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“ Futuri esperimenti sulle oscillazioni di neutrini"

- Introduzione
- Primi timidi segnali di non-zero θ_{13}
- La prossima generazione di esperimenti: θ_{13} .
  - Acceleratori: T2K, poi Noνa.
  - Reattori: Double Chooz, Daya Bay.
- La generazione successiva: $\delta_{\rm CP}$and $\mathrm{sign}(\Delta m^2_{23})$.
  - Super Beams
  - Beta Beams
  - Neutrino Factories
  - Il possibile ruolo del Gran Sasso

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)!**

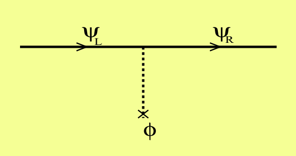
$$U_{MNSP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

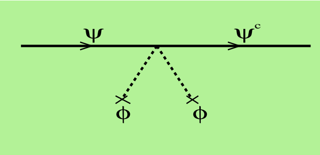
$\theta_{13} \to 0 \quad \Rightarrow$ The 3x3 mixing matrix becomes a trivial product of two 2x2 matrixes.

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

$u \sim 5$ 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?





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

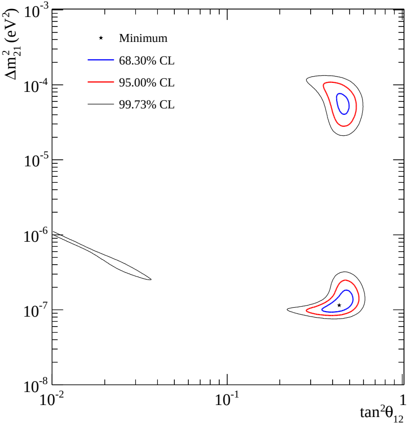
$$\frac{\alpha_\nu}{M} \nu_L^T C \tilde{\Phi}^T \tilde{\Phi} \nu_L + h.c.$$
$$m_f = \alpha_\nu \frac{v^2}{M}$$
$$\not{L}$$

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.

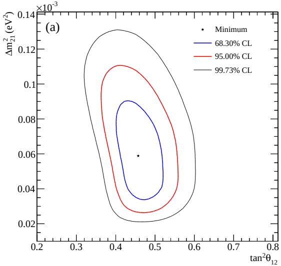
Recent hints of non-zero θ_{13} values: SNO-Solars-Kamland

SNO: arXiv:0910.2984, see also Fogli et al.PRL. 101, 141801 (2008) , Balantekin et al. J.Phys.G35:075007,2008

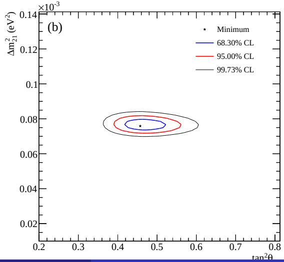
SNO Only



All solar experiments



Solars+Kamland

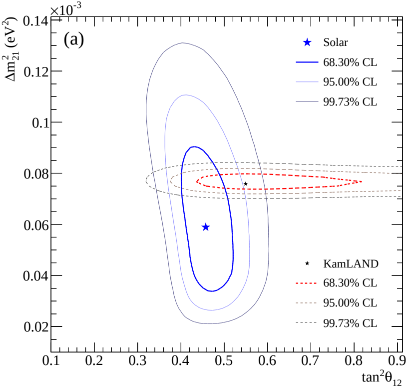


SNO-Solars-Kamland (II)

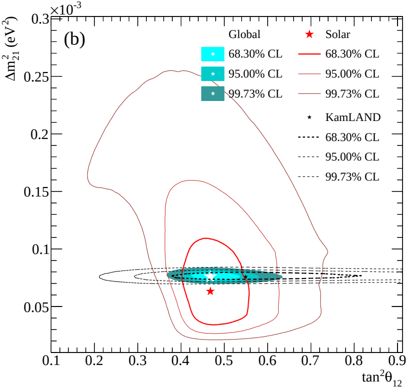
SNO: arXiv:0910.2984, see also Fogli et al.PRL. 101, 141801 (2008) , Balantekin et al. J.Phys.G35:075007,2008

$$\sin^2\theta_{13} = 2.00^{+2.09}_{-1.63} \times 10^{-2}.\ \sin^2\theta_{13} < 0.057\ (95\%\ \mathrm{C.\ L.}).$$

Solar+Kamland: two-flavors fit.



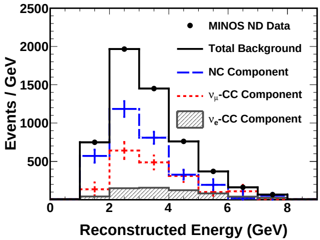
Solar+Kamland: three-flavors fit.



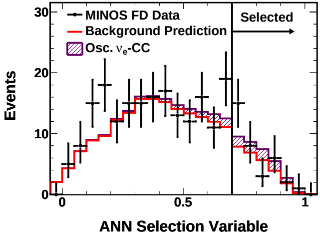
Recent hints of non-zero θ_{13} values: Minos

Minos collaboration: arXiv:0909.4996

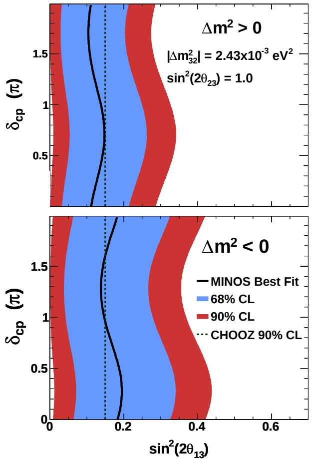
Events: 35
Backgrounds: $27 \pm 5(\mathrm{stat}) \pm 2(\mathrm{syst})$



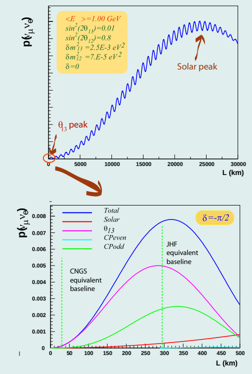
ν_e-like events in the close detector: dominated by NC events (how to extract ν energy in NC events?)



ann variable to select ν_e-like events. Signal excess very unstable to a variation of the cut position



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



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

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

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

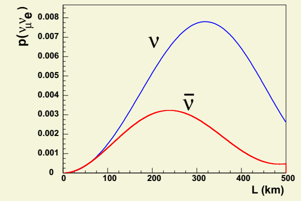
$$+ 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta\} \sin\frac{\Delta m_{12}^2 L}{4E} \quad \text{solar driven}$$

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

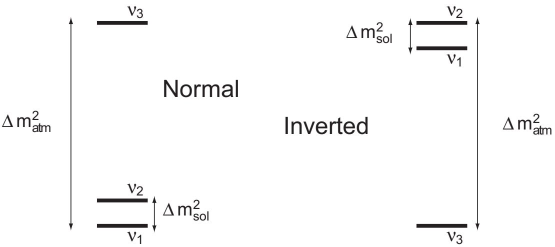
θ_{13} discovery requires a signal ($\propto \sin^2 2\theta_{13}$) greater than the solar driven probability

Leptonic CP discovery requires

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



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



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

Neutrino Oscillations in Matter

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

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

Matter effects require long “long baselines"

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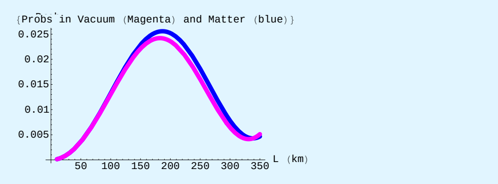
Matter effects require long "long baselines"

$\boldsymbol{E_\nu = 0.35\mathrm{GeV}}$



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Matter effects require long "long baselines"

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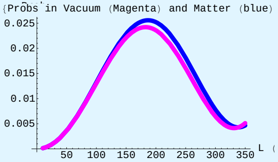
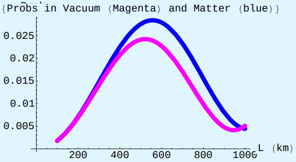


$\boldsymbol{E_\nu = 1\mathrm{GeV}}$



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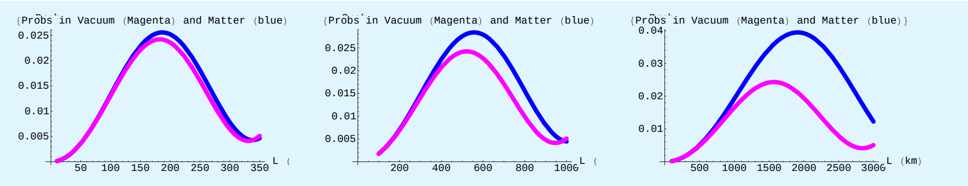
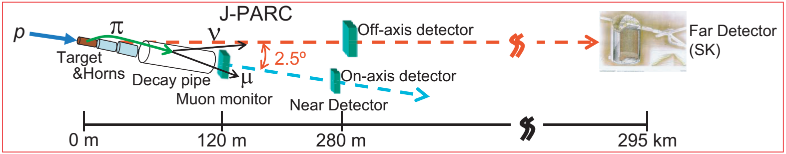
Matter effects require long "long baselines"

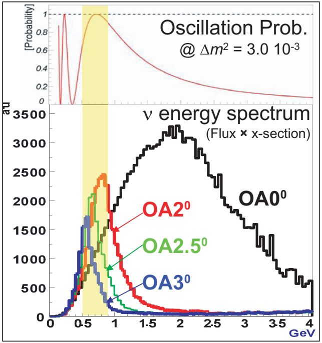
$E_\nu = 0.35\mathrm{GeV}$ **$E_\nu = 1\mathrm{GeV}$** **$E_\nu = 3\mathrm{GeV}$**



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

The T2K collaboration

Canada
TRIUMF
U. Alberta
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly
LPNHE Paris

Germany
U. Aachen

Japan
U. Hiroshima
ICRR
ICRR Kashiwa
ICCR RCCN
KEK
U. Kobe
U. Kyoto
U. Miyagi
U. Osaka City
U. Tokyo

Switzerland
U. Bern
U. Geneva
ETH Zurich

Poland
A.Soltan, Warsaw
H.Niewodniczanski, Cracow
T.U. Warsaw
U. Silesia, Katowice
U. Warsaw
U. Wroklaw

S.Korea
N.U. Chonnam
U. Dongshin
N.U. Gyeongsang
N.U. Kyungpook
U. Sejong
N.U. Seoul
U. Sungkyunkwan

Spain
IFIC, Valencia
U.A. Barcelona

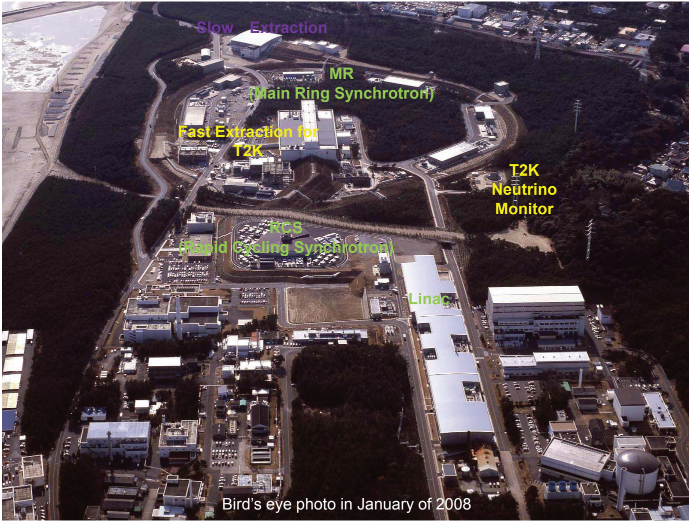
USA
Boston U.
BNL
Colorado S.U.
Duke U.
Louisiana S.U.
Stony Brook U.
U.C.Irvine
U.Colorado
U.Pittsburgh
U.Rochester
U. Washington

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

UK
Imperial C. London
Queen Mary U.L.
Lancaster U.
Liverpool U
Oxford U.
Sheffield U.
Warwick U.
STFC/RAL
STFC/Daresbury

