THE DEEP UNDERGROUND NEUTRINO EXPERIMENT PHYSICS PROGRAM

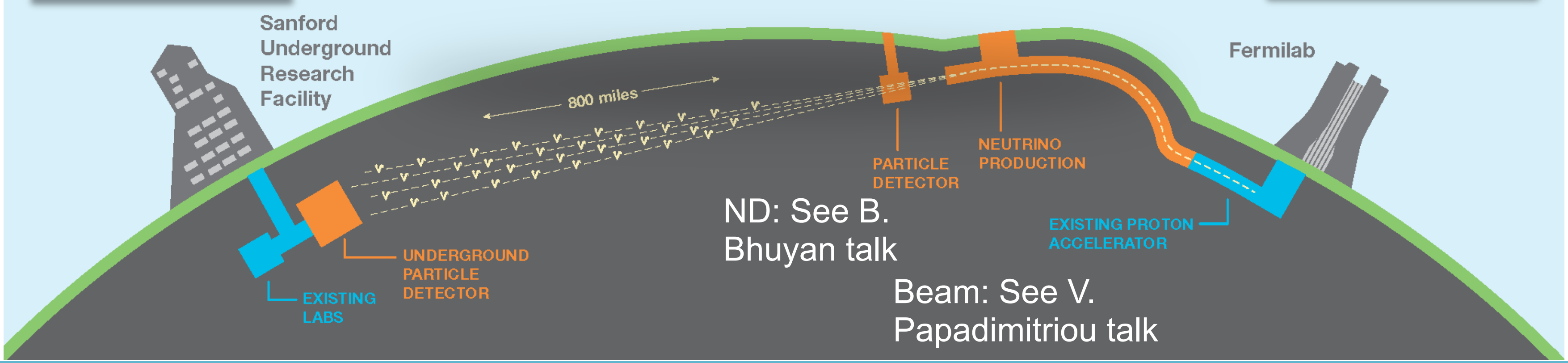
Elizabeth Worcester for the DUNE Collaboration

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 MH, CPV, and neutrino mixing parameters in a single experiment. Large detector, deep underground provides sensitivity to nucleon decay and supernova burst neutrinos.

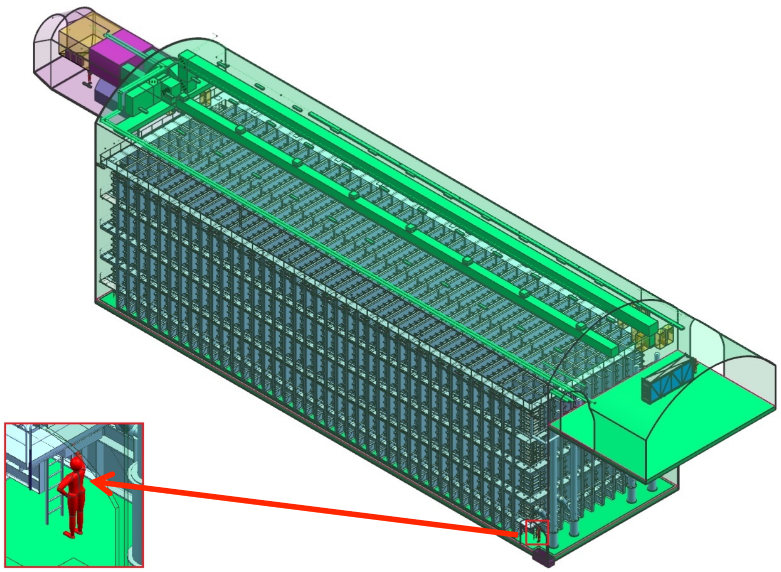


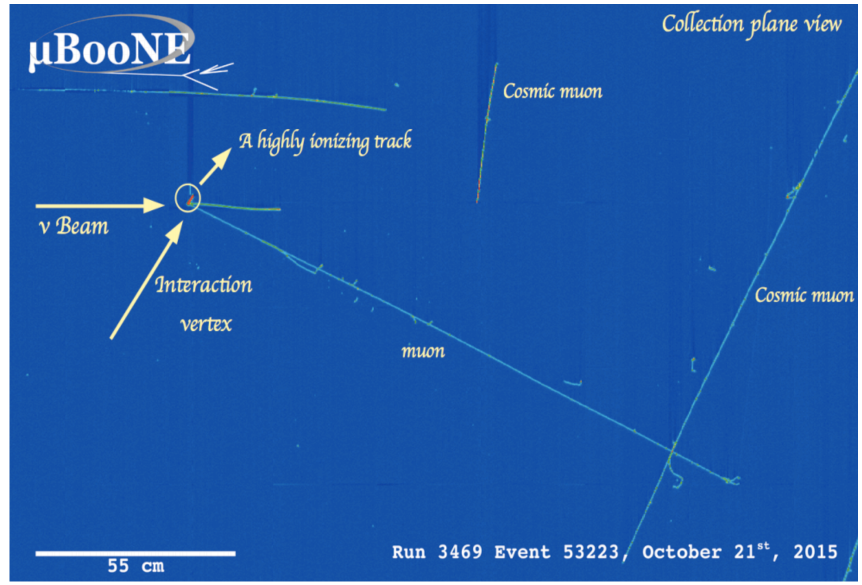
DUNE Collaboration

856 collaborators from 149 institutions in 29 nations

DUNE Far Detector

See A. Himmel talk





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

- 40-kt liquid argon TPC, at 4850L of SURF; four 10-kt modules
- First module will be a single phase LArTPC
- Modules installed in stages; later modules may not be identical

ν_e Appearance

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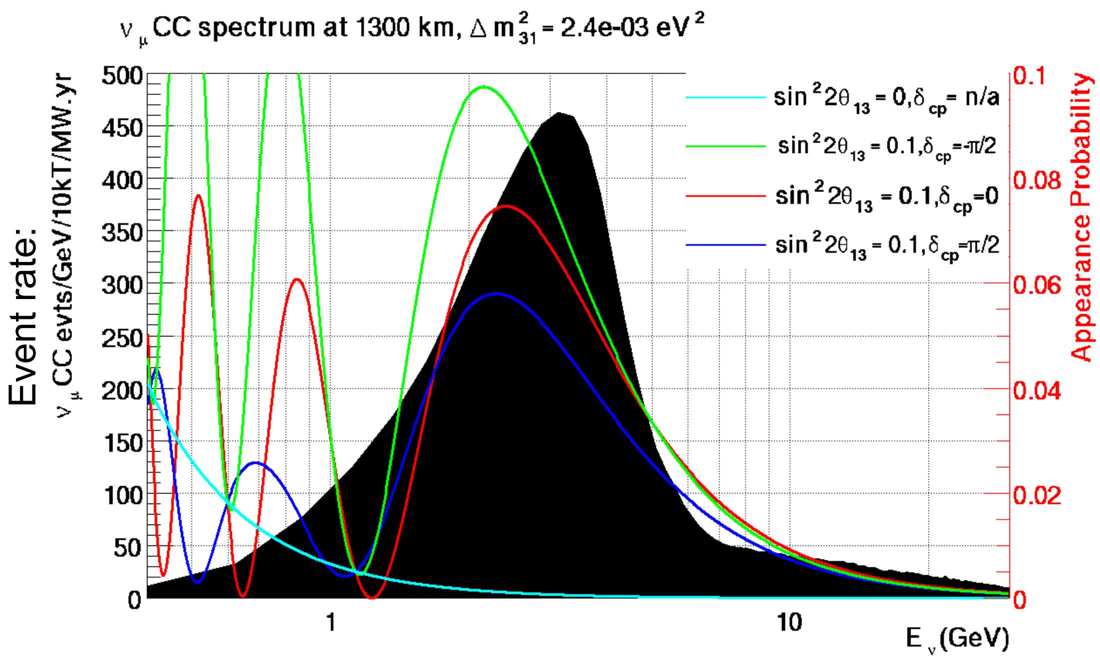
$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP}) +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

