DUNE

Oscillation Physics

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For the DUNE Collaboration

NuFact 2016

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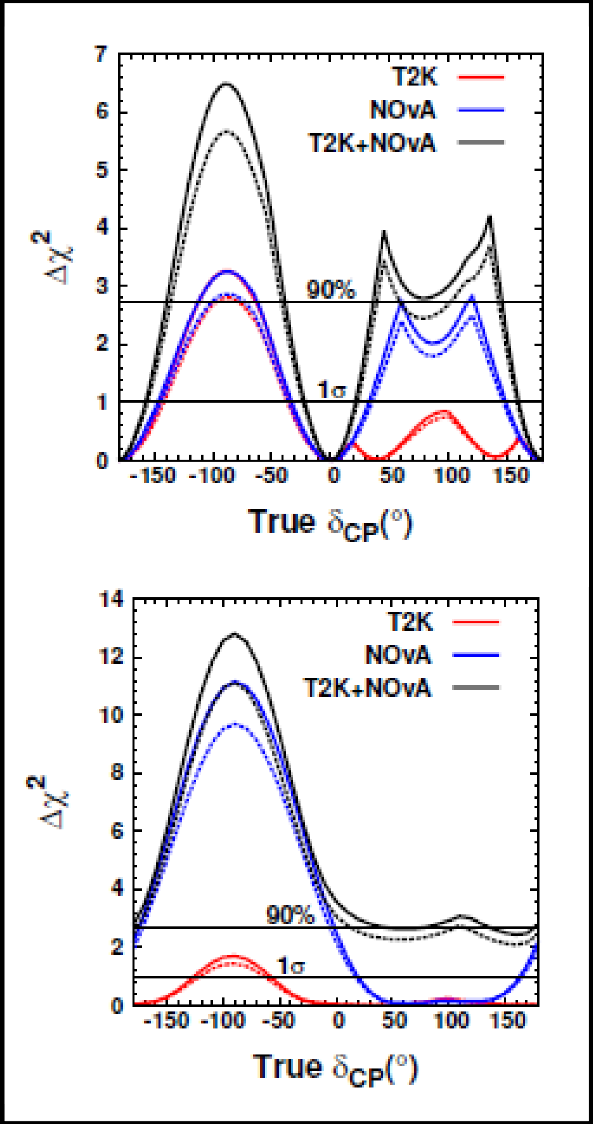
ICISE, Quy Nhon, Vietnam

The Deep Underground Neutrino Experiment

- September 2015 collaboration meeting at FNAL
- 886 Collaborators
- 26+ countries
- 153 institutions
- Members from LBNE, LBNO and more

Potential of Current Experiments

- T2K and NOνA will continue to run over next several years
  - measure ν_e appearance and ν_μ disappearance
  - Run in both ν mode and $\bar{\nu}$ mode
  - Provide sensitivity to CPV and MH determination
  - A combined analysis has “indication” potential
- Reactor experiments
  - Continue to constrain θ_{13} from $\bar{\nu}_e$ disappearance
  - Constraints help T2K and NOνA
- MH determination may come from several sources like INO, PINGU, JUNO, and $0\nu\beta\beta$
- SK will continue to asymptotically approach limits on nucleon decay, and atmospheric neutrino measurements



PTEP 2015 (2015) 4, 043C01

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  - Run in both ν mode and $\bar{\nu}$ mode

To measure δ_{cp}, θ_{13}, θ_{23} and determine the MH to high precision in a single experiment will require a next generation long-baseline neutrino experiment

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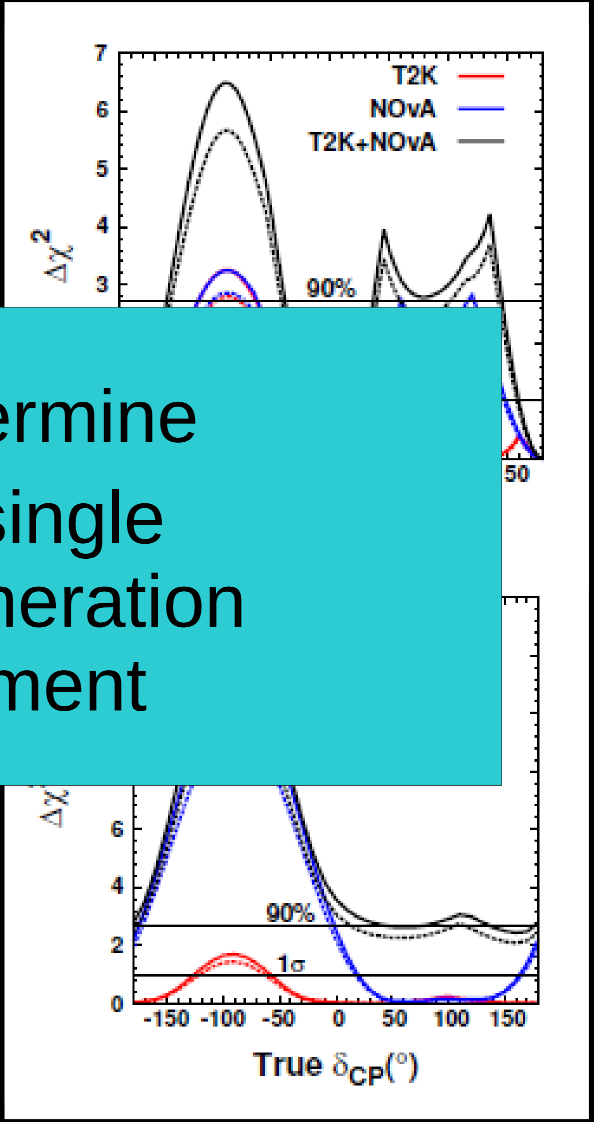

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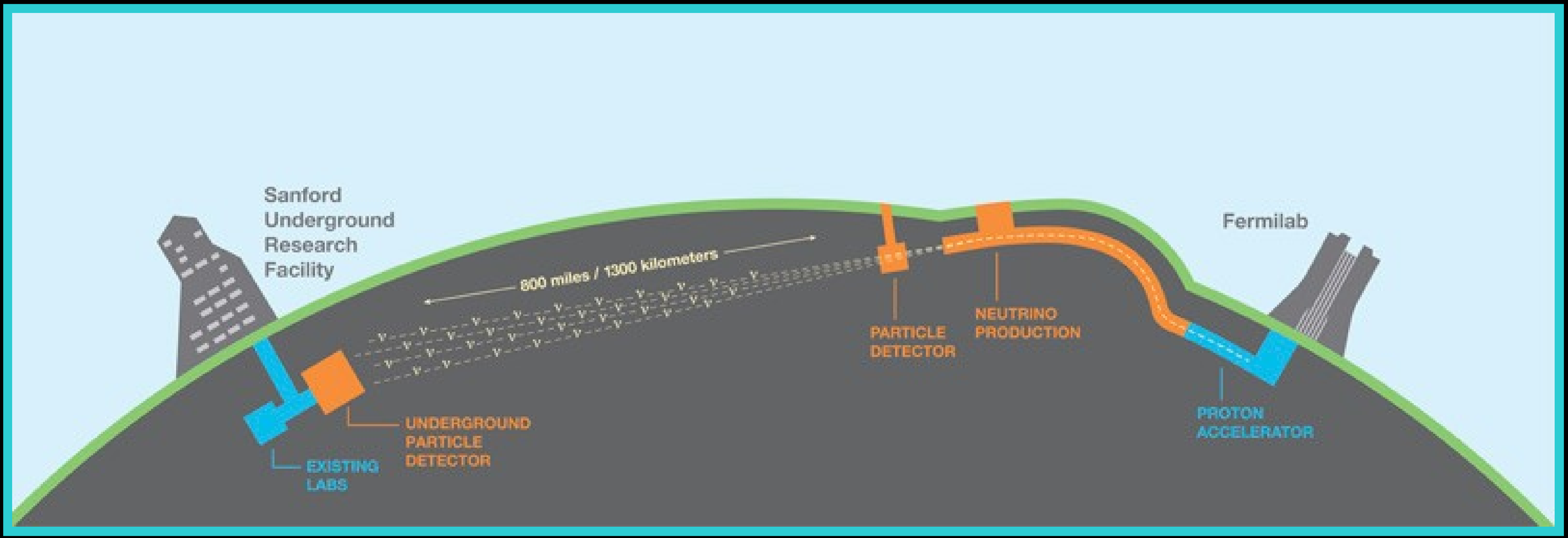
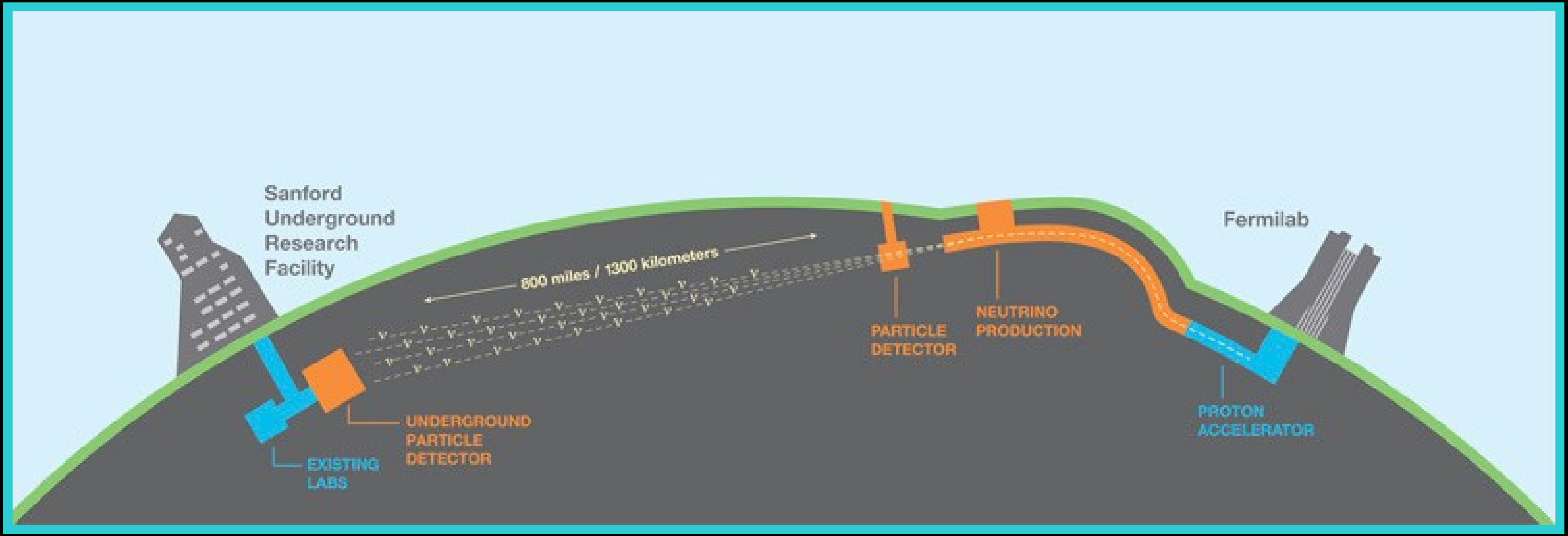
The DUNE Experimental Setup



- DUNE is designed to provide a broad program of:
  - ν oscillation physics
  - ν interaction physics
  - Proton decay
  - Supernova physics
  - BSM physics

The DUNE Experimental Setup



- Oscillation Physics:
  - Baseline of 1300 km
  - A megawatt class beam covering the 1st and 2nd oscillation maxima
  - A highly capable ND to constrain the FD event rate prediction

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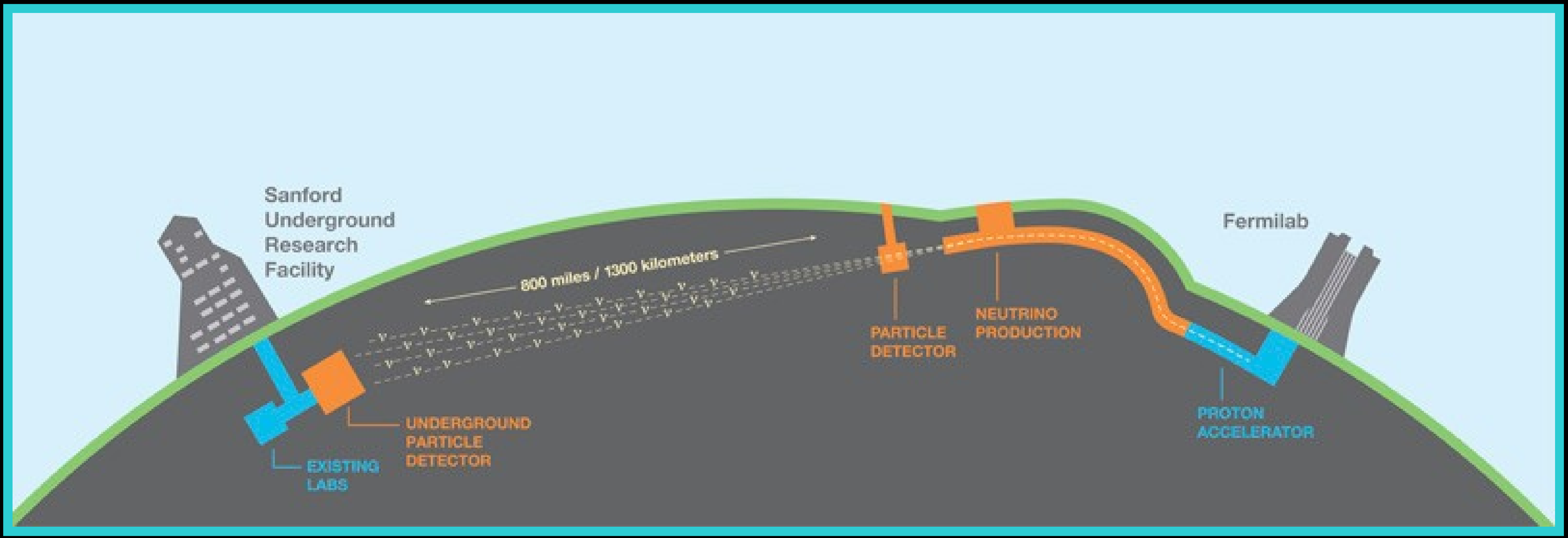

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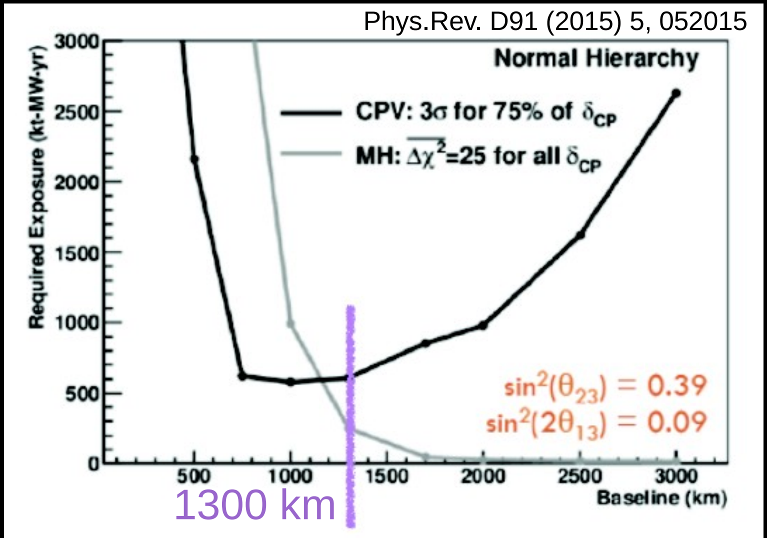

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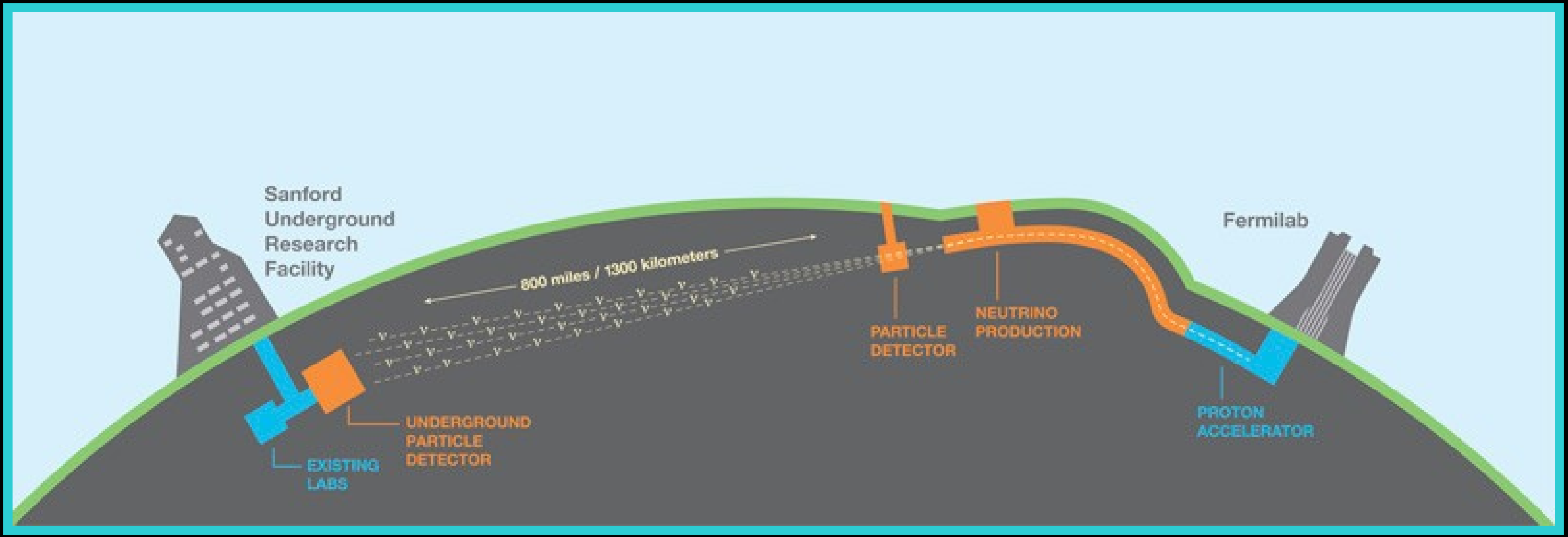
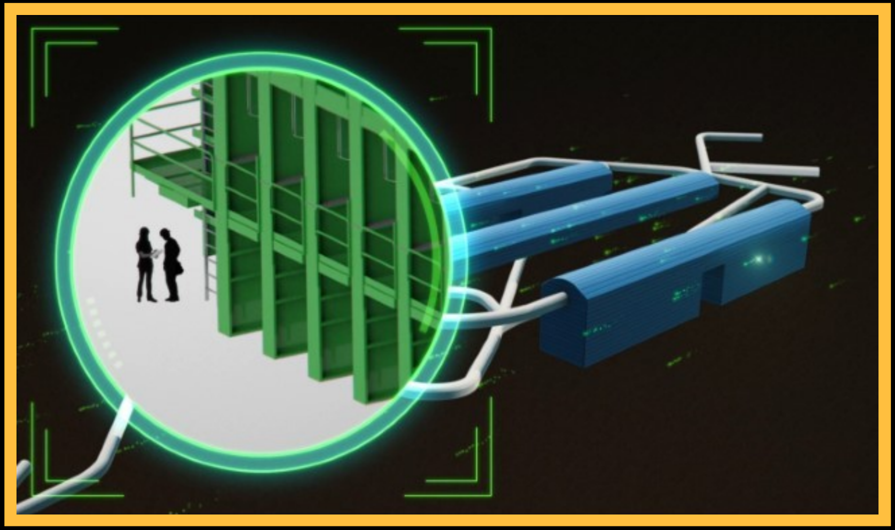
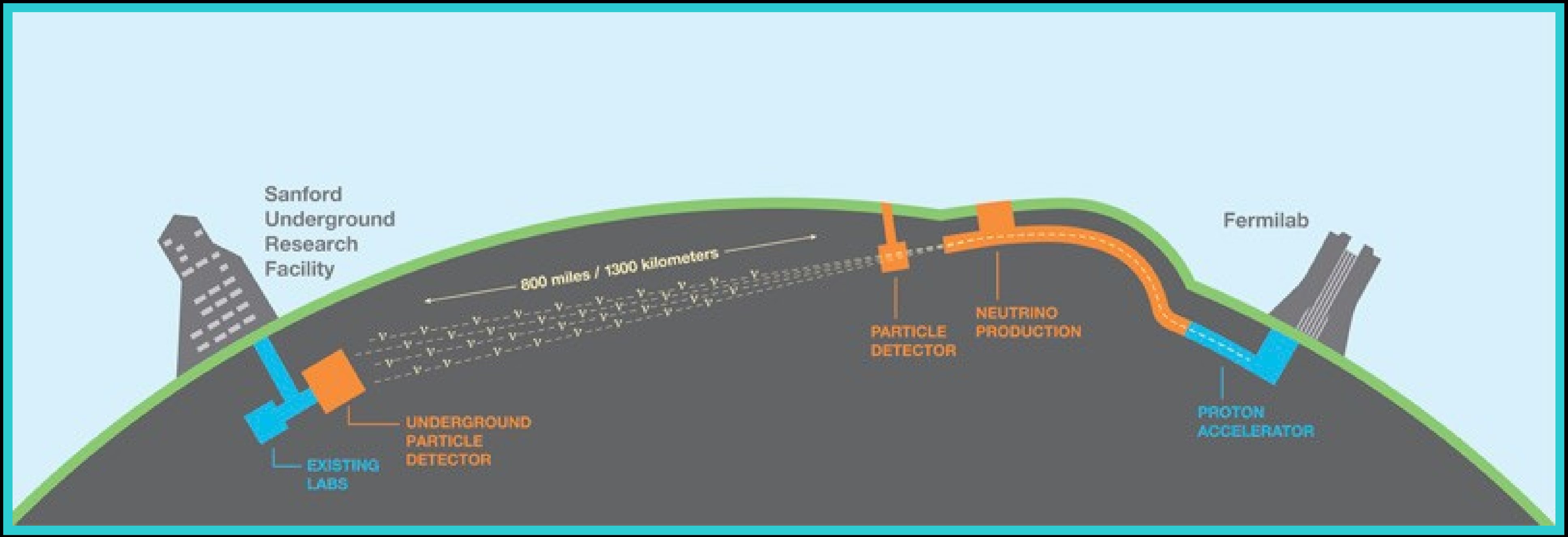
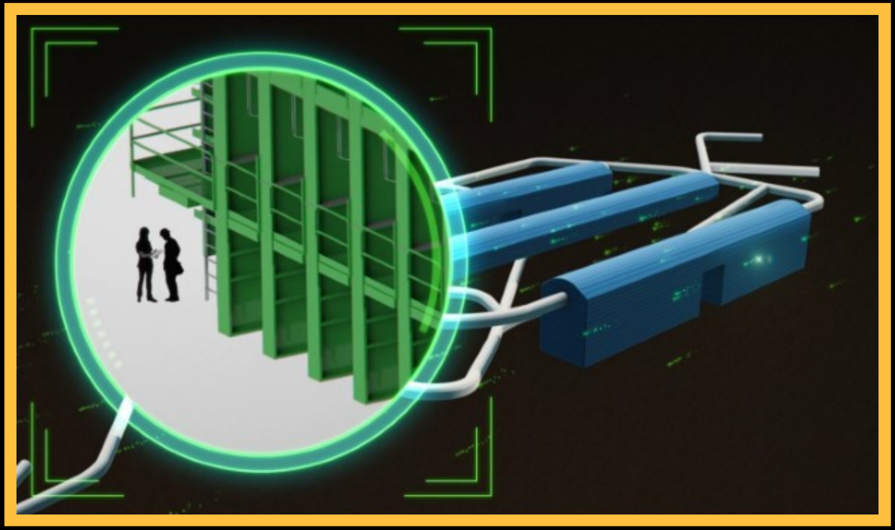




