ν ν ν

Neutrino Experiments:
ν Questions for a New Decade…

Part II

Part I: Neutrino Basics…

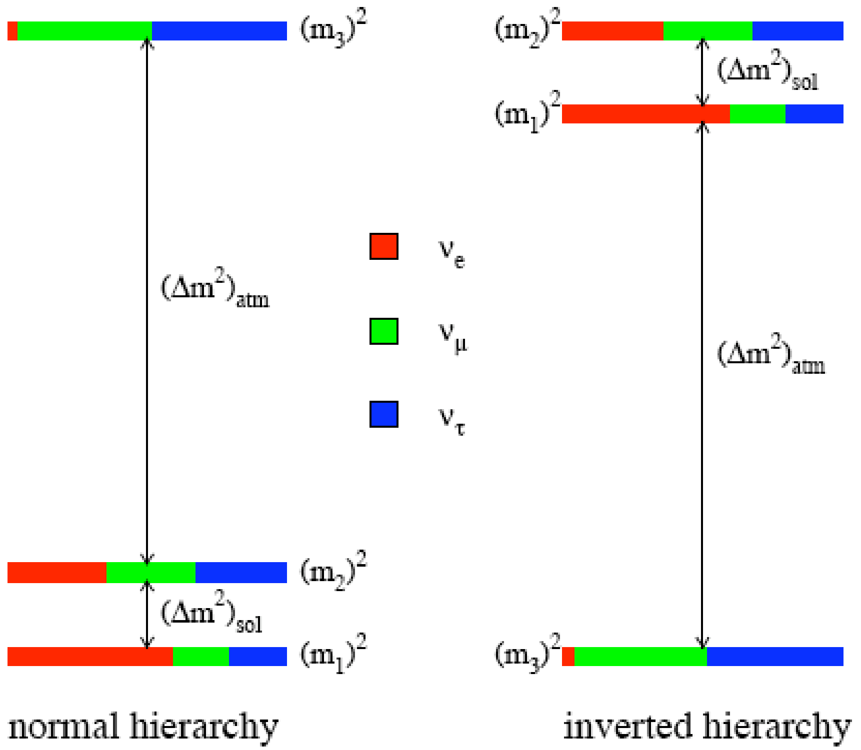
- The neutrino we once knew and loved
- Neutrino Oscillations
- A “nu” Standard Model

Part II: The Oscillation Puzzle Pieces

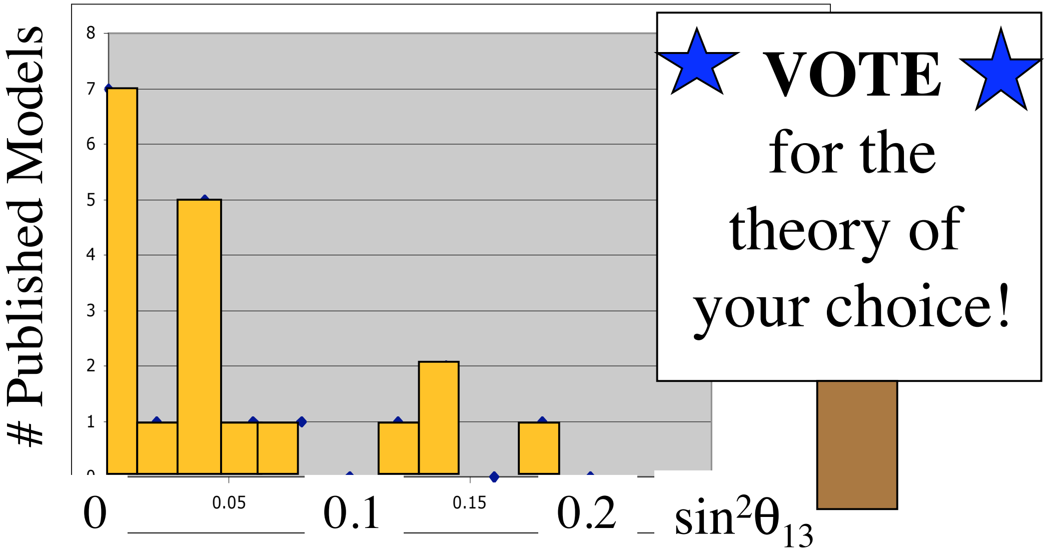
- How the pieces fit together…
- What’s the present strategy?
- A novel approach: DAEδALUS

Quick Review: The Known Unknowns are:

1. The mass hierarchy -- how different are neutrinos? what do we really know about mass?



2. The value of θ_{13} --- differentiates New Physics models…

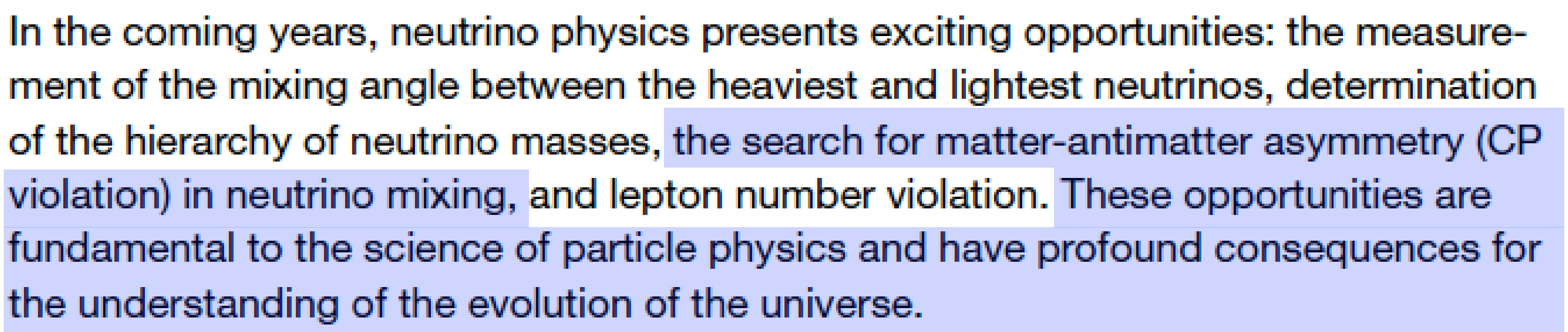


VOTE
for the
theory of
your choice!

Especially models with…

quark-lepton unification,
or a μ-τ symmetry
at high energy scales

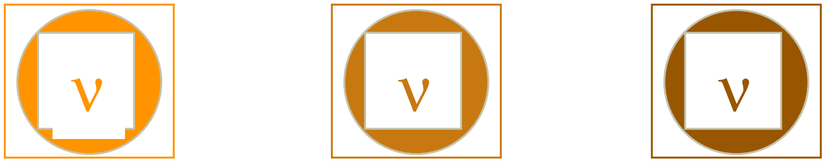
3. δ -- the CP violating parameter



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.

US Particle Physics:
Scientific Opportunities
A Strategic Plan
for the Next Ten Years

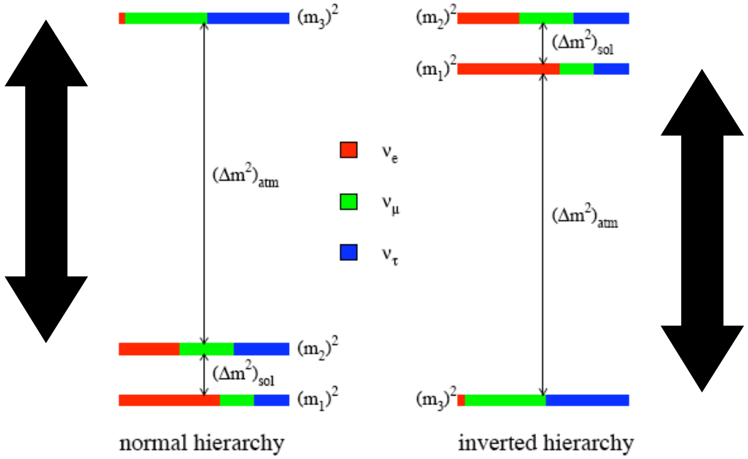
These are all connected…



How do the pieces fit together?

Starting with θ_{13}

The littlest mixing angle…



The place to look is in
the "big jump"
$\Delta m^2 \sim 3E\text{-}3\ eV^2$
and with electron flavor

ν_e disappearance experiments has simple dependence on θ_{13}

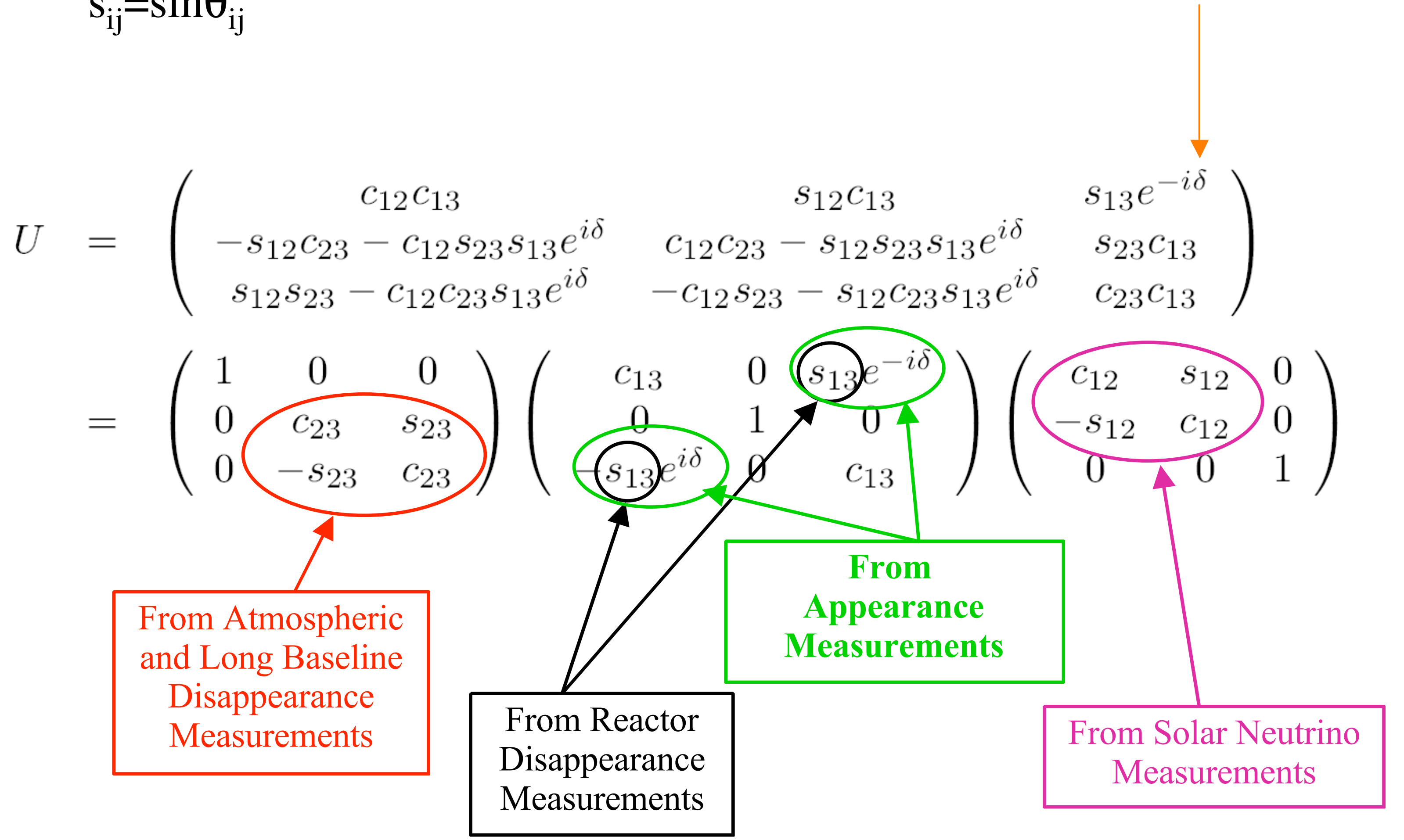
$$P_{\text{disapp}} \simeq \sin^2 2\theta_{13} \sin^2 \Delta + \alpha^2 \Delta^2 \cos^4 \theta_{13} \sin^2 2\theta_{12},$$

$$\alpha \equiv \Delta m^2_{21}/\Delta m^2_{23} \text{ and } \Delta \equiv \Delta m^2_{31} L/(4E_\nu).$$

Next there is δ

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

The CP Violation Parameter



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

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

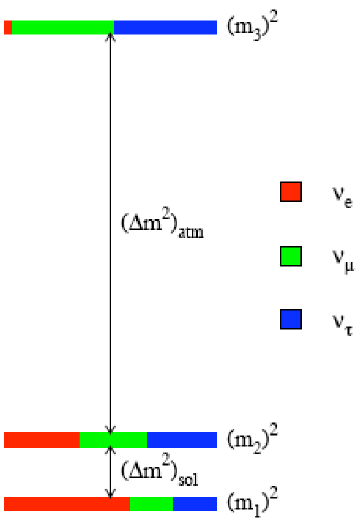
From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

From Appearance Measurements

From Solar Neutrino Measurements

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



in a vacuum…

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

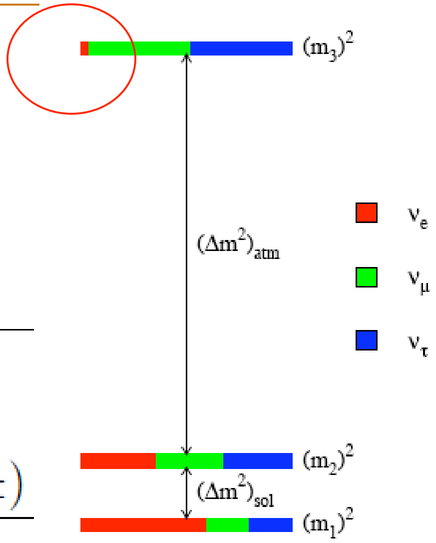
We want to see if δ is nonzero

terms depending on mixing angles

terms depending on mass splittings

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

Most parameters are well known…

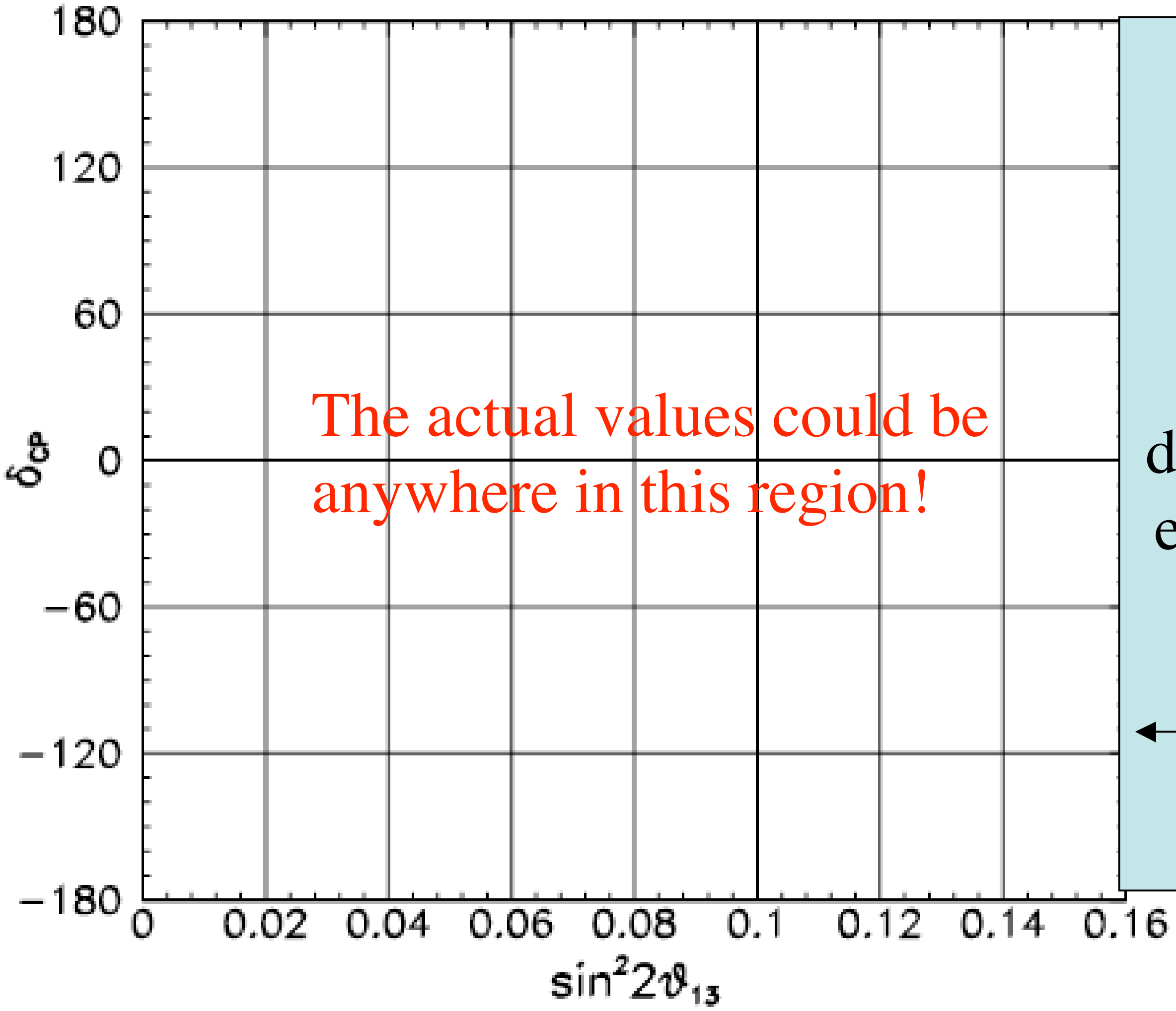


Parameter	Present: Value	Uncert. (±)	Assumed Future: Value	Uncert. (±)
$\Delta m^2_{21} \times 10^{-5}\mathrm{eV}^2$	7.65	0.23	7.65	N/A
$\Delta m^2_{31} \times 10^{-3}\mathrm{eV}^2$	2.40	0.12	2.40	0.02
$\sin^2(2\theta_{12})$	0.846	0.033	0.846	N/A
$\sin^2(2\theta_{23})$	1.00	0.02	1.00	0.005
$\sin^2(2\theta_{13})$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

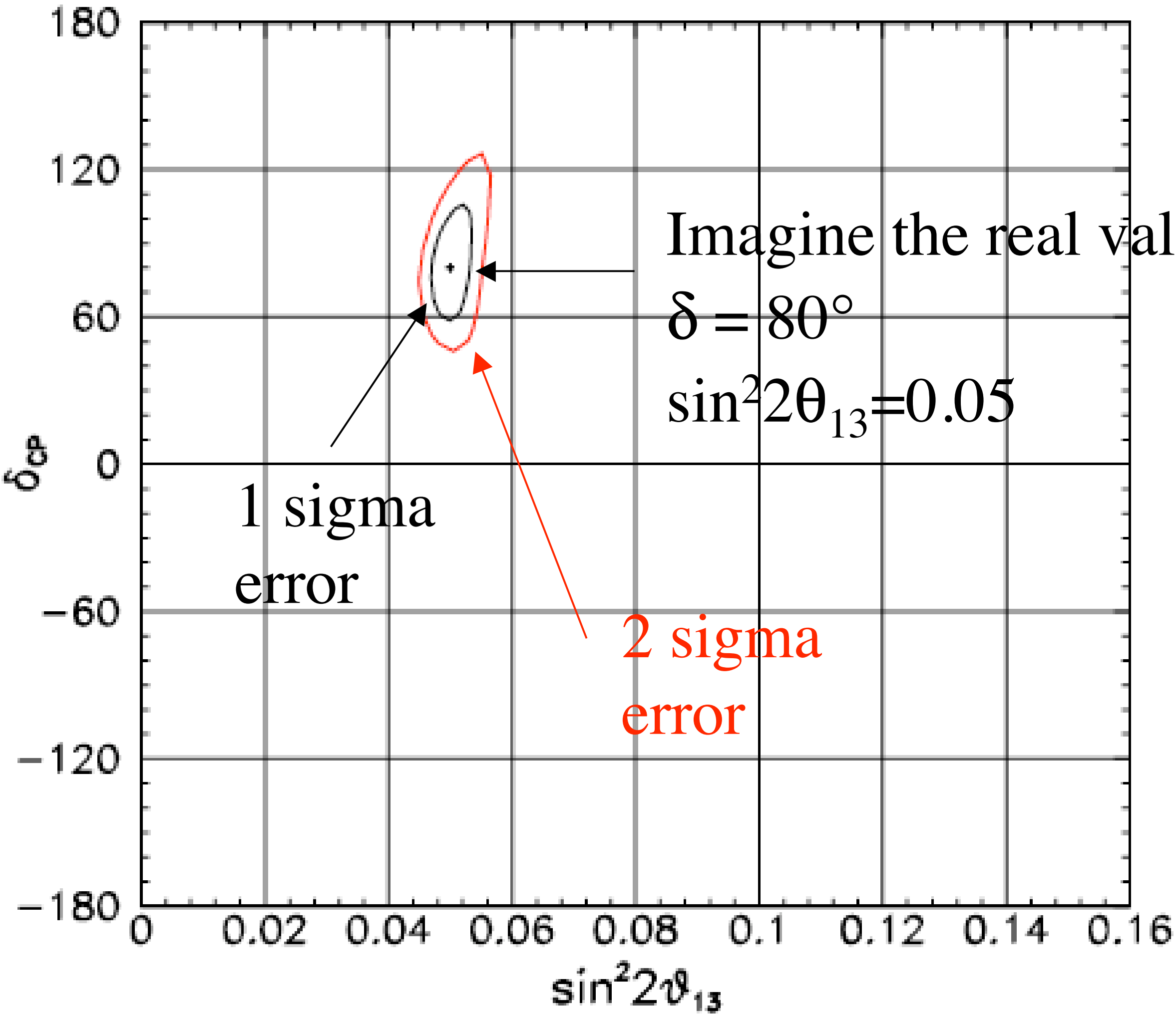
So what do we know about δ vs θ_{13} ???



The actual values could be anywhere in this region!

