DEEP UNDERGROUND
NEUTRINO EXPERIMENT

University of CINCINNATI

CAFAna Sterile Analysis Updates & Plans

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DUNE BSM Meeting

4/26/2022

CAFAna-Based Sterile Analysis

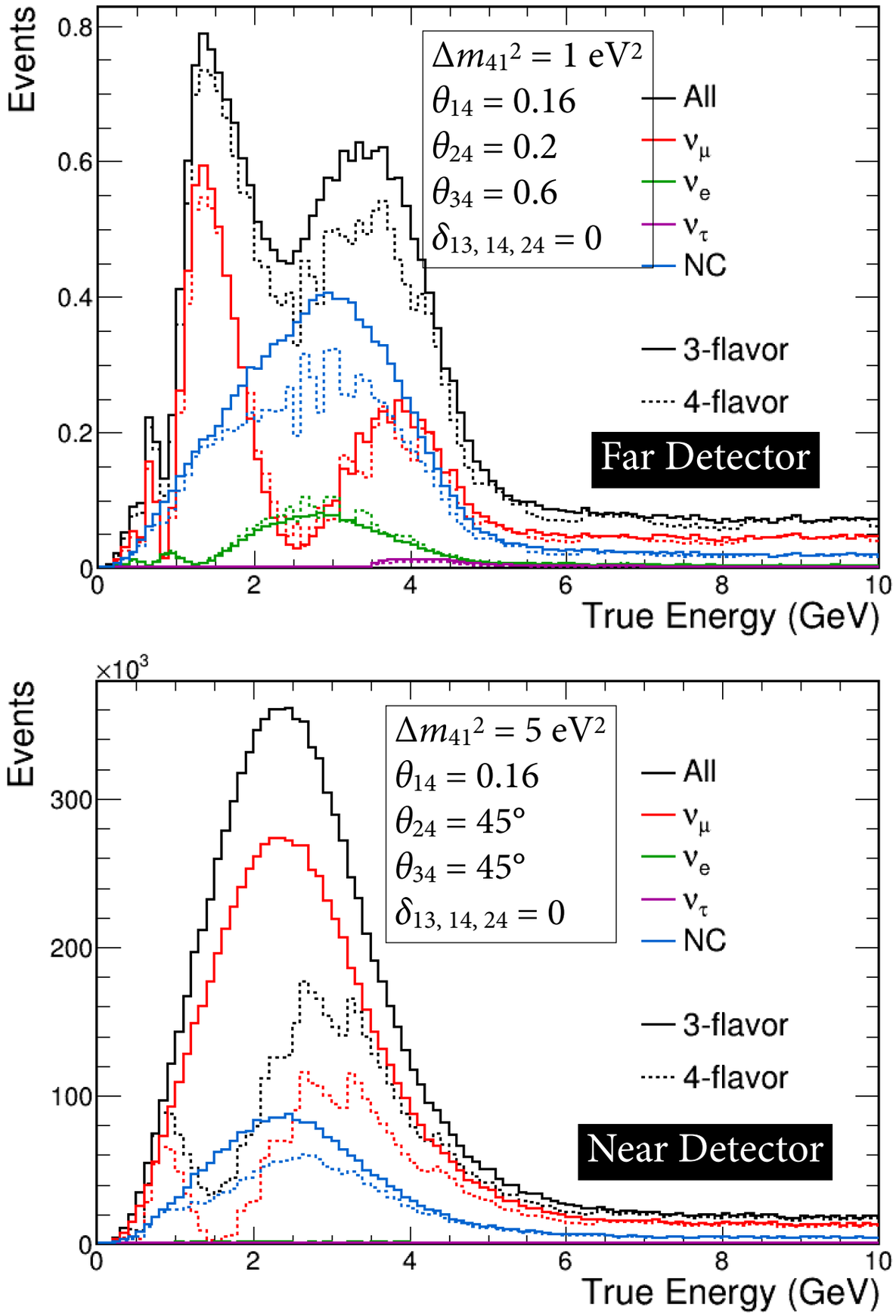
- The first DUNE sterile/LED analysis uses the GLoBES framework.
  - Inclusion of shape systematics in GLoBES is challenging.
  - Aiming to complete analysis with improved systematics over FD TDR results soon.

- In parallel, we are developing a sterile analysis in the CAFAna framework.
  - CAFAna was developed for NOvA analyses and used by the LBL group for the DUNE TDR studies.
  - Designed, among other things, to allow a simpler implementation of systematics uncertainties and to be a unified framework for all analyses.
  - Utilizes a standard data format, CAF (Common Analysis Format/File).

- NOvA has completed multiple sterile searches using CAFAna-based analyses, which contain portable software for similar analyses in DUNE.
  - Working on transitioning analysis to DUNE, using the DUNE-CAFAna framework.

CAFAna Development

- Developed the DUNE CAFAna framework to provide BSM oscillations (including NC-disappearance, ND oscillations) and confirmed the oscillation calculator works with sterile oscillations (3+1 specifically).
  - Previous update: https://indico.fnal.gov/event/46502/contributions/206939/
- With this machinery in place, we are moving on to develop the fitting and parameter extraction framework to reproduce the full sterile analysis.



