Super-Kamiokande after upgrade. Jan 2006

Future long-baseline program

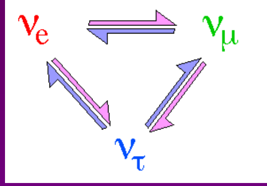
- What remains to be measured via neutrino oscillations
- Which problems need to be solved (degeneracies)
- Current experiments:
  - MiniBoone
  - Minos (K. Grzelak – coming soon!)
- Future experiments
  - Double-Chooz
  - T2K
  - NOvA
  - J2K (Japan to Korea)
  - Super-NOvA

Four new initiatives approved by DoE HEP office Nov. 2005 (CriticalDecision0 level)

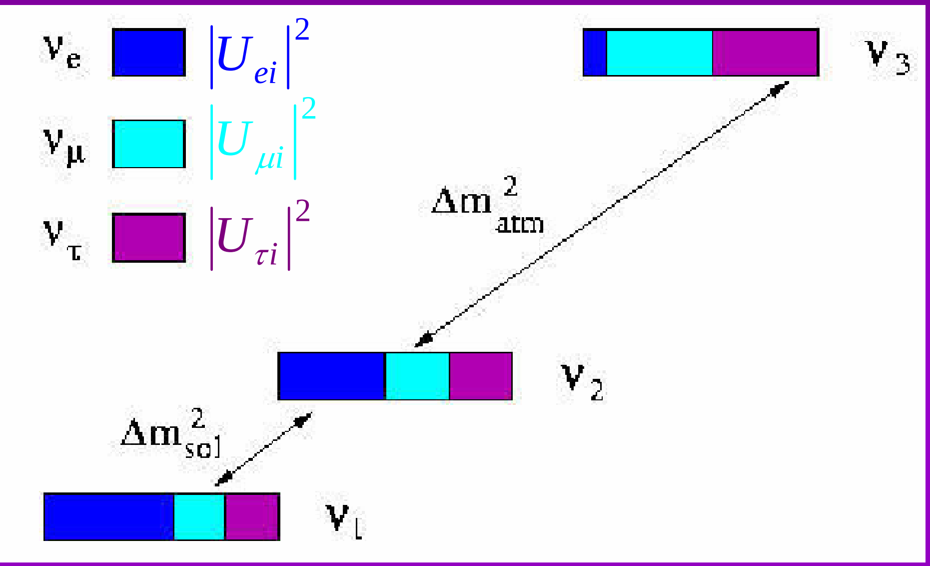
http://www.science.doe.gov/hep/newinitiatives.shtm

- A generic accelerator-based electron neutrino appearance experiment to measure neutrino mixing and to probe the neutrino mass hierarchy
  1) NOvA   2) T2K   3) do nothing
- A generic reactor-based neutrino detector to precisely measure neutrino mixing
  1) Double Chooz, 2) Daya Bay, 3) Braidwood   4) do nothing
- A generic ground-based dark energy experiment
- A generic neutrinoless double beta decay experiment to probe the Majorana nature and an absolute mass scale of neutrinos

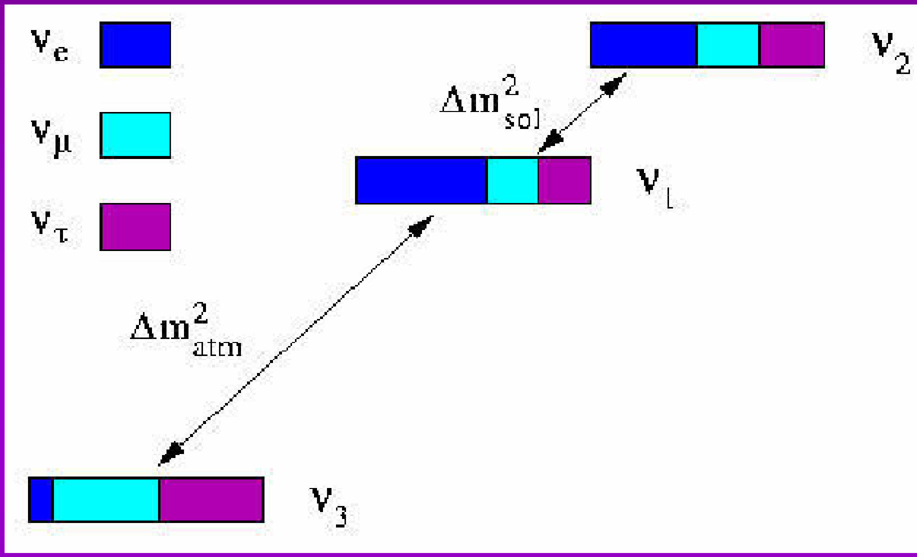
Status of: Neutrino masses



Normal hierarchy



Reversed hierarchy



Already measured:

$$\left|\Delta m^2_{23}\right| = (1.9 - 3.0)\times 10^{-3}\ \mathrm{eV}^2 \quad @\ 90\%\ \mathrm{c.l.}$$

$$\Delta m^2_{21} = 7.9 \pm 0.6 \times 10^{-5}\ \mathrm{eV}^2$$

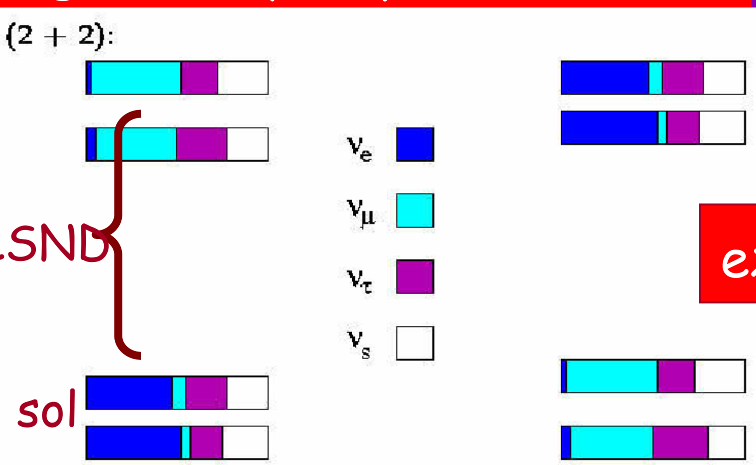
Unless MiniBoone complicates the whole picture…

What about LSND observations

or „Is there a 4-th light neutrino – a sterile ν ?"

$$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$$

significantly coupled with active



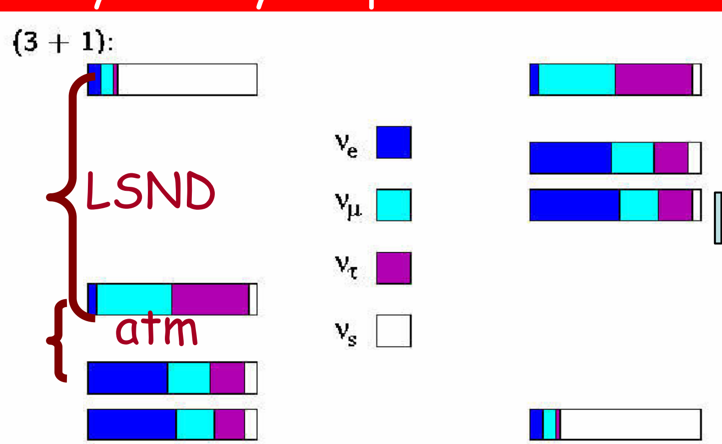
excluded at 5.1 σ

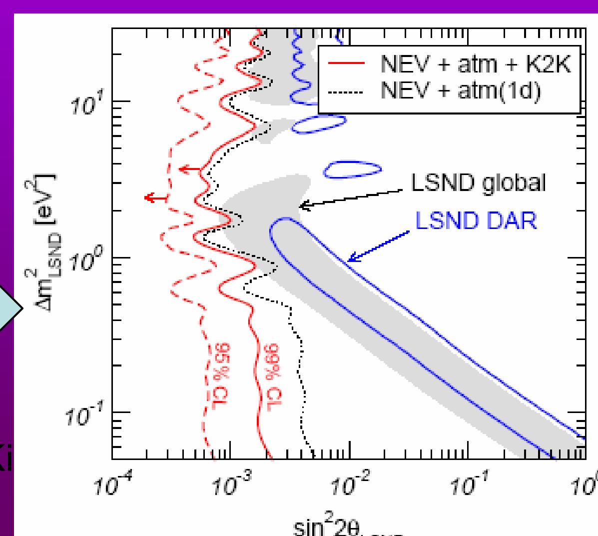
A global analysis of all atmosph., solar, accelerator and reactor data by:

M. Maltoni et al, hep-ph/0405172

Mini-Boone results?

very weakly coupled with active

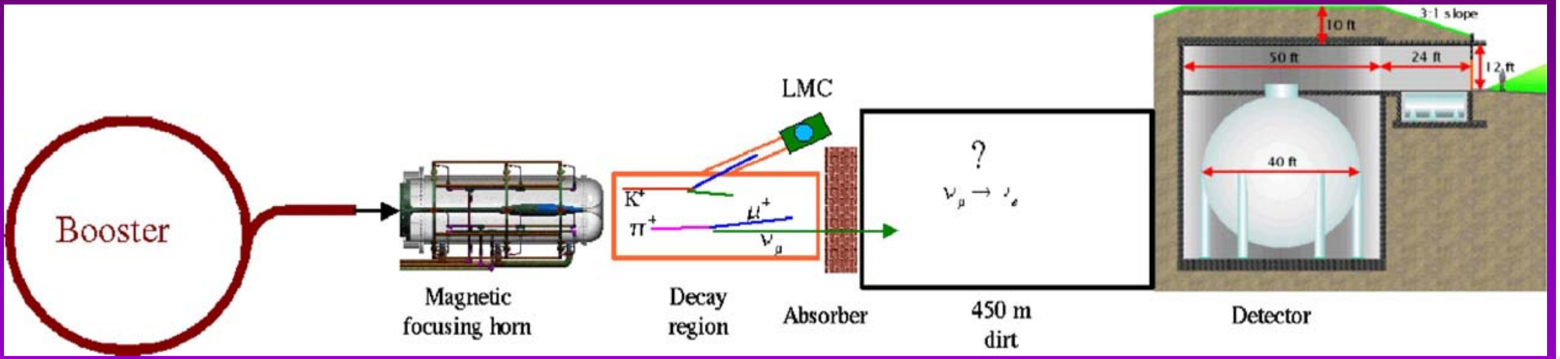


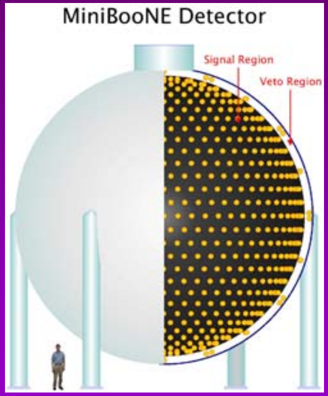


also inconsistent with existing data

D. Ki

MiniBooNE (2002~) (Fermilab)

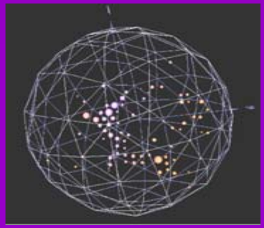




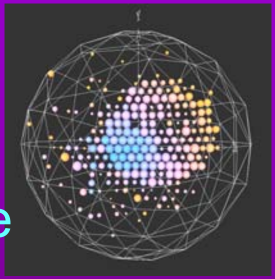
$\nu_\mu \to \nu_e$ at $\Delta m^2 \sim 1 eV^2$ (LSND)

- 8 GeV proton beam (Be target)
  - $E\nu \sim 700$ MeV, $L \sim 541$m ($L/E \sim 0.77$)
- Mineral Oil Cherenkov Detector
  - 800 tons
  - 1280 eight-inch PMT's
  - 240 PMT for VETO.
  - 611,000 ν events.

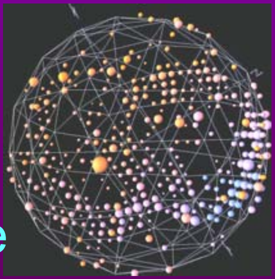
Michel e from μ decay



μ candidate



π^0 candidate

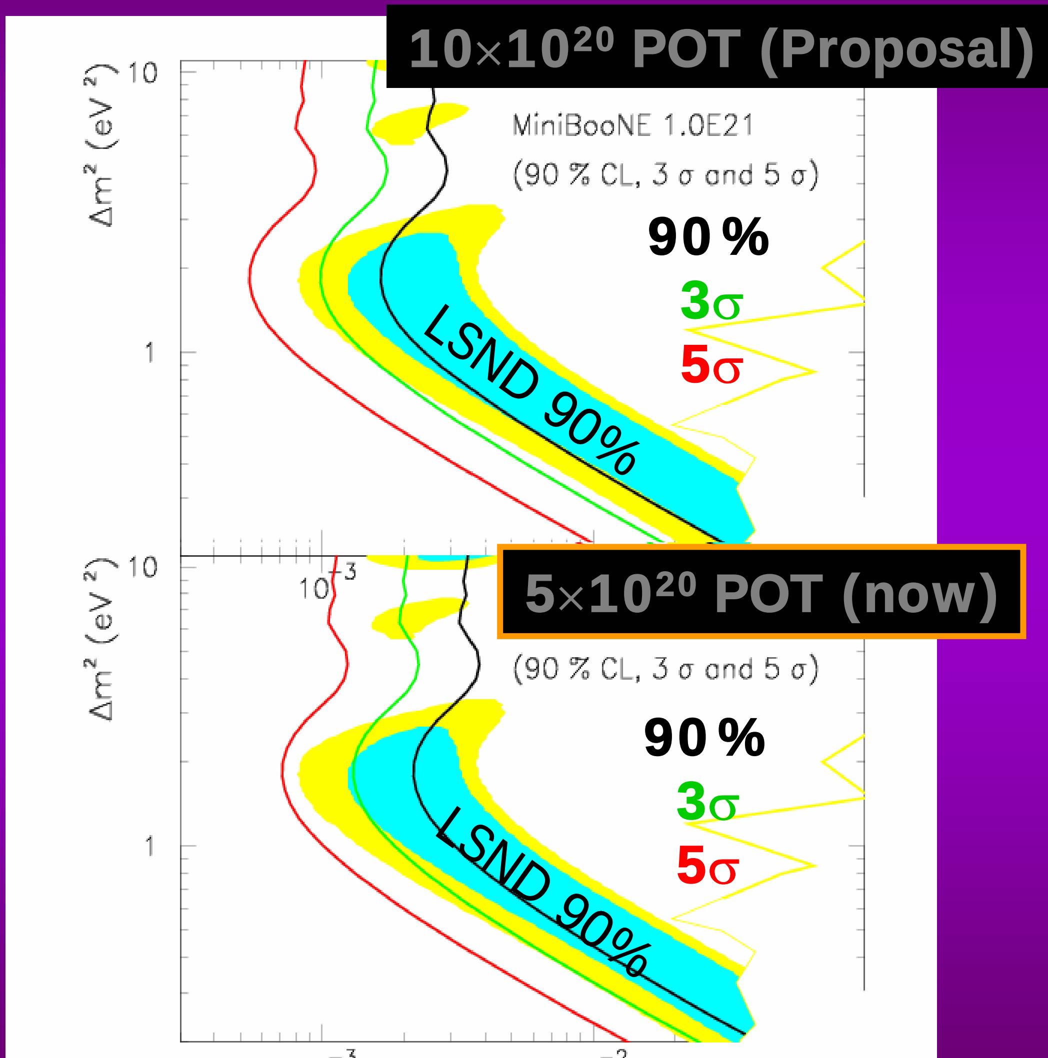


MiniBoone results soon...

PANIC, Oct 05

„At the current time have collected 6.5x10[20] p.o.t. Plan is to "open the box" when analysis is ready.

ν_μ



Problems with cross sections

Next step:

⇒ Need to run with $\bar{\nu}_\mu$ since LSND signal was

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

Jan 2006: Started to run Antineutrinos

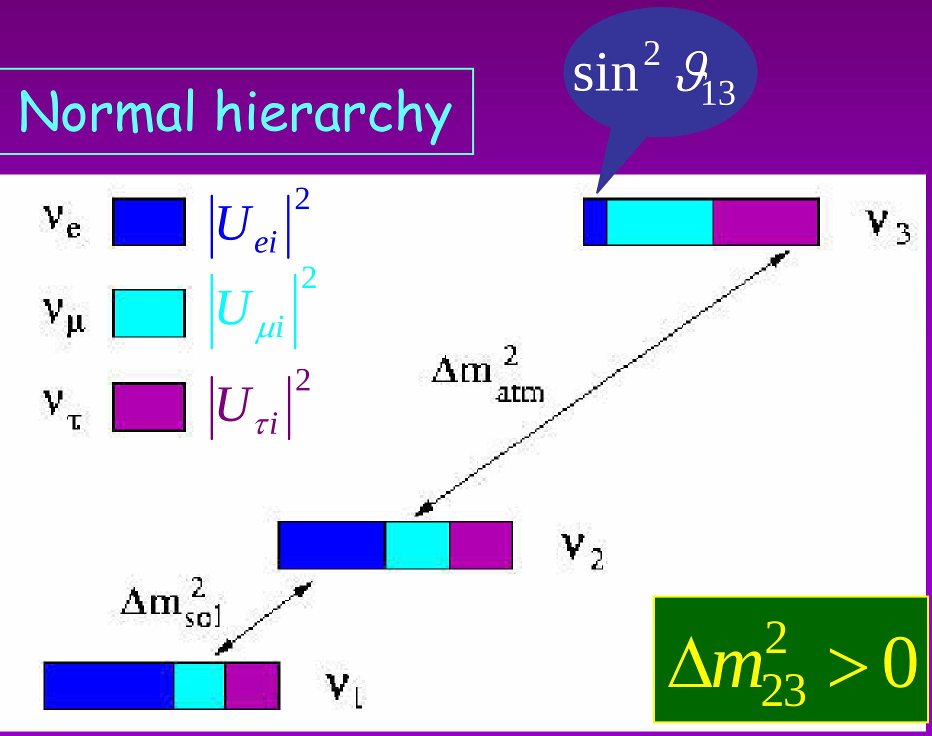
MiniBooNE has the sensitivity now.

Djurcic, PANIC05

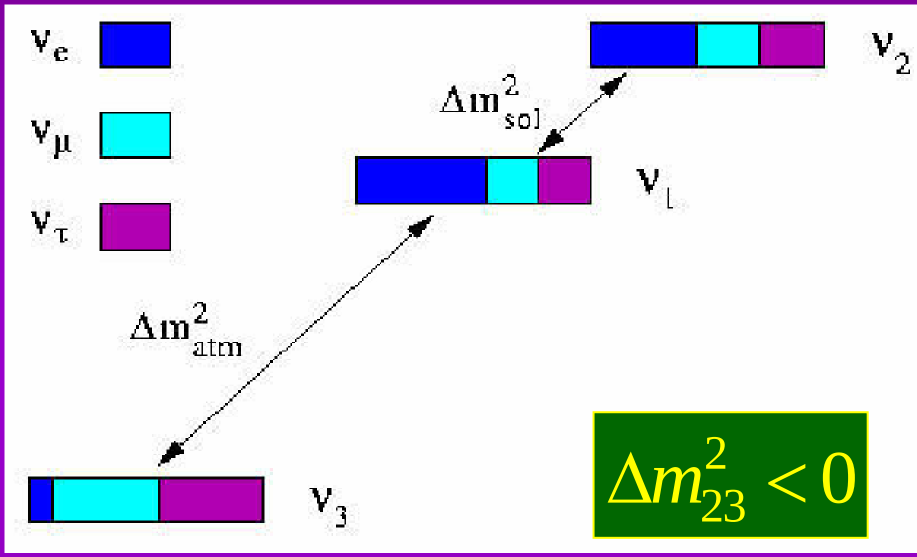
Dalej zakładamy
tylko
3 stany masowe

Neutrino masses – to be measured

Normal hierarchy



Reversed hierarchy



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$$\Delta m^2_{21} = 7.9 \pm 0.6 \times 10^{-5}\ \mathrm{eV}^2$$

To be measured:

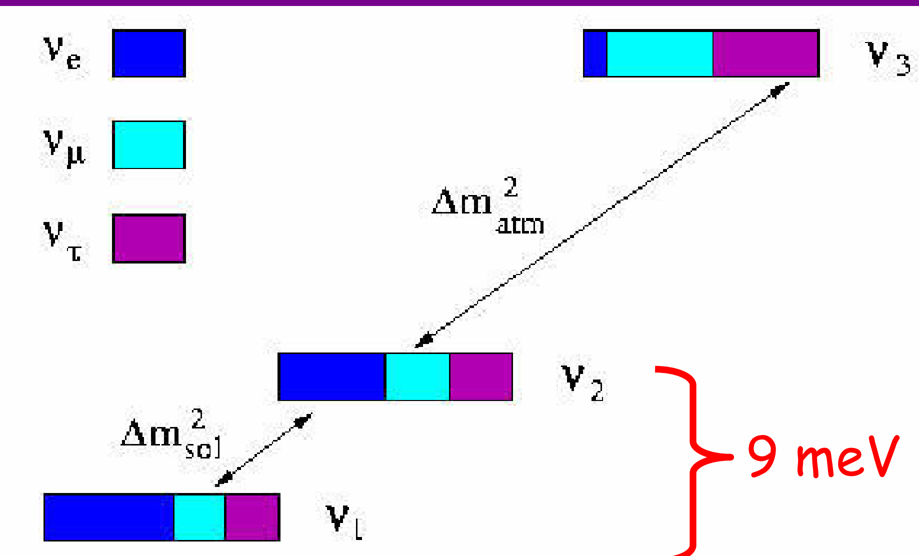
$$\mathrm{sgn}(\Delta m^2_{23})$$

And improve precision of:

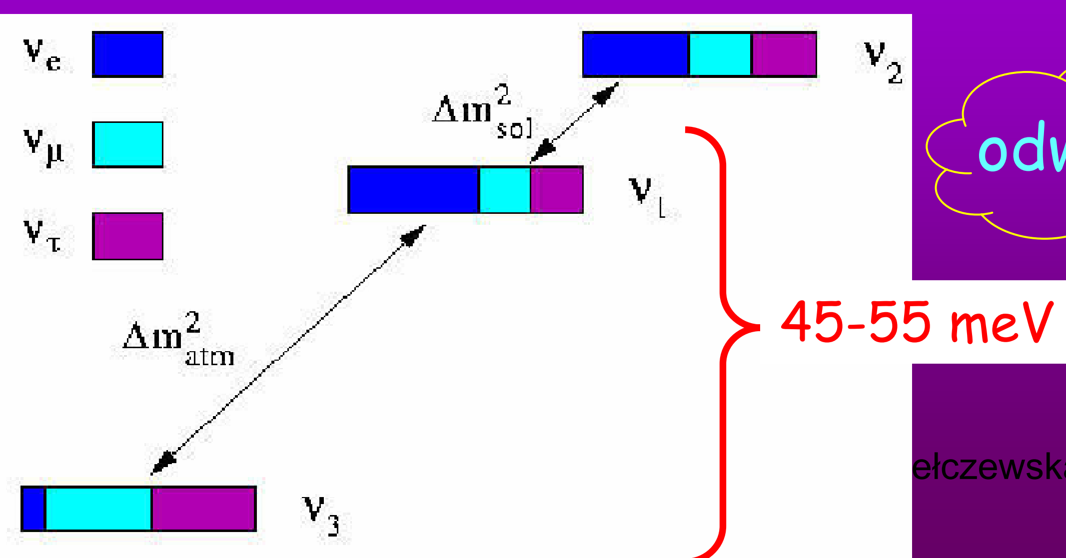
$$\left|\Delta m^2_{23}\right|$$

Dlaczego ustalenie hierarchii jest ważne?

