

THE DEEP UNDERGROUND NEUTRINO EXPERIMENT PHYSICS PROGRAM

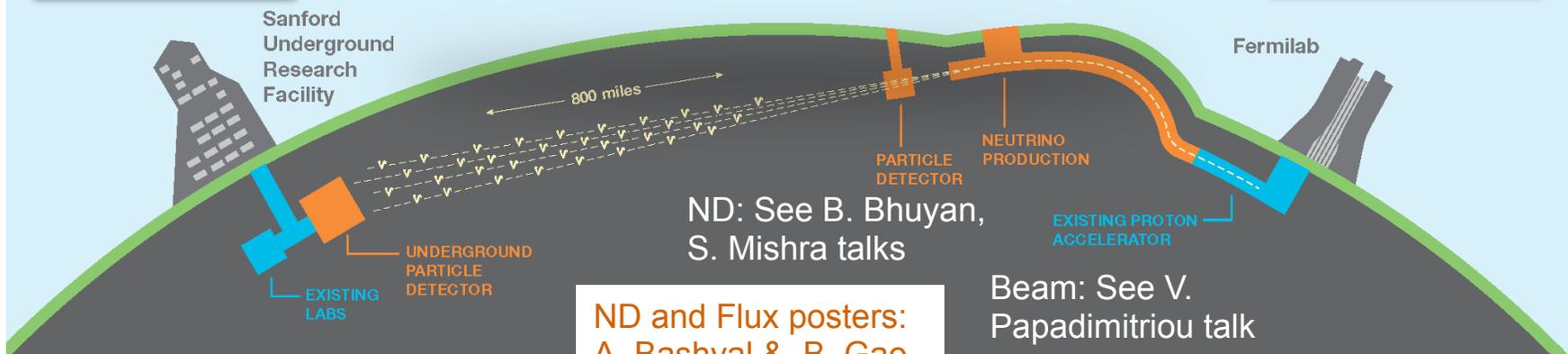
Elizabeth Worcester for the DUNE Collaboration
ICHEP, August 3-10, 2016
Chicago



DUNE



Measure ν_e appearance and ν_μ disappearance in a wideband neutrino beam at 1300 km to measure θ_{13} , CPV, and neutrino mixing parameters in a single experiment. Large detector, deep underground provides sensitivity to nucleon decay and supernova burst neutrinos.



DUNE Collaboration



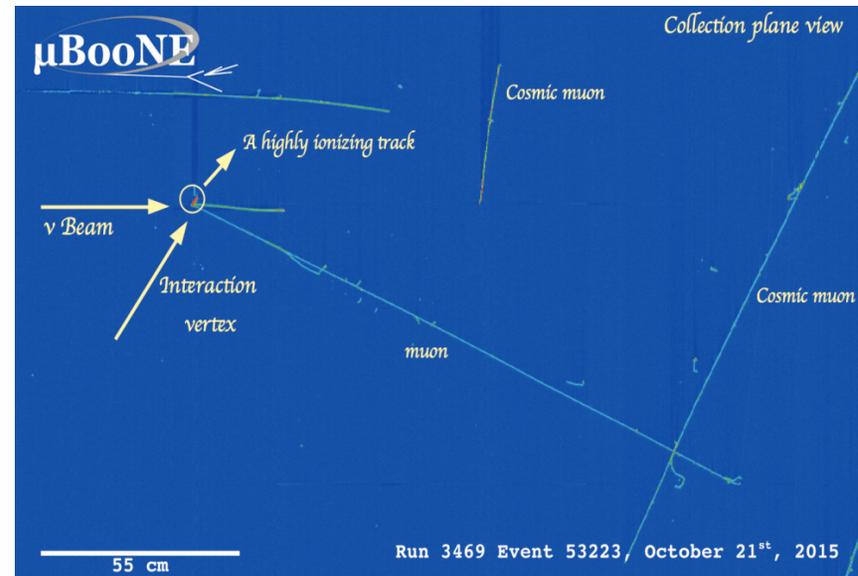
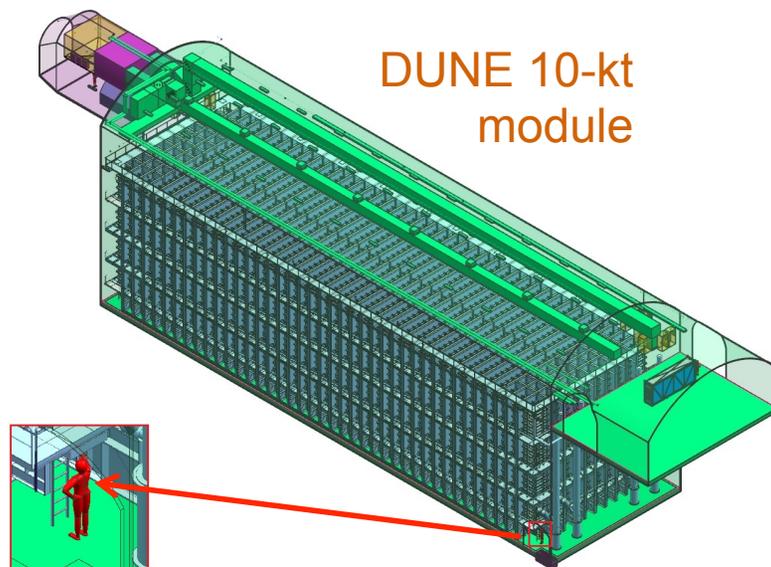
890 collaborators from 154 institutions in 28 nations



May 2016

DUNE Far Detector

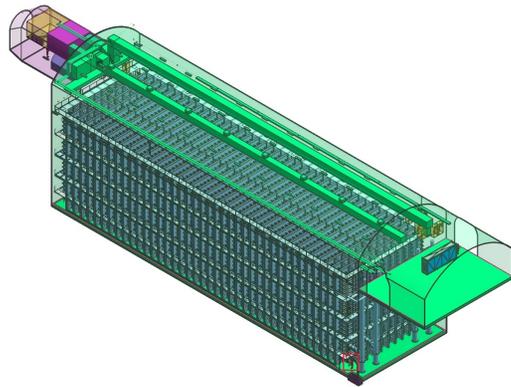
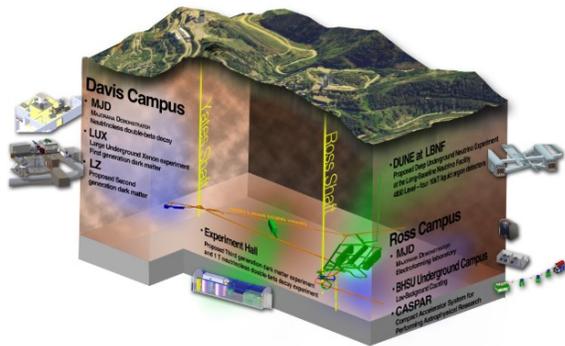
See A. Himmel talk



Getting from signals on wires to reconstructed events is non-trivial. See T. Yang talk.

- 40-kt (fiducial) liquid argon TPC at 4850L of SURF
 - Four 10-kt (fiducial) modules
- First module will be a single phase LArTPC
- Modules installed in stages; modules probably will not be identical

DUNE Timeline



2017: Far Site Construction Begins



2018: protoDUNEs at CERN



2021: Far Detector Installation Begins

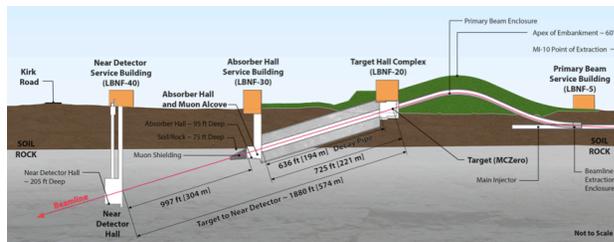
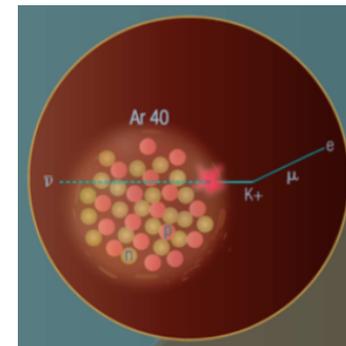


2024: Physics Data Begins (20 kt)



