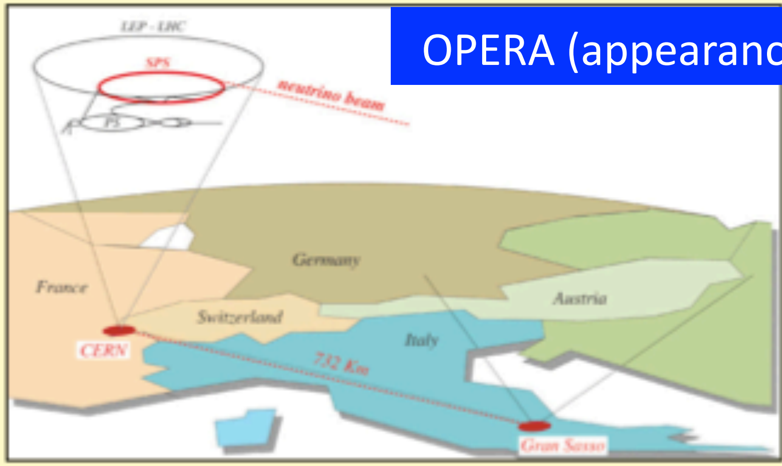
"Reproducing atmospheric ν_μ physics" in controlled conditions

MINOS (disappearance)





K2K (disappearance)



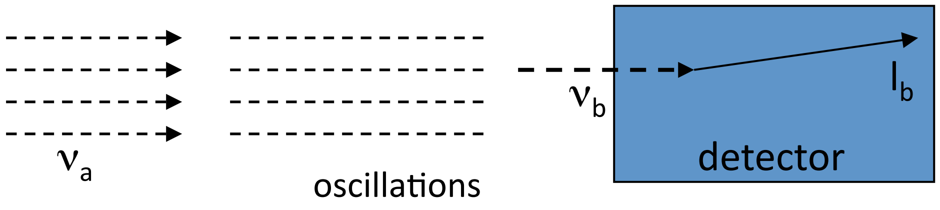
OPERA (appearance)

end of 90': re-creating the same L/E conditions of atmospheric neutrino experiments (Super-Kamiokande signal)

Disappearance vs appearance experiments

APPEARANCE experiments

$\nu_a - \nu_b$ oscillations



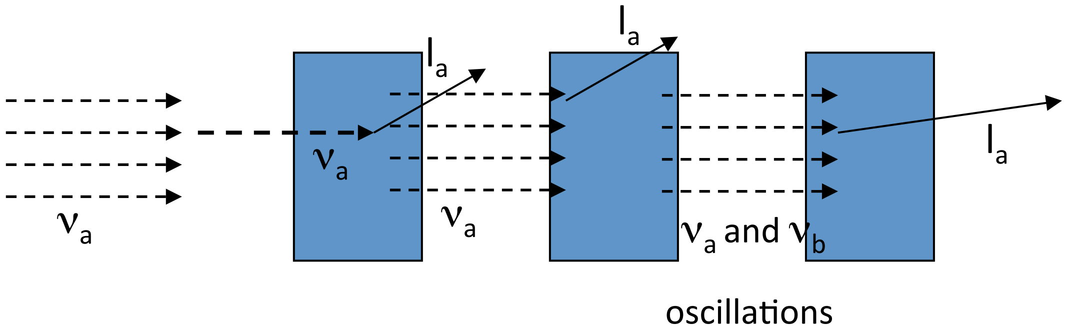
CC interaction of ν_b producing the charged lepton b, whose appearance is detected

NEED:

1) no ν_b in the initial beam (or a small fraction very well known)
2) E_ν sufficient to produce a b lepton
3) high efficiency in detecting the b lepton

DISAPPEARANCE experiments

$\nu_a - \nu_x$ oscillations

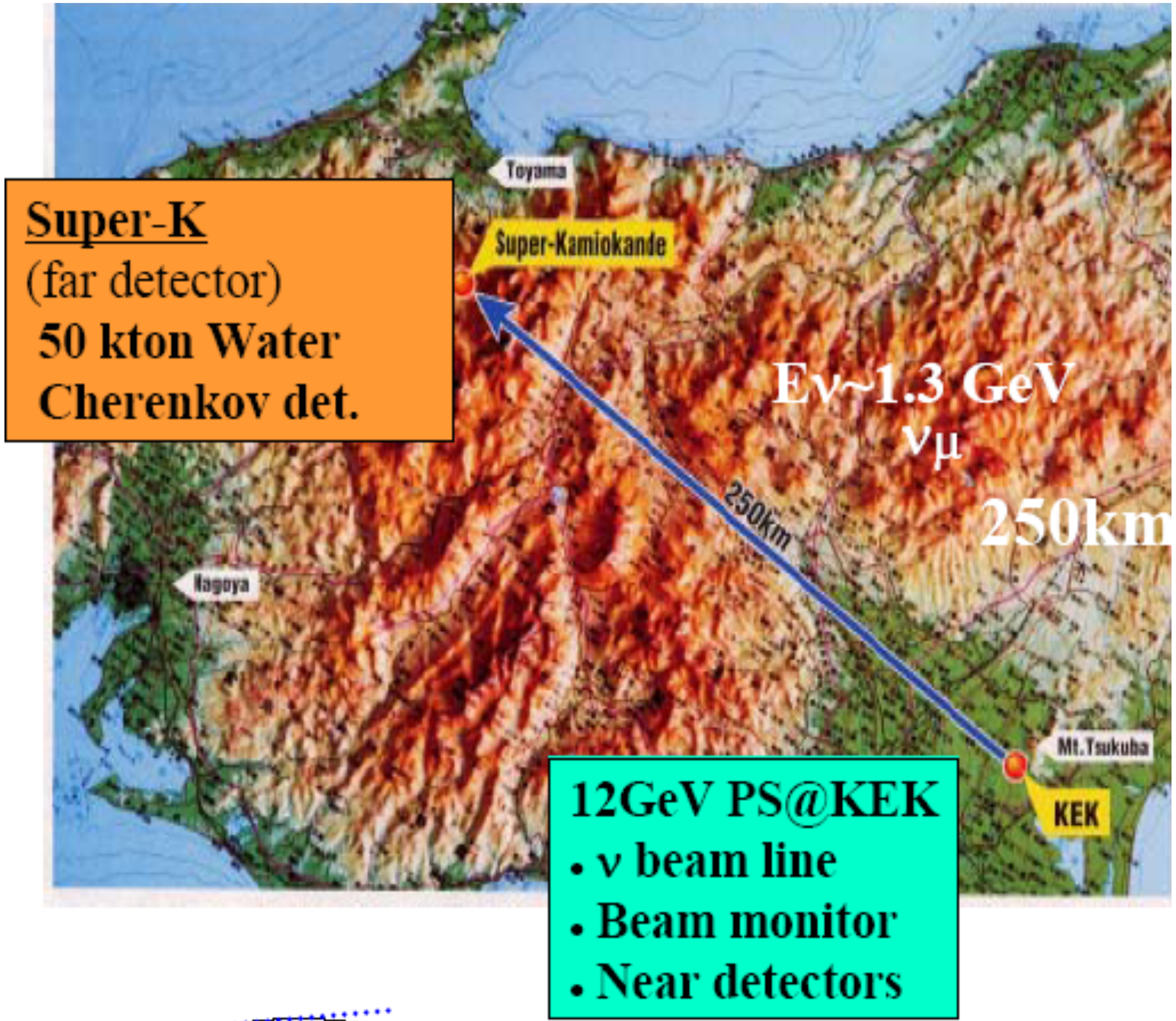


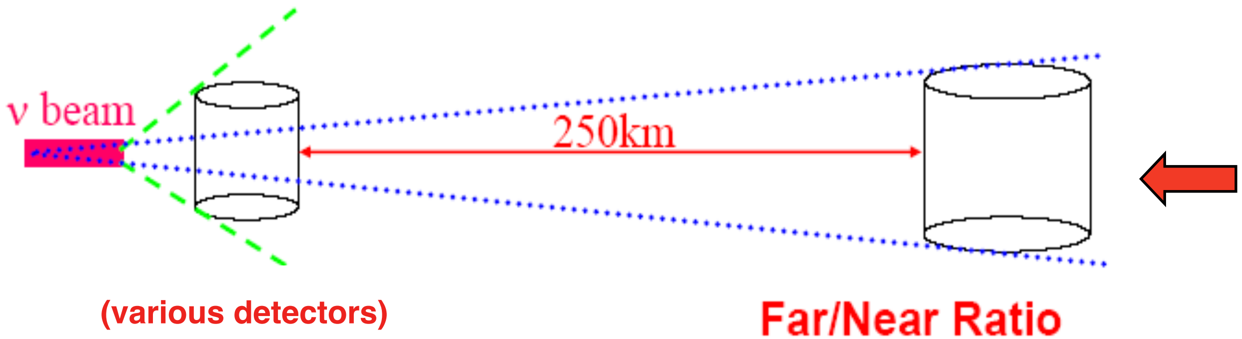
CC interaction of ν_a producing the charged lepton a, measured where oscillations do-not/do occur

NEED:

1) tiny effects: very good knowledge of the beam, and good control of detector systematics
2) useful to have 'near' and 'far' detector of the same type (mass scaling with L^2)
3) look for spectrum distortions

K2K… the mother of all LBL experiments

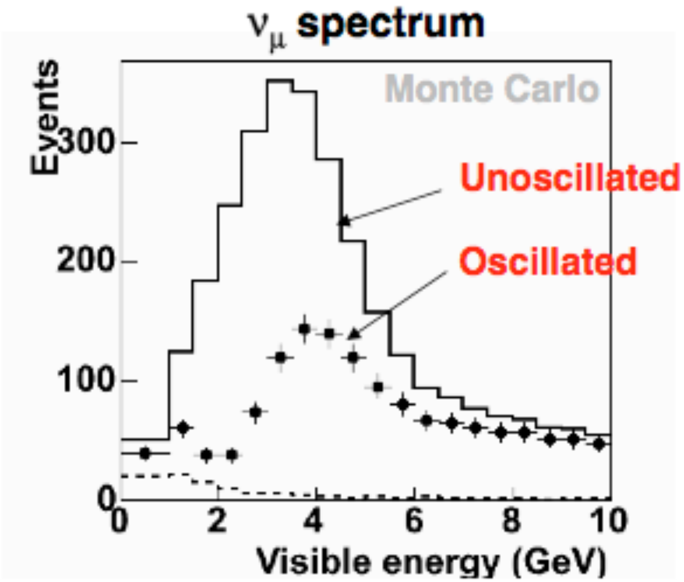


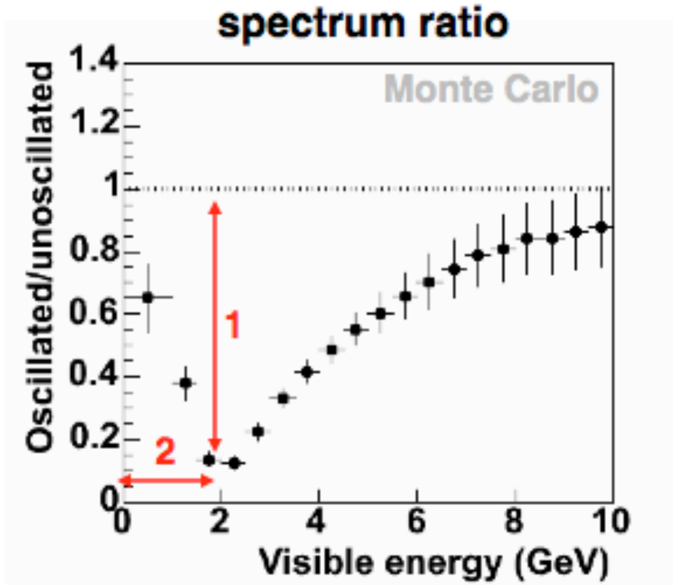


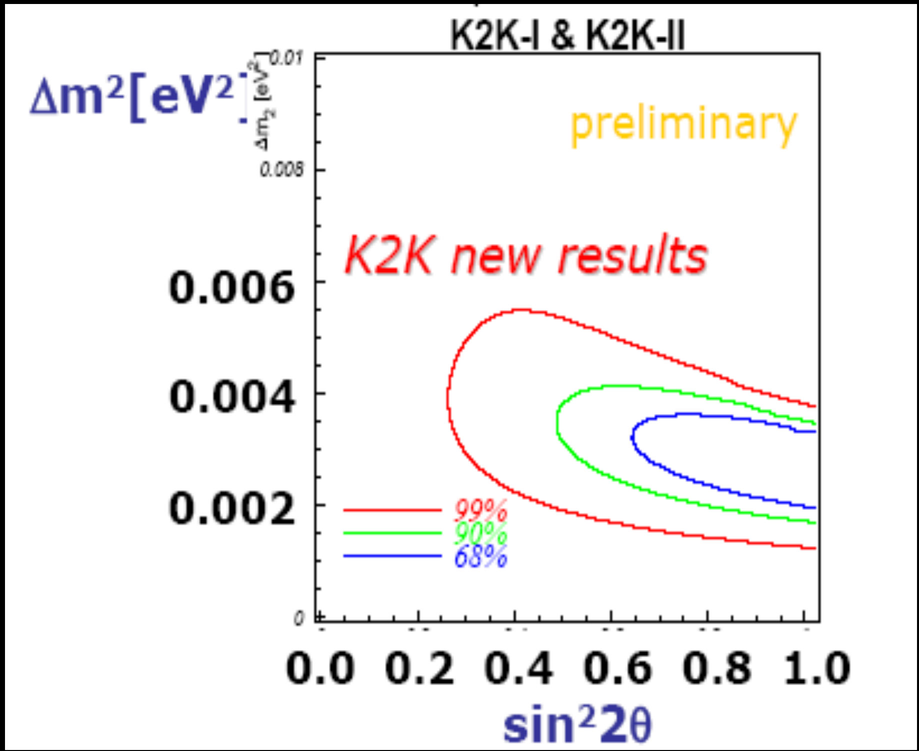
near/far detectors comparison: event rate and energy spectrum shape

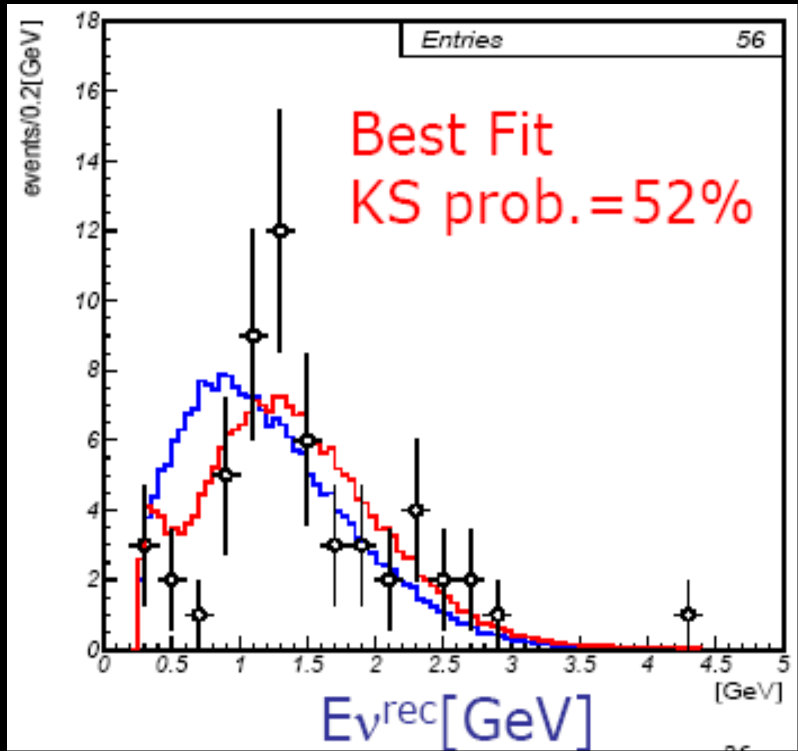
Example of a ν_μ disappearance measurement

$$P(\nu_\mu \to \nu_\mu) = 1 - \boxed{\sin^2 2\theta}_{1} \sin^2(1.267 \boxed{\Delta m^2}_{2} L/E)$$









K2K results (confirming SK- atm):

$1.7 < \Delta m^2 < 3.5$ eV^2 for $\sin^2 2\theta = 1$ (90% CL)

(ν_μ disappearance plus shape distortion)

oscillation hypothesis confirmed at 3.9 σ

Focus now on the oscillation "appearance" studies of OPERA and T2K

OPERA

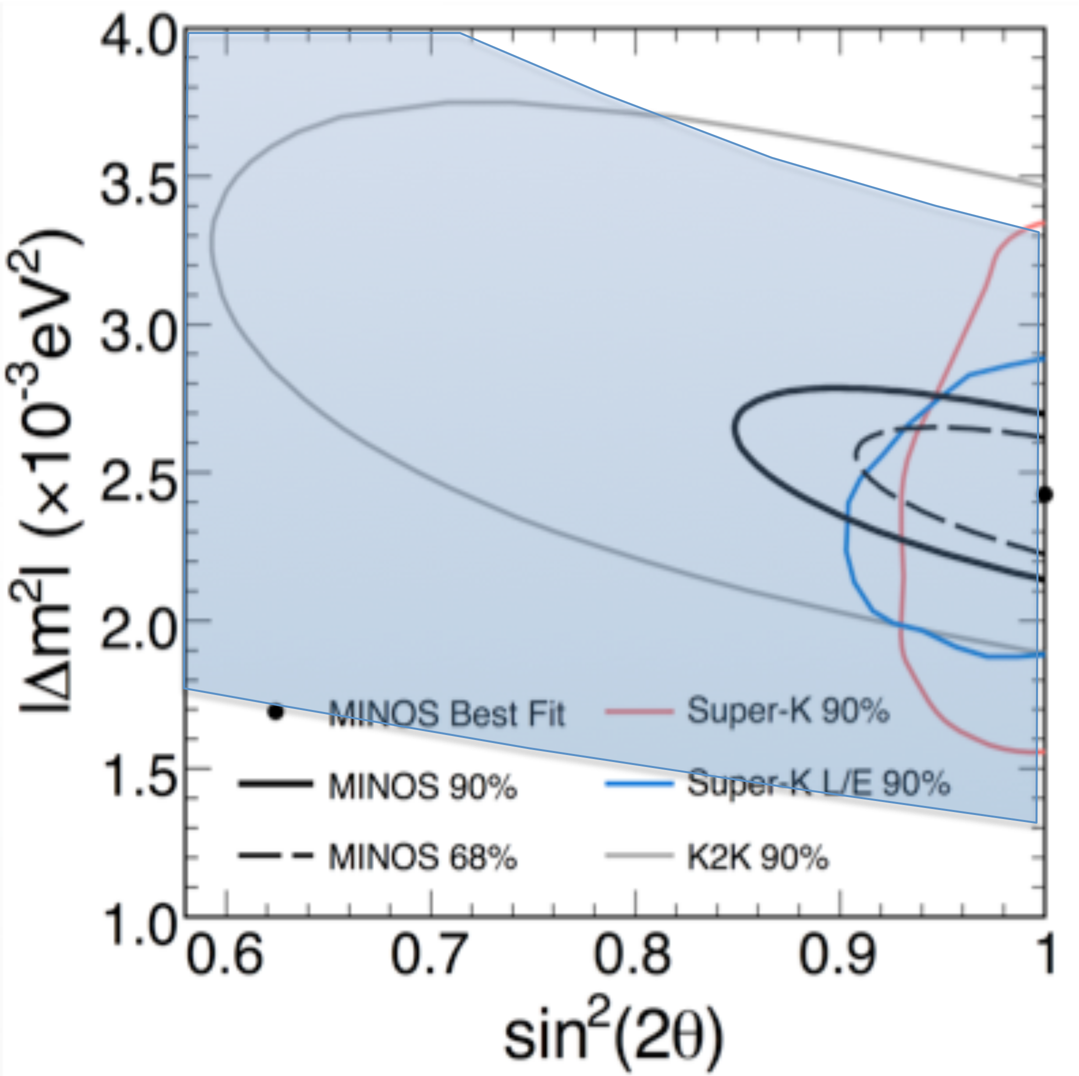
direct detection of neutrino oscillations in appearance mode

$$P(\nu_\mu \rightarrow \nu_\tau) \sim \sin^2 2\theta_{23} \cos^4\theta_{13} \sin^2(\Delta m^2_{23} L/4E)$$

Requirements:

1) long baseline
2) high neutrino energy
3) high beam intensity
4) detect short lived τ's

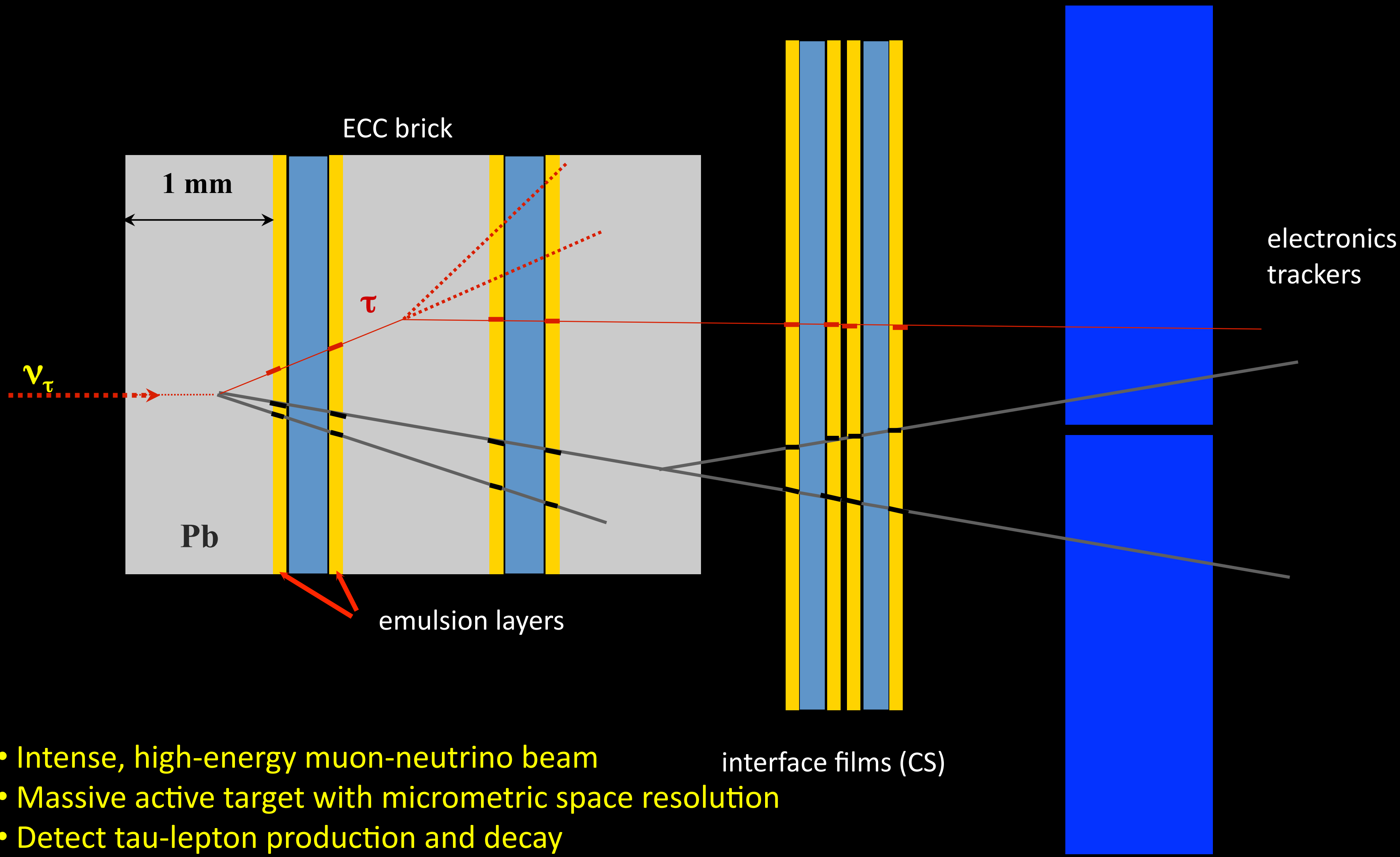
Oscillation parameter sensitivity



Full mixing and
$\Delta m^2_{23} \sim 2.4 \times 10^{-3}$ eV^2

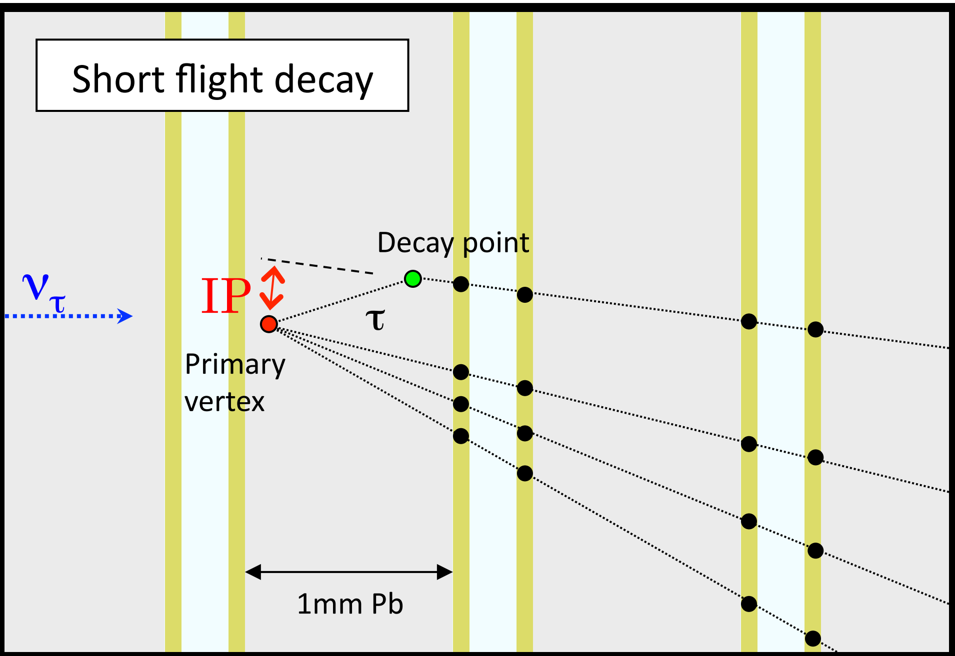
The grey band indicates the OPERA allowed region (90% CL) for the above parameter values for 22.5×10^{19} pot

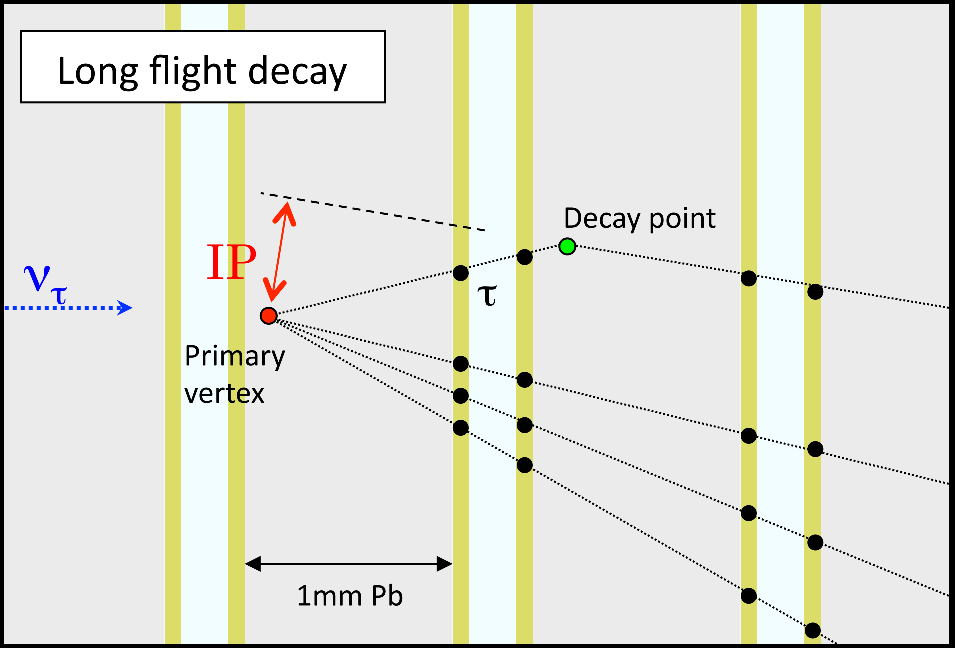
THE PRINCIPLE OF THE EXPERIMENT: ECC + ELECTRONIC DETECTORS



- Intense, high-energy muon-neutrino beam
- Massive active target with micrometric space resolution
- Detect tau-lepton production and decay
- Use electronic detectors to provide "time resolution" to the emulsions and preselect the interaction region

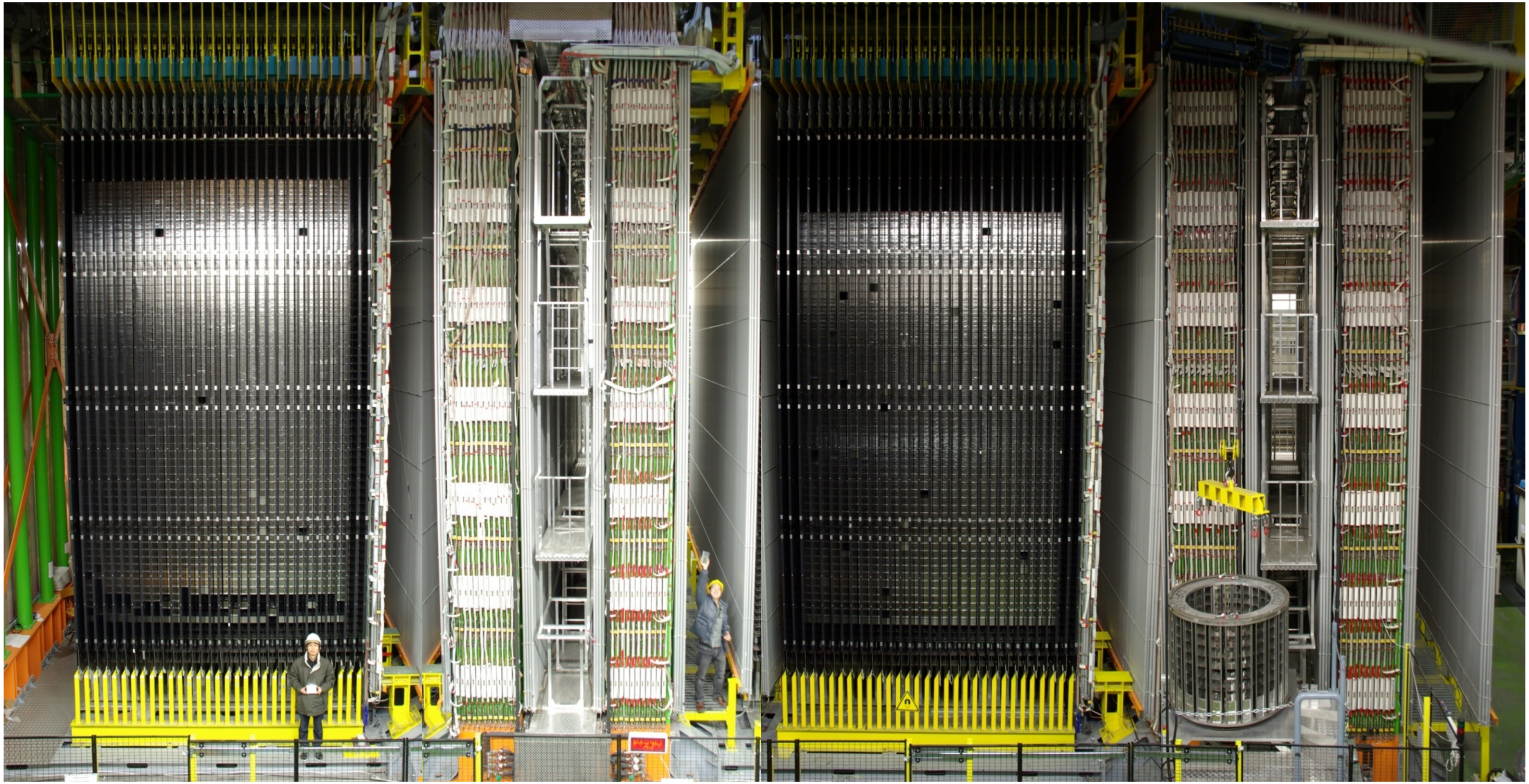
ν_τ CC detection





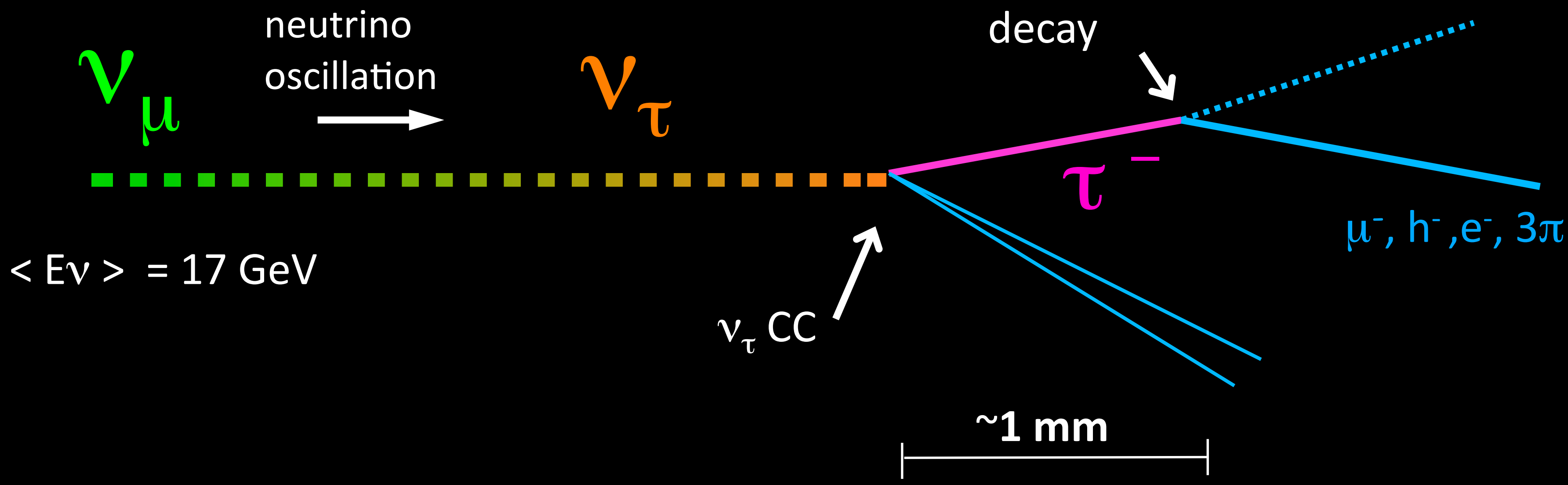
THE IMPLEMENTATION OF THE PRINCIPLE

SM1 SM2



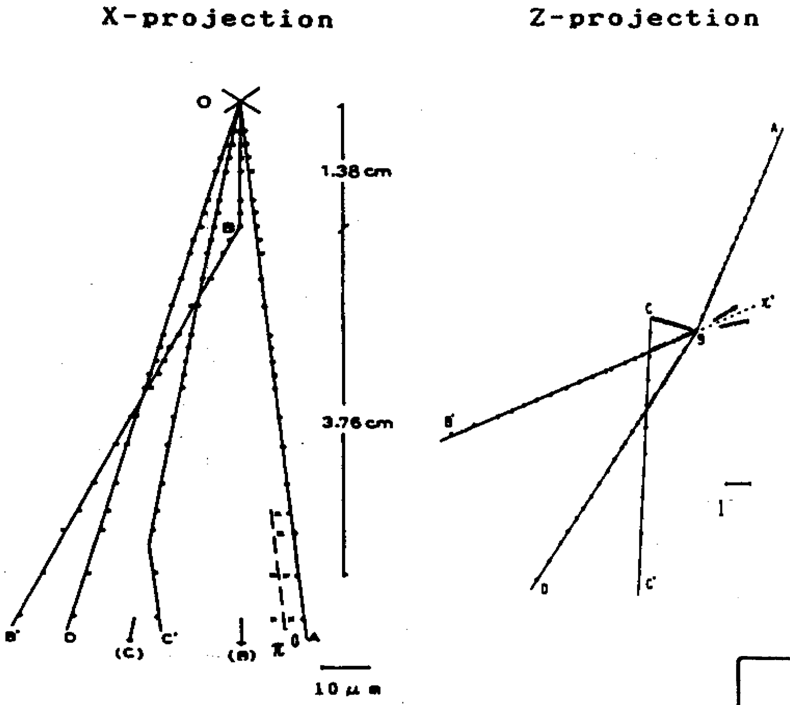
Target area   Muon spectrometer

τ decay modes



Topology	decay mode	BR	exp. evts. for 22.5×10^{19} pot	BG events
Kink	$\tau^- \to e^-$	17.8 %	1.8	0.09
	$\tau^- \to \mu^-$	17.4 %	2.9	0.22
	$\tau^- \to h^-$	49.5 %	2.2	0.24
Trident	$\tau^- \to h^- h^- h$ +	15.2 %	0.7	0.18
Total			**7.6**	**0.73**

The ECC: evidence for charm in cosmic-rays by K. Niu (1971)

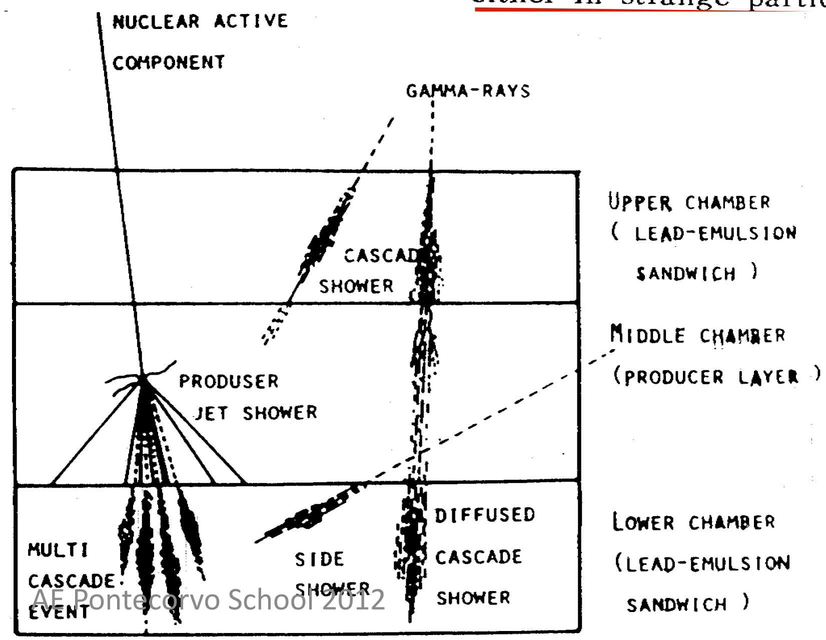


Prog. Theor. Phys. Vol. 46 (1971), No. 5

A Possible Decay in Flight of a New Type Particle

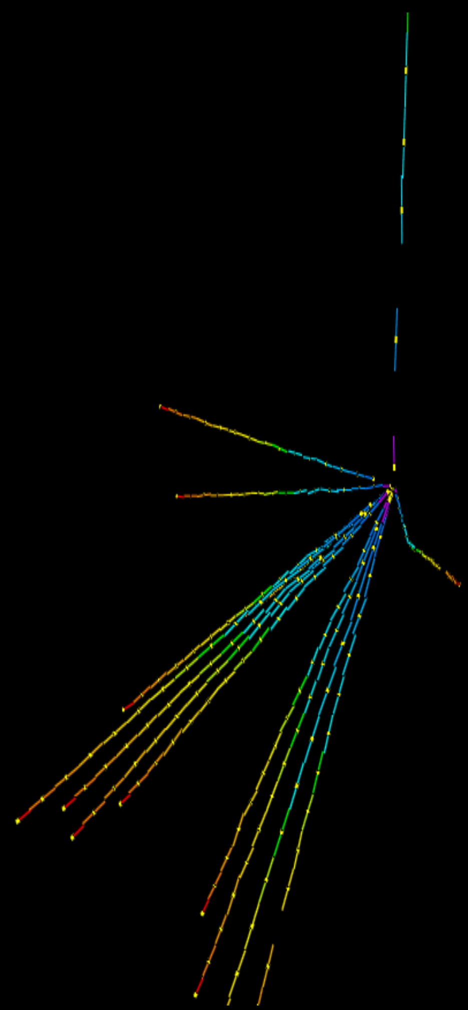
Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA

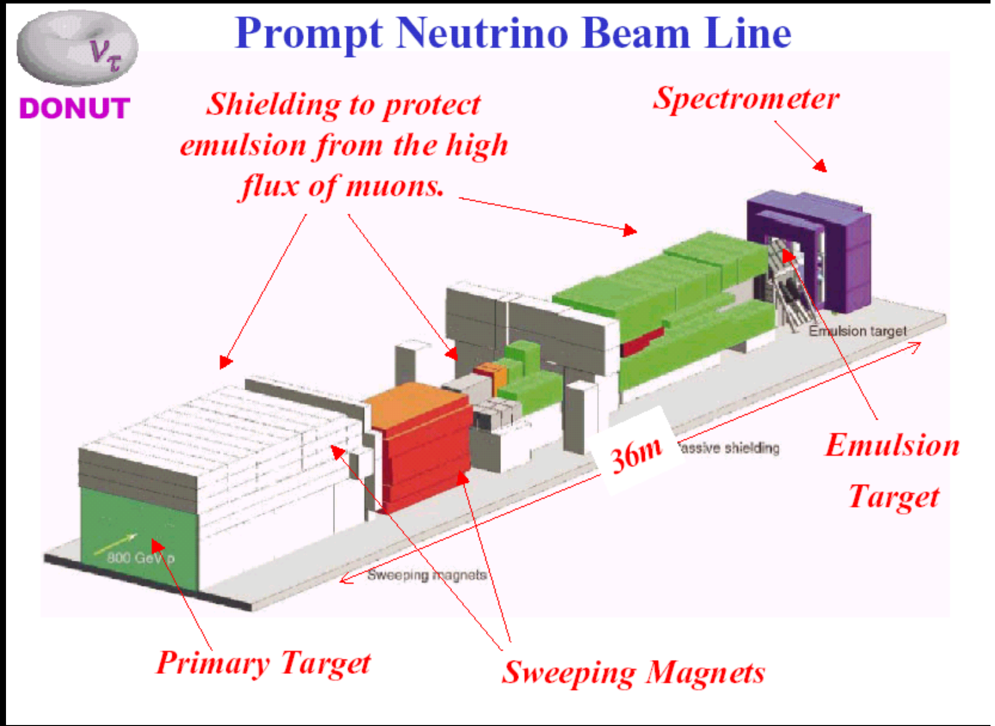
As for the characteristics of X particle, the transverse momentum of daughter π^0 meson, 627 ± 90 MeV/c, is much higher than the maximum momentum of decay products of the existing strange particles. The proper life time of X particle is several times 10^{-14} seconds, and this is extremely longer than those of resonance particles. Therefore, our X particle could not be included either in strange particle or in resonance



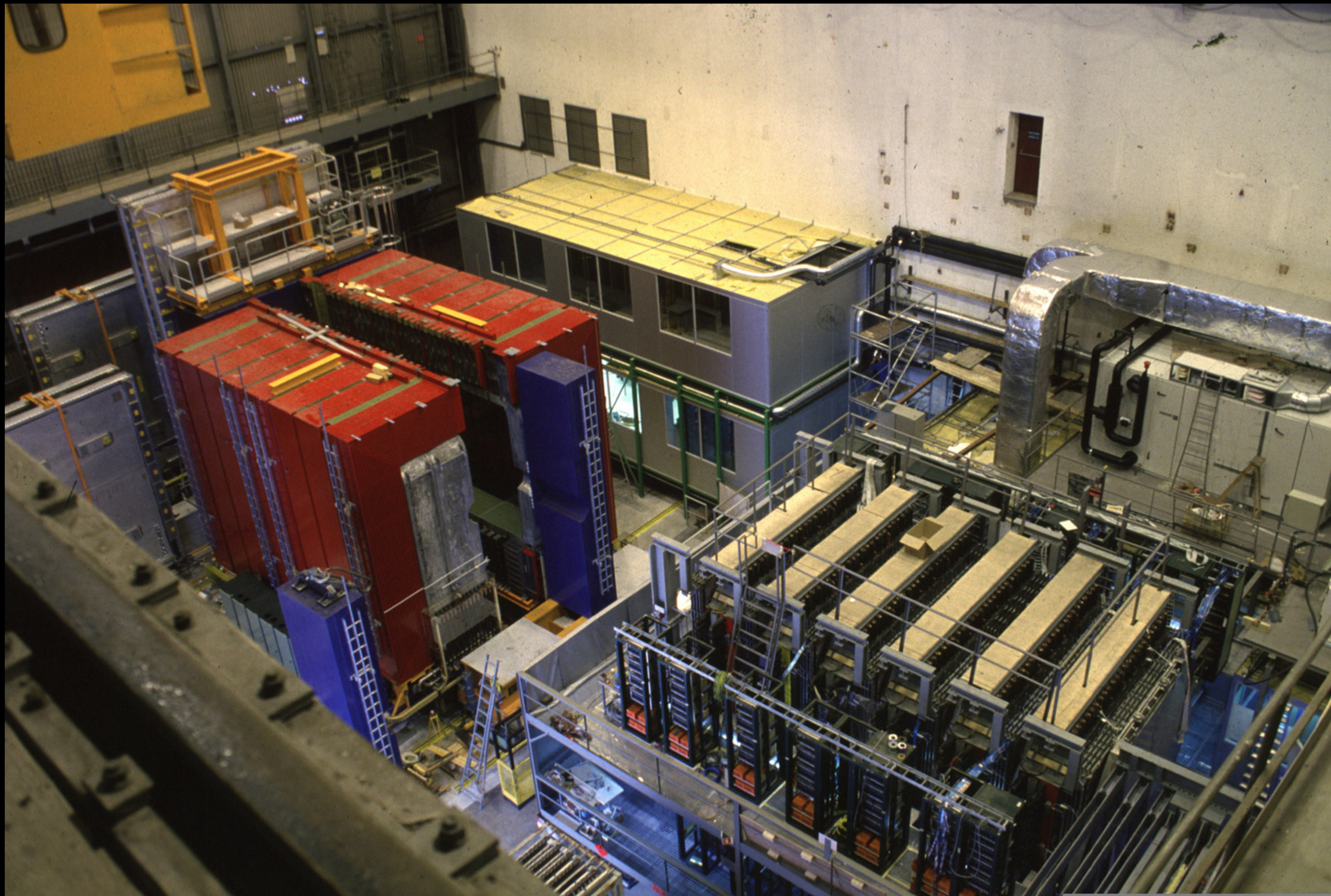
DONUT experiment at FERMILAB: first detection of ν_τ with an ECC based detector (K. Niwa and collaborators): 9 τ events, 1.5 BG.

