Accelerator Neutrino Physics

prepared with help from many colleagues of
MiniBooNE, Minos, ICARUS, Opera, Minerva,
Nova, T2K and other collaborations

Koichiro Nishikawa
KEK/J-PARC
2011 EPS meeting@Grenoble
2011.7.26

- New results
  - ν_e appearance
  - ν_μ disappearance
- Questions remain to be solved
  - ν_τ appearance
  - sterile neutrinos ?
  - Δm^2 (neutrino)$\neq\Delta m^2$ (anti-neutrino)?
- Flux & cross section
  - particle productions measurements
  - neutrino cross sections measurements
- Future projects
  - Long baseline
  - Beta beam
  - Neutrino factory
- Issues for accelerator

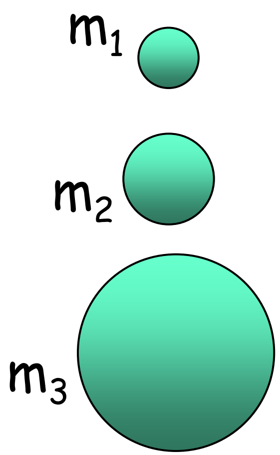
Present status of the measurements of mixing parameters in three generation

Six independent parameters

Weak eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{MNS} \, V_M^{CP} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

mass eigenstates



$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

$$V_M^{CP} = \begin{bmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

θ_{12}, θ_{23}, θ_{13}
$+ \ \delta$ (+2 Majorana phase)
Δm_{12}^2, Δm_{23}^2, Δm_{13}^2

θ_{12}

ν_1 to be the largest component in ν_e $\theta_{12} < \pi/4$

solar neutrino experiments, reactor (KamLAND)

matter effect fix the sign of $m^2{}_{12}$, ν_1 the lighter one

$\Delta m^2_{12} = m^2_2 - m^2_1 = 7.65^{+0.23}_{\;0.02} \times 10^{-5}\,\mathrm{eV}^2\left(\Delta m^2_{12} > 0\right)$ $\sin^2\theta_{12} = 0.304^{+0.022}_{-0.016}$

θ_{23}

atmospheric neutrino (SK), long-baseline (K2K, MINOS)

No matter effect has been measured

$\sin^2\theta_{23} > 0.93$ 90%CL (SK) $\theta_{23} = 45^0 \pm 5^0$

$|\Delta m^2{}_{23}| = 2.32^{+0.12}_{-0.08}$ x 10^{-3} eV^2 ($\pm$unkown)

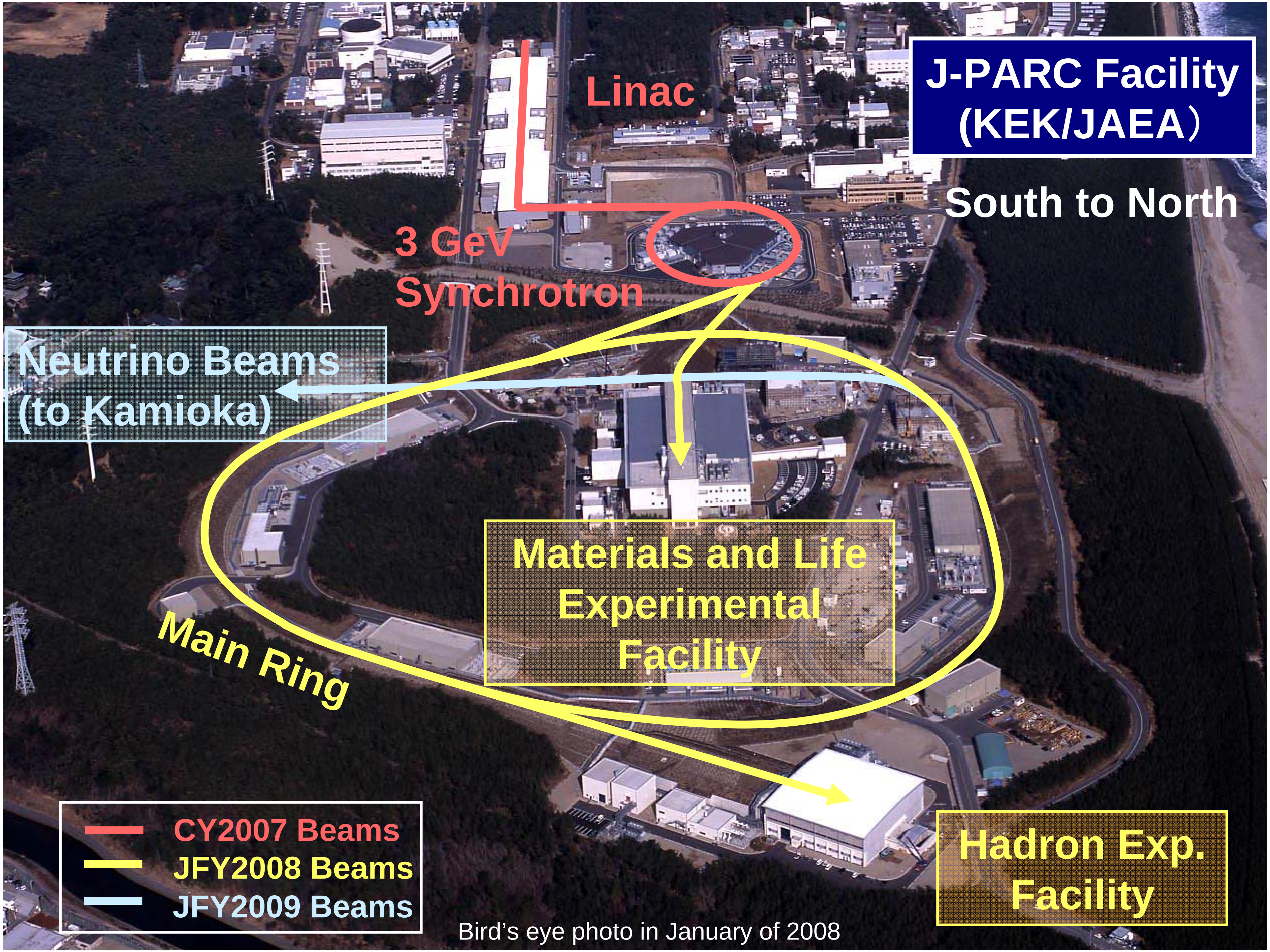
θ_{13}

ν_1 to be the larger component in ν_e $\theta_{13} < \pi/4$

CHOOZ 90%CL allowed region

$|\Delta m^2{}_{13}| \sim 2.3 \mathrm{x} 10^{-3}$ eV^2 ($\pm$unknown)

$\sin^2 2\theta_{13} < 0.16$ (upper limit)

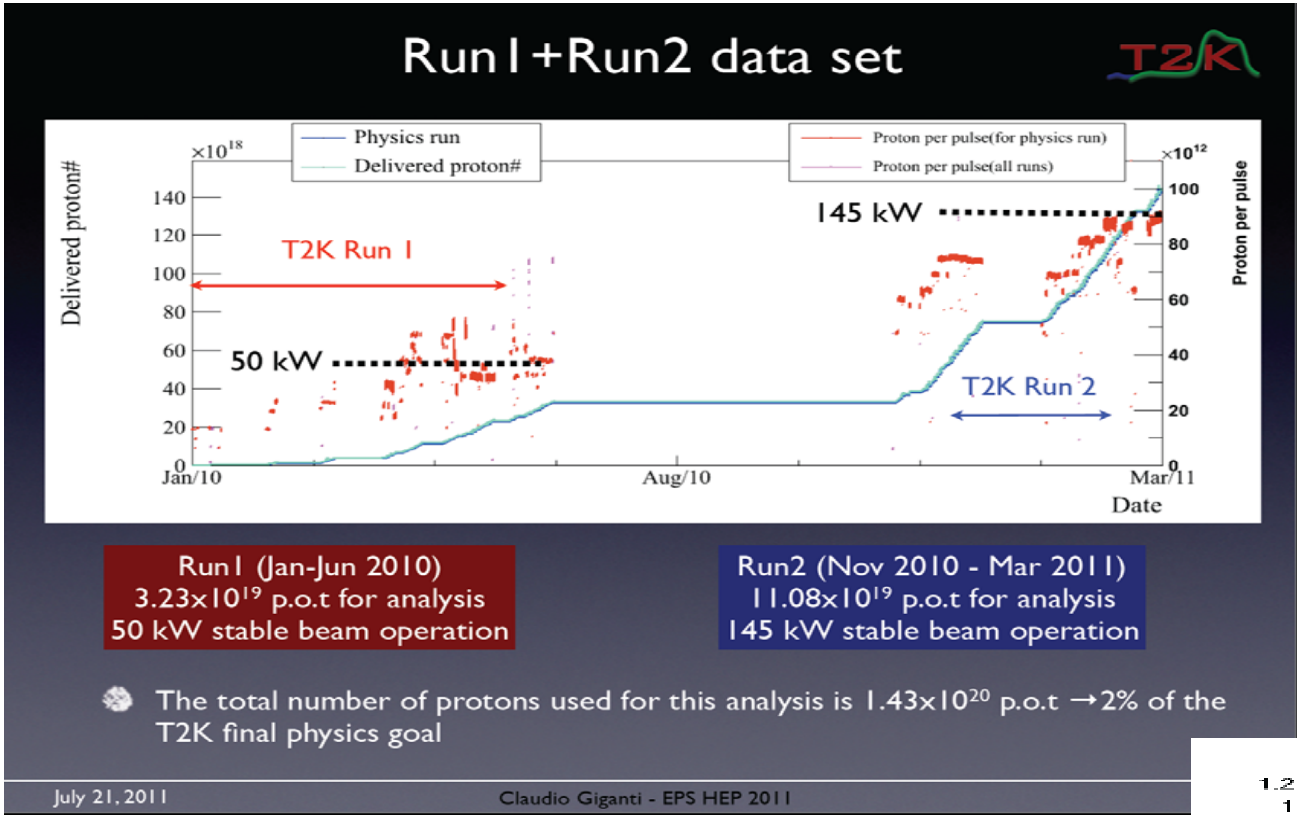


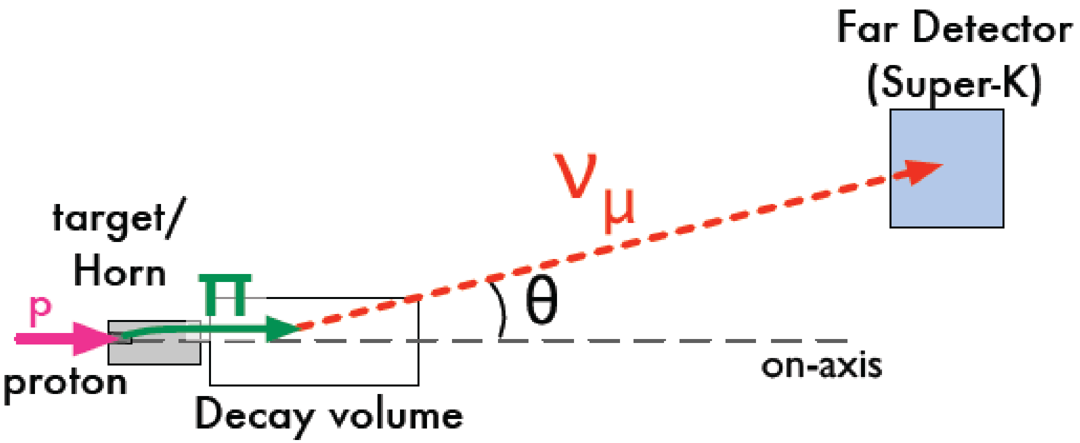
Bird's eye photo in January of 2008

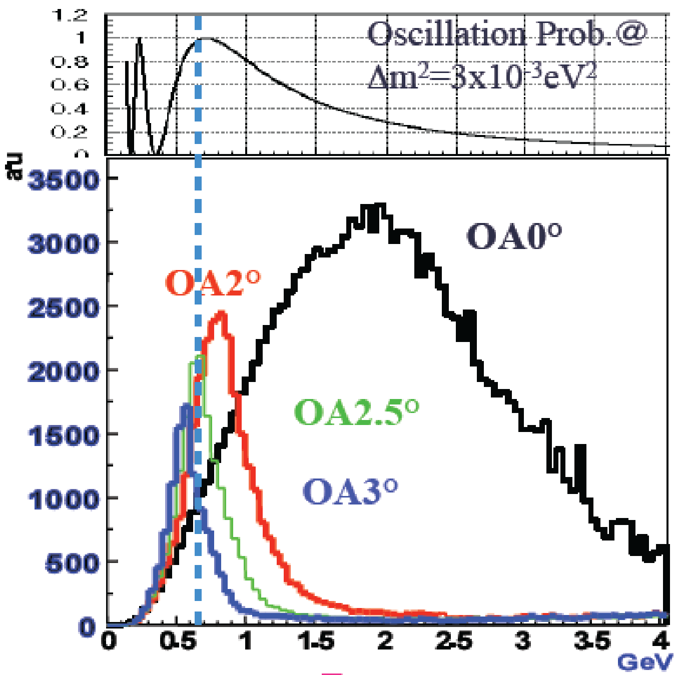
New results from the T2K experiment

Claudio Giganti
IFAE (Barcelona)
on behalf of the T2K Collaboration

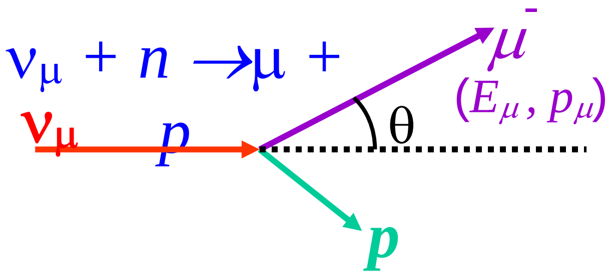
EPS-HEP 2011 - Grenoble (France)
July 21, 2011