2026: Neutrino Beam Available

The CERN Neutrino Platform

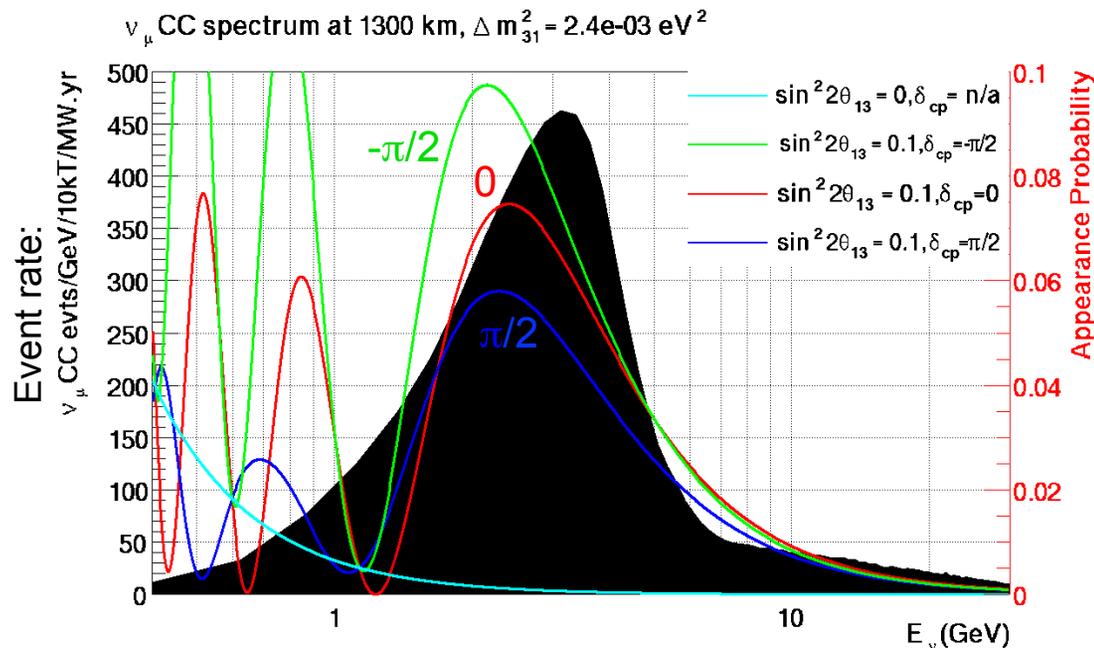


ν_e Appearance

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) \simeq & \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 \\
 & + \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \frac{\sin(aL)}{aL} \Delta_{21} \cos(\Delta_{31} - \delta_{CP}) \\
 & + \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{aL^2} \Delta_{21}^2,
 \end{aligned}$$

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

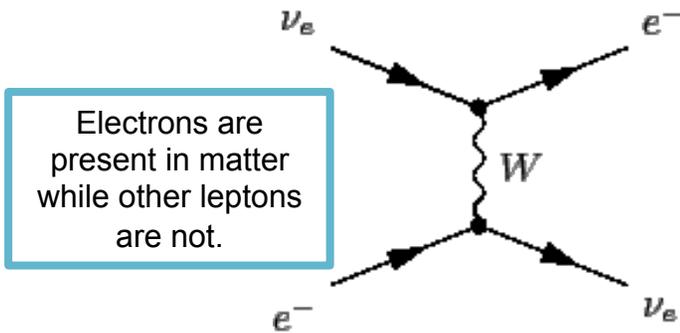
$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$



- ν_e appearance amplitude depends on θ_{13} , θ_{23} , δ_{CP} , and matter effects – measurements of all four possible in a single experiment
- Large value of $\sin^2(2\theta_{13})$ allows significant ν_e appearance sample

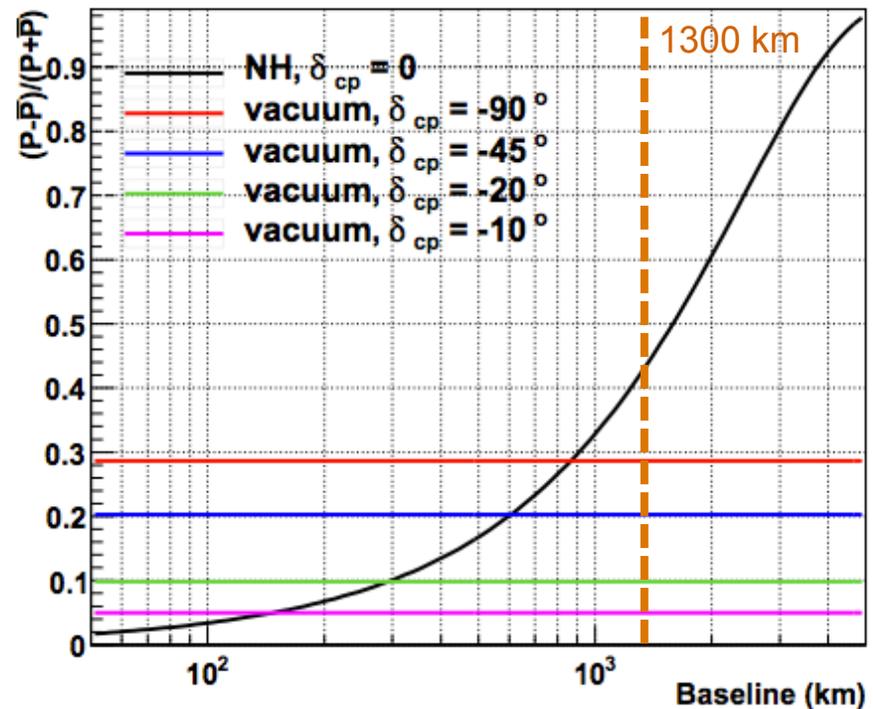
Matter and CP Asymmetry

Charged-current coherent forward scattering on electrons:



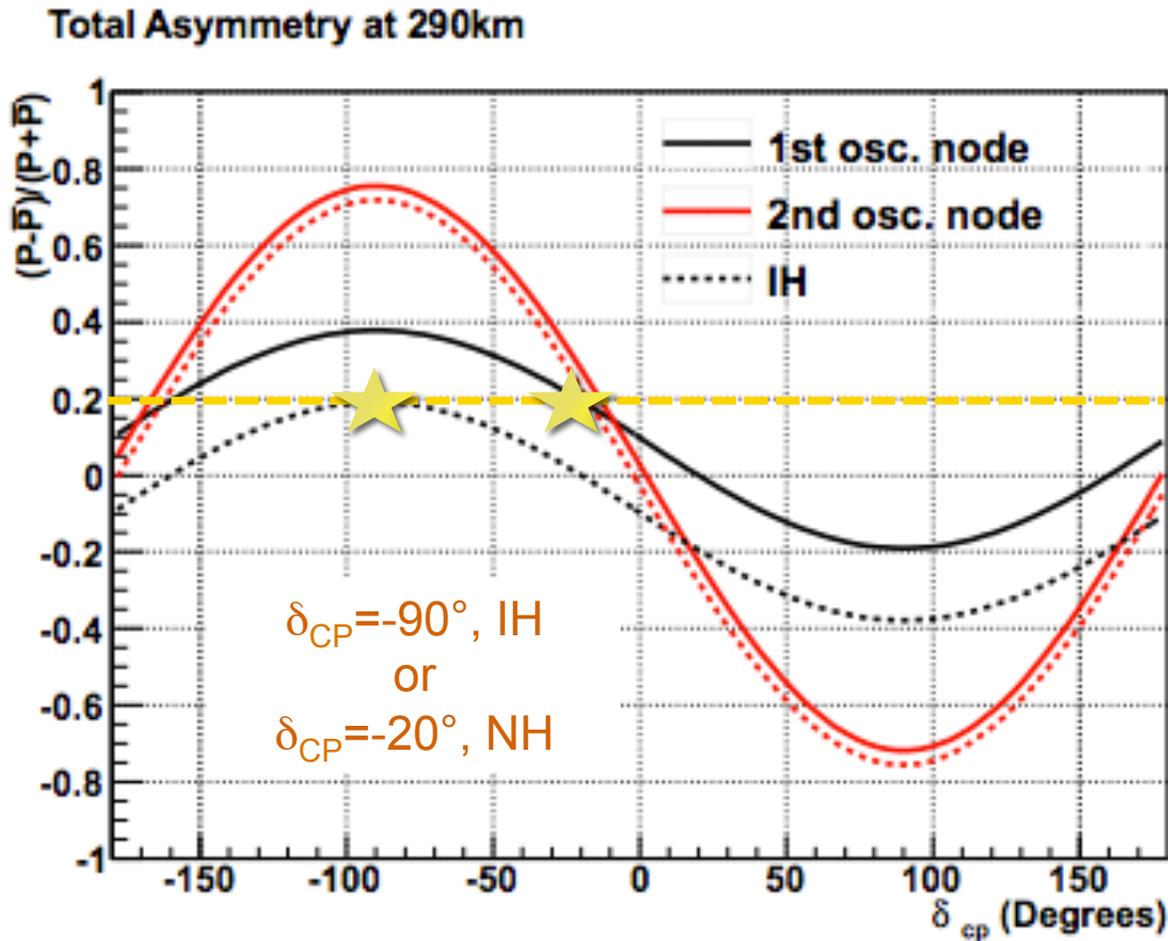
- CC process occurs for electron neutrinos only; muon and tau have only NC interactions with electrons
- Normal hierarchy: matter effect enhances appearance probability for neutrinos and suppresses it for antineutrinos (opposite for IH)