K. Kodama et al. (DONuT Collaboration), Phys. Lett. B 504, 218 (2001).





From CHORUS and NOMAD to OPERA



OPERA

>10 years since the conceptual design of the experiment…

ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Napoli

INFN/AE–97/06
27 Gennaio 1997

DAPNU–97–07

A. Ereditato, K. Niwa, P. Strolin:
THE EMULSION TECHNIQUE FOR SHORT, MEDIUM AND LONG BASELINE $\nu_\mu - \nu_\tau$ OSCILLATION EXPERIMENTS

N·H ELSEVIER

P63

Nuclear Physics B (Proc. Suppl.) 66 (1998) 423–427

NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS

OPERA: an emulsion detector for a long baseline $\nu_\mu - \nu_\tau$ oscillation search

A. Ereditato[a*], K. Niwa[b] and P. Strolin[a]

[a]Università "Federico II" and INFN, Naples, Italy

[b]University of Nagoya, Japan

In this paper we outline the design of a new experiment for the search of $\nu_\mu - \nu_\tau$ oscillation in a long-baseline configuration. The apparatus exploits a novel application of nuclear emulsion for the direct detection of the τ lepton, allowing for an unambiguous signature of the neutrino oscillation. The experiment, sensitive to the oscillation parameter region indicated by the atmospheric neutrino anomaly, could run in the Gran Sasso Laboratory, in the foreseen beam from the CERN SPS.

OPERA

Belgium
ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPNL Lyon
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

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

Japan
Aichi edu.
Kobe
Nagoya
Toho
Utsunomiya

Korea
Jinju

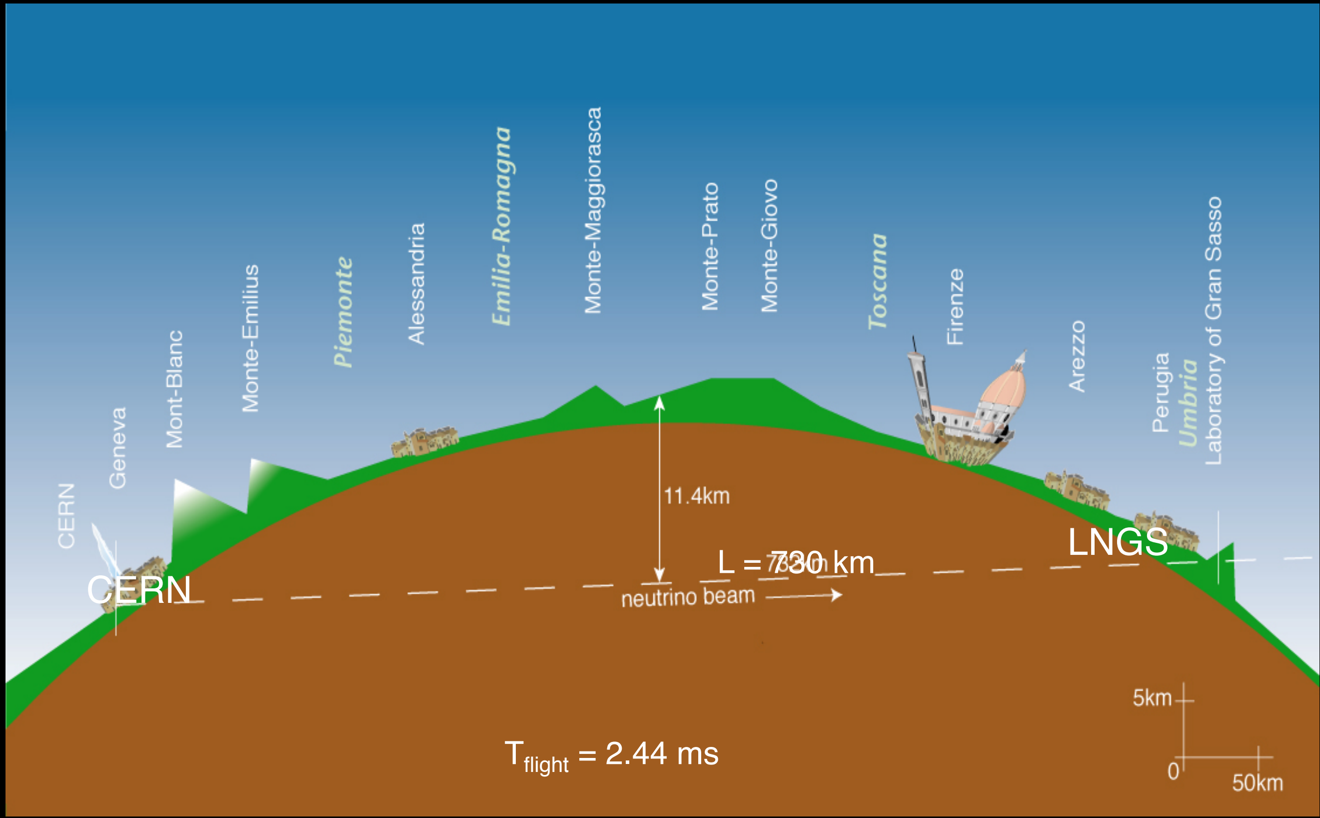
Russia
INR RAS Moscow
LPI RAS Moscow
ITEP Moscow
SINP MSU Moscow
JINR Dubna

Switzerland
Bern
ETH Zurich

Turkey
METU Ankara

(11 countries, 30 Institutes, 160 researchers)

CNGS beam: tuned for ν_τ-appearance at LNGS (730 km away from CERN)

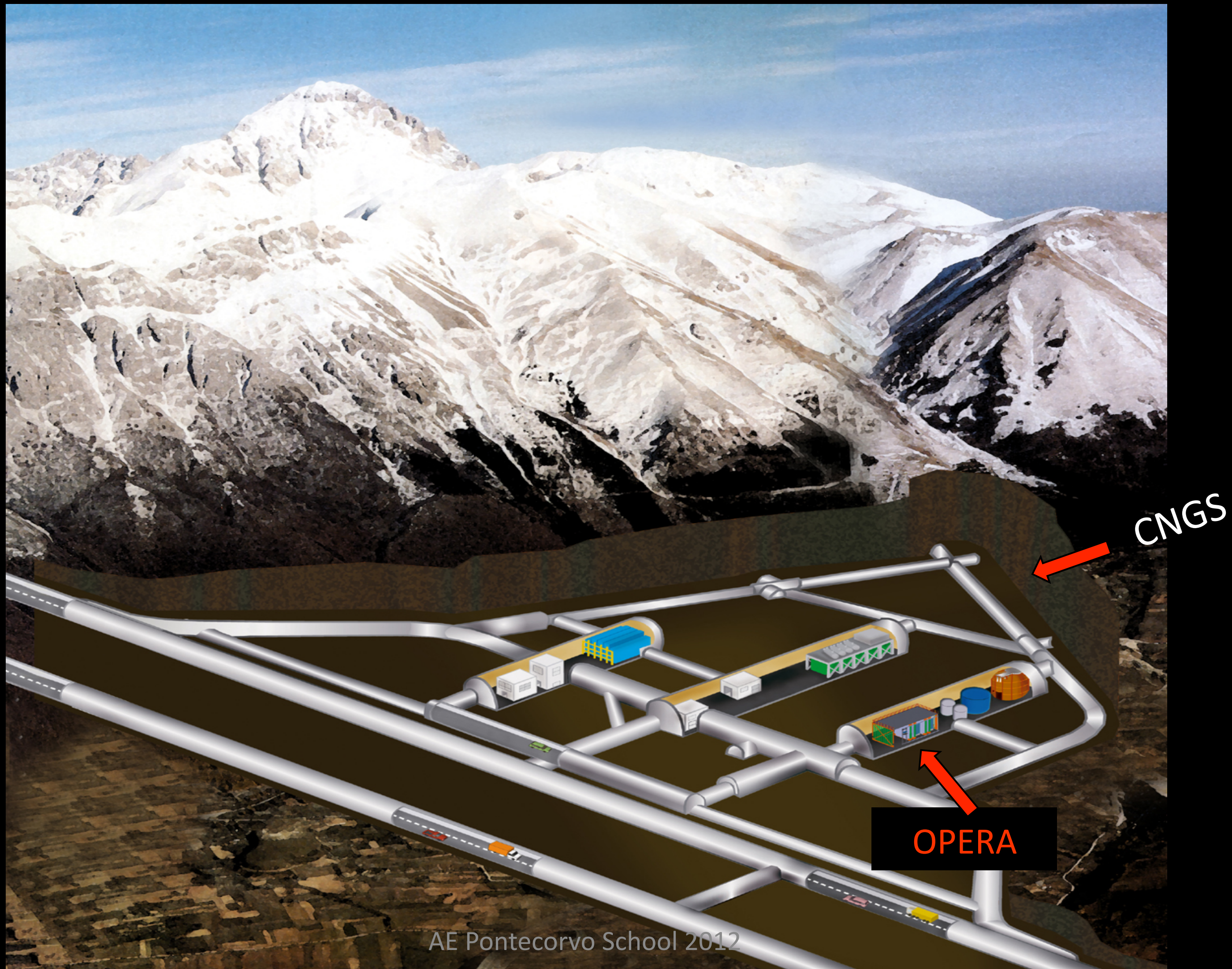


< E >	17 GeV
L	730 km
$(\nu_e + \nu_e) / \nu_\mu$ (CC)	0.87%
ν_μ / ν_μ (CC)	2.1%
ν_τ prompt	negligible

Expected neutrino interactions for 22.5×10^{19} pot:
~ 23600 ν_μ CC + NC
~ 160 $\nu_e + \overline{\nu}_e$ CC
~ 115 ν_τ CC ($\Delta m^2 = 2.5 \times 10^{-3}$ eV^2)

LNGS: the world largest underground physics laboratory:

~180'000 m^3 caverns' volume, ~3'100 m.w.e. overburden, ~1 cosmic μ / m^2 x hour, experimental infrastructure, variety of experiments. Perfectly fit to host detector and related facilities, caverns oriented towards CERN.



Status of the CNGS data taking

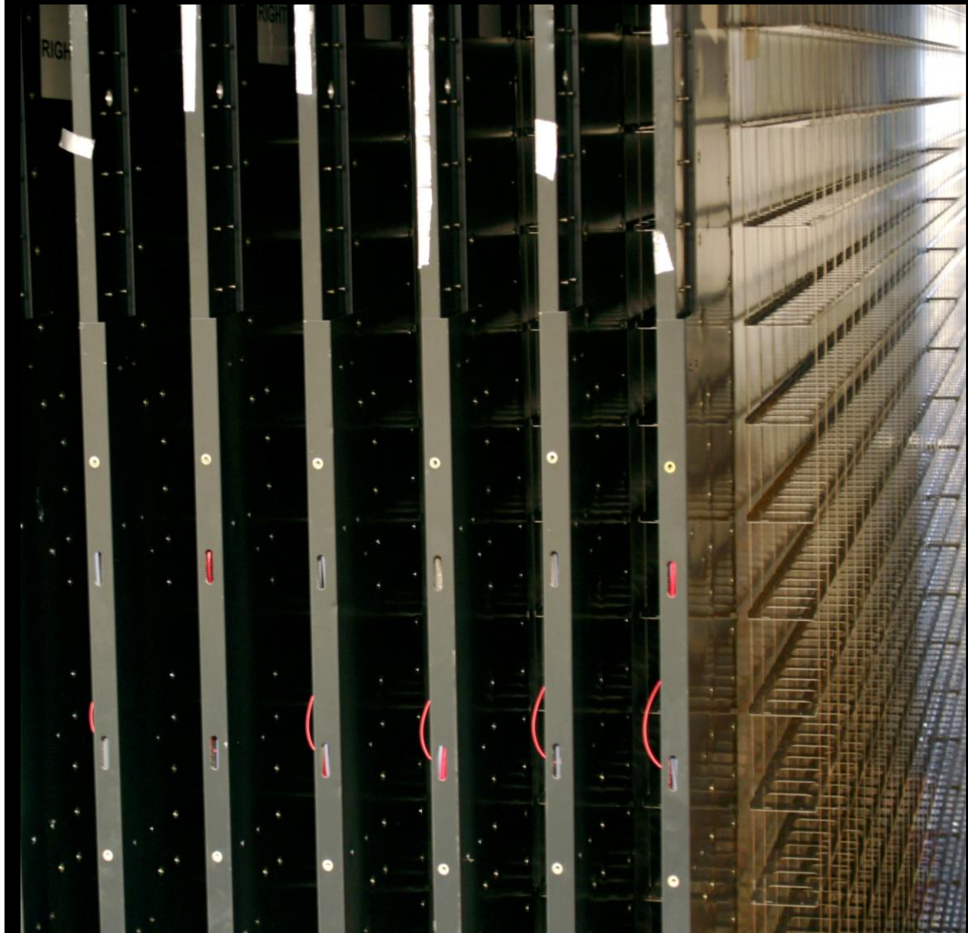
Year	Protons on target (pot)	Number of neutrino Interactions	Integrated pot /proposal value
2008	1.78×10^{19}	1698	7.9%
2009	3.52×10^{19}	3557	23.6%
2010	4.04×10^{19}	3912	41.5%
2011	4.84×10^{19}	4210	63.0%
2012	$(\sim 4.7 \times 10^{19})$	(~4050)	(~84%)

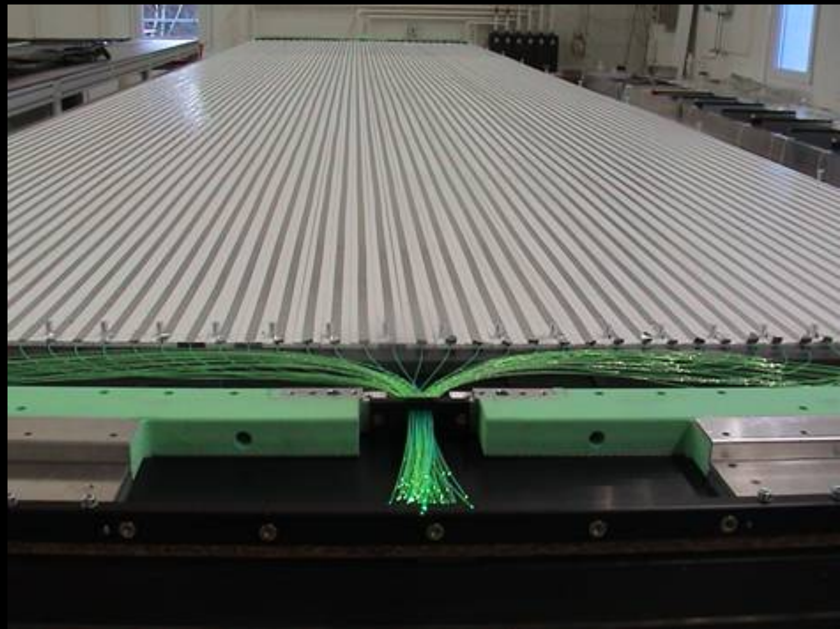
14.2×10^{19} pot up to 2011

Expected pot after 2012 run
18.9×10^{19} (22.5×10^{19} proposal)

Two target super-modules, each with an iron spectrometer for muon detection (BG rejection and tau-into-muon decay channel)

SCINTILLATOR STRIPS TARGET TRACKER AND BRICK TRAYS





> 5 p.e. for a m.i.p.

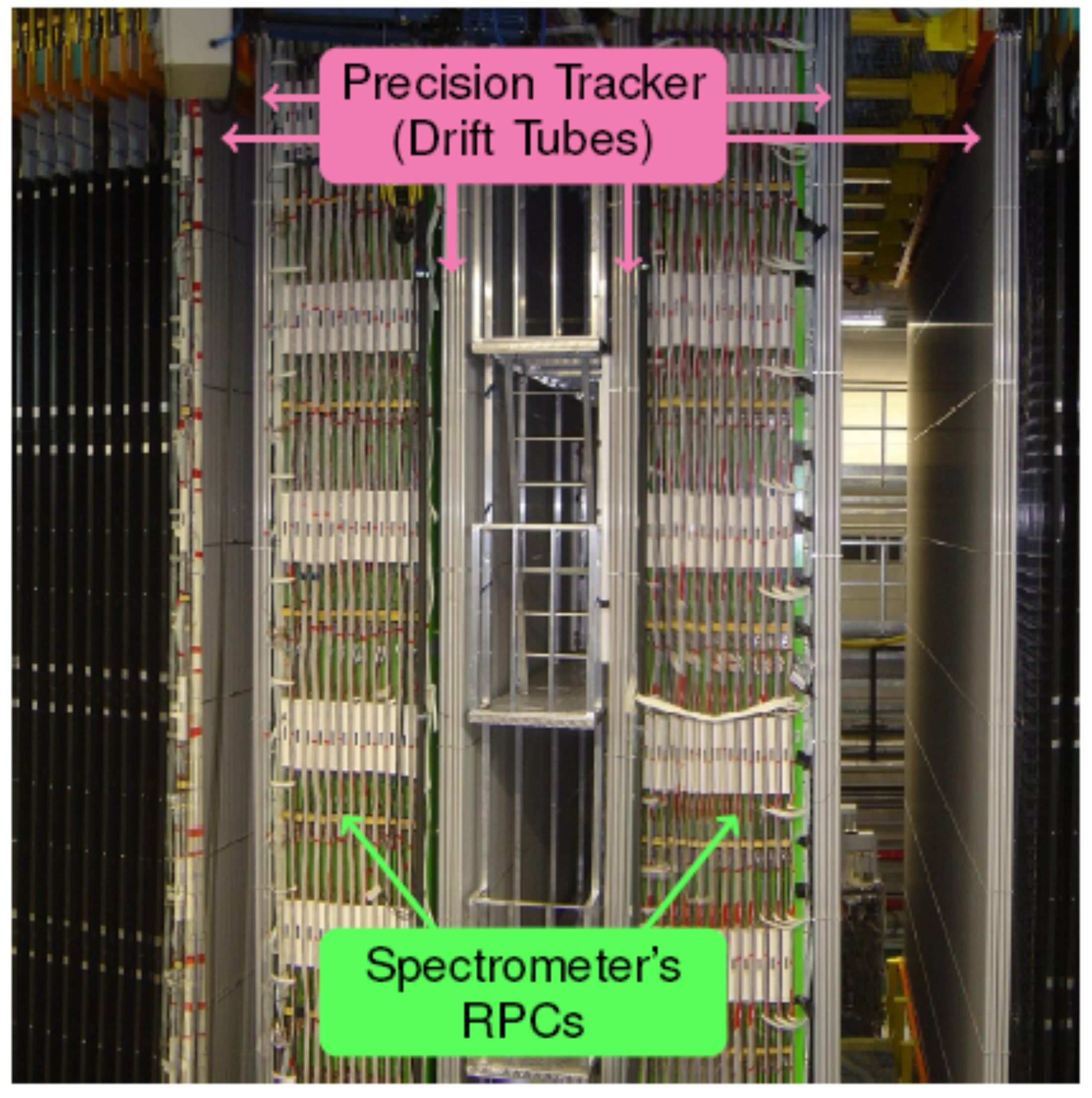
~ 99% detection efficiency ⇒ trigger

position accuracy: ~8 mm

angular accuracy: ~ 20 mrad

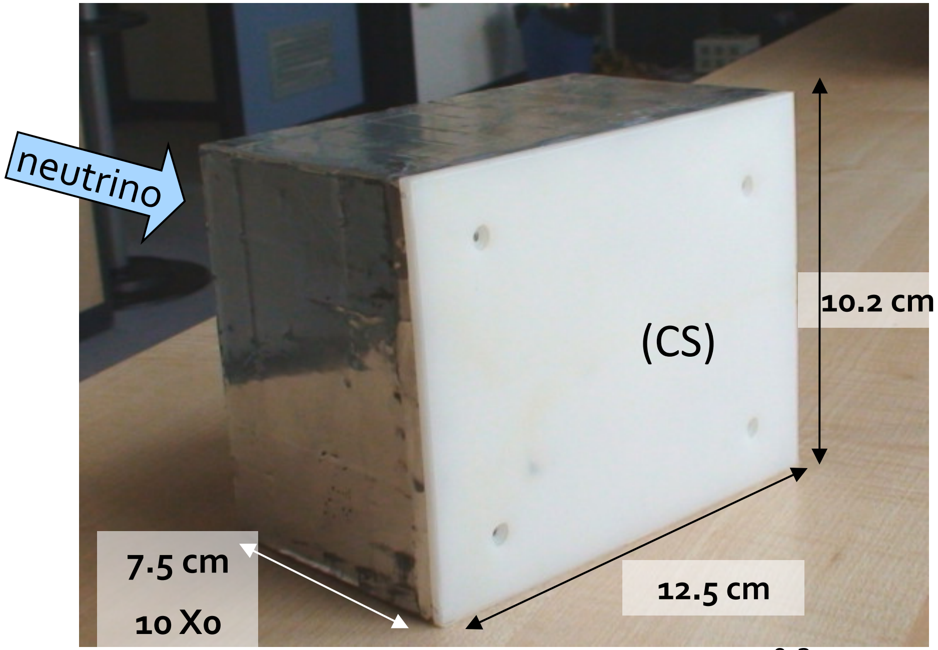
mechanical structure:
brick trays: only 0.5% of target mass

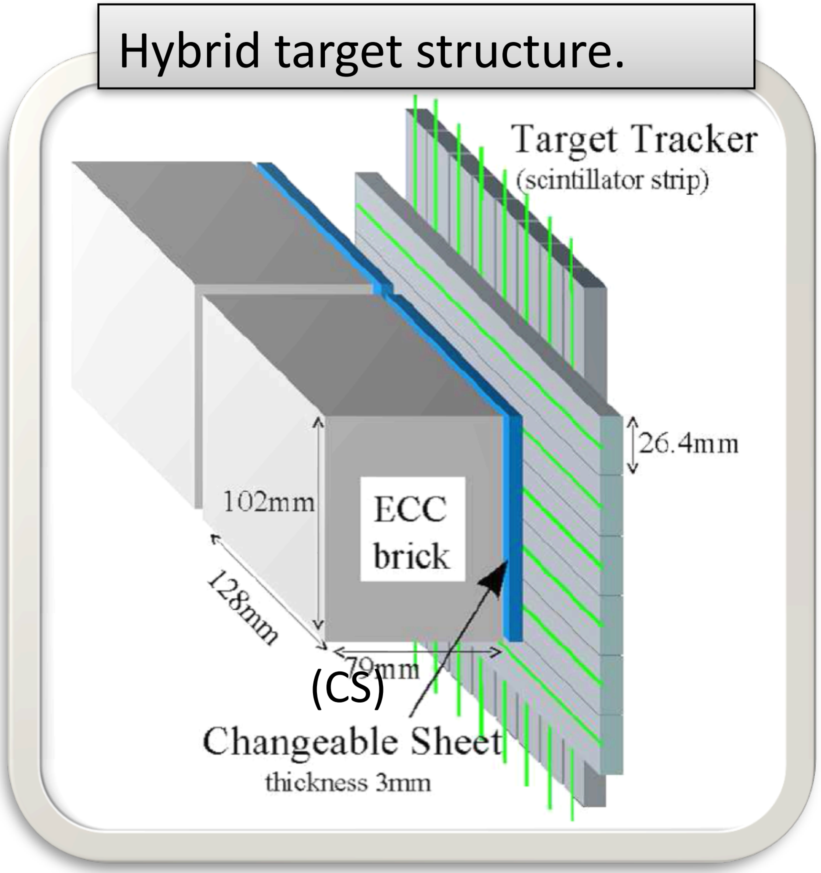
THE MAGNETIC SPECTROMETERS

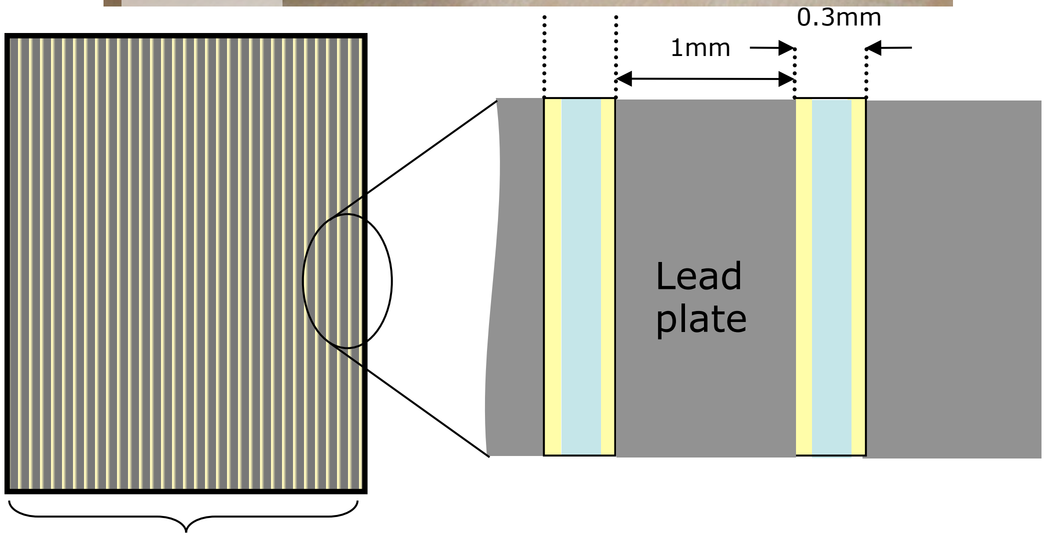


- 1.52 T magnetic field bending particles in the horizontal plane
- 24 slabs of magnetized iron interleaved with 24 RPC planes
- 6 drift tube stations for precision measurement of the angular deflection
- momentum resolution: 20% below 30 GeV

The heart of the experiment:
THE ECC TARGET BRICKS







57 OPERA films, 56 lead plates

The OPERA target consists of 150’000 ECC bricks.

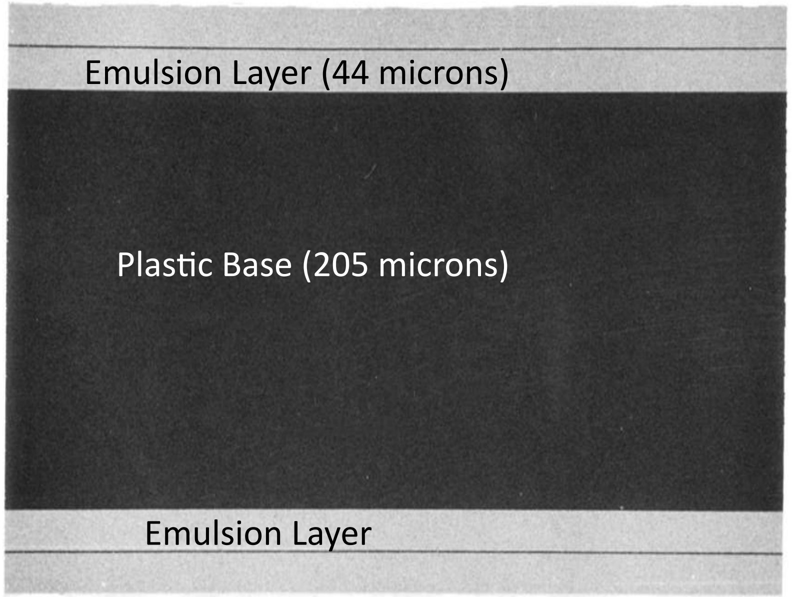
Total 105000 m^2 of lead surface

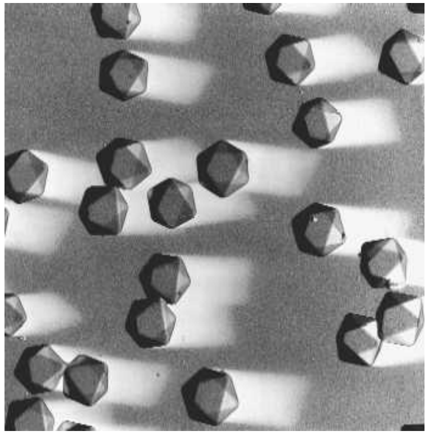
and 111000 m^2 of film surface

(~ 8.9 million films)

Total target mass: 1.25 kton

INDUSTRIAL EMULSION FILMS BY *FUJI FILM*





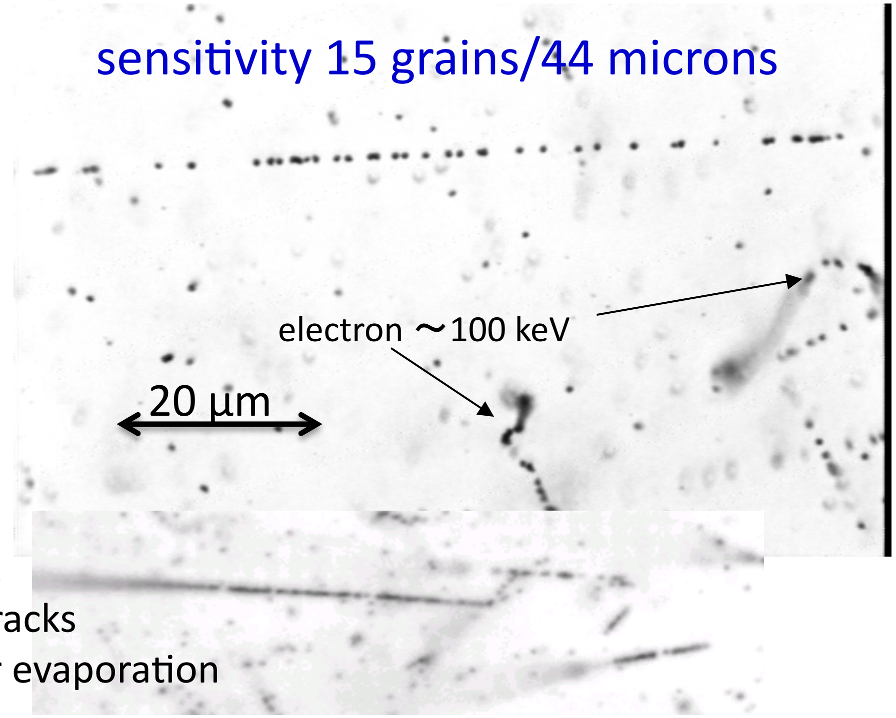
basic detector: AgBr crystal,

size = 0.2 micron

detection eff.= 0.16/crystal

10^{13} "detectors" per film

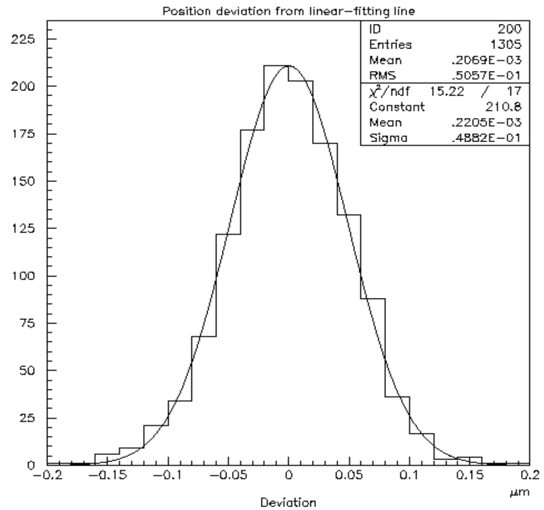
mip



high dE/dx tracks
from nuclear evaporation

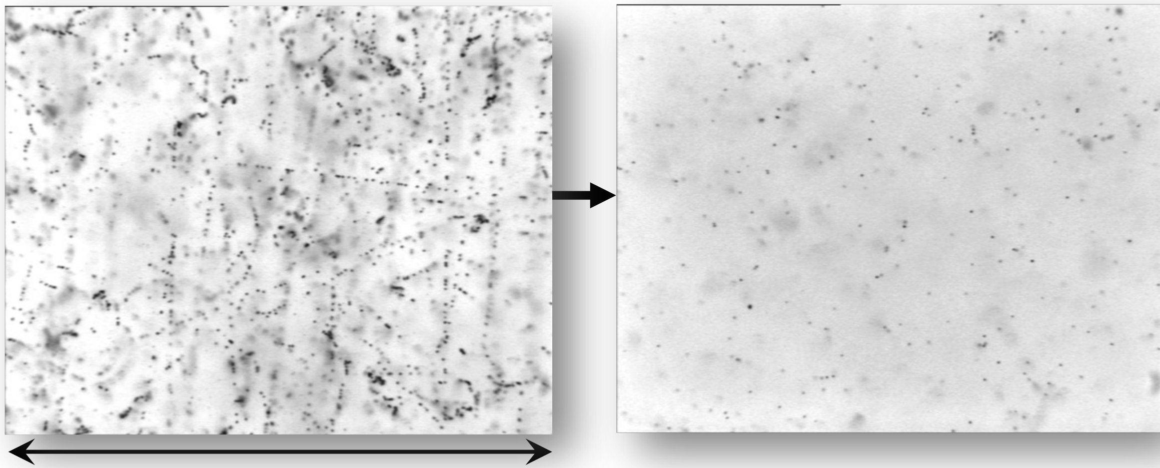
intrinsic resolution: 50 nm

deviation from linear-fit line. (2D)



Tono-mine film refreshing facility in Japan

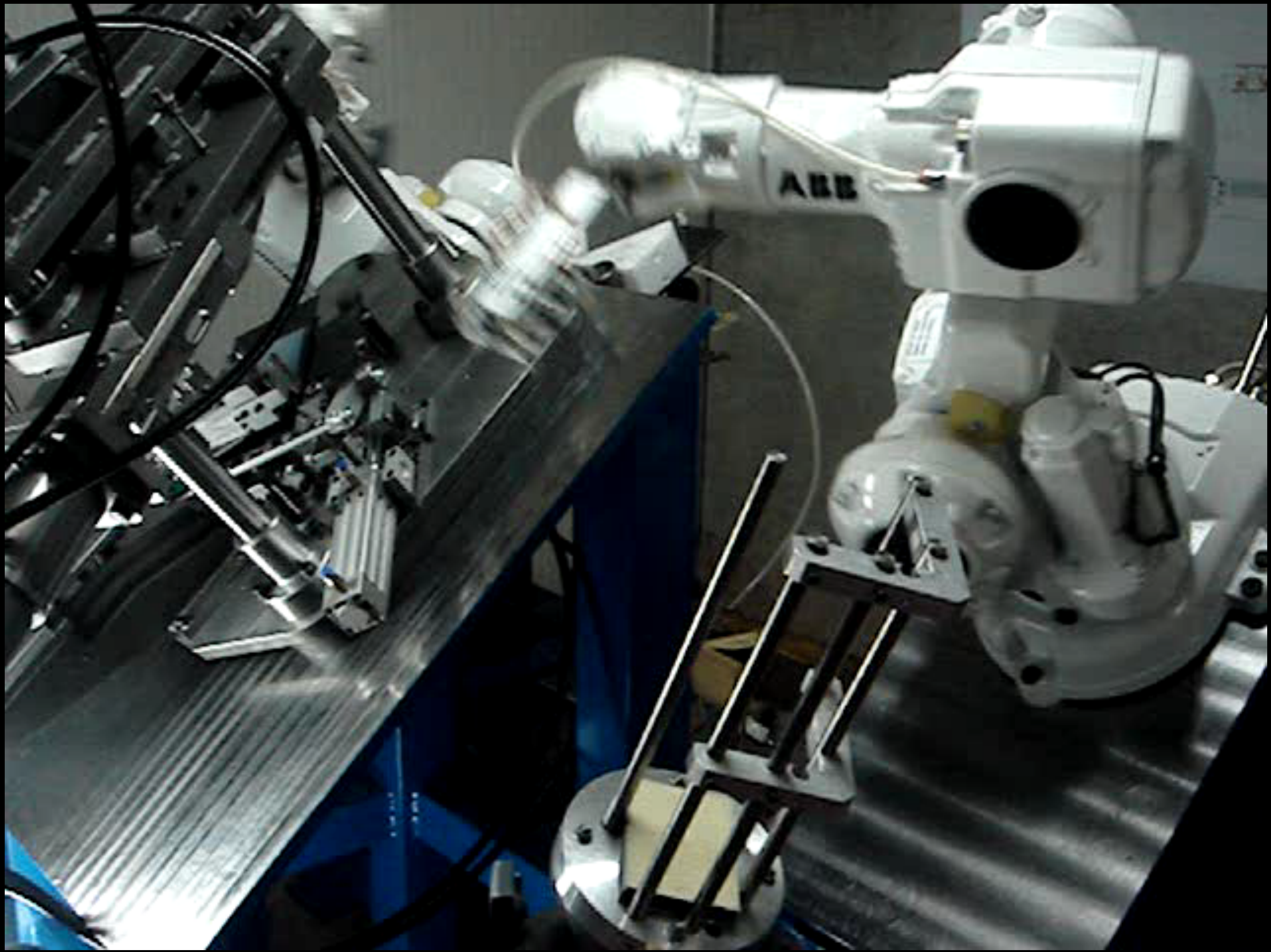
before refreshing after



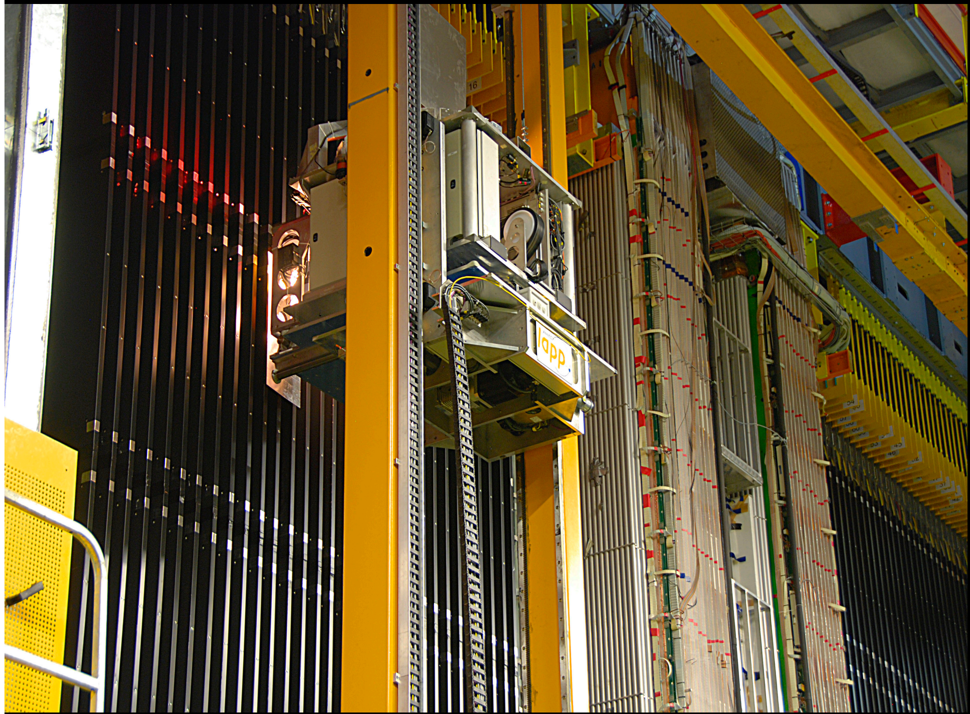
refreshing: erase cosmic-ray induced tracks accumulated during film production at FUJI.

BRICK ASSEMBLY MACHINE (BAM)

Major engineering infrastructure: automatic production of 150000 bricks (2006-2008)



BRICK MANIPULATOR SYSTEM (BMS)



Extraction of “hit” bricks in parallel with CNGS data taking:

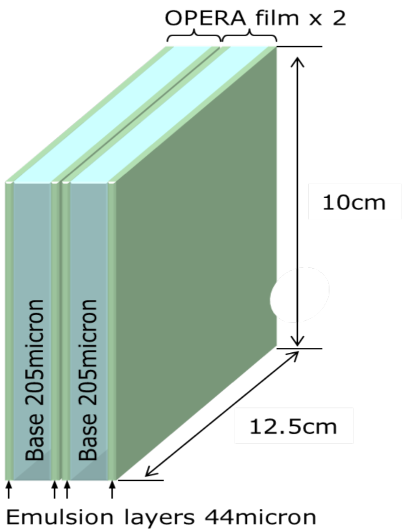
- initially used to fill the brick target (two twin devices at either detector sides)
- fully automatic extraction of 25 bricks/8 hour shift (neutrino interactions)

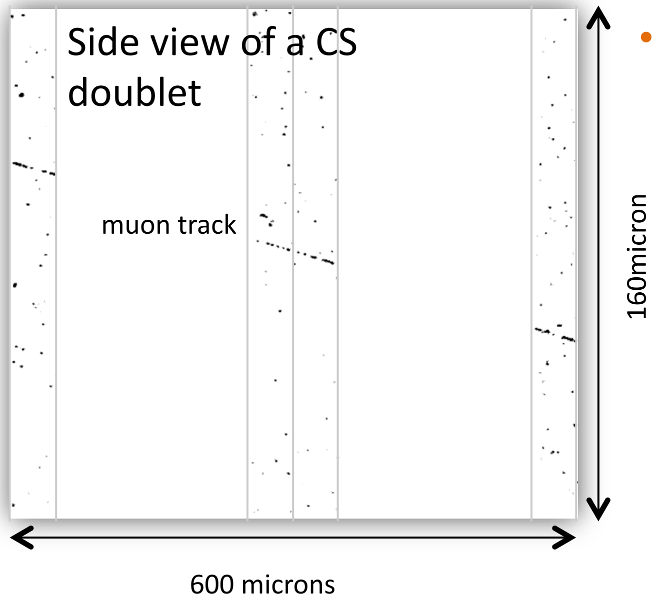
FILM DEVELOPMENT FACILITY

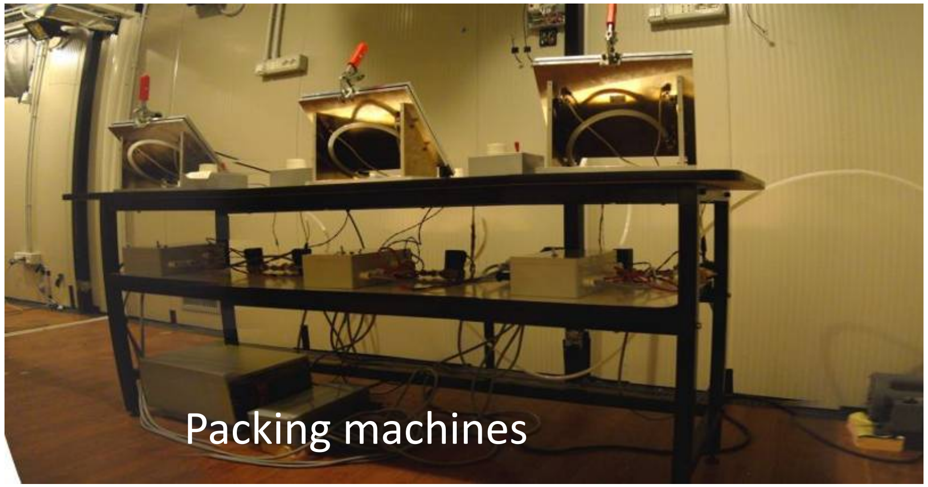
- 6 automatic lines running in parallel, in dark
- maximum rate: 150 bricks/week
- additional facility underground for CS: max 300 CS/week

Changeable Sheet (CS) assembly facility at LNGS underground

- To pick up event related tracks.
- On-site refreshing and doublet packing: very low background emulsion tracker.
- 160000 CS produced in 2006-2008.