This region ruled out by past disappearance experiments Chooz and Palo Verde

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

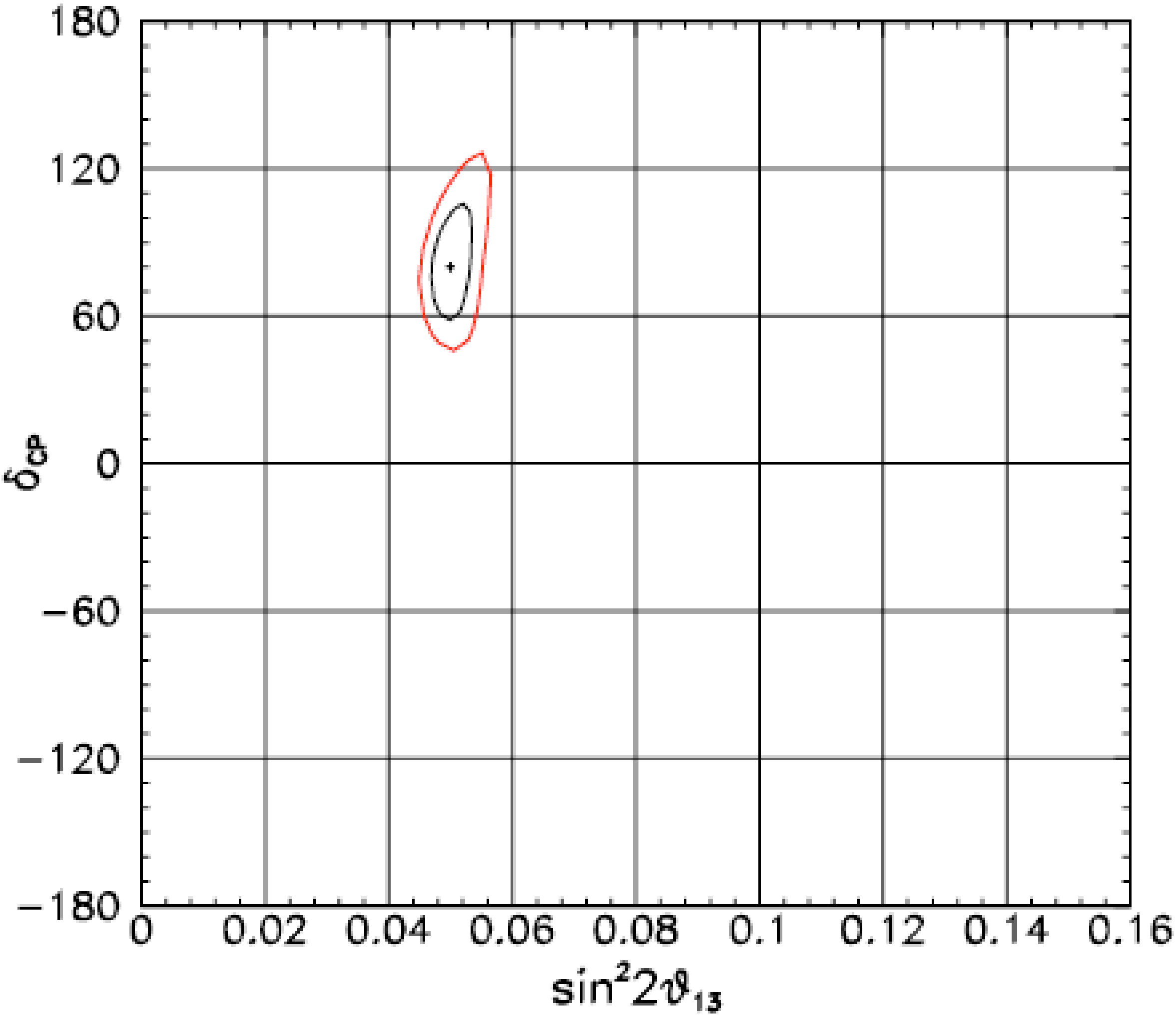


Imagine the real values are:
$\delta = 80°$
$\sin^2 2\theta_{13} = 0.05$

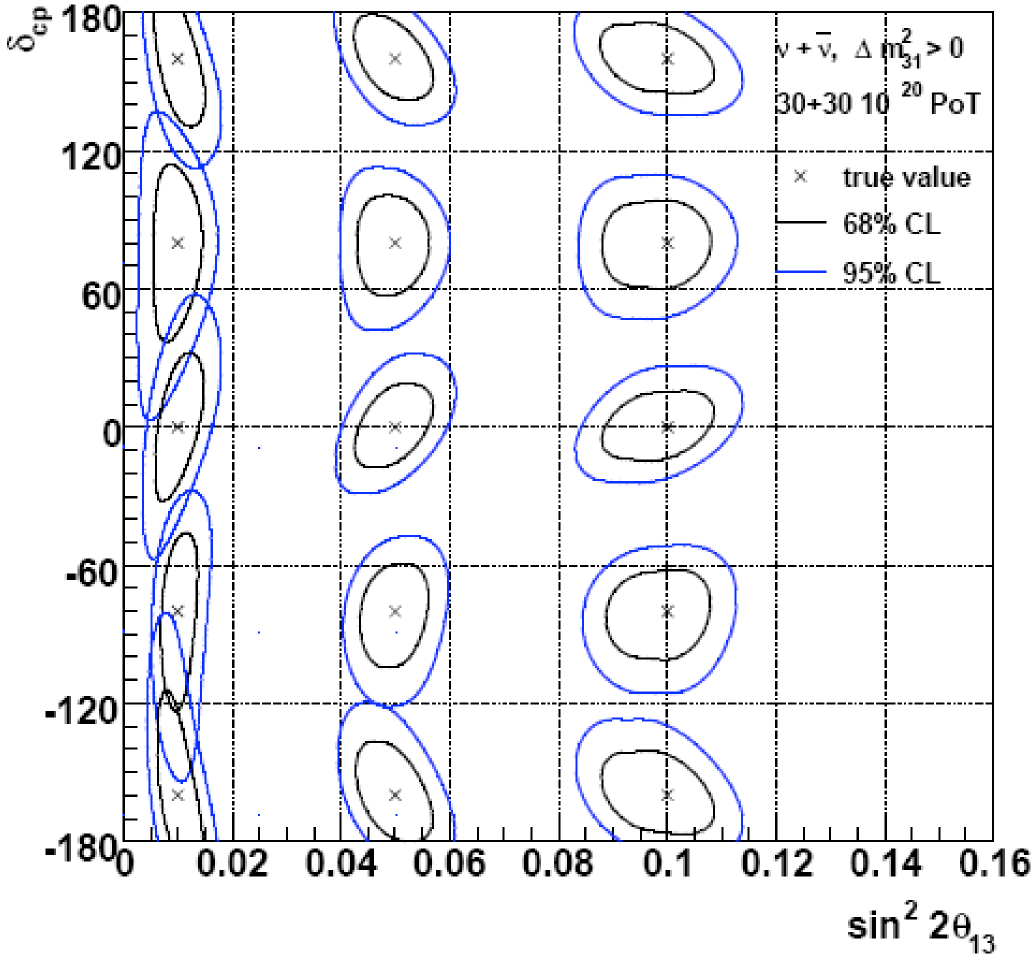
1 sigma
error

2 sigma
error

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

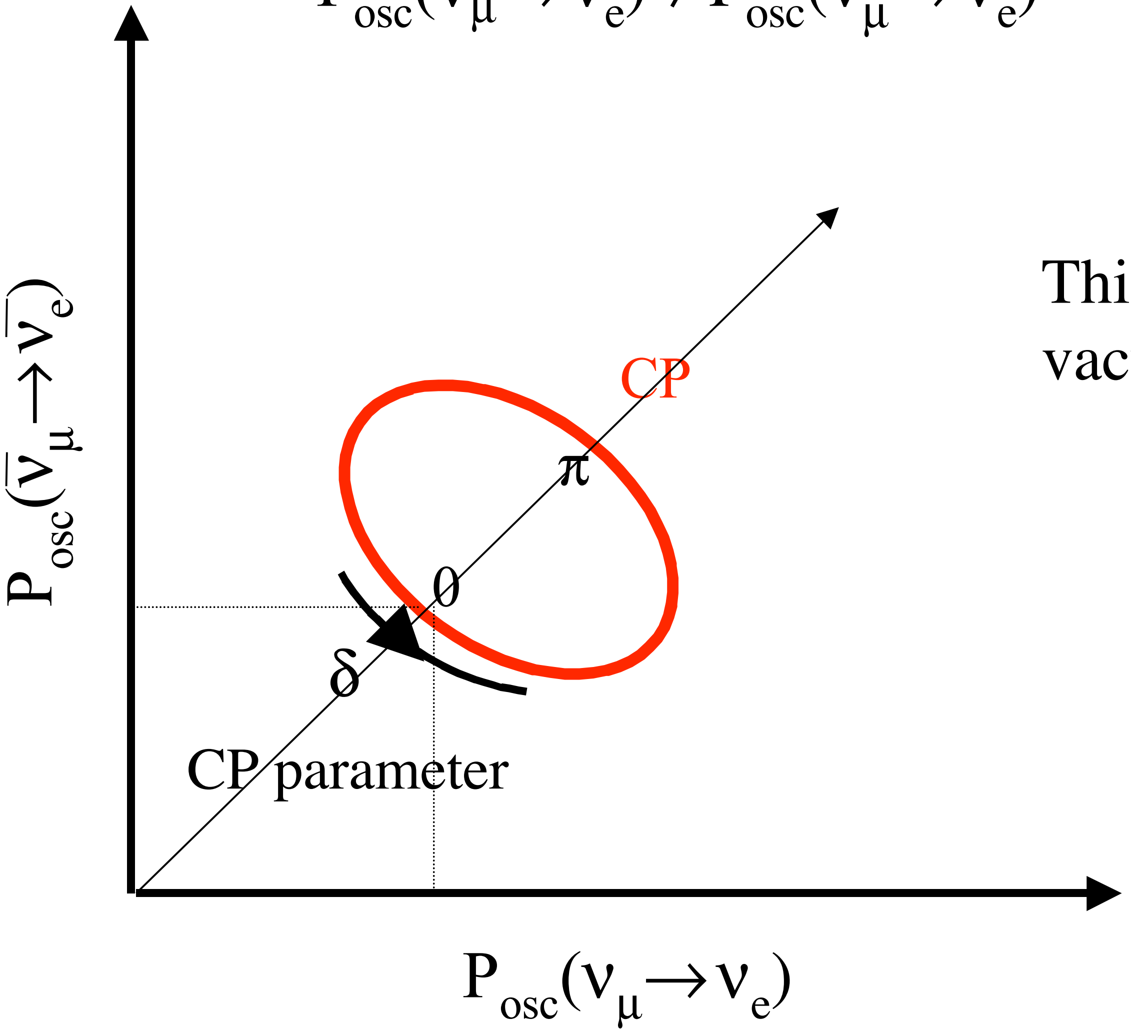
terms depending on mixing angles

terms depending on mass splittings

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

The classic idea for how to see CP violation:

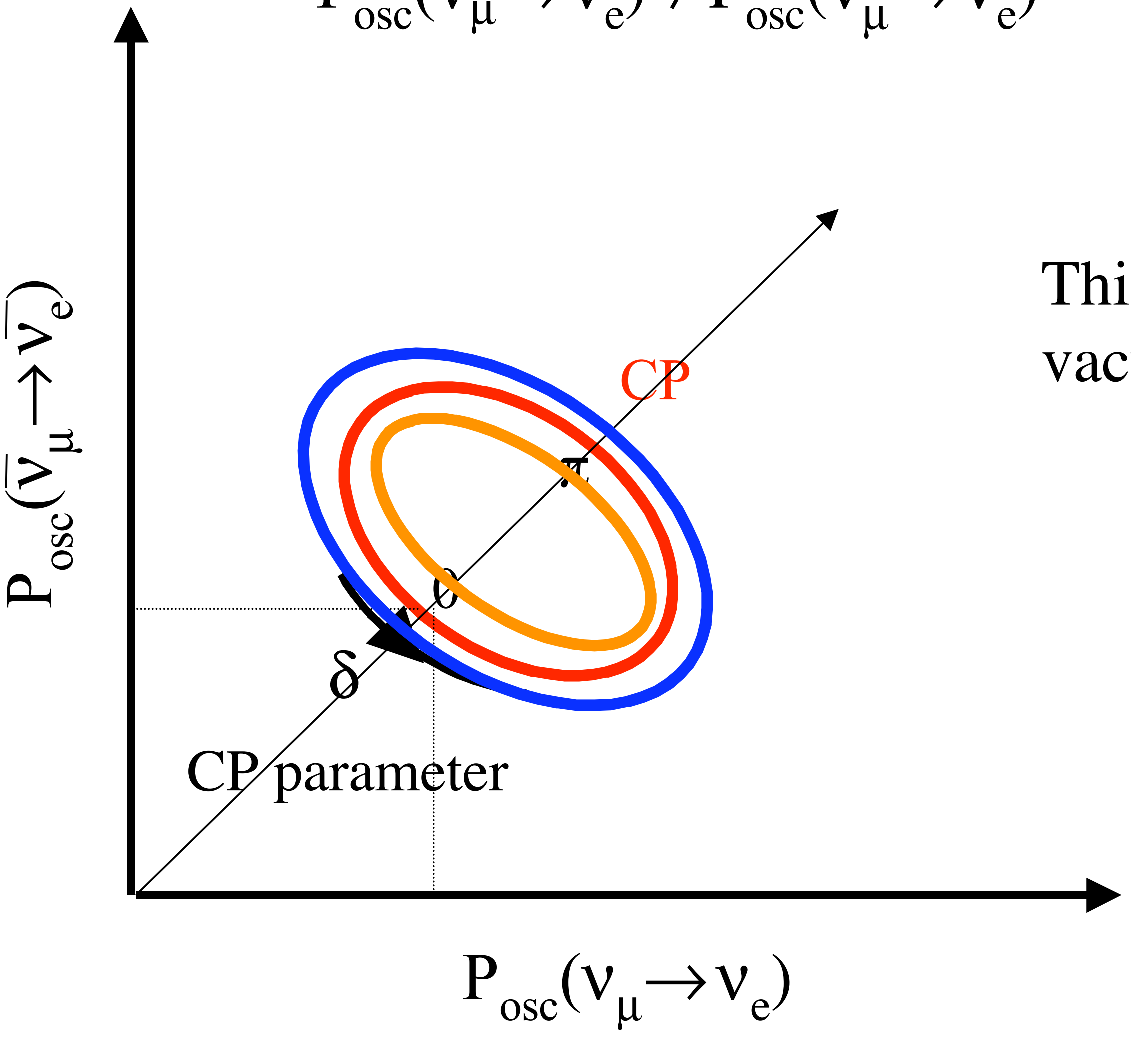
$$P_{osc}(\nu_\mu \to \nu_e) \neq P_{osc}(\bar{\nu}_\mu \to \bar{\nu}_e)$$



This is in a vacuum (or air).

Varying the value of θ_{13} reduces or enhances the effect

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

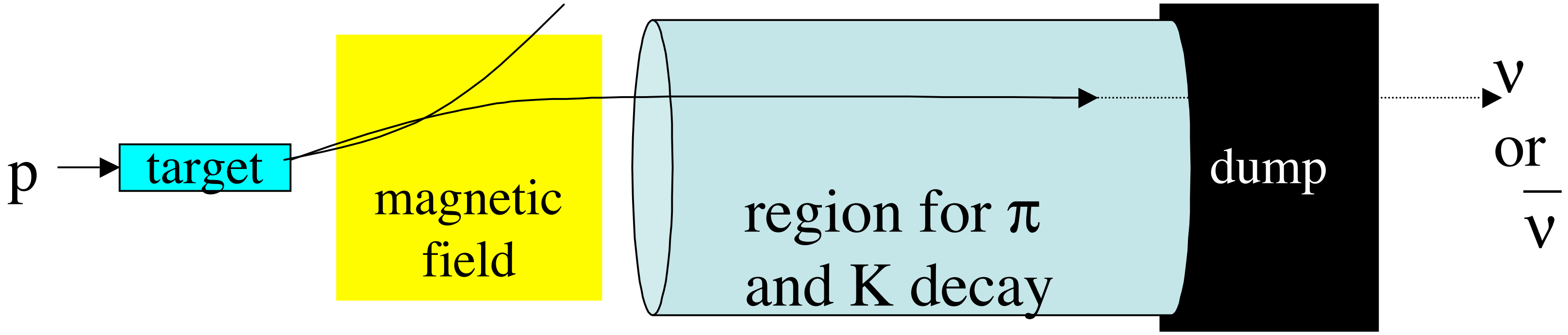


This is in a vacuum (or air).

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 $\bar{\nu}$:

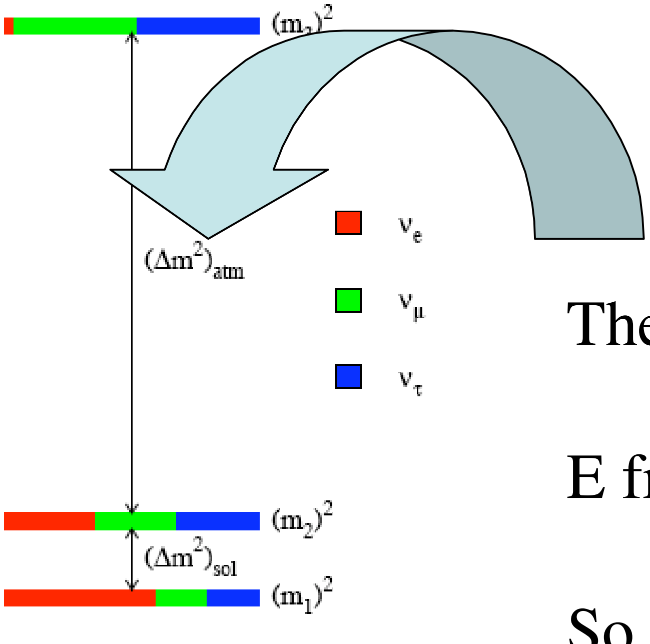


“Conventional neutrino beam” -- 100’s of MeV to a few GeV

The Probability for Oscillations...

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

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



normal hierarchy

The atmospheric $\Delta m^2 \sim 0.001$ eV^2

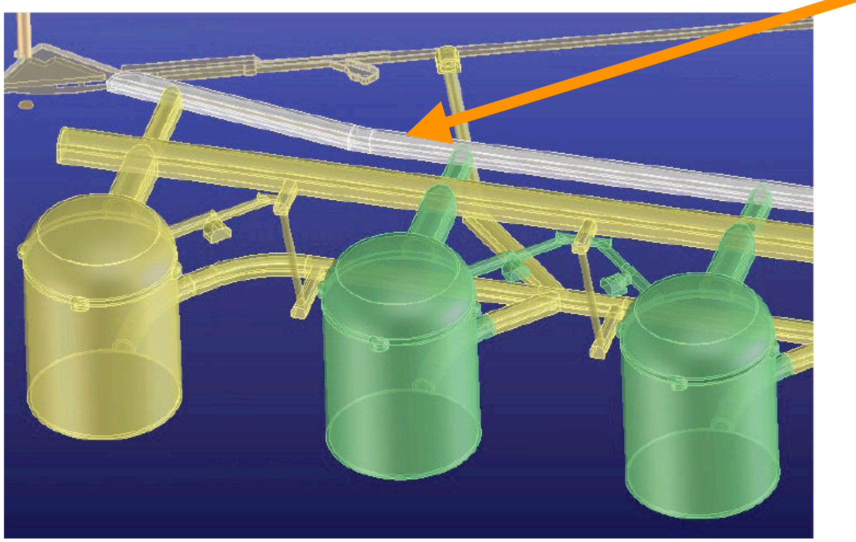
E from a convention beam is ~ 1 GeV

So L = 1000 km !!!

Using LBNE as an example…

Beam from Fermilab

Shoots to detectors in South Dakota
1300 km

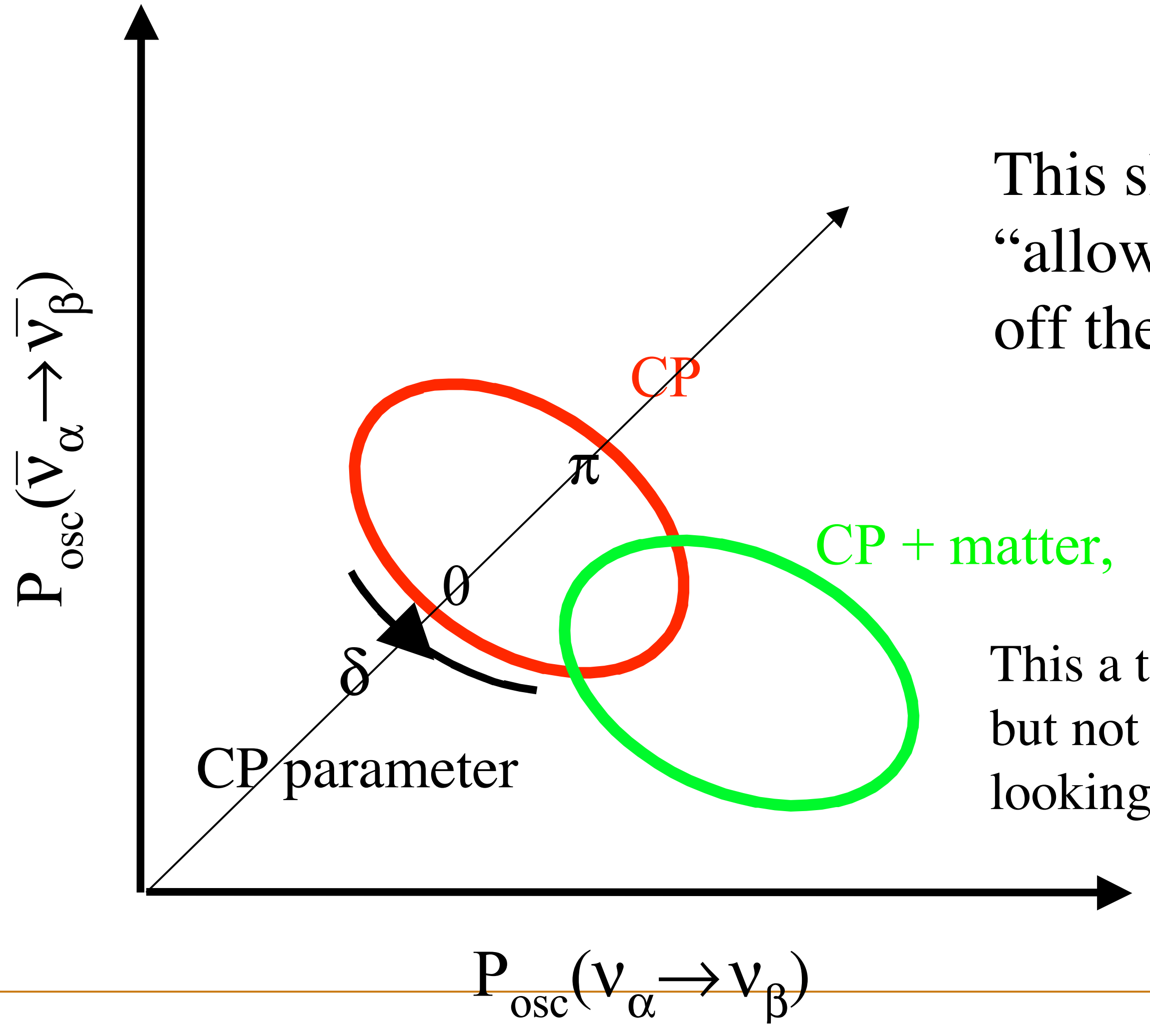


And there is **lots and lots**
of matter along a 1300 km path!

also true for LENA, MEMPHYS and HyperK designs

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

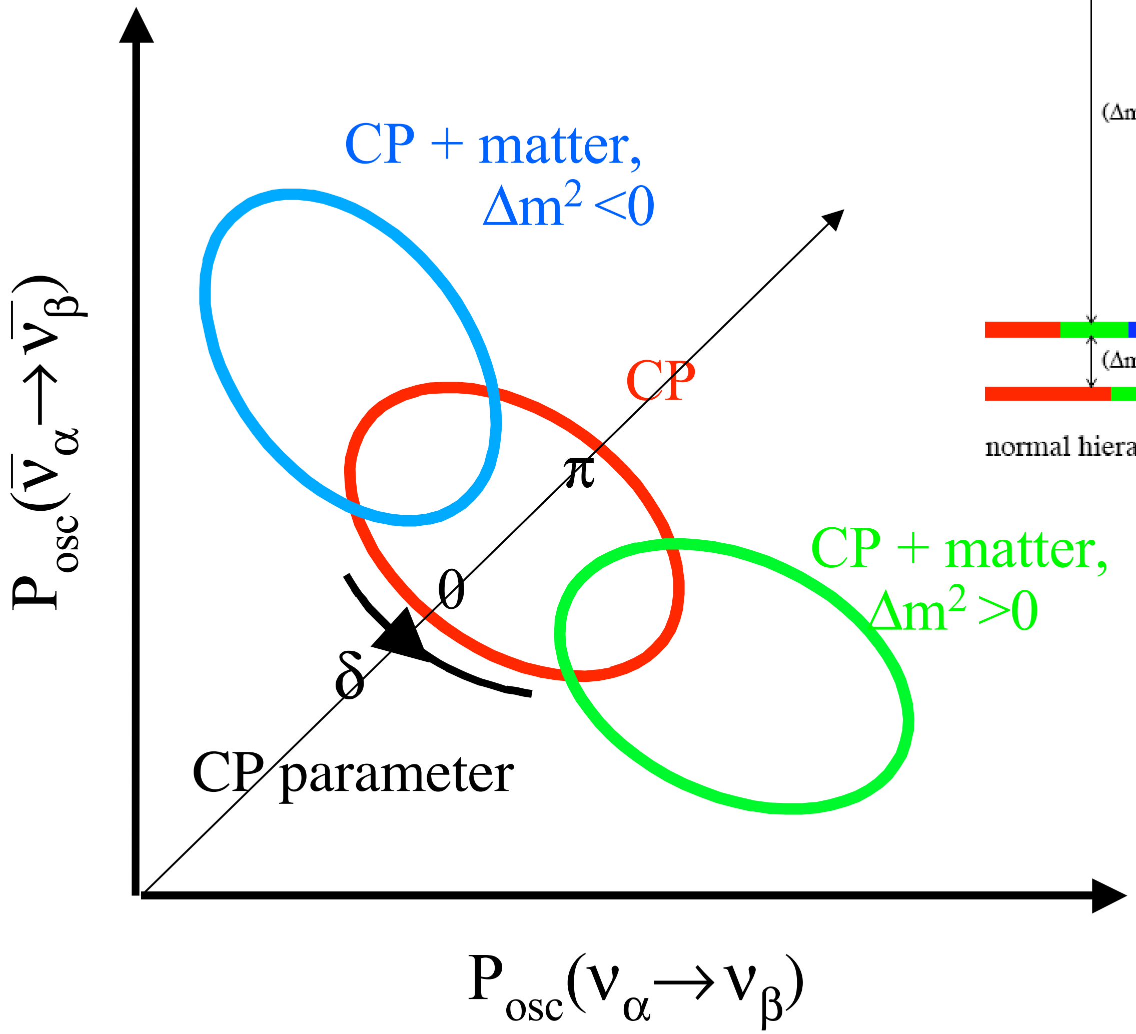
Forward scattering affects neutrinos differently than antineutrinos.

