The Deep Undergroud Neutrino Experiment (DUNE)

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on behalf of the DUNE Collaboration

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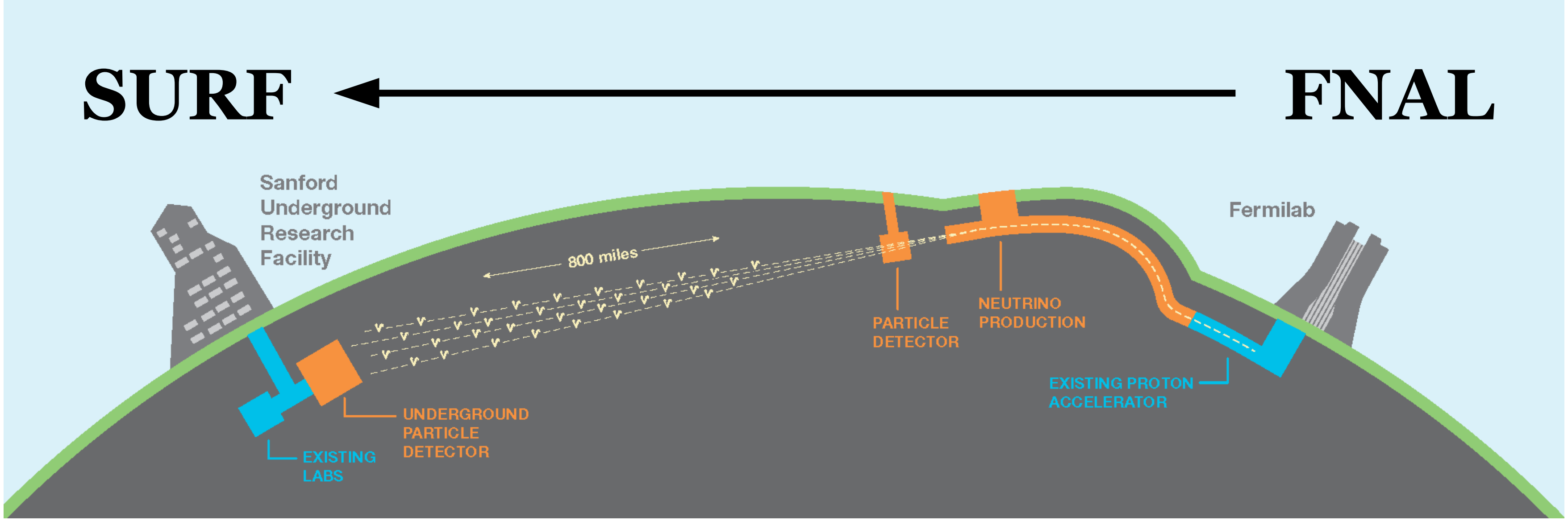
DUNE Overview

- Features of DUNE:
  - **1300 km** baseline: "LBL"
  - Large (**40 kt**) LArTPC far detector and near detector
  - Far detector **1.5 km** underground
  - Wide-band, on-axis beam
- Primary physics goals:
  - ν oscillations ($\nu_\mu/\bar{\nu}_\mu$ disappearance, $\nu_e/\bar{\nu}_e$ appearance)
    - **MH, $\boldsymbol{\delta_{CP}}$, $\boldsymbol{\theta_{23}}$, $\boldsymbol{\theta_{13}}$**
  - Nucleon decay
  - Supernova burst neutrinos



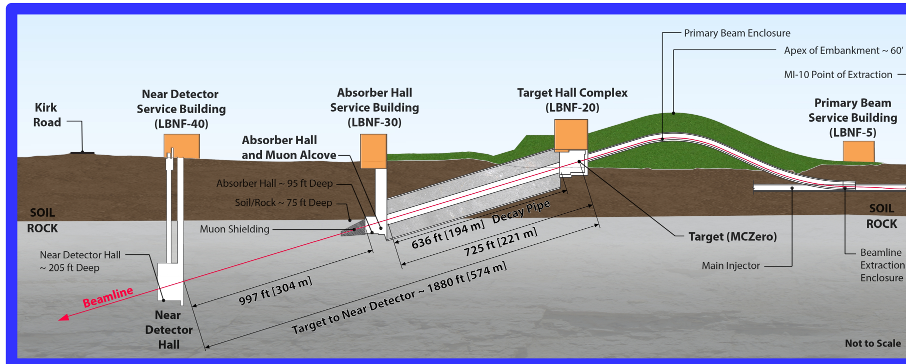
DUNE Collaboration

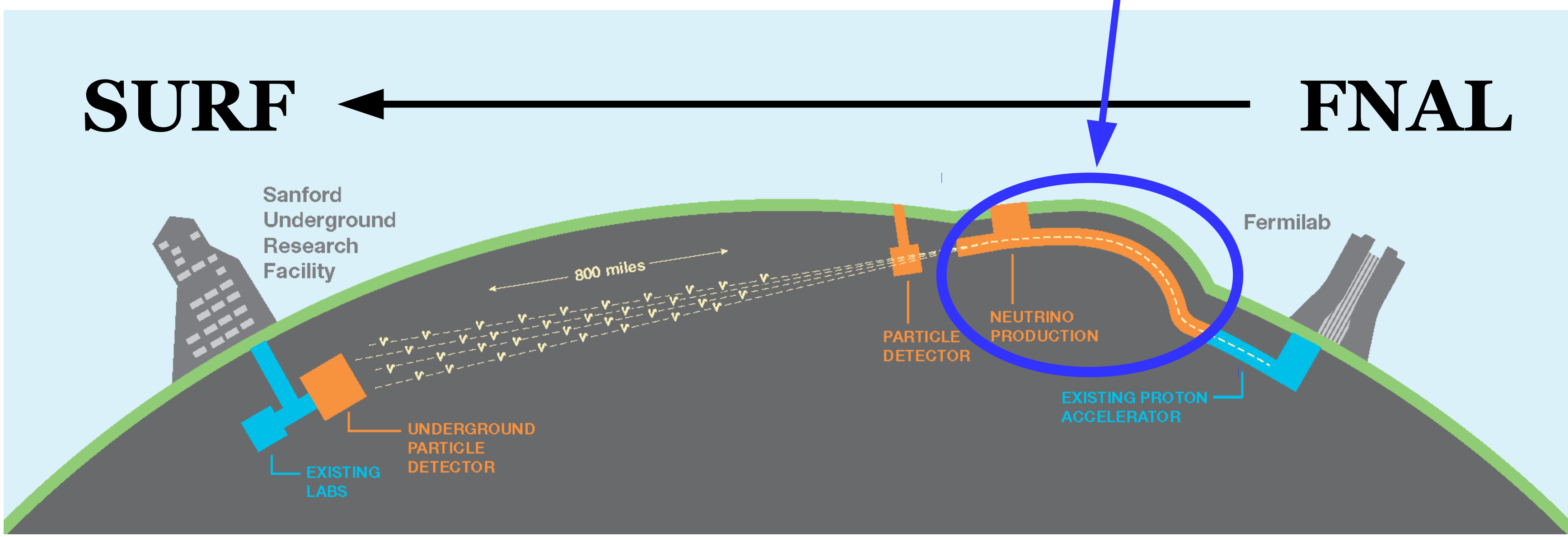
- *Large* collaboration: **894** collaborators from **154** institutions
- *International* collaboration: **28** countries in total

Beam Line, Near/Far Detectors, and Prototypes

Roadmap

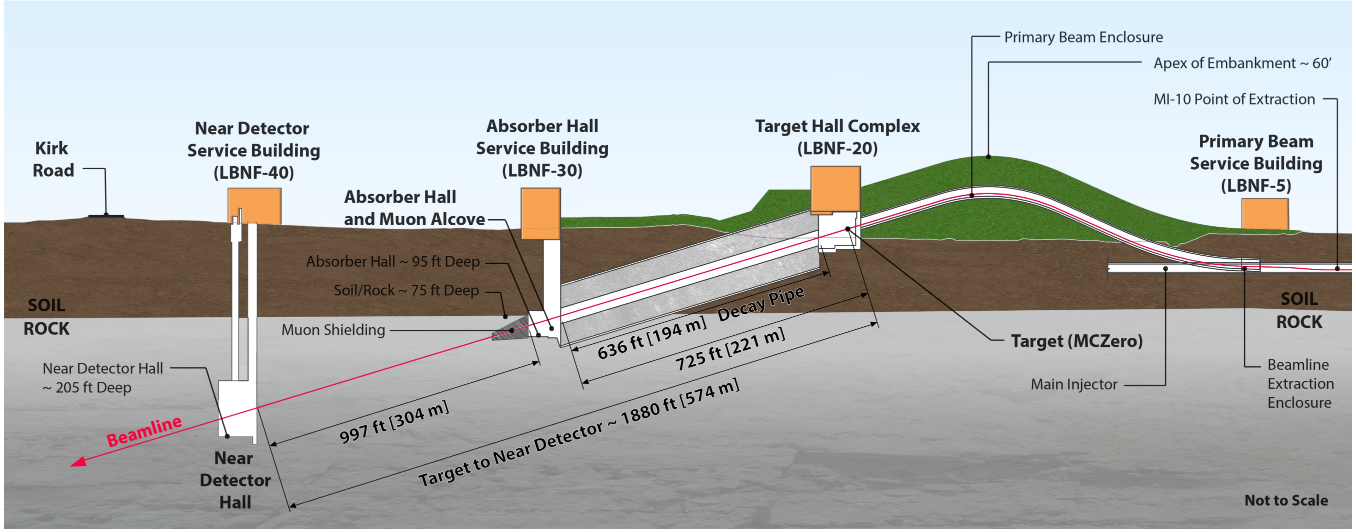
Beam Line





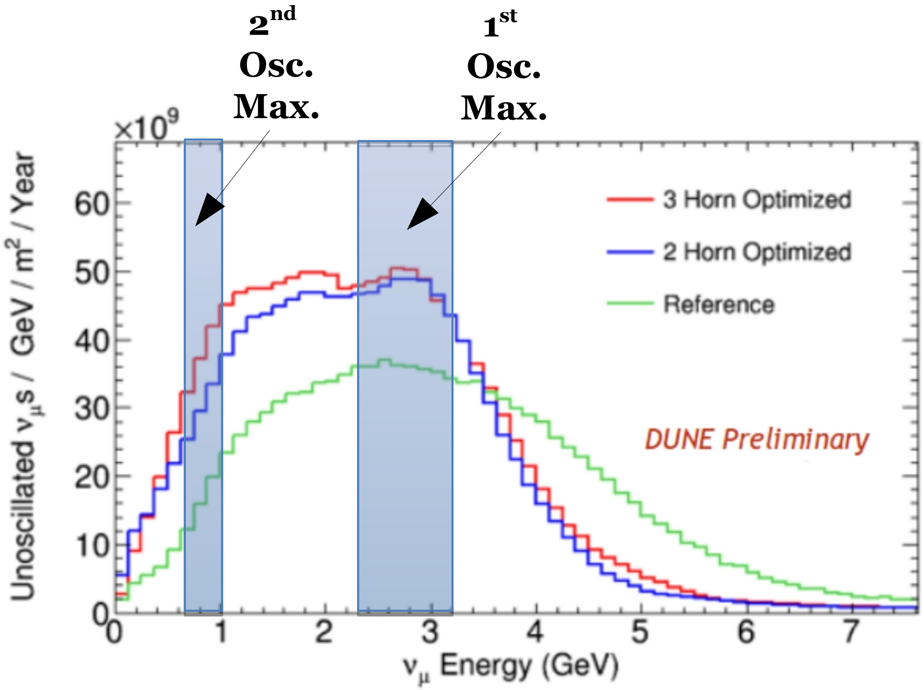
LBNF Neutrino Beam

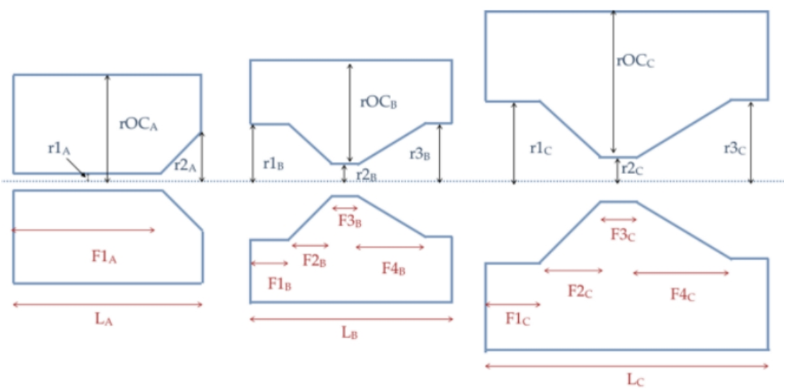
- **LBNF** (Long Baseline Neutrino Facility): DOE/Fermilab hosted project with international participation
  - LBNF houses, and delivers beam to, detectors built by DUNE collaboration
- Horn-focused beam line similar to NuMI beam line
  - **60-120 GeV** protons from Fermilab Main Injector
  - **200 m** decay pipe at **~5.8°** pitch, angled at South Dakota (SURF)



Beam Optimization

- LBNF beam line optimized beyond design referenced in DUNE CDR
- Optimization done with **genetic algorithm**
- Horn shape/current and decay pipe changed → gains in oscillation physics sensitivity





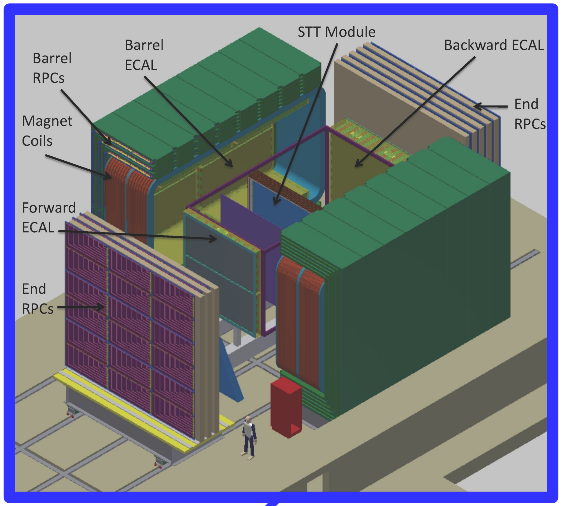
Horn Shape Parameters

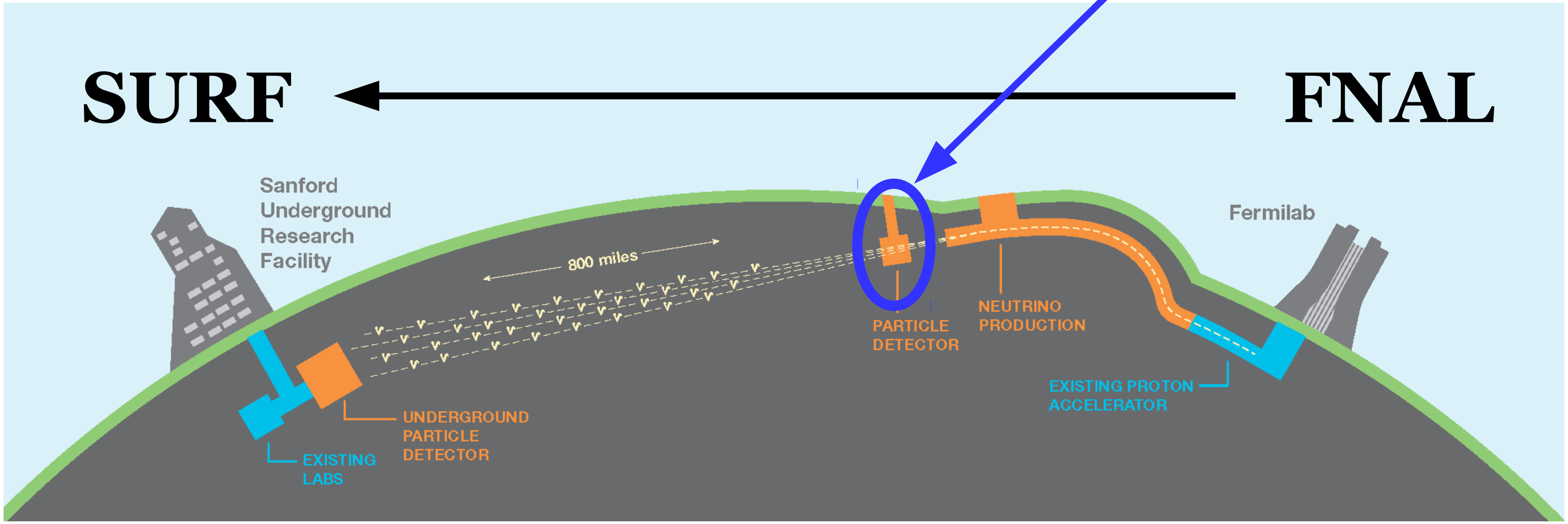
Parameter	CDR Reference Design	Optimized Design
Proton Beam Energy	80 GeV	80 GeV
Proton Beam Power	1.07 MW	1.07 MW
Target	Graphite	Graphite
Horn Current	230 kA	297 kA
Horn Design	NuMI-style	Genetic Optimization
Decay Pipe Length	204 m	241 m
Decay Pipe Diameter	4 m	4 m

See NuFact 2016 LBNF Beam/Target talks by Eric Zimmerman for more detail

Roadmap

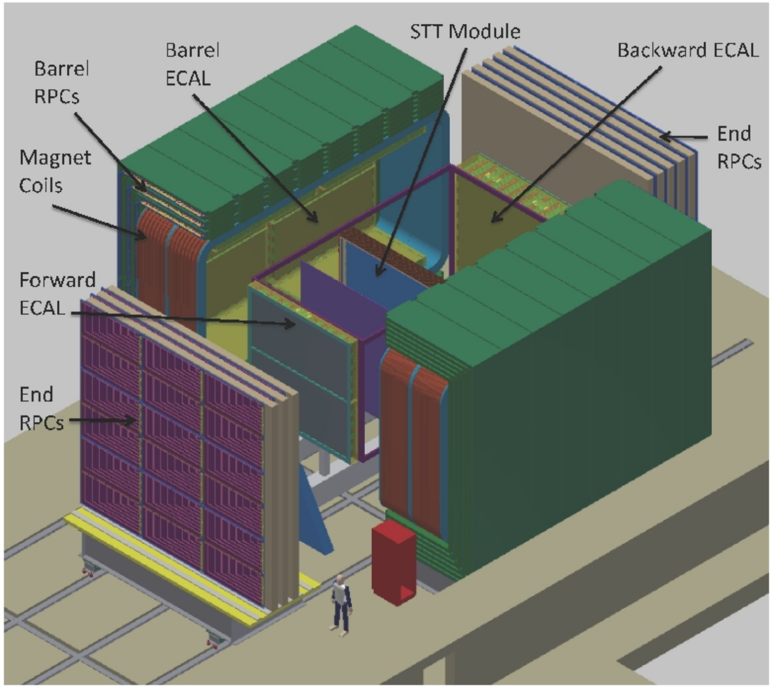
Near Detector





Near Detector

- ND important for measuring flux, constraining nuclear effects and backgrounds (also exotic physics)
- DUNE near detector reference design: **fine-grained tracker** inspired by NOMAD
  - Magnetized straw-tube based tracking system
  - Pb-scintillator sampling ECAL
  - RPC-based muon tracker
  - Multiple targets (including Ar)

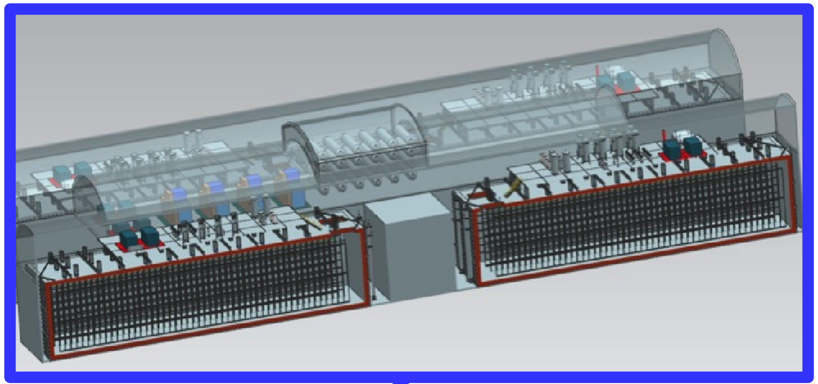


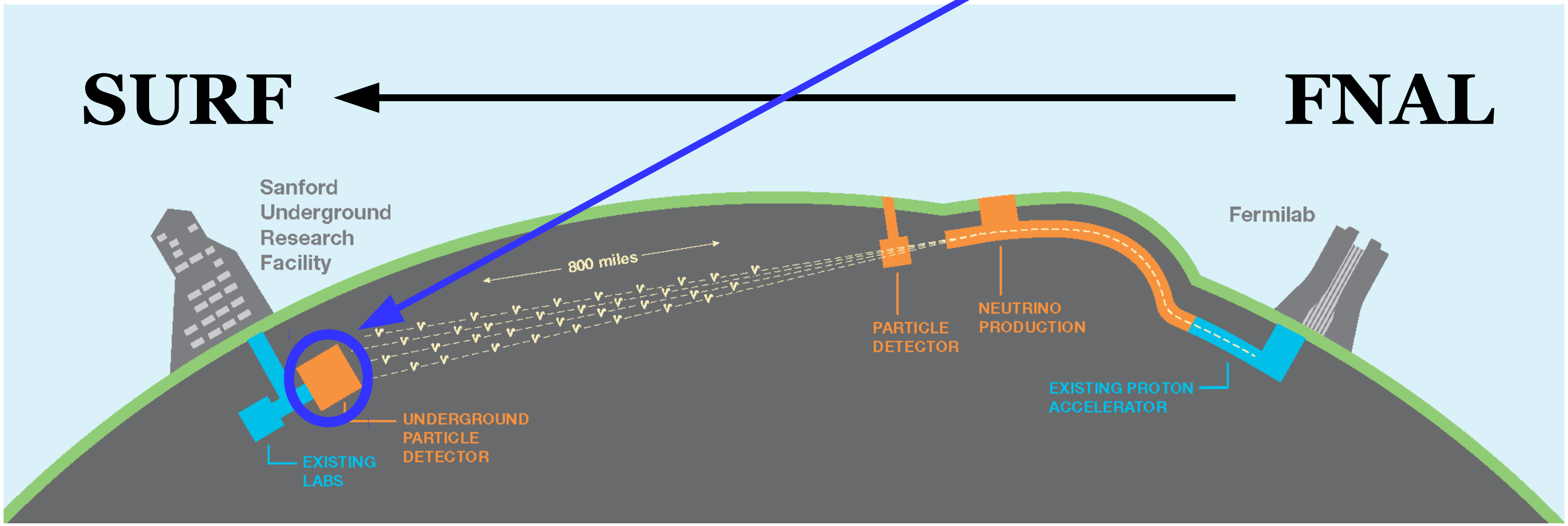
- Alternative/augmented near detector systems being investigated
  - e.g. high-pressure GArTPC, LArTPC (a la ArgonCube)

