Current* Neutrino Oscillation Experiments

PPAP Meeting
Birmingham
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Def. current: running or under construction

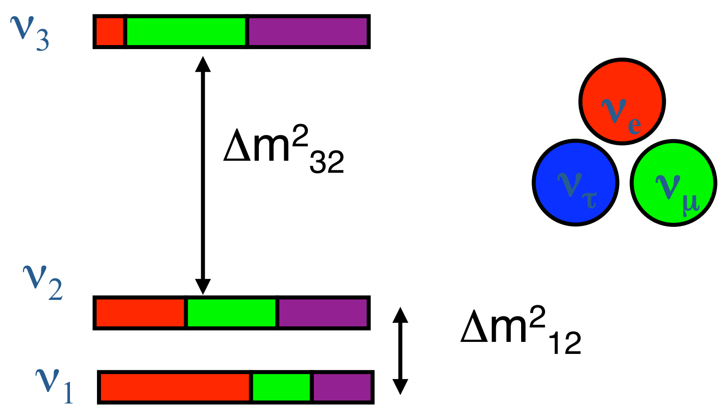
Outline

- Neutrino-oscillation experiments: what to measure, and how
- Accelerator-based experiments
- Reactor experiments
- Conclusions and outlook

What to measure, and how

Neutrino Mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\text{MNSP}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Unknown CP-violating phase

$$U_{\text{MNSP}} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{\text{CP}}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{\text{CP}}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times U^{\text{diag}}_{\text{Maj}}$$

Solar ν + KamLAND:
$\theta_{12} = (34 \pm 3)^\circ$
$\Delta m^2_{12} = 7.6 \times 10^{-5}\ \text{eV}^2$

Reactor ν (CHOOZ):
$\sin^2 2\theta_{13} < 0.11$ @ 90% CL
(or $\theta_{13} <\sim 10^\circ$)
$\Delta m^2_{31} \sim \Delta m^2_{32}$

Atmospheric ν + MINOS, K2K:
$\theta_{23} = (45 \pm 7)^\circ$
$\Delta m^2_{32} = 2.5 \times 10^{-3}\ \text{eV}^2$

Accelerator-Based vs. Reactor Experiments

LBL accelerator experiments:

$\sin^2\theta_{12}$, Δm^2_{32}:

- Look for disappearance ($\nu_\mu \rightarrow \nu_\mu$) as a fnc of *L* and *E*
- Near detector to measure unoscillated spectrum

θ_{13}, δ_{CP}, sign(Δm^2_{32}):

- Look for appearance ($\nu_\mu \rightarrow \nu_e$) in ν_μ beam vs. *L* and *E*
- Near detector to measure background ν_es (beam + mis-id)
- $P(\nu_\mu \rightarrow \nu_e) = f(\delta, \text{sign}(\Delta m_{31}^2))$

Reactor experiments:

θ_{13} only:

- Look for disappearance ($\overline{\nu}_e \rightarrow \overline{\nu}_e$) as a fnc of *L* and *E*
- Near detector to measure unoscillated flux
- $P(\overline{\nu}_e \rightarrow \overline{\nu}_e)$ independent of δ; matter effects small

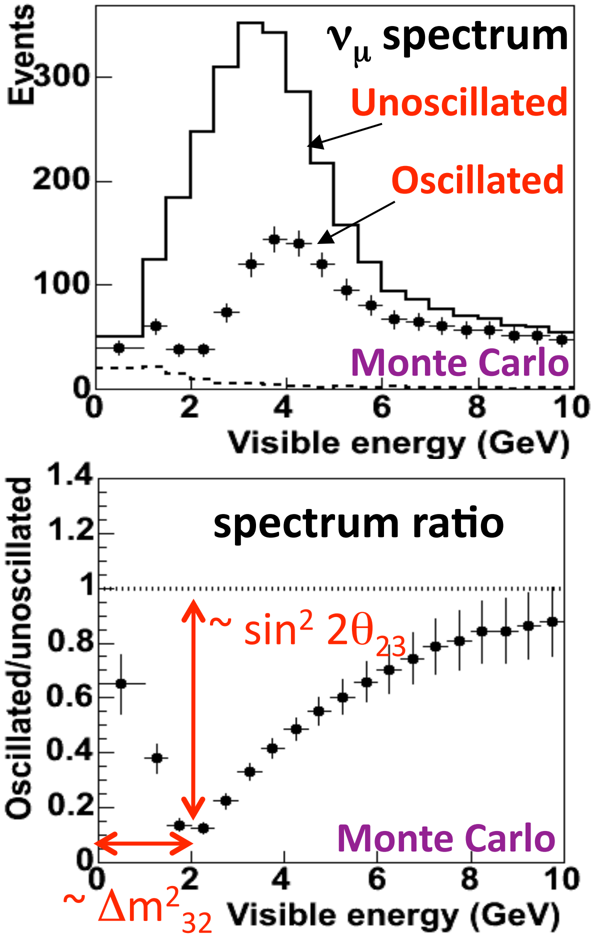
Accelerator-based and reactor experiments complementary

MINOS, T2K, NOνA

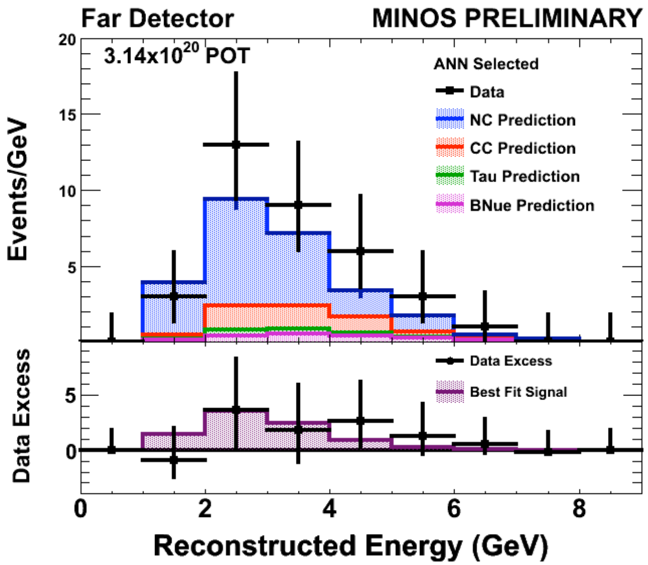
Double Chooz, Daya Bay, RENO

Experimental Approach

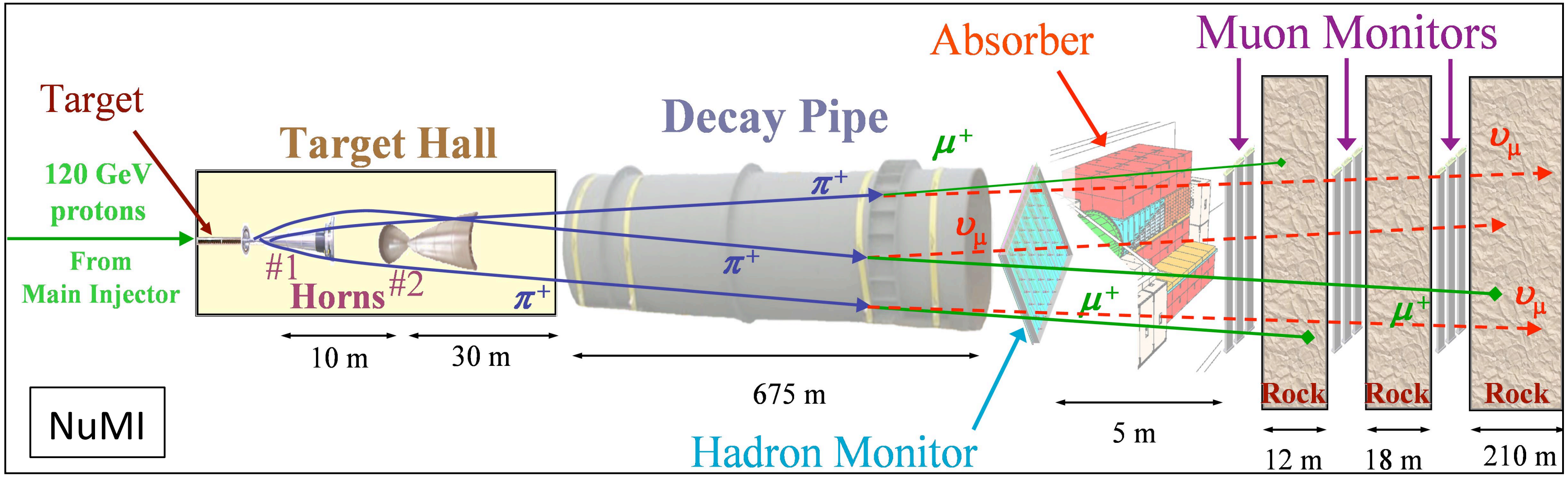
- (ν_μ) disappearance measurements:
  - Measure unoscillated ν_μ spectrum at Near Detector
    - Extrapolate using MC
  - Compare to measured spectrum at Far Detector



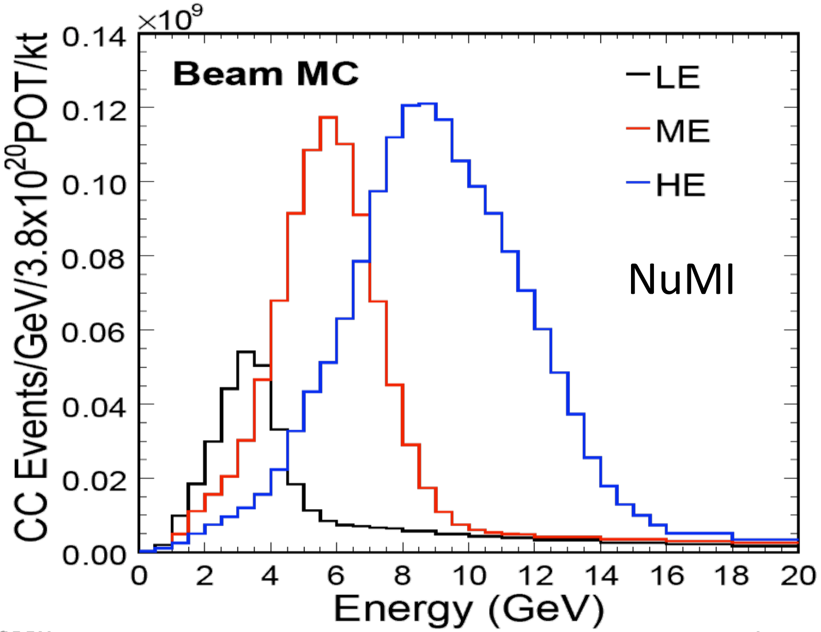
- ν_e appearance measurements:
  - Measure ν_e spectrum at Far Detector
  - Near Detector to measure background ν_es (beam + mis-id)
    - Predict Far Detector background using MC



Neutrino Beam



- Protons strike graphite target
- Magnetic horns focus secondary π/K
  - Decay of π/K produces (mostly) muon neutrinos



Accelerator-based experiments

Players: MINOS, T2K, NOνA

MINOS:

- NuMI (Fermilab) to Soudan mine, MN
  - 735 km baseline
- Magnetised sci/steel calorimeters
- Taken beam data since 2005
  - Two more years of data-taking
- Large UK involvement
  - All ana/working groups have UK co-convener(s)
  - Made significant h/w & DAQ contributions

T2K:

- J-PARC (Tokai) to Kamioka mine
  - 295 km baseline, off-axis
  - New beam
- FD: Super-K (water Cerenkov)
- Start data-taking in 2010
- Large UK involvement
  - ND280 off-axis detector (P0D, ECAL, DAQ, ….)

NOνA:

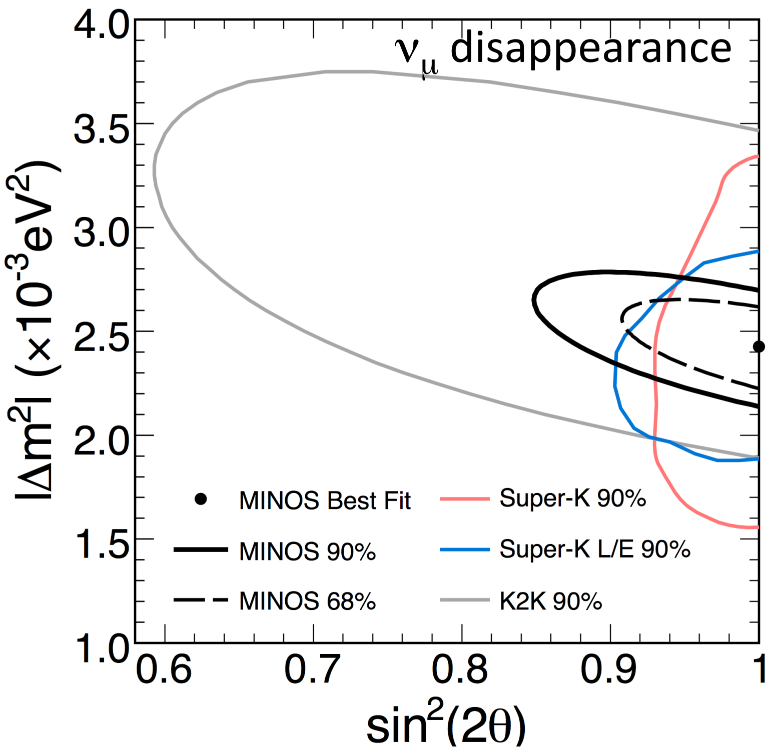
- NuMI (Fermilab) to Ash River, MN
  - 810 km baseline, off axis
  - Upgrade beam power
- “Totally active” tracking liquid sci calorimeters
- Start data-taking in 2013
- No UK involvement

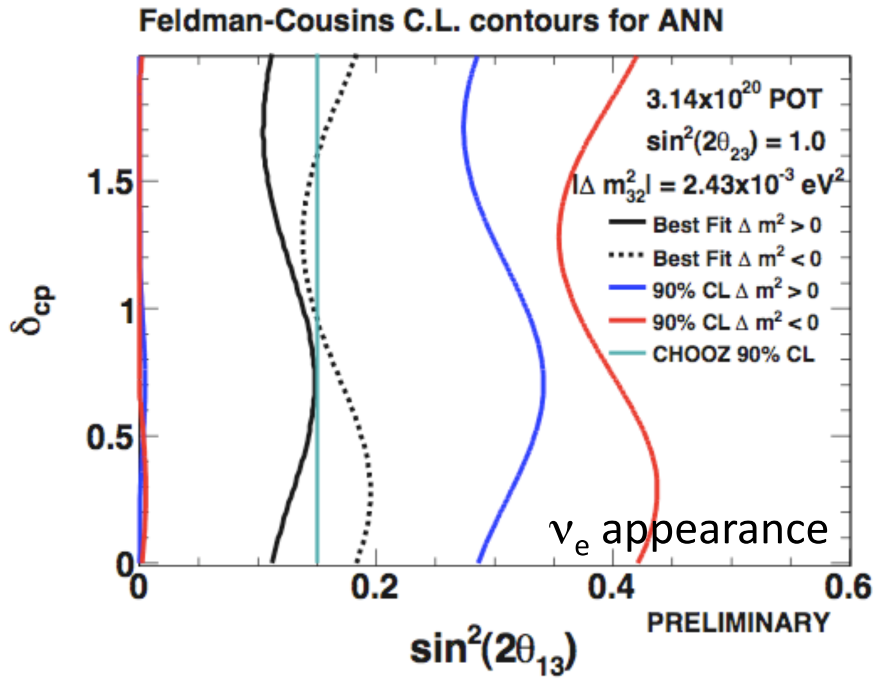
MINOS

Main physics results to date:

- ν_μ disappearance:
  $|\Delta m^2_{32}|=(2.43 \pm 0.13) \times 10^{-3}\ eV^2$
  at 68% C.L.

