ν oscillations are the most important discovery in hep of the last 15 years.

They measure fundamental parameters of the standard model. Mixing angles, neutrino masses and the CP phase δ_{CP} are fundamental constants of the standard model.

They are a probe of the GUT scales . The smallness of neutrino masses is connected to the GUT scale through the see-saw mechanism.

They are directly linked to many fields in astrophysics and cosmology : baryogenesis, leptogenesis, galaxies formation, dynamic of supernovae explosion, power spectrum of energy anisotropies, etc.

They open the perspective of the measure of **leptonic CP violation.**

If you are skeptical about that ....

Experimental articles with more than 500 cites in the last 15 years in the QSPIRES database (at 04/04/03):

1	SK	Evidence for Oscillation of Atmospheric Neutrinos.	1705
2	SCP	Measurements of Ω and Λ from 42 High Redshift SN.	1311
3	SST	Observational Evidence from SuperNovae for an Accelerating Universe and a Cosmological Constant.	1293
4	COBE	Structure in the COBE DMR First Year Maps.	1036
5	CDF	Observation of TOP Quark Production in $\overline{p}-p$ Collisions.	930
6	D0	Observation of the Top Quark.	889
7	SK	Atmospheric ν_μ/ν_e Ratio in the MultiGeV Energy Range.	751
8	Chooz	Initial Results from CHOOZ.	683
9	Boomerang	A Flat Universe from High Resolution Maps of the CMB.	644
10	Chooz	Limits on Neutrino Oscillations from the CHOOZ Experiment.	635
11	Kamiokande	Observation of a Small Atmospheric ν_μ/ν_e Ratio.	628
12	CLEO	First Measurement of the Rate for the Inclusive b —> $s\gamma$.	618
13	SNO	Measurement of the rate of ν_e + d –> p + p + e- ...	592
14	Homestake	Measurement of the Solar ν_e Flux ...	565
15	LSND	Evidence for $\overline{\nu}_\mu$ —> $\overline{\nu}_e$ Oscillations from LSND.	563
16	SK	Measurement of a Small Atmospheric ν_μ/ν_e Ratio.	561
17	CDF	Evidence for TOP Quark Production in $\overline{p}-p$	550
18	SK	Study of the Atm. ν Flux in the MultiGeV Energy Range.	547
19	IMB	The ν_e and ν_μ Content of the Atmospheric Flux.	535
20	SK	Solar Neutrino Data Covering Solar Cycle 22.	504
21	LSND	Neutrino Oscillations from LSND.	500

Most of the parameters are waiting to be measured

δm^2_{12} ✓ SOLARS+KAMLAND $\delta m^2_{12} = (7 +/- 1)\ 10^{-5}\ eV^2$

θ_{12} ✓ SOLARS+KAMLAND $0.2 < \sin^2(\theta_{12}) < 0.5$

Addressed by a SuperBeam/Nufact experiment

δm^2_{23} ✓ ATMOSPHERICS $\delta m^2_{23} = (2.0 +/- 0.4)\ 10^{-3}\ eV^2$

θ_{23} ✓ ATMOSPHERICS $0.9 < \sin^2(\theta_{23}) < 1$

θ_{13} CHOOZ LIMIT $\theta_{13} < 14^0$

δ_{CP}

Mass hierarchy

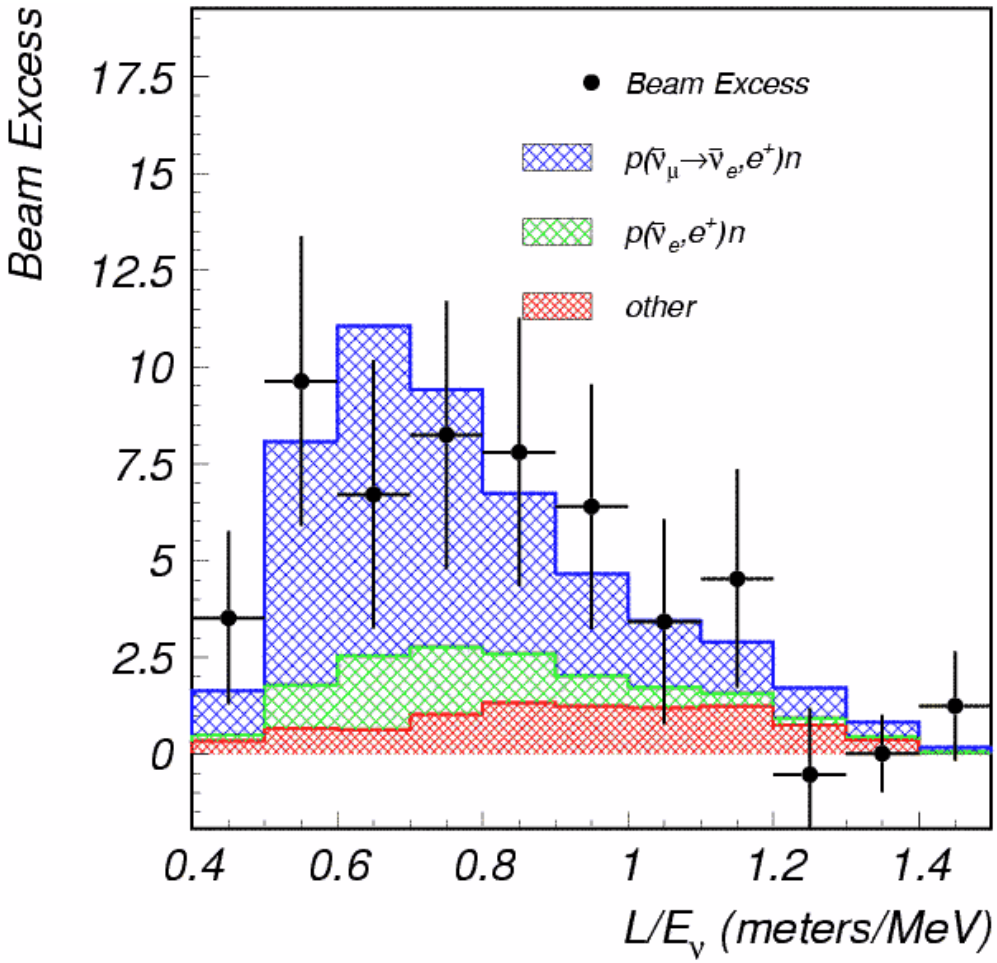
Σm_ν BETA DECAY END POINT $\Sigma m_\nu < 6.6$ eV

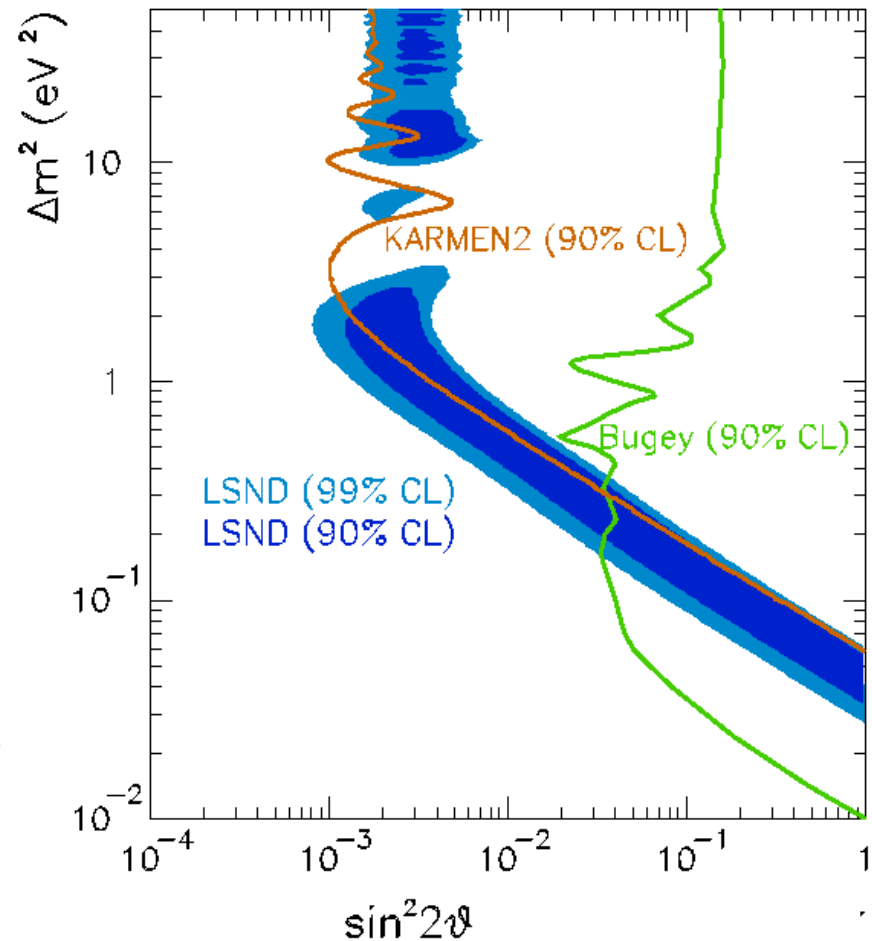
Dirac/Majorana

LSND:

Evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$\bar{\nu}_\mu$ beam from μ+ decay at rest
energy 20-53 MeV
baseline 30 m
L/E ~ 1 m/MeV





87.9±22.4±6.0 events

Δm^2~0.2-10 eV^2

(Bugey is $\bar{\nu}_e$ disappearance)

Too many Δm^2's?

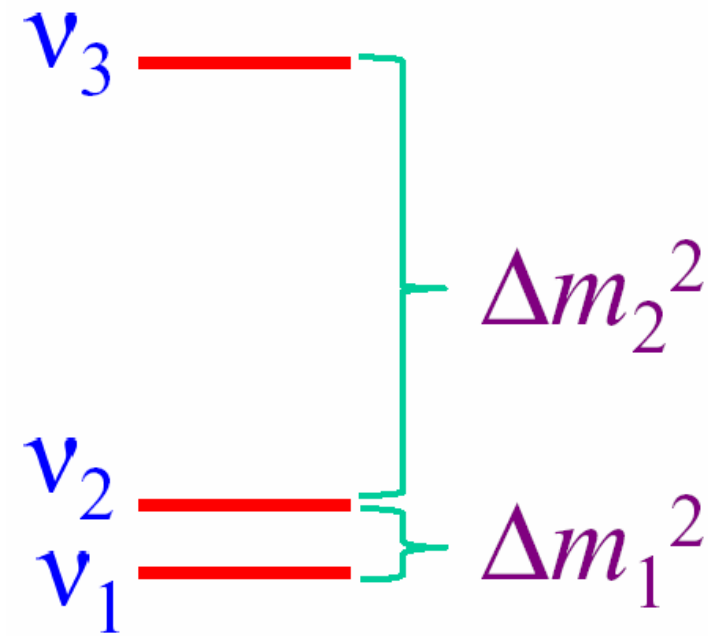
3 light neutrino flavors

Solar (+KamLAND) neutrinos:

- $\Delta m^2 \approx 7 \times 10^{-5} eV^2$
- mostly $\nu_e \rightarrow \nu_{\mu,\tau}$

Atmospheric (+K2K) neutrinos:

- $\Delta m^2 \approx 2 \times 10^{-3} eV^2$
- mostly $\nu_\mu \rightarrow \nu_\tau$



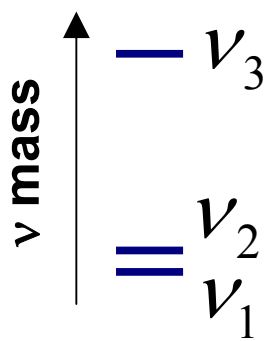
$$\Delta m_3^2 = \Delta m_1^2 + \Delta m_2^2$$

Where does LSND's Δm^2~0.2-10 eV^2 fit in this picture??

ν Oscillation Scenarios:

With current results from solar, atmospheric, and LSND ν–oscillation searches (3 Δm^2s), we have an interesting situation:

Only 3 active ν:

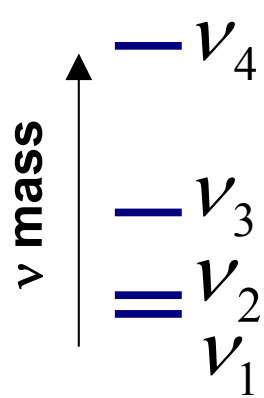


OR...

$$\text{solar}: \nu_e \to \nu_\mu$$
$$\text{atmos}: \nu_\mu \to \nu_e, \nu_\tau$$
$$\text{LSND}: \bar{\nu}_\mu \to \bar{\nu}_\tau \to \bar{\nu}_e$$

- not a good fit to data

3 active+1 sterile ν:

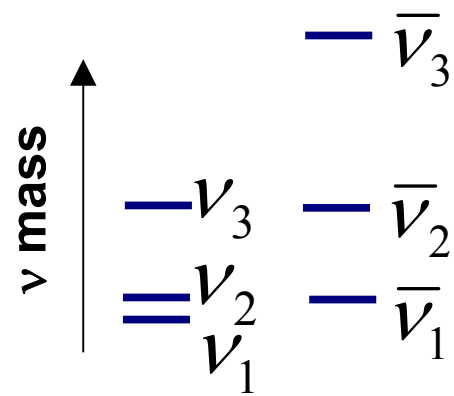


OR...

$$\text{solar}: \nu_e \to \nu_\mu, \nu_\tau$$
$$\text{atmos}: \nu_\mu \to \nu_\tau$$
$$\text{LSND}: \bar{\nu}_\mu \to \bar{\nu}_s \to \bar{\nu}_e$$

- possible(?)

