

# Leptons are VERY different from quarks. (I)

$$U_{MN\text{SP}} \sim \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

Solar+Atmospherics indicate a quasi bi-maximal mixing matrix, **VERY DIFFERENT from CKM matrix (almost diagonal)!**

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

$\theta_{13} \rightarrow 0 \Rightarrow$  The 3x3 mixing matrix becomes a trivial product of two 2x2 matrixes.

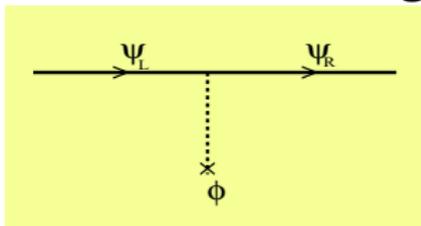
$\theta_{13}$  drives  $\nu_{\mu} \rightarrow \nu_e$  subleading transitions  $\Rightarrow$   
the necessary milestone for any subsequent search:  
neutrino mass hierarchy and leptonic CP searches.

# Leptons are VERY different from quarks. (II)

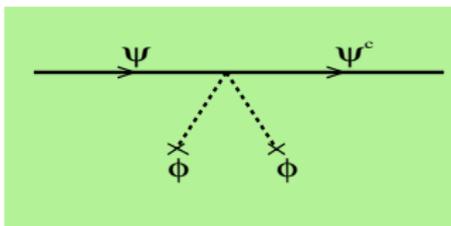
$$\begin{array}{lll}
 u \sim 5 \text{ MeV} & c \sim 1 \text{ GeV} & t \sim 175 \text{ GeV} \\
 d \sim 8 \text{ MeV} & s \sim 0.1 \text{ GeV} & b \sim 5 \text{ GeV}
 \end{array}$$

$$\begin{array}{lll}
 e \sim 0.5 \text{ MeV} & \mu \sim 0.1 \text{ GeV} & \tau \sim 2 \text{ GeV} \\
 \nu_e \leq \mathcal{O}(1 \text{ eV}) & \nu_\mu \leq \mathcal{O}(1 \text{ eV}) & \nu_\tau \leq \mathcal{O}(1 \text{ eV})
 \end{array}$$

How can the same model generate mass ratio so different?



$$\begin{aligned}
 & \lambda_\nu \bar{\Psi}_R \Phi \Psi_L + h.c. \\
 & m_f = \lambda_f \nu_L
 \end{aligned}$$



$$\begin{aligned}
 & \frac{\alpha_\nu}{M} \nu_L^T C \tilde{\Phi}^T \tilde{\Phi} \nu_L + h.c. \\
 & m_f = \alpha_\nu \frac{\nu^2}{M}
 \end{aligned}$$

A new physics scale,  $M$ , can explain the new hierarchy (if at the GUT scale) and is associated to the breaking of a global symmetry of the SM: total lepton number  $L$ .

# Most of the neutrino oscillation parameters are waiting to be measured

$$\delta m_{12}^2$$



SOLARS+KAMLAND

$$\delta m_{12}^2 = (7.9 \pm 0.7) 10^{-5} \text{ eV}^2$$

$$\theta_{12}$$



SOLARS+KAMLAND

$$\sin^2(2\theta_{12}) = 0.82 \pm 0.055$$

Addressed by a SuperBeam/Nufact experiment

$$\delta m_{23}^2$$



ATMOSPHERICS

$$\delta m^2 = (2.4 \pm 0.4) 10^3 \text{ eV}^2$$

$$\theta_{23}$$



ATMOSPHERICS

$$\sin^2(2\theta_{23}) > 0.95$$

$$\theta_{13}$$



CHOOZ LIMIT  
 $\sin^2 2\theta_{13} < 14^0$

LSND/Steriles



$$\delta_{CP}$$



Mass hierarchy



$$\Sigma m_\nu$$



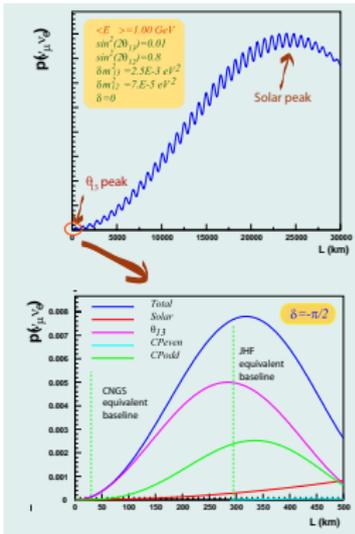
BETA DECAY END POINT

$$\Sigma m_\nu < 6.6 \text{ eV}$$

Dirac/Majorana



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

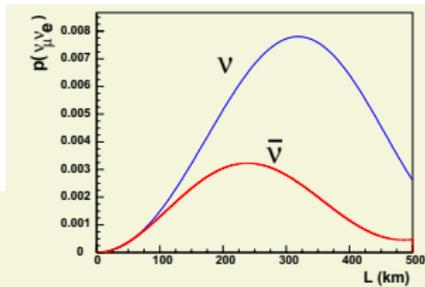


$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) = & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \times \left[ 1 \pm \frac{2a}{\Delta m_{13}^2} (1 - 2s_{13}^2) \right] && \theta_{13} \text{ driven} \\
 & + 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos \delta - s_{12} s_{13} s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} && \text{CP even} \\
 & \mp 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin \delta \sin \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} && \text{CP odd} \\
 & + 4s_{12}^2 c_{13}^2 \{ c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos \delta \} \sin \frac{\Delta m_{12}^2 L}{4E} && \text{solar driven} \\
 & \mp 8c_{12}^2 s_{13}^2 s_{23}^2 \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E} (1 - 2s_{13}^2) && \text{matter effect (CP odd)}
 \end{aligned}$$

$\theta_{13}$  discovery requires a signal ( $\propto \sin^2 2\theta_{13}$ ) greater than the solar driven probability

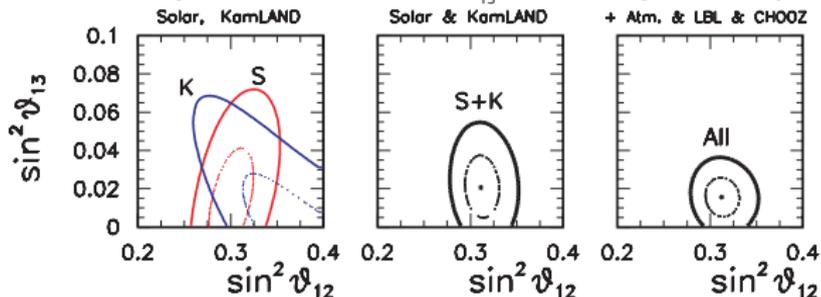
Leptonic CP discovery requires

$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \neq 0$$

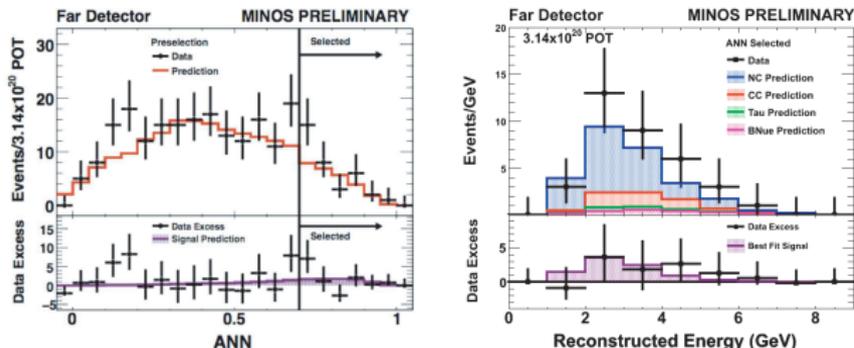


# Recent hints of non-zero $\theta_{13}$ values

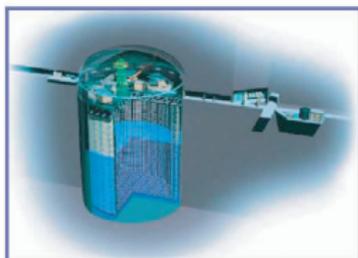
Fits to the solar + kamland gets a non-zero value of  $\theta_{13}$ , 90%CL (Fogli et al., Phys.Rev.Lett.101:141801,2008)



Preliminary data from MINOS show a  $1.5 \sigma$  excess of electron-like events  
(Observed: 35, Expected: 27 +/- 5 (stat) +/-2 (syst))



# The T2K Experiment



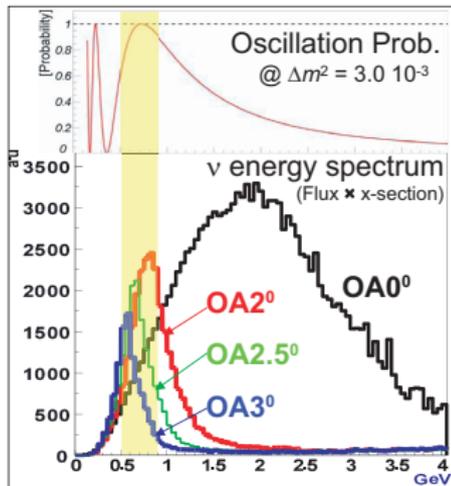
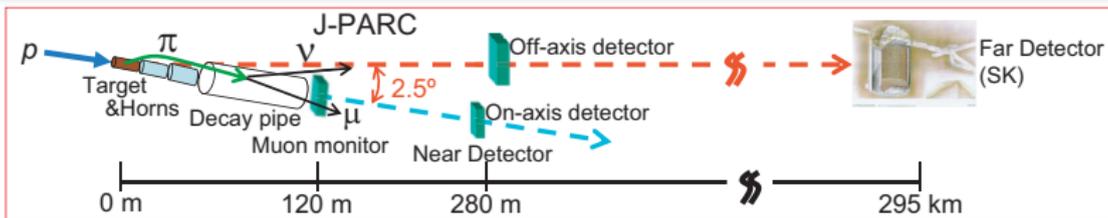
**Super-Kamiokande**  
(ICRR, Univ. Tokyo)