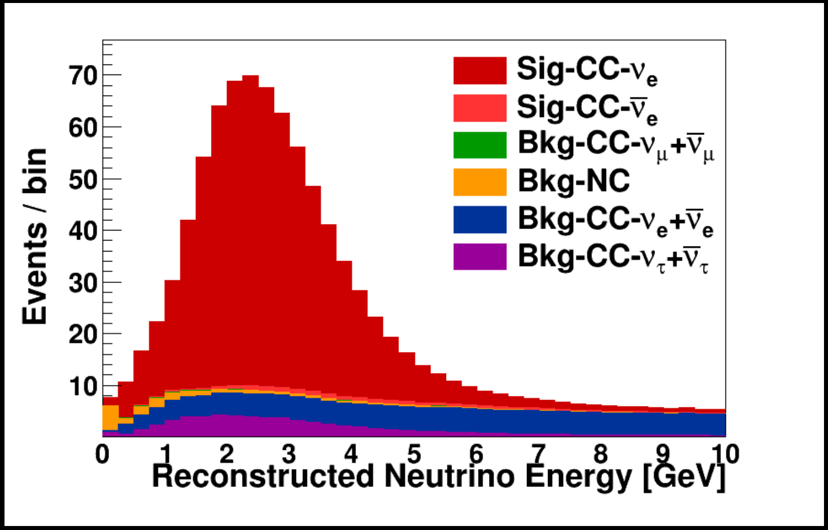
- Oscillation Physics:
  - Baseline of 1300 km
  - A large (~ 40 kt), high resolution FD deployed deep underground
  - Exposure of 6-12 yr with ~ 50% / 50% ν / $\bar{\nu}$ running

The DUNE Experimental Setup

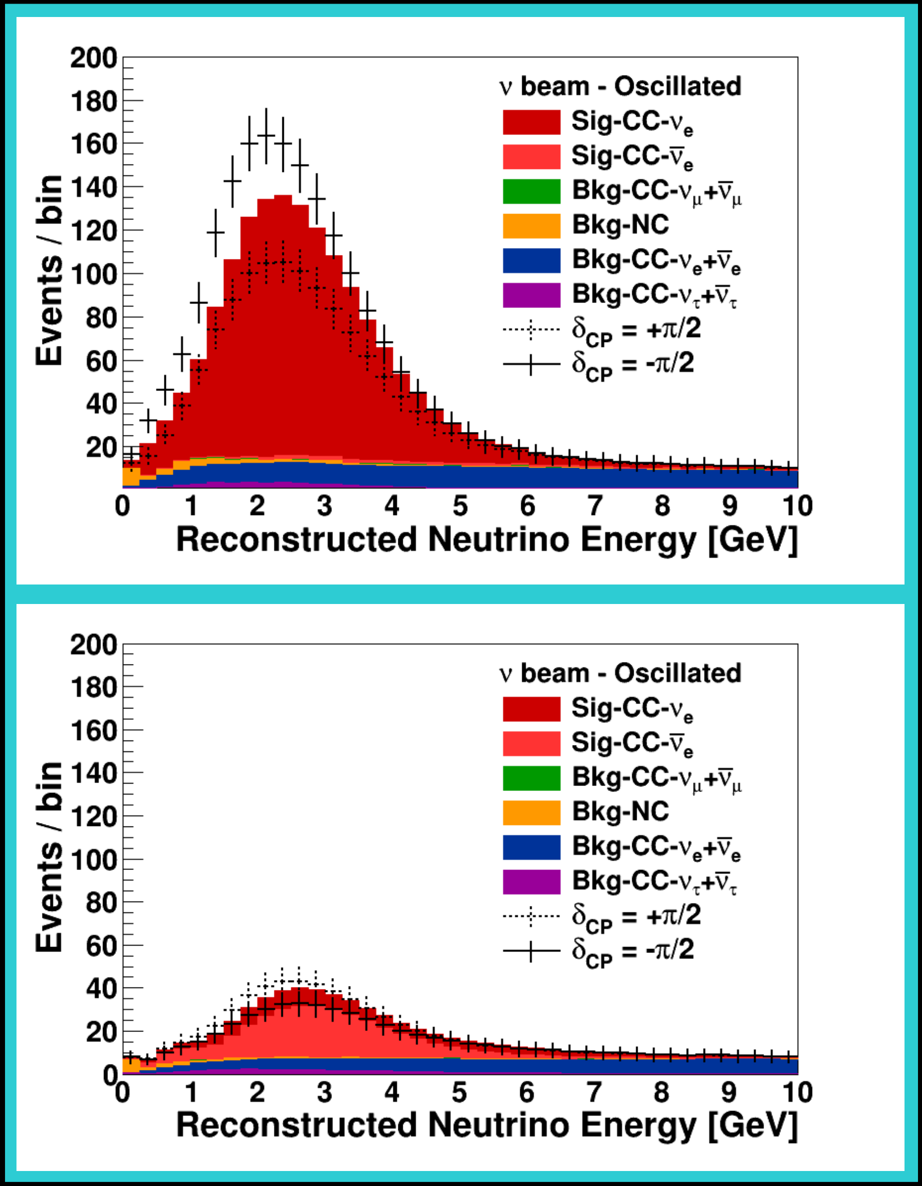




DUNE ν_e appearance

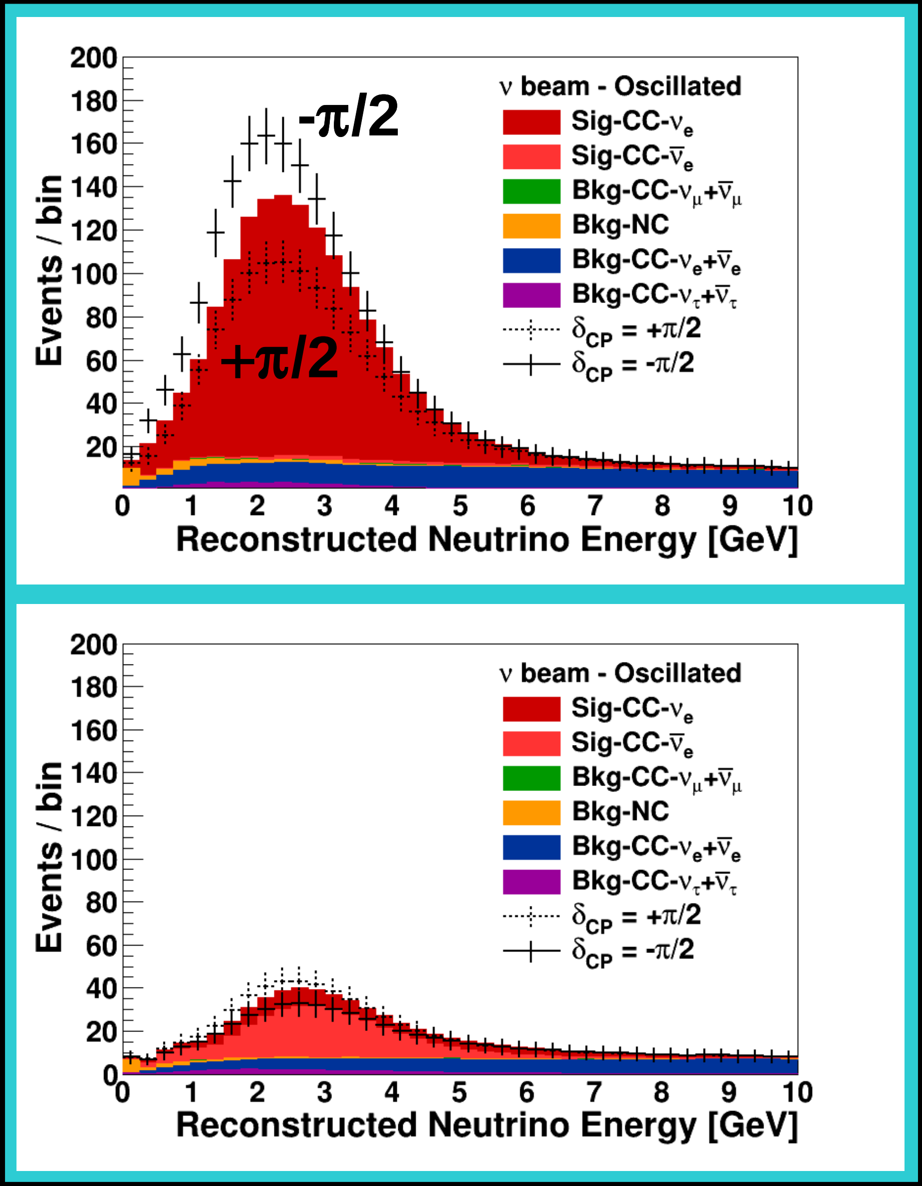


Expected FD Spectra



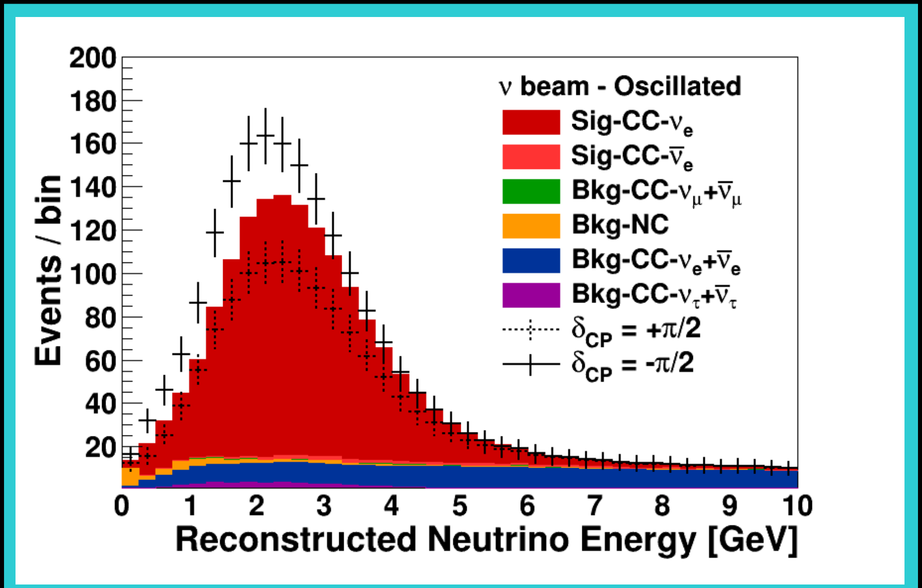
- Spectra produced by a Fast MC
- Fast MC inputs:
  - Full G4LBNE flux simulation
  - GENIE cross sections and FSI
  - Parameterized detector response applied to individual particles that exit the nucleus
  - Event selection based on PID of lepton candidates
- Fast MC outputs (all event-by-event):
  - Reconstructed quantities e.g. E_ν, Q^2, W^2, x, y, etc
  - Etrue → Ereco smearing functions
  - Efficiencies for signal and backgrounds
  - Weights for most sources of systematic uncertainty and spectral response functions

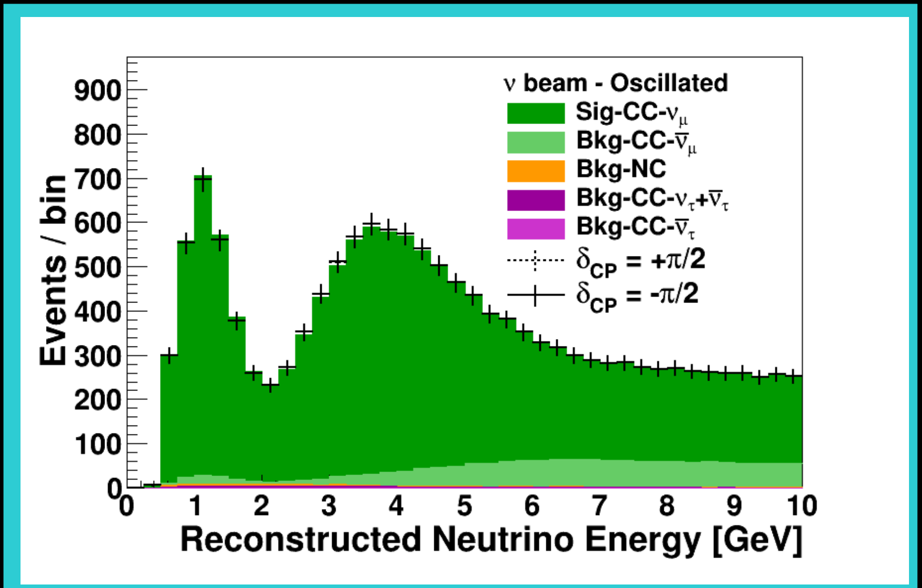
Expected FD Spectra

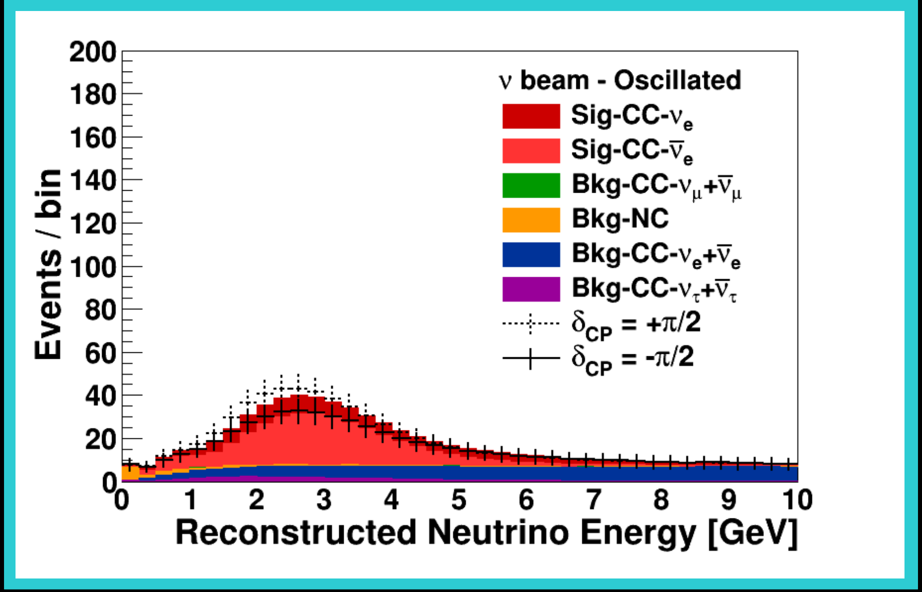


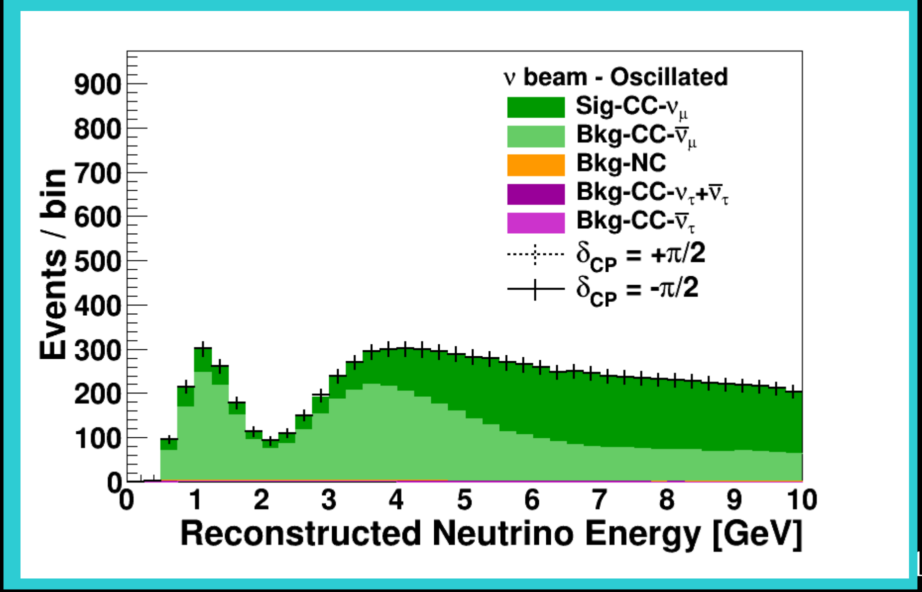
- Assumed exposure:
  - 40 kton LAr TPC FD
  - 1.2 MW beam
    - NuMI style horns
    - 120 GeV protons
    - Many possible optimizations
  - 6 yr ν / 6 yr $\bar{\nu}$ (56% up time)
- Oscillation Parameters
  - NuFit 2014 NH results
  - Choose $\delta_{cp} = 0$
- Opposite effects on ν and $\bar{\nu}$ spectra for $\delta_{cp} \rightarrow \pm \pi/2$

Expected FD Spectra

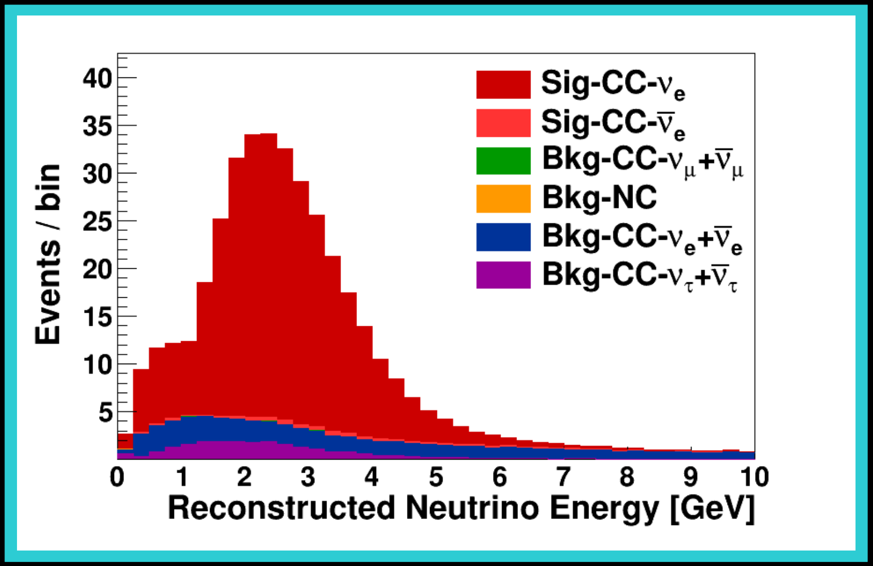




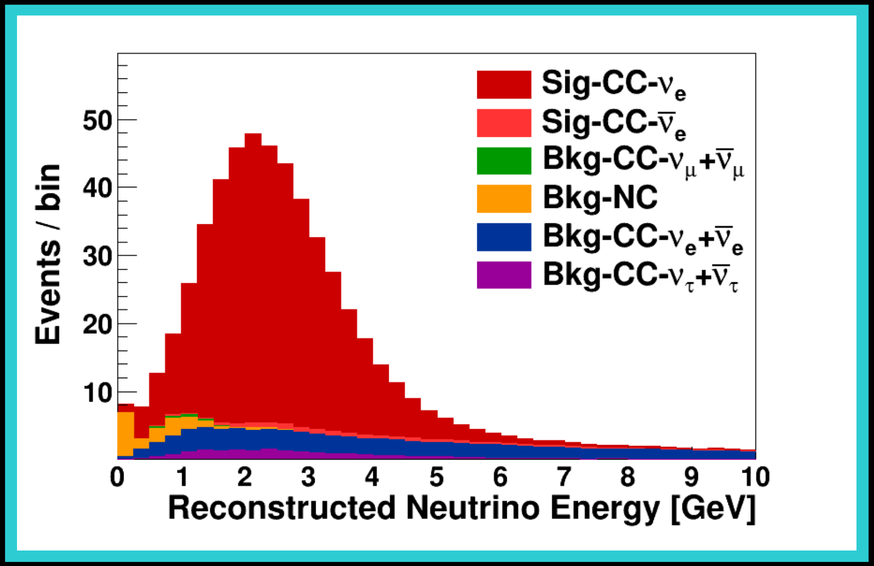




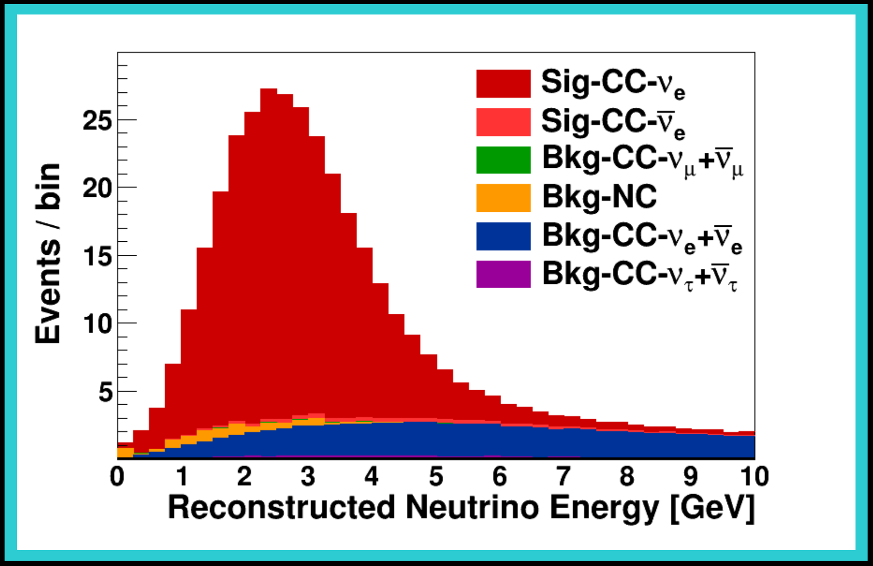
Spectra By Cross Section Model



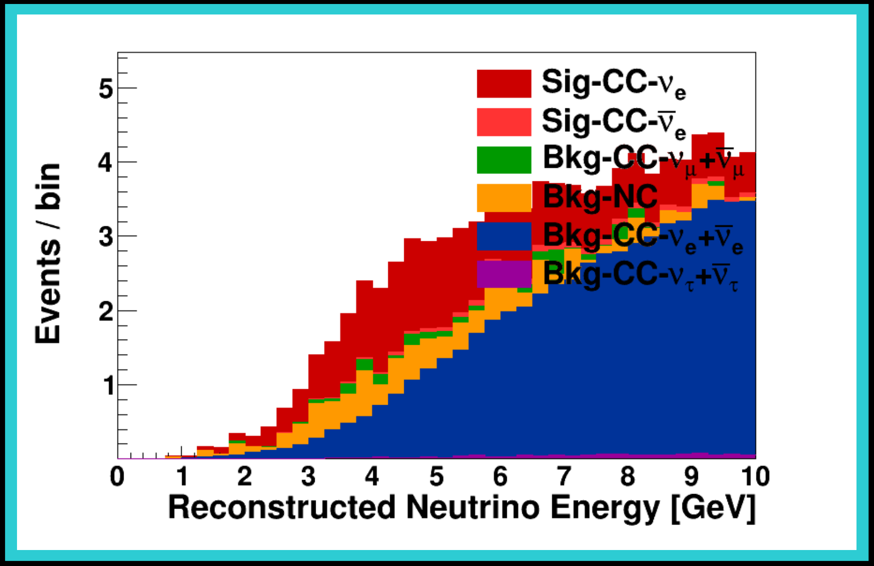
Quasi-elastic



Resonance Production



DIS (W < 2.7 GeV)



DIS (W > 2.7 GeV)

The DUNE Experimental Setup

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.

