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" Experimental perspectives of neutrino oscillation physics"

- Today and near future
  - θ_{13} at the accelerators
  - θ_{13} at the reactors
- Next: leptonic CP violation and mass hierarchy
  - Super Beams
  - Beta Beams
  - Neutrino Factories

Neutrino Mixing Matrix (PMNS)

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 !**

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

$\theta_{13} \rightarrow 0 \quad \Rightarrow$ 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.

Shopping list for future experiments

δm^2_{12} ✓ SOLARS+KAMLAND δm^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} 23 ✓ ATMOSPHERICS δm^2 = (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 ✓?

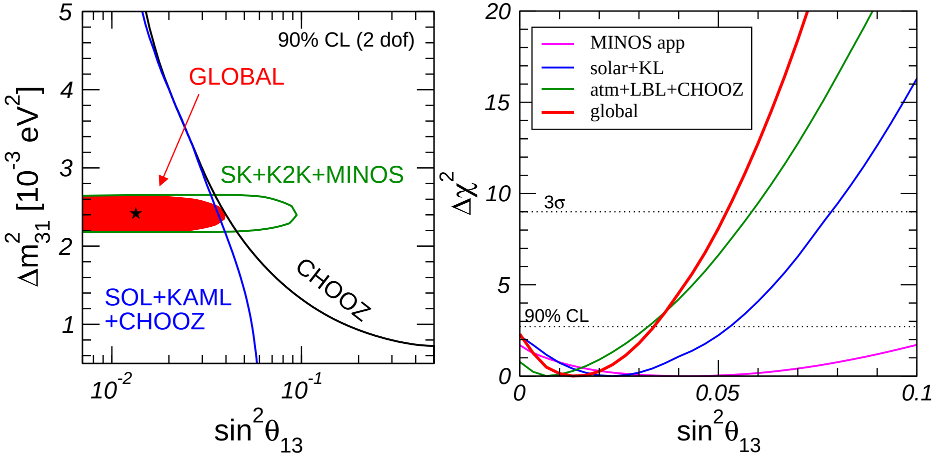
δ_{CP} ☐

Mass hierarchy ☐

Σm_ν ☐ BETA DECAY END POINT Σm_ν < 6.6 eV

Dirac/Majorana ☐

Status of θ_{13}



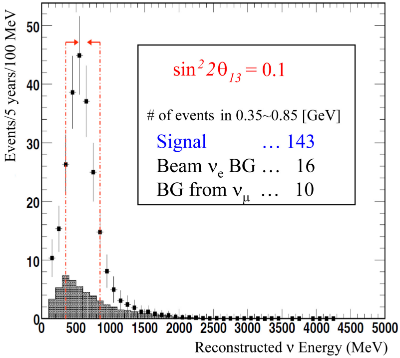
$$\begin{aligned} \sin^2\theta_{13} &\leq 0.034 \quad (0.053) \\ \sin^2 2\theta_{13} &\leq 0.13 \quad (0.20) \qquad 90\%\ (3\sigma)\ \text{CL}\,. \\ \theta_{13} &\leq 10.6^\circ \quad (13.3^\circ) \end{aligned}$$

θ_{13} at Reactors

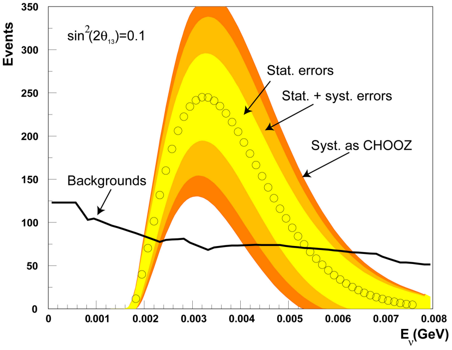
$$1 - P_{\bar{\nu}_e\bar{\nu}_e} \simeq \sin^2 2\theta_{13}\, \sin^2(\Delta m^2_{31} L/4E) + (\Delta m^2_{21}/\Delta m^2_{31})^2)\,(\Delta m^2_{31} L/4E)^2 \cos^4\theta_{13}\, \sin^2 2\theta_{12}$$

- Direct connection with θ_{13} , no interference with $\delta_{\rm CP}$ and $\mathrm{sign}(\Delta m^2_{23})$.
- No way to directly measure leptonic CP violation and mass hierarchy.
- Truly complementary to the accelerator experiments.
- Disappearance experiments: systematic errors dominate over statistics.

T2K appearance signal in 5 years



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



Reactor Experiments

CHOOZ Result

$$R = 1.01 \pm 2.8\%(\mathrm{stat}) \pm 2.7\%(\mathrm{syst})\,.$$

Goal:

- Improve by at least a factor 5 the statistical error (25 times more neutrinos):
  - bigger detectors than CHOOZ (fiducial: 5 ton)
  - more stable in time (CHOOZ took data for 8761.7 h, then it had to stop because of strong deterioration of the liquid scintillator, due to the diluted gadolinium).
- Improve by at lease a factor 5 systematic errors:
  - Add a close detector
  - Design of the detector such to reduce backgrounds and systematics associated to the definition of the fiducial volume.

Neutrinos from nuclear reactors

Nuclear reactors are a very intense source of $\overline{\nu}_e$ from β decays of the fission fragments.

Every fission reaction emits about 200 MeV of energy and 6 $\overline{\nu}_e$.

$$\Downarrow$$

Flux $\sim 2 \cdot 10^{20}\ \overline{\nu}_e\ s^{-1}\ \mathrm{GWatt}^{-1}$, isotropic, $\langle E(\overline{\nu}_e)\rangle \simeq 0.5\, MeV$.

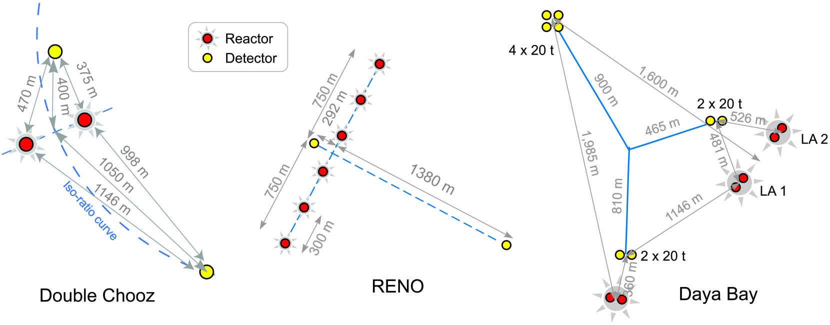
Oscillation experiments look for $\overline{\nu}_e$ disappearance at different baselines:

- $L = \mathcal{O}(1\mathrm{km}) \quad \Rightarrow$ atmospheric regime: Double Chooz, RENO, Daya Bay.
- $L = \mathcal{O}(150\mathrm{km}) \quad \Rightarrow$ solar regime: Kamland

The three players

From M.M. and T. Schwetz, arXiv:1003.5800

Setup	$P_{\rm Th}$ [GW]	L [m]	$m_{\rm Det}$ [t]	Events/year	Bck/day	Start
Daya Bay	17.4	1700	80	$10 \cdot 10^4$	0.4	12/2011
Double Chooz	8.6	1050	8.3	$1.5 \cdot 10^4$	3.6	6/2010
RENO	16.4	1400	15.4	$3 \cdot 10^4$	2.6	12/2010



Double Chooz

2 cores – 1 site – 8.5 GW_{th}

1 near position, 1 far

- target: 2 x 8.3 t

Civil engineering

- 1 near lab ~ Depth 40 m, Ø 6 m
- 1 available lab

Statistics (including ε)