**J-PARC Main Ring**  
(KEK-JAEA, Tokai)

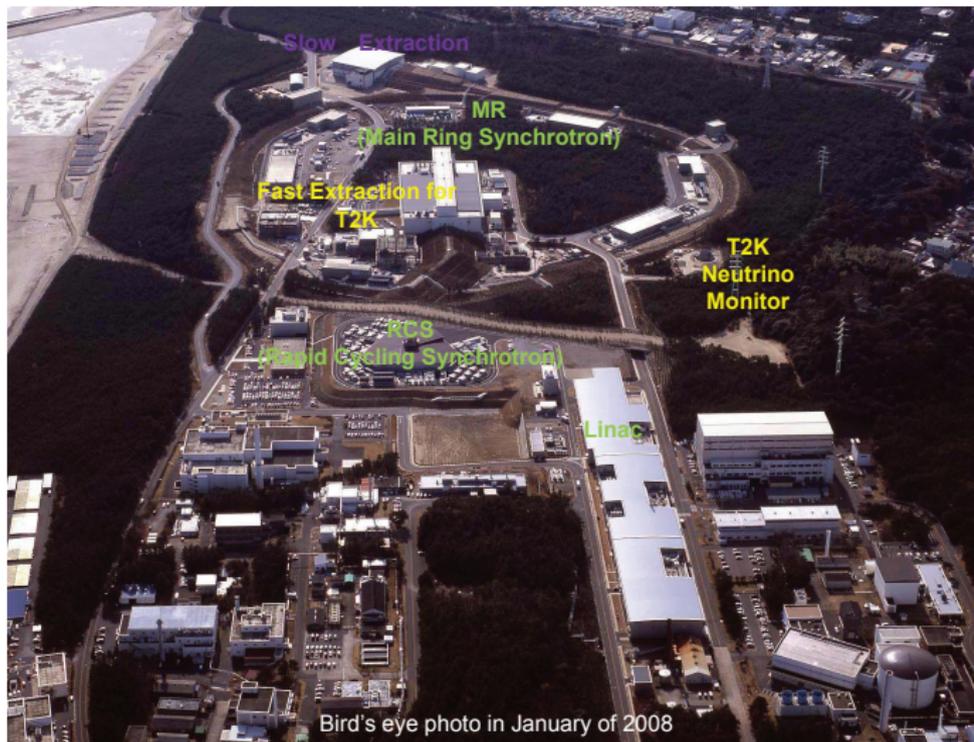


# Experimental apparatus and neutrino beam



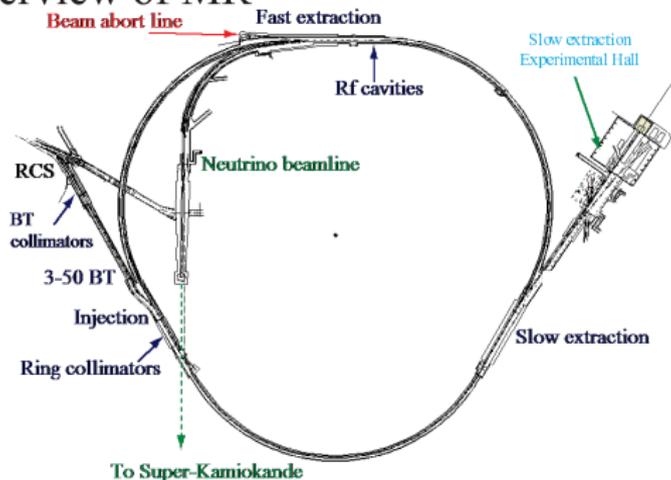
- Off-axis beam technique
  - Intense narrow band beam
- $2.5^\circ$  off-axis
  - Energy peak tuned at oscillation max.  $\sim 0.7$  GeV
- Statistics at Super-K
  - $\sim 1600$   $\nu_\mu$  CC int./22.5kt/year (with 0.75kW beam, no oscillation case)
- Pure  $\nu_\mu$  beam
  - Beam  $\nu_e$  contamination  $\sim 0.4\%$  at  $\nu_\mu$  peak energy

# J-PARC Accelerator and Experimental Facility



## Overview of MR

Circumference	1567.5 m
Repetition rate	0.3 Hz@Start Up
Injection energy	3 GeV
Extraction energy	30 GeV
Superperiodicity	3
$h$	9
No. of bunches	8
Transition $\gamma$	31.7(imaginary)
Typical tune	22.4, 20.8
Transverse emittance	
At injection	$\sim 54 \pi \text{mm-mrad}$
At extraction	$\sim 10 \pi \text{mm-mrad}$
Beam power	0.75MW



Three dispersion free straight sections of 116-m long:

- Injection and collimator systems
- Fast extraction (beam is extracted inside/outside of the ring) and RF cavities
  - inside: Neutrino Beamline ( intense  $\nu$  beam to SK located 295 km west)
  - outside: Beam abort line (at any energies when hardware failure occurs)
- Slow extraction
  - to Slow extraction Experimental Hall (K Rare decay, hyper nucleus..)

- **Linac : Fully Commissioned**

- ▶ 181 MeV (day 1 beam energy) achieved Jan 2007
- ▶ Good beam stability

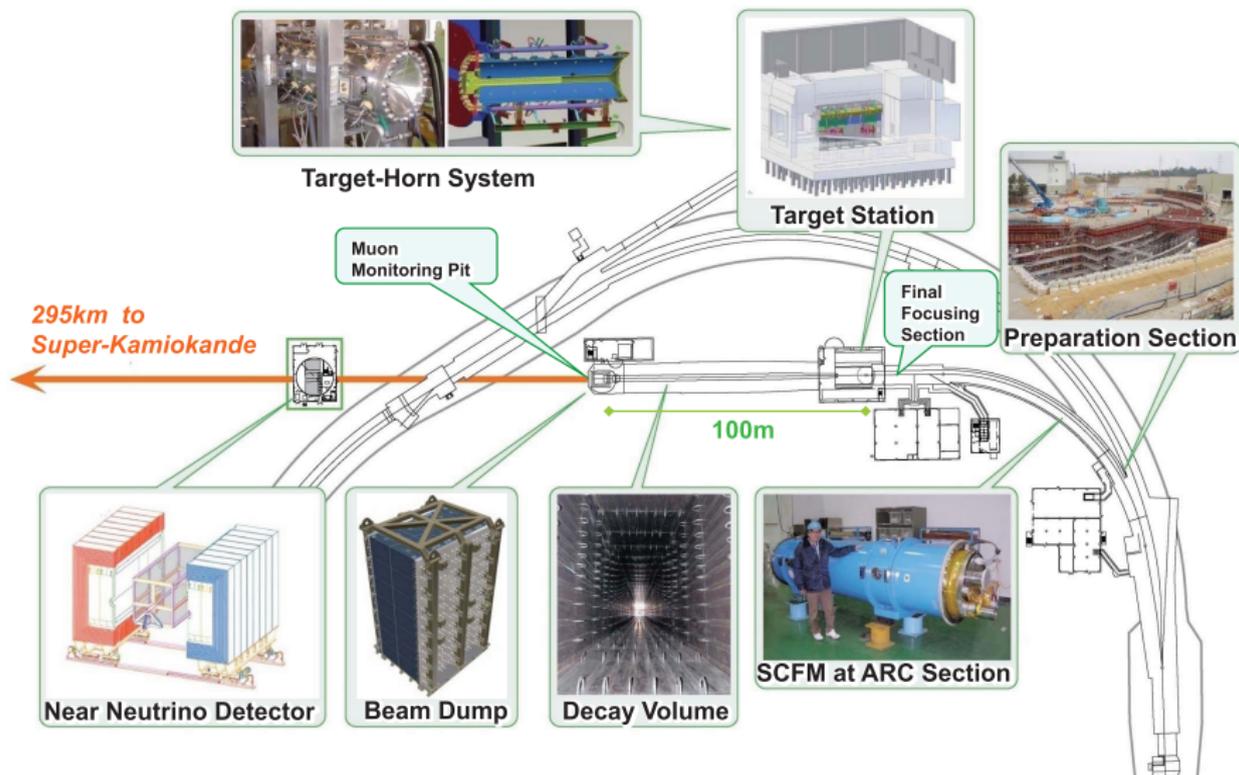
- **3 GeV Synchrotron (RCS) : Fully Commissioned**

- ▶ 3 GeV acceleration and extraction Oct 2007
- ▶  $4.4 \times 10^{12}$  particles per bunch
- ▶ Aiming for 100 kW operation at 25 Hz

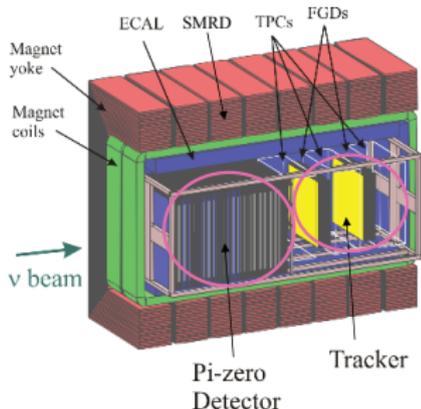
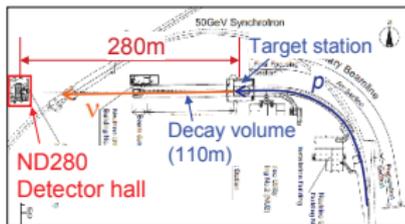
- **Main Ring Synchrotron**

- ▶ Beam has been captured and circulated from RCS May 2008
- ▶ Acceleration to 30 GeV: achieved on December 23, 2008
- ▶ Extraction to neutrino beamline Apr 2009

# T2K experiment: the neutrino beam line



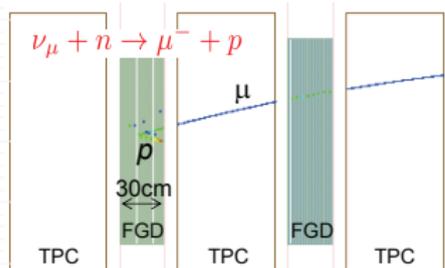
# The Close Detector ND280



- Near off-axis detector located at 280 m downstream of the target
- Consists of 5 subdetectors:
  - Pi-zero detector (PØD)
    - measures  $NC\pi^0$  interactions
  - Tracker: fine-grained detector (FGD) and time projection chambers (TPC)
    - measures CC interactions
  - Electromagnetic calorimeter (ECAL)
    - detects EM activities coming from PØD/Tracker
  - Side muon range detector (SMRD)
    - measures side-going muon energy
- All detectors housed in UA1/NOMAD magnet: B-field = 0.2 T
- $0.8M \nu_\mu$  and  $16k \nu_e$  interactions per ton after  $0.75kW \times 5yr$  accumulation

