Neutrino Mixing

ν Beams
T2K and NoνA

Current Expts
LBNE

Future Long Baseline Expts
T2HK

Summary

Accelerator Neutrinos in the 21st Century

DuRA Meeting, Fermilab Jan 19, 2012

Mary Bishai
Brookhaven National Laboratory

January 19, 2012

Outline

1 Neutrino Mixing

2 ν Beams

3 Current Expts
- T2K and NoνA

4 Future Long Baseline Expts
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5 Summary

Discovery of Neutrino Flavor

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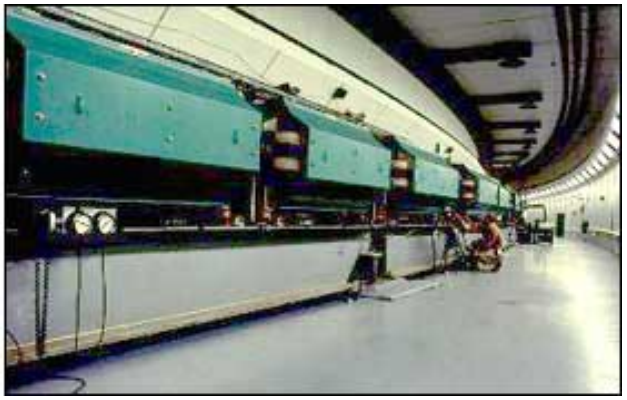
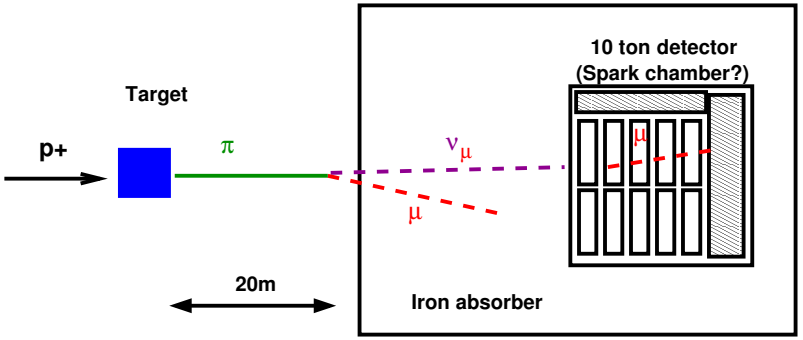
1962: Leon Lederman, Melvin Schwartz and Jack Steinberger use BNL's Alternating Gradient Synchrotron (AGS) to produce a beam of neutrinos using the decay $\pi^+ \longrightarrow \mu^+ \nu_x$



The AGS



Making ν's

Result: 40 neutrino interactions recorded in the detector, 6 of the resultant particles where identified as background and 34 identified as $\mu \Rightarrow \nu_x = \nu_\mu$

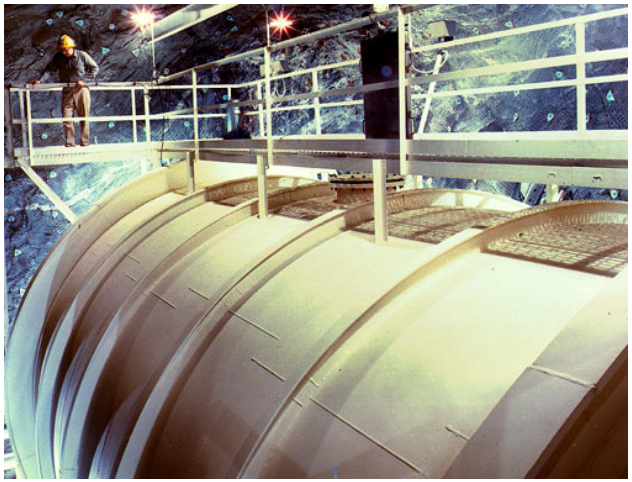
The first accelerator neutrino experiment was at the AGS.

The Homestake Experiment

1967: Ray Davis from BNL installs a large detector, containing 615 tons of tetrachloroethylene (cleaning fluid), 1.6km underground in Homestake mine, SD.

1. $\nu_e^{sun} + ^{37}\text{CL} \rightarrow e^- + ^{37}\text{Ar}$, $\tau(^{37}\text{Ar}) = 35$ days.
2. Number of Ar atoms $\approx$ number of ν_e^{sun} interactions.

Ray Davis



Results: 1969 - 1993 Measured 2.5 ± 0.2 SNU (1 SNU = 1 neutrino interaction per second for 10^{36} target atoms) while theory predicts 8 SNU. This is a ν_e^{sun} deficit of 69%.

Solar ν_e disappearance $\Rightarrow$

first experimental hint of oscillations

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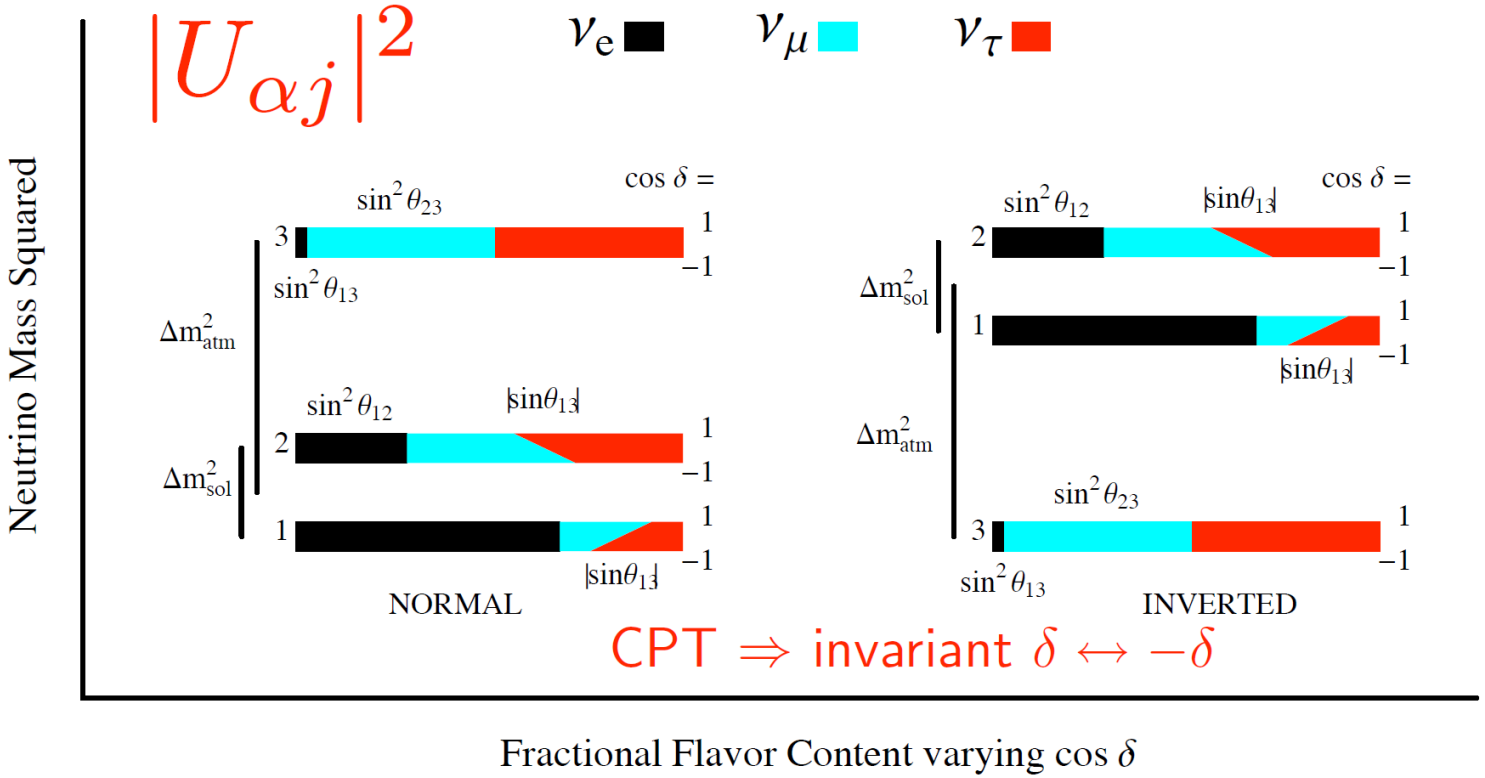

$\sin^2\theta_{13}$: Amount of ν_e in ν_3

$\tan^2\theta_{23}$: Ratio of $\frac{\nu_\mu}{\nu_\tau}$ in ν_3

$\tan^2\theta_{12}$: $\frac{\text{Amount of } \nu_e \text{ in } \nu_2}{\text{Amount of } \nu_e \text{ in } \nu_1}$

WE DONT KNOW: $\sin^2 2\theta_{13}$, δ_{cp}, $\text{sign}(\Delta m^2_{31})$

Measuring neutrino mixing - ν_e oscillations

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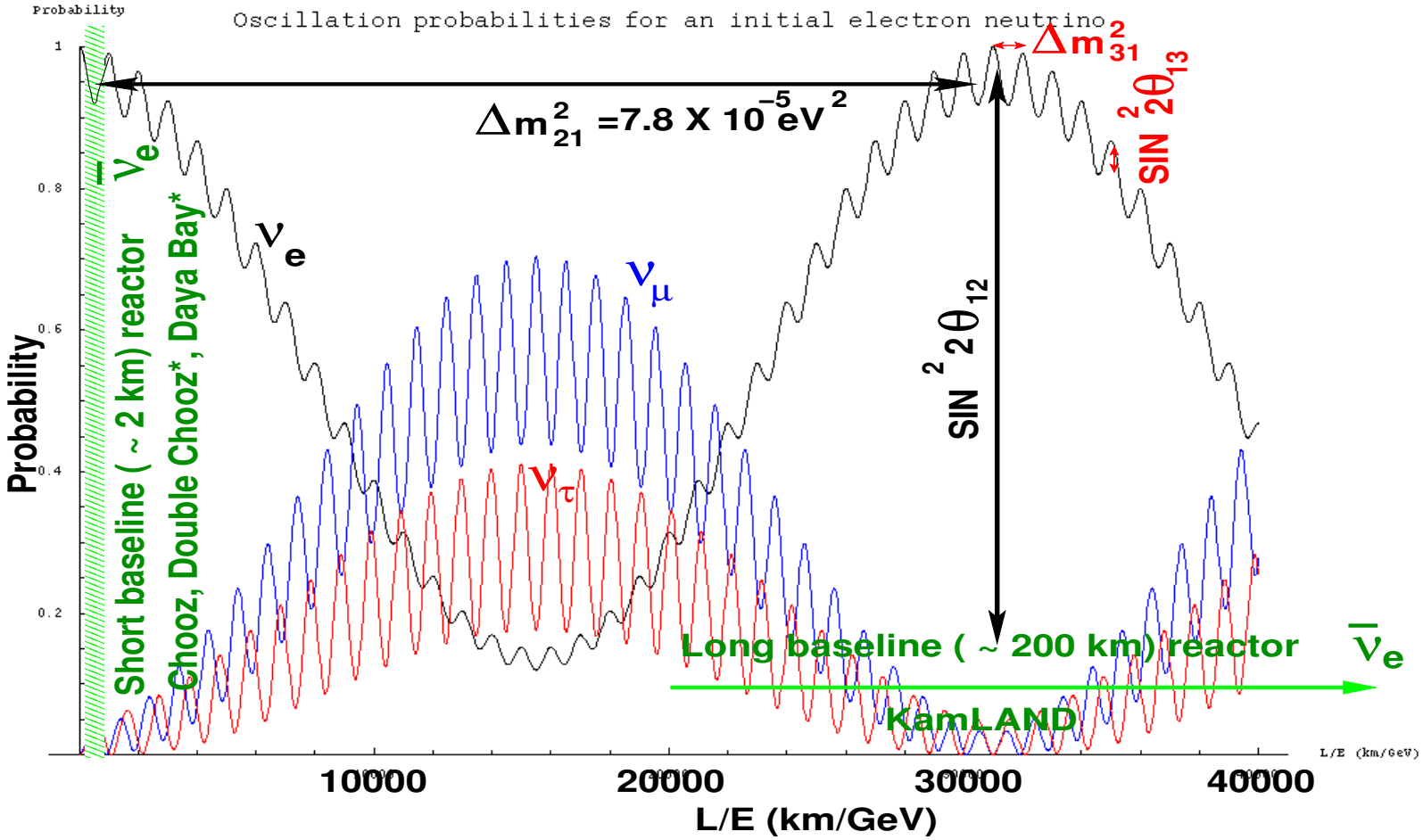
Solar ν_e disappearance constrained 1 $\longrightarrow$ 2 mixing. Precision from reactor $\bar{\nu}_e$ experiments :