$\mathrm{sgn}(\Delta m^2_{23})$



normalne



odwrócone

Większa szansa na pomiar

$2\beta0\nu$

$\langle m_{\beta\beta} \rangle$ większe

ełczewska

Parametrization of mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} e^{i\alpha_1/2}\nu_1 \\ e^{i\alpha_2/2}\nu_2 \\ \nu_3 \end{pmatrix}$$

α are Majorana phases

$$c_{ij} = \cos\theta_{ij} \quad s_{ij} = \sin\theta_{ij}$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

θ_{12} θ_{23} θ_{13} δ (CP violation)

Status of: the mixing matrix

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

CP

solar

atmospheric

$c_{ij}=\cos\theta_{ij} \quad s_{ij}=\sin\theta_{ij}$

$\sin^2 2\vartheta_{23} > 0.90$ at 90% c.l. $(37^o\text{-}53^o)$ - is it maximal? Which octant?

$\sin^2 2\vartheta_{12} = 0.82 + 0.07 \qquad (\vartheta_{12} = 33.9^{+2.4}_{-2.2})$

$\sin^2 2\vartheta_{13} < 0.14$ at 90% c.l. $(\vartheta_{13} < 10^o)$ - is it zero?

To be measured:

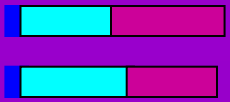
- more precisely ϑ_{23}

→ ϑ_{13}

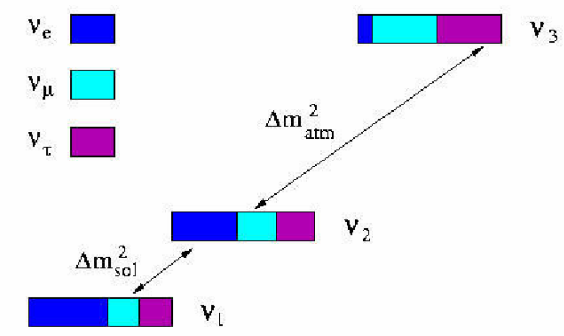
→ δ

Czyli pozostają pytania:

- Jak duży jest ϑ_{13}
- Czy ϑ_{23} jest maksymalny czy też:



- Czy widmo mas „normalne" (podobne do kwarkowego) czy „odwrócone"?
- Czy neutrina zachowują CP?



„Degeneracja" ϑ_{23}

ϑ_{23} wyznaczamy z eksperymentu „disappearance":

$$P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2 2\vartheta_{23} \sin^2 \frac{1.27\Delta m_{23}^2 L}{E}$$

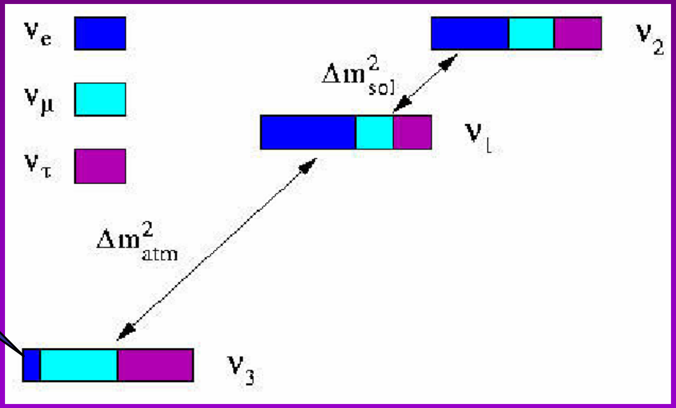
Jeżeli $\vartheta_{23} \neq 45^\circ$ to niepewność

ϑ_{23} lub $90^\circ - \vartheta_{23}$

propaguje się w formułach zawierających $\sin\vartheta_{23}$

How to measure ϑ_{13}

$\sin^2 \vartheta_{13}$



We need:

- an experiment sensitive to Δm^2_{atm}
  i.e. L/E ~500 km/GeV
- involving ν_e

- Reactor $\bar{\nu}_e \rightarrow \bar{\nu}_e$ disappearance

  e.g. Chooz - the best current limit: $\sin^2 2\vartheta_{13} <$ 0.14 for $\Delta m^2_{13} = 0.025\ \text{eV}^2$; 0.18 for $\Delta m^2_{13} = 0.020\ \text{eV}^2$

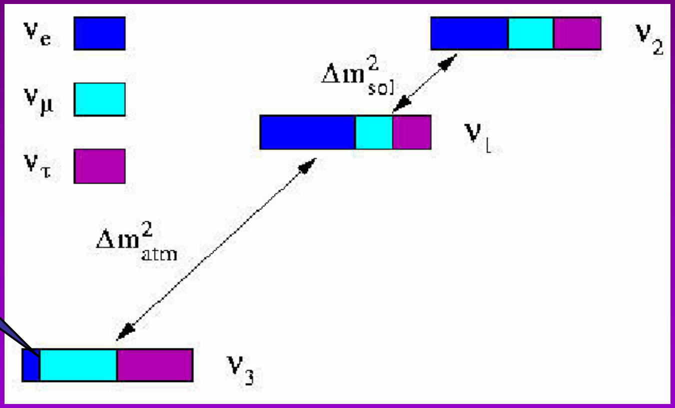
- Accelerator $\nu_\mu \rightarrow \nu_e$ appearance

$$P_{vac}(\nu_\mu \rightarrow \nu_e) \sim \sin^2 2\vartheta_{13} \cdot \sin^2 \vartheta_{23} \cdot \sin^2 \frac{1.27\Delta m^2_{13} \cdot L}{E}$$

at one of the prob. max: $P_{vac}(\nu_\mu \rightarrow \nu_e) = \frac{1}{2}\sin^2 2\vartheta_{13}$

How to measure ϑ_{13}

$\sin^2\vartheta_{13}$



We need:

- an experiment sensitive to Δm^2_{atm}
  i.e. L/E ~300 km/GeV
- involving ν_e

$$\frac{L}{E} \sim 300\,\frac{\text{km}}{\text{GeV}}$$

reactor at L~1 km ($\bar{\nu}_e$ of a few MeV)

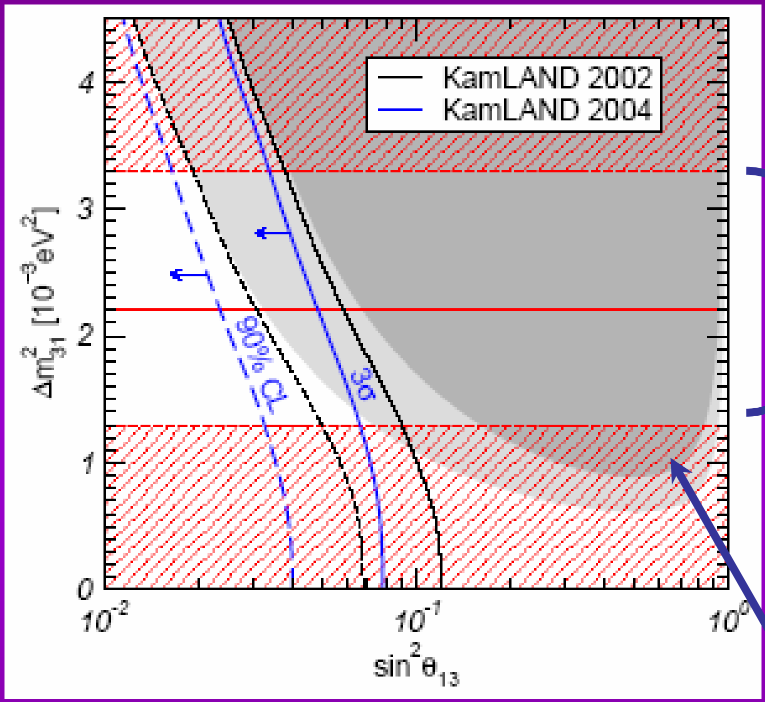
disappearance: $\bar{\nu}_e \rightarrow \bar{\nu}_e$

accelerator – „long baseline" ($\nu_\mu, \bar{\nu}_\mu$ of GeV)

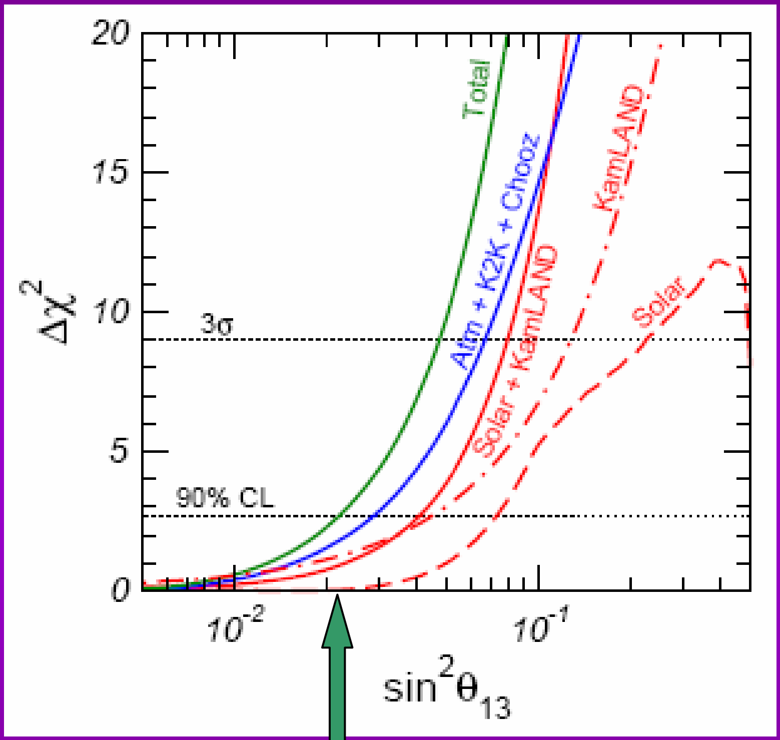
appearance: $\nu_\mu \rightarrow \nu_e$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

θ_{13} mixing angle from global analysis



Δm^2_{atm} at 3σ



from solar, KamLAND and CHOOZ (90%,3σ)

$\sin^2 \vartheta_{13} < 0.022$ at 90%

3sigma: $\sin^2 \vartheta_{13} < 0.051$

M. Maltoni, T. Schwetz, M. Tortola and J. Valle, hep-ph/0405172

Eksperymenty typu „disappearance"

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin^2 \Delta_{ij}$$

$$\pm 2\sum_{i>j} \mathrm{Im}\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin 2\Delta_{ij}$$

$$\Delta_{ij} \equiv \frac{1.27\Delta m^2_{ij} L}{E_\nu}$$

- for neutrinos
+ for antineutrinos

W eksperymentach „disappearnce":

$$\mathrm{Im}\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) = 0$$

for $\alpha = \beta$

W szczególności w eksperymentach reaktorowych:

$$P(\bar{\nu}_e \to \bar{\nu}_e) \cong 1 - \sin^2 2\vartheta_{13} \sin^2 \frac{1.27\Delta m^2_{13} L}{E} + \cos^4 \vartheta_{13} \sin^2 2\vartheta_{12} \sin^2 \frac{1.27\Delta m^2_{12} L}{E}$$

Czysty pomiar ϑ_{13} ale nic więcej!

W szczególności nie ma zależności od fazy CPV

Efekt <10%

$\nu_\mu \to \nu_e$ appearance

$\Delta_{12} \ll \Delta_{13}$

$$P(\nu_\mu \to \nu_e) =$$

$$4s_{23}^2 s_{13}^2 c_{13}^2 \sin^2 \Delta_{13}$$

$$+8 s_{12} s_{23} s_{13} c_{13}^2 \left(c_{12} c_{23} \cos\delta - s_{12} s_{23} s_{13}\right) \sin\Delta_{13} \sin\Delta_{12} \cos\Delta_{23}$$

$$-8 s_{12} s_{23} s_{13} c_{12} c_{23} c_{13}^2 \sin\delta \sin\Delta_{13} \sin\Delta_{12} \sin\Delta_{23}$$

CP violation

$$+4 s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{23}^2 s_{13}^2 c_{13}^2 - 2 s_{12} s_{23} s_{13} c_{12} c_{23} \cos\delta) \sin^2 \Delta_{12}$$

solar

$$-8 s_{13}^2 s_{23}^2 c_{13}^2 (1 - 2 s_{13}^2) \frac{\alpha L}{4E} \sin\Delta_{13} \cos\Delta_{23}$$

matter effects

where:

$$s_{ij} \equiv \sin\vartheta_{ij}, \quad c_{ij} \equiv \cos\vartheta_{ij}$$

$$\Delta_{ij} \equiv \frac{1.27 \Delta m_{ij}^2 L}{E_\nu}$$

$$\alpha = 2\sqrt{2} G_F n_e E$$

matter effects

s_{12} large is a good news!

How to measure…(cont.)

Reactor experiments which have relatively short baselines and very low energies will measure:

$\sin^2 2\vartheta_{13}$ down to 0.02

but not:

$\delta, \quad \mathrm{sgn}(\Delta m^2_{13}), \quad \text{nor} \ \ \Delta m^2_{13}, \quad \sin^2 2\vartheta_{23}$

A number of different sites for reactor experiments are considered:
- Brasil, China (Daya Bay), France (Double Chooz), Japan (KASKA), Russia, Taiwan
and USA (Braidwood…)

Complementary to accelerator experiments

	Double Chooz	Braidwood	Daya Bay
Reactor Power	8.4 GW_{th}	7.2 GW_{th}	11.6 $\rightarrow$ 17.4 GW_{th}
Near Dist/Depth	100 m/60 m.w.e.	270 m/450 m.w.e.	500 m/330 m.w.e.
Mid Dist/Depth	---	---	1111-796 m/560m.w.e
Far Dist/Depth	1100 m/330 m.w.e.	1510 m/450 m.w.e.	2227-1801 m/1143 m.w.e
Mass (Near-Far)	12.7-12.7 tons	2 × 65 - 2 × 65 tons	2 × 40 - 3 × 40 tons
Geometry	Cylindrical	Spherical	Cylindrical
Gamma catcher	Yes	No	Yes
Detector systematics	0.6%	0.3%	0.36% $\rightarrow$ 0.12%
$\sin^2 2\theta_{13}$ at 90% CL	0.02	0.005	0.008 $\rightarrow$ 0.006
Approval/Start	2006/2007 Far	2007/2010	2006/2007 Near-Mid.
	2006/2008 Near		2006/2009 Near-Far
Detector swapping	No	Yes	Yes

Why Double Chooz ?

Main limitations of Chooz

- **Poor statistics** ($\sigma_{stat} = 2.8\ \%$)
- **Limited knowledge of source & detector** ($\sigma_{sys} = 2.7\ \%$)

→ **Potential of reactor-based search not fully exploited !**

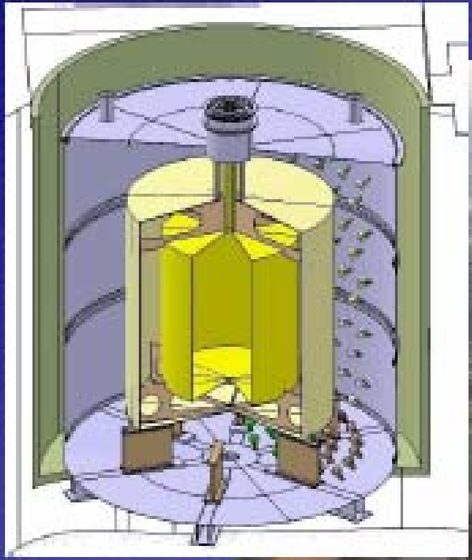
Proposed approach

- Improve statistics by running longer with a larger target mass
- Cancel most of the systematics with a 2-detector concept
- Improve design to control detector-related systematics

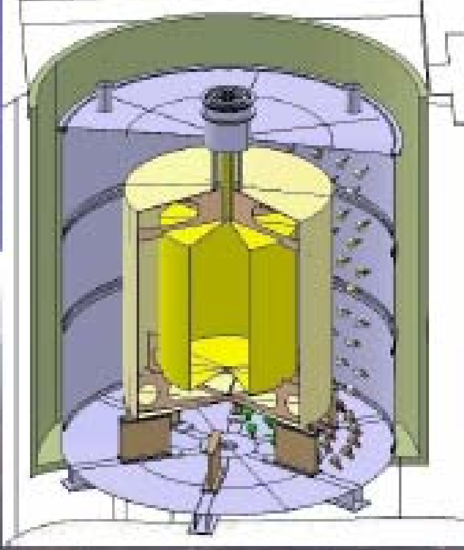
→ **$\sin^2 2\theta_{13} \lesssim 0.02 - 0.03$**
feasible with
new experiment @ Chooz

Near site ~ 200-300 m (to build, ~ 80 mwe)

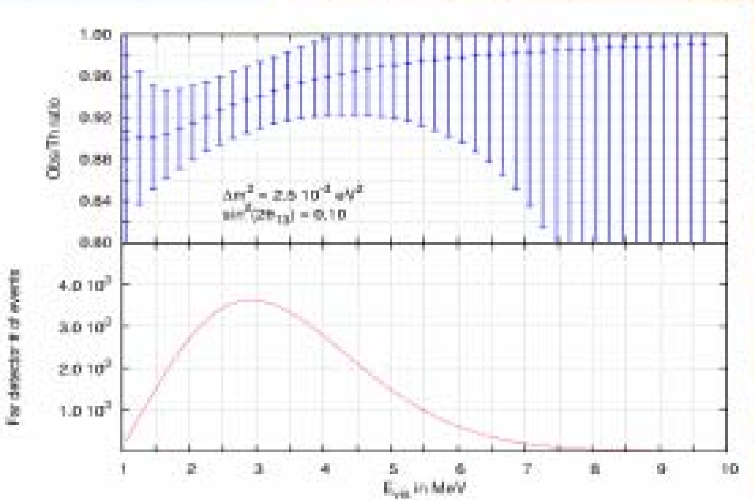
Far site ~ 1km (old Chooz lab, 300 mwe)



~ 1000 $\bar{\nu}$ interactions/day in target



~ 70 $\bar{\nu}$ interactions/day in target



Integral rate ratio & Spectral deformations

Detector layout

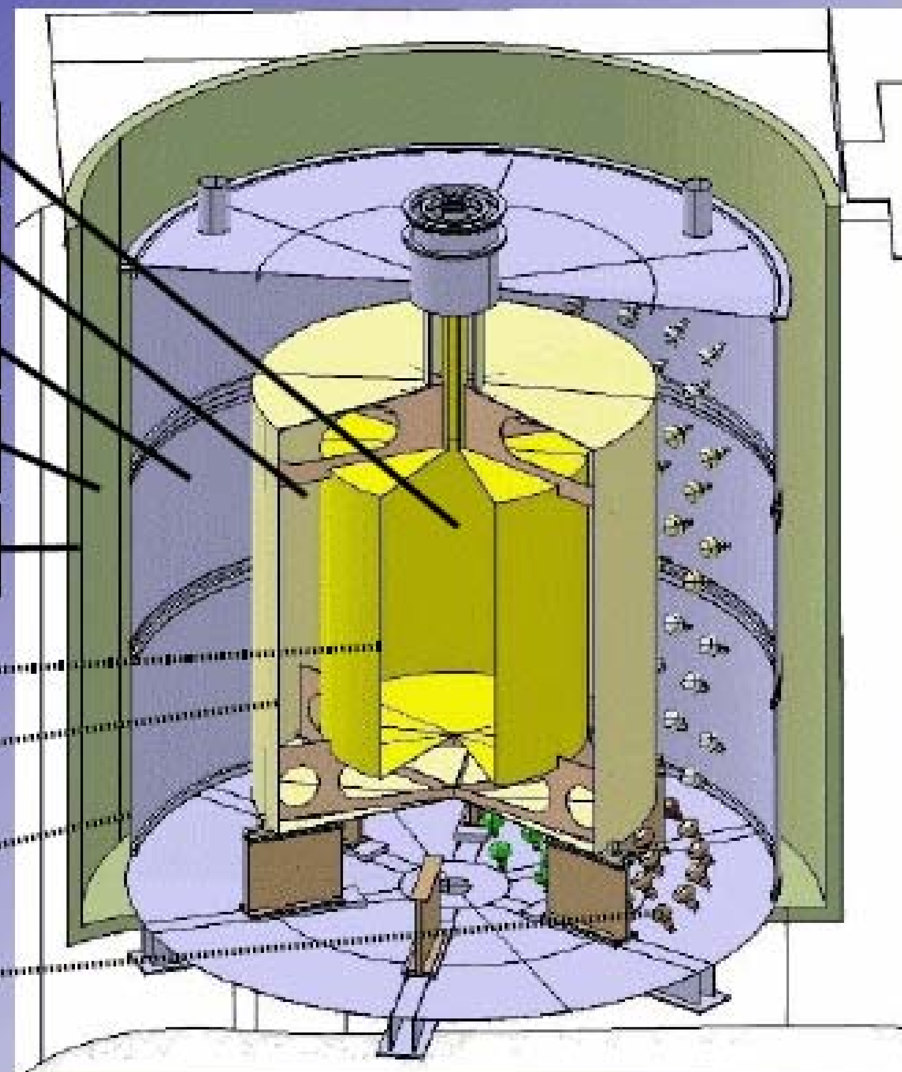
$\bar{\nu}_e + p \rightarrow e^+ + n$ (Q = 1.8 MeV)

$n_{th} + Gd \rightarrow Gd^* \rightarrow Gd + \sim 8MeV$

Design near to finalization
(all dimensions subjected to MC studies)

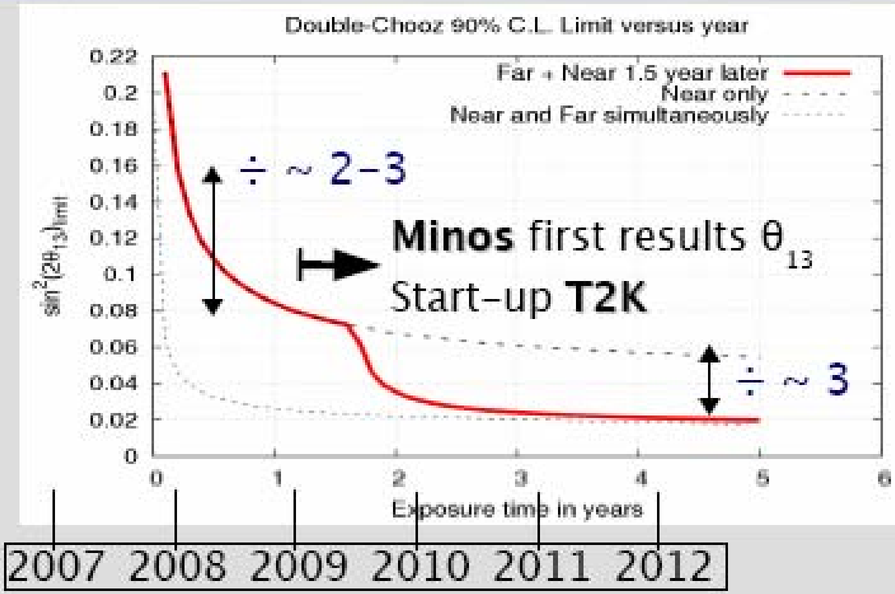
- $\bar{\nu}$ **Target** (~ 10 tons Gd-loaded scintillator)
- γ **-catcher** (t=55 cm, unloaded scintillator)
- **Buffer** (t= 105 cm, mineral oil)
- **Veto** (t=50 cm, mineral oil + fluors)
- **Shielding** (17 cm steel)

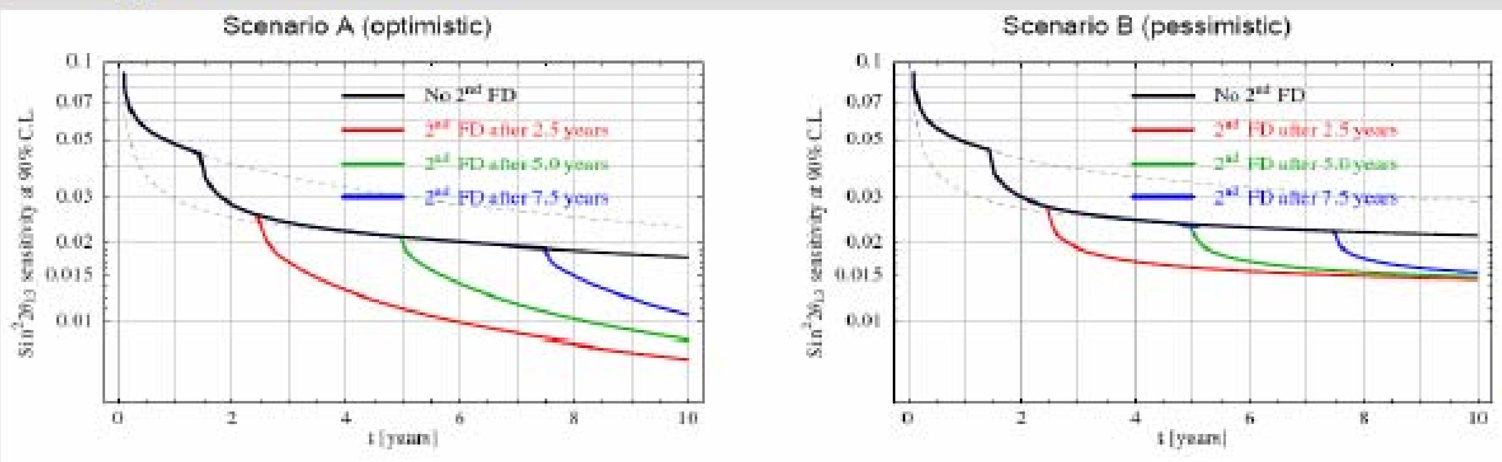
- Acrylic target vessel
- Acrylic γ -catcher vessel
- Buffer tank (stainless steel) & PMT support structure
- PMTs (534, 8")



Outlook

- Full proposal being edited
- R&D mostly finalized, ready to build !
- No other reactor experiment with competitive schedule
- First experiment to lower Chooz limit
- Best sensitivity until > 2011
- Complementarity with T2K
- Concrete discovery potential
- Triple Chooz next ?!