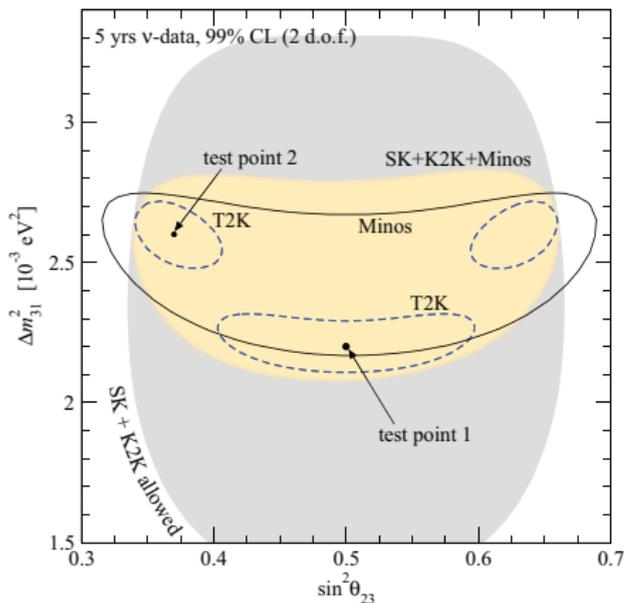
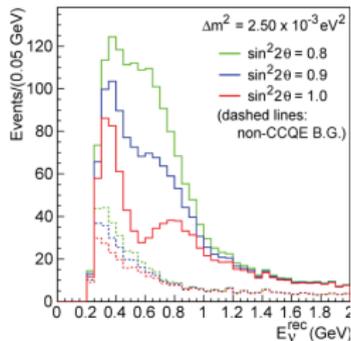
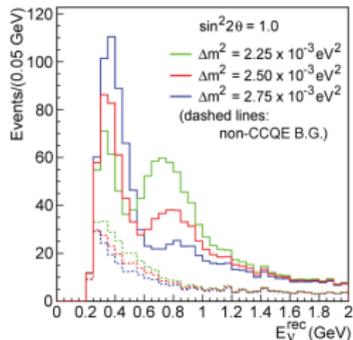
# The Close Detector ND280

- **Key for good  $E_\nu$  spectrum and background estimations**
  - CCQE / non-CCQE separations
  - Neutrino interaction models
    - Cross sections
    - Fermi motion
    - Nuclear effects ...
- **Finely segmented (1cm x 1cm) FGD with  $10\mu\text{s}$  time window**
  - short 2<sup>nd</sup> (and more) tracks' activities
  - $\pi \rightarrow \mu \rightarrow e$  decays from non-CCQE
- **TPC following the FGD**
  - particles' charge:  $\mu^- / \pi^+$  separation
  - momentum of  $\pi$  from non-CCQE as well as  $\mu$
- **ECAL surrounding the Tracker**
  - detects  $\gamma$ 's from  $\pi^0$  from non-CCQE

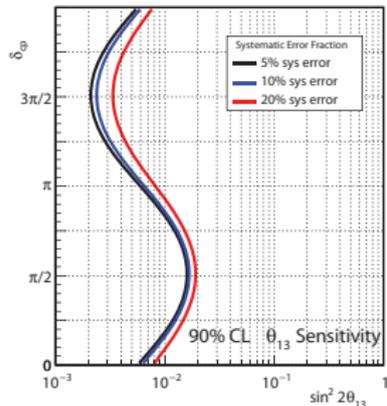
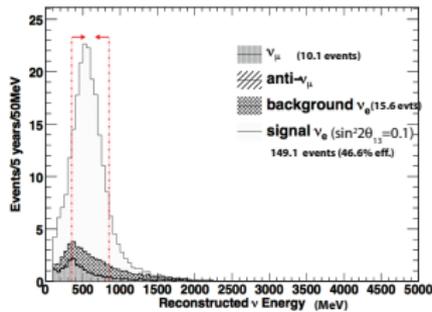
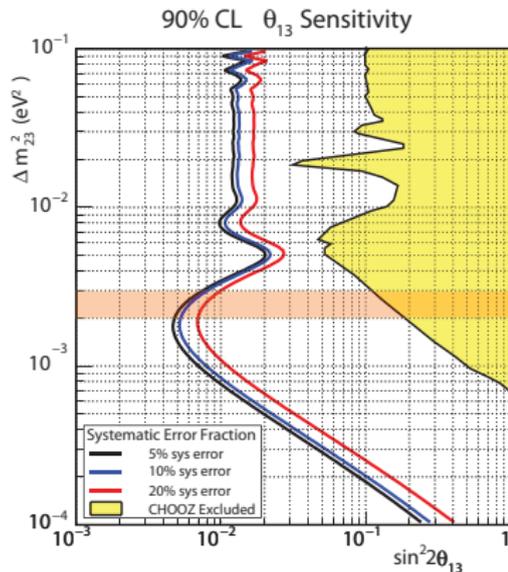


- **Two independent CCQE / non-CCQE separation in a single detector:**
    - Final state particles
    - Kinematics of 2<sup>nd</sup> track
  - **Kinematics of final state particles:**
    - Fermi motions, nuclear effects, ...
- **intensive study of the neutrino interactions**

# T2K Performances: atmospheric parameters



# T2K Performances: $\theta_{13}$



# T2K Schedule

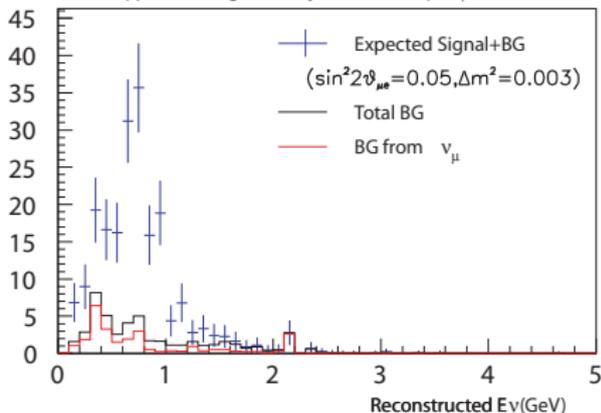
- Neutrino beam line commissioning started on 24 April, 2009.
- Complete the ND280 installation and the neutrino beam line installation by December 2009.
- Start data taking at December 2009. Accumulate  $0.1 \text{ MW} \times 10^5$  by summer 2010  $\Rightarrow \sin^2(2\theta_{13})$  sensitivity about 0.1.
- Continue data taking accumulating  $5 \times 0.75 \text{ MW} \times 10^7 \text{ s}$

# Reactor experiments

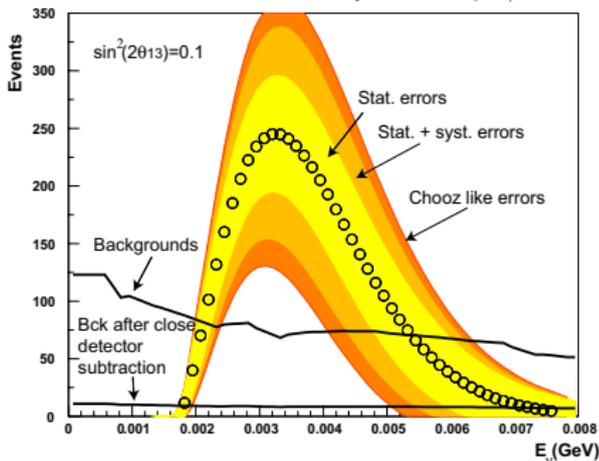
$$1 - P_{\bar{e}\bar{e}} \simeq \sin^2 2\theta_{13} \sin^2(\Delta m_{31}^2 L/4E) + (\Delta m_{21}^2/\Delta m_{31}^2)^2 (\Delta m_{31}^2 L/4E)^2 \cos^4 \theta_{13} \sin^2 2\theta_{12}$$

- Direct connection between  $P_{\bar{e}\bar{e}}$  and  $\theta_{13}$ , no interference with  $\delta_{CP}$  and  $\text{sign}(\Delta m_{23}^2)$ .
- No way to directly measure leptonic CP violation and mass hierarchy.
- Truly complementary to the accelerator experiments.
- Disappearance experiments: systematic errors dominate over statistics.

T2K appearance signal in 5 years, from hep-ex/0106019



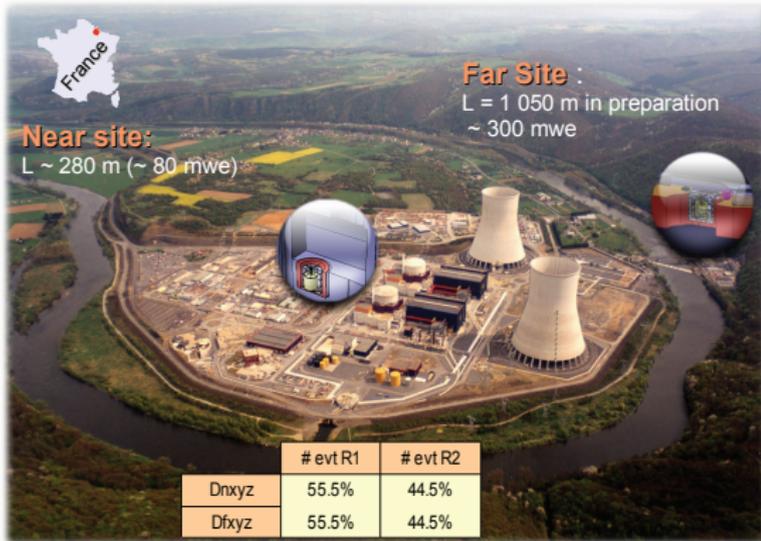
Double Chooz FAR-Near difference in 5 years, from hep-ex/0606025





# Double Chooz

Talk by J. Dawson



**2 cores – 1 site – 8.5 GW<sub>th</sub>**

**1 near position, 1 far**

- target: 2 x 8.3 t

**Civil engineering**

- 1 near lab ~ Depth 40 m, Ø 6 m

- 1 available lab

**Statistics (including  $\epsilon$ )**

- far: ~ 40 evts/day

- near: ~ 460 evts/day

**Systematics**

- reactor : ~ 0.2%

- detector : ~ 0.5%

**Backgrounds**

-  $\sigma_{b2b}$  at far site: ~ 1%

-  $\sigma_{b2b}$  at near site: ~ 0.5%

**Planning**

1. Far detector only

- Sensitivity (1.5 ans) ~ 0.06

2. Far + Near sites

- available from 2010

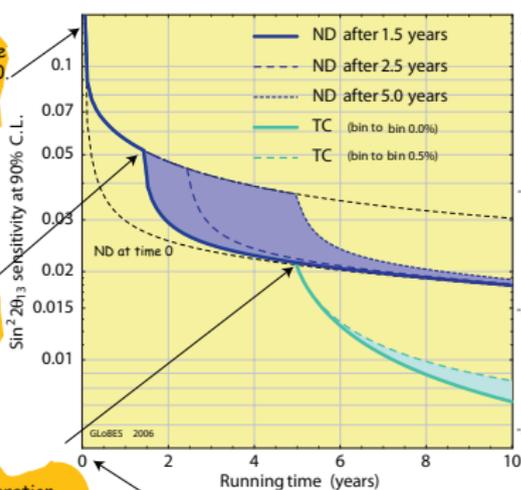
- Sensitivity (3 years) ~ 0.025

# Evolution of the Double Chooz sensitivity

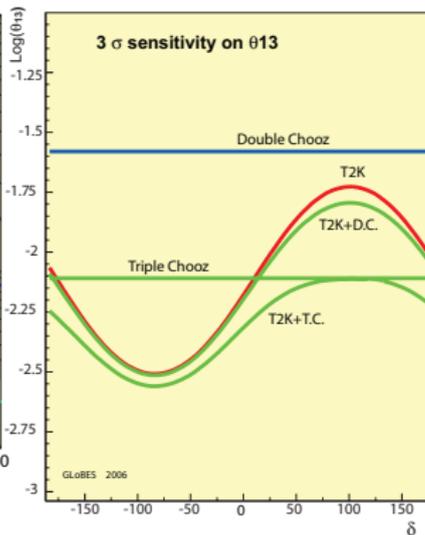
Start the operation of the far detector, 10 m<sup>3</sup>, at t<sub>0</sub>.  
With no close detector, systematics dominate.