See NuFact 2016 DUNE ND talk by Hongyue Duyang for more detail

Roadmap

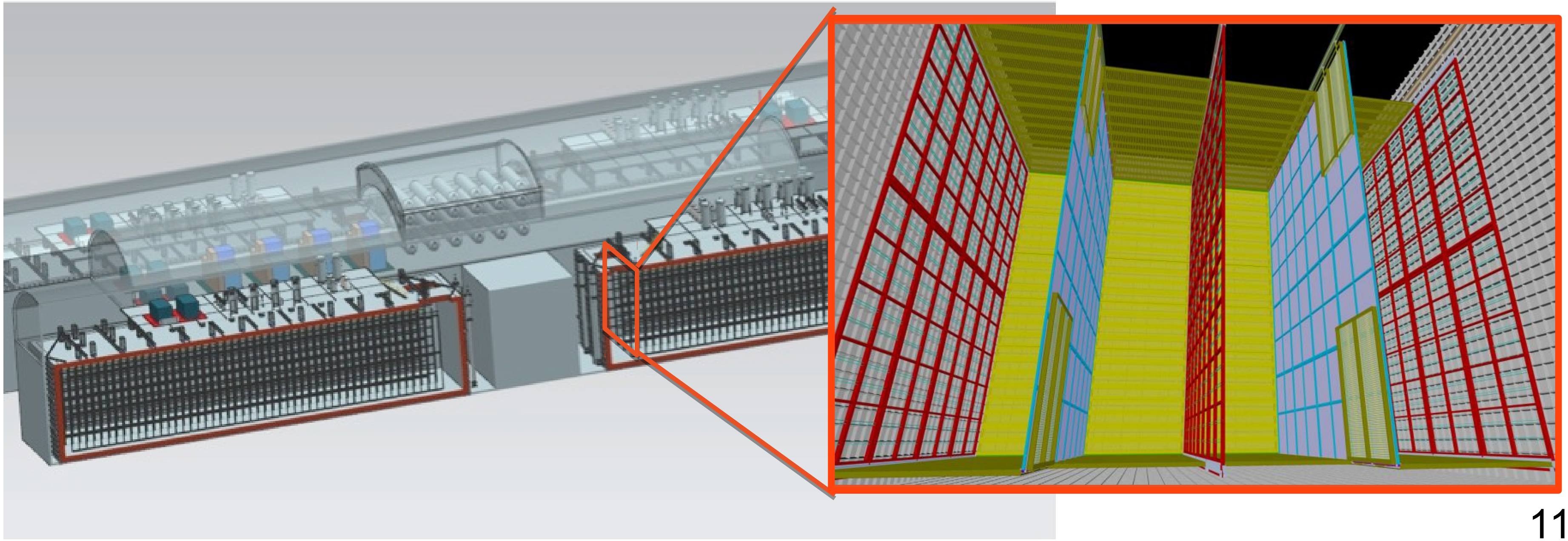
Far Detector





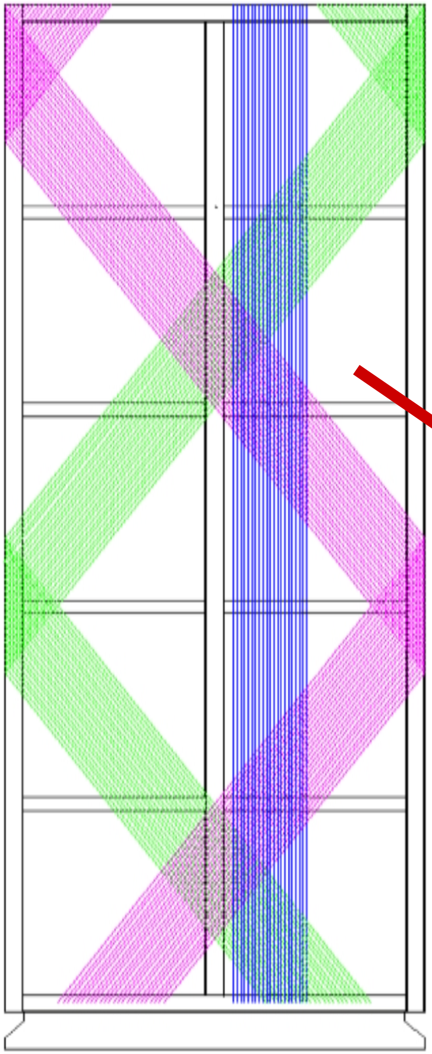
Far Detector: Single Phase

- Two far detector (FD) designs being considered: single phase (LAr) and dual phase (LAr + GAr)
- Single phase FD based on LBNE modular drift cells
  - Suspended Anode and Cathode Plane Assemblies (APAs and CPAs)
  - **3.6 m** drift with **500 V/cm** E field
  - **Cold digital electronics** to reduce noise levels (maximize S/N)

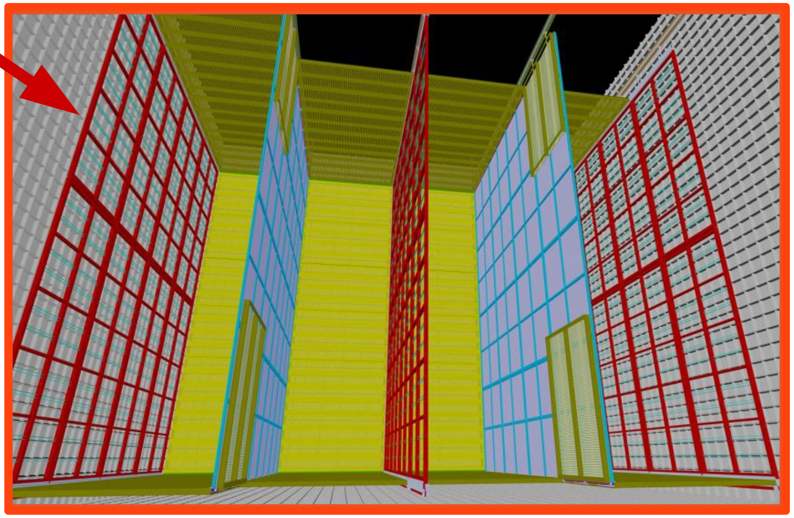


Single Phase FD Readout

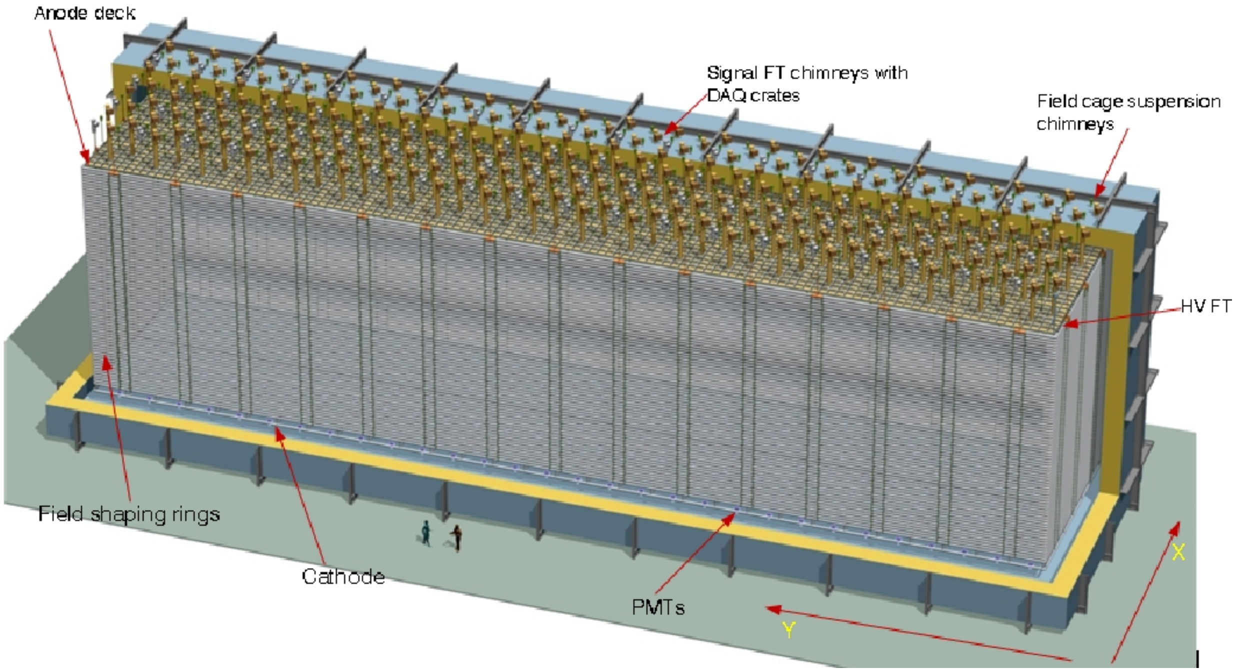
APA Geometry

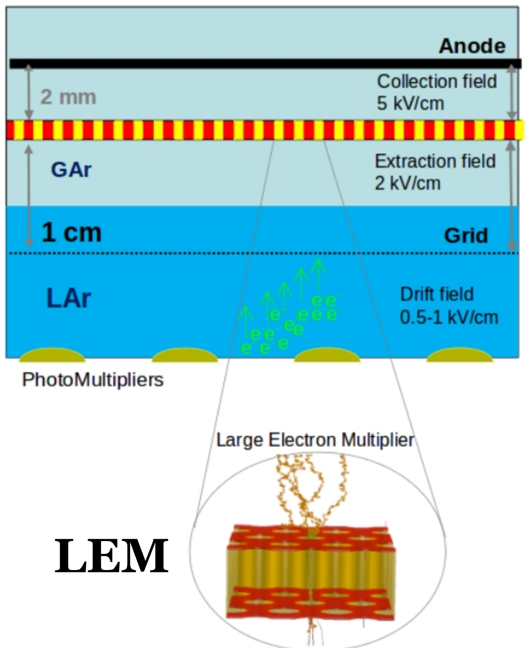


- Three wire plane views:
  - First induction plane (wrapped, 35.7°)
  - Second induction plane (wrapped, 35.7°)
  - Collection plane (vertical)
- Wrapping reduces complexity of cold cabling and number of readout channels
- Photon detectors sit within frames



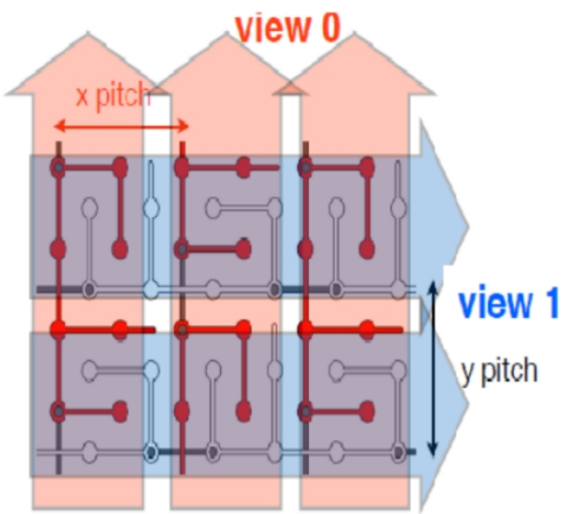
Far Detector: Dual Phase

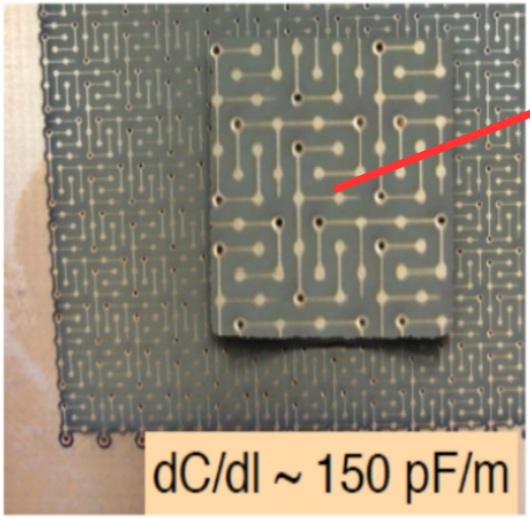


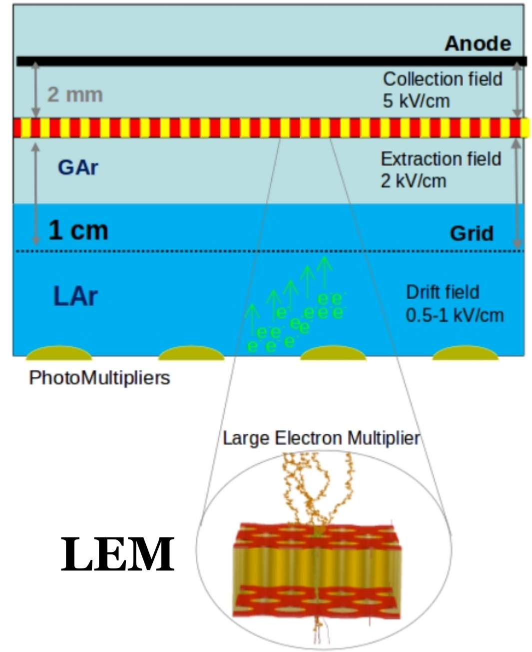


- Dual phase TPC inspired by LBNO design
- **12 m** vertical drift, **500 V/cm** (1.5-4.5 kV/cm) E field in LAr (GAr)
- Amplification via Large Electron Multiplier (LEM) – a "big GEM"
- Partially cold electronics which are still accessible for maintenance

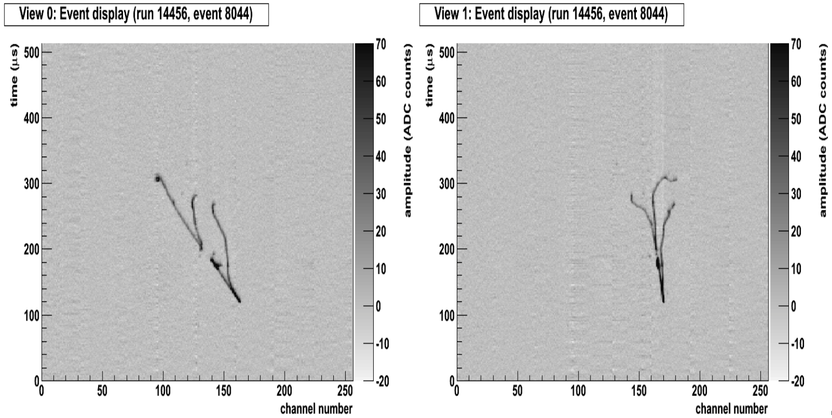
Dual Phase FD Readout





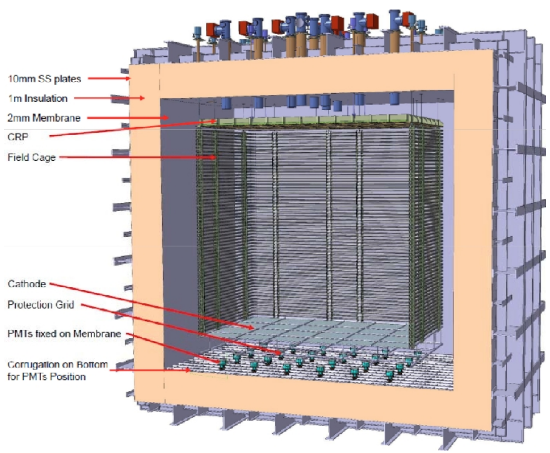


- Two orthogonal collection plane views, interleaved
    - Interleaving evenly distributes electrons between planes
- Excellent S/N via gain obtained with GAr
- PMTs at bottom of cryostat

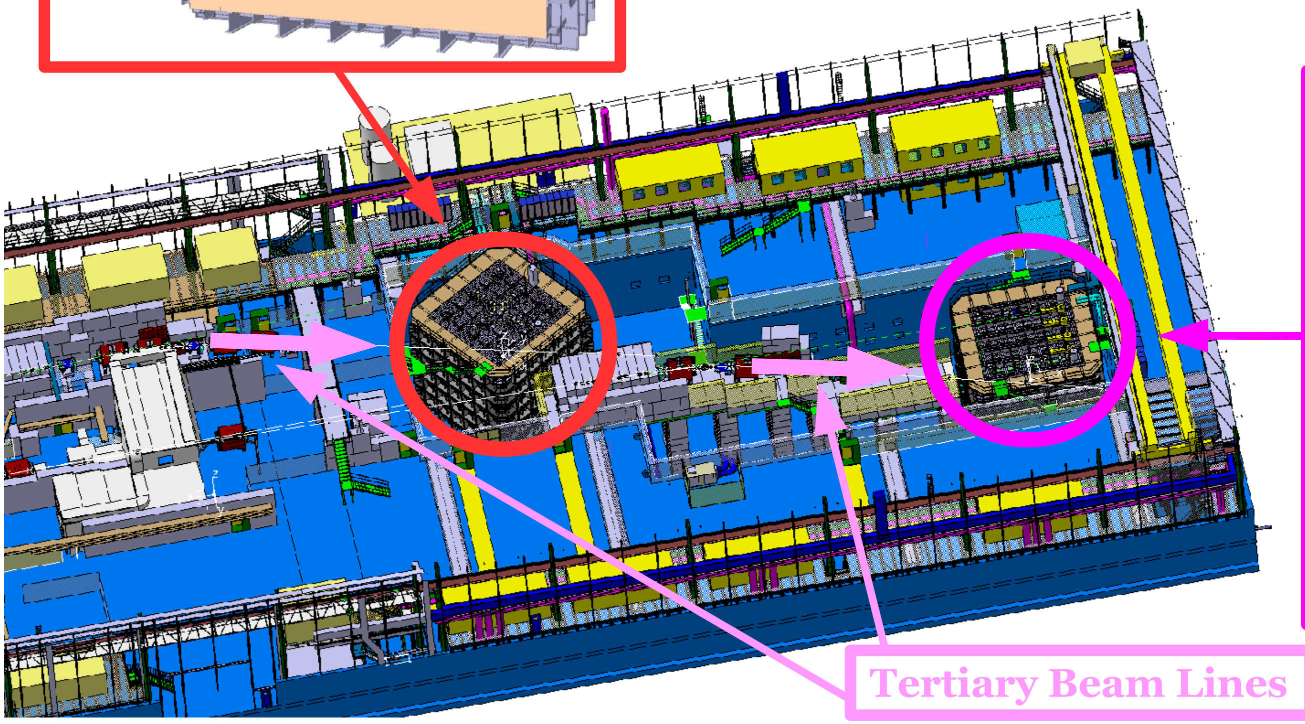


Far Detector Prototypes

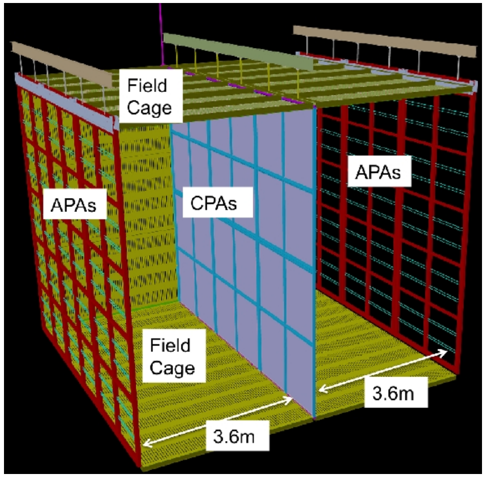
Dual Phase ProtoDUNE



- Two FD prototypes being built at CERN (one for each FD design) – in test beam
  - Detectors operational in 2018
- Tertiary beam lines aiming to provide **0.5-5 GeV** $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$



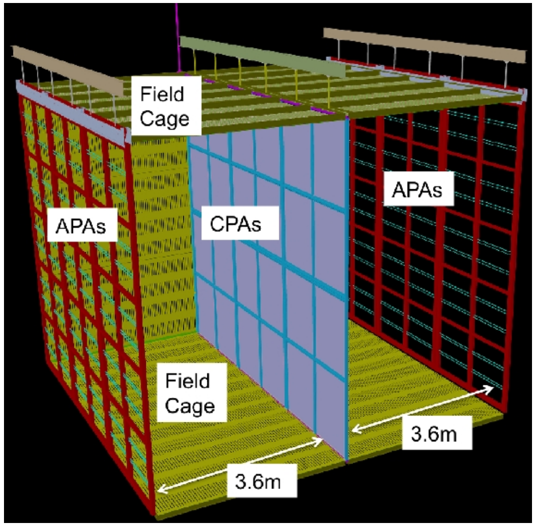
Single Phase ProtoDUNE

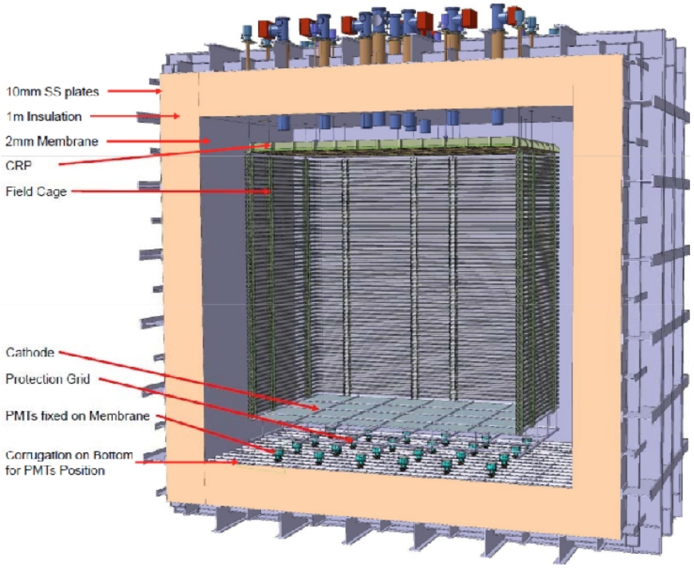


Two ProtoDUNEs

- **Full-scale** engineering prototypes for far detectors
  - Single phase: full-sized APAs and CPAs, full drift distance and E field
  - Dual phase: full-sized readout/cathodes, half drift distance, operating at full and double E field
  - Test of component installation, commissioning, and performance
- Also important for tests of FD calibration and reconstruction software tools

Single Phase ProtoDUNE





Dual Phase ProtoDUNE

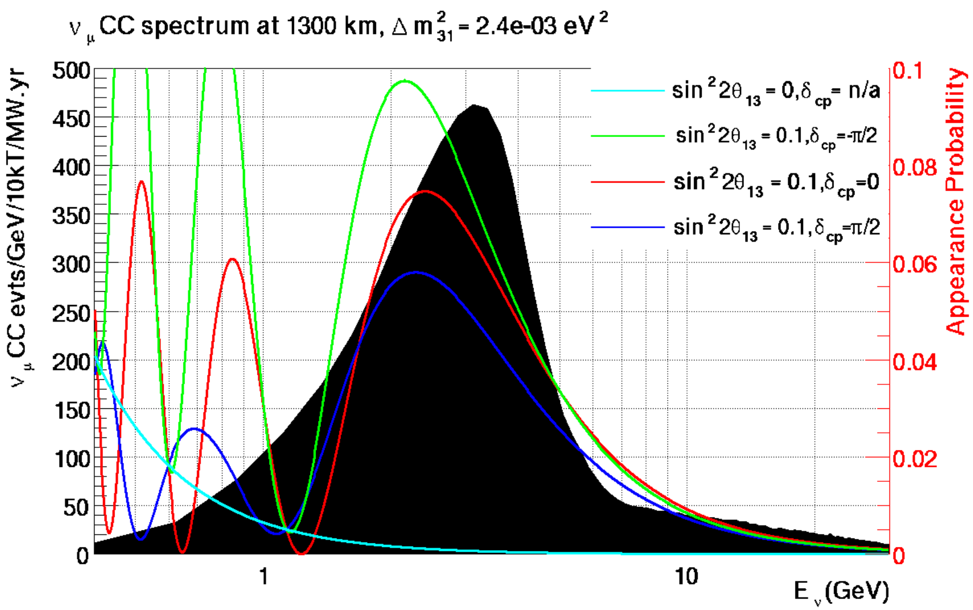
Physics Reach

Neutrino Oscillations

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

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

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

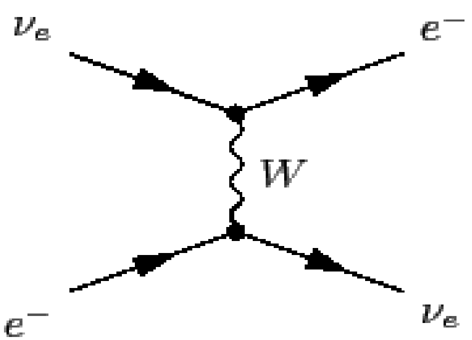


See NuFact 2016 DUNE Oscillations talk by Dan Cherdack for <u>much</u> more detail

