Systematic uncertainties in DUNE

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DUNE

Outline

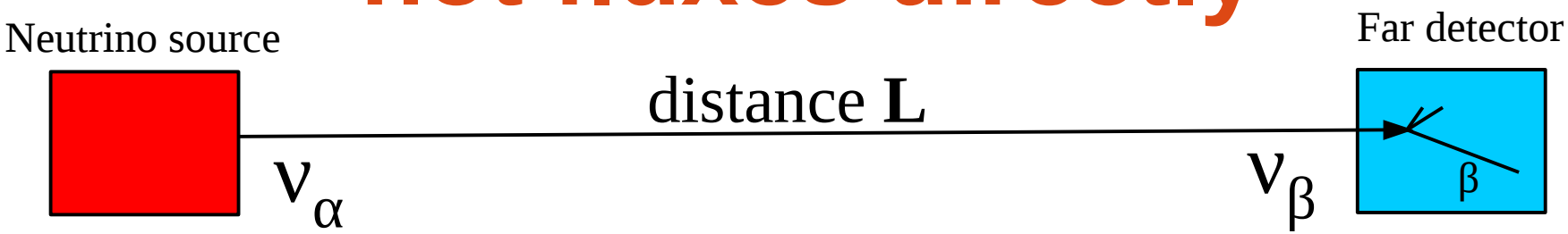
- A generic long-baseline oscillation measurement, and how systematic uncertainties arise
- The DUNE near detector
- Flux uncertainty in DUNE
- Neutrino interaction & energy reconstruction uncertainties

Neutrino oscillation probability

$$P(\nu_\alpha \to \nu_\beta) = \frac{\Phi_{\nu_\beta}(E_\nu, L)}{\Phi_{\nu_\alpha}(E_\nu, 0)}$$

- The goal of any neutrino oscillation experiment:
  - Measure the flux of neutrinos of flavor β at a distance *L*
  - Compare it to the flux of neutrinos of flavor α at the source
  - As a function of neutrino energy
  - Disappearance (α = β) and appearance (α ≠ β)

We measure neutrino interactions, not fluxes directly



$$N(E_\nu) = \Phi(E_\nu) \times \sigma(E_\nu) \times \epsilon(E_\nu)$$

- Observed interaction rate, *N*, depends on fluxes, but also cross sections (σ), and detector acceptance (ε)
- Cross sections, in particular, are highly uncertain

Energy reconstruction is challenging

$$N(E_{reco}) = \int \Phi(E_\nu) \times \sigma(E_\nu) \times \epsilon(E_\nu) \times \mathbf{D}(E_\nu \rightarrow E_{reco}) dE_\nu$$

- And the observed rate is measured as a function of *reconstructed* energy, which is connected to neutrino energy E_ν by some smearing matrix **D**
- This matrix dependent on your particular detector, but also depends strongly on neutrino interactions

Uncertainties are reduced with near detector measurements

$$\frac{N^{far}(E_{reco}) = \int \Phi(E_\nu, L) \times \sigma(E_\nu) \times \epsilon(E_\nu) \times \mathbf{D}(E_\nu \to E_{reco}) dE_\nu}{N^{near}(E_{reco}) = \int \Phi(E_\nu, 0) \times \sigma(E_\nu) \times \epsilon(E_\nu) \times \mathbf{D}(E_\nu \to E_{reco}) dE_\nu}$$

- Near detector in the same flux, with the same nuclear target, and a similar detector technology, will constrain many uncertain parameters

But there is no magical "cancellation"

$$\frac{N^{far}_{\nu_\beta}(E_{reco}) = \int \Phi_{\nu_\beta}(E_\nu, L) \times \sigma_{\nu_\beta}(E_\nu) \times \epsilon^{far}_{\nu_\beta}(E_\nu) \times \mathbf{D}^{far}_{\nu_\beta}(E_\nu \rightarrow E_{reco}) dE_\nu}{N^{near}_{\nu_\alpha}(E_{reco}) = \int \Phi_{\nu_\alpha}(E_\nu, 0) \times \sigma_{\nu_\alpha}(E_\nu) \times \epsilon^{near}_{\nu_\alpha}(E_\nu) \times \mathbf{D}^{near}_{\nu_\alpha}(E_\nu \rightarrow E_{reco}) dE_\nu}$$

- There are many differences between the observed interaction rates at the near and far detectors, which lead to systematic uncertainties:
  - Fluxes are different primarily due to oscillations
  - Cross sections are strongly energy-dependent, potentially different nucleus, or different neutrino flavor
  - Even if ND and FD are "functionally identical," acceptance and energy reconstruction will be somewhat different due to the sizes

But there is no magical "cancellation"

?

$$\frac{N^{far}_{\nu_\beta}(E_{reco}) = \int \Phi_{\nu_\beta}(E_\nu, L) \times \sigma_{\nu_\beta}(E_\nu) \times \epsilon^{far}_{\nu_\beta}(E_\nu) \times \mathbf{D}^{far}_{\nu_\beta}(E_\nu \to E_{reco}) dE_\nu}{N^{near}_{\nu_\alpha}(E_{reco}) = \int \Phi_{\nu_\alpha}(E_\nu, 0) \times \sigma_{\nu_\alpha}(E_\nu) \times \epsilon^{near}_{\nu_\alpha}(E_\nu) \times \mathbf{D}^{near}_{\nu_\alpha}(E_\nu \to E_{reco}) dE_\nu}$$

- All of these terms depend on E_ν, so this product cannot be factorized
- Even if the ND and FD were literally identical, the flux differences mean that nothing actually cancels
- Independent knowledge of flux and cross sections is very helpful

But there is no magical "cancellation"

no

$$\frac{N^{far}_{\nu_\beta}(E_{reco}) = \int \Phi_{\nu_\beta}(E_\nu, L) \times \sigma_{\nu_\beta}(E_\nu) \times \epsilon^{far}_{\nu_\beta}(E_\nu) \times \mathbf{D}^{far}_{\nu_\beta}(E_\nu \to E_{reco}) dE_\nu}{N^{near}_{\nu_\alpha}(E_{reco}) = \int \Phi_{\nu_\alpha}(E_\nu, 0) \times \sigma_{\nu_\alpha}(E_\nu) \times \epsilon^{near}_{\nu_\alpha}(E_\nu) \times \mathbf{D}^{near}_{\nu_\alpha}(E_\nu \to E_{reco}) dE_\nu}$$

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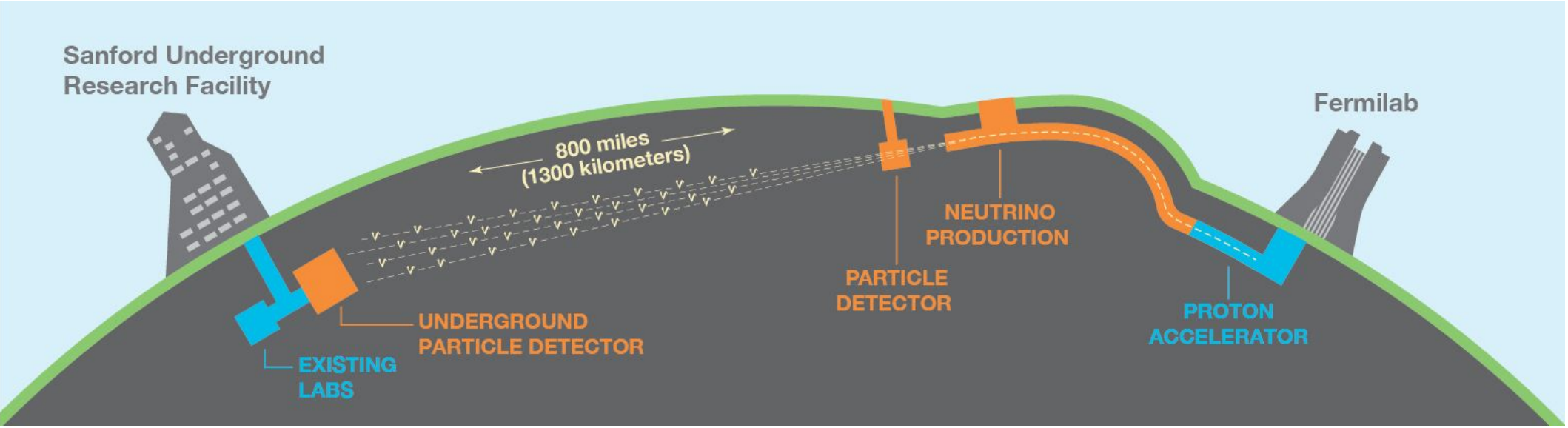
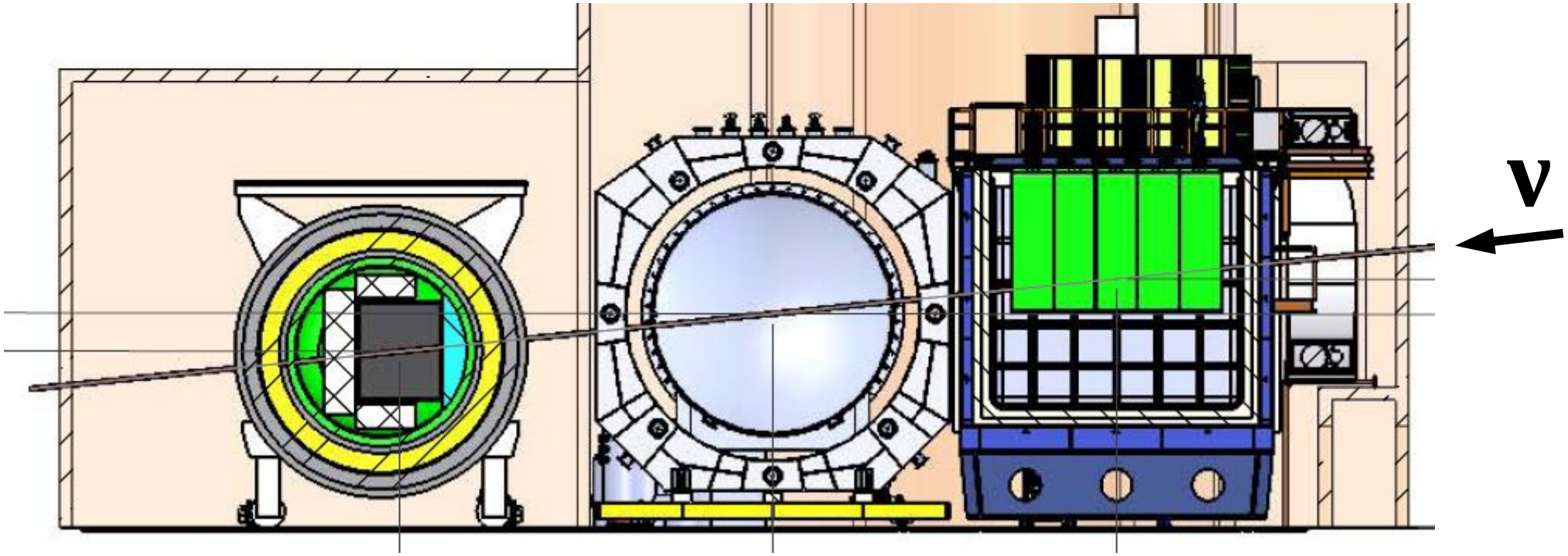
DEEP UNDERGROUND NEUTRINO EXPERIMENT



