Mauro Mezzetto,
Istituto Nazionale di Fisica Nucleare, Sezione di Padova

" Future Long Baseline Experiments"

- Introduction
- Super Beams
- Beta Beams
- Neutrino Factories

Parameters of the Standard Model

Symbol	Description	Renormalization scheme (point)	Value
m_e	Electron mass		511 keV
m_μ	Muon mass		106 MeV
m_τ	Tauon mass		1.78 GeV
m_u	Up quark mass	$\mu_{\overline{MS}}$ = 2 GeV	1.9 MeV
m_d	Down quark mass	$\mu_{\overline{MS}}$ = 2 GeV	4.4 MeV
m_s	Strange quark mass	$\mu_{\overline{MS}}$ = 2 GeV	87 MeV
m_c	Charm quark mass	$\mu_{\overline{MS}} = m_c$	1.32 GeV
m_b	Bottom quark mass	$\mu_{\overline{MS}} = m_b$	4.24 GeV
m_t	Top quark mass	On-shell scheme	172.7 GeV
θ_{12}	CKM 12-mixing angle		13.1°
θ_{23}	CKM 23-mixing angle		2.4°
θ_{13}	CKM 13-mixing angle		0.2°
δ	CKM CP-violating Phase		0.995
g_1	U(1) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.357
g_2	SU(2) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.652
g_3	SU(3) gauge coupling	$\mu_{\overline{MS}} = m_Z$	1.221
θ_{QCD}	QCD vacuum angle		~0
μ	Higgs quadratic coupling		Unknown
λ	Higgs self-coupling strength		Unknown

Parameters added after neutrino oscillations

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$m_{\nu e}$	Electron neutrino mass	Unknown
$m_{\nu\mu}$	Muon neutrino mass	Unknown
$m_{\nu\tau}$	Tau neutrino mass	Unknown
θ_{12}	MNSP 12 – mix angle	34.4^0
θ_{23}	MNSP 23 – mix angle	45.0^0
θ_{13}	MNSP 13 – mix angle	Unknown
δ	MNSP CP-violating phase	Unknown
Higgs scheme	Higgs mechanism for neutrino masses	Unknown (See –Saw?)

$\Delta m^2_{12} = 7.6\ 10^{-5}\ eV^2$
$\Delta m^2_{23} = 2.4\ 10^{-3}\ eV^2$
Sign(Δm^2_{23}): Unknown
Absolute scale: Unknown

To be measured by Long Baseline neutrino oscillation experiments

Leptons are VERY different from quarks. (I)

Neutrinos $U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$

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

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

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

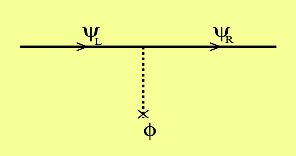
$\theta_{13} \rightarrow 0 \quad \Rightarrow$ The 3x3 mixing matrix becomes a trivial product of two 2x2 matrixes.

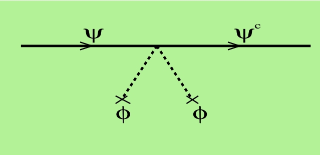
θ_{13} drives $\nu_\mu \rightarrow \nu_e$ subleading transitions $\Rightarrow$
the necessary milestone for any subsequent search:
neutrino mass hierarchy and leptonic CP searches.

Leptons are VERY different from quarks. (II)

$u \sim 5$ MeV	$c \sim 1$ GeV	$t \sim 175$GeV	$e \sim 0.5$ MeV	$\mu \sim 0.1$ GeV	$\tau \sim 2$GeV
$d \sim 8$ MeV	$s \sim 0.1$ GeV	$b \sim 5$GeV	$\nu_e \leq \mathcal{O}(1\, eV)$	$\nu_\mu \leq \mathcal{O}(1\, eV)$	$\nu_\tau \ \leq \mathcal{O}(1\, eV$

How can the same model generate mass ratio so different?



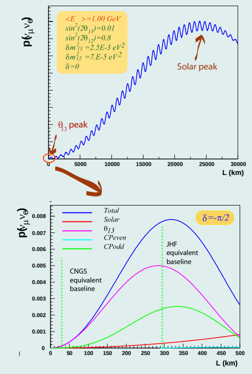


$$\lambda_\nu \overline{\Psi}_R \Phi \Psi_L + h.c.$$
$$m_f = \lambda_f v$$
$$L$$

$$\frac{\alpha_\nu}{M} \nu_L^T C \tilde{\Phi}^T \tilde{\Phi} \nu_L + h.c.$$
$$m_f = \alpha_\nu \frac{v^2}{M}$$
$$\not{L}$$

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.

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



$$p(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \times \left[1 \pm \frac{2a}{\Delta m_{13}^2}(1-2s_{13}^2)\right] \quad \theta_{13} \text{ dri}$$

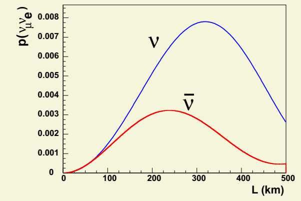
$$+ 8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23}) \cos\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{12}^2 L}{4E} \text{CPev}$$

$$\mp 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{12}^2 L}{4E} \quad \text{CPodd}$$

$$+ 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta\} \sin\frac{\Delta m_{12}^2 L}{4E} \quad \text{solar driven}$$

$$\mp 8c_{12}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E}(1-2s_{13}^2) \quad \text{matter effect (CP odd)}$$

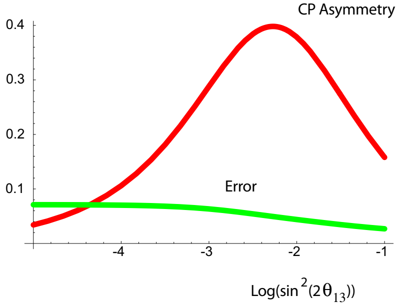
θ_{13} discovery requires a signal ($\propto \sin^2 2\theta_{13}$) greater than the solar driven probability



Leptonic CP discovery requires $A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar\nu_\mu \to \bar\nu_e)}{P(\nu_\mu \to \nu_e) + P(\bar\nu_\mu \to \bar\nu_e)} \neq 0$

Measuring Leptonic CP violation

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)}$$



LCPV asymmetry at the first oscillation maximum, $\delta = 1$, Error curve: dependence of the statistical+systematic (2%) computed for a beta beam the fixed energy $E_\nu = 0.4$ GeV, $L = 130$ km.