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

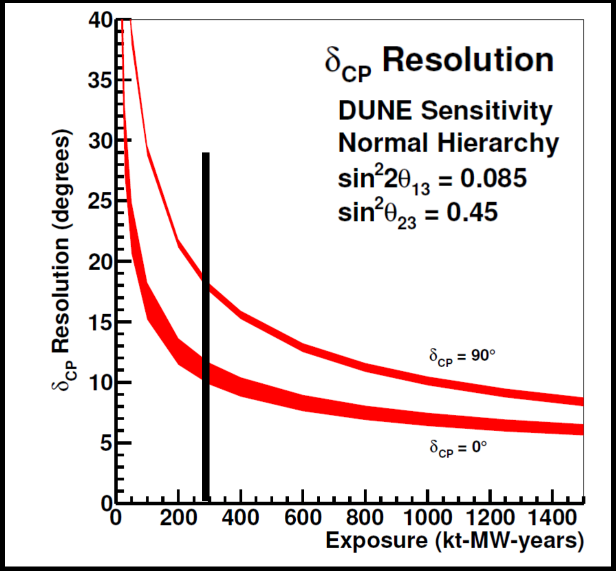
- Estimate uncertainties after ND and external data constraints
- Understand advantages of LAr TPC, and cancellations in FD 4-sample fits
- Consider experience from T2K and MINOS
  - MINOS similarities
    - Flux shape, ν energies
    - Longer baseline
    - Similar cross sections
  - T2K similarities
    - 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			$5\% \oplus 2\%$

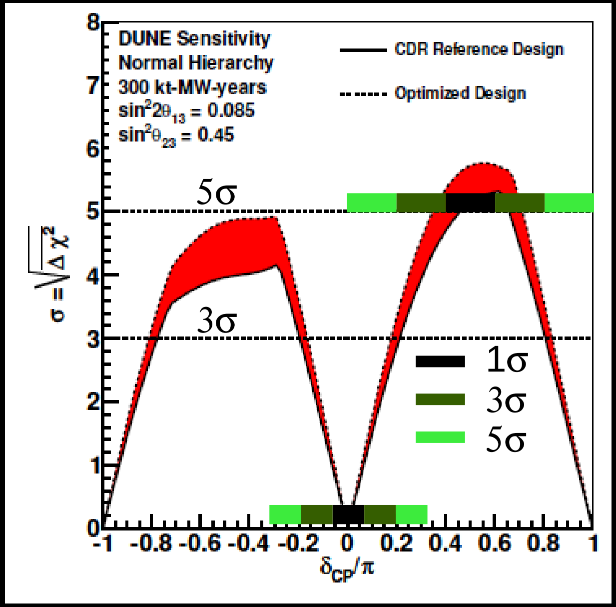
The Physics of DUNE:

Long-Baseline Physics: δ_{cp} and CPV

- DUNE measurement of δ_{cp}
  - Resolution on δ_{cp} gets better as $\sin(\delta_{cp}) \rightarrow 0$
  - Range on δ_{cp} resolution from 6°-10° (~10 yr exposure)
- Sensitivity to CPV strongly depends on:
  - Statistics (thus the beam intensity, detector mass, run time)
  - The true value of $\sin^2\theta_{23}$, δ_{cp}, and the MH
  - Resolution on δ_{cp} near $\sin(\delta_{cp}) = 0$
  - Ability to constrain systematic uncertainties



arxiv:1512.06148



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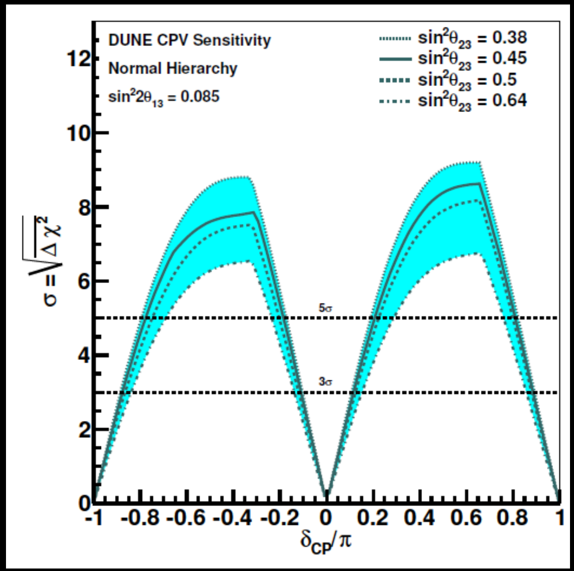
Sensitivity variation bands for $\sin^2\theta_{23}$



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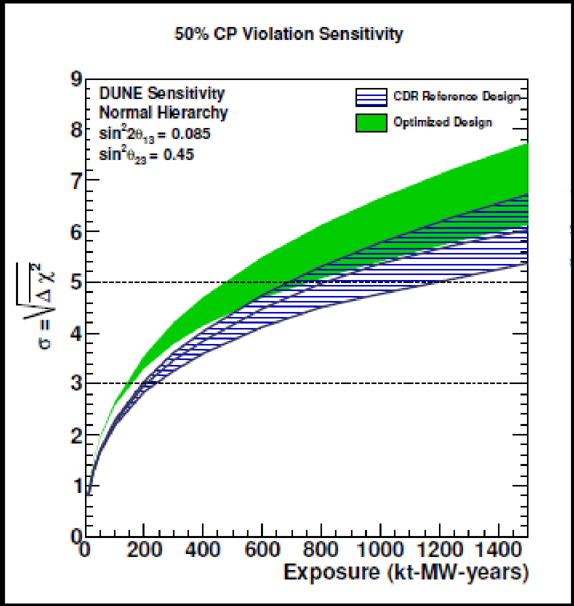
Sensitivity changes with systematic uncertainties



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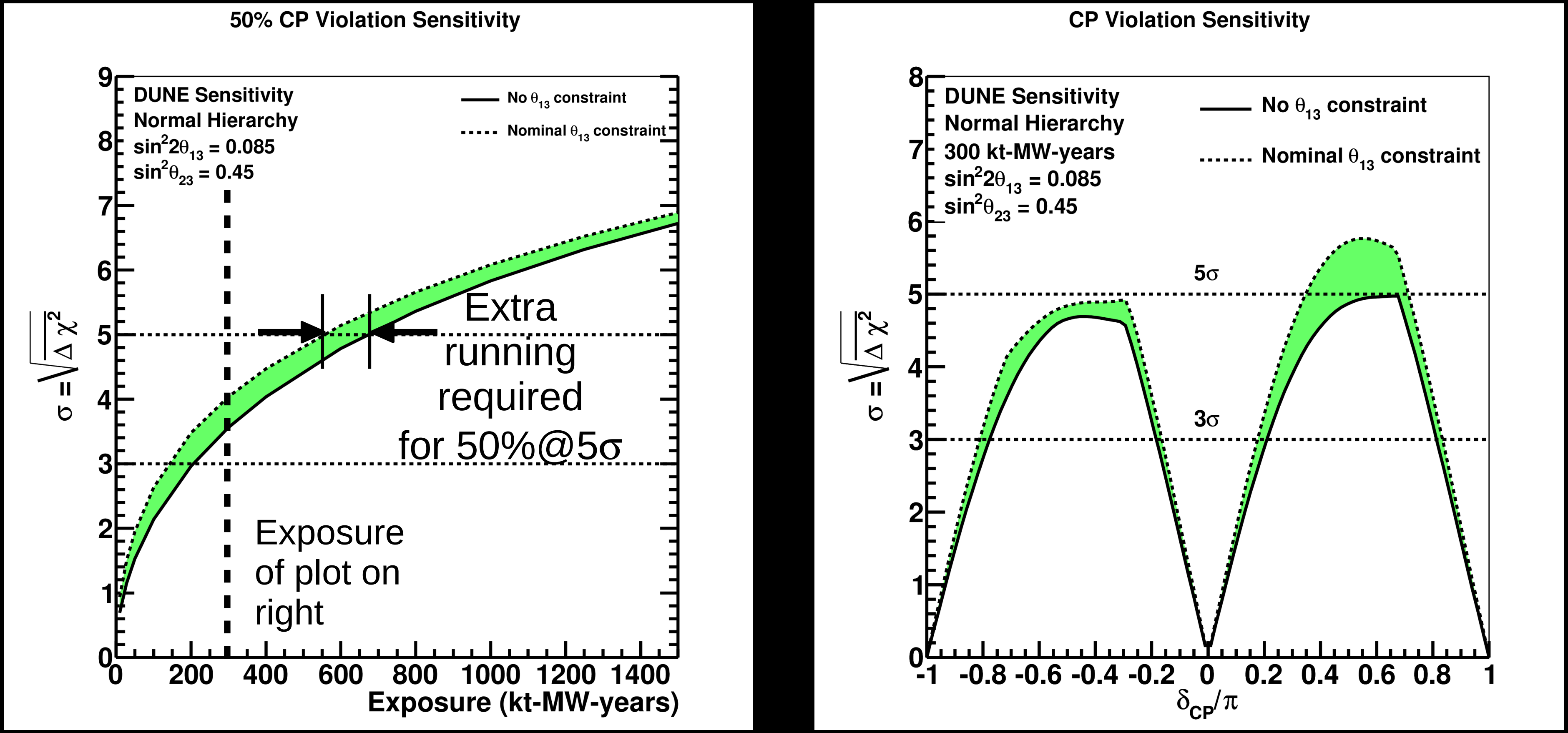
Effect of Reactor θ_{13} Constraint



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- DUNE will be able to measure δ_{CP} with the same sensitivity without the reactor constraint with a bit more running

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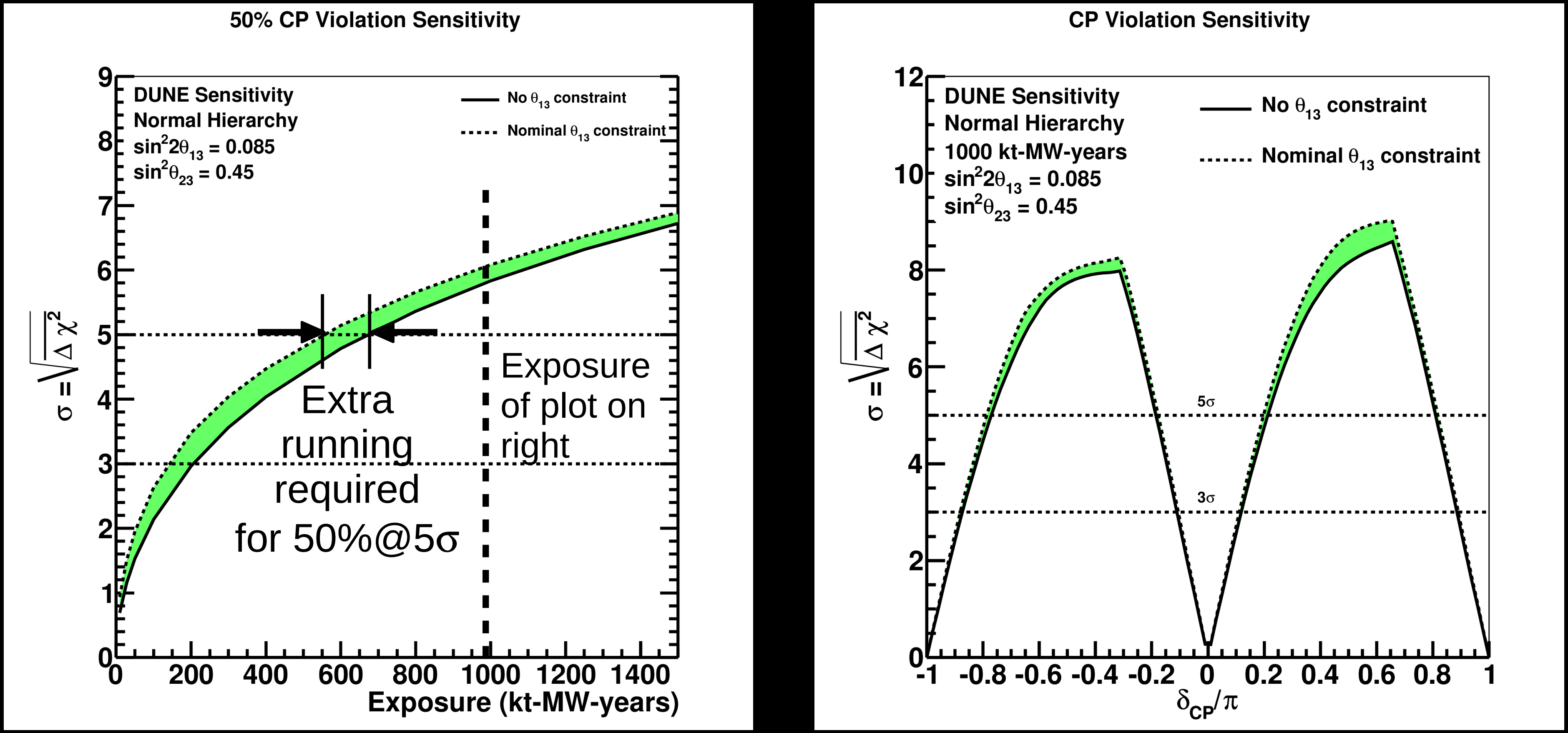

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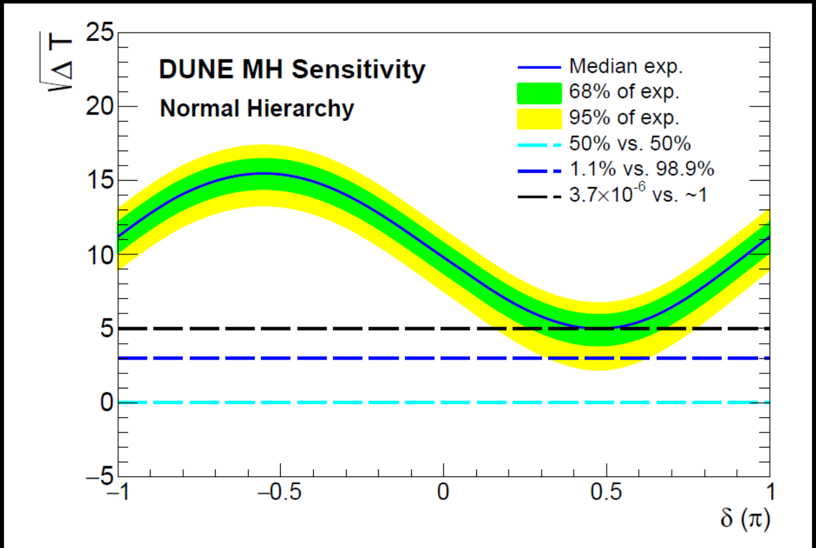
The Physics of DUNE:

Long-Baseline Physics: MH and the Rest

- DUNE will exclude the wrong MH at the 99% C.L. for all values of δ_{cp}
- The 99% C.L. result will come sooner for more favorable δ_{cp} values
- DUNE will also constrain $\sin^2(\theta_{13})$, $\sin^2(\theta_{23})$, and ΔM^2_{31}
- And has the potential to determine the θ_{23} octant, and measure ν_τ appearance
- DUNE long-baseline physics goals also include:
  - Over-constrain the PMNS matrix
  - Search for exotic physics like NSI, LRI, CPT/Lorentz violation, compact extra dimensions, and sterile neutrinos



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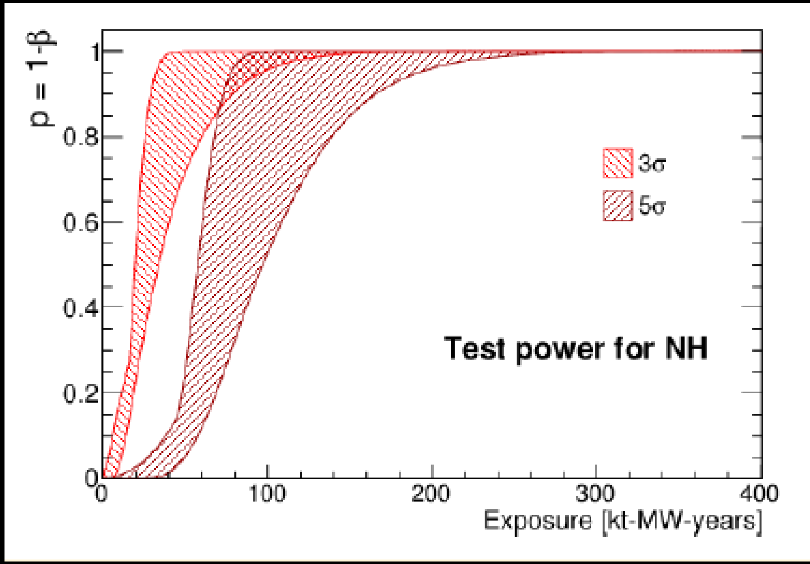

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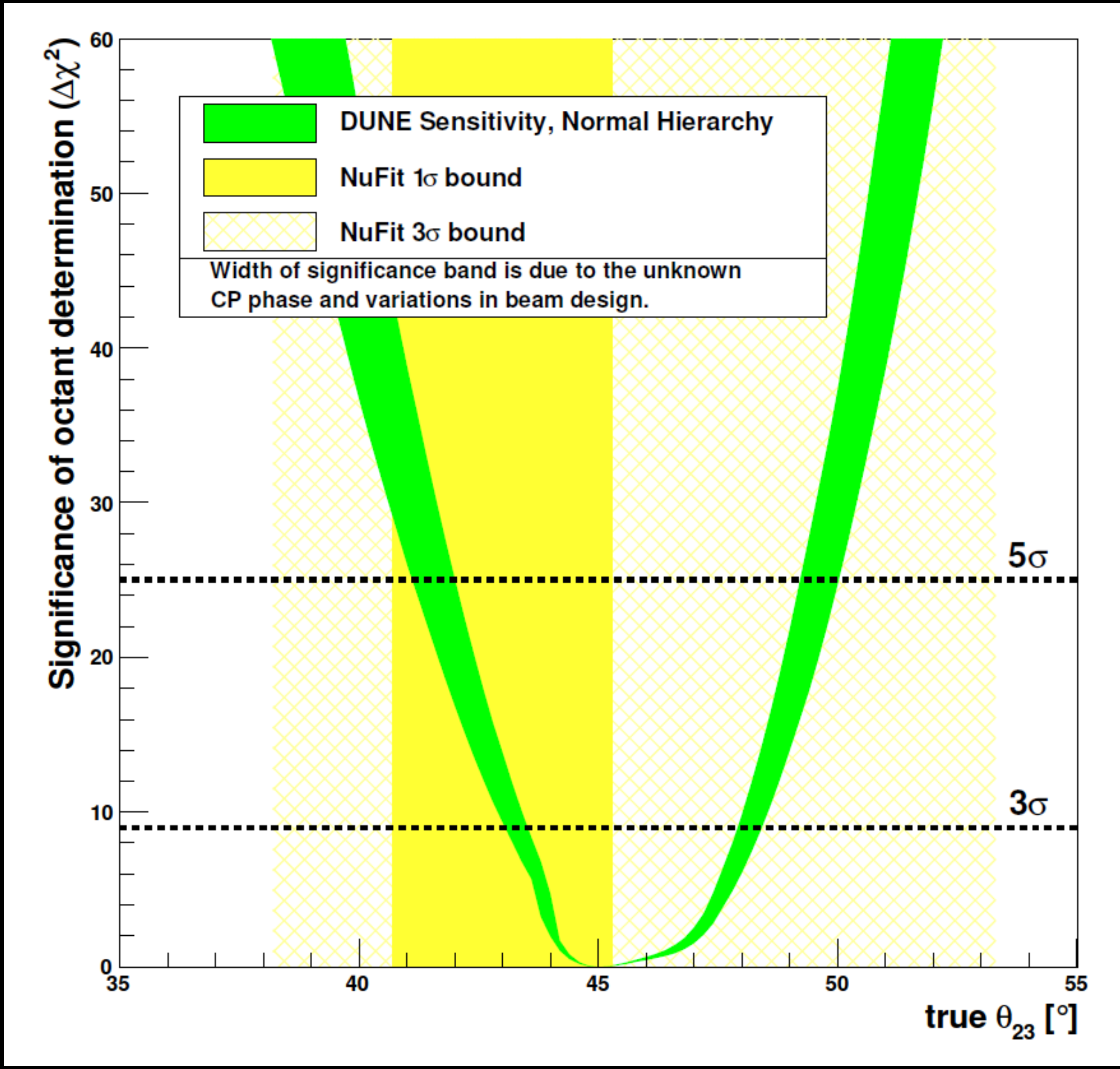
Octant Sensitivity



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- Mostly between 3σ and 5σ for NuFit 2014 band