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

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



- 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

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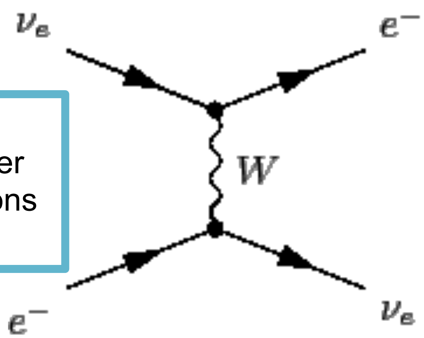
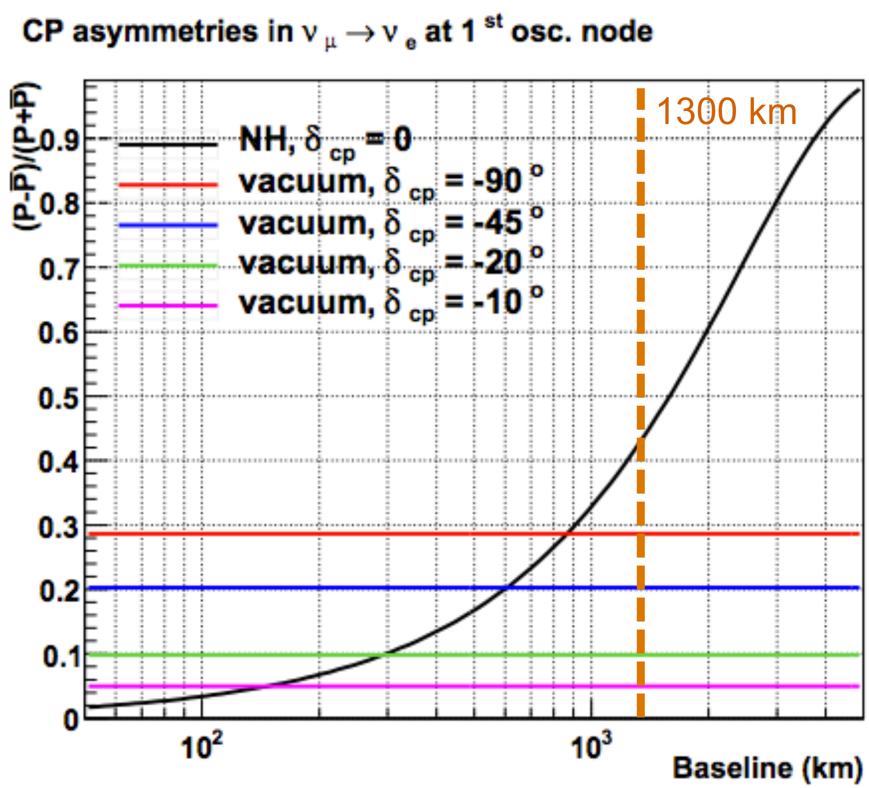
Charged-current coherent forward scattering on electrons:

Electrons are present in matter while other leptons are not.

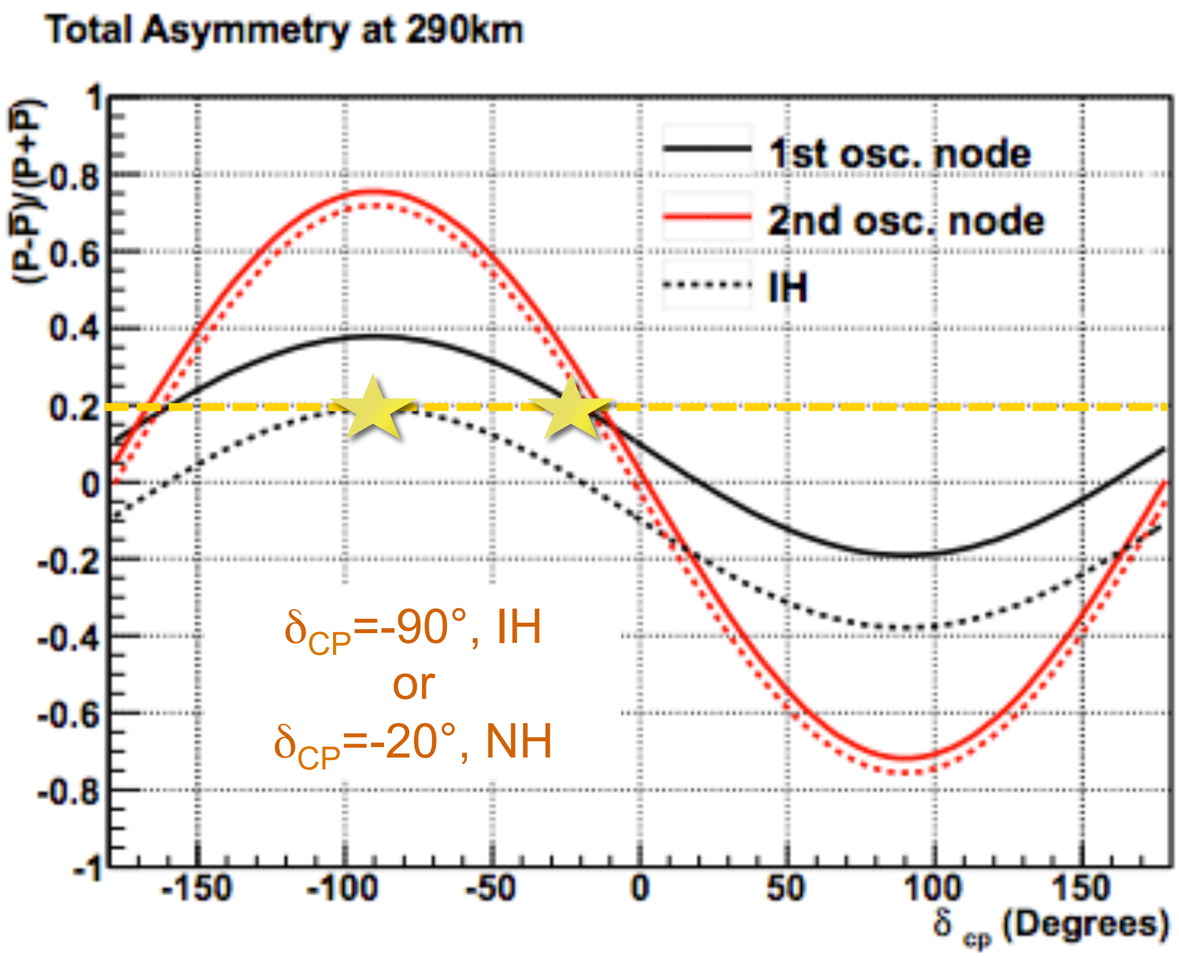


- CC process occurs for electron neutrinos only; muon and tau have only NC interactions with electrons
- Normal hierarchy: matter effect enhances appearance probability for neutrinos and suppresses it for antineutrinos (opposite for IH)



