DAEδALUS

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LAGUNA-LBNO Meeting
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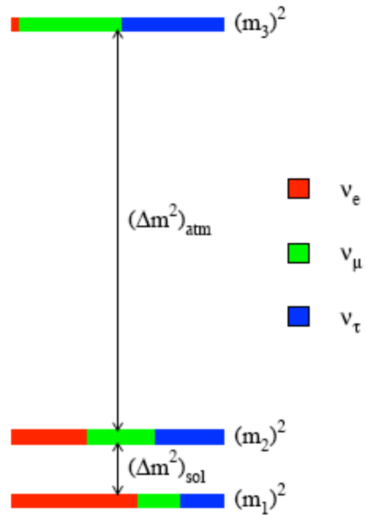
Decay
At rest
Experiment
for δ_{cp} studies
At the
Laboratory for
Underground
Science

- New $\bar{\nu}$ source for large H_2O detector
  - Enhanced neutrino oscillation program
  - New experiments possible
- Complementary to the long baseline proposals
  - Comparable measurements for osc parameters
  - Much improved measurements by combining DAEdALUS and long baseline!

The oscillation of muon-flavor to electron-flavor at the atmospheric Δm^2 may show CP-violation dependence!



in a vacuum…

$$
\begin{aligned}
P = \; & (\sin^2\theta_{23}\sin^2 2\theta_{13})\,(\sin^2\Delta_{31}) \\
& \mp \underline{\sin\delta}\,(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\,(\sin^2\Delta_{31}\sin\Delta_{21}) \\
& + \underline{\cos\delta}\,(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\,(\sin\Delta_{31}\cos\Delta_{31}\sin\Delta_{21}) \\
& + (\cos^2\theta_{23}\sin^2 2\theta_{12})\,(\sin^2\Delta_{21}).
\end{aligned}
$$

We want to see if δ is nonzero

terms depending on mixing angles

terms depending on mass splittings

$$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$

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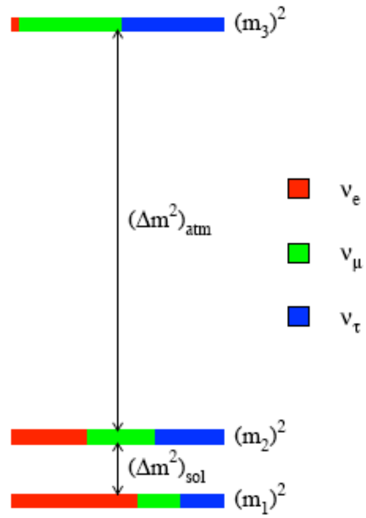

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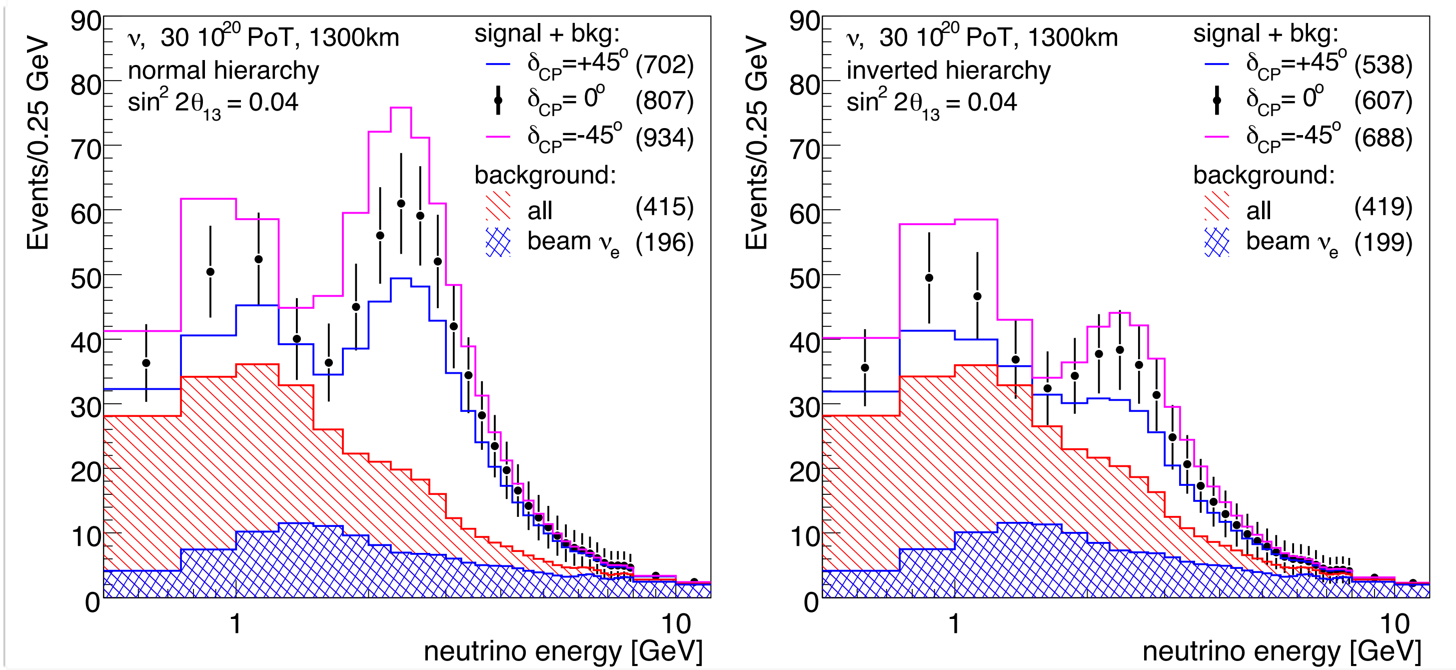
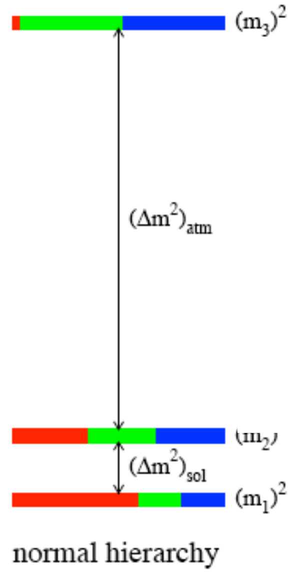
\end{aligned}
$$

We want to see if δ is nonzero

CP violation is all about interference.

The δ-dependent terms arise from interference between the $\Delta m_{13}{}^2$ and $\Delta m_{12}{}^2$ oscillations





- Long baseline experiment fluxes cover 1st and 2nd oscillation maxima
  - Different energies yield L/E variation

- DAEdALUS concept is to use different baselines to yield L/E variation

Introducing DAEδALUS

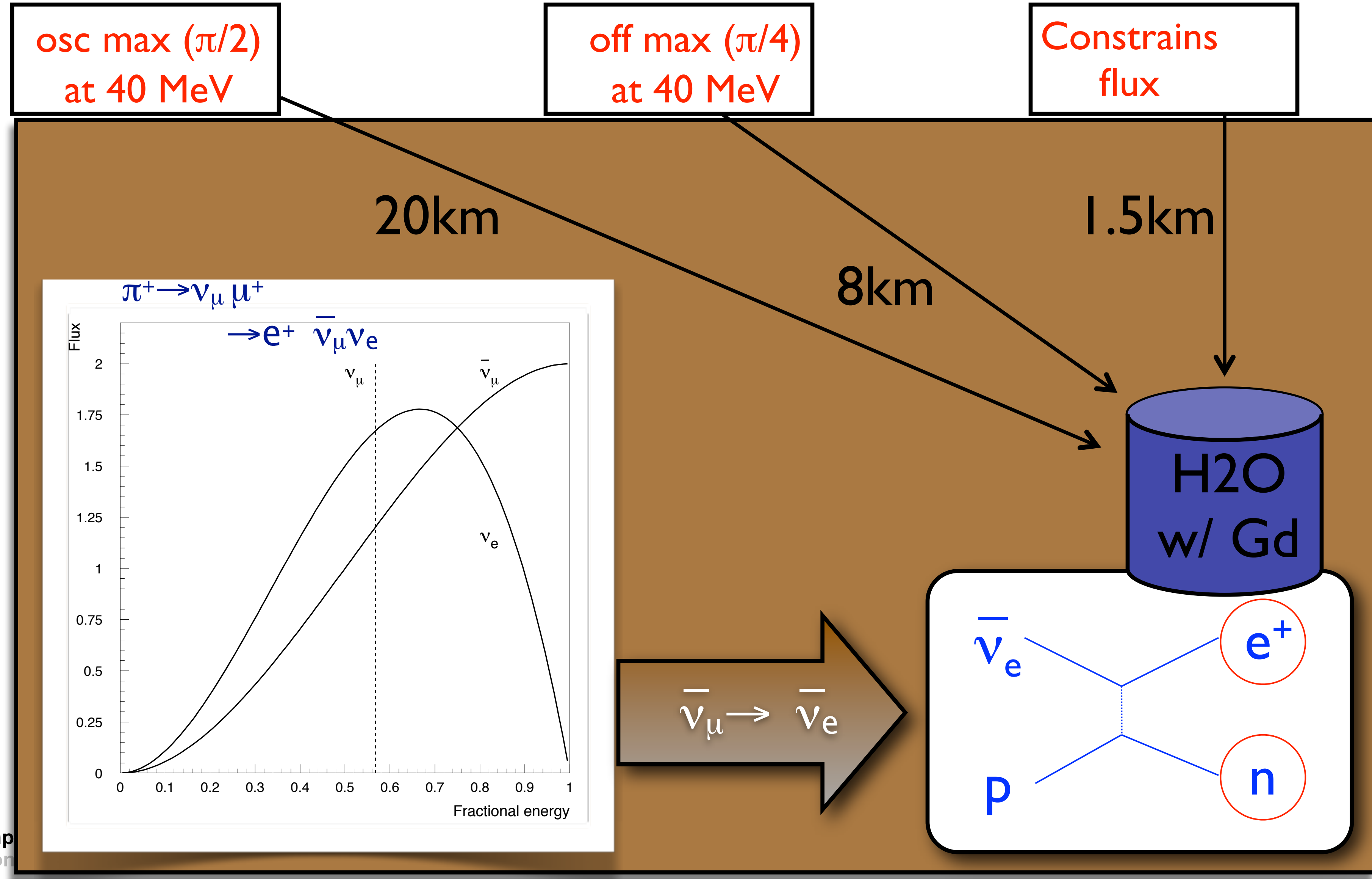
Expression of Interest for A Novel Search for CP Violation in the Neutrino Sector:

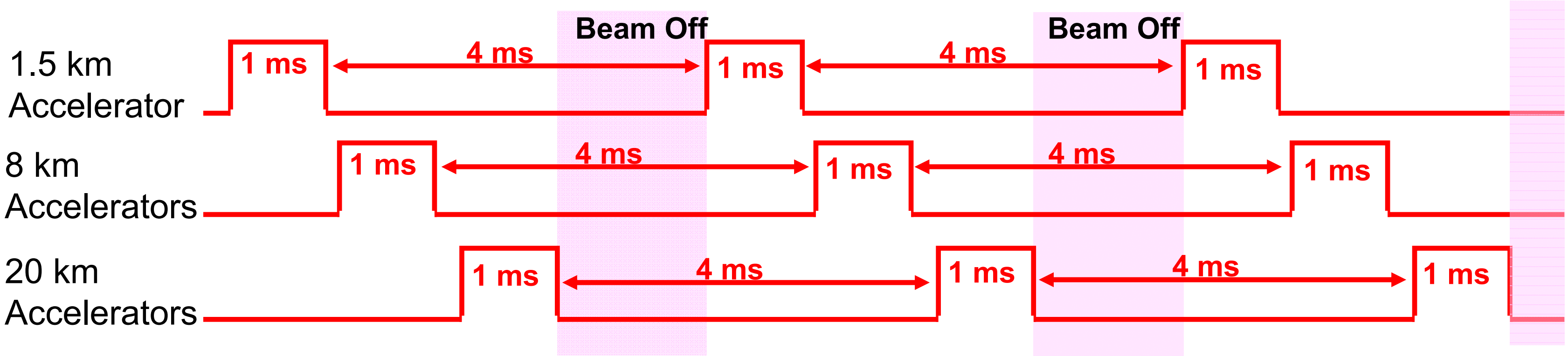
DAEδALUS

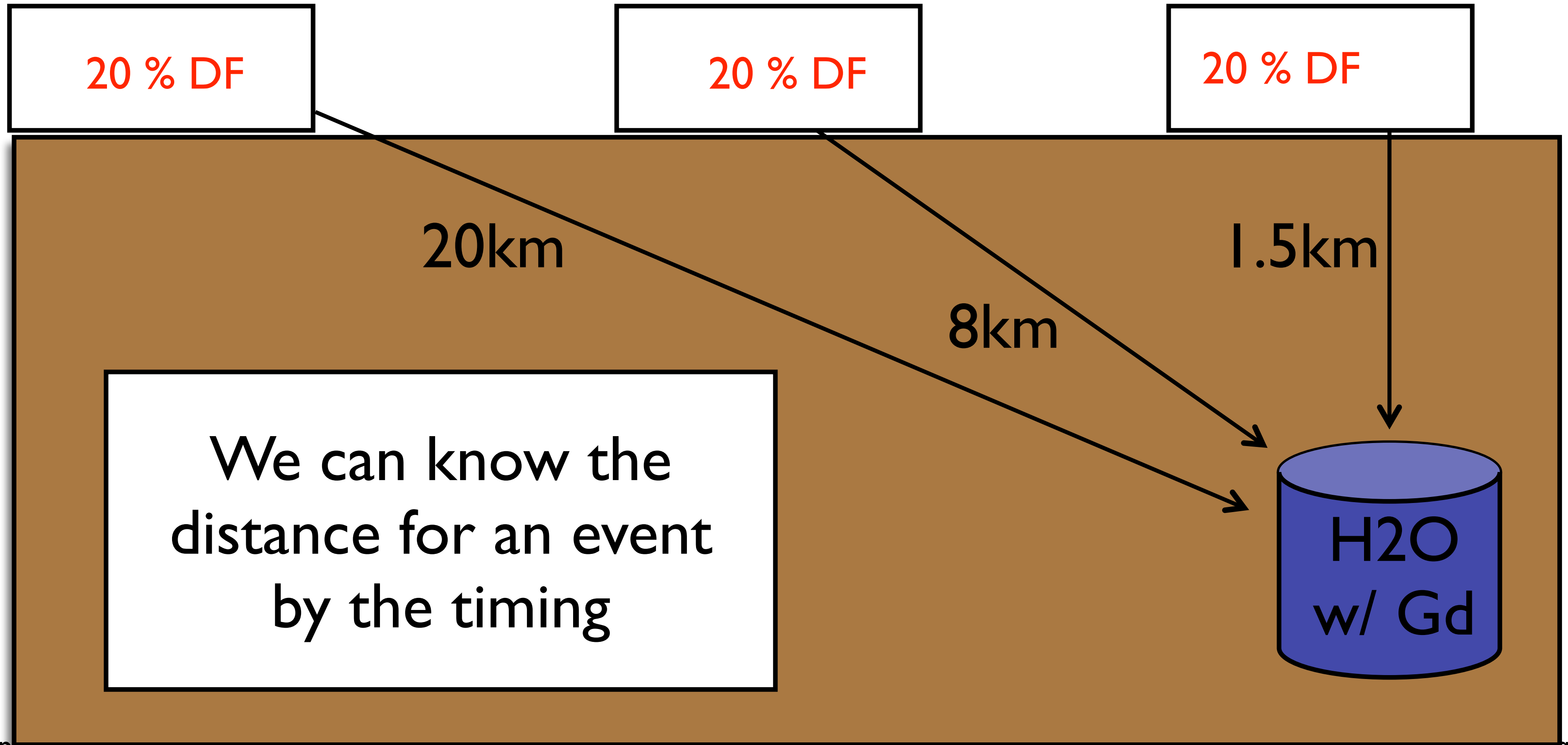
J. Alonso, F.T. Avignone, W.A. Barletta, R. Barlow, H.T. Baumgartner, A. Bernstein, E. Blucher, L. Bugel, L. Camilleri, R. Carr, J.M. Conrad, Z. Djurcuc, A. de Gouvêa, P.H. Fisher, C.M. Ignarra, B.J.P. Jones, C. Jones, G. Karagiorgi, T. Katori, S.E. Kopp, R.C. Lanza, W.A. Loinaz, P. McIntyre, G.B. Mills, V. Papavassiliou, M. Sanchez, K. Scholberg, W.G. Seligman, M.H. Shaevitz, S. Shalgar, T. Smidt, J. Spitz, H.-K. Tanaka, K. Terao, C. Tschalaer, M. Vagins, R. Van de Water, M.O. Wascko, R. Wendell, L. Winslow

http://arxiv.org/abs/1006.0260

We need 3 distances and we cannot have 3 300-kton detectors!




1.5 km Accelerator
8 km Accelerators
20 km Accelerators
Beam Off
Beam Off
1 ms
4 ms


20 % DF
20 % DF
20 % DF
20km
8km
1.5km
We can know the distance for an event by the timing
H2O w/ Gd

Approaches using cyclotrons:

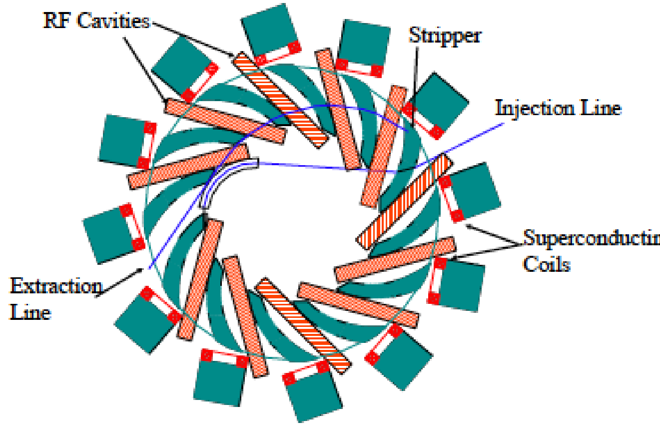
The compact cyclotron with self-extraction

under development for DTRA at MIT

An H_2^+ accelerator

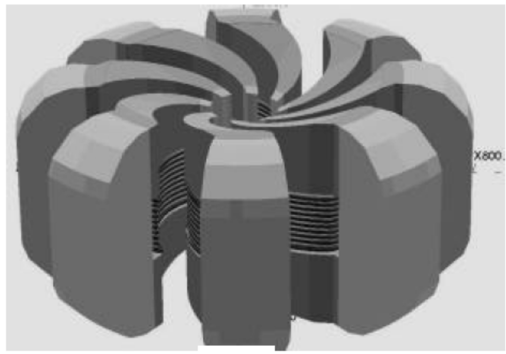
for ADS applications

Under dev.
by INFN, Catania



The stacked cyclotron:

7 cyclotrons
in one
flux
return



Under dev. for ADS at TAMU

Measurement strategy:

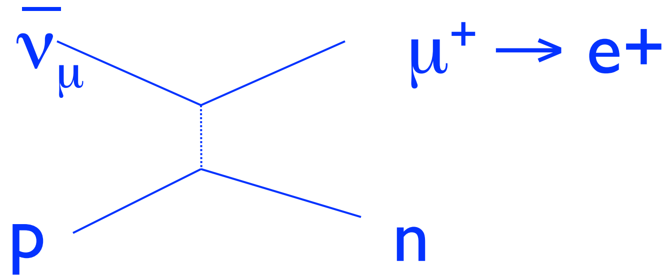
Using **near accelerator**
measure **absolute flux normalisation** with ν-e events to ~1%,
Also, measure the ν_eO event rate.

At far and mid accelerator,
Compare predicted to measured ν_eO event rates
to get the **relative flux normalisations between 3 accelerators**

In all three accelerators,
given the known flux, **fit for the** $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ **signal**
with free parameters: θ_{13} **and** δ

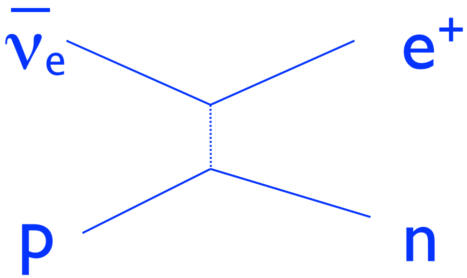
Non Beam Backgrounds

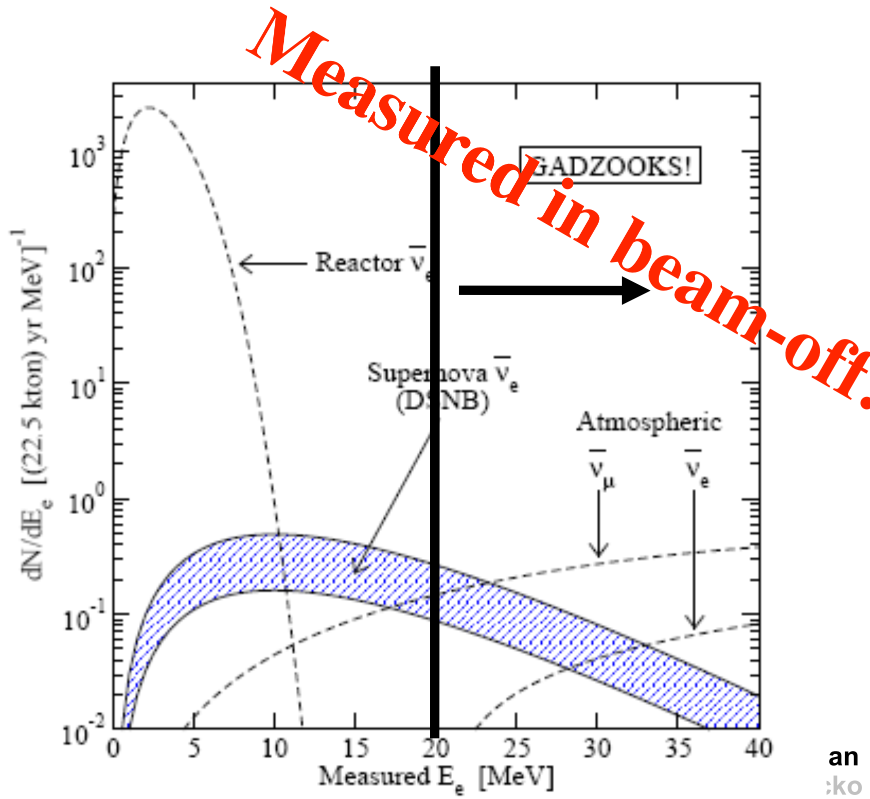
- Atmospheric $\bar{\nu}_\mu$ "Invisible muons":
  $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ where
  μ^+ is below Cherenkov threshold,
  stops and decays.



- Atmospheric $\bar{\nu}_e$ IBD events:
  $\bar{\nu}_e + p \rightarrow e^+ + n$

- Diffuse supernova neutrinos





Beam-related backgrounds

- Intrinsic $\bar{\nu}_e$ in beam

  From $\pi^- \rightarrow \mu^-$ events which don't capture in the beam stop

  $\sim 4\times 10^{-4}$ ν_e rate (low)

- Beam ν_e in coincidence with random neutron capture signal

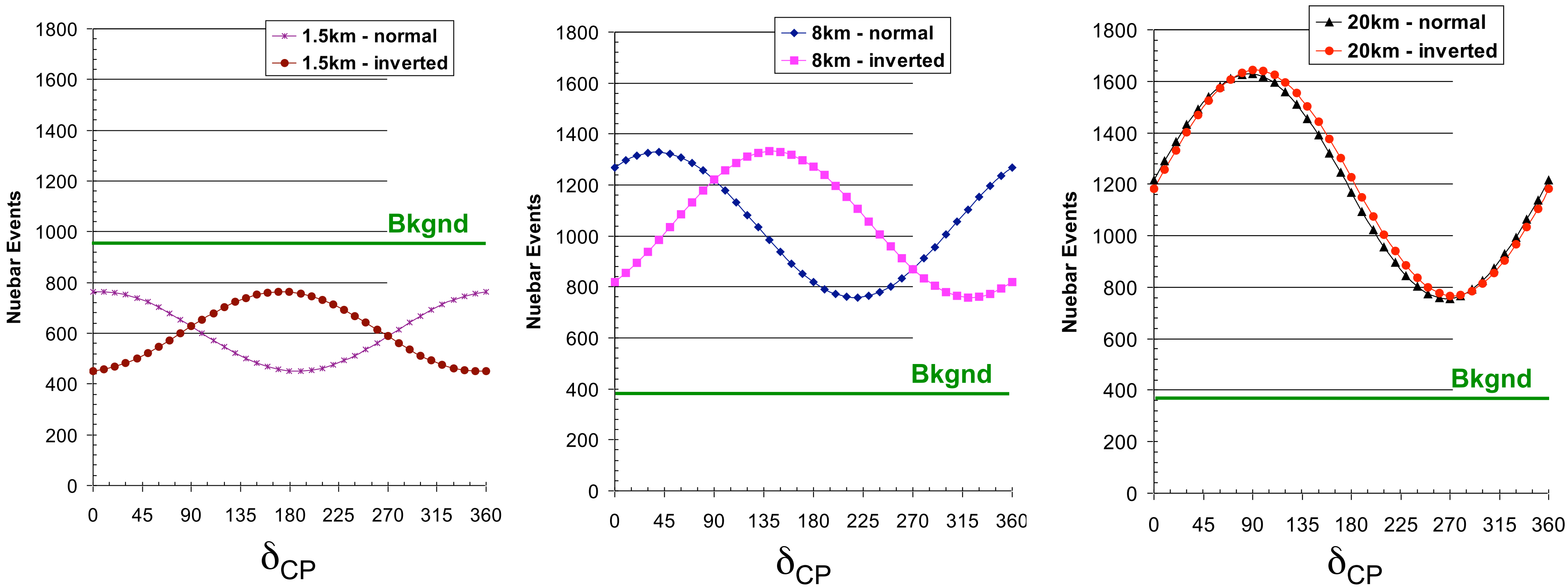
  Estimated to be very small from Super-K rates

- ν_e-Oxygen CC scatters producing an e^- + n signal

  Subsequent n from nuclear de-excitation should be very small.

All fall as $1/r^2$ from the 3 accelerators,
near accelerator provides a measurement

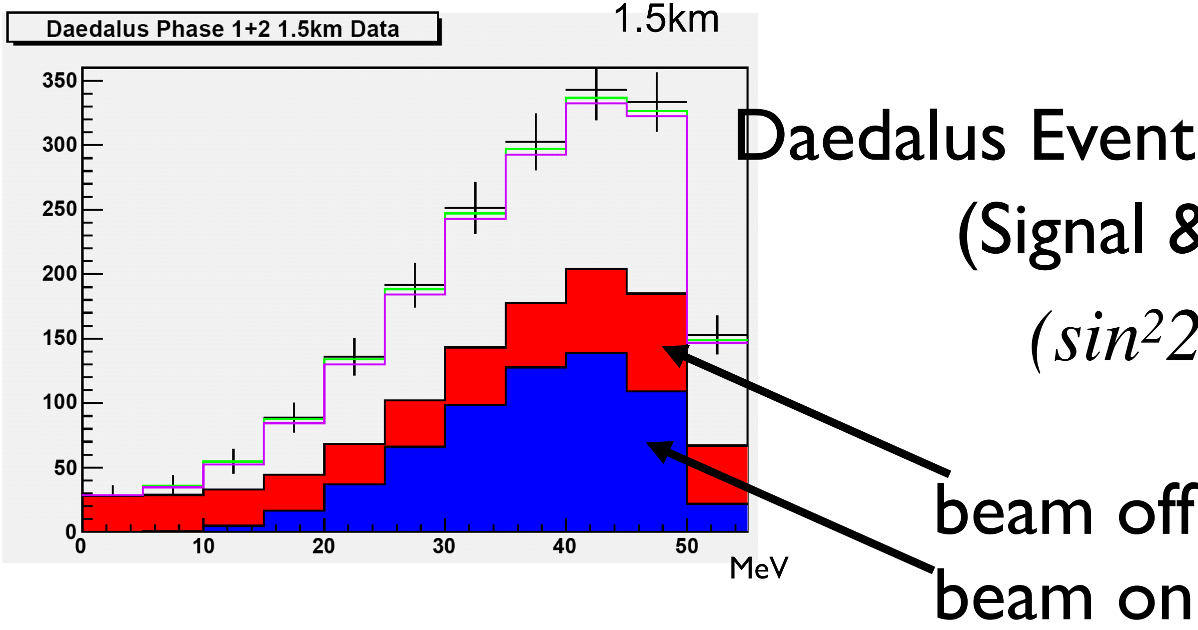
Total Events and background level, for $\sin^2 2\theta_{13}=0.05$

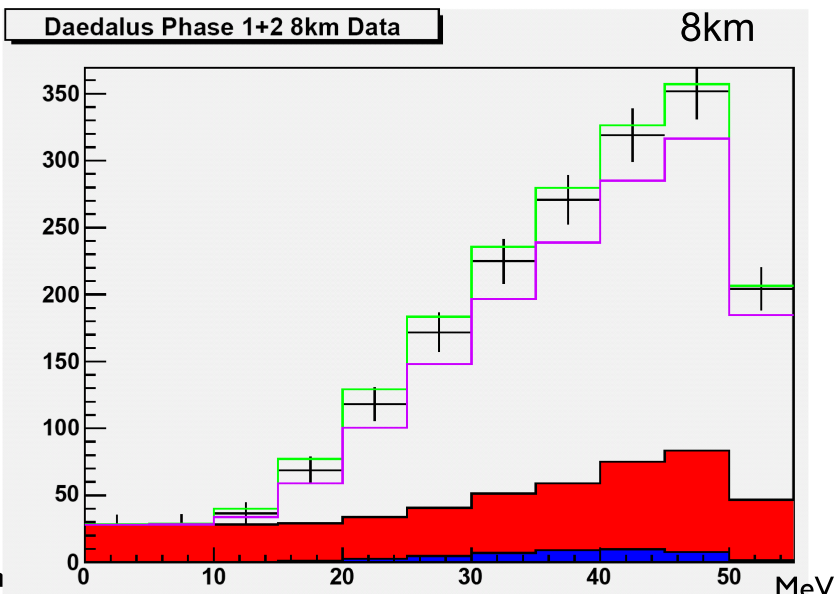


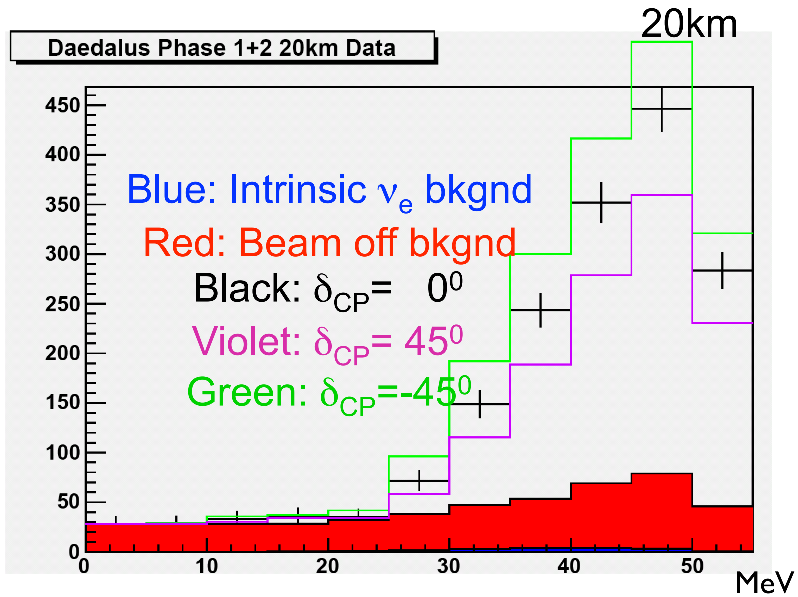
For the "signal accelerators" signal-to-background is excellent!