Measuring neutrino mixing - ν_μ oscillations

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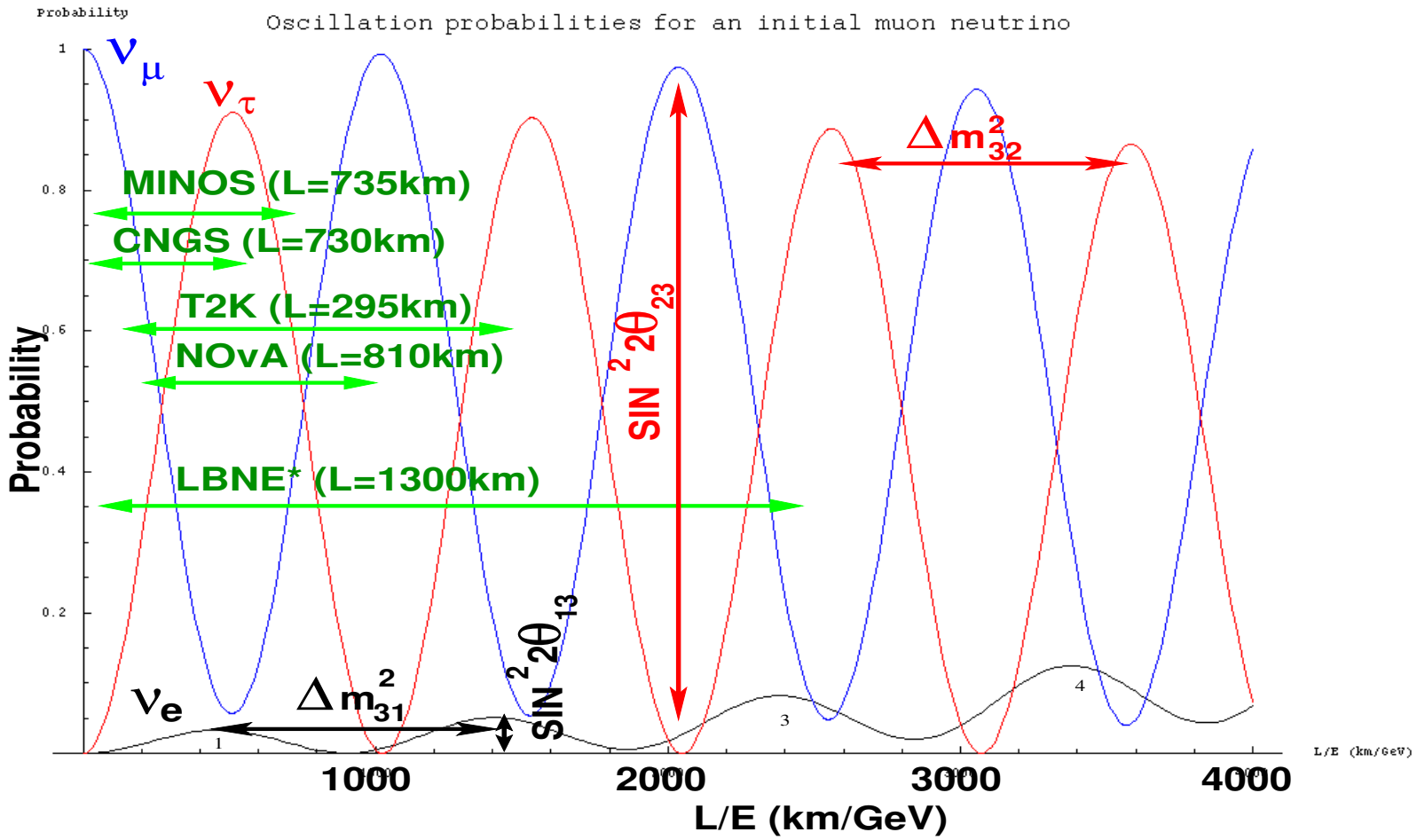

$$E_\nu^{max\ 1}(\mathrm{GeV}) = L(\mathrm{km})/515(\mathrm{km/GeV}),\ E_\nu^{max\ 2} = E_{nu}^{max\ 1}/3$$

Current state of neutrino mixing parameters

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Numerical 1σ, 2σ, 3σ ranges

Parameter	$\delta m^2/10^{-5}$ eV^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\Delta m^2/10^{-3}$ eV^2
Best fit	7.58	0.306 (0.312)	0.021 (0.025)	0.42	2.35
1σ range	7.32 – 7.80	0.291 – 0.324 (0.296 – 0.329)	0.013 – 0.028 (0.018 – 0.032)	0.39 – 0.50	2.26 – 2.47
2σ range	7.16 – 7.99	0.275 – 0.342 (0.280 – 0.347)	0.008 – 0.036 (0.012 – 0.041)	0.36 – 0.60	2.17 – 2.57
3σ range	6.99 – 8.18	0.259 – 0.359 (0.265 – 0.364)	0.001 – 0.044 (0.005 – 0.050)	0.34 – 0.64	2.06 – 2.67

By considering the typical 1σ accuracy [defined as 1/6 of $\pm 3\sigma$ range] ...

δm^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	Δm^2
2.6%	5.4%	0.7×10^{-2} (abs.err.)	12%	4.3%

... we can conclude that we are already in the precision era for ν physics!

Gianluigi Fogli — Frontiers in Neutrino Physics, APC Paris, October 4, 2011 — 31

Evidence accumulating for non-zero θ_{13}. $0.004 < \sin^2(2\theta_{13}) < 0.19$ at 3σ

Charge-Parity Symmetry

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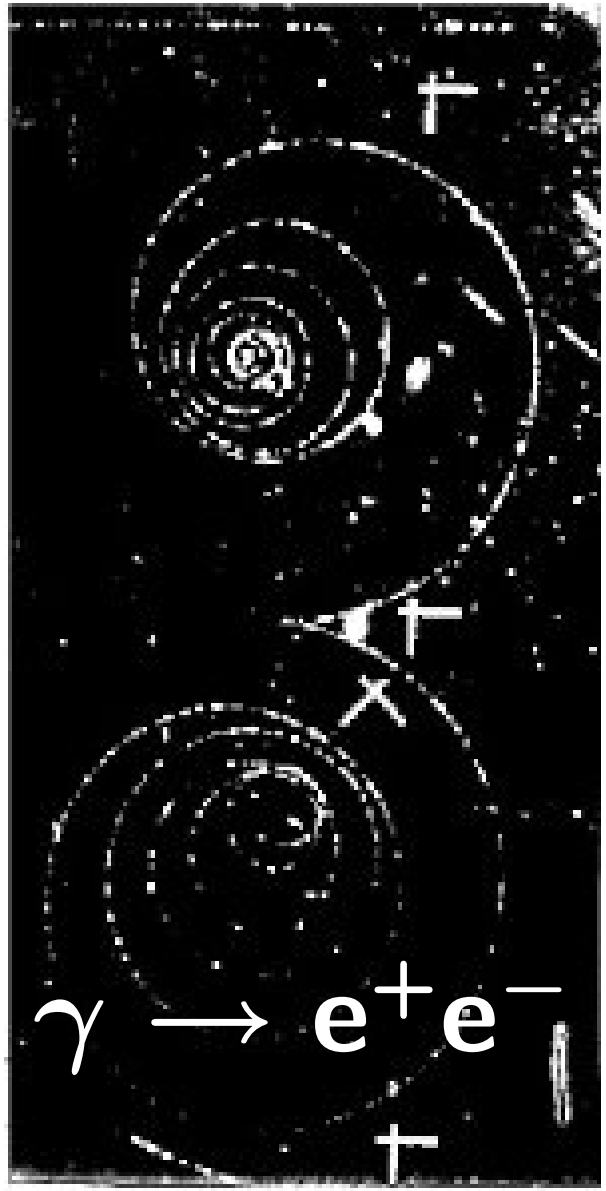
Charge-parity symmetry: **laws of physics are the same if a part icle is interchanged with its anti-particle and left and right are swapped.**

A violation of CP $\Rightarrow$ matter/anti-mattery asymmetry.



Measuring the CP asymmetry in ν mixing

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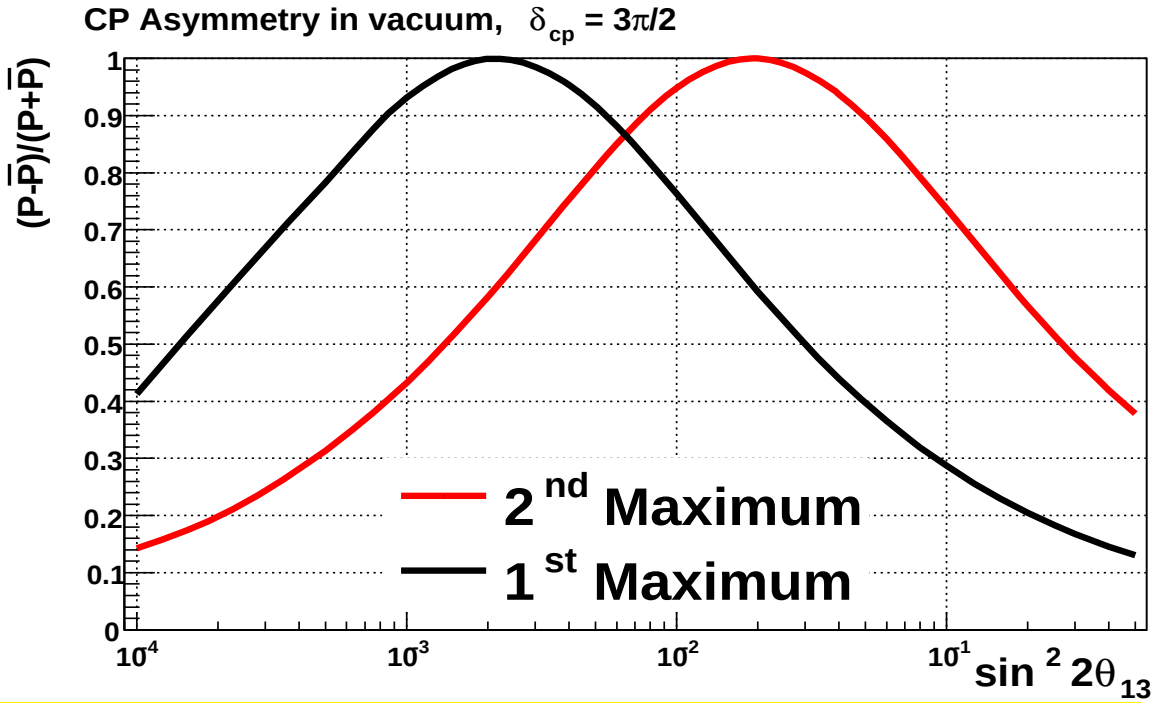
ν CP violation is only possible if $\theta_{13}! = 0$ and $\delta_{cp}! = 0$ or π

$$\mathcal{A}(E_\nu) = \left[\frac{P(\nu_\mu \to \nu_e) - \bar{P}(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + \bar{P}(\bar{\nu}_\mu \to \bar{\nu}_e)}\right]$$



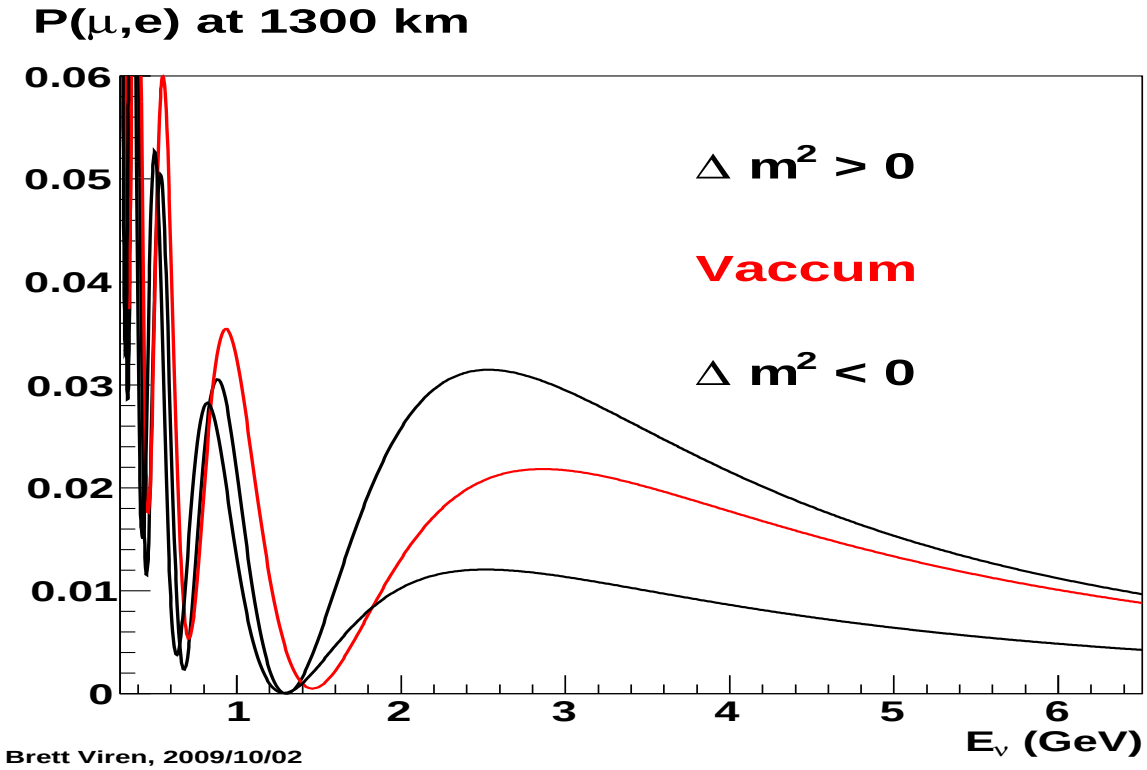
For $\sin^2 2\theta_{13} > 0.02$, $\mathcal{A}(E_{max2}) \approx 2 \times \mathcal{A}(E_{max1})$ AND

$\mathcal{A}(E_{max1}) \propto 1/\sin^2 2\theta_{13}$

Matter Effect on Neutrino Oscillation

1978 and 1986: L. Wolfenstein, S. Mikheyev and A. Smirnov propose the scattering of ν_e on electrons in matter acts as a refrective index $\Rightarrow$ neutrinos in matter have different effective mass than in vacuum.