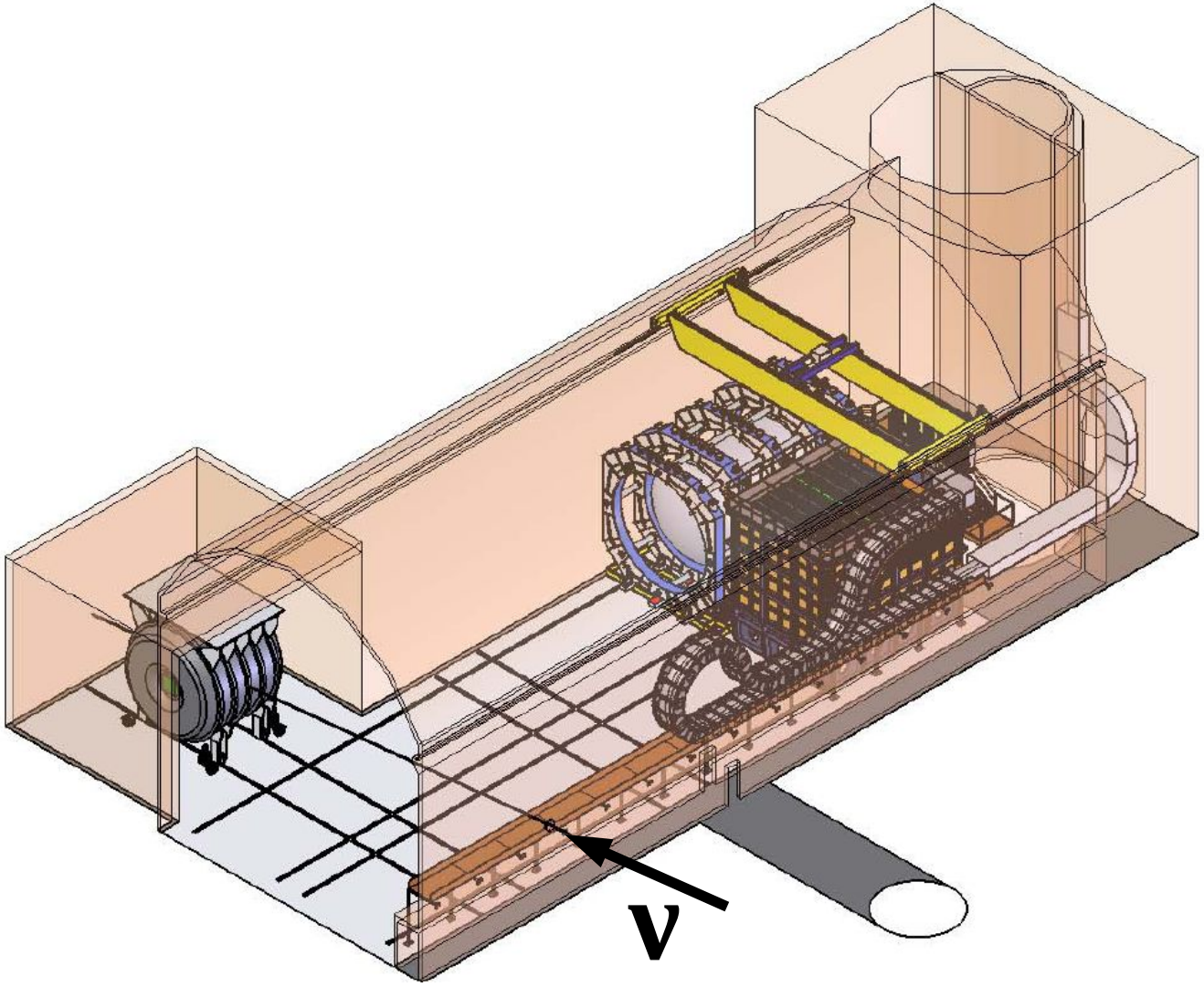
- 40 kt fiducial LAr TPC far detector at SURF, 1300 km baseline
- Upgraded conventional neutrino beam at Fermilab, peaked at 2.5 GeV
- Near detector system at Fermilab is critical for constraining systematic uncertainties

The DUNE Near Detector



- LAr TPC functionally similar to far detector
- Magnetized, high-pressure gaseous Ar TPC with high-performance calorimeter
- Magnetized plastic scintillator tracker & on-axis beam monitor

Movable detectors for on- and off-axis measurements



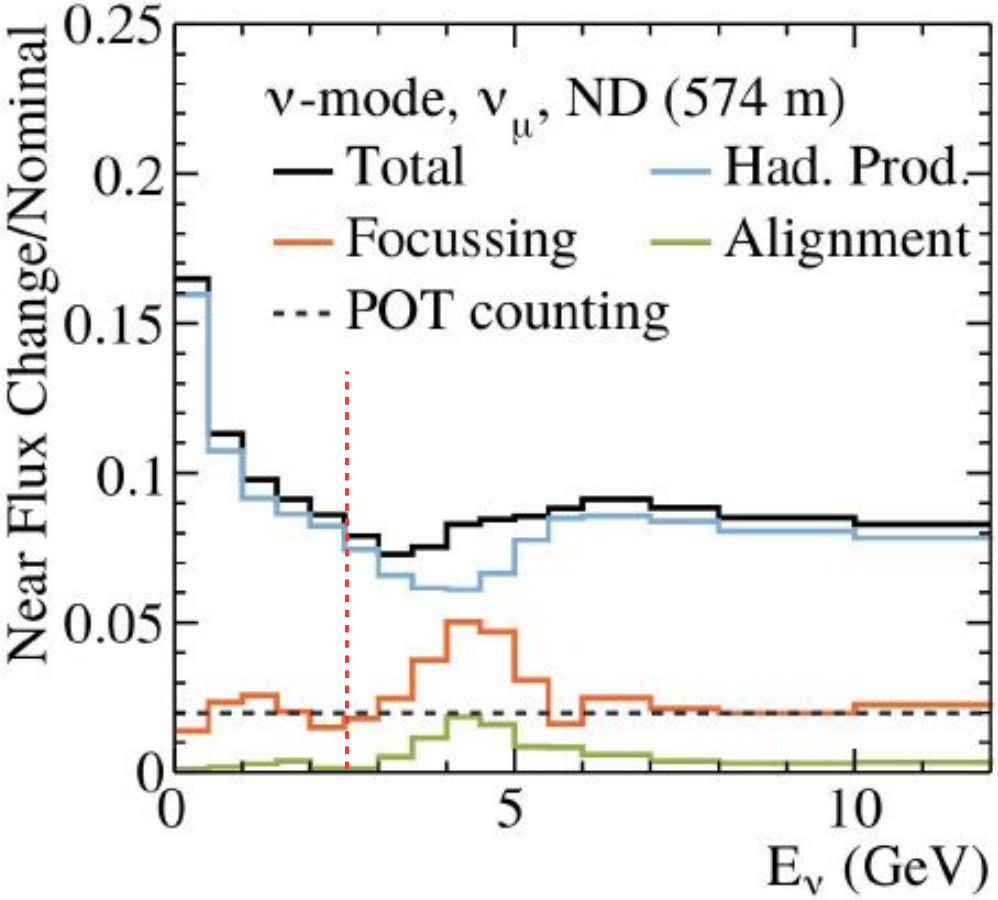
- LAr + HPgTPC system will move up to 33m off axis to sample different energy spectra in the same beam
- Next talk will provide details about what this does for uncertainties

DUNE ND philosophy

- LAr TPC
  - High rate (30M ν_μ CC, 5k ν+e elastic events/yr) enables many simultaneous exclusive measurements, and a direct flux constraint
  - Similar technology to FD enables use of PRISM technique to directly probe energy response in different fluxes
- High-pressure gaseous Ar TPC
  - Excellent PID, 4π coverage, sign selection, very low thresholds → study ν-Ar interactions in exquisite detail, much better than FD
- Robust monitoring of beam spectrum vs. time

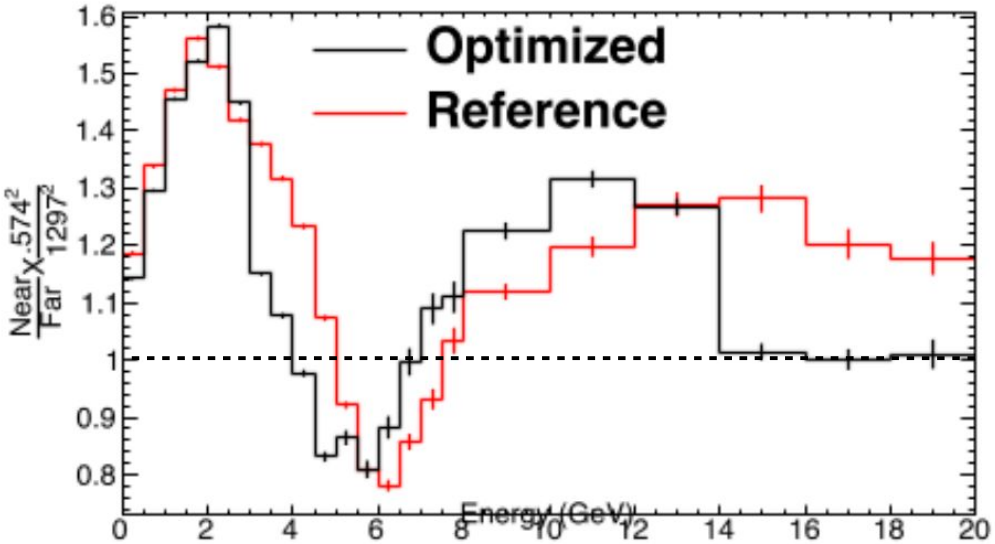
Flux uncertainties in DUNE

- Absolute flux uncertainty is ~8% and dominated by hadron production uncertainties
- This includes currently available constraints from hadron production experiments (i.e. NA49), but not future constraints (i.e. EMPHATIC, NA61), or *in situ* measurements (i.e. ν+e elastic, low-ν)



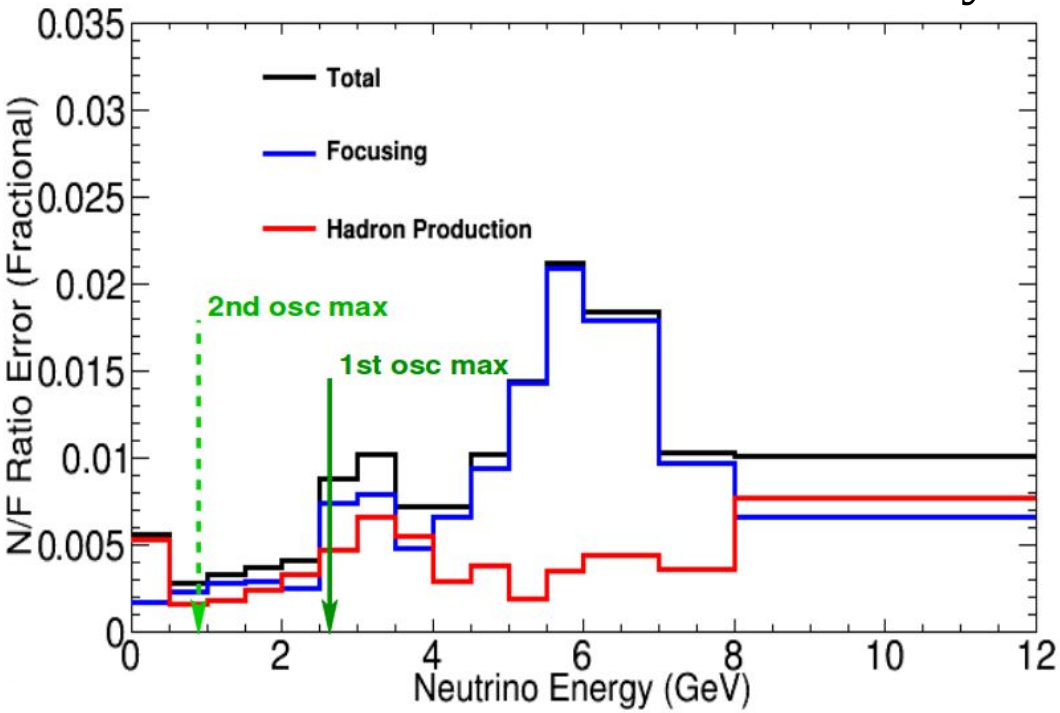
Near/Far flux ratio

DUNE ND/FD flux ratio



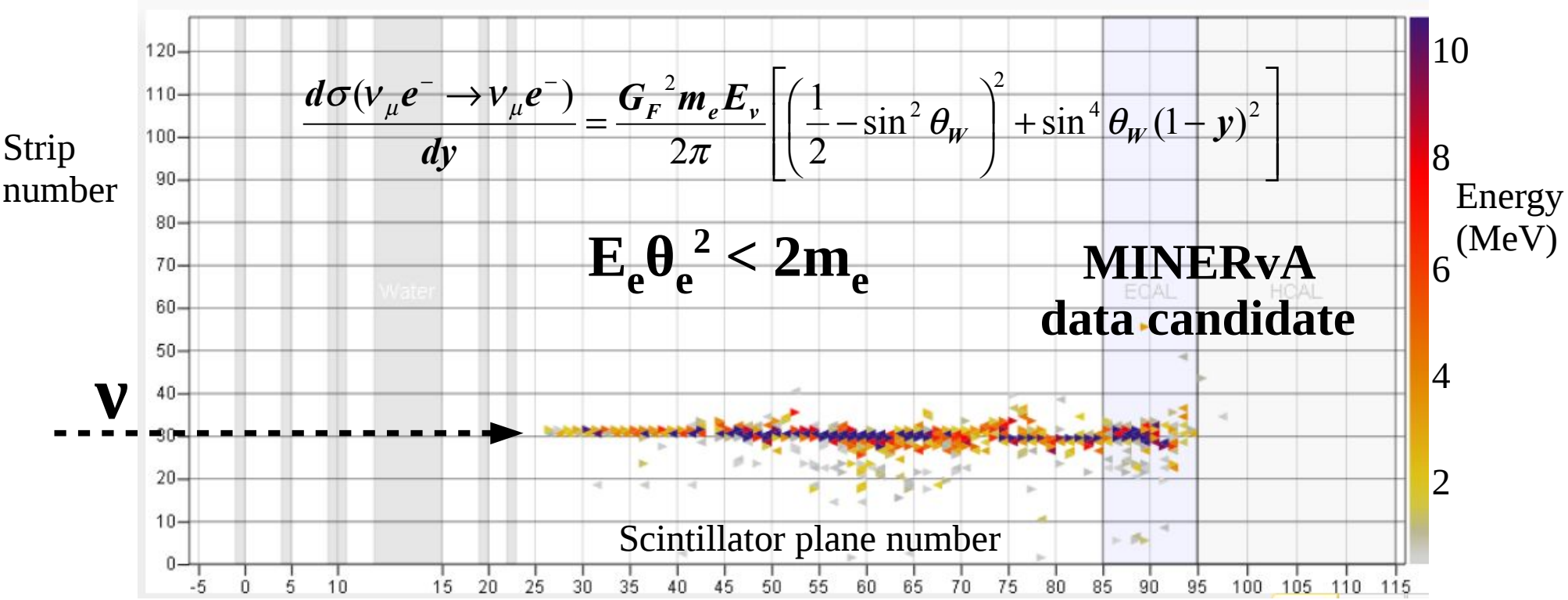
Neutrino energy (GeV)