- far: ~ 40 evts/day
- near: ~ 460 evts/day

Systematics

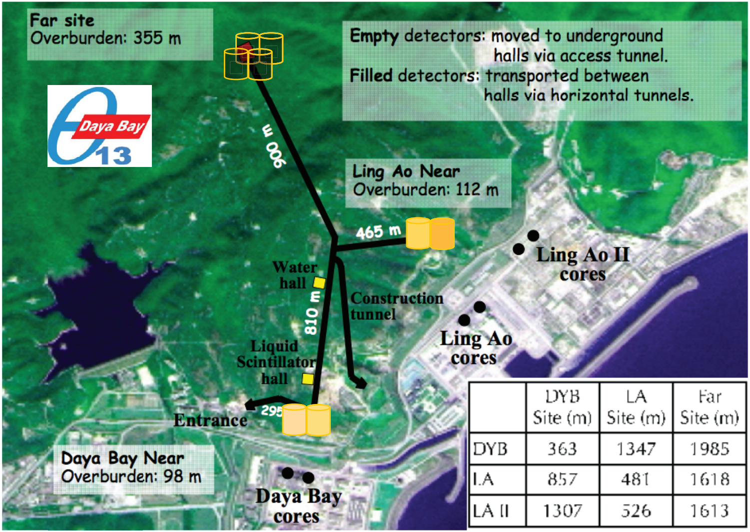
- reactor : ~ 0.2%
- detector : ~ 0.5%

Backgrounds

- σ_{b2b} at far site: ~ 1%
- σ_{b2b} at near site: ~ 0.5%

Planning

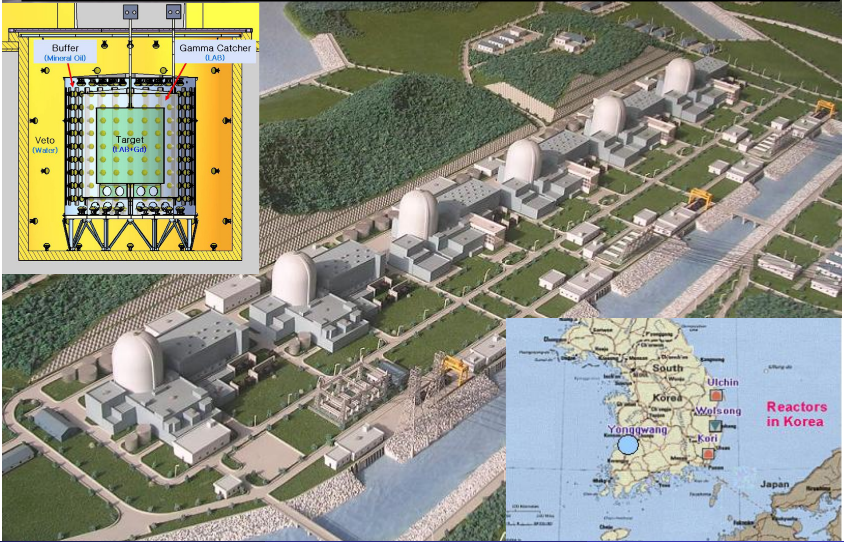
1. Far detector only
   - Sensitivity (1.5 ans) ~ 0.06
2. Far + Near sites
   - available from 2010
   - Sensitivity (3 years) ~ 0.025



	DYB Site (m)	LA Site (m)	Far Site (m)
DYB	363	1347	1985
LA	857	481	1618
LA II	1307	526	1613

RENO

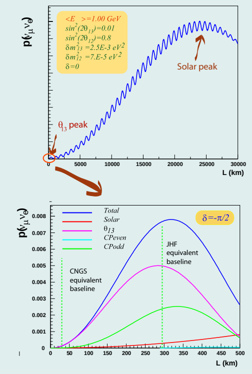
	Location	Thermal Power	Distances Near/Far (m)	Depth (mwe)	Target Mass (tons)	Cost
RENO	Korea	17.3 GW	290/1380	120/450	16/16 ton	~10M$



Reactors systematic business

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

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



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

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

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

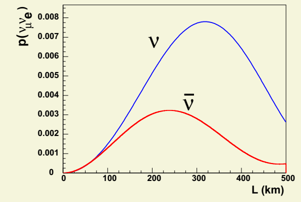
$$+ 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta\} \sin \frac{\Delta m_{12}^2 L}{4E} \qquad \text{solar driven}$$

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

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

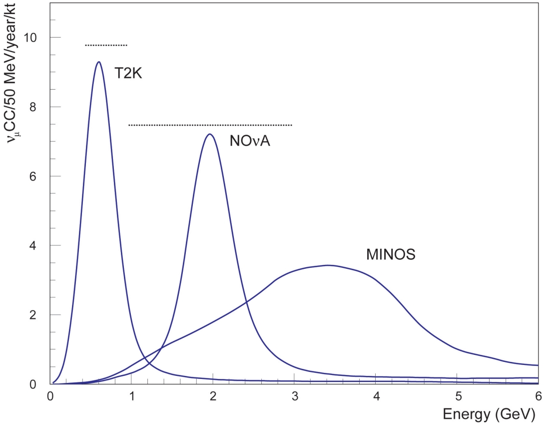
Leptonic CP discovery requires

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



The two players

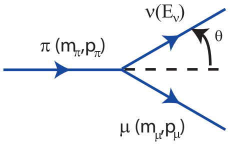
- **T2K** Started 12/2009, at J-Parc, Japan. No result yet.
- **NOνA** scheduled to start in 2013



Horizontal lines: regions where $P(\nu_\mu \to \nu_e) \geq 0.5$

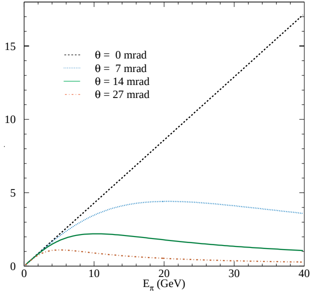
Off Axis Neutrino Beams.

Decay Kinematics

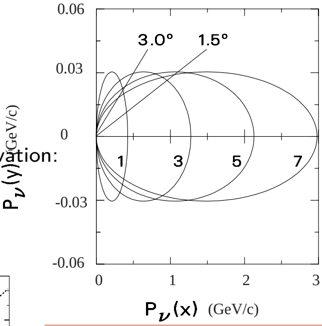


From momentum energy conservation:

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



A qualitative argument:

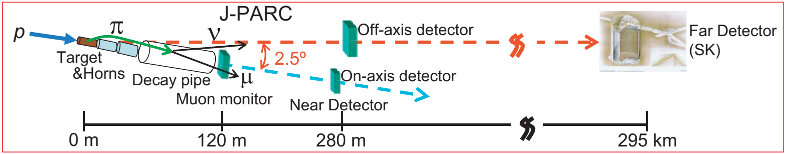


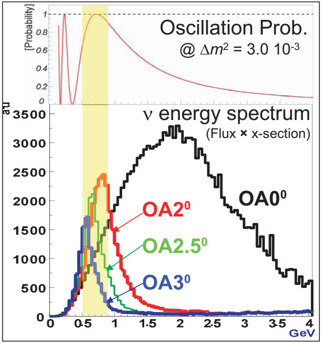
- Transverse momentum, Lorentz invariant: $m_\pi - m_\mu$.
- Longitudinal momentum is Lorentz boosted.
- At an angle θ there is an accumulation of lower energies neutrinos

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

The T2K Experiment

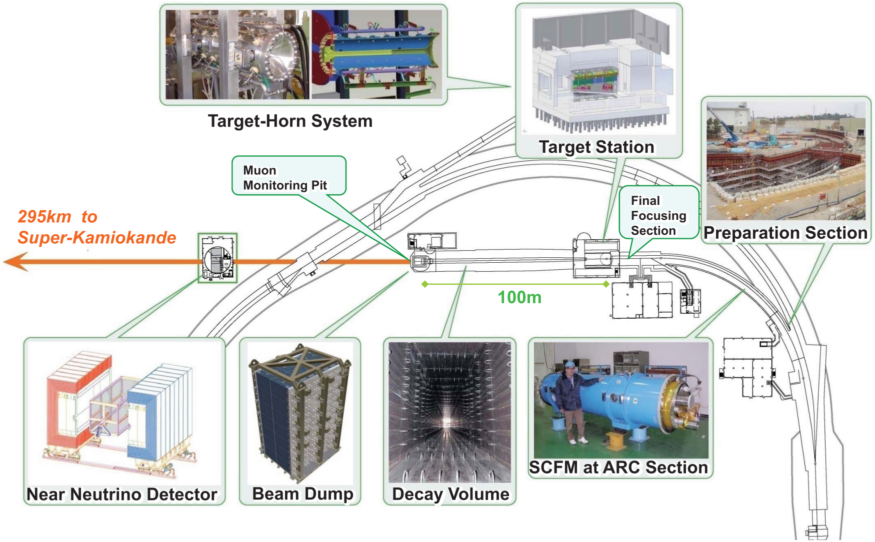
Experimental apparatus and neutrino beam