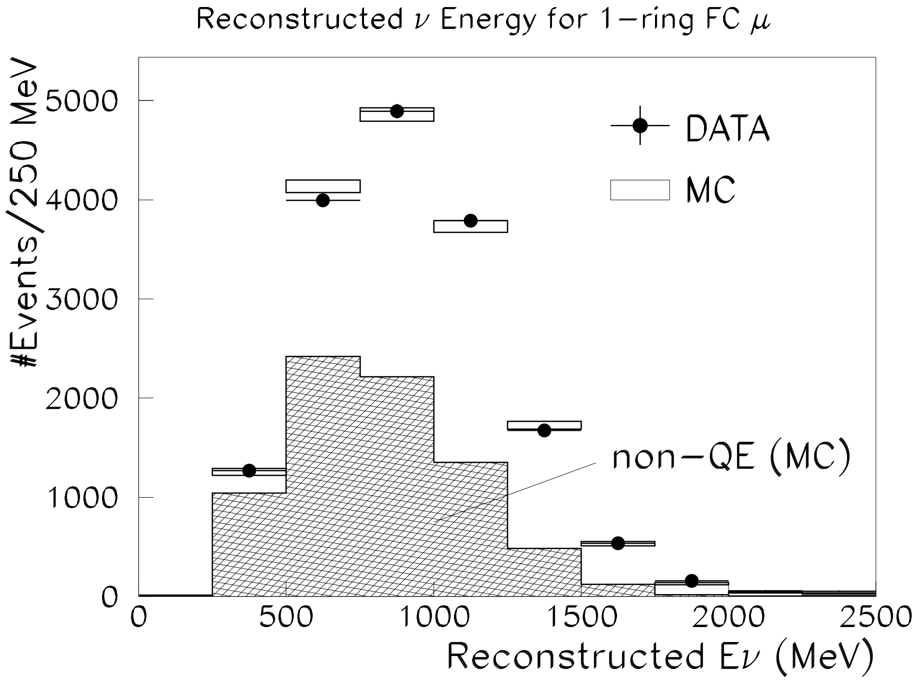

Run1+Run2 data set
T2K
Physics run
Delivered proton#
Proton per pulse(for physics run)
Proton per pulse(all runs)
Delivered proton#
×10^18
×10^12
Proton per pulse
T2K Run 1
50 kW
145 kW
T2K Run 2
Jan/10
Aug/10
Mar/11
Date
Run1 (Jan-Jun 2010)
3.23x10^19 p.o.t for analysis
50 kW stable beam operation
Run2 (Nov 2010 - Mar 2011)
11.08x10^19 p.o.t for analysis
145 kW stable beam operation
The total number of protons used for this analysis is 1.43x10^20 p.o.t →2% of the T2K final physics goal
July 21, 2011
Claudio Giganti - EPS HEP 2011


Far Detector
(Super-K)
target/
Horn
p
proton
π
νμ
θ
Decay volume
on-axis

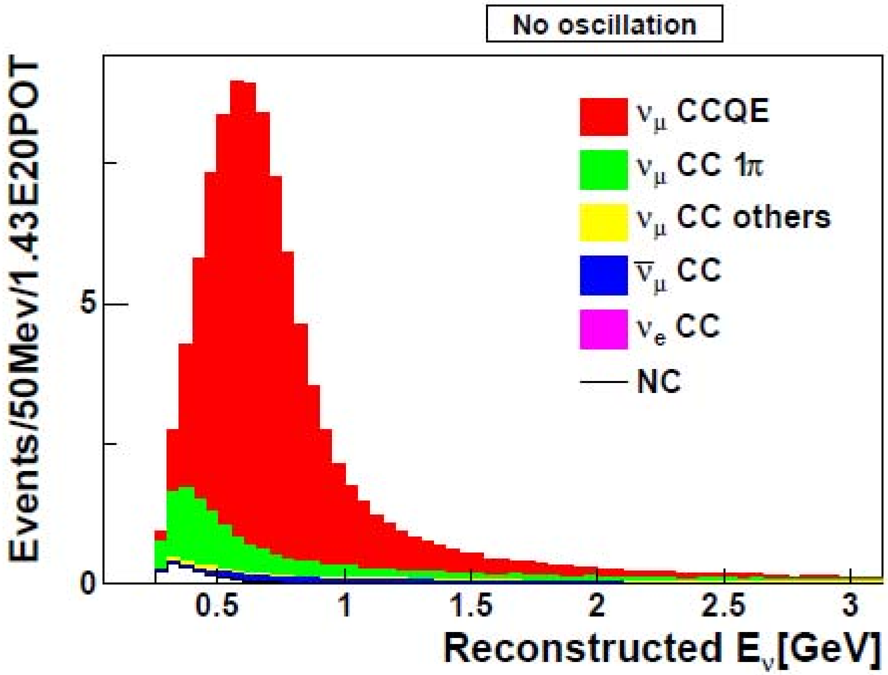

Oscillation Prob.@
Δm²=3x10⁻³eV²
a.u.
OA0°
OA2°
OA2.5°
OA3°
GeV

Neutrino energy reconstruction and beam with small high energy tail in T2K





K2K horn focused on-axis beam
12 GeV proton beam

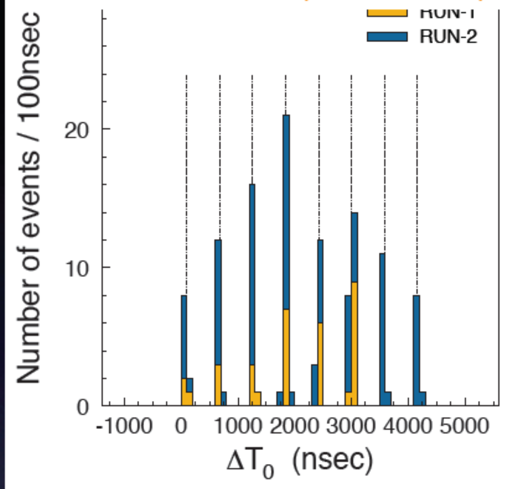


T2K off-axis beam

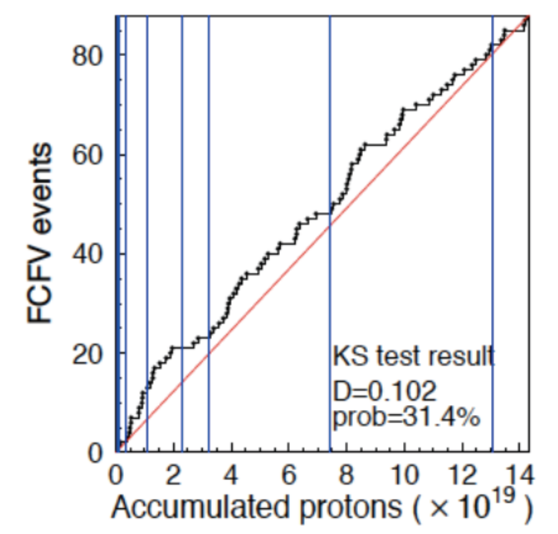
Super-Kamiokande event selection

- Predefined event selection for ν_μ and ν_e
- First steps that are common:
  - SK synchronized to beam timing using GPS
  - Fully contained events in the Inner Detector, minimal activity in the Outer Detector
  - Starting in the FV (FCFV)
  - Number of rings = 1
  - PID algorithm to distinguish e-like and μ-like events

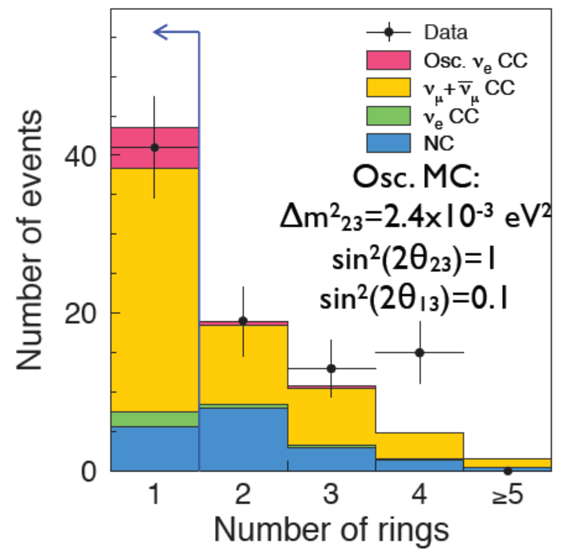
121 FC events (8 bunches)



88 FCFV events

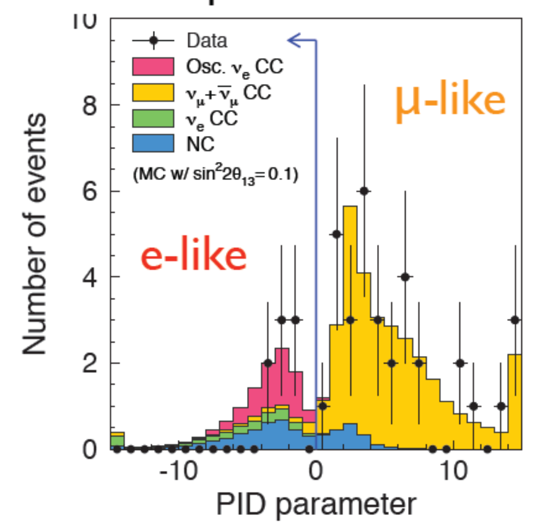


41 single ring



8 e-like events

33 μ-like events

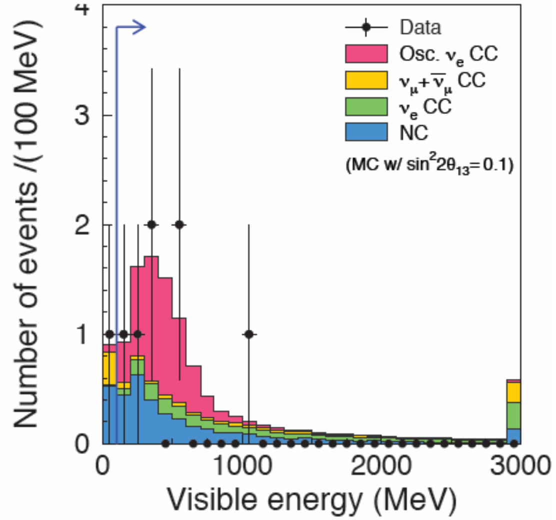


SK ν_e event reduction

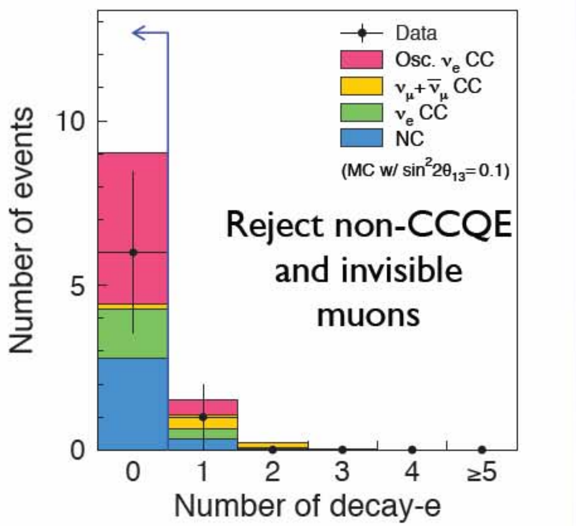
- After ring counting 8 single ring e-like events are selected
- SK "tight" cuts are applied to further reject the background:

Signal efficiency: 67%
Bkg rejection: 99% for NC,
77% for beam ν_e

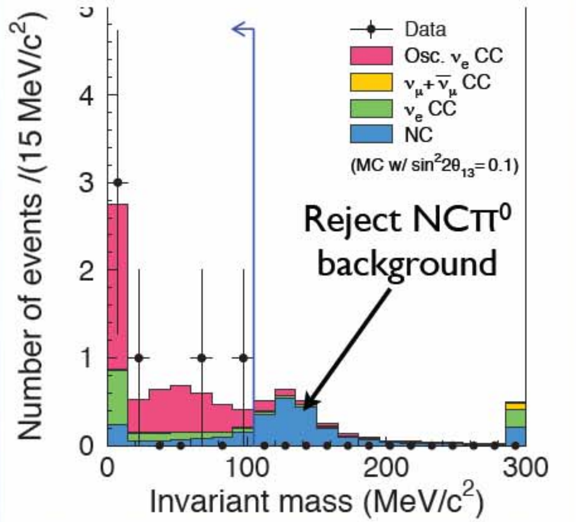
1) E(vis)>100 MeV → N=7



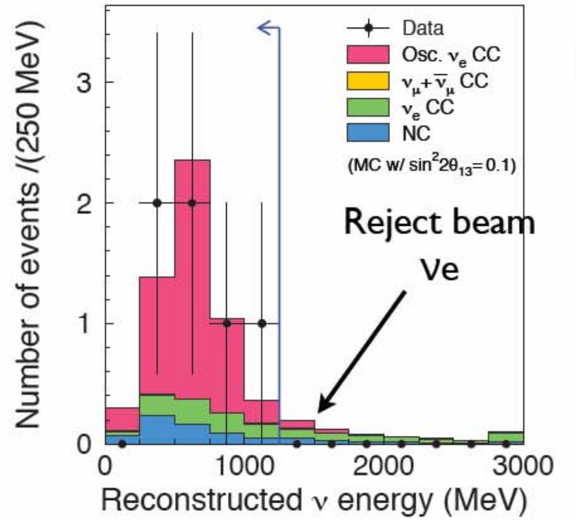
2) No decay electrons → N=6



3) M_{inv} with forced 2nd ring <105 MeV → N=6



4) Rec neutrino energy <1250 MeV → N=6



Number of expected events

- We observed 6 ν_e candidates
- The expected number of events from un-oscillated neutrinos is 1.5

Source	Nexp
Beam ν_e	0.8
ν_μ Neutral Current	0.6
ν_μ Charged Current	0.1
Total	1.5±0.3

Syst for θ_{13}=0 → Nexp = 1.5±0.3

error source	syst. error
ν flux	$\pm 8.5\%$
ν int. cross section	$\pm 14.0\%$
Near detector	$^{+5.6}_{-5.2}\%$
Far detector	$\pm 14.7\%$
Near det. statistics	$\pm 2.7\%$
Total	$^{+22.8}_{-22.7}\%$

Dominated by hadron production NA61

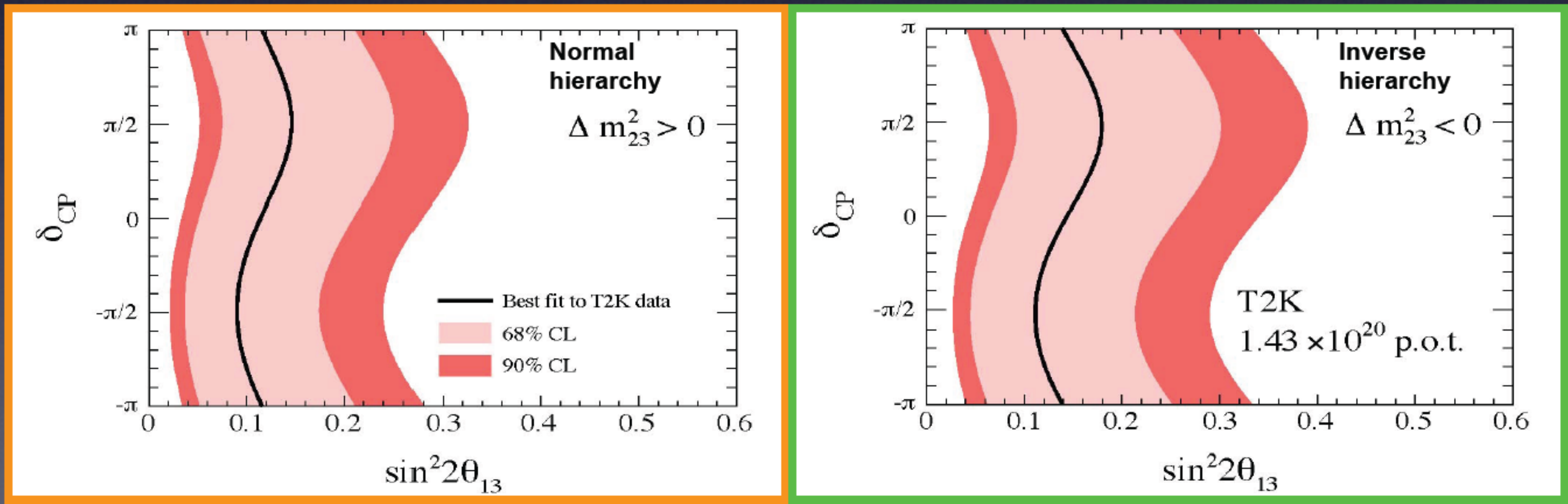
Dominated by FSI and NCπ0 cross-section uncertainties

ND280 dominated by TPC tracking efficiency and ionization in the gas

SK dominated by ring counting, PID and π^0 mass systematics

ν_e appearance analysis

- Probability of observing 6 events if $\sin^2(2\theta_{13})=0 \rightarrow 0.7\%$ (2.5σ significance)
- Feldman-Cousins unified method used to produce the confidence intervals
- For $\sin^2(2\theta_{23})=1$ and $\Delta m^2_{23}=2.4\times10^{-3}$ eV^2:
  - Normal hierarchy, $\delta=0$:
    - Best fit $\rightarrow$ $\sin^2(2\theta_{13})=0.11$ and $0.03<\sin^2(2\theta_{13})<0.28$ at 90% C.L.
  - Inverted hierarchy, $\delta=0$:
    - Best fit $\rightarrow$ $\sin^2(2\theta_{13})=0.14$ and $0.04<\sin^2(2\theta_{13})<0.34$ at 90% C.L.



