DAEδALUS

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Seminar @ LBL
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Decay
At rest
Experiment
for δ_{cp} studies
At the
Laboratory for
Underground
Science

Use *decay-at-rest neutrino beams*,
and one of the planned ultra-large detectors
with free protons (H_2O, oil)
to search for CP violation in the neutrino sector

Outline:

- Physics Motivation: CP Violation

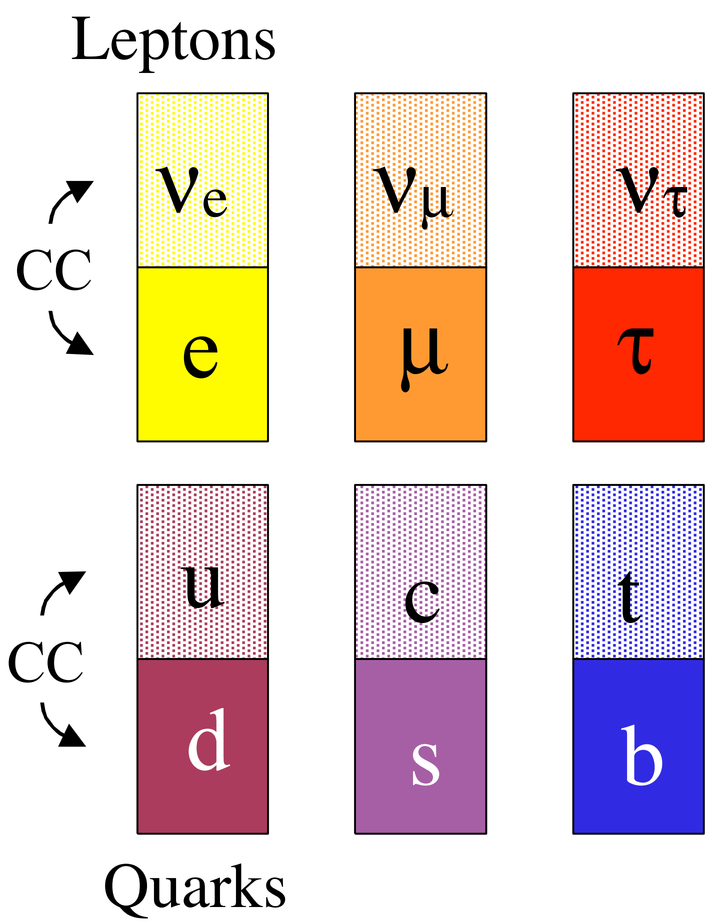
- Approaches to the Problem
  - The “Conventional Wisdom” -- long baseline
  - An unconventional approach: DAEδALUS
  - Playing well together!

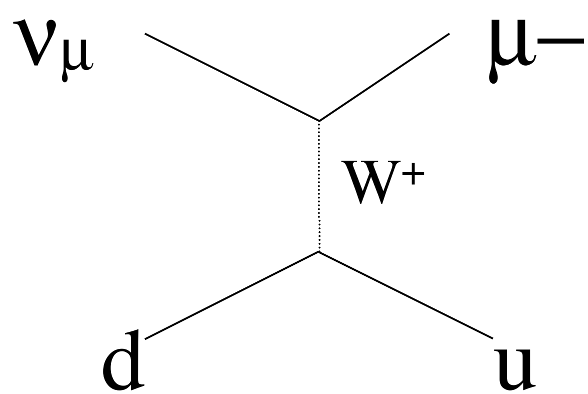
- How real are the cyclotrons?

MOTIVATION

CP violation in the Neutrino Sector

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



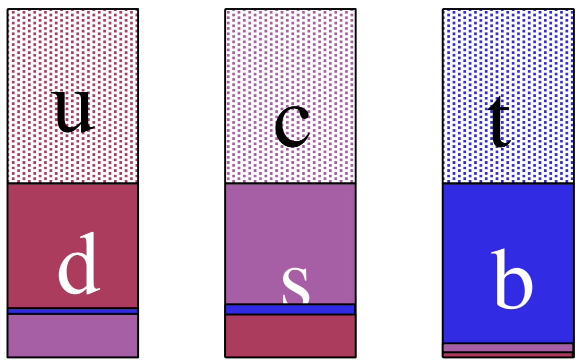


We identify the
neutrino flavor
via the CC interaction

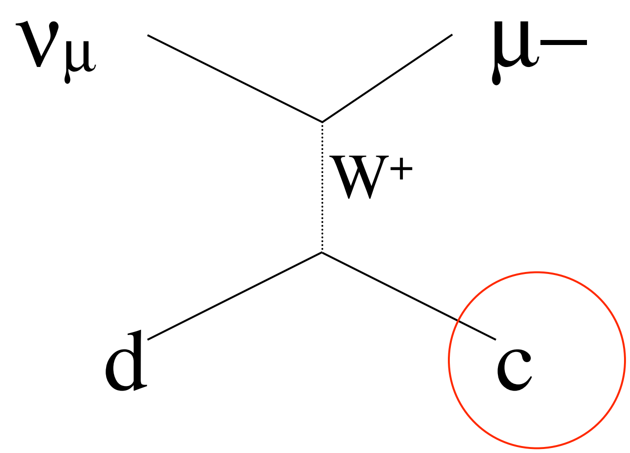
The quarks also form weak doublets…

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 quark mixing matrix has to be unitary,
but not "simple"

Any 3×3 unitary matrix has

3 associated free parameters (Euler angles)

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

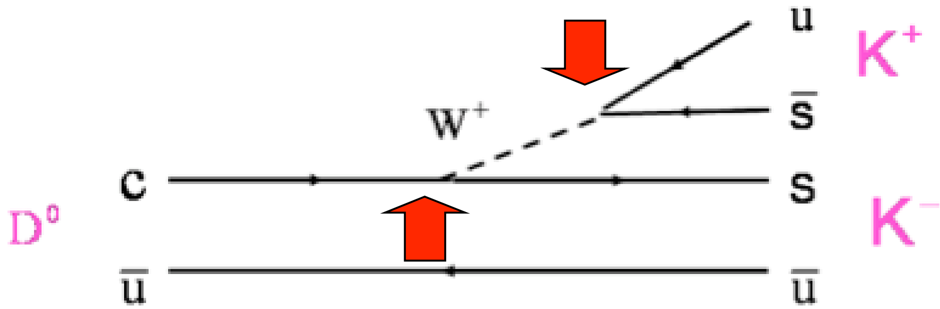
& can have a complex phase hidden in it!

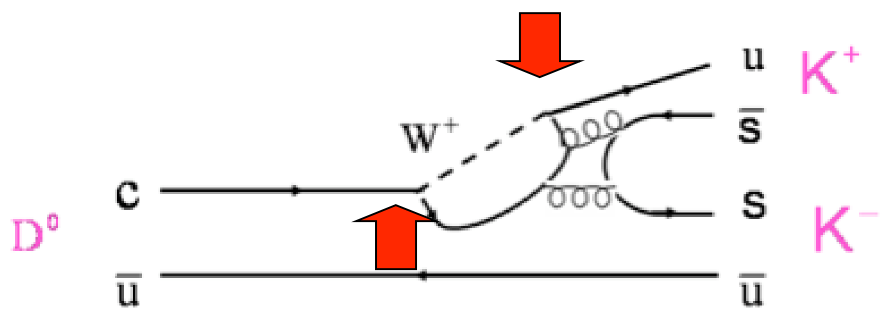
$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix},$$

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

The effect shows up in weak decays

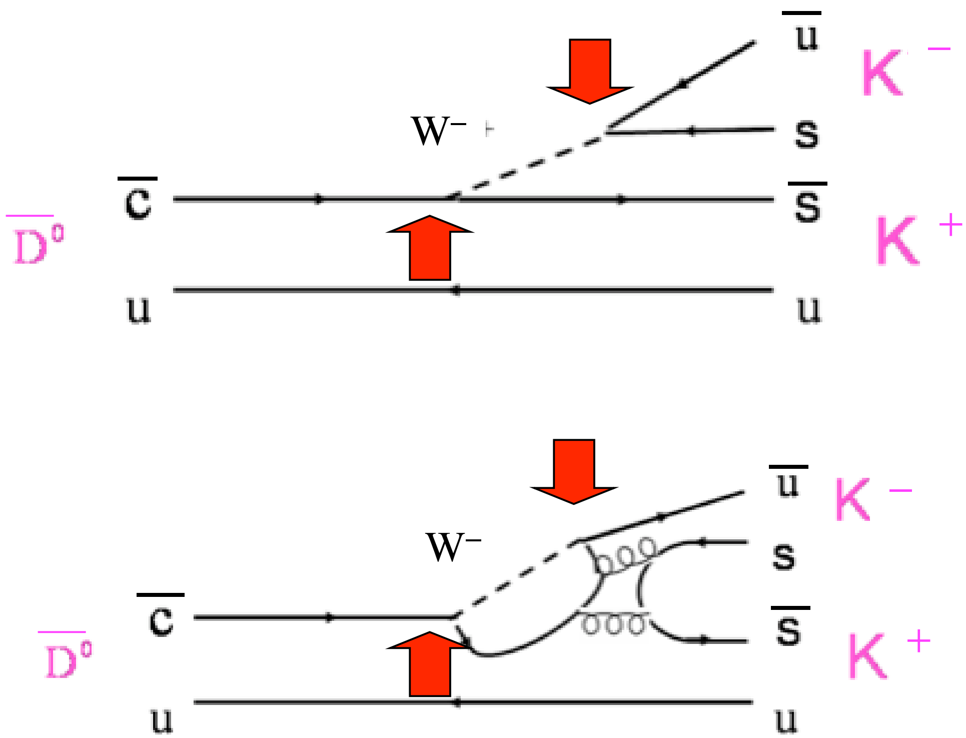
when you have 2 paths to the same outcome…





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 flavor 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…

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

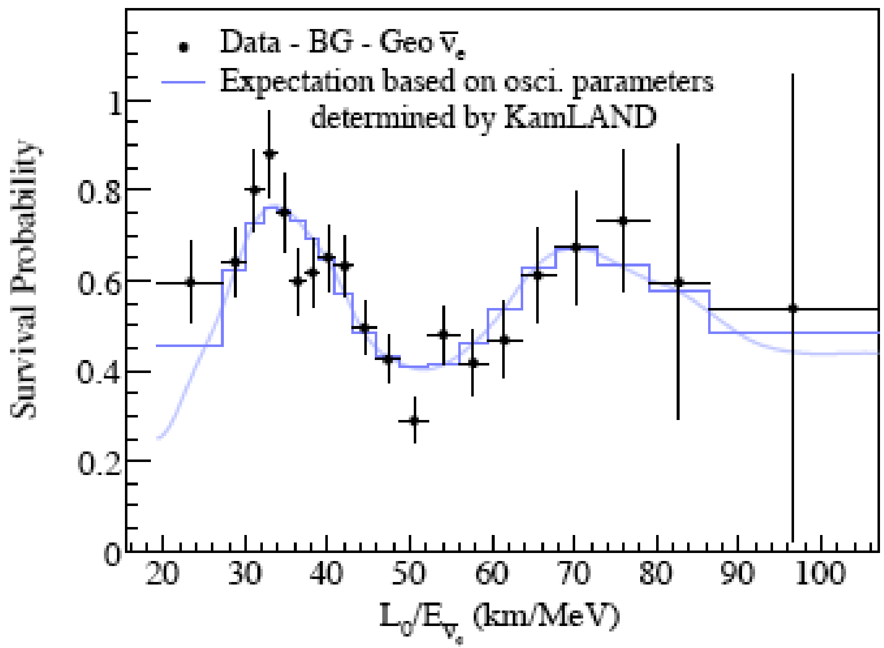
Observe mixing…?

The Probability for Oscillations...

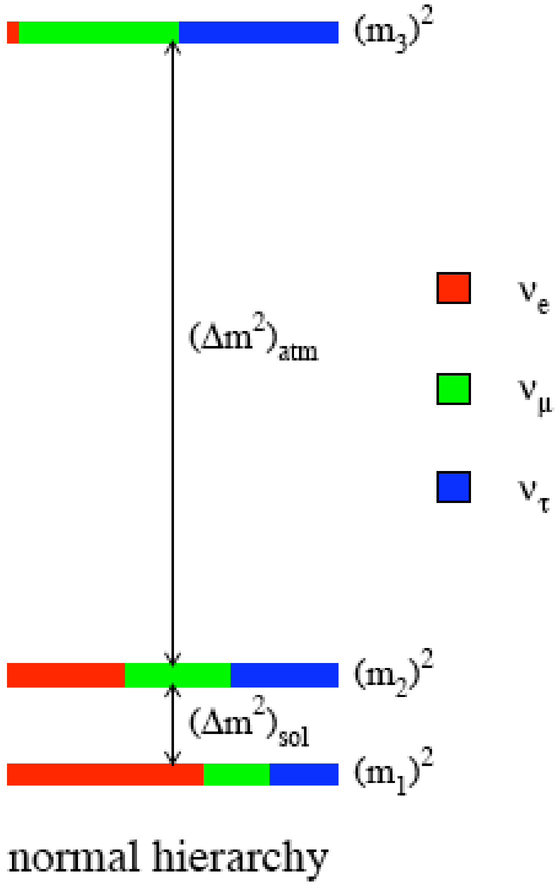
$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

YES!

For example, in Kamland!



Observed at 2 different Δm^2 values
in many experiments!

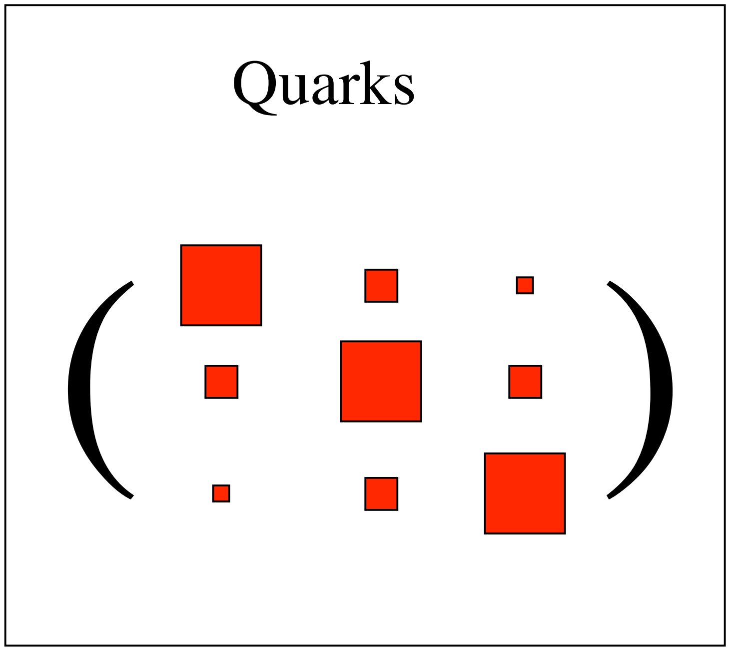


Our Model

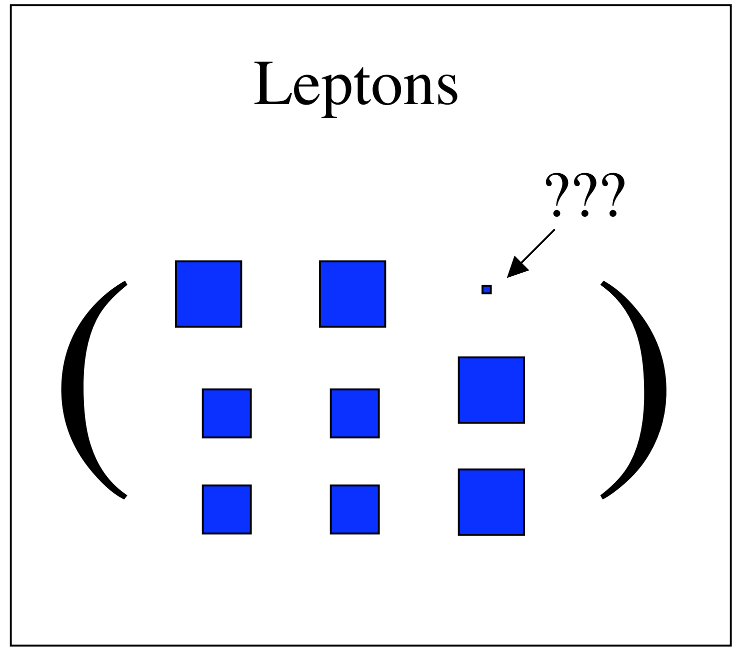
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

"mixing" between neutrinos
is parameterized by
three "mixing angles"
$\theta_{12}, \theta_{13}, \theta_{23}$

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…

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

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

From Atmospheric and Long Baseline Disappearance Measurements

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& this matrix is well-known

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

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

Super K,
SNO,
KamLAND

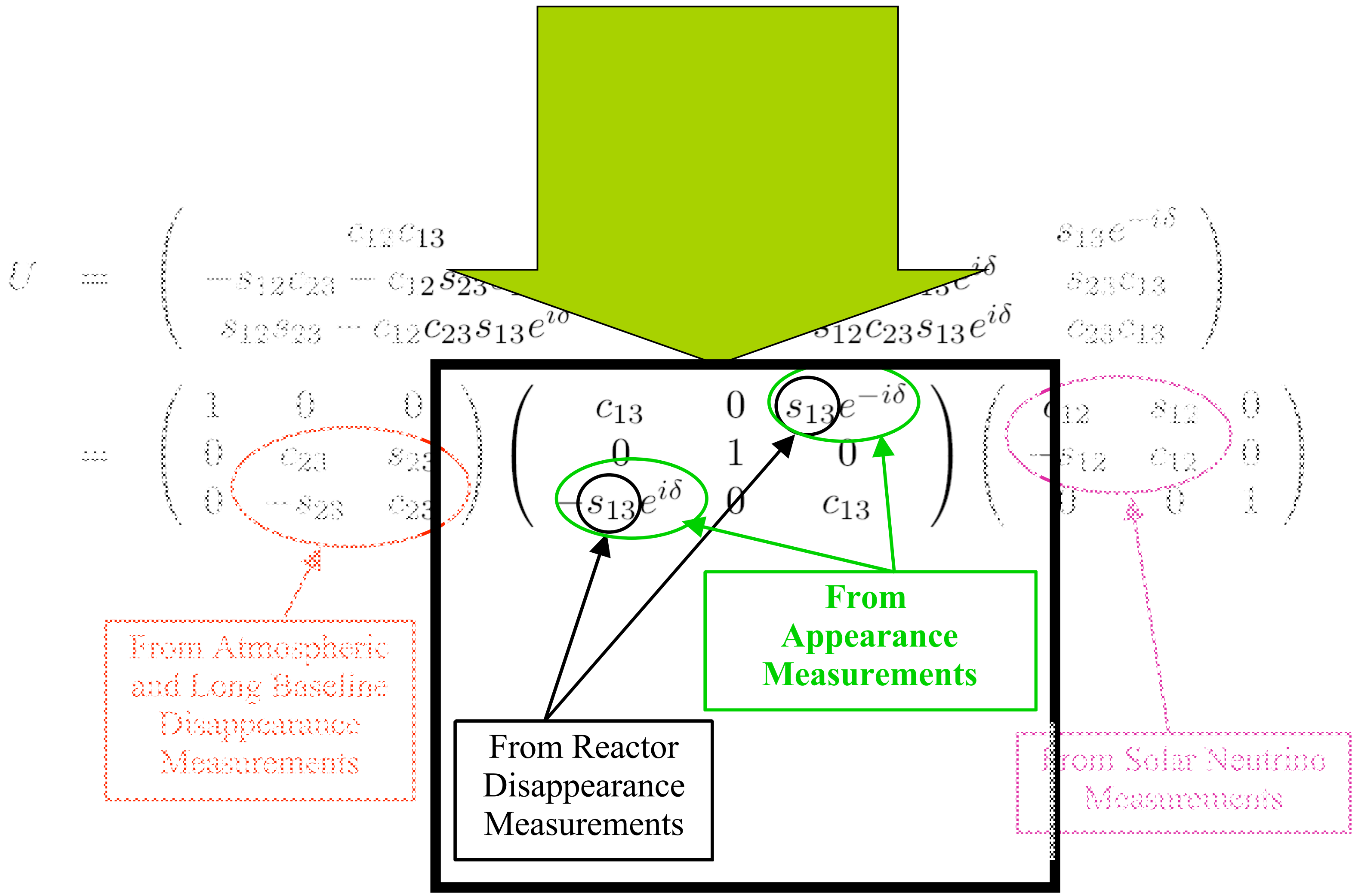
From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

From Appearance Measurements

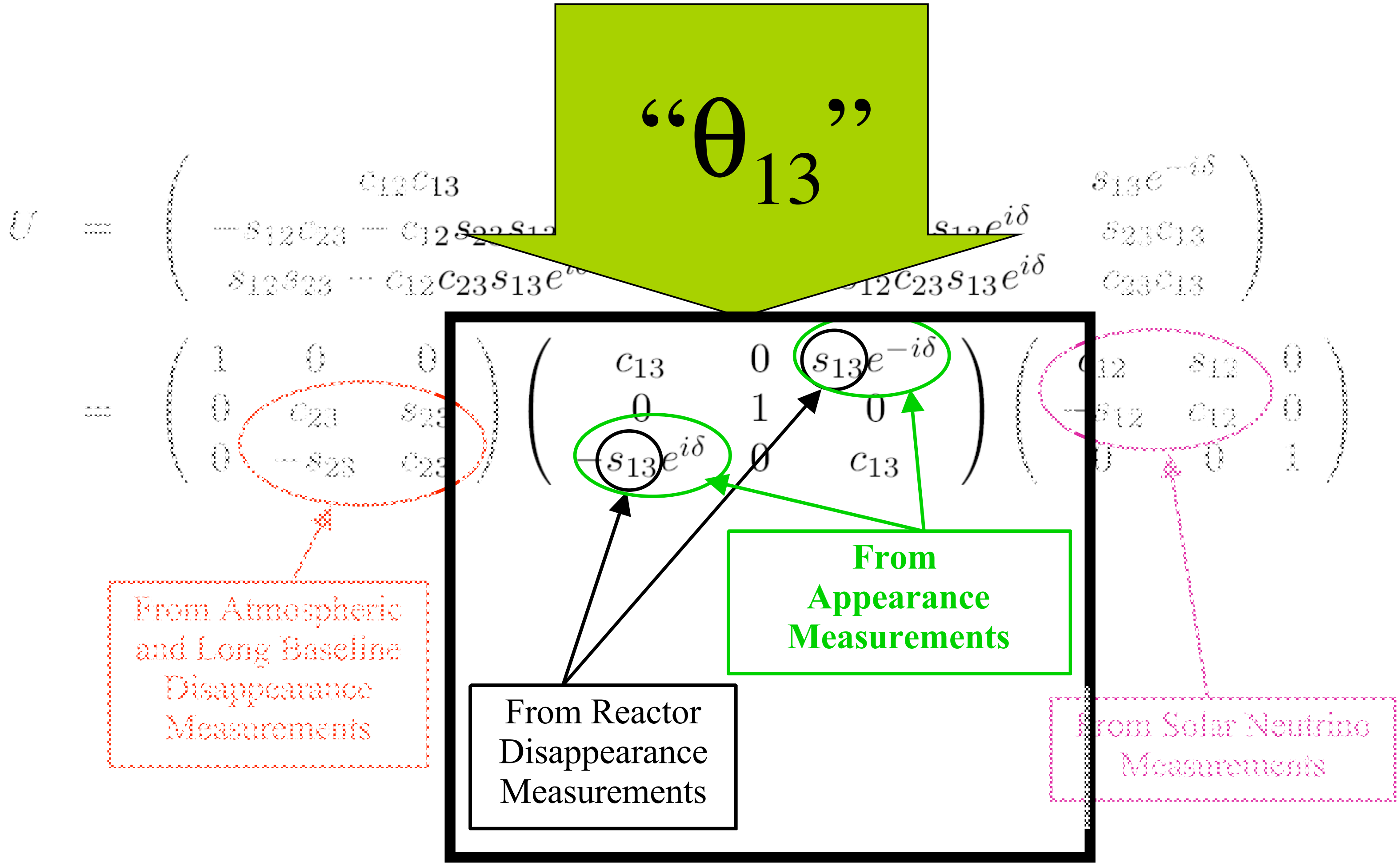
From Solar Neutrino Measurements

But this one is not known at all!

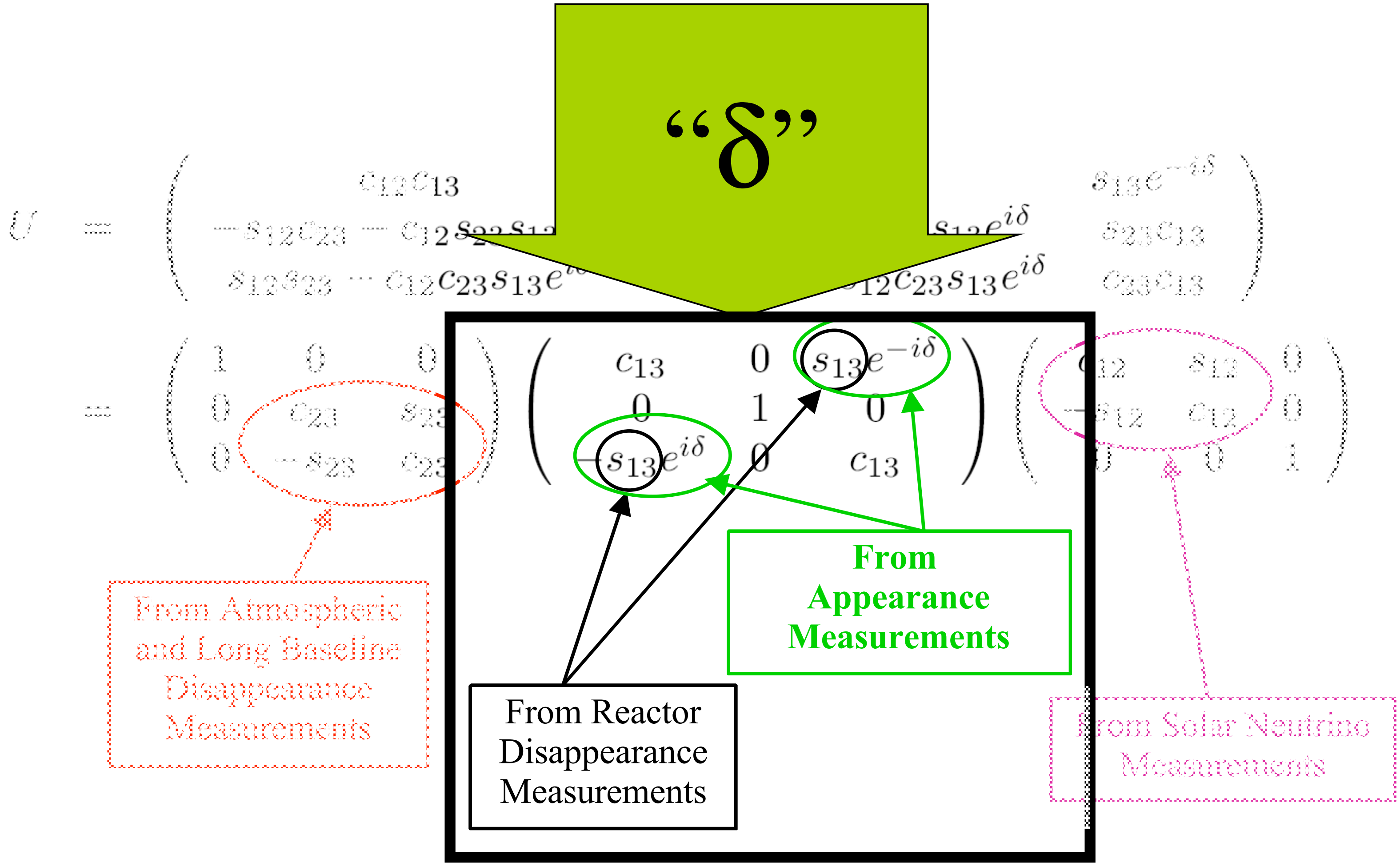


Many experiments are searching for the last mixing angle

e.g. Double Chooz, Daya Bay



DAEδALUS will search for



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

… though the theoretical connection between GUT scale and light neutrino $\not{CP}$ is unclear!

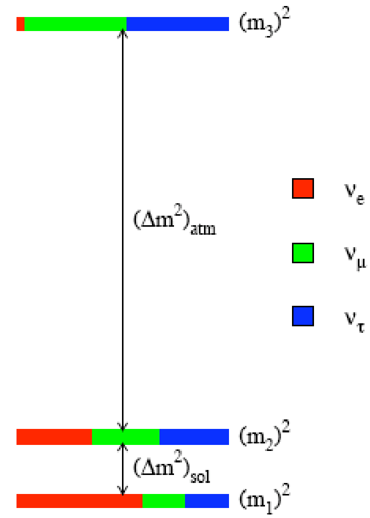
Searching for CP violation in the neutrino sector is a priority of our field

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.