PISCES Development

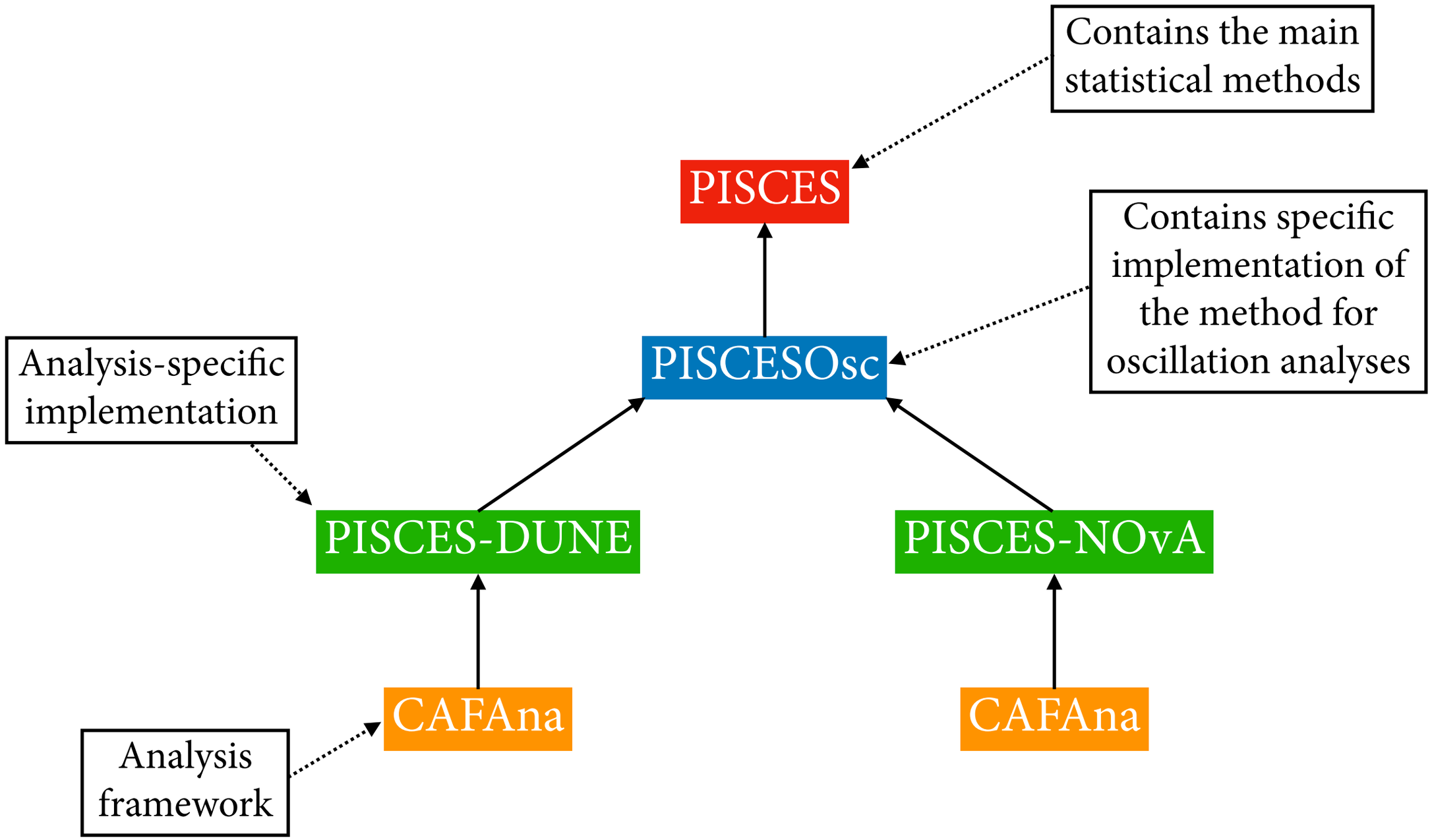
- One of the NOvA sterile analyses is based on the PISCES (Parameter Inference with Systematic Covariance and Exact Statistics) framework, which provides the machinery to produce covariance matrices and fit the data.
  - Novel method which contains a Poisson treatment for statistical uncertainties and Gaussian multivariate for systematics.
  - See V Hewes, DPF 2021, https://indico.cern.ch/event/1034469/contributions/4434547/.

- A lot of the framework was ported across and used to produce example matrices from the DUNE LBL files, but given the active development it quickly diverged from the version used on NOvA.

- I am currently actively working on centralizing the code-base by making the fitting parts stand-alone and a common dependency for both NOvA and DUNE.
  - PISCES and CAFAnaCore will then be external dependencies for the main DUNE CAFAna framework.
  - A lot of code refactoring and validation is required to complete this, but it makes sense at this stage to approach the work like this rather than letting the frameworks diverge too much.

Software Framework

- Planned structure:



Software Framework

- Given the current structure of the code, which was developed on NOvA and has lots of intermingled dependencies, the refactoring will need to be done piece-by-piece.
  - This is also a lot more complicated than I initially thought it would be, and I was expecting it to be slightly challenging!

- I have had to start and restart multiple times as I figure out the correct place to start disentangling and making generic all the relevant parts of the software.
  - I haven't been able to make as much progress as I was anticipating, and need to keep re-motivating myself!

- Current status:
  - I have made `PISCESOsc` stand-alone package and built it!
  - I have figured out how to use DUNE's mrb software setup with GitHub integration to build all the packages together (have previously used this, but only with LArSoft and not custom packages).
  - I have begun to develop the DUNE interface to the `PISCESOsc` in the dunepisces package: https://github.com/DUNE/dunepisces

Plans

- I have had a poster abstract accepted for Neutrino 2022 describing the DUNE sterile analyses.
  - The original plan was to try to develop all of these frameworks to get full sensitivities for the conference, but this feels a little ambitious at this point (and probably even when submitting the abstract)!
  - The poster will likely contain some of the oscillation plots and plans, with an advertisement for the PISCES method.

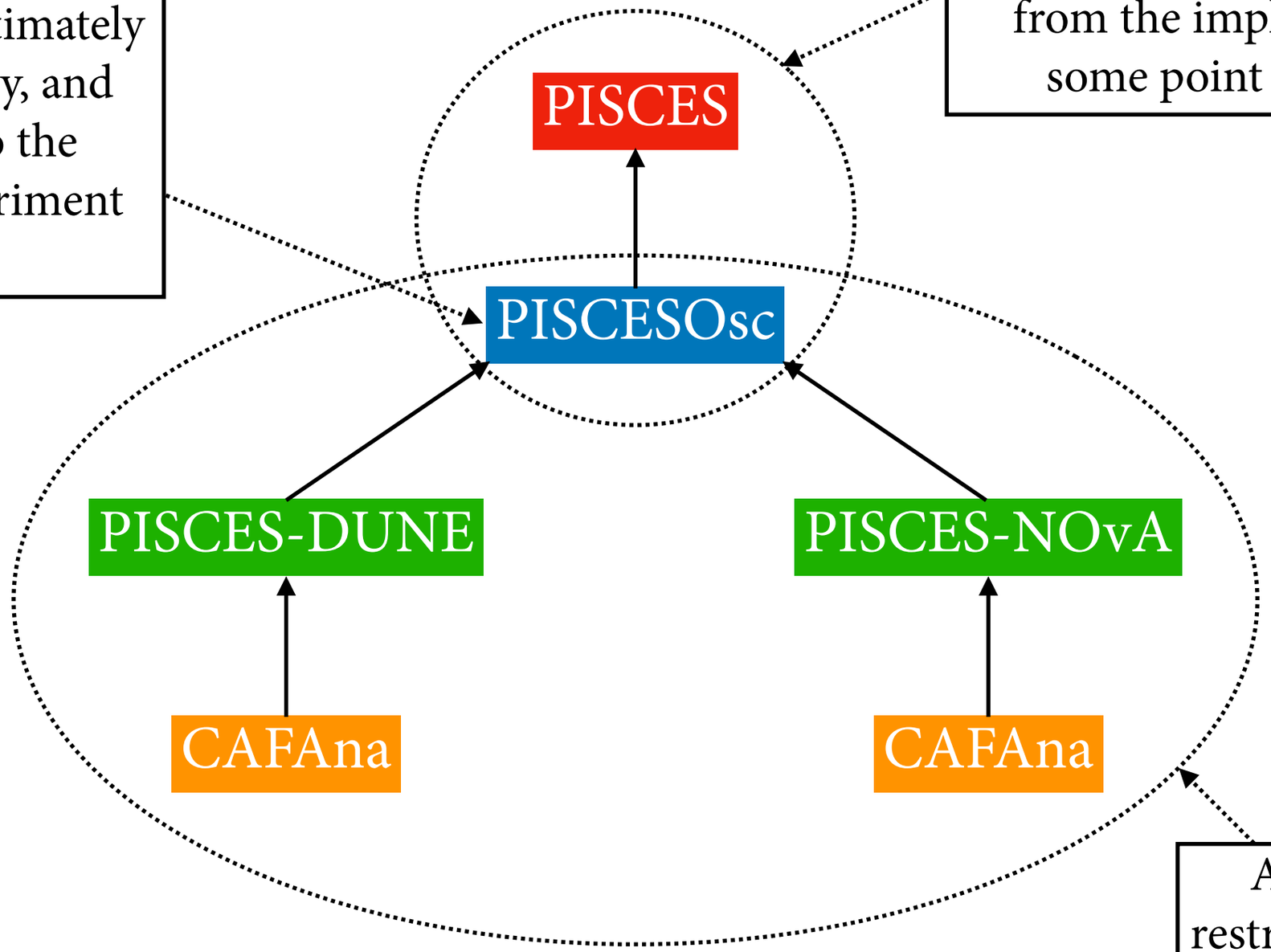
- Happy to pick a conference later in the year to aim to have some results for, maybe as part of a general BSM talk, if that fits in the with the group's plans.