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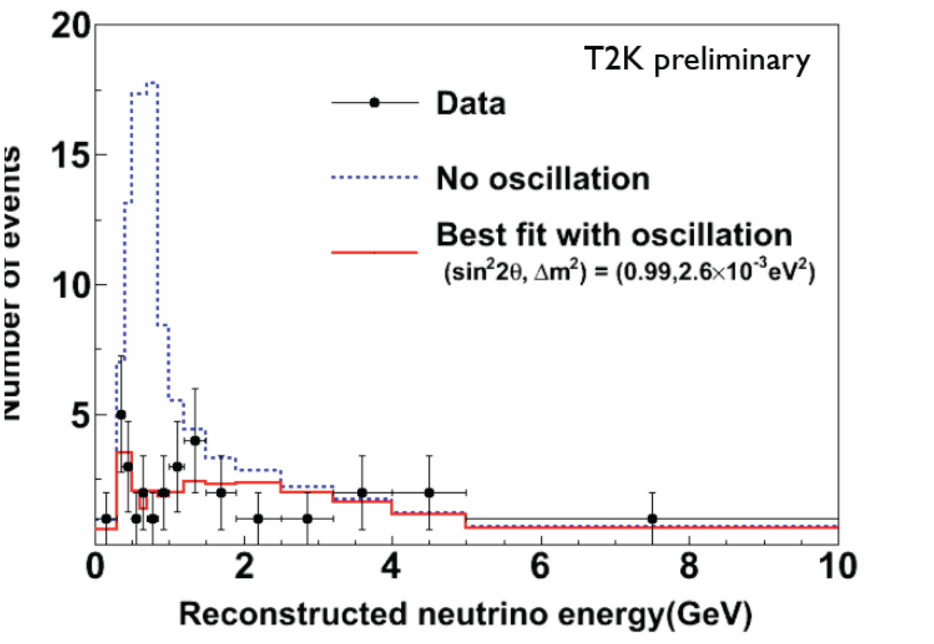
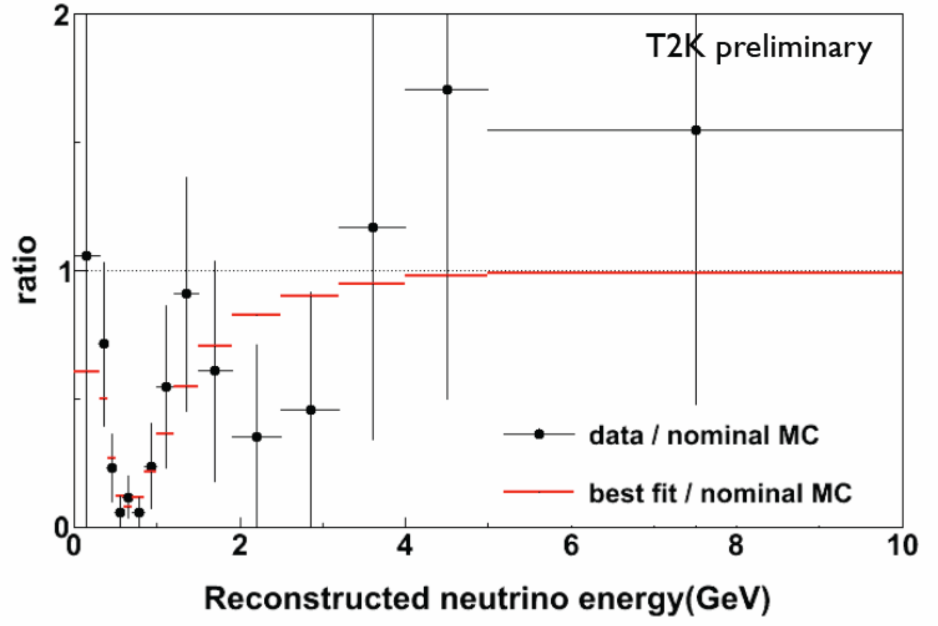
ν_μ disappearance measurement

Single μ events

- Observed events at SK satisfying ν_μ disappearance criteria: 31
- Oscillation parameters extracted from an oscillation fit on $E(\nu)^{rec}$
- The oscillation pattern due to the disappearance of ν_μ is clearly visible in the reconstructed energy spectrum → advantage of using off-axis configuration

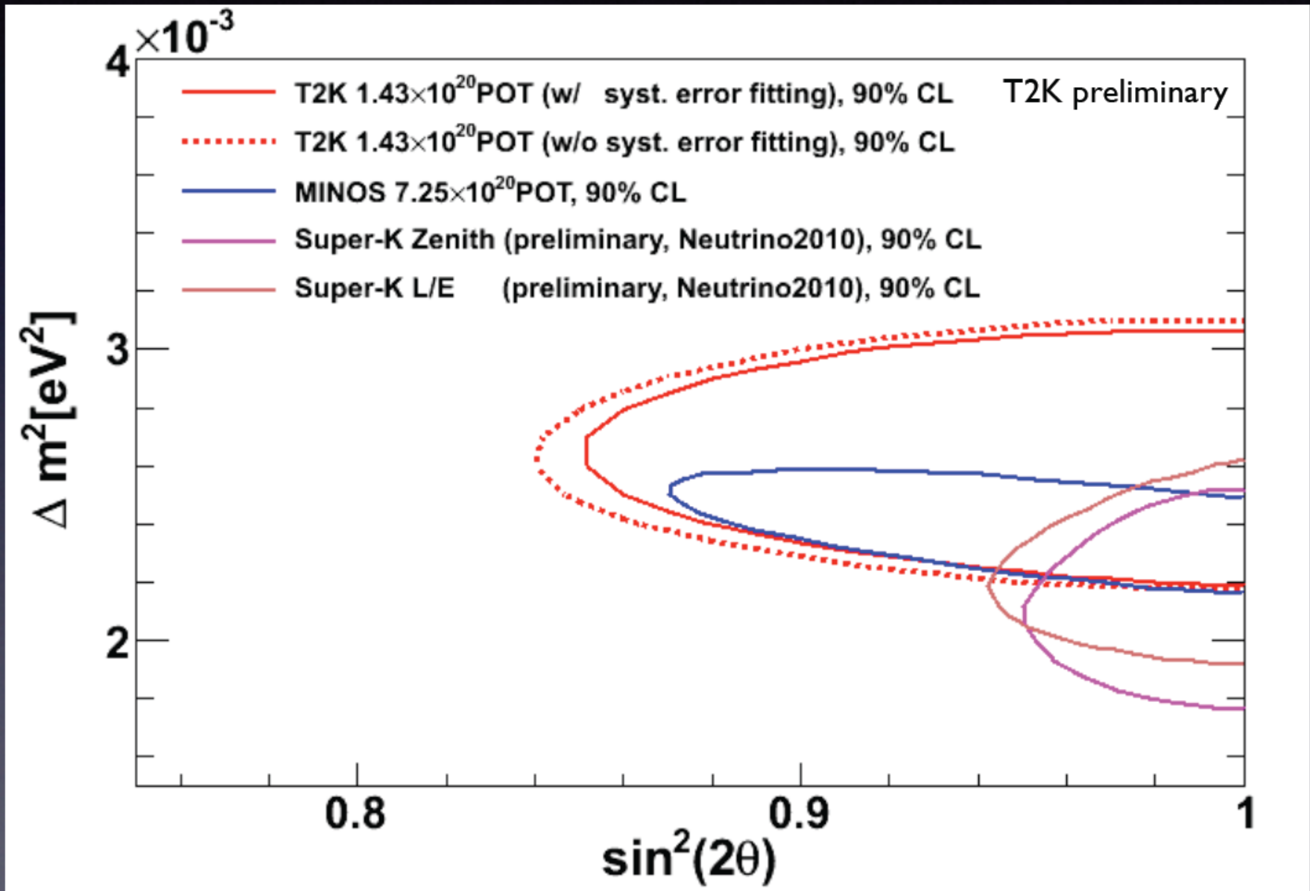


Ratio between data and MC without oscillation



Comparison with SK and MINOS

- T2K results are in good agreement with results from SK and MINOS



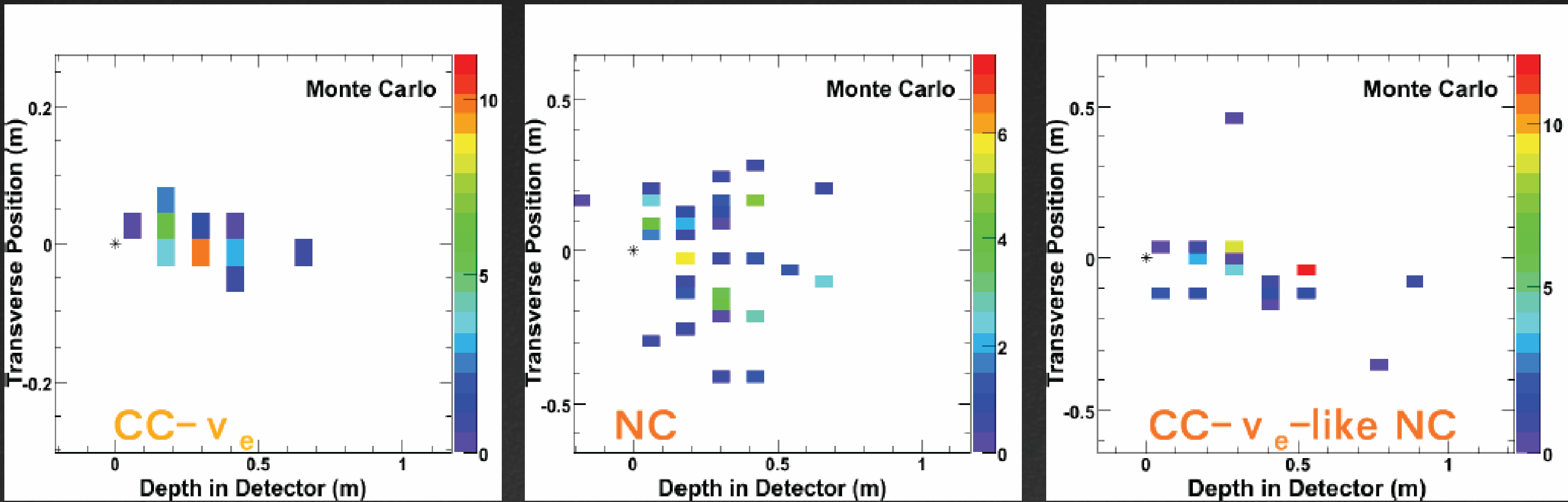
New Results from MINOS

Anna Holin
University College London

22.07.2010

Electron Neutrino Analysis Procedure

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13}) \sin^2\theta_{23} \sin^2\left(\frac{\Delta m^2_{atm} L}{4E}\right)$$

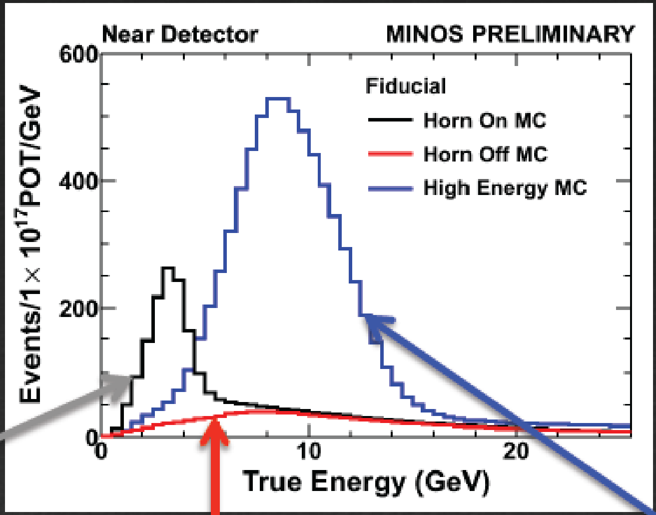


- Determine the criteria for selecting electron neutrino CC events from a background of predominantly NC events
- Translate the observed ND data spectrum into a background prediction for the FD
- Compare the data to the prediction and fit observed spectrum to obtain final exclusion limits
- New for this analysis: shape fitting in 15 bins – 3 bins in PID and 5 in energy

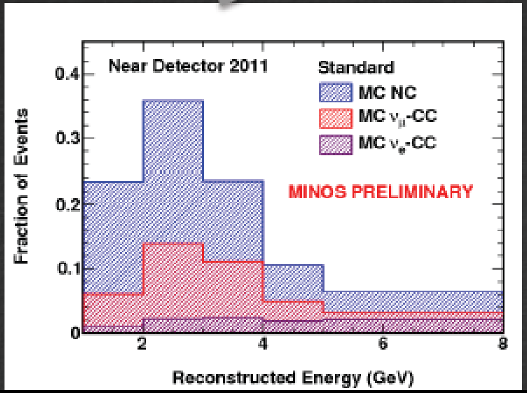
Near Detector Background Decomposition

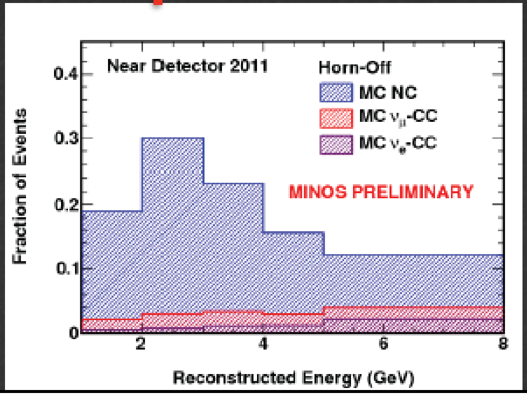
To calculate each background component, ND data taken in different beam configurations can be used:

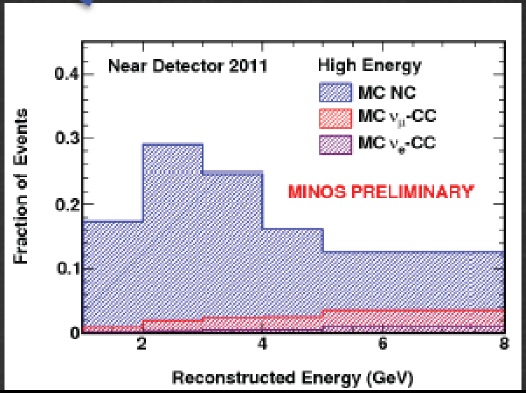
- Can use the total measured data in each beam configuration
- Can use the MC simulations for the relative interaction rates for each background



- Can thus fit for the background components in the standard LE sample







- LEM – Library Event Matching Algorithm – it uses a library of 20 million signal and 30 million NC events
- The 50 best matches are found for each event – 3 discriminant variables are constructed and combined in a neural network to obtain the PID

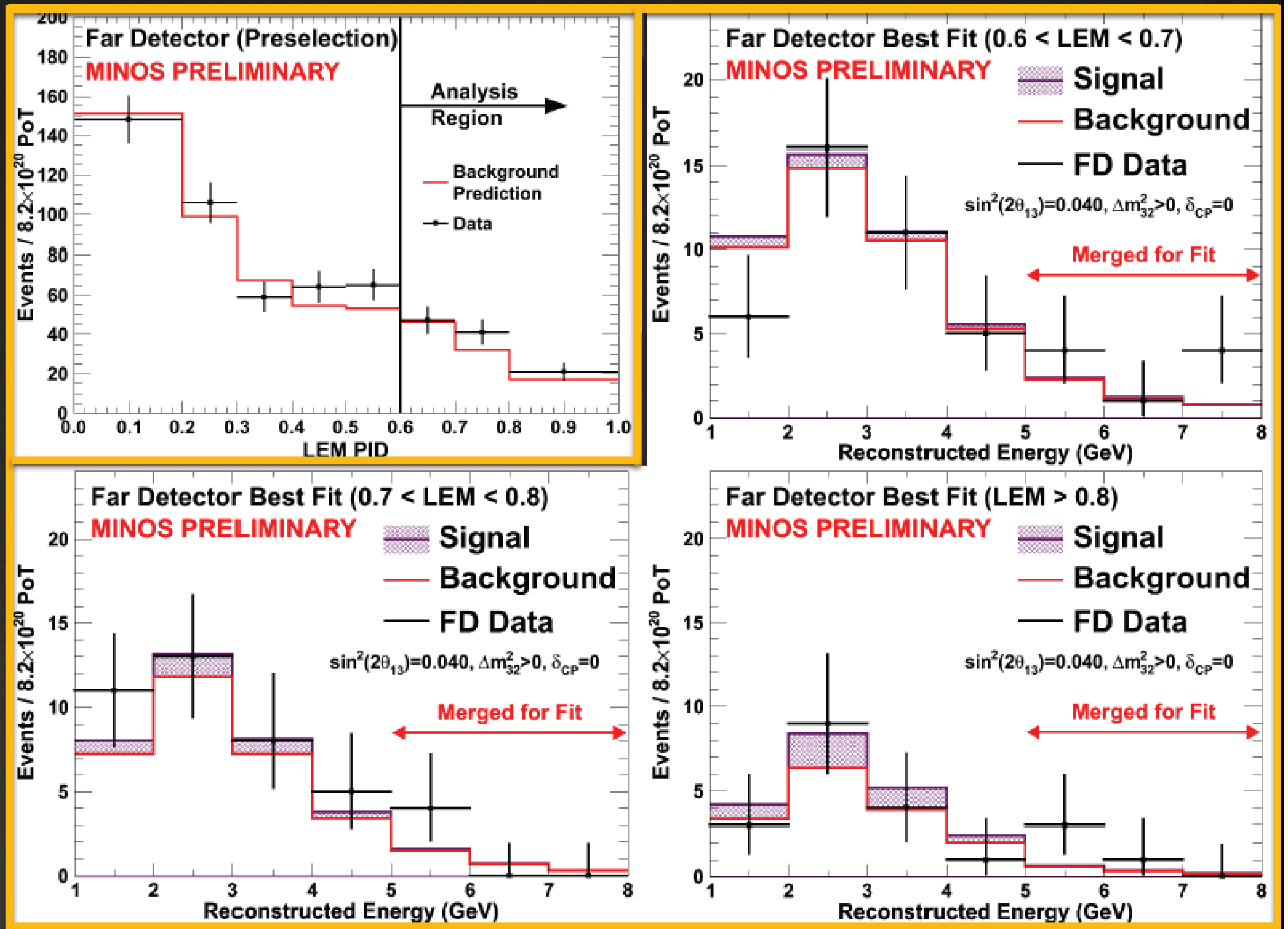
Appearance Result for 15-Bin Fitting

The fit uses 15 bins – three in PID and 5 in reconstructed energy.

Best Fit:

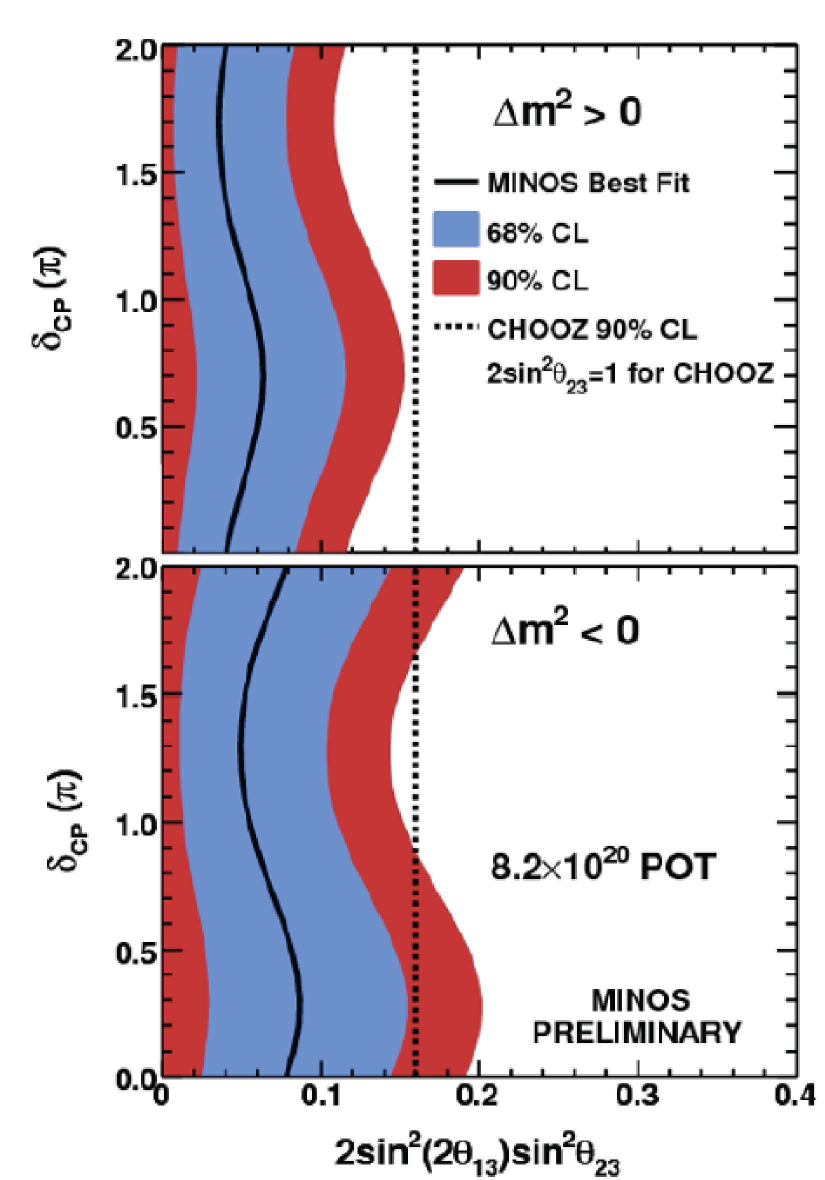
$\sin^2 2\theta_{13} = 0.040$

for δ=0 and $\sin^2 2\theta_{23}$=1, normal mass hierarchy



Signal enhanced region LEM>0.7:
expect 49.5 ± 7.0(stat.) ± 2.8(syst.), observed 62 events in the FD

Region Allowed by Fit



MINOS has updated its electron neutrino appearance analysis **for an exposure of 8.2×10^{20} POT, with shape fitting and a new selection variable**

$\sin^2(2\theta_{13})$<0.12 for normal mass hierarchy, <0.19 for inverted hierarchy, at 90% C.L., for δ=0

$\sin^2(2\theta_{13})$=0.04 (0.08) are the best fit values

$\sin^2(2\theta_{13})$=0 excluded at 89% C.L.

For the first time, an experiment has been able to exclude beyond the Chooz limit in all of the parameter space for the normal mass hierarchy

Muon Neutrino Disappearance

Muon neutrinos are observed to disappear as they travel. The most precise result in Δm^2 was obtained by MINOS:

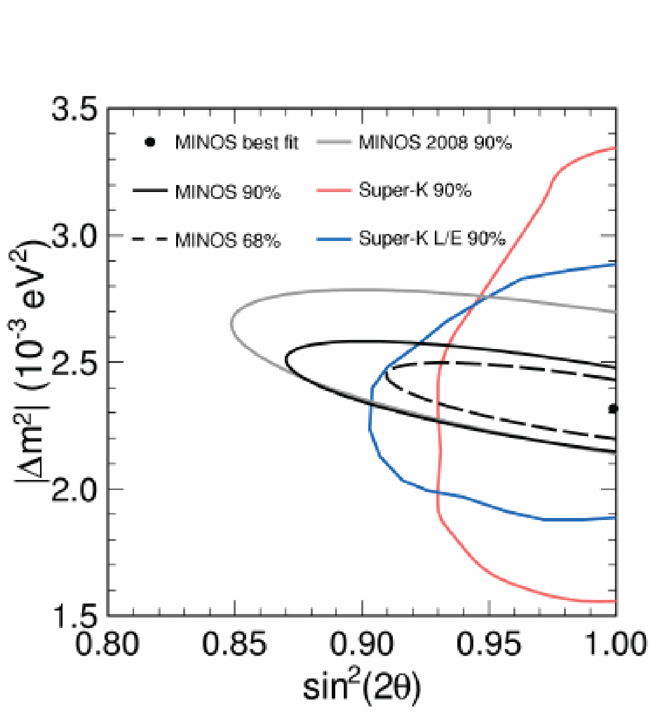
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2(1.27 \Delta m^2_{32} L/E)$$

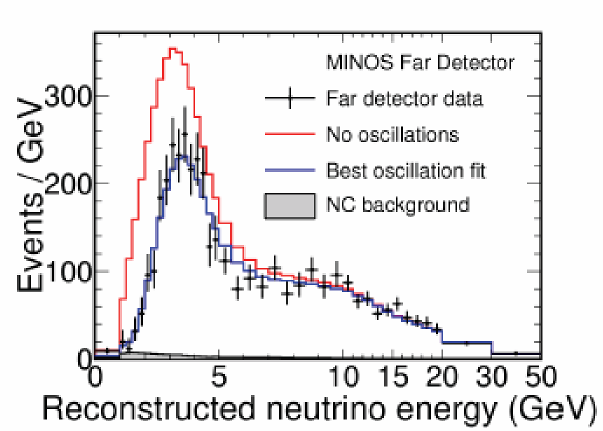
$$|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3} eV^2$$

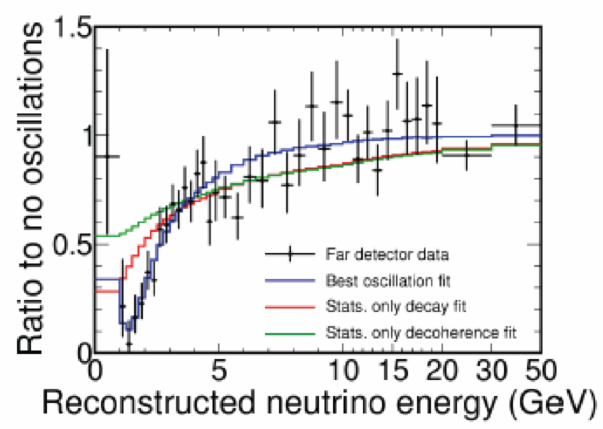
$$\sin^2(2\theta) > 0.90 (90\% C.L.)$$

Expected 2451 events
Observed 1986 events

Exclude decay at 7 σ
Exclude decoherence at 9 σ







Phys. Rev. Lett. 106, 181801 (2011)

Present Knowledge

θ_{12}

ν_1 to be the largest component in ν_e $\theta_{12} < \pi/4$

solar neutrino experiments, reactor (KamLAND)

matter effect fix the sign of $m^2{}_{12}$, ν_1 the lighter one

$\Delta m^2_{12} = m^2_2 - m^2_1 = 7.50^{+0.17}_{\ 0.23} \times 10^{-5}\,\mathrm{eV}^2 \left(\Delta m^2_{12} > 0\right)$ $\sin^2\theta_{12} = 0.304^{+0.022}_{-0.016}$

θ_{23}

atmospheric neutrinos (SK), long-baseline (MINOS,T2K)

No matter effect has been measured

$\sin^2 2\theta_{23} > 0.9$ 90%CL (SK) $\theta_{23} = 45^0 \pm 5^0$

$|\Delta m^2{}_{23}| = 2.32^{+0.12}{}_{-0.08}$ x 10^{-3} eV^2 ($\pm$unkown)

θ_{13}

ν_1 to be the larger component in ν_e $\theta_{13} < \pi/4$

$|\Delta m^2{}_{13}| \sim 2.3\mathrm{x}10^{-3}$ eV^2 ($\pm$unknown)

T2K 90%CL allowed region

$0.03 < \sin^2 2\theta_{13} < 0.28$ (N.H.)

$0.04 < \sin^2 2\theta_{13} < 0.34$ (I.H.)

MINOS allowed region

$\sin^2 2\theta_{13} = 0$ excluded at 89%CL

<0.12 (N.H.), <0.19 (I.H.)