CP asymmetries in $\nu_\mu \rightarrow \nu_e$ at 1st osc. node



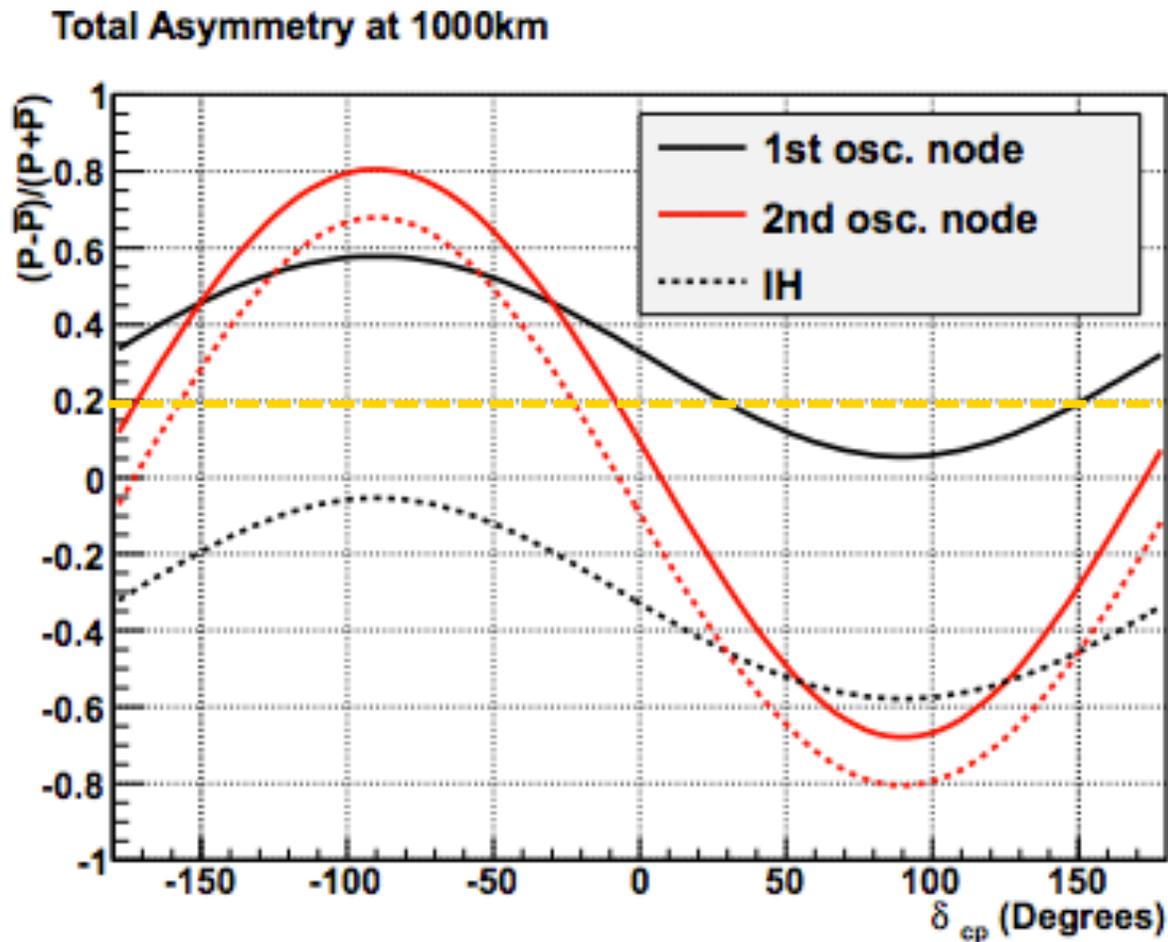
Matter asymmetry very important for long-baseline experiments!

Matter and CP Asymmetry



Degeneracy between CP and matter asymmetry
for 1st oscillation node at short baseline

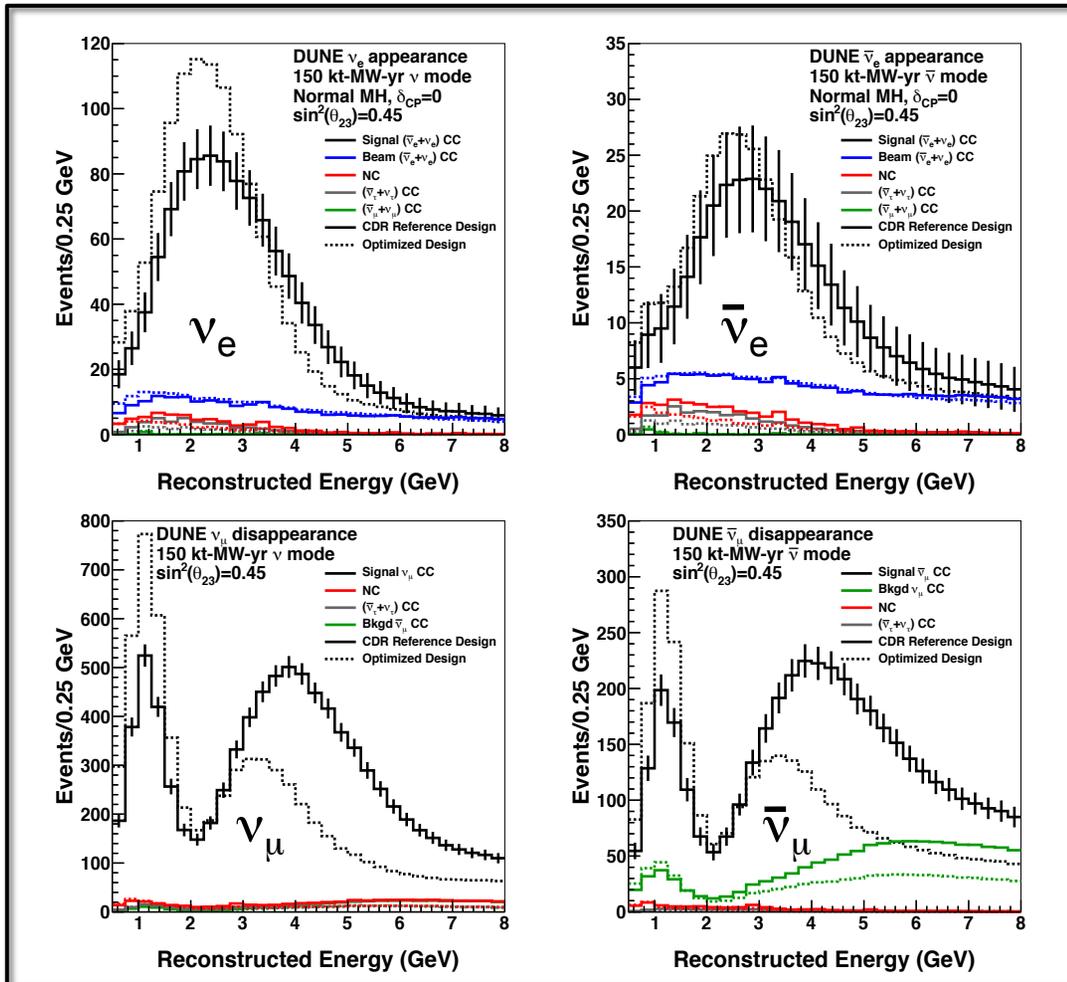
Matter and CP Asymmetry



Longer baseline breaks degeneracy between CP and matter asymmetry
– 1300 km is a near optimal baseline for these measurements

Oscillation Sensitivity Calculations

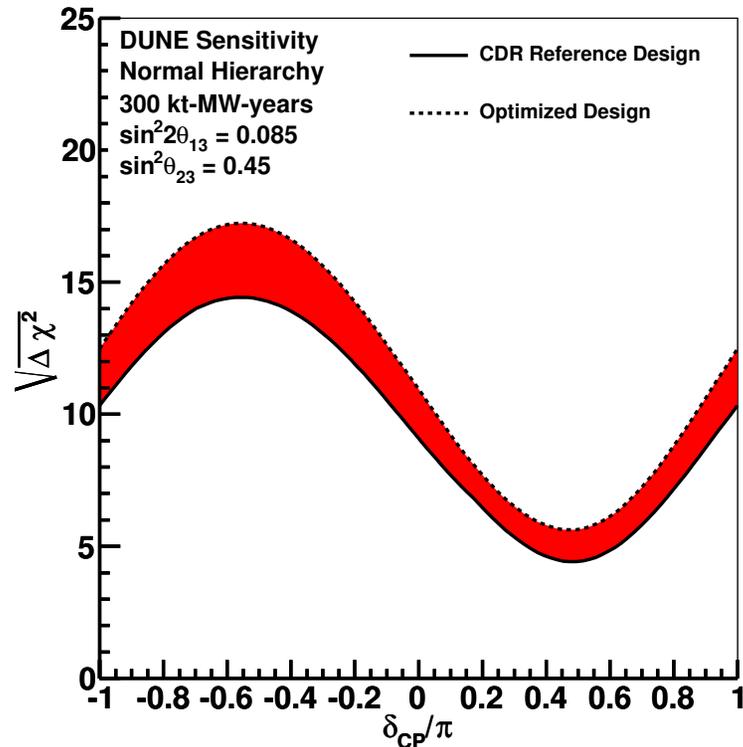
DUNE CDR:



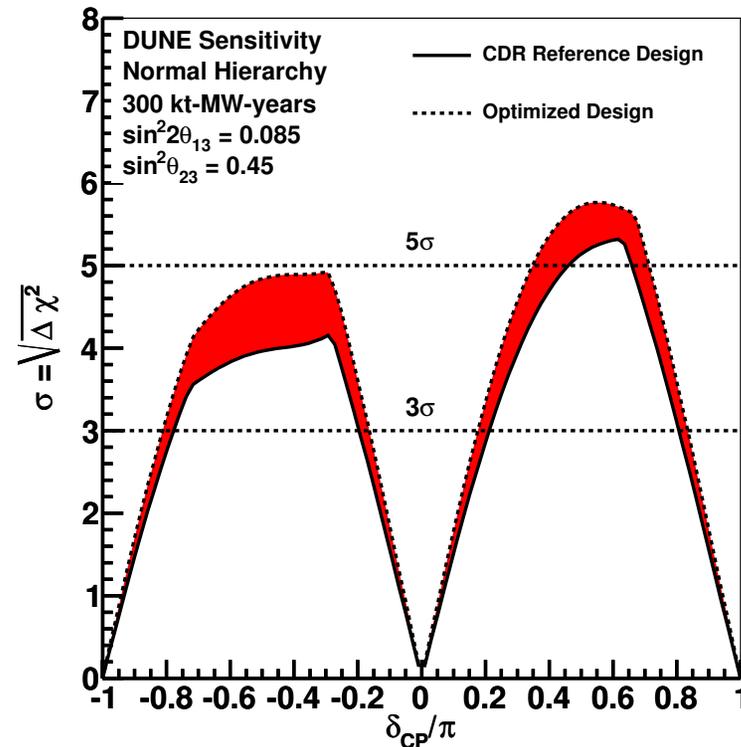
- GLoBES-based fit to four FD samples
- Two neutrino beam line designs shown: optimization of beam design is ongoing
- GENIE event generator
- Reconstructed spectra predicted using detector response parameterized at the single particle level
- Order 1000 ν_e appearance events in ~ 7 years of equal running in neutrino and antineutrino mode
- Simple systematics treatment
- GLoBES configurations
arXiv:1606.09550