- Ultimately would like to have a robust set of software packages which contain the correct level of dependency and with functionality appropriate to be split out as necessary.
  - Actively working with the investing NOvA team, in particular V Hewes (primary developer of lots of these tools), to ensure we work together towards this goal.

Software Plans

This part may ultimately not be necessary, and absorbed into the individual experiment parts

Currently these two things are lumped together, need to go through and split out the method from the implementation at some point in the future



A lot of CAFAna restructuring would be needed to implement this as I would ideally like; in discussions with Chris Backhouse

- The staged approach we are taking will allow us to make progress and get results whilst still keeping the big picture in mind and ensuring we're working towards the ultimate end goal.

Summary

- Made a lot of progress recently in the next part of the CAFAna-based sterile analysis on DUNE.
  - A lot of this 'progress' has been days wasted banging my head against the huge software stack and figuring out how best to refactor things, so is mostly transparent!
  - It has been very helpful in making me understand the best paths forward though, and made me realize I was way too ambitious with my initial attempts and plans.

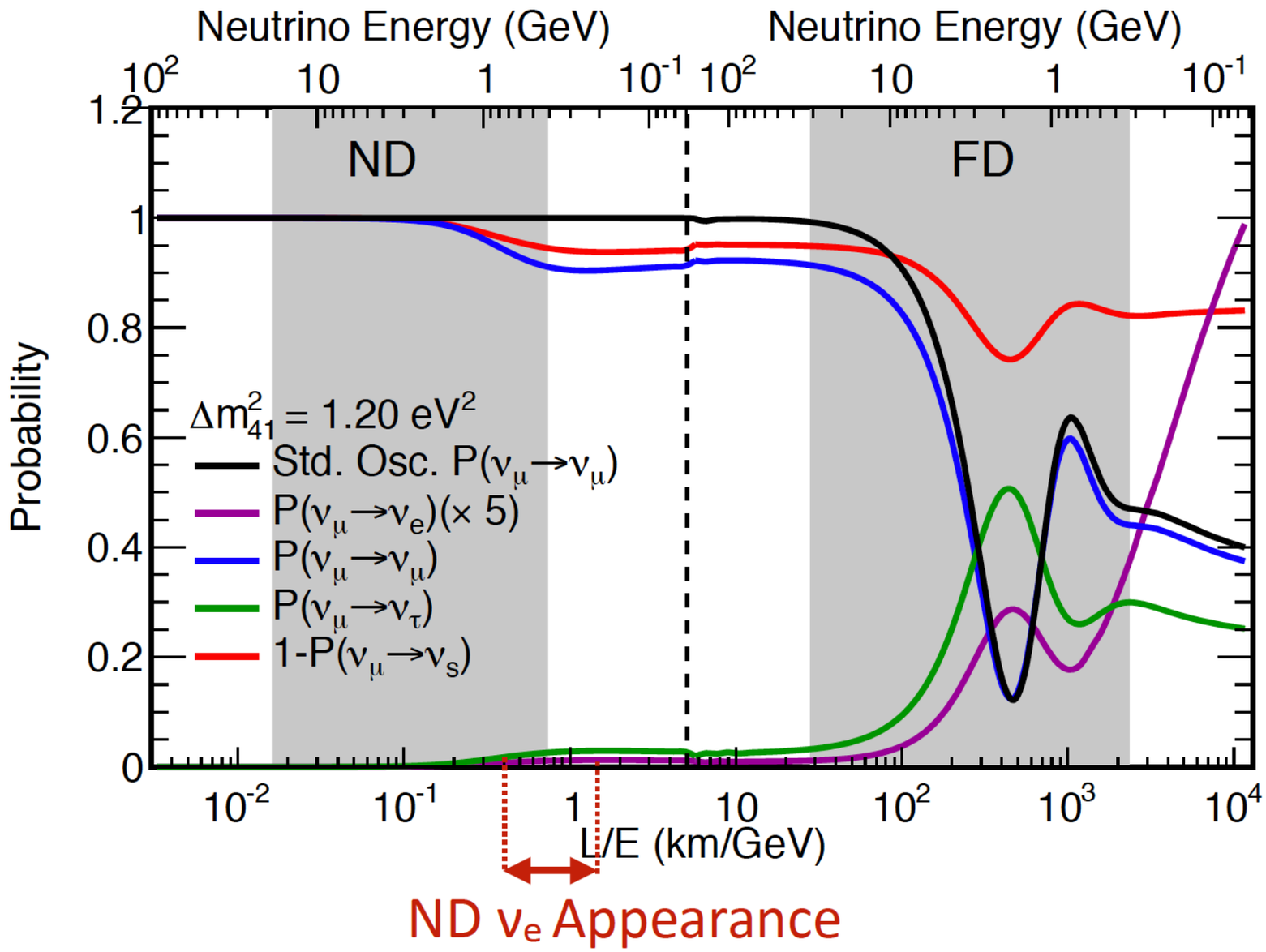
- Aim to have these tools developed and in place this year, so we can run a basic analysis and make sensitivities.

