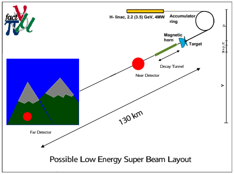
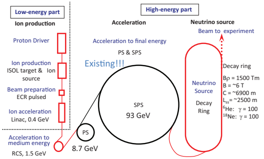
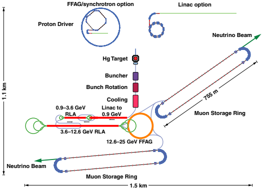
Mauro Mezzetto

Istituto Nazionale di Fisica Nucleare, Sezione di Padova

"Future neutrino facilities and neutrino oscillation experiments."







- What is left to measure in neutrino oscillations
- Experimental challenges in detecting leptonic CP violation
- Super Beams
- Beta Beams
- Neutrino Factories
- Some Comparison.

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?)

Δm^2_{12}= 7.6 10^{-5} eV^2
Δm^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)!**

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

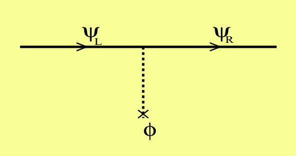
$\theta_{13} \rightarrow 0 \quad \Rightarrow$ The 3x3 mixing matrix becomes a trivial product of two 2x2 matrixes.

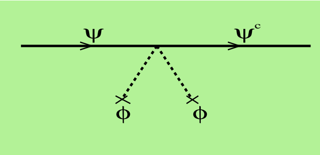
θ_{13} drives $\nu_\mu \rightarrow \nu_e$ subleading transitions $\Rightarrow$
the necessary milestone for any subsequent search:
neutrino mass hierarchy and leptonic CP searches.

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.

Shopping list for future experiments

δm^2_{12} ✓ SOLARS+KAMLAND $\delta m^2_{12} = (7.9 +/- 0.7)\ 10^{-5} eV^2$

θ_{12} ✓ SOLARS+KAMLAND $\sin^2(2\theta_{12}) = 0.82 +/- 0.055$

Addressed by a SuperBeam/Nufact experiment

δm^2_{23} ✓ ATMOSPHERICS $\delta m^2_{23} = (2.4 +/- 0.4)\ 10^{-3}\ eV^2$

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

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

LSND/Steriles ✓?

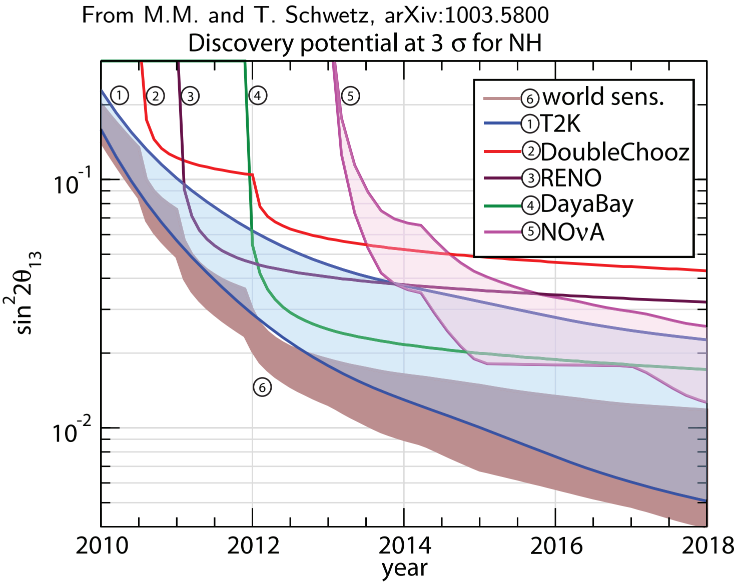
δ_{CP}

Mass hierarchy

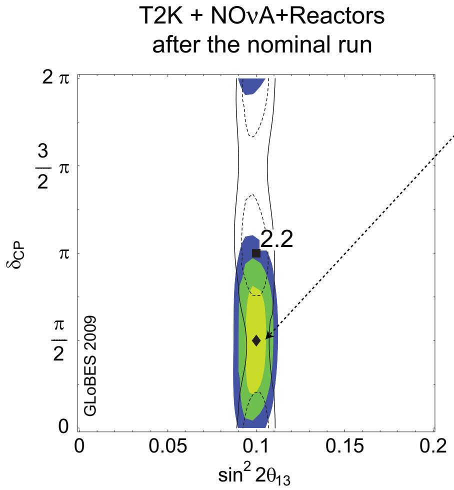
Σm_ν BETA DECAY END POINT $\Sigma m_\nu < 6.6$ eV

Dirac/Majorana

Status after this generation of LBL experiments: θ_{13}



From P. Huber et al., JHEP 0911:044,2009.



1) Choose a test point, this is the most favorable: max δ_{CP} and max θ_{13}

Status after this generation of LBL experiments: CPV

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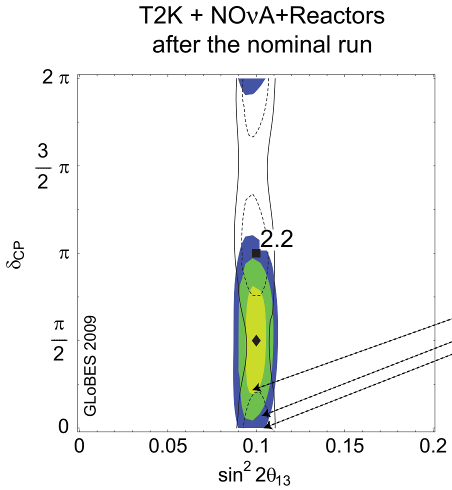

1) Choose a test point, this is the most favorable: max δ_{CP} and max θ_{13}

2) Fit to the expected sensitivity of the experiments: 1σ, 2σ, 3σ

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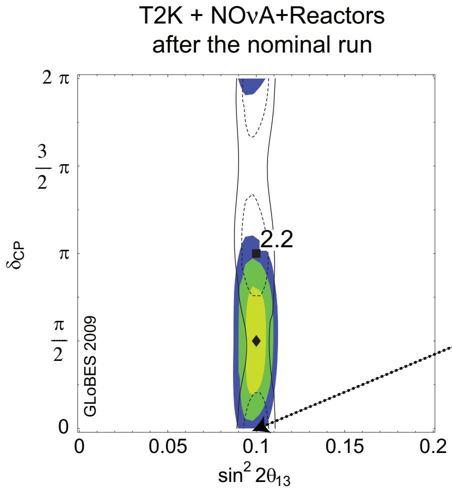


1) Choose a test point, this is the most favorable: max δ_{CP} and max θ_{13}

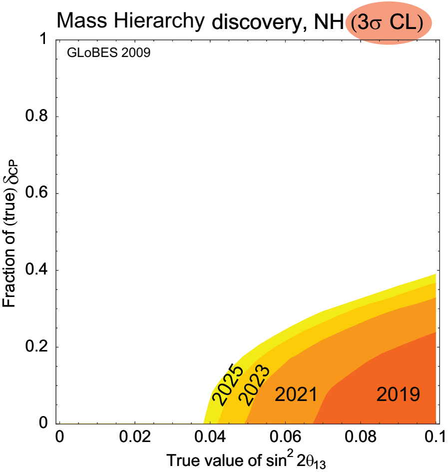
2) Fit to the expected sensitivity of the experiments: 1σ, 2σ, 3σ

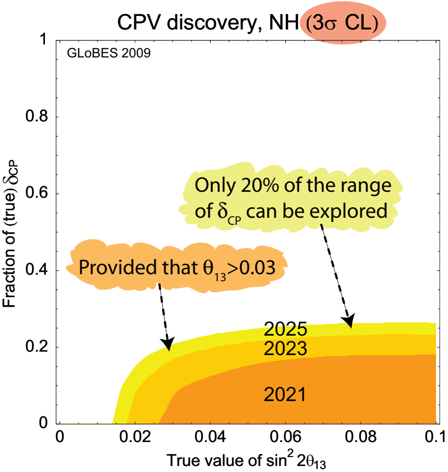
3) Null CP is compatible with data already at 2σ

Status after accelerator upgrades

From P. Huber et al., JHEP 0911:044,2009.

Prediction of sensitivity including a **fully optimized global run** (antineutrinos in T2K and NOνA) and **full upgrade of the accelerators**: 1.6 MW at J-PARC and 2.4 MW at FNAL (Project-X)





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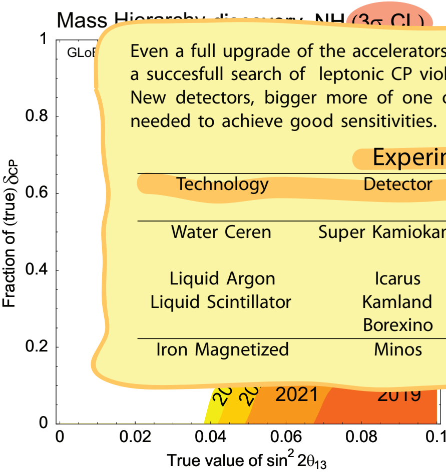
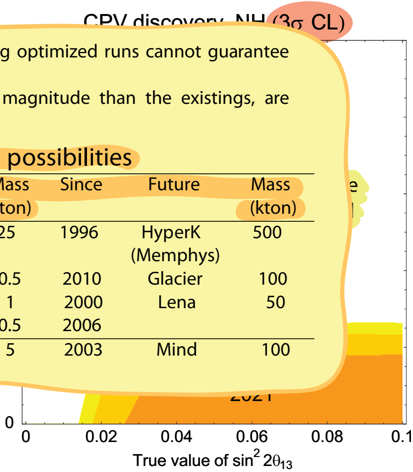




Even a full upgrade of the accelerators and long optimized runs cannot guarantee a succesfull search of leptonic CP violation.

New detectors, bigger more of one order of magnitude than the existings, are needed to achieve good sensitivities.

Experimental possibilities

Technology	Detector	Mass (kton)	Since	Future	Mass (kton)
Water Ceren	Super Kamiokande	25	1996	HyperK (Memphys)	500
Liquid Argon	Icarus	0.5	2010	Glacier	100
Liquid Scintillator	Kamland	1	2000	Lena	50
	Borexino	0.5	2006		
Iron Magnetized	Minos	5	2003	Mind	100

Where to look for leptonic CP violation

Disappearance experiments, $\nu_x \to \nu_x$ are by definition T invariant. They can't violate CP if CPT holds.
We are left with $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_e$
As a first approximation the probability of transition P is linked to the amplitude A and the CP phase δ_{CP} by:

$$P \propto A^2 + A \sin \delta_{\mathrm{CP}}$$

CP violation process probability over the CP non-violating probability:

$$\frac{CPV}{CPC} \simeq \frac{\sin \delta_{\mathrm{CP}}}{A}$$

- $\nu_\mu \to \nu_\tau \quad \Rightarrow A \simeq 1$ and very challenging to detect (furthermore energy reconstruction of ν_τ events very poor since most of the energy goes into neutrinos)
- $\boldsymbol{\nu_\mu \to \nu_e \quad \Rightarrow A \leq 0.1}$.

These searches, at short baselines, had been already performed by BEBC, CHARM, CCFR, NOMAD.
At long baselines by K2K and MINOS.
Now used by T2K and soon by NOνA to look for θ_{13} .

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

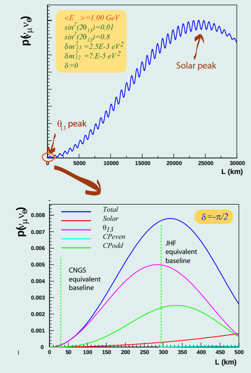
$$p(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \times \left[1 \pm \frac{2a}{\Delta m_{13}^2}(1-2s_{13}^2)\right] \quad \theta_{13} \text{ dri}$$

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

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

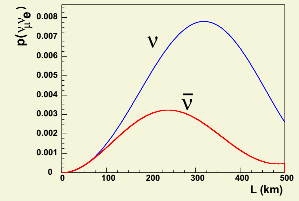
$$+ 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta\} \sin \frac{\Delta m_{12}^2 L}{4E} \quad \text{solar driven}$$

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



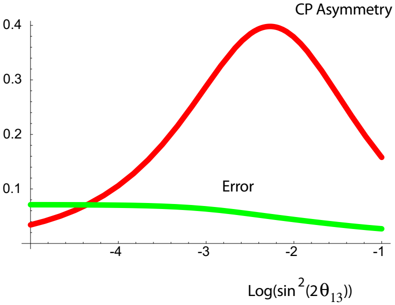
θ_{13} discovery requires a signal ($\propto \sin^2 2\theta_{13}$) greater than the solar driven probability

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



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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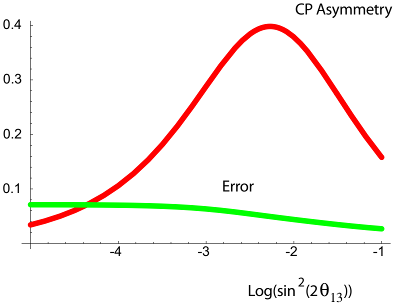

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- **The detection of such asymmetry is an evidence of Leptonic CP violation only in absence of competitive processes (i.e. matter effects, see following slides) $\Rightarrow$ "short" Long Baseline experiments**

Measuring Leptonic CP violation

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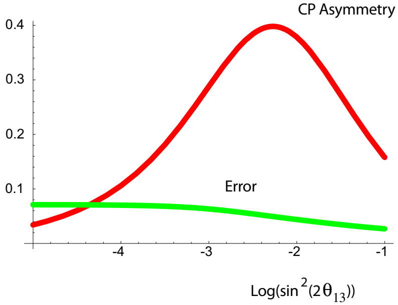

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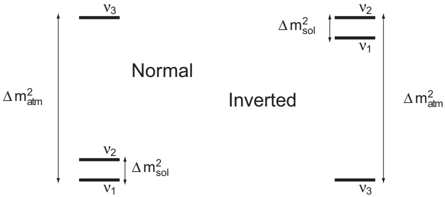
- **The detection of such asymmetry is an evidence of Leptonic CP violation only in absence of competitive processes (i.e. matter effects, see following slides) $\Rightarrow$ "short" Long Baseline experiments**
- Statistics and systematics play different roles at different values of $\theta_{13} \Rightarrow$ 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}: $\mathrm{sign}(\Delta m^2_{23})$.



This parameter decides how mass eigenstates are coupled to flavor eigenstates with important consequencies to direct neutrino mass and double beta decay experiments.

Neutrino Oscillations in Matter

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

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

Matter effects require long “long baselines"

Neutrino Oscillations in Matter

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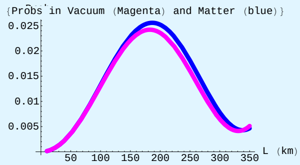
Matter effects require long "long baselines"

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



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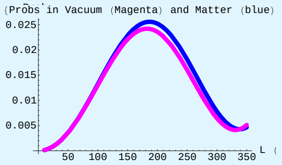
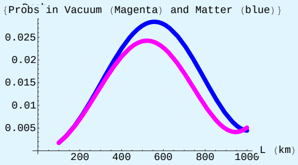
The $\hat{A}$ term changes sign with $\mathrm{sign}(\Delta m^2_{23})$

Matter effects require long "long baselines"

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





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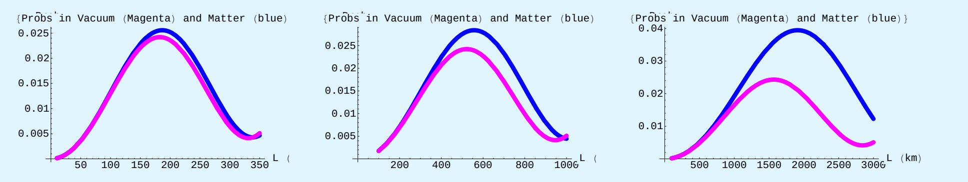
$\alpha = \mathrm{Abs}(\Delta m^2_{21}/\Delta m^2_{31})$; $\hat{\Delta} = \frac{L\Delta m^2_{31}}{4E}$ $\zeta = \cos\theta_{13}\ \sin 2\theta_{12} \sin 2\theta_{23}$

$\boldsymbol{\hat{A} = \pm a/\Delta m^2_{31}}$; $a = 7.6 \cdot 10^{-5} \rho \cdot E_\nu(GeV)$ $\quad \rho = \mathrm{matter\ density\ (g\,cm^{-3})}$

The $\hat{A}$ term changes sign with $\mathrm{sign}(\Delta m^2_{23})$

Matter effects require long “long baselines”

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



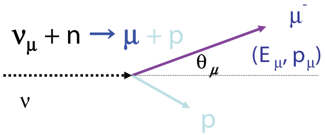
Experimental challenges

- Energy reconstruction
- Backgrounds
- Systematic errors
- Degeneracies

Energy reconstruction for beam neutrinos

The quasi elastic case

Select single ring events and assume they are Quasi Elastic

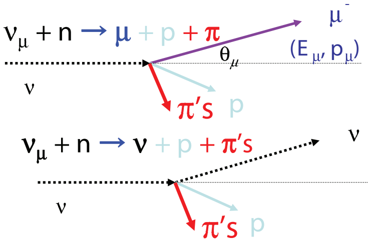


- **CC QE**
  - can reconstruct $E_\nu \leftarrow (\theta_\mu, p_\mu)$

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

$\delta E \sim 60$ MeV $\quad \delta E/E \sim 10\%$

Single ring non Quasi Elastic are badly measured

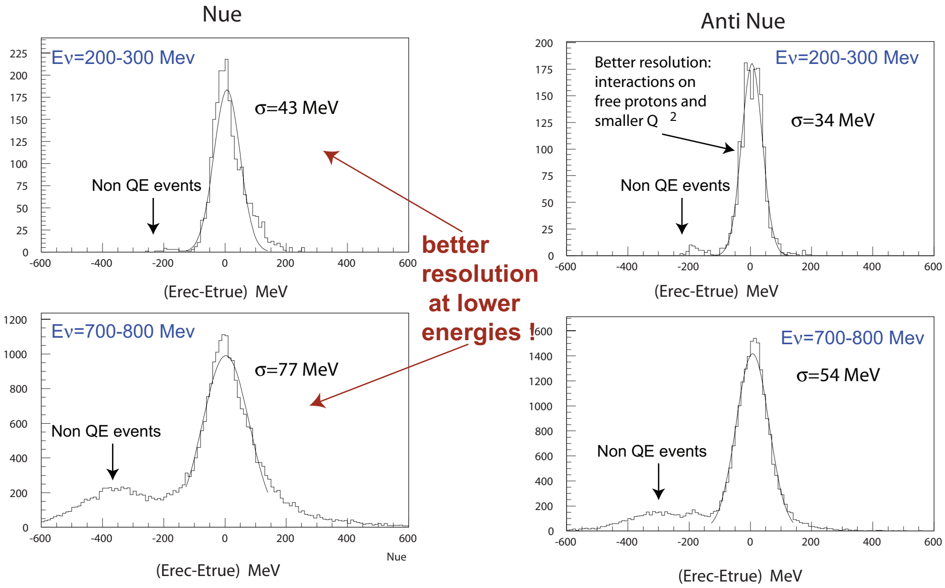


- bkg. for E_ν measurement

High energy part

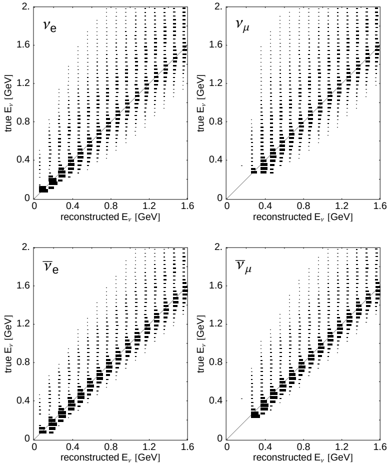
- bkg.for e-appearance

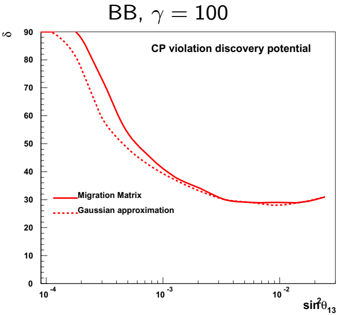
Goodness of energy reconstruction



Migration Matrixes

A gaussian assumption for energy resolution is a too crude approximation





N.B. DIS event reconstruction requires to precisely measure the hadronic shower $\rightarrow$ introducing again non-gaussianity of the energy resolution

Backgrounds

The ultimate limit for CPV and θ_{13} sensitivity are background rates and systematic errors.

In a Super Beam setup bacgkrounds come mainly from

- Intrinsic ν_e contamination: 0.5-1%
- π° produced by CC (the muon missed) and NC events. The rate depends from the quality of the detector.
- muons mis-identified as electrons. Again a detector background.

In leptonic CP violation searches the wrong helicity neutrino contamination is also an important source of backgrounds.

Beta Beams and Nufacts have no intrinsic backgrounds and the detector backgrounds are different. Discussed later.

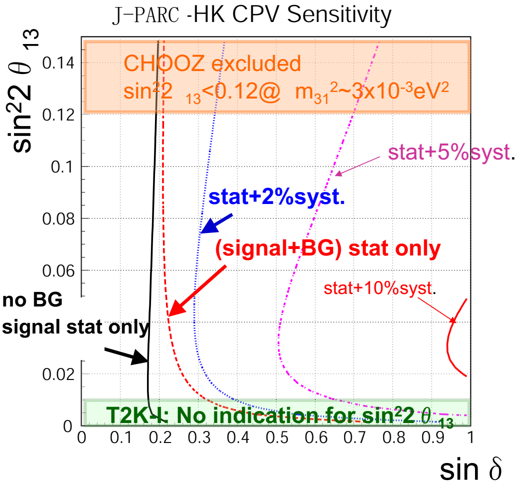
Background events are dangerouse under many aspects:

- Reduce the statistical significance of the (tiny) signals
- Fuzzy the energy shape of the detected signals, which is an important signature
- Confuse the close detector making difficult to disentangle the single components.

They could completely destroy leptonic CP violation sensitivity.

Default value are often 5% for SuperBeams, 2% for Neutrino Factory and 2-5% for Beta Beams.

Are
them realistic goals? Are close detectors powerful enough?



SuperBeams

$$\mathrm{N}^{\mathrm{far}}_{\mathrm{events}} = \left(\sigma_{\nu_e}\epsilon_{\nu_e}\mathrm{P}_{\nu_\mu\nu_e} + \sigma^{\mathrm{NC}}_{\nu_\mu}\epsilon_{\mathrm{NC}} + \sigma^{\mathrm{CC}}_{\nu_\mu}\epsilon_{\mathrm{CC}}\mathrm{P}_{\nu_\mu\nu_\mu}\right)\phi_{\nu_\mu} + \sigma^{\mathrm{CC}}_{\nu_e}\epsilon_{\nu_e}\phi_{\nu_e}$$

$$\mathrm{N}^{\mathrm{close}}_{\mathrm{events}} = \left(\sigma^{\mathrm{NC}}_{\nu_\mu}\epsilon'_{\mathrm{NC}} + \sigma^{\mathrm{CC}}_{\nu_\mu}\epsilon'_{\mathrm{CC}}\right)\phi'_{\nu_\mu} + \sigma^{\mathrm{CC}}_{\nu_e}\epsilon_{\nu_e}\phi'_{\nu_e}$$

- The close detector measures the product of fluxes $\times$ cross section $\times$ efficiency
- Reduced $\nu_e$flux: small statistics to determine the cross section
- NC backgrounds must be separated from beam ν_e.