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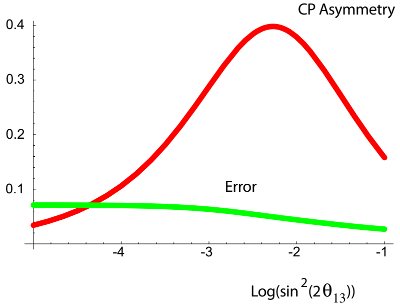

LCPV asymmetry at the first oscillation maximum, $\delta = 1$, Error curve: dependence of the statistical+systematic (2%) computed for a beta beam the fixed energy $E_\nu = 0.4$ GeV, $L = 130$ km.

- **The detection of such asymmetry is an evidence of Leptonic CP violation only in absence of competitive processes (i.e. matter effects, see following slides) ⇒ ”short“ Long Baseline experiments**

Measuring Leptonic CP violation

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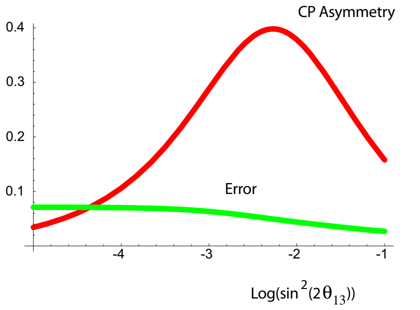

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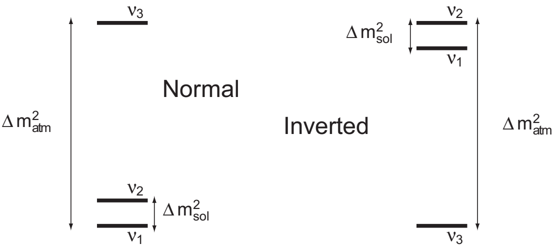
- **The detection of such asymmetry is an evidence of Leptonic CP violation only in absence of competitive processes (i.e. matter effects, see following slides) $\Rightarrow$ "short" Long Baseline experiments**
- Statistics and systematics play different roles at different values of $\theta_{13} \Rightarrow$ impossible to optimize the experiment without a prior knowledge of θ_{13}
- Contrary to the common belief, the highest values of θ_{13} are not the easiest condition for LCPV discovery

Measuring mass hierarchy

An internal degree of freedom of neutrino masses is the sign of Δm^2_{31}: $\mathrm{sign}(\Delta m^2_{23})$.



Due to the couplings of $\nu_{1,2,3}$ to $\nu_{e,\mu,\tau}$ this parameter decides if ν_e is the lightest or the heaviest neutrino, with important practical consequencies to direct neutrino mass and double beta decay experiments.

Neutrino Oscillations in Matter

$$P_{\theta_{13}} = \sin^2(2\theta_{13})\sin\theta_{23}{}^2 \sin^2((\hat{A}-1)\hat{\Delta})/(\hat{A}-1)^2;$$
$$p_{\sin\delta} = \alpha \sin(2\theta_{13})\zeta \sin\delta \sin(L\hat{\Delta}) \sin(\hat{A}\hat{\Delta}) \sin((1-\hat{A})\hat{\Delta})/((1-\hat{A})\hat{A});$$
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$$p_{\mathrm{solar}} = \alpha^2 \cos\theta_{23}{}^2 \sin^2 2\theta_{12} \sin^2(\hat{A}\hat{\Delta})/\hat{A}^2;$$

$\alpha = \mathrm{Abs}(\Delta m^2_{21}/\Delta m^2_{31})$; $\hat{\Delta} = \frac{L\Delta m^2_{31}}{4E}$ $\zeta = \cos\theta_{13}\ \sin 2\theta_{12} \sin 2\theta_{23}$
$\boldsymbol{\hat{A} = \pm a/\Delta m^2_{31}}$; $a = 7.6 \cdot 10^{-5} \rho \cdot E_\nu(GeV)$ $\quad \rho = \text{matter density }(\mathrm{g\,cm^{-3}})$
The $\hat{A}$ term changes sign with $\mathrm{sign}(\Delta m^2_{23})$

Matter effects require long “long baselines"

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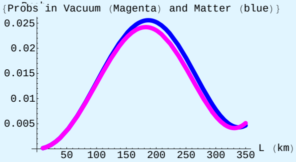
$\boldsymbol{E_\nu = 0.35\mathrm{GeV}\ L \simeq 130\ \mathrm{km}}$



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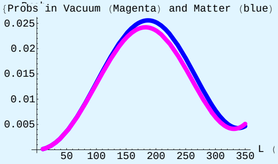
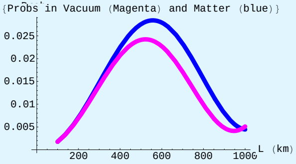
Matter effects require long "long baselines"

$\boldsymbol{E_\nu = 0.35\mathrm{GeV}\ L \simeq 130}$ **km** $\quad \boldsymbol{E_\nu = 1\mathrm{GeV}\ L \simeq 500}$ **km**





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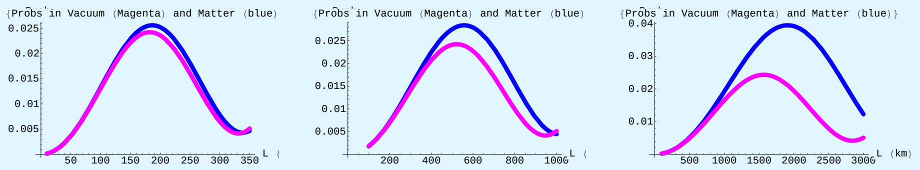
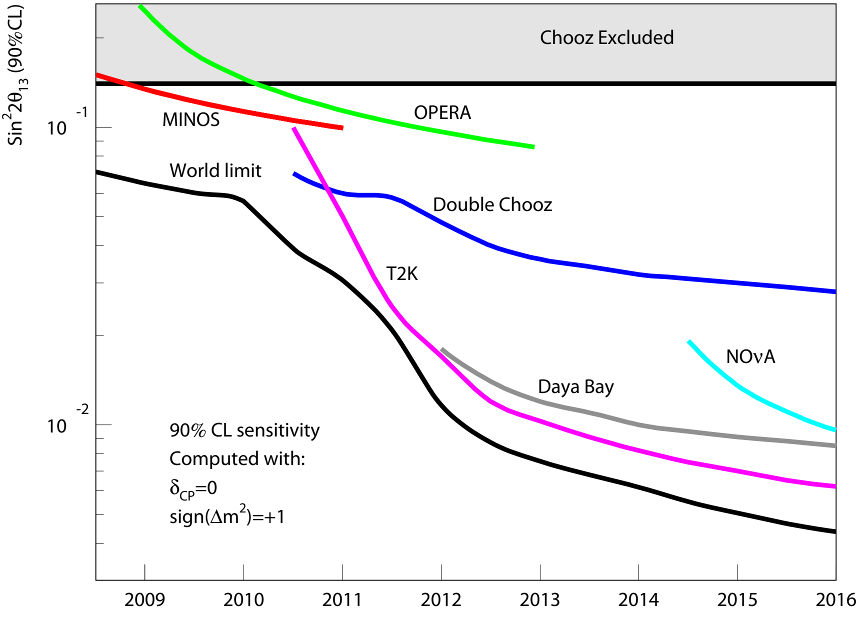
Matter effects require long "long baselines"