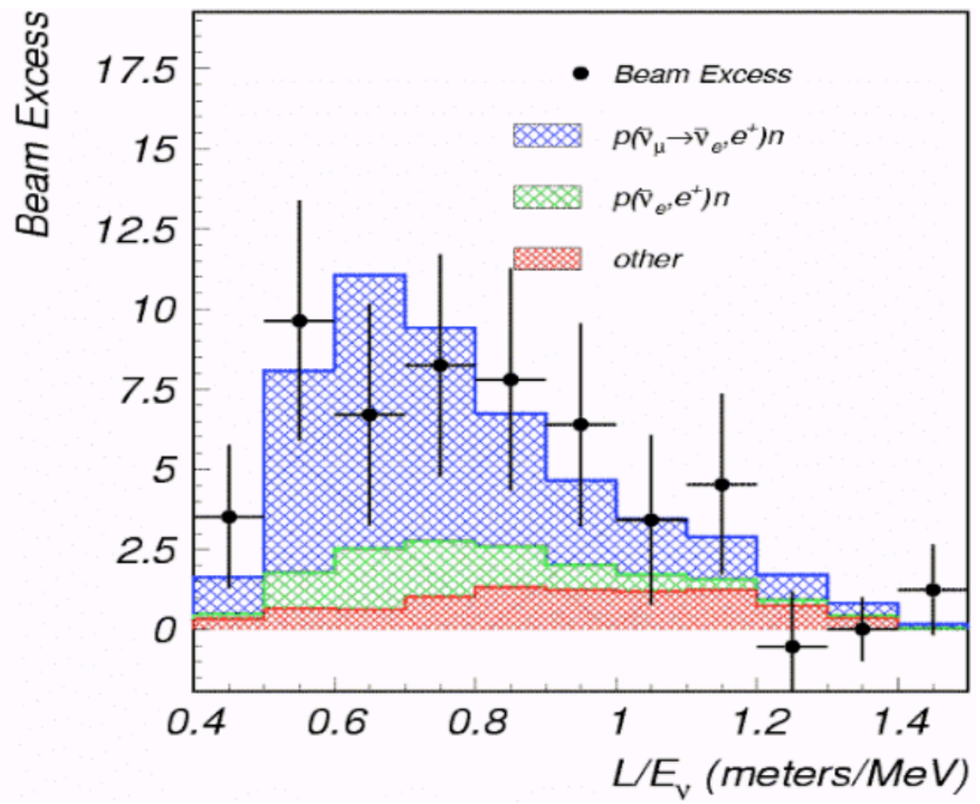
- Will give more regular updates to this group as I continue to make progress!
  - Any thoughts/suggestions welcome.

Back-Ups

Sterile Neutrinos

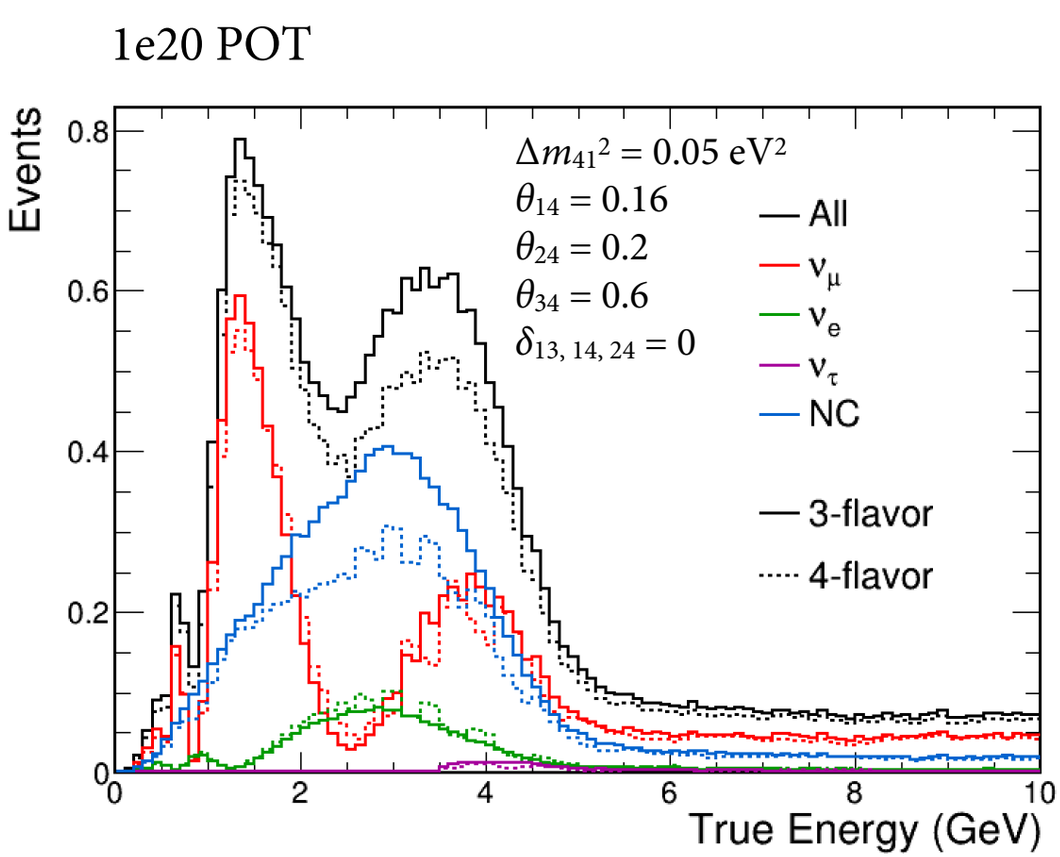
- Motivated by anomalous LSND and MiniBooNE observations, can probe sterile neutrino oscillations in DUNE by studying long-baseline ν_μ- and NC-disappearance and ν_e- ν_τ-appearance over ND baseline.