APPROACHES

1. Conventional Long Baseline
2. DAEδALUS
3. Combining the two

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



in a vacuum…

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

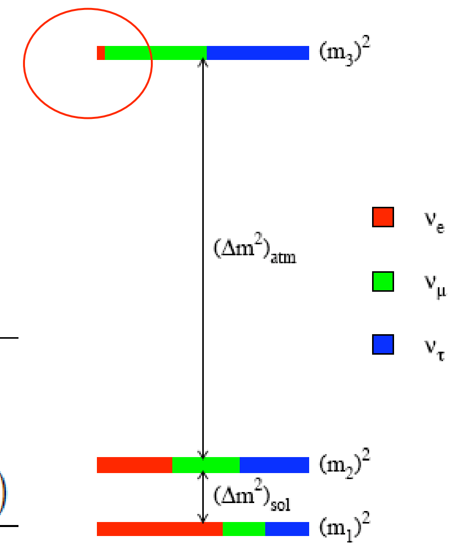
We want to see if δ is nonzero

terms depending on mixing angles

terms depending on mass splittings

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

Most parameters are well known…

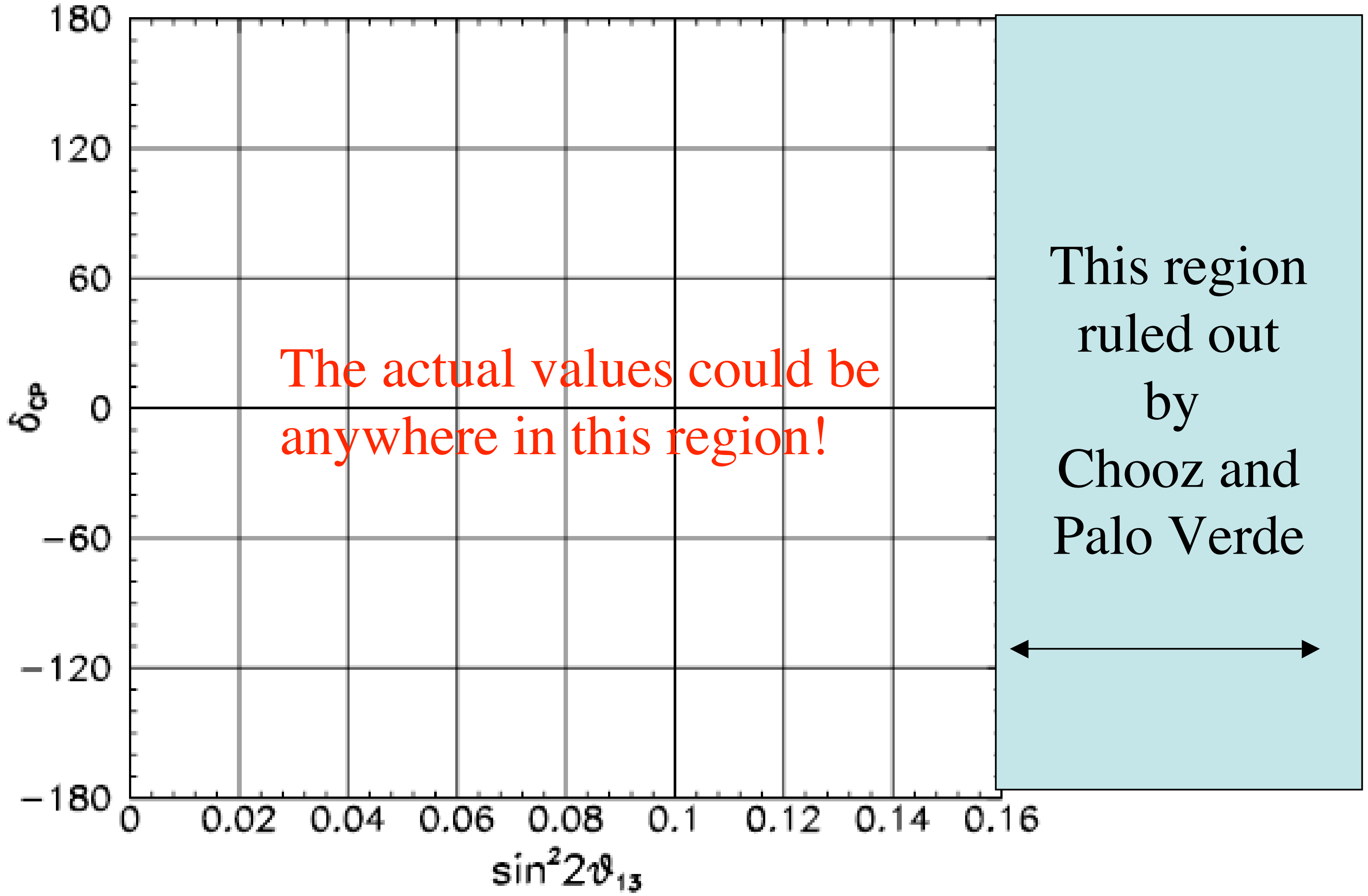


Parameter	Present: Value	Present: Uncert. (±)	Assumed Future: Value	Assumed Future: Uncert. (±)
$\Delta m^2_{21} \times 10^{-5}\mathrm{eV}^2$	7.65	0.23	7.65	N/A
$\Delta m^2_{31} \times 10^{-3}\mathrm{eV}^2$	2.40	0.12	2.40	0.02
$\sin^2(2\theta_{12})$	0.846	0.033	0.846	N/A
$\sin^2(2\theta_{23})$	1.00	0.02	1.00	0.005
$\sin^2(2\theta_{13})$	0.11	0.06	0.05	0.005

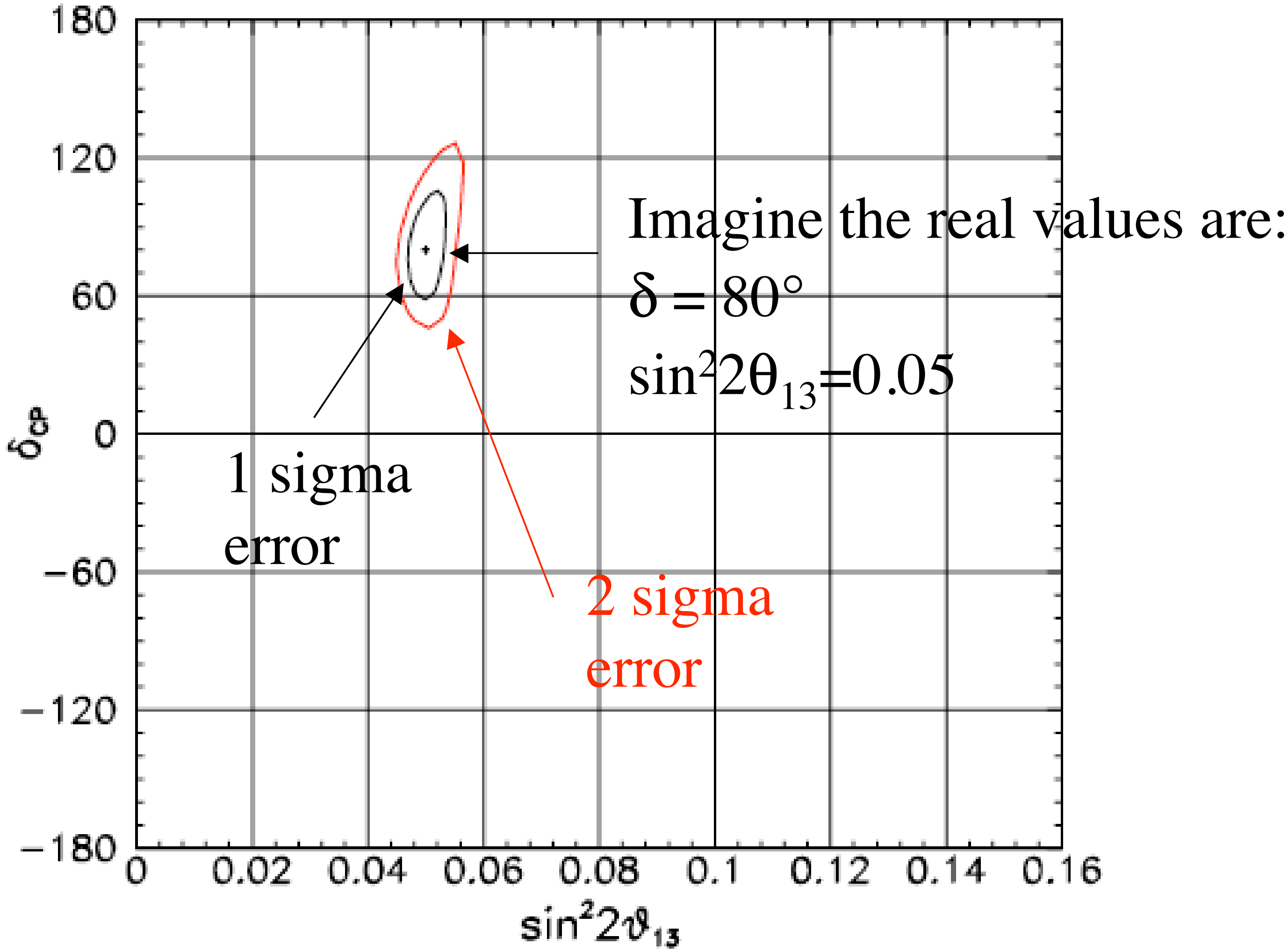
Except for that pesky θ_{13}!

We will end up having to quote our sensitivity as allowed regions in both θ_{13} and δ

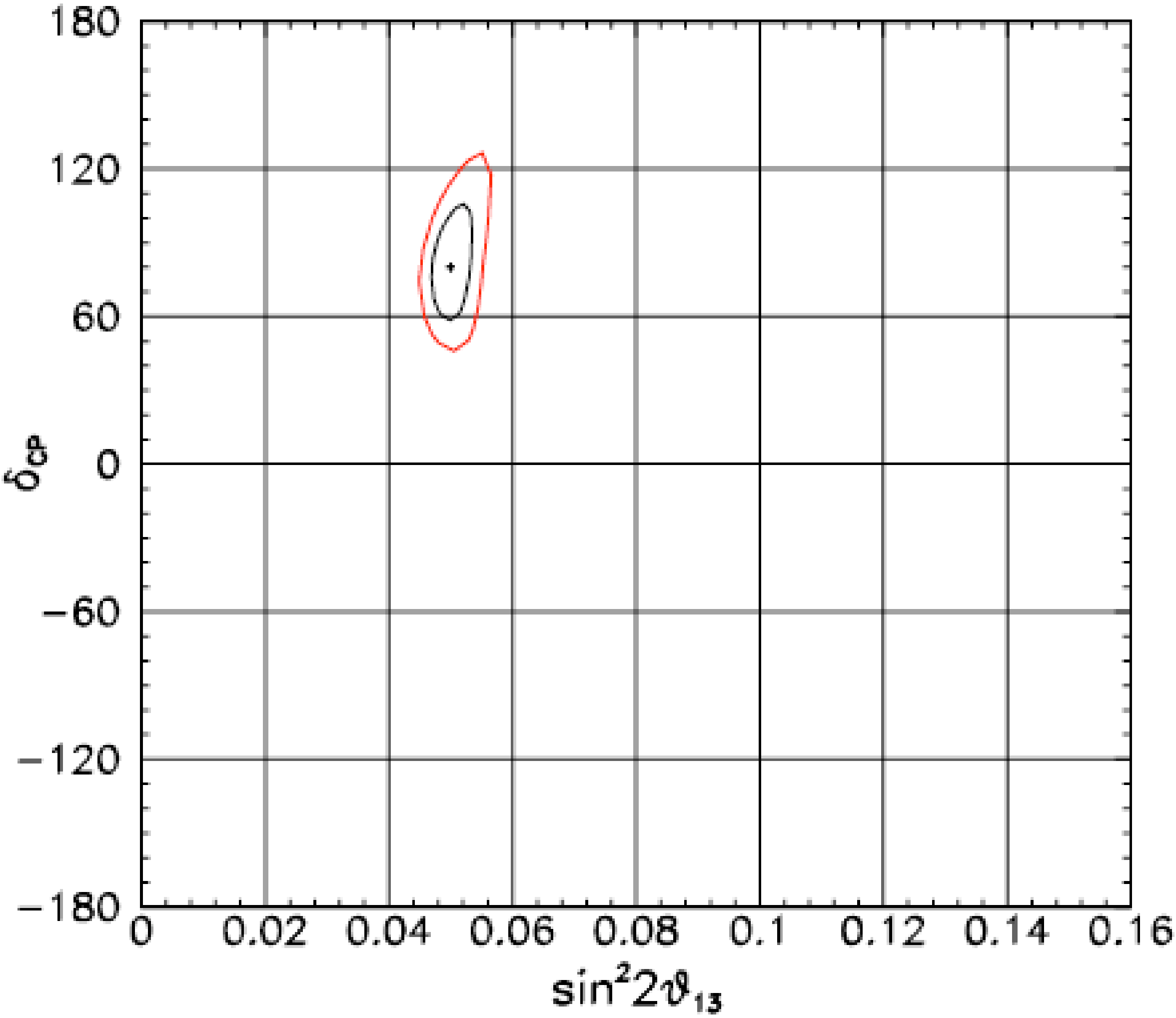
So what do we know about δ vs θ_{13} ???



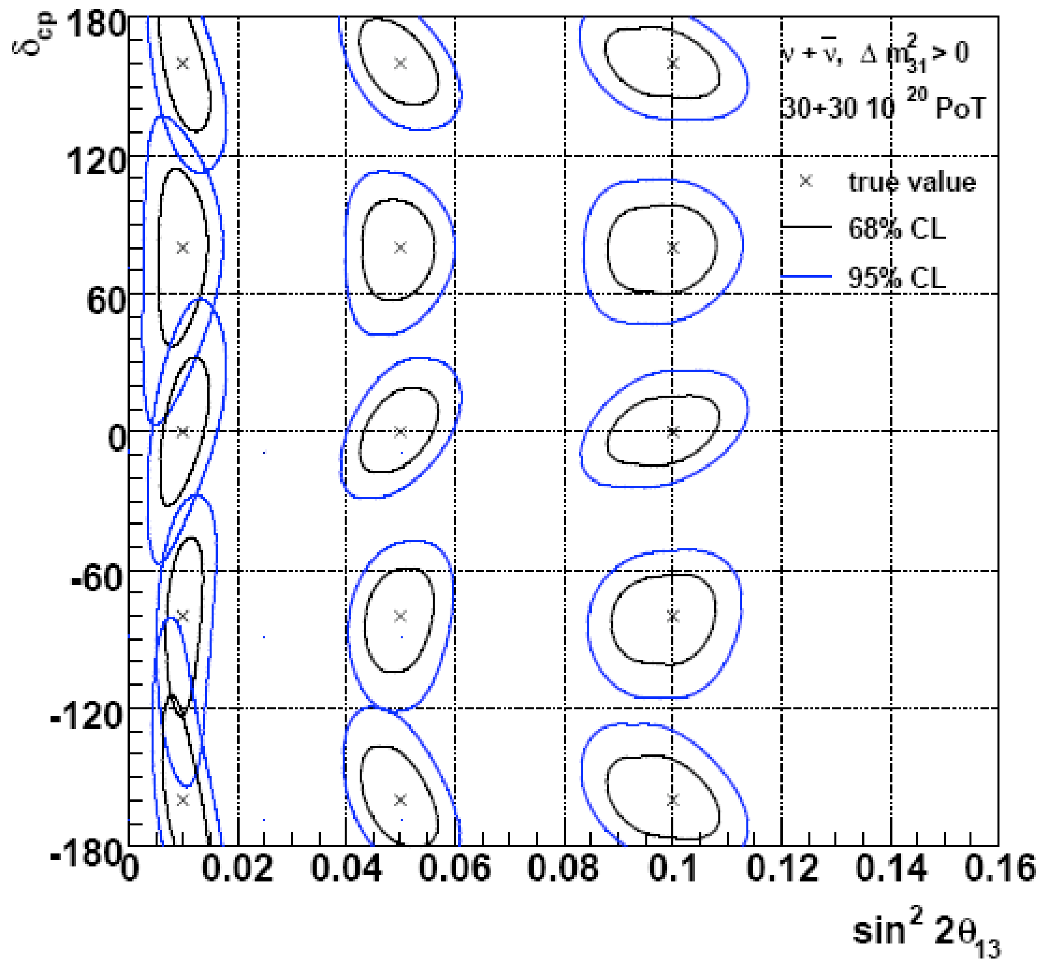
If we succeeded in observing a signal,
what would this plot look like?



You get a “jelly bean”



"Jelly bean plots" identify hypothetical values of δ and θ_{13} and show the expected contours at 1σ and 2σ



Our equation flips sign between

$\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$

in a vacuum…

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

what we want to measure

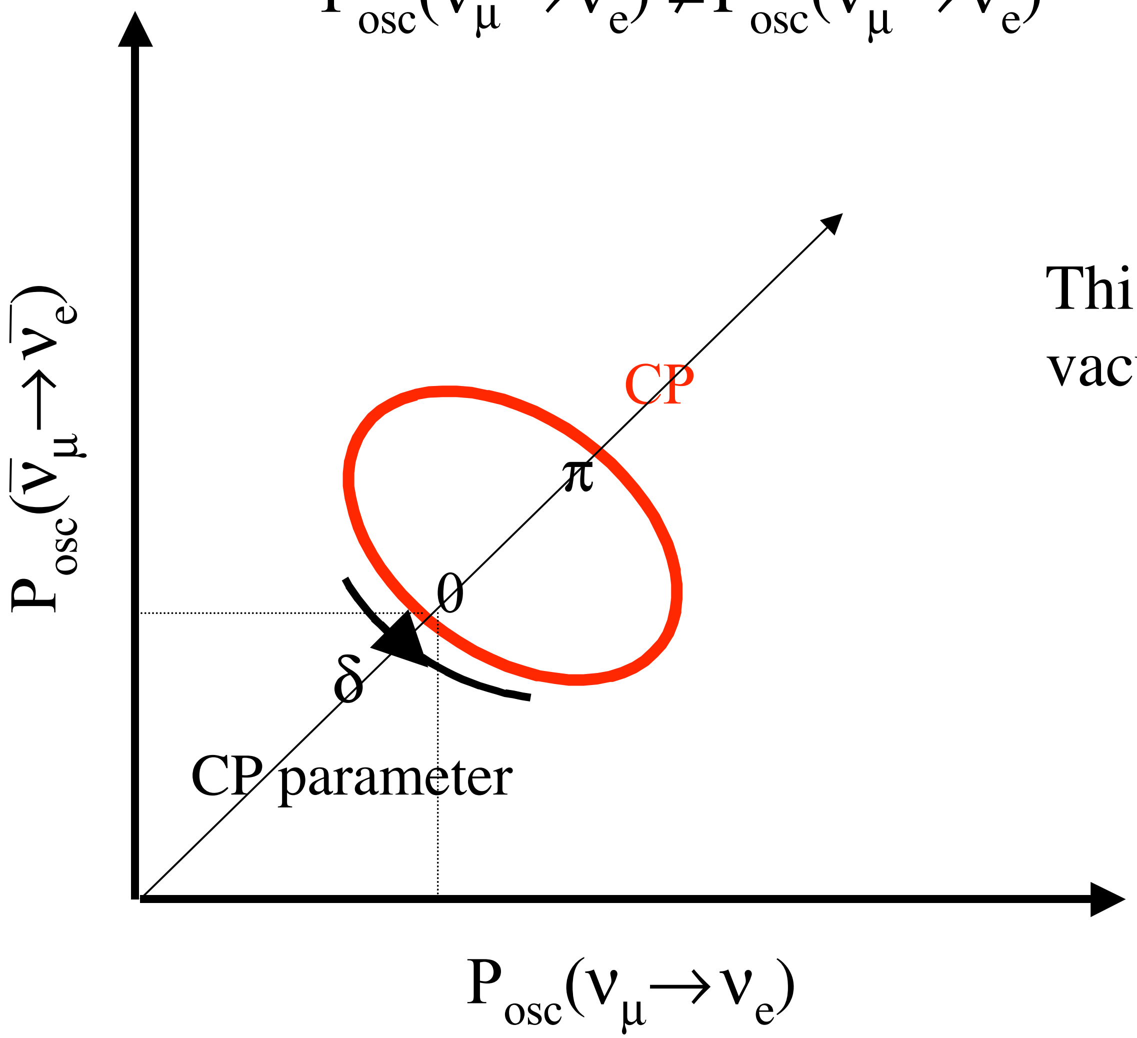
terms depending on mixing angles

terms depending on mass splittings

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

The classic idea for how to see CP violation:

$$P_{osc}(\nu_\mu \rightarrow \nu_e) \neq P_{osc}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

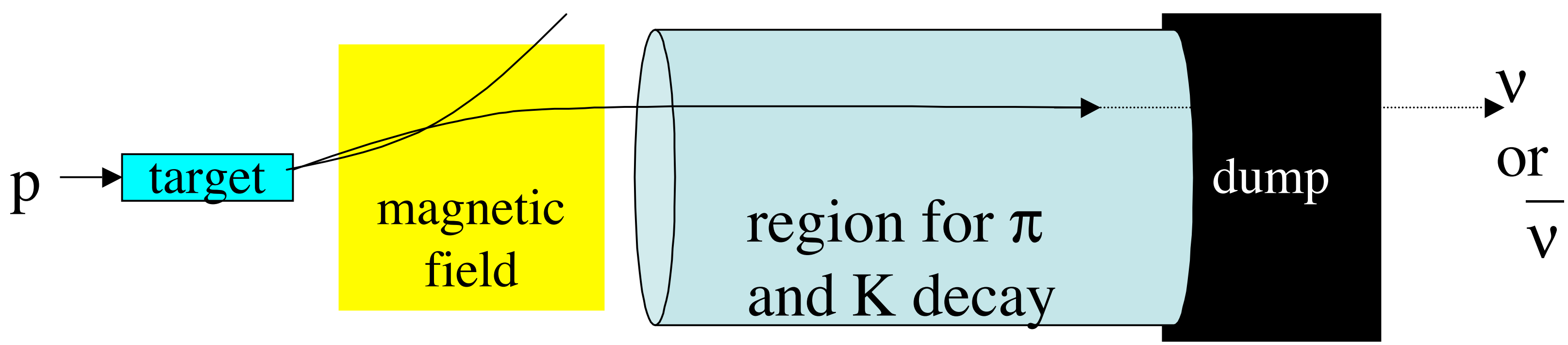


This is in a vacuum (or air).

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

Here's why…

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

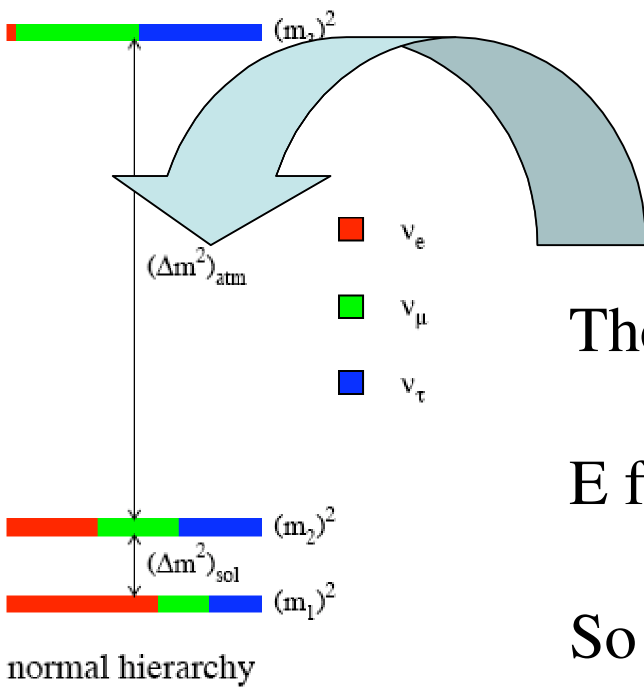


"Conventional neutrino beam" -- 100's of MeV to a few GeV

The Probability for Oscillations...

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

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



The atmospheric Δm^2 ~0.001 eV^2

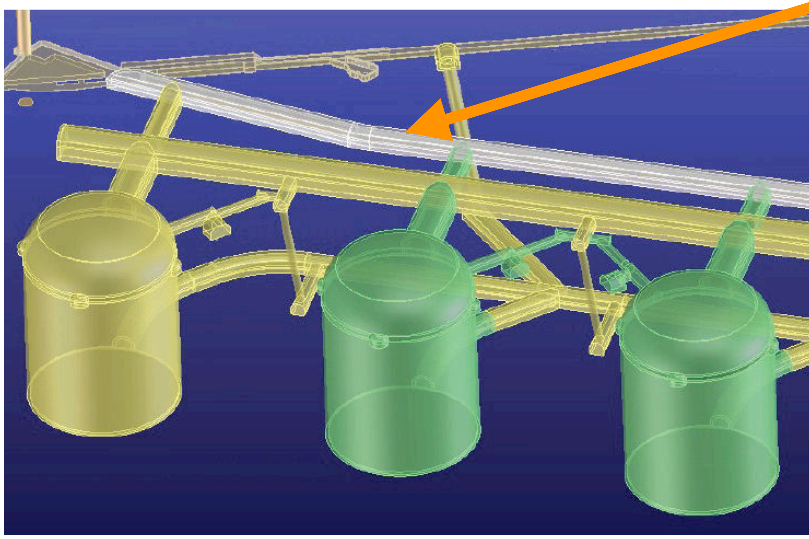
E from a convention beam is ~ 1 GeV

So L = 1000 km !!!

Using LBNE as an example…

Beam from Fermilab

Shoots to detectors in South Dakota
1300 km

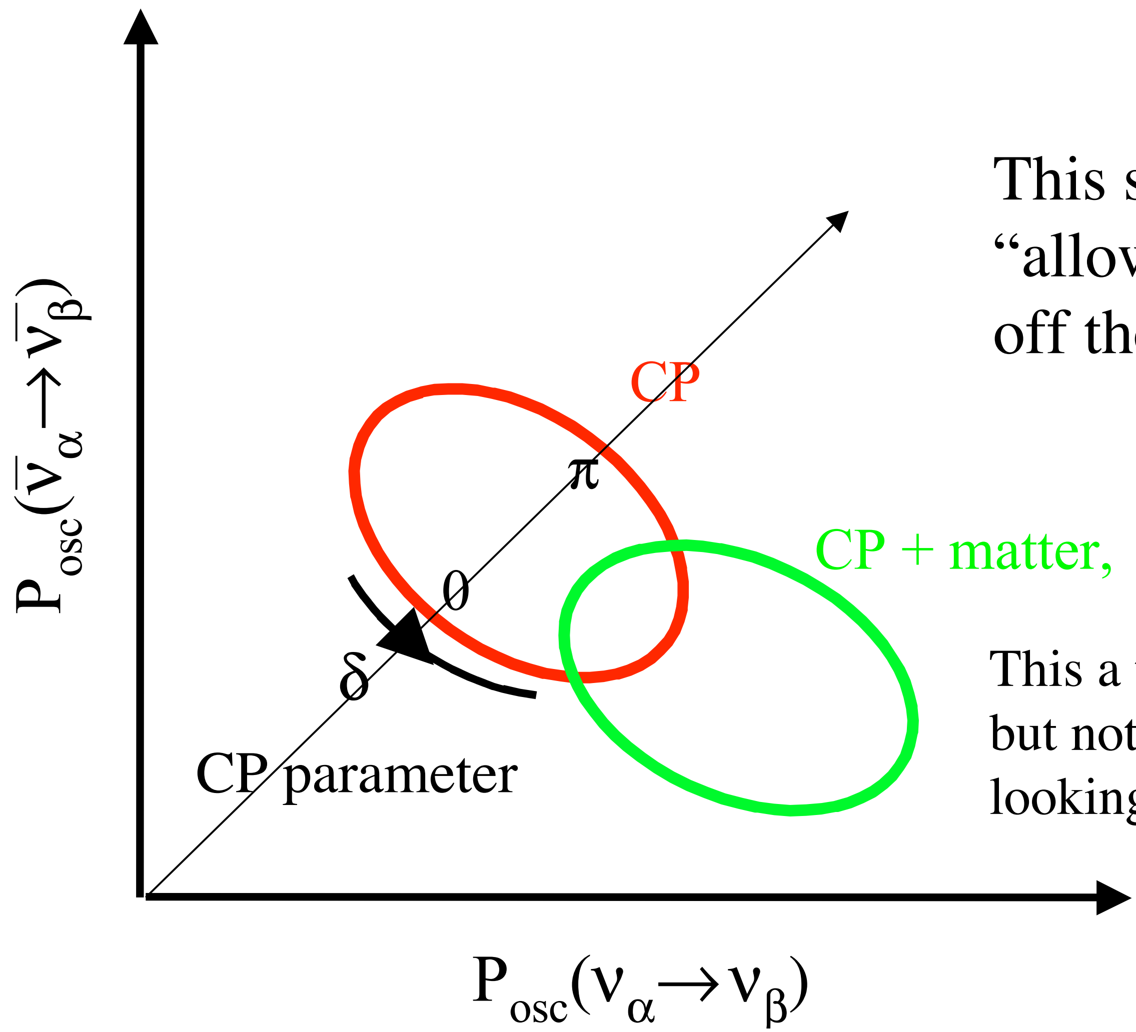


And there is **lots and lots** of matter along a 1300 km path!

also true for LENA, MEMPHYS and HyperK designs

And the ground is made of matter (electrons)
not antimatter (positrons)

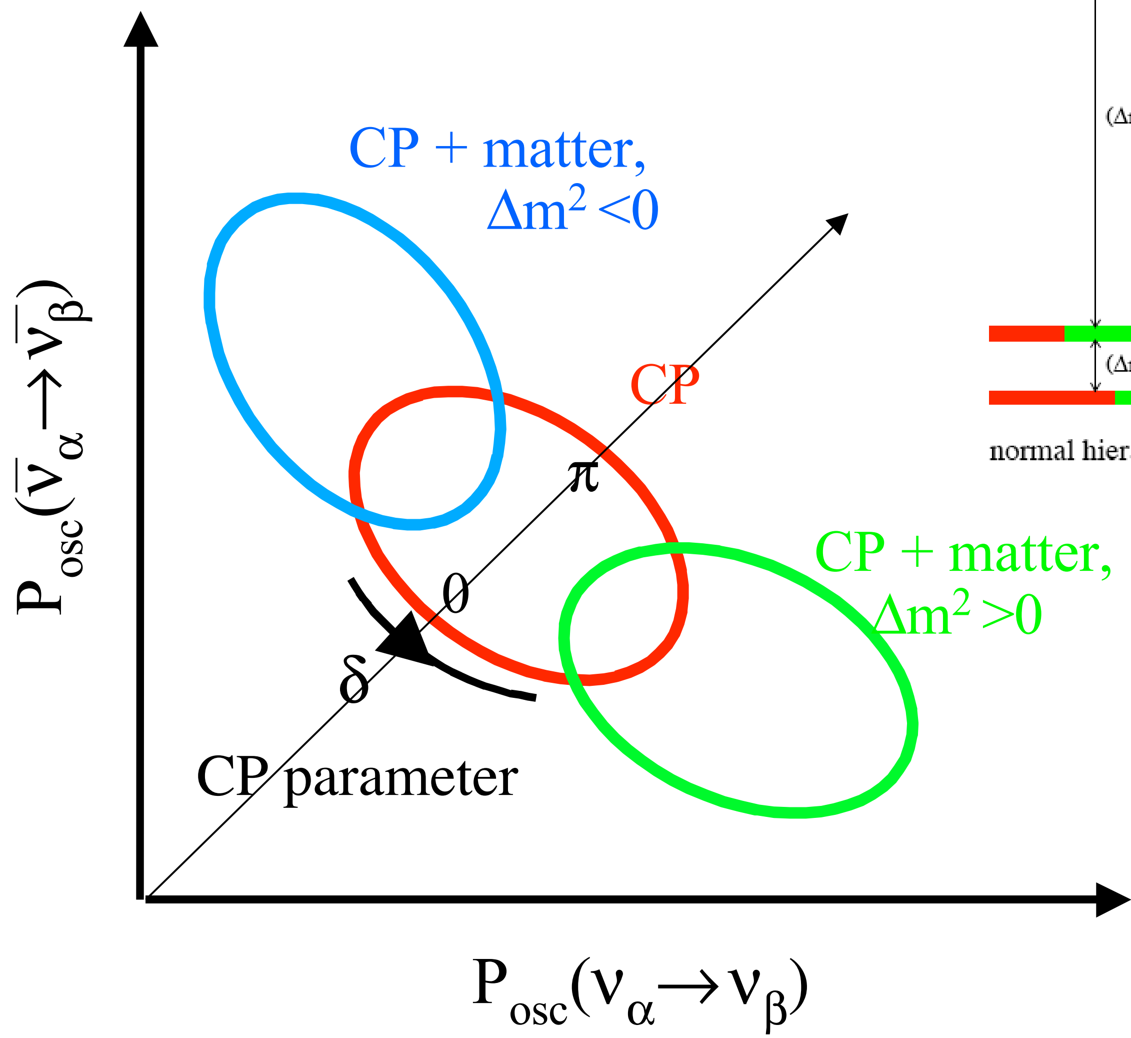
Forward scattering affects neutrinos differently than antineutrinos.