Beta Beams

$$\mathrm{N}^{\mathrm{far}}_{\mathrm{events}} = \left(\sigma_{\nu_\mu}\epsilon_{\nu_\mu}\mathrm{P}_{\nu_e\nu_\mu} + \sigma^{\mathrm{NC}}_{\nu_e}\epsilon_{\mathrm{NC}} + \sigma^{\mathrm{CC}}_{\nu_e}\epsilon_{\mathrm{CC}}\mathrm{P}_{\nu_e\nu_e}\right)\phi_{\nu_e}$$

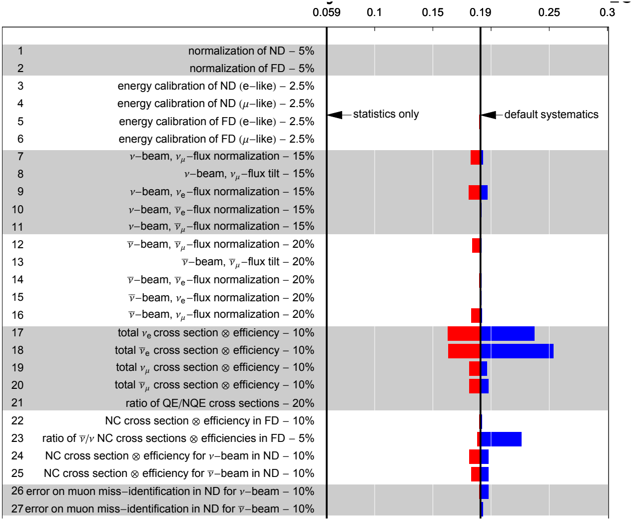
$$\mathrm{N}^{\mathrm{close}}_{\mathrm{events}} = \left(\sigma^{\mathrm{NC}}_{\nu_e}\epsilon'_{\mathrm{NC}} + \sigma^{\mathrm{CC}}_{\nu_e}\epsilon'_{\mathrm{CC}}\right)\phi_{\nu_e}$$

Flux known at priori, no intrinsic contamination (direct measure of NC backgrounds), no problems with the close-far extrapolation BUT no events to measure signal (ν_μ) cross sections.

Systematic errors and their pulls

Computed for T2HK sensitivity on LCPV at $\sin^2 2\theta_{13} = 0.03$

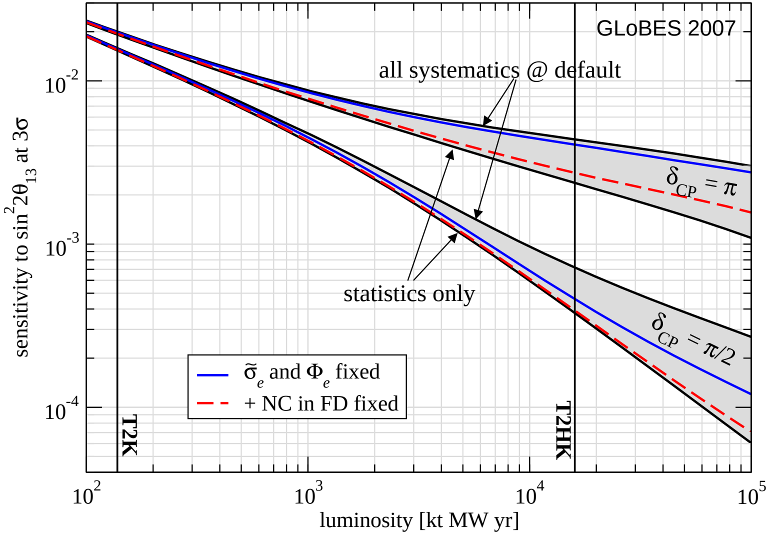
From P. Huber, MM, T. Schwetz, JHEP **0803** (2008) 021 [arXiv:0711.2950 [hep-ph]].



RED: Systematic error switched off. BLUE: Systematic error multiplied by 5

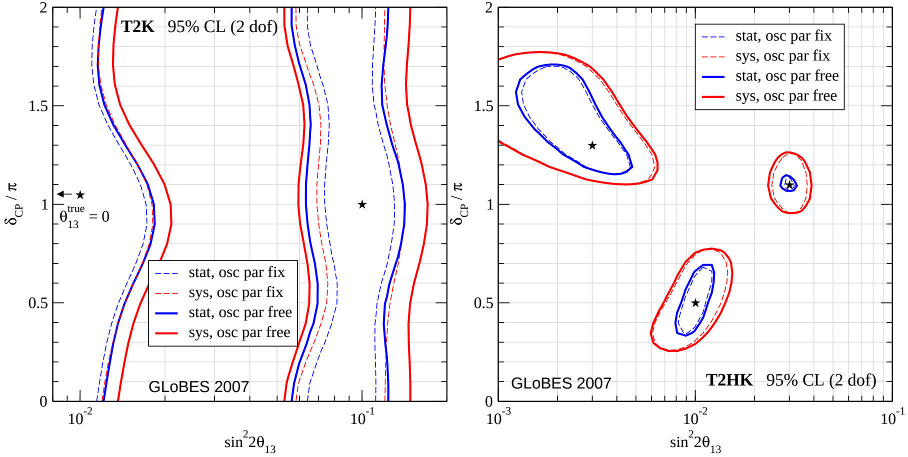
θ_{13} vs. luminosity

3 σ sensitivity to θ_{13} . ν_μ and $\overline{\nu}_\mu$ running time: 1 : 3.



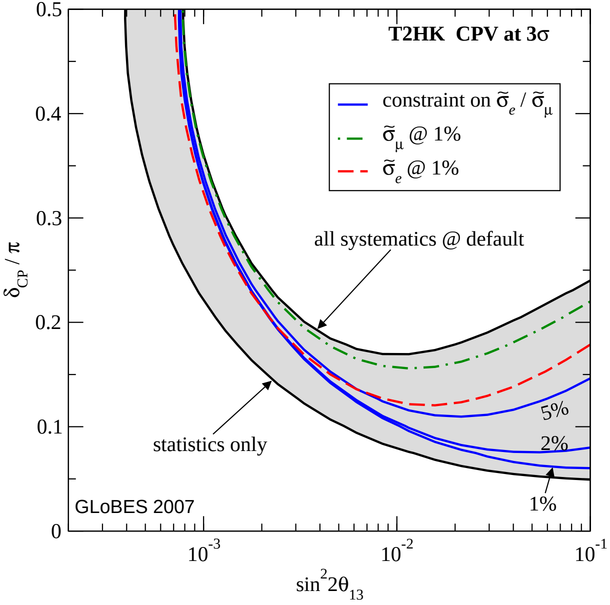
Allowed θ_{13} regions

In case of signal the impact of systematics is more important.



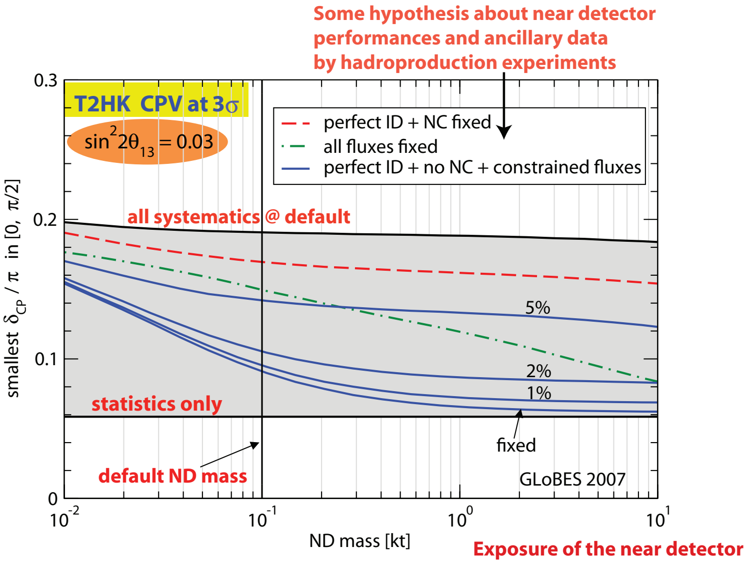
Disappearance channel is taken into consideration, in case of T2K anyway it is not enough to eliminate the sizable decrease of sensitivity once the errors on the other oscillation parameters are taken into account. In T2HK the effect almost disappears

3 σ LCPV Sensitivity

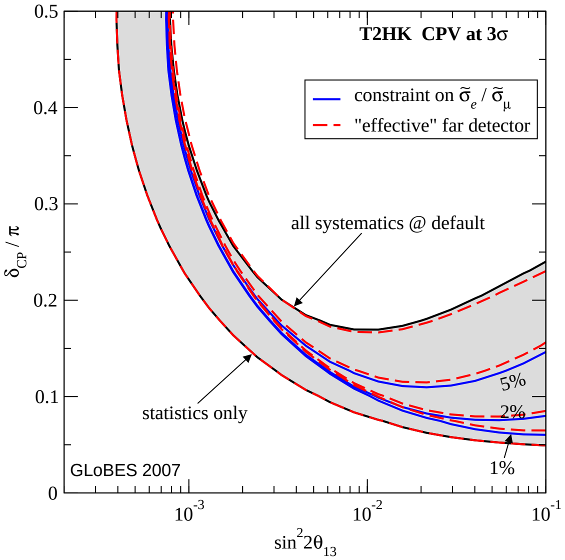


Systematic errors, statistics in the close detector

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



Comparison with the effective FD description

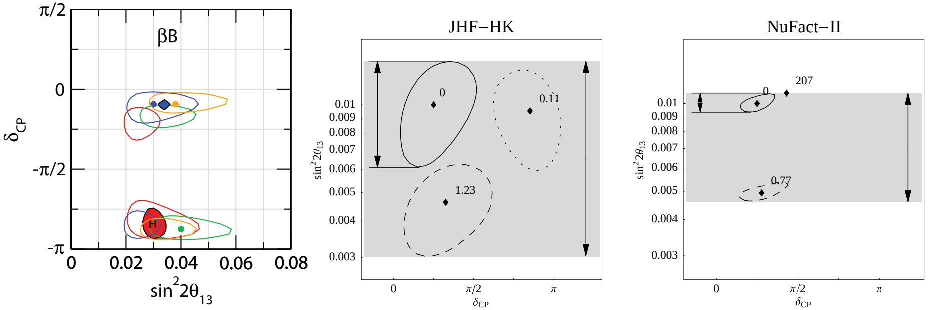


The 2 km close detector implementation is equivalent to overall systematic errors of 10% on signal and 3.5% on backgrounds.

How to extract θ_{13} and δ_{CP}

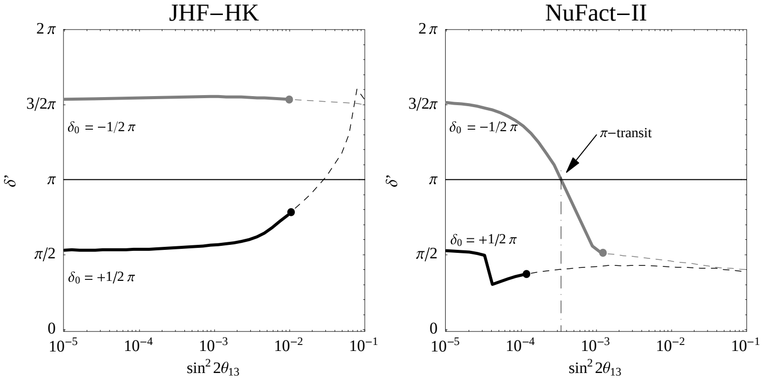
The problem is not that simple

- The 3 ν oscillation formula contains all the mixing matrix parameters and Δm^2. The parameters already measured do have errors that will influence the extraction of the unknown parameters.
- Several parameters still unknown: θ_{13} , δ_{CP}, sign(Δm^2) (hierarchy), the octant of θ_{23}. Different combinations of the above unknowns can fit the same data: $\Rightarrow$ **The eightfold degeneracy**



The π-transit problem

From Huber, Lindner, Winter, Nucl. Phys B645:3-48, 2002
The $\mathrm{sign}(\Delta m^2_{23})$degenerate solution could show up at $\delta_{\mathrm{CP}} = \pi$ destroying any CPV sensitivity. Its position is function of θ_{13} and depends from the baseline.

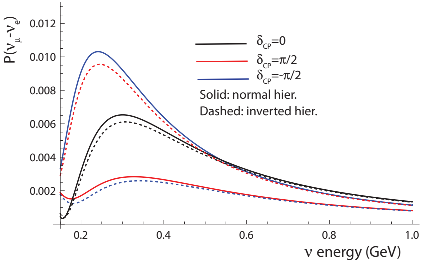


To solve degeneracies:

- A single experiment, single channel, can't get rid of degeneracies.
- The combination of different channels in the same detector can solve degeneracies, i.e. first a second oscillation maxima measurement in LBNE or at Okinoshima.
- Different signals in the same detector can also do the job, i.e. beta beams and atmospheric neutrinos.
- A third possibility is to combine the information of different detectors along the same neutrino beam, as exploited by several proposed neutrino factory configurations.
- Of course the combination of the above combinations can also measure all the unknown parameters: can we define an optimal strategy?

CPV vs. mass hierarchy

At 130 km matter effects are negligible. Inverse hierarchy solutions are very similar to direct hierarchy (changing sign of $\delta_{\rm CP}$is equivalent of change of $\mathrm{sign}(\Delta m^2_{23})$sign) $\Rightarrow$ No degeneracies for CP searches but no sensitivity on mass hierarchy.



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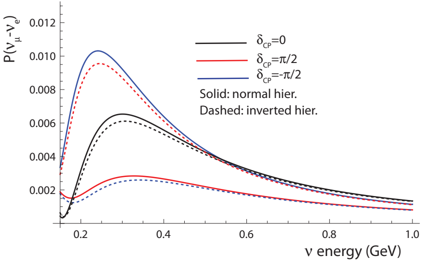
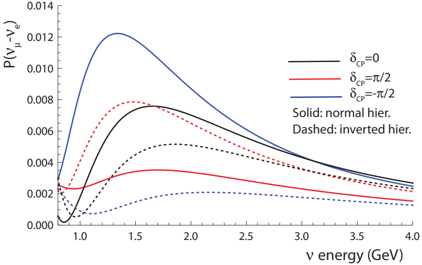
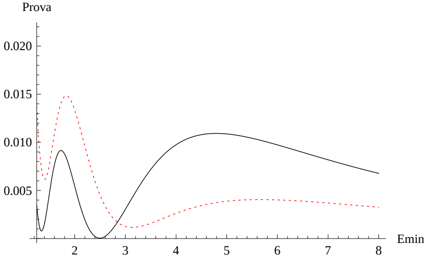


At 730 km matter effects are sizable. Probabilities differ.
Note however as the normal hierarchy $\delta_{\mathrm{CP}} = 0$ probability is very similar to inverse hierarchy $\delta_{\mathrm{CP}} = \pi/2$, $\Rightarrow$ very difficult to experimentally disentangle the two.

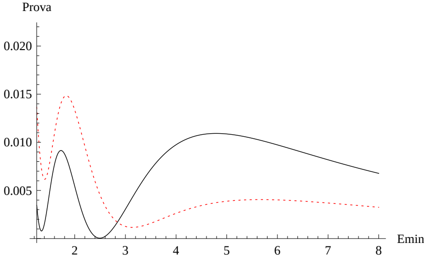


CPV vs. mass hierarchy

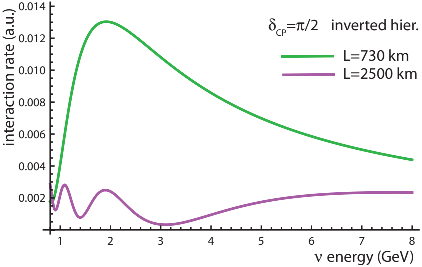
Let's move at 2500 km where the matter effects are bigger. Note how the two probabilities are more different and note how their behaviour is very much different at the second oscillation maximum.



Let's move at 2500 km where the matter effects are bigger. Note how the two probabilities are more different and note how their behaviour is very much different at the second oscillation maximum.



Do we pay a price for that? Of course yes. Fluxes go like $1/L^2$, $\Rightarrow$ ten time less flux at 2500 km. Partially compensated by the rise of cross sections: $\sigma \propto E$. Lets compare interaction rates $I \propto P \times \sigma \times L^{-2}$



The synergy with atmospheric neutrinos

P. Huber et al., Phys. Rev. D 71, 053006 (2005): 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.

Do we have some tool for this job?

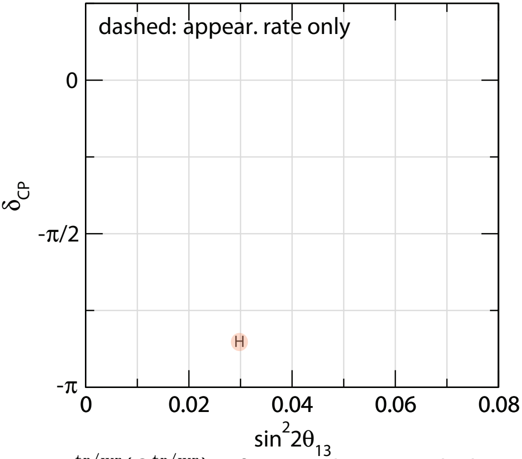
What should be done:

- Describe the experiment: fluxes, signal efficiencies, backgrounds.
- Describe the cross sections.
- Take care of systematic errors
- Take care of known parameter errors
- Manage several complicated 3 ν formulas ($P(\nu_\mu \to \nu_\mu)$, $P(\nu_e \to \nu_e)$, $P(\nu_\mu \to \nu_e)$, etc.)
- Manage matter effects with the correct matter densities in the earth.
- Multi parameters fit and search for different solutions for the fit
- Combine different experimental results

Happily enough a powerful open source tool has been developed: **Globes**.
http://www.mpi-hd.mpg.de/personalhomes/globes/

Degeneracy removal: SPL

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



95% CL allowed regions. $\mathrm{H}^{\mathrm{tr/wr}}(\mathrm{O}^{\mathrm{tr/wr}})$ refers to solutions with the true/wrong mass hierarchy (octant of θ_{23}). The true parameter values are $\delta_{\mathrm{CP}} = -0.85\pi$, $\sin^2 2\theta_{13} = 0.03$, $\sin^2\theta_{23} = 0.6$. The running time is $(2\nu + 8\bar{\nu})$ yrs.

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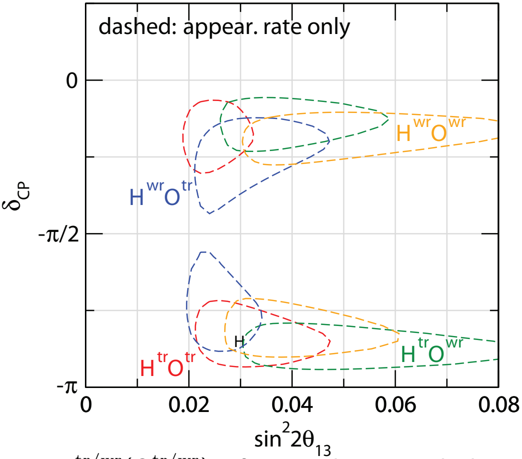

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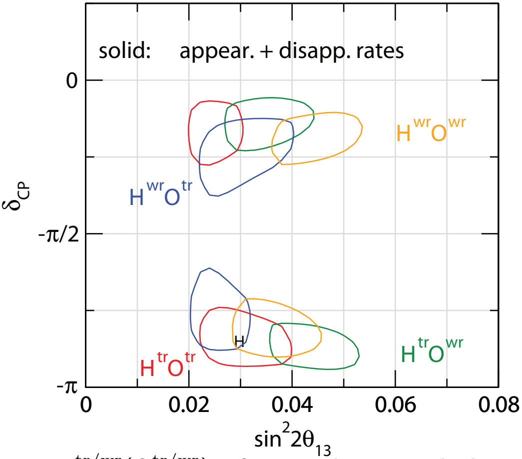

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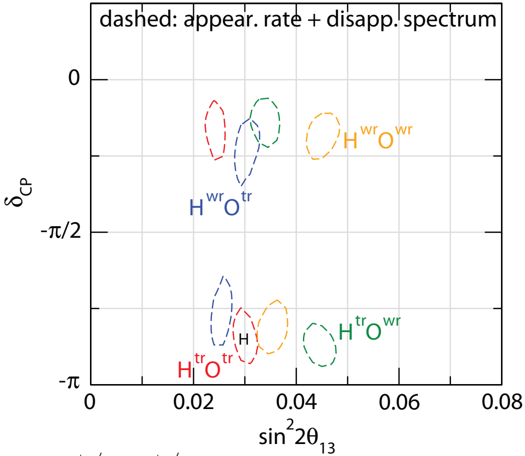

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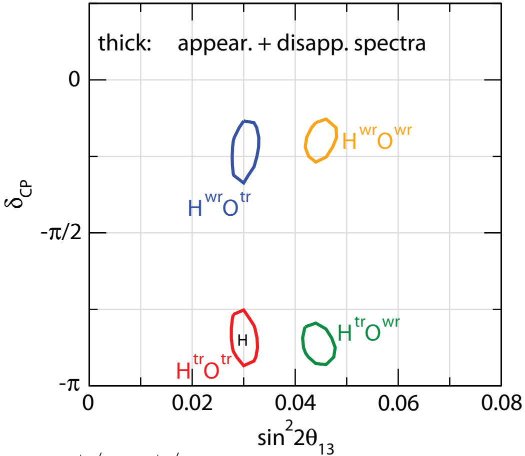

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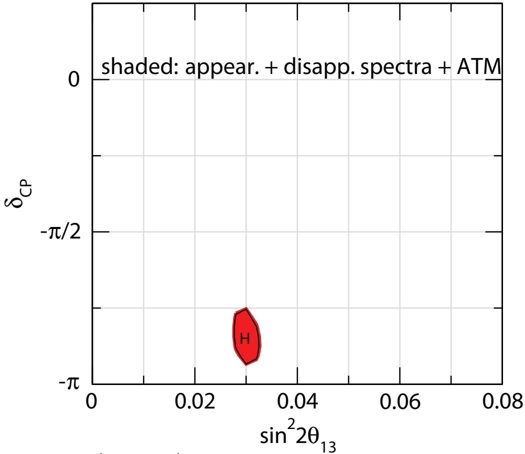

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Setups

We have discussed and maybe understood the following points:

- The importance of leptonic CP violation and mass hierarchy
- The process with which perform these searches
- The experimental problems
- The different strategies

Let's discuss about the possible setups:

- Super Beams
- Beta Beams
- Neutrino Factories

The SuperBeam way

A very simple approach:

- Push accelerators power to their ultimate limits
- Push detectors size to their ultimate limits

The SuperBeam way

A very simple approach:

- Push accelerators power to their ultimate limits
- Push detectors size to their ultimate limits

This should bring to the factor 100 in neutrino statistics that is roughly needed to bring the T2K sensitivity to the level of sensitive discovery potential of leptonic CP violation.

The SuperBeam way

T2K $\Rightarrow$ **T2HK** or **T2KK** or **T2OK**.

NOνA $\Rightarrow$ **Super NOνA** (abandoned)

Wide band beam fired from Fermilab to a gigantic water Cerenkov detector at Dusel (**LBNE**).