P. Huber, JK, M. Lindner, M. Rolinec and W. Winter, in prepapration

Availability of a large cavern next to the far lab after complete dismantling of the old Chooz reactor (2011)

Eksperymenty reaktorowe - NUSAG

2 or more identical liquid scint

Double Chooz   syst 2.7% to 0.3-0.6%, 65 ton/detek
Braidwood, Ill, 4 identyczne detek, 3 różne odl,, przesuwane
ta sama głębokość żeby odjąć tlo od mionów
Daya Bay

Źródła tła:

- przypadkowe koincydencje e+ - gamma - ocena z pomiarów
- neutrony z mionów CR – duże weto na miony i absorber neutronow naokoło
- dlugozyciowe (>100ms) izotopy (8He i 9Li) produkowane przez mion i rozpadajace się na e+ + n

Starzenie się scyntyl:
CHOOZ atenuacja światła 5m, starzenie 0.4%/dzień
Nowe scyntyl: 15 m; stała > 220dni

Eksperymenty reaktorowe - czułości

	Double-Chooz	Braidwood
błąd syst	0.6%	0.3% det + 0.14% tlo
5 lat s2t13 90%	0.02	0.005
disc 3s	0.03	0.01
Dane od:		
daleki detek	2007-	2010
bliski	2009	
	czułośc raczej stat	
koszt		65M$

How to measure CP violating phase δ

In vacuum the shift in oscil. prob. due to δ is:

$$\Delta P_\delta(\nu_\mu \to \nu_e) \approx 0.9 \cdot \sin 2\vartheta_{13} \cdot \sin\Delta_{sol} \cdot \sin\Delta_{atm} \cdot (\cos\delta\cos\Delta_{atm} \mp \sin\delta\sin\Delta_{atm})$$

$$\Delta_{atm} = \frac{1.27\,\Delta m_{32}^2 L}{E}$$

$$\Delta_{sol} = \frac{1.27\,\Delta m_{12}^2 L}{E}$$

- for ν

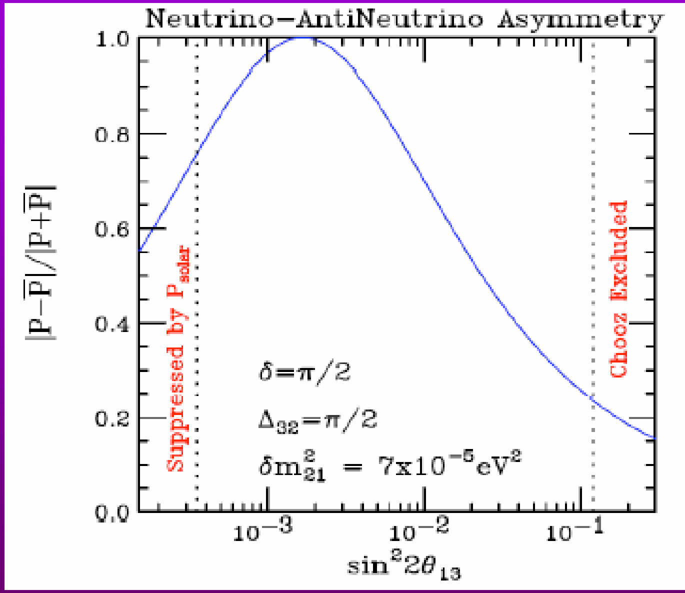
+ for $\bar{\nu}$

Asymmetry:

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

measures δ

(if CP is violated through δ)



from „Nova” proposal

CP violation

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin^2 \Delta_{ij}$$

$$\pm 2\sum_{i>j} \mathrm{Im}\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin 2\Delta_{ij}$$

$$\Delta_{ij} \equiv \frac{1.27 \Delta m^2_{ij} L}{E_\nu}$$

- for neutrinos
+ for antineutrinos

CP violation can be observed only in appearance experiments because :

$$\mathrm{Im}\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) = 0$$
$$\text{for} \quad \alpha = \beta$$

CPV:

$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

but CPT invariance implies:

$$P(\nu_\alpha \to \nu_\alpha) = P(\bar{\nu}_\alpha \to \bar{\nu}_\alpha)$$

$\nu_\mu \rightarrow \nu_e$ - efekty w materii

W eksperymencie „appearance”:

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 \vartheta_{23} \sin^2 2\vartheta_{13} \sin^2 \frac{1.27 \Delta m_{13}^2 L}{E}$$

w próżni

W materii mamy elektywny kąt mieszania

$$\sin^2 2\vartheta_m \cong \sin^2 2\vartheta_{13} \left(1 \pm s \frac{E}{6\ \text{GeV}}\right)$$

\+ neutrina
\- antyneutrin
s=1 normalne widmo
s=-1 odwrócone widmo

- czułość na charakter widma zależy od ϑ_{13}
- wyraźnie większa dla eksperymentu z energią wiązki ~ 2 GeV (Nova) niż 0.6 GeV (T2K)

How to measure $\mathrm{sgn}(\Delta m^2_{32})$

Matter effects: due to a difference in interactions of $\nu\,(\bar{\nu})$ of different flavors with electrons:

$$\Delta V = \sqrt{2}\, G_F\, n_e$$

$$\delta m^2 \Rightarrow \delta m^2 \pm \frac{2E(\Delta V)}{\cos 2\vartheta}$$

different sign for ν and $\bar{\nu}$

Effective mixing angle:

$$\sin^2 2\vartheta_m \cong \sin^2 2\vartheta_{13}\left(1 \pm s\,\frac{E}{6\ \mathrm{GeV}}\right)$$

+ neutrinos
- antyneutrinos

s=1 normal
s=-1 reversed

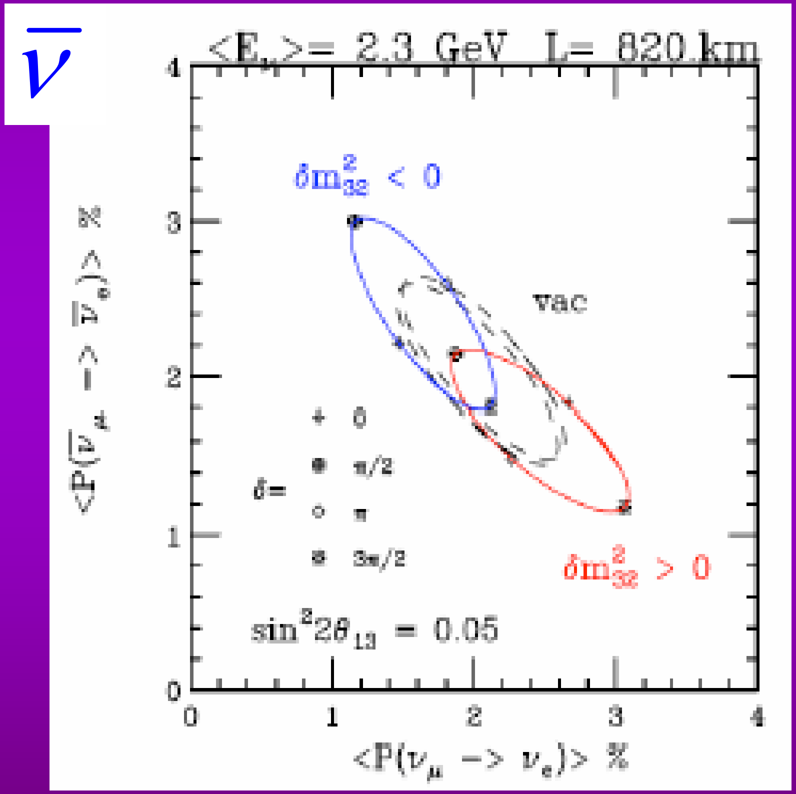
Note:
matter effects grow with energy

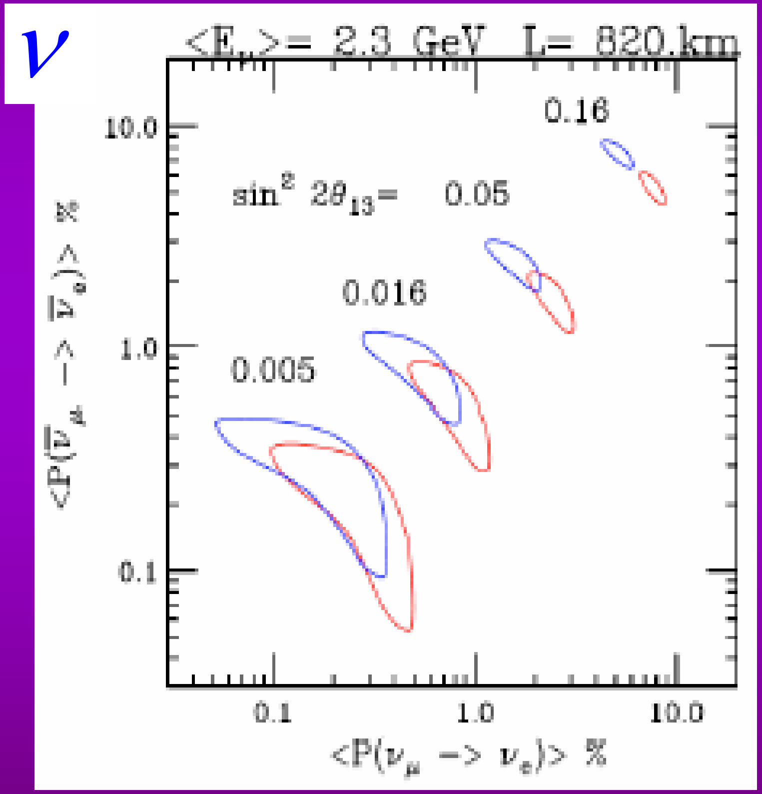
Good news: matter effects are sensitive to $\mathrm{sgn}(\Delta m^2_{32})$

Bad news: matter effects can mimic CP violation in vacuum

How to measure $\mathrm{sgn}(\Delta m^2_{32})$

- matter effects can be confused with CP violation (in vacuum)





from „Nova" proposal

Program for long-baseline experiments (next ~10-15 years)

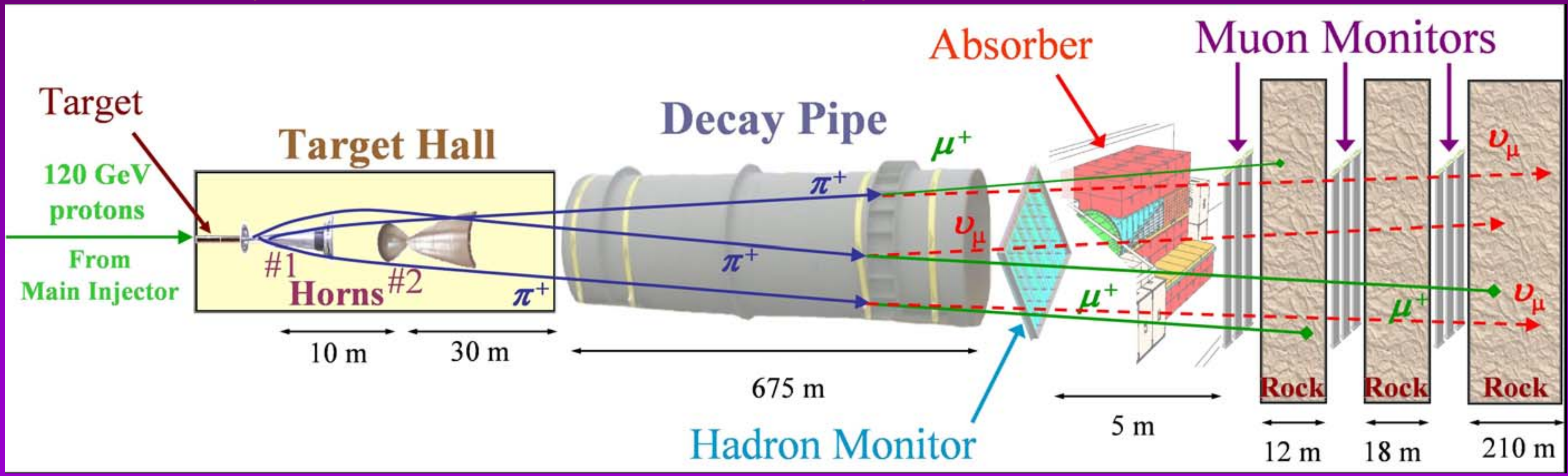
Measurement	Method	Experiments	Why?
$\left\|\Delta m^2_{32}\right\|$	ν_μ disapp.	Minos	Better precision for further studies
ϑ_{23}	as above	T2K, Nova	Max. mixing (a symmetry? or which octant
ϑ_{13}	ν_e appear.	Minos, T2K, Nova	=0 ? A symmetry? Essential for Hierarchy and CP
	$\bar{\nu}_e$ disapp.	Reactor	
Hierarchy $\not{CP}$	$\bar{\nu}_e$ vs ν_e appearance	J2K, Super-Nova, „BNL"	Unification, Leptogenesis, Ω_ν
$\nu_\mu \to \nu_\tau$	τ appear.	OPERA	To check oscil. scenario

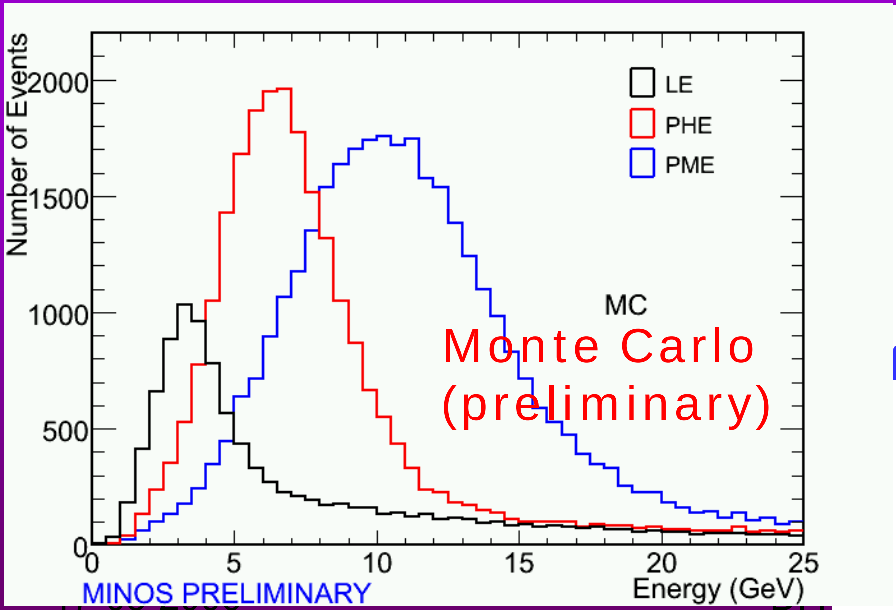
NuMi Beam @ Fermilab (Neutrinos at the Main INjector)

- started in Jan 2005 with MINOS detector
- next Super-BEAM with detectors
  - NOvA (approved)
  - „Super-Nova" – discussed

K. Lang, Como, Oct 05

Experimental setup: NuMI beam





ν_μ CC Events/kt/year in Far Det (no oscillations)

Low	Medium	High
470	1,270	2,740

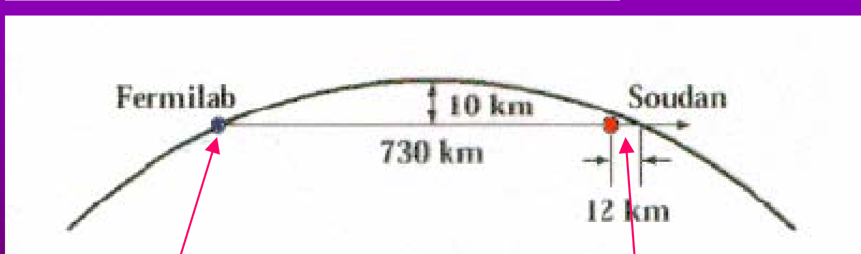
(for 4×10^{20} protons on target/year)

Far Det Now: 1 event / ~4hrs

K. Lang, Como, Oct 05

MINOS
(Main Injector Neutrino Oscillation Search)

- Two detectors
- Iron (magnetized) – scintillator sampling calorimeter
- ND 980tons @1km, FD 5400tons @730km
- Far detector fully operational since 2003



Near detector

Far detector

Far Detector

NuMi beam

Def:
„pot" – protons on target

- 1×10^{20} pot/yr achieved in 2005
- MINOS would like to integrate
  25×10^{20} (in a ~5 yr run)
- Original MINOS proposal
  2 yrs @ 3.7×10^{20} pot = 7.4×10^{20} pot
- Proposals at Fermilab to upgrade the accelerator complex
  - Upgraded NuMi beam 6.5×10^{20} pot/year
  - „Proton Driver" to reach 7.2×10^{20} pot/yr by 2009
    up to 25×10^{20} pot/year

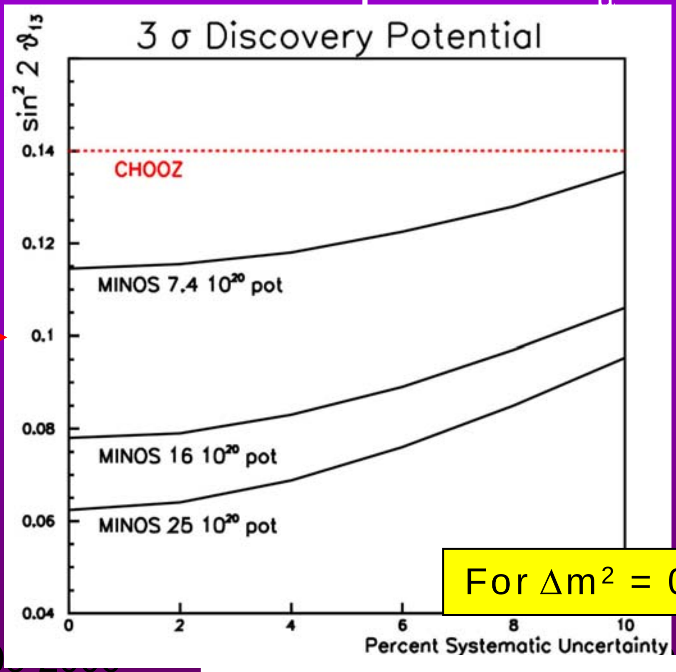
NuMi future according to NUSAG (Mar 2006)

In the era after Run II at Fermilab ends, it is estimated that the Main Injector will be able to deliver 6.5×10^{20} protons per year to the NuMI target, corresponding to ~0.6 MW of protons at 120 GeV. Fermilab contemplates upgrades to this beam power. Under consideration is a Proton Driver replacing the lower-energy accelerators feeding the Main Injector, perhaps with a superconducting linac using technology similar to that proposed for the International Linear Collider. With upgrades to the Main Injector to handle the increased flux, the power to the neutrino production target would increase to 2 MW. As an alternative, if priorities and budgets do not allow a Proton Driver, Fermilab could pursue a more incremental path that might yield 1 MW or more.