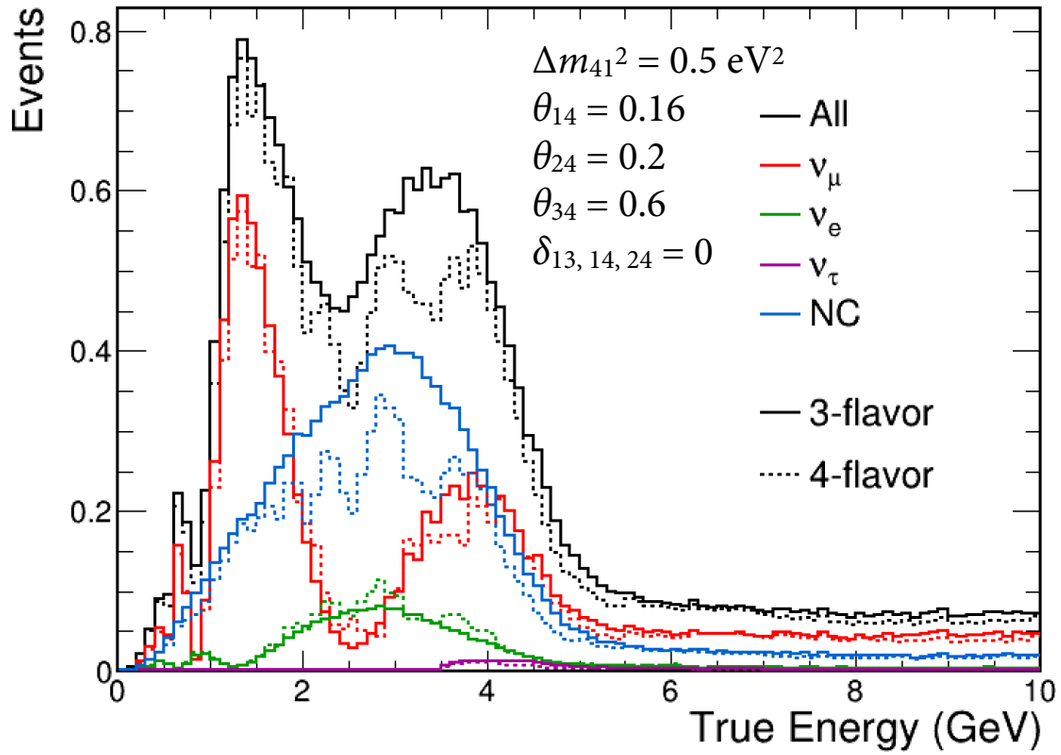


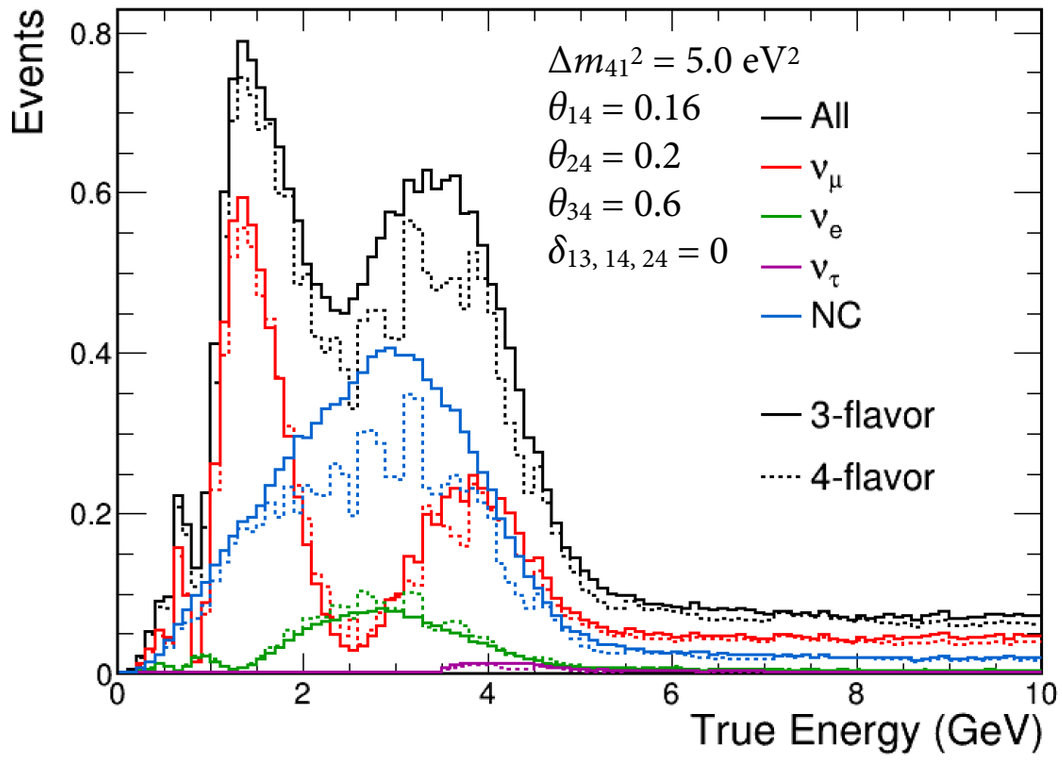


LNSD Collab,, Phys. Rev. D 64, 112007 (2001)