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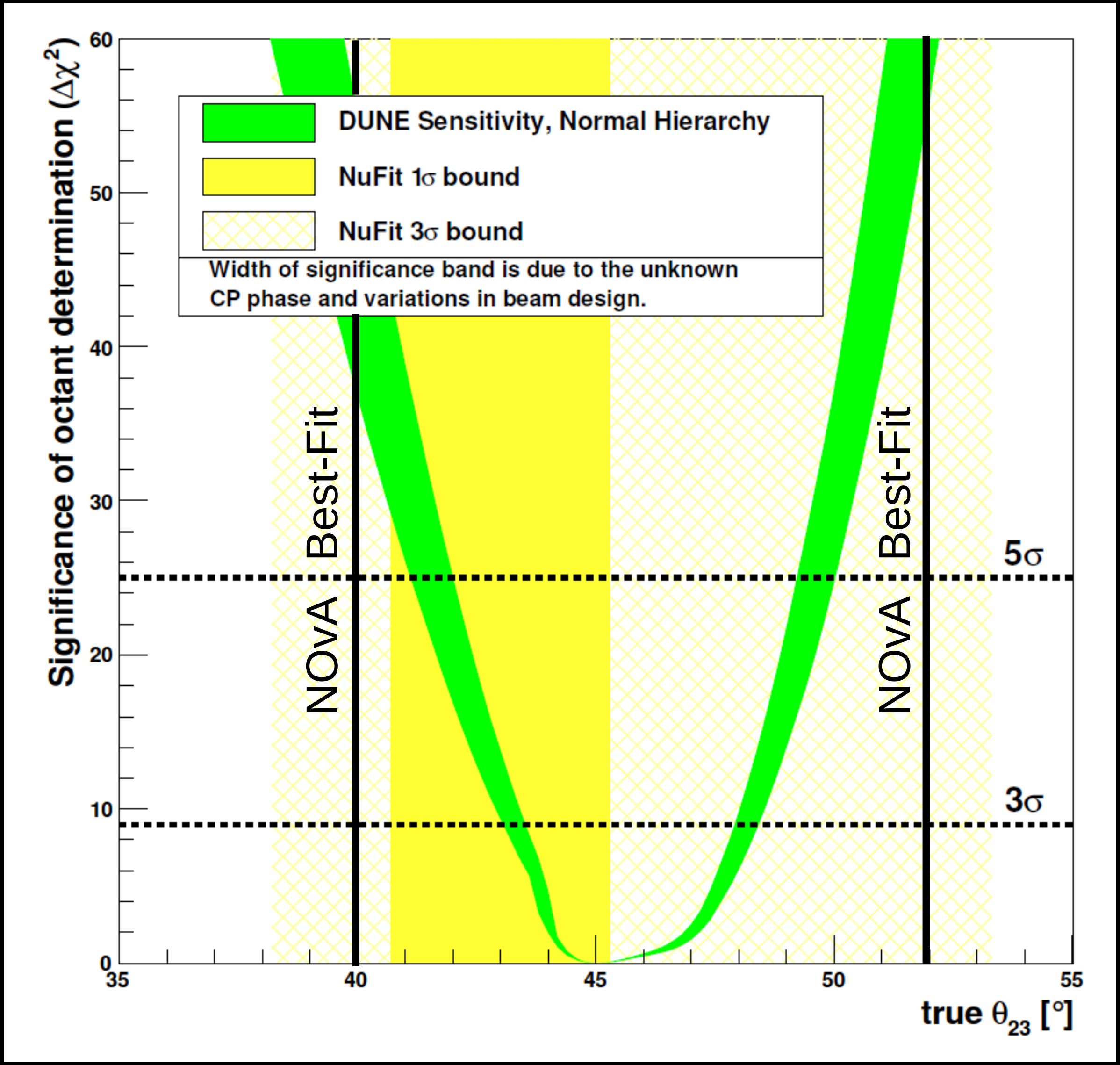

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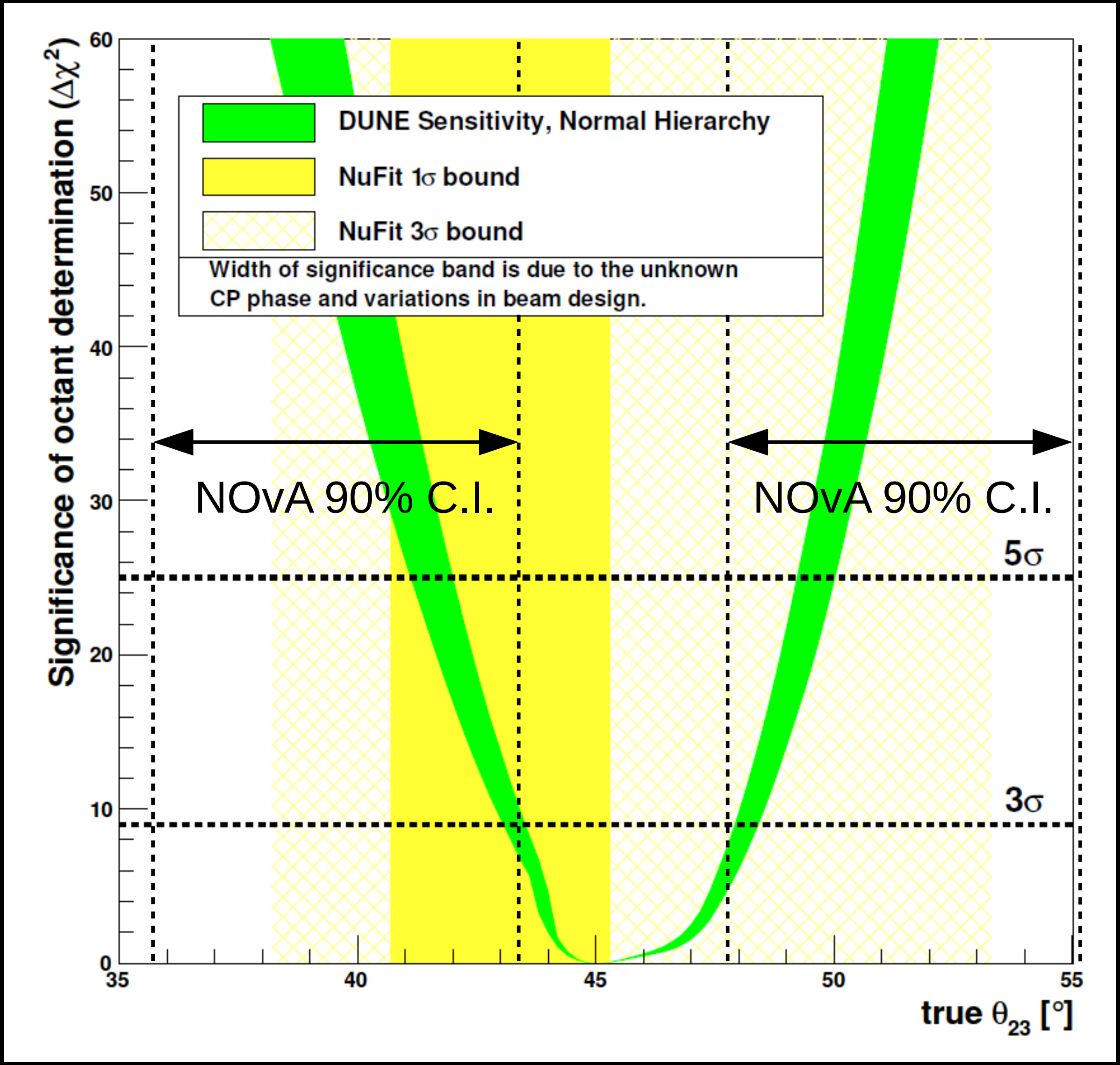
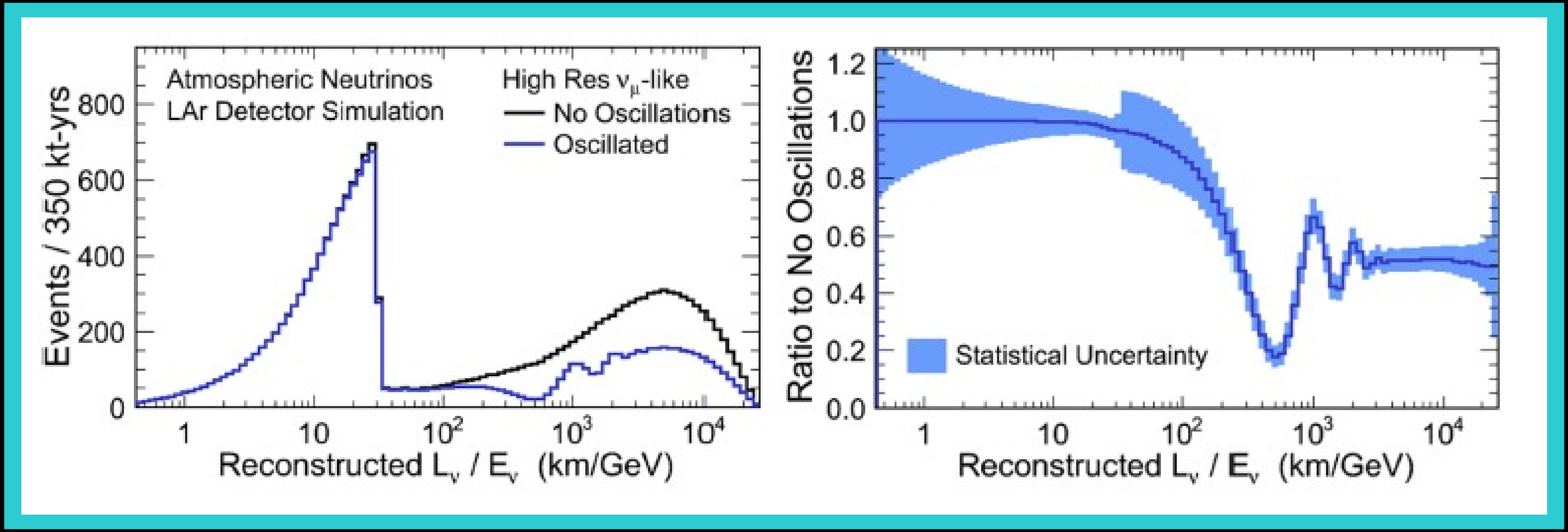


- Sensitivity is high a few degrees away from 45°
- Mostly between 3σ and 5σ for NuFit 2014 band
- At NovA best-fit values DUNE will easily achieve 5σ
- Sensitivity above 3s for all of the NoVA 90% C.I.

Atmospheric ν Oscillations

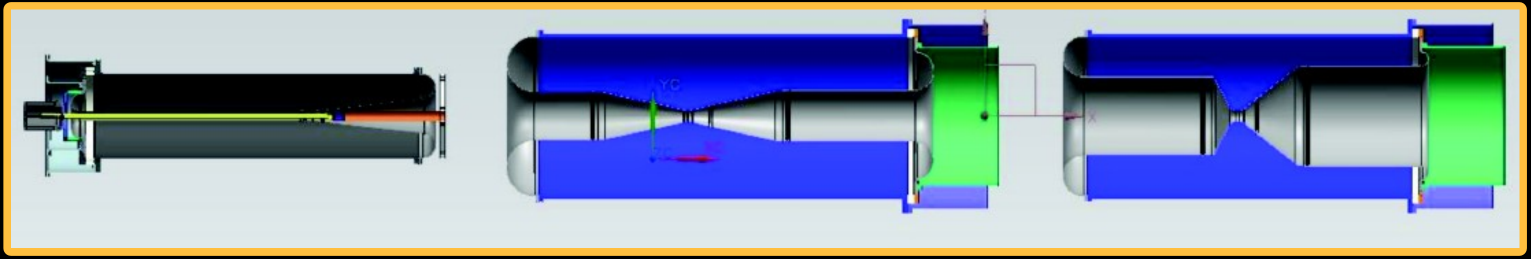
- Low energy thresholds gives superior L/E resolution
  - Fully reconstruct hadronic system
  - Low missing p_T improves angular resolution
- Good sensitivity to MH and θ_{23} octant
- Combine with accelerator ν data to improve oscillation physics measurements
- Sensitive to PMNS extensions / new physics
- Expect ~14k contained ν_e- like events, and ~20k contained ν_μ- like events for a 350kt-yr exposure

arxiv:1512.06148

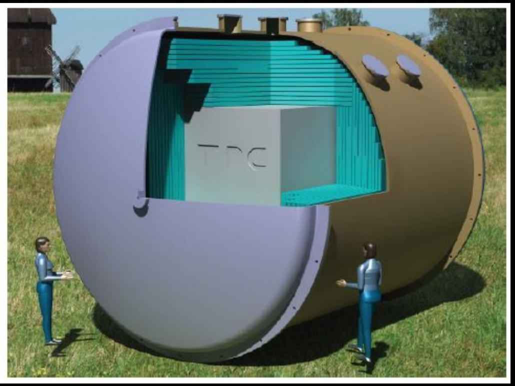


DUNE Task Forces

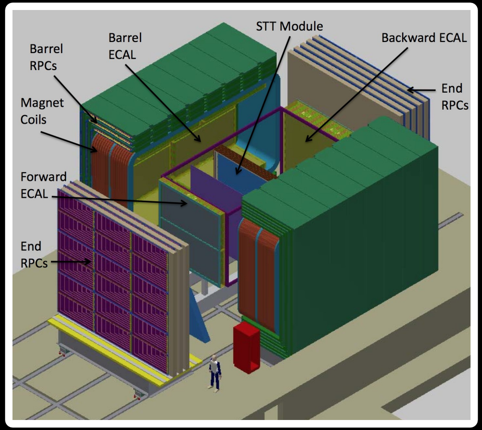
- Cross-working-group teams charged with simulating, evaluating, and optimizing the performance of the three main components of the experimental design
- Beam Optimization



- Near Detector Optimization

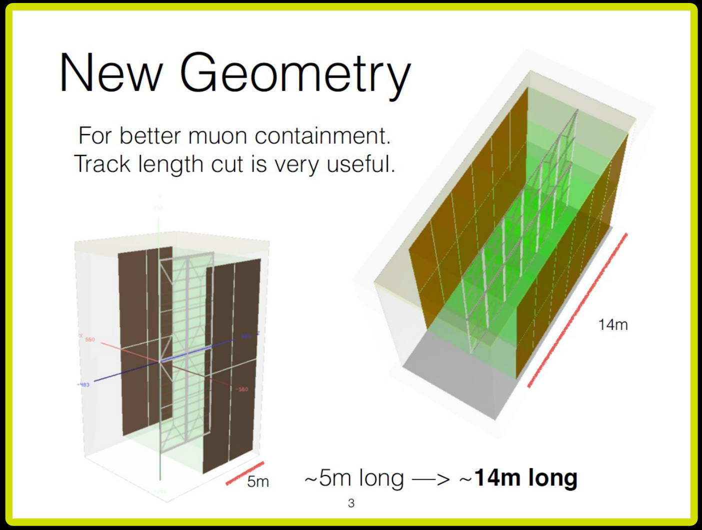


High-Pressure GAr TPC



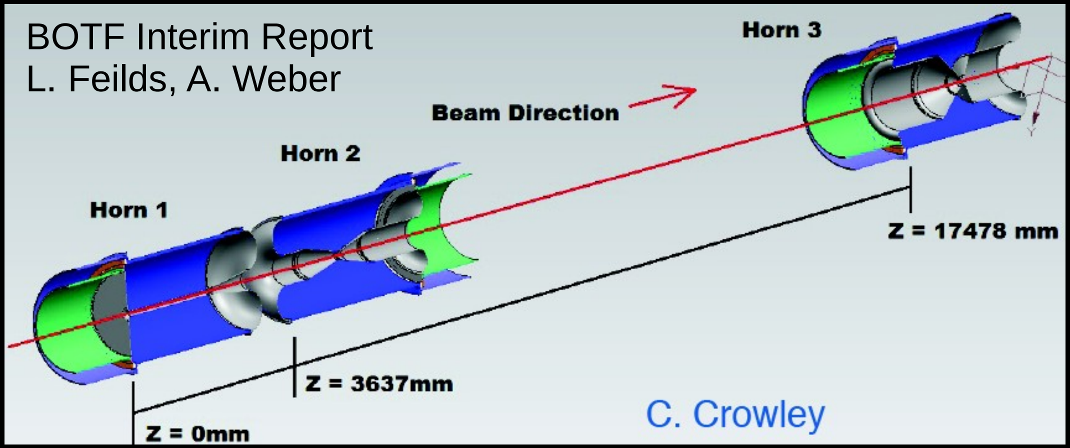
Fine-Grained Tracker

- Far Detector Optimization



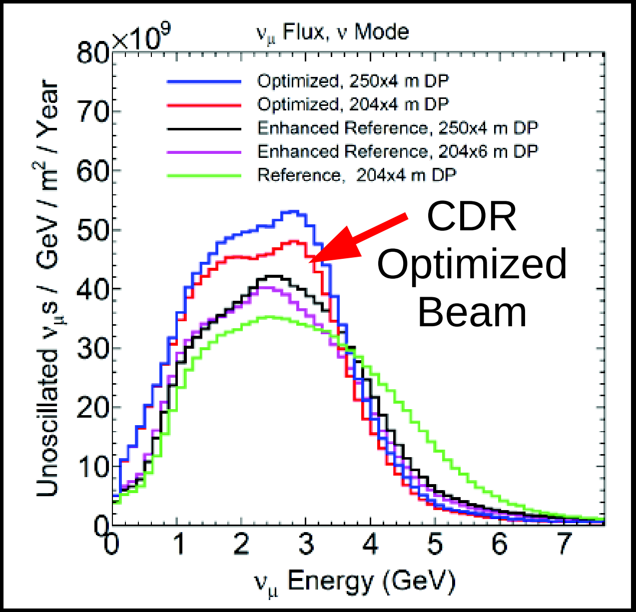
Beam Optimization Task Force

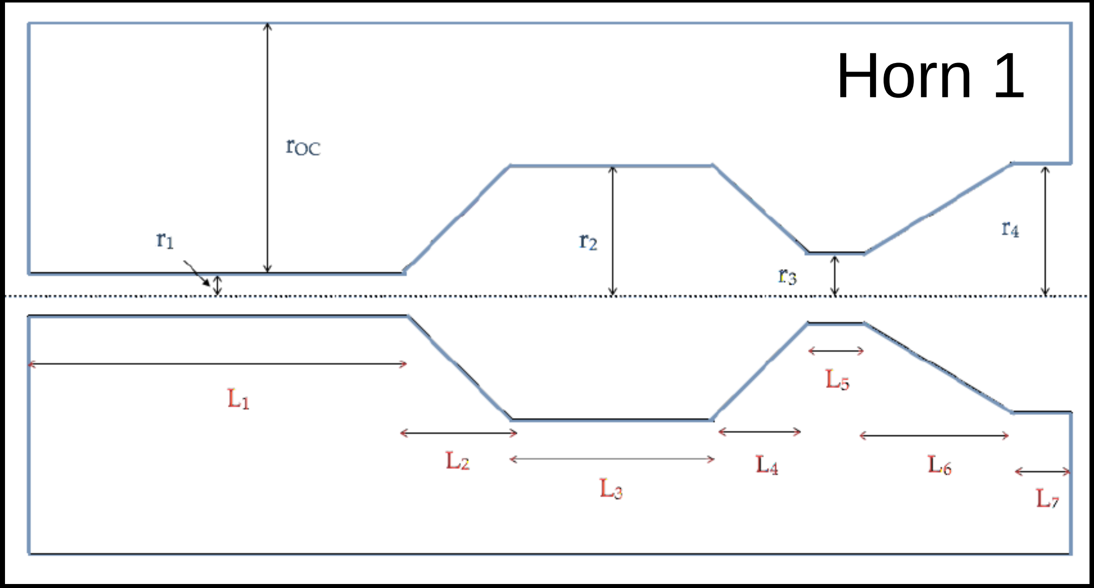
- Charge:
  - Physics driven optimization of the beam line (target, horns, etc)
  - Study alternate designs and develop a cost benefit analysis
- Status:
  - Design has been optimized for multiple component sets (2 vs. 3 horns, multiple target designs, etc)
  - Realistic design based optimizations in advanced stages
  - Detailed studies of the design are in progress:
    - Physics sensitivities
    - Optimal run plan ($\nu/\bar{\nu}$)
    - Cost implications
    - Alternate metrics
    - Alternate optimization routines

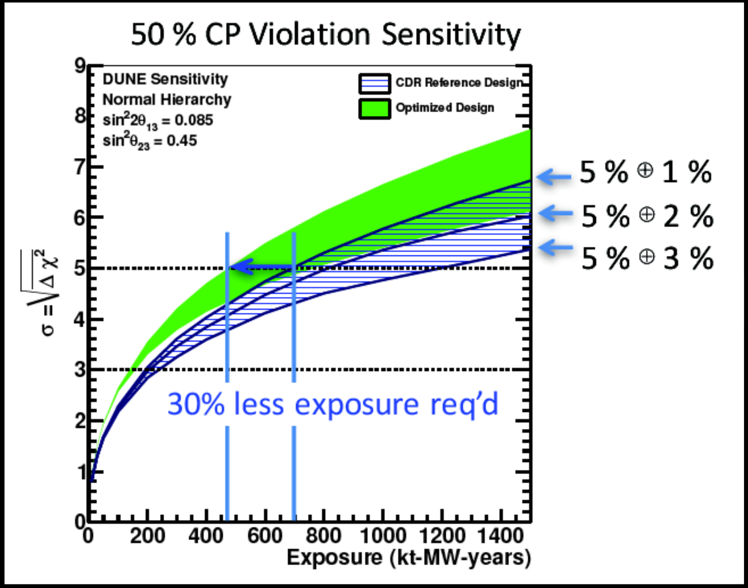


Beam line Genetic Optimization

- Optimizations studies conducted for the DUNE CDR
- Genetic optimization of:
  - Target and horn dimensions
  - Proton momentum
  - Decay pipe length
- Metric based on CPV sensitivity

