Status/Preview of the Physics Volume of the DUNE TDR

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What we aim to convey

- **The Physics TDR should present the science opportunities for which DUNE has been developed, and describe its capabilities to realize them**

- **Presentation of capabilities is ideally based on realistic treatments of:**
  - **Physics signatures** (including, *e.g.*, neutrino interaction modeling)
  - Properties of the **LBNF beam line** (flux…)
  - **Detector response** (signal characteristics, noise, calibration, *etc.*)
  - **Event reconstruction & performance** (tracking, calorimetry, particle ID, *etc.*)
  - **Experimental challenges**: backgrounds, systematic error sources, *etc.*

- **In practice, many elements above are under active development**
  - For primary science goals, insisting on ~fully realistic analyses…
  - …so for these, must also convey the provisional nature of current analyses.

Top Level Outline – target: ~25 pages/chapter

1. Executive Summary
2. Introduction to LBNF and DUNE
3. Scientific Landscape
4. Tools and Methods Employed
5. Neutrino Oscillation Physics Program
6. GeV-scale Non-accelerator Physics Program
7. Supernova Neutrino Bursts and Physics with Low-Energy Neutrinos
8. Precision Physics with the Near Detector
9. Beyond Standard Model Physics
10. Summary/Outlook

What we have as of Dec 1 (“1st Draft” deadline)

1. Executive Summary
2. Introduction to LBNF and DUNE
3. Scientific Landscape
4. **Tools and Methods Employed** ***(27 pages + 12 for calibration)***
5. **Neutrino Oscillation Physics Program** ***(55 pages)***
6. **GeV-scale Non-accelerator Physics Program** ***(17 pages)***
7. **Supernova Neutrino Bursts and Physics with Low-Energy Neutrinos** ***(25 pages)***
8. Precision Physics with the Near Detector
9. **Beyond Standard Model Physics** ***(42 pages)***
10. Summary/Outlook

Going through these chapters

- **Start with "most advanced" ones**
  - Tools and Methods Employed
  - Supernova / Low-energy Neutrinos
  - Beyond Standard Model Physics

- **Then onto chapters where full analyses are in progress**
  - Long-Baseline Oscillation Physics (3-flavor oscillations of beam neutrinos)
  - GeV-Scale Non-accelerator Physics (Nucleon decay, atmospheric neutrinos, etc)

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Chapter 4: Tools and Methods Employed

- **Current status:**
  - Basic elements of DUNE simulations & reconstruction are well described
  - Separate discussion of calibration strategy is written, ready to be incorporated
- **What needs to be done for 2nd draft**
  - **Reco/Sim Working Group focus is now on generating/updating high-level performance plots;**
  - **Need to make level of technical detail more uniform**
    - Too much in some places, too little in others
  - **Work needed to integrate better within this chapter & with other chapters**
    - This will allow filling in of some “missing” content (i.e., flux modeling, trigger simulation..)
  - **Possibility of inclusion of some ProtoDUNE-SP data**

Chapter 4: Tools and Methods Employed

is track-like or shower-like. A 3D vertex position is calculated for each of the reconstructed particles in the hierarchy, based on the point of closest approach between parent and daughter particles.

1.2.7.3 Performance

The performance of the Pandora pattern recognition is assessed by matching reconstructed PFParticles to the simulated Monte Carlo Particles (MCParticles). These matches are used to evaluate the efficiency with which MCParticles are reconstructed as PFParticles, and to calculate the completeness and purity of each reconstructed PFParticle.

The following procedure is used to match reconstructed PFParticles with simulated MCParticles:

- **Selection of MCParticles:** The full hierarchy of true particles is extracted from the simulated neutrino interaction. A list of "target" particles is then compiled by navigating through this hierarchy and selecting the final-state "visible" particles (allowed to be: $e^{\pm}$, $\mu^{\pm}$, γ, $\pi^{\pm}$, $\kappa^{\pm}$, p). Any downstream daughter particles are folded in these target particles.
- **Matching of Reconstructed 2D Hits to MCParticles:** Each reconstructed 2D hit is matched to the target MCParticle responsible for depositing the most energy within the region of space covered by the hit. The collection of 2D hits matched to each target MCParticle is known as its "true hits".
- **Matching of MCParticles to reconstructed PFParticles:** The reconstructed PFParticles are matched to target MCParticles by analysing their shared 2D hits. A PFParticle and MCParticle will be matched if the MCParticle contributes the most hits to the PFParticle, and if the PFParticle contains the the largest collection of hits from the MCParticle. The matching procedure is iterative, such that once each set of matched particles has been identified, these PFParticles and MCParticles are removed from consideration when making the next set of matches.