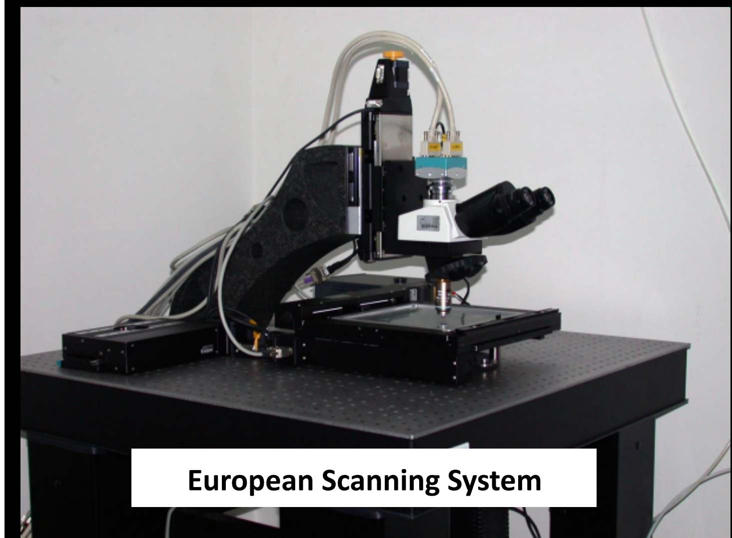




Packing machines

Refreshing chambers

CHANGEABLE SHEET SCANNING STATIONS



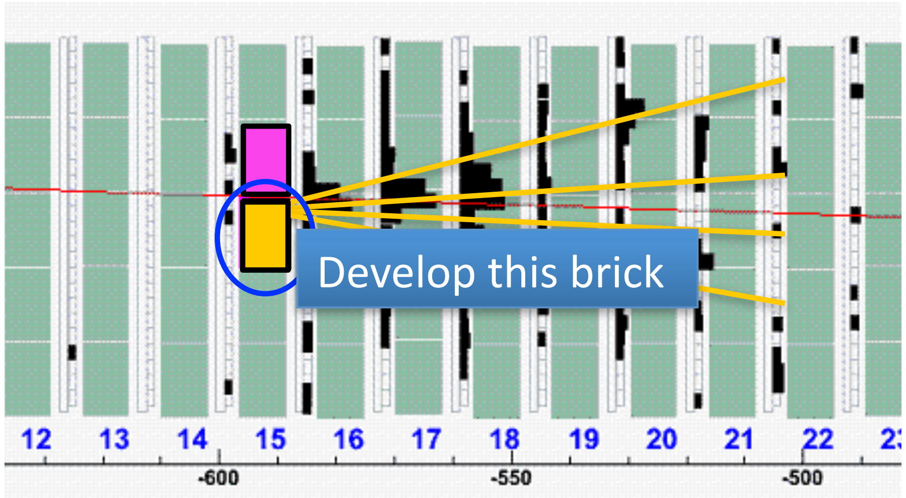
High speed automatic microscopes:

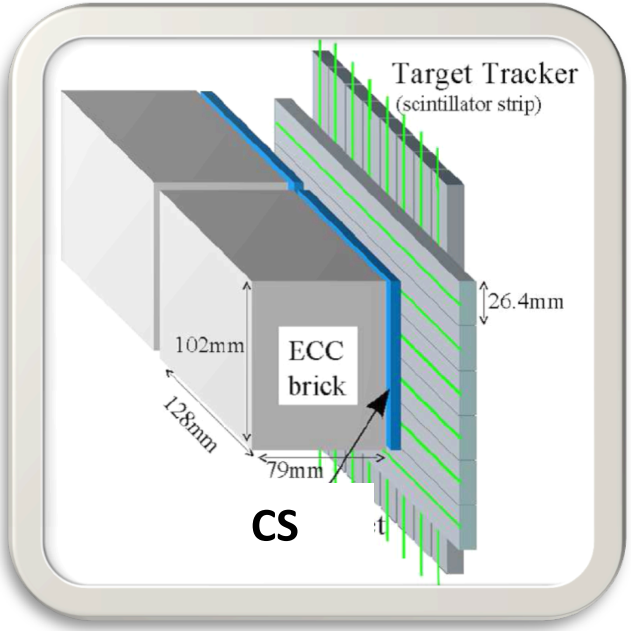
~ 200 cm^2 emulsion film surface/hour/facility

Based on state of the art technologies:

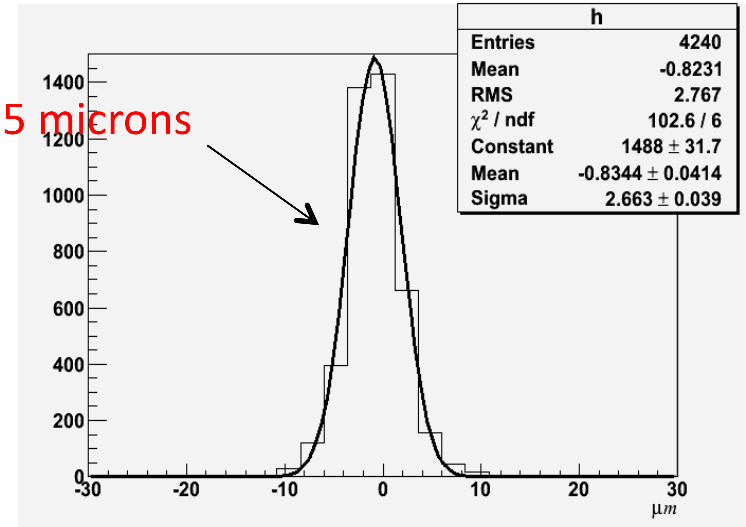
precision mechanics, stepping motors, CCD readout, pattern recognition, image analysis,…

BRICK VALIDATION BY THE CS





CS doublet alignment by Compton electrons: 2.5 microns



Scanning effort/event: CHORUS 1x1 mm^2

DONUT 5x5 mm^2

OPERA 100x100 mm^2

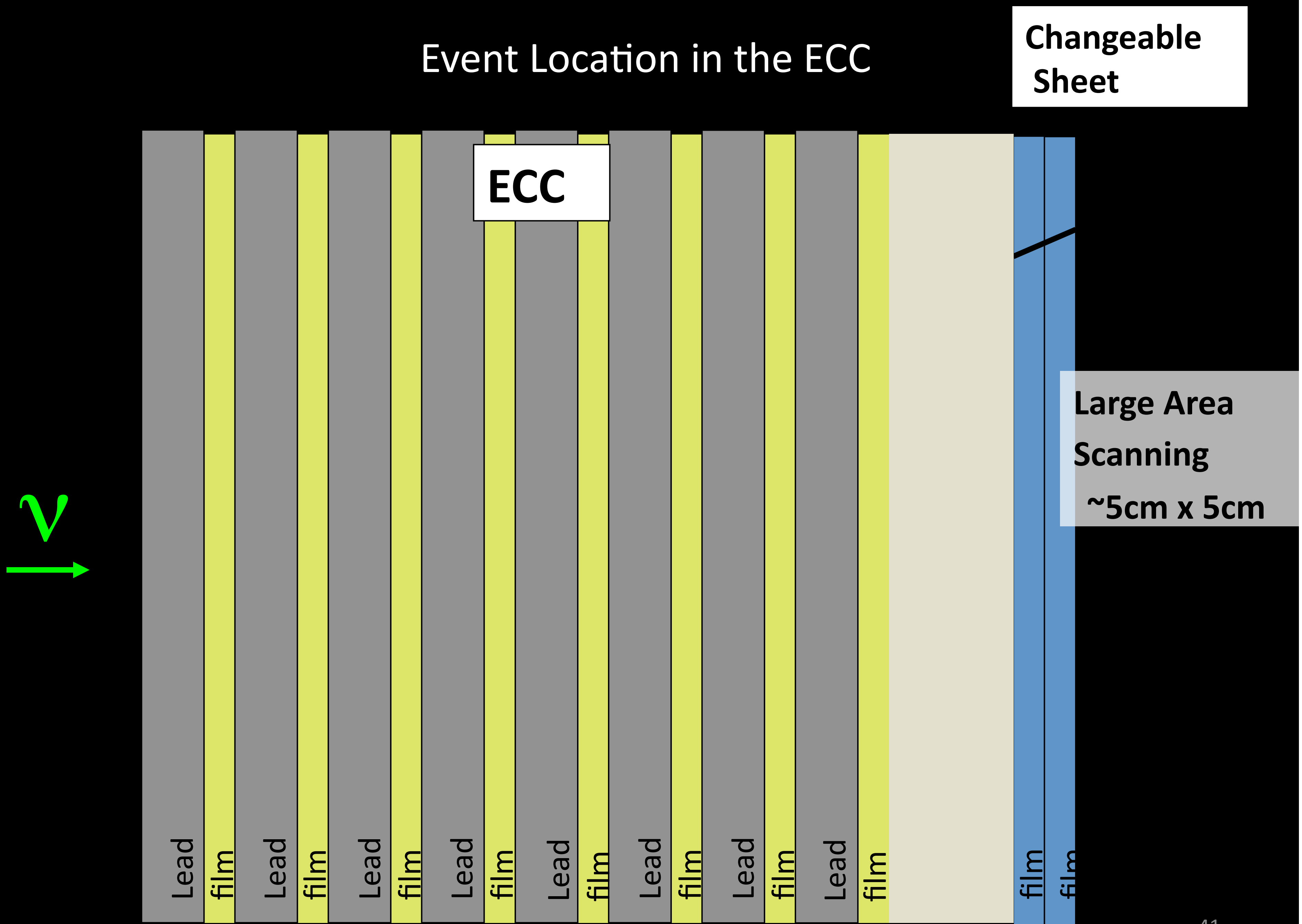
So far, ~ 1 million cm^2 of CS surface have been scanned in OPERA

PARALLEL ANALYSIS OF BRICKS

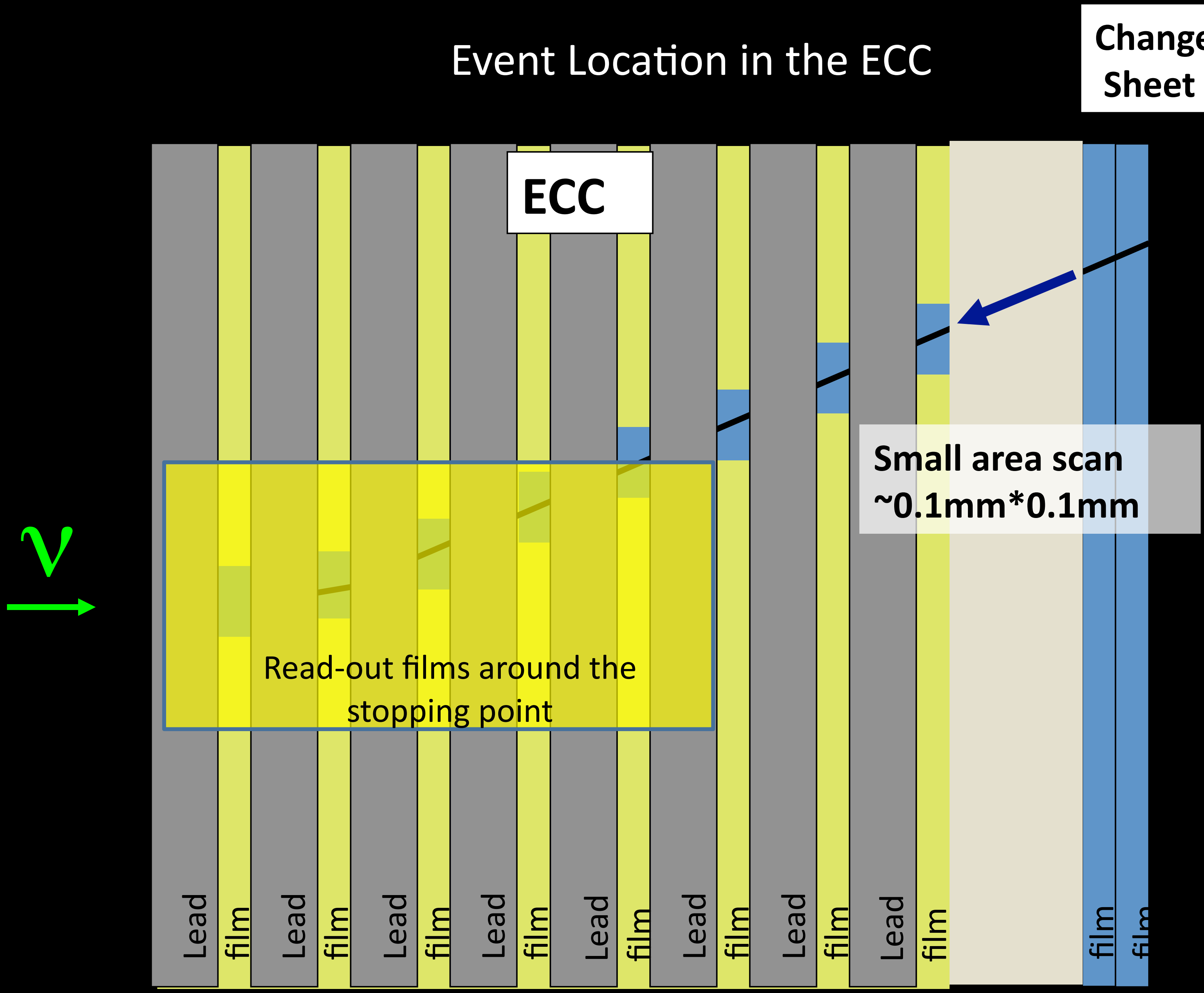
selected bricks sent to scanning labs (**presently 12**)

Bern brick scanning lab, the 2nd largest in the Collaboration

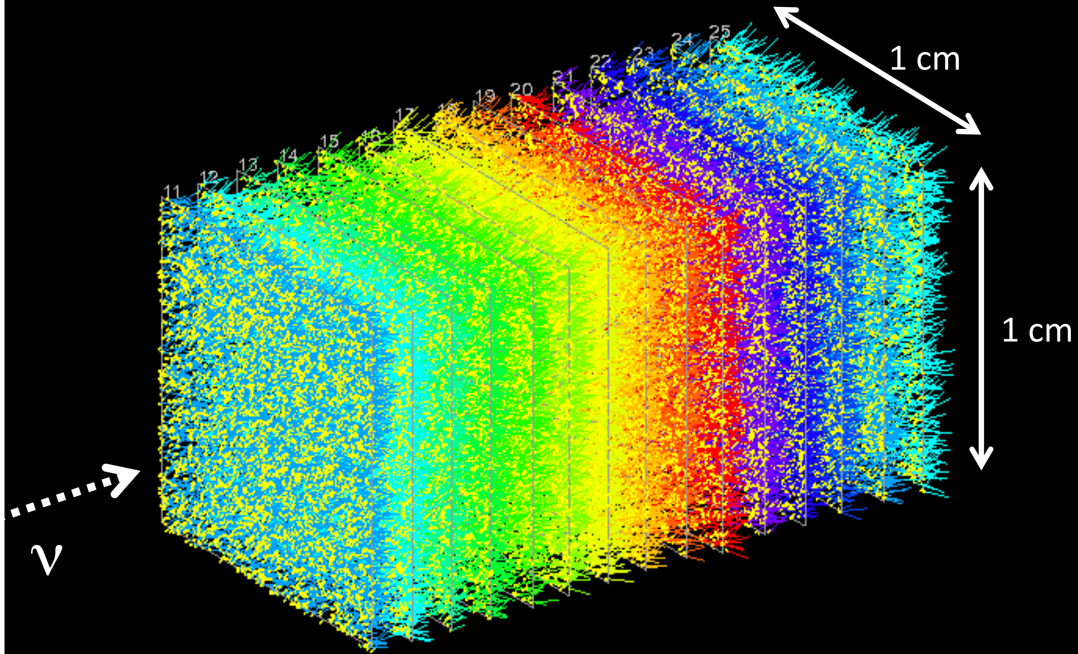
Event Location in the ECC



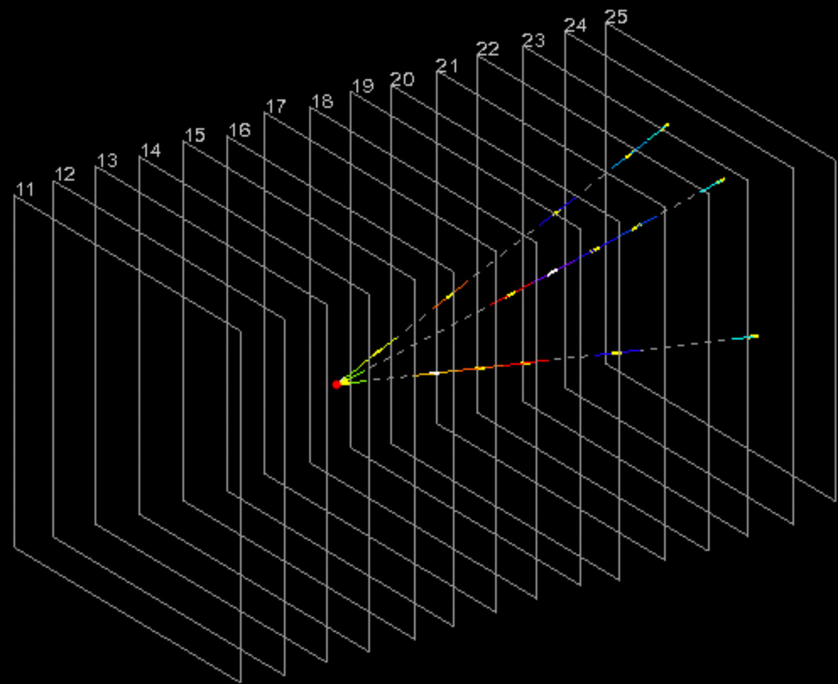
Event Location in the ECC



Interaction vertex confirmation & decay search



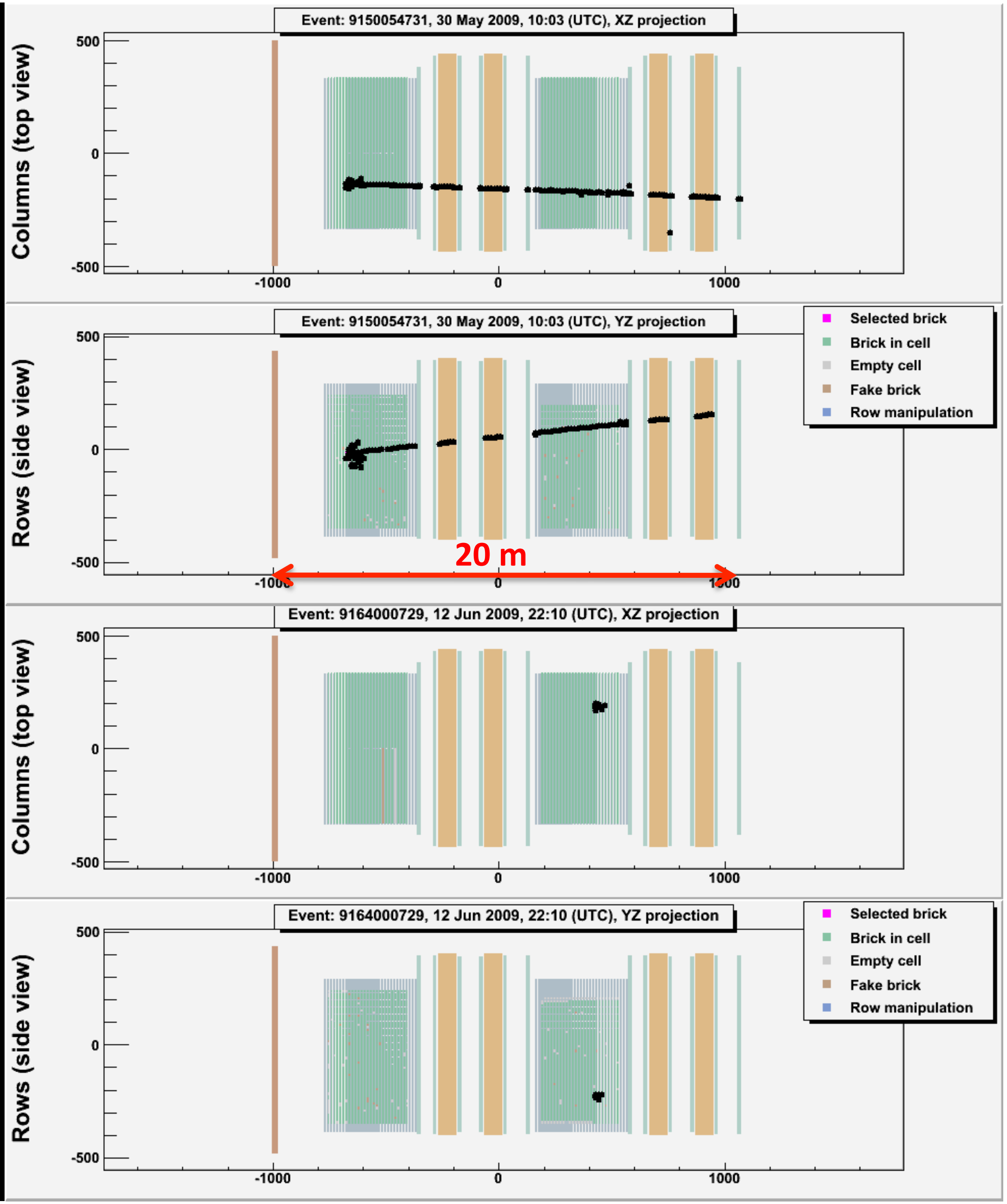
Cloud of low energy tracks



After the selection of high energy tracks connecting across the lead

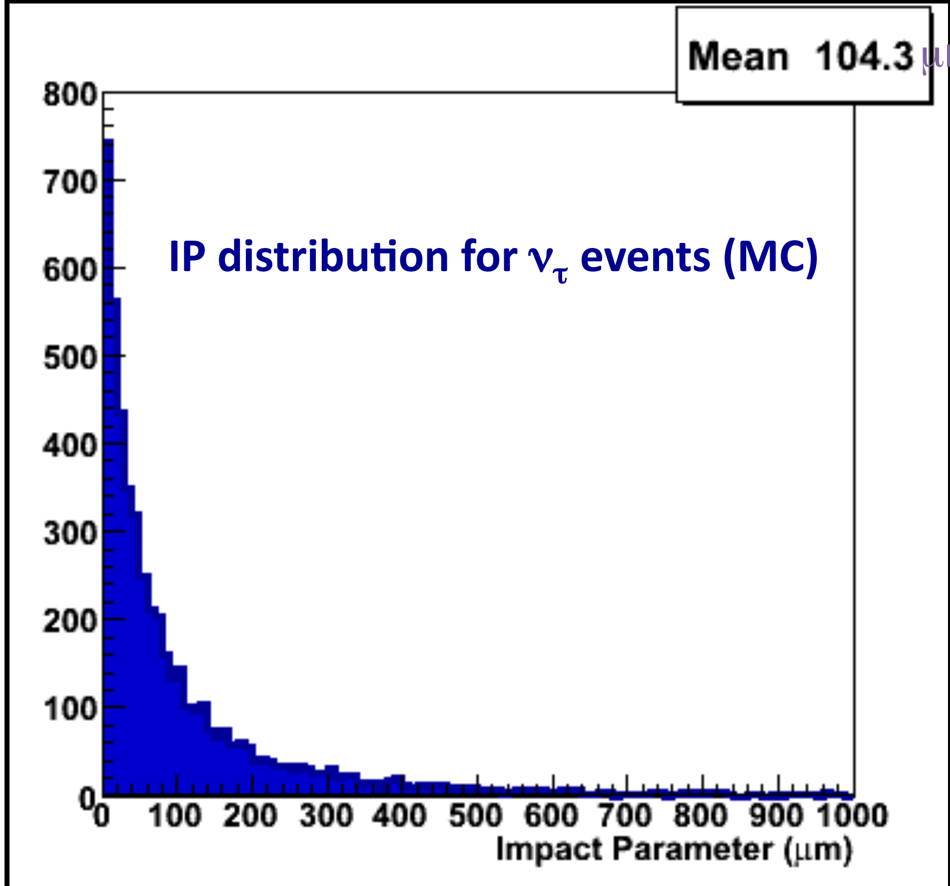
Typical ν_μ CC- and NC-like events

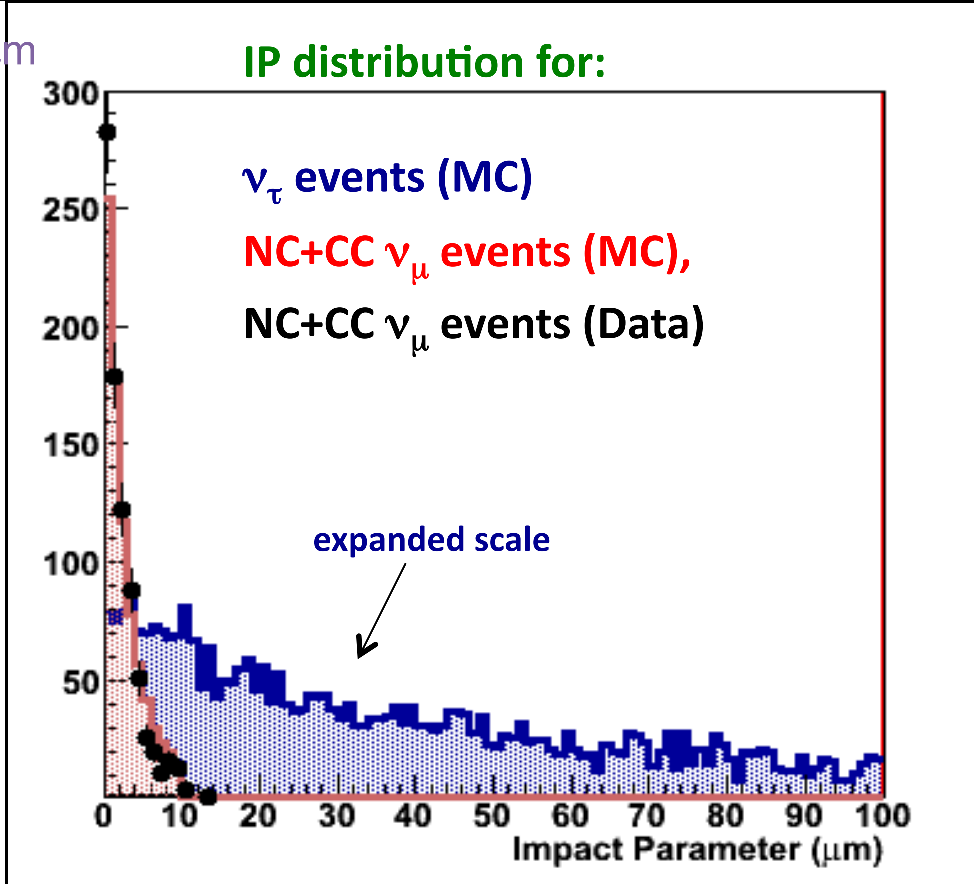
The measured ratio of NC-like/CC-like events after muon ID and event location is ~20%, as expected from simulations



GLOBAL ANALYSIS PERFORMANCE

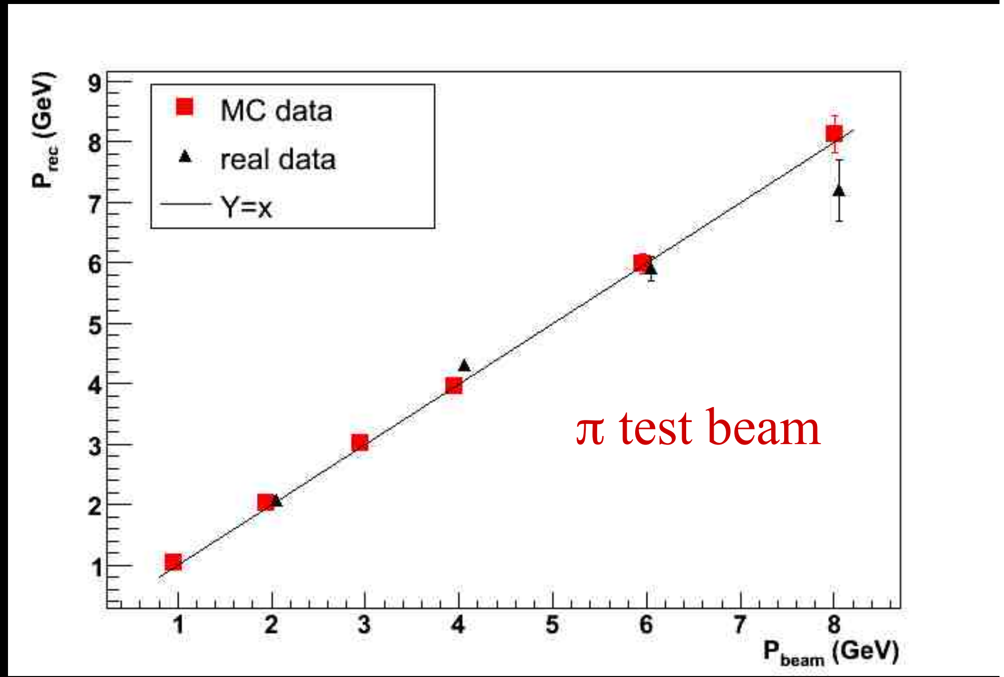
Impact parameter measurement

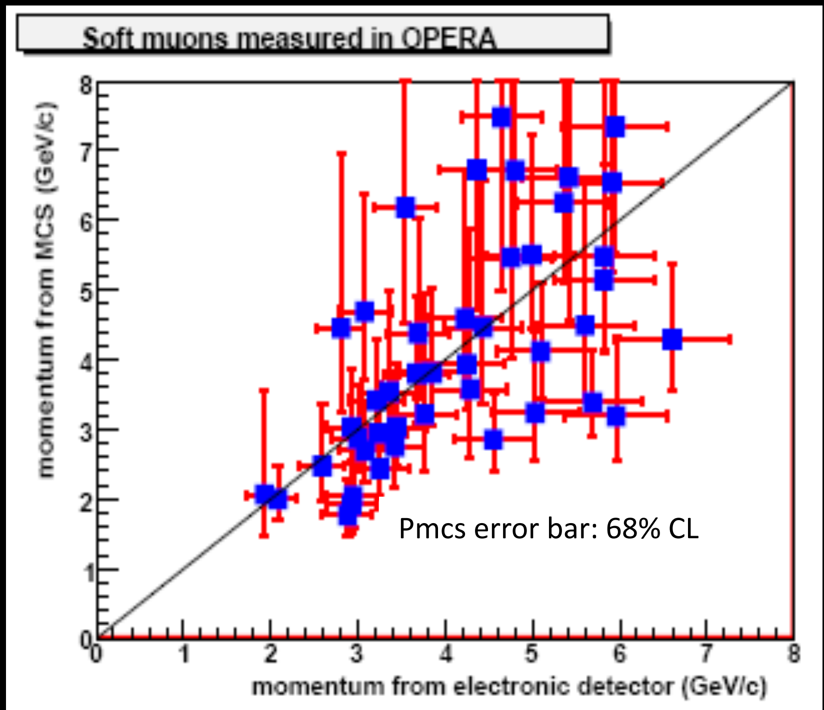


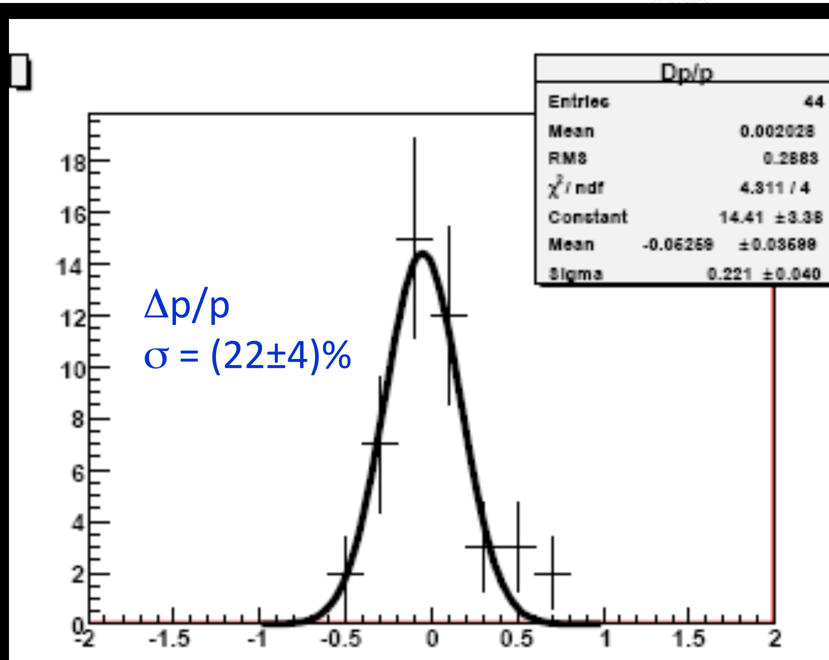


Momentum measurement by Multiple Coulomb Scattering…

…in the lead/emulsion film sandwich and comparison with electronic detector measurements

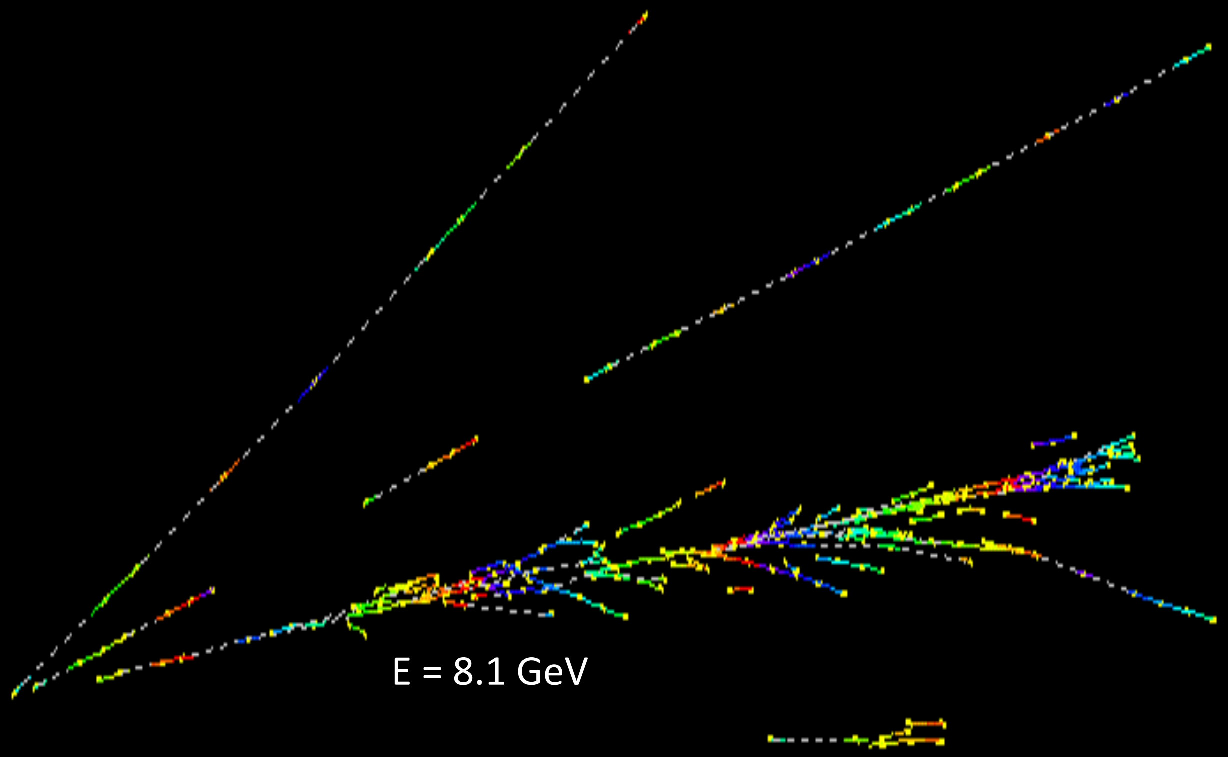






γ detection and π^0 mass reconstruction

2 EM showers give a reconstructed mass ~ 160 MeV

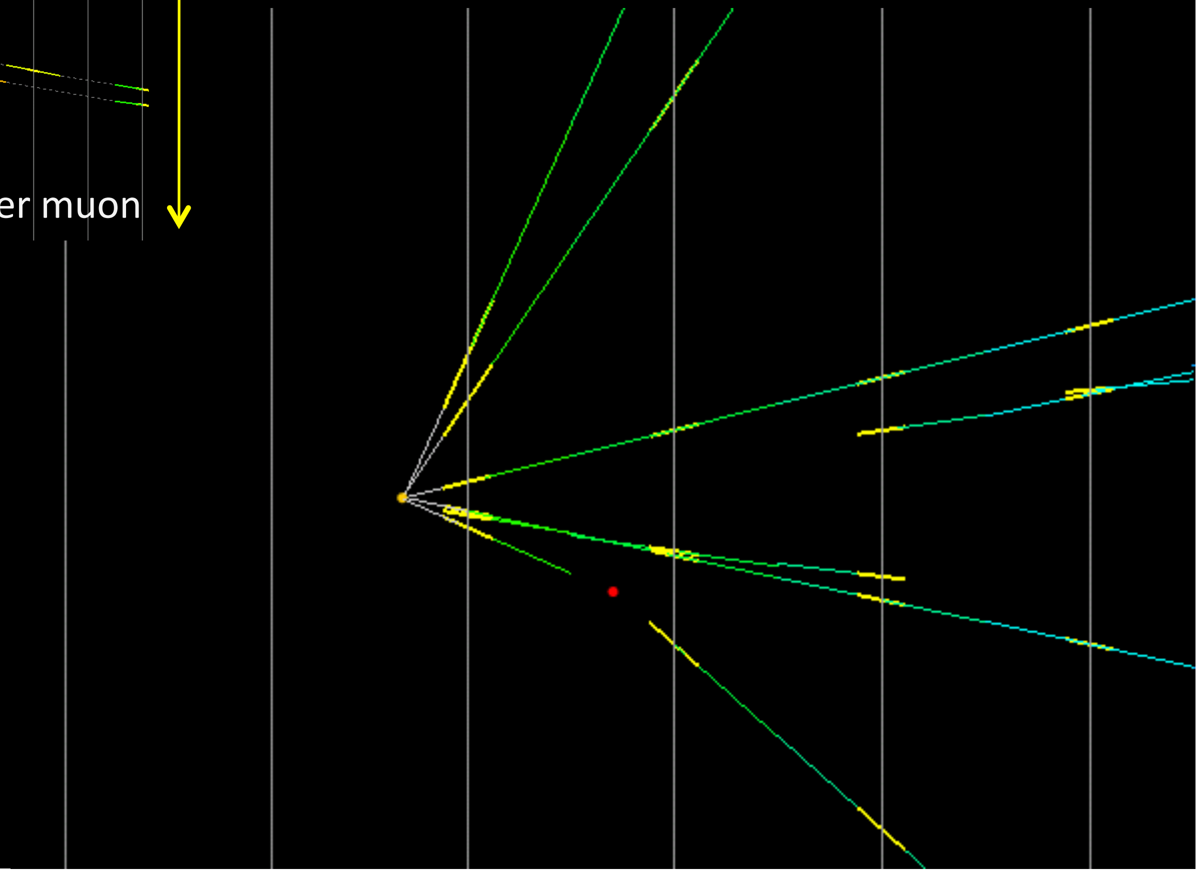


EM shower energy measured by shower shape analysis and Multiple Scattering method

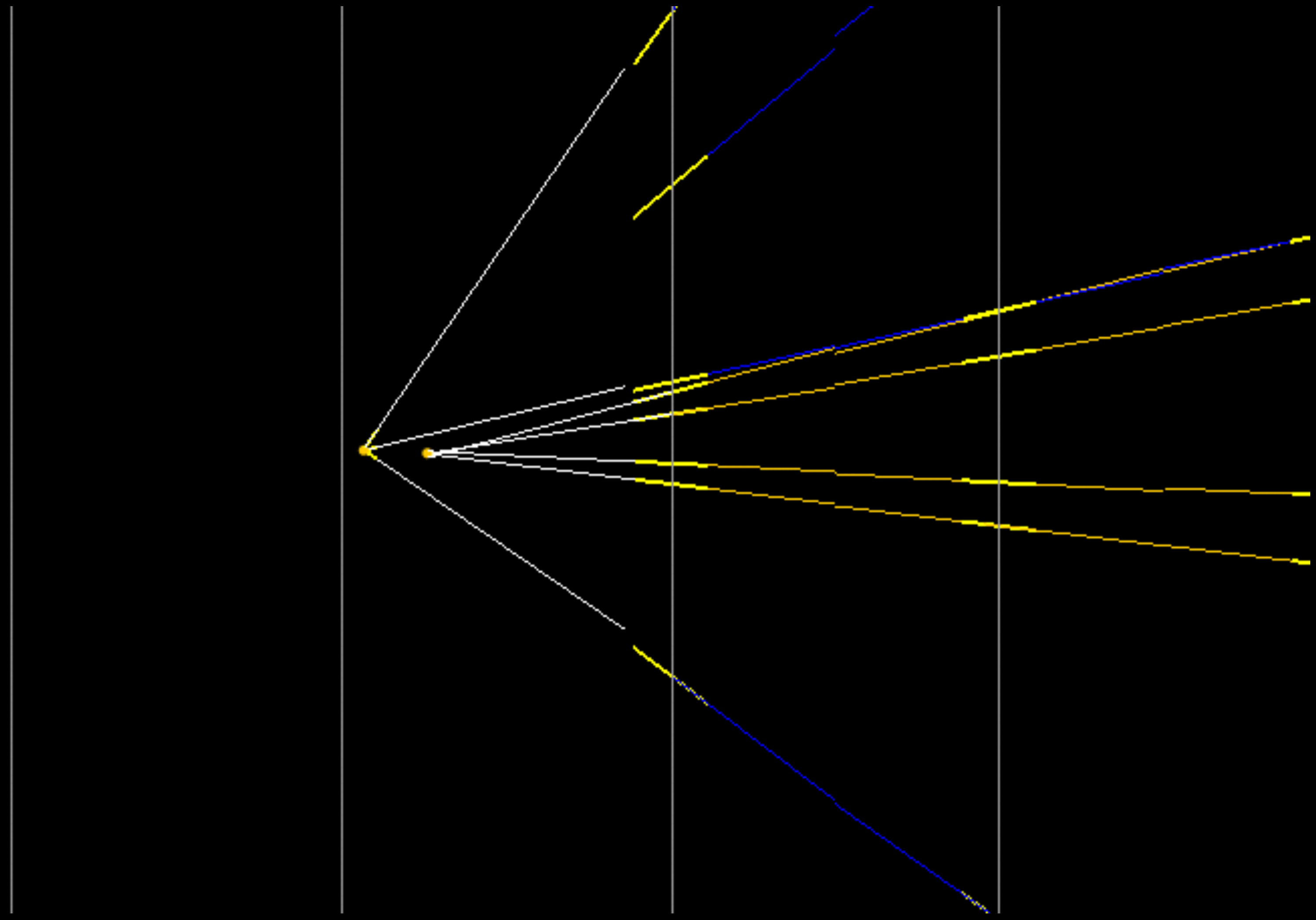
CHARM EVENTS: a test sample and a physics BG

Charm candidate event (dimuon)

flight length: 1330 microns
kink angle: 209 mrad
IP of daughter: 262 microns
daughter muon: 2.2 GeV/c
decay Pt: 0.46 GeV/c

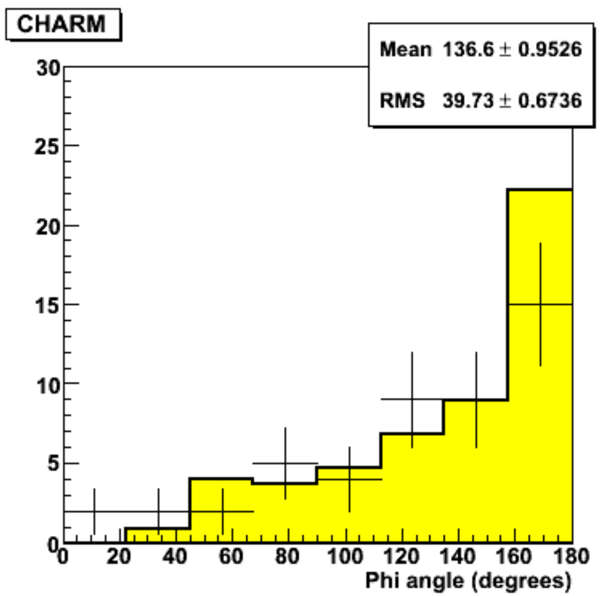


Charm candidate event (4-prong)

