DAEδALUS Experiment

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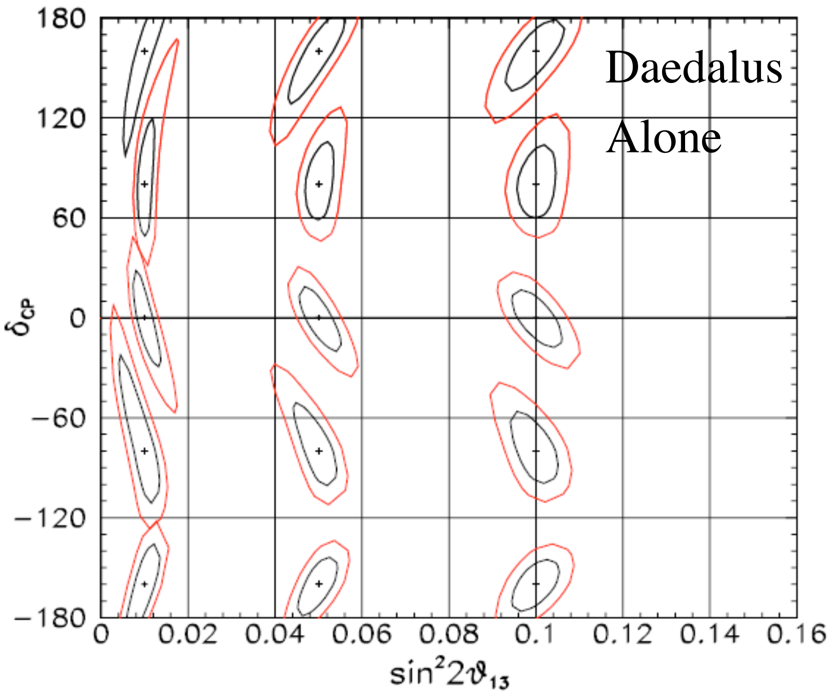
DAEδALUS

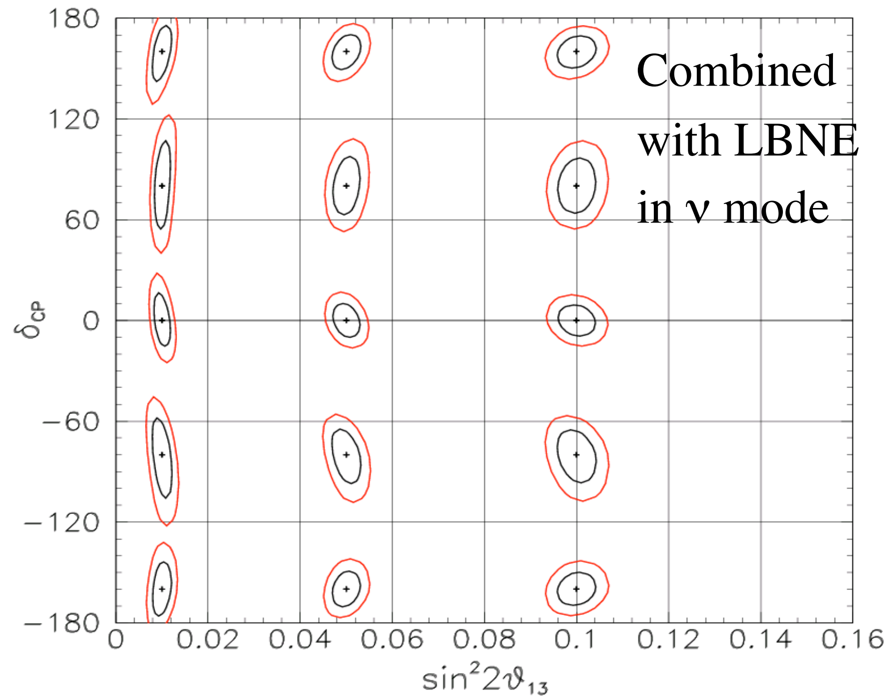
Decay-At-rest Experiment for δ_{CP} studies At the Laboratory for Underground Science

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search, exploiting the L/E dependence of the CP-interference term to extract δ.

Complementary to LBNE:

- -High Statistics
- -Low Background
- -No matter effects





References:

J. Conrad and M. Shaevitz, PRL 104, 141802 (2010).

Expression of Interest for A Novel Search for CP Violation in the Neutrino Sector: DAEδALUS, arXiv: 1006.0260.

A Study of Detector Configurations for the DUSEL CP Violation Searches Combining LBNE and DAEdALUS, arXiv: 1008.4967 (submitted to PRD).

J. Alonso[13], F.T. Avignone[18], W.A. Barletta[13], R. Barlow[5], H.T. Baumgartner[13], A. Bernstein[11], E. Blucher[4], L. Bugel[13], L. Calabretta[9], L. Camilleri[6], R. Carr[6], J.M. Conrad[13,*], S.A. Dazeley[11], Z. Djurcic[2], A. de Gouvêa[17], P.H. Fisher[13], C.M. Ignarra[13], B.J.P. Jones[13], C.L. Jones[13], G. Karagiorgi[13], T. Katori[13], S.E. Kopp[20], R.C. Lanza[13], W.A. Loinaz[1], P. McIntyre[19], G. McLaughlin[16], G.B. Mills[12], J.A. Nolen[2], V. Papavassiliou[15], M. Sanchez[2,10], K. Scholberg[7], W.G. Seligman[6], M.H. Shaevitz[6,*], S. Shalgar[17], T. Smidt[13], M.J. Syphers[14], J. Spitz[22], H.-K. Tanaka[13], K. Terao[13], C. Tschalaer[13], M. Vagins[3,21], R. Van de Water[12], M.O. Wascko[8], R. Wendell[7], L. Winslow[13]

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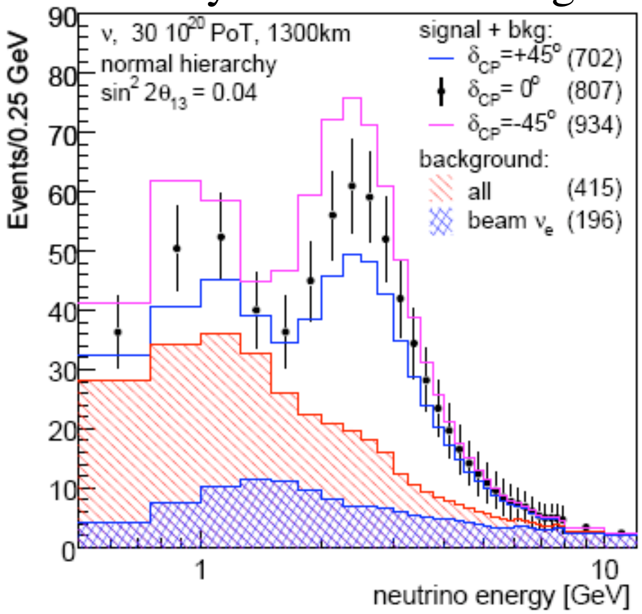
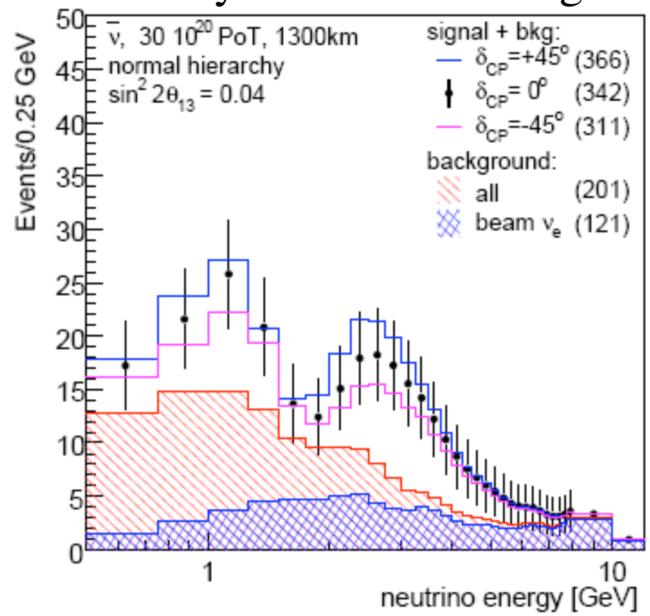
Comments on LBNE

5 years of ν Running



5 years of $\bar{\nu}$ Running



Large neutrino flux covering 1st and 2nd oscillation max points (0.8 and 2.4 GeV).
Fairly pure ν_μ flux with small ν_e contamination.
Minimize flux with energy above 5 GeV that causes background.

However,

Still substantial neutral current π^0 events that mimic ν_e events.
Difficult to collect large antineutrino statistics.
Antineutrino running has significant neutrino contamination.

Come up with an improved source for antineutrinos $\Rightarrow$ DAEδALUS

Daedalus Experiment

-Multiple beam sources using high-power cyclotrons.

-Cyclotron beam impinges on dump where produced π^+ and μ^+ decay to neutrinos (almost all π^- capture before decay).