DUNE ND/FD flux uncertainty



- Near/Far ratio has ~20-50% deviations from unity, before accounting for oscillations
- Leads to an uncertainty that is ~0.5% in the peak, but rising to ~2% in the falling edge, and dominated by focusing effects
- This cannot be constrained by the near detector

Neutrino-electron elastic scattering

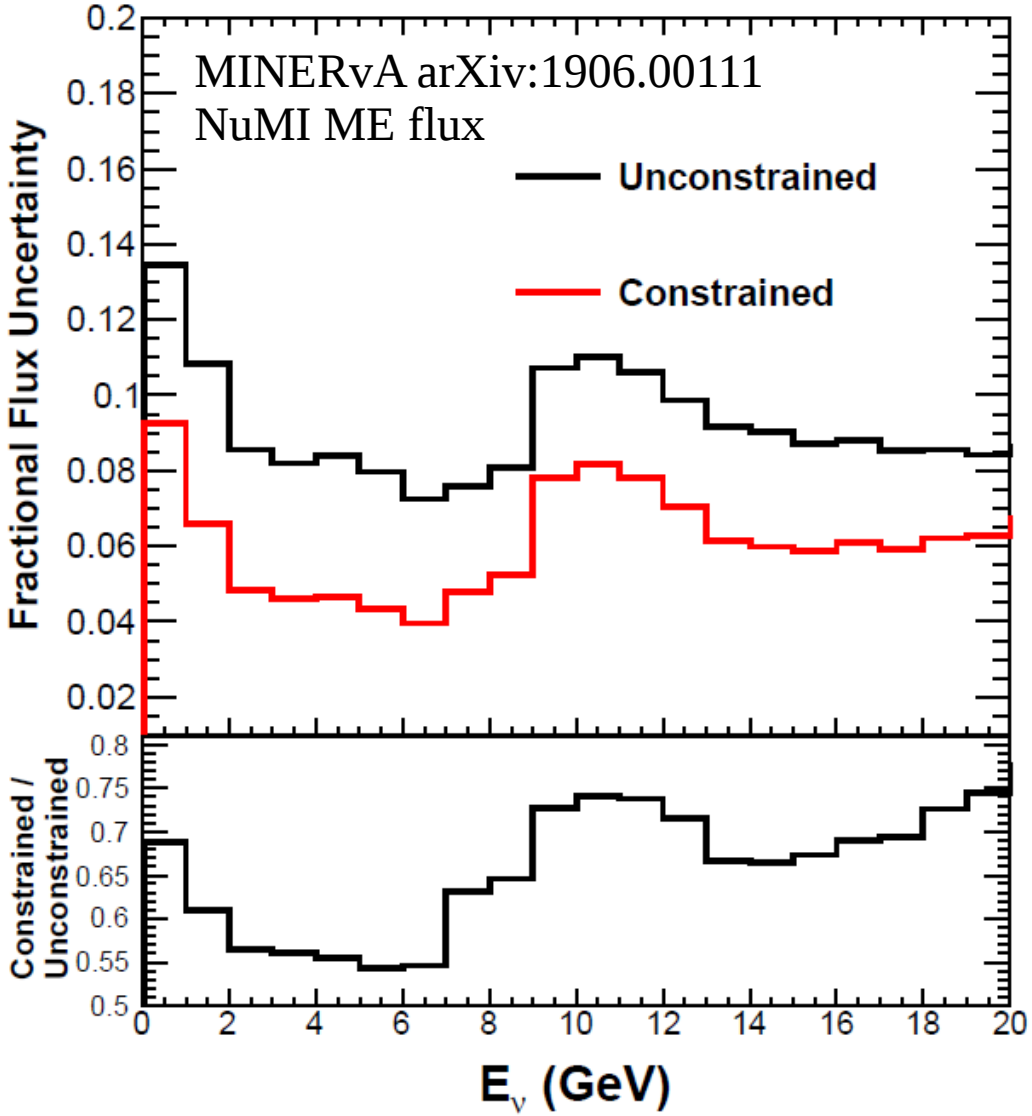


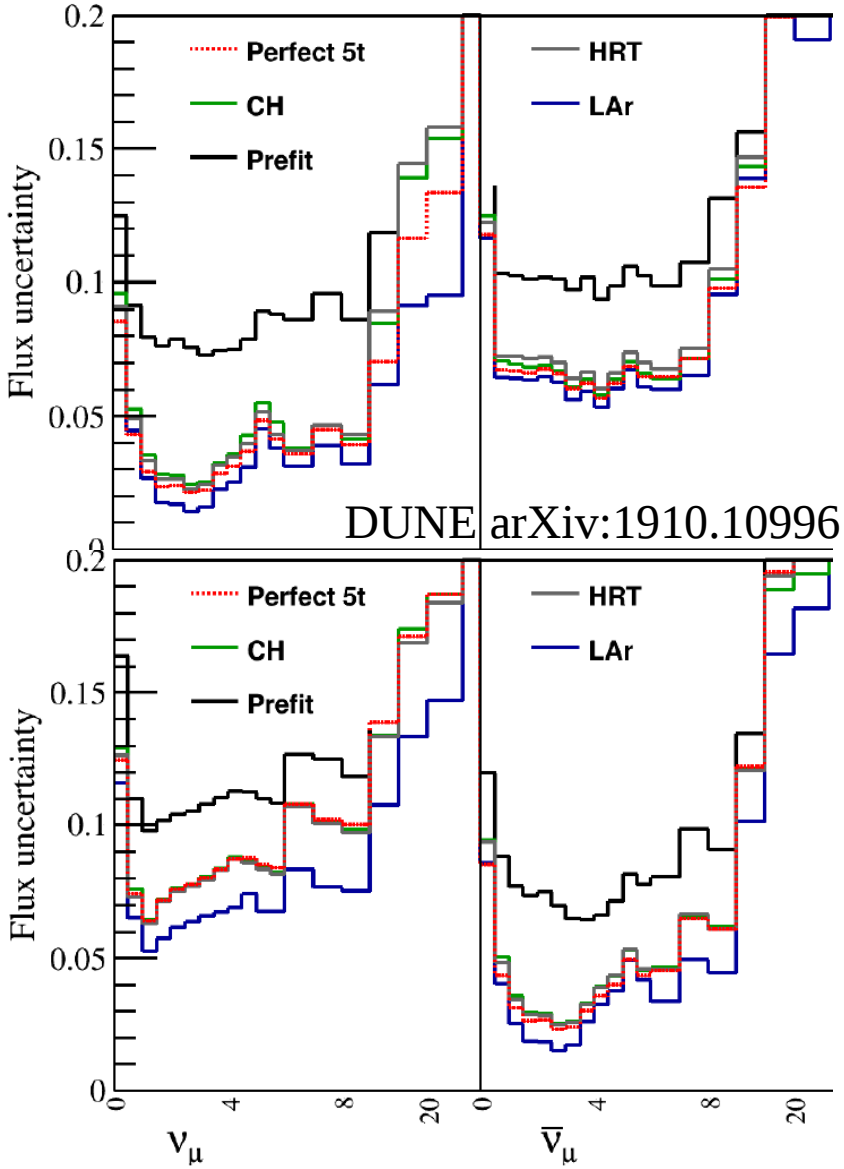
$$\frac{d\sigma(\nu_\mu e^- \to \nu_\mu e^-)}{dy} = \frac{G_F^2 m_e E_\nu}{2\pi}\left[\left(\frac{1}{2} - \sin^2\theta_W\right)^2 + \sin^4\theta_W (1-y)^2\right]$$

- Pure electroweak process with known cross section at tree level
- Signal is a single, forward electron with no other particles
- MINERvA has demonstrated using ν+e to constrain the NuMI flux

Phys. Rev. D 93, 112007 (2016) arXiv:1906.00111 Wine & Cheese Nov. 15

ν+e flux constraint: ~5% for MINERvA, ~2% for DUNE





Cross section uncertainties

- DUNE has evaluated ~60 cross section uncertainties, affecting quasi-elastic scattering, resonance production, deeply inelastic scattering, nuclear effects, ν_μ/ν_e differences
- Starts with, but greatly expands on GENIE reweighting framework
- Used in oscillation fits in forthcoming physics TDR

Cross section uncertainties

MaCCQE
VecFFCCQEshape
CCQEPauliSupViaKF
MaNCEL
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

Mnv2p2hGaussEnhancement
MKSPP_ReWeight
E2p2h_A_nu
E2p2h_B_nu
E2p2h_A_nubar
E2p2h_B_nubar
BeRPA_A
BeRPA_B
BeRPA_D
C12ToAr40_2p2hScaling_nu
C12ToAr40_2p2hScaling_nubar
nuenuebar_xsec_ratio
nuenumu_xsec_ratio
SPPLowQ2Suppression

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

Cross section uncertainties

MaCCQE
VecFFCCQEshape
CCQEPauliSupViaKF
MaNCEL
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