MH & CPV Sensitivity

DUNE CDR: Mass Hierarchy



CP Violation



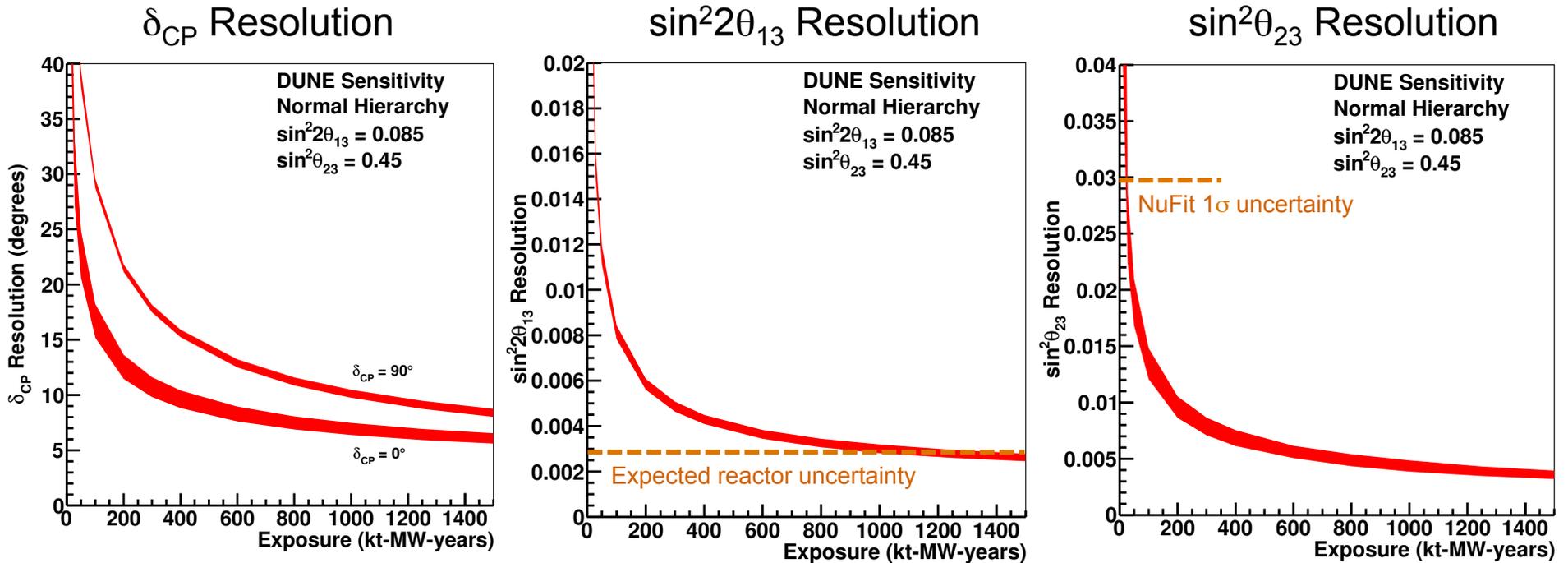
Width of band indicates variation among differing neutrino beam designs.

(See poster by L. Fields for updated beam optimization)

Exposure is 300 kt-MW-yr = 40 kt x 1.07 MW x (3.5 ν +3.5 $\bar{\nu}$) years.
Includes simple normalization systematics and oscillation parameter variations.

Oscillation Parameter Sensitivity

DUNE CDR:

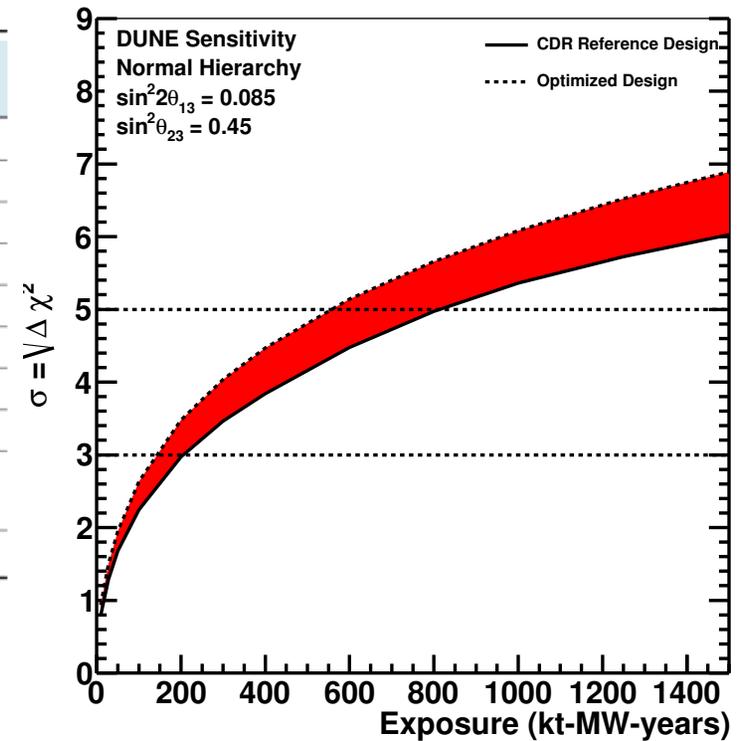


Sensitivity Over Time

DUNE CDR:

CP Violation (50% δ_{CP})

Physics milestone	Exposure kt · MW · year (reference beam)	Exposure kt · MW · year (optimized beam)
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	70	45
CPV at 3 σ ($\delta_{CP} = +\pi/2$)	70	60
CPV at 3 σ ($\delta_{CP} = -\pi/2$)	160	100
CPV at 5 σ ($\delta_{CP} = +\pi/2$)	280	210
MH at 5 σ (worst point)	400	230
10° resolution ($\delta_{CP} = 0$)	450	290
CPV at 5 σ ($\delta_{CP} = -\pi/2$)	525	320
CPV at 5 σ 50% of δ_{CP}	810	550
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	1200	850
CPV at 3 σ 75% of δ_{CP}	1320	850



Interesting measurements will be made throughout the DUNE physics program!

Initial beam power: 1.07 MW at 80 GeV
Planned upgrade to > 2 MW

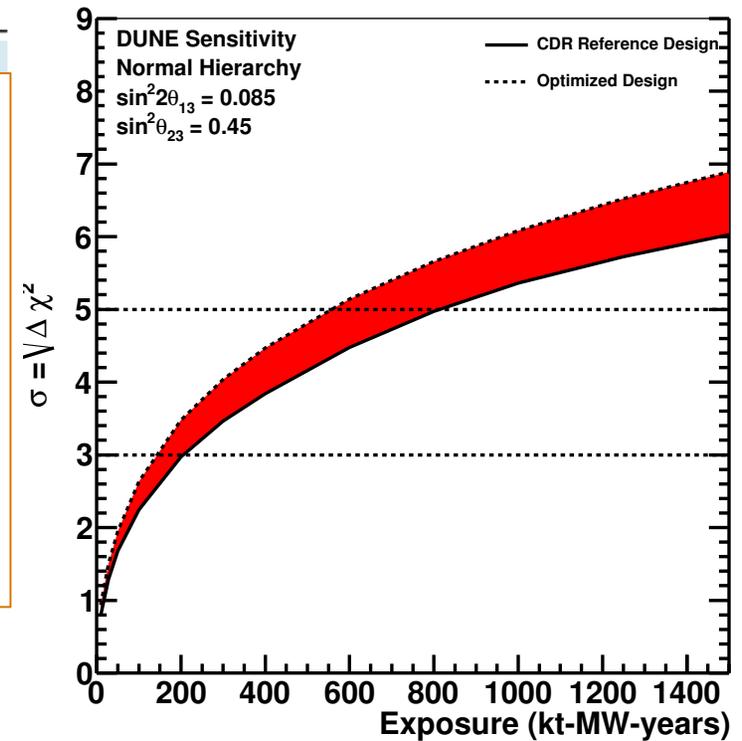
Sensitivity Over Time

DUNE CDR:

Physics milestone	Exposure kt · MW · year	Exposure kt · MW · year
$1^\circ \theta_{23}$ resolution ($\theta_{23} = 42^\circ$):	45 kt-MW-years	
Definitive MH determination ($\geq 5\sigma$ for all values of δ_{CP}):	230 kt-MW-years	
CPV at 5σ ($\delta_{CP} = -\pi/2$):	320 kt-MW-years	
Reactor θ_{13} resolution:	850 kt-MW-years	

Interesting measurements will be made throughout the DUNE physics program!