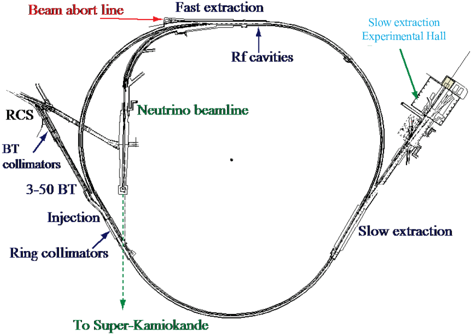
Russia
INR

J-PARC Accelerator and Experimental Facility



Overview of MR

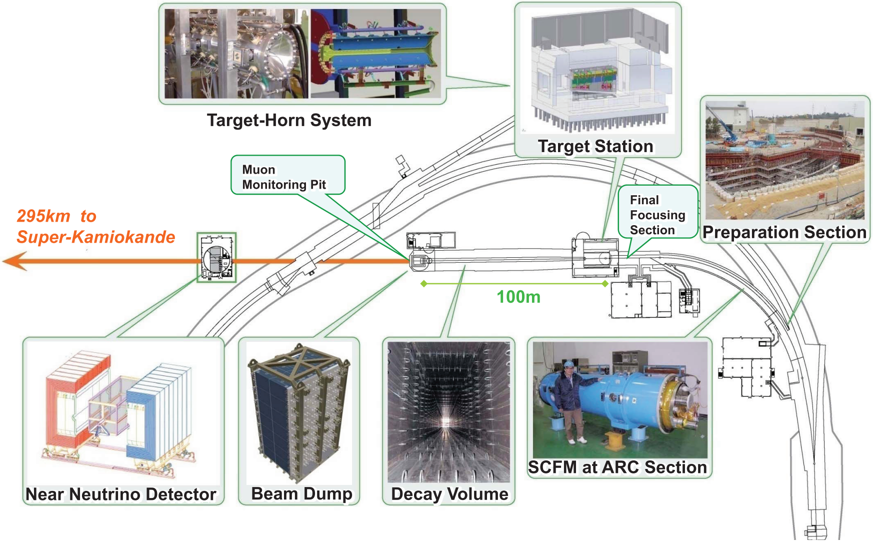
Circumference	**1567.5 m**
Repetition rate	**0.3 Hz@Start Up**
Injection energy	**3 GeV**
Extraction energy	**30 GeV**
Superperiodicity	**3**
h	**9**
No. of bunches	**8**
Transition γ	**31.7(imaginary)**
Typical tune	**22.4, 20.8**
Transverse emittance	
At injection	**~54 πmm-mrad**
At extraction	**~10 πmm-mrad**
Beam power	**0.75MW**



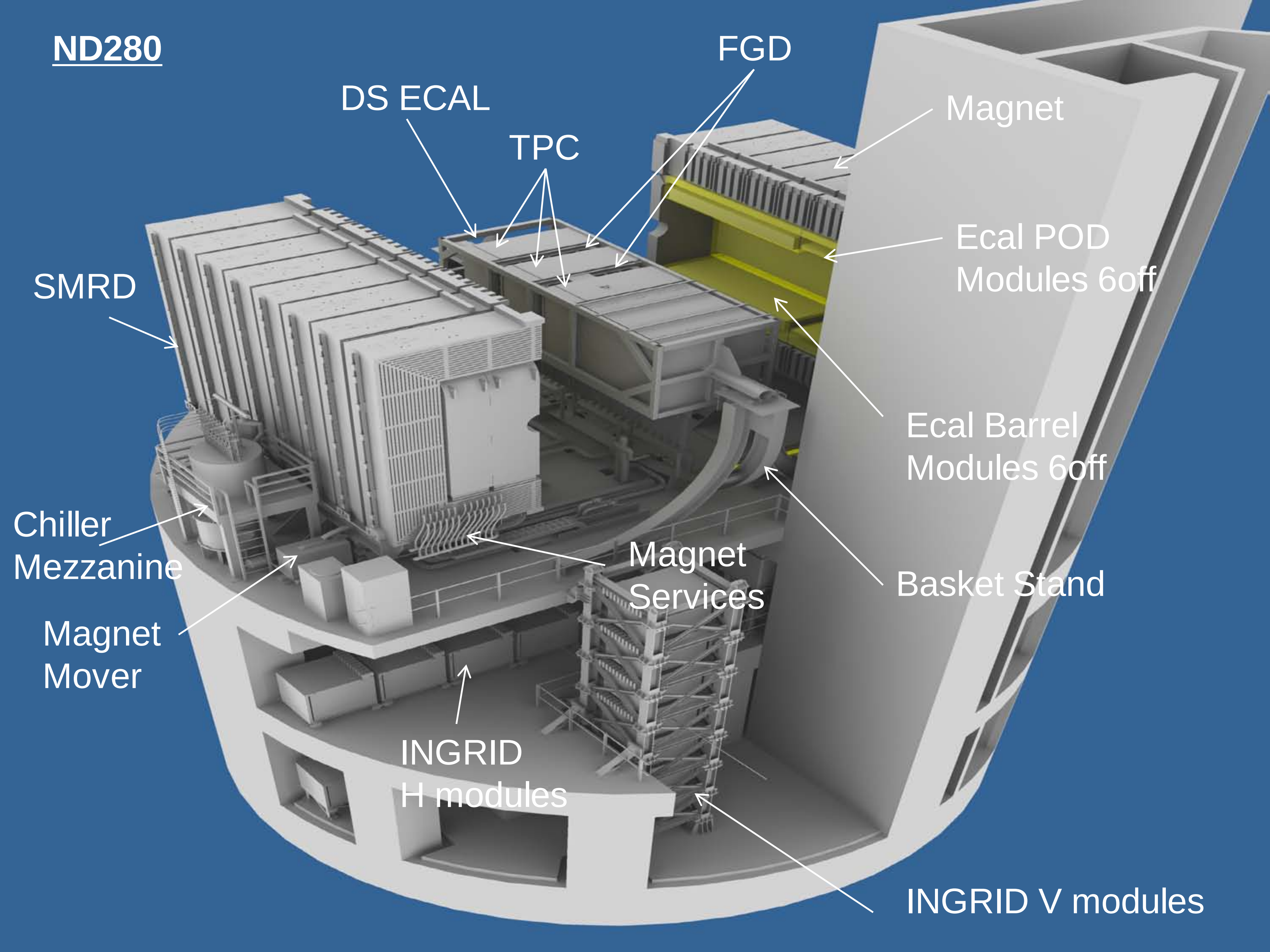
Three dispersion free straight sections of 116-m long:

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

T2K experiment: the neutrino beam line

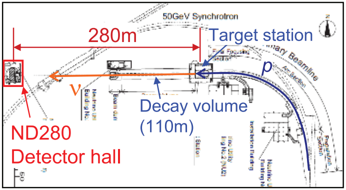


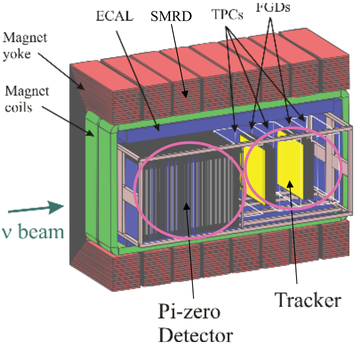
ND280



DS ECAL
TPC
FGD
Magnet
SMRD
Ecal POD
Modules 6off
Ecal Barrel
Modules 6off
Chiller
Mezzanine
Magnet
Services
Basket Stand
Magnet
Mover
INGRID
H modules
INGRID V modules

The Close Detector ND280

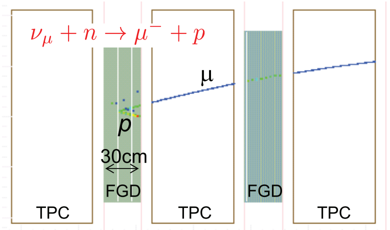




- Near off-axis detector located at 280 m downstream of the target
- Consists of 5 subdetectors:
  - Pi-zero detector (PØD)
    - measures NCπ^0 interactions
  - Tracker: fine-grained detector (FGD) and time projection chambers (TPC)
    - measures CC interactions
  - Electromagnetic calorimeter (ECAL)
    - 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

The Close Detector ND280

- Key for good E_ν spectrum and background estimations
  - CCQE / non-CCQE separations
  - Neutrino interaction models
    - Cross sections
    - Fermi motion
    - Nuclear effects …
- Finely segmented (1cm x 1cm) FGD with 10μs time window
  - short 2nd (and more) tracks' activities
  - π → μ → e decays from non-CCQE
- TPC following the FGD
  - particles' charge: μ^- / π^+ separation
  - momentum of π from non-CCQE as well as μ
- ECAL surrounding the Tracker
  - detects γ's from π^0 from non-CCQE

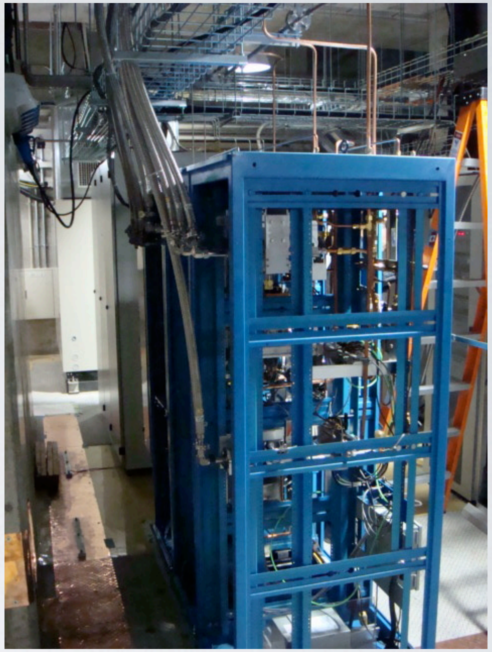


- Two independent CCQE / non-CCQE separation in a single detector:
  - Final state particles
  - Kinematics of 2nd track
- Kinematics of final state particles:
  - Fermi motions, nuclear effects, …

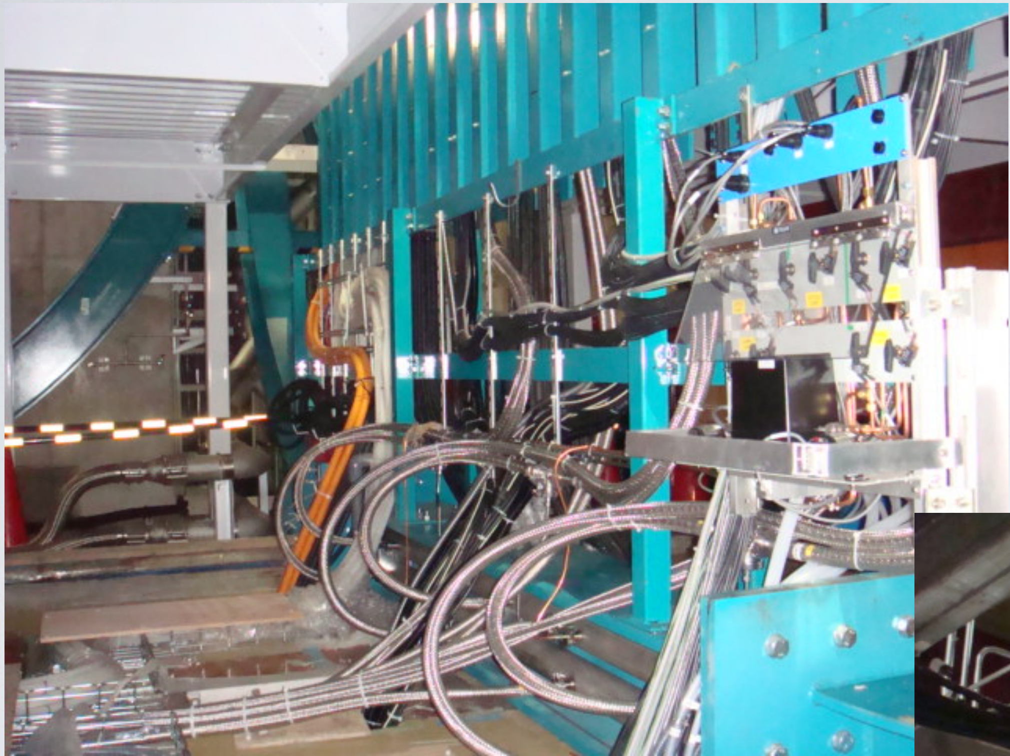
→ intensive study of the neutrino interactions