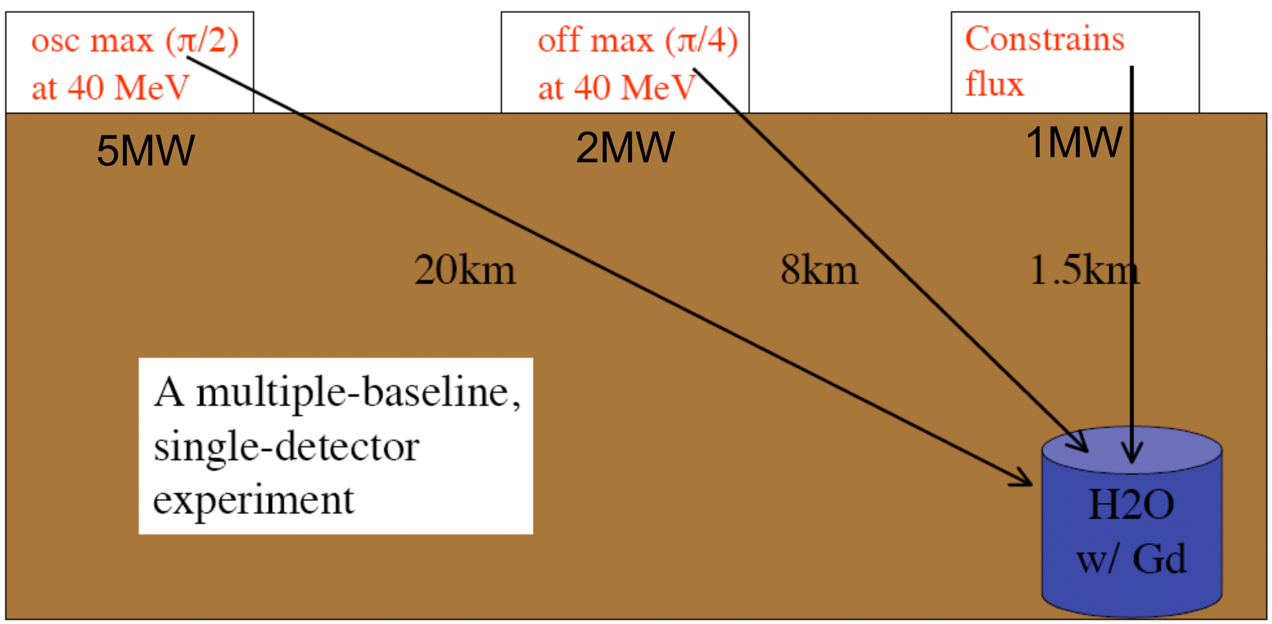
$\rightarrow$ Very few $\bar{\nu}_e$ produced so can do precise $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search.

-For study assume each cyclotron 1 MW at some proton energy in 0.6 to 1.4 GeV range.

-Detector is assumed to be 300 kton water Cerenkov detector with gadolinium doping.

-Osc signal events are $\bar{\nu}_e + p \rightarrow e^+ + n$ (Inverse-beta decay) which can be well identified by a two part delayed coincidence.

-Flux normalization can be determined by using ~15,000 $\nu_e + e^- \rightarrow \nu_e + e^-$ events.



Neutrino Beam Production

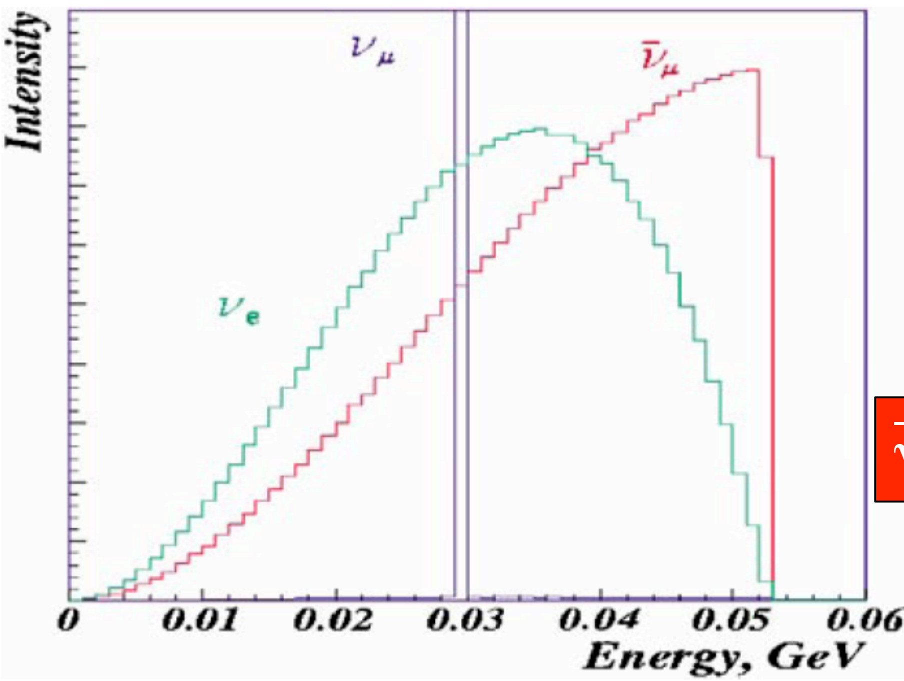
Proton beam produces pions in a carbon plus copper beam dump:

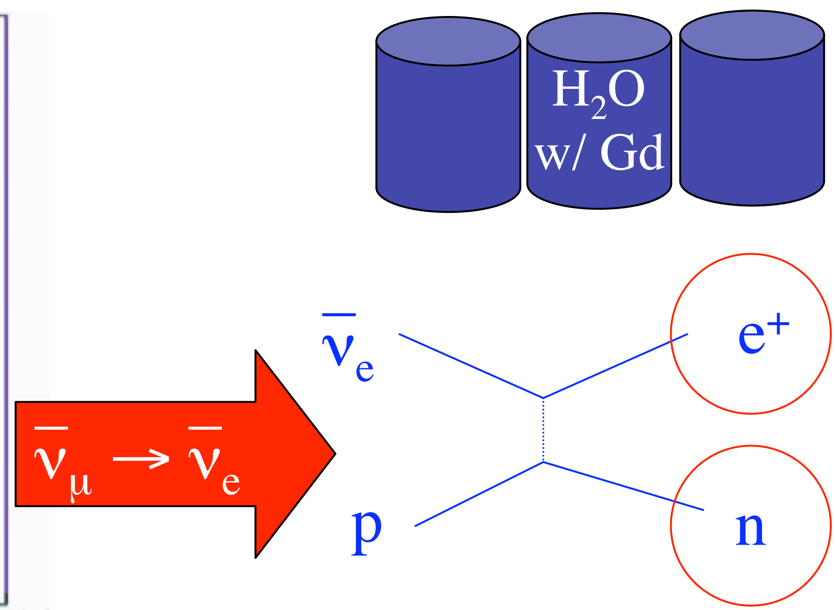
Protons $\rightarrow$ π^+ (stop) $\rightarrow \mu^+ + \nu_\mu$

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

$\rightarrow$ π^- (captures before decay)

Energy Spectrum for π^+ Decay-at-Rest Beam
(No uncertainty in energy spectrum)





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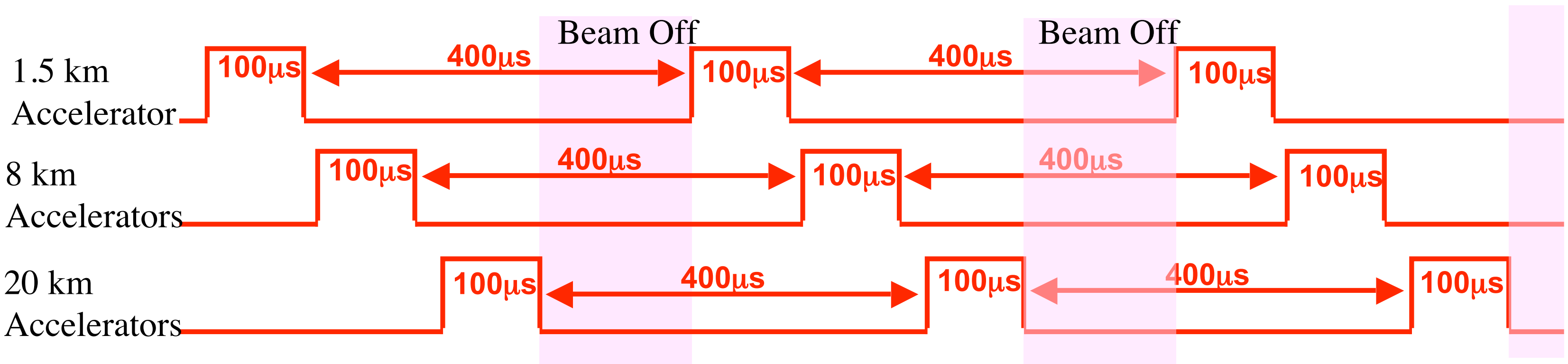
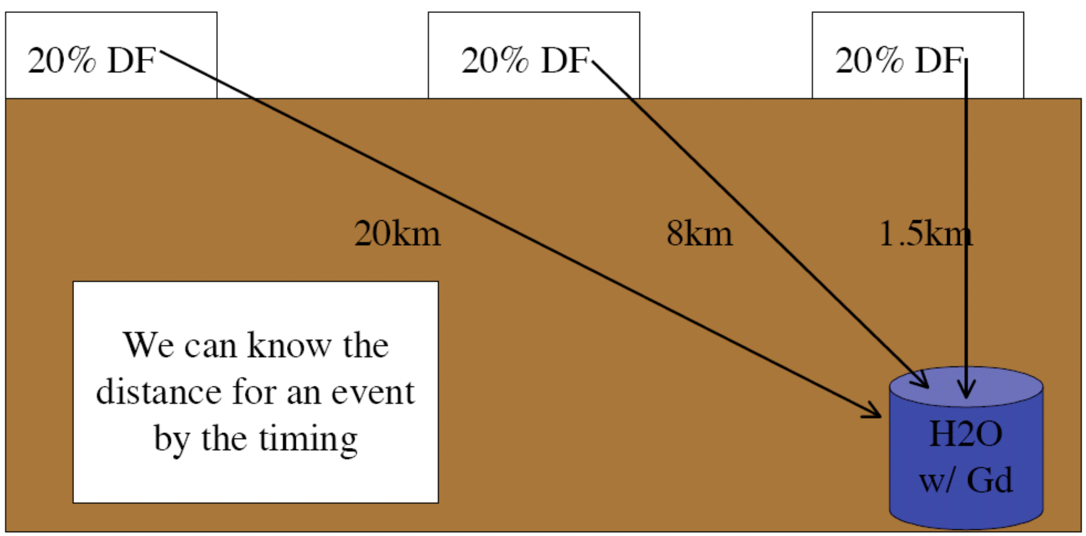
$\rightarrow \pi^-$ (captures before decay)