- ν_e appearance amplitude depends on θ_{13}, θ_{23}, δ_{CP}, and **matter effects**
  - Measurement of all osc. parameters possible in DUNE
- Large value of $\sin^2(2\theta_{13})$ allows significant ν_e appearance sample

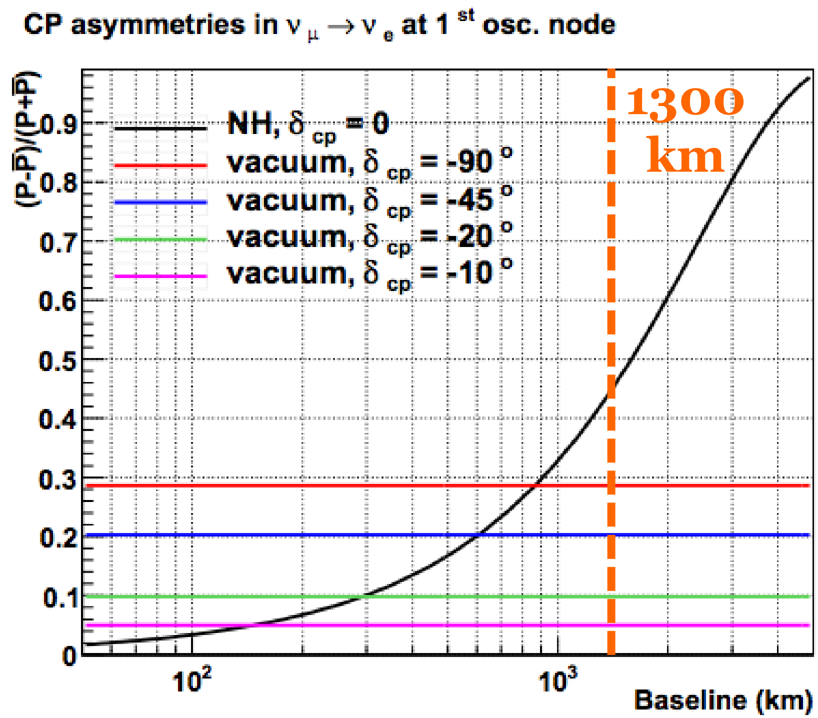
Matter Asymmetry

Electrons are present in matter while positrons and other leptons are not.



Charged-Current Coherent Forward Scattering on Electrons:

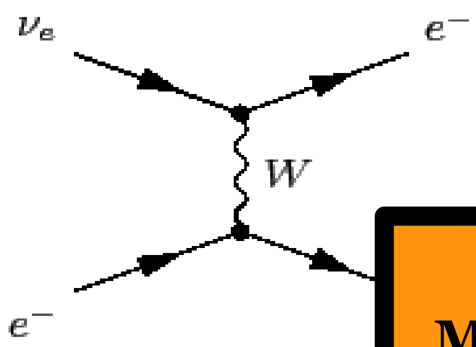
ν_e only



- CC matter effects occur for ν_e only – $\bar{\nu}_e$ (and ν_μ, ν_τ) have only NC matter effect interactions
- Normal hierarchy: matter effect enhances ν_e appearance probability and suppresses $\bar{\nu}_e$ appearance probability (opposite for inverted hierarchy)

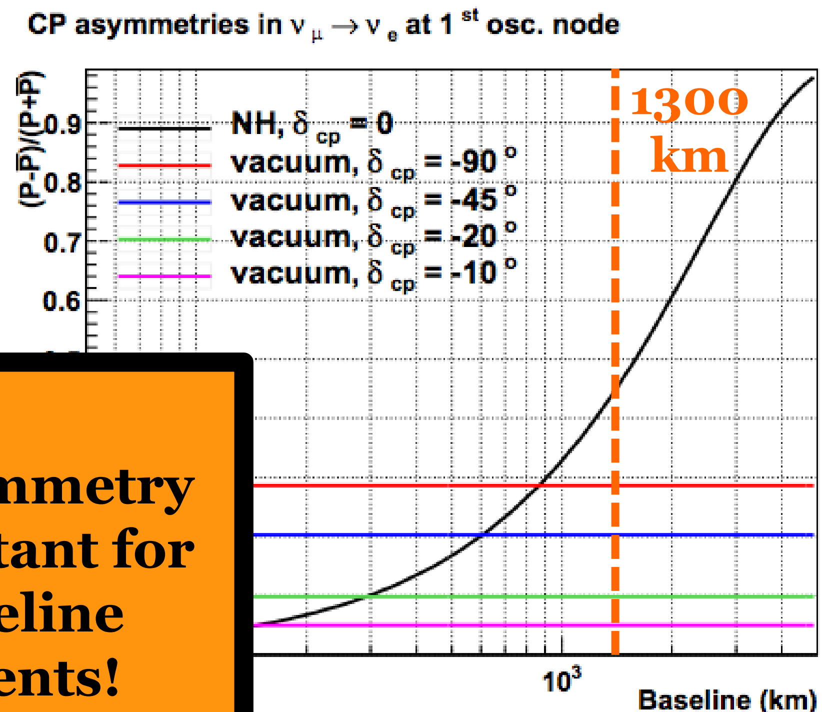
Matter Asymmetry

Electrons are present in matter while positrons and other leptons are not.



Charged-Current Cohere… Scattering on Elect…

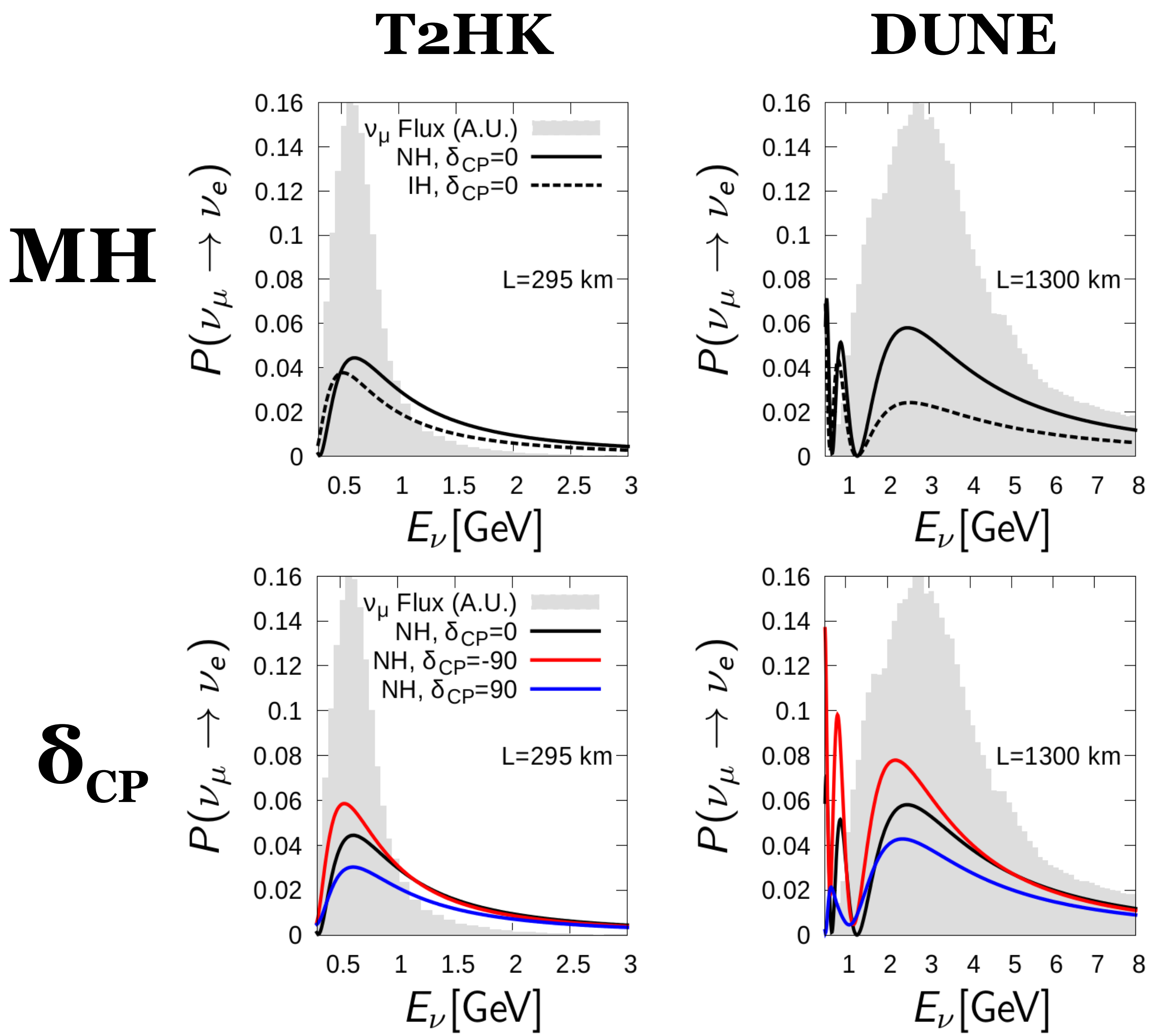
ν_e only



Matter asymmetry very important for long-baseline experiments!

- CC matter effects oc… ν_μ, ν_τ) have only NC matter effect interactions
- Normal hierarchy: matter effect enhances ν_e appearance probability and suppresses $\bar{\nu}_e$ appearance probability (opposite for inverted hierarchy)

Appearance Prob. vs. MH/δ_{CP}

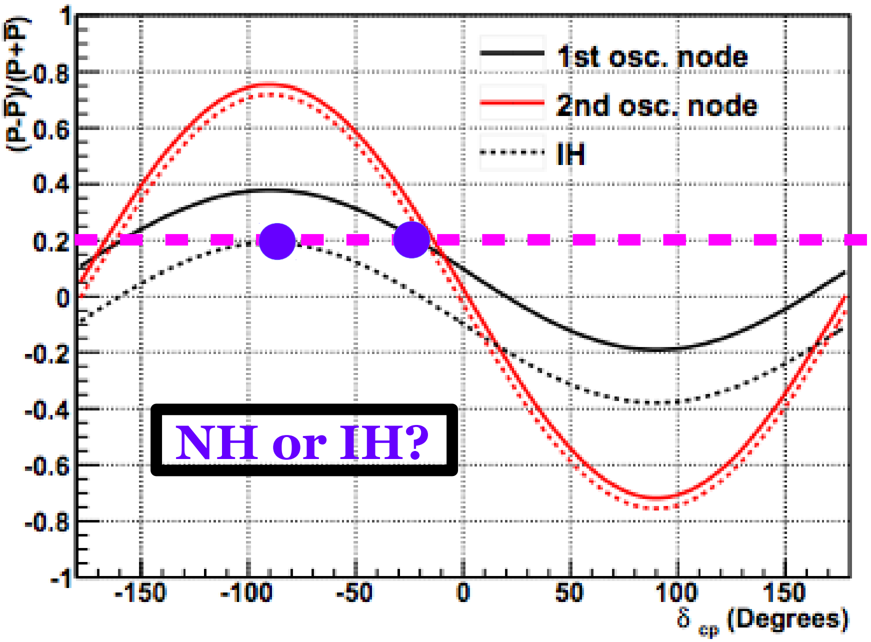


Note: DUNE flux has been updated from that shown in these plots

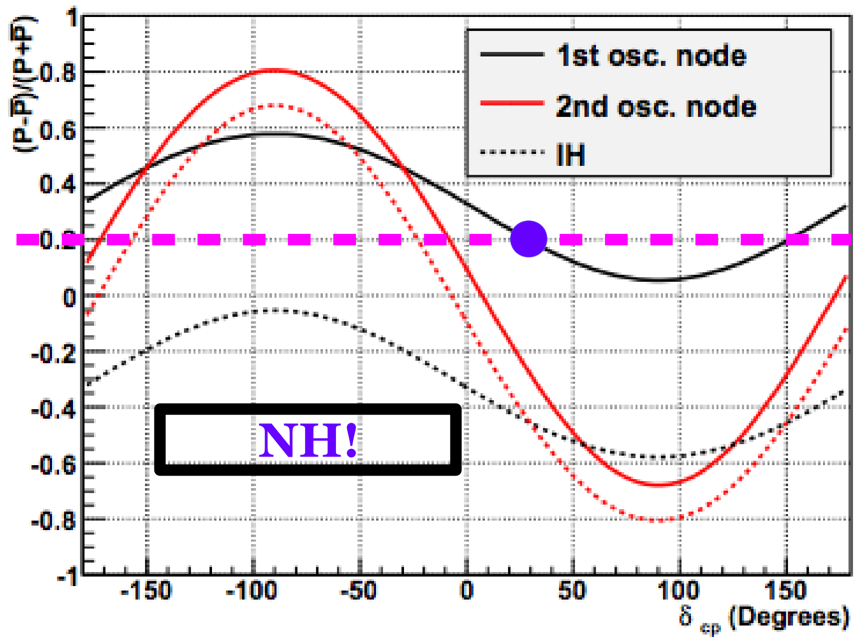
Longer baseline enables the extraction of both MH and δ_{CP}, even w/ 1st osc. maximum only (but 2nd helps)

Impact of Baseline Length

290 km Baseline

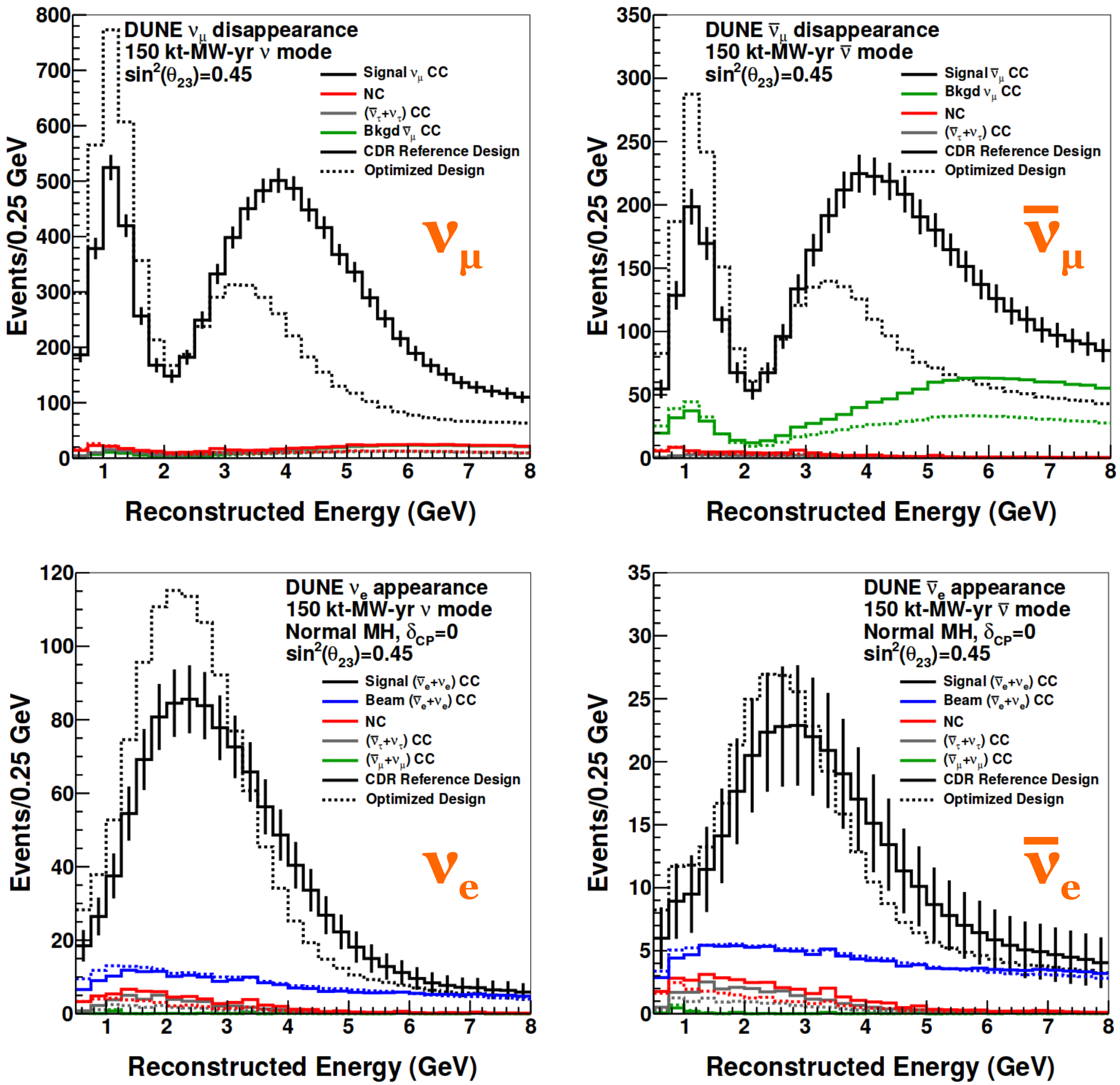


1000 km Baseline



- Example of impact of baseline length: say you measure neutrino-antineutrino appearance asymmetry of **0.2**
- Using 1st oscillation node (focus on **black lines**), MH ambiguous at shorter baselines but degeneracy broken at longer baselines
  - 1300 km is near optimal baseline for these measurements

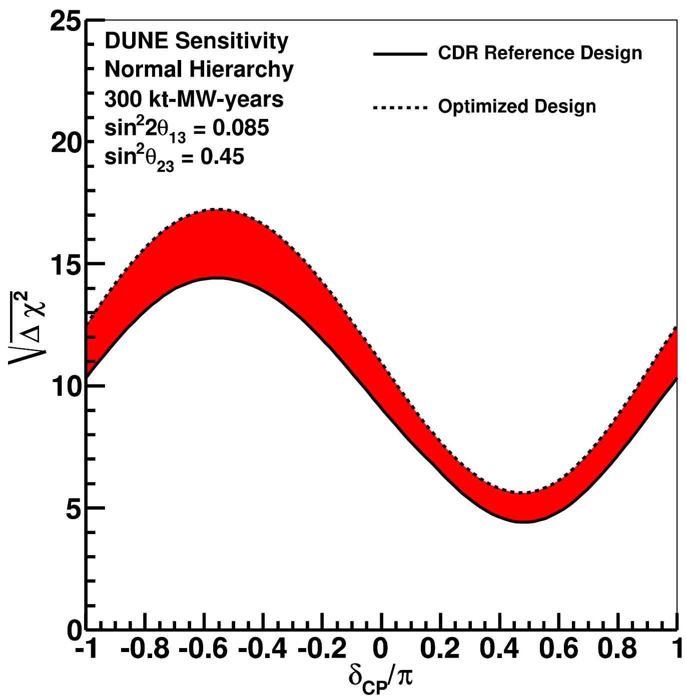
Calculating Sensitivities



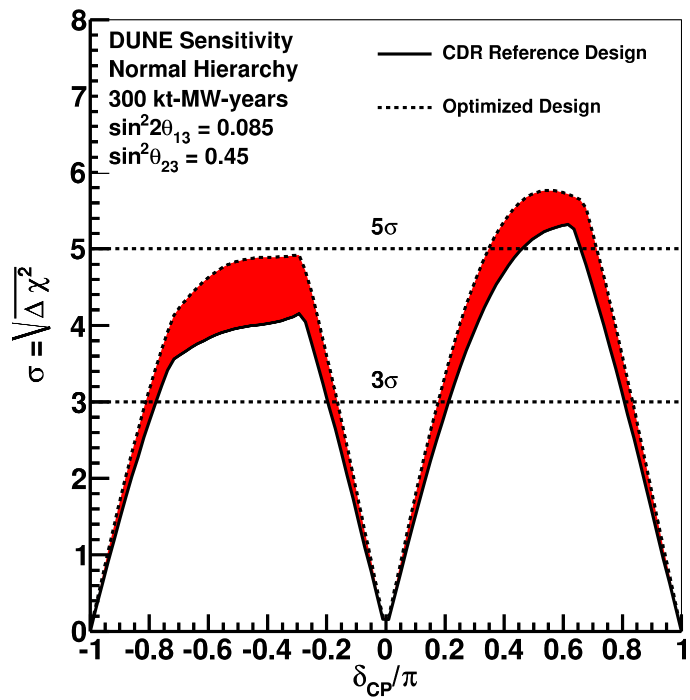
- GLoBES-based fit to four samples in FD
  - ν_e / $\bar{\nu}_e$ appearance
  - ν_μ / $\bar{\nu}_\mu$ disappearance
- Both reference and optimized beam design shown
- Reconstructed spectra predicted using detector response parameterized at single particle level
- Simple systematics treatment for now