  $\sin^2(2\theta_{23}) > 0.90$ at 90% C.L.
  - Most precise result for $|\Delta m^2_{32}|$ to date
- ν_e appearance:
  - 1.5σ excess (within realms statistical fluctuation):
  - Normal hierarchy ($\delta_{CP} = 0$):
    $\sin^2(2\theta_{13}) < 0.29$ (90% C.L.)
  - Inverted hierarchy ($\delta_{CP} = 0$):
    $\sin^2(2\theta_{13}) < 0.42$ (90% C.L.)
- $\overline{\nu}_\mu$ disappearance:
  - Study 7% $\overline{\nu}_\mu$ component
  - See 1.9σ fewer events than CPT-conserving
- Neutral-current interaction rate:
  - Limit on sterile neutrinos:
    $f_s < 0.68$ (90% C.L.)

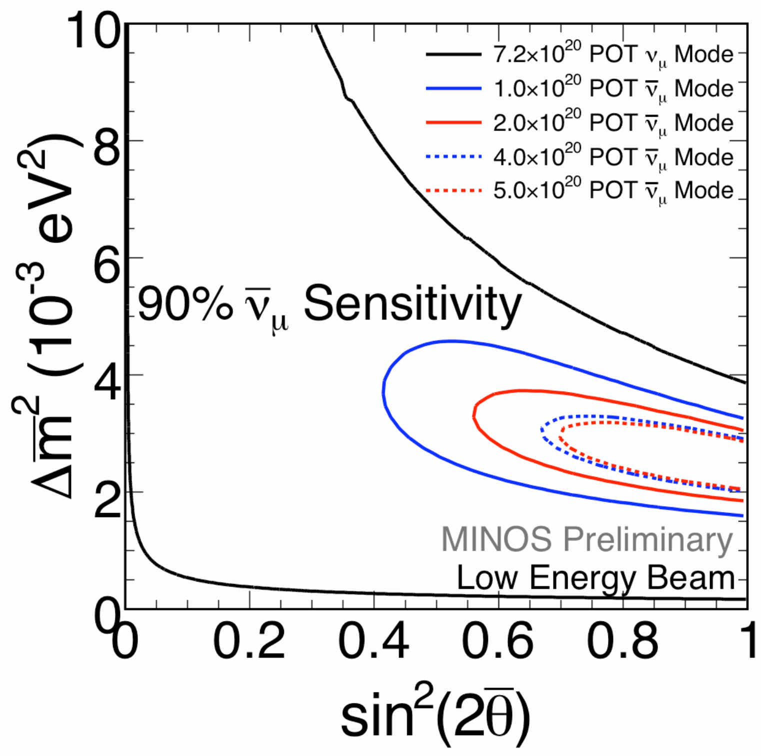




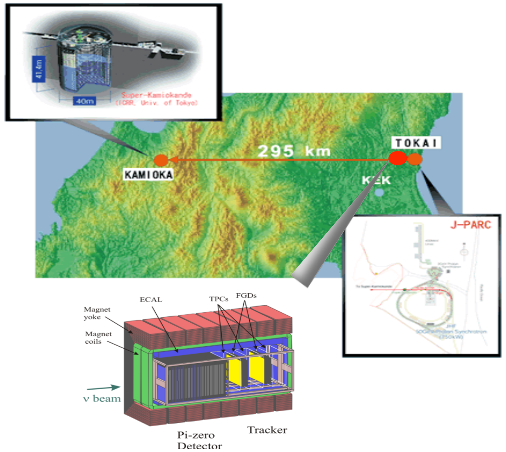
MINOS

Future plans:

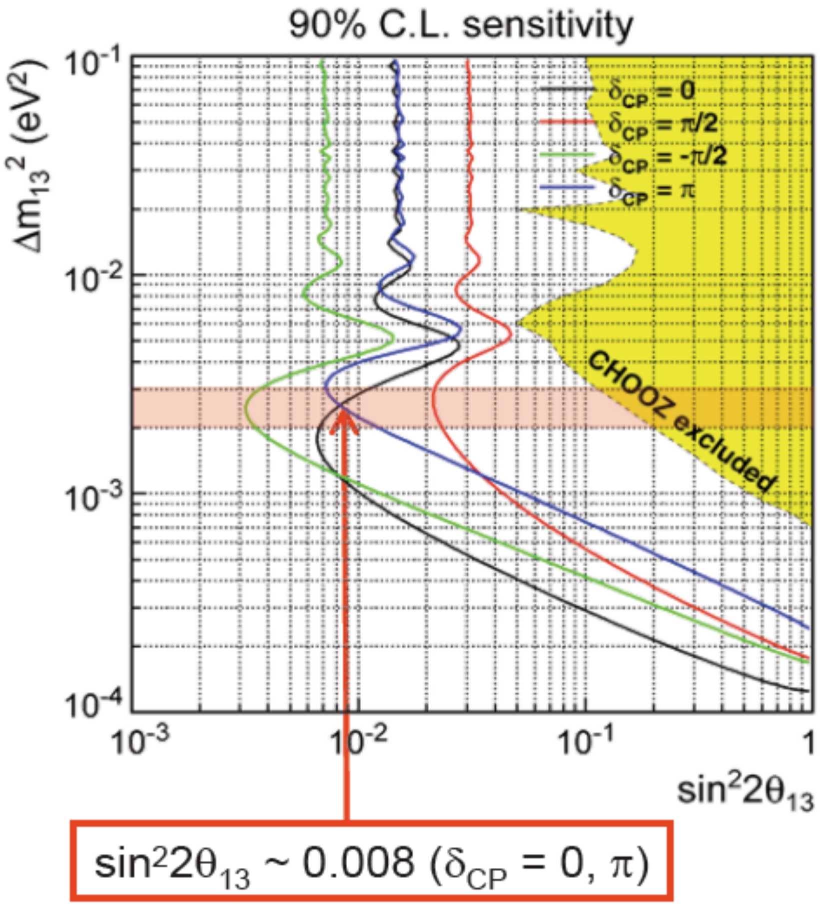
- Update all analyses with more than double the data set
  - Data in the can (3.2 → 7E20 POT)
- Muon antineutrino running
  - Switch beam magnetic horns to focus π^-
    - Start in September this year
  - Make the first direct measurement
    - Reduce uncertainty on $\overline{\Delta m^2_{32}}$ by an order of magnitude
    - $\bar{\nu}_\mu$ mode for 2E20 POT, or until July 2010



T2K

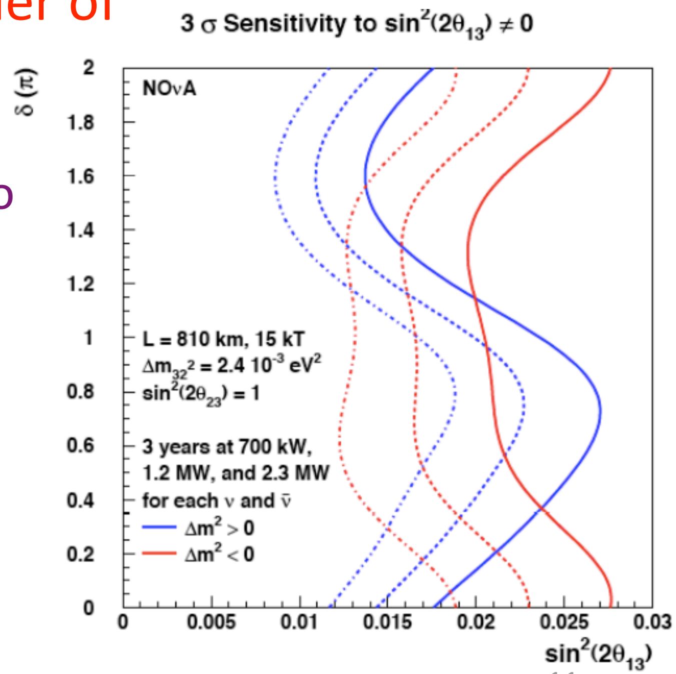


- Physics programme:
  - Phase I:
    - Discovery/measurement of θ_{13}
    - $\Delta(\sin^2 2\theta_{23}) \sim 0.01$ (1%)
      $\Delta|\Delta m^2_{32}| < 1 \times 10^{-4}$ eV (a few %)
      (90% CL)
  - Potential phase 2:
    - Search for CP violation
- Milestones:
  - ND suite operational by end of 2009
  - Beam power ramped over next few years
    (2009: 30 kW; 2010: 100 kW; 2011: 300 kW; + "a few years": 750 kW
  - Phase 1: total of 5E21 POT



NOνA

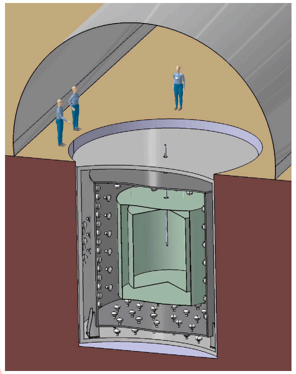
- Significant injection of funds via US stimulus package revived NOνA
- Physics programme:
  - Optimised for ν_e appearance
    - An order of magnitude more sensitive than MINOS
  - Improve $\sin^2 2\theta_{23}$ and $|\Delta m^2_{32}|$ by an order of magnitude (compared to MINOS)
  - Mass hierarchy (sign (Δm^2_{32}))
    - Long baseline: only experiment sensitive to this
- Milestones:
  - 1 May 2009: FD groundbreaking
  - Autumn 2011: Start of beam upgrades (400 kW → 700 kW)
  - 2013: Data-taking with full FD



Measuring θ_{13}: $\bar{\nu}_e$ Disappearance

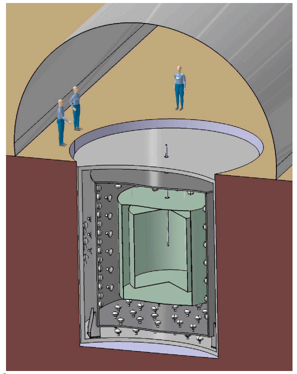
Nuclear power station

$\bar{\nu}_e$



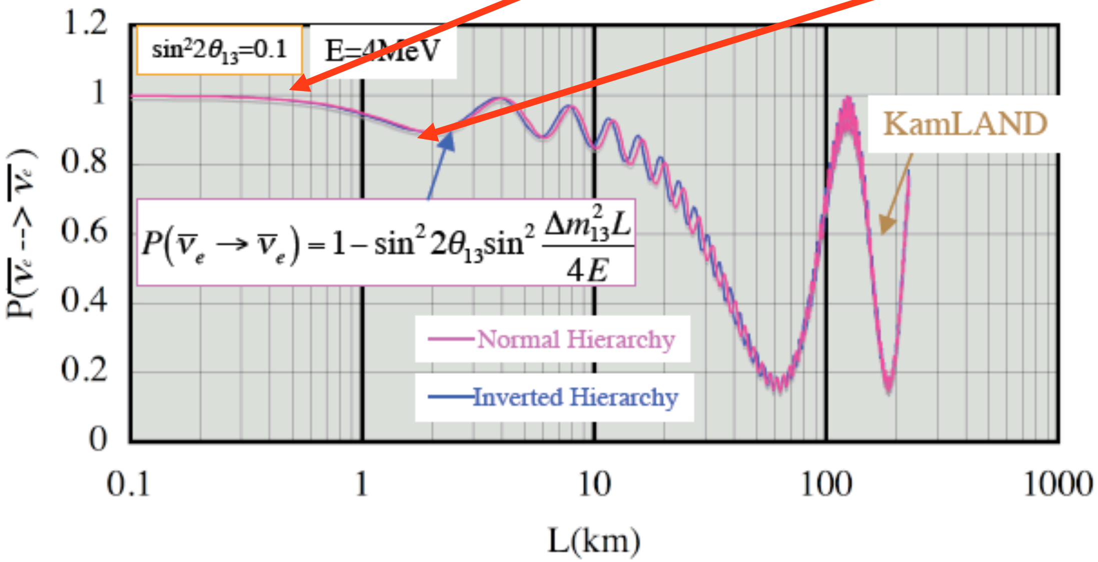
Near Detector
d = 300 - 400 m

$\bar{\nu}_e$
$(\bar{\nu}_{\mu,\tau})$



Far Detector
d = 1 - 1.8 km

Reactor Neutrino Oscillation



Present limit from CHOOZ:
$\sin^2(2\theta_{13}) < 0.15$ (90% C.L.) at
$\Delta m^2_{31} = 2.5 \times 10^{-3}\ eV^2$