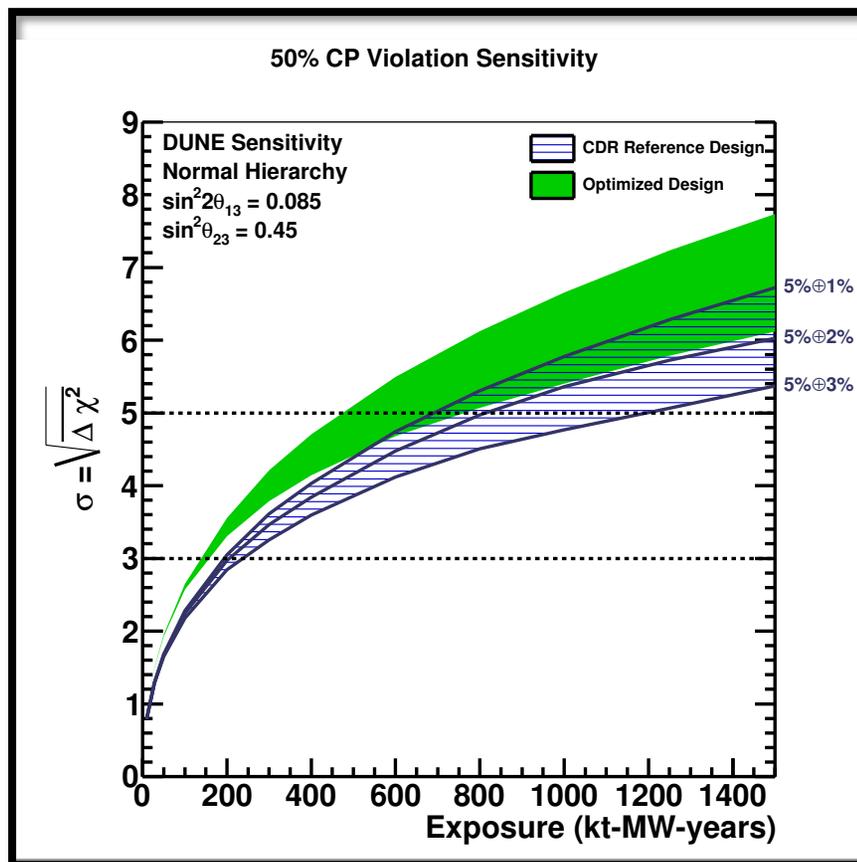
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Systematic Uncertainty

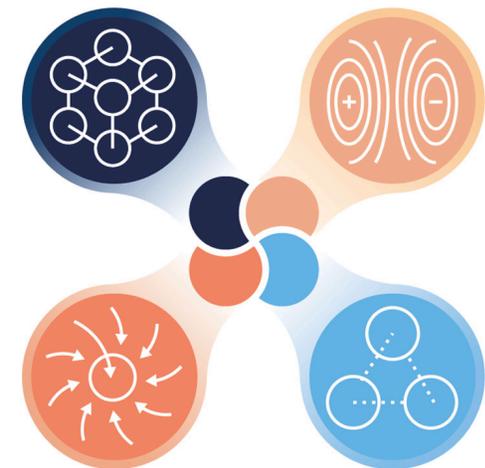
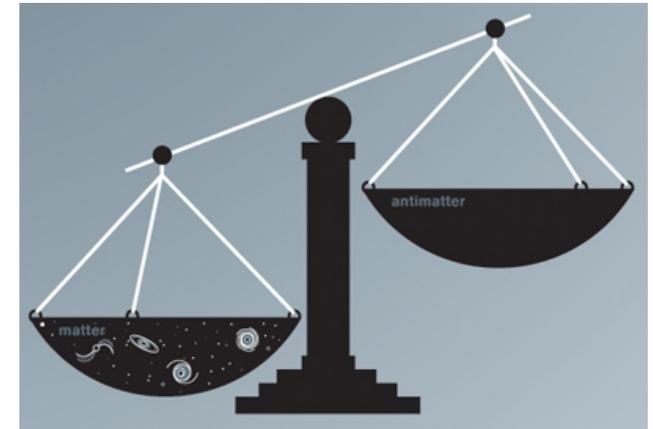
DUNE CDR:



- CPV measurement statistically limited for ~ 100 kt-MW-years
- Sensitivities in DUNE CDR are based on GLoBES calculations in which the effect of systematic uncertainty is approximated using uncorrelated signal normalization uncertainties.
 - $\nu_{\mu} = \bar{\nu}_{\mu} = 5\%$
 - $\nu_e = \bar{\nu}_e = 2\%$
- Uncertainty in ν_e appearance sample normalization must be $\sim 5\% \oplus 2\%$ to discover CPV in a timely manner.

Proton Decay

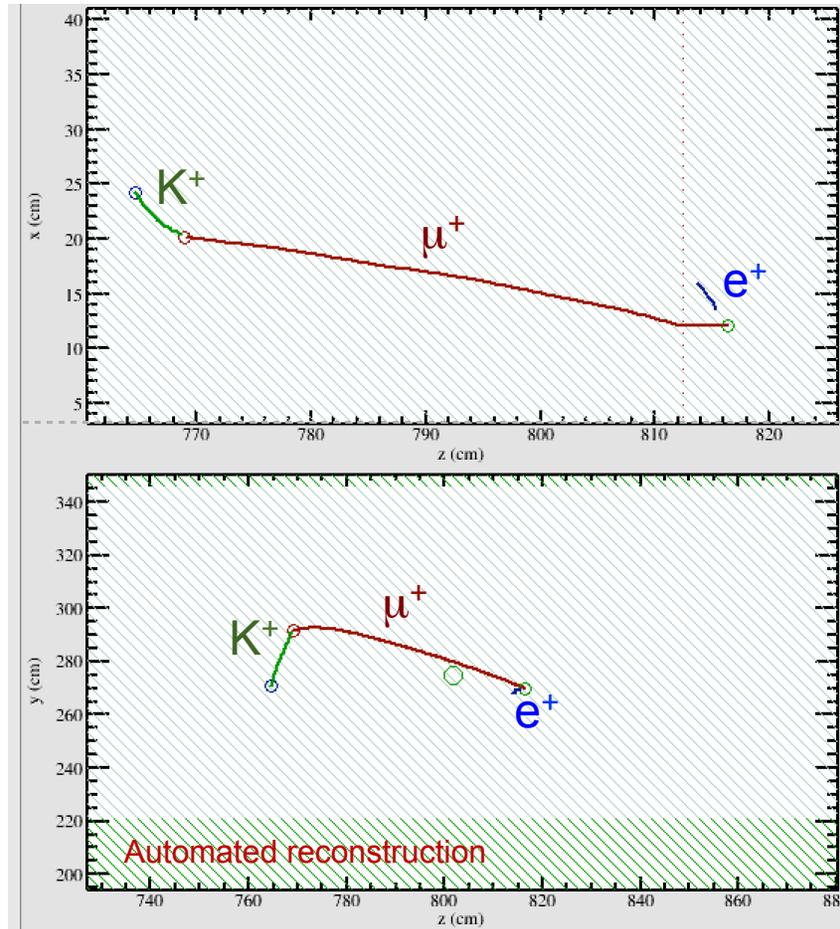
- Test of fundamental symmetries
 - We (so far!) observe conservation of baryon number, but there is no known reason why this must be so
 - Matter-antimatter asymmetry requires baryon number non-conservation (Sakharov)
- Well-motivated Grand Unification Theory models suggest proton decay may exist and be observable
 - GUTs make specific predictions about proton decay modes and branching fractions – we can test these models



Sensitivity to Nucleon Decay

- Detector requirements
 - Low background rate
 - Cosmogenic background (primarily entering neutral kaons and neutrons) reduced by deep underground location
 - Atmospheric neutrinos also a source of background
 - High signal efficiency
 - Precision tracking in LArTPC especially effective for modes with kaons, neutrinos, or complex final state
 - Large exposure (detector mass \times time)
 - 40-kt detector expected to run for 20+ years

Simulated $p \rightarrow \bar{\nu} K^+$ event:

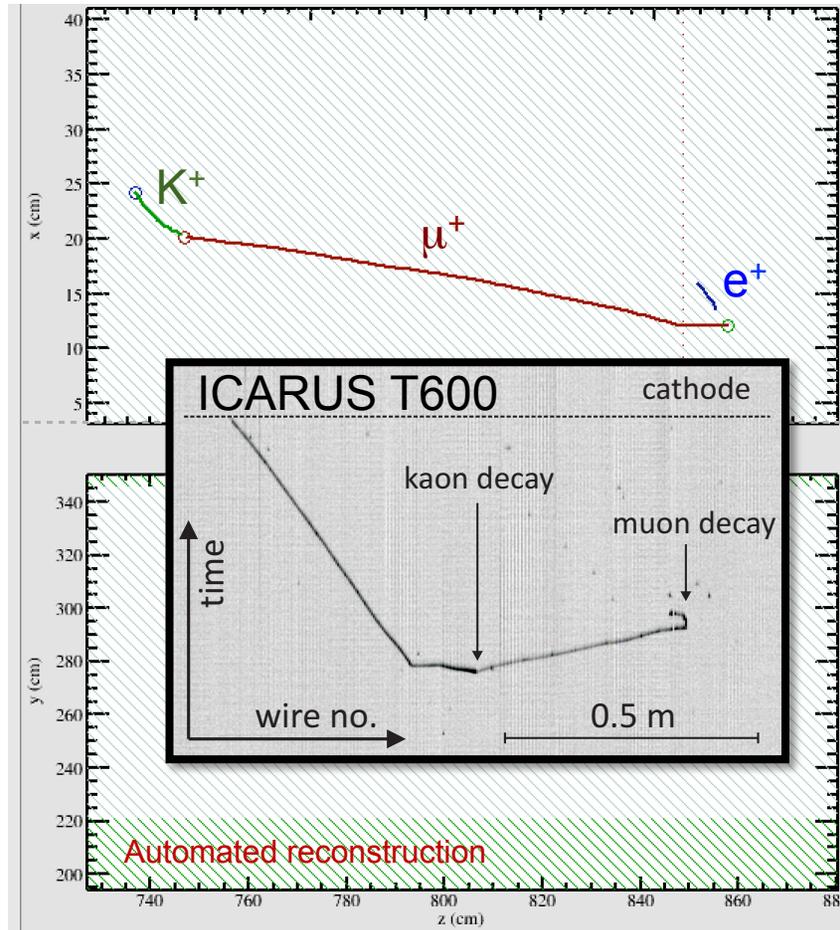


See G. Santucchi poster for more on nucleon decay reconstruction & K. Warburton poster for more on nucleon decay background