CNGS $\Rightarrow$ off-axis CNGS fired on a gigantic liquid argon detector (almost abandoned for what concerns CPV: CNGS cannot scaled up in intensity)

CERN-SPL (HP-SPL R&D still funded at CERN)

PS2-Slanic CERN-PS2 SuperBeam fired to 100 kton LAr detector at Slanic, as computed by A. Rubbia, arXiv:1003.1921. (PS2 recently abandoned by CERN)

Partial list of challenges of high intensity proton beam

Neutrino beam line with MW protons

- Shock wave
  - Graphite for target and dump core
- Heat generation
  - Various sources including dE/dX
    - magnets and their power water cooling
    - Target Horn TS-DV-BD wall /BD core water cooling
- Radioactive water and air
  - radioactive water (must be diluted to dispose)

    ⇒ many tanks, ion exchange filter, backup loop

  ⇒radioactive He (must be diluted to dispose)

  ⇒Production cross section of Tritium in He is 1/10 of air

⇒He vessel

⇒To be discussed at Tokai

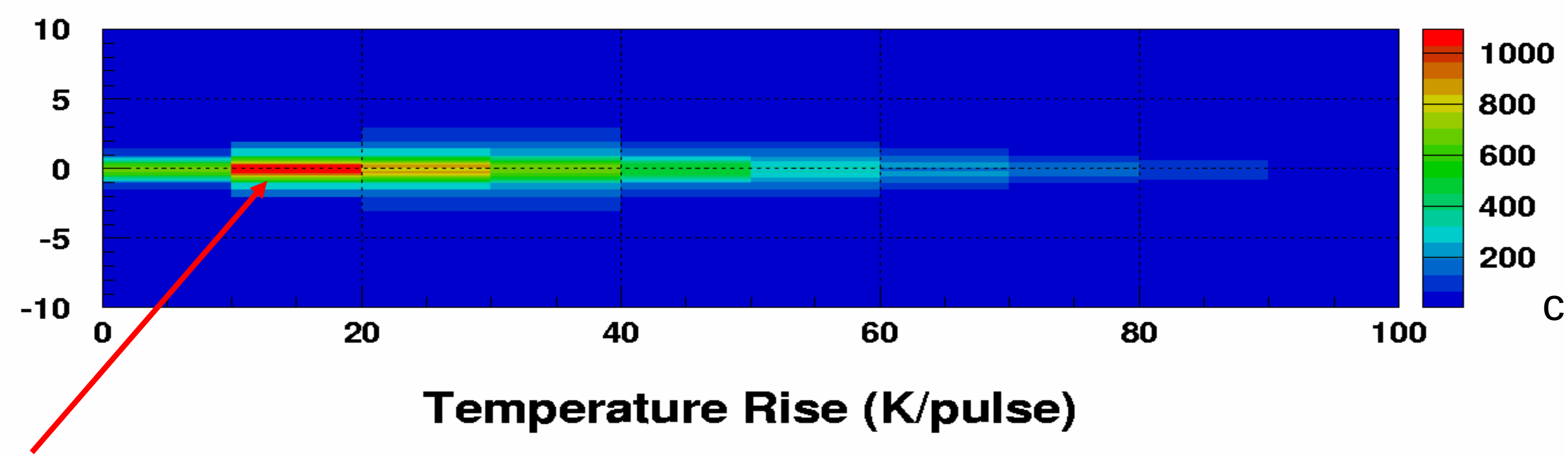
First high enrgy MW fast-ext'ed beam !

3.3E14 ppp w/ 5μs pulse

Residual radiation

cm When this beam hits an iron block,

> 1000Sv/h



1100º

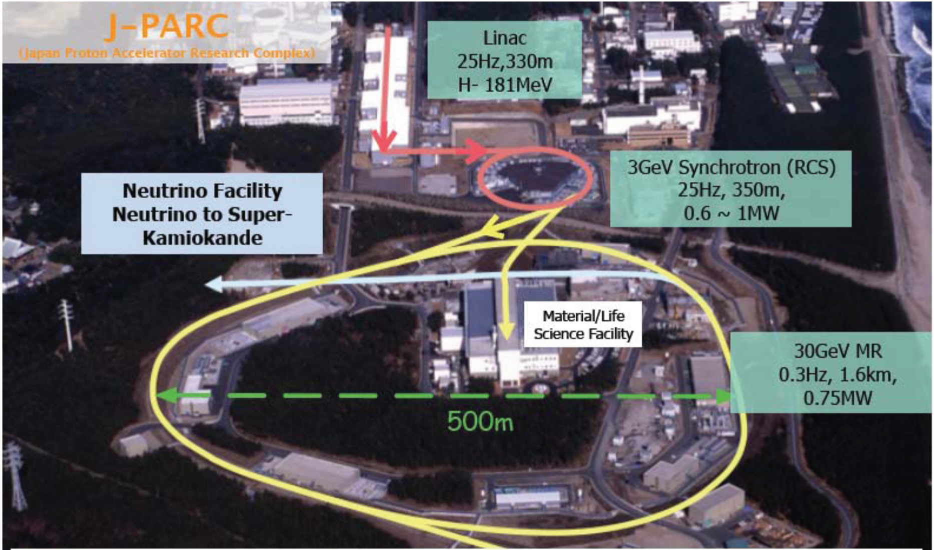
(cf. melting point 1536º)

ü Material heavier than iron would melt.

ü Thermal shock stress $\approx E\alpha\Delta T \approx 3GPa$

(max stress ~300 MPa)

Material heavier than Ti might be destroyed.

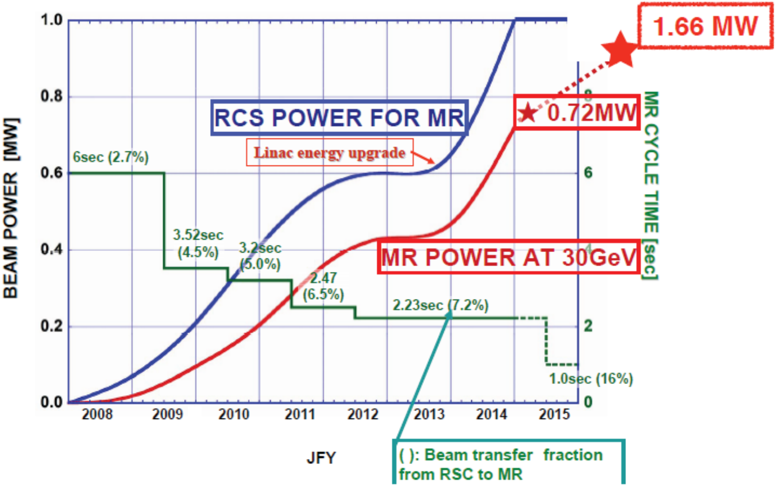


MR & Neutrino beam facility operation :

- ~0.05 MW continuous operation
  → next step is beyond 0.1MW toward 0.75MW after this summer shut down
- beam loss control is in progress toward high power operation

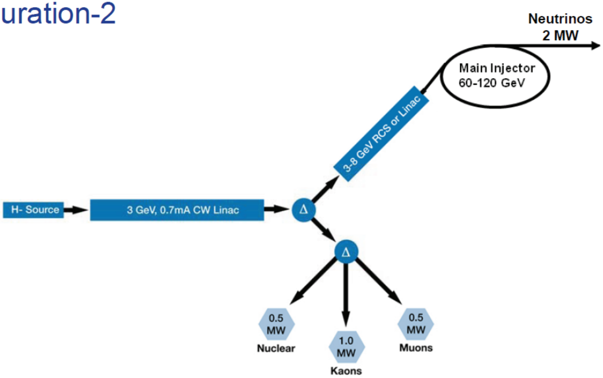
MR Power Improvement Scenario

Increase rep. rate and/or increase # of protons toward high power (~1.66MW)



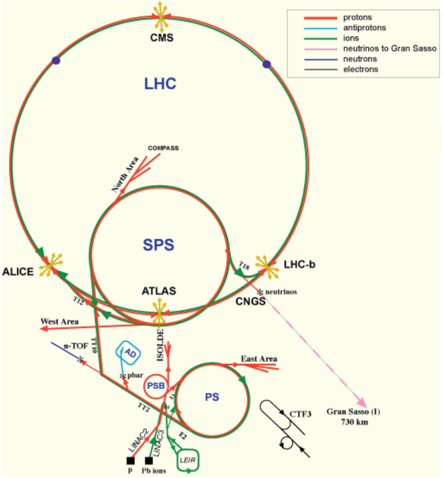
Fermilab and Project X

- Initial Configuration-2

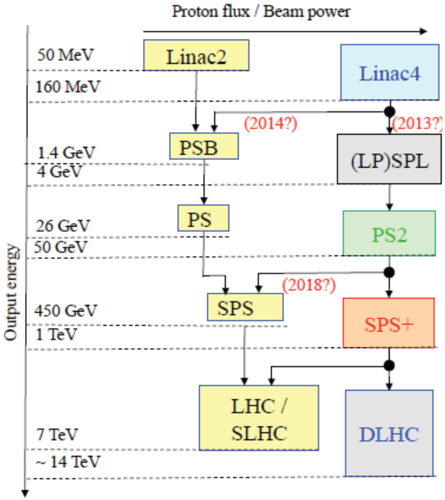


- Current configuration:
  - >2 MW at 60-120 GeV, simultaneous with 3 MW at 3 GeV
  - Flexibility for supporting multiple experiments
  - CW linac is unique for this application, and offers capabilities that would be hard/impossible to duplicate in a synchrotron
- Project X could be constructed over the period ~2015 - 2019

Present accelerator complex

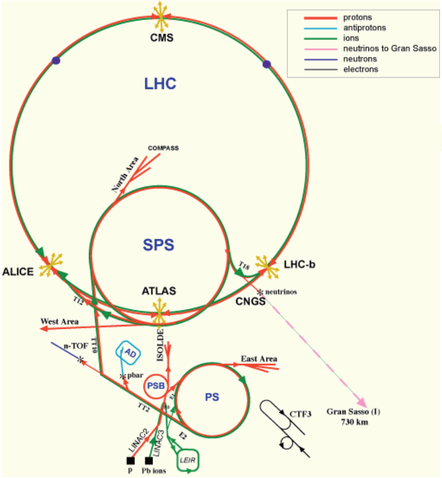


Various POSSIBLE scenarios



CERN and LHC upgrades

Present accelerator complex



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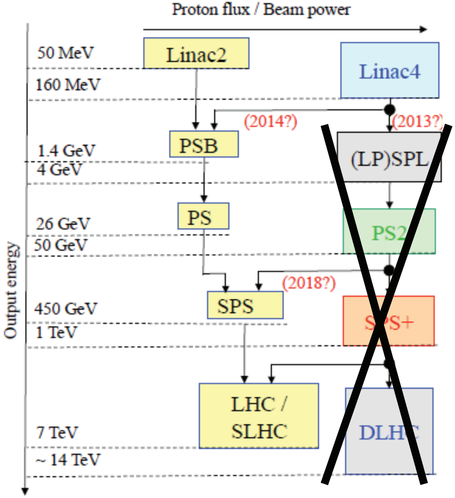
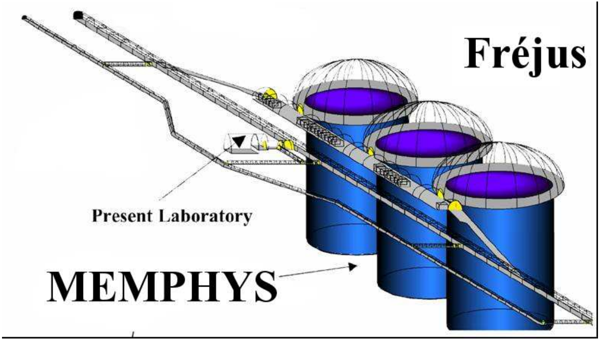


The Memphys detector (hep-ex/0607026)



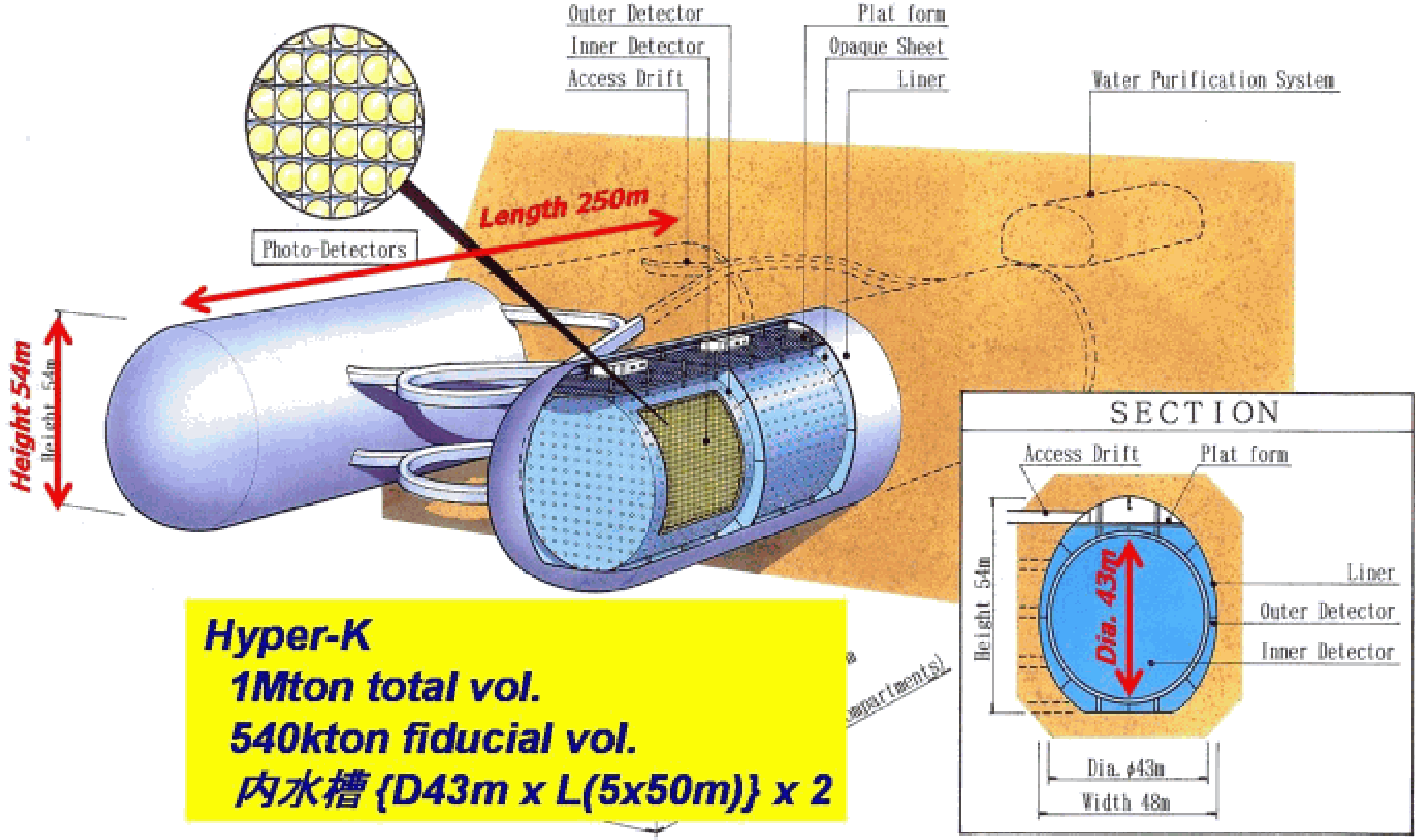
In the middle of the Frejus tunnel at a depth of 4800 m.w.e a preliminary investigation shows the feasibility to excavate up to five shafts of about 250,000 m^3 each ($\Phi = 65\,m$, full height=80 m).

Fiducial of 3 shafts: 440 kton.

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

Hyper-Kamiokande

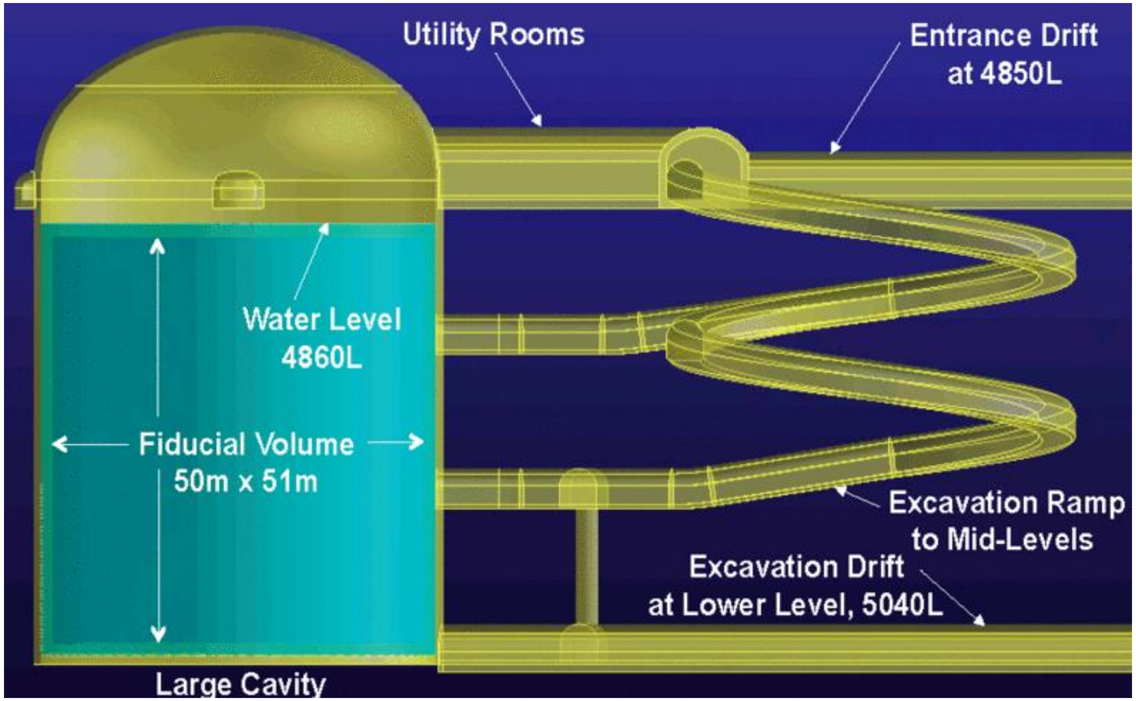
- **Total 1Mton (FV 540kt)**
- **Site study is on-going at Tochibora mine in Kamioka**
- **Design report is under preparation**



LBNE: Water Cherenkov Detector

http://lbne.fnal.gov/

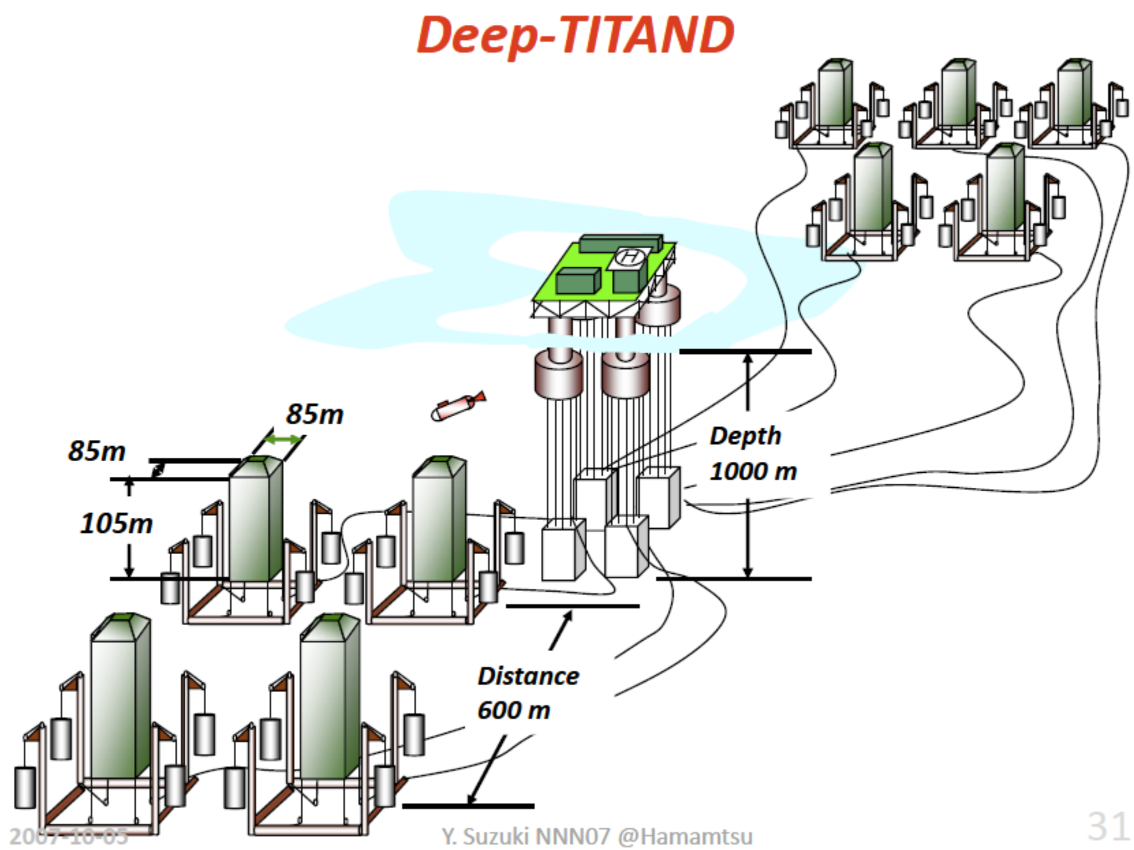
- Long-Baseline Neutrino Experiment
- Project started in 2008
- DUSEL at Homestake
- Total 300kt water (or more)
- A large water Cherenkov detector and a large liquid-argon detector are under study



Deep-TITAND

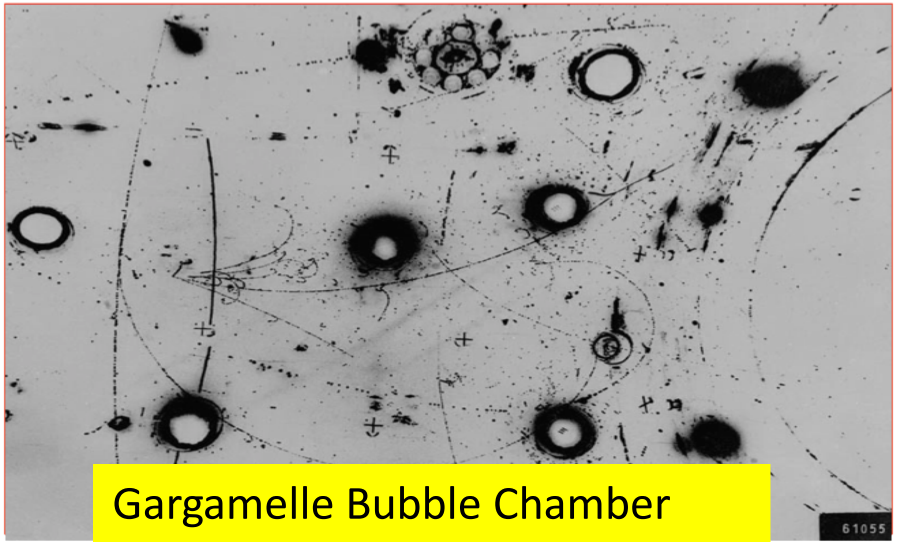
http://www-rccn.icrr.u-tokyo.ac.jp/workshop/NNN07/Oct5/01-suzuki-TITAND.pdf

- ~1000m depth, under the sea
- FV 5Mt (85m x 85m x 105m, 9units)
- Energy threshold: several MEV

