Future experiments aiming at the measurement of the PMNS matrix elements

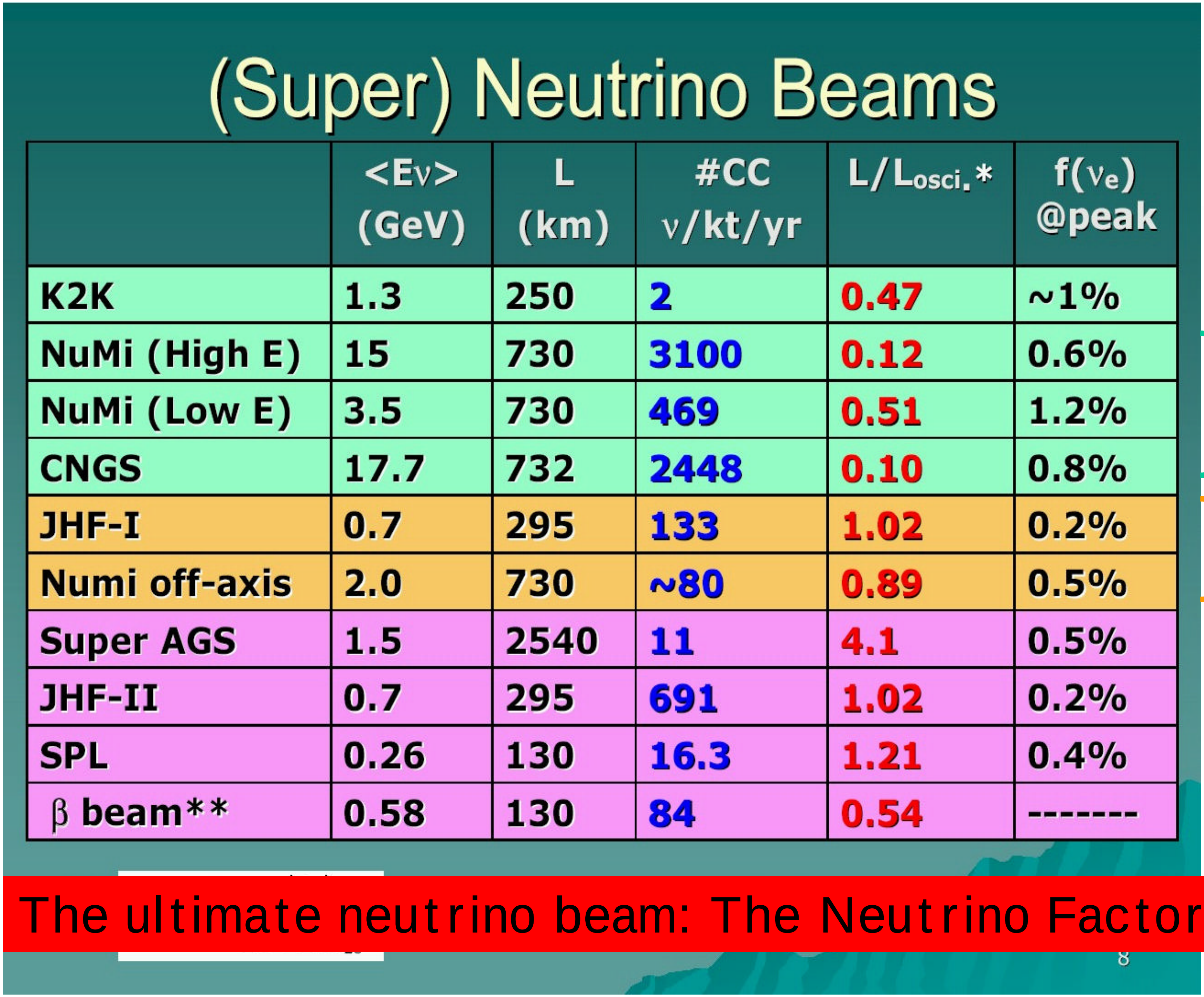
What still we have to measure?

Discovery

Precision meas.

- Three angles (θ_{12}, θ_{13}, θ_{23})
- Two mass differences (δm^2, Δm^2)
- The sign of the mass difference Δm^2 ($\pm\Delta m^2$)
- One CP phase (δ)
- The source of atmospheric oscillations (detect τ appearance)
- Are there more - sterile - neutrinos?
- The absolute masse scale
- Are neutrino Dirac or Majorana particles (or both)?

All the underlined items can be studied with LBL experiments



(Super) Neutrino Beams

	<Eν> (GeV)	L (km)	#CC ν/kt/yr	$L/L_{osci.}$*	$f(\nu_e)$ @peak
K2K	1.3	250	2	0.47	~1%
NuMi (High E)	15	730	3100	0.12	0.6%
NuMi (Low E)	3.5	730	469	0.51	1.2%
CNGS	17.7	732	2448	0.10	0.8%
JHF-I	0.7	295	133	1.02	0.2%
Numi off-axis	2.0	730	~80	0.89	0.5%
Super AGS	1.5	2540	11	4.1	0.5%
JHF-II	0.7	295	691	1.02	0.2%
SPL	0.26	130	16.3	1.21	0.4%
β beam**	0.58	130	84	0.54	-------

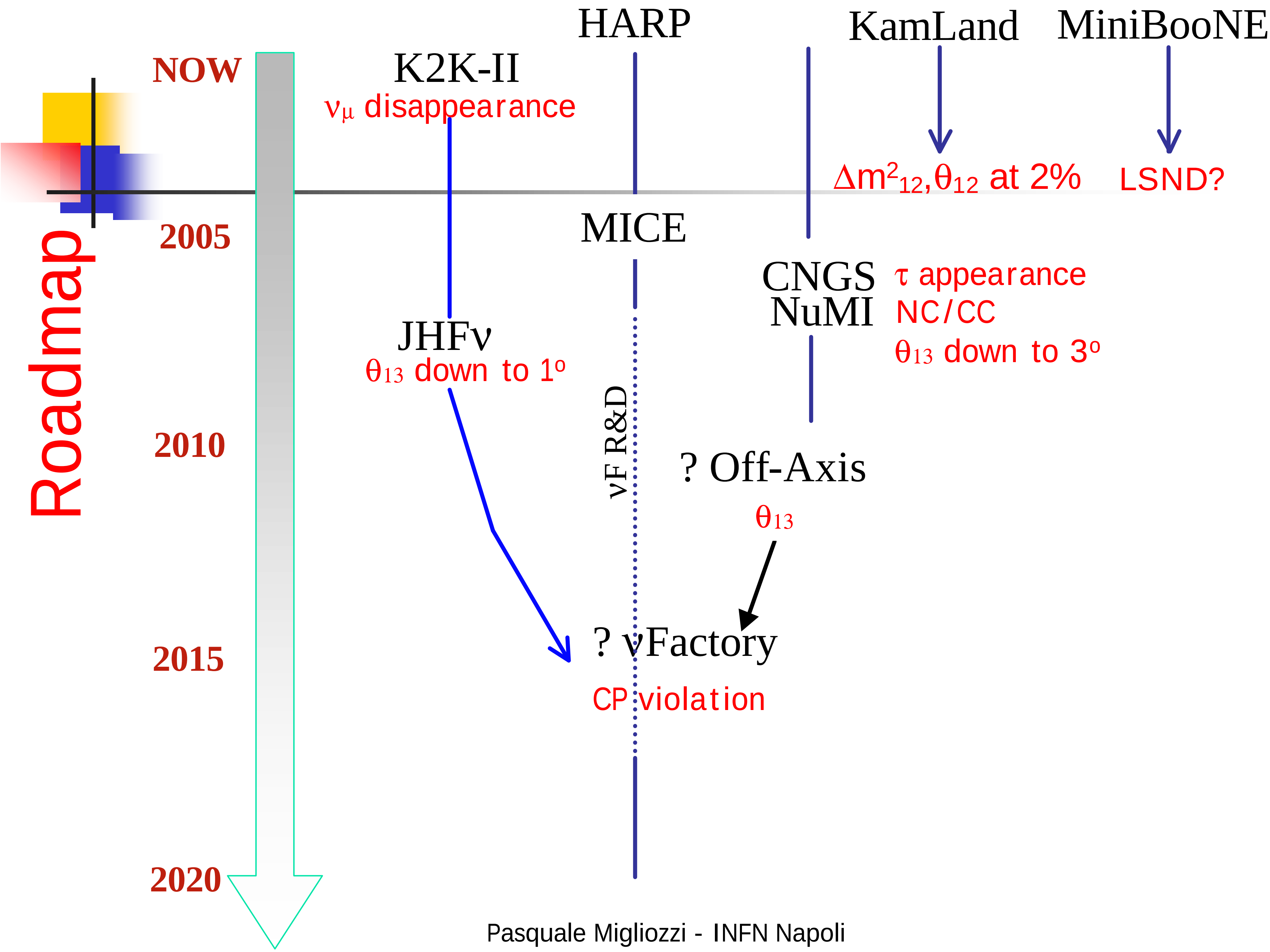
1st gen.

2nd gen.

3rd gen.

The ultimate neutrino beam: The Neutrino Factory

Roadmap



NOW

2005

2010

2015

2020

K2K-II

ν_μ disappearance

HARP

KamLand

$\Delta m^2_{12}, \theta_{12}$ at 2%

MiniBooNE

LSND?

MICE

CNGS

NuMI

τ appearance

NC/CC

θ_{13} down to 3°

JHFν

θ_{13} down to 1°

νF R&D

? Off-Axis

θ_{13}

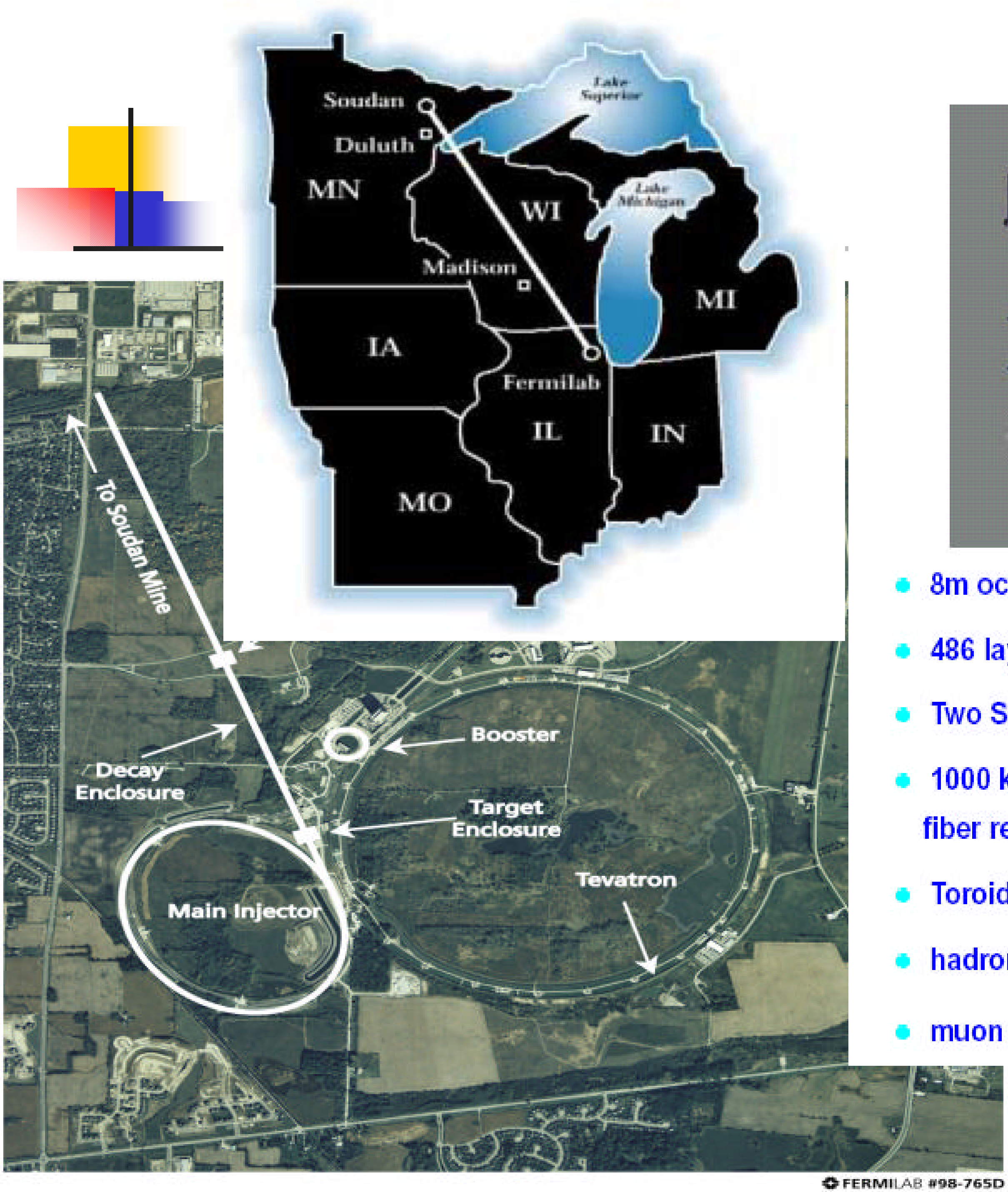
? νFactory

CP violation

Goals of 1st generation of Long Baseline Experiments

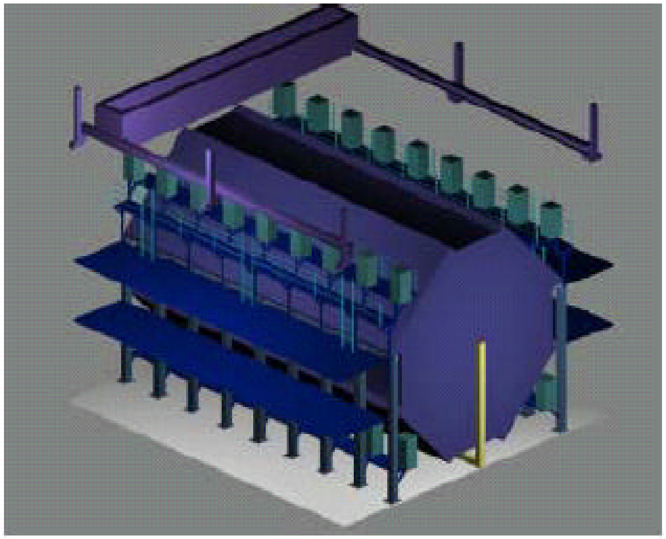
- Confront emerging picture with precision data
  - confirm deficit of ν_μ in accelerator-based experiment
  - confirm oscillation hypothesis:
    - must measure/know E & L precisely to see oscillations in L/E
    - pin down oscillation parameters (with 10% precision)
  - demonstrate $\nu_\mu \rightarrow \nu_\tau$ is dominant mode:

    Tau appearance ! (CNGS → direct, MINOS → NC/CC)
- Look for new phenomena
  - evidence for non-zero $\theta_{13} \rightarrow$ detection of ν_e appearance
  - test for possible CPT violation?
  - etc. etc.



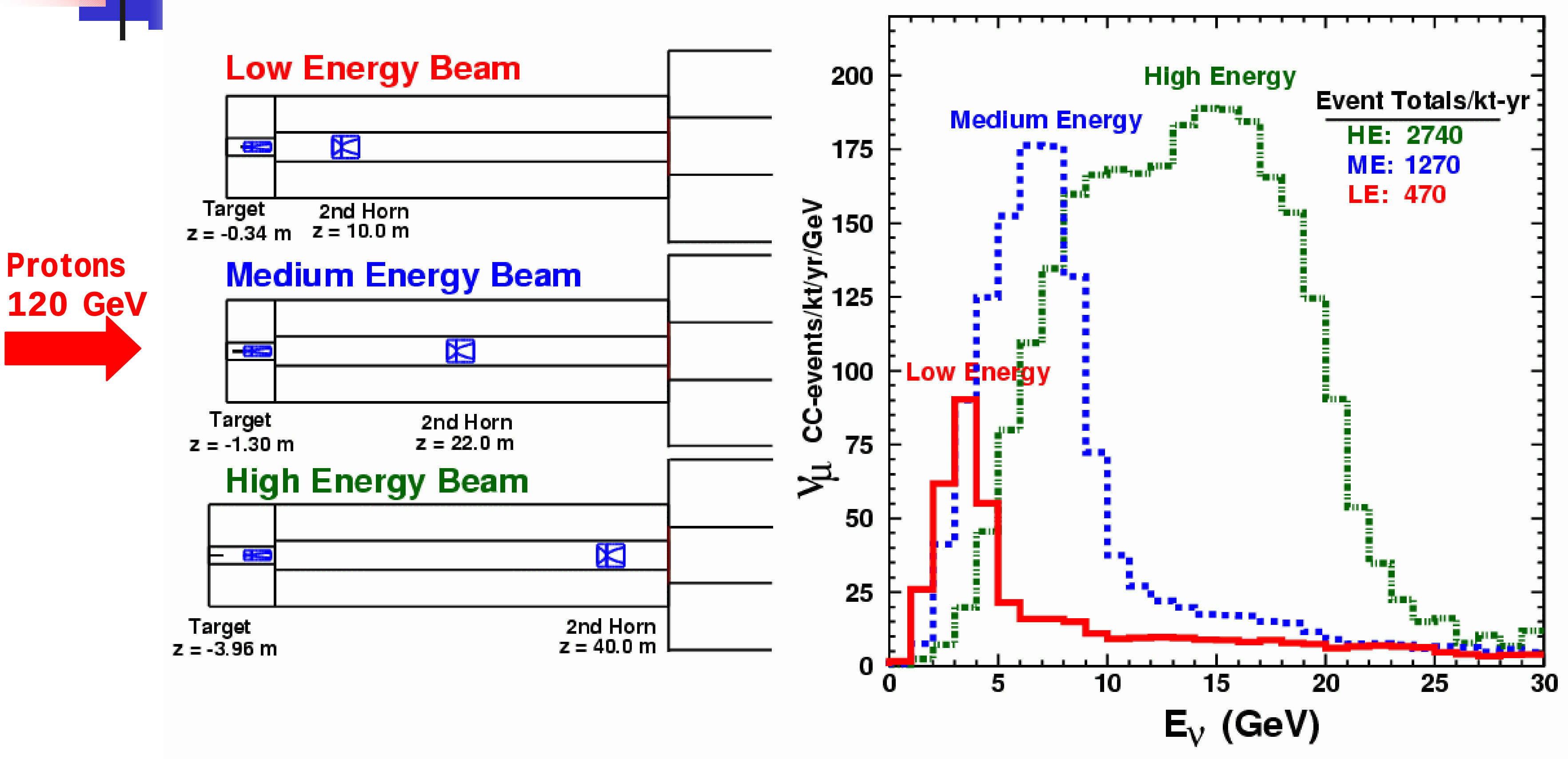
FERMILAB #98-765D

MINOS Far Detector



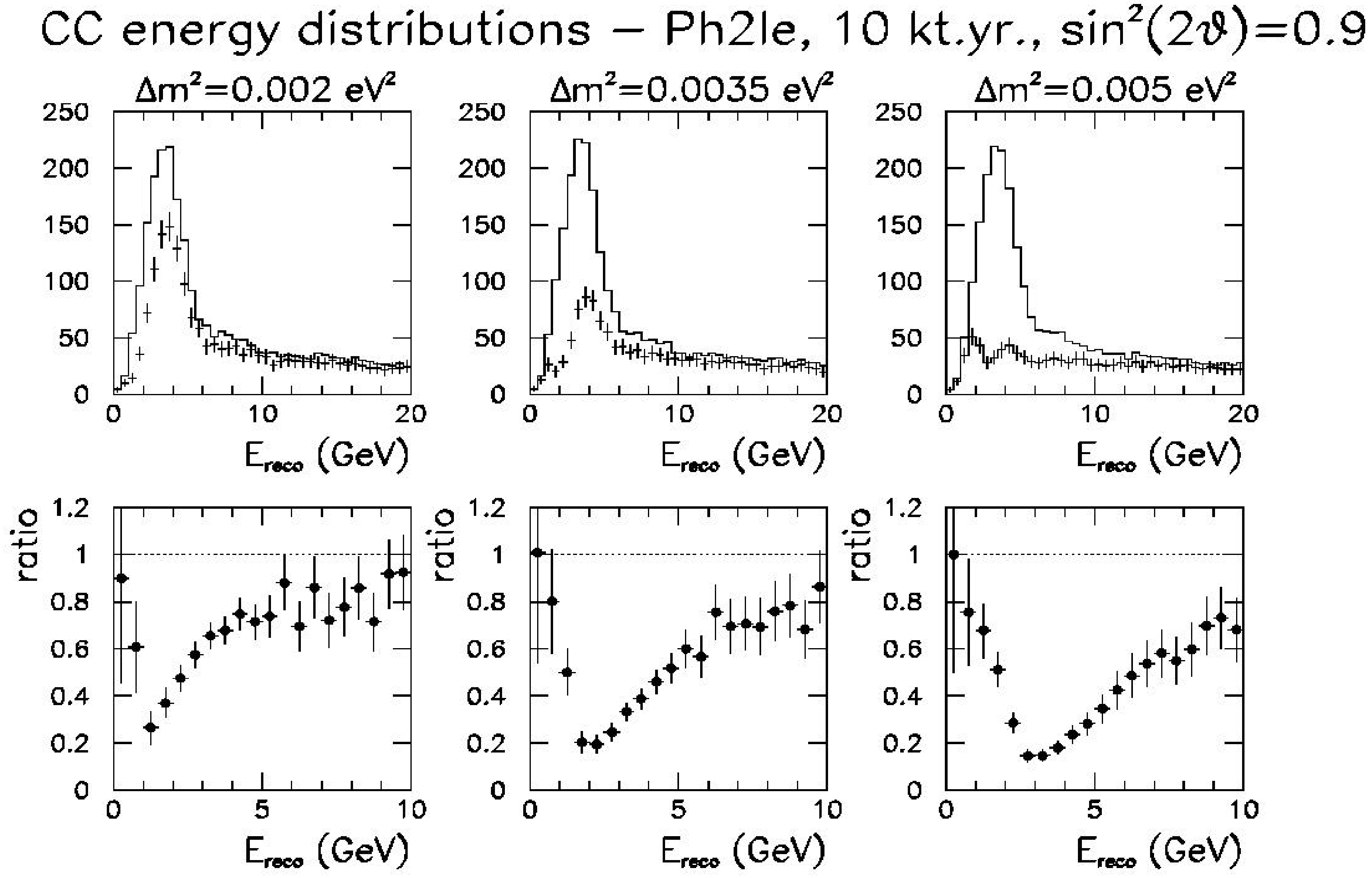
- 8m octagonal tracking calorimeter
- 486 layers of 2.54 cm Fe
- Two Supermodules (15m each)
- 1000 km of scintillator, 2000 km of WLS and clear fiber readout (25,800 m^2 of active detector planes)
- Toroidal $\langle B \rangle \approx 1.3T$. Total mass 5.4 kT
- hadron energy : $\frac{\Delta E}{E} \approx \frac{55\%}{\sqrt{E}}$
- muon momentum : $\frac{\Delta p}{p} \approx 12\%$ (by curvature)