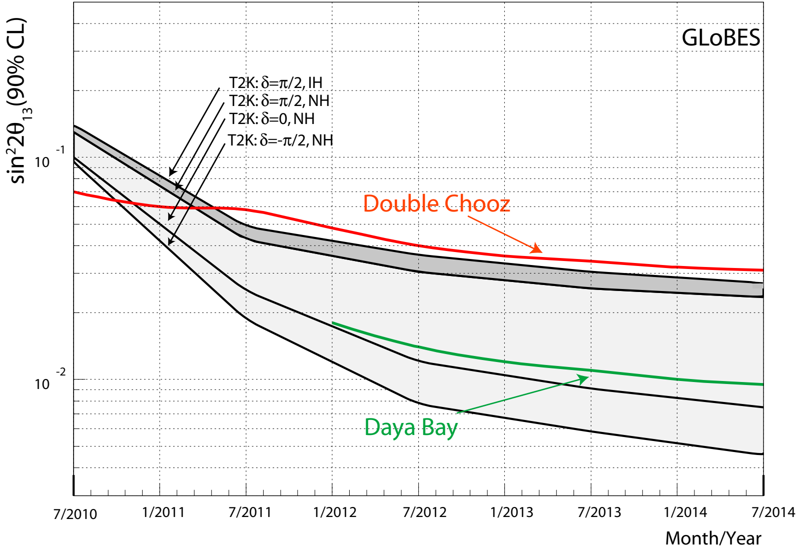
$E_\nu = 0.35\mathrm{GeV}$ $L \simeq 130$ km **$E_\nu = 1\mathrm{GeV}$ $L \simeq 500$ km** **$E_\nu = 3\mathrm{GeV}$ $L \simeq 1500$ km**



Status after this generation of LBL experiments



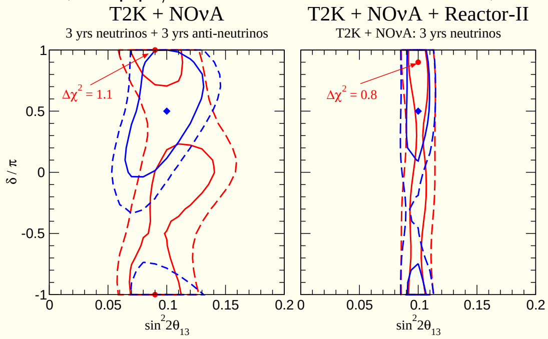
Status after this generation of LBL experiments (a better view



Status after the first and second generation: δ_{CP}

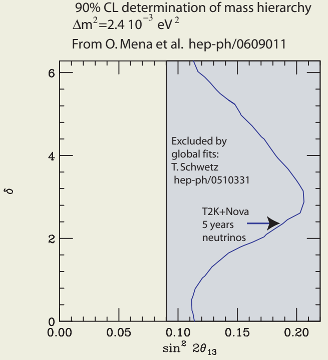
No hope to see any CP signal at 3σ

P. Huber et al., hep-ph/0412133 and JHEP 0911:044,2009.



(dotted lines: 3σ, solid are 90%CL)

. . . and mass hierarchy



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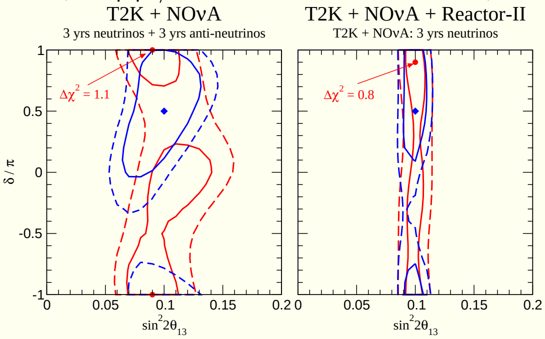

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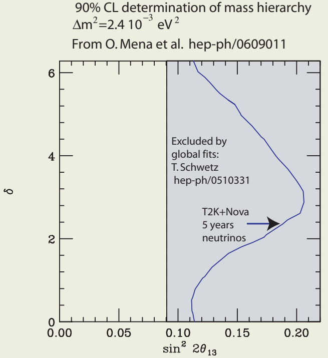


To address leptonic CP violation: improve of at least one order of magnitude the sensitivity of $\mathbf{\sin^2 2\theta_{13}}$; two order of magnitudes more neutrinos !!!

The SuperBeam way

Proposals based on upgrades of existing facilities:

- T2K $\Rightarrow$ T2HK or T2KK
- Noνa $\Rightarrow$ Super Noνa
- 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). Talk by S. Parke yesterday.

Proposals based on new facilities

- CERN-SPL SuperBeam

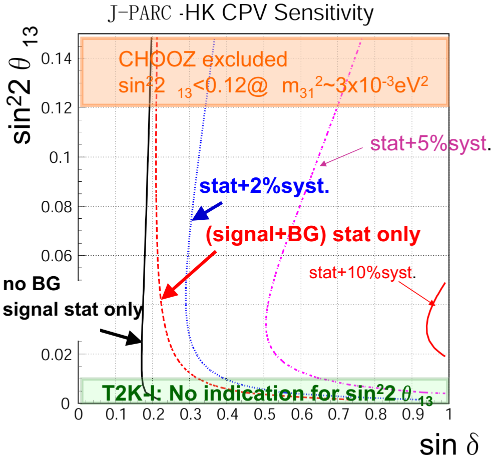
SuperBeams - J-PARC phase 2 (T2HK)

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

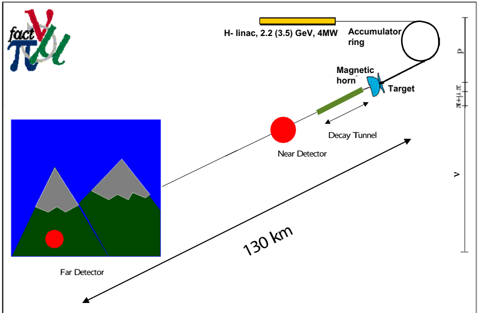
The detector would have valuable physics potential in proton decay, SN neutrinos, solar neutrinos.