MH/CPV Sensitivity

Mass Hierarchy

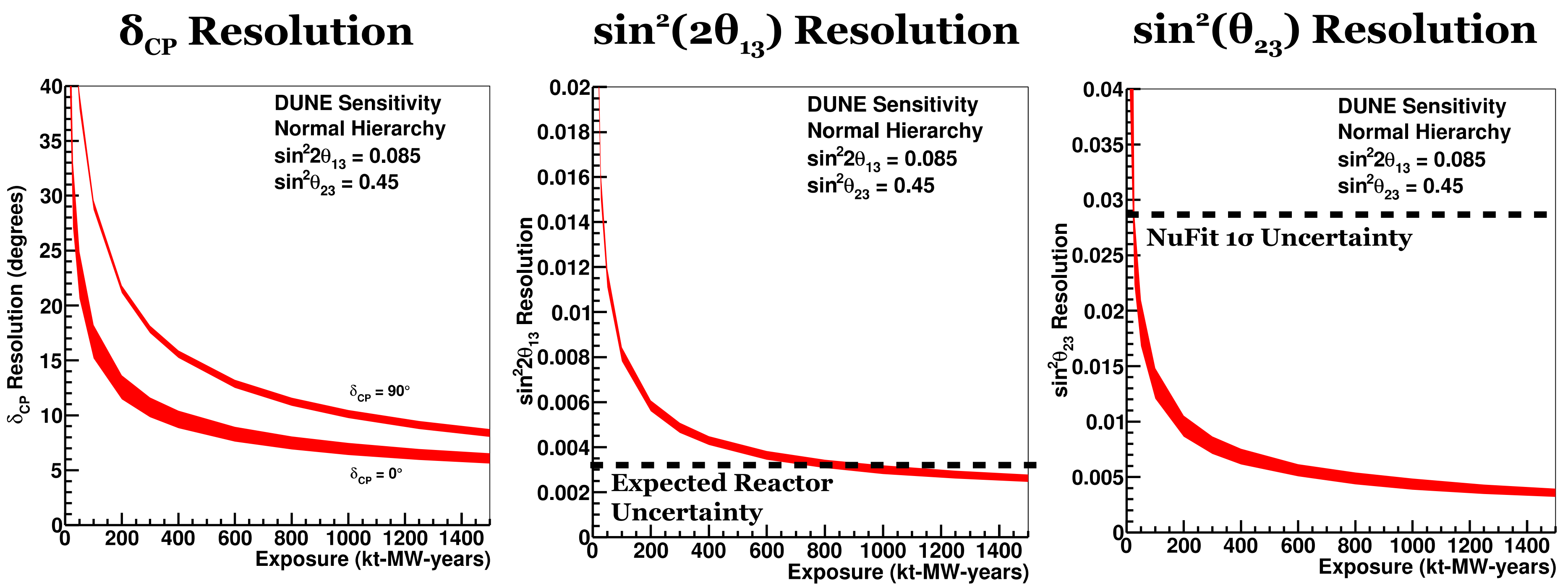


CP Violation



- Exposure: 300 kt-MW-yr = 40 kt × 1.07 MW × (3.5 ν + 3.5 $\bar{\nu}$) years
- Includes simple normalization systematics and oscillation parameter variations
- At this exposure, already determine MH, ~5σ CPV for $\delta_{CP} = \pm\pi/2$

Osc. Parameter Resolution

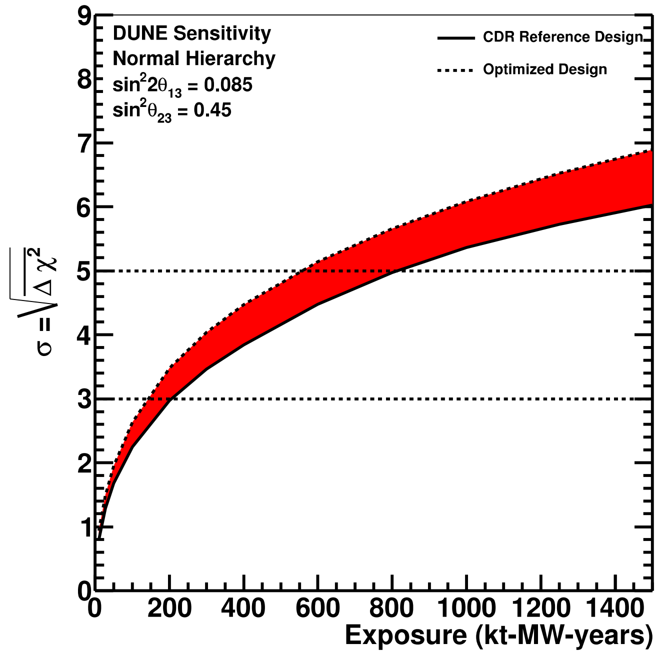


- Exposure as a function of time in kt-MW-years
- Near end of experimental run:
  - Below **10°** in δ_{CP} resolution → important for constraining CPV models
  - Test of unitarity with independent measurement of θ_{13} (using ν_e / $\bar{\nu}_e$ appearance vs. $\bar{\nu}_e$ disappearance from reactor experiments)

Sensitivity Benchmarks

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

CP Violation (50% Coverage)

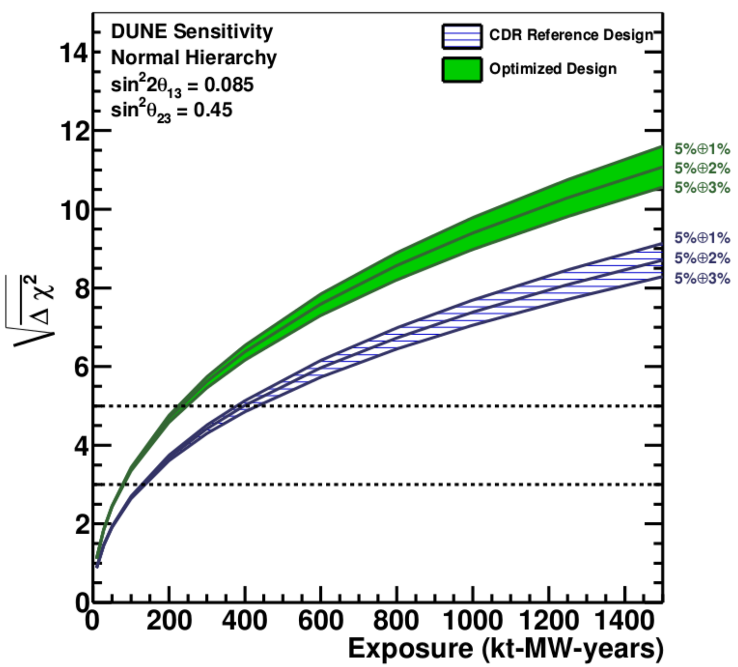


- Many milestones expected throughout experimental run:
  - 1% θ_{23} resolution ($\theta_{23} = 42^\circ$): **45** kt-MW-years
  - Definitive MH determination ($\geq 5\sigma$ for all values of δ_{CP}): **230** kt-MW-years
  - CPV at 5σ ($\delta_{CP} = -\pi/2$): **320** kt-MW-years
  - Reactor θ_{13} resolution: **850** kt-MW-years

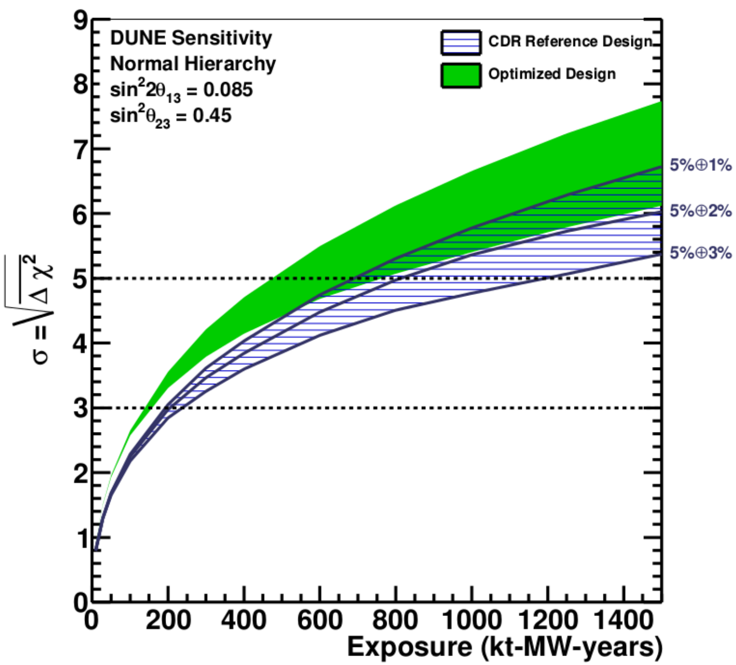
Impact of Systematics

- Sensitivities based on GLoBES calculations in which systematics approximated using uncorrelated signal normalization uncertainties
  - $\nu_\mu / \bar{\nu}_\mu$: **5%**; $\nu_e / \bar{\nu}_e$: **2%** → **goal** for CPV discovery in timely manner
  - Scheme approximates case of 5% correlated uncertainty (shared between all samples) and 2% uncorrelated uncertainty (for $\nu_e / \bar{\nu}_e$)

Mass Hierarchy (100% Coverage)

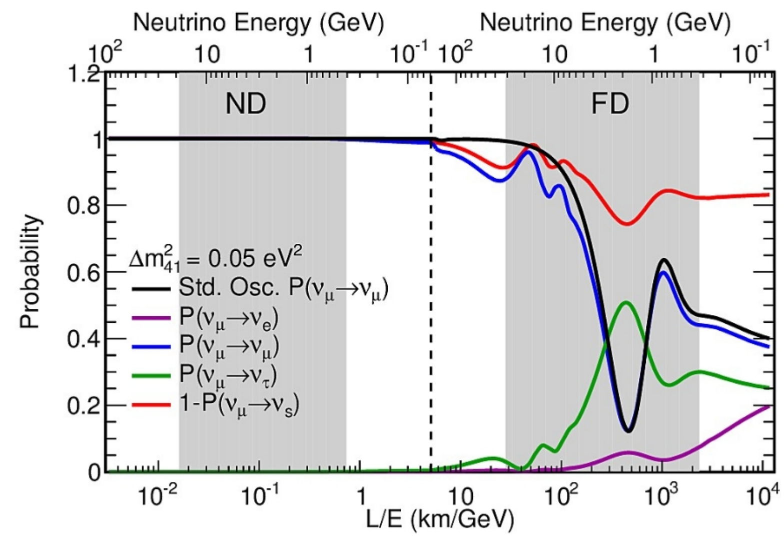


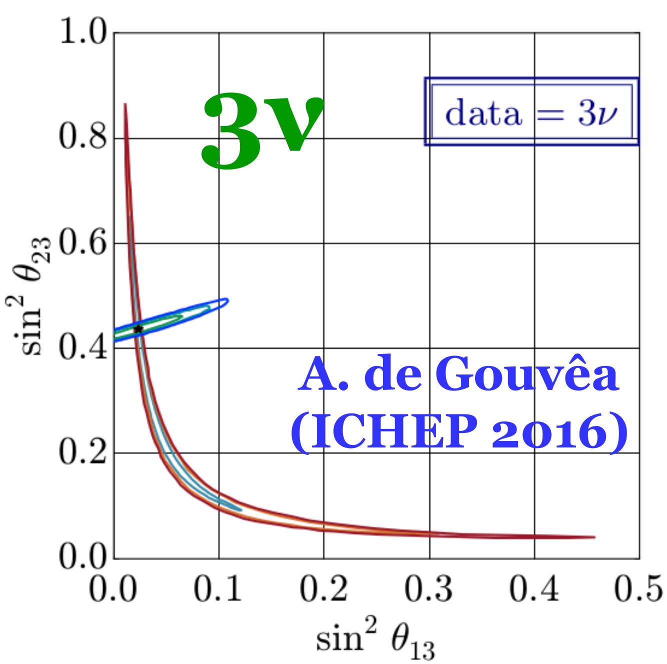
CP Violation (50% Coverage)

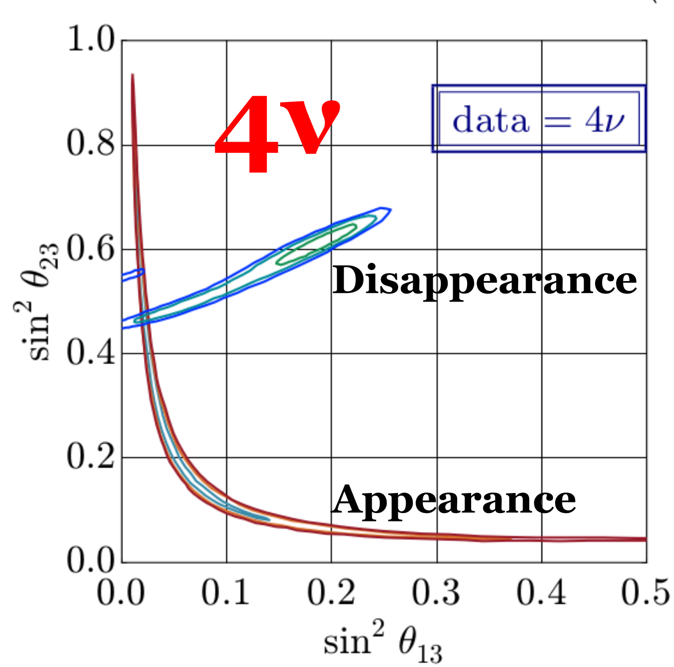


Sterile Neutrinos

- Searches for sterile neutrinos at DUNE can be done using both the ND and FD
- One sign of failure of 3ν paradigm: different best-fit parameters for appearance, disappearance modes



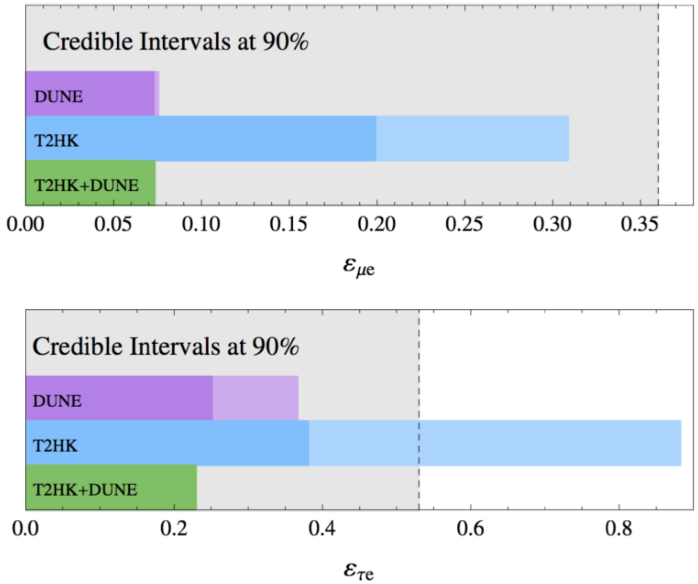


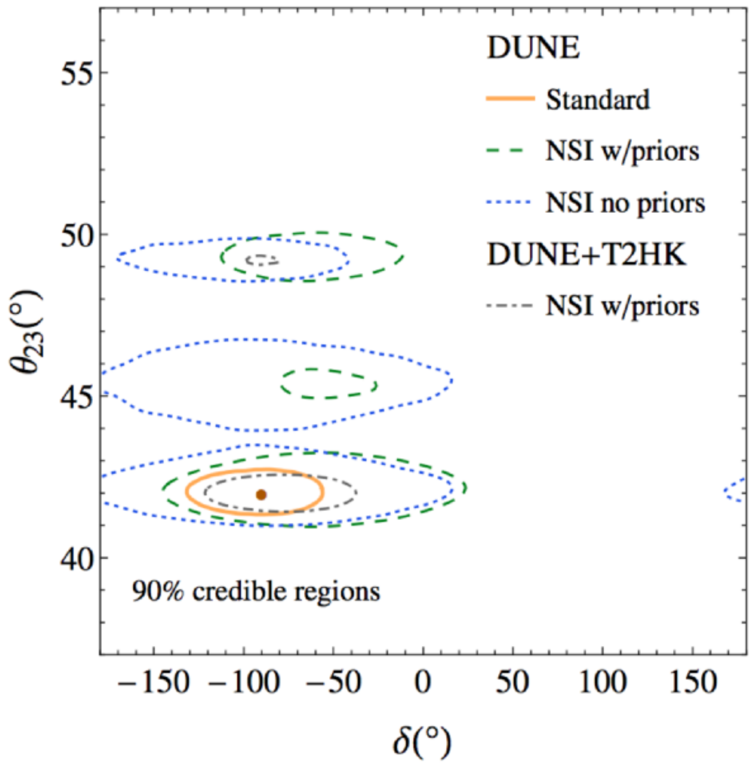


3ν fits to both datasets

Experiment Complementarity

P. Coloma (ICHEP 2016)



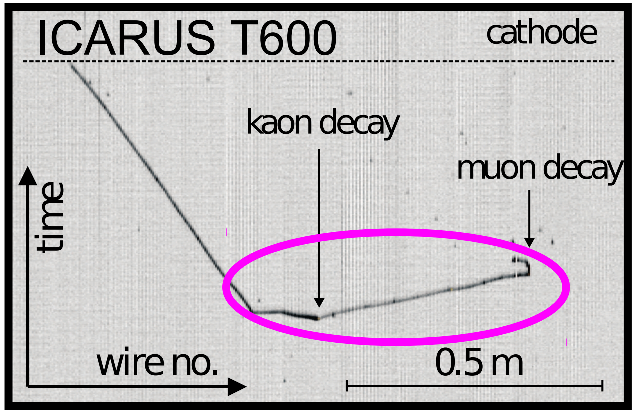


- DUNE has the potential to constraint effects from NSI
  - DUNE most capable to do this (greater matter effects at 1300 km)
- However: if NSI effects significant, DUNE could find degeneracies in the θ_{23}-δ_{CP} plane → break degeneracies with **T2HK**

Nucleon Decay

- Test of fundamental symmetries very exciting prospect in modern physics → for example, **baryon number conservation**
  - No reason for this to be required
  - **Matter-antimatter asymmetry** requires baryon number **non-conservation** (Sakharov conditions)
- Grand Unified Theories (GUTs) make specific predictions for decay modes, lifetimes, branching ratios
  - Smoking gun: observation of **nucleon decay** → e.g. in **DUNE FD**
  - Also neutron-antineutron oscillations (another DUNE physics topic)

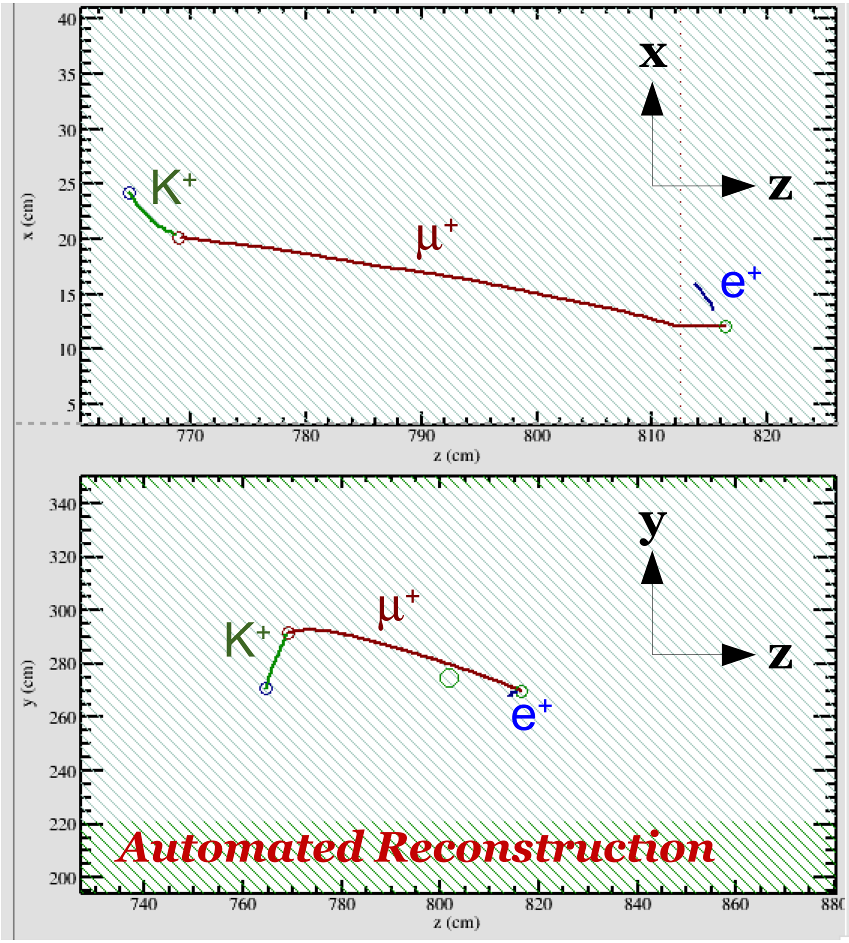
Low thresholds and precision tracking of LArTPC technology enables kaon decay modes



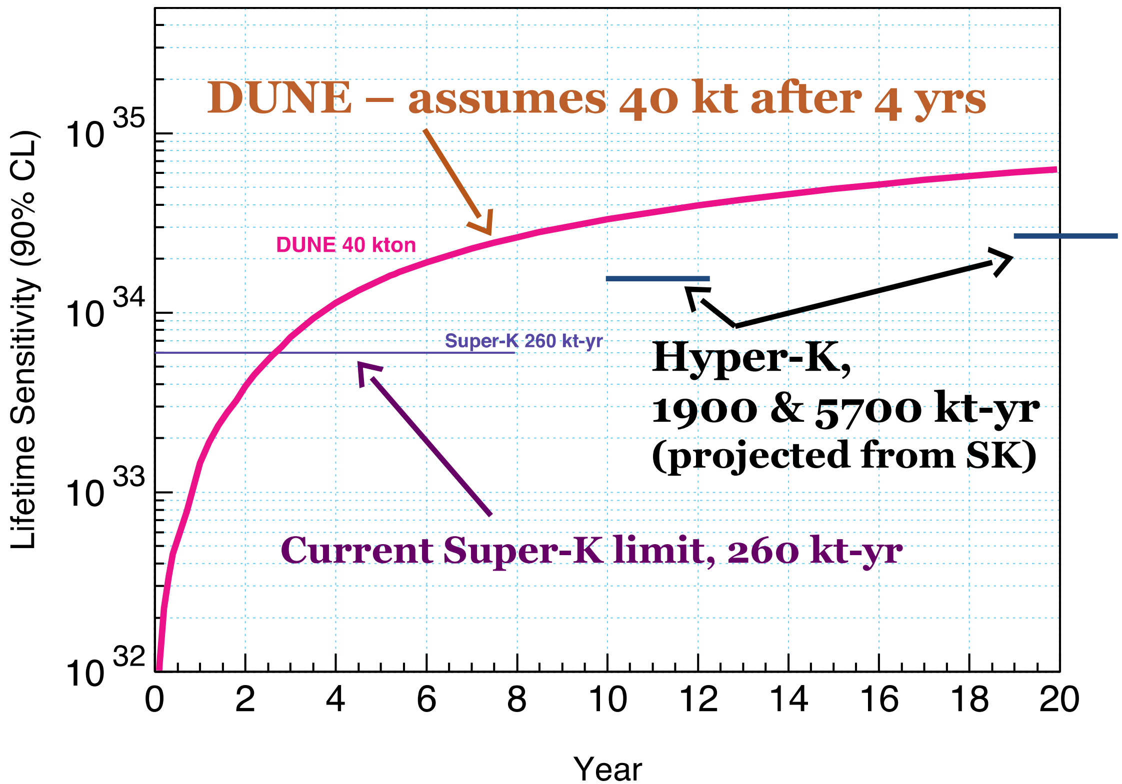
Proton Decay Search Needs

- Detector requirements:
  - Low background rate – cosmogenic background reduced by **deep underground** location of DUNE FD (atmospheric neutrinos another source to deal with)
  - High signal efficiency – **precision tracking** in LArTPC helpful for **kaons** and **complex final states**
  - Large exposure – **40-kt** DUNE FD running **20+ years**
- DUNE FD meets all of these requirements