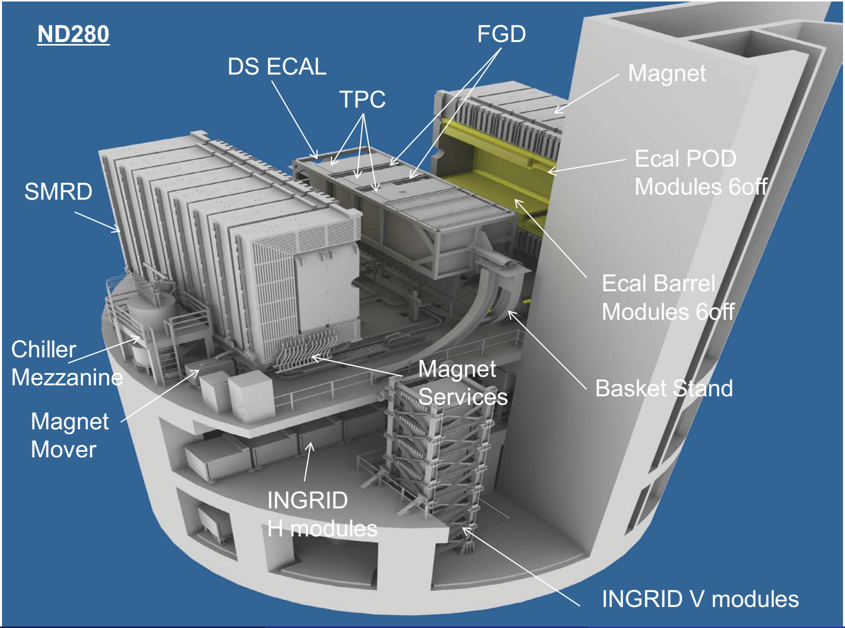


- Off-axis beam technique
  - Intense narrow band beam
- 2.5° off-axis
  - Energy peak tuned at oscillation max. ~ 0.7 GeV
- Statistics at Super-K
  - ~1600 ν_μ CC int./22.5kt/year (with 0.75kW beam, no oscillation case)
- Pure ν_μ beam
  - Beam ν_e contamination ~0.4% at ν_μ peak energy

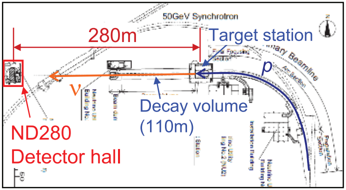
T2K experiment: the neutrino beam line

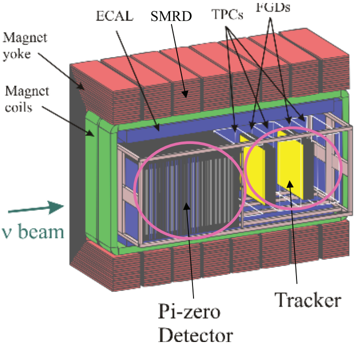


The Close Detector Station



The Close Detector ND280



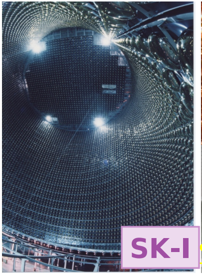


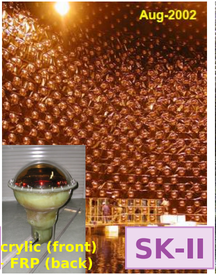
- Near off-axis detector located at 280 m downstream of the target
- Consists of 5 subdetectors:
  - Pi-zero detector (PØD)
    - measures $NC\pi^0$ interactions
  - Tracker: fine-grained detector (FGD) and time projection chambers (TPC)
    - measures CC interactions
  - Electromagnetic calorimeter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

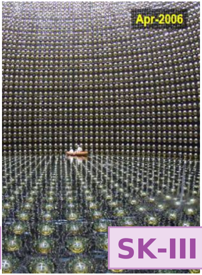
History of Super-Kamiokande detector

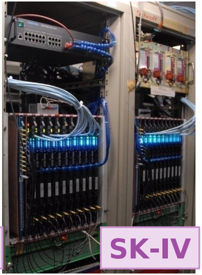
1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009

SK-I **SK-II** **SK-III** **SK-IV**



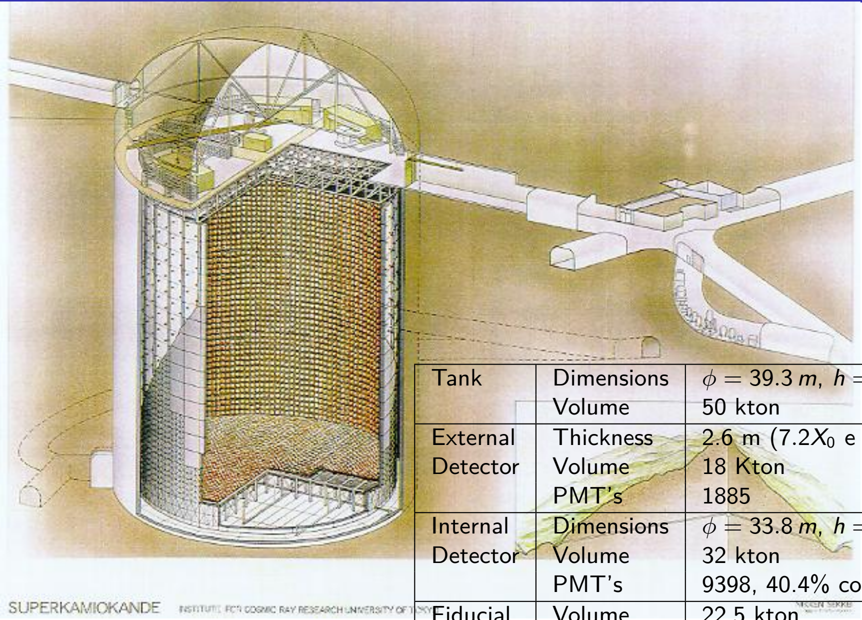






SK-I	SK-II	SK-III	SK-IV
11146 ID PMTs (40% coverage)	5182 ID PMTs (19% coverage)	11129 ID PMTs (40% coverage)	Electronics Upgrade
Energy Threshold (total electron **5.0 MeV**	**7.0 MeV**	**4.5 MeV** work in progress	**< 4.0 MeV** target