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
Toho
Kobe
Nagoya
Utsunomiya

Korea
Jinju

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

Switzerland
Bern
ETH Zurich

Turkey
METU Ankara

Updated results of the OPERA long baseline neutrino experiment

On behalf of the OPERA Collaboration

S.Dusini - INFN Padova

Paper submitted to Physics Letter B, (arXiv:1107.2594 [hep-ex]).

Updated OPERA sensitivity

Including all the improvements in the analysis

Decay channel	Number of signal events expected for $Dm^2 = 2.5\times10^{-3}\ eV^2$	
	22.5×10^{19} p.o.t.	Analysed sample
$\tau \to \mu$	1.79	0.39
$\tau \to e$	2.89	0.63
$\tau \to h$	2.25	0.49
$\tau \to 3h$	0.71	0.15
Total	7.63	1.65

In the analyzed sample (92% of '08+'09 data) one ν_τ observed in the $\tau \to h$ channel compatible with the expectation of 1.65 signal events.

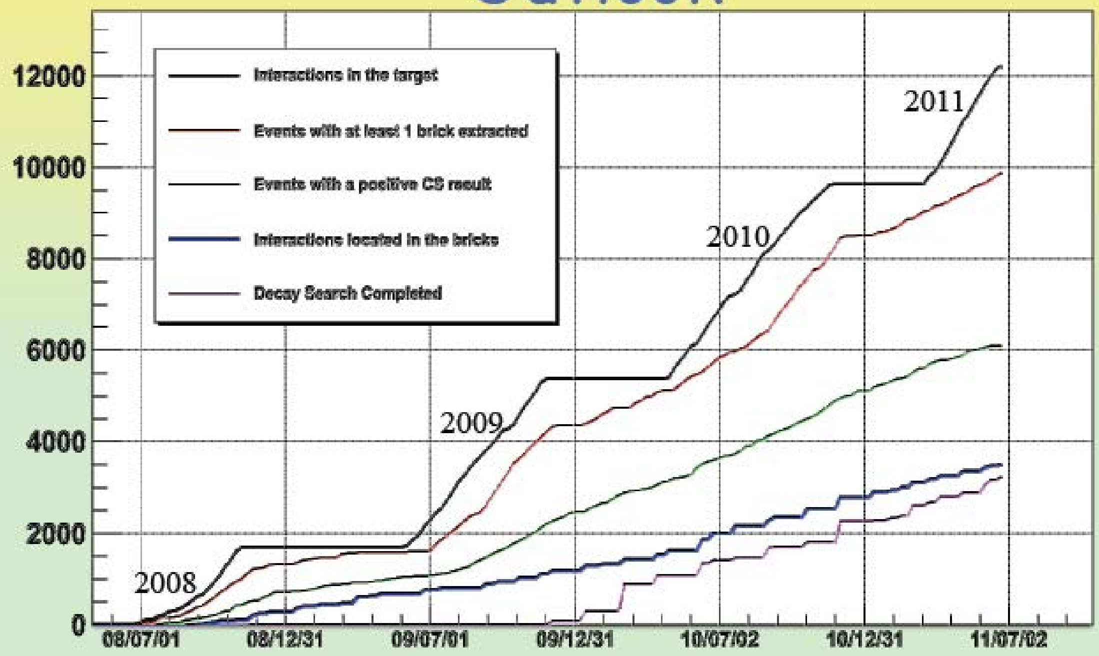
Summary of background

Very clean channel

Decay channel	Number of background events for:							
	22.5×10^{19} p.o.t.				Analysed sample			
	Charm	Hadron	Muon	Total	Charm	Hadron	Muon	Total
$\tau \to \mu$	0.025	0.00	0.07	0.09±0.04	0.00	0.00	0.02	0.02±0.01
$\tau \to e$	0.22	0	0	0.22±0.05	0.05	0	0	0.05±0.01
$\tau \to h$	0.14	0.11	0	0.24±0.06	0.03	0.02	0	0.05±0.01
$\tau \to 3h$	0.18	0	0	0.18±0.04	0.04	0	0	0.04±0.01
Total	0.55	0.11	0.07	0.73±0.15	0.12	0.02	0.02	0.16±0.03

The expected background in the $\tau \to h$ channel is 0.05 ± 0.01
The probability of a background fluctuation up to at least one event is 5%.
The total expected background is 0.16 ± 0.03 and the probability a background fluctuation is 15%.

Outlook



One event was observed so far, which is consistent with 1.65 events expected

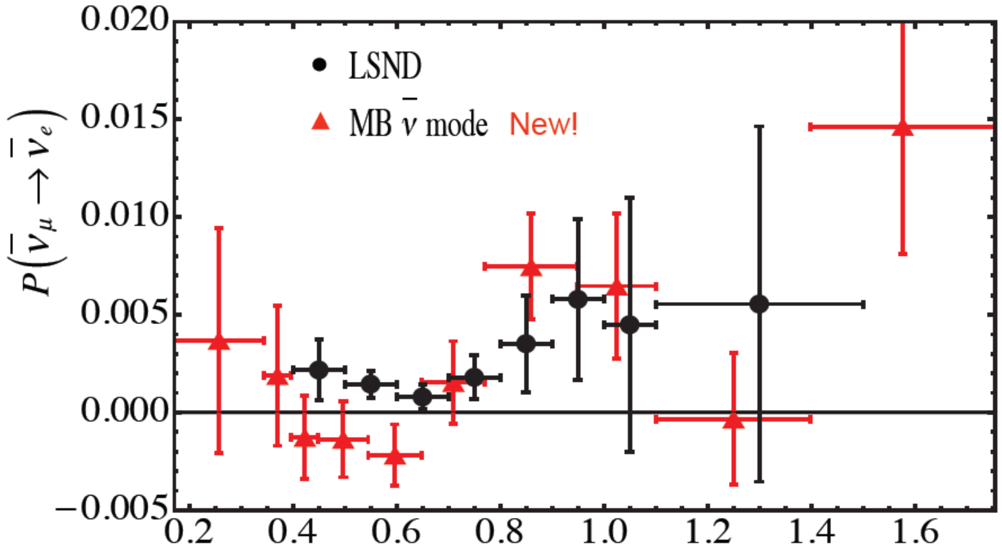
Can close the chapter ?

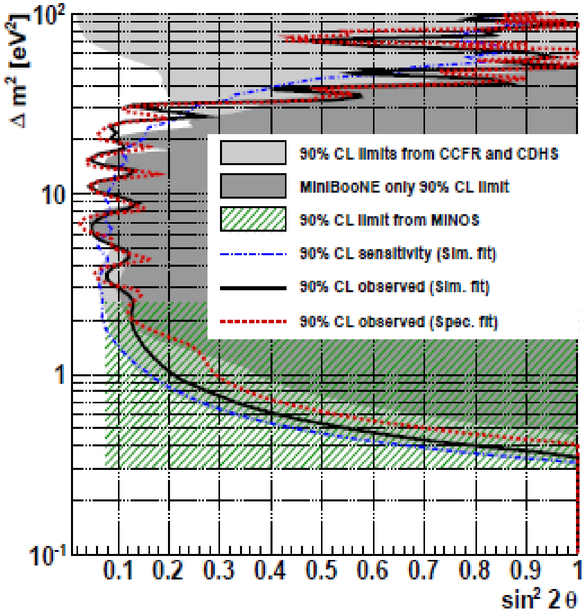
Questions remained to be solved

- ν_μ disappearance
- 3^{rd} Δm^2 region ?
  - LSND, MiniBooNE(anti-neutrino data)
  - Possible difference of mass eigenvalues in neutrinos and anti-neutrinos

Direct MiniBooNE-LSND Comparison of $\bar{\nu}$ Data

NEUTRINO 2010



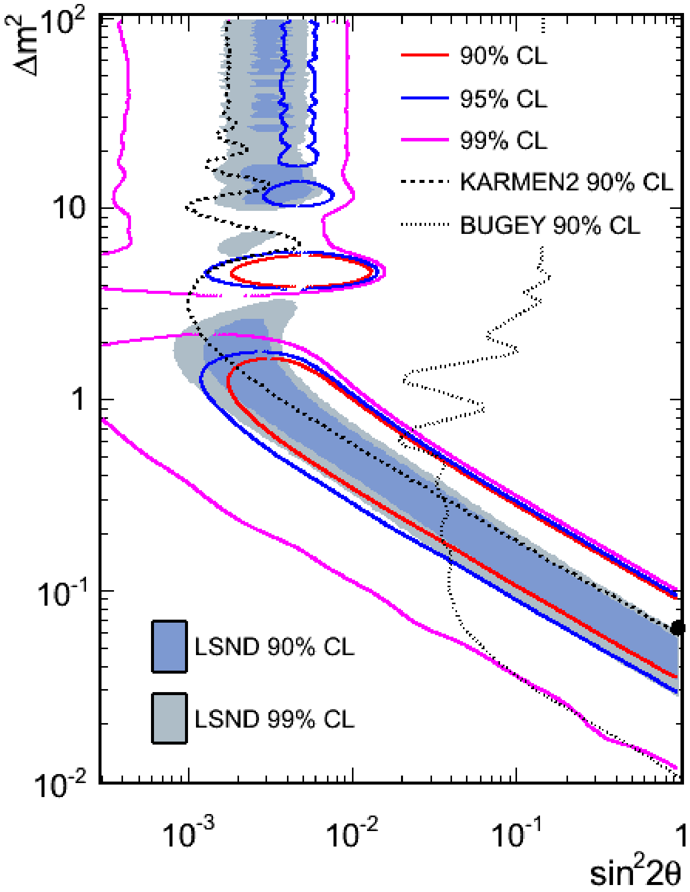


90%CL exclusion region

arXiv:1106.5685v1 [hep-ex] 28 jun 2011

SciBooNE and MiniBooNE

Current: 5.66E20 POT: E > 475 MeV



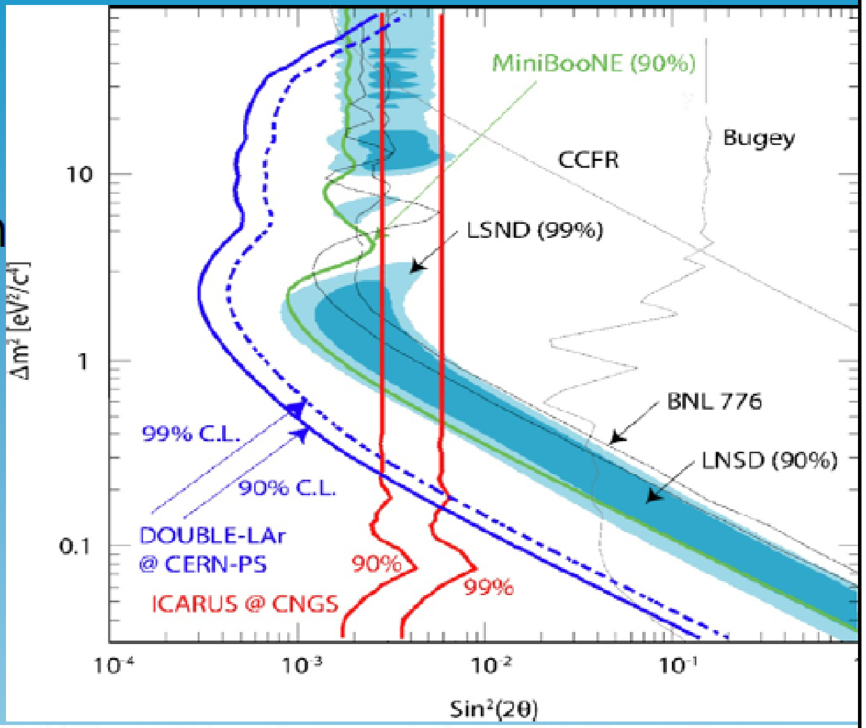
- Reactor anomaly ?
- MiniBooNE low E ν anomaly

Sterile neutrinos with ICARUS

ICARUS@LNGS can search for sterile neutrinos through $\nu_\mu \to \nu_e$ appearance in the $10<E_\nu<30$ GeV window:

- Signal well above intrinsic ν_e contamination
- No effect from $\nu_\mu \to \nu_\tau \to$ e and NC in this energy region
- For $\Delta m^2=0.4$ eV^2 and $\sin^2 2\theta=0.02$ signal ~ 30 events, bkg ~ 12

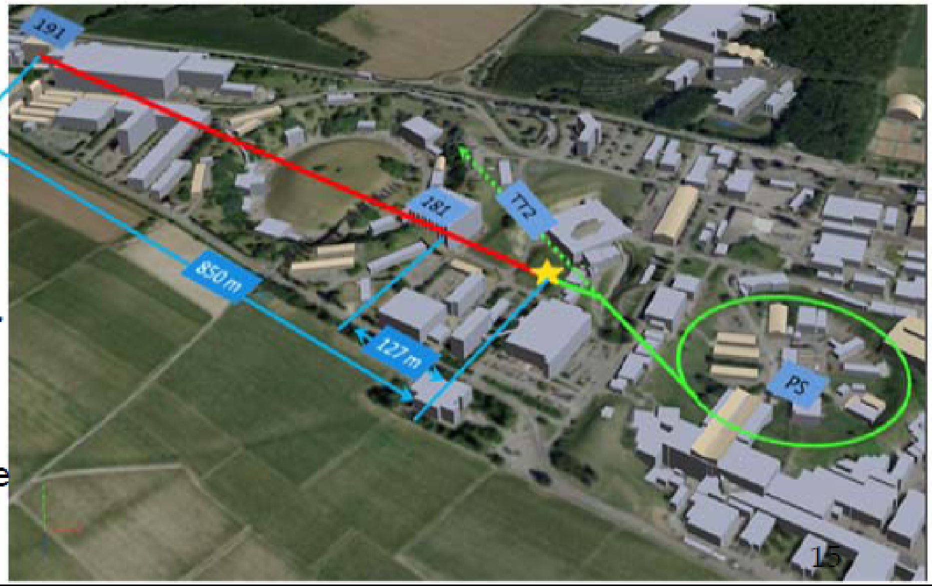
A significant fraction of LSND parameter space can be covered



Also MicroBooNE at Fermilab

DEDICATED EXPERIMENT PROPOSED AT CERN-PS:

- From 2013, after CNGS shutdown
- Identical near(T150) and far(ICARUS T600) LAr TPCs
- Capability to cover all LSND parameter space with ν and anti-ν
- Disappearance measurements using ν_e contamination