Dominant source of systematic error in CHOOZ:
Reactor neutrino spectrum
~ Cancels out with two detectors

The Detectors

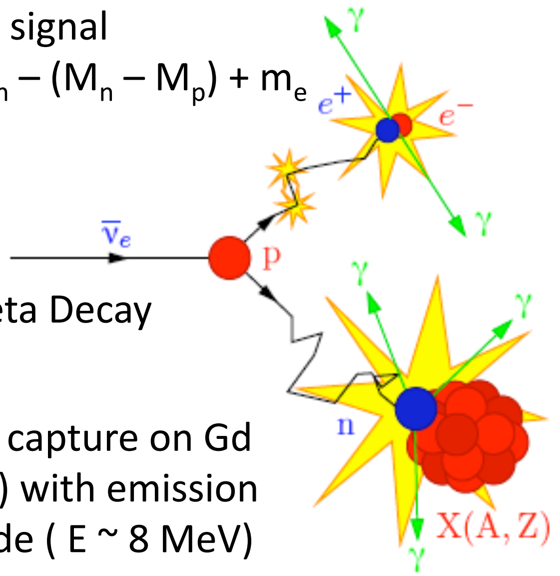
Example: Double Chooz

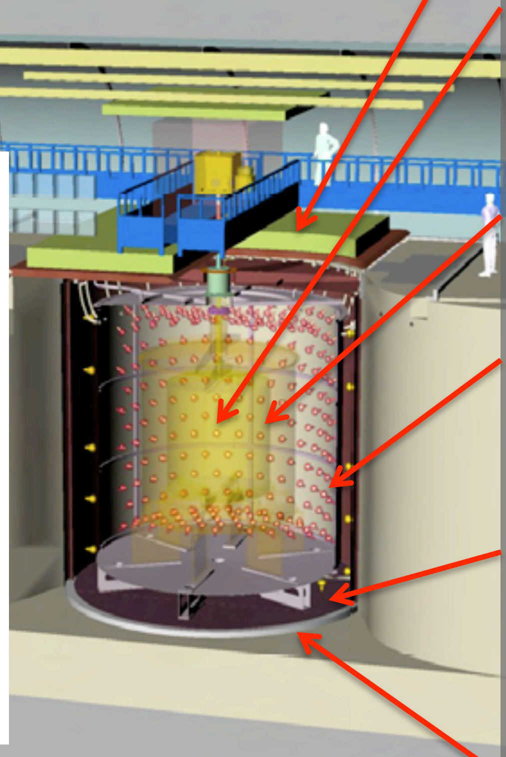
Prompt e^+ signal

$E_{prompt} = E_n - (M_n - M_p) + m_e$

Inverse Beta Decay

Delayed n capture on Gd (t ~ 30 ms) with emission of γ cascade (E ~ 8 MeV)





Outer Veto:
Plastic scintillator panels

ν Target:
10 m^3 liquid scintillator doped with 0.1% Gd

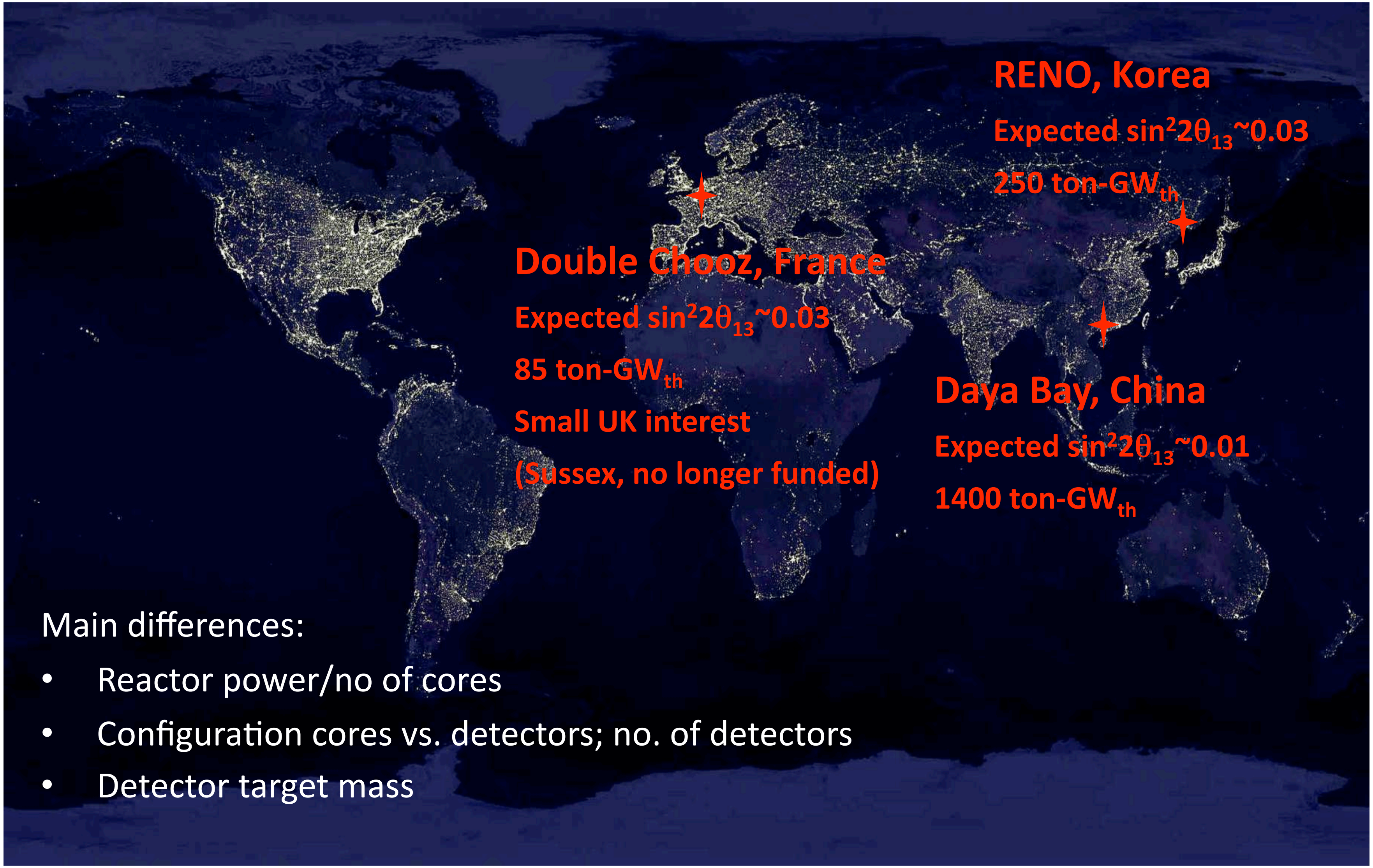
γ Catcher:
23 m^3 liquid scintillator

Buffer:
114 m^3 mineral oil with ~400 PMTs

Inner Veto:
90 m^3 liquid scintillator with 80 PMTs

Shielding:
15 cm steel

Players: Double Chooz, RENO, Daya Bay

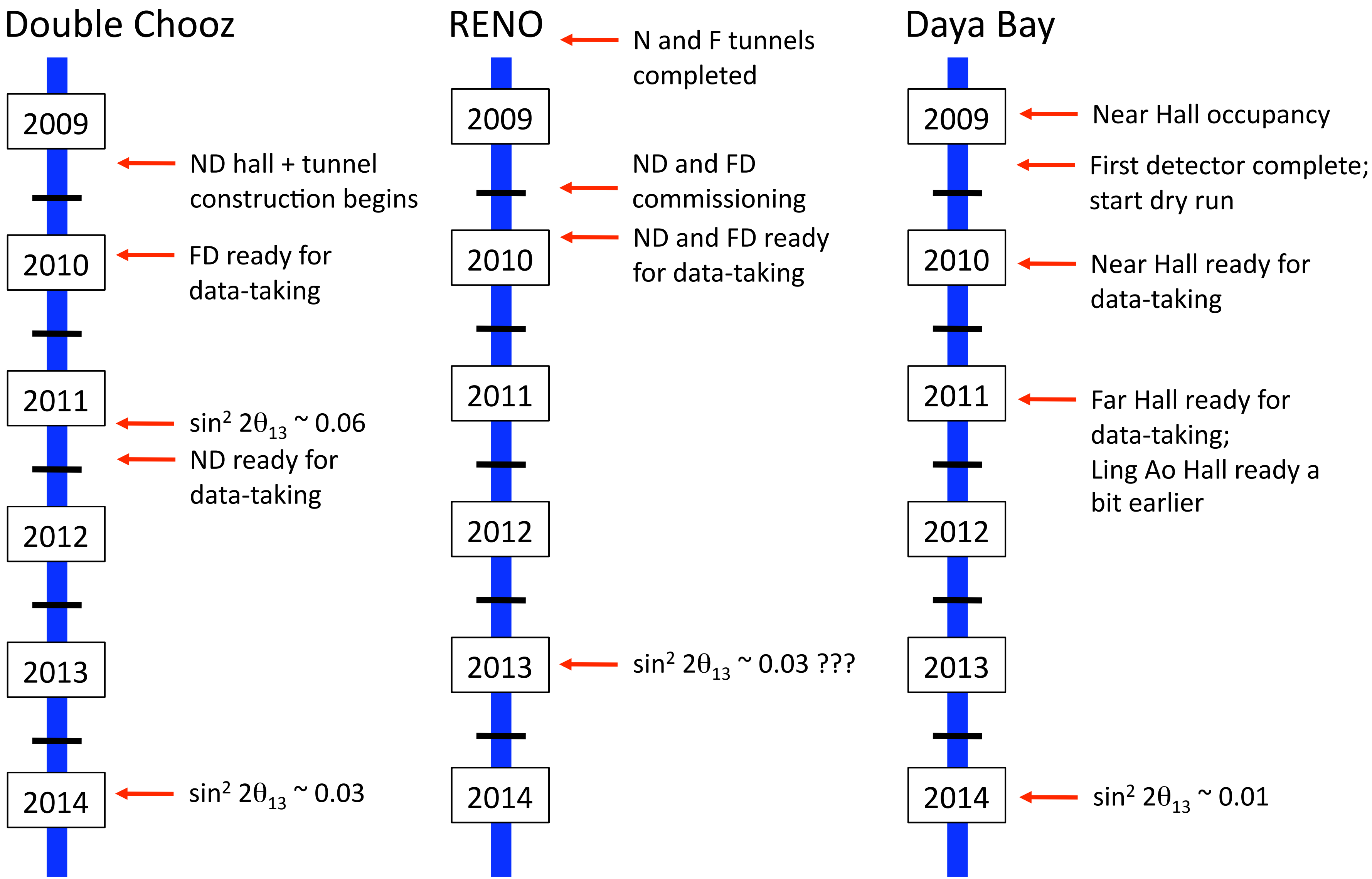


Main differences:

- Reactor power/no of cores
- Configuration cores vs. detectors; no. of detectors
- Detector target mass

