Unit 4: Current and future experiments at accelerator

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HEP PostGraduate Lectures

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What have we learnt?

There are compelling evidences that all 3 active neutrinos participate to neutrino oscillations (atmospheric: $\nu_\mu \to \nu_\tau$, solar: $\nu_e \to$ to other active flavors)

We have a framework for interpreting 3 flavor ν-mixing with 3 mass eigenstates

$$U_{MNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

PMNS matrix

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

$s_{ij} = \sin\theta_{ij}$

$c_{ij} = \cos\theta_{ij}$

Atmospheric
+ Accelerator
L/E ~500 km/GeV

Solar + Reactor
L/E ~15,000 km/GeV

Within this framework we know:

$\Delta m^2_{23} = \Delta m^2_{atm} \sim 2.5\ 10^{-3} eV^2$

$\sin^2 2\theta_{23} \sim 1$

$\Delta m^2_{12} = \Delta m^2_{sol} \sim 8\ 10^{-5}\ eV^2$

$\sin^2 2\theta_{12} \sim 0.8$

SINCE 2012 ⇨

Accelerator
+Reactors
L/E ~500 km/GeV

$\sin^2 2\theta_{13} \sim 0.1$

How to measure θ_{13}

Recall the formula for 3 family mixing:

$$
\boxed{
\begin{aligned}
P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} + \\
& - 4\sum_{i>j} \mathcal{Real}(U^*{}_{\alpha i} U^*{}_{\beta i} U_{\alpha j} U_{\beta j}) \sin^2[(\Delta m^2_{ij} L)/(4E)] \\
& \pm\ 2\sum_{i>j} Im(U^*{}_{\alpha i} U^*{}_{\beta i} U_{\alpha j} U_{\beta j}) \sin^2[(\Delta m^2_{ij} L)/(2E)]
\end{aligned}
}
$$

$\Delta m^2_{12} = \Delta m^2_{sol} \sim 8 \times 10^{-5}\ eV^2$

$\Delta m^2_{23} \cong \Delta m^2_{13} = \Delta m^2_{atm} \sim 2 \times 10^{-3}\ eV^2$

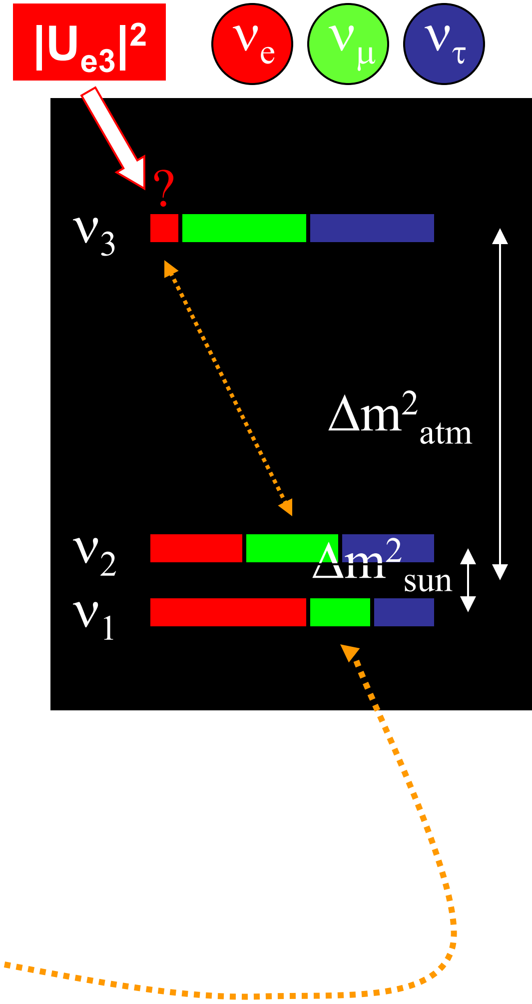
For an experiment with E_ν (GeV) = Δm^2_{23} x L (km) the contribution of Δm^2_{12} is small and the oscillation probabilities simplify:

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

$\nu_\mu \rightarrow \nu_e$ *longbaseline appearance experiment at accelerator*

$P(\nu_e \rightarrow \nu_e) \cong 1 -$ **$\sin^2 2\theta_{13}$ $\sin^2 (1.27\ \Delta m^2_{23}\ L/E)$**

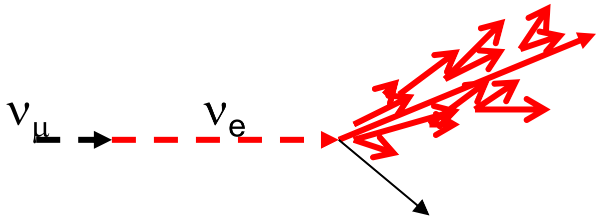
longbaseline disappearance experiments at reactor



$\nu_\mu \rightarrow \nu_e$ appearance

$\sin^2 2\theta_{13} < 0.15$ ⇒ We have to measure a SMALL probability
Needs High Statistics (intense flux, big detectors,..)
Needs small Background (how?)

Signal



ν_e N → e X

X can be low momentum nucleon

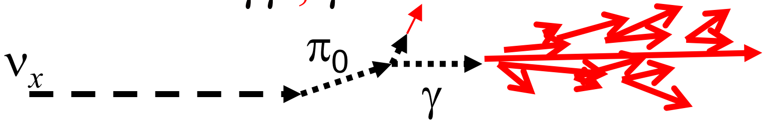
Detect electron:

Single EM shower

Background

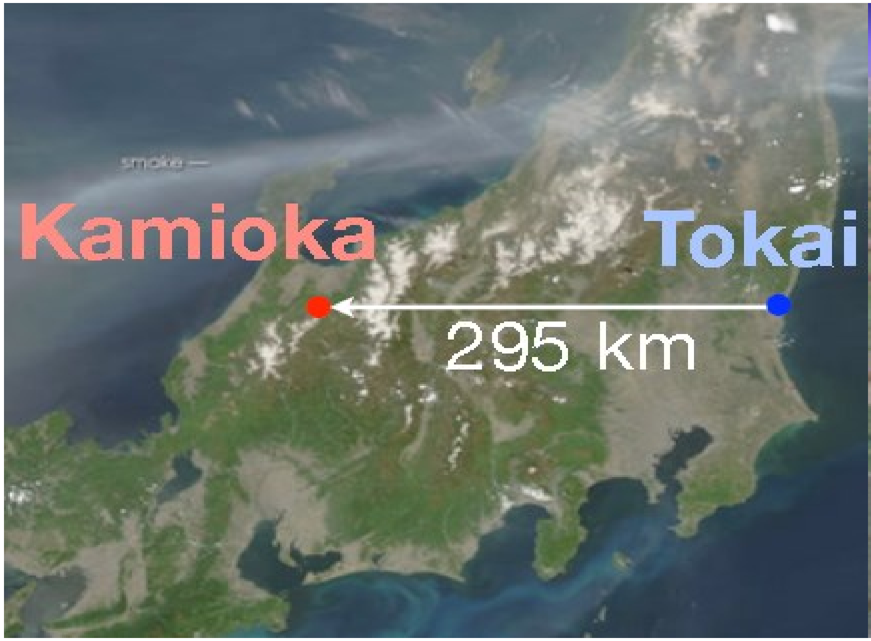
1. Beam intrinsic ν_e contamination
   Identical signature w/ signal
   Different energy distribution
2. π^0 production $\nu N \rightarrow \nu \pi^0 N$

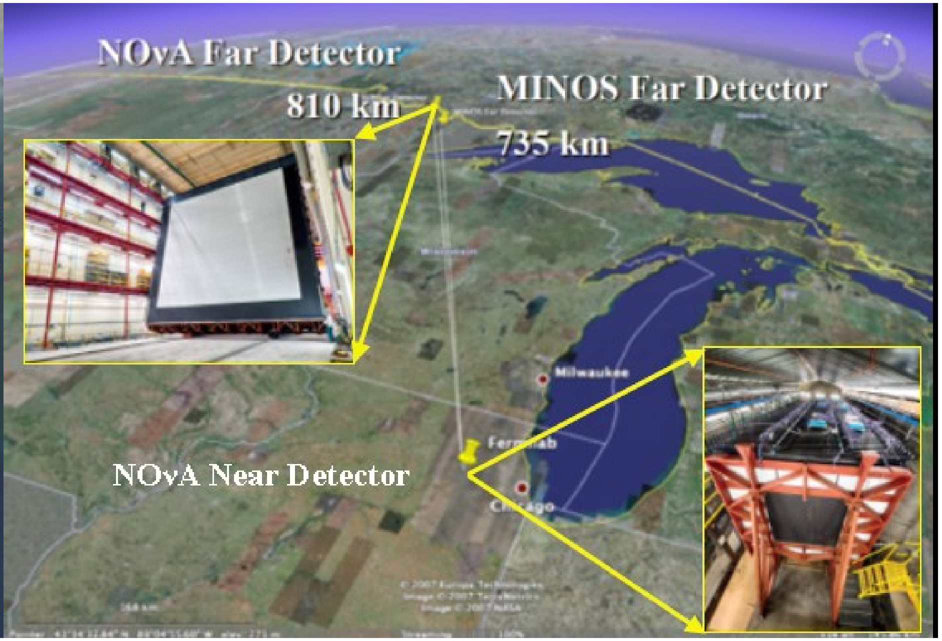
$\pi^0 \rightarrow \gamma\gamma$, $\gamma \rightarrow e^+e^-$



Background if one photon is missed
And 2 EM showers from the other γ overlap

Second-generation LBL: off-axis

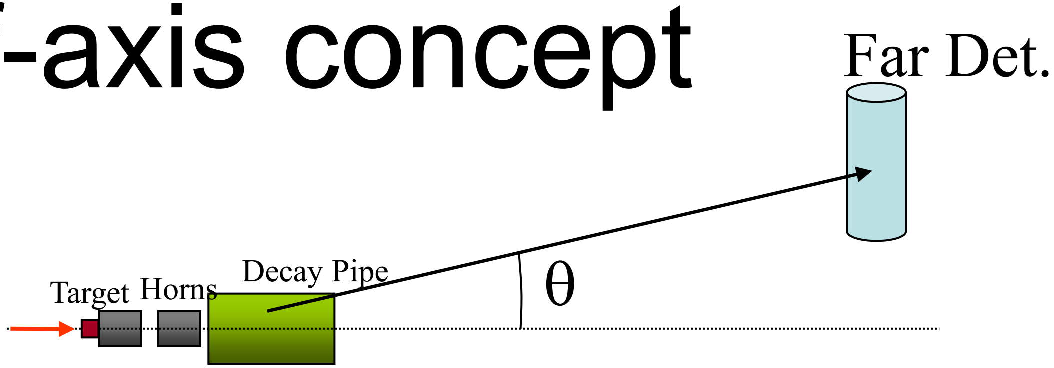




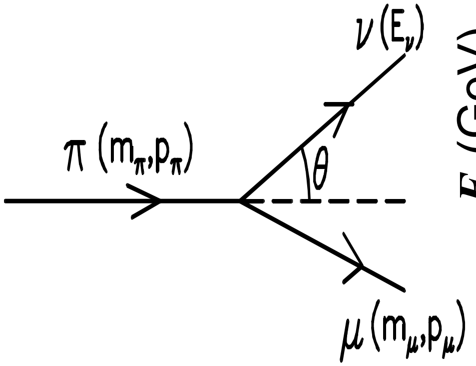
Running experiments:

- Japan (JPARC) T2K: off-axis→SK/HK
- USA (FNAL) NOVA: off-axis NuMI to new Detector