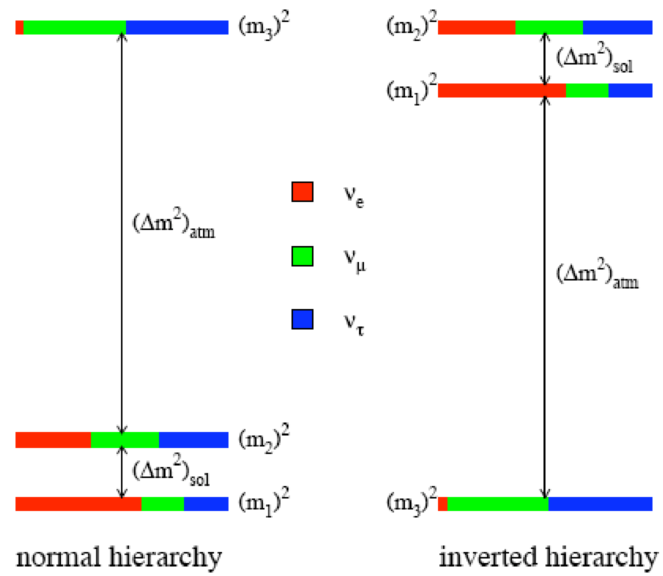


This slides the "allowed ring" off the diagonal

This a type of CP violation, but not what we are looking for!

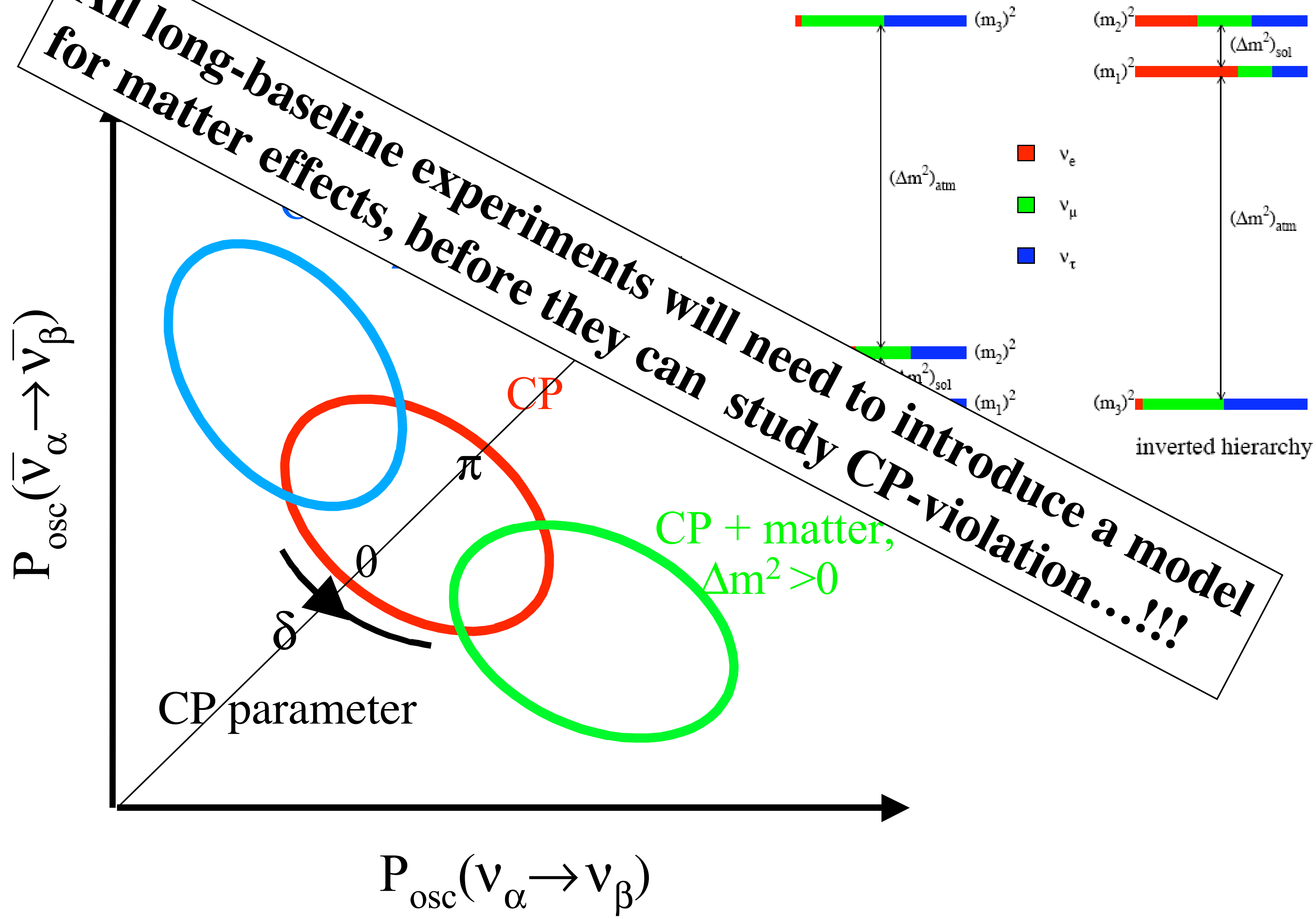
Worse, we actually don’t know which direction…





Worse, we actually don't know which direction…

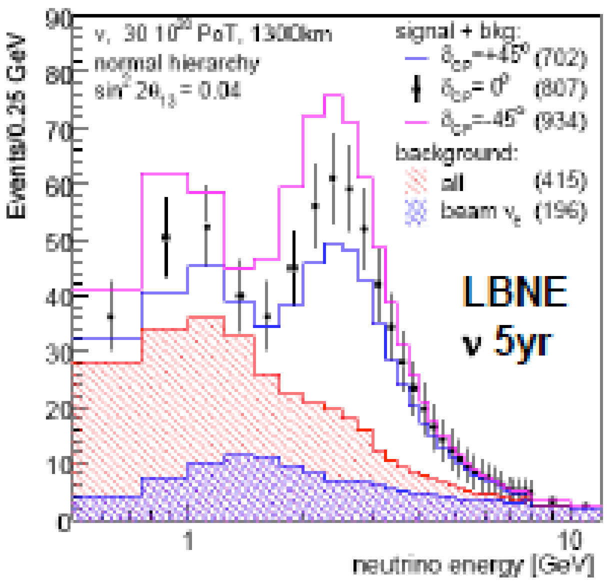
All long-baseline experiments will need to introduce a model for matter effects, before they can study CP-violation…!!!

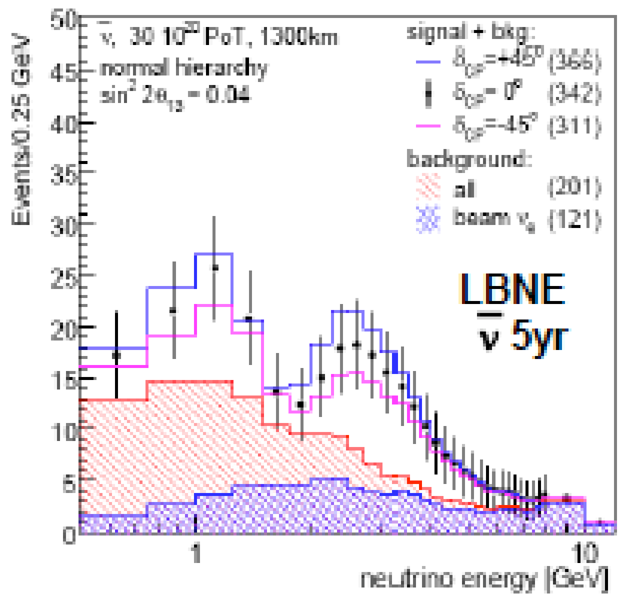


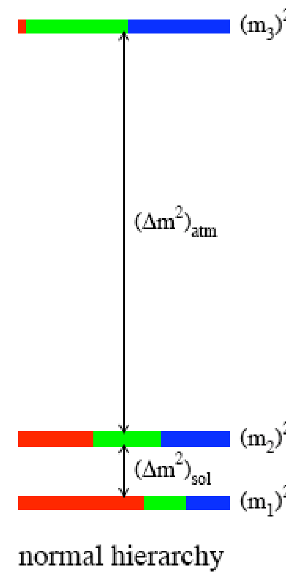
Other problems…

Long Baseline experiments are usually low in antineutrino statistics

→ a combination of style of beam and cross section

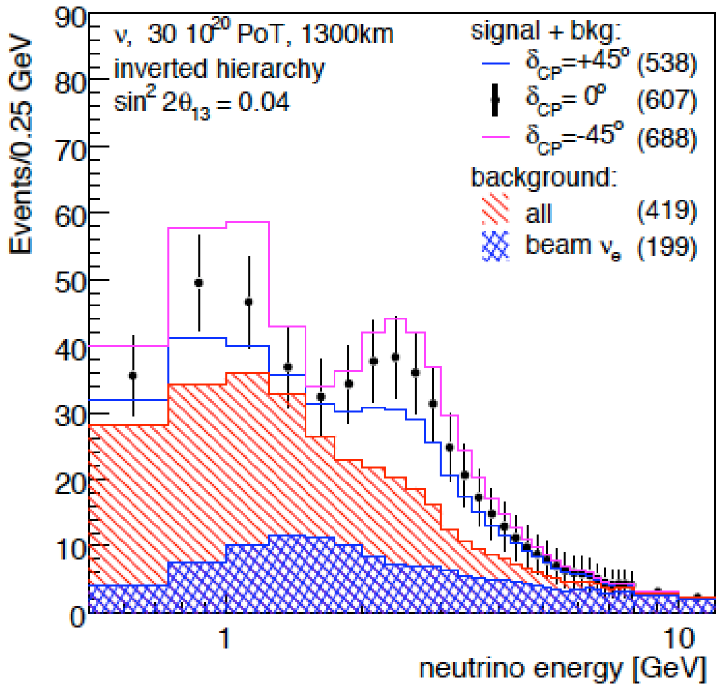


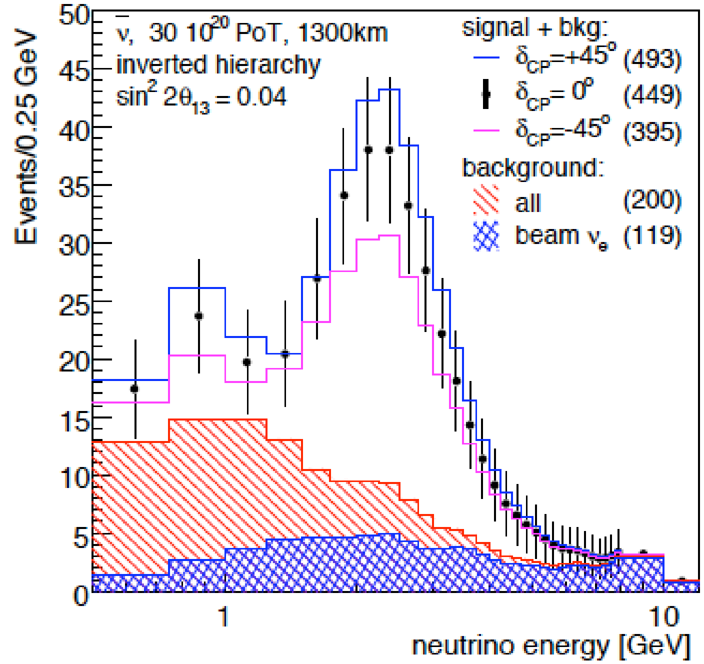


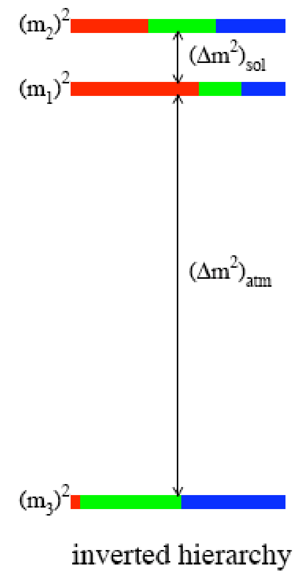


… and the backgrounds are larger compared to signal

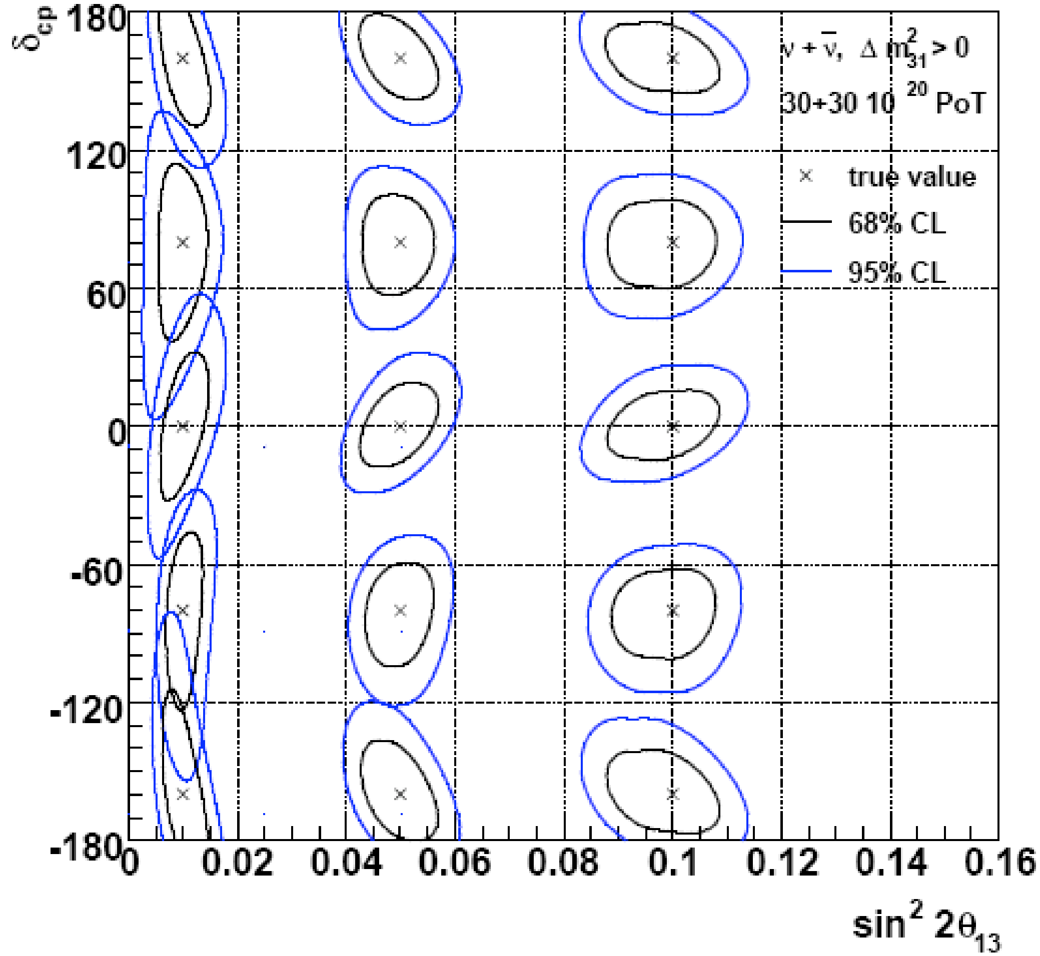
Expectation for inverted hierarchy:





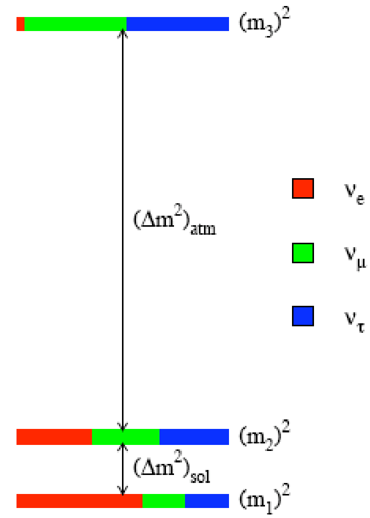


If we know the mass hierarchy,
then this is how well LBNE can do
in 10 years of running (*e.g.* without Project X)



Decay
At rest
Experiment
for δ_{cp} studies
At the
Laboratory for
Underground
Science

An unconventional approach
to the problem



in a vacuum…

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

We want to see if δ is nonzero

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

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

in a vacuum…

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

We want to see if δ is nonzero

terms depending on mixing angles

terms depending on mass splittings

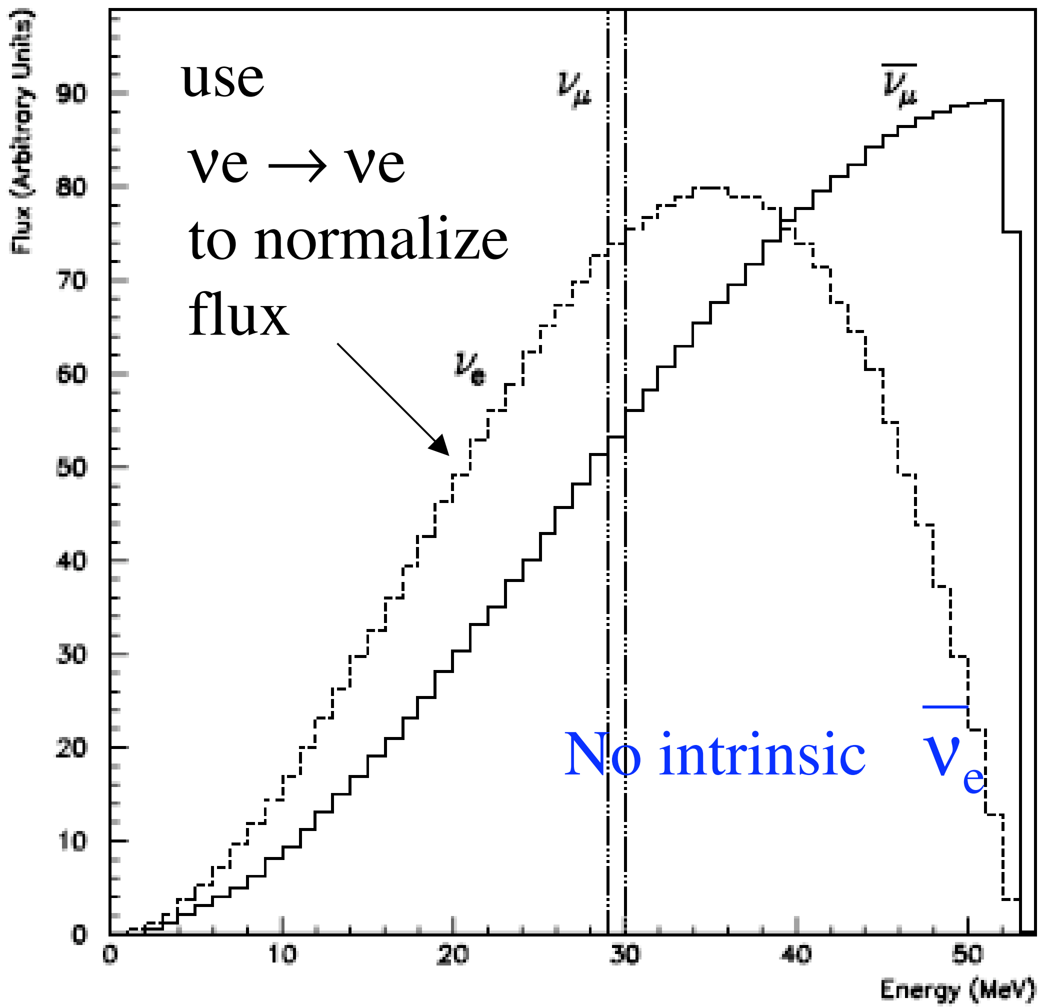
$$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$

A π^+ decay at rest beam:

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

Shape driven by nature!

Only the normalization varies from beam to beam



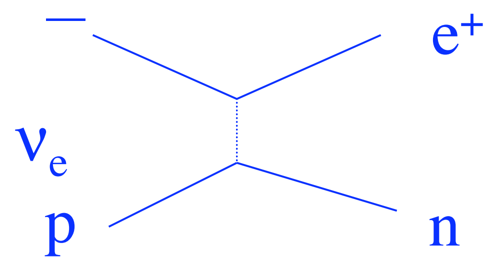
Perfect for a

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

search

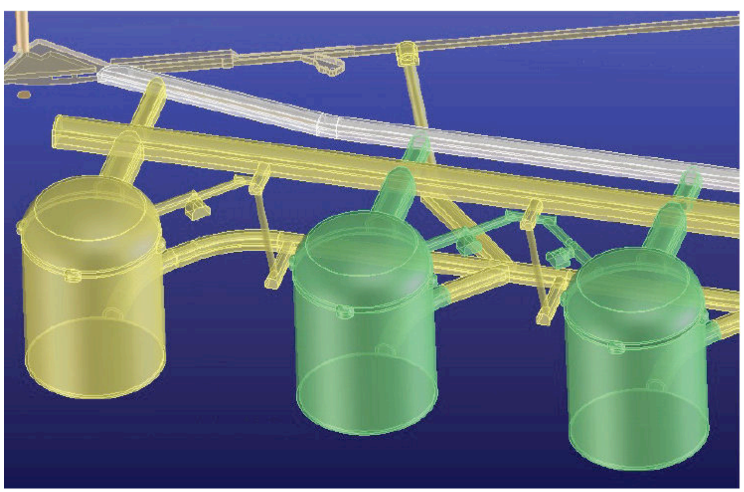
How do you observe ~50 MeV $\bar{\nu}_e$ events?

The signal:
inverse beta decay, IBD



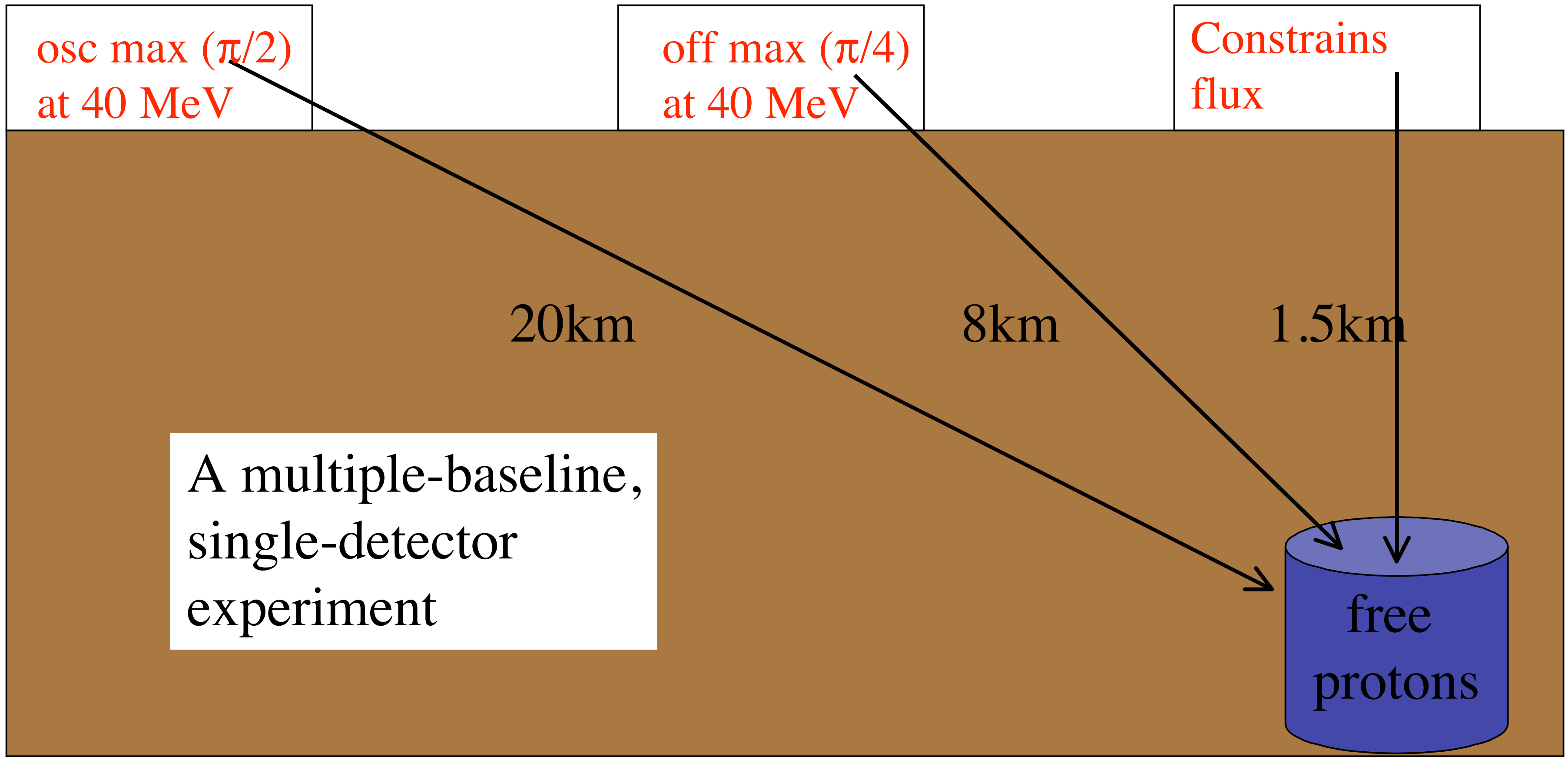
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

You need a lot of **free protons**!