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



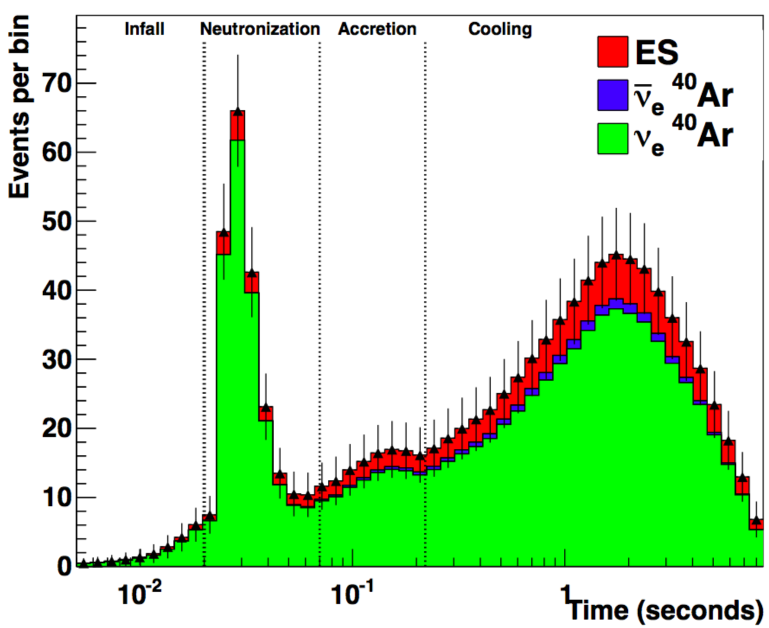
Proton Decay Sensitivity

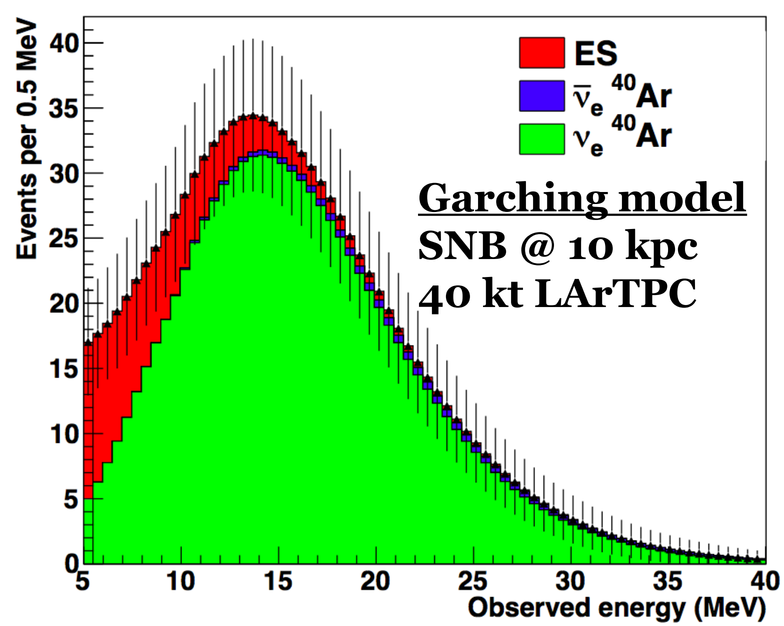


- Sensitivity shown above for $\mathbf{p \rightarrow \bar{\nu} K^{+}}$ mode
- <u>Note</u>: likely longer than 4 years to reach 40 kt
- Hyper-K does better with other modes (larger fiducial volume)

Supernova Burst Neutrinos

- More than 99% of energy in supernova burst emitted in the form of O(10 MeV) neutrinos – **SN1987a** observation yielded insights, but many details left to be understood
- Can search for these events with low thresholds of DUNE LArTPCs
- **Timing** and **calorimetric** information can differentiate models of supernova burst from stellar core collapse





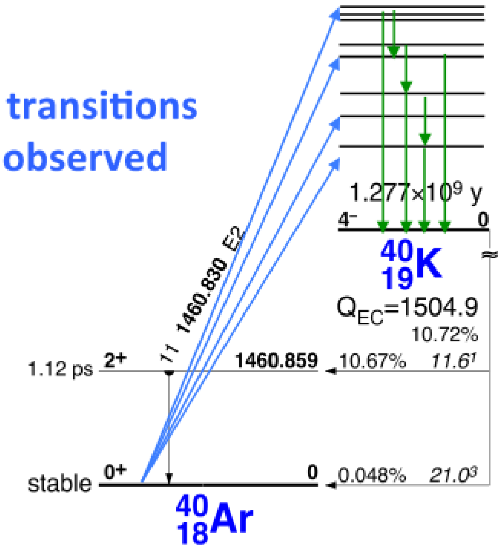
SN ν Detection

Charged-current absorption:

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

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

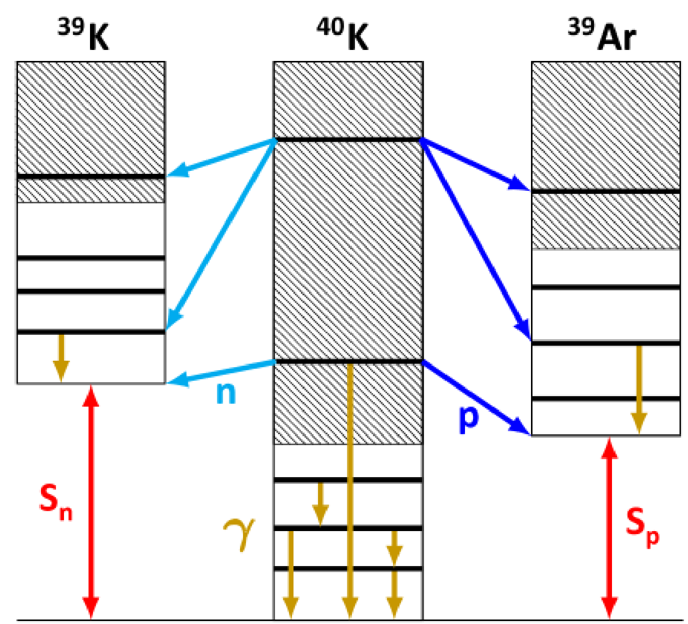
Large uncertainties in nuclear data and models complicate energy reconstruction

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)

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



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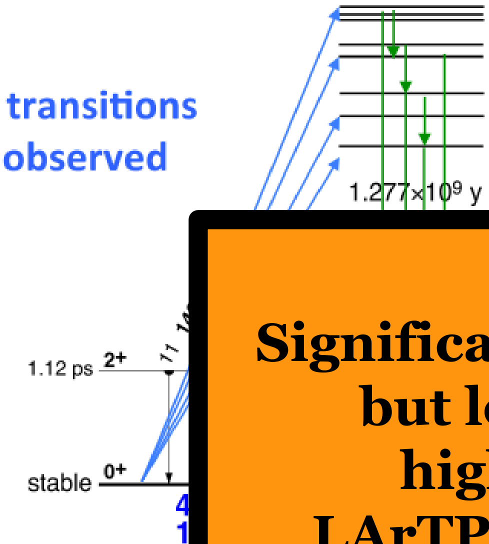

Transition levels are de[…] observing de-excitation[…]

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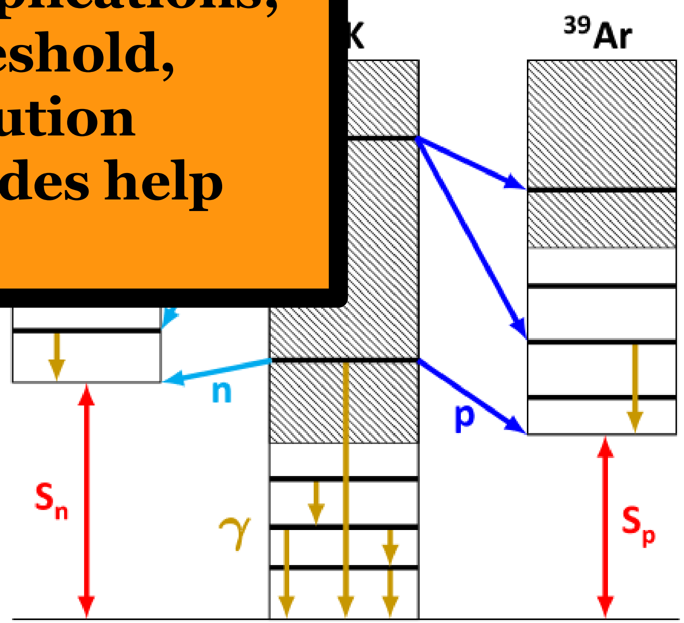
Outgoing e⁻ Energy

Energy donated to transition

Recoil Energy of Nucleus (negligible)

$+ K_{\text{recoil}}$

Significant complications, but low-threshold, high-resolution LArTPC provides help



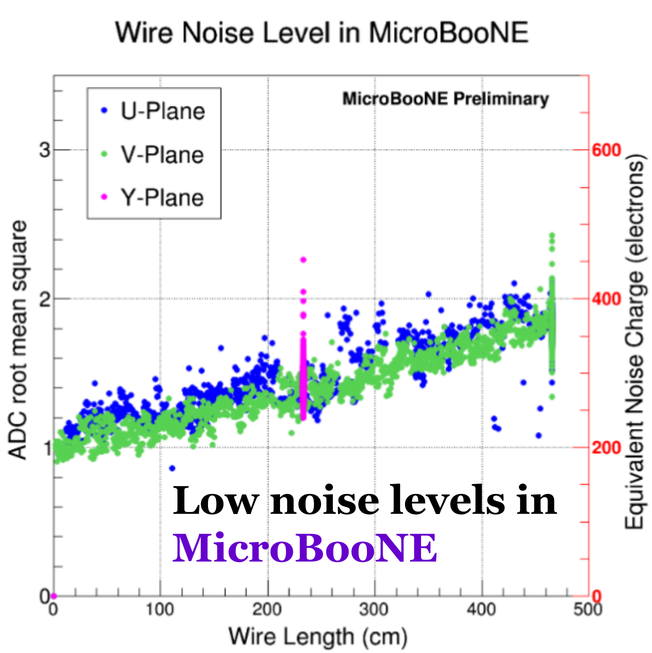
Status, Plans, and Outlook

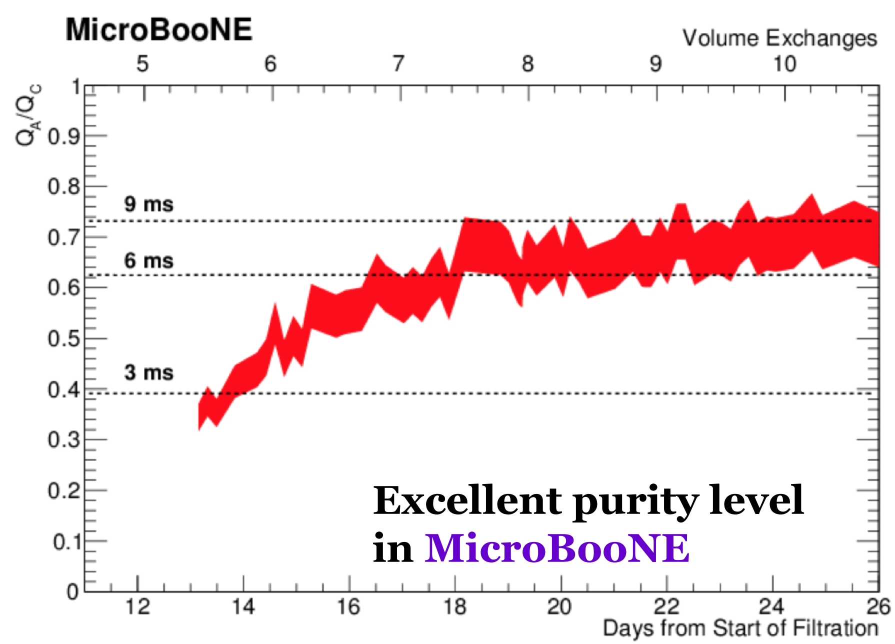
DUNE Timeline

- **2014** – Decision made by DOE to pursue LBL physics with an international effort
- **2015** – New collaboration structure w/ LBNF and DUNE (based on LHC model)
- **2016** – **NOW**
- **2017** – Start of excavation at the far site (SURF)
- **2018** – Two ProtoDUNE Detectors (SP & DP) operational at CERN
- **2019**
- **2020**
- **2021** – Start of FD installation: 1^{st} module (single phase)
- **2022**
- **2023** – Continue FD installation: 2^{nd} module (not necessarily the same design)
- **2024** – 20 kt operational
- **2025**
- **2026** – **Beam operations begin at nominal power and proton energy**

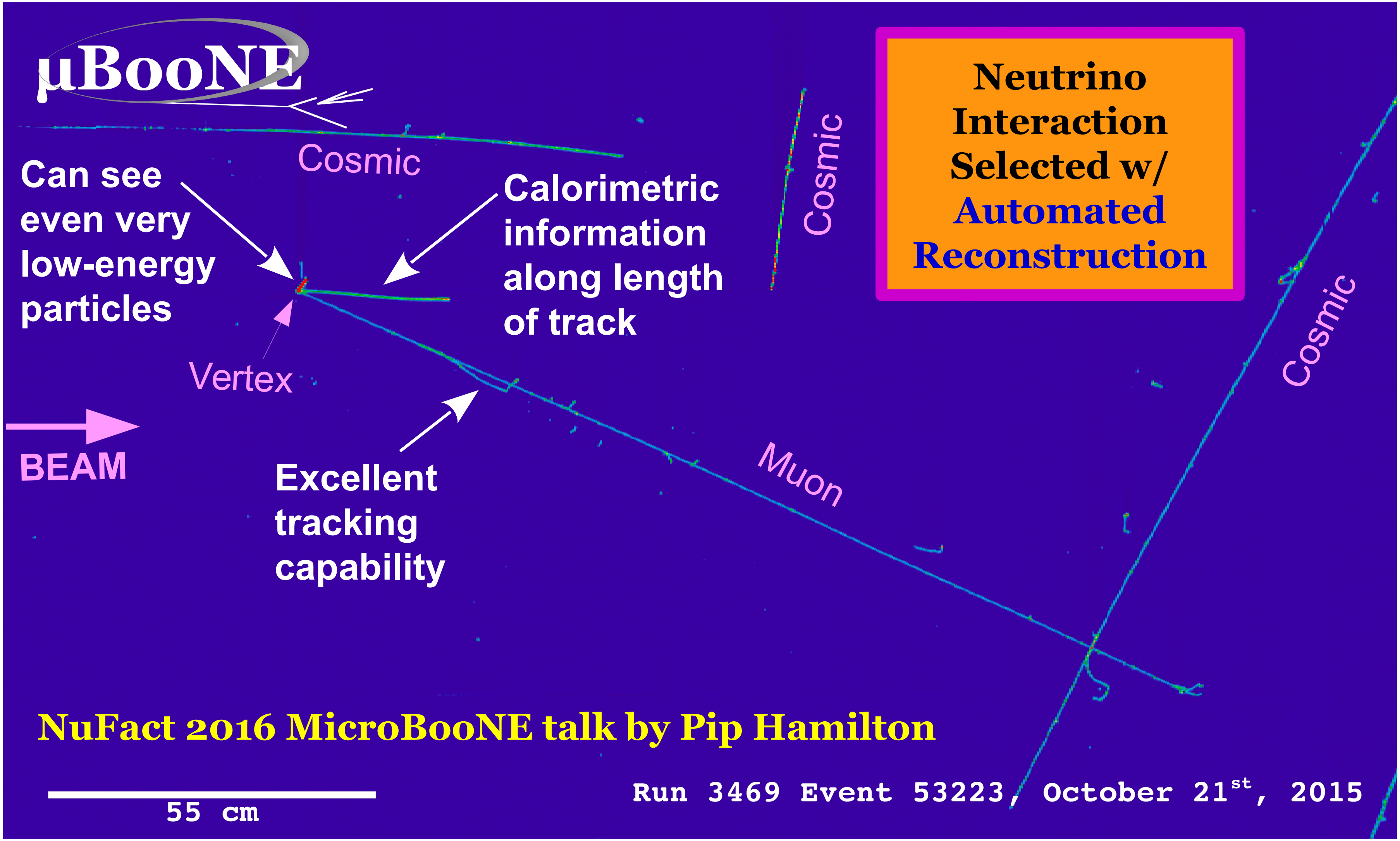
LArTPC Experience

- While waiting for protons on target in **2026**, we will continue to gain experience with the LArTPC technology
  - MicroBooNE (2015–2018) and SBN program (2018–2021)
  - DUNE 35-ton/311 tests (2016) and ProtoDUNEs (2018)
- **Operational experience** and high-performance **automated reconstruction** of events in data necessary for success



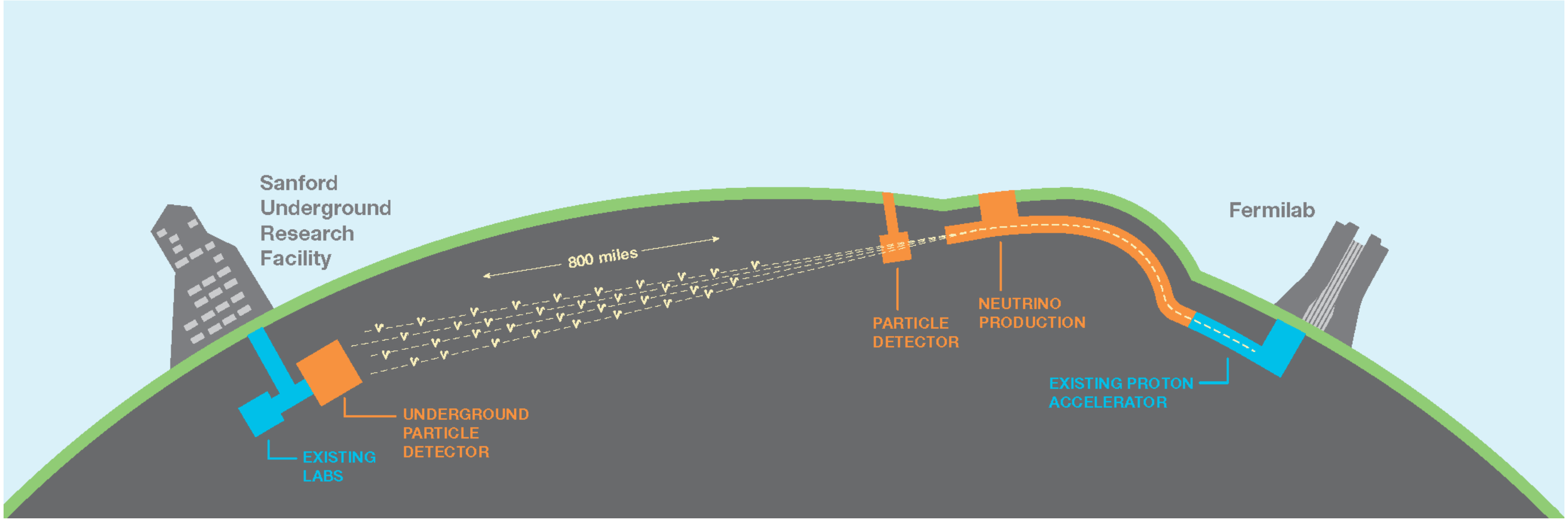


MicroBooNE Event (Data)



Summary

- DUNE has a lot to offer the physics community:
  - Pinning down mass hierarchy, δ_{CP}, θ_{23}, and θ_{13} in a **single experiment**, enabled by long baseline (1300 km), wideband beam
  - Sensitivity to sterile neutrinos, nucleon decay, and SN burst ν
- DUNE is positioned to determine MH and see CPV at **5σ**
- Much overlap with Hyper-K/T2HK, but also a lot of complementarity by having **both experiments**
  - Verification of results with different detector technologies
  - Combination of experiments allows resolving of oscillation parameter degeneracies originating from new physics
- LArTPC technology is continually being better understood with a variety of experiments (e.g. MicroBooNE)
- Beginning excavation of far site next year – stay tuned!

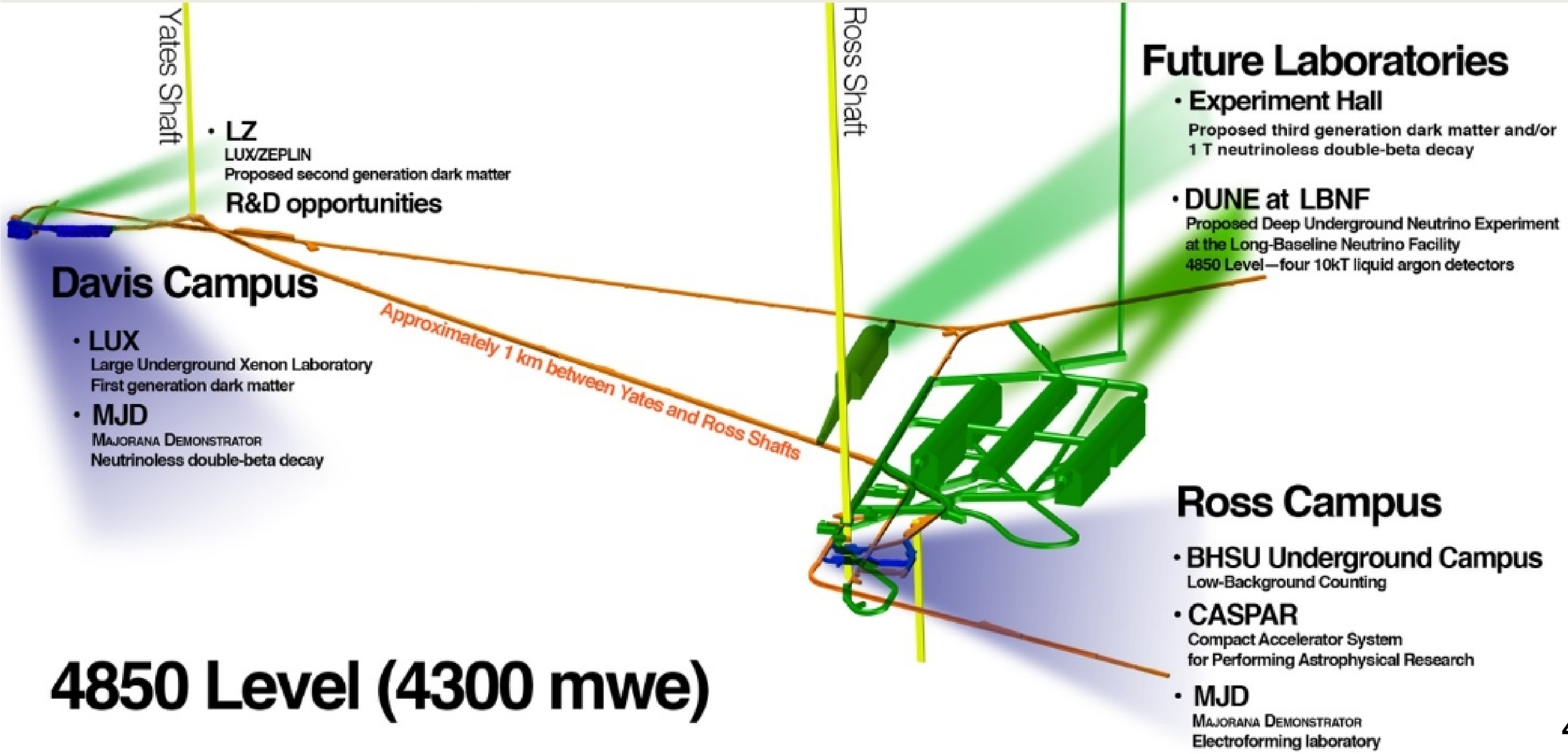

Sanford
Underground
Research
Facility
800 miles
Fermilab
PARTICLE
DETECTOR
NEUTRINO
PRODUCTION
EXISTING PROTON
ACCELERATOR
UNDERGROUND
PARTICLE
DETECTOR
EXISTING
LABS

Thanks!