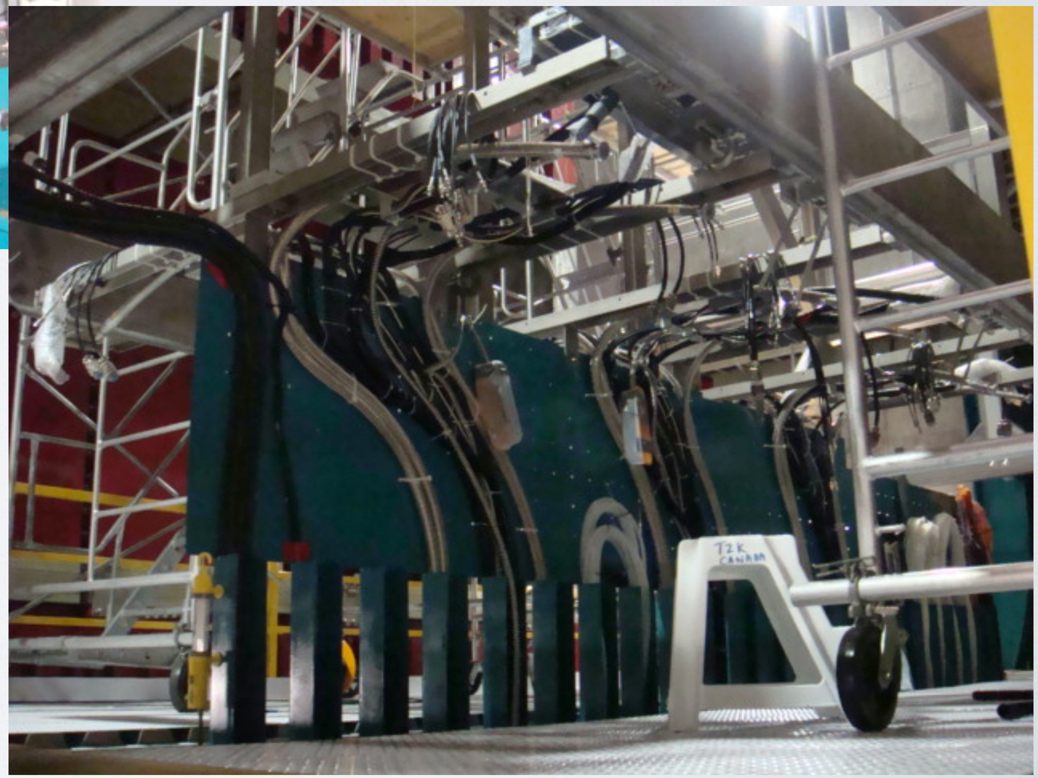
INGRID

TPC

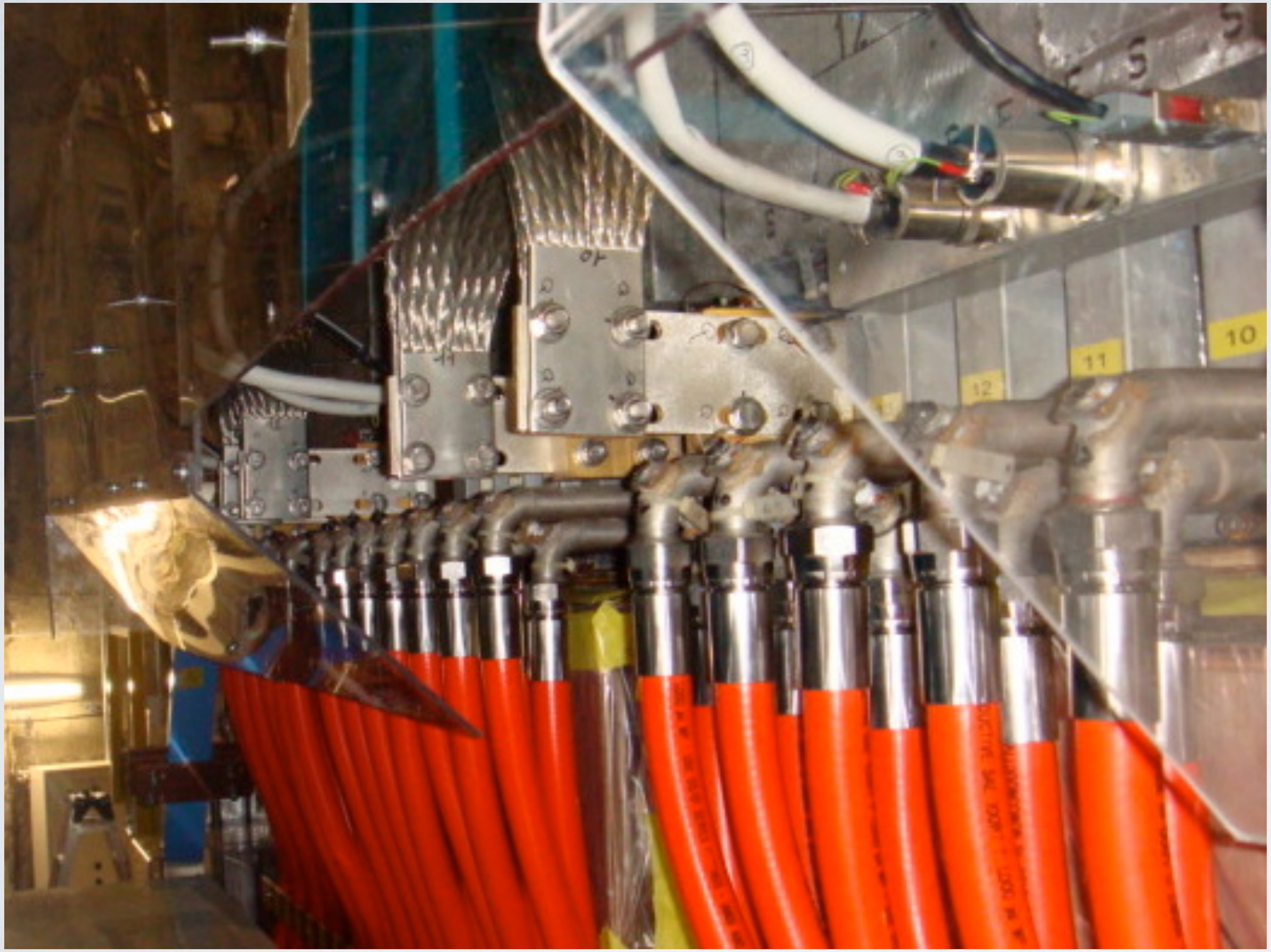


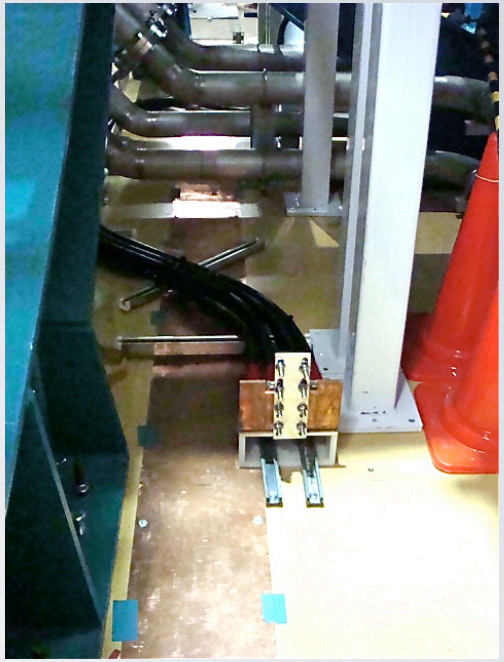
Services

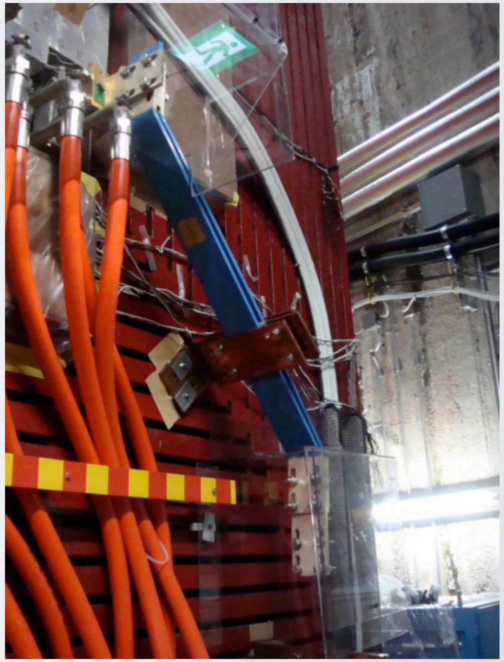




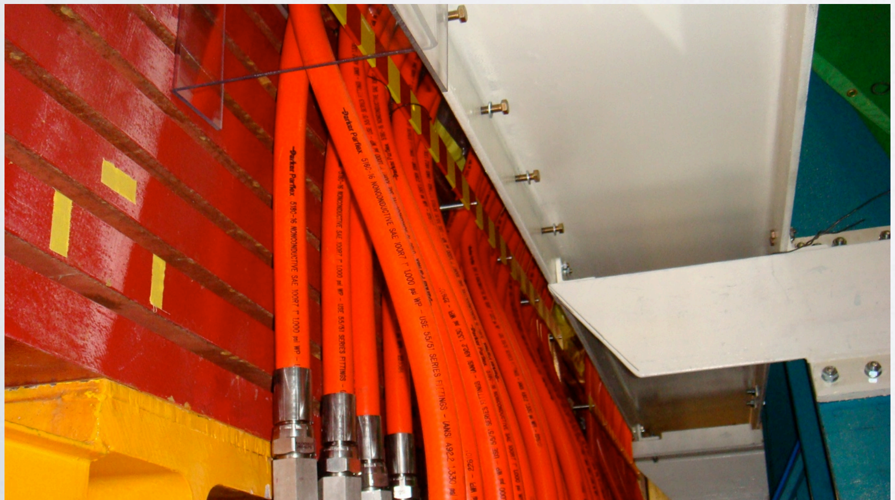
Coil Power

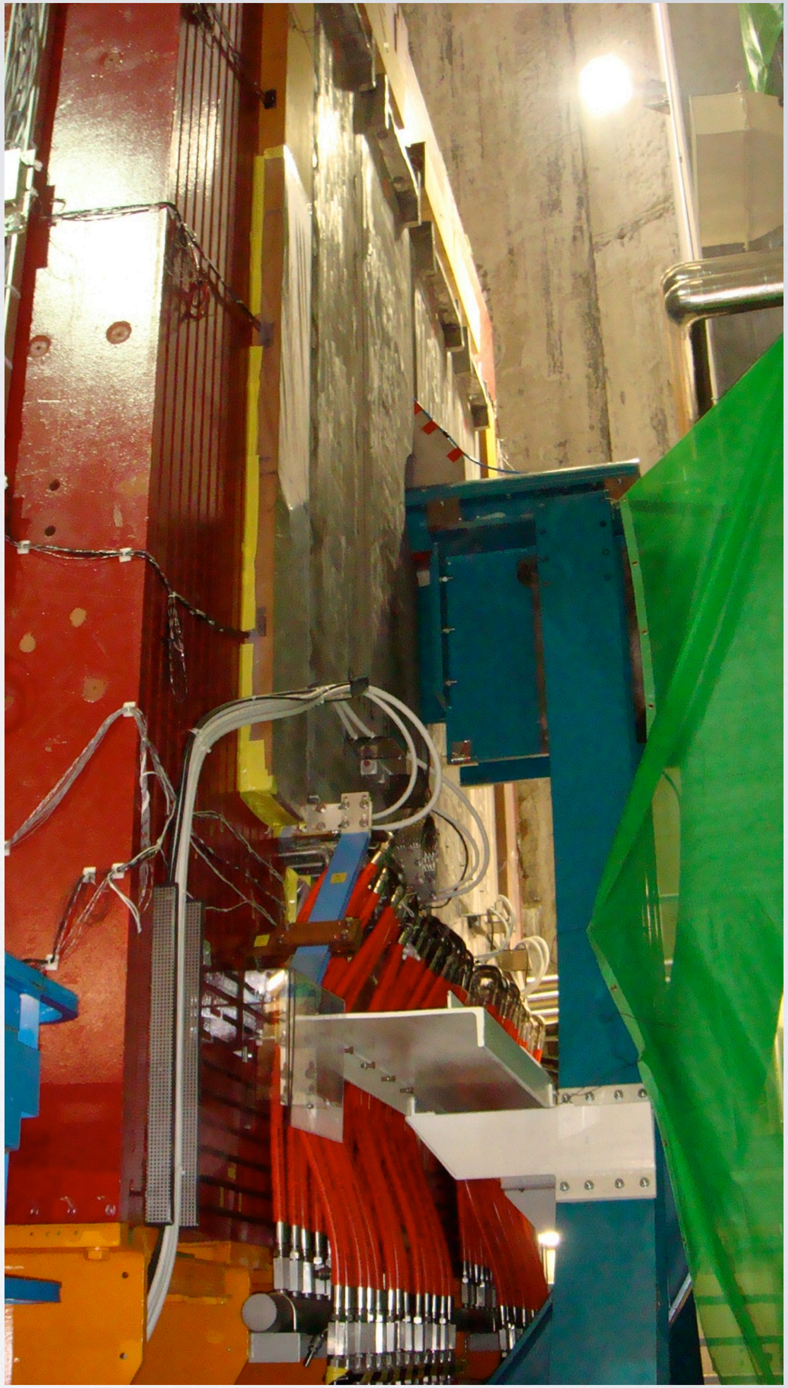






Magnet Closure





B-Field Mapping

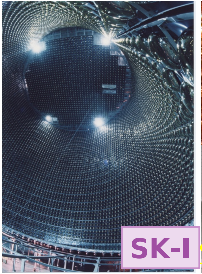
FGD and Detector Cooling

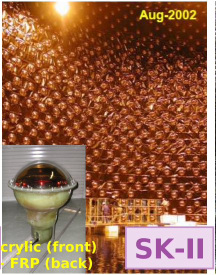

POD

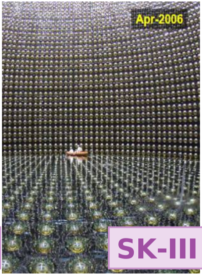
History of Super-Kamiokande detector

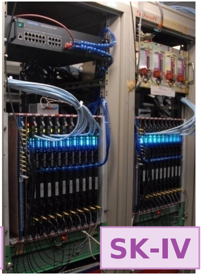
1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009

