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" Ricerche Sperimentali su θ_{13}"

- Introduzione
- La prossima generazione di esperimenti: θ_{13}.
  - Acceleratori: T2K, poi Noνa.
  - Reattori: Double Chooz, Daya Bay.
- Confronti, evoluzioni temporali.
- La generazione successiva: $\delta_{\rm CP}$ and $\mathrm{sign}(\Delta m^2_{23})$.
  - Super Beams
  - Beta Beams
  - Neutrino Factories

Parameters of the Standard Model

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

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Parameters added after neutrino oscillations

$m_{\nu e}$	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

Matrice di mixing dei neutrini

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

La matrice di mixing dei neutrini U_{MNSP} è molto diversa dalla matrice di mixing dei quark U_{CKM}

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

Neutrini Atmosferici — Unknown — Neutrini Solari

$\theta_{13} \to 0 \quad \Rightarrow$ La matrice 3x3 di mixing diventa il prodotto di due matrici 2x2.
La conoscenza di θ_{13} prelude ad ogni futura ricerca di violazione di CP leptonica.

La maggior parte dei parametri di oscillazione aspetta di essre misurata

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

θ_{12} ✓ — SOLARS+KAMLAND: $\sin^2(2\theta_{12}) = 0.82 \pm 0.055$

Addressed by a SuperBeam/Nufact experiment

δm^2_{23} ✓ — ATMOSPHERICS: $\delta m^2_{23} = (2.4 \pm 0.4)\, 10^{-3}\, eV^2$

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

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

LSND/Steriles ✓?

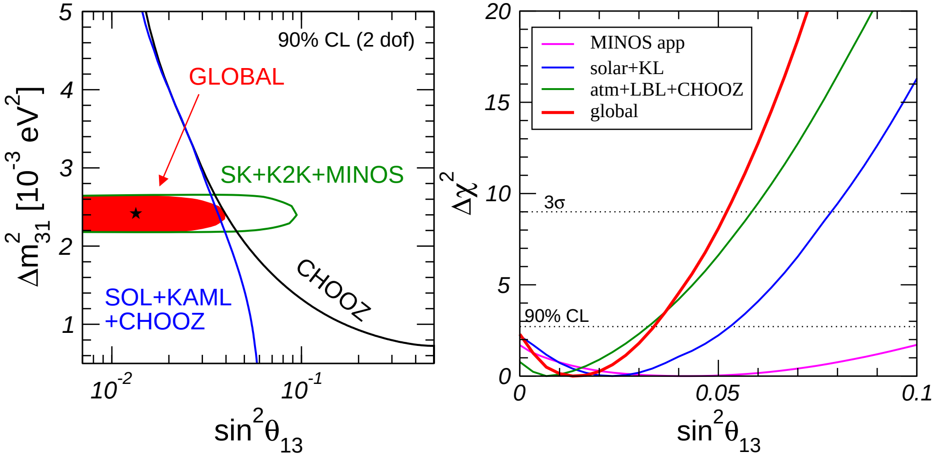
δ_{CP} ☐

Mass hierarchy ☐

Σm_ν ☐ — BETA DECAY END POINT: $\Sigma m_\nu < 6.6\, eV$

Dirac/Majorana ☐

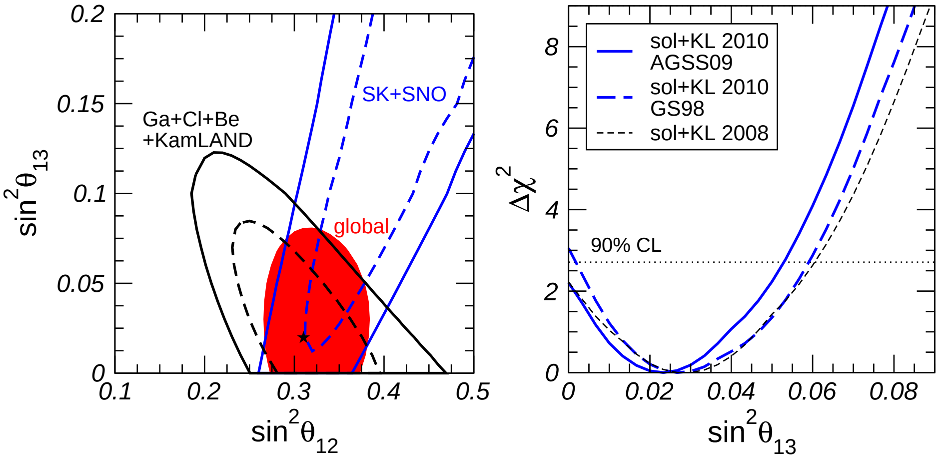
Stato delle conoscenze su θ_{13}



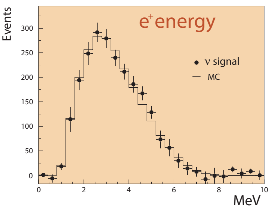
$$\begin{aligned} \sin^2\theta_{13} &\le 0.034 \quad (0.053) \\ \sin^2 2\theta_{13} &\le 0.13 \quad (0.20) \qquad 90\%\ (3\sigma)\ \text{CL}\,. \\ \theta_{13} &\le 10.6^\circ \quad (13.3^\circ) \end{aligned}$$

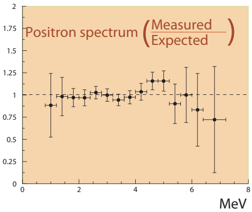
I neutrini solari favoriscono $\theta_{13} \neq 0$

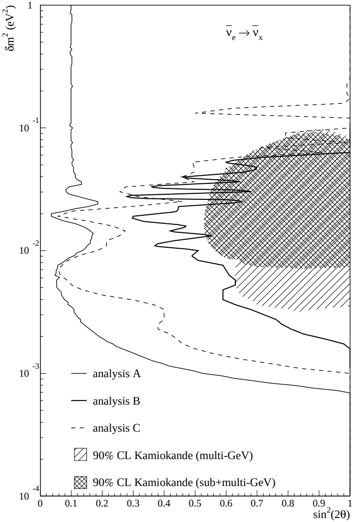
La tensione dei dati dei solari e di Kamland favorisce un fit a $\theta_{13} \neq 0$



CHOOZ ai Reattori (1998)



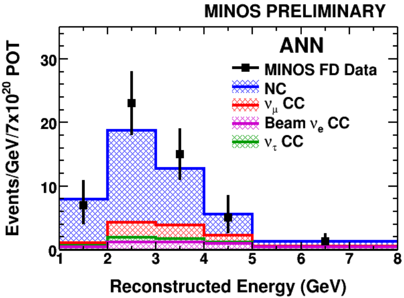


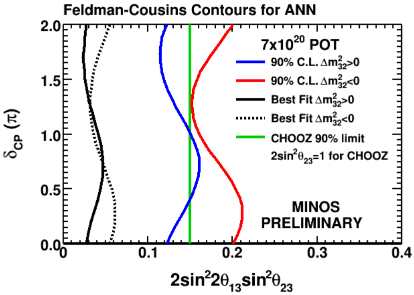


$$R = 1.01 \pm 2.8\%(\mathrm{stat}) \pm 2.7\%(\mathrm{syst})\,.$$

Esperimenti ai Reattori e Acceleratori non vedono segnale

Minos agli acceleratori (2010)



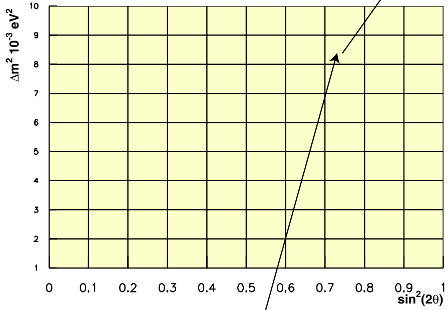


Eventi misurati 54

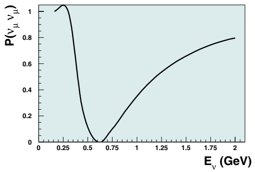
Backgrounds: $49.1 \pm 7(\mathrm{stat}) \pm 2.7(\mathrm{syst})$

How to build the signal/exclusion plot

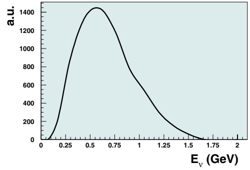
Grid in the $\sin^2 2\theta, \Delta m^2$ **plane**



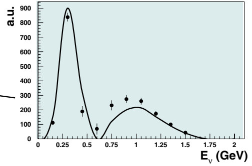
Every $\sin^2 2\theta$, Δm^2 cell defines $P_{\nu_\mu \nu_\mu}$



That modulates the non-oscillated predicted spectrum



The prediction is compared to the data



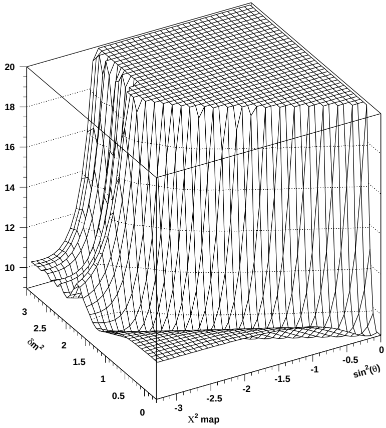
Fill the grid with the χ^2

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



Esperimenti in fase di avvio

- Ai Reattori
  - Double Chooz (Just Started)
  - RENO (Just Starting)
  - Daya Bay (12/2011)
- Agli Acceleratori
  - T2K (1/2010)
  - NOνA(2013)

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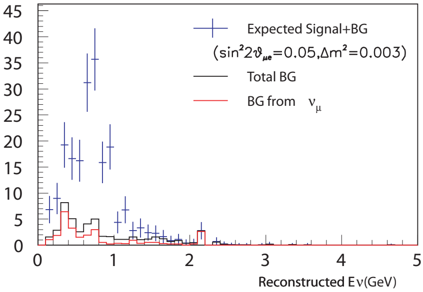
θ_{13} ai reattori

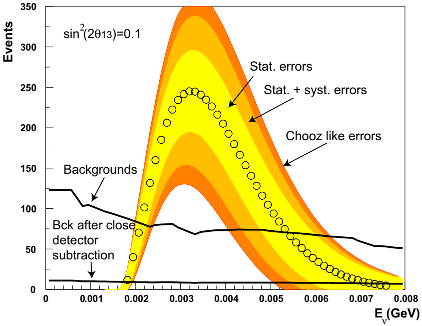
$$1 - P_{\bar\nu_e\bar\nu_e} \simeq \sin^2 2\theta_{13} \sin^2(\Delta m^2_{31} L/4E) + (\Delta m^2_{21}/\Delta m^2_{31})^2 (\Delta m^2_{31} L/4E)^2 \cos^4\theta_{13} \sin^2 2\theta_{12}$$

- Connessione diretta fra $P_{\bar e\bar e}$ e θ_{13}, senza interferenze da termini con $\delta_{\rm CP}$ e ${\rm sign}(\Delta m^2_{23})$.
- Preclusa ogni possibilità di misurare violazione di CP e mass hierarchy.
- Complementeari con gli esperimenti agli acceleratori.
- Esperimenti di scomparsa (disappearance) di neutrini: dominati dagli errori sistematici.

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



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



Esperimenti ai reattori

Risultato di CHOOZ

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

Goal:

- Migliorare di un fattore almeno 5 l'errore statistico (25 volte più neutrini):
  - rivelatori più massivi (CHOOZ aveva un fiduciale di 5 ton)
  - più stabili nel tempo (CHOOZ prese dati per 8761.7 h, poi chiuse per il deteriorarsi della qualità dello scintillatore liquido a causa del gadolinio disciolto)
- Migliorare di un fattore almeno 5 gli errori sistematici:
  - close detector
  - disegno del rivelatore ottimizzato per ridurre ulteriormente i fondi e alcuni errori sistematici quali la definizione del volume fiduciale.

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:

- $L = \mathcal{O}(1\mathrm{km})$ $\Rightarrow$ atmospheric regime: Double Chooz, RENO, Daya Bay.
- $L = \mathcal{O}(200\mathrm{km})$ $\Rightarrow$ solar regime: Kamland

Neutrino flux

Detect absolute number of neutrino interaction and distortions of their spectrum

prompt positron signal, energy range.

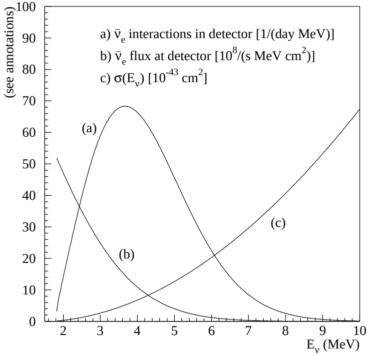
$\overline{\nu_e} p \rightarrow e^+ n$

$$n + p \underset{\tau \simeq 186\ \mu s}{\longrightarrow} d + \gamma(2.2\ MeV)$$

delayed correlated photon.

To determine neutrino flux:

1. **Measure of the reactor thermal power**
2. **Determination of the neutrino spectrum**
3. **Definition of the experimental observable: positron momentum spectrum.**

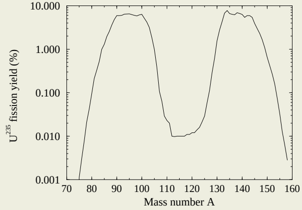


Thermal power of the reactor

The leading reaction is ^{235}U fission:

$$^{235}U + n \rightarrow X_1 + X_2 + 2n$$

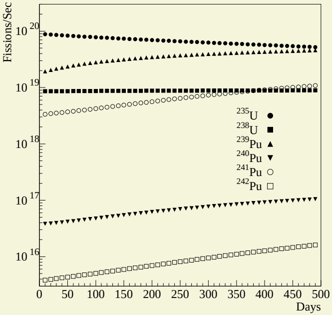
The lightest fragment have on average $A \simeq 94$, the heavier: $A \simeq 140$. Stable nuclei with $A = 94$, 140 are $_{40}Zr^{94}$ e $_{58}Ce^{140}$. ^{235}U has 98 protons and 142 neutrons $\Rightarrow$ to reach the stability, on average it needs 6 neutron β decays $\Rightarrow$ 6 $\overline{\nu}_e$.



The interaction process $\overline{\nu}_e + p \rightarrow n + e^+$ has a threshold of $\sim 1.8\,MeV$ $\Rightarrow$ only $\sim 25\%$ of neutrinos can be detected.

All the neutrinos from low Q-value processes, as nuclear fuel stored in the reactors and radioactivity induced in the nuclear plant structures, don't produce detectable neutrinos.

The fuel composition of the reactor core changes with the time, it's under monitor (reactor power depends from its composition).



From fission rate to the $\overline{\nu}_e$spectrum

The $\overline{\nu}_e$spectrum of three of the four principal fission nuclei: (^{235}U, ^{239}Pu, ^{241}Pu), has been derived by measuring the electron spectrum. The fourth: ^{238}U, has been computed from nuclear models, as well all the processes in the decay chain. Systematic error: $\sim 1\%$.

From $\overline{\nu}_e$to positrons

$\overline{\nu}_e + p \rightarrow n + e^+$ cross section:

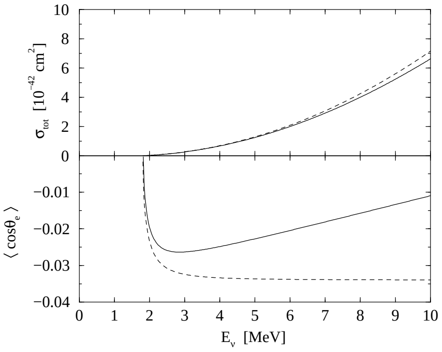
$$\begin{aligned} \sigma_{tot}^{(0)} &= \sigma_0 \, (f^2 + 3g^2) \, E_e^{(0)} p_e^{(0)} \\ &= 0.0952 \left(\frac{E_e^{(0)} p_e^{(0)}}{1 \text{ MeV}^2} \right) \times 10^{-42} \text{ cm}^2 \end{aligned} \quad (1)$$

$E_e^{(0)} = E_\nu - (M_n - M_p)$: positron energy (neglecting neutron recoil, marginal effect) $p_e^{(0)}$ momentum,

$f = 1, g = 1.26$ vector and axial coupling constants

$$\sigma_0 = \frac{G_F^2 \cos^2 \theta_C}{\pi} (1 + \Delta_{inner}^R) \; , \quad (2)$$

radiative corrections: $\Delta_{inner}^R \simeq 0.024$.

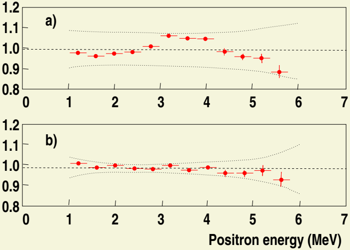


Solid lines: predictions at$\mathcal{O}(1/M_n)$, dashed $\mathcal{O}(1)$.

Data/prediction agreement (??)

Experiment Bugey 3 (years 80', the very recent reanalysis of reactor antineutrino flux yields interprets its result as a $\sim$ 3% deficit): expected and measured $\overline{\nu}_e$ spectrum.

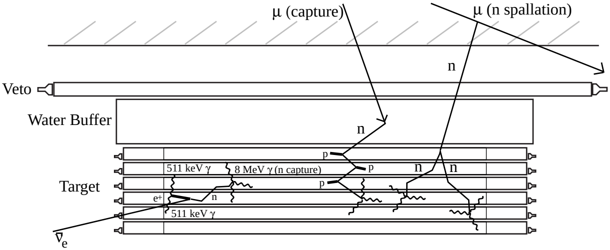
Curve b) is the most updated prediction.



Systematic errors summary (from `hep-ph/0107277`) Origin and magnitude of systematic errors in Palo Verde and Chooz. Note that the two experiments offer different breakdowns of their systematics. For simplicity we do not show the systematics for the Palo Verde ON-OFF analysis. The Palo Verde results are from the analysis of the full data set (Boehm *et al.* 2001).

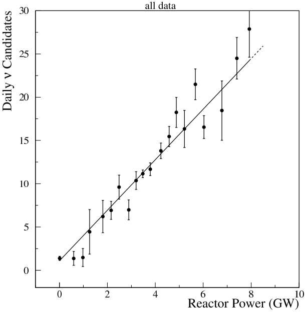
Systematic	Chooz (%)		P.V. (%)	
$\sigma(\overline{\nu}_e + p \to n + e^+)$	1.9		-	
Number of p in target	0.8		-	
W_{th}	0.7		-	
Energy abs. per fission	0.6		-	
Total rate prediction		2.3		2.1
e^+ trigger eff.	-		2.0	
n trigger eff.	-		2.1	
$\overline{\nu}_e$selection cuts	-		2.1	
$(1-\epsilon_1)B_{pn}$ estimate	-		3.3	
Total $\overline{\nu}_e$efficiency		1.5		4.9
Total		2.7		5.3

Experimental backgrounds



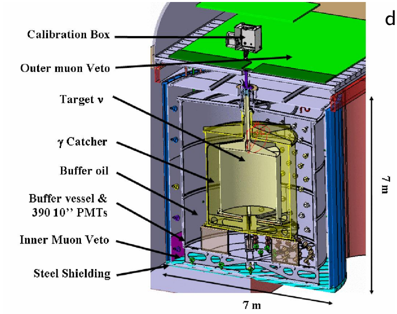
Two main categories:

- Accidental backgrounds from the random superposition of a “positron-like" and “neutron-like" signals. Directly estimated from the measured rates of the two processes.
- Backgrounds from neutrons induced by cosmic rays. They can be measured only if the reactor is off (impossible to pay to have a reactor shutdown).



Chooz counting rate as function of the reactors power.

Disegno di un rivelatore ai reattori



Inner detector Scintillatore liquido drogato con Gadolinio (0.1%) in un recipiente acrilico. Il Gadolinio aumenta la sezione d'urto dei neutroni, diminuendo il tempo di cattura da $\sim 170\,\mu$s a $\sim 27\,\mu$s $\Rightarrow$ riduzione del rumore non correlato. Inoltre aumenta l'energia dei gamma prodotti dalla cattura da ~ 2 MeV a ~ 8 MeV.

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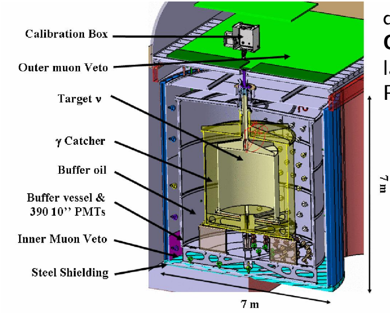

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Gamma catcher: Scintillatore liquido non drogato per la cattura dei gamma emessi dalla cattura dei neutroni. Permette una migliore definizione del volume fiduciale.

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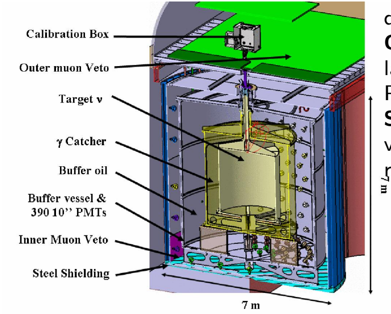

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Schermo per i fototubi: Olio non scintillatore, separa il volume attivo dai fototubi, che sono la maggior sorgente di radioattività all'interno del rivelatore.