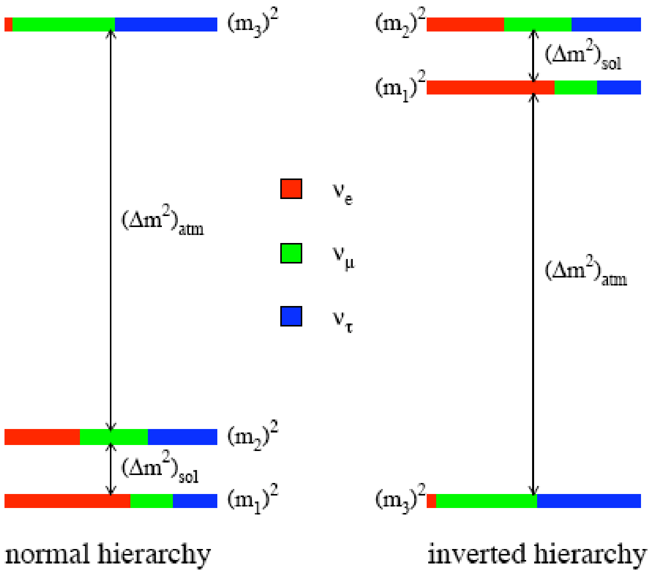


This slides the
"allowed ring"
off the diagonal

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

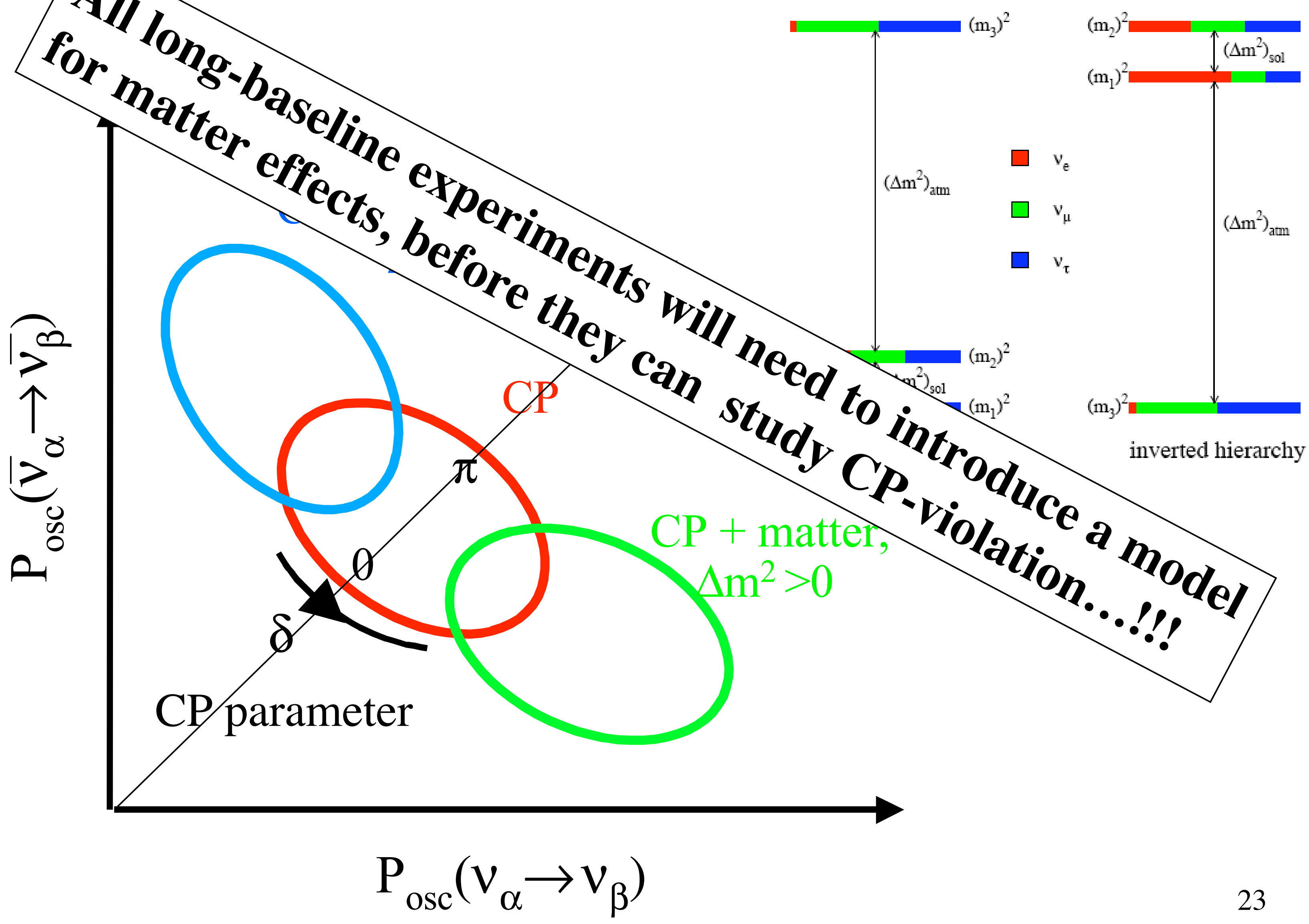
Worse, we actually don't know which direction…





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…!!!



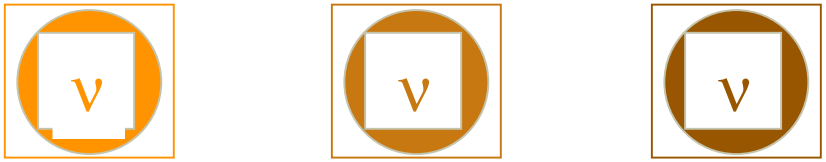
Including matter effects in the formula

(Reduces to the previous formula
for short distances and low energies)

$$a = \frac{G_F N_e}{\sqrt{2}}$$

$$\begin{aligned}
P_{\rm mat} \quad = \quad & \\
& \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)^2}\Delta_{31}^2 \\
& \mp \sin\delta \sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\sin\Delta_{31}\frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21} \\
& + \cos\delta \sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\cos\Delta_{31}\frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21} \\
& + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2. \qquad (2.4)
\end{aligned}$$

YUCK!



What’s the strategy?

There is an obvious path…

$\theta_{13} \rightarrow \delta \rightarrow$ mass hierarchy

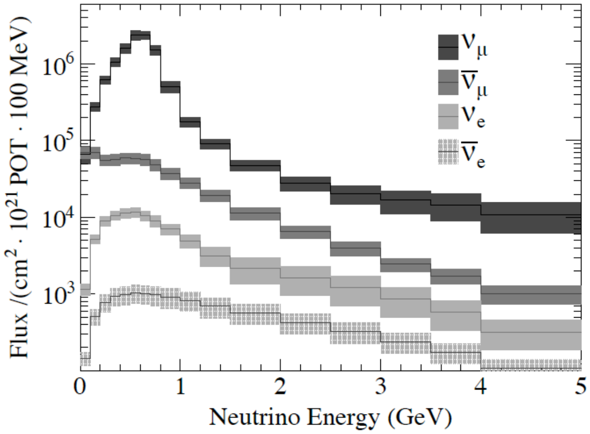
But we are physicists so…

Attack in all directions!

Where we are right now…

This summer, the T2K $\nu_\mu \rightarrow \nu_e$ appearance experiment saw an excess of electron-like events

Uses a 2.5° off-axis beam



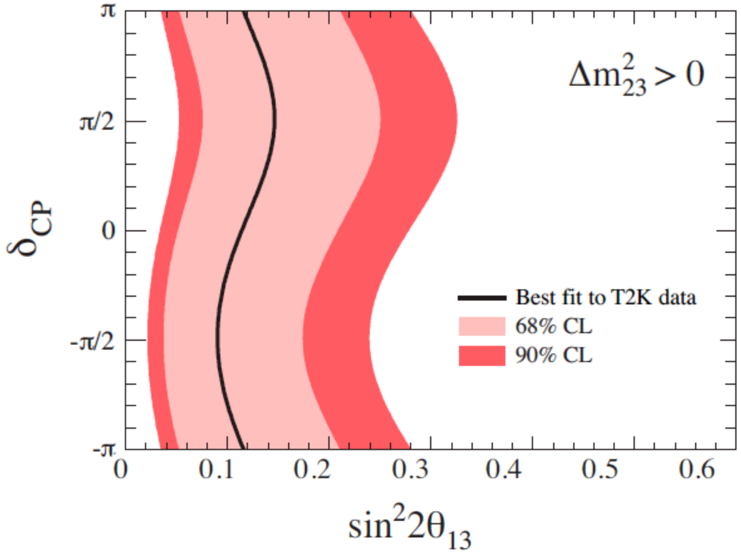
.. and the Super-K detector

In principle, this experiment is sensitive to all 3 parameters but it is at a relatively short distance & low energy for matter effects

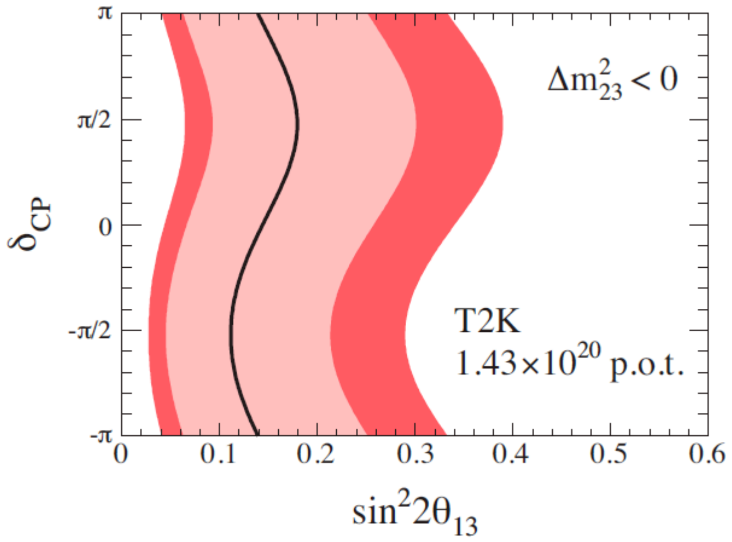
How do you plot 3 unknowns clearly?

-- Better to use 2 plots each showing δ vs $\sin^2 2\theta_{13}$

normal



inverted heirarchies



- Shows θ_{13} is nonzero @ 90% CL for either hierarchy
- No jelly-beans yet -- the δ measurement is not precise enough
- As expected -- little difference between hierarchies

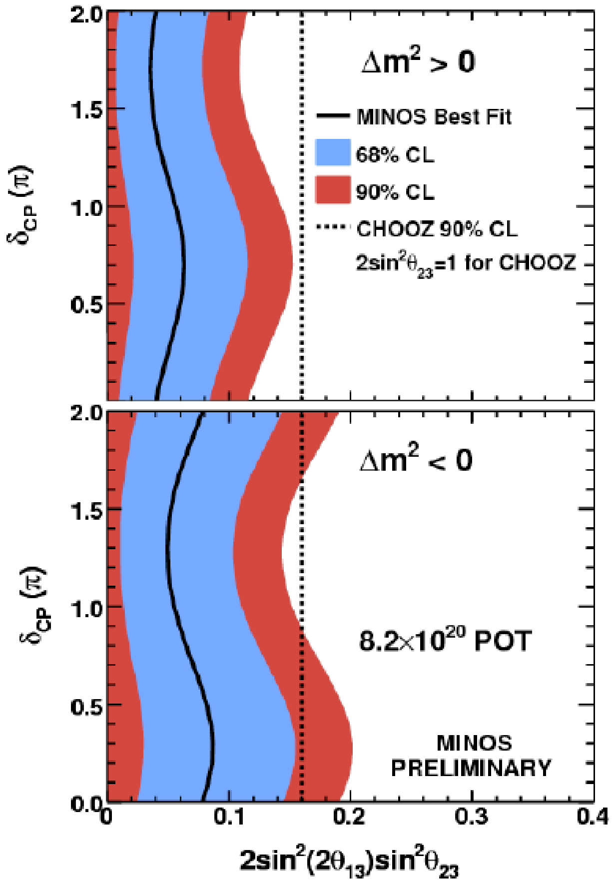
Shortly following T2K, Minos set a limit at 90% CL

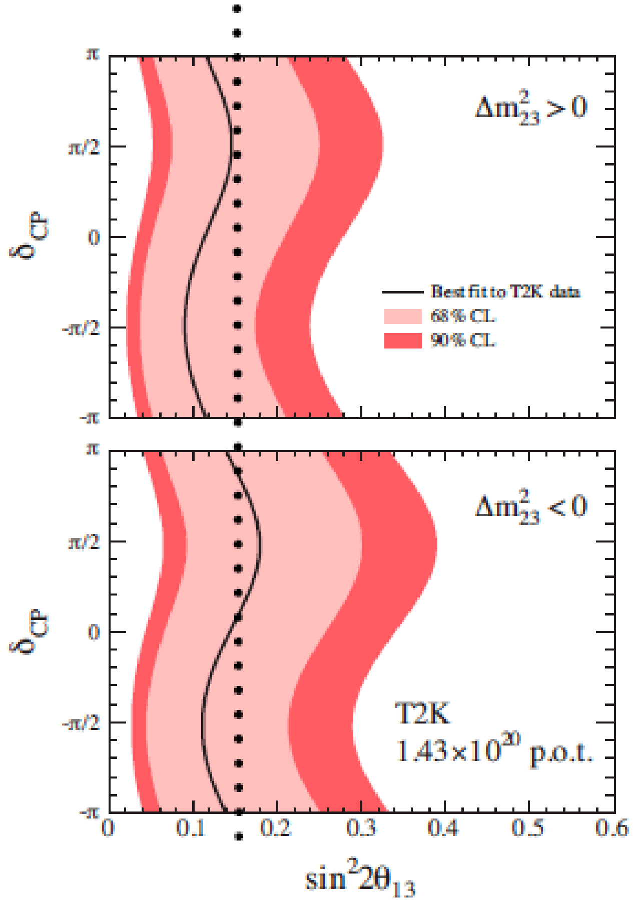
MINOS:

T2K:

long baseline appearance, FNAL to Minnesota, & higher energy beam,

so a bit more hierarchy dependence.





dotted lines is the bound from previous searches

Interesting!

It seems likely that θ_{13} is nonzero.
It is unclear how large it is.

Ready for the next step!

Enter … The Reactor Experiments!

Using $\bar{\nu}_e$ Disappearance

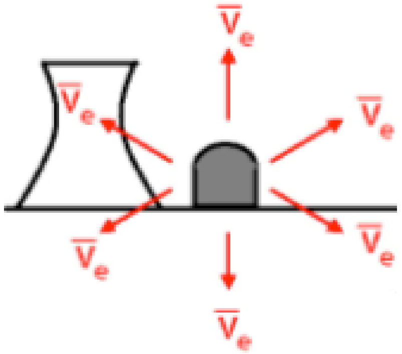
$$P_{reactor} \simeq \sin^2 2\theta_{13} \sin^2\Delta + \alpha^2\,\Delta^2 \cos^4\theta_{13} \sin^2 2\theta_{12},$$

$$\alpha \equiv \Delta m^2_{21}/\Delta m^2_{23}$$

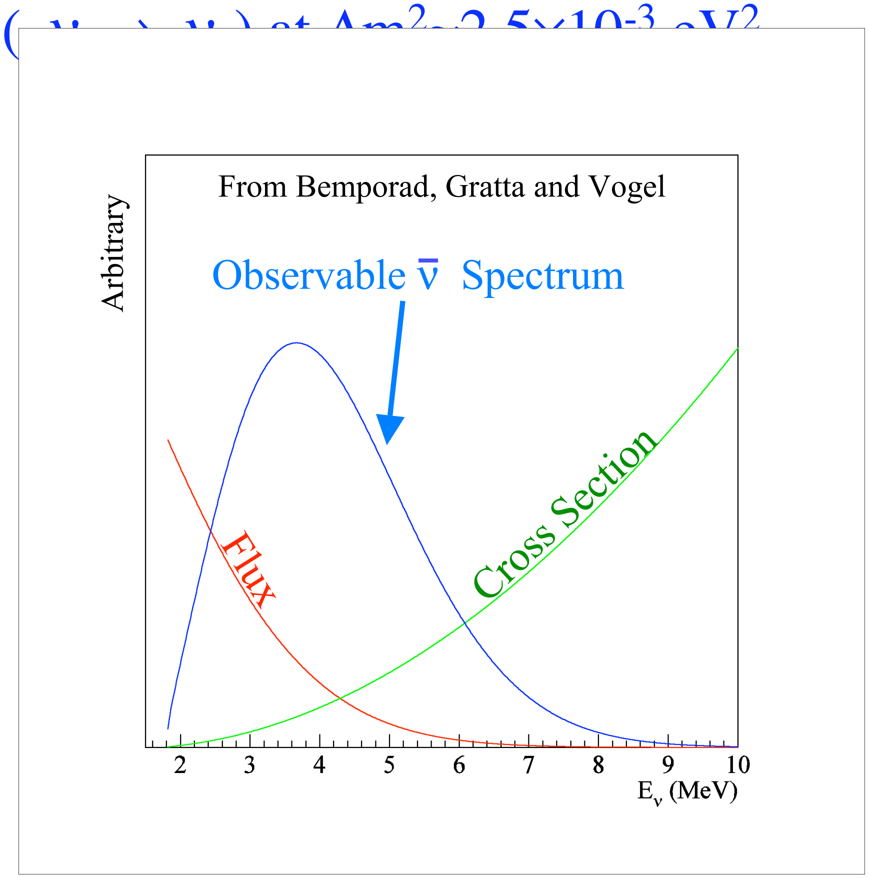
$$\Delta \equiv \Delta m^2_{31} L/(4E_\nu).$$

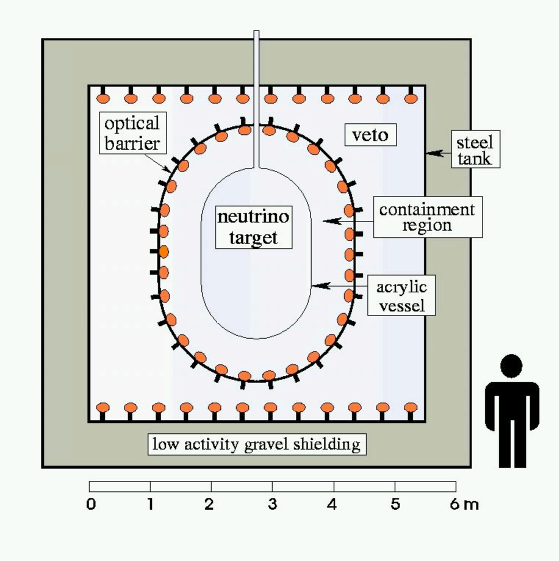
The goal is to discover and measure θ_{13}

Reactors: Disappearance ($\bar{\nu}$ → $\bar{\nu}$) at $\Delta m^2 \sim 2.5\times10^{-3}$ eV^2



for Δm^2 L/E ~ 1
you need L ~ 1000 m





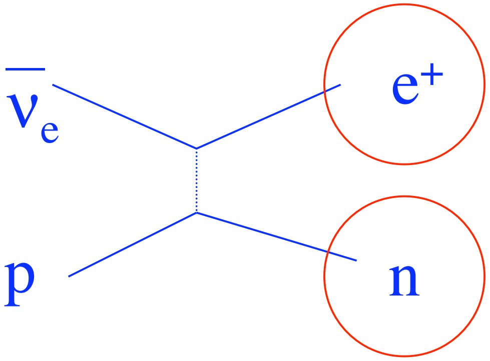
A nice method for observing the $\bar{\nu}$:

$\bar{\nu} + p \rightarrow e^+ + n$ (then n captures)

Use Gd-doped Scintillator oil detectors

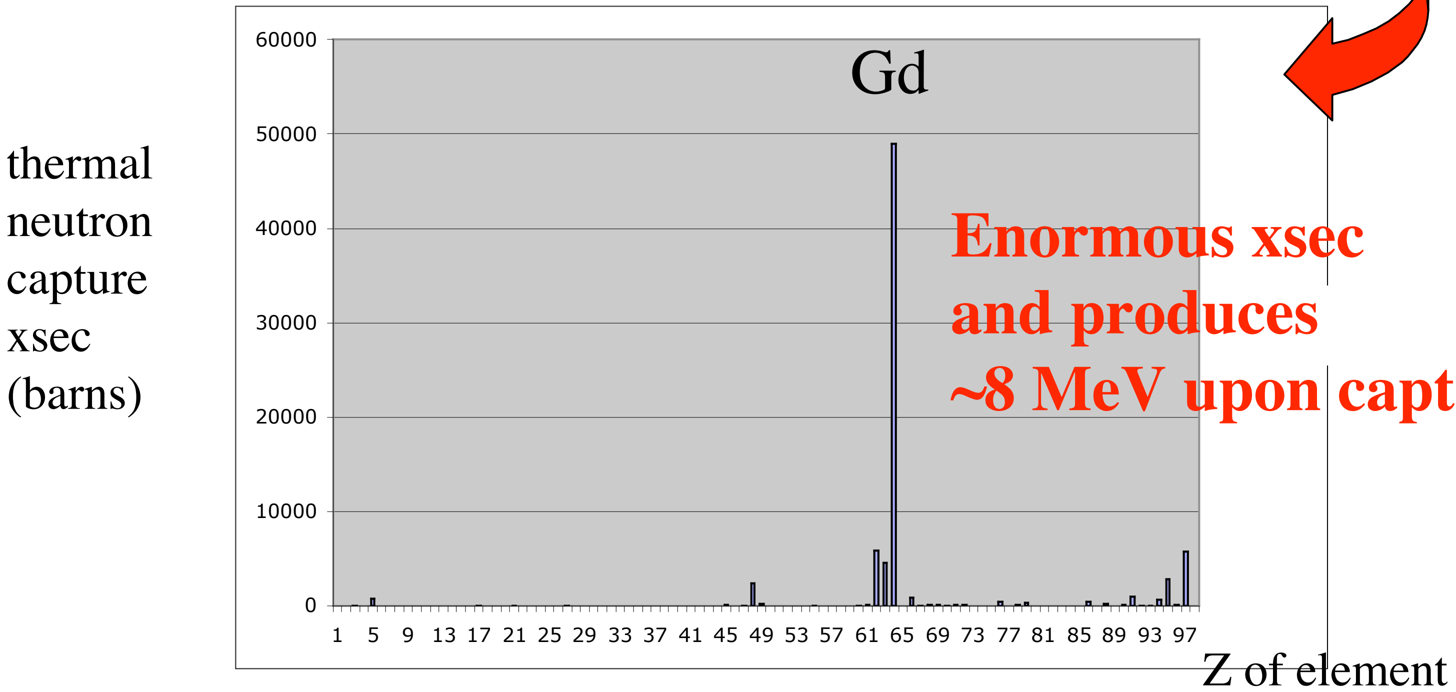
The signal:

inverse beta decay, IBD



1st signal

2nd-- from capture



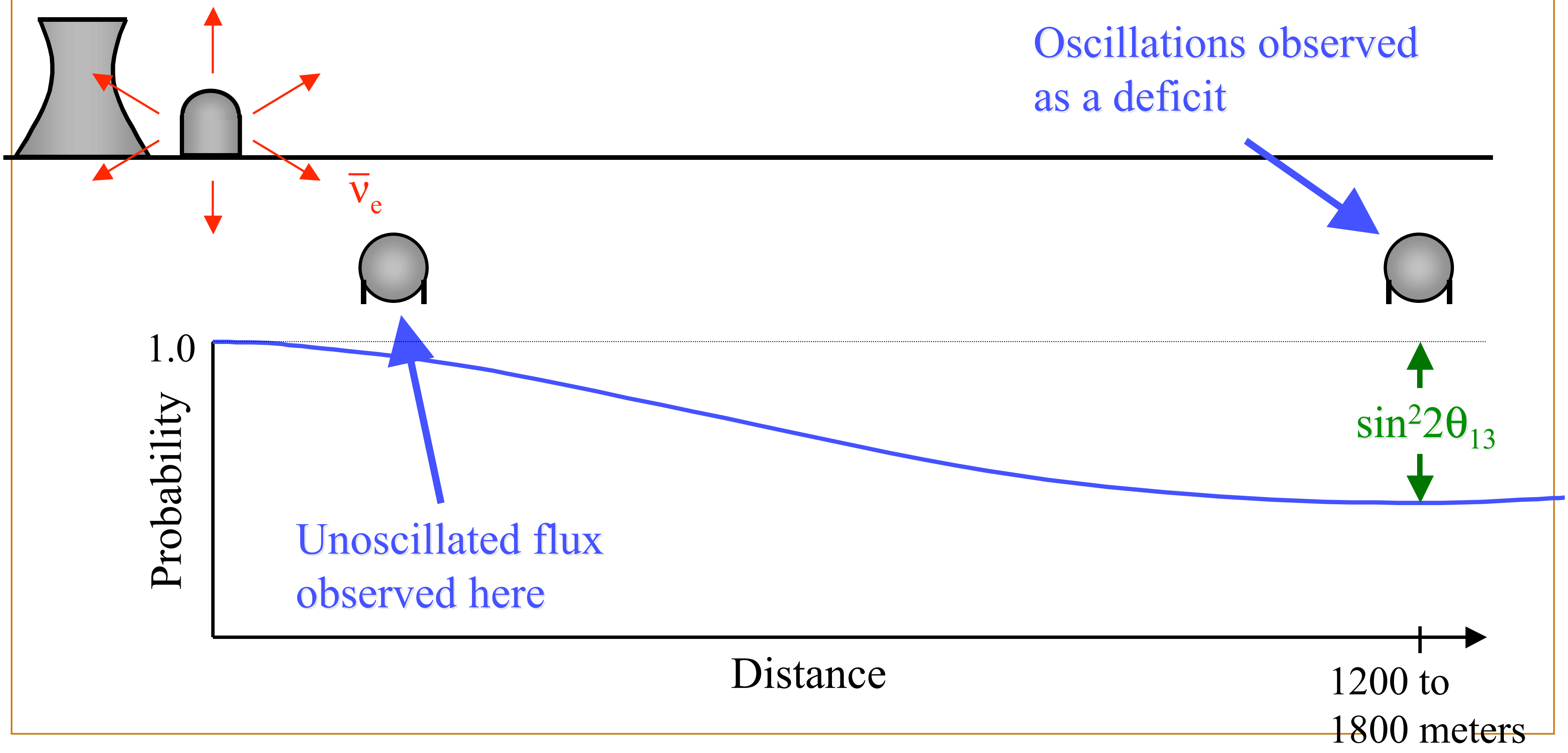
Enormous xsec and produces ~8 MeV upon capture!