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



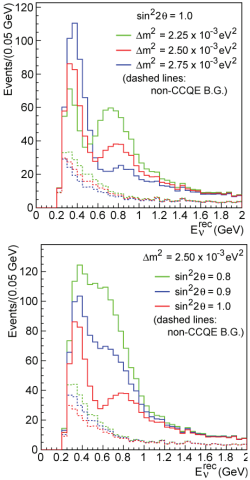


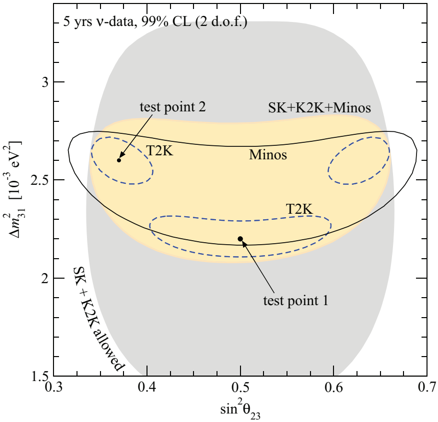




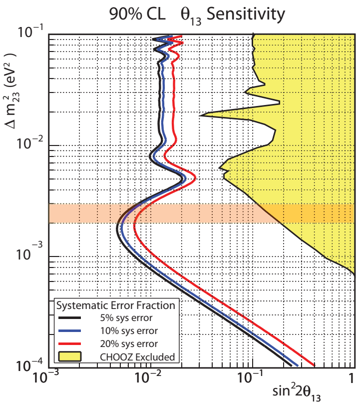
	SK-I	SK-II	SK-III	SK-IV
	11146 ID PMTs (40% coverage)	5182 ID PMTs (19% coverage)	11129 ID PMTs (40% coverage)	Electronics Upgrade
Energy Threshold (total electron	**5.0 MeV**	**7.0 MeV**	**4.5 MeV** work in progress	**< 4.0 MeV** target

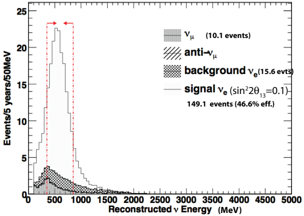
T2K Performances: atmospheric parameters

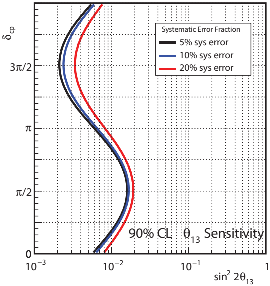




T2K Performances: θ_{13}







T2K Schedule

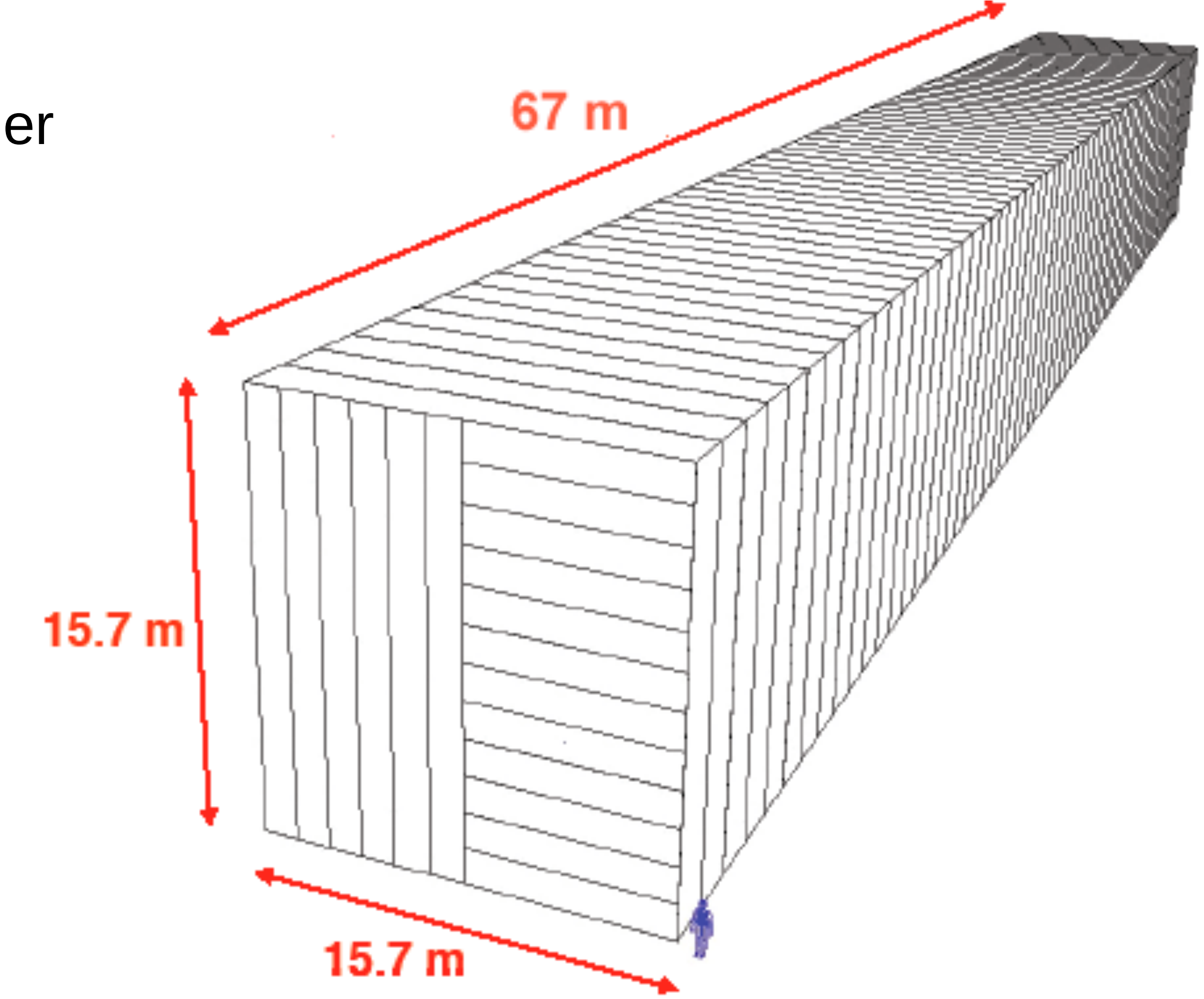
- Start neutrino beam commissioning: April 2009.
- Complete the ND280 installation and the neutrino beam line installation by December 2009.
- Start data taking at December 2009. Accumulate 0.1 MW$\times 10^7 s$ by summer 2010 $\Rightarrow$ $\sin^2(2\theta_{13})$ sensitivity about 0.1.
- Continue data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