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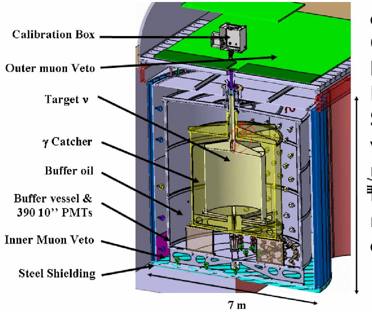

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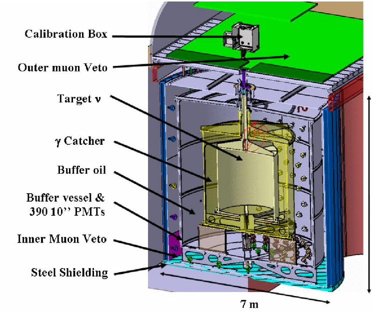
Inner veto: Per schermare i Compton indotti da radioattività esterna e da muoni passanti. È equipaggiato da fototubi.

Disegno di un rivelatore ai reattori



Inner detector Scintillatore liquido drogato con Gadolinio (0.1%) in un recipiente acrilico. Il Gadolinio aumenta la sezione d'urto dei neutroni, diminuendo il tempo di cattura da $\sim$ 170 μs a $\sim$ 27 μs $\Rightarrow$ riduzione del rumore non correlato. Inoltre aumenta l'energia dei gamma prodotti dalla cattura da $\sim$ 2 MeV a $\sim$ 8 MeV.

Gamma catcher: Scintillatore liquido non drogato per la cattura dei gamma emessi dalla cattura dei neutroni. Permette una migliore definizione del volume fiduciale.

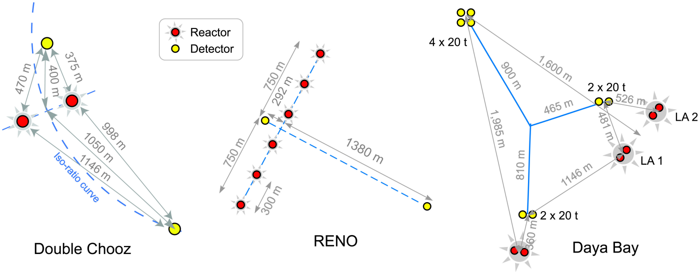
Schermo per i fototubi: Olio non scintillatore, separa il volume attivo dai fototubi, che sono la maggior sorgente di radioattività all'interno del rivelatore.

Inner veto: Per schermare i Compton indotti da radioattività esterna e da muoni passanti. È equipaggiato da fototubi.

Outer veto: Scintillatore solido (Double Chooz) o water Cherenkov (RENO e Daya Bay). Per vetare i μ passanti. Necessaria una profondità di almeno 100 m.w.e (dove i tempi morti indotti sono del 25%). Alcuni elementi prodotti dai iμ, come ^{8}He and ^{9}Li, con tempi di decadimento di 119 ms and 174 ms non possono comunque essere vetati.

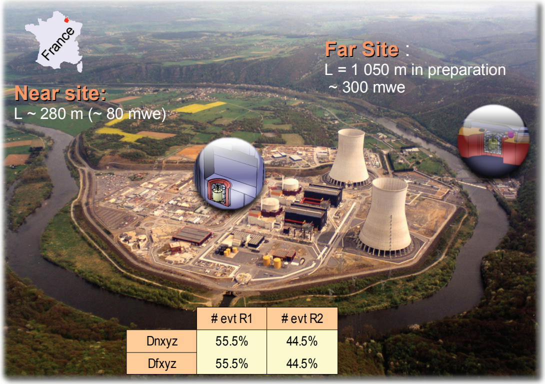
I tre player

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



Double Chooz

Talk by J. Dawson



	# 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%

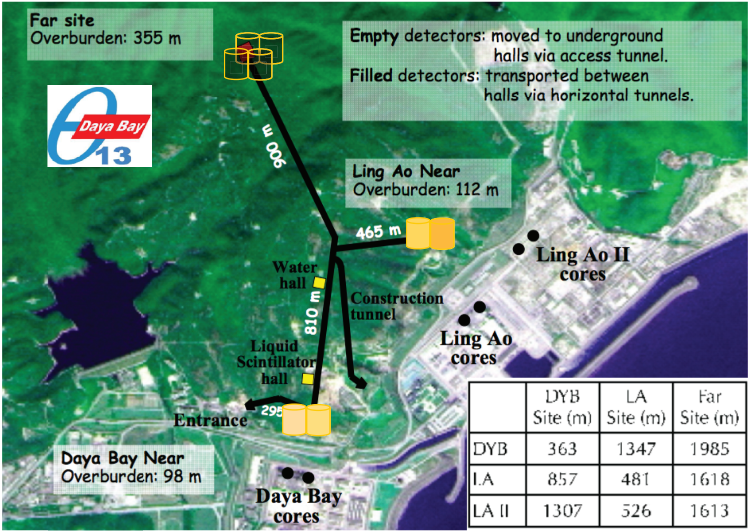
Backgrounds

- 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

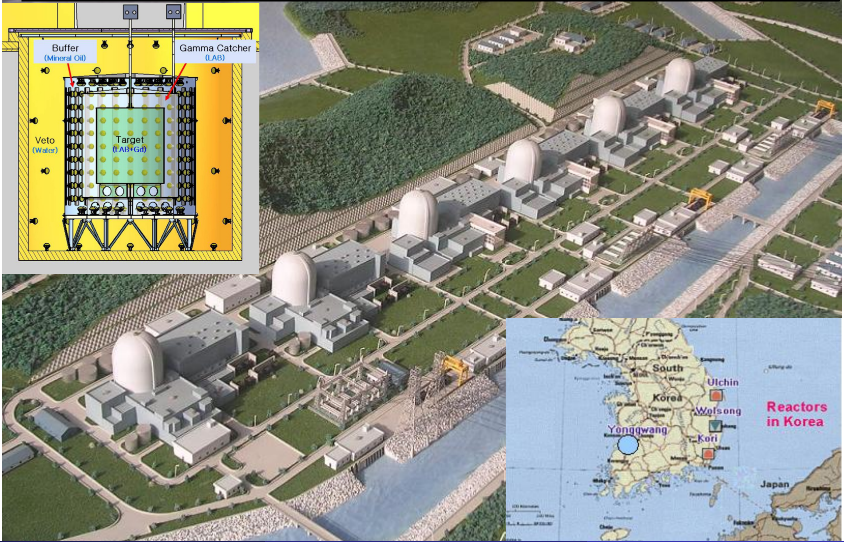
Daya Bay



	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$

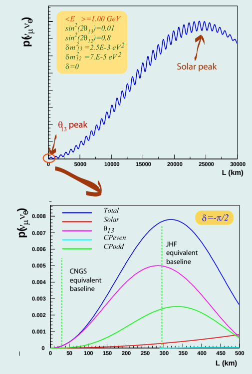


Reactors systematic business

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 %**

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



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

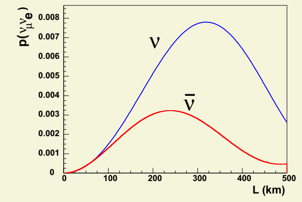
$$+ 8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23}) \cos\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{12}^2 L}{4E} \text{ CPev}$$

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

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

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

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

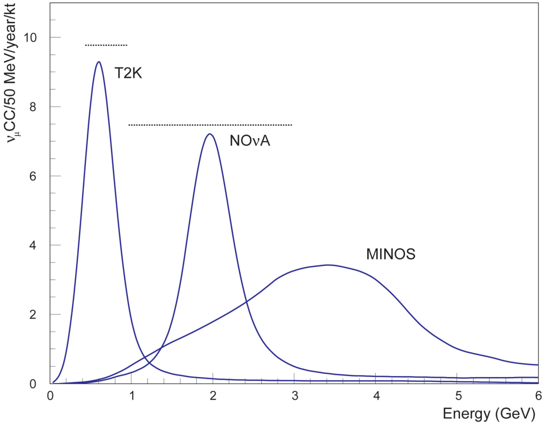


Leptonic CP discovery requires

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

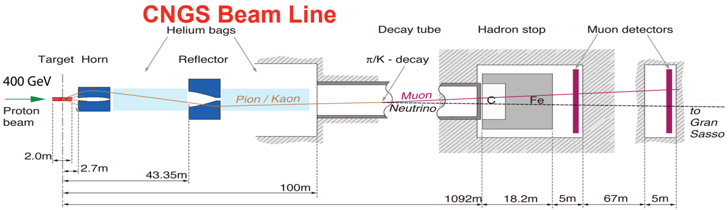
I due players

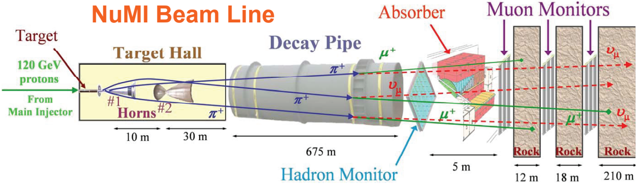
- **T2K** Started 12/2009, at J-Parc, Japan
- **NOνA** scheduled to start in 2013

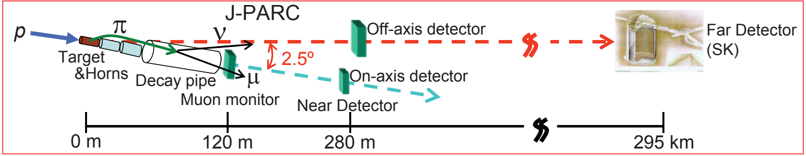


Linee orizzontali: regioni dove la probabilità di oscillazione è $P(\nu_\mu \to \nu_e) > 0.5$

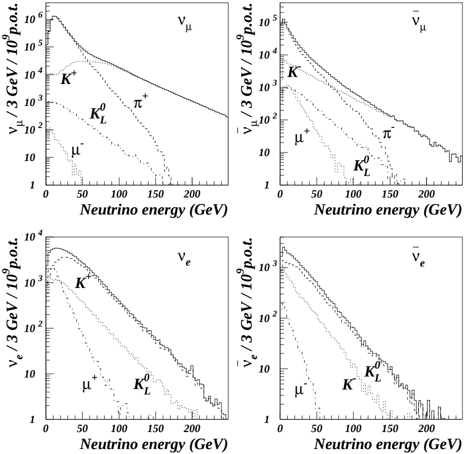
FASCI DI NEUTRINI







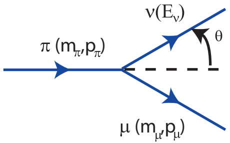
Neutrino beam composition



ν species	Flux Abund.	Flux $\langle E_\nu \rangle$	π^+ or π^- %	π^+ or π^- $\langle E_\nu \rangle$	K^+ or km %	K^+ or km $\langle E_\nu \rangle$	K^0_L %	K^0_L $\langle E_\nu \rangle$	μ^+ or μ^- %	μ^+ or μ^- $\langle E_\nu \rangle$
ν_μ	1.0	24.3	90.4	19.1	9.5	73.0	0.1	26.8	<0.1	11.4
$\overline{\nu}_\mu$	0.0678	17.2	84.0	13.8	12.8	38.1	1.9	26.9	1.2	17.0
ν_e	0.0102	36.4	–	–	68.0	41.8	17.8	30.3	13.6	16.8
$\overline{\nu}_e$	0.0027	27.6	–	–	25.1	22.8	68.2	30.4	3.5	11.1

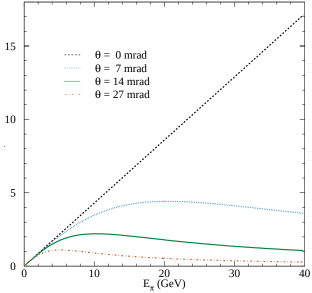
Off Axis Neutrino Beams.

Decay Kinematics

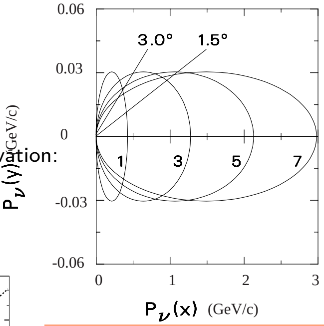


From momentum energy conservation:

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

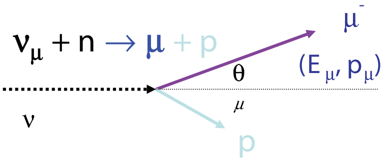


A qualitative argument:



- 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

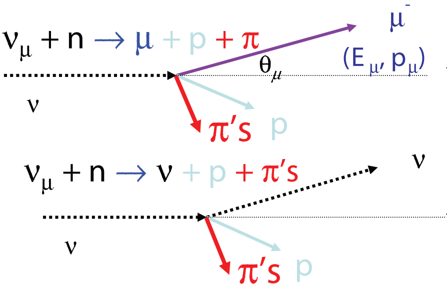
- **Maximum neutrino flux at** 0°**.**
- **Off axis is the most efficient way to have a narrow band beam.**
- ν_e **come from 3 body decays (kaons or muons) while off-axis is optimized on the pion 2 body decay**$\Rightarrow$ **the** ν_e **contamination below the peak is reduced.**



- 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 $\delta E/E \sim 10\%$



- bkg. for E_ν measurement

High energy part

- bkg.for e-appearance

The T2K Experiment

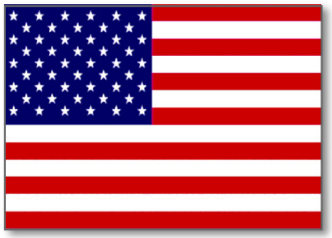
T2K Collaboration

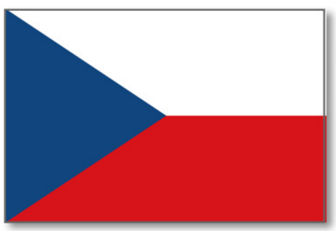
12 countries, 59 institutions, ~500 members

Canada
U. Alberta – U. B. Columbia – U. Regina – U. Toronto – TRIUMF – U. Victoria – York U.
France
CEA Saclay – IPN Lyon – LLR E. Poly. – LPNHE Paris
Germany
RWTH – Aachen U.
Italy
INFN, U. Bari – INFN, U. Napoli – INFN, U. Padova – INFN, U. Roma
Japan
ICRR Kamioka – ICRR RCCN – KEK – Kobe U. – Kyoto U. – Miyagi U. Edu. – Osaka City U. – U. Tokyo
Poland
A. Soltan, Warsaw – H.Niewodniczanski, Cracow – U. Silesia, Katowice – T. U. Warsaw – U. Warsaw – U. Wroclaw
Russia
INR
S Korea
N. U. Chonnam – U. Dongshin – N. U. Seoul
Spain
IFIC, Valencia – U. A. Barcelona
Switzerland
ETH Zurich – U. Bern – U. Geneva
UK
Imperial C. L. – Lancaster U. – Liverpool U. – Queen Mary U. L. – Oxford U. – Sheffield U. – STFC/RAL – STFC/Daresbury – Warwick U.
USA
Boston U. – B.N.L. – Colorado S. U. – U. Colorado – Duke U. – U. C. Irvine – Louisiana S. U. – U. Pittsburgh – U. Rochester – Stony Brook U. – U. Washington

The NOvA Collaboration

140 Collaborators in 26 Institutions from 4 Countries





Argonne, Athens, Caltech, Charles, CTU Prague, Fermilab, FZU, Harvard, Indiana, Lebedev Physical Institute, Michigan State, Minnesota-Twin Cities, Minnesota-Duluth, INR Moscow, Iowa State, P.U.C. Rio de Janeiro, South Carolina, SMU, Stanford, Tennessee, Texas-Austin,Texas-Dallas, Tufts, Virginia, Wichita State, William & Mary

Double Chooz Collaboration

Brazil
CBPF
UNICAMP
UFABC

France
APC
CEA/DSM/IRFU:
SPP
SPhN
SEDI
SIS
SENAC
CNRS/IN2P3:
Subatech
IPHC
ULB

Germany
EKU Tübingen
MPIK Heidelberg
TU München
U. Aachen
U. Hamburg

Japan
Tohoku U.
Tokyo Inst. Tech.
Tokyo Metro. U.
Niigata U.
Kobe U.
Tohoku Gakuin U.
Hiroshima InstTech.

Russia
INR RAS
IPC RAS
RRC Kurchatov

Spain
CIEMAT-Madrid

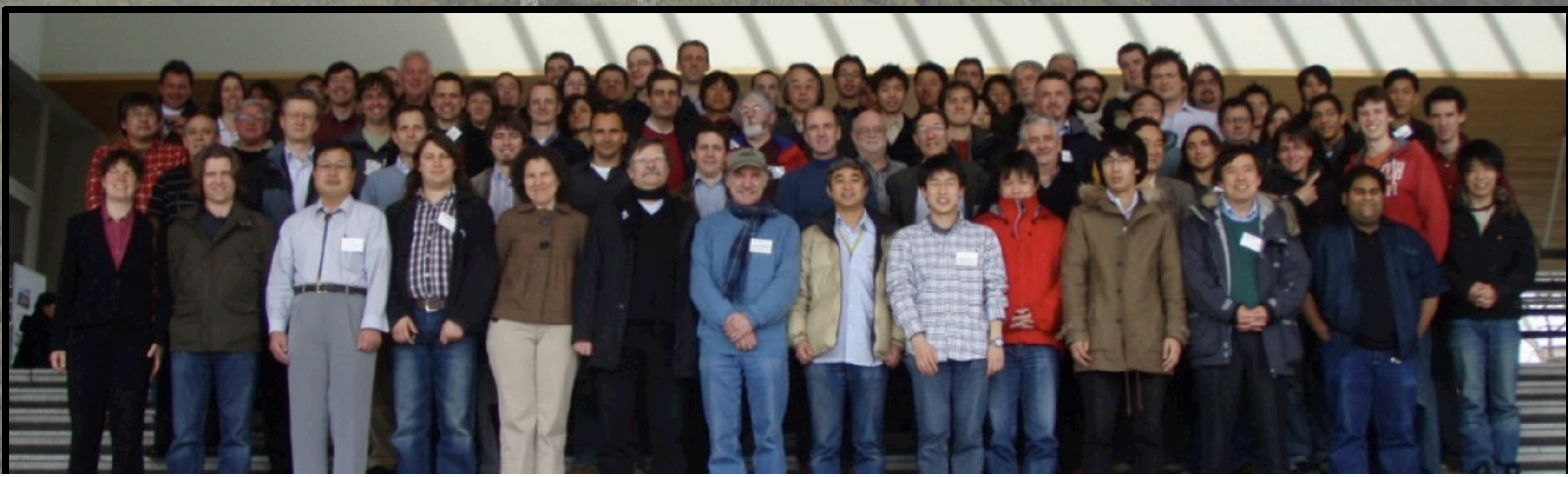
UK
Sussex

USA
U. Alabama
ANL
U. Chicago
Columbia U.
UCDavis
Drexel U.
IIT
KSU
LLNL
MIT
U. Notre Dame
Sandia National Laboratories
U. Tennessee

!!!all DC Japanese colleagues safe!!!