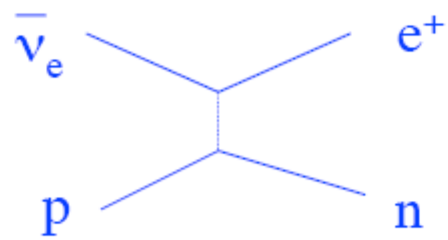
(options with times on/off with 1ms/4ms studied)



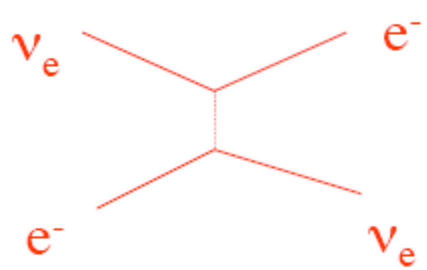
Event Types in Water Detector

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ then $\bar{\nu}_e + p \rightarrow e^+ + n$ (IBD events)

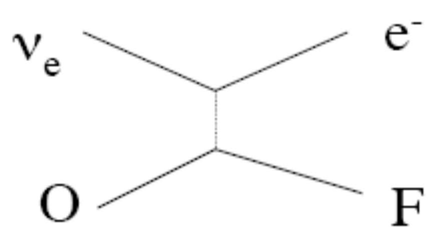
The signal:
(inverse beta decay, IBD)



Use Gd doping to identify the n (67% effic)

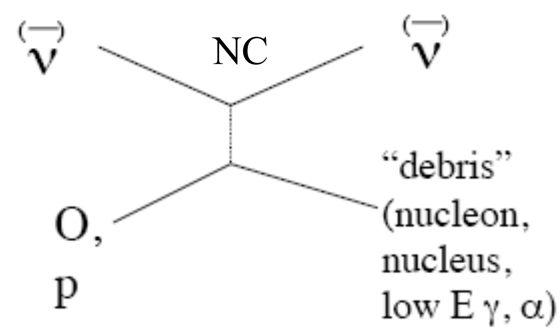


& other νe scattering diagrams -- essential to normalization.
(Also $\nu_\mu e$ and $\bar{\nu}_\mu e$)



Lower than IBD by ×10 because of binding, & no associated n

Used for relative normalization of different distances



Will not reconstruct as an IBD event

Measurement Strategy

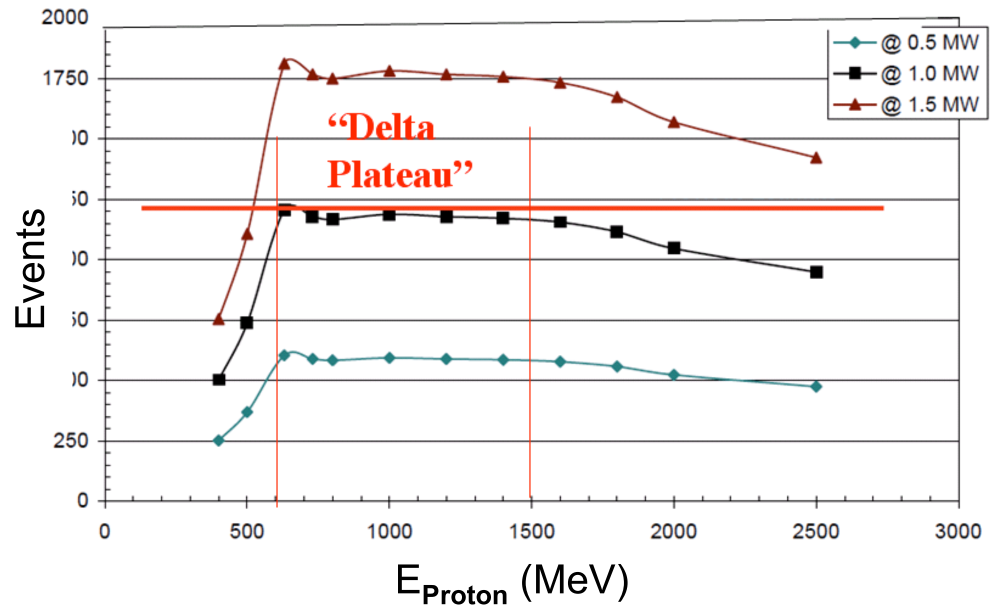
Using **near accelerator**
measure **absolute flux normalization** with ν-e events to ~1%,
Also, measure the ν_eO event rate.

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**

Beam Requirements

Need high intensity proton beams with 600 to 1500 MeV to maximize pion production (in the "Delta Plateau" region).



Best candidate is high-power superconducting cyclotrons.

– Being developed for:

"ADS" – accelerator driven systems for subcritical reactors.

"DTRA"- Defense Threat Reduction Agency → Homeland security apps.

A year-long study of 3 cyclotron designs has begun

The compact cyclotron with self-extraction

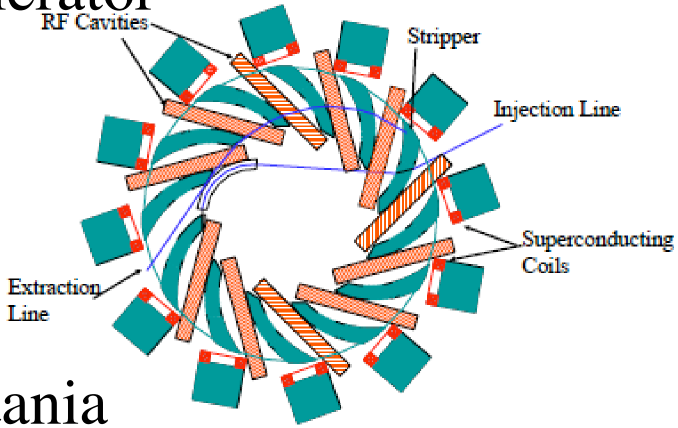
under development for DTRA at MIT

Design energies under consideration: 650-1500 MeV

An H2+ accelerator

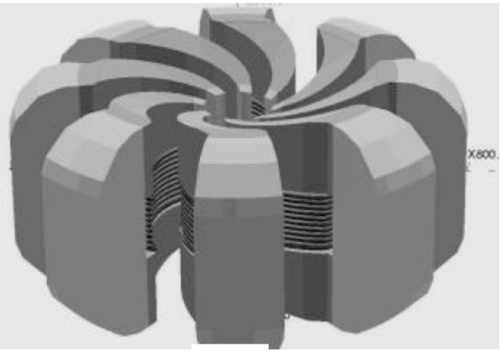
for ADS applications

Under dev. by INFN, Catania



The stacked cyclotron:

7 cyclotrons in one flux return



Under dev. for ADS at TAMU

L. Calabretta et. al., "A Multi Megawatt Cyclotron Complex to Search for CP Violation in the Neutrino Sector", arXiv:1010.1493 (2010).
J. Alonso, "The DAEδALUS Project: Rationale and Beam Requirements", arXiv: 1010.0971 (2010).

DAEδALUS three-phase Run Plan

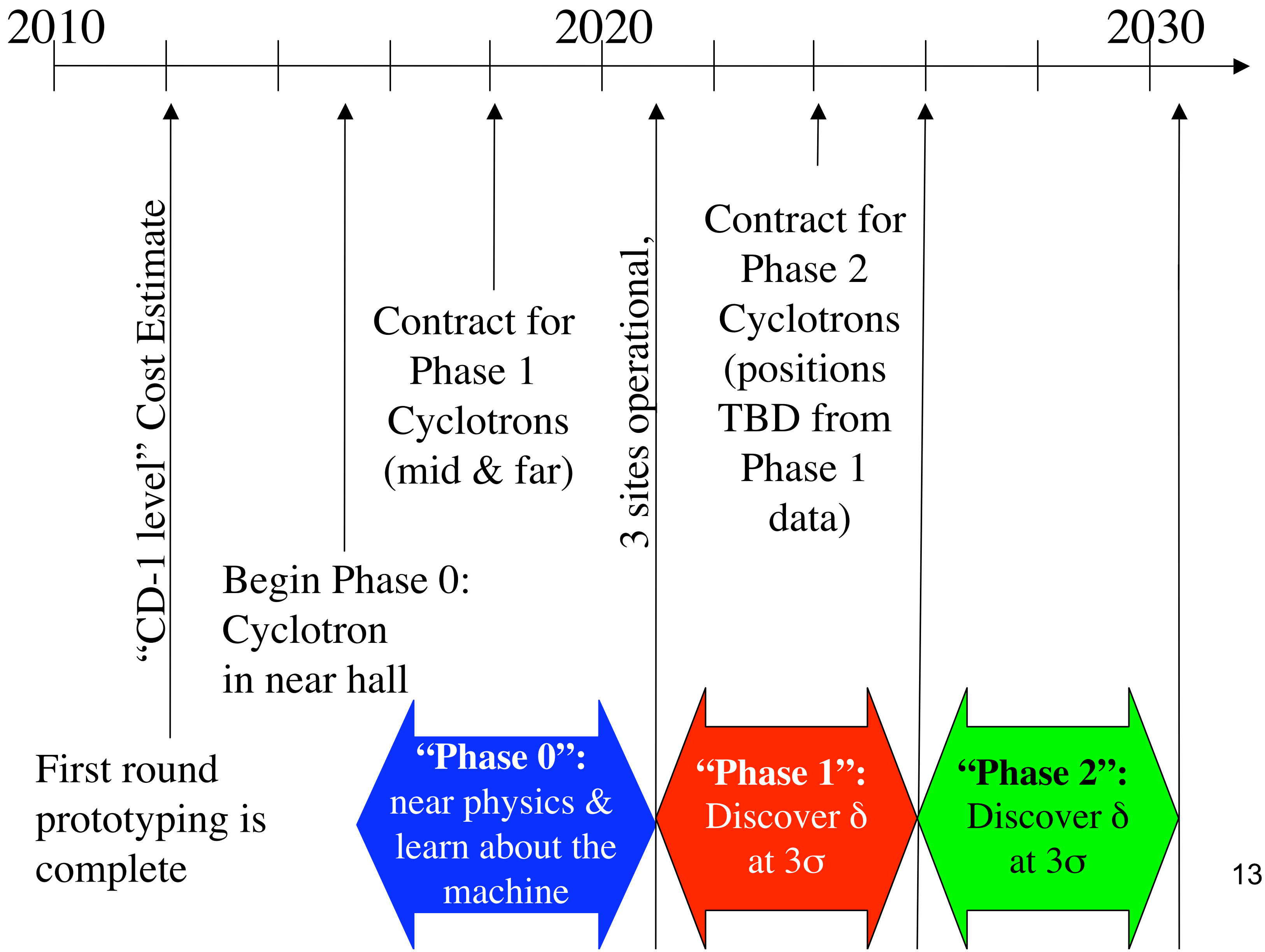
Three-phase run-plan consists of:

0. Learn: Run the near accelerator to learn more about operations, and make useful preliminary cross section measurements.