The NuMi beam

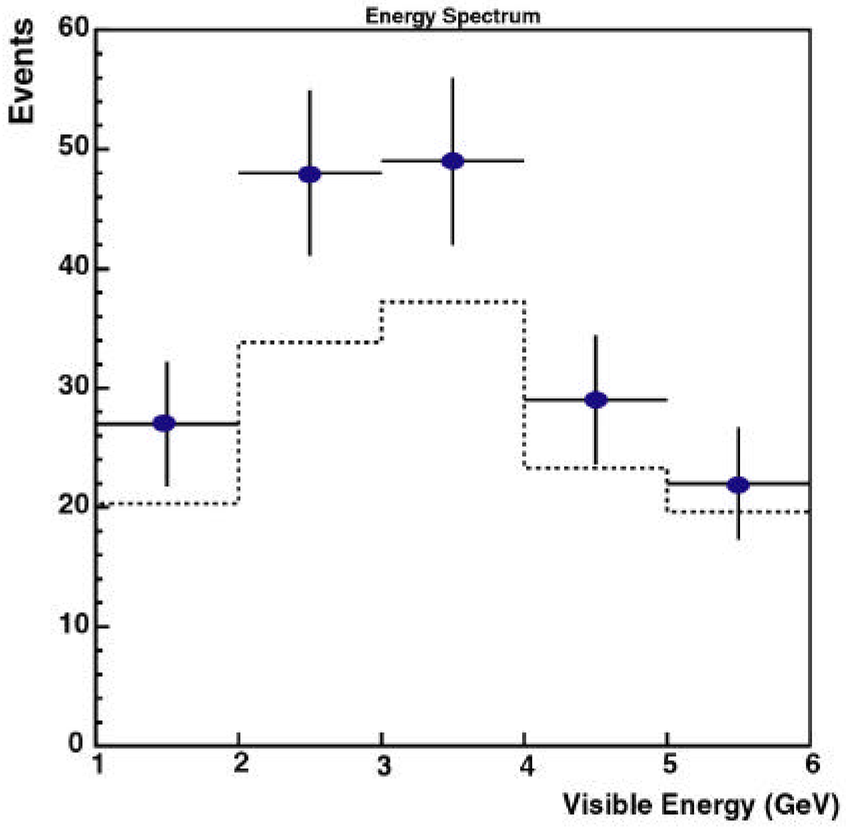


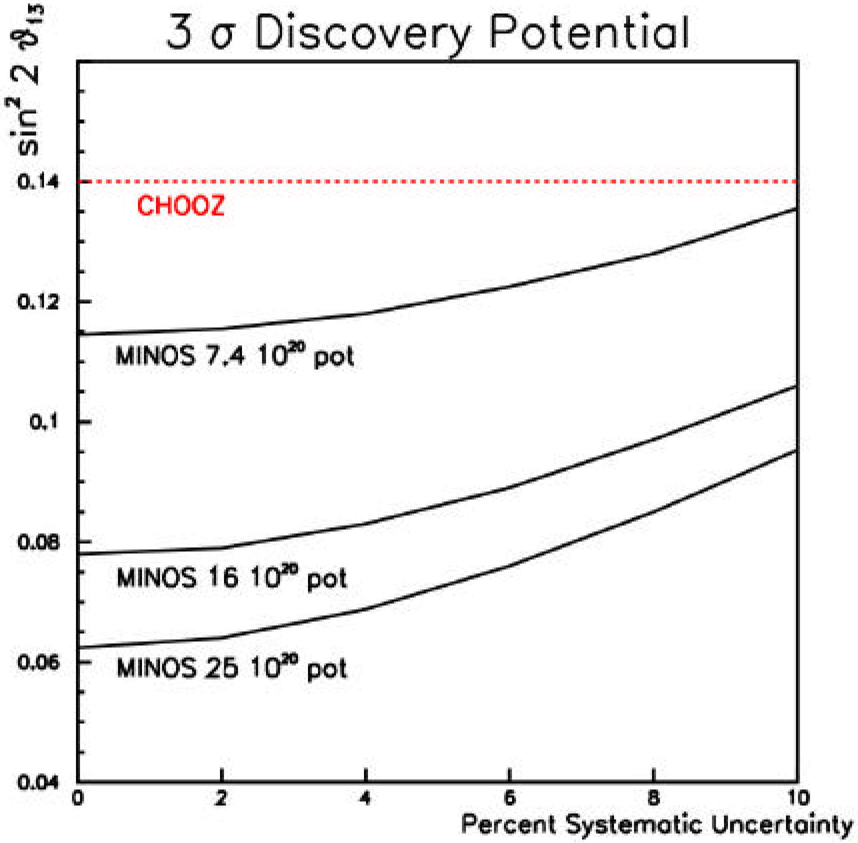
- Low energy beam: less flux, but better match to Δm^2
- Still plenty of events: ~ 5000 ν_μ CC events in 2 yrs

Expected Neutrino Energy Distributions in 2 years



Appearance of electrons





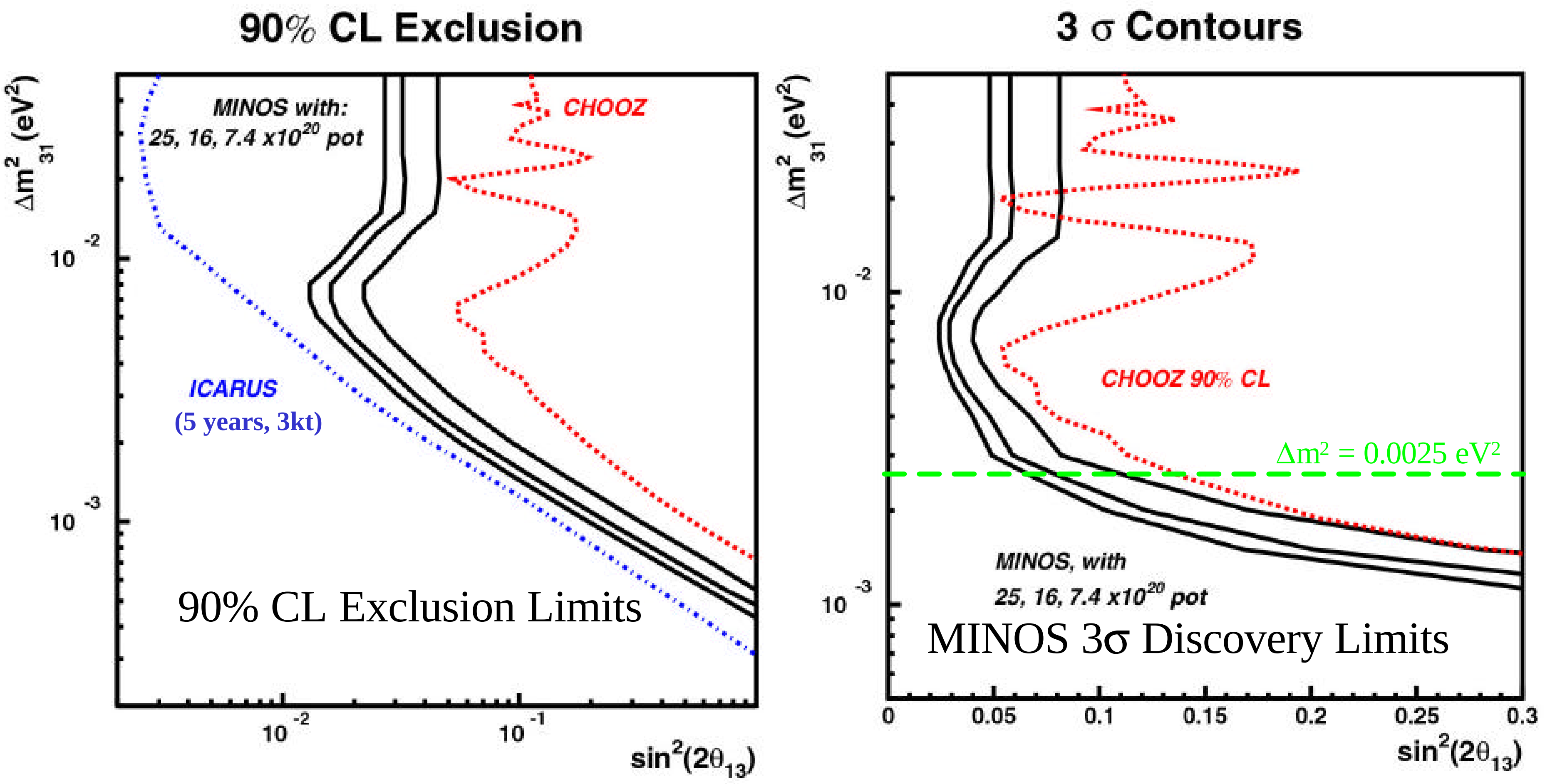
For $\Delta m^2 = 0.0025$ eV^2, $\sin^2 2\theta_{13} = 0.067$

Observed number of events identified as coming from ν_e CC interactions with and without oscillations. 25×10^{20} protons on target.

For $\Delta m^2 = 0.0025$ eV^2

3 σ discovery potential for three different levels of protons on target and versus systematic uncertainty on the background.

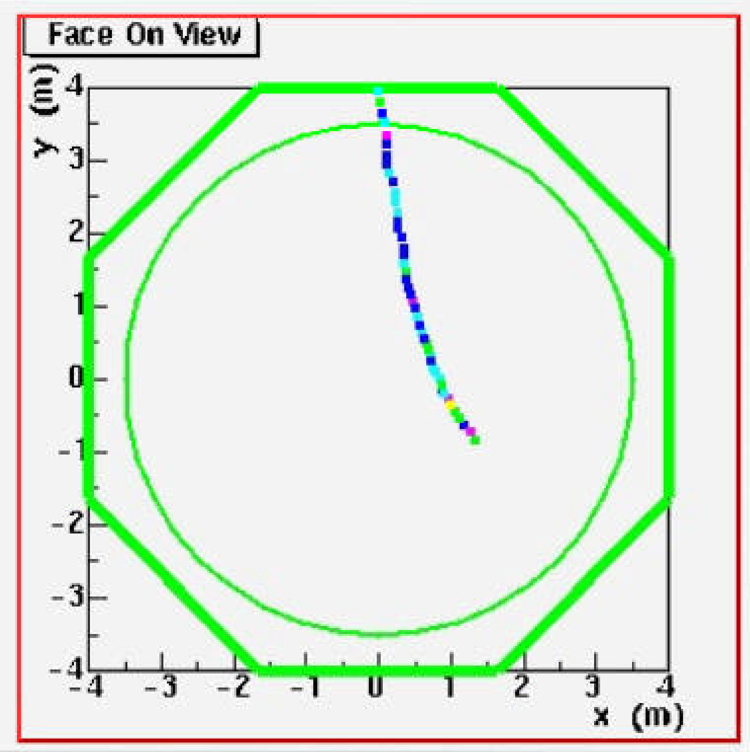
Appearance of electrons



- MINOS sensitivities based on varying numbers of protons on target

1st Supermodule (1/2 detector) done, other well begun

Meanwhile first magnetized data on atmospheric ν



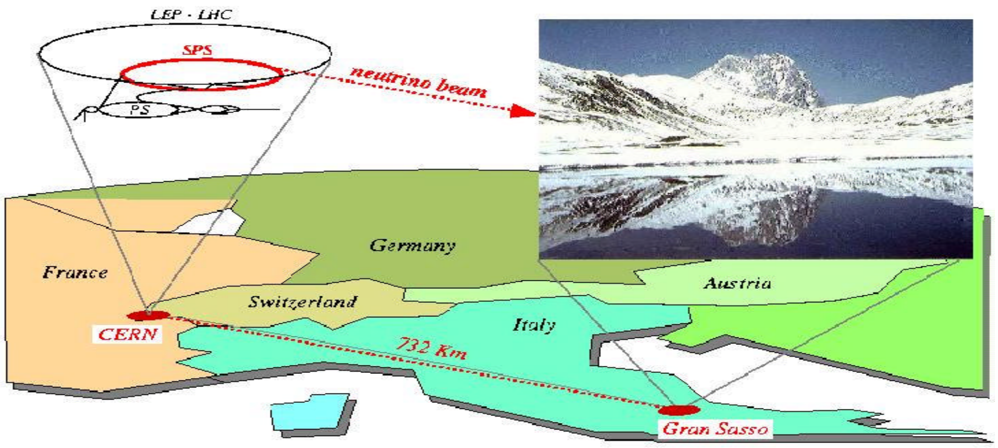
Summary of MINOS

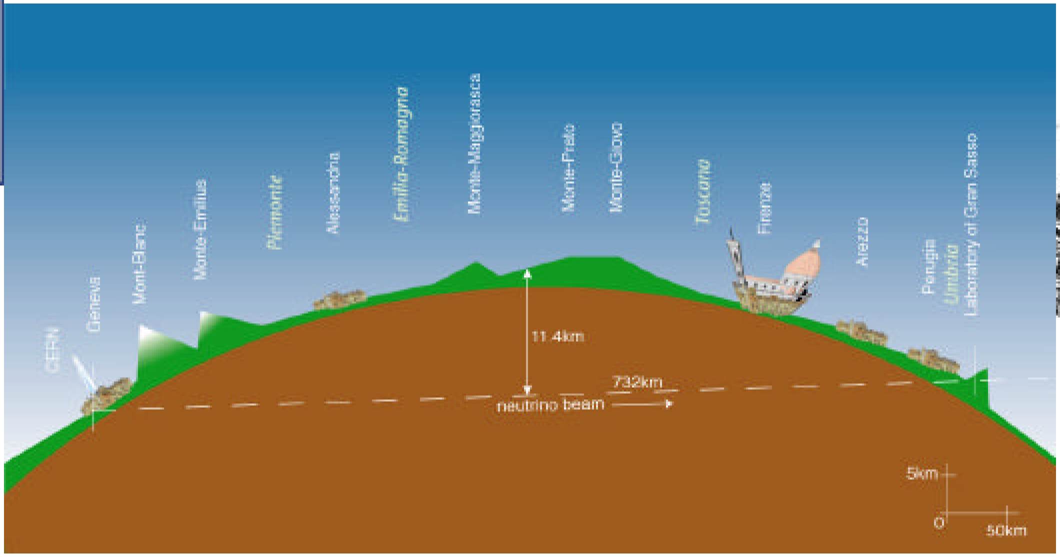
- Data-taking with NuMI beam will begin early 2005
  - Far & Near detector on schedule, Far det. already ½ complete (detector very stable: < 1 ns timing drifts, ~ 1% pulse height drifts)
  - Calibration detector running & data analysis will be complete
  - much progress on NuMI: civil & technical components
- By 2007, they will provide a precise measurements
  - oscillation parameters: $\nu_\mu \rightarrow \nu_\tau$ case;(NC/CC ratio for mode id)
  - search for subdominant $\nu_\mu \rightarrow \nu_e$ (discussed later)
- Also ~ 24 kiloton-year exposure to atm. ν's
  - energy, direction resolution → competitive on $\nu_\mu \rightarrow \nu_\tau$
  - 1st direct search for CPT non-cons. ($\nu_\mu \rightarrow \nu_\mu$ vs $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$)

The CNGS neutrino beam

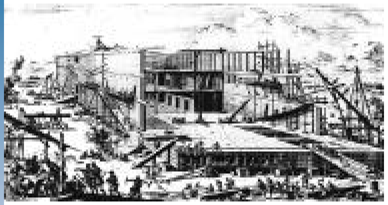
The beam will start in may 2006

CERN to Gran Sasso Neutrino Beam





OPERA

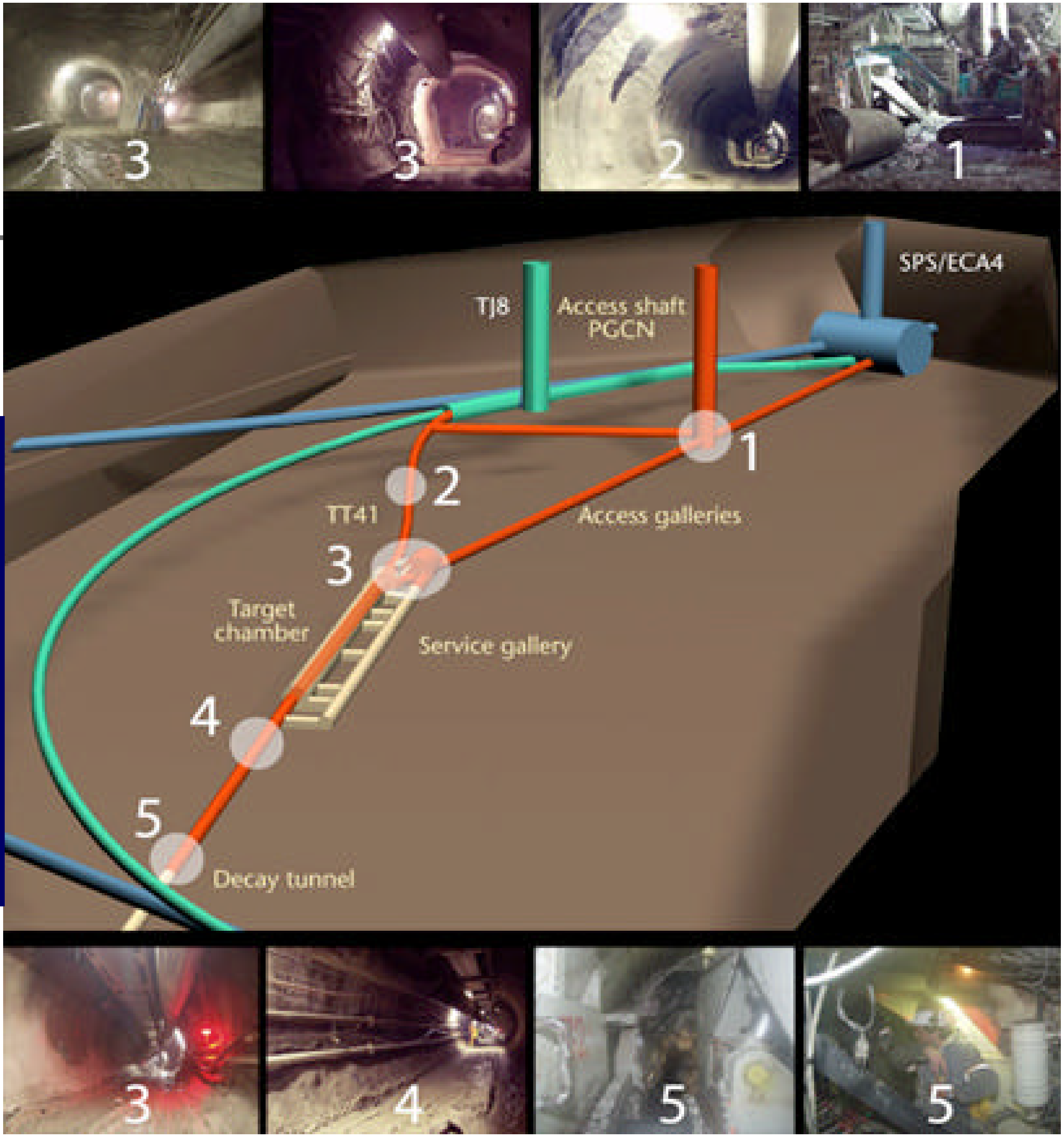


ICARUS

CNGS beam layout at CERN site.

Progress in the civil engineering work:
excavation completed
concreting started

CNGS commissioning:
May 2006



The CNGS and the expected number of events

Nominal ν beam (Nov. 2000)

Shared SPS operation

200 days/year

4.5×10^{19} pot / year

Average ν_μ energy 17 GeV

5 year run

Expected interactions in 1kton detector

~ 18000 n_m **NC+CC**

~ 80 n_t **CC**

at $\Delta m^2 = 2.5\times10^{-3}$ eV^2 and full mixing

An updated CNGS with a flux 1.5 more intense than the one approved in 2000 is now considered as the baseline option

Limiting factor for θ_{13} search:
ν_e + anti-ν_e beam contamination ~0.87%

$\nu_\mu \rightarrow \nu_\tau$ oscillations

- Analysis of the electron sample
  - ✓ Exploit the small intrinsic ν_e contamination of the beam (0.8% of ν_μ CC)
  - ✓ Exploit the unique e/p^0 separation

At $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2 165 $\tau \rightarrow$ e events are expected

Main background from charged current interactions of ν_e in the beam 700 events are expected

Statistical excess visible before cuts ⇒ this is the main reason for performing this experiment at long baseline !

$\tau \rightarrow e$ search: 3D likelihood

A simple analysis approach: a likelihood method based on 3 variables

- 3 variables

$E_{visible}$, P_T^{miss}, $\rho_l \equiv P_T^{lep} / (P_T^{lep} + P_T^{had} + P_T^{miss})$

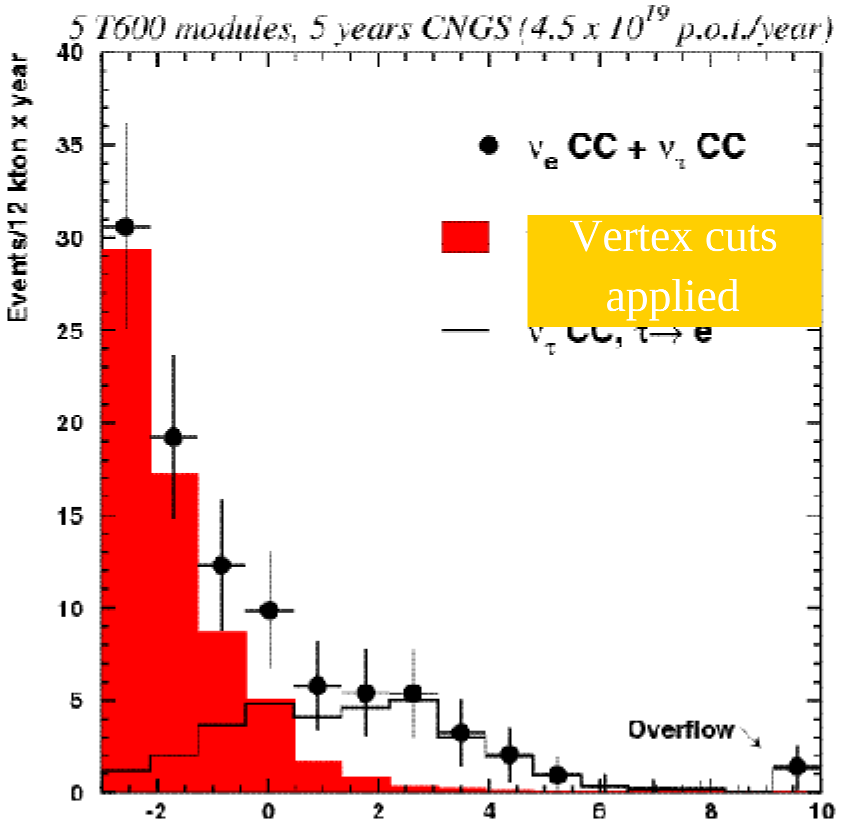
- Exploit correlation between them

L_S ([$E_{visible}$, P_T^{miss}, ρ_l]) (signal)

L_B ([$E_{visible}$, P_T^{miss}, ρ_l]) (ν_e CC back)

Discrimination given by

lnl °L([$E_{visible}$, $\mathbf{P_T^{miss}}$, r_l]) = L_s / L_B



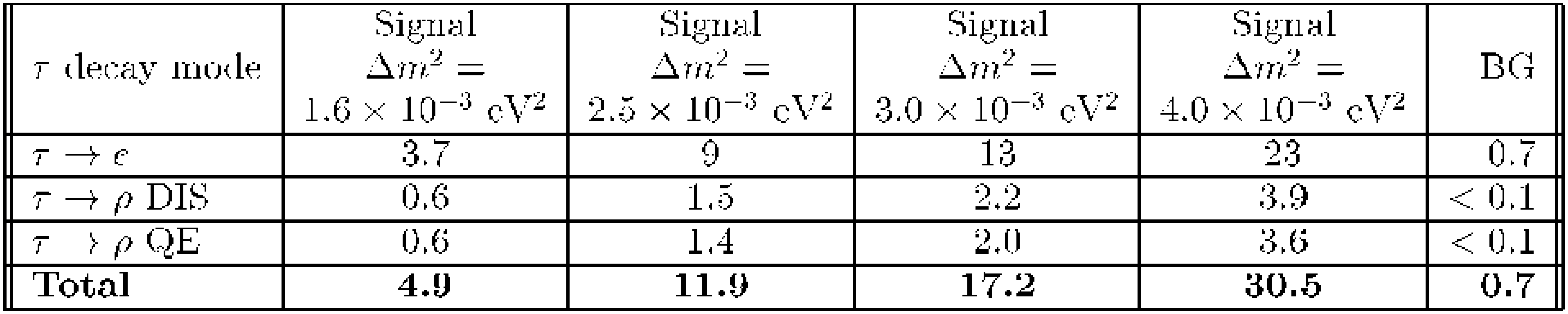
Vertex cuts applied

lnl

$\nu_\mu \to \nu_\tau$ appearance search summary

- T3000 detector (2.35 kton active, **1.5 kton fiducial**)
- Integrated pots = 2.25 $\times 10^{20}$

Super-Kamiokande: 1.6 < Δm^2 < 4.0 at 90% C.L.