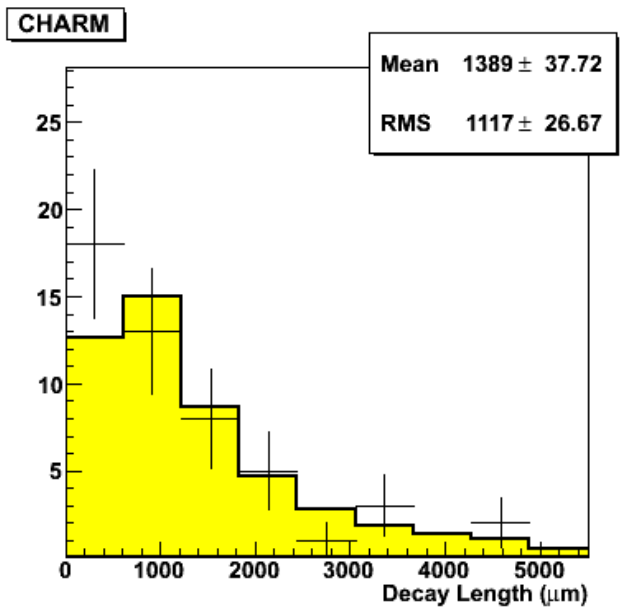


D_0 hypothesis: F.L.: 313.1 μm, ϕ : 173.2^0, invariant mass: 1.7 GeV

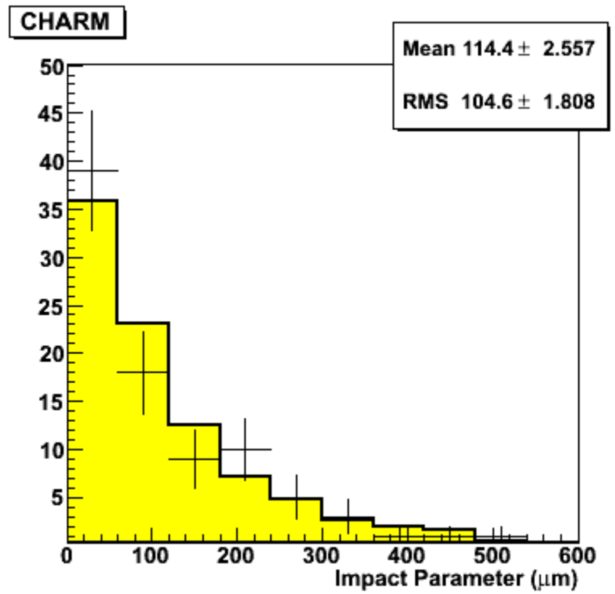
CHARM events: detected 49, expected 51±7.5



Phi angle



Decay length



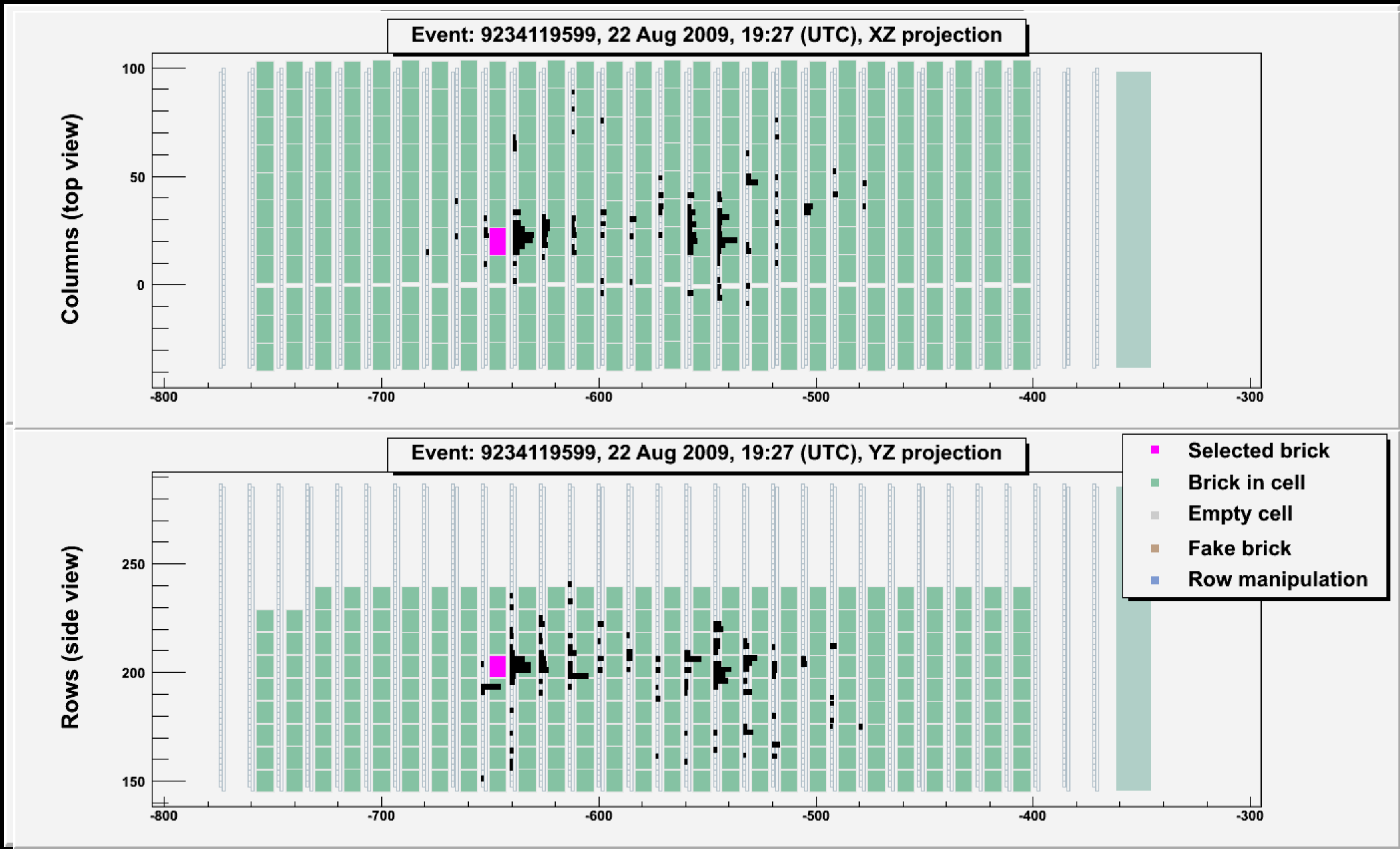
Impact Parameter

ν_τ *CANDIDATE EVENTS*

Present statistics (NEUTRINO12 conference)

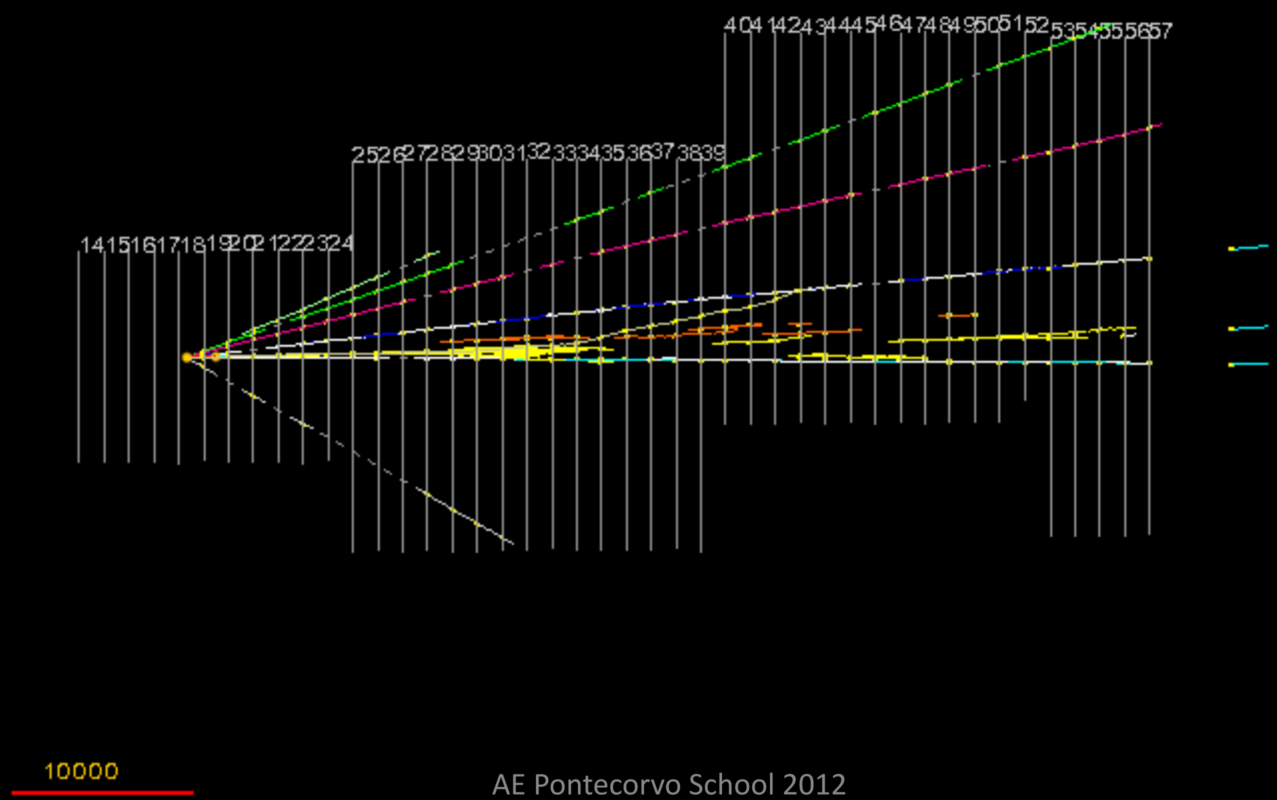
Years	Status of analysis	# of events for decay search	Expected ν_τ events (Preliminary)	Observed ν_τ candidate events	Expected BG for ν_τ (Preliminary)
2008-2009	completed	2783		1	
2010-2011	in progress	1343		**1**	
2012	started				
Total		4126	2.1	**2**	0.2

Electronic detectors' display: first candidate event

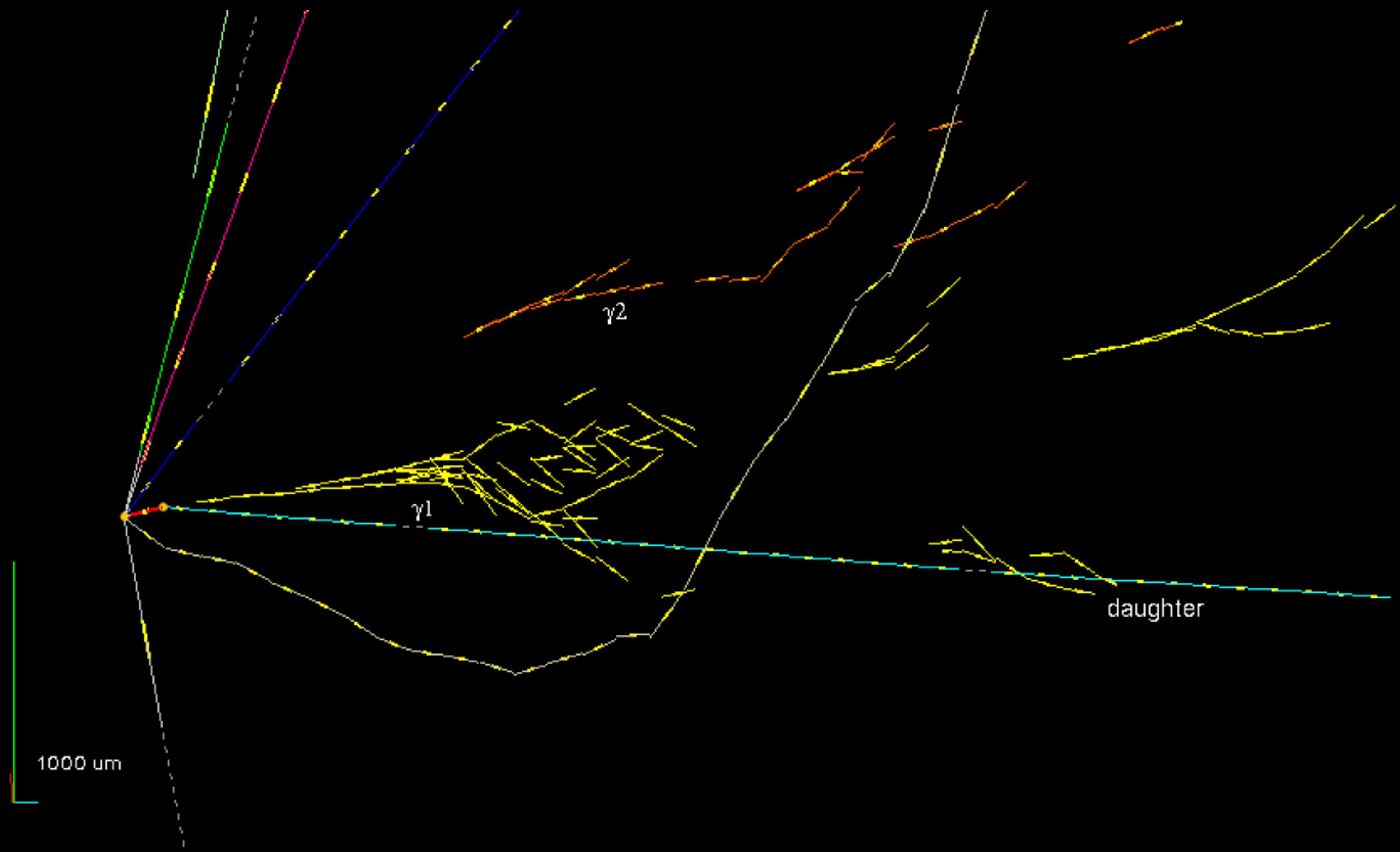


From CS to vertex location

Large area scanning
Full reconstruction of vertices and gammas

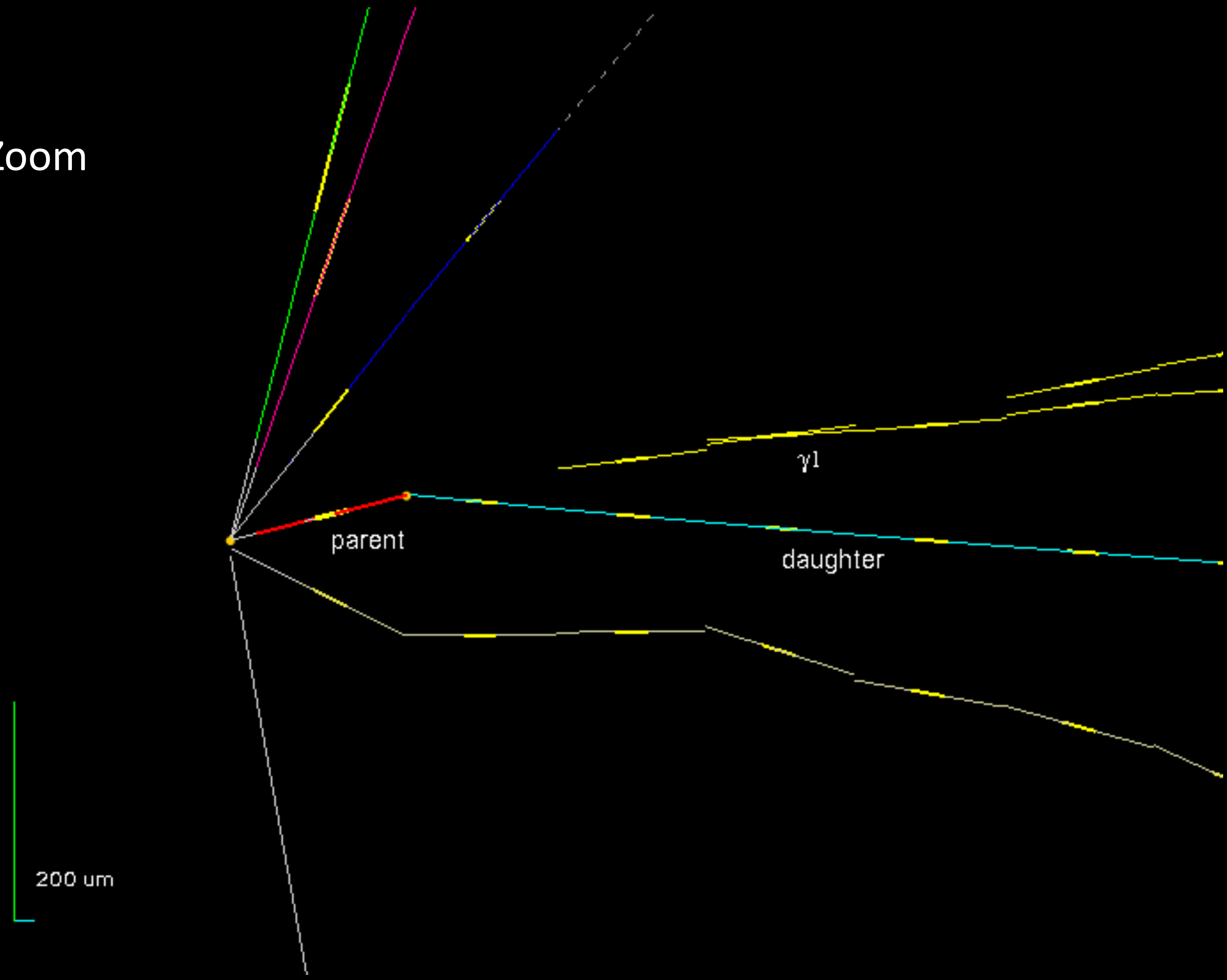


Event reconstruction (1)



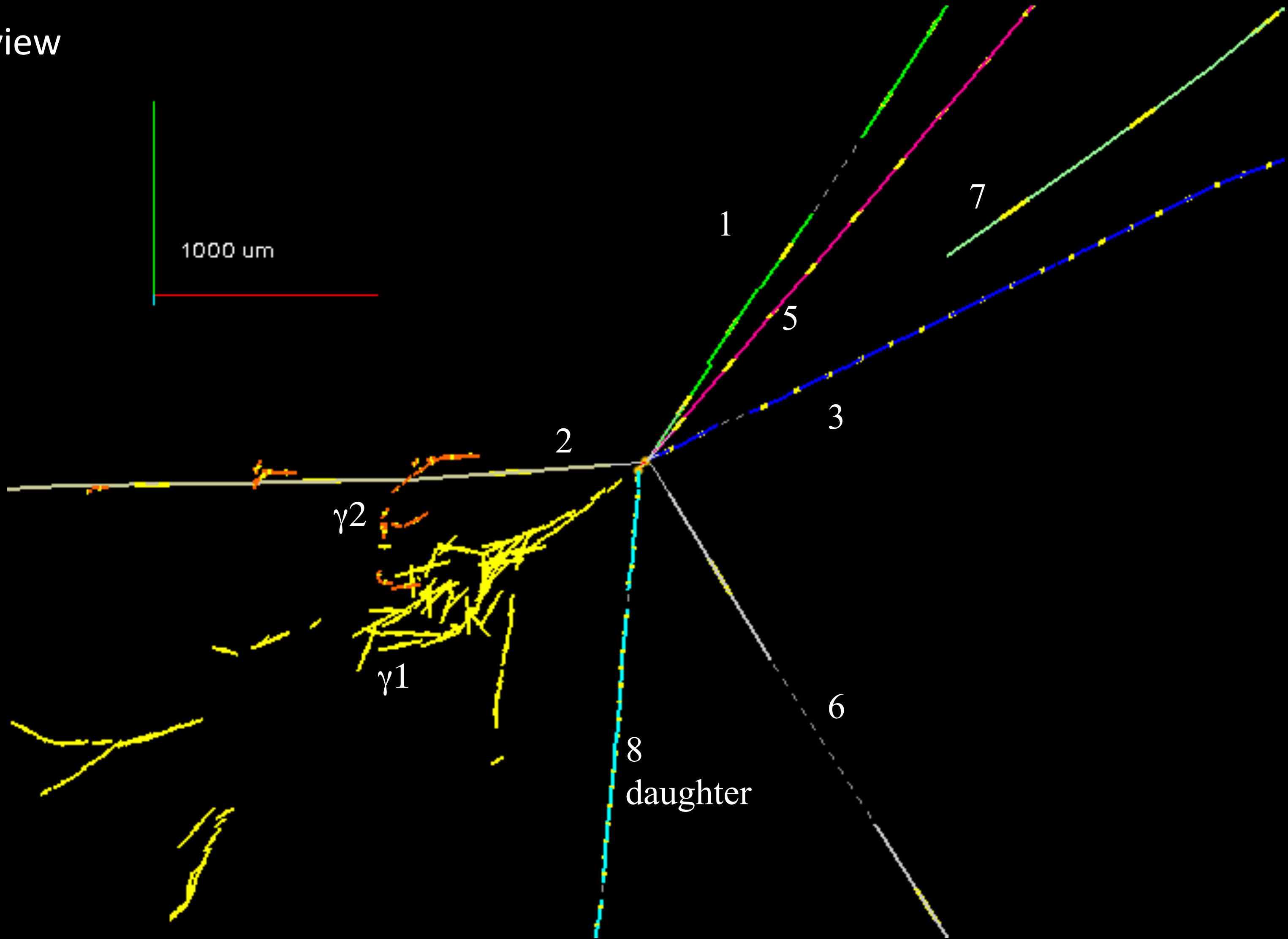
Event reconstruction (2)

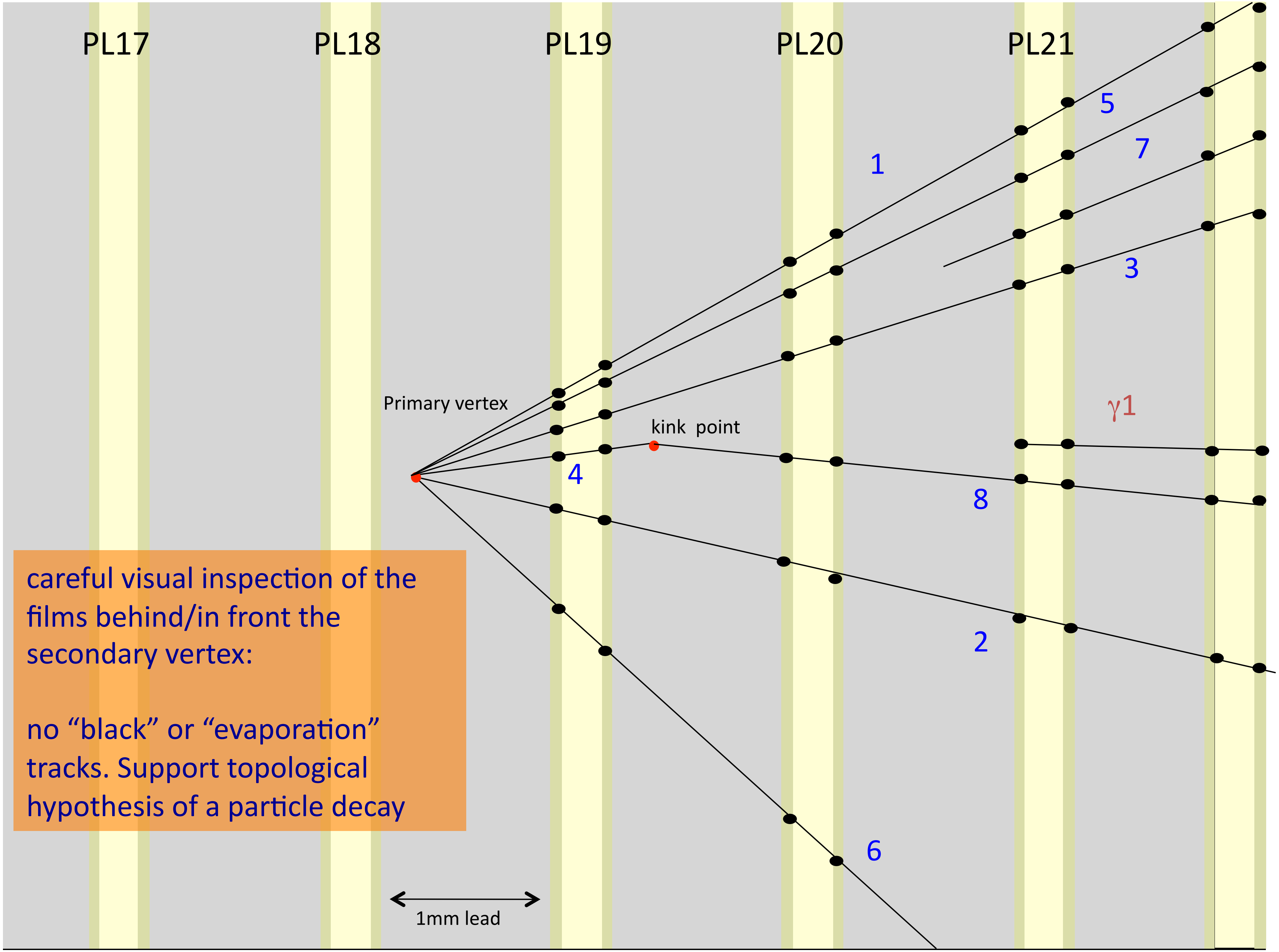
Zoom



Event topological features

Beam view





careful visual inspection of the films behind/in front the secondary vertex:

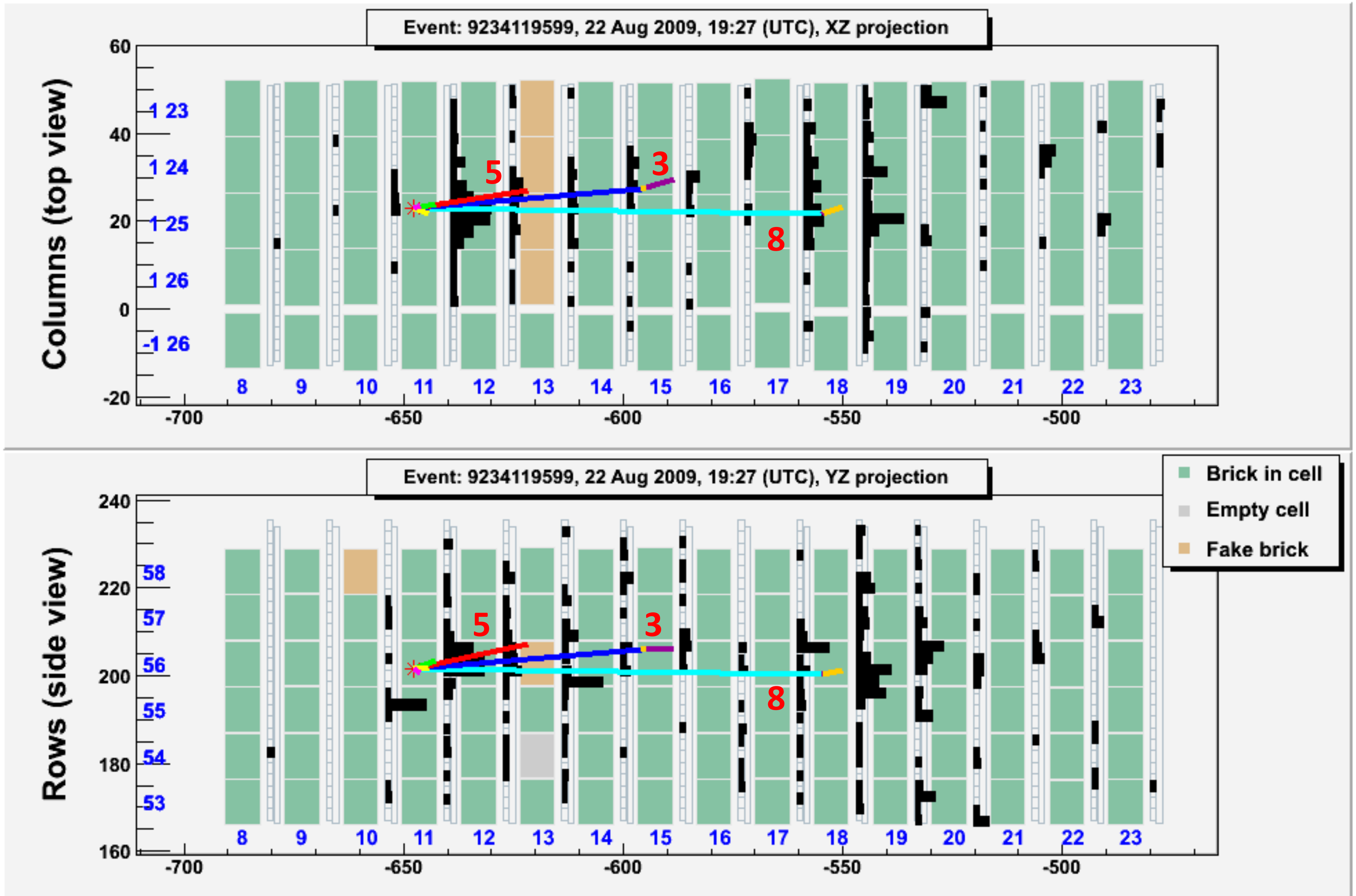
no “black” or “evaporation” tracks. Support topological hypothesis of a particle decay

Event tracks' features

TRACK NUMBER	PID	Probability	MEASUREMENT 1			MEASUREMENT 2		
			tan Θ_X	tan Θ_Y	P (GeV/c)	tan Θ_X	tan Θ_Y	P (GeV/c)
1	HADRON range in Pb/ emul=4.1/1.2 cm	Prob(μ)≈10^{-3}	0.177	0.368	0.77 [0.66,0.93]	0.175	0.357	0.80 [0.65,1.05]
2	PROTON	range, scattering and dE/dx	-0.646	-0.001	0.60 [0.55,0.65]	-0.653	0.001	
3	HADRON	interaction seen	0.105	0.113	2.16 [1.80,2.69]	0.110	0.113	1.71 [1.42,2.15]
4 (PARENT)			-0.023	0.026		-0.030	0.018	
5	HADRON: range in Pb/ emul=9.5/2.8 cm	Prob(μ)≈10^{-3}	0.165	0.275	1.33 [1.13,1.61]	0.149	0.259	1.23 [0.98,1.64]
6	HADRON: range in Pb/ emul=1.6/0.5 cm	Prob(μ)≈10^{-3}				0.334	-0.584	0.36 [0.27,0.54]
7	From a prompt neutral particle		0.430	0.419	0.34 [0.22,0.69]	0.445	0.419	0.58 [0.39,1.16]
8 (DAUGHTER)	HADRON	interaction seen	-0.004	-0.008	12 [9,18]	-0.009	-0.020	

muonless event (favored hypothesis)

Vertex tracks followed down (through several bricks) to assess the muonless nature of the event. Residual probability of ν_μCC event (due to a possibly undetected large angle muon) ~1%. **“Nominal” value of 5% assumed**



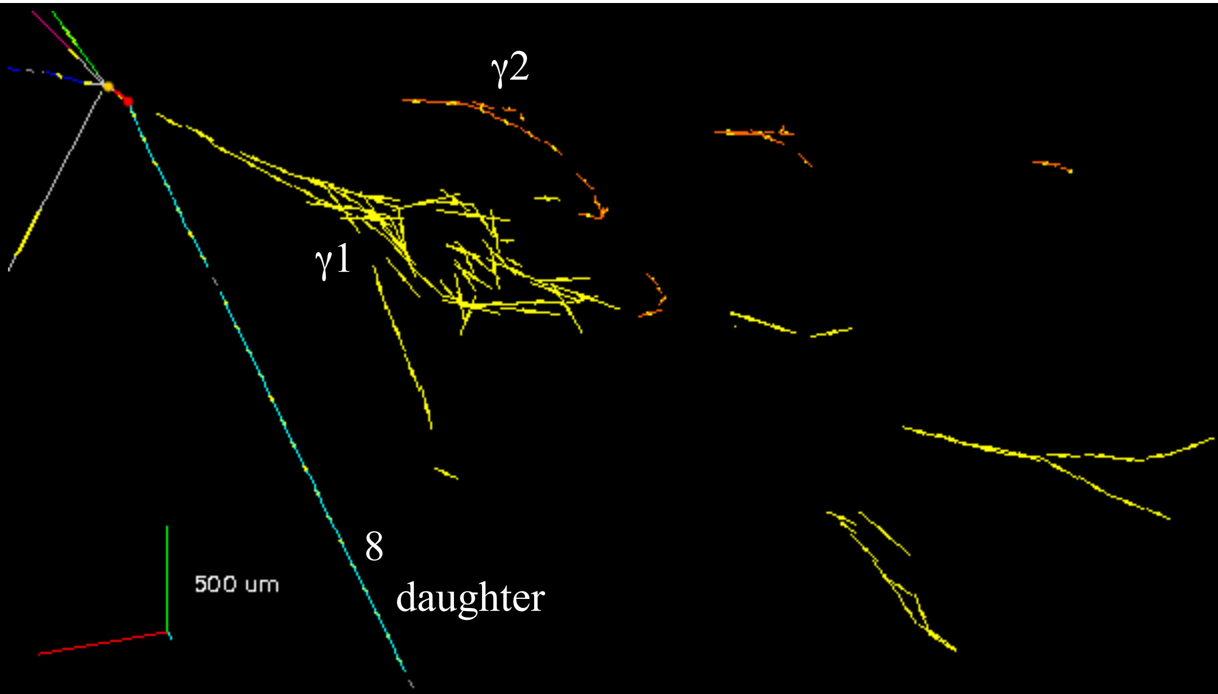
ANALYSIS

OPERA nominal analysis flow applied to the hadronic kink candidates:

(more refined selection criteria being developed were not considered here not to bias our analysis)

- kink occurring within 2 lead plates downstream of the primary vertex
- kink angle larger than 20 mrad
- daughter momentum higher than 2 GeV/c
- decay Pt higher than 600 MeV/c, 300 MeV/c if ≥ 1 gamma pointing to the decay vertex
- missing Pt at primary vertex lower than 1 GeV/c
- azimuthal angle between the resulting hadron momentum direction and the parent track direction larger than $\pi/2$ rad

γ detection



- total radiation length downstream the vertices: 6.5 X_0
- gamma search performed in the whole scanned volume
- careful visual scanning checks
- high probability of being attached to secondary vertex

	Distance from 2ry vertex (mm)	Energy (GeV)
1st γ	2.2	5.6 ± 1.0 ± 1.7
2nd γ	12.6	1.2 ± 0.4 ± 0.4

Kinematical variables

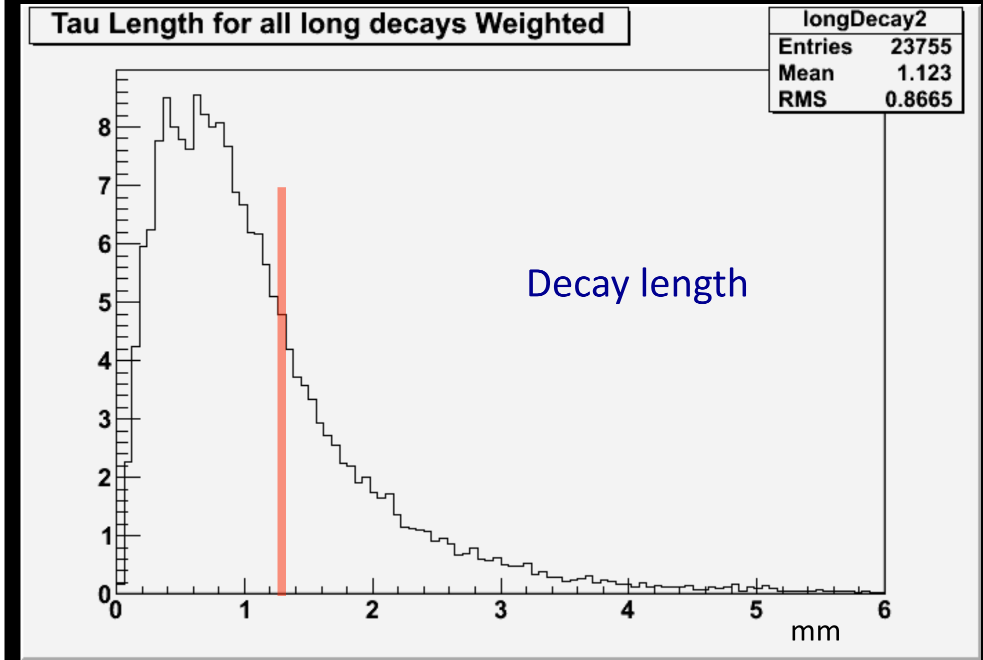
• The kinematical variables are computed by averaging the two sets of track parameter measurements

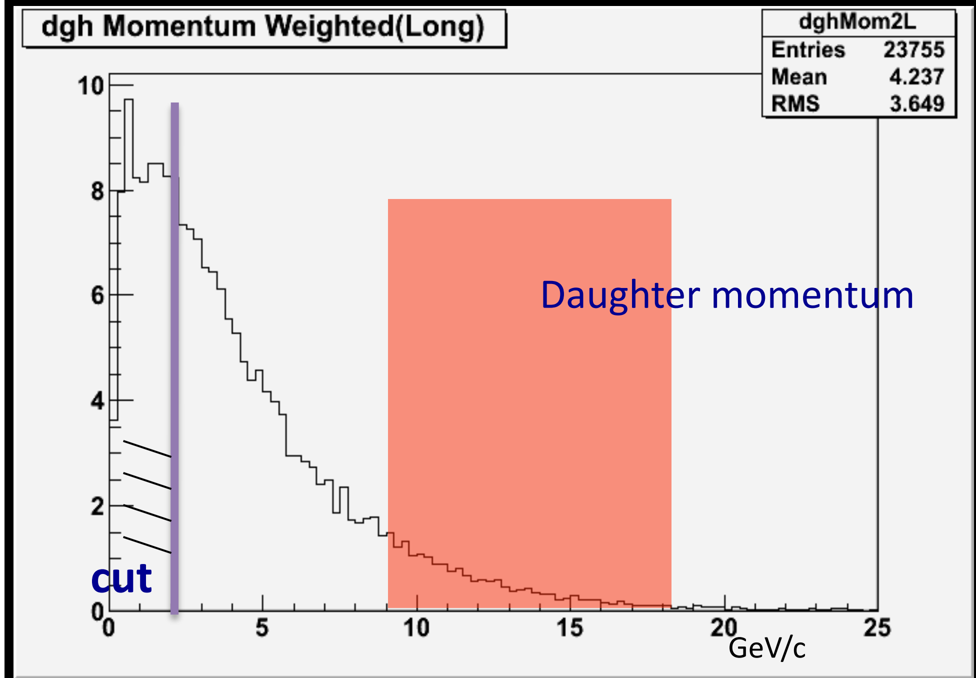
• Assume that:
γ1 and γ2 are both attached to 2^{ry} vertex

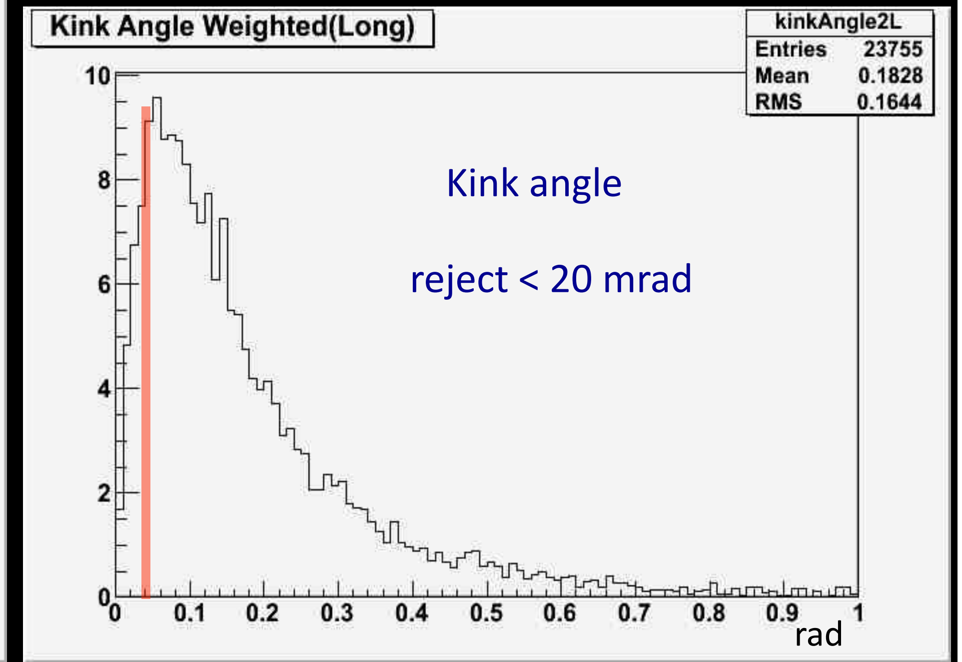
VARIABLE	AVERAGE
kink (mrad)	**41 ± 2**
decay length (μm)	**1335 ± 35**
P daughter (GeV/c)	**12^{+6}_{-3}**
Pt daughter (MeV/c)	**470^{+230}_{-120}**
missing Pt (MeV/c)	**570^{+320}_{-170}**
ϕ (deg)	**173 ± 2**

Features of the decay topology

red bands: values for the candidate event with uncertainties

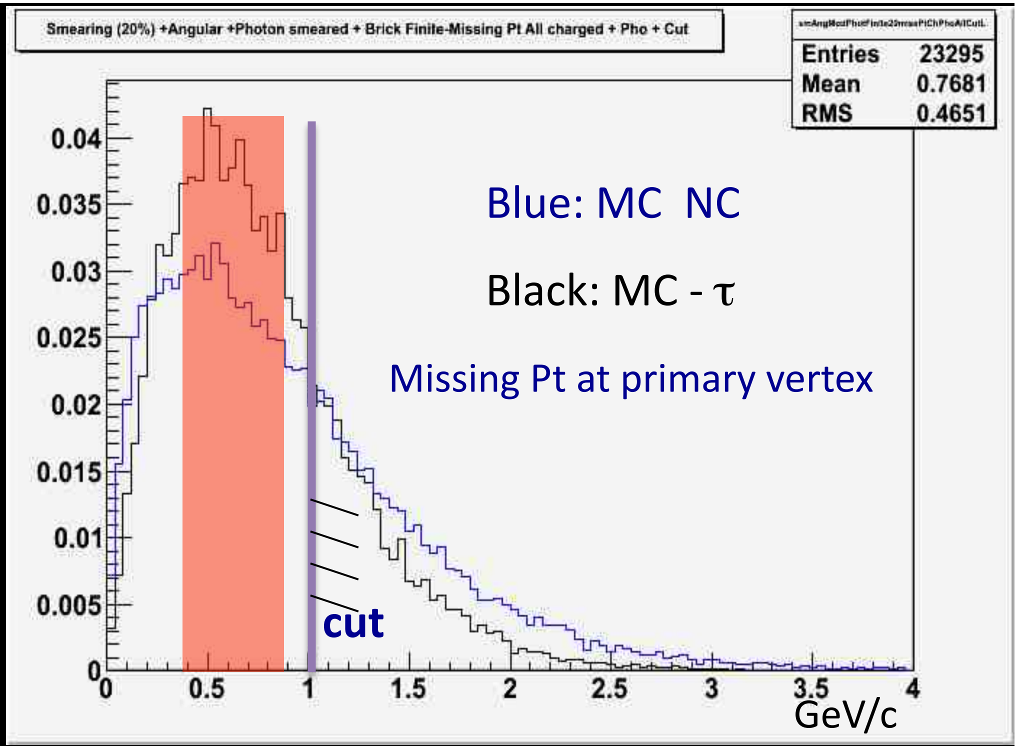




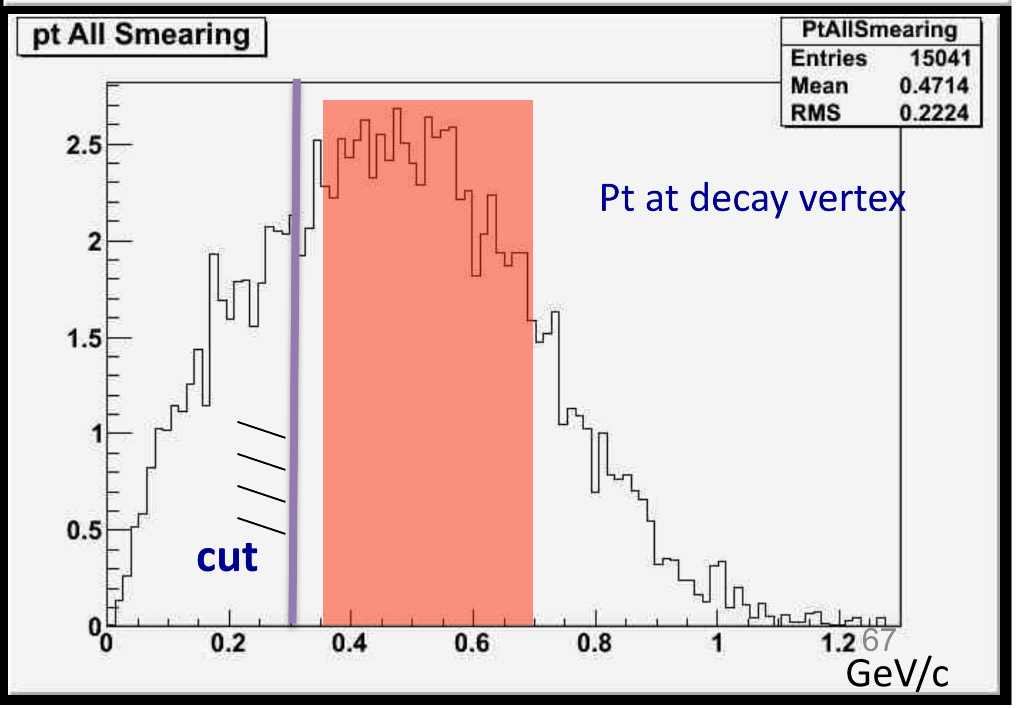


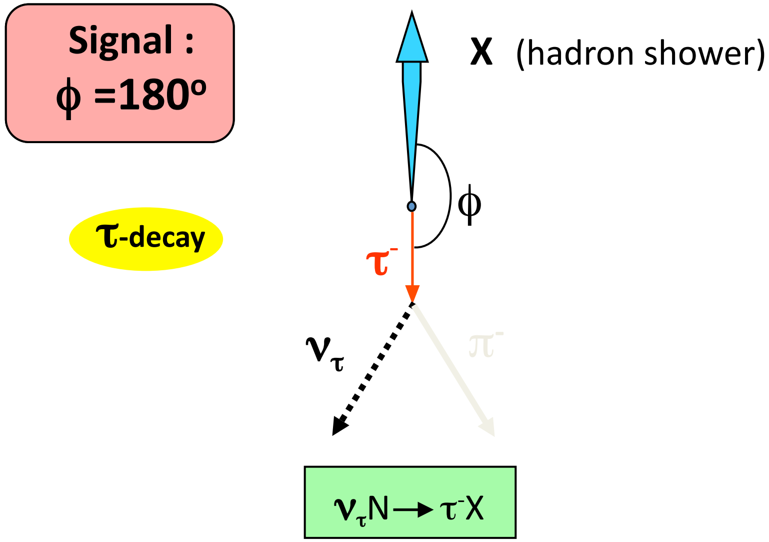
Kinematical cuts to be passed

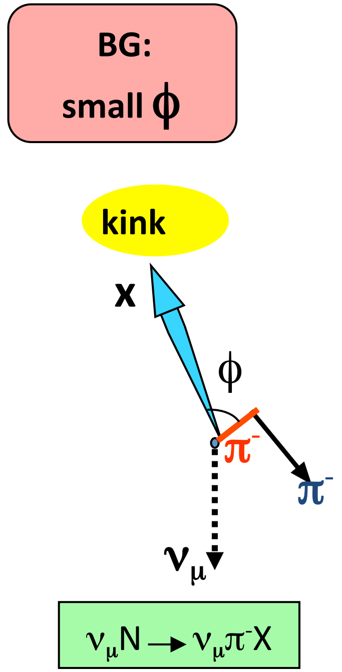
Reject NC events with larger missing Pt (neutrino)