Daedalus Event Energy Distributions (Signal & Background)

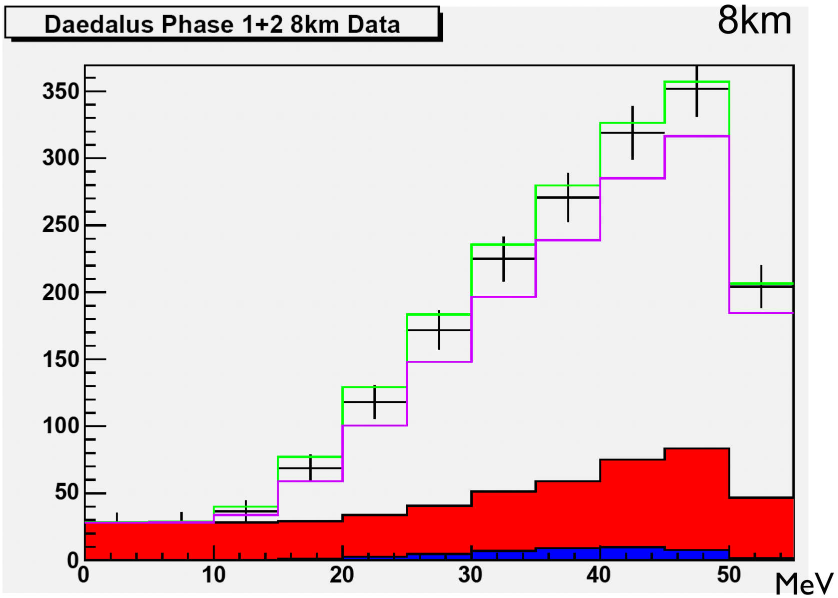
$(sin^2 2\theta_{13} = 0.04)$

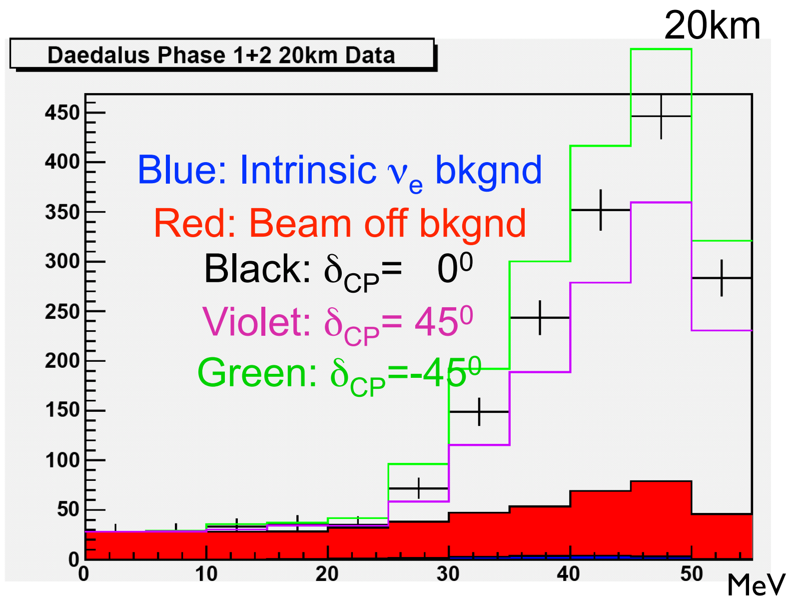




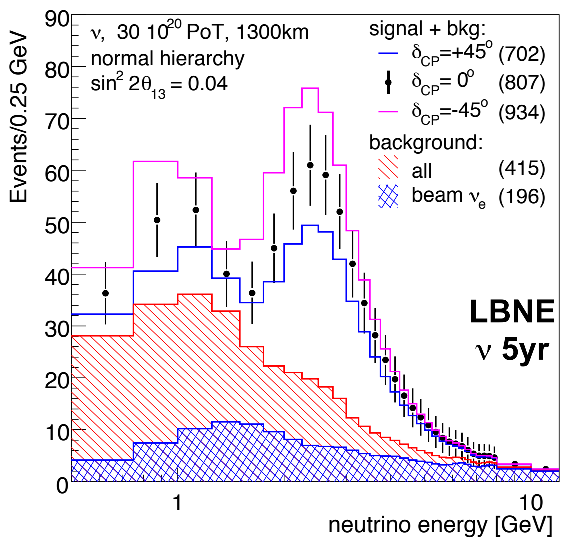


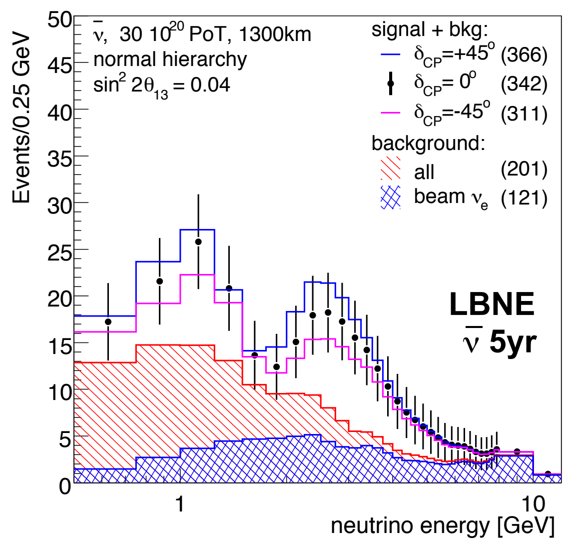
Compare signal to-background





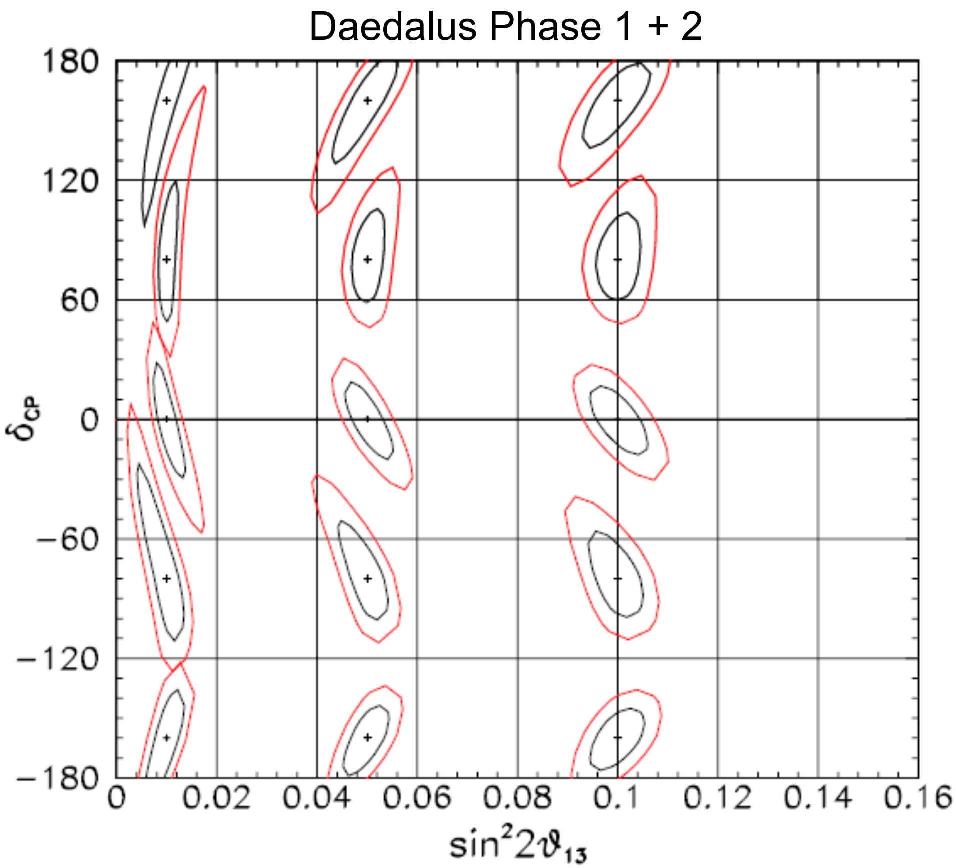
With LBNE...

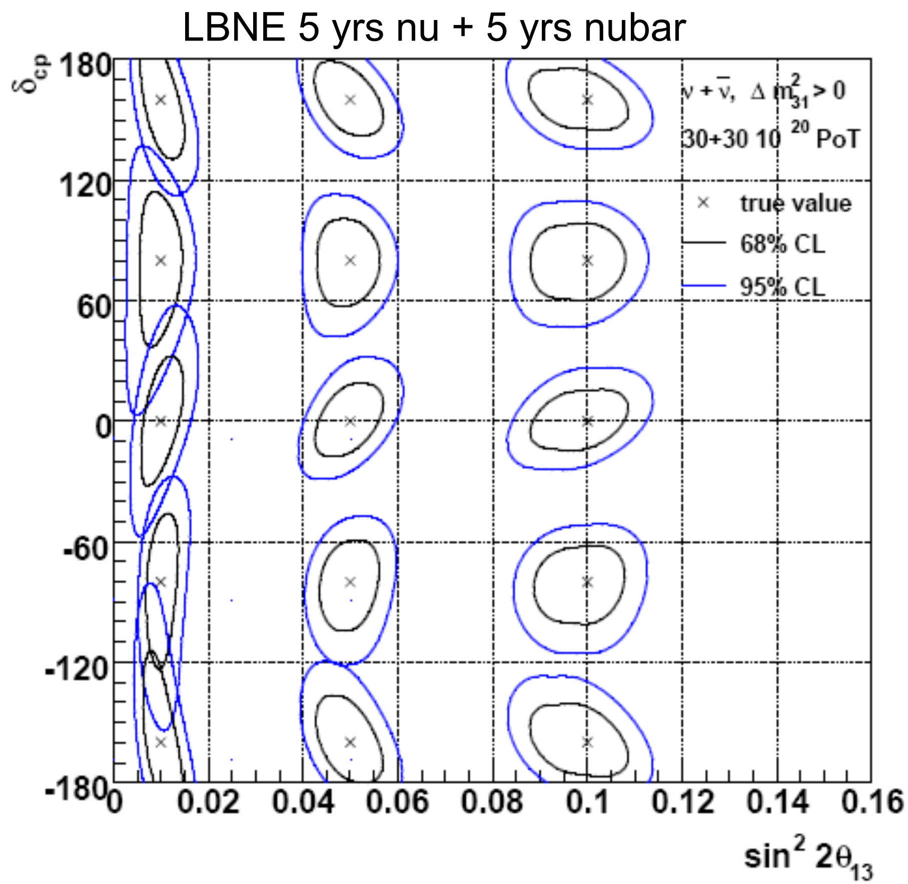




How well do we do?

By construction our capability is equal to LBNE,
But our measurement has completely different issues.





Combining experiments

These are complementary experiments

LBNE is mainly a ν experiment
DAEdALUS is entirely $\bar{\nu}$

LBNE is a high energy experiment (300 MeV - 10 GeV)
DAEdALUS is a low energy experiment

LBNE varies beam energy
DAEdALUS varies beam distance

How well do both work together?

Consider 4 scenarios:

1) "Standard DAEδALUS" -- 10 years, Phase I and II

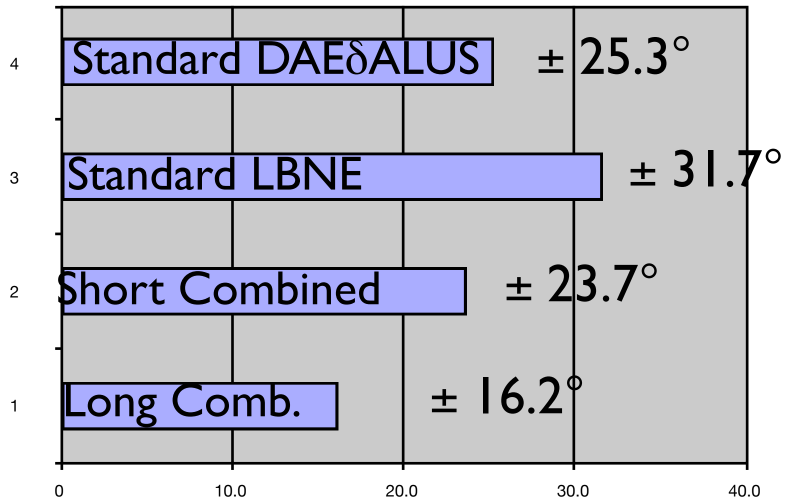
2) "Standard LBNE" -- 5 years ν and 5 years $\bar{\nu}$

3) "Short Combined" --5 years total,
with ν data from LBNE and
and $\bar{\nu}$ data from DAEδALUS I

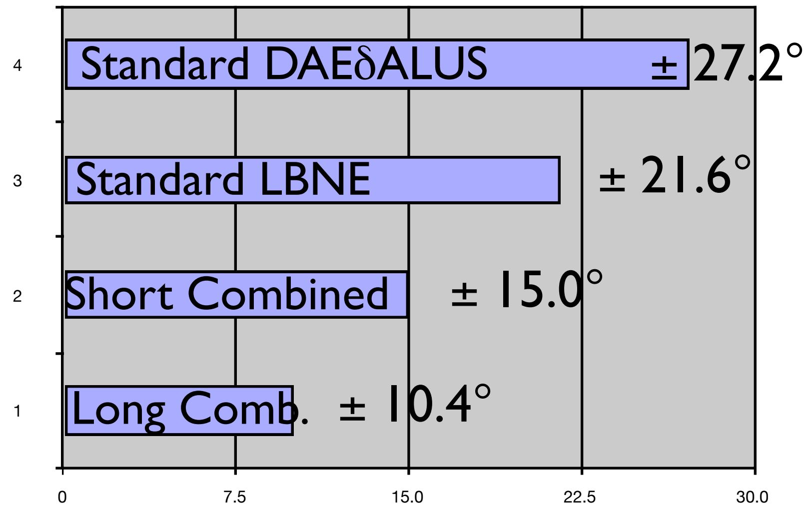
4) "Long Combined" -- 10 years total,
with only ν data from LBNE and
and $\bar{\nu}$ data from DAEδALUS I+II

For $\sin^2 2\theta_{13} = 0.05$

if $\delta = -80°$
then the error on δ would be..



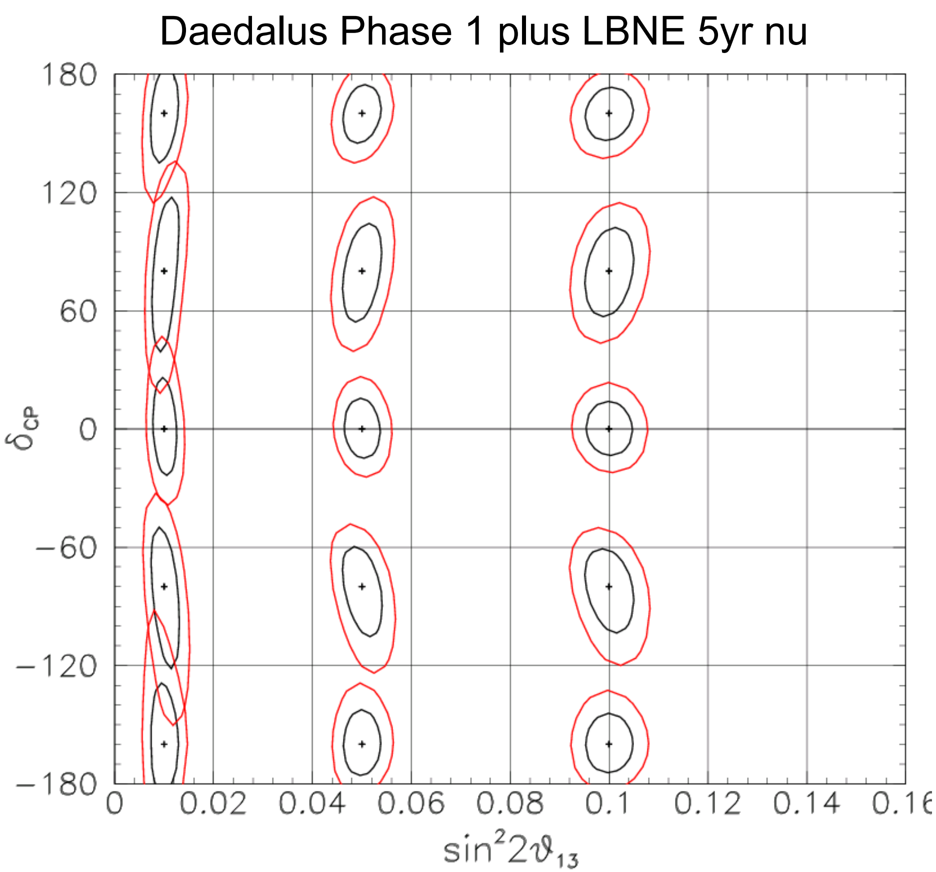
if $\delta = 160°$
then the error on δ would be..



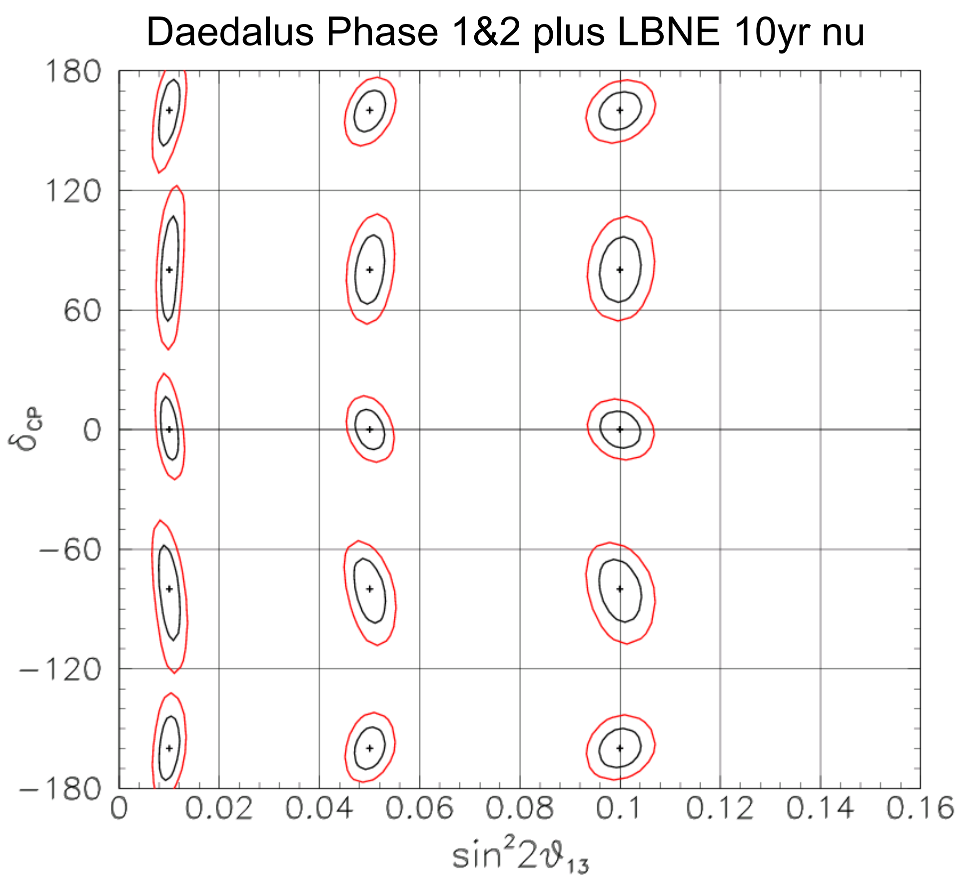
Whatever the value of δ,
the error from a combined analysis is smaller in 1/2 the time!

What the Combined Experiments can do

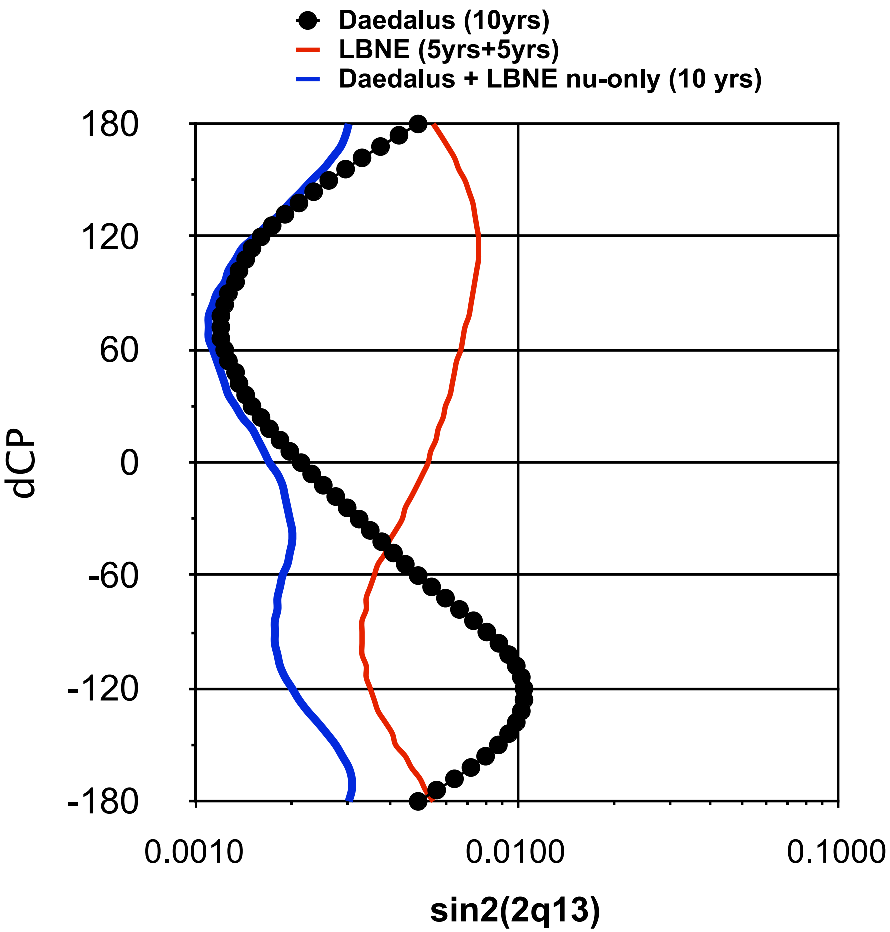
5yr Combined Running

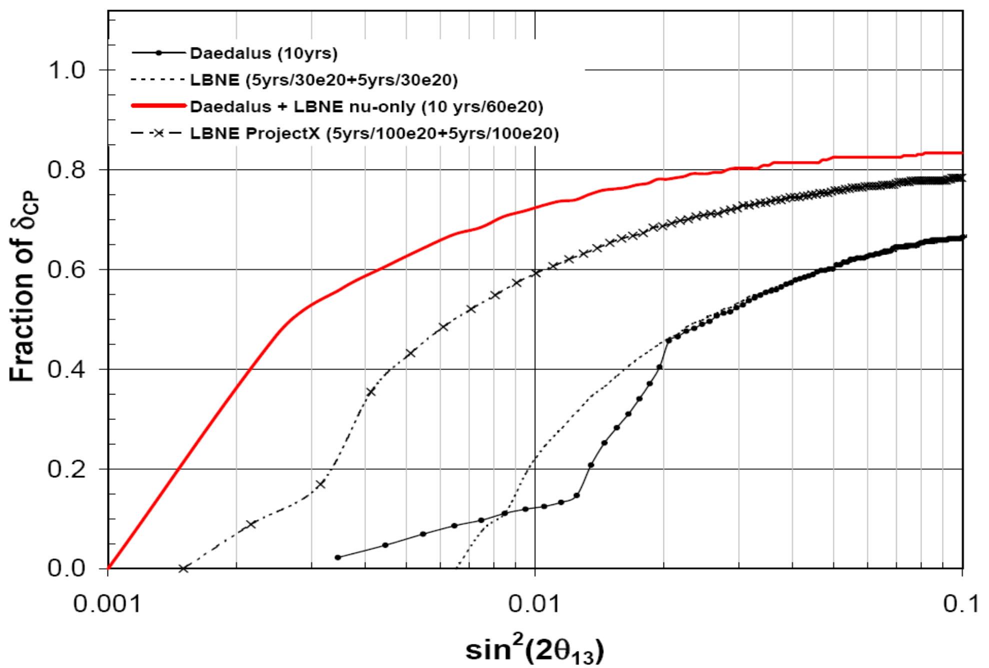


10yr Combined Running



Performance curves





Considerations for LBNO

- Need free protons for signal reaction
  - LAr not feasible
  - Scintillator will work
- Need direction of ν-e elastic scattering events.
  - Can scintillator work?
  - LAr will work.
- If no H_20, then combined scintillator and LAr might do it. More discussions needed.

Conclusions

- DAEdALUS is a novel approach to the search for CP violation.
- By design, the capability matches long baseline. DAEdALUS is statistics limited.
- Combining the DAEdALUS $\bar{\nu}$ data with long baseline ν data is very powerful, with sensitivity better than superbeams alone.

Contact information

- Morgan Wascko <m.wascko@imperial.ac.uk>

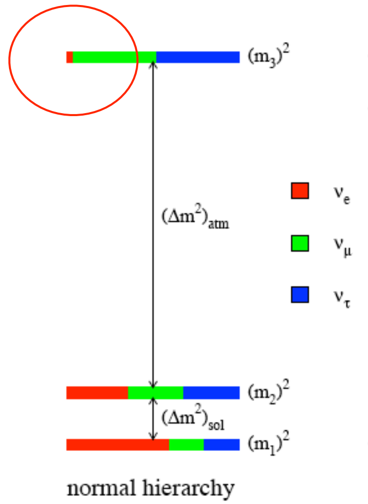
- Janet Conrad <conrad@mit.edu>
- Mike Shaevitz <shaevitz@nevis.columbia.edu>

Backups

Much Better Sensitivity by Combining Daedalus and LBNE Measurements

- Daedalus can provide a high-statistics antineutrino sample with low background and small systematics to be combined with LBNE ν-only data.
- LBNE sensitivity estimates use:
  - Standard neutrino flux files from the LBNE
  - 300kt Water Cherenkov
  - Proton rate = 6×10^{20} pot/yr
- Results calculated for four scenarios
  - "Standard DAEdALUS" -- 10 years `ν data
  - "Standard LBNE" -- 5 years ν and 5 years $\bar{\nu}$
  - "Short Combined" -- 5yrs Daedalus`ν data + 5yrs LBNE ν-**only** data

– "Long Combined" -- 10yrs Daedalus`ν data + 10yrs LBNE ν-**only** data



Most parameters are well known…

Parameter	Present: Value	Present: Uncert. (±)	Assumed Future: Value	Assumed Future: Uncert. (±)
$\Delta m^2_{21} \times 10^{-5}\text{eV}^2$	7.65	0.23	7.65	N/A
$\Delta m^2_{31} \times 10^{-3}\text{eV}^2$	2.40	0.12	2.40	0.02
$\sin^2(2\theta_{12})$	0.846	0.033	0.846	N/A
$\sin^2(2\theta_{23})$	1.00	0.02	1.00	0.005
$\sin^2(2\theta_{13})$	0.06	0.04	0.05	0.005

Except for θ_{13}!