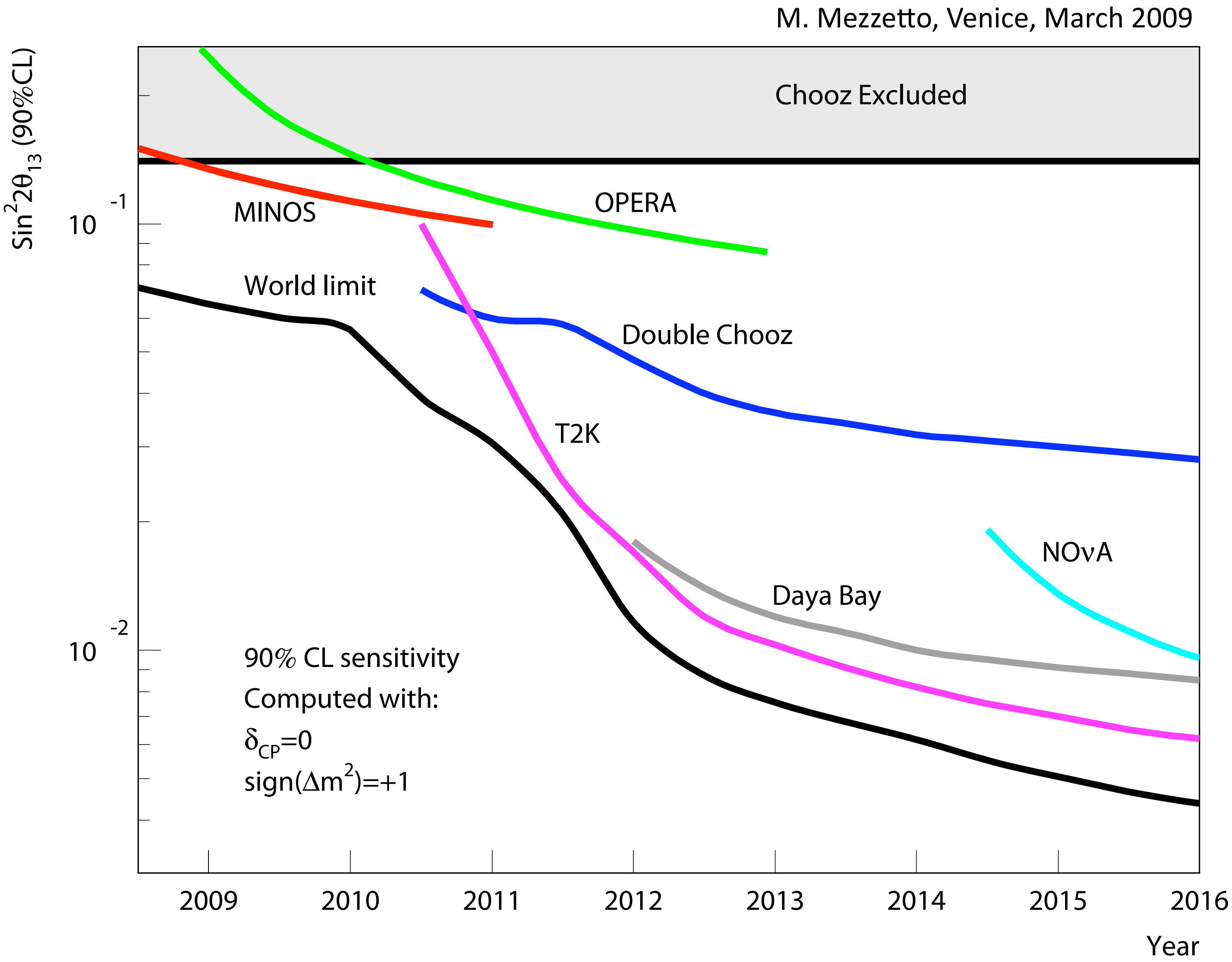
Reactor experiments

Status and Expected Milestones*



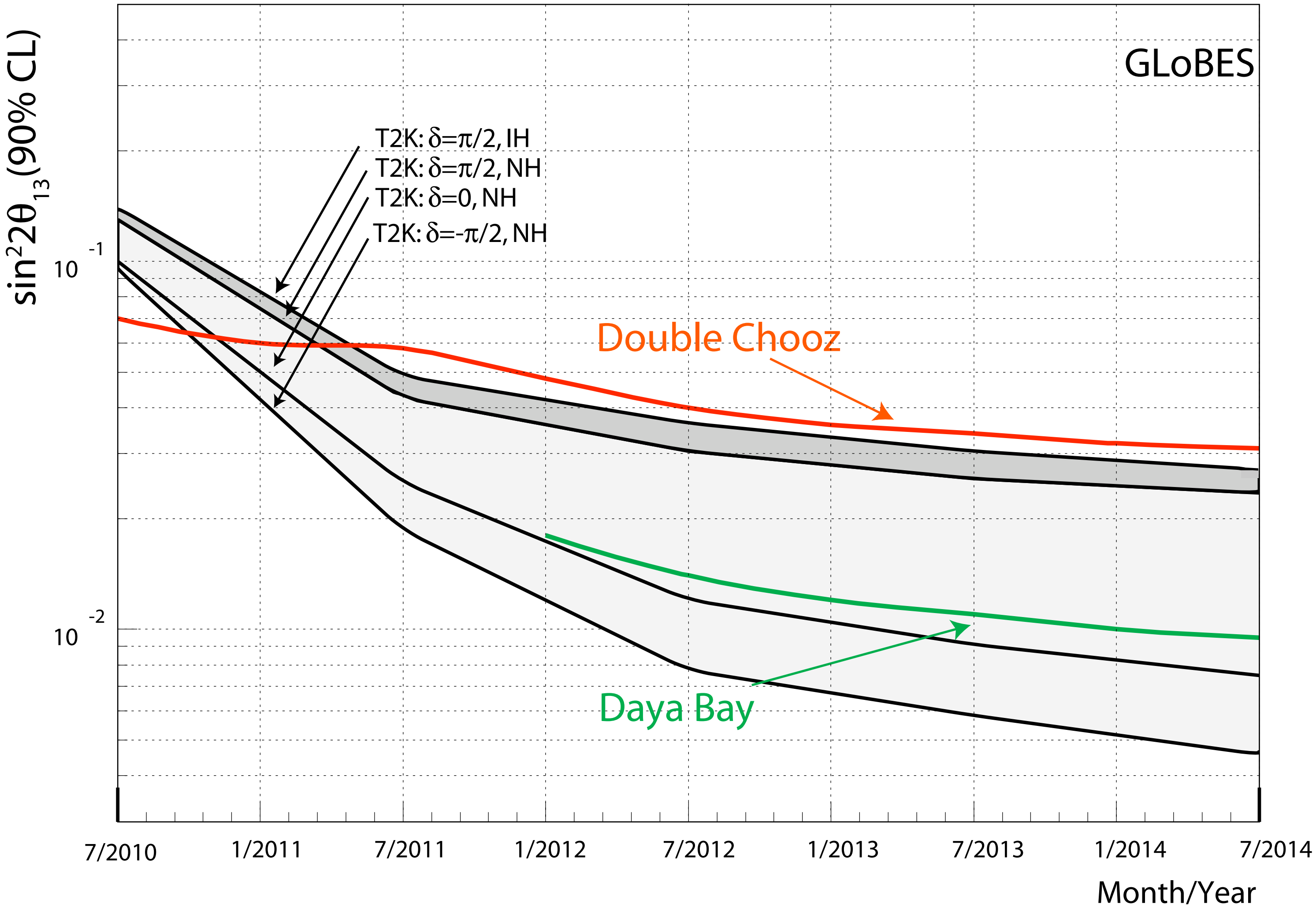
* DC schedule includes my estimated delays – not official, so don't quote it!
RENO, DB official schedules, but at least DB will likely be delayed by a few months

Comparison of θ_{13} Sensitivities



Comparison of θ_{13} Sensitivities

M. Mezzetto, Venice, March 2009



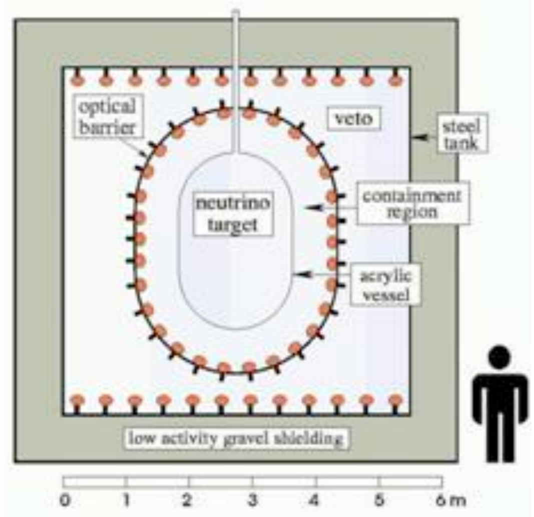
Conclusions and Outlook

- Past and present experiments have pinned down θ_{13}, Δm^2_{12}, θ_{23}, Δm^2_{32}
- MINOS recently announced 1.5σ result for θ_{13}
- T2K and reactor experiments come on-line within ~a year from now
- Next 5 years will see sensitivity to $\sin^2 2\theta_{13}$ to ~0.01, plus order of magnitude improvement on θ_{23} and Δm^2_{32}
- Need combination of different baselines + reactor to resolve θ_{13}, δ_{CP}, sign (Δm^2_{32})
- Would be difficult to search for δ_{CP} if $\sin^2 2\theta_{13} < 0.01$

Reactor Experiment Howto:
Improve on Chooz

CHOOZ : R_{osc} = 1.01 ± 2.8% (stat) ± 2.7% (syst)

- Statistics
  - More powerful reactor (multi-core)
  - Larger detection volume
  - Longer exposure
- Experimental error:
  ν flux and cross-section uncertainty
  - Multi-detector
  - Identical detectors
    - Reduce inter-detector systematics (normalisation, calibration...)
- Background
  - Improve detector design
  - Increase overburden
  - Improve knowledge of background by direct measurement



Larger *S*/*B*

Reach ~1% precision

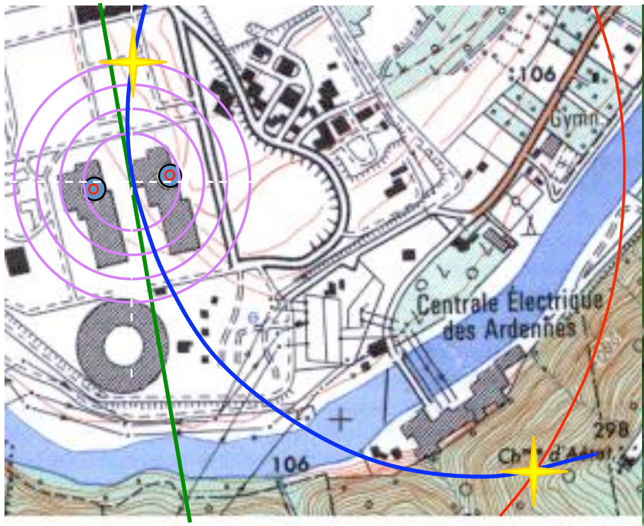
Double Chooz Systematic Uncertainties

		Chooz	Double-Chooz	
Reactor-induced	ν flux and σ	1.9 %	<0.1 %	Two "identical" detectors, Low bkg
	Reactor power	0.7 %	<0.1 %	
	Energy per fission	0.6 %	<0.1 %	
Detector - induced	Solid angle	0.3 %	<0.1 %	Distance measured @ 10 cm + monitor core barycenter
	Target Mass	0.3 %	0.2 %	Same weight sensor for both det.
	Density	0.3 %	<0.1 %	Accurate T control (near/far)
	H/C ratio & Gd concentration	1.2 %	<0.2%	Same scintillator batch + Stability
	Spatial effects	1.0 %	<0.1 %	"identical" Target geometry & LS
	Live time	few %	0.25 %	Measured with several methods
Analysis	From 7 to 3 cuts	1.5 %	0.2 - 0.3 %	n energy, Δt, (distance e^+ - n)
	Total	2.7 %	< 0.6 %	(Total ~0.45% without contigency ....)