Spokesperson: H. de Kerret (CNRS/IN2P3-APC)
Project Manager: Ch. Veyssière (CEA-Saclay)

Web Site: www.doublechooz.in2p3.fr/

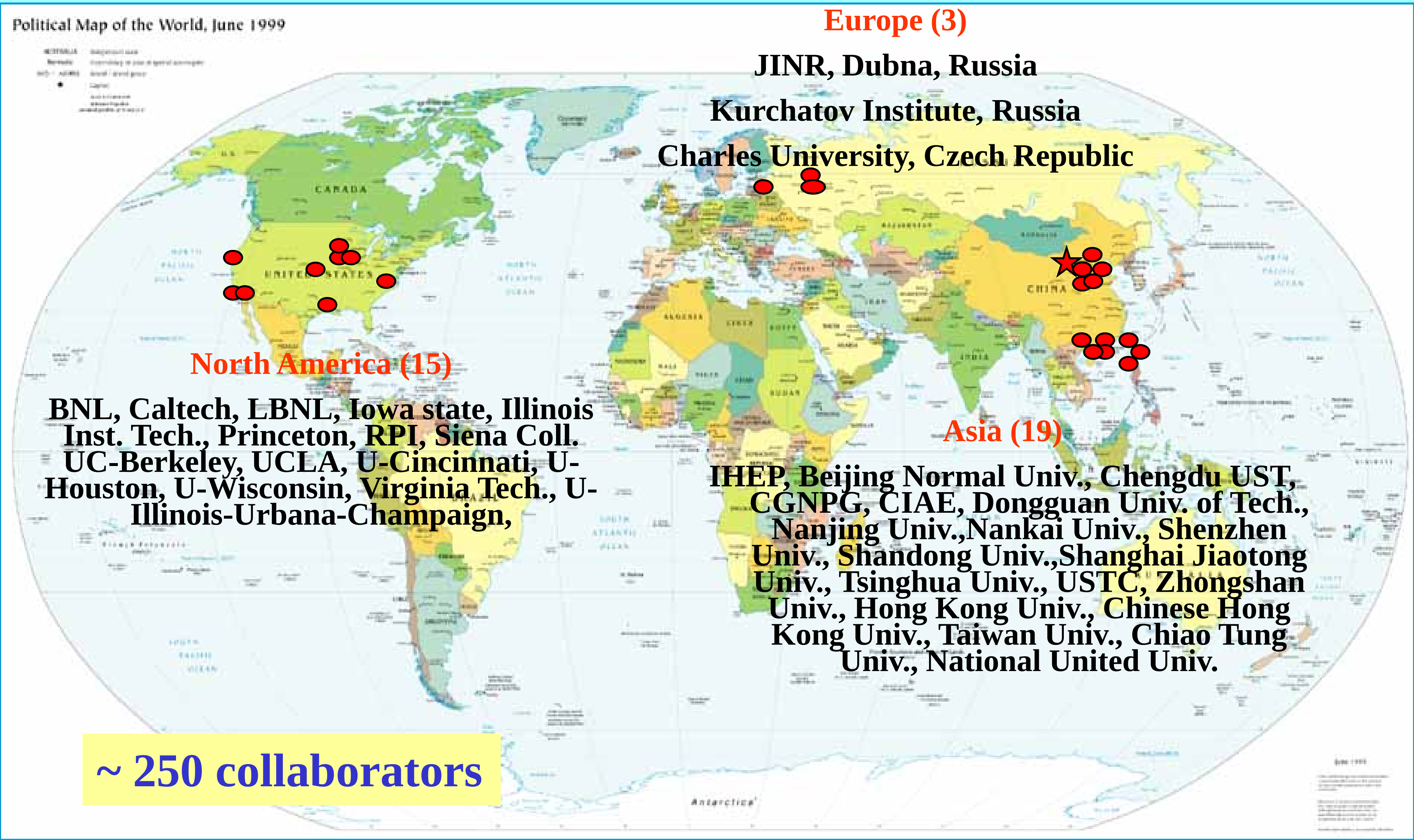


RENO Collaboration

(13 institutions and 40 physicists)

- Chonnam National University
- Chonbuk National University
- Chung-Ang University
- Dongshin University
- Gyeongsang National University
- Kyungpook National University
- Pusan National University
- Sejong University
- Seokang Information University
- Seokyeong University
- Seoul National University
- Sungkyunkwan University
- California State University Dominguez Hills (USA)

Daya Bay collaboration



Europe (3)

JINR, Dubna, Russia

Kurchatov Institute, Russia

Charles University, Czech Republic

North America (15)

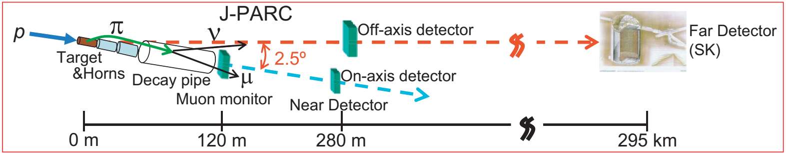
BNL, Caltech, LBNL, Iowa state, Illinois Inst. Tech., Princeton, RPI, Siena Coll. UC-Berkeley, UCLA, U-Cincinnati, U-Houston, U-Wisconsin, Virginia Tech., U-Illinois-Urbana-Champaign,

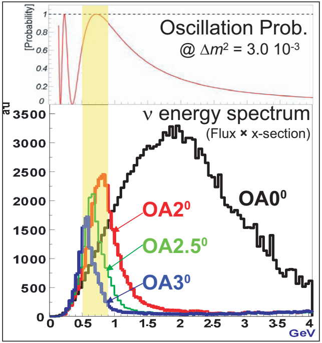
Asia (19)

IHEP, Beijing Normal Univ., Chengdu UST, CGNPG, CIAE, Dongguan Univ. of Tech., Nanjing Univ.,Nankai Univ., Shenzhen Univ., Shandong Univ.,Shanghai Jiaotong Univ., Tsinghua Univ., USTC, Zhongshan Univ., Hong Kong Univ., Chinese Hong Kong Univ., Taiwan Univ., Chiao Tung Univ., National United Univ.

~ 250 collaborators

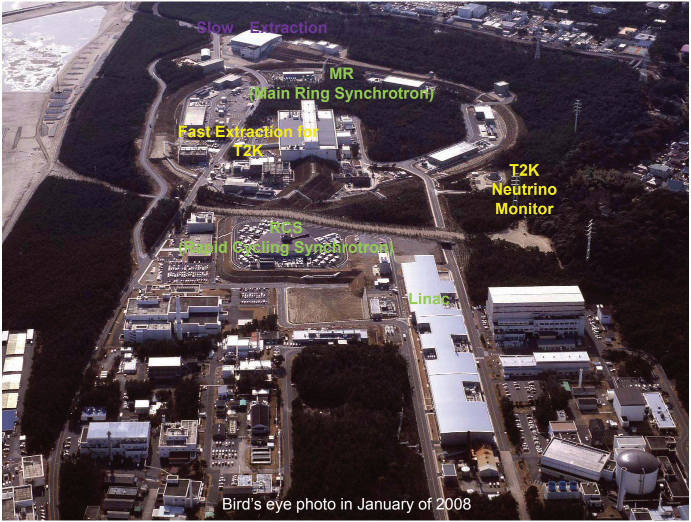
Experimental apparatus and neutrino beam



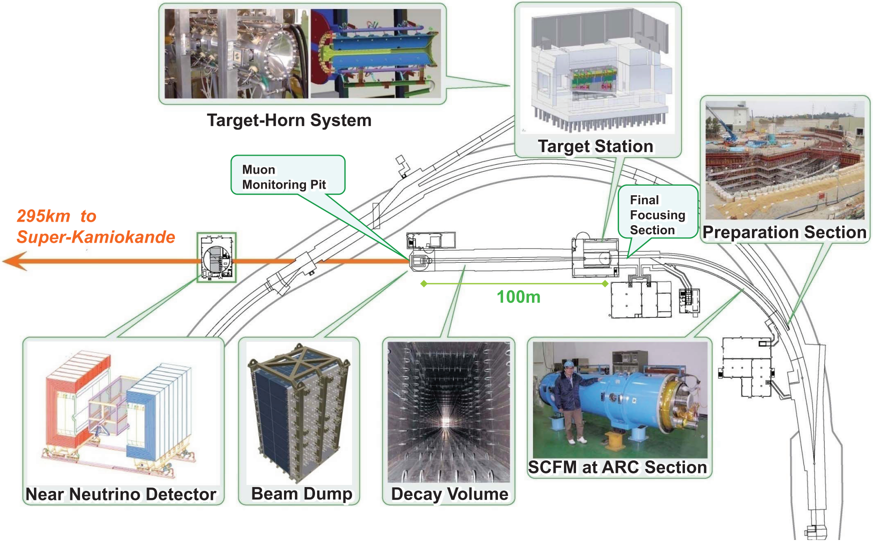


- Off-axis beam technique
  - Intense narrow band beam
- 2.5° off-axis
  - Energy peak tuned at oscillation max. ~ 0.7 GeV
- Statistics at Super-K
  - ~1600 ν_μ CC int./22.5kt/year (with 0.75kW beam, no oscillation case)
- Pure ν_μ beam
  - Beam ν_e contamination ~0.4% at ν_μ peak energy

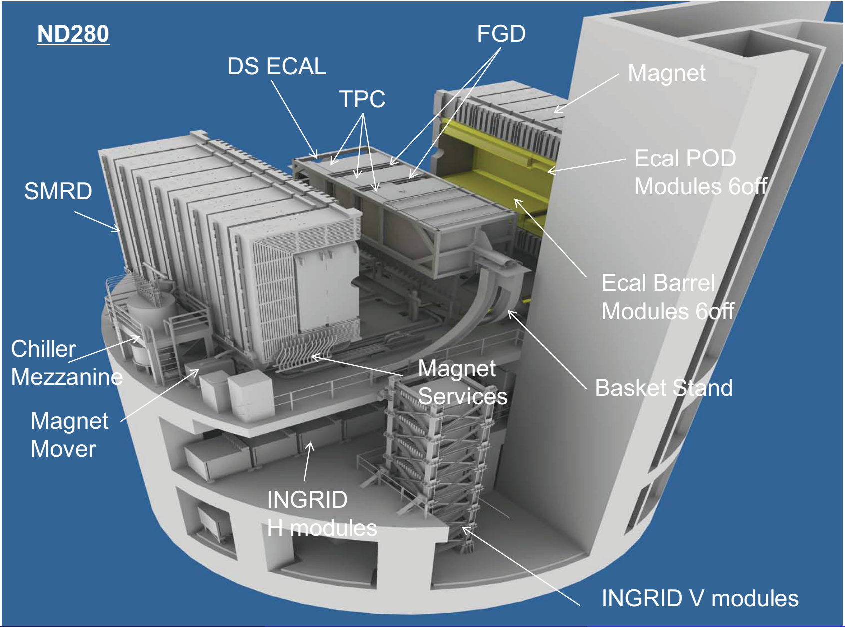
J-PARC Accelerator and Experimental Facility

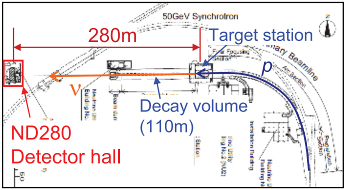


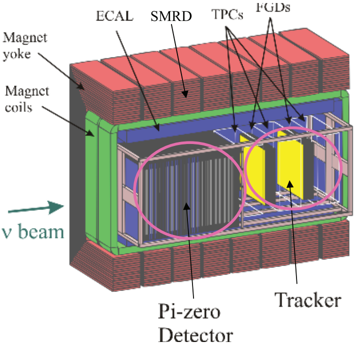
T2K experiment: the neutrino beam line



The Close Detector Station



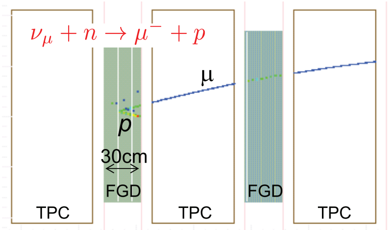




- Near off-axis detector located at 280 m downstream of the target
- Consists of 5 subdetectors:
  - Pi-zero detector (PØD)
    - measures NCπ^0 interactions
  - Tracker: fine-grained detector (FGD) and time projection chambers (TPC)
    - measures CC interactions
  - Electromagnetic calorimeter (ECAL)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



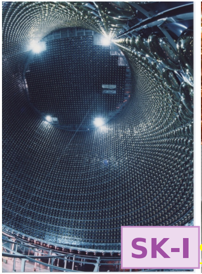
- Two independent CCQE / non-CCQE separation in a single detector:
  - Final state particles
  - Kinematics of 2nd track
- Kinematics of final state particles:
  - Fermi motions, nuclear effects, …

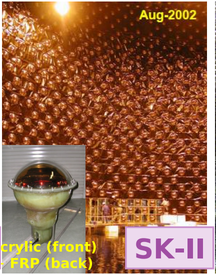
→ intensive study of the neutrino interactions

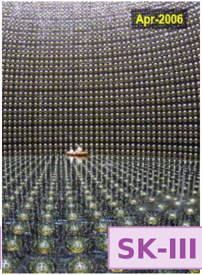
History of Super-Kamiokande detector

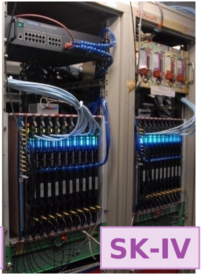
1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009

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



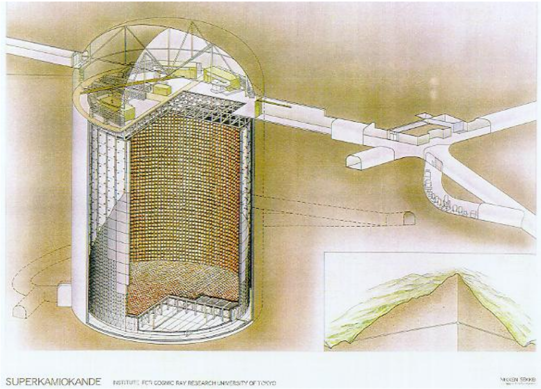






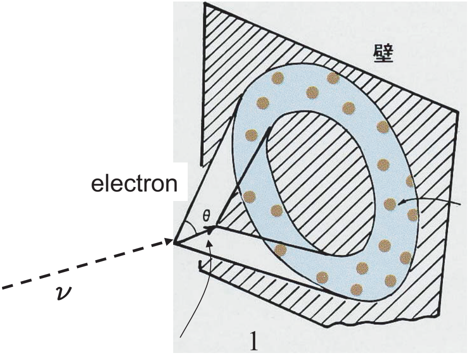
	SK-I	SK-II	SK-III	SK-IV
	11146 ID PMTs (40% coverage)	5182 ID PMTs (19% coverage)	11129 ID PMTs (40% coverage)	Electronics Upgrade
Energy Threshold (total electron	**5.0 MeV**	**7.0 MeV**	**4.5 MeV** work in progress	**< 4.0 MeV** target

SuperKamiokande detector



Tank	Dimensions Volume	$\phi = 39.3\,m,\ h = 41$ 50 kton
External Detector	Thickness Volume PMT's	2.6 m ($7.2X_0$ e 4.3λ 18 Kton 302 (top), 308 (bott
Internal Detector	Dimensions Volume PMT's	$\phi = 33.8\,m,\ h = 36$ 32 kton 1748 (top/bottom),
Fiducial	Thickness Volume	2m ($5.5X_0$, $3.3\lambda_0$) f 22 kton

Detecting Cherenkov photons



cos $\frac{1}{n}$

n (refractive index)=1.34
in water

⇨ θ =42deg. for β =1

Number of Ch. photons with λ =300-600 nm emitted by a relativistic particle per cm = 340.

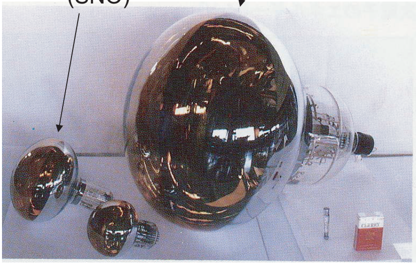
⇩

Need an efficient detection of the photons. ⇨ Large PMTs

Photomultiplier tube (PMT)

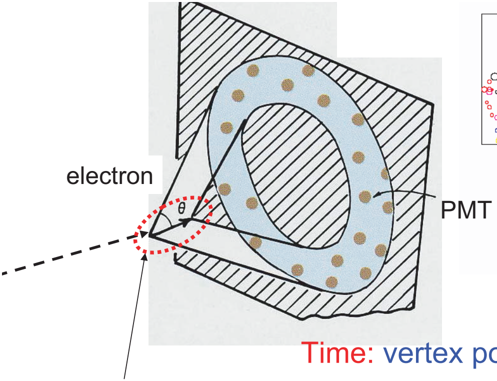
50cm ϕ (Super-K)

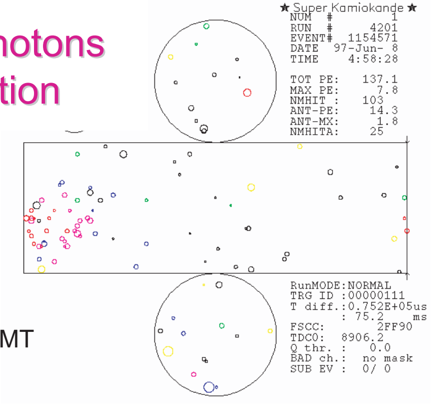
20cm ϕ (SNO)



T. Kajita - Nufact 05 School

Detecting Cherenkov photons and event reconstruction





Color: timing

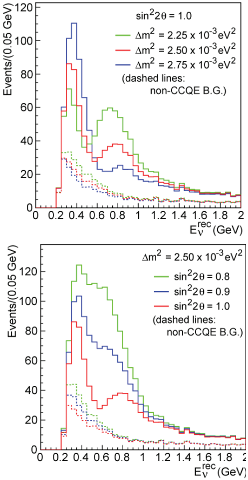
Size: pulse height

Time: vertex position

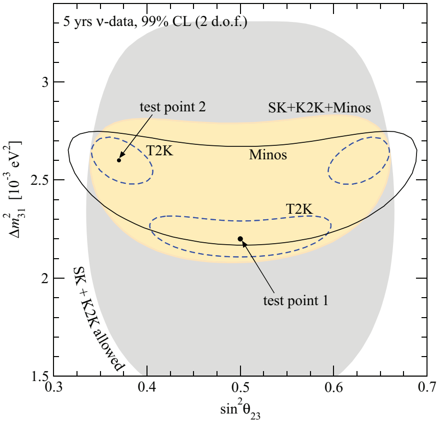
→ direction

Pulse height (number of pe's): energy

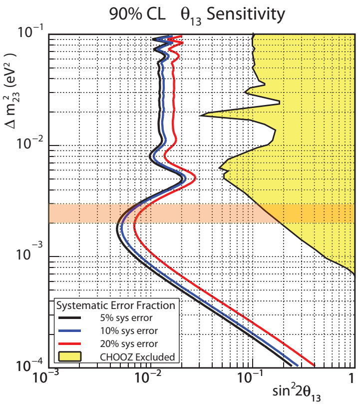
T. Kajita - Nufact 05 School

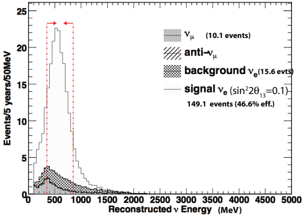


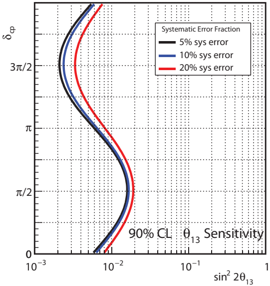
sin²2θ = 1.0
Δm² = 2.25 x 10⁻³eV²
Δm² = 2.50 x 10⁻³eV²
Δm² = 2.75 x 10⁻³eV²
(dashed lines: non-CCQE B.G.)
Events/(0.05 GeV)
E_ν^rec (GeV)
Δm² = 2.50 x 10⁻³eV²
sin²2θ = 0.8
sin²2θ = 0.9
sin²2θ = 1.0
(dashed lines: non-CCQE B.G.)
Events/(0.05 GeV)
E_ν^rec (GeV)



5 yrs ν-data, 99% CL (2 d.o.f.)
test point 2
SK+K2K+Minos
T2K
Minos
T2K
test point 1
SK + K2K allowed
Δm²₃₁ [10⁻³ eV²]
sin²θ₂₃


90% CL θ13 Sensitivity
Δ m²23 (eV²)
sin²2θ13
Systematic Error Fraction
5% sys error
10% sys error
20% sys error
CHOOZ Excluded


Events/5 years/50MeV
νμ (10.1 events)
anti-νμ
background νe (15.6 evts)
signal νe (sin²2θ13=0.1)
149.1 events (46.6% eff.)
Reconstructed ν Energy (MeV)


δCP
Systematic Error Fraction
5% sys error
10% sys error
20% sys error
90% CL θ13 Sensitivity
sin² 2θ13

Analysis strategies (2010a)

(A) ν_μ disappearance analysis:

- *T2K-SK data reduction 1-ring μ-like*
- *Prediction of expected events under two hypotheses:*
    1. *null oscillation*
    2. *oscillations with* $\Delta m^2_{23}=2.4\times10^{-3}eV^2$, $\sin^2 2\theta_{23}=1.0$
- *Comparison observed with expectation*

(B) ν_e appearance analysis:

- *T2K-SK data reduction 1-ring e-like*
- *Additional cuts for background suppression*
- *Prediction of expected events under two hypotheses:*
    1. *"background only" = oscillations with* $\Delta m^2_{23}=2.4\times10^{-3}eV^2$, $\sin^2 2\theta_{23}=1.0$, *and* $\theta_{13}\equiv0$
    2. *"signal+background" = same as 1. but with* $\sin^2 2\theta_{13}=0.1$
- *Oscillation parameters fit*

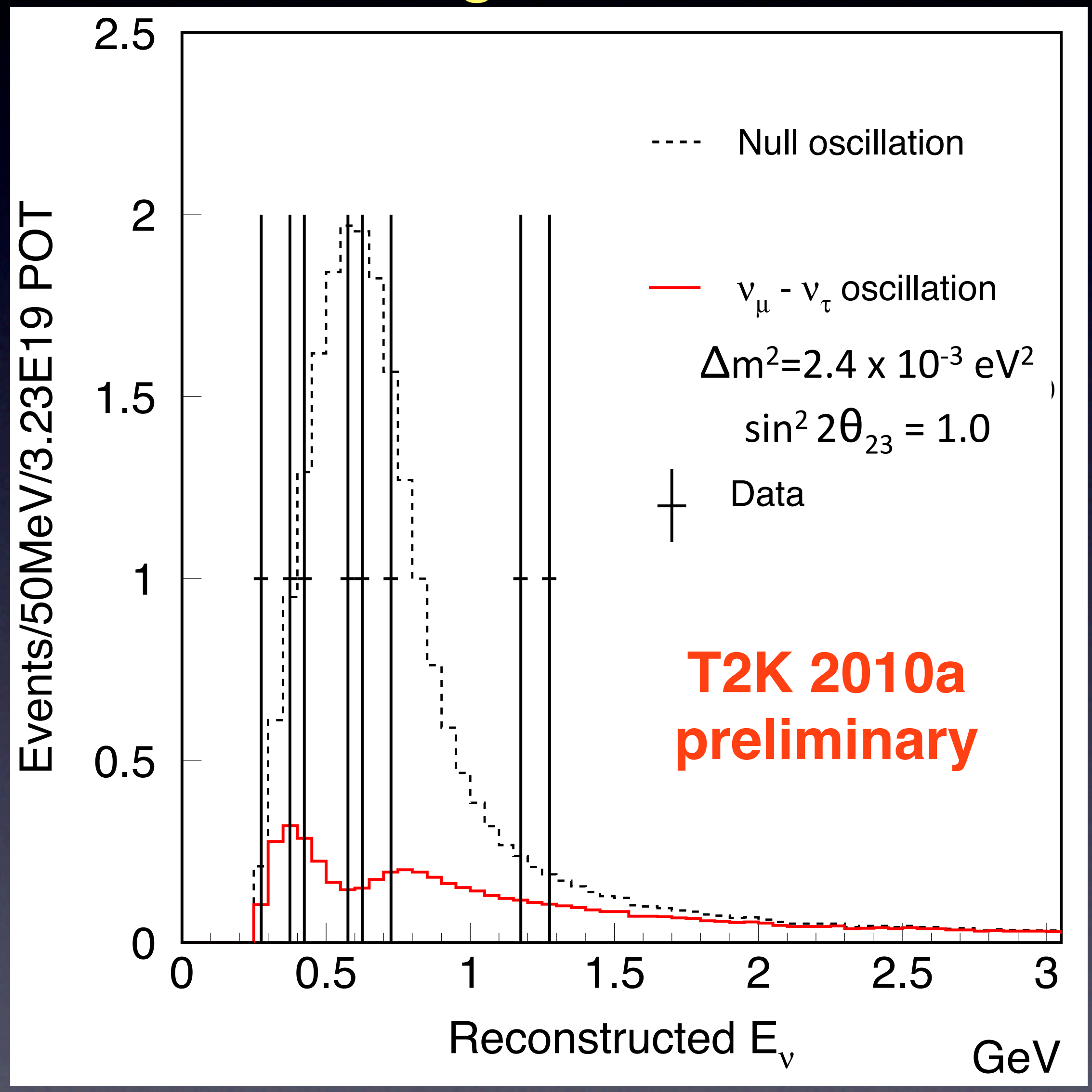
ν_μ disappearance analysis

Event selection for muon disappearance measurement

T2K-SK events	Data	MC No oscillation	MC W/ oscillation	Acc.BG (12μs window)
Fully-Contained	**33**	54.5	24.6	0.0094
Fiducial Volume, E_{vis} > 30MeV	**23**	36.8	16.7	0.0011
Single-ring μ-like P_μ>200MeV/c	**8**	24.5±3.9	7.1±1.3	-
+ number decay-e <=1 & Erec<10 GeV	**8**	22.8±3.2	6.3±1.0	-