Must show sensitivity
as function of both θ_{13} and δ

Our equation flips sign between $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

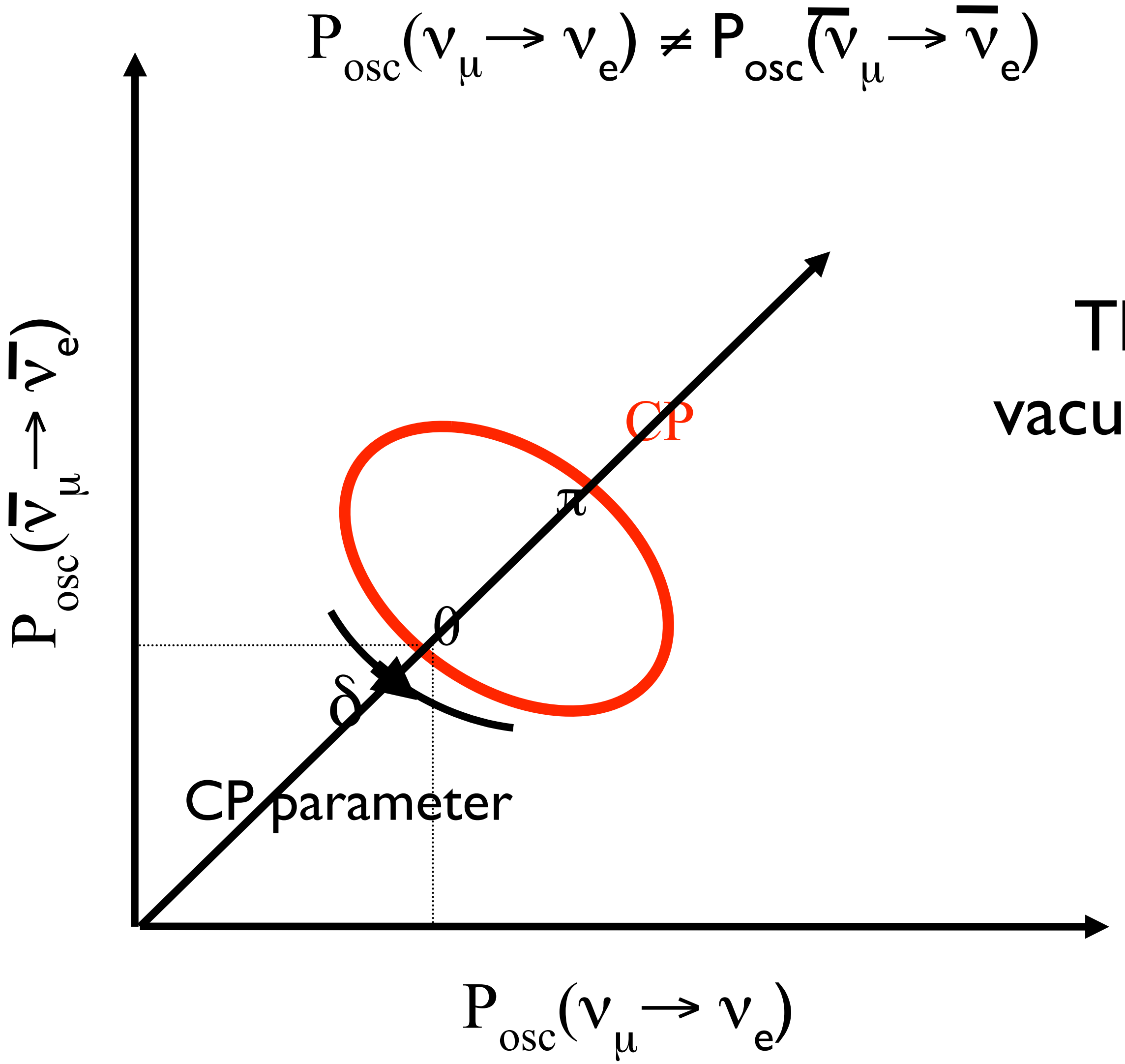
in a vacuum…

$$
\begin{aligned}
P = \quad & (\sin^2\theta_{23}\sin^2 2\theta_{13})\,(\sin^2\Delta_{31}) \\
& \mp \underline{\sin\delta}\;(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\,(\sin^2\Delta_{31}\sin\Delta_{21}) \\
& + \underline{\cos\delta}\;(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\,(\sin\Delta_{31}\cos\Delta_{31}\sin\Delta_{21}) \\
& + \underbrace{(\cos^2\theta_{23}\sin^2 2\theta_{12})}_{\text{terms depending on mixing angles}}\,\underbrace{(\sin^2\Delta_{21})}_{\text{terms depending on mass splittings}}.
\end{aligned}
$$

what we want to measure

$$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$

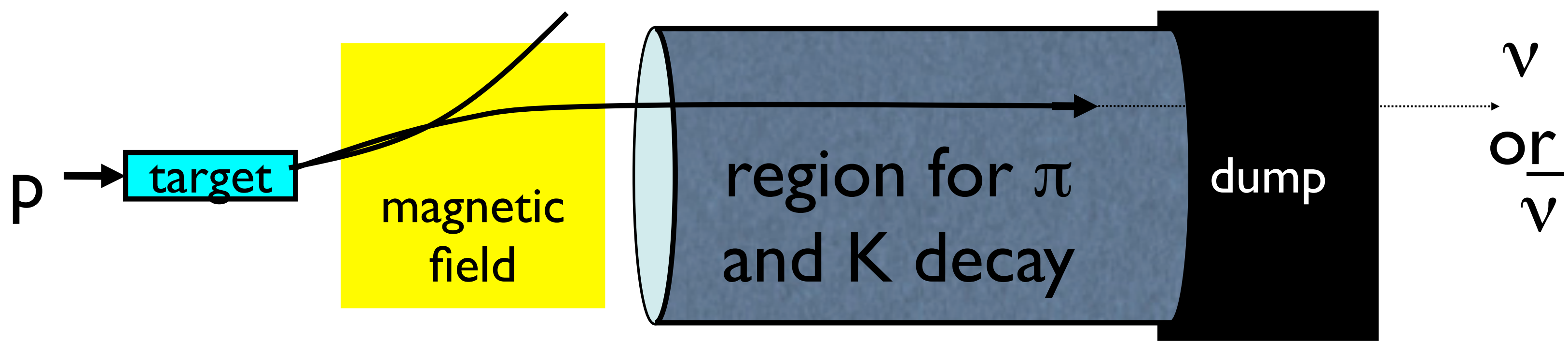
The classic idea for how to see CP violation:



This is in a vacuum (or air).

But the proposed experiments to search for CP violation shoot the neutrinos through a lot of matter

The most straightforward way to make a high-flux beam which switches from ν to $\bar{\nu}$:

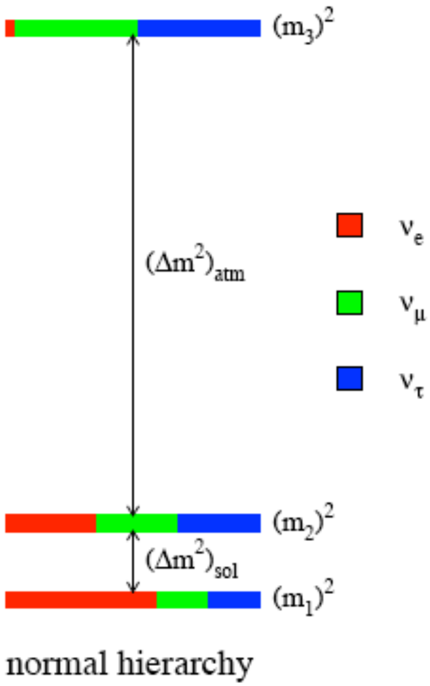


"Conventional neutrino beam" -- 100's of MeV to a few GeV

The Probability for Oscillations...

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

P is maximised when $\Delta m^2(L/E) \sim 1$



The atmospheric Δm^2 ~0.001 eV^2

E from a convention beam is ~ 1 GeV

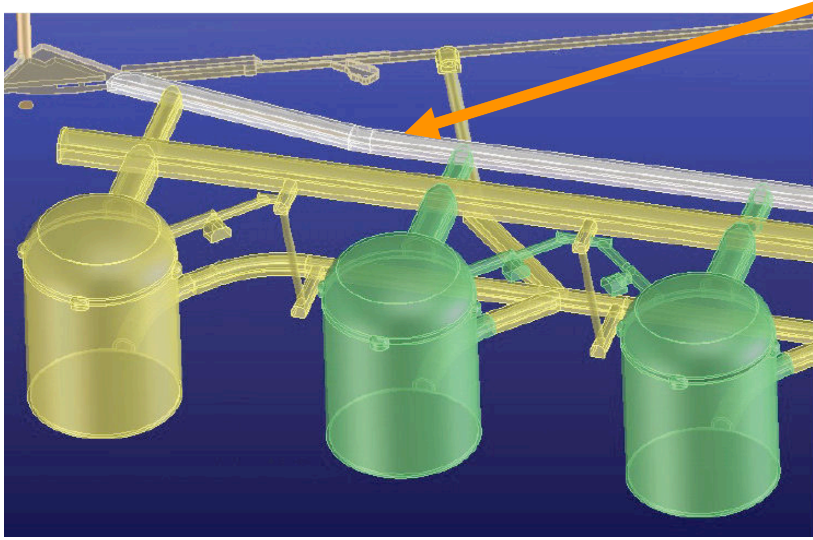
So L = 1000 km !!!

E.g., LBNE -- starting in 2020

Beam from Fermilab

Shoots to detectors in South Dakota

1300 km



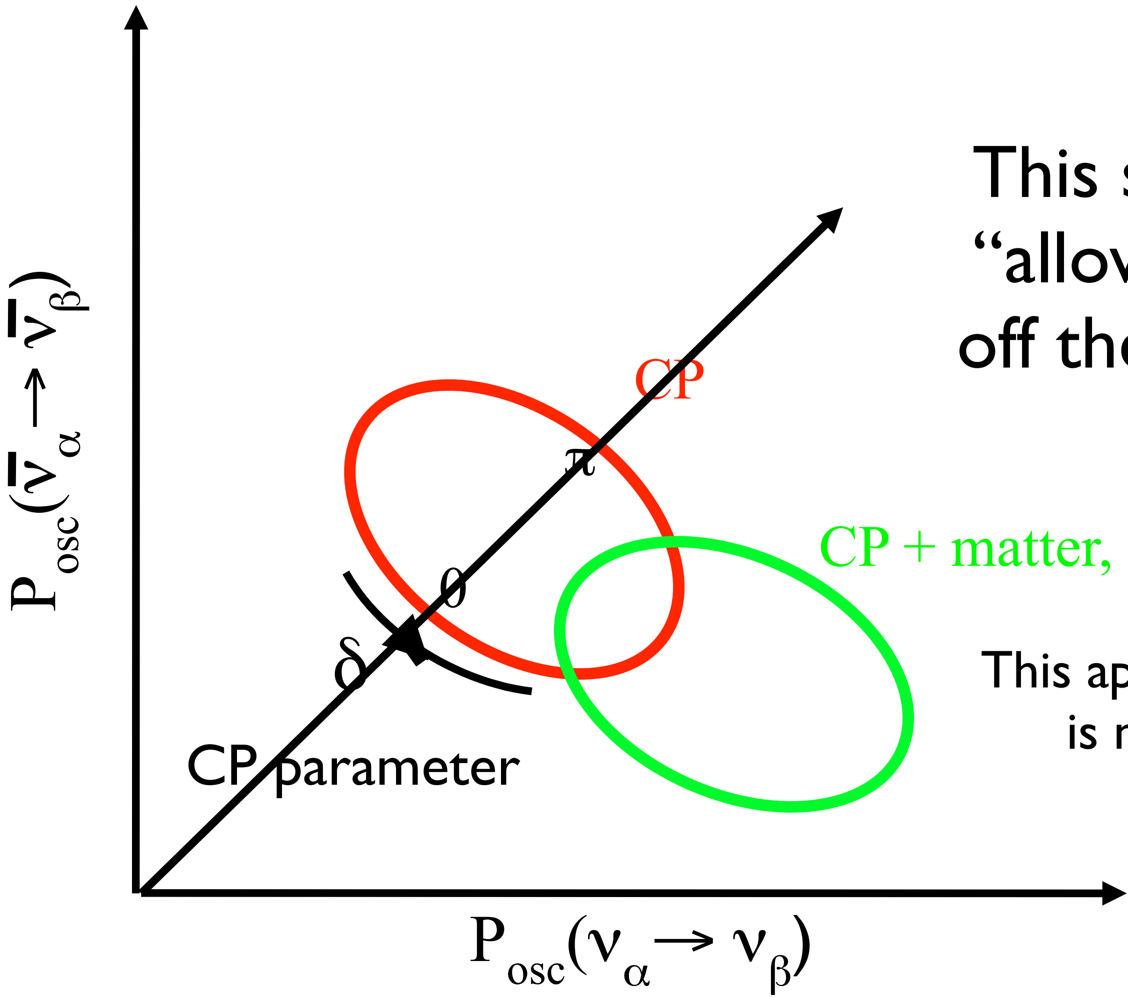
And there is **lots and lots** of matter along a 1300 km path!

also true for MEMPHYS and HyperK designs

The Earth is made of matter (electrons)

not antimatter (positrons)

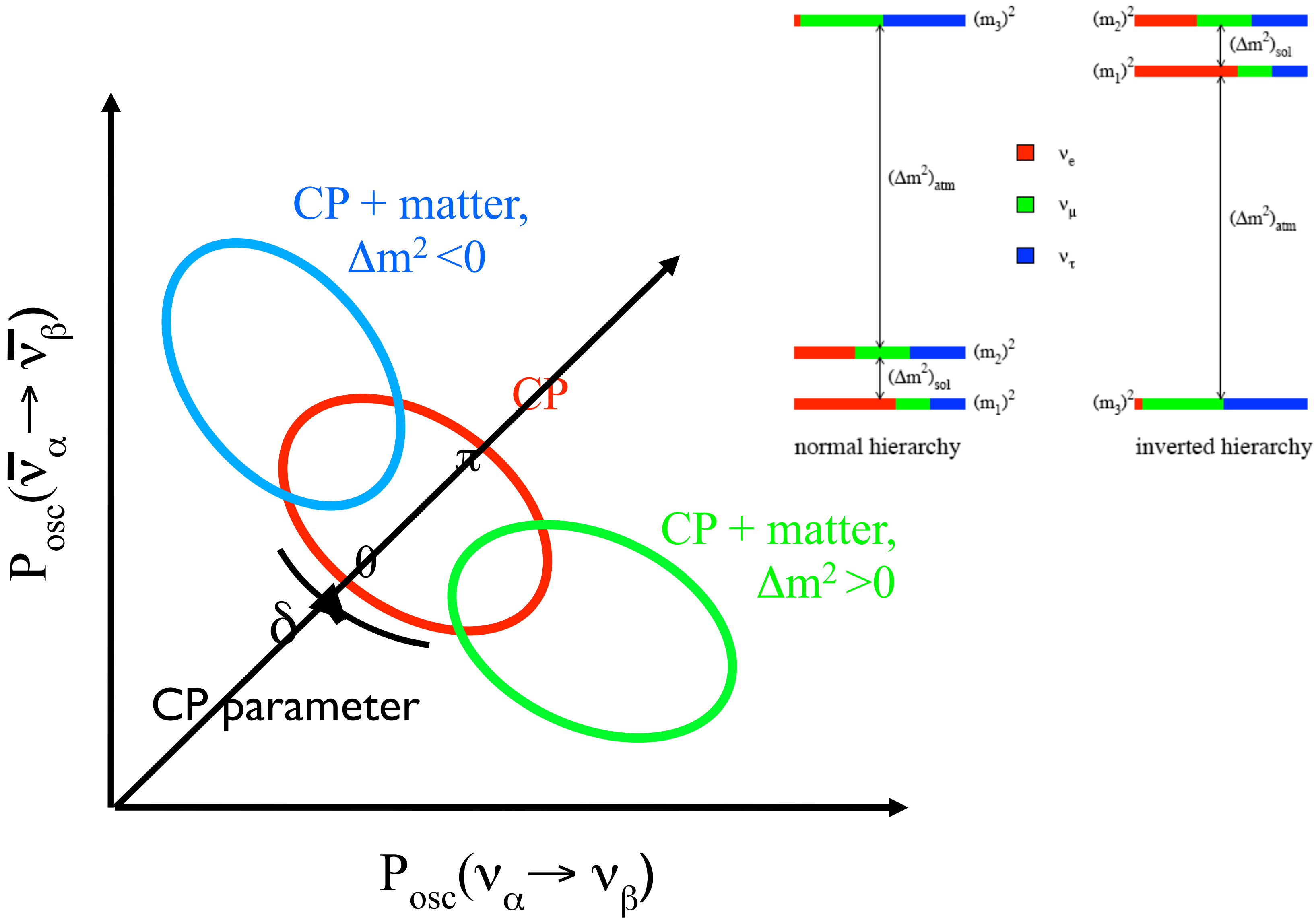
Forward scattering affects neutrinos differently than antineutrinos.



This slides the "allowed ring" off the diagonal

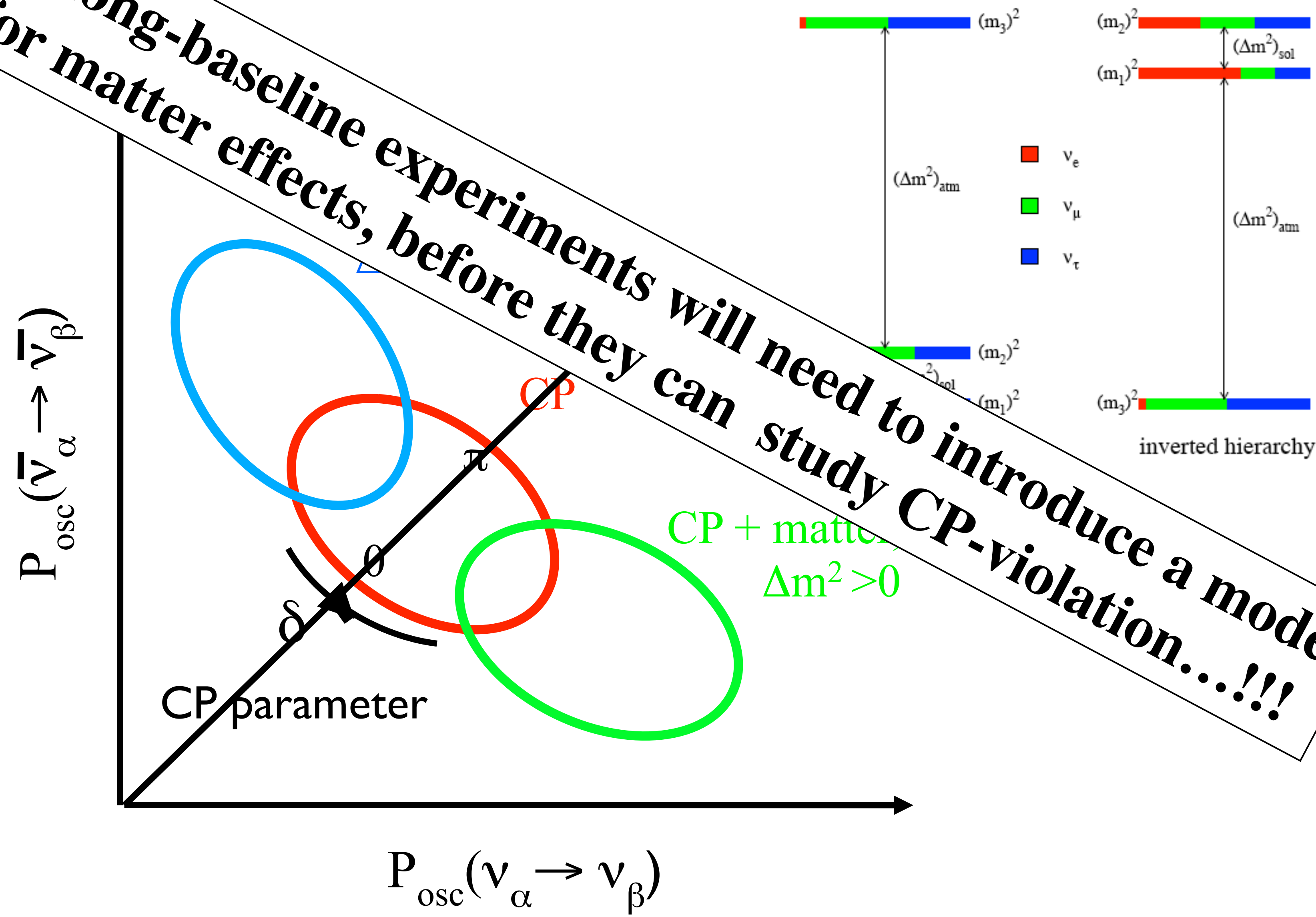
This apparent CP violation is not what we are looking for!

Worse, we actually don't know which direction…

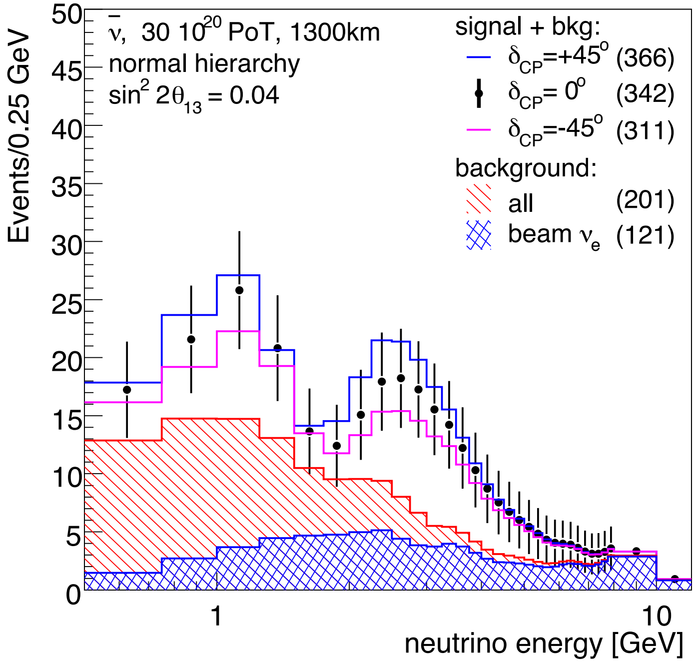


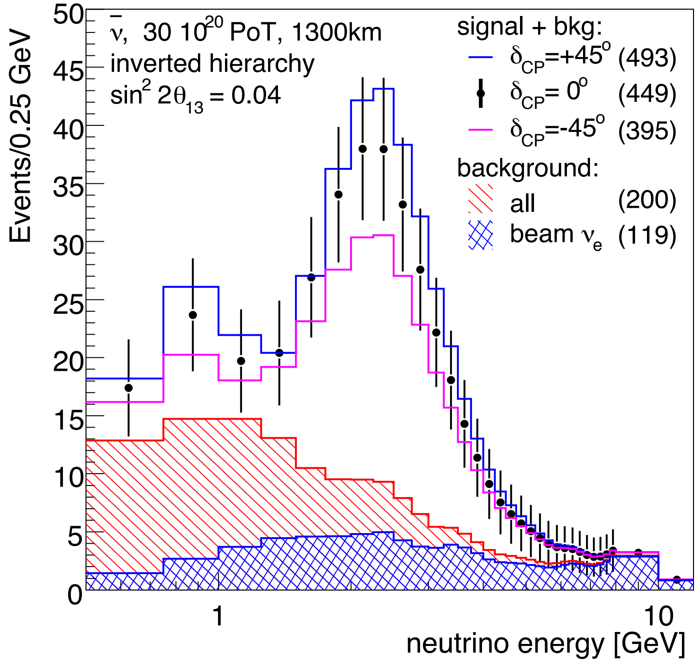
Worse, we actually don't know which direction…

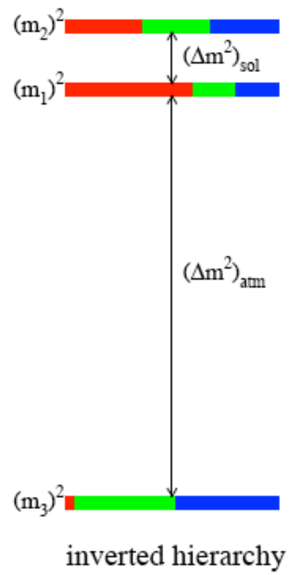
All long-baseline experiments will need to introduce a model for matter effects, before they can study CP-violation…!!!



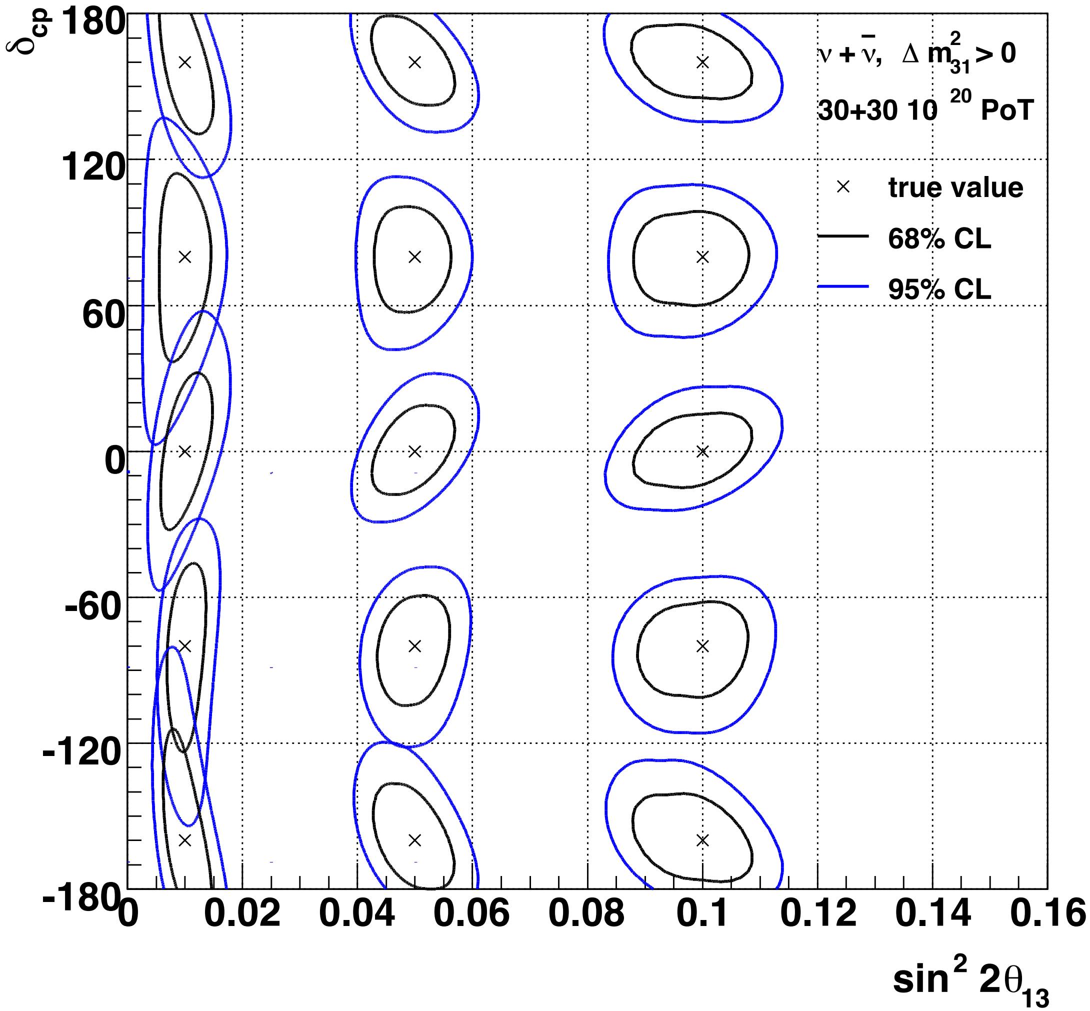
Expectation for inverted hierarchy:







If we know the mass hierarchy, then this is how well LBNE can do in 10 years of running (*e.g.* without Project X)

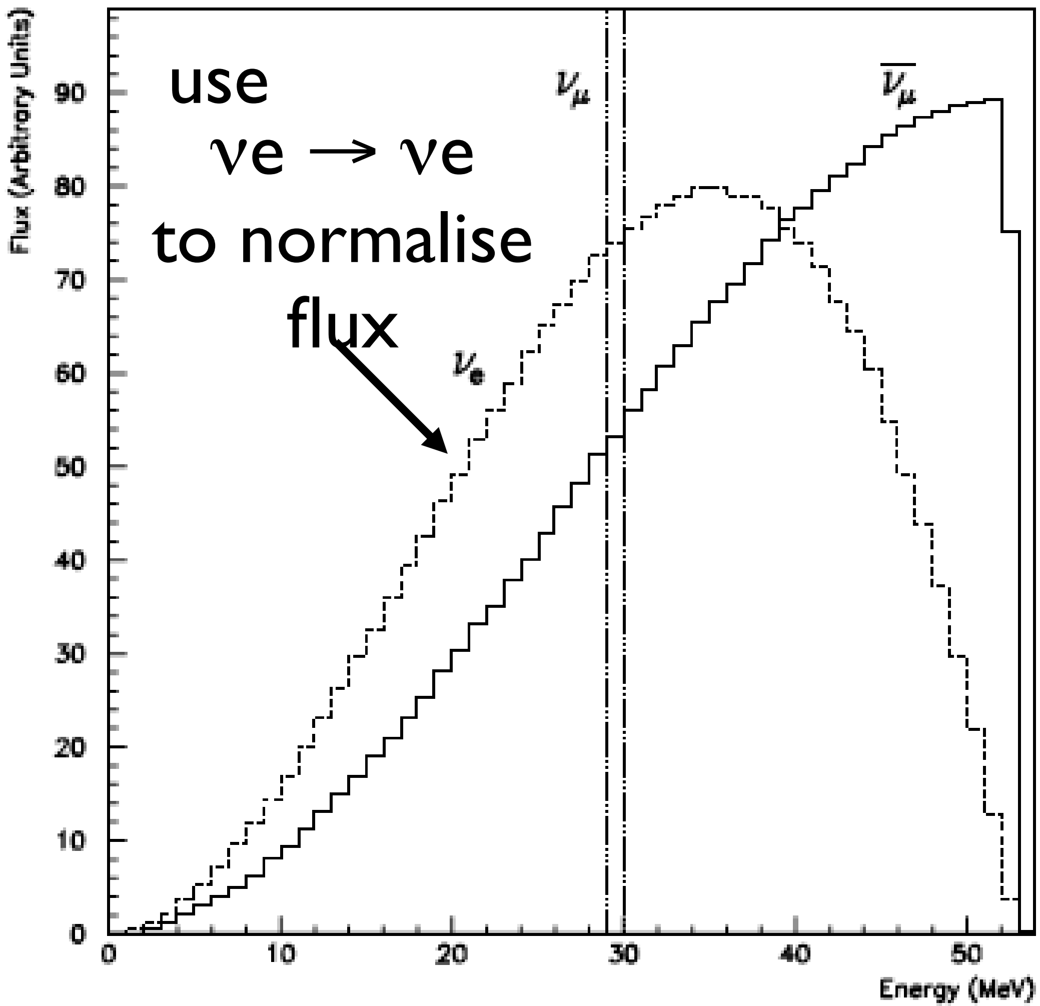


A π^+ decay at rest beam:

$$p+C \rightarrow \pi^+ \rightarrow \nu_\mu + \mu^+ \\ \hookrightarrow e^+ \bar{\nu}_\mu \nu_e,$$

Shape driven by nature!