BACKUP SLIDES

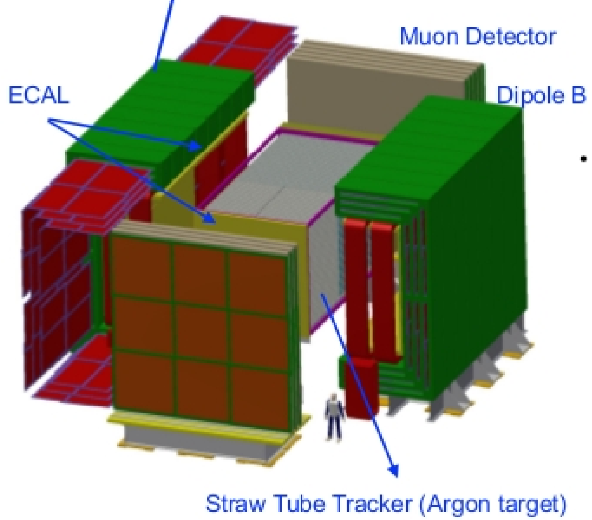
SURF (Lead, S. Dakota)

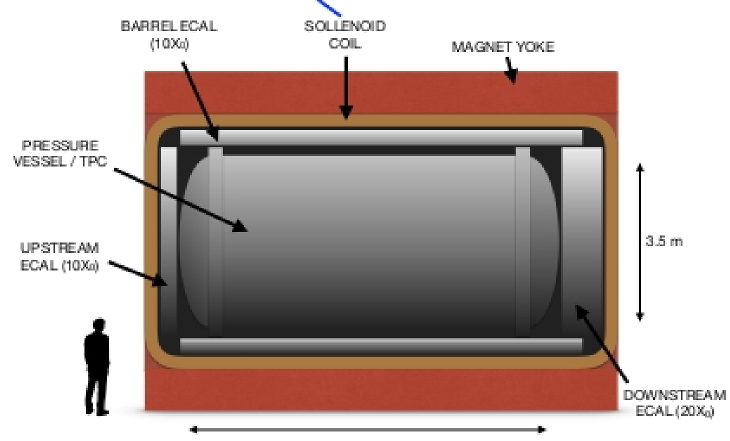
- Site has long & storied history as home to neutrino experiments
- **LBNF scope:** 4 detector chambers, utility cavern, connecting drifts
- **Extensive preparatory work** for LBNF/DUNE already done
- **DOE approval pending** to begin excavation & surface building

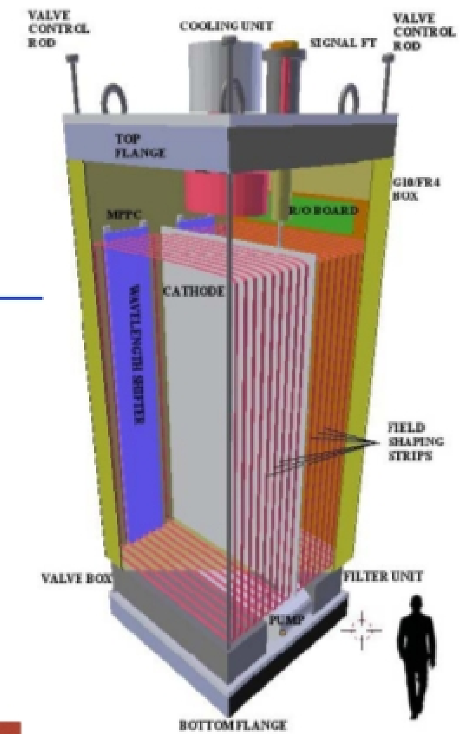


Near Detector Options

- Currently we have 3 ND options under study:
  - Fine-Grained Tracker (CDR reference design)
  - LAr TPC (ArgonCube)
  - High-Pressure Ar Gas TPC







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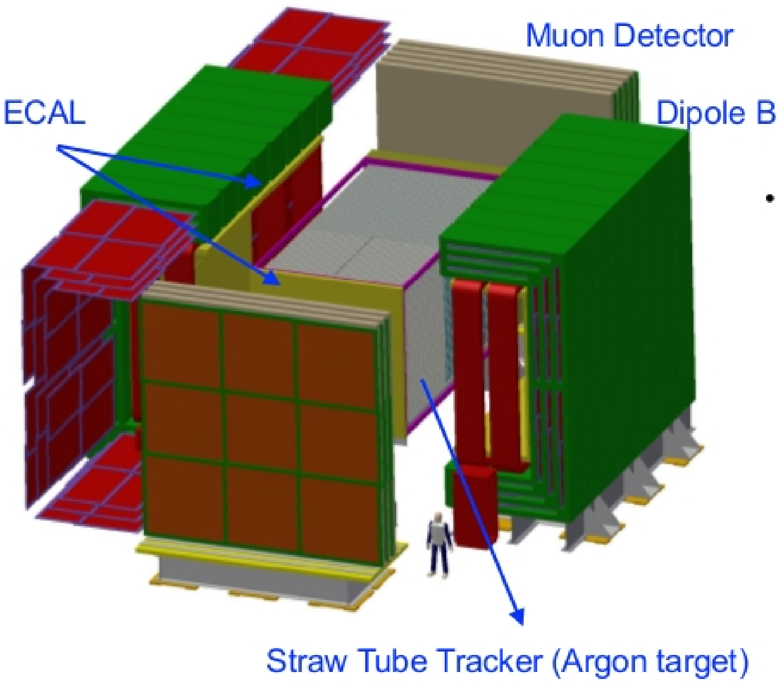
Fine-Grained Tracker

Fine-Grained Tracker (FGT)

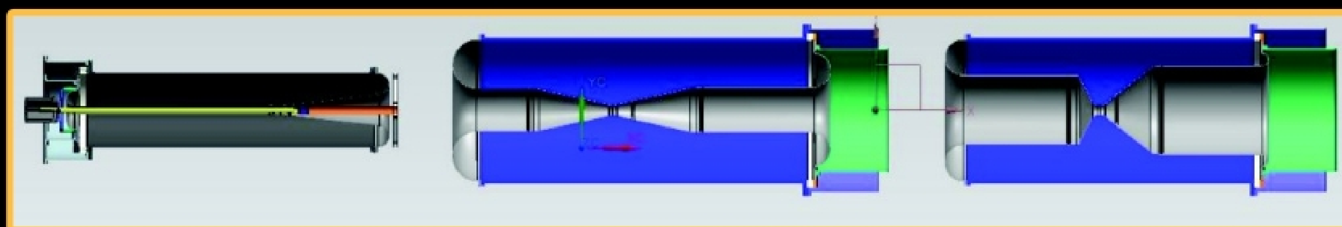


Radiator (Target) Mass	7 tons
Other Nuclear Target Mass	1–2 tons
Vertex Resolution	0.1 mm
Angular Resolution	2 mrad
E_e Resolution	$6\%/\sqrt{E}$ (4% at 3 GeV)
E_μ Resolution	3.5%
$\nu_\mu/\bar{\nu}_\mu$ ID	Yes
$\nu_e/\bar{\nu}_e$ ID	Yes
π^- .vs. π^+ ID	Yes
π^+ .vs. *proton* .vs. K^+	Yes
NCπ^0/CCe Rejection	0.1%
NCγ/CCe Rejection	0.2%
CCμ/CCe Rejection	0.01%

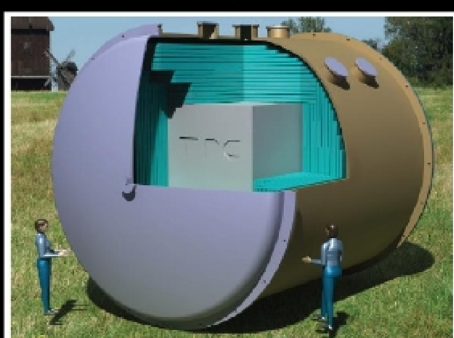
- ~3.5m×3.5m×6.5m Straw Tube Tracker (STT) ($\rho \simeq 0.1$ g/cm^3, $X_0 \simeq 6$m).
- Dipole magnetic field (B = 0.4 T).
- 4π ECAL coverage.
- 4π MuID (RPC) in dipole and up/downstream.
- Pressurized ^{40}Ar target ≃ ×10 FD statistics, and ^{40}Ca target.

DUNE Task Forces

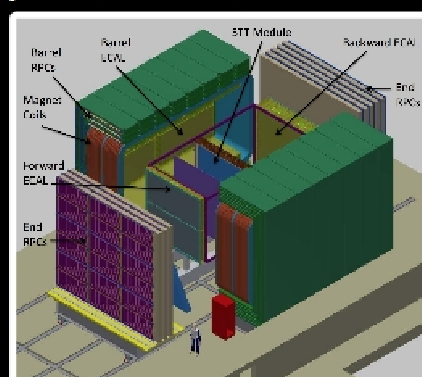
- Cross-working-group teams charged with simulating, evaluating, and optimizing the performance of the three main components of the experimental design
- Beam Optimization



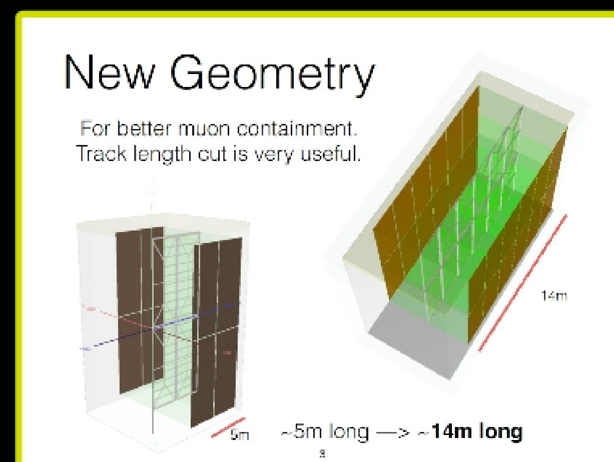
- Near Detector Optimization
- Far Detector Optimization



High-Pressure GAr TPC



Fine-Grained Tracker



Example Event Yields

arxiv:1512.06148	CDR Reference Design	Optimized Design
ν mode (150 kt · MW · year)		
ν_e Signal NH (IH)	861 (495)	945 (521)
$\bar{\nu}_e$ Signal NH (IH)	13 (26)	10 (22)
Total Signal NH (IH)	874 (521)	955 (543)
Beam $\nu_e + \bar{\nu}_e$ CC Bkgd	159	204
NC Bkgd	22	17
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	42	19
$\nu_\mu + \bar{\nu}_\mu$ CC Bkgd	3	3
Total Bkgd	226	243
$\bar{\nu}$ mode (150 kt · MW · year)		
ν_e Signal NH (IH)	61 (37)	47 (28)
$\bar{\nu}_e$ Signal NH (IH)	167 (378)	168 (436)
Total Signal NH (IH)	228 (415)	215 (464)
Beam $\nu_e + \bar{\nu}_e$ CC Bkgd	89	105
NC Bkgd	12	9
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	23	11
$\nu_\mu + \bar{\nu}_\mu$ CC Bkgd	2	2
Total Bkgd	126	127

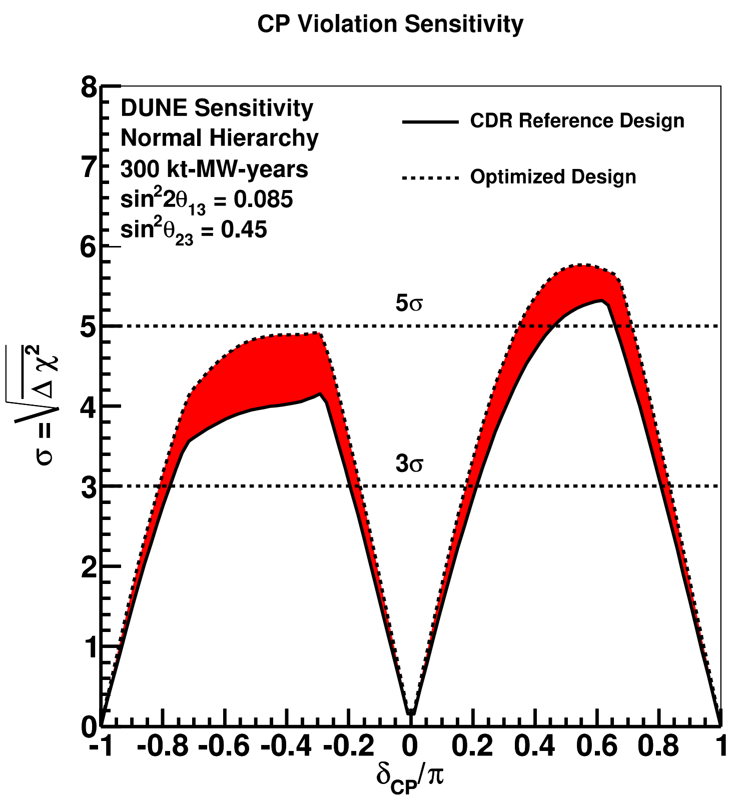
ν

$\bar{\nu}$

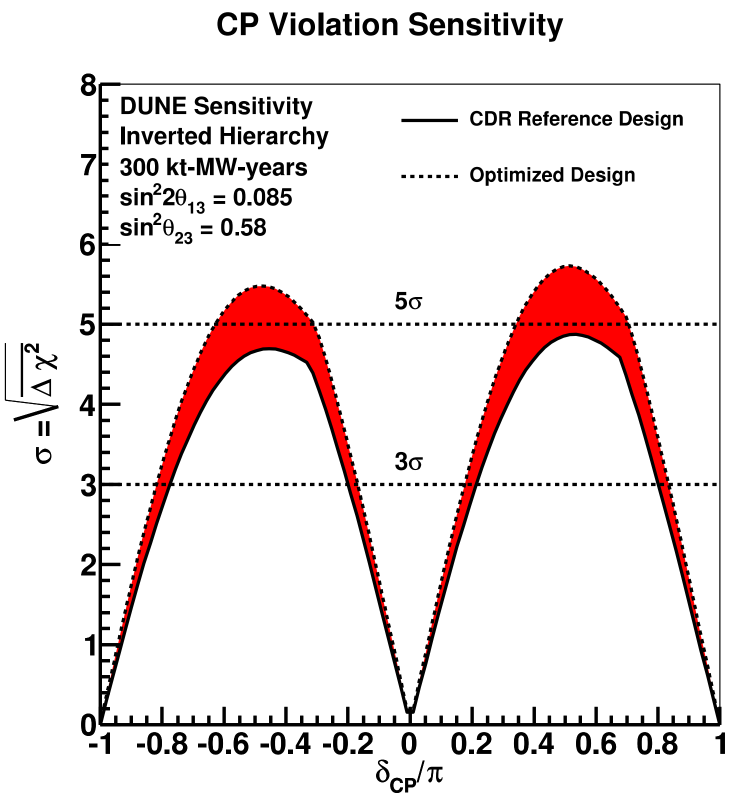
Number of events in the $0.5 < E_\nu < 8.0$ GeV range, assuming 150 kt-MW-yr in each of the ν and $\bar{\nu}$ beam modes, $\delta_{cp} = 0.0$, and the NuFit 2014 oscillation parameters.

CPV: Hierarchy Comparison

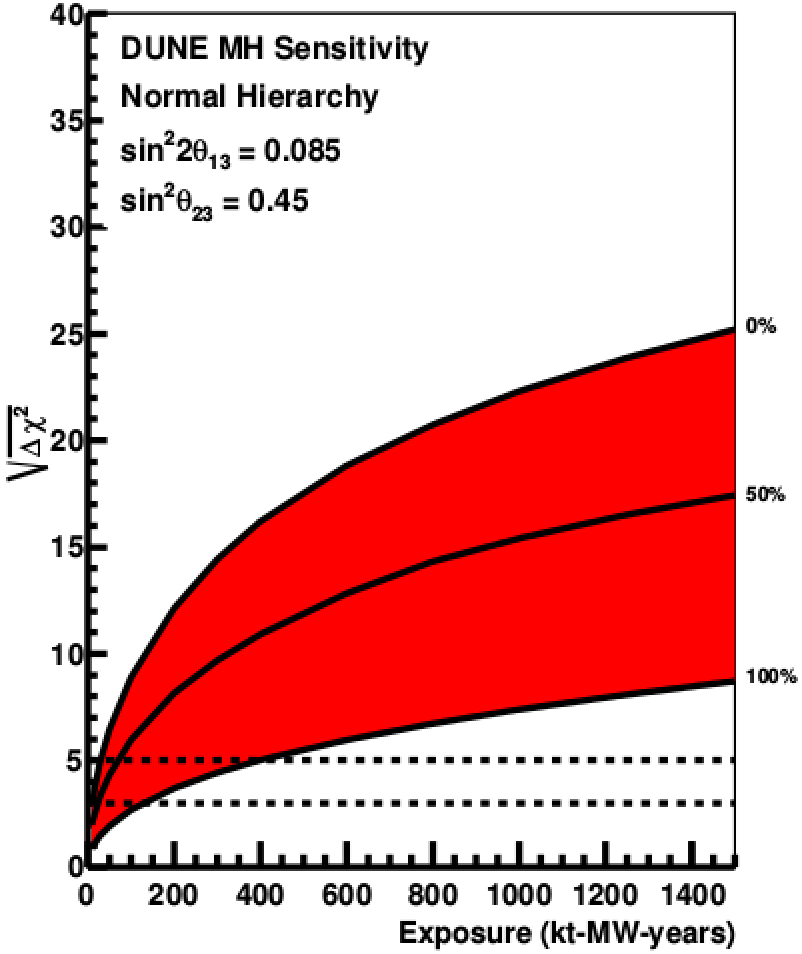
CPV Sensitivity for NH



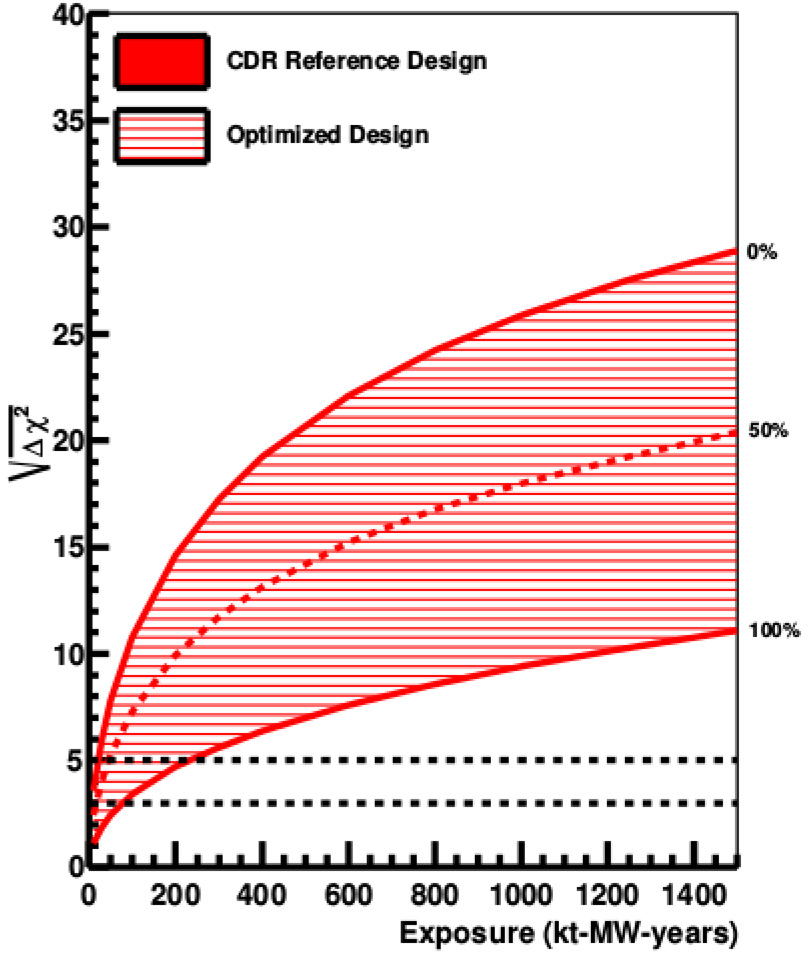
CPV Sensitivity for IH



MH Coverage

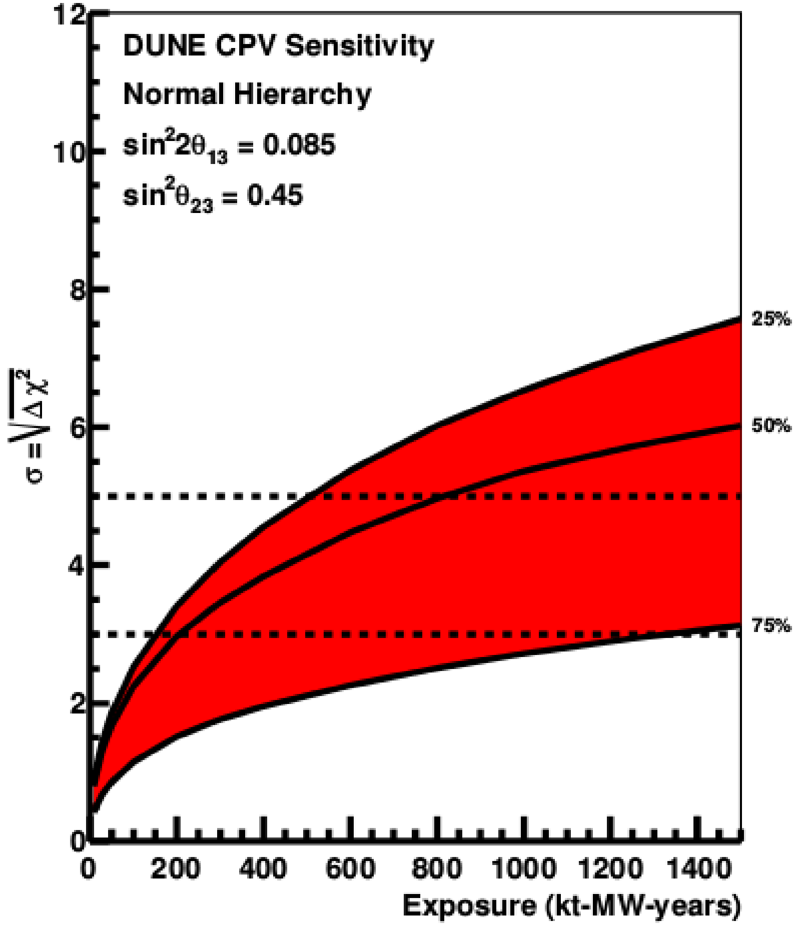


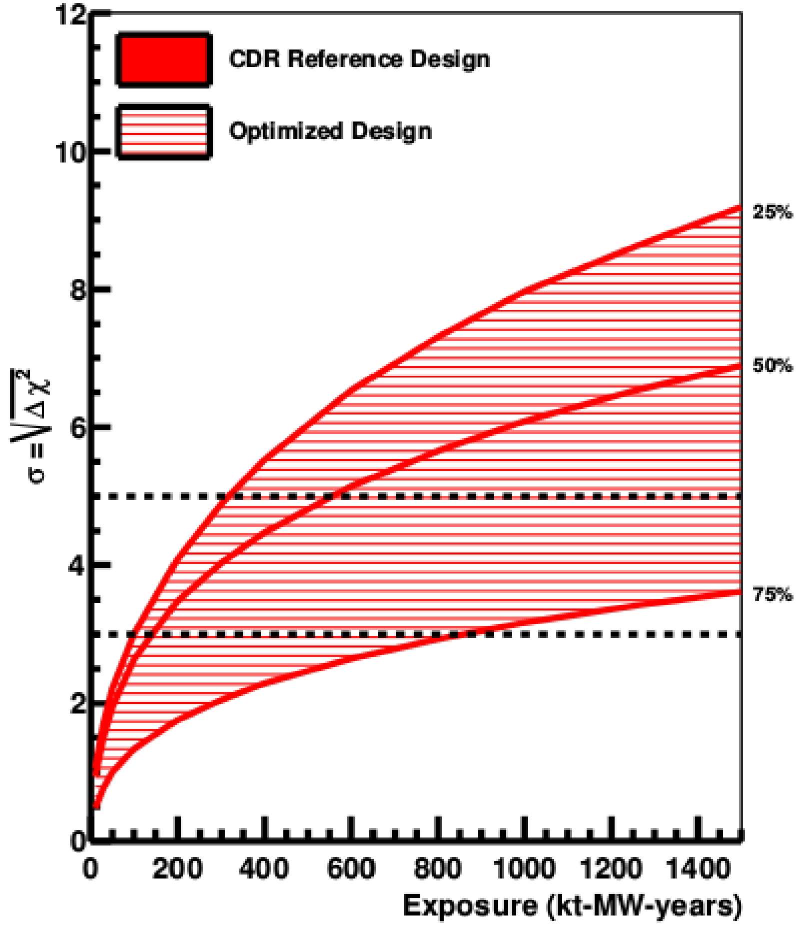
DUNE MH Sensitivity
Normal Hierarchy
$\sin^2 2\theta_{13} = 0.085$
$\sin^2\theta_{23} = 0.45$
$\sqrt{\Delta\chi^2}$
Exposure (kt-MW-years)
0%
50%
100%
0
200
400
600
800
1000
1200
1400
0
5
10
15
20
25
30
35
40