Oscillations Validation — FD

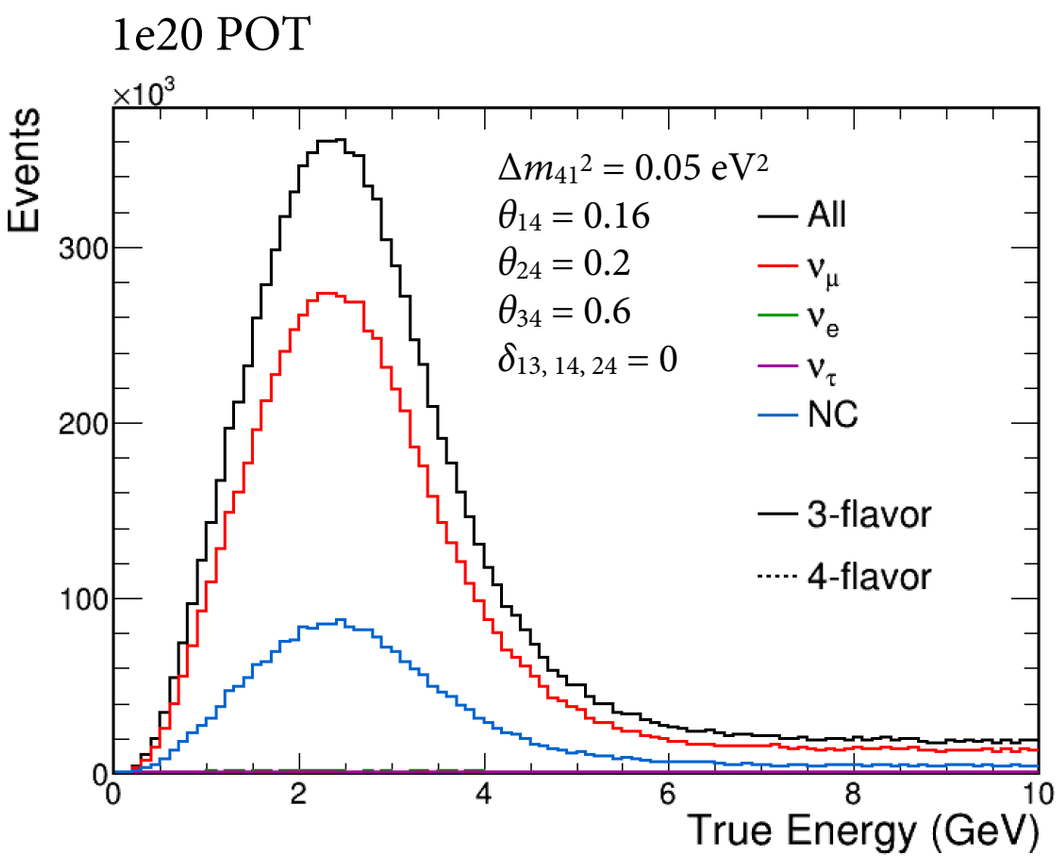


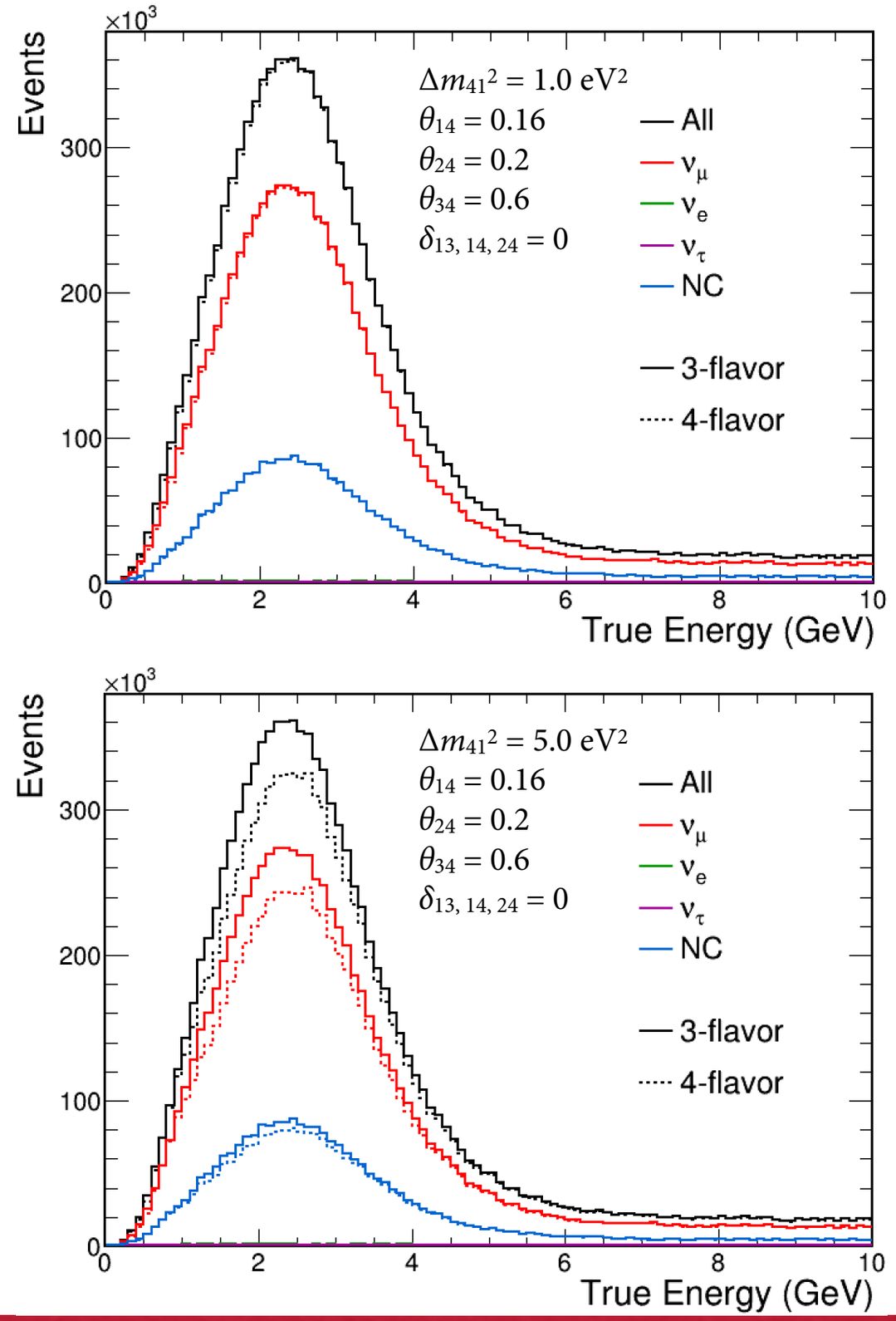




- Oscillator spectra (all events) for different values of the new sterile mass splitting.
- Far Detector.

Oscillations Validation — ND





- Oscillator spectra (all events) for different values of the new sterile mass splitting.
- Near Detector.