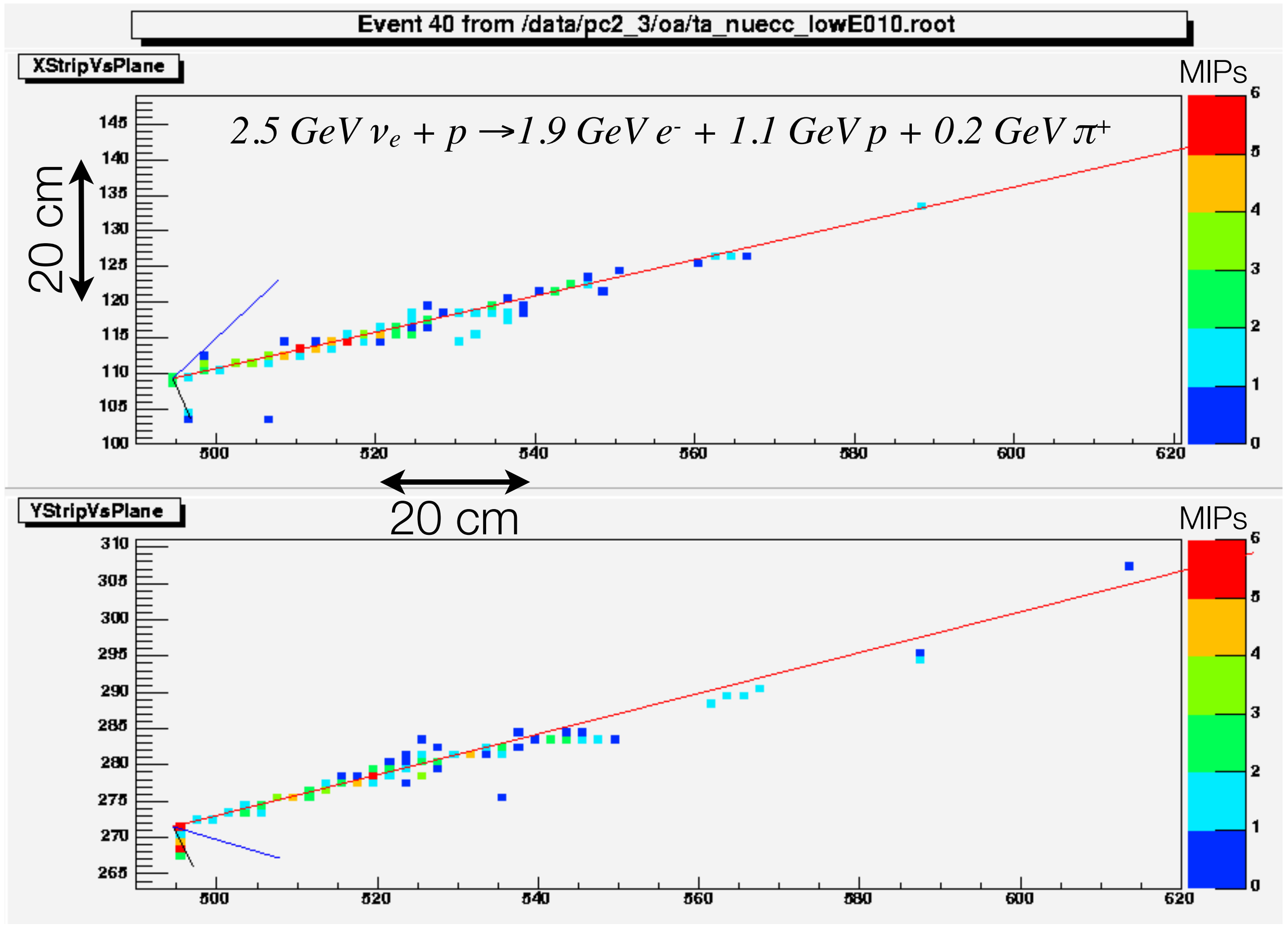
Slides: courtesy of Mark Messier

The NOvA Experiment

28 Institutions 180 scientists and engineers

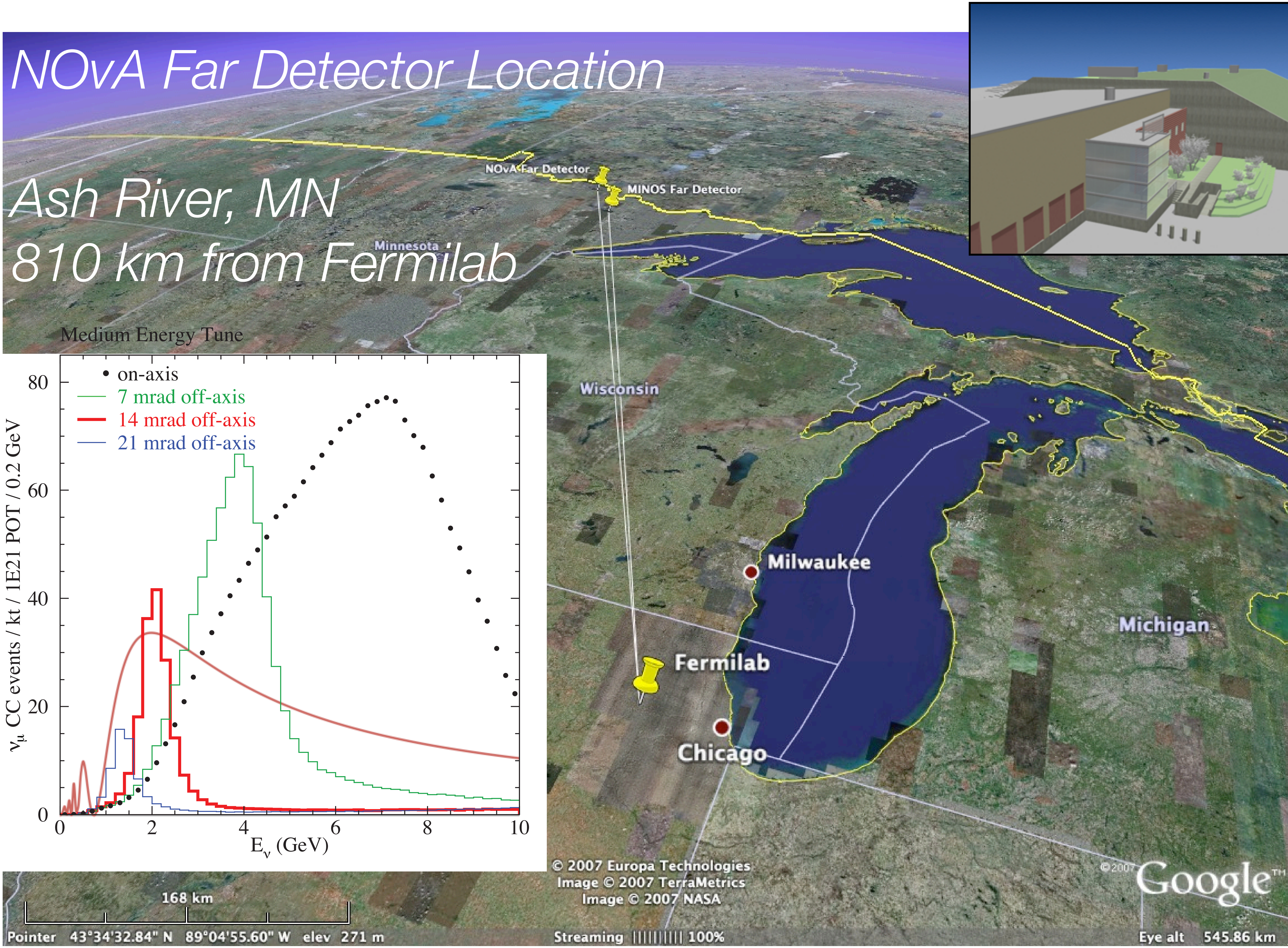
- NOvA is a second generation experiment on the NuMI beamline which is optimized for the detection of $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations
- NOvA is:
  - An upgrade of the NuMI beam intensity from 400 kW to 700 kW
  - A 15 kt “totally active” 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