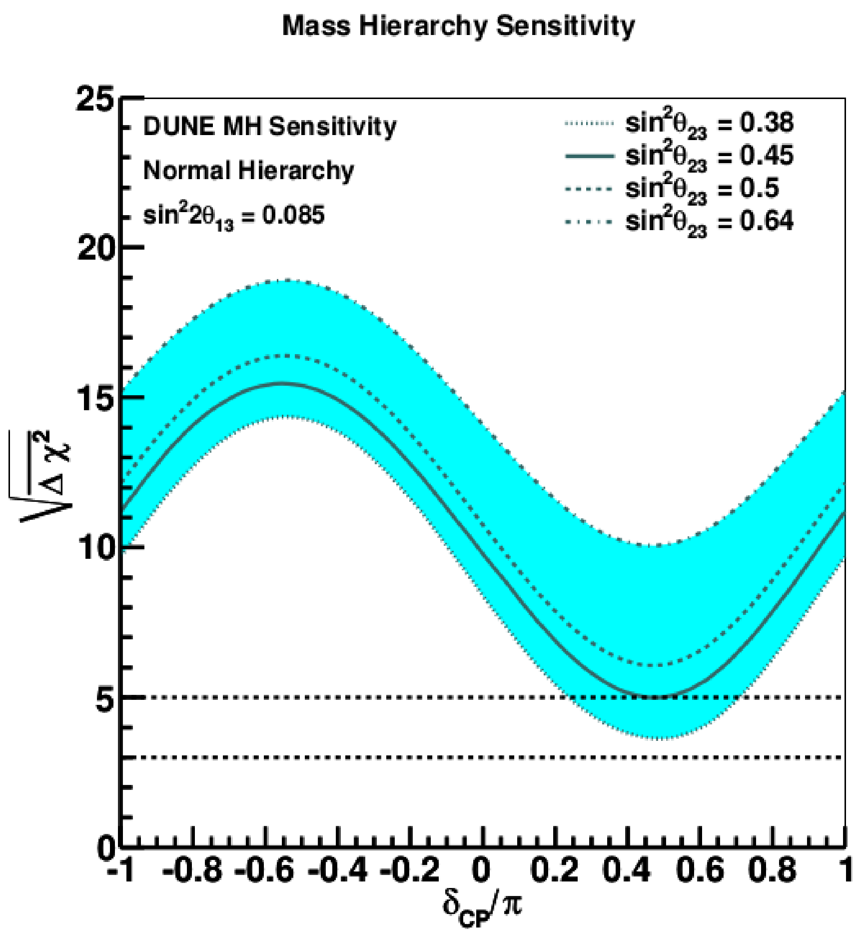
CDR Reference Design
Optimized Design
$\sqrt{\Delta\chi^2}$
Exposure (kt-MW-years)
0%
50%
100%
0
200
400
600
800
1000
1200
1400
0
5
10
15
20
25
30
35
40

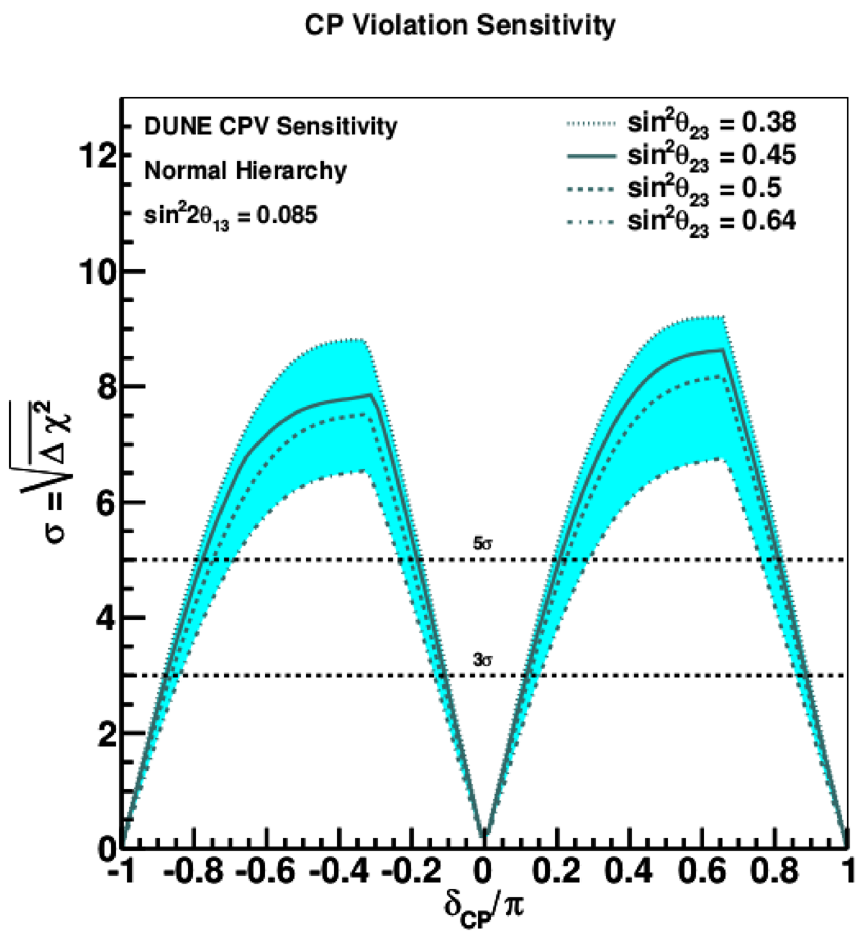
CPV Coverage



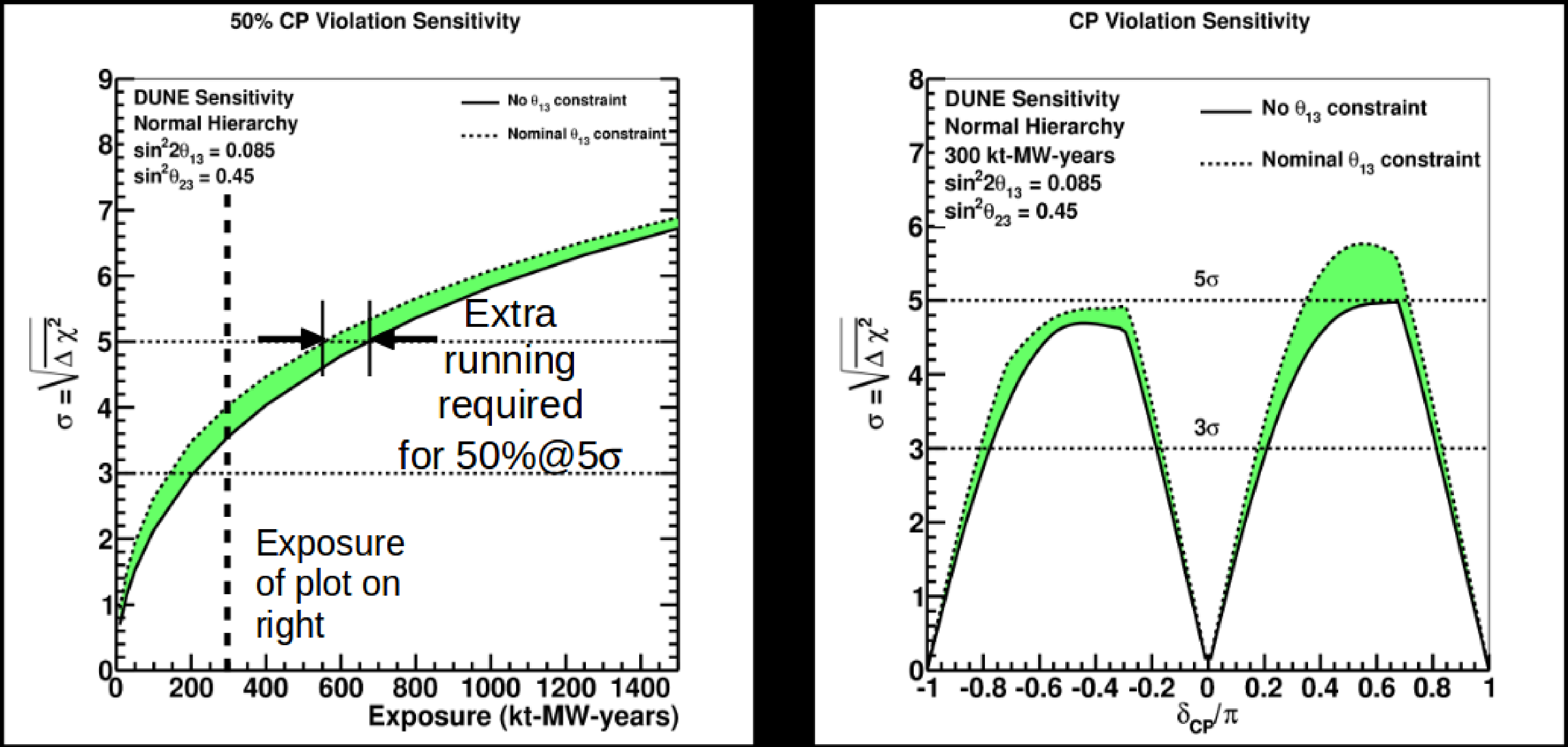


Sensitivites vs. θ_{23}



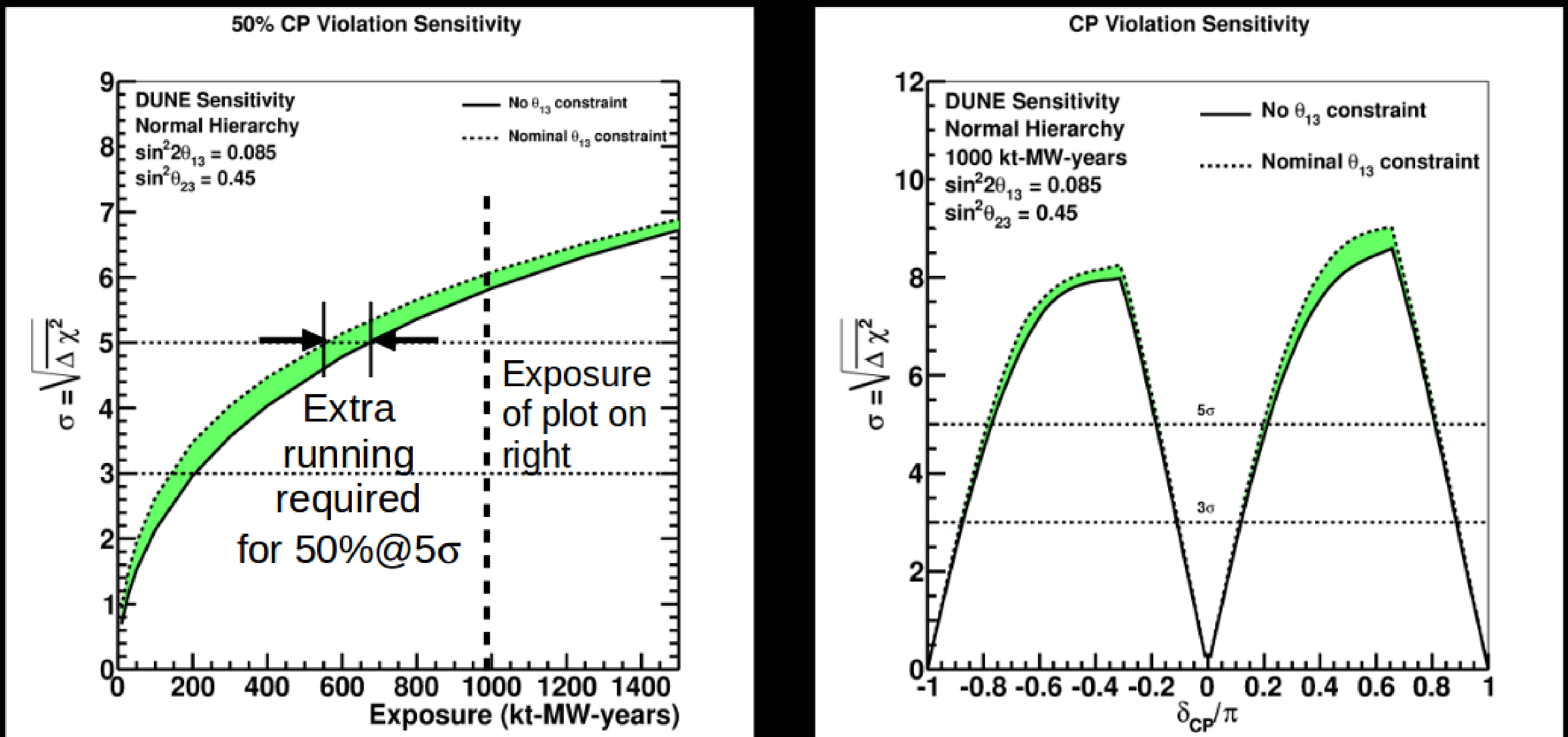


Impact of θ_{13} Reactor Constraint



- Current long-baseline experimental sensitivity to δ_{CP} is enhanced by tension with reactor constraints
- DUNE will be able to measure δ_{CP} with the same sensitivity without the reactor constraint with a bit more running

Impact of θ_{13} Reactor Constraint



- Current long-baseline experimental sensitivity to δ_{CP} is enhanced by tension with reactor constraints
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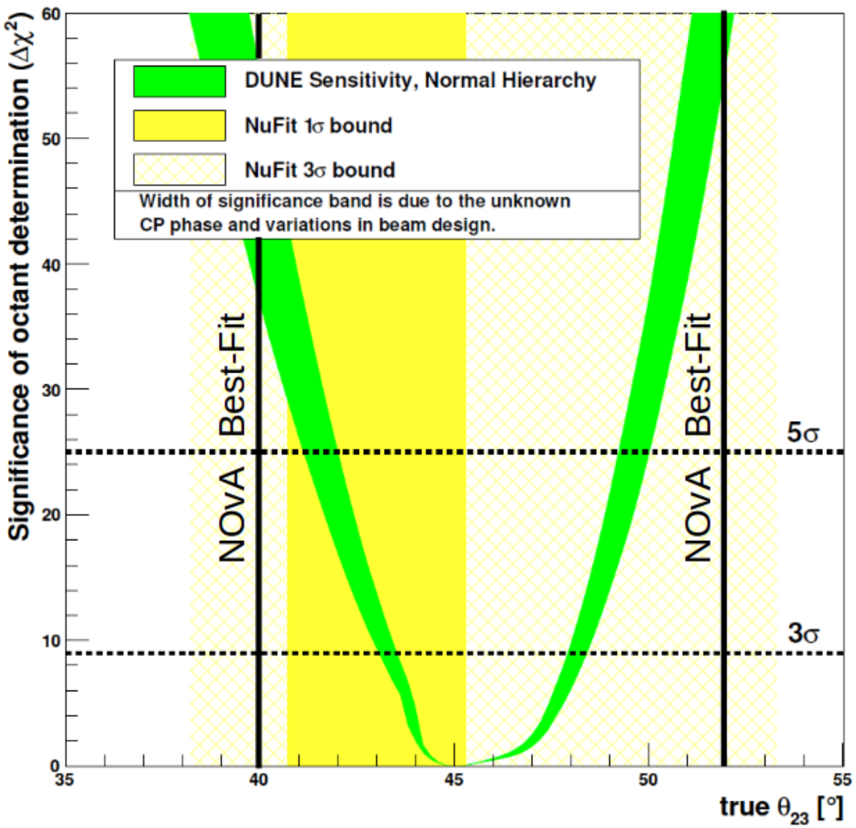
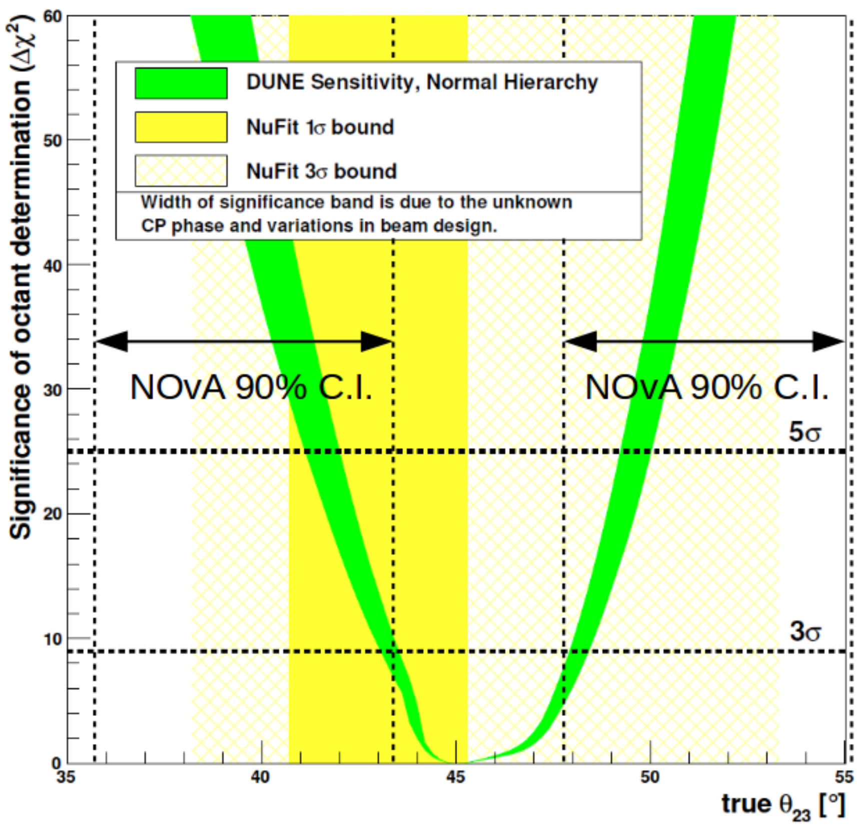
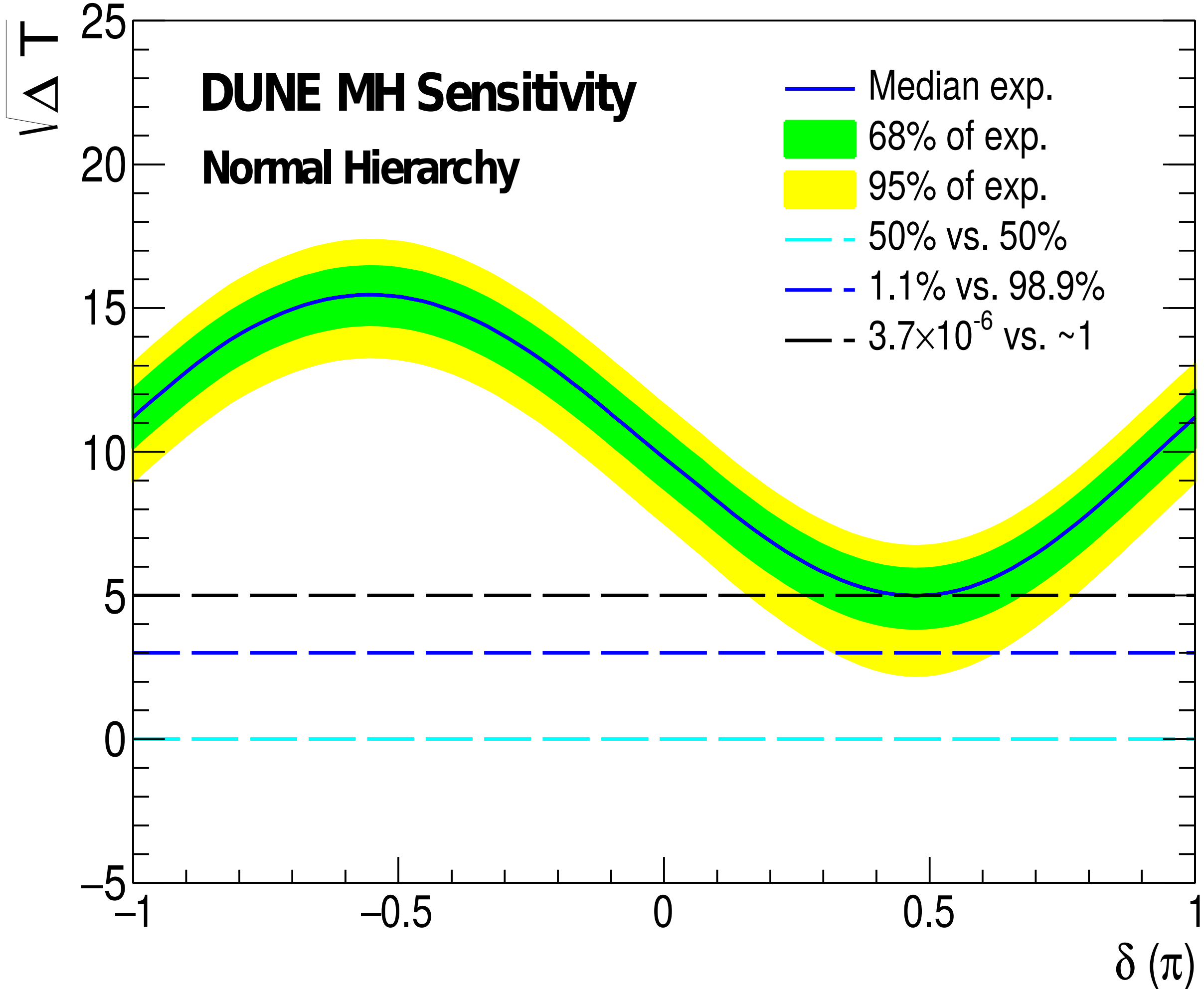
Octant Sensitivity