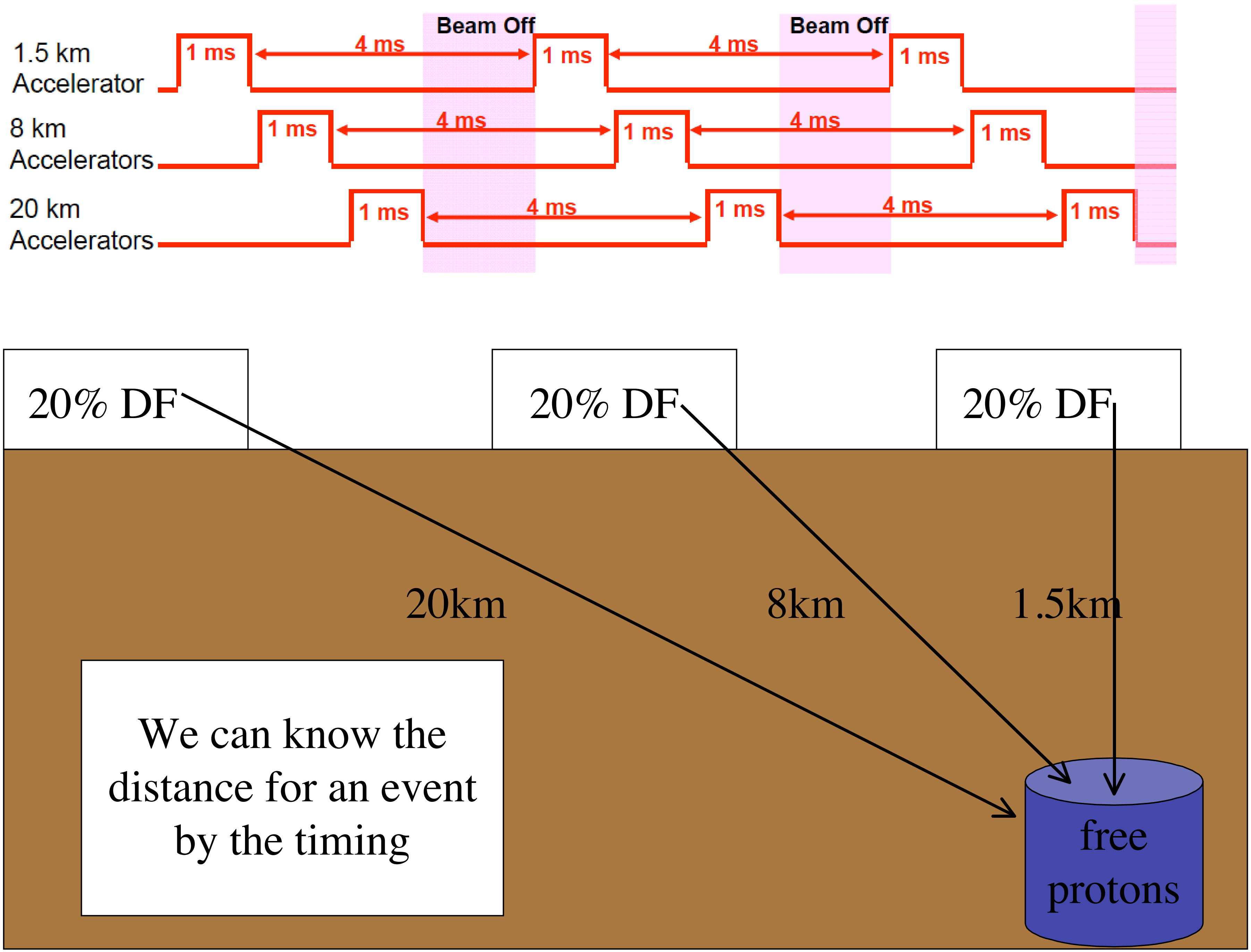


Use the <u>same</u> ultra-large detector system as the long baseline

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



An advantage: Nature assures decay-at-rest beams will be identical in flavor and energy

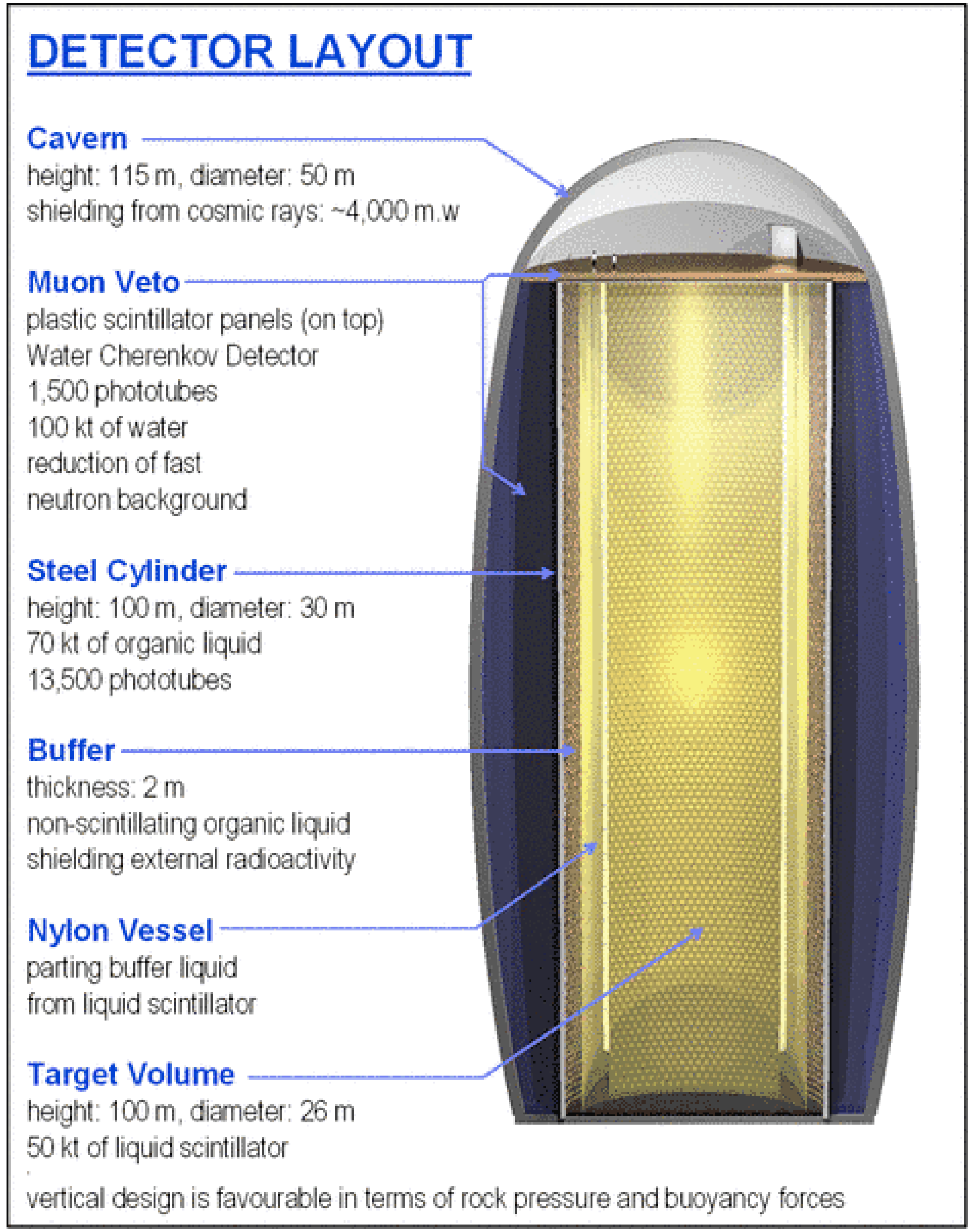


1.5 km Accelerator
8 km Accelerators
20 km Accelerators
Beam Off
Beam Off
1 ms
4 ms
20% DF
20% DF
20% DF
20km
8km
1.5km
We can know the distance for an event by the timing
free protons

SITE OPTIONS:

Large water detectors:
LBNE
MEMPHYS
Hyper-K

Or scintillation oil
-based detectors:
LENA, Hano-Hano



Big-liquid-detector designs seem to be fluid in time…

Hee hee!

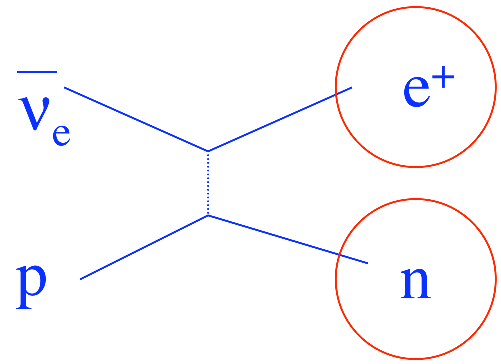
In order to tell a consistent story, I will use the example of a 300 kt H2O, Gd-doped detector at Homestake for both LBNE & DAEδALUS.

DAEδALUS is statistics limited -- so you can just scale.

I will point out some distinctions between oil and water.

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

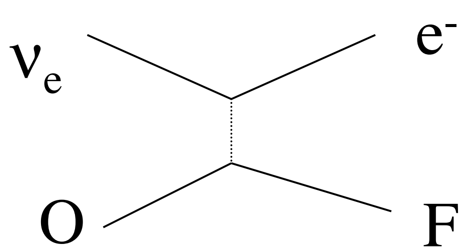
The signal:
inverse beta decay, IBD



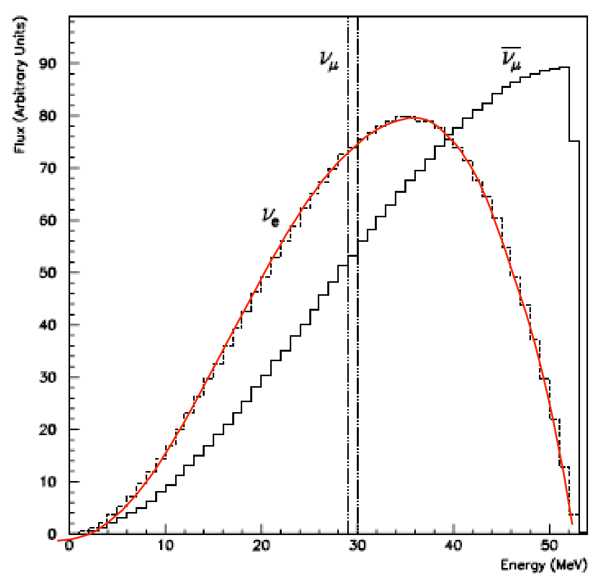
1st signal

2nd-- from capture

We need to reject:



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



But even if the xsec is small…

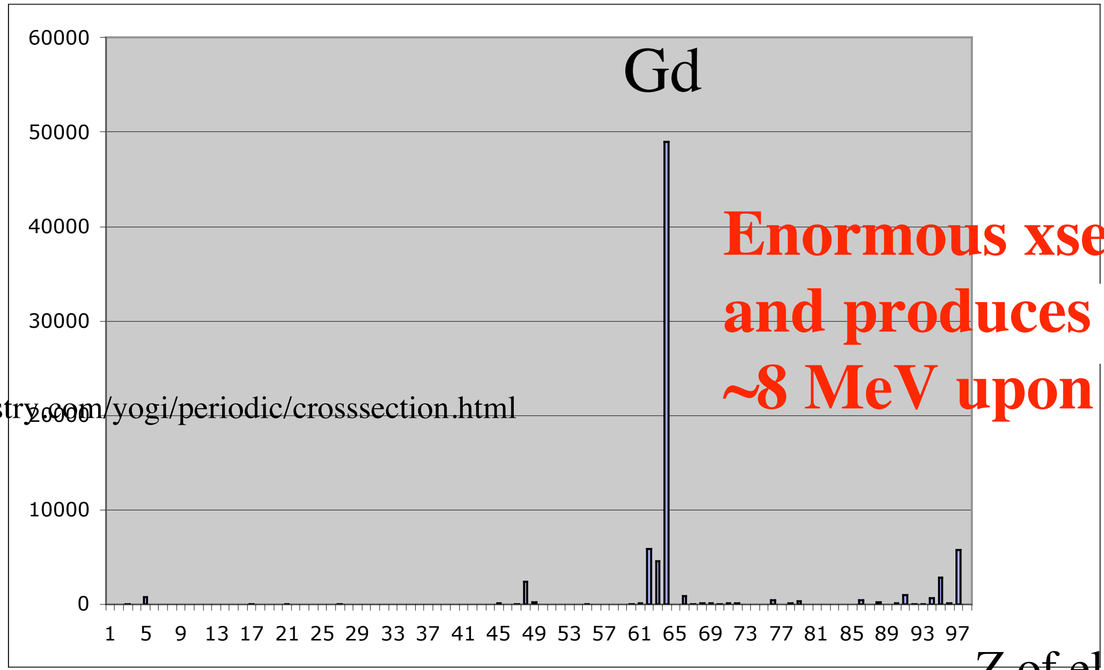
there are a lot of ν_es in the beam!

For the water design

enhance the signal from n-capture, add gadolinium!

thermal
neutron
capture
xsec

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



Z of element

Enormous xsec
and produces
~8 MeV upon capture!

EGADS!

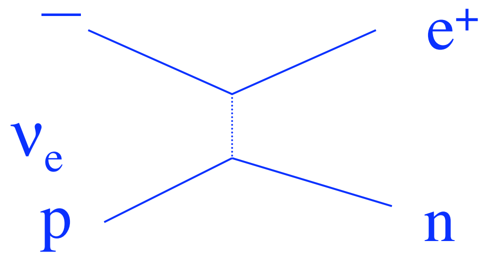
good progress
is being made

Scintillator
Oil does
not require
Gd-doping

Energy Dependence of IBD events

The signal:

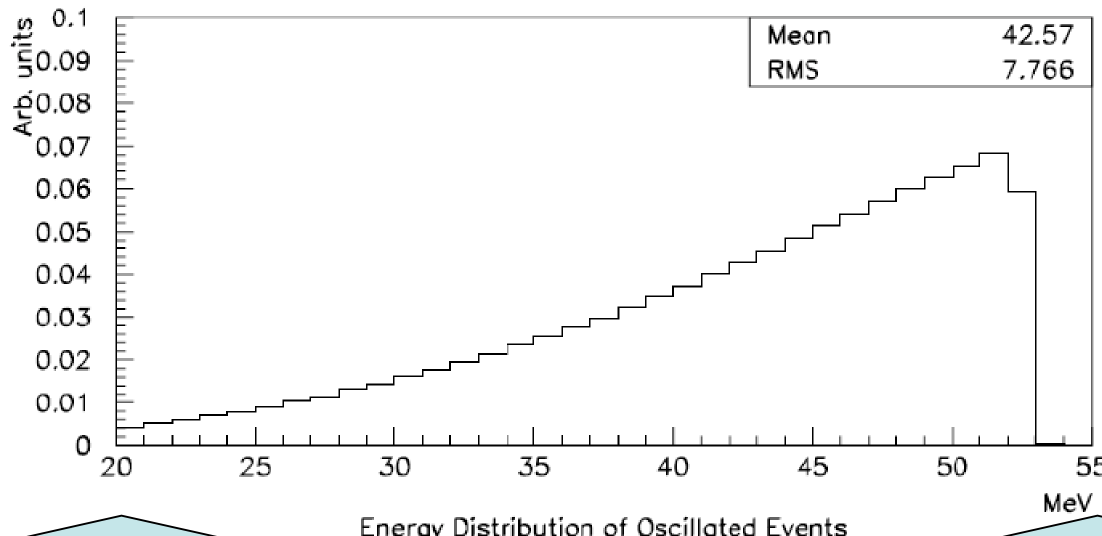
inverse beta decay, IBD



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

Event range is

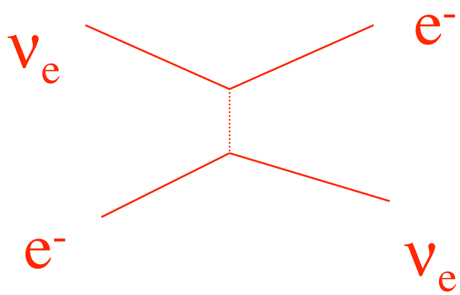
$20 < E_\nu < 55$ MeV

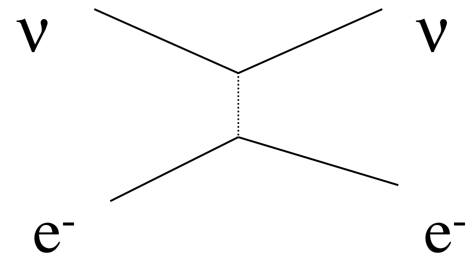


20 MeV

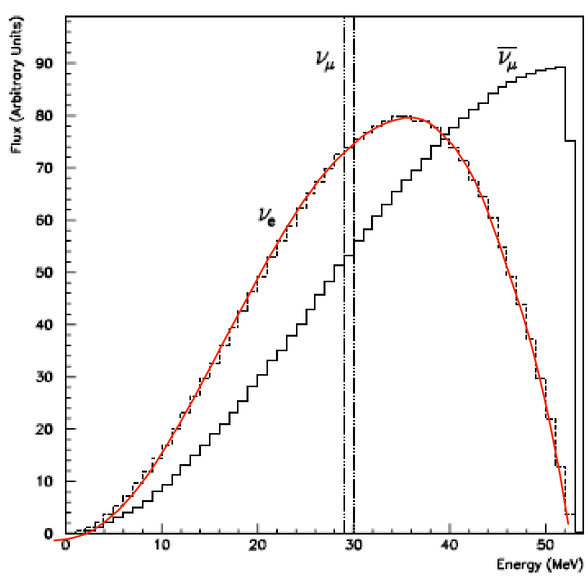
55 MeV

Neutrino-electron scattering is also very important!





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



Mostly from ν_es

about 20% from muon flavor

Measurement strategy:

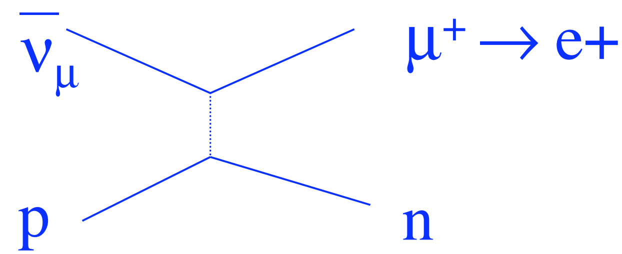
Using **near accelerator**
measure **absolute flux normalization** with ν-e events to ~1%,
Also, measure the ν_eO event rate.

At far and mid accelerator,
Compare predicted to measured ν_eO event rates
to get the **relative flux normalizations 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**

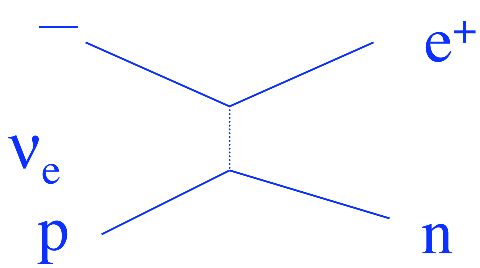
Non-beam backgrounds

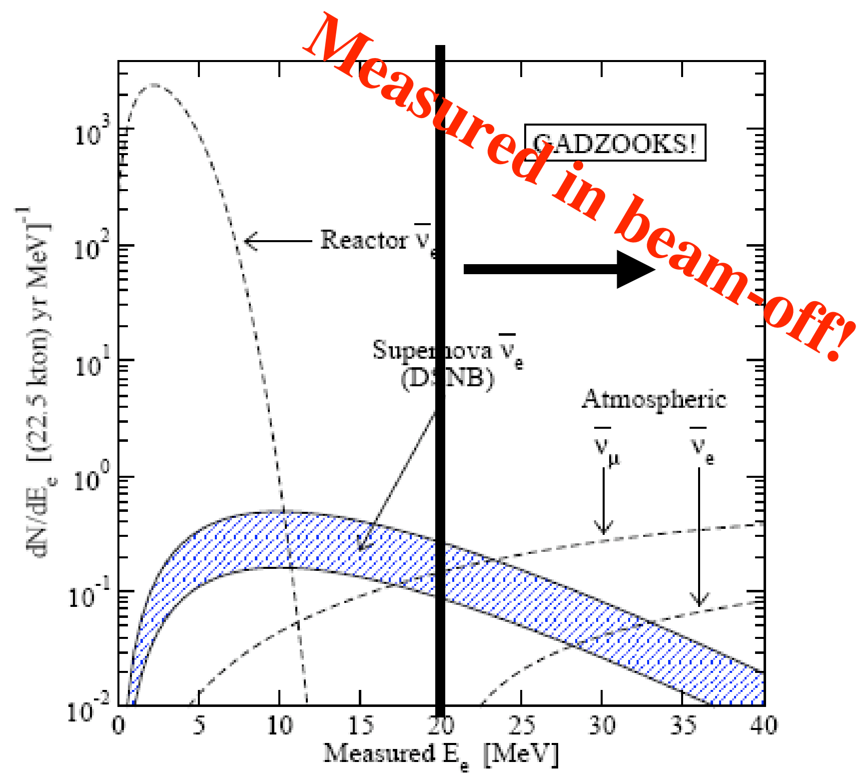
- Atmospheric $\bar{\nu}_\mu$ "Invisible muons":
  $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ where
  μ^+ is below Cherenkov threshold,
  stops and decays. ONLY IN WATER



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

- Diffuse supernova neutrinos





Beam-related Background

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

  From $\pi^- \rightarrow \mu^-$ events which failed to capture in the beam stop

  $\sim 4\times10^{-4}$ ν_e rate (low)

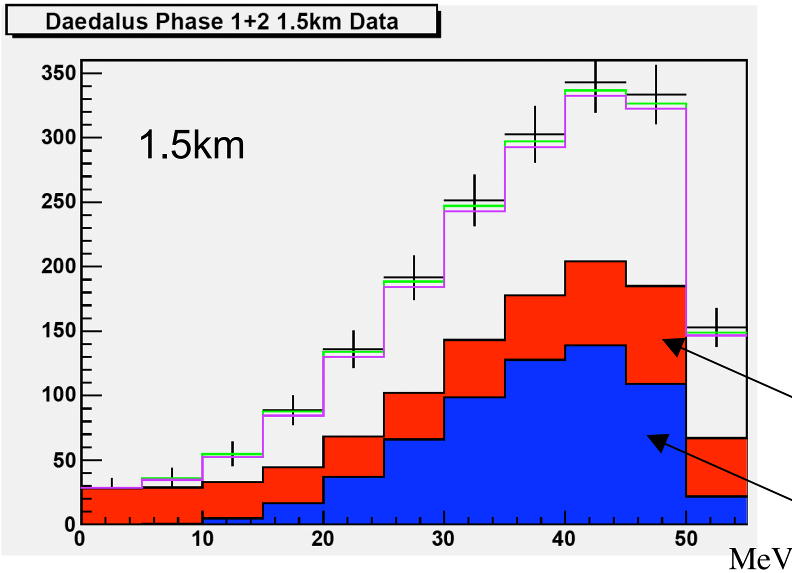
- Beam ν_e in coincidence with random neutron capture signal
  Estimated to be very small from Super-K rates

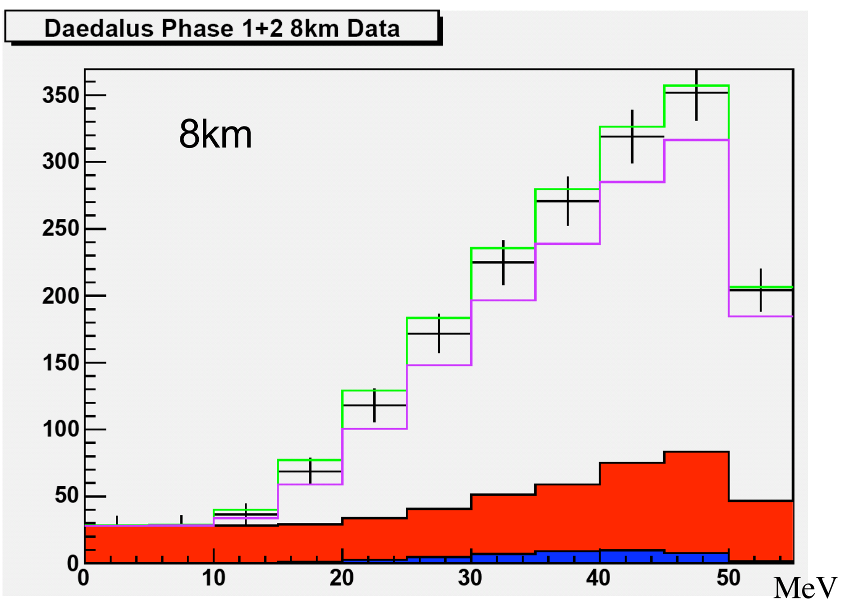
- ν_e-Oxygen CC scatters producing an electron+ n signal
  Subsequent n from nuclear de-excitation should be very small.

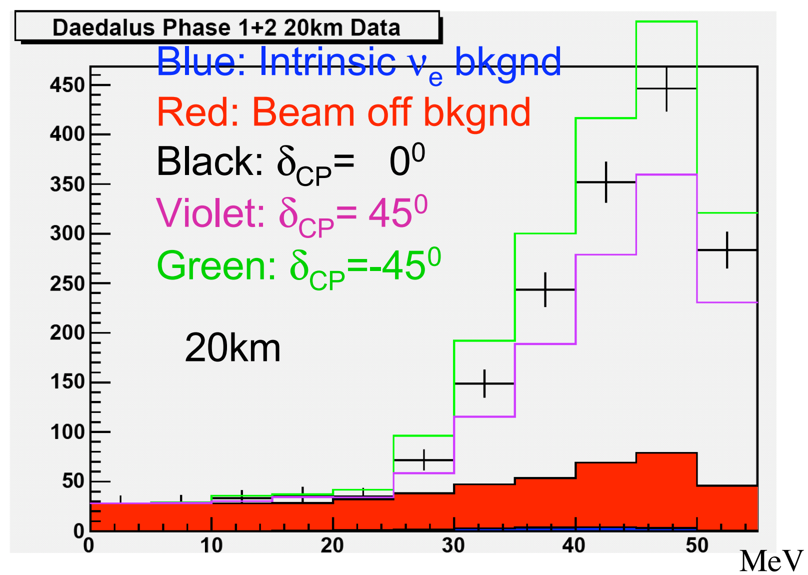
All fall as $1/r^2$ from the 3 accelerators,
near accelerator provides a measurement

Daedalus Event Energy Distributions (Signal & Background)