The Off-axis concept

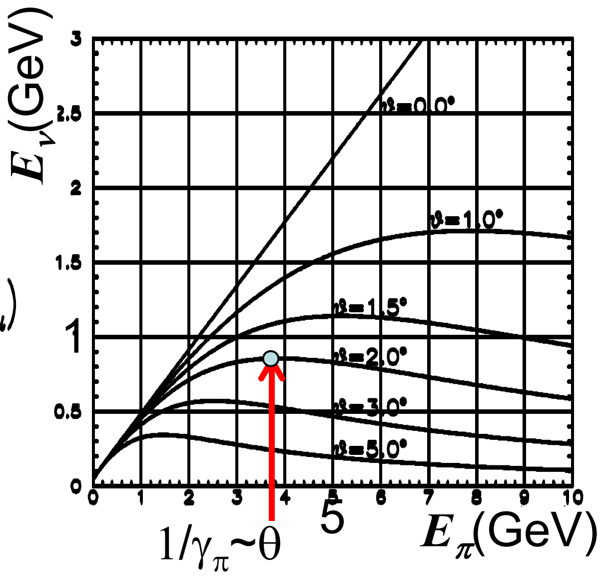


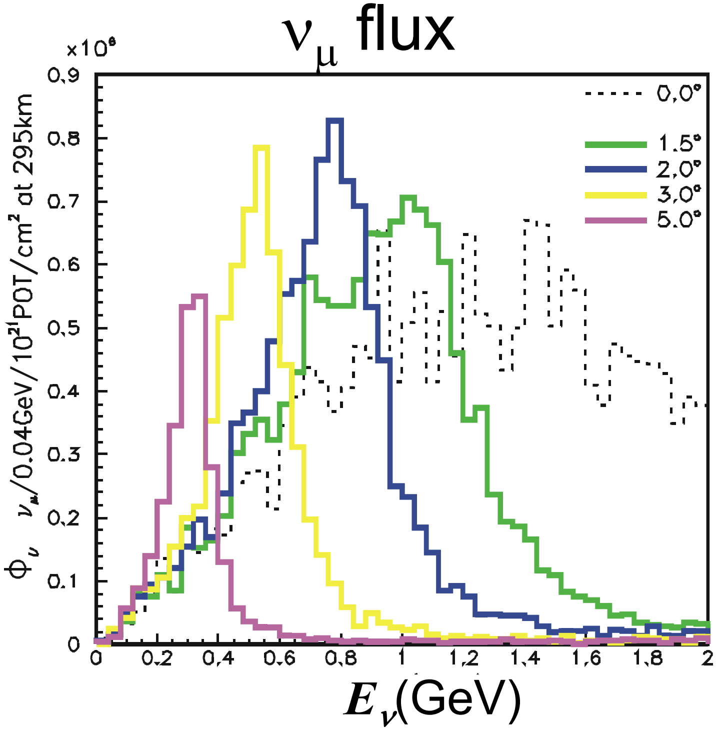
Decay Kinematics



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

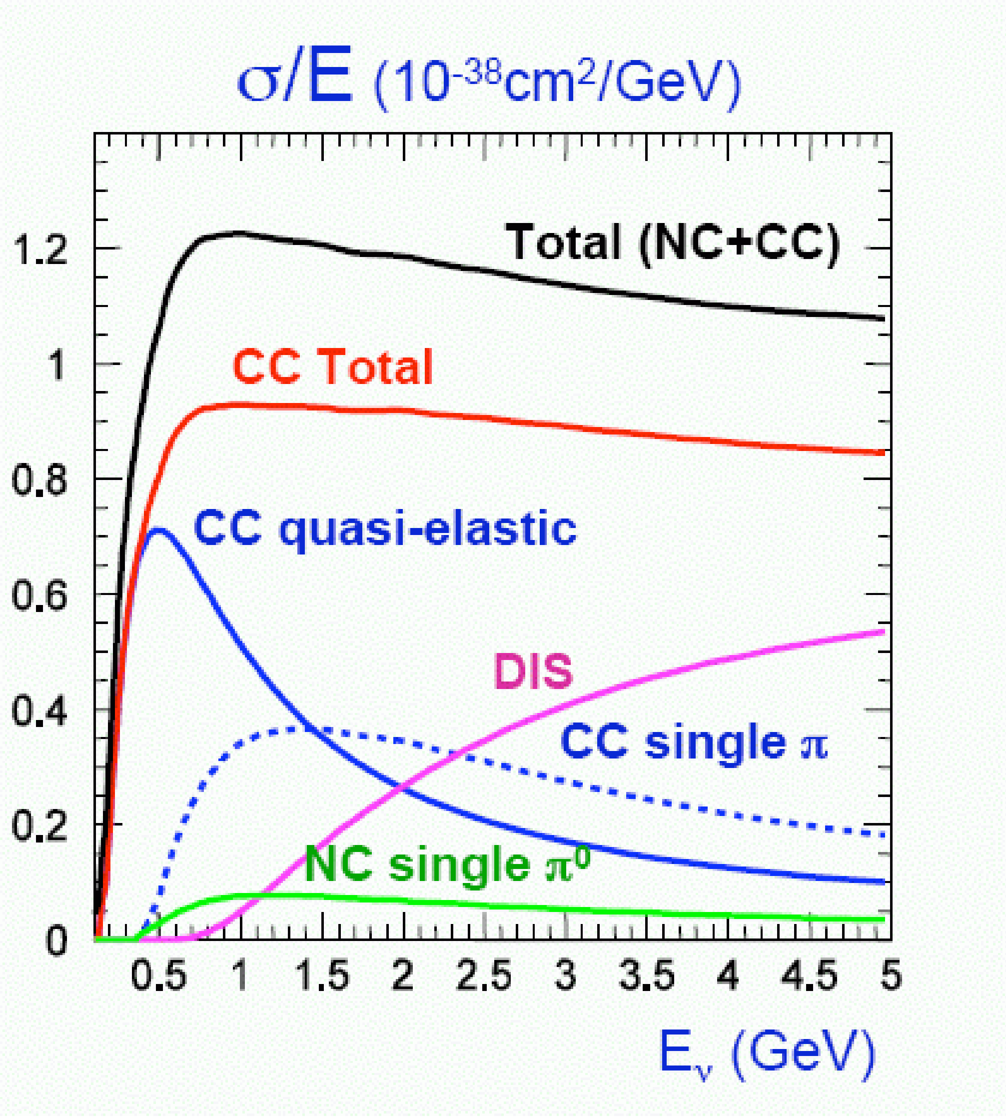
$$E_\nu^{\max}[\mathrm{GeV}] \approx \frac{30}{\theta[\mathrm{mrad}]}$$





- ➢ Increase yield @ osc. max.
- ➢ Reduce energy spread and therefore background from HE tail

Neutrino Cross Sections



QE dominate <1GeV

Inelastic dominate >1GeV

High Energy
Background

E_ν reconstruction for QE events

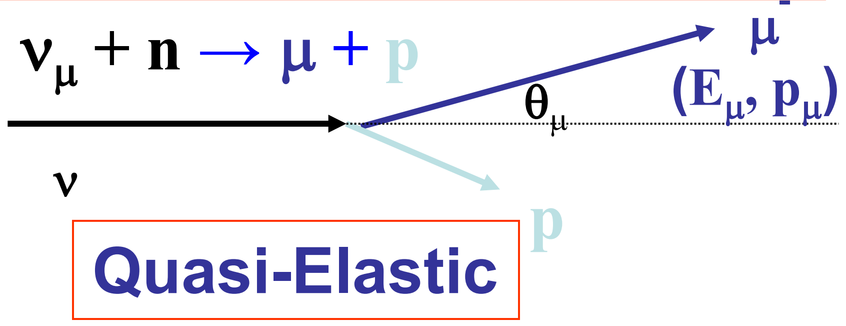
Quasi-elastic reaction
offers an additional advantage: neutrino energy reconstruction from scattering angle and energy of lepton (μ or electron)

⇔

$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

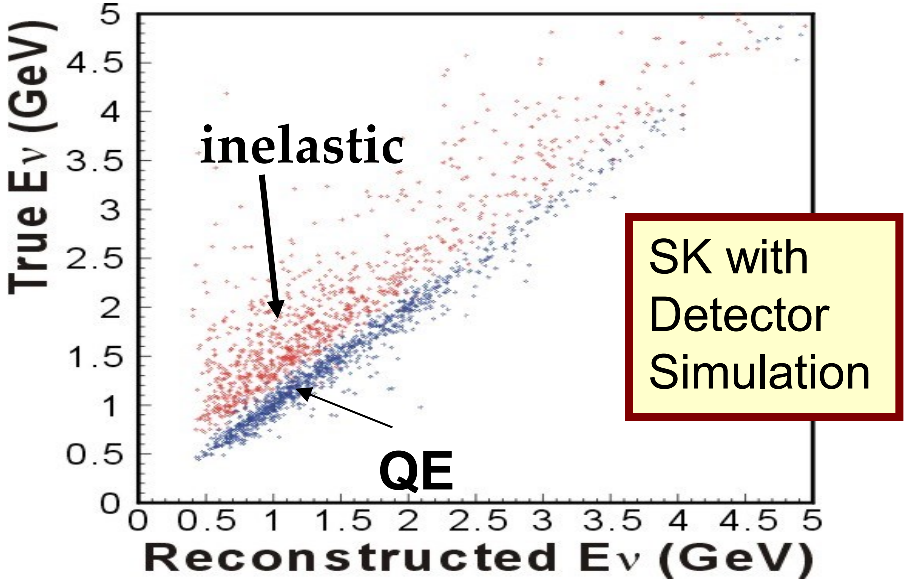
For NUCLEON at REST in LAB

$\nu_\mu + n \rightarrow \mu + p$

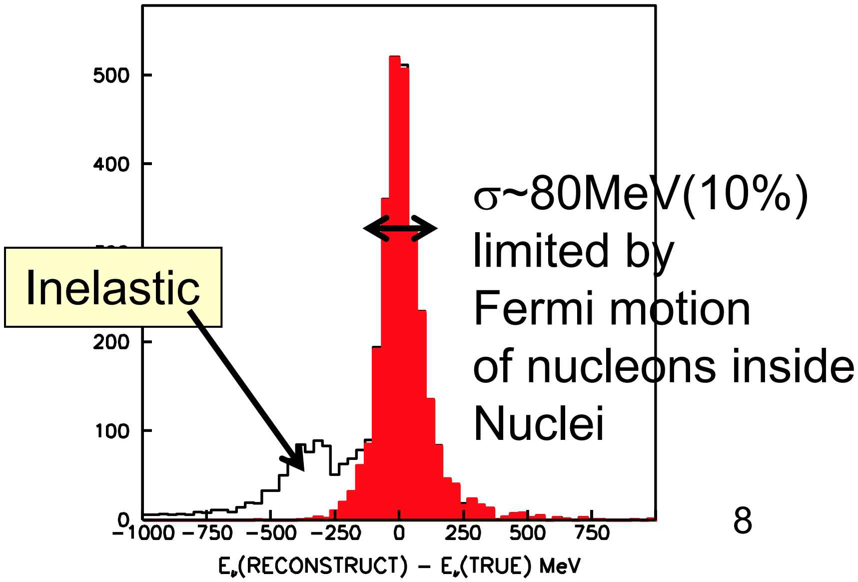


Quasi-Elastic

For resonance and Inelastic production when produced hadrons NOT detected, Reconstructed energy Is lower.