Other possibility:
displace half detector in Korea at the second oscillation maximum (T2KK) for better sensitivity on $\mathrm{sign}(\Delta m^2_{23})$ and better degeneracy removal

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



SuperBeams - SPL ν beam at CERN

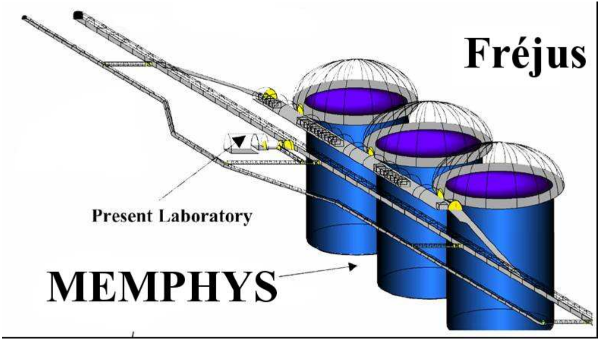


Possible Low Energy Super Beam Layout

- 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 Memphys detector (hep-ex/0607026)

Talks by M. Marafini and L. Mosca this morning



In the middle of the Frejus 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^3 each ($\Phi = 65\,m$, full height=80 m).

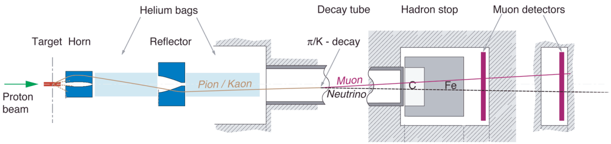
Fiducial of 3 shafts: 440 kton.

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

Some consideration about the SPL-SB

- At the SPL energies the kaon contamination in the beam line is very small. So the intrinsic ν_e contamination is smaller than any other on-axis neutrino beam line. Furthermore since both $\nu_\mu$and ν_e come from the same parents (π^+ parent chain) it can be claimed that the systematics coming from the intrinsic ν_e contamination are smaller than any other neutrino beam line.
- The short baselines are the absolute optimal configuration as far as regards leptonic CP violation. No competition with mass hierarchy and any degenerate solution does not weaken the LCPV discovery potential.
- The Linac configuration is perhaps the only way to reach 4 MW power. To be noted that the J-Parc ultimate power, initially set at 4 MW, is now estimated to be 1.66 MW. The T2HK and T2KK sensitivities have been recently rescaled to this value by their authors.

Conventional neutrino beams are going to hit their ultimate limitations.



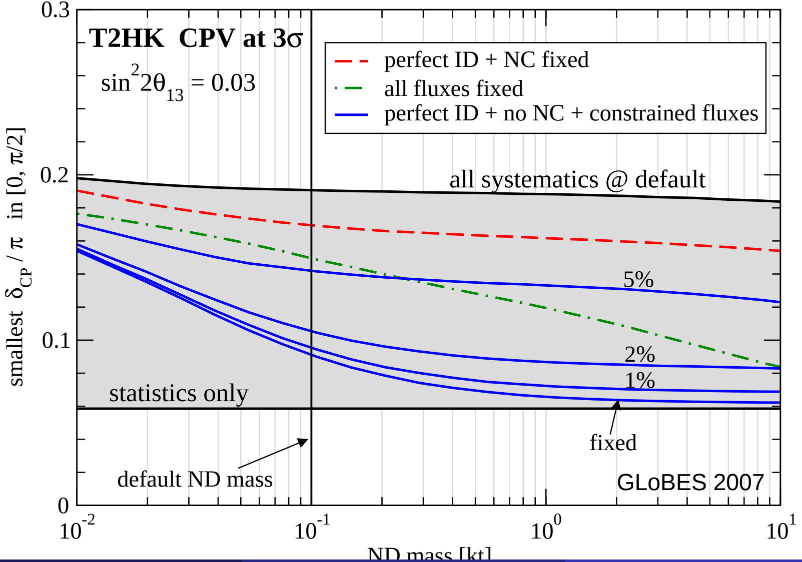
In a **conventional neutrino beam**, neutrinos are produced SECONDARY particle decays (mostly pions and kaons).
Given the short life time of the pions ($2.6 \cdot 10^{-8}$s), they can only be focused (and charge selected) by means of magnetic horns. Then they are let to decay in a decay tunnel, short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

- Besides the main component (ν_μ) at least 3 other neutrino flavors are present ($\overline{\nu}_\mu$, ν_e, $\overline{\nu}_e$), generated by wrong sign pions, kaons and muon decays. $\nu_e$contamination is a background for θ_{13} and δ, $\overline{\nu}_\mu$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.

About Systematic errors and Close detectors

5% is the realistic target for systematics in a Super Beam

From P. Huber, MM, T. Schwetz, JHEP **0803** (2008) 021 [arXiv:0711.2950 [hep-ph]].



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 γ of the parent ion.
- Flux normalization given by the number of ions circulating in the decay ring.
- Beam divergence given by γ.

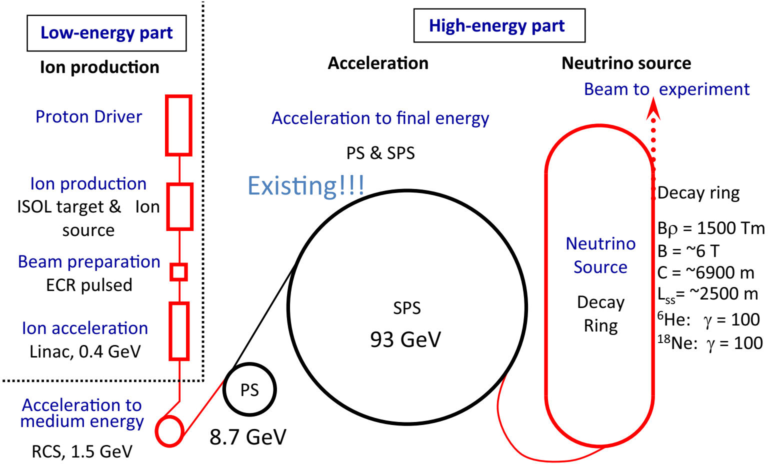
The full ^{6}He flux MonteCarlo code

```
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
```