Mnv2p2hGaussEnhancement
MKSPP_ReWeight

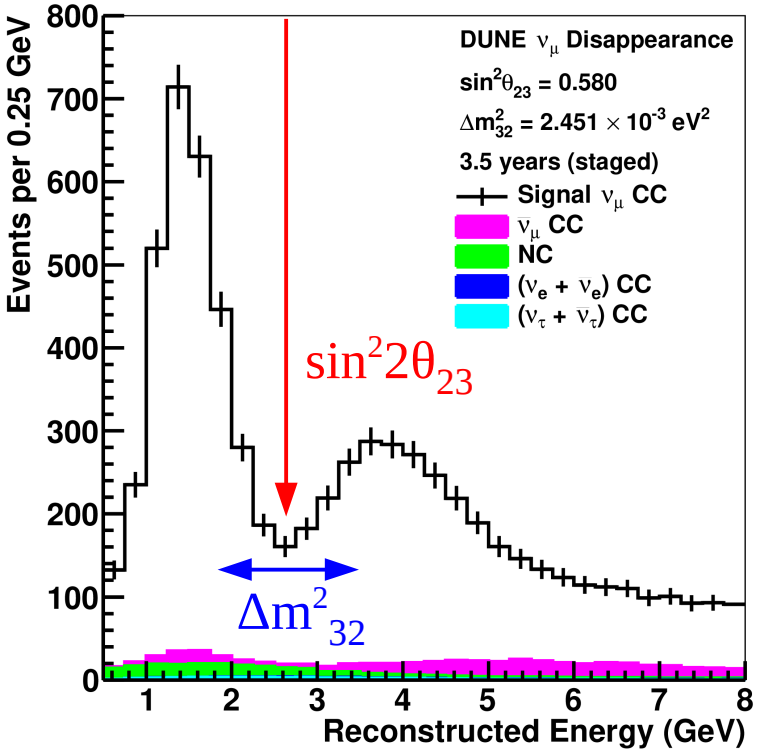
nuenumu_xsec_ratio
SPPLowQ2Suppression

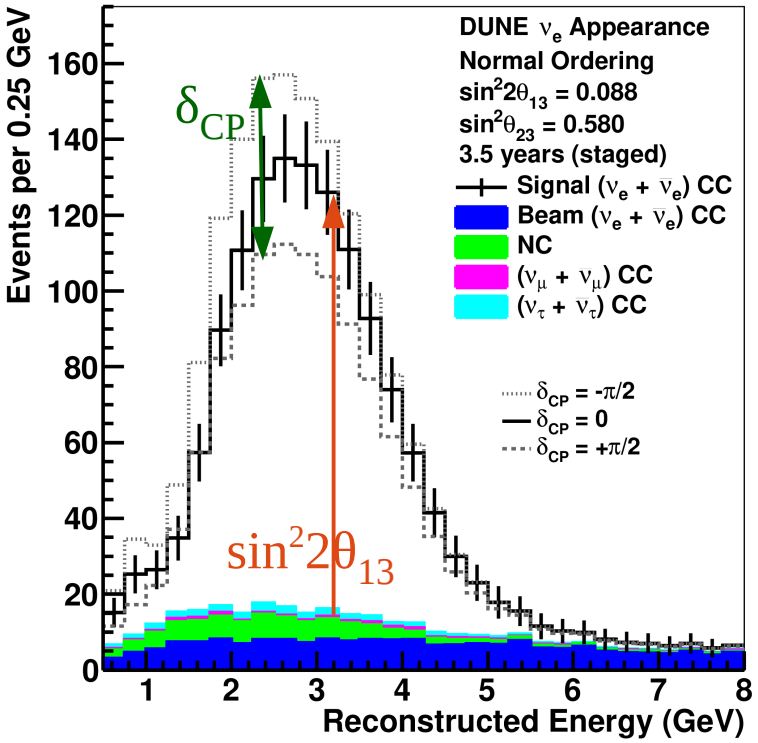
NR_nu_n_CC_2Pi
NR_nu_n_CC_3Pi
NR_nu_p_CC_2Pi
NR_nu_p_CC_3Pi
NR_nu_np_CC_1Pi
NR_nu_n_NC_1Pi
u_n_NC_2Pi
u_n_NC_3Pi
u_p_NC_1Pi
u_p_NC_2Pi
u_p_NC_3Pi
ubar_n_CC_1Pi
ubar_n_CC_2Pi
ubar_n_CC_3Pi
ubar_p_CC_1Pi
ubar_p_CC_2Pi
NR_nubar_p_CC_3Pi
NR_nubar_n_NC_1Pi
NR_nubar_n_NC_2Pi
NR_nubar_n_NC_3Pi
NR_nubar_p_NC_1Pi
NR_nubar_p_NC_2Pi
NR_nubar_p_NC_3Pi

I'm going to spare you the details, and instead explain more qualitatively how cross section uncertainties impact DUNE

Cross section uncertainties

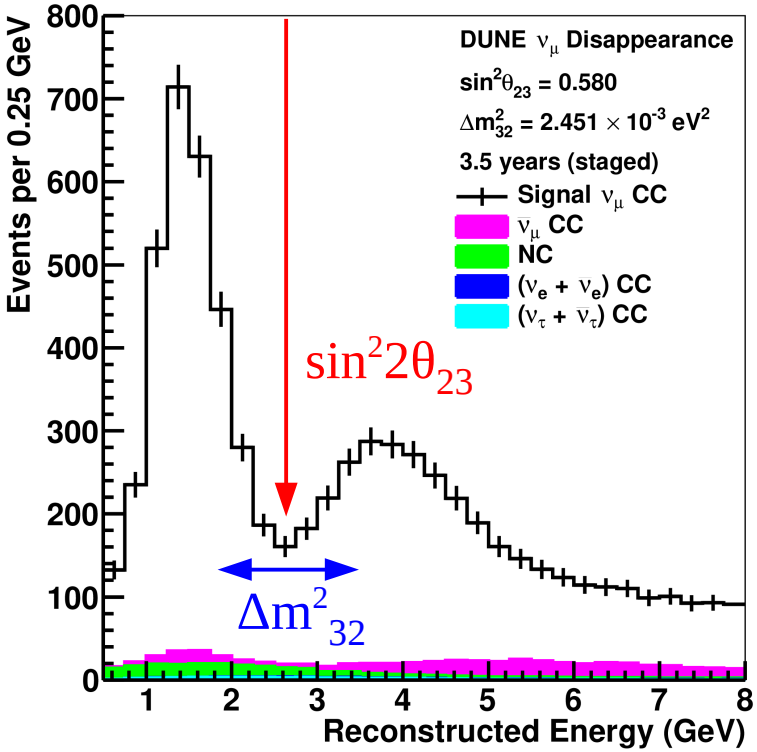
- DUNE is sensitive to effects that impact the rate of ν_μ and ν_e CC interactions at the Far Detector as a function of *reconstructed* neutrino energy

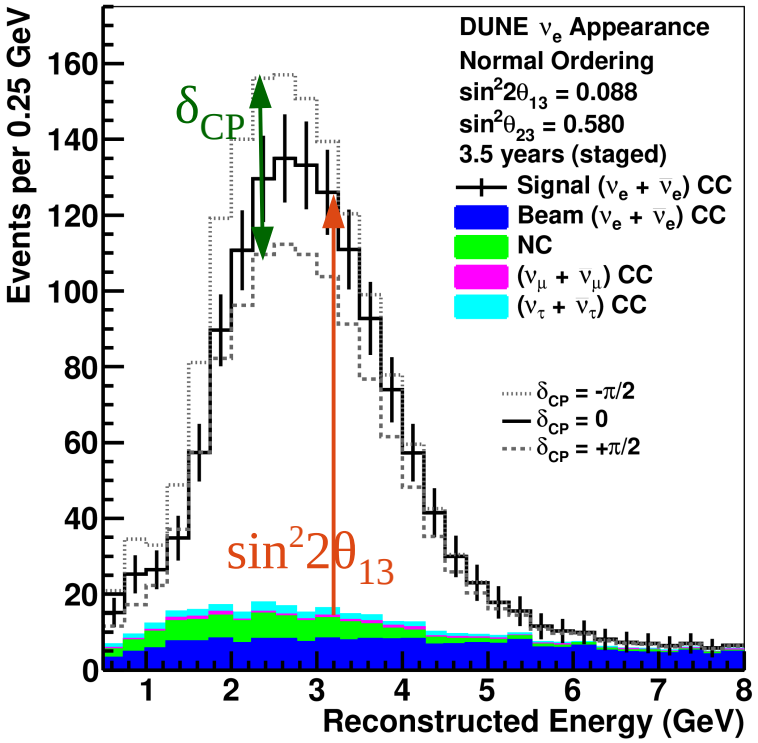




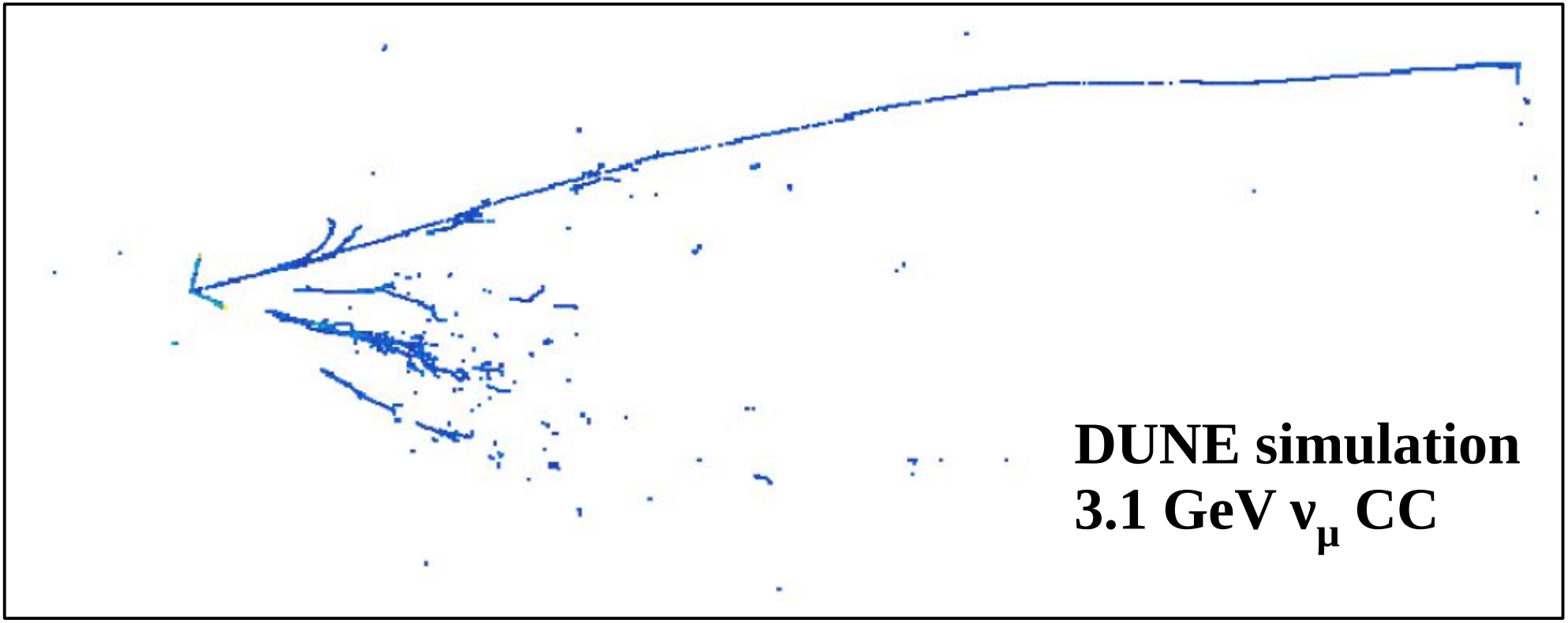
Cross section uncertainties

- ν_μ and ν_e total CC cross sections
- But also *exclusive* cross sections, which change the makeup of the final state, and thus impact how much of the neutrino energy is visible to DUNE