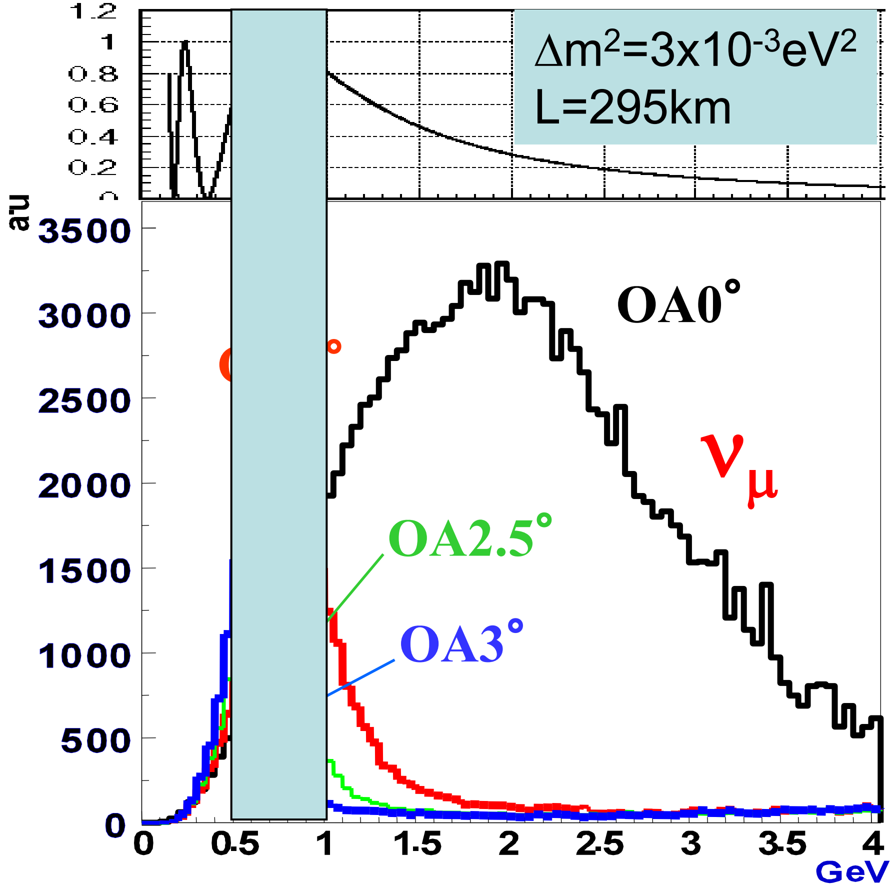
SK with Detector Simulation



σ~80MeV(10%) limited by Fermi motion of nucleons inside Nuclei

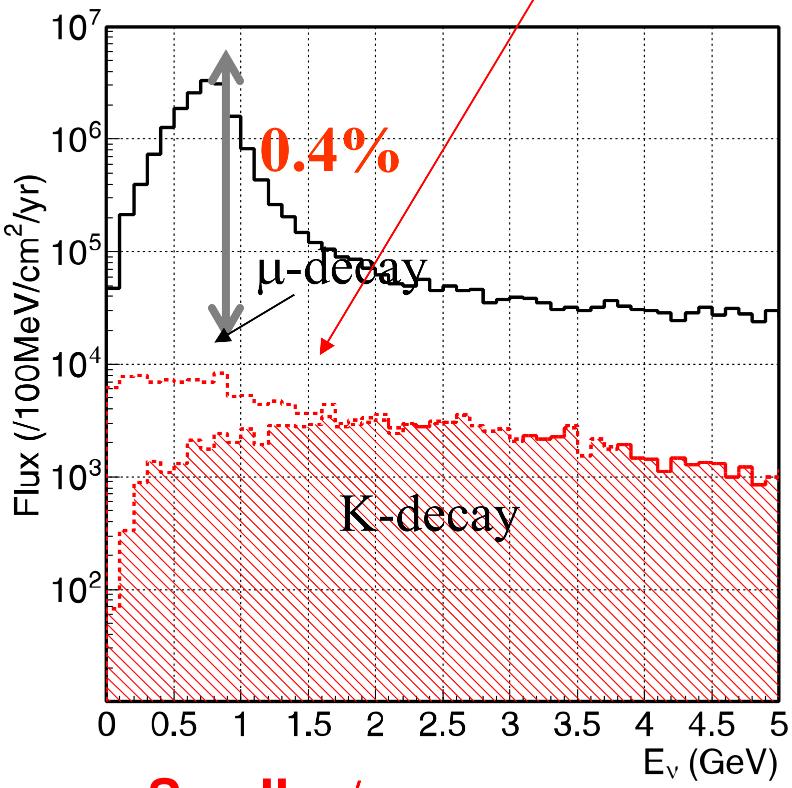
Expected flux spectra for T2K

Osc. Prob. ~ $\sin^2(1.27\Delta m^2 L/E_\nu)$



Number of events at SK for OA 2.5º
~2200 tot int/22.5kt/yr
~1600 CC int/22.5kt/yr

ν_e contamination



Small ν_e/ν_μ
0.4% @ ν_μ peak
for OA 2.5°

Key for ν_e appearance experiment

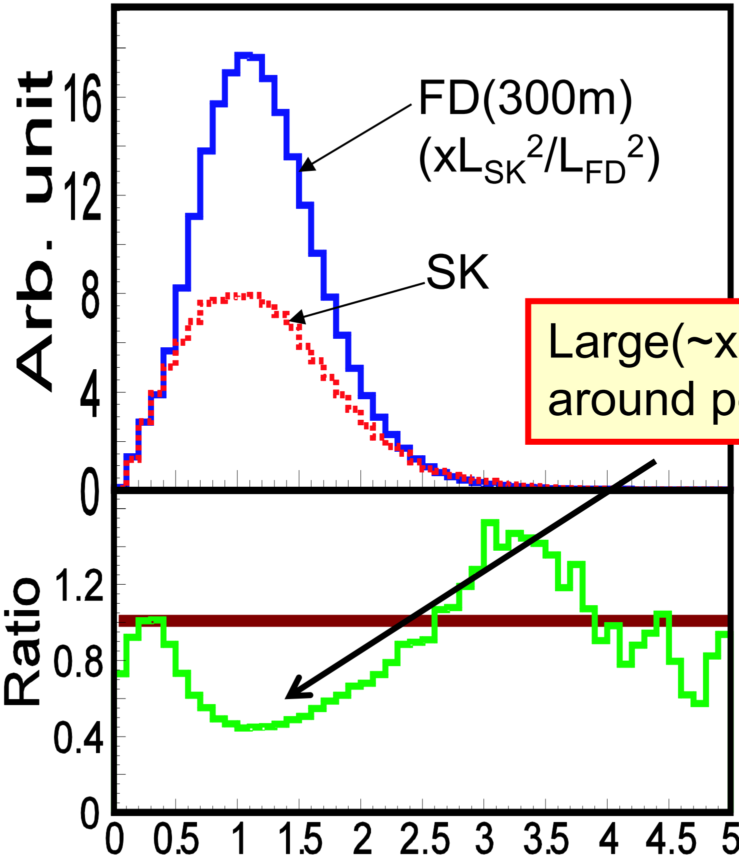
$$N_{near,\mu}(E) = \Phi_{near,\mu}\sigma_{\mu}(E)\varepsilon_{\mu}(E)$$

$$N_{far,e}(E) = \Phi_{far,\mu}\sigma_{e}(E)\varepsilon_{e}(E)P_{(\mu\to e)}(E) + N_{Background}$$

- High statistics – high flux @oscillation maximum
- Small beam background contamination
  - intrinsic ν_e → short decay pipe,…
  - low E_ν → less inelastic
  - off-axis → less high energy tail → less inelastic
- Good experimental background rejection
  - Particle ID (e/π_0)
  - narrow spectrum beam offers an additional kinematical constraint (compare expected with reconstructed neutrino energy)
- Small systematic error on background
  - near/far spectrum differences should be SMALL to extrapolate background measurement from near to far detector
  - Significant efforts by all long-baseline experiments on a program of understanding the flux and the cross-section

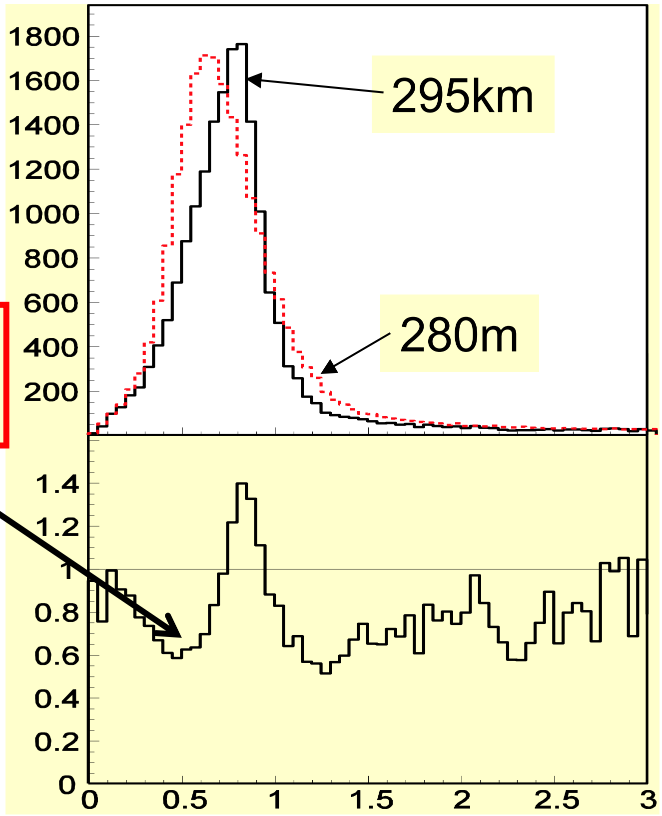
Far/near detector spectrum difference

K2K case



Large(~x2) effect around peak!!

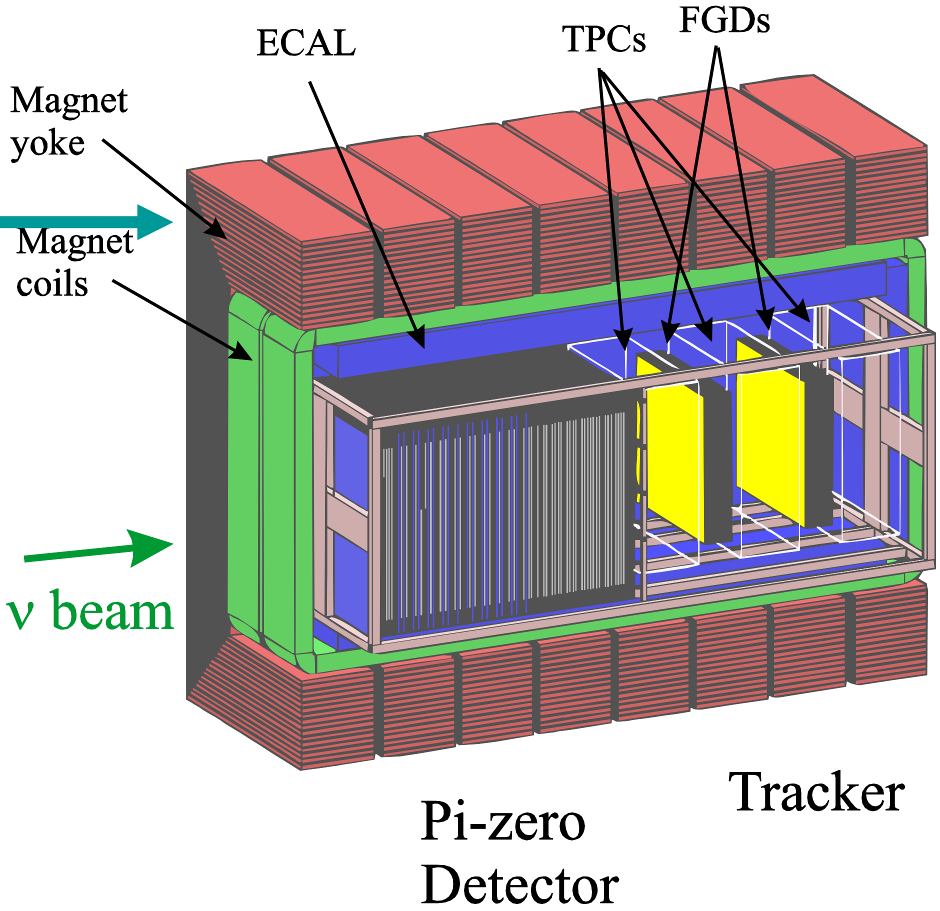
Typical OA beam

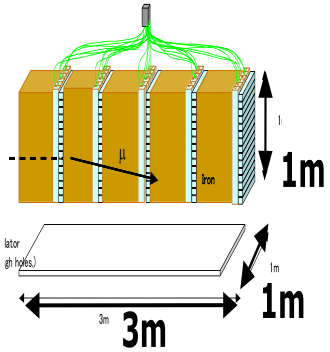


300 m too near, ν source is not seen as point-like $\Rightarrow$ flux does not scale with $1/L^2$
Small far/near spectrum difference important
both for ν_e appearance (error on background)
And for ν_μ disappearance (error on signal)

T2K near detectors at 280 m

Off-axis Detector @ 280m
- Built inside UA1/NOMAD magnet (CERN donation to T2K)
- Precision beam spectrum and composition measurement.