Only the normalisation varies from beam to beam



use
$\nu e \rightarrow \nu e$
to normalise flux

No intrinsic $\bar{\nu}_e$

Perfect for a $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search

(And previously employed by KARMEN, LSND, etc...)

The plan:
Use $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
and use the L/E dependence to extract δ

in a vacuum…

$$
\begin{aligned}
P = \quad & (\sin^2\theta_{23}\sin^2 2\theta_{13})\ (\sin^2\Delta_{31}) \\
& \mp \underline{\sin\delta}\ (\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\ (\sin^2\Delta_{31}\sin\Delta_{21}) \\
& + \underline{\cos\delta}\ (\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\ (\sin\Delta_{31}\cos\Delta_{31}\sin\Delta_{21}) \\
& + (\cos^2\theta_{23}\sin^2 2\theta_{12})\ (\sin^2\Delta_{21}).
\end{aligned}
$$

We want to see if δ is nonzero

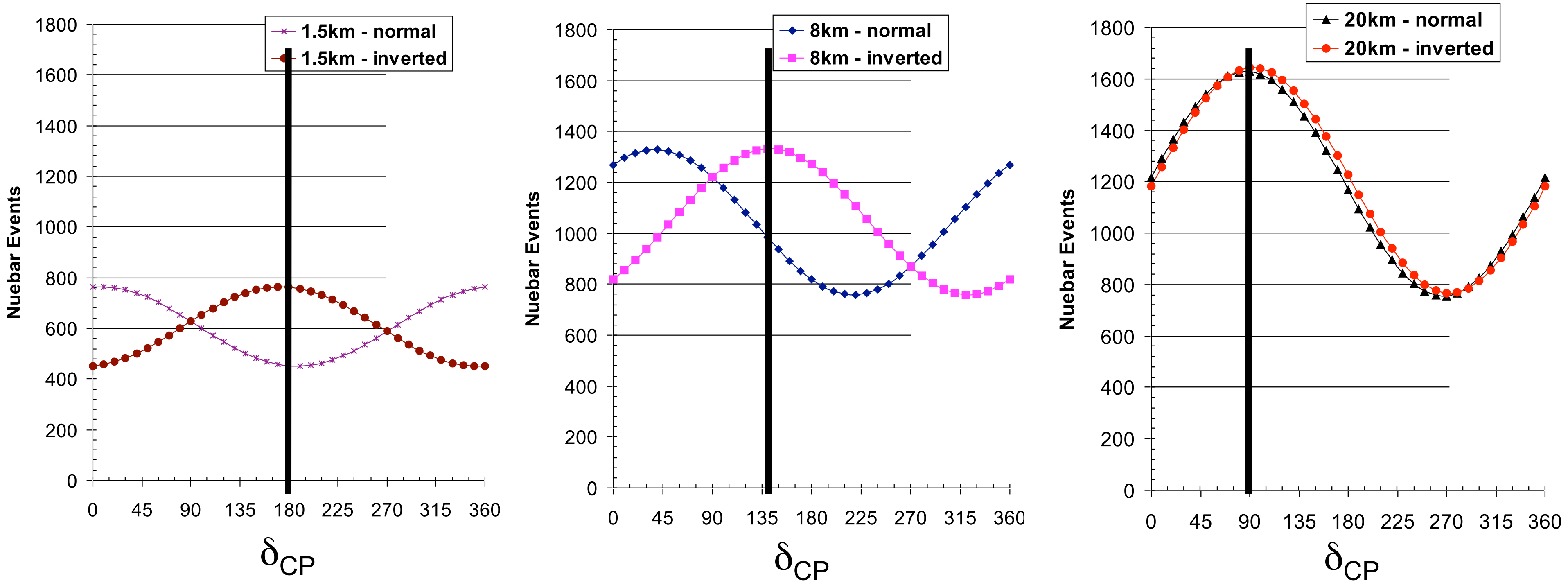
terms depending on mixing angles

terms depending on mass splittings

$$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$

For E=50 MeV

L=1.5 km 8 km 20 km

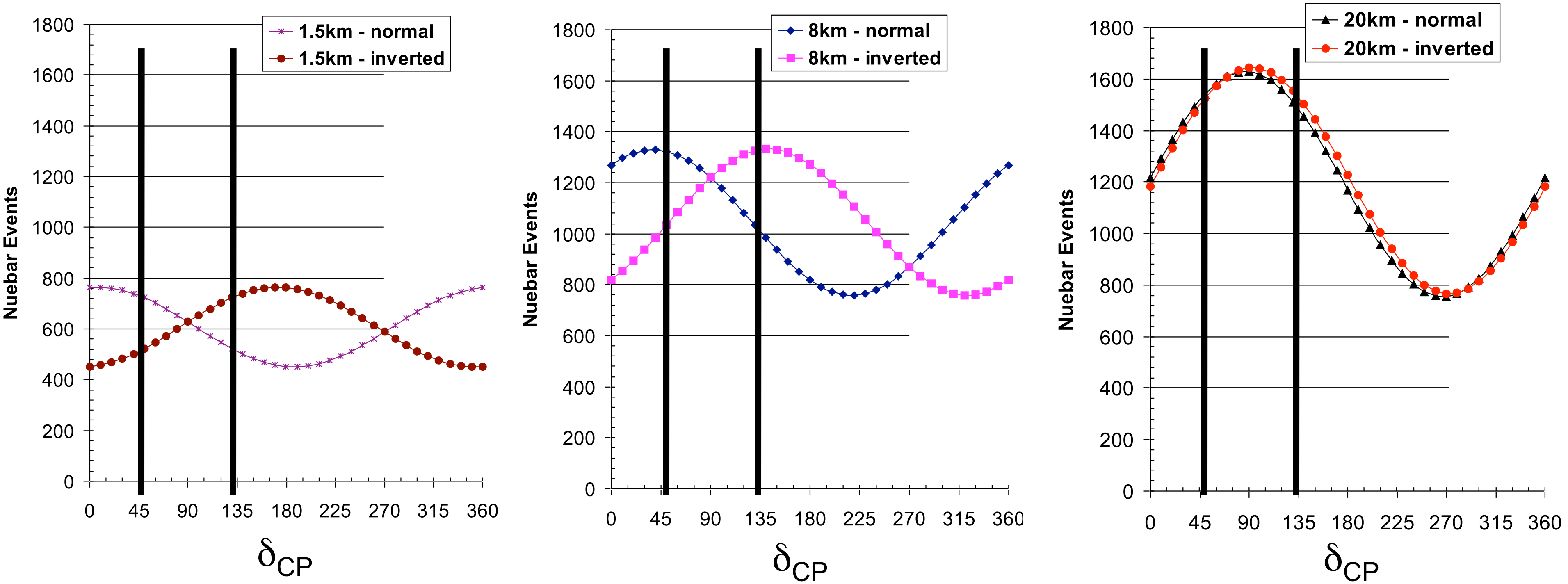


Close to source   Osc mid ($\pi/4$)   Osc max ($\pi/2$)

Find δ by comparing the number of events at multiple locations

For E=50 MeV

L=1.5 km 8 km 20 km



There will be a degeneracy with hierarchy:

We cannot tell the difference between δ=45° and normal hierarchy

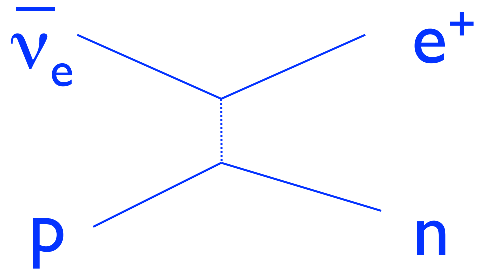
and δ=135° and inverted

DAEδALUS cannot differentiate the hierarchy

How do you observe ~50 MeV $\bar{\nu}_e$ events?

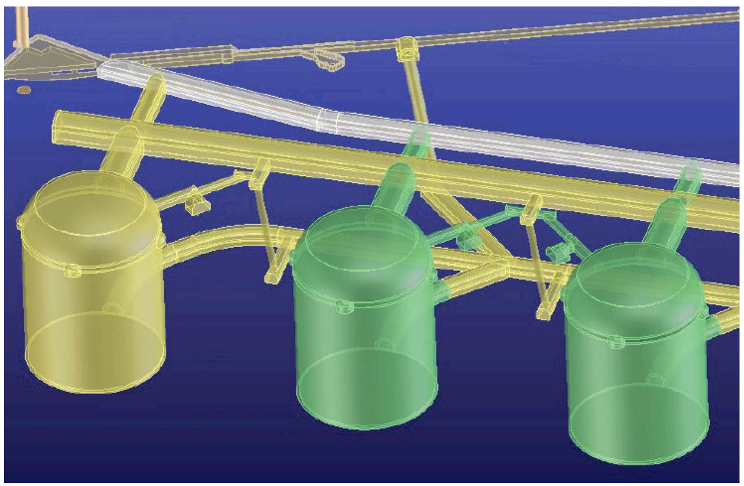
The signal:

inverse beta decay, IBD



$$\bar{\nu}_e + p \rightarrow e^+ + n$$

You need a lot of free protons!

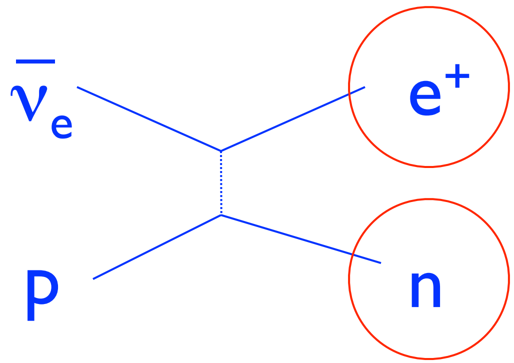


Use the <u>same</u> ultra-large water Cherenkov detector system as LBNE at DUSEL

300 kton fiducial volume

We want to observe a 2-fold signature in time…

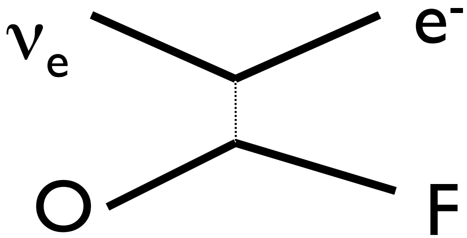
The signal:
inverse beta decay, IBD



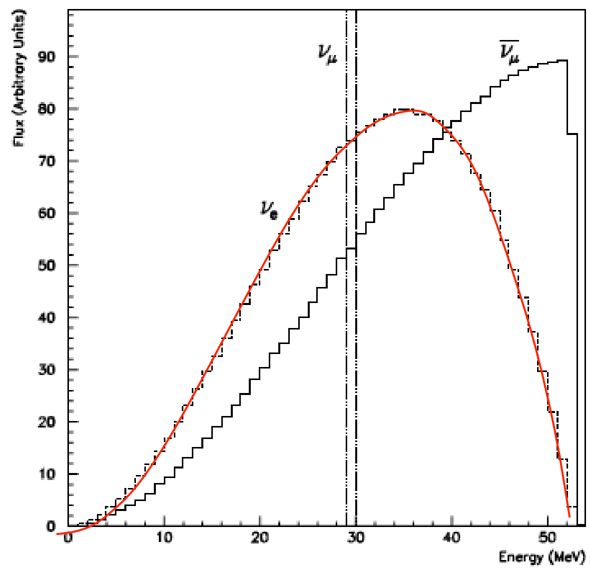
1st signal

2nd-- from capture

We need to reject:



Lower xsec than IBD by $\times 10$ because of binding

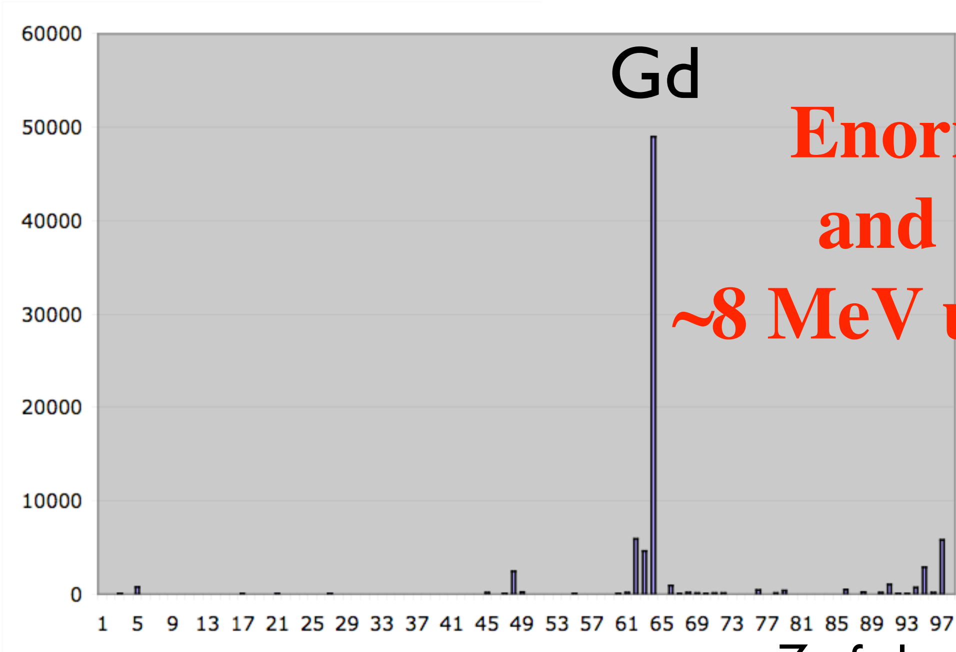


But even if the xsec is small…

there are a lot of ν_es in the beam!

To enhance the signal from n-capture, add gadolinium!

thermal neutron capture xsec (barns)



Z of element

Enormous xsec and produces ~8 MeV upon capture!

http://environmentalchemistry.com/yogi/periodic/crosssection.html

Adding Gd is technically difficult

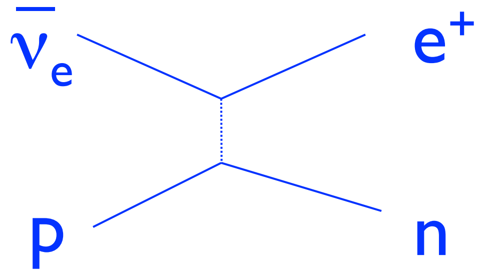
But others need it too:
Supernova Relic Neutrino Search
Non-proliferation studies

good progress is being made

Energy Dependence of IBD events

The signal:

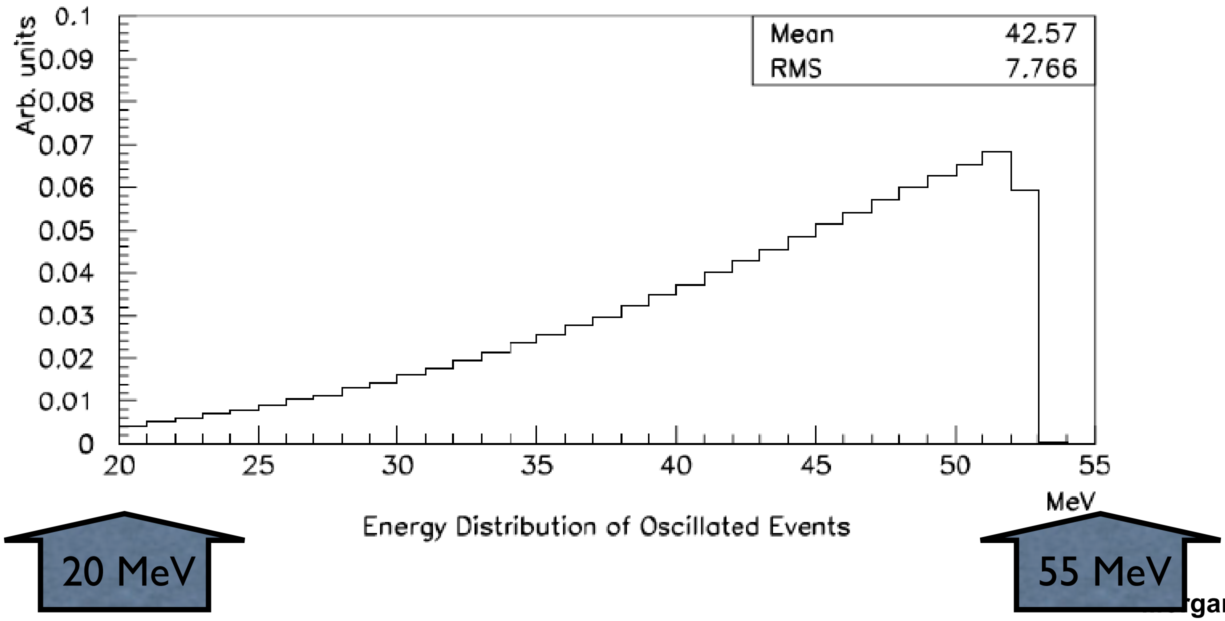
inverse beta decay, IBD



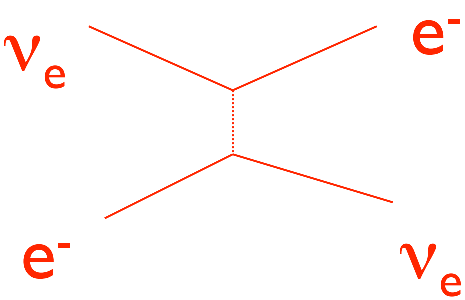
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

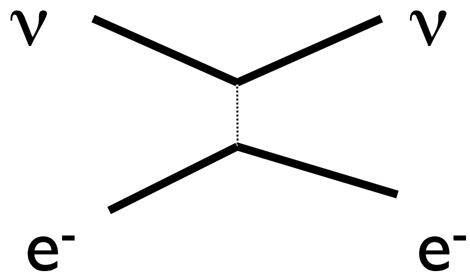
Event range is

$20 < E_\nu < 55$ MeV

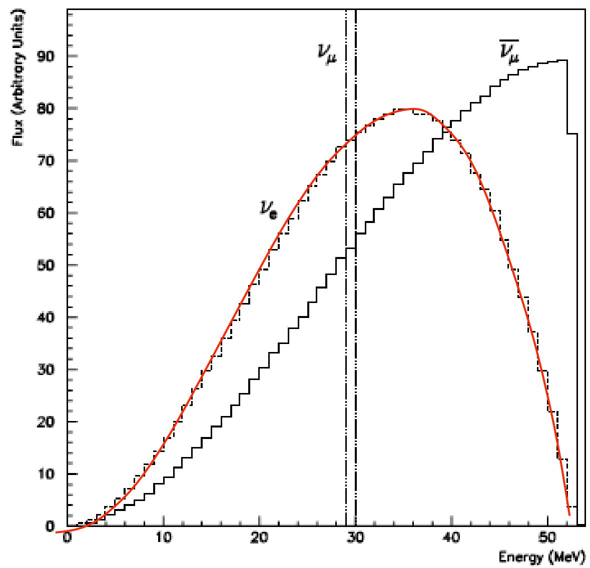


Neutrino-electron scattering is also very important!





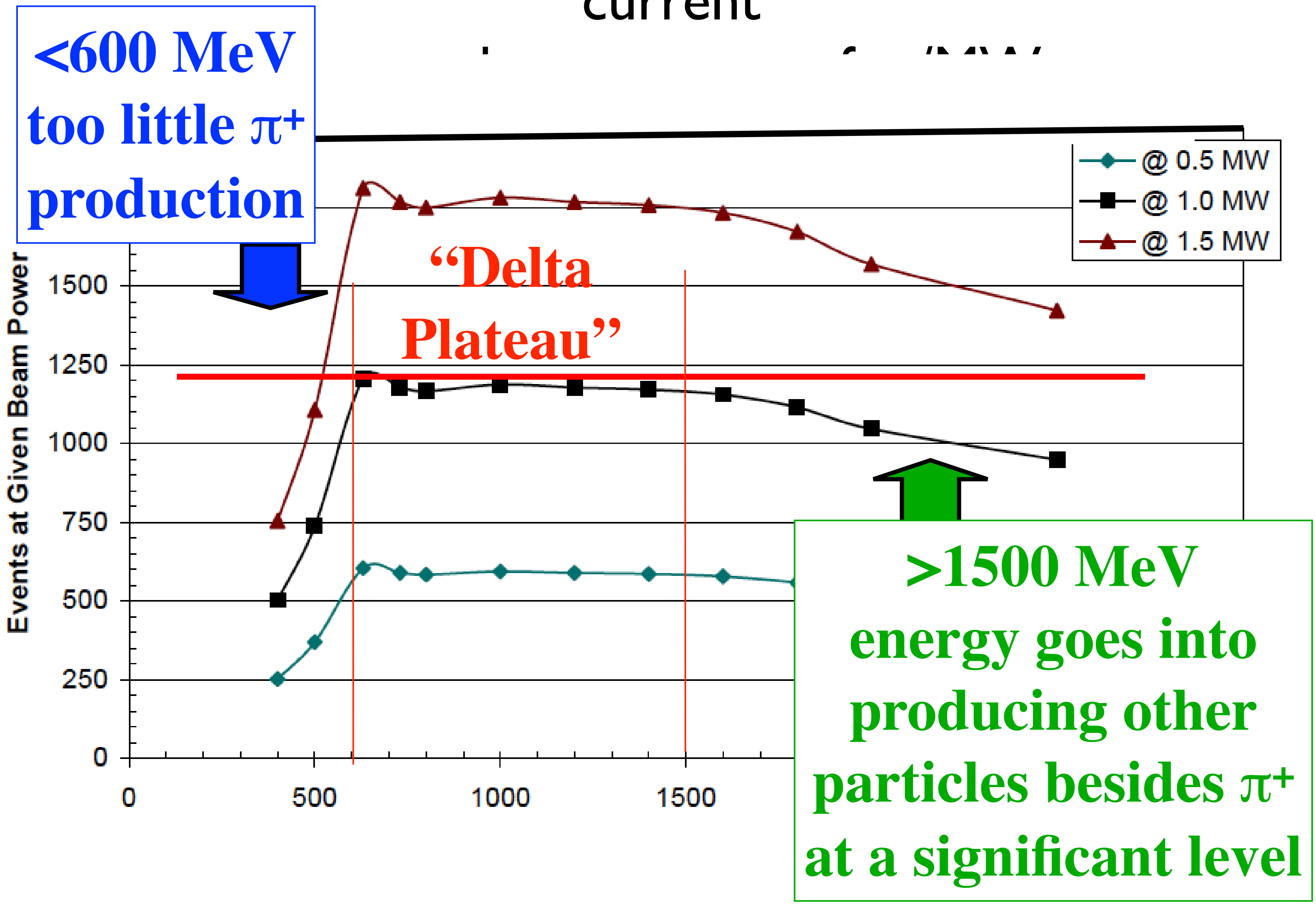
Provides the normalisation of the flux since the xsec is known to 1%



Mostly from ν_es

about 20% from muon flavour

What proton energy is required?
There is a "Delta plateau" where you can trade energy for current



Wanted: ~1 MW sources of protons, w/ energy > 600 MeV and <1500 MeV for a reasonable price

What isn't needed:

1. A fancy beam structure -- CW is fine. (run 100 μs on and 400 μs off)

2. Ability to inject into another accelerator or need to make clean secondary beams.

3. Flexibility on beam energy.

Wanted: ~1 MW sources of protons, w/ energy > 600 MeV and <1500 MeV for a reasonable price

Currently looking into cyclotron designs...

But also open to linear accelerator options.

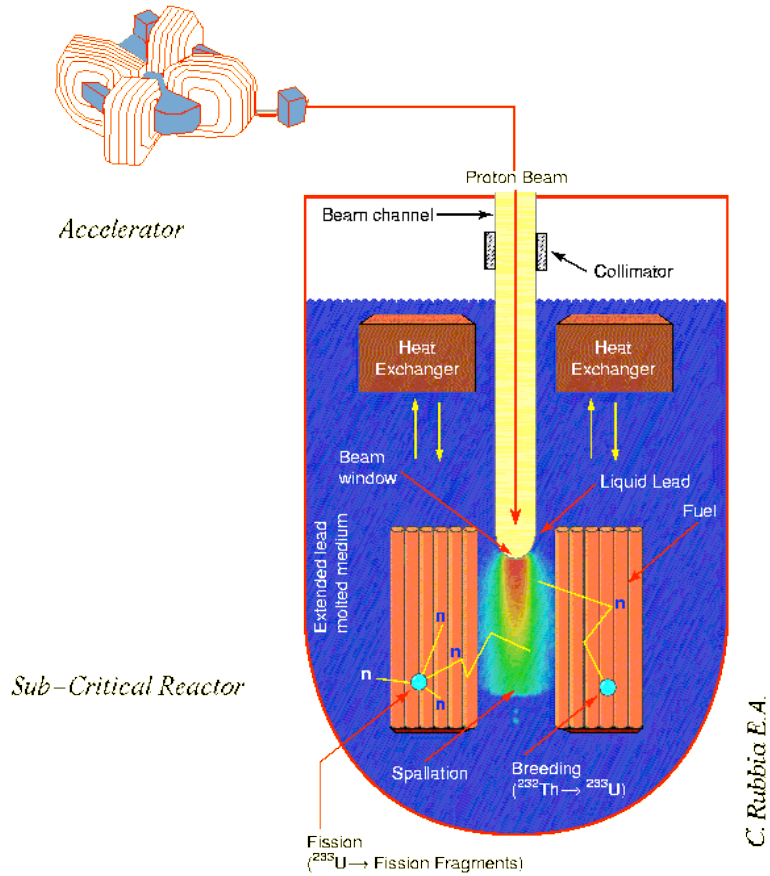
Synergy with other communities, cost sharing for multi-purpose facilities.

Most important feature is reliability!

Wanted: ~1 MW sources of protons, w/ energy > 600 MeV and <1500 MeV for a reasonable price

Luckily there are others looking for this too!

"ADS" -- accelerator driven systems for subcritical reactors.

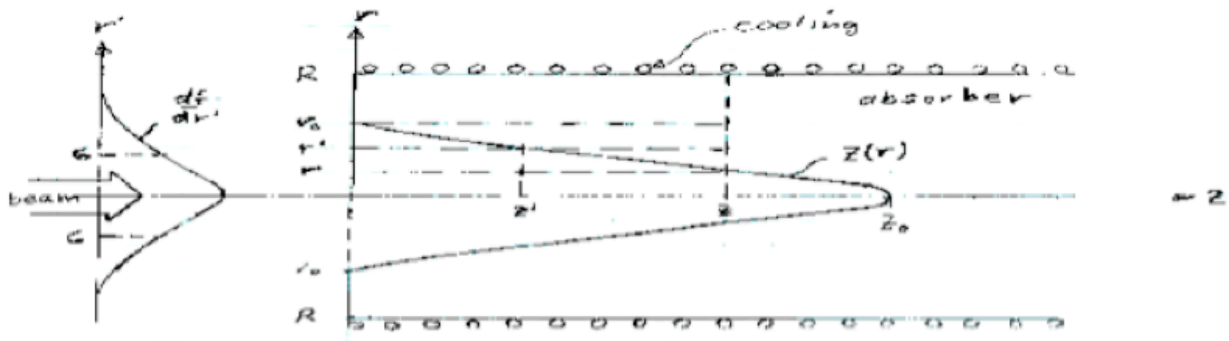


Also "DTRA"-- Defense Threat Reduction Agency

We can gain a lot from what is learned in these efforts!