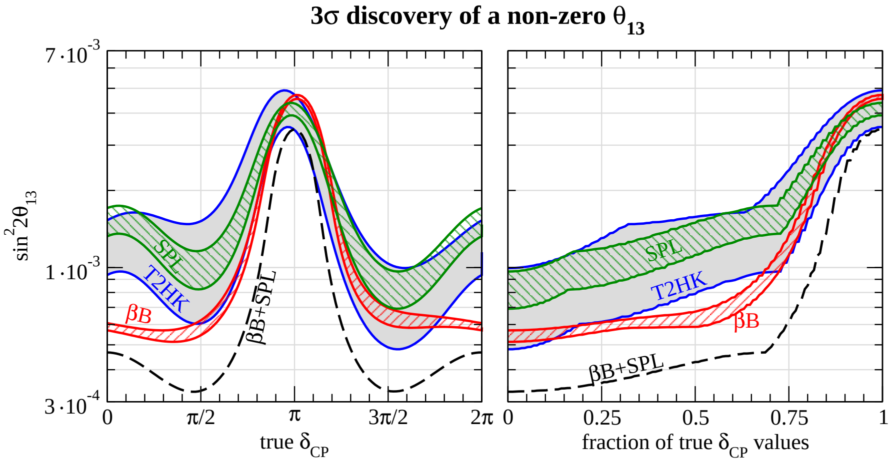
Beta Beam (P. Zucchelli: Phys. Lett. B532:166, 2002)

M. Lindroos M. Mezzetto, "Beta Beams", Imperial College Press, 2009

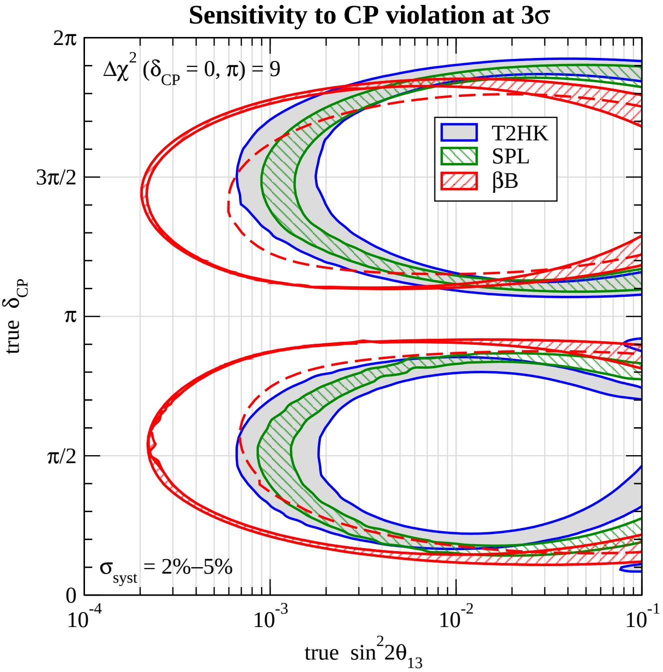
Talk by E. Wildner yesterday



- $\overline{\nu}_e$ generated by He^6, 100 μA, $\Rightarrow 2.9 \cdot 10^{18}$ ion decays/straight session/year.
- ν_e generated by Ne^{18}, 100 μA, $\Rightarrow 1.1 \cdot 10^{18}$ ion decays/straight session/year.



Line width: 2% and 5% systematic errors.


Sensitivity to CP violation at 3σ
Δχ² (δCP = 0, π) = 9
T2HK
SPL
βB
σsyst = 2%–5%
2π
3π/2
π
π/2
0
true δCP
10^-4
10^-3
10^-2
10^-1
true sin²2θ13

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 θ_{13} and LCPV searches
- The neutrino mass hierarchy can be measured
- The θ_{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 atmospherics are a true synergy. They add to each other much more that a simple gain in statistics. Atmospherics alone could not measure the hierarchy, the octant, θ_{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 atmospherics are taken from J.E.Campagne, M.Maltoni, M.M., T.Schwetz, hep-ph/0603172

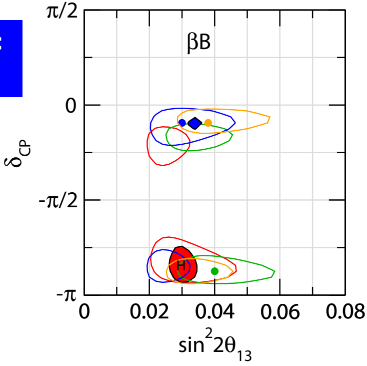
Beta Beam plus atmospherics: degeneracy removal

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.

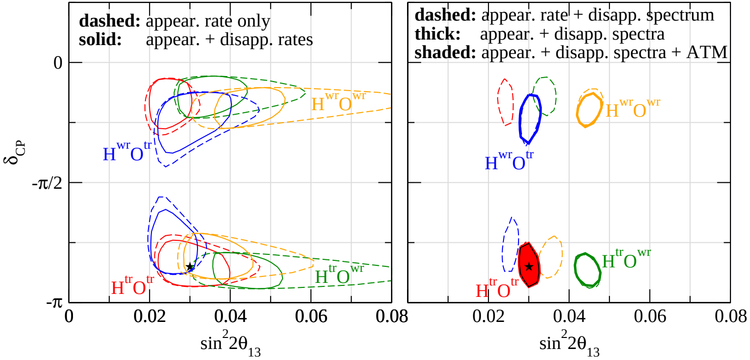
95% CL regions for the ($H^{tr}O^{tr}$), ($H^{tr}O^{wr}$), ($H^{wr}O^{tr}$), ($H^{wr}O^{wr}$) solutions



$\delta=-0.85\,\pi$
$\sin^2(2\theta_{13})=0.03$
$\sin^2(2\theta_{23})=0.6$

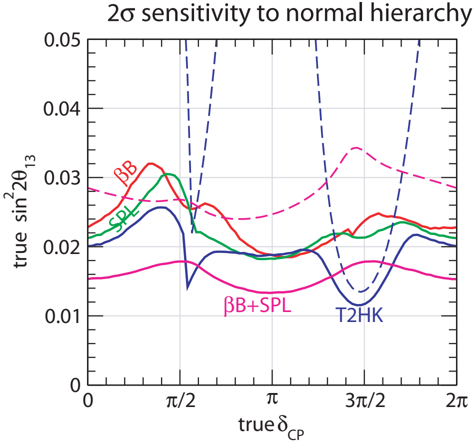
Degeneracy removal: SPL

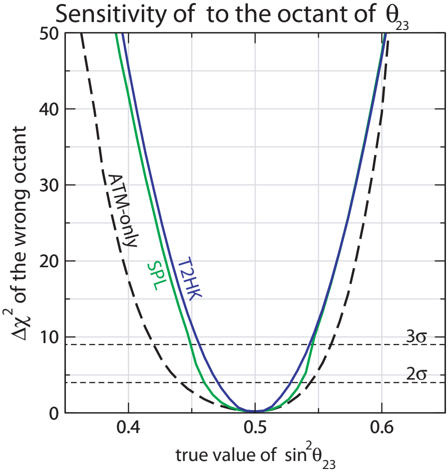
J.E.Campagne, M.Maltoni, M.M., T.Schwetz, JHEP **0704** (2007) 003