Using the output of this matching scheme, the following performance metrics can be calculated:

- **Efficiency:** Fraction of MCParticles with a matched PFParticle.
- **Completeness:** The fraction of 2D hits in a MCParticle that are shared with its matched reconstructed PFParticle.
- **Purity:** The fraction of 2D hits in a PFParticle that are shared with its matched MCParticle.

The performance of the Pandora pattern recognition has been evaluated using a sample of accelerator neutrino interactions simulated using the reference DUNE neutrino energy spectrum and the 10 kton Far Detector geometry.

Figure 1.7 shows the reconstruction efficiency as a function of the number of true 2D hits for a range

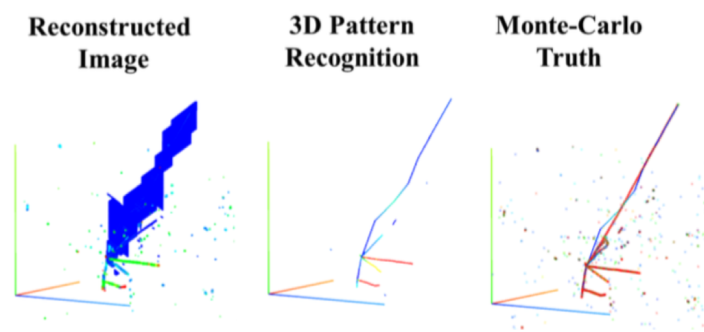

Figure 1.13: The reconstructed image is shown on the left panel for one neutrino interaction event. The image was passed through the 3D pattern recognition program with tracks identified (middle panel). The identified pattern is compared with Monte-Carlo truth (right panel).

merged cells and the merged wires. This equation can be expanded into a chi-square function:

$$\chi^2 = (B \cdot W - G \cdot C)^T V_{BW}^{-1} (B \cdot W - G \cdot C), \tag{1.11}$$

which also takes into account the uncertainties of the measured charge in wires. In particular, $V_{BW} \equiv B \cdot V_W \cdot B^T$ is the covariance matrix describing the uncertainty in (merged) wire charges.

The minimum of the above chi-square function can be found by calculating the first derivative

$$\frac{\partial \chi^2}{\partial C} = 0 \rightarrow G^T V_{BW}^{-1} (B \cdot W - G \cdot C) + (B \cdot W - G \cdot C)^T V_{BW}^{-1} G = 0, \tag{1.12}$$

and the solution can be written as:

$$C = \left(G^T \cdot V_{BW}^{-1} \cdot G\right)^{-1} \cdot G^T \cdot V_{BW}^{-1} \cdot B \cdot W. \tag{1.13}$$

The core of the Eq. (1.13) is the inversion of the matrix $G^T \cdot V_{BW}^{-1} \cdot G$, which will be referred to as M. When this matrix can be inverted, the charge of merged cells can be derived directly. For faked hits (merged cells without any ionization charge), the derived charge is likely to be close to zero. For real hits (merged cells with ionization charge), the derived charge is like to be large and close to the actual true value. On the other hand, if this matrix can not be inverted, additional assumptions and more advanced techniques are needed to derive the solution. The details of these techniques are beyond the current scope of technote, and will be added in the future.

Chapter 7: Supernova/Low-Energy Neutrinos

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Chapter 7: Supernova/Low-Energy Neutrinos

- **Current Status:**
  - Main analyses are based on combination of simulated/parametrized detector response simulation (including impacts of de-excitation gamma & nucleon emission) with dedicated reconstruction studies
  - Key Physics Results in hand:
    - neutronization-burst mass-ordering sensitivity study
    - thermal parameter sensitivity study.
    - pointing capability for elastic scattering events ($\nu_e + e \rightarrow \nu_e + e$)
  - Text for chapter not complete yet, but getting close.