Start the operations of an identical close detector after 1.5 yrs. Reactors flux is identical in the two detectors. Systematics reduced.

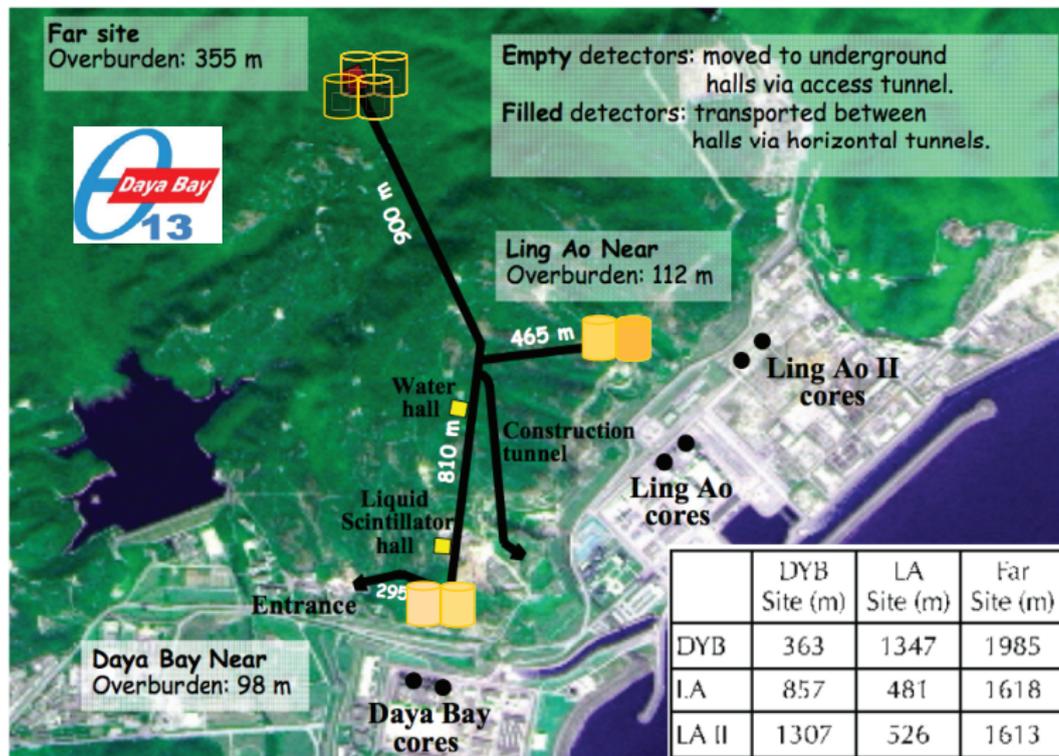
Triple Chooz: put in operation a 200 ton far detector in a already existing cavern. Experimental sensitivity improved. See JHEP 605 (2006) 72



Time 0: fall 2009



# Daya Bay

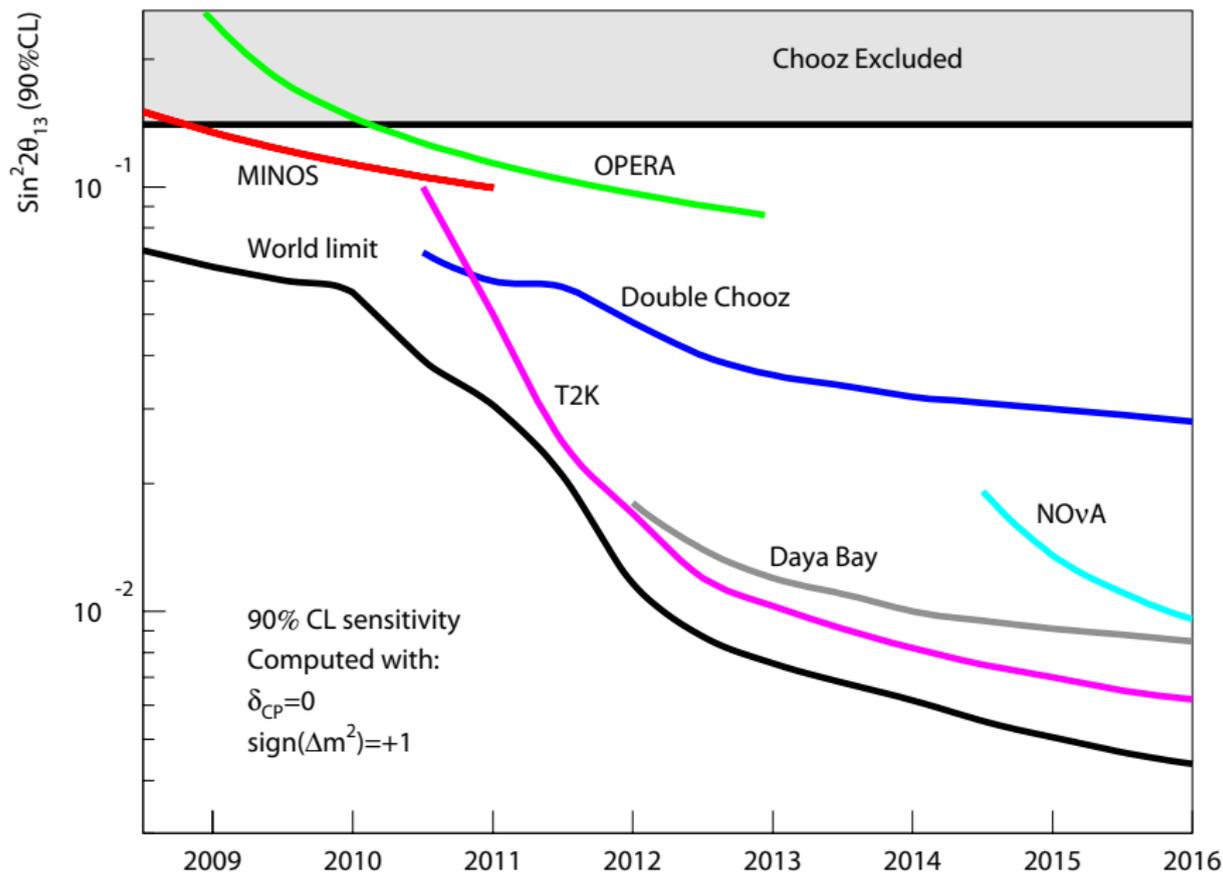


# Reactors systematic business

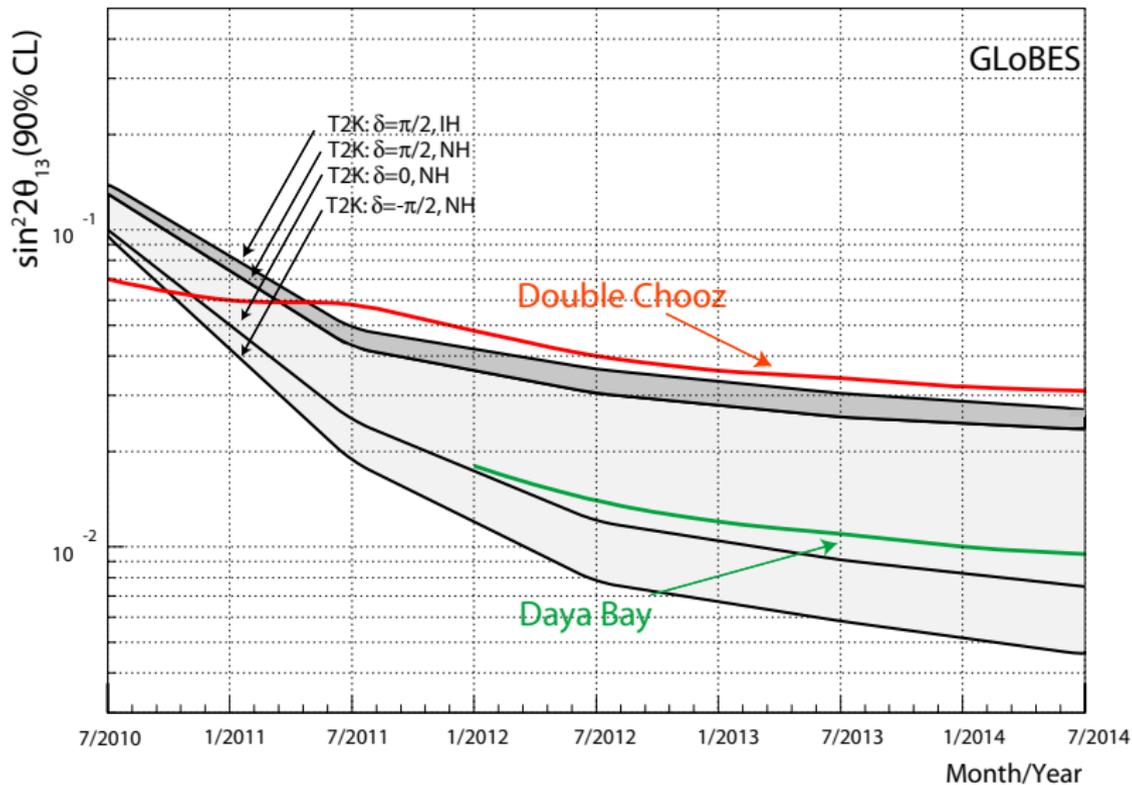
G. Mention, T. Lasserre and D. Motta, arXiv:0704.0498 [hep-ex].