For $P_{osc} = P(\nu_\mu \rightarrow \nu_e)$:



We can determine the mass hierarchy using $\nu_\mu \rightarrow \nu_e$ oscillations

The Matter Asymmetry vs Baseline ($\delta_{cp} = 0$)

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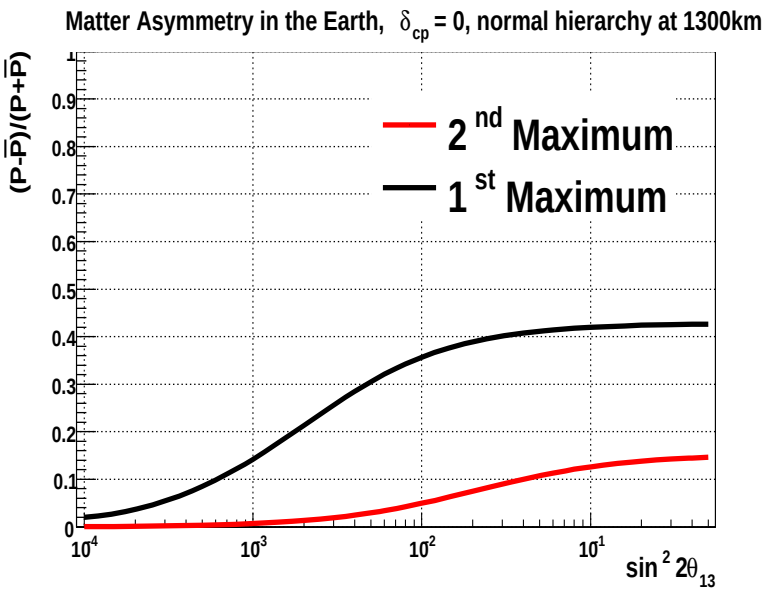
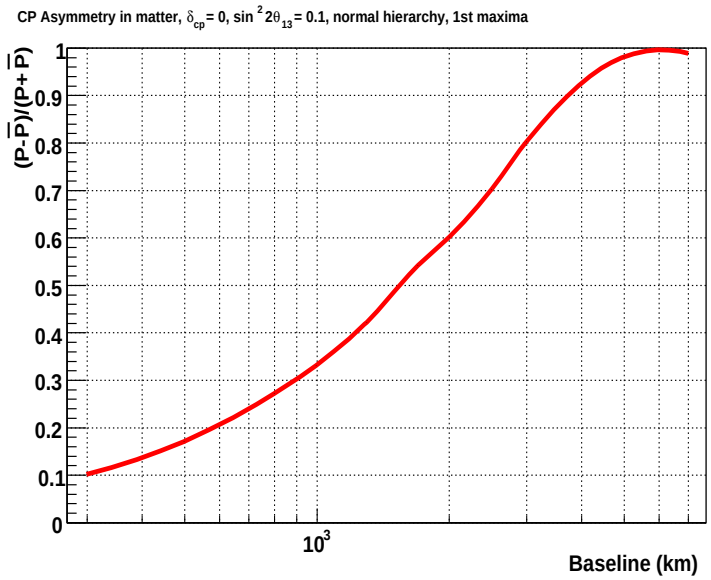
$$\mathcal{A}(E_\nu) = \left[\frac{P(\nu_\mu \to \nu_e) - \bar{P}(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + \bar{P}(\bar{\nu}_\mu \to \bar{\nu}_e)}\right]$$

Matter asymmetry at 1300km



Asymmetry at E_ν^{max1} vs. baseline



The matter asymmetry dominates at the 1st maximum.

Sign of asymmetry $\equiv$ signΔm^3_{31}.

The asymmetry is constant for $\sin^2 2\theta_{13} > 0.02$: $\mathcal{A}(E_{max1}) = \pm 0.4$

Recap

- **Neutrinos come in 3 observed "flavors": ν_e, ν_μ, ν_τ.**
- **Each type of neutrino is a mix of 3 different quantum mechanical states ν_1, ν_2, ν_3 with 3 very small but different masses.**
- **Mixing between the 3 different mass states leads to the phenomenon of neutrino flavor oscillation as neutrinos propagate.**
- **Measurements of $\nu_\mu/\bar{\nu}_\mu$ and $\nu_e/\bar{\nu}_e$ oscillations from solar, atmospheric and terrestrial experiments. allow us to measure the parameters that govern mixing.**
- **Given strong evidence for non-zero θ_{13}, the current and next generation of accelerator neutrino experiment will allow us to search for CP violation in $\nu/\bar{\nu}$ oscillations and measure the mass ordering of the ν_1 and ν_3 state.**

Neutrinos at the Main Injector

The longest baseline accel. ν expt in operation. Average power = 320 kW. Upgrade to 700kW in 2012.

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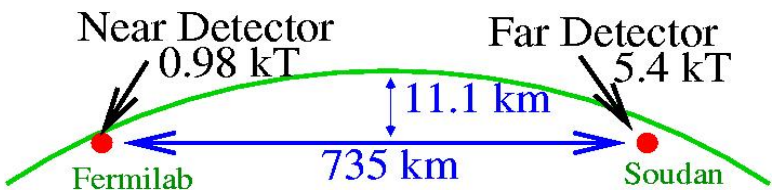
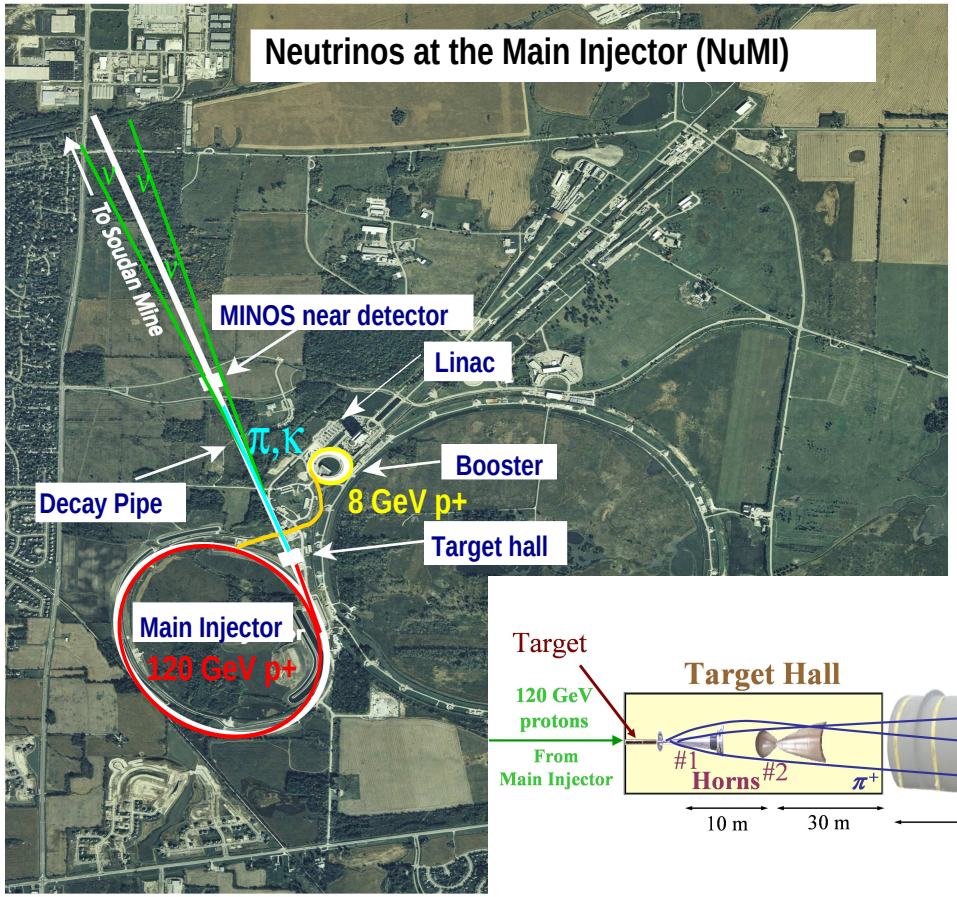
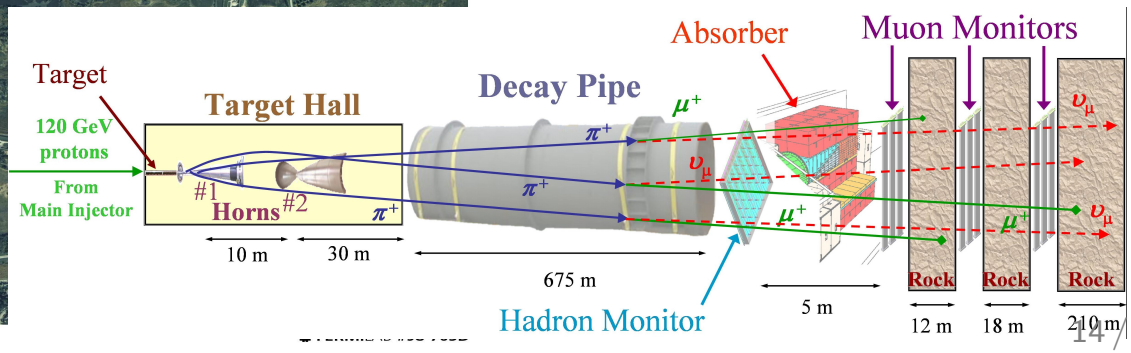


Fermi Natl. Lab., IL **Soudan Underground Lab, MN**

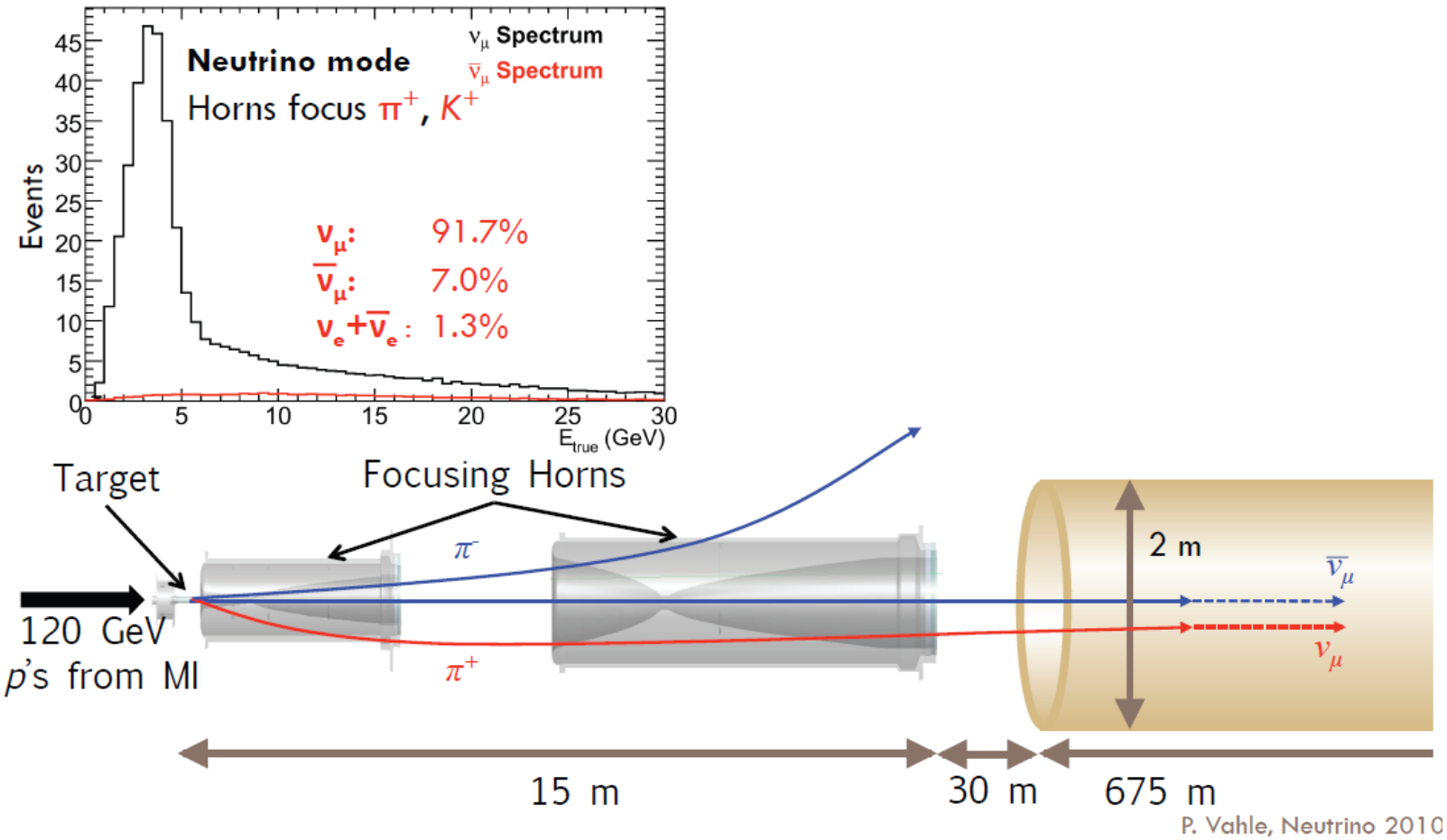
NuMI Horn 2 inner conductor
Radial field, B $\propto$ 1/r