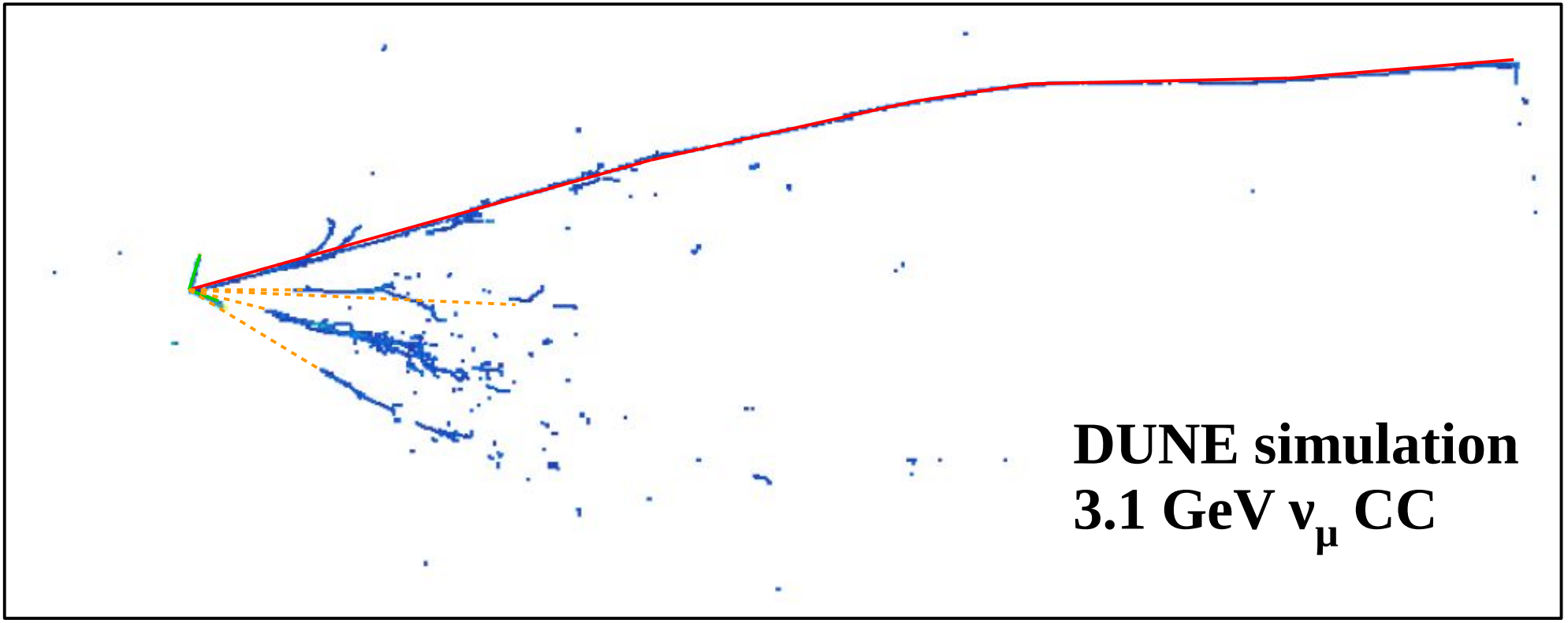


Neutrino energy reconstruction



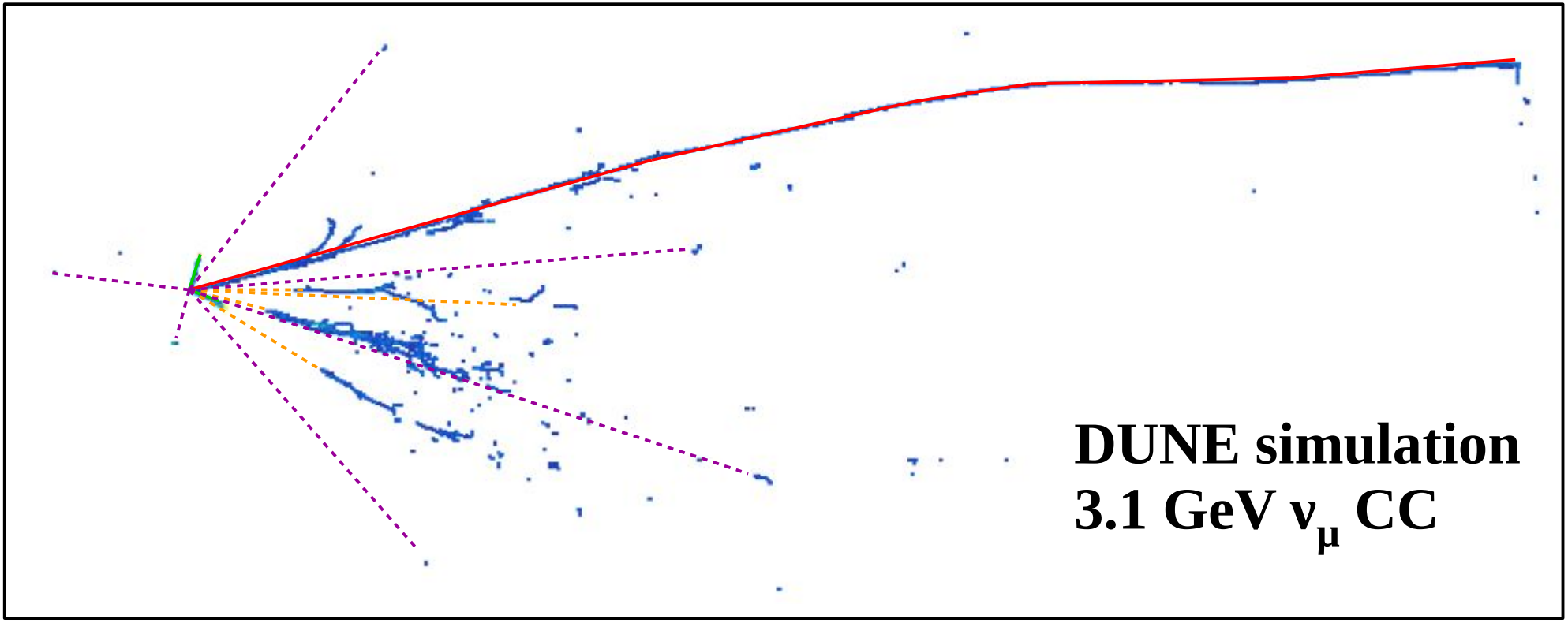
- Muon energy is reconstructed by range for fully-contained events
- Hadronic energy is reconstructed calorimetrically
- $E_\nu = E_\mu + E_{\pi^\pm} + E_{\pi^0} + E_p + E_n + \ldots$

Neutrino energy reconstruction



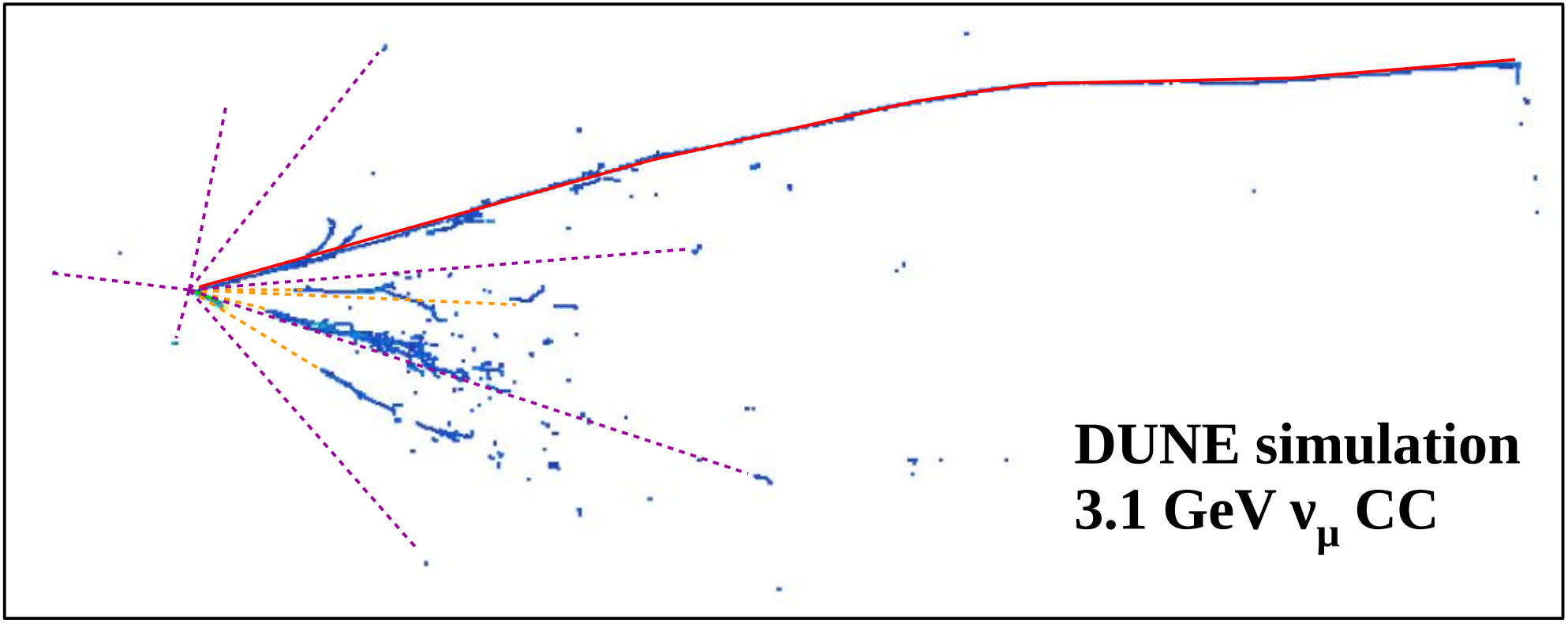
- Leptons, pions, and protons are all seen by DUNE, and can be reconstructed, albeit with somewhat different response functions
- $E_\nu = E_\mu + E_{\pi^\pm} + E_{\pi^0} + E_p + E_n + \ldots$

Neutrino energy reconstruction



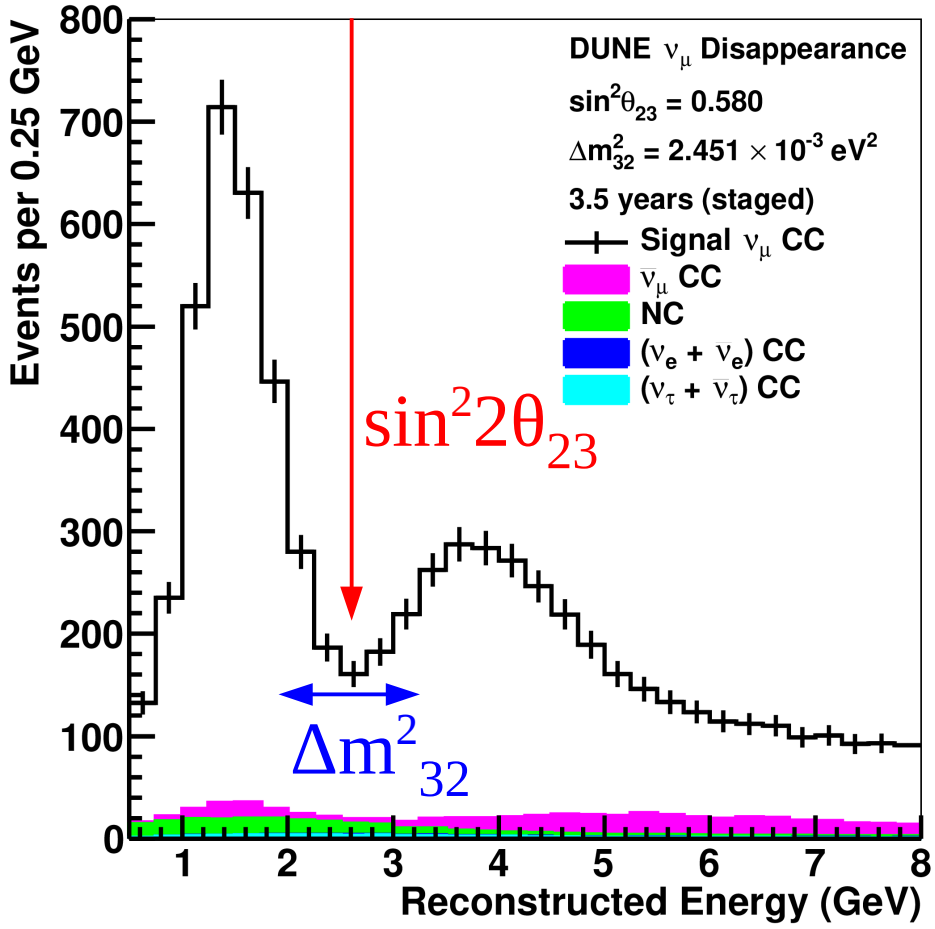
- Neutrons show up as small blips in the detector, and their energy is mostly lost, i.e. "missing energy"
- $E_\nu = E_\mu + E_{\pi^\pm} + E_{\pi^0} + E_p + E_n + \ldots$