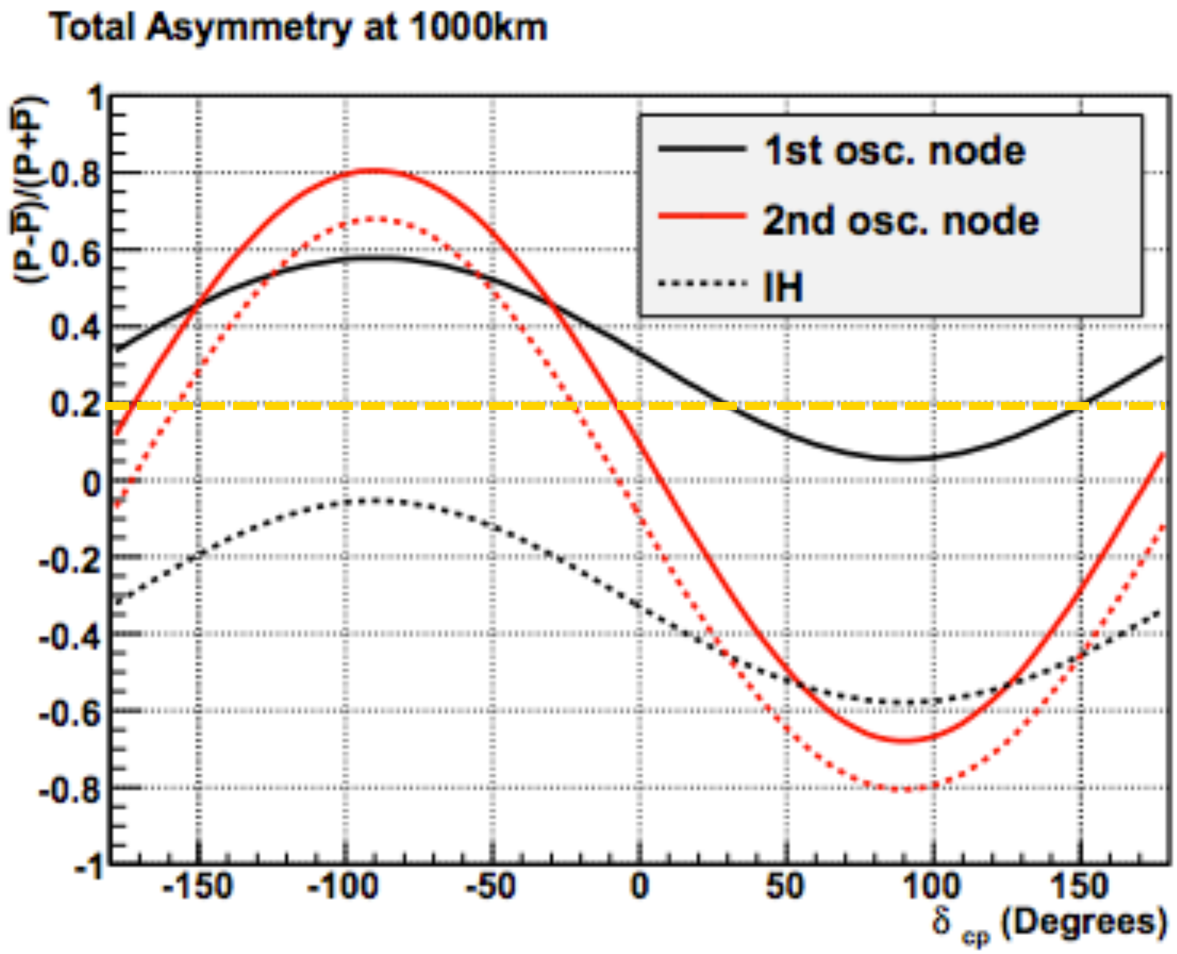
Matter asymmetry very important for long-baseline experiments!