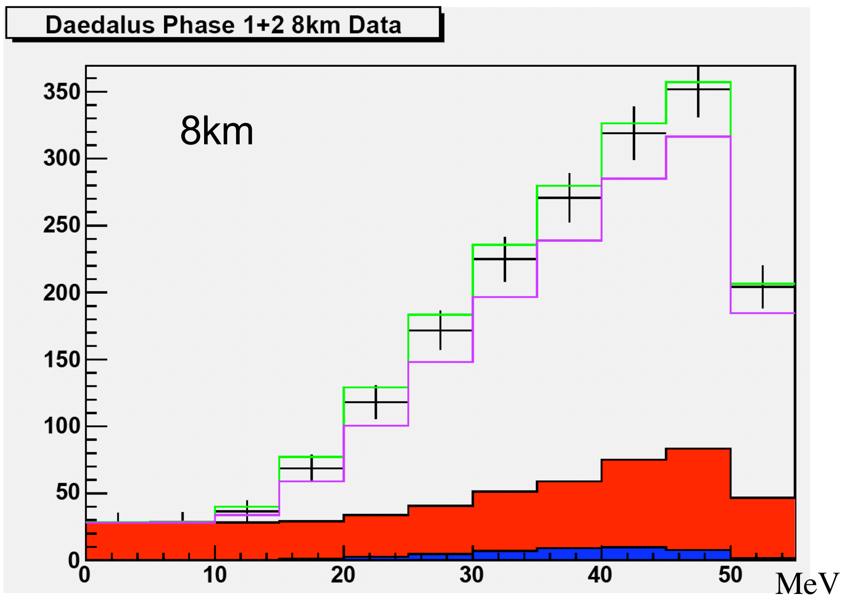
$(\sin^2 2\theta_{13} = 0.04)$

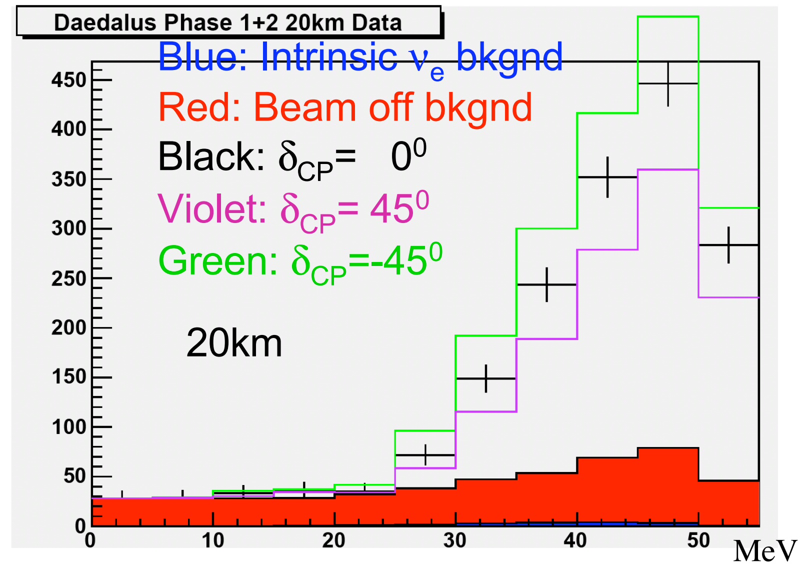




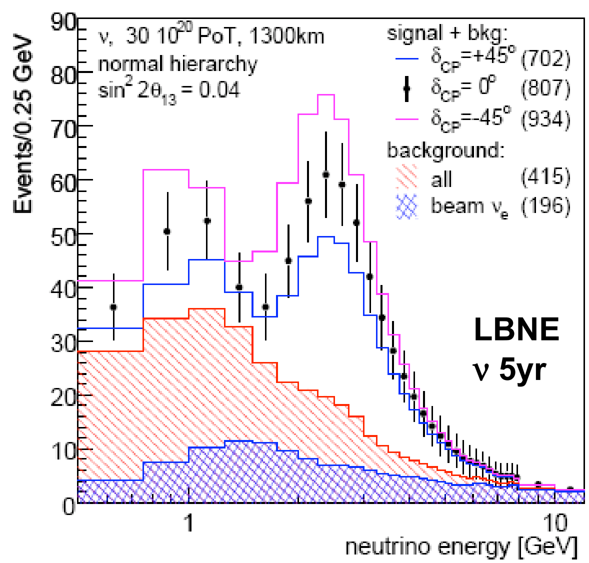


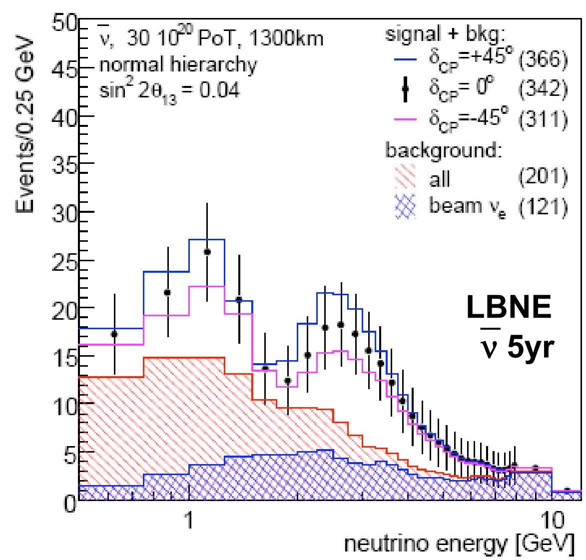
Compare signal to-background



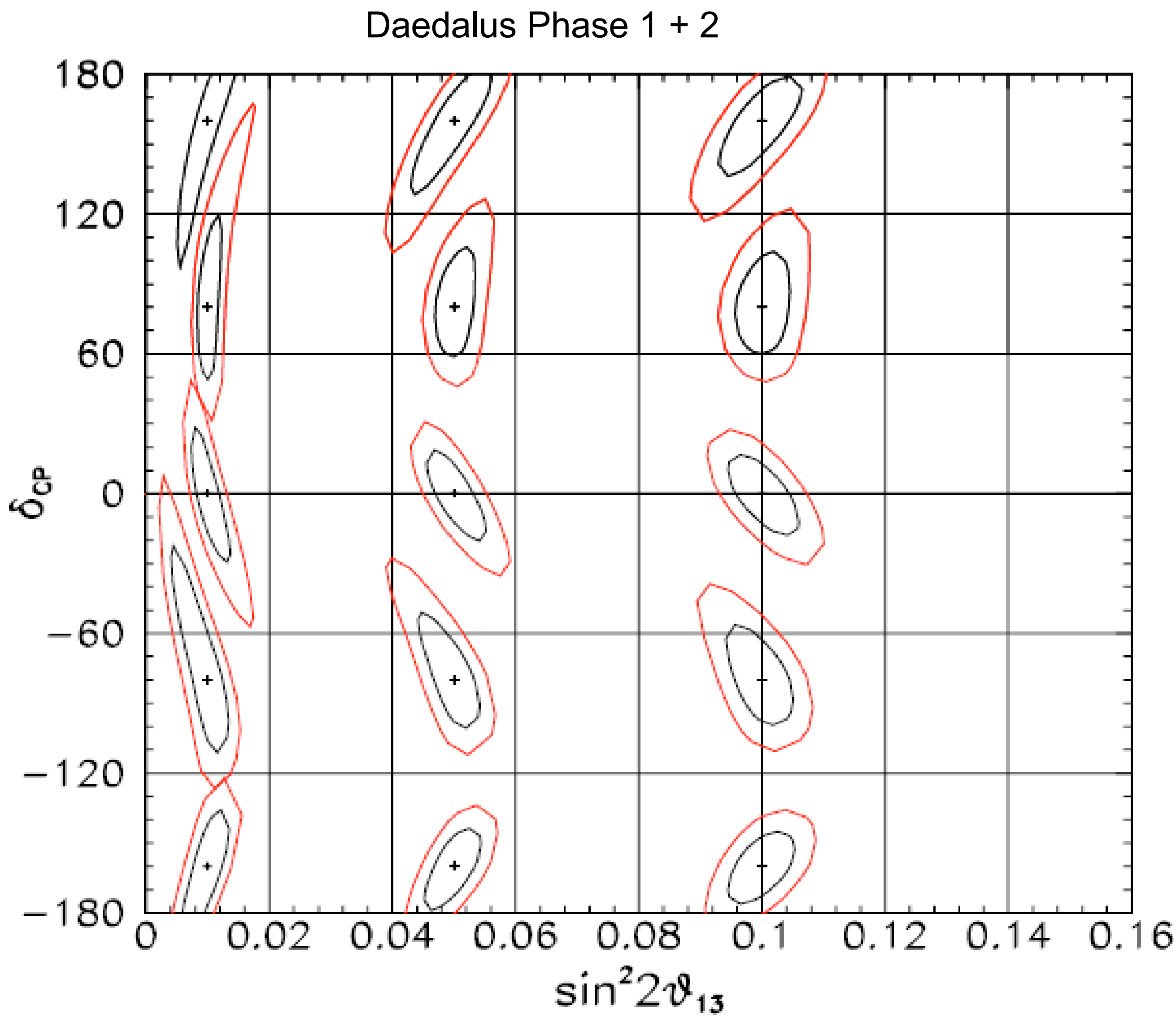


With LBNE…





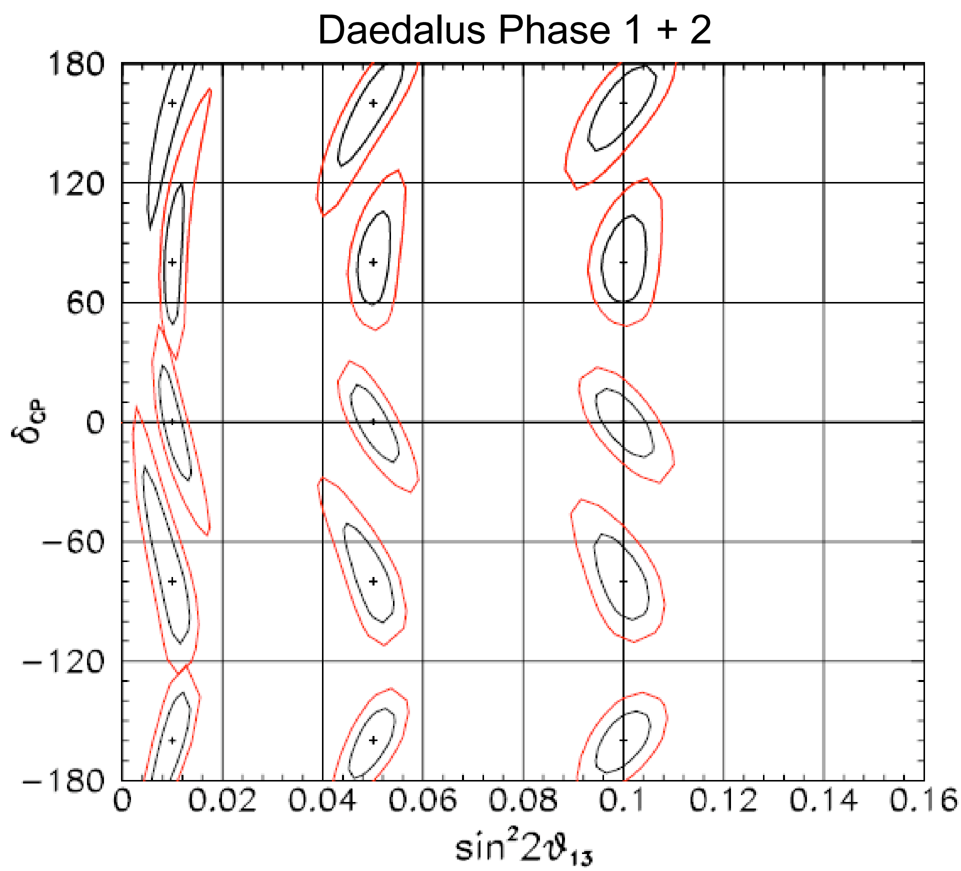
How well do we do?

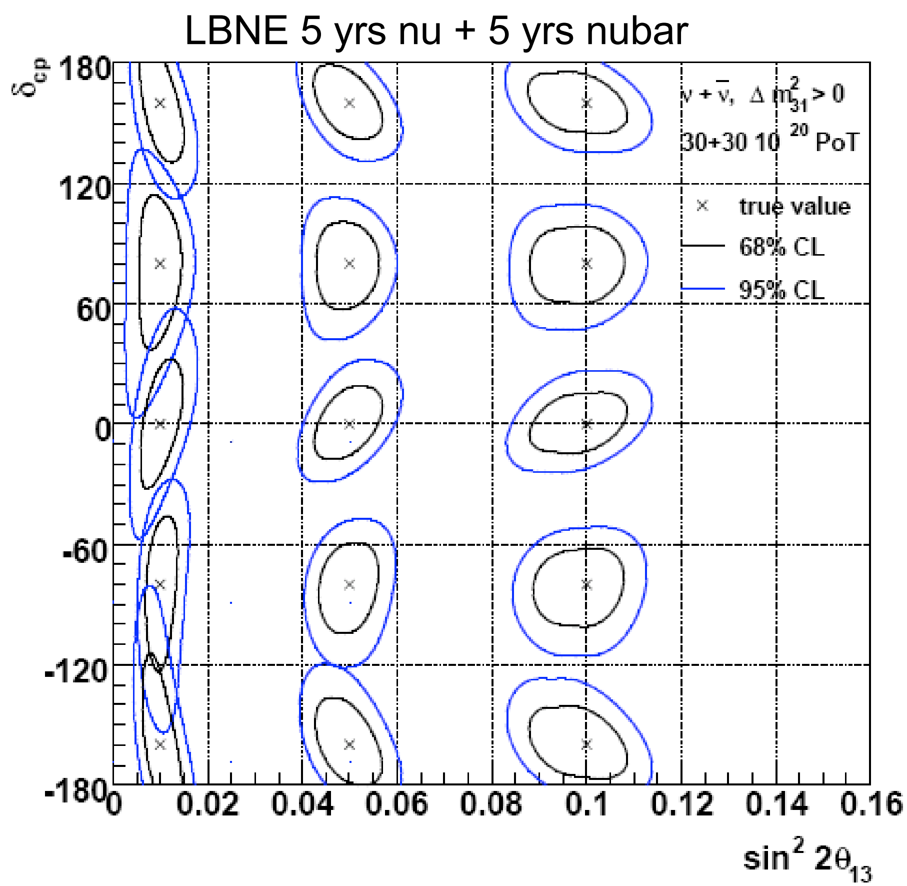


We can clearly observe CP violation!

How well do we do?

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





But this works even better,
when you combine with LBNE!

These are complementary experiments

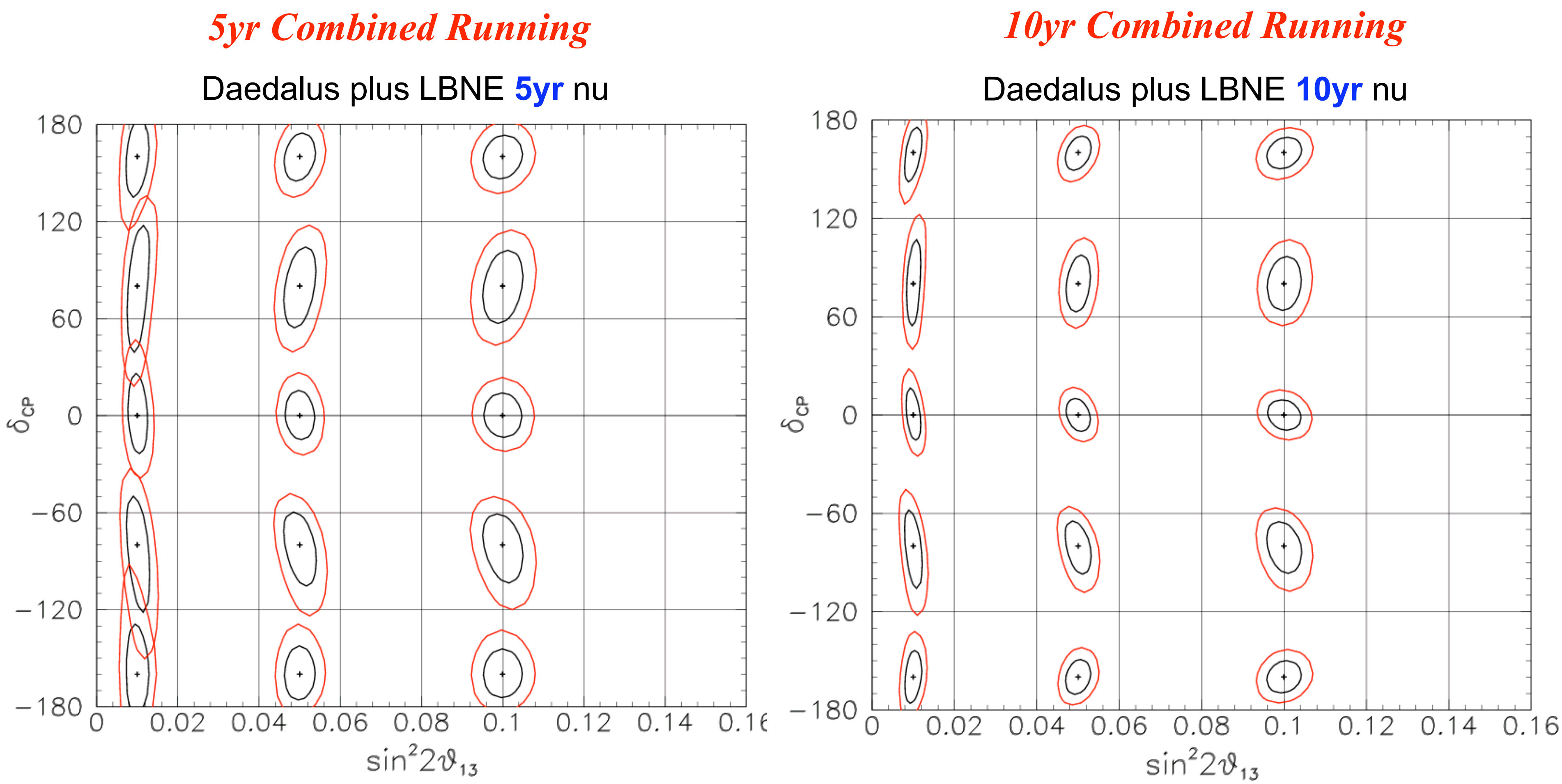
LBNE is mainly a ν experiment
DAEdALUS is entirely $\bar{\nu}$

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

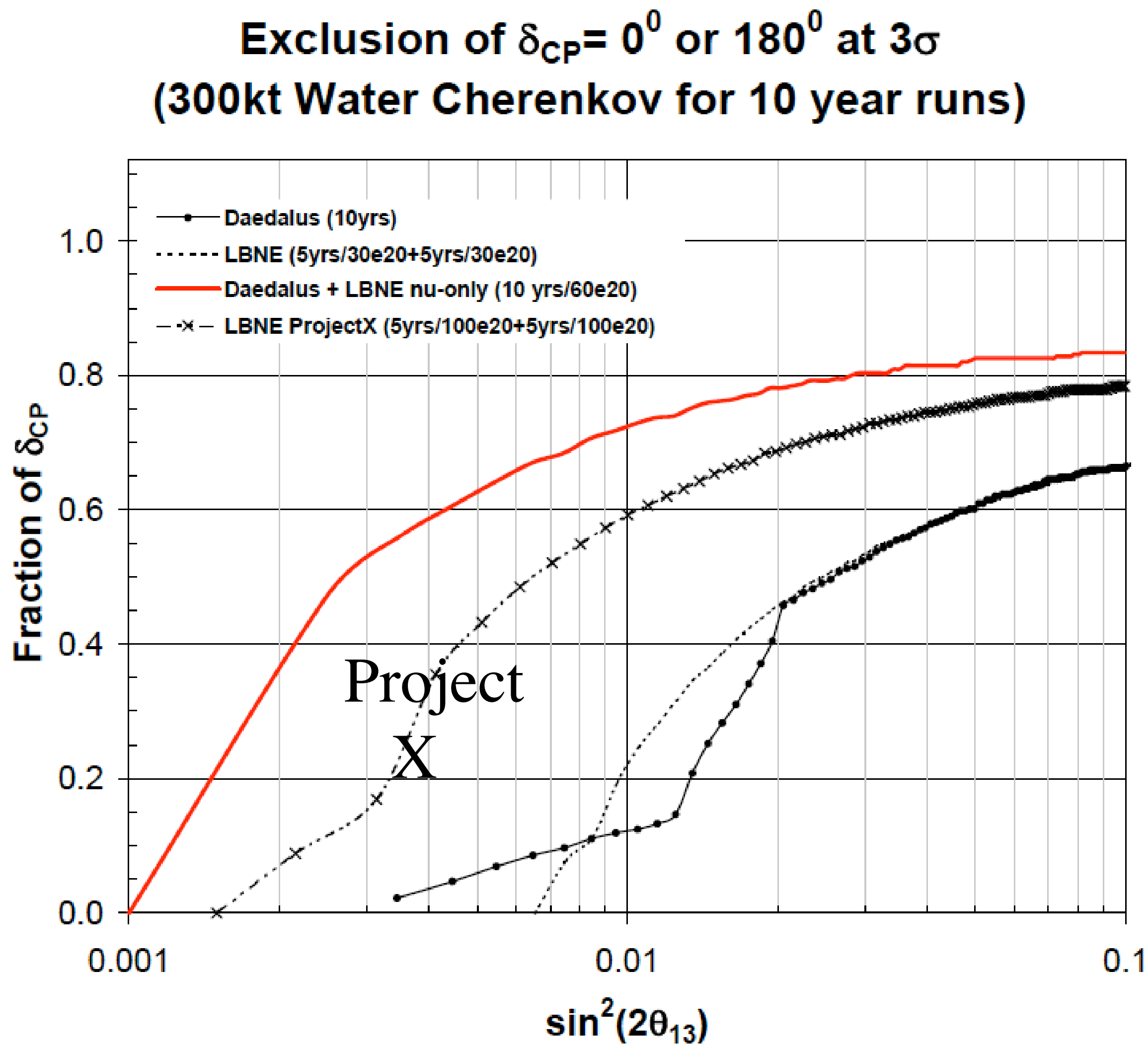
LBNE varies beam energy
DAEdALUS varies beam distance

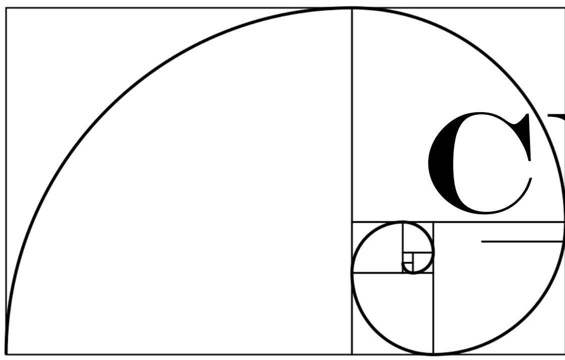
What happens when the two are put together?

What the Combined Experiments can do!



The fraction of "δ-space" where a measurement will be >3σ





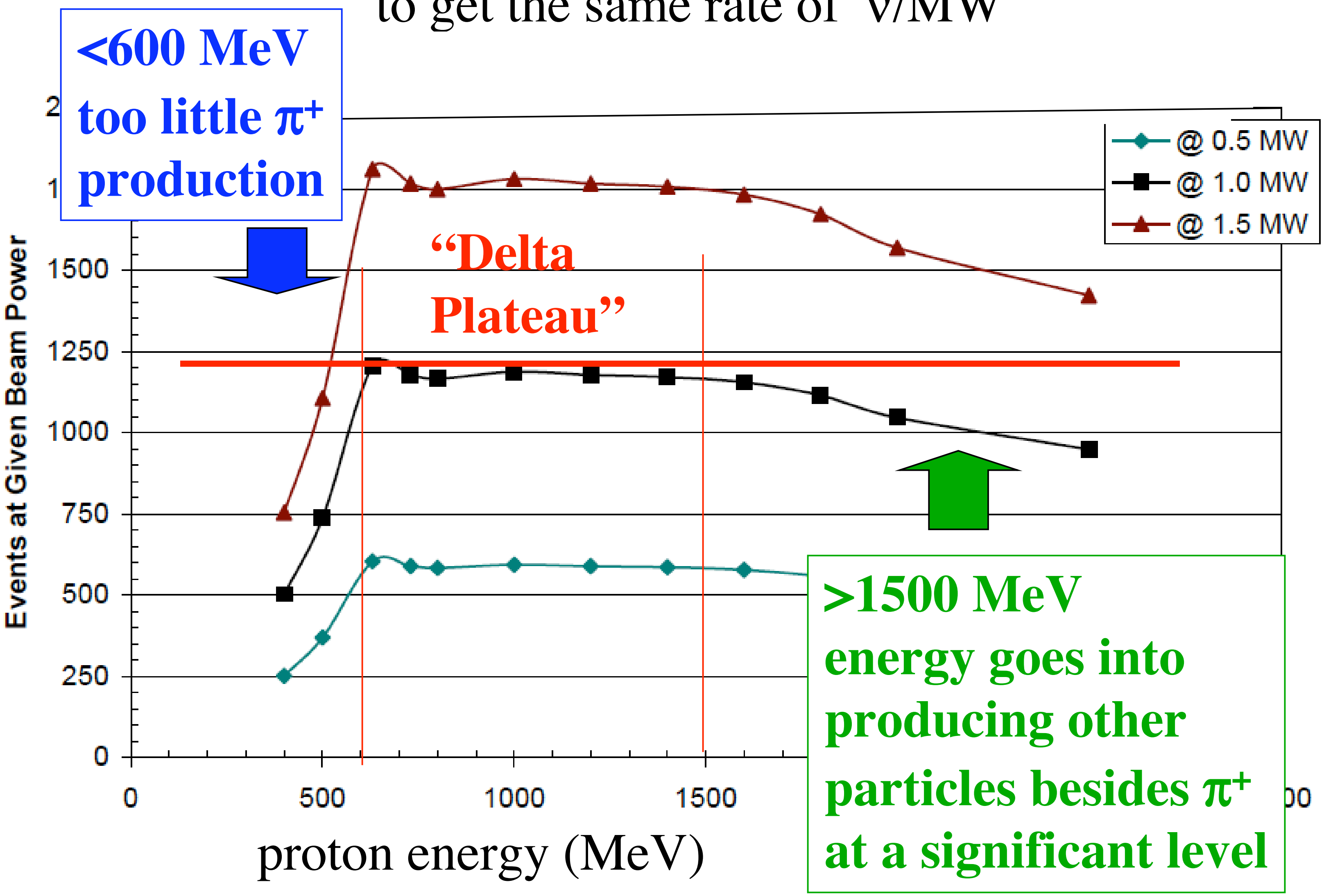
Why

CYCLOTRONS

& how real are they?

What proton energy is required?

There is a "Delta plateau" where you can trade energy for current to get the same rate of ν/MW



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

What helps:

1. No fancy beam structure -- CW is fine.
   (run 100 ms on and 400 m soff)

2. No need to inject into another accelerator

3. Constant energy -- no need for an energy upgrade path

… Unlike Project-X or SNS,
which need all of the above.

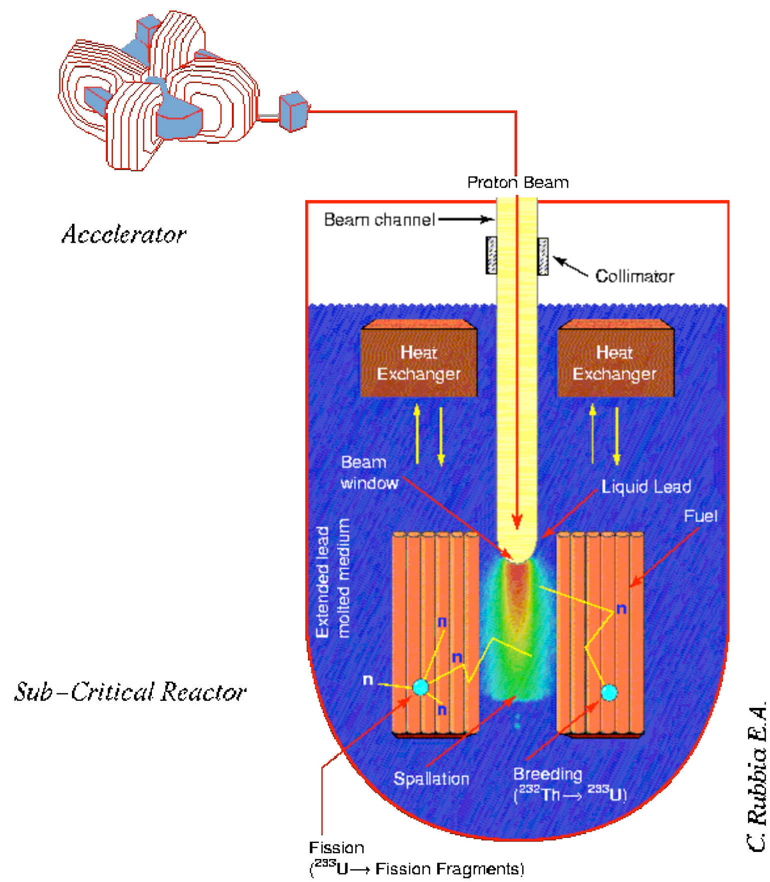
Wanted: ~1 MW sources of protons,
w/ energy > 600 MeV and <1500 MeV
for a reasonable price

Luckily there are others looking for this too!

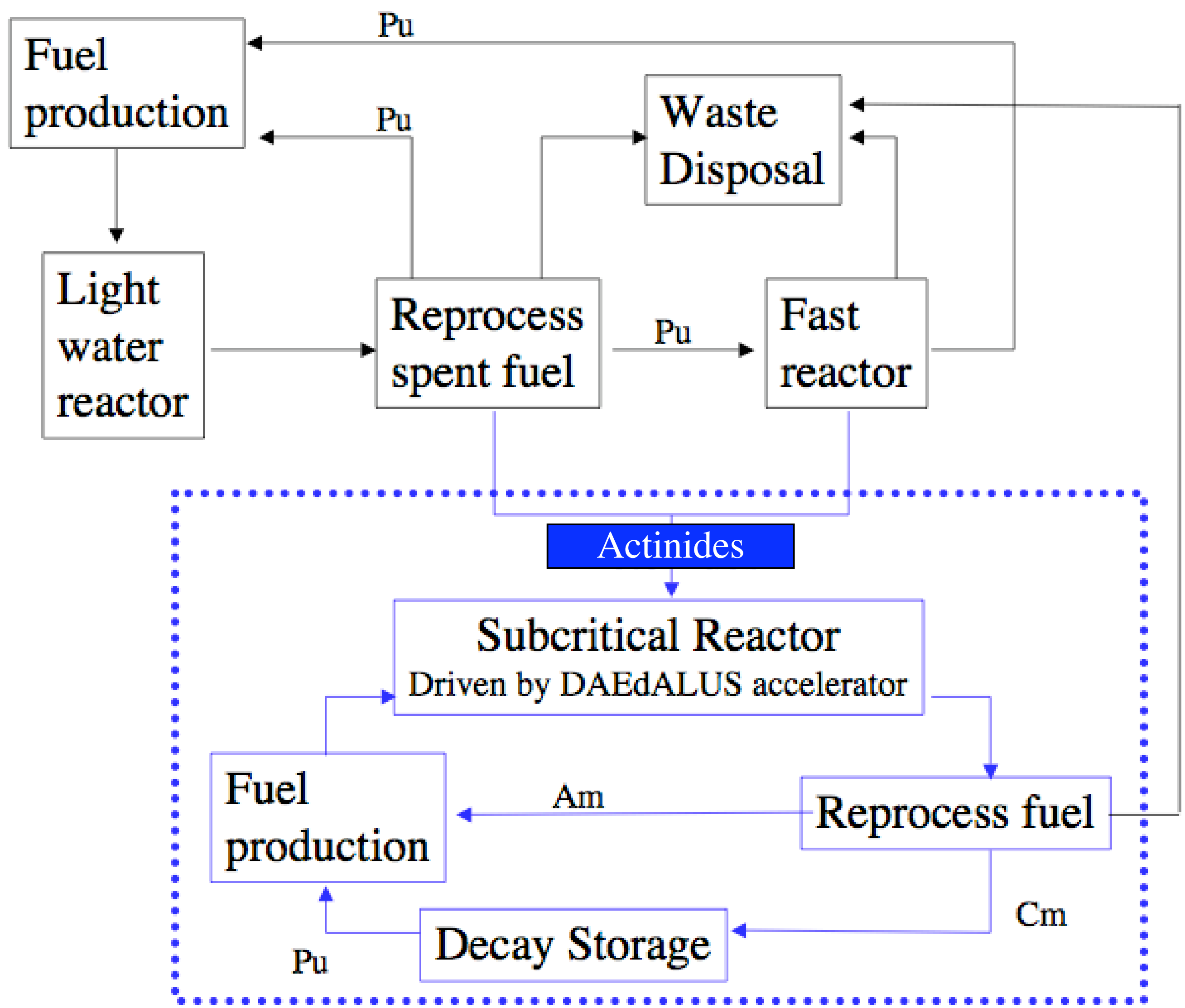
"ADS" -- accelerator driven systems for subcritical reactors.