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

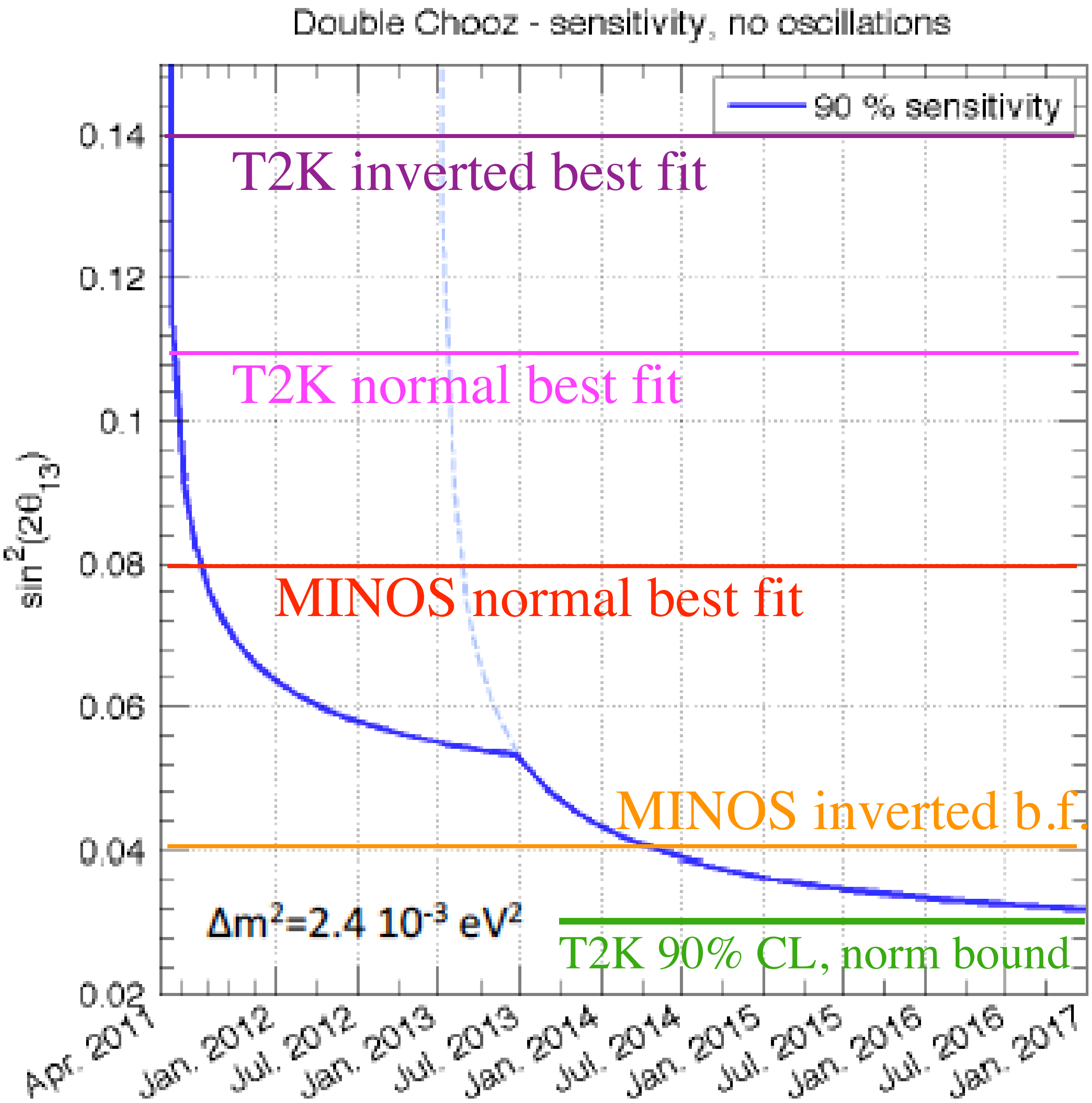
How this new generation improves on past:

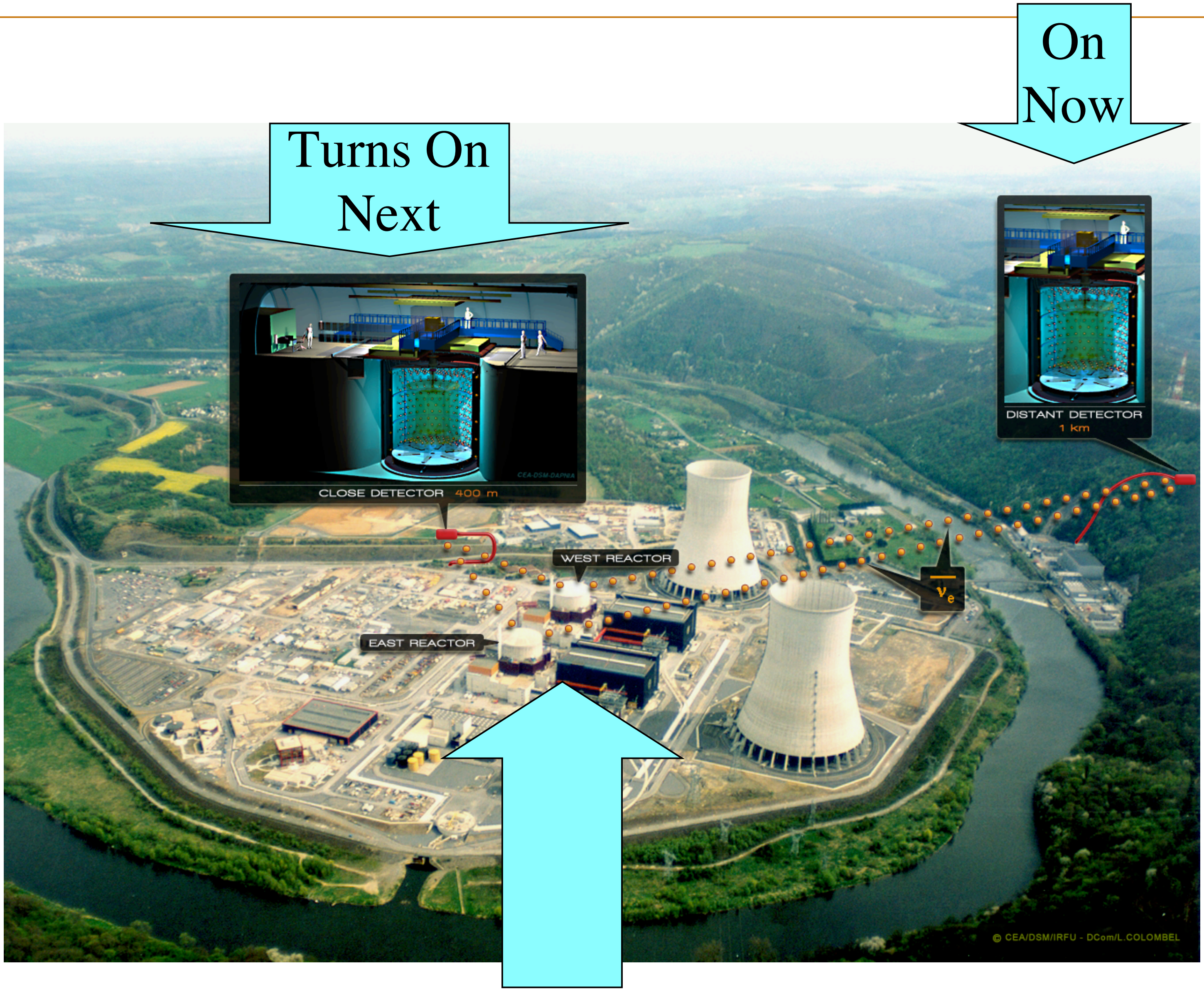
- near and far detectors
- ability to switch detectors
- better shielding from cosmic rays

the art is in control of the systematics



The first reactor experiment to weigh in will be Double Chooz





Turns On Next

On Now

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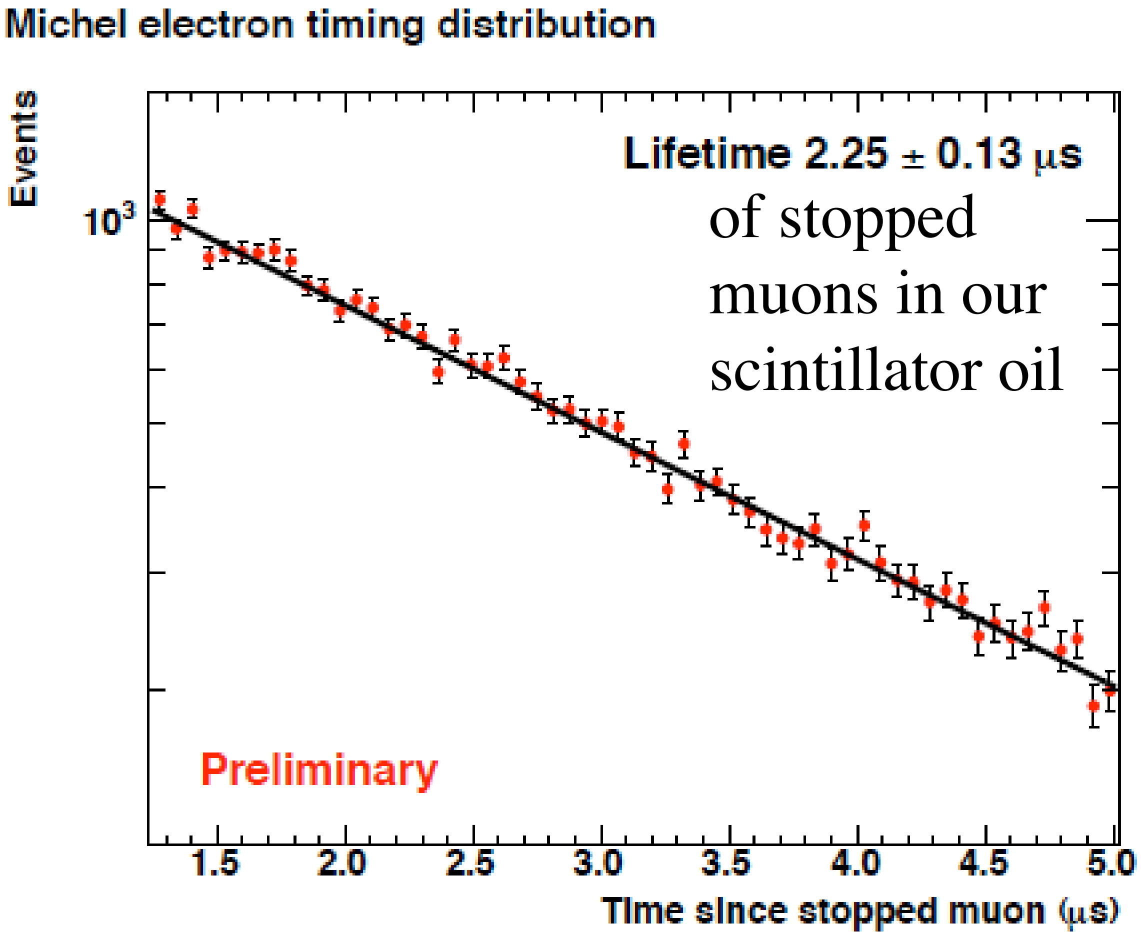
An advantage: having only 2 reactors means there are times when one or both reactors are off (allows background studies)

We are in the process of understanding the detector, busy making plots like this…



of stopped muons in our scintillator oil

We are aiming for results this autumn!

The Race is ON!!!!

✦ = reactor based,
$\bar{\nu}_e$ disappearance

The next 3-5 years
should yield a clear measurement
of θ_{13}!
(and I think we will be glad
for multiple experiments)

if we put disappearance together with appearance

In principle in the next ~ 6-10 years we can also get a $>2\sigma$ measurement of the mass hierarchy

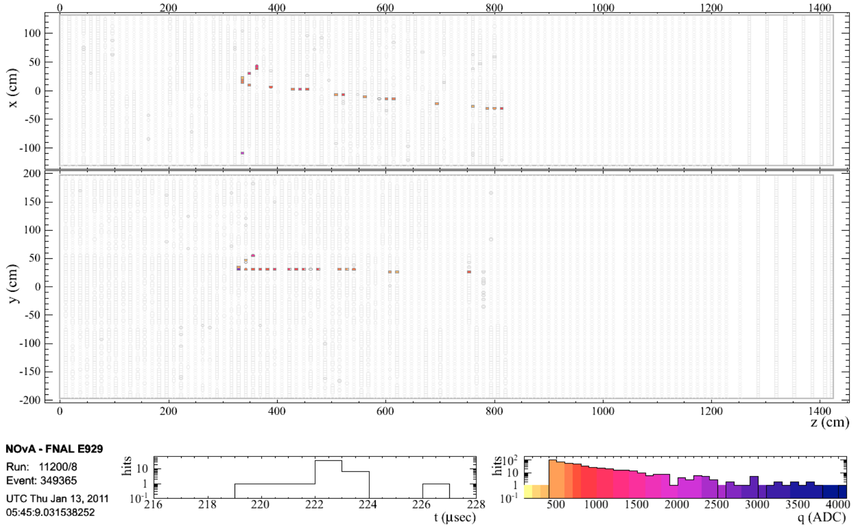
This will come from playing the NOvA Experiment, against the reactor and T2K measurements…

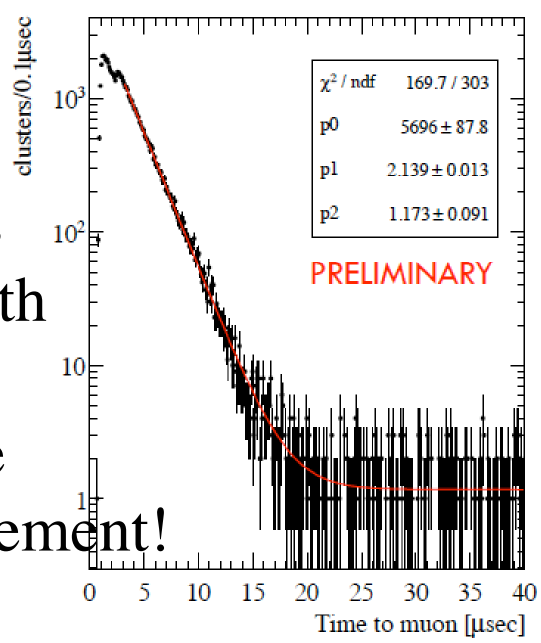
T2K	295 km	smaller effect
Minos	730 km	↕
NOvA	810 km	larger effect

NOvA sends a beam from FNAL to Ash River, Minnesota

The detector will go here.
15 kt of liquid scintillator.

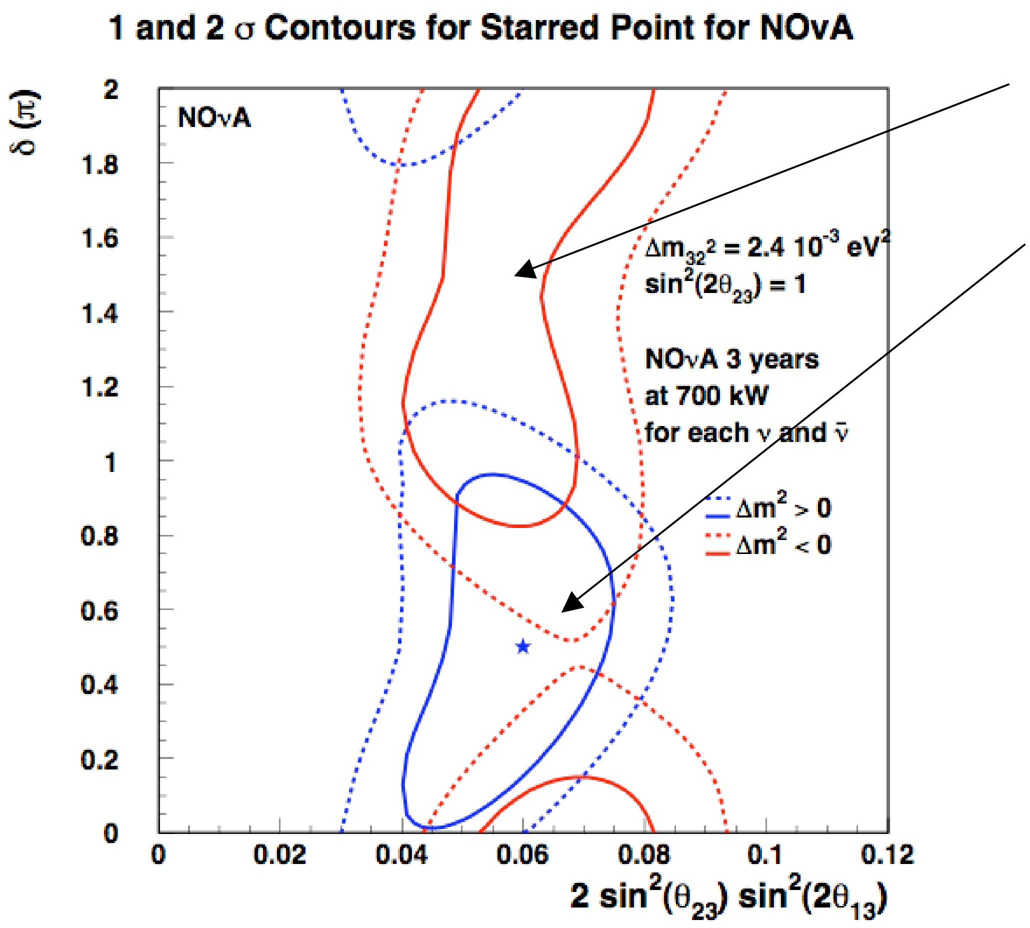
But they already have a near-detector prototype going…





Always start with a muon lifetime measurement!

NOvA Jelly Beans if $\sin^2 2\theta_{13}$=0.06



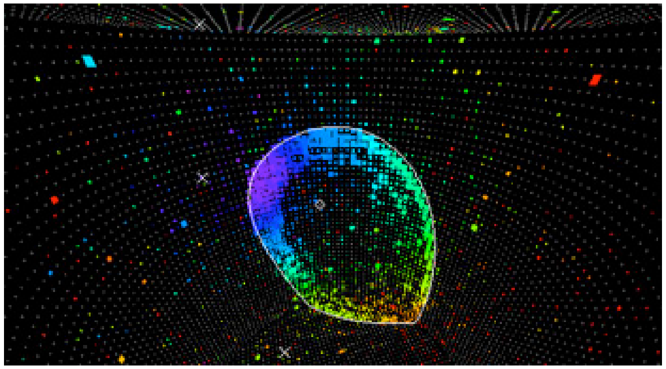
inverted hierarchy
and
normal hierarchy

But you cannot differentiate the two hierarchies!

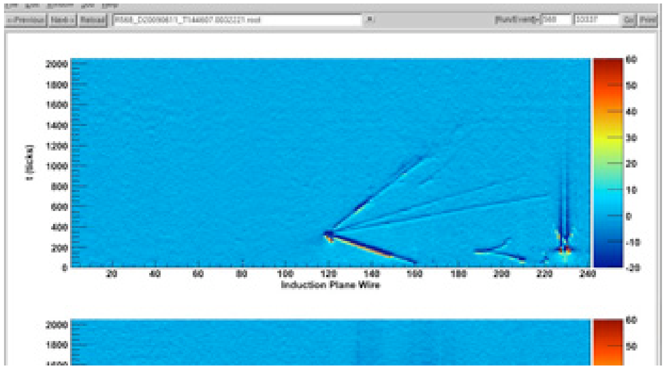
It turns out measuring the hierarchy to >2σ is our hardest problem!

What’s next?

There are many strategies for ultra-large detectors world-wide.
I think we will build “LBNE” in South Dakota (Homestake)



We will most likely have
a water Cerenkov detector,
~100 kt or more

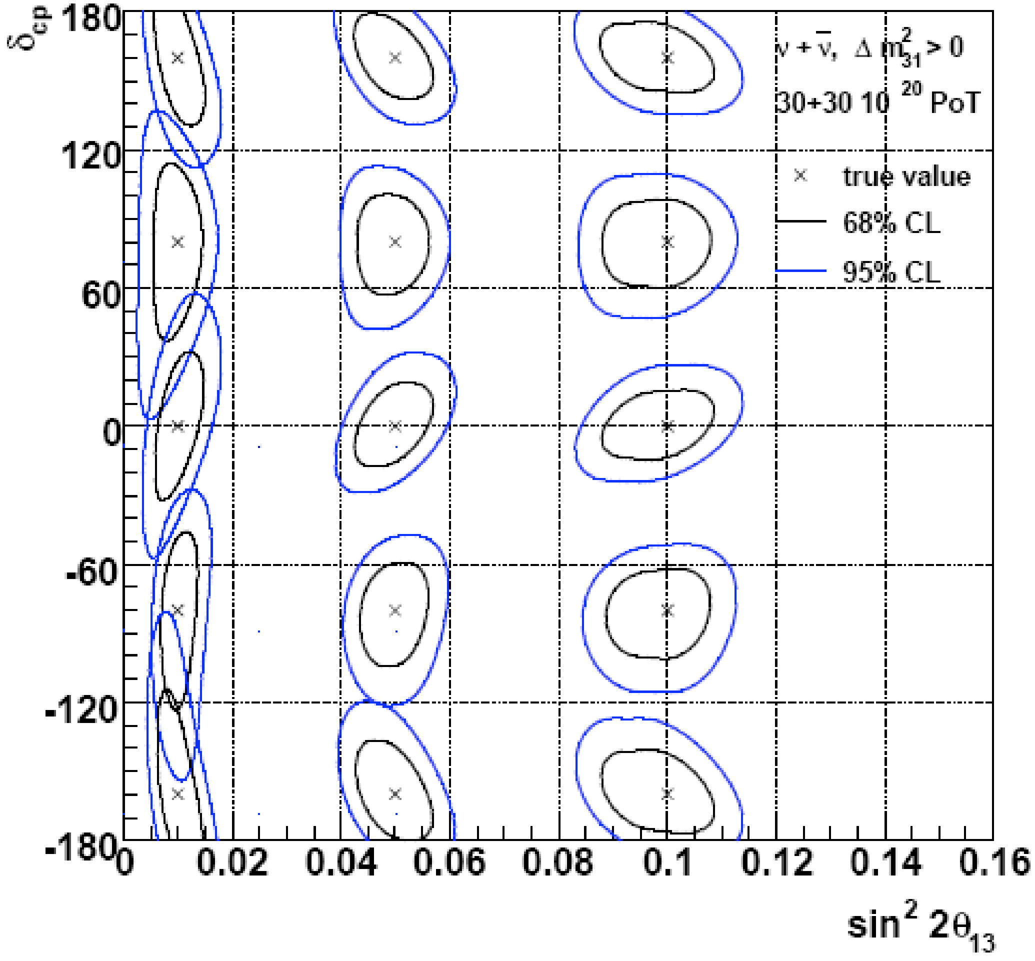


It is possible we will have
an LAr detector too,
but this is more speculative.