1. Discover: Run in the 1-2-3 MW configuration to discover the value of δ, while maintaining flexibility of design.
2. Measure: Run for the remainder of the experiment with the most optimal accelerator design.

DAEδALUS three-phase Run Plan

A 3-phase schedule: *learn* -- ***discover*** -- ***measure***



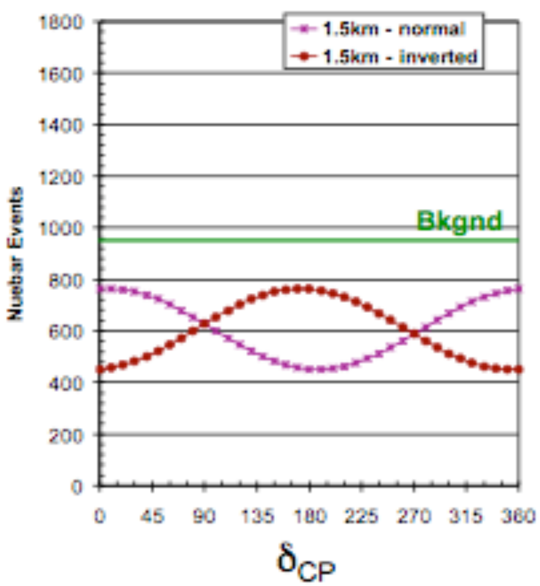
Events in Detectors

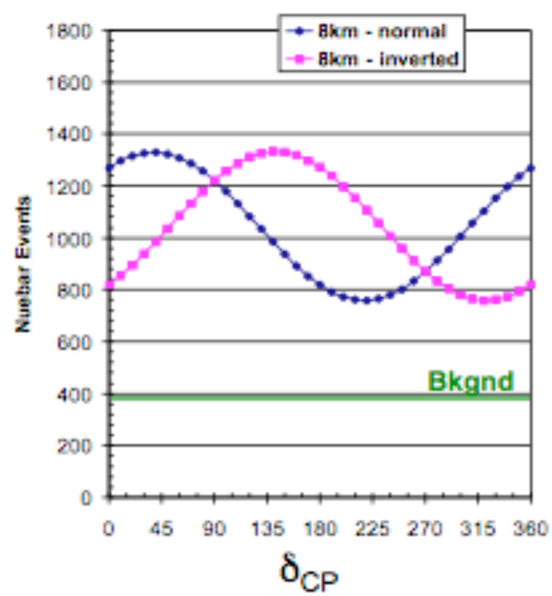
Assume: 300 kton Water Cerenkov det., 10 year run.

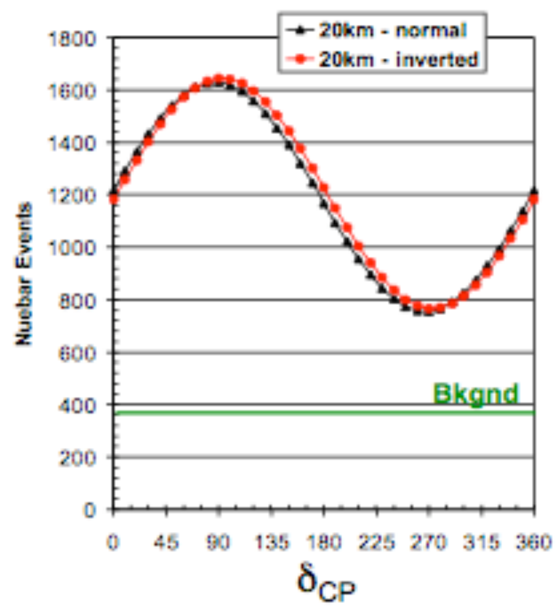
Event samples for signal with $\sin^2 2\theta_{13} = 0.05$.

Event Type	1.5 km	8 km	20 km
IBD Oscillation Events ($E_{vis} > 20$ 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 $\overline{\nu}_e$ ($E_{vis} > 20$ MeV)	600	42	17
IBD Non-Beam ($E_{vis} > 20$ MeV)			
atmospheric $\nu_\mu p$ "invisible muons"	270	270	270
atmospheric IBD	55	55	55
diffuse SN neutrinos	23	23	23
$\nu-e$ Elastic ($E_{vis} > 10$ MeV)	21570	1516	605
ν_e-oxygen ($E_{vis} > 20$ MeV)	101218	7116	2840

Oscillation event and bkg. distributions as Function of δ_{CP} from each accelerator.





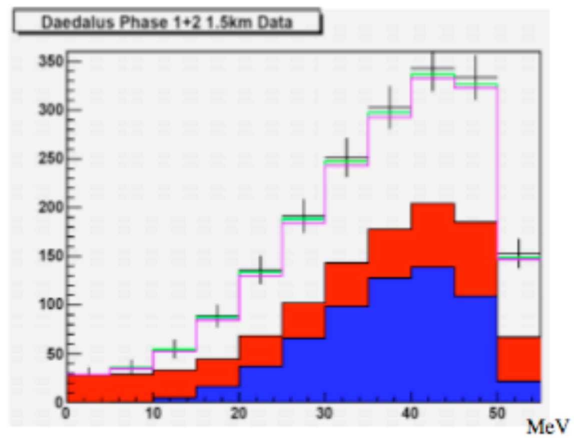


Events in Detectors

Assume: 300 kton Water Cerenkov det., 10 year run.

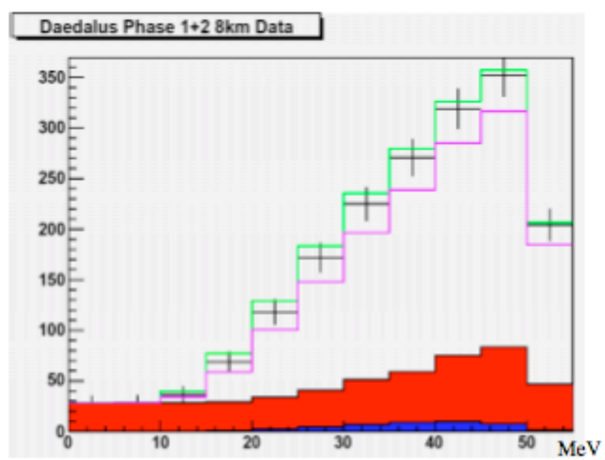
Event energy distributions for signal and background at $\sin^2 2\theta_{13} = 0.04$.

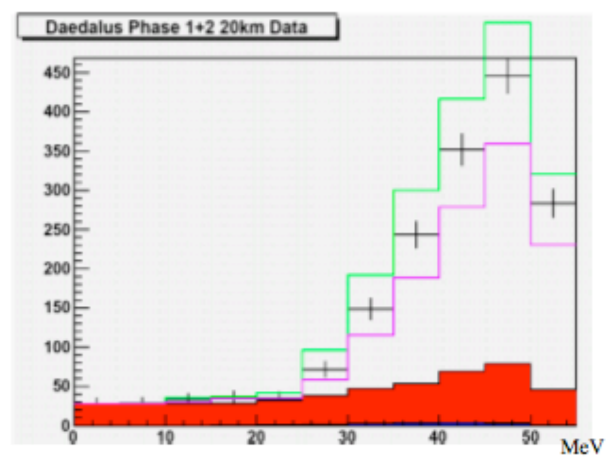
Near (1.5 km) accelerator events.



Blue: Intrinsic $\bar{\nu}_e$ bkgnd
Red: Beam off bkgnd
Black: δ_{CP}= 0^0
Violet: δ_{CP}= 45^0
Green: δ_{CP}=-45^0
} signals

Events in signal accelerators (left) 8 km, (right) 20 km.