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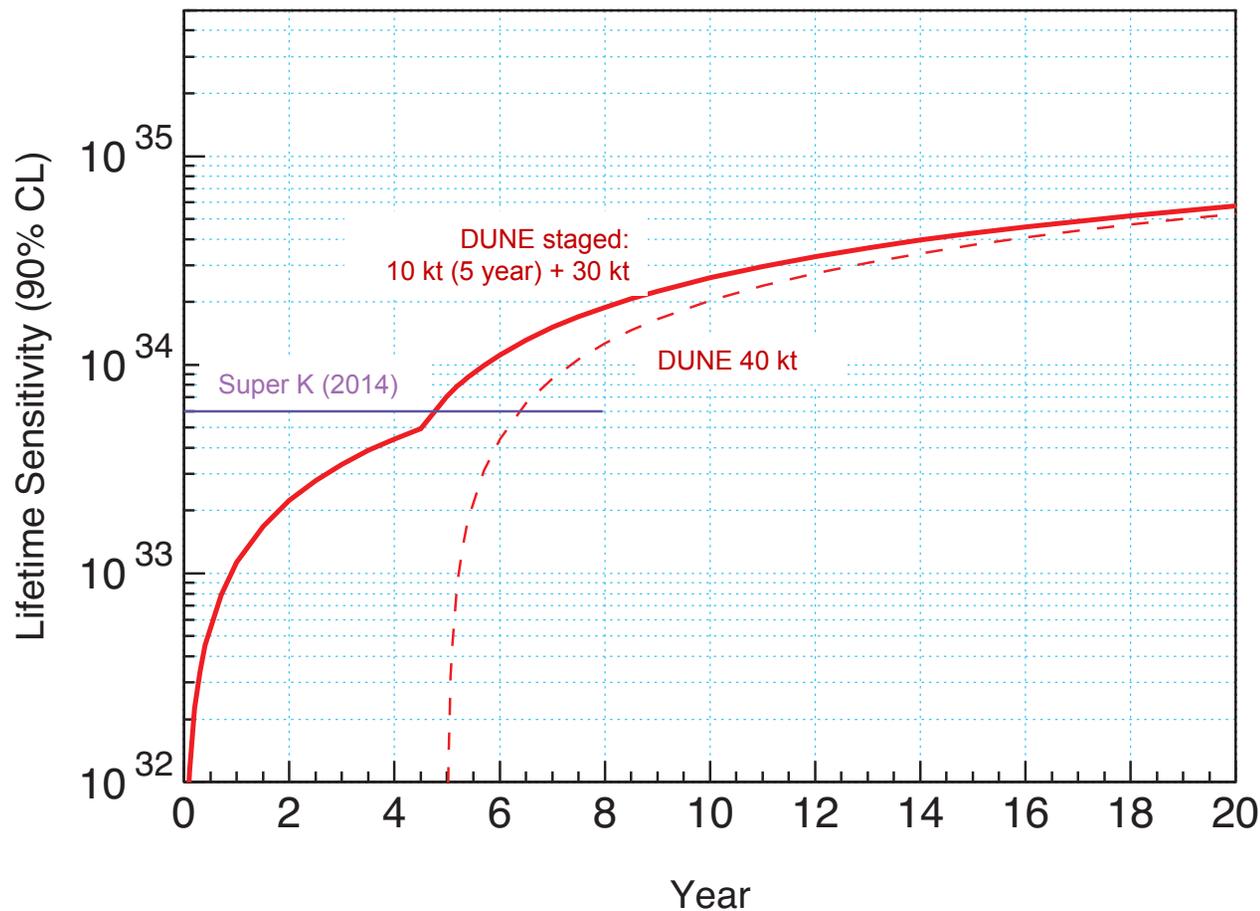
Simulated $p \rightarrow \bar{\nu} K^+$ event:



See G. Santucchi poster for more on nucleon decay reconstruction & K. Warburton poster for more on nucleon decay background

Sensitivity for $p \rightarrow \bar{\nu} K^+$

Low-background mode with high detection efficiency.
DUNE will do well in decay modes with kaons, and modes with neutrinos or with complicated topologies.



$p \rightarrow \bar{\nu} K^+$ in DUNE:

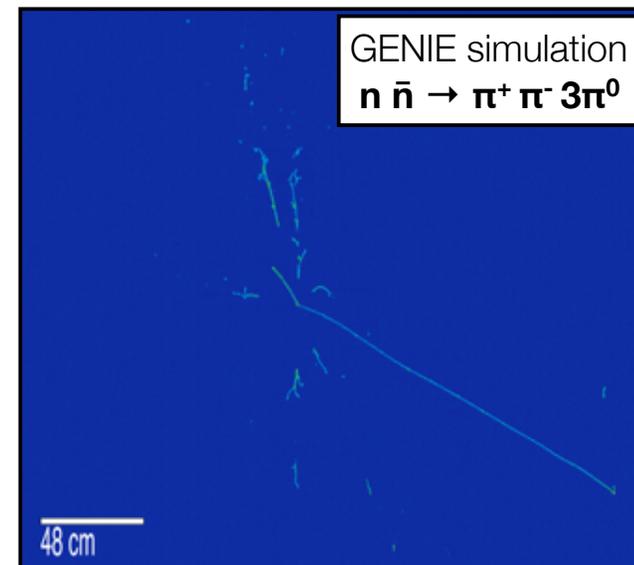
- ~97% signal efficiency
- ~1 background event/Mt-year

SuperK result:
Phys. Rev. D 90,
072005 (2014)

Neutron-antineutron Oscillation

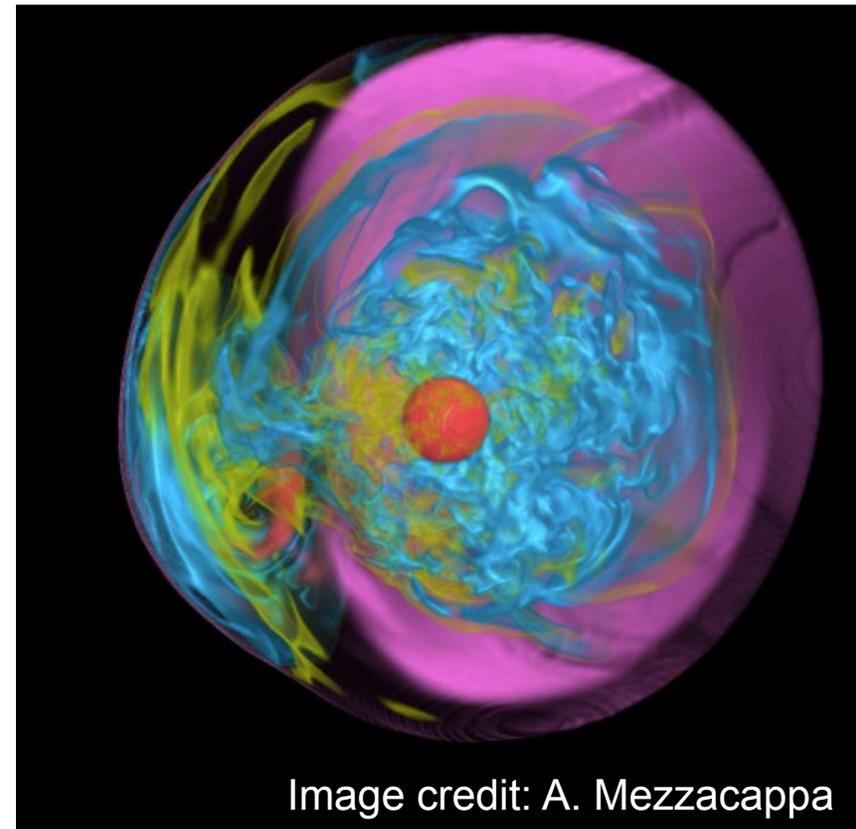
- Beyond Standard Model $|\Delta B=2|$ process, sibling to proton decay.
- Current limit $\tau > 2.7 \times 10^8$ s (90% CL) from Super-Kamiokande. [Phys. Rev. D 91, 072006 \(2015\)](#)
- Signature in LArTPC is spherical cascade of π s with total $\mathbf{E} = \sim 2$ GeV & $\mathbf{p} < \sim 300$ MeV.
- Potential for improvement in DUNE:
 - Large exposure.
 - Good spatial resolution.
 - Improved particle ID.
 - Low background rate.