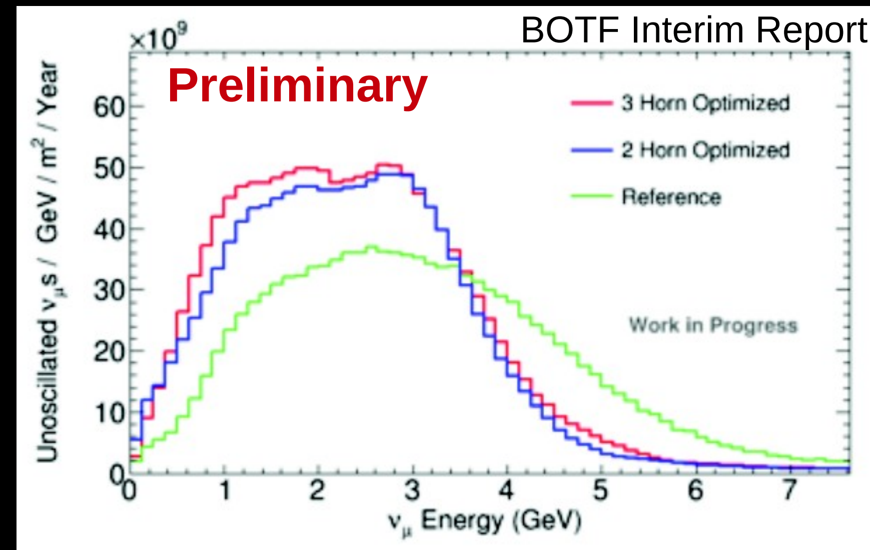


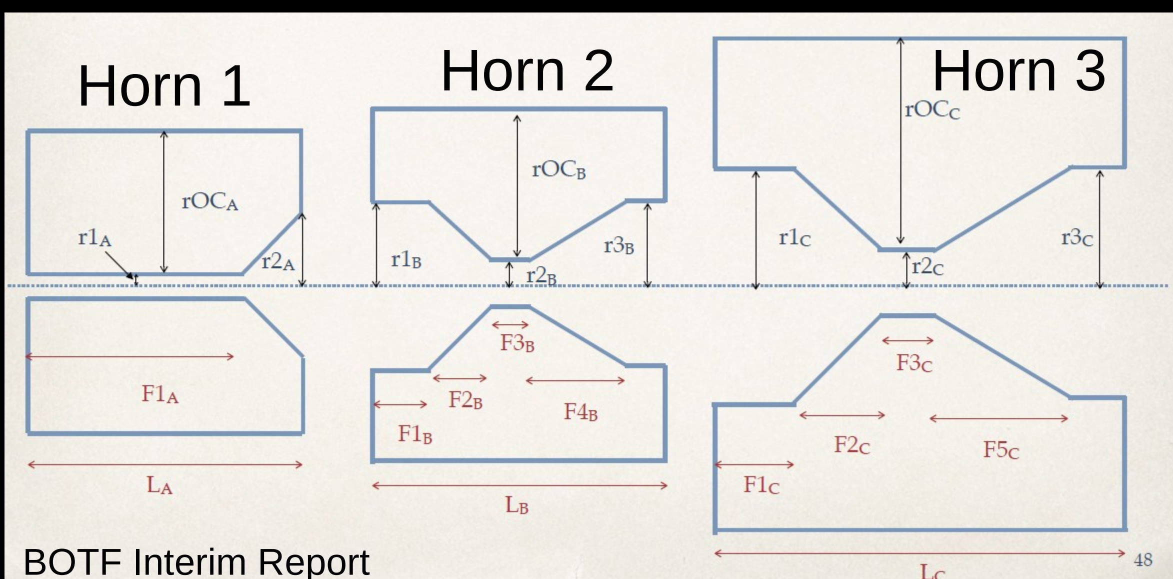


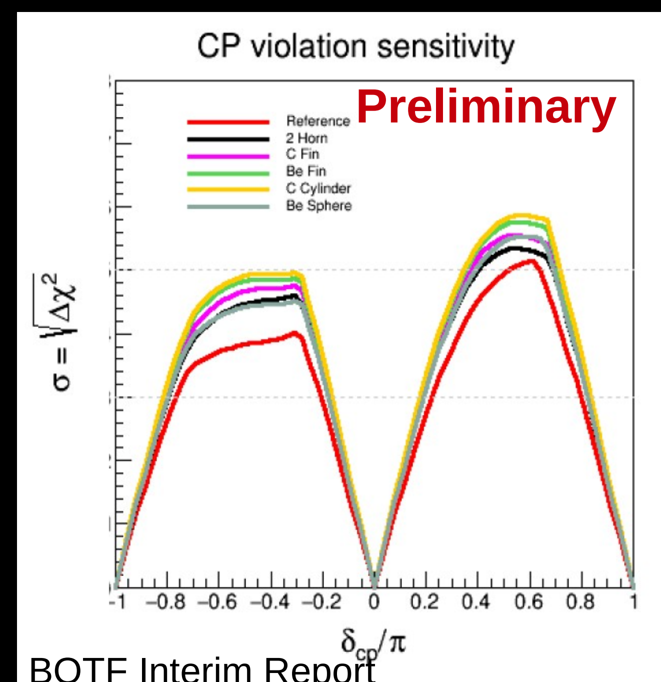


Beam line Genetic Optimization

- Task force is building on the success of the CDR studies
- Optimization of 2 vs 3 horn design
- Studies of several target designs
- Shifted focus to engineering feasibility and design flexibility







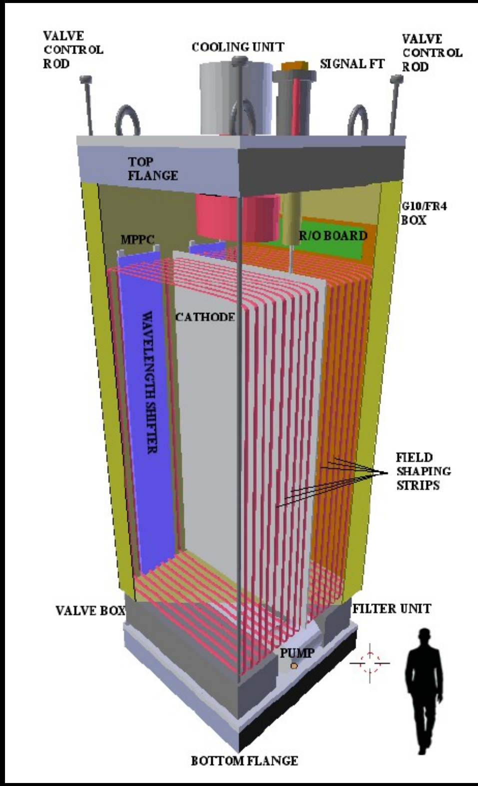
Uncertainty "Highlights"

- For systematics to be dangerous they must be able to replicate the effects of shifting δ_{cp} in all 4 analysis samples
- Absolute flux normalization and shape
  - Secondary and tertiary hadron production
  - Flux shape differences at the Near and Far detectors
- Uncertainties from cross section models and nuclear initial state models need to be factorized
- A coherent picture of nuclear initial state effects is required
- Cross section flavor differences and rates for exclusive final state channels require theoretical input
- The convolution of flux, cross section, FSI and detector effects in determining energy scale will be difficult to untangle
  - Both FSI and detector effects can be different for ν and $\bar{\nu}$
  - Relative $\bar{\nu}/\nu$ uncertainties currently provide freedom to mimic δ_{cp}-like effects
- Biases in the energy scale from mis-reconstruction and/or poorly modeled/constrained missing energy (neutrons) must be eliminated

Near Detector Task Force

- Charge:
  - Develop full GEANT4 simulation of 3 technology options
    - Fine-Grained Tracker (FGT)
    - Modular Liquid Argon TPC (LAr TPC / ArgonCube)
    - High-Pressure Gaseous Argon TPC (HP GAr TPC)
  - Develop end-to-end simulation and analysis chain to evaluate the impact of each ND on CPV sensitivity
- Status:
  - Each step in the simulation and analysis chain, and interfaces between each step, have been developed
  - Full GEANT4 simulations have been completed
  - The VALOR framework is used for ND fits and a DUNE specific oscillation analysis has been developed
  - Progress on event reconstruction is hard fought
  - Detector uncertainties represent the next (and last) big challenge

ArgonCube

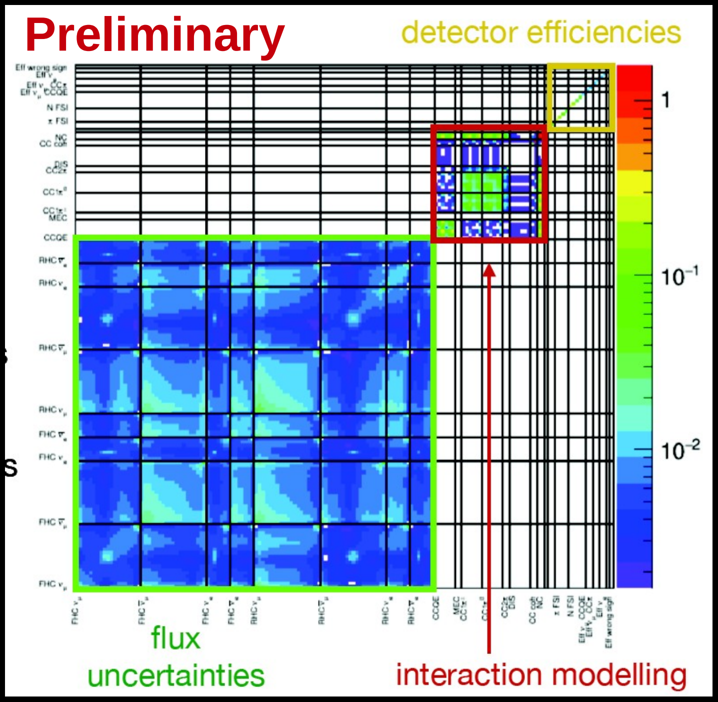


SPSC-I-243

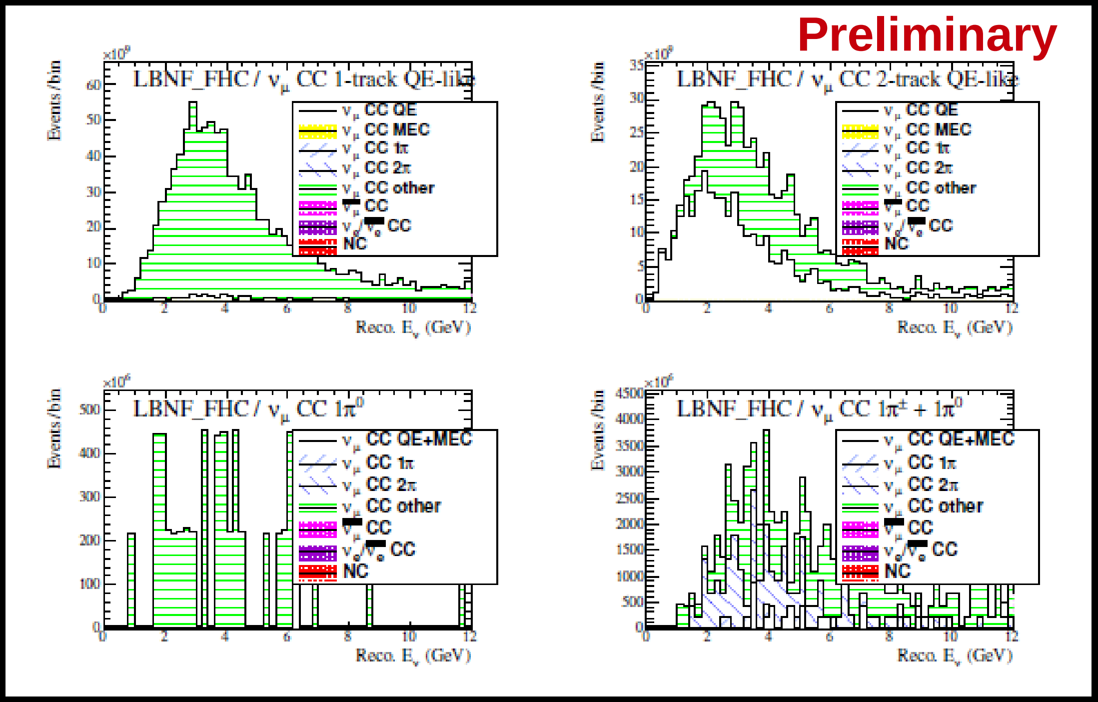
VALOR Fits to ND Samples

- Inputs (examples below):
  - Covariance matrix of priors on flux, xsec, and detector uncertainties
  - Topologically classified event samples
- Fit ND event samples to toy data (> 150 parameters)
- Output: covariance matrix containing constraints on input parameters → FD oscillation fits

The VALOR Group



The VALOR Group

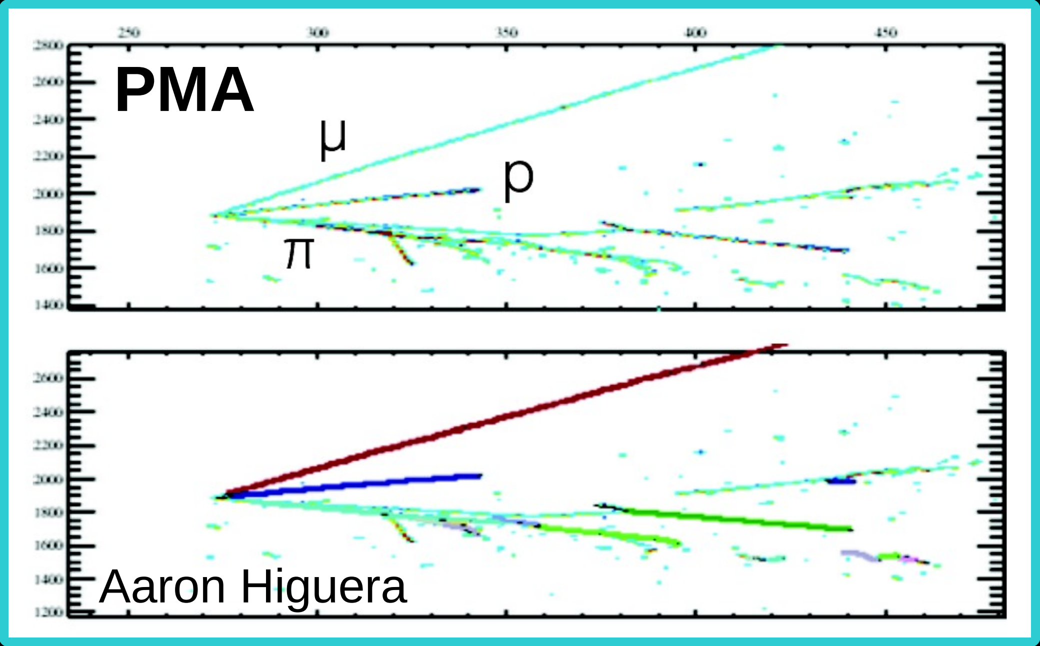


Far Detector Optimization

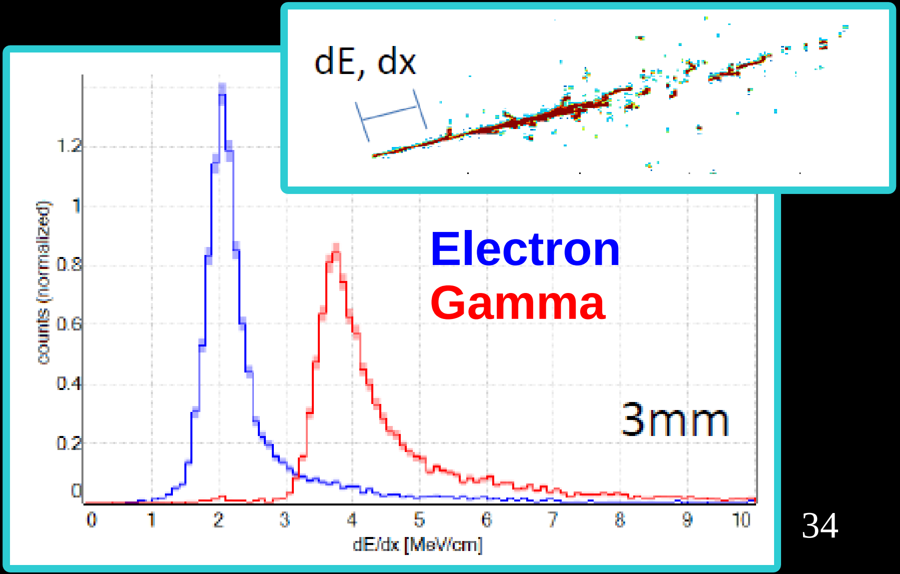
- Charge:
  - Full GEANT4 simulation and reconstruction for reference and alternate designs
  - Optimization studies for FD components and configurations
  - Evaluate full range of FD physics topics
    - Oscillation: accelerator, atmospheric
    - Non-oscillation: proton decay, supernova bursts
- Status:
  - Detector simulation in advanced stages, including 2-phase
  - Recent non-accelerator event generation improvements
  - Reconstruction and PID algorithms in development
  - First round of optimization studies using full simulation tools underway
  - More progress on reconstruction required to draw conclusions

LAr TPC 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



Aaron Higuera

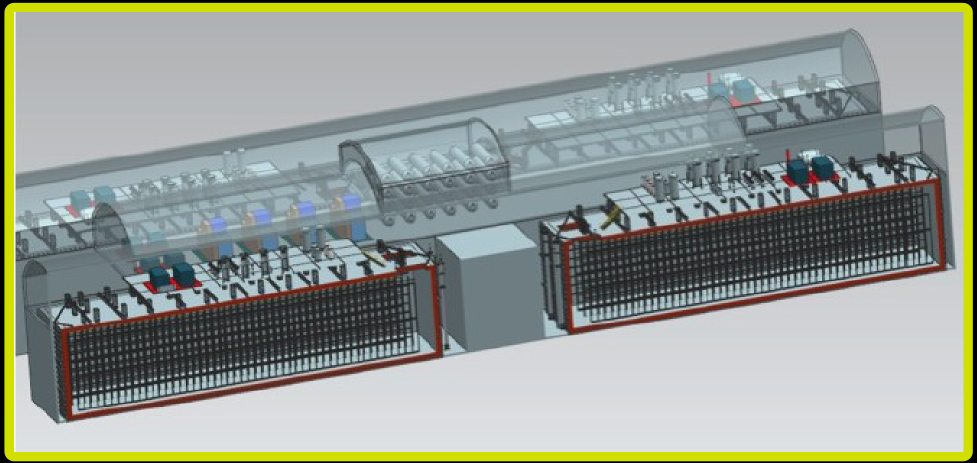


Dorota Stefan & Robert Sulej

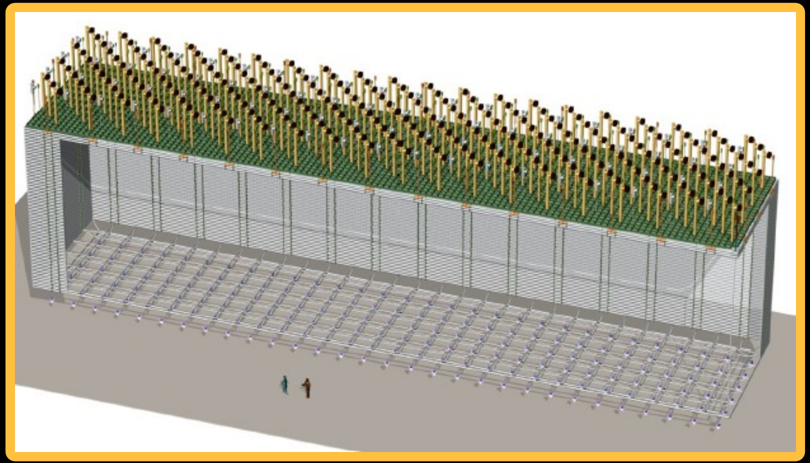
Far Detector Options and R&D

- Two FD detector options:
- Single Phase
  - 35 ton (completed)
  - ProtoDune (2018)
  - Far Detector (1st module)
- Dual Phase
  - 311 (coming soon)
  - ProtoDune (2018)
  - Far Detector
- Important contribution from SBN Program detectors

Single phase, 2 modules



Dual phase, 1 module



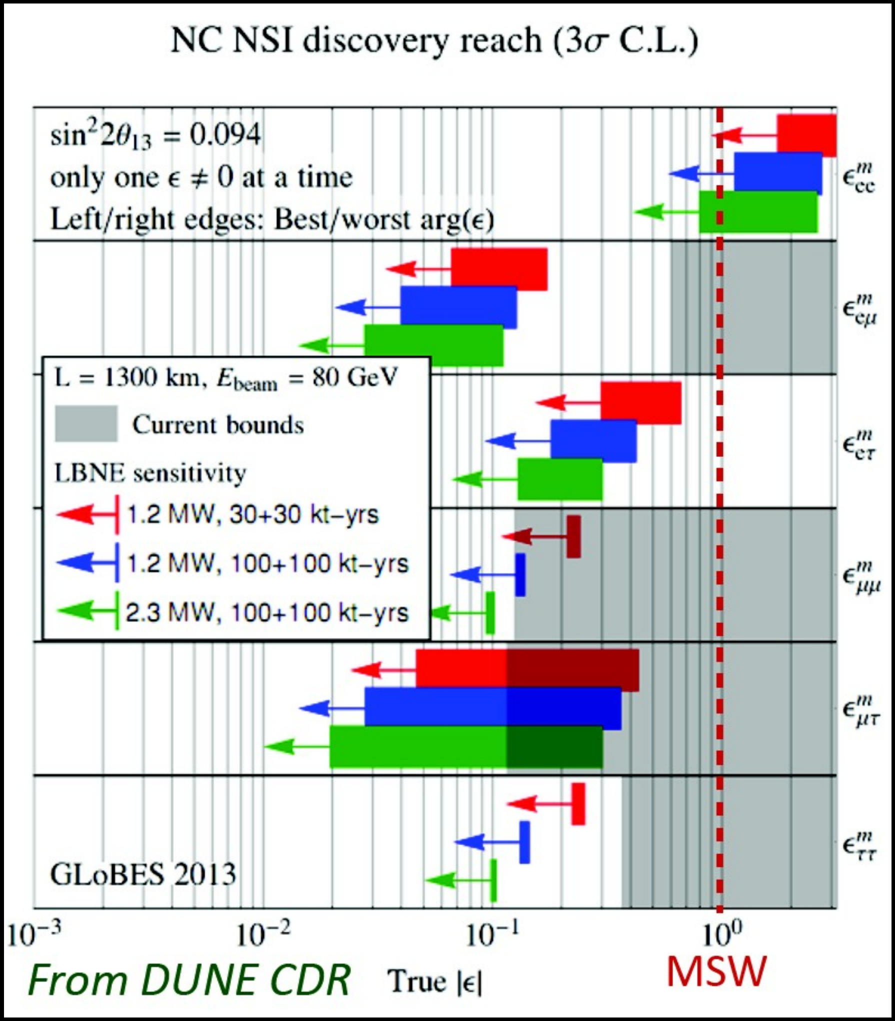
DUNE CDR Volume 4 (http://arxiv.org/pdf/1601.02984v1.pdf)