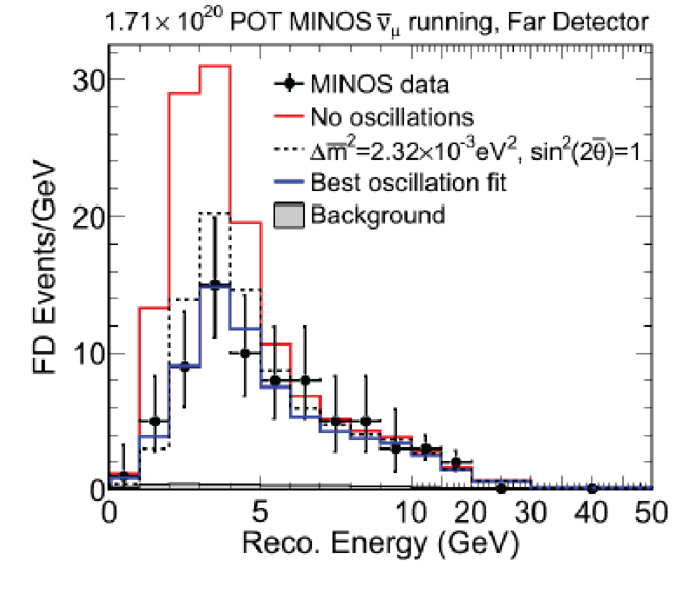
Muon Anti-Neutrino Disappearance

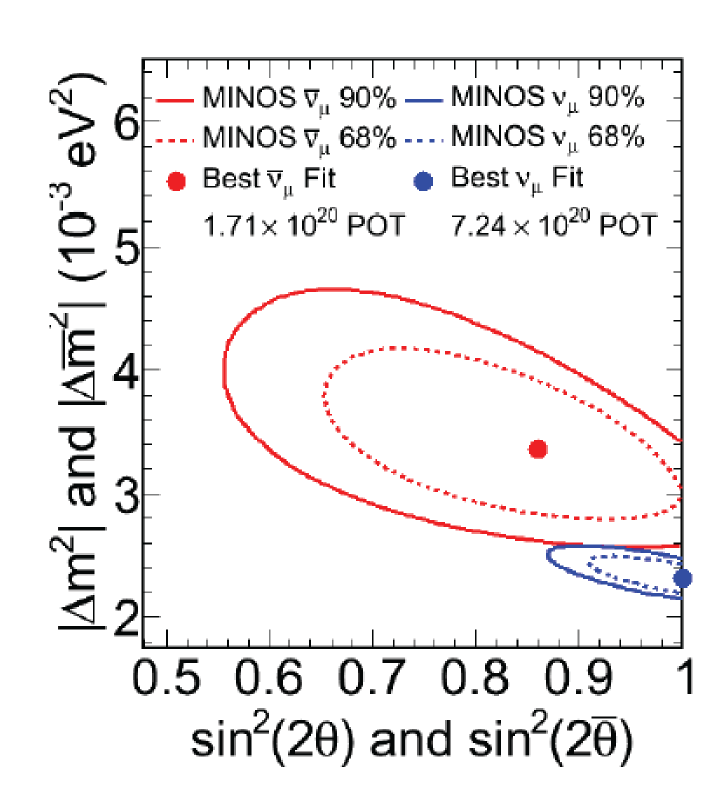
By reversing the horn current, NuMI can create an anti-neutrino beam, can analyze the resulting data in a similar way to the neutrino data

No oscillation Prediction: **156 events**

Observe: **97 events**

No oscillations disfavored at 6.3 σ





$$\left|\overline{\Delta m^2}\right| = (3.36^{+0.46}_{-0.40}(stat.) \pm 0.06(syst.)) \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2(2\overline{\theta}) = 0.86^{+0.11}_{-0.12}(stat.) \pm 0.01(syst.)$$

Phys. Rev. Lett. 107, 021801 (2011)

Works for improving neutrino experiments

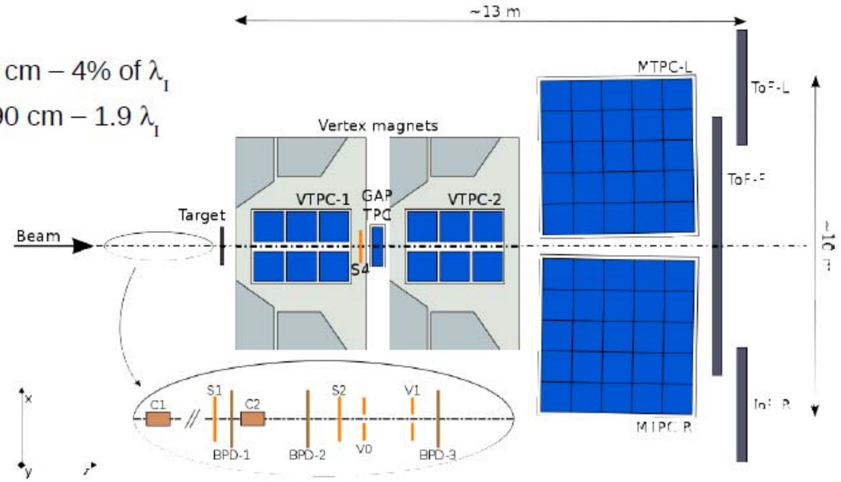
Available observables are always flux times cross section

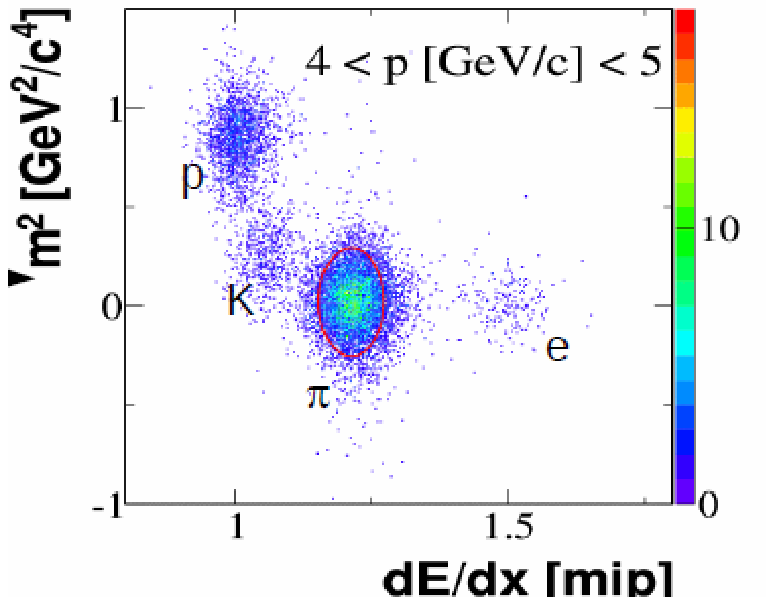
NA61 experiment in CERN/SPS

- ~140 physicists from 25 institutes
- One of main goals: Hadron production in p-C interaction to improve the prediction for the neutrino flux in T2K
- 31 GeV/*c* secondary hadron beam
- Tracking detectors: 5 TPCs and 3 MWPCs (beam telescope)
- Particle identification: TPC (*dE/dx*) and TOF

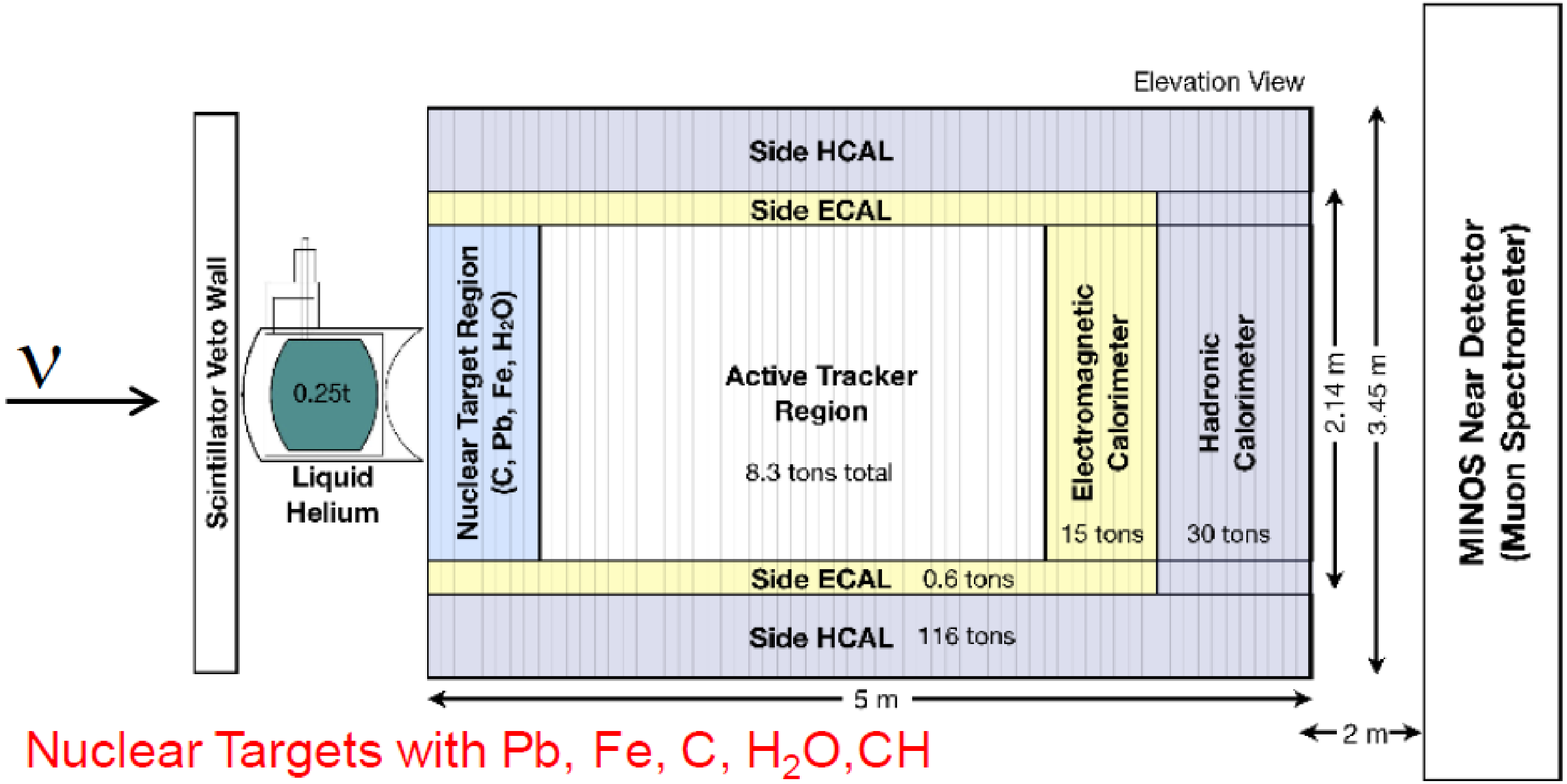
Thin target: 2 cm – 4% of λ_I

Replica targ: 90 cm – 1.9 λ_I





MINERνA Detector



Nuclear Targets with Pb, Fe, C, H_2O,CH

In same experiment reduces systematic errors between nuclei

Side and downstream Calorimetry: Both Electomagnetic and Hadronic

- Made of 120 planar "modules".
  - Total Mass: 200 tons
  - Total channels: ~32K

Future accelerator neutrino experiments

12:10	Long Baseline Neutrino Oscillation Experiments	RUBBIA, Andre
12:30	Beta Beams	WILDNER, elena
12:45	Neutrino oscillation physics with a Neutrino Factory	SOLER, Paul

General requirements

A general view in neutrino physics with accelerator

- Neutrino oscillation studies are still at the stage, equivalent to the discovery of K_L in cosmic rays (Gell-Mann – Pais concept of K_L : co-existence of mass and strong eigen-states)
  - Flavor and mass eigen-states with different masses co-exist and mix.
  - Neutrino oscillation between flavor eigen-states exist.and mix
- The unexpected discovery of CP violation in neutral kaon system
- CPV is one of the necessary ingredients of matter dominated Universe, motivated rigorous experimental studies
- Kobayashi-Maskawa theory explain both CPV in K, B in term of 3 angles and 1 phase in the 3x3 mixing matrix without 'new interaction'

- The studies of CPV in neutrinos will start with an analogy of K.M. theory. i.e. complex phase in 3x3 PMNS matrix.
- how to prove the effects is due to KM type complex phase ?
- Are there additional CPV source in leptons?
  - No bug constant, no long distance effects, no need for final state int., etc

3 generation light neutrinos (+ Heavy neutrinos(SeeSaw))

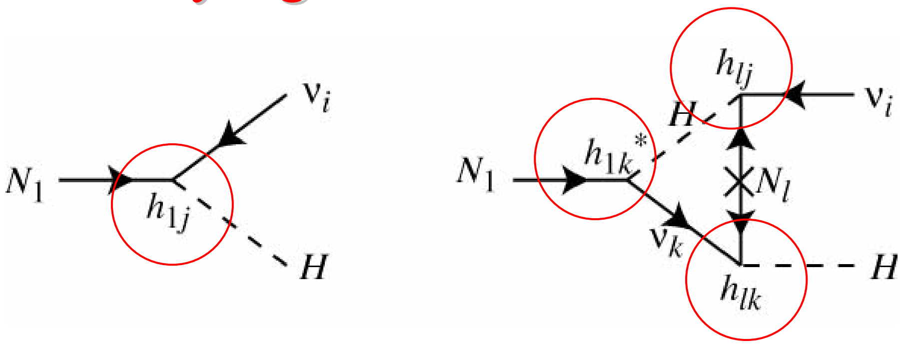
light neutrinos 9 parameters

- neutrino masses
  - $m_1\ \ m_2\ \ m_3$
- mixing angles
  - $\theta_{12}\ \ \theta_{23}\ \ \theta_{13}$
- CP phase
  - δ
- Majorana phases
  - $\phi_1\ \ \phi_2$

oscillation 6 parameters

- squared-differences
  - $\delta m^2_{12}\ \ \delta m^2_{13}\,(\equiv m^2_3 - m^2_1)$
- mixing angles
  - $\theta_{12}\ \ \theta_{23}\ \ \theta_{13}$
- CP phase
  - δ
- Majorana phases
  - <u>no sensitivity</u>

Heavy right-handed neutrinos



Leptogenesis

$$\varepsilon = \frac{\Gamma(N_1 \to \nu_i H) - \Gamma(N_1 \to \bar{\nu}_i H)}{\Gamma(N_1 \to \nu_i H) + \Gamma(N_1 \to \bar{\nu}_i H)} \neq 0$$

Complex h_{ij} 's

Advantage of $\nu_\mu \rightarrow \nu_e$ at around 2.5×10^{-3} eV^2

δ : CP Violation in Lepton Sector
in 3 generations scheme

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{j>i} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2 \frac{(m_j^2 - m_i^2)L}{4E_\nu}$$

$$\mp 2\sum_{j>i} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin \frac{(m_j^2 - m_i^2)L}{2E_\nu}$$

CPV $\propto \sin\theta_{12} \sin\theta_{23}$ **$\sin\theta_{13}$** Δm^2_{12} (L/E) **$\sin\delta$**

- νe disappearance 1- P_{ee} : $\alpha=\beta$ $|U_{\alpha i}|^2$ Real
- $\nu_\mu \rightarrow \nu_e$: interference of two Δm^2's
  (small U_{e3} small Δm_{12}^2) Two comparable terms → CPV
- Δm_{12}^2 term gives relatively larger contribution at longer distance