- **What needs to be done for 2nd draft**
  - **Addition of missing material (imminent)**
  - **More coordination with Tools and Scientific Landscape chapters.**

Chapter 7: Supernova/Low-Energy Neutrinos

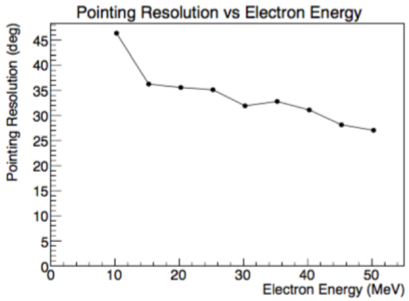


Figure 7.6: Pointing resolution for single electron events versus electron energy.

coordinates in DUNE's time projection chambers (TPCs), it is not known which end of a track was created first. The values near -1 correspond to events with tracks reconstructed backwards relative to the true direction. We are exploring possibilities for resolving this ambiguity, for example by using the directionality of Compton scatters from bremsstrahlung gammas with respect

The pointing resolution is defined in this study as the angle at which 68% of angular differences are closer to truth. The pointing resolutions for single electrons were calculated from the absolute value distributions of cosines of angular differences, such as in Figure **??**, and plotted as a function of energy, as shown in Figure 7.6.

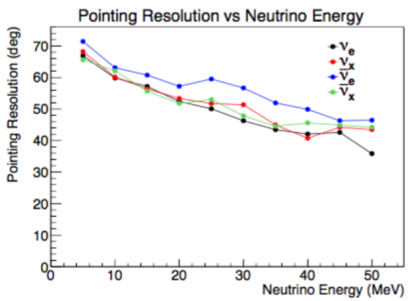
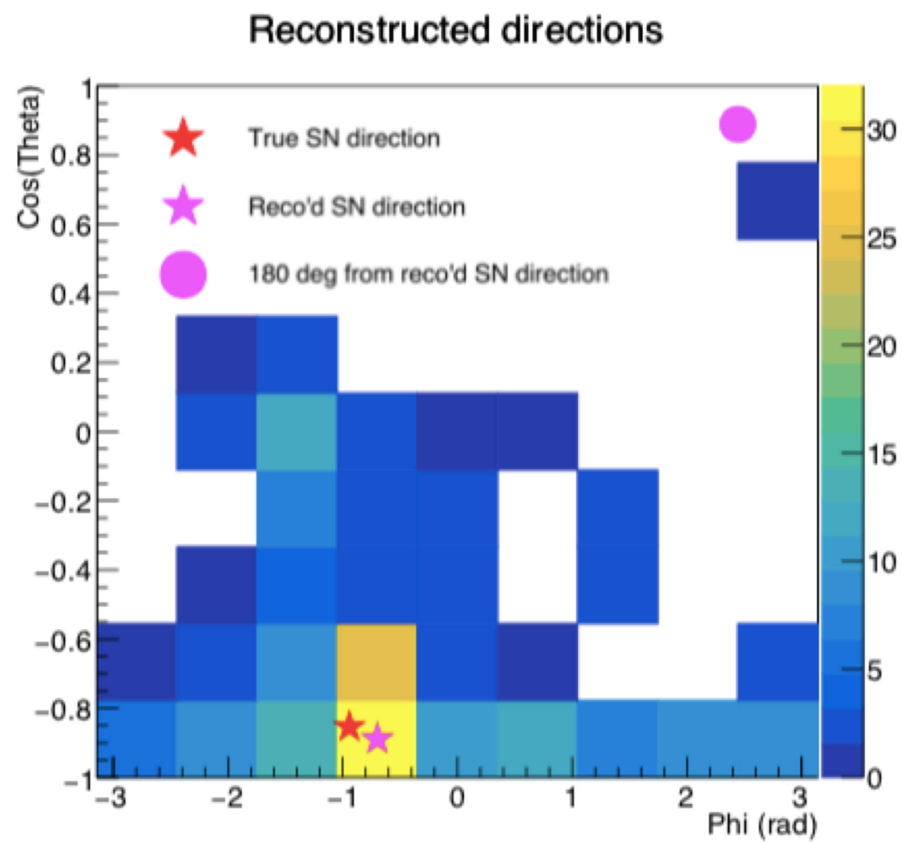


Figure 7.7: Pointing resolution of elastic scattering events versus neutrino energy for each neutrino flavor.