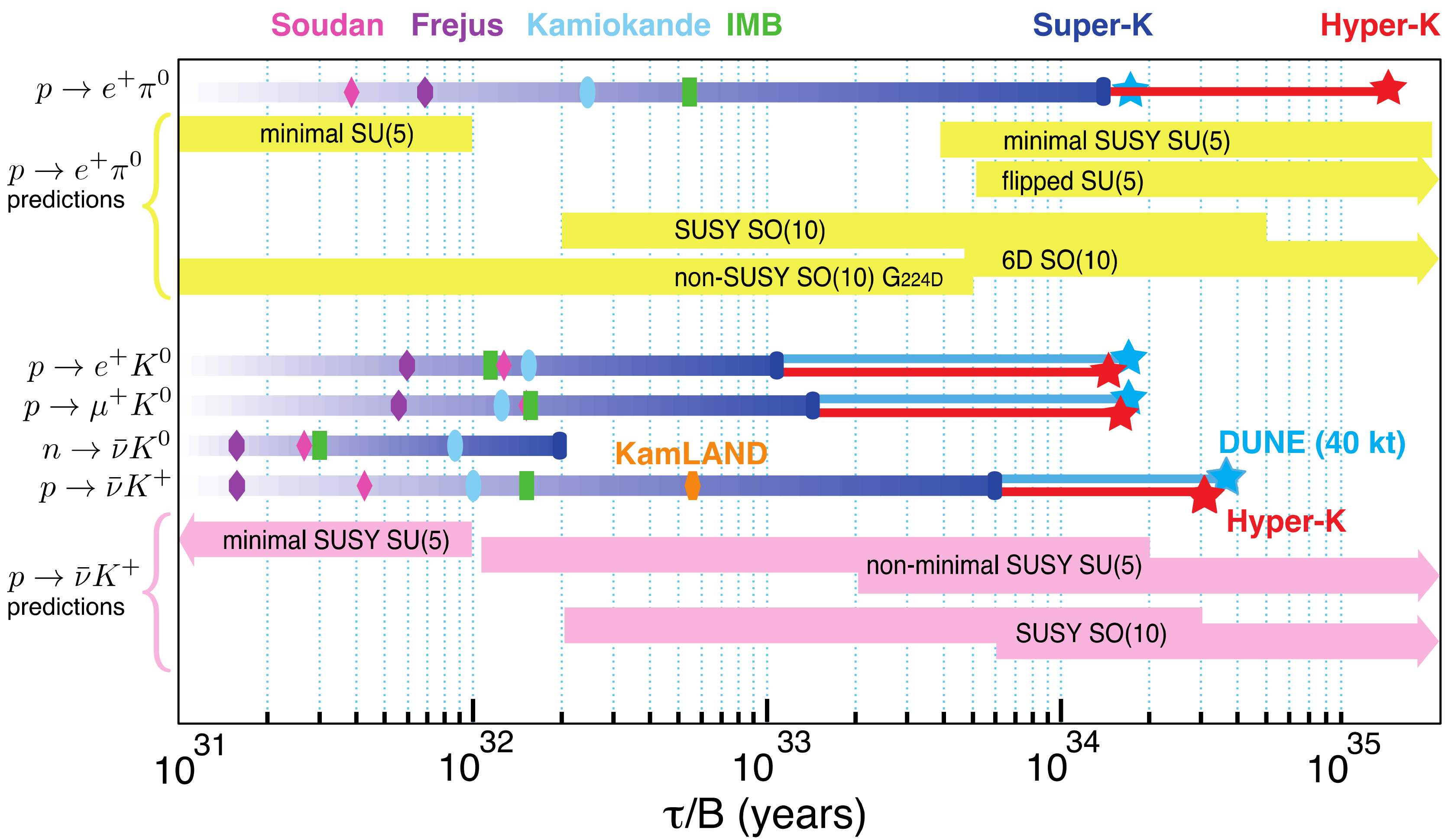


Dependence on Fluctuations



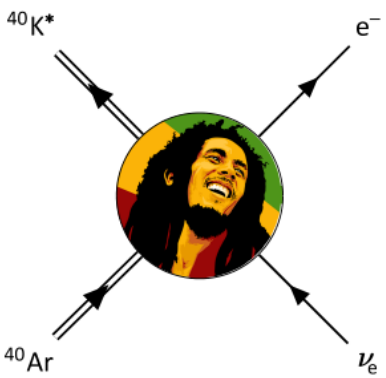
Proton Decay Sensitivity

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



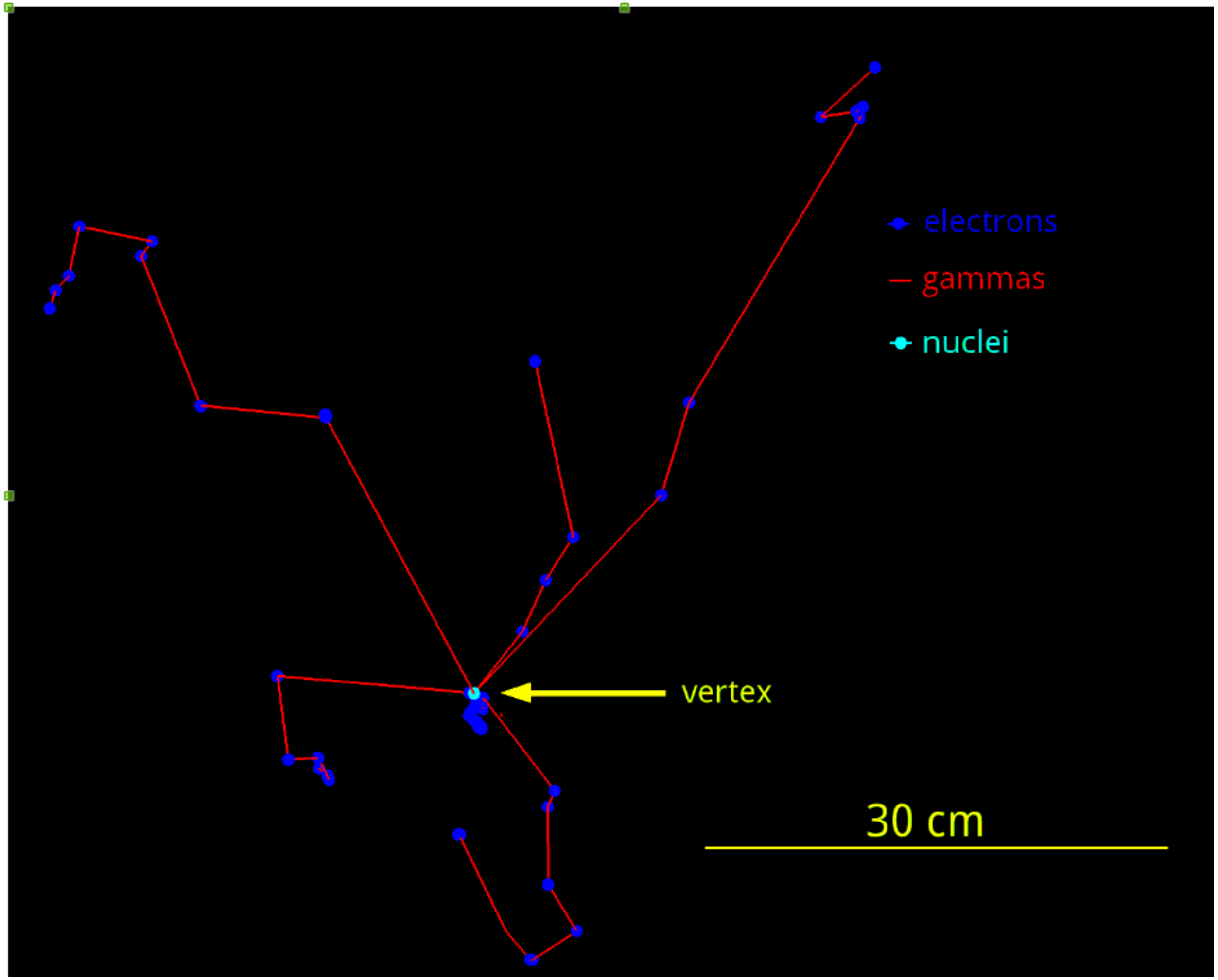
SN ν Simulations

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

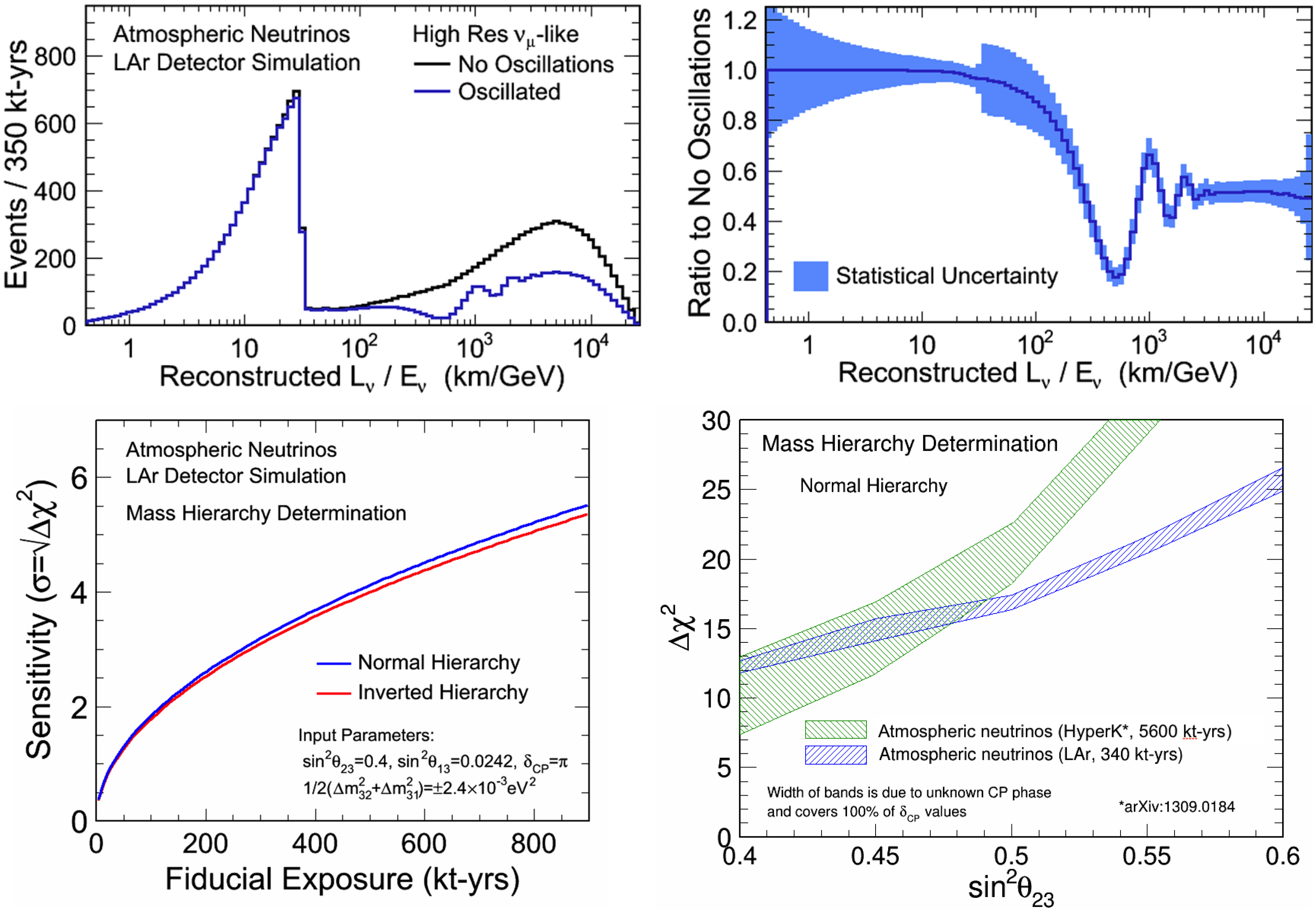


MARLEY: Model of **A**rgon **R**eaction **L**ow-**E**nergy **Y**ields
An event generator for supernova neutrinos in liquid argon

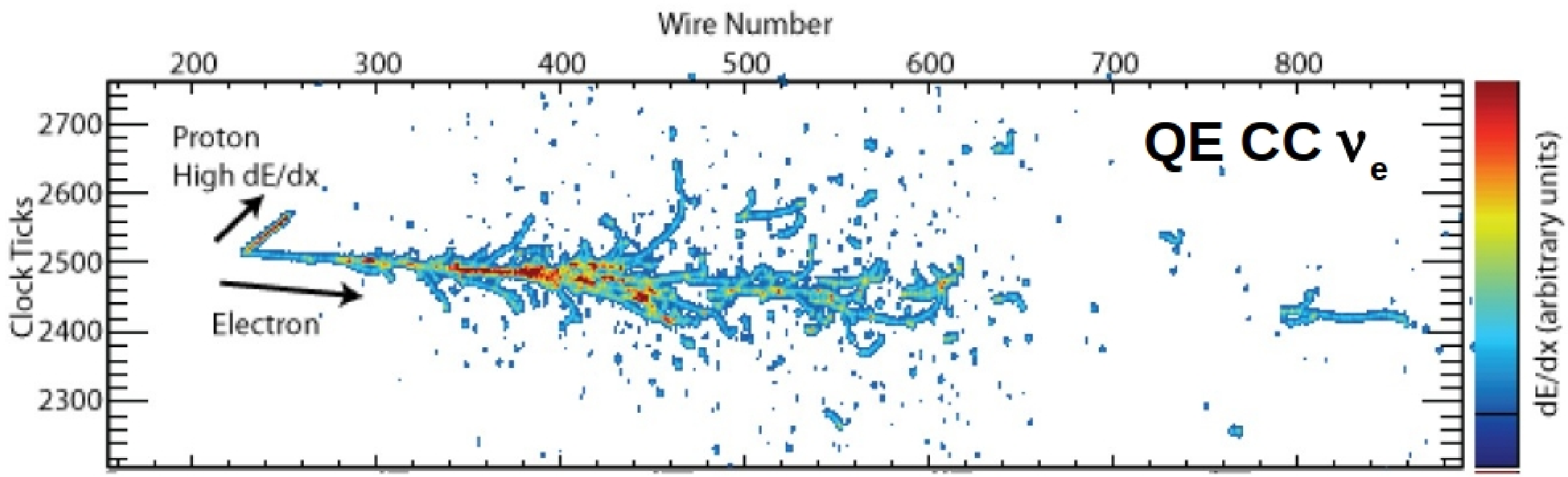
Simulated charged-current supernova ν_e event



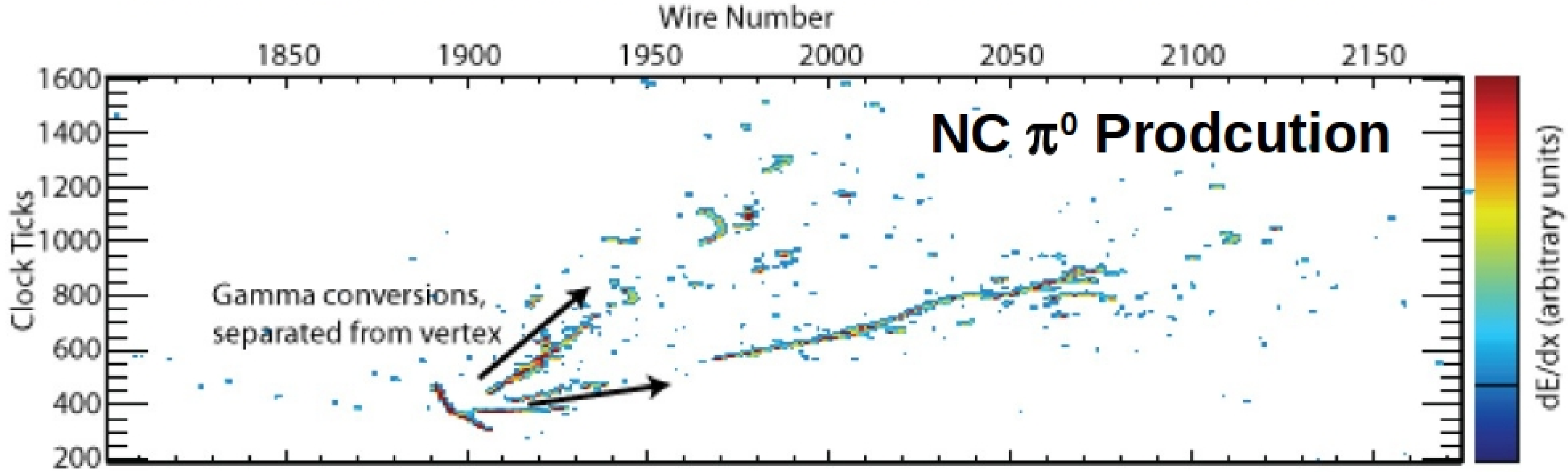
Atmospheric Neutrinos



LArTPC Neutrino Interactions

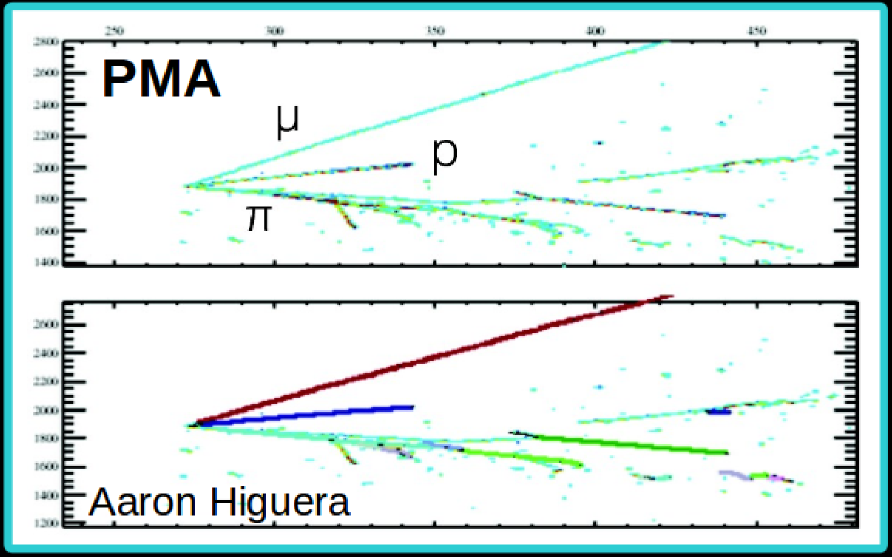


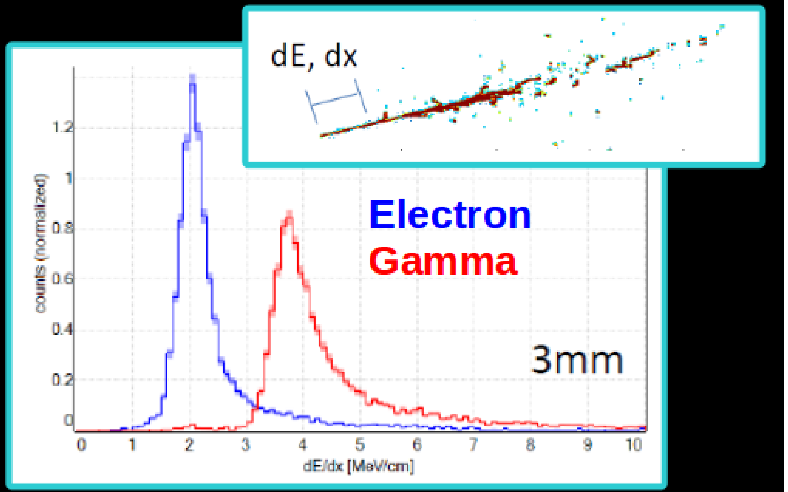
MicroBooNE simulation of ν interactions in a LArTPC



LArTPC Reconstruction

- Full simulation of beam ν, atmospheric ν, PDK, and Supernova events
- Huge progress has been made on reconstruction
  - Three reconstruction packages (PMA, Pandora, WireCell)
  - Exploring other options including machine learning techniques
  - Shower / track selection, particle ID, momentum and angle reconstruction
- Use of centralized software tools and infrastructure is crucial
  - LArSoft allows for easy collaboration with other LAr TPC experiments





Dorota Stefan & Robert Sulej

Determining CDR Sensitivities

- Define CPV sensitivity as:

$$\Delta\chi^2_{CPV} = \mathrm{Min}(\ \chi^2_{test}(\delta_{cp}=0),\ \chi^2_{test}(\delta_{cp}=\pi)\ ) - \chi^2_{true}$$

- Define MH sensitivity as:

$$\Delta T_{NH(IH)} = \chi^2_{IH(NH)} - \chi^2_{NH(IH)}$$

- Use Asimov data sets; gives mean $\Delta\chi^2$
- Allow oscillation parameters, and systematics to vary
  - Constrain oscillation parameter values with NuFit2014 results; use 1/3rd of the 3 σ ranges
  - Estimate non-oscillation systematics with normalization parameters
  - Consider channel-to-channel and sample-to-sample correlations

Signal uncertainties of
5% on ν_μ disappearance
and
5⊕2% on ν_e appearance
assume a relative calibration in the 4-sample fits

Background	Normalization Uncertainty	Correlations
For $\nu_e/\bar{\nu}_e$ appearance:		
Beam ν_e	5%	Uncorrelated in ν_e and $\bar{\nu}_e$ samples
NC	5%	Correlated in ν_e and $\bar{\nu}_e$ samples
ν_μ CC	5%	Correlated to NC
ν_τ CC	20%	Correlated in ν_e and $\bar{\nu}_e$ samples
For $\nu_\mu/\bar{\nu}_\mu$ disappearance:		
NC	5%	Uncorrelated to $\nu_e/\bar{\nu}_e$ NC background
ν_τ	20%	Correlated to $\nu_e/\bar{\nu}_e$ ν_τ background

Normalization Uncertainties

- Estimate uncertainties after ND and external data constraints
- Understand advantages of LAr TPC, and cancellations in FD 4-sample fits
- Consider experience from T2K and MINOS
  - MINOS similarities
    - Flux shape, ν energies
    - Longer baseline
    - Similar cross sections
  - T2K similarities
    - Different near and far detector technologies
    - Similar analysis strategies
  - Strategies to address required increase in precision

Source of Uncertainty	MINOS ν_e	T2K ν_e	DUNE ν_e
Beam Flux after N/F extrapolation	0.3%	3.2%	2%
Interaction Model	2.7%	5.3%	$\sim 2\%$
Energy scale (ν_μ)	3.5%	included above	(2%)
Energy scale (ν_e)	2.7%	2.5% includes all FD effects	2%
Fiducial volume	2.4%	1%	1%
Total	5.7%	6.8%	3.6 %
Used in DUNE Sensitivity Calculations			$5\% \oplus 2\%$