Input From the Intermediate ν Program

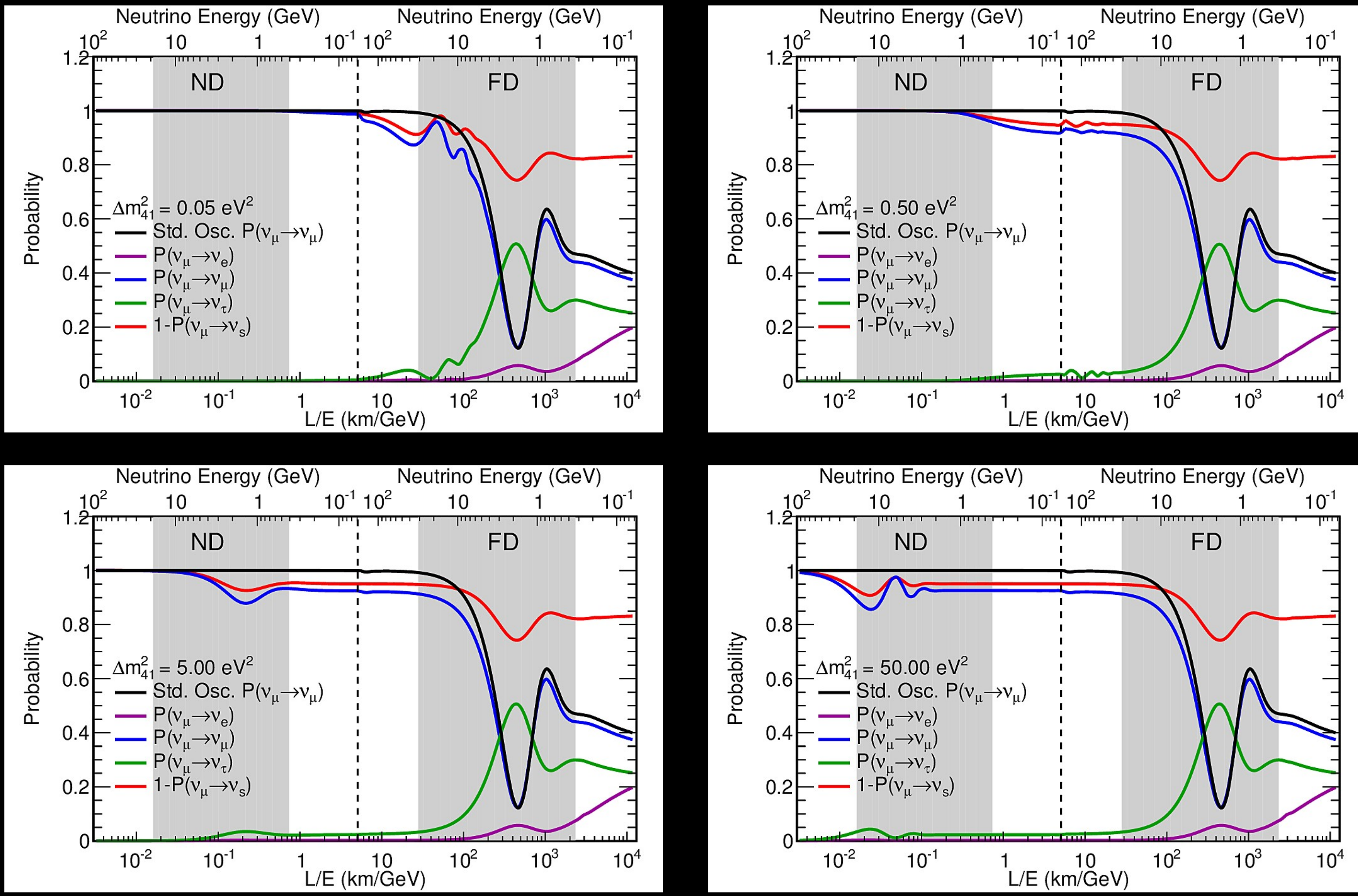
- In addition to the in-situ measurements from the beamline monitoring, and the DUNE ND and FD, many external measurements are required
- NA61/SHINE and MIPP will provide data for hadron production model tuning used in beamline simulations
- Electron scattering at JLab will provide data on the nuclear structure of Ar
- Test beam LAr TPCs: CAPTAIN, LArIAT, CERN Prototypes
  - High statistics data on detector response required for calibrations
  - Allows for in-situ tests of detector components and comparison of detector technologies
- LArTPCs in neutrino beams from FNAL SBN Program
  - Test and refine reconstruction algorithms and calibration methods
  - Measure cross sections and nuclear effects on Ar_{40}
- Other cross section experiments like Minerva and ND280 (T2K) will map out cross sections over a wide energy range and on a multitude of nuclear targets
- Neutrino event generator development and tuning

BSM Physics in DUNE

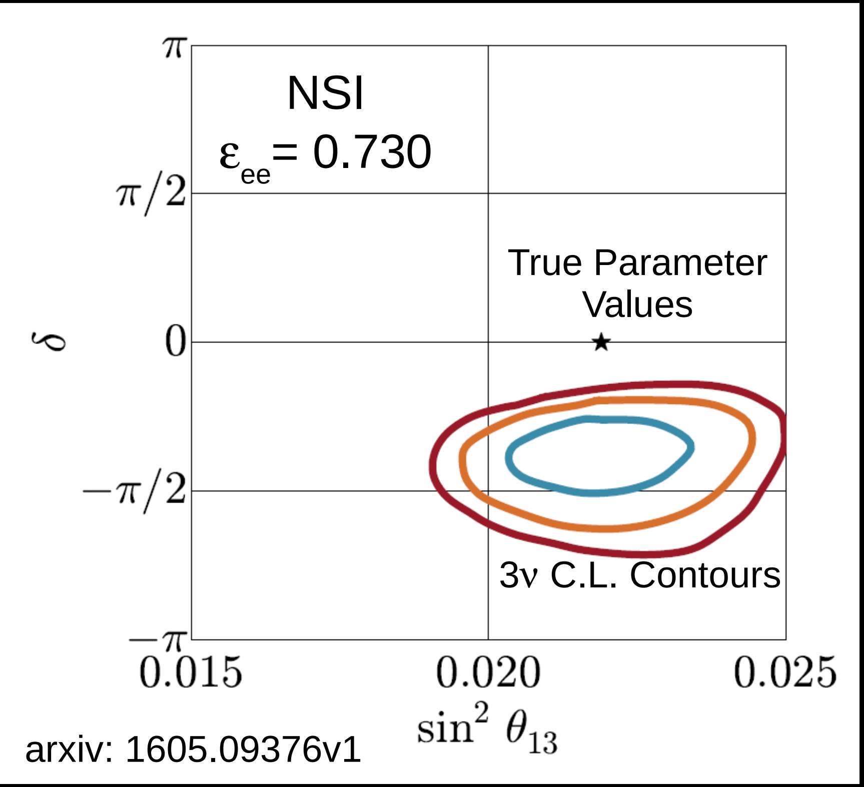
- DUNE is beginning to study sensitivities to BSM physics
- Topics related to oscillation physics include:
  - Sterile neutrinos
  - Non-standard interactions
  - Non-unitarity of the PMNS matrix
  - Large extra dimensions
- Initial studies on the changes to event rate predictions have been performed
- Current work is focused on simulations and reconstruction
- Effects on 3ν CPV searches are also planned
- Impact of atmospheric neutrino samples?

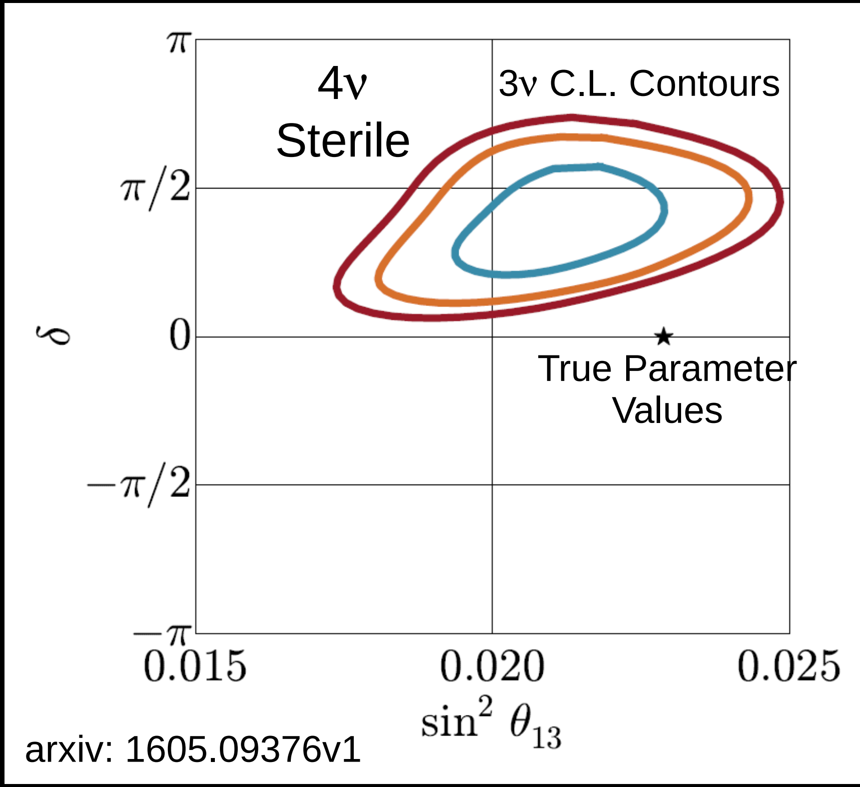


Measuring Sterile ν's in DUNE



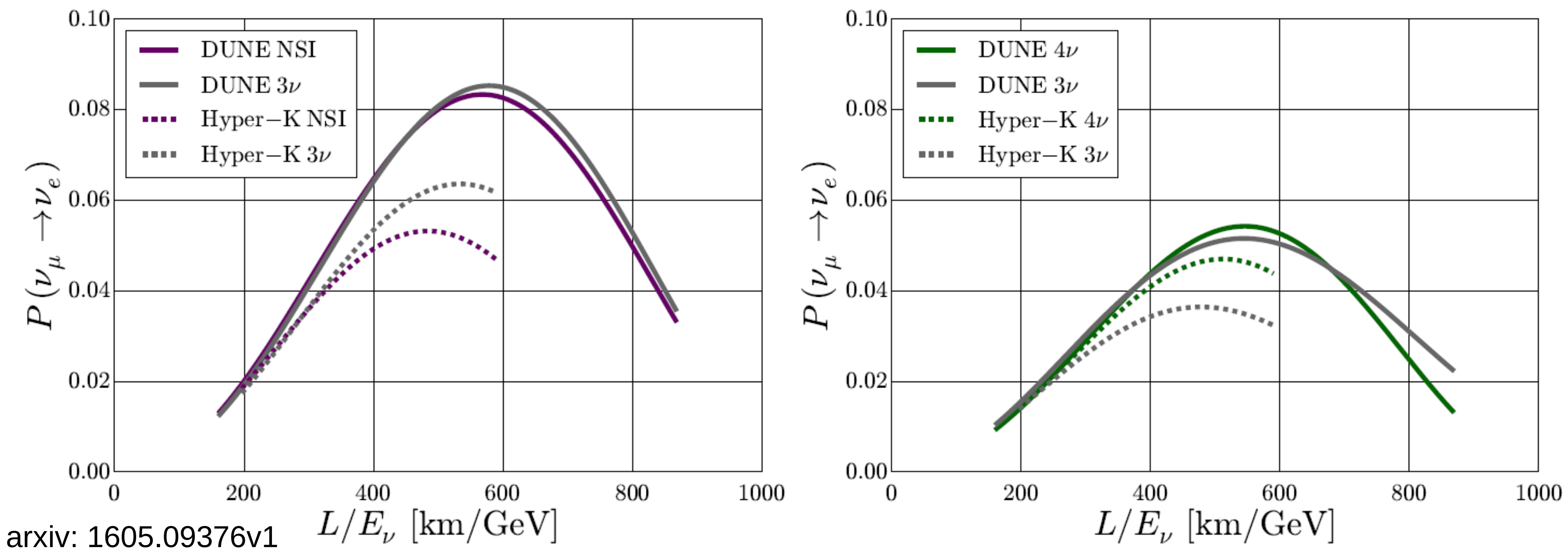
Sterile ν and NSI Degeneracies for CPV Measurements





- It is possible (and not particularly difficult) to contrive a set of NSI or sterile parameters to fake a CPV signal
- The degeneracy can be broken with different L, but same L/E, e.g. DUNE and HK

Sterile ν and NSI Degeneracies for CPV Measurements



arxiv: 1605.09376v1

- It is possible (and not particularly difficult) to contrive a set of NSI or sterile parameters to fake a CPV signal
- The degeneracy can be broken with different L, but same L/E, e.g. DUNE and HK

Many Papers on These Topics

- Capabilities of long-baseline experiments in the presence of a sterile neutrino, Debajyoti Dutta, Raj Gandhi, Boris Kayser, Mehedi Masud, and Suprabh Prakashe, e-Print: arXiv:1607.02152v1.
- Non-standard interactions and the resolution of ordering of neutrino masses at DUNE and other long baseline experiments , Mehedi Masud (Harish-Chandra Res. Inst.), Poonam Mehta (Nehru U.). Jun 17, 2016. 30 pp. e-Print: arXiv:1606.05662
- Nonstandard interactions spoiling the CP violation sensitivity at DUNE and other long baseline experiments, Mehedi Masud (Harish-Chandra Res. Inst.), Poonam Mehta (Nehru U.). Mar 4, 2016. 20 pp. Published in Phys.Rev. D94 (2016) 013014 DOI: 10.1103/PhysRevD.94.013014 e-Print: arXiv:1606.05662
- Probing CP violation signal at DUNE in presence of non-standard neutrino interactions, Mehedi Masud (Harish-Chandra Res. Inst.), Animesh Chatterjee (Texas U., Arlington), Poonam Mehta (Nehru U.). Oct 28, 2015. 19 pp. Published in J.Phys. G43 (2016) no.9, 095005 DOI: 10.1088/0954-3899/43/9/095005/meta, 10.1088/0954-3899/43/9/095005, e-Print: arXiv:1510.08261
- Non-standard Neutrino Interactions at DUNE, André de Gouvêa, Kevin J. Kelly, e-Print: arXiv:1511.05562
- A Sterile Neutrino at DUNE, Jeffrey M. Berryman, Andre de Gouvea, Kevin J. Kelly, Andrew Kobach, e-Print: arXiv:1507.03986
- Large, Extra Dimensions at the Deep Underground Neutrino Experiment, Jeffrey M. Berryman, André de Gouvêa, Kevin J. Kelly, O.L.G. Peres, Zahra Tabrizi, e-Print: arXiv:1603.00018
- False Signals of CP-Invariance Violation at DUNE, André de Gouvêa, Kevin J. Kelly, e-Print: arXiv:1605.09376

Conclusions

- DUNE has demonstrated sensitivity to θ_{13}, θ_{23} (including octant), ΔM^2_{32} (including MH), and δ_{CP} in a single experiment
- Current work is focused on:
  - Beam line optimization
  - Full GEANT4 detector simulations
  - Event selection and reconstruction
- Improvements in simulations will usher in a new era of detailed sensitivity studies that will include:
  - Detailed flux and detector uncertainties
  - Realistic ND constraints for a variety of ND options
  - Sensitivity to exotic physics and degeneracies with the 3ν analysis

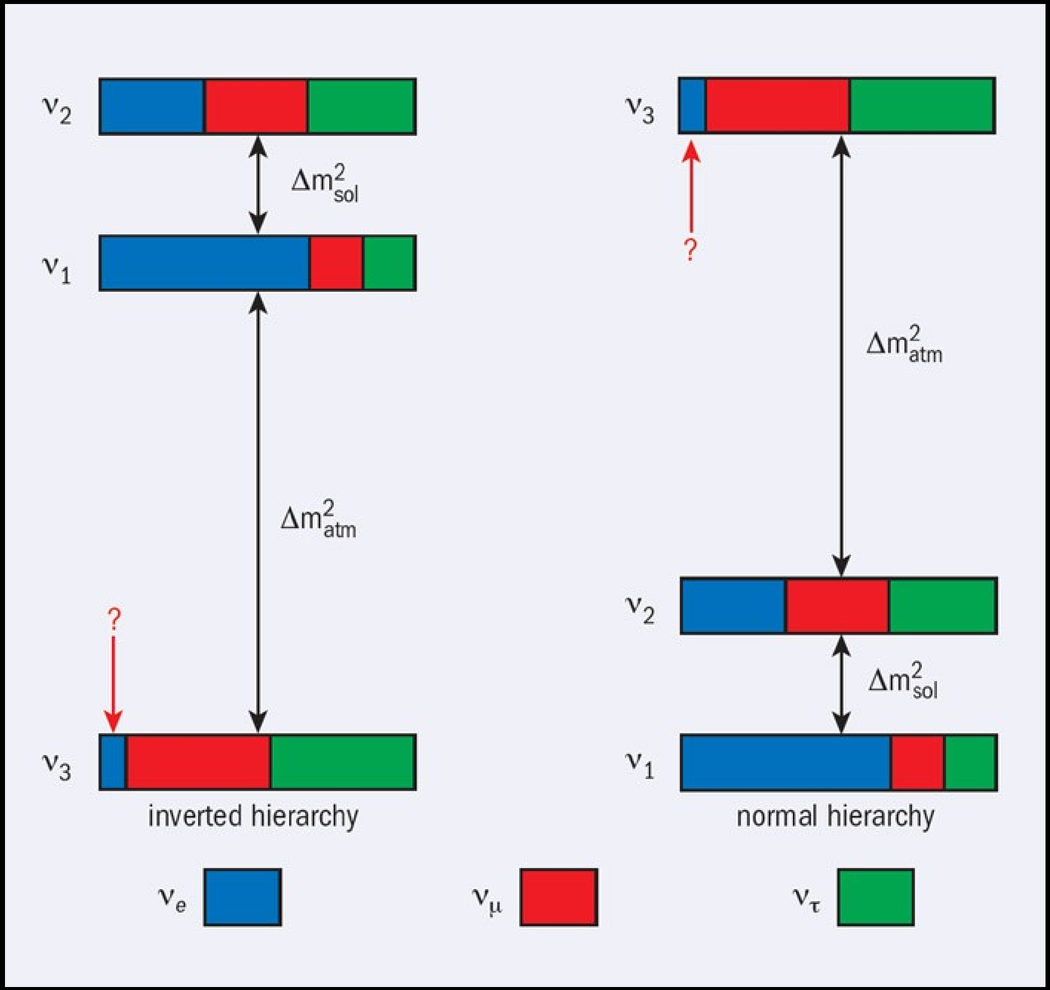
Backup Slides

Overview

- Physics potential of current ν oscillation experiments
- The DUNE experimental setup
- The physics of DUNE
- The plan for DUNE infrastructure
- Inputs from the intermediate neutrino program
- Conclusions

Unanswered Questions

- What are the ν masses?
- Are ν their own antiparticle?
- What is the ν mass ordering?
- Is there CP violation (CPV) in the lepton sector, and what is the value of δ_{cp}?
- What is the θ_{23} octant?
- Do protons decay?



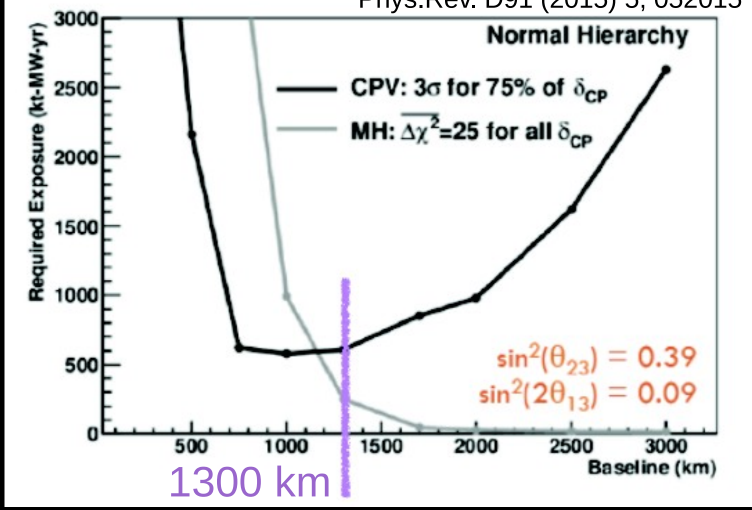
DUNE and LBNF

- Detectors and science collaboration will be managed separately from the neutrino facility and infrastructure
- Long-Baseline Neutrino Facility (LBNF)
  - Neutrino beam line
  - Near detector complex (but not the ND)
  - Far site (Sanford Lab) conventional facilities; detector hall, cryogenic systems
  - Operating costs for all of the above
- Deep-Underground Neutrino Experiment (DUNE)
  - Definition of **scientific goals** and **design requirements** for all facilities
  - The Near and Far Detectors
  - The scientific research program
- Close and continuous coordination between DUNE and LBNF will be required

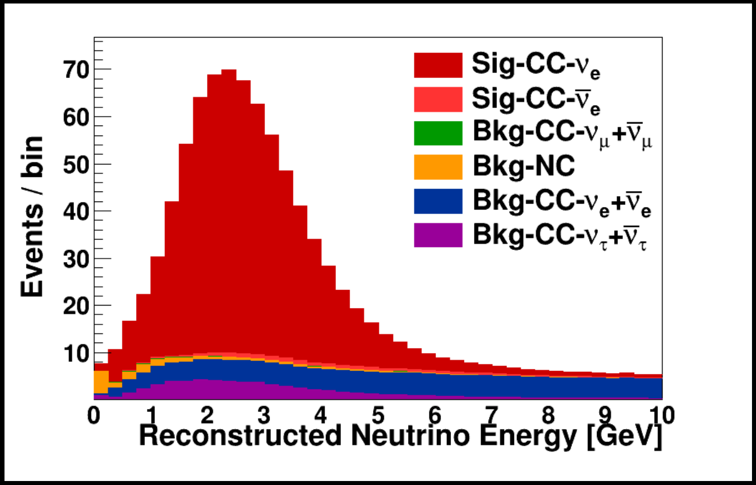
The DUNE Experimental Setup

- DUNE is designed to provide a broad program of ν oscillation physics, ν interaction physics, proton decay, supernova physics, and BSM physics
- Oscillation Physics:
  - Baseline of 1300 km
  - A megawatt class beam covering the 1st and 2nd oscillation maxima
  - A highly capable ND to constrain the FD event rate prediction
  - A large (40 kt), high resolution FD deployed deep underground
  - Exposure of 6-12 yr with ~50% / 50% ν / $\bar{\nu}$ running
  - Sensitivity to δ_{cp} and the MH in the same experiment