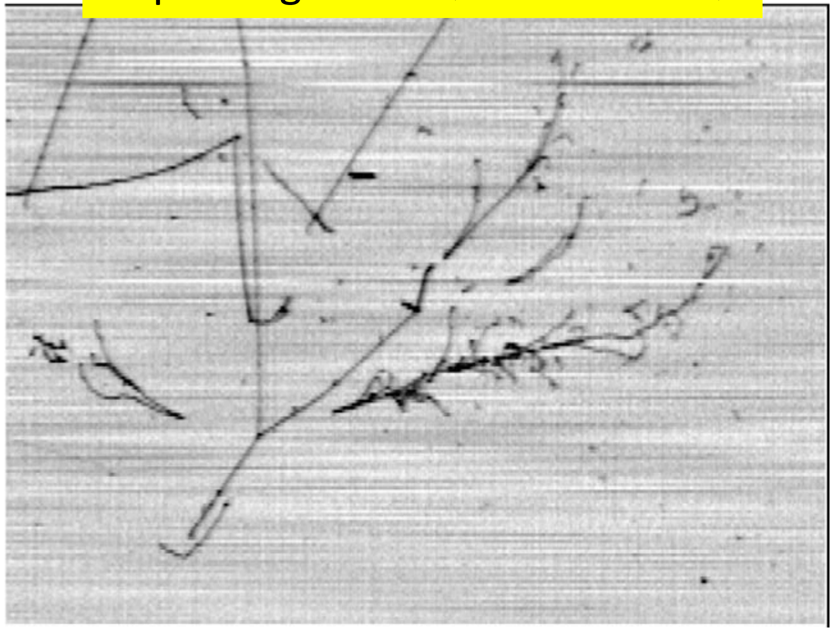


Giant (~100kt) Liquid Argon TPC

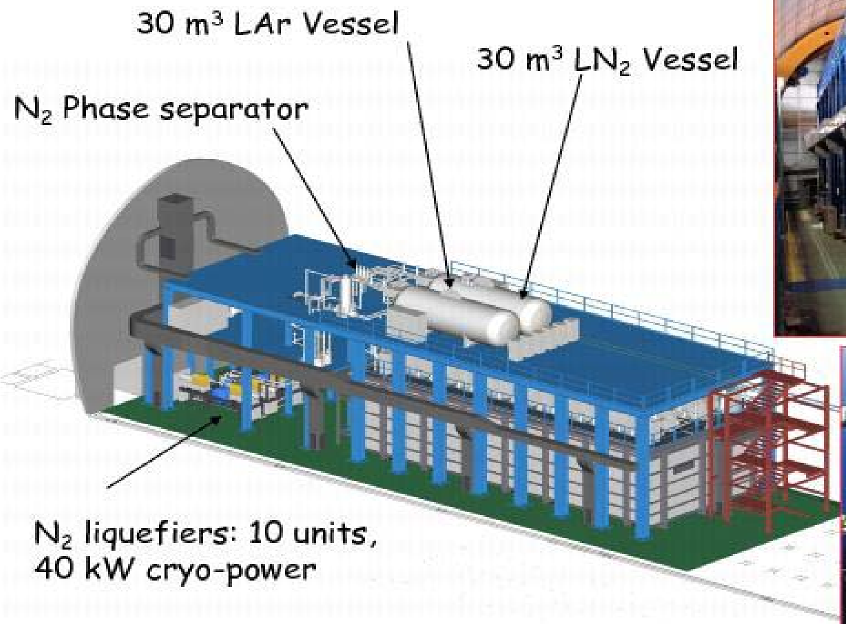
- Using recent technologies, we can obtain fine event information as a “bubble chamber image” with high rate.
- 3D tracking detector
  - We can obtain precise geometrical event information.
  - Very low energy particles can be measured.
- Local energy loss with mm level can be obtained.
  - Range and dE/dx are quite useful for particle ID.
- Total absorption, all fiducial, homogeneous calorimeter.
- Good e/π^0 separation.
- Good energy reconstruction



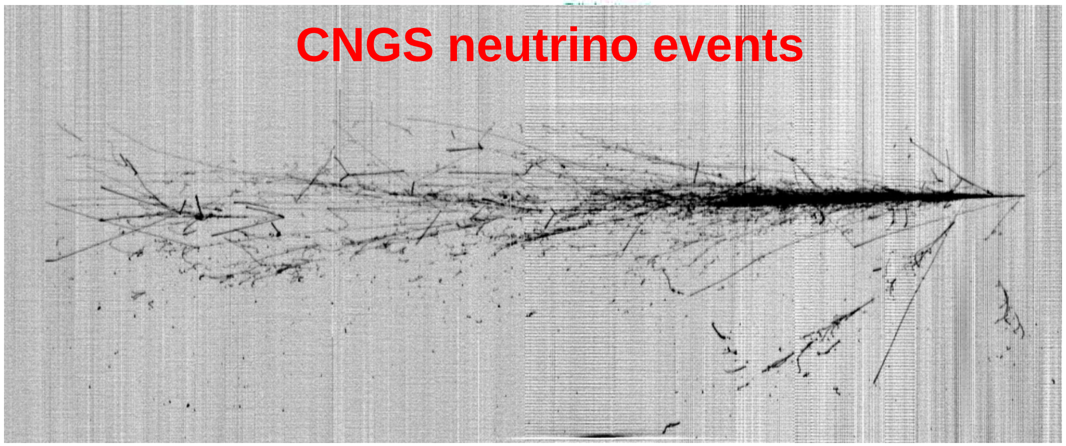
Gargamelle Bubble Chamber

Liquid Argon TPC（ICARUS T300）


ICARUS T600 in LNGS Hall B



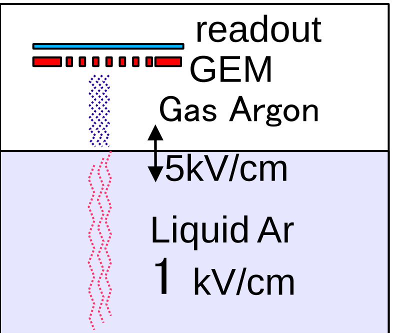
Neu2010



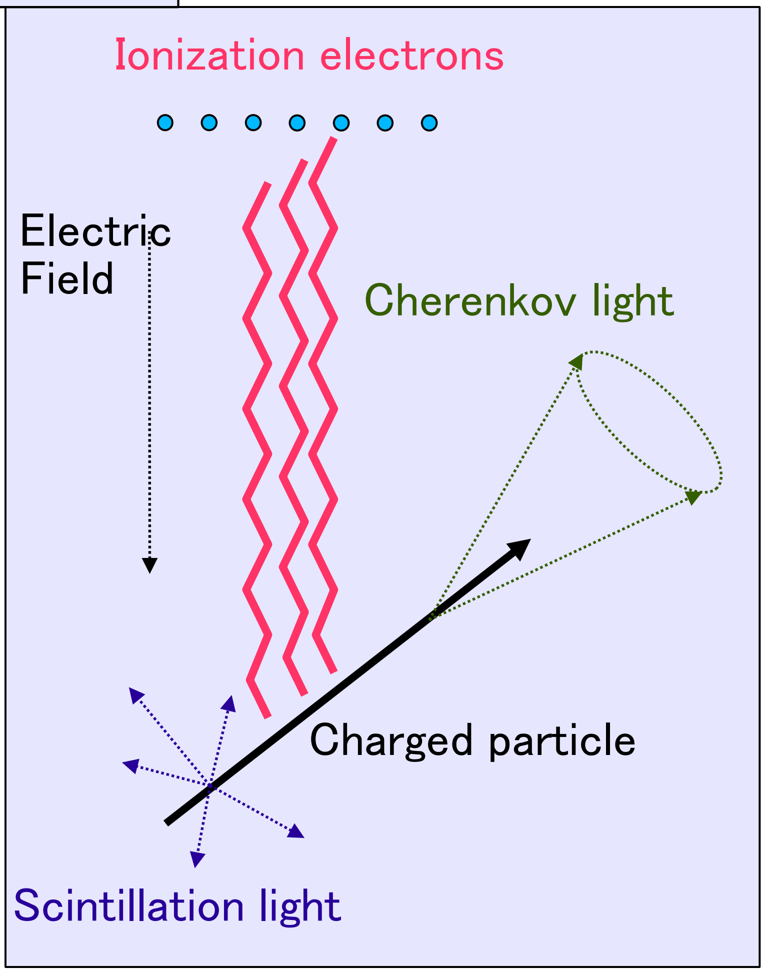
CNGS neutrino beam direction

- **Commissioning concluded, now in data taking with neutrino events from CERN. (~1000ev /year for CNGS ν using ~500t detector)**

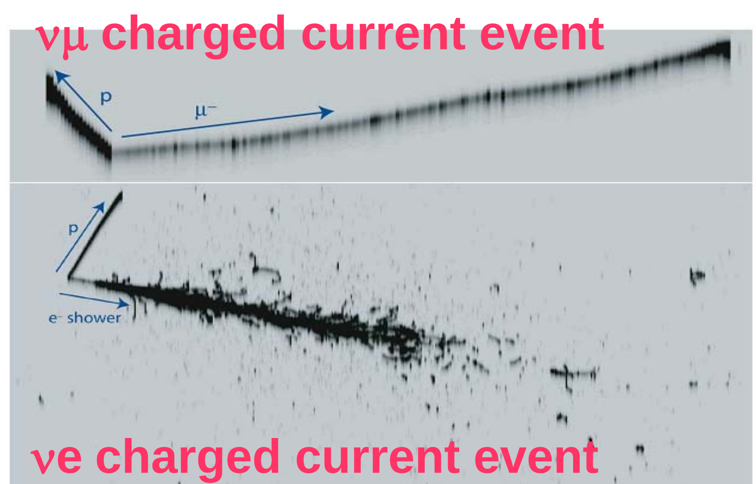
Concept of the LAr TPC



Double phase



- Ionization electron signal
  - ~5x10^{4}e/cm MIP
  - 3D track reconstruction as a TPC
  - drift velocity is ~mm/μs with ~kV/cm electric field
  - LAr purity affects the attenuation of the drift electrons.
  - No amplification inside LAr
  - Diffusion of the drift electrons is about 3mm after 20m drift



A. Bueno, et.al.,, hep-ph/0701101

One candidate in Japan

- Cover Oscillation 1st and 2nd Maximum
- Neutrino Run Only 5 Years x 1.66MW
- 100kt Liq. Ar TPC
    - -Good Energy Resolution
    - -Good e/π^0 discrimination
- Keeping Reasonable Statistics

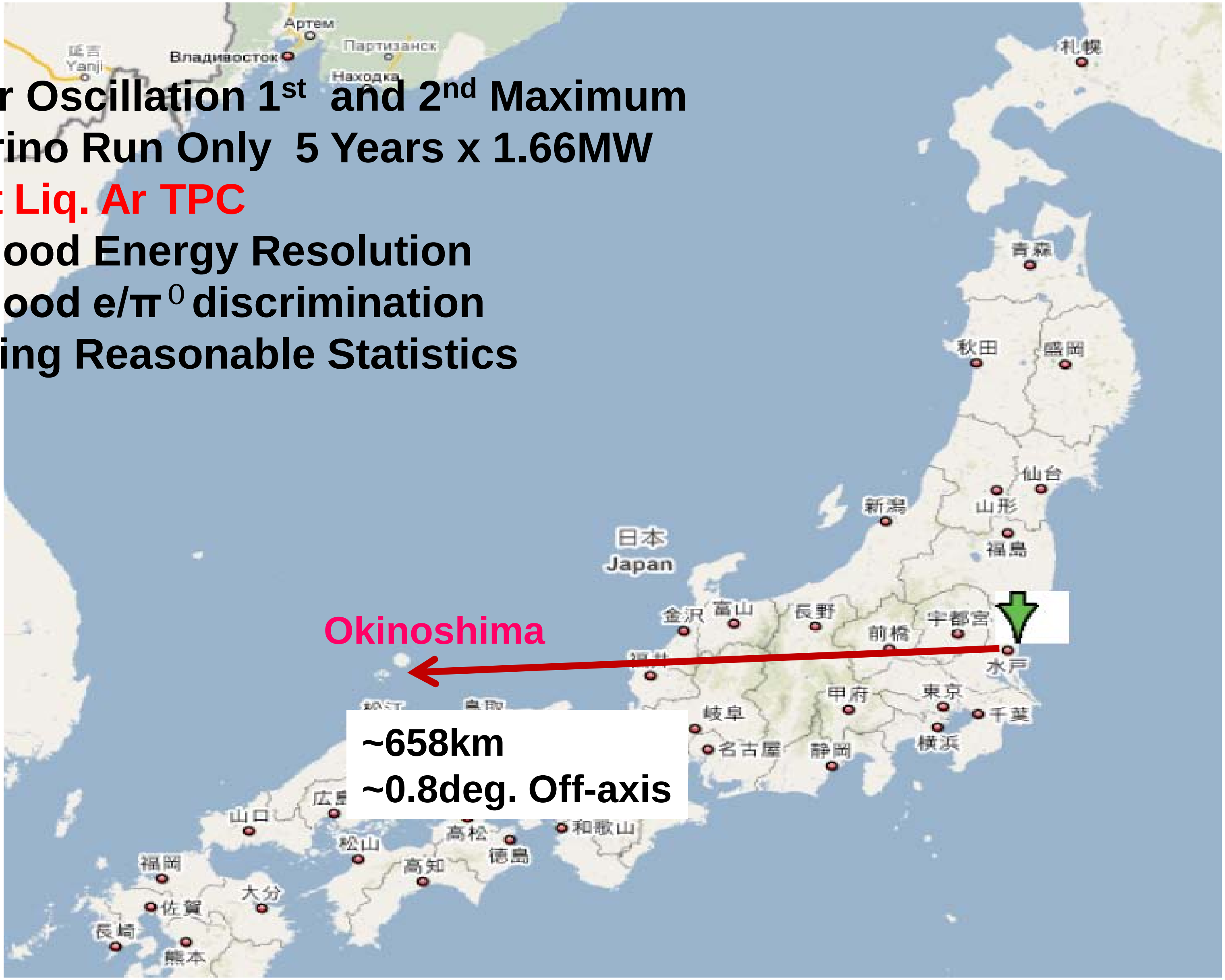
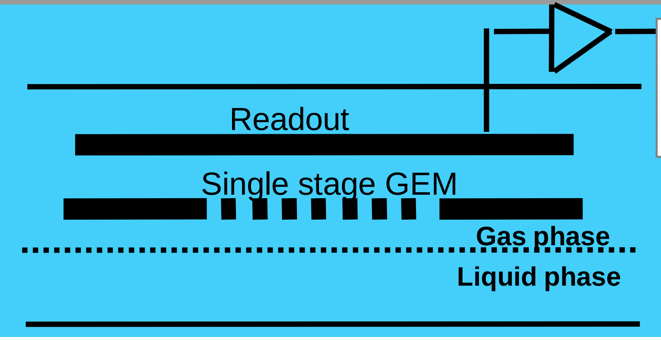
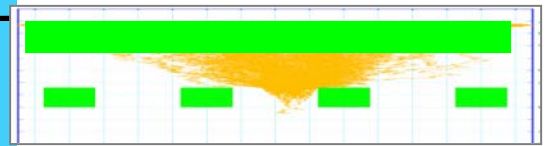


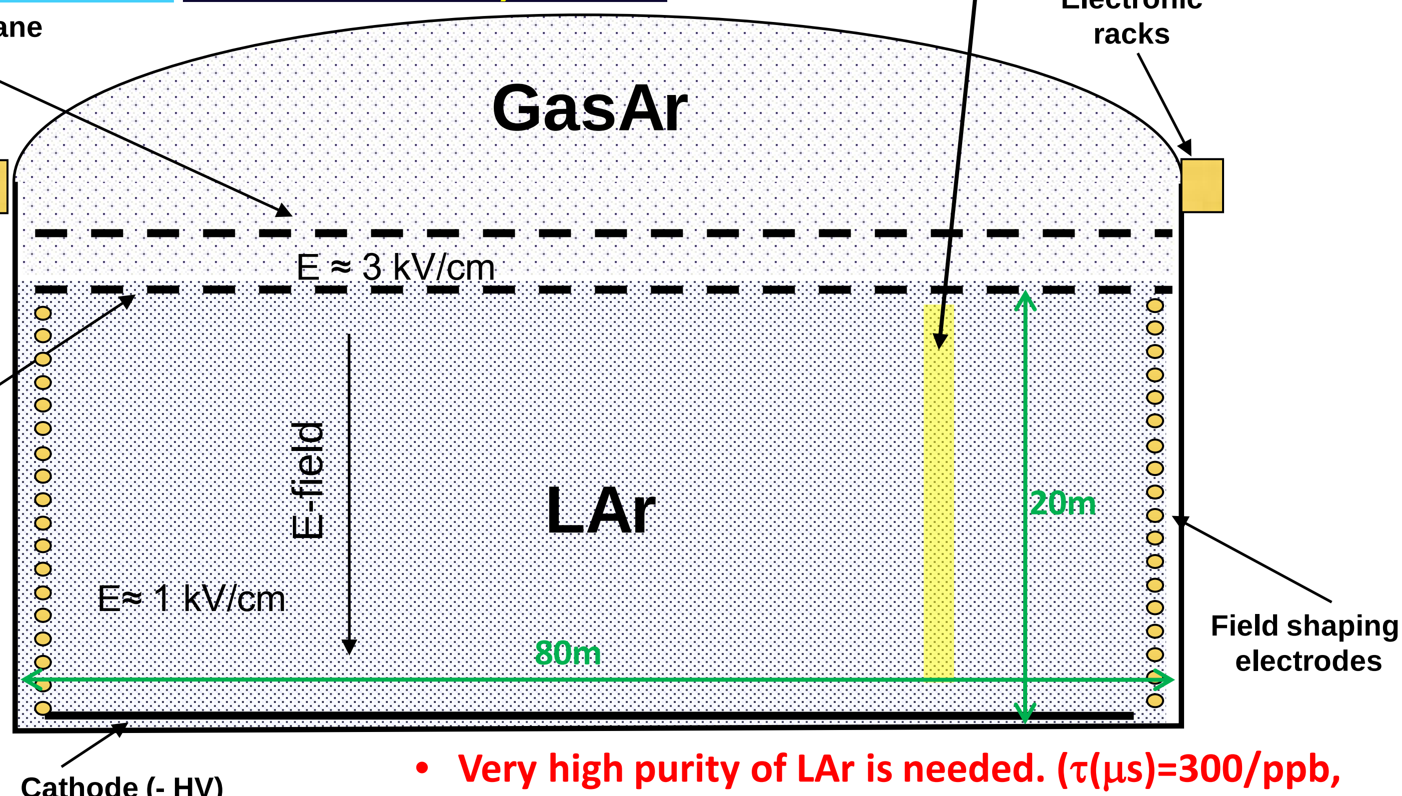
Image of ~100kt LAr and important R&D components





Double phase detector readout using both liquid and gas Argon phases (with GEM/LEM)

Test for long drift distance of ionized electrons using cylindrical cryostat

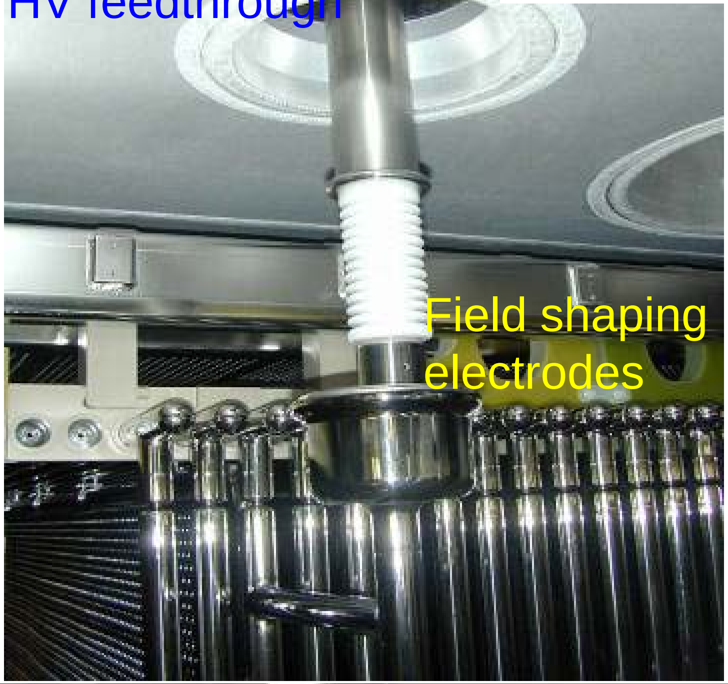


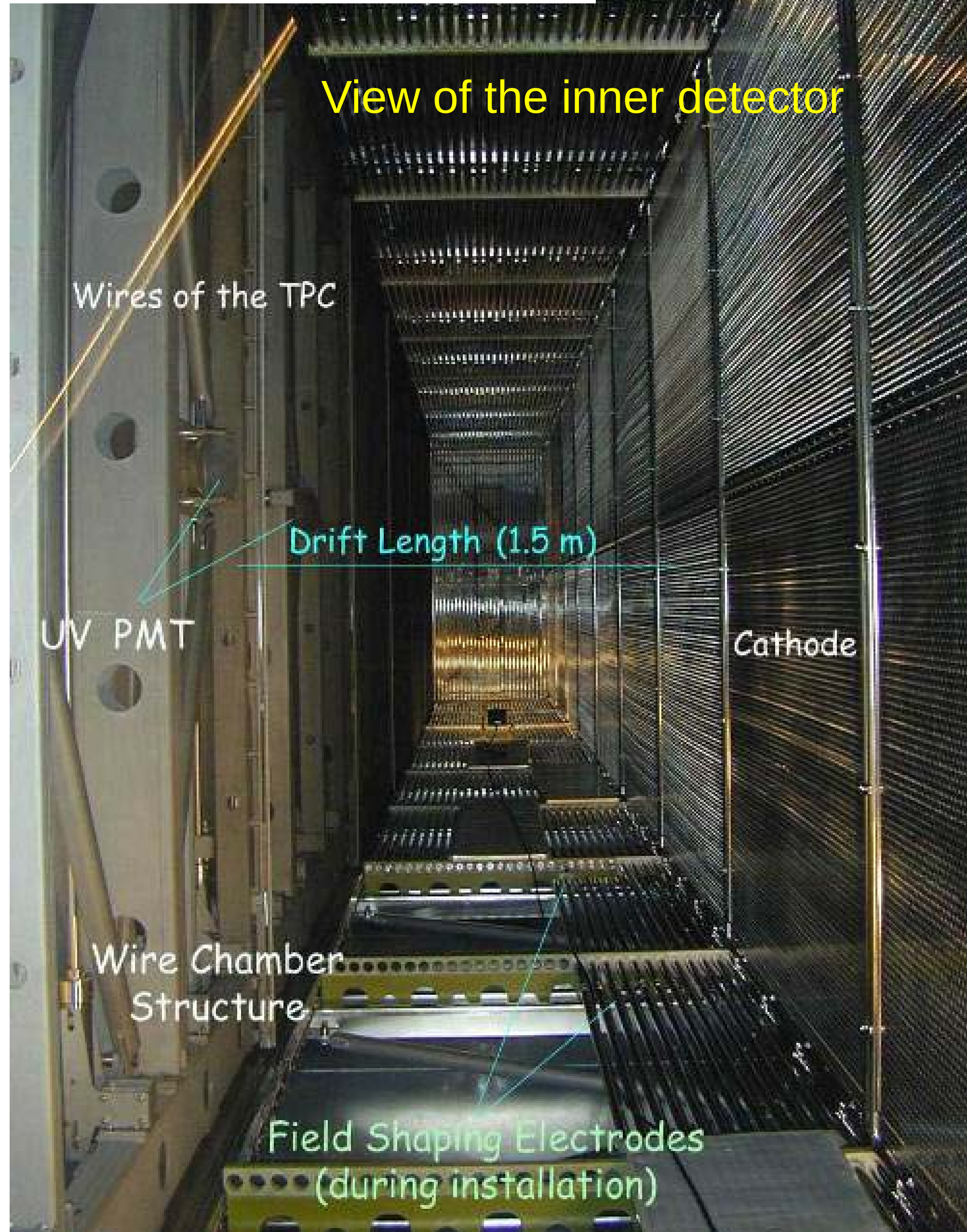
A.Rubbia
Venice 2003,
hep-ph/0402110

High Voltage up to ~MV

- Very high purity of LAr is needed. ($\tau(\mu s)$=300/ppb, e.g: 1/e at ~5cm of 10ppb with 1kV/cm)
- Drift velocity is slower with lower voltage, and it affects more attenuation in LAr.
- To provide better S/N, GAr is used, too.