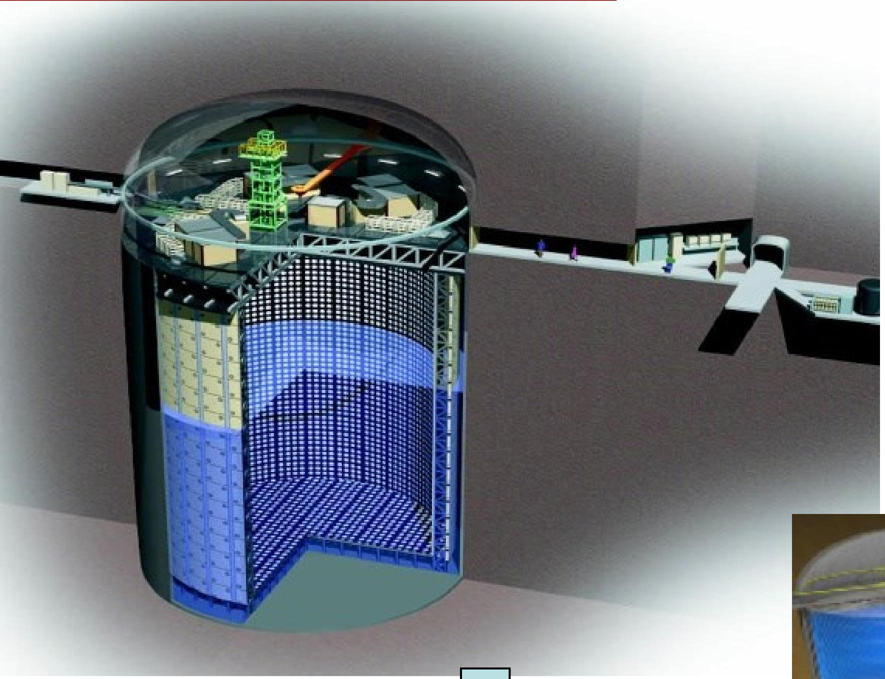


INGRID – the on-axis Detector @ 280m
- Determine beam direction and profile.

Slide from M.Zito ES07

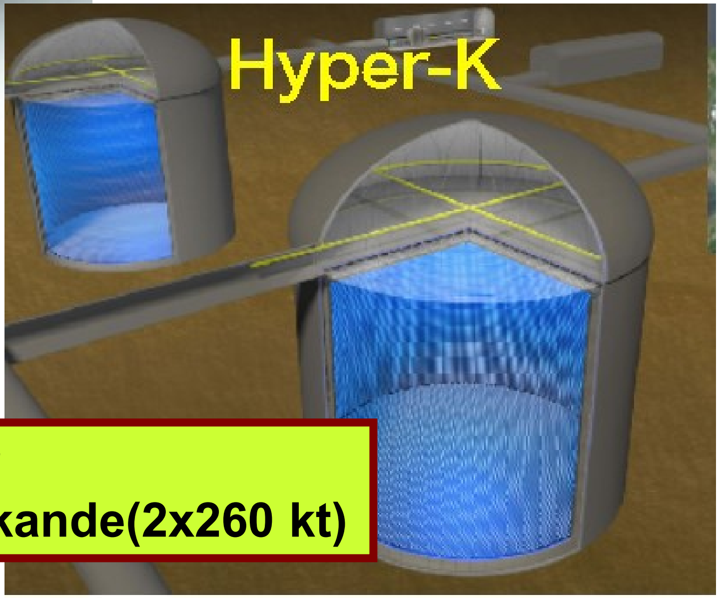
T2K far detector

Since 2010->2026?
Super-Kamiokande(50kt)



- 420 kW (today)
- ~1MW (2020)
- 1.3 MW (2025)

Nakaya, CERN, 10/11/2016

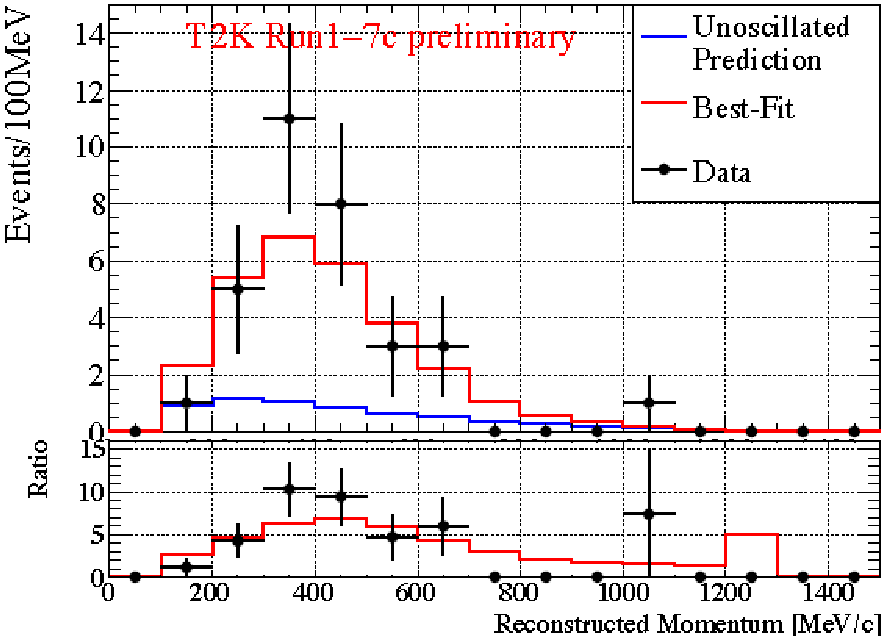


From 2026->?
Hyper-Kamiokande(2x260 kt)

T2K results : ν_e and $\overline{\nu}_e$ appearance

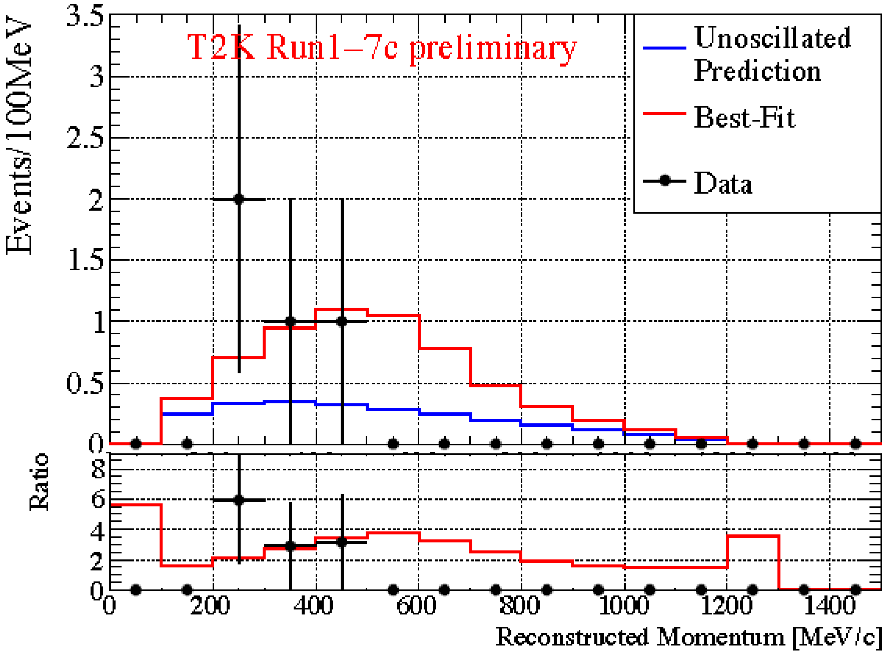
Full Joint Fit Analysis

ν_e



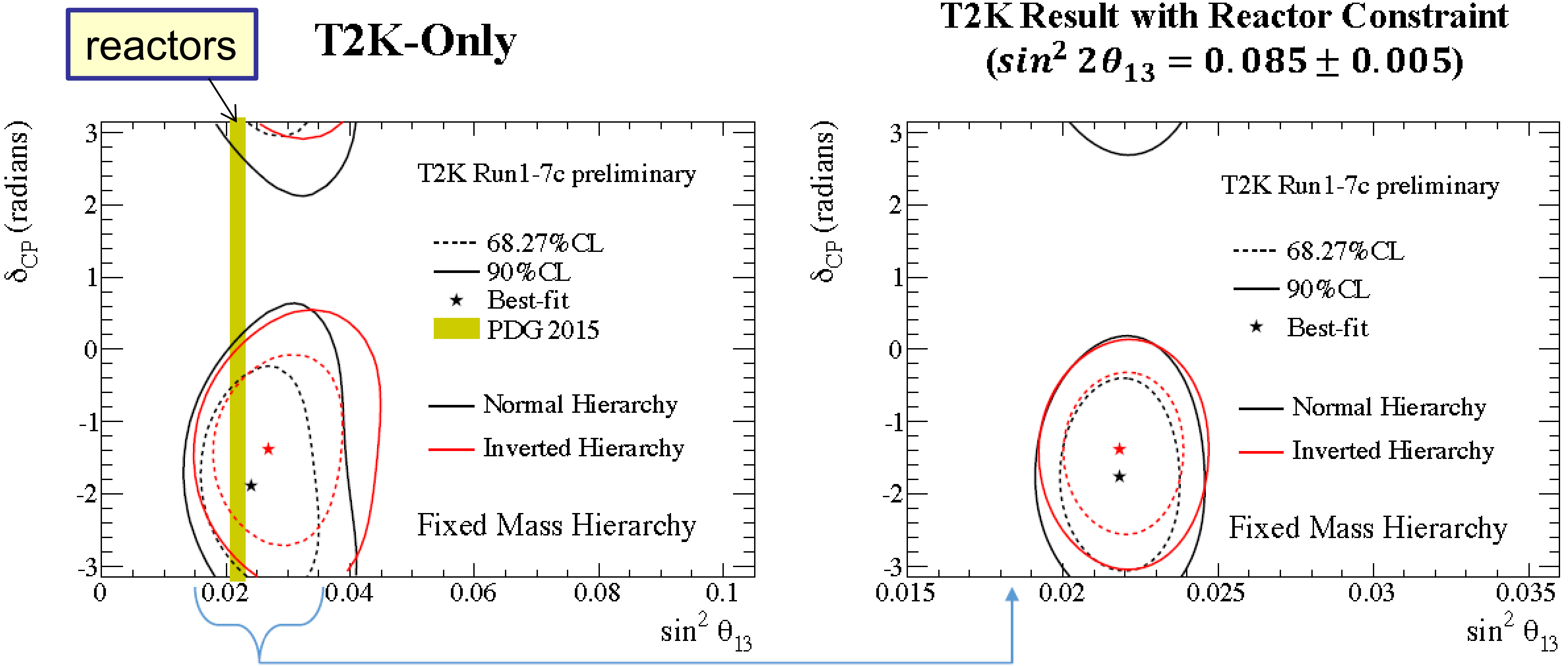
32 events observed

$\overline{\nu}_e$



4 events observed

θ_{13} and δ_{CP}



reactors

T2K-Only

T2K Result with Reactor Constraint
$(sin^2 2\theta_{13} = 0.085 \pm 0.005)$

- T2K-only result consistent with the reactor measurement
- Favors the $\delta_{cp} \sim -\frac{\pi}{2}$ region

NOνA: NuMI Off-axis ν_e Appearance

High power NuMI beam

- 700 kW expected 2016

Low-Z tracking calorimeters (liquid scintillator in PVC cells)