Th. Lasserre 07/02/2007

Baselines and Reactor Power

Double Chooz

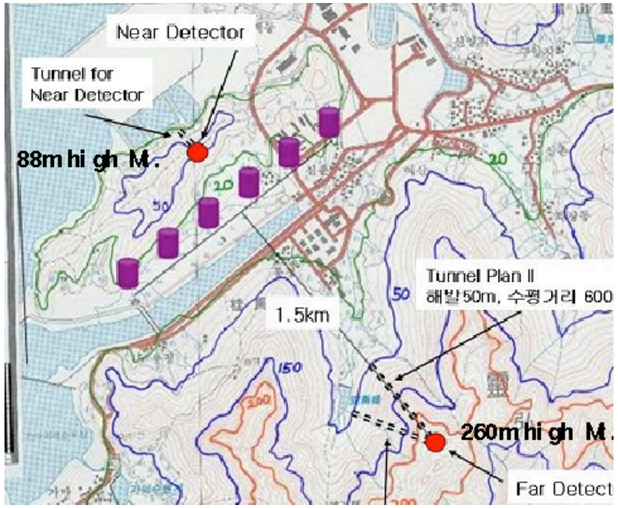


P = 8.2 GW_{th}/2 cores
L = 1.05 km

Daya Bay

P = 11.6 GW_{th}/4 cores
~2011:
17.4 GW_{th}/6 cores
L ~ 1.8 km

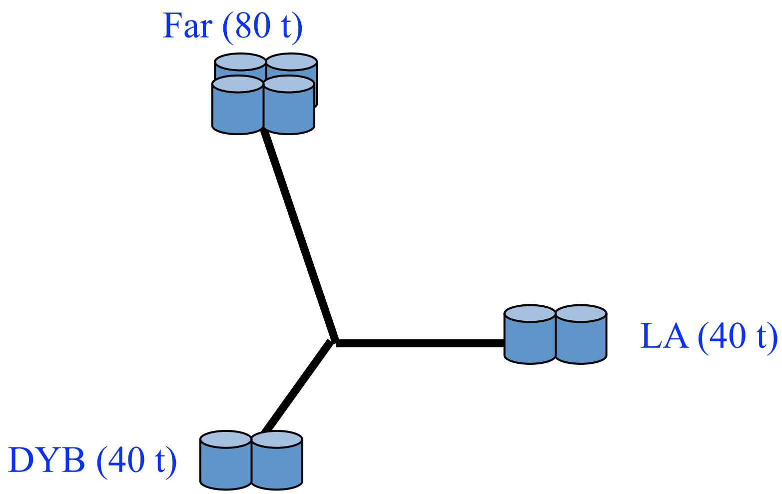
RENO



P = 16.1 GW_{th}/6 cores
L ~ 1.4 km

Daya Bay and Ling Ao Nuclear Power Plant

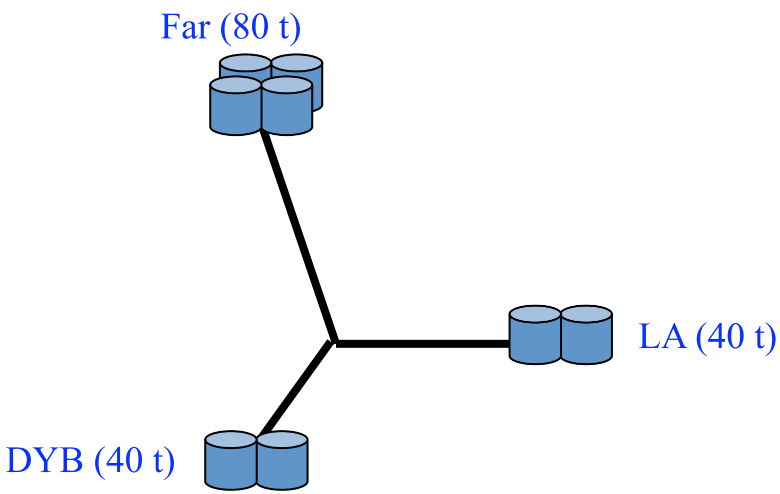
Daya Bay Run Plan



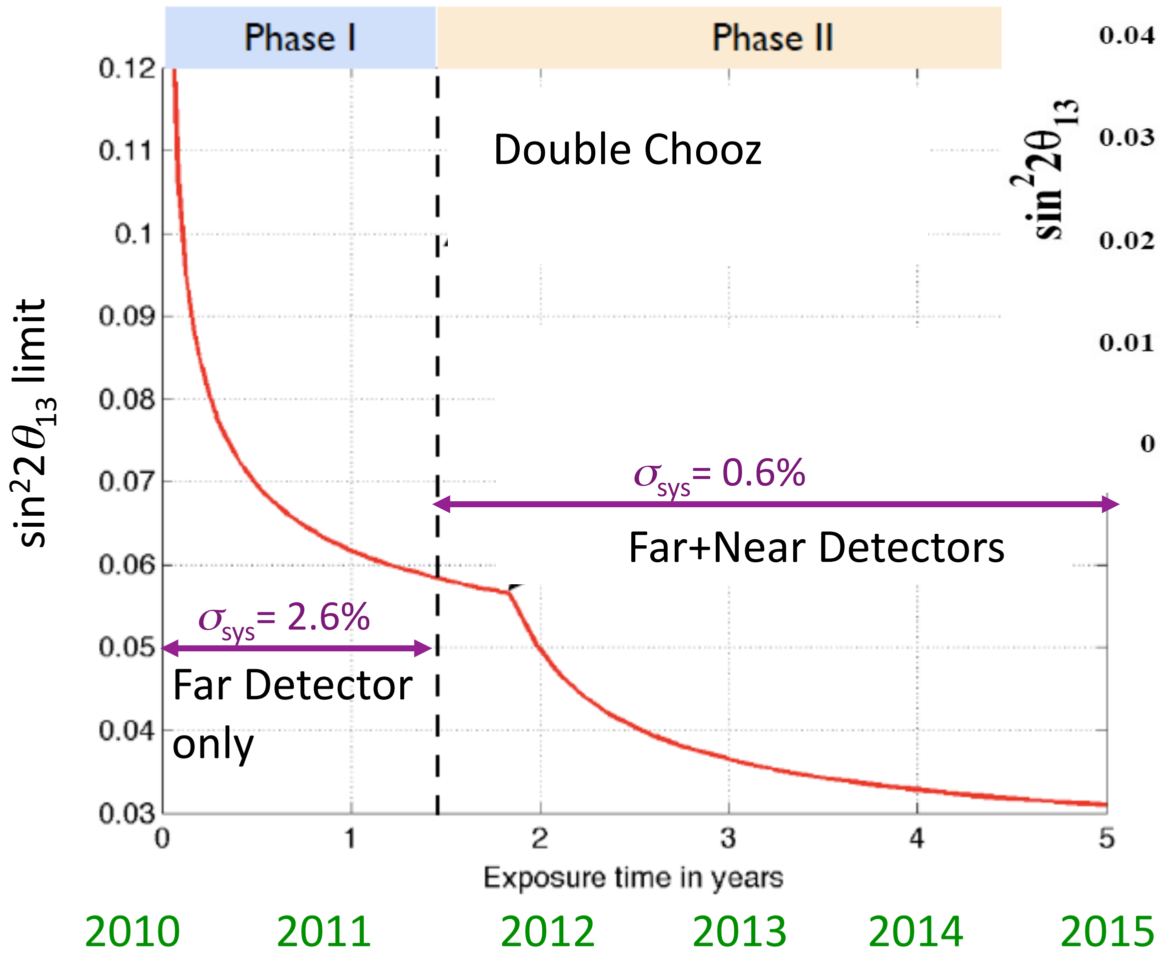
- Istall first two detectors in DB Near Hall within a year from now
- Take data (engineering run) while Ling Ao and Far Halls completed
- Additional detectors deployed in pairs, one in Ling Ao and one in Far Hall, as they become ready – except last pair
- One detector to be moved from Near to Far Hall
- Last pair deployed in Near + Far Halls
- Run for three years
- Publish

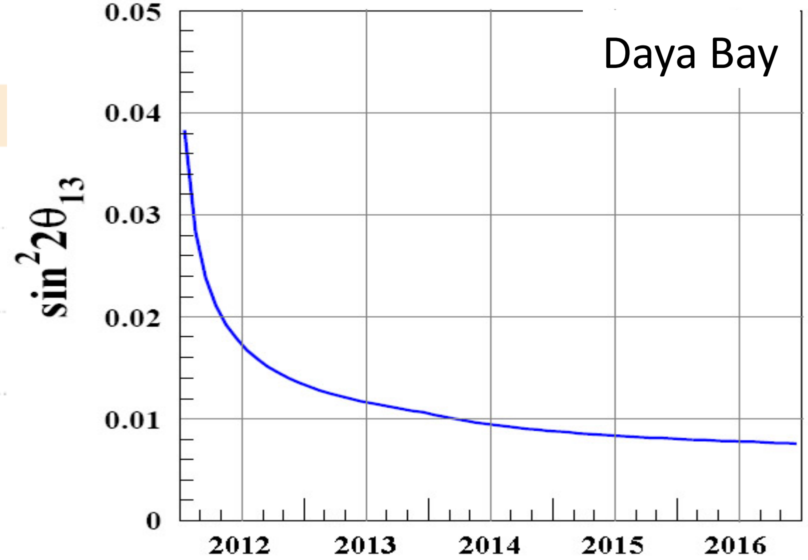
Daya Bay: Redundancy

- Measuring $\sin^2 2\theta_{13}$ to 0.01 need to control systematic errors very well.
- We believe that the relative (near/far) detector systematic error could be lowered to 0.38%, with near/far cancellation and improved detector design.
- **Side-by-side calibration**: Event rates and spectra in two detectors at the same near site can be compared → How IDENTICAL our detectors are?
- **Detector swapping**: Daya Bay antineutrino detectors are designed to be MOVABLE. All detectors are assembled and filled with liquids at the same place. Detectors at the near sites and the far site can be swapped, although not necessary to reach our designed sensitivity, to cross check the sensitivity and further reduce the systematic errors.



Comparison of θ_{13} Sensitivities





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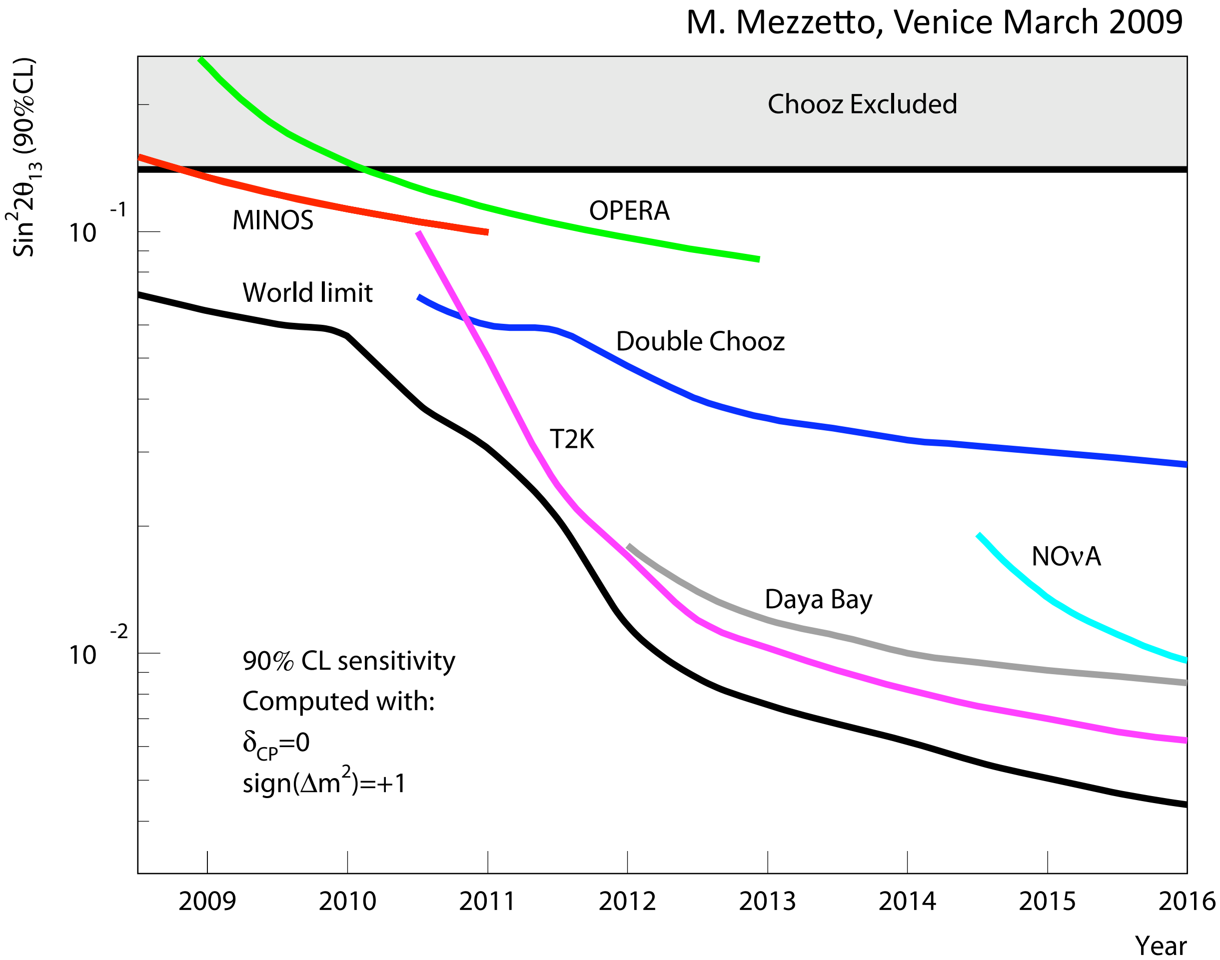
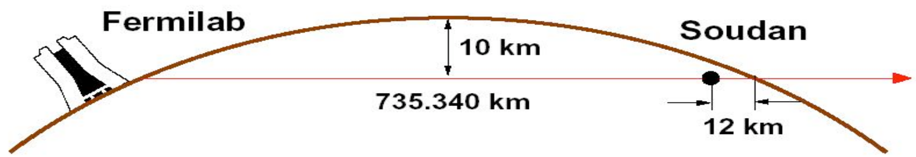


Assumptions:

- DC to start end of 2009; ND 1.5 yrs later
  - More likely 2nd quarter of 2010 (my estimate)
- DB to start mid 2011
  - From C. White: Schedule slipping by a few months
- T2K: 0.1 MW in 2010; 0.45 MW in 2011; 0.75 MW thereafter
  - From D. Wark: 0.1 MW in 2010; 0.3 MW in 2011; ramp to 0.75 MW over a few years
- MINOS, OPERA: sensitivity as per proposal, scaled by POT

Overview

- Long baseline
  Fermilab ← 735 km → Soudan
- Near detector at Fermilab
  - Measure beam composition, energy spectrum
- Far detector in Minnesota
  - Search for and study oscillations
- Test the $\nu_\mu \rightarrow \nu_x$ oscillation hypothesis
  - Measure precisely $|\Delta m^2_{32}|$ and $\sin^2(2\theta_{23})$
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations
  - Sensitive to θ_{13}
- Other MINOS physics:
  - Search for sterile neutrinos, CPT/ Lorentz violation
  - Compare ν_μ, $\overline{\nu}_\mu$ oscillations
  - Studies of cosmic rays and atmospheric neutrinos
  - Neutrino interaction studies in the Near Detector

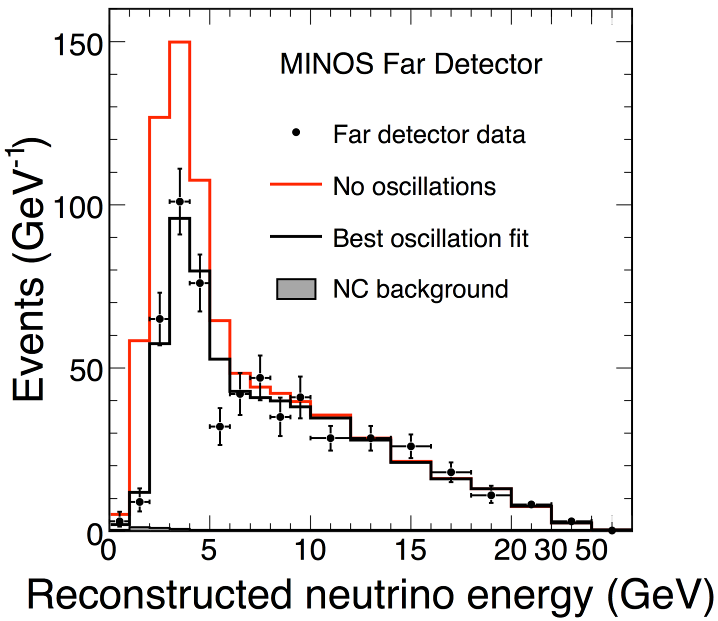


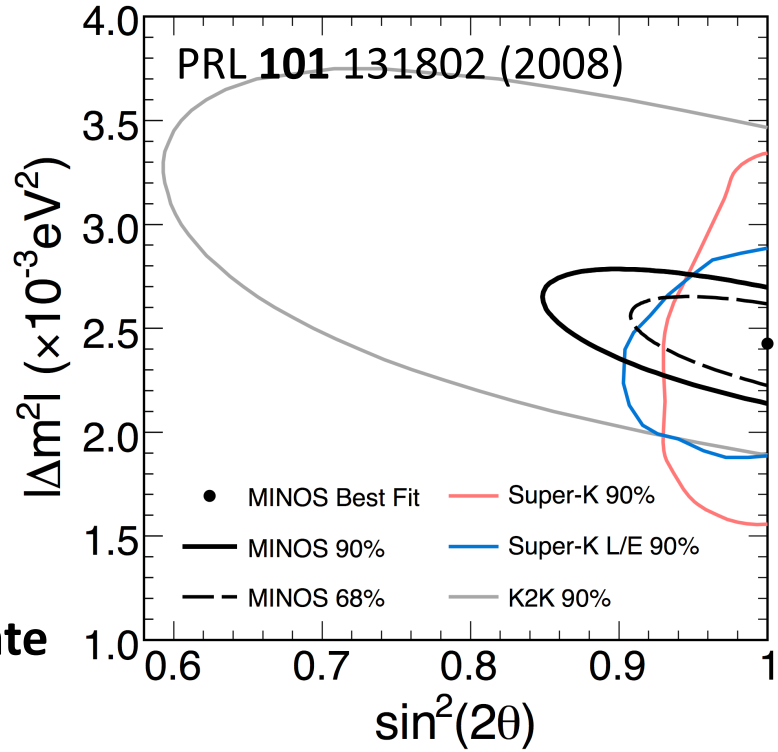
Muon-Neutrino Disappearance Analysis

- Strong energy-dependent spectrum distortion
- Spectrum fit with two-flavour oscillation hypothesis
- Fit constrained to physical region + includes three largest systematics
- Results:

$|\Delta m^2_{32}|=(2.43 \pm 0.13) \times 10^{-3}\ eV^2$
at 68% C.L.