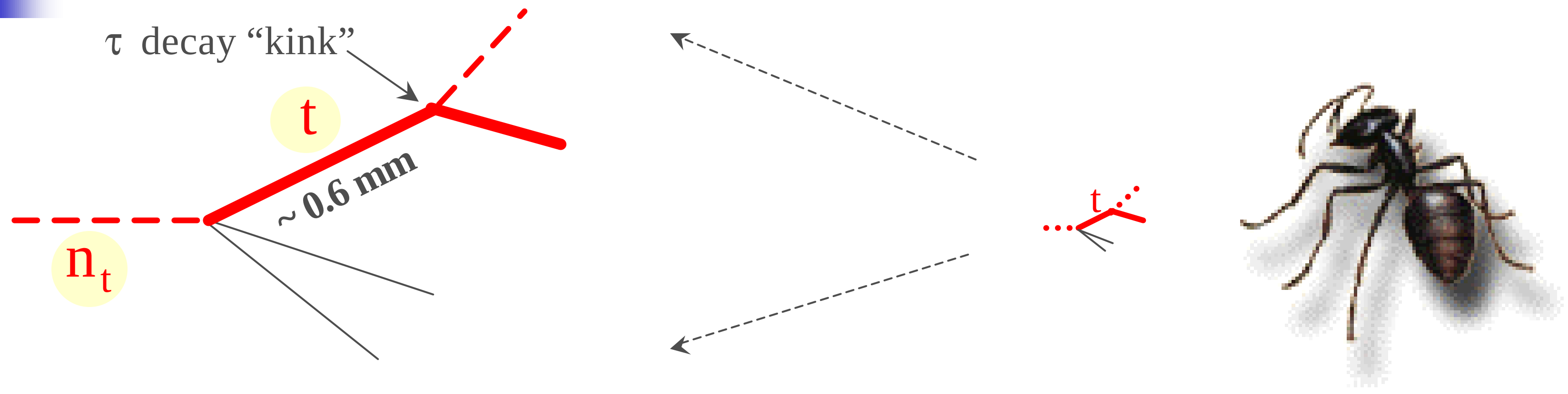


τ decay mode	Signal $\Delta m^2 =$ 1.6×10^{-3} eV^2	Signal $\Delta m^2 =$ 2.5×10^{-3} eV^2	Signal $\Delta m^2 =$ 3.0×10^{-3} eV^2	Signal $\Delta m^2 =$ 4.0×10^{-3} eV^2	BG
$\tau \to e$	3.7	9	13	23	0.7
$\tau \to \rho$ DIS	0.6	1.5	2.2	3.9	< 0.1
$\tau \to \rho$ QE	0.6	1.4	2.0	3.6	< 0.1
Total	**4.9**	**11.9**	**17.2**	**30.5**	**0.7**

(these numbers have to be multiplied by a factor 1.5)

- Several decay channels are exploited (golden channel = electron)
- (Low) backgrounds measured in situ (control samples)
- High sensitivity to signal, and oscillation parameters determination

To identify τ leptons, "see" their decay topology



The challenge

n oscillation ® <u>massive</u> target **<u>AND</u>** **decay topology ® <u>micron</u> resolution**

Lead – nuclear emulsion sandwich

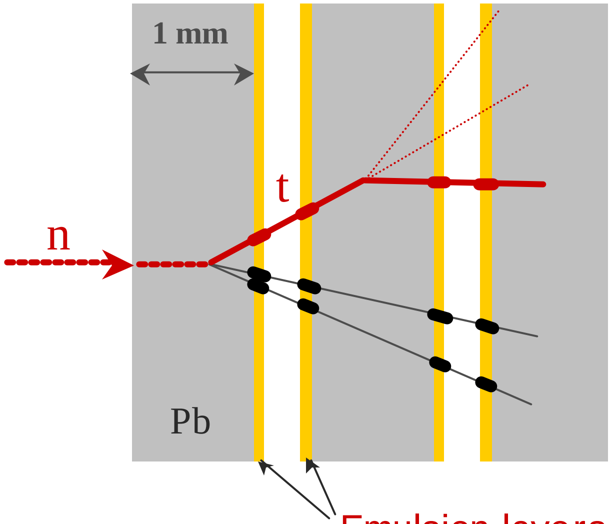
"Emulsion Cloud Chamber", in brief "ECC"

The Emulsion Cloud Chamber (ECC)

- Emulsions for tracking, passive material as target

  ↳ < mm space res. ↳ mass

  - Established technique
    - charmed "X-particle" first observed in cosmic rays (1971)
    - DONUT/FNAL beam-dump experiment: 7 ν_{τ} observed (2000)



$Dm^2 = O(10^{-3}\ eV^2)$ ® $M_{target} \sim 2$ kton

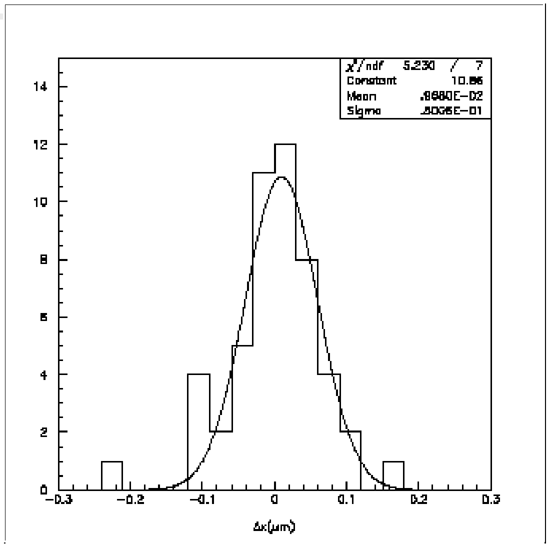
modular structure ("bricks"): basic performance is preserved
large detector → sensitivity, complexity
required: "industrial" emulsions, fast automatic scanning

Experience with emulsions and/or ν_{τ} searches :
E531, CHORUS, NOMAD and DONUT

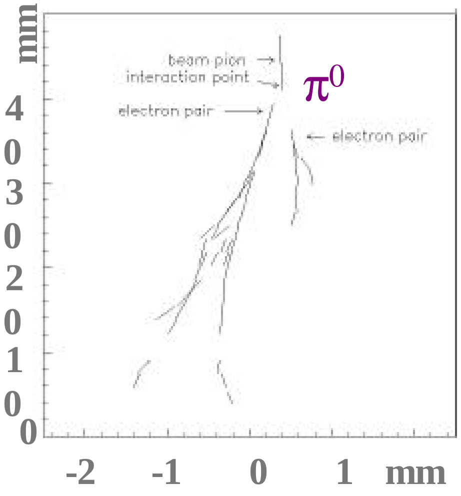
Event reconstruction with an ECC

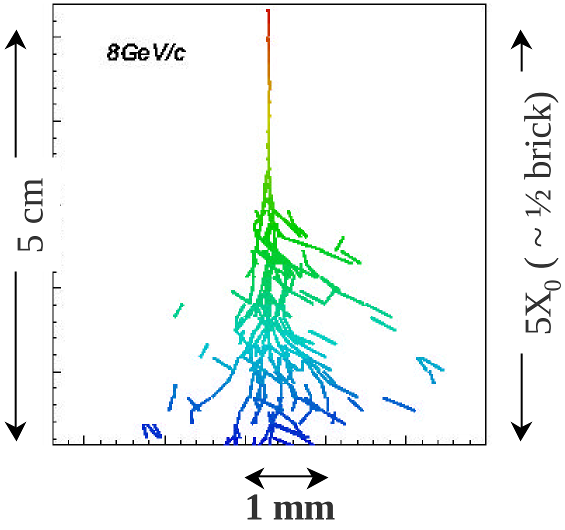
- High precision tracking ($\delta x < 1\mu m$; $\delta\theta < 1 mrad$)
  - Kink decay topology
  - Electron and γ/π^0 identification
- Energy measurement
  - Multiple Coulomb Scattering
  - Track counting (calorimetric measurement)
- Ionization (dE/dx meas.)
  - π/μ separation
  - e/π^0 separation

Topological and kinematical analysis event by event



ECC exposure at CERN-PS





Cell structure; exploited τ decay channels and topologies

- **“Long” decays**

  kink angle q$_{kink}$ > 20 mrad

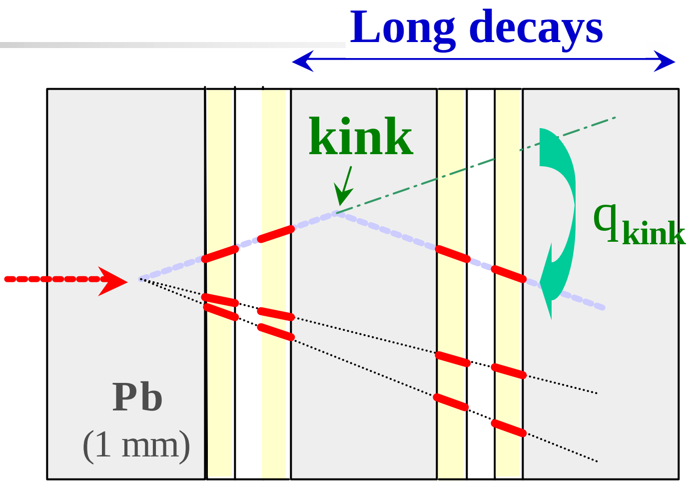
t ® **e**	Progr. Rep.	1999
t ® m	Progr. Rep.	1999
t ® **h (np^0)**	Proposal	2000
+ r **search**	Status Rep.	2001

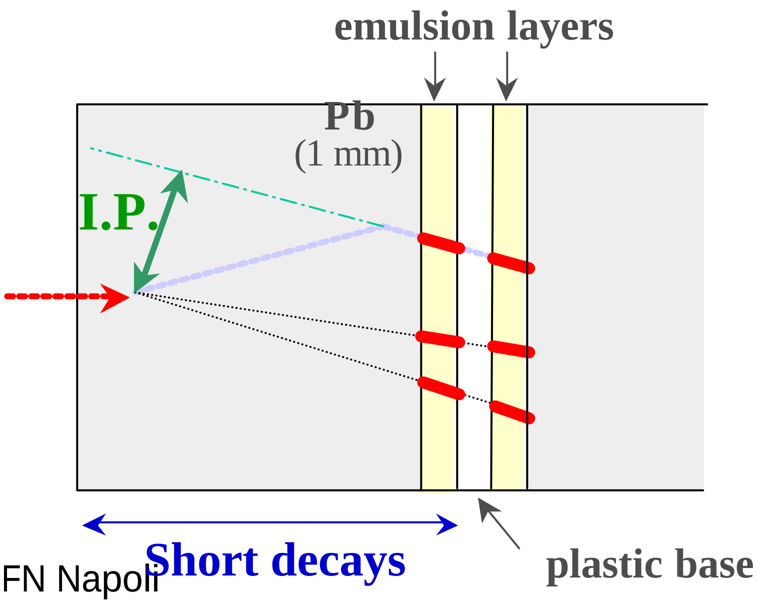
- **“Short” decays**

  impact parameter I.P. > 5 to 20 mm

t ® **e**	Proposal	2000
t ® m	Status Rep.	2001

An optimized channel by channel analysis is in progress. Ready by summer





Backgrounds for the $\nu_\mu \rightarrow \nu_\tau$ search

- Charm production
  - Cross-section and charmed fractions based on neutrino data
- Large angle μ scattering
  - Rate of μ scattering off lead estimated by using
    - MC simulation including nuclear form factors (cross-checked with NOMAD data)
    - data from 7.3 GeV/c μ scattering off copper
    - μ scanned in the CHORUS emulsions
  - Scattering off lead of μ (p= 6-10 GeV/c) experimentally studied by the Collaboration. Results in agreement with expectations
- Hadron reinteractions with kink topology
  - the present estimate is based on a FLUKA simulation
  - consistent with preliminary results from dedicated experiments

Expected number of events

full mixing; 5 years run @ $4.5\text{x}10^{19}$ pot / year

	signal ($\Delta m^2 = 1.8 \times 10^{-3}$ eV^2)	signal ($\Delta m^2 = 2.5 \times 10^{-3}$ eV^2)	signal ($\Delta m^2 = 4.0 \times 10^{-3}$ eV^2)	Back
Final Design CNGSx1.5 *)	9.0	17.2	43.8	1.06
With possible improvements	10.3	19.8	50.4	0.67

Aim at the evidence of ν_τ appearance after a few years of data taking

*) An updated CNGS with a flux 1.5 more intense than the one approved in 1999 is now considered as the baseline option

Probability of $\geq n\sigma$ significance for different Δm^2

Δm^2(eV^2)	3 years (20.3×10^{19} pot)		5 years (33.8×10^{19} pot)	
	$P_{3\sigma}$(%)	$P_{4\sigma}$	$P_{3\sigma}$(%)	$P_{4\sigma}$
1.8×10^{-3}	77.2(91.1)	46.8(68.2)	97.2(99.5)	87.4(96.2)
2.2×10^{-3}	94.9(98.9)	80.5(93.0)	99.9(100)	99.0(99.9)
2.5×10^{-3}	98.9(99.9)	93.9(98.6)	199(100)	99.9(100)
3.0×10^{-3}	100(100)	99.6(100)	100(100)	100(100)
4.0×10^{-3}	100(100)	100(100)	100(100)	100(100)

Best fit of SK + K2K is $\Delta m^2 = (2.6 \pm 0.4)$ eV^2 Fogli et al. hep-ph/0303064
The number in parenthesis are obtained assuming possible improvements

$\nu_\mu \rightarrow \nu_e$ search with OPERA

(interesting by product)

A similar analysis can also be performed with the ICARUS detector

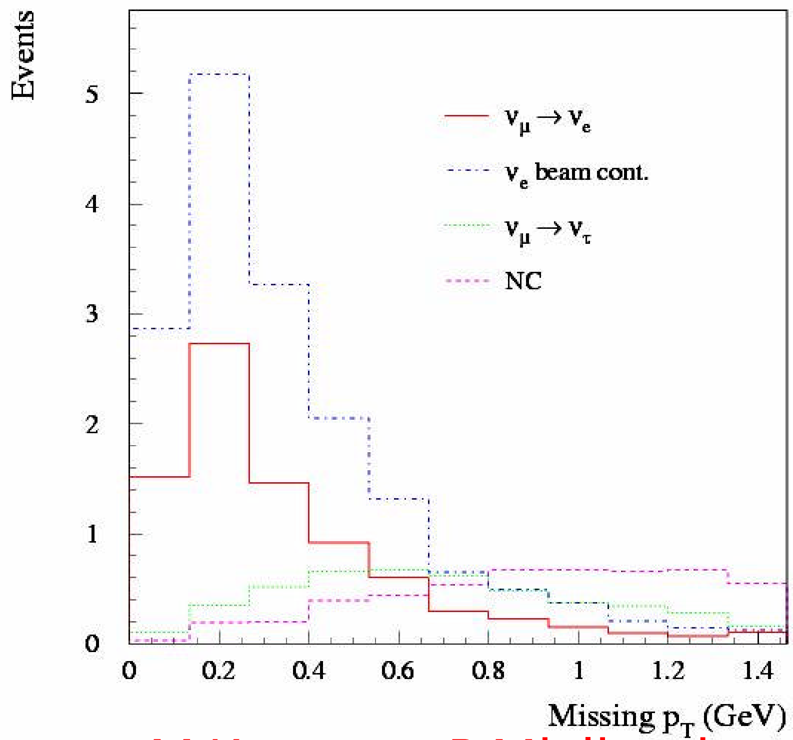
Backgrounds for the $\nu_\mu \rightarrow \nu_e$ search

- π^0 identified as electrons produced in ν_μ NC and ν_μ CC with the μ not identified
- ν_e beam contamination (main background)
- $\tau \rightarrow e$ from $\nu_\mu \rightarrow \nu_\tau$ oscillations (strongly reduced thanks to the capability in detecting decay topologies)

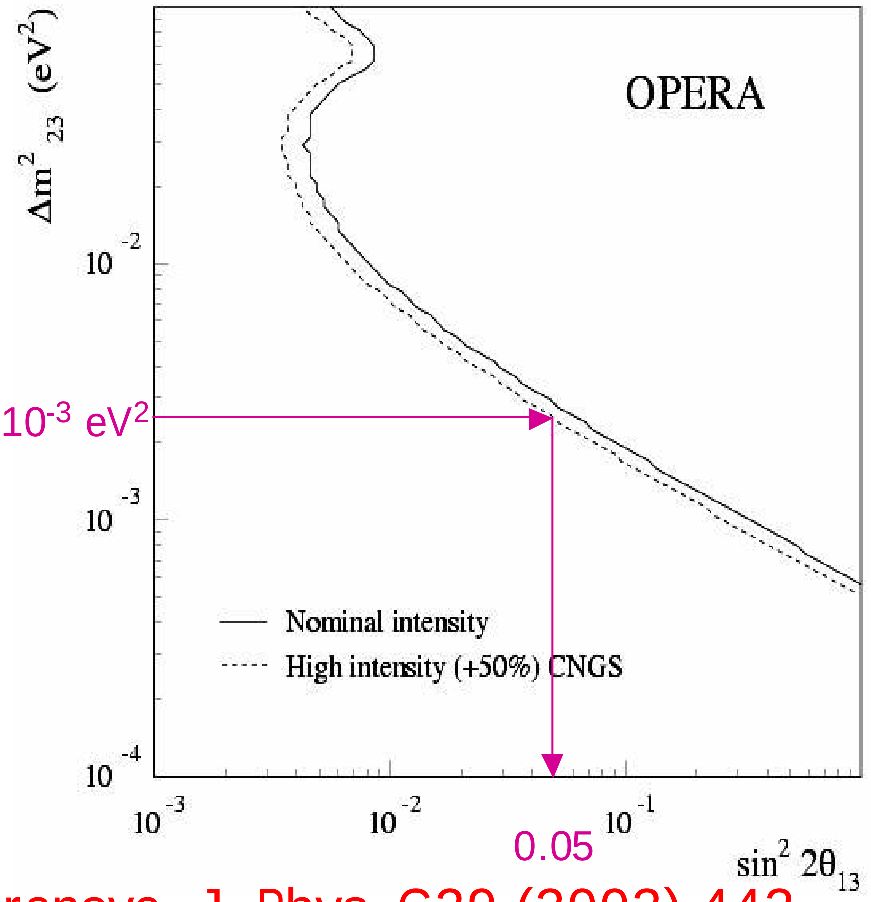
In the following we assume a three family mixing scenario with $\theta_{23} = 45^\circ$

OPERA sensitivity to θ_{13}

By fitting simultaneously the E_e, missing p_T and E_{vis} distributions we got the sensitivity at 90%



5years data taking



2.5×10^{-3} eV^2

0.05

M.Komatsu, P.Migliozzi and F.Terranova, J. Phys. G29 (2003) 443

Summary of the CNGS project

- Construction of CNGS is well underway. The tunnel excavation is complete. The remaining construction work is on schedule (Beam starts by mid 2006)
- The ICARUS and OPERA experiments will permit
  - An unambiguous direct evidence of τ appearance in a ν_μ beam
  - A measurement of Δm^2 at 10-20%
  - Extend sensitivity for small $\nu_\mu \rightarrow \nu_e$ mixings (competitive with other experiments)
- The construction of the detectors is in progress and it is planned to be completed by mid 2006

Goals of 2nd generation of Long Baseline Experiments

- Precision measurement of PMNS matrix elements
  - $\sin^2 2\theta_{23}$ with 1% accuracy
  - Δm^2 with few% accuracy
- Discovery (if not done by 1st generation experiments) and measure non-zero θ_{13}
  - They could give the 1st evidence of 3-flavor mixing
  - In case of non-zero θ_{13} precision measurement
  - 1st step to CP measurement

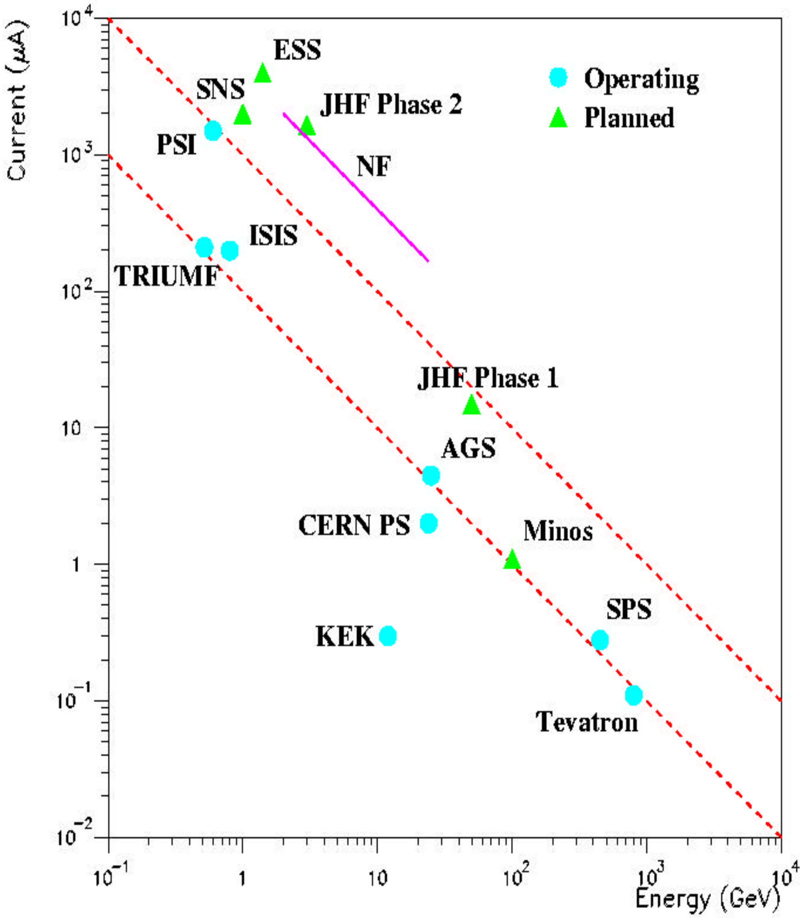
NB If $\theta_{13} < 1^\circ$ impossible to assess CP violation in the leptonic sector. The other condition to make CP in the leptonic sector detectable has been fulfilled by KamLAND (LMA solution)