$\bar{n}+p$		$\bar{n}+n$	
$\pi^+\pi^0$	1%	$\pi^+\pi^-$	2%
$\pi^+2\pi^0$	8%	$2\pi^0$	1.5%
$\pi^+3\pi^0$	10%	$\pi^+\pi^-\pi^0$	6.5%
$2\pi^+\pi^-\pi^0$	22%	$\pi^+\pi^-2\pi^0$	11%
$2\pi^+\pi^-2\pi^0$	36%	$\pi^+\pi^-3\pi^0$	28%
$2\pi^+\pi^-2\omega$	16%	$2\pi^+2\pi^-$	7%
$3\pi^+2\pi^-\pi^0$	7%	$2\pi^+2\pi^-\pi^0$	24%
		$\pi^+\pi^-\omega$	10%
		$2\pi^+2\pi^-2\pi^0$	10%



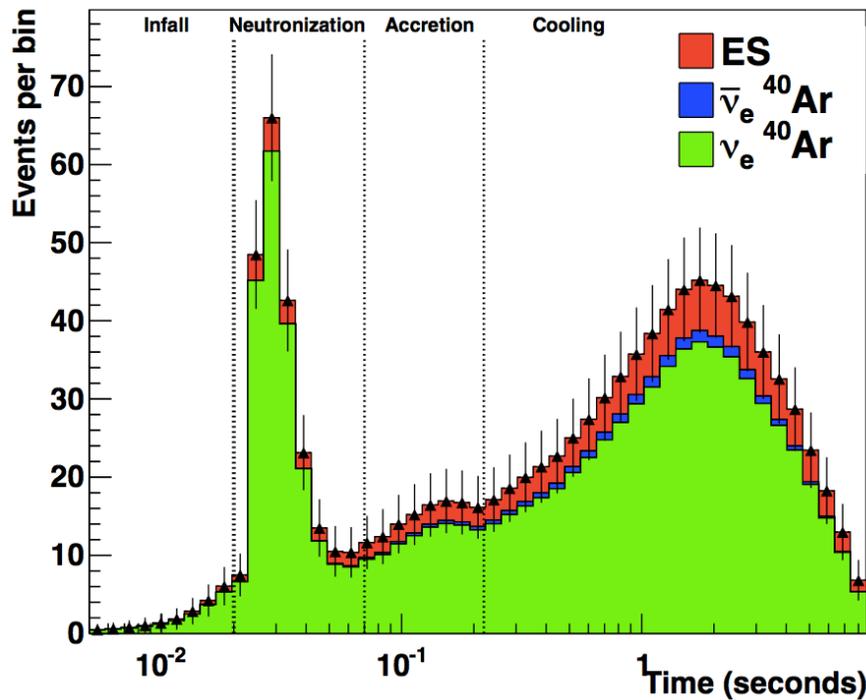
Neutrinos from Stellar Core Collapse

- More than 99% of energy in supernova burst is emitted in the form of neutrinos with energy $\mathcal{O}(10 \text{ MeV})$
- Basic physical model of SNB understood and confirmed by observation of SN1987a but many details remain to be understood
- High-statistics observation of SNB neutrinos, with sensitivity to flavor components, of interest both for astrophysics and neutrino physics

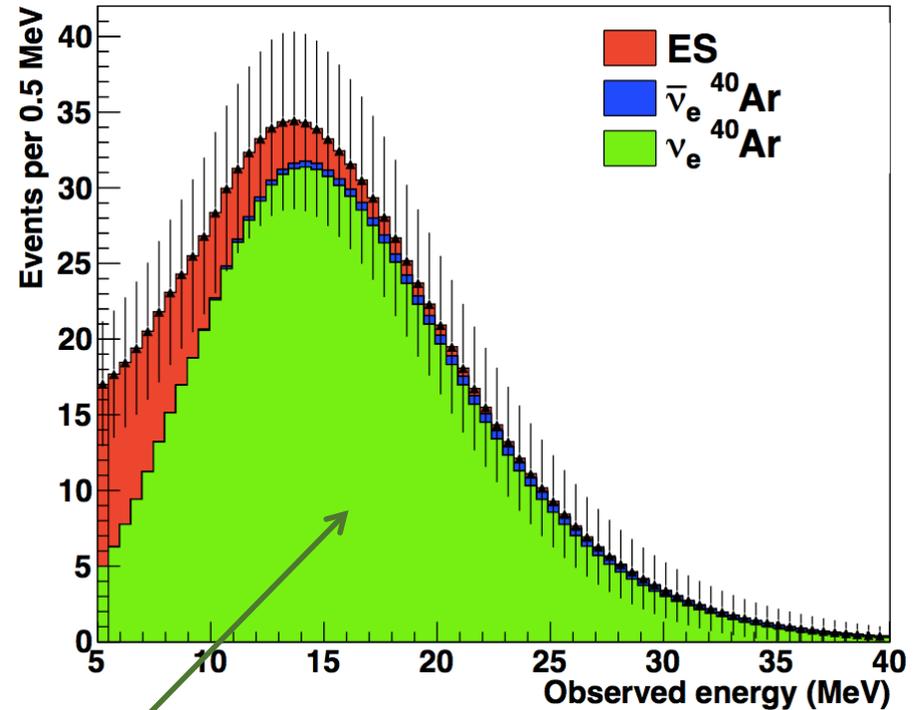


Supernova Signal in DUNE

Flavor composition as function of time:



Energy spectra integrated over time:



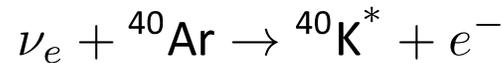
Electron flavor dominant

Allows mapping of neutronization burst, which is dominated by ν_e

For 40-kt LArTPC, SNB @ 10 kpc, “Garching” model (Significant variation among models)

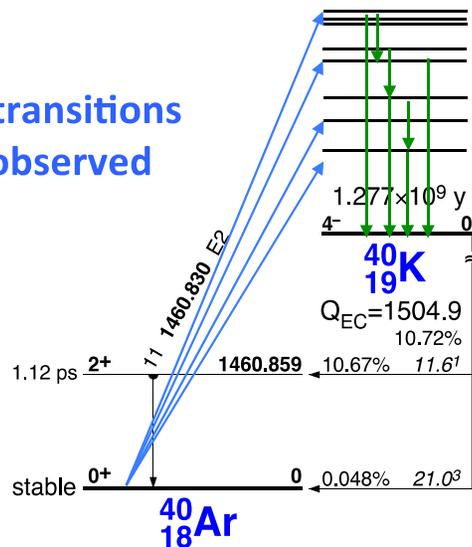
Supernova Neutrino Detection

Charged-current absorption:



At least 25 transitions have been observed indirectly

(g.s. to g.s. is 3rd forbidden transition)



Transition levels are determined by observing de-excitations (γ 's and nucleons)

Transitions to particle-unbound levels occur with many competing de-excitation channels

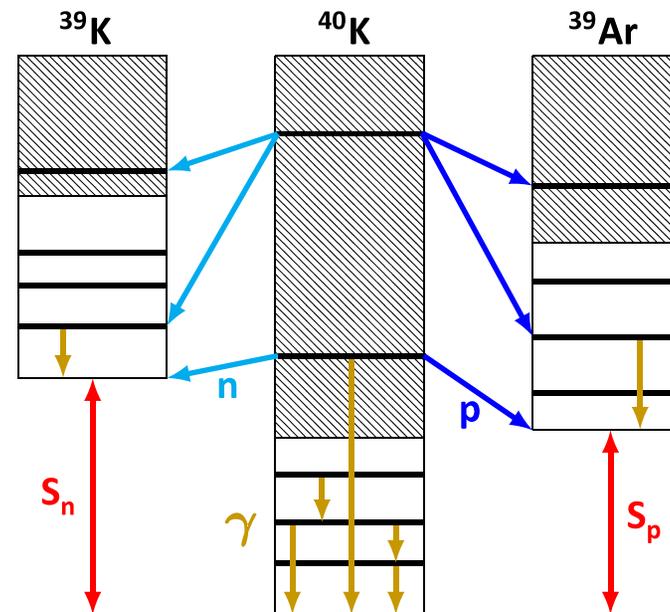
Large uncertainties in nuclear data and models complicate energy reconstruction

Reconstructing true neutrino energy:

Q is determined by measuring de-excitation gammas and nucleons

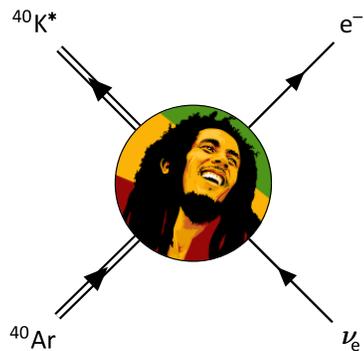
Outgoing e^- Energy Energy donated to transition Recoil Energy of Nucleus (negligible)