Error Description	CHOOZ	Double Chooz		Daya Bay		R&D
	Absolute	Absolute	Relative	Absolute	No R&D Relative	Relative
<b>Reactor</b>						
Production cross section	1.90 %	1.90 %		1.90 %		
Core powers	0.70 %	2.00 %		2.00 %		
Energy per fission	0.60 %	0.50 %		0.50 %		
Solid angle/Bary. displct.			0.07 %		0.08 %	0.08 %
<b>Detector</b>						
Detection cross section	0.30 %	0.10 %		0.10 %		
Target mass	0.30 %	0.20 %	0.20 %	0.20 %	0.20 %	0.02 %
Fiducial volume	0.20 %					
Target free H fraction	0.80 %	0.50 %		?	0.20 %	0.10 %
Dead time (electronics)	0.25 %					
<b>Analysis (particle id.)</b>						
$e^+$ escape (D)	0.10 %					
$e^+$ capture (C)						
$e^+$ identification cut (E)	0.80 %	0.10 %	0.10 %			
$n$ escape (D)	0.10 %					
$n$ capture (% Gd) (C)	0.85 %	0.30 %	0.30 %	0.10 %	0.10 %	0.10 %
$n$ identification cut (E)	0.40 %	0.20 %	0.20 %	0.20 %	0.20 %	0.10 %
$\bar{\nu}_e$ time cut (T)	0.40 %	0.10 %	0.10 %	0.10 %	0.10 %	0.03 %
$\bar{\nu}_e$ distance cut (D)	0.30 %					
uncity ( $n$ multiplicity)	0.50 %				0.05 %	0.05 %
<b>Total</b>	<b>2.72 %</b>	<b>2.88 %</b>	<b>0.44 %</b>	<b>2.82 %</b>	<b>0.39 %</b>	<b>0.20 %</b>

# Guessing the Future (I)



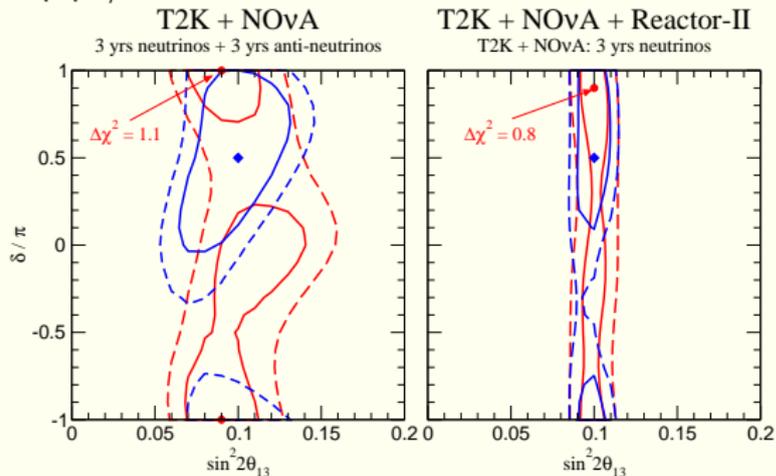
# Guessing the Future (II)



# Status after the first and second generation: $\delta_{CP}$

No hope to see any CP signal at  $3\sigma$

From P. Huber, M. Lindner, M. Rolinec, T. Schwetz and W. Winter, hep-ph/0412133.

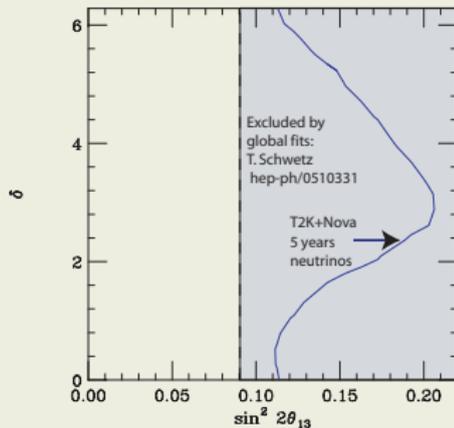


(dotted lines:  $3\sigma$ , solid are 90%CL)

... and mass hierarchy

90% CL determination of mass hierarchy  
 $\Delta m^2 = 2.4 \cdot 10^{-3} \text{ eV}^2$

From O. Mena et al. hep-ph/0609011



To address leptonic CP violation: improve of at least one order of magnitude the sensitivity of  $\sin^2 2\theta_{13}$ ; two order of magnitudes more neutrinos !!!

## Proposals based on upgrades of existing facilities:

- T2K  $\Rightarrow$  T2HK or T2KK
- *No $\nu$ a*  $\Rightarrow$  Super *No $\nu$ a*
- CNGS  $\Rightarrow$   
off-axis CNGS fired on a gigantic liquid argon detector
- Wide band beam fired from Fermilab to a gigantic water Cerenkov detector at DUSEL (Homestake).

## Proposals based on new facilities

- CERN-SPL SuperBeam

# SuperBeams - J-PARC phase 2 (T2HK)

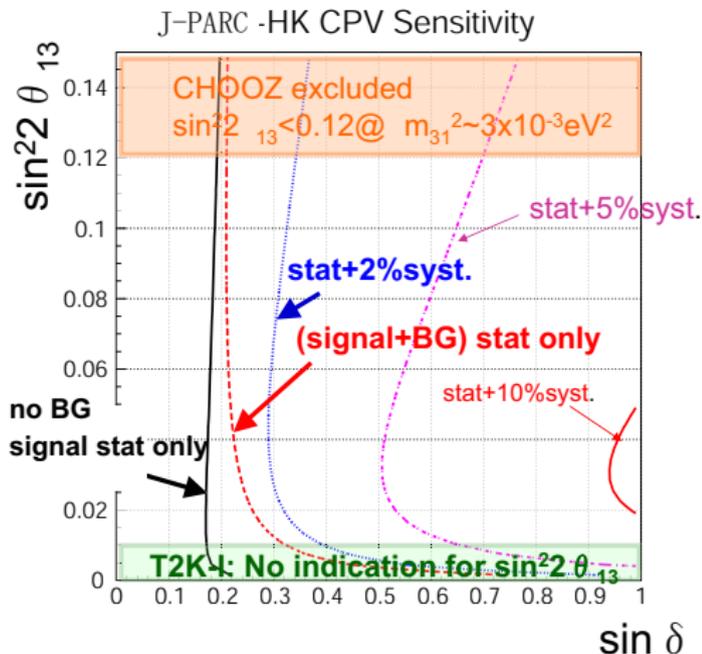
Upgrade the proton driver from 0.75 MW to 4 MW  
Upgrade SuperKamiokande by a factor  $\sim 20 \Rightarrow$  HyperKamiokande  
Both upgrades are necessary to address leptonic CP searches.

The detector would have valuable physics potential in proton decay, SN neutrinos, solar neutrinos.

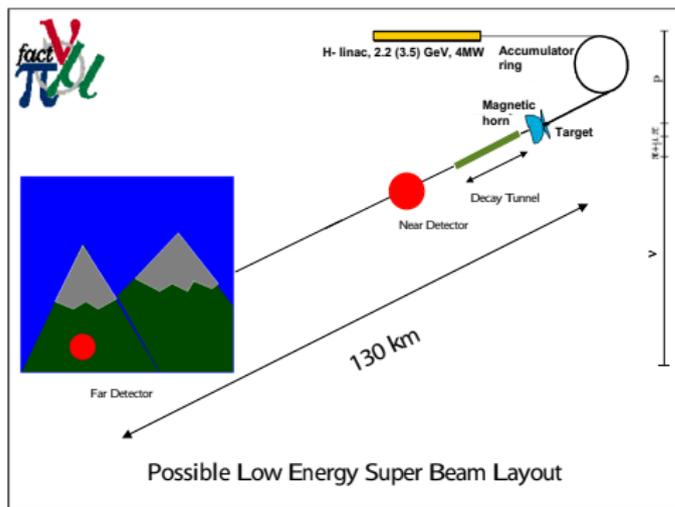
Its cost:  $\sim 0.5$  G\$

Systematics at 2% are difficult  
4 MW at 50 GeV/c are difficult  
Targetry and optics at 4 MW are difficult and will probably require some compromise

T. Kobayashi, J.Phys.G29:1493(2003)

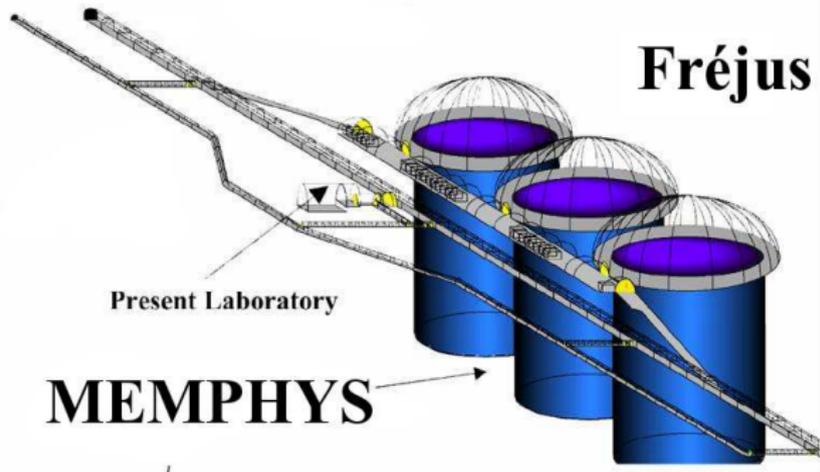


# SuperBeams - SPL $\nu$ beam at CERN



- A 3.5 GeV, 4MW Linac: the SPL.
- A liquid mercury target station capable to manage the 4 MW proton beam. R&D required.
- A conventional neutrino beam optics capable to survive to the beam power, the radiation and the mercury. Already prototyped.
- Up to here is the first stage of a neutrino factory complex.
- A sophisticated close detector to measure at 2% signal and backgrounds.
- A megaton class detector under the Frejus, L=130 km: Memphys.

# The Memphis detector (hep-ex/0607026)



In the middle of the Fréjus tunnel at a depth of 4800 m.w.e a preliminary investigation shows the feasibility to excavate up to five shafts of about 250,000 m<sup>3</sup> each ( $\Phi = 65$  m, full height=80 m).

Fiducial of 3 shafts: 440 kton.