Matter and CP Asymmetry



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

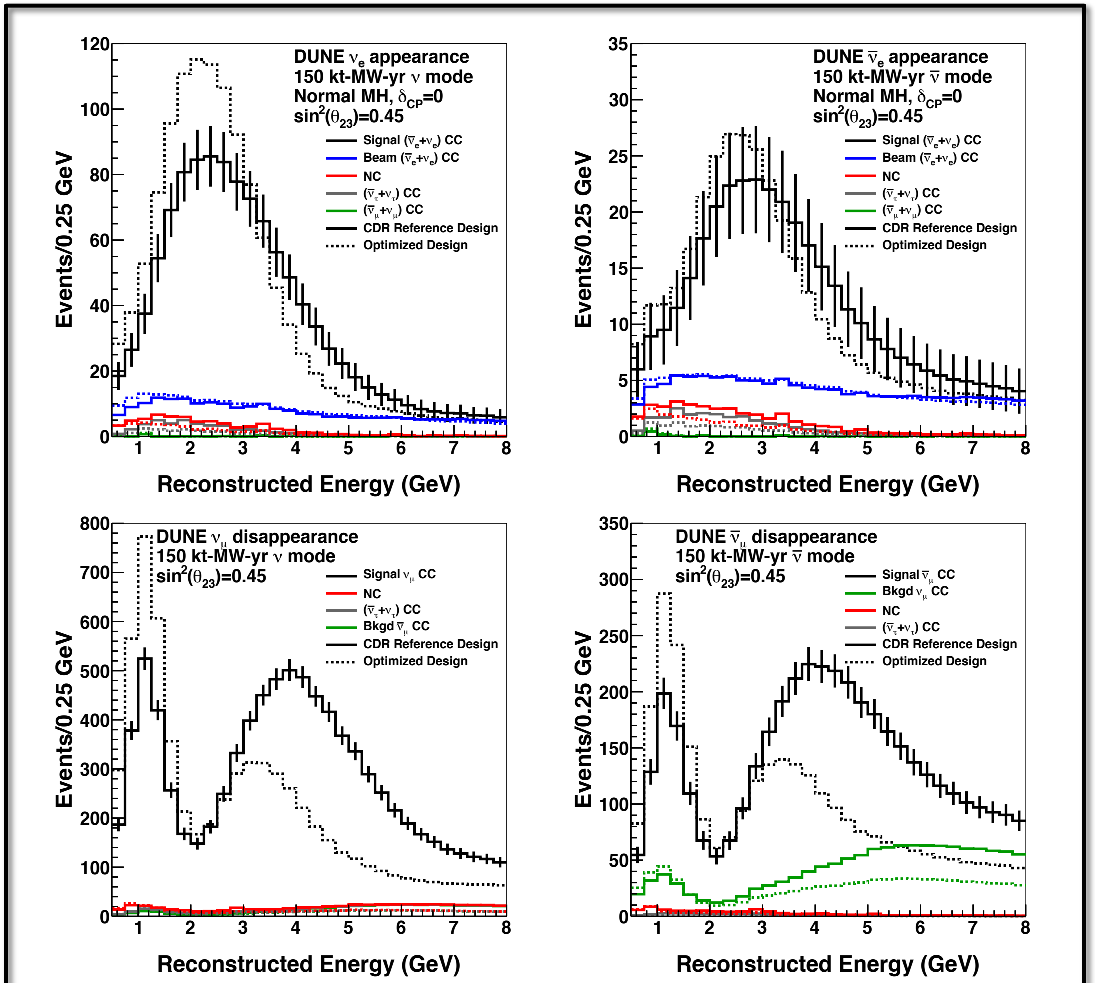
Matter and CP Asymmetry



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

Oscillation Sensitivity Calculations

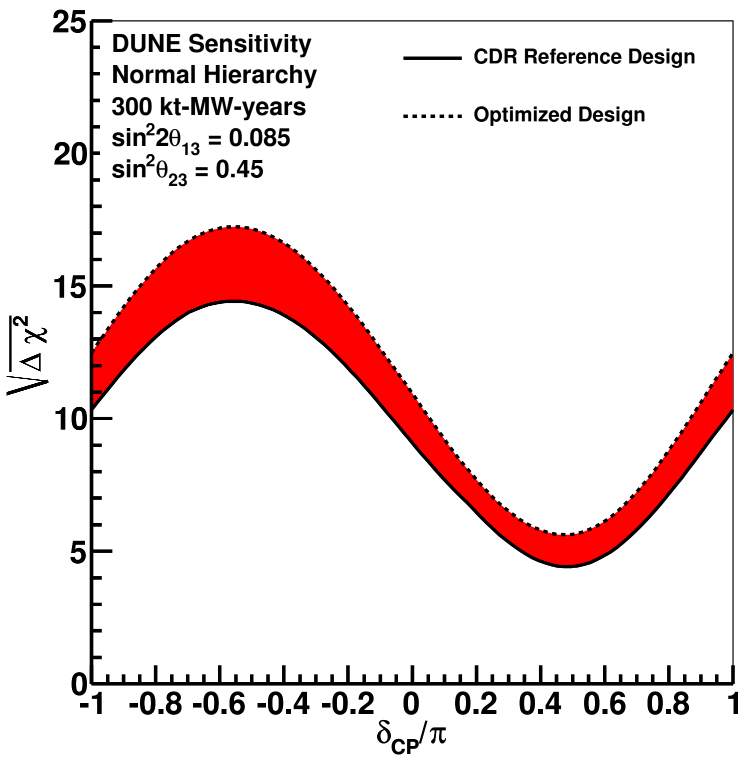
DUNE CDR:

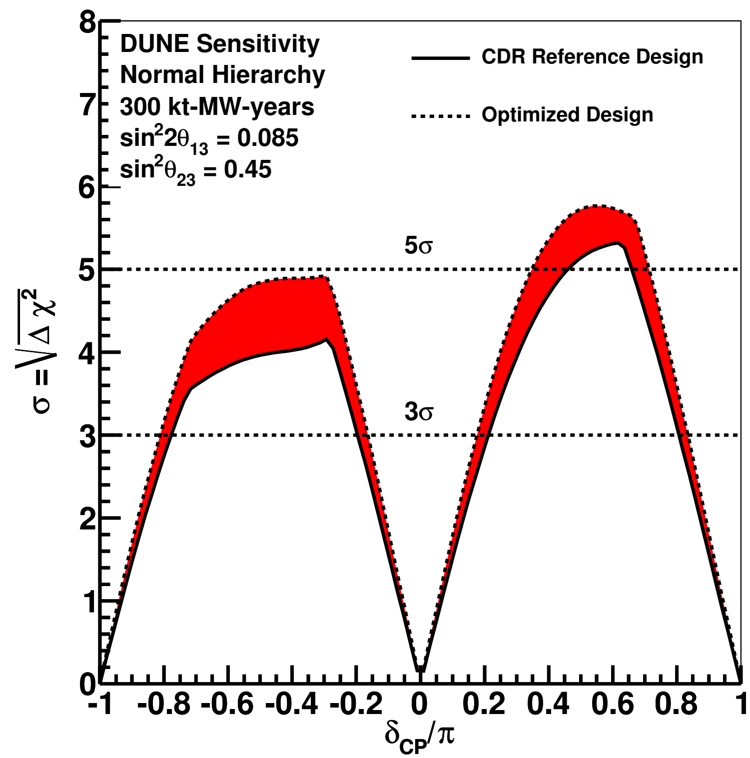


- GLoBES-based fit to four FD samples
- Two neutrino beam line designs considered
- GENIE event generator
- Reconstructed spectra predicted using detector response parameterized at the single particle level
- Simple systematics treatment
- GLoBES configurations arXiv:1606.09550

MH & CPV Sensitivity

DUNE CDR: Mass Hierarchy CP Violation



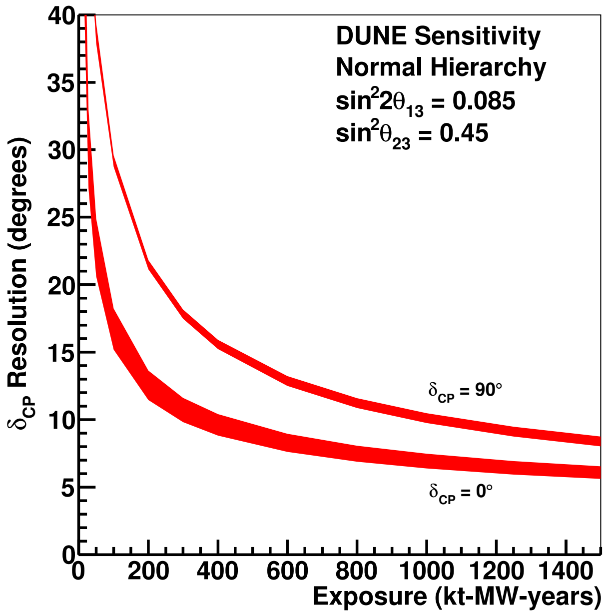


Width of band indicates variation among differing neutrino beam designs.
See poster by L. Fields for updated beam optimization.
Exposure is 300 kt-MW-yr = 40 kt x 1.07 MW x ($3.5\nu+3.5\bar{\nu}$) years.
Includes simple normalization systematics and oscillation parameter variations.

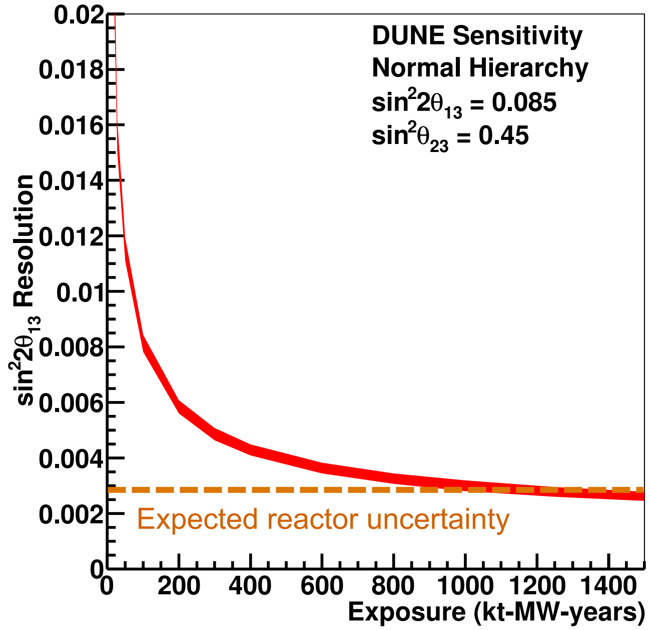
Oscillation Parameter Sensitivity

DUNE CDR:

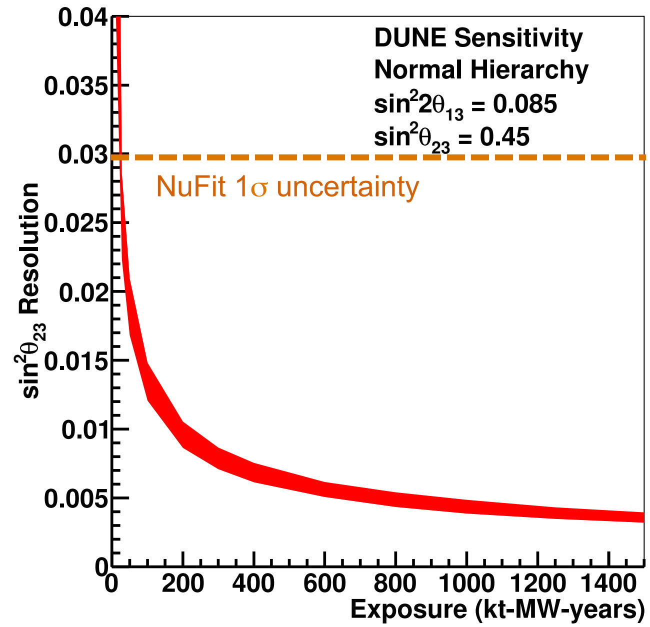
δ_{CP} Resolution



$\sin^2 2\theta_{13}$ Resolution



$\sin^2\theta_{23}$ Resolution



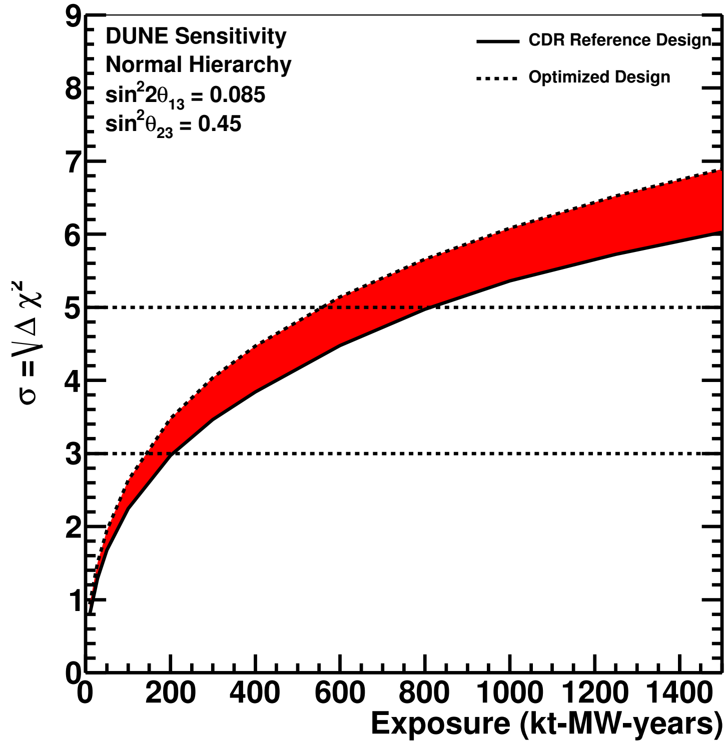
Sensitivity Over Time

DUNE CDR:

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 3σ ($\delta_{CP} = +\pi/2$)	70	60
CPV at 3σ ($\delta_{CP} = -\pi/2$)	160	100
CPV at 5σ ($\delta_{CP} = +\pi/2$)	280	210
MH at 5σ (worst point)	400	230
10° resolution ($\delta_{CP} = 0$)	450	290
CPV at 5σ ($\delta_{CP} = -\pi/2$)	525	320
CPV at 5σ 50% of δ_{CP}	810	550
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	1200	850
CPV at 3σ 75% of δ_{CP}	1320	850

Interesting measurements will be made throughout the DUNE physics program!

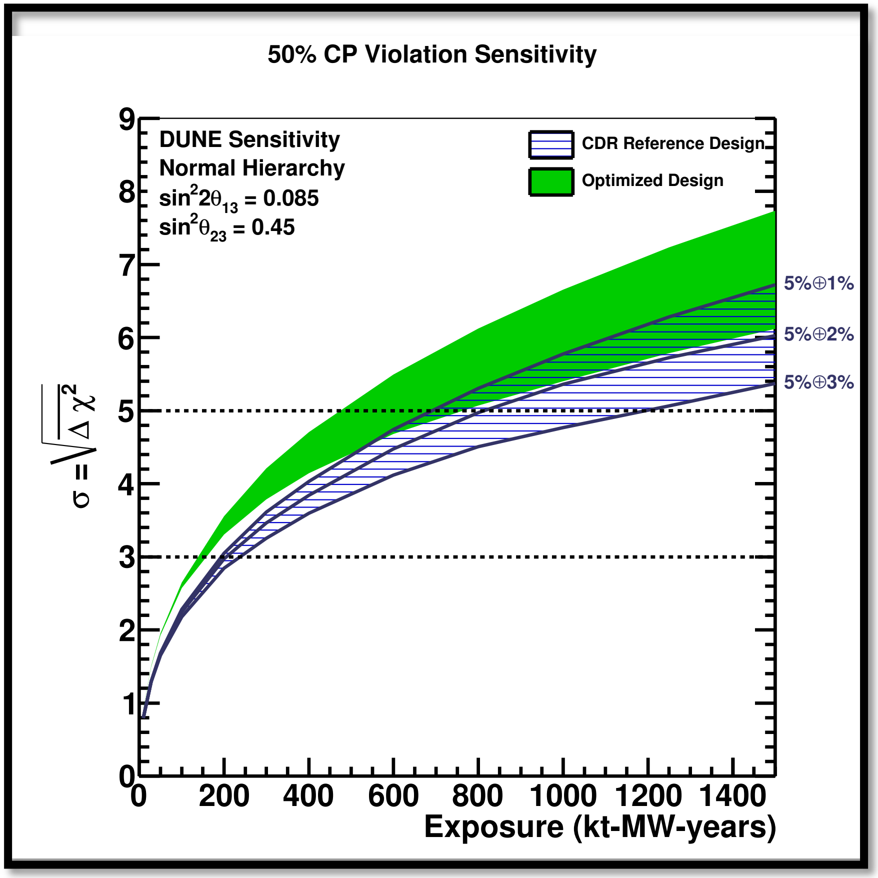
CP Violation



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

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 ~5% ⊕ 2% to discover CPV in a timely manner.

Proton Decay

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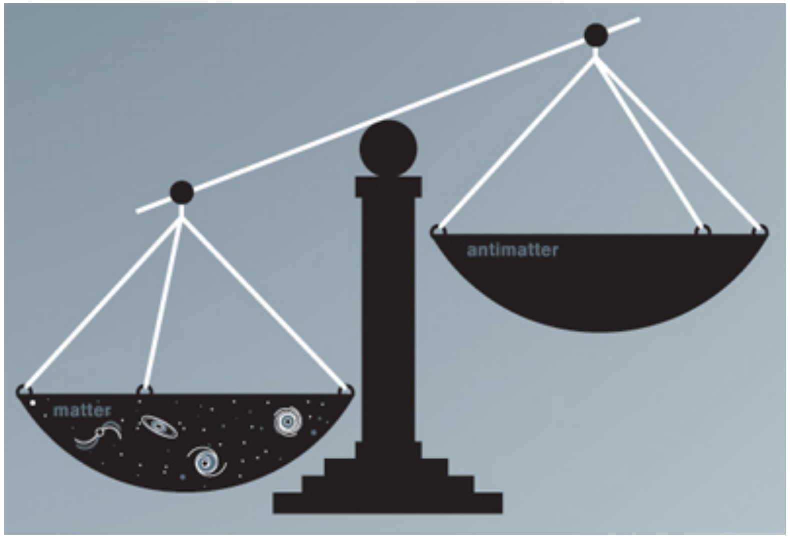
- Test of fundamental symmetries
  - We (so far!) observe conservation of baryon number, but there is no known reason why this must be so
  - Matter-antimatter asymmetry requires baryon number non-conservation (Sakharov)
- Well-motivated models suggest proton decay may exist and be observable
  - GUTs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