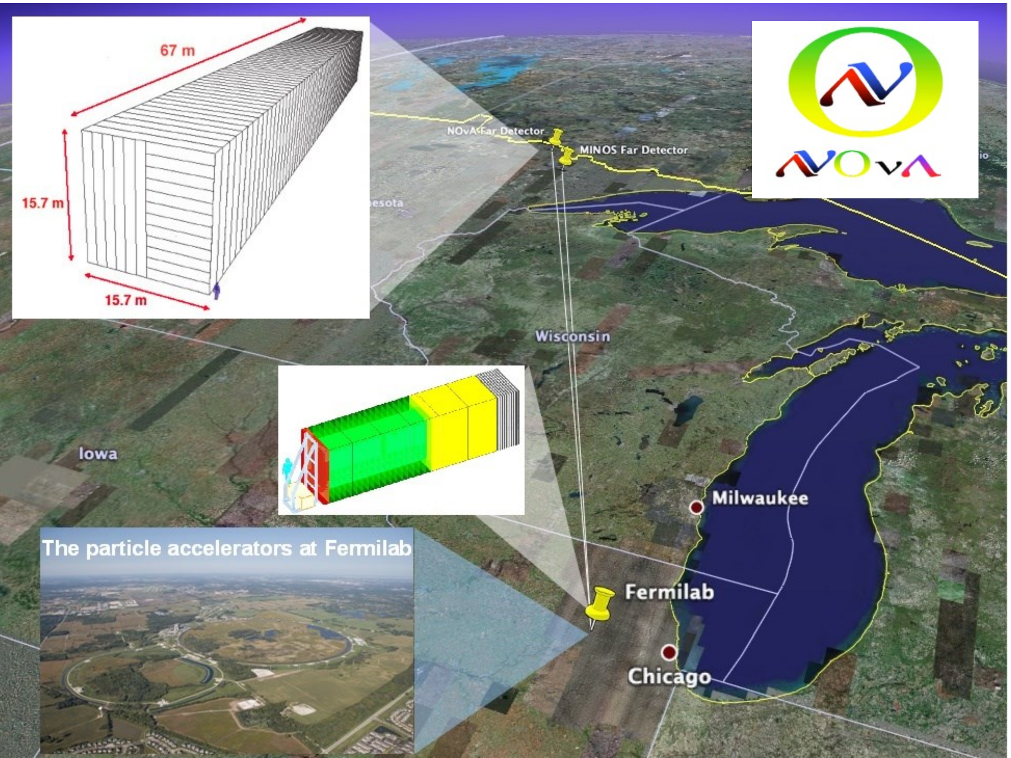
- 14kt far detector (surface), 300t near detector

810 km baseline

- Fermilab to Ash River, Minnesota

Data taking with complete detectors

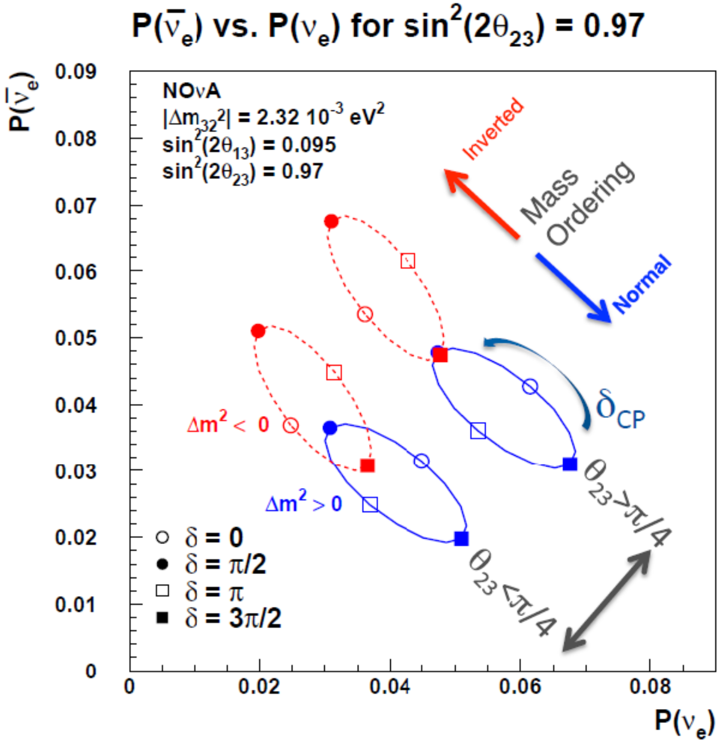
- started in November 2014



Mass hierarchy:

Matter (MSW) effect due to presence of electrons in matter

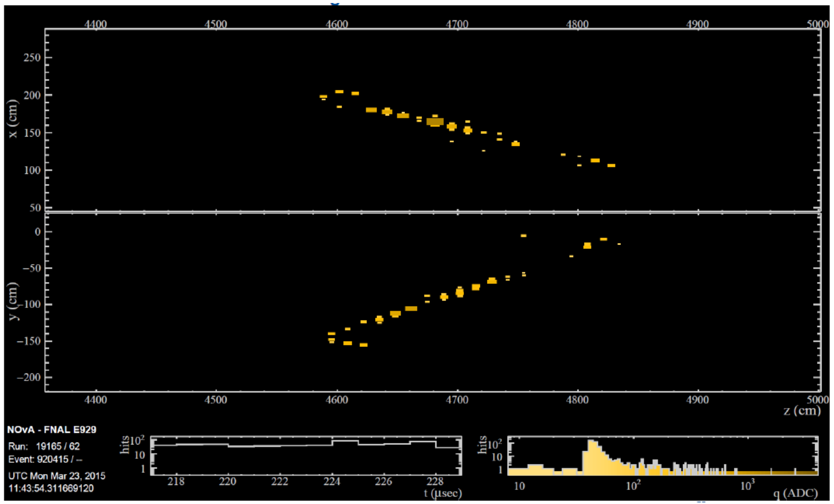
- ~30% effect for NOνA (11% for T2K)



For some values of δ, the mass hierarchy can be measured to ~3σ by NOνA alone

NOνA: preliminary results

Far detector ν_e CC candidate

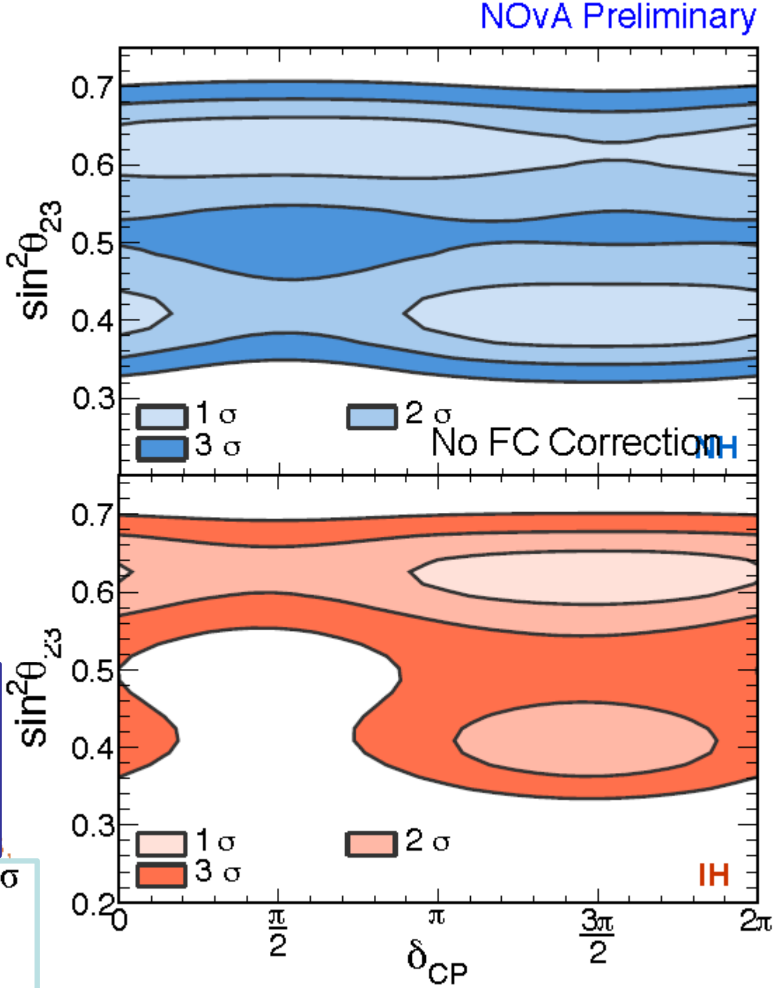


New results (Hartnell, CERN seminar, 15/11/2016)

- 33 ν_e candidates (8.2+/-0.8 background)
- >8σ for ν_e appearance
- Tendency to prefer normal mass hierarchy

Fit for hierarchy, $\boldsymbol{\delta}_{\mathrm{CP}}$, $\sin^2\theta_{23}$

- Constrain Δm^2 and $\sin^2\theta_{23}$ with NOvA disappearance results



Global best fit Normal Hierarchy

$$\delta_{CP} = 1.49\pi$$

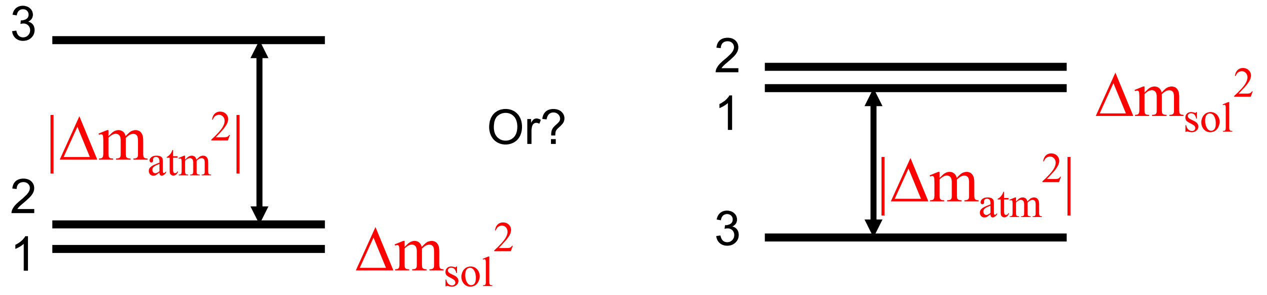
$$\sin^2(\theta_{23}) = 0.40$$

- both octants & hierarchies allowed at 1σ
- 3σ exclusion in IH, lower octant around $\boldsymbol{\delta}_{\mathrm{CP}}=\pi/2$

Antineutrino data will help resolve degeneracies (planned for spring 2017)

Neutrino mixing: Current open questions

- Is $\delta>0$? i.e., Is there **CP violation** in the lepton sector? Contributions to Baryogenesis via Leptogenesis?
- What is the **mass hierarchy**, i.e., sign of Δm^2_{23}?



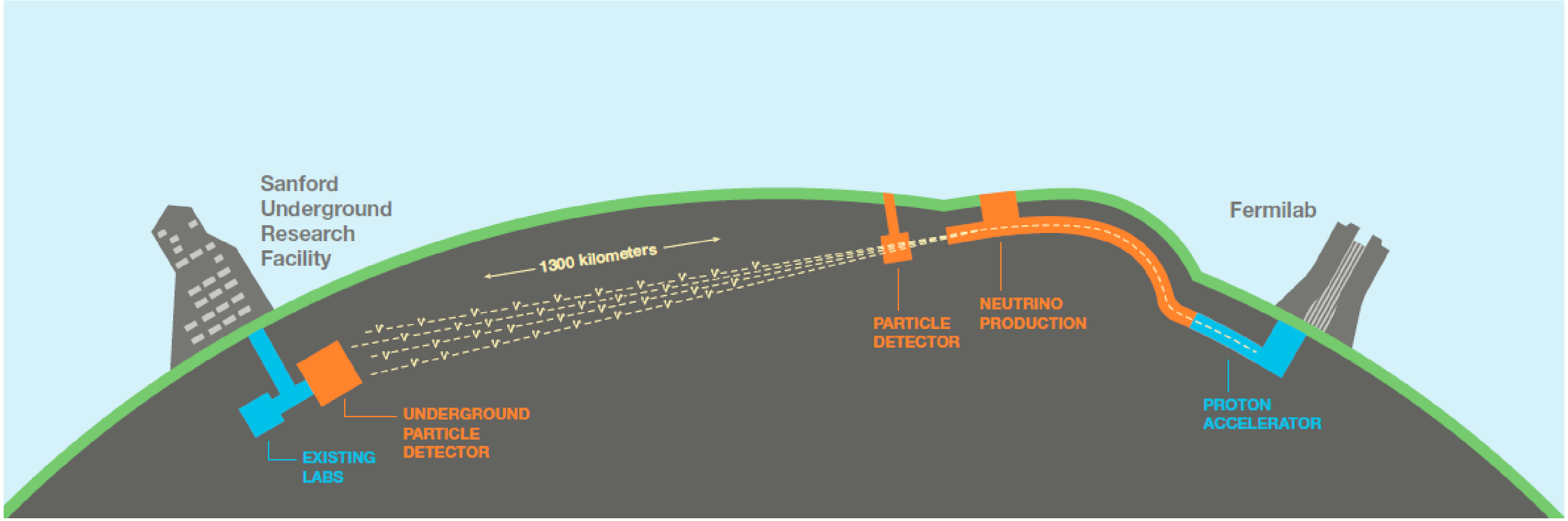
- Is $\sin^2 2\theta_{23}=1$? If not, what is the **octant** == sign $(\theta_{23}-45°)$?