MINOS Physics Program

- Decisive low-systematics observation of $\nu_\mu \rightarrow \nu_\tau$ (oscillatory pattern)
- Determine Δm_{23}^2 with ~10% accuracy
- Measure (or improve limits) on $\nu_\mu \rightarrow \nu_e$ / $\nu_\mu \rightarrow \nu_{sterile}$ / exotics
  improve CHOOZ limit by a factor of 2 in ϑ_{13}
- Test CPT in atmospheric CC_μ charge-separated interactions

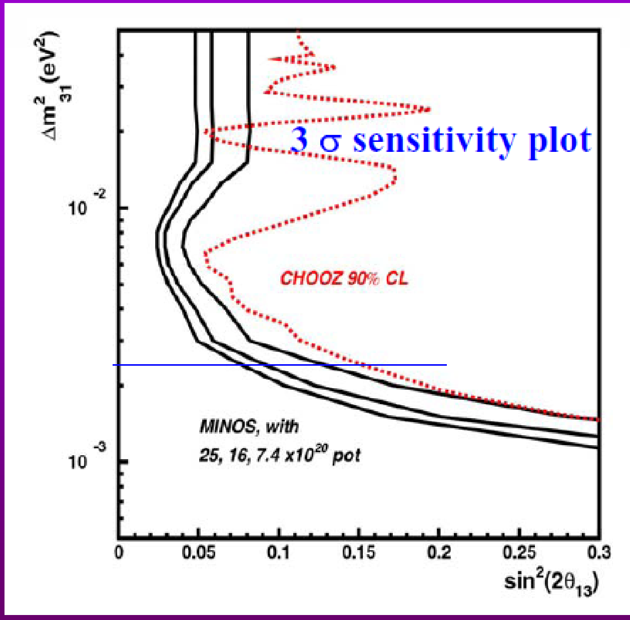
0.1



For $\Delta m^2 = 0.0025$ eV^2

Systematic uncertainty

Sensitivity is determined by statistical fluctuation



PANIC, Oct 05

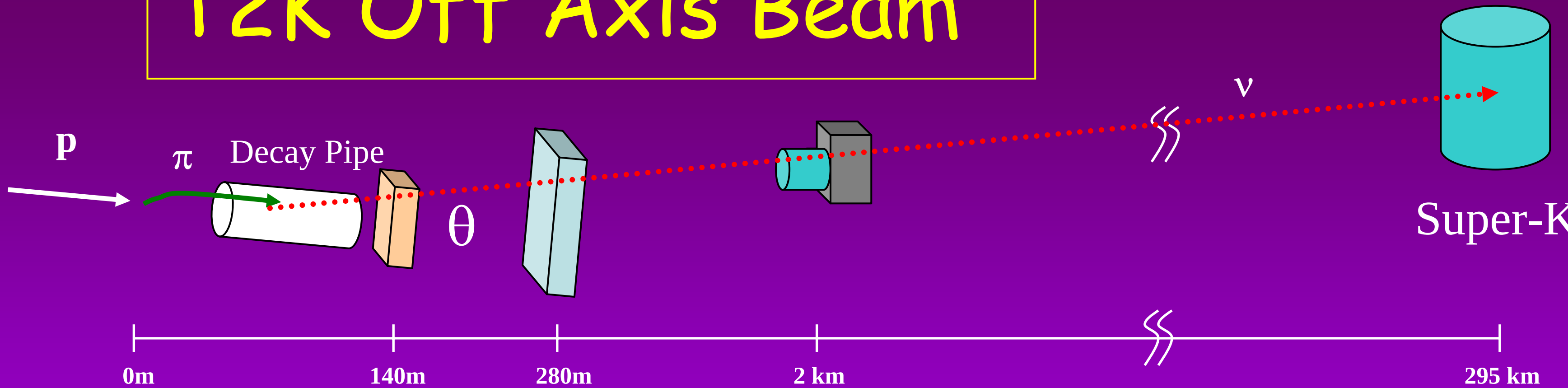
Oscillation experiments with Super Beams

- Intense conventional (π decays) neutrino sources (>0.5 MW)
- Off axis technology

	T2K	Nova
site	Japan	USA
beam	being constructed	NuMi (upgraded)
E_ν (peak)	0.76 GeV	2.22 GeV
distance	295 km	812 km
Far detector	Super-Kamiokande	to be built
of mass (FV)	22.5 kton	30 kton

Owing to higher energy, NOvA will have a three-fold bigger matter effect.
Combining the NOvA and T2K results will facilitate the separation of CP from matter effects.

T2K Off Axis Beam

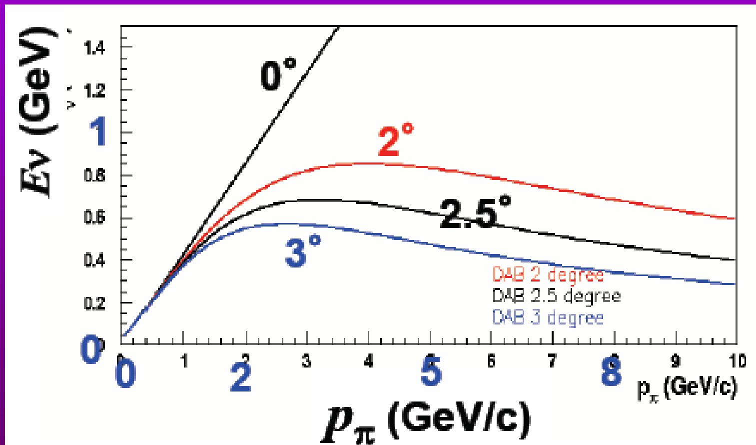


- Muon monitors @ ~140m
- First front detector @280m
- Second front detector @ ~2km
- Far detector @ 295km
  – Super–Kamiokande

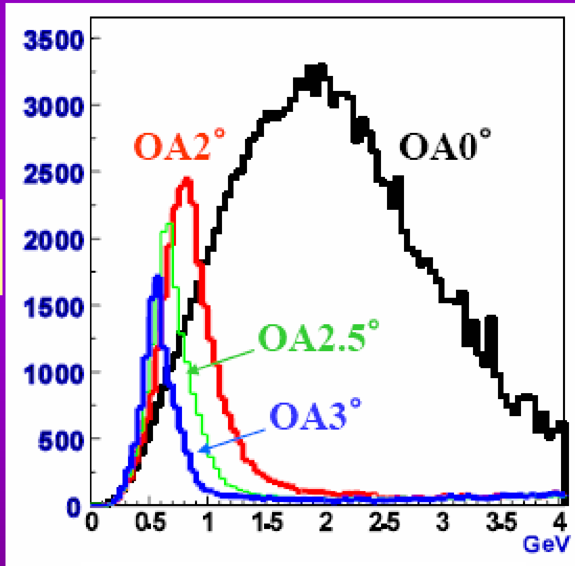
Kinematics of π decay

$$E_\nu = \frac{0.43 \cdot E_\pi}{1+\gamma^2\theta^2}$$

Tunable at oscillation max



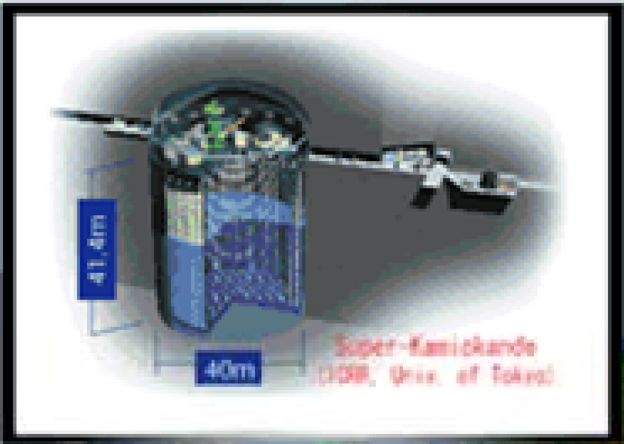
Quasi monochromatic beam

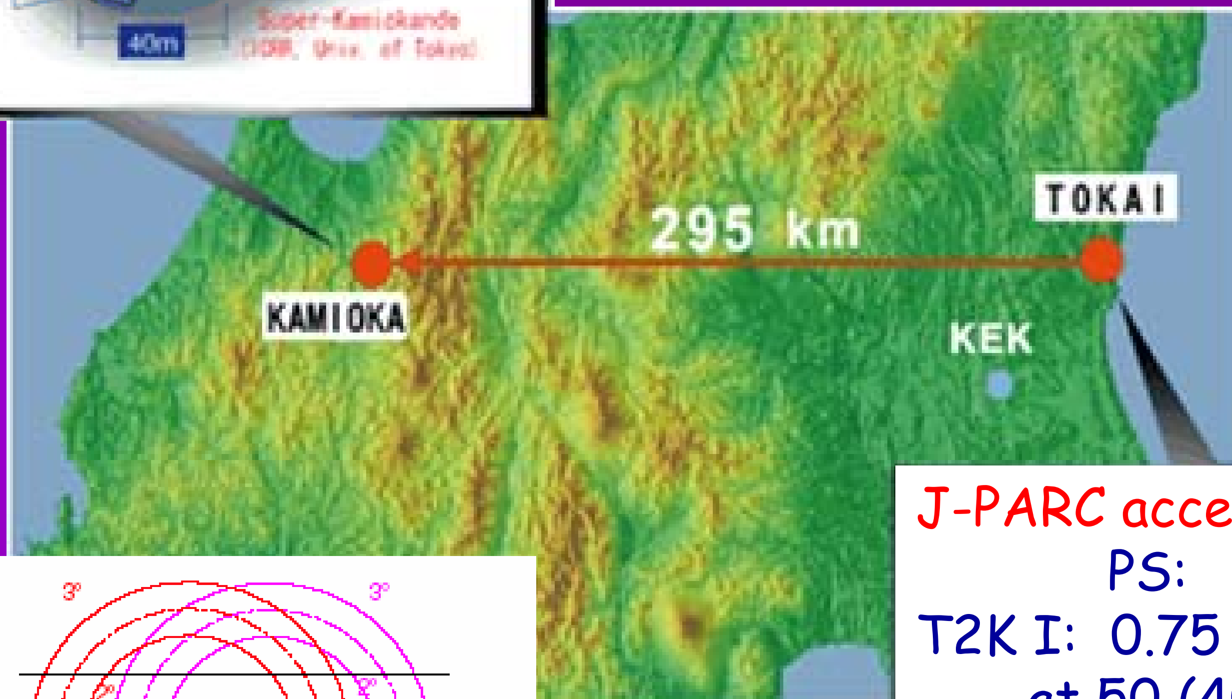


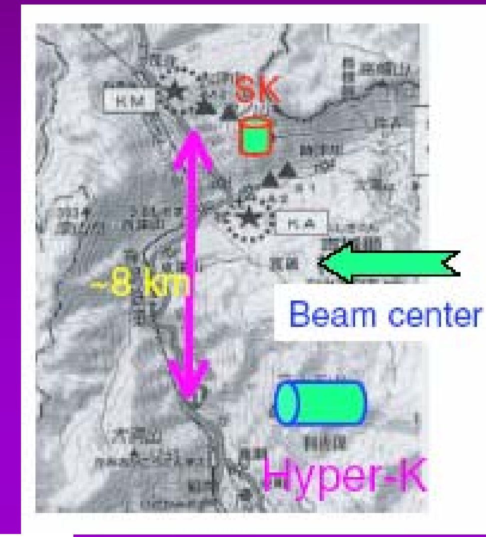
Neutrino energy

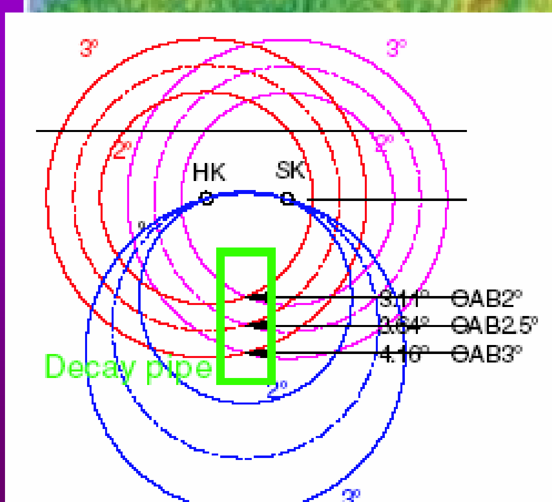
Reduced tail at high ν energies helps to reduce background due to π^0 production

T2K (Tokai to Kamioka)









beams-eye view

J-PARC accel.
PS:
T2K I: 0.75 MW
at 50 (40) GeV
(20xK2K)
1.5 G$ (7 years)
T2K II: 4 MW
0.4 G$

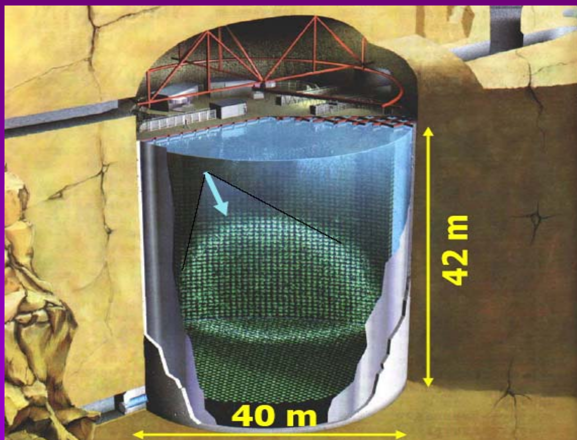
beam designed for both: phase I and phase II: 4 MW @ Hyper-Kamiok.

D. Kielczewska

Data taking starts in 2009

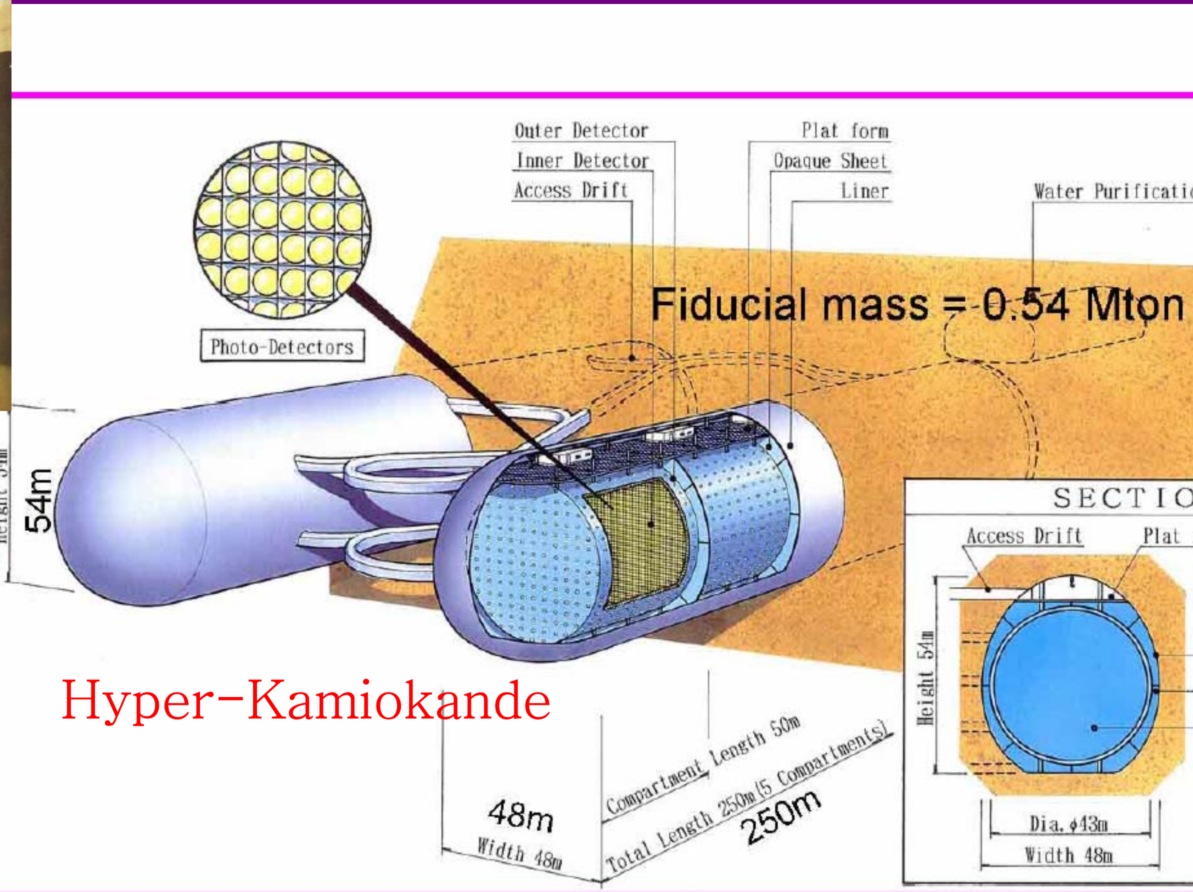
Far Detector

Phase I

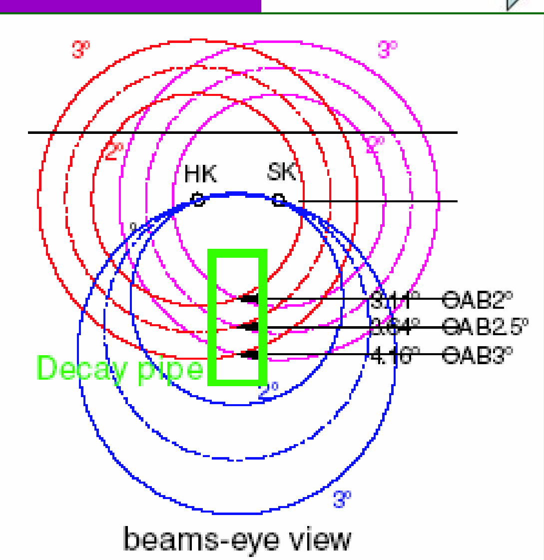


Super-Kamiokande

Phase II



Hyper-Kamiokande



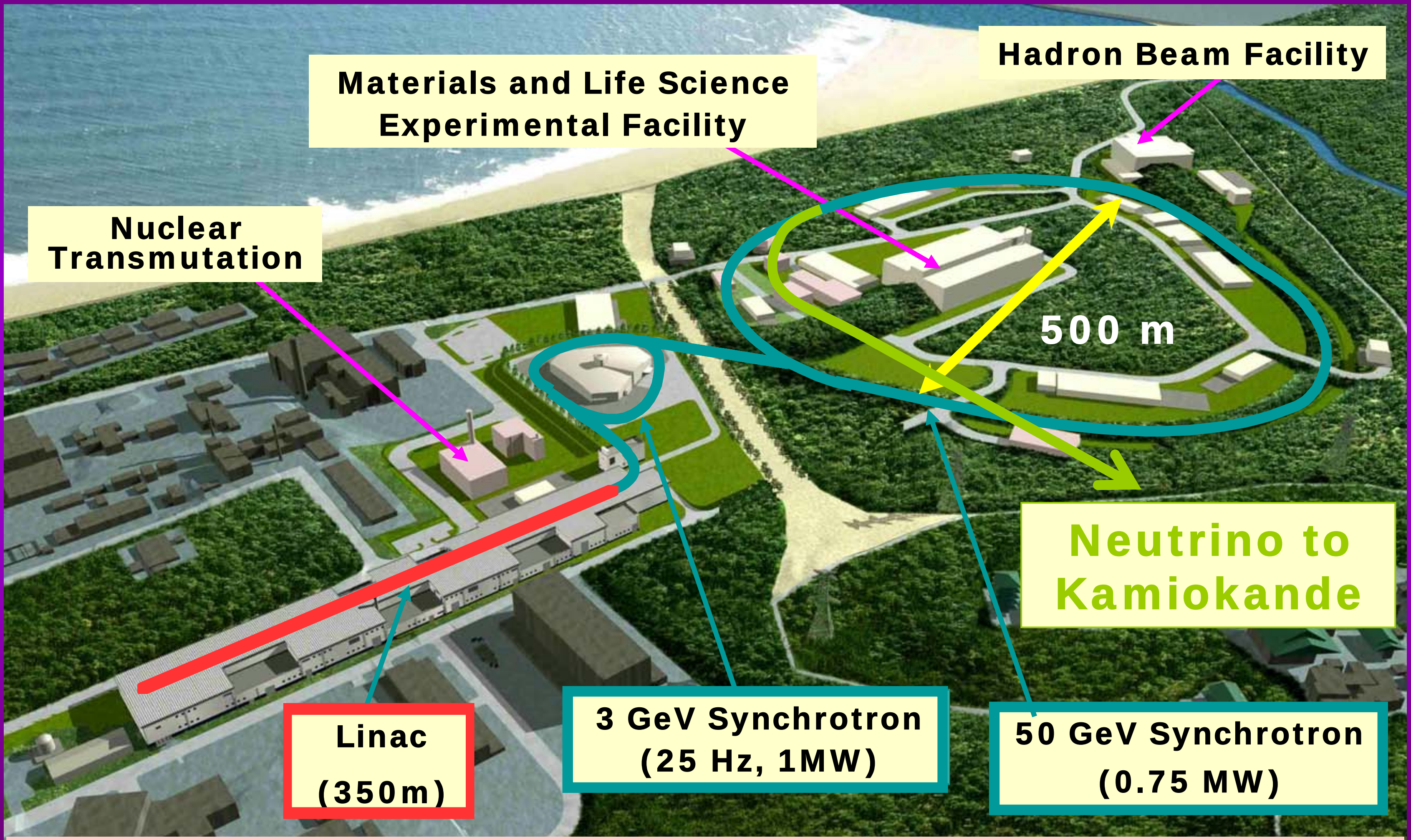
- JPARC 2-3° OA beam will cover both sites
- Good Hyper-K site in another mine nearby

D. Kiełczewska

T2K Collaboration (formed in 2003)

- 12 countries, 53 institutions
- ~150 collaborators (not incl. students)

J-PARC Facility



J-PARC = Japan Proton Accelerator Research Complex

K. Nishikawa, Korea

J-PARC Facility (TOKAI - Japan)

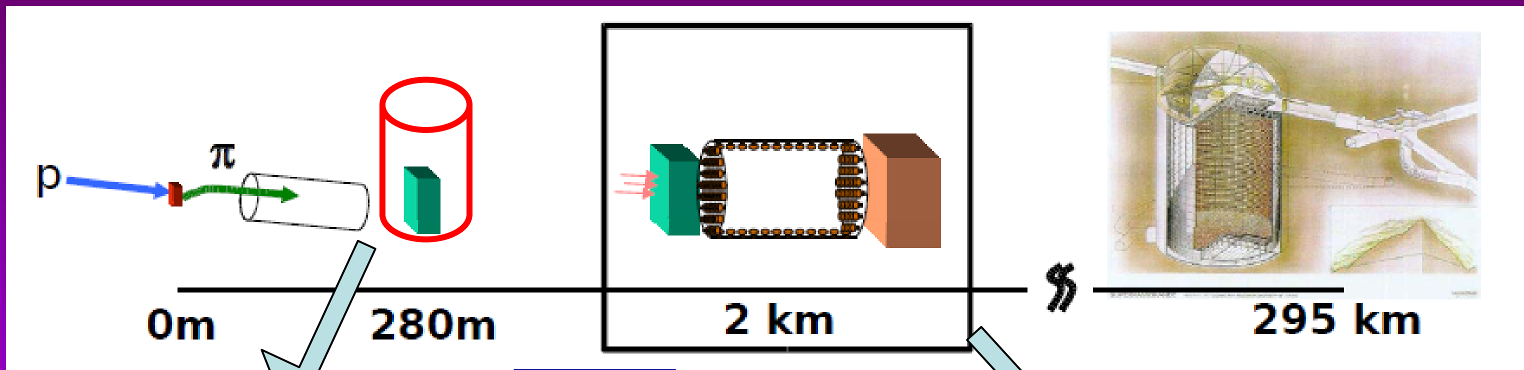
Construction for Buildings (Sept., 2005)

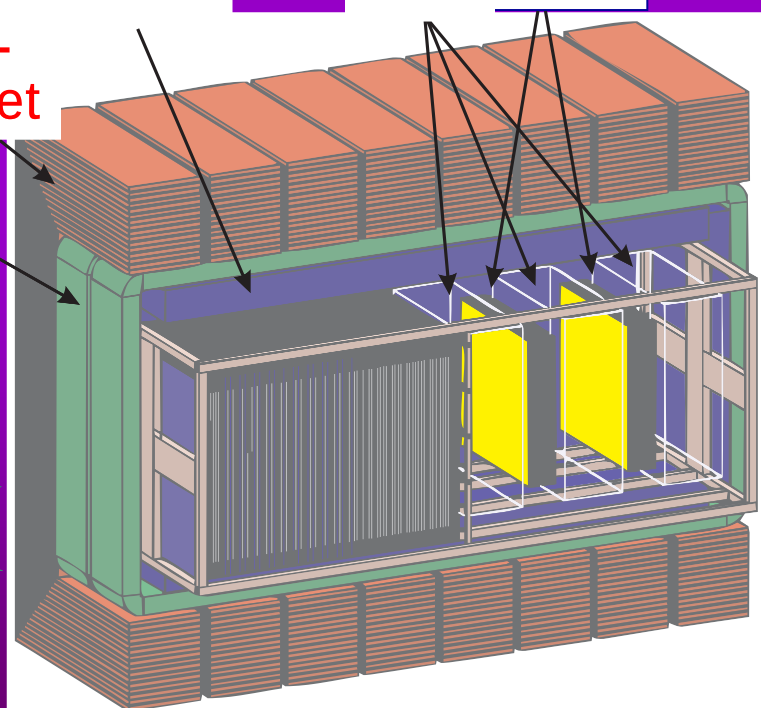
J-PARC Facility (TOKAI – Japan)