Physics Topic	WCD	LAr
$\nu_\mu \rightarrow \nu_e$	**High Discovery Potential** as described in text	**High Discovery Potential** as described in text
ν_μ disappearance $(\nu/\bar{\nu})$	$\delta(\Delta m^2) : \pm 0.013/0.015$ $\delta(\sin^2 2\theta_{23}) : \pm 0.005/0.007$	$\delta(\Delta m^2) : \pm 0.016/0.025$ $\delta(\sin^2 2\theta_{23}) : \pm 0.006/0.009$
Proton Decay	$P \rightarrow e^+\pi^0$ search: $\sim 6 \times 10^{34}$ years $P \rightarrow K^+\bar{\nu}$ search: $\sim 1 \times 10^{35}$ years w/ scint. upgrade	$P \rightarrow K^+\bar{\nu}$ search: $\sim 3 \times 10^{34}$ years w/o photodetectors $\sim 4 \times 10^{34}$ years w/ photodetector coverage
Supernova Burst at 10 kpc	$\sim 30,000$ evts (primarily $\bar{\nu}$)	$\sim$3000 evts (primarly ν) w/ photodetector coverage
Tagged SN Burst	IBD-tagged evts w/ Gd Upgrade	
Supernova Relic Neutrinos	9 to 50 evts/year w/ 40 bkgd $\times 2$ coverage + Gd Upgrade	
Solar Day/Night	0.5% on A_{DN} w/ $\times 2$ coverage Upgrade	
DAEδALUS	Increased δ_{CP} Discovery Potential Cyclotrons $+ \times 2$ coverage + Gd Upgrade	
Geoneutrinos	>3000 evts/year w/ Scint + coverage upgrade	
Technology Transfer	Improved Photomultiplier Tubes Water-based Gd for neutron dets. Large-Area Fast Photosensors	LAr Technology

Color coding: Purple – under research (no large scale prototypes of needed technology)
Blue – under development (large scale prototypes of technology are running)
Black – Established Technology

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

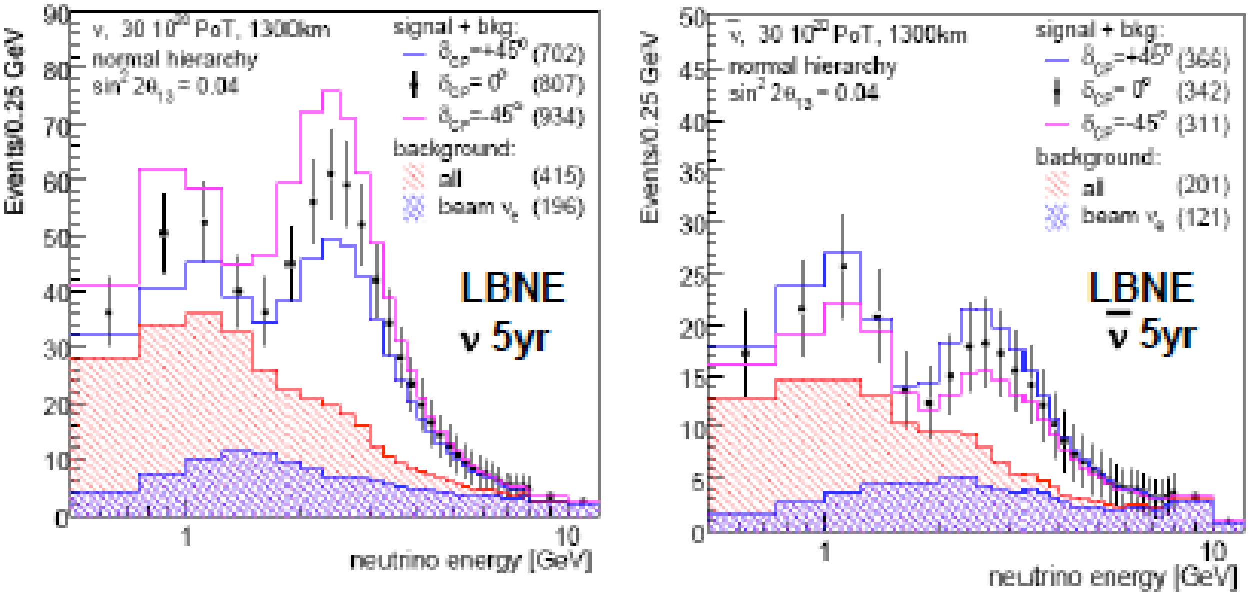


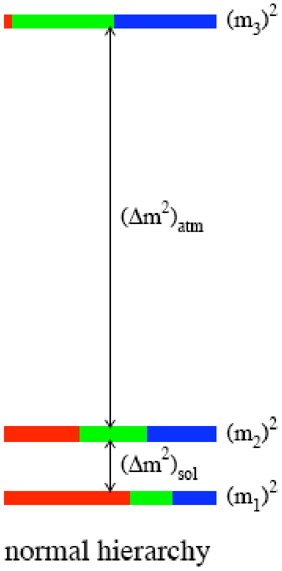
(Water
Cerenkov)

But there are problems…

Long Baseline experiments are usually low in antineutrino statistics

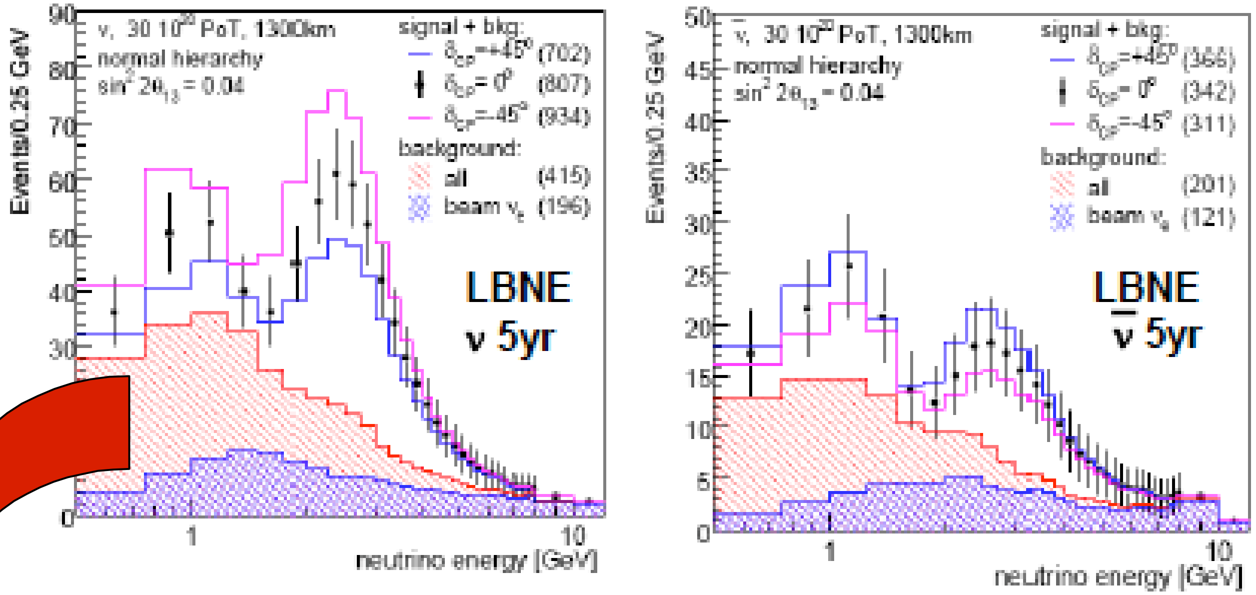
→ a combination of style of beam and cross section





… and the backgrounds are larger compared to signal

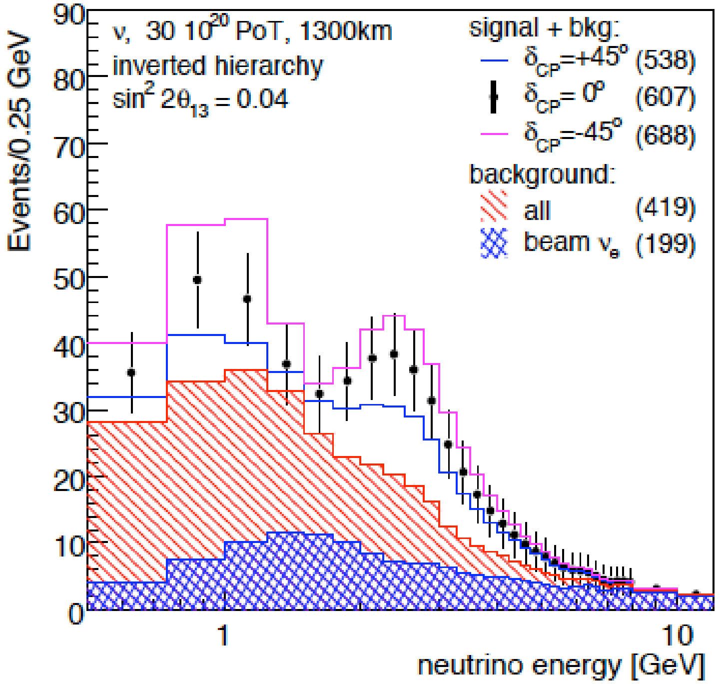
Where do these backgrounds come from?

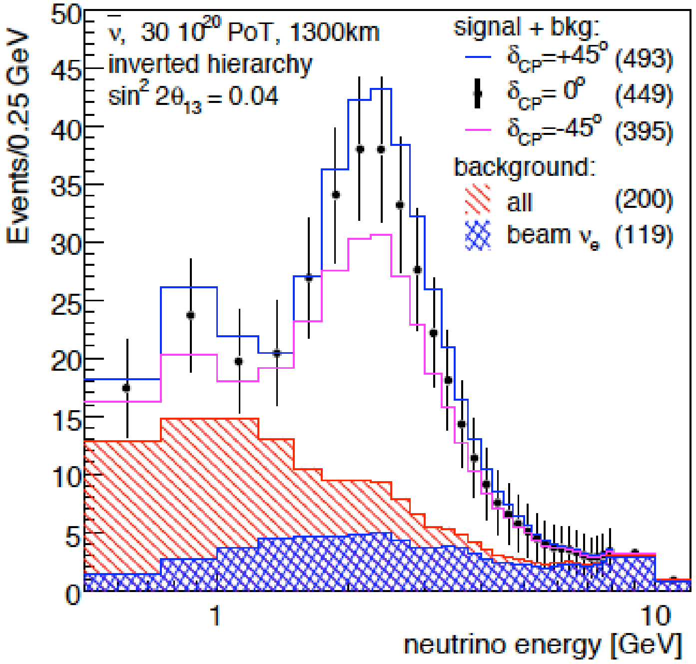


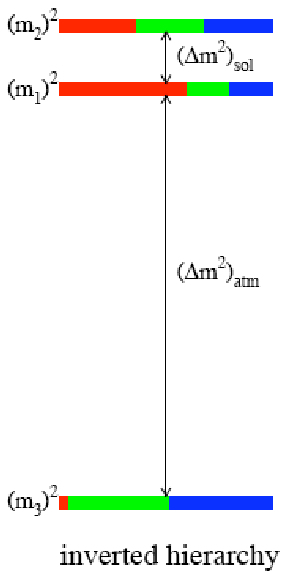
Mis-ID -- mostly π^0 events where you lose evidence of one photon

Intrinsic ν_e -- from the m and K decays in the beamline

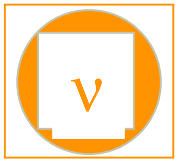
Expectation for inverted hierarchy:

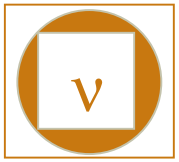


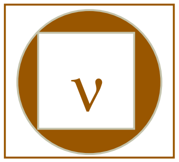




Understanding the shape of the background is crucial to differentiating the hierarchy…

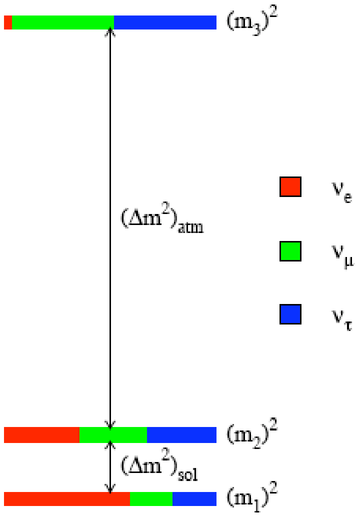






What might be an alternative approach?

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



Lets go back to the appearance probability…

in a vacuum…

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

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 $\bar{\nu}_\mu \to \bar{\nu}_e$
and use the L/E dependence to extract δ

in a vacuum…

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

We want to see
if δ is nonzero

terms depending on
mixing angles

terms depending on
mass splittings

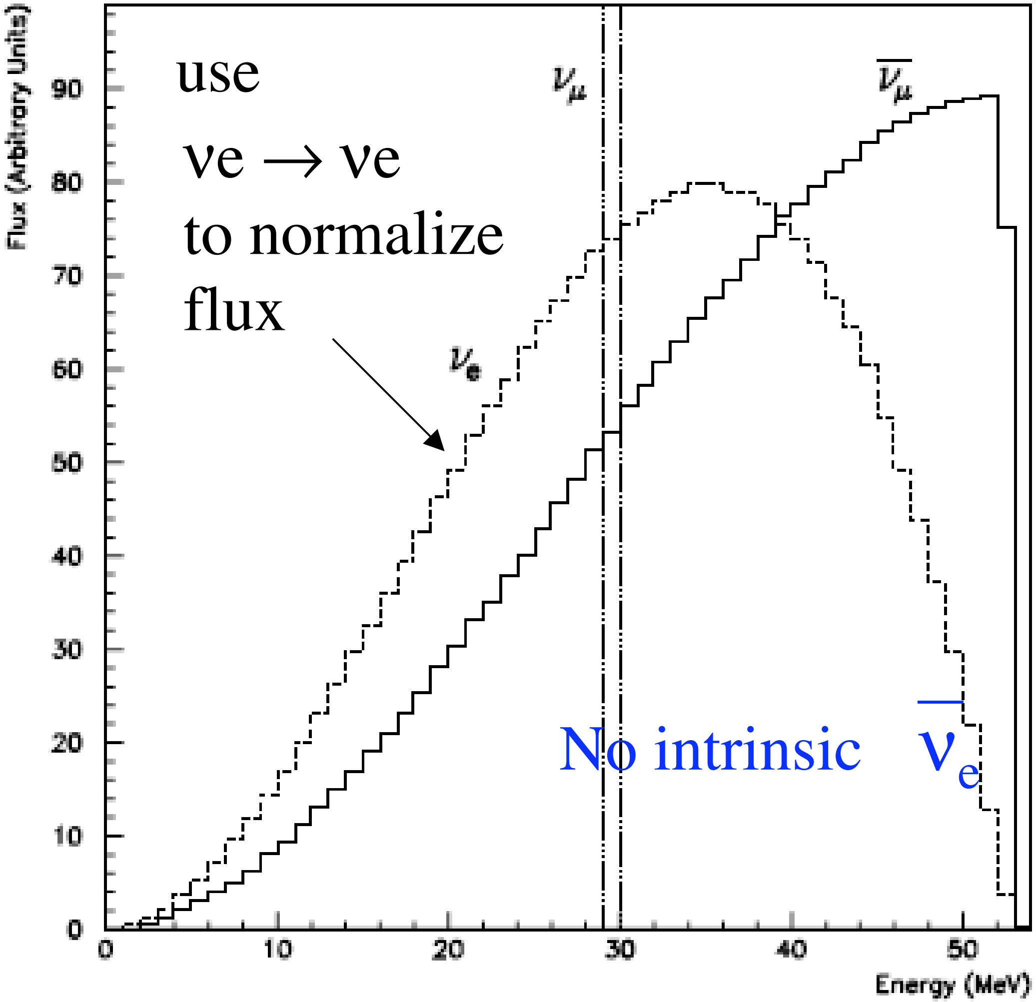
$$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$

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



use

$\nu e \rightarrow \nu e$

to normalize

flux

No intrinsic $\overline{\nu}_e$

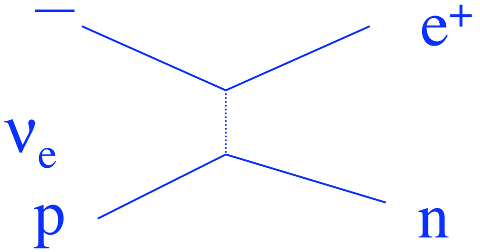
Perfect for a

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

search

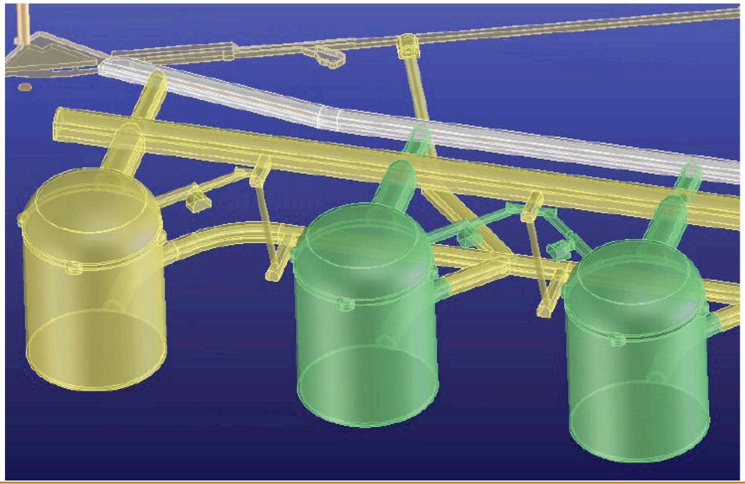
How do you observe ~50 MeV $\bar{\nu}_e$ events?

The signal:
inverse beta decay, IBD



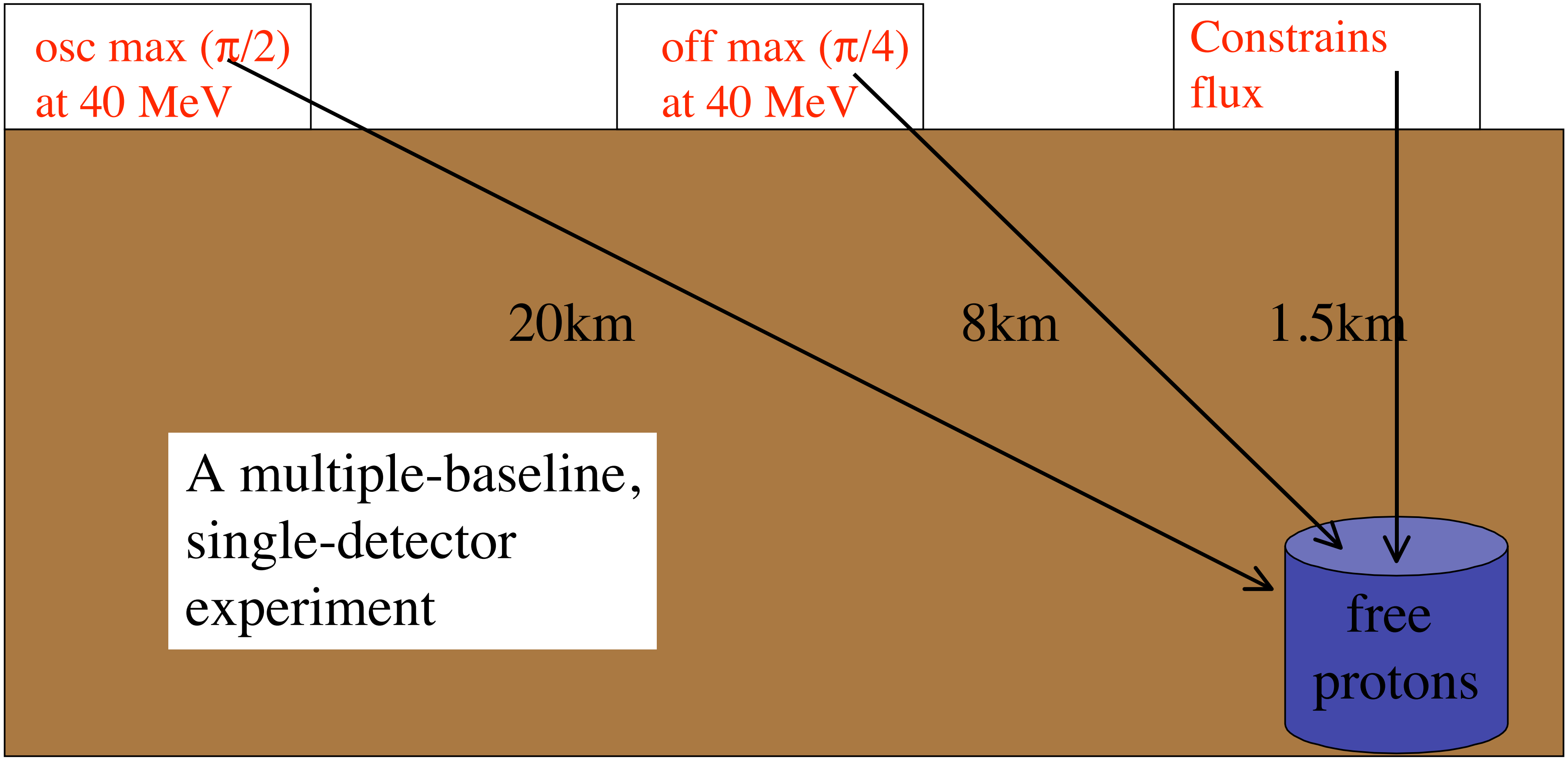
$$\bar{\nu}_e + p \to e^+ + n$$

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



Use the same ultra-large detector system as the long baseline

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



osc max (π/2)
at 40 MeV

off max (π/4)
at 40 MeV

Constrains
flux

20km

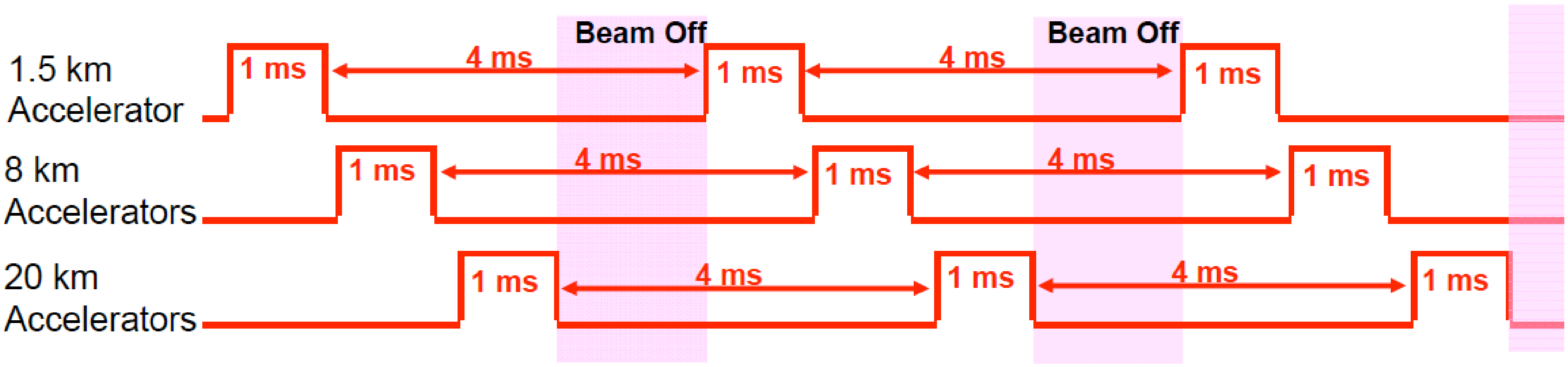
8km

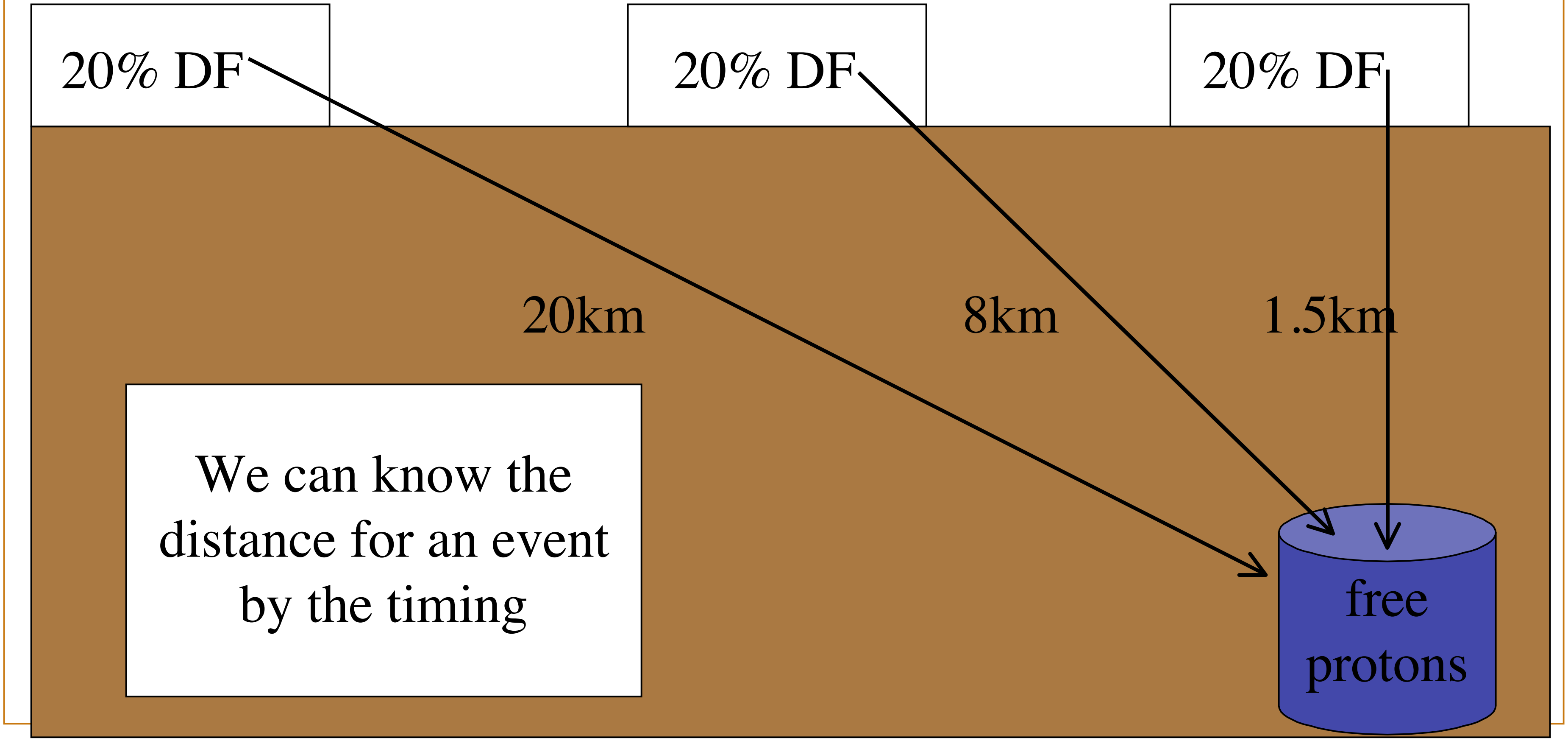
1.5km

A multiple-baseline,
single-detector
experiment

free
protons

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





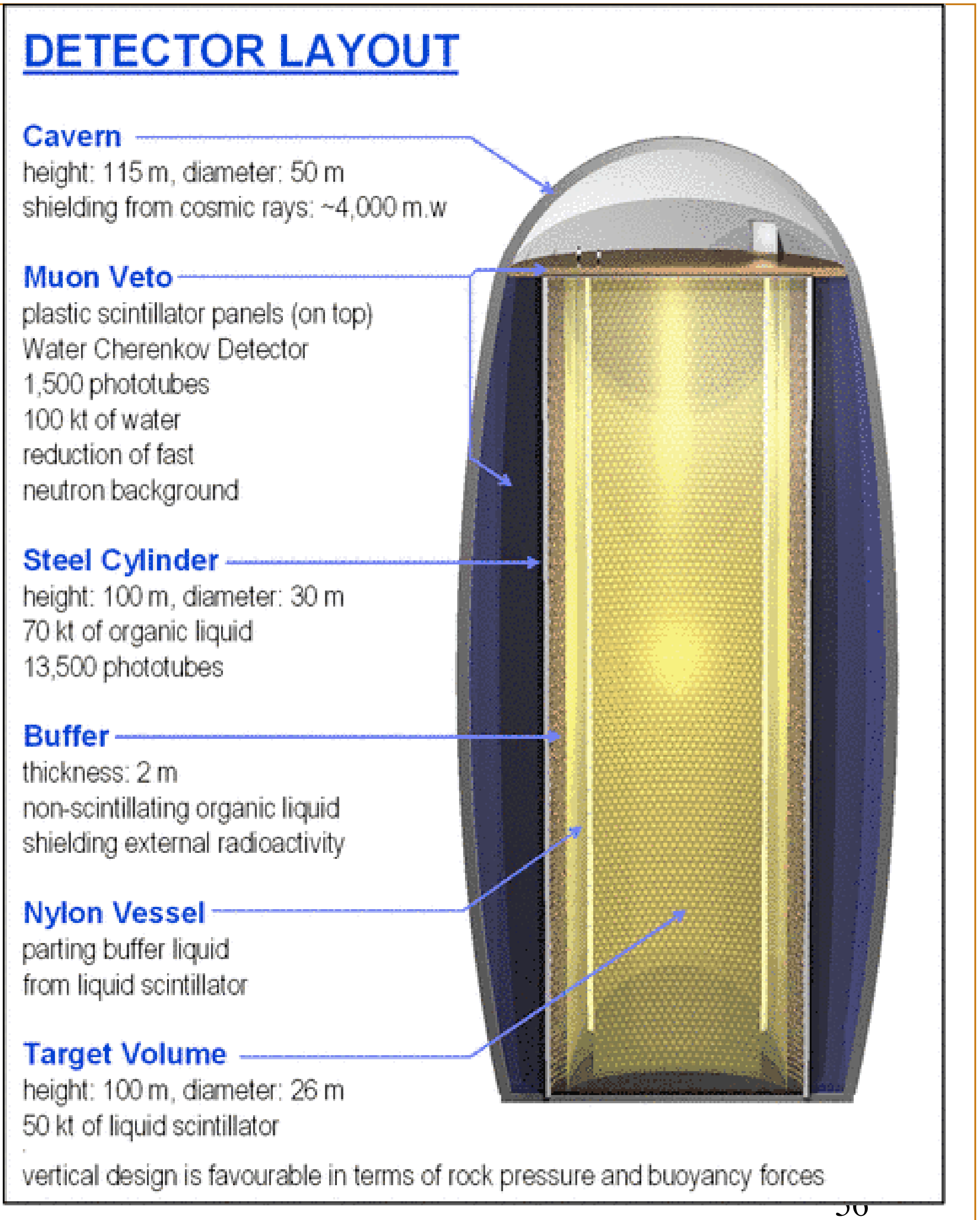
We can know the distance for an event by the timing

SITE OPTIONS:

Large water detectors:
LBNE
MEMPHYS
Hyper-K

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

A new paper LENA
paper that includes
DAEδALUS is coming
at the end of April!