Resolving degeneracies in SPL by successively using the appearance rate measurement, disappearance channel rate and spectrum, spectral information in the appearance channel, and atmospheric neutrinos. Allowed regions in $\sin^2 2\theta_{13}$ and $\delta_{\rm CP}$ are shown at 95% CL, and $\mathrm{H}^{\rm tr/wr}(\mathrm{O}^{\rm tr/wr})$ refers to solutions with the true/wrong mass hierarchy (octant of θ_{23}). The true parameter values are $\delta_{\rm CP} = -0.85\pi$, $\sin^2 2\theta_{13} = 0.03$, $\sin^2\theta_{23} = 0.6$. The running time is $(2\nu + 8\bar{\nu})$ yrs.

Beta Beam plus atmo: determining mass hierarchy and the octant





The Beta Beam - SPL Super Beam synergy

MM, Nucl. Phys. Proc. Suppl. **149** (2005) 179.

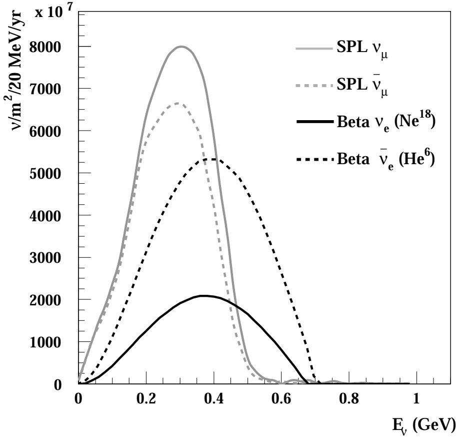
A Beta Beam has the same energy spectrum than the SPL SuperBeams and consumes 5% of the SPL protons.

The two beams could be fired to the same detector ⇒ LCPV searches through CP and T channels (with the possibility of using just neutrinos).

Access to CPTV direct searches.

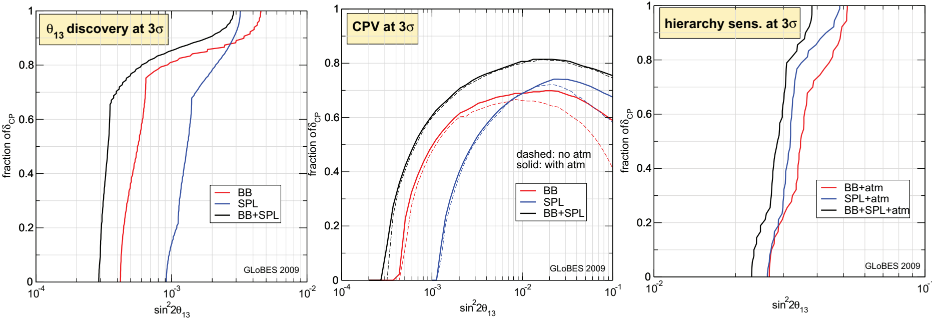
Cross measurement of signal cross section in the close detectors

Yearly Fluxes



Updated sensitivities of SPL, BB and SPL+BB

Courtesy of T. Schwetz, 5% systematics, the ISS curves were too pessimistic



Ways to improve beta-beam performances

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Ways to have more neutrinos in the far detector

1. More ions
2. Higher γ

Some scaling laws in Beta Beams

β^+ emitters			β^- emitters		
Ion	Q_{eff} (MeV)	Z/A	Ion	Q_{eff} (MeV)	Z/A
^{18}Ne	3.30	5/9	^{6}He	3.508	1/3
^{8}B	13.92	5/8	^{8}Li	12.96	3/8

- Proton accelerators can accelerate ions up to Z/A $\times$ the proton energy.
- Lorentz boost: end point of neutrino energy $\Rightarrow 2\gamma Q$
- In the CM neutrinos are emitted isotropically $\Rightarrow$ neutrino beam from accelerated ions gets more collimated $\propto \gamma^2$
- Merit factor for an experiment at the atmospheric oscillation maximum: $\boldsymbol{\mathcal{M} = \frac{\gamma}{Q}}$

  (End point energy of a muon decay $=$ 68 MeV $\Rightarrow$ merit factor of a Beta Beam about 20 times better than a Neutrino Factory.)
- Ion lifetime must be:
  - As long as possible: to avoid ion decays during acceleration
  - As short as possible: to avoid to accumulate too many ions in the decay ring

  $\Rightarrow$ optimal window: lifetimes around 1 s.
- Decay ring length scales $\propto \gamma$, following the magnetic rigidity of the ions.
- Two body decay kinematics : going off-axis the neutrino energy changes (feature used in some ECB setup and in the low energy setup)

Other Beta Beam options

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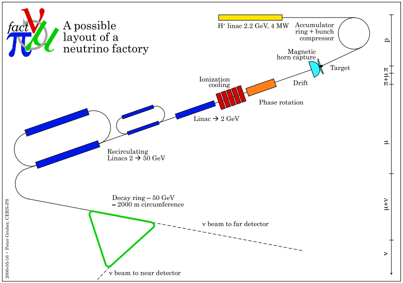
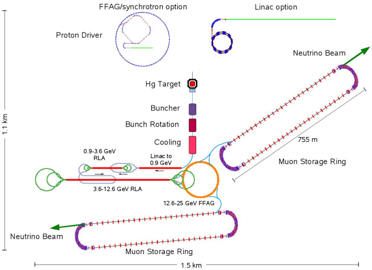
- **Electron capture Beta Beams**: monochromatic neutrino beams, a very attractive option
  - They require long lived, high-A, far from the stability valley ions, r$\Rightarrow$ challenging R&D to match the needed fluxes.

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: $\sim 10^{21}$ μ decays per straight section per year**





Oscillation signals at the neutrino factory

μ^- (μ^+) decay in (ν_μ, $\overline{\nu}_e$) (($\overline{\nu}_\mu$, ν_e)).