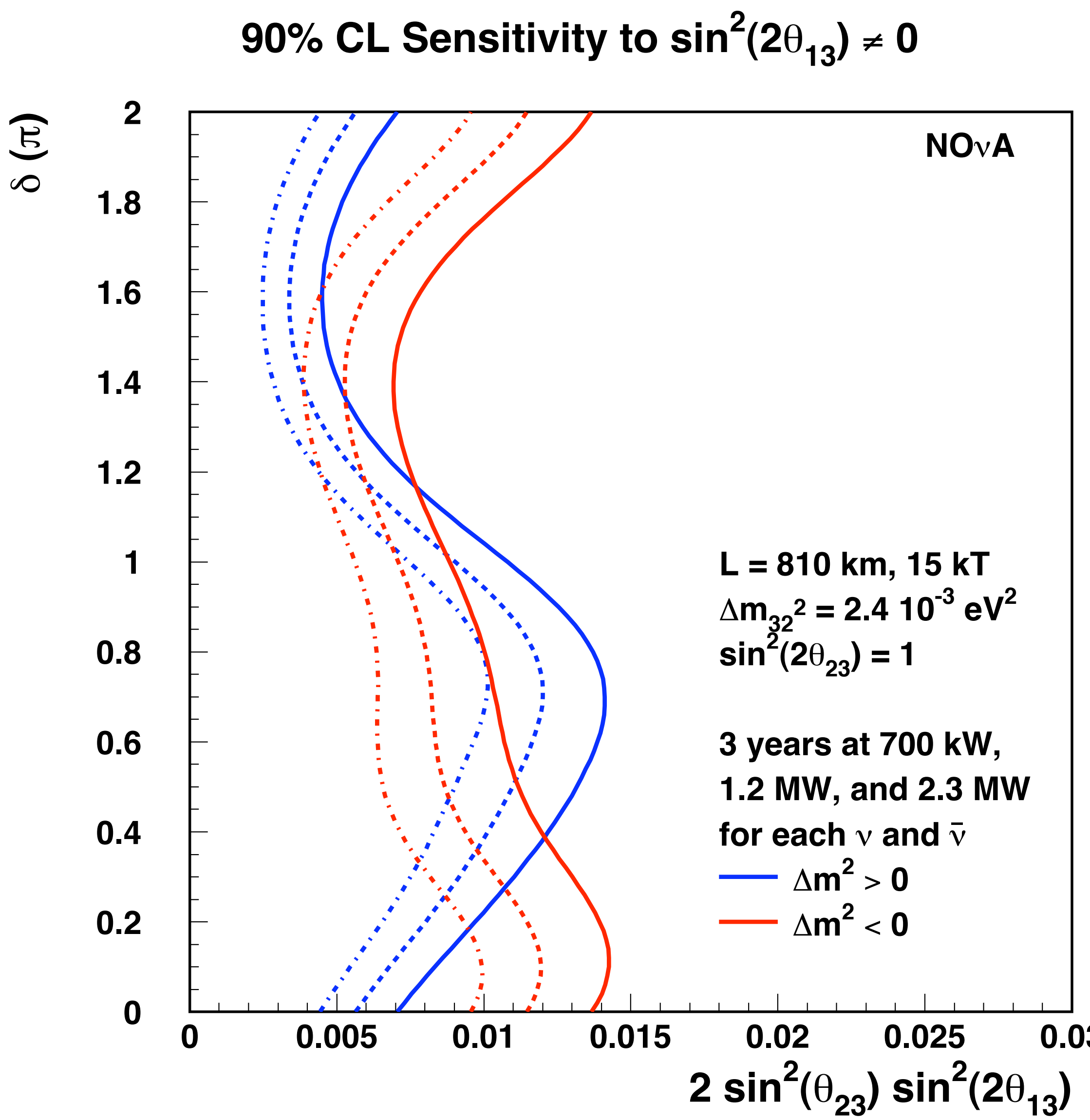


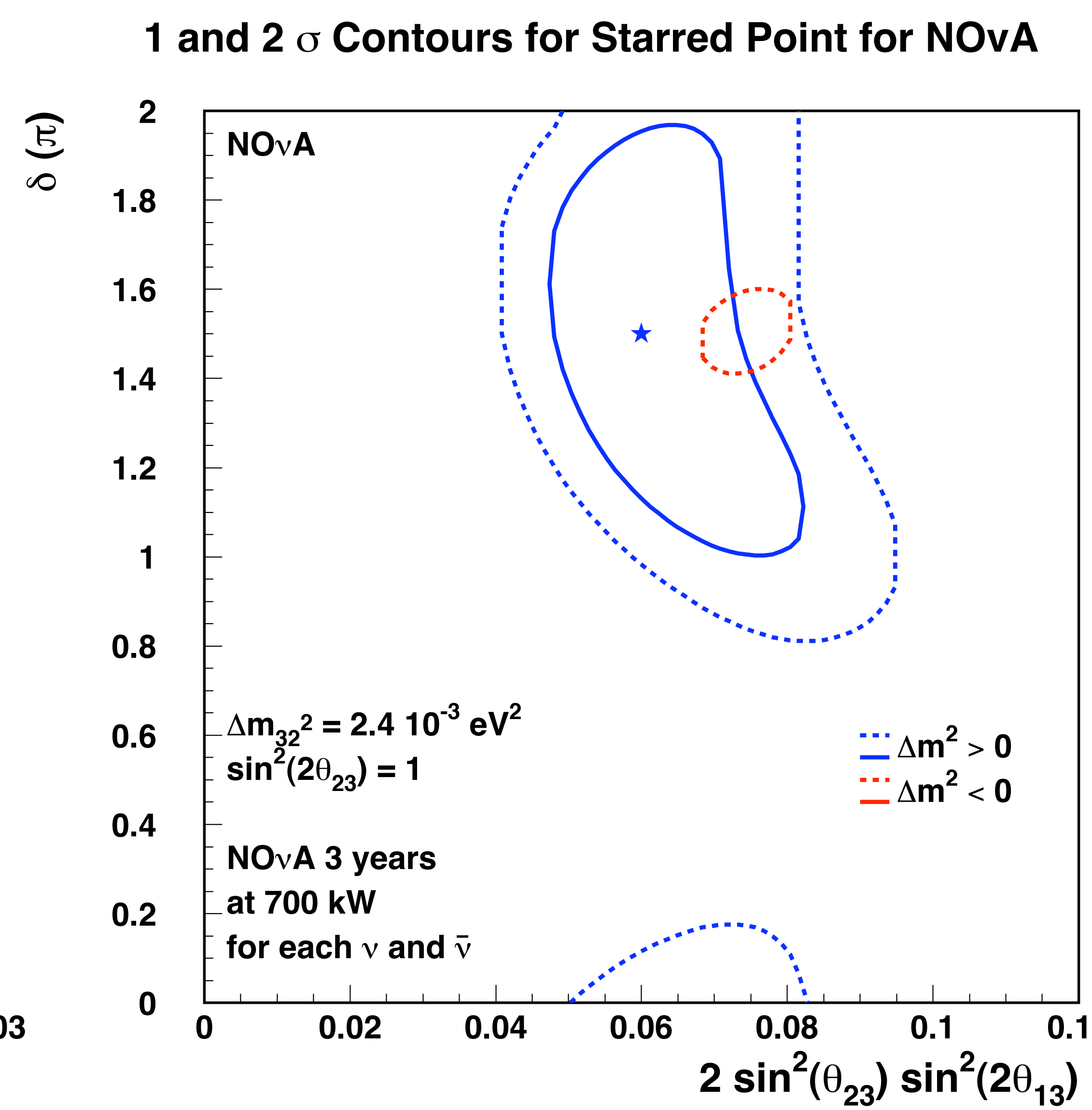


NOvA Far Detector Location

Ash River, MN
810 km from Fermilab

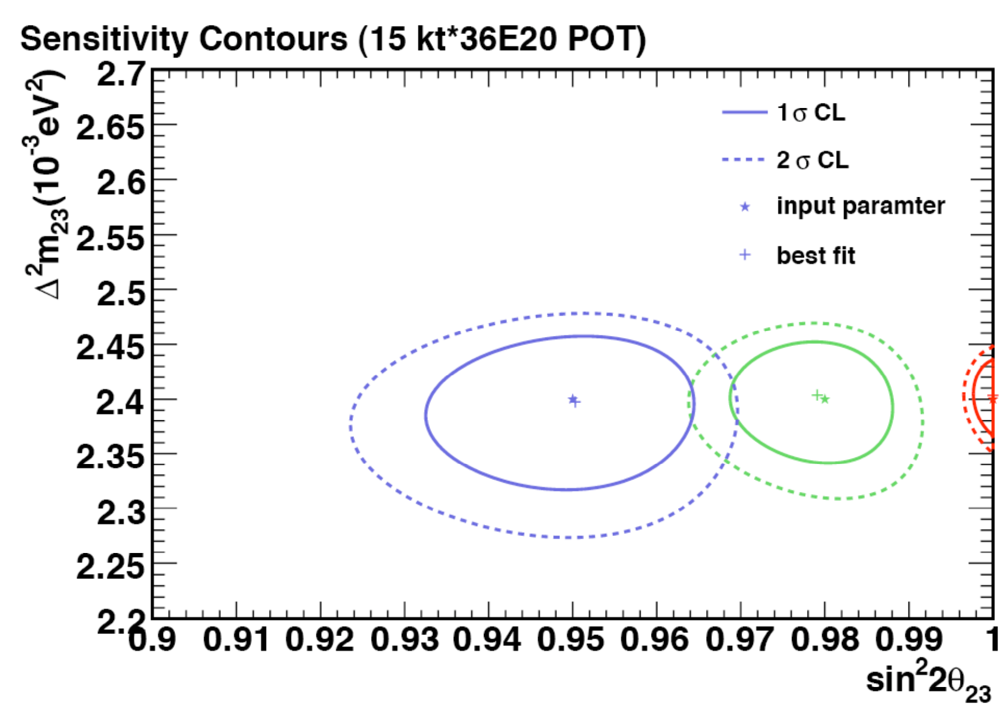






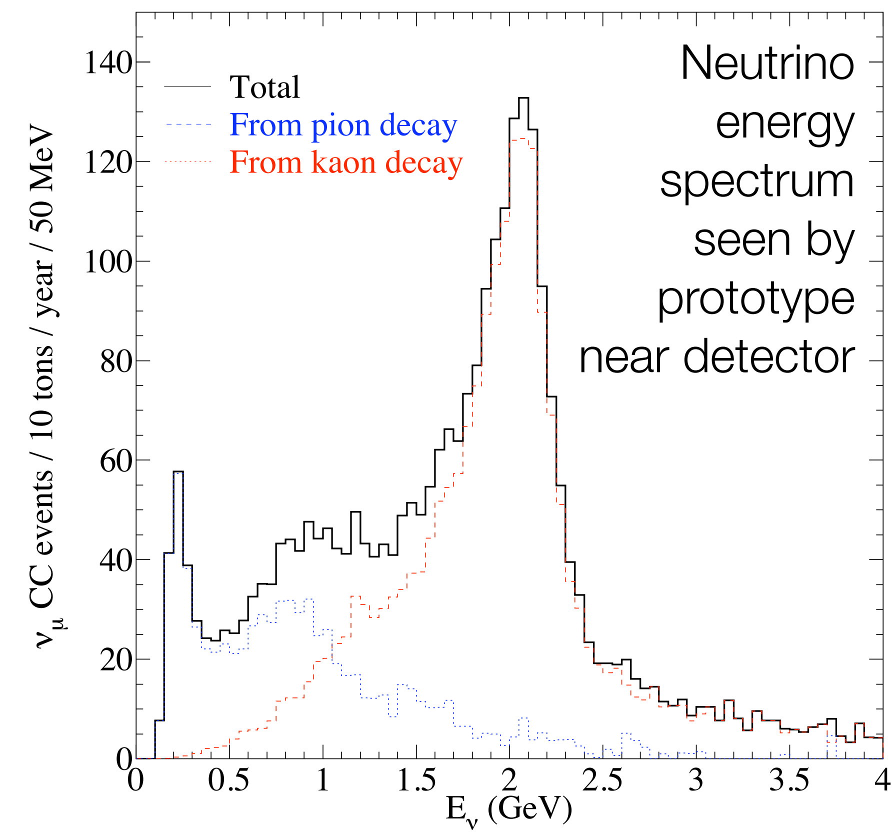
NOvA plans to run 3 years in neutrino mode, 3 years in anti-neutrino mode operating NuMI at 700 kW.

- 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

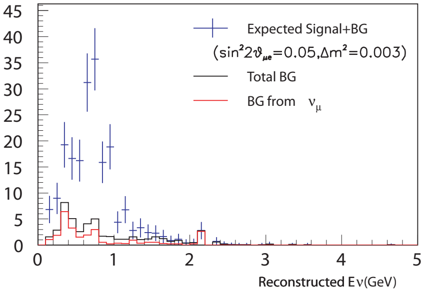


Neutrino energy spectrum seen by prototype near detector

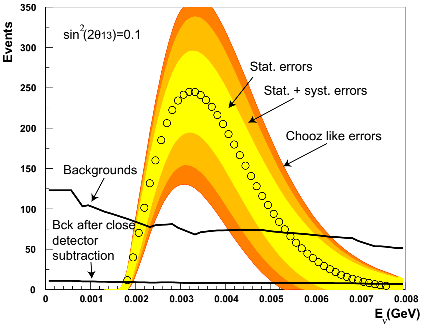
$$1 - P_{\bar{e}\bar{e}} \simeq \sin^2 2\theta_{13} \sin^2(\Delta m^2_{31} L/4E) + (\Delta m^2_{21}/\Delta m^2_{31})^2)\,(\Delta m^2_{31} L/4E)^2 \cos^4\theta_{13} \sin^2 2\theta_{12}$$

- Direct connection between $P_{\bar{e}\bar{e}}$ and θ_{13} , no interference with δ_{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.

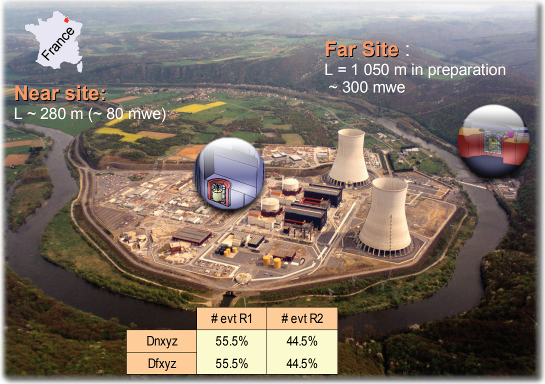
T2K appearance signal in 5 years, from hep-ex/0106019



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



Double Chooz



	# evt R1	# evt R2
Dnxyz	55.5%	44.5%
Dfxyz	55.5%	44.5%

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

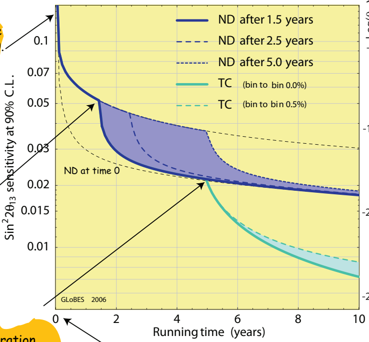
1. Far detector only
   - Sensitivity (1.5 ans) ~ 0.06
2. Far + Near sites
   - available from 2010
   - Sensitivity (3 years) ~ 0.025

Evolution of the Double Chooz sensitivity

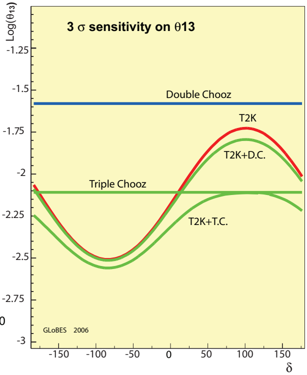
Start the operation of the **far detector**, 10 m3, at t0. With no close detector, systematics dominate.

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

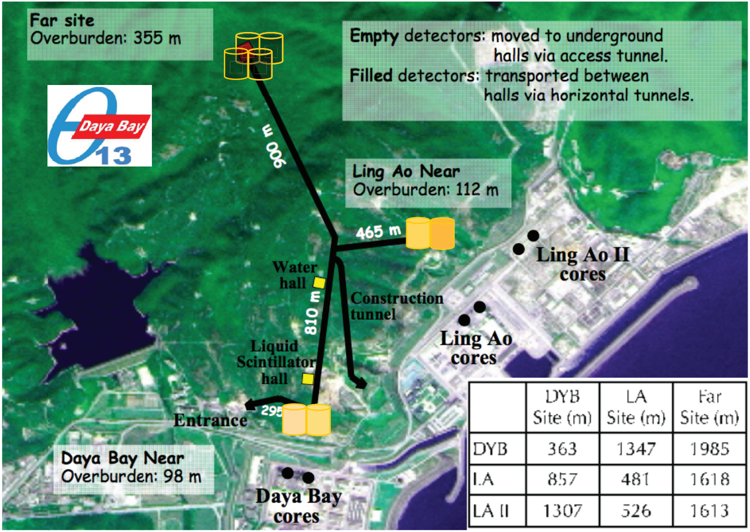
Triple Chooz: put in operation a 200 ton far detector in a already existing cavern. Experimental sensitivity improved. See JHEP 605 (2006) 72



Time 0: fall 2009



Daya Bay



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

Daya Bay

Start: end 2010 with two near sites and one far site

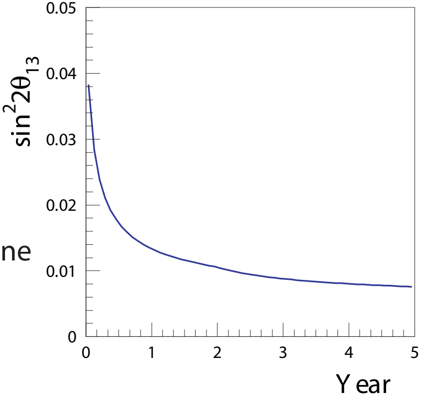


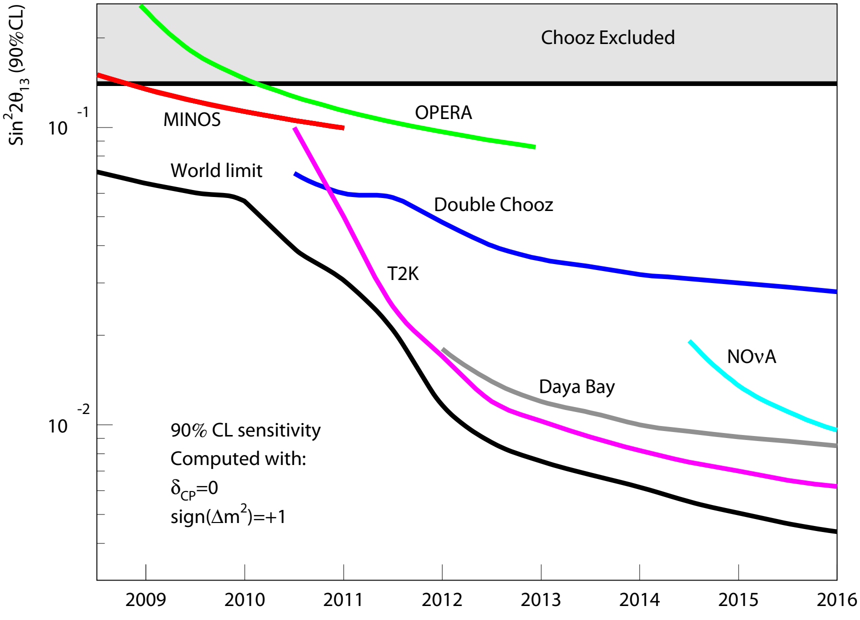
Fig. 3.14. Expected $\sin^2 2\theta_{13}$ sensitivity at 90% C.L. versus year of data taking of the full measurement, with two near sites and one far site. The value of Δm^2_{31} is taken to be 2.5×10^{-3} eV^2.

Reactors systematic business

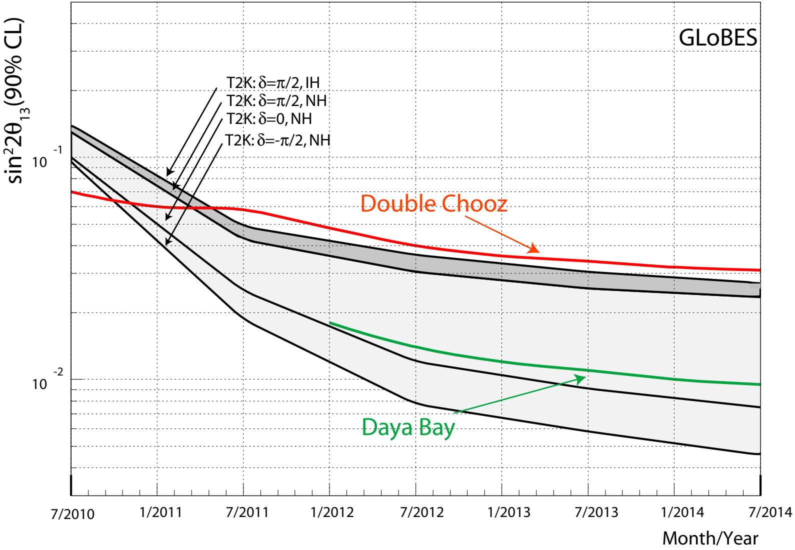
G. Mention, T. Lasserre and D. Motta, arXiv:0704.0498 [hep-ex].