The angular distribution for scattering of electron neutrinos with electrons is given by



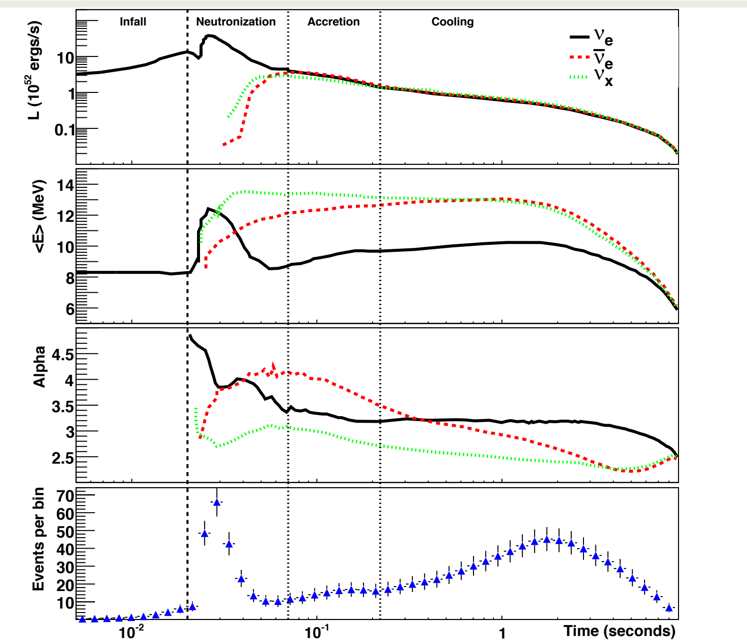
Realistic reconstruction of SN direction using 260 fully simulated elastic scattering events (expected sample for SN at 10 kpc), after resolving electron direction ambiguity by majority rule…

Chapter 7: Supernova/Low-Energy Neutrinos

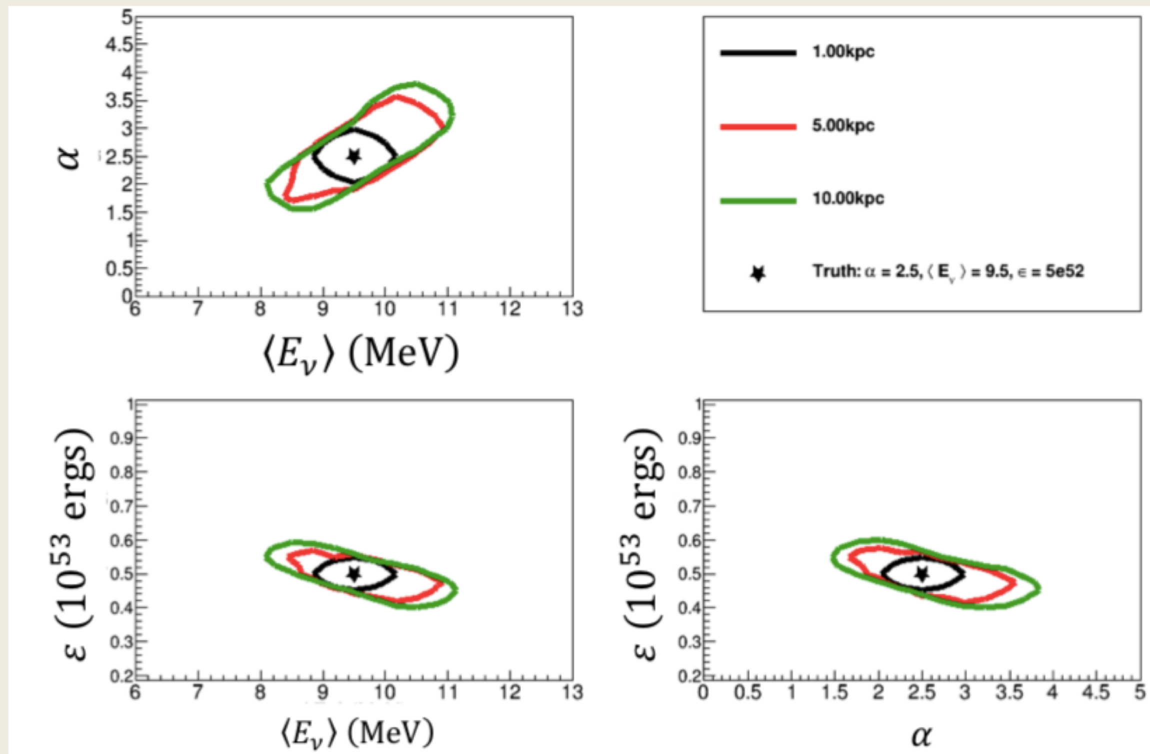
$$\phi(E_\nu) = \mathcal{N}\left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^{\alpha} \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu\rangle}\right]$$