CPT violation:



OR...

$$\text{solar}: \nu_e \to \nu_\mu$$
$$\text{atmos}: \nu_\mu \to \nu_\tau$$
$$\text{LSND}: \bar{\nu}_\mu \to \bar{\nu}_e$$

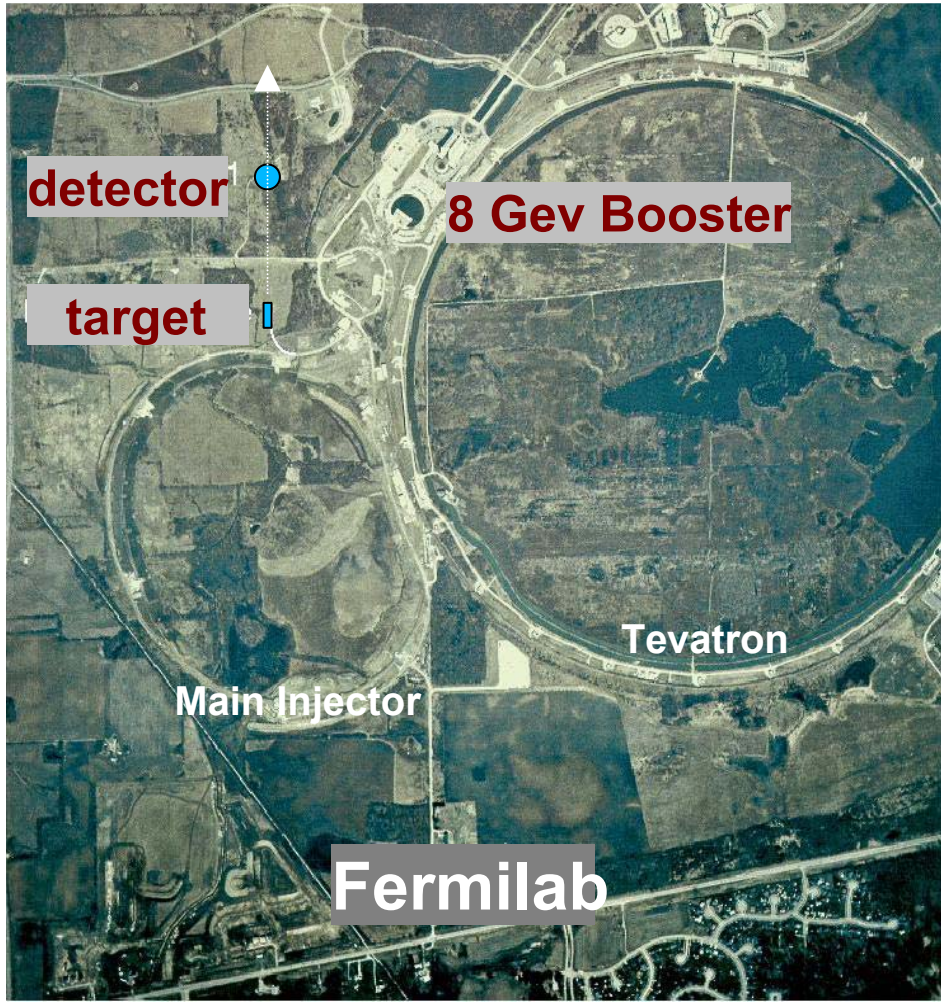
- possible(?)

Need to definitively check the LSND result.

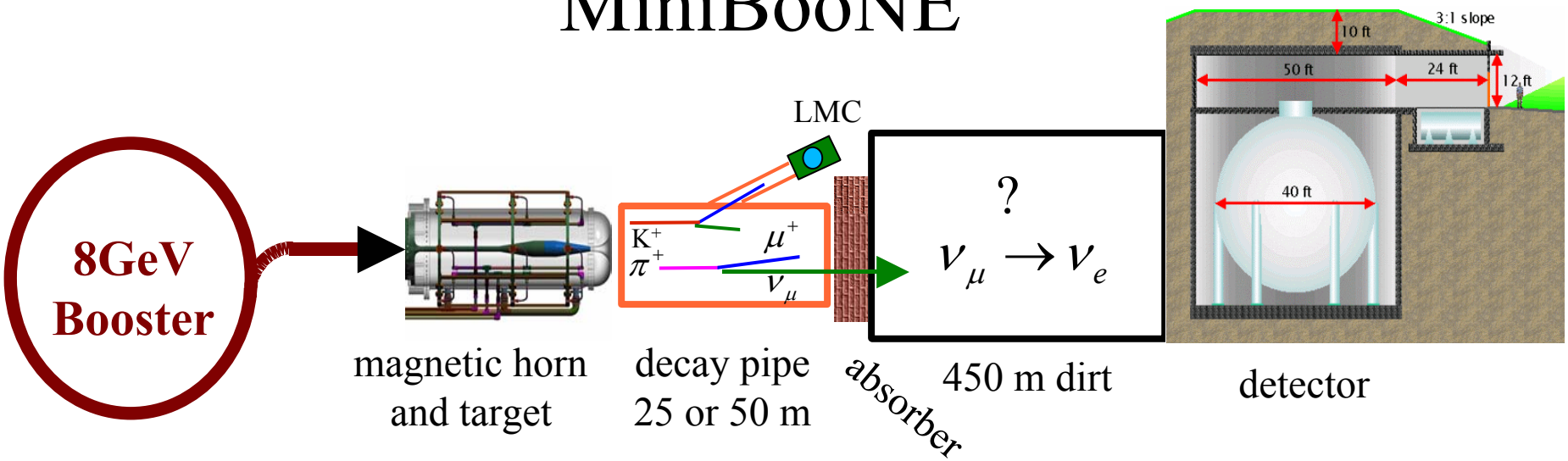
Goal: test LSND with 5-σ sensitivity over whole allowed range

- higher statistics
- different signature
- different backgrounds
- different systematics

MiniBooNE!



MiniBooNE



8-GeV protons on Be target →

π^+, K^+,…, focused by horn

decay in 50-m pipe, mostly to ν_μ

all but ν absorbed in steel and dirt

ν's interact in 40-ft tank of mineral oil

charged particles produce light

detected by phototube array

Look for electrons produced by mostly-ν_μ beam

The Booster

8 GeV proton accelerator supplies beam to all Fermilab experiments

It must now run at record intensity

MiniBooNE runs simultaneously with the collider program; goals:

Booster → MiniBooNE

5×10^{20} p.o.t per year (1×10^{21} total)

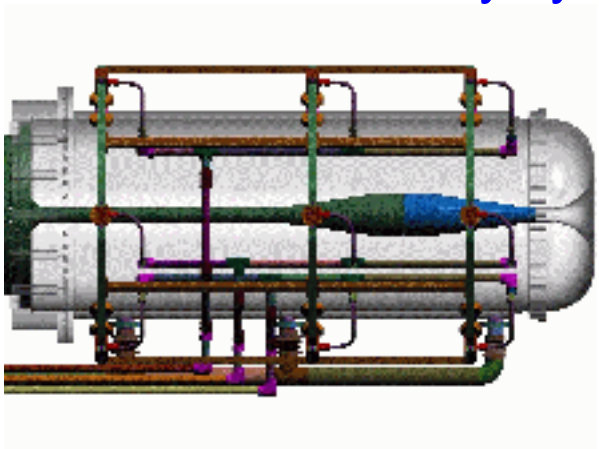
MiniBooNE: negligible impact on collider; improvements to Booster good for NuMI

Booster → Main Injector → antiproton source, TeVatron, NuMI, 120 GeV fixed target

Target and magnetic horn

Increases neutrino intensity by 7x

protons →



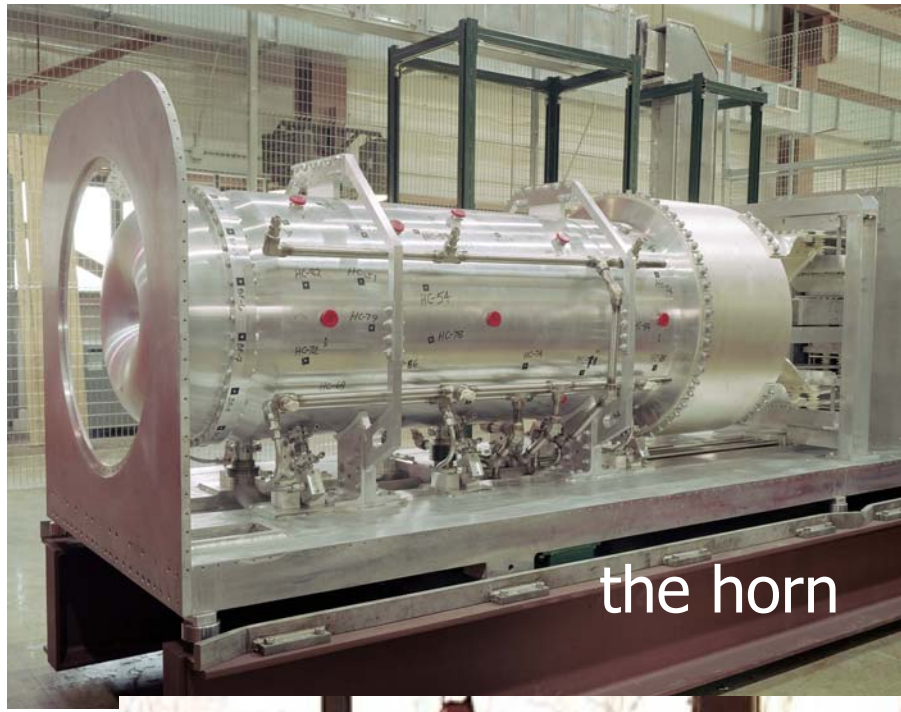
170 kA in 140 μsec pulses @ 5 Hz

Currently positive particles are being focused, selecting neutrinos $\pi^+ \rightarrow \mu^+ \nu_\mu$

the horn current can be reversed to select antineutrinos $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$

Prior to run, tested to
11M pulses
has performed flawlessly:
40M pulses in situ

World's longest-lived horn



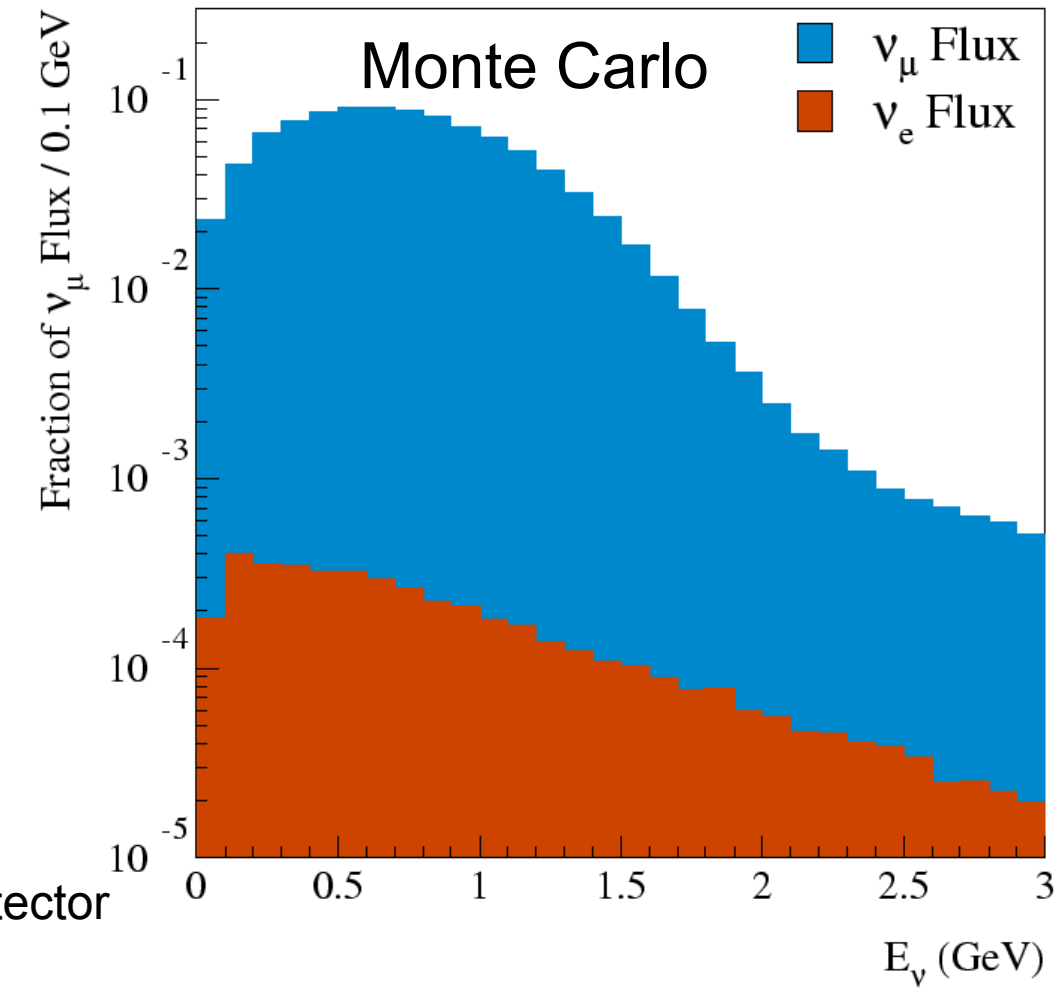
Intrinsic ν_e in the beam

$\pi^+ \rightarrow \mu^+ \nu_\mu$

$\quad\quad\quad\quad \hookrightarrow e^+ \nu_e \bar{\nu}_\mu$

$K^+ \rightarrow \pi^0 e^+ \nu_e$

$K_L \rightarrow \pi^- e^+ \nu_e$



important bkgd to osc search

Tackle this background with
- half-million ν_μ interactions in detector
- HARP experiment (CERN)
- E910 (Brookhaven)
- "Little Muon Counter"
- 25 m / 50 m decay length option