$\sin^2(2\theta_{23}) > 0.90$
at 90% C.L.



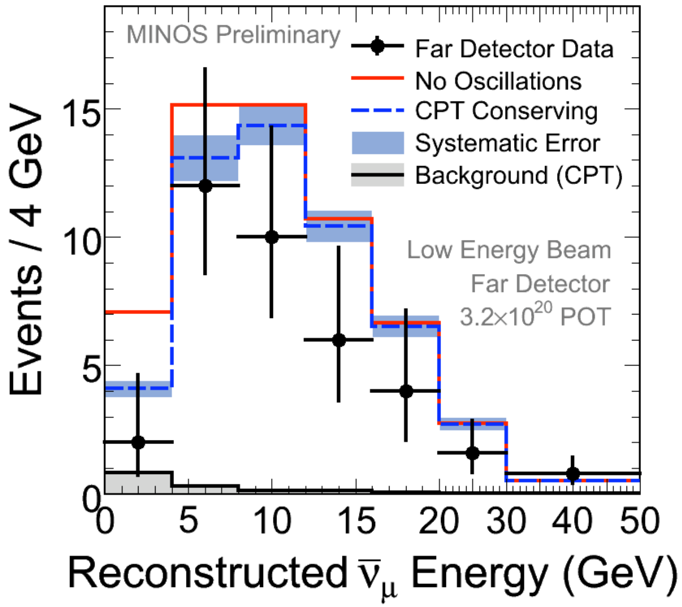


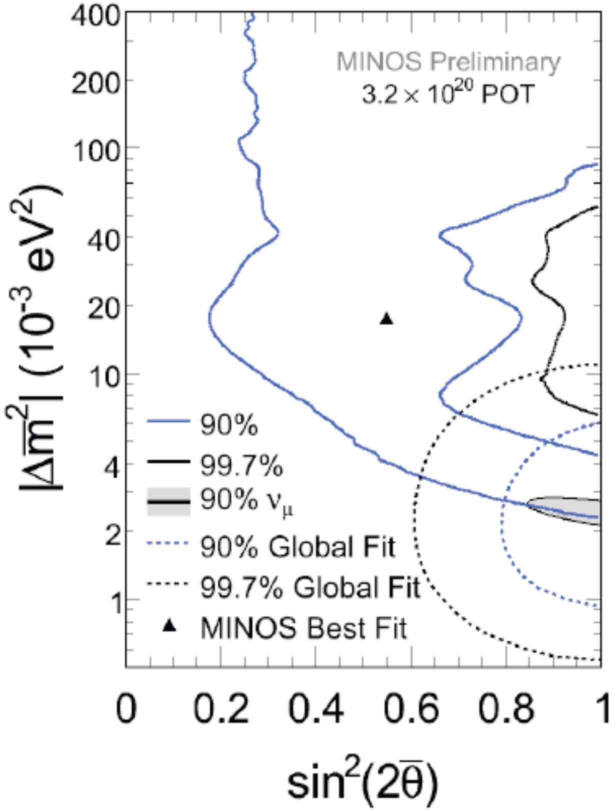
Most precise measurement of $|\Delta m^2_{32}|$ to date

Antimuon-Neutrino Disappearance Analysis

- Measure $|\Delta\overline{m}^2_{32}|$, $\sin^2(2\overline{\theta}_{23})$
- Test CPT
- FNAL Wine & Cheese three weeks ago
- $\overline{\nu}_\mu$ CC events are 7% of beam
  - Mis-ID muon and NC backgrounds relatively larger
  - As CC analysis, but with extra cuts
    - Track-length likelihood, charge-sign significance

Far Prediction (no oscillations): 64.6±8(stat)±3.9(sys)
Far Prediction (CPT conserving): 58.3±7.6(stat)±3.6(sys)
Far Data: 42 events
1.9σ less than CPT conserving oscillations





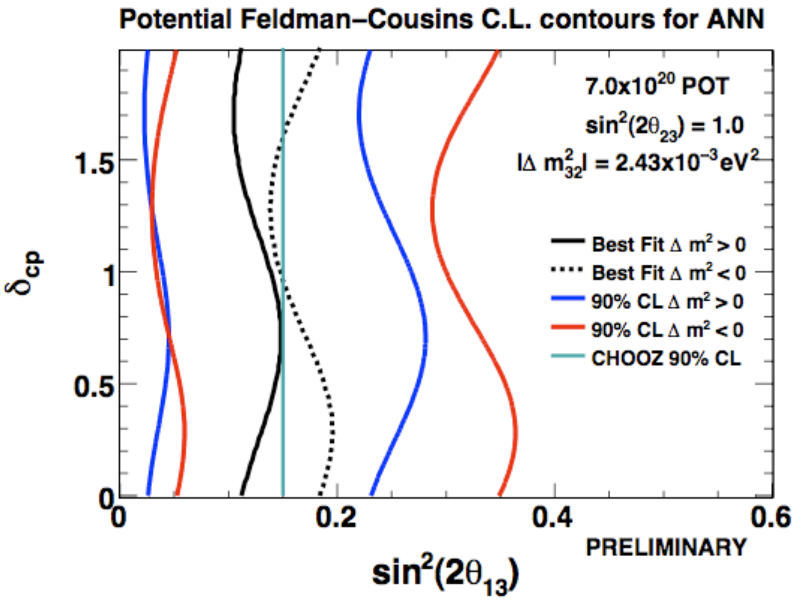
The Future

All these analyses have used 3x10[20] of the 7x10[20] protons-on-target that have been recorded
- As of this June's summer shutdown

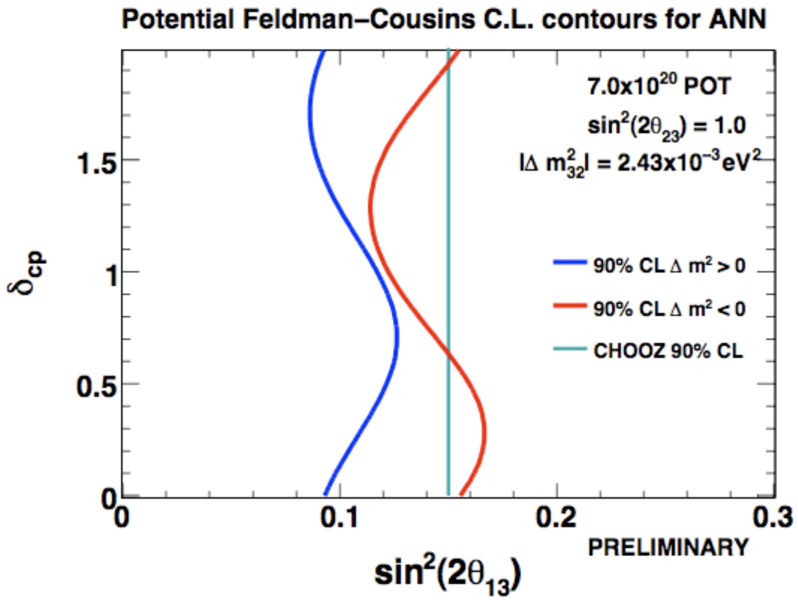
Over the next year, the analyses will be updated with the increased dataset
- Using the blind analysis policy on the new data

Graphs below show the θ_{13} sensitivity for 7x10[20] PoT

If the excess persists



If the excess goes away



Electron-Neutrino Appearance Analysis

- Sub-dominant neutrino oscillations

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E)$$

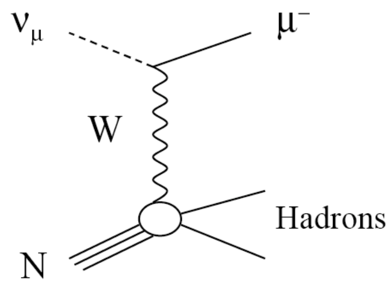
  - Also CPv and matter effects: not shown here but included in fit

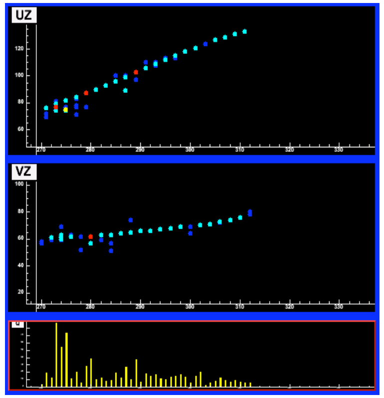
- ANN algorithm to select ν_e events

- Background measured in ND
  - NC events, high-y ν_μ CC, beam ν_e, oscillated ν_τ at FD
  - Data-driven technique: compare horn on/off data

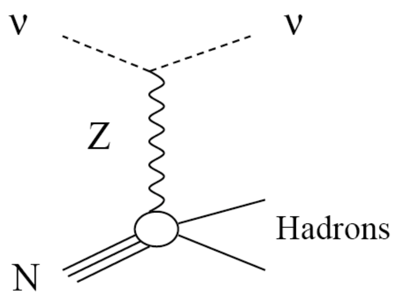
- Predict FD background from measured ND background + MC