- E_ν: Neutrino energy
- $\mathcal{N}$: Normalization constant (related to luminosity, ϵ)
- $\langle E_\nu\rangle$: Mean neutrino energy
- α: Pinching parameter; large α corresponds to more pinched spectrum

Results from fits of the observed spectrum to “pinched-thermal” form ready for inclusion, but not in TDR draft yet…



Thermal parameters vs time from “Garching Model”



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Chapter 9: Beyond Standard Model Physics

- **Current Status:**
  - Analyses are based mainly on parametrized detector response simulation, utilizing GLoBES framework.
  - Many Key Physics Results in hand:
    - distortions of oscillation patterns in Far Detector due to BSM phenomena including NSI’s, non-unitarity, CPT symmetry violation;
    - boosted Dark Matter signatures from cosmic sources;
    - studies of neutrino ”tridents” in the Near Detector.
  - Other analyses nearly complete but dealing with issues pertaining to Near Detector configuration and its use in constraining systematic errors
    - e.g., beam-induced light DM particle searches, sensitivity to sterile neutrinos
  - Text for chapter is essentially complete

- **What needs to be done for 2nd draft**
  - **Need final numbers/plots for several analyses**
  - **More coordination with Tools and other physics chapters.**

Chapter 9: Beyond Standard Model Physics

The right panel of figure 1.6 reports model-dependent sensitivities for $\bar{\ell}^{\rm max}_{\rm lab} = 0$ m and 100 m corresponding to the experiments in the left panel. Note that this way of presentation is reminiscent of the widely known scheme for showing the experimental reaches in various DM direct detection experiments, i.e., $m_{\rm DM} - \sigma_{\rm DM-target}$ where $m_{\rm DM}$ is the mass of DM and $\sigma_{\rm DM-target}$ is the cross section between the DM and target. For the case of non-relativistic DM scattering in the direct detection experiments, $m_{\rm DM}$ determines the kinetic energy scale of the incoming DM, just like m_{χ_0} sets out the incoming energy of boosted χ_1 in the iBDM search.

1.4.4 Discussions and Conclusions

In this work, we have conducted simulation studies of the light dark matter model described in eq. (1.1) in terms of their detection prospects at the DUNE near and far detectors.

In the case of the ND, we assumed that the relativistic DM is being produced directly at the target (i.e., intensity-frontier approach) and leaves an experimental signature through an elastic electron scattering. Using two constrained parameters of the light DM model and a range of two free parameters, a sensitivity map was produced. Within the context of the vector portal DM model and the chosen parameter constraints along with the electron scattering as the signal event, this result sets the stringent limits on DM parameters which are comparable or even better than recent experimental bounds in the sub-GeV mass range.