- Is 3-flavor mixing the correct framework or do we need in addition sterile neutrinos, or CPT violation, or other exotic phenomena (unstable neutrinos, extra-dimensions..)?

Future neutrino experimental program seeks to answer these questions.
3rd generation LBL at accelerator: Hyper-K, Dune

Future conventional beam (2026?) DUNE = Deep Underground Neutrino Experiment

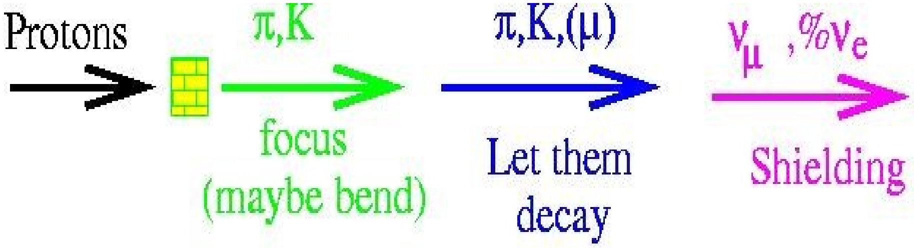
- Large (4x10 kt) liquid argon TPCs in the Homestake Mine + new, intense neutrino beam from Fermilab
  - Longer baseline (1300Km), more intense (MW proton source), tunable energy



- Primary goal: precision measurement of neutrino oscillation parameters
  - 3σ sensitivity to δ_{CP} for 75% of the possible values of δ_{CP} after 850-1300 kt-MW-years
  - 5σ sensitivity neutrino mass hierarchy for all possible values of δ_{CP} after 400 kt-MW-years

Conventional vs Nu Factory Beam

Conventional beams: neutrinos mostly from pion decays



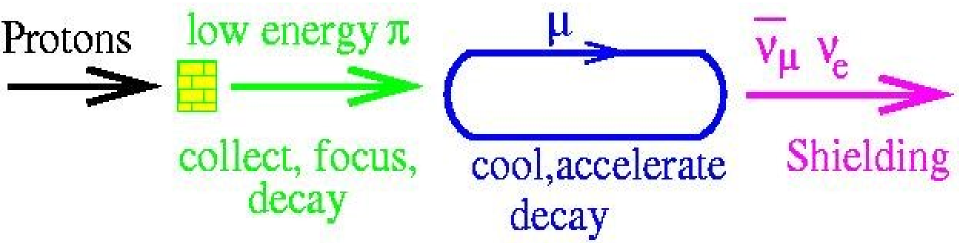
- Beam:

  mostly ν_μ, few % ν_e , $\bar{\nu}_{e,}$ $\bar{\nu}_\mu$

  or

  mostly $\bar{\nu}_\mu$, some % ν_e , $\bar{\nu}_{e,}$ ν_μ

Neutrino factory beam: neutrinos from muon decays



–$\mu^+ \rightarrow e^+ \nu_{e,} \bar{\nu}_\mu$: 50% $\bar{\nu}_\mu$ and 50% ν_e

Or

–$\mu^- \rightarrow e^- \bar{\nu}_{e,} \nu_\mu$: 50% ν_μ and 50% $\bar{\nu}_e$

τ_μ = 100 x τ_π so a muon storage ring is needed
With long straight sections

Conventional vs NuFactory: appearance and disappearance

Conventional beams: neutrinos mostly from pion decays

- Beam: mostly ν_μ, few % ν_e , anti-$\nu_{e,}$ ν_μ
- Disappearance: ν_μ (count μ)
- Appearance: look for $\nu_\mu \rightarrow \nu_e$ (and $\nu_\mu \rightarrow \nu_\tau$) above background

Sensitivity ultimately limited by intrinsic beam contamination

Cannot measure oscillation probability much below % for $\nu_\mu \rightarrow \nu_e$

Neutrino factory beam: neutrinos from muon decays

- μ^+ Beam: 50% $\overline{\nu}_\mu$ and 50% ν_ε
- Disappearance: $\overline{\nu_\mu}$ (measure μ^+)
- Appearance: $\nu_e \rightarrow \nu_\mu$ (measure μ^-)

$\mu^+ \rightarrow e^+ \nu_{e,} \overline{\nu}_\mu$ (detect μ^+

$\Downarrow$ *oscillation*

ν_μ (detect μ^-

Essentially no beam related background.

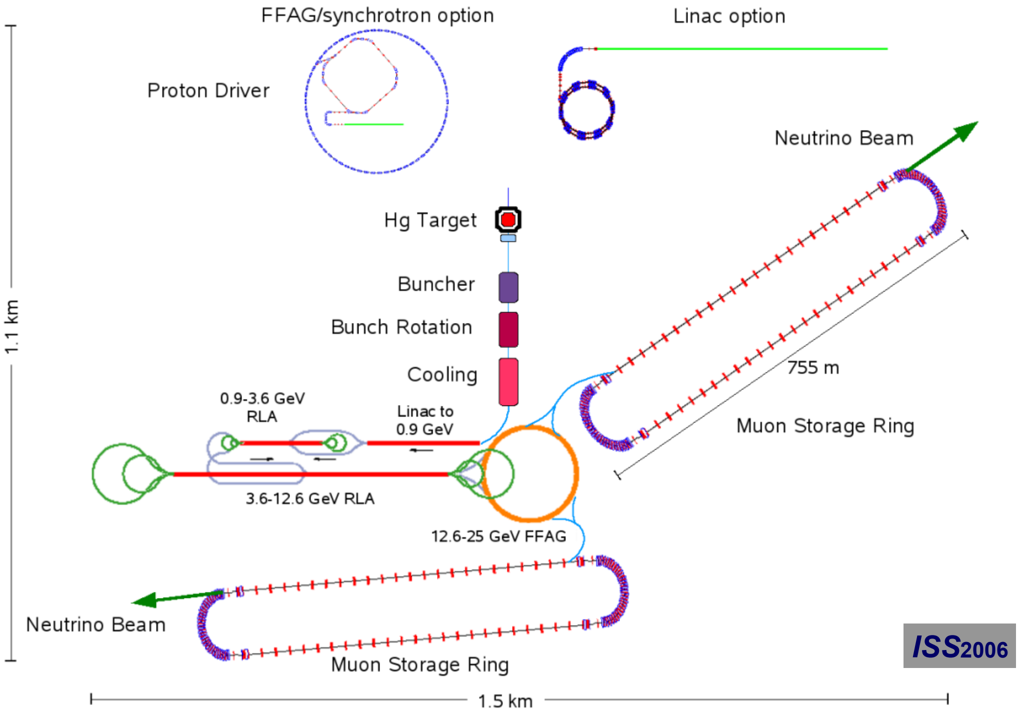
Can measure oscillation probabilities as small as 10^{-5} (Sensitivity Superbeam x100!)

Wrong-sign” muon identifies oscillation appearance ⇒Needs a magnetic detector!

Background by muon misid, wrong-sign assignment. But much easier to identify μ than electrons.

The basic concept of a neutrino factory ((ISS 2006)

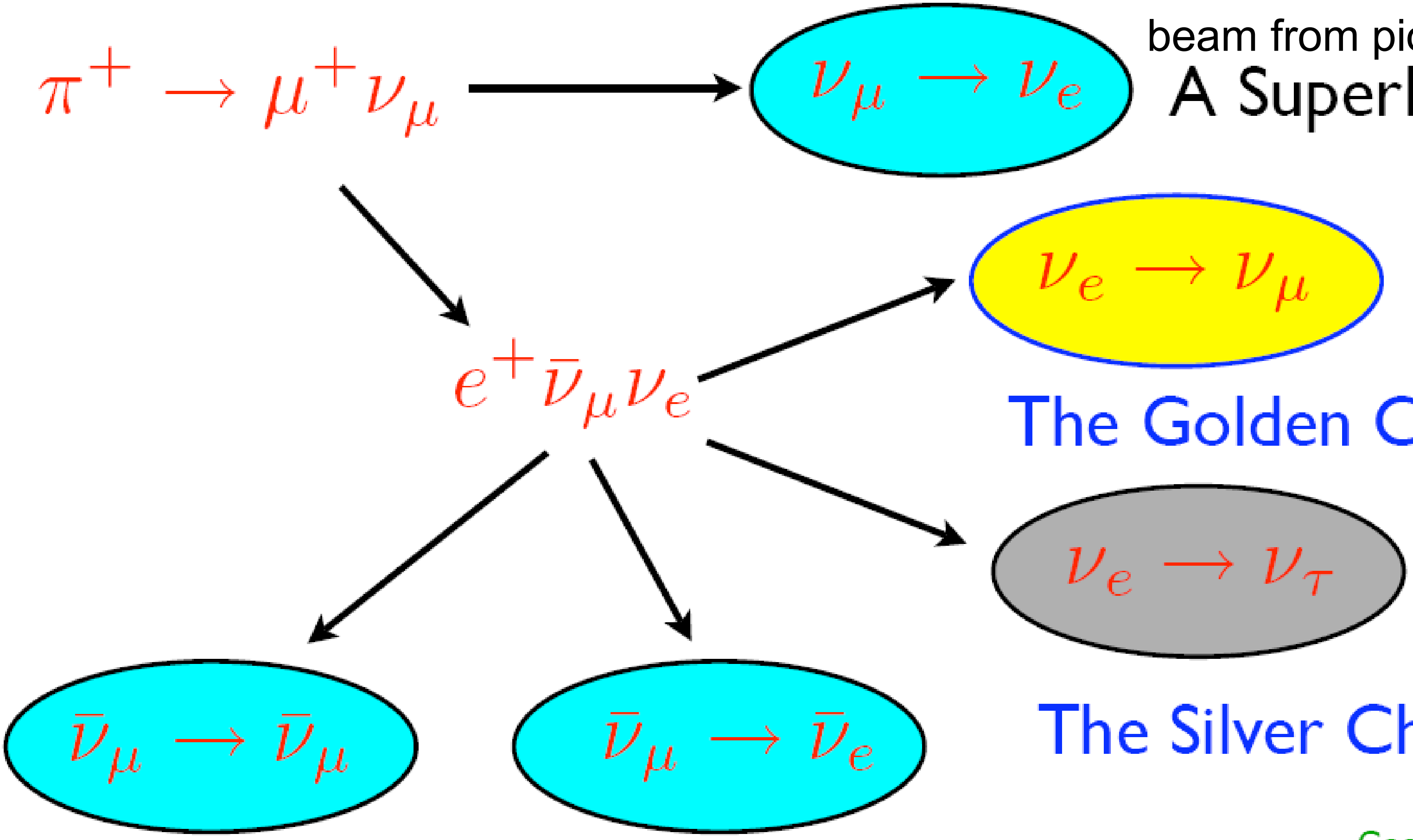
- High power (4 MW) proton beam onto a liquid mercury target.
- System for collection of the produced pions and their decay products, the muons.
- Energy spread and transverse emittance have to be reduced: “phase rotation” and ionization cooling
- Acceleration of the muon beam with a LINAC and Recirculating Linear Accelerators.
- Muons are injected into a storage ring (decay ring), where they decay in long straight sections in order to deliver the desired neutrino beams.
- **GOAL: $\geq 10^{20}$ μ decays per straight section per year**



Current baseline scenario for large θ_{13}:
- 10 GeV muons
- Far detector at 2000 Km
- Single muon storage ring

Note: nufactory is a compact complex of accelerators
In the words of Fermilab Director:
“It can fit inside the Tevatron ring”…

The Neutrino Factory



$\pi^+ \rightarrow \mu^+ \nu_\mu$

$\nu_\mu \rightarrow \nu_e$

For “free” a conventional beam from pion decay

A SuperBeam

$e^+ \bar{\nu}_\mu \nu_e$

$\nu_e \rightarrow \nu_\mu$

The Golden Channel

$\nu_e \rightarrow \nu_\tau$

The Silver Channel

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

ν_μ disappearance

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

The Platinum Channel

Geer ‘97
De Rujula, Gavela and Hernandez ‘98

What are we waiting for?