Conventional superbeams

- Exploit extremely intense proton sources to produce beam from π-decay
- Intermediate step to neutrino factory
  - π beam necessary for μ beam
- Sensitivity intermediate between near-term experiments and neutrino factory
- Cost also intermediate
- Technical hill less steep to climb
  - Proton drivers essentially designed (or existing)
  - Radiation damage near target station may be important

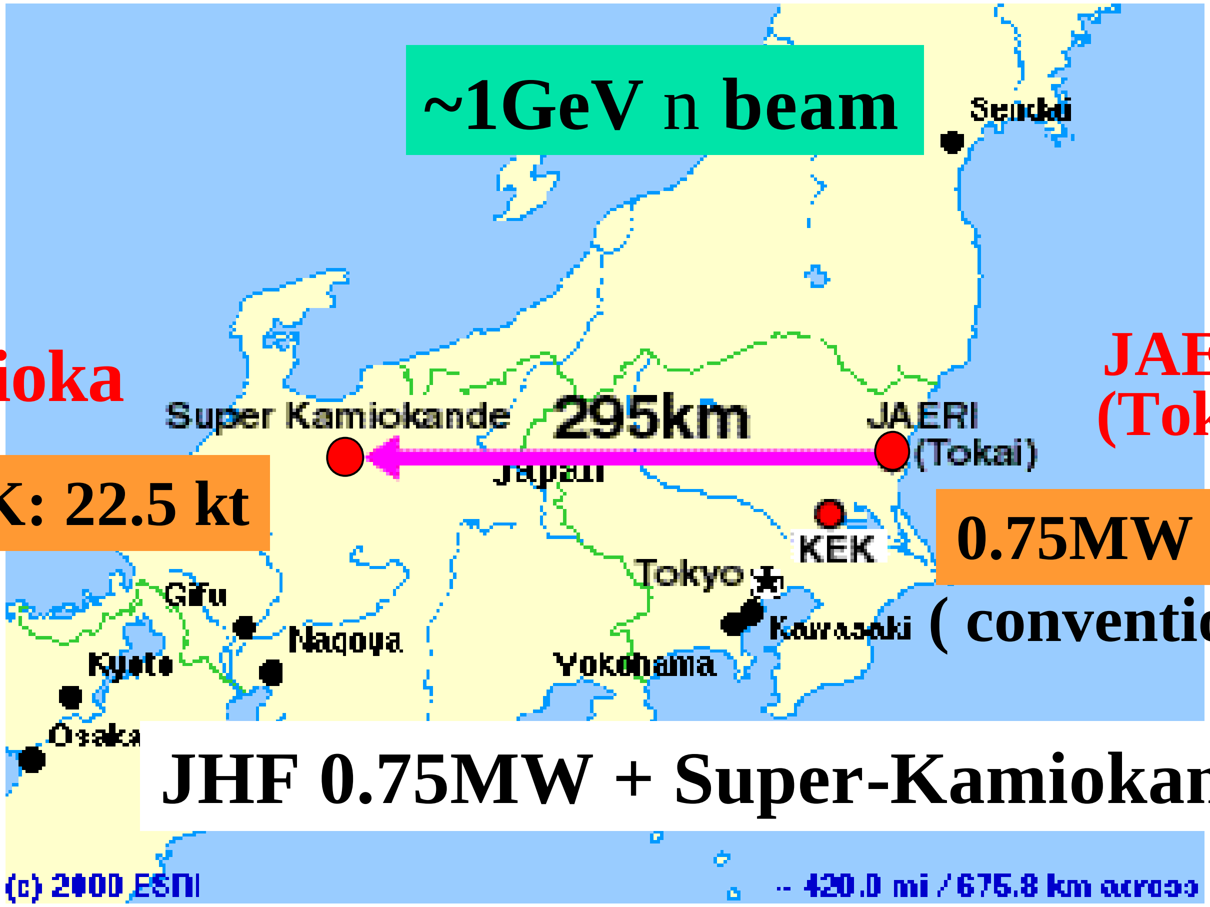
Possible Future Proton Drivers

Source	Place	Proton Energy (GeV)	Power (MW)
Upgr. Booster	FNAL	16	1?
Upgr. NUMI	FNAL	120	1.6
50 GeV PS	JHF	50	0.77 (→4)
SPL	CERN	2.2	4



JHF-Super-Kamiokande Neutrino Experiment

Plan to start in 2008-9



~1GeV n beam

Kamioka

Super-K: 22.5 kt

JAERI (Tokai)

0.75MW 50 GeV PS

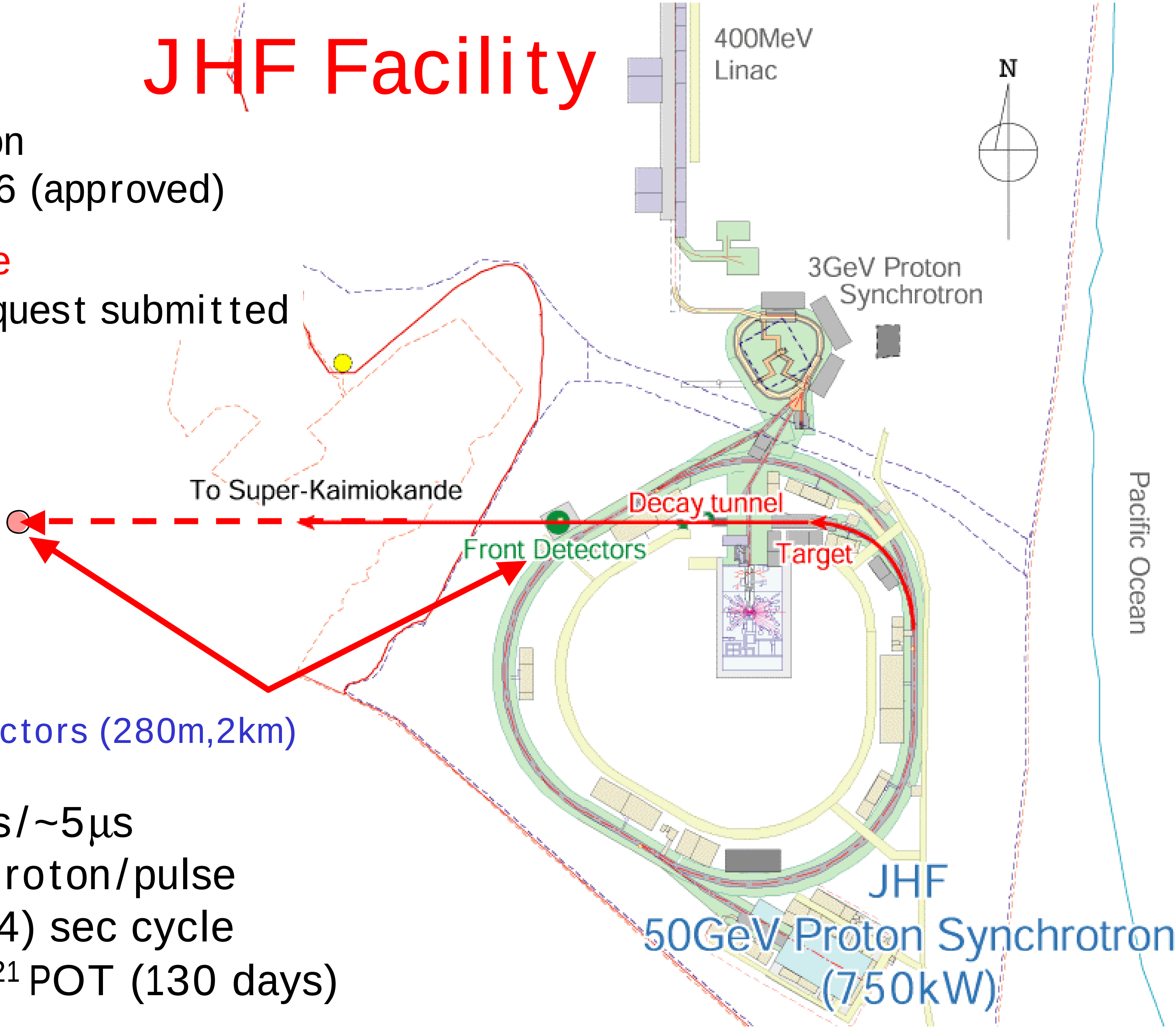
(conventional n beam)

JHF 0.75MW + Super-Kamiokande

JHF Facility

Construction
2001~ 2006 (approved)

ν beam-line
budget request submitted

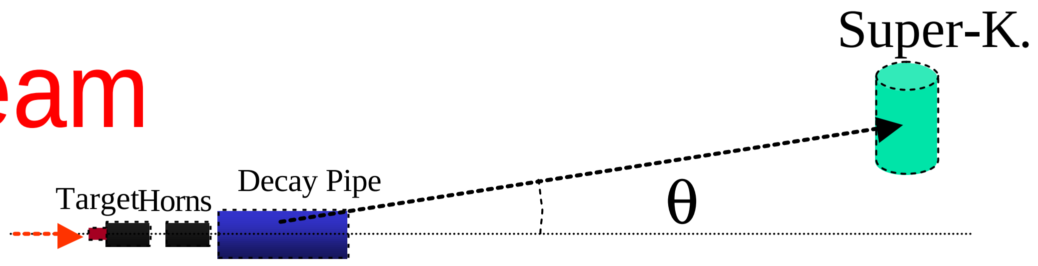


Near detectors (280m,2km)

- ➢8 bunches/~5μs
- ➢3.3×10^{14}proton/pulse
- ➢3.94 (3.64) sec cycle
- ➢1yr = 10^{21} POT (130 days)

Off Axis Beam

(ref.: BNL-E889 Proposal)



- Quasi Monochromatic Beam
- x2~3 intense than NBB

Statistics at SK

(OAB2deg, 1yr,22.5kt)

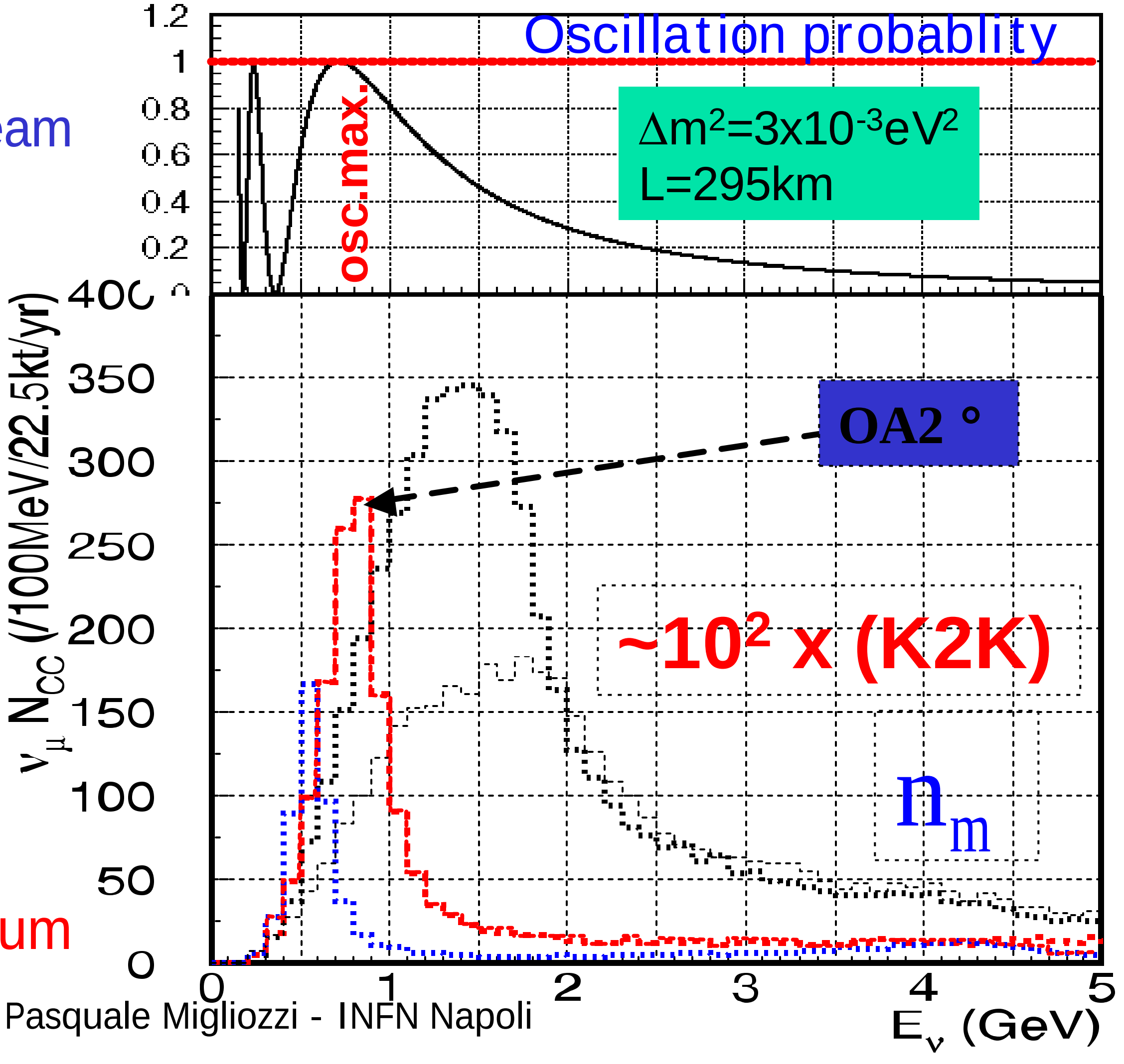
~4500 ν_μ tot

~3000 ν_μ CC

ν_e ~0.2% at ν_μ peak

Tuned at oscillation maximum

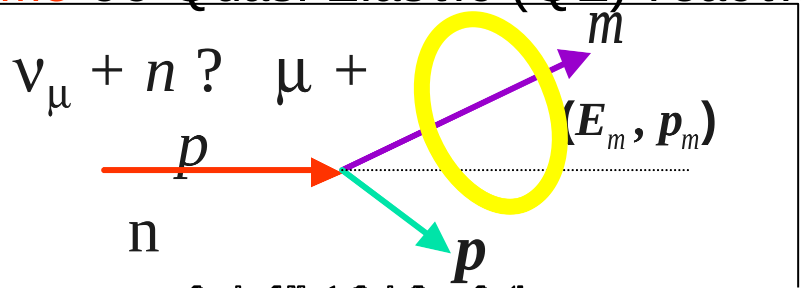
Osc. Prob.=$\sin^2(1.27\Delta m^2 L/E_\nu)$

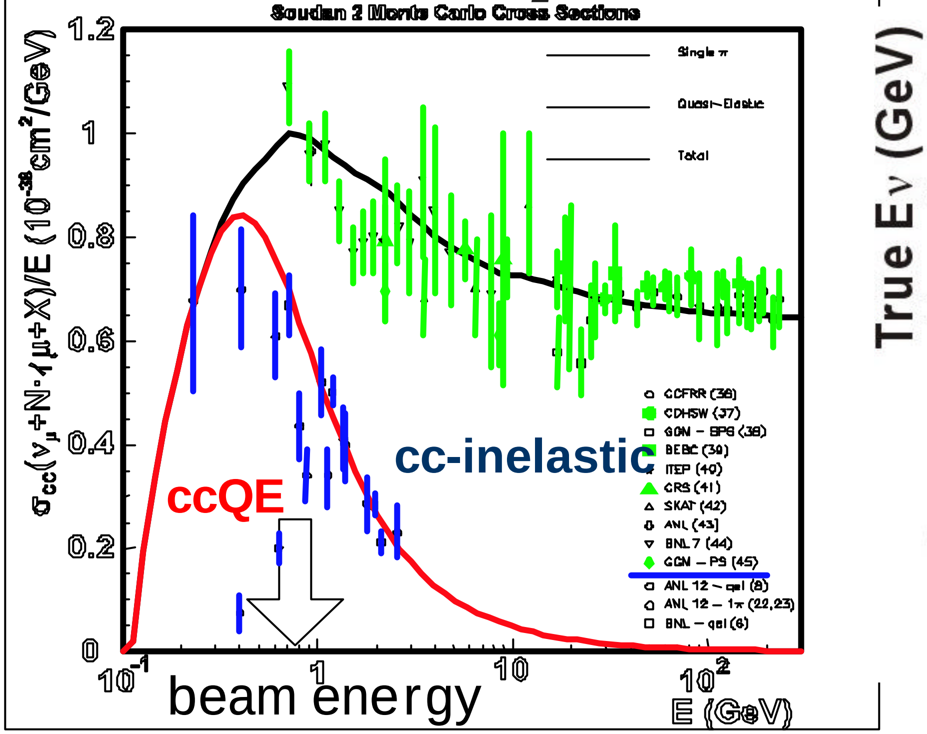


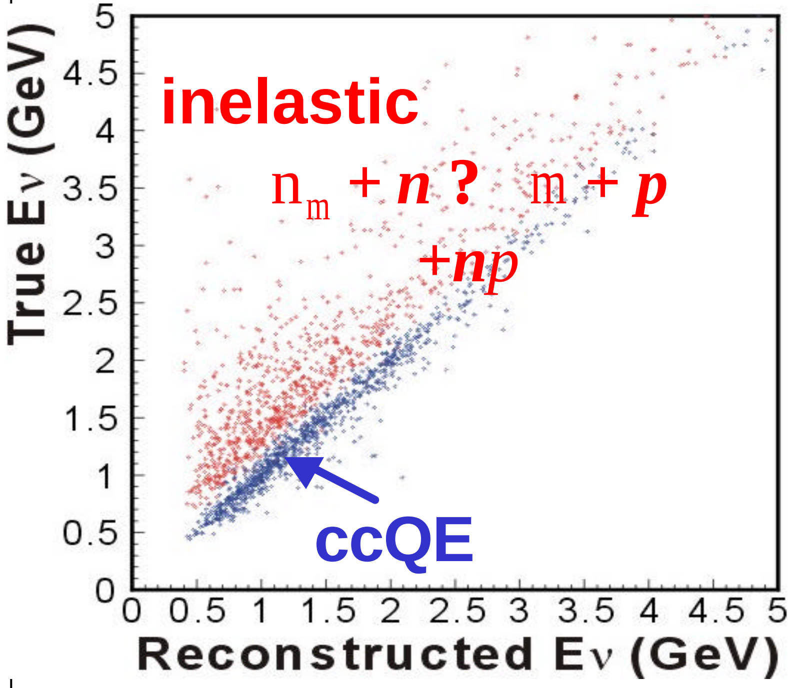
E_ν reconstruction in water Cerenkov

Assume CC Quasi Elastic (QE) reaction

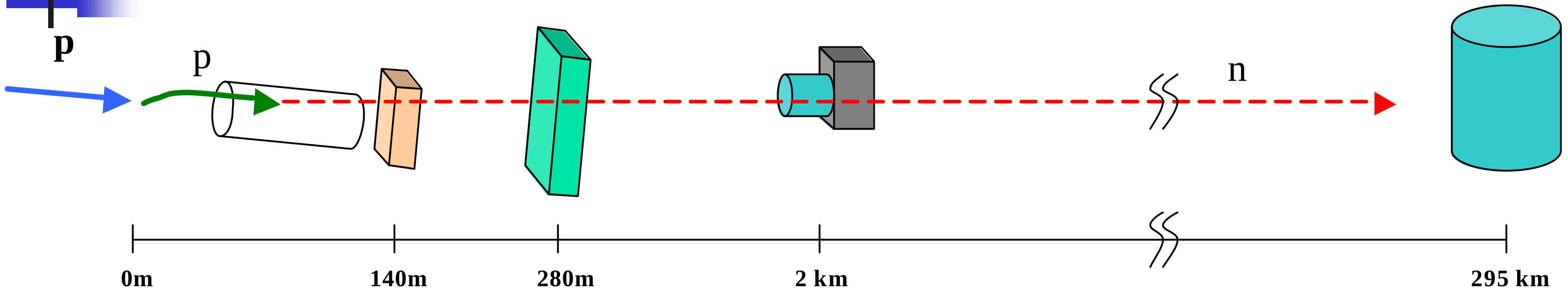
$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$