SuperKamiokande detector

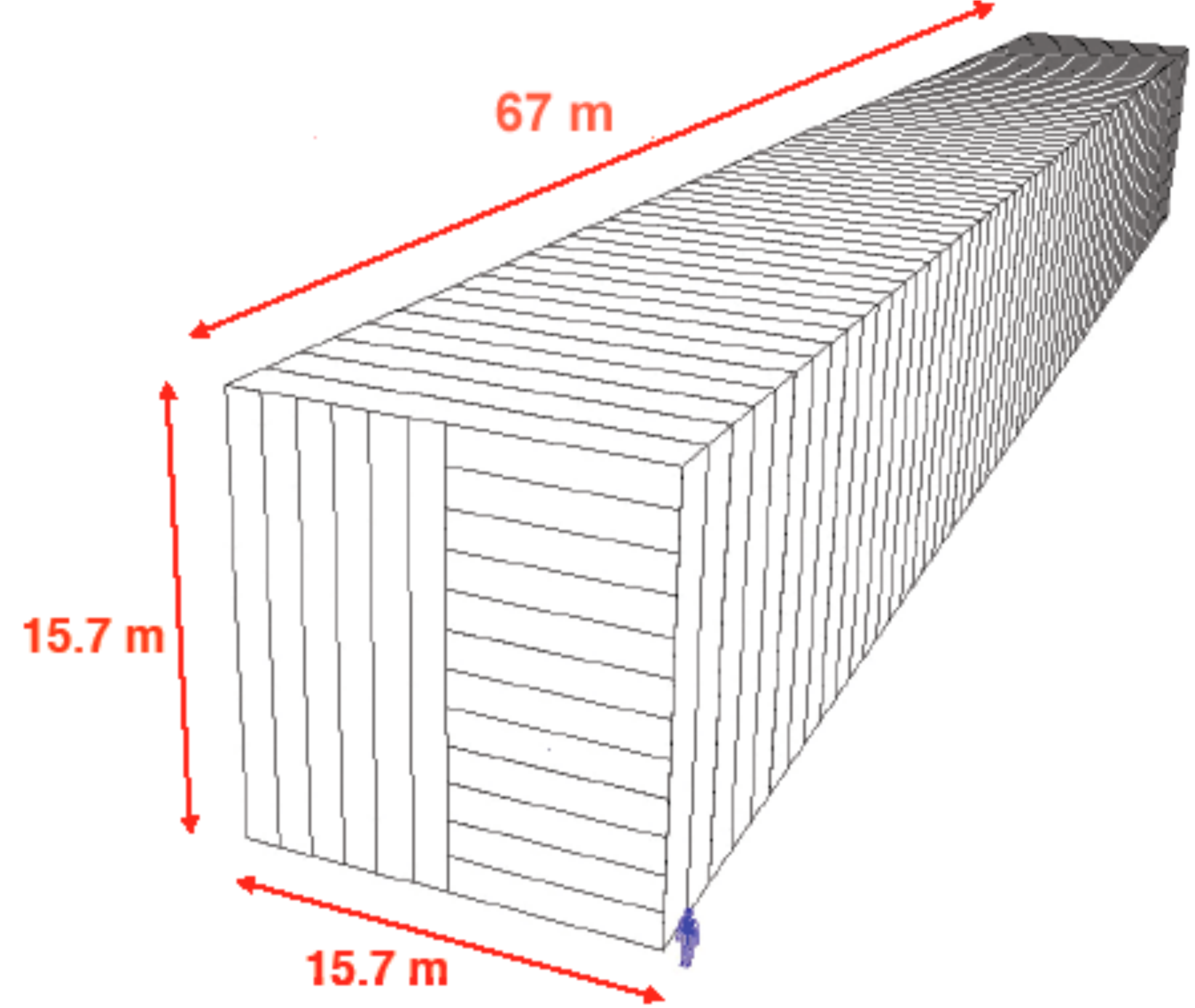


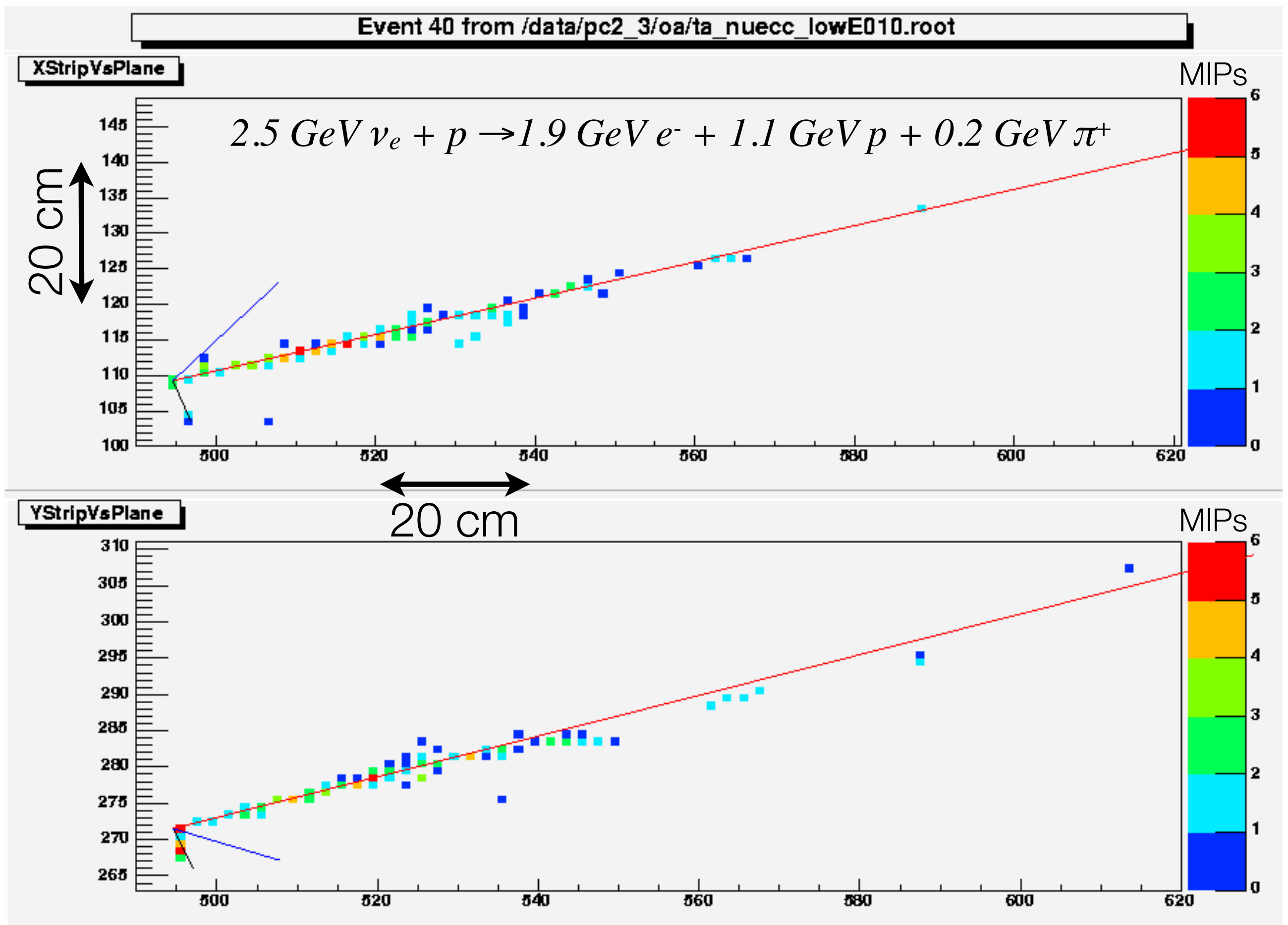
Tank	Dimensions	$\phi = 39.3\,m,\ h = 41.4\,m$
	Volume	50 kton
External Detector	Thickness	2.6 m ($7.2X_0$ e $4.3\lambda_0$)
	Volume	18 Kton
	PMT's	1885
Internal Detector	Dimensions	$\phi = 33.8\,m,\ h = 36.2\,m$
	Volume	32 kton
	PMT's	9398, 40.4% coverage
Fiducial	Volume	22.5 kton

The NOvA Experiment

28 Institutions 180 scientists and engineers

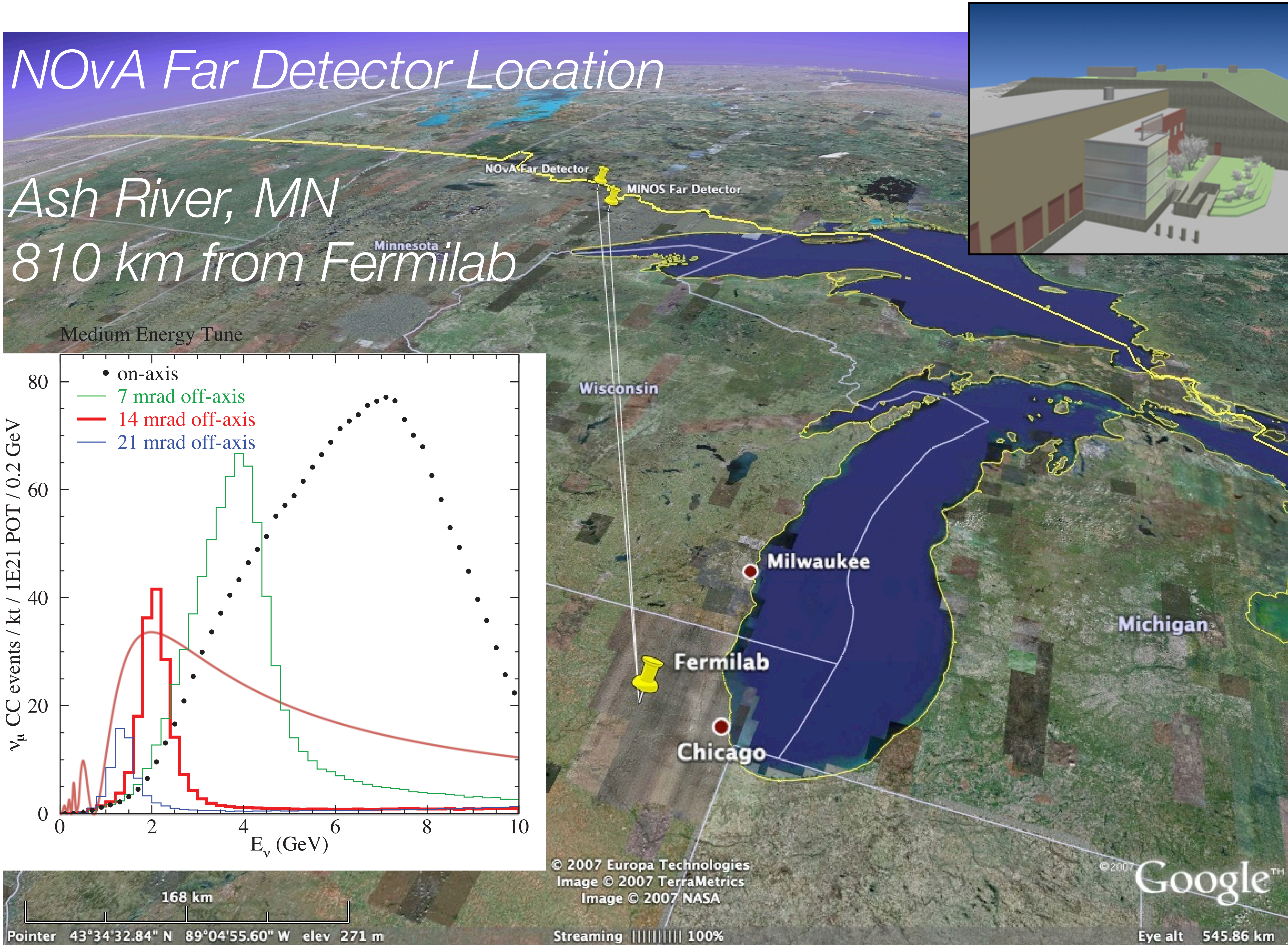
- NOvA is a second generation experiment on the NuMI beamline which is optimized for the detection of $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations
- NOvA is:
  - An upgrade of the NuMI beam intensity from 400 kW to 700 kW
  - A 15 kt “totally active” tracking liquid scintillator calorimeter sited 14 mrad off the NuMI beam axis at a distance of 810 km
  - A 215 ton near detector identical to the far detector sited 14 mrad off the NuMI beam axis at a distance of 1 km