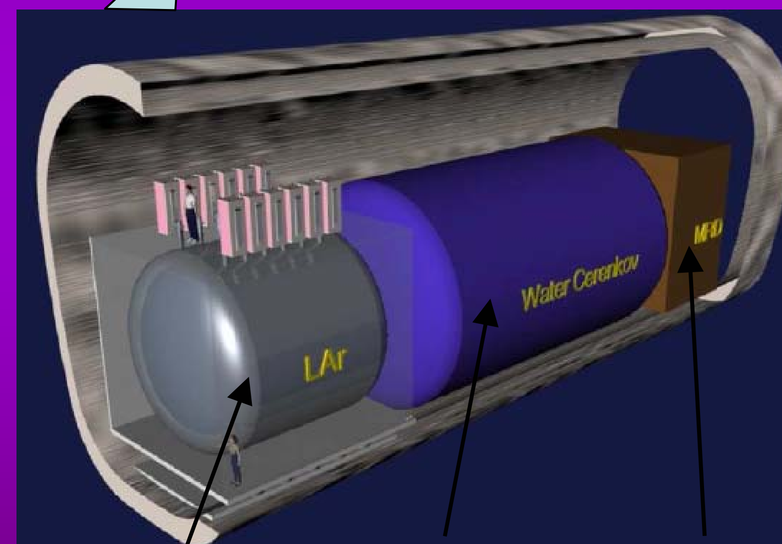
Decay pipe construction

Main Ring

T2K - Near/Intermediate detectors



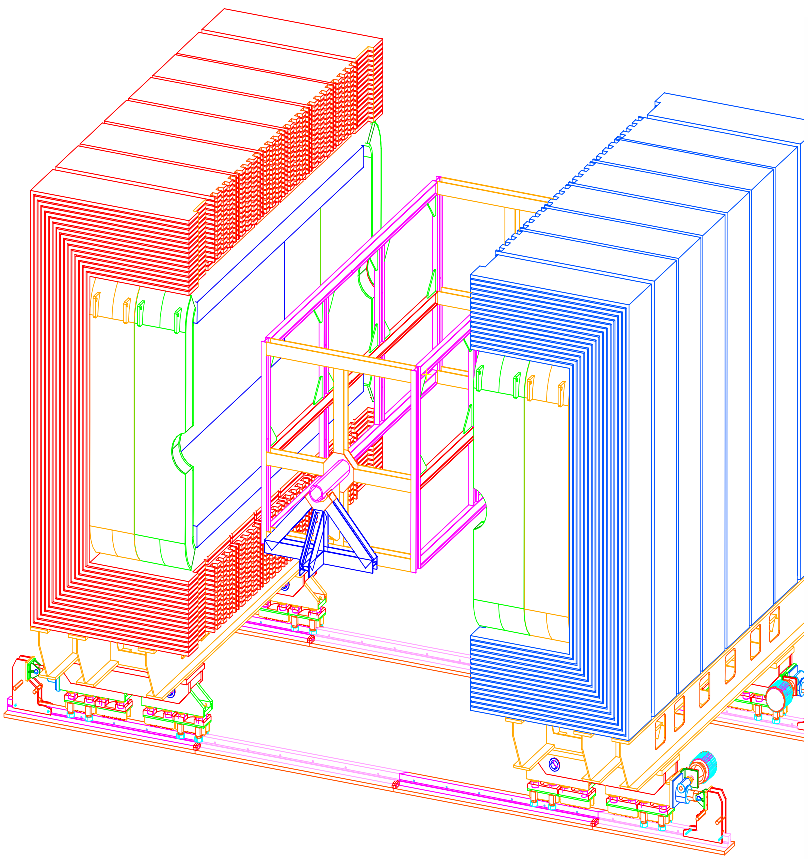


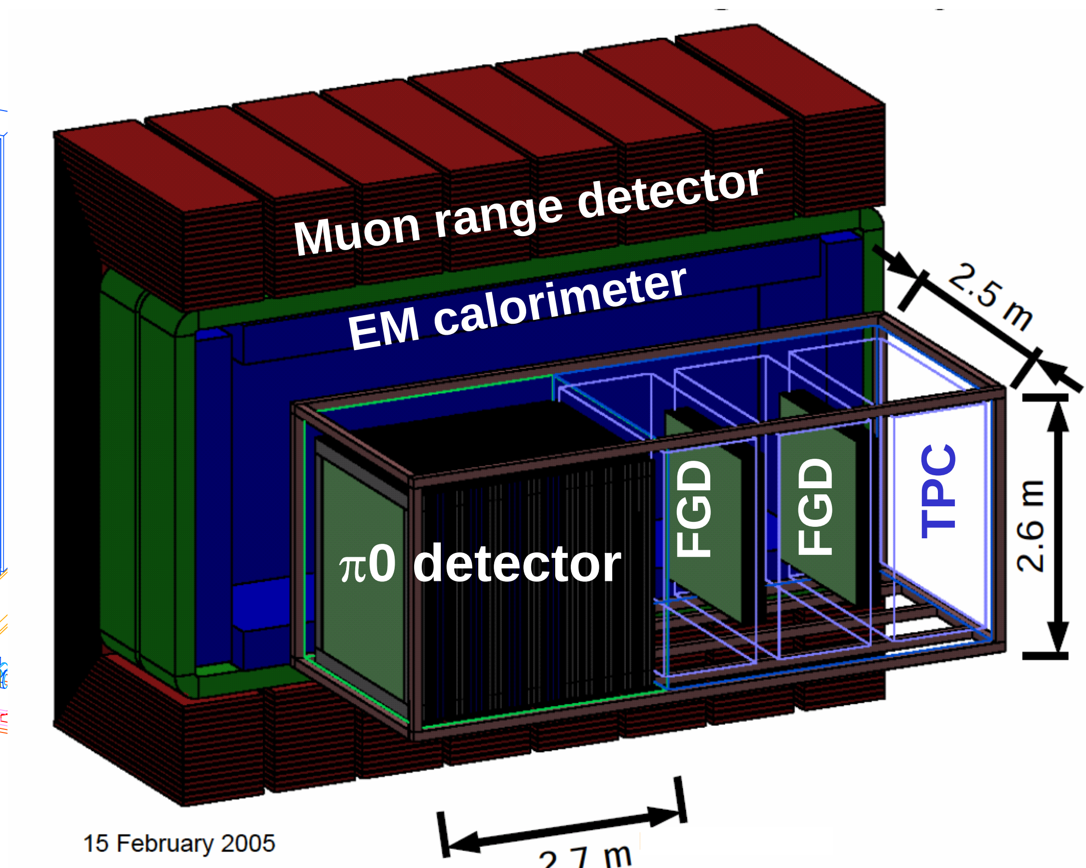


The Experimental facility at 2km is not approved yet.

New near neutrino detector for T2K

UA1 Magnet is proposed by Euopean collaborators.
(Italian group takes a responsibility.)



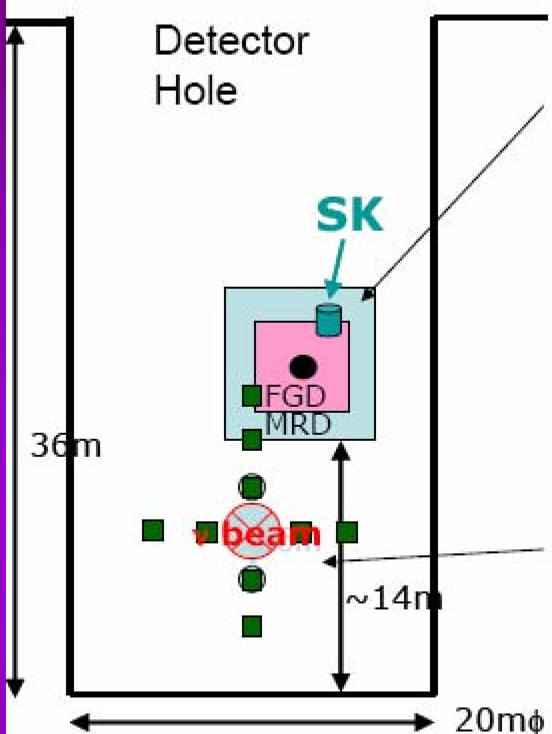


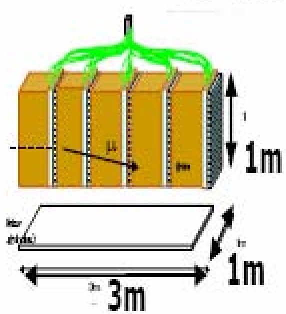
FGD: Fine-Grained Detector

The detector is under DESIGN.

Nakaya, Venice 2005

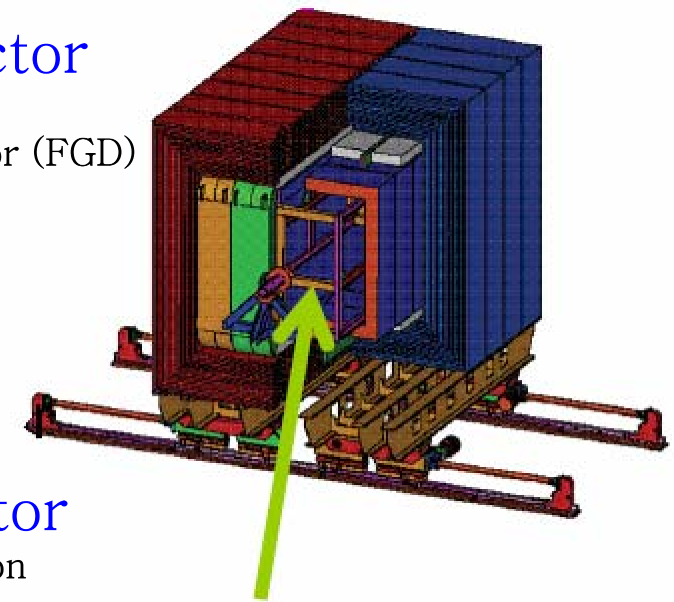
Conceptual Design for Near Detector @280m(ND280





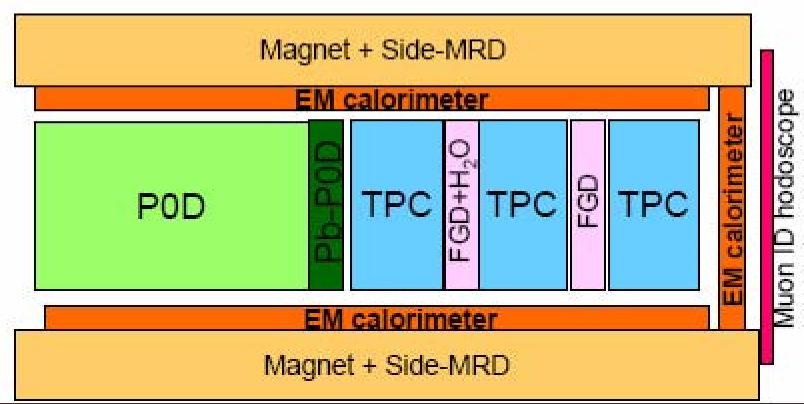
Off-Axis detector

- UA1 magnet
- Fine Grained Detector (FGD)
- TPC
- P0D
- ECAL, etc



On-Axis detector

- Monitor beam direction
- Grid layout



θ_{13} measurement (ν_e appearance search)

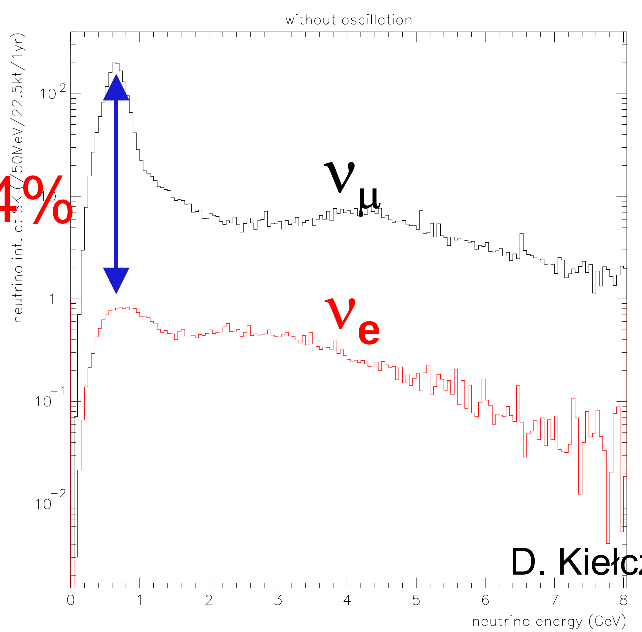
$\sin^2 2\theta_{23}=1$ and $\delta=0$ are assumed.

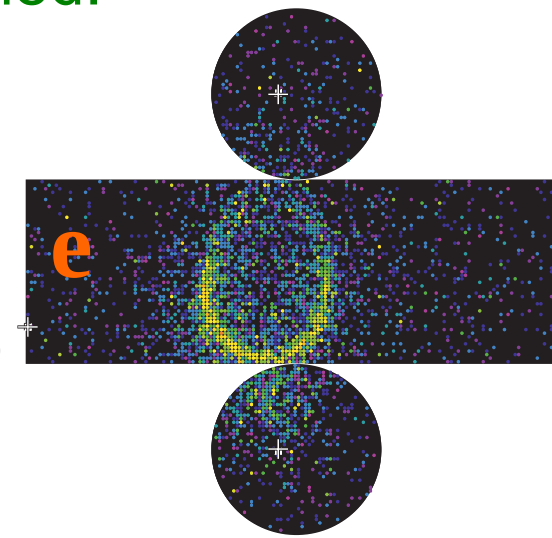
Signal:

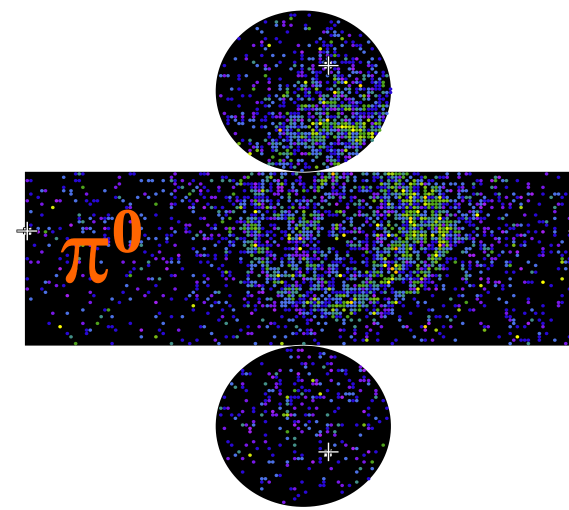
- 1ring e-like event (CC QE sample)

Background:

- beam ν_e contamination (0.4% of ν_μ)
- mis-reconstructed π^0 event

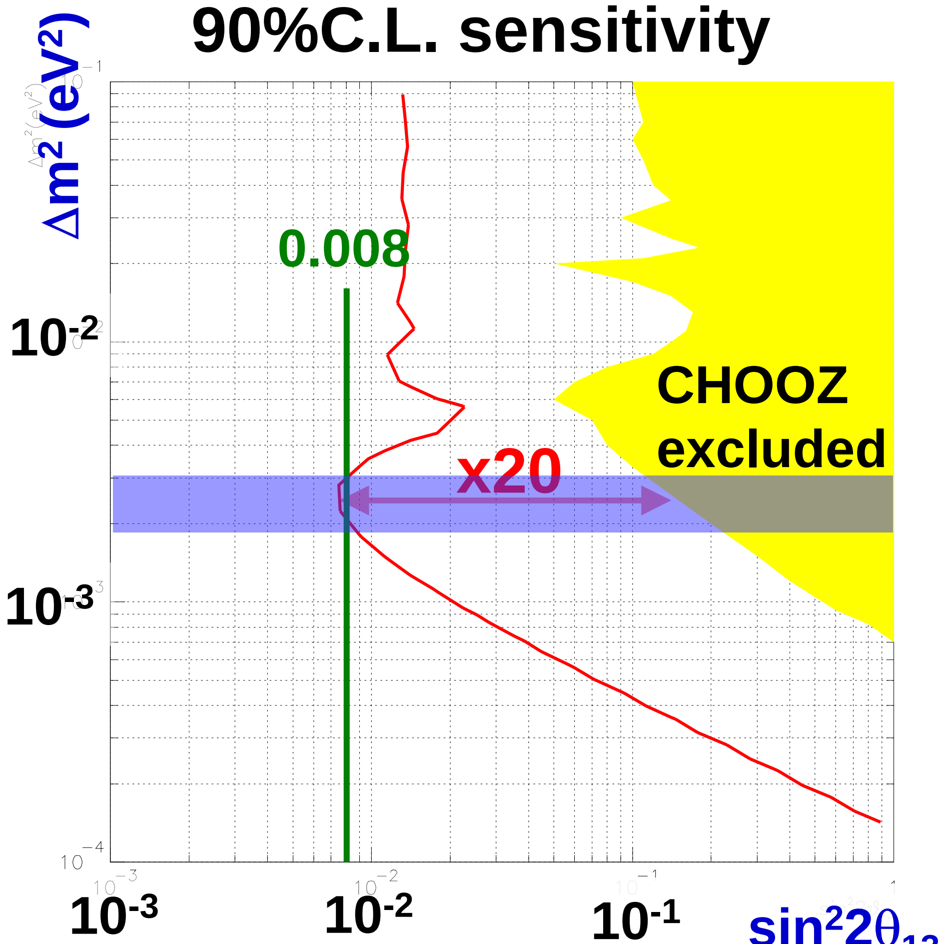




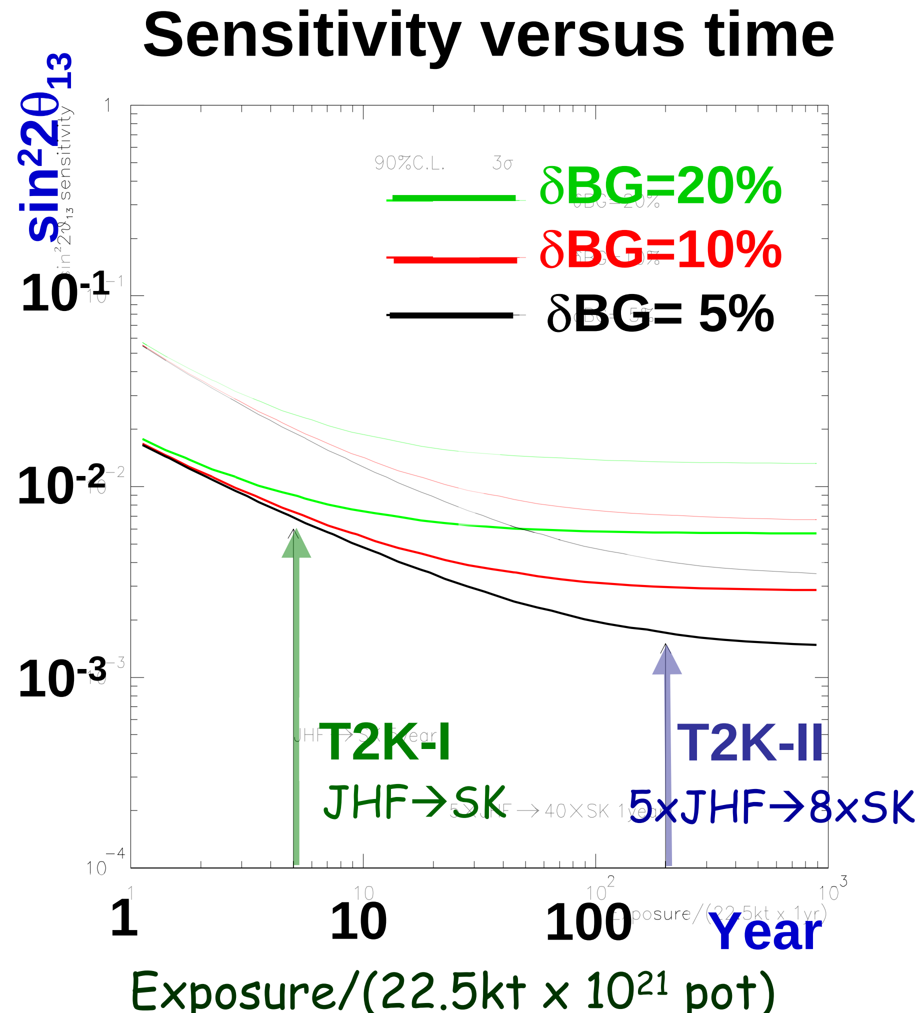


Nakaya, Venice 2005

θ_{13} Sensitivity (w/ δBG_{sys}=10%)



for δ=0

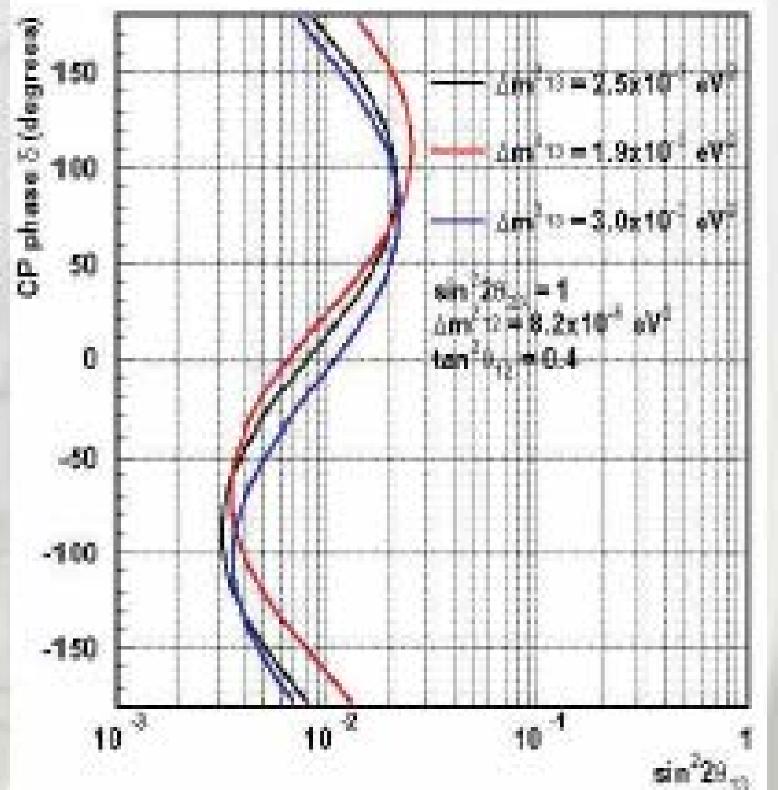


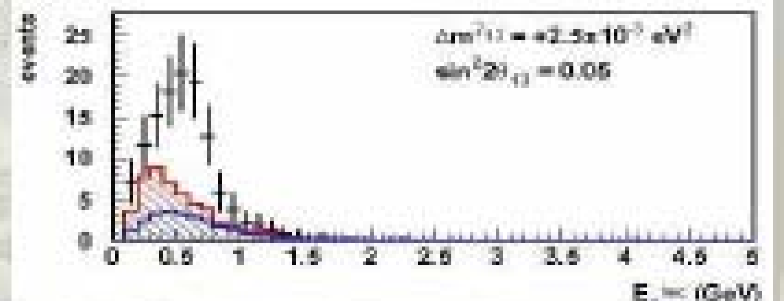
Nakaya, Venice 2005

Super Beams: T2K

Two phases

- first with 0.75MW and SK as far detector. Starts spring 2009.
  - $\sin^2\theta_{13}$<0.006@90%CL and $\delta_{CP}=0$
  - Main limitation: intrinsic ν_e contamination and π^0 production.
- second phase with 4MW and HK ($\frac{1}{2}$ megaton) for *CP* violation.
  - $\sin^2\theta_{13}$<0.001@90%CL.
  - Sensitivity to $\delta \sim 20°$