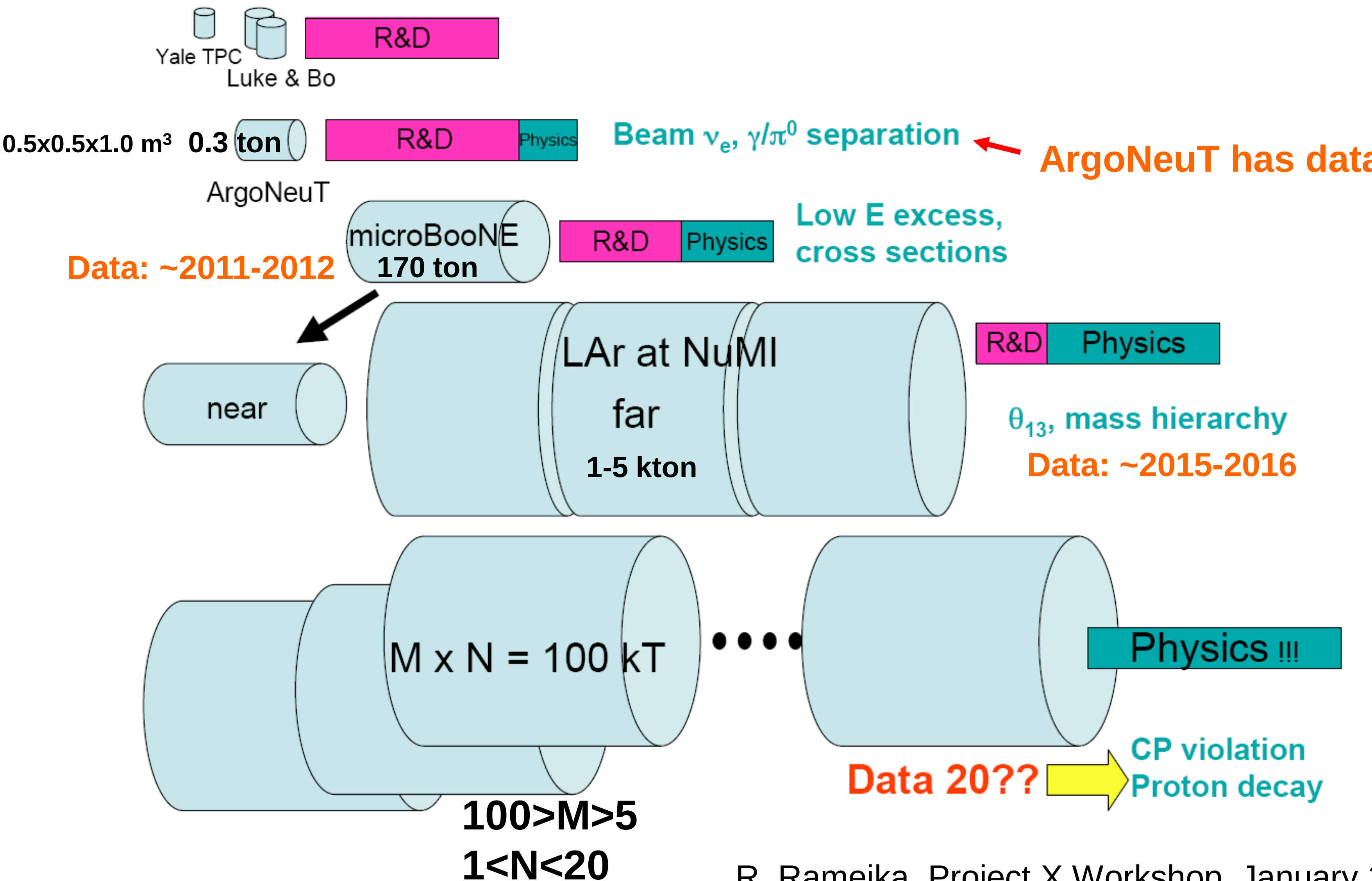
ICARUS T300 Prototype





Proposed Strategy @ Fermilab

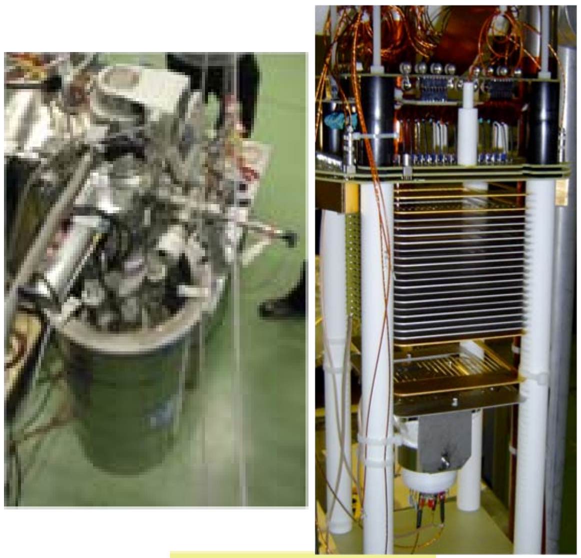
Evolution of the Liquid Argon Physics Program



R. Rameika, Project X Workshop, January 2008

LAr experiment prototyping

To solve technical challenges posed by Giant Liquid Argon Experiment



3 lt @ CERN,
10 lt @ KEK

small test setups for readout method development, electronics

250 lt @ KEK

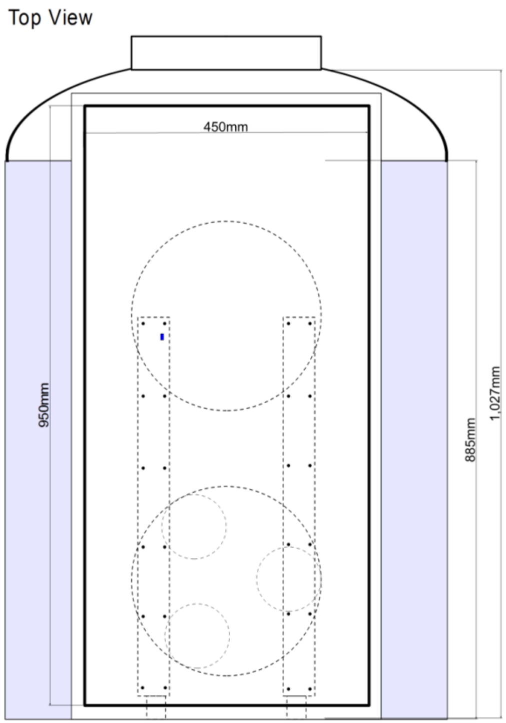
0.4 ton LAr, vacuum, cryogenic system, gas purging, argon liquefaction, optimized for test beam

ArDM (RE18) @ CERN

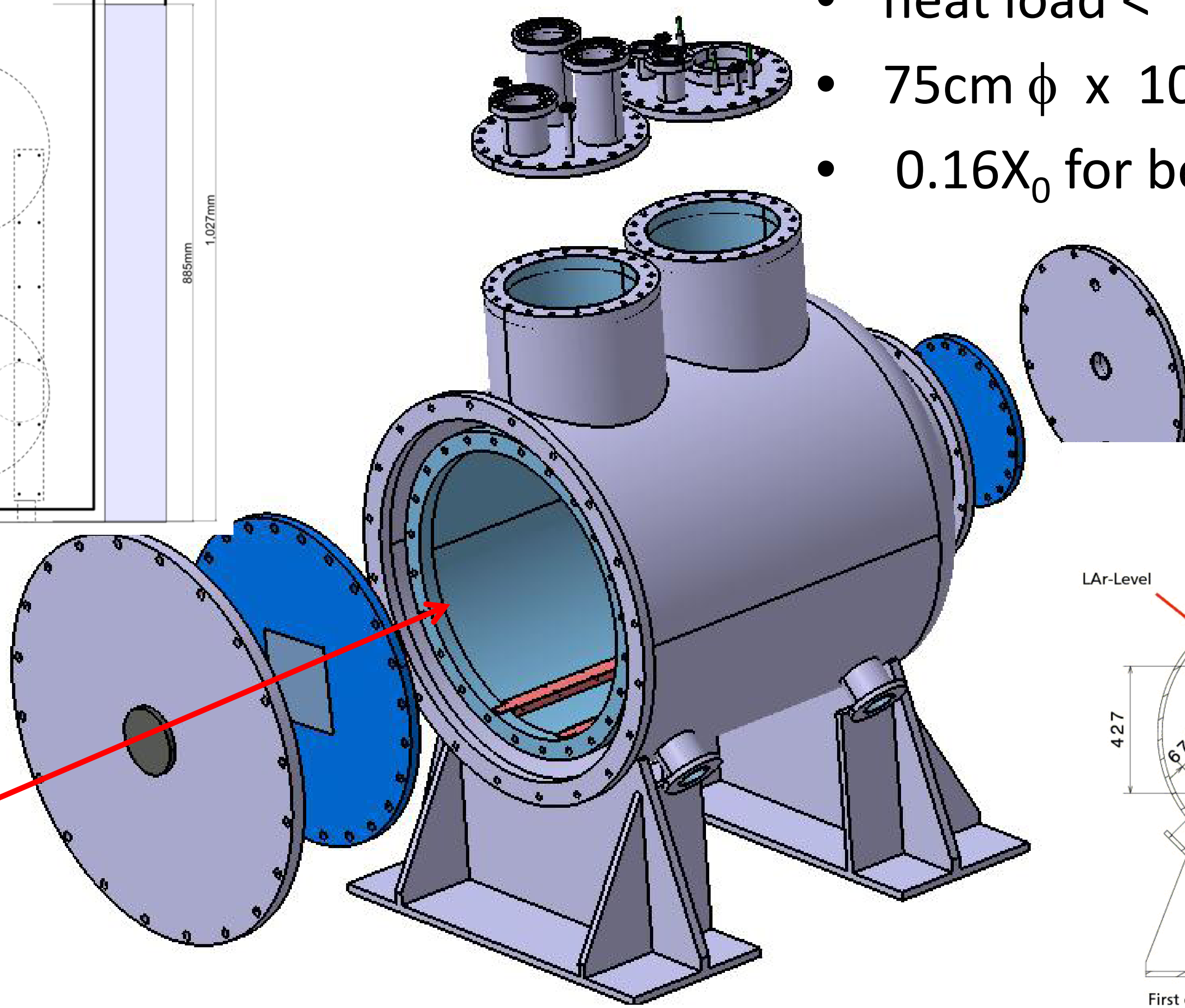
J.Phys.Conf.Ser.39:129-132,2006

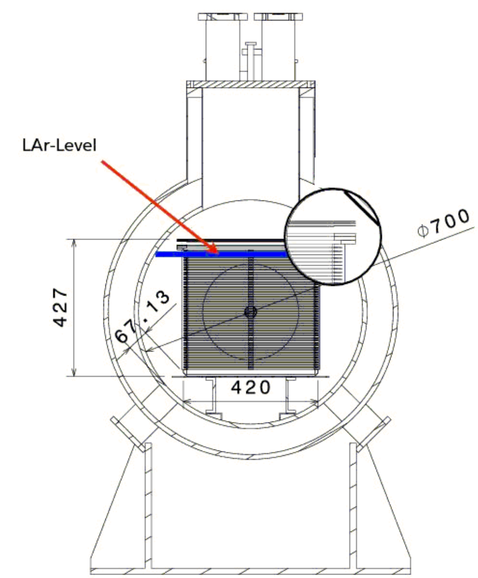
1 ton LAr, large area readout, 1m drift with Cockroft-Walton, LAr recirculation and purification, electronics, safety, optimized for dark matter searches

Drawings of 250L



- Borrow MEG prototype
- heat load < ~70W
- 75cm ϕ x 100cm (inner)
- $0.16X_0$ for beam window





First draft of a 400 x 800 x 400 detector
(Designstudy and very preliminary)

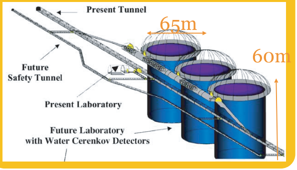
Laguna

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. Funded as a EU FP7 design study. Three detection techniques are investigated:

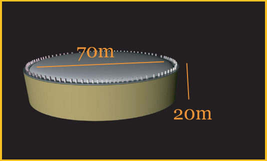
- Water Cerenkov imaging, $\sim$ 500 kton, with synergy with HK (Japan) and UNO (USA).
- Liquid argon time-projection chamber, $\sim$ 100 kton. Technology pioneered in Europe by the ICARUS R&D programme.
- Liquid scintillator, $\sim$ 50 kton connected to Borexino R&D programme

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

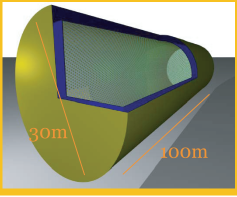
MEMPHYS



GLACIER



LENA

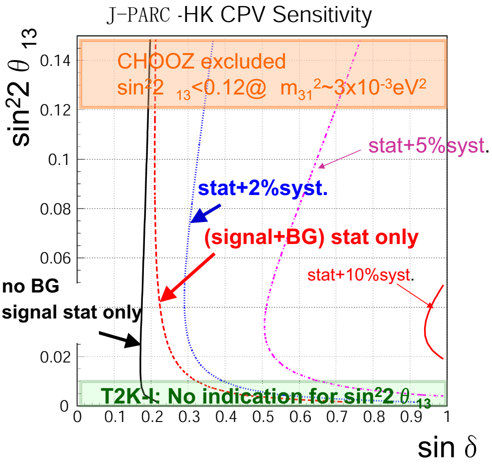


SuperBeams - J-PARC phase 2 (T2HK)

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.

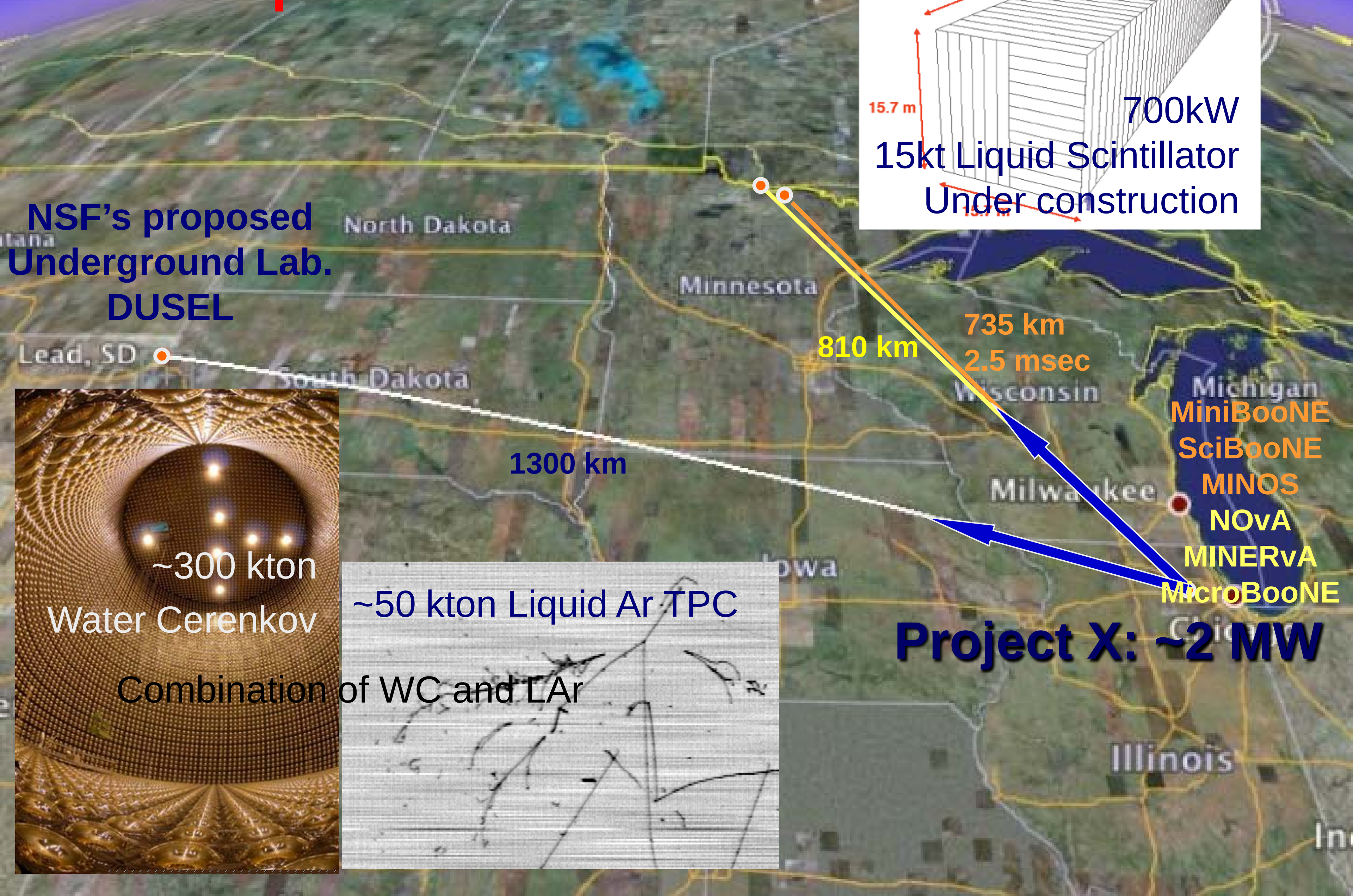
The detector would have valuable physics potential in proton decay, SN neutrinos, solar neutrinos.
Its cost: $\sim$ 0.5 G\$
Systematics at 2% are difficult
4 MW at 50 GeV/c are difficult
Targetry and optics at 4 MW are difficult and will probably require some compromise

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

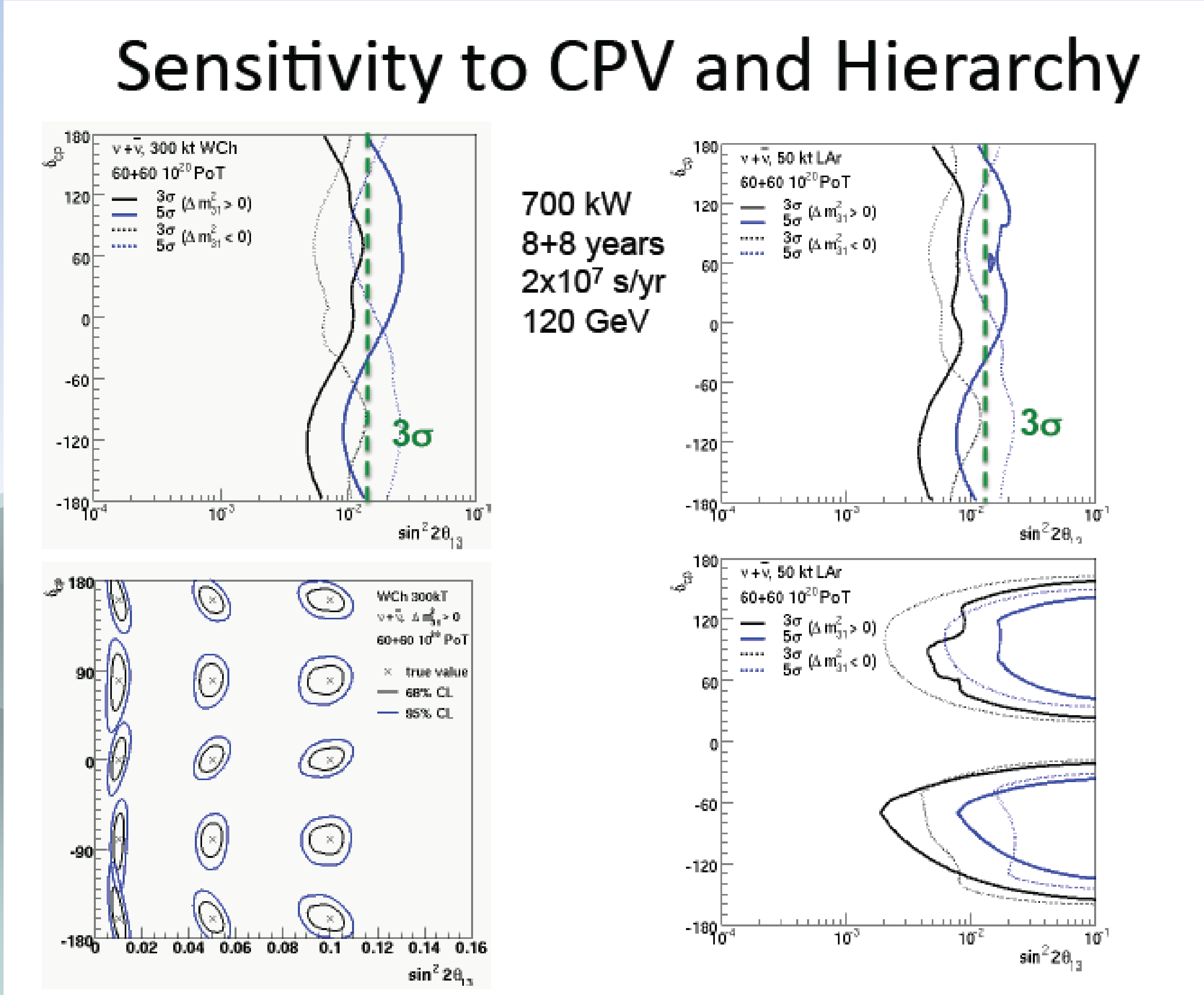


Possible scenarios in Japan

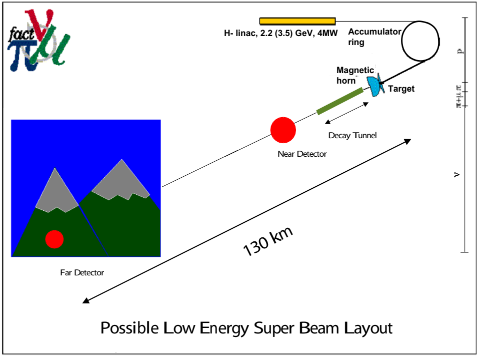
FNAL possibilities



FNAL-DUSEL potential



SuperBeams - SPL ν beam at CERN

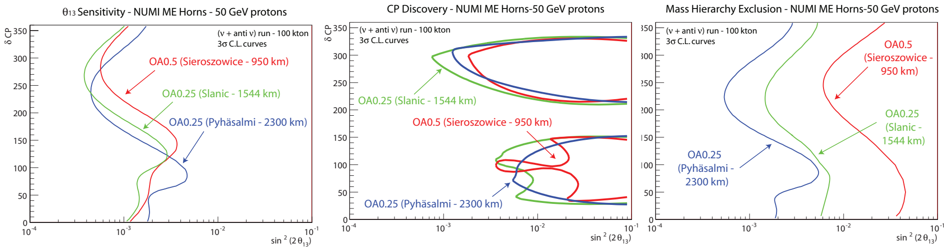


- A 3.5 GeV, 4MW Linac: the SPL.
- A liquid mercury target station capable to manage the 4 MW proton beam. R&D required.
- A conventional neutrino beam optics capable to survive to the beam power, the radiation and the mercury. Already prototyped.
- Up to here is the first stage of a neutrino factory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

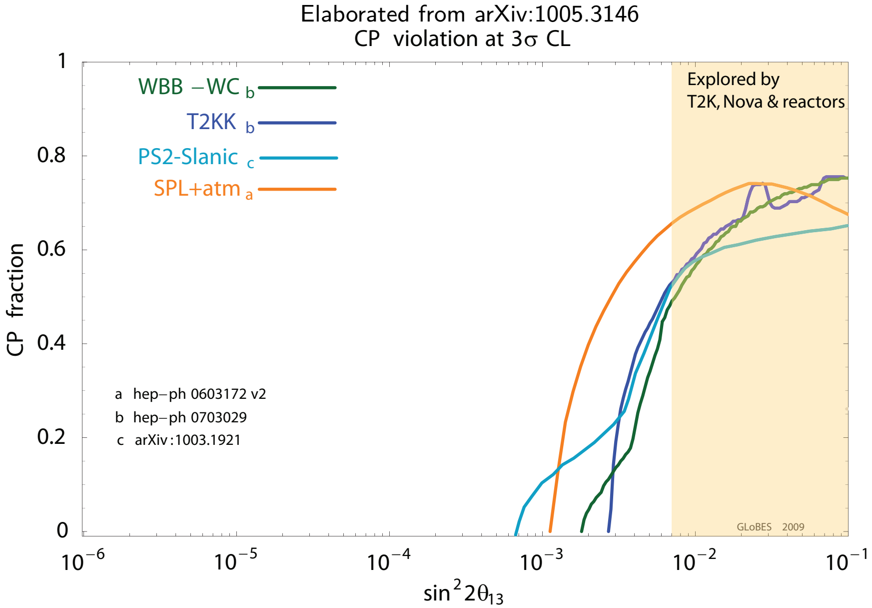
PS2 Super Beams

A. Rubbia: arXiv.1003.1921

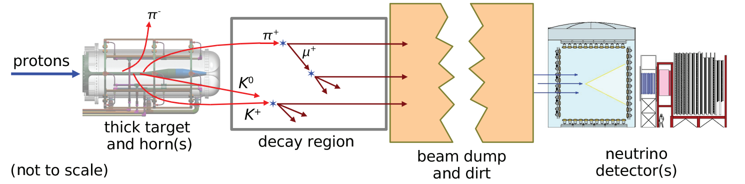
Assume 2 MW from a 50 GeV PS2.
An on-axis wide band neutrino beam.
Three possible sites: Sieroszowice at 950 km, Slanic at 1544 km or Pyhasalmi at 2300 km.
A 100 kton liquid argon detector capable of measuring neutrino oscillations at both the first and second oscillation maxima with optimal perfromance on reconstruction of neutrino energy and background rejection.