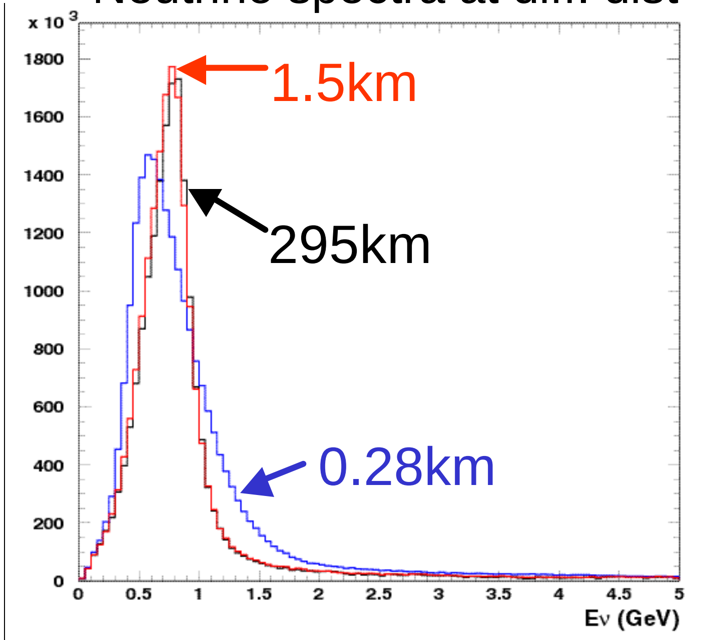


Detectors



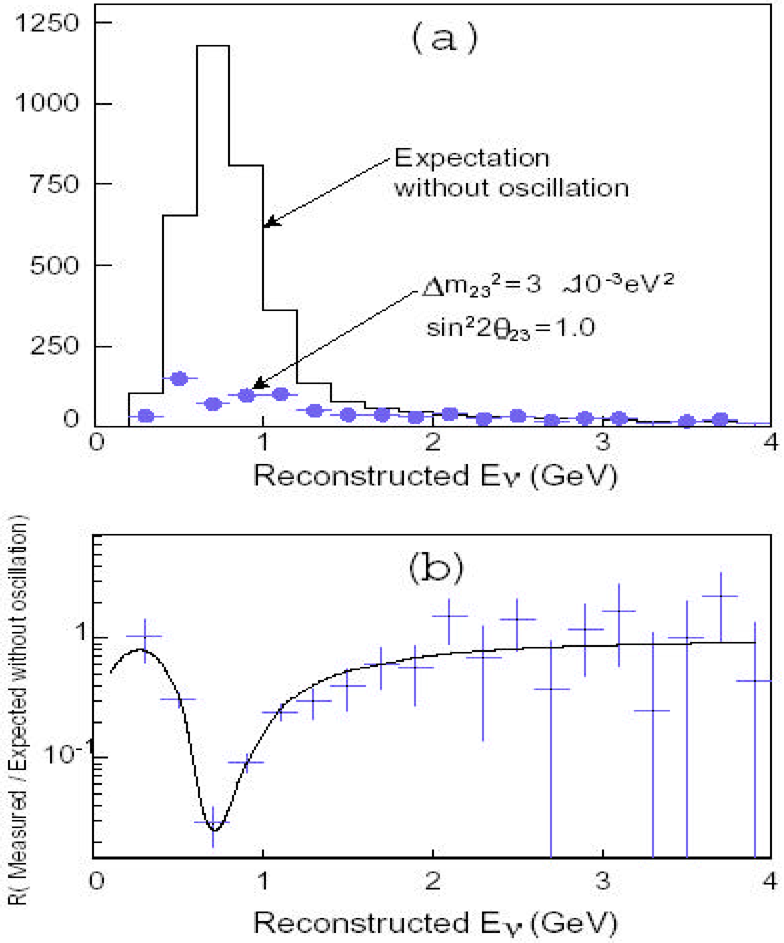
- Muon monitors @ ~140m
  - Spill-by-spill monitoring of beam direction
- First Front detector @280m
  - Neutrino intensity/direction
- Second Front Detector @ ~2km
  - Almost same E_n spectrum as for SK
  - Water Cherenkov can work
- Far detector @ 295km
  - Super-Kamiokande (50kt)

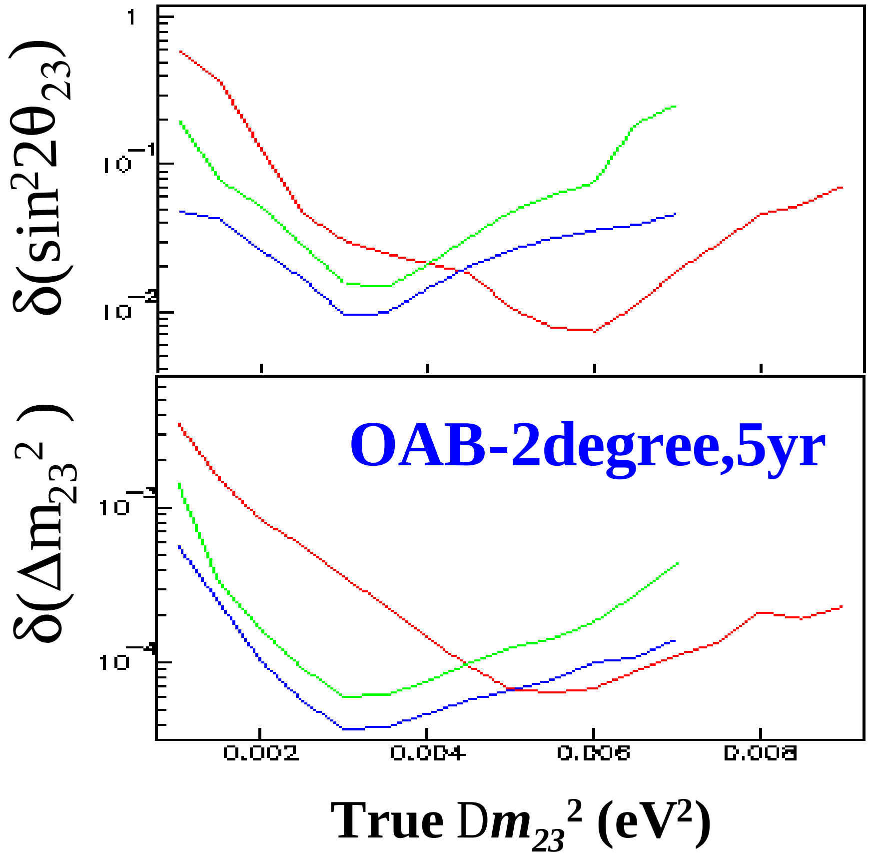
Neutrino spectra at diff. dist



dominant syst. in K2K

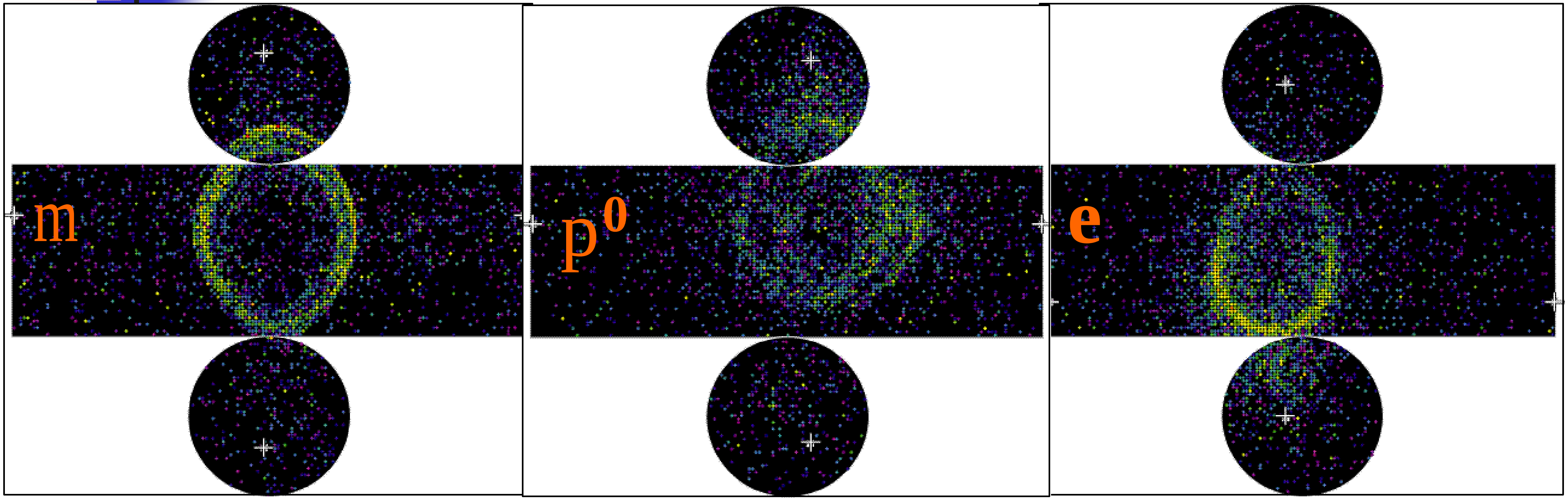
Measurement of $\sin^2 2\theta_{23}$-Δm^2_{23}





$\delta(\sin^2 2\theta)$~0.01 $\delta(\Delta m^2)$~<1 × 10^{-4}

ν_e appearance in JHF-Kamioka

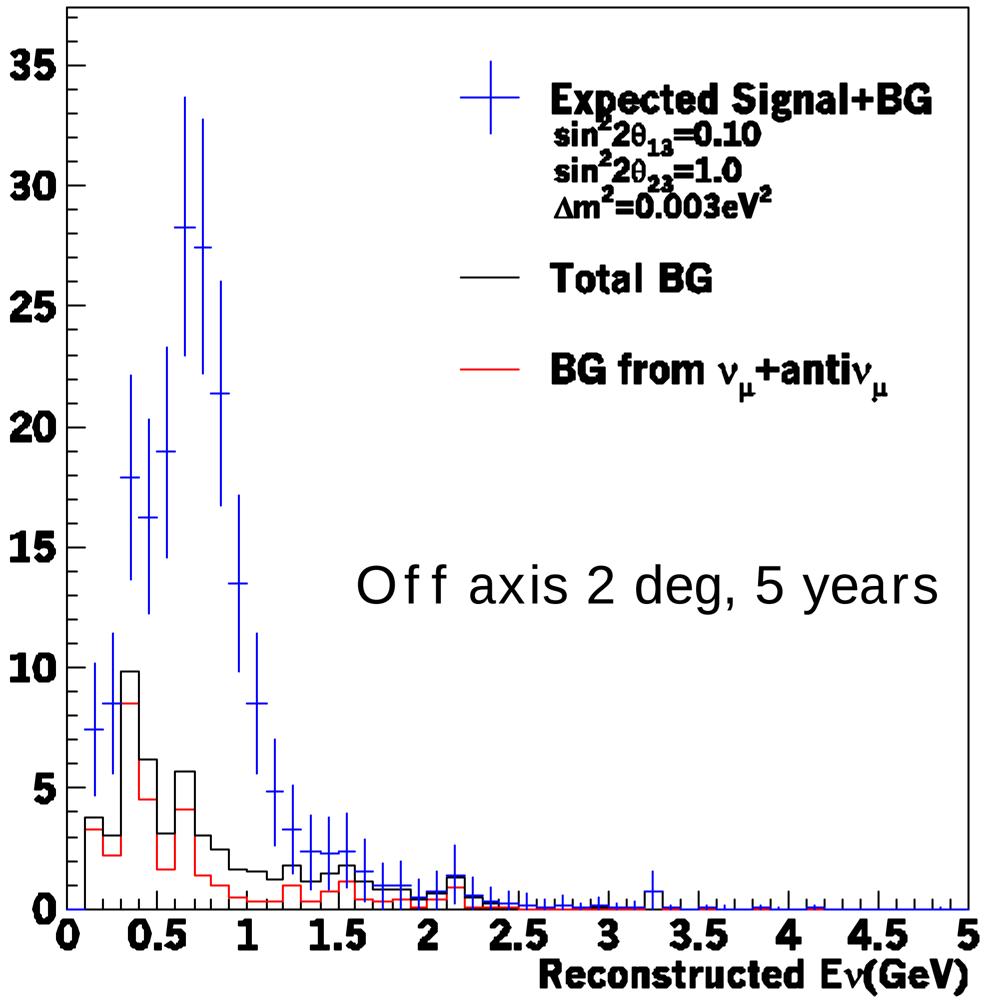


Background for ν_e appearance search

- Intrinsic ν_e component in initial beam
- Merged π^0 ring from ν_μ interactions

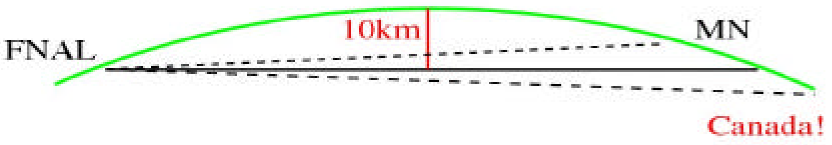
10% uncertainty for BG estimation

$\sin^2 2\theta_{13}$ from ν_e appearance



Off axis 2 deg, 5 years

NuMI Off-Axis



Two possible sites

- Closer site, in Minnesota
  - About 711 km from Fermilab
  - Close to Soudan Laboratory
  - Unused former mine
  - Utilities available
  - Flexible regarding exact location
- Further site, in Canada, along Trans-Canada highway
  - About 985 km from Fermilab
  - There are two possibilities:
    - About 3 km to the west, south of Stewart Lodge
    - About 2 km to the east, at the gravel pit site, near compressor station

θ_{13} sensitivity

- How the sensitivity to θ_{13} depends on the CP phase?
- In case of null results, what we can say about future (JHF-HK, Neutrino Factory) expts?

Some remarks

(see in the following for details)

- JHF-SK and NUMI off-axis are tuned to maximize discovery potential:
  - Energy tuned to maximum of oscillation probability
  - Enhance the dependence of subdominant terms to be sensitive to δ (CP phase)
  - Small dependence on matter effects (short baseline).
  - ⇒ Problems with JHF-SK and NUMI off-axis in case of null results because they run only with neutrinos

    (P.Huber, M.Lindner, W.Winter Nucl.Phys. B 645 (2002) 3)

    (T. Kajita, H. Minakata, H. Nunokawa Phys. Lett. B 528 (2002) 245)
- If JHF-SK and/or NUMI off-axis finds evidence of ν_e appearance:
  - measure θ_{13} with high accuracy (see later) and future projects (JHF-HK, Neutrino Factories) will be based on solid grounds

Oscillation probability

$$P_{n_m \to n_e} \cong \sin^2 2q_{13} \sin^2 q_{23} \frac{\sin^2\left[\left(1-\hat{A}\right)\Delta\right]}{\left(1-\hat{A}\right)^2}$$

$$- a \sin q_{13} x \sin d_{CP} \sin \Delta \frac{\sin\left(\hat{A}\Delta\right)}{\hat{A}} \frac{\sin\left[\left(1-\hat{A}\right)\Delta\right]}{\left(1-\hat{A}\right)}$$

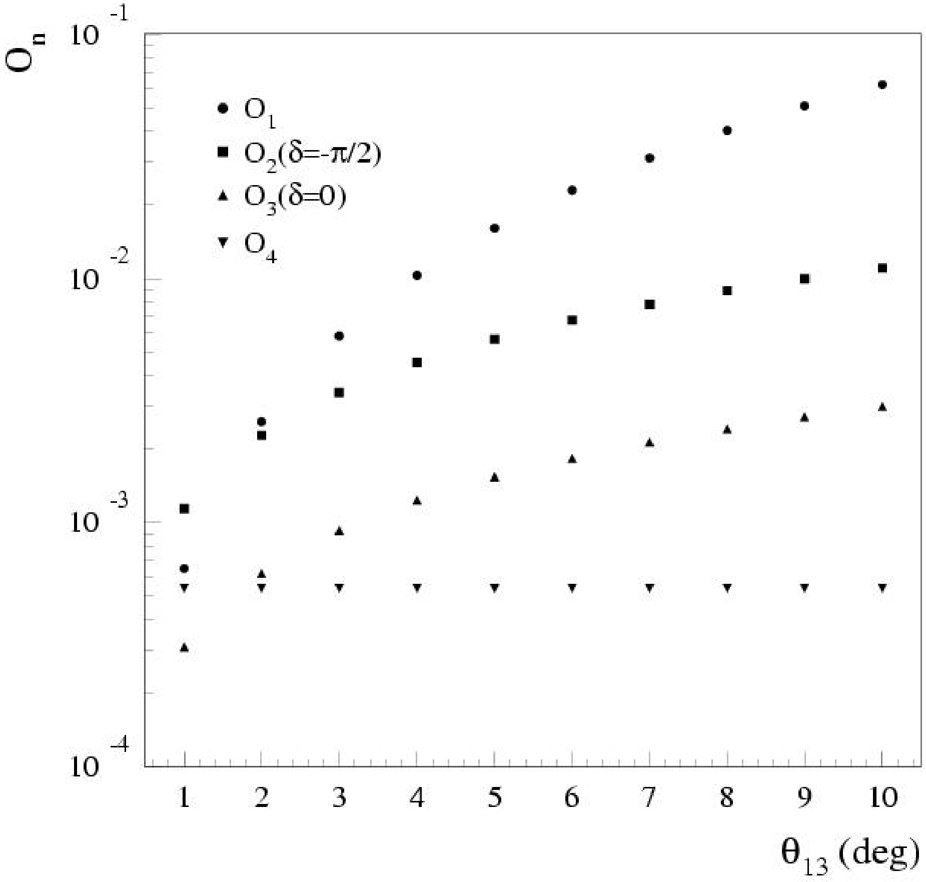
$$+ a \sin q_{13} x \cos d_{CP} \cos \Delta \frac{\sin\left(\hat{A}\Delta\right)}{\hat{A}} \frac{\sin\left[\left(1-\hat{A}\right)\Delta\right]}{\left(1-\hat{A}\right)}$$

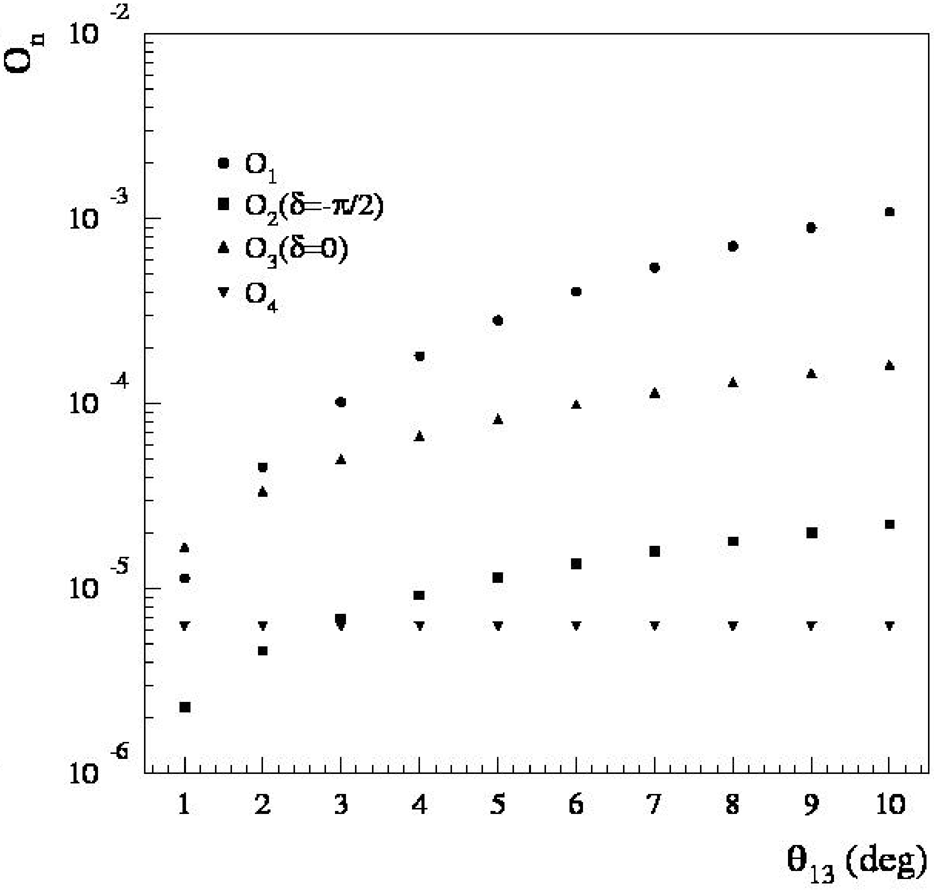
$$+ a^2 \cos^2 q_{23} \sin^2 2q_{12} \frac{\sin^2\left(\hat{A}\Delta\right)}{\hat{A}^2}$$

$$\equiv O_1 + O_2(d) + O_3(d) + O_4$$

$$a = \frac{\Delta m^2_{21}}{\left|\Delta m^2_{31}\right|}$$

O_i terms in osc. prob. vs θ_{13}


JHF


CNGS

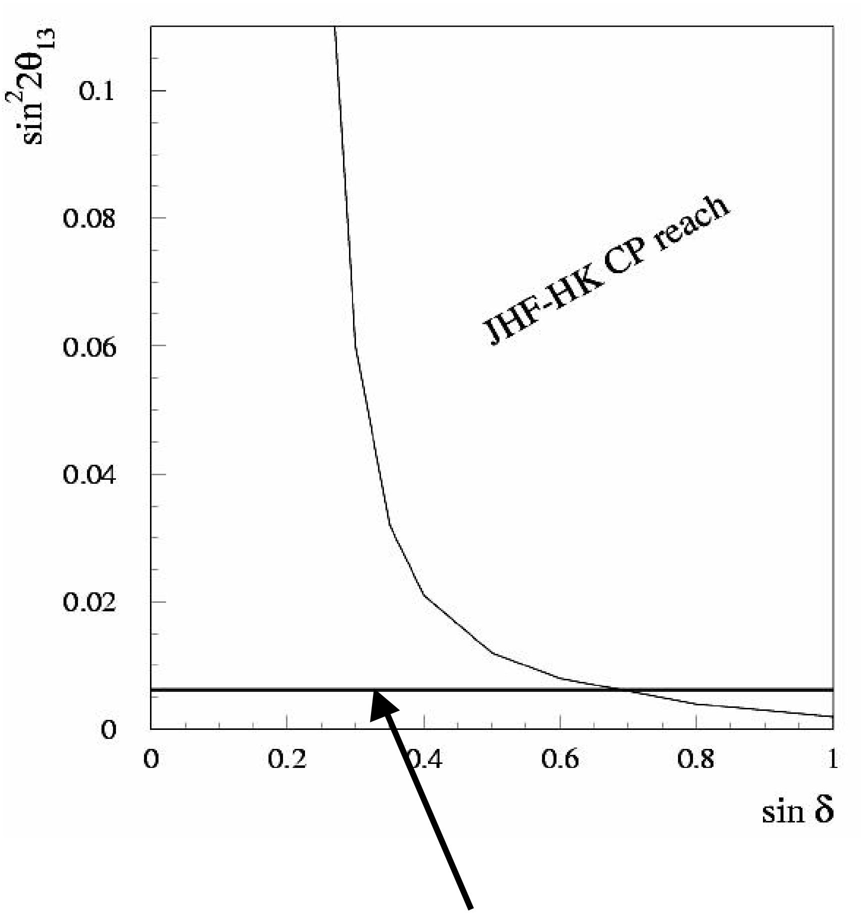
Several observations

- The first and the forth terms are independent of the CP violating parameter δ
- If θ_{13} is very small (= 1º) the second term (subdominant oscillation) competes with 1st
- For small θ_{13}, the CP terms are proportional to θ_{13}; the first (non-CP term) to θ_{13}^2
- The CP violating terms grow with decreasing E_ν (for a given L)
- There is a strong correlation between different parameters
- CP violation is observable only if all angles ? 0

θ_{13} issue

- The measurement of θ_{13} is made complicated by the fact that oscillation probability is affected by matter effects and possible CP violation
- Because of this, there is not a unique mathematical relationship between oscillation probability and θ_{13}
- Especially for low values of θ_{13}, sensitivity of an experiment to seeing $\nu_\mu \rightarrow \nu_e$ depends very much on δ
- Several experiments with different conditions and with both $\bar{\nu}$ and ν will be necessary to disentangle these effects
- θ_{13} needs to be sufficiently large if one is to have a chance to investigate CP violation in ν sector