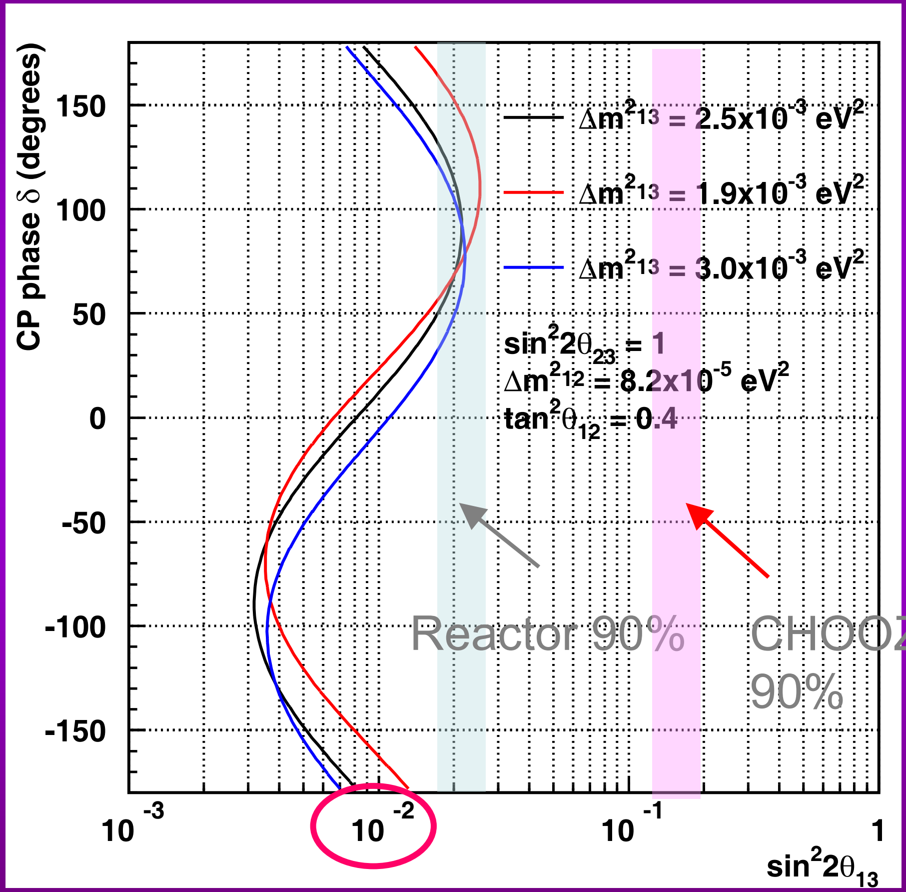




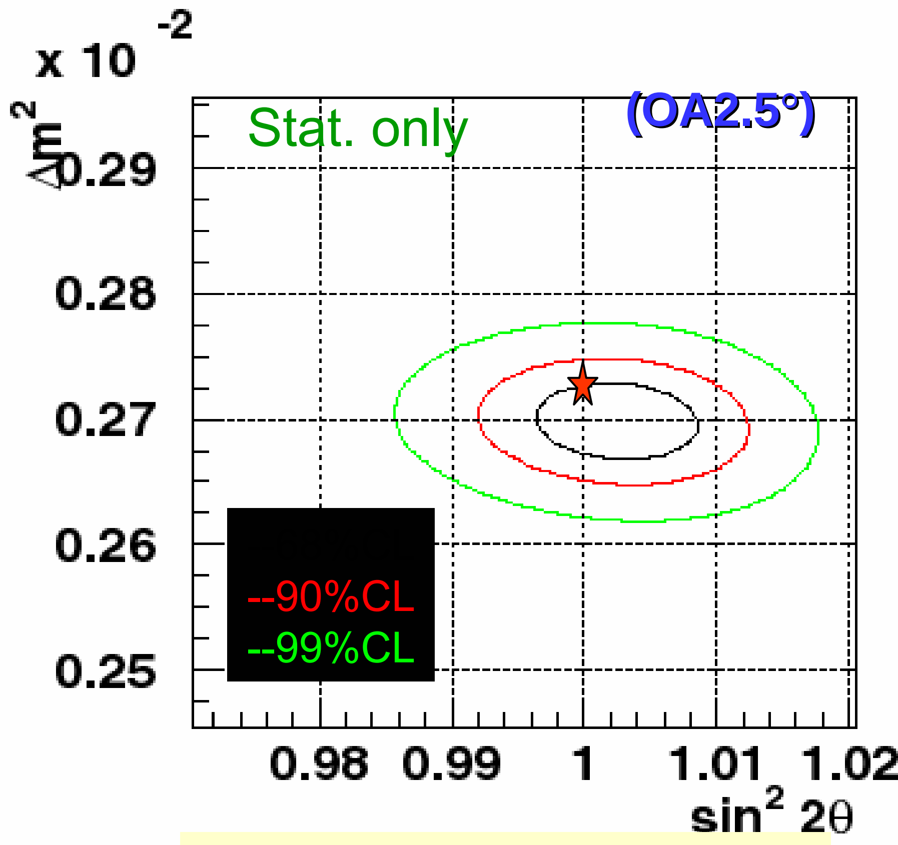
JPARC is investigating the possibility of increasing the power on target already in phase I by a factor ~2 by changing the number of bunches, reducing energy and increasing the repetition rate.

T2K Sensitivities

ν_e appearance



ν_μ disappearance



Goal

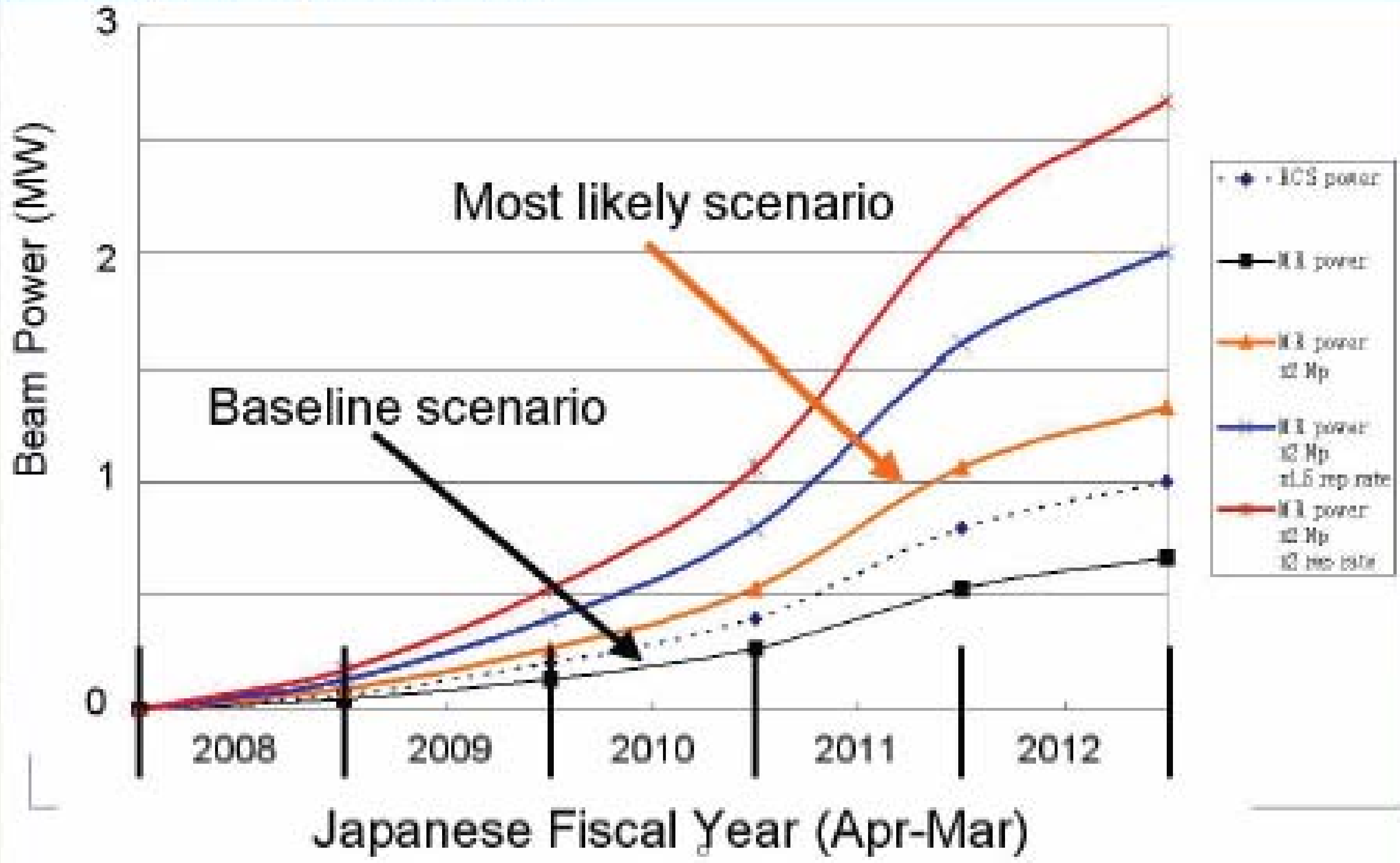
$\delta(\sin^2 2\theta_{23}) \sim 0.01$

$\delta(\Delta m_{23}{}^2) \sim < 1 \times 10^{-4}$

>10 times improvement from CHOOZ

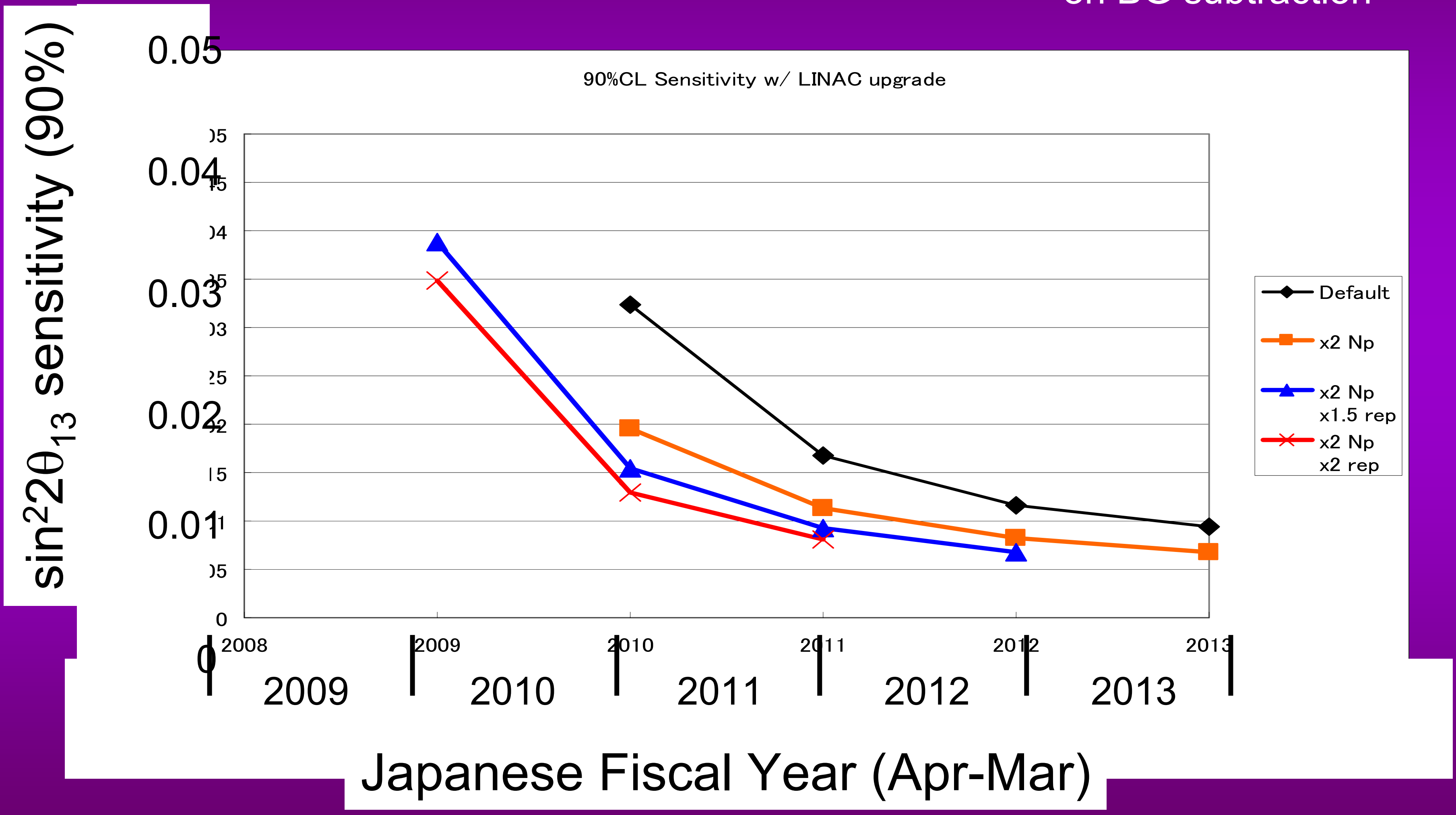
Super Beams: T2K

JPARC is investigating the possibility of increasing the power on target already in phase I by a factor ~2 by changing the number of bunches and increasing the repetition rate.



T2K sensitivity v.s. exposure

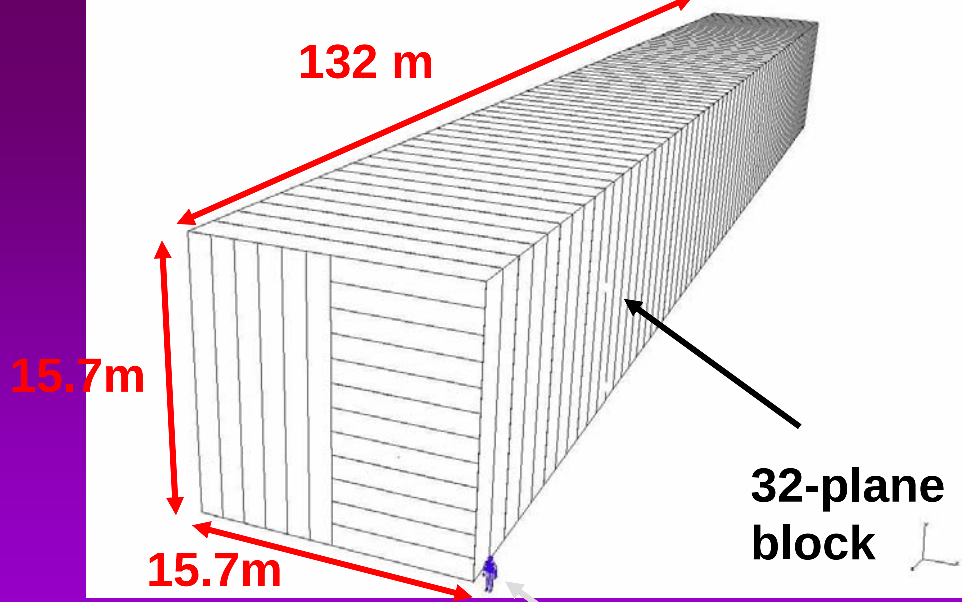
10% syst. err assumed
on BG subtraction



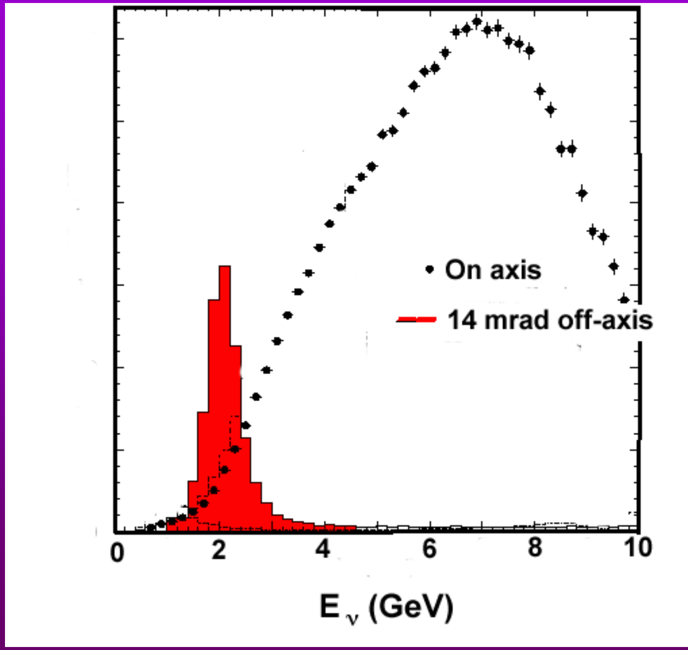
NOνA

Approved by FNAL PAC in April, 2005.

- 30kton liquid scintill. detector
  24% effic. for ν_e detection
- Upgraded NuMi beam
  - ~14mrad off-axis
  - 6.5×10^{20} POT/year
    (25×10^{20} with Proton Driver)



Far detector



- Baseline: 810 km
- $<E_\nu>$ 2.22 GeV

better sensitivity to matter effects and mass hierarchy than T2K

D. Kiełczewska

planned for 2010

Nova – więcej o detektorach

- Ciekły scyntylator w plastikowych pojemnikach
  o rozmiarach wzdłuż wiązki z~0.15 długości prom.
  - odczyt za pomocą włókien w.l.s
  - fotodiody lawinowe
- Daleki detektor
  na powierzchni lub pod kilkumetrową warstwą ziemi
- Bliski detektor:
  - 262 tony ale FV=20 tony
  - kilka pozycji (>1km) – żadna nie daje takiego samego widma jak daleki
- Przekroje czynne na produkcję π^0 (NC) będą mierzone
  na wiązce NuMi w eksperymentach MINERvA i MIPP

Nova – czułość

T2K
10% błędu na tło (7.5% z 2km)
5 lat wiązki 10^{21} pot/rok
(0,75 MW przy 40 GeV w 2011
czułość 90%: $\sin^2 2\vartheta_{13} \sim 0.01$
(sygnał 10.3, tło 23 przyp)

Założenie: syst. błąd na tło: 5% syst.
5 lat wiązki 6.5×10^{20} pot/rok

sygnał 3 sigma dla: $\sin^2 2\vartheta_{13} \sim 0.01$
(sygnał 14 przyp, tło 19.5 przyp)

Czułość na hierarchię mas: przy powyższej wiązce tylko
jeśli θ_{13} bliskie obecnemu limitowi

Dla CP oraz mniejszego θ_{13} konieczna 2ga faza:
silniejsza wiązka oraz drugi detektor przy 2gim max

Koszt: $165M, budowa 2007 - 2011

Inne źródła:
„Plan: Construction starts in 2008 (4-5 years)
Cost: 235M$ (dominated by plastic and mineral oil)"

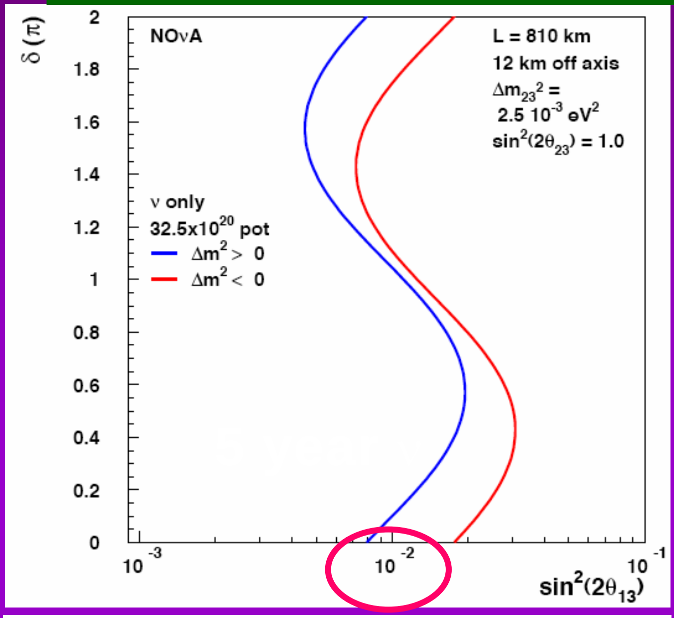
NUSAG o T2K

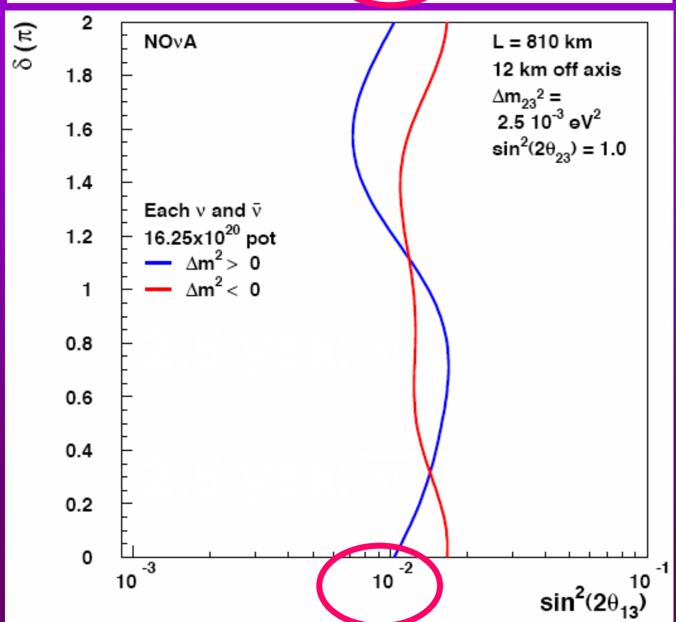
syst błędy: 10% 280, 7.5% 2km
„2km: modest improvement ale gdyby był sygnal to podnosi wiarygodność
Przy 4 MW – po roku stat=syst chyba ze syst <5%

LAr TPC: signal effic 80%   for 99% hadronic events rejection
For Cher and scint: signal effic 30-40%

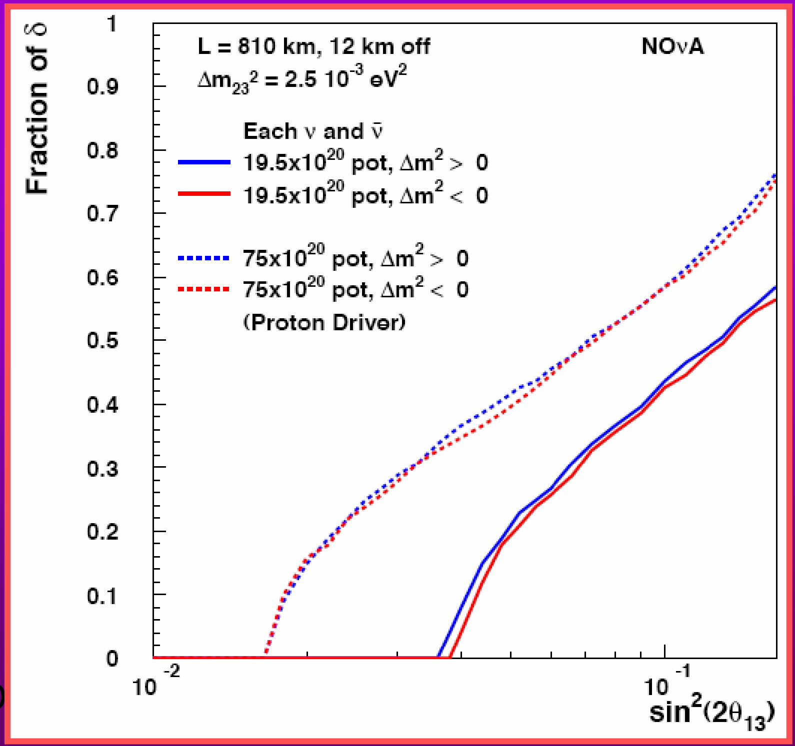
NOvA Sensitivity

5 years@6.5x10^{20}pot/year





- NOνA has a sensitivity to determine the ν mass hierarchy.