By contrast, in the case of FDs, we assumed that the signal events are due to DM coming from

the galactic halo (i.e., cosmic-frontier approach) with a significant boost factor. The DM scatters off either electron or proton in the detector material into a heavier unstable dark-sector state (i.e., *in*elastic scattering). The heavier state, by construction, decays back to DM and an electron-positron pair via a dark photon exchange. Therefore, in the final state, a signal event comes with an electron or proton recoil plus an electron-positron pair. This distinctive signal feature enabled us to perform (almost) background-free analyses. As ProtoDUNE detectors are prototypes of DUNE FDs, the same study was conducted and corresponding results were compared with the ones of the DUNE FDs. We first investigated the experimental sensitivity in a dark photon parameter space, dark photon mass m_V versus kinetic mixing parameter ϵ. The results were shown separately for Scenario 1 and 2. They suggested that ProtoDUNE and DUNE FDs would probe a broad range of unexplored regions; they would allow for reaching $\sim 1-2$ orders of magnitude smaller ϵ values than the current limits along MeV to sub-GeV-range dark photon. We also examined model-independent reaches at both ProtoDUNE detectors and DUNE FDs, providing limits for models conceiving iBDM (or iBDM-like) signals (i.e., a target recoil and a fermion pair).

1.5 Sterile Neutrino Searches

Experimental results in tension with the three-neutrino-flavor paradigm [1, 30, 31, 32], which may be interpreted as mixing between the known active neutrinos and one or more *sterile* states, have led to a rich and diverse program of searches for oscillations into sterile neutrinos. Having a longer baseline, a more intense beam, and a high-resolution large-mass Far detector, when compared to previous experiments, DUNE provides a unique opportunity to improve significantly on the sensitivities of existing probes, and to enhance the ability to map the extended parameter space if a sterile neutrino is discovered.

NSI parameters, and a fit is then attempted assuming no NSI. If the fit is incompatible with the simulated data at a given confidence level, the chosen *true* values of the NSI parameters are considered to be within the experimental discovery reach.

In this analysis, we use GLoBES with the Monte Carlo Utility Based Experiment Simulator (MonteCUBES) C library [75], a plugin that replaces the deterministic GLoBES minimizer by a Markov Chain Monte Carlo (MCMC) method that is able to handle higher dimensional parameter spaces. In the simulations we use the configuration for the DUNE CDR [21]. Each point scanned by the MCMC is stored and a frequentist χ^2 analysis is performed with the results.

Considering that NSI exists, conducting the analysis with all the NSI parameters free to vary, we obtain the sensitivity regions in figure 1.16. We omit the superscript m that appears in equation 1.19. The credible regions are given in terms of percent Confidence Level (CL). We note,

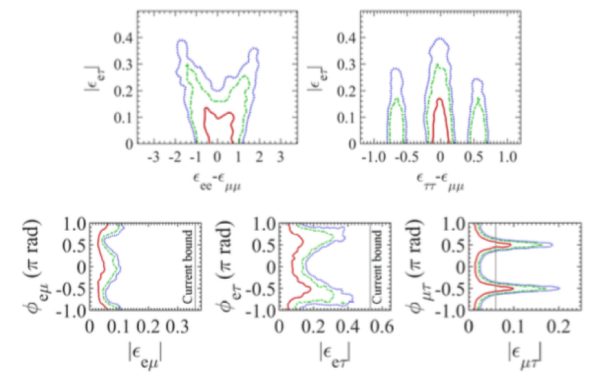

Figure 1.16: Allowed regions of the non-standard oscillation parameters in which we see important degeneracies (top) and the complex non-diagonal ones (bottom). We conduct the analysis considering all the NSI parameters non-negligible. The sensitivity regions are for 68% (red line (left)), 90% (green dashed line (middle)), and 95% CL (blue dotted line (right)). Current bounds are taken from [76].

however, that constraints on $\epsilon_{\tau\tau} - \epsilon_{\mu\mu}$ coming from global fit analysis [76, 66, 67, 77] can remove the left and right solutions of $\epsilon_{\tau\tau} - \epsilon_{\mu\mu}$ in figure 1.16.

In order to constrain the standard oscillation parameters when NSI is present, we use the fit for three neutrino mixing from [76] and implement prior constraints to restrict the region sampled by the MCMC. The sampling of the parameter space is explained in [64] and the priors that we use can be found in table 1.6.