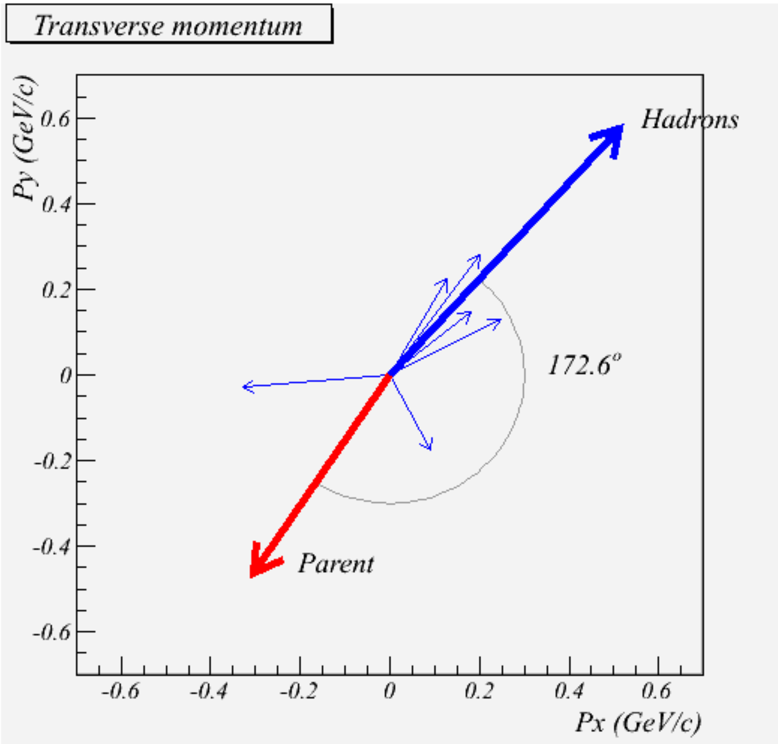
Reject hadron interactions

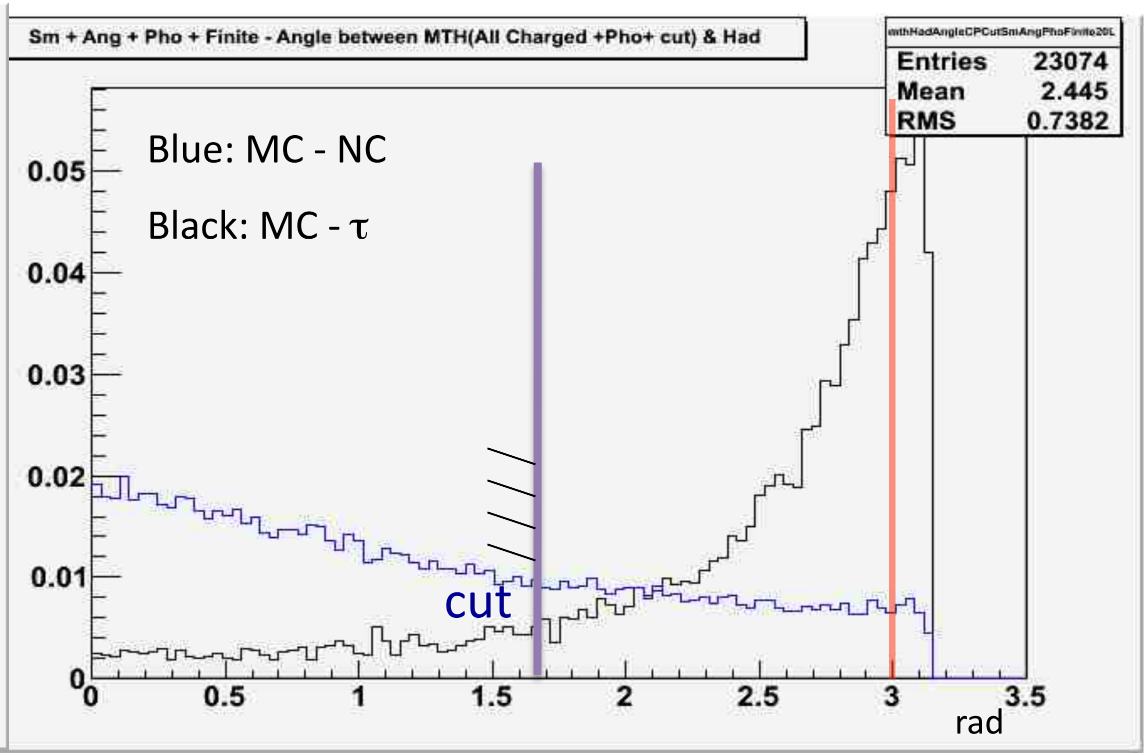






Azimuthal angle between the resulting hadron momentum direction and the parent track direction





Event nature and invariant mass reconstruction

• The event passes all cuts, with the presence of at least 1 gamma pointing to the secondary vertex, and is therefore a candidate to the $\tau \rightarrow$ 1-prong hadron decay mode.

• The invariant mass of the two detected gammas is consistent with the π^0 mass value (see table below).

• The invariant mass of the $\pi^- \ \gamma \ \gamma$ system has a value (see below) compatible with that of the ρ (770). The ρ appears in about 25% of the τ decays: $\tau \rightarrow \rho\ (\pi^- \pi^0)\ \nu_\tau$.

π^o mass	ρ mass
120 ± 20 ± 35 MeV	$640\ ^{+125}_{-80}\ ^{+100}_{-90}$ MeV

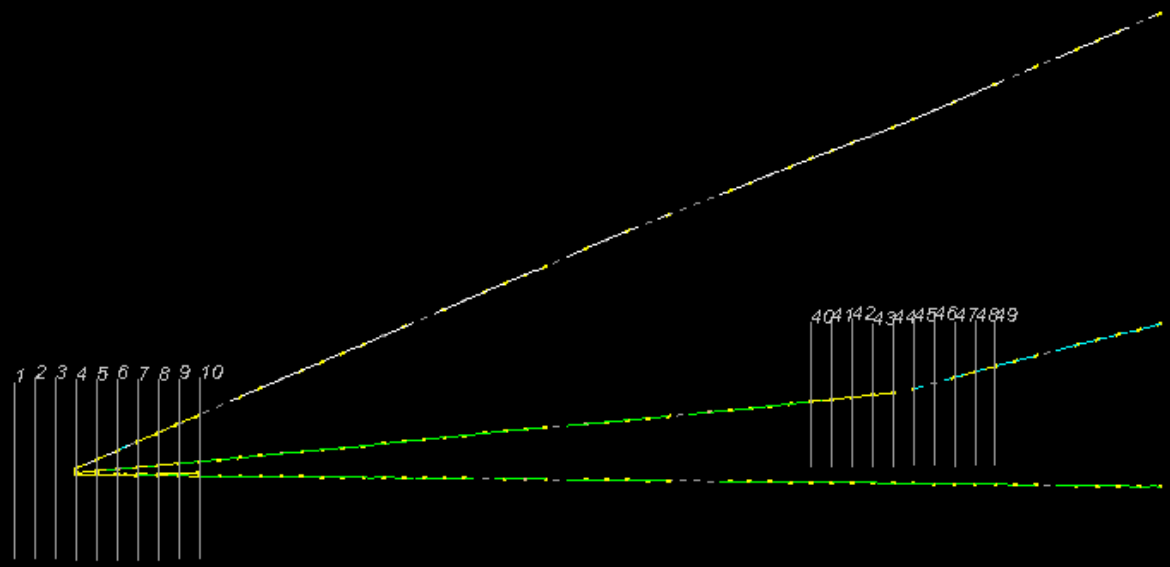
BACKGROUND SOURCES

- Prompt ν_τ ~ 10^{-7}/CC
- Decay of charmed particles produced in ν_e interactions ~ 10^{-6}/CC
- Double charm production ~ 10^{-6}/CC

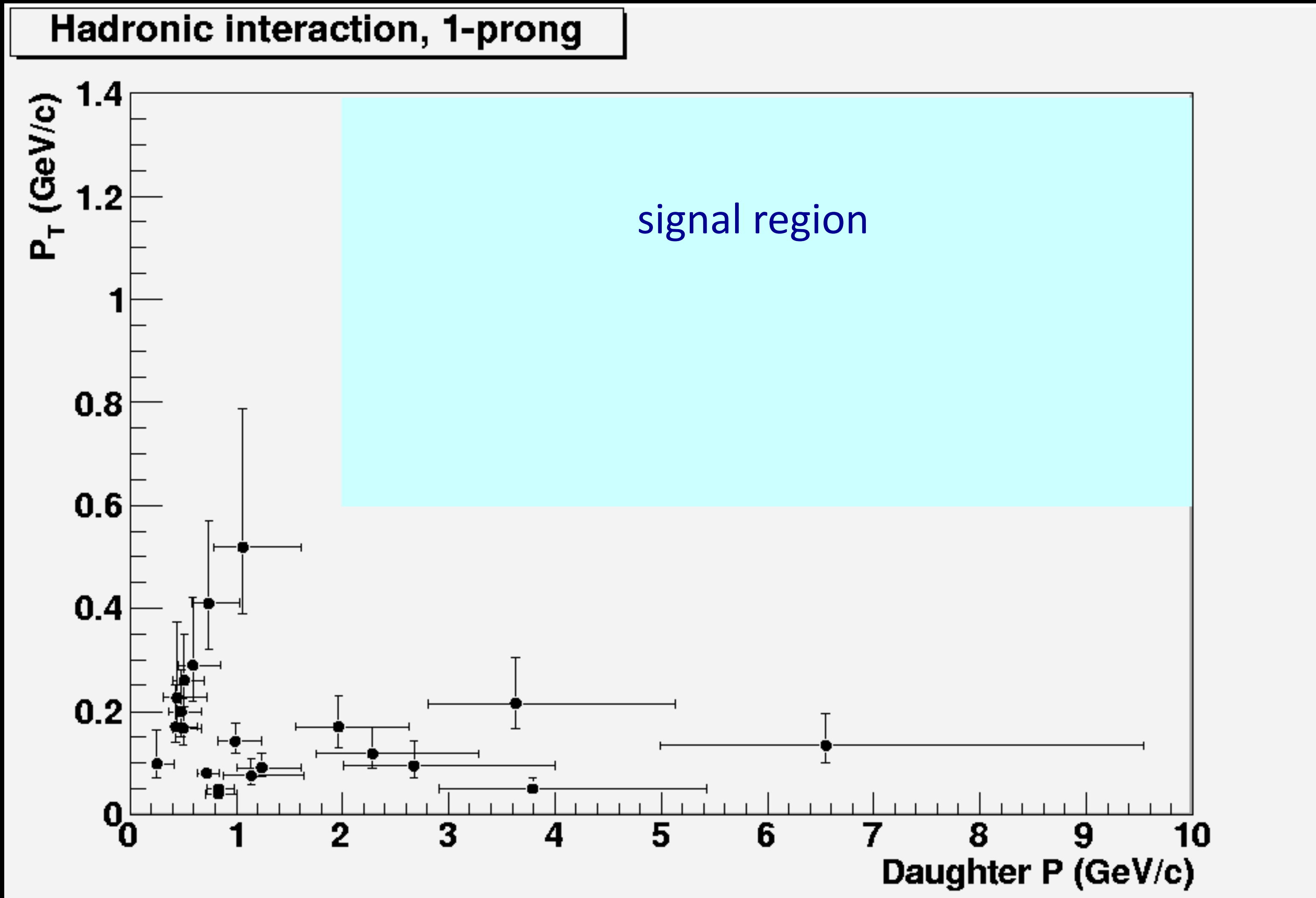
- Decay of charmed particles produced in ν_μ interactions ~ 10^{-5}/CC
- Hadronic reinteractions ~ 10^{-5}/CC

Measure interaction BG far from the τ-decay region

- Search for “kinks” and interactions along a total of 9 m of hadron track measured for scanned events. This is about a factor 8 larger than the so far scanned track length for NC events (number of NC x hadron multiplicity x 2 mm decay length).
- Goal: ~100 m as needed to fully validate (eventually replace) the MC information

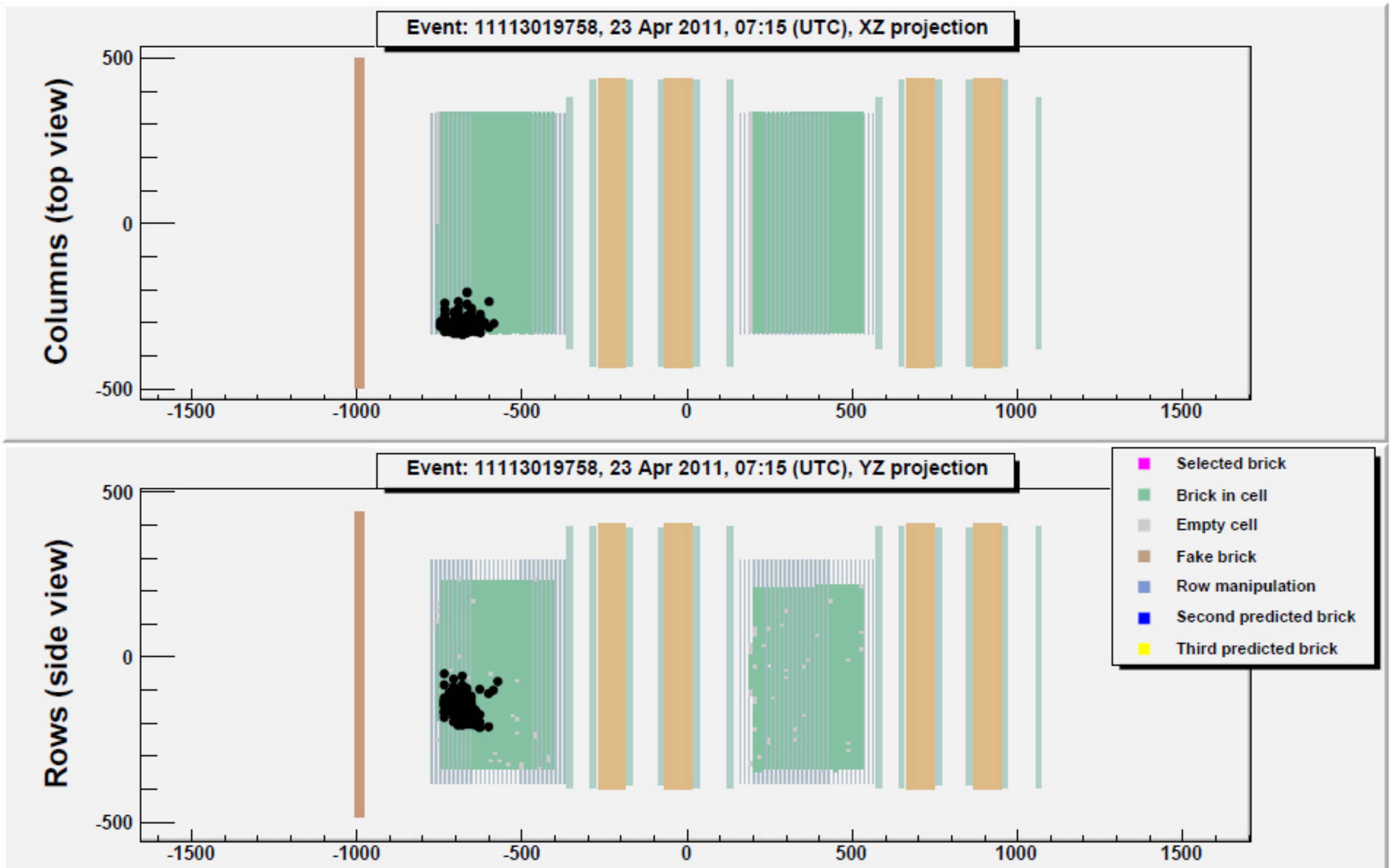


1 cm

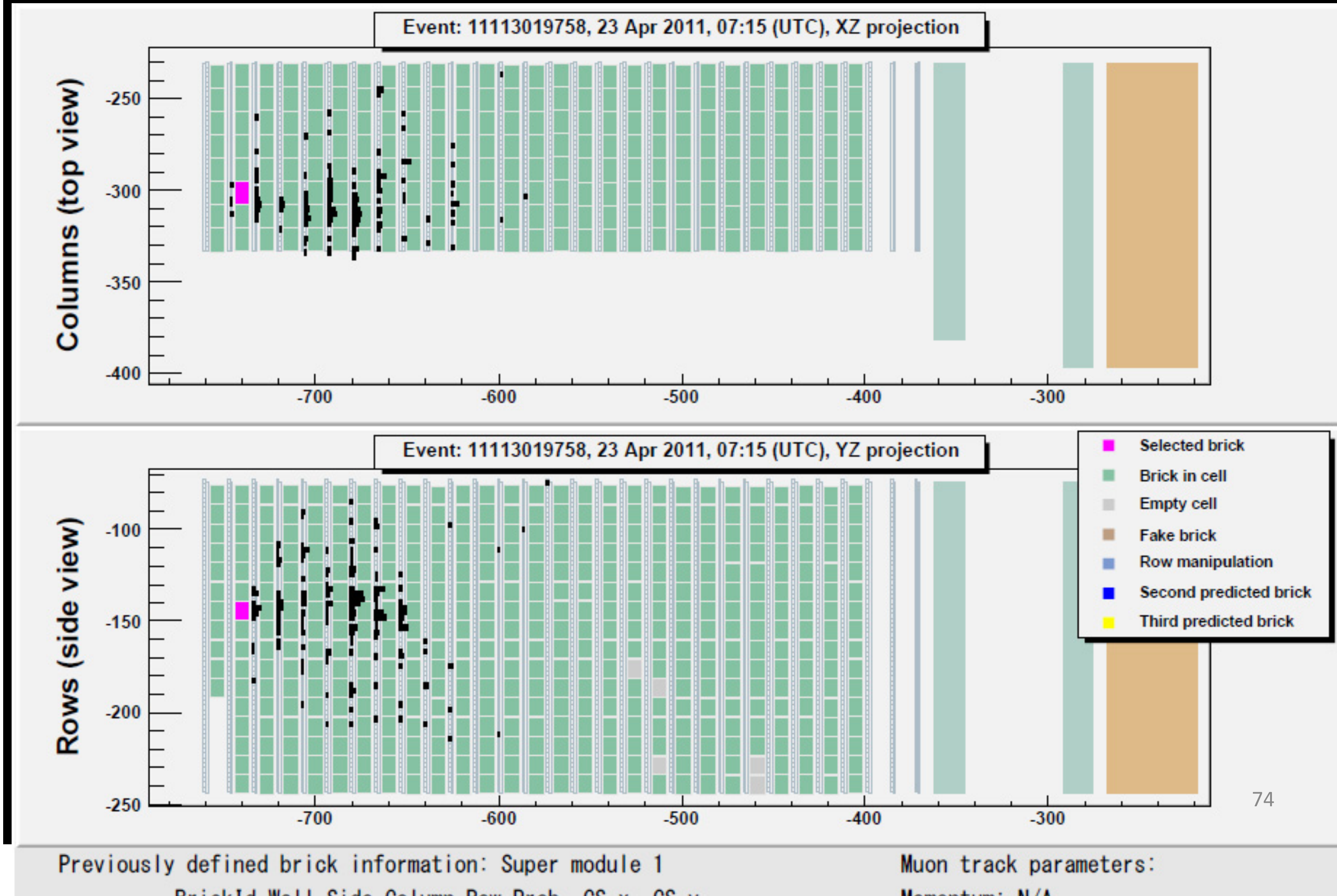


- no events in the signal region
- 90% CL upper limit of 1.54 x 10^{-3} kinks/NC event
- the number of events outside the signal region is confirmed by MC (within the ~30% statistical accuracy of the measurement)

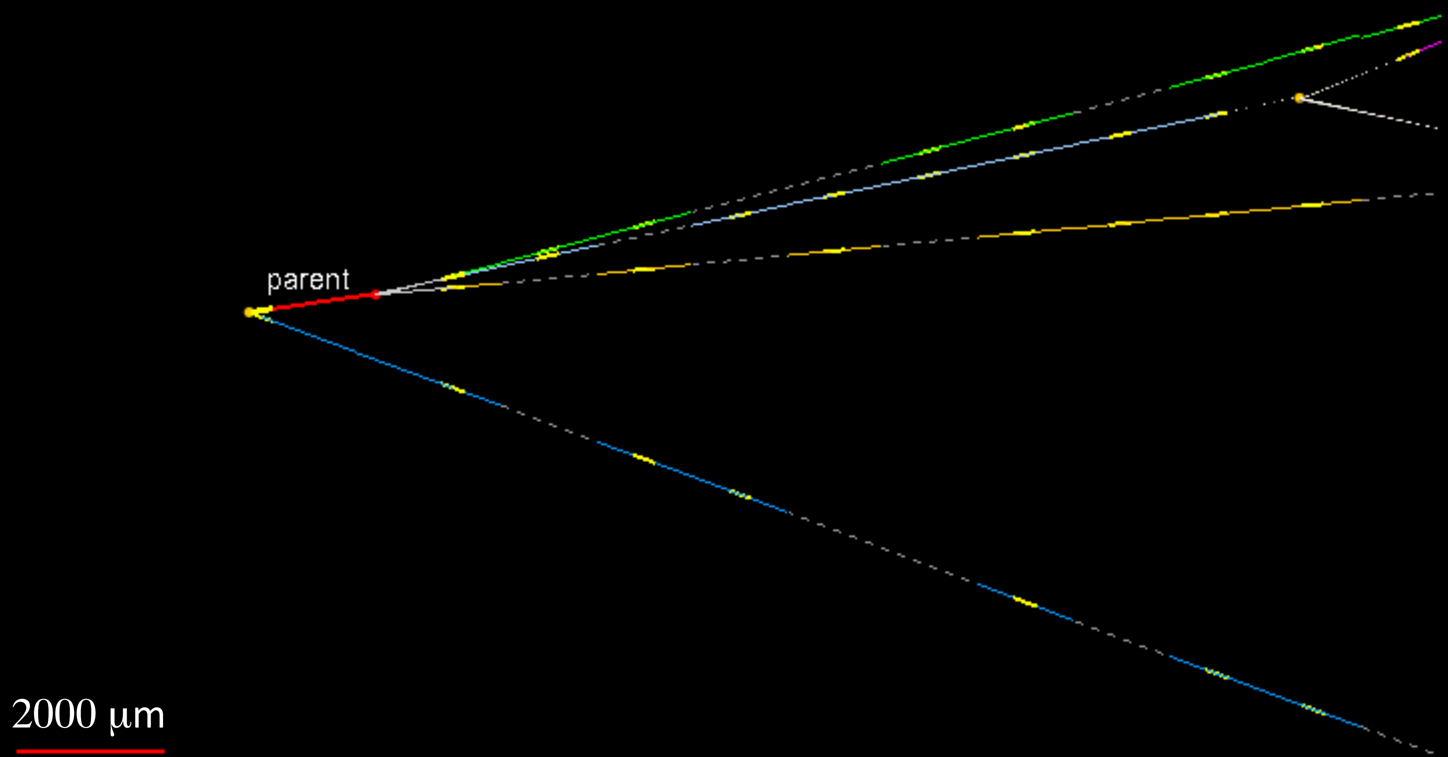
Electronic detectors' display: second candidate event



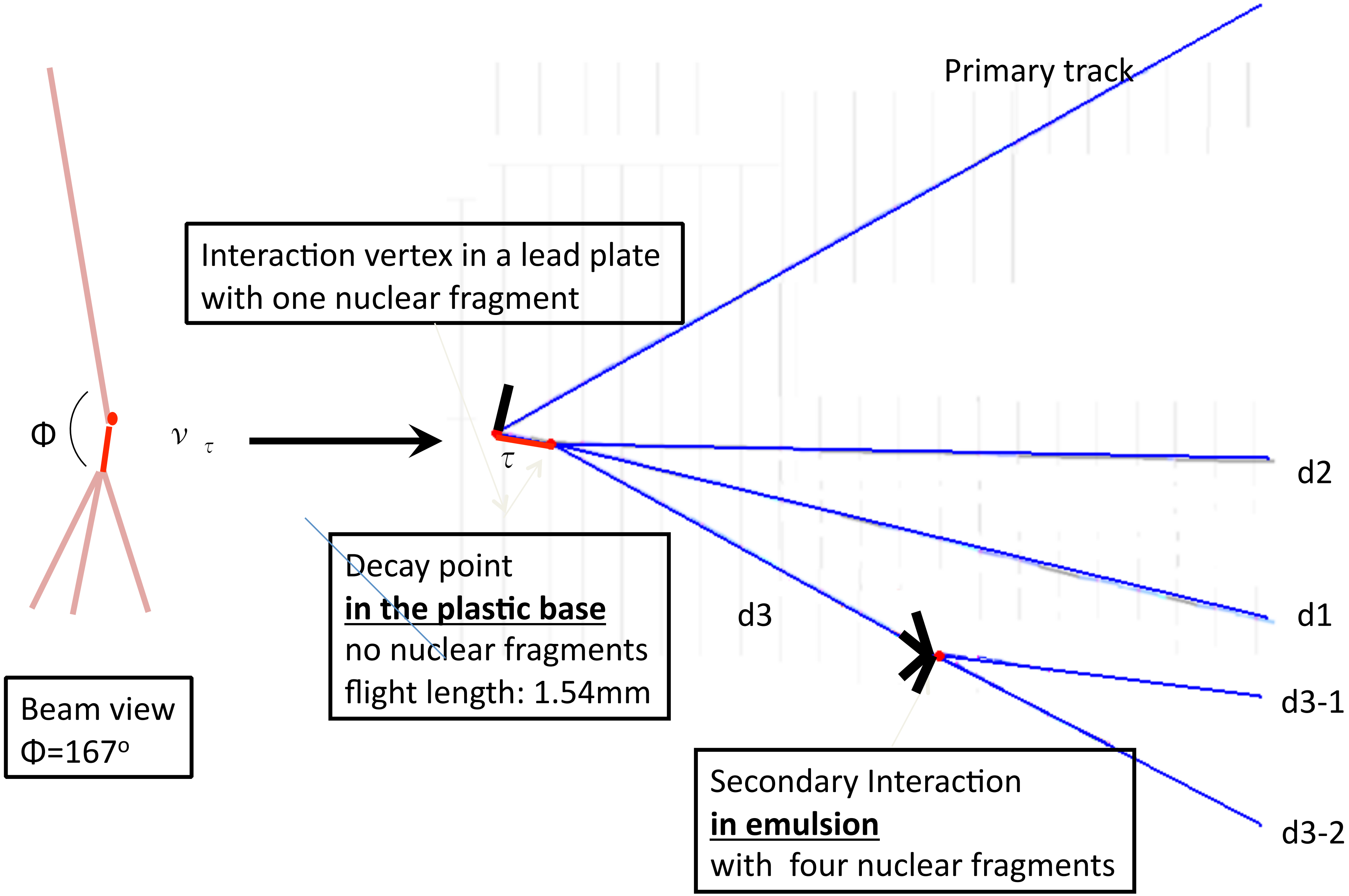
Electronic detectors' display: second candidate event (zoom)



Event reconstruction



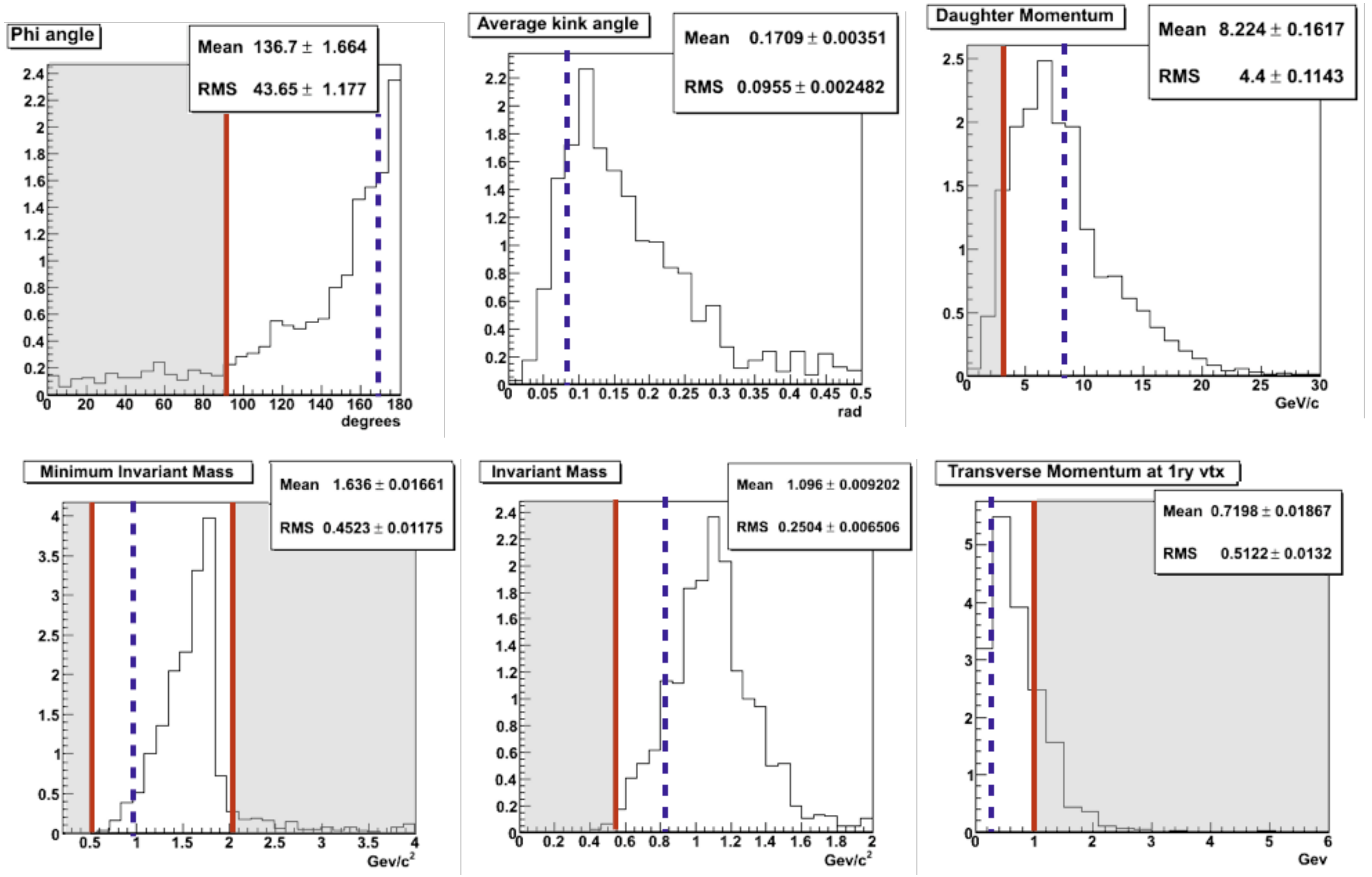
Event topology



Event tracks' features

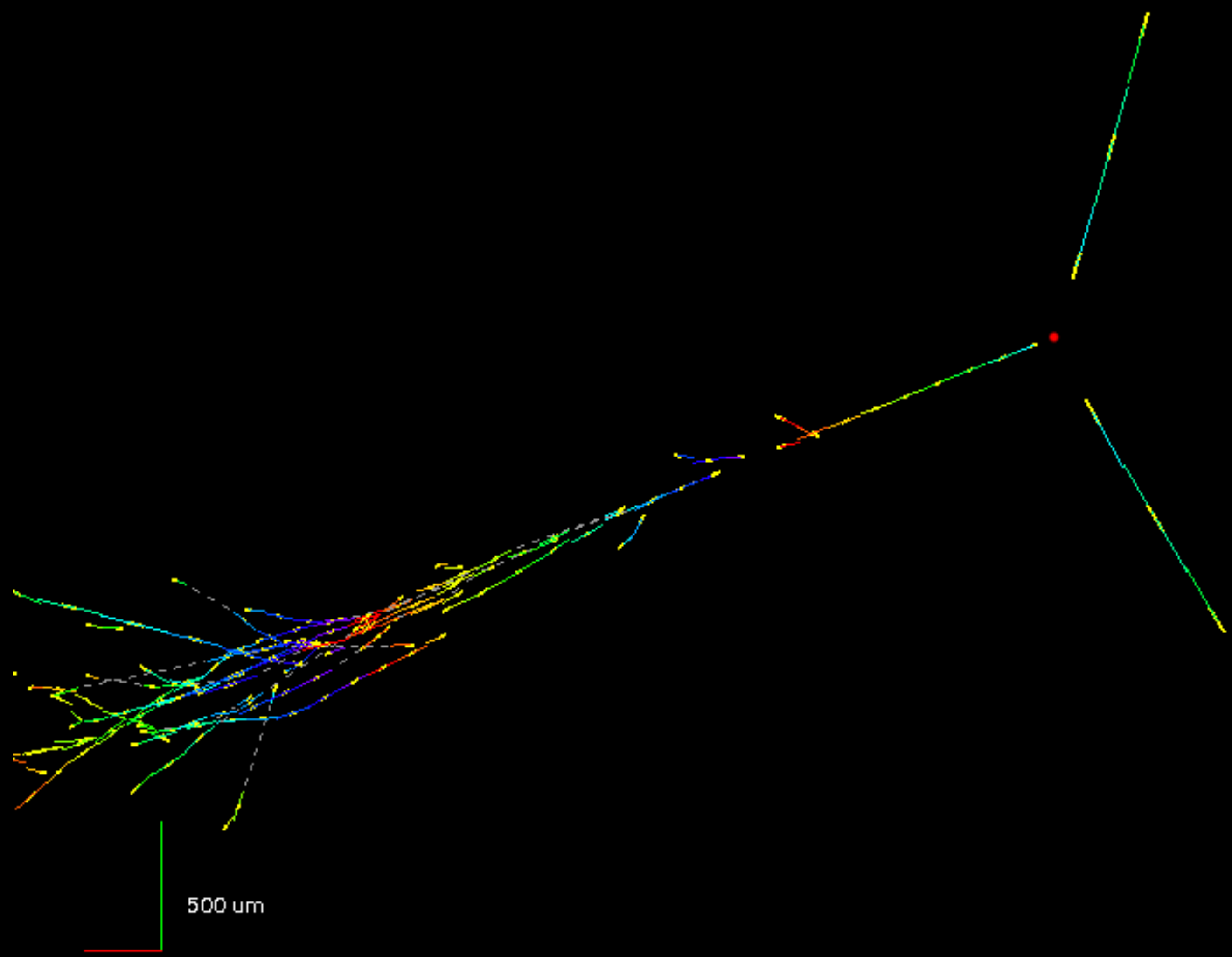
Track	Momentum (1σ interval) [GeV/c]	Particle ID	Method / comments
Primary	2.8 (2.1-3.5)	Hadron	Momentum-range consistency Stops after 2 brick walls Incompatible with a muon (26~44 brick walls)
d1	6.6 (5.2 - 8.6)	Hadron	Momentum-range consistency
d2	1.3 (1.1 -1.5)	Hadron	Momentum-range consistency
d3	2.0 (1.4 - 2.9)	Hadron	Interaction in the brick @ 1.3 cm downstream

Kinematical cuts to be passed

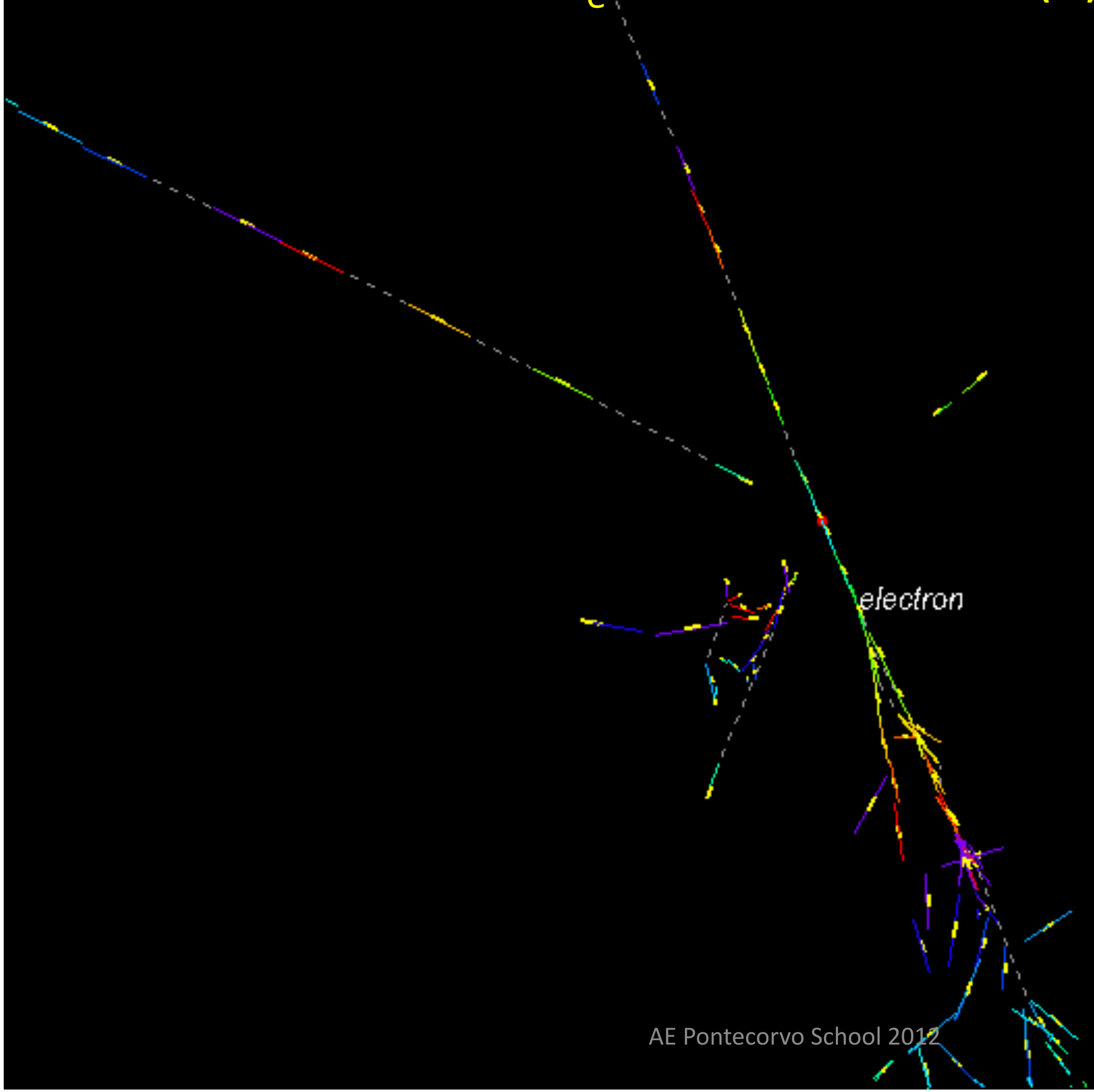


AN INTERESTING BY-PRODUCT: SEARCH FOR ν_e APPEARANCE

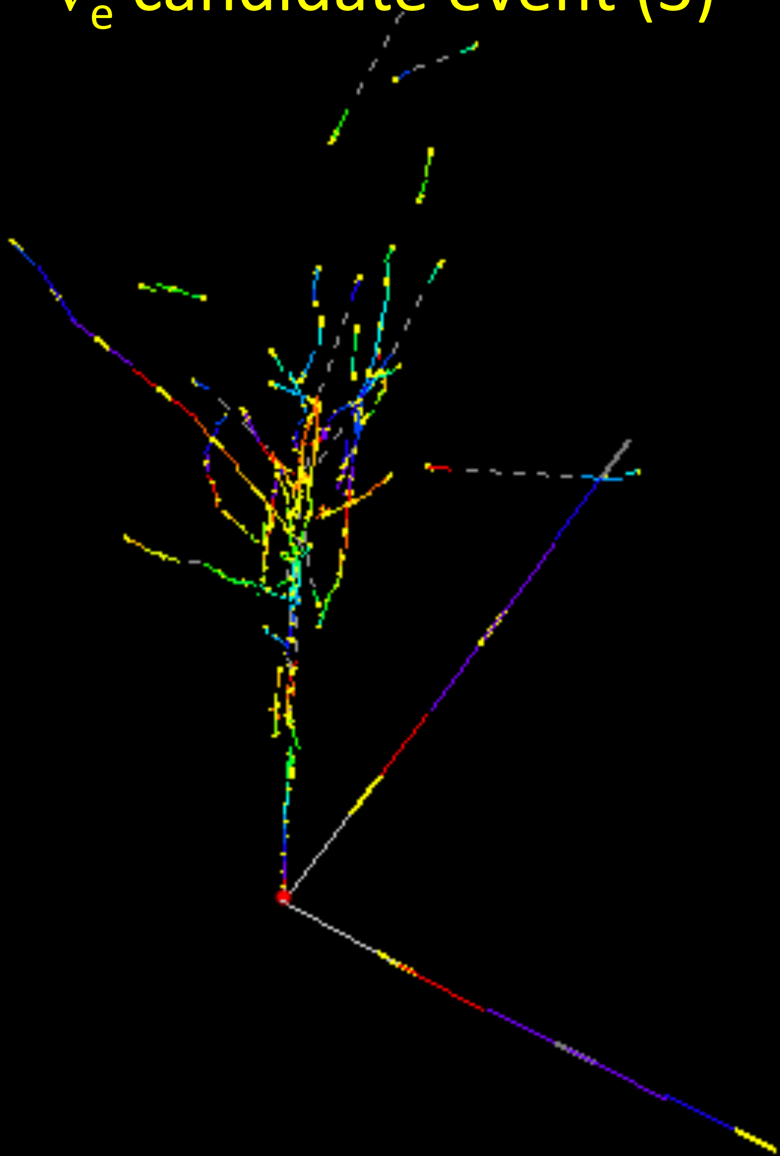
ν_e candidate event (1)



ν_e candidate event (2)



ν_e candidate event (3)



Systematic ν_e search for 2008/2009 located events

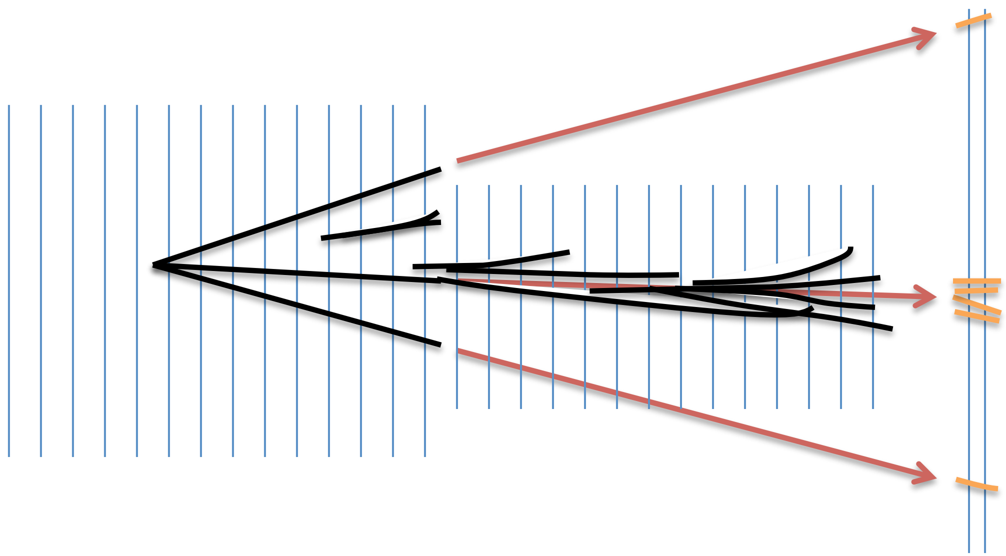
Event sample: 505 NC-like events in 2008 and 2009

For each located event

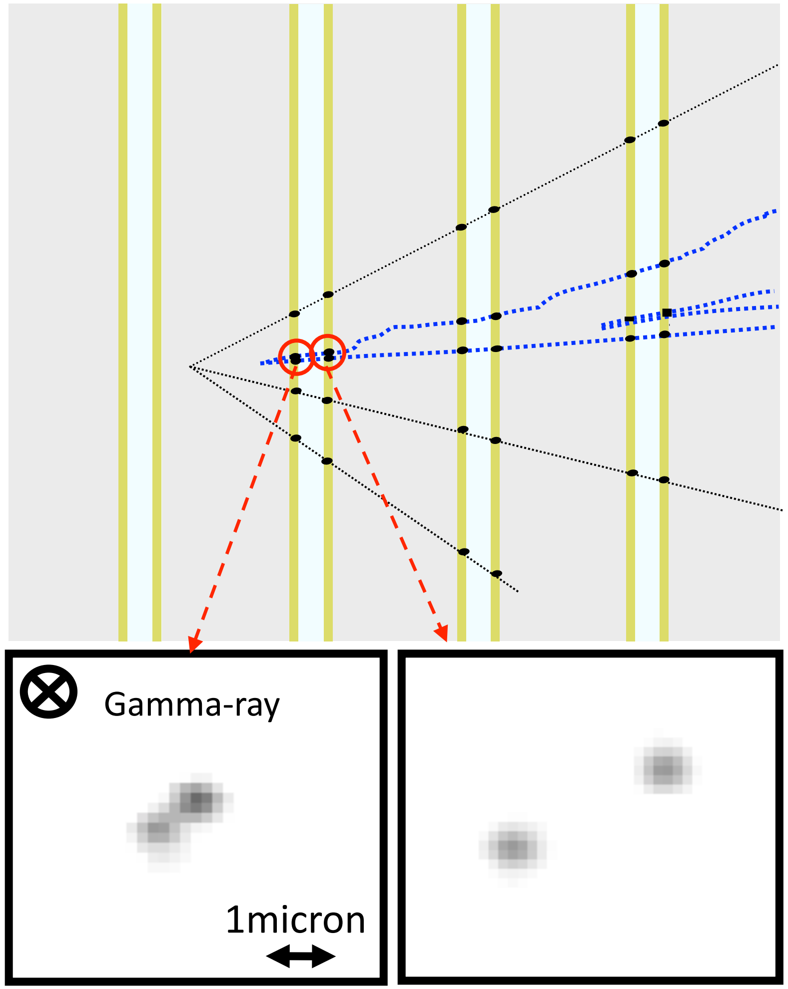
- Extrapolate 1ry tracks to CS.
- Search shower on CS
- If shower-like tracks are found on CS, open additional volume.