DETECTOR LAYOUT

Cavern
height: 115 m, diameter: 50 m
shielding from cosmic rays: ~4,000 m.w

Muon Veto
plastic scintillator panels (on top)
Water Cherenkov Detector
1,500 phototubes
100 kt of water
reduction of fast
neutron background

Steel Cylinder
height: 100 m, diameter: 30 m
70 kt of organic liquid
13,500 phototubes

Buffer
thickness: 2 m
non-scintillating organic liquid
shielding external radioactivity

Nylon Vessel
parting buffer liquid
from liquid scintillator

Target Volume
height: 100 m, diameter: 26 m
50 kt of liquid scintillator

vertical design is favourable in terms of rock pressure and buoyancy forces

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 H_2O, Gd-doped detector at Homestake for both LBNE & DAEδALUS.

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

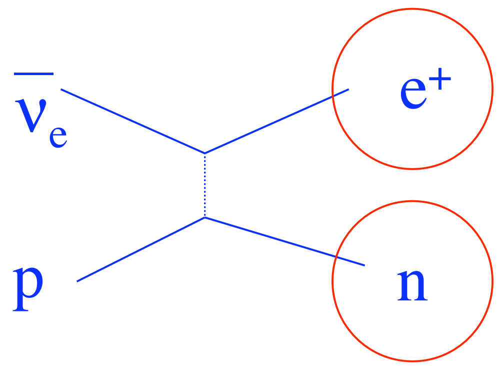
I will point out some distinctions between oil and water.

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

Just as in the case of the reactors…

The signal:

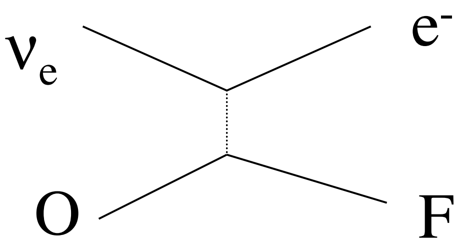
inverse beta decay, IBD



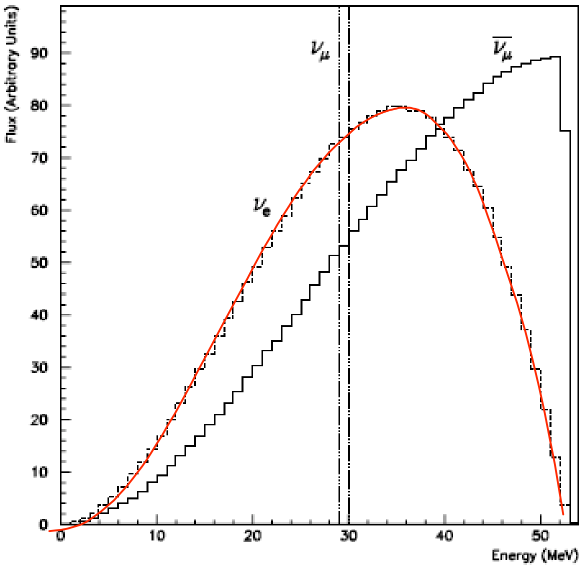
1st signal

2nd-- from capture

We need to reject:



Lower xsec than IBD by ×10 because of binding



But even if the xsec is small…

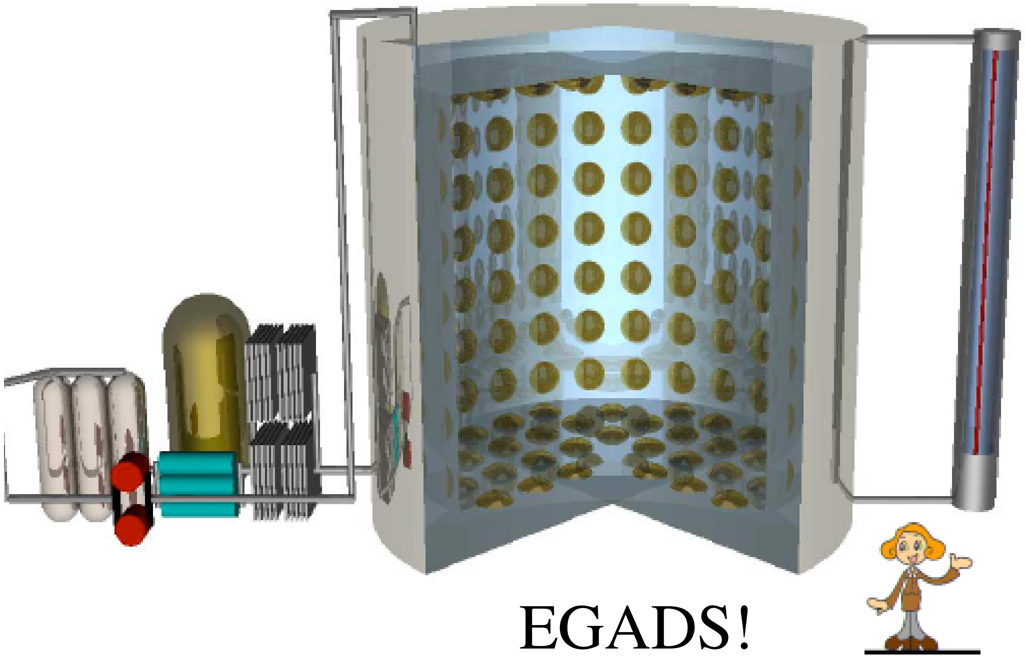
there are a lot of ν_es in the beam!

For the water design
enhance the signal from n-capture, add gadolinium!

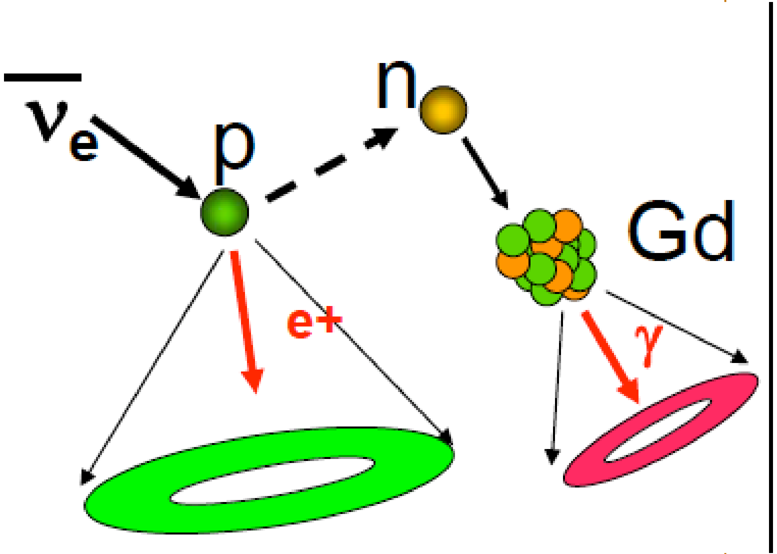
Adding Gd to water is technically difficult

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

Oil does not need Gd



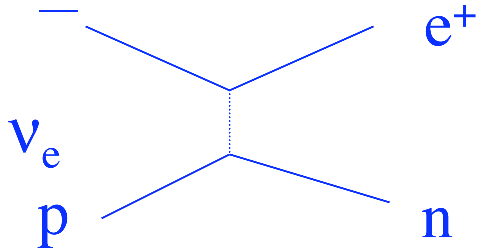
EGADS!



Energy Dependence of IBD events

The signal:

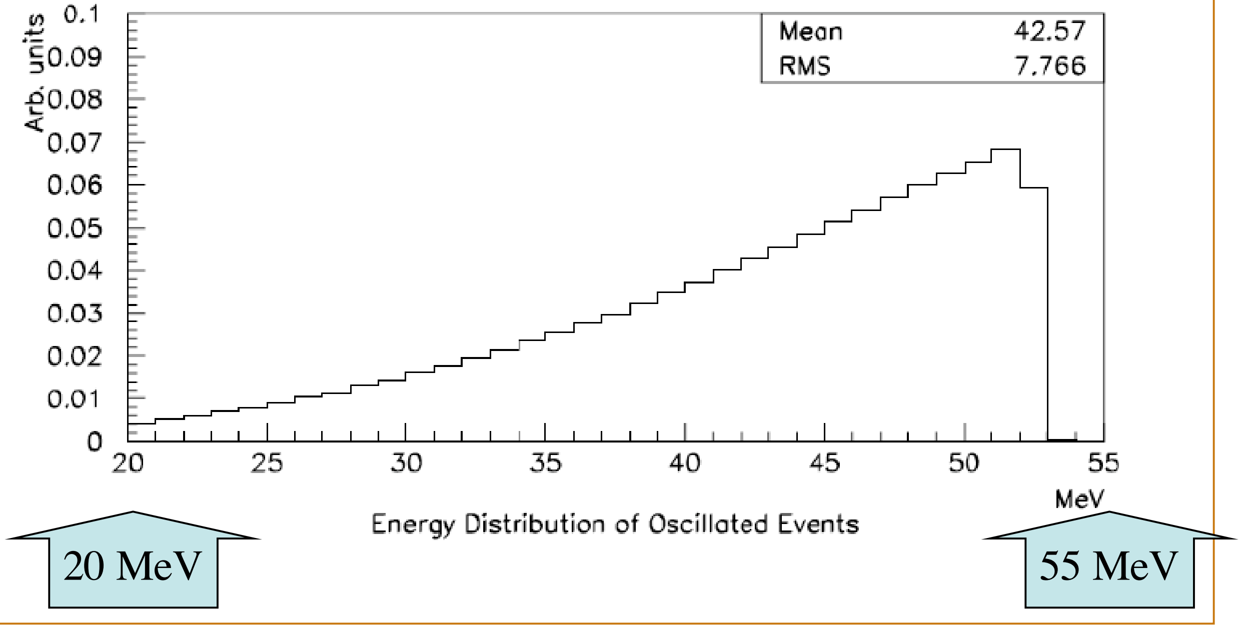
inverse beta decay, IBD



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

Event range is

$20 < E_\nu < 55$ MeV

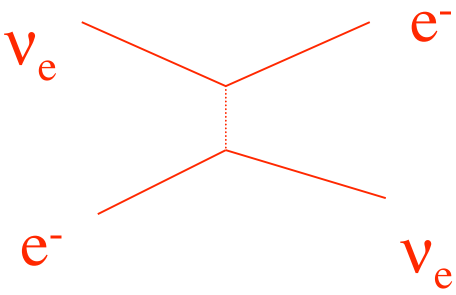


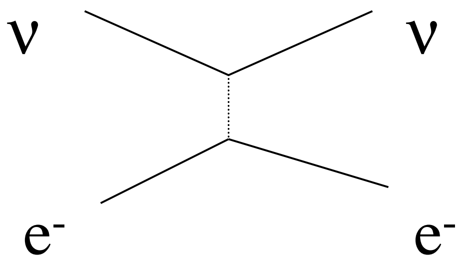
Energy Distribution of Oscillated Events

20 MeV

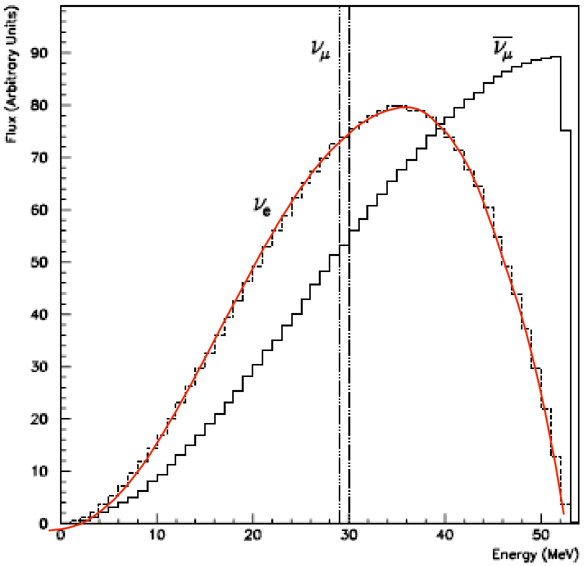
55 MeV

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:

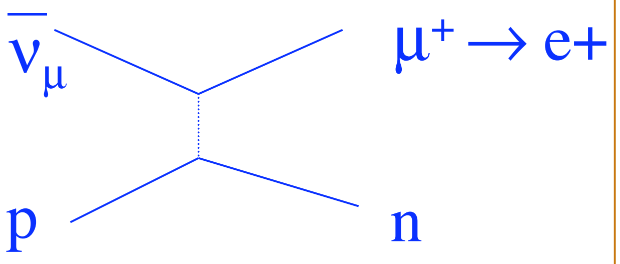
Using **near accelerator**
measure **absolute flux normalization** with ν-e events to ~1%,
Also, measure the ν_eO event rate.

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** $\bar{\nu}_\mu \to \bar{\nu}_e$ **signal**
with free parameters: $\boldsymbol{\theta_{13}}$ **and** $\boldsymbol{\delta}$

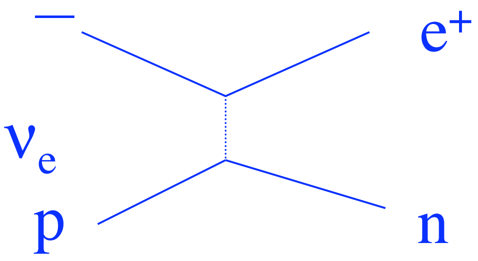
Non-beam backgrounds

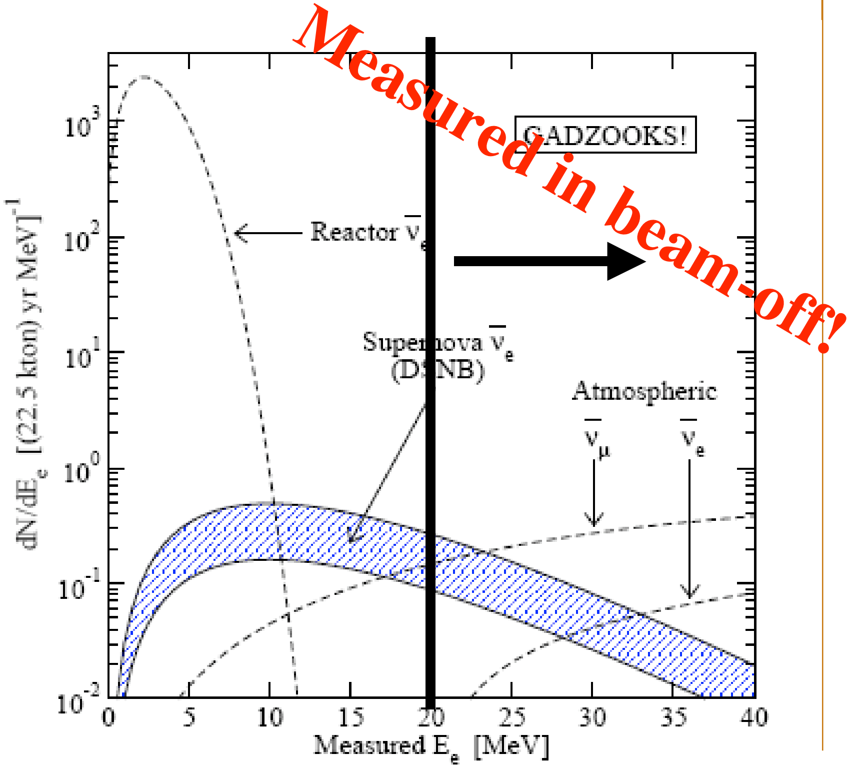
- Atmospheric $\bar{\nu}_\mu$ "Invisible muons":
  $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ where
  μ^+ is below Cherenkov threshold,
  stops and decays. ONLY IN WATER



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

- Diffuse supernova neutrinos





Measured in beam-off!

Beam-related Background

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

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

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

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

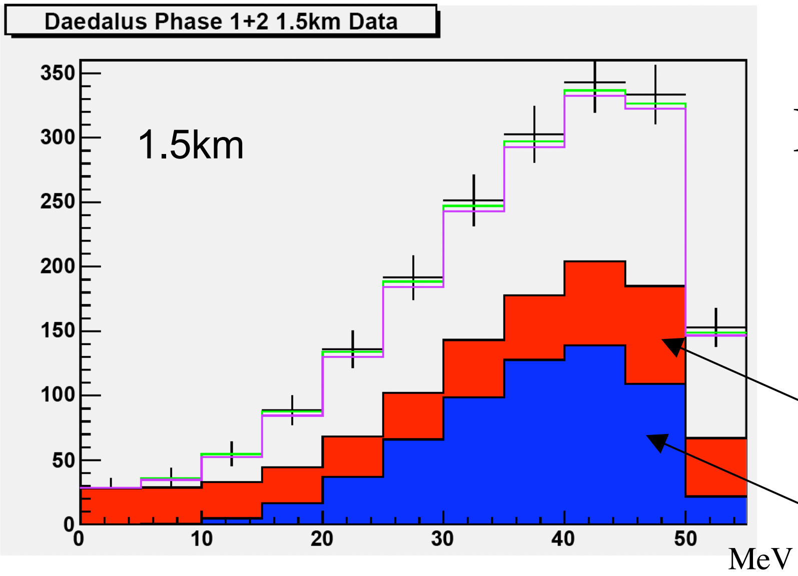
- ν_e-Oxygen CC scatters producing an electron+ n signal

  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

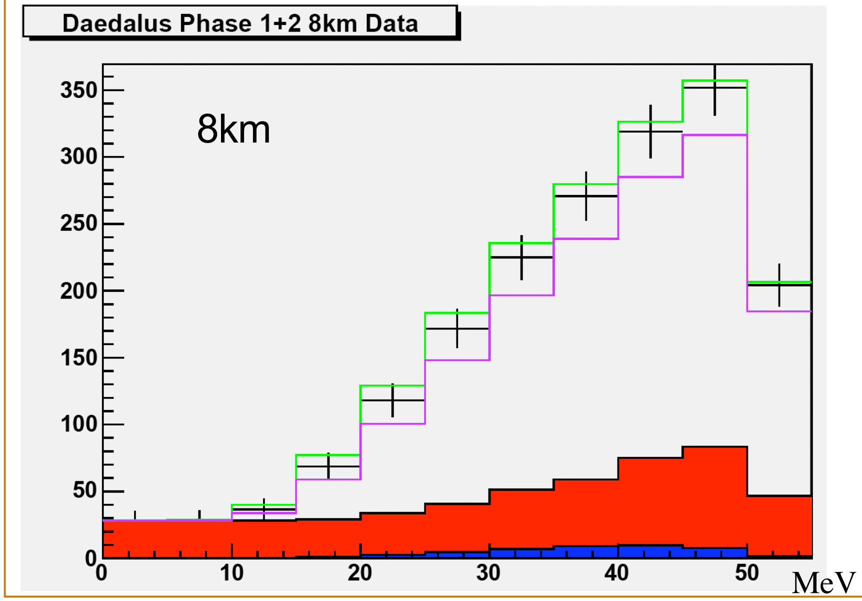
Daedalus Event Energy Distributions (Signal & Background)