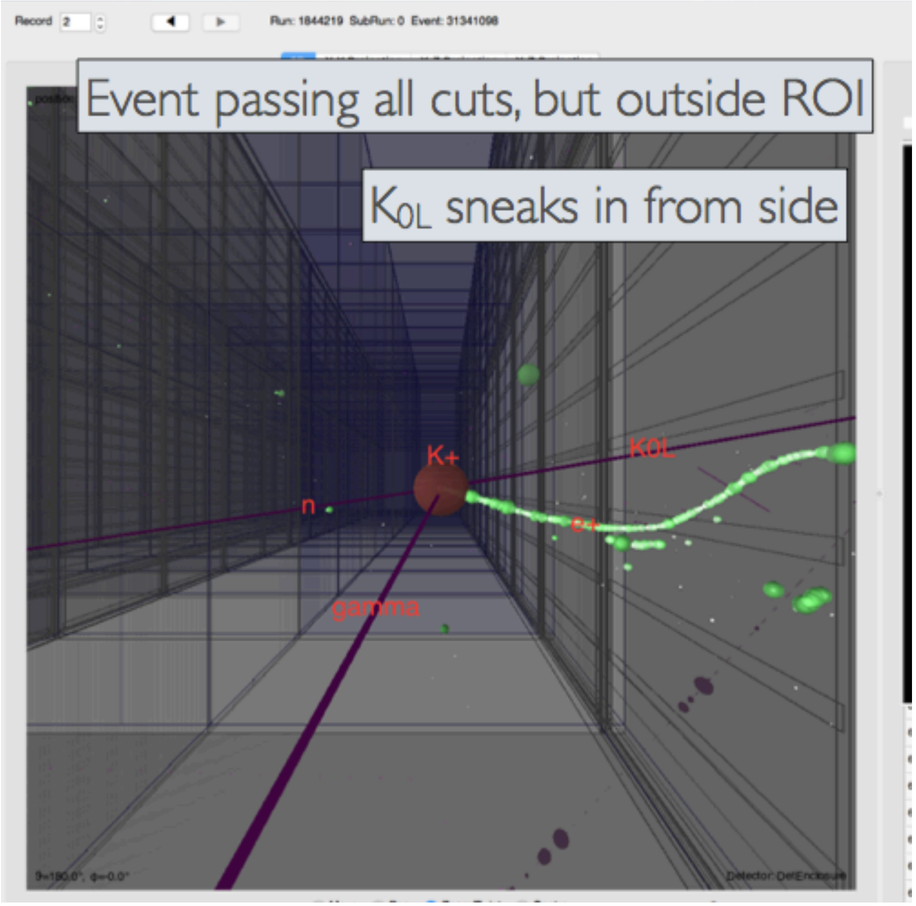


Grand Unification Theories: unify strong, weak, and EM forces into a single underlying force at high energies and can explain many outstanding questions in particle physics, including quantization of electric charge, co-existence of quarks and leptons, and quantum numbers of quarks and leptons.

Sensitivity to Nucleon Decay

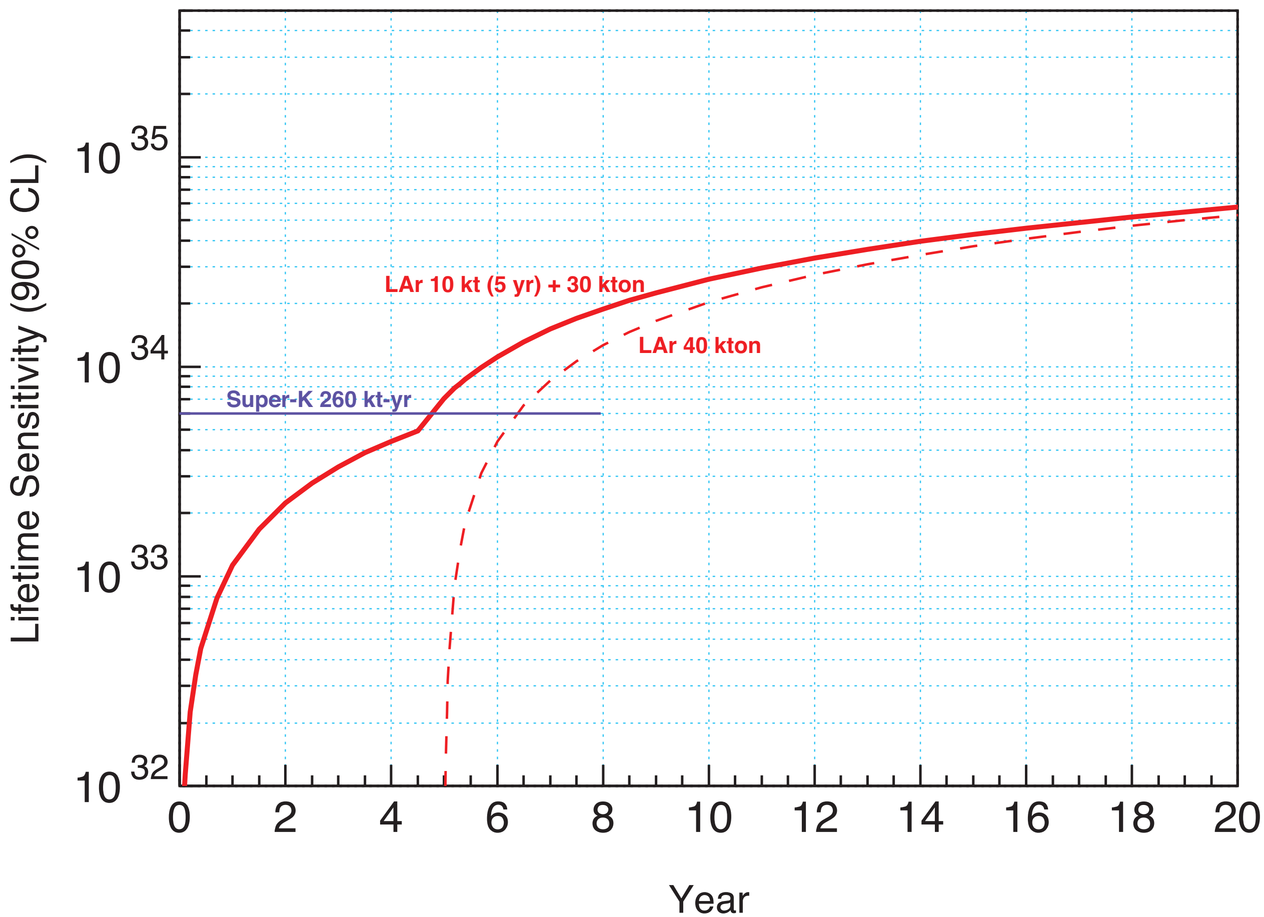
- Detector requirements
  - Low background rate
    - Primary background from entering neutral kaons and neutrons
    - Cosmogenic background reduced by deep underground location
    - Atmospheric neutrinos also a source of background
  - High signal efficiency
    - Precision tracking in LArTPC especially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

Example event from background study:



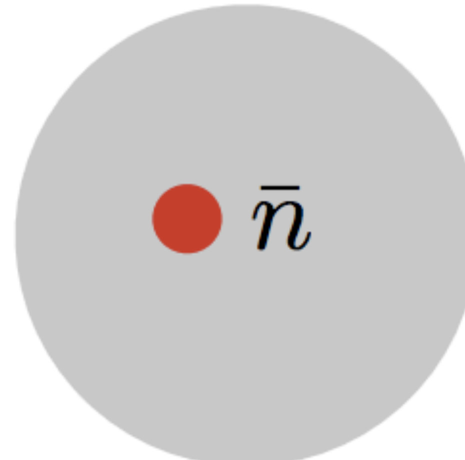
Sensitivity for p→νK^+

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



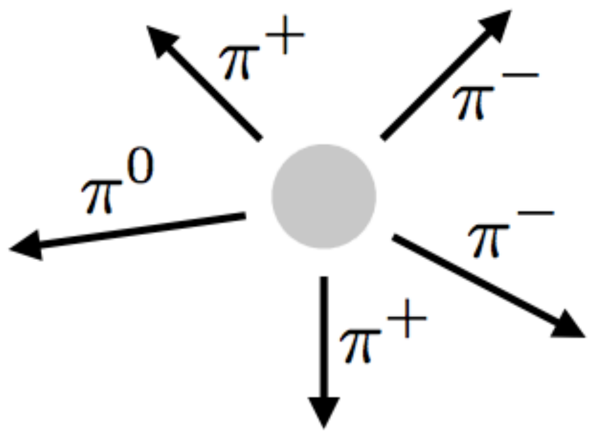
Neutron-antineutron Oscillation

- Neutron spontaneously oscillates into antineutron.
- Antineutron annihilates with nucleon inside nucleus.
- Left with 2-6 pions, inside atomic nucleus.



$\bar{n}+p$		$\bar{n}+n$	
$\pi^+\pi^0$	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%

arXiv 1109.422



$$\sum p < 300\text{MeV}$$
$$\sum E \simeq 1.5\text{GeV}$$

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 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

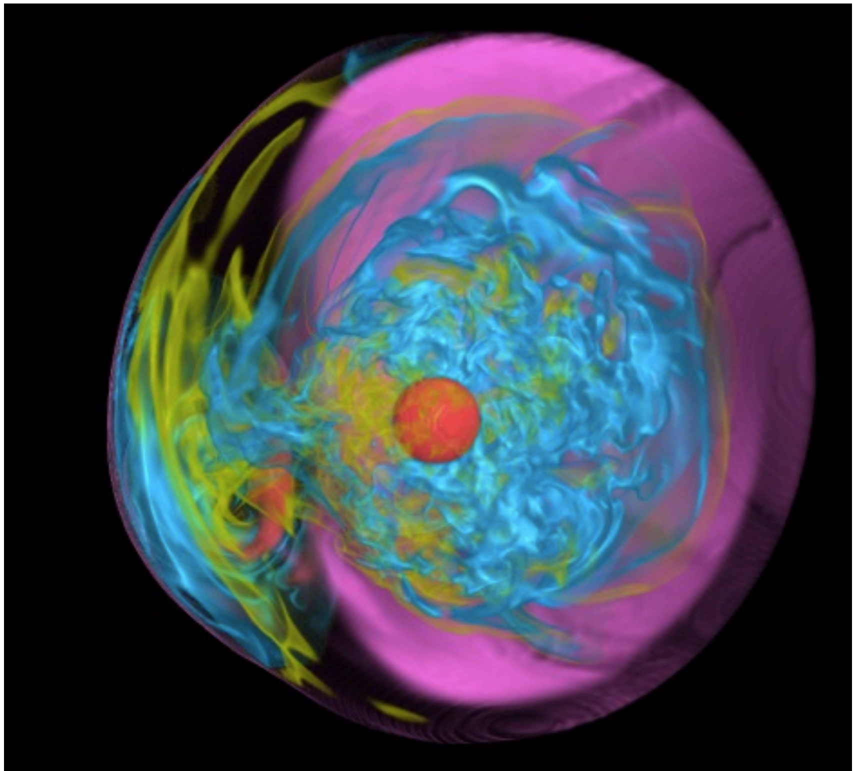


Image credit: A. Mezzacappa

Supernova Neutrino Detection

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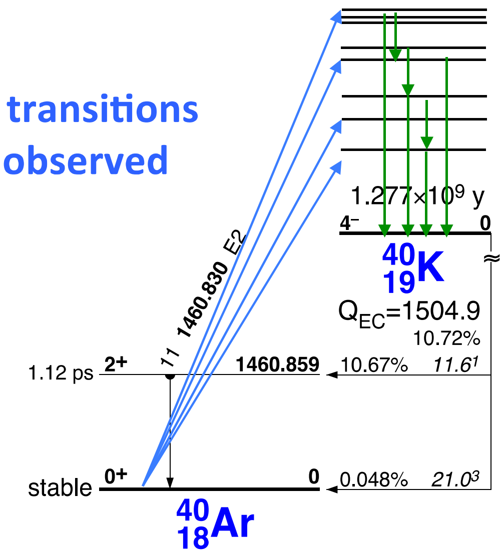
Charged-current absorption:

$$\nu_e + {}^{40}\text{Ar} \rightarrow {}^{40}\text{K}^* + e^-$$

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:

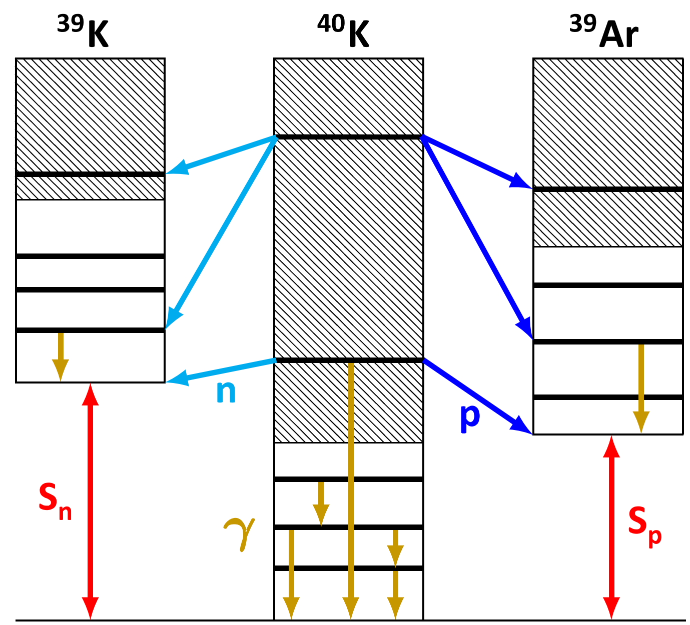
Q is determined by measuring de-excitation gammas and nucleons

Outgoing e⁻ Energy

Energy donated to transition

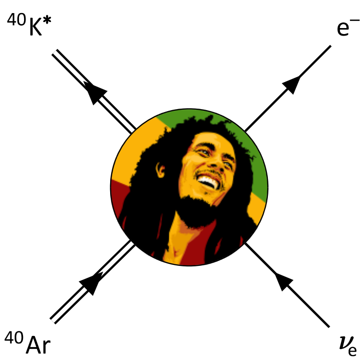
Recoil Energy of Nucleus (negligible)