Beam stop:

use low Z material
to enhance pion production and
dissipate heat



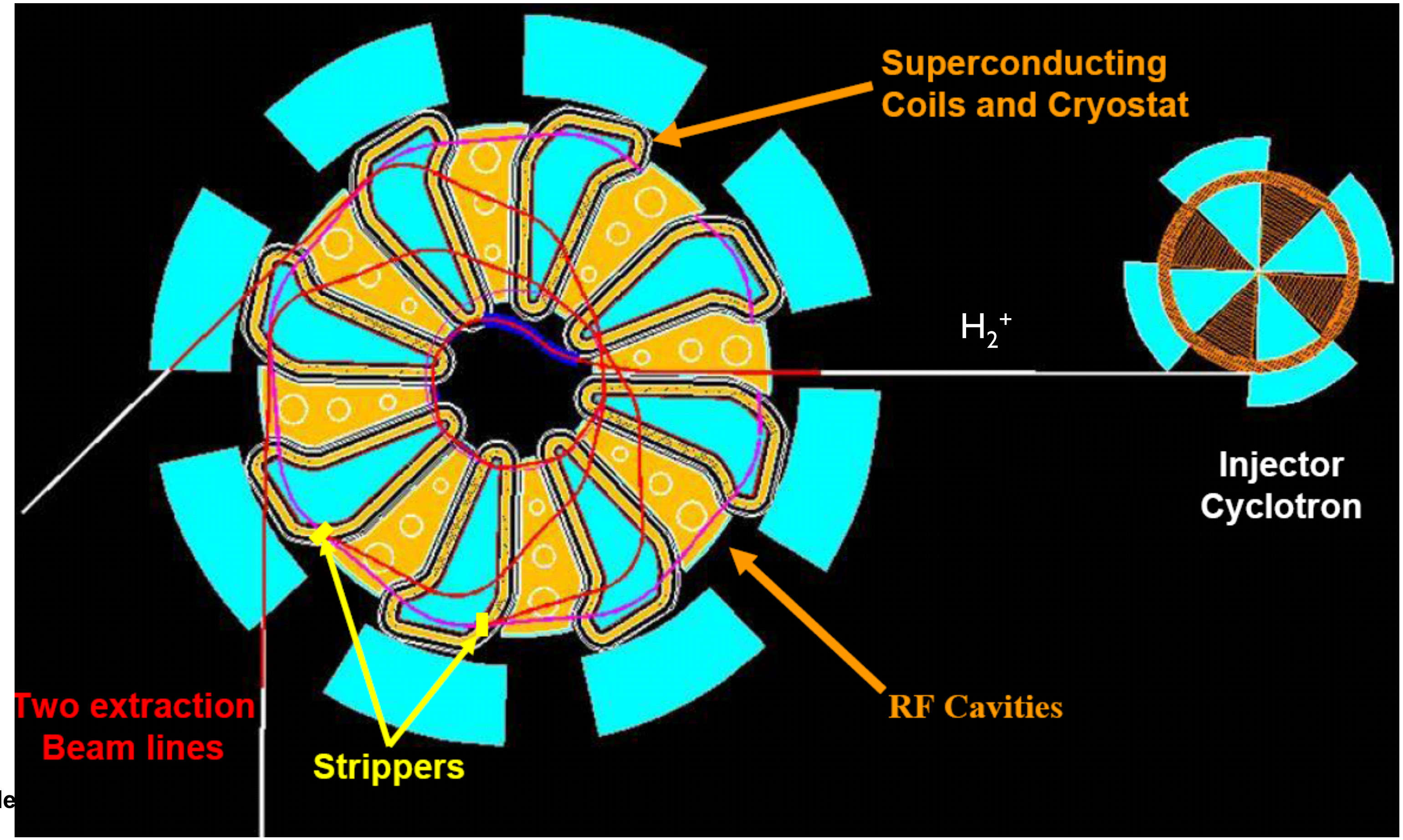
conceptual design for beam stop

Beam stop design ongoing ...

Areas of Active Research

- Moving to higher power and better extraction with different options
  - Conventional approach – high RF voltage giving large turn separation
  - Self-extraction techniques
  - Stripping extraction with either H^- or H_2^+
- Examples:
  - Conventional approach
    - For PSI there has been steady improvements in current/power to 2.2mA/1.3MW with 99.98% extraction efficiency

Luciano Calabretta, Mario Maggiore, Leandro Piazza, Danilo Rifuggiato
Laboratorio Nazionale del Sud - Istituto Nazionale di Fisica Nucleare
Alessandra Calanna,
CSFN&SM, Catania



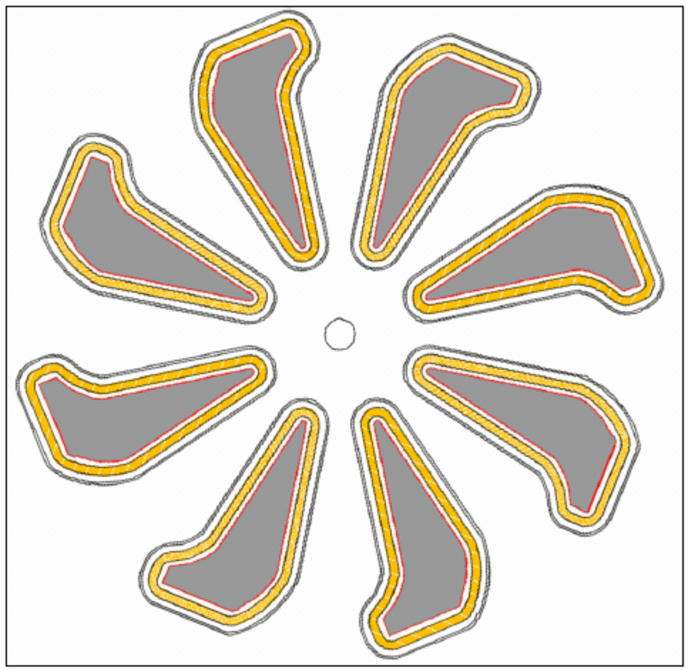
Based on slide from

Daedalus, who was very clever, designed the labyrinth (maze) to keep the Minotaur inside. But then King Minos trapped Daedalus inside. So, he escaped by flying away.

We are designing the Daedalus Cyclotron. But we do not want the protons to be trapped inside since they cannot escape by flying but need to be carefully extracted.

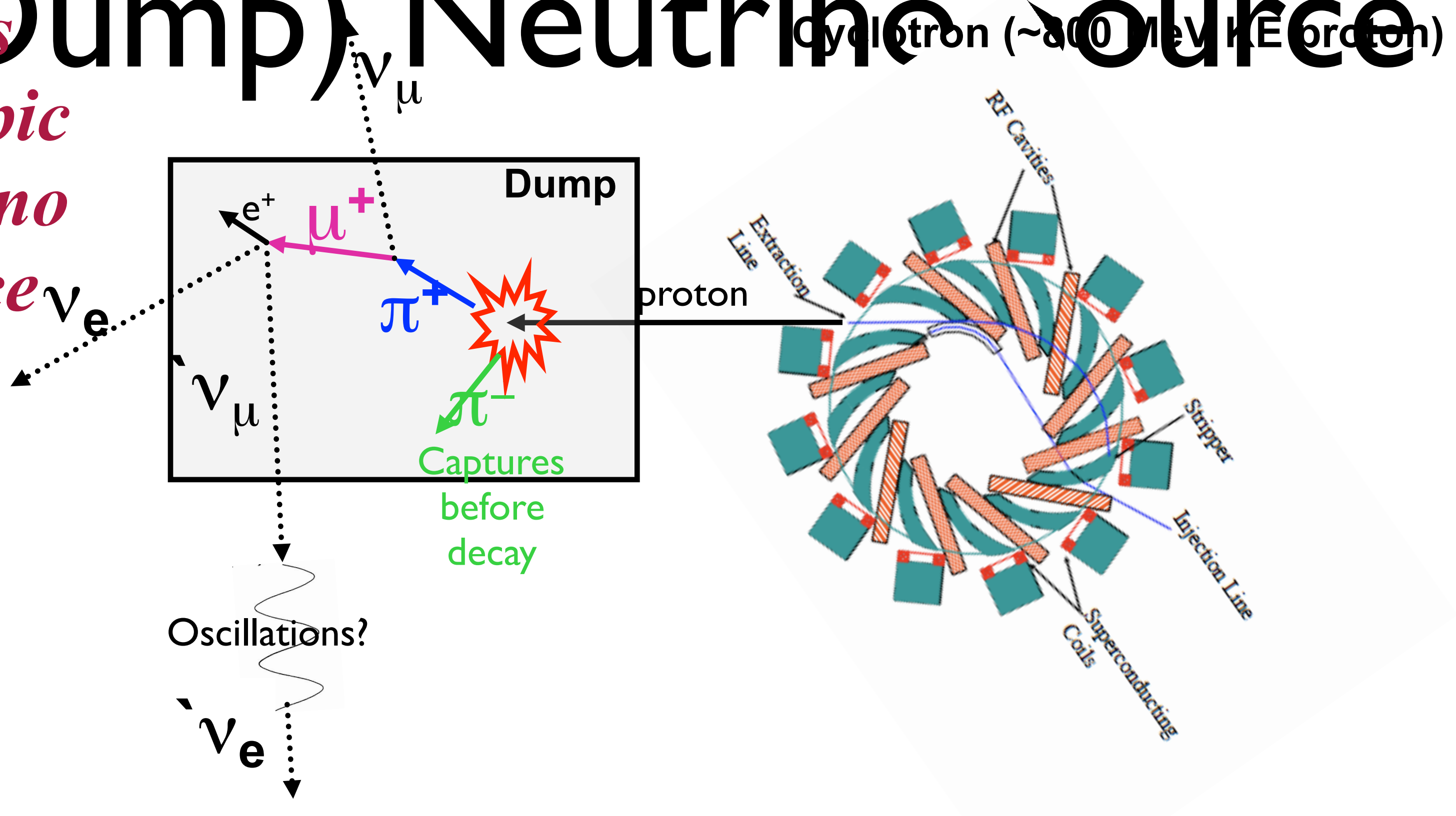
Daedalus Labyrinth

Daedalus Ring Cyclotron



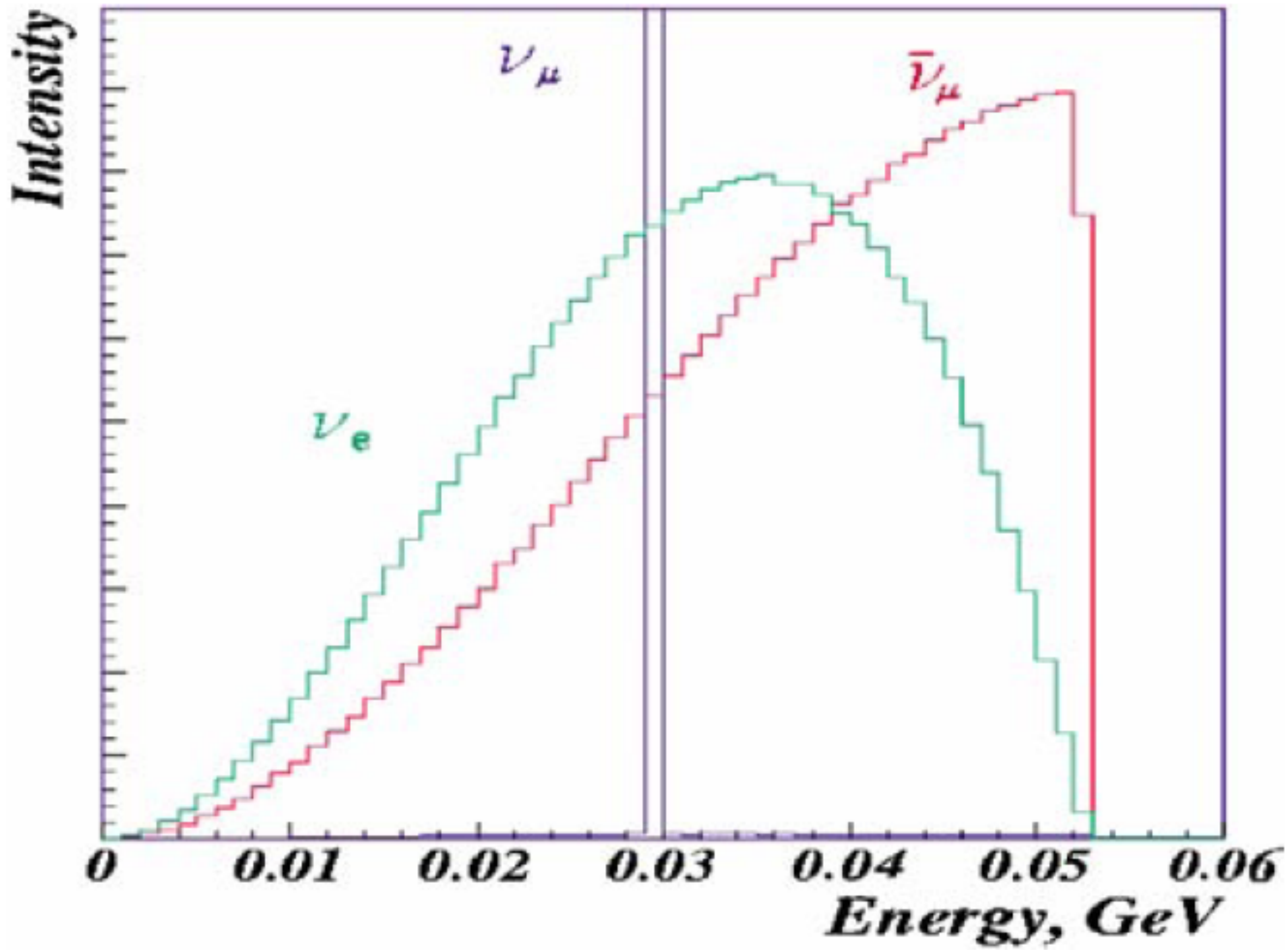
Decay-at-Rest (or Beam Dump) Neutrino Source

Decay-at-Rest gives isotropic neutrino source



Each π^+ decay gives one ν_μ, one ν_e, and one $\bar{\nu}_\mu$ so measuring any of these will set the neutrino flux normalization.

Energy Spectrum for π



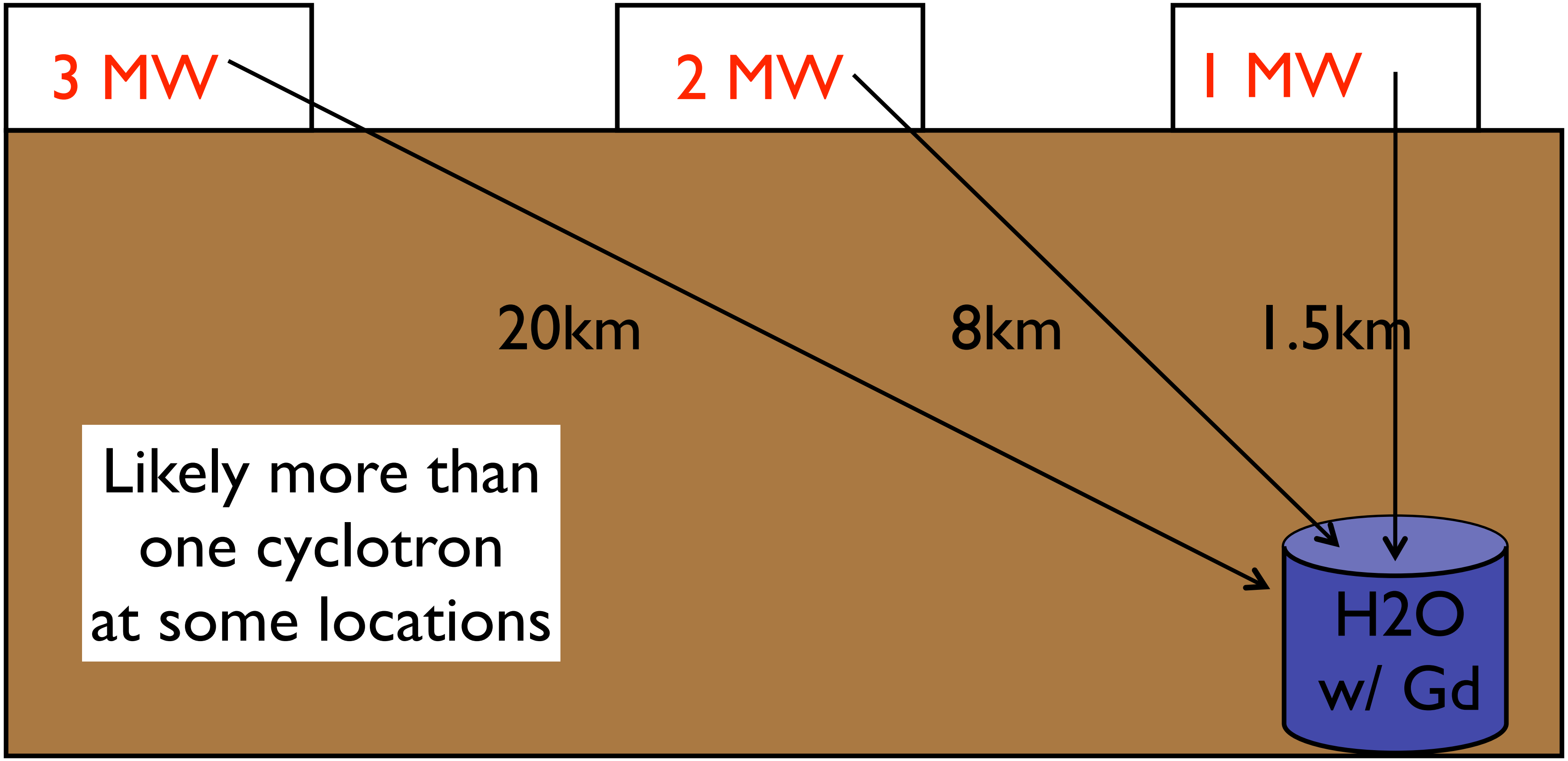
No $\bar{\nu}_e$ so can do sensitive search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Strategy: Phase I -- find it

The "canonical" comparison point

In 5 years, a 3σ measurement -- $\delta = (-90 \pm 32)°$

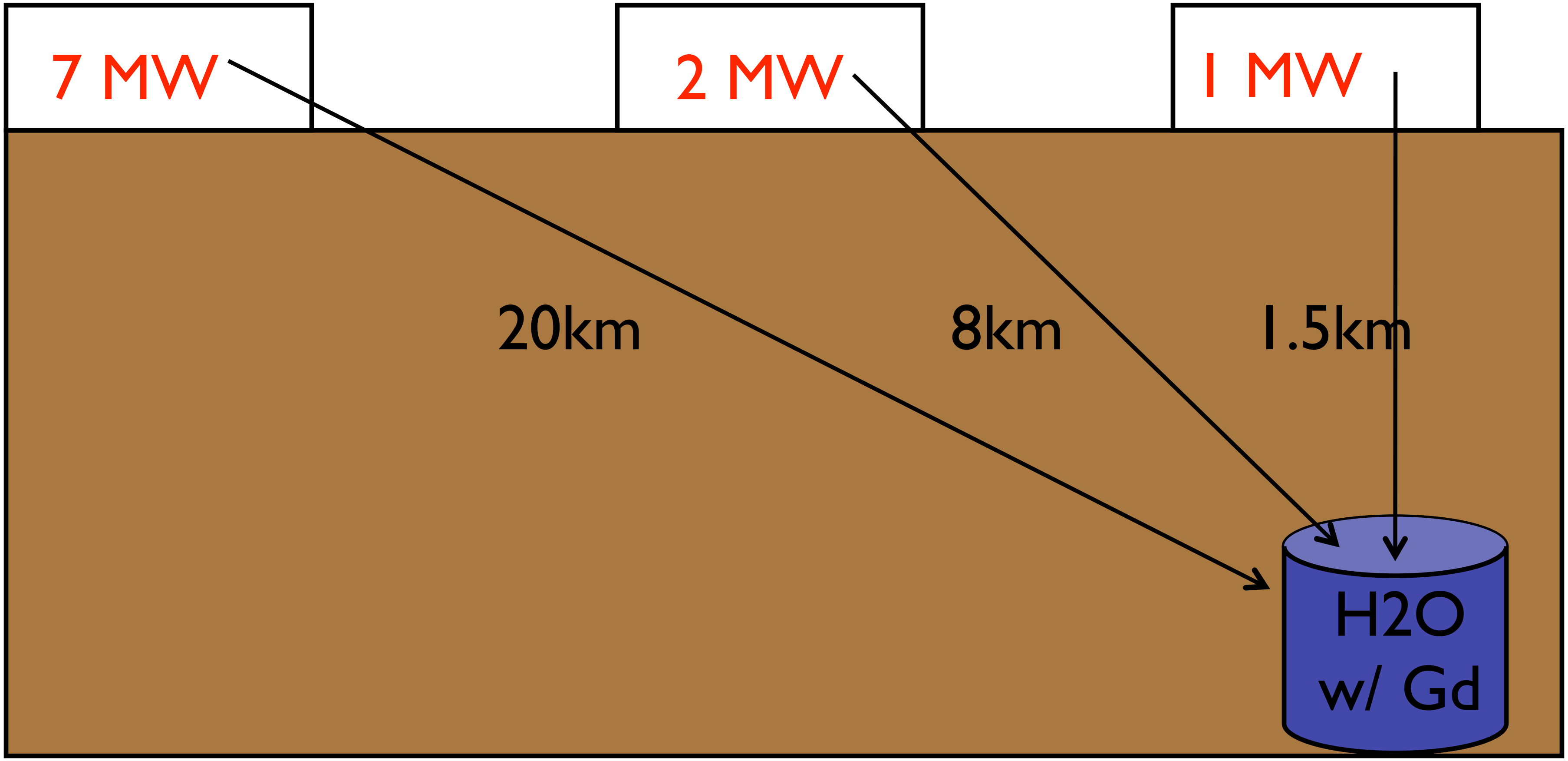
@$\sin^2 2\theta_{13} = 0.05$



Strategy: Phase II -- measure it

In an additional 5 years: LBNE-level sensitivity

$\delta = -(90 \pm 22)°$
@ $\sin^2 2\theta_{13} = 0.05$

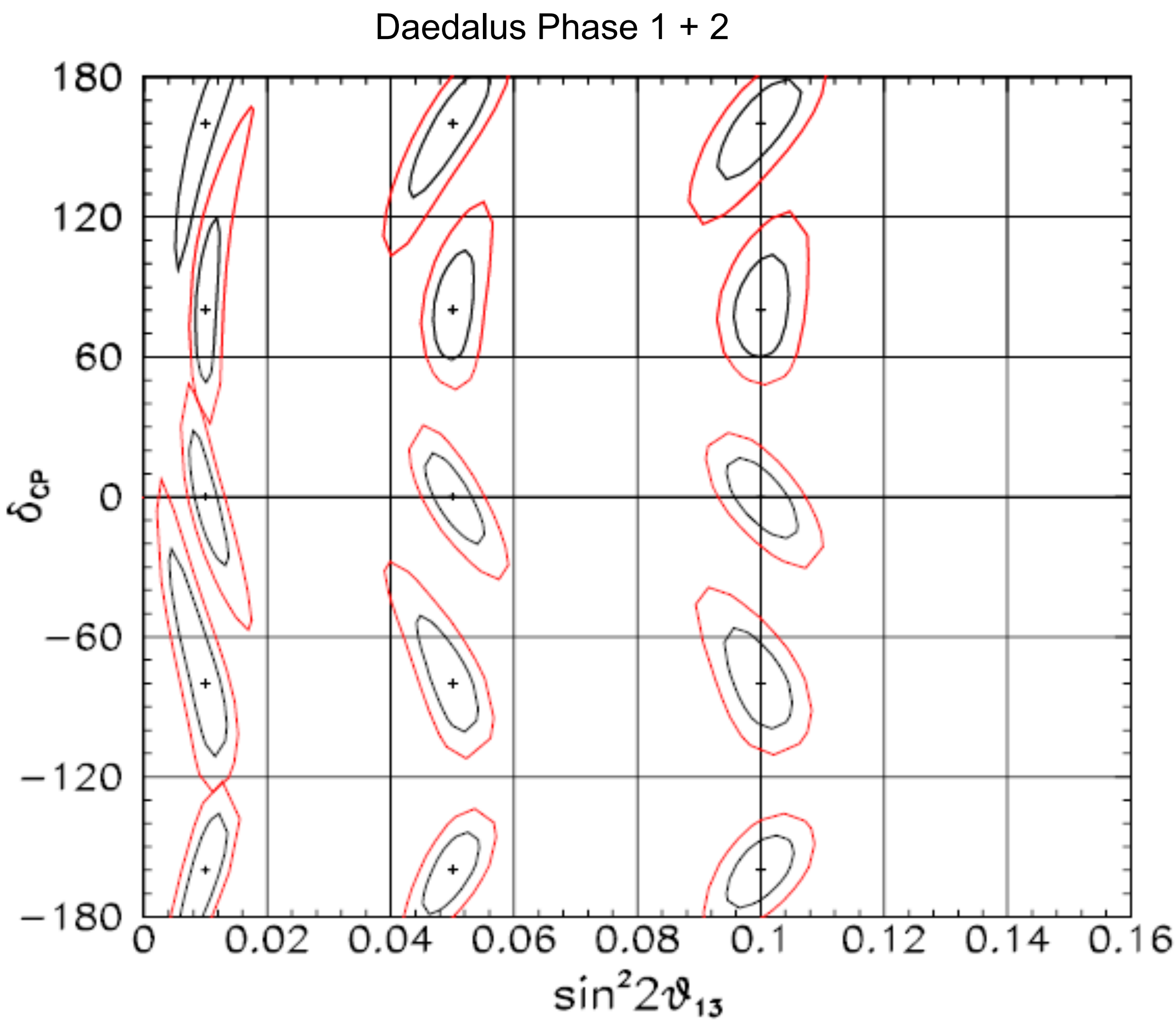


Systematic Uncertainties before fits

IBD from osc nuebar	Fractional Uncertainty
eff neutron detection	0.005
pi+ prod/proton	0.100
Fiducial volume	0.000
Total	0.100
nue-e scattering	
xsec error from NuTeV sin2thW error	0.005
2.1% escale for e>10MeV	0.010
electron to mass ratio	0.000
nuebar IBD missing neutron	0.000
Total	0.011
IBD from intrinsic nuebar from mu- decay	
pi- production	0.100
pi- decay in flight	0.100
mu- decay before capture	0.050
Total	0.150
Non-Beam background constraint from beam off	
Phase I	0.054
Phase II	0.038
nue-Oxygen scattering	
xsec error	0.100

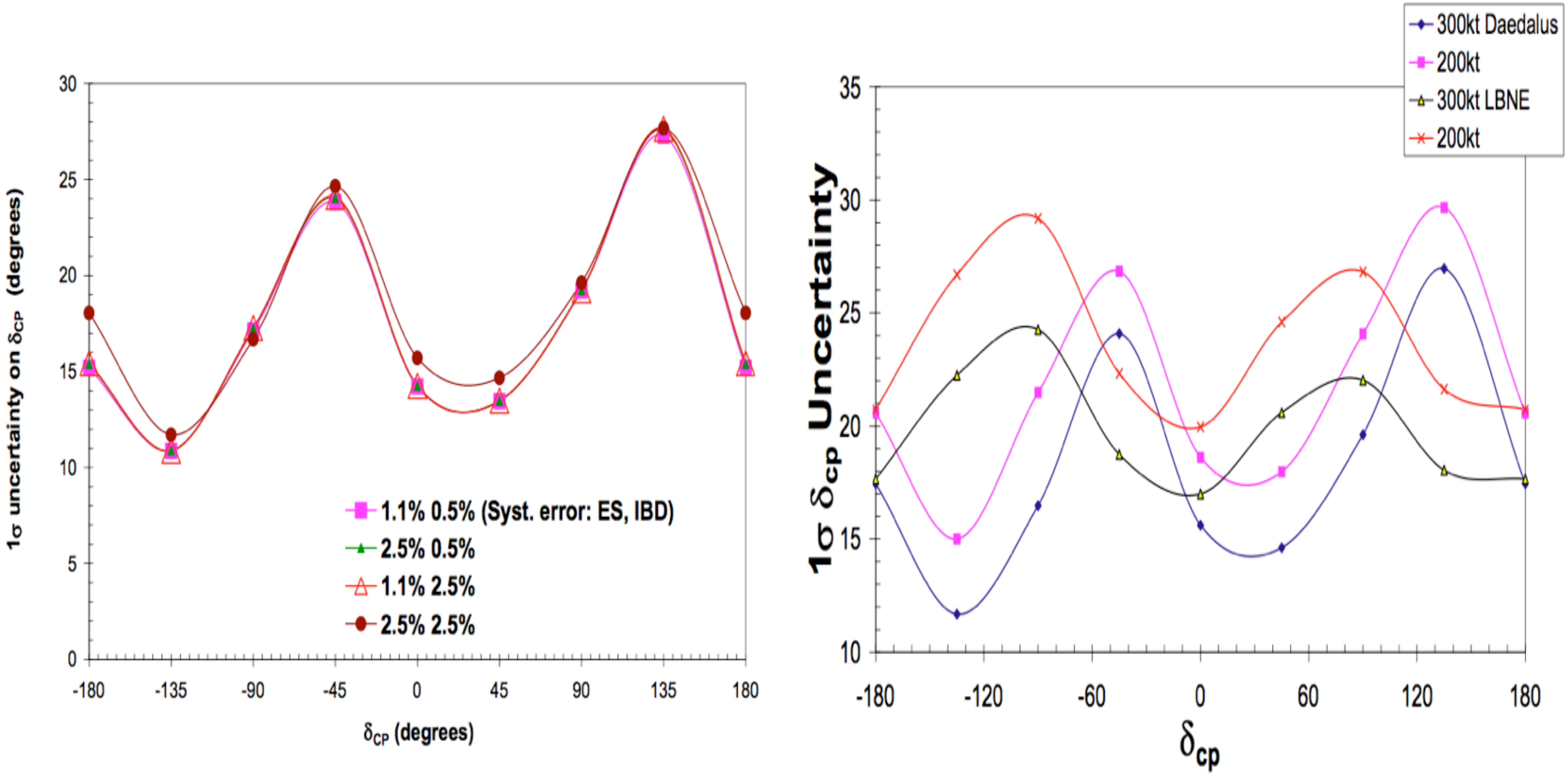
By comparing measurements in the 3 accelerators, several of these systematics effectively cancel.