D

New ideas for CPV sensitivity

Need to solve the problem:
CP violating solution can be confused with CP conserving one due to unknown mass hierarchy

- J2K – Japan to Korea experiment
  - two detectors on the same beam (J-PARC 4MW)
    (identical detectors: FV=0.27Mton, water Cher.)
  - spectrum analysis (the same beam spectra)
  - 4 years ν + 4 years $\bar{\nu}_\mu$ (if $\sin^2 2\vartheta_{13} > 0.03\ (0.055)$ at $2\sigma\ (3\sigma)$)

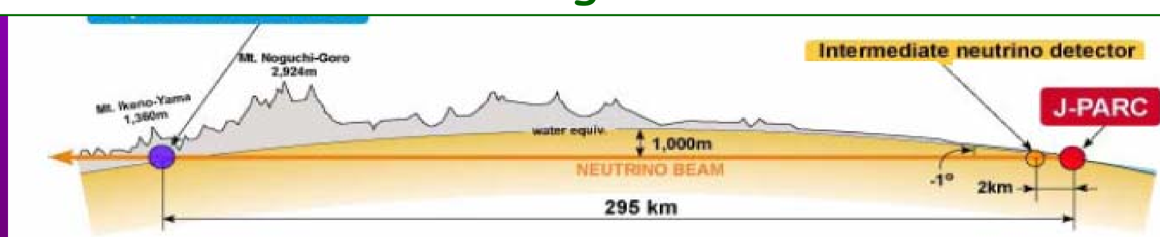
- Super-NOvA
  - 2 detectors at the same (L/E) (but different baseline and different off axis angle and thus different spectra)

Minakata & Nunokawa, Phys. Lett. B 413, 369 (1997)
Ishitsuka, Kajita, Minakata, Nunokawa, hep-ph/0504026
Mena et al., hep-ph/0504015, hep-ph/0510182

T2K Phase-I and Phase-II

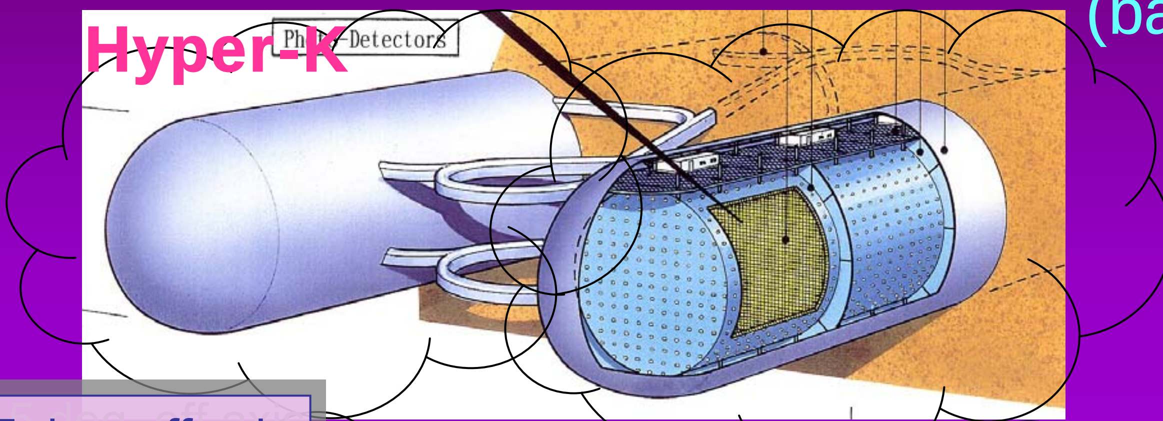
KK Joo
Seoul National University

actually: the direction J-PARC -> SK is 1.3 deg below the horizon
The beam axis is 3.0 to 4.1 deg below the horizon.



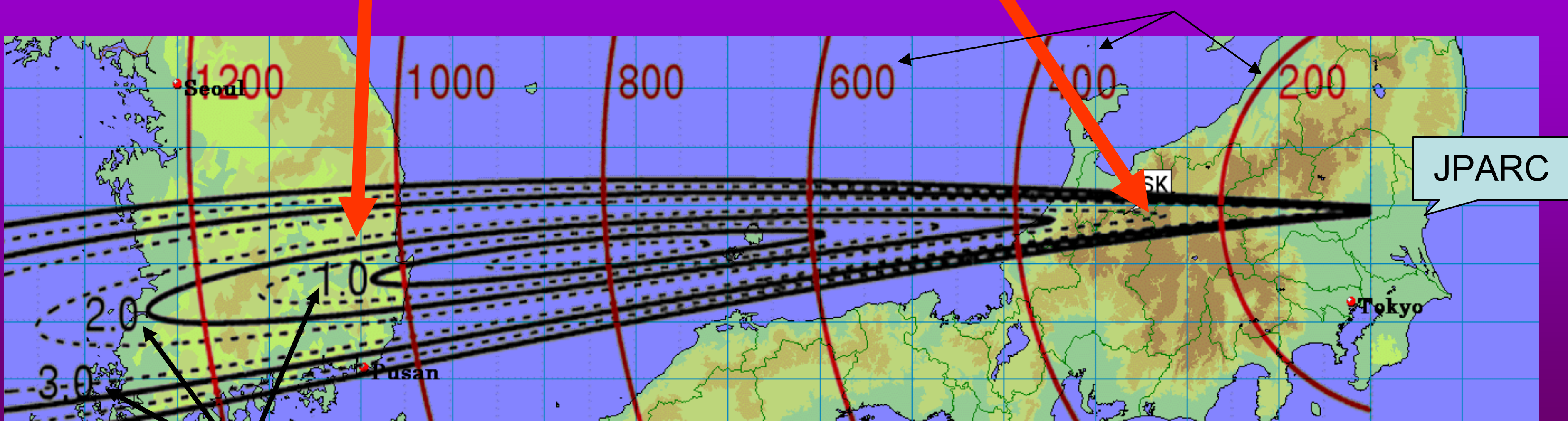
T2K2-Korea?

The second detector in Korea at the 2nd osc. maximum (baseline ~1050km)



2.5 deg. off axis

2.5 deg. off axis

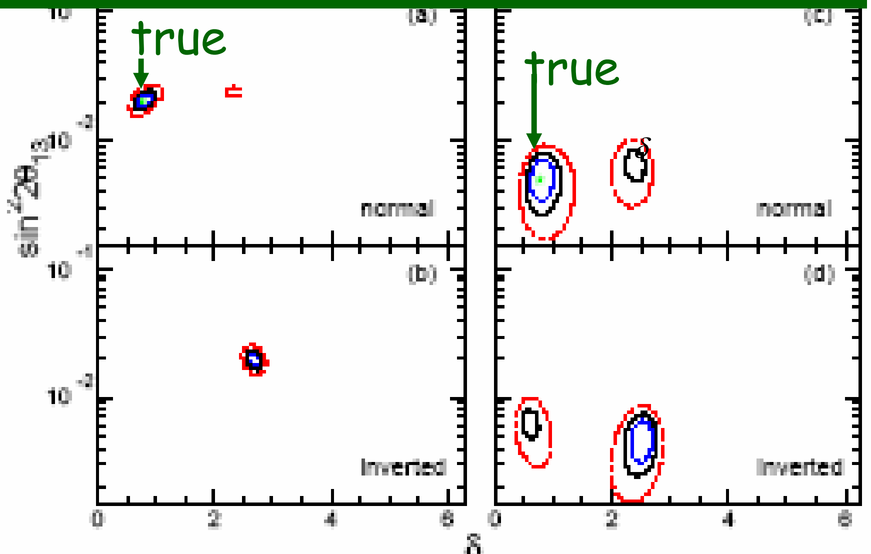


see hep-ph/0504061)

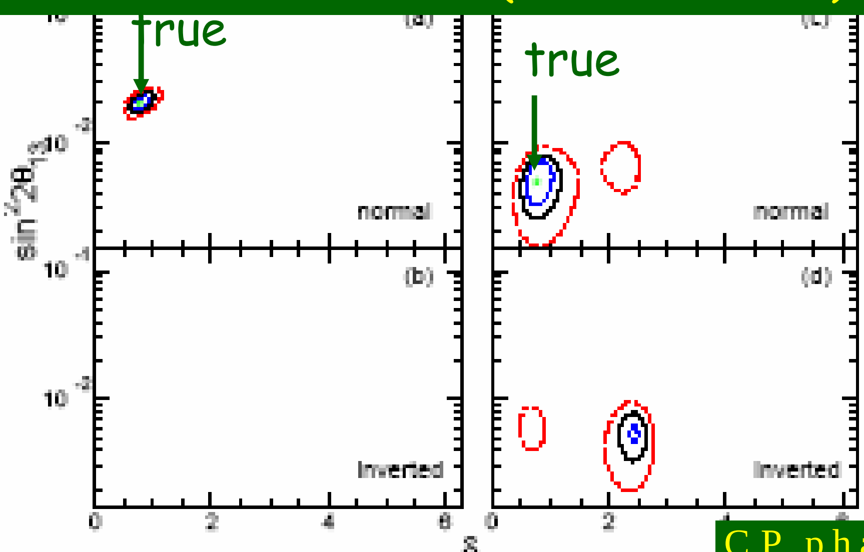
hep-ph/0504026

J2K – 2 identical detectors

1 detector of 0.54 Mton in Kamioka



2 detect. of 0.27 Mton (Kamioka &Korea)



CP phase δ

How to lift 4-fold degeneracies in: CP phase δ and sign(Δm^2_{13})

Analysis of data expected after 8 years total of 4MW beam: ν and $\bar{\nu}$

The contours crrespondto different c.l. solutions

With 2 detectors

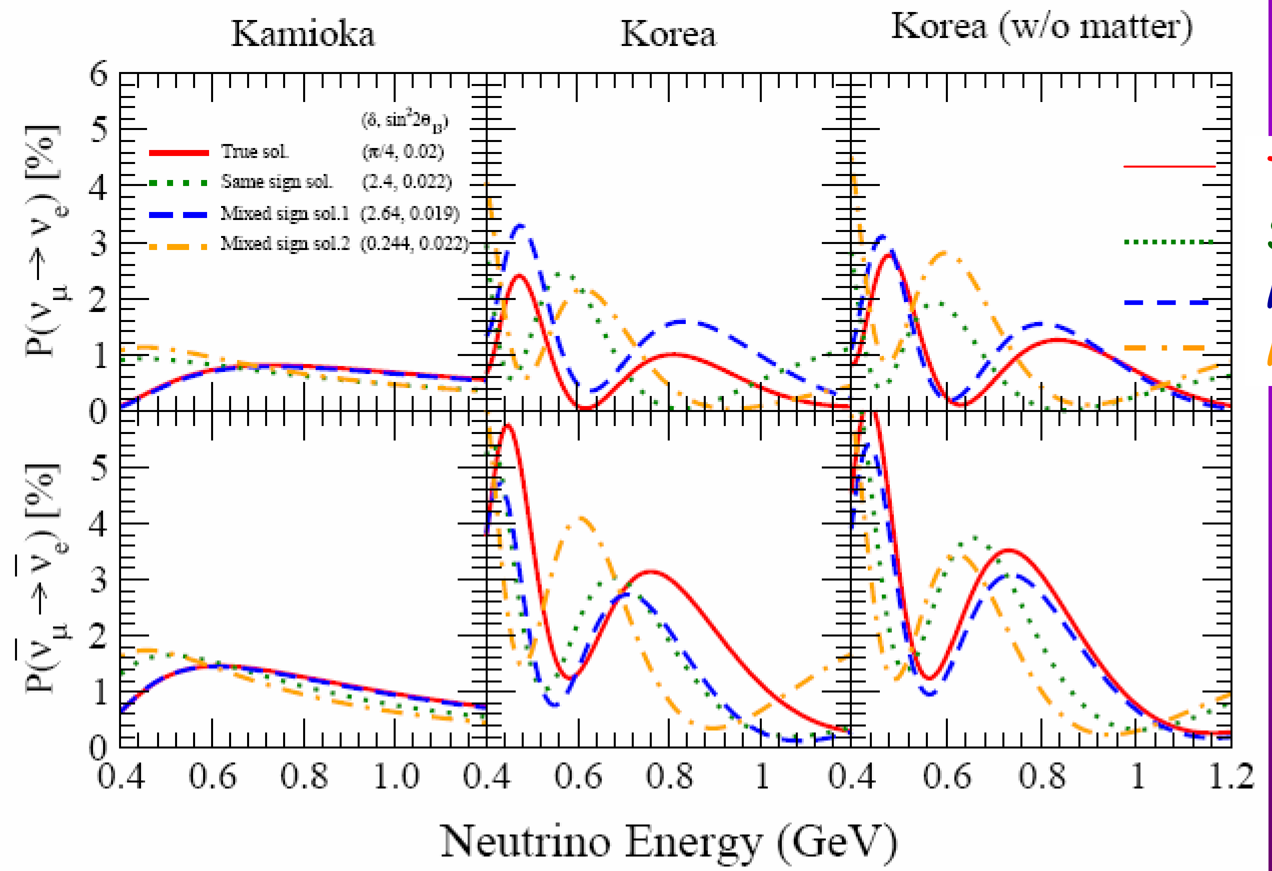
Assumed set of parameters	Result
Left panels: $\delta = \frac{\pi}{4},\ \sin^2 2\vartheta_{13} = 0.02,\ \Delta m^2_{13} > 0$	only true solution found
Right panels: $\delta = \frac{\pi}{4},\ \sin^2 2\vartheta_{13} = 0.005,\ \Delta m^2_{13} > 0$	some degeneracy remains

Kiełczewsk

This is due to spectrum analysis

J2K – 2 identical detectors

- When going to the second max the rates alone not a solution because although CPV effect gets larger the matter effects stay approx the same
- However the spectrum modification is very sensitive to sign(Δm^2)



$(\delta, \sin^2 2\vartheta_{13})$

True solution $(\pi/4, 0.02)$
Same sign sol. (2.4, 0.022)
Mixed sign sol.1 (2.54, 0.019)
Mixed sign sol.2 (0.244, 0.022

From the rate only analysis at SK one gets only 1 degenerate solution with the above parameters.

hep-ph/0504026

Super-NOvA – 2 off-axis detectors

Mena et al., hep-ph/0504015, hep-ph/0510182

Two detectors at the same (L/E):

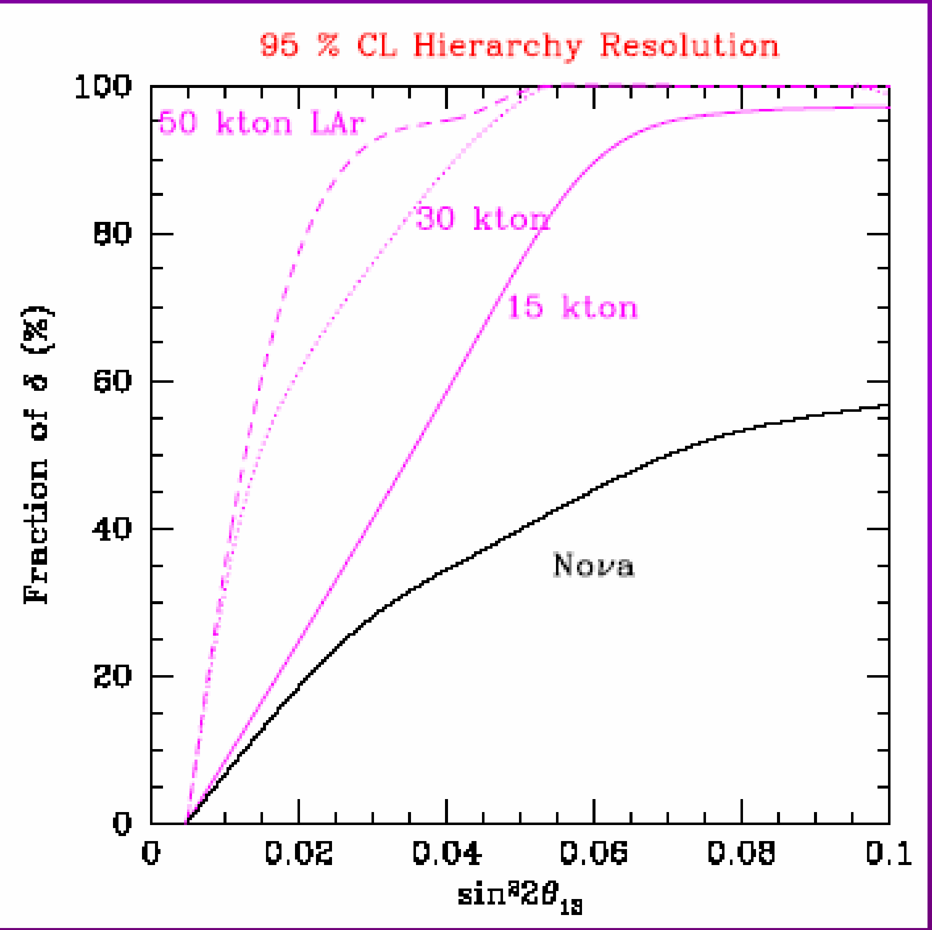
- the first at L_f~800 km (regular NOvA site)
- the second at L_n=200 or 434 km at an off-axis angle such that:

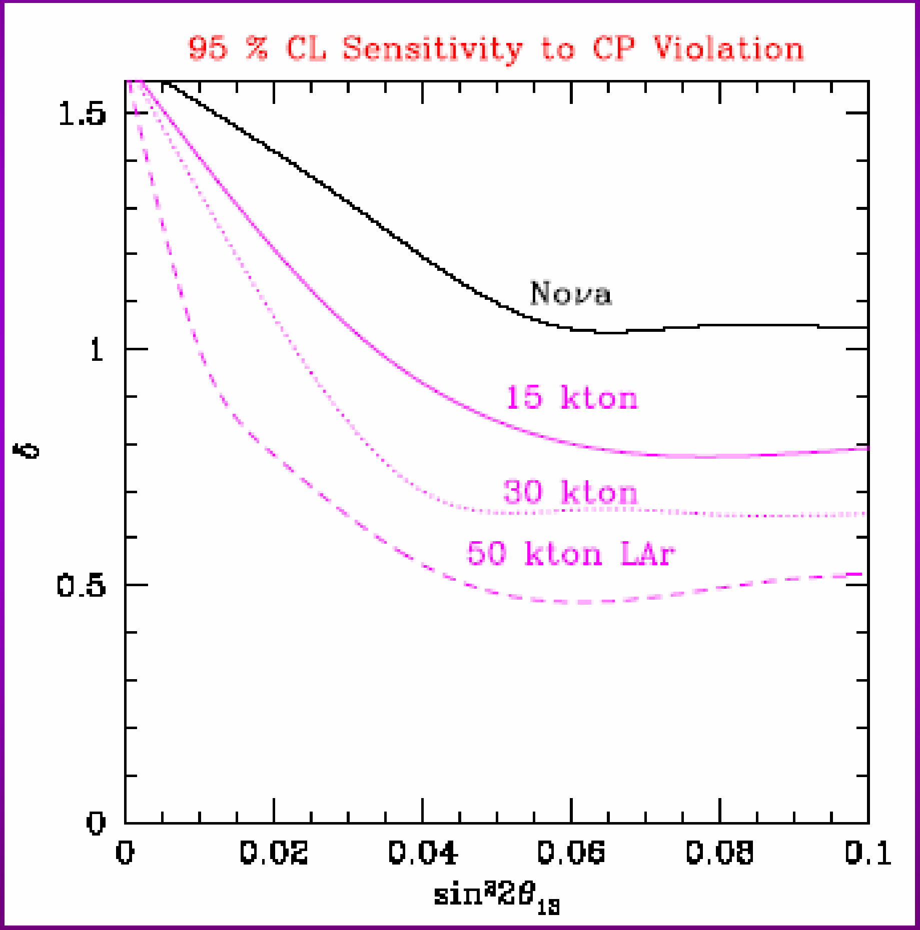
$$E_n = E_f \frac{L_n}{L_f}$$

- Upgraded NuMi beam (6.5×10^{20} pot/yr)
- 9 years of ν + 5 years of $\bar{\nu}$
- second detector is LAr TPC (15, 30 or 50 kt)