3T at 200 kA

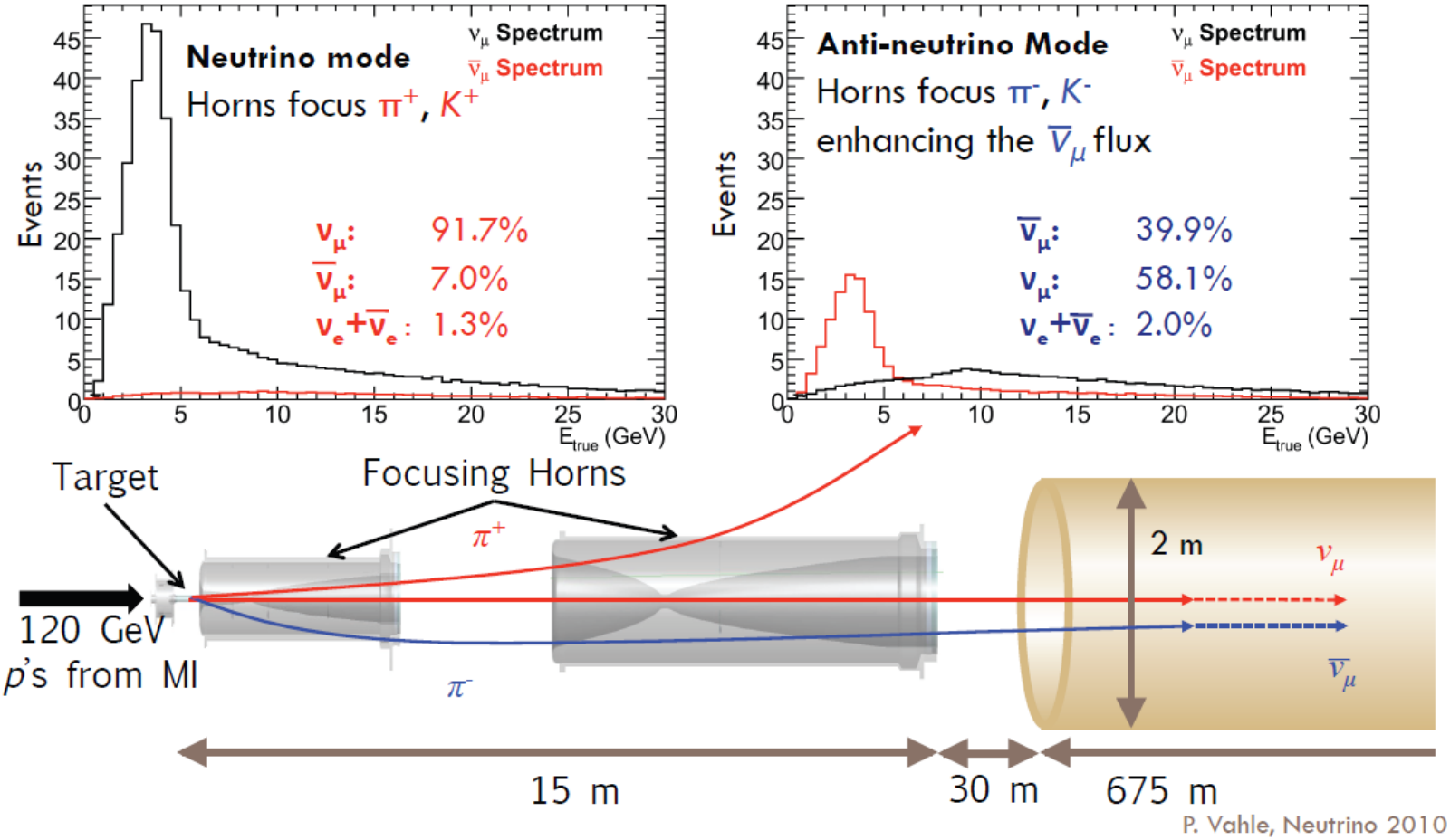




Making Neutrinos and Anti-Neutrinos



Making Neutrinos and Anti-Neutrinos



P. Vahle, Neutrino 2010

NuMI Beam Tunes

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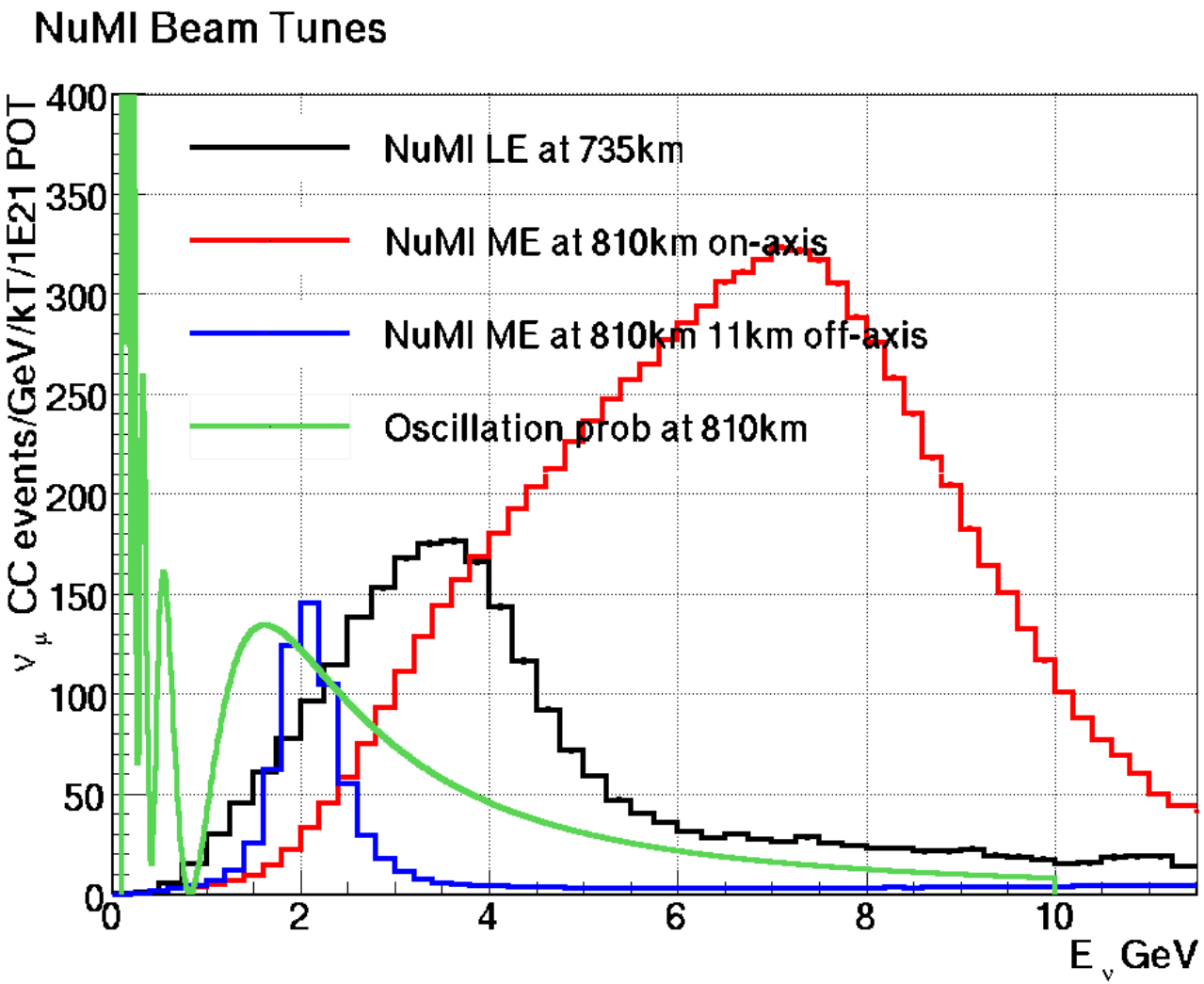
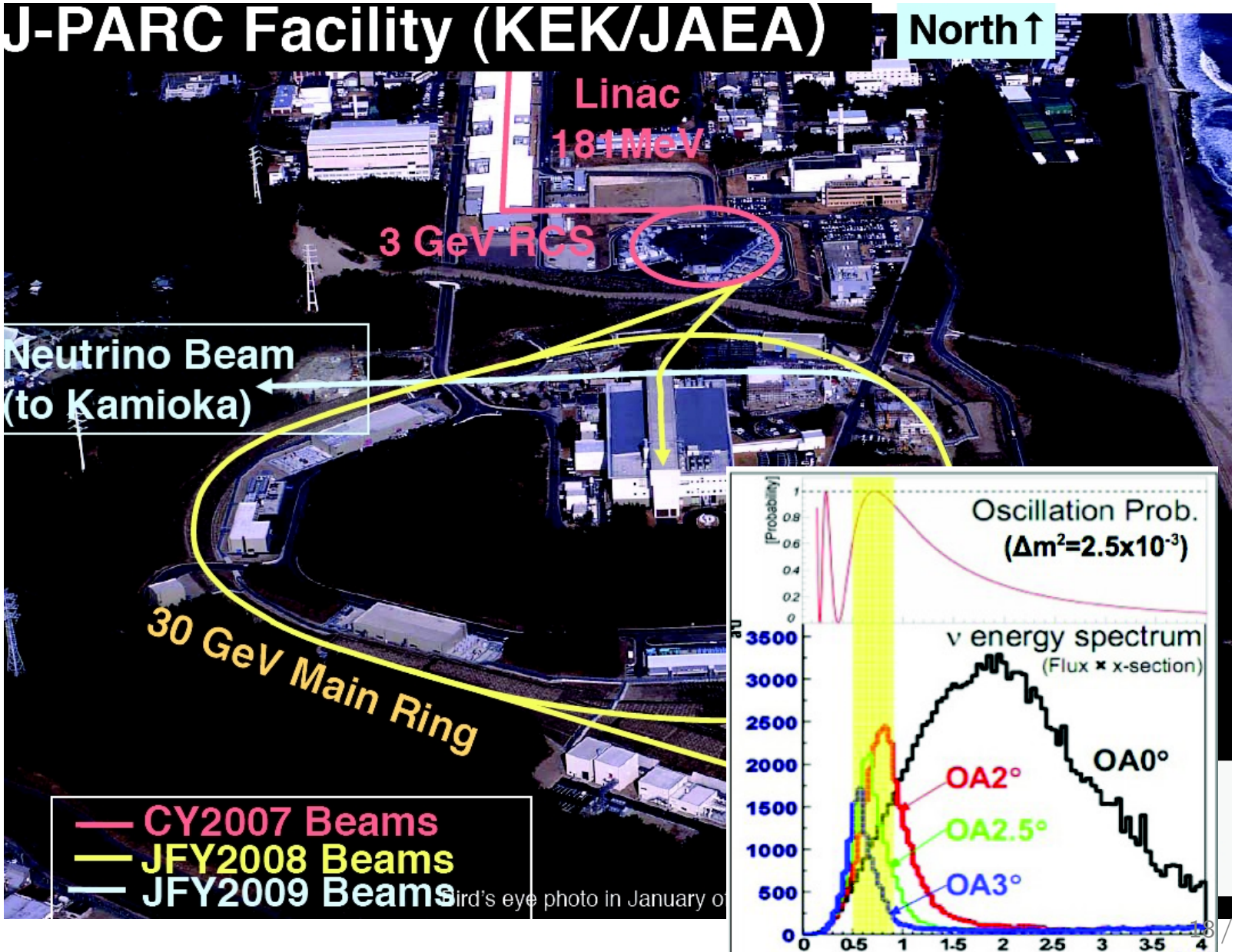


Difficult to obtain low energy νs from high energy proton accelerators.

The JPARC ν Beamline in Japan (designed for 750kW)



$\nu_\mu \longrightarrow \nu_e$ Event Rates - Various Beams

For a given neutrino energy at the first oscillation maximum for a baseline L is

$$E_{nu}^{max\ 1}(\mathrm{GeV}) = L(\mathrm{km})/515(\mathrm{km/GeV})$$

For $\sin^2 2\theta_{13} = 0.04, \delta_{cp} = 0, \Delta m^2_{31} > 0$:

Baseline (km)	E_ν^{max1} (GeV)	σ (10^{-38}cm^2/N)	Beam	Signal Rates (/100kt.MW.yr)
300	0.6	0.5	LBNE 2° OA	380*
810	1.6	1.2	NuMI 0.8° OA	300
1300	2.5	2.0	LBNE LE	540
2500	4.9	3.4	LBNE ME	420

* Signal rate in T2K with JParc beam is lower

Any precision measurement requires 1000-10,000 events which requires 100kT MW year exposures regardless of detector type OR baseline.

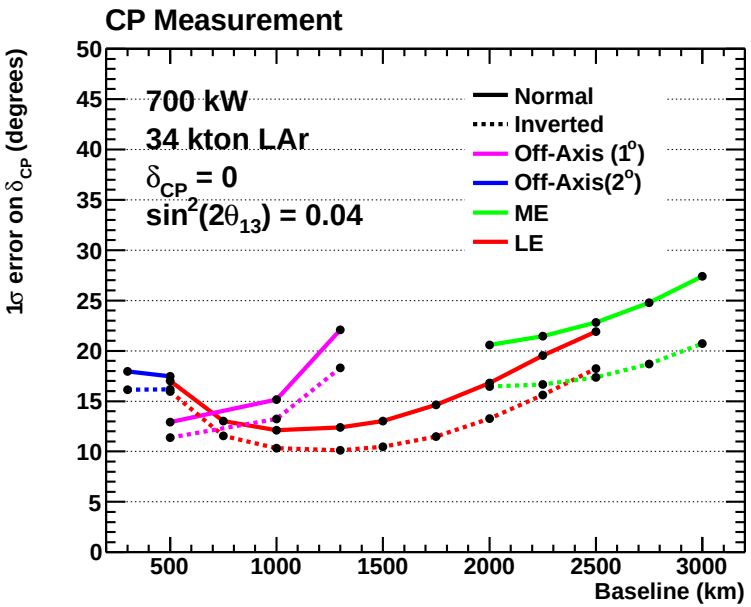
Detector must be MASSIVE with MW beams

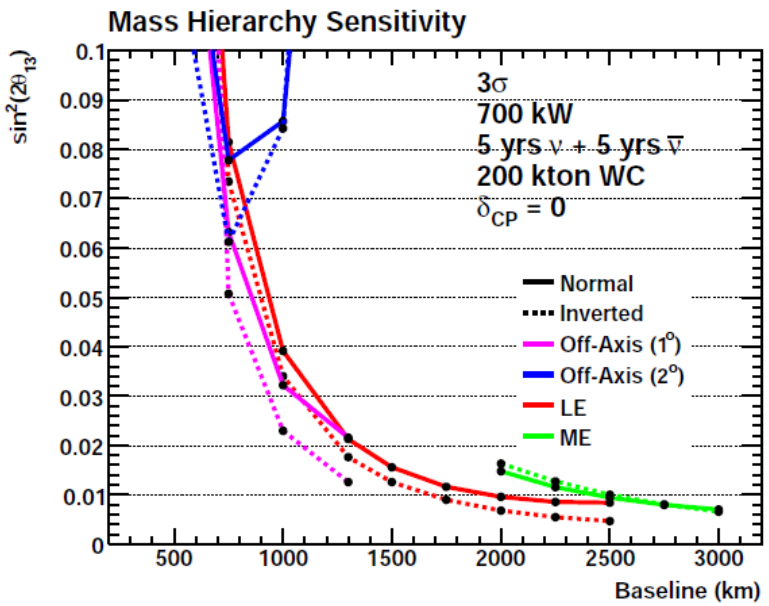
Largest ν_e appearance signal at L $\approx$ 1300km!!