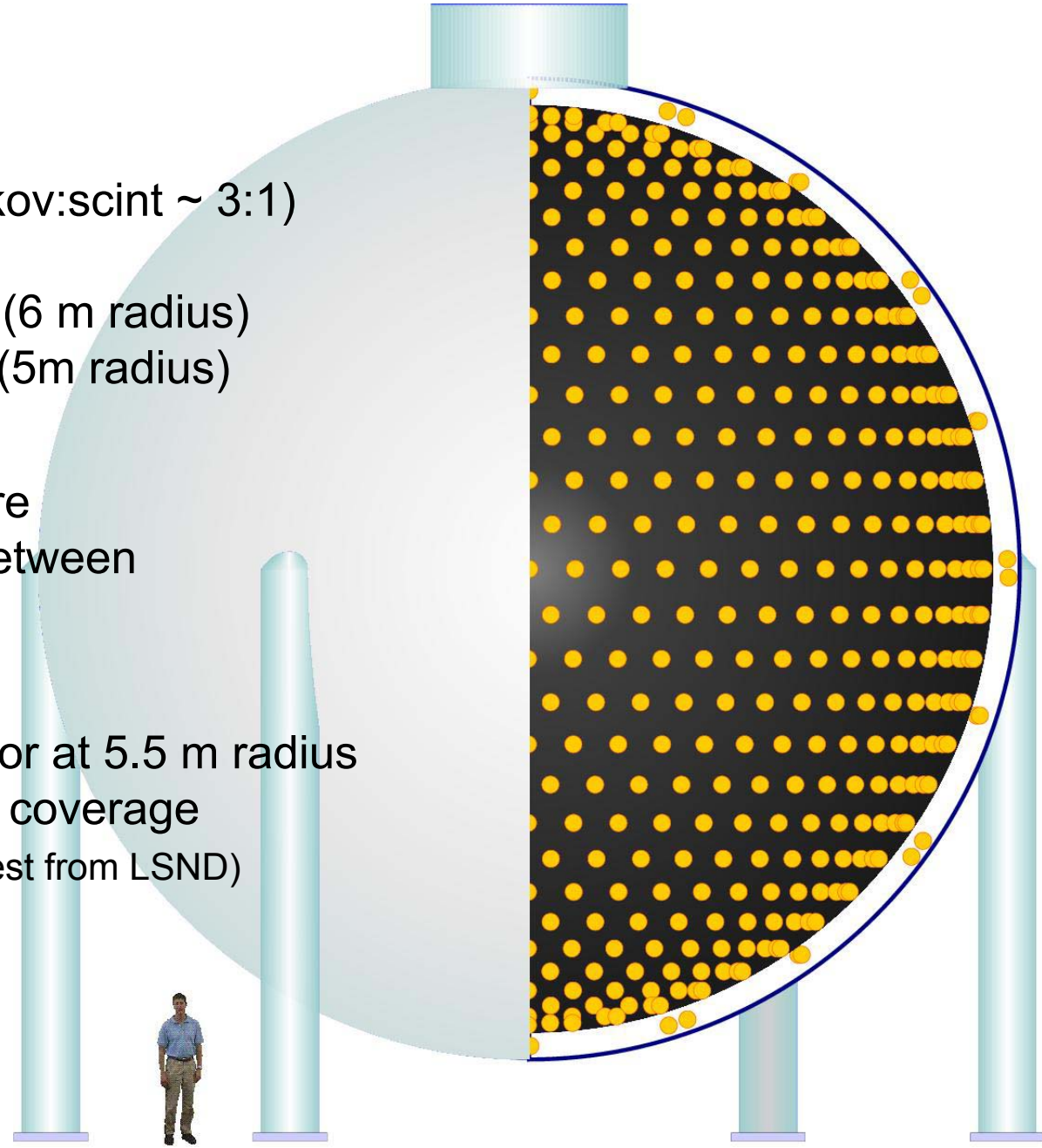
MiniBooNE detector

pure mineral oil (Cherenkov:scint ~ 3:1)

total volume: 800 tons (6 m radius)
fiducial volume: 445 tons (5m radius)

Phototube support structure
provides opaque barrier between
veto and main volumes

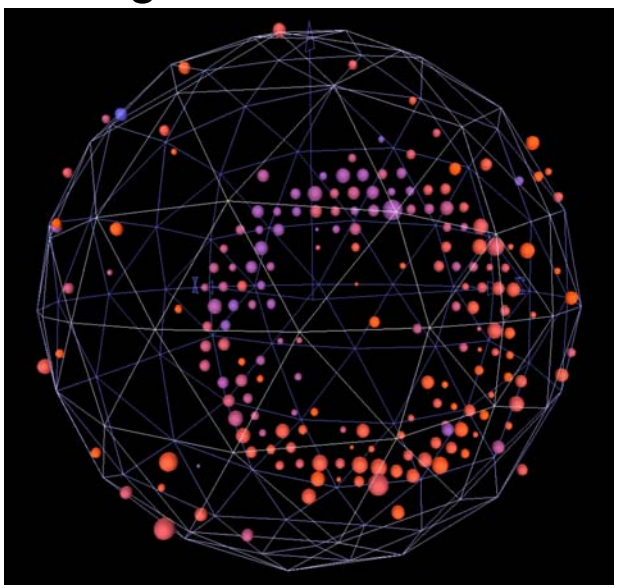
1280 20-cm PMTs in detector at 5.5 m radius
→ 10% photocathode coverage
(330 new tubes, the rest from LSND)
240 PMTs in veto



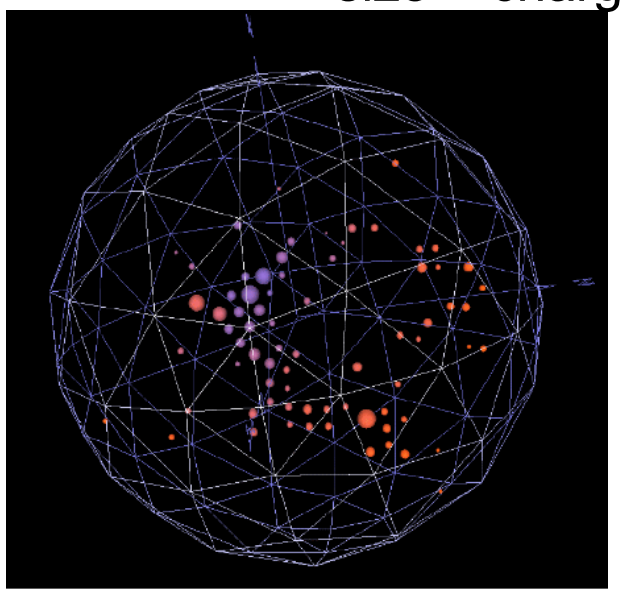
Pattern of hit tubes (with charge and time information)
allows reconstruction of track location and direction
and separation of different event types.

e.g. candidate events:

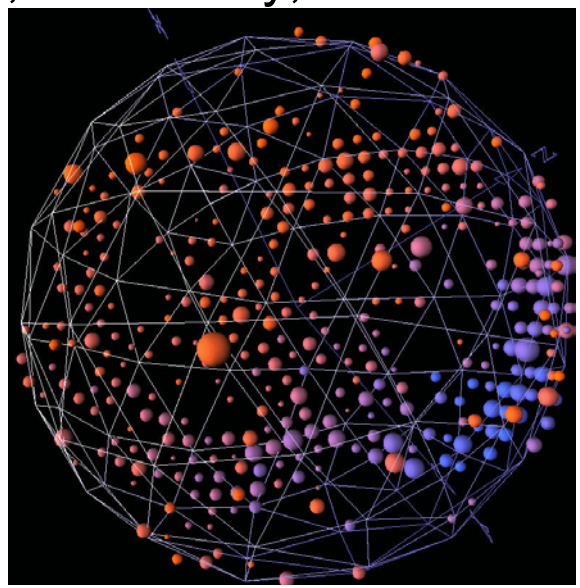
size = charge; red = early, blue = late



muon
from ν_μ interaction



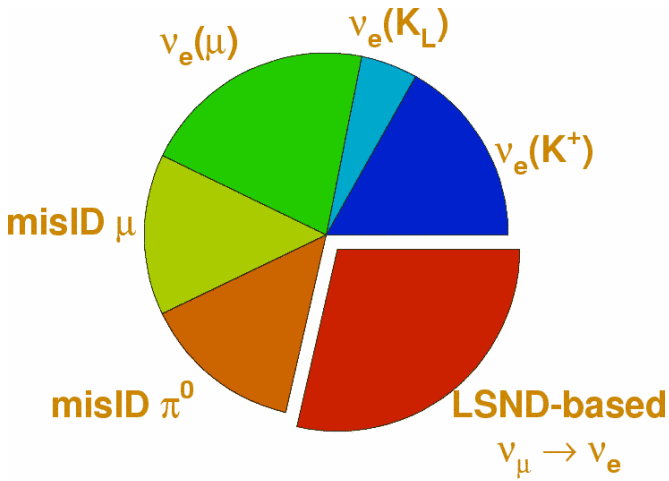
Michel electron
from stopped μ decay
after ν_μ interaction



$\pi^0 \rightarrow$ two photons
from ν_μ interaction

ν_e appearance sensitivity

preliminary estimates, backgrounds and signal

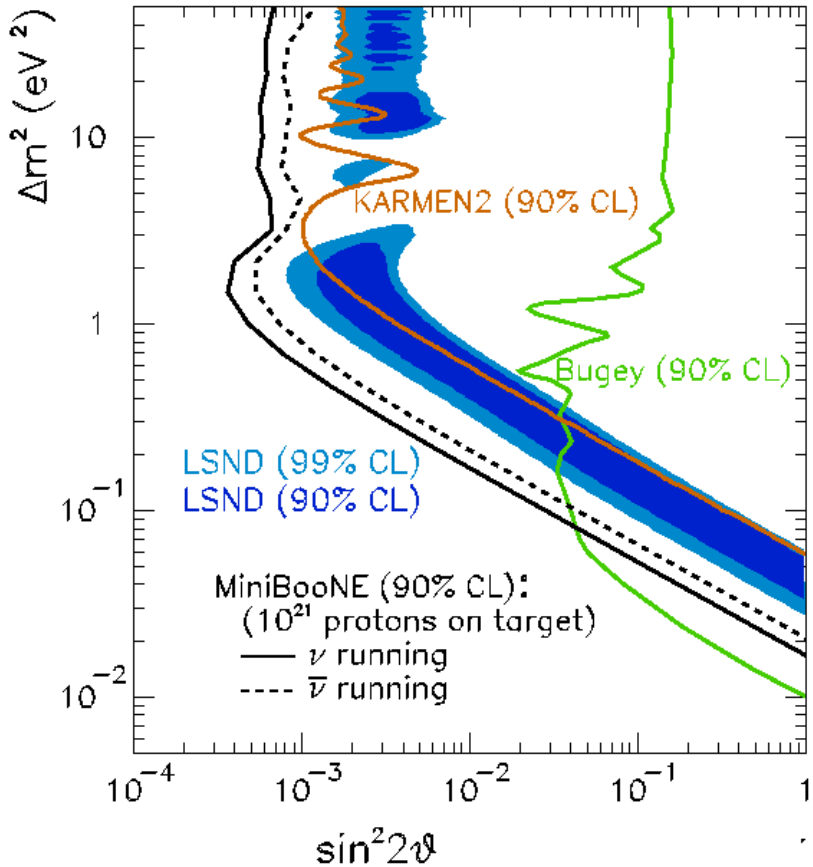


1500 intrinsic ν_e

500 μ mis-ID

500 π^0 mis-ID

1000 LSND-based $\nu_\mu \rightarrow \nu_e$



cover LSND allowed region at 5 σ

updated estimates coming

currently expect results in 2005

I Leptoni nel modello standard hanno caratteristiche MOLTO diverse dai quark

$u \sim 5$ MeV	$c \sim 1$ GeV	$t \sim 175$GeV
$d \sim 8$ MeV	$s \sim 0.1$ GeV	$b \sim 5$GeV

$e \sim 0.5$ MeV	$\mu \sim 0.1$ GeV	$\tau \sim 2$GeV
$\nu_e \leq \mathcal{O}(1\,eV)$	$\nu_\mu \leq \mathcal{O}(1\,eV)$	$\nu_\tau \leq \mathcal{O}(1\,eV)$

Com'e' possibile nello stesso modello generare rapporti di massa cosi' diversi? $\Rightarrow$ **See-saw mechanism**

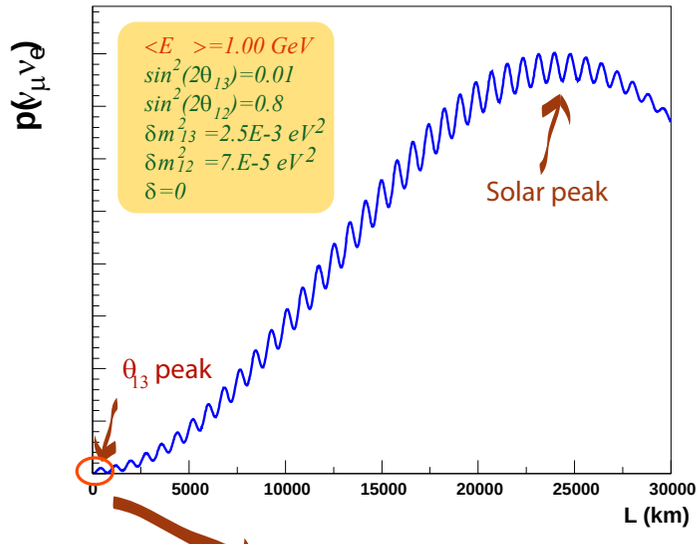
Solar+Atmospherics indicano una matrice di mixing quasi bi-maximal, **MOLTO DIFFERENTE dalla matrice CKM (quasi diagonale)!**

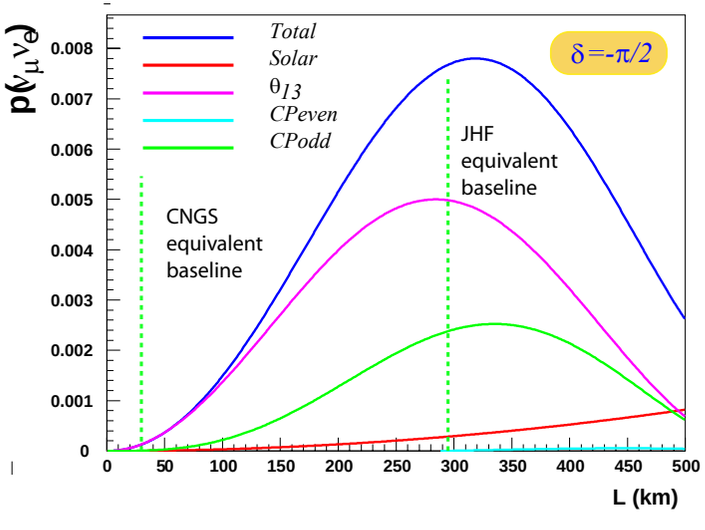
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

$\theta_{13} \to 0 \quad \Rightarrow$ La matrice 3x3 rimane un semplice prodotto di due matrici 2x2.