Super-NOvA – 2 off-axis detectors

Mena et al., hep-ph/0504015, hep-ph/0510182





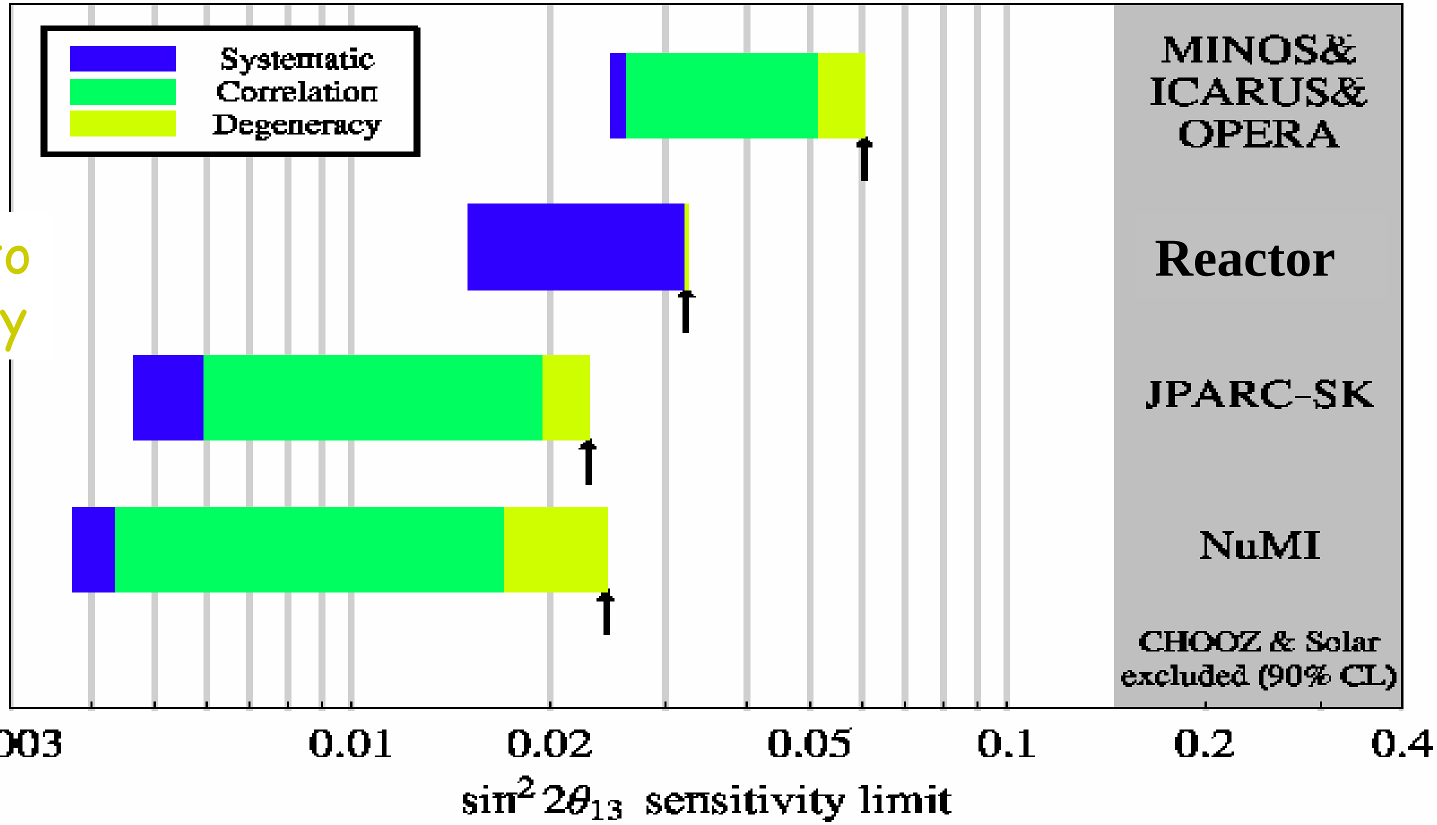
Experimental Sensitivity to $\sin^2(2\theta_{13})$

hep-ph/0403068

Syst: $\delta=0$

Correlation with other parameters

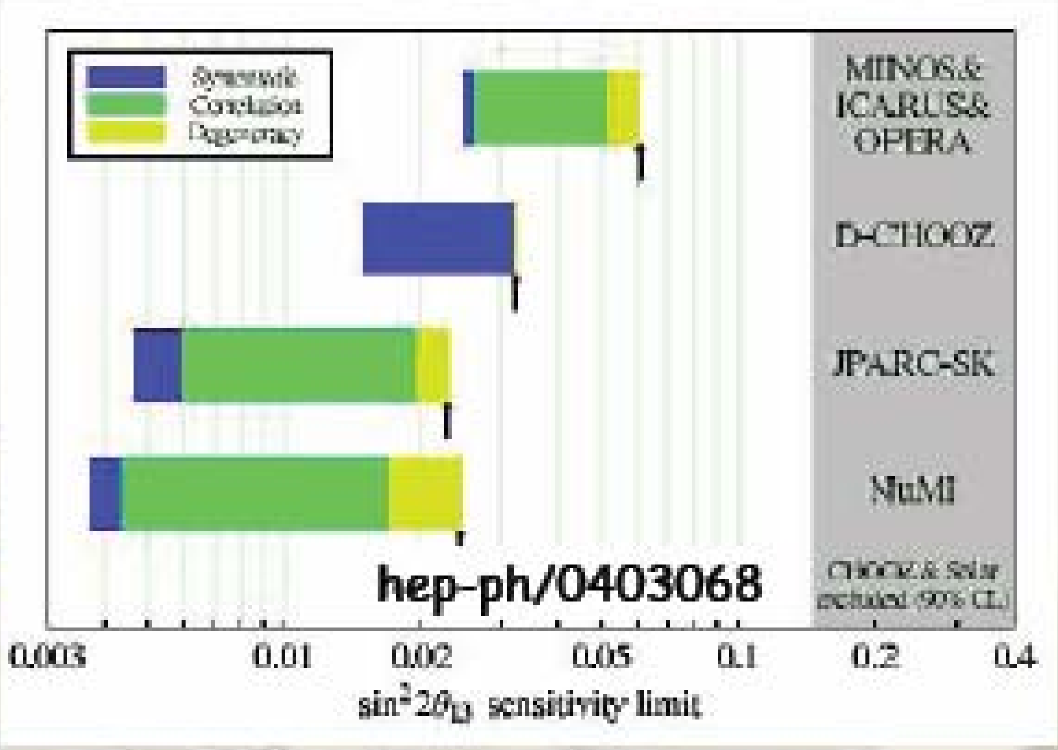
Degeneracy due to unknown hierarchy



Osc. Experiments: comparison

Relative importance of the different experiments.

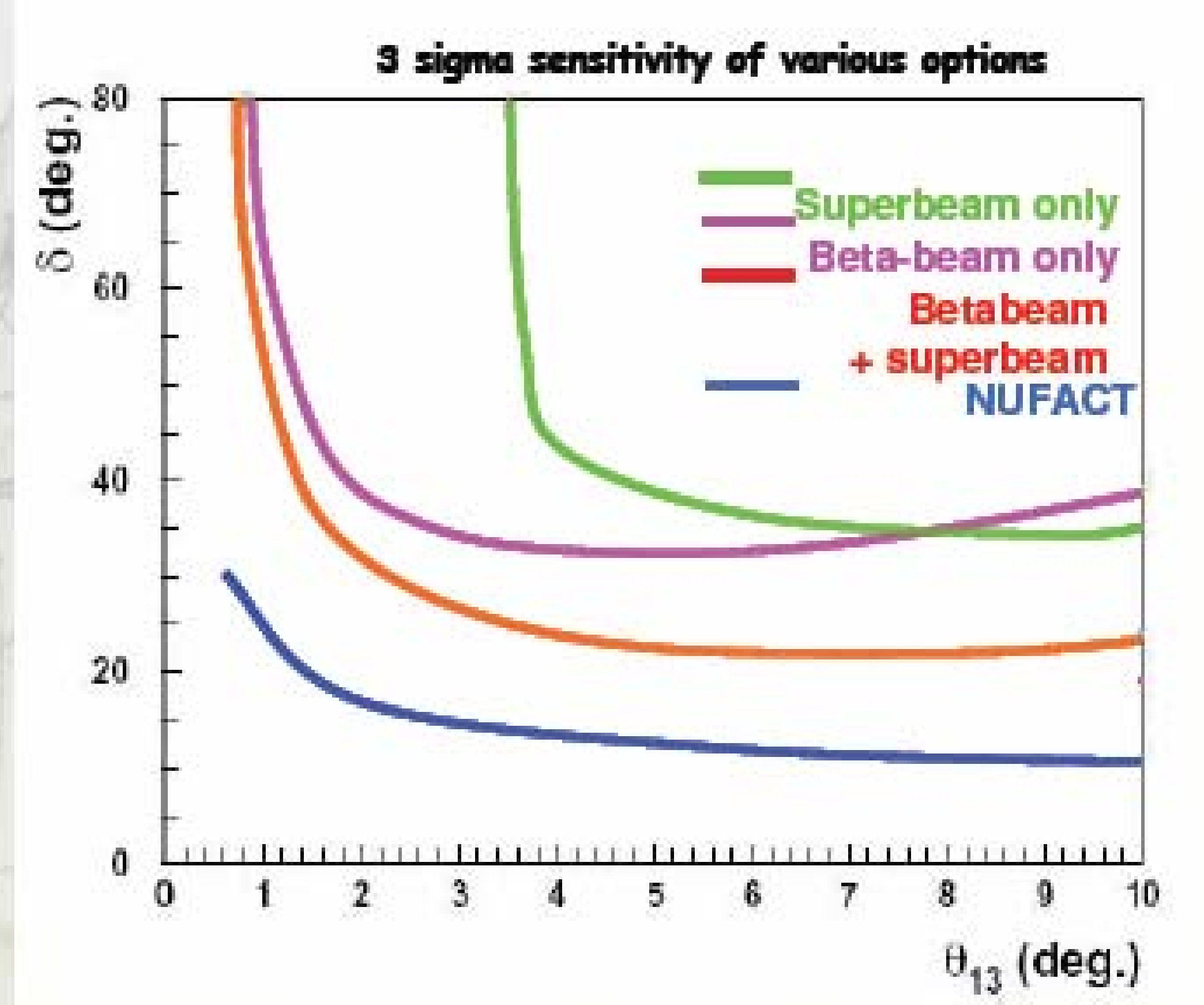
- Effective θ_{13} limit, by fixing $\delta_{CP}=0$ and other parameters to best fit. Potential to observe signal.
- Correlation with other parameters: δ_{cp}, θ_{23}, θ_{12}, ...
- Degeneracy: impact of sign (Δm^2_{13}).



- Reactor experiments could help to resolve δ_{cp} together with superbeams.
- NUMI very long base line gives chance to resolve mass hierarchy combining with the other experiment results.

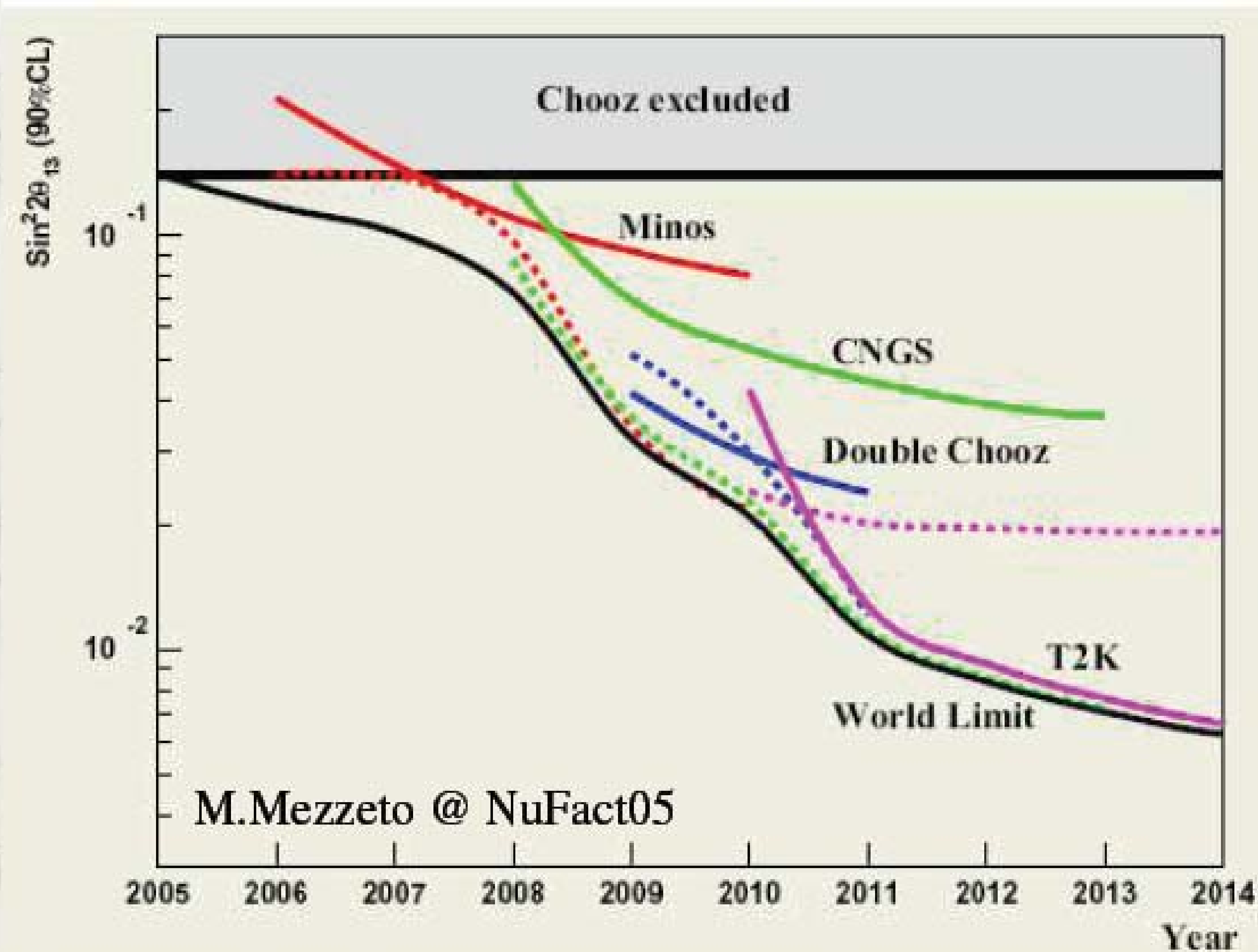
Second phase exp. : ν factory

- Sensitivity to δ down to $\sin^2\theta_{13} \sim 3 \times 10^{-4}$ ($\theta_{13} \sim 1°$)



F.Sánchez (UAB/IFAE), EPS Conference, Lisboa July 2005.

Prospects: θ_{13} sensitivity

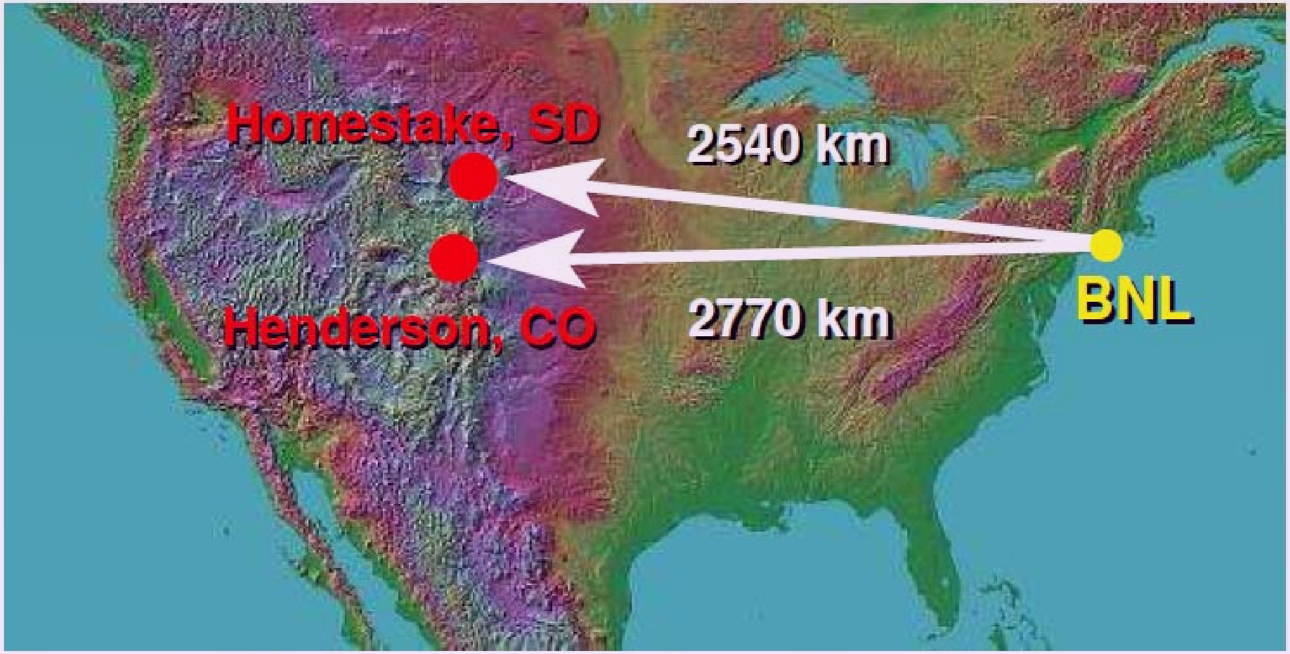


Approved experiments

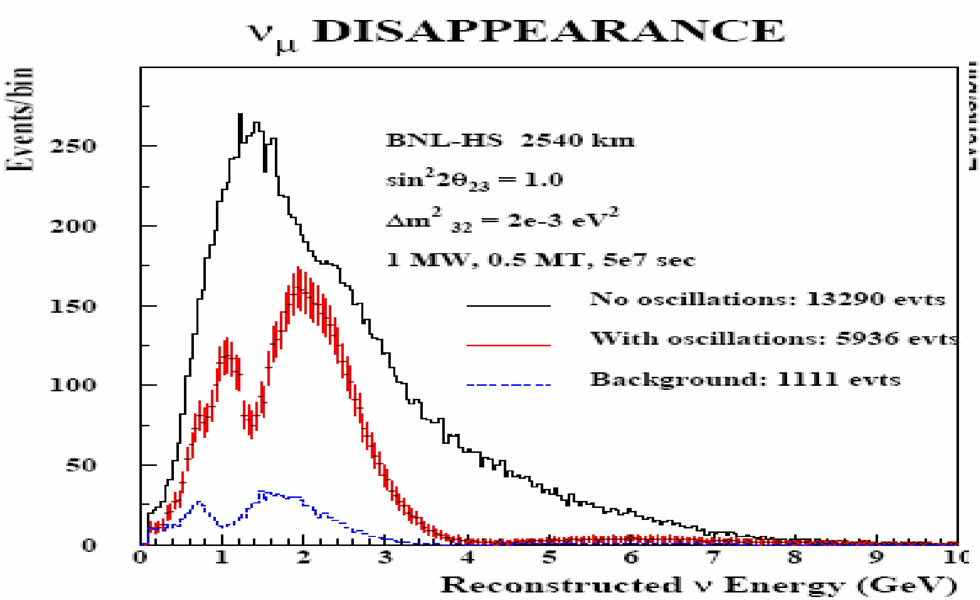
F.Sánchez (UAB/IFAE), EPS Conference, Lisboa July 2005.

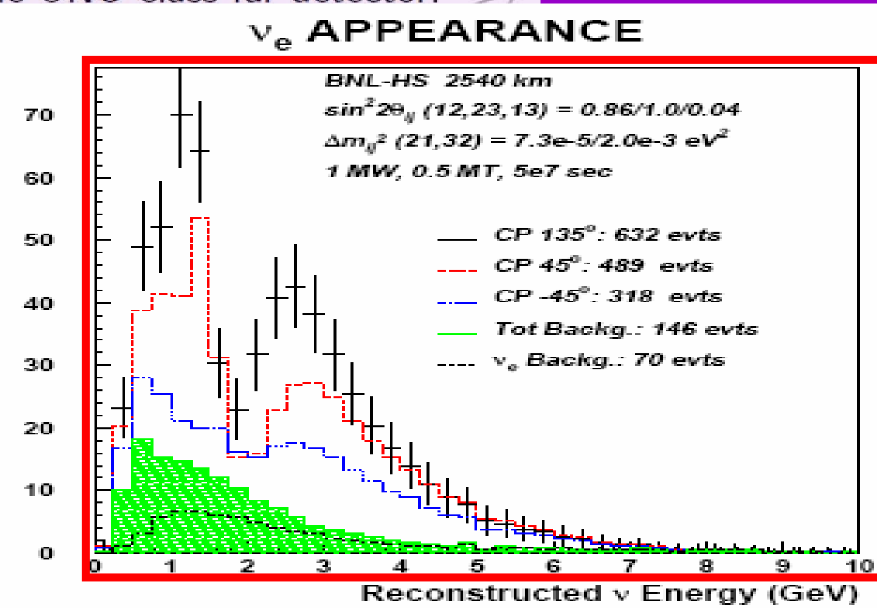
BNL – Very Long Baseline

Example Baseline: 2540 km



Homestake & Henderson equivalent. Assume UNO class far detector.





Very long baseline scenario (BNL proposal)

N~1/L²

$$\sin\Delta_{12} = \sin\frac{1.27\Delta m_{12}^2 L}{E} \sim L$$

$$P(\nu_\mu \to \nu_e) =$$

$$4s_{23}^2 s_{13}^2 c_{13}^2 \sin^2\Delta_{13}$$

N_e~1/L²

$$+8s_{12}s_{23}s_{13}c_{13}^2\left(c_{12}c_{23}\cos\delta - s_{12}s_{23}s_{13}\right)\sin\Delta_{13}\sin\Delta_{12}\cos\Delta_{23}$$

$$-8s_{12}s_{23}s_{13}c_{12}c_{23}c_{13}^2\sin\delta\sin\Delta_{13}\sin\Delta_{12}\sin\Delta_{23}$$

N_e~1/L

$$+4s_{12}^2c_{13}^2(c_{12}^2c_{23}^2 + s_{23}^2s_{13}^2c_{13}^2 - 2s_{12}s_{23}s_{13}c_{12}c_{23}\cos\delta)\sin^2\Delta_{12}$$

$$-8s_{13}^2s_{23}^2c_{13}^2(1-2s_{13}^2)\frac{\alpha L}{4E}\sin\Delta_{13}\cos\Delta_{23}$$

$$A \equiv \frac{P(\nu_\mu \to \nu_e) - P(\bar\nu_\mu \to \bar\nu_e)}{P(\nu_\mu \to \nu_e) + P(\bar\nu_\mu \to \bar\nu_e)} \simeq \frac{\sin 2\vartheta_{12}}{\sin\vartheta_{13}}\frac{\Delta m_{12}^2 L}{4E_\nu}\sin\delta$$

→ Some like very long baselines

w/out matter effects and smaller terms

Summary

- CP violation in quark sector too small to explain the observed dominance of matter in the universe.

- CP violation in neutrinos provides a chance to understand matter-antimatter asymmetry

- Both CP violation and determination of spectrum hierarchy (normal or inverted) depend on θ_{13}

- Current exper (MINOS, OPERA) are probably not sensitive enough to θ_{13}

- Synergy between various experiments needed to resolve degeneracies (T2K , NOvA, reactor experiments)

- Maybe extended T2K and/or NOvA projects needed to determine δ_{CP}

Japan to Korea

2 large off-axis detectors

ϑ_{13}

Różne klasy modeli:

$$\sin^2 2\vartheta_{13} \sim \Delta m^2_{sol} / \Delta m^2_{atm} \simeq 1/30 \Rightarrow \sin^2 2\vartheta_{13} \sim 0.004$$

albo

$$\sin^2 2\vartheta_{13} \sim \sqrt{\Delta m^2_{sol} / \Delta m^2_{atm}} \simeq 1/6 \Rightarrow \sin^2 2\vartheta_{13} \sim 0.1$$

Czułość na CP zależy od:

$\sin^2 2\vartheta_{13}$

- > 0,01 konwencjonalne wiązki (z rozpadów π)
- < 0,01 fabryki neutrin lub wiązki beta

Summary - NUSAG

Both T2K and NOvA would establish q13 non-zero if s22q13>0.01
Wtedy hierarchy and CP with conventional but MW beams
Nova even with current beam if q13 near the current limit

MSW effect

One can define effective (matter) mixing angle and mass difference :

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{\left(\frac{2\sqrt{2}G_F \rho E_\nu}{\delta m^2} - \cos 2\theta\right)^2 + \sin^2 2\theta}$$

resonant condition if =0

$$\Delta M^2 = \delta m^2 \sqrt{\left(\frac{2\sqrt{2}G_F \rho E_\nu}{\delta m^2} - \cos 2\theta\right)^2 + \sin^2 2\theta}$$

- Effective mixing θ_m may be large even if θ small
- At resonance effective ΔM much smaller than δm
- A neutrino passing through various local densities ρ can easily get into a resonant condition

Note that

- matter effects are sensitive to $\vartheta' \rightarrow \frac{\pi}{2} - \vartheta$
- for antineutrinos : $\delta m^2 \rightarrow -\delta m^2$

Dlaczego badanie CPV jest ważne?

Bo daje eleganckie wytłumaczenie asymetrii barionowej we Wszechświecie.

Wg. mechanizmu huśtawki lekkie neutrina ν mają bardzo ciężkich (10^{15} GeV) partnerów N. W tym modelu zarówno ν jak i N sa cząstkami Majorany czyli:

$$\bar{\nu} \equiv \nu$$

$$\bar{N} \equiv N$$

N byłyby produkowane w BB i rozpadałyby się:

$$N \rightarrow l + H \quad \text{oraz} \quad N \rightarrow \bar{l} + \bar{H}$$

Jeżeli CP niezachowane to prawdop. rozpadów różne i pojawia się asymetria leptonowa a w konsekwencji dalej asymetria barionowa.