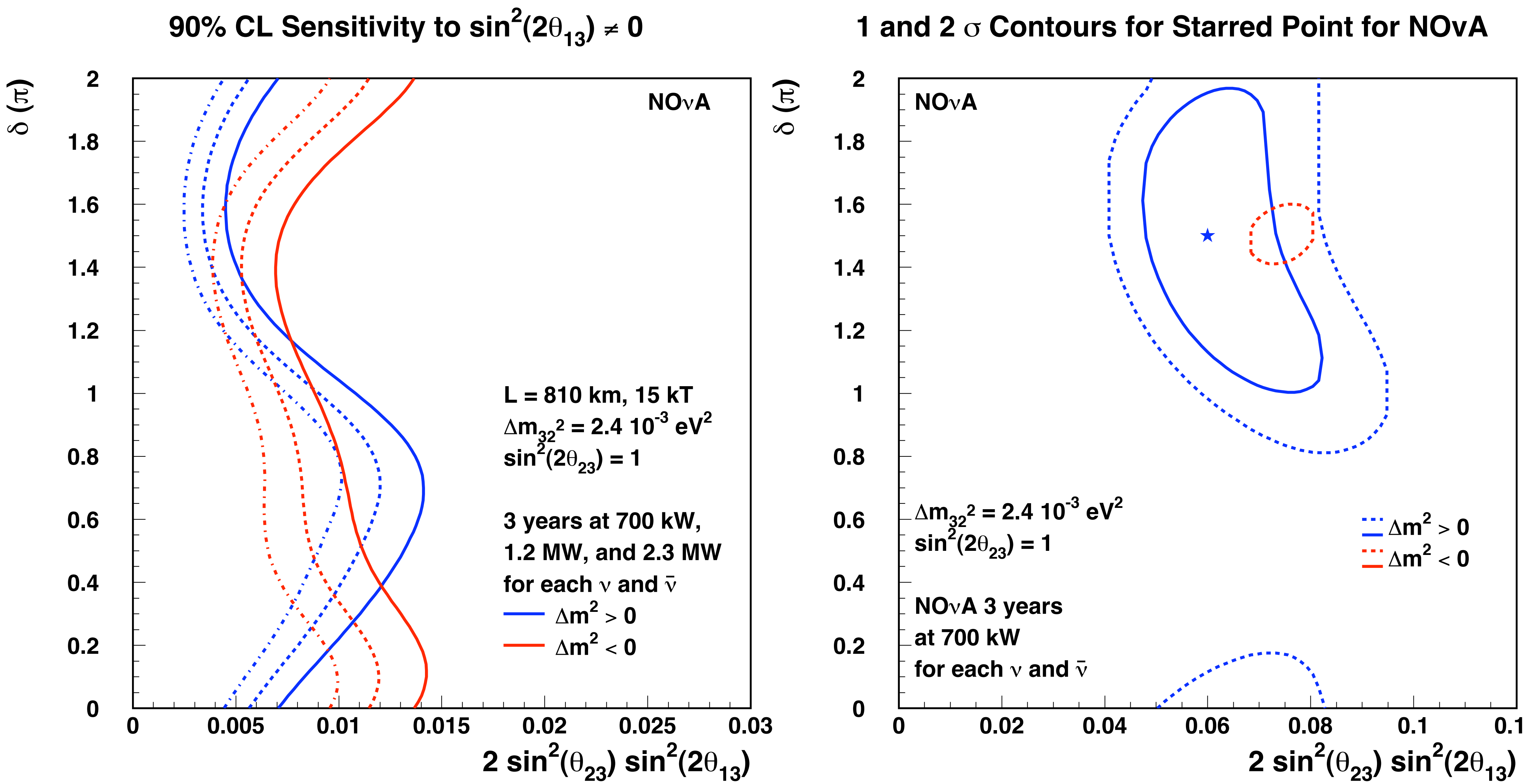




NOvA Far Detector Location

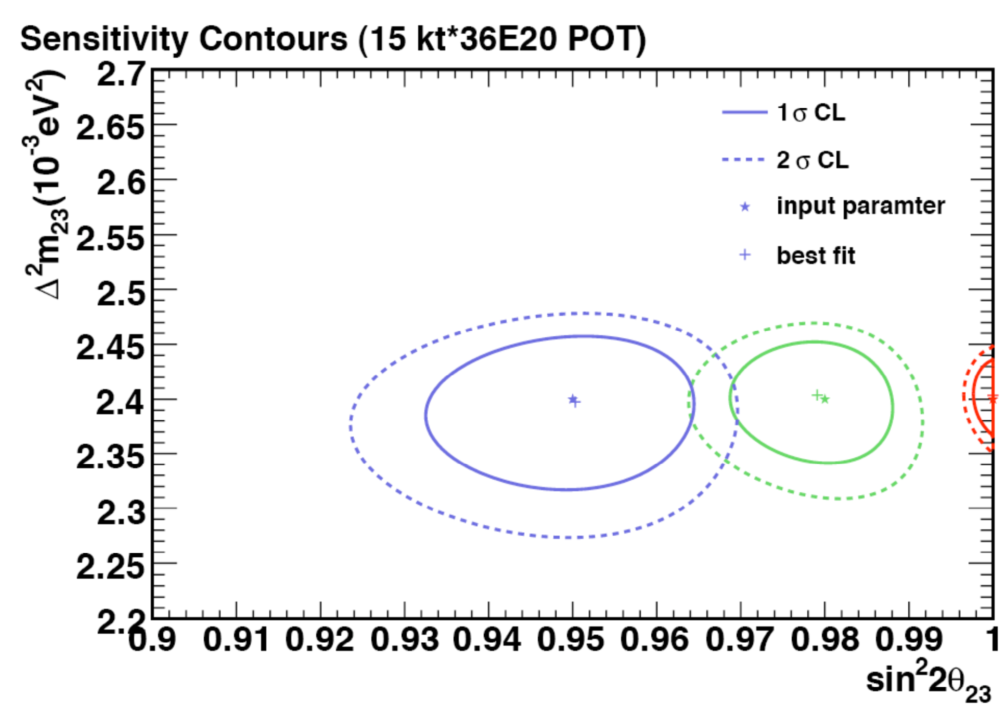
Ash River, MN
810 km from Fermilab





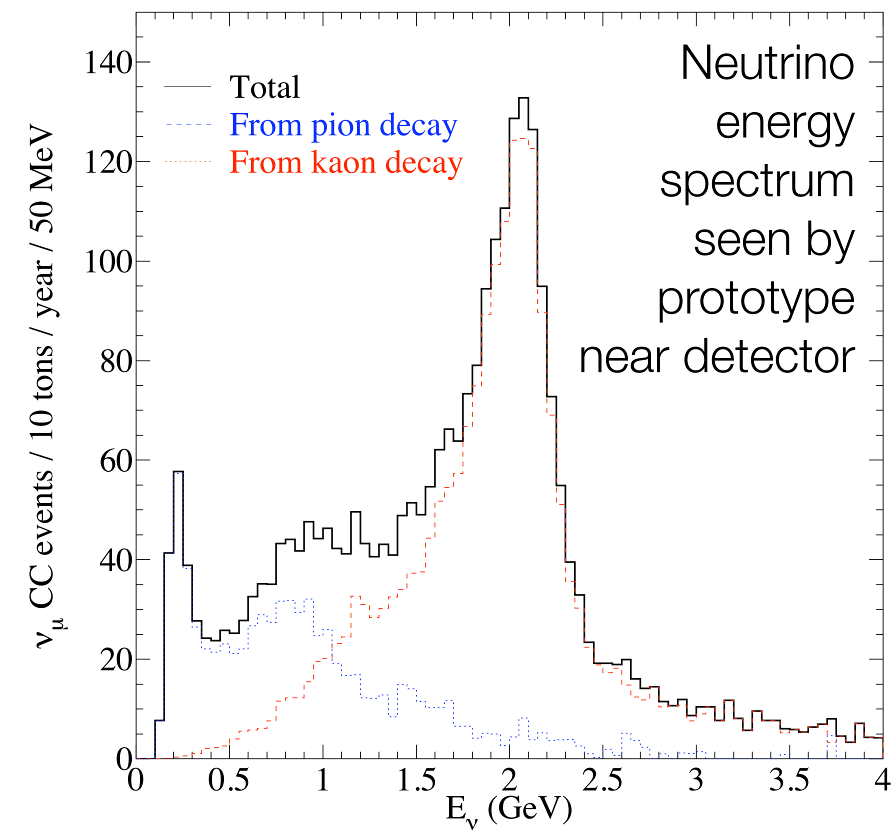
NOvA plans to run 3 years in neutrino mode, 3 years in anti-neutrino mode operating NuMI at 700 kW.