θ_{13} drives $\nu_\mu \to \nu_e$ subleading transitions $\Rightarrow$
the necessary milestone for any subsequent search:
neutrino mass hierarchy and leptonic CP searches.

Sub leading $\nu_\mu - \nu_e$ oscillations





$p(\nu_\mu \to \nu_e)$ developed at the first order of matter effects

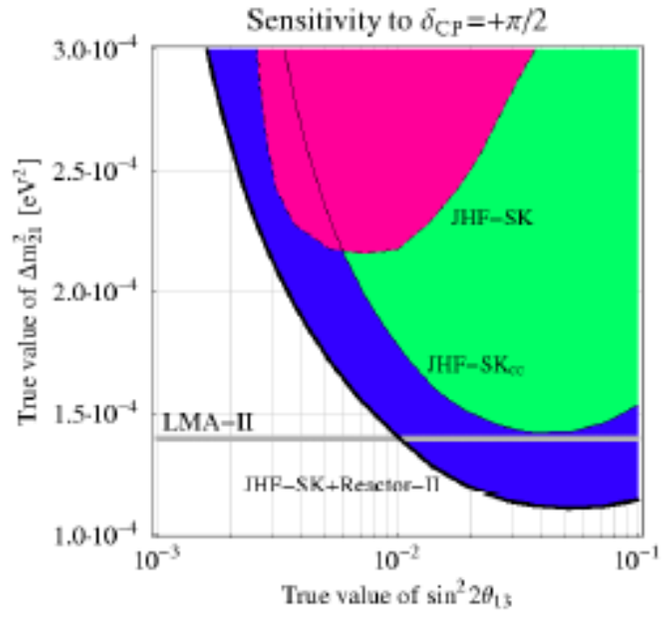
$$
\begin{aligned}
p(\nu_\mu \to \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} && \theta_{13} \text{ driven} \\
& + 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} cos\delta - s_{12} s_{13} s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} && \text{CPeven} \\
& - 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} && \text{CPodd} \\
& + 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} cos\delta\} \sin \frac{\Delta m_{12}^2 L}{4E} && \text{solar driven} \\
& - 8c_{12}^2 s_{13}^2 s_{23}^2 \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E} (1 - 2s_{13}^2) && \text{matter effect (CP odd)}
\end{aligned}
$$

where $a = \pm 2\sqrt{2} G_F n_e E_\nu = 7.6 \cdot 10^{-5} \rho[g/cm^3] E_\nu [GeV] \quad [eV^2]$

Almeno 4 fasi di esperimenti Long Baseline

1) 2001-2010. K2K, Opera, Icarus, Minos. Ottimizzati per confermare il risultato sperimentale di SuperKamiokande/atmosferici, attraverso ν_μ disappearance o ν_τ appearance. Limitato progresso nella misura dei parametri. Non ottimizzati per ν_e appearance (θ_{13})

2) 2009-2015. T2K (approvato), Minos off-axis, Chooz II. Ottimizzati per la misura di θ_{13} (Chooz $\times$ 20) attraverso ν_e appearance o ν_e disappearance. Misura di precisione dei parametri atmosferici. Sensitivitá sulla fase di CP δ molto limitata, anche combinando assieme i loro eventuali risultati.



3) 2015 - 2025. SuperBeam e/o Beta Beam. Migliore sensitivitá su θ_{13} (Chooz $\times$ 200). A queste sensitivitá θ_{13} e δ sono cosi' fortemente accoppiate che ogni sensitivitá va definita nel piano (θ_{13} ,δ). Sensitivitá su δ e mass hyerarchy.

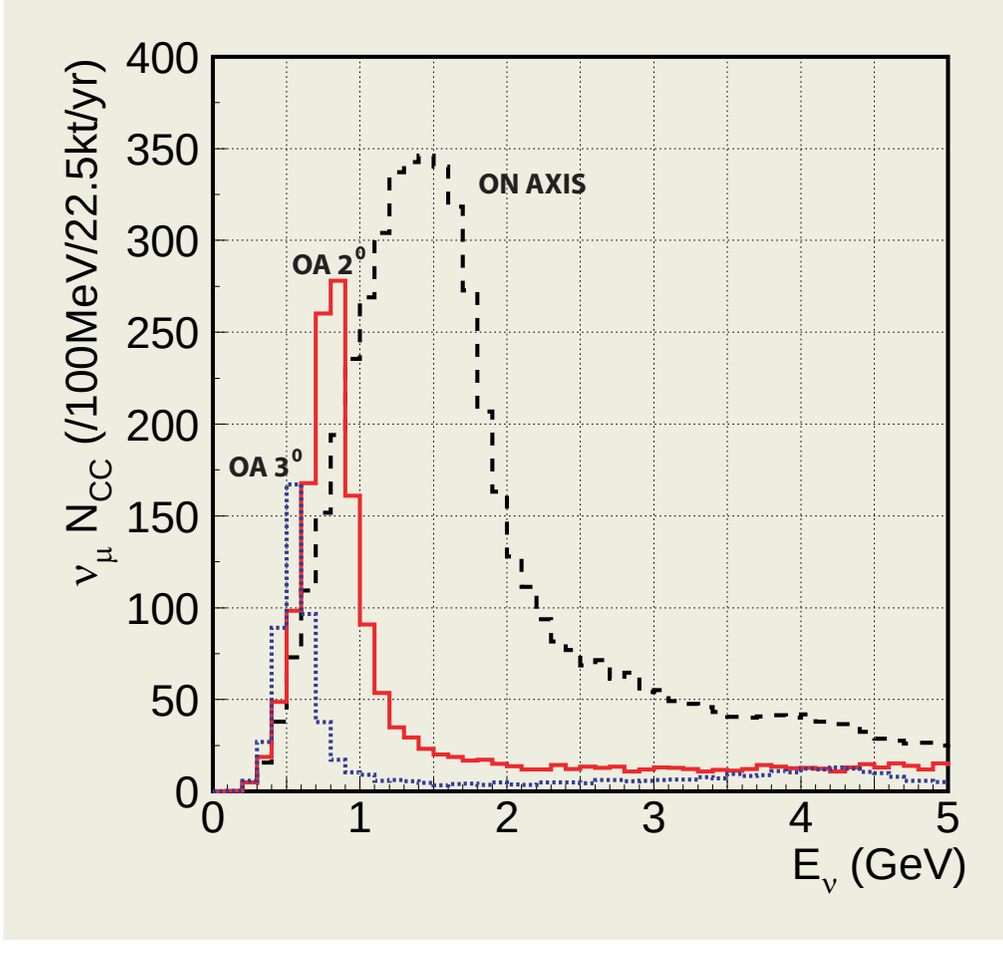
4) Pericolosamente vicino al mio orizzonte temporale. Neutrino Factories. Ultimate sensitivity sulla fase δ. Misura di precisione di tutti i parametri dell'oscillazione di neutrini.

JHF-Japan Hadron Facility at Jaeri

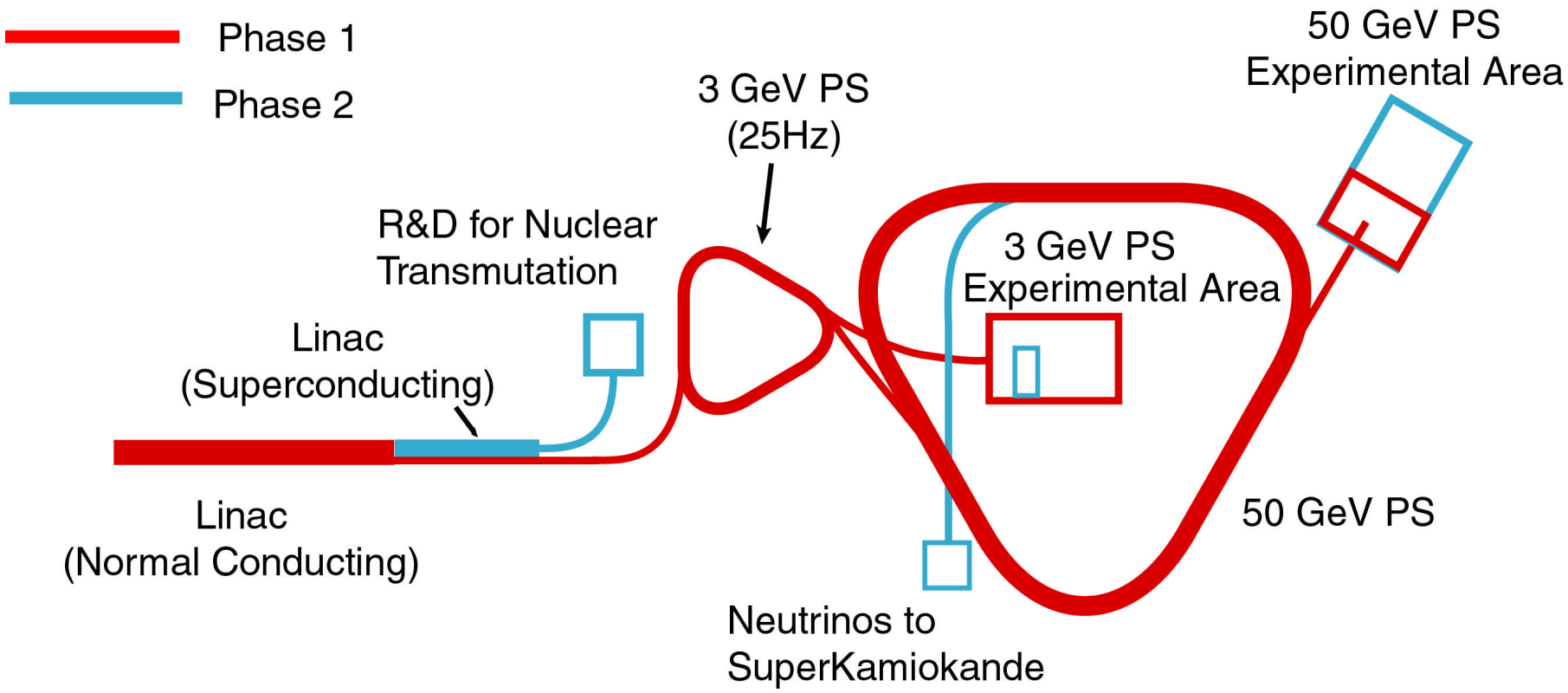
Neutrino beam from the 50 GeV - 0.75 MW proton beam at the Hadron Facility at Jaeri, Japan.

Taken off-axis to better match the oscillation maximum at the SuperKamiokande location (295 km).