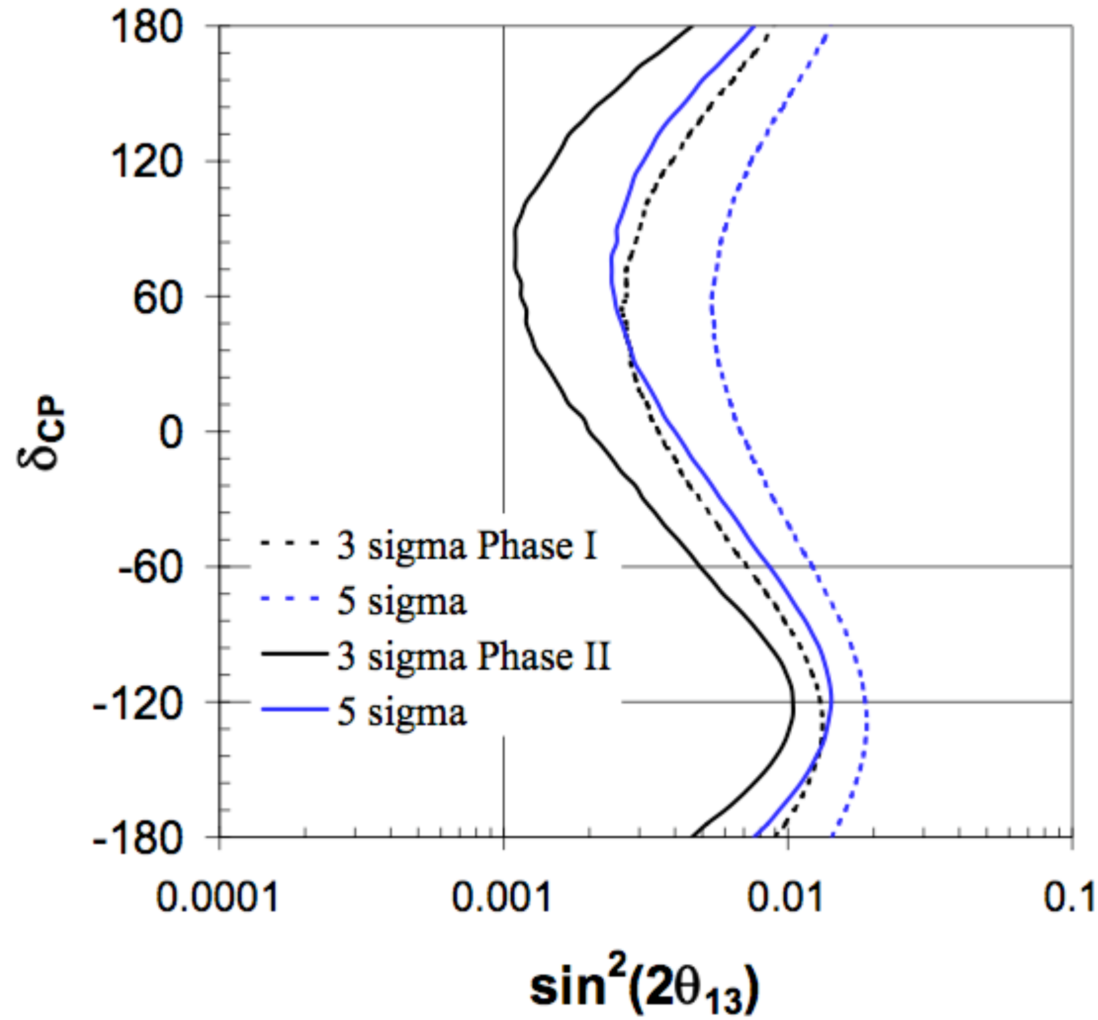




DAEδALUS Sensitivity

One (inner contour) and two (outer contour) σ sensitivities for DAEδALUS Phase 1 and 2 combined (10 years of running).

Phase-1 and Combined-phase 1+2 sensitivity to θ_{13} at 3σ and 5σ.



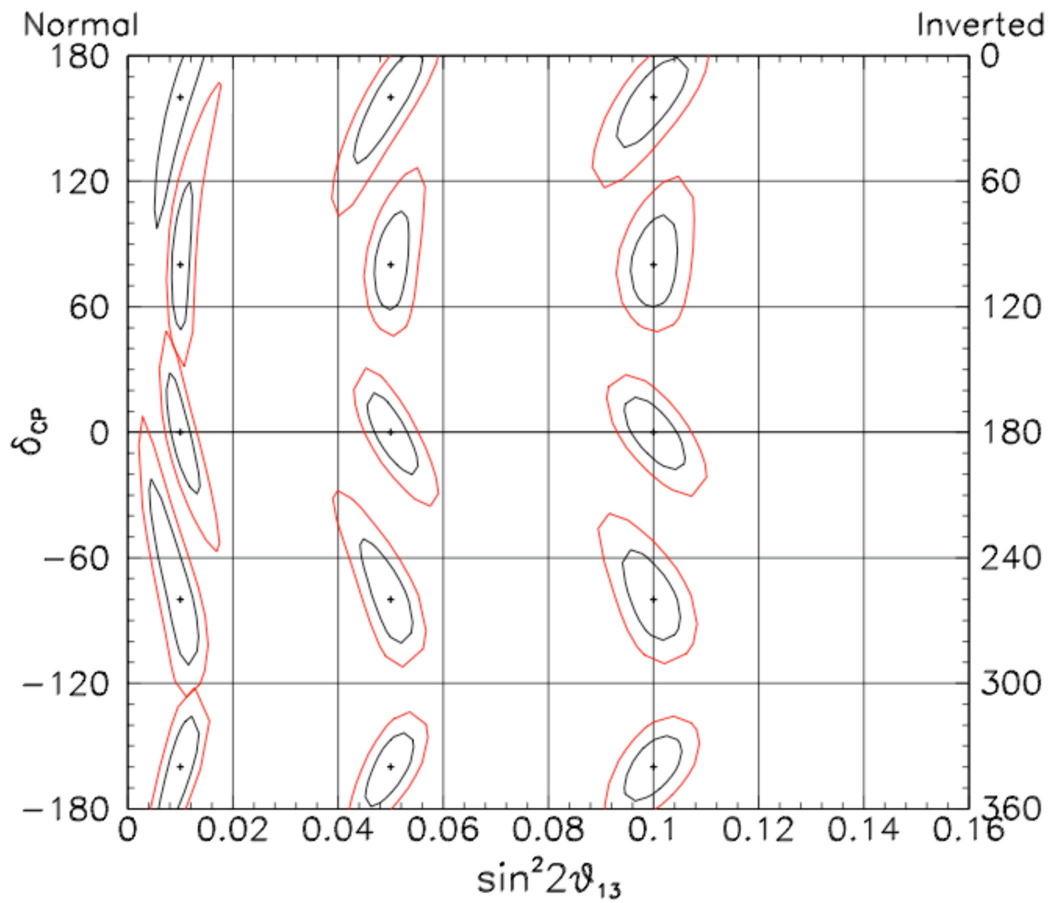
DAEδALUS Sensitivity

One (inner contour) and two (outer contour) σ sensitivities for DAEδALUS Phase 1 and 2 combined (10 years of running).

DAEδALUS is not sensitive to matter effects ⇒ degeneracy between two mass hierarchies.

δ_{CP} scale for normal hierarchy shown on the left, inverted on the right.

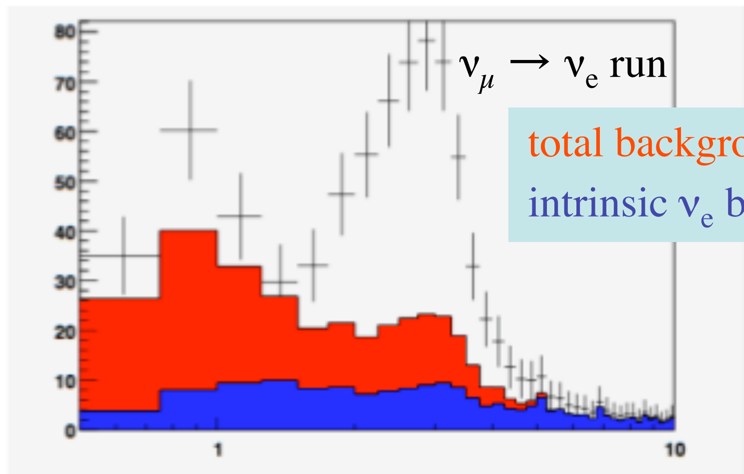
DAEδALUS can determine if there is CP violation (i.e. $\delta_{CP} \neq 0$ or 180◦) without knowing hierarchy.



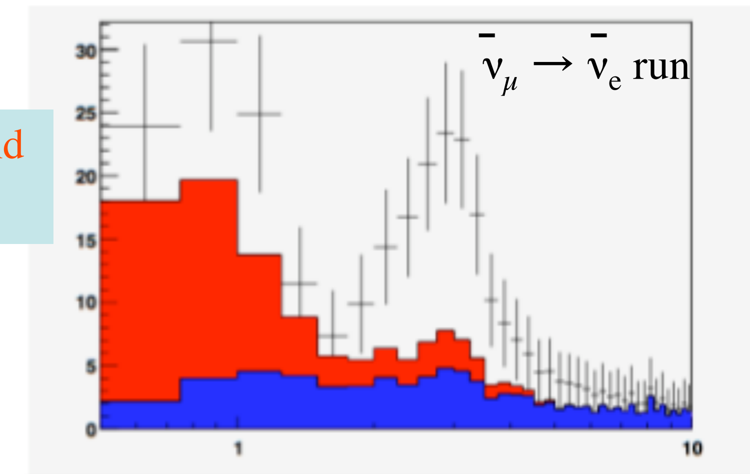
LBNE Sensitivity

LBNE expected events (E[GeV]) in 300 kton water Cherenkov detector at 1300 km for ν (5 yr) + ν (5 yr) running.

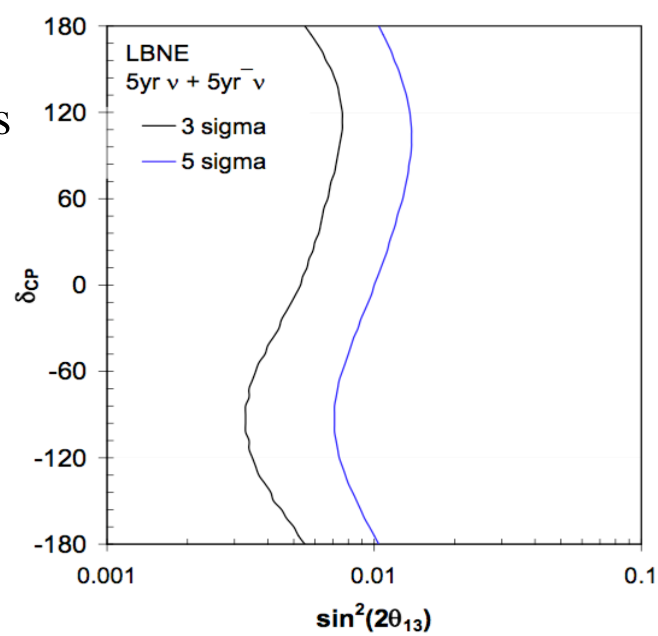
Black points:
rate with stat. error,
$\sin^2 2\theta_{13} = 0.04$,
$\delta_{CP} = 0^\circ$,
normal hierarchy.