Then we can observe the effects of NSI on the measurements of the standard oscillation parameters at DUNE. In figure 1.17, we superpose the allowed regions with non-negligible NSI and the

Going through these chapters

- Start with "most advanced" ones
  - Tools and Methods Employed
  - Supernova / Low-energy Neutrinos
  - Beyond Standard Model Physics

- Then onto chapters where full analyses are in progress
  - Long-Baseline Oscillation Physics (3-flavor oscillations of beam neutrinos)
  - GeV-Scale Non-accelerator Physics (Nucleon decay, atmospheric neutrinos, etc)

Chapter 4: Long-Baseline Oscillation Physics

- First, a reminder of CDR-era sensitivity projections (from IDR)
  - Analysis was based on parameterized detector response

Table 2.1: The exposure in mass (kt) × proton beam power (MW) × time (years) and calendar years assuming the staging plan described in this chapter needed to reach certain oscillation physics milestones. The numbers are for normal hierarchy using the NuFit 2016 best fit values of the known oscillation parameters.

Physics milestone	Exposure (kt · MW · year)	Exposure (years)
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	29	1
CPV at 3σ ($\delta_{CP} = -\pi/2$)	77	3
MH at 5σ (worst point)	209	6
10° δ_{CP} resolution ($\delta_{CP} = 0$)	252	6.5
CPV at 5σ ($\delta_{CP} = -\pi/2$)	253	6.5
CPV at 5σ 50% of δ_{CP}	483	9
CPV at 3σ 75% of δ_{CP}	775	12.5
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	857	13.5

- We are aiming to provide an updated version of these projections
  - But with fully realistic analysis, including direct incorporation of ND data

Chapter 4: Long-Baseline Oscillation Physics

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Chapter 4: Long-Baseline Oscillation Physics

- **Current Status:**
  - Chapter has well-defined structure; writing assignments clearly distributed.
  - Lots of descriptive text in place. Very detailed.
  - Presentations to LBNC in May & October demonstrated the substantial progress toward a "fully realistic" analysis, with benchmark results meeting/exceeding expectations.
  - But a fully realistic analysis aiming for well justified projections of sensitivity – including systematic errors – is a complex undertaking with lots of moving parts, including integrated analysis with Near Detector elements.
    - See presentations by C. Marshall & M. Wilking at October LBNC meeting.
  - This ambitious push for our most prominent Physics Program element will continue on into January (at least)

- **What needs to be done for 2nd draft**
  - **Need (close-to) final numbers, plots, and discussion**
  - **More coordination with Tools and Landscape chapters**

Chapter 5: GeV-Scale Non-accelerator Physics

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Chapter 5: GeV-Scale Non-accelerator Physics

- **Current Status:**
  - Main focus is on nucleon decay, one of our primary science goals, with fully realistic analysis.
    - Emphasis on marquee Proton → K+ nu channel; progress toward high efficiency while maintaining zero background face substantial event reconstruction challenges, especially considering impact of Final State Interactions; work ongoing.
    - Simultaneous progress on other channels (such as n → K+ e), now incorporated into the text
  - N-Nbar oscillation physics analysis is complete;
  - more work needed to bring atmospheric neutrino analysis to appropriate level for presentation, but much text already in place.

- **What needs to be done for 2nd draft**
  - **Need to reach endpoint on "fully realistic" nucleon decay analyses.**
  - **More coordination with Tools and other Landscape chapters.**

Wrap-up: Other Chapters & Next Stages

- **Introductory Chapters (Executive Summary, DUNE Overview, Scientific Landscape) remain in early stages. Authors assigned to most sections, working.**

- **Near Detector Physics Chapter**
  - Would like to have this
  - Content will likely focus more on "opportunities" than "capabilities"
  - Some starter text in place, but clearly needs development
  - Coupling to ND CDR as well as ND Summary in TDR Volume I

- **Linking of detector specifications to physics goals**
  - Editors will be working with chapter authors to incorporate more explicitly.

- **For 2nd Draft, we are working toward (but don't guarantee)**
  - Mostly complete, mostly readable chapters
  - Unified level of detail appropriate for TDR (maybe relegate material to appendices)
  - But please expect some rough spots: complex physics, complex analyses !!