K2K		T2K
$6 \cdot 10^{12}$	Protons per pulse	$3 \cdot 10^{14}$
2.2 s	Cycle	3.4 s
12 GeV	Proton energy	50 GeV
40	Events in SK per year (no osc.)	2200
1.5	Mean neutrino energy	0.8



Phase 1 and Phase 2



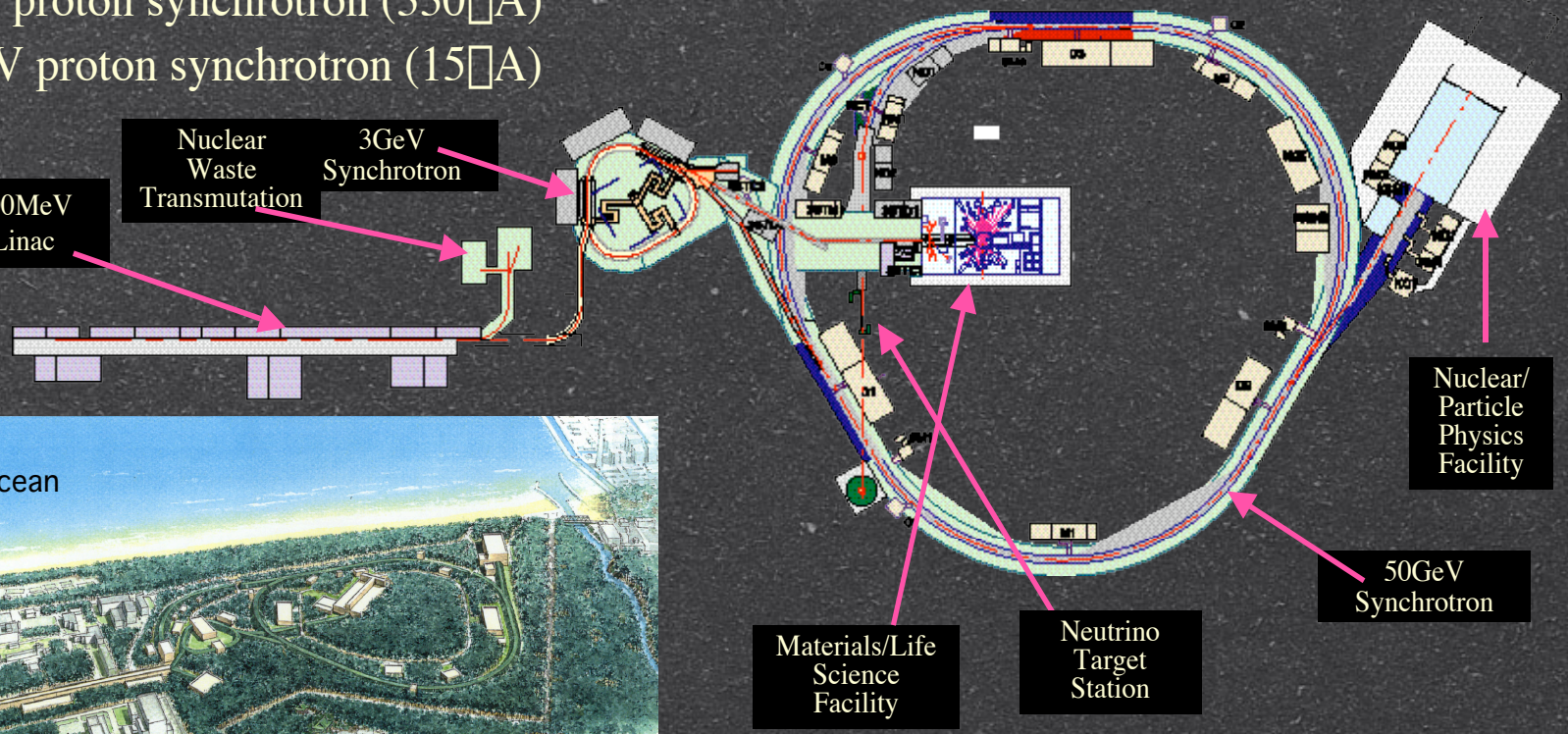
- Phase 1 + Phase 2 = 189 billion Yen (= $1.89 billion if $1 = 100 Yen).
- Phase 1 = 133.5 billion Yen for 6 years (= 2/3 of 189 billion Yen).
- Construction budget does not include salaries.

Proton Driver

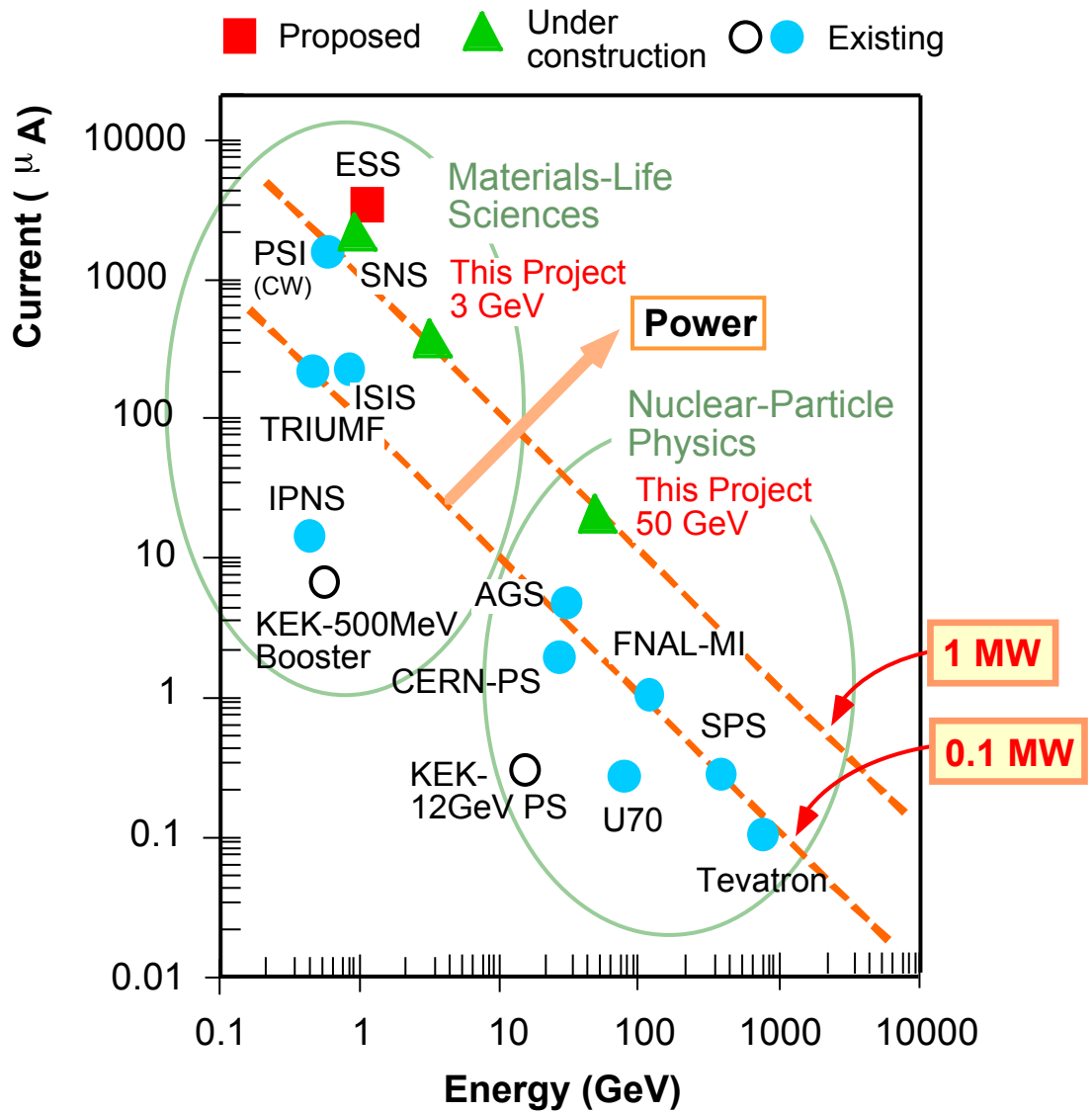
J-PARC = Japan Proton Accelerator Research Complex

400 (200) MeV proton linac
3 GeV proton synchrotron (330□A)
50 GeV proton synchrotron (15□A)
(40)

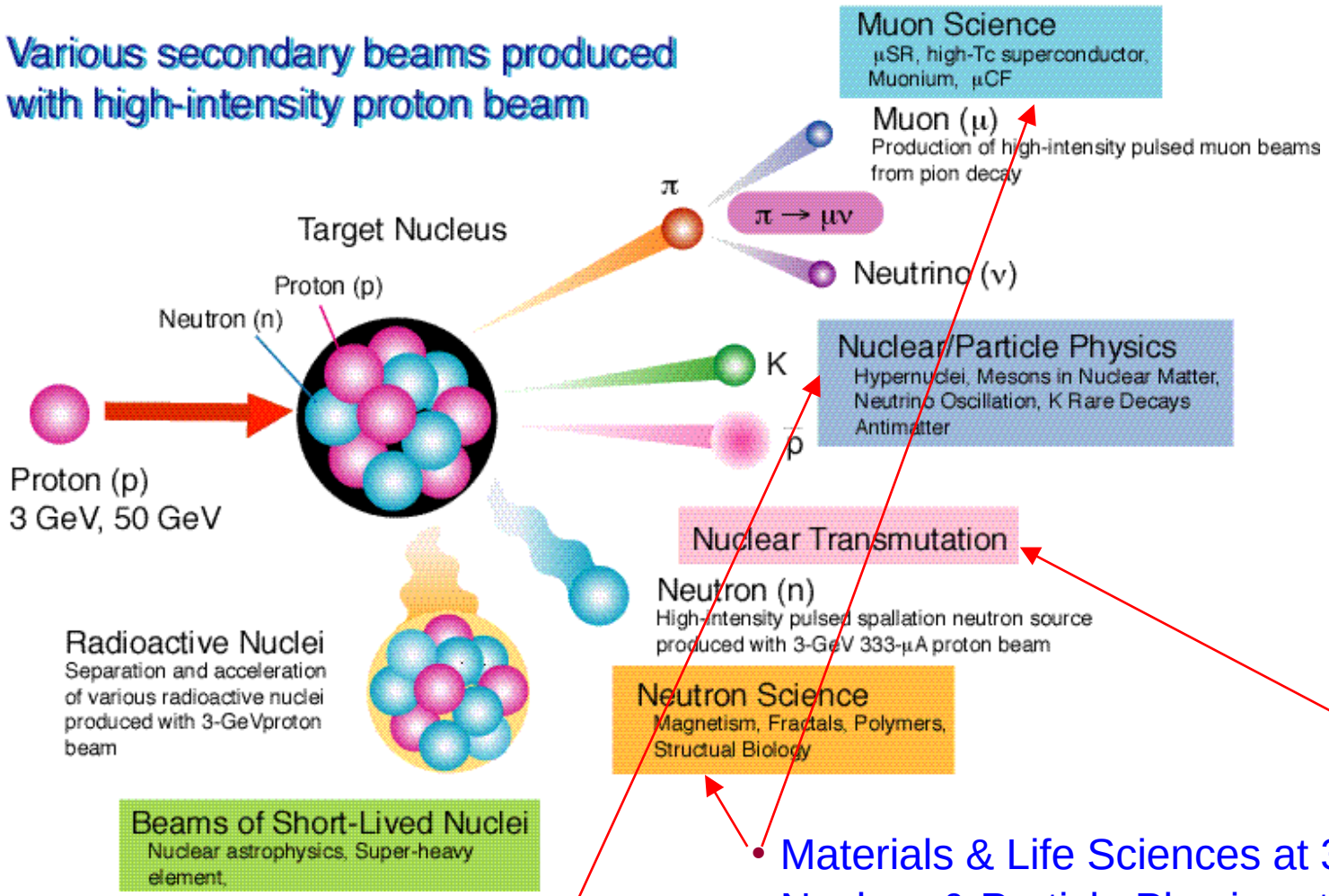
At Tokai



World's Proton Accelerators



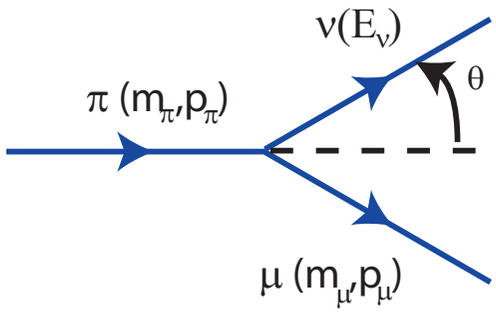
Why Do We Need High Intensity Protons?



- Materials & Life Sciences at 3 GeV
- Nuclear & Particle Physics at 50 GeV
- R&D toward Transmutation at 0.6 GeV

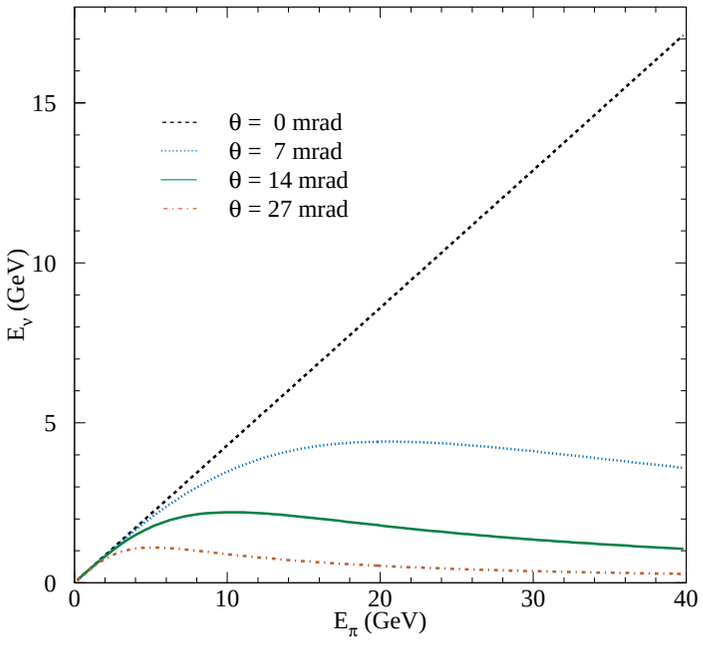
Off Axis Neutrino Beams. BNL-E889 proposal: http://minos.phy.bnl.gov/nwg/papers/E889