How well do we do?



We can clearly observe CP violation!

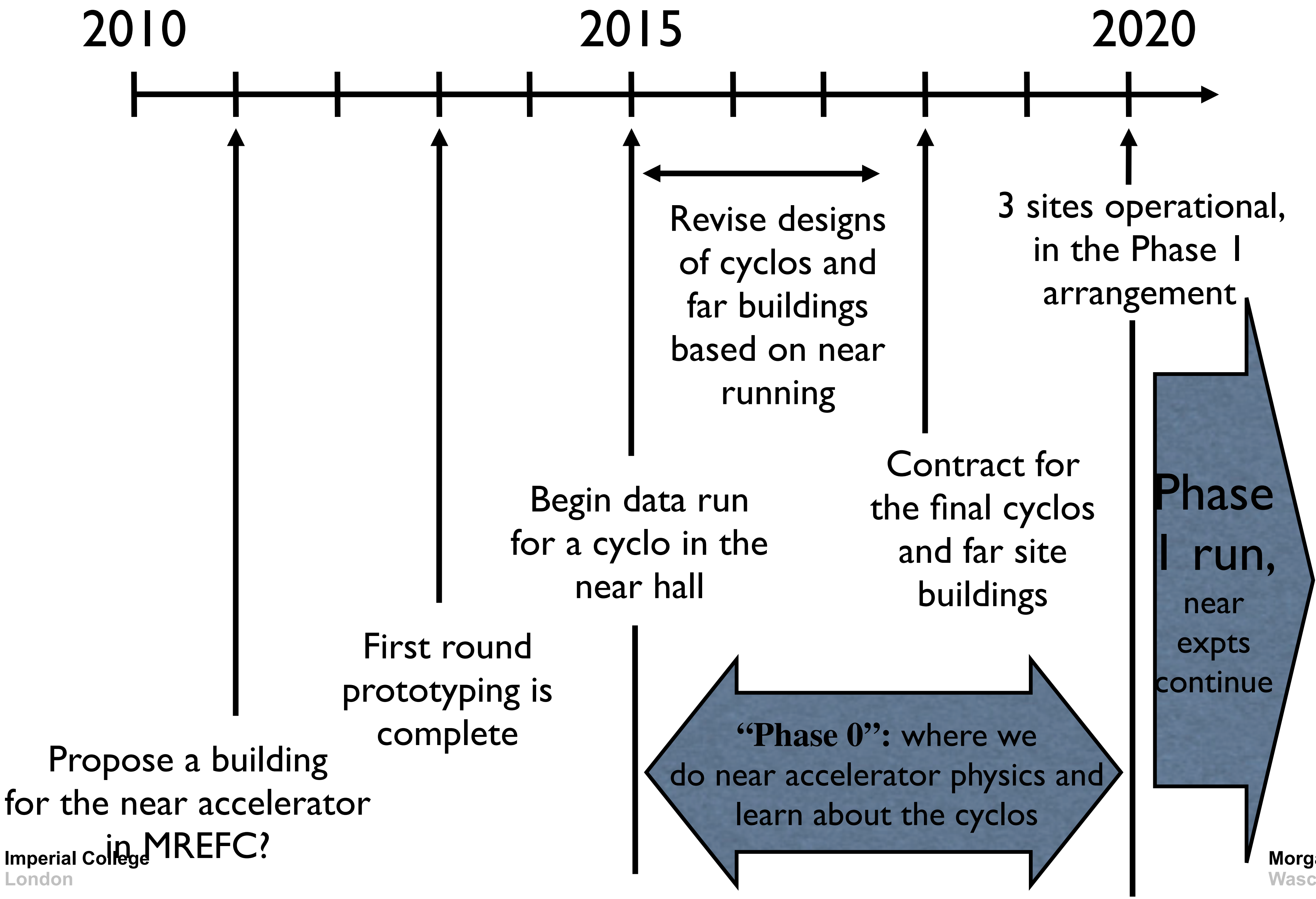
Systematics vs Statistics



DAEdALUS is limited by statistics, not systematics!

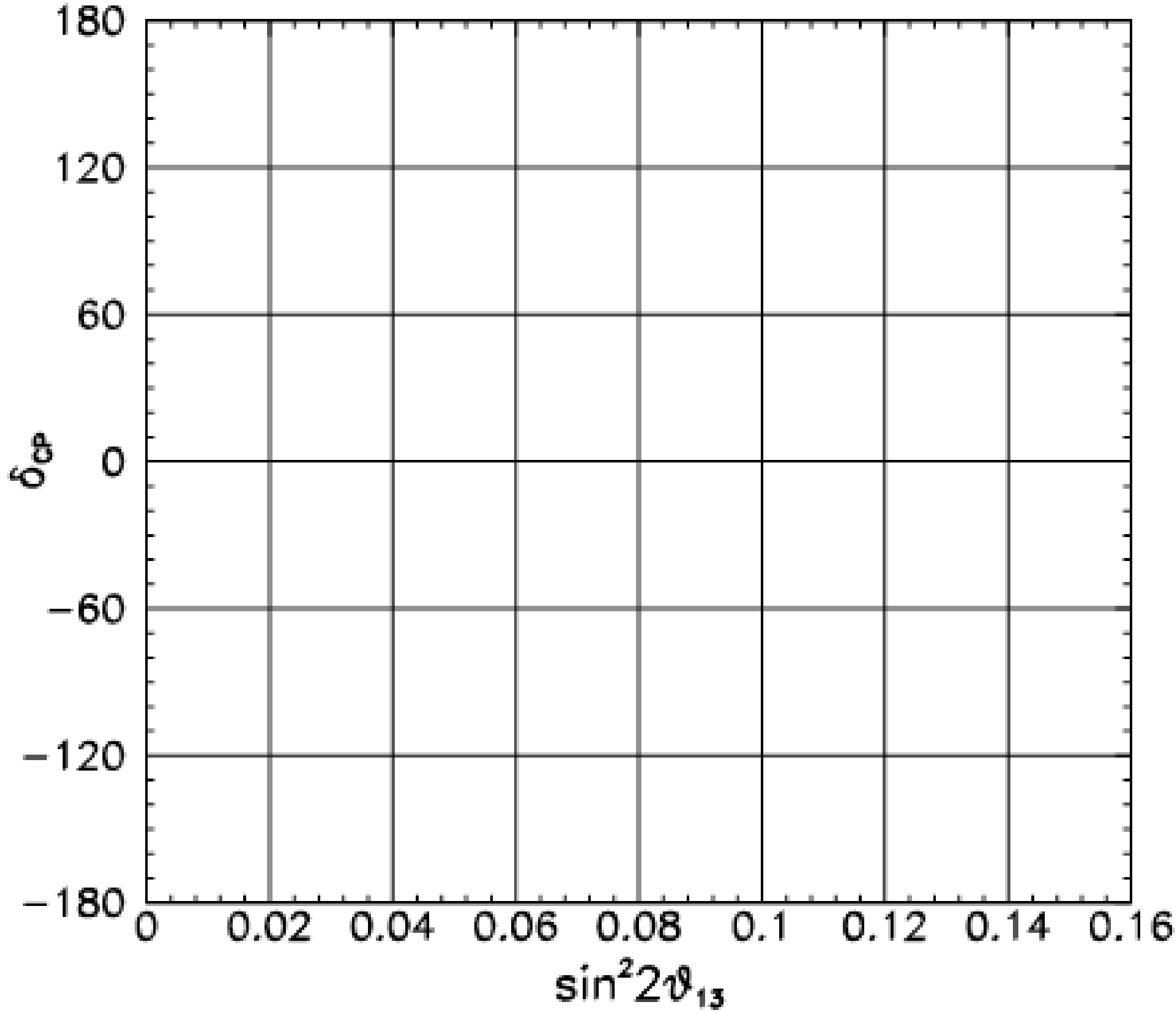
Part IV:
Synergy with LBNE

A tentative schedule for discussion…

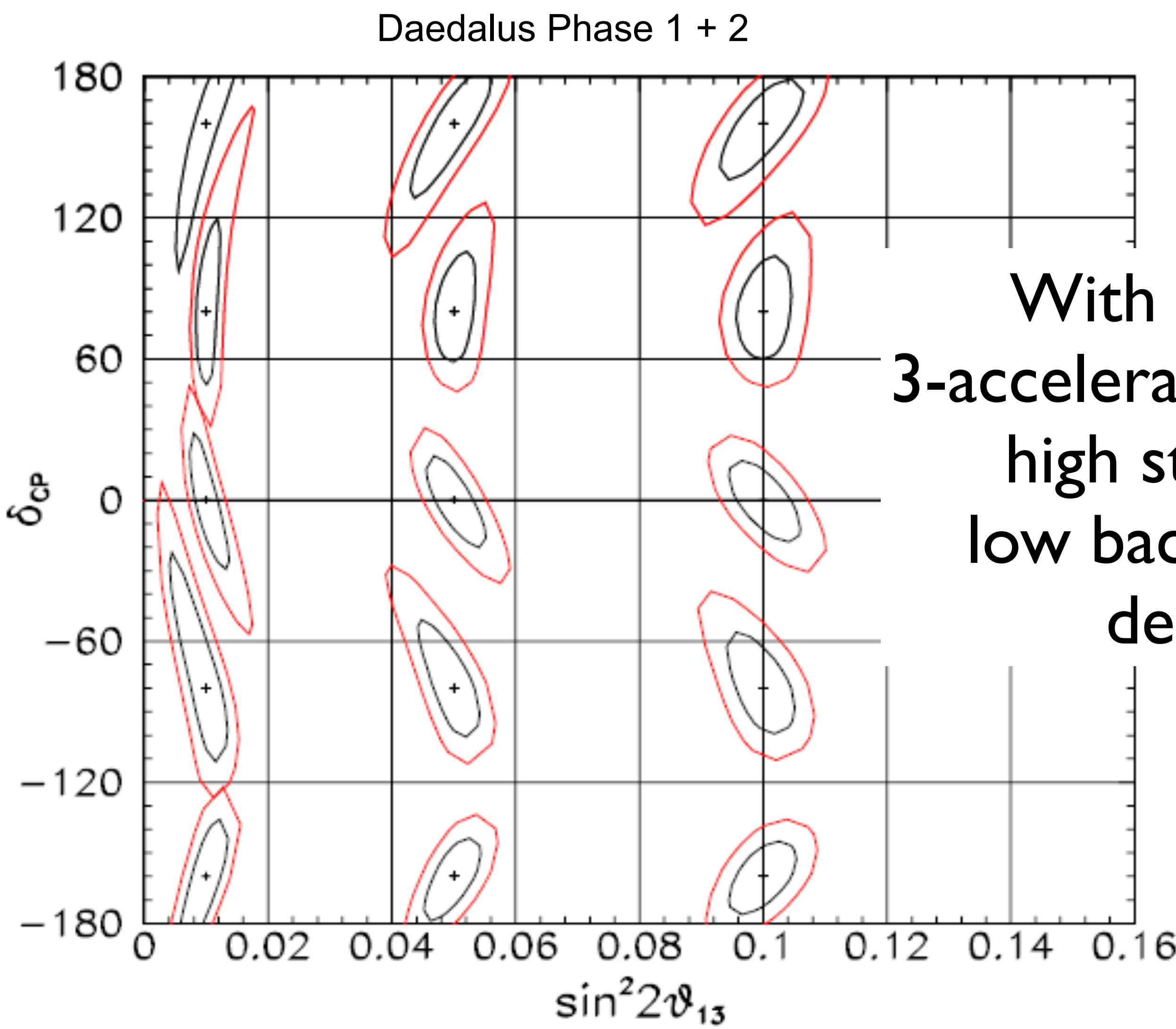


Conclusion

We can potentially go from here:

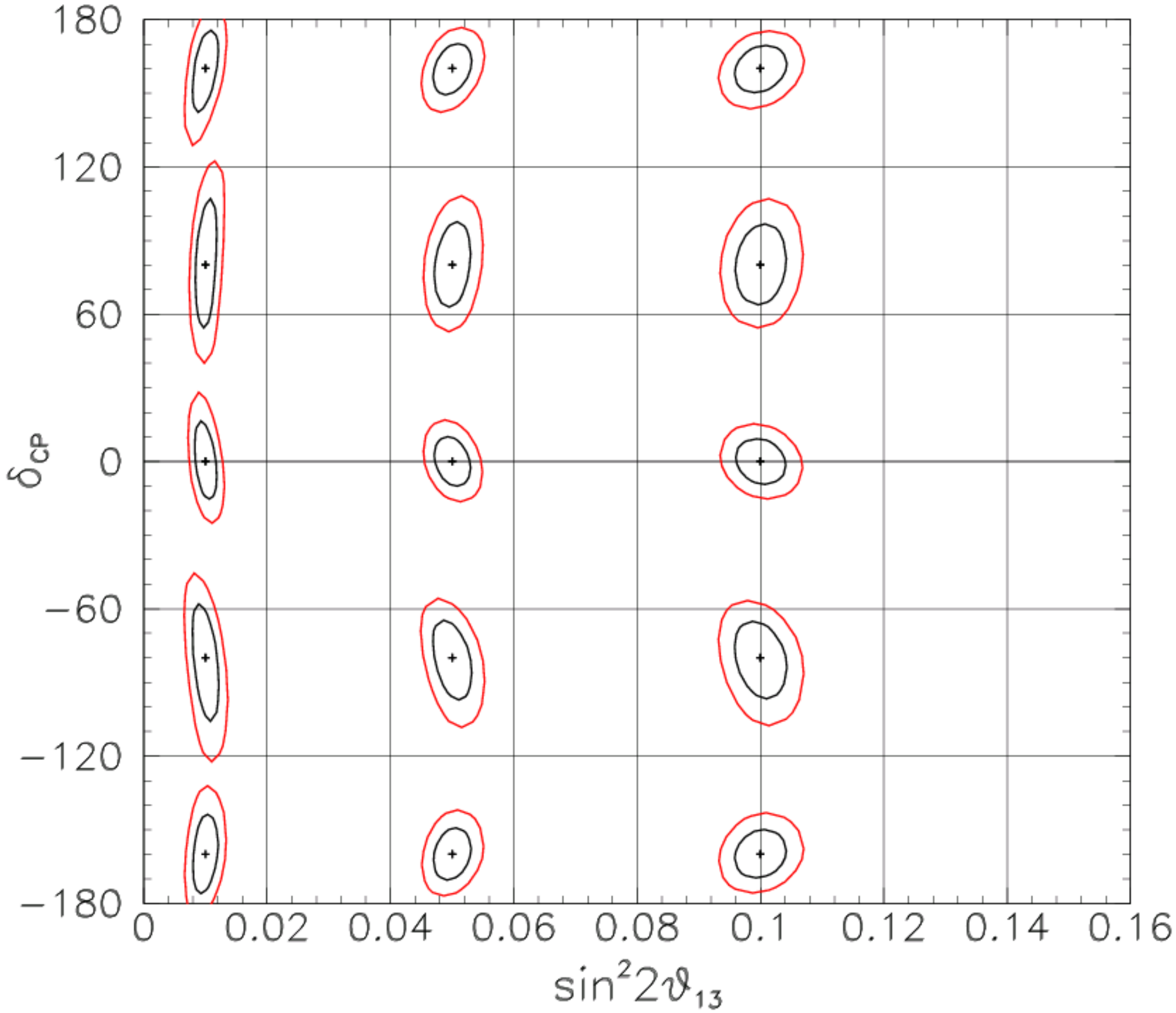


To here, in a 10 year run



With a novel
3-accelerator source,
high statistics
low background
design

The design is complementary to LBNE, and offers even better possibilities when combined…



Main challenge:
~1 MW sources of protons,
w/ energy > 600 MeV and <1500 MeV, with stable operation,
for a reasonable price

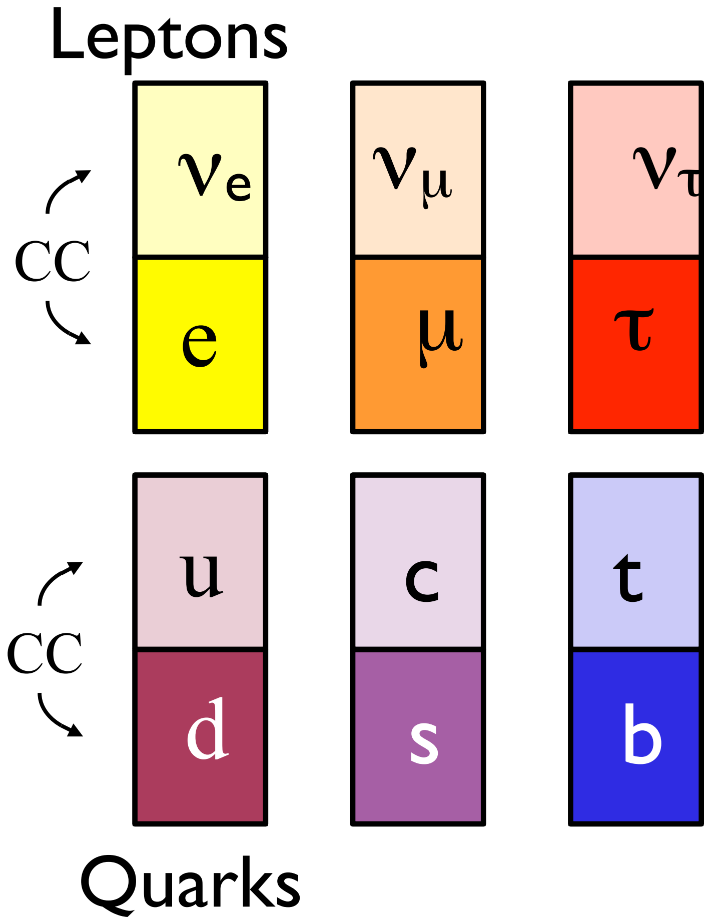
Help wanted!

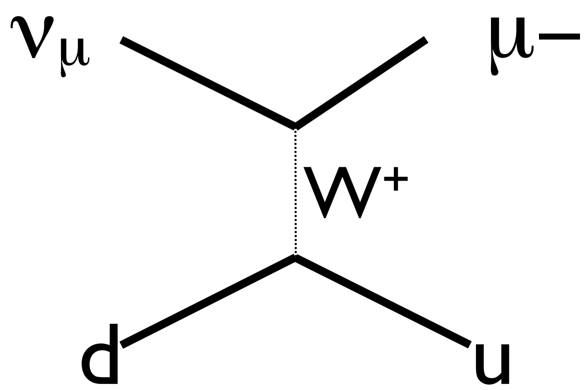
Lets discover that CP violation jelly bean!

Thank you!

http://arxiv.org/abs/1006.0260

In the Standard Model,
Neutrinos are part of the lepton “weak doublets”



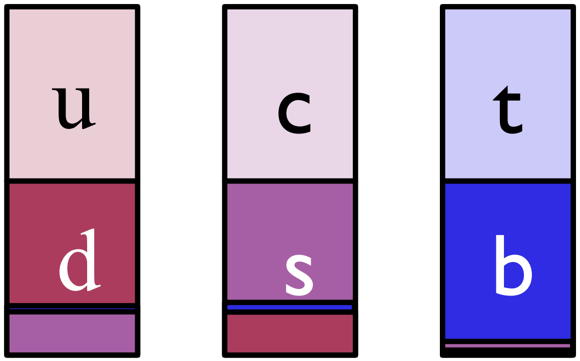


We identify the
neutrino <u>flavour</u>
via the CC interaction

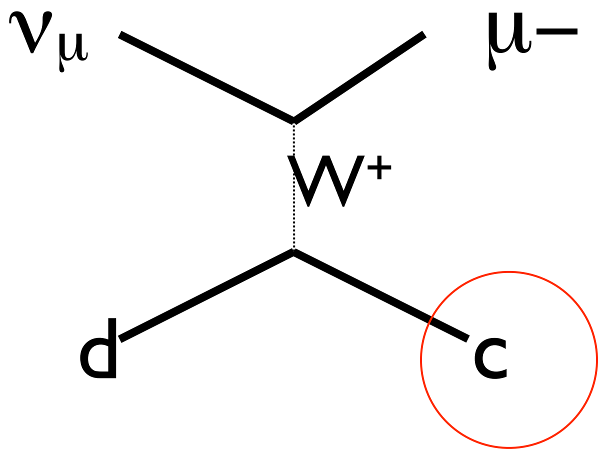
The quarks also form weak doublets…

In the quark sector, we have "mixing"

quark mass eigenstates $\neq$ quark weak eigenstates



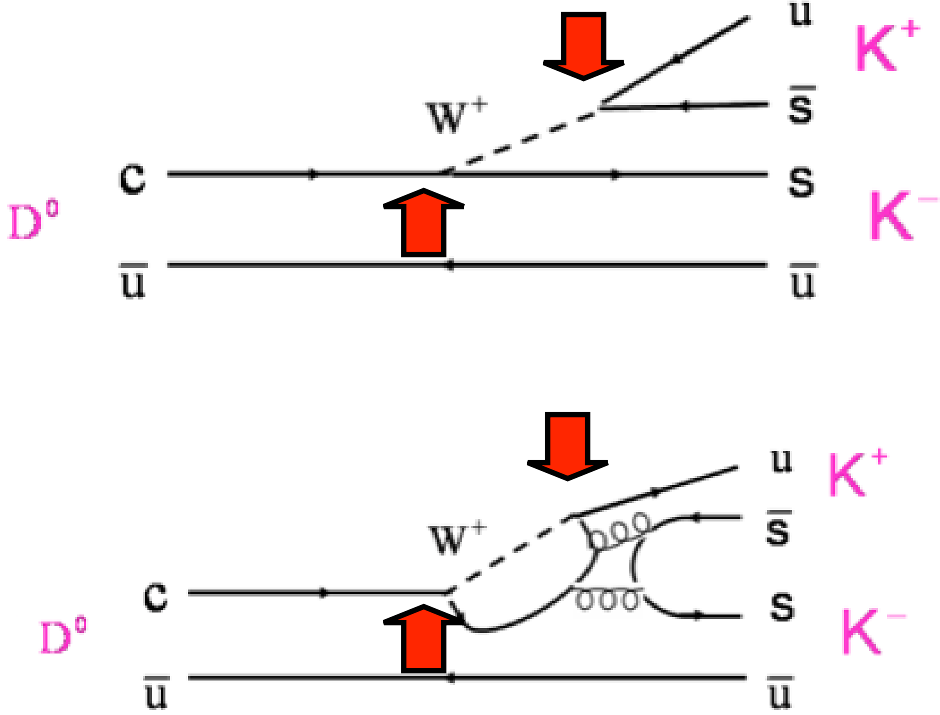
Small effect, but clearly seen in weak interactions...



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}.$$

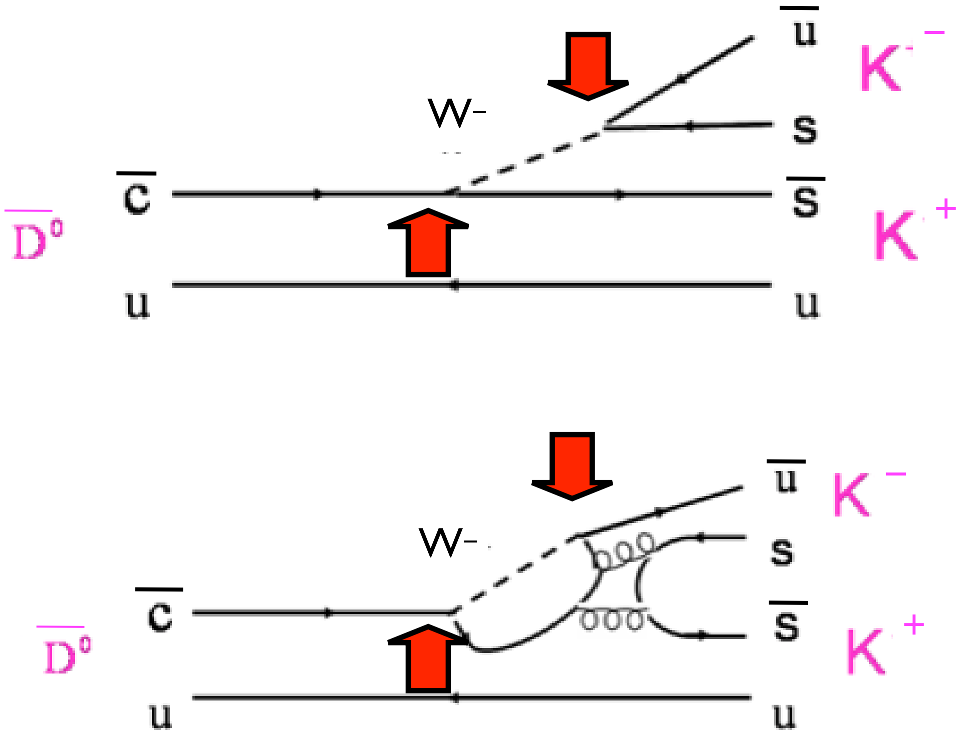
... and kaon decays, D meson decays, etc.

The effect shows up in weak decays when you have 2 paths to the same outcome…



You will get an interference term in the decay probability…

Now consider the $\overline{D^0}$



There are still 2 paths to the outcome.

Compared to the D^0 the interference term changes sign!

e.g. D^0 and $\overline{D^0}$ decays can have different decay rates if δ is nonzero!

Does the lepton sector show similar phenomena?

If not, *Why Not*?

If so,

how similar is it to the quark sector?
and what are the implications?

Step 1: Observe mixing…

Consider the simple case of 2 flavour mixing…

If we postulate:

- Neutrinos have (different) masses
- The Weak Eigenstate is a mixture of Mass Eigenstates:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Then a pure ν_μ beam at $t = 0$,
may evolve a ν_e component with time!

The Probability for Oscillations…

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

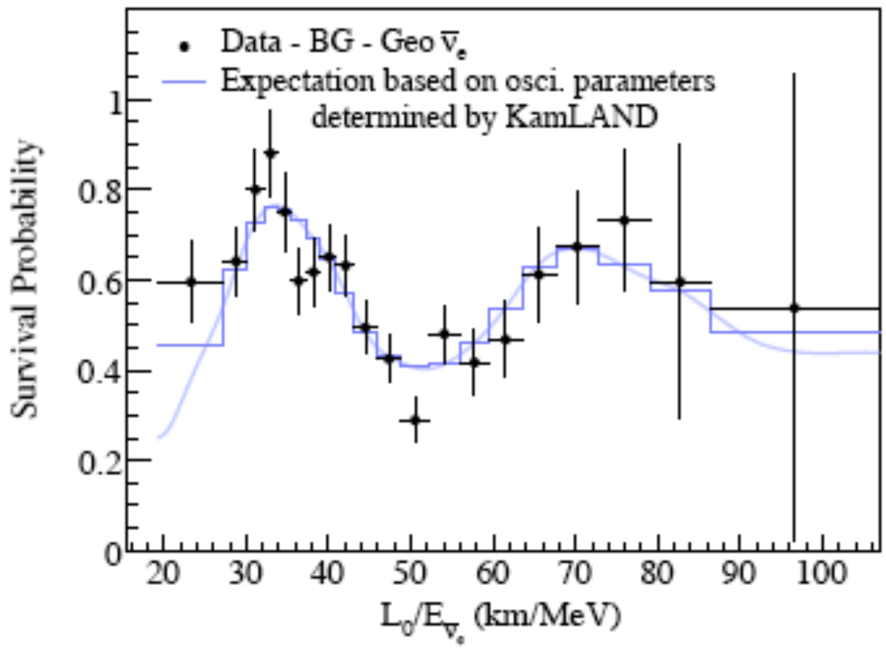
Observe mixing...?

The Probability for Oscillations...

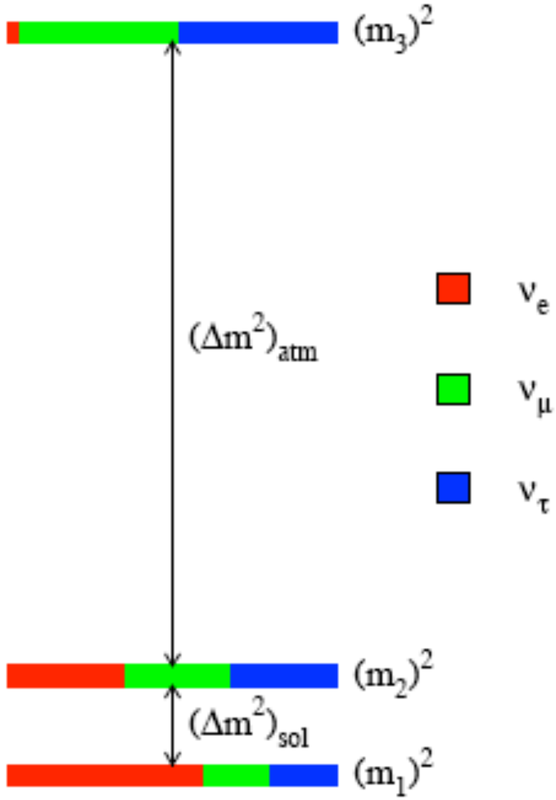
$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

DONE!

For example, in KamLAND!