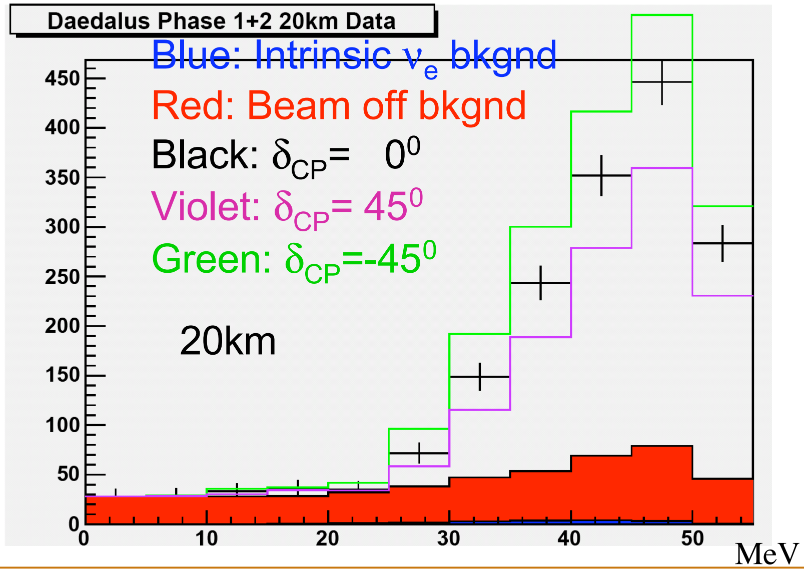
$(\sin^2 2\theta_{13} = 0.04)$



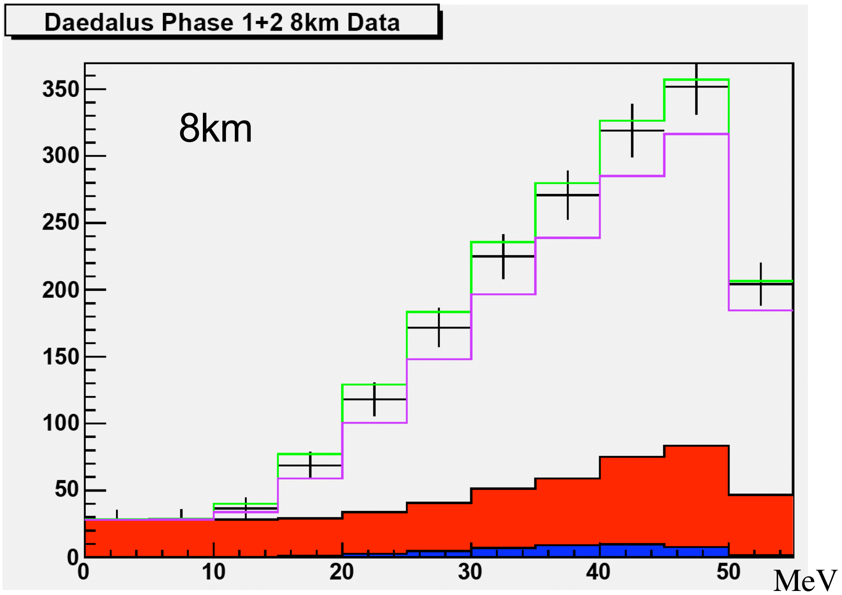
beam off

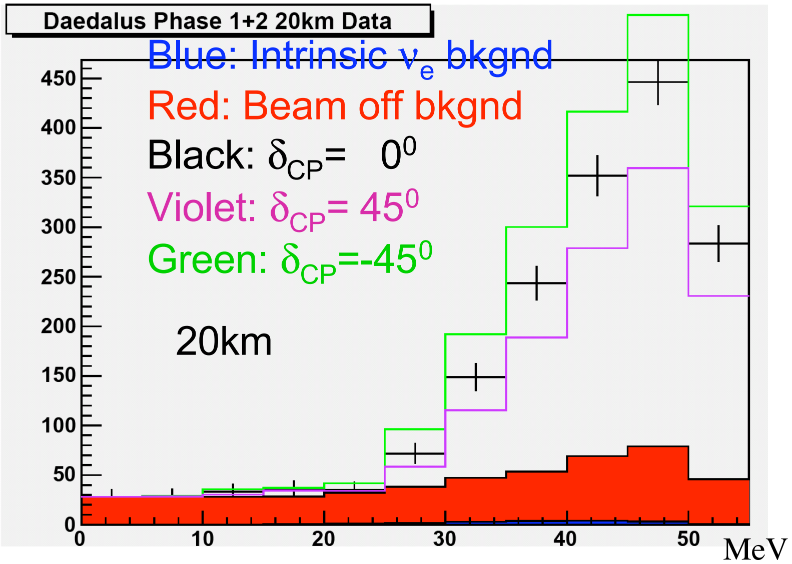
beam on



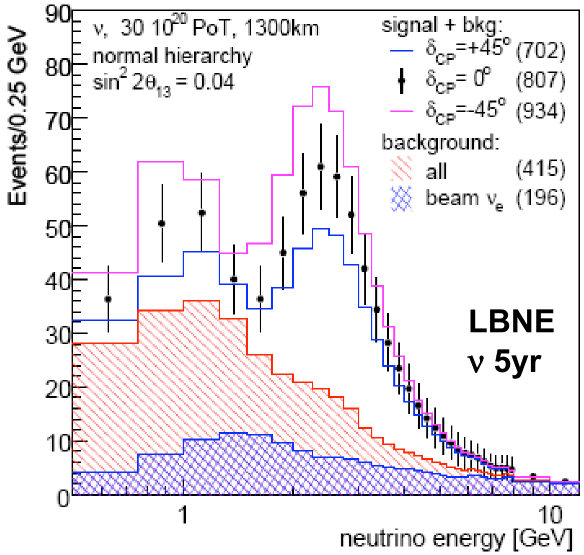


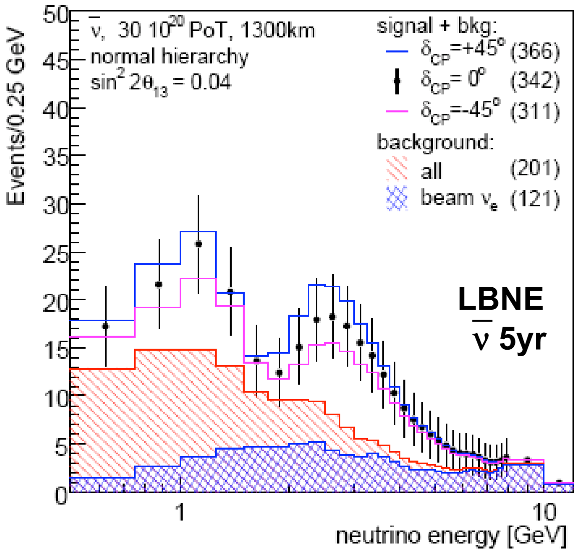
Compare signal to-background



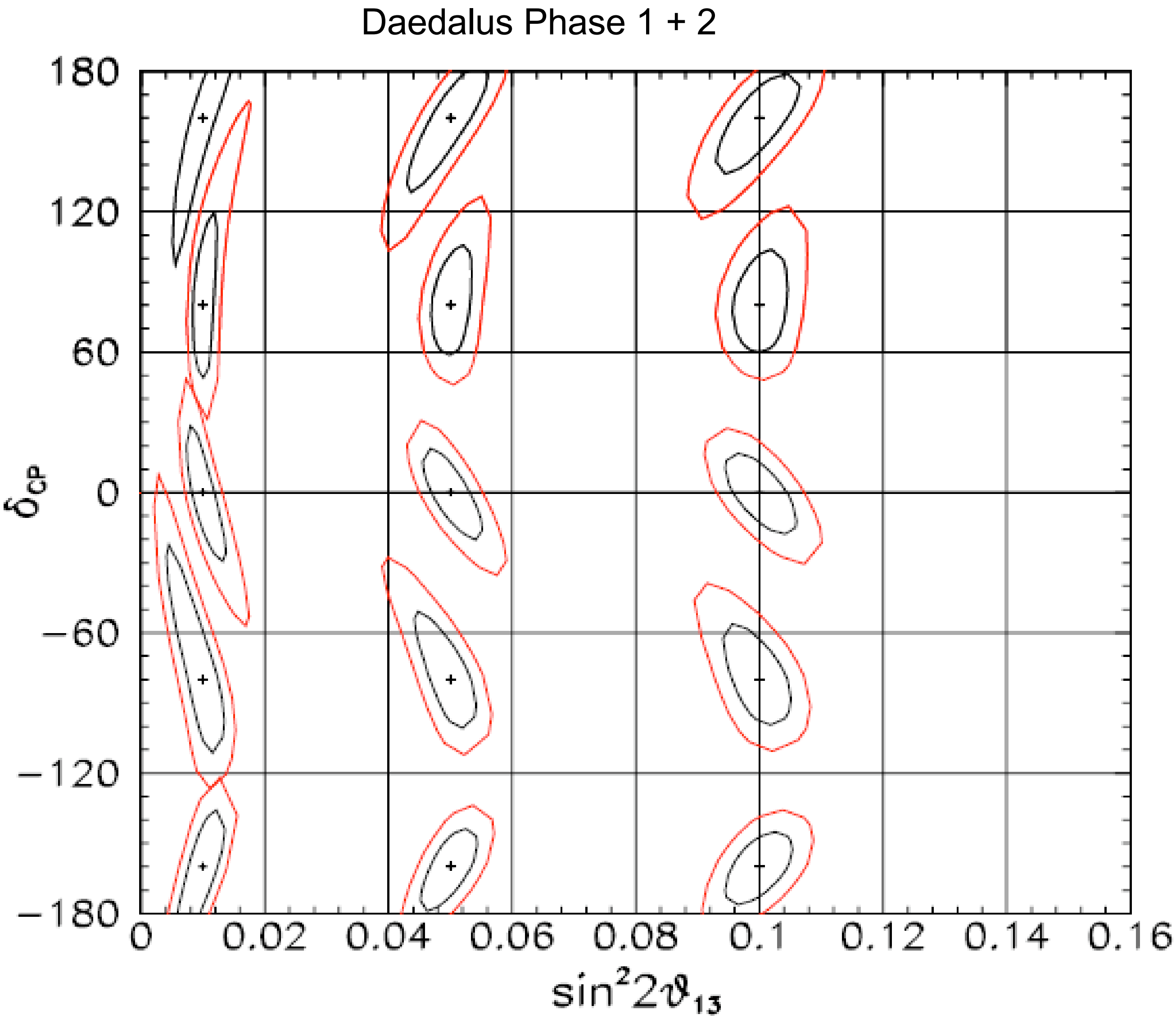


With LBNE…





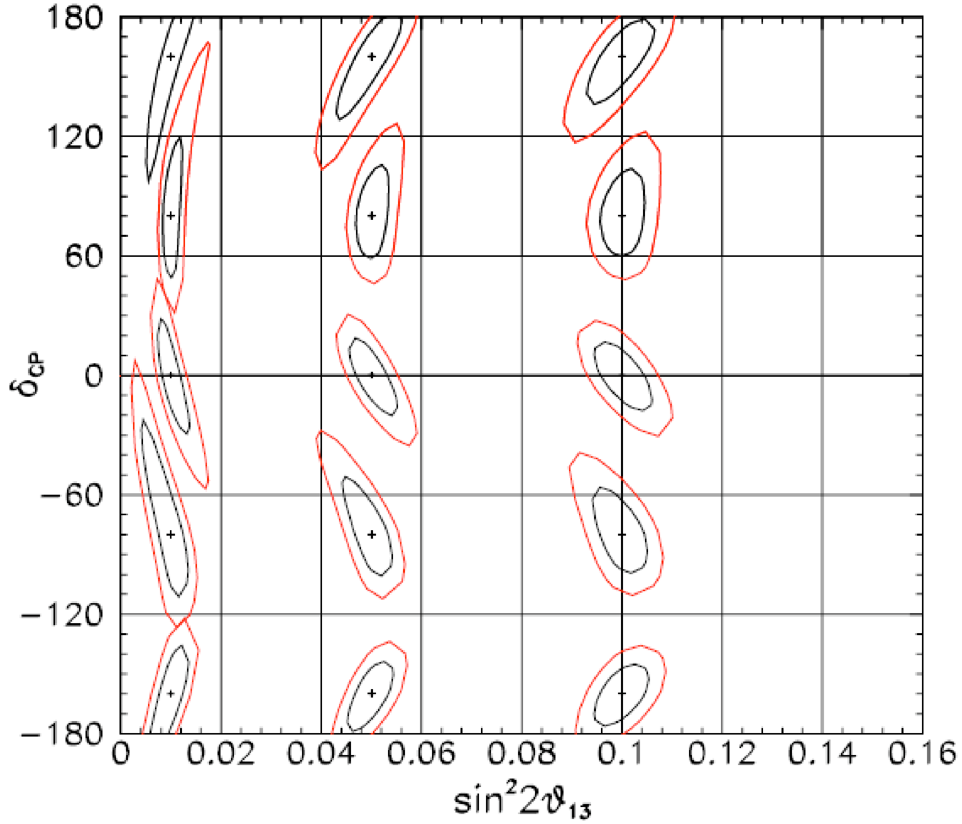
How well do we do?

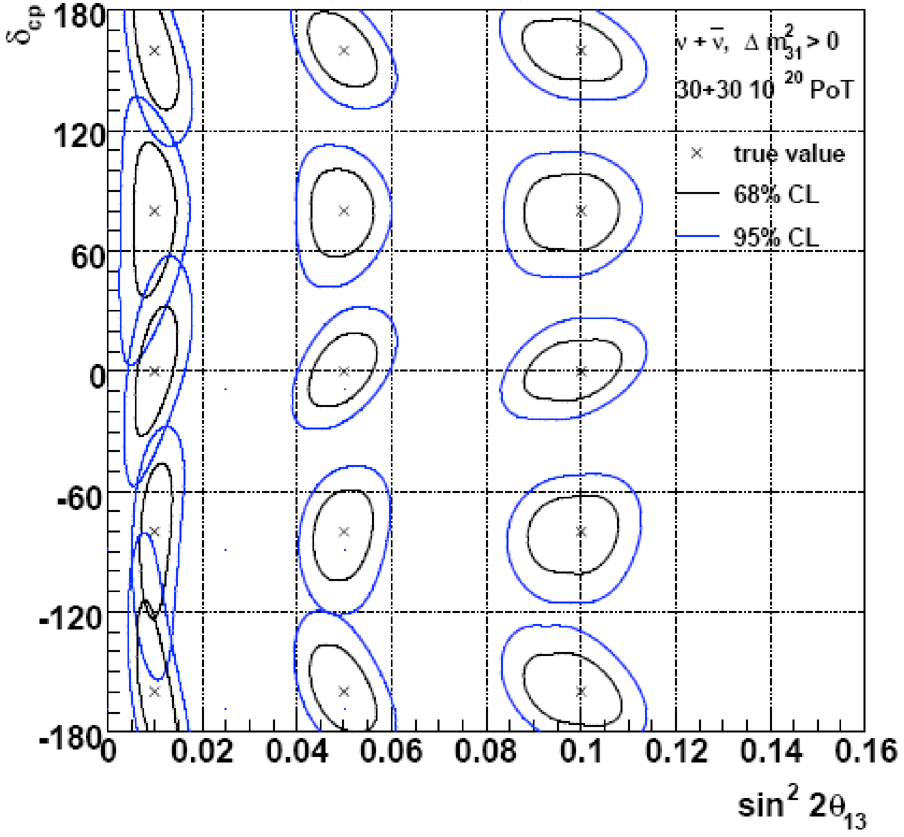


We can clearly observe CP violation!

How well do we do?

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


Daedalus Phase 1 + 2


LBNE 5 yrs nu + 5 yrs nubar

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

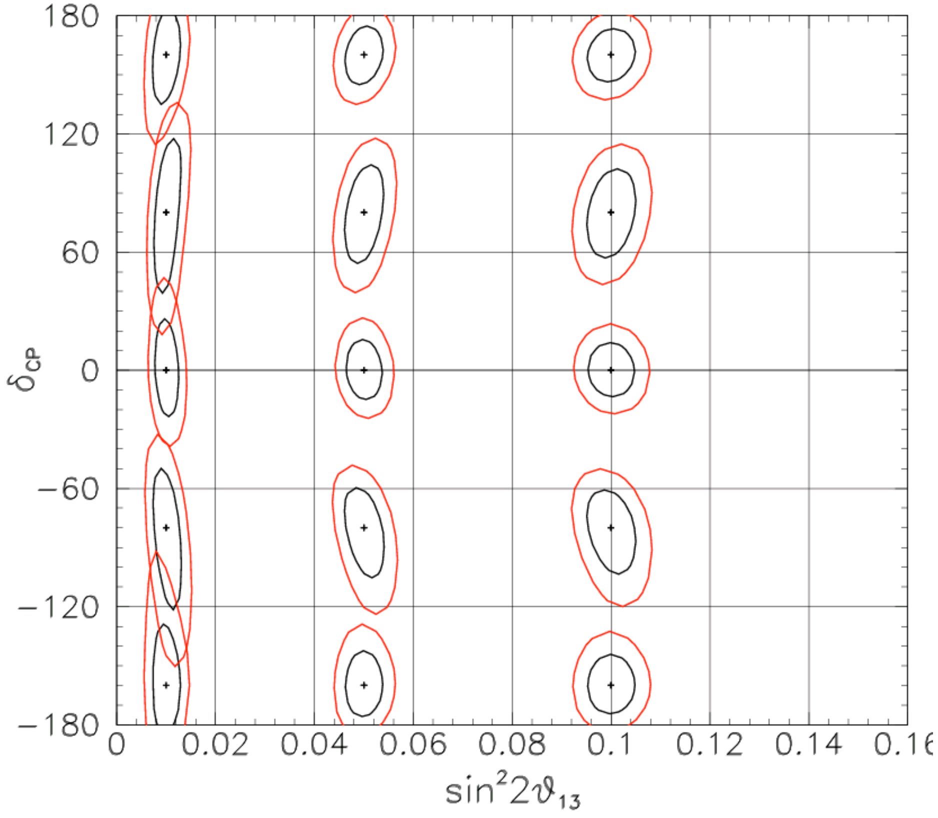
LBNE varies beam energy
DAEdALUS varies beam distance

What happens when the two are put together?

What the Combined Experiments can do!

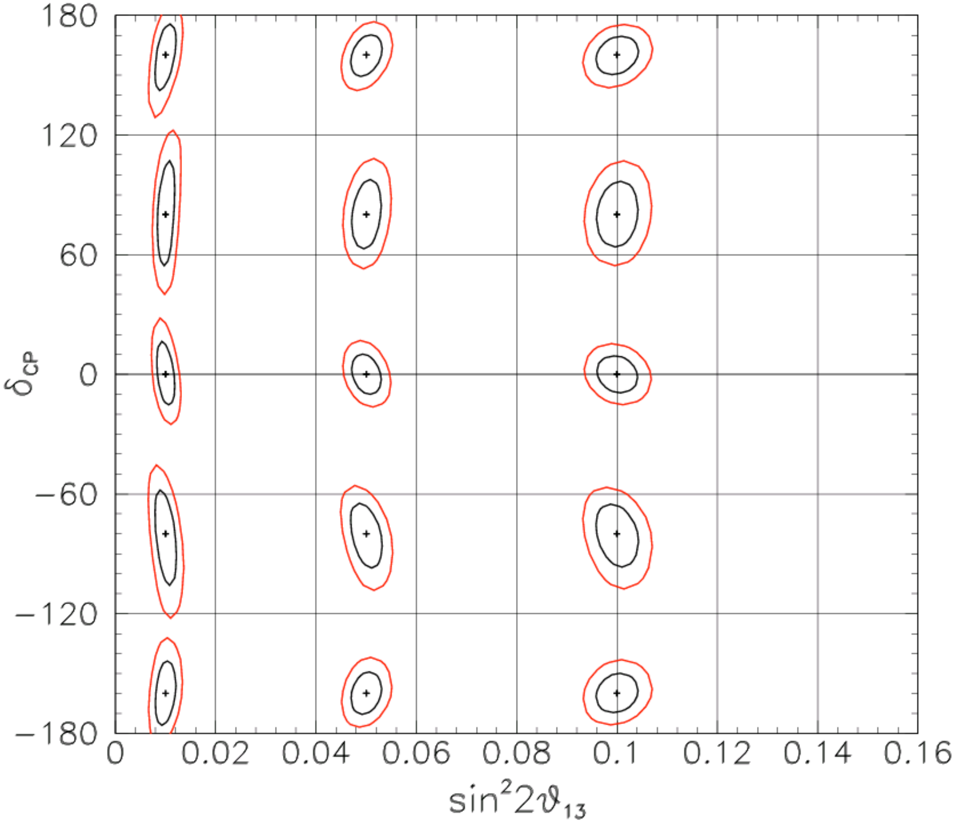
5yr Combined Running

Daedalus plus LBNE **5yr** nu

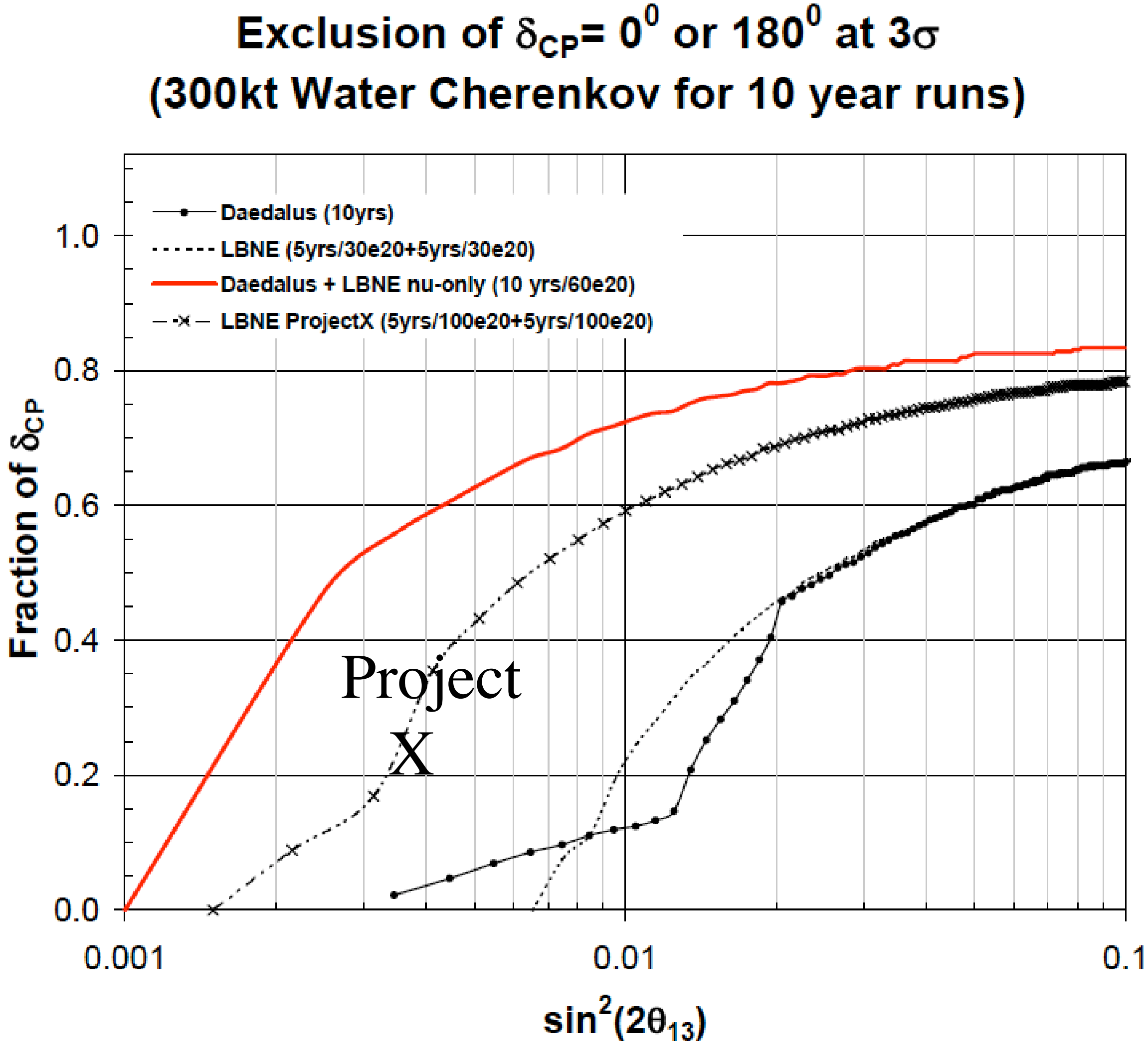


10yr Combined Running

Daedalus plus LBNE **10yr** nu



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

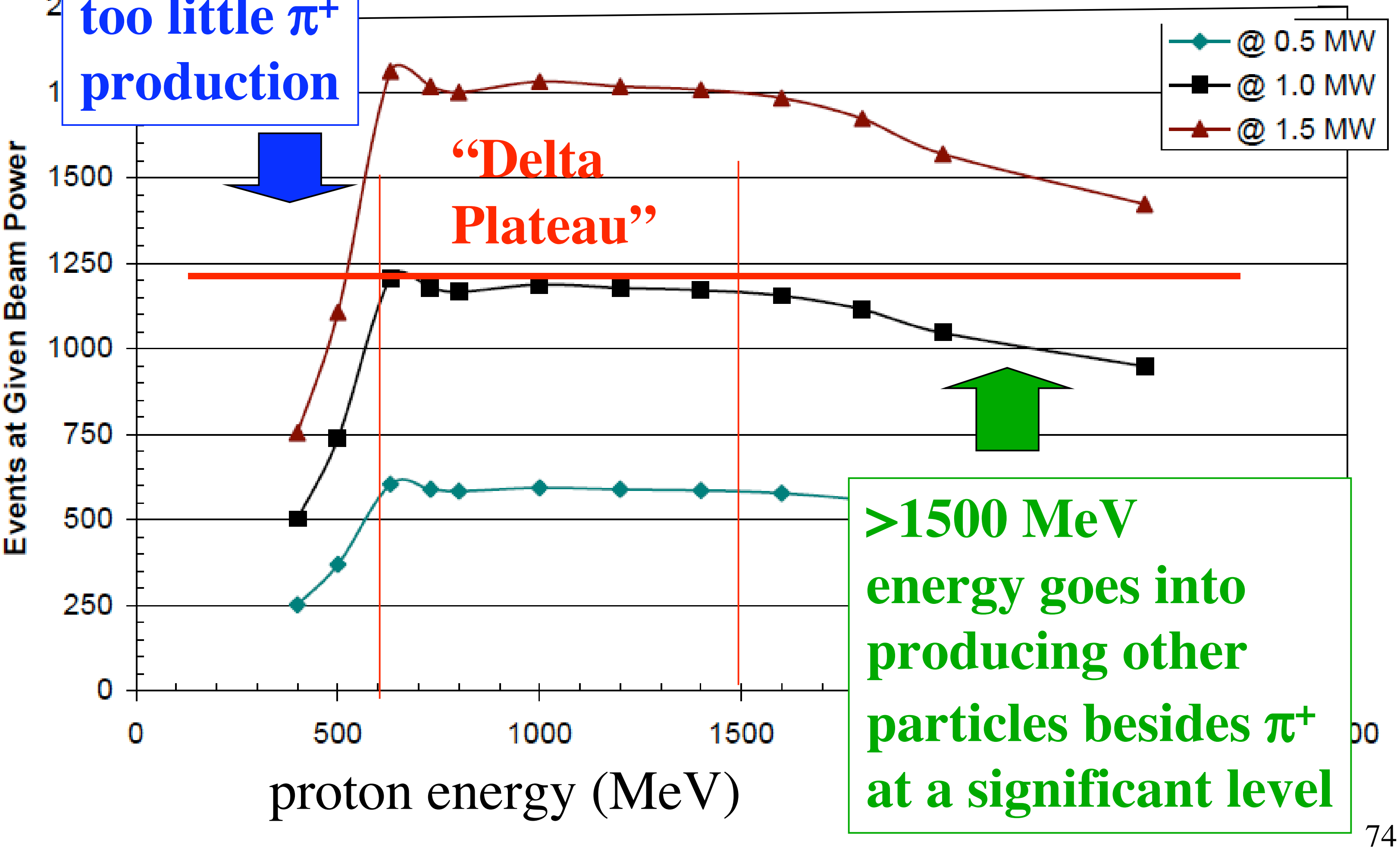


That looks great… BUT

But can we build the machines?