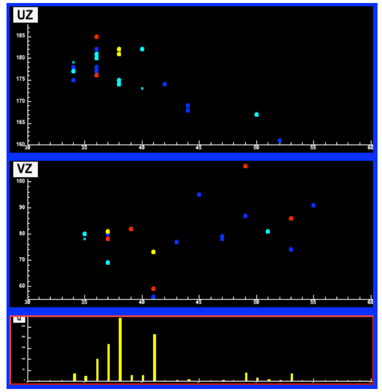
ν_μCC Event



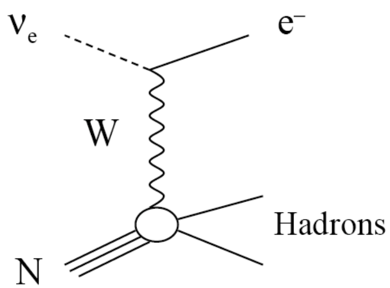


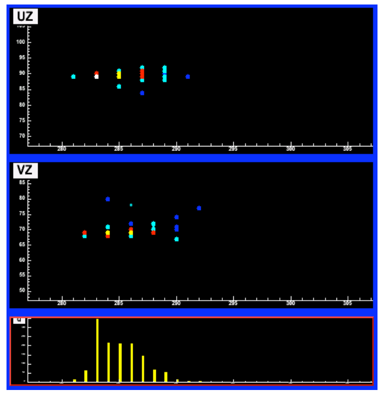
NC Event





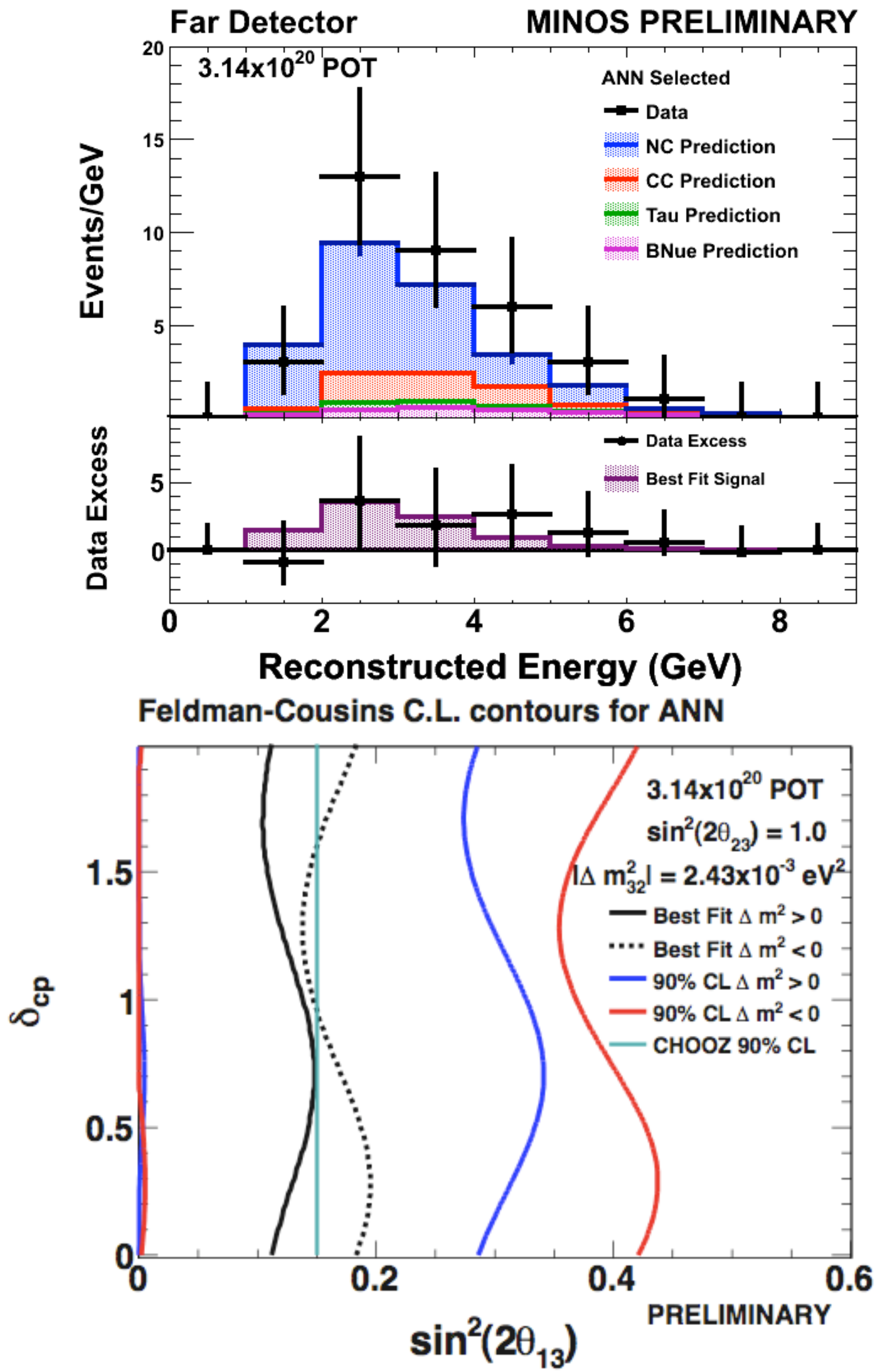
ν_eCC Event





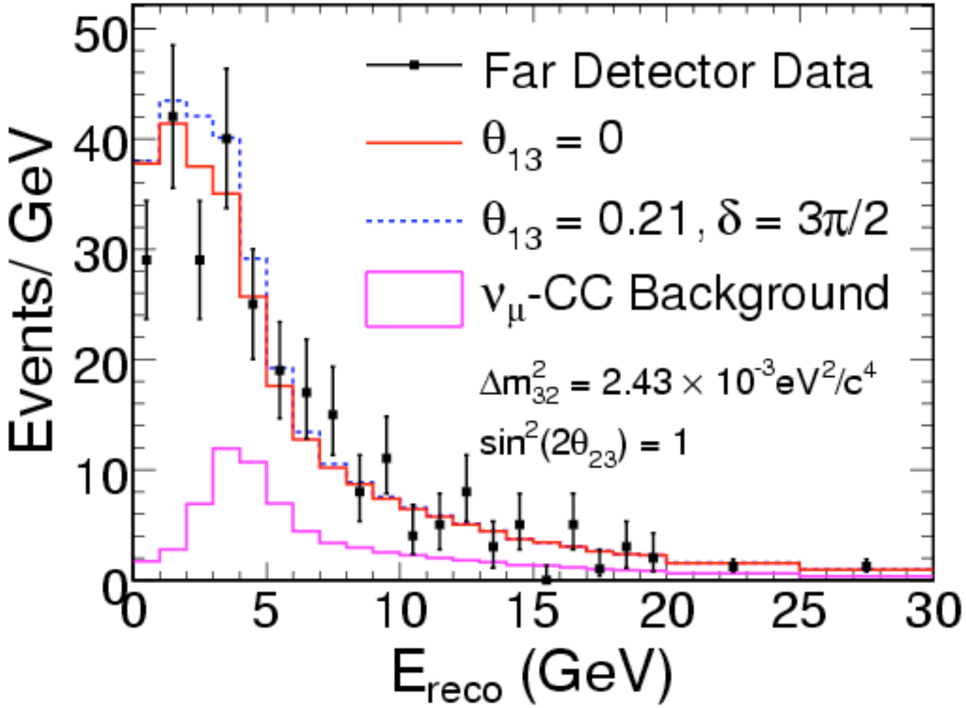
Electron-Neutrino Appearance Analysis

- Far Detector spectrum obtained after blind analysis
- Expected background:
  27 ± 5(stat) ± 2(syst)
- Contours from Feldman-Cousins method
  - Fit to number of events
- Observed events:
  37
- Results:
  - Normal hierarchy (δ_{CP} = 0):
    $\sin^2(2\theta_{13}) < 0.29$ (90% C.L.)
  - Inverted hierarchy (δ_{CP} = 0):
    $\sin^2(2\theta_{13}) < 0.42$ (90% C.L.)
- 1.5σ excess
  - Well within realms of statistical fluctuation



Neutral Current Analysis

- General NC analysis overview:
  - All active neutrino flavours participate in NC interaction
  - Mixing to a sterile ν will cause a deficit of NC events in Far Detector
  - Assume one sterile neutrino and that mixing between ν_μ, ν_s and ν_τ occurs at a single Δm^2



- Survival and sterile oscillation probabilities become:

$$P(\nu_\mu - \nu_\mu) = 1 - \alpha_\mu \sin^2(1.27\Delta m^2 L / E)$$

$$P(\nu_\mu - \nu_s) = \alpha_s \sin^2(1.27\Delta m^2 L / E)$$

($\alpha_{\mu,s}$ = mixing fractions)

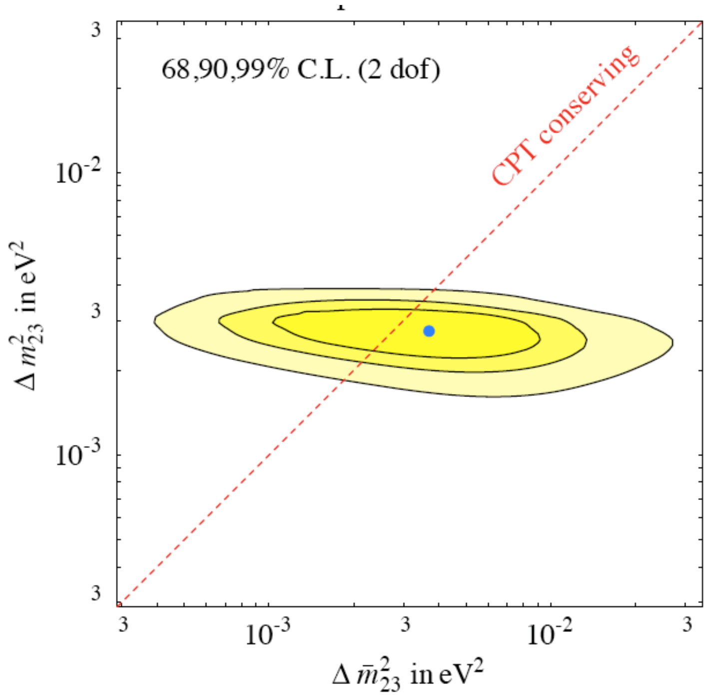
Simultaneous fit to CC and NC energy spectra yields the fraction of ν_μ that oscillate to ν_s:

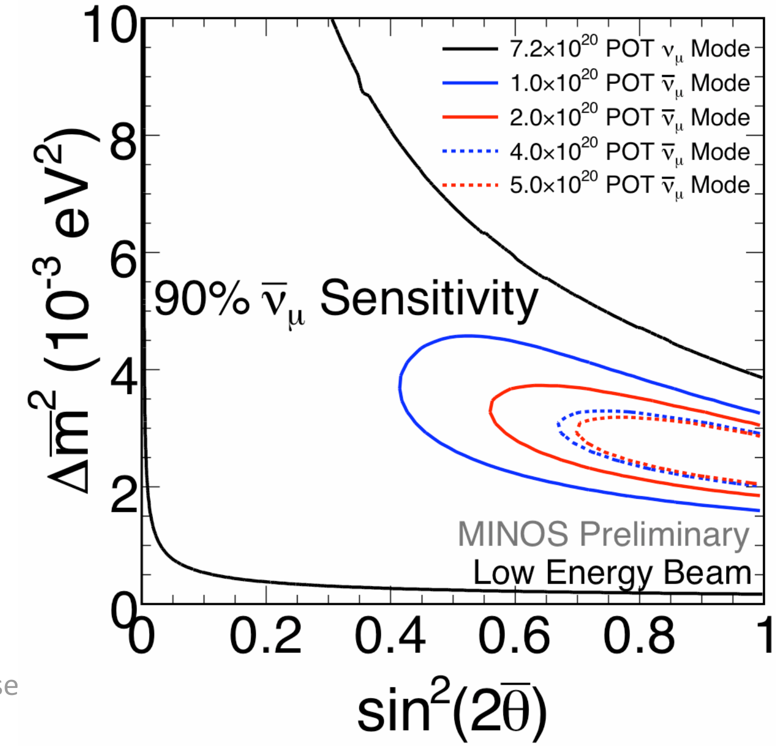
$$f_s = \frac{P(\nu_\mu \to \nu_s)}{1 - P(\nu_\mu \to \nu_\mu)} = 0.28^{+0.25}_{-0.28}(\text{stat.+syst.})$$

$$f_s < 0.68 \quad (90\% \text{ C.L.})$$

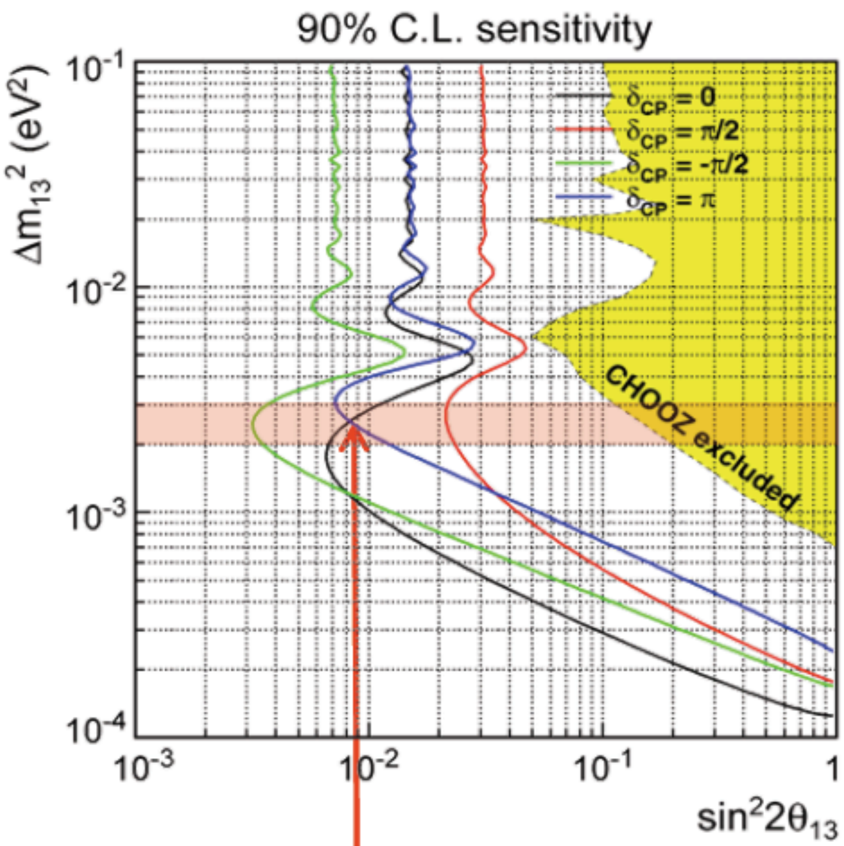
Future Plans

- Update all analyses with more than double the data set
- Muon antineutrino possibilities
  - Switch beam magnetic horns to focus π^-
  - MINOS can make the first direct measurement
    - Reduce uncertainty on $\Delta\overline{m}^2_{32}$ by an order of magnitude

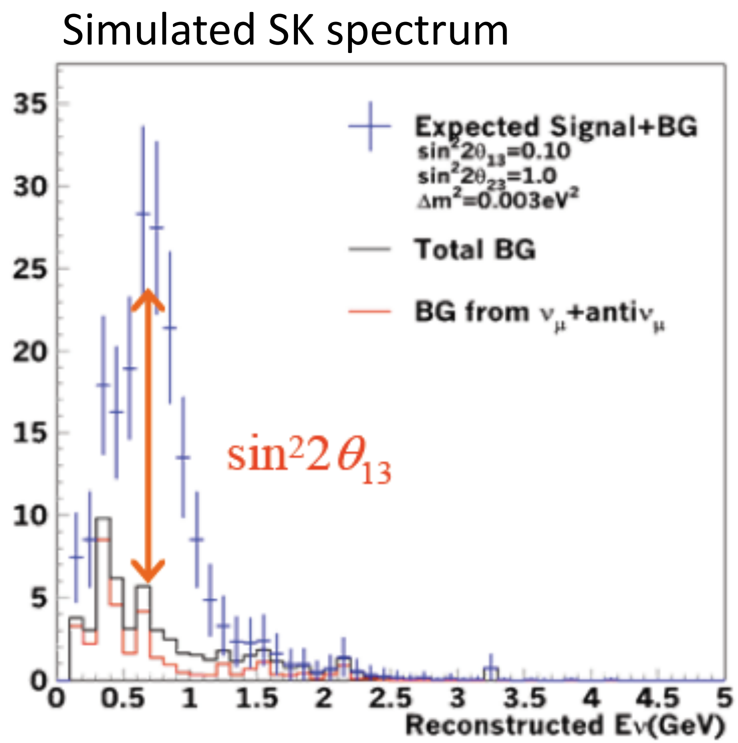




Main Measurements: $\sin^2\theta_{13}$



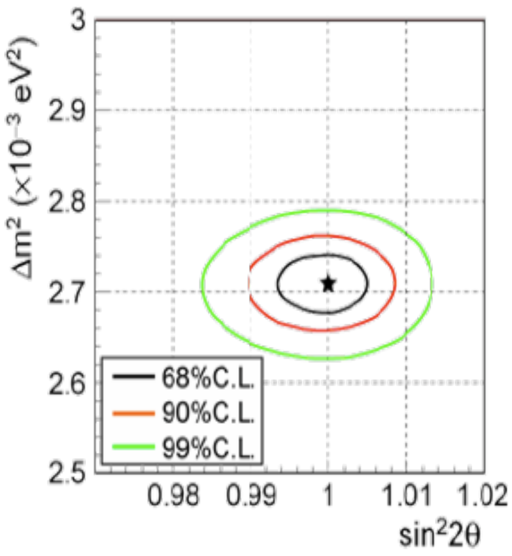
$\sin^2 2\theta_{13} \sim 0.008$ ($\delta_{CP} = 0, \pi$)