Δm^2=2.4 x 10^{-3} eV^2 and $\sin^2 2\theta_{23}$ = 1.0

Reconstructed energy assuming QE kinematics



- Consistent with oscillation parameters measured by MINOS / SK / K2K
- Parameter fitting underway – T2K plans to release result in the near future

ν_e appearance analysis

Event selection for electron appearance search

T2K-SK events	Data	MC: No oscillation	MC: With oscillation and θ_{13}=0	Acc. BG (12μs window)
Fully-Contained	**33**	54.5	24.6	0.0094
Fiducial Volume, E_{vis} > 30MeV	**23**	36.8	16.7	0.0011
Single-ring e-like P_e>100MeV/c	**2**	1.5±0.7	1.3±0.6	-

Assumed oscillation parameters: Δm^2=2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$ = 1.0 and θ_{13} = 0

Apply additional background reduction cuts:

- # of decay electron ($\mu \rightarrow e + \nu_e$) =0
- Reconstructed invariant mass assuming 2γ rings exist <105MeV
- Reconstructed ν energy < 1250 MeV

Cut criteria were frozen before data collection to avoid bias

After all cuts: 65.9% signal efficiency

Sequential selection cuts

Sequential cuts - surviving number of events

Cut	Events
Fully contained, fiducial cut (FCFV)	23
Single ring e-like, E>100 MeV	2
# of decay electron =0	1
Reconstructed invariant mass assuming 2γ rings exist <105MeV	1
Reconstructed ν energy < 1250 MeV	1
Events in 2010a sample	**1**

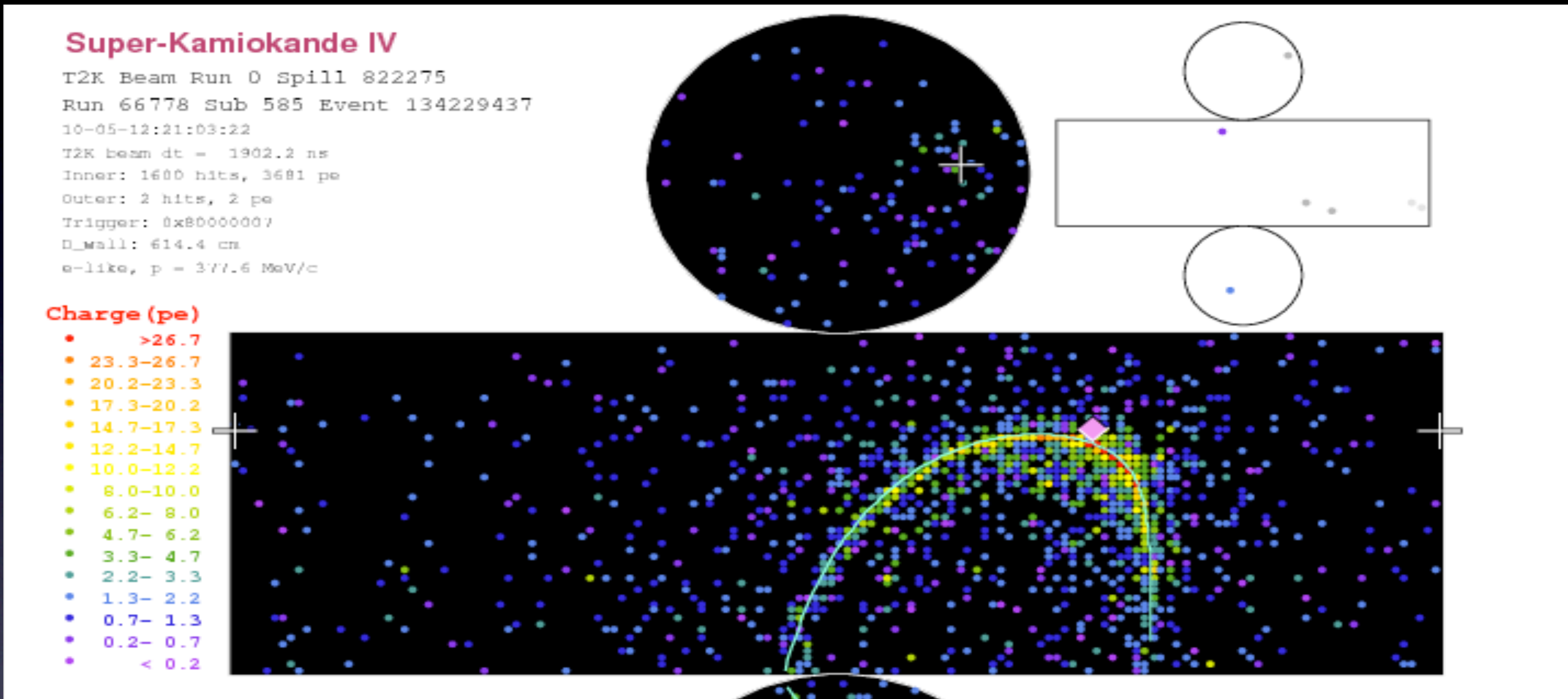
1 candidate exists!

$N_{SK}^{obs} = 1$

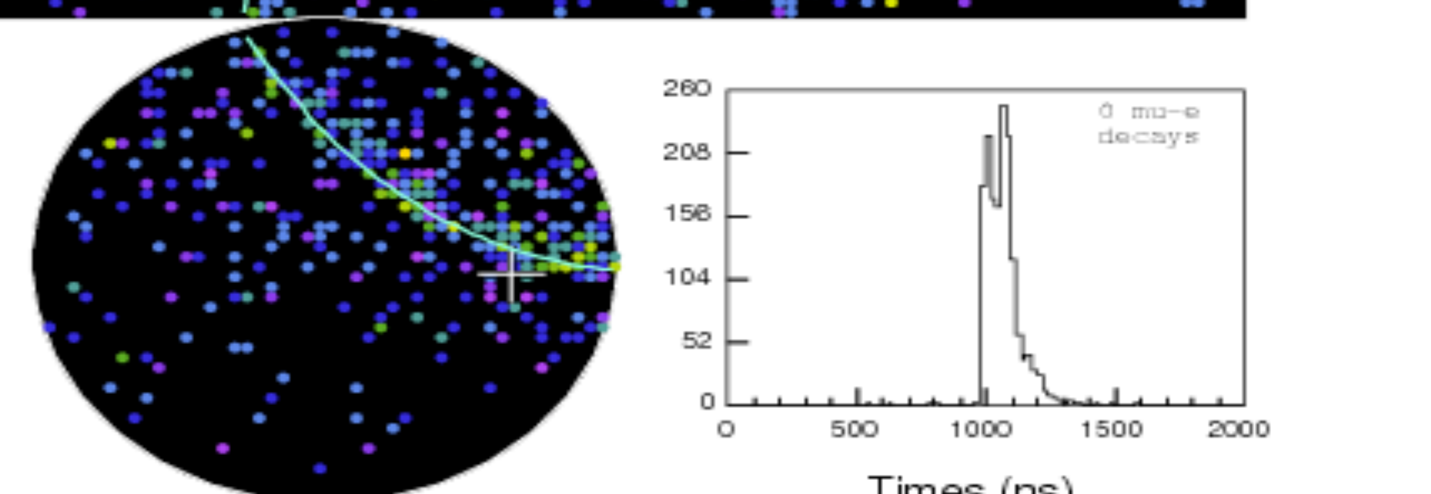
T2K preliminary (2010a)

T2K ν_e CC signal candidate (2010a)

Signal candidate event passing all cuts



Item	Event	T2K cut
Date (JST)	2010 May 12th 21:3:22	
Ring, PID	1-Ring electron-like	OK
Momentum	378 MeV	>100
N_{dcy}	0	0
$\cos(\theta_{\nu e})$	0.55 (57 degree)	N/A
$Mass$	0.13 MeV	<105
E_{rec}	496 MeV	<1250

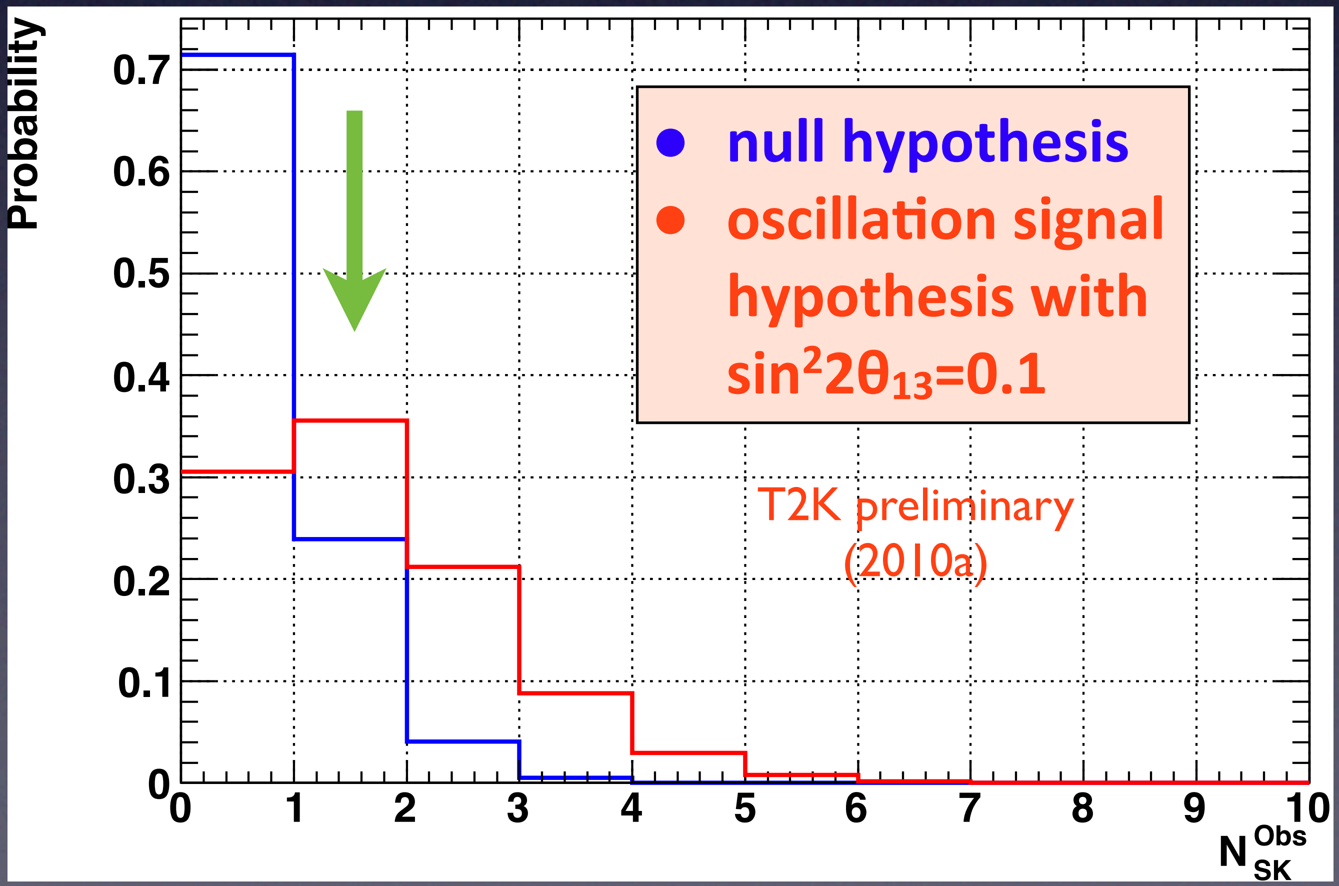


Expected #SK events

Source	Estimated number
Beam ν_μ (CC+NC)	0.13
Beam $\bar{\nu}_\mu$ (CC+NC)	0.01
Beam ν_e (CC)	0.16
Total background	**0.30 ± 0.07 (syst.)**
Total sig.+background	**1.20 ± 0.23 (syst.)**

- #events normalized to p.o.t. and corrected for ND280 ν_μ CC measured normalization
- Assumed oscillation parameters for signal:

$\Delta m^2_{23}=2.4\cdot 10^{-3}eV^2$
$\sin^2 2\theta_{23}=1.0$
$\sin^2 2\theta_{13}=0.1$
$\delta_{CP} = 0$



T2K preliminary (2010a)

~29% probability to observe >=1 event when expected average = 0.3 event

1 data candidate!

$N_{SK}^{obs} = 1$

Expected #SK events

Source	Estimated number
Beam ν_μ (CC+NC)	0.13
Beam $\bar{\nu}_\mu$ (CC+NC)	0.01
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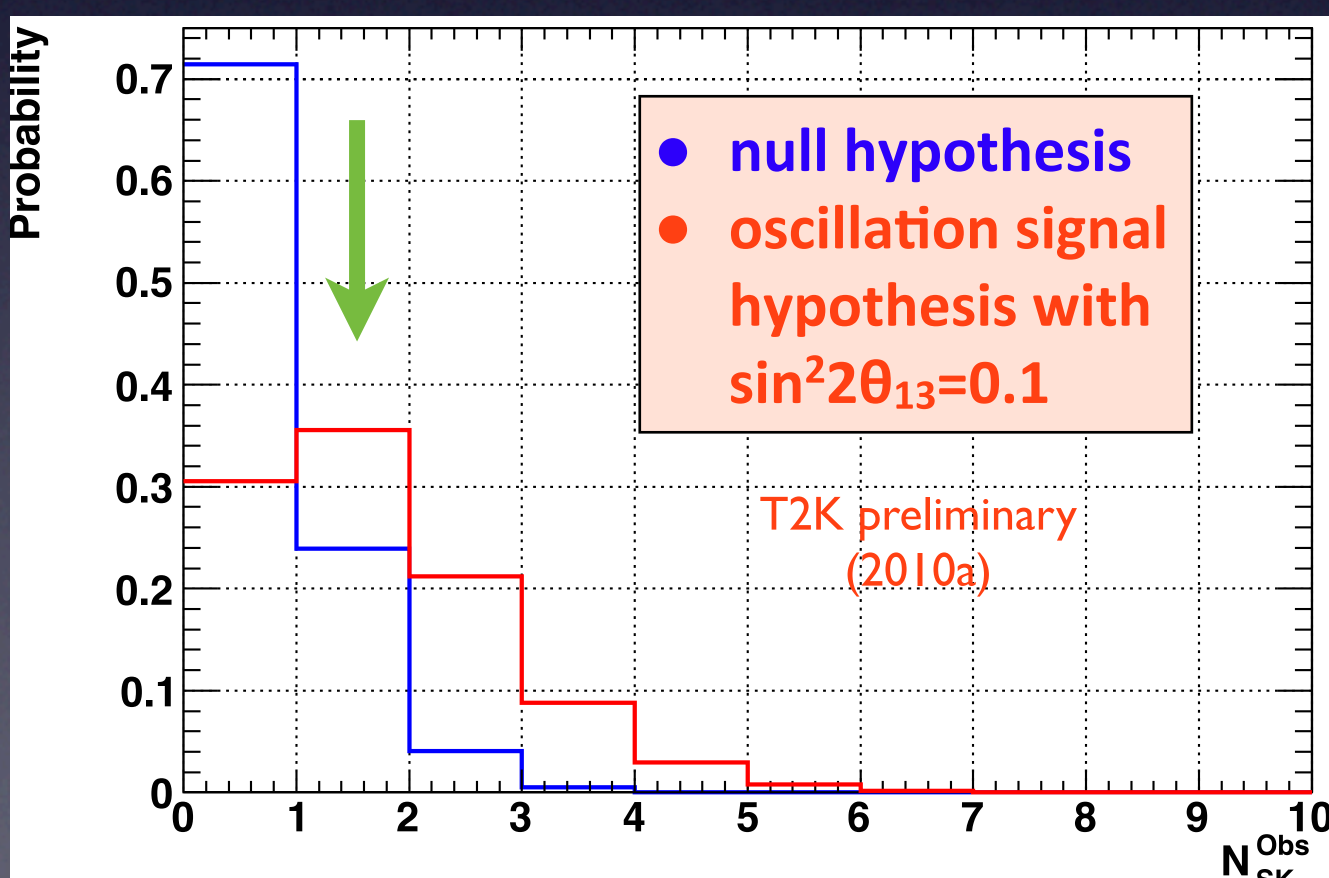
Total sig.+background	**1.20 ± 0.23 (syst.)**

- #events normalized to p.o.t. and corrected for ND280 ν_μ CC measured normalization
- Assumed oscillation parameters for signal:

$\Delta m^2_{23}=2.4\cdot10^{-3}eV^2$
$\sin^2 2\theta_{23}=1.0$
$\sin^2 2\theta_{13}=0.1$
$\delta_{CP} = 0$



T2K preliminary (2010a)

~29% probability to observe >=1 event when expected average = 0.3 event

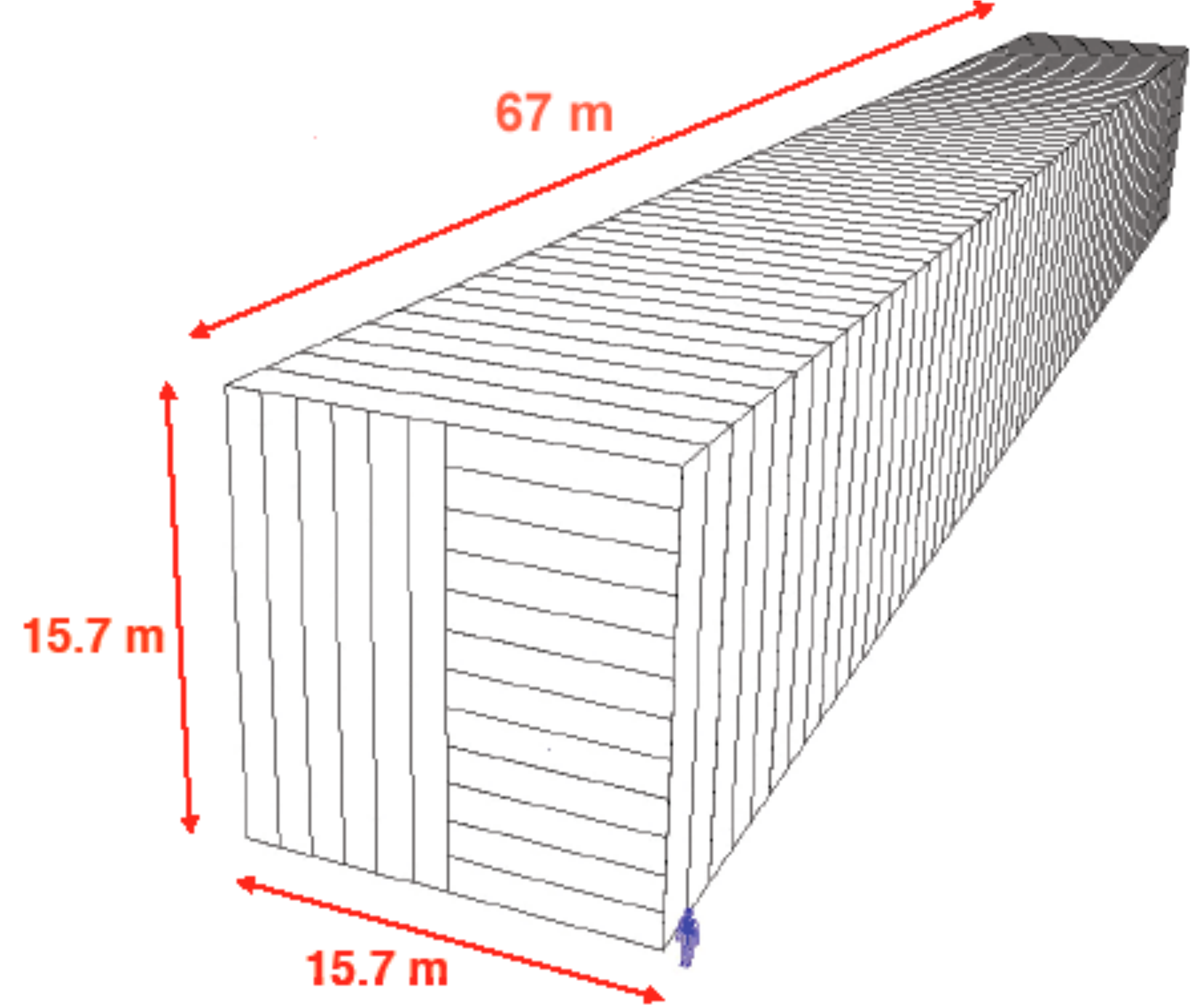
1 data candidate!