30% coverage by using 12" PMT's from Photonis, 81k per shaft (with the same photostatistics of SuperKamiokande with 40% coverage)

# Laguna

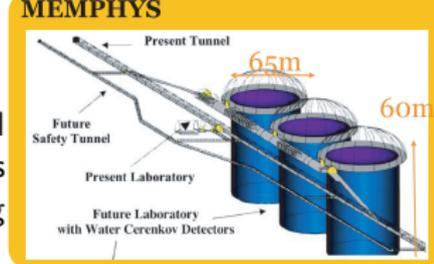
A coordinated European effort aimed towards conceptual designs for European large underground detectors. Physics focus: proton decay, low energy neutrino astronomy, long baseline neutrino beam.

Three detection techniques are currently investigated:

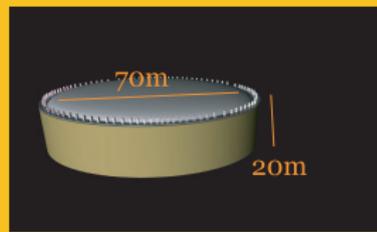
- Water Cerenkov imaging,  $\sim 500$  kton, with synergy with HK (Japan) and UNO (USA).
- Liquid argon time-projection chamber,  $\sim 100$  kton. Technology pioneered in Europe by the ICARUS R&D programme.
- Liquid scintillator,  $\sim 50$  kton connected to Borexino R&D programme

Feasibility studies for site excavation are mandatory to build the required infrastructure to host these very large detectors, also under controlled cost boundaries.

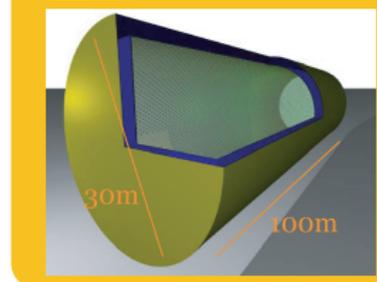
The Design Study has been recently approved inside the Europe FP7



## GLACIER



## LENA



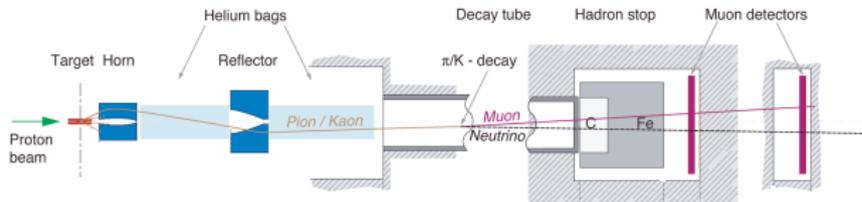
# The merits of the “short baselines”

- Absolutely negligible matter effects: the cleanest possible environment for direct leptonic CP violation and  $\theta_{13}$  searches.
- Almost all the events are quasi elastics: very reduced problems from the QE-not QE ratios.
- Energy shape it's not a problem, a reasonable binning can be achieved (see later frames).
- In principle the same energy of a SPS based beta beam. The two beams could be fired to the same detector.

## On the other hand

- Mass hierarchy cannot be directly measured. A not trivial sensitivity on  $\text{sign}(\Delta m_{23}^2)$  can however been recovered combining accelerator neutrino signals with the atmospheric' (see later frames).
- Small cross sections, loosely known and with important influence of nuclear effects.

# Conventional neutrino beams are going to hit their ultimate limitations.



In a **conventional neutrino beam**, neutrinos are produced **SECONDARY** particle decays (mostly pions and kaons).

Given the short life time of the pions ( $2.6 \cdot 10^{-8}$ s), they can only be focused (and charge selected) by means of magnetic horns. Then they are let to decay in a decay tunnel, short enough to prevent most of the muon decays.

- Besides the main component ( $\nu_\mu$ ) at least 3 other neutrino flavors are present ( $\bar{\nu}_\mu$ ,  $\nu_e$ ,  $\bar{\nu}_e$ ), generated by wrong sign pions, kaons and muon decays.  $\nu_e$  contamination is a background for  $\theta_{13}$  and  $\delta$ ,  $\bar{\nu}_\mu$  contamination dilutes any CP asymmetry.
- Hard to predict the details of the neutrino beam starting from the primary proton beam, the problems being on the secondary particle production side.
- Difficult to tune the energy of the beam in case of ongoing optimizations.

## All these limitations are overcome if secondary particles become primary

Collect, focus and accelerate the neutrino parents at a given energy. This is impossible within the pion lifetime, but can be tempted within the muon lifetime (**Neutrino Factories**) or within some radioactive ion lifetime (**Beta Beams**):

- Just one flavor in the beam
- Energy shape defined by just two parameters: the endpoint energy of the beta decay and the  $\gamma$  of the parent ion.
- Flux normalization given by the number of ions circulating in the decay ring.
- Beam divergence given by  $\gamma$ .

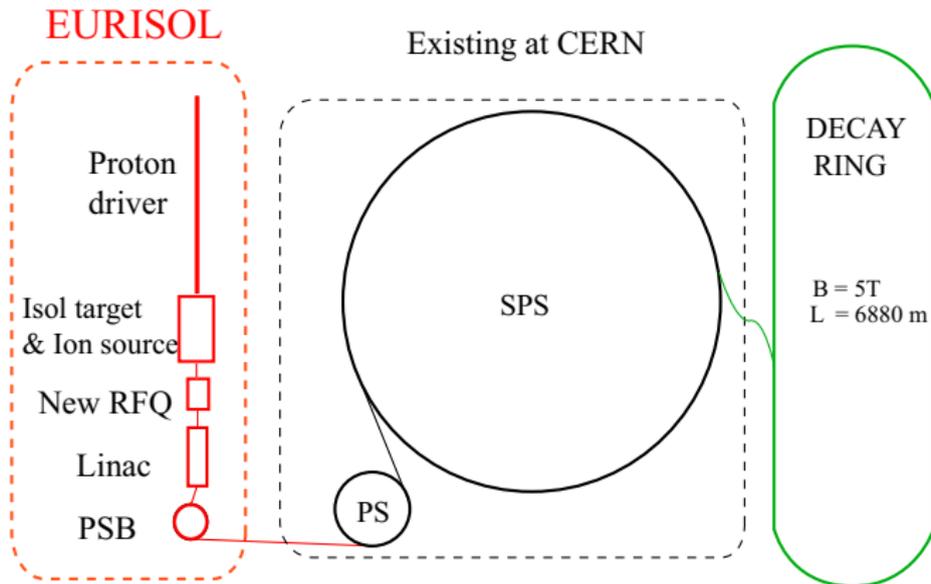
### The full ${}^6\text{He}$ flux MonteCarlo code

```
Function Flux(E)
Data Endp/3.5078/
Data Decays /2.9E18/

ye=me/EndP
c ...For ge(ye) see hep-ph0312068
ge=0.0300615
2gE0=2*gamma*EndP
c ... Kinematical Limits
If(E.gt.(1-ye)*2gE0)THEN
    Flux=0.
    Return
Endif
c ...Here is the Flux
Flux=Decays*gamma**2/(pi*L**2*ge)*(E**2*(2gE0-E
+ 2gE0**4*Sqrt((1-E/2gE0)**2-ye**2)

Return
```

M. Lindroos et al., see <http://beta-beam.web.ch/beta-beam>

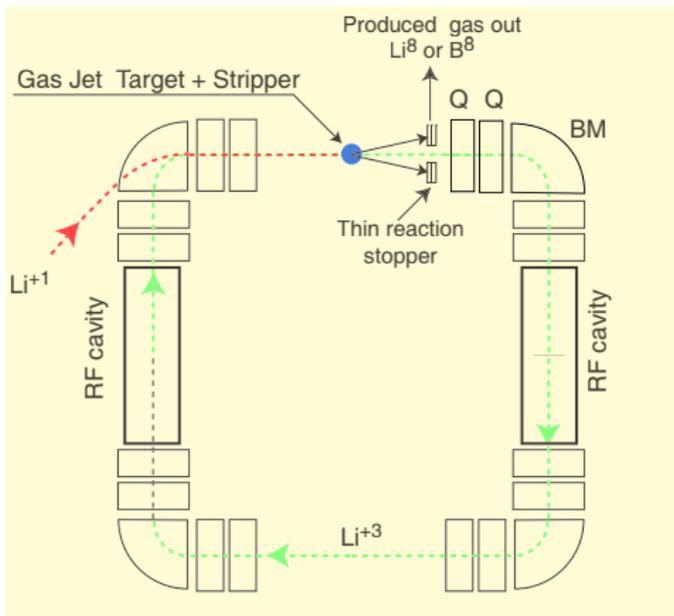


- 1 ISOL target to produce  $\text{He}^6$ ,  $100 \mu A$ ,  $\Rightarrow 2.9 \cdot 10^{18}$  ion decays/straight session/year.  $\Rightarrow \bar{\nu}_e$ .
- 3 ISOL targets to produce  $\text{Ne}^{18}$ ,  $100 \mu A$ ,  $\Rightarrow 1.1 \cdot 10^{18}$  ion decays/straight session/year.  $\Rightarrow \nu_e$ .
- These fluxes apply if the two ions are run separately

# Exciting new ideas about radioactive ion production

C. Rubbia et al., hep-ph/0602032

C. Rubbia hep-ph/0609235



- It could deliver up to two order of magnitudes more radioactive ions than the Eurisol targets.
- ${}^8\text{B}$  and  ${}^8\text{Li}$  have a  $Q$  factor about 8 times larger than  ${}^6\text{He}$  and  ${}^{18}\text{Ne}$ , allowing higher neutrino energies for the same  $\gamma$  value (on the other hand for the same neutrino energy the relative flux is lower by  $1/\gamma$  due to the smaller Lorenz boost.)
- They have a more favorable  $Z/A$  factor, allowing for higher  $\gamma$  at the same accelerator.
- If realistic, this production method could bring to a completely different Beta Beam optimization scheme.