Leptonic CP violation sensitivity of Super Beams



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.

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
```

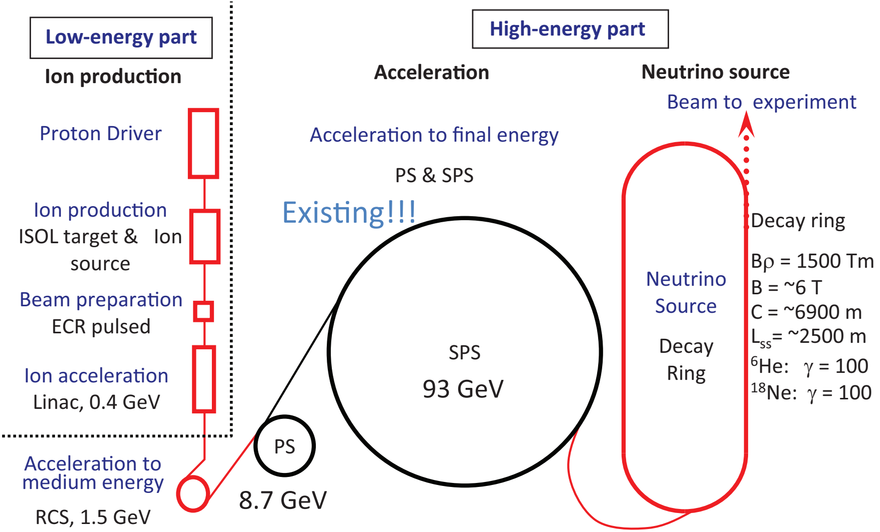
Distinctive features of Beta Beams

...limitations not so well advertized ...

- Don't need a magnetized detector $\Rightarrow$ make use of next generation megaton water Cerenkov detectors or 100 kton liquid argons.
- Can re-use part of the CERN accelerator complex (this can be seen as a limitation)
- Synergies with Nuclear Physics (share an intense radioactive ion source), SPL Super Beam (two neutrino beams in the same detector), atmospheric neutrinos (physics case of both beams greatly enhanced by this synergy).
- An evolving concept with several interesting possible upgrades.
- Not too far R&D needed.

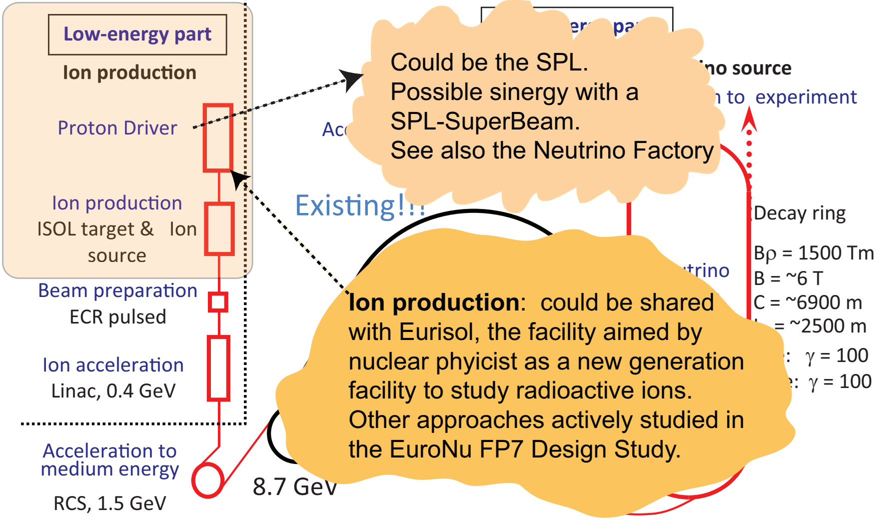
Beta Beam (P. Zucchelli: Phys. Lett. B532:166, 2002)

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



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

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



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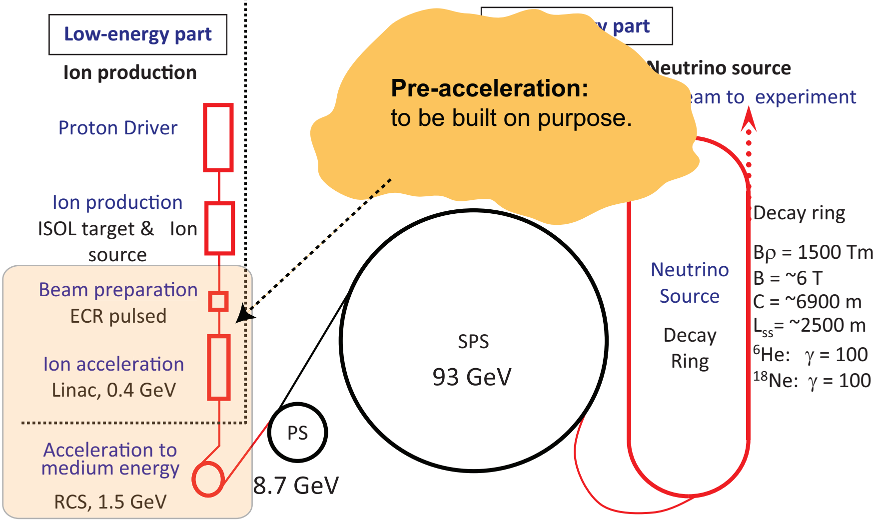

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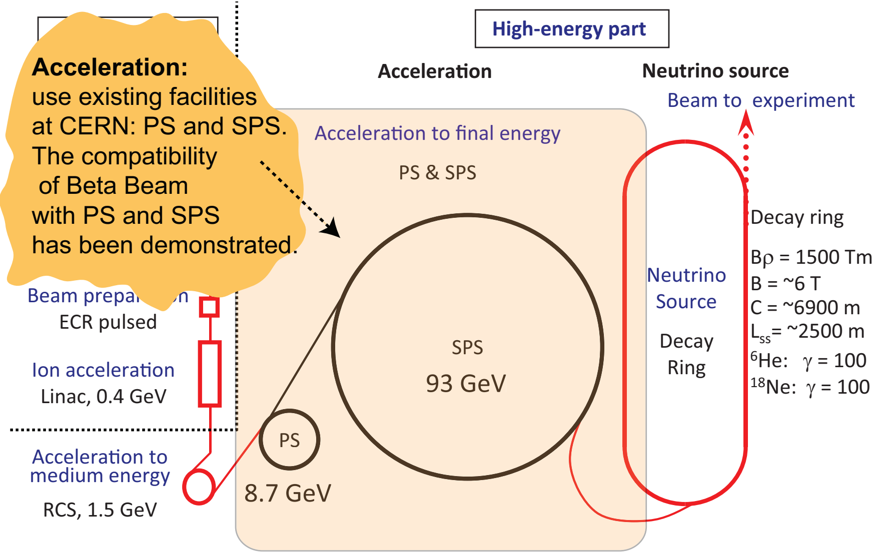

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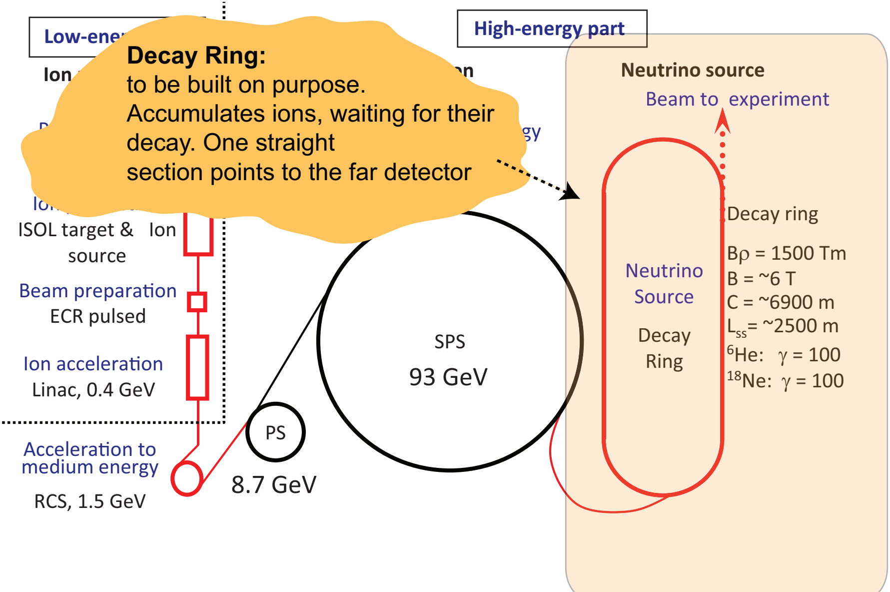

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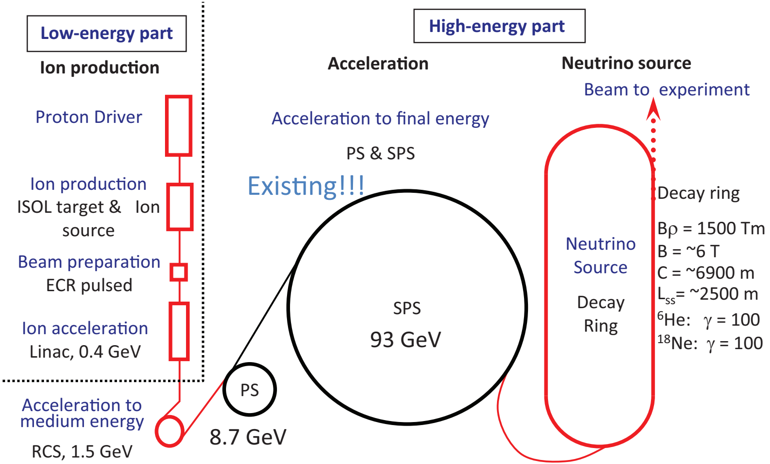
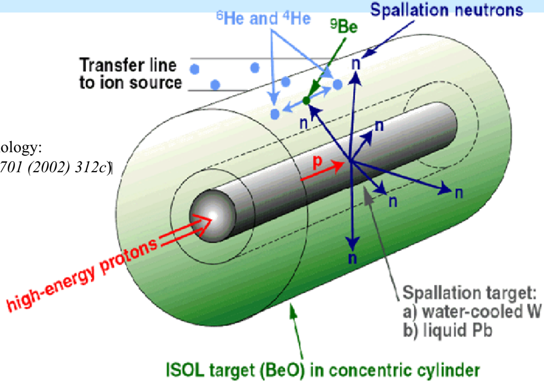


- $\overline{\nu}_e$ generated by He^6, 100 μA, $\Rightarrow 2.9 \cdot 10^{18}$ ion decays/straight session/year.
- ν_e generated by Ne^{18}, 100 μA, $\Rightarrow 1.1 \cdot 10^{18}$ ion decays/straight session/year.

^{6}He production from ^{9}Be(n,α)



Converter technology:
(*J. Nolen, NPA 701 (2002) 312c*)

- **Converter technology preferred to direct irradiation (heat transfer and efficient cooling allows higher power compared to insulating BeO).**
- **^{6}He production rate is ~2x10^{13} ions/s (dc) for ~200 kW on target.**

Beta-beam team

Possible β^- emitters ($\bar{\nu}_e$)

Isotope	Z	A	A/Z	$T_{1/2}$	$Q_{\beta\ (gs>gs)}$	$Q_{\beta\ eff.}$	$E_{\beta\ av.}$	$E_{\nu\ av.}$	<E_LAB> (MeV)
				s	MeV	MeV	MeV	MeV	(@ 450 GeV/p)
6He	2	6	3.0	0.807	3.5	3.5	1.57	1.94	582
8He	2	8	4.0	0.119	10.7	9.1	4.35	4.80	1079
8Li	3	8	2.7	0.838	16.0	13.0	6.24	6.72	2268
9Li	3	9	3.0	0.178	13.6	11.9	5.73	6.20	1860
11Be	4	11	2.8	13.81	11.5	9.8	4.65	5.11	1671
15C	6	15	2.5	2.449	9.8	6.4	2.87	3.55	1279
16C	6	16	2.7	0.747	8.0	4.5	2.05	2.46	830
16N	7	16	2.3	7.13	10.4	5.9	4.59	1.33	525
17N	7	17	2.4	4.173	8.7	3.8	1.71	2.10	779
18N	7	18	2.6	0.624	13.9	8.0	5.33	2.67	933
23Ne	10	23	2.3	37.24	4.4	4.2	1.90	2.31	904
25Ne	10	25	2.5	0.602	7.3	6.9	3.18	3.73	1344
25Na	11	25	2.3	59.1	3.8	3.4	1.51	1.90	750
26Na	11	26	2.4	1.072	9.3	7.2	3.34	3.81	1450

From P..Zucchelli talk at Nufact 03. Table compiled by U. Koster

Possible β^+ emitters (ν_e)

Isotope	Z	A	A/Z	$T_{1/2}$	$Q_{\beta\ (gs>gs)}$	$Q_{\beta\ eff.}$	$E_{\beta\ av.}$	$E_{\nu\ av.}$	<E_LAB> (MeV)
				s	MeV	MeV	MeV	MeV	(@450 GeV/p)
8B	5	8	1.6	0.77	17.0	13.9	6.55	7.37	4145
10C	6	10	1.7	19.3	2.6	1.9	0.81	1.08	585
14O	8	14	1.8	70.6	4.1	1.8	0.78	1.05	538
15O	8	15	1.9	122.2	1.7	1.7	0.74	1.00	479
18Ne	10	18	1.8	1.67	3.4	3.4	1.50	1.86	930
19Ne	10	19	1.9	17.34	2.2	2.2	0.96	1.25	594
21Na	11	21	1.9	22.49	2.5	2.5	1.10	1.41	662
33Ar	18	33	1.8	0.173	10.6	8.2	3.97	4.19	2058
34Ar	18	34	1.9	0.845	5.0	5.0	2.29	2.67	1270
35Ar	18	35	1.9	1.775	4.9	4.9	2.27	2.65	1227
37K	19	37	1.9	1.226	5.1	5.1	2.35	2.72	1259
80Rb	37	80	2.2	34	4.7	4.5	2.04	2.48	1031

From P..Zucchelli talk at Nufact 03. Table compiled by U. Koster

Exercise

Characterize a Beta Beam as function of γ and Q.

Take ^{6}He, with end point energy $Q = 3.5$ MeV.
Discuss neutrino charged current rate of events as function of γ, in the range $0 < \gamma \leq 150$, having the detector at the first oscillation maximum.

Keep $\gamma = 150$, what are the arguments in favour of a ion with Q bigger than ^{6}He and those in favor of a smaller Q?
Compare these results with a Neutrino Factory running at 20 GeV.

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: $\boxed{\mathcal{M} = \frac{\gamma}{Q}}$
- 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)

Beta Beam baseline scenario

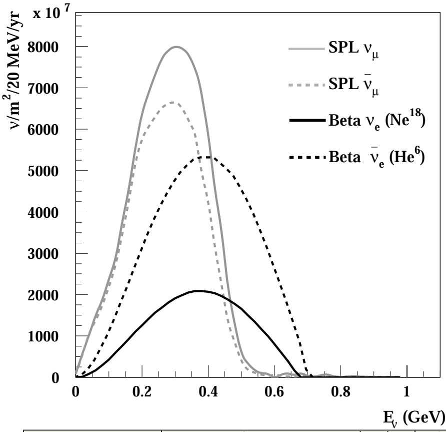
Boundary conditions:

- CERN SPS can accelerate $^{6}\mathrm{He}$ up to $\gamma = 150 \Rightarrow E_\nu \simeq 0.5\,GeV$ $\Rightarrow$ baselines within 300 km.
- The only viable candidate to host a megaton detector is Frejus lab, 130 km away from CERN

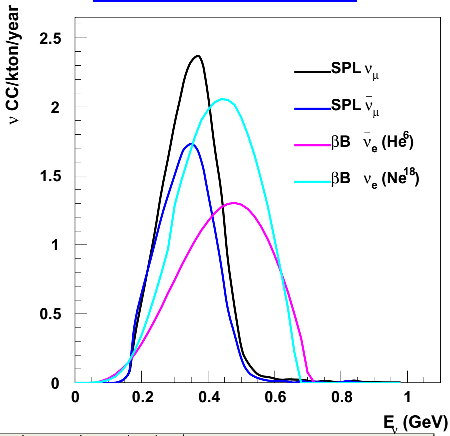
Optimal γ: $\gamma = 100$.

This is the option studied by the Eurisol design study and now by the EuroNu design study

Yearly Fluxes



CC rates, 440 kton/yr



	Fluxes @ 130 km $\nu/m^2/yr$	$\langle E_\nu \rangle$ (GeV)	CC rate (no osc) events/kton/yr	$\langle E_\nu \rangle$ (GeV)	Years	Integrated events (4400 kton/yr)
SPL Super Beam						
ν_μ	$11.80 \cdot 10^{11}$	0.29	121.7	0.36	2	107127
$\overline{\nu}_\mu$	$9.66 \cdot 10^{11}$	0.28	23.1	0.35	8	81164
Beta Beam						
$\overline{\nu}_e(\gamma = 100)$	$10.92 \cdot 10^{11}$	0.40	46.0	0.46	5	101262
$\nu_e(\gamma = 100)$	$4.06 \cdot 10^{11}$	0.38	65.4	0.44	5	143887

Experimental strategy

Beta Beam signal is $\nu_\mu$appearance.
To profit of the no-background beam, detector backgrounds should be taken at minimum:

- ν_e events mis-identified as ν_μ events
- Charged pions from NC and NC-like ν_e interactions mis-identified as muons.
- Atmospheric neutrinos

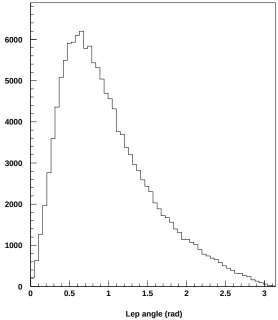
Atmospheric neutrino background

Why are they dangerous?

Atmospheric neutrinos come in two flavors: ν_e and ν_μ so they can fake any signal.

Their energy spectrum fully covers Beta Beam spectrum.

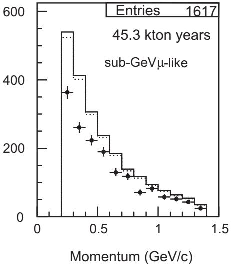
They don't necessary come from the decay ring, but outgoing lepton direction is loosely correlated with the neutrino energy direction in QE events.



The only viable tool to keep them at a negligible rate is to keep very short the live time of the neutrino beam. This is a tight requirement for the Beta Beam accelerator complex.

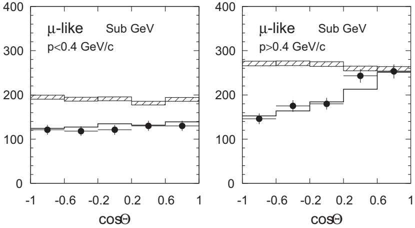
Question: why atmospherics are not a great concern at T2K phase 1, that has much smaller signal neutrino fluxes?

Atmospheric neutrino background

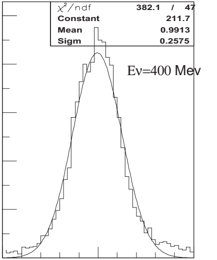


Sub-GeV μ-like events in SK integrated over the solid angle. 45.3 kton year exposure

Sub-GeV μ-like events zenithal distribution