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 %**

Guessing the Future (I)



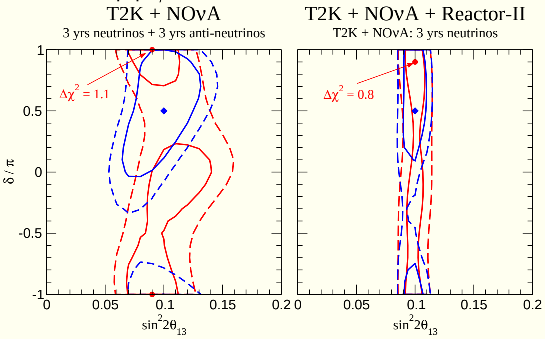
Guessing the Future (II)



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

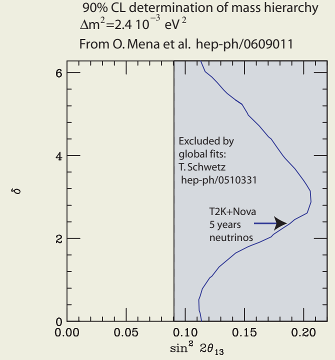
No hope to see any CP signal at 3σ

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



(dotted lines: 3σ, solid are 90%CL)

. . . and mass hierarchy



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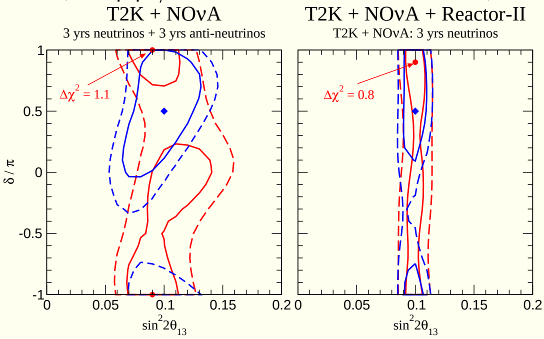

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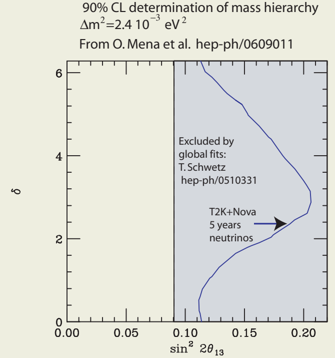


To address leptonic CP violation: improve of at least one order of magnitude the sensitivity of $\mathbf{\sin^2 2\theta_{13}}$; two order of magnitudes more neutrinos !!!

The SuperBeam way

Proposals based on upgrades of existing facilities:

- T2K ⇒ T2HK or T2KK
- Noνa ⇒ Super Noνa
- CNGS ⇒
  off-axis CNGS fired on a gigantic liquid argon detector
- Wide band beam fired from Fermilab to a gigantic water Cerenkov detector at Dusel (Homestake).

Proposals based on new facilities

- CERN-SPL SuperBeam

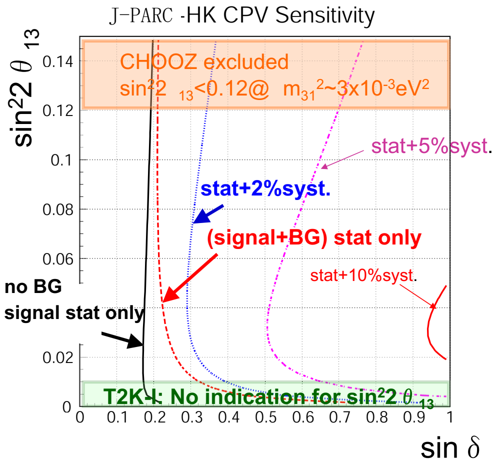
SuperBeams - J-PARC phase 2 (T2HK)

Upgrade the proton driver from 0.75 MW to 4 MW
Upgrade SuperKamiokande by a factor $\sim$ 20 $\Longrightarrow$ 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)



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

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

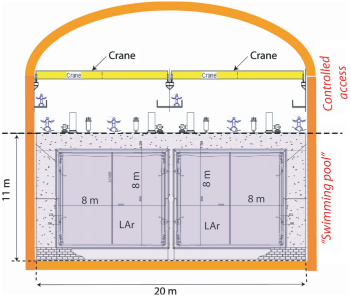
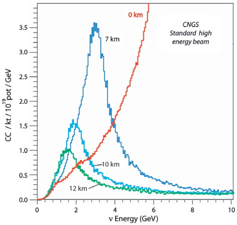
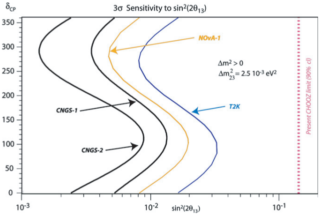


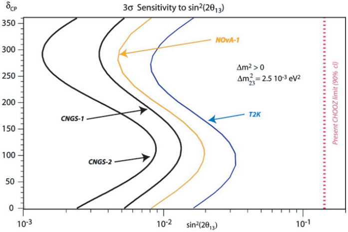
Fig. 1. Indicative cross-section of the T600 "clone " in the dedicated "swimming pool like" underground hall. The lower part is made of two twin separate LAr containers made of aluminum extruded structures, thermally stabilized with forced N2 circulation. Outside the structure an about 1.5 m thick per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

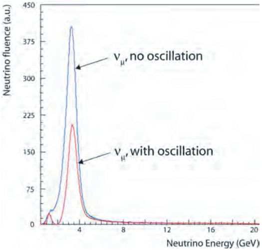


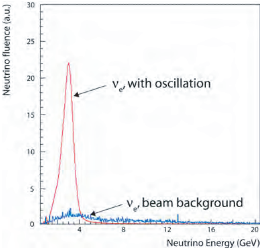


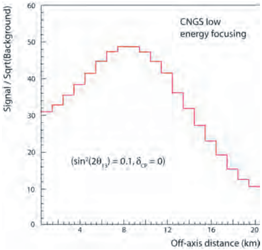
Thanks to A. Guglielmi

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

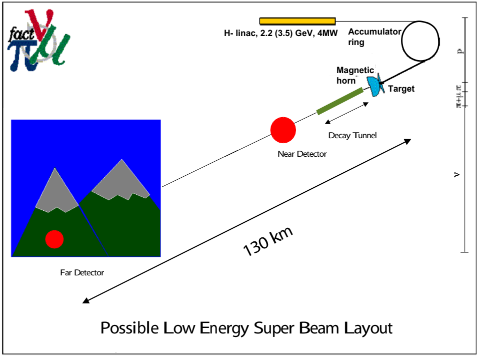






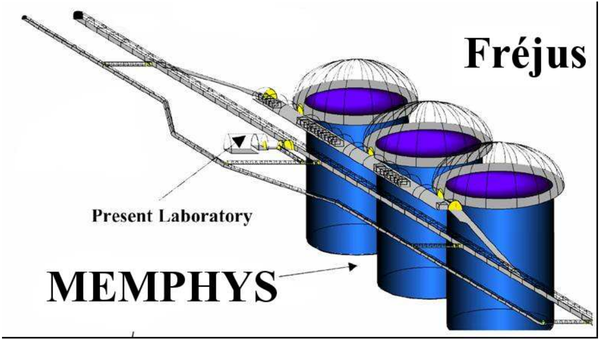


SuperBeams - SPL ν beam at CERN



- 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.

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)

Laguna

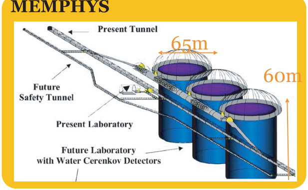
A coordinated European effort aimed towards conceptual designs for European large underground detectors.Physics focus: proton decay, low energy neutrino astronomy, long baseline neutrino beam.

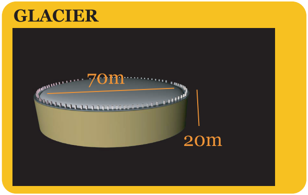
Three detection techniques are currently investigated:

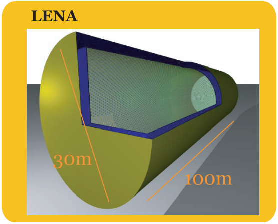
- Water Cerenkov imaging, $\sim$ 500 kton, with synergy with HK (Japan) and UNO (USA).
- Liquid argon time-projection chamber, $\sim$ 100 kton. Technology pioneered in Europe by the ICARUS R&D programme.
- Liquid scintillator, $\sim$ 50 kton connected to Borexino R&D programme

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

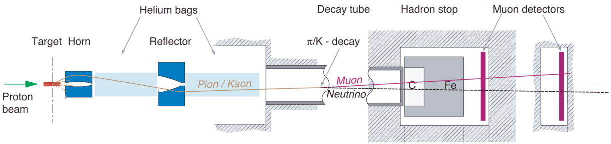
The Design Study has been recently approved inside the Europe FP7







Conventional neutrino beams are going to hit their ultimate limitations.



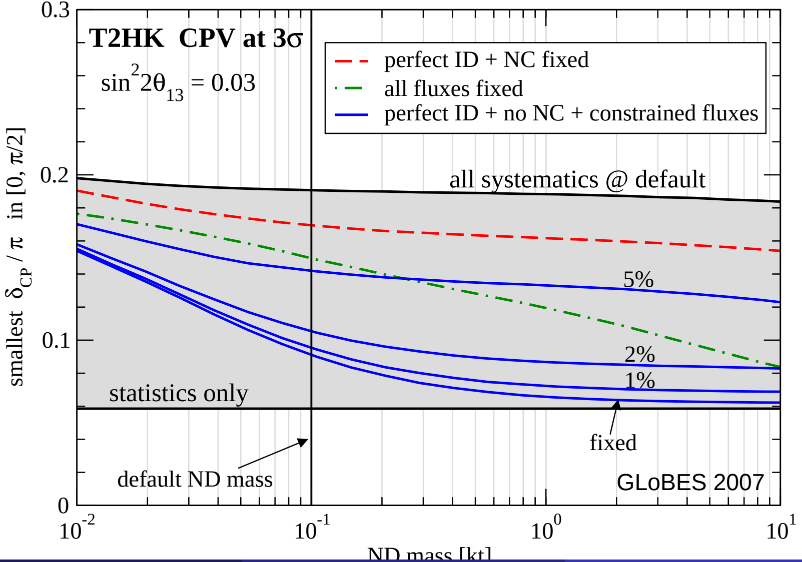
In a **conventional neutrino beam**, neutrinos are produced SECONDARY particle decays (mostly pions and kaons).
Given the short life time of the pions ($2.6 \cdot 10^{-8}$s), they can only be focused (and charge selected) by means of magnetic horns. Then they are let to decay in a decay tunnel, short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

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

About Systematic errors and Close detectors

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

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



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

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

The full ^{6}He flux MonteCarlo code

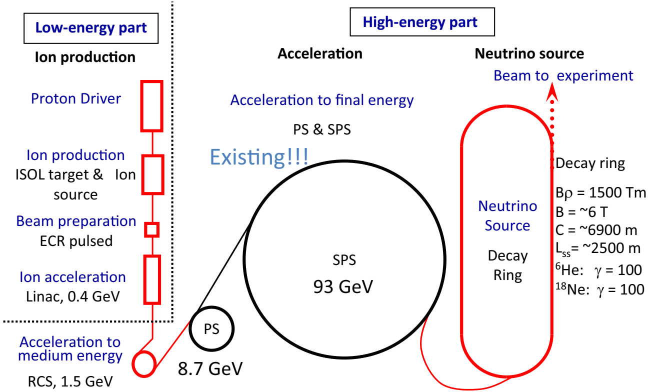
```
Function Flux(E)
Data Endp/3.5078/
Data Decays /2.9E18/

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

Return
```