Also "DTRA"-- Defense Threat Reduction Agency

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



ADS: Transmutation of nuclear waste from reactors



Among all of the types of accelerators out there…

Cyclotrons
Synchrotrons
Linacs
FFAGs
etc.

Why cyclotrons?

Inexpensive,
Only practical below ~1 GeV (ok for us!)
Only good if you don't need timing structure (ok!)
Typically single-energy (ok!)
Taps into existing industry

Very interesting R&D ongoing, but these machines are not yet proven

Can do what we need right now, but are expensive.

Use linacs if you want a nice beam for transfer to another line and flexibility on energy (We don't)

We do not rule out other options, but cyclotrons seem like a good fit.

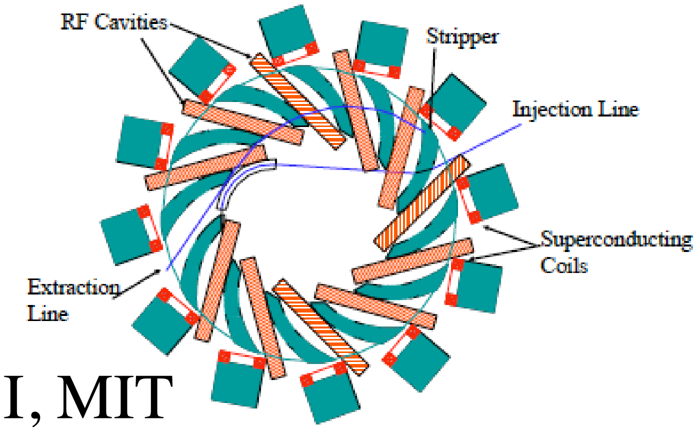
Approaches using cyclotrons:

The compact cyclotron with self-extraction

under development for DTRA at MIT

An H2+ accelerator

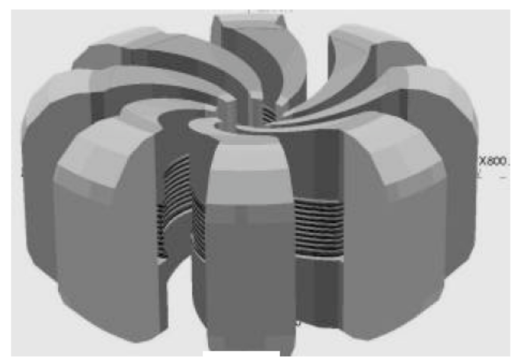
for ADS applications



Under dev. by INFN, PSI, MIT Cockcroft Inst.

The stacked cyclotron:

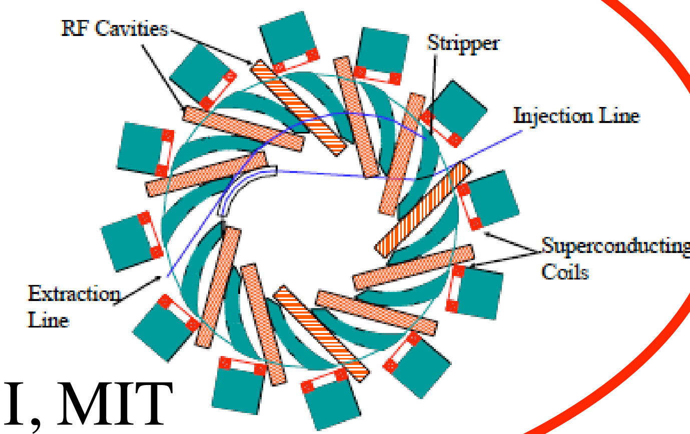
7 cyclotrons in one flux return



Under dev. for ADS at TAMU

An H2+ accelerator

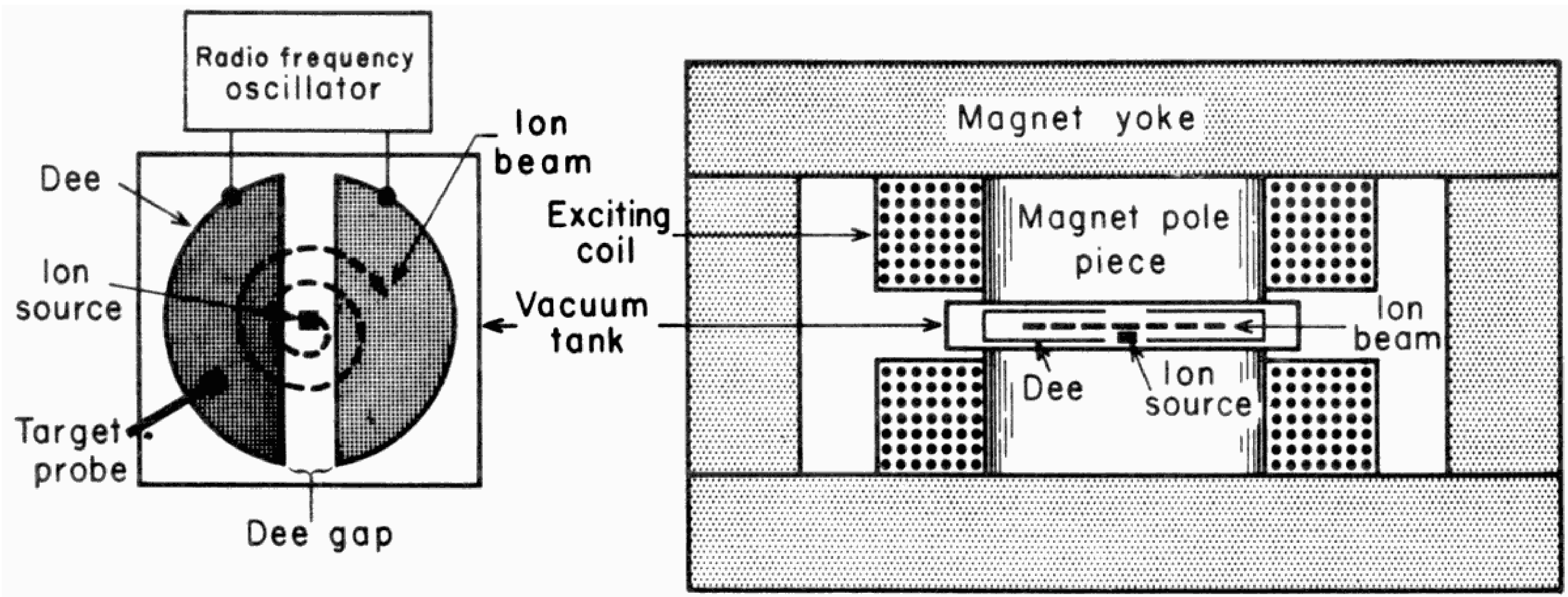
for ADS
applications



Under dev.
by INFN, PSI, MIT
Cockcroft Inst

The example design I will describe today

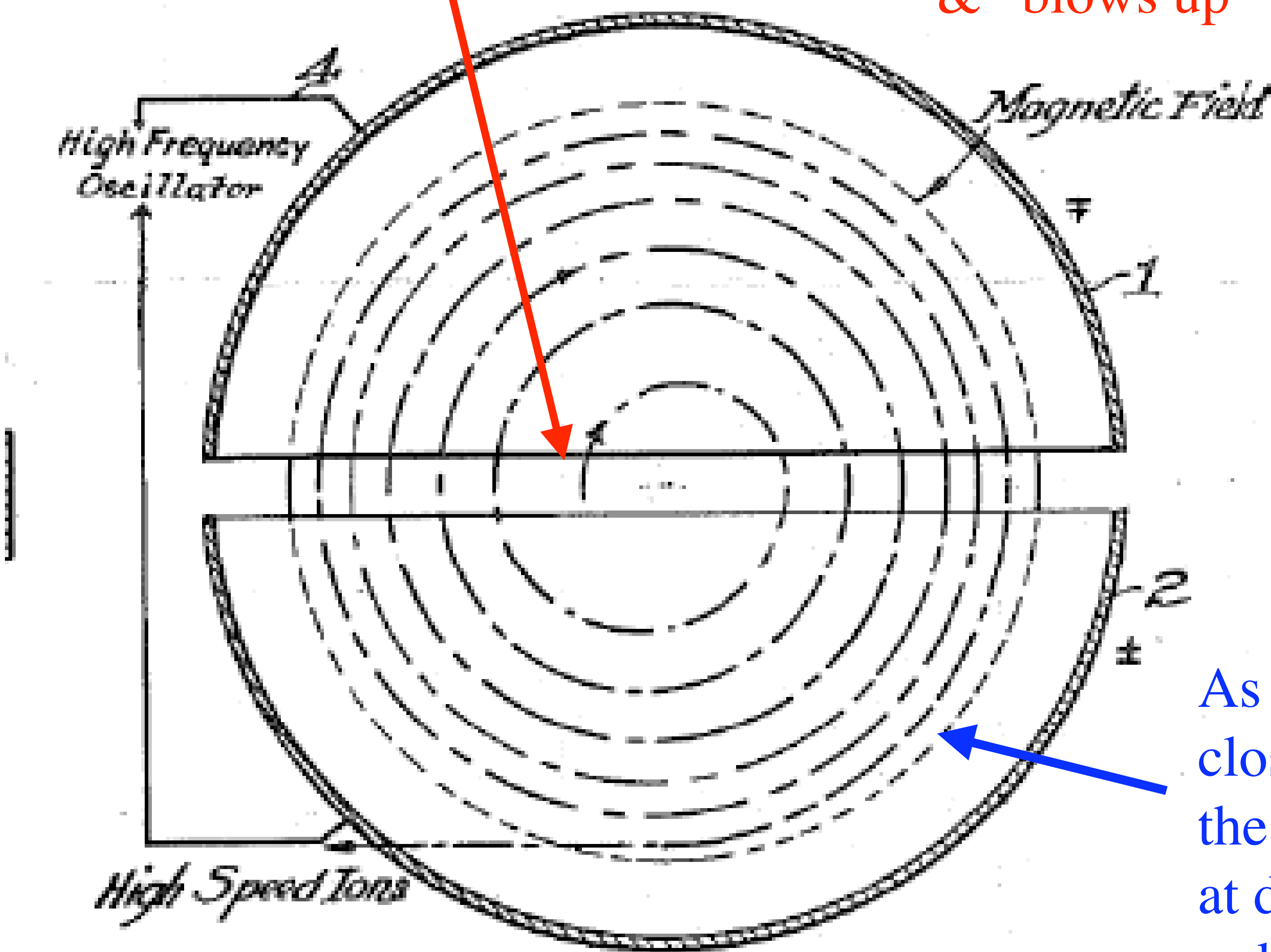
Cyclotrons 101



We emply an “isochonous cyclotron” design where the magnetic field changes with radius. This can accelerate many bunches at once.

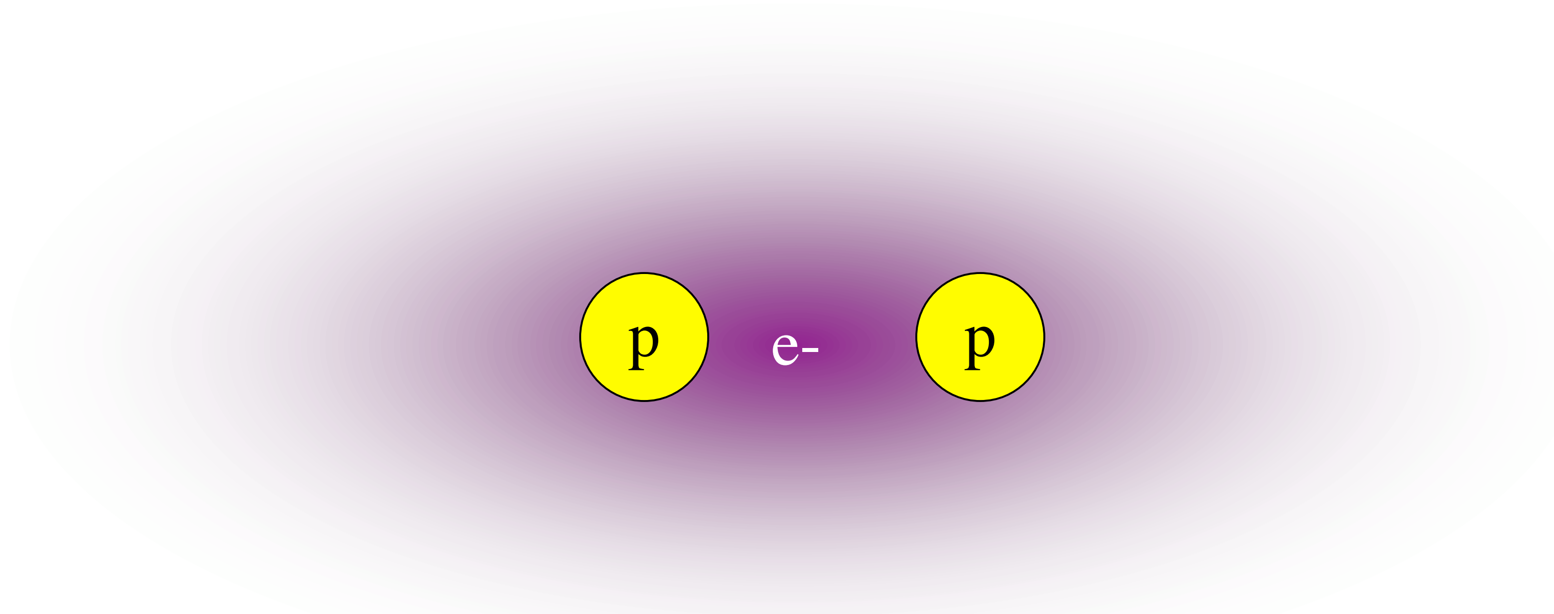
The big issue…

If you inject a lot of charge here, it repells & “blows up”



As radii get closer together the bunches at different radii interact

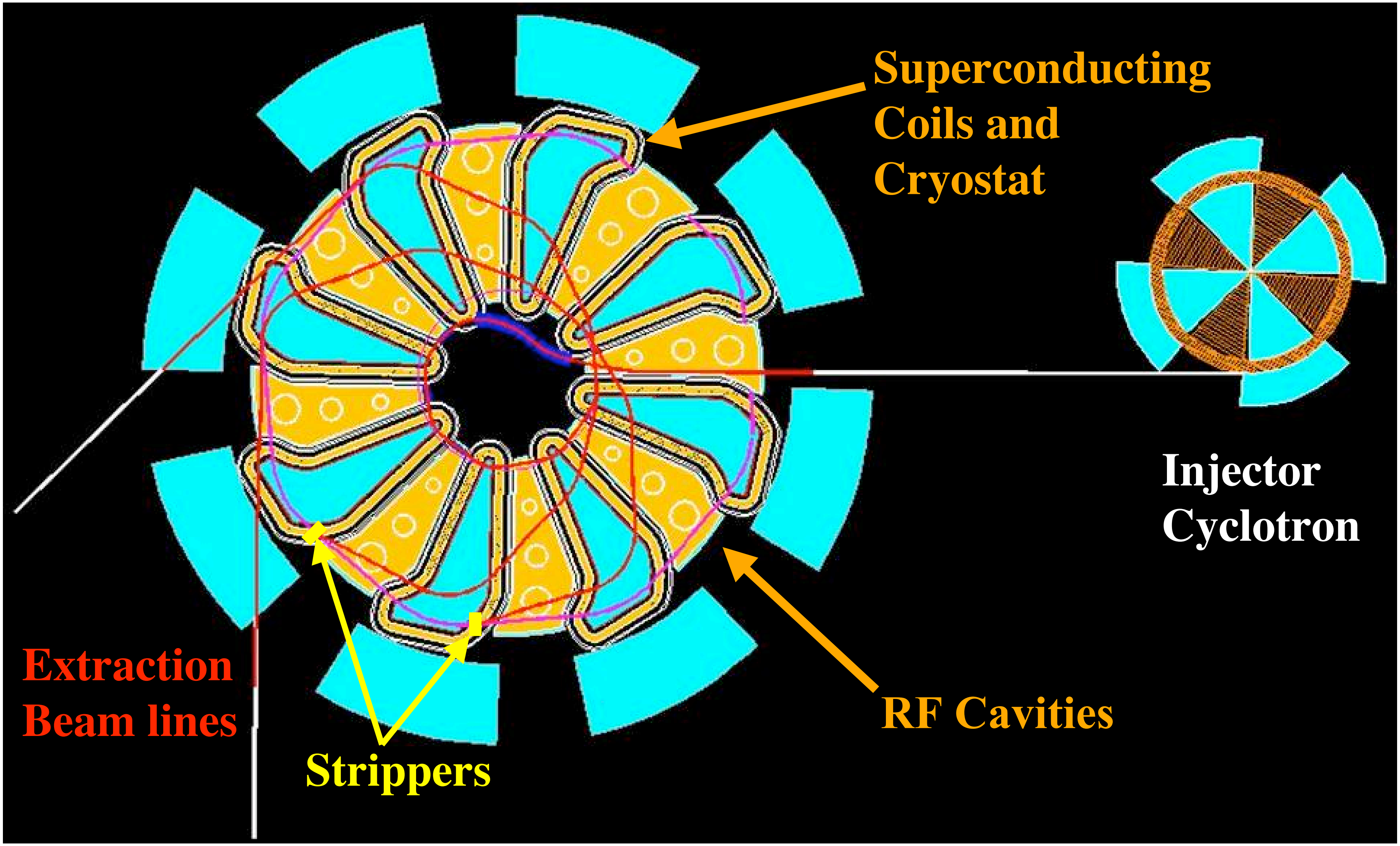
We need to reduce "space charge" at the start…



H2+ gives you 2 protons out for 1 unit of +1 charge in!

Simple to extract! Just strip the electron w/ a foil

Injector Cyclotron delivers ~ 50 MeV/n H_2^+ beam to Ring Cyclotron
800 MeV/n beam stripped at outer radius,
Proton orbits designed to cleanly exit machine



Working examples of each component exist.
Now we need to optimize.

The ion source: prototype built at Catania

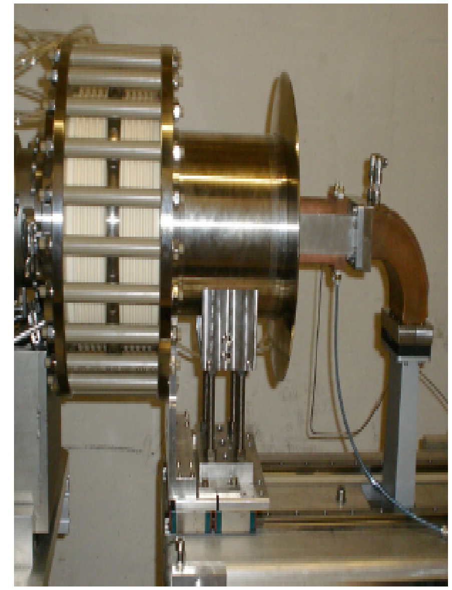
The injector cyclotron: modest modification to off-shelf model from, *e.g.*, BEST Cyclotron Systems Inc.

The booster cyclotron: smaller, simpler version of Rikken (Japan)

The extraction foils: well tested at many cyclotron facilities, including PSI and TRIUMF

The target/dumps: we may have multiple extraction lines to stay below 1 MW on each dump (to be similar to existing dumps)
Design being done at MIT

Some highlights of progress & plans



- We have a 1st generation design

- We have a prototype ion source,
  which produced 20 mA immediately

- NSF funding to test acceleration has been approved.

- The large magnet specifications are nearly complete,
  and we expect to go to engineers for costing within 6 months.
  This is the cost driver.

Given a full design,it takes ~1 year to build the machines

CONCLUSIONS

DAEdALUS is an example of what a new lab can inspire

This idea is completely new.
It happened because we were inspired by
the possibility of Homestake.

This has opened a new direction for 24 US scientists who
have never worked in underground labs before.

Many non-US accelerator physicists are involved!

This project promotes
strong connections between industry and basic science

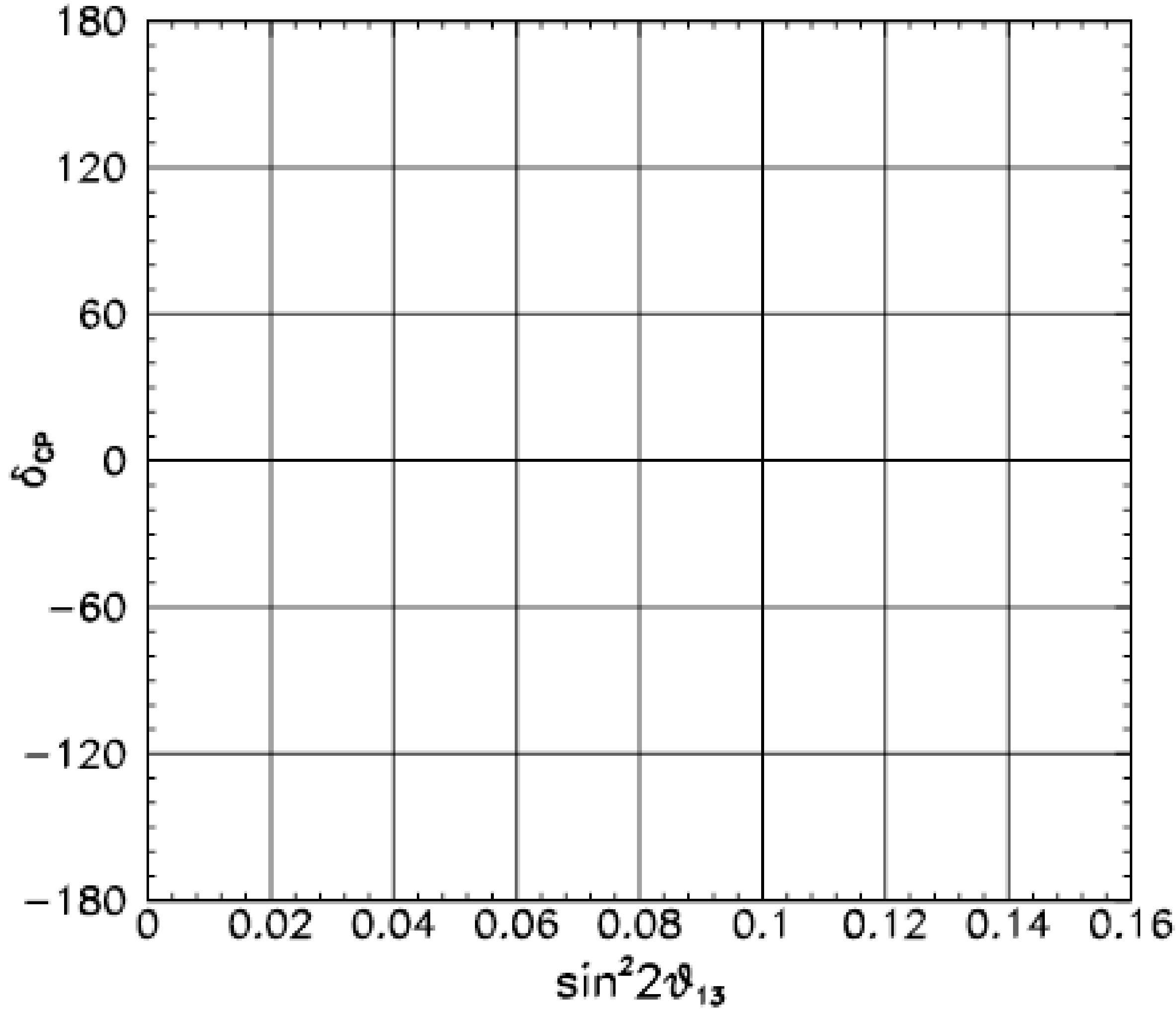
We are in conversations with EBCO, IBA and BEST,
all are interested in our technical developments
and are candidates to provide the H_2+ injector machine.

Re the compact cyclotron development,
we are discussing ideas with Still River Systems

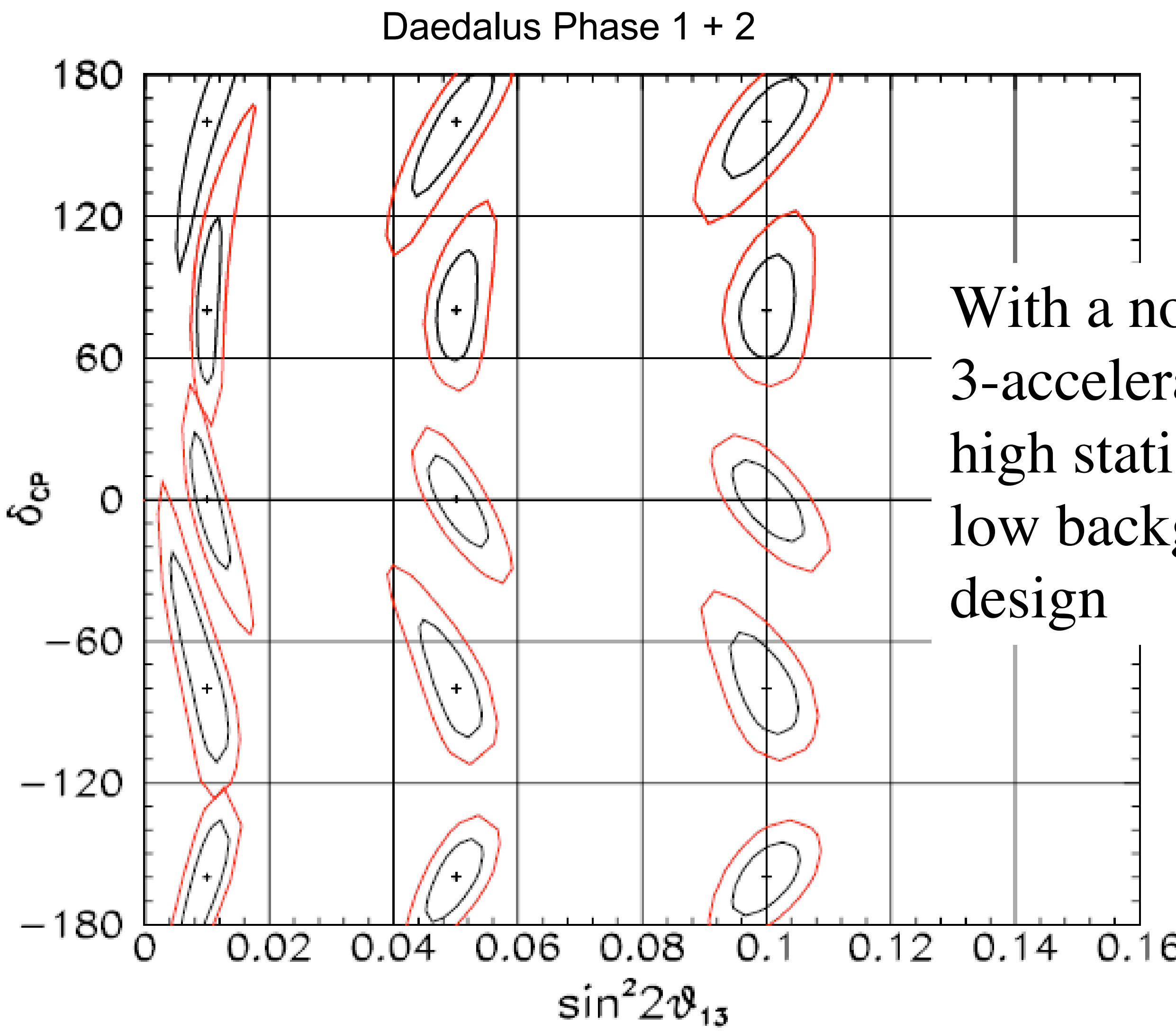
The driving industrial interests are:

- ADS technology (we are a perfect match!)
- Homeland security
- (also Molybdenum production -- in particular, IBA)

But most importantly…
We can potentially go from here:

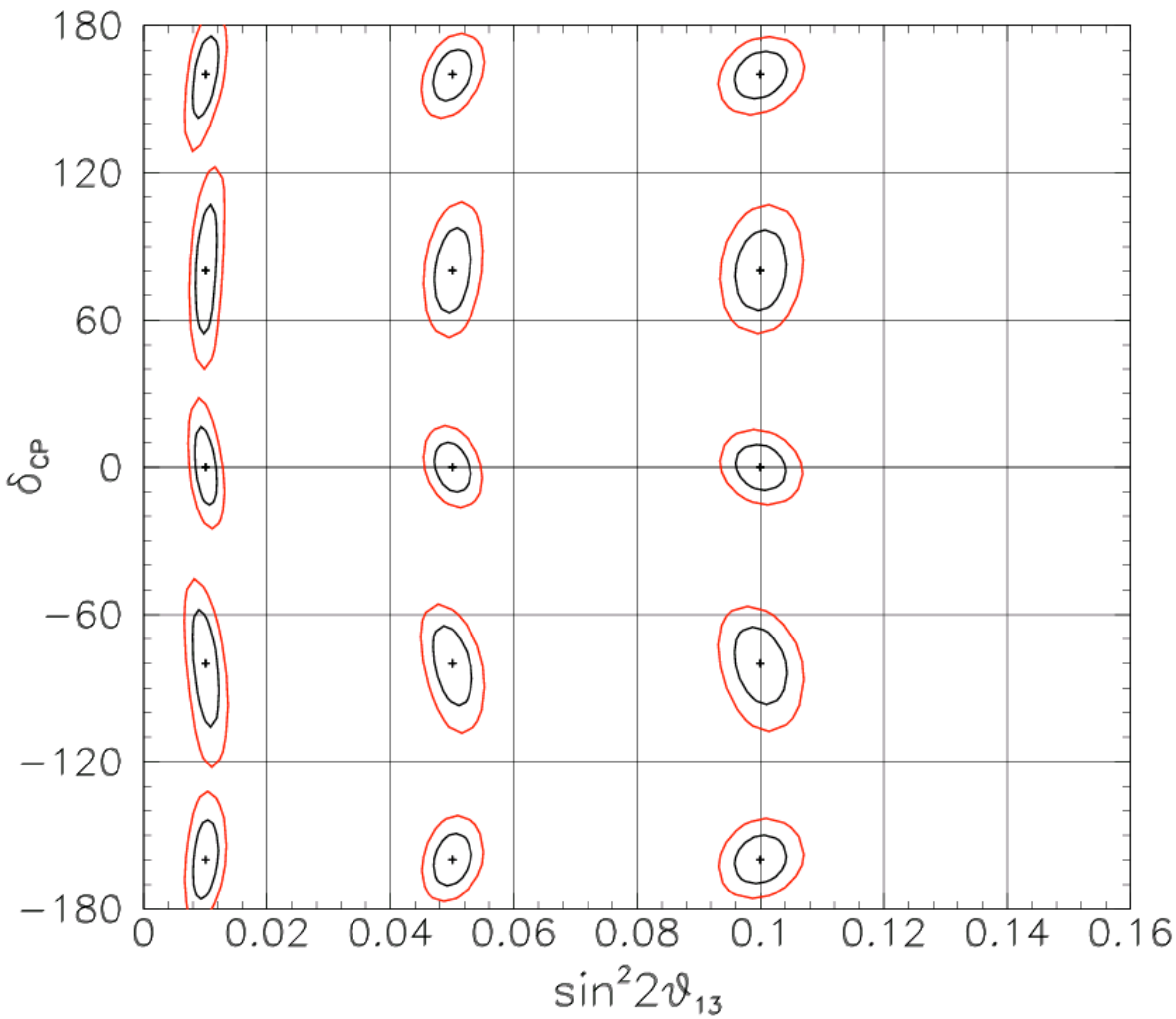


To here, in a 10 year run



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

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



Lets discover that CP violation jelly bean!