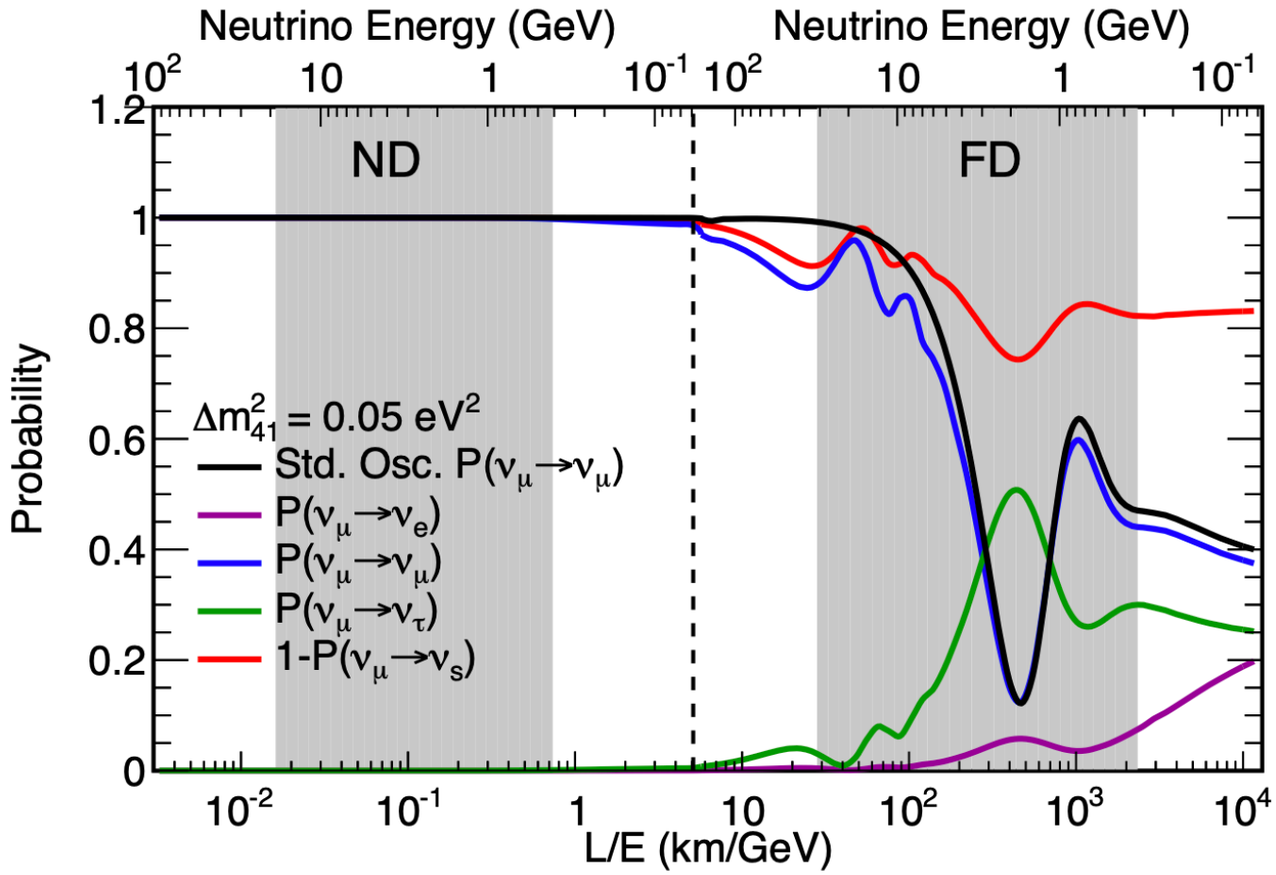
3+1 Oscillations

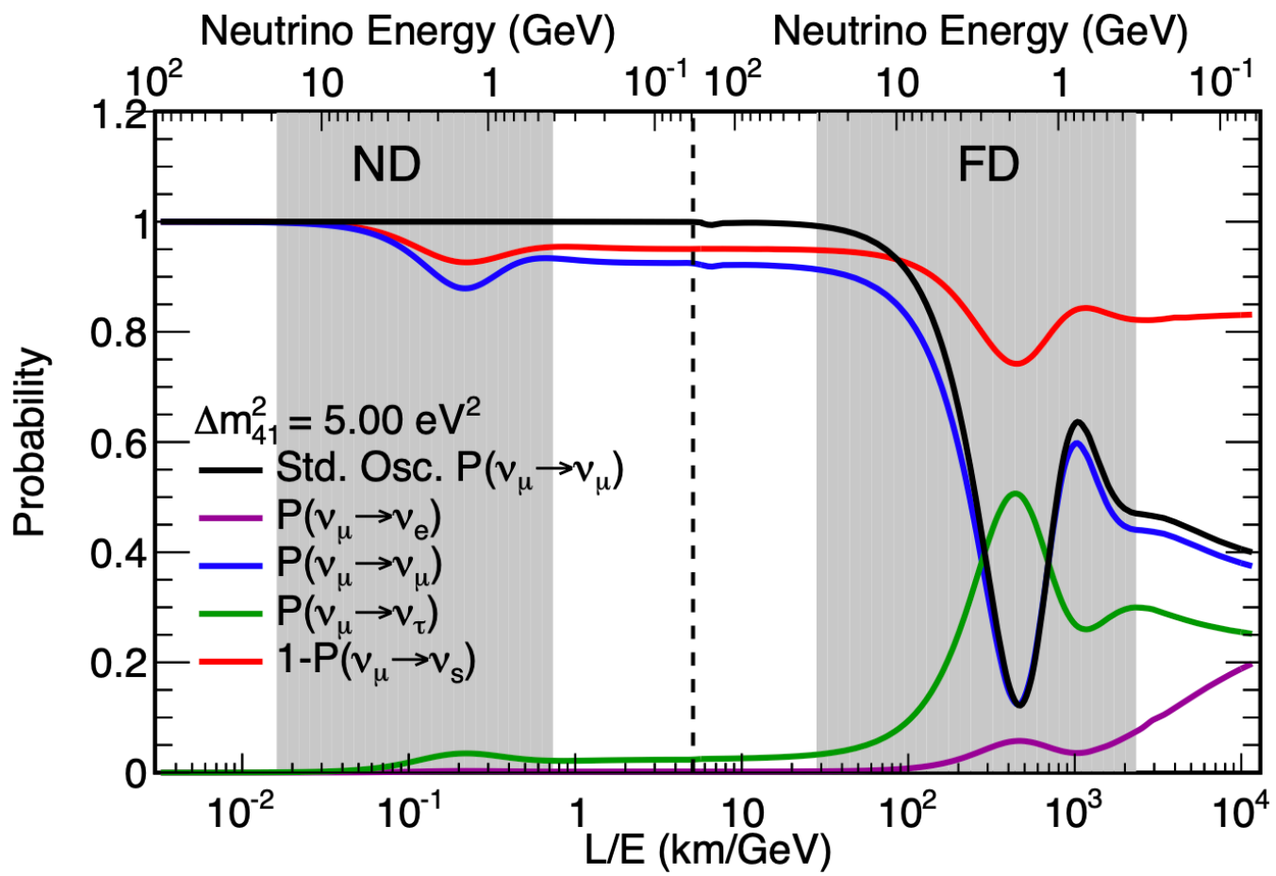
- Expected 3+1 oscillations in the ND and FD for different values of the sterile mass splitting.

- Taken from Alex's talk: https://indico.fnal.gov/event/11417/#1-dune-l-over-e-plots-for-a-31

dm21 = 7.54e-05
dm32 = 2.43e-3 //positive sign implies normal hierarchy
th12 = 0.588
th13 = 0.154
th23 = 0.722
th14 = 0.16
th24 = 0.2
th34 = 0.6
delta13 = 0
delta14 = 0
delta24 = 0
Ne = 1.4 //matter effects