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



<600 MeV too little π^+ production

“Delta Plateau”

>1500 MeV energy goes into producing other particles besides π^+ at a significant level

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

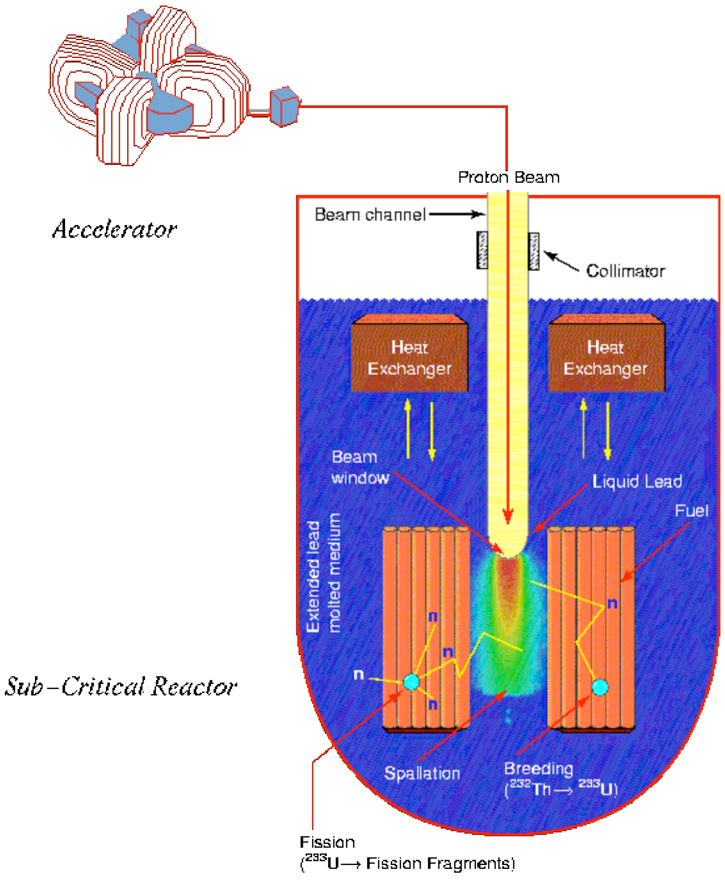
… Unlike Project-X or SNS,
which need all of the above.

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.

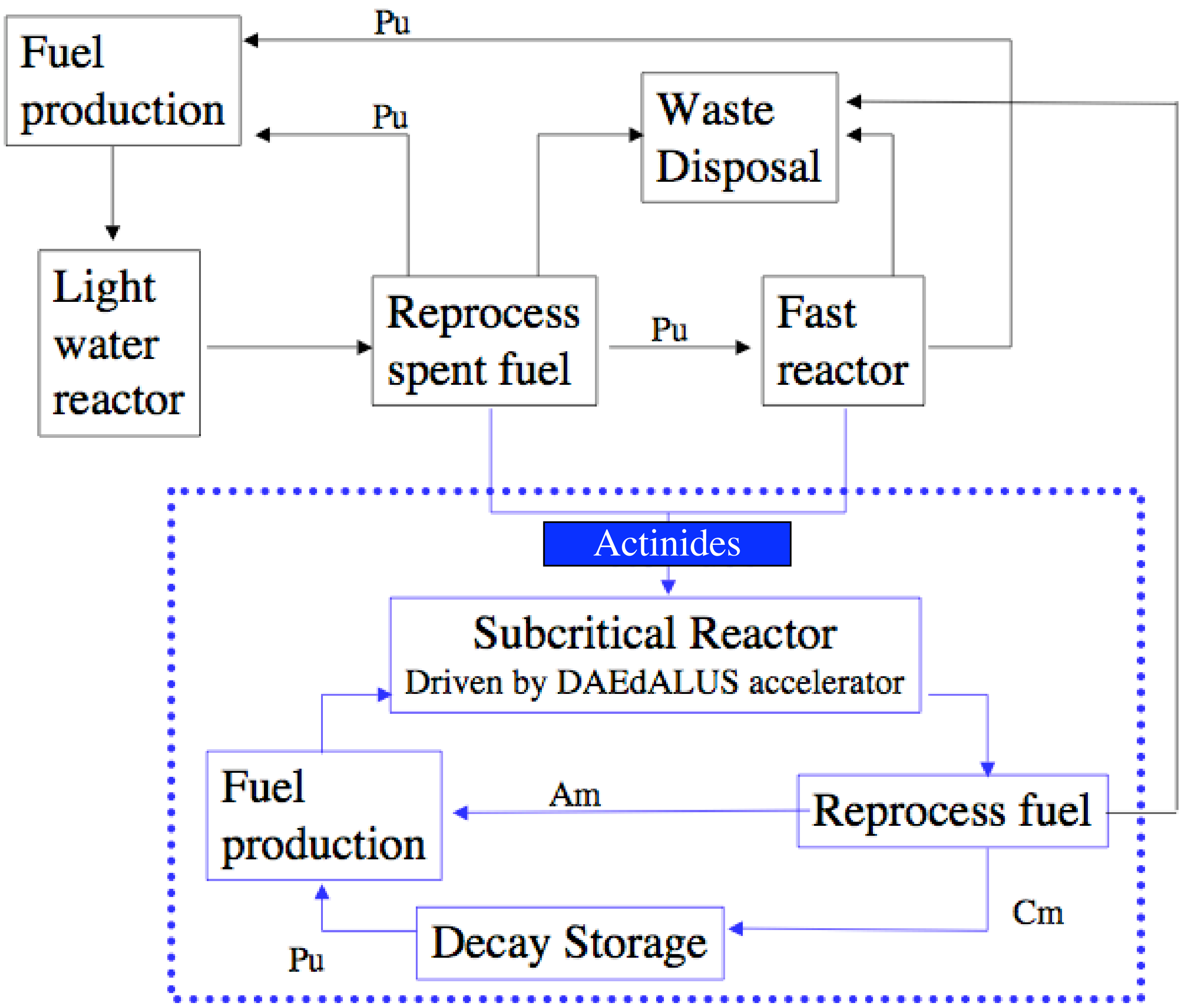
Also “DTRA”-- Defense Threat Reduction Agency



C. Rubbia E.A.

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:

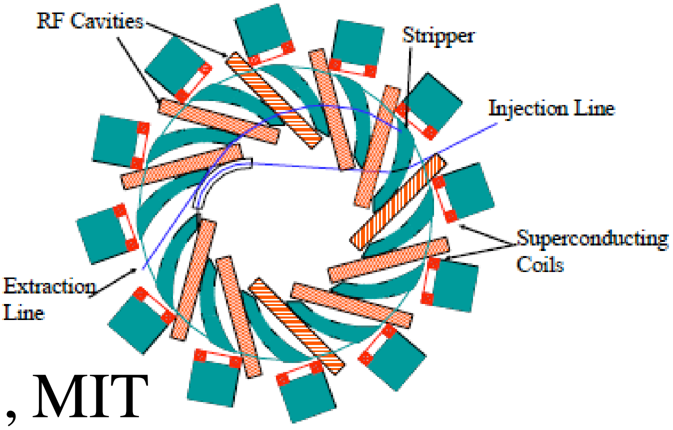
The compact cyclotron with self-extraction

under development for DTRA at MIT

An H2+ accelerator

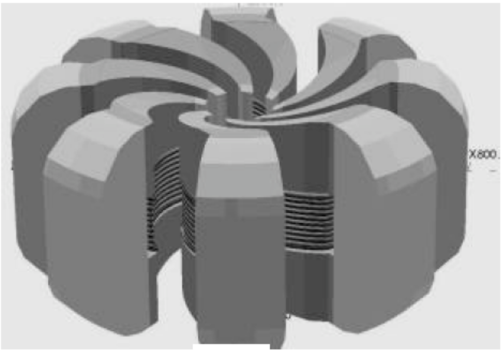
for ADS applications

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



The stacked cyclotron:

7 cyclotrons in one flux return

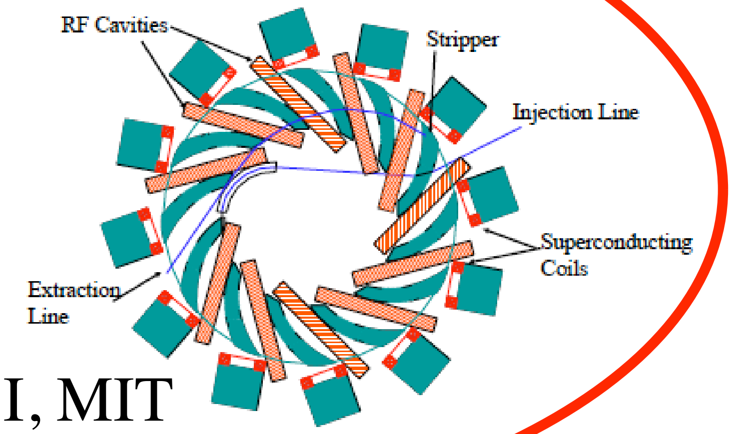


Under dev. for ADS at TAMU

An H2+ accelerator

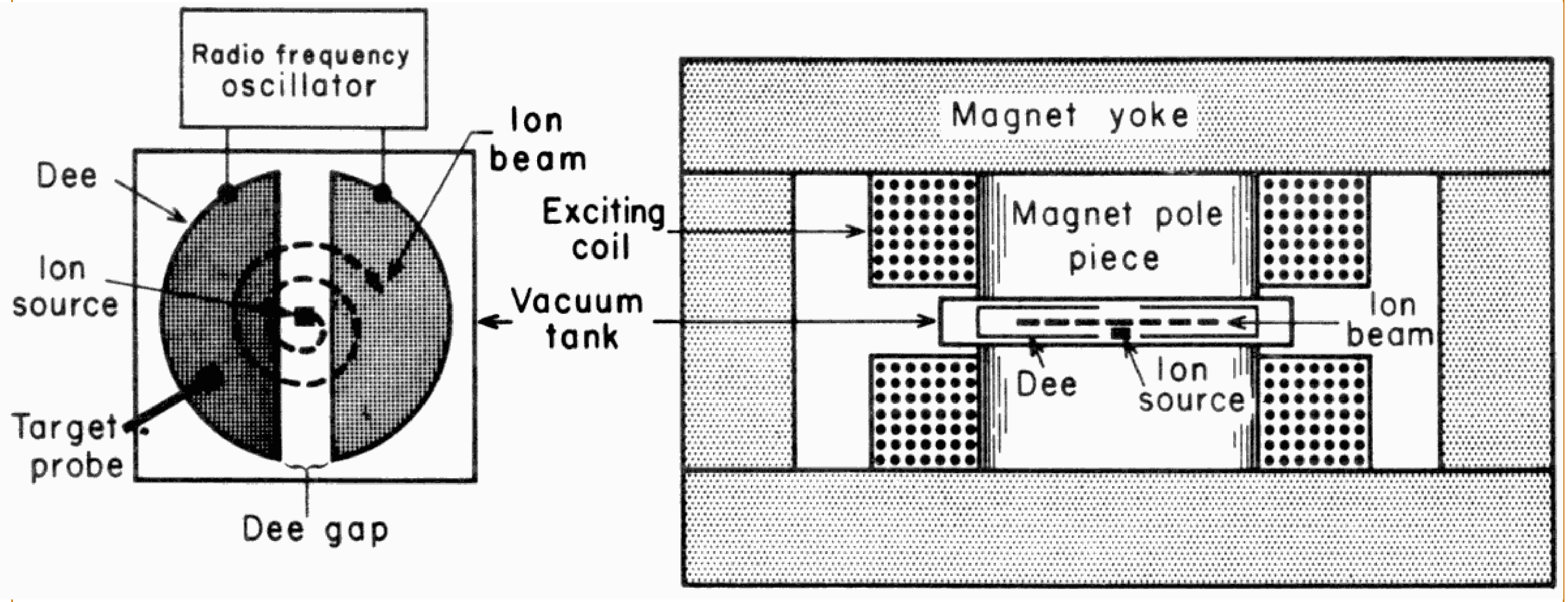
for ADS
applications

Under dev.
by INFN, PSI, MIT
Cockcroft Inst



The example design I will describe today

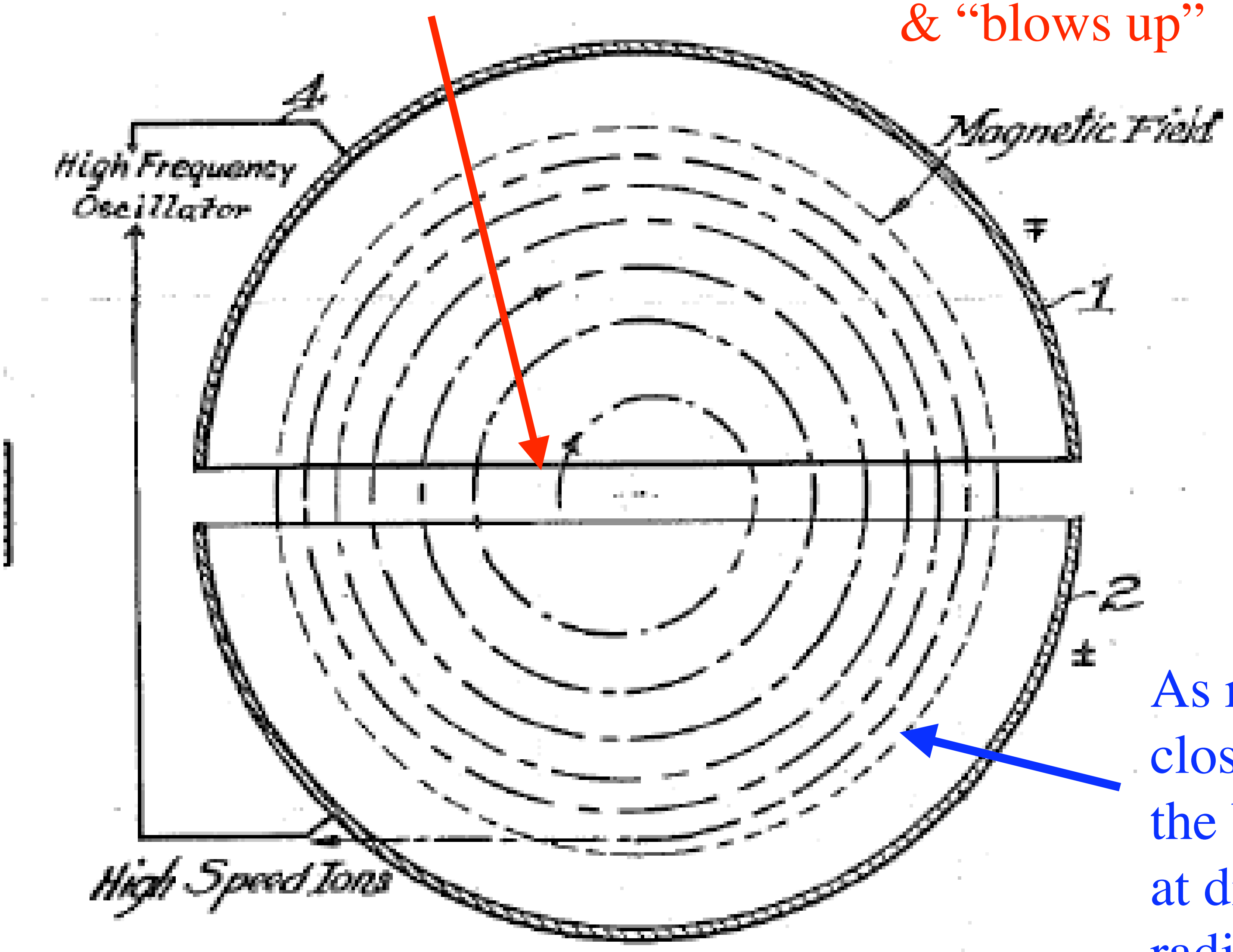
Cyclotrons 101



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

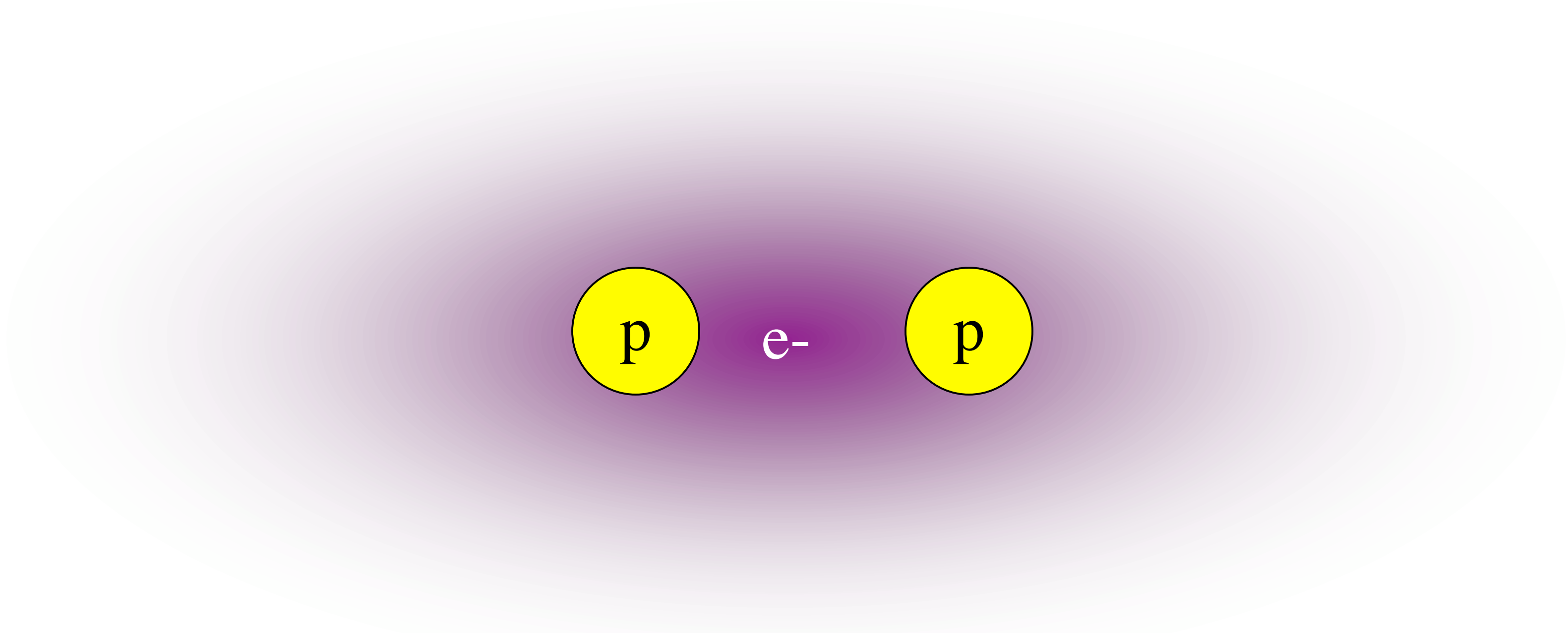
The big issue…

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



As radii get
closer together
the bunches
at different
radii interact

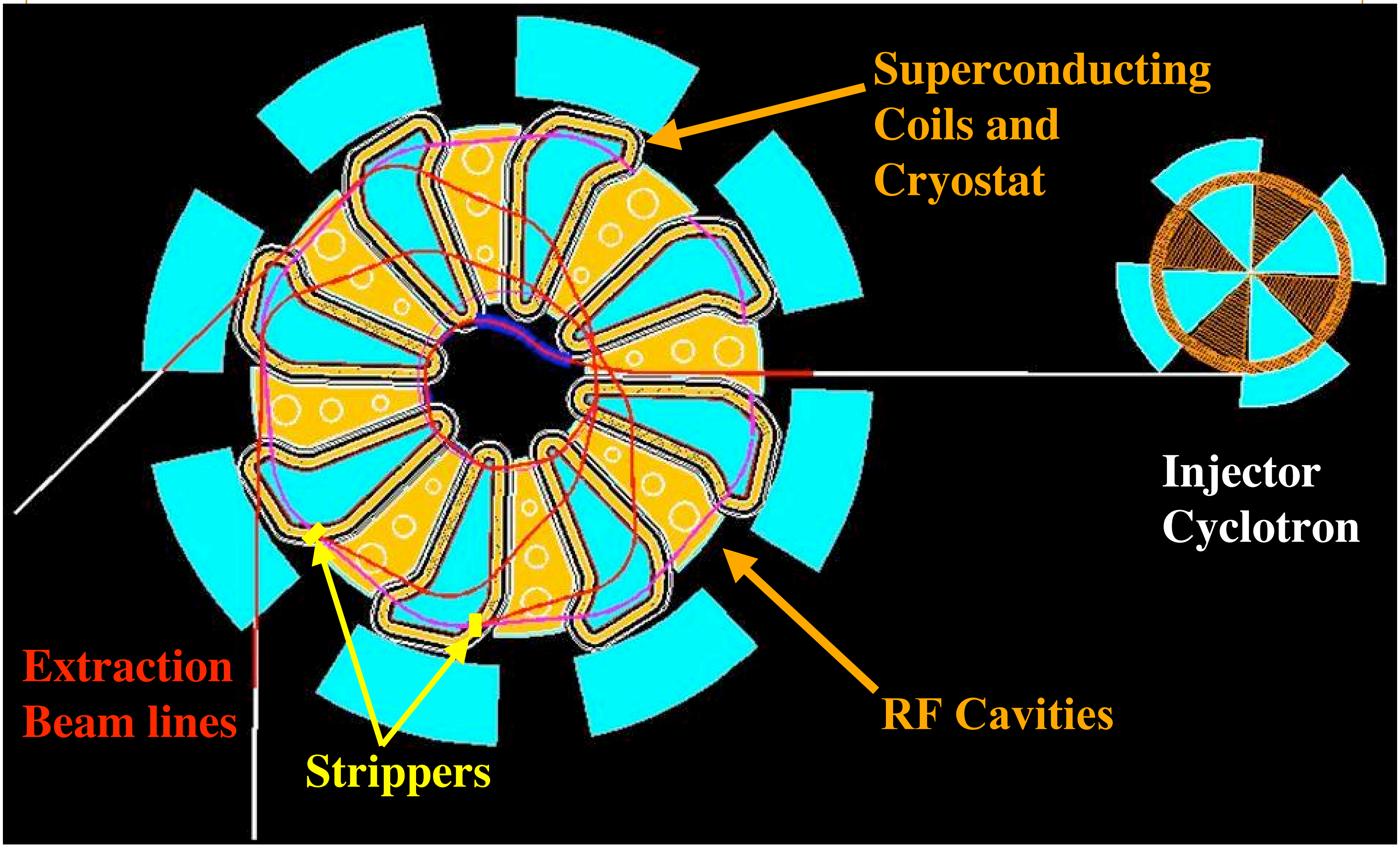
We need to reduce “space charge” at the start…



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

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

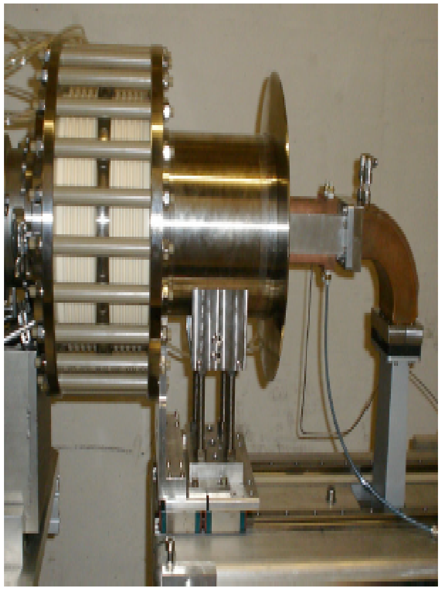
Injector Cyclotron delivers ~ 50 MeV/n H_2^+ beam to Ring Cyclotron
800 MeV/n beam stripped at outer radius,
Proton orbits designed to cleanly exit machine



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

The ion source: prototype built at INFN-Catania (Italy)
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 will 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
- The large magnet specifications are nearly complete,
  and we expect to go to engineers for costing within 6 months.
  This is the cost driver.

The above was reported at the
Particle Accelerator Conference 2 months ago.

On track for entering the CD process in a couple of years

Wrapping this whirlwind tour…

My theme:

If I were a graduating student or recent postdoc, and considering working in neutrino physics, what would I consider working on?

New(ish) over the next few years…

Antares, CUORE, DAEδALUS, Daya Bay, Double Chooz, EGADs, EXO, GERDA, GLACIER, ICARUS, ICECube, KATRIN, LBNE, LENA, Majorana, MEMPhys, MicroBooNE, MINERvA, NOvA,Project 8, RENO, SNO+, SuperNEMO, T2K, XEN

PLUS

… established experiments w/ lots of data already
Cuoricino, NEMO, Super K, MINOS, MiniBooNE, CNGS…

… and some that are accelerator related
Muon Collider/Neutrino Factory, Beta Beams

… and some I accidentally missed
Sorry! There are just so many!

This is an exciting field
& there is lots of room for you!

The End