Just to mention a couple of challenges for a nuFactory :

INTENSE PROTON SOURCE

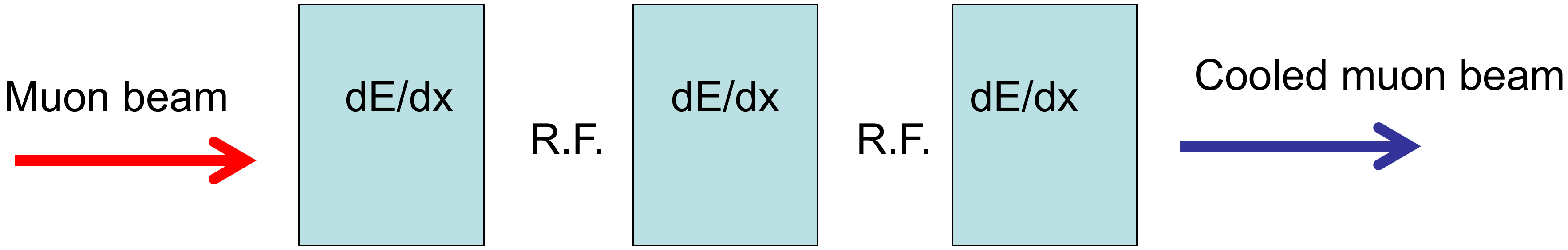
- Power density in the proton target –

target becomes thermally and radioactively hot + mechanical shock can break easily a standard solid target. Solutions considered:

  - liquid metal jets; rapidly rotating solid target; powder target

CAPTURE and FOCALIZE muons before decay

- squeeze muon transverse phase space by Muon Cooling
  (MICE exp at RAL to demonstrate the concept)



Muon beam

dE/dx

R.F.

dE/dx

R.F.

dE/dx

Cooled muon beam

Layers of suitable absorber
(muons looses both transverse and longitudinal momentum by dE/dx)
and radio-frequencies cavities (to recover the longitudinal momentum)

BETA BEAMS

NUFACTORY will produce ν_e and antinue beams using muon decays
Can we produce a ν_e and anti-ν_e beams in any other way?
A simple and genial idea [P.Zucchelli, Phys.Lett.B, 532(2002),166] :
accelerate β-decaying ions
e.g.,

$^{6}He^{++} \to {}^{6}Li^{++}\ e^{-}\ \bar{\nu}_e$ Q = 3.6 MeV $\tau_{1/2} = 0.8$ s
$^{18}Ne \to {}^{18}F\ e^{+}\ \nu_e$ Q = 3.4 MeV $\tau_{1/2} = 1.7$ s

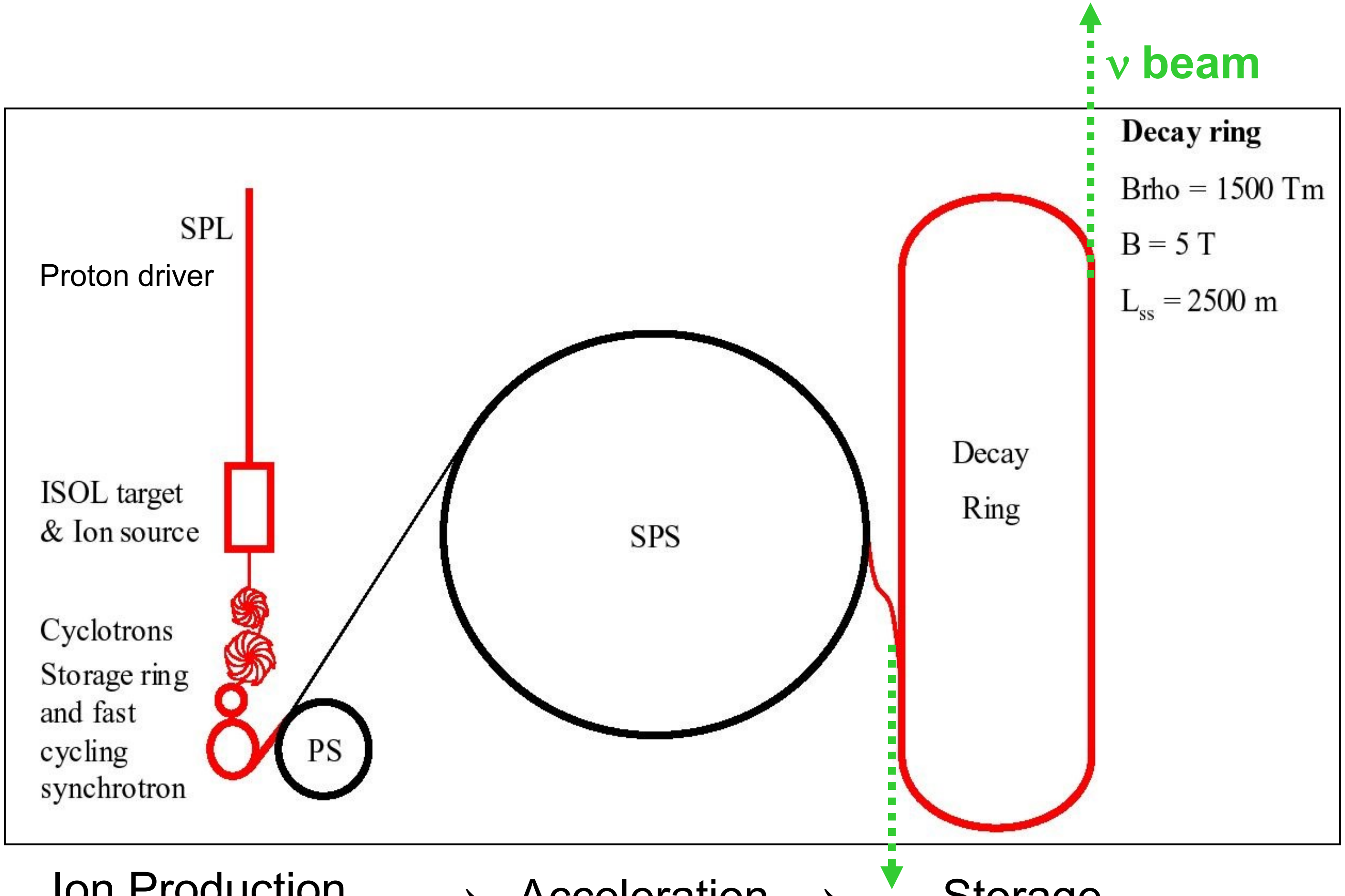
☺ strongly focussed ν beam (due to boost~100 and small Q value of β decays)
☺ very pure flavour composition (electron neutrinos or anti-neutrinos only)
No need for charge measurement.
☺ perfectly known energy spectrum
☺ Energies O(100 MeV) ⇒ detector at O(100km). No matter effects.

Combined with SuperBeam approach, can measure T, CP, CPT Violation

T $\nu_e \to \nu_\mu \ =?\ \nu_\mu \to \nu_e$ (BB vs SB)
CP $\bar{\nu}_e \to \bar{\nu}_\mu \ =?\ \nu_e \to \nu_\mu$ (BB alone)
CPT $\nu_e \to \nu_\mu \ =?\ \bar{\nu}_\mu \to \bar{\nu}_e$ (BB vs SB)

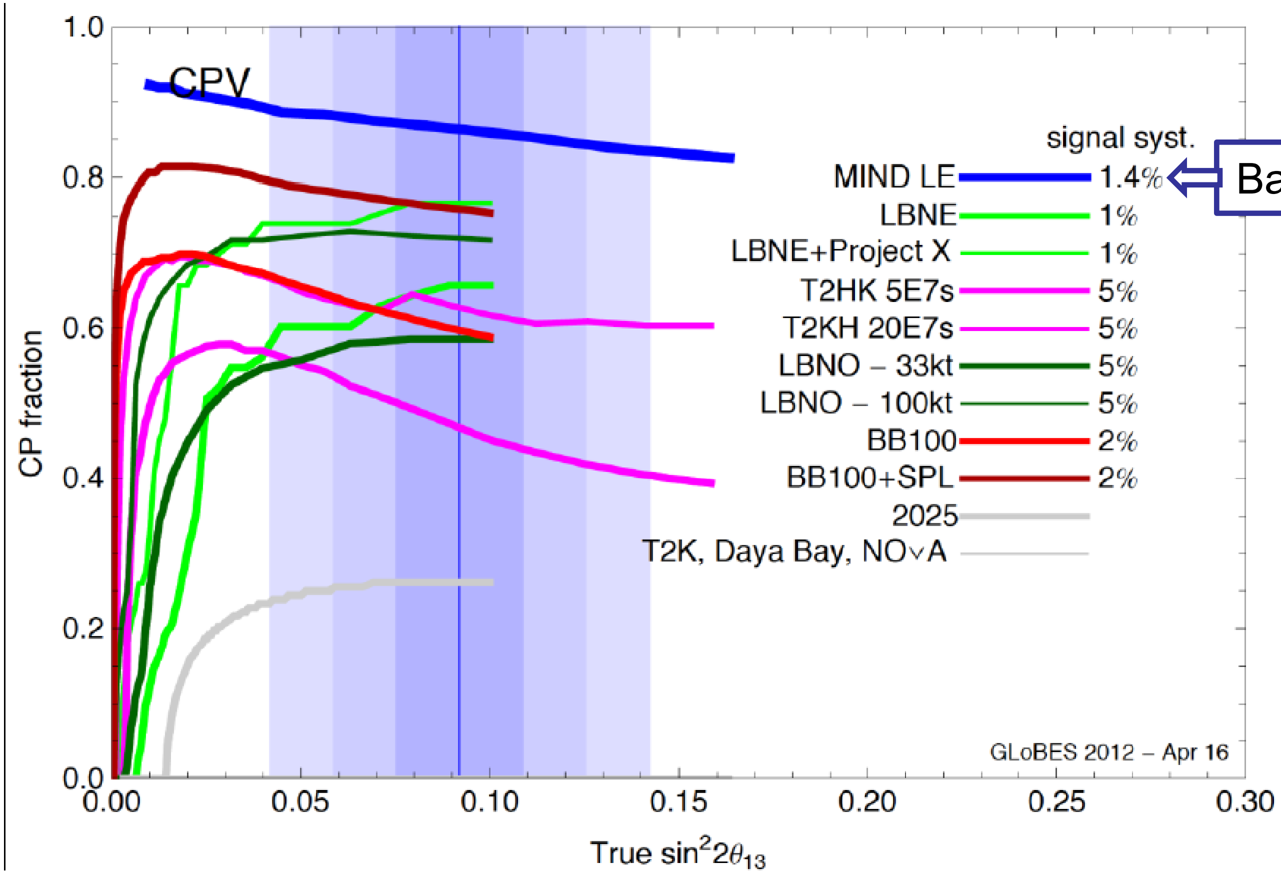
Sensitivity not far from NUFactory. Scenario studied at CERN

β-beam initial baseline scenario



Ion Production → Acceleration → Storage

World effort to formulate future direction(s)