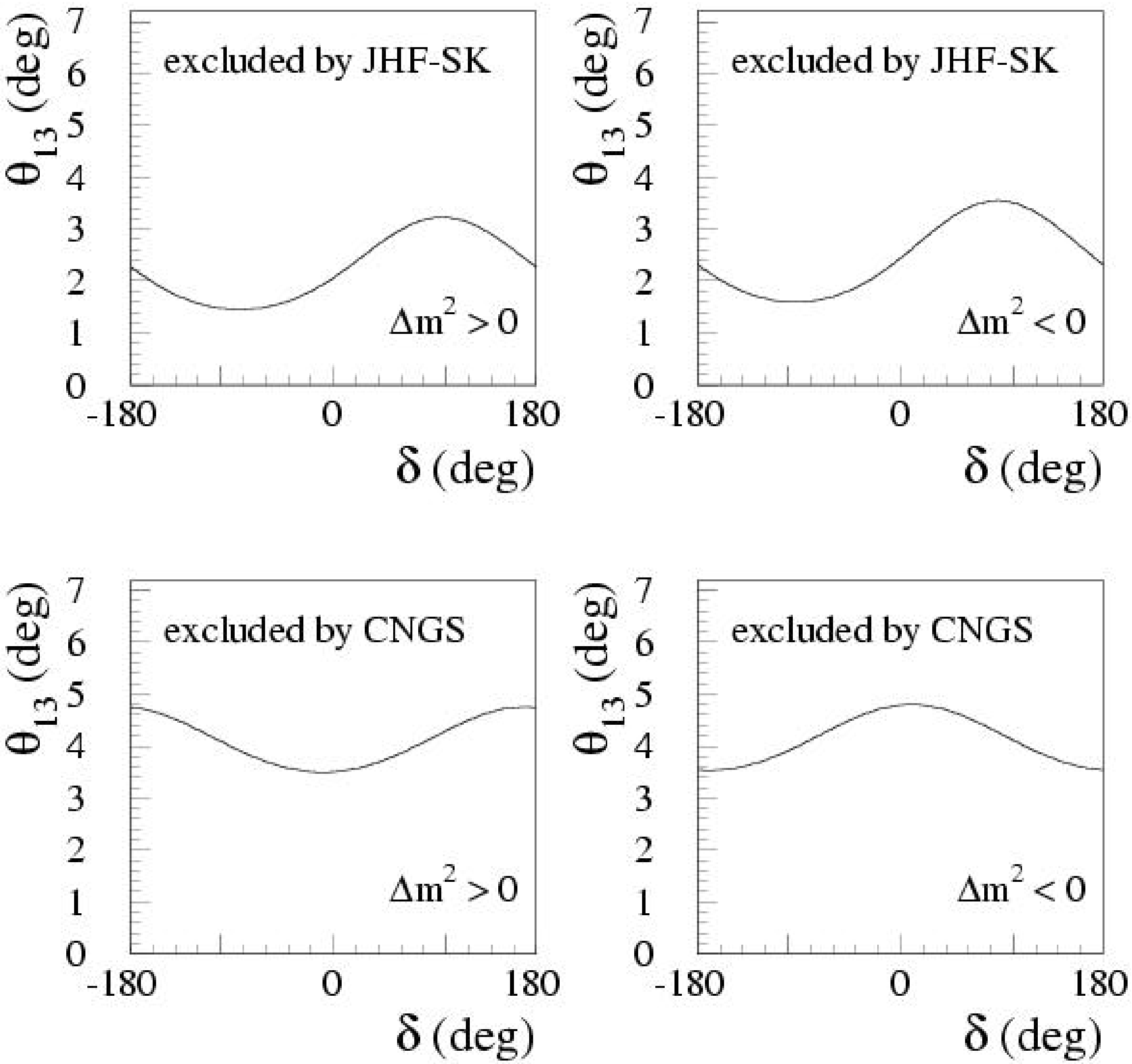
JHF-SK were a “pure θ_{13} exp” as reactors



Sensitivity of a pure θ_{13} exp

Figure taken from Nakaya talk at Neutrino 2002

Accelerator expts. sensitivity vs δ_{CP} (1)



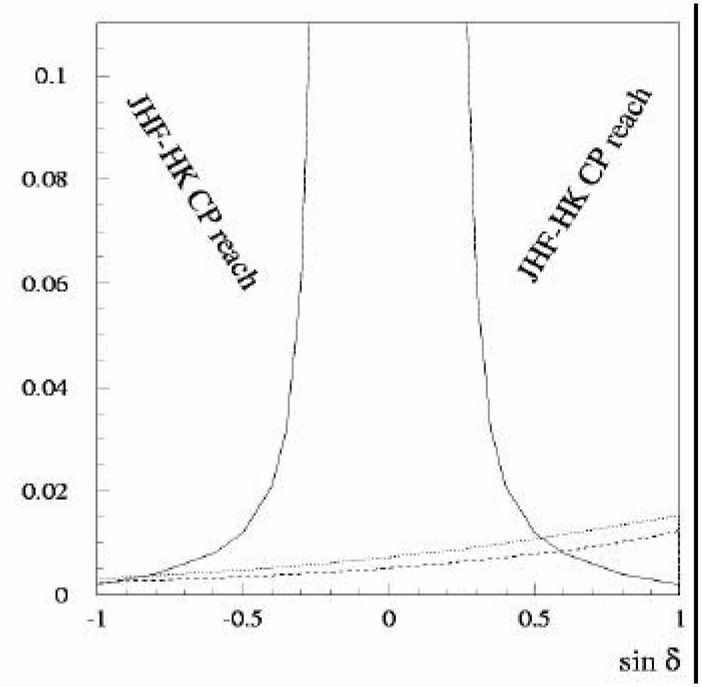
There are δ_{CP} values for which the sensitivity on θ_{13} is even better than the one compute in the 2-flavor approximation (δ_{CP}=0).

Notice the different behaviour on Δm^2 of the CNGS sensitivity

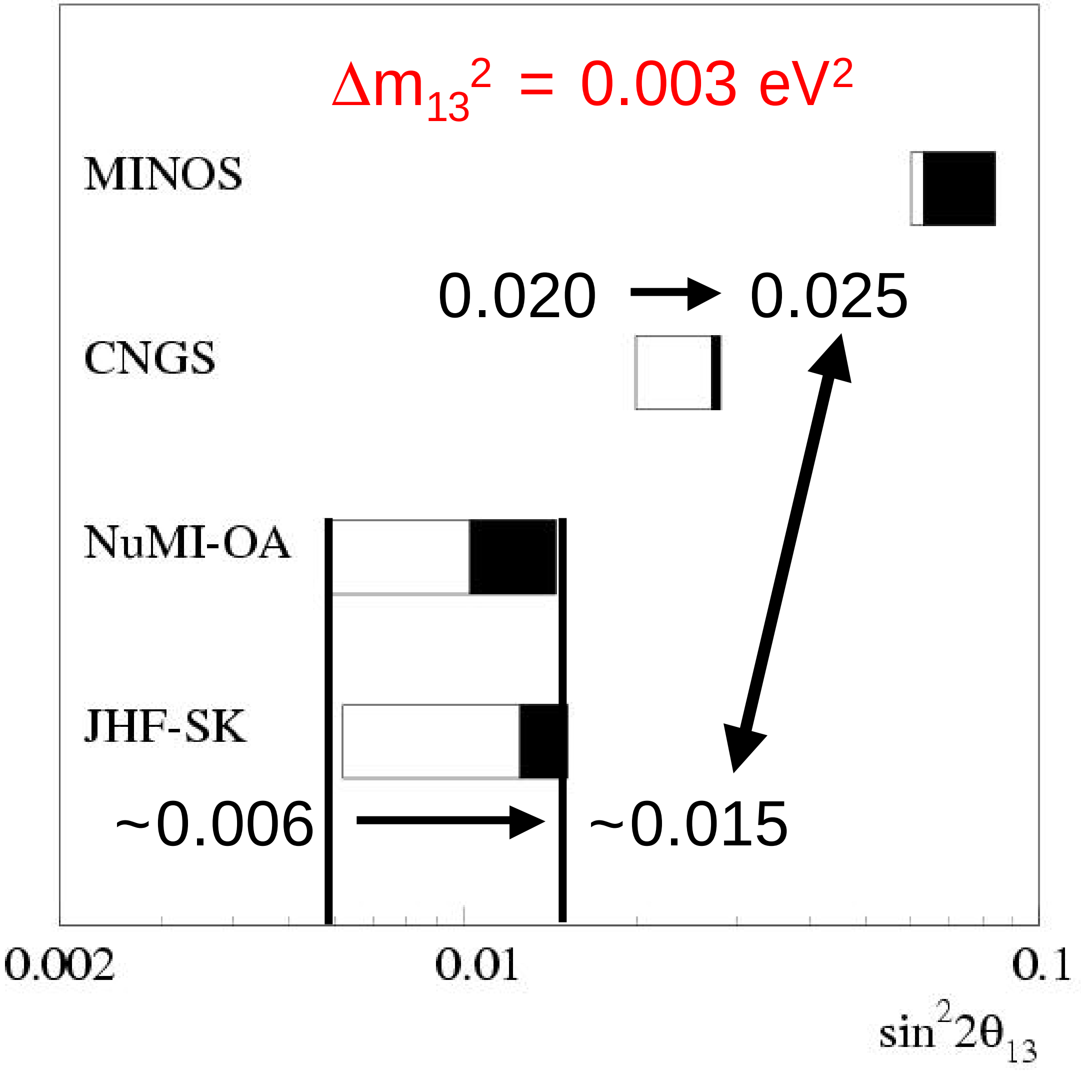
$\Rightarrow$ Possible measurement of the sign of Δm^2_{31}?

Accelerator expts. sensitivity vs δ_{CP} (2)

- Given the sensitivity dependence on δ_{CP} and sign of Δm^2_{31} in case of null results two hypotheses
  - θ_{13} is too small → give up JHF-HK and Neutrino Factory
  - δ_{CP} is positive and very large → giving up JHF-HK and Neutrino Factory would be a tremendous mistake because after an anti-ν run one would have a "monumental" signal



Sensitivity reduction of accelerator expts.



$\Delta m_{13}^2 = 0.003\ \mathrm{eV}^2$

$0.020 \rightarrow 0.025$

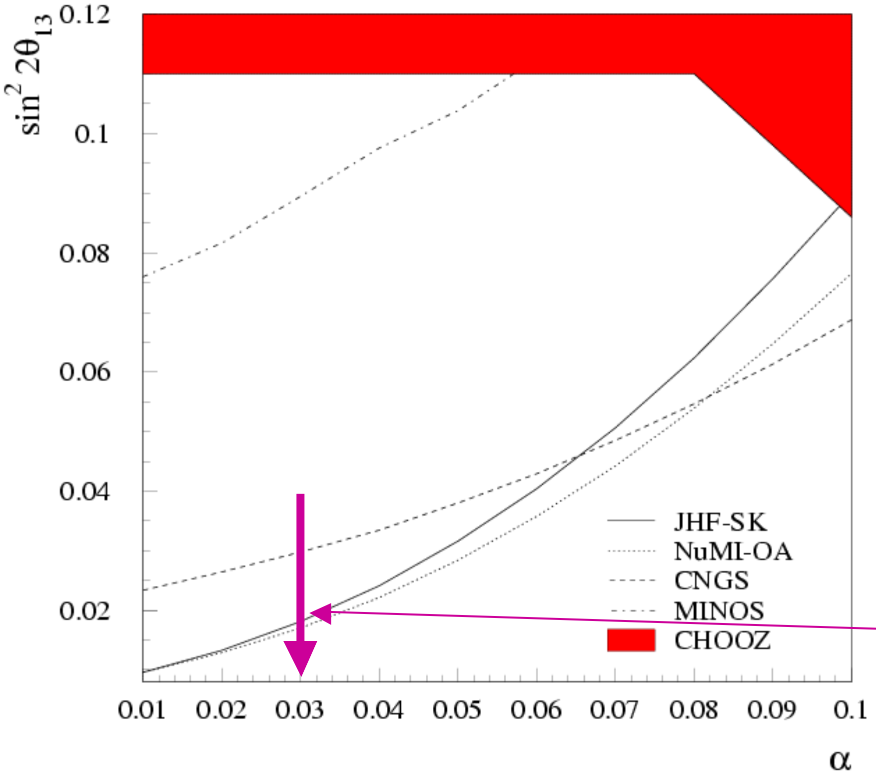
$\sim 0.006 \rightarrow \sim 0.015$

Hence assuming complete ignorance on δ_{CP} and on the sign of Δm^2_{31} and using no other information to lift the ambiguities, the actual excluded $\sin^2 2\theta_{13}$ is

and this is even worse for large values of $\alpha = \Delta m^2_{sol} / |\Delta m^2_{atmo}|$

Conclusion in case of null result

- JHF-SK and NUMI off-axis will provide a excellent measurement of θ_{23} and $|\Delta m^2_{31}|$.
- The sensitivity of JHF-SK/NUMI off axis is comparable with the one of the CNGS program for high values of α and for certain values of δ_{CP}.



Of course, an additional anti-ν run would help in increasing the sensitivity of JHF-SK for large values of α.

Another possibility is to perform a pure θ_{13} measurement with reactors (H.Minakata et al. hep-ph/0211111)

From G.L. Fogli et al. hep-ph/0212127

If $\nu_\mu \rightarrow \nu_e$ is observed

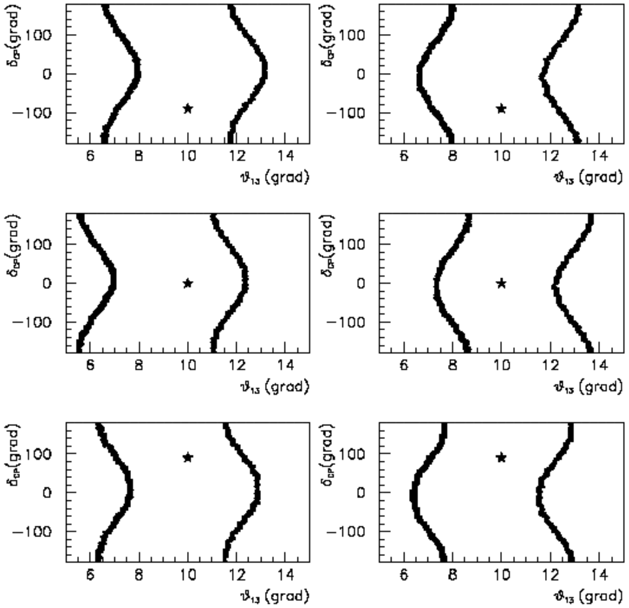
In the following: assume ICARUS and OPERA taking data from 2006 on

CNGS at the start-up of JHF-SK

- 3 years data taking at the CNGS
  - Sensitivity: $\sin^2 2\theta_{13} < 0.035$ @ 90% C.L. (a factor 4 better than CHOOZ)
  - Indication (90% C.L) of ν_e appearance if $\theta_{13} > 7°$

$\theta_{13}\vert_{true}$	$\theta_{13}\vert_{min}$	$\theta_{13}\vert_{max}$	
1°	---	5.5°	---
2.5°	---	5.8°	---
5.0°	---	7.0°	---
7.5°	1.2°	11.4°	$(7.5^{+3.9}_{-6.3})°$
10°	5.6°	13.7°	$(10.^{+3.7}_{-4.4})°$

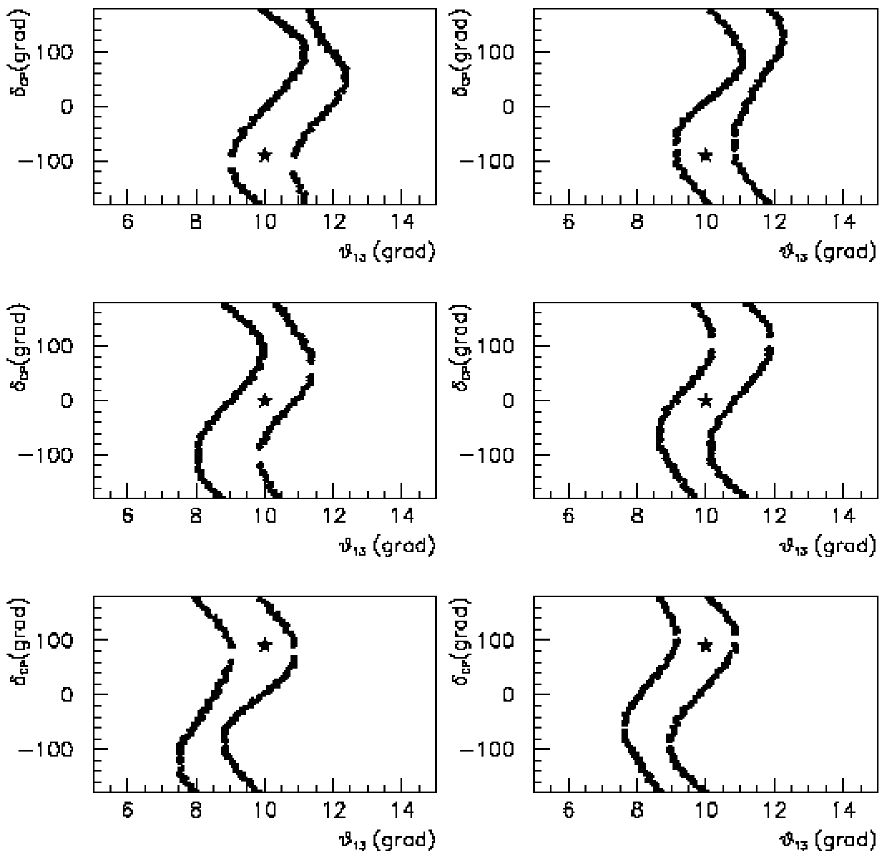
90% C.L. allowed region



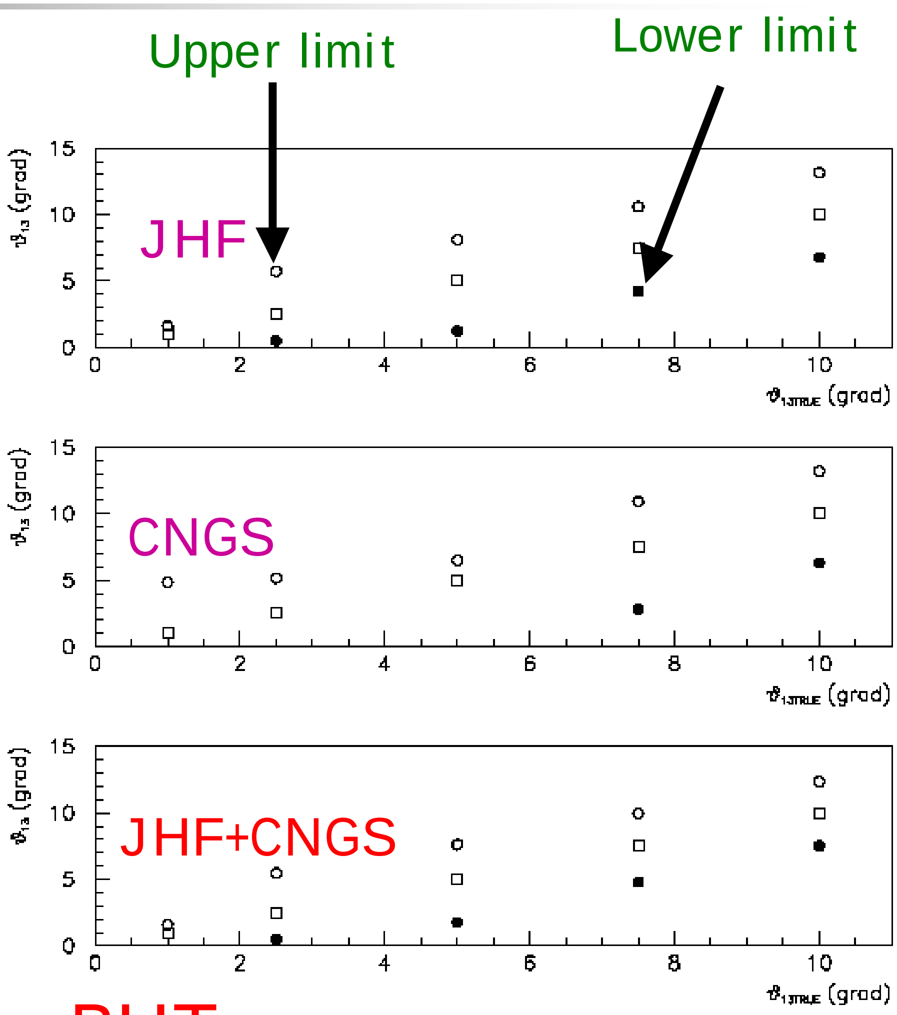
$\Delta m^2 < 0$ $\Delta m^2 > 0$

Allowed region in the θ_{13}- δ_{CP}

Allowed regions for JHF+CNGS
(5 years for each program)



$\Delta m^2<0$ $\Delta m^2>0$



BUT…

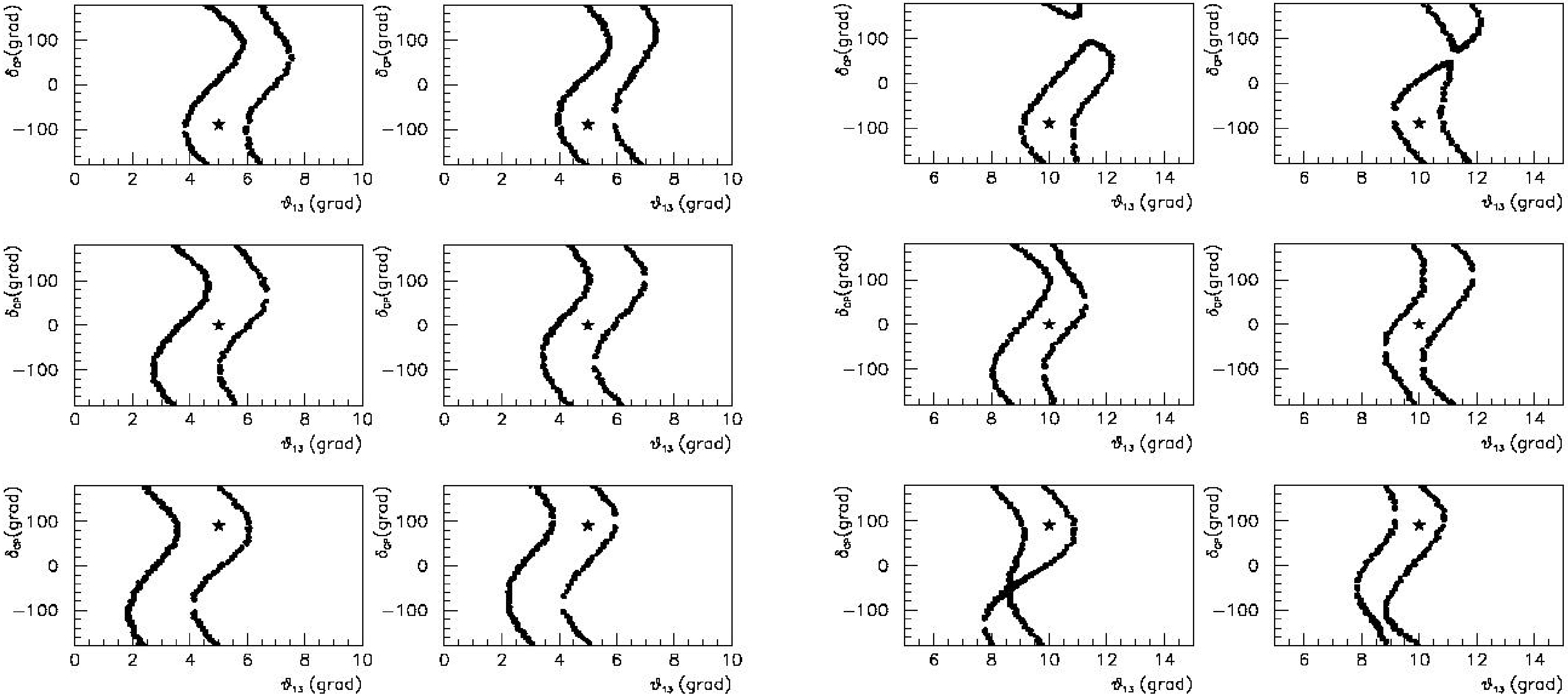
But …

- While JHF-SK is taking data, CNGS could do so as well. Therefore:
  - ⇨ At the end of the JHF-SK ν-run one should combine it with 8 years at the CNGS
- Remind that the CNGS is an off-peak beam, therefore it has a different pattern from JHF-SK ⇒ they can be used in synergy