Neutrino energy reconstruction



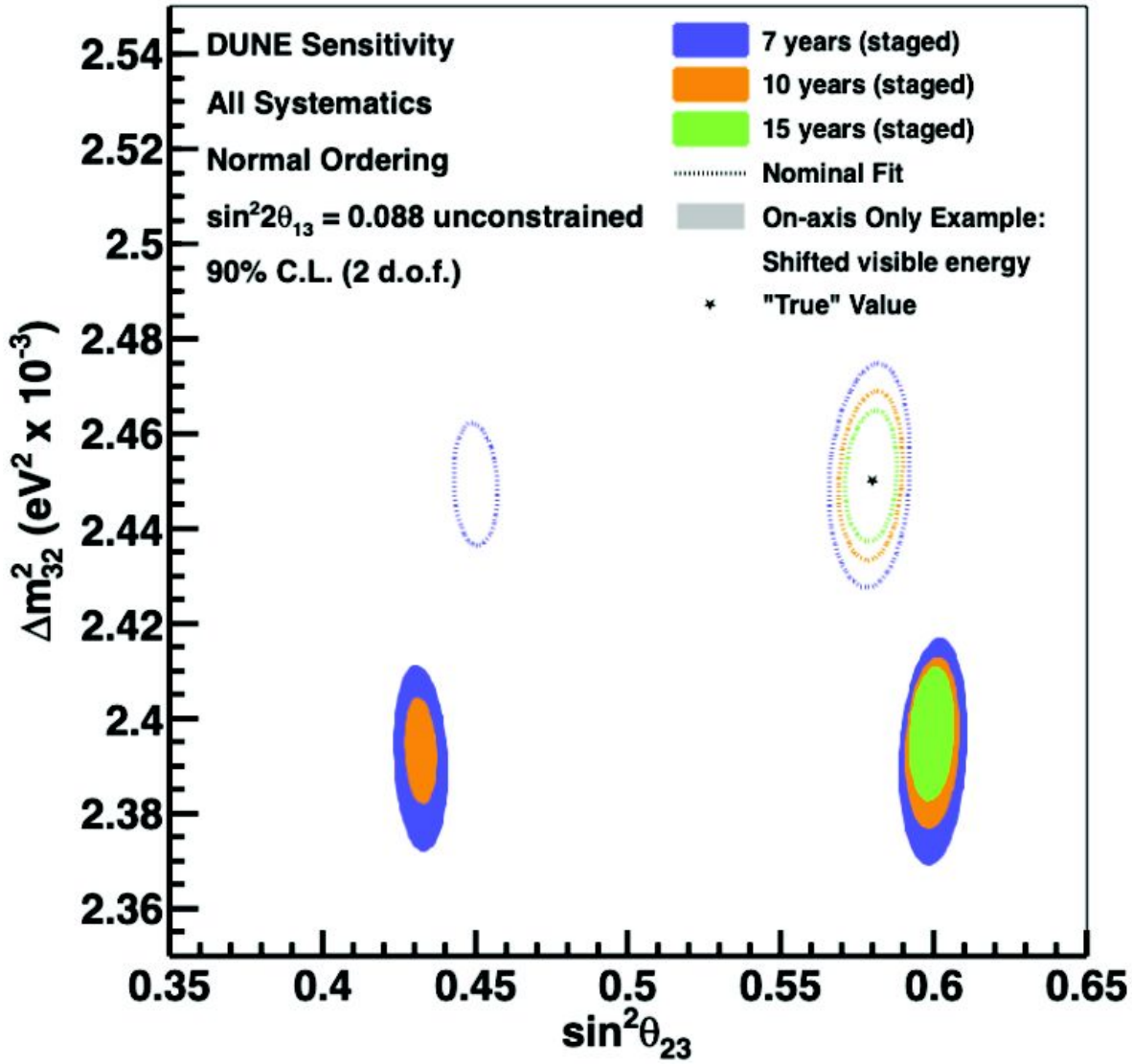
- If you change the composition of the final state, i.e. if there are more neutrons and fewer protons, then the reconstructed energy will be impacted
- $E_\nu = E_\mu + E_{\pi^\pm} + E_{\pi^0} + E_p + E_n + \ldots$

Neutrino energy reconstruction impacts oscillation parameters



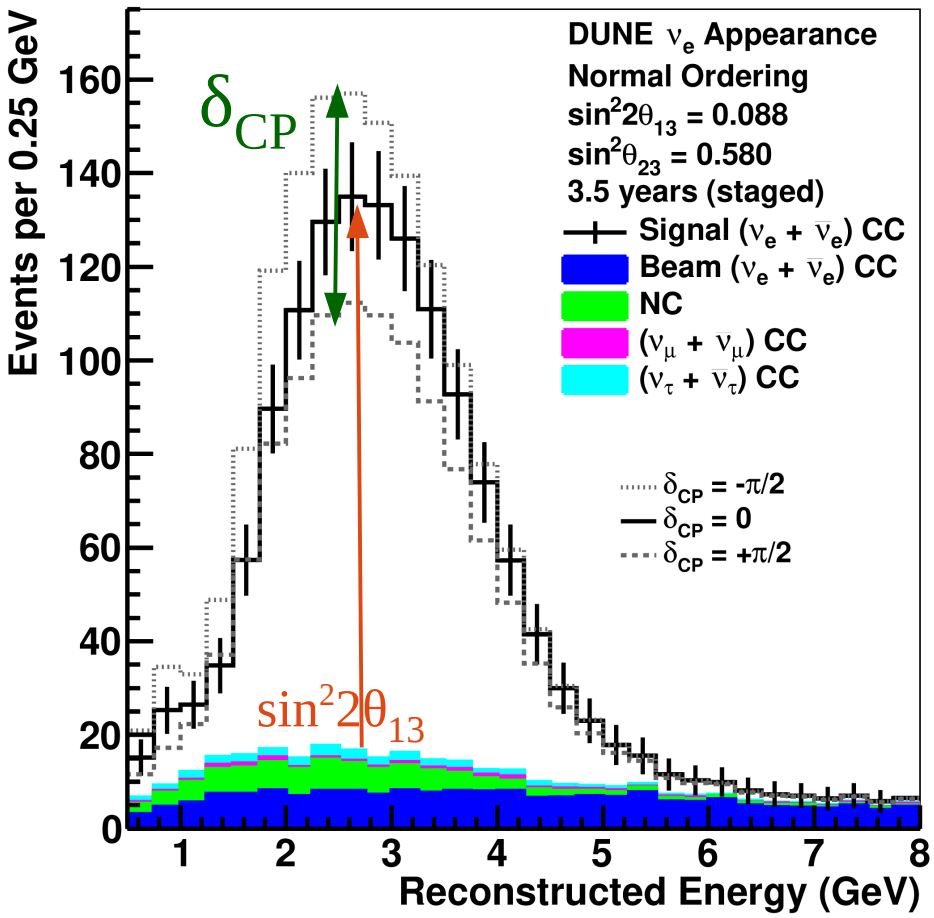
- ν_μ disappearance parameters are especially sensitive to energy misreconstruction
  - Absolute scale shift directly pulls Δm^2
  - Resolution uncertainties fill in the "dip" and drive $\sin^2 2\theta_{23}$
- Uncertainties in reconstructed energy can be due to detector effects (i.e. calibration uncertainties) or cross sections (i.e. neutron production uncertainties)

Example: 20% of final-state proton energy becomes neutrons



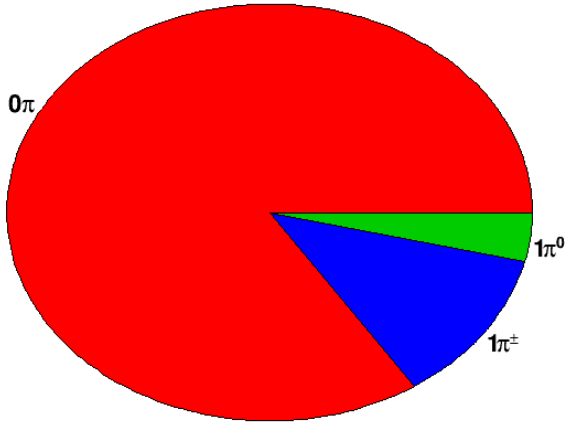
- Suppose the kinetic energy of final-state protons is decreased 20% (i.e. by giving energy to neutrons)
- Results in a ~3% shift in best-fit Δm^2
- In the next talk, Mike will describe how our ND design mitigates this type of uncertainty
- Similar effects could be obtained with shifts to detector absolute energy scale, for example

Important cross section & reconstruction systematics for δ_{CP}

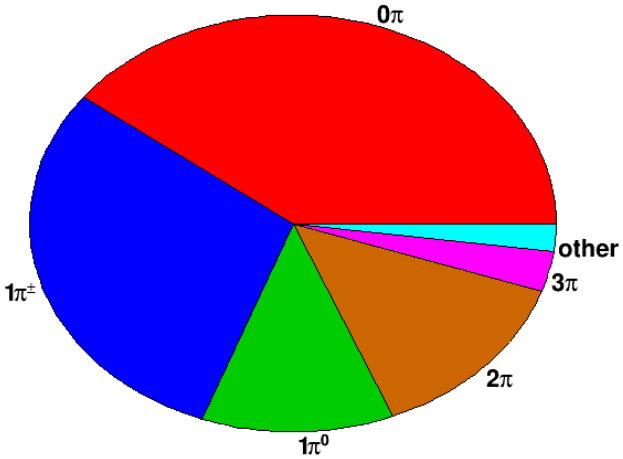


- Appearance spectra are less sensitive to absolute energy reconstruction
- But several other effects have significant impact on appearance:
  - Absolute EM energy scale in FD
  - Cross section uncertainties that only impact ν_e, i.e. effects in phase space forbidden in ν_μ CC
  - Cross section uncertainties that affect $\nu_e/\bar{\nu}_e$ ratio
- Beam ν_e is ~5% of total sample in the peak (thanks, large θ_{13}!)
- NC backgrounds are <5%, but large uncertainties on NC π^0

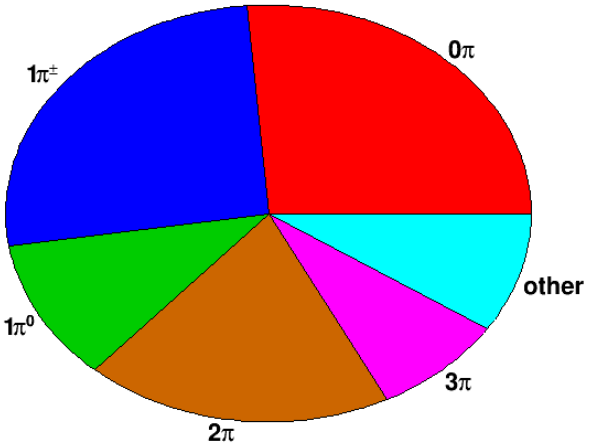
Event mixture in DUNE oscillation sample is very different from T2K



$0.4 < E_\nu < 0.8$ GeV



$2.3 < E_\nu < 2.7$ GeV

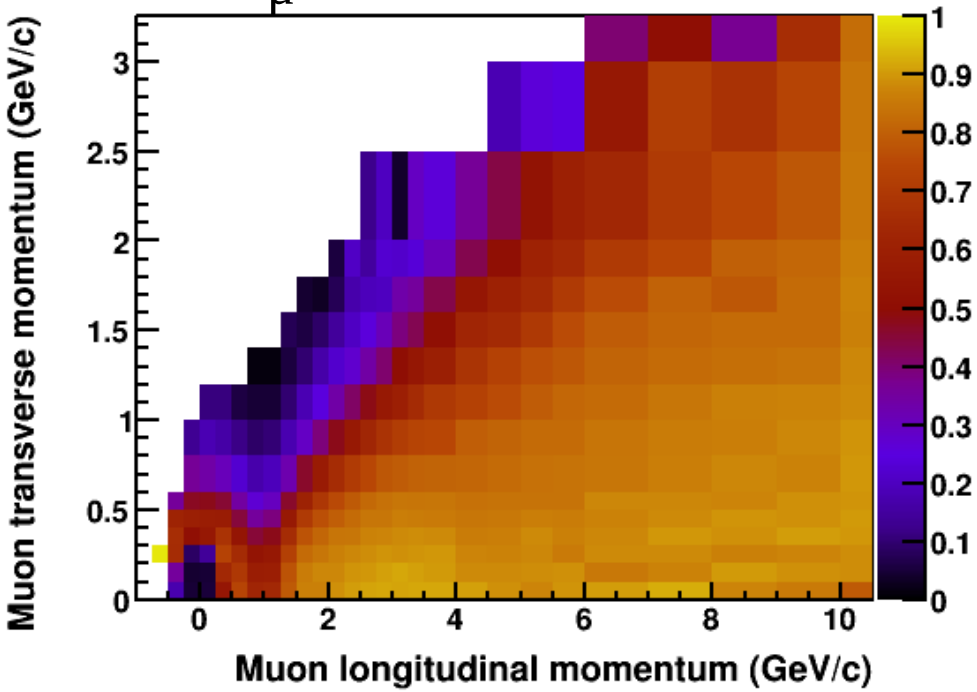


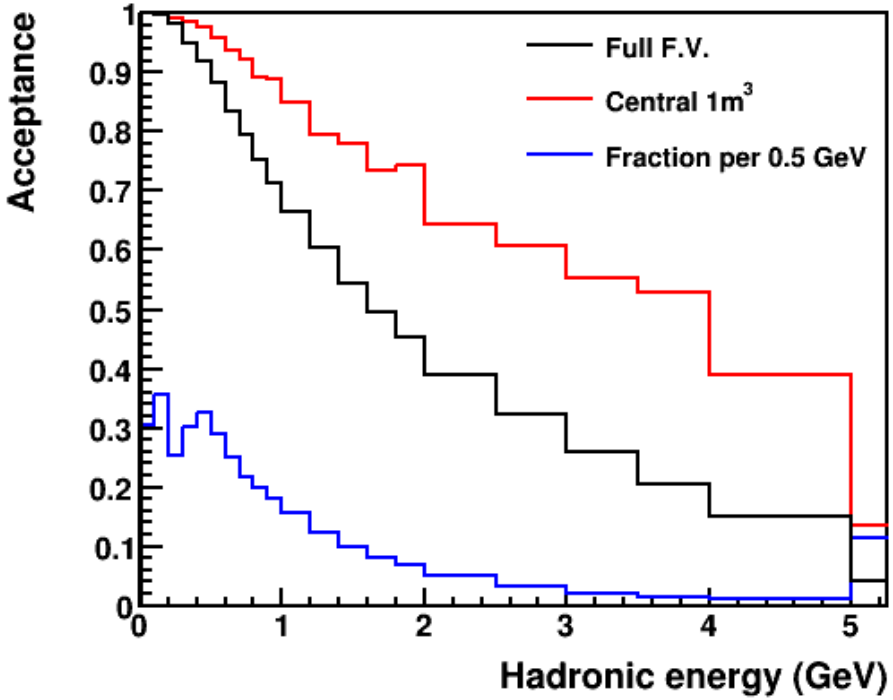
$4.0 < E_\nu < 4.5$ GeV

- GENIE "DefaultPlusValenciaMEC" on Ar
- DUNE oscillation peak region is roughly 40% 0π, 40% 1π, 20% 2+π
  - Compared to T2K ~85% 0π
- Huge amount of theory work has dramatically improved our modeling of CC0π – we need this same commitment to 1π, 2π, SIS/DIS, etc. for DUNE