Thank you!

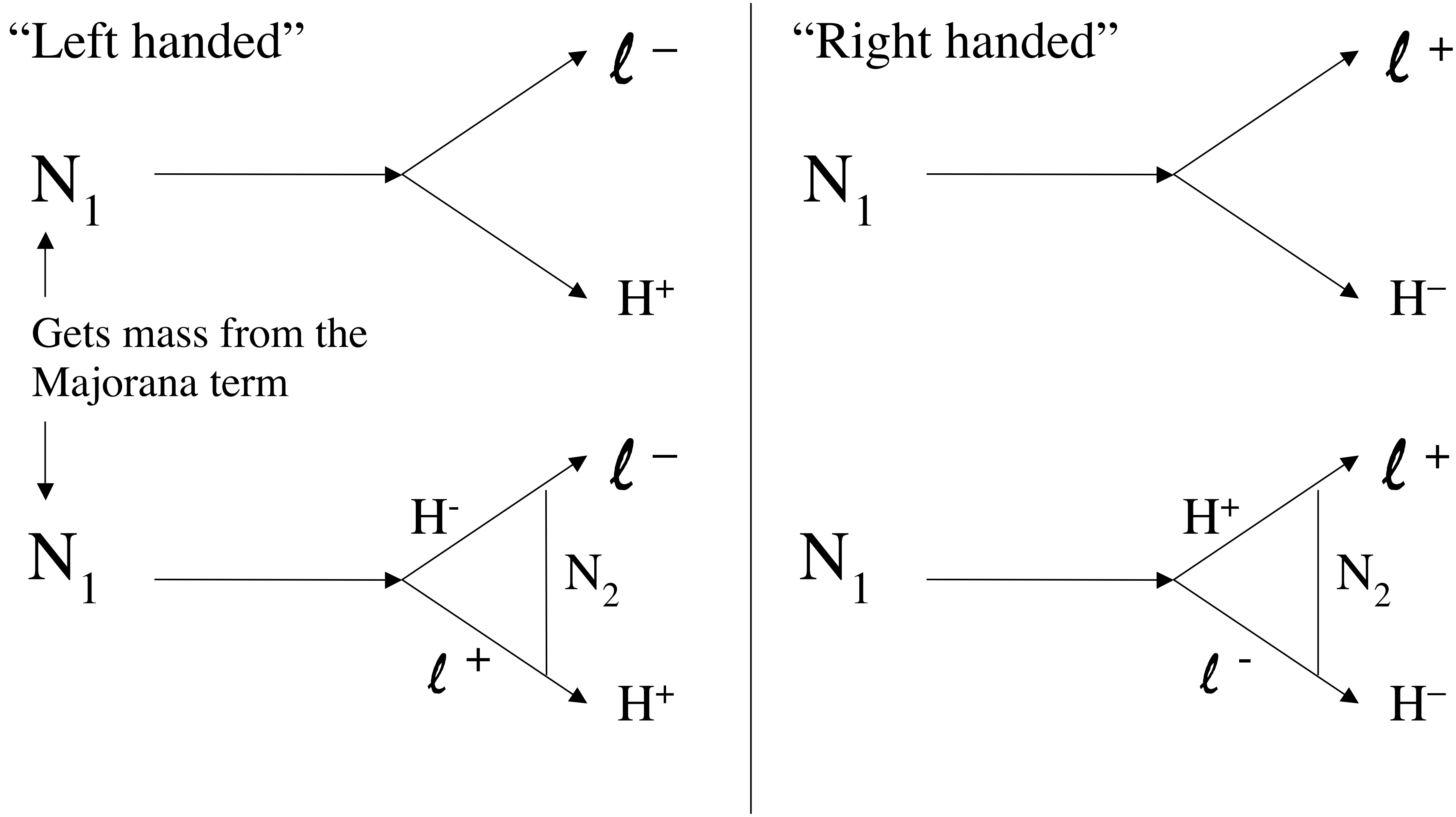
Expression of Interest: arXiv:1006.0260

see also…

- Multiple Cyclotron Method to Search for CP Violation in the Neutrino Sector, arXiv:0912.4079, Phys.Rev.Lett.104:141802,2010
- A Study of Detector Configurations for the DUSEL CP Violation Searches Combining LBNE and DAEdALUS, arXiv:1008.4967
- The DAEδALUS Project: Rationale and Beam Requirements, arXiv:1010.0971
- A Multi Megawatt Cyclotron Complex to Search for CP Violation in the Neutrino Sector, arXiv:1010.1493

Backup

Before the electroweak phase transition…



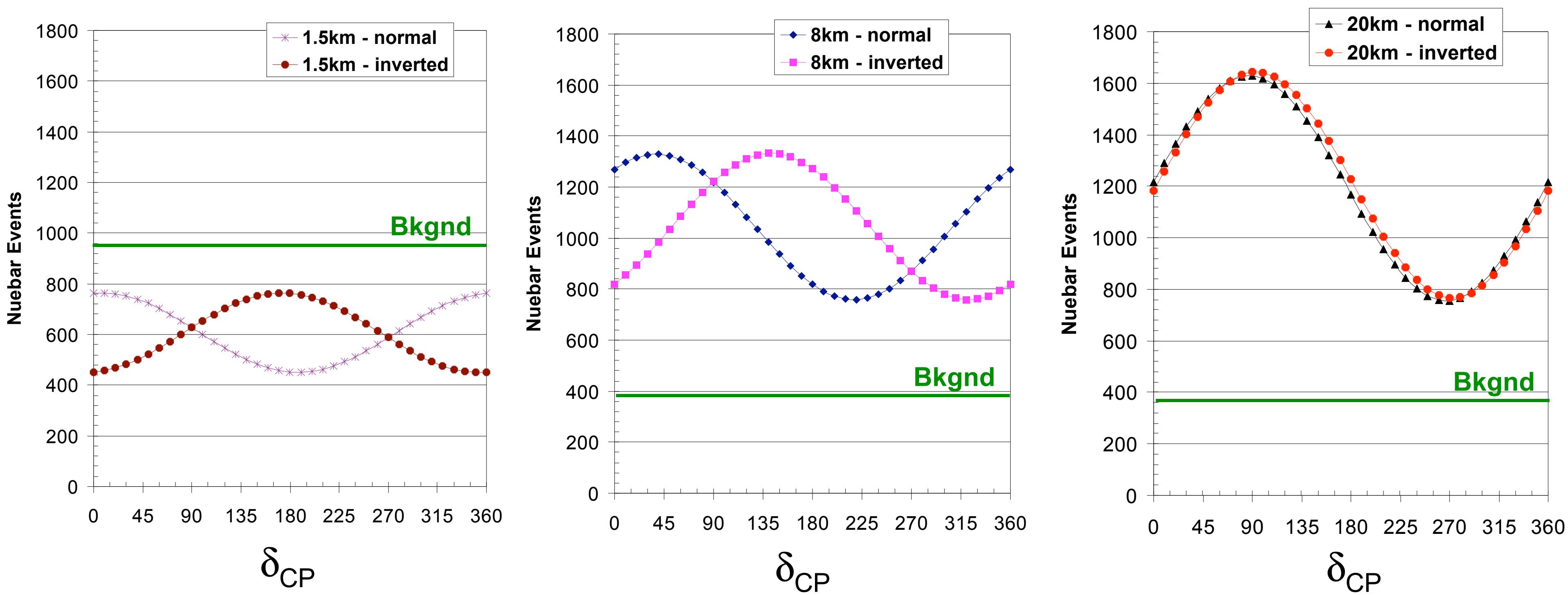
The interference terms will have opposite sign!

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

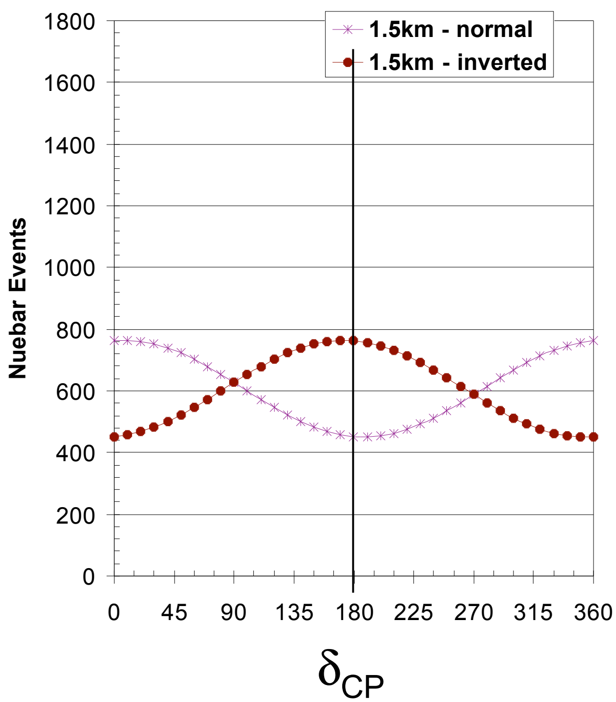
Total Events and background level, for $\sin^2 2\theta_{13}=0.05$



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

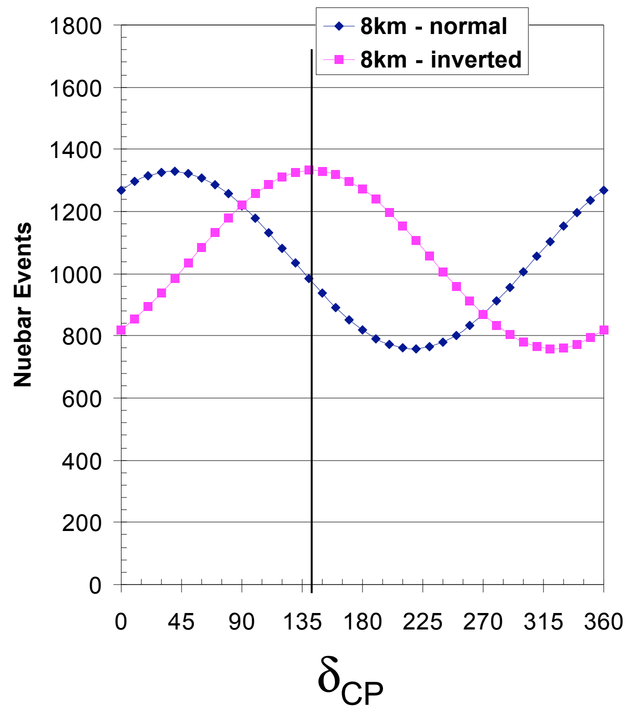
For E=50 MeV

L=1.5 km



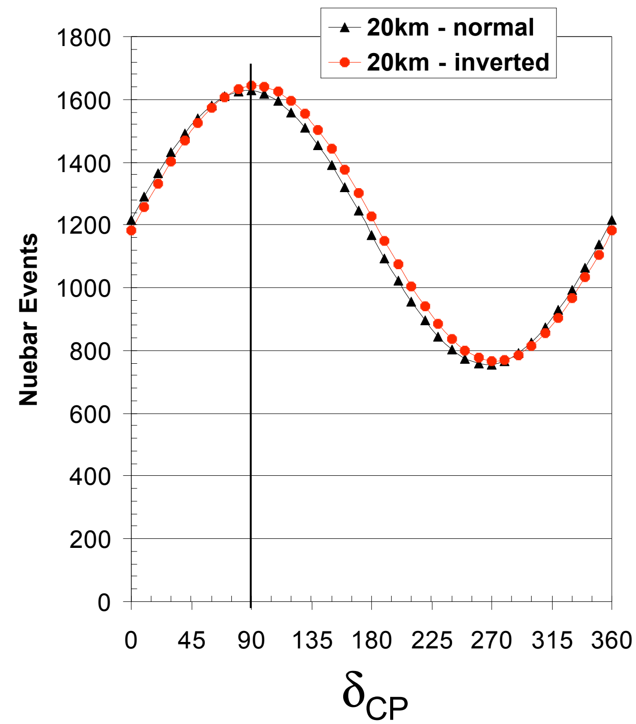
Close to source

8 km



Osc mid ($\pi/4$)

20 km

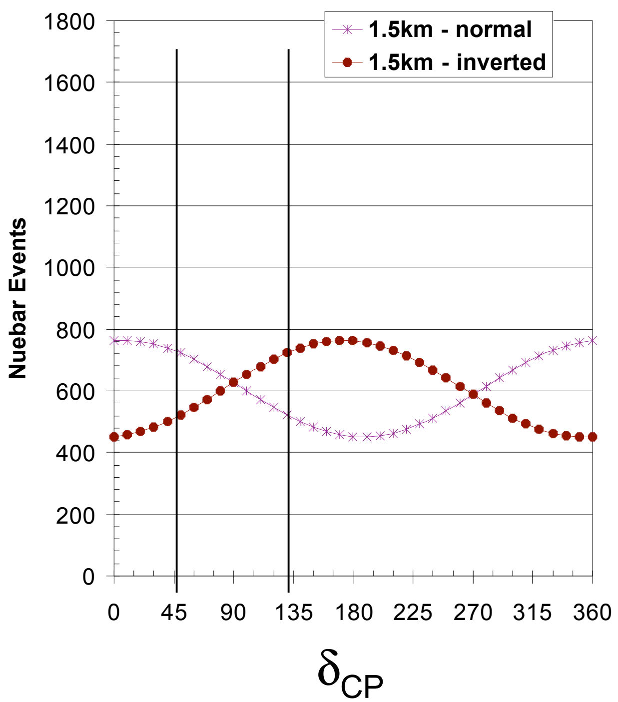


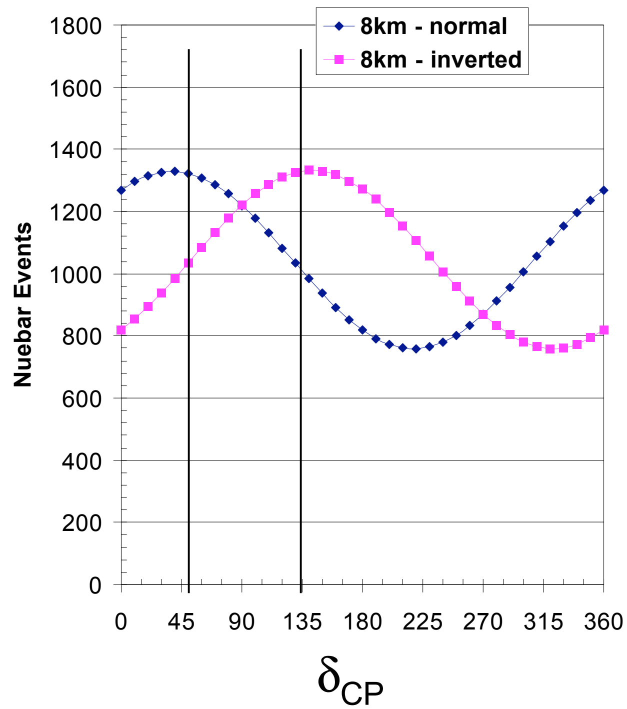
Osc max ($\pi/2$)

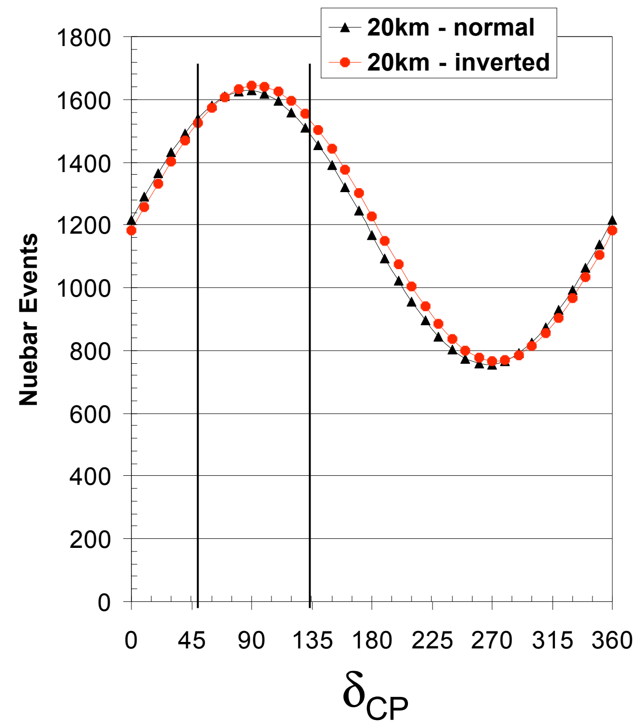
Find δ by comparing the number of events at multiple locations

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 $\delta=45°$ and normal hierarchy

and $\delta=135°$ and inverted

DAEδALUS cannot differentiate the hierarchy

Consider 4 scenarios:

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

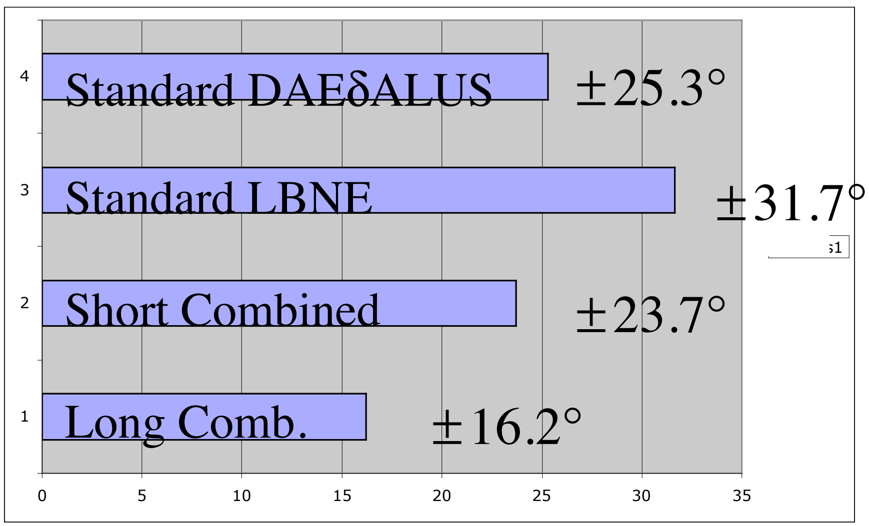
2) "Standard LBNE" -- 5 years ν and 5 years $\bar{\nu}$

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

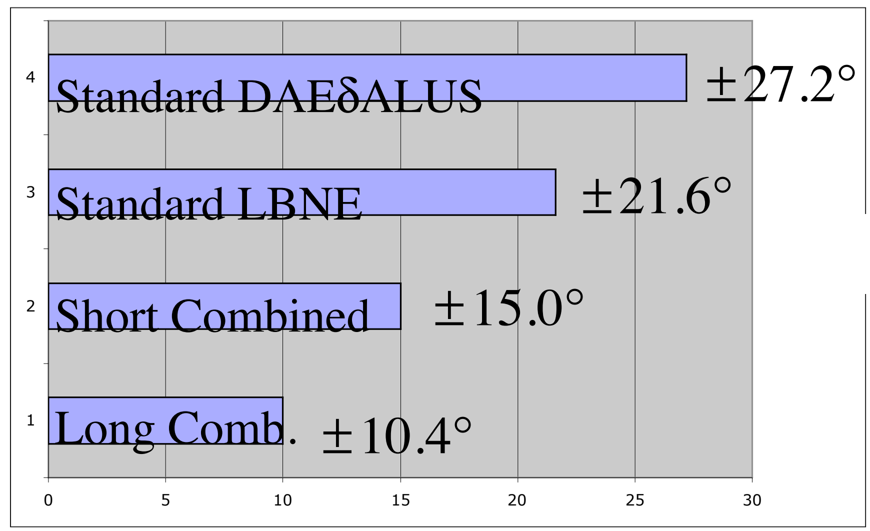
4) "Long Combined" -- 10 years total,
with only ν data from LBNE and
and $\bar{\nu}$ data from DAEδALUS I+II

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

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

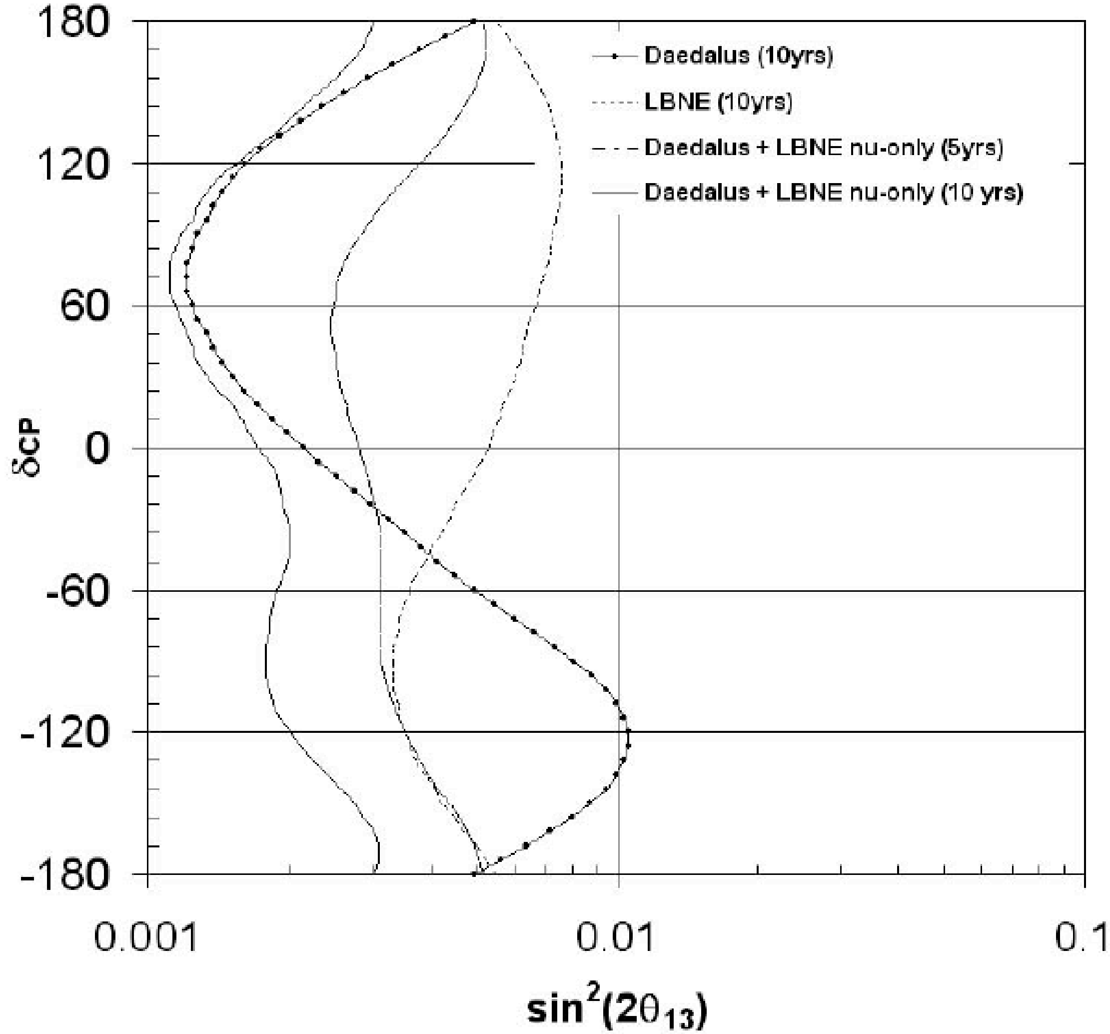


if $\delta = 160°$
then the error on δ would be..



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

3 σ



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

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

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.

Total of each type of event:

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

	Normalization	Off Osc Max	Osc Max
Event Type	1.5 km	8 km	20 km
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

Among all of the types of accelerators out there…

Cyclotrons
Synchrotrons
Linacs
FFAGs
etc.

Why cyclotrons?

Inexpensive,
Only practical below ~1 GeV
(ok for us!)
Only good if you don't need
timing structure (ok!)
Typically single-energy (ok!)
Taps into existing industry

Very interesting R&D ongoing, but these machines are not yet proven

Can do what we need right now, but are expensive.

Use linacs if you want a nice beam for transfer to another line and flexibility on energy (We don't)

We do not rule out other options, but cyclotrons seem like a good fit.

Who are the accelerator physicists who are authors on the EOI?

J. Alonso, F.T. Avignone, W.A. Barletta,
R. Barlow, H.T. Baumgartner, A. Bernstein, E. Blucher,
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J.M. Conrad, S.A. Dazeley, Z. Djurcic,
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C. Jones, G. Karagiorgi, T. Katori, S.E. Kopp,
R.C. Lanza, W.A. Loinaz, P. McIntyre, G. McLaughlin,
G.B. Mills, J.A. Nolen, V. Papavassiliou, M. Sanchez,
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What are the issues to achieving this?

These are covered in detail in our EOI.

The biggest issue by far is space charge effects at injection which lead to difficulties in extraction.

Extraction issues are exacerbated by compact size. But compact size leads to lower cost.

We have recently formed a collaboration with Andreas Adelmann at PSI to address the space-charge question through simulations

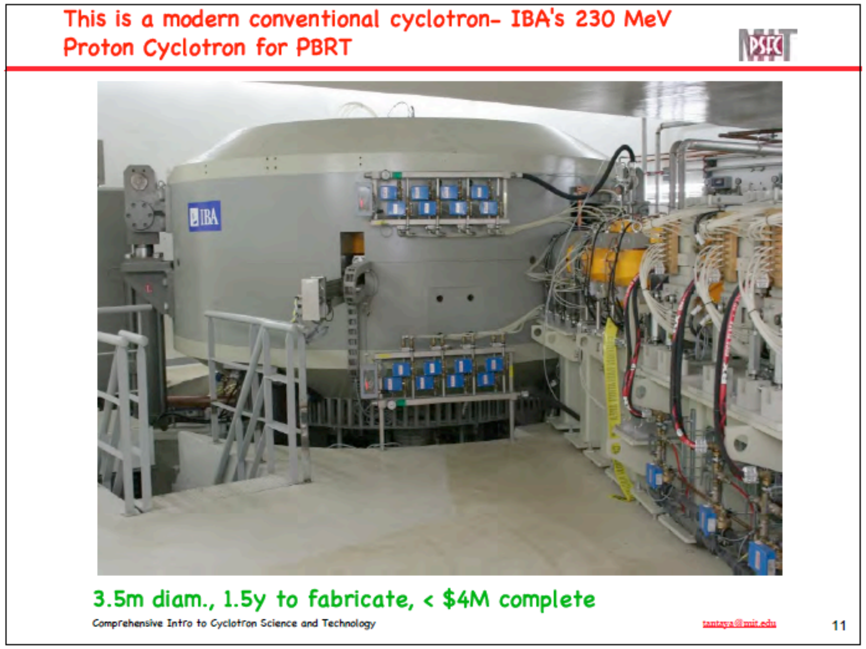
Introducing the designs…

Design #1: A Compact Cyclotron

The cheapest by far if it works.