- NOvA will search for ν_μ - ν_e oscillations down to 1% oscillation probability at 90% CL
- Of the next generation NOvA uniquely provides data on the neutrino mass hierarchy and CP violating phase delta.
- Using quasi-elastic channel, NOvA will make ~1% measurements of ν_μ - ν_τ oscillations

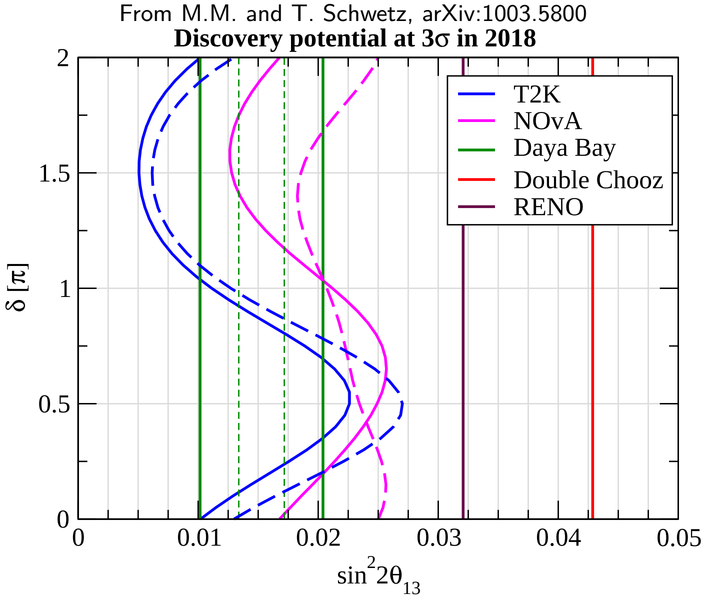


NOvA Status

- NOvA has passed Department of Energy CD2 and 3a reviews and is ready to start construction. Progress slowed by lack of FY08 funding, but NOvA construction is funded in FY09 budget.
- Schedule
  - *April 2009*: Notice to proceed on construction at far detector site
  - *October 2009*: Complete Department of Energy CD3 process
  - *Spring 2010*: Begin operation of prototype near detector in NuMI beam at Fermilab.
  - *May 2011*: Far detector enclosure completed
  - *August 2012*: 2.5kt of far detector operational
  - *December 2013*: Completed far detector operational

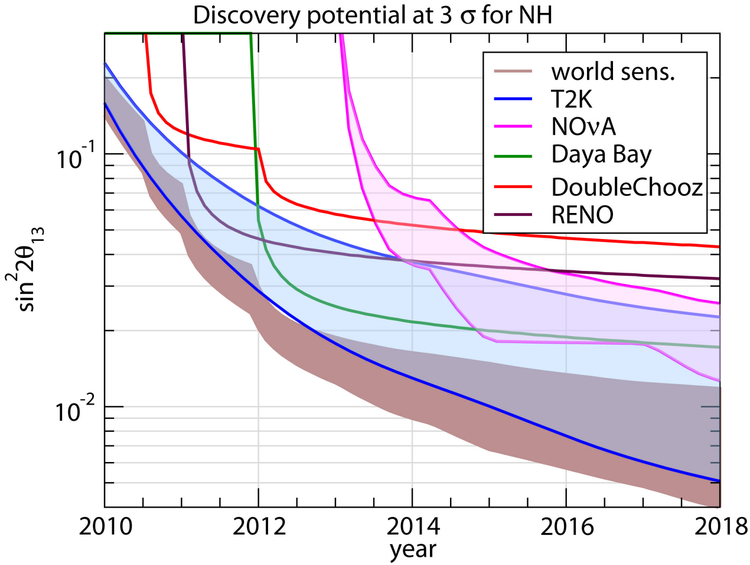


Status after this generation of LBL experiments



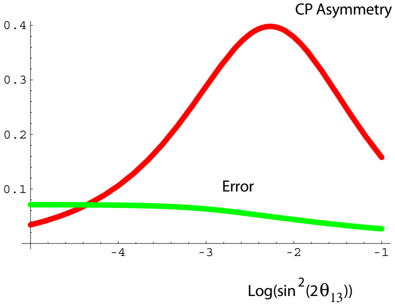
Time Evolution

From M.M. and T. Schwetz, arXiv:1003.5800



Measuring Leptonic CP violation

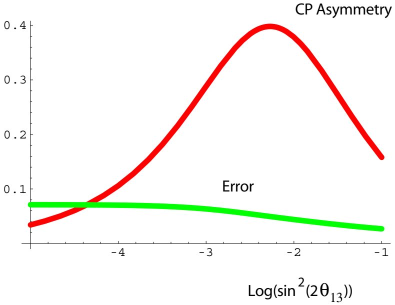
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)}$$



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.

Measuring Leptonic CP violation

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

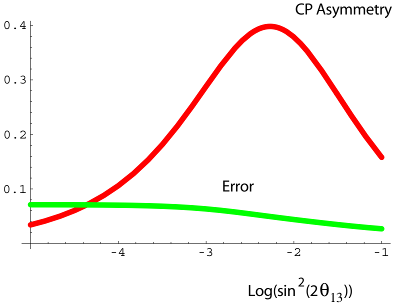


LCPV asymmetry at the first oscillation maximum, $\delta = 1$, Error curve: dependence of the statistical+systematic (2%) computed for a beta beam the fixed energy $E_\nu = 0.4$ GeV, $L = 130$ km.

- **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

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



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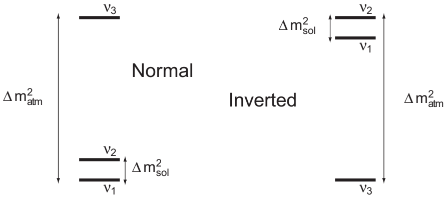
- **The detection of such asymmetry is an evidence of Leptonic CP violation only in absence of competitive processes (i.e. matter effects, see following slides) ⇒ "short" Long Baseline experiments**
- Statistics and systematics play different roles at different values of $\theta_{13} \Rightarrow$ impossible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

$$P_{\theta_{13}} = \sin^2(2\theta_{13}) \sin\theta_{23}{}^2 \sin^2((\hat{A}-1)\hat{\Delta})/(\hat{A}-1)^2;$$
$$p_{\sin\delta} = \alpha \sin(2\theta_{13})\zeta \sin\delta \sin(L\hat{\Delta}) \sin(\hat{A}\hat{\Delta}) \sin((1-\hat{A})\hat{\Delta})/((1-\hat{A})\hat{A});$$
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$\alpha = \mathrm{Abs}(\Delta m^2_{21}/\Delta m^2_{31})$; $\hat{\Delta} = \frac{L\Delta m^2_{31}}{4E}$ $\zeta = \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$
$\boldsymbol{\hat{A} = \pm a/\Delta m^2_{31}}$; $a = 7.6 \cdot 10^{-5} \rho \cdot E_\nu(GeV)$ $\rho = \text{matter density } (\mathrm{g\,cm^{-3}})$
The $\hat{A}$ term changes sign with $\mathrm{sign}(\Delta m^2_{23})$

Matter effects require long “long baselines"

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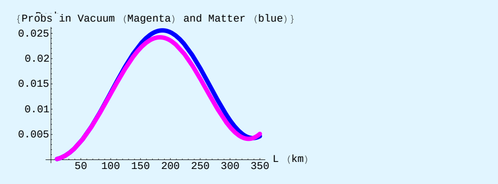

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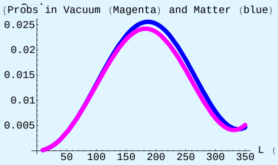

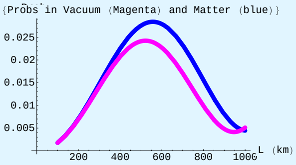

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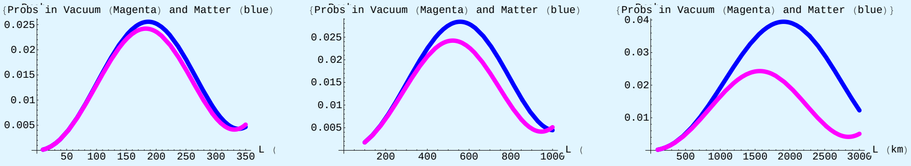
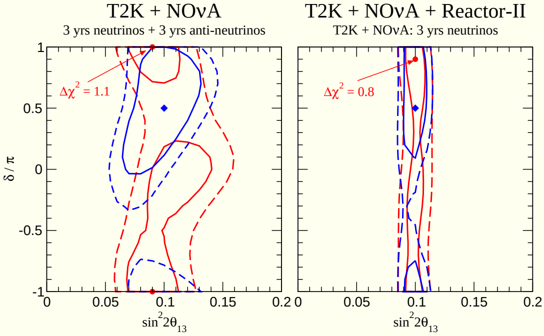
$E_\nu = 0.35\mathrm{GeV}$ $L \simeq 130$ km $E_\nu = 1\mathrm{GeV}$ $L \simeq 500$ km $E_\nu = 3\mathrm{GeV}$ $L \simeq 1500$ km