$$E_\nu = E_e + Q + K_{\text{recoil}}$$



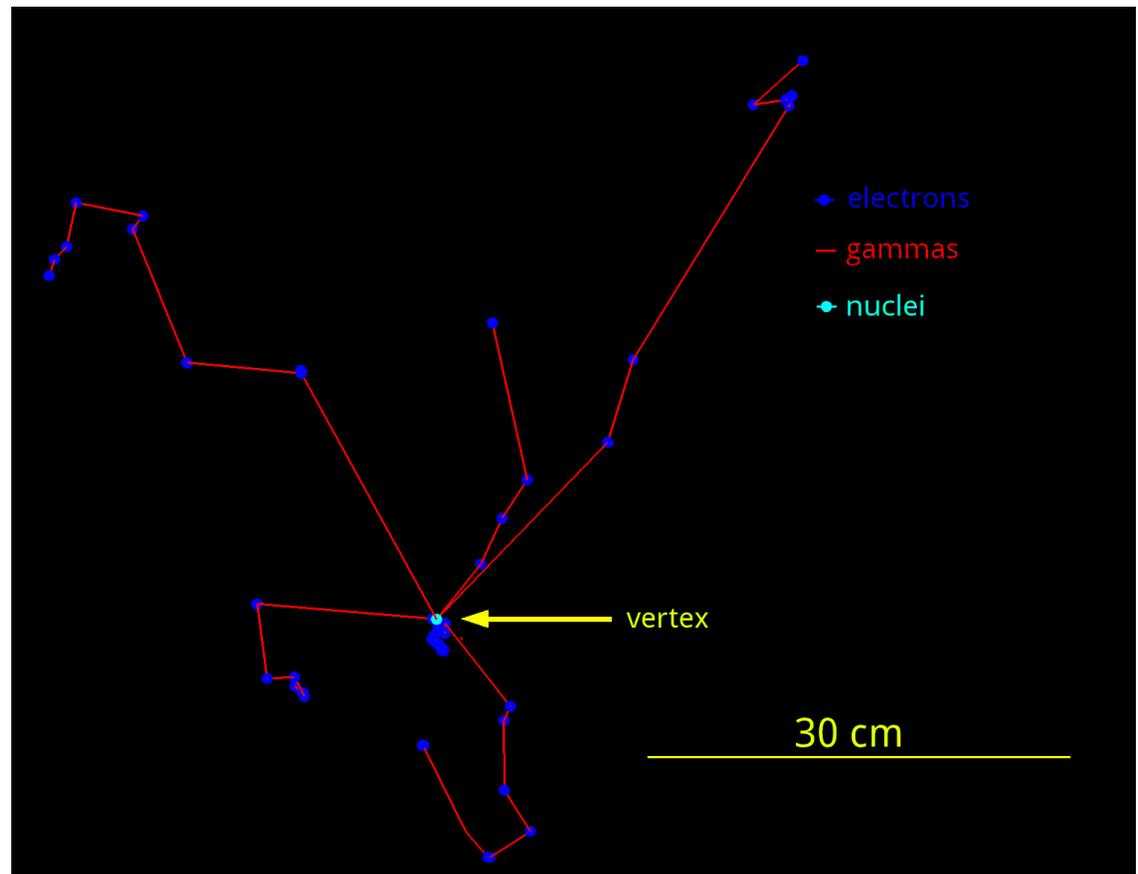
SNB Neutrino Simulation

LArSoft: A multi-experiment LArTPC simulation package
Contributed to and used by DUNE collaborators



MARLEY: Model of Argon Reaction Low-Energy Yields
An event generator for supernova neutrinos in liquid argon

Simulated charged-current supernova ν_e event:



Summary



- DUNE will address fundamental physics questions
 - Baryon asymmetry (CP violation + nucleon decay)
 - Grand unified theories
 - Supernovae
- Long-baseline neutrino oscillation experiment in a broad band beam allows simultaneous measurement of mass hierarchy, CP-violating phase, and neutrino mixing angles
 - Comparison to other oscillation channels allows unitarity test
 - Sensitive to new physics affecting oscillation probabilities ([see phenomenology talks later today](#))
- Deep underground location and precision tracking facilitates sensitivity to baryon non-conservation and supernova burst neutrinos
- DUNE physics program will produce interesting results at each stage of 20+ year operation

Thanks!



Lead, SD

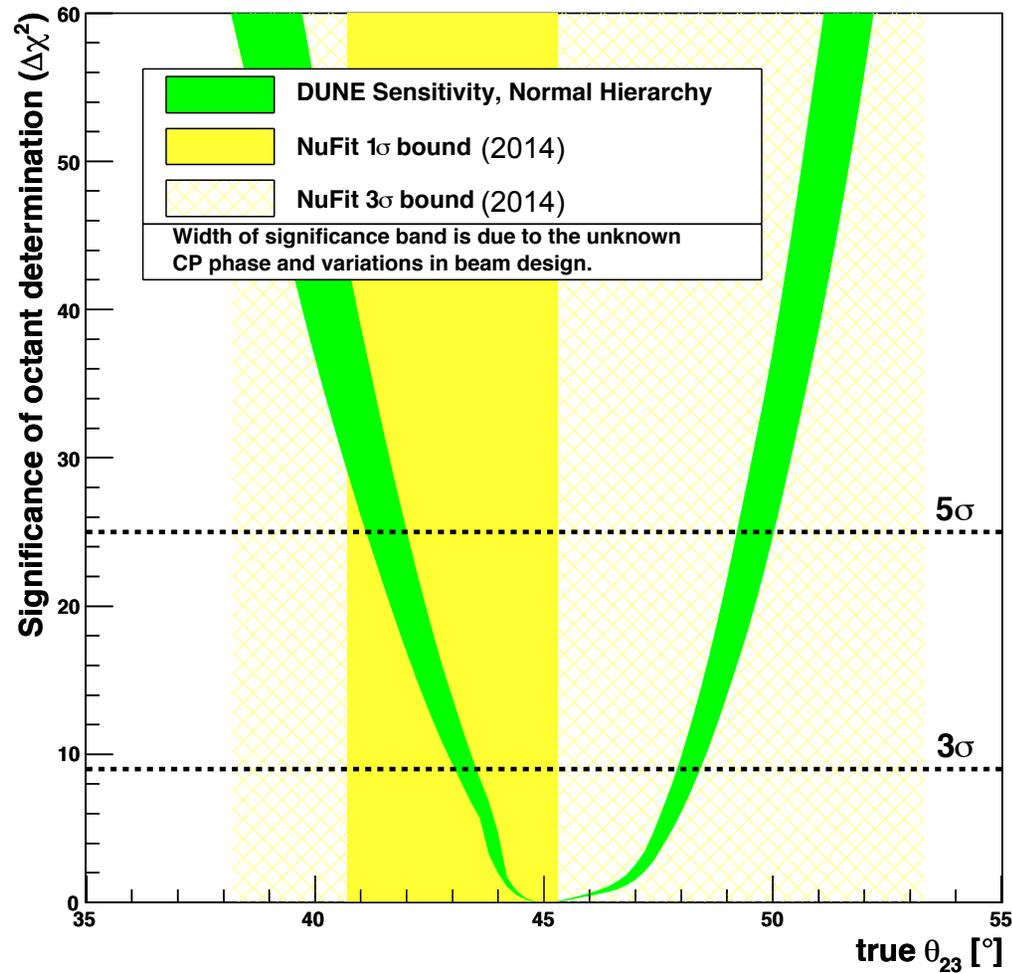
Additional Slides



Octant Sensitivity

DUNE CDR:

Octant Sensitivity



MH Statistics

DUNE CDR:

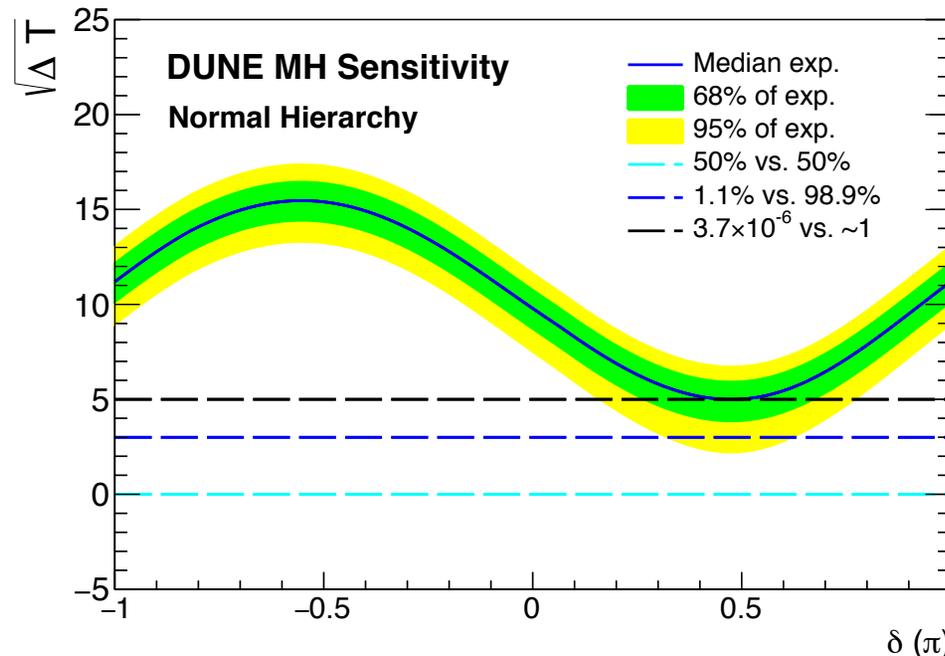


Figure 3.12: The sensitivity, given by $\sqrt{\Delta T} = \sqrt{\Delta\chi^2}$ for a typical experiment (solid blue line), is compared to the bands within which 68% (green) and 95% (yellow) of experiments are expected to fall due to statistical fluctuations. The solid blue line (representing a minimum significance of $\sqrt{\Delta T} = 5$ for 100% of δ_{CP} values) is the expected sensitivity in our standard treatment. (See Figure 3.8 for the possible range of exposures to achieve this level of significance.) The dashed lines show the values of the $\sqrt{\Delta T}$ metric an experiment must measure for the probability of determining the correct neutrino MH to be 50% (cyan), 98.9% (blue), or 1 to 3.7×10^{-6} (black), following the convention in [21]. In the legend, the numbers corresponding to the dashed lines indicate [probability of determining MH *incorrectly*] vs. [probability of determining the MH *correctly*].

Proton Decay Sensitivity

Example “benchmark” decay modes, but many others will also be studied.