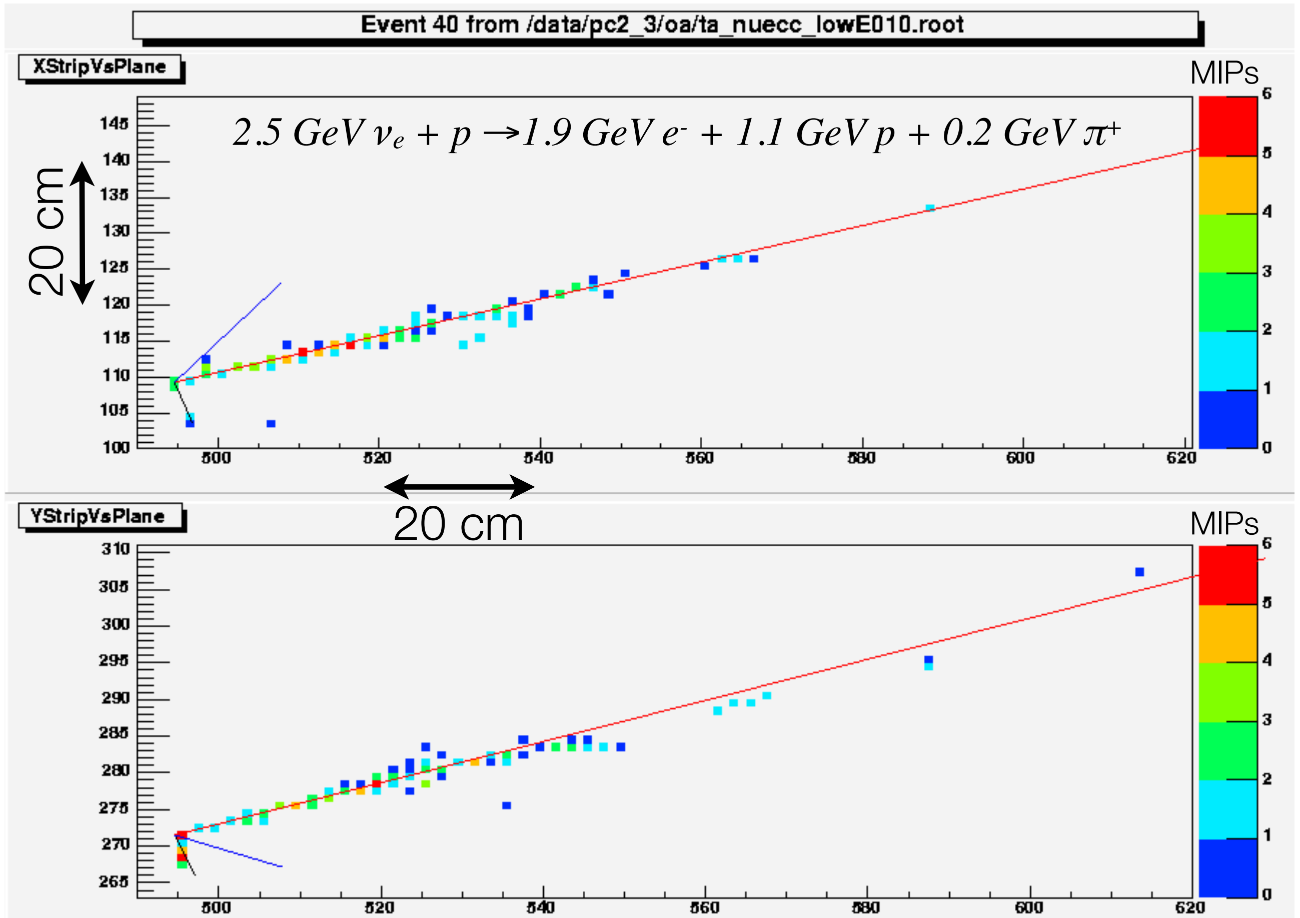
$N_{SK}^{obs} = 1$

The NOvA Experiment

28 Institutions 180 scientists and engineers

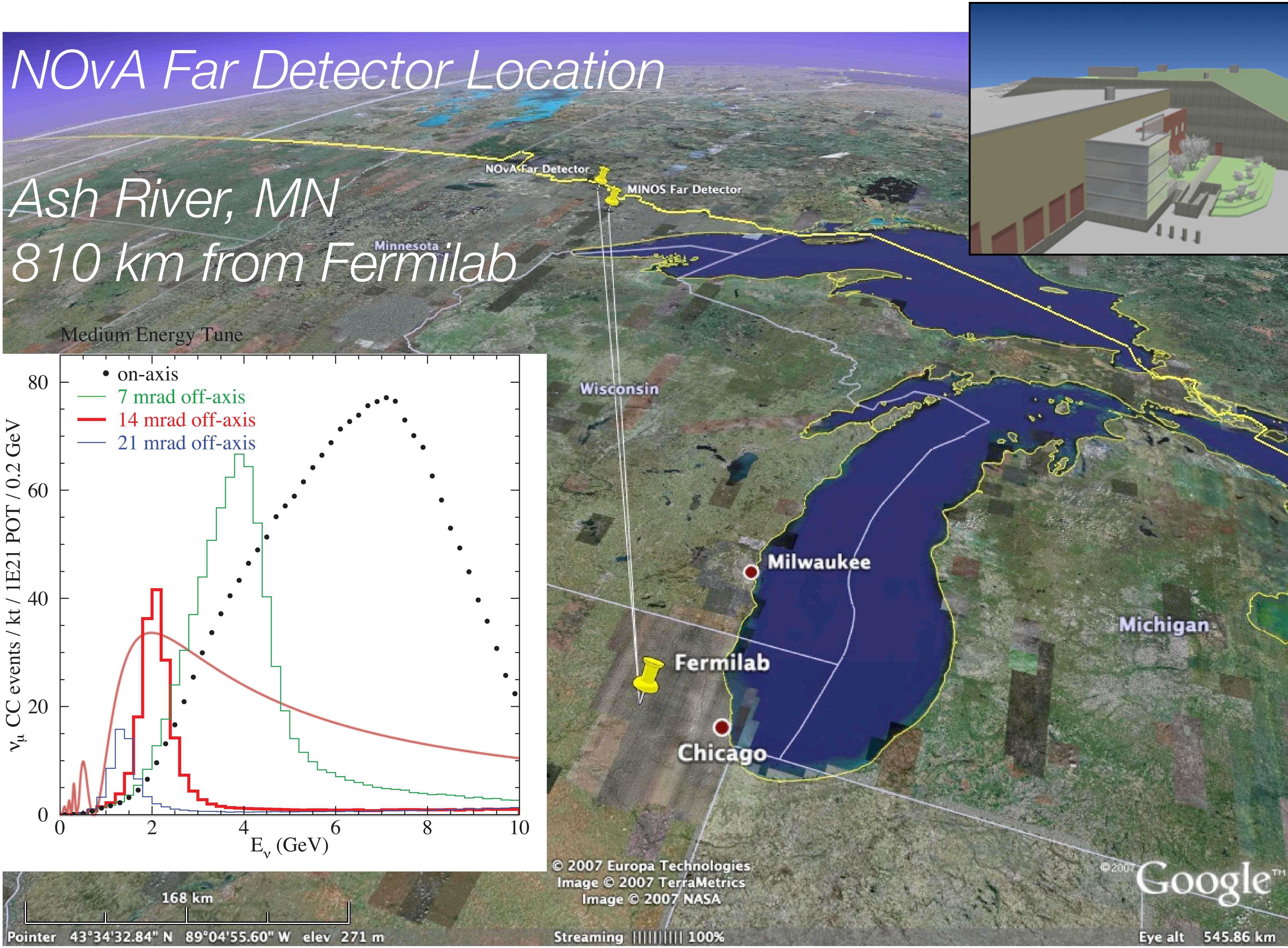
- NOvA is a second generation experiment on the NuMI beamline which is optimized for the detection of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations
- NOvA is:
    - An upgrade of the NuMI beam intensity from 400 kW to 700 kW
    - A 15 kt “totally active” tracking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

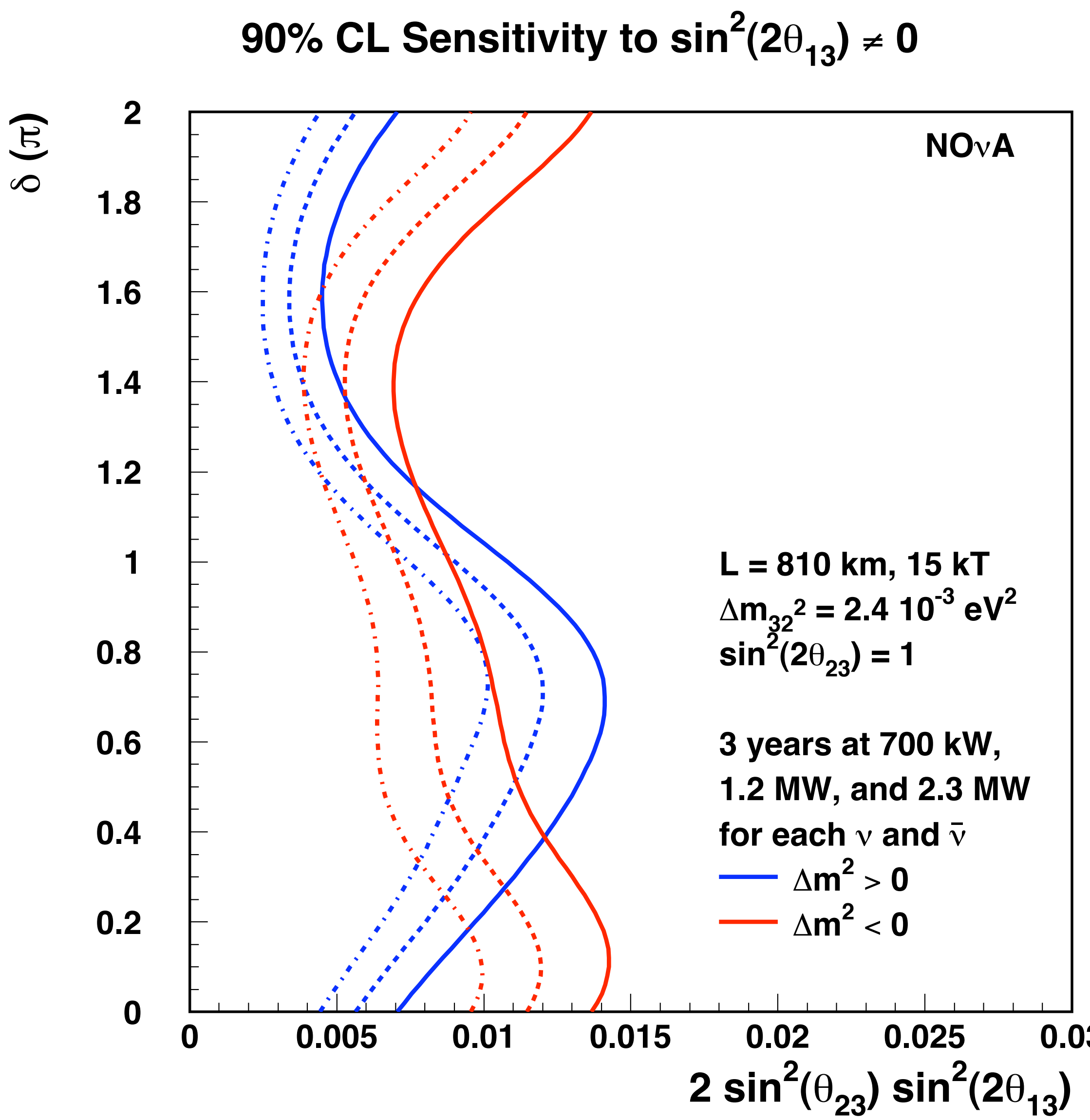


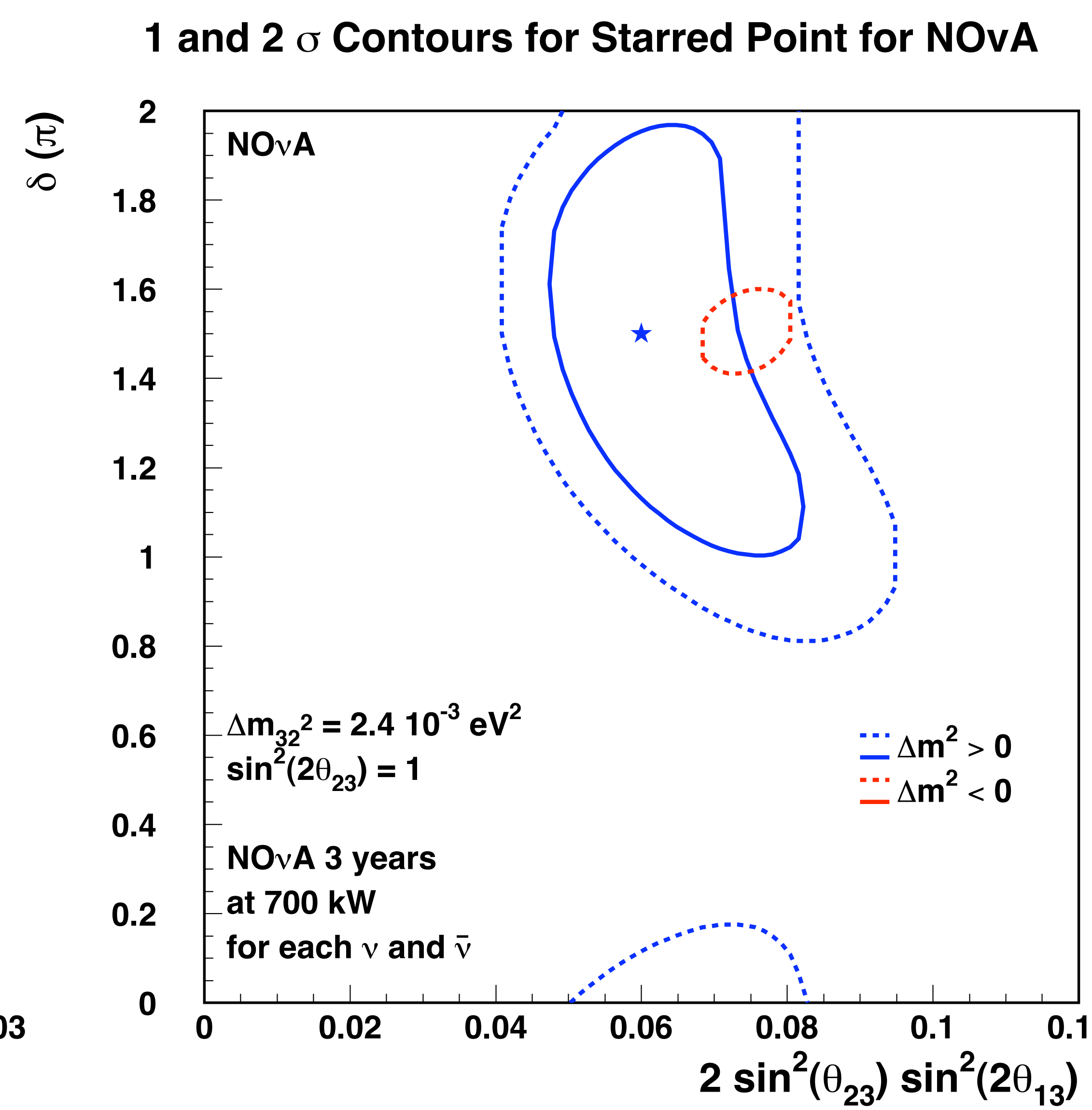


NOvA Far Detector Location

Ash River, MN
810 km from Fermilab

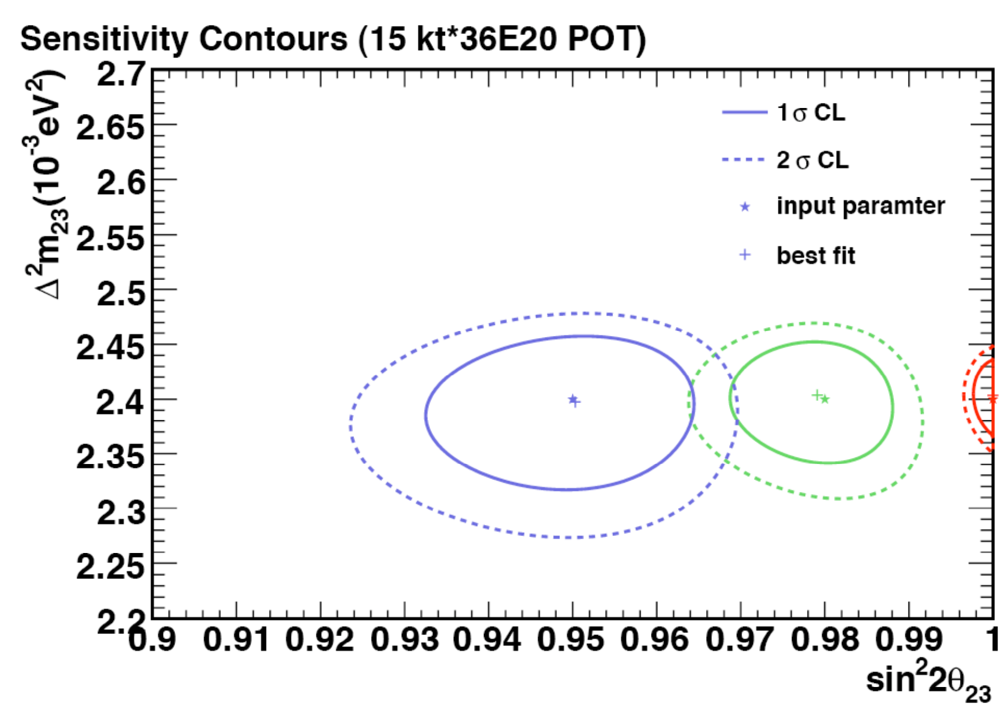






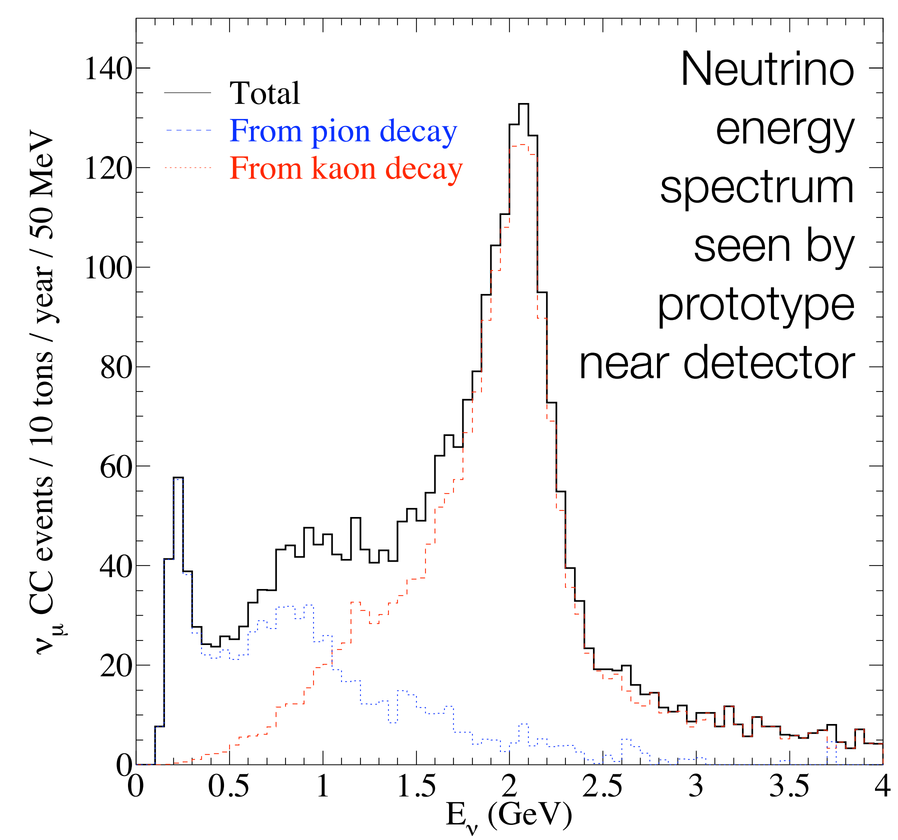
NOvA plans to run 3 years in neutrino mode, 3 years in anti-neutrino mode operating NuMI at 700 kW.