Observed at 2 different Δm^2 values in multiple experiments.



normal hierarchy

Our Model

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

"mixing" between neutrinos is parameterised by three "mixing angles" θ_{12}, θ_{13}, θ_{23}

Outline:

- Physics Motivation
- The “Conventional Wisdom”
- An unconventional approach: DAEδALUS
- Synergies

Physics Motivation:
Searching for CP violation in the Neutrino Sector

The quark mixing matrix has to be unitary,
but it doesn't have to be "simple"

Any 3 × 3 unitary matrix has
3 associated free parameters (Euler angles)

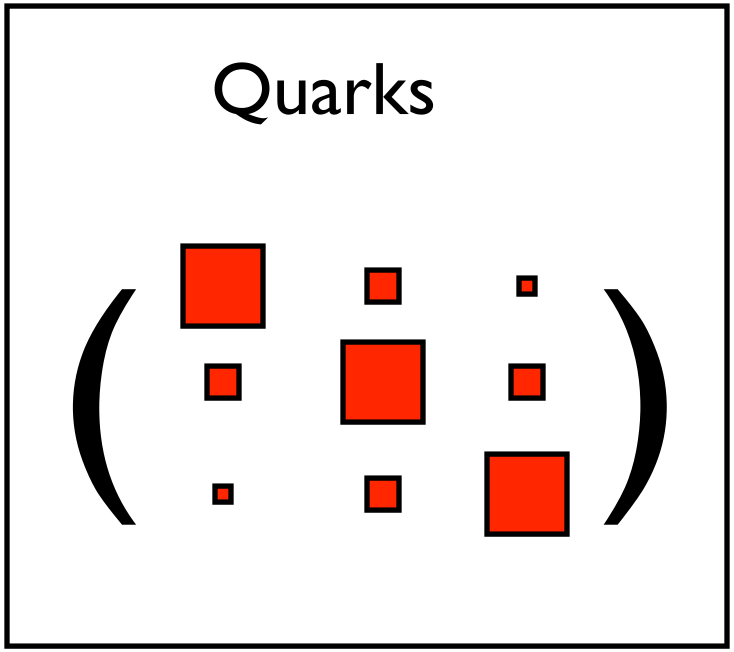
$c_{ij}=\cos\theta_{ij}$ $s_{ij}=\sin\theta_{ij}$

& can have a complex phase hidden in it!

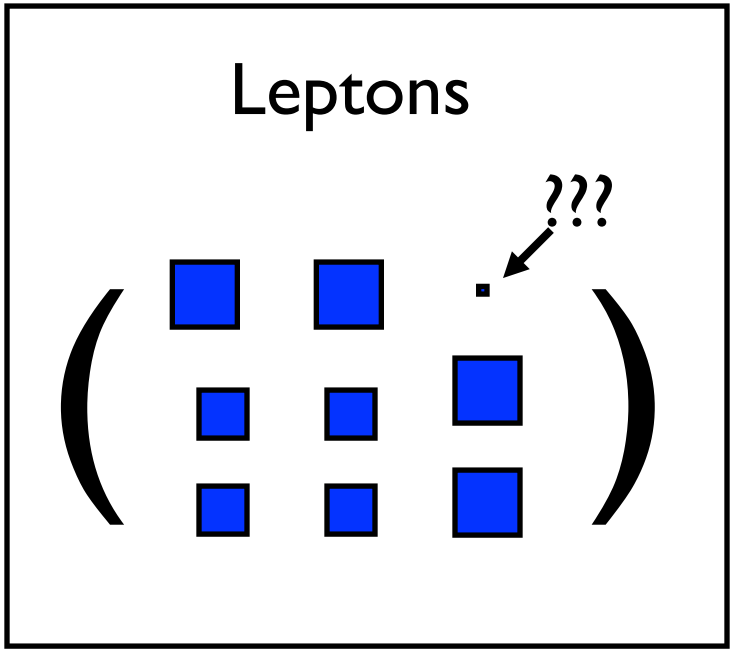
$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix},$$

This "CP violating phase" can lead to a different decay rate
for matter vs. antimatter

What we know about mixing



vs.



Large entries on diagonal
small off diagonal

Moderately large entries
except for one,
which might be zero!

Adding CP violation & rewriting as the product of 3 matrices…

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

The CP Violation Parameter

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

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

From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

From Appearance Measurements

From Solar Neutrino Measurements

This matrix is well-known

Super K, K2K, MINOS, soon T2K…

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

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

From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

From Appearance Measurements

From Solar Neutrino Measurements

& this matrix is well-known

Super K, SNO, KamLAND

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

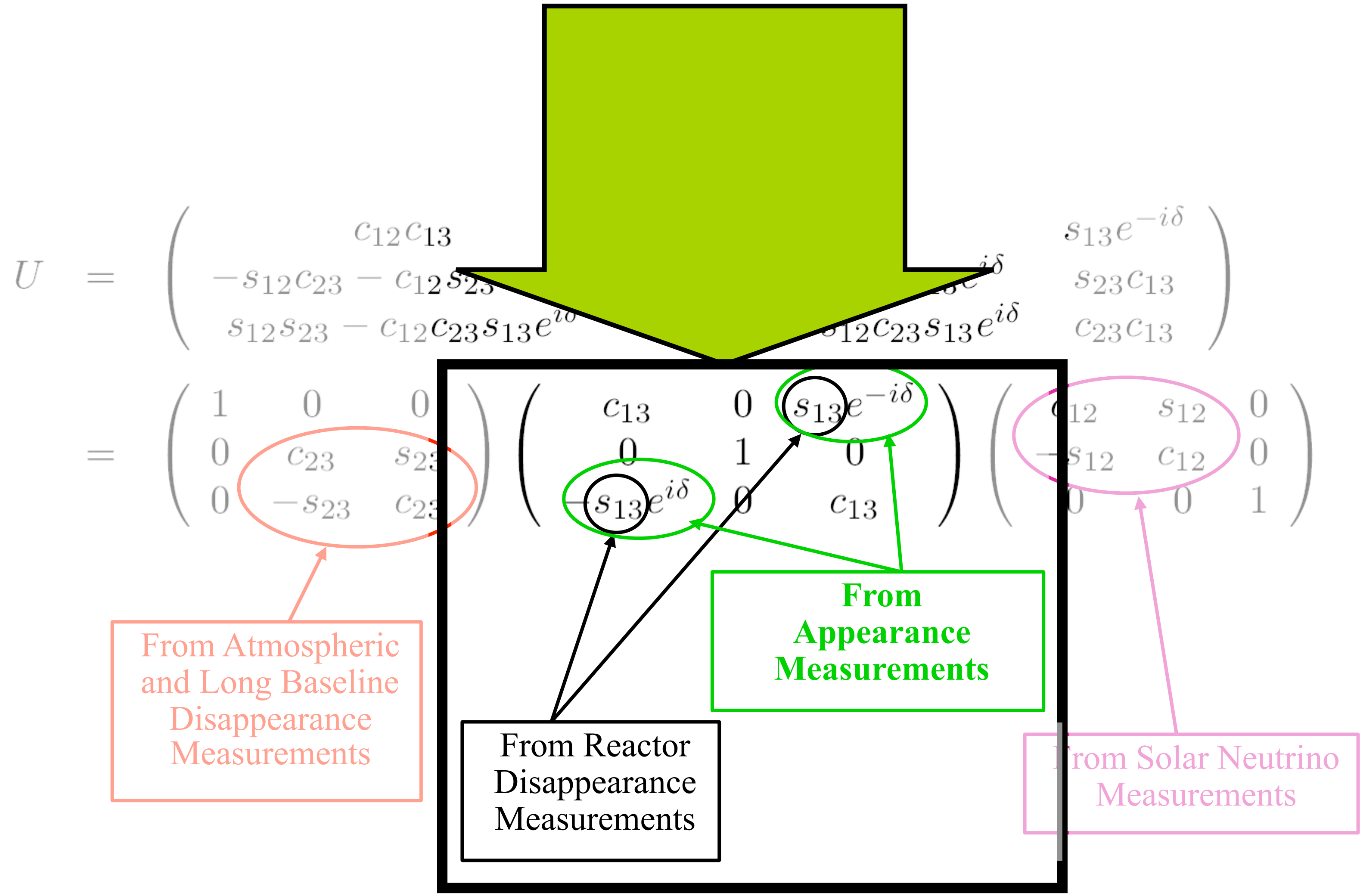
From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

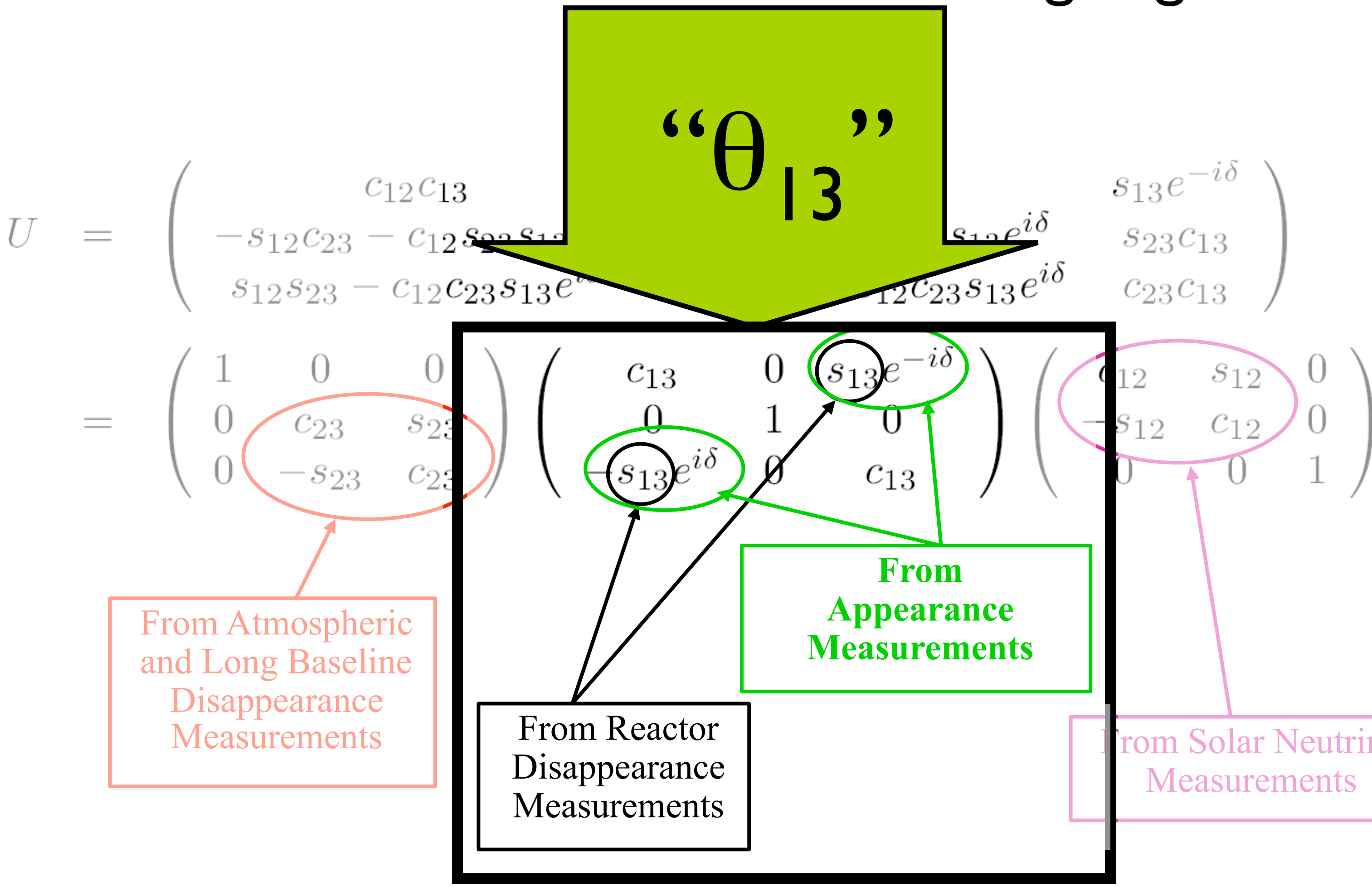
From Appearance Measurements

From Solar Neutrino Measurements

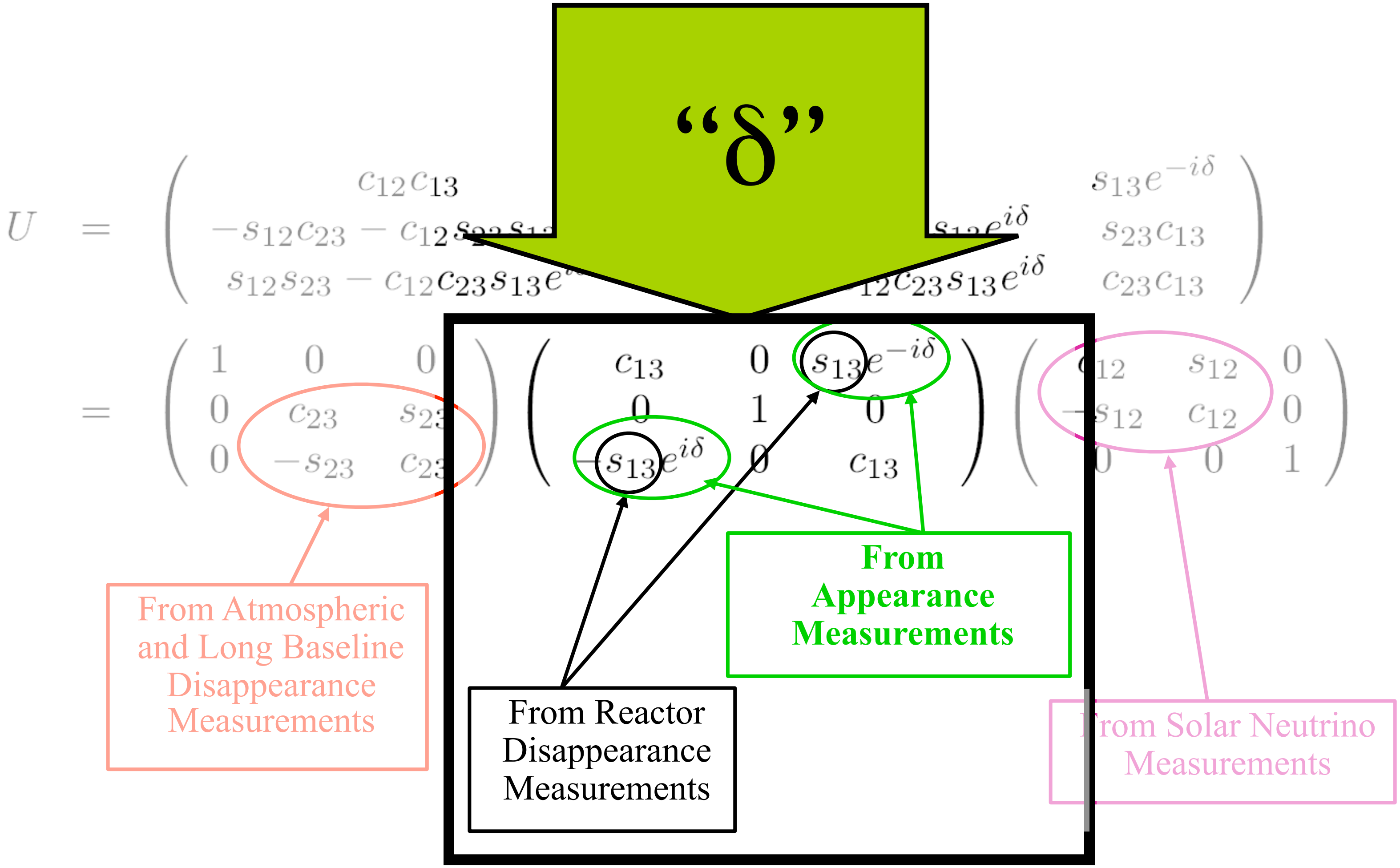
But this one is not known at all!



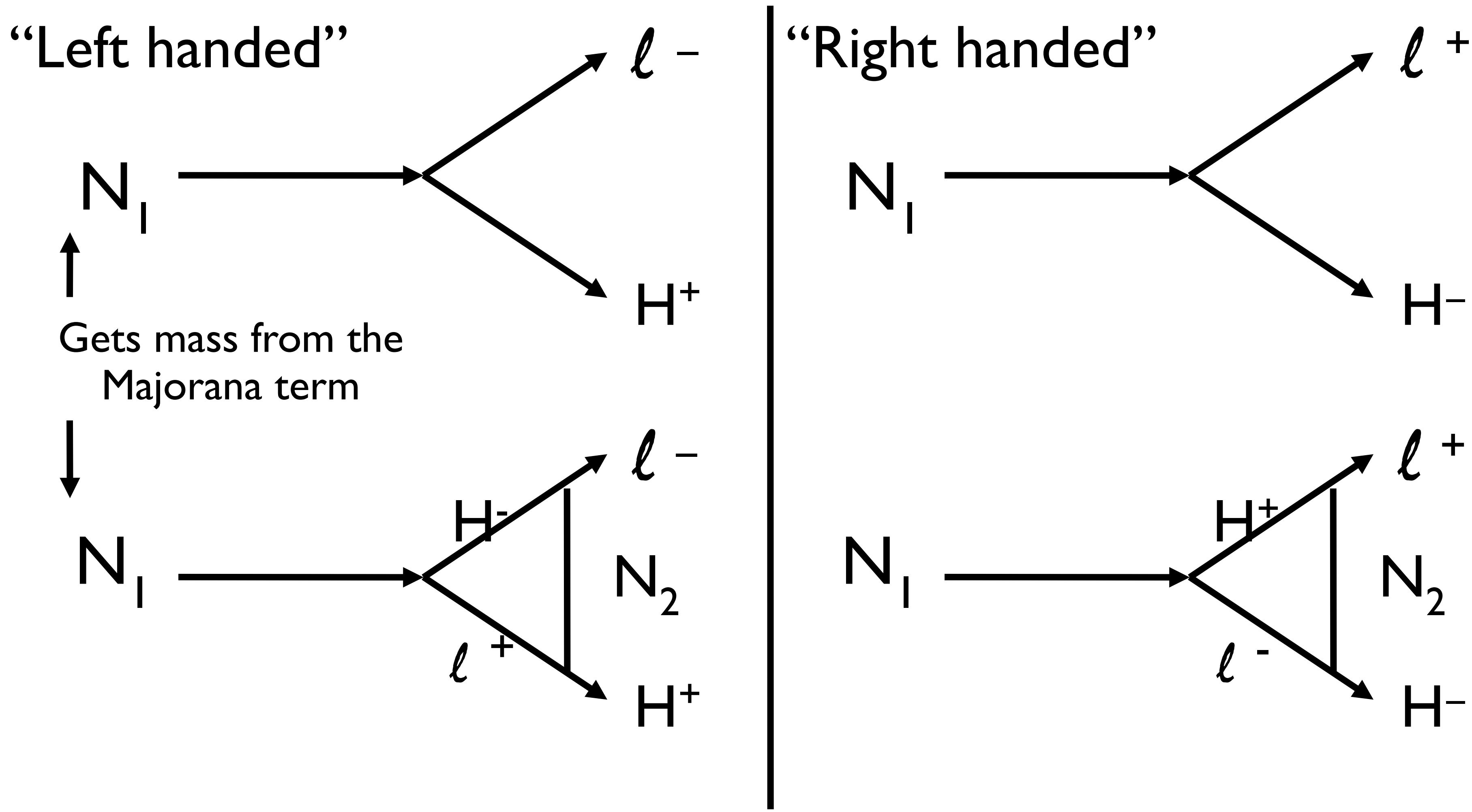
The T2K Experiment
searches for the last mixing angle



DAEδALUS will search for



Before the electroweak phase transition…



The interference terms will have opposite sign!

Leptonic CP violation could have big consequences, because if incorporated into a larger model where

1. Neutrinos are Majorana particles
2. With GUT scale partners
3. And there is CP violation…

Then…
CP violation in the neutrino sector may explain the matter-antimatter asymmetry in the universe

Are neutrinos the reason we exist?

It’s a big question and
it turns out to be
very hard to answer!

A first step would be observation
of CP violation in the light neutrinos

Searching for CP violation in the neutrino sector is a priority of our field

In the coming years, neutrino physics presents exciting opportunities: the measurement of the mixing angle between the heaviest and lightest neutrinos, determination of the hierarchy of neutrino masses, the search for matter-antimatter asymmetry (CP violation) in neutrino mixing, and lepton number violation. These opportunities are fundamental to the science of particle physics and have profound consequences for the understanding of the evolution of the universe.

Some more examples for various $\sin^2 2\theta_{13}$ and δ

$\sin^2 2\theta_{13} \backslash\ \delta_{CP}$	-160	-80	0	80	160
0.010	41.5	45.3	29.6	35.7	50.0
0.025	21.8	33.3	22.9	27.2	36.3
0.050	17.7	25.3	19.6	23.6	27.2
0.075	16.3	22.9	18.1	22.5	23.5
0.100	15.6	21.9	17.4	22.0	21.6

Standard DAEδALUS

$\sin^2 2\theta_{13} \backslash\ \delta_{CP}$	-160	-80	0	80	160
0.010	28.2	36.6	24.9	39.7	24.4
0.025	20.0	27.4	18.1	30.1	17.6
0.050	16.8	23.7	15.3	25.5	15.0
0.075	15.7	22.5	14.3	23.9	14.0
0.100	15.1	22.0	13.7	23.1	13.6

Short Combined

$\sin^2 2\theta_{13} \backslash\ \delta_{CP}$	-160	-80	0	80	160
0.010	45.5	52.4	35.8	50.2	36.8
0.025	30.1	38.5	25.6	37.1	26.1
0.050	24.5	31.6	21.3	30.8	21.6
0.075	22.3	28.9	19.5	28.3	19.7
0.100	21.2	27.5	18.5	27.1	18.7

Standard LBNE

$\sin^2 2\theta_{13} \backslash\ \delta_{CP}$	-160	-80	0	80	160
0.010	16.1	23.9	15.9	26.3	16.7
0.025	12.2	18.3	11.8	19.9	12.2
0.050	10.6	16.2	10.1	17.3	10.4
0.075	10.1	15.8	9.5	16.6	9.9
0.100	9.9	15.8	9.3	16.5	9.6

Long Combined

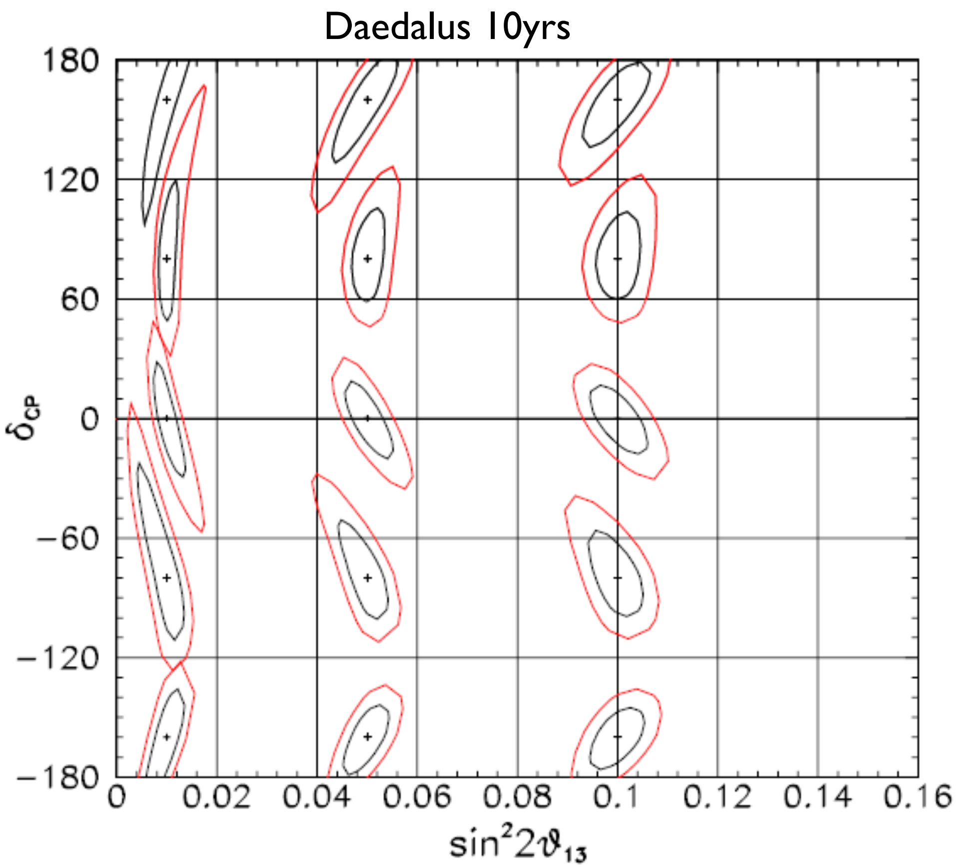
Total of each type of event:

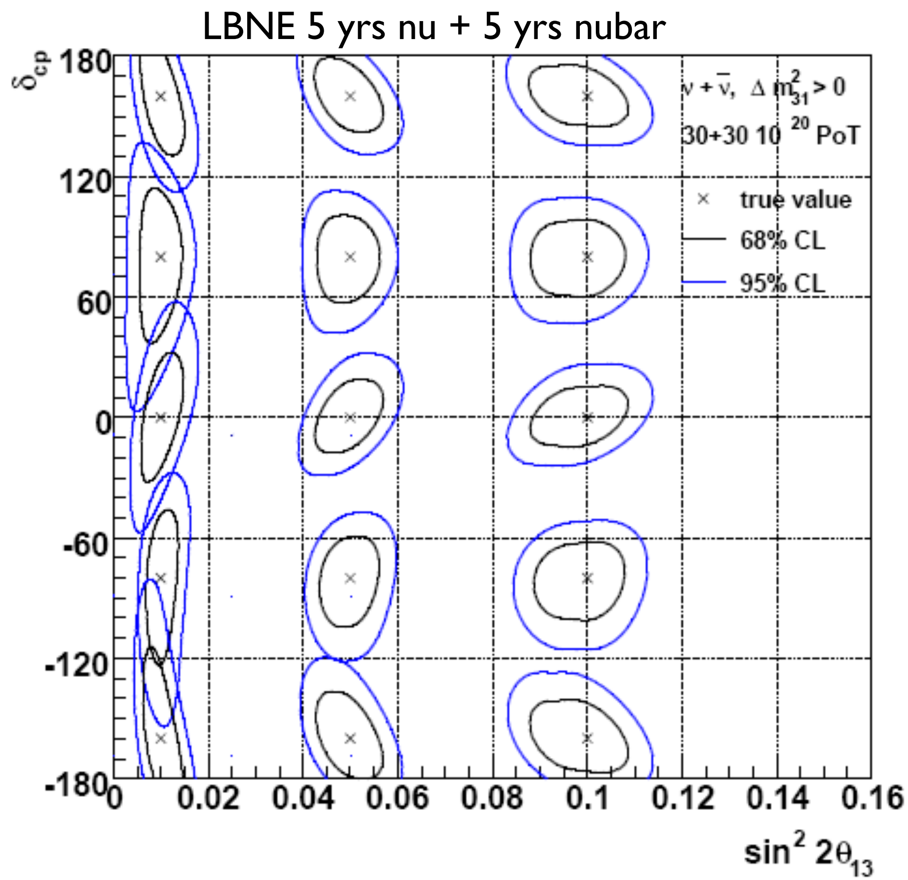
$\sin^2 2\theta_{13} = 0.05$
Phase 1 + Phase 2 Running

Event Type	1.5 km (Normalization)	8 km (Off Osc Max)	20 km (Osc Max)
IBD Oscillation Events ($E_\nu > 20$ MeV)			
$\delta_{CP} = 0^0$, Normal Hierarchy	763	1270	1215
" , Inverted Hierarchy	452	820	1179
$\delta_{CP} = 90^0$, Normal Hierarchy	628	1220	1625
" , Inverted Hierarchy	628	1220	1642
$\delta_{CP} = 180^0$, Normal Hierarchy	452	818	1169
" , Inverted Hierarchy	764	1272	1225
$\delta_{CP} = 270^0$, Normal Hierarchy	588	870	756
" , Inverted Hierarchy	588	870	766
IBD from Intrinsic $\overline{\nu}_e$ ($E_\nu > 20$ MeV)	600	42	17
IBD Non-Beam ($E_\nu > 20$ MeV)			
atmospheric $\nu_\mu p$ "invisible muons"	270	270	270
atmospheric IBD	55	55	55
diffuse SN neutrinos	23	23	23
ν_e−e Elastic ($E_\nu > 10$ MeV)	16750	1178	470
ν_e−Oxygen ($E_\nu > 20$ MeV)	101218	7116	2840

Correlated Measurements

Daedalus 10yr again comparable to LBNE(5yr+5yr)