Phys.Rev. D91 (2015) 5, 052015

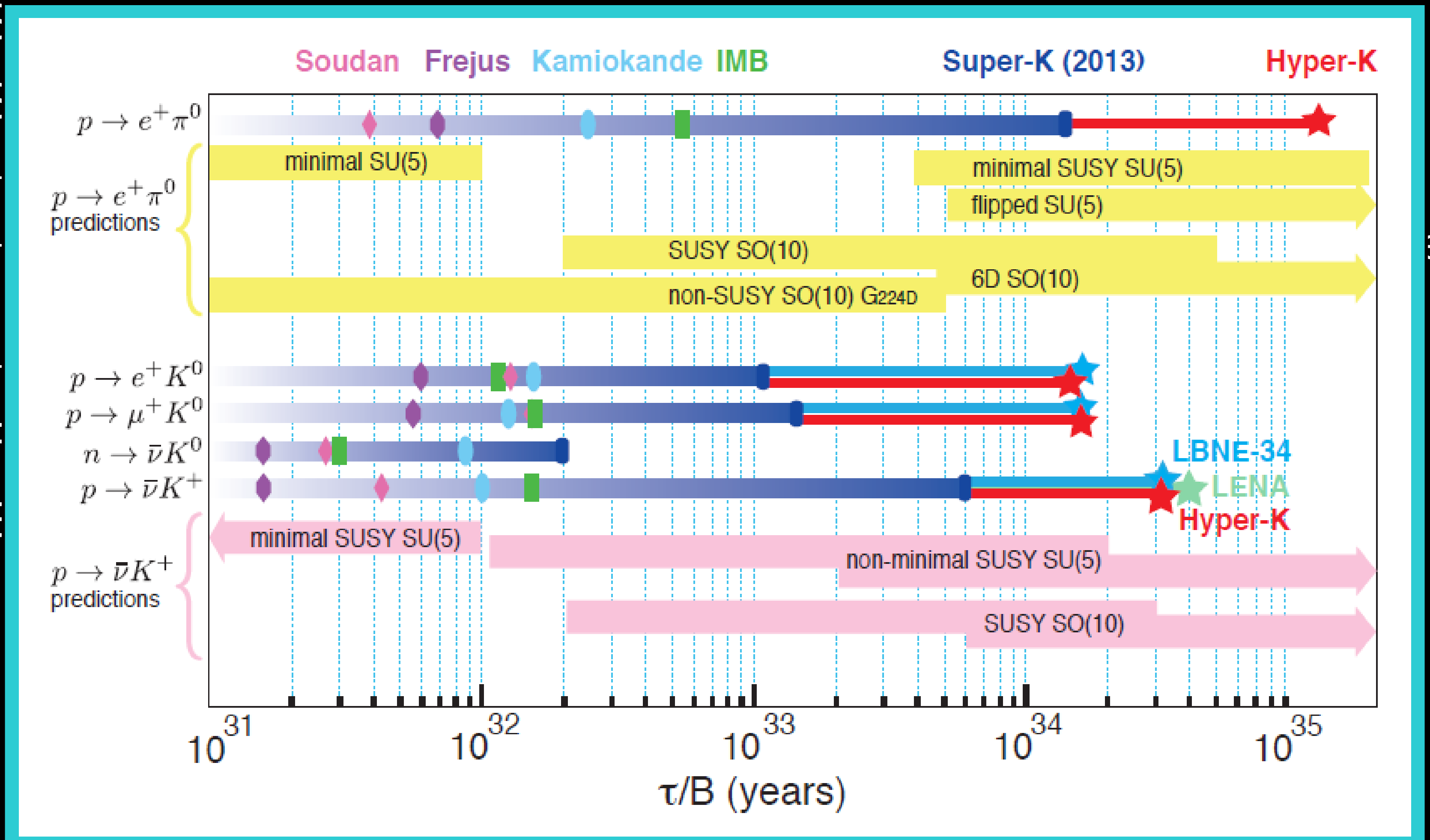


DUNE ν_e appearance



The Physics of DUNE:
Underground Physics: Proton Decay

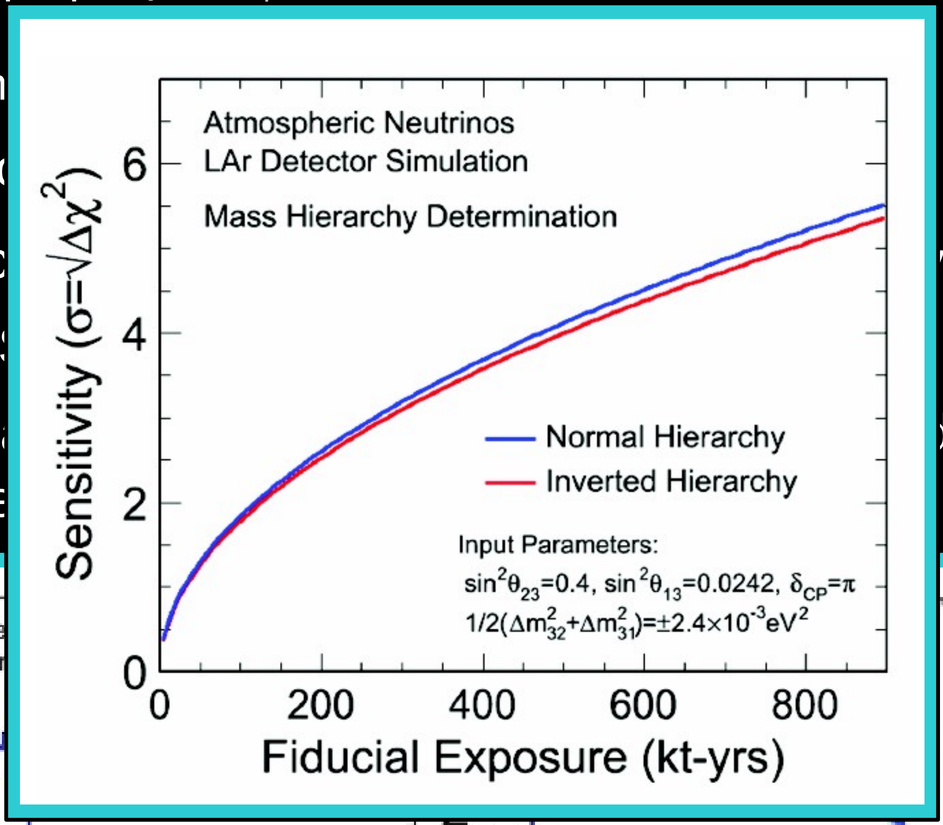
- S
- S
  -
  - eric
  - K^0
- F
- E

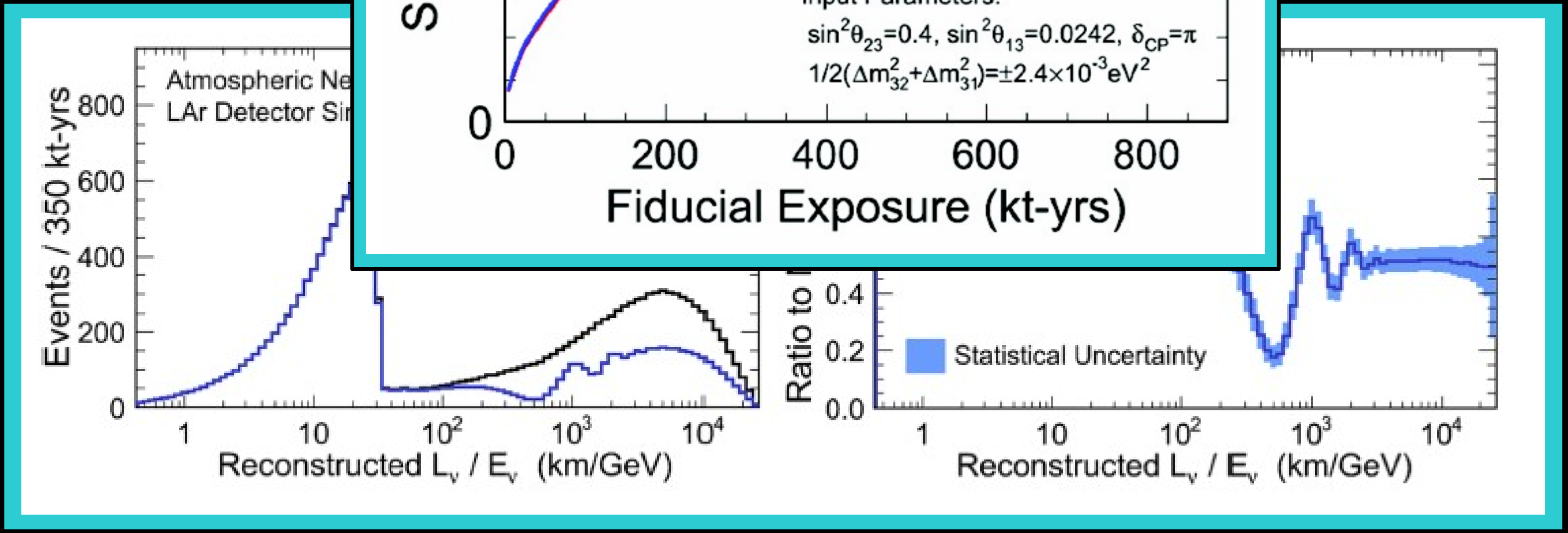


$n \to K^+e^-$	10%	3	96%	< 2
$n \to e^+\pi^-$	19%	2	44%	0.8

The Physics of DUNE:
Underground Physics: Atmospheric ν

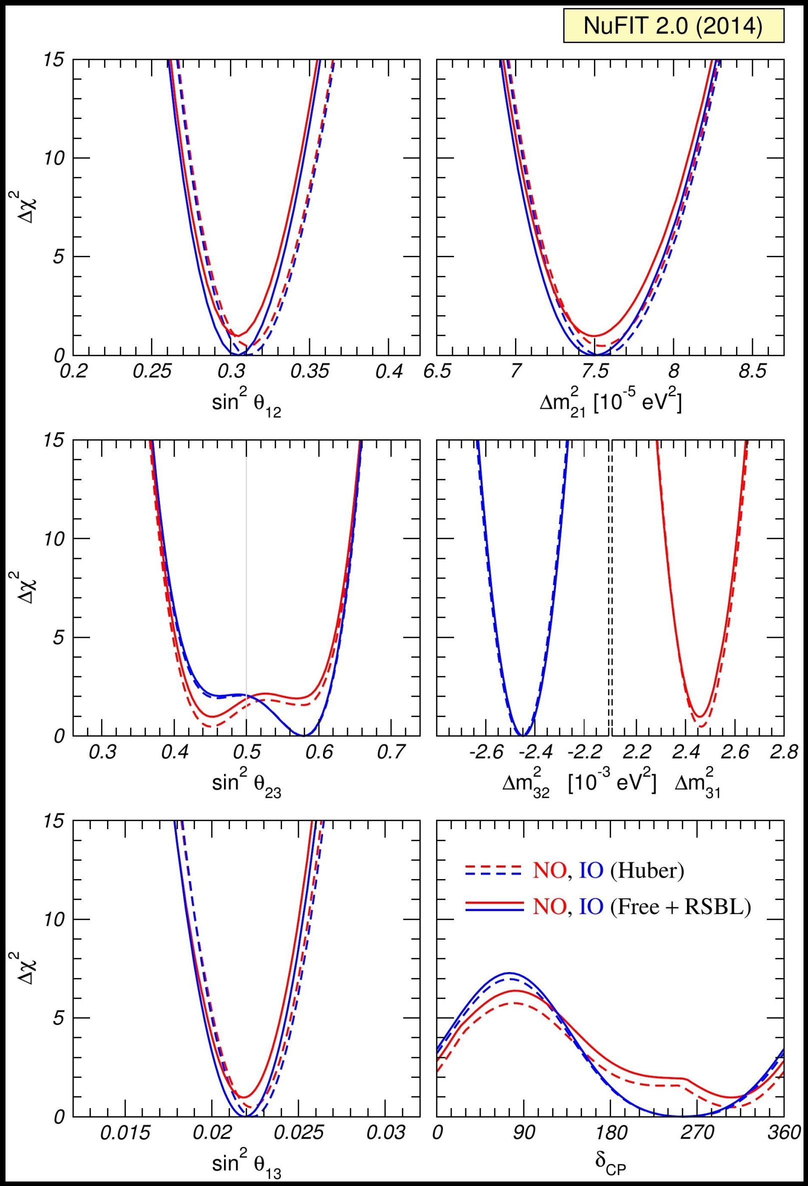
- Low energy thresholds gives superior L/E resolution
  - Fully reconstruct i
  - Low missing p_T in
- Good sensitivity t
- Combine with acc … sics measurements
- Sensitive to PMN
- Expect ~14k cont … d ν_μ- like events for a 350kt-yr exposure





The Current State of ν Oscillation Measurements

- PMNS matrix, factorized
- Numu → nue oscillation probability
- NuFit14 results

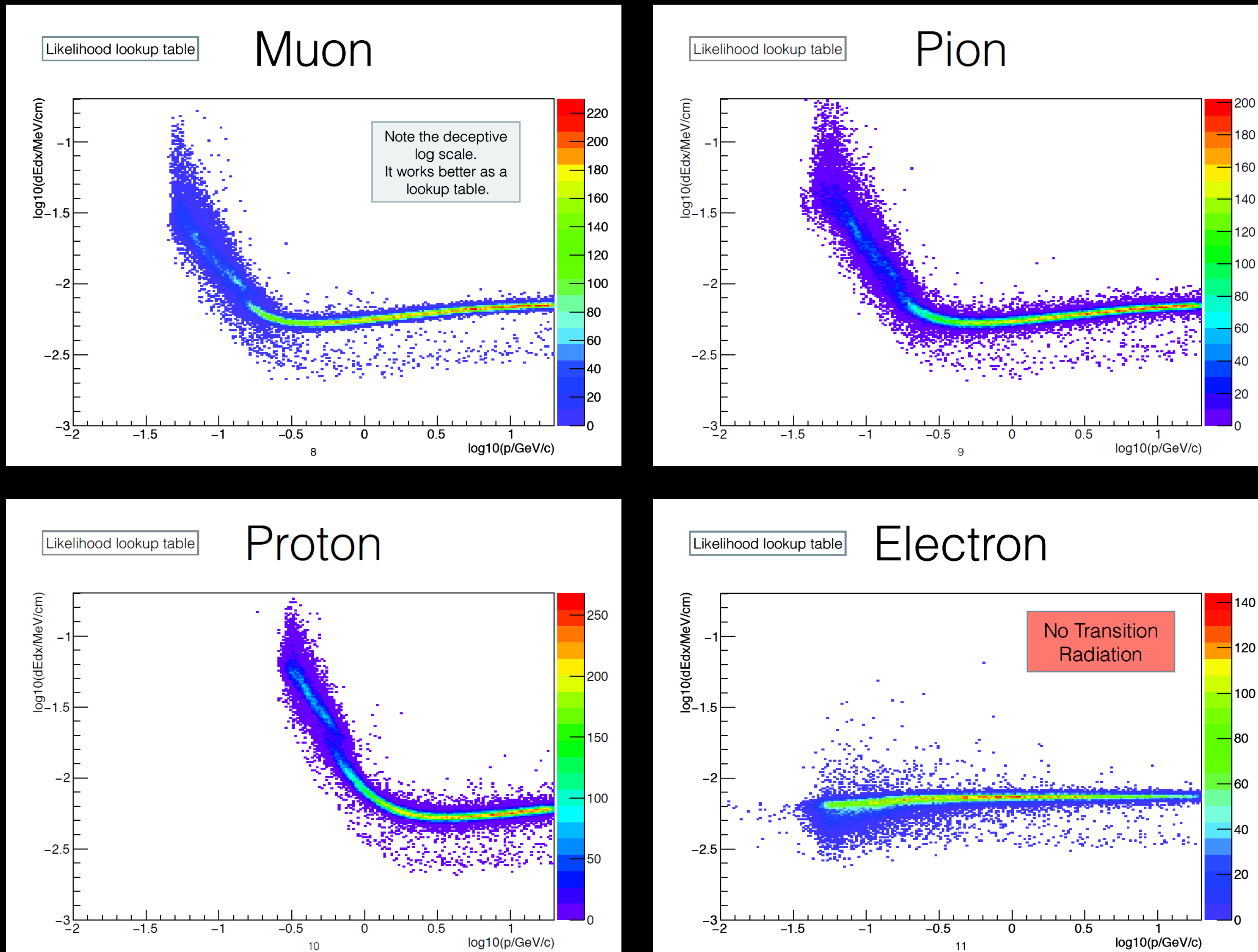


NuFit: http://www.nu-fit.org/?q=node/92

The Physics of DUNE:
Near Detector Physics

- The high resolution fine grained tracker (FGT) required for DUNE oscillation physics will allow for a multitude of ν and other weak interaction physics measurements
- High statistics with excellent particle ID and reconstruction will allow for World leading measurements
- Full phase space differential measurements from 4π coverage
- Precision cross section measurements of exclusive and inclusive channels, including many rare processes
- Variety of nuclear targets will help disentangle nuclear effects (both the nuclear initial state and final state interactions) from ν interaction physics
- Precision electroweak and isospin measurements
- Exotic physics searches including heavy sterile neutrinos, light dark matter searches, and large Δm^2 sterile ν oscillations

FGT dE/dx Profiles



VALOR DUNE: Final state samples

2016a (2nd pass-through)

- ν_μ **CC**
  1. 1-track QE enhanced (μ^- only)
  2. 2-track QE enhanced (μ^- + p)
  3. $1\pi^\pm$ ($\mu^- + 1\pi^\pm$ + X)
  4. $1\pi^0$ ($\mu^- + 1\pi^0$ + X)
  5. $1\pi^\pm + 1\pi^0$ ($\mu^- + 1\pi^\pm + 1\pi^0$ + X)
  6. Other
- **Wrong-sign** ν_μ **CC**
  7. Inclusive (μ^+ + X)
- ν_e **CC**
  8. Inclusive (e^- + X)
- **NC**
  9. Inclusive

FHC + RHC

2016b (3rd pass-through)

- ν_μ **CC**
  1. 1-track 0π (μ^- only)
  2. 2-track 0π (μ^- + nucleon)
  3. N-track 0π (μ^- + (>1) nucleons)
  4. 3-track Δ-enhanced ($\mu^- + \pi^+$ + p, with $W_{reco} \approx 1.2$ GeV)
  5. $1\pi^\pm$ ($\mu^- + 1\pi^\pm$ + X)
  6. $1\pi^0$ ($\mu^- + 1\pi^0$ + X)
  7. $1\pi^\pm + 1\pi^0$ ($\mu^- + 1\pi^\pm + 1\pi^0$ + X)
  8. Other
- **Wrong-sign** ν_μ **CC**
  9. 0π (μ^+ + X)
  10. $1\pi^\pm$ ($\mu^+ + \pi^\pm$ + X)
  11. $1\pi^0$ ($\mu^+ + \pi^0$ + X)
  12. Other
- ν_e **CC**
  13. 0π (e^- + X)
  14. $1\pi^\pm$ ($e^- + \pi^\pm$ + X)
  15. $1\pi^0$ ($e^- + \pi^0$ + X)
  16. Other
- **NC**
  17. 0π (nucleon(s))
  18. $1\pi^\pm$ ($\pi^\pm$ + X)
  19. $1\pi^0$ (π^0 + X)
  20. Other
- νe
  21. $\nu_e + e^-$ elastic
  22. Inverse muon decay $\bar{\nu}_e + e^- \rightarrow \mu^- + \bar{\nu}_\mu$

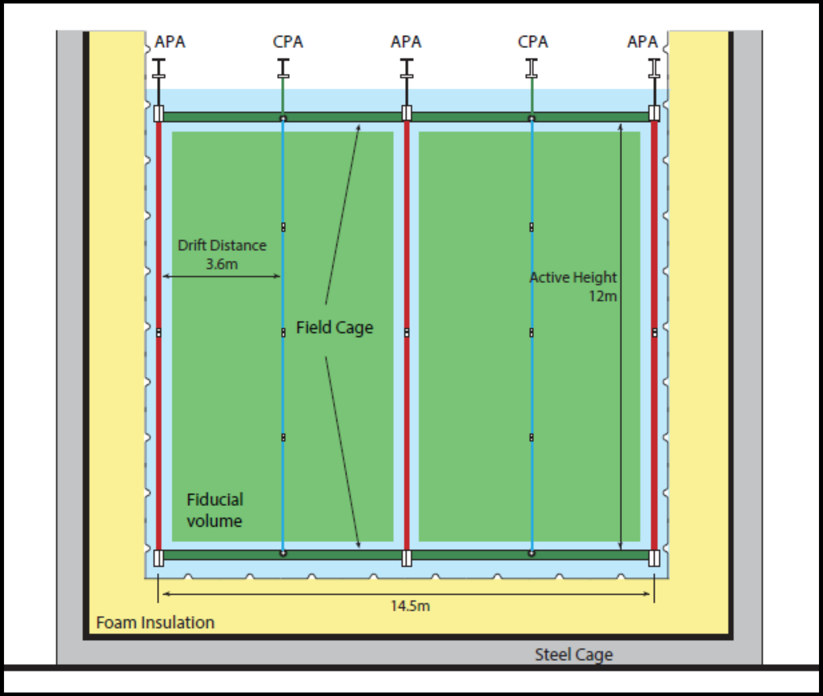
FHC + RHC

Lorena Escudero

Experimental Infrastructure:
The DUNE Far Detector

- Heart of a deep underground neutrino and nucleon decay observatory
- Liquid Argon (LAr) Time Projection Chamber (TPC) with a 40 kt fiducial mass
- Staged construction with the goal of the first 10 kt by 2021/22
- Two potential designs:

➔ Single phase
  - Current reference design
  - Based on ICARUS design
  - Horizontal drift ~3.6 m
  - Wire pitch of 5 mm
  - Detection and electronics in liquid
  - Modular approach
  - Well known cost and schedule



Experimental Infrastructure:
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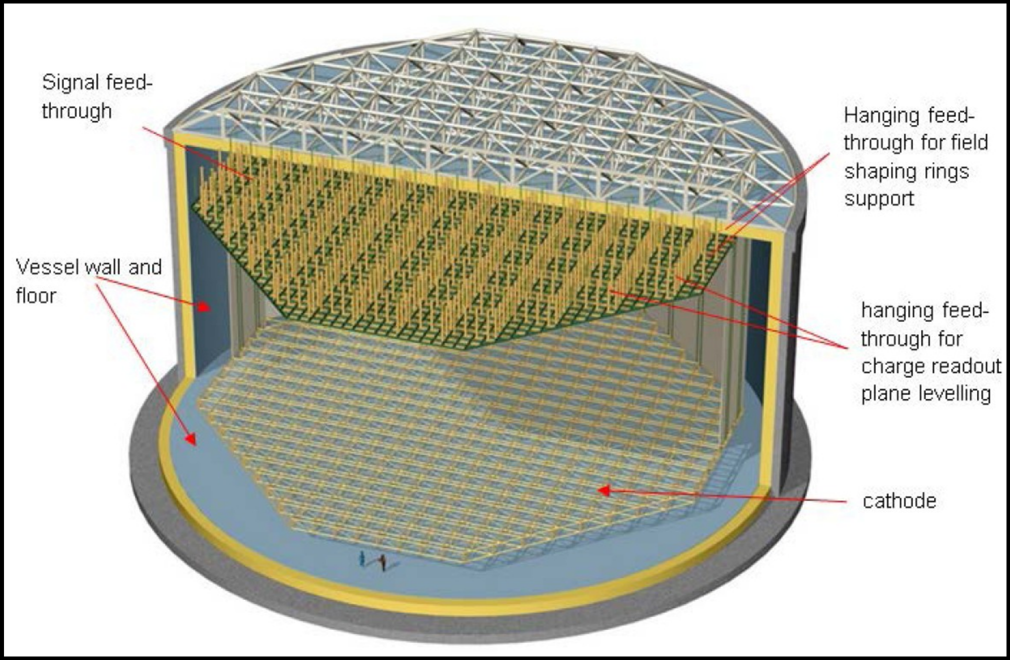


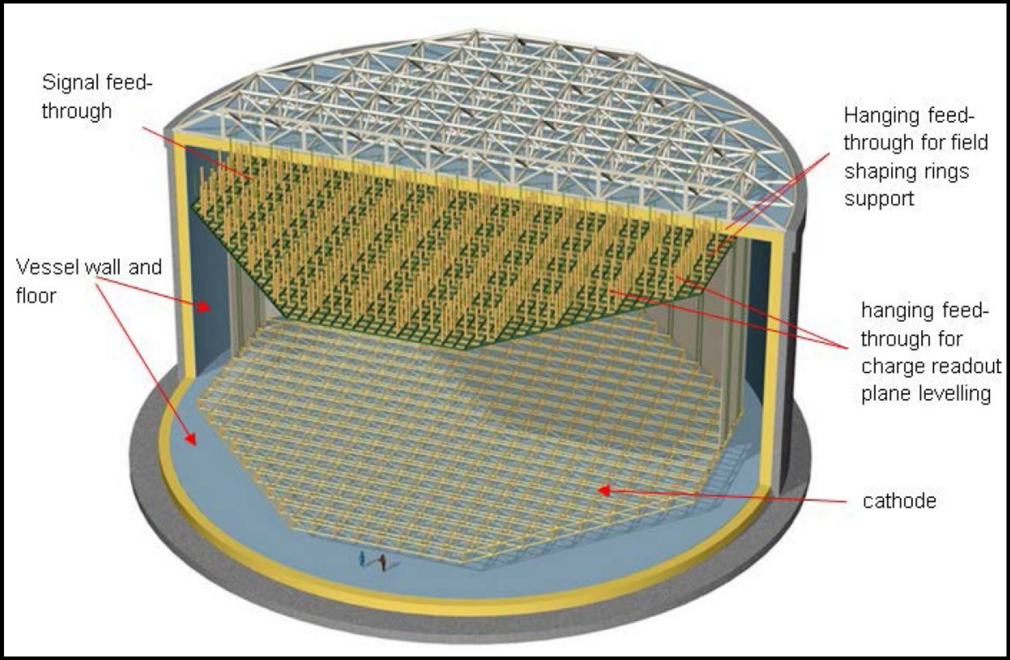
- Dual phase
  - Alternate design
  - New technique; signal amplification
  - Vertical drift ~10 - 20 m
  - Detection and electronics in gas
  - Adaptable to cryostat shape
  - Low thresholds, high S/N ratio
  - Pitch of 3 mm or less