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



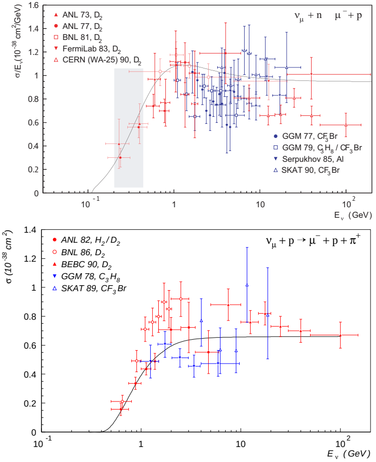
True-Reconstructed ν direction

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%).

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.

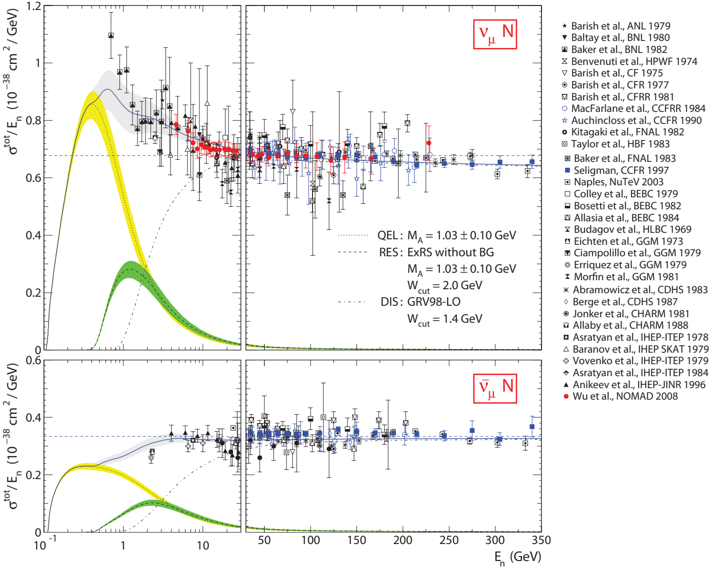
On the other hand: Beta Beam is the ideal place where to measure neutrino cross sections

- 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 systematic error ranging from 2% to 5% both in signal and backgrounds is used in the following

Neutrino Cross Sections

From: NOMAD Collaboration, Eur. Phys. J. C **63** (2009) 355 [arXiv:0812.4543 [hep-ex]].

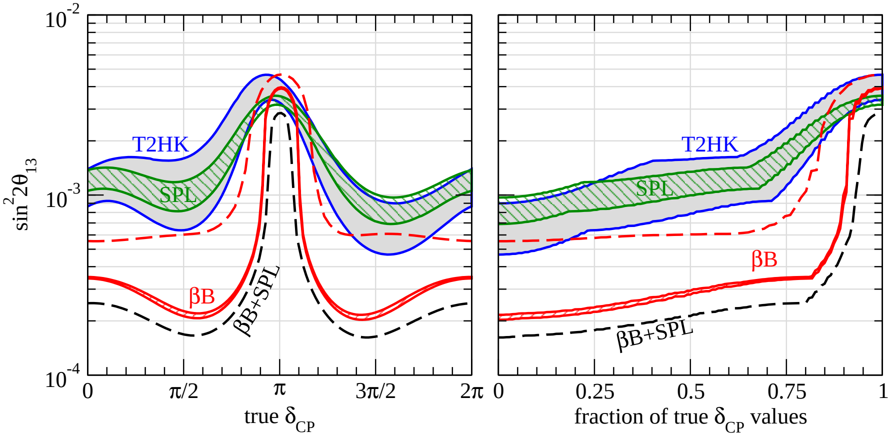


Oscillation signals

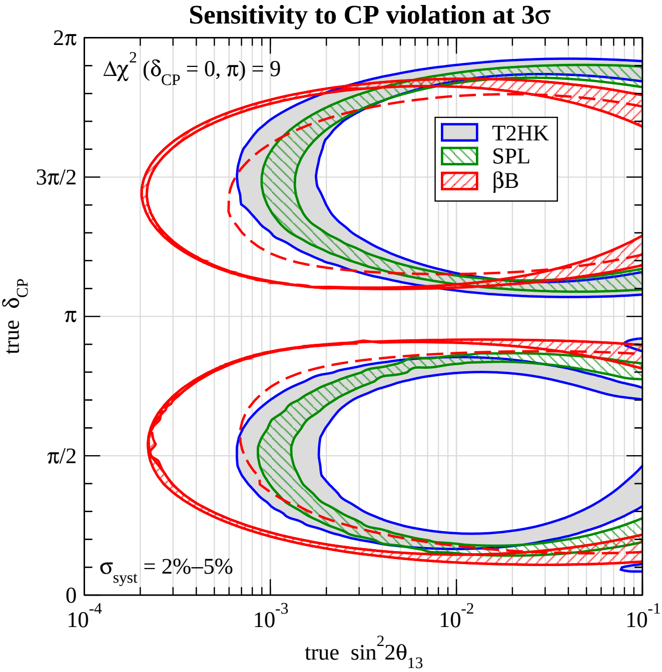
From J.E.Campagne, M. Maltoni, M.M., T.Schwetz, hep-ph/0603172, revised

	βB		SPL		T2HK	
	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$
appearance ν						
background	113		600		1017	
$\sin^2 2\theta_{13} = 0$	24		41		84	
$\sin^2 2\theta_{13} = 10^{-3}$	66	76	93	10	181	18
$\sin^2 2\theta_{13} = 10^{-2}$	285	314	387	126	754	240
appearance $\bar{\nu}$						
background	127		500		1428	
$\sin^2 2\theta_{13} = 0$	23		36		90	
$\sin^2 2\theta_{13} = 10^{-3}$	64	10	74	104	188	261
$\sin^2 2\theta_{13} = 10^{-2}$	271	100	297	390	746	977

Sensitivity to a non-zero θ_{13} at 3σ



Line width: 2% and 5% systematic errors.


Sensitivity to CP violation at 3σ
$\Delta\chi^2 (\delta_{CP} = 0, \pi) = 9$
T2HK
SPL
βB
σ_{syst} = 2%–5%
true δ_{CP}
2π
$3\pi/2$
π
$\pi/2$
0
10^{-4}
10^{-3}
10^{-2}
10^{-1}
true $\sin^2 2\theta_{13}$

Additional signals at the Frejus detector.

Can the θ_{13} and LCPV searches be improved?
Two pathways explored so far. In order of comparison:

- Fire a conventional neutrino beam (the SPL-SuperBeam) to the same detector.
- Combine BB information with the atmospheric neutrinos that the megaton detector will record for free

P.S. Also ν_e disappearance could help in determining θ_{13} and in removing degeneracies (it's the same channel of reactor experiments). However it would help if systematic errors could be pushed below 0.5%. At present 2% seems to be the ultimate level of systematics for a Beta Beam. You should consider that is very unpractical to build a close detector IDENTICAL to the far detector.

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

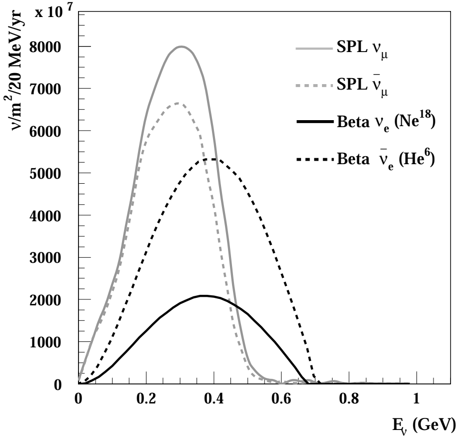
A Beta Beam has the same energy spectrum than the SPL SuperBeams and consumes 5% of the SPL protons.

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



The synergy with atmospheric neutrinos

P. Huber et al., Phys. Rev. D 71, 053006 (2005): Combining Long Baseline data with atmospheric neutrinos (that come for free in the megaton detector):

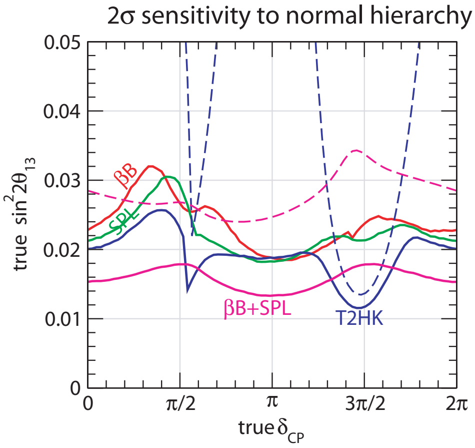
- Degeneracies can be canceled, allowing for better performances in θ_{13} and LCPV searches
- The neutrino mass hierarchy can be measured
- The θ_{23} octant can be determined.

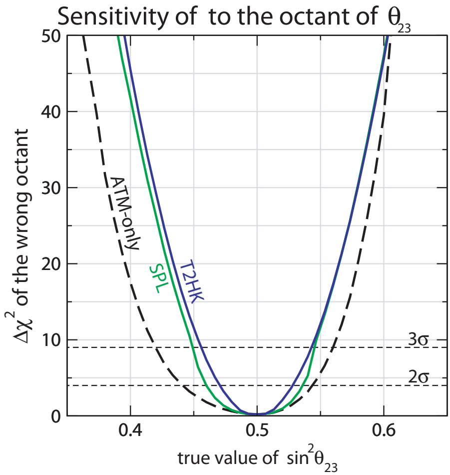
The main reasons are:

- **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.

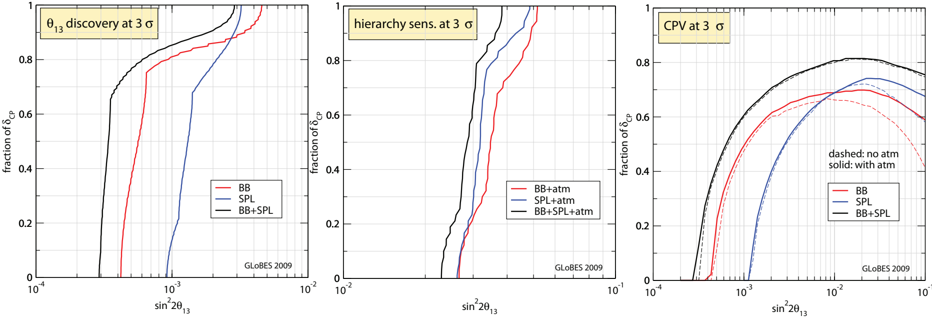
Beta Beam plus atmo: determining mass hierarchy and the octant





Updated sensitivities of SPL, BB and SPL+BB

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



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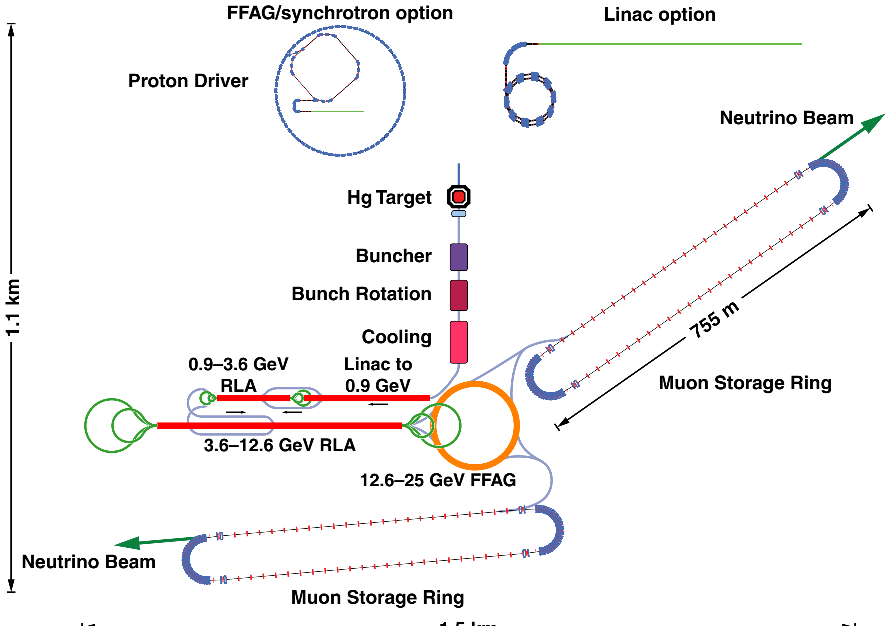
- **Electron capture Beta Beams**: monochromatic neutrino beams, a very attractive option
  - They require long lived, high-A, far from the stability valley ions, r$\Rightarrow$ challenging R&D to match the needed fluxes.

Layout of a Neutrino Factory



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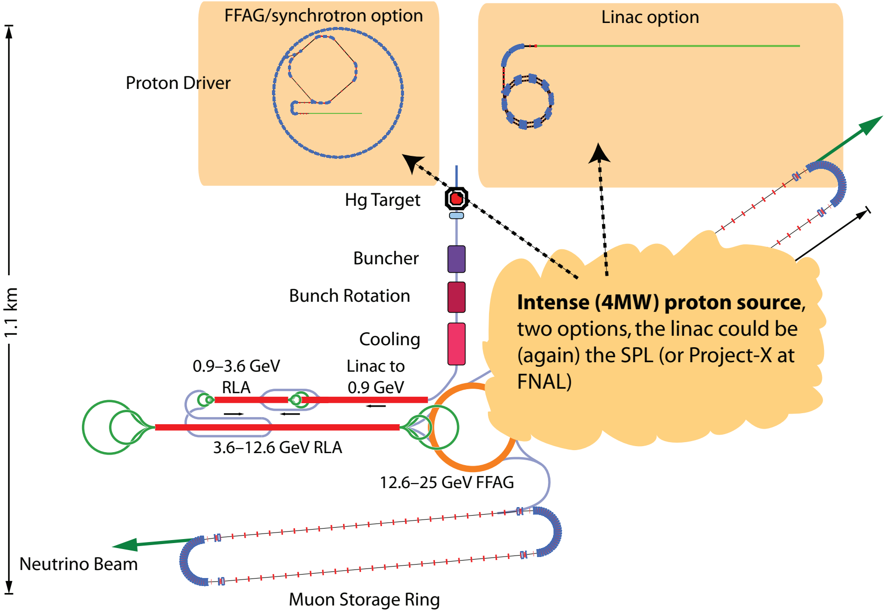

Intense (4MW) proton source, two options, the linac could be (again) the SPL (or Project-X at FNAL)

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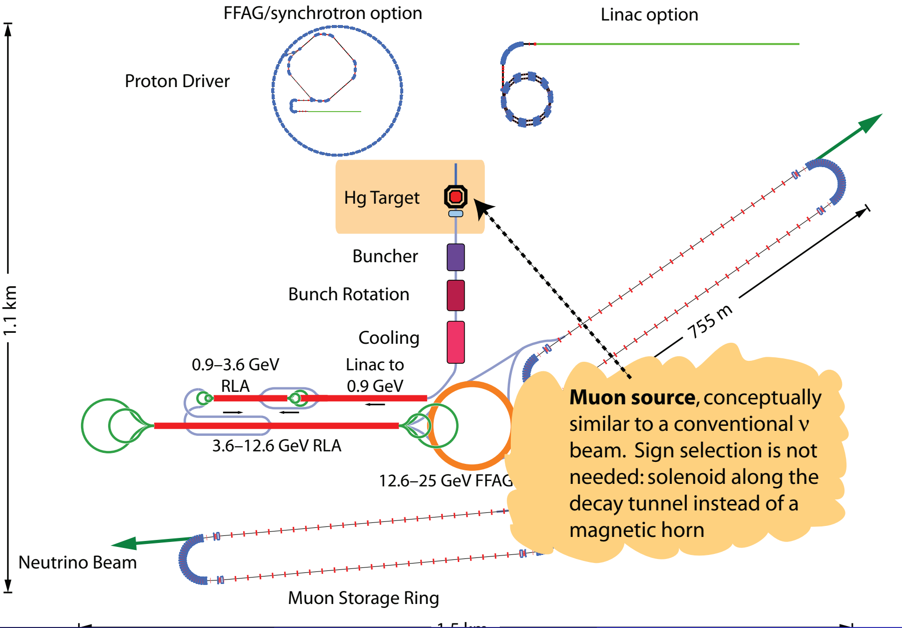

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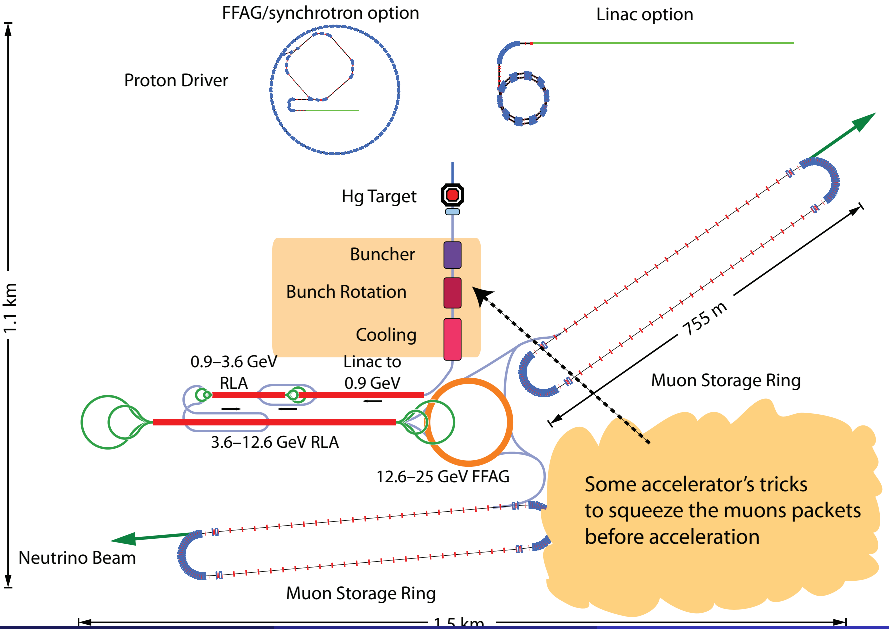
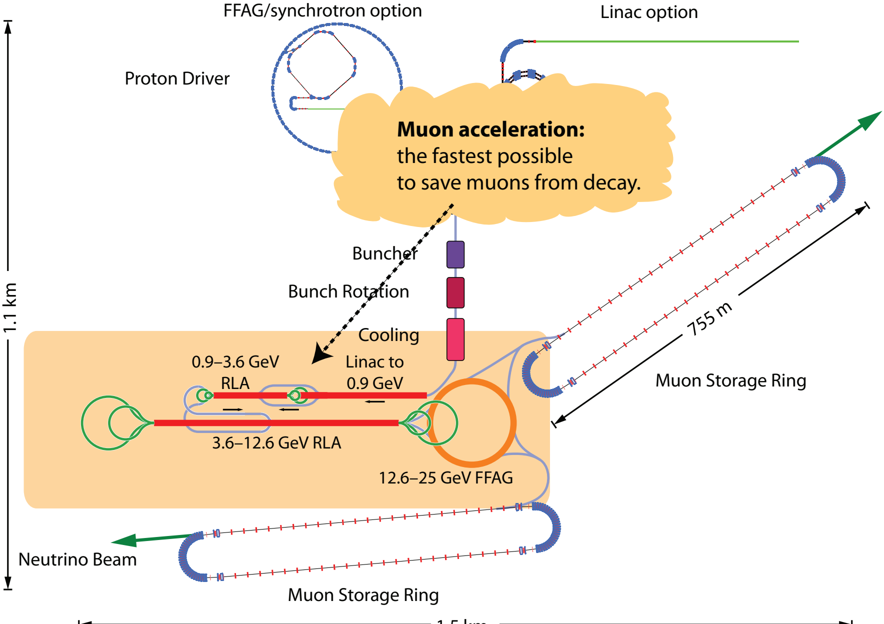


Some accelerator's tricks
to squeeze the muons packets
before acceleration

Layout of a Neutrino Factory



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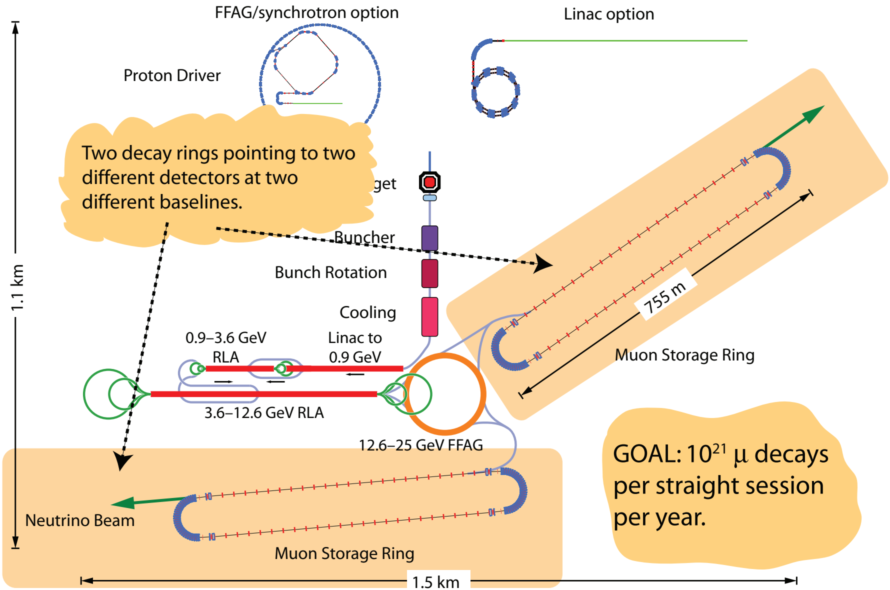
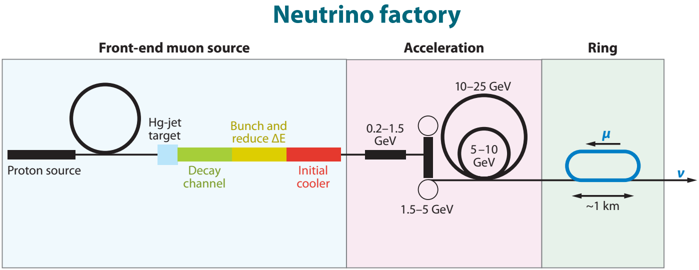
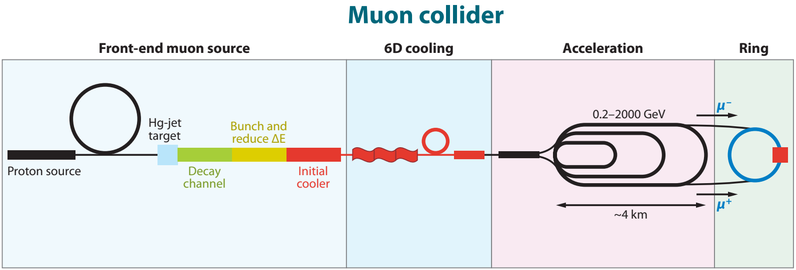


Neutrino Factory as a first stage of a Muon Collider

From S. Geer, Ann.Rev.Nucl.Part.Sci.59:347-365,2009.





Oscillation signals at the neutrino factory

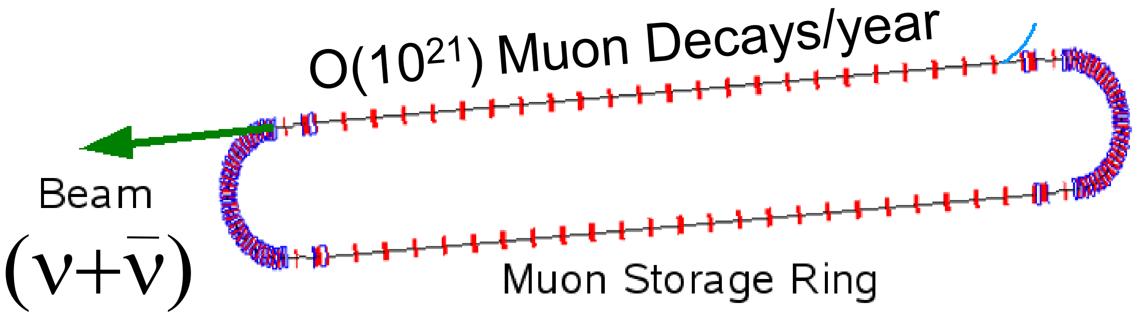
μ^- (μ^+) decay in $(\nu_\mu, \overline{\nu}_e)$ $((\overline{\nu}_\mu, \nu_e))$.

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

Silver channel: search for $\nu_e \rightarrow \nu_\tau$ transitions by detecting ν_τ appearance.
Ideal detectors: $4\times$ Opera or 20 Kton LAr detector.

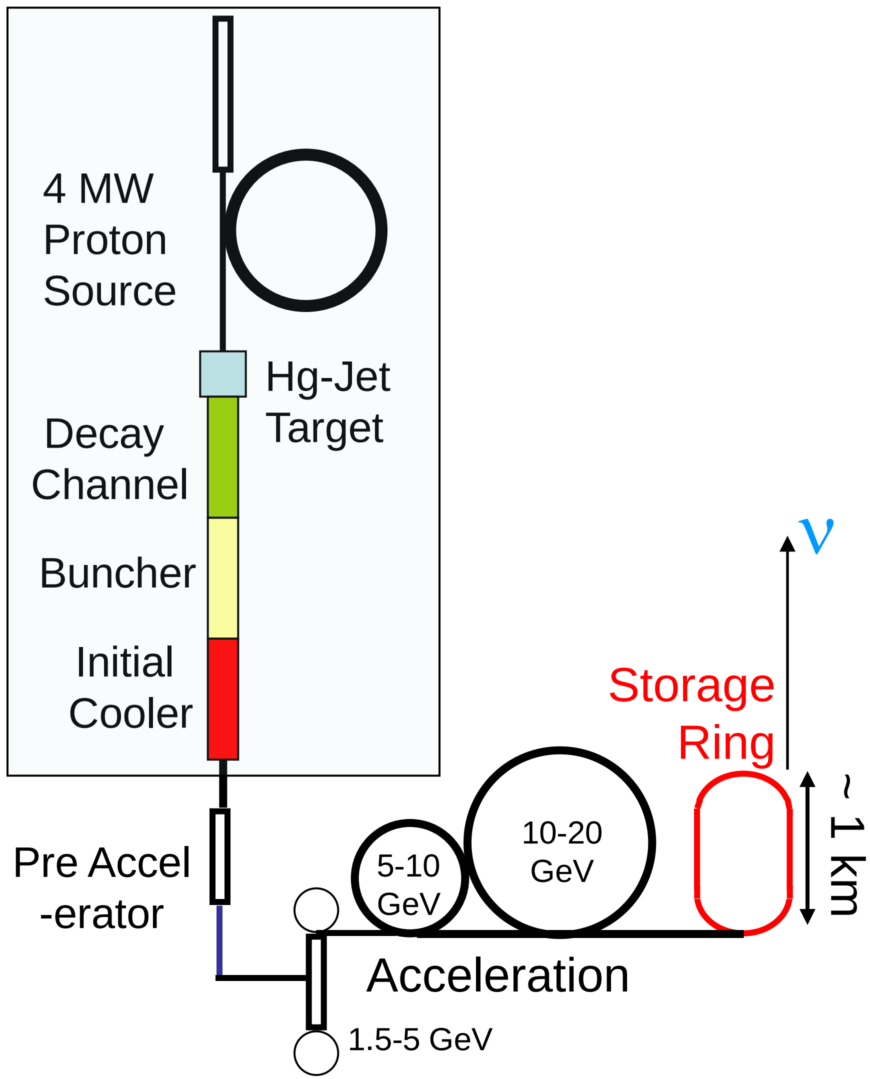
A New Tool

- We desire precision for the long-term neutrino oscillation program → exploit muon decays.
- Muons live a “long” time (τ_0 = 2μs) … to be efficient, a straight muon decay channel would have to be impractically long.
- Solution: inject muons into a storage ring with long straight sections; L(straight) / circumference ~ 1/3
- NEUTRINO FACTORIES: muons decaying in the straight section of a storage ring create a neutrino beam with unique properties for precision neutrino oscillation measurements.



HIGH-INTENSITY MUON SOURCE

- Proton Source
  - Beam power ≥ 4MW
  - E ≥ few GeV
  - Short bunches (≤ 3ns)
- Target, capture & decay
  - Create $\pi^{\pm}$, decay into $\mu^{\pm}$
- Bunching & Phase Rotation
  - Capture into bunches
  - Reduce ΔE
- Cooling
  - Use Ionization Cooling to reduce transverse emittance to fit within an accelerator



Beam Properties - 1

- Neutrino Factories produce n beams by storing muons in a ring with long straight sections → O(10^{21}) muon decays/year

- Muon decays produce a beam consisting of 50% $\nu_e(\bar{\nu}_e)$ & 50% $\bar{\nu}_\mu(\nu_\mu)$

$$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu \Rightarrow 50\% \nu_e + 50\% \overline{\nu}_\mu$$

$$\mu^- \to e^- \overline{\nu}_e \nu_\mu \Rightarrow 50\% \overline{\nu}_e + 50\% \nu_\mu$$

- Advantages c.f. conventional neutrino beams:

- well known beam flux & spectra (low systematic uncertainties)
- can search for $\nu_e \to \nu_\mu$ oscillations with very low backgrounds (wrong-sign muon signature)