$\nu_\mu \rightarrow \nu_e$ with matter effect

Approximate formula (M. Freund)

quadratic dep. on θ_{13}

matter effect ~E

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta)$$

~7500 km magic bln

CPV term approximate dependence ~L/E

$$+\alpha\frac{8J_{CP}}{\hat{A}(1-\hat{A})}\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

~2540 km magic bln

$$+\alpha\frac{8I_{CP}}{\hat{A}(1-\hat{A})}\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

$$+\alpha^2\frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\Delta)$$

solar term

linear dep. on θ_{13}

$$J_{CP} = 1/8\sin\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

$$I_{CP} = 1/8\cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

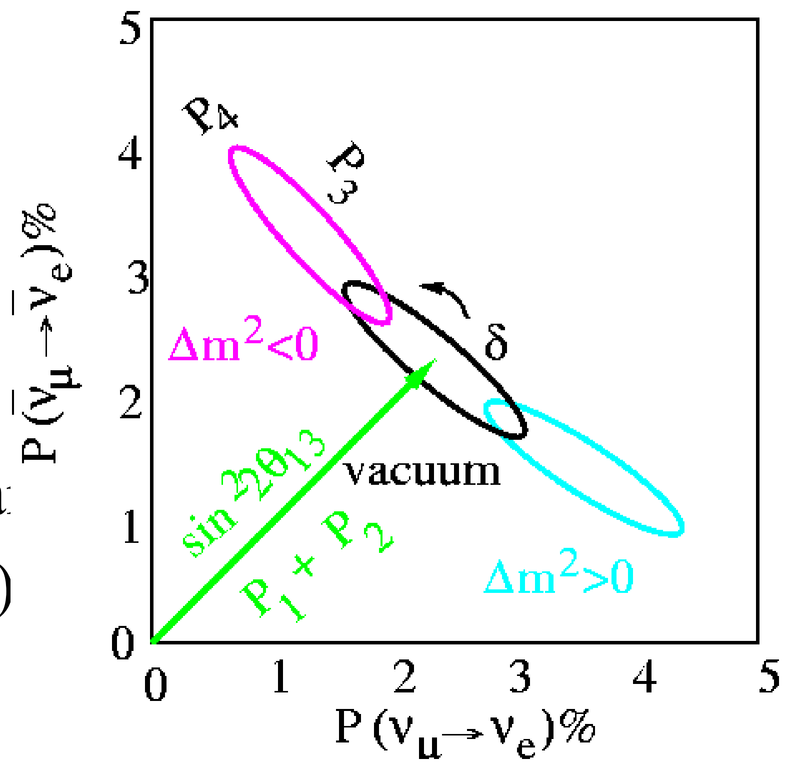
$\alpha = \Delta m^2_{21}/\Delta m^2_{31}$, $\Delta = \Delta m^2_{31}L/4E$

$\hat{A} = 2VE/\Delta m^2_{31} \approx (E_\nu/GeV)/11$ For Earth's crust.

CP asymmetry grows as θ_{13} becomes smaller !

CP violating effects in neutrino oscillation in 3 generation scheme

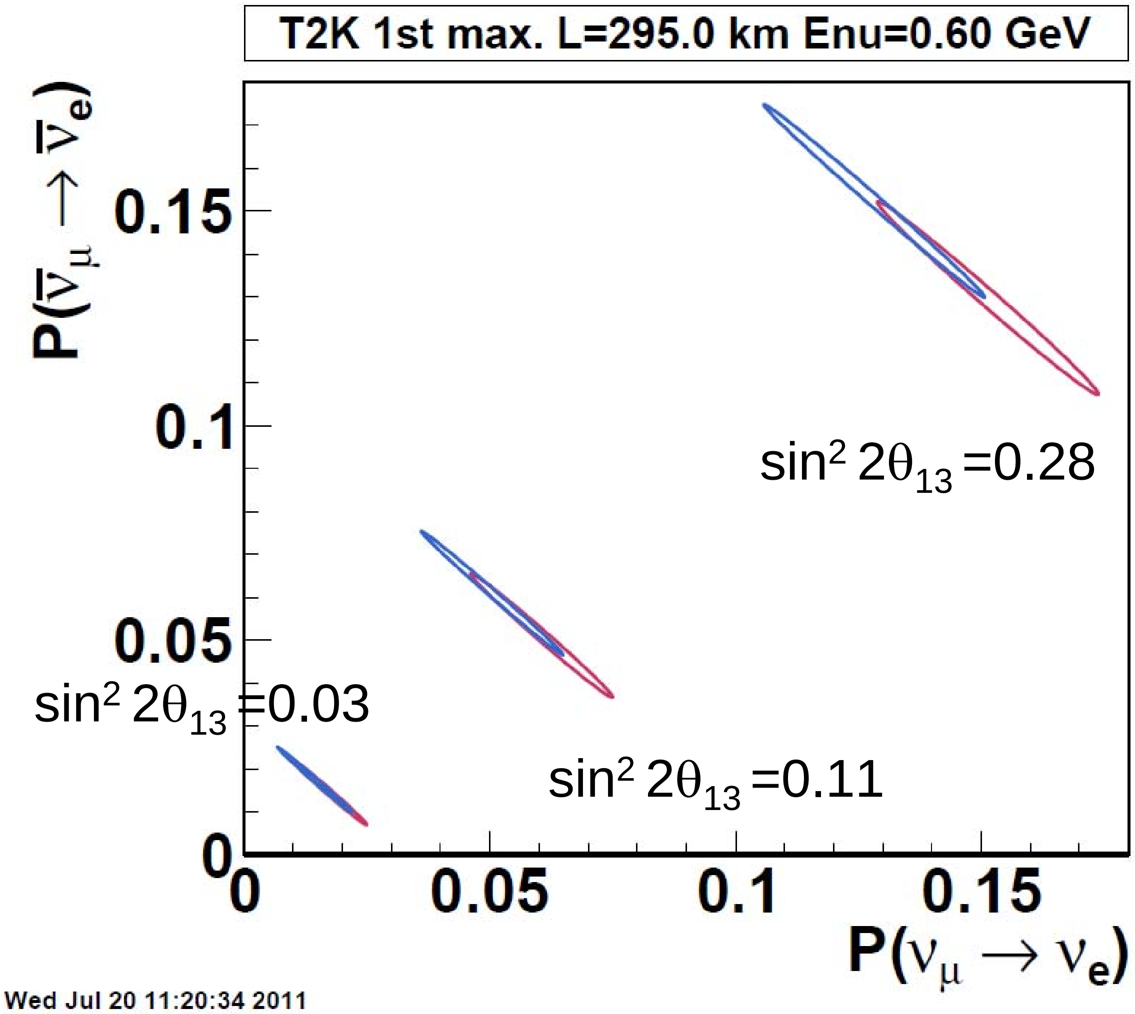
- 3 mixing angle, 2 Δm^2 , matter density and distance, E_ν fix the contribution to the neutrino and anti-neutrino oscillation probabilities. must be separated from CPV term.
- If KM type CPV is the source, measurements in neutrinos and anti-neutrinos should sit on either pink or blue ellipse in the right figure
- With mass hierarchy ambiguity, may need measurements at more tha one condition (energies or distances)



An implication of larger θ_{13}
matter effect become not negligible

$\sin^2 2\theta_{12} = 0.8704$
$\sin2\ 2\theta_{23} = 1.0$
$\Delta m^2_{12} = 7.6\text{x}10^{-5}\ \text{eV}^2$
$\Delta m^2_{23} = 2.4\text{x}10^{-3}\ \text{eV}^2$
$A = 7.56\text{x}10^{-5}\ \rho(\text{g/cm3})\ E(\text{GeV})$
density $\rho = 2.8$ g/cm3

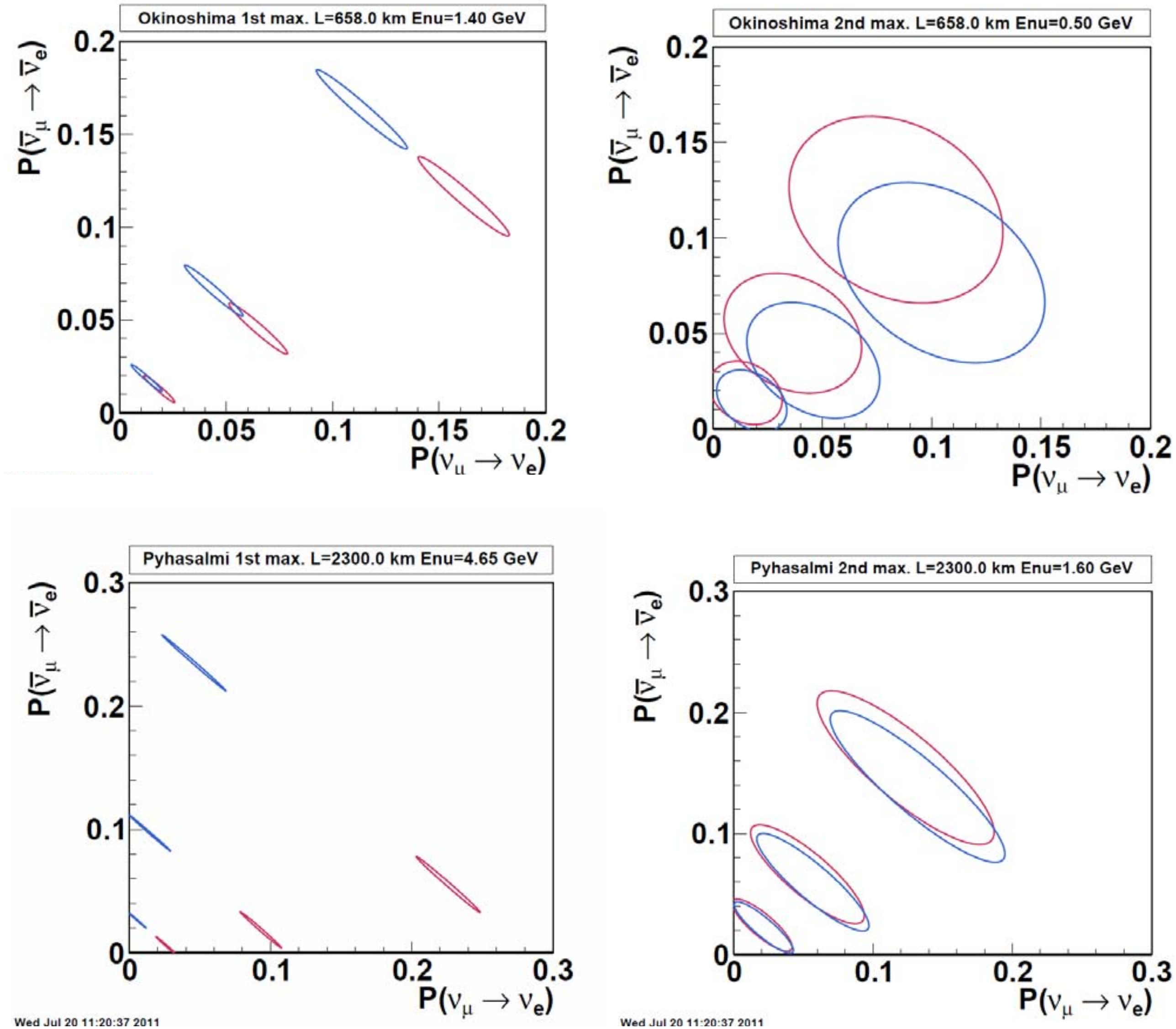
CPV maynot be able to be distinguished from matter effect
or need the knowledge of mass hierarchy