Golden channel: search for $\nu_e \to \nu_\mu$ ($\overline{\nu}_e \to \overline{\nu}_\mu$) transitions by detecting wrong sign muons.
Default detector: 40-100 kton iron magnetized calorimeter (Minos like)

Silver channel: search for $\nu_e \to \nu_\tau$ transitions by detecting ν_τ appearance.
Ideal detectors: $4\times$ Opera or 10 Kton LAr detector.

The possible role of LNGS

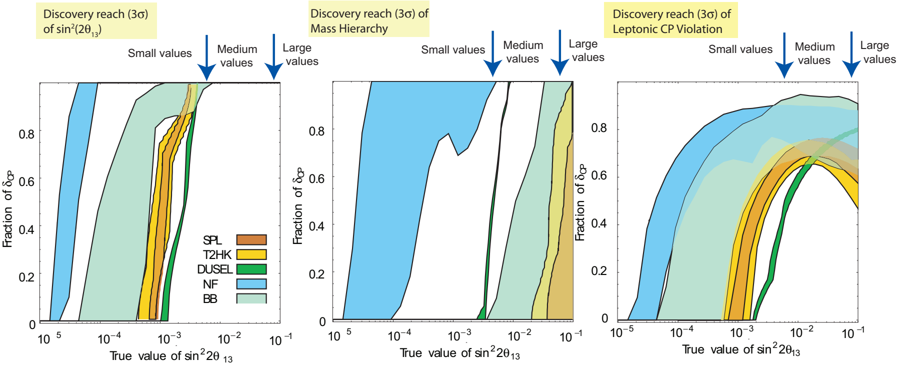
Battiston, Mezzetto, Migliozzi, Terranova arXiv:0912.3372

Can the LNGS Hall-C be used to host a future Long Baseline neutrino oscillation experiment?

- Hall-C is about 40000 m^3, too small a gigantic liquid argon (max 5-8 kton) or water Cerenkov (max 10-15 kton) detector. so it can't host a detectory for any SuperBeam or standard Beta Beam configuration.
- It could host an iron magnetized detector, suitable for high-energy beta beams (F. Terranova et al., Eur. Phys. J. C 38 (2004) 69) or as a golden detector for the neutrino factory.
- It could host an upgraded Opera detector (x4), as a silver detector for the Neutrino Factory (Donini, Meloni, Migliozzi, Nucl.Phys.B646:321-349,2002)

LNGS opportunities are directly linked to advanced neutrino beam options.

Sensitivity Comparison



Line widths reflect different assumptions on machine configuration, fluxes, detector performances and systematic errors.
Several of these curves, computed in 2006, already need to be updated.

Conclusions

- We have several different possible strategies to attack LCPV searches.
- Super Beams could reach a 3σ sensitivity in case of moderately large values of θ_{13} . But it's difficult to immagine further upgrades. They require anyway huge investements. Is this the right way? Especially if you don't have a conventional neutrino beam suitable to be upgraded like in Europe?
- Innovative concepts like beta beams and neutrino factories can guarantee higher sensitivities. More important, they can be upgraded to allow for future searches like non-standard neutrino interactions, checks of the unitarity triangle, searches of CPT violation.
- A beta beam setup can make use of existing CERN infrastructures like the PS and the SPS. The injector side can be shared with nuclear physicists (Eurisol). The far detector is the same detector aimed for proton decay searches and astrophysics (Laguna). Under this perspective a super beam built around the SPL could offer very interesting synergies.
- A neutrino factory can offer the ultimate performances in neutrino oscillations and can be seen as the first stage of a muon collider.
- Any super beam, beta beam or neutrino factory at CERN require the SPL.

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- Any super beam, beta beam or neutrino factory at CERN require the SPL.
- **Most of the developments in this field in Europe happened thanks to the illuminated collaboration of Jacques Bouchez.**

Backup slides

Astroparticle Physics 29 (2008) 174-187 and 2009 Jinst 4 P02003

- 21.5 kton of Liquid Argon in 4 modules "600 ton" like.
- At shallow depth, 7 or 10 km off-axis from CNGS.
- Modified CNGS optics and target to lower the mean $\nu_\mu$energy.
- Assume $1.2 \cdot 10^{20}$ pot/yr (CNGS-1, 0.5 MW) or $4.4 \cdot 10^{20}$ pot/yr (CNGS-2, 1.6 MW). At present, CNGS: $4.5 \cdot 10^{19}$ pot/yr.

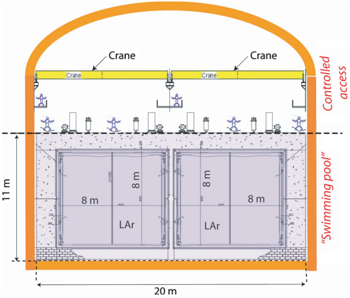
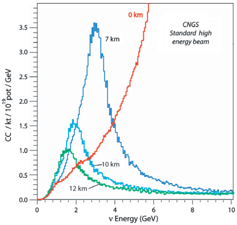
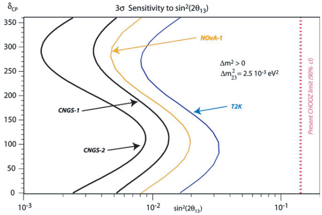
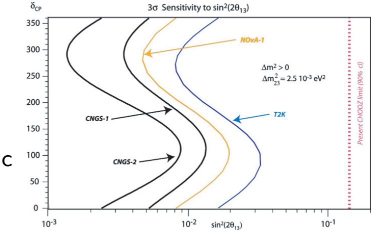


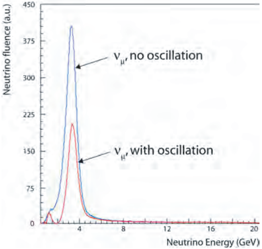
Fig. 1. Indicative cross-section of the T600 "clone " in the dedicated "swimming pool like" underground hall. The lower part is made of two twin separate LAr containers made of aluminum extruded structures, thermally stabilized with forced N2 circulation. Outside the structure an about 1.5 m thick per wall provides spontaneous, passive heat insulation. The region on top of the "swimming pool" is accessible to auxiliary equipments. Personnel access is strictly controlled.