- can measure spectra for events tagged by right-sign muons, wrong-sign muons, electrons, τ^+, τ^-, or no leptons; and do all this when there are positive muons stored and when there are negative muons stored → a wealth of information.

Beam Properties - 2

Consider an ensemble of negatively charged muons. In the muon rest-frame:

$$\nu_\mu: \quad \frac{d^2N}{dx\ d\Omega_{cm}} \propto \frac{2x^2}{4\pi}\left[(3-2x) + (1-2x) P \cos\theta_{cm} \right]$$

$$\bar{\nu}_e: \quad \frac{d^2N}{dx\ d\Omega_{cm}} \propto \frac{12x^2}{4\pi}\left[(1-x) + (1-x) P \cos\theta_{cm} \right]$$

For μ^+ decays $P \rightarrow -P$

$x = 2E_\nu/m_\mu$, θ is angle between the neutrino & muon spin, P is muon polarization.

In the lab frame & forward direction ($\cos\theta_{lab} \sim 1$), $E_\nu = xE_{max} = x\,\gamma(1+\beta\cos\theta_{cm})\,m_\mu/2$,

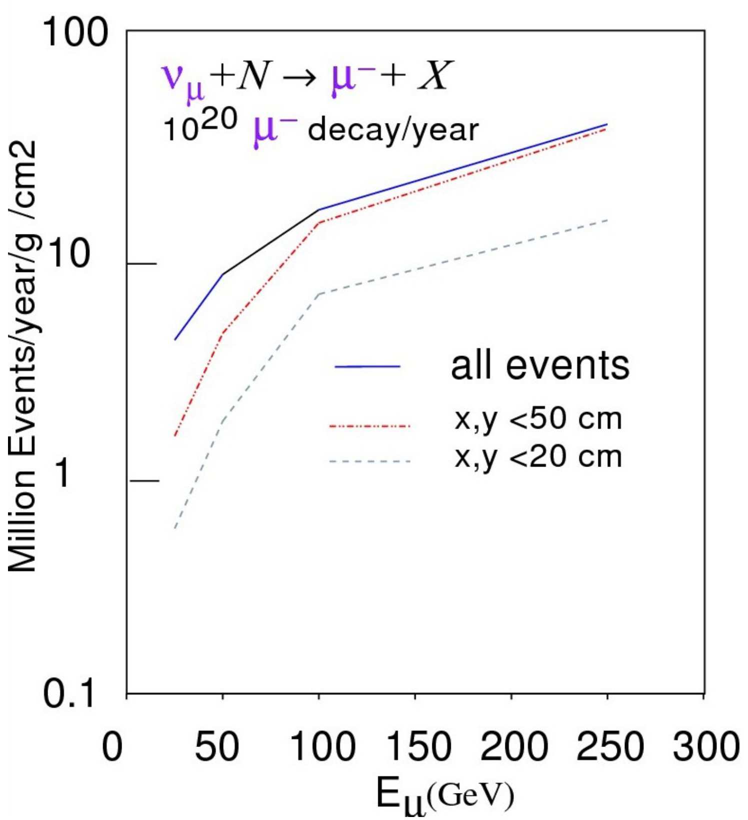
$$\nu_\mu: \quad \frac{d^2N}{dx\ d\Omega_{lab}} \propto \frac{1}{\gamma^2(1-\beta\cos\theta_{lab})^2}\ \frac{2x^2}{4\pi}\left[(3-2x) + (1-2x) P \cos\theta_{cm} \right]$$

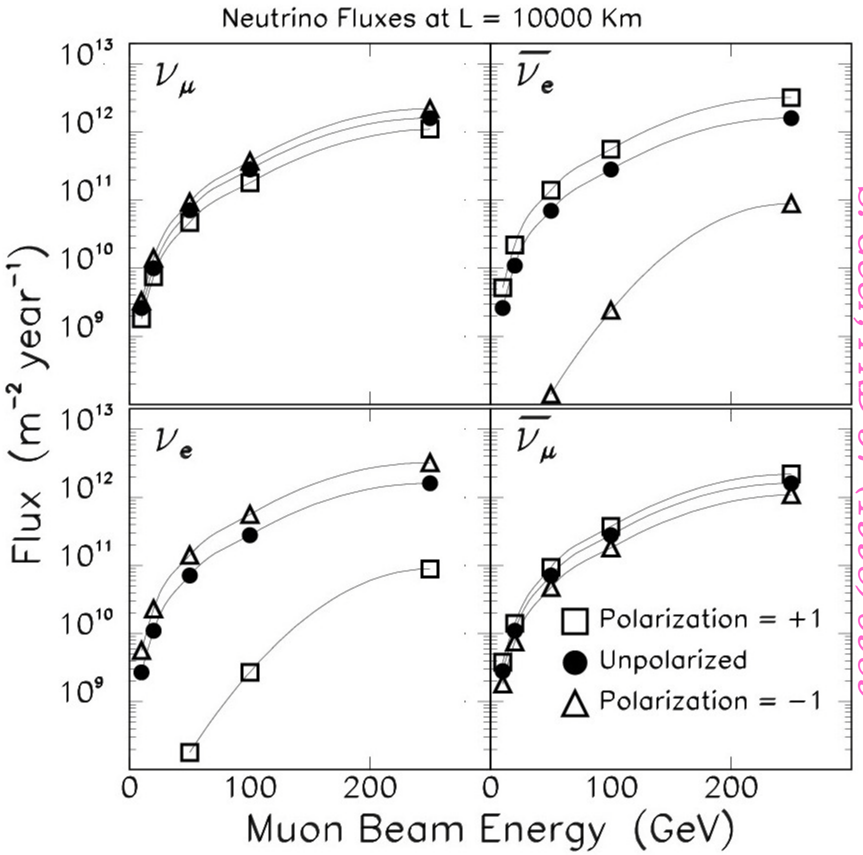
$$\bar{\nu}_e: \quad \frac{d^2N}{dx\ d\Omega_{lab}} \propto \frac{1}{\gamma^2(1-\beta\cos\theta_{lab})^2}\ \frac{12x^2}{4\pi}\left[(1-x) + (1-x) P \cos\theta_{cm} \right]$$

Note that polarization can, in principle, be used to switch on/off the ν_e ($\bar{\nu}_e$) flux.

Beam Properties - 3

The neutrino flux provided by a Neutrino Factory is sufficient to produce millions of events/g in a near detector, and thousands of events/yr in a few kt detector on the other side of the Earth.





S. Geer, PRD 57 (1998) 6989

Key Experimental Signature

- The primary motivation for interest in neutrino factories is that they provide electron neutrinos (antineutrinos) in addition to muon anti-neutrinos (neutrinos). This enables a sensitive search for $\nu_e \rightarrow \nu_\mu$ oscillations.

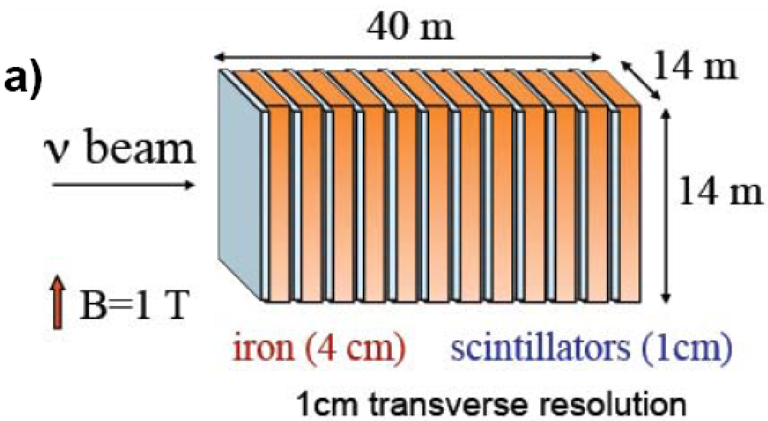
$$\mu^+ \rightarrow e^+ \, \nu_e \, \bar{\nu}_\mu \qquad \bar{\nu}_\mu \xrightarrow{\text{CC}} \mu^+$$

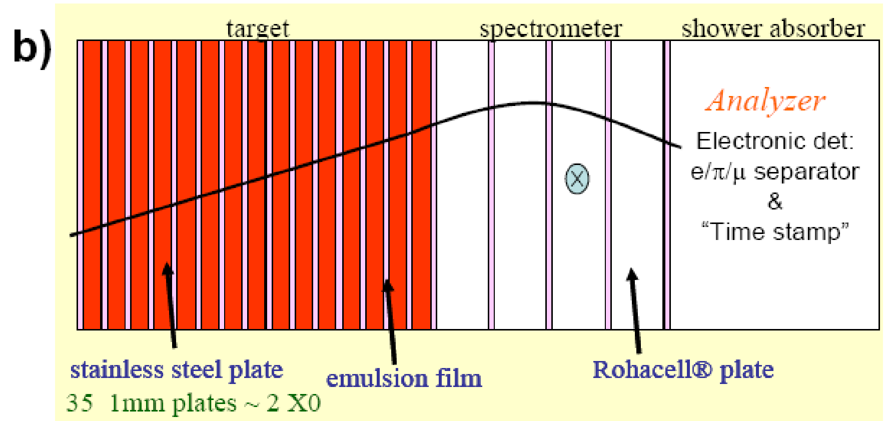
$$\nu_e \downarrow \qquad \nu_\mu \xrightarrow[\text{CC}]{} \mu^-$$

$\nu_e \rightarrow \nu_\mu$ oscillations at a neutrino factory result in appearance of a "wrong-sign" muon … one with opposite charge to those stored in the ring:

- Backgrounds to the detection of a wrong-sign muon are expected to be at the 10^{-4} level $\longrightarrow$ background-free $\nu_e \rightarrow \nu_\mu$ oscillations with probabilities of $O(10^{-4})$ can be measured !

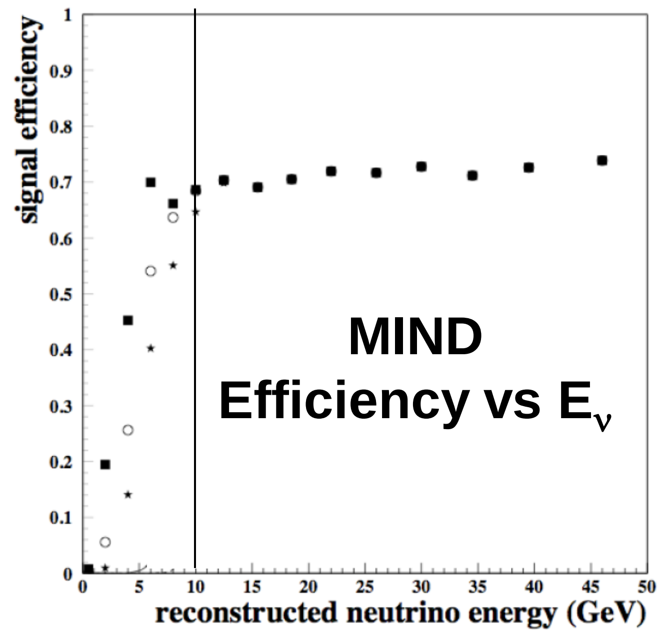
"High Energy" Neutrino Factory Detector





- *Magnetised Iron Neutrino Detector* (MIND) at each location, M=50KT. Efficiency good for CC neutrino interactions with $E_\nu \gtrsim$ ~10 GeV

- *Magnetised Emulsion Cloud Chamber* at intermediate baseline for tau detection



Sensitivity Comparison

Based to arXiv:1005.3146, the EuroNu midterm physics report

WBB: Fermilab to Dusel, 1 MW for ν running, proton energy: 120 GeV, 2 MW for $\overline{\nu}$ running (5+5 yr), 100 kton liquid argon detector, according to Barger et al, Phys. Rev. D76:053005, 2007 (hep-ph/0703029). This setup is different from the proposed LBNE experiment.

T2KK: J-Parc ν beam running at 4 MW. 270 kton WC detector at Kamioka (295 km) and 270 kton WC detector in Korea (1050 km), Barger et al, Phys. Rev. D76:053005, 2007 (hep-ph/0703029).

PS2-Slanic CERN-PS2 SuperBeam fired to 100 kton LAr detector at Slanic, as computed by A. Rubbia, arXiv:1003.1921.

SPL: Neutrino beam from CERN-SPL running at 3.5 GeV, 4 MW. 440 kton WC detector at Frejus (130 km). Campagne et al. JHEP **0704** (2007) 003 (hep-ph/0603172).

Beta Beam $\gamma = 100$ Eurisol Beta Beam to Frejus (440 kton WC detector). Campagne et al. JHEP **0704** (2007) 003 (hep-ph/0603172).

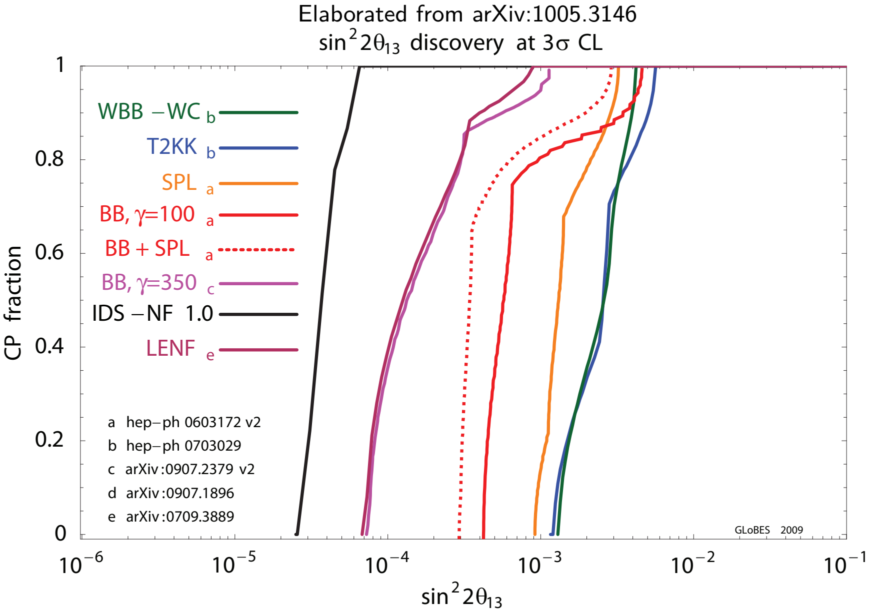
Beta Beam + SPL The combination of the above two.

Beta Beam $\gamma = 350$ Beta Beam at $\gamma = 350$, running $^{6}\mathrm{He}$ and $^{18}\mathrm{Ne}$ at the same decay rates as the Eurosol Beta Beam. WC detector of 500 kton at Canfranc (650 km). S. Choubey et al., JHEP 0912:020,2009 (arXiv:0907.2379)

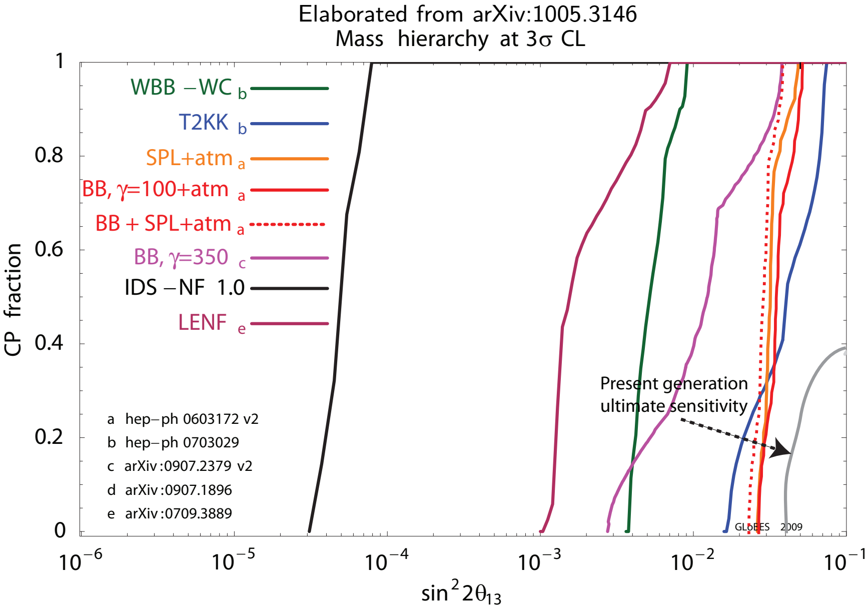
Low Energy Neutrino Factory (LENF) Neutrino Factory running at 4.12 GeV delivering 10^{21} muon decays/year for each sign, 30 kton Noνa like detector, fully magnetized (!) at 1480 km (Fermilab-Henderson mine). A. Bross et al, Phys.Rev.D77:093012,2008. (arXiv:0709.3889)

IDS 1.0 Neutrino Factory 25 GeV neutrino factory delivering $0.5 \cdot 10^{21}$ muon decays/year for each sign, a 50 kton iron magnetized detector and a 10 kton Emulsion Cloud Chamber, at 4000 km and a 50 kton iron magnetized detector at 7500 km.

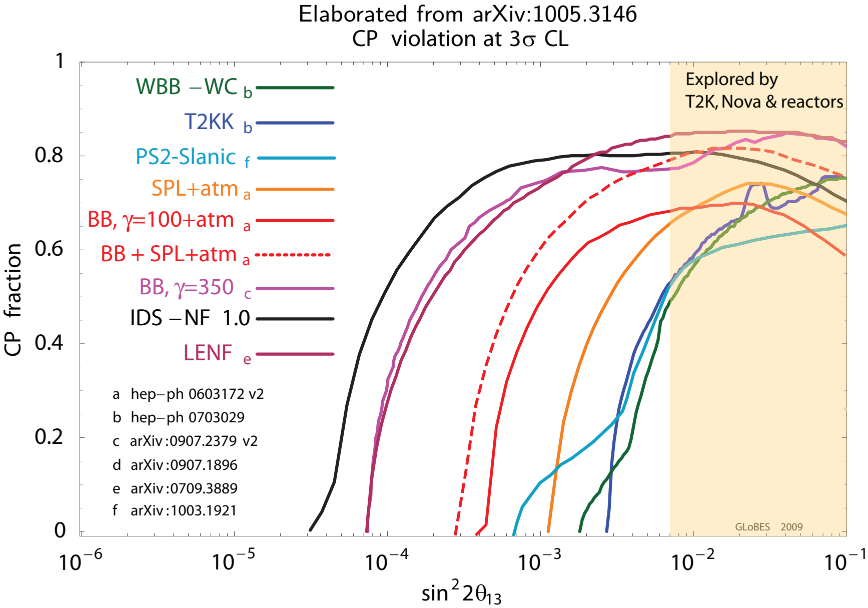
Sensitivity Comparison: θ_{13}



Sensitivity Comparison: $\mathrm{sign}(\Delta m^2_{23})$



Sensitivity Comparison: LCPV



Additional Slides

Solution

The scaling law for Q (constant γ) is:
- Q for neutrino cross-section
- $1/Q^2$ for $1/L^2$ distance factor for L/E = constant

hence, $\propto Q \times 1/Q^2 = 1/Q$

So, at a fixed gamma, a beam with isotope with say Q=10 MeV must have 3 times higher flux than a Q=3 MeV isotope to have comparable performance at a far detector located at 1st oscillation maximum.

The scaling law for γ (same ion, same decay rates) is:
- $\propto \gamma^2$ for neutrino flux at far detector
- $\propto \gamma$ for neutrino cross-section
- $\propto 1/\gamma^2$ L=distance, keeping L/E = constant

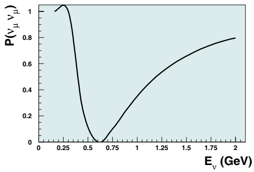
hence, $\propto \gamma^2 \times \gamma \times 1/\gamma^2 = \gamma$

So the merit factor of a Beta Beam can be defined as

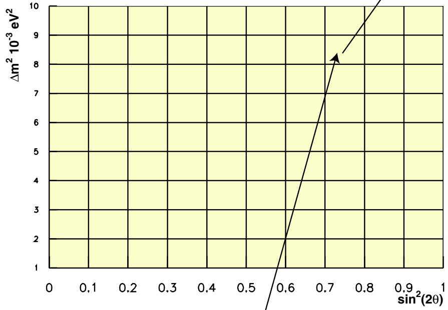
$$\mathcal{M} = \frac{\gamma}{Q}$$

How to build the signal/exclusion plot

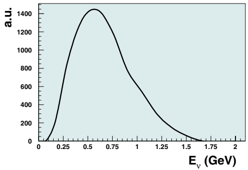
Every $\sin^2 2\theta$, Δm^2 cell defines $P_{\nu_\mu \nu_\mu}$



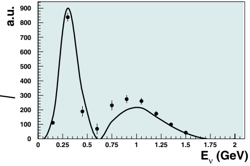
Grid in the $\sin^2 2\theta, \Delta m^2$ **plane**



That modulates the non-oscillated predicted spectrum



The prediction is compared to the data



Fill the grid with the χ^2

How to build the signal/exclusion plot (II)

- The minimum of the χ^2 distribution is the best fit
- The region at a given confidence level (CL) is defined by the contour at a given $\Delta\chi^2$ from the minimum.
- The CL is computed from the probability distribution of a χ^2 at two degrees of freedom $(\sin^2 2\theta, \Delta m^2)$

Question: Why $\Delta\chi^2$ and not χ^2?
Hint: Why two degrees of freedom?

A more formal approach in G.Feldman and R.Cousins, Phys.Rev.D57:3873-3889,1998