As a result

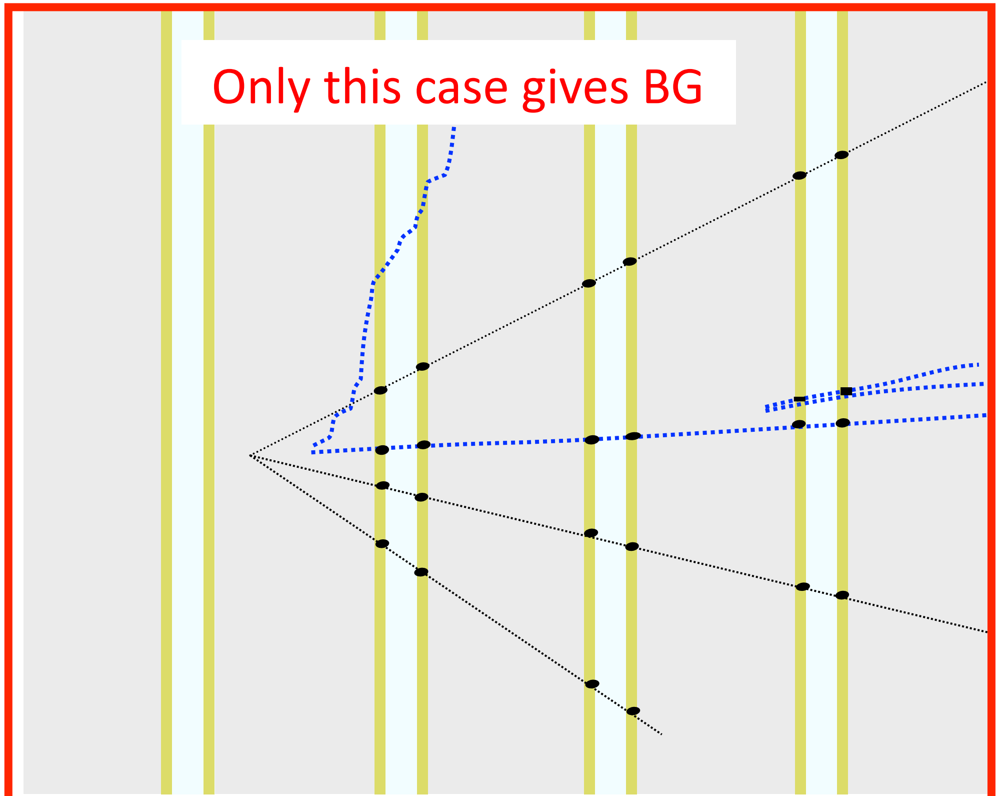
- **96 events are selected**
- **Total 19 ν_e confirmed**



Background from ν_μNC ($\pi^0 \rightarrow 2\gamma$)



Close-up of an electron pair

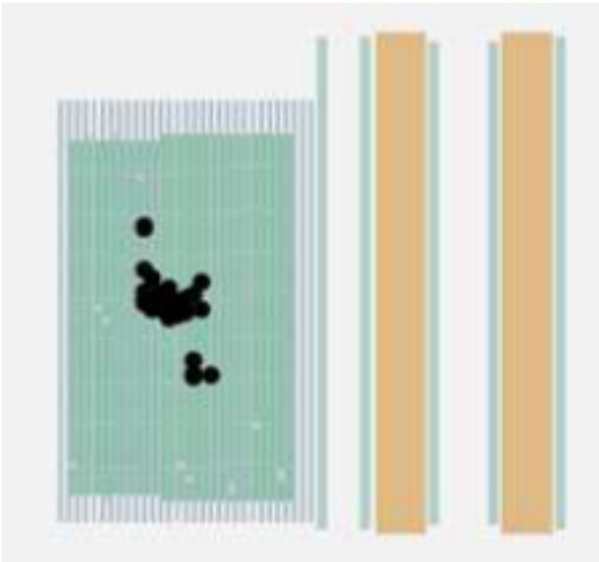


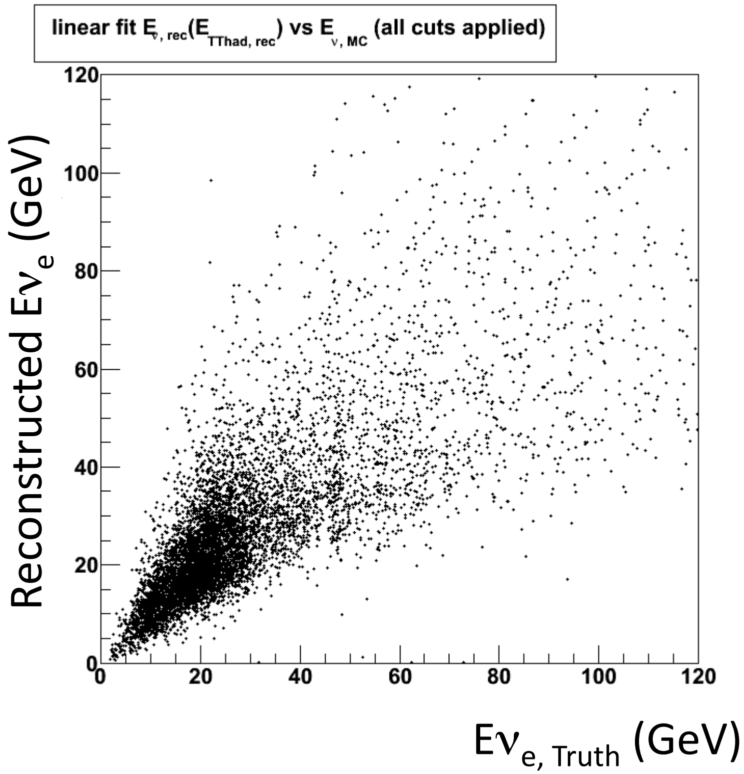
since one electron has low energy and hard to be associated to the pair

BG for 2008+2009 statistics : 0.16 events

Neutrino energy by electronic detectors

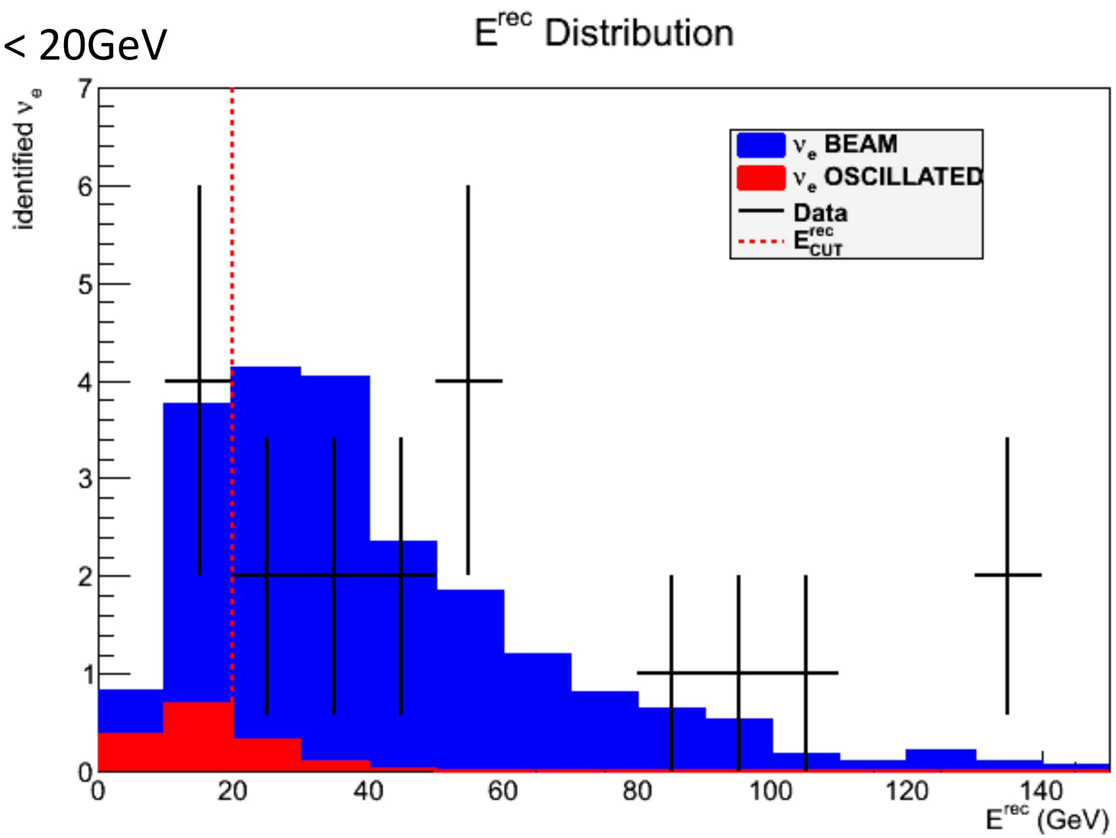
Calorimetric energy measurement





Event energy distribution

$E^{rec} < 20GeV$



expected events:

oscillated ν_e 1.5
beam ν_e BG 19.2

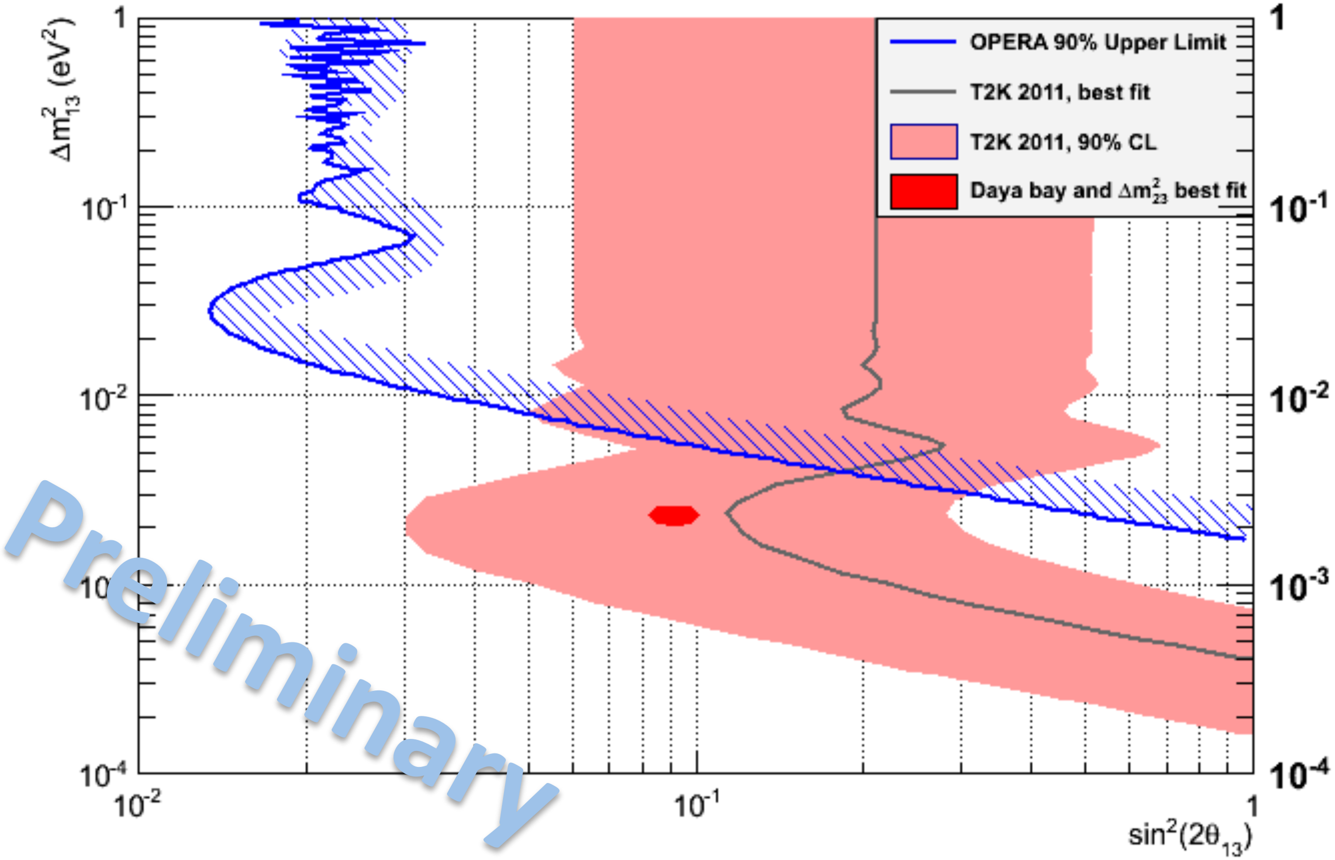
observed ν_e: 19

After low-energy event selection ($E\nu < 20GeV$)

Expected events: oscillated 1.1, beam BG 3.7

Observed events: 4

OPERA $\nu_\mu \rightarrow \nu_e$ oscillation result



Δm_{23}=2.45x10^{-3} eV^2
$\sin^2\theta_{23}$= 0.51

Future improvements:

1) Statistics increased by x3
2) better efficiency

The T2K Collaboration
(12 countries, ~500 people)

USA
Boston U.
Colorado S. U.
U. Colorado
Duke U.
U. C. Irvine
Louisiana S. U.
U. Pittsburgh
U. Rochester
Stony Brook U.
U. Washington

Poland
NCBJ, Warsaw
IFJ PAN, Cracow
T. U. Warsaw
U. Silesia, Katowice
U. Warsaw
U. Wroklaw

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

S Korea
N. U. Chonnam
U. Dongshin
N. U. Seoul

Switzerland
ETH Zurich
U. Bern
U. Geneva

Canada
U. Alberta
U. B. Columbia
U. Regina
U. Toronto
TRIUMF
U. Victoria
U. Winnipeg
York U.

Germany
U. Aachen

Japan
ICRR Kamioka
ICRR RCCN
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Osaka City U.
U. Tokyo

Russia
INR

Spain
IFIC, Valencia
IFAE, Barcelona

UK
Imperial C. L.
Lancaster U.
Liverpool U.
Queen Mary U. L.
Oxford U.
Sheffield U.
STFC/RAL
STFC/Daresbury
Warwick U.

A brief history

- 1999: Nishikawa and Totsuka proposed to measure ν_e appearance as the next step towards the discovery of CP violation in the lepton sector
- 2001: "The JHF-Kamioka Neutrino Project" report (hep-ex/0106019) was issued
- April 2004:
  - Approved by the Japanese Government: construction started
  - T2K international Collaboration setup
- March 2009: Construction completed on schedule
- 23 April 2009: First neutrino beam production
- 24 February 2010: First T2K Event in Super-Kamiokande

The T2K LOI (2003)

Letter of Intent
Neutrino Oscillation Experiment at JHF

Summary

The first stage of a next-generation long baseline neutrino oscillation experiment is proposed to explore the physics beyond the Standard Model. The experiment will use the high intensity proton beam from the JHF 50 GeV proton synchrotron (JHF PS), and Super-Kamiokande as a far detector. The baseline length will be 295 km. The beam power of JHF PS is capable of delivering 3.3×10^{14} 50 GeV protons every 3.5 seconds (0.75 MW). The experiment assumes 130 days of operation at full intensity for five years. The high intensity neutrino beam is produced in an off-axis configuration. The peak neutrino energy is tuned to the oscillation maximum of ~0.8 GeV to maximize the sensitivity to neutrino oscillations.

The merits of this experiment can be summarized as follows:

- The off-axis beam can produce the highest possible intensity with a narrow energy spread. The oscillation maximum will be ~0.8 GeV for the distance of 295 km and $\Delta m^2 \sim 3 \times 10^{-3} eV^2$. The corresponding angle of the beam line axis relative to the direction of far detector is about 2 degrees.
- The far detector, Super-Kamiokande (SK), already exists. Experience in operating SK, including analysis tools, already exists. SK has excellent performance in detecting low-energy neutrinos.
- The neutrino events at sub-GeV are dominated by charged current quasi-elastic interactions, hence the neutrino energy E_ν can be reconstructed by two body kinematics.

The expected sensitivities in the first stage, assuming 0.75 MW and 130 days operation for five years are:

- Discovery of $\nu_\mu \to \nu_e$ at $\Delta m^2 \sim 3 \times 10^{-3} eV^2$ down to $sin^2 2\theta_{13} \sim 0.006$. This is a factor of twenty improvement in sensitivity over past experiments.
- Precision measurements of oscillation parameters in ν_μ disappearance down to $\delta(\Delta m^2_{23}) = 10^{-4}$ eV^2 and $\delta(\sin^2 2\theta_{23}) = 0.01$.
- Search for a sterile component in ν_μ disappearance by detecting neutral current events.

With successful completion of the first stage, a second stage of the experiment can be envisaged. In the second stage with the 1 Mt Hyper-Kamiokande detector and upgraded 4 MW PS, CP violation in the lepton sector can be probed, if $\sin^2 2\theta_{13}$ is in the discovery range of the first stage of the experiment. Sensitivity to proton decay is significantly extended up to 10^{35} $((2 \sim 3) \times 10^{34})$ years lifetime for the $p \to e^+\pi^0$ $(p \to \bar{\nu} K^+)$ mode.

T2K

Disappearance search: $P(\nu_\mu \rightarrow \nu_x) \sim 1-\cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2(\Delta m^2_{23}L/4E)$

Appearance search (sensitive to θ_{13}): $P(\nu_\mu \rightarrow \nu_e) \sim \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2(\Delta m^2_{23}L/4E)$

Knowledge of θ_{13}

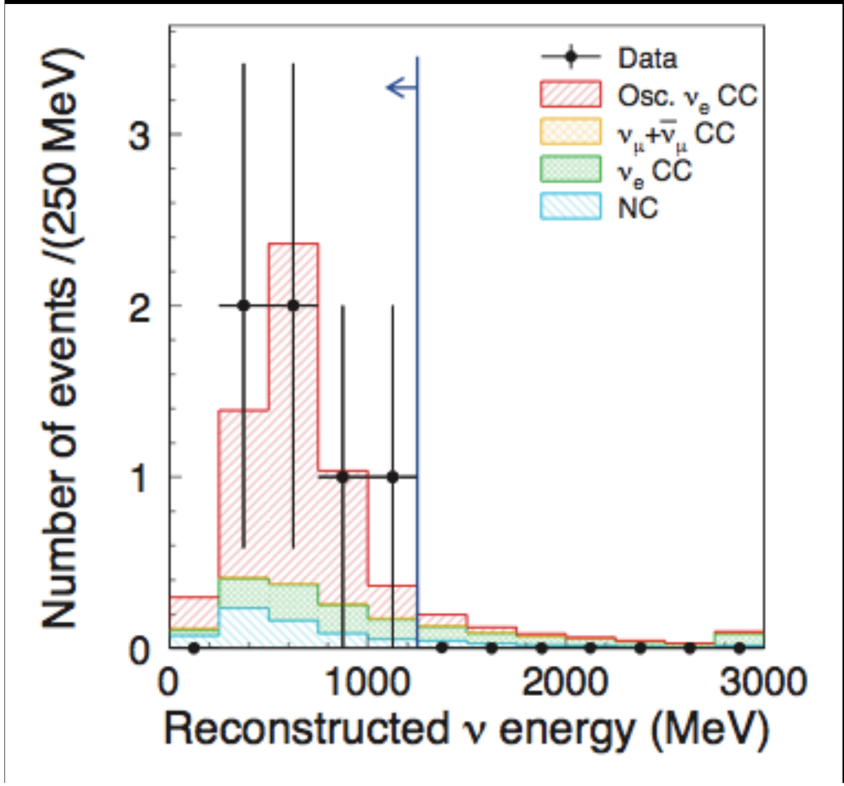
Before T2K:

only a limit: $\sin^2 2\theta_{13} < 0.15$ (CHOOZ)

and some "hints" of $\theta_{13} > 0$ (~1σ from global fits of solar ν + KamLAND)

June 2011:

with ~ 1.4×10^{20} pot, T2K detects 6 ν_e candidate events (BG = 1.5 ± 0.3 events)



$\sin^2 2\theta_{13} = 0.11^{+0.10}_{-0.06}$ (T2K 2011)

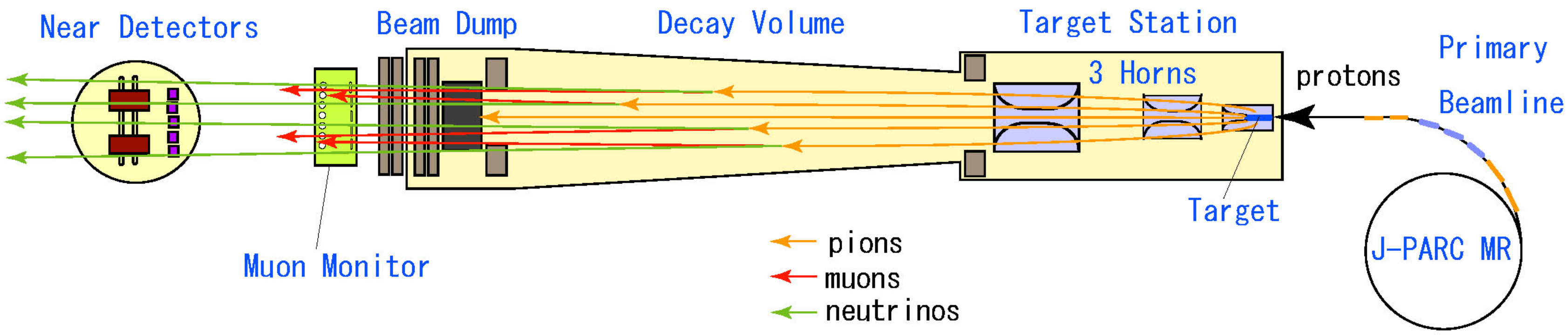
(assuming $\delta_{CP}=0$, $\sin^2 2\theta_{23}=1$, $\Delta m^2_{32}=2.4 \times 10^{-3}$ (NH))

p-value for $\theta_{13}=0$ was 0.007 (2.5σ)

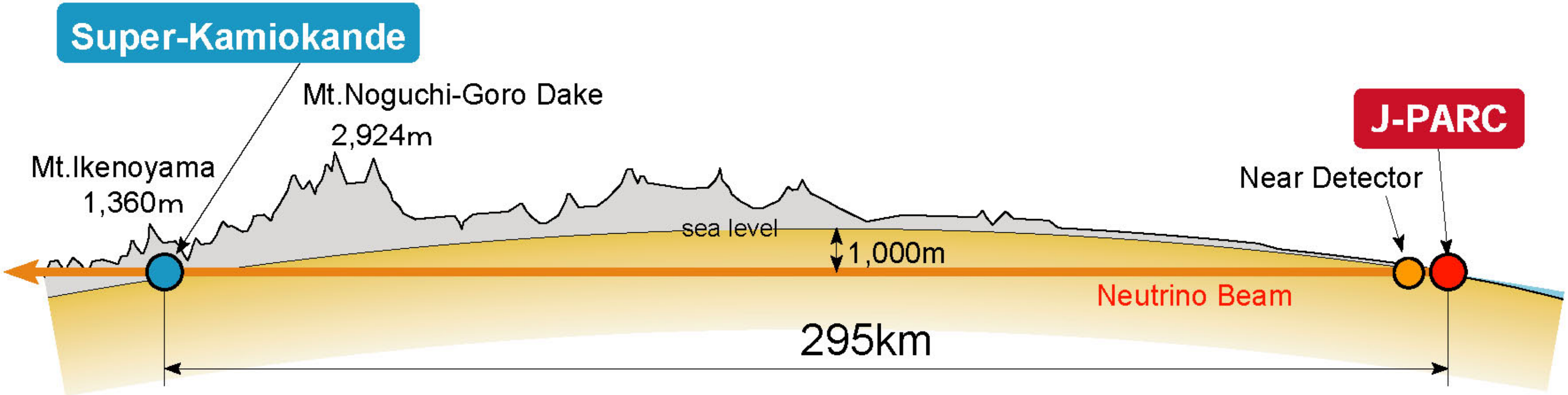
First indication of non-zero θ_{13}

Phys.Rev.Lett. 107, 041801, 2011

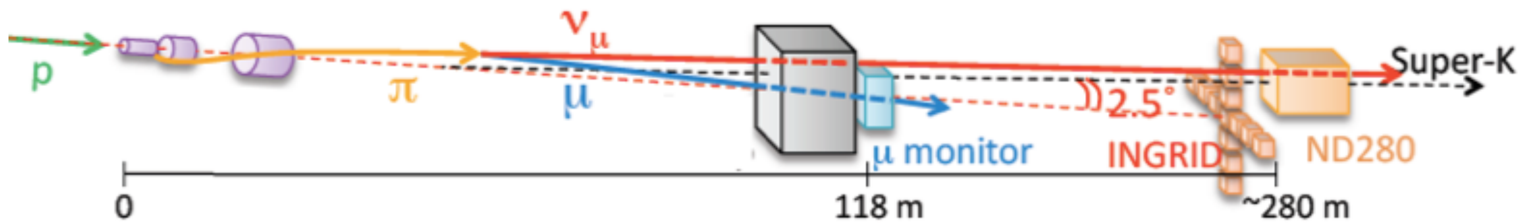
The J-PARC neutrino beam

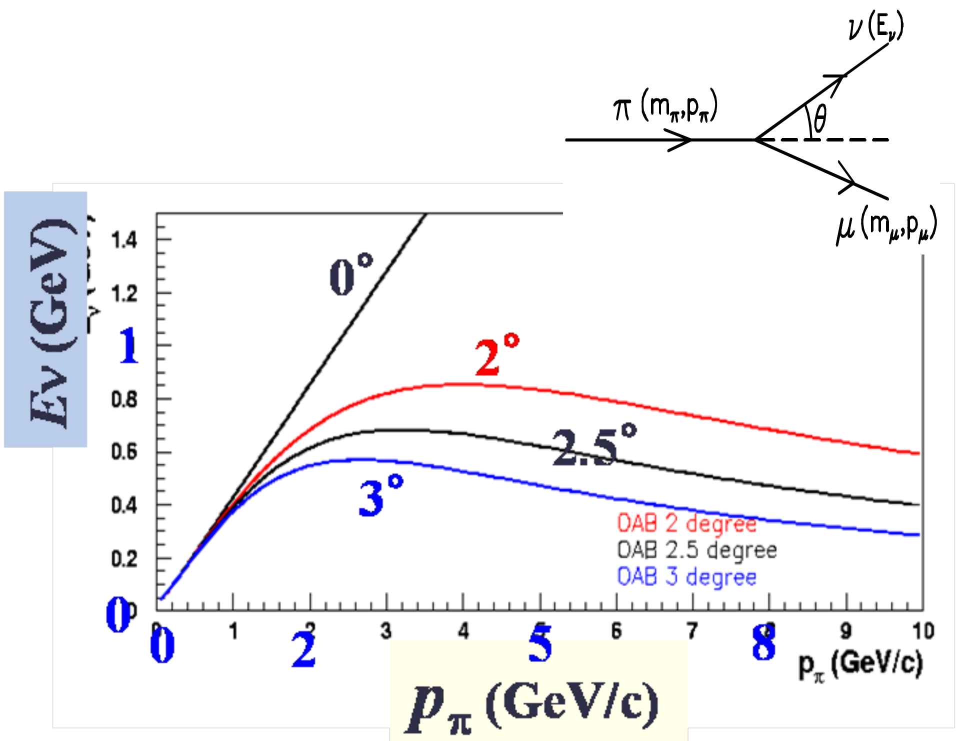


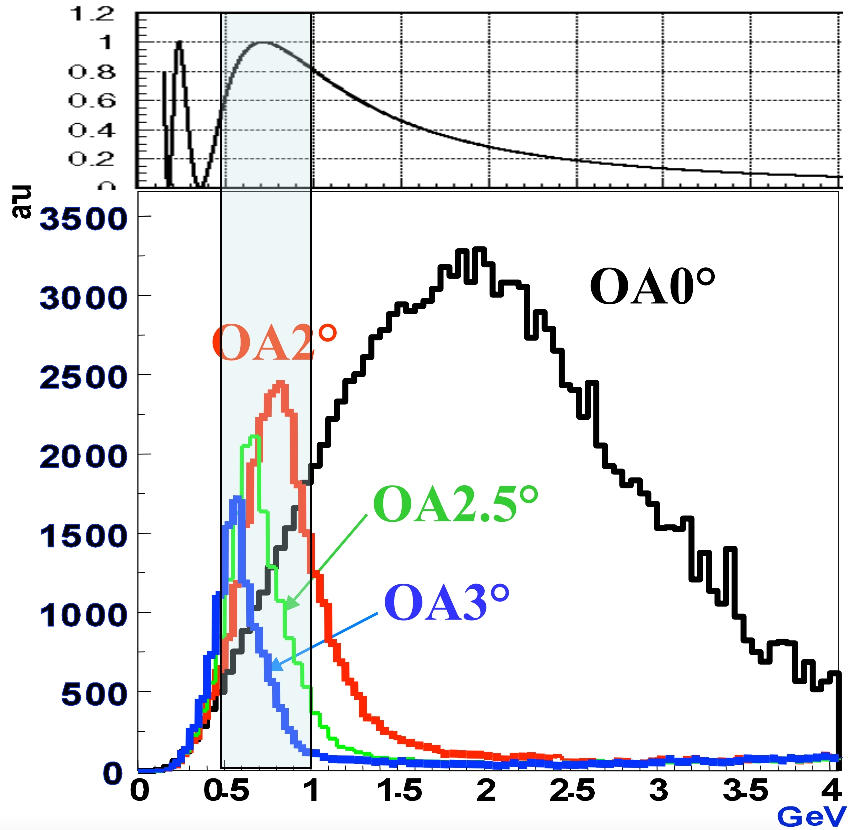
~10^{14} protons (30 GeV) sent on a C target every 2.5~3 s



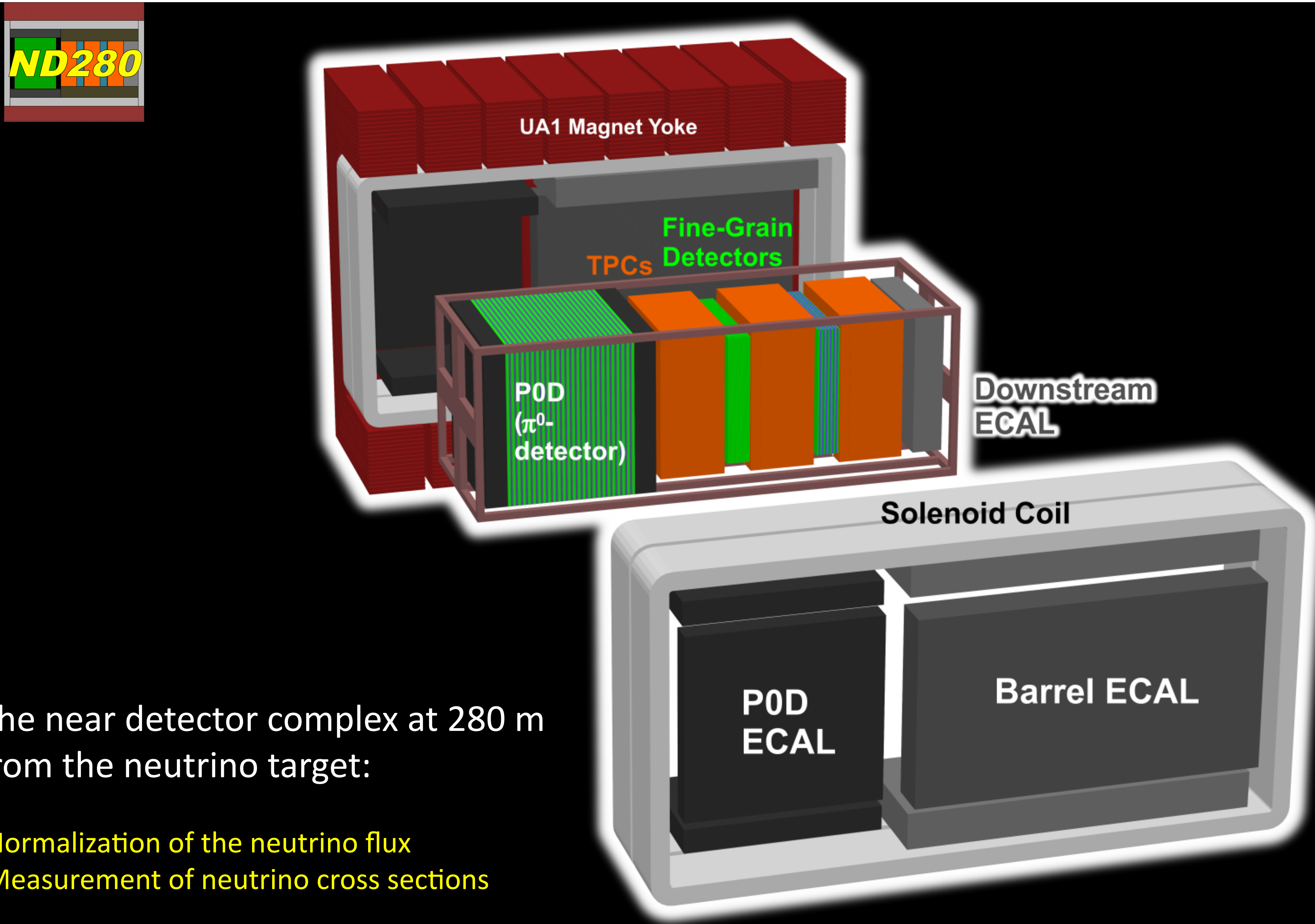
The first off-axis neutrino beam (original idea BNL-E889 Proposal)





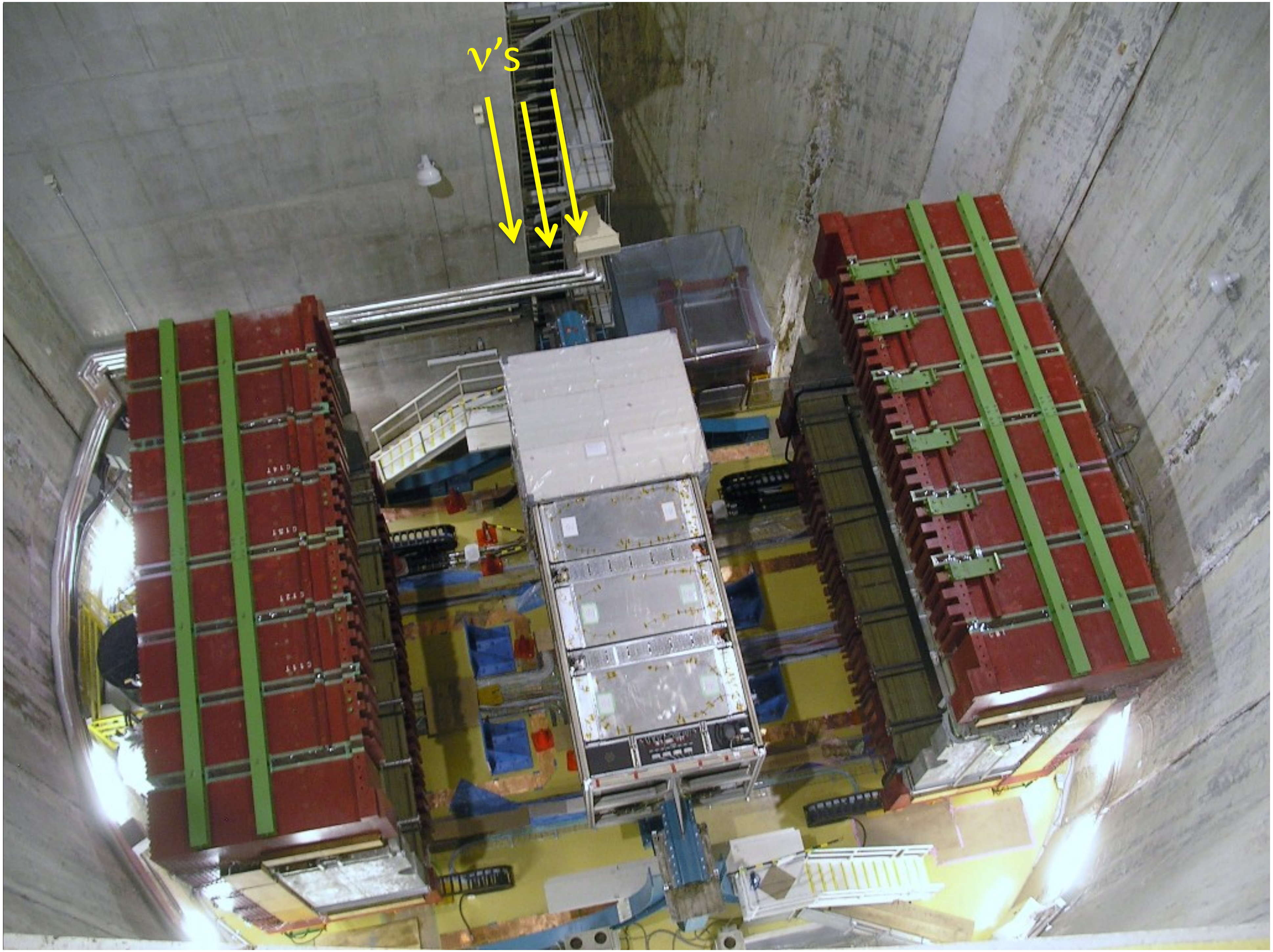


for 2.5^0: L = 295 km and $\Delta m_{23} = 2.5 \times 10^{-3}$ eV^2 → E (first maximum) ~ 0.6 GeV

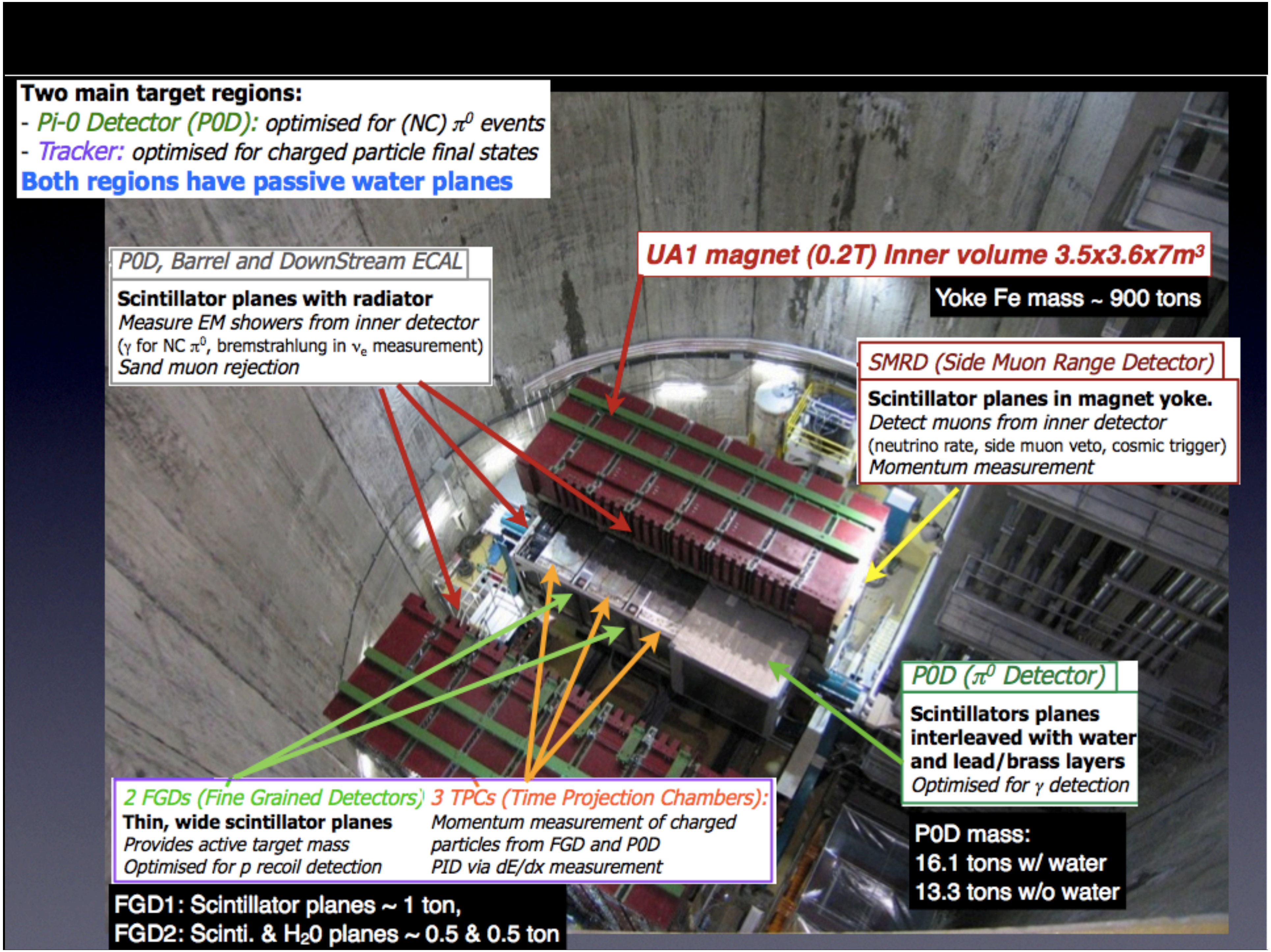


The near detector complex at 280 m from the neutrino target:

Normalization of the neutrino flux
Measurement of neutrino cross sections



ν's



Two main target regions:
- Pi-0 Detector (P0D): optimised for (NC) π^0 events
- Tracker: optimised for charged particle final states
Both regions have passive water planes
P0D, Barrel and DownStream ECAL
Scintillator planes with radiator
Measure EM showers from inner detector
(γ for NC π^0, bremstrahlung in ν_e measurement)
Sand muon rejection
UA1 magnet (0.2T) Inner volume 3.5x3.6x7m^3
Yoke Fe mass ~ 900 tons
SMRD (Side Muon Range Detector)
Scintillator planes in magnet yoke.
Detect muons from inner detector
(neutrino rate, side muon veto, cosmic trigger)
Momentum measurement
P0D (π^0 Detector)
Scintillators planes interleaved with water and lead/brass layers
Optimised for γ detection
P0D mass:
16.1 tons w/ water
13.3 tons w/o water
2 FGDs (Fine Grained Detectors)
Thin, wide scintillator planes
Provides active target mass
Optimised for p recoil detection
3 TPCs (Time Projection Chambers):
Momentum measurement of charged particles from FGD and P0D
PID via dE/dx measurement
FGD1: Scintillator planes ~ 1 ton,
FGD2: Scinti. & H_2O planes ~ 0.5 & 0.5 ton

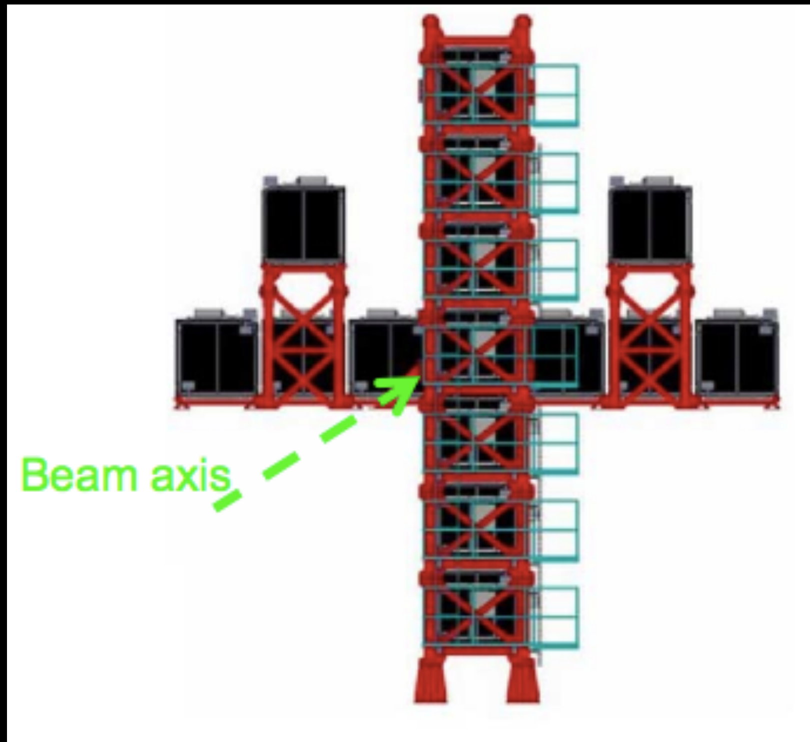
The INGRID detector

on-axis (0^0) detector:

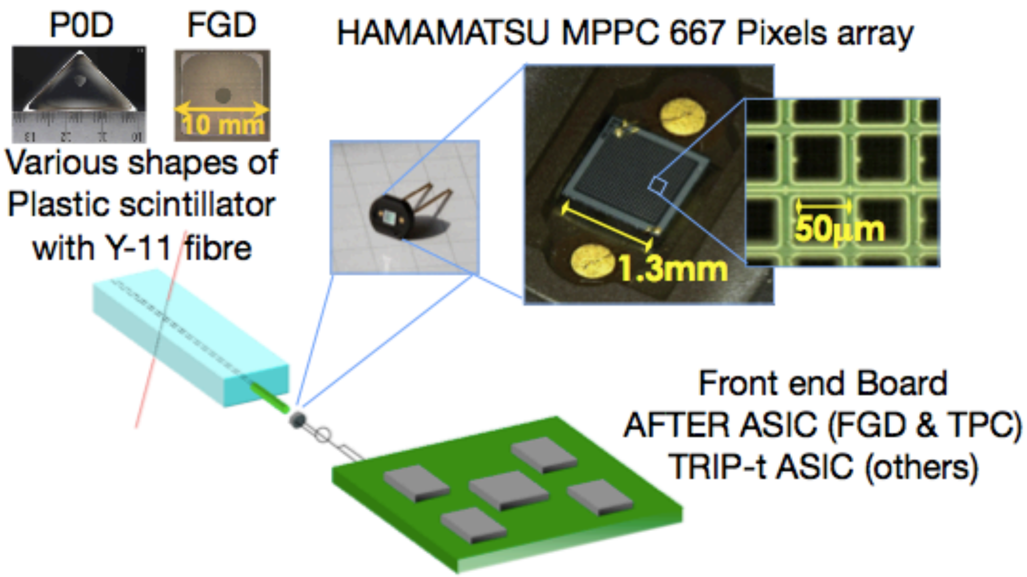
14 iron/scintillator calorimeter modules

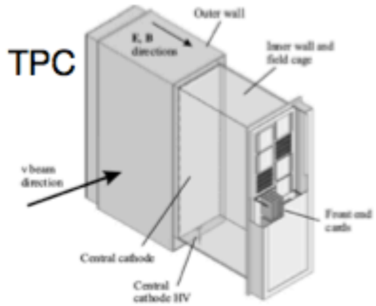
~ 11000 Multi Pixel Photon Counters (MPPC)

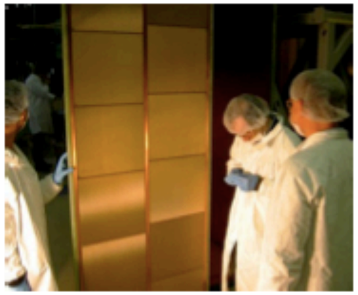
ν beam monitor: rate, direction, and stability



ND280 detector technologies







Scintillator + WLS fibre read out by novel MPPC ND280

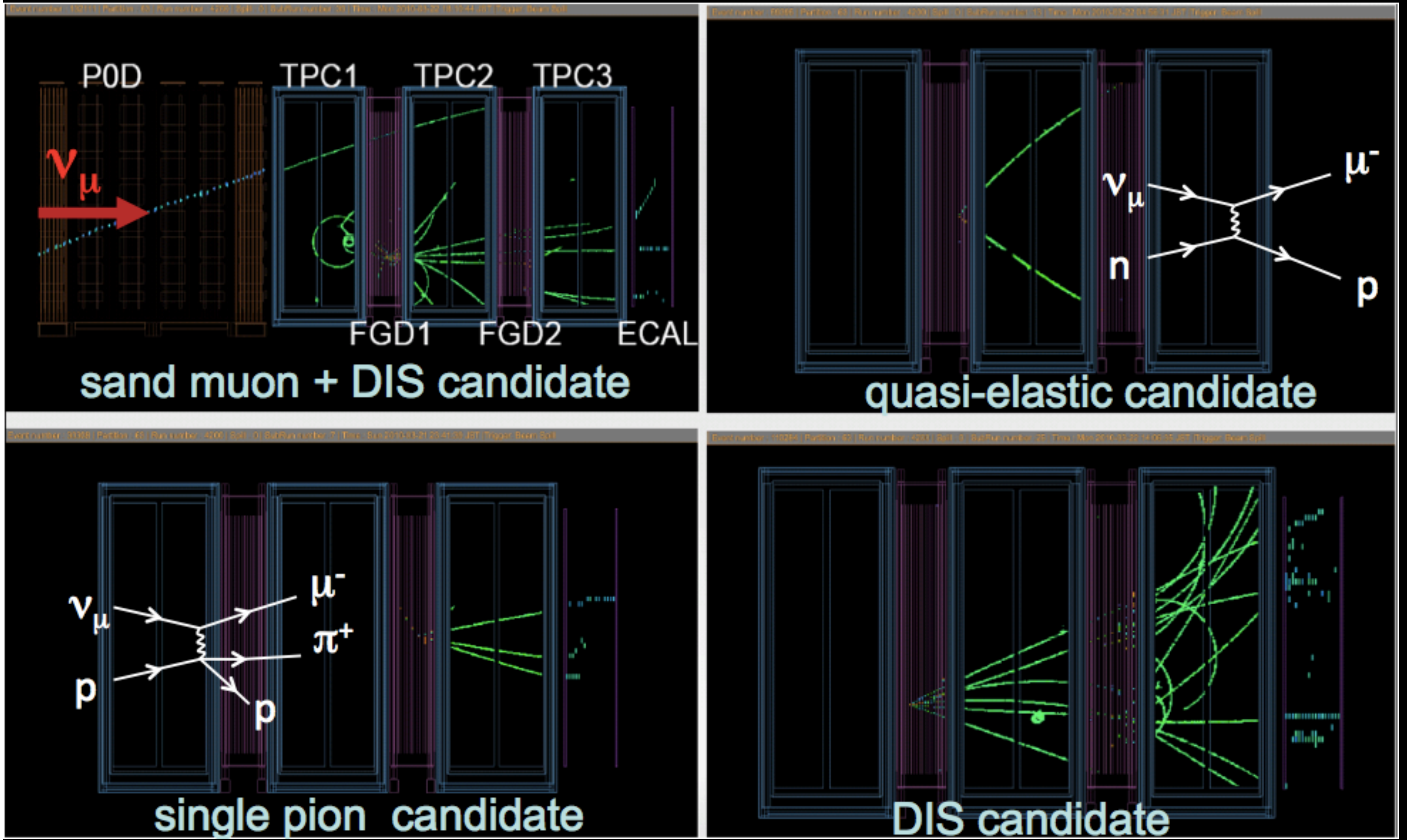
- Low cost high performance and uniformity detector element
- novel solid state photosensor insensitive to magnetic field

- Photon counting, high PDE, low power consumption, ceramic package
- ~ 56 800 channels
- T2K first experiment to use MPPC at such a large scale

Very Large TPC based on MicroMegas read out

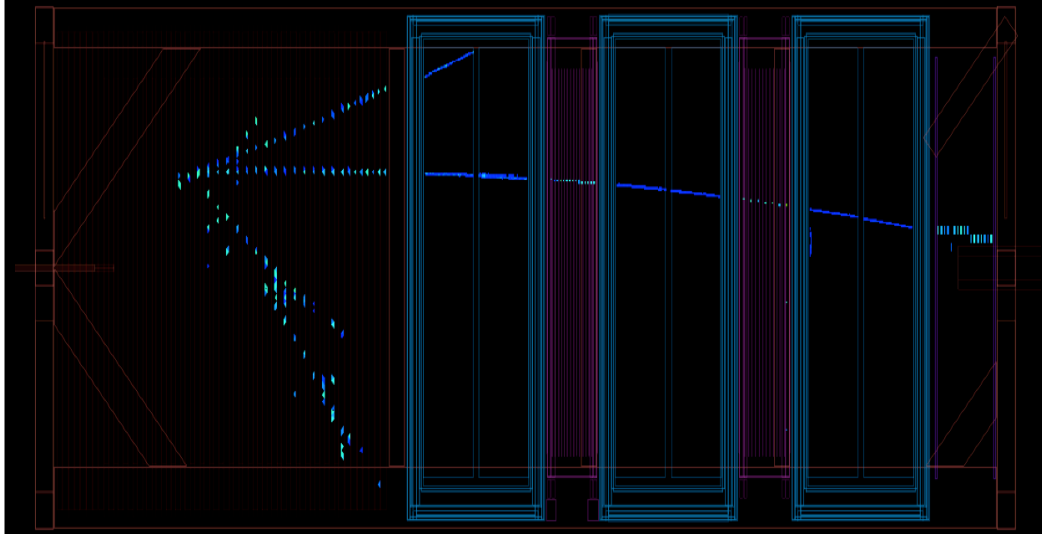
- 3x large modules with double wall structure
- Sensitive volume 180 x 200 x 70 cm
- Precise assembly, commissioning and alignment within mm
- 124 000 channels

ND280 event gallery



ND280 global performance

ν event interacting in the P0D with tracks through FGDs, TPCs and ECAL

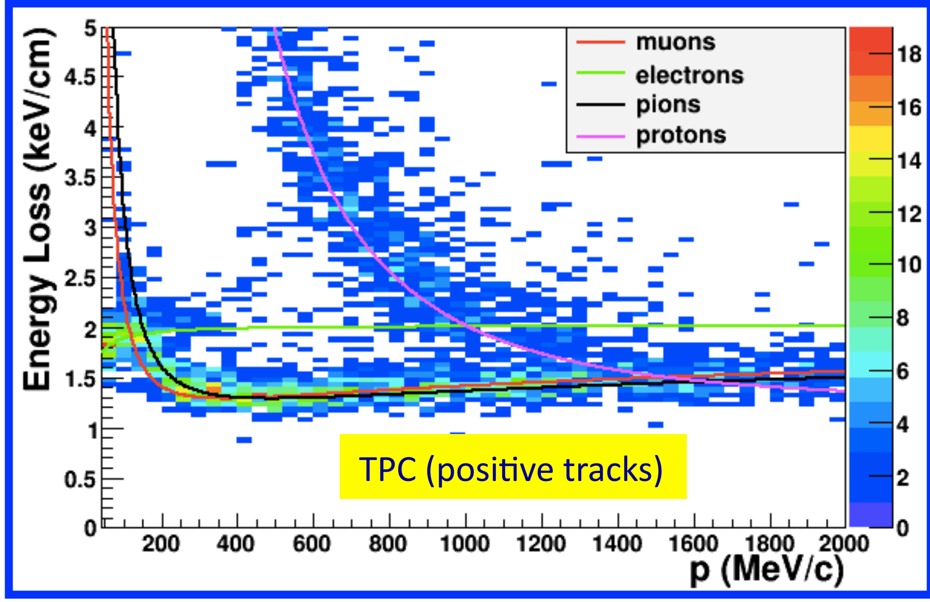


- INGRID, beam direction:

  -0.01±0.33 mrad (x)
  -0.11±0.37 mrad (y)

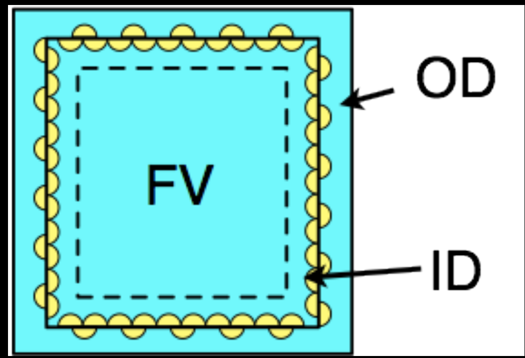
- ND280

  excellent PID and tracking capability, ID of neutrino interactions



Detector	Channels	Bad ch.	Bad fraction
ECAL (DSECAL)	22,336 (3,400)	35 (11)	0.16% (0.32%)
SMRD	4,016	7	0.17%
P0D	10,400	7	0.07%
FGD	8,448	20	0.24 %
INGRID	10,796	18	0.17 %
TPC	124,416	160	0.13 %

The "far" Super-Kamiokande detector

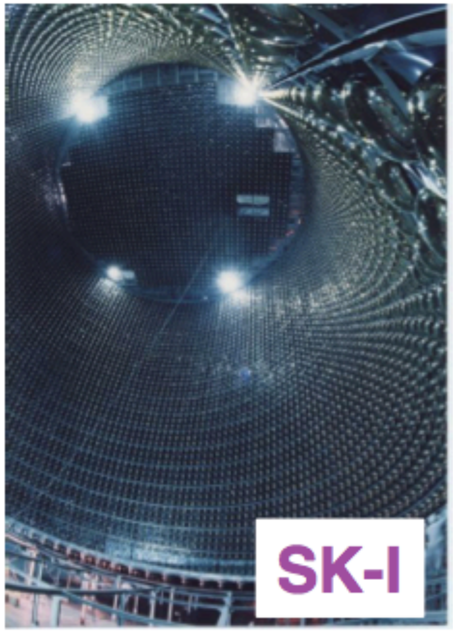


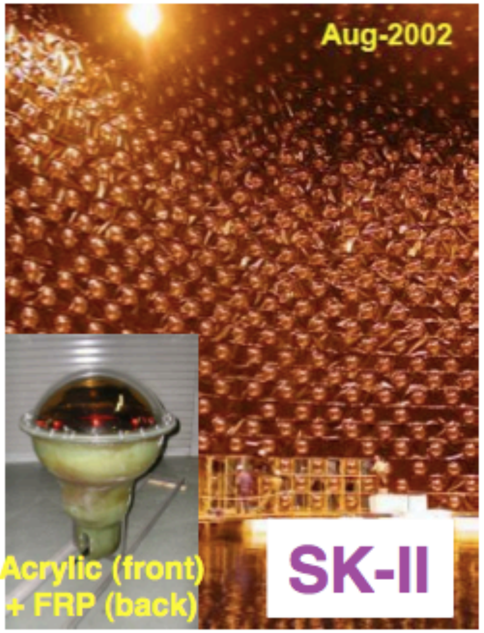
- 50 kton (22.5 kton fiducial) water Cherenkov, 1 km underground
- Well known performance: momentum and position resolution, PID, for sub-GeV neutrinos
- 61% efficiency for T2K ν_e with 95% NC-1π^0 rejection
- GPS timing information recorded: interactions within ± 500 µs around neutrino arrival time

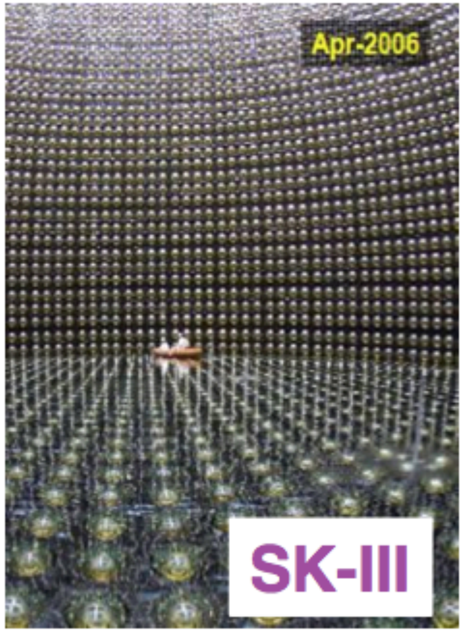
Super-Kamiokande story

1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010

SK-I SK-II SK-III SK-IV



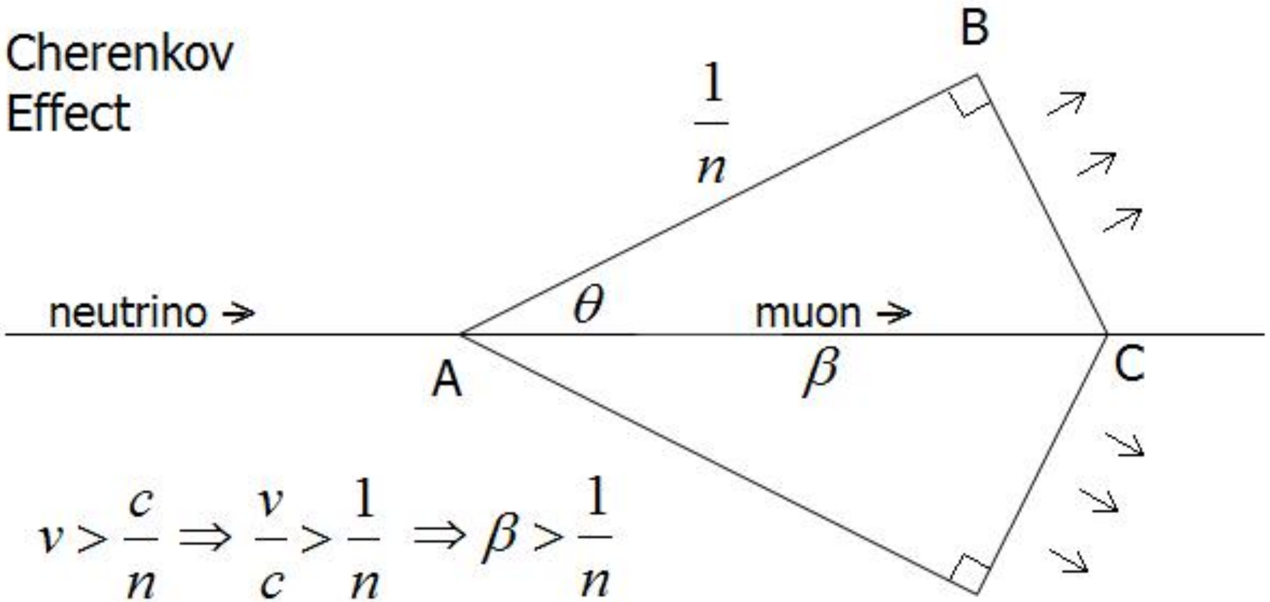




Energy Threshold	11146 ID PMTs (40% coverage)	5182 ID PMTs (19% coverage)	11129 ID PMTs (40% coverage)	Electronics Upgrade
(Total energy)	5.0 MeV	7.0 MeV	5.0 MeV	~4.5 MeV → 4.0 MeV
(Kinetic energy)	~4.5 MeV	~6.5 MeV	~4.5 MeV	~4.0 MeV → ~3.5 MeV
				Current → Target

21

Cherenkov effect

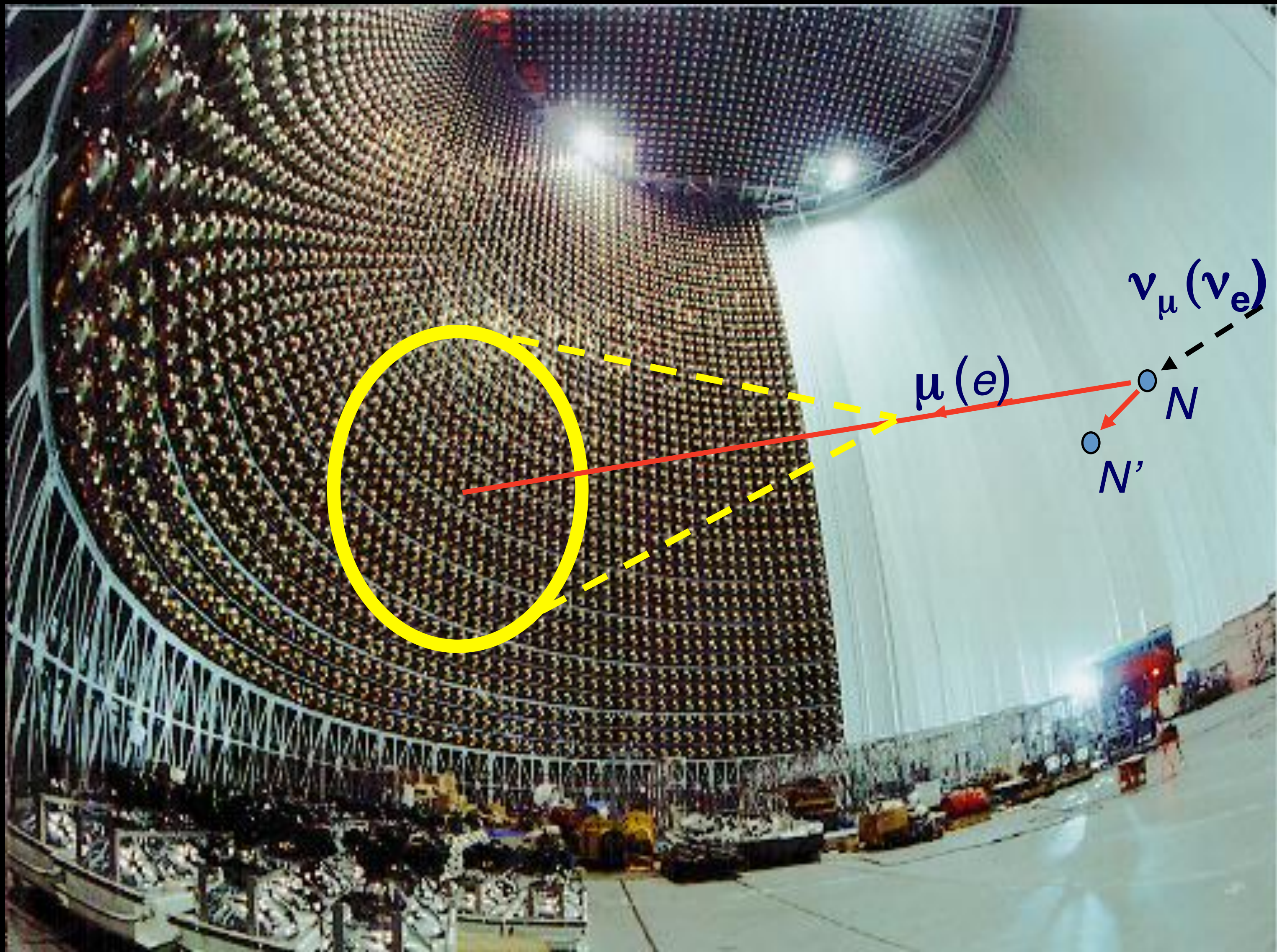


$$v > \frac{c}{n} \Rightarrow \frac{v}{c} > \frac{1}{n} \Rightarrow \beta > \frac{1}{n}$$

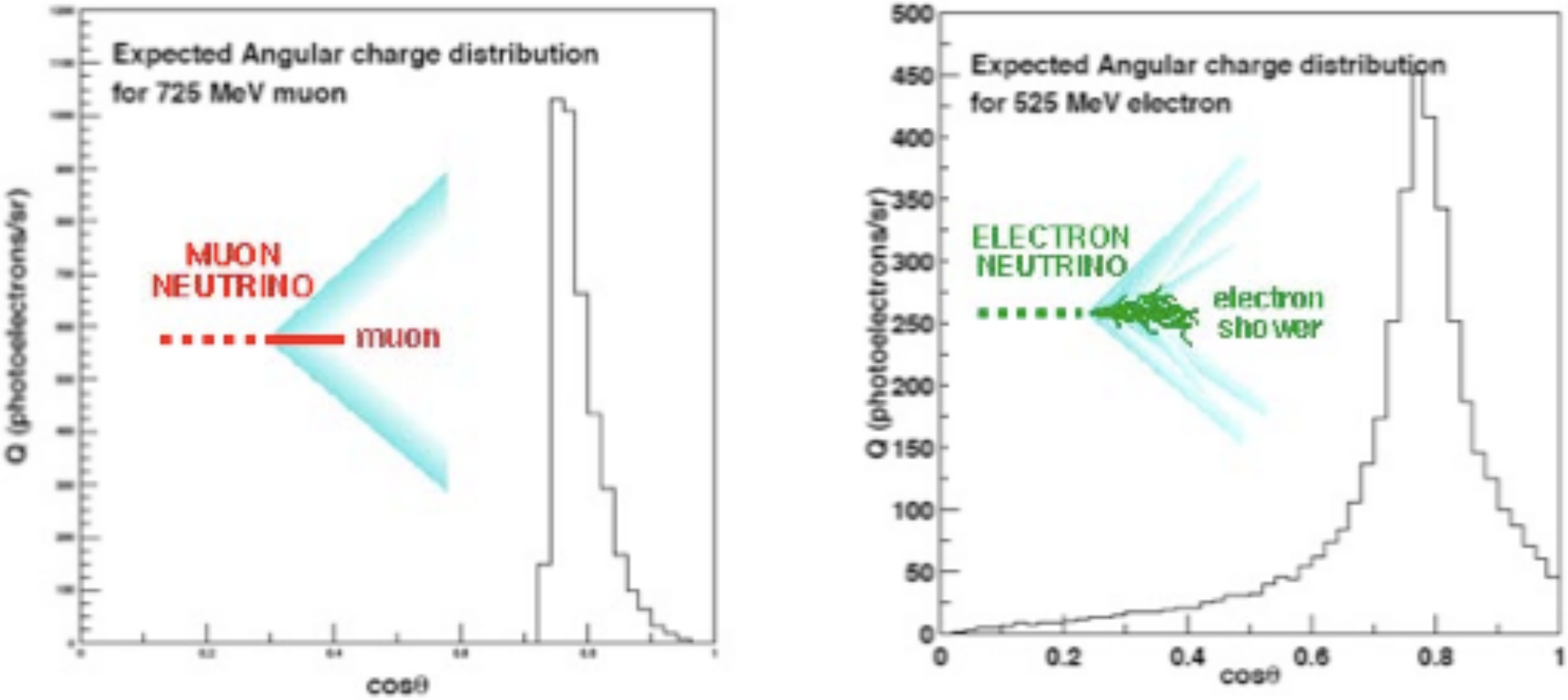
$$\cos\theta = \frac{AB}{AC} = \frac{1/n}{\beta} = \frac{1}{n\beta} = \frac{1}{n}$$

in water: n = 1.33
$\theta = 41^0$ for $\beta \rightarrow 1$

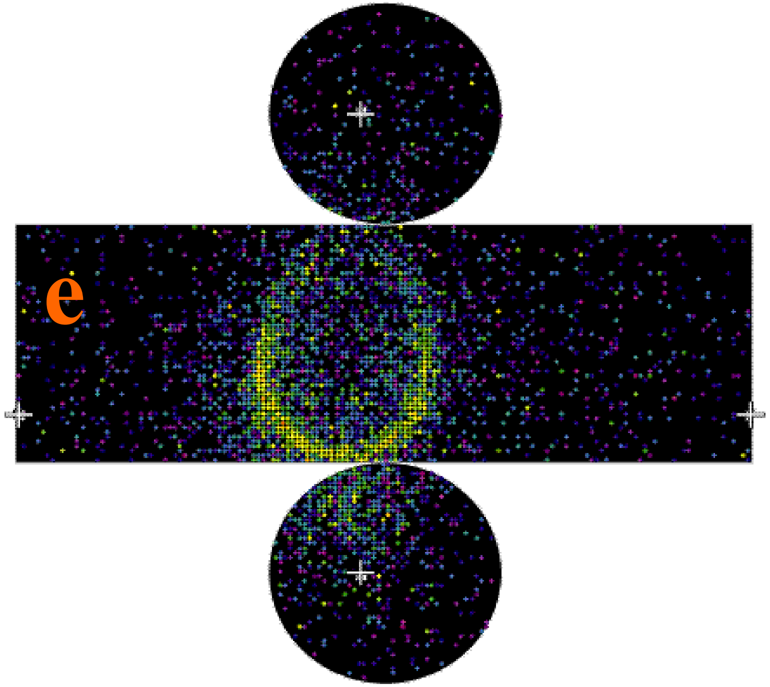
Cherenkov rings in Super-Kamiokande



Electron/muon discrimination

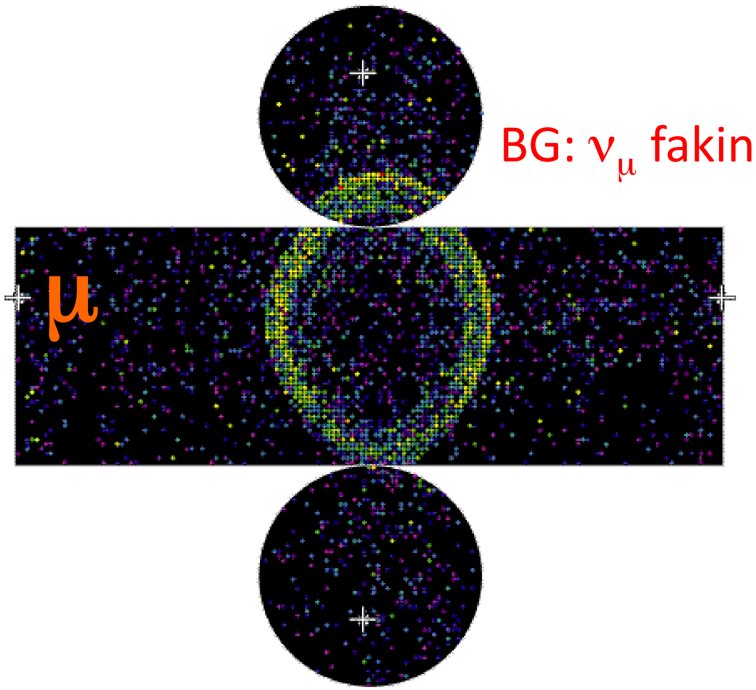


ν_e appearance in SK

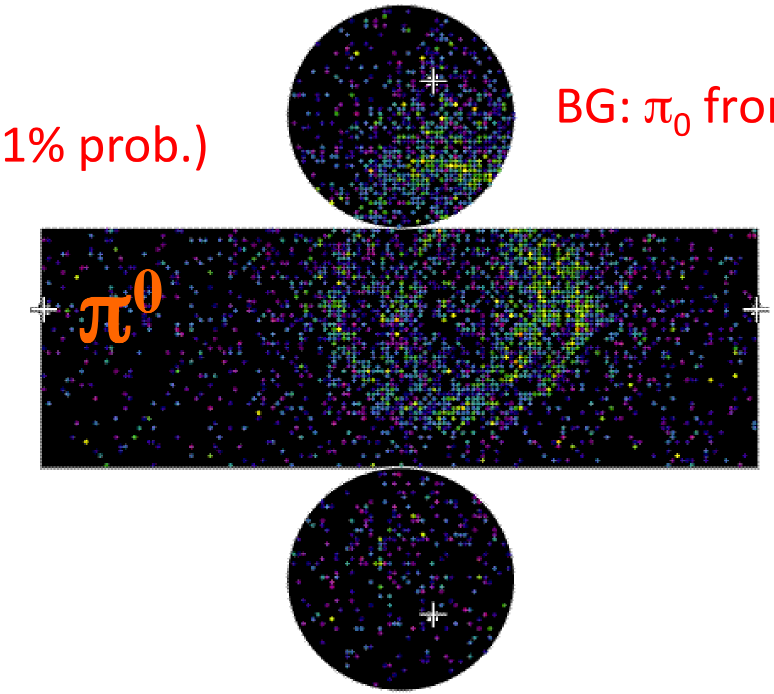


signal: electron from a ν_e from an oscillated ν_μ

BG: prompt ν_e in the beam (exploit ND280)

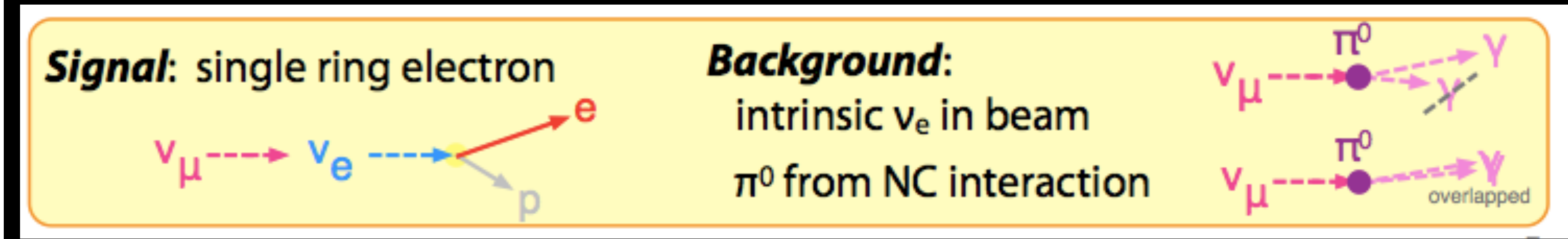


BG: ν_μ faking a ν_e (~1% prob.)



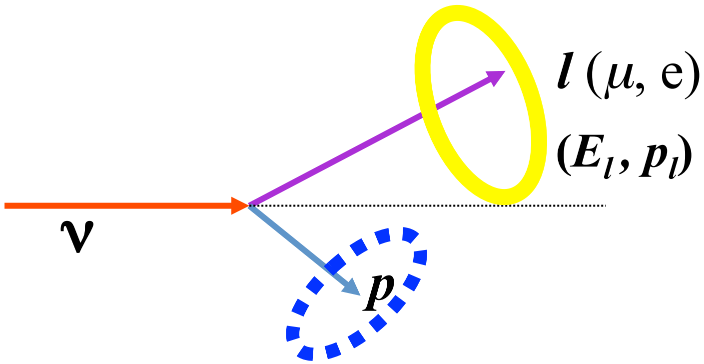
BG: π_0 from ν_μ int.

Signal vs BG

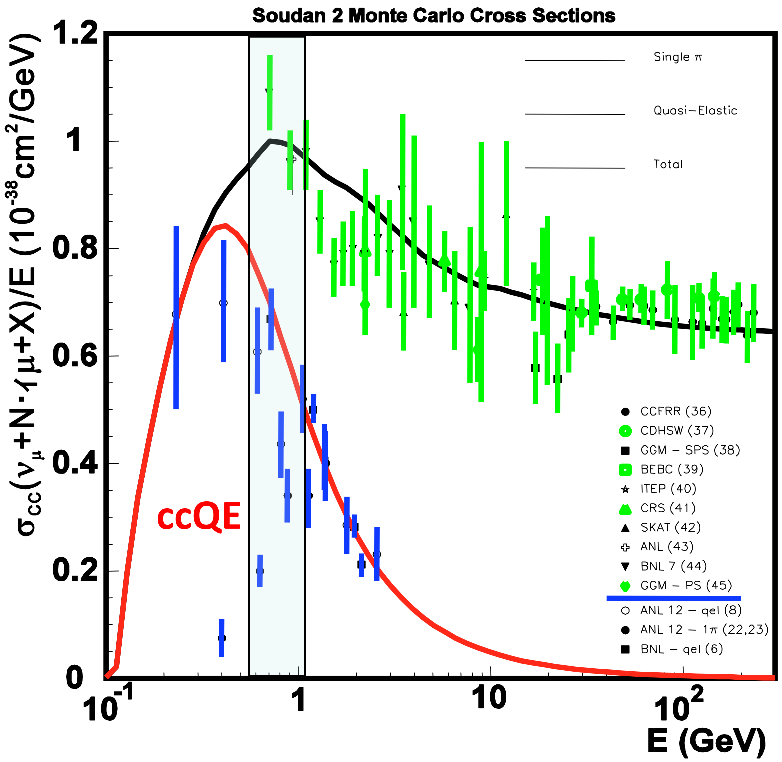

Signal: single ring electron
νμ νe e p
Background:
intrinsic νe in beam
π0 from NC interaction
νμ π0 γ
overlapped

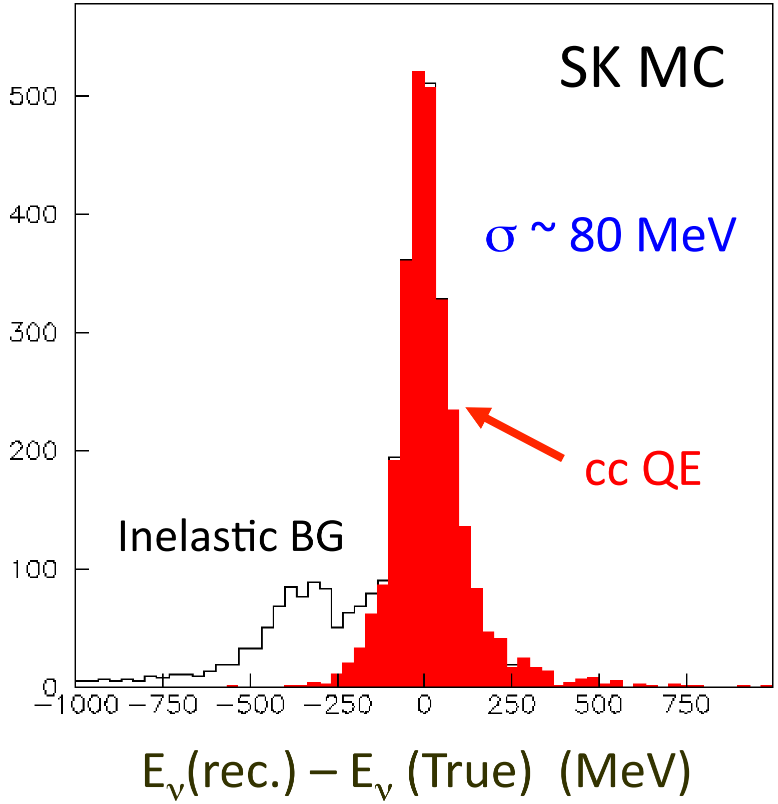
E_ν reconstruction in SK

CC quasi elastic (QE) reaction: $\nu_\mu + n \rightarrow \boldsymbol{l} + p$

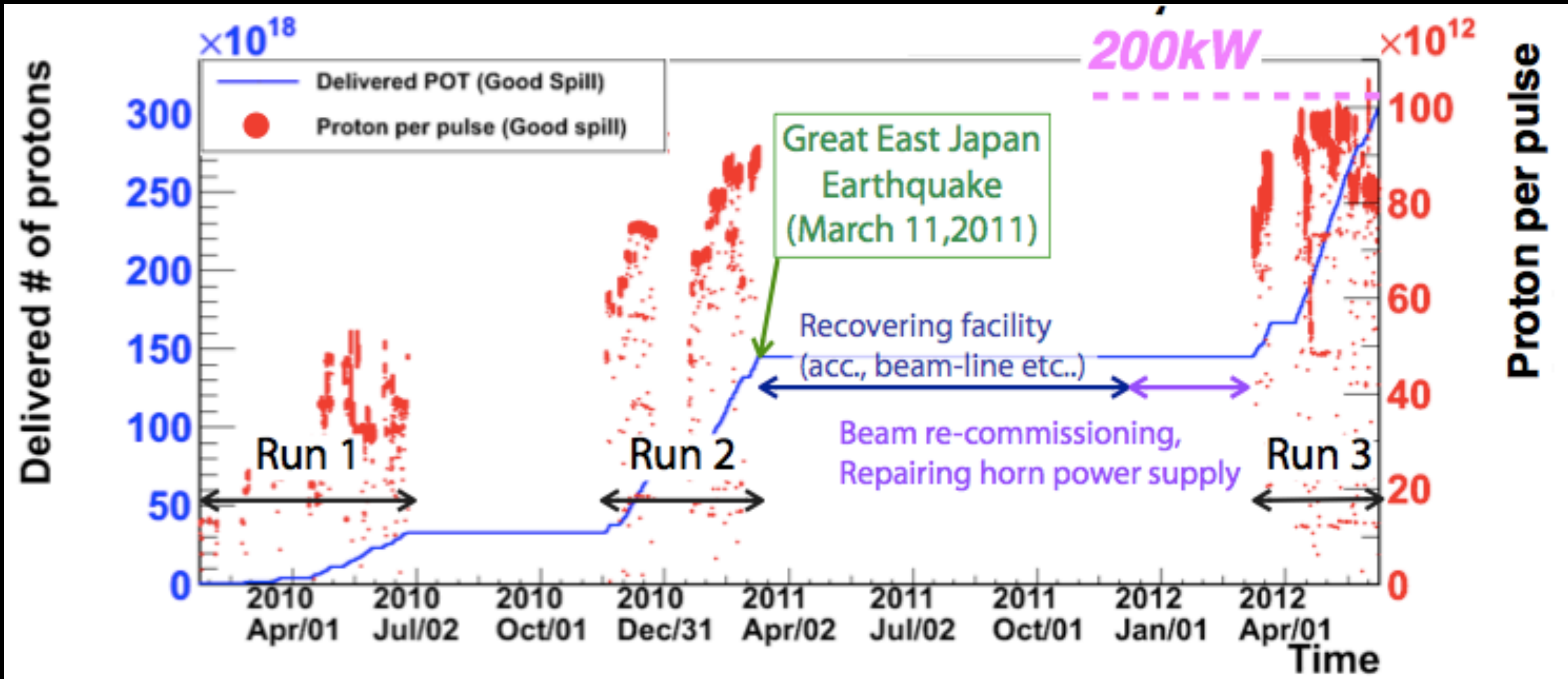


$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$



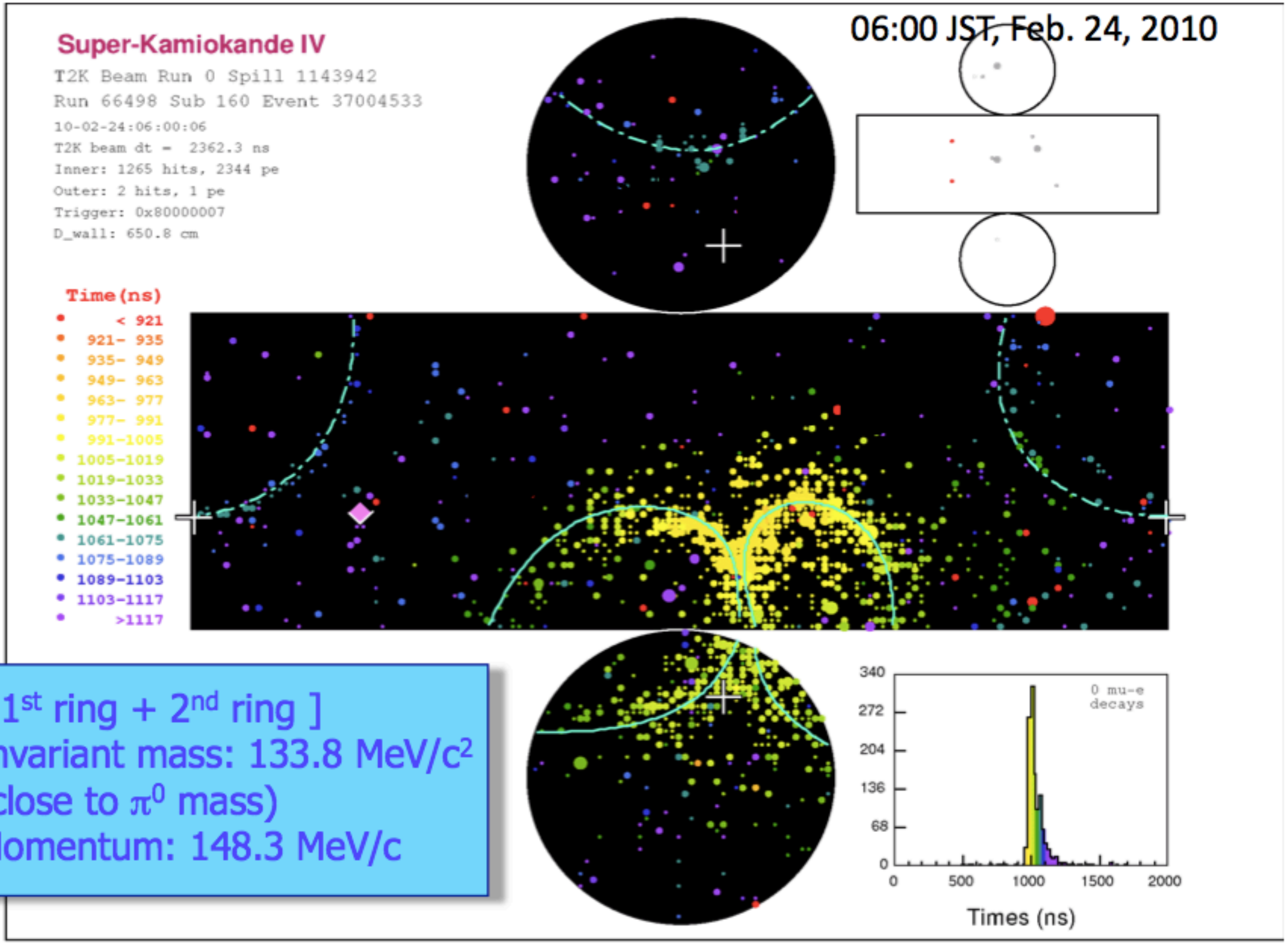


Neutrino beam performance



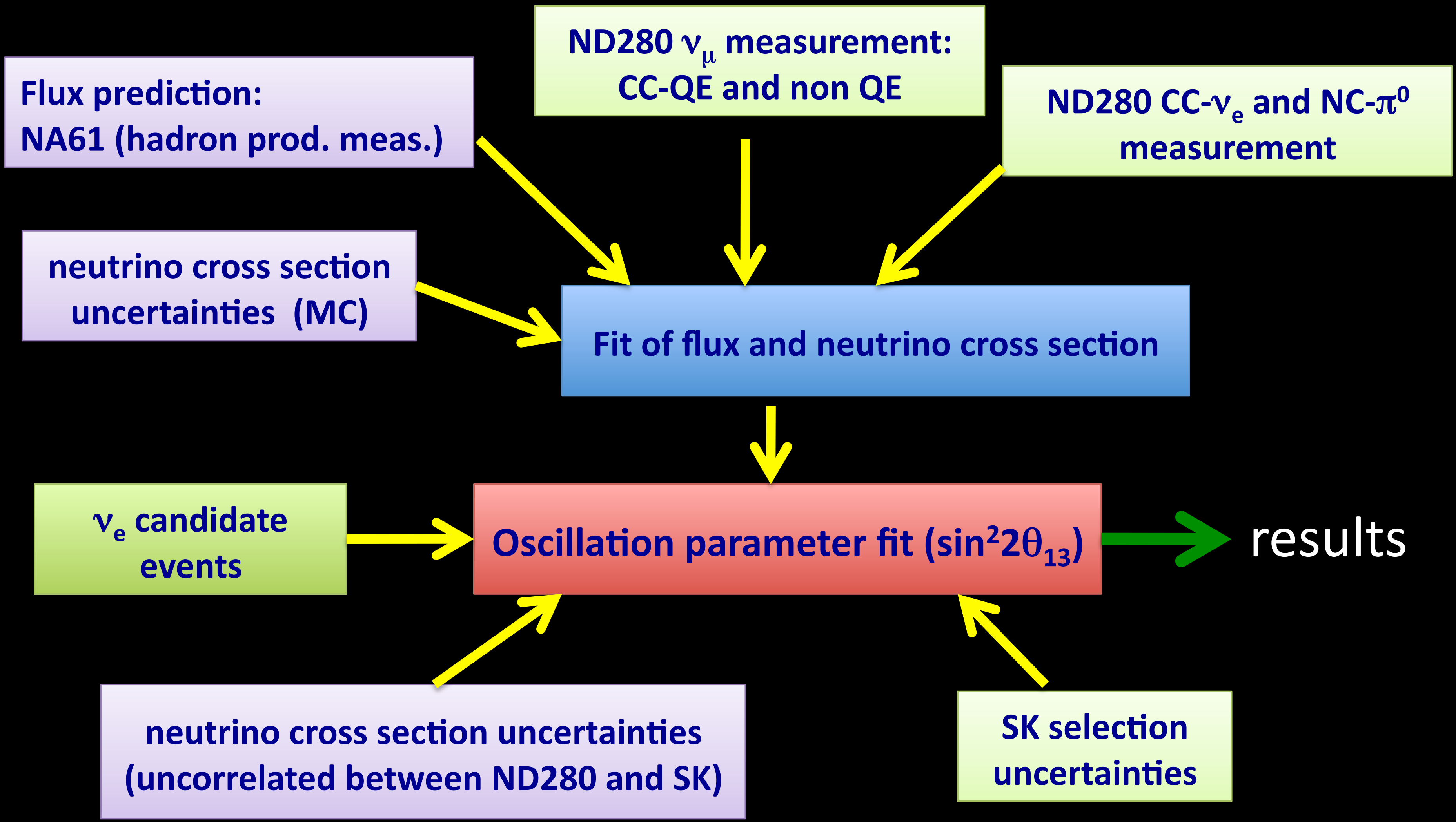
ICHEP 2012: 3.01×10^{20} pot (0.32 RUN 1 + 1.11 RUN 2 +1.58 RUN3)