- 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



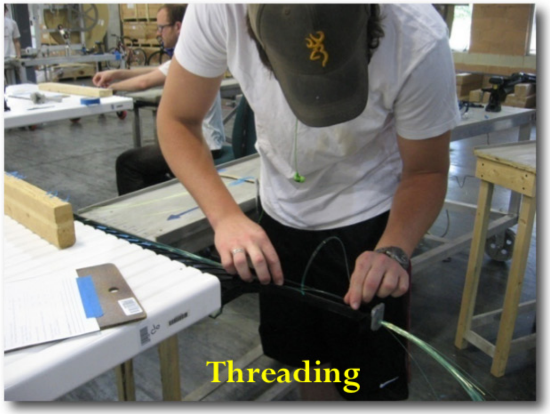
Far Detector Factory

- Industrial-scale production and storage of FD modules will proceed in large warehouse at University of Minnesota - Expect participation of ~200 undergraduate students


Far Detector Factory


2 to 1 Gluing


Stringing


Threading


Leak testing


Painting


Stacking & packing

- Module assembly into blocks will happen at the Far Detector Building in Ash River

Reattori vs Acceleratori

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

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

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

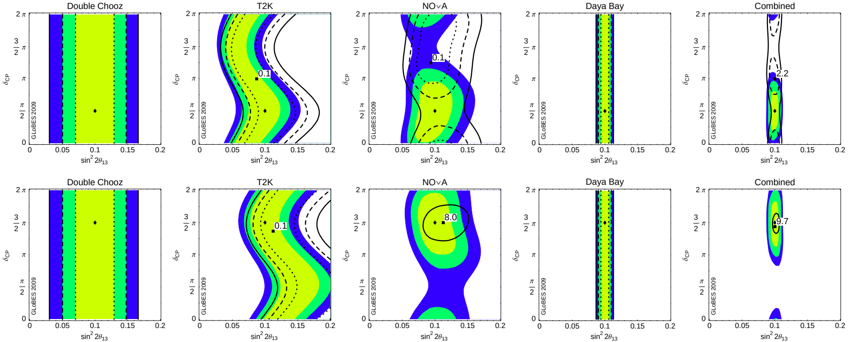
$$+ 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta\} \sin\frac{\Delta m_{12}^2 L}{4E} \qquad \text{solar driven}$$

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

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

Reattori vs Acceleratori: 2018

Fit a $\sin^2 2\theta_{13}$=0.1 (1,2,3 σ)



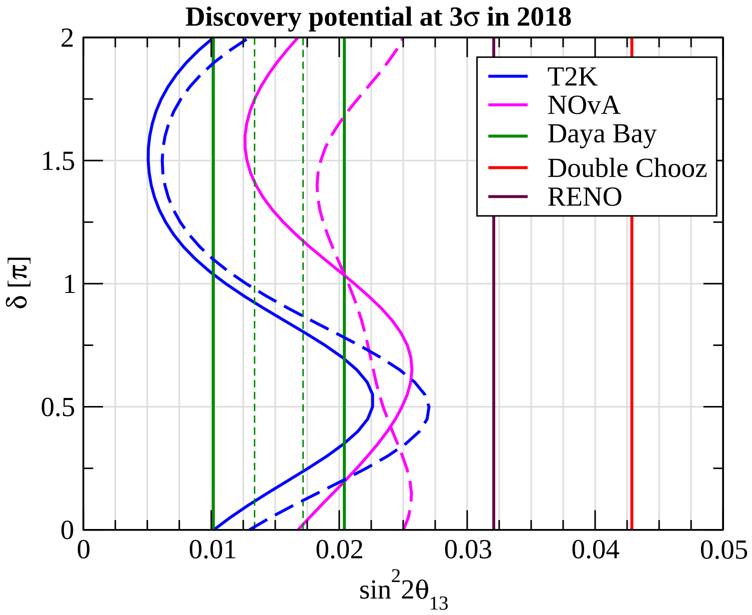
Cosa confrontare

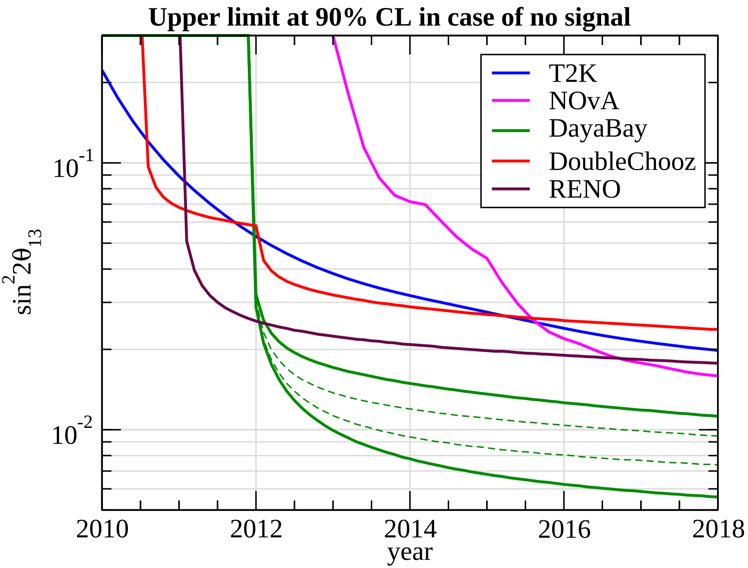
Sensitivity Il più grande valore di $\sin^2 2\theta_{13}$che può essere escluso ad una data C.L. in caso di mancanza di segnale.
θ_{13}: True value $= 0$; fit value $\neq 0$

Discovery potential Il più piccolo valore di $\sin^2 2\theta_{13}$che può dare un segnale non nullo ad una data C.L.
θ_{13}: True value $\neq 0$; fit value $= 0$

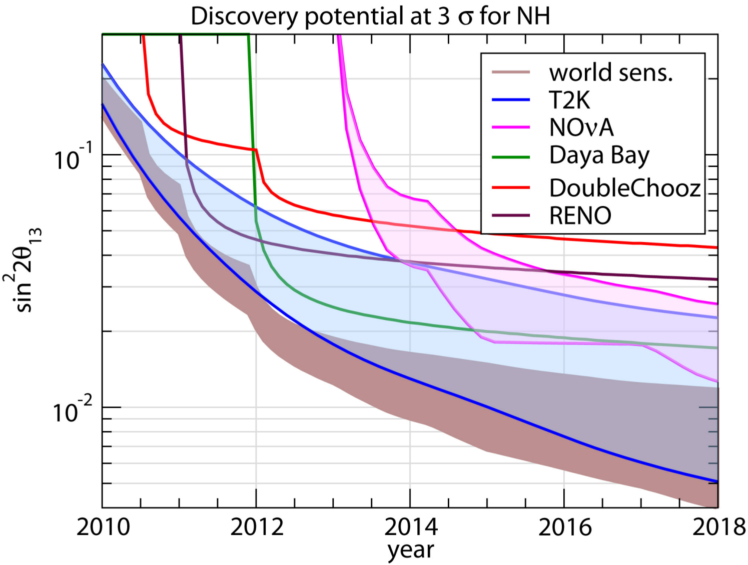
Probabilità di scoperta: La probabilità che un dato valore di θ_{13} dia un segnale non nullo ad una data C.L.

Discovery potential at 3 σ: 2018

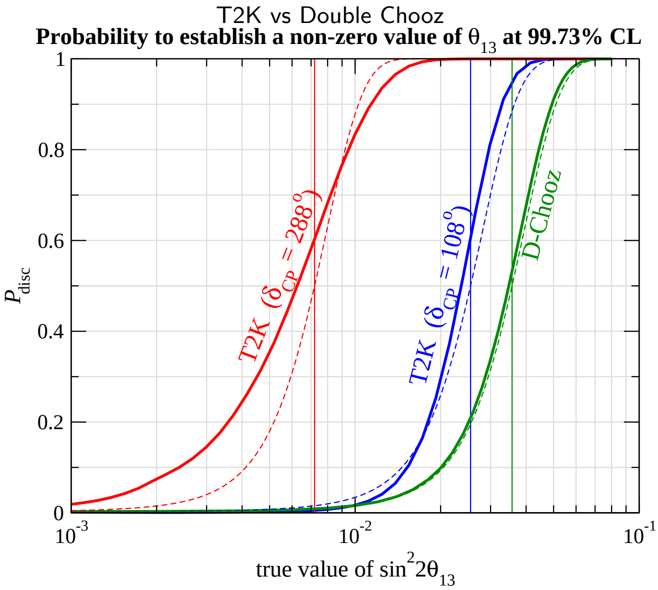



Upper limit at 90% CL in case of no signal
T2K
NOvA
DayaBay
DoubleChooz
RENO
10^{-1}
10^{-2}
$\sin^2 2\theta_{13}$
2010
2012
2014
2016
2018
year

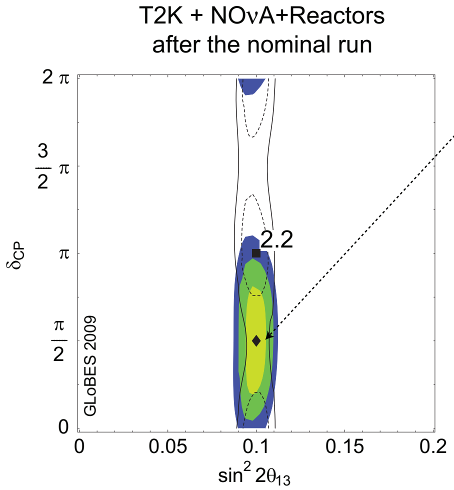
Discovery Potential: evoluzione temporale



Probabilità di escludere $\theta_{13} = 0$ (3σ)

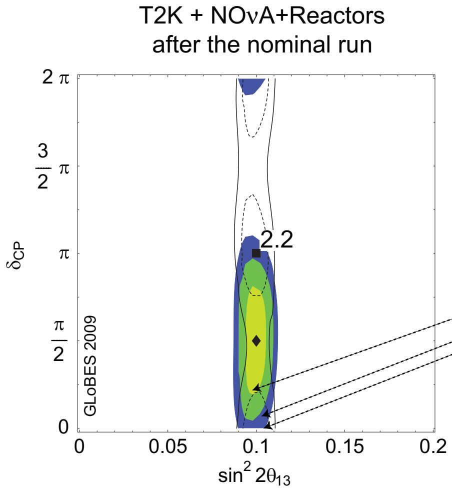


Status after this generation of LBL experiments: CPV



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

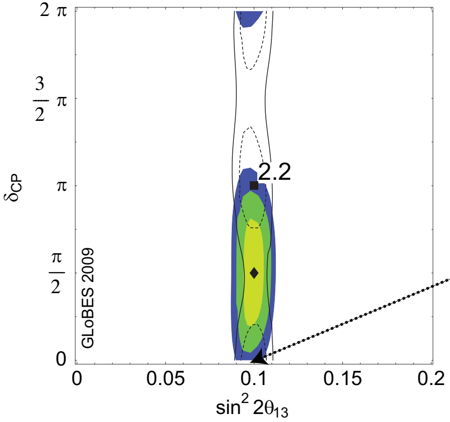


1) Choose a test point, this is the most favorable: max δ_{CP} and max θ_{13}

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

Status after this generation of LBL experiments: CPV

T2K + NOνA+Reactors
after the nominal run



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

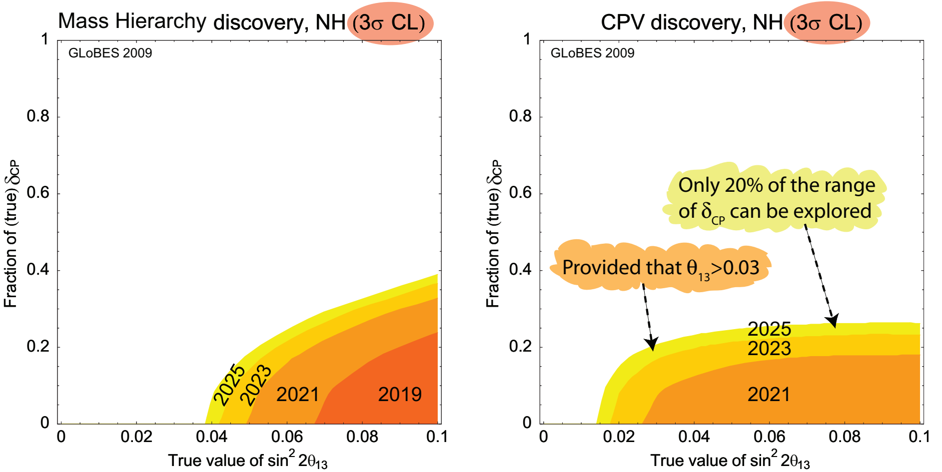
2) Fit to the expected sensitivity of the experiments: 1σ, 2σ, 3σ

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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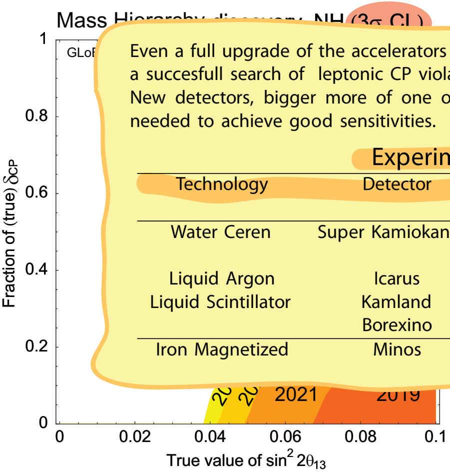
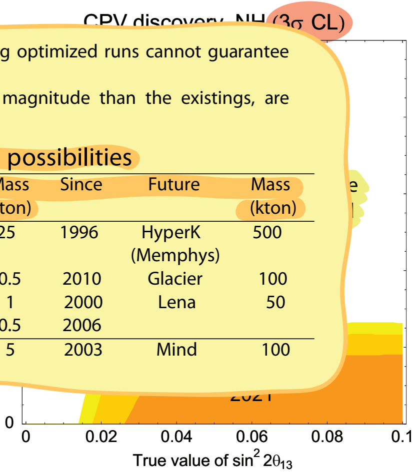




Even a full upgrade of the accelerators and long optimized runs cannot guarantee a succesfull search of leptonic CP violation.

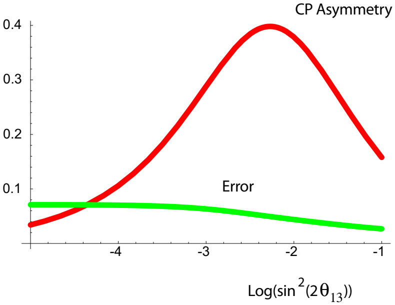
New detectors, bigger more of one order of magnitude than the existings, are needed to achieve good sensitivities.

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

Measuring Leptonic CP violation

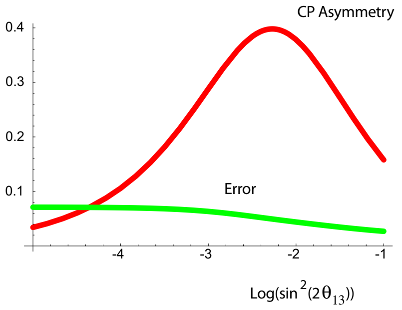
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)}$$



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

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

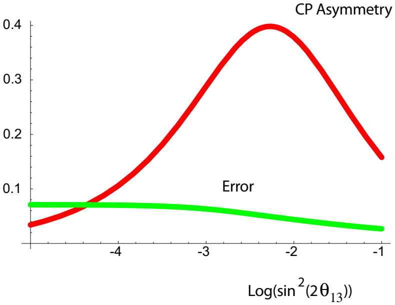


LCPV asymmetry at the first oscillation maximum, $\delta = 1$, Error curve: dependence of the statistical+systematic (2%) computed for a beta beam the fixed energy $E_\nu = 0.4$ GeV, $L = 130$ km.

- **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) ⇒ "short" Long Baseline experiments**

Measuring Leptonic CP violation

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



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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 θ_{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

Neutrino Oscillations in Matter

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

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

Matter effects require long “long baselines"

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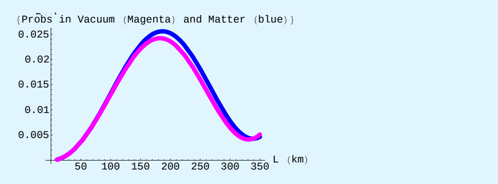
Matter effects require long "long baselines"
$\boldsymbol{E_\nu = 0.35\mathrm{GeV}\ L \simeq 130\ \mathrm{km}}$



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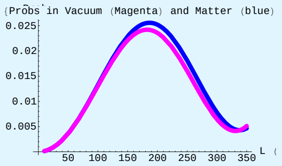

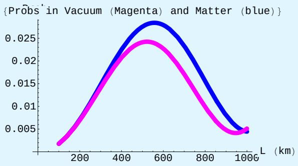

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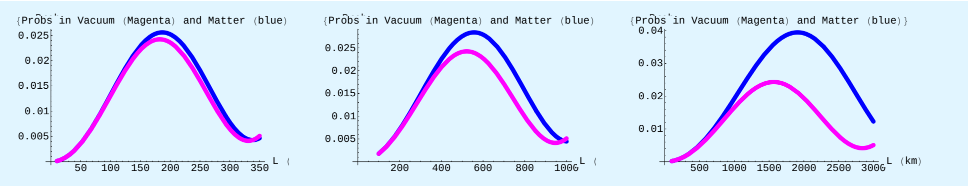
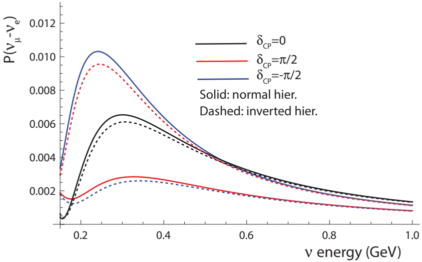
Matter effects require long "long baselines"

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



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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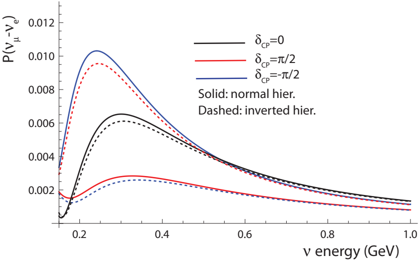
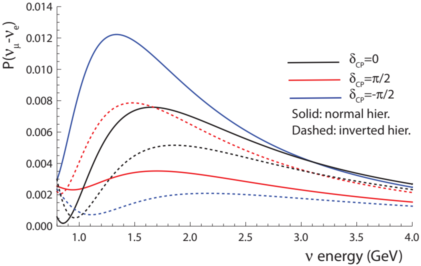
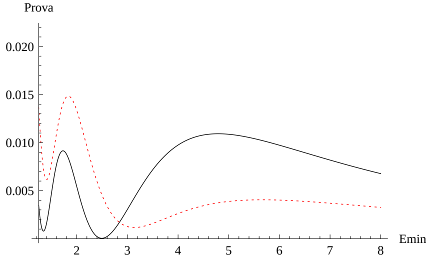


At 730 km matter effects are sizable. Probabilities differ.
Note however as the normal hierarchy $\delta_{\rm CP} = 0$ probability is very similar to inverse hierarchy $\delta_{\rm CP} = \pi/2$, $\Rightarrow$ very difficult to experimentally disentangle the two.



CPV vs. mass hierarchy

At 2500 km the two probabilities are more different and their the second oscillation maximum behaviour is very much different.



CPV vs. mass hierarchy

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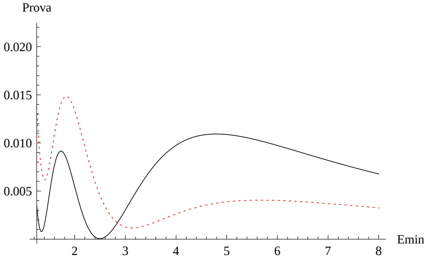
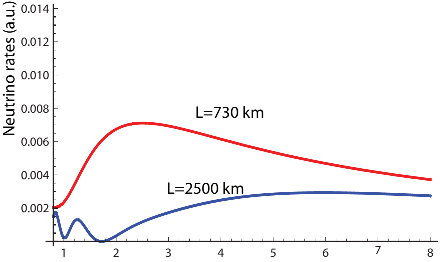
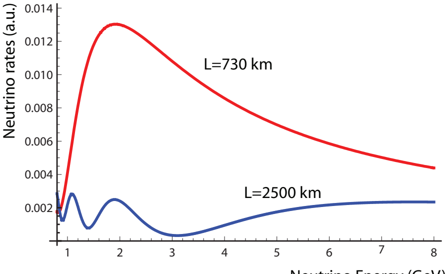


Any price for that? Of course yes. Fluxes go like $1/L^2$, $\Rightarrow$ ten time less flux at 2500 km. Partially recoverd by the rise of cross sections: $\sigma \propto E$ and the MSW resonance (if in the lucky hierarchy). Let's compare interaction rates $I \propto P \times \sigma \times L^{-2}$



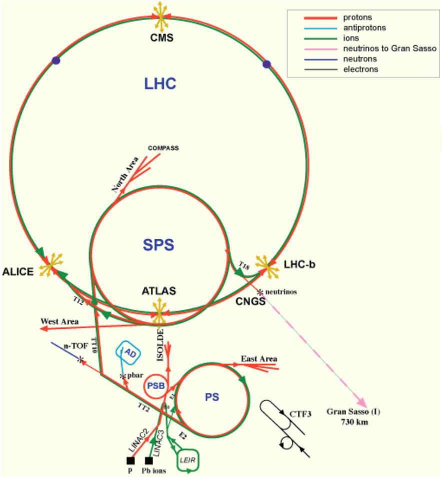


Super Beam ideas in Europe

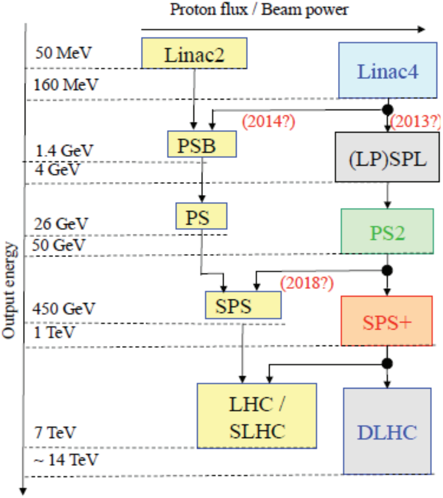
- Super Beams based on the SPL.
- Super Beams based on the SPS: CNGS upgrades. To match the required sensitivity of next generation exeriments need $10\times$ more pot/year than CNGS at present. This appears not very much realistic.
- Super Beams based on the PS2.