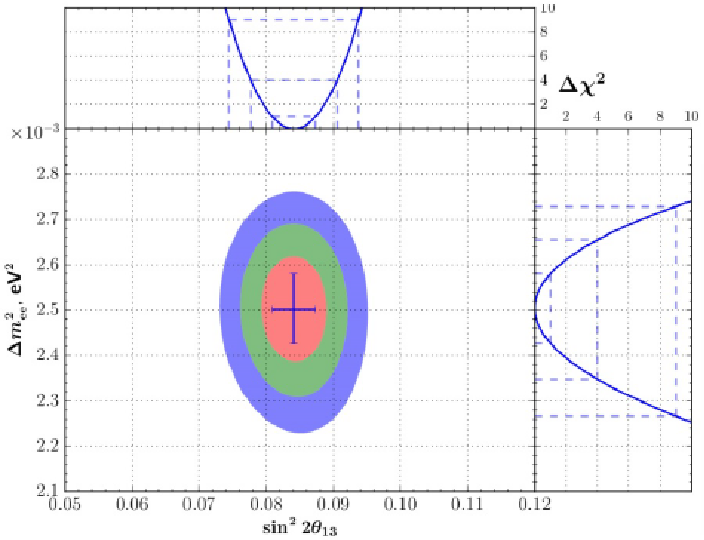
Baseline NuFactory

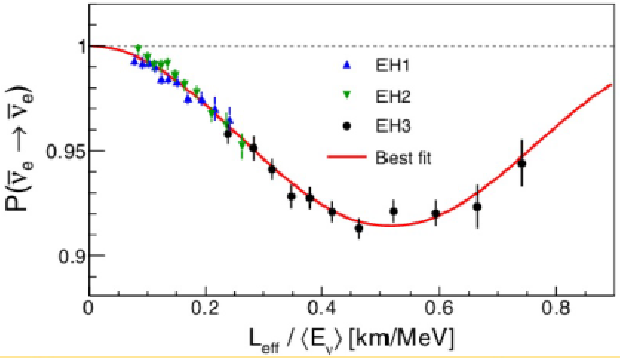
Neutrino Factory recognised to offer ultimate sensitivity and precision

ADDITIONAL MATERIAL

Daya Bay: new results: 1230 days data

θ_{13}

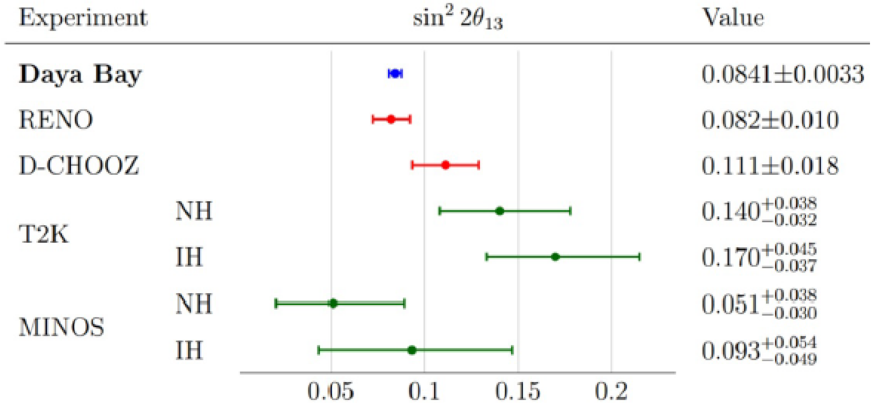




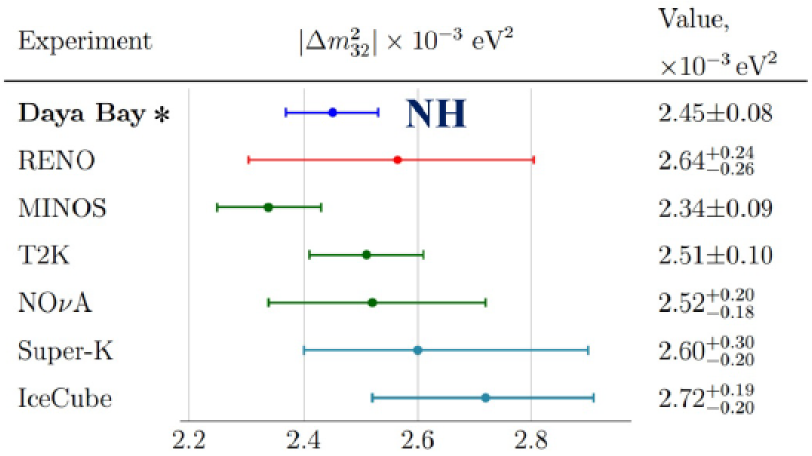
$\sin^2 2\theta_{13}$ = [8.41 ± 0.27(stat.) ± 0.19(syst.)] × 10^{-2}

$|\Delta m^2_{ee}|$ = [2.50 ± 0.06(stat.) ± 0.06(syst.)] × 10^{-3} eV^2

χ^2/NDF = 232.6/263



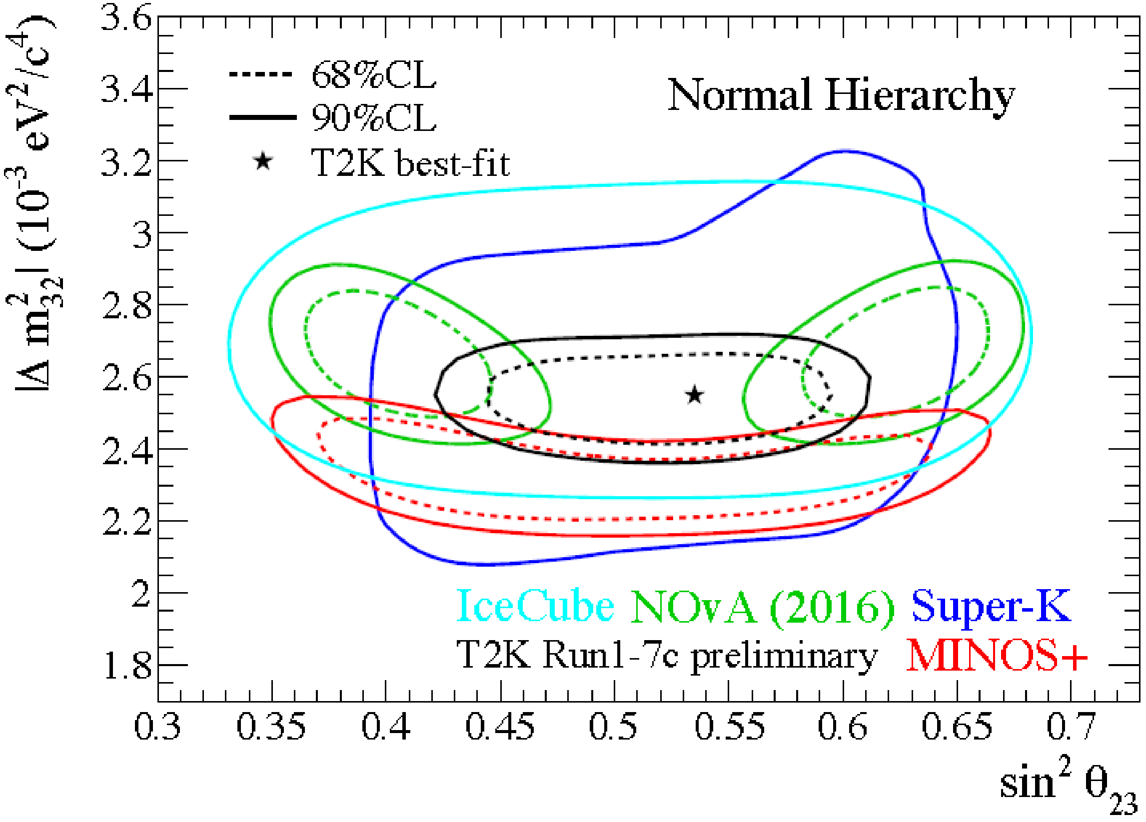
Experiment		Value
Daya Bay		0.0841 ± 0.0033
RENO		0.082 ± 0.010
D-CHOOZ		0.111 ± 0.018
T2K	NH	$0.140^{+0.038}_{-0.032}$
	IH	$0.170^{+0.045}_{-0.037}$
MINOS	NH	$0.051^{+0.038}_{-0.030}$
	IH	$0.093^{+0.054}_{-0.049}$



Experiment	Value, $\times10^{-3}$ eV^2
Daya Bay *	2.45 ± 0.08
RENO	$2.64^{+0.24}_{-0.26}$
MINOS	2.34 ± 0.09
T2K	2.51 ± 0.10
NOνA	$2.52^{+0.20}_{-0.18}$
Super-K	$2.60^{+0.30}_{-0.20}$
IceCube	$2.72^{+0.19}_{-0.20}$

θ_{23} and Δm^2_{32}

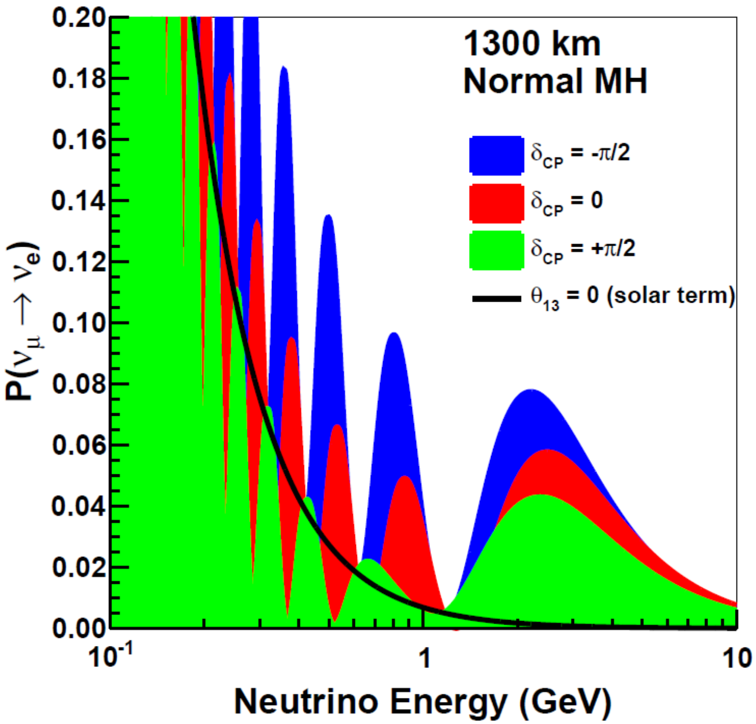
- Consistent with maximal mixing

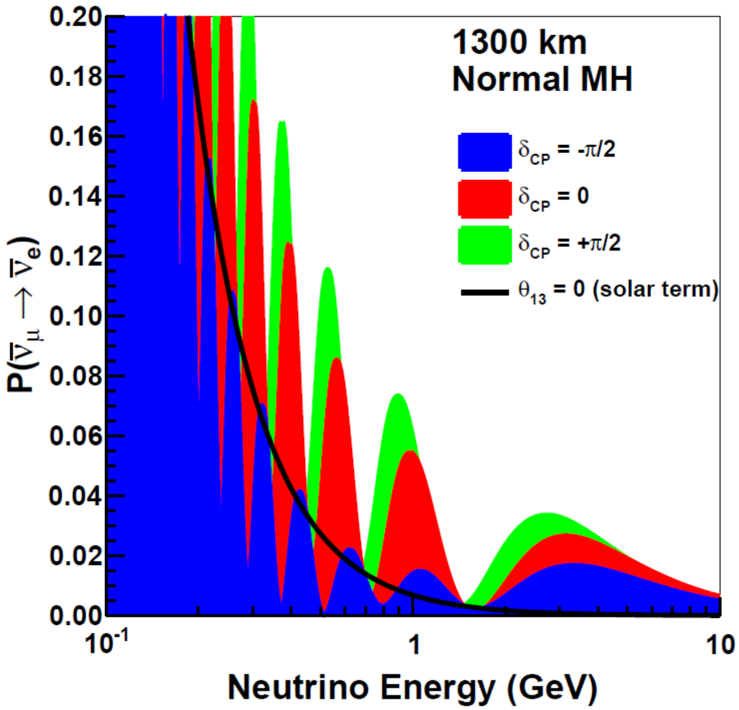


Daya Bay:
$|\Delta m^2_{ee}| = (2.45 \pm 0.08)\times 10^{-3} eV^2$
90% CL (NH)

DUNE: what is the signal?

- Measure probability of $\nu_\mu \rightarrow \nu_e$ oscillation for both neutrinos and antineutrinos
  - Compare to expectations for different δ_{CP}, mass hierarchies





Neutrino-factory to provide similar precision to CKM