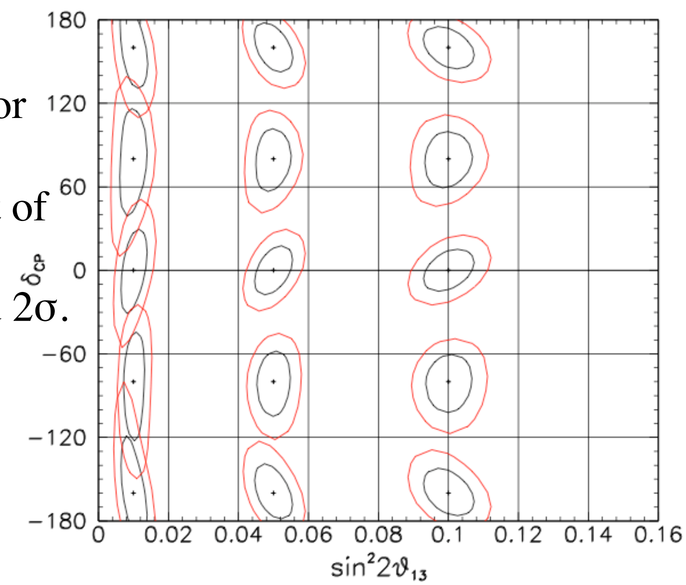
total background
intrinsic ν_e bkg



3σ and 5σ CL Exclusion limits for determining θ_{13} vs δ_{CP}.



Estimates of uncertainty for correlated measurement of $\sin^2 2\theta_{13}$ and δ_{CP} at 1σ and 2σ.



DAEδALUS and LBNE Complementarity

- The DAEδALUS signal is entirely in antineutrino mode, while the statistical strength of LBNE is in neutrino running.

- DAEδALUS is a short-baseline experiment with no matter effects, while LBNE is a long-baseline experiment with matter effects.

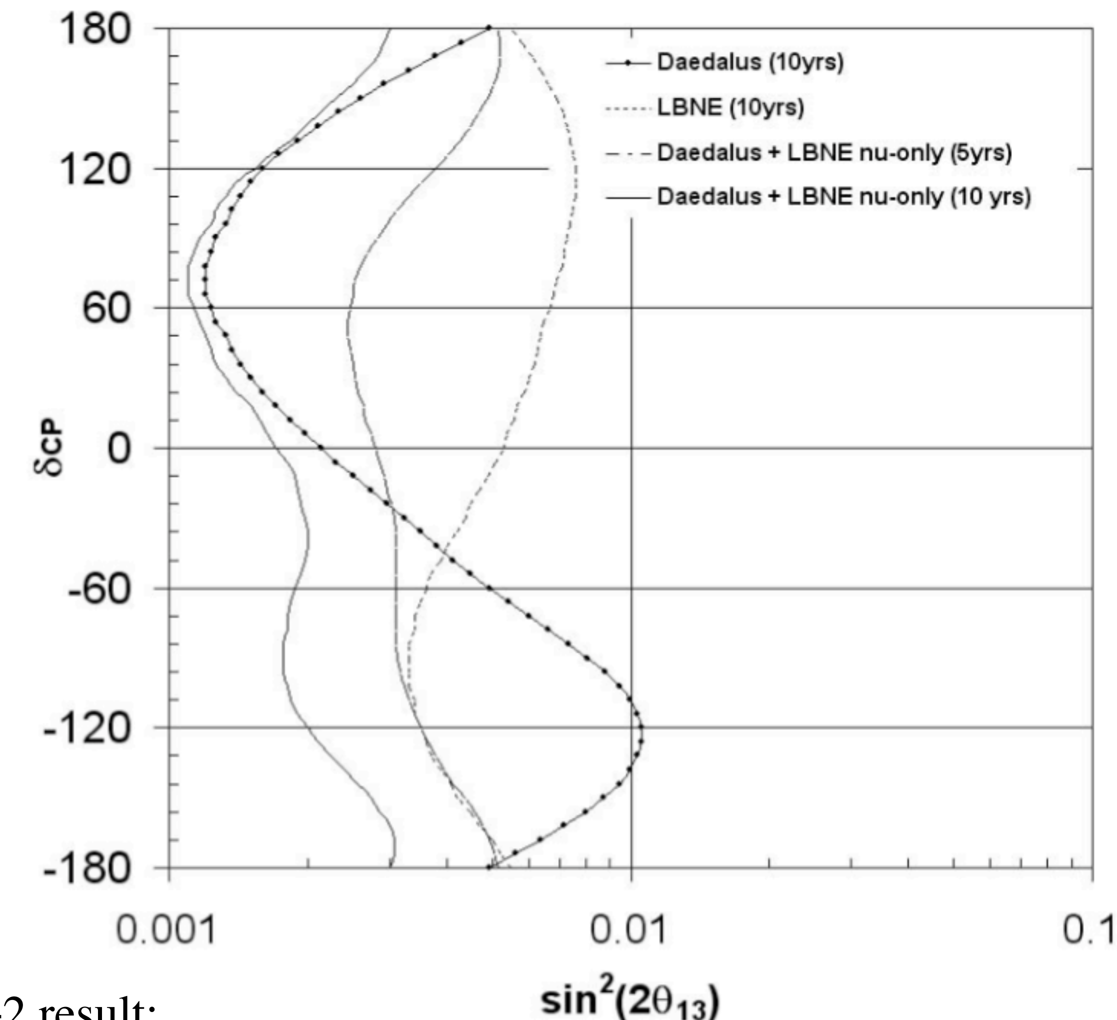
- DAEδALUS events are at low energy and in a narrow energy-window from 20 to 52.8 MeV, while LBNE has a high energy, wide-band (300 MeV to about 10 GeV) signal.

- DAEδALUS has very low backgrounds, coming mainly from beam-off sources which can be well measured from beam-off running, while LBNE has a poorer signal-to-background ratio, but with very different systematics.

As a result of the complementarity, when the two experiments are combined, the sensitivity is substantially improved.

Combining DAEδALUS and LBNE

3σ CL sensitivity for determining non-zero value for θ_{13} as a function of $\sin^2 2\theta_{13}$ and δ_{CP} .



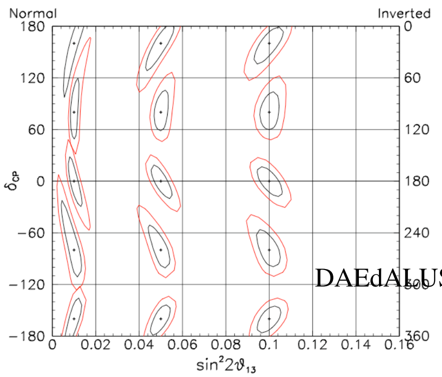
Solid-with-dots: DAEδALUS phase 1+2 result;
Dashed: LBNE proposed running (30×10^{20} POT in ν mode and 30×10^{20} POT in $\overline{\nu}$ mode);
Solid (Dot-dashed): the combined DAEδALUS plus LBNE ν -only result for 10 years (5 years).

For the LBNE input, which is affected by matter effects, we assume normal hierarchy.

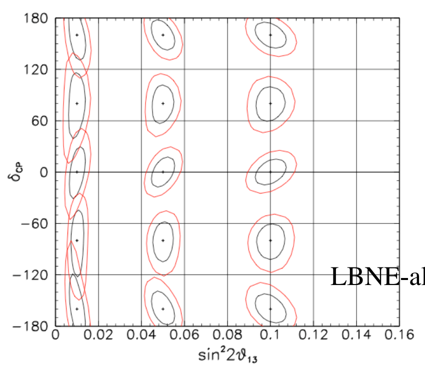
Combining DAEδALUS and LBNE

-One (inner contour) and two (outer contour) σ sensitivities for DAEδALUS + (LBNE ν — 10 yr) scenario.