CERN and LHC upgrades

Present accelerator complex



Various POSSIBLE scenarios



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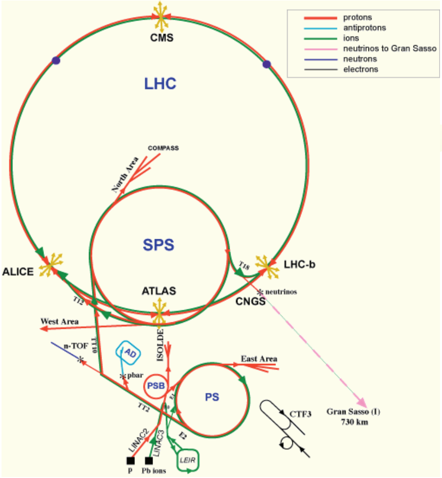

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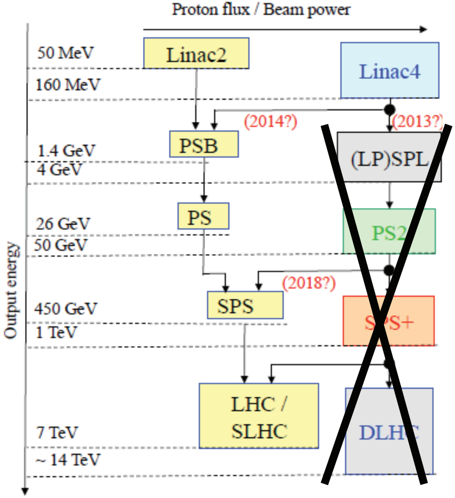
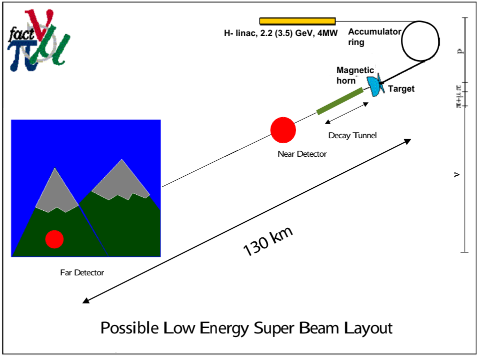
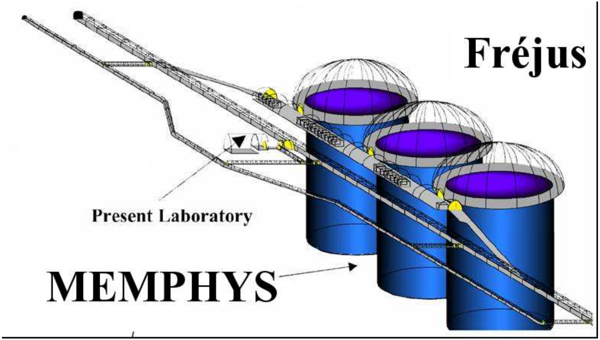


SuperBeams - SPL ν beam at CERN



- A 3.5 GeV, 4MW Linac: the SPL.
- A target station capable of managing 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 precisely measure signal and backgrounds.
- A megaton class detector under the Frejus, L=130 km: Memphys.

The Memphys detector (hep-ex/0607026)



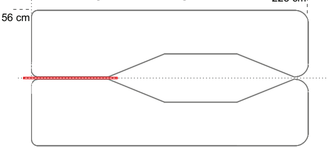
In the middle of the Frejus tunnel at a depth of 4800 m.w.e a preliminary investigation shows the feasibility to excavate up to five shafts of about 250,000 m^3 each ($\Phi = 65\,m$, full height=80 m).

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)

SPL revised (A. Longhin, paper in preparation)

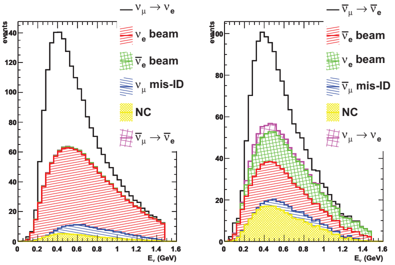
Shape of the optimal horn



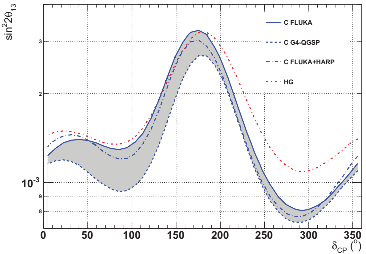
L_1	58.9	$r_1 = r_2$	10.8
L_2	46.8	R_1	1.2
L_3	60.3	$R_1 + R_2 + R_3$	56.2
L_4	47.5	$R_1 + R_2$	20.3
L_5	1.08	z_0^{tg}	-6.8
L^{tg}	78	R^{tg}	1.5
L^{tun}	2500	R^{tun}	200

Parameters of the optimized system expressed in cm.

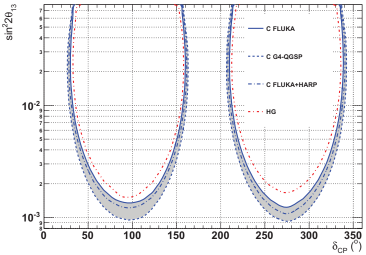
Event rates in MEMPHYS for $\sin^2 2\theta_{13}$ = 0 01 and δ_{CP} = 0.



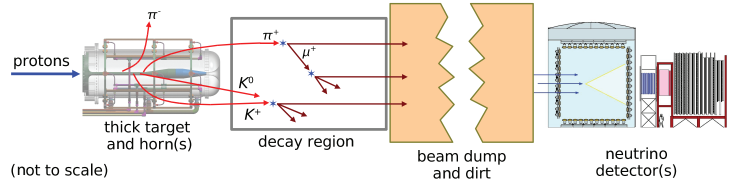
θ_{13} discovery at 3 σ ($\Delta\chi^2$ = 9). 5% sys.



CP violation discovery at 3 σ ($\Delta\chi^2$ = 9). 5% sys.



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. ν_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.

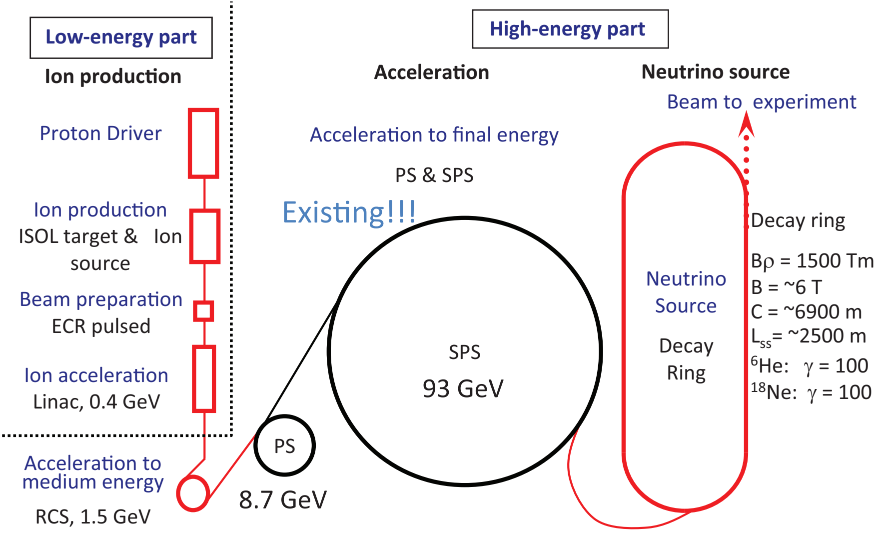
All these limitations are overcome if secondary particles become primary

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



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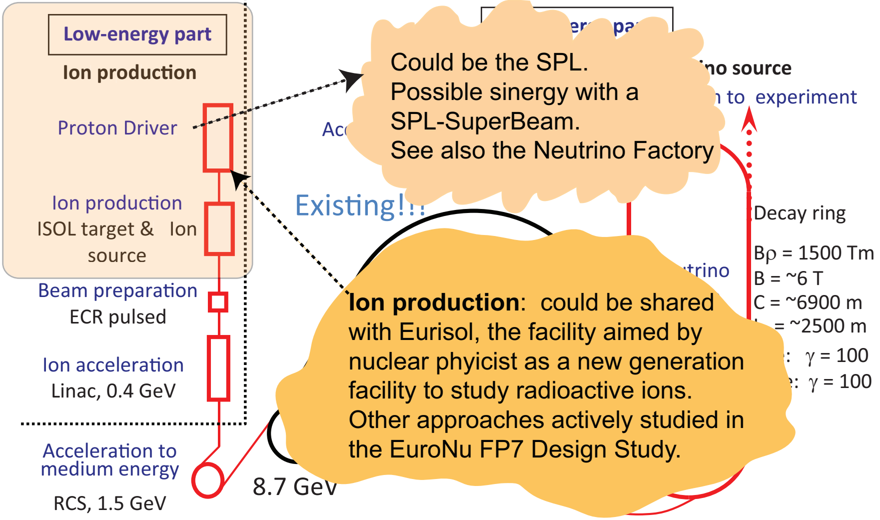

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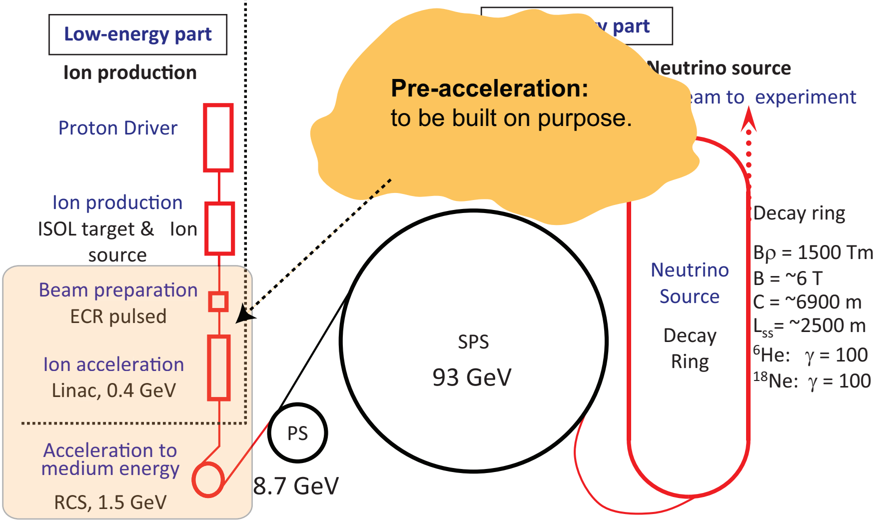

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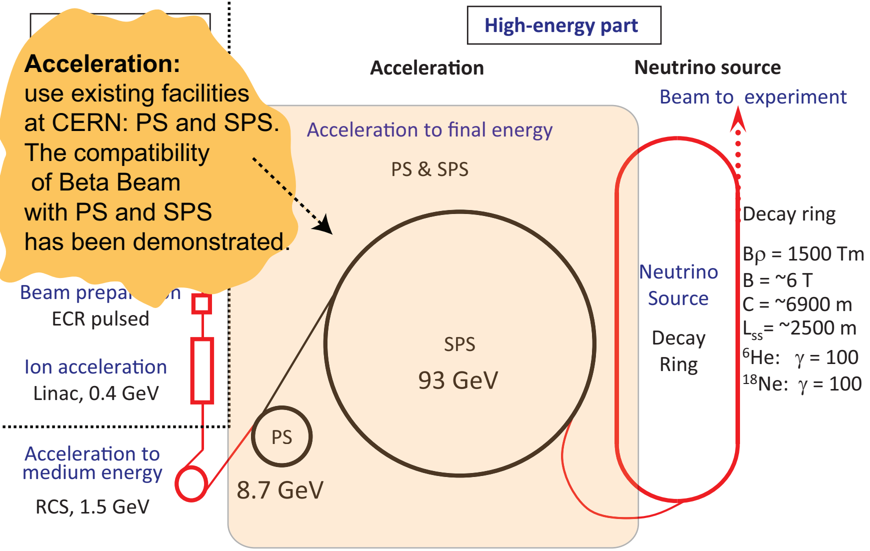
Acceleration:
use existing facilities at CERN: PS and SPS. The compatibility of Beta Beam with PS and SPS has been demonstrated.



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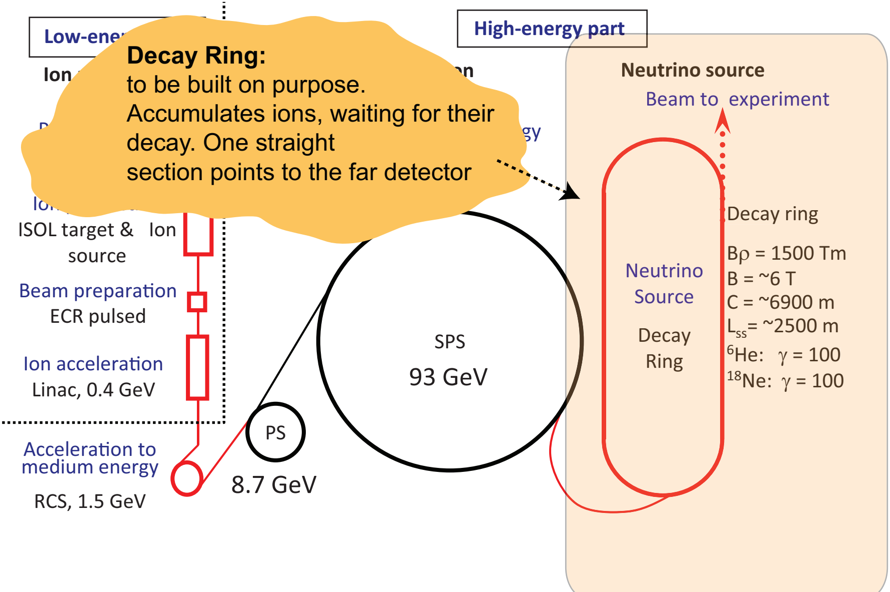

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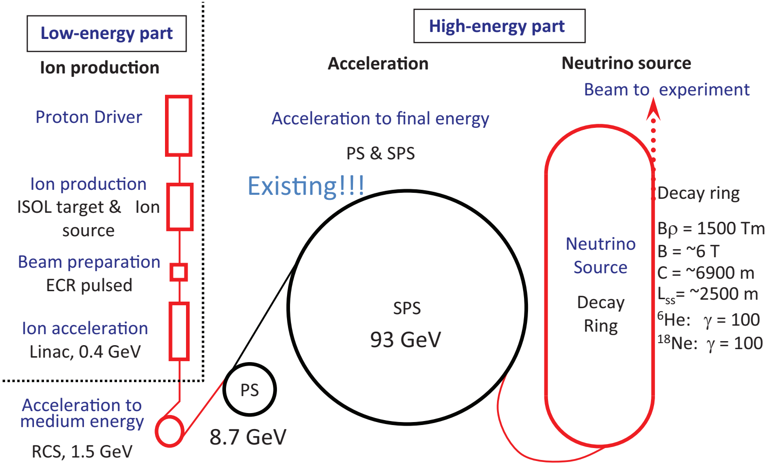
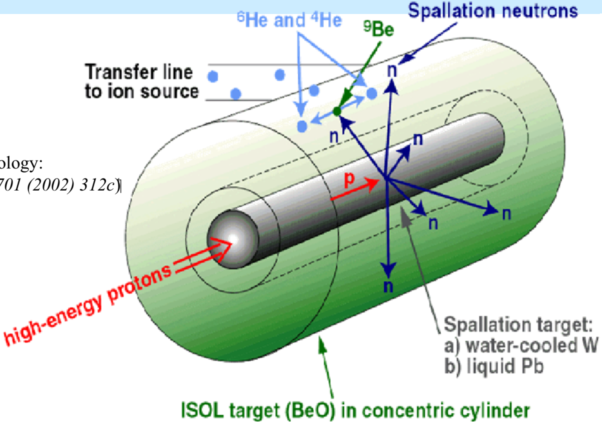


- $\overline{\nu}_e$ generated by He^6, 100 μA, $\Rightarrow 2.9 \cdot 10^{18}$ ion decays/straight session/year.
- ν_e generated by Ne^{18}, 100 μA, $\Rightarrow 1.1 \cdot 10^{18}$ ion decays/straight session/year.

^{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

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

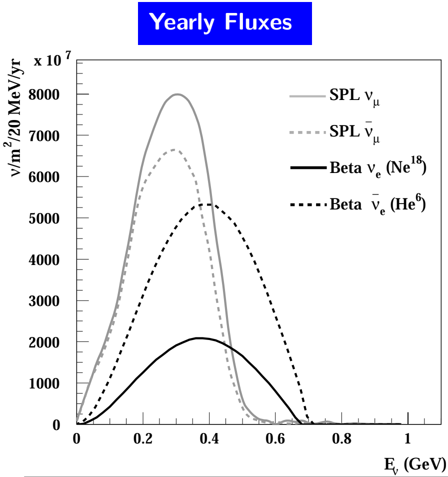
Beta Beam baseline scenario

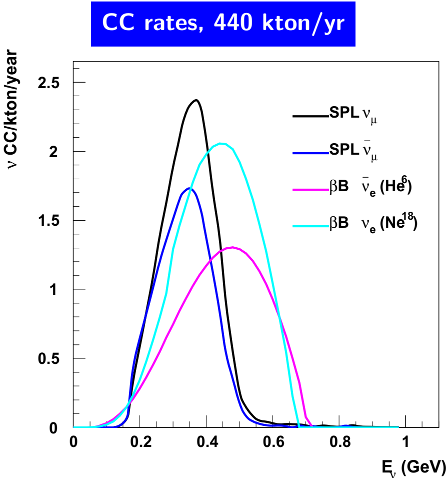
Boundary conditions:

- 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





	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

The Beta Beam - SPL Super Beam synergy

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

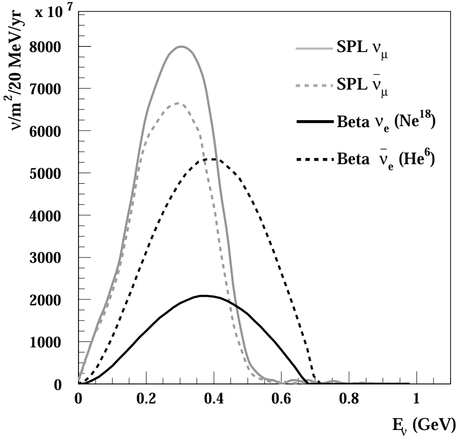
A Beta Beam has the same energy spectrum than the SPL SuperBeams and consumes 5% of the SPL protons.

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 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.

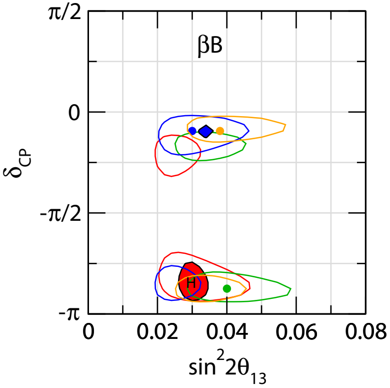
NOTE: LBL and atmospherics are a true synergy. They add to each other much more that a simple gain in statistics. Atmospherics alone could not measure the hierarchy, the octant, θ_{13} and LCPV. While the Beta Beam at short baselines could not measure the hierarchy as well as the octant.

Synergy with atm. neutrinos: degeneracy removal

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

The red region is what is left after the atmospheric analysis.
Note how degeneracies were not influencing LCPV sensitivity too much.

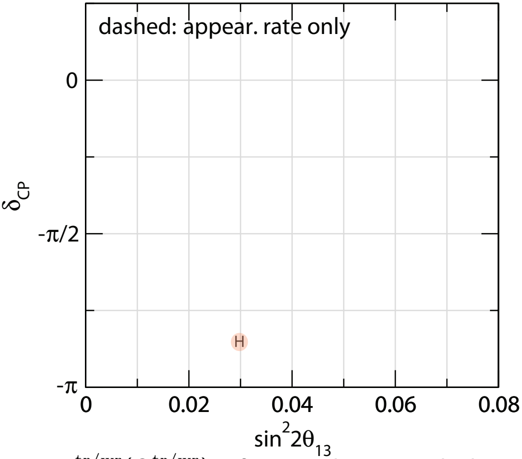
95% CL regions for the $(H^{tr}O^{tr})$, $(H^{tr}O^{wr})$, $(H^{wr}O^{tr})$, $(H^{wr}O^{wr})$ solutions



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

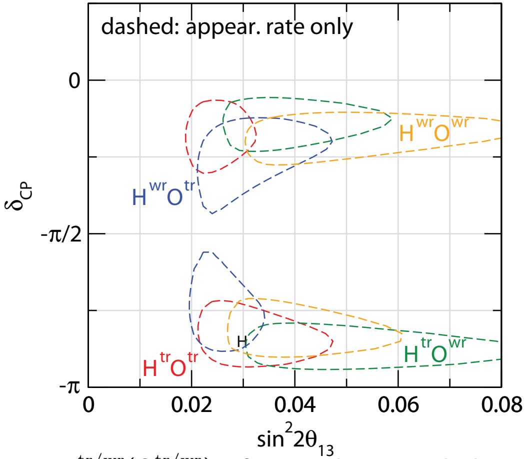
Degeneracy removal: SPL

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



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.