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

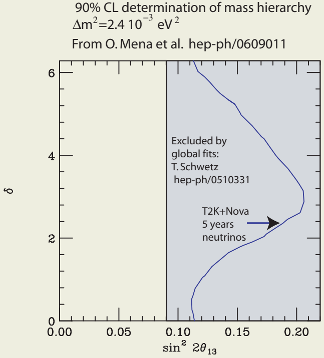
No hope to see any CP signal at 3σ

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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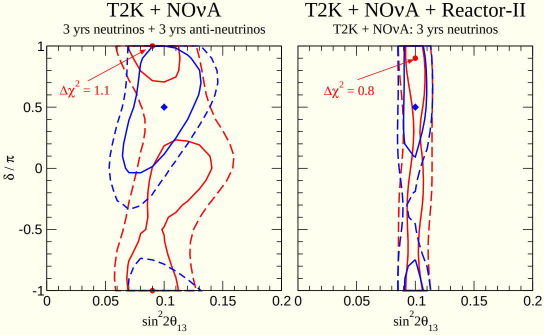

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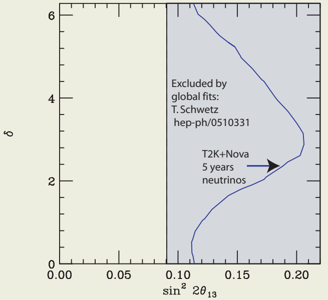


To address leptonic CP violation: improve of at least one order of magnitude the sensitivity of $\mathbf{sin^2 2\theta_{13}}$; two order of magnitudes more neutrinos !!!

The SuperBeam way

Upgrade existing or future accelerators to several MW power and build WC detectors 10 $\times$ Super Kamiokande or 300 $\times$ Icarus

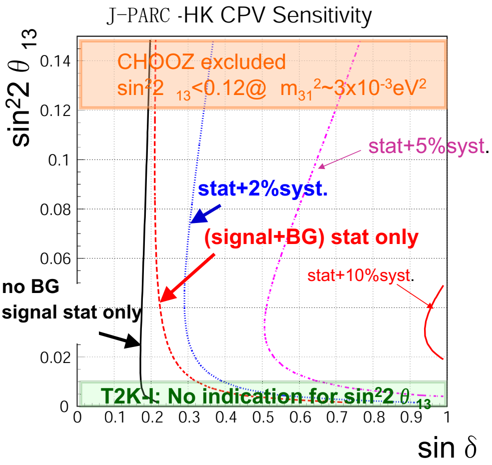
- **Japan.**
  J-Parc: 0.75 $\Rightarrow$ 2 MW + Super Kamiokande $\Rightarrow$ Hyper Kamiokande (500 kton fiducial: 20 $\times$ bigger)
- **USA.**
  FNAL: Project X to a 300 kton water Cherenkov detector (or $3-6\times$ 20kton liquid argon) at Dusel, $L \sim 1300$ km.
- **Europe**
  10$\times$CNGS $\Rightarrow$ off-axis CNGS fired on a 20-100 kton liquid argon detector
  - 4 MW SPL fired on 500 kton water Cherenkov (Memphys) at Frejus at 130 km
  - 2 MW PS2 fired on 100 kton liquid Argon (Glacier) at Slanic (RO) at 1570 km

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.

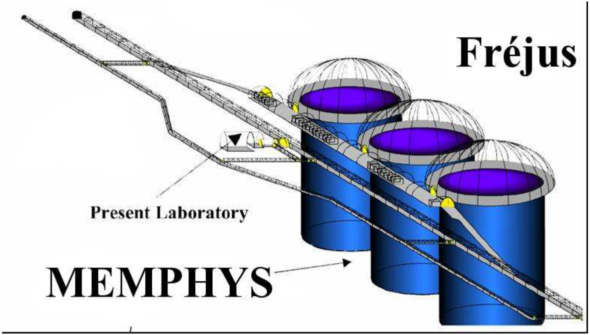
The detector would have valuable physics potential in proton decay, SN neutrinos, solar neutrinos.

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)



The Memphys detector (hep-ex/0607026)



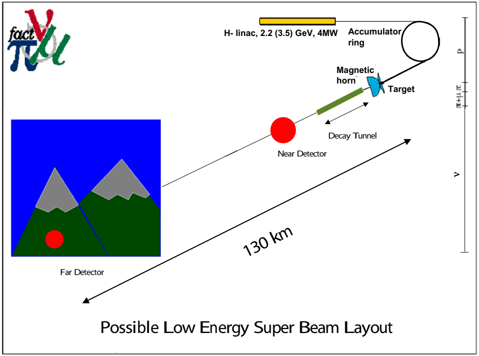
In the middle of the Frejus tunnel at a depth of 4800 m.w.e excavate three shafts of about 250,000 m^3 each ($\Phi = 65\,m$, full height=80 m). 440 kton fiducial volume

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

Physics scope, independently from the beam

- Proton decay
- Super Nova neutrinos
- Relic Super Nova neutrinos
- Solar and Atmospheric neutrinos
- Indirect searches of DM annihilation in the sun

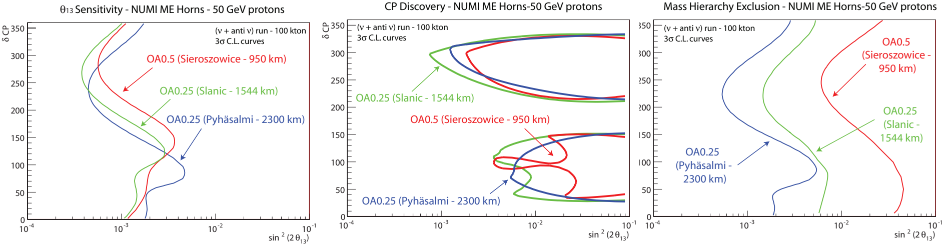
SuperBeams - SPL ν beam at CERN



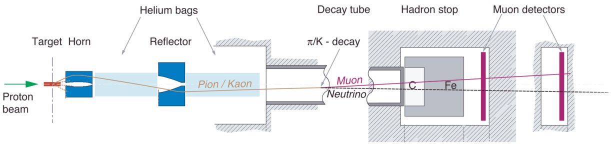
- A 3.5 GeV, 4MW Linac: the HP-SPL.
- A liquid mercury (or carbon) target capable to manage the 4 MW proton beam. R&D required.
- A conventional neutrino beam optics capable to survive to the beam power, the radiation and the mercury. Already prototyped.
- Up to here is the first stage of a neutrino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

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.



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.

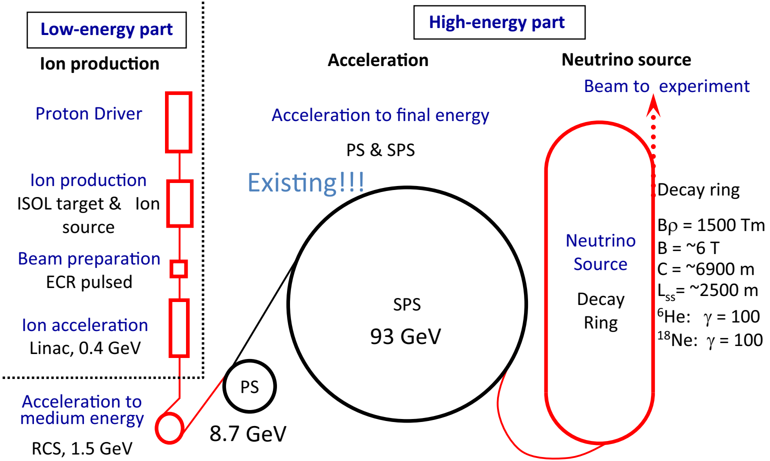
All these limitations are overcome if secondary particles become primary

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.

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

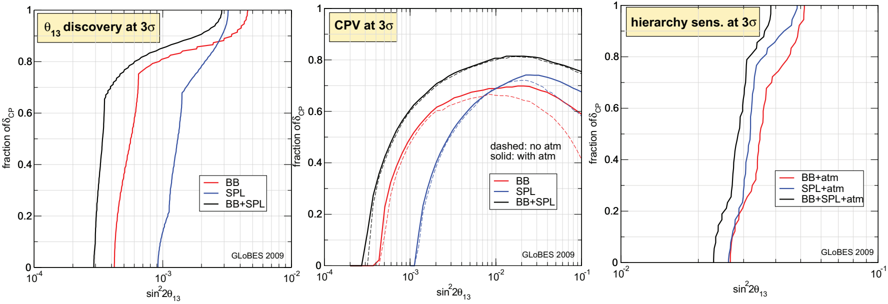
M. Lindroos M. Mezzetto, "Beta Beams", Imperial College Press, 2009



- $\overline{\nu}_e$ 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.