Decay Kinematics

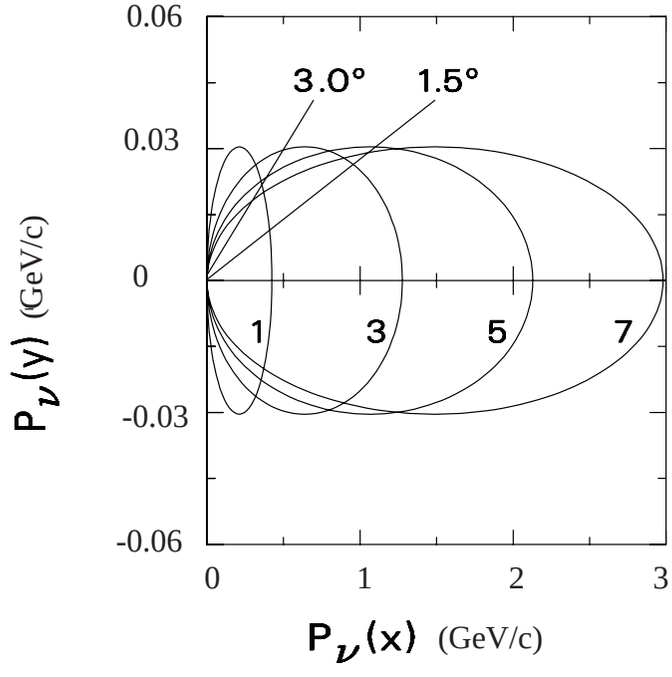


From momentum energy conservation:

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi cos\theta)}$$



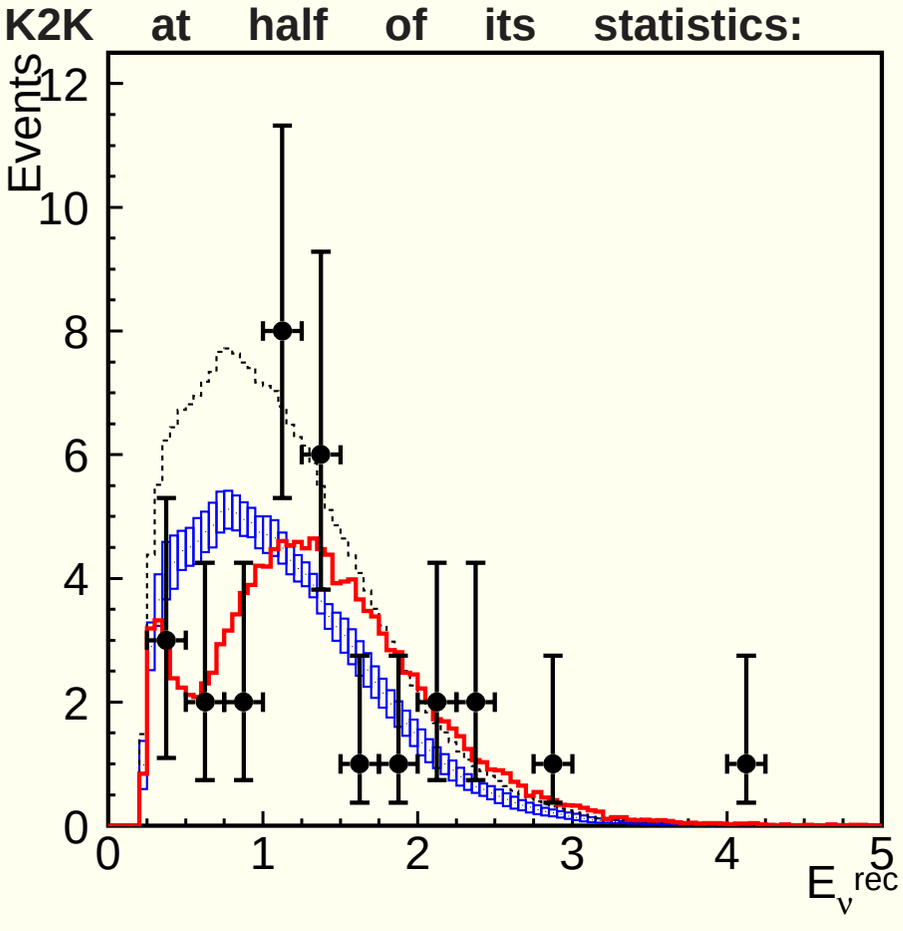
A qualitative argument:



- Transverse momentum, Lorentz invariant: $m_\pi - m_\mu$.
- Longitudinal momentum is Lorentz boosted.
- At an angle θ there is an accumulation of lower energies neutrinos

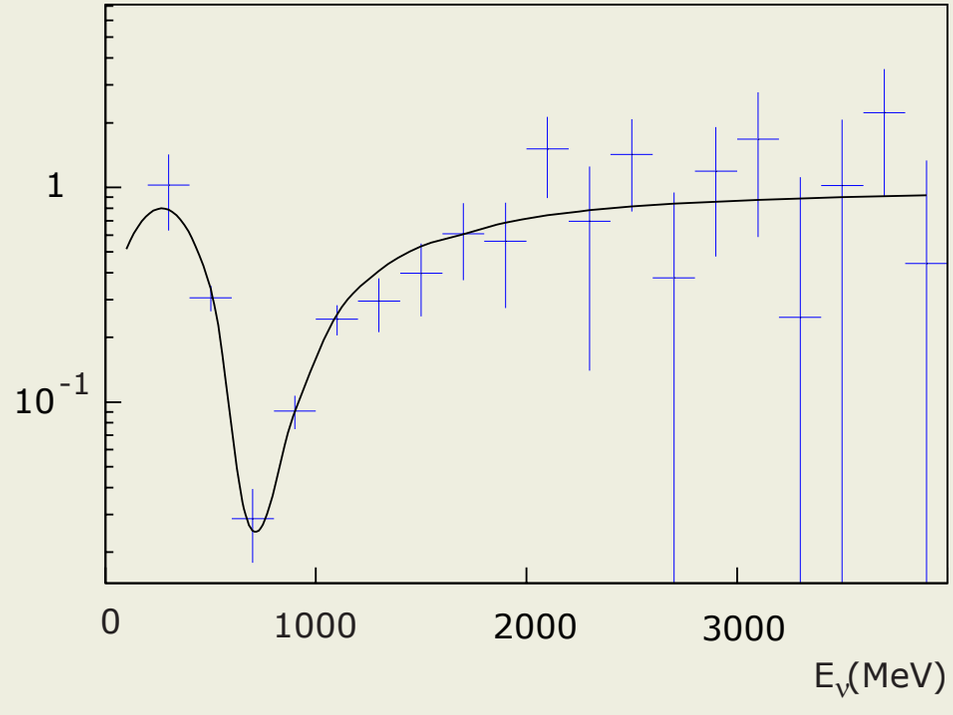
- **Maximum neutrino flux at $0°$.**
- **Off axis is the most efficient way to have a narrow band beam.**
- **ν_e come from 3 body decays (kaons or muons) while off-axis is optimized on the pion 2 body decay$\Rightarrow$ the ν_e contamination below the peak is reduced.**

T2K: ν_μ disappearance



JHF in 5 years

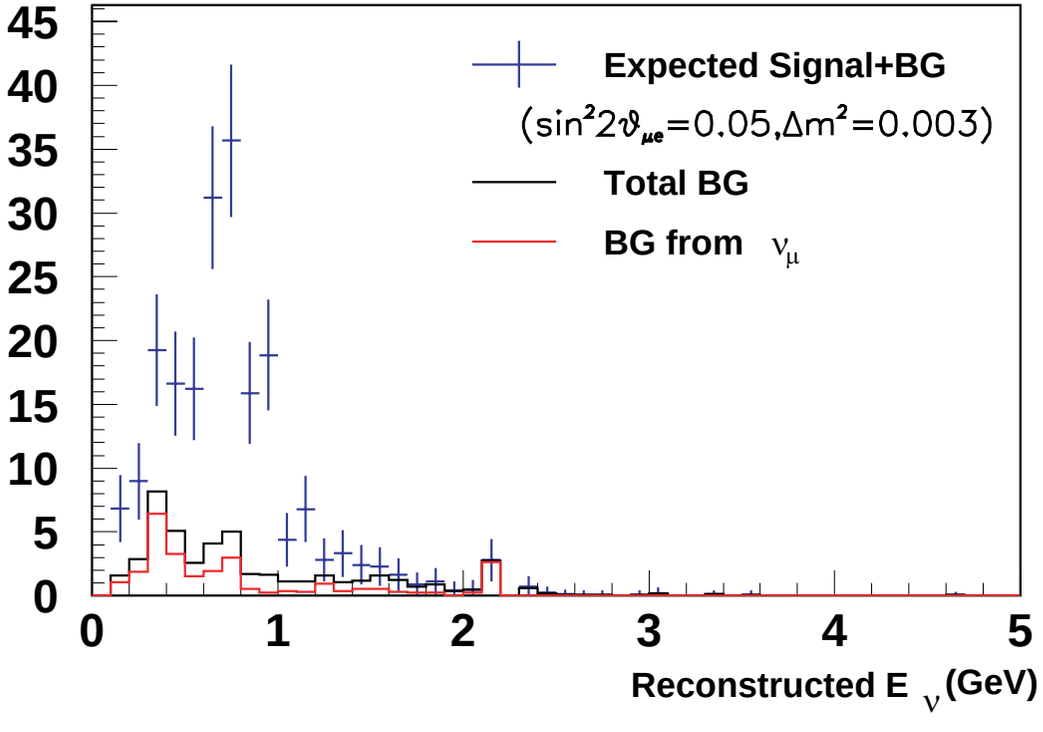
- δm^2_{23} with a resolution of 10^{-4} eV^2.
- $\sin^2 2\theta_{23}$ at $1 \div 2$ %.



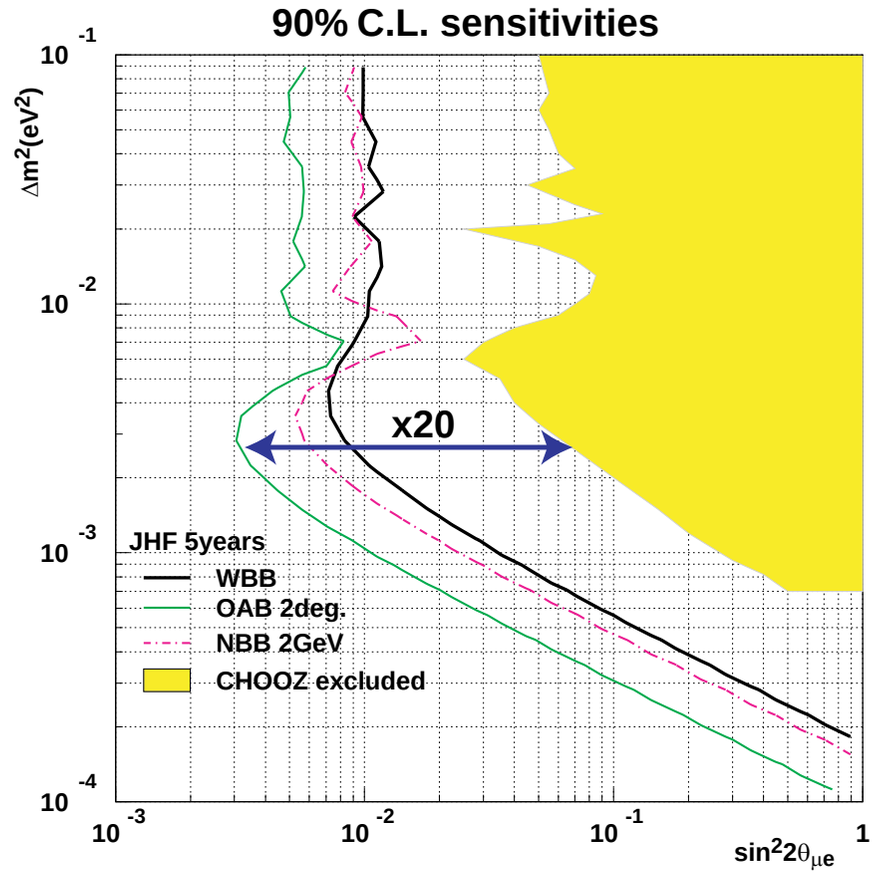
Ratio of the measured ν_μ spectrum with respect to the non-oscillation prediction in case of oscillation.

T2K ν_e appearance

OAB 2°	ν_μ CC	ν_μ NC	ν_e CC	Osc. ν_e
Generated in F.V.	10713.6	4080.3	292.1	301.6
1R e-like	14.3	247.1	68.4	203.7
e/π^0 separation	3.5	23.0	21.9	152.2
0.4 GeV$< E_{rec} < 1.2$ GeV	1.8	9.3	11.1	123.2



Sensitivity to θ_{13}

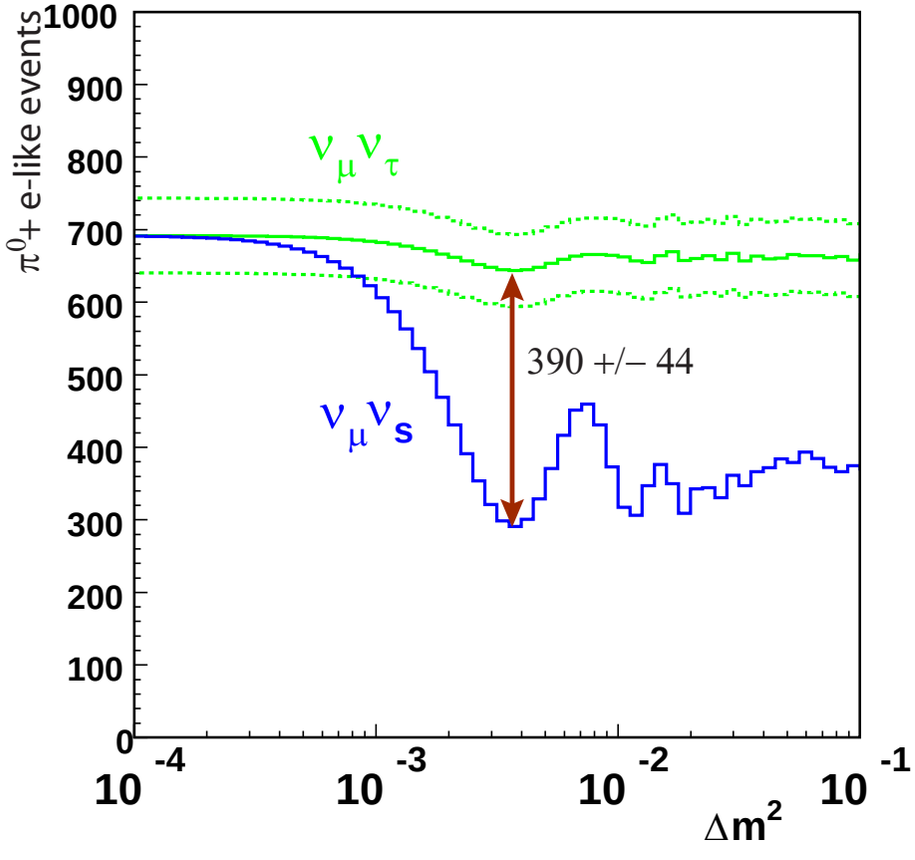


Separazione ν_τ — ν_{sterili}

Tag delle correnti neutre con i π° (metodo Vissani-Smirnov), usato anche in SK ($\nu + N \rightarrow \nu + N + \pi^\circ$)

Le sistematiche sulla sezione d'urto di produzione risonante di π° in eventi di NC verranno fortemente ridotte dal close detector di K2K e dai close detectors di JHF.