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



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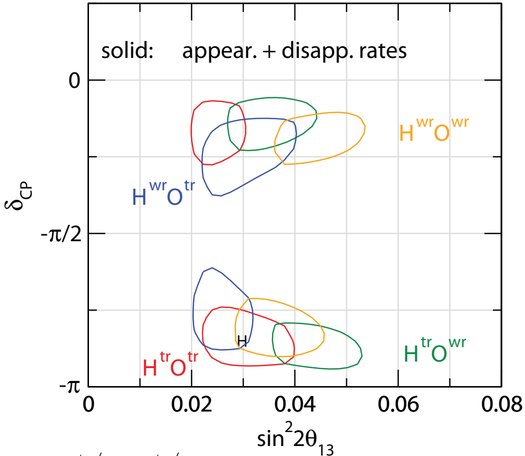

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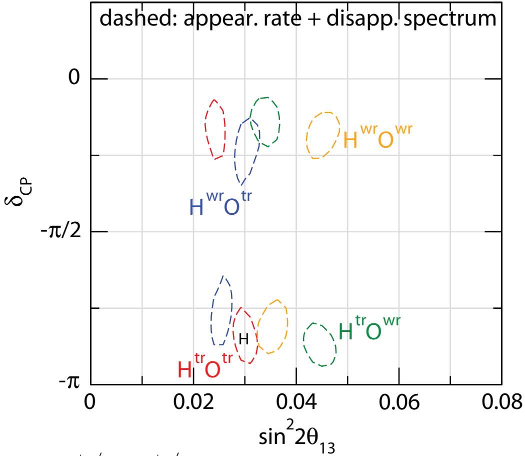

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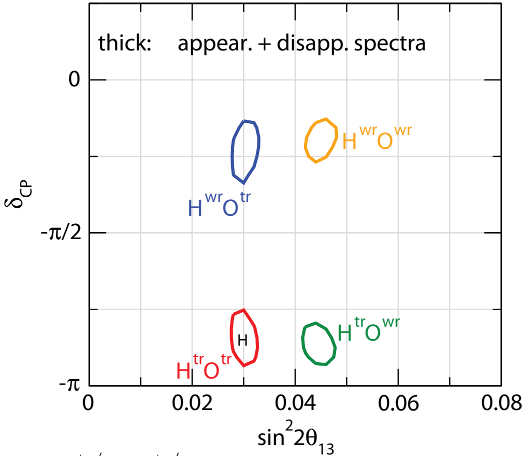

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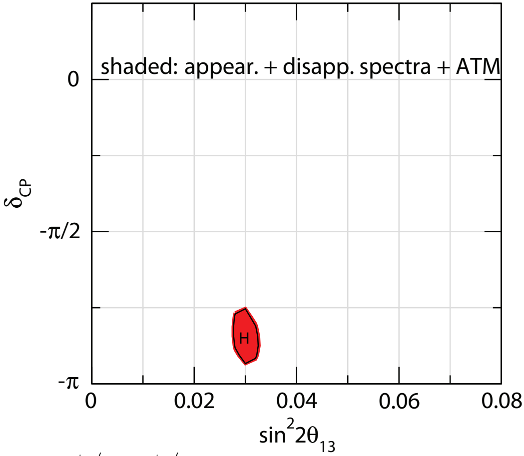

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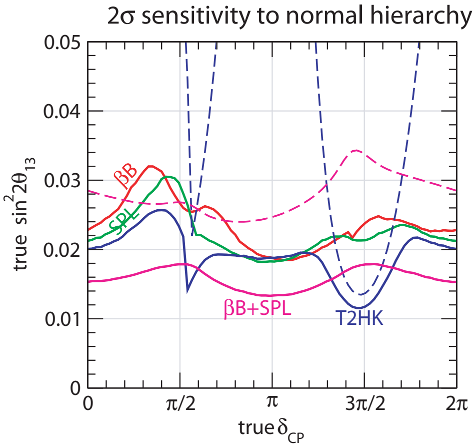
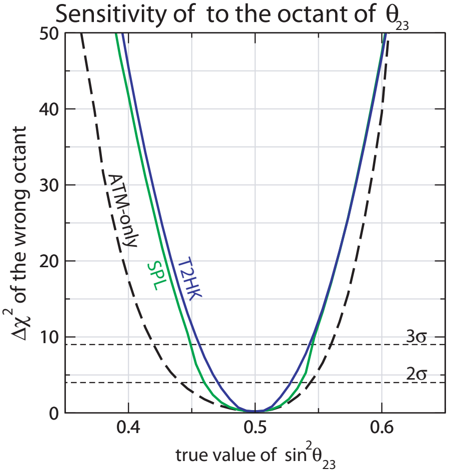
Beta Beam plus atmo: determining mass hierarchy and the octant





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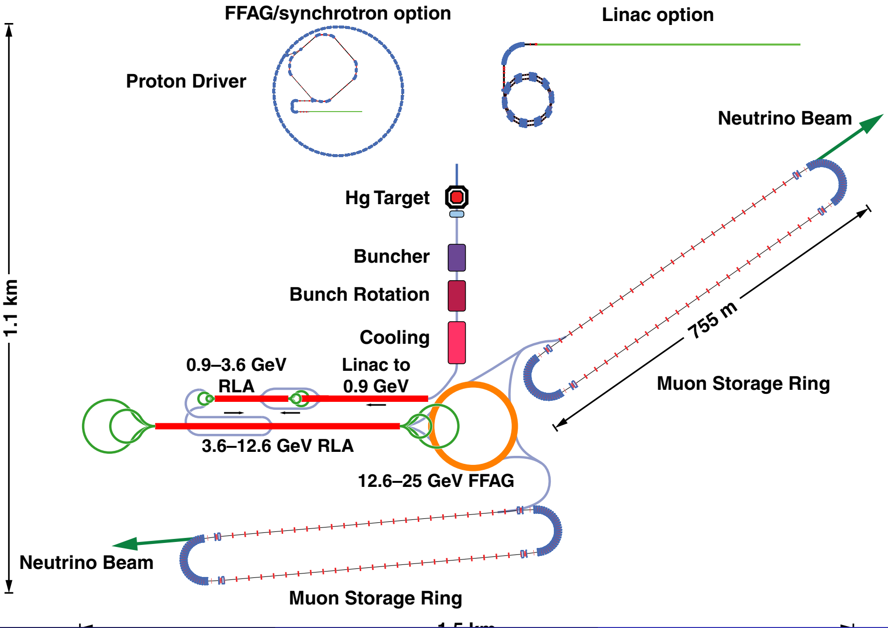
- **Electron capture Beta Beams**: monochromatic neutrino beams, a very attractive option
  - They require long lived, high-A, far from the stability valley ions, r$\Rightarrow$ challenging R&D to match the needed fluxes.

Layout of a Neutrino Factory



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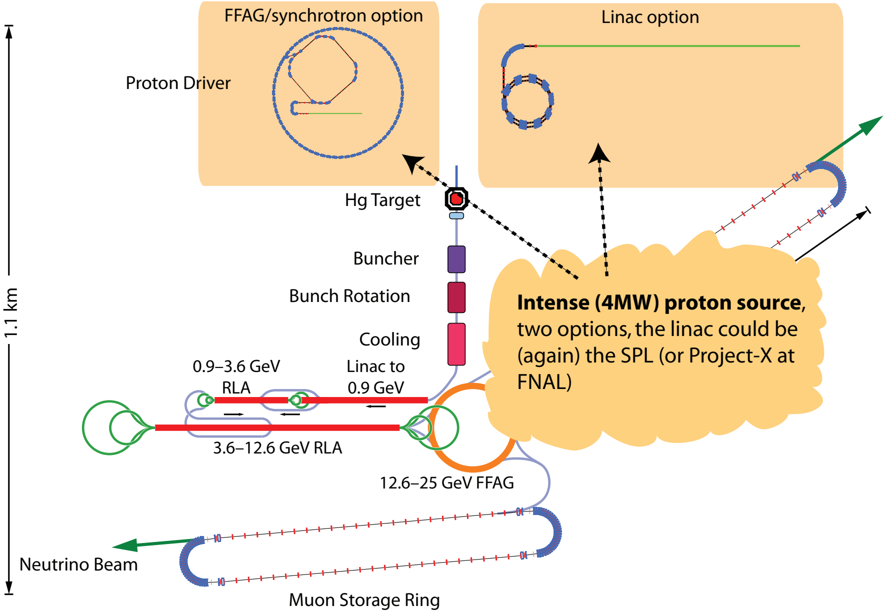

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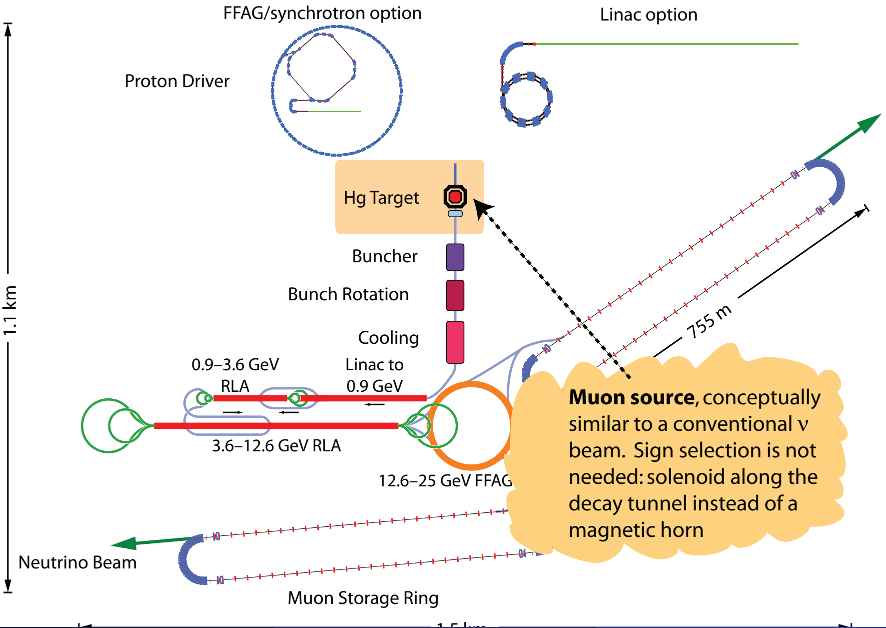

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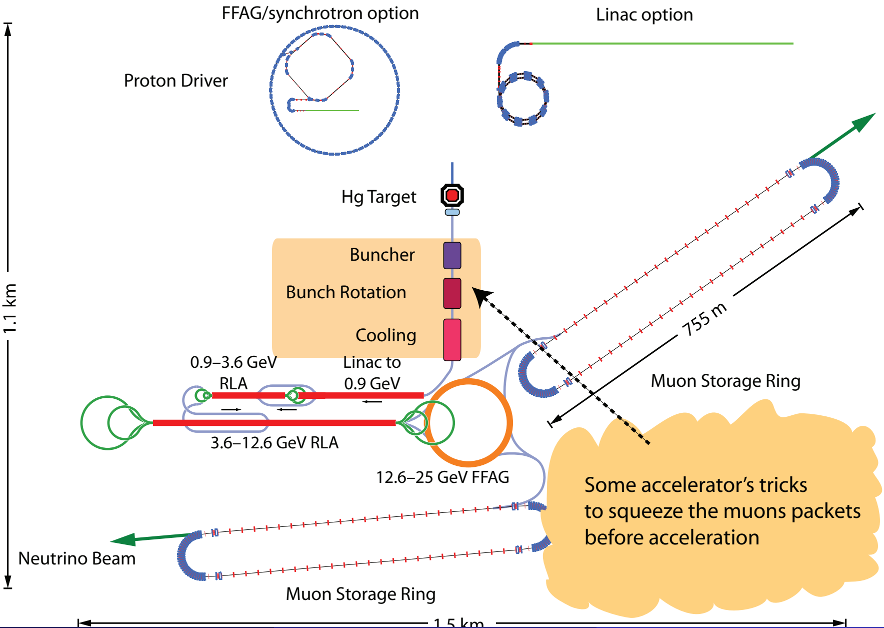

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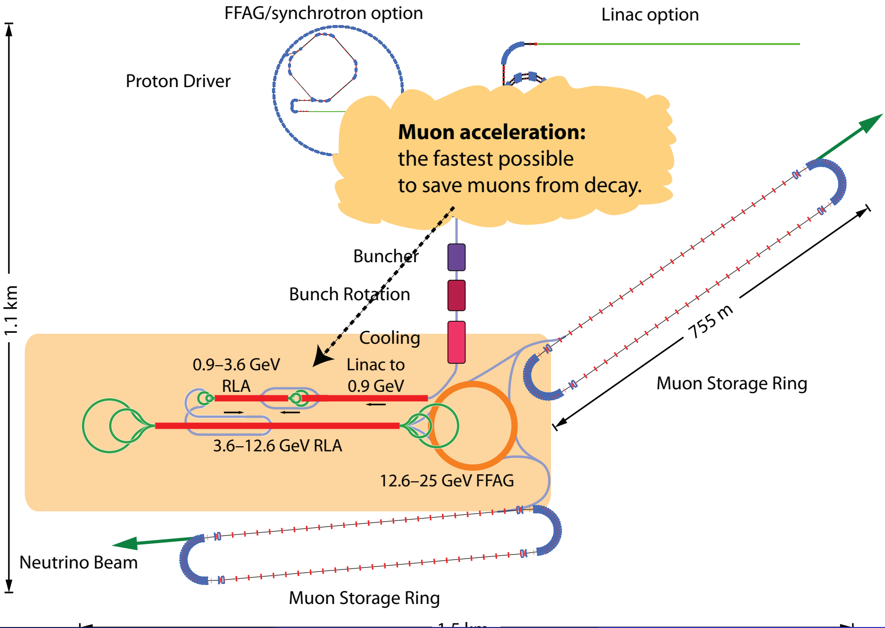

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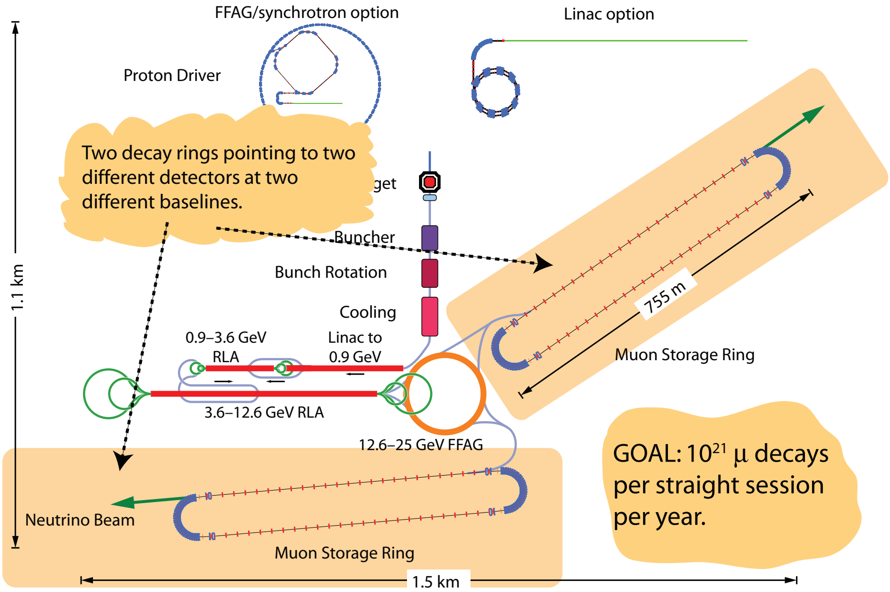
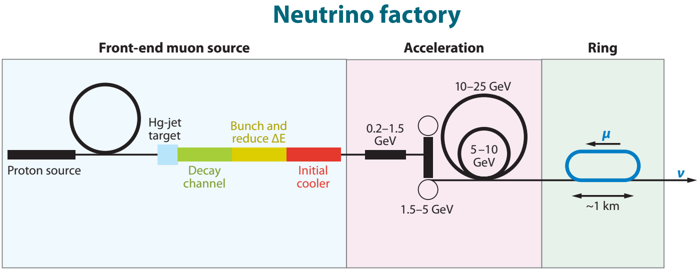
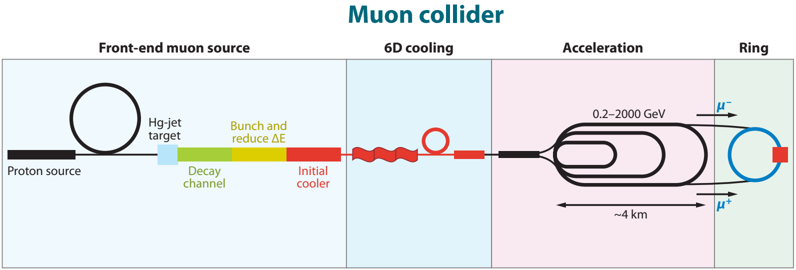


Neutrino Factory as a first stage of a Muon Collider

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





Oscillation signals at the neutrino factory

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

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).

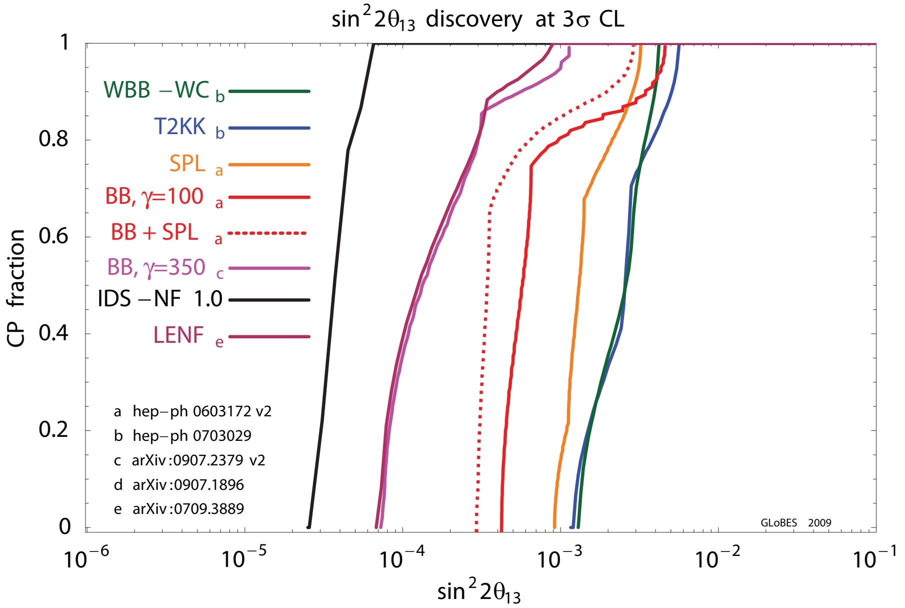
Beta Beam + SPL The combination of the above two.

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)

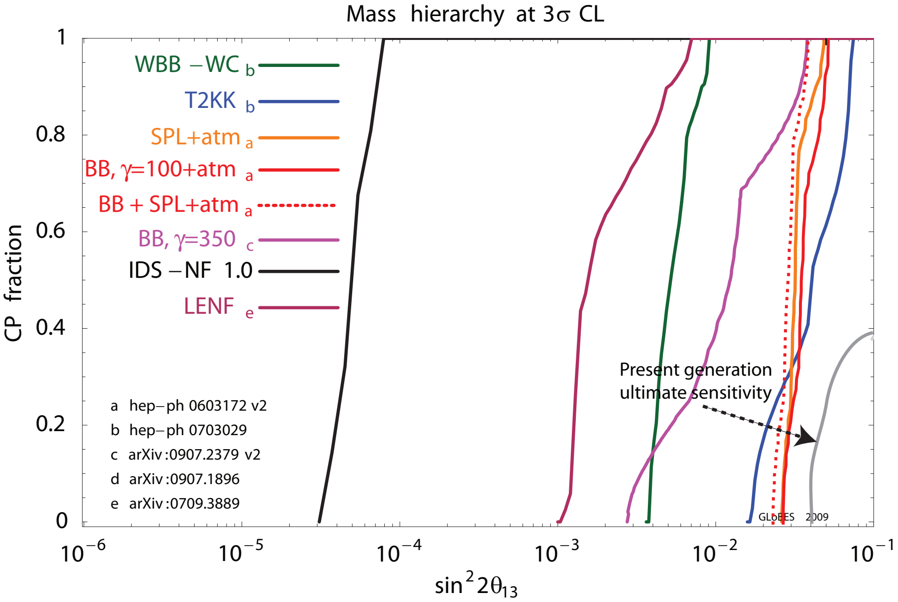
Low Energy Neutrino Factory (LENF) Neutrino Factory running at 4.12 GeV delivering 10^{21} muon decays/year for each sign, 30 kton Noνa like detector, fully magnetized (!) at 1480 km (Fermilab-Henderson mine). A. Bross et al, Phys.Rev.D77:093012,2008. (arXiv:0709.3889)

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