Sensitivities vs Baseline

Assuming the same massive detector - study optimal baseline for determining δ_{cp} and mass ordering. LBNE beam is optimized for each location:

$\delta_{cp} = 0$ 1σ resolution **Mass hierarchy sensitivity at 3σ**



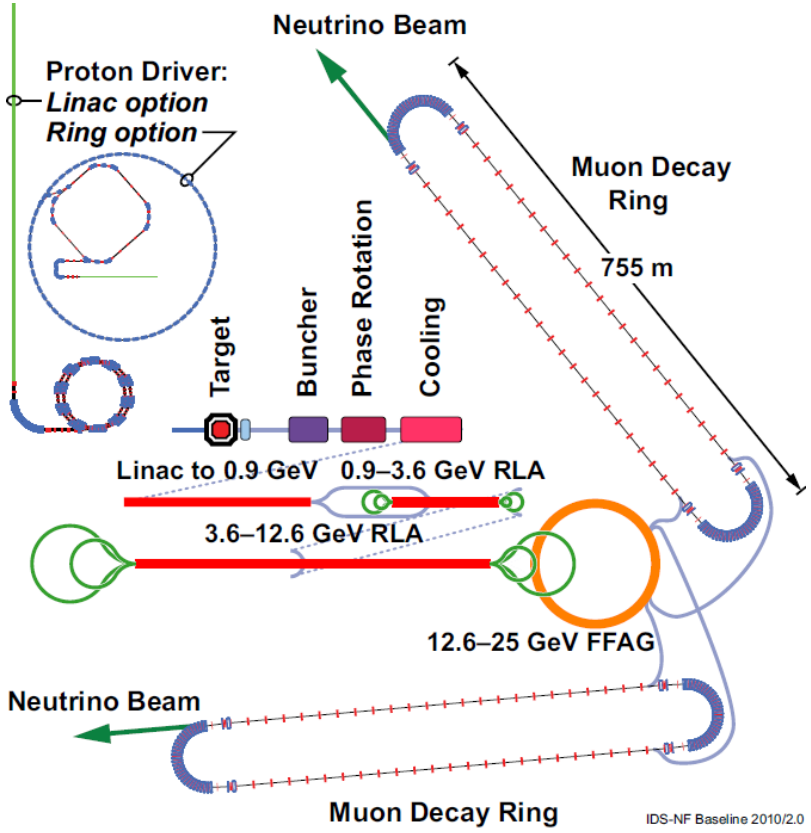


Baselines at $\approx$ 1500km are optimal

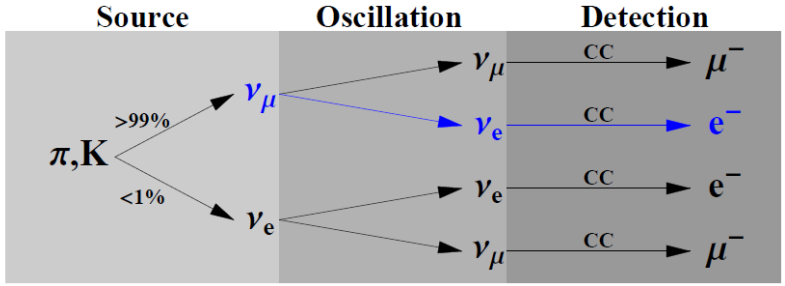
Short baselines have mass hierarchy/δ_{cp} ambiguities

Neutrino Factories (with multi-MW beams/ProjectX)

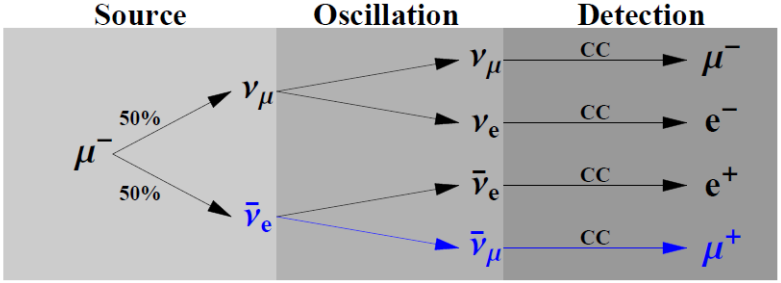
Collect μ from pion decays in a storage/decay. Use $\nu_e \rightarrow \nu_\mu$ oscillations:



Neutrino superbeam signal:



Neutrino factory signal (needs magnetized far detector):



Timescale: couple of decades?

Why neutrino factories?

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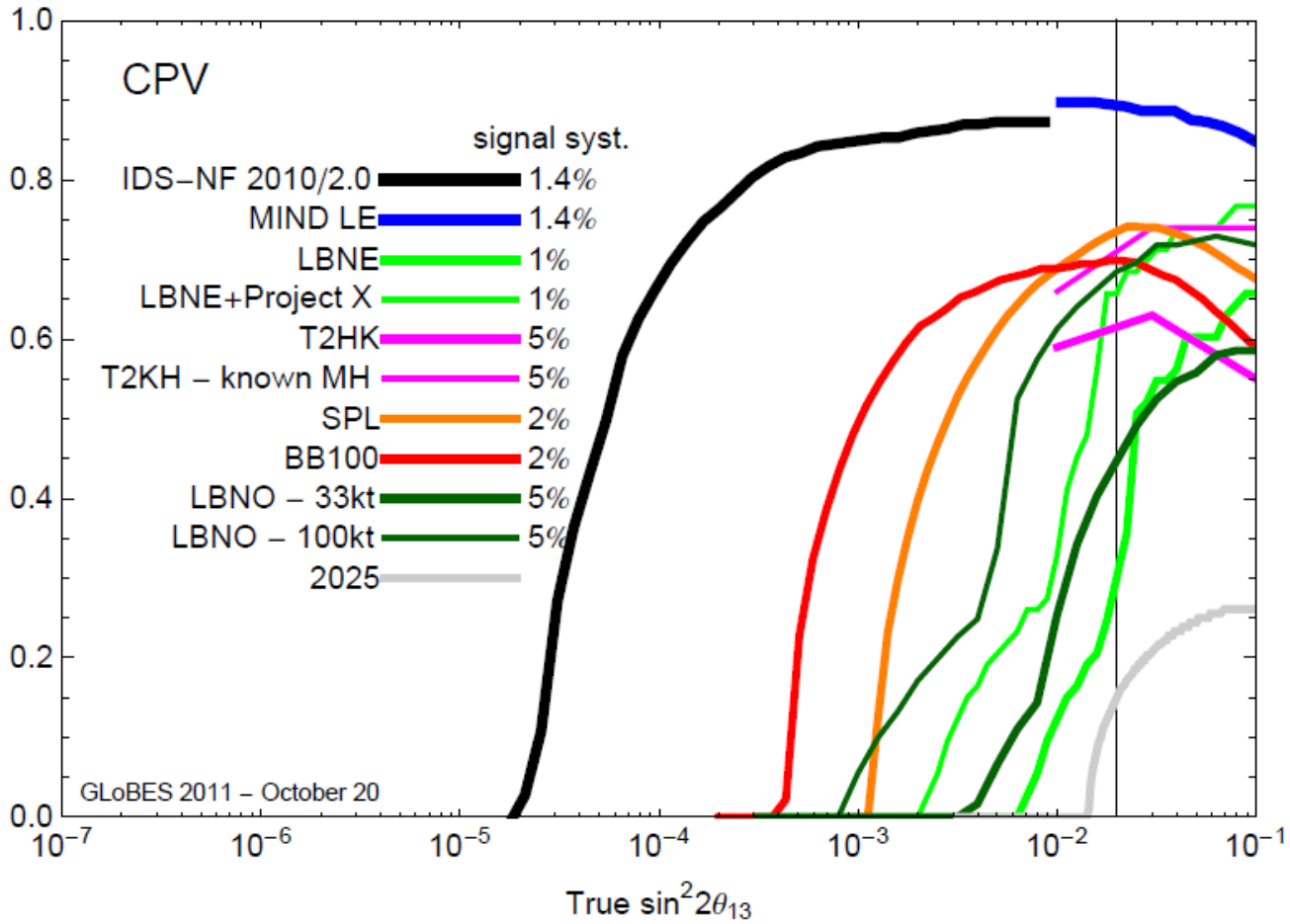
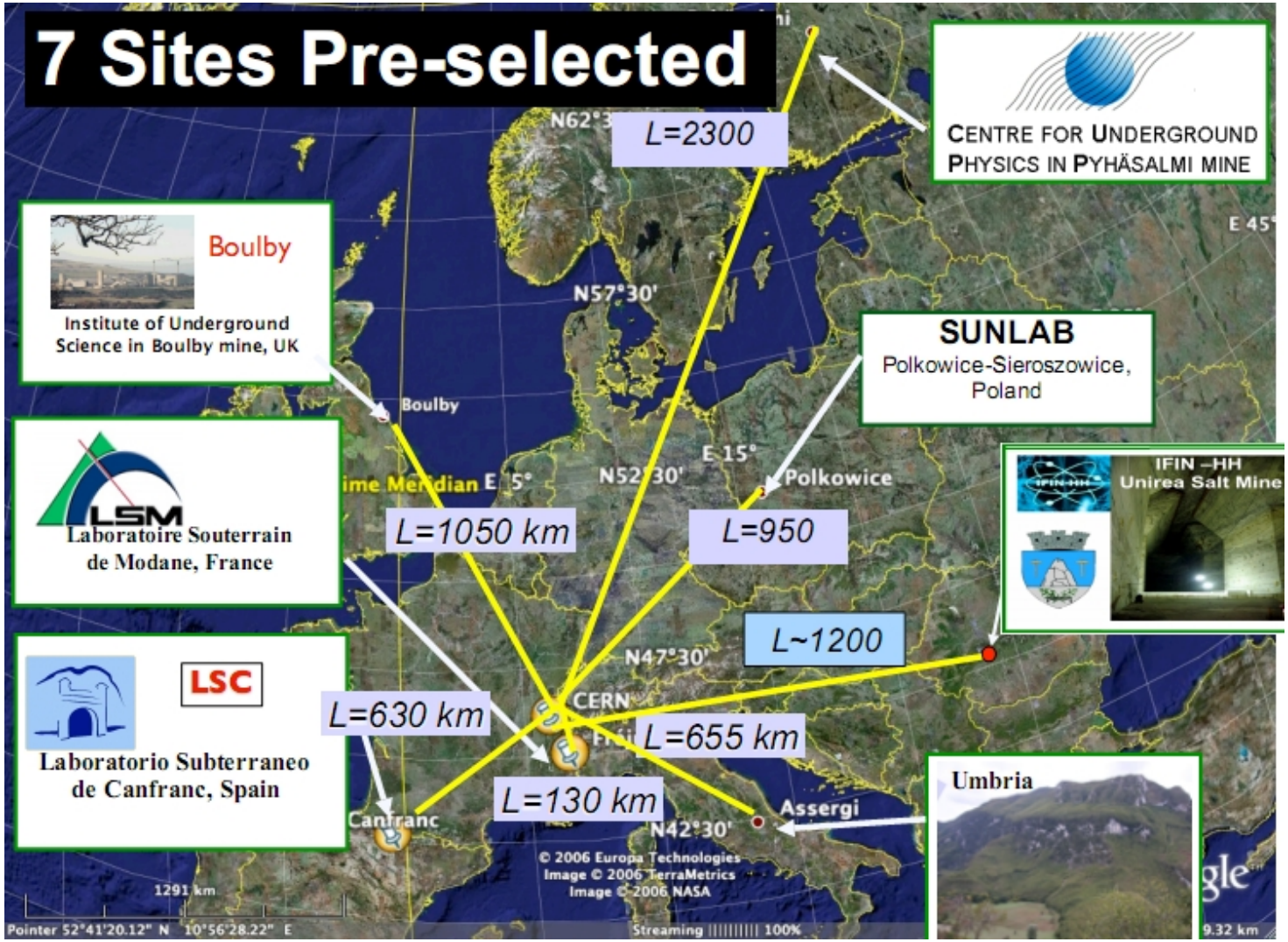
Fraction of δ_{cp} values measurable by different experiments:



Neutrino factories cover the most δ_{cp} space even at large $\sin^2 2\theta_{13}$

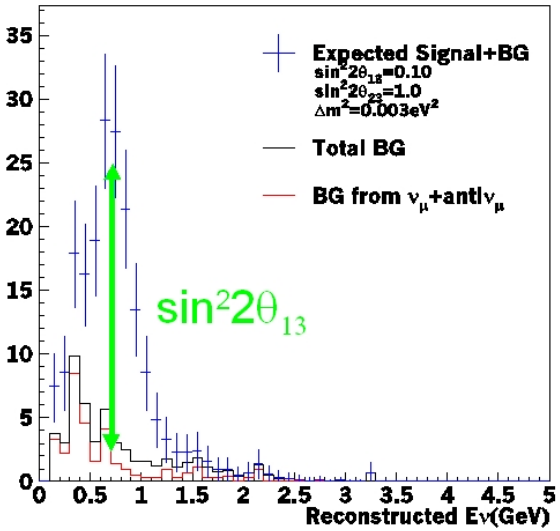
Superbeams/Beta Beams/ν Factories in Europe

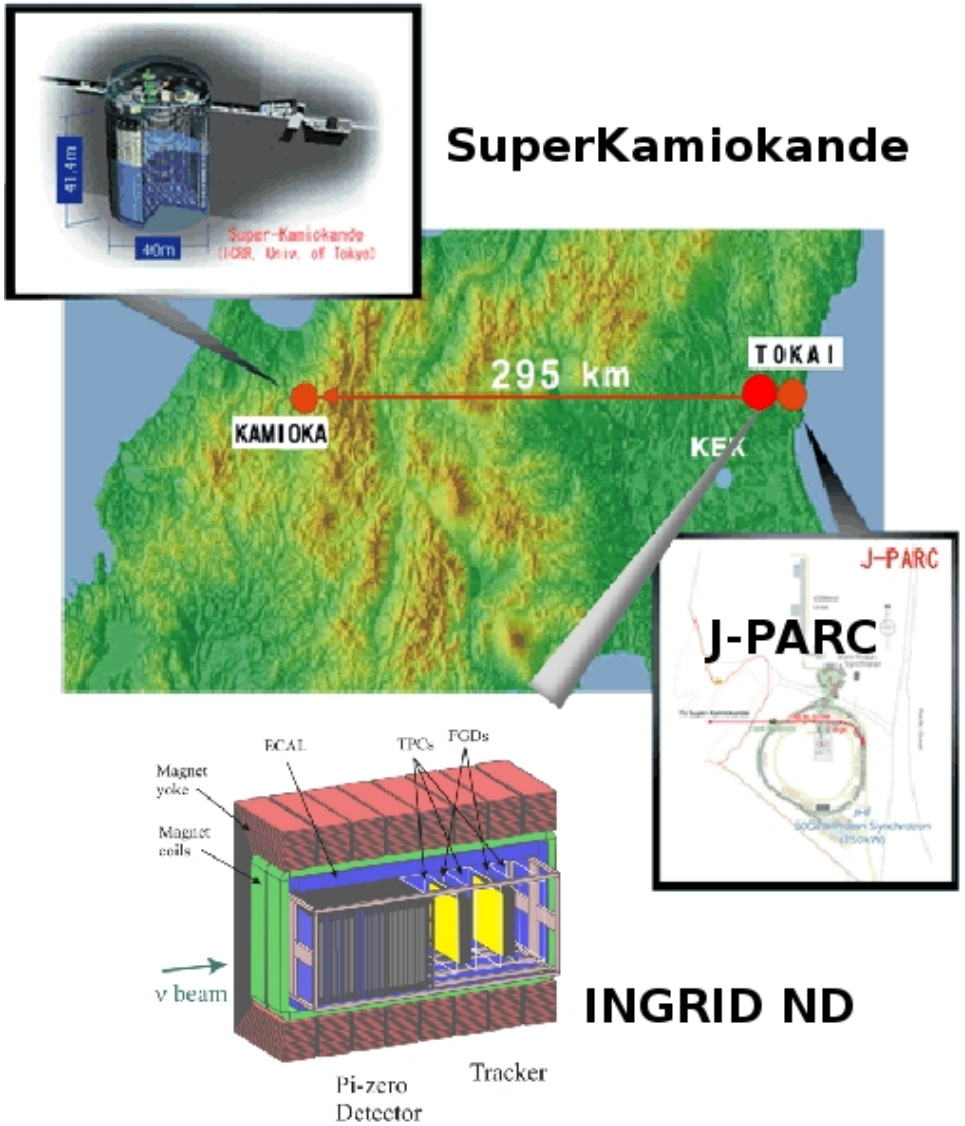


Off-axis high intensity ν_μ beams: T2K

First proposed for BNL E-889 (1995): A narrow beam of ν can be achieved by going off-axis to the π beam. Better S:B at oscillation max.