First T2K neutrino event @SK



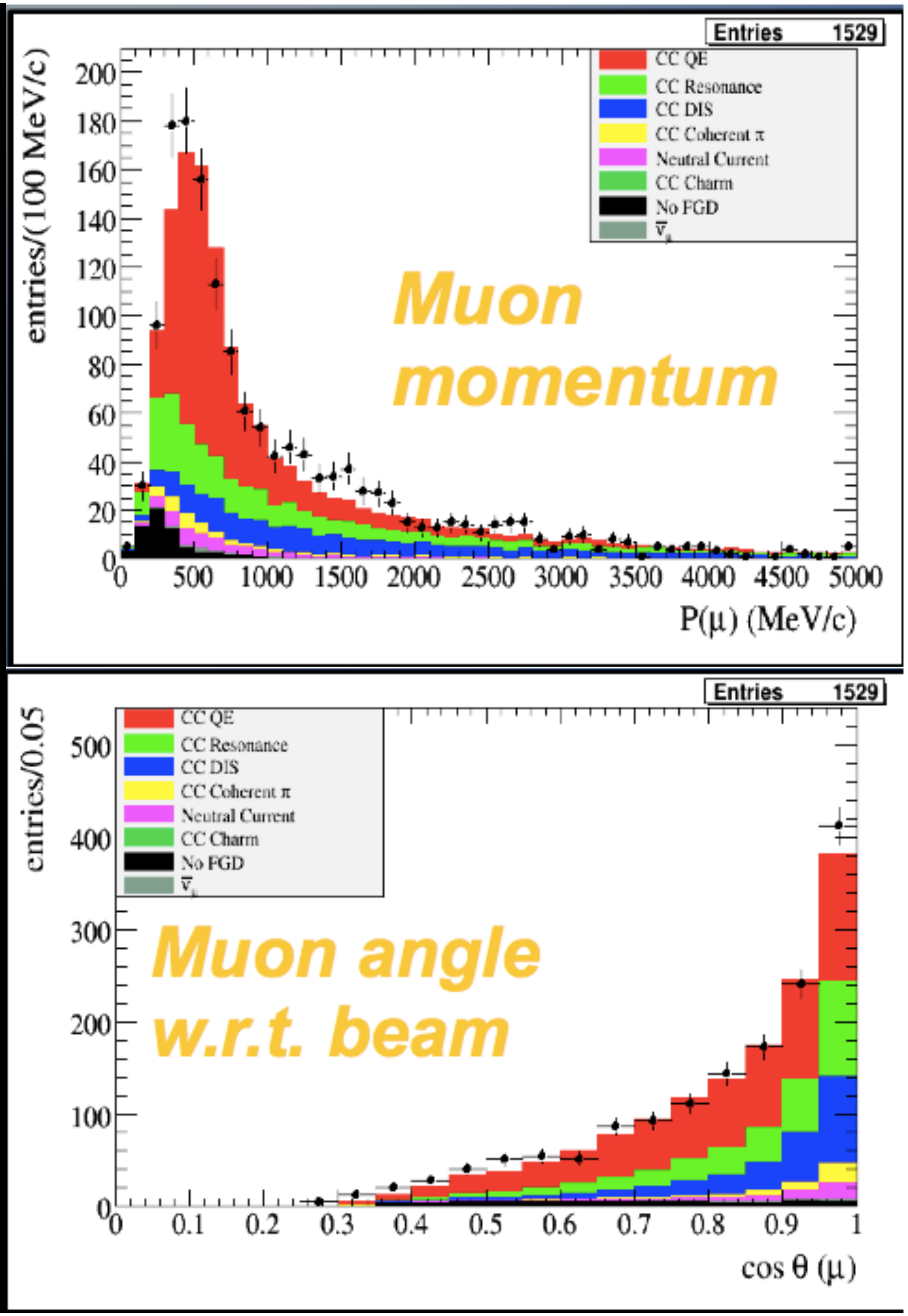
[1st ring + 2nd ring]
Invariant mass: 133.8 MeV/c^2
(close to π^0 mass)
Momentum: 148.3 MeV/c

Oscillation appearance analysis method

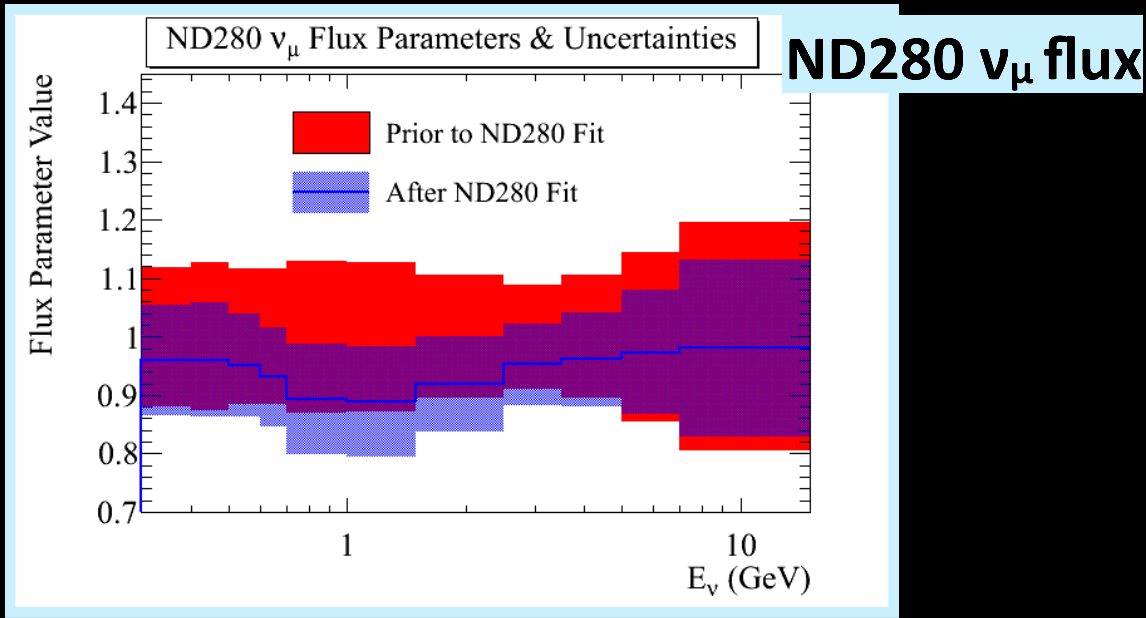


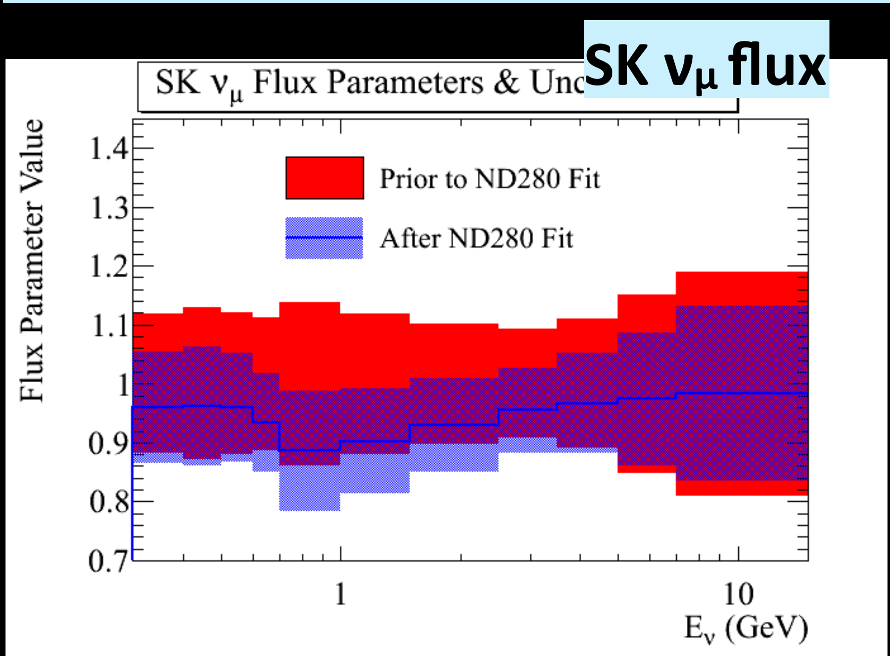
ND280 ν_μ measurement: CC-QE and non QE

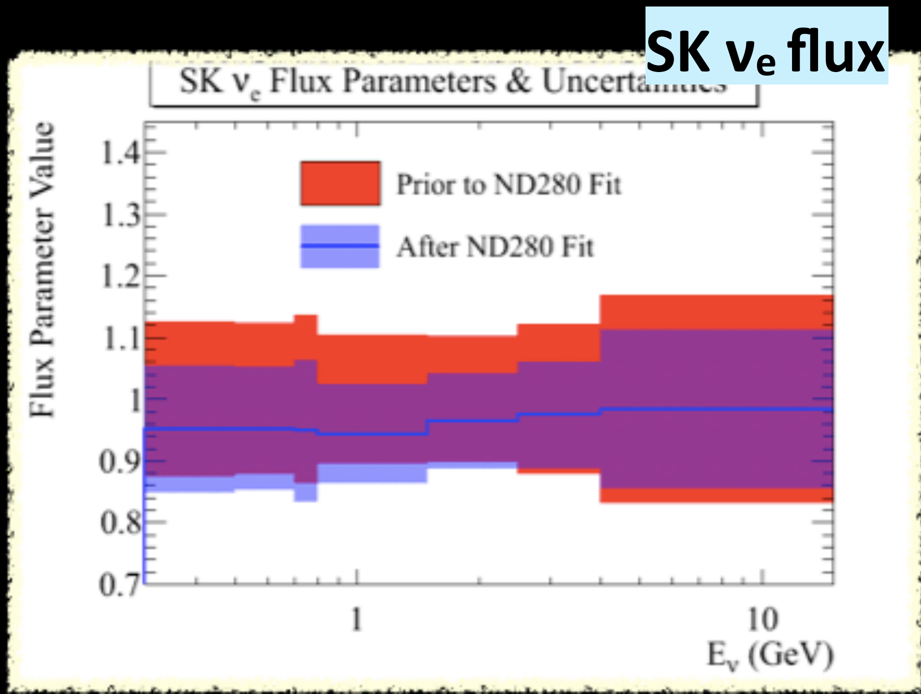
P_μ vs. θ_μ distributions are fitted for CC-QE and non QE events to constrain flux and ν cross sections (MC predictions at ND280 and SK)



The results of the ND280 fit are extrapolated to SK (predictions)







From ND280 to SK

ND280 (near) Detector Measurements

- νμ CC inclusive selection
- Measure: $R_{Data/MC} = \dfrac{N^{Data}_{\mu CC,ND280}}{N^{MC}_{\mu CC,ND280}}$

SK (far) Detector Measurements

- Data reduction and classification
- Compute signal and background expectations

$$N^{MC}_{signal} = \int dE_\nu \, \underbrace{\Phi_\mu(E_\nu)}_{\text{flux}} \times \underbrace{\sigma(E_\nu)}_{\text{cross-section}} \times \underbrace{\varepsilon(E_\nu)}_{\text{efficiency}} \times \underbrace{P(\nu_\mu \to \nu_e; E_\nu; \theta_{13}, \Delta m^2_{13})}_{\text{oscillation}}$$

- Correct normalization using ND280 measurement

$$N^{exp}_{SK} = R_{Data/MC} \times \left(N^{MC}_{signal} + N^{MC}_{bkg}\right)$$

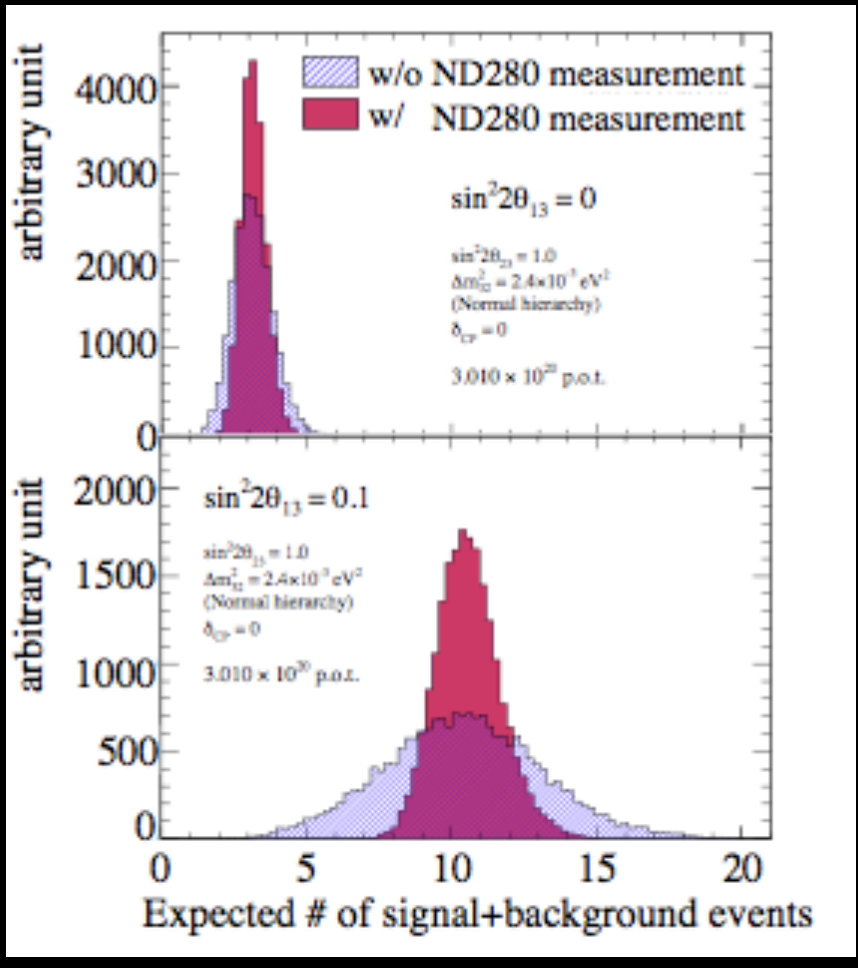
- Evaluate systematic errors
- Extract oscillation parameters

Predicted events @ SK

Event category	$\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Total	3.22±0.43	10.71±1.10
ν_e signal	0.18	7.79
ν_e background	1.67	1.56
ν_μ background (mainly NCπ^0)	1.21	1.21
$\bar{\nu}_\mu + \bar{\nu}_e$ background	0.16	0.16

Systematic uncertainties

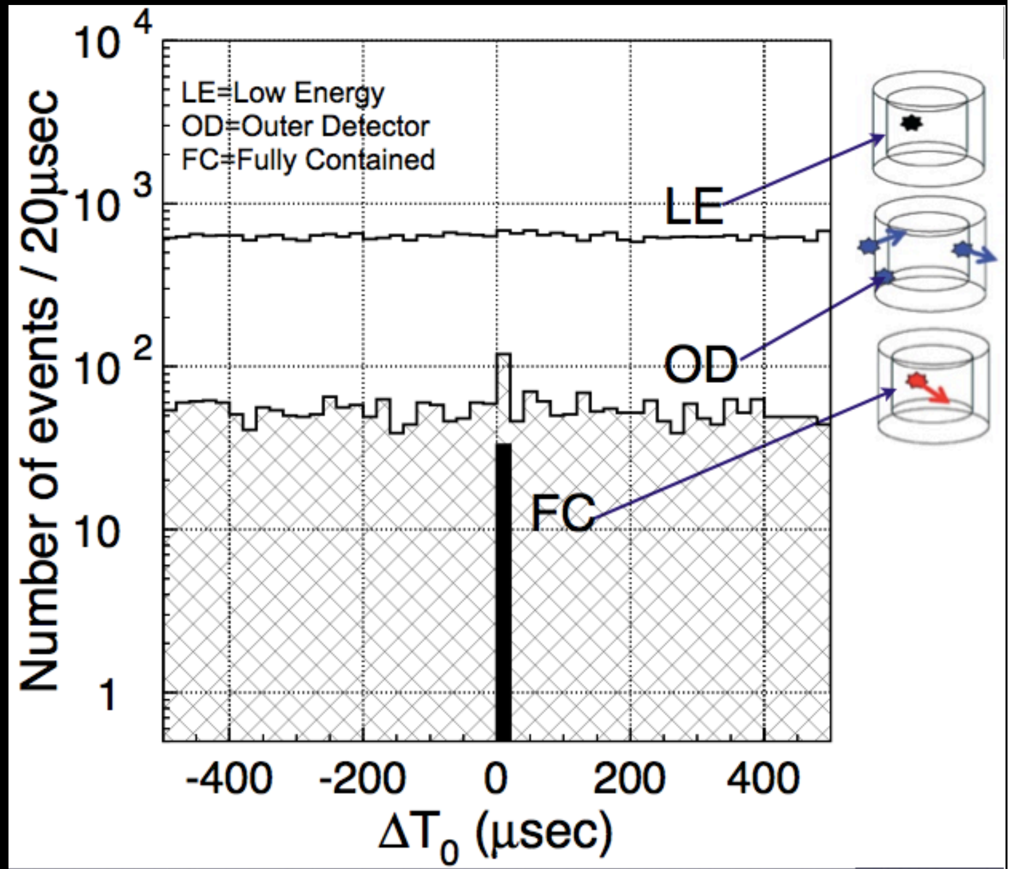
Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
Beam flux+ν int. in T2K fit	8.7 %	5.7 %
ν int. (from other exp.)	5.9 %	7.5 %
Final state interaction	3.1 %	2.4 %
Far detector	7.1 %	3.1 %
Total	13.4 %	10.3 %
(T2K 2011 results:	~23%	~18%)



Uncertainties are reduced by exploiting ND280

Neutrino event selection @SK

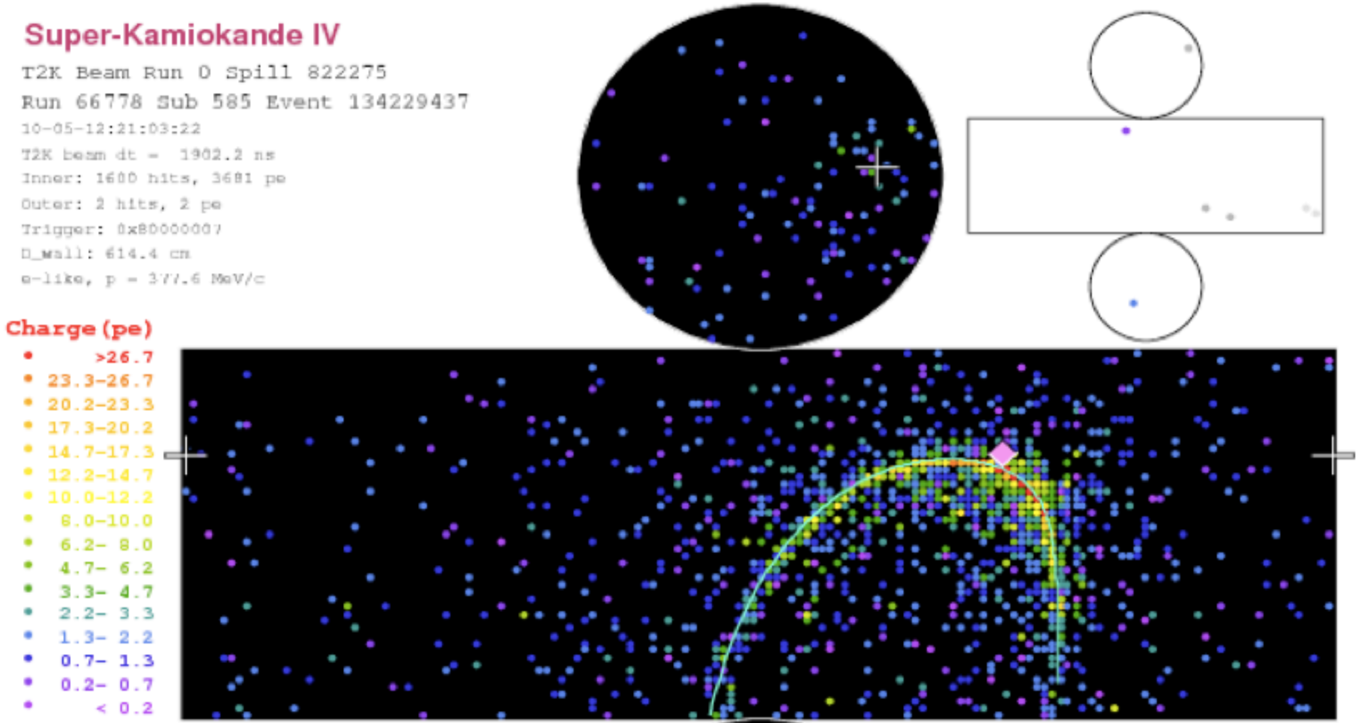
- T2K Beam timing
- Fully-Contaned events (FC)
- Vertex is in the fiducial volume
- 1 electron-like Cherenkov ring
- Visible energy > 100 MeV
- No electron signal possibly generated by muon decay



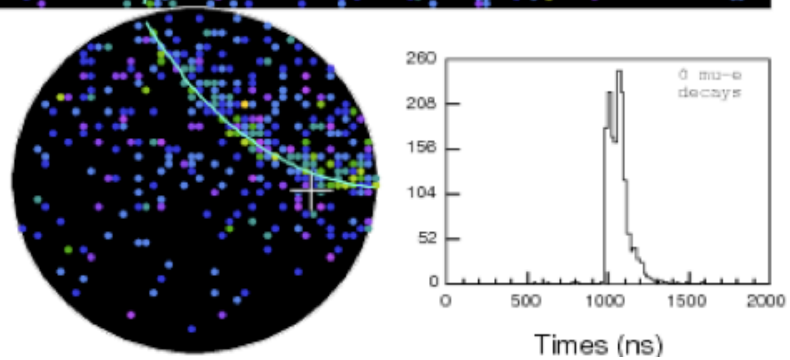
Event statistics

RUN 1+2+3 3.010×10^{20} POT	Data	MC Expectation w/ $\sin^2 2\theta_{13}=0.1$				
		Signal $\nu_\mu \to \nu_e$	BG total	CC ($\nu_\mu+\bar{\nu}_\mu$)	CC($\nu_e+\bar{\nu}_e$)	NC
Fully contained FV at beam timing	174	12.35	165.47	117.33	7.67	40.48
Single ring	88	10.39	82.78	66.41	4.82	11.55
e-like	22	10.27	15.60	2.72	4.79	8.10
E_{vis}>100MeV	21	10.04	13.53	1.76	4.75	7.01
No decay-e	16	8.63	10.09	0.33	3.76	6.00
2γ invariant mass cut	11	8.05	4.32	0.09	2.60	1.64
E_ν^{rec} < 1250 MeV (MC $\sin^2 2\theta_{13}=0$ case)	11	7.81 (0.18)	2.92 (3.04)	0.06 (0.06)	1.61 (1.73)	1.25 (1.25)
Efficiency [%]		60.7	1.0	0.0	20.0	0.9

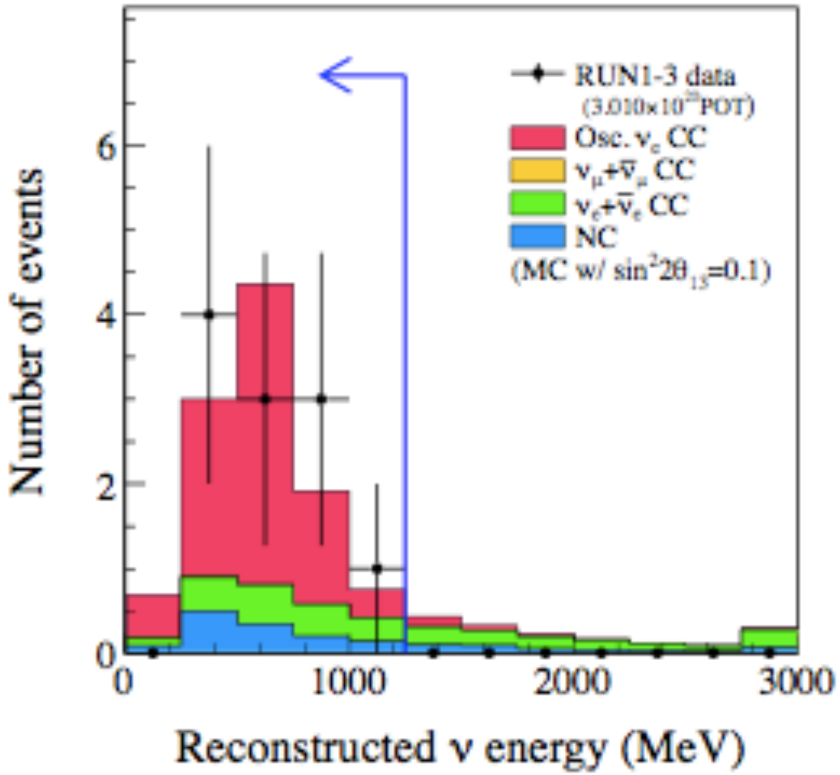
One SK ν_e candidate event



Item	Event	T2K cut
Date (JST)	2010 May 12th 21:3:22	
Ring, PID	1-Ring electron-like	OK
Momentum	378 MeV	>100
N_{dcy}	0	0
$\cos(\theta_{\nu e})$	0.55 (57 degree)	N/A
$Mass$	0.13 MeV	<105
E_{rec}	496 MeV	<1250



Evidence for electron appearance



11 candidate events are observed

N_{exp}=3.22±0.43 for $\sin^2 2\theta_{13}=0$

The probability (p-value) to observe 11 or more events with $\theta_{13}=0$ is 0.08% (3.2σ)

Evidence of ν_e appearance

Extracting θ_{13}

Performing an extended maximum likelihood fit to extract $\sin^2 2\theta_{13}$

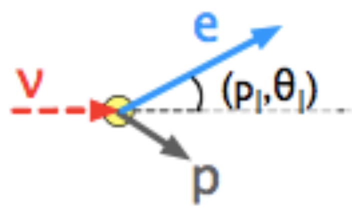
$$\mathcal{L}(N_{obs.}, \boldsymbol{x}; \boldsymbol{o}, \boldsymbol{f}) = \mathcal{L}_{norm}(N_{obs.}; \boldsymbol{o}, \boldsymbol{f}) \times \mathcal{L}_{shape}(\boldsymbol{x}; \boldsymbol{o}, \boldsymbol{f}) \times \mathcal{L}_{syst.}(\boldsymbol{f})$$

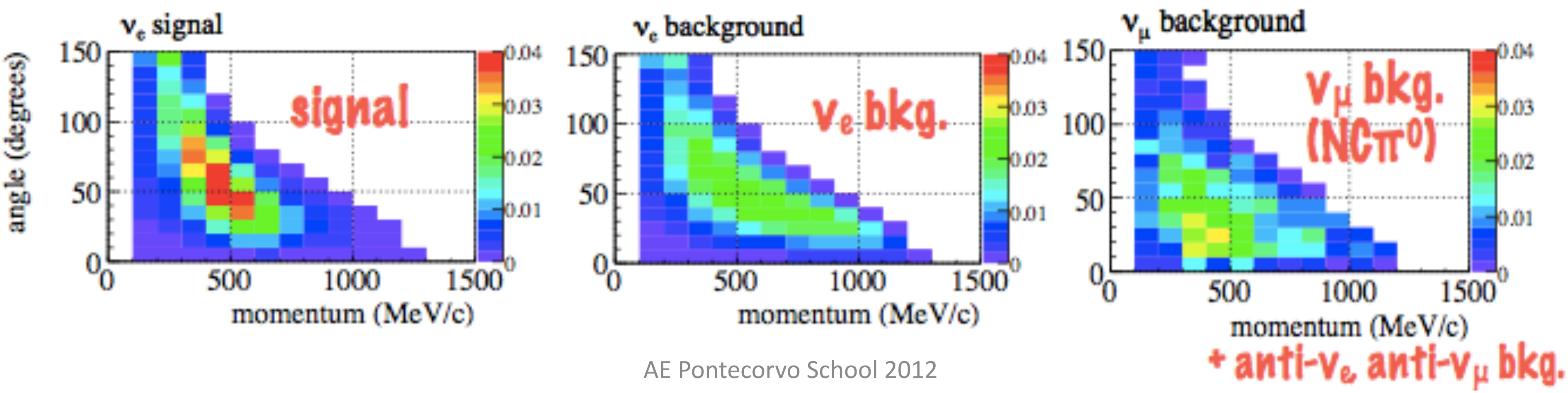
measurement variables | oscillation parameter | systematic parameters (prior: ND280 results)

ν oscillation parameters fixed:

- $\Delta m_{21}^2 = 7.6\times10^{-5}\ eV^2$
- $\Delta m_{32}^2 = \pm 2.4\times10^{-3}\ eV^2$
- $\sin^2 2\theta_{12} = 0.8704$, $\sin^2 2\theta_{23} = 1.0$

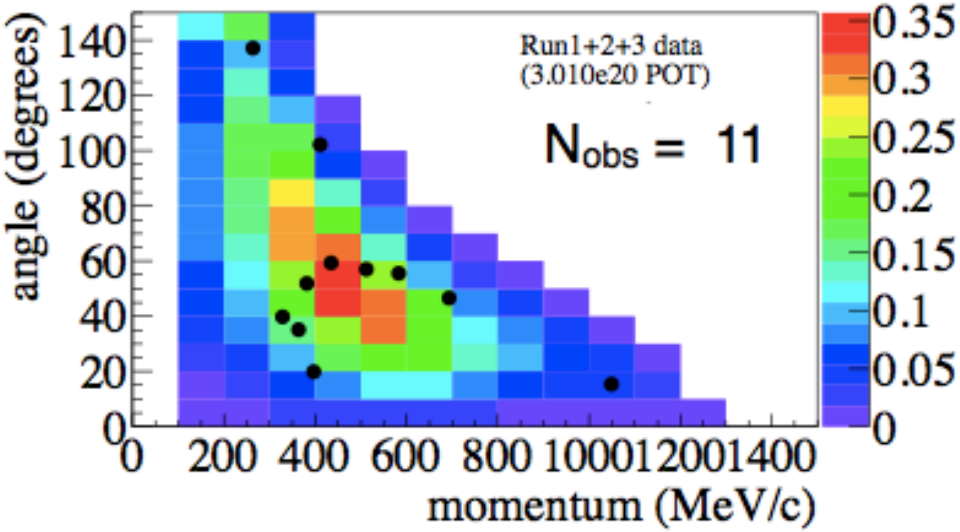
Exploit differences in p_e and θ_e for signal and BG for a better discrimination



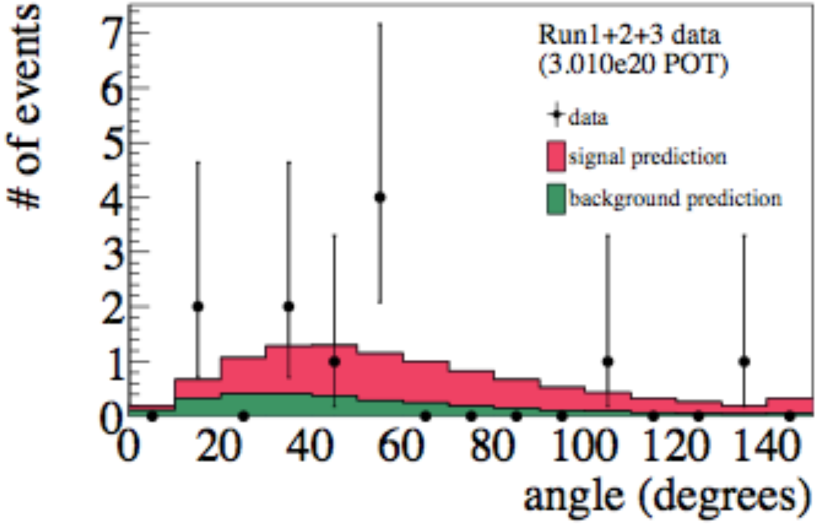


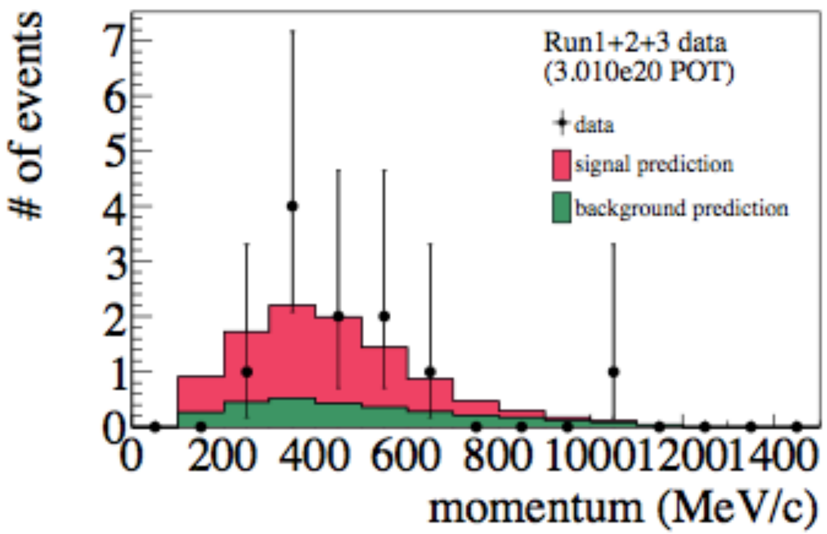
Results

assuming $\delta_{CP}=0$, normal hierarchy
$|\Delta m^2_{32}|=2.4\times10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$



(prediction histograms are based with best-fit $\sin^2 2\theta_{13}$)





preliminary

best fit w/ 68% CL error:

$$\sin^2 2\theta_{13} = 0.094^{+0.053}_{-0.040}$$

90% C.L. Allowed region:

$$0.033 < \sin^2 2\theta_{13} < 0.188$$

Results

Allowed region of $\sin^2 2\theta_{13}$ for each value of δ_{CP}

best fit w/ 68% CL error @δ_{CP}=0

normal hierarchy:

$$\sin^2 2\theta_{13} = 0.094^{+0.053}_{-0.040}$$

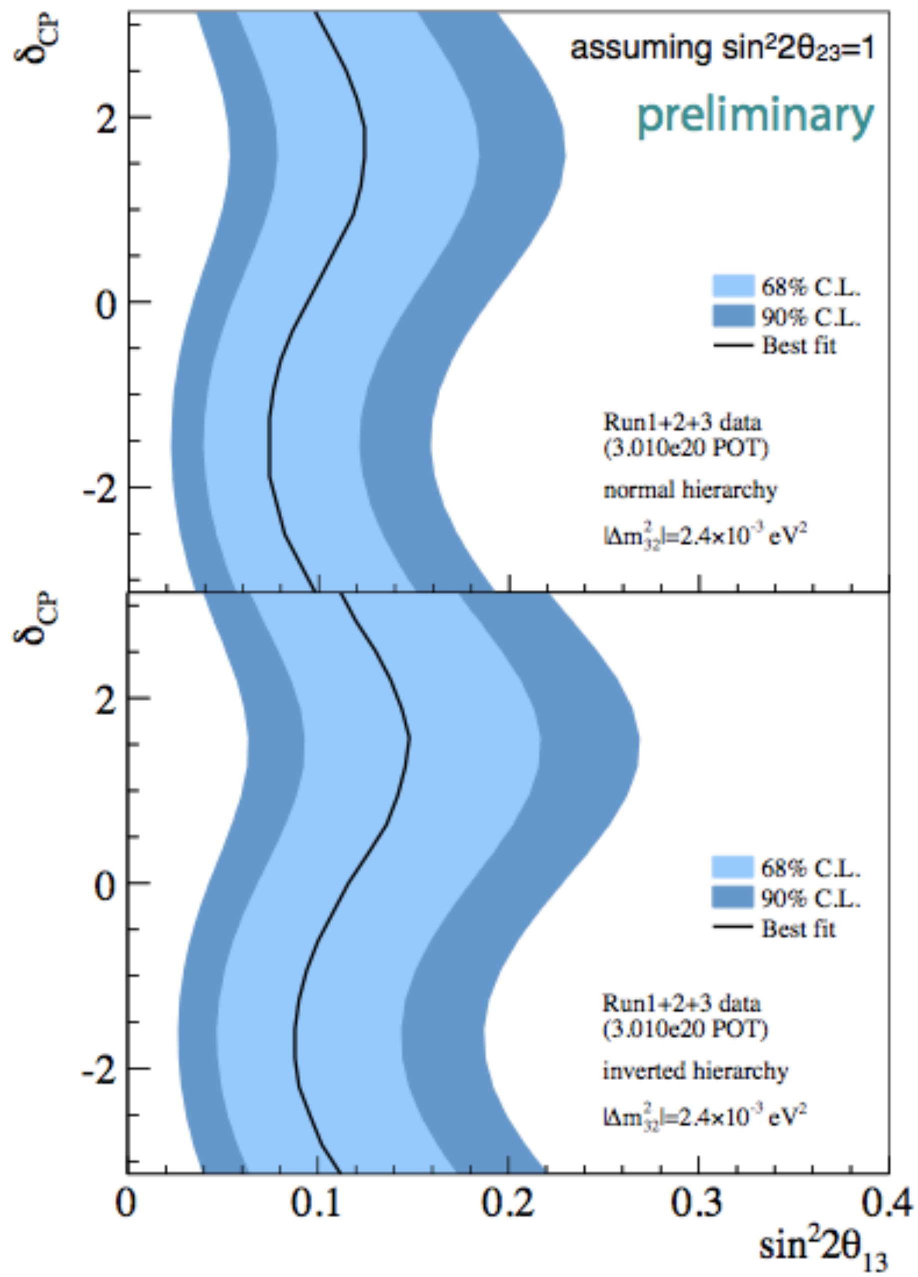
inverted hierarchy:

$$\sin^2 2\theta_{13} = 0.116^{+0.063}_{-0.049}$$

This result is consistent with rate+shape (rec. E_ν) method and rate only method

c.f 2011 result for normal (inverted) hierarchy

$$\sin^2 2\theta_{13} = 0.11^{+0.10}_{-0.06} \ (0.14^{+0.12}_{-0.07})$$



Daya-Bay: $\sin^2 2\theta_{13}$ = 0.089 ± 0.010 (stat) ± 0.005 (syst)

Outlook

• Data taking will continue with hopefully increasing beam performance:

•3.01 x 10^{20} pot so far, ~ 8 x 10^{20} (2013), 12 x 10^{20} (2014), 18 x 10^{20} (2015)

• Improve precision on the measurement of P ($\nu_\mu \rightarrow \nu_e$):
a tool to assess sub-leading effects such as CP violation, matter effects, possible new physics manifesting from ν_e appearance

• Discovery of oscillation appearance (statistically significant)

• Update on results from ν_μ disappearance: measurement of the θ_{23} with the θ_{13} value taken from high precision reactor experiments. Relevant to explore sub-leading terms.

OPERA and T2K

• The discovery of the appearance of neutrino oscillations is close: OPERA and T2K have already provided important indications from the $\nu_{\mu} - \nu_{\tau}$ and $\nu_{\mu} - \nu_{e}$ channels

• As far as ν_{τ} appearance is concerned, there are also interesting results from SK with atmospheric neutrinos: statistical method analysis. No competitors for T2K in the near future on electron appearance

Stay tuned and thank you for the attention!