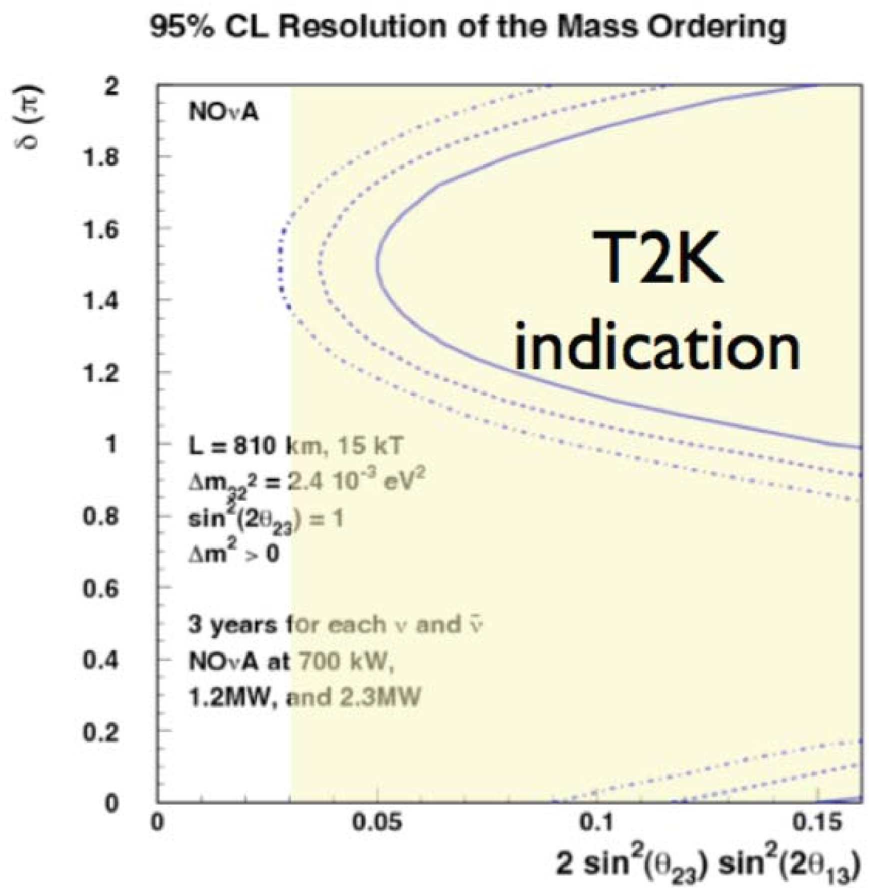
At longer distance

658km

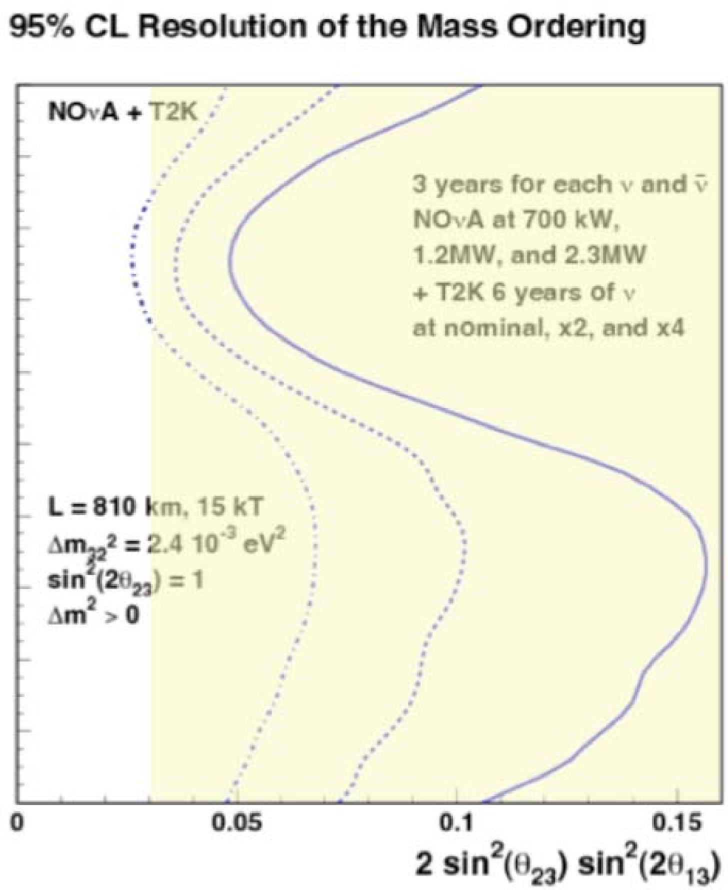
2300km



Or determine mass hierarchy by measurements at different distances



Compare NOvA's neutrinos to NOvA's anti-neutrinos



Compare NOvA's neutrinos w/ matter effect to T2K's neutrinos ~w/o matter effect

Courtesy Nova collaboration

Andre Rubbia

EU, Japan, US world tour

	Proton driver	Baseline L	Detector / Fiducial mass	Method
LAGUNA Fréjus	CERN SPL 4MW	130 km	WC 440kt (MEMPHYS) (*)	$\nu/\bar{\nu}$ asymmetry
J-PARC-Kamioka	J-PARC MR (1.66MW)	295 km	WC 600kt (HyperK)	$\nu/\bar{\nu}$ asymmetry
J-PARC-Okinoshima	J-PARC MR (1.66MW)	658 km	LAr 100 kt	WBB
LBNE	FNAL MI 750kW (2.3MW ProjectX)	1300 km	WC 200kt or LAr 34kt	WBB
LAGUNA Slanic (**)	CERN SPS 700kW (1.6MW HP-PS)	1570 km	LAr 100 kt	WBB
LAGUNA Pyhäsalmi	CERN SPS 700kW (1.6MW HP-PS)	2300 km	LAr 100 kt (*)	WBB

(*) physics reach of LENA option under investigation in LAGUNA - not considered here
(**) site provides only shallow depth - lower priority

Andre Rubbia

All based on the powerful accelerator

Critical path toward high power operation-(J-PARC case)

Space charge

Beam power is limited by beam loss, rep. rate

- 150kW at 30GeV at 0.3Hz correspond to ~10^{14} protons/5μsec pulse

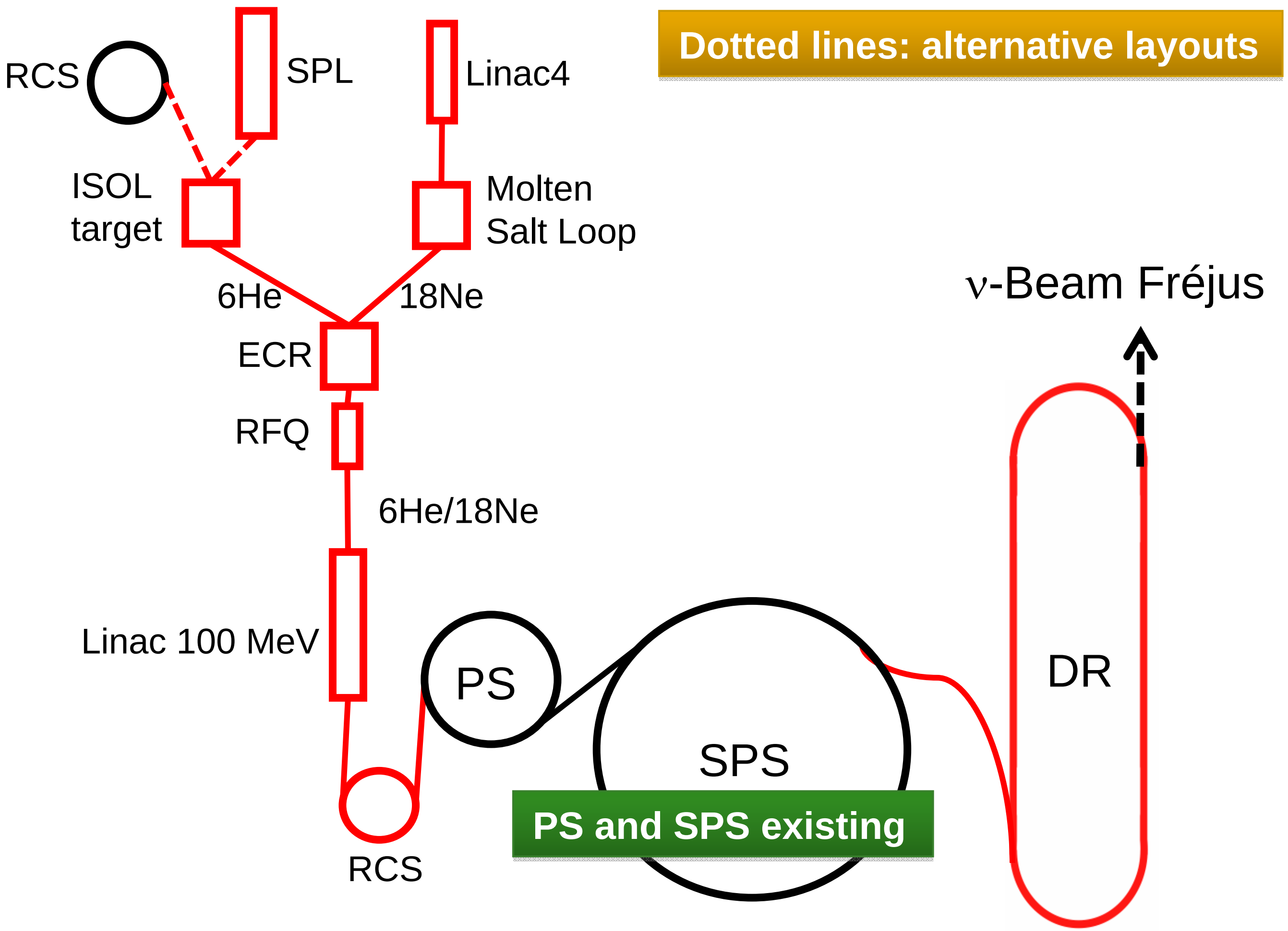
  ~ 10^{13} protons/500nsec bunch
- At what intensity, does the space charge effect become non-linear
  - MR Beam break-up instabilities observed in MR at 1.5e13 ppb (design is 4 e13 ppb). Behavior similar to other high intensity accelerators driven by broadband impedance and/or electron cloud. (J-PARC ATAC report)
  - RF with 2nd harmonic installed ….

Long term project

- Work on more systematic studies on the nature of collective instabilities and impedance sources including possible electron cloud effects, rapid cycling, power supply, RF system …
- LINAC 400MeV upgrade
- Availability and operational experience

New kind of neutrino beam

CERN Beta Beams, Synoptic



$B\rho$ ~ 500 Tm, B = ~6 T, C = ~6900 m, L_{ss}= ~2500 m, γ = 100, all ions

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Status, technologies

- SF in Decay Ring (CERN, Cockroft)
  - RF hardware seems feasible
- 60 GHz Ion Source (LPSC, CNRS, Grenoble)
  - Tests of magnetic field for plasma containment ok
  - Tests of assembly with 28 GHz (emmittances and efficiencies)
  - 60 GHz gyrotron: awaiting reception 2012
- Collection of high-Q ions from production ring (UCL, Louvain)
  - Collection ok
  - Efficiencies now measured
- Measurements of x-sections 8B and 8Li (INFN, Legnaro)
  - Analysis of results available in September
- Decay Ring Redesigned (CEA)
  - Collective effects less important
- Collimation in Decay Ring (CERN)
  - Needs good solution

Optimization of the facility on-going

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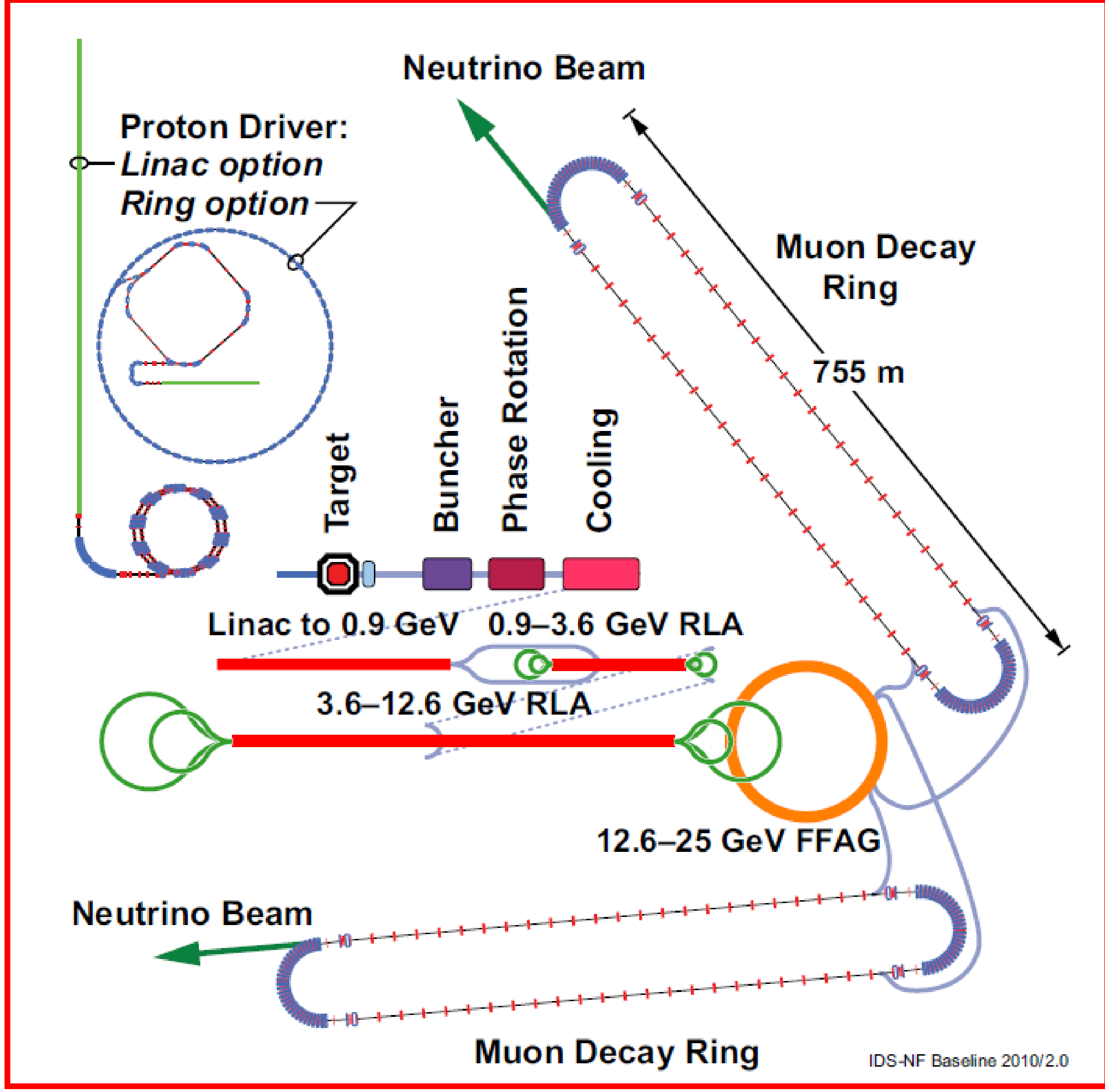
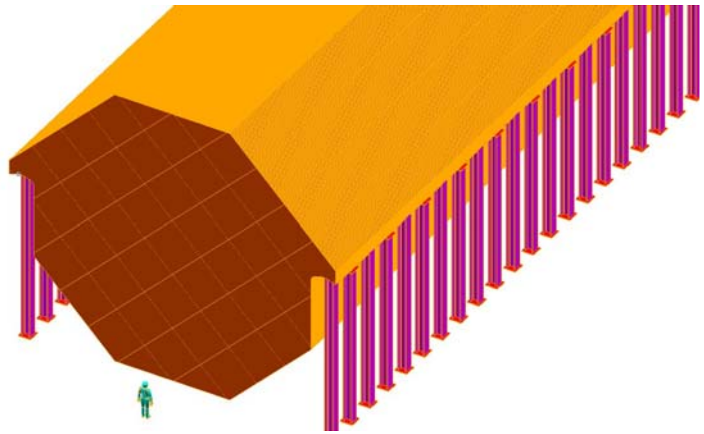
Neutrino Factory Baseline



- Two Magnetised Iron Neutrino Detectors (MIND):
  - 100 kton at 2500-5000 km
  - 50 kton at 7000-8000 km



Baseline constantly under review in light of new physics results

Summary for neutrino factory presentation

- International Design Study is progressing on course
  - Interim Design Report delivered March 2011
  - We had successful ECFA review May 2011 (final report due soon)
  - On target to produce Reference Design Report, including performance and costs by 2013
- Main concepts for accelerator systems have been defined
  - Main areas of work are at interfaces between components
- Two Magnetised Iron Neutrino Detectors (MIND) at standard Neutrino Factory (25 GeV) is small θ_{13} baseline:
  - 2500-5000 km with100 kton mass
  - 7000-8000 km (magic baseline) with 50 kton
- 10 GeV Neutrino Factory with one 100 kton MIND shows best performance for large θ_{13} ($\sin^2 \theta_{13} > 10^{-2}$)
- Conceptual design for near detector being established

Summary

- Precision measurements of oscillation mixing parameters
  - indication of $\theta_{13} \neq 0$
  - establish $\theta_{13} \neq 0$ and its value,
  - $\theta_{23} = 45^0$?, Δm^2_{23}
  - confirmation of $\nu_\mu - \nu_\tau$ oscillation
- Sterile neutrinos?
- Mass eigenvalues different for neutrino and anti-neutrino?
- Works on hadron production and cross section measurements

- Search for CP violating effects in neutrino oscillation and its source ?
  - KM type complex phase in 3x3 PMNS matrix
  - additional source ?
- >1MW proton accelerator
- High power neutrino beam, capable to deliver neutrino over ~1000km baseline to deal with matter effect
- Massive detector, capable neutrino energy reconstruction and lepton ID for wide range of E_ν

The J-PARC accelerator and T2K experiment will be back into operation in December this year.

I thank you for the messages of solidarity and sympathy.

Thank you for your attention