This work is supported by DTRA for active interrogation.

The research is fully funded, but must pass milestones.
The next milestone review is in October, and is being organized by LANL.



250 MeV, high intensity,
7 T, small radius (<0.33 m),
is under construction at MIT

deliver to DTRA in 2013 --$9M

Unit cost once in production ~$3M

800 MeV needs 9T, ~3m radius (size of the above)

cost est in production in about 2020 ~$15M,

PHASE 0 to II = 10 machines (1,2,7)

This new cyclotron will use “resonant self-extraction”

This has worked at low energies, but at 250 - 800 MeV
is extracted beam under good control?

Still River is also using resonant extraction @250 MeV

Cheap cyclotron + expensive shielding = no net gain,
so we need clean extraction!!!

Design #2: The H2+ machine

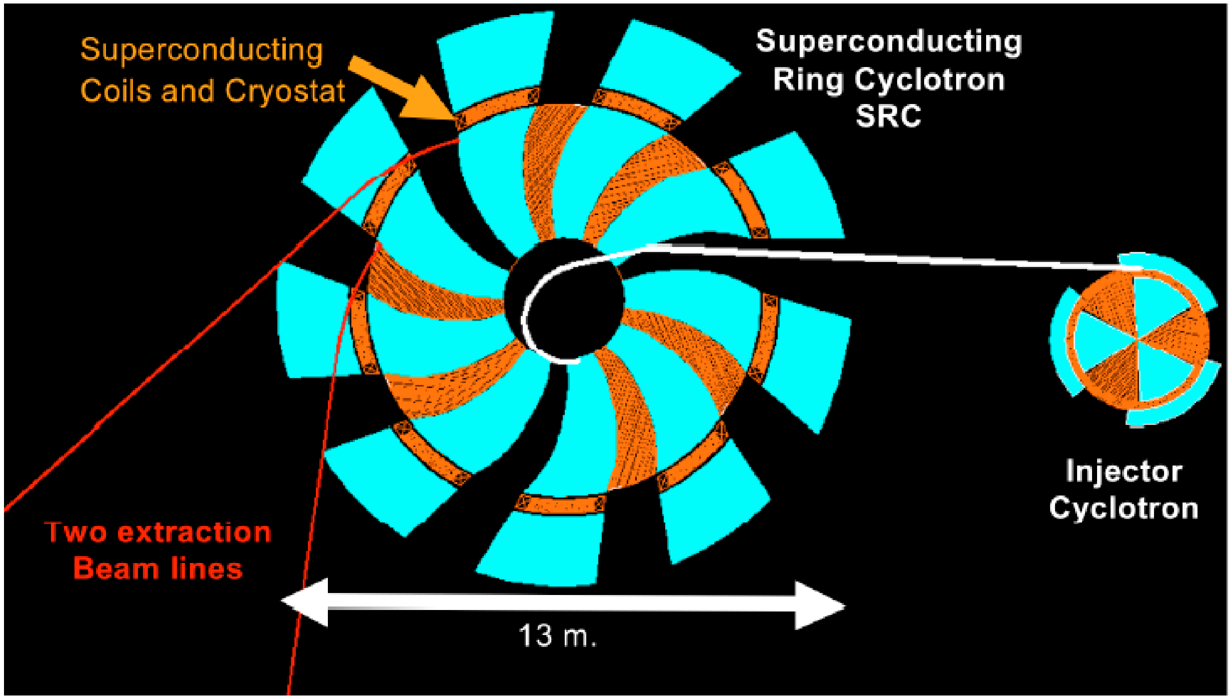
Many cyclotron experts favor this design!

This is work by Luciano Calabretta at INFN-Catania

This machine gives 1.5 MW in the 20% DF
(more power = fewer machines)

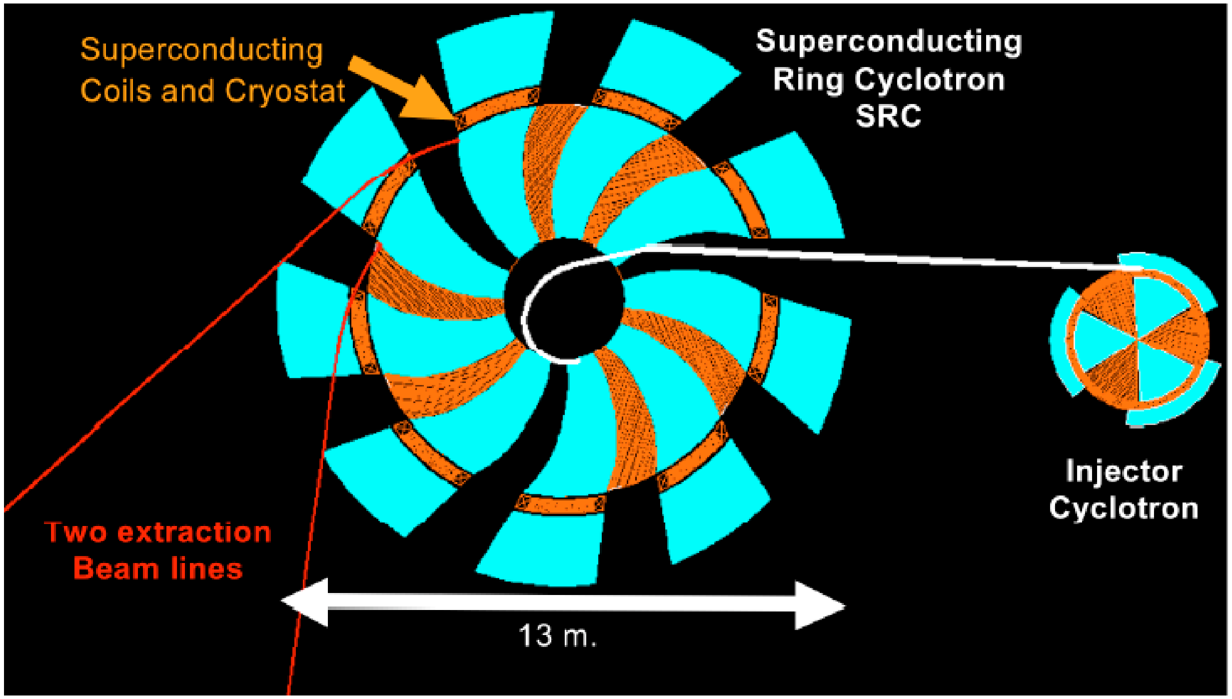
Elegant features:

1. Injector cyclotron -- today's technology, but running H2+
   Get control of the beam at low energy where activation is low!
   This gives a clean injection into SCR w/ large radius of first bend.



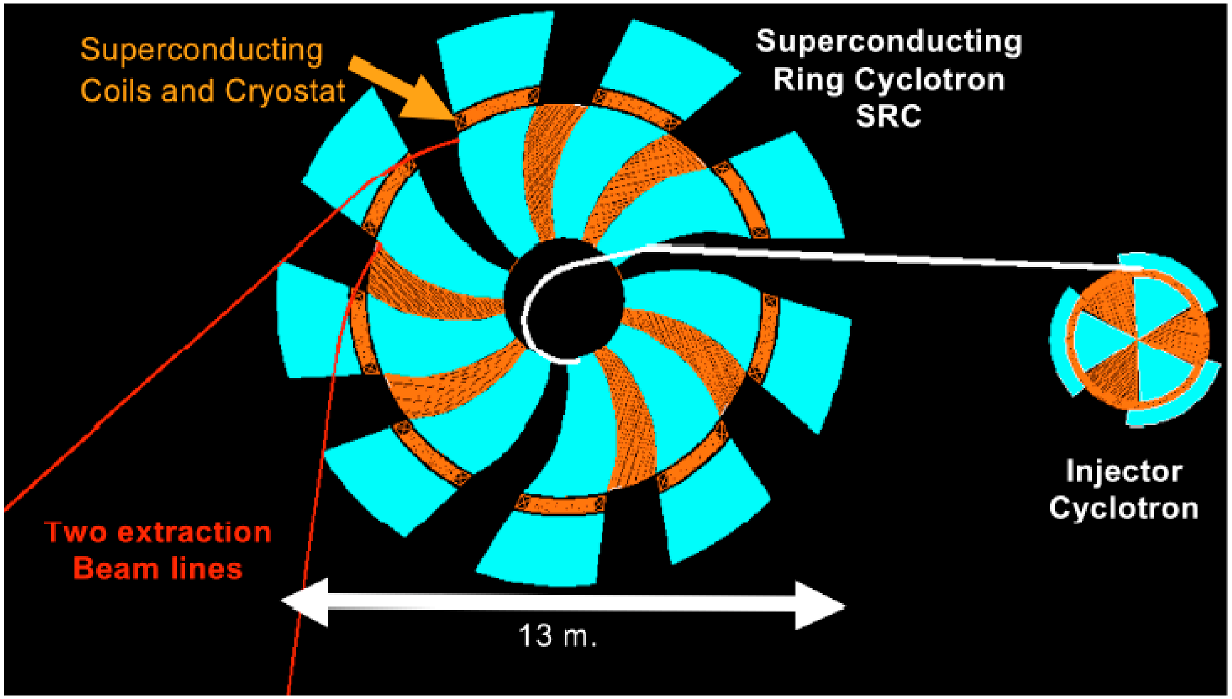
Elegant features:

2. Extraction by stripping w/ foils (like H- machines) -- very clean!
   Some questions were raised about the lifetime of the foils,
   but experts in this area say this is not a problem.



Elegant features:

3. Multiple extraction lines make targeting feasible, given very high power.
   2 MW (13 mA) is initial goal for phase I (1,1,1 or 2)
   We may be able to go to 3 MW or phase II (1,1,3 or 4)



Design #3: The stacked cyclotron

Many PSI beams in one flux return!

This has been developed by Peter McIntyre, TAMU

In principle we only need 3 machines,
each with a different number of stacks

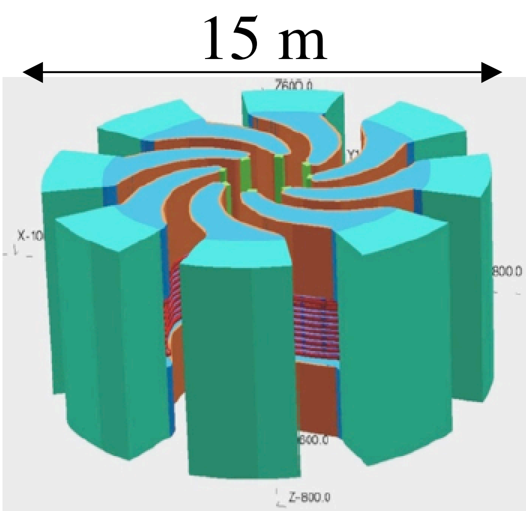
Has both ADS and FRIB applications

There is a machine which runs at the energy we need right now: PSI
But not enough intensity (2 mA).

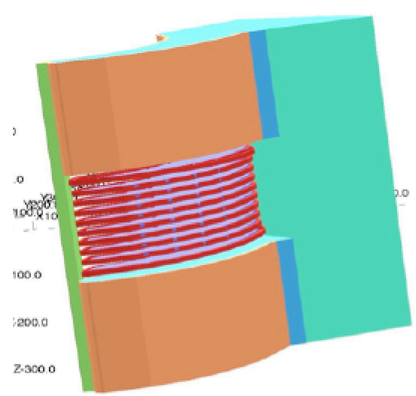
To produce many PSI machines would be cost prohibitive,
mostly because of <u>the cost of the iron</u> in the giant machine.

This proposal stacks many beams into one magnet.

For example a machine that gives 2 MW in the 20% DF,
has 7 beams at 2 mA



(a)

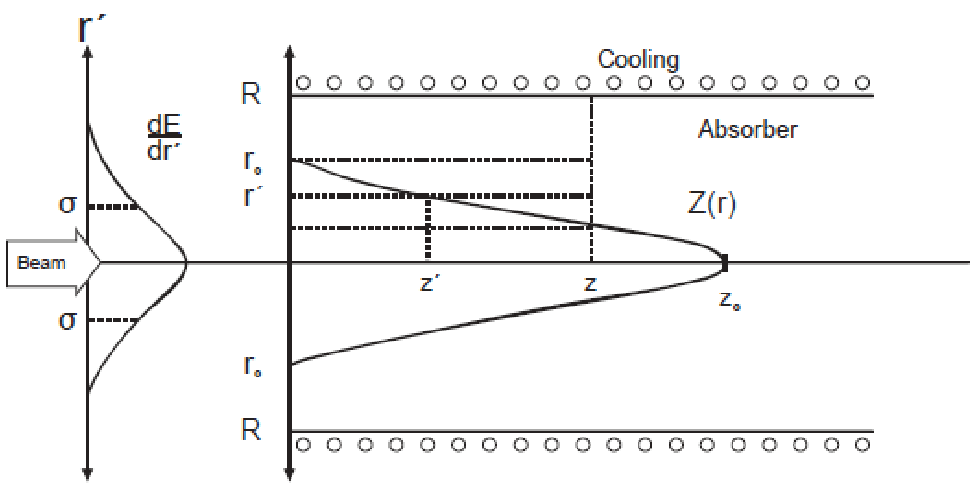


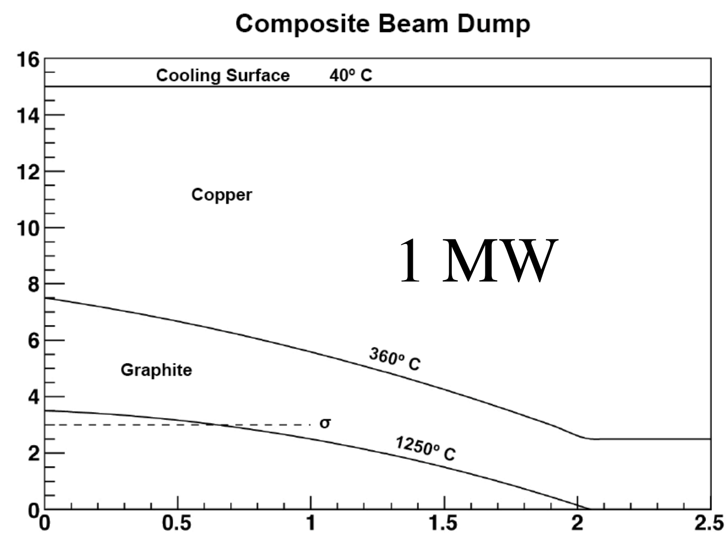
(b)

Each beam hits a separate region on target, making targeting much simpler.

Thoughts on targeting:

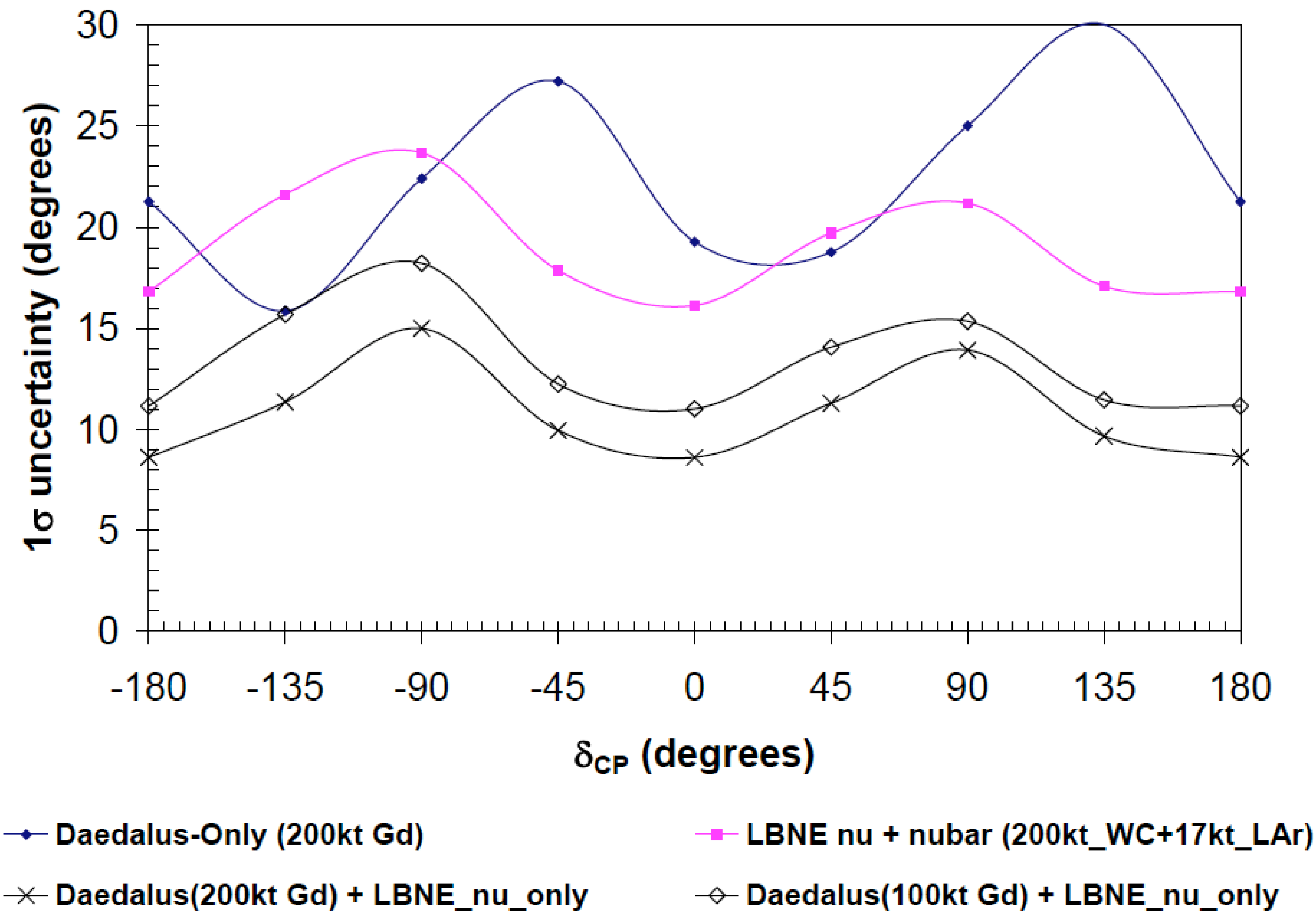
We plan to use carbon (graphite).
As long as we keep the intensity $\lesssim$ 1MW
we can base our design on existing targets.

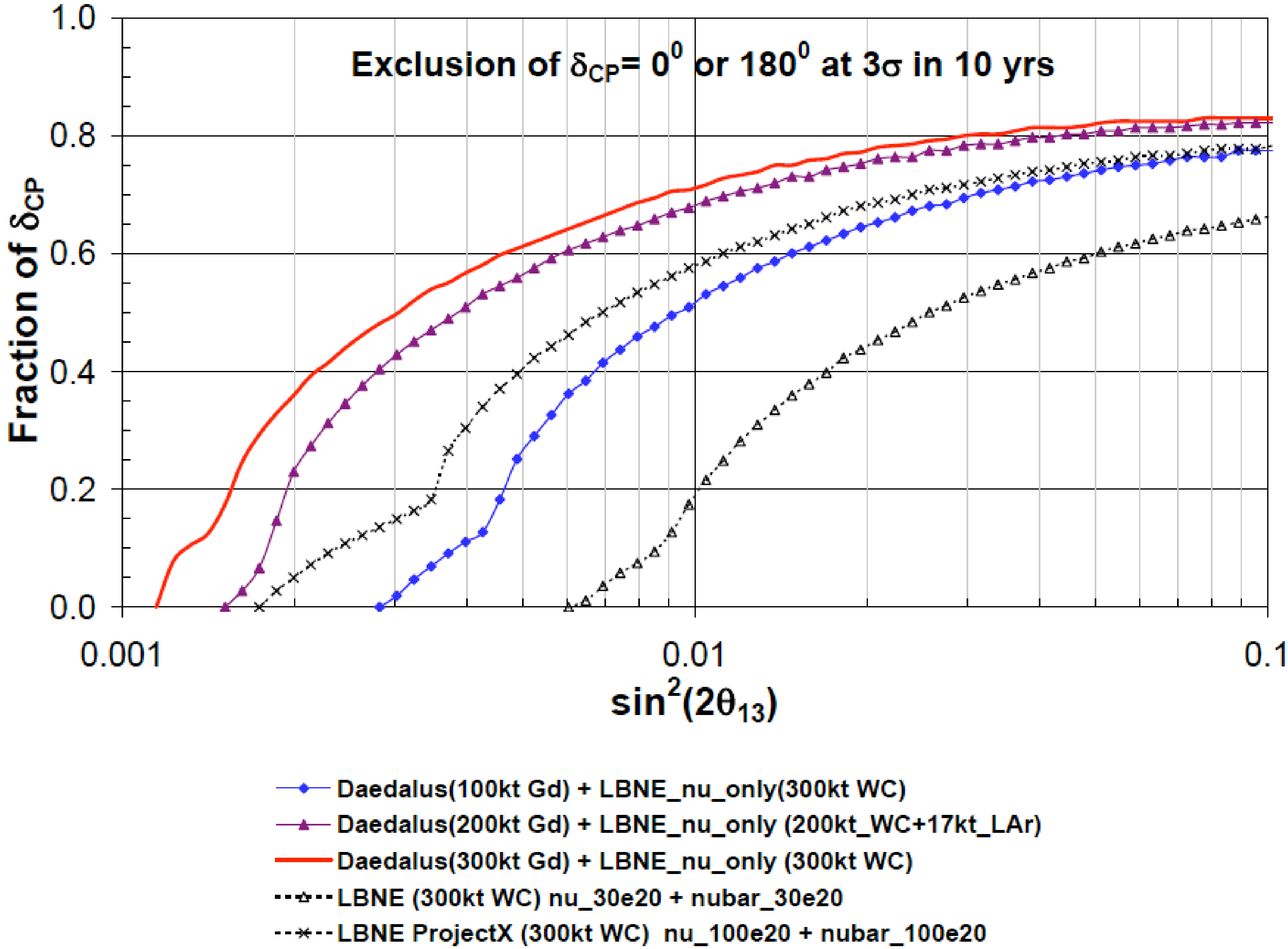




- Low A -- minimize energy lost to n production,
- No stringers! (reduce decay-in-flight)

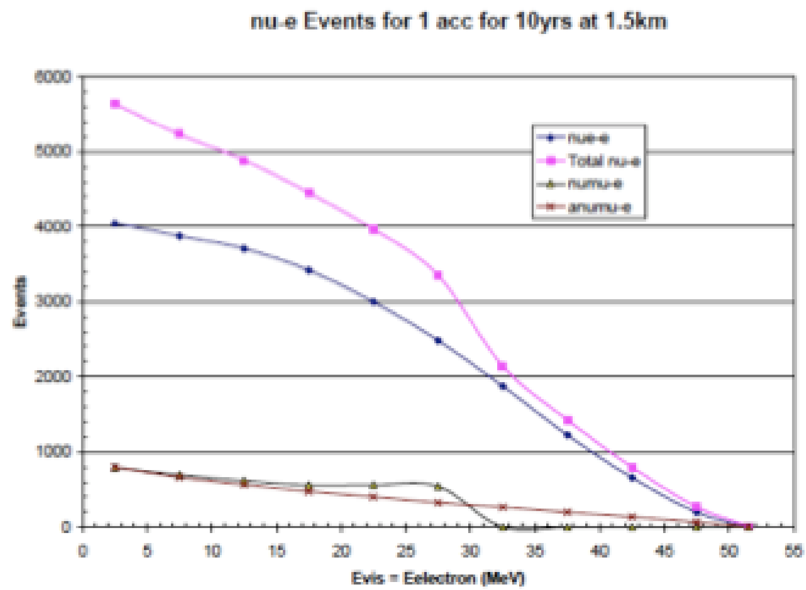
What about other design configurations?



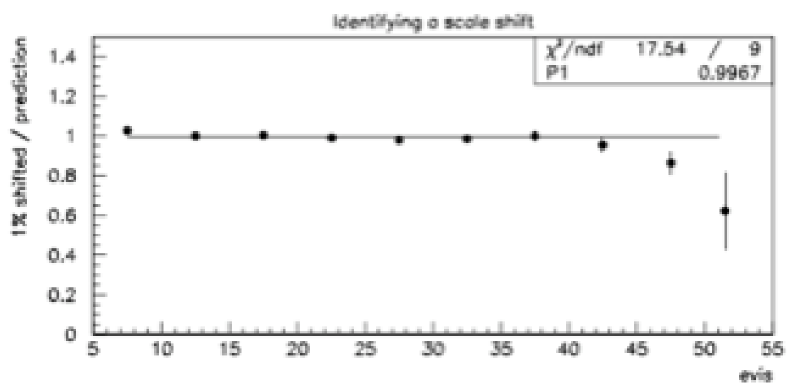


Exclusion of δ_{CP}= 0^0 or 180^0 at 3σ in 10 yrs
Fraction of δ_{CP}
1.0
0.8
0.6
0.4
0.2
0.0
0.001
0.01
0.1
$\sin^2(2\theta_{13})$
Daedalus(100kt Gd) + LBNE_nu_only(300kt WC)
Daedalus(200kt Gd) + LBNE_nu_only (200kt_WC+17kt_LAr)
Daedalus(300kt Gd) + LBNE_nu_only (300kt WC)
LBNE (300kt WC) nu_30e20 + nubar_30e20
LBNE ProjectX (300kt WC) nu_100e20 + nubar_100e20

Calibrating the large water Cerenkov Detector with ν-e scatters



1% miscalibrations
can be observed



Near accelerator opportunities

(Install in area in front of the 300 ft Campus)

Ideas contributed to our EOI:

Coherent neutrino nucleus scattering

Measurement of $\sin^2\theta_W$

Nonstandard interactions

Cross section measurements

for Supernova detectors

for nucleosynthesis

Neutrino Magnetic Moment

Strange spin of the nucleon

Two new papers : Argawalla & Huber-- 1005.1254,

Lauzuaskas & Volpe-- 1004.0310

…Many opportunities for small scale experiments!

If the LSND/MB signals persist,
what does this mean for DAEδALUS and LBNE?

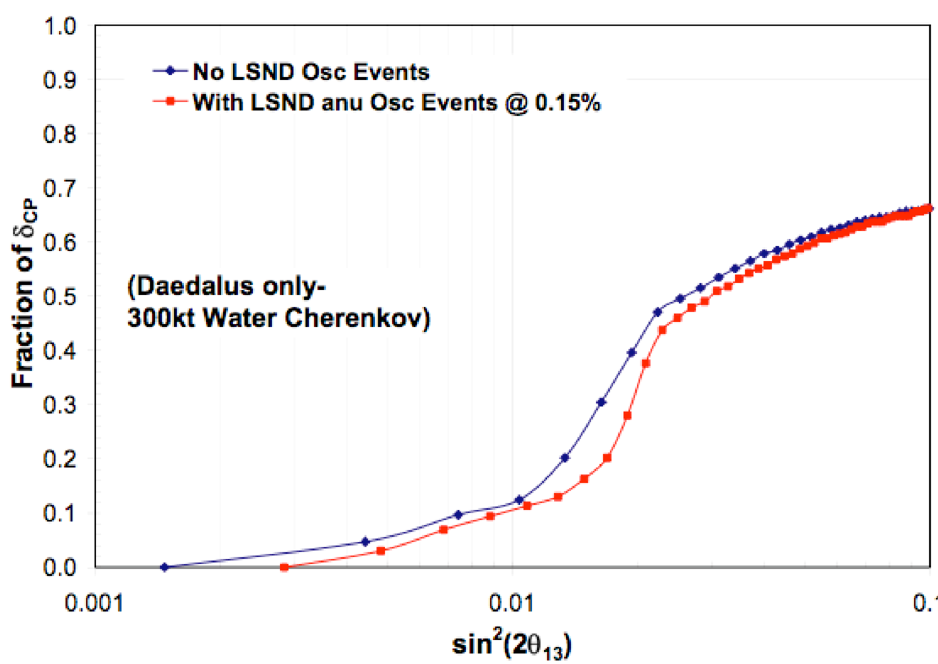
For DAEdALUS:

Issue is only $\bar{\nu}$

- λ_{osc} @ 50 MeV < 1.5 km (1st accelerator) -- $<\sin^2(\Delta m^2 L/E)>=1/2$
- P_{osc} is independent of distance -- use near accelerator to measure well!

Effect comes largely from statistical error on the subtracted background, since systematics from 3 accels cancel well.

Exclusion of δ_{CP}= 0^0 or 180^0 at 3σ (10yrs)



If the LSND/MB signals persist,
what does this mean for DAEδALUS and LBNE?

For LBNE:

Issue is in $\bar{\nu}$…

- λ_{osc} @ 3 GeV > distance to near detector -- $\sin^2(\Delta m^2 L/E)$ dependence!
- P_{osc} cannot be measured well in near detector
  - -- needs an outside precision measurement.
  - -- complicates total $\bar{\nu}_e$ background measurement in LBNE

…As well as in ν

- How does ν low-E excess scale with L and E? -- needs a model!

How does
Low E excess
affect first bins??!