Detector acceptance (LAr ND)

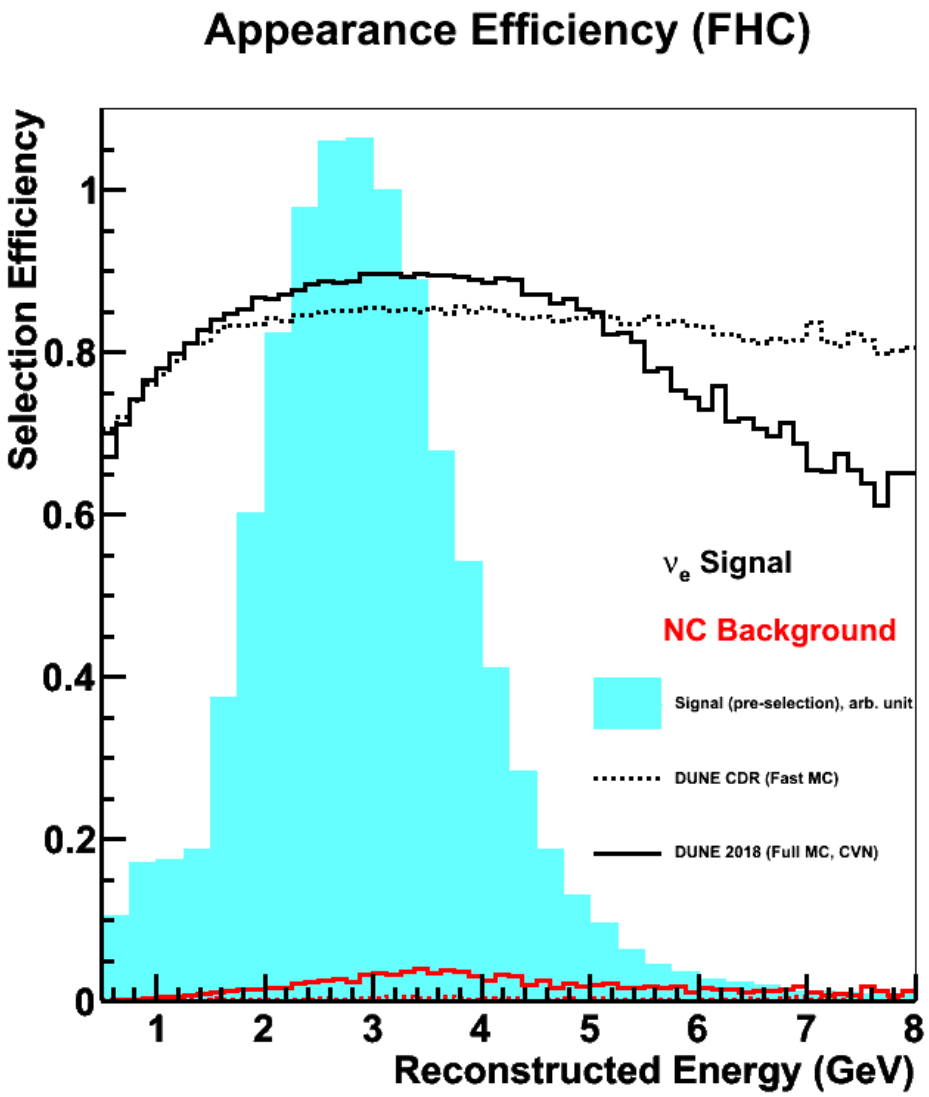
ν_μ CC acceptance





- LAr ND has reduced acceptance due to non-containment of muons and/or hadronic showers, but is designed such that there are no holes in the accepted phase space
- Differences in ND and FD acceptance will need to be corrected, but this is largely due to geometric effects
- HPgTPC in ND will also have 4π acceptance

Far detector selection efficiency



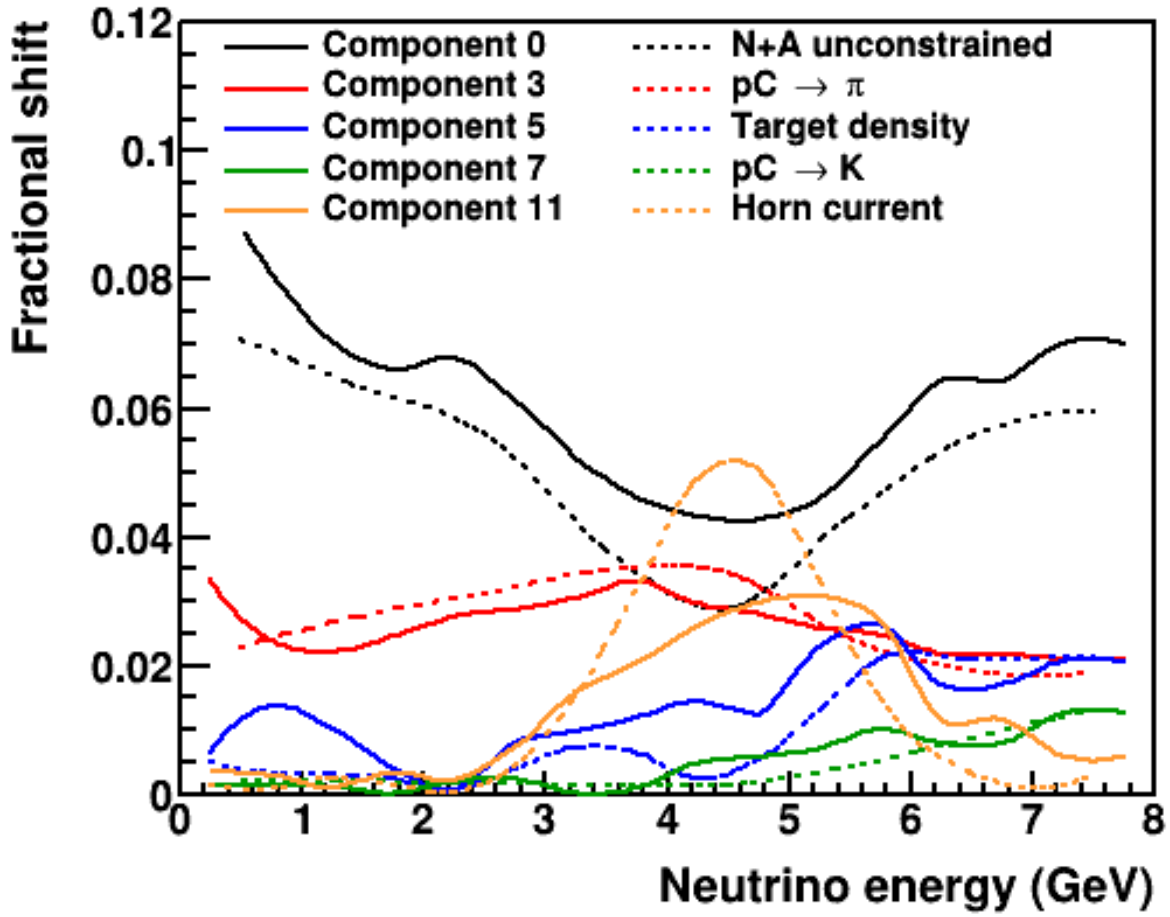
- ν_e CC in neutrino mode
- Full MC with CVN event selection (solid curve) is comparable to fast MC from CDR (dashed curve)
- 85-90% efficient in the region where most events are expected
- Must ensure that this efficiency is robust against interaction & detector models

Summary

- DUNE is sensitive to systematic uncertainties due to the flux prediction, neutrino interaction model, energy reconstruction, and detector acceptance & efficiency
- Highly-capable multi-system near detector is designed to reduce these uncertainties, as well as to resolve broad categories of potential effects (unknown unknowns)