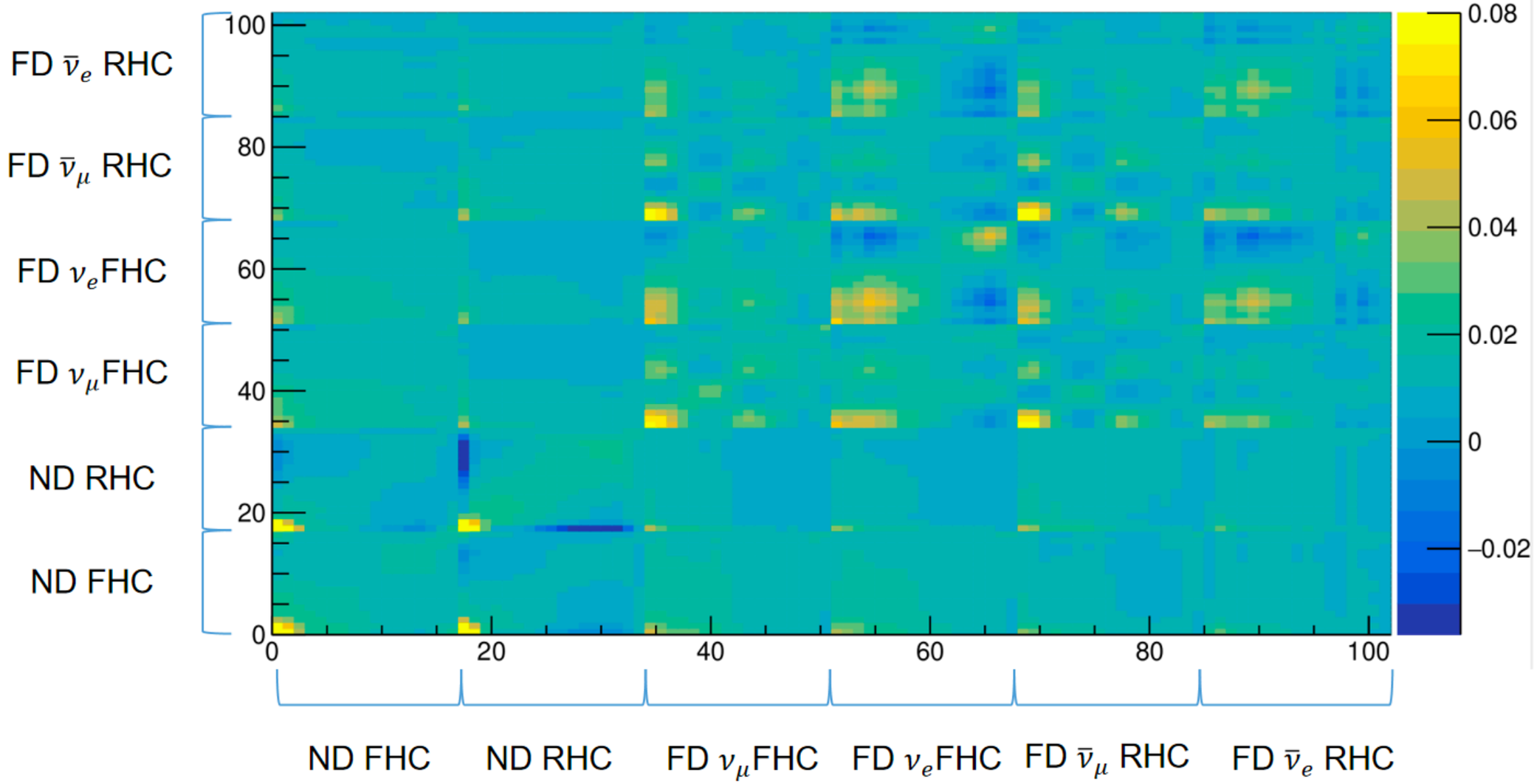
- Parameters used in 3+1 model





LBL Covariance Matrix

Herilala Razafinime



- 17 energy bins from 0—10 GeV for each sample.
- Includes all flux, cross-section, FD and ND systematics (see back-ups for full list).

ND/FD Systematics

- flux (30 components)
- EnergyScaleFD
- UncorrFDTotSqrt
- UncorrFDTotInvSqrt
- UncorrFDHadSqrt
- UncorrFDHadInvSqrt
- UncorrFDMuSqrt
- UncorrFDMuInvSqrt
- UncorrFDNSqrt
- UncorrFDNInvSqrt
- UncorrFDEMSqrt
- UncorrFDEMInvSqrt
- EScaleMuLArFD
- ChargedHadUncorrFD
- NUncorrFD
- EMUncorrFD
- MuonResFD
- EMResFD
- ChargedHadResFD
- NResFD
- FDRecoNumuSyst
- FDRecoNueSyst
- FVNumuFD
- FVNueFD
- RecoNCSyst
- FVNumuND
- MaCCQE
- VecFFCCQEshape
- MaCCRES
- MvCCRES
- MaNCRES
- MvNCRES
- Theta_Delta2Npi
- AhtBY
- BhtBY
- CV1uBY
- CV2uBY
- FrCEx_pi
- FrElas_pi
- FrInel_pi
- FrAbs_pi
- FrPiProd_pi
- FrCEx_N
- FrElas_N
- FrInel_N
- FrAbs_N
- FrPiProd_N
- CCQEPauliSupViaKF
- E2p2h_A_nu
- E2p2h_B_nu
- E2p2h_A_nubar
- E2p2h_B_nubar
- NR_nu_n_CC_2Pi
- NR_nu_n_CC_3Pi
- NR_nu_p_CC_2Pi
- NR_nu_p_CC_3Pi
- NR_nu_np_CC_1Pi
- NR_nu_n_NC_1Pi
- NR_nu_n_NC_2Pi
- NR_nu_n_NC_3Pi
- NR_nu_p_NC_1Pi
- NR_nu_p_NC_2Pi
- NR_nu_p_NC_3Pi
- NR_nubar_n_CC_1Pi
- NR_nubar_n_CC_2Pi
- NR_nubar_n_CC_3Pi
- NR_nubar_p_CC_1Pi
- NR_nubar_p_CC_2Pi
- NR_nubar_p_CC_3Pi
- NR_nubar_n_NC_1Pi
- NR_nubar_n_NC_2Pi
- NR_nubar_n_NC_3Pi
- NR_nubar_p_NC_1Pi
- NR_nubar_p_NC_2Pi
- NR_nubar_p_NC_3Pi
- BeRPA_A
- BeRPA_B
- BeRPA_D
- C12ToAr40_2p2hScaling_nu
- C12ToAr40_2p2hScaling_nubar
- nuenuebar_xsec_ratio
- nuenumu_xsec_ratio
-

ND Systematics

- EnergyScaleND
- UncorrNDTotSqrt
- UncorrNDTotInvSqrt
- UncorrNDHadSqrt
- UncorrNDHadInvSqrt
- UncorrNDMuLArSqrt
- UncorrNDMuLArInvSqrt
- UncorrNDMuSpectSqrt
- UncorrNDMuSpectInvSqrt
- UncorrNDNSqrt
- UncorrNDNInvSqrt
- UncorrNDEMSqrt
- UncorrNDEMInvSqrt
- EScaleMuLArND
- EScaleMuSpectND
- ChargedHadUncorrND
- NUncorrND
- EMUncorrND
- MuonResND
- EMResND
- ChargedHadResND
- NResND
- HadronAccSyst
- LeptonAccSyst