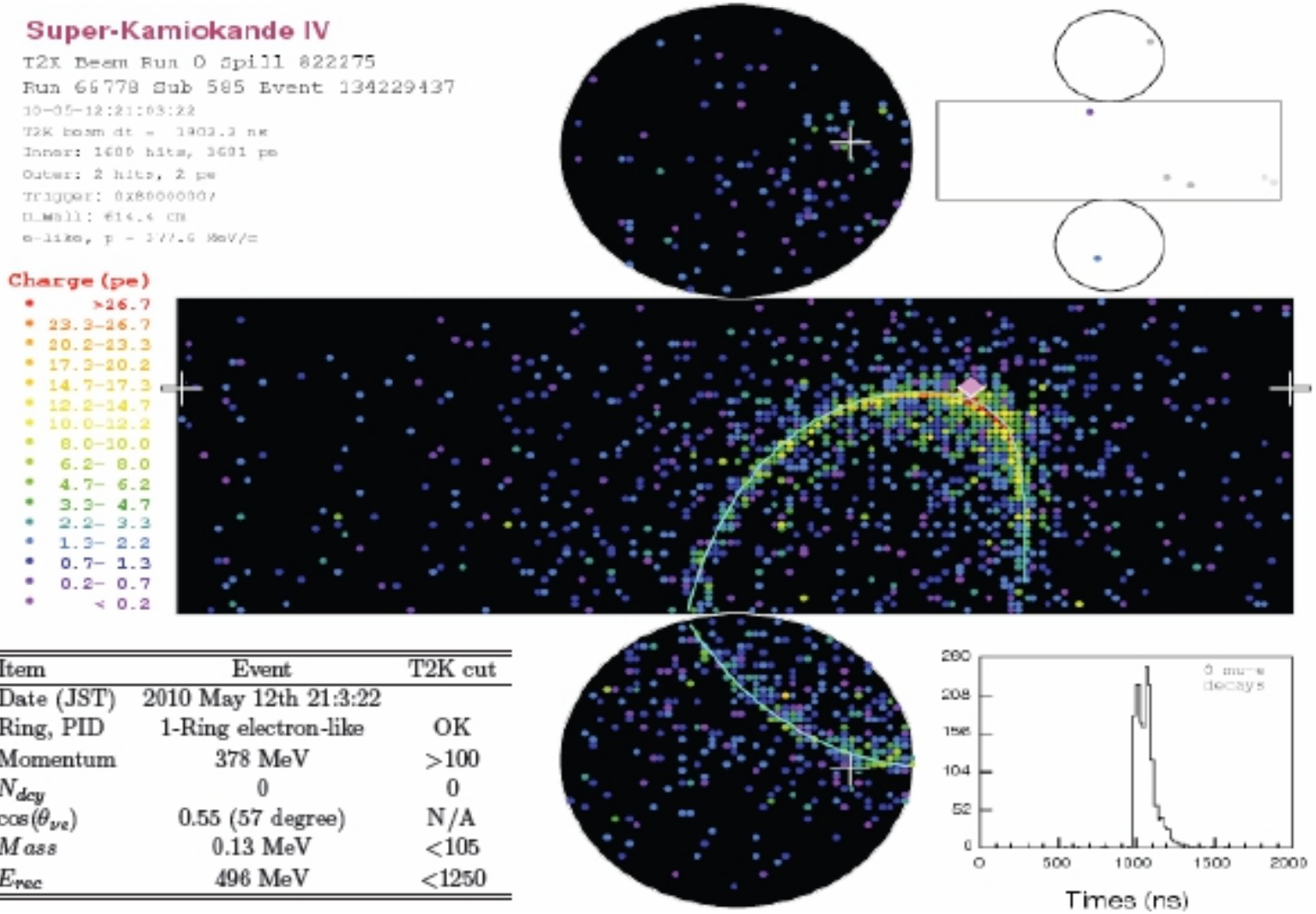
Signal at $\sin^2 2\theta_{13} = 0.1$:





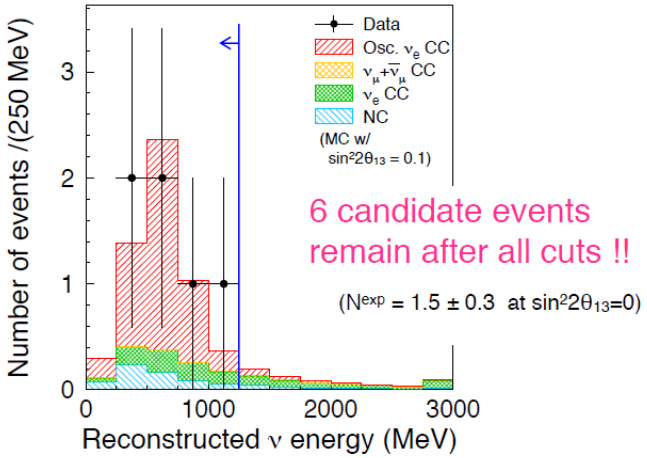
T2K first results announced in March 2011

T2K ν_e Candidate Event 2010

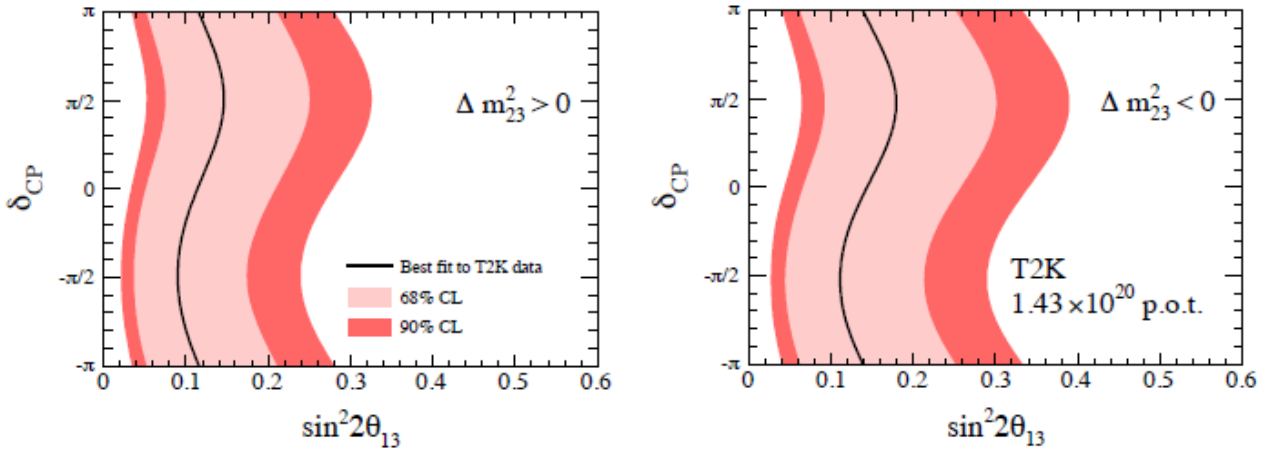


Item	Event	T2K cut
Date (JST)	2010 May 12th 21:3:22	
Ring, PID	1-Ring electron-like	OK
Momentum	378 MeV	>100
N_{dcy}	0	0
$\cos(\theta_{\nu e})$	0.55 (57 degree)	N/A
$Mass$	0.13 MeV	<105
E_{rec}	496 MeV	<1250

First results from T2K June 2011



(assuming $\Delta m^2_{23}=2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$)



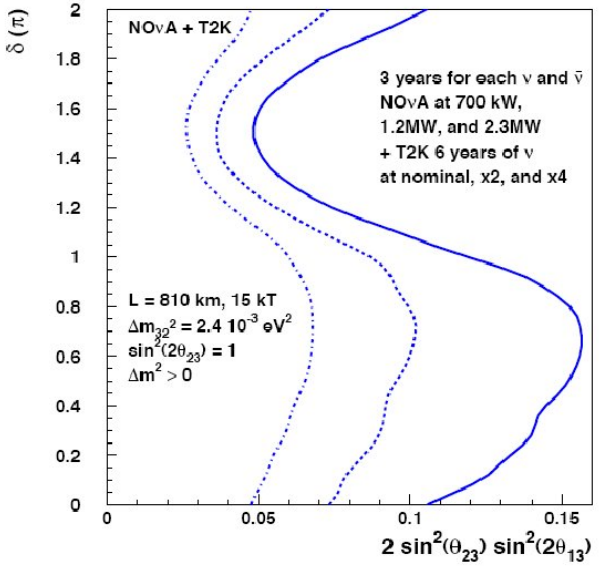
90% C.L. interval & Best fit point (assuming $\Delta m^2_{23}=2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$)

$0.03 < \sin^2 2\theta_{13} < 0.28$	$0.04 < \sin^2 2\theta_{13} < 0.34$
$\sin^2 2\theta_{13} = 0.11$	$\sin^2 2\theta_{13} = 0.14$

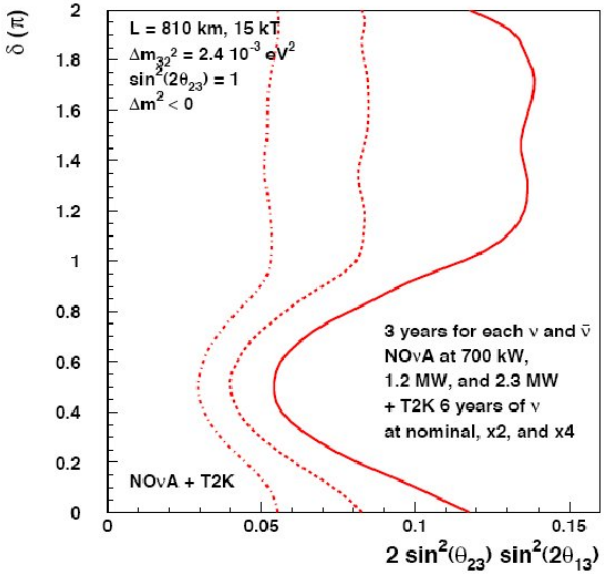
NOνA and T2K

The NOνA experiment is at a baseline of 810km off-axis to the NuMI beam. Detector is 14kT of active scintillator on the surface. Operational by 2013.

95% CL Resolution of the Mass Ordering
NOνA Plus T2K



Normal Ordering

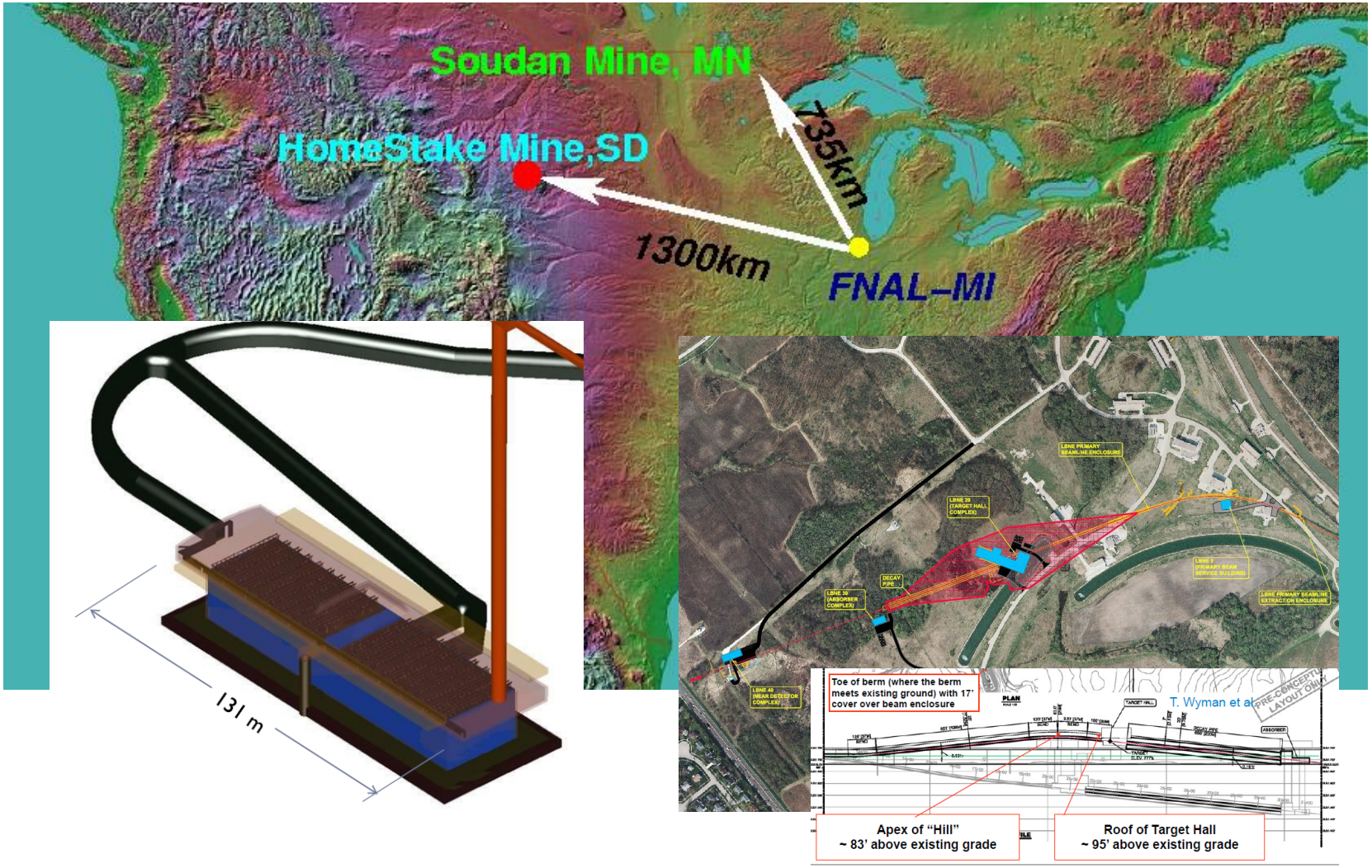


Inverted Ordering

Some sensitivity to mass hierarchy at large θ_{13}

The Long Baseline Neutrino Experiment

A Long Baseline Neutrino Experiment (LBNE) from Fermilab to large scale neutrino detectors at Homestake is now being designed. CDR 2012.