Limite alla frazione di ν_s a circa 0.1 (90% CL).



Il problema degli errori sistematici.

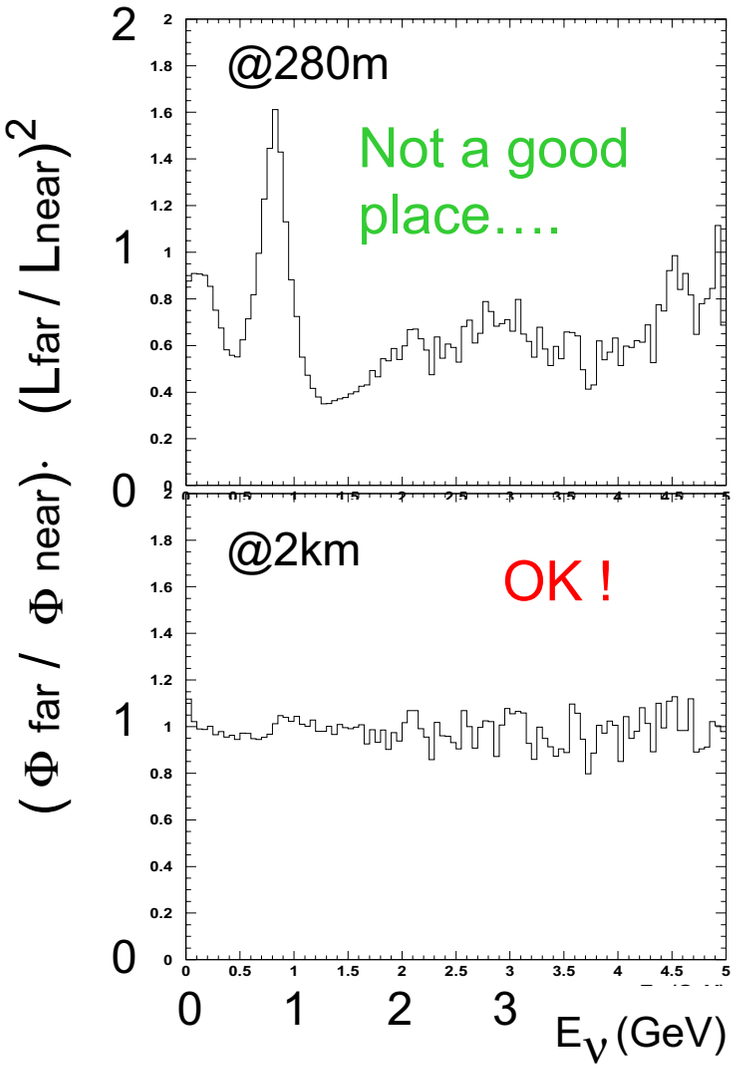
Un fascio di neutrini tradizionali puó essere simulato da un MonteCarlo, ma con errori sistematici non minori del 5%:

- La produzione di neutrini dipende dalla stima del flusso di pioni secondari generati dalle interazioni dei protoni primari.
- La produzione di pioni (adroproduzione) non é mai stata misurata al livello di accuratezza necessario per stime precise dei flussi (numero di pioni prodotti, spettro energetico, distribuzioni angolari)
- Un esperimento dedicato (Harp) é in fase di analisi dati
- La produzione di altri flavor di neutrini ($\overline{\nu}_\mu$, ν_e , $\overline{\nu}_e$) dipende dalla produzione di kaoni e dal decadimento dei muoni generati dai pioni

Un rivelatore abbastanza vicino al bersaglio da misurare neutrini non oscillati (close detector) é indispensabile per ridurre gli errori sistematici, ma:

- Misura il flusso $\times$ sezione d'urto, per estrapolare il flusso al far detector le sezioni d'urto devono essere note, e questo non é vero alle precisioni necessarie, soprattutto alle basse energie (sotto i 5 GeV).
- Un rivelatore troppo vicino vede un flusso diverso dal far detector perché la lunghezza del decay tunnel (80 m a JHF, 1 km al CNGS) non é trascurabile: far/near ratio.

Inoltre la stima dei flavor secondari, in particolare dei ν_e , richiede che non ci sia contaminazione di π° negli eventi selezionati $\Rightarrow$ rivelatore raffinato come close detector.



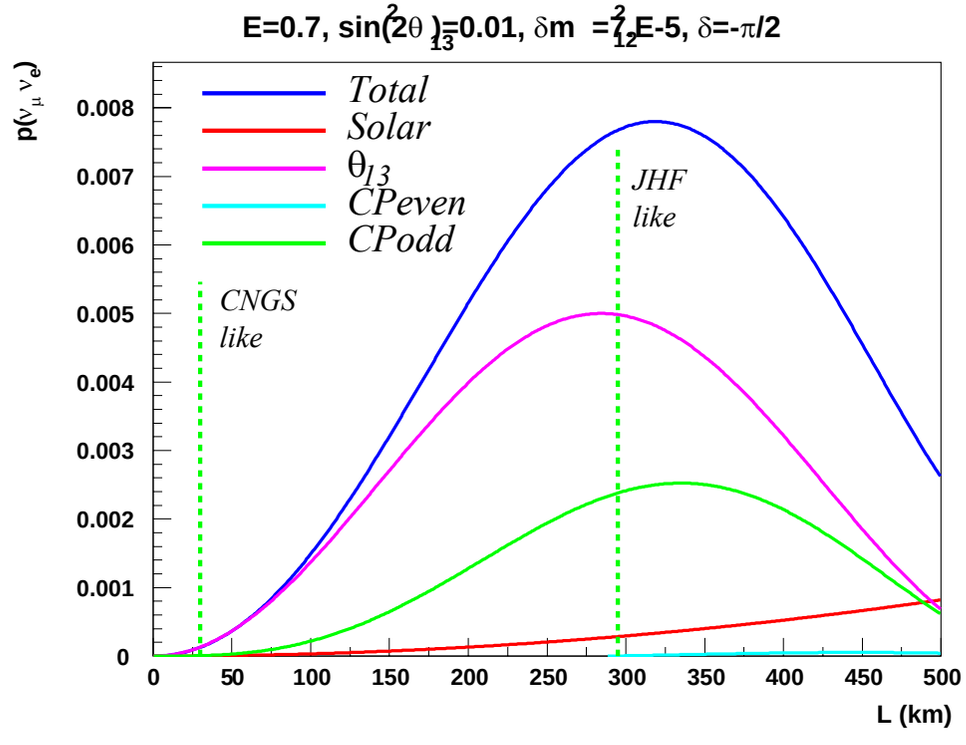
Degeneracies, correlations and ambiguities.

δ/θ_{13} **degeneracy**:

θ_{13} and δ are strongly degenerate in $p(\nu_\mu \rightarrow \nu_e)$.

In a neutrino run, positive δ values tend to cancel the θ_{13} oscillating term. The effect rises if δm^2_{12} rises.

Should we paradoxically conclude that this is a problem? Certainly NOT: δ_{CP} is A SIGNAL. With an antineutrino run the sign of the CP violating term (obviously) reverses, and for large values of δ_{CP} and δm^2_{12} JHF could fit BOTH θ_{13} and δ_{CP}.



- $\theta_{23}/\pi/2-\theta_{23}$ **ambiguity**: ν_μ disappearance measures $\sin^2(2\theta_{23})$ while $p(\nu_\mu \rightarrow \nu_e)$ depends by $\sin^2(\theta_{23})$. For $\theta_{23} \neq \pi/2$ this creates two different solutions.
- **sign of δm^2_{23} ambiguity**: Changing the sign of δm^2_{23} $p(\nu_\mu \rightarrow \nu_e)$ changes, mainly for the matter effects. This creates two different solutions (small effect on JHF).

Off Axis

NuMI Off-Axis Proposal

- The Off-Axis experiment is proposed to be
  - 50 kT
  - Medium-Z sandwich detector
    - Particle board absorber
    - Liquid scintillator strip detectors with APD readout
    - Glass RPC detectors backup option
    - We will re-evaluate the technology decision in a year.
  - 810 km baseline, about 12 km off-axis (Ash River, MN)
  - Current cost estimate about 170 M$
  - Collaboration of 33 institutions from 8 countries; seeking additional collaborators
    - One day meeting in Cambridge, England, January 12

$P(\nu_1 \to \nu_e)$ (in Matter)

- In matter, P_1 will be approximately multiplied by $(1 \pm 2E/E_R)$ and P_3 and P_4 will be approximately multiplied by $(1 \pm E/E_R)$, where the top sign is for neutrinos with normal mass hierarchy and antineutrinos with inverted mass hierarchy.

$$E_R = \frac{\Delta m_{13}^2}{2\sqrt{2}G_F N_e} \approx 11 \text{ GeV for the earth's crust.}$$

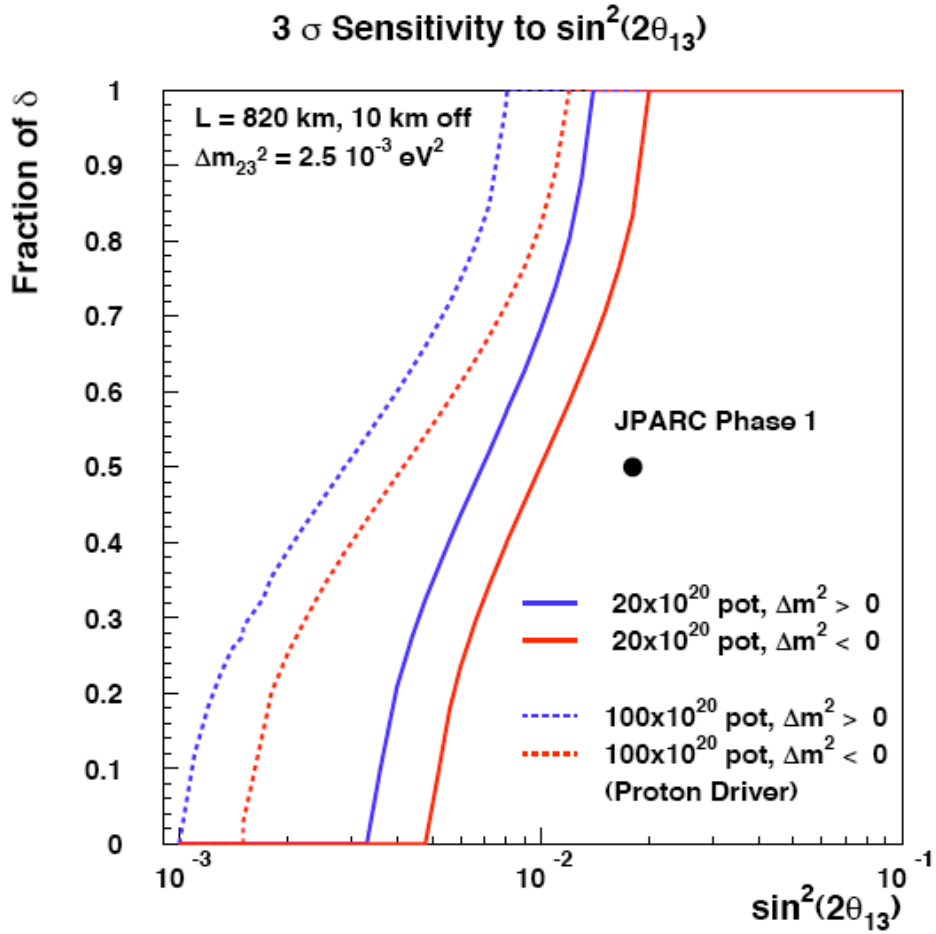
About a ±23% effect for NuMI, but only a ±10% effect for JPARC .