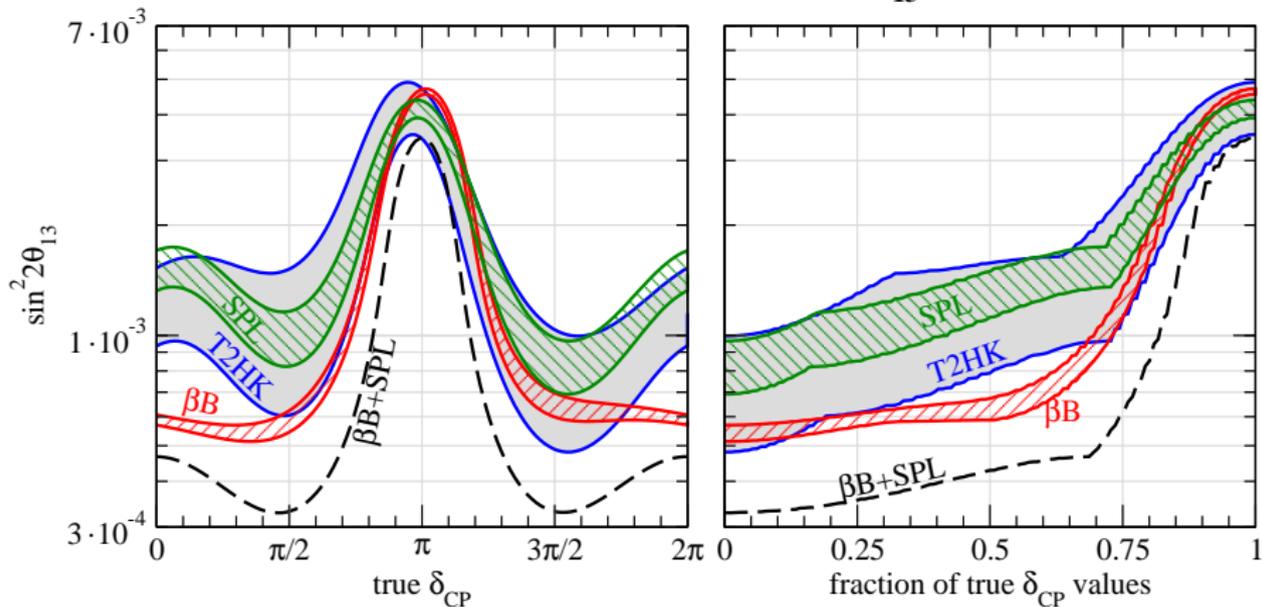
# Oscillation signals

From J.E.Campagne, M. Maltoni, M.M., T.Schwetz, JHEP **0704** (2007) 003.

	$\beta B$		SPL		T2HK	
	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$
appearance $\nu$						
background		143		600		1017
$\sin^2 2\theta_{13} = 0$		25		41		84
$\sin^2 2\theta_{13} = 10^{-3}$	72	81	93	10	181	18
$\sin^2 2\theta_{13} = 10^{-2}$	310	339	387	126	754	240
appearance $\bar{\nu}$						
background		157		500		1428
$\sin^2 2\theta_{13} = 0$		30		36		90
$\sin^2 2\theta_{13} = 10^{-3}$	82	12	74	104	188	261
$\sin^2 2\theta_{13} = 10^{-2}$	346	125	297	390	746	977

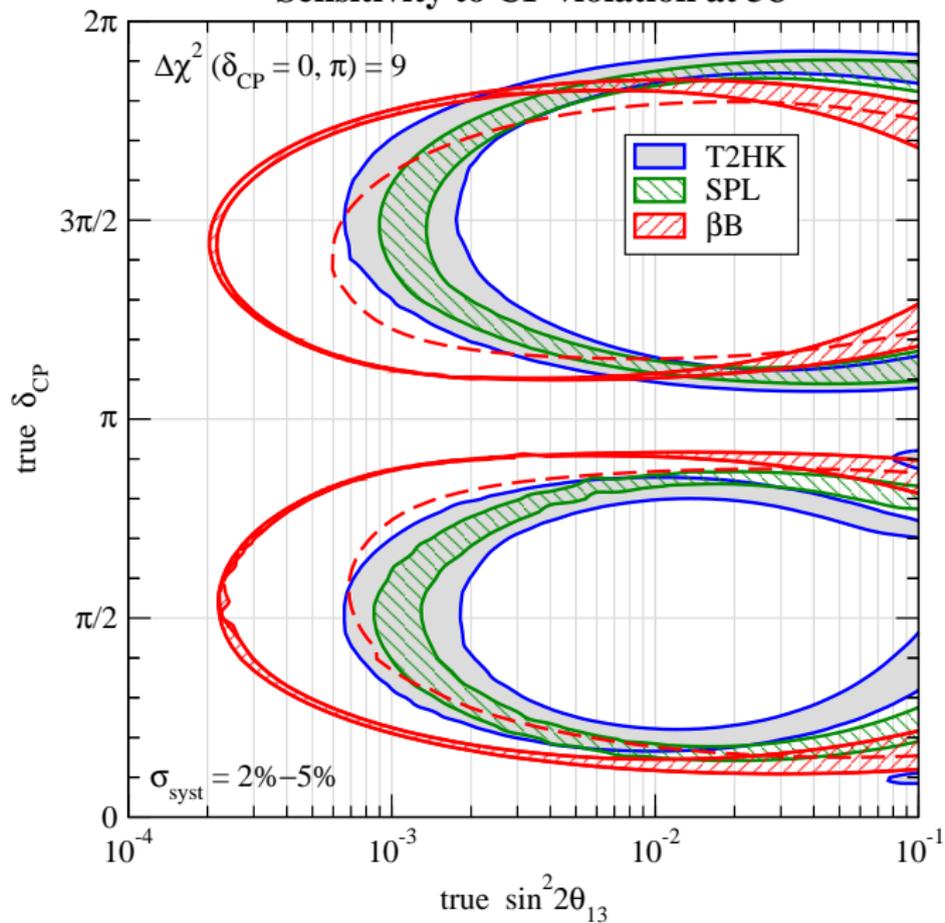
Computed with  $\Delta m_{31}^2 = +2.4 \times 10^{-3} \text{ eV}^2$ ,  $\sin^2 \theta_{23} = 0.5$ ,  $\Delta m_{21}^2 = 7.9 \times 10^{-5} \text{ eV}^2$ ,  $\sin^2 \theta_{12} = 0.3$ . with an accuracy of 10% for  $\theta_{12}$ ,  $\theta_{23}$ ,  $\Delta m_{31}^2$ , and 4% for  $\Delta m_{21}^2$  at  $1\sigma$ .

### $3\sigma$ discovery of a non-zero $\theta_{13}$



Line width: 2% and 5% systematic errors.

# Sensitivity to CP violation at $3\sigma$

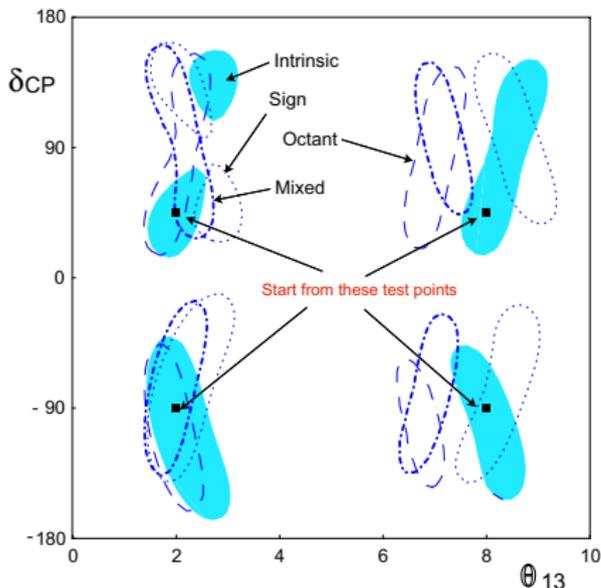


## The degeneracy problem

The sub-leading  $\nu_\mu \rightarrow \nu_e$  formula leaves room for clone solutions of the fit to  $\theta_{13}$  and  $\delta_{CP}$ . The eightfold degeneracies arise from

- **sign( $\Delta m_{23}^2$ )**. Changing  $\text{sign}(\Delta m_{23}^2)$  the  $P(\nu_\mu \rightarrow \nu_e)$  terms  $\propto \sin(\Delta m_{23}^2)$  change sign. Two separate solutions can be created by  $(\theta_{13}, \delta_{CP}, \text{sign}(\Delta m_{23}^2))$  and by  $(\theta'_{13}, \delta'_{CP}, -\text{sign}(\Delta m_{23}^2))$ .
- **$\pi/2 - \theta_{23}$  (octant)**.  $\nu_\mu$  disappearance measures  $\sin^2 2\theta_{23}$  but some terms in the oscillation formula depend from  $\sin \theta_{23}$ . At present the experimental best fit is  $\sin^2 2\theta_{23} = 1$  allowing no ambiguity, but the experimental not excluded values smaller than unity allow for a twofold  $\pi/2 - \theta_{23}$  ambiguity.
- **Mixed** The product of the above two

These eightfold discrete degeneracies (or twofold in case  $\sin^2 2\theta_{23} \simeq 1$ ) can be solved by combining information of different experiments running at different energies or looking to different processes (i.e. combining  $\nu_\mu \rightarrow \nu_e$  transitions with  $\nu_e$  disappearance or with  $\nu_e \rightarrow \nu_\tau$  transitions). A single experiment cannot solve all these degeneracies by itself.



# The synergy with atmospheric neutrinos

**P. Huber et al., hep-ph/0501037:** Combining Long Baseline data with atmospheric neutrinos (that come for free in the megaton detector):

- Degeneracies can be canceled, allowing for better performances in  $\theta_{13}$  and LCPV searches
- The neutrino mass hierarchy can be measured
- The  $\theta_{23}$  octant can be determined.

The main reasons are:

- **Octant** e-like events in the Sub-GeV data is  $\propto \cos^2 \theta_{23}$
- **Sign** e-like events in the Multi-GeV data, thanks to matter effects, especially for zenith angles corresponding to neutrino trajectories crossing the mantle and core where a resonantly enhancement occurs.

**NOTE:** LBL and atmospheric neutrinos are a true synergy. They add to each other much more than a simple gain in statistics. Atmospheric neutrinos alone could not measure the hierarchy, the octant,  $\theta_{13}$  and LCPV. While the Beta Beam at short baselines could not measure the hierarchy as well as the octant.

In the following sensitivities of the Beta Beam combined with the atmospheric neutrinos are taken from J.E.Campagne, M.Maltoni, M.M., T.Schwetz, hep-ph/0603172

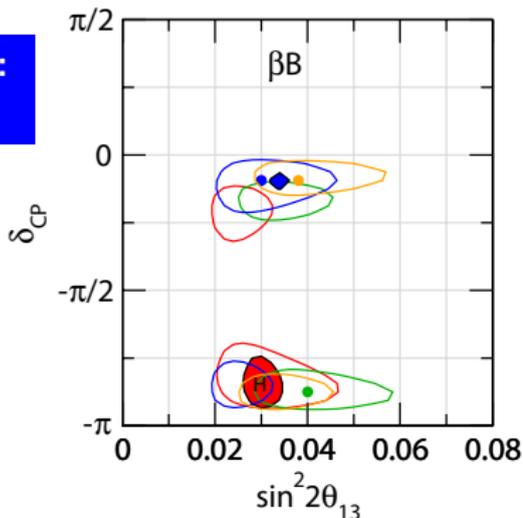
## Beta Beam plus atmospheric: degeneracy removal

J.E.Campagne, M.Maltoni, M.M.,  
T.Schwetz, JHEP **0704** (2007) 003

The red region is what is left after the  
atmospheric analysis.