Note: After 5 years of data taking sacrifice the $\tau \rightarrow \mu$ channel in order to save bricks and scanning power -> scan only NC (25% of the total)

Allowed regions for JHF (5 years) + CNGS (8years)

$\theta_{13}=5°$ $\theta_{13}=10°$



$\Delta m^2<0$ $\Delta m^2>0$ $\Delta m^2<0$ $\Delta m^2>0$

Conclusion in case ν_e appearance is observed

- If $\theta_{13} > 7°$, CNGS could give a first indication of ν_e appearance after three years data taking
- The CNGS is an off-peak beam, therefore it has a different pattern from JHF-SK ⇒ they can be used in synergy
  - We are investigating the possibility to constrain the sign of Δm^2
- After the completion of the approved CNGS program, one could continue the data taking

⇨ CNGS (8y) + JHF-SK(5y) could measure θ_{13} with 20% accuracy and constrain δ_{CP}

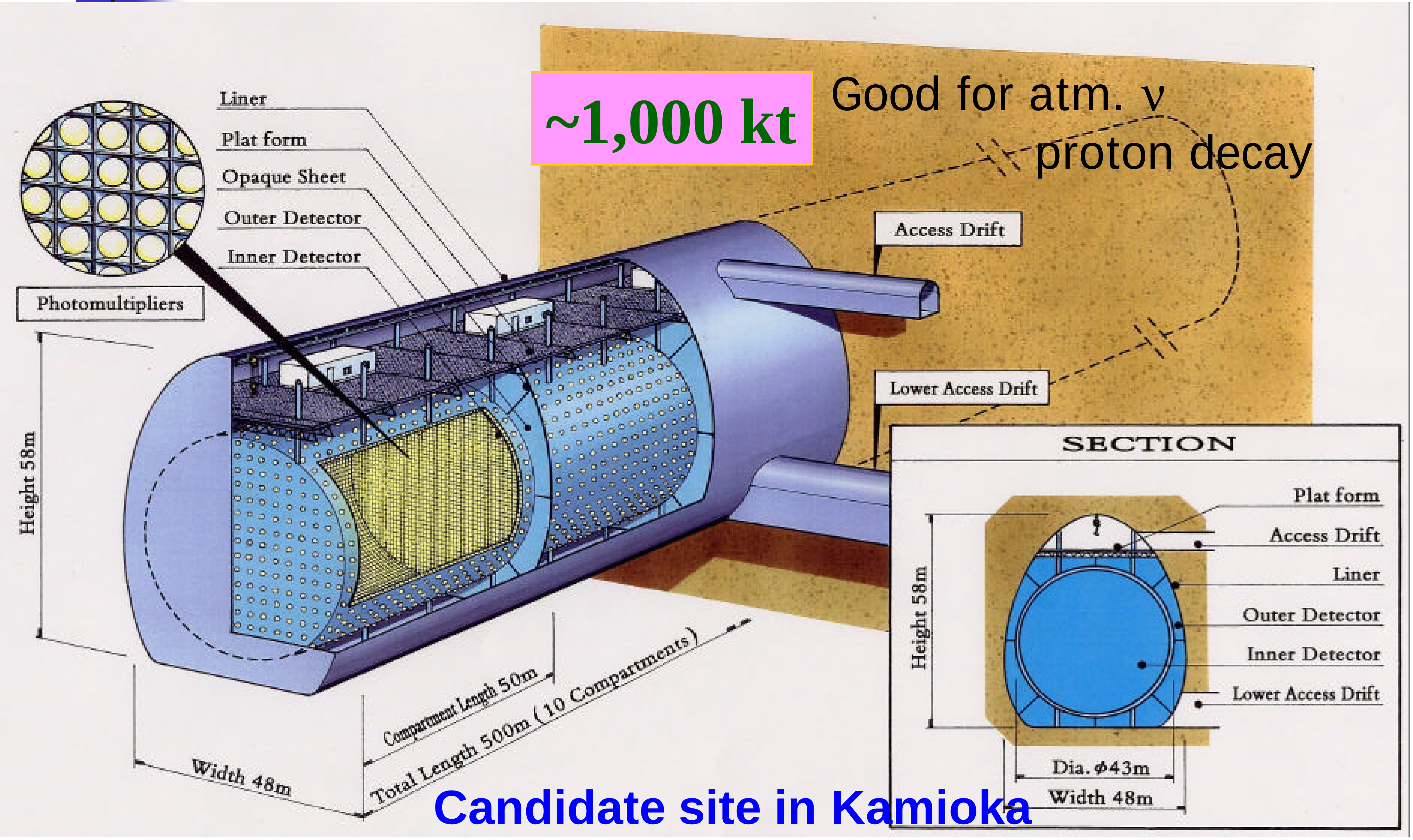
Goals of 3^{rd} generation of Long Baseline Experiments

- Precision measurement of PMNS matrix elements
- Discovery and measure non-zero δ_{CP}, and determine the mass hierarchy (if not done by 2^{st} generation experiments)
  - several experiments with different running conditions will be required in order to disentangle the true solution from degenerate solutions

NB If $\theta_{13} < 1^{\circ}$ impossible to assess CP violation in the leptonic sector. However, correlation effects could mimic small θ_{13} I.e. :

δ_{CP} is positive and very large → giving up JHF-HK and Neutrino Factory would be a tremendous mistake because after an anti-ν run one would have a “monumental” signal

Super-JHF(4MW)+Hyper-K(1Mt)



~1,000 kt

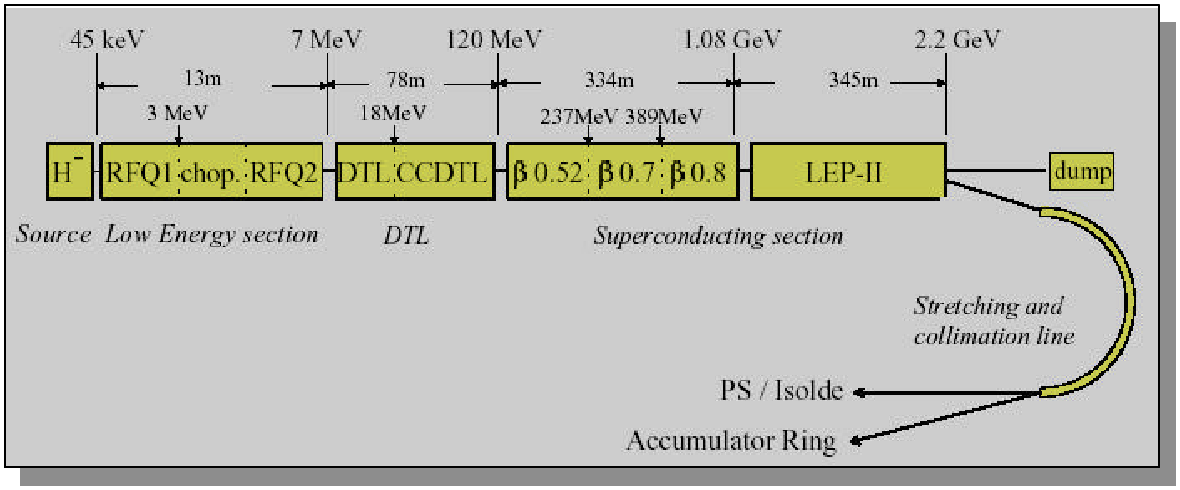
Good for atm. ν

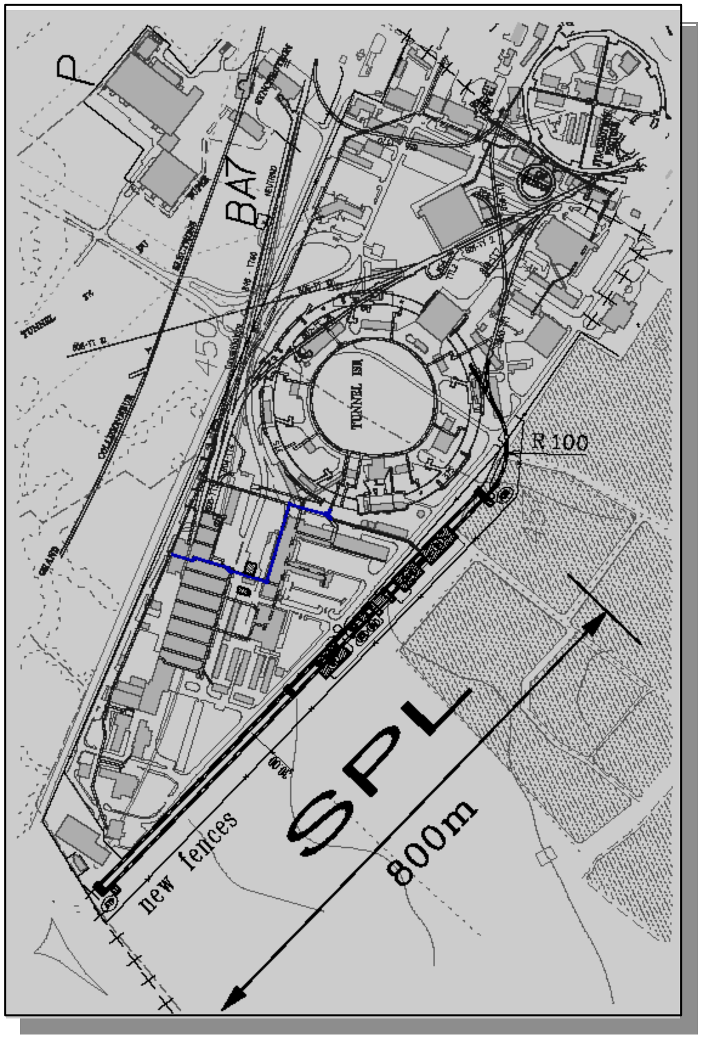
proton decay

Candidate site in Kamioka

CERN/SPL

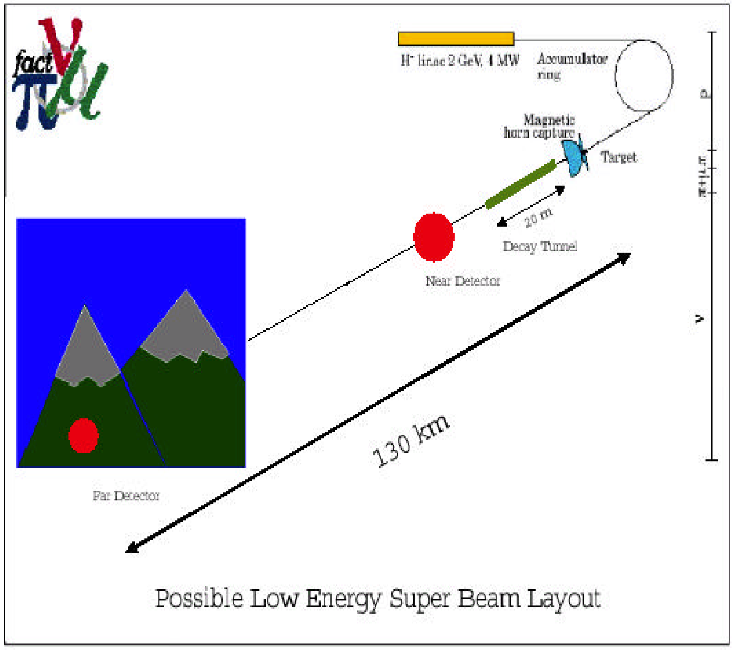
- Proposed:
  - Recycle LEP RF cavities into proton linac
  - Proton kinetic energy: 2.2 GeV
  - Power: 4 MW
  - Protons/s=10^{16}
- Outlook:
  - Feasibility study





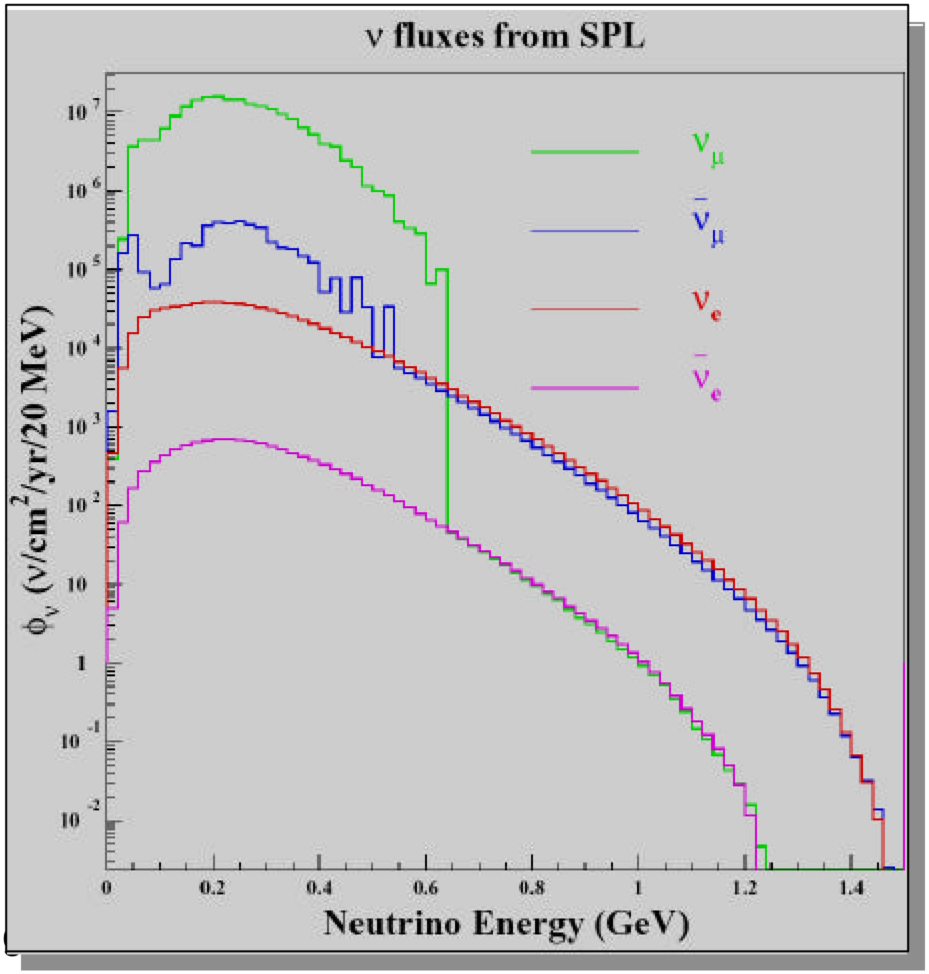
SPL Neutrino Beam

- Liquid Hg jet target
- 20 m decay tunnel
- Kaon production negligible
- Few ‰ n_e content
- E_ν ~ 250 MeV



Possible Low Energy Super Beam Layout

M. Mezzetto, "SuperBeam studies at CERN", *Nufact 01*, Tsukuba, May 24-30, 2001 3



The β beam

1. Produce a radioactive ion with a short beta-decay lifetime

2. Accelerate the ion in a conventional way (PS) to "high" energy

3. Store the ion in a decay ring with straight sections.

4. By its β-decay, ν_e ($\bar{\nu}_e$) will be produced.

Muons:
g~500
E_{cms}~34 MeV
QF~15

- SINGLE flavour (ν_e)
- Known spectrum/intensity
- Focussed ($1/\gamma$)
- Low energy (E_ν = 58ȗ MeV)

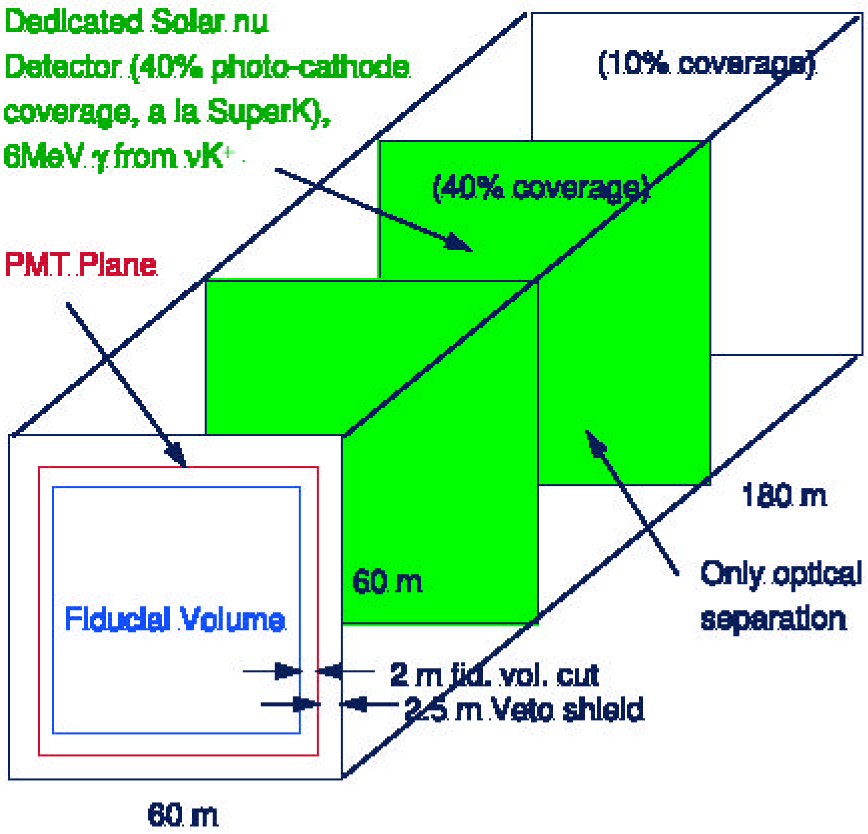
^{6}He Beta-:
g~150
E_{cms}~1.9 MeV
QF~79

^{18}Ne Beta+:
g~250
E_{cms}~1.86 MeV
QF~135

The "quality factor" QF=γ/E_{cms} ($N_{int} \propto \gamma/ E_{cms}$) is bigger than in a conventional neutrino factory. In addition, ion production and collection is easier. Then, 500000X more time to accelerate.

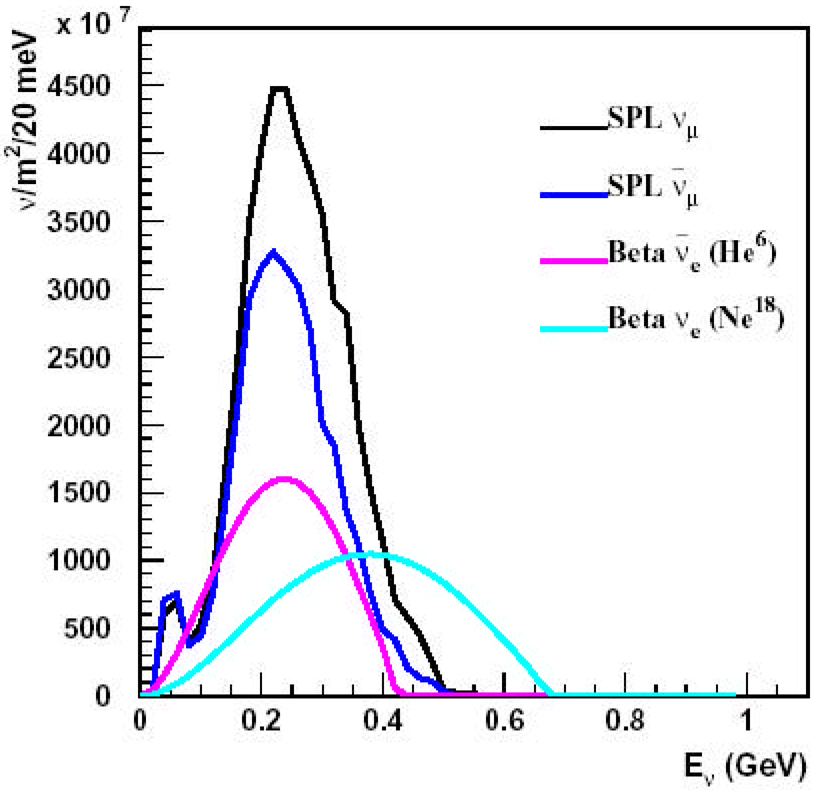
The SPL and β-beam synergy

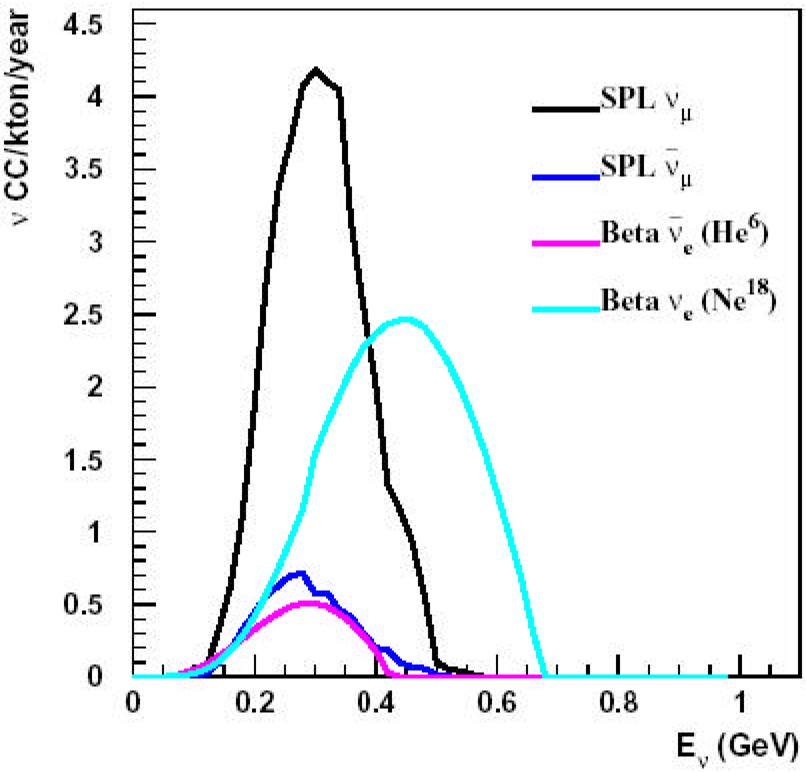
UNO detector



- Fiducial volume: 440 kton: 20 times SuperK.
- 60000 PMTs (20”) in the inner detector, 15000 PMTs in the outer veto detector.
- Energy resolution is poor for multitrack events but quite adequate for sub-GeV neutrino interactions.
- It would be hosted at the Frejus laboratory, 130 km from CERN, in a 10^6 m^3 cavern to be excavated.