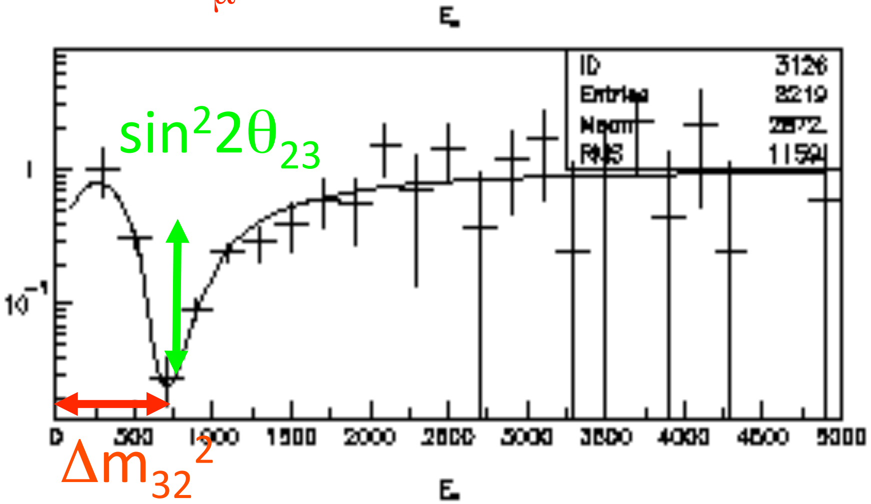
- Use CCQE: $\nu_e + n \rightarrow e^- + p$
- Main backgrounds:
  - Beam ν_e contamination
  - NC π^0 events

Main Measurements: $\sin^2\theta_{23}$, Δm^2_{32}

- Use CC quasi-elastic events:
  $\nu_\mu + n \rightarrow \mu^- + p$
  – Background from non-CCQE interactions



ν_μ disappearance

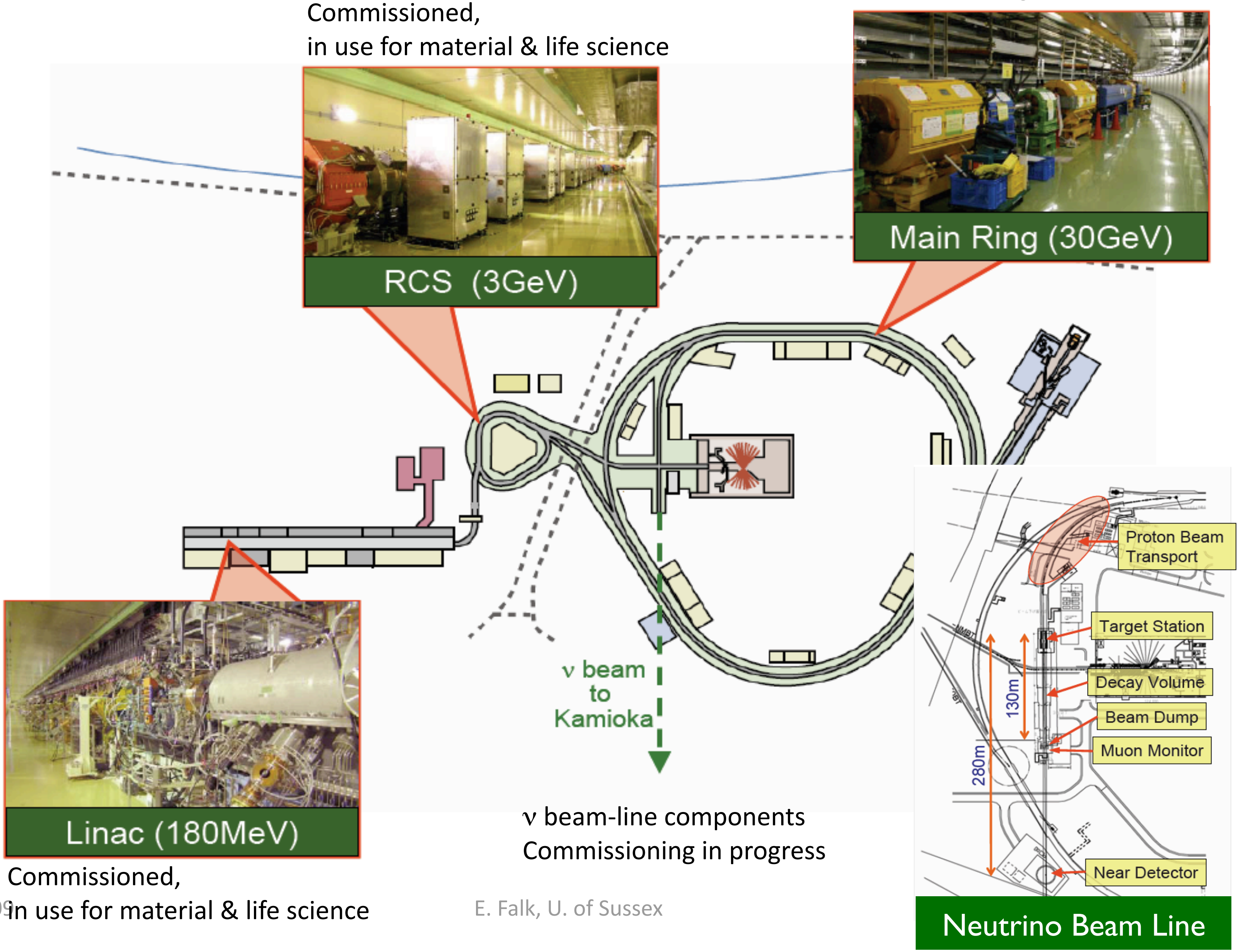


- Precision prospect:
  $\Delta(\sin^2 2\theta_{23}) \sim 0.01$ (1%)
  $\Delta(\Delta m^2_{32}) < 1 \times 10^{-4}$ eV^2 (a few %)
  at 90% C.L.
- @ $\Delta m^2 \sim 2.5 \times 10^{-3}$ eV^2

J-PARC Accelerator Complex

Protons to 30 GeV on 23/12/08
Commissioning is on time

Commissioned,
in use for material & life science



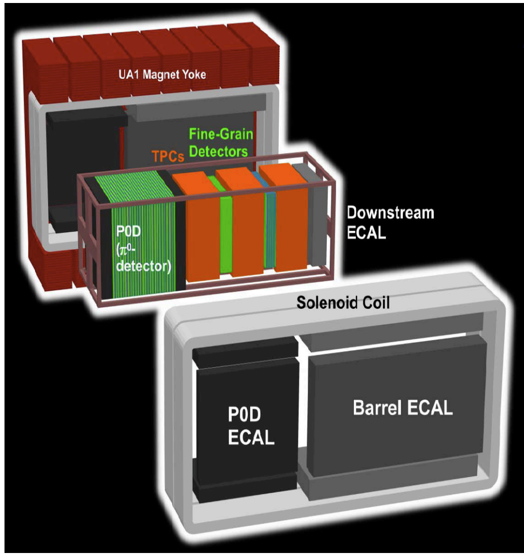
ν beam-line components
Commissioning in progress

Commissioned,
in use for material & life science

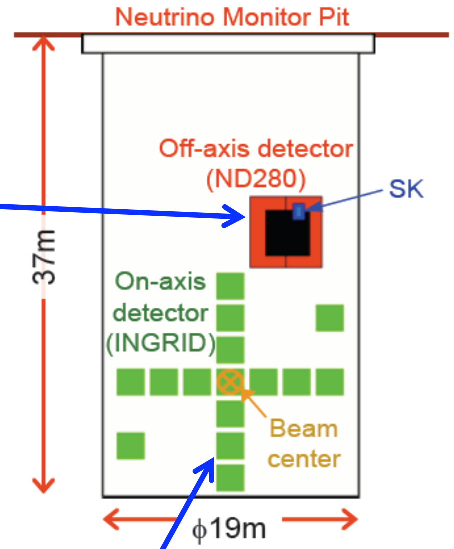
Near Detectors at 280 m

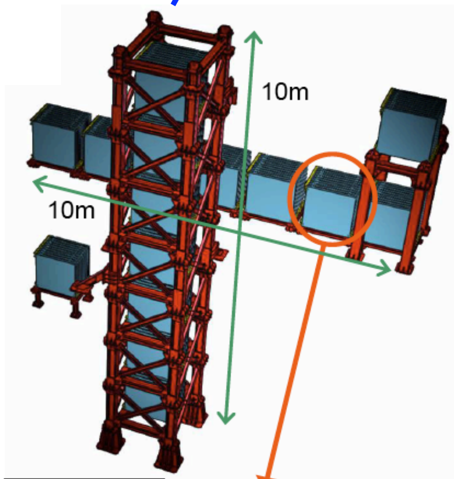
- On- and off-axis detectors 280 m downstream of target
  - Understand the neutrino beam before oscillations occur

- T2K timeline
  - Apr 09: Beam-line commissioning 10 days
  - Summer-autumn 09: Install INGRID & ND280
  - Oct 09: Restart beam commissioning
  - Dec 09-June 10: Physics run
    - Aim to improve CHOOZ limit

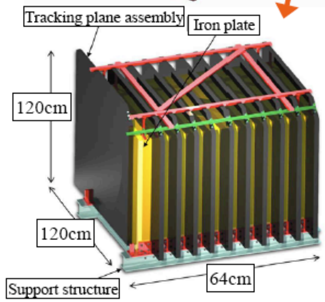


ND 280: Off-axis detectors inside UA1 magnet

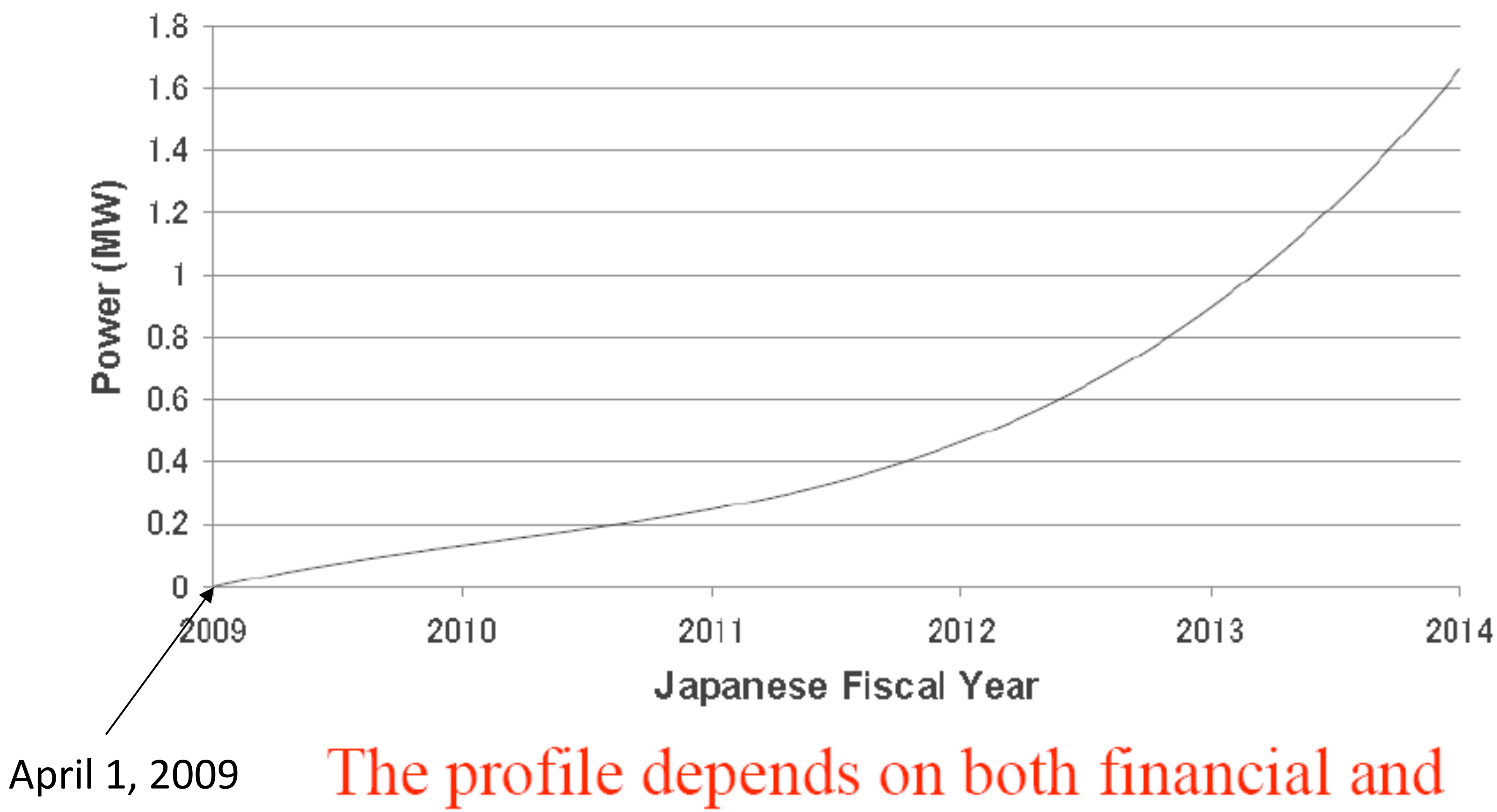




On-axis: INGRID Scintillator/iron modules



Beam Power Projections



The profile depends on both financial and technical developments

Discovery Potential