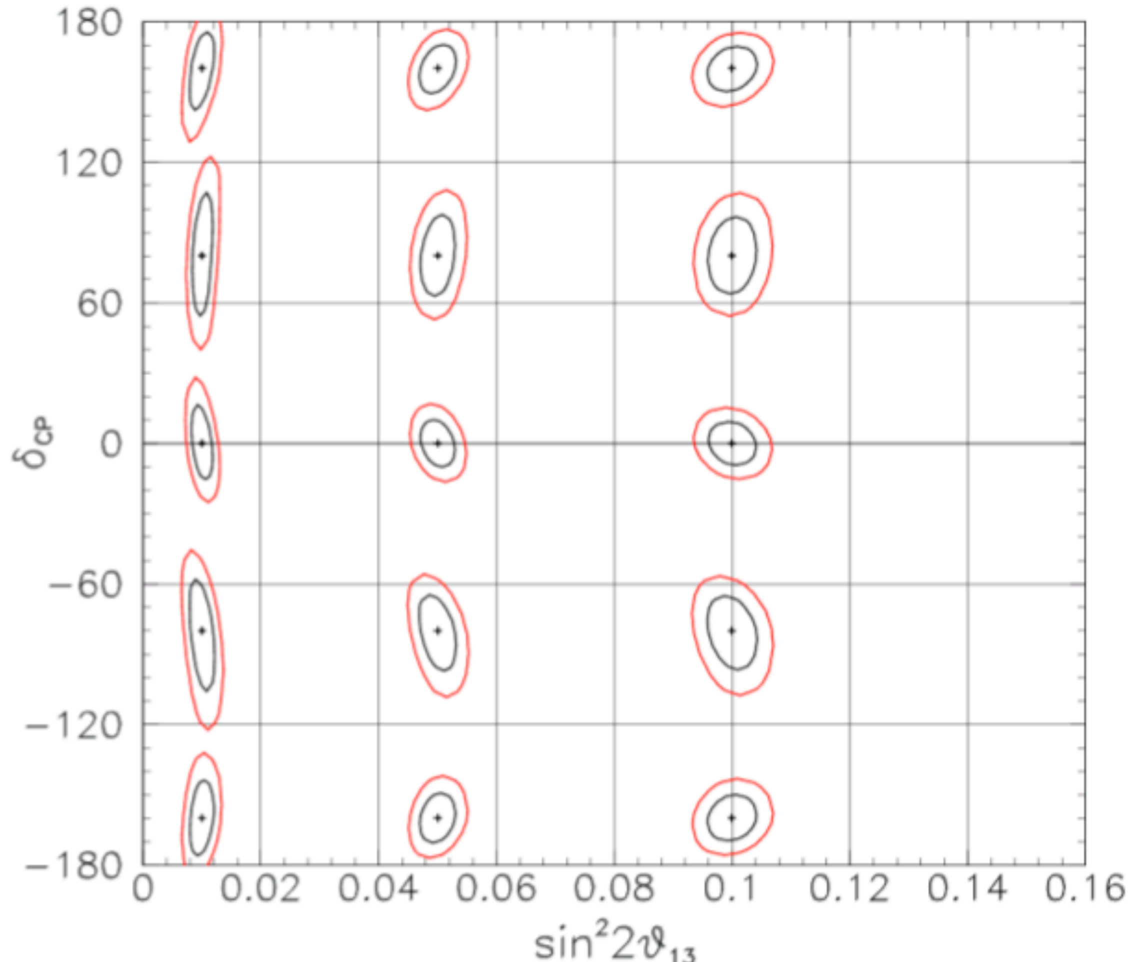
-Normal mass hierarchy assumed for LBNE.



DAEdALUS-alone



LBNE-alone



δ_{CP}	−160°	−80°	0°	80°	160°
LBNE ν (5 yr) + $\bar{\nu}$ (5 yr)	24.5	31.6	21.3	30.8	21.6
DAEδALUS Phase 1+2	17.7	25.3	19.6	23.6	27.2
DAEδALUS+LBNEν –5 yr	16.8	23.7	15.3	25.5	15.0
DAEδALUS+LBNEν –10 yr	10.6	16.2	10.1	17.3	10.4

1σ measurement uncertainty on δ_{CP} for various scenarios and $\sin^2 2\theta_{13} = 0.05$.

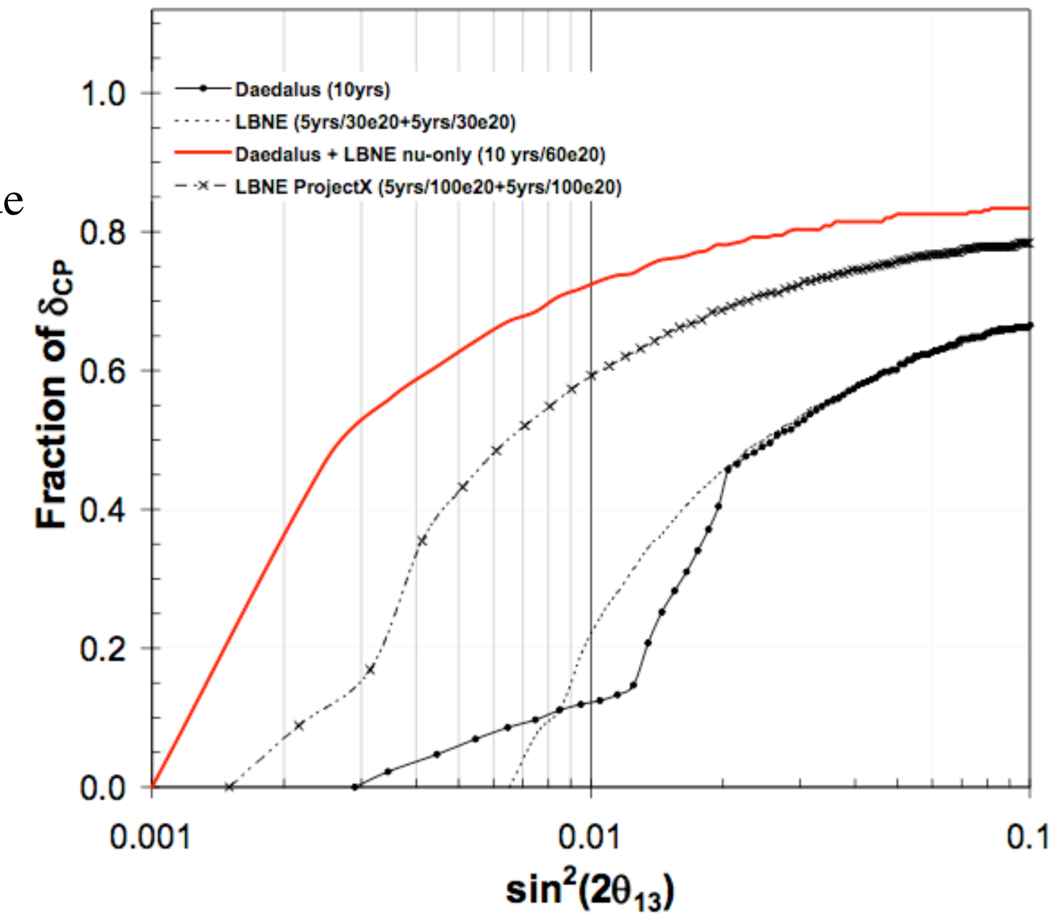
3 σ Discovery of CP-violation: Comparing to Project X

Project X proposal at Fermilab would supply 100×10^{20} protons on target to LBNE beamline in a 5 year time period.

Assume a "Project-X scenario" for LBNE: 5 year run in ν mode + 5 year run in $\bar{\nu}$ mode

Region in δ_{CP} and $\sin^2 2\theta_{13}$ space over which measurement can be differentiated from 0 or 180° at 3σ.

Normal mass hierarchy is assumed for LBNE.



Combining DAEδALUS and LBNE: Various Configurations

Consider three types of detector "units":

-WCGd: 100 kt Gd-doped water Cerenkov detector with ≈ 20% high quantum efficiency PMT cover-age and/or light concentrators to realize good efficiency for ~5 MeV Cherenkov light signal expected from neutron capture on Gd.

-WC: 100 kt water Cerenkov detector modules with 15% high quantum efficiency PMT coverage.

-LAr: 17 kt of LAr.

arXiv: 1008.4967
(submitted to PRD)

Consider three types of neutrino sources, with 10 year running-periods:

-LBNE alone: 30×10^{20} POT in ν mode + 30×10^{20} POT in $\bar{\nu}$ mode.

-DAEδALUS alone: only $\bar{\nu}$ mode: 1MW at 1.5 km, 2 MW at 8 km, and 5 MW at 20 km.

-DAEδALUS + LBNE combined: LBNE in ν mode only + standard DAEδALUS.

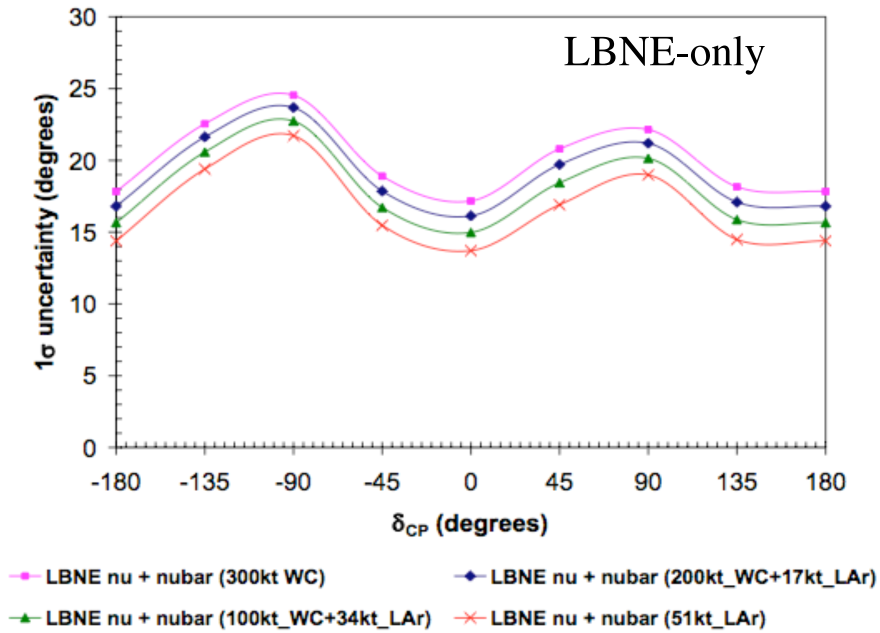
Study the following configurations:

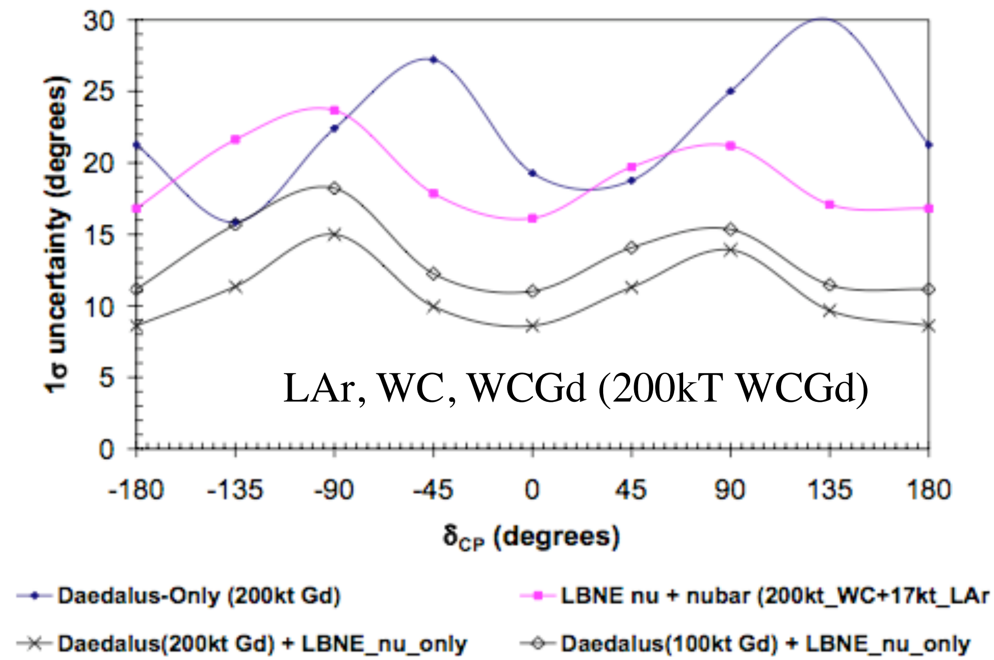
Rank	Source	Configuration	1σ error
1.	DAEδALUS alone	1×WCGd	34°
2.	LBNE alone	3×WC	25°
3.	LBNE alone	2×WC+1×LAr	24°
4.	LBNE alone	1×WC+2×LAr	23°
5.	DAEδALUS alone	2×WCGd	22°
6.	DAEδALUS + LBNE	1×WCGd+2×WC	18°
7.	DAEδALUS alone	3×WCGd	17°
8.	DAEδALUS + LBNE	2×WCGd+1×WC	15°
9.	DAEδALUS + LBNE	2×WCGd+1×LAr	15°
10.	DAEδALUS + LBNE	3×WCGd	13°

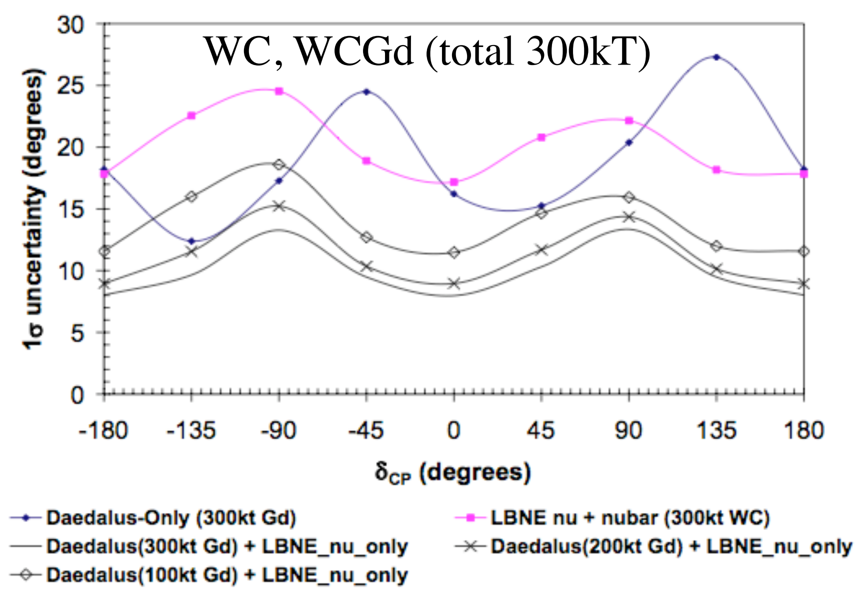
Comparison of configurations for $\sin^2 2\theta_{13} = 0.05$ and $\delta_{CP} = -90^0$. Rank=1 is worst, Rank=10 is best.

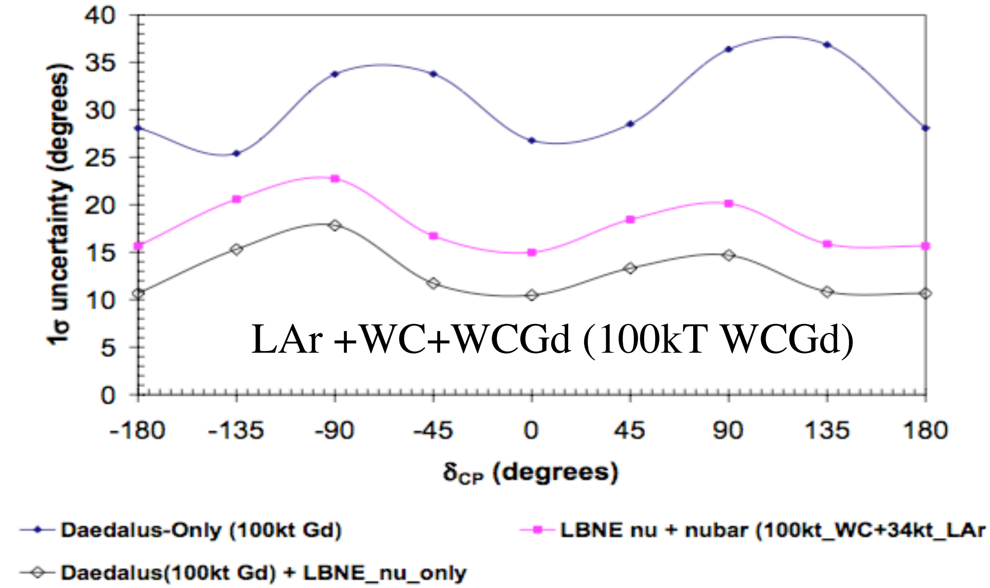
Combining DAEδALUS and LBNE: Various Configurations

The δ_{CP} sensitivity at 1σ as a function of δ_{CP} for various configurations of WC, WCGd, and Lar.









Physics Opportunities with the DAEδALUS Near Accelerator

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

-Calibration beam for LBNE.

-Beam can also be used by short baseline experiments using small detectors made of various materials.

-Coherent neutrino nucleus scattering.

-Measurement of $\sin^2\theta_w$.

-Nonstandard interactions (i.e. n mass or SUSY effects).

-Cross section measurements on various targets.

-Relevant for Supernova detection.

-Relevant for nucleosynthesis.

-Neutrino Magnetic Moment.

-Strange spin of the nucleon.

-Many opportunities for small scale experiments!

Conclusion

-DAEδALUS will broaden the reach of DUSEL for exploring neutrino oscillation physics and especially δ_{CP}.

- -Daedalus will provide a high precision measurement of CP violation that is unique in that it utilizes antineutrinos.
  - -Low backgrounds with high statistics.
  - -No matter effects.
- -Combining the Daedalus antineutrino data and LBNE neutrino sample is very powerful for extracting the oscillation physics.
- -The near accelerator will also provide a large data set for:
  - -Physics studies of leptonic processes.
  - -Calibration data for the large water Cerenkov detector.

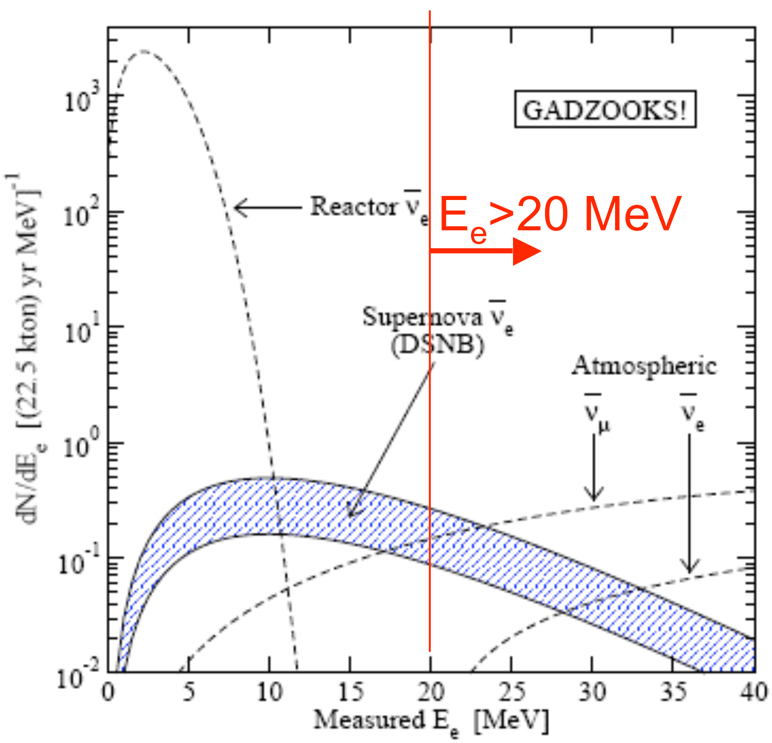
-Technical issues:

- -Need to develop low-cost high-power (1-3 MW) cyclotrons → under way.
- -Need to dope Water Cerenkov detectors with Gadolinium and have PMT coverage to detect neutron capture.

Backup Slides

Background Processes and Rates

- Non-beam IBD backgrounds (E_{vis} > 20 MeV):
  - Atmospheric $\bar{\nu}_\mu$ Invisible muons: $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ where μ^+ is below Cherenkov threshold.
  - Atmospheric $\bar{\nu}_e$ IBD events: $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Diffuse supernova neutrinos



- Beam related IBD backgrounds
  - Intrinsic $\bar{\nu}_e$ in beam
    - ~4 × 10^{-4} ν_e rate
  - Beam ν_e in coincidence with random neutron capture
    - Estimated to be very small from Super-K rates
  - ν_e-Oxygen CC scatters producing an electron
    - Subsequent neutrons from nuclear de-excitation are very small.

Systematic Uncertainties

-Before the fit

IBD from osc nuebar	Fractional Uncertainty
eff neutron detection	0.025
pi+ prod/proton	0.100
Fiducial volume	0.000
Total	0.110
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	
	0.040
nue-Oxygen scattering	
xsec error	0.200