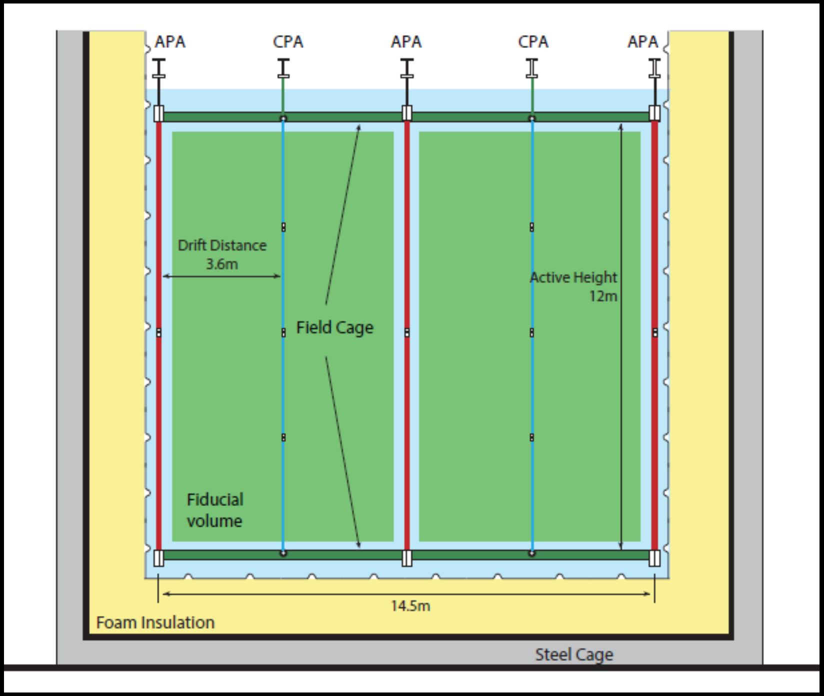
Experimental Infrastructure:
The DUNE Far Detector

- Heart of a deep underground neutrino and nucleon decay

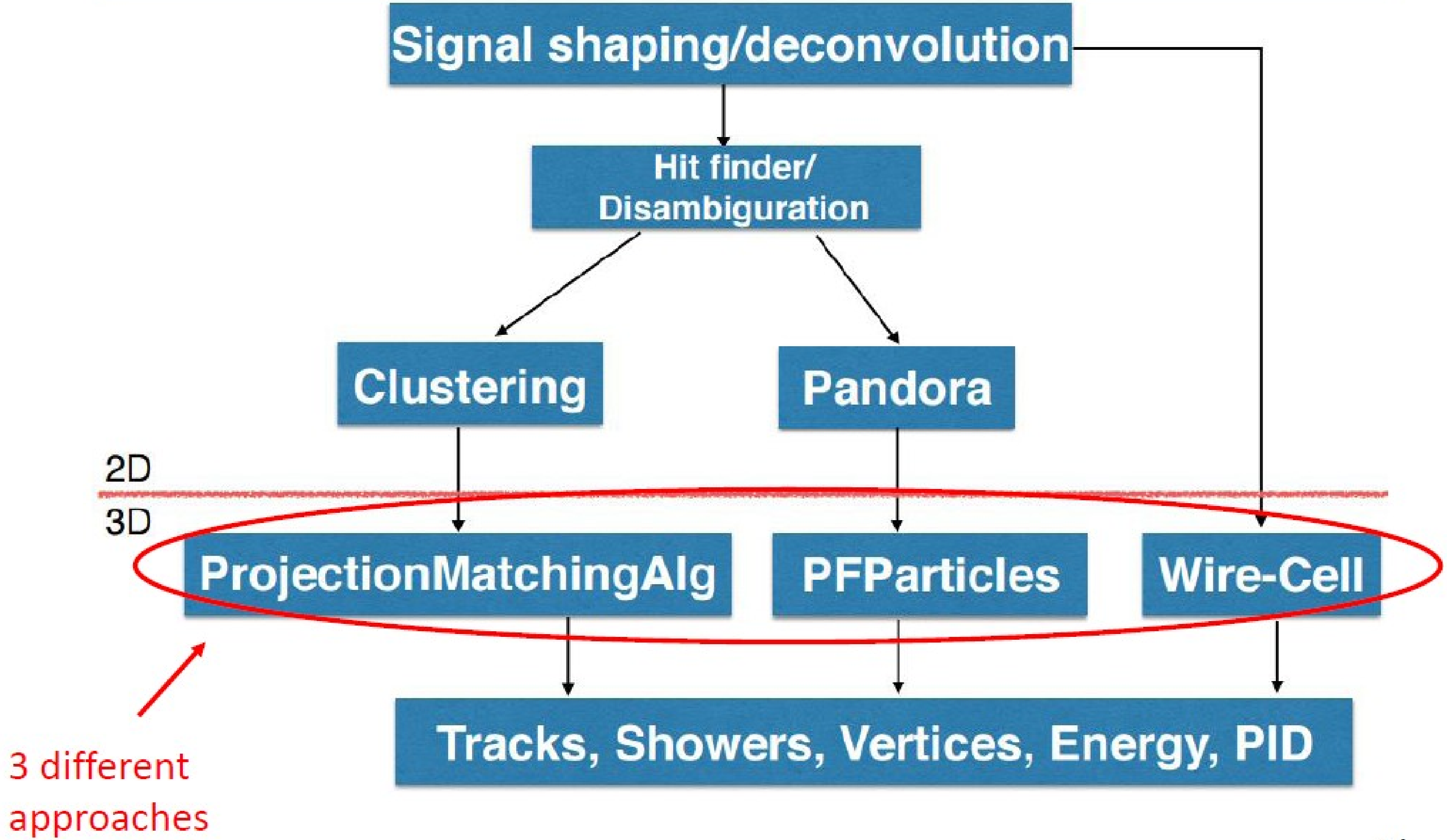
The CERN Neutrino Platform is working to build ~6 m^3 prototype detectors for both designs, and deploy them in CERN a charged particle test beam

- Two potential designs:



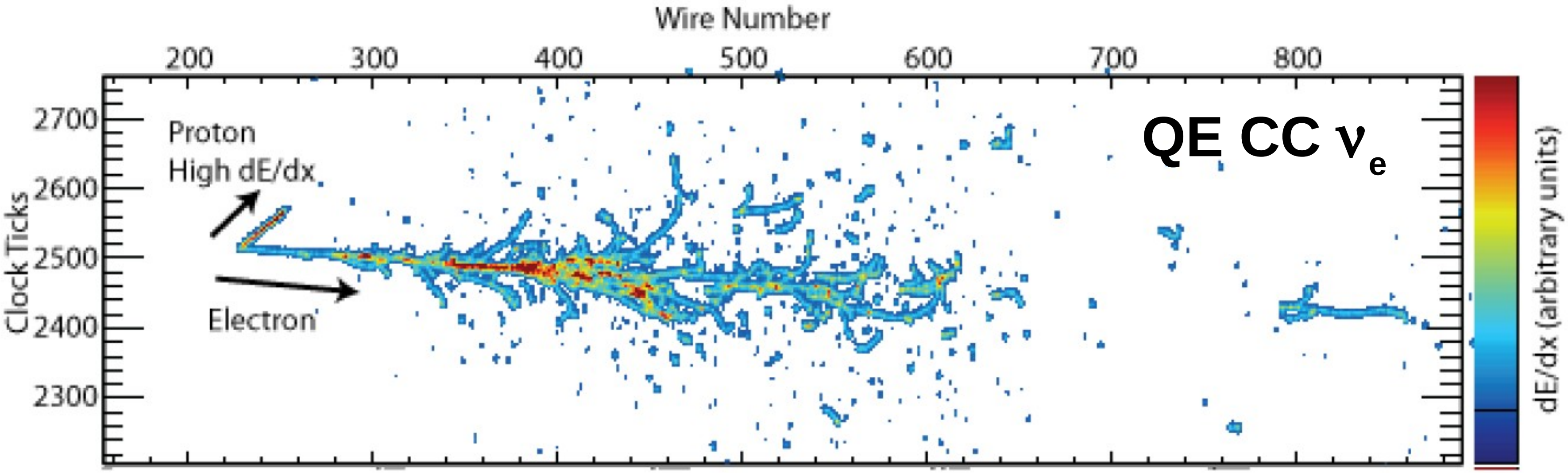


Reminder: Reconstruction Chain

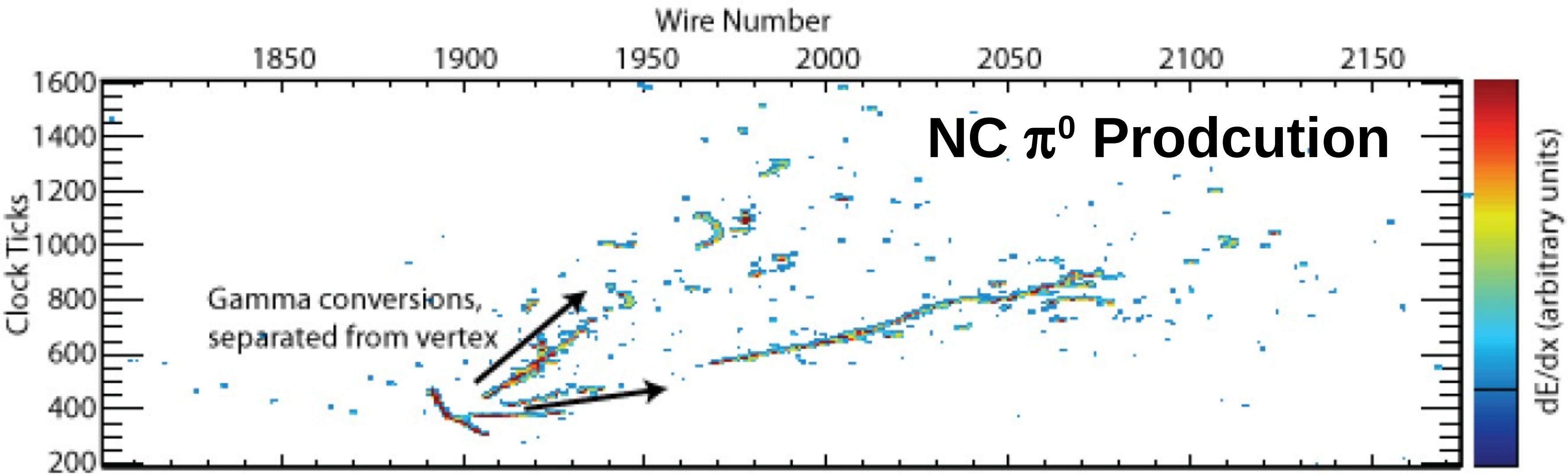


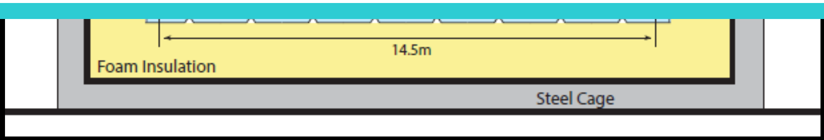
Tingjun Yang

Experimental Infrastructure:



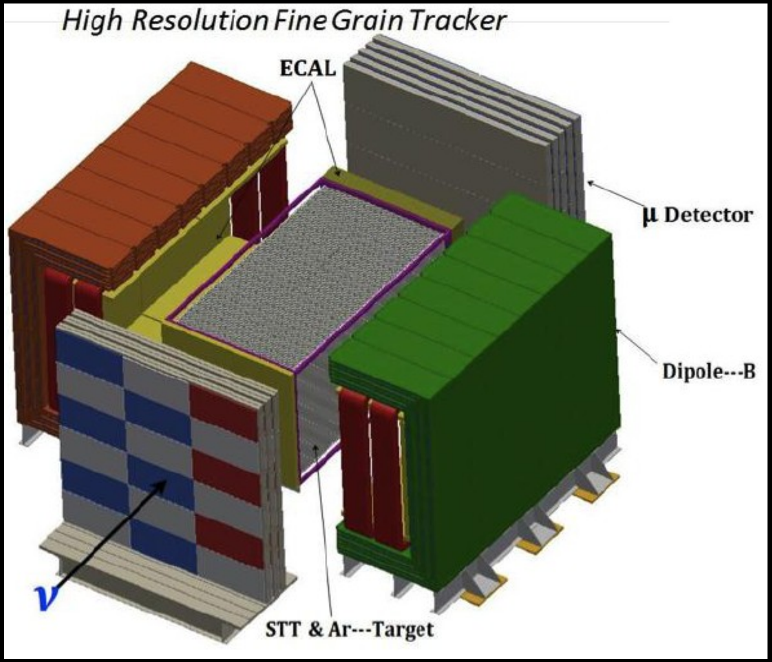
MicroBooNE simulation of ν interactions in a LArTPC

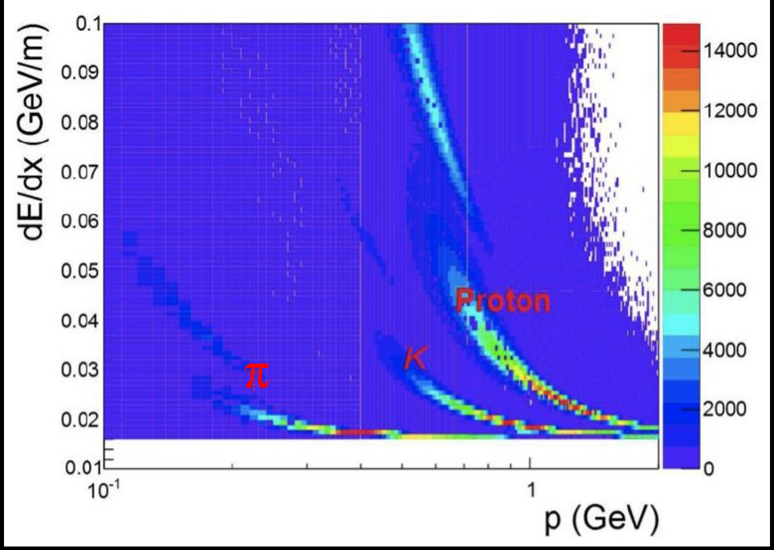




Experimental Infrastructure:
The DUNE Near Detector

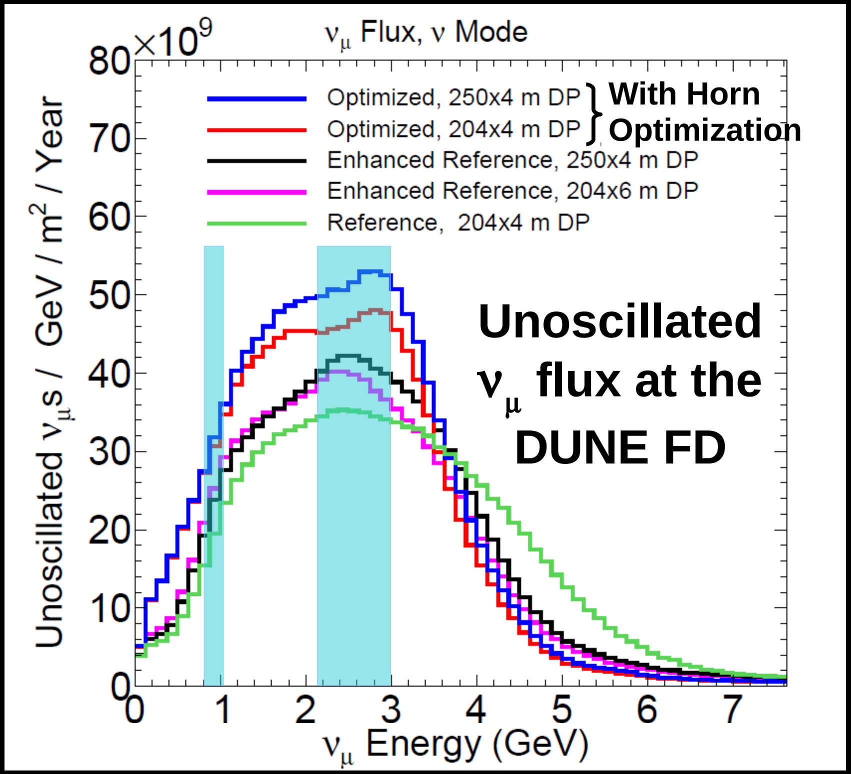
- Detector requirements
  - Constrain **flux rate and shape** to the few % level
  - Charge ($\nu/\bar{\nu}$) separation
  - Hadronic shower composition
    - Ar40 & Ca40 nuclei
    - $\nu/\bar{\nu}$ differences
  - Constrain relevant cross sections
  - Provide a wealth of physics measurements
- Detector Options
  - Fine Grained Tracker (reference)
  - LArTPC
  - High pressure GArTPC
  - Hybrid detector (ArTPC + FGT)





Experimental Infrastructure:
The FNAL → SURF Beam

- Beam requirements
  - 1.2 MW, upgradeable to 2.3 MW (120GeV protons):
    - POT/pulse: 7.5×10^{13} p
    - Cycle time: 1.2 sec
    - Uptime: 56%
  - Direction 5.8° downward
  - Wide-band spectrum covering the 1st and 2nd oscillation maxima
- Upgrades from reference design
  - PIPII: increase p throughput
  - Horn current: 200 kA → 230 kA
  - Target design: C → Be, shape
  - Decay Pipe: 204 m → 250 m
  - Horn design optimization



- Can use 60 - 80 GeV protons
  - Increase flux at 2nd max
  - Reduces high energy tail
  - Need more POT to maintain power

The Path to the Full Exposure

- A “Conceptual Design Review” is being held next month
- Goal: Install the first 10 kt underground on the 2021/22 timescale
  - Begin underground physics program, and engage collaboration
  - Test all aspects of the the underground installation and detector performance
  - Ready for beam physics program when beam turns on
- Remaining modules, up to 40 kt, installed in rapid succession
  - Initial 10 kt installation provides infrastructure for required conventional facilities
  - Opportunity for combination of multiple detector technologies
- Leverage intermediate neutrino program to inform design, and improve detector performance
- Construction of a fine grained near detector
- Collect beam data by 2024, and run for ~10 exposure-yr

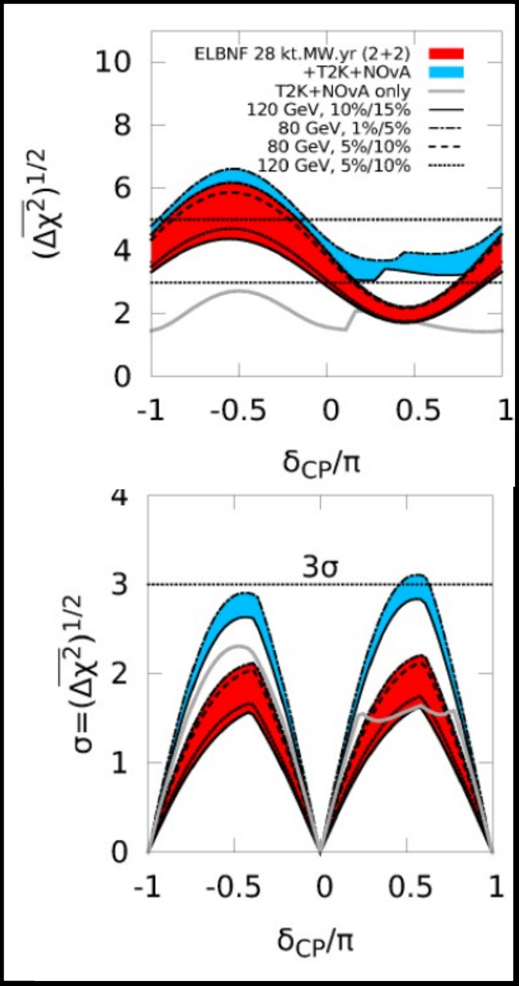
Input From the Intermediate ν Program

- In addition to the in-situ measurements from the beamline monitoring, and the DUNE ND and FD, many external measurements are required
- NA61/SHINE and MIPP will provide data for hadron production model tuning used in beamline simulations
- Electron scattering at JLab will provide data on the nuclear structure of Ar
- Test beam LArTPCs: CAPTAIN, LArIAT, ProtoDUNE (single & double phase)
  - High statistics data on detector response required for calibrations
  - Allows for in-situ tests of detector components and comparison of detector technologies
- LArTPCs in neutrino beams: MicroBooNE, SBND, and ICARUS
  - Test and refine reconstruction algorithms and calibration methods
  - Measure cross sections and nuclear effects on Ar40
- Other cross section experiments like Minerva and ND280 (T2K) will map out cross sections over a wide energy range and nuclear targets
- Neutrino event generator development and tuning

Physics with the First 10 kt*

*Assuming a 50 kt-yr exposure

- Baryon number violation
  - 50 kt-yr will competitive limits / signal events for $p \rightarrow K + \bar{\nu}$
  - Early measurements of background rates for other decay channels
- Core-collapse supernova neutrinos
  - Largest detector sensitive to ν_e via $\nu_e + Ar^{40} \rightarrow e + K^{*40}$
  - Prompt supernova alert due to early ν_e production
  - 100's to ~1,000 events at ~10 kpc
- Atmospheric neutrinos
  - Provide ~2500 ν_e CC events
  - Test reconstruction and allow for leptonic and hadronic energy scale calibrations
- Accelerator neutrino (right)
  - Expected events: ν_e 94±23, $\bar{\nu}_e$ 23±5 (NH, δ_{cp} = [$-\pi/2$, 0, $\pi/2$])
  - Improved MH sensitivity over NOνA+T2K, even better combined
  - CPV sensitivity commensurate with NOνA+T2K, better combined



Novel Features of the Experimental Design

- DUNE calls for unprecedented precision in a ν experiment
- Achieving this precision will require hard work, innovation, and a start-of-the-art experimental design
- LArTPCs allows for high resolution of final state particle 4-momenta
  - The resolution δ_{cp} largely limited by energy scale uncertainties which are limited by hadronic system reconstruction
  - Nearly background free to proton decay searches
  - Access to ν_e flux from supernovas
- The DUNE FGT ND