The LBNE Beam at Fermilab

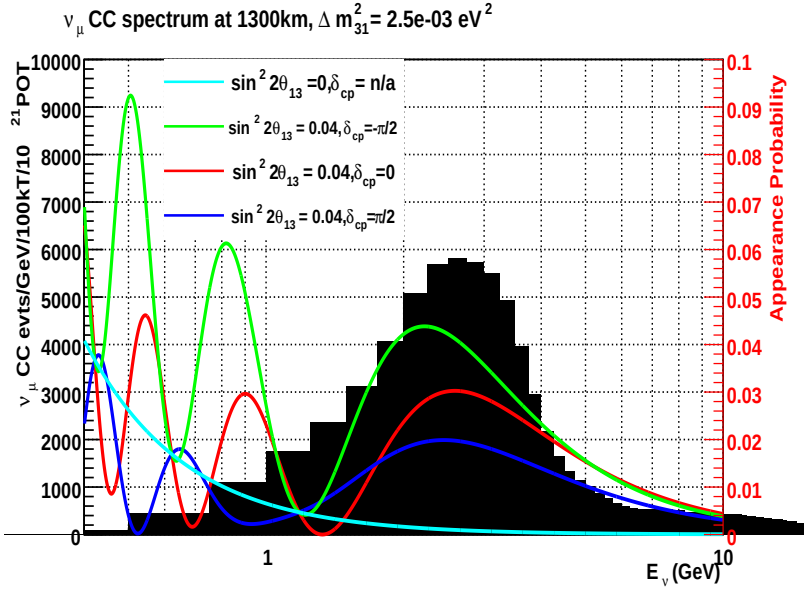
The LBNE project will start with a 700kW beam with 80-120 GeV p

In the future will profit from the 2.3 MW Project X beam

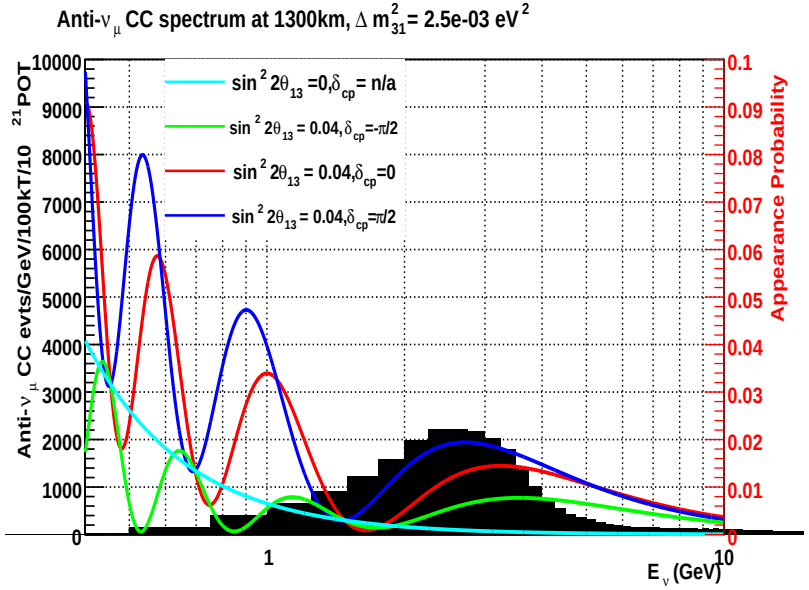
Wide-band beam to cover BOTH oscillation maxima for best CP Violation/Mass Hierarchy sensitivity

Normal Ordering

Neutrinos



Anti-Neutrinos



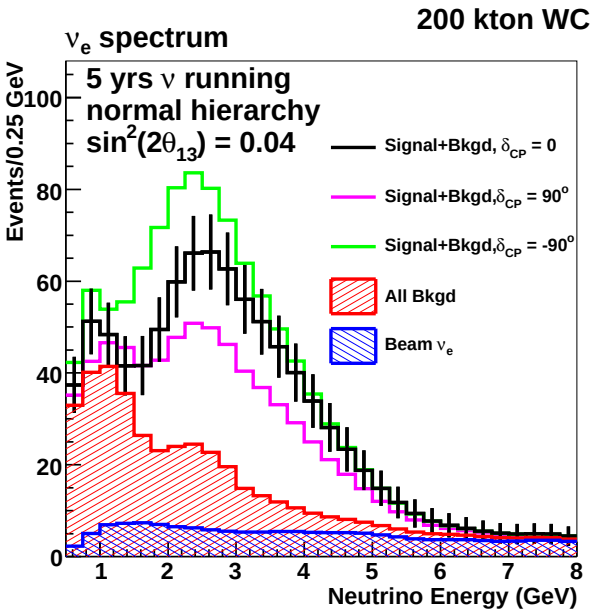
Interaction rates per 100kT.MW.yr

ν_μ CC	ν_μ CC osc	ν_e CC beam	$\nu_\mu \rightarrow \nu_e$ CC	$\nu_\mu \rightarrow \nu_\tau$ CC
29K	11K	520	560	140

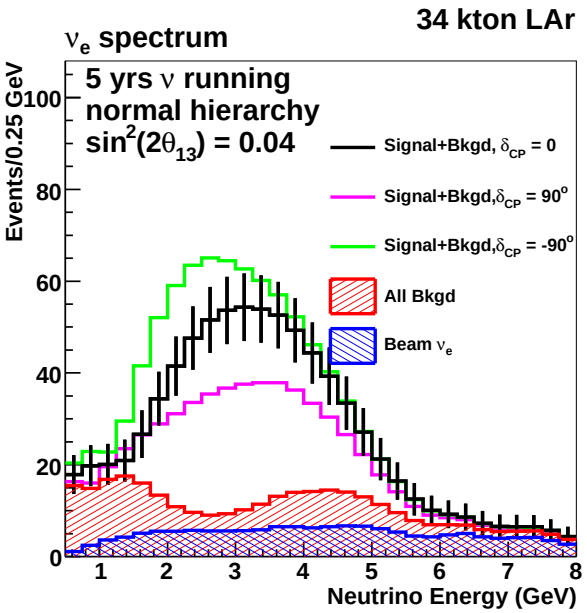
LBNE spectra and event rates

On-axis wide-band beam (NuMI focusing). Water Cerenkov response is based on the SuperK MC. LAr is modeled as a near-perfect detector. *Exposure is 3.5 MW. yr ν with* $\sin^2 2\theta_{13} = 0.04$:

200 kt WCD



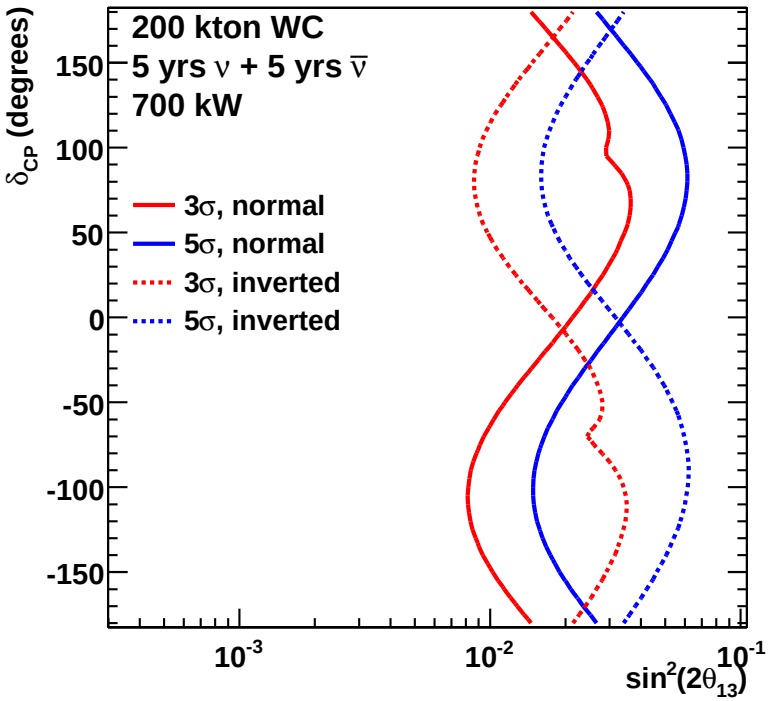
34 kt LAr

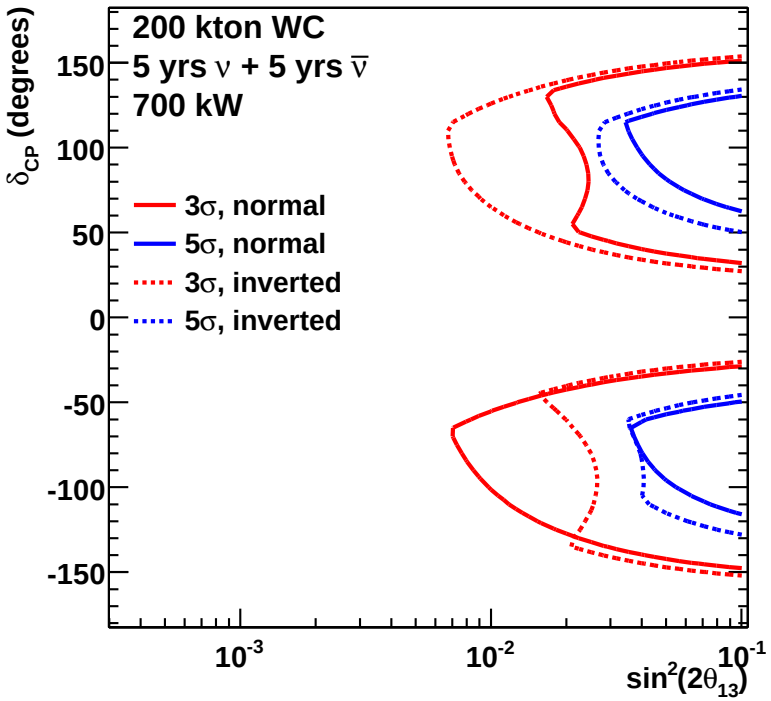


Measurements of CPV and MH in LBNE

200 kt WCD detector and 5 yrs of ν + 5 yrs of $\bar{\nu}$ running with 700kW:

Mass Hierarchy **CP Violation**





Measurements of CPV and MH in LBNE

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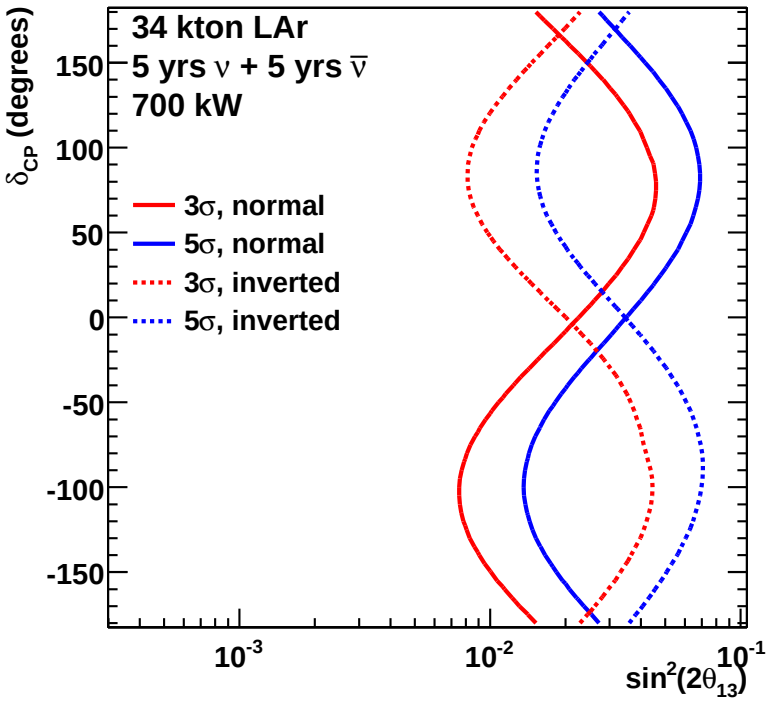
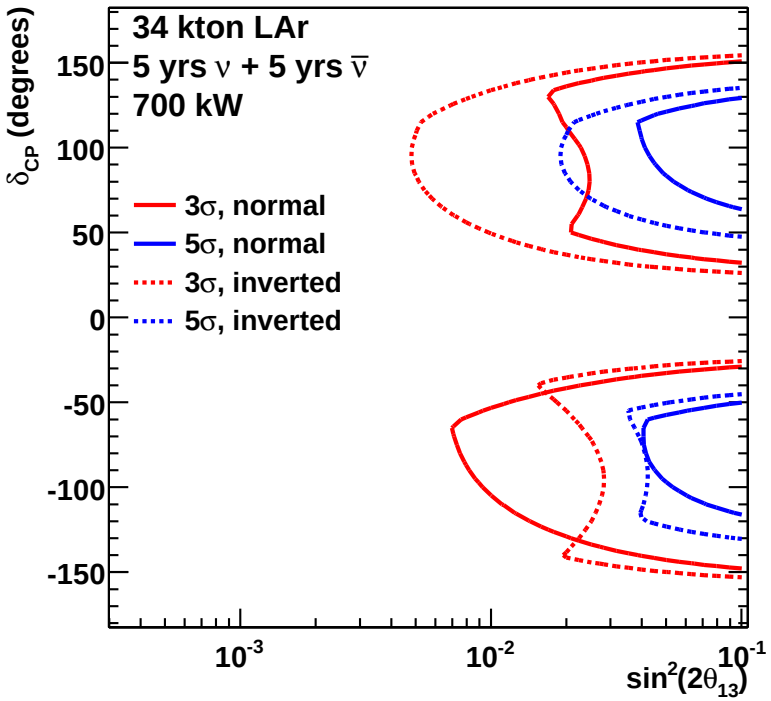
34 kt LAr detector and 5 yrs of ν + 5 yrs of $\bar{\nu}$ running with 700kW:

Mass Hierarchy **CP Violation**





Ultimate LBNE ν Oscillation Sensitivities

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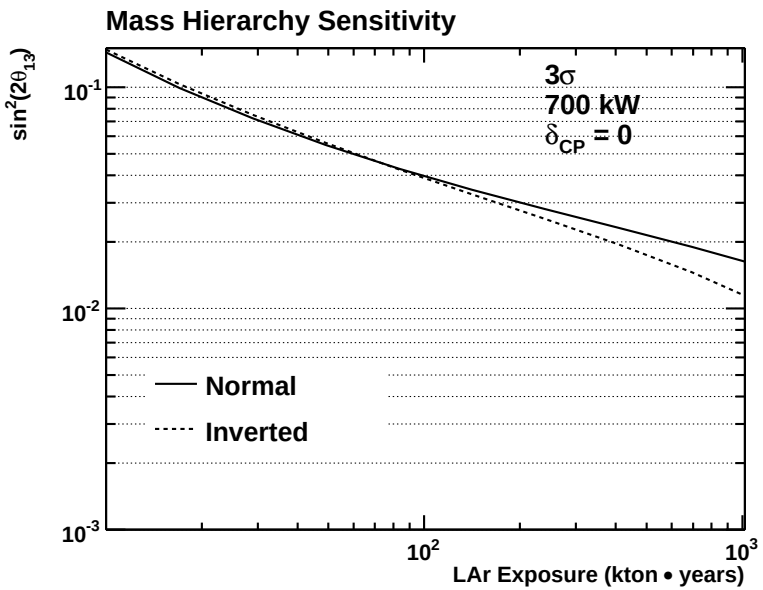
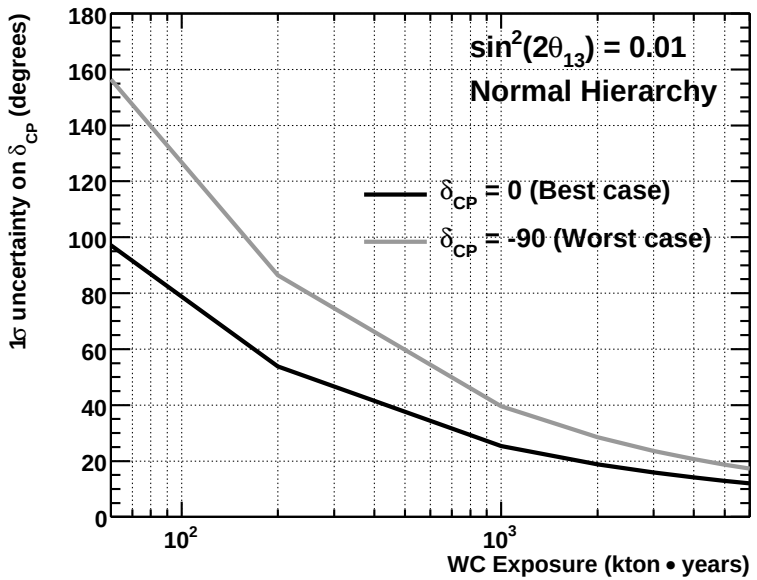
MH Sensitivity at 3σ



Resolution of δ_{cp}



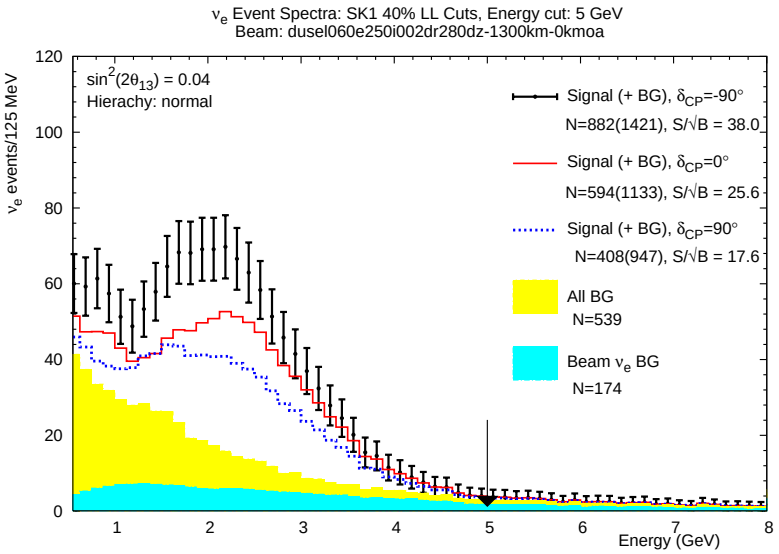
Sensitivity to MH at 3σ for all δ_{cp} for $\sin^2 2\theta_{13} \geq 0.01$

Precision measurement of δ_{cp} for $\sin^2 2\theta_{13} \geq 0.01$

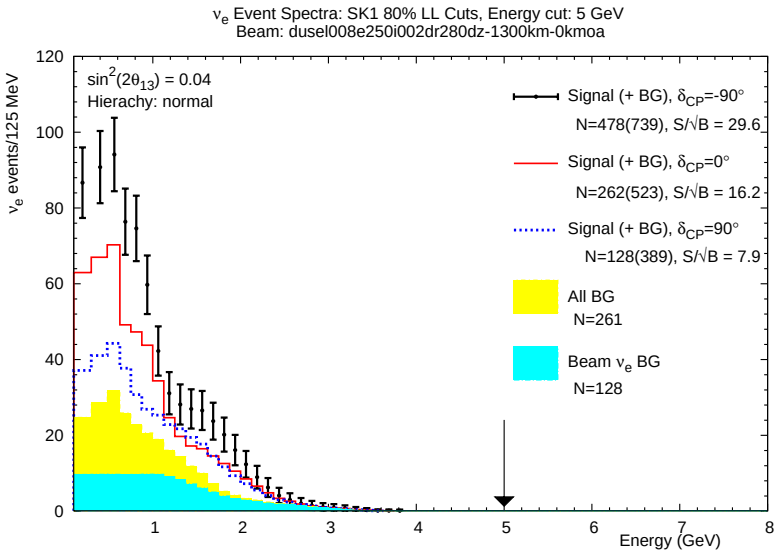
LBNE with Project X

ProjectX beams: 60 GeV at 2 MW (Phase II) and 8 GeV at 4MW (Phase III) with 200kt WCD:

60 GeV, 2MW, $\sin^2 2\theta_{13} = 0.04$



8 GeV, 3MW, $\sin^2 2\theta_{13} = 0.04$

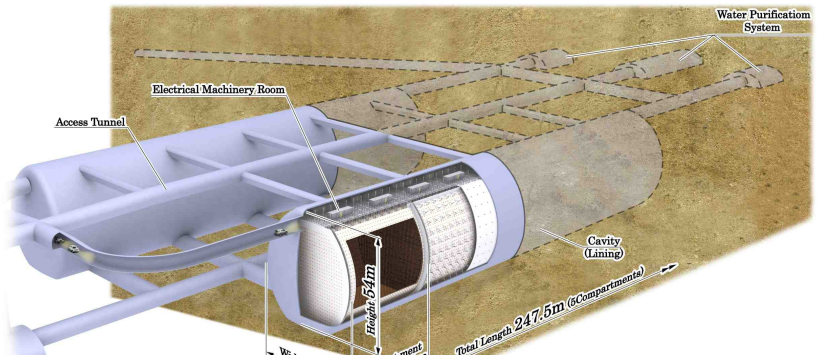


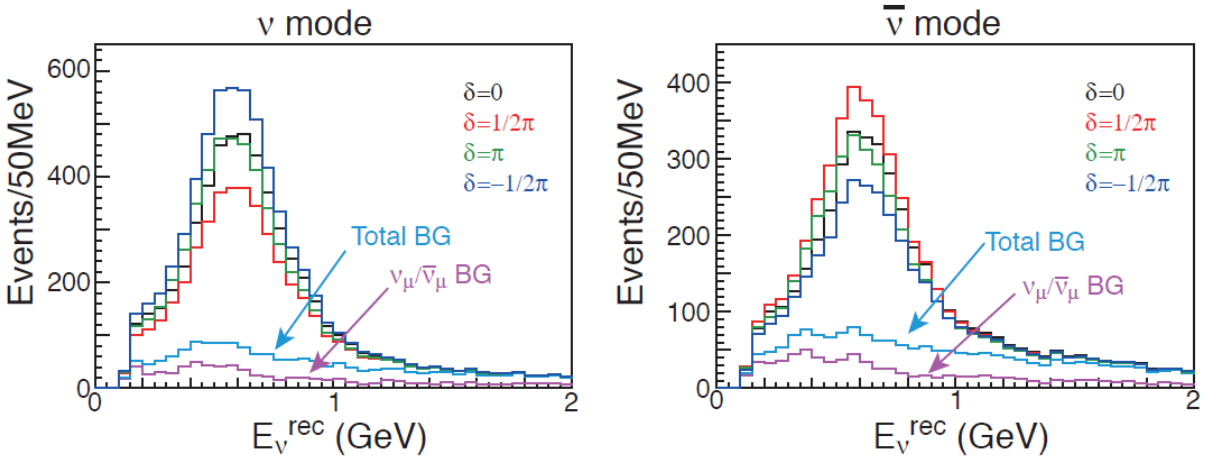
Complementary measurement of δ_{cp} with 8GeV beam,

large CP effects, small matter asymmetry. **Is LAr too small?**

Tokai to HyperKamiokance (T2HK)

JPARC beam upgraded from 750kW to 1.66MW sent 295km to Hyper-Kamiokande (Hyper-K). Hyper-K is a water Cherenkov detector with total (fiducial) mass = 990 (560) kt.





$\sin^2 2\theta_{13} = 0.1$:

T2HK vs LBNE

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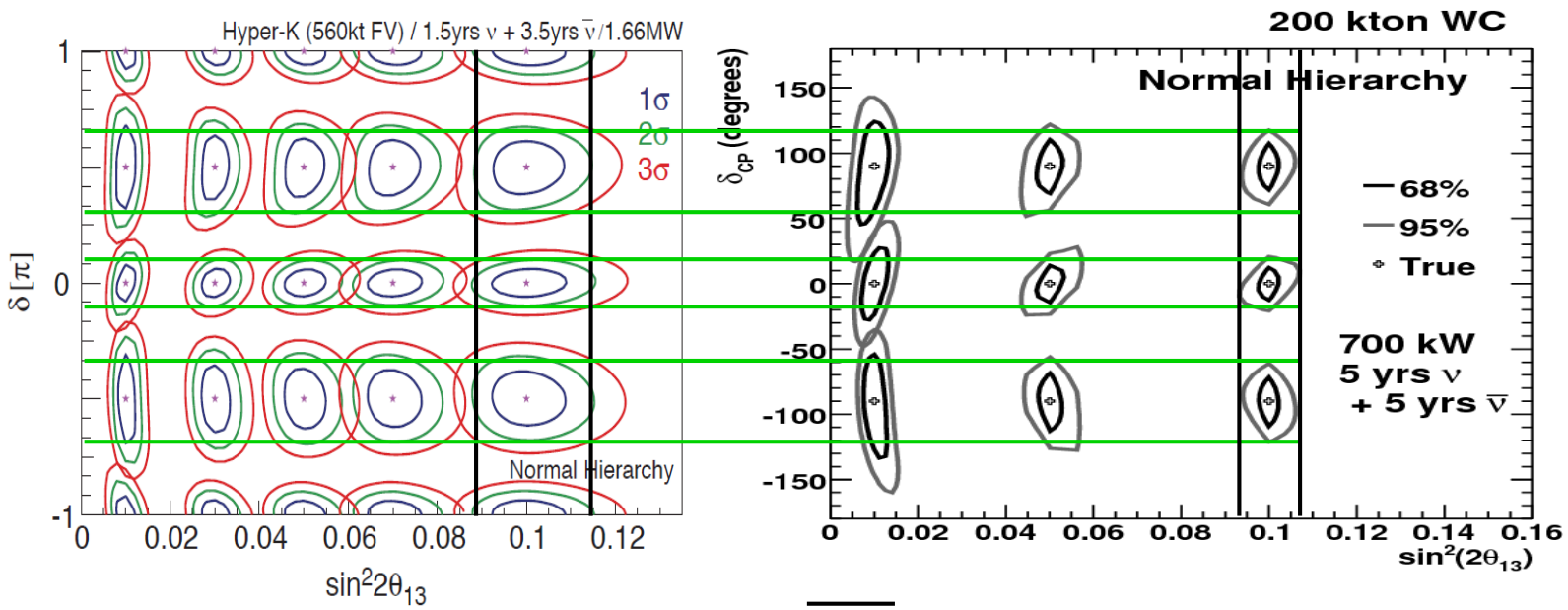

Similar resolutions on δ_{cp} from T2HK and LBNE

LBNE has significantly better measurements of $\sin^2 2\theta_{13}$

Summary and Conclusions

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- **Long baseline neutrino experiments using conventional neutrino beams (horn focused) in the Japan, Europe, US (T2K/CNGS/MINOS) are currently operating.**
- **Precision measurements of $\Delta m^2_{32}/\Delta\bar{m}^2_{32}$ from MINOS. $\nu_\mu \rightarrow \nu_\tau$ oscillation candidate in CNGS/OPERA.**
  Hint of $\nu_\mu \rightarrow \nu_e$ in T2K! .
- **In designing the next generation of long baseline experiment the largest ν_e signal and optimal CPV sensitivity is at $\approx$ 1300km. Requires $\mathcal{O}$(100)kt detectors.**
- **LBNE (1300km, 200kt WCD/34 kt LAr, 700kW) and T2HK (295km, 560kt WCD, 1.66MW) have similar δ_{cp} resolution. LBNE has significantly better $\sin^2 2\theta_{13}$ resolution.**
- **LBNE with Phase III Project X 8 GeV beam can measure oscillation at the 2nd maximum separate from the 1st maximum - a unique measurement.**
- **For high precision neutrino mixing, neutrino factories are needed. Technically challenging, need magnetized detectors and multi MW beams.**

CAUTION
NO ONE BEYOND
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DANGER
ROSS 4100

THANK YOU!