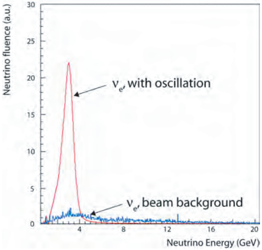


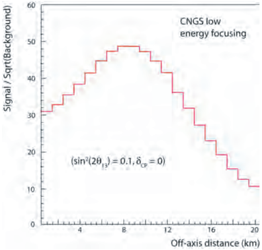


- Place the detector **on surface**, at the LNGS Assergi site, 7 km off-axis.
- CNGS neutrinos are detectable on surface:
  - Full drift time, 2.7 ms, less than one crossing muon every 2 m^2.
  - The PMTs allow to reduce the window to the 10.5 μs SPS time window, 0.5 cosmic events per spill per semi-module.
  - Additional reduction of a factor 2 by splitting the PMTs upstream and downstream the semimodule.





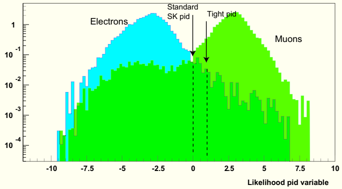




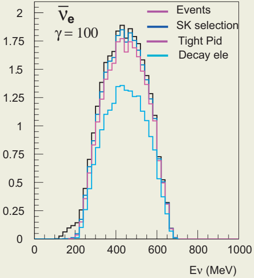
Particle identification and signal efficiency

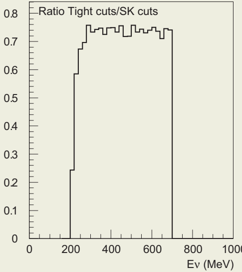
Electron/muon misidentification must be suppressed much more than in standard SK analysis to guarantee a negligible background level.

Pid in SK is performed through a Likelihood, $Pid > 0$ identifies muons. Use $Pid > 1$



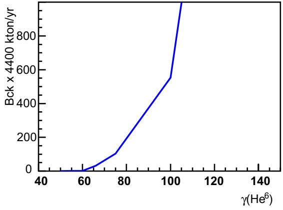
To further suppress electron background ask for the signal of the Michel electron from μ decay. Final efficiency for positive muons. Negative muons have an efficiency smaller by $\sim 22\%$ because they can be absorbed before decaying. **Electron mis-identification suppressed to $\sim 10^{-5}$.**





The pion background

Pion backgrounds as function of γ

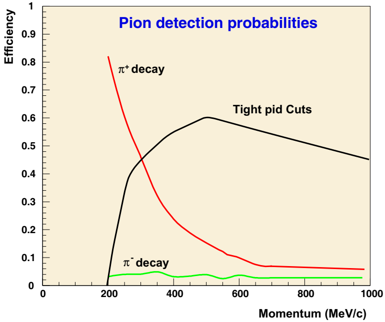


The pions generated in NC events can fake the muon signal.

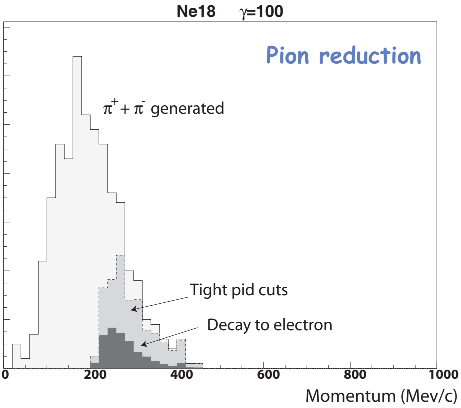
They are the main concern at high gammas.

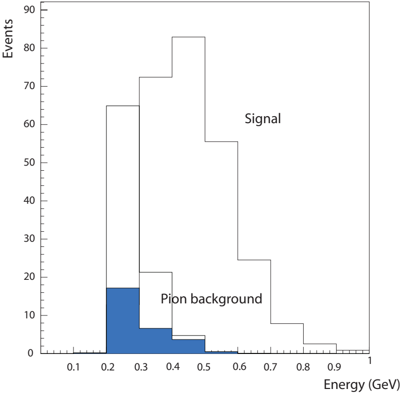
To estimate these backgrounds

- Generate CC and NC events with Nuance
- Count events with a pion and no other track above the Čerenkov threshold (single ring events)
- Apply the tight pid cuts of SuperKamiokande
- Follow pions in water (Geant 3.21) to compute the probability for $\pi \to \mu \to e$.
- Reconstruct the neutrino energy from the survived pions treating them as the signal muons

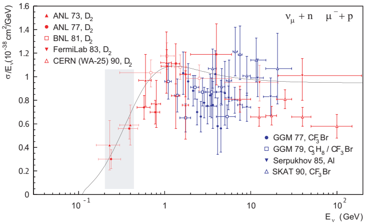


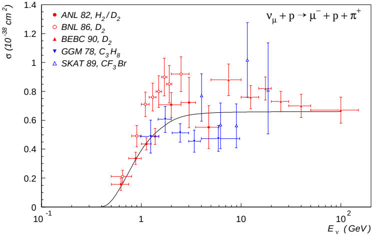
The pion background (cont.)





The cross sections problem



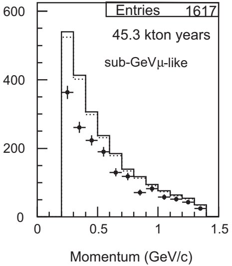


Neutrino cross-sections are poorly measured around 300 MeV.
Nuclear effects are very important at these energies.
No surprise that different MonteCarlo codes predict rates with a 50% spread.

On the other hand: 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.
- Just one neutrino flavour in the beam.
- 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.

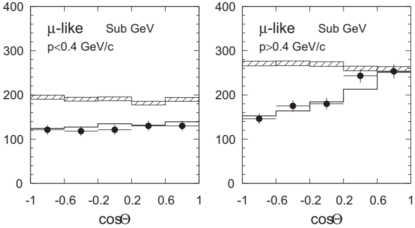
A 2% systematic error both in signal and backgrounds is used in the following



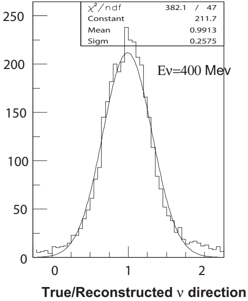
Atmospheric neutrino background

Sub-GeV μ-like events in SK integrated over the solid angle. 45.3 kton year exposure

Sub-GeV μ-like events zenithal distribution



Event direction resolution at 400 MeV. Take $\pm 2\sigma$ as acceptance, equivalent to $\pm 40^{\circ}$. Solid angle reduced to 1/8



Kamioka to Frejus flux correction: + 20%

Signal efficiency with respect to standard SK algorithms: 54% (flat in energy)

A duty cycle of 1% would keep the atmospheric background rate below the pion bkg rate (Eurisol DS duty cycle: 0.45%).