The
killer detector for proton decay, atmospheric neutrinos, supernovae neutrinos.


Fluxes


CC Rates

	Fluxes @ 130 km $\nu/m^2/yr$	$< E_\nu >$ (GeV)	CC rate (no osc) events/kton/yr	$< E_\nu >$ (GeV)	Years	Integrated events (440 kton × 10 years)
SPL Super Beam						
ν_μ	$4.78 \cdot 10^{11}$	0.27	41.7	0.32	2	36698
$\overline{\nu}_\mu$	$3.33 \cdot 10^{11}$	0.25	6.6	0.30	8	23320
Beta Beam						
$\overline{\nu}_e\ (\gamma = 60)$	$1.97 \cdot 10^{11}$	0.24	5.2	0.28	10	28880
$\nu_e\ (\gamma = 100)$	$1.88 \cdot 10^{11}$	0.36	39.2	0.43	10	172683

Beta Beam Backgrounds

Computed with a full simulation and reconstruction program. (Nuance + Dave Casper).

π from NC interactions

The main source of background comes from pions generated by resonant processes (Δ^{++} production) in NC interactions.

Pions cannot be separated from muons.

However the threshold for this process is $\simeq 400$ MeV.

Angular cuts have not be considered.

e/μ mis-identification

The full simulation shows that they can be kept well below 10^{-3} applying the following criteria:

- One ring event.
- Standard SuperK particle identification with likelihood functions.
- A delayed decay electron.

Atmospheric neutrinos

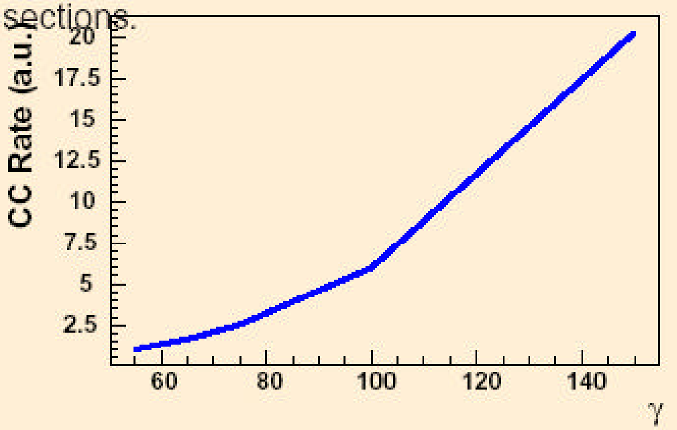
Atmospheric neutrino background can be kept low only by a very short duty cycle of the Beta Beam. A reduction factor bigger than 10^{3} is needed.

This is achieved by building 10 ns long Ion bunches.

Optimizing the Lorentz Boost γ (L=130 km): preferred values: $\gamma = 55 \div 75$

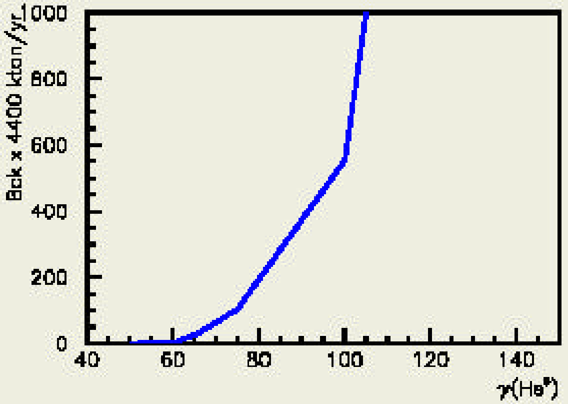
Higher γ produce more CC interactions

More collimated neutrino production and higher cross sections.

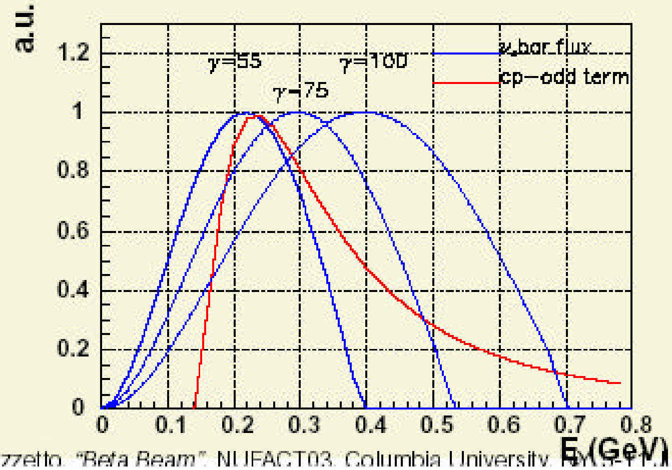


Background rate rises much faster than CC interactions

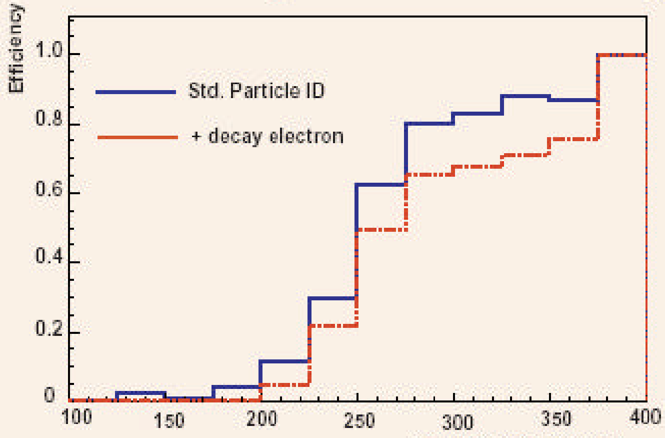
From resonant pion production in $\overline{\nu}_e$ NC interactions



ν flux must match the CP-odd oscillating term



Detection efficiency as function of ν energy



Other sources of errors

Systematic errors: Beta Beam is the ideal place where to measure neutrino cross sections

- Neutrino flux and spectrum are completely defined by the parent ion characteristics and by the Lorentz boost γ.
- Only one neutrino flavour in the beam. in the storage ring.
- You can scan different γ values starting from below the Δ production threshold.
- A close detector can then measure neutrino cross sections with unprecedent precision

A 2% uncertitude level on the systematics will be assumed in the following.

Errors on the other parameters

$p(\nu_\mu \rightarrow \nu_e)$ depends from all the mixing matrix parameters: errors on parameters influence the sensitivity of a CP search.

At the time of BetaBeam

- JHF will have measured δm^2_{23} with a $\sim 10\%$ resolution and $\sin^2 2\theta_{23}$ with $1 \div 2$ % resolution.
- Solar LMA parameters measured at $\sim 10\%$ precision level by Kamland (after 3 years, see hep-ph/0107277).

Only diagonal contributions from δm^2_{23}, δm^2_{12} and $\sin^2\theta_{12}$ will be taken into account. Their contribution is anyway marginal.

Statistical method

If the number of events is greater than 12 use the classical gaussian chi2 with all the systematics included. If lower use the Poisson chi2, no systematic included. Given the above errors this approximation is largely acceptable.

The SuperBeam - BetaBeam synergy: CP, T and CPT

No other realistic scenario can offer CP, T and CPT searches at the same time in the same detector!!!!

CP Searches

- SuperBeam running with ν_μ and $\overline{\nu}_\mu$.
- Beta Beam running with ^{6}He ($\overline{\nu}_e$) and ^{18}Ne (ν_e).

T searches

- Compare Super Beam $p(\nu_\mu \rightarrow \nu_e)$ with Beta Beam ^{18}Ne $p(\nu_e \rightarrow \nu_\mu)$
- Compare Super Beam $p(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$ with Beta Beam ^{6}He $p(\overline{\nu}_e \rightarrow \overline{\nu}_\mu)$.

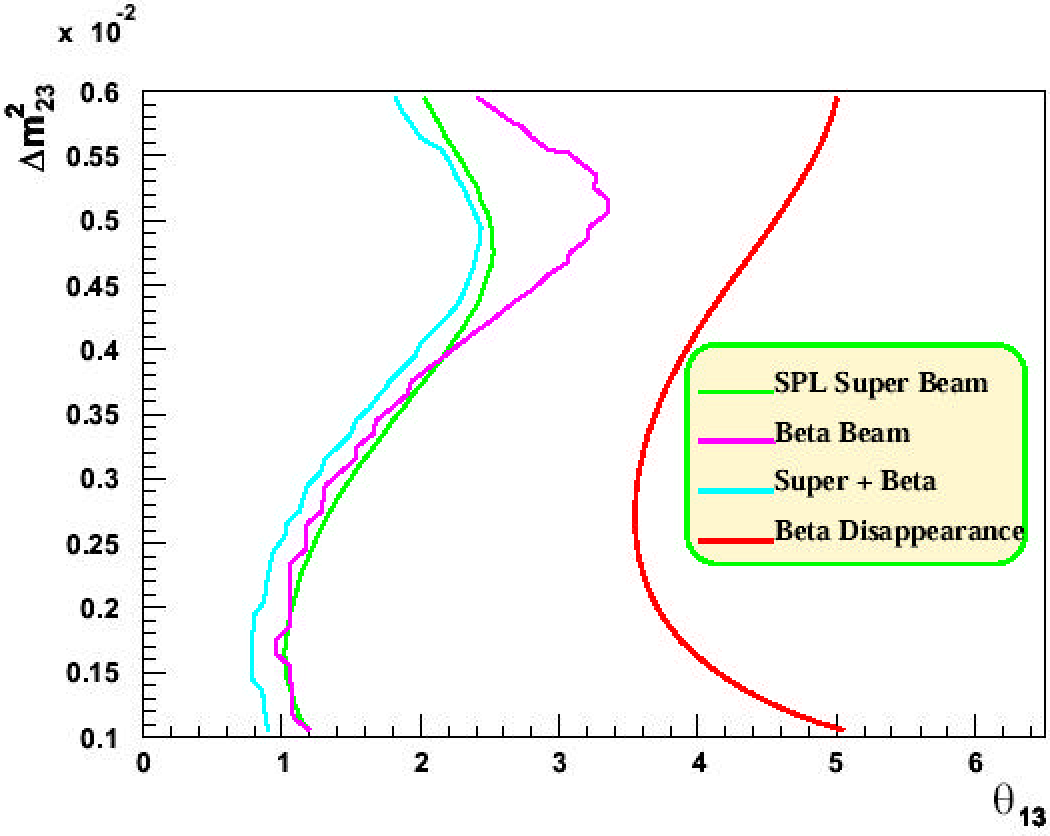
CPT searches

- Compare Super Beam $p(\nu_\mu \rightarrow \nu_e)$ with Beta Beam ^{6}He $p(\overline{\nu}_e \rightarrow \overline{\nu}_\mu)$.
- Compare Super Beam p($\overline{\nu}_\mu \rightarrow \overline{\nu}_e$) with Beta Beam ^{18}Ne $p(\nu_e \rightarrow \nu_\mu)$

The SuperBeam - BetaBeam synergy: a benchmark on θ_{13} sensitivity

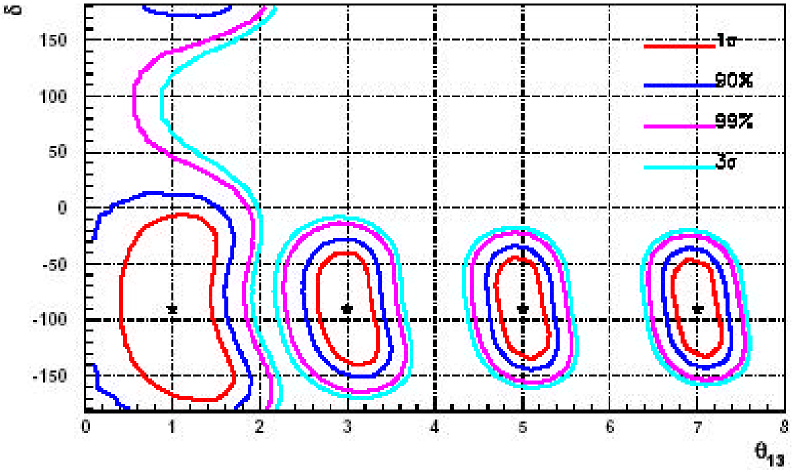
Computed for $\delta_{CP} = 0$ and 5 years running.

- Super Beam → $96\times$ CHOOZ.
- Super Beam + Beta Beam → $160\times$ CHOOZ.
- **Beta Beam can measure θ_{13} both in appearance and in disappearance mode. All the ambiguities can be removed for $\theta_{13} \geq 3.4^\circ$**

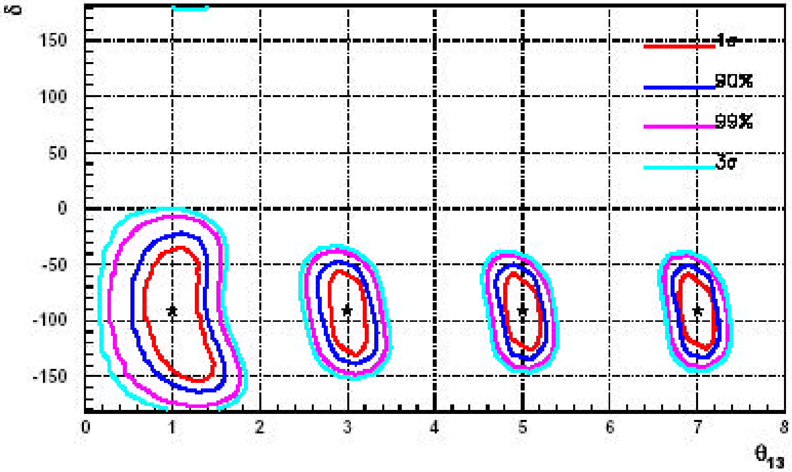


Beta Beam - Super Beam synergy: CP sensitivity

SUPER BEAM ONLY



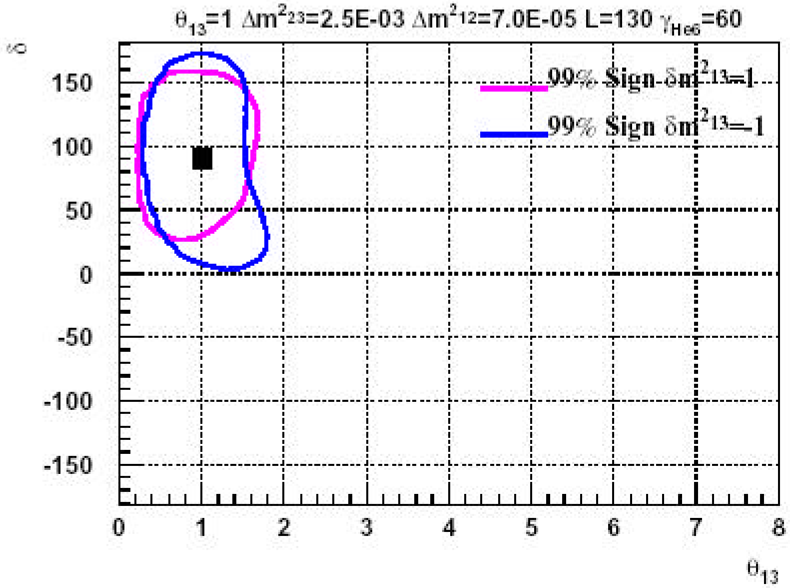
SUPER BEAM + BETA BEAM

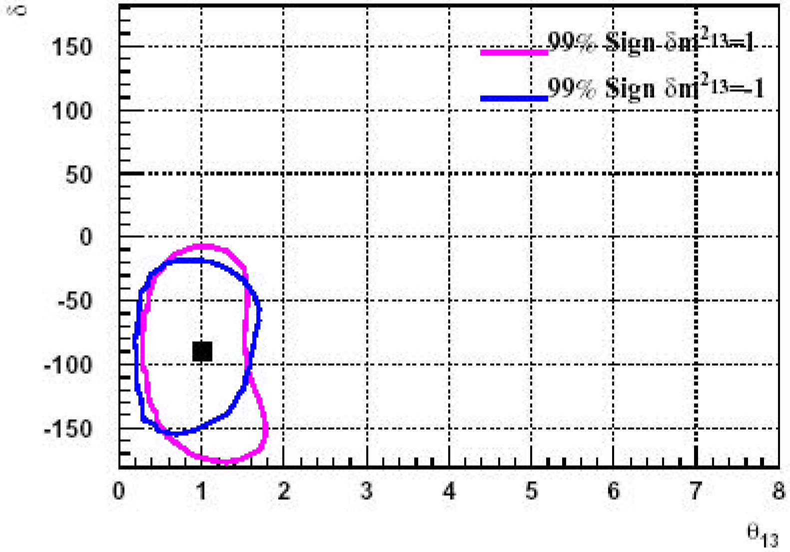


$\delta m^2_{12} = 7 \cdot 10^{-5}\ eV^2, \quad \theta_{13} = 1^\circ, \quad \delta_{CP} = \pi/2$

10 yrs (4400 kton/yr)	SuperBeam		Beta Beam	
	ν_μ	$\overline{\nu}_\mu$	$\overline{\nu}_e$ (He^6)	ν_e (Ne^{18})
	(2 yrs)	(8 yrs)	$\gamma = 60$	$\gamma = 100$
CC events (no osc, no cut)	36698	23320	28880	172683
Total oscillated	1.7	33.3	0.5	84.2
CP-Odd oscillated	-25.5	16.9	-11.9	41
Beam backgrounds	141	113	/	/
Detector backgrounds	37	50	1	299
Statistical Error	13.4	13.6	1.5	21.9
Error on θ_{23}	2.1	1.7	0.5	4.7
Error on δm^2_{12}	2.8	1.9	0.3	8.1
Total Error	13.9	14.6	1.7	25.7

Ambiguities





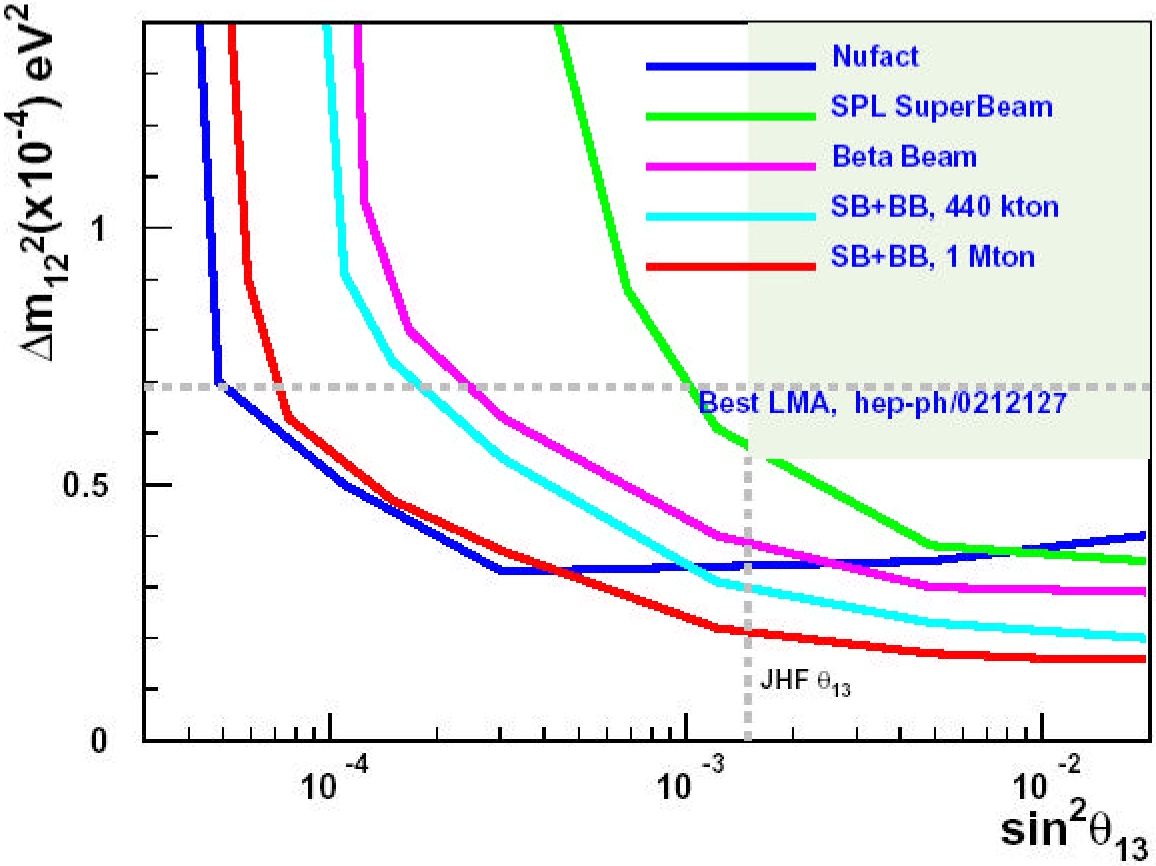
- The asymmetric statistics and background rates in the ν_e and $\overline{\nu}_e$ beams produce an asymmetric response to the positive and negative values of δ.
- Even if the matter effects are negligible, the $p(\nu_\mu \rightarrow \nu_e)$ formula contains odd $\mathrm{sign}(\delta \mathrm{m}^2_{13})$ terms .
- The change of $\mathrm{sign}(\delta m^2_{13})$ produces non negligible changes in the oscillation formula. No attempt made so far to fit $\mathrm{sign}(\delta m^2_{13})$, θ_{13} and δ at the same time.
- Results are shown in the following for positive values of δ and $\mathrm{sign}(\delta m^2_{13})$.
  - $\sin^2 2\theta_{23} = 1.0$
  - $\delta m^2_{23} = 2.5 \cdot 10^{-3}$ eV^2.
  - $\sin^2 2\theta_{12} = 0.8$

A comparison of CP sensitivities: Beta Beam vs. Nufact

CP sensitivity, defined as the capacity to separate at 99%CL max CP ($\delta = \pi/2$) from no CP ($\delta = 0$).

Nufact sensitivity as computed in J. Burguet-Castell et al., Nucl. Phys. B **608** (2001) 301:

- 50 GeV/c μ.
- $2 \cdot 10^{20}$ useful μ decays/year.
- 5+5 years.
- 2 iron magnetized detectors, 40 kton, at 3000 and 7000 km.
- Full detector simulation, including backgrounds and systematics.



Conclusion

- Neutrino Physics appears to be an exciting field for many years to come
- In the short period (less than 10 years) LBL experiments like CNGS, NuMI and (mainly) JHF
  - will measure some of the PMNS matrix elements (Δm^2_{13}, $\sin^2\theta_{23}$) with a per cent accuracy
  - will determine unambiguously the source of the atmospheric neutrino deficit (τ appearance)
  - have a good opportunity to observe for the first time the mixing angle θ_{13} ($\geq 2^o$)
- In the long term period, most likely several experiments with different running conditions will be required in order to disentangle the true solution from degenerate solutions and extract δ_{CP} and the mass hierarchy (unfortunately I had no time to discuss the dozens of proposals to solve the ambiguities, for details we refer to A. Donini, D. Meloni and P. Migliozzi Nucl. Phys. B646:321-349,2002 and references therein)