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



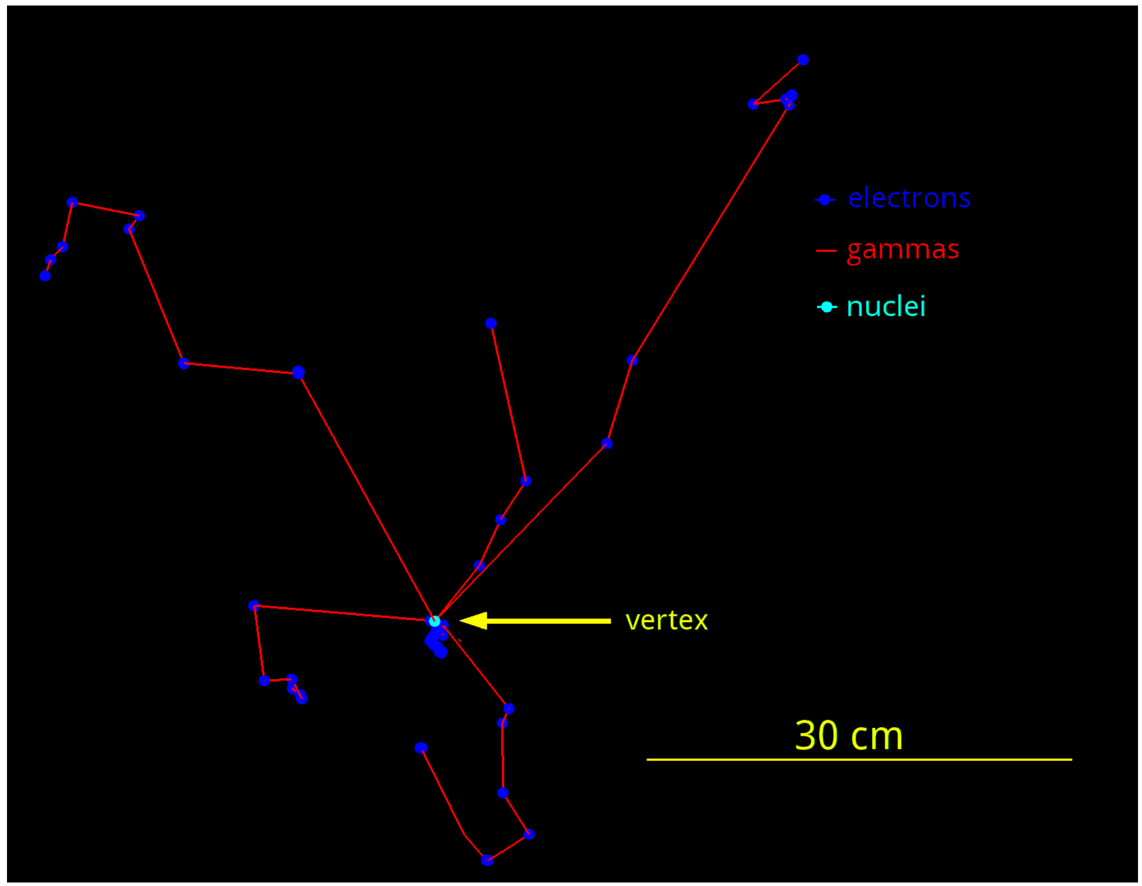
SNB Neutrino Simulation

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



MARLEY: Model of **A**rgon **R**eaction **L**ow-**E**nergy **Y**ields
An event generator for supernova neutrinos in liquid argon

Simulated charged-current supernova ν_e event:



Expected Supernova Signal

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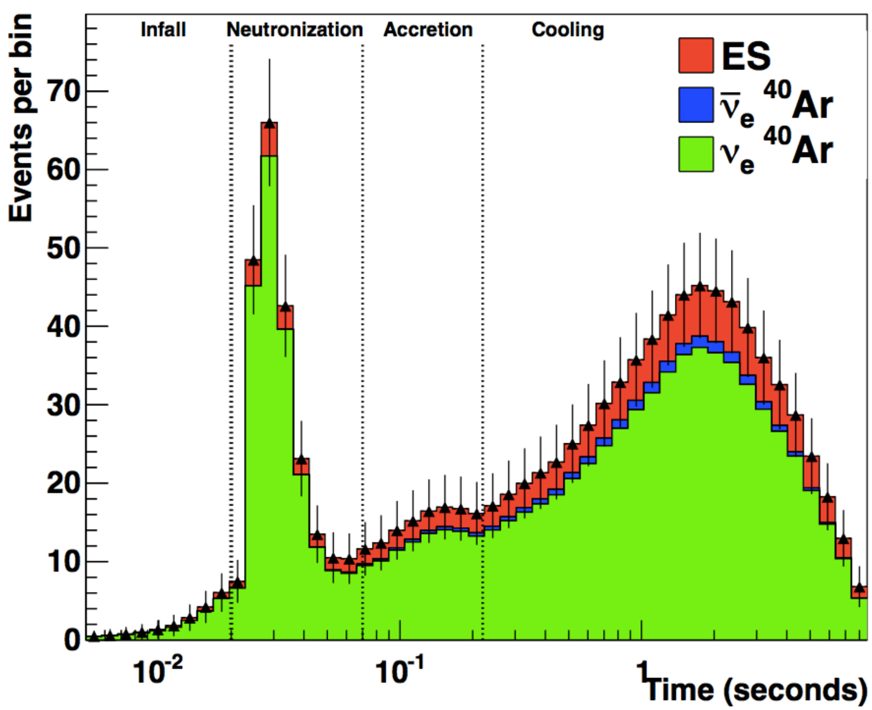
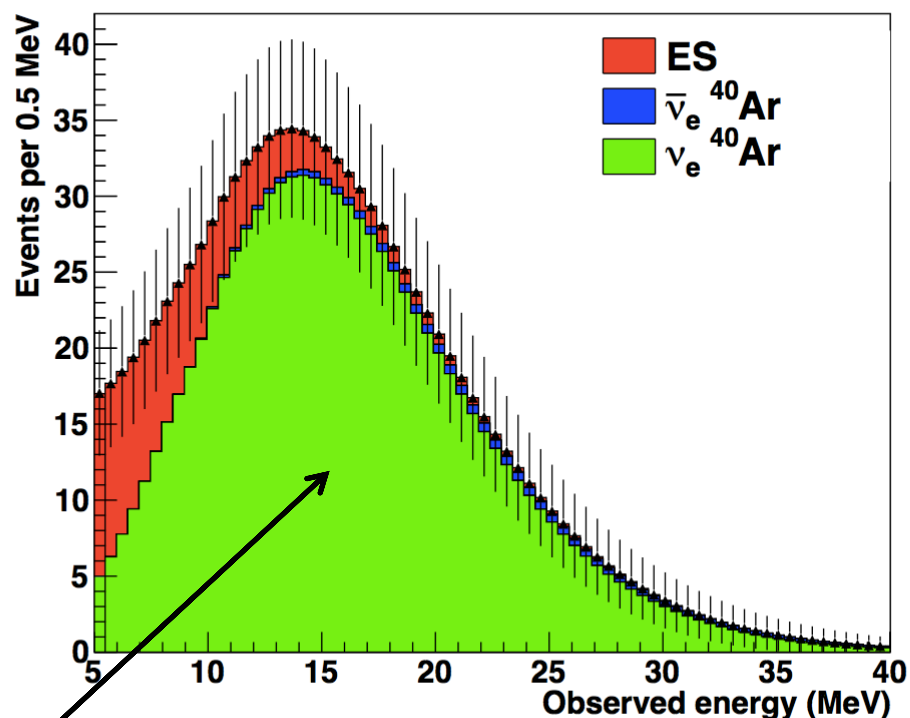
Flavor composition as function of time:



Energy spectra integrated over time:



Electron flavor dominant

For 40-kt detector, SNB @ 10 kpc, "Garching" model (no oscillations)

Summary

- DUNE will address fundamental physics questions
  - Baryon asymmetry (CP violation + nucleon decay)
  - Grand unified theories
  - Matter formation in supernovae
- Long-baseline neutrino oscillation experiment in a broad band beam allows simultaneous measurement of mass hierarchy, CP-violating phase, and neutrino mixing angles
  - Sensitive to new physics affecting oscillation probabilities
  - Comparison to other oscillation channels allows unitarity test
- 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

Additional Slides

Proton Decay Sensitivity