Note how degeneracies were not  
influencing LCPV sensitivity too much.

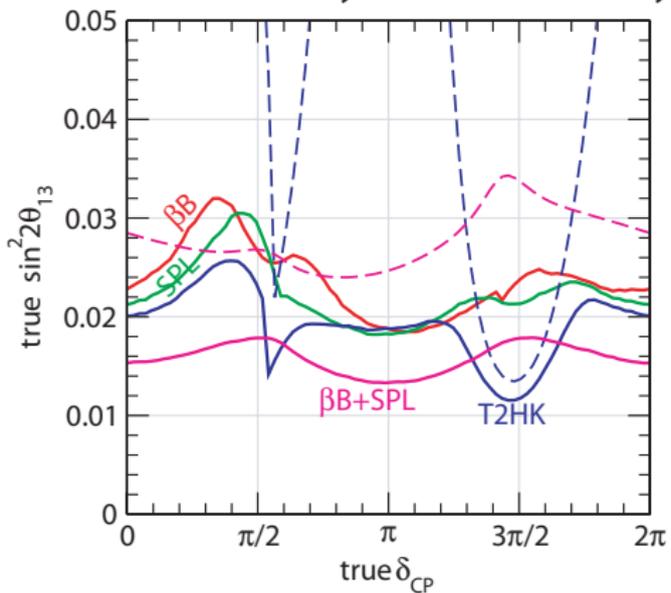
95% CL regions for the  $(H^{tr}O^{tr})$ ,  
 $(H^{tr}O^{wr})$ ,  $(H^{wr}O^{tr})$ ,  $(H^{wr}O^{wr})$   
solutions



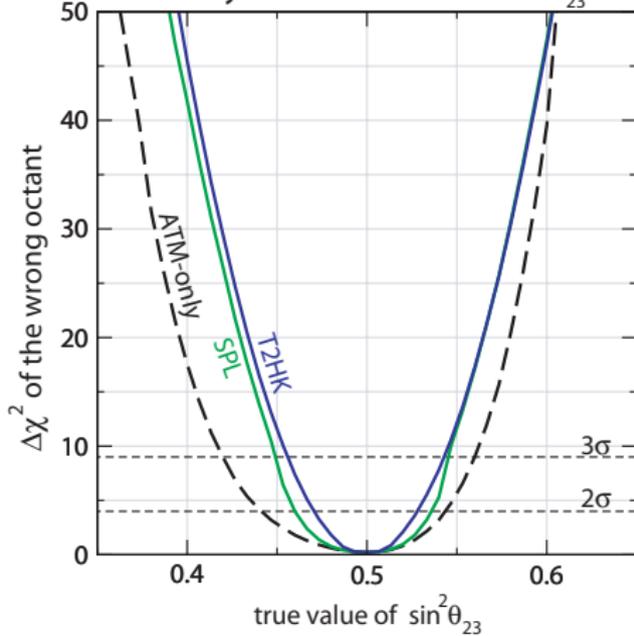
$$\begin{aligned}\delta &= -0.85 \pi \\ \sin^2(2\theta_{13}) &= 0.03 \\ \sin^2(2\theta_{23}) &= 0.6\end{aligned}$$

# Beam plus atmospheric: determining mass hierarchy and the

2 $\sigma$  sensitivity to normal hierarchy



Sensitivity of to the octant of  $\theta_{23}$



# The high energy options

Several papers explored the physics potential of higher energy beta beams, showing how the experimental sensitivities can be improved if a higher energy accelerator than the SPS could be used (performances shown in later frames):

- J. Burguet-Castell et al., Nucl. Phys. B **695**, 217 (2004), Nucl. Phys. B 725, 306 (2005) ( $\gamma = 150, 350$ )
- F. Terranova et al., Eur. Phys. J. C **38** (2004) 69:  $\gamma = 2500, \gamma = 4158$
- P. Huber, M. Lindner, M. Rolinec and W. Winter, Phys. Rev. D 73,053002 (with a discussion of fluxes vs.  $\gamma$ ).
- S. Agarwalla et al.: Phys. Rev. D **75**, 097302 (2007), Nucl. Phys. B **798**, 124 (2008), arXiv:0802.3621 [hep-ex], arXiv:0804.3007 [hep-ph].
- W. Winter, arXiv:0804.4000
  - Need a proton machine of 1 TeV energy (LHC cannot be used at such high fluxes)
  - Assume the same ion decay rates of the SPS option.
  - The decay ring length rises linearly with  $\gamma$

# Electron capture beams

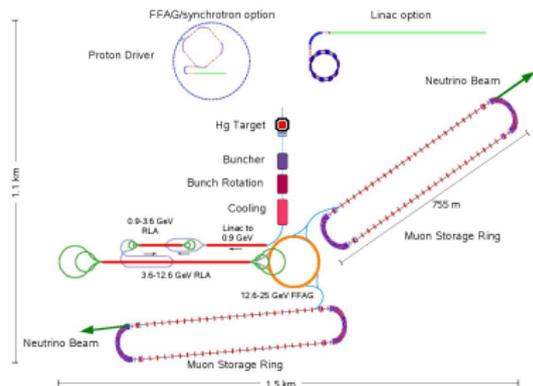
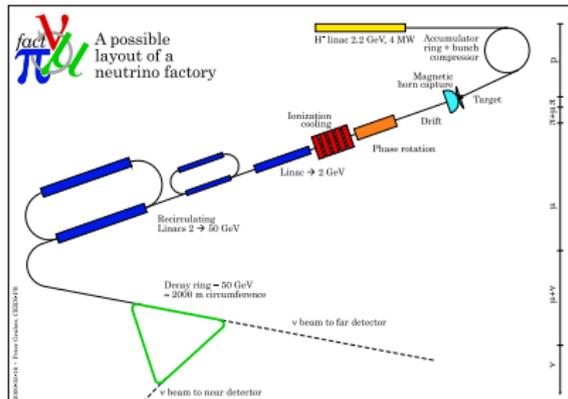
Radioactive ions can produce neutrinos also through electron capture.

## **Monochromatic, single flavor neutrino beams!**

- J. Bernabeu, J. Burguet-Castell, C. Espinoza and M. Lindroos, hep-ph/0505054
- J. Sato, hep-ph/0503144. M. Rolinec and J. Sato, hep-ph/0612148.
  
- The same complex could run either beta or electron capture beams.
- No way to have  $\bar{\nu}_e$  beams.
- Ions should be partially (and not fully) stripped. Technologically challenging.
- Ion candidates are much heavier than beta candidates and have longer lifetimes (more difficult to stack them in the decay ring)

# The basic concept of a neutrino factory

- High power (4 MW) proton beam onto a liquid mercury target.
- System for collection of the produced pions and their decay products, the muons.
- Energy spread and transverse emittance have to be reduced: "phase rotation" and ionization cooling
- Acceleration of the muon beam with a LINAC and Recirculating Linear Accelerators.
- Muons are injected into a storage ring (decay ring), where they decay in long straight sections in order to deliver the desired neutrino beams.
- **GOAL:**  $\sim 10^{21}$   $\mu$  decays per straight section per year



# Oscillation signals at the neutrino factory

$\mu^- (\mu^+)$  decay in  $(\nu_\mu, \bar{\nu}_e)$  ( $(\bar{\nu}_\mu, \nu_e)$ ).

**Golden channel:** search for  $\nu_e \rightarrow \nu_\mu$  ( $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ ) transitions by detecting wrong sign muons.

Default detector: 40-100 kton iron magnetized calorimeter (Minos like)

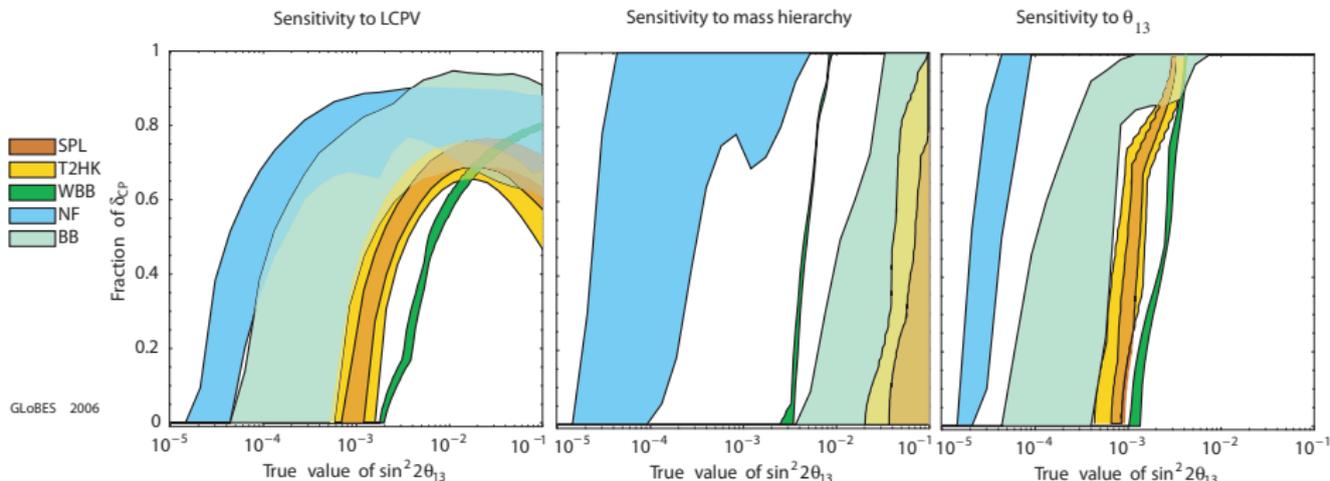
**Silver channel:** search for  $\nu_e \rightarrow \nu_\tau$  transitions by detecting  $\nu_\tau$  appearance.

Ideal detectors: 4× Opera or 10 Kton LAr detector.

All these detectors can be accomodate at LNGS.

Ideal baseline for a 50 GeV Neutrino Factory is  $\sim 3000$  km.

# Sensitivity Comparison



Line widths reflect different assumptions on machine configuration, fluxes, detector performances and systematic errors.