Updated sensitivities of SPL, BB and SPL+BB

Campagne,Maltoni,MM, Schwetz JHEP, 2007, 04, 003



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

  (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)

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  - The injection ring proposed by C. Rubbia (C. Rubbia et al.,NIM A **568** (2006) 475), now actively studied in the EuroNu WP4 package, could match the ion production, but apparently the PS-SPS chain cannot digest all those ions.

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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 Beta Beam - SPL Super Beam synergy

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

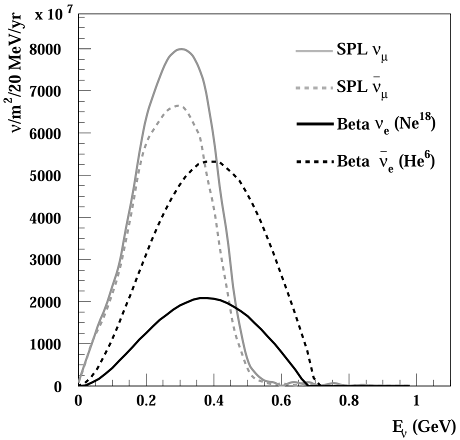
A Beta Beam has the same energy spectrum than the SPL SuperBeams and consumes 5% of the SPL protons.

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



The basic concept of a neutrino factory

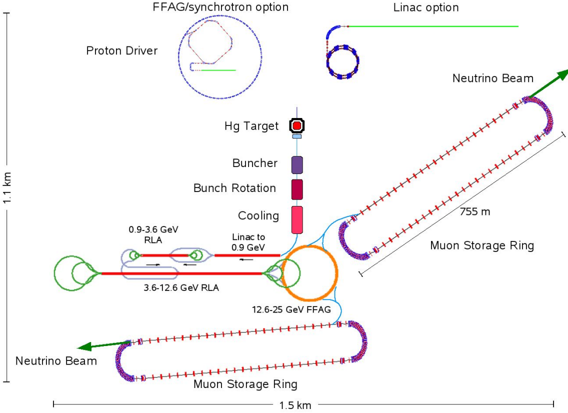
High power (4 MW) proton beam onto a liquid mercury target.

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 muons to 20 GeV.

Muons are injected into a storage ring (decay ring), where they decay in long straight sections in order to deliver the desired neutrino beams.



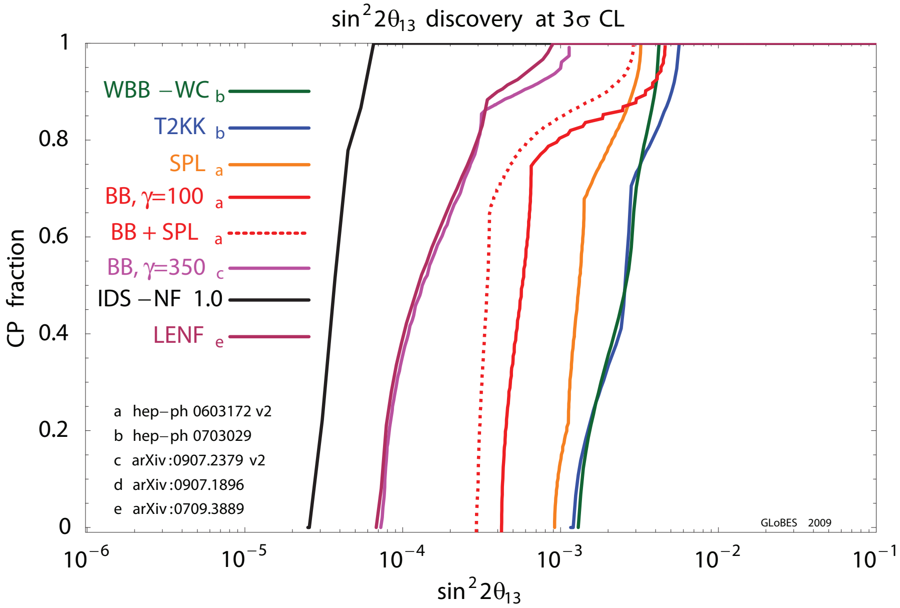
Oscillation signals at the neutrino factory

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

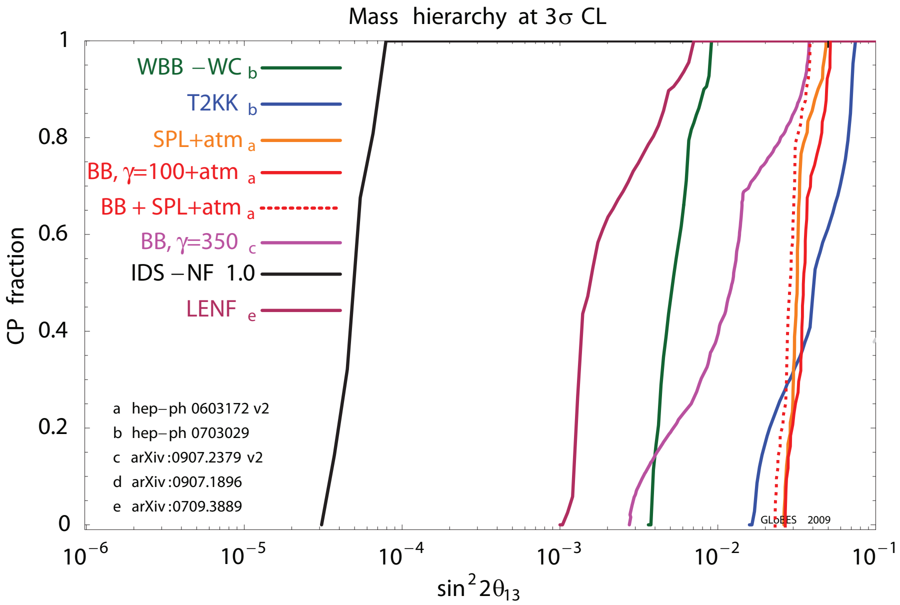
Golden channel: search for $\nu_e \rightarrow \nu_\mu$ $(\overline{\nu}_e \rightarrow \overline{\nu}_\mu)$ transitions by detecting wrong sign muons.
Default detector: 40-100 kton iron magnetized calorimeter (Minos like)

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.

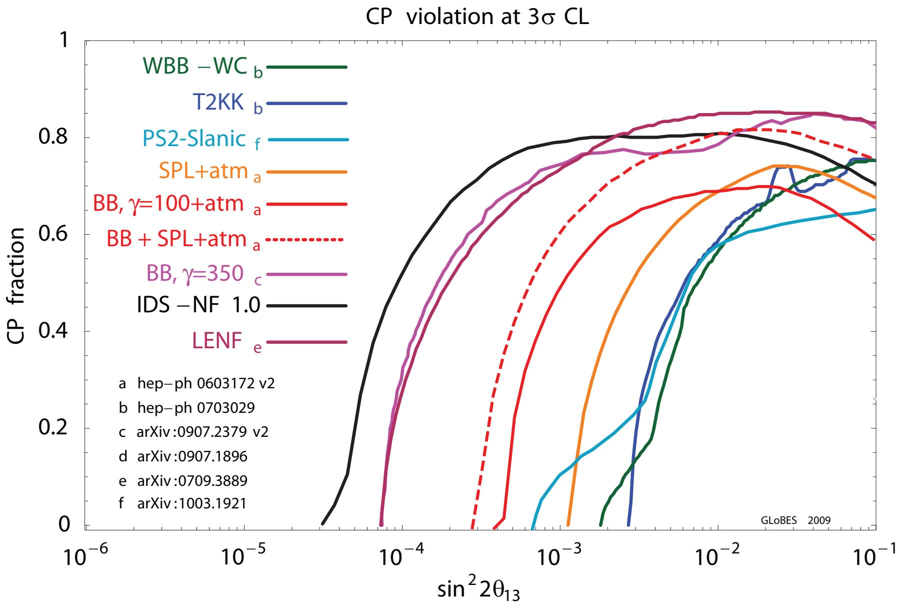
Sensitivity Comparison: θ_{13}



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



Sensitivity Comparison: LCPV



Conclusions

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- They won't anyway have enough sensitivity to attack mass hierarchy and leptonic CP violation searches with sufficient sensitivity. Further upgrades are needed.

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- A neutrino factory can offer the ultimate performances in neutrino oscillations and can be seen as the first stage of a muon collider.