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

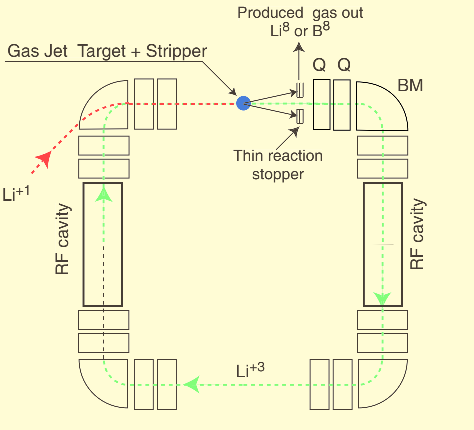
M. Lindroos M. Mezzetto, "Beta Beams", Imperial College Press, 2009



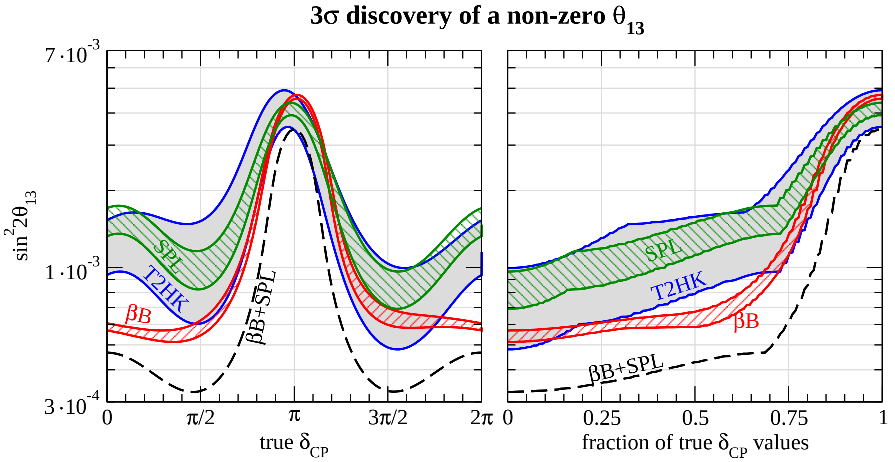
- 1 ISOL target to produce He^6, 100 μA, $\Rightarrow 2.9 \cdot 10^{18}$ ion decays/straight session/year. $\Rightarrow \overline{\nu}_e$.
- 3 ISOL targets to produce Ne^{18}, 100 μA, $\Rightarrow 1.1 \cdot 10^{18}$ ion decays/straight session/year. $\Rightarrow \nu_e$.
- These fluxes apply if the two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

Exciting new ideas about radioactive ion production

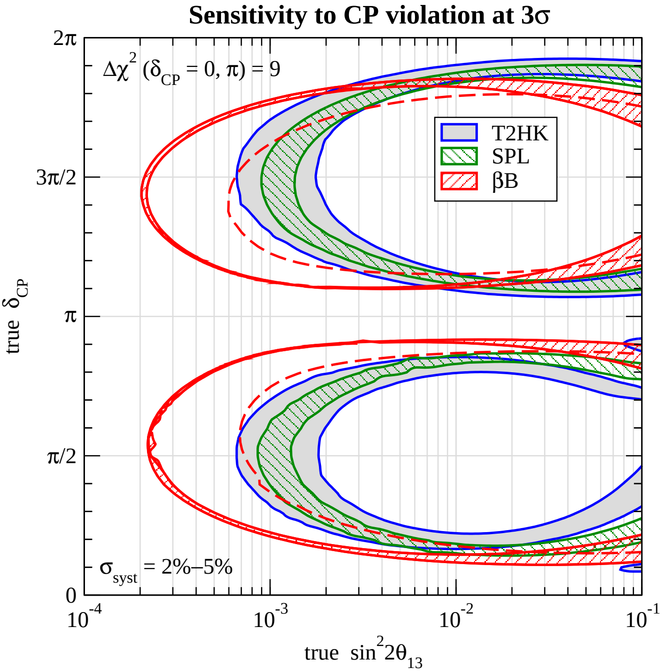
C. Rubbia et al., hep-ph/0602032
C. Rubbia hep-ph/0609235



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

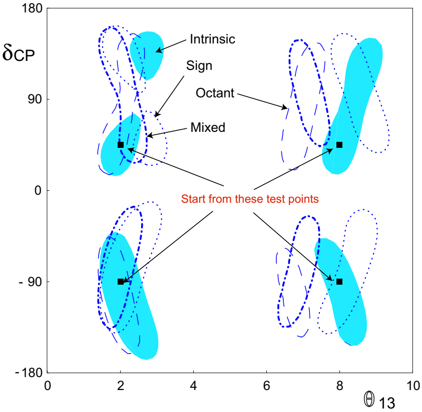


Line width: 2% and 5% systematic errors.


Sensitivity to CP violation at 3σ
Δχ² (δ_CP = 0, π) = 9
T2HK
SPL
βB
σ_syst = 2%–5%
2π
3π/2
π
π/2
0
true δ_CP
10^-4
10^-3
10^-2
10^-1
true sin²2θ_13

The degeneracy problem

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



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

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

The synergy with atmospheric neutrinos

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

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

The main reasons are:

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

NOTE: LBL and atmospherics are a true synergy. They add to each other much more that a simple gain in statistics. Atmospherics alone could not measure the hierarchy, the octant, θ_{13} and LCPV. While the Beta Beam at short baselines could not measure the hierarchy as well as the octant.
In the following sensitivities of the Beta Beam combined with the atmospherics are taken from J.E.Campagne, M.Maltoni, M.M., T.Schwetz, hep-ph/0603172

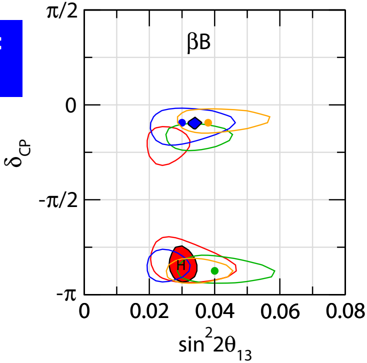
Beta Beam plus atmospherics: degeneracy removal

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

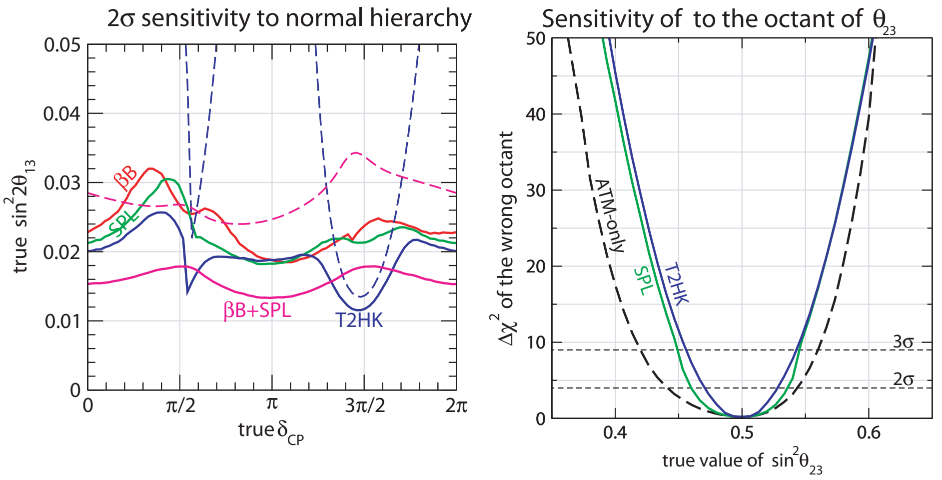
The red region is what is left after the atmospheric analysis.

Note how degeneracies were not influencing LCPV sensitivity too much.

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



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


2σ sensitivity to normal hierarchy
true sin²2θ13
true δCP
0
0.01
0.02
0.03
0.04
0.05
0
π/2
π
3π/2
2π
βB
SPL
βB+SPL
T2HK
Sensitivity of to the octant of θ23
Δχ² of the wrong octant
true value of sin²θ23
0
10
20
30
40
50
0.4
0.5
0.6
ATM-only
SPL
T2HK
3σ
2σ

The high energy options

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

- J. Burguet-Castell et al., Nucl. Phys. B **695**, 217 (2004), Nucl. Phys. B 725, 306 (2005) ($\gamma = 150, 350$)
- F. Terranova et al., Eur. Phys. J. C **38** (2004) 69: $\gamma = 2500$, $\gamma = 4158$
- P. Huber, M. Lindner, M. Rolinec and W. Winter, Phys. Rev. D 73,053002 (with a discussion of fluxes vs. γ).
- S. Agarwalla et al.: Phys. Rev. D **75**, 097302 (2007), Nucl. Phys. B **798**, 124 (2008), arXiv:0802.3621 [hep-ex], arXiv:0804.3007 [hep-ph].
- W. Winter, arXiv:0804.4000

> - Need a proton machine of 1 TeV energy (LHC cannot be used at such high fluxes)
> - Assume the same ion decay rates of the SPS option.
> - The decay ring length rises linearly with γ

Electron capture beams

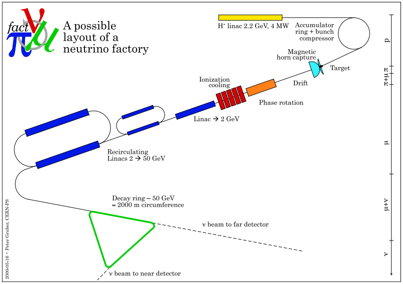
Radioactive ions can produce neutrinos also through electron capture.
Monochromatic, single flavor neutrino beams!

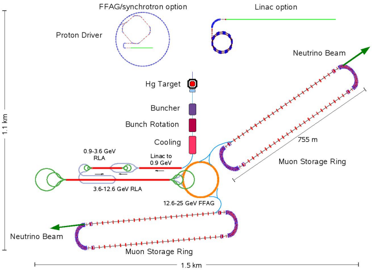
- J. Bernabeu, J. Burguet-Castell, C. Espinoza and M. Lindroos, hep-ph/0505054
- J. Sato, hep-ph/0503144. M. Rolinec and J. Sato, hep-ph/0612148.

- The same complex could run either beta or electron capture beams.
- No way to have $\overline{\nu}_e$ beams.
- Ions should be partially (and not fully) stripped. Technologically challenging.
- Ion candidates are much heavier than beta candidates and have longer lifetimes (more difficult to stack them in the decay ring)

The basic concept of a neutrino factory

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





Oscillation signals at the neutrino factory

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

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

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

All these detectors can be accomodate at LNGS.
Ideal baseline for a 50 GeV Neutrino Factory is $\sim$ 3000 km.

The possible role of LNGS

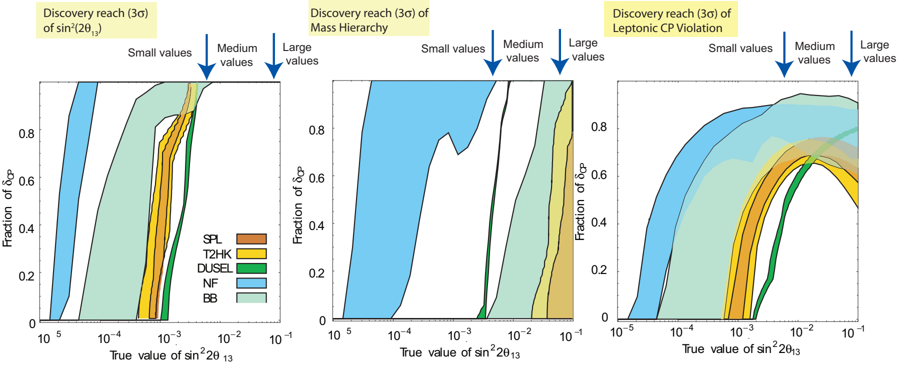
Battiston, Mezzetto, Migliozzi, Terranova submitted to Rivista NC

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

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

LNGS opportunities are directly linked to advanced neutrino beam options.

Sensitivity Comparison



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

Conclusions

- Sta cominciando una seconda generazione di esperimenti Long Baseline, ottimizzata per la ricerca di θ_{13} . T2K guida la corsa degli esperimenti agli acceleratori, in competizione/sinergia con Double Chooz e Daya Bay ai reattori.
- I risultati di questa ricerca saranno fondamentali per ottimizzare la generazione successiva, che dovrá iniziare la ricerca di violazione di CP leptonica e la misura della mass hierarchy.
- Per questa terza generazione di esperimenti saranno probabilmente necessari fasci di neutrini di nuova concezione quali Beta Beam e Neutrino Factory.
- L'Europa, attraverso il CERN, puó ritornare prepotentemente in gioco in questa nuova generazione di esperimenti