Goals of the Off-Axis Experiment

- **Primary goal: Find evidence for $\nu_\mu \to \nu_e$, determining $\sin^2(2\theta_{13})$ to a factor of 2.**
- **Longer term goal: Determine the mass hierarchy.**
- **Ultimate goal: Precision measurement of the CP-violating phase δ.**

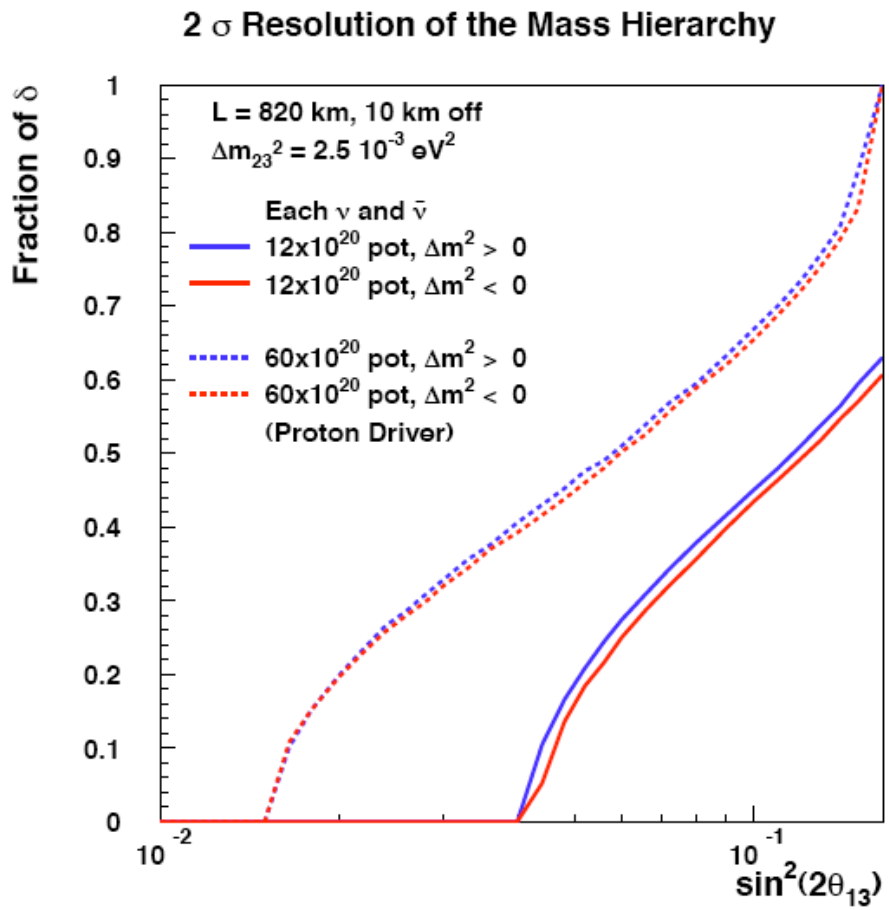
Off Axis

3 σ Discovery Potential for $\nu_\mu \to \nu_e$



Off Axis

95% CL Resolution of the Mass Hierarchy



Off Axis

Status and Prospects

- **Proposal**
  - **Letter of Intent Submitted 2002**
  - **Progress Report just submitted this week**
  - **Full proposal will be submitted in March 2004**
- **Interest in neutrino oscillations has greatly increased during the past year**
  - **HEPAP request APS study beginning next week**
  - **Fermilab Long-Range Planning committee sees neutrino oscillations as a major part of Fermilab's future program**
  - **Secretary of Energy lists a neutrino superbeam as one of four high-energy projects in "Facilities for the Future of Science."**

$$\Delta_{ij} = \frac{(m_j^2 - m_i^2)\, L}{4E}$$

DISAPPEARANCE

$$P_{ee} = 1 - \underbrace{\sin^2 2\theta_{13}}_{\text{SMALL}} \underbrace{\sin^2 \Delta_{13}}_{\sim 1} - \underbrace{c_{13}^4}_{1} \underbrace{\sin^2 2\theta_{13}}_{\sim 1/3} \underbrace{\sin^2 \Delta_{13}}_{\text{SMALL}}$$

← Atmosph. → ← Solar →

$4\,10^{-4}$ at $L_{opt.}$

Atmospheric term will always be dominant in sensitivity domain

$$P_{ee} = 1 - 4\,\theta_{13}^2 \sin^2 \Delta_{13}$$

- No sensitivity to very low θ_{13}
- No CP effects

⇒ Disappearance experiments will be systematics limited

Rem = $P_{ee} = 1 - 2\,\theta_{\mu e}^2 \sin^2 \Delta_{13}$ should not be used (confusing!)

REACTOR EXPERIMENT

CHOOZ = Single detector

⇒ relies on predicted flux

Active mass

Absolute efficiency

SYSTEMATICS = 2.8%

⇒ USE 2 IDENTICAL DETECTORS TO LOWER SYSTEMATICS AT 1% BY COMPARING NEAR AND FAR MEAS

<u>Remarks</u>

- 2 detectors are never "identical"
  - Background rates will be different (⇒ dead times will be ≠)
  - S/N will be different

BUGEY3 1.7%

Better design to decrease background.

- Energy scale is very important (scale + non linearities)

See H. de KERRET's talk

TWO COMPETING PHILOSOPHIES

1 - Go fast, to start before or at the same time as LBL (JHF1, NuMI off-axis)

EUROPE
JAPAN

⇒ Detectors at fixed locations
Reuse if possible existing infrastructures (CHOOZ)

2 - No need to hurry, reactors are complementary to LBL appearance expts

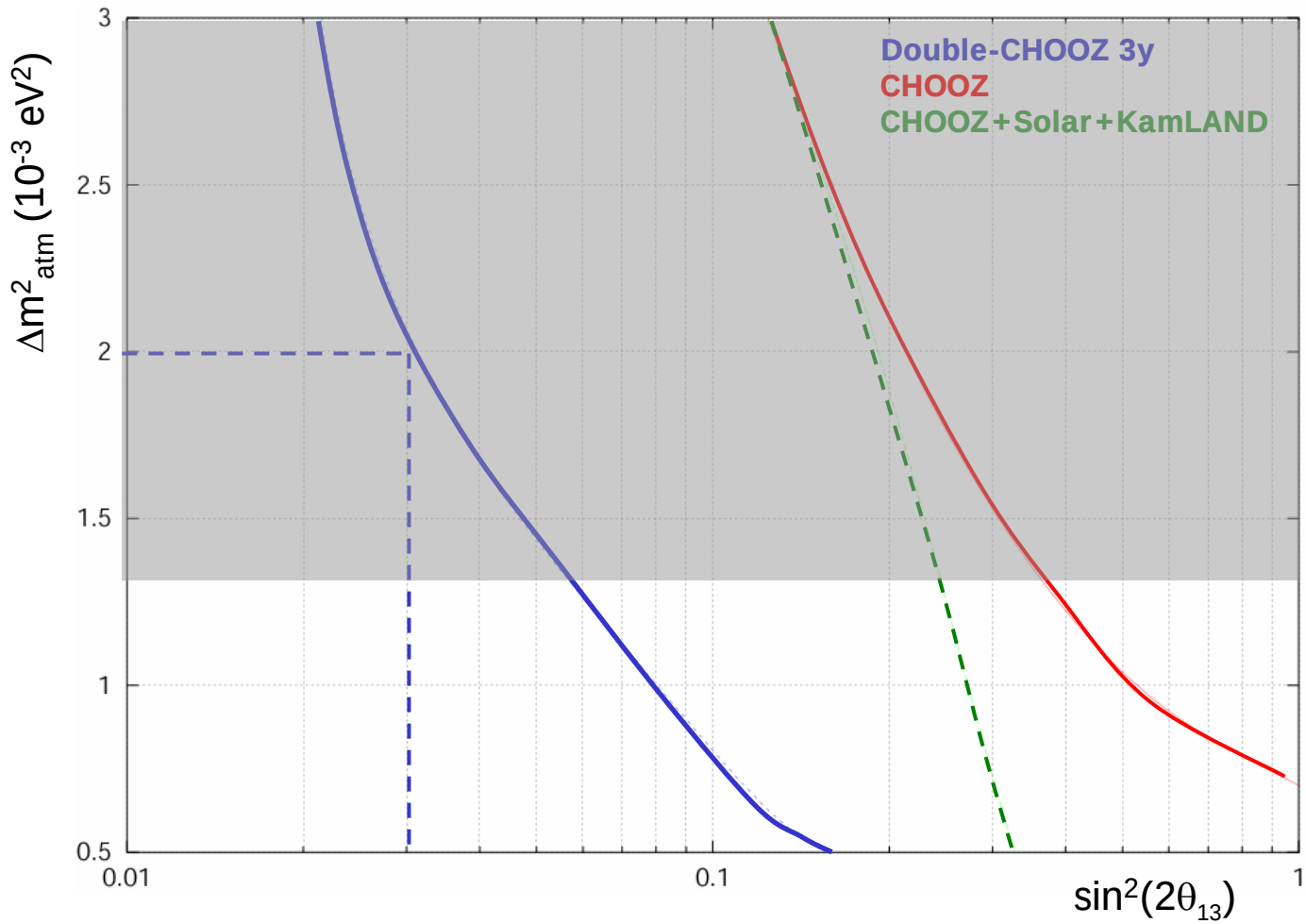
⇒ More sophisticated design
(movable detectors)

USA

But more expensive and later start

There is matter for debate.

Contours


Double-CHOOZ 3y
CHOOZ
CHOOZ+Solar+KamLAND
Δm^2_{atm} (10^{-3} eV^2)
3
2.5
2
1.5
1
0.5
0.01
0.1
1
$\sin^2(2\theta_{13})$

systematics

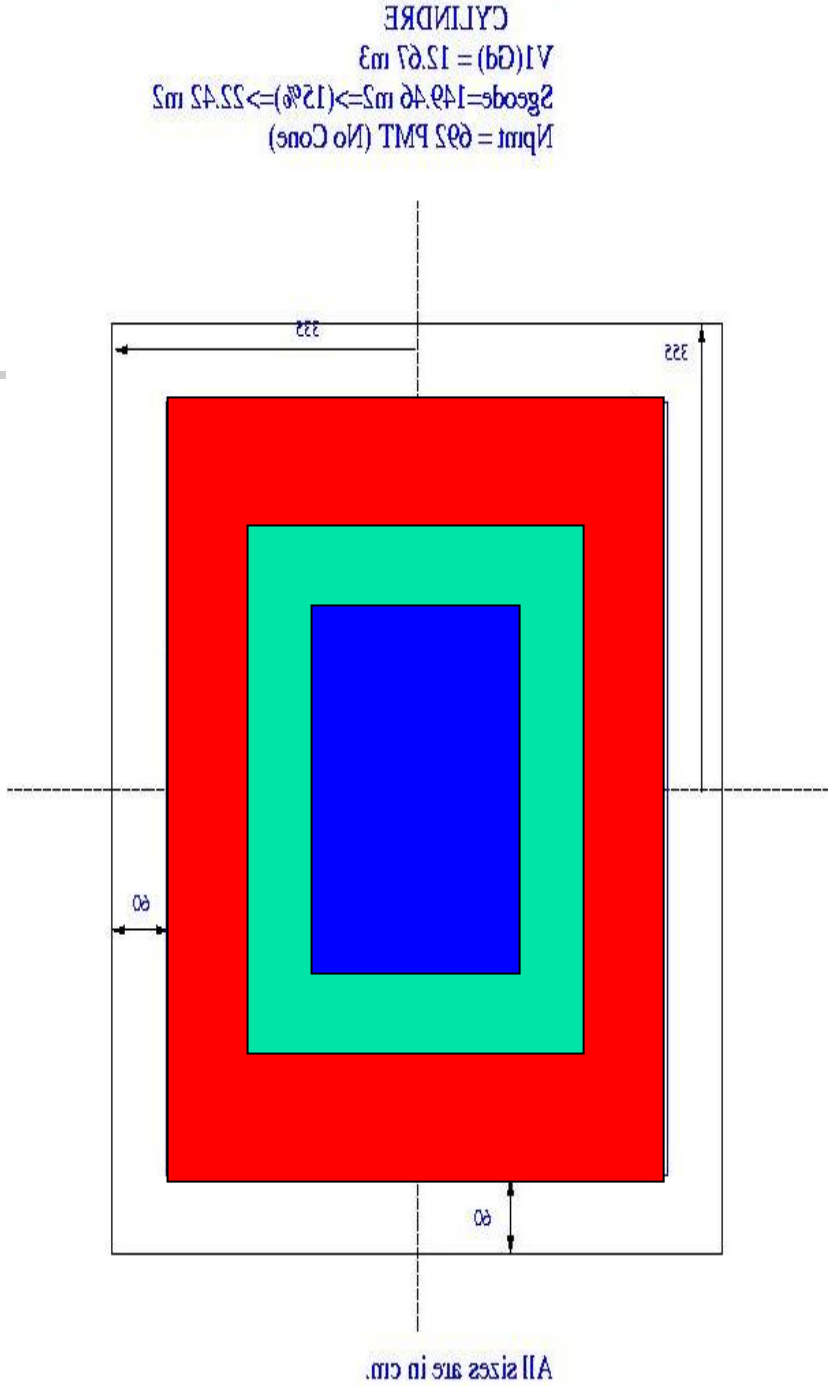
- 2 detectors (suppress the physical uncertainties)
- detector design to control the effect of some calibration uncertainties

  ➔Less accidentals → less cuts
- Address the few remaining source of uncertainties

→ .5% on the relative normalisation of the 2 detectors

Detector design

- A scintillating buffer around the target (to see the gammas from positron capture and Gd decays) ~60 cm
- A non scintillating buffer in front of pmts (reduce the single rates) ~ 1m
- Increase as much as possible the active buffer for the fast neutrons coming from outside



schedule

- Far detector : install end of 2006
- NEAR “ : 2007

→ FIRST RESULT 2008

→ Detectors cost <10 Meuros