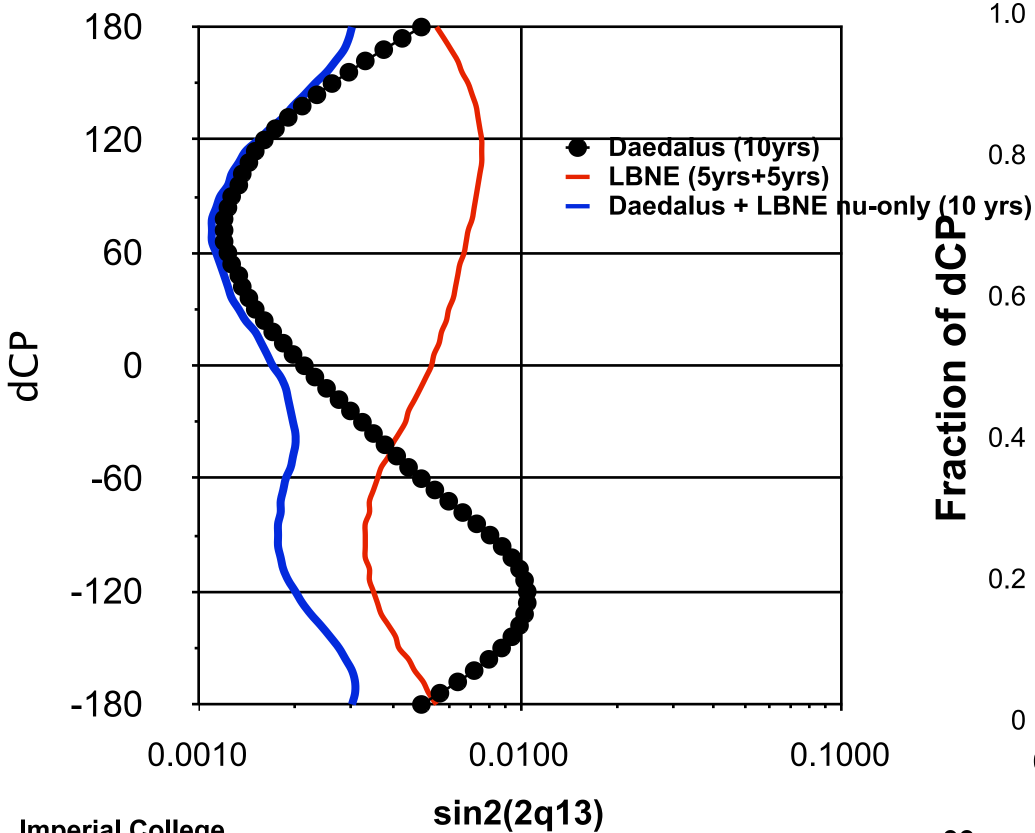


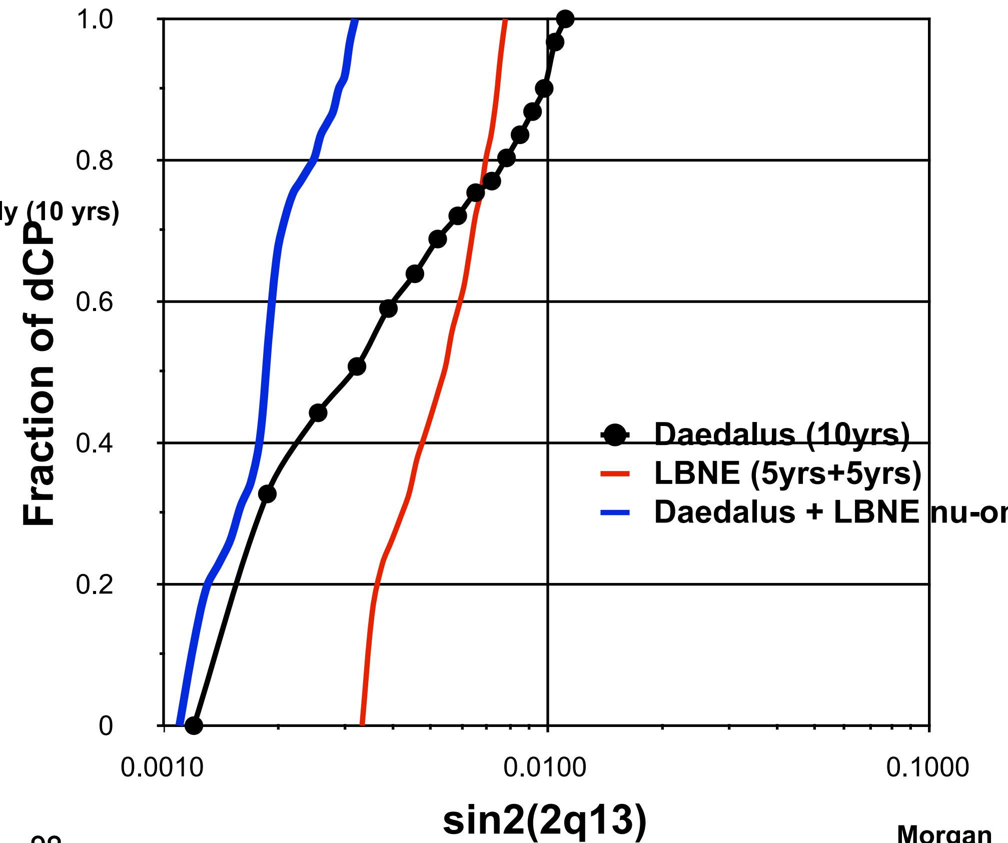
Much Better Sensitivity by Combining Daedalus and LBNE Measurements

- Daedalus can provide a high-statistics antineutrino sample with low background and small systematics to be combined with LBNE ν-only data.
    - Use 10yrs Daedalus $\bar{\nu}$ data + 10yrs LBNE ν-**only** data
- LBNE sensitivity estimates use:
    - dusel120e250i002dr280dz1300km_flux.txt (neutrinos)
    - dusel120e250ni002dr280dz1300km_flux.txt (anti-neutrinos)
    - 300kt Water Cherenkov
    - Proton rate = 6×10^{20} pot/yr

$\sin^2 2\theta_{13}$ Measurement Regions where $\sin^2 2\theta_{13} \neq 0$ at 3σ

- Daedalus and LBNE(5yr+5yr) comparable but complementary in sensitivity
- Combination (Daedalus + LBNE ν-only) gives significantly better coverage by x2 to x3

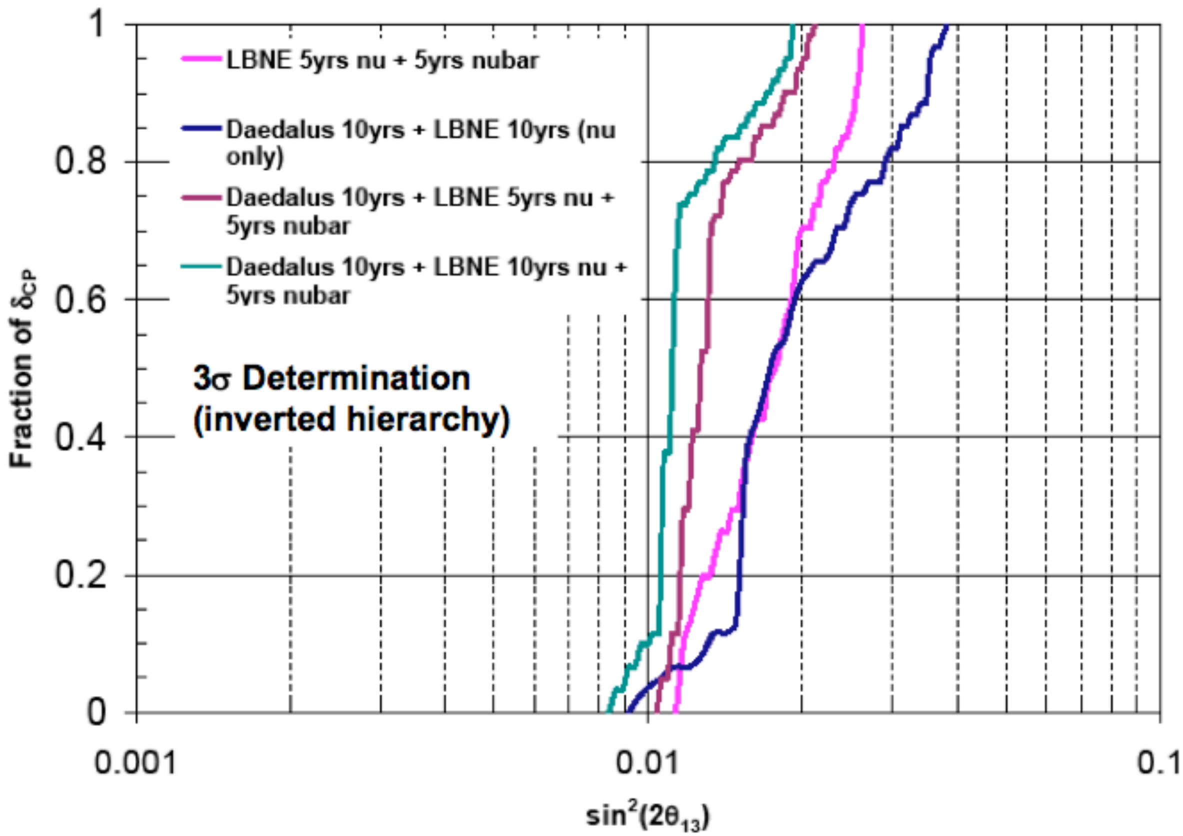




Mass Hierarchy Determination at 3σ

- Daedalus plus LBNE(ν-only) has good sensitivity for hierarchy determination comparable to LBNE(ν + $\bar{\nu}$) around the 50% point.

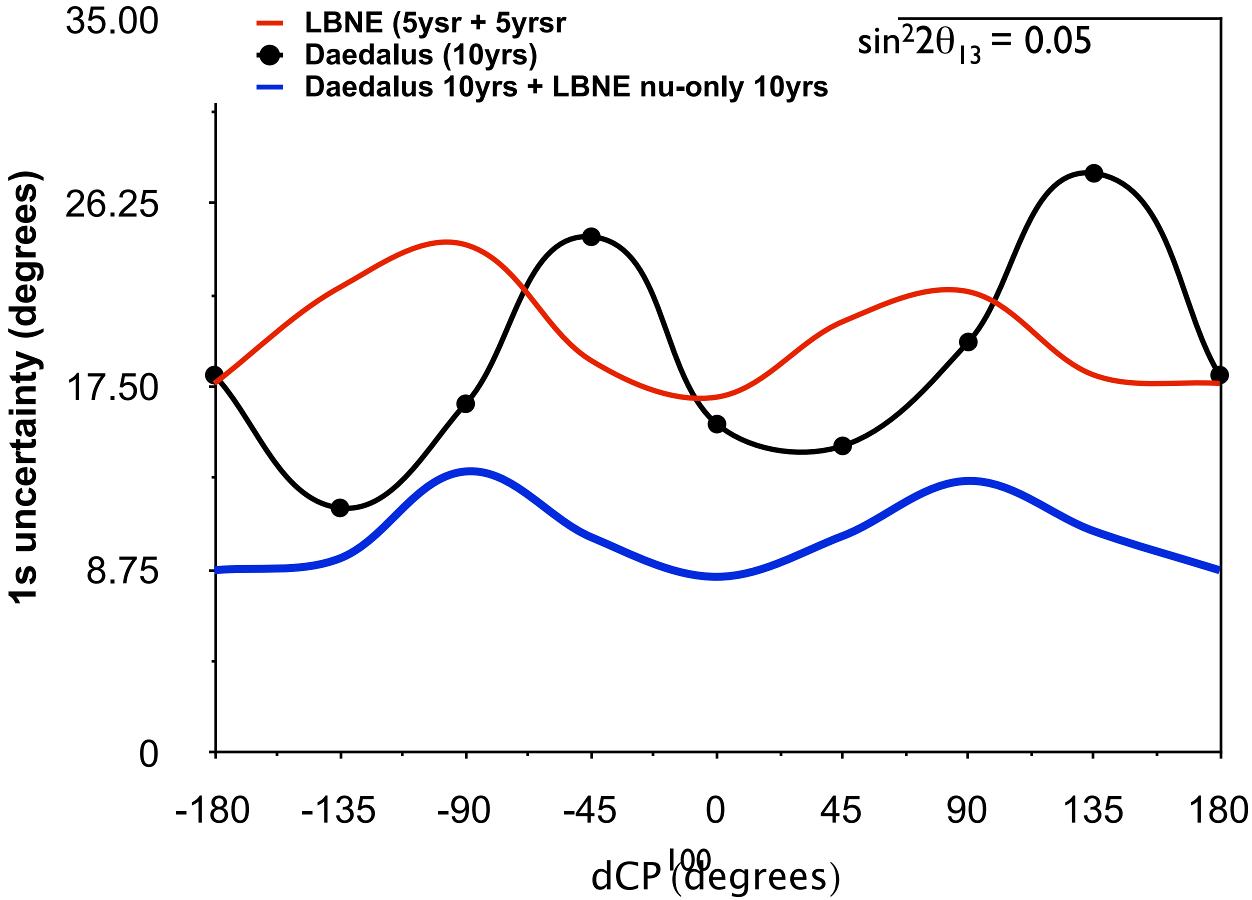
- If hierarchy is not determined with Daedalus plus LBNE(ν-only), then run with LBNE antineutrinos
  ⇒ Combination of Daedalus plus LBNE(ν + $\bar{\nu}$) better by almost x2



Combined Daedalus and LBNE

- Combining the high statistics Daedalus antineutrinos with the high statistics LBNE neutrino data sets gives improved sensitivity for measuring CP violation (δ_{CP})

- Plot below gives 1 σ error for measuring δ_{CP} as a function of δ_{CP} for $\sin^2 2\theta_{13} = 0.05$



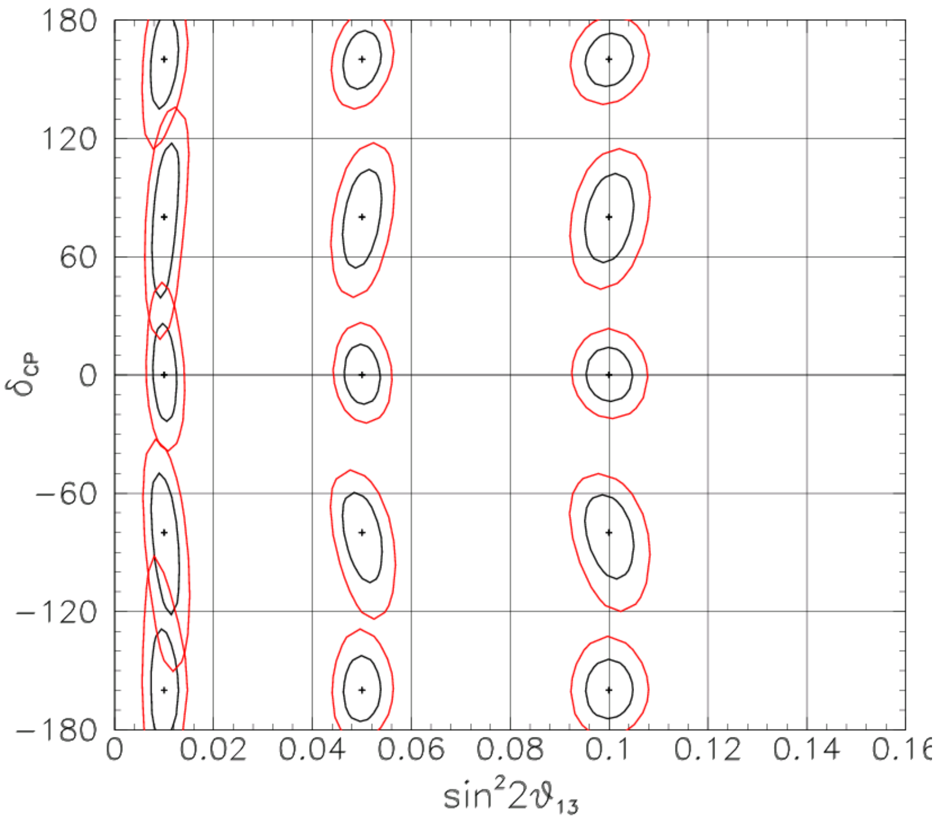
Combined Daedalus and LBNE

$\Rightarrow$ 5yr combined sensitivity as good as separate 10yr running

$\Rightarrow$ 10yr combined much better than either

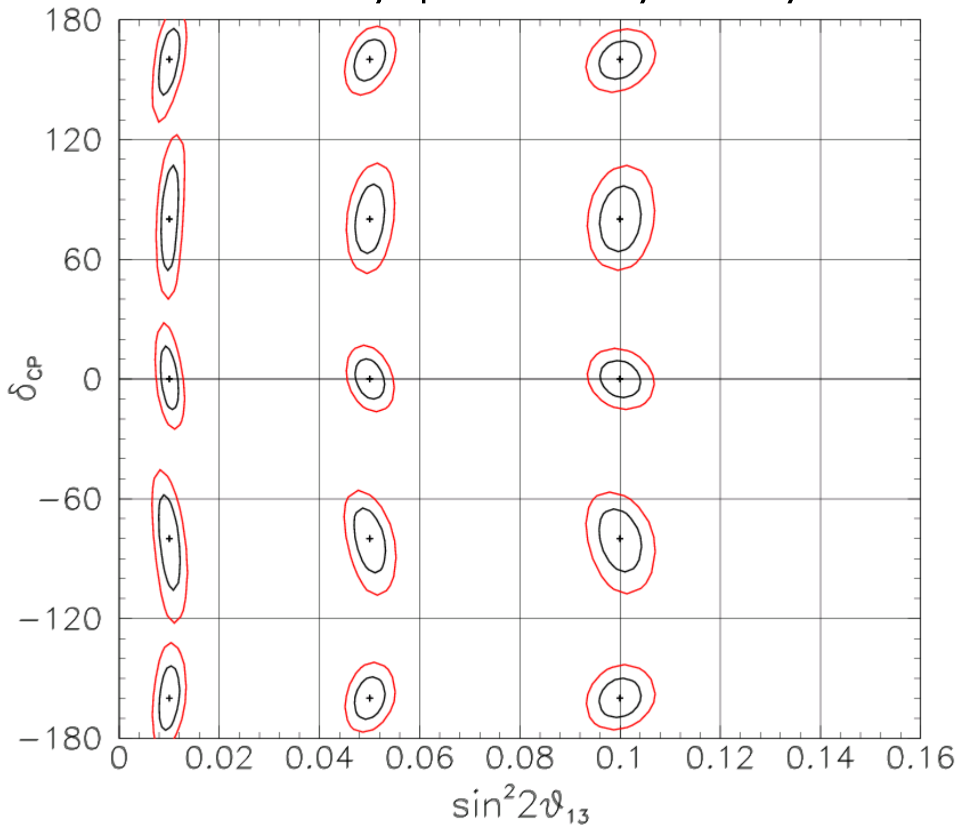
5yr Combined Running

Daedalus 5yr plus LBNE 5yr nu-only



10yr Combined Running

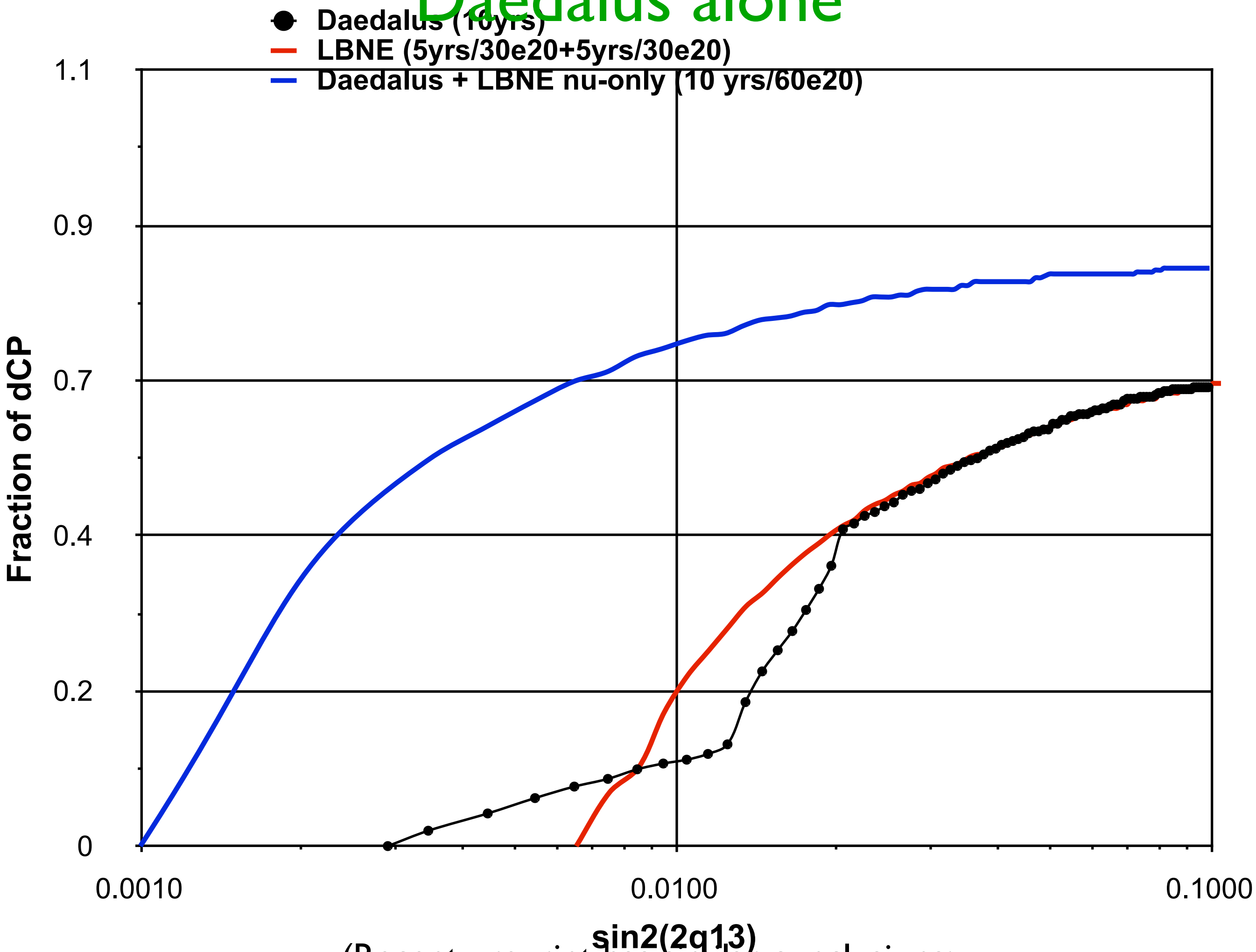
Daedalus 10yr plus LBNE 10yr nu-only



1 and 2 σ contours

Exclusion of δ_{CP}= 0^0 or 180^0 at

Combined running substantially better than either LBNE or Daedalus alone



(Recent preprint has similar conclusions:
Agarwalla,Huber,Link,Mohapatra - http://arxiv.org/abs/1005.4055)

Other Physics Opportunities with the Daedalus Near Accelerator

The near accelerator provides a high intensity beam with very well known flux that can be used by various experiments

- Calibration beam for LBNE and possibly dark-mater detectors
  Beam can also be used by short baseline experiments using small detectors made of various materials.
- Coherent neutrino nucleus scattering
  - Measurement of $\sin^2\theta_w$
  - Nonstandard interactions (i.e. ν mass or SUSY effects)
- Cross section measurements on various targets
  - Relevant for Supernova detection
  - Relevant for nucleosynthesis
- Neutrino Magnetic Moment
- Strange spin of the nucleon

… Many opportunities for small scale experiments!
… Bringing a new constituency to DUSEL

Conclusions

- Daedalus will broaden the reach of DUSEL for exploring neutrino oscillation physics and especially δ_{CP}
  - Daedalus will provide a high precision measurement of CP violation that is unique in that it utilizes antineutrinos
    - Low backgrounds with high statistics
    - No matter effects
  - Combining the Daedalus antineutrino data and LBNE neutrino sample is very powerful for extracting the oscillation physics.
  - The near accelerator will also provide a large data set for:
    - Physics studies of leptonic processes
    - Calibration data for the large water Cerenkov detector
- Technical issues:
  - Need to develop low-cost (15-30M$) high-power (1-3 MW) cyclotrons
  - Need to dope Water Cerenkov detectors with Gadolinium and have PMT coverage to detect neutron capture

- Plan to submit a Daedalus EOI to the DUSEL Lab soon.

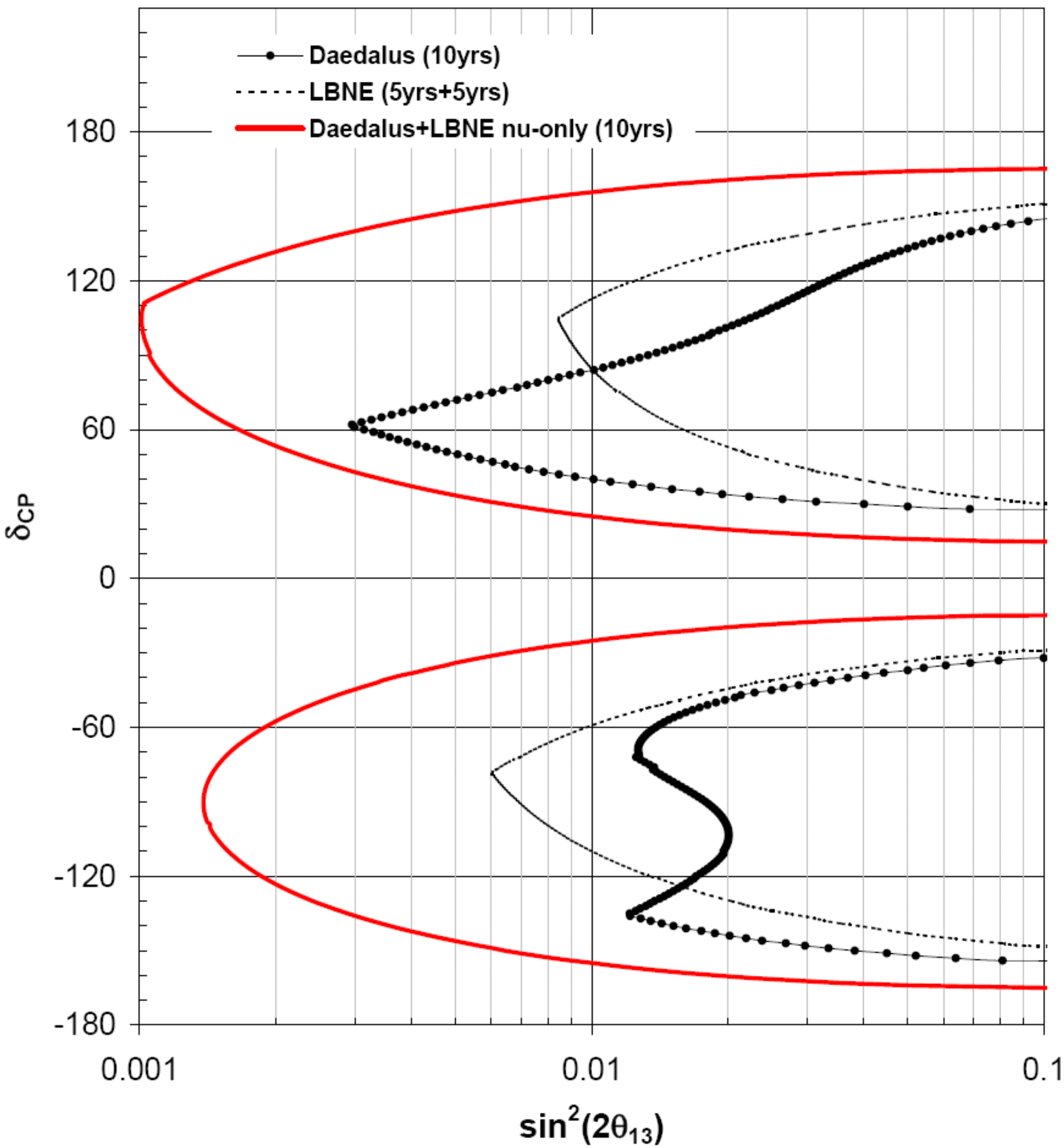
Impact of Daedalus on Other Measurements

(We have experts from all of these analyses in our group)

- Long baseline, atmospheric and proton decay
  Not affected because the analysis energy is above 50 MeV:
  (but we share an interest with proton decay to have good PMT coverage)
- Solar (and other n-e scattering analyses)
  These are not affected because one can cut on the direction
- SN burst
  The mean number of IBD events occurring in the SRN window is 0.04
  There is no issue except for the very low multiplicity SRN burst analyses, which may want to gate out the 20% DF near accelerator.
- SRN
  Need to gate out Daedalus running or subtract small contribution

Change in SNR Sensitivity

Energy bin	10-15 MeV	15-20 MeV
Change with DAEδALUS, 5% SRN sys	1.14	1.24
Change with DAEδALUS, 10% SRN sys	1.09	1.14
Change, gating out DAEδALUS, 5% SRN sys	1.12	1.19
Change, gating out DAEδALUS, 10% SRN sys	1.08	1.12


Daedalus (10yrs)
LBNE (5yrs+5yrs)
Daedalus+LBNE nu-only (10yrs)
180
120
60
0
-60
-120
-180
δCP
0.001
0.01
0.1
sin²(2θ13)

From the LSND paper

The symmetrical chain starting with π^- might lead to an intolerable number of $\bar{\nu}_e$, but three factors result in a large suppression of this background. First, for the LAMPF proton beam and beam stop configuration, positive pion production exceeds that of negative pions by a factor of about eight. Second, negative pions which come to rest in the beam stop are captured through strong interactions before they can decay, so only the 5% which DIF can contribute to a $\bar{\nu}_e$ background. (Note that 5% of π^- and 3.4% of π^+ produced in the beam stop decay in flight.) Third, virtually all of the negative muons arising from such pion DIF come to rest in the beam stop before decaying. Most are captured from atomic orbit, a process which leads to a ν_μ but no $\bar{\nu}_e$, leaving only 12% of them to decay into $\bar{\nu}_e$. Hence one can estimate the relative yield, compared to the positive channel, to be $\sim (1/8) * 0.05 * 0.12 \approx 7.5 \times 10^{-4}$. Thus, it is expected that $\bar{\nu}_e$ are present only at this level in the isotropic flux of neutrinos from the source. A detailed Monte Carlo simulation [12] gives a value of 7.8×10^{-4} for the ratio of $\bar{\nu}_e$ from μ^- DAR to $\bar{\nu}_\mu$ from μ^+ DAR.