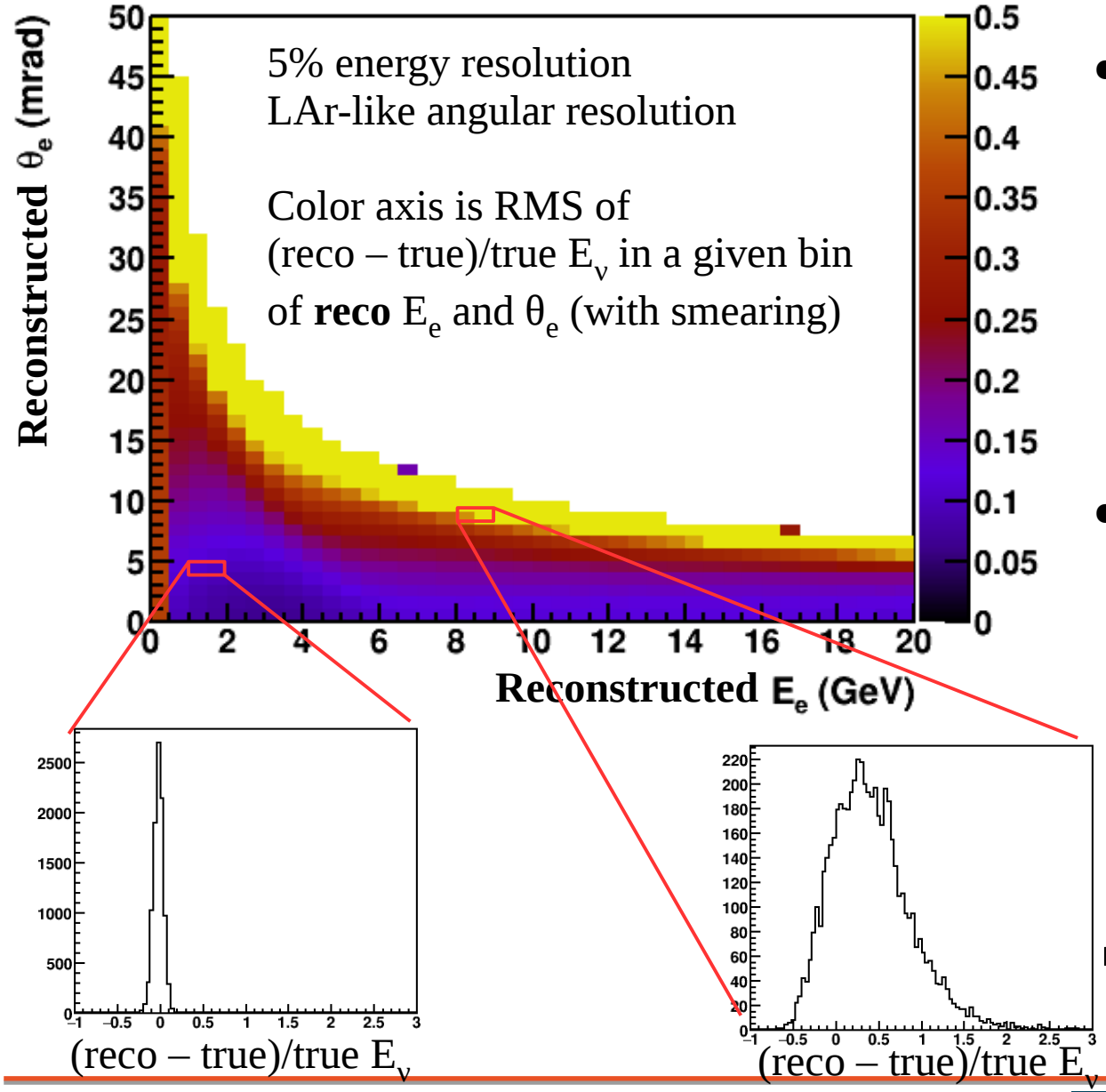
Backups

Flux uncertainty principal component analysis



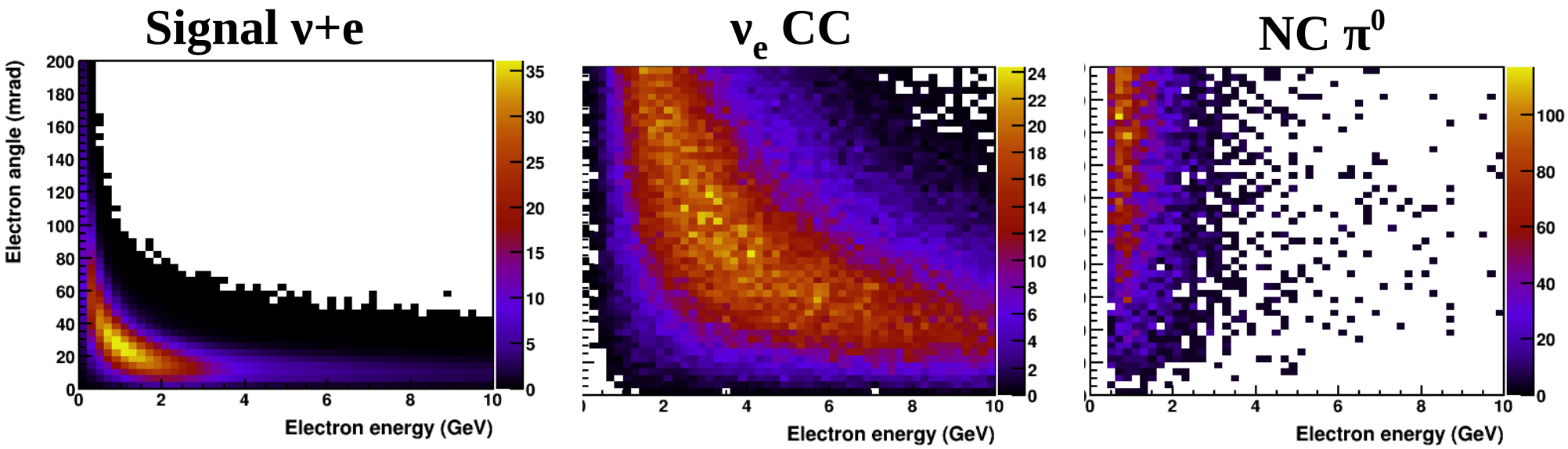
- The largest HP & focusing uncertainties show up as principal components of the full flux covariance
- The largest 30 components are treated as nuisance parameters in DUNE TDR sensitivity analysis

E_ν resolution vs. (E_e, θ_e)



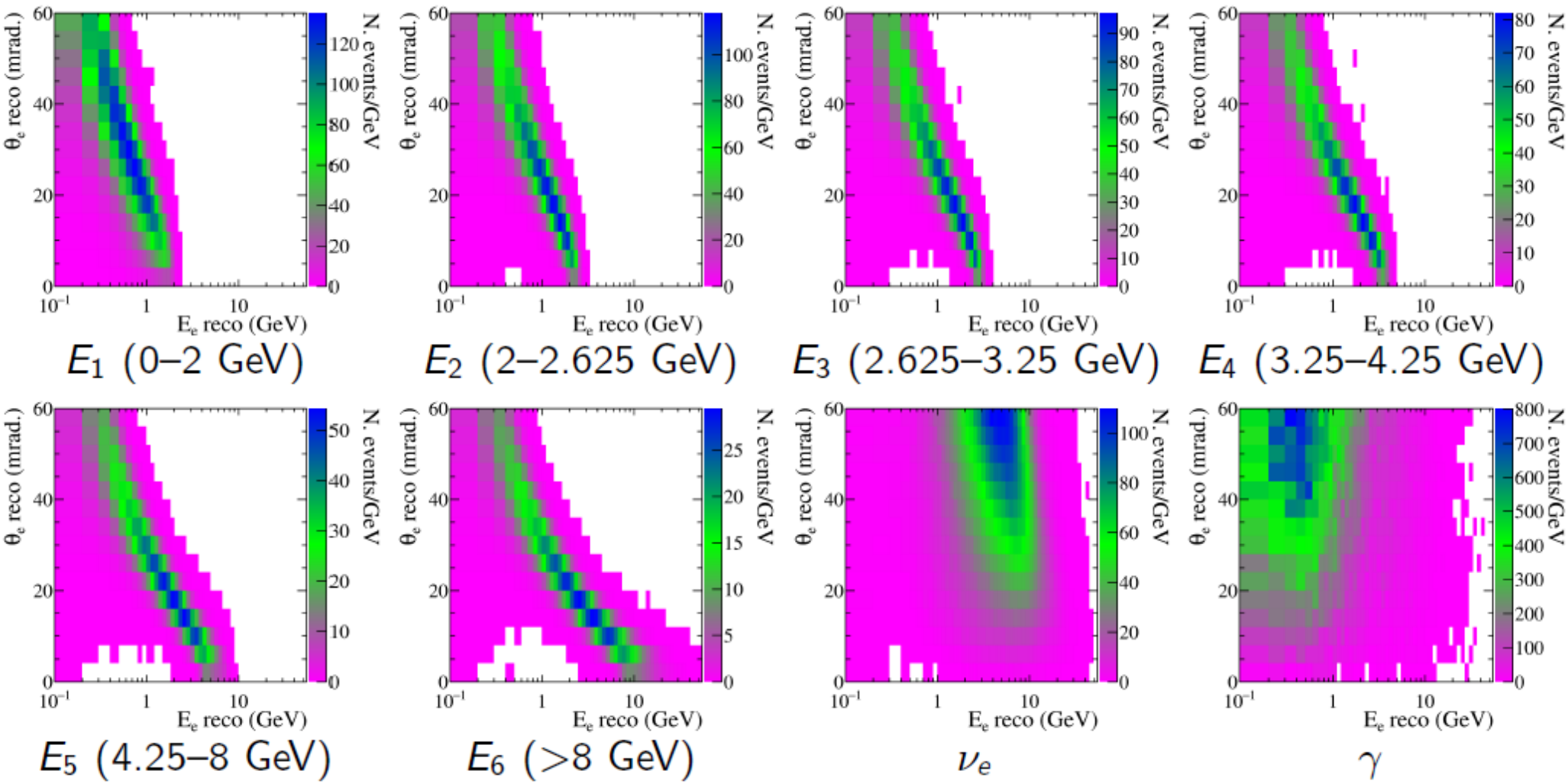
- Energy resolution is quite good in a region of (E,θ), basically where $E\theta^2$ is very small
- Effectively, select a subsample of good, and unbiased energy resolution and measure shape from it
- Requires very high statistics

ν+e scattering signal and backgrounds in E,θ



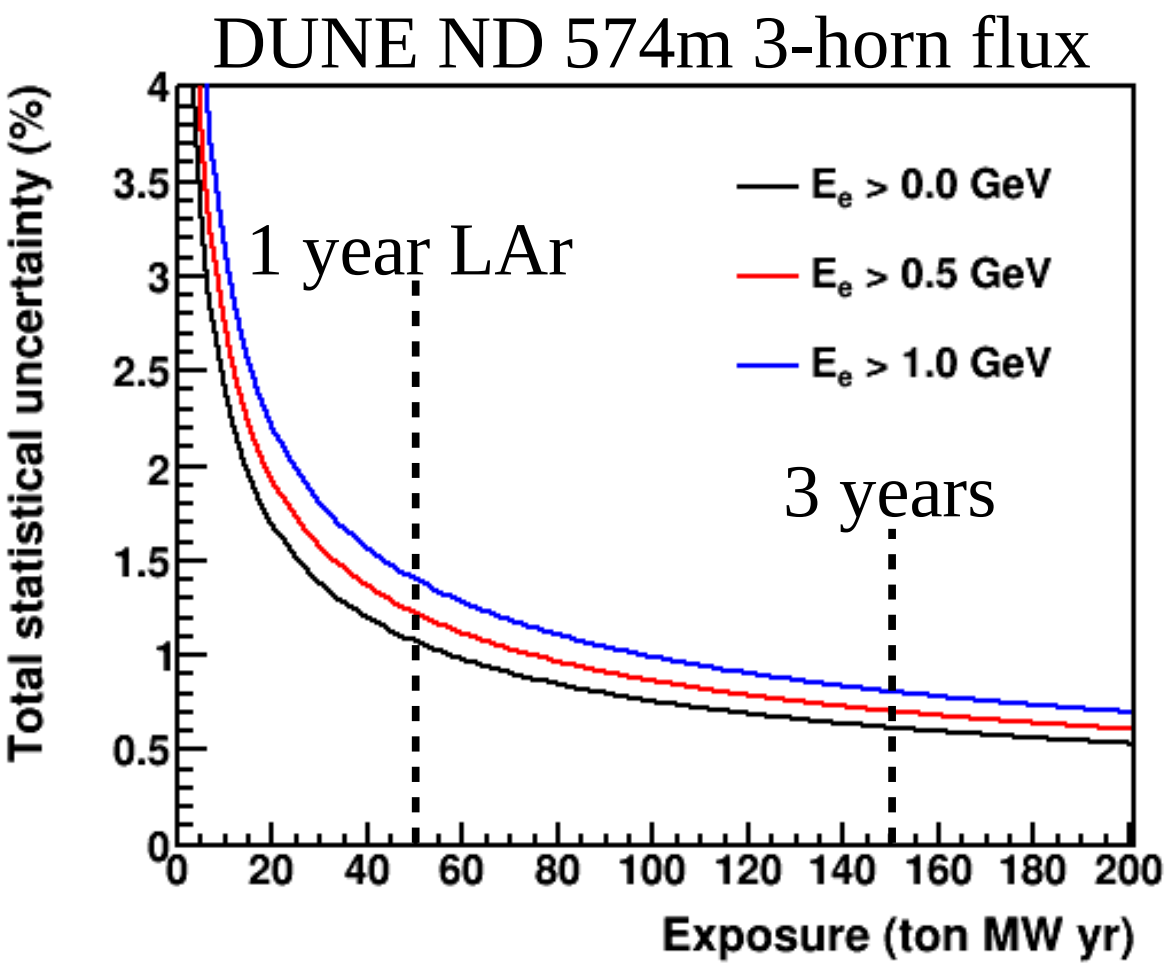
- Signal is subject to kinematic constraint $E_e\theta_e^2 < 2m_e$
- Dominant background is ν_e CC at very low Q^2
- But background shape in E, θ is very different from signal, and realistic uncertainties on background shape still do not produce signal-like distribution

2D templates for ν+e signal



- Each template is a bin of neutrino energy, and adds events in (E,θ)

DUNE ND ν+e statistics



- DUNE LAr ND at ~50t F.V. will have ~15k events in 3 years, even with very conservative thresholds
- >100x more statistics than MINERvA LE analysis

Cross section uncertainties

MaCCQE
VecFFCCQEshape
CCQEPauliSupViaKF
MaNCEL
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

Mnv2p2hGaussEnhancement
MKSPP_ReWeight
E2p2h_A_nu
E2p2h_B_nu
E2p2h_A_nubar
E2p2h_B_nubar
BeRPA_A
BeRPA_B
BeRPA_D
C12ToAr40_2p2hScaling_nu
C12ToAr40_2p2hScaling_nubar
nuenuebar_xsec_ratio
nuenumu_xsec_ratio
SPPLowQ2Suppression

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

GENIE ReWeight

MaCCQE
VecFFCCQEshape
CCQEPauliSupViaKF
MaNCEL
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

GENIE reweight parameters affecting

CC quasi-elastic

CC resonance production

CC deep inelastic scattering

Final-state interactions

Neutral currents

DUNEint not covered in GENIE

Additional parameters:

CC QE

CC Resonance

2p2h

Scaling C → Ar

ν_e/ν_μ or $\nu_e/\bar{\nu}_e$

Mnv2p2hGaussEnhancement
MKSPP_ReWeight
E2p2h_A_nu
E2p2h_B_nu
E2p2h_A_nubar
E2p2h_B_nubar
BeRPA_A
BeRPA_B
BeRPA_D
C12ToAr40_2p2hScaling_nu
C12ToAr40_2p2hScaling_nubar
nuenuebar_xsec_ratio
nuenumu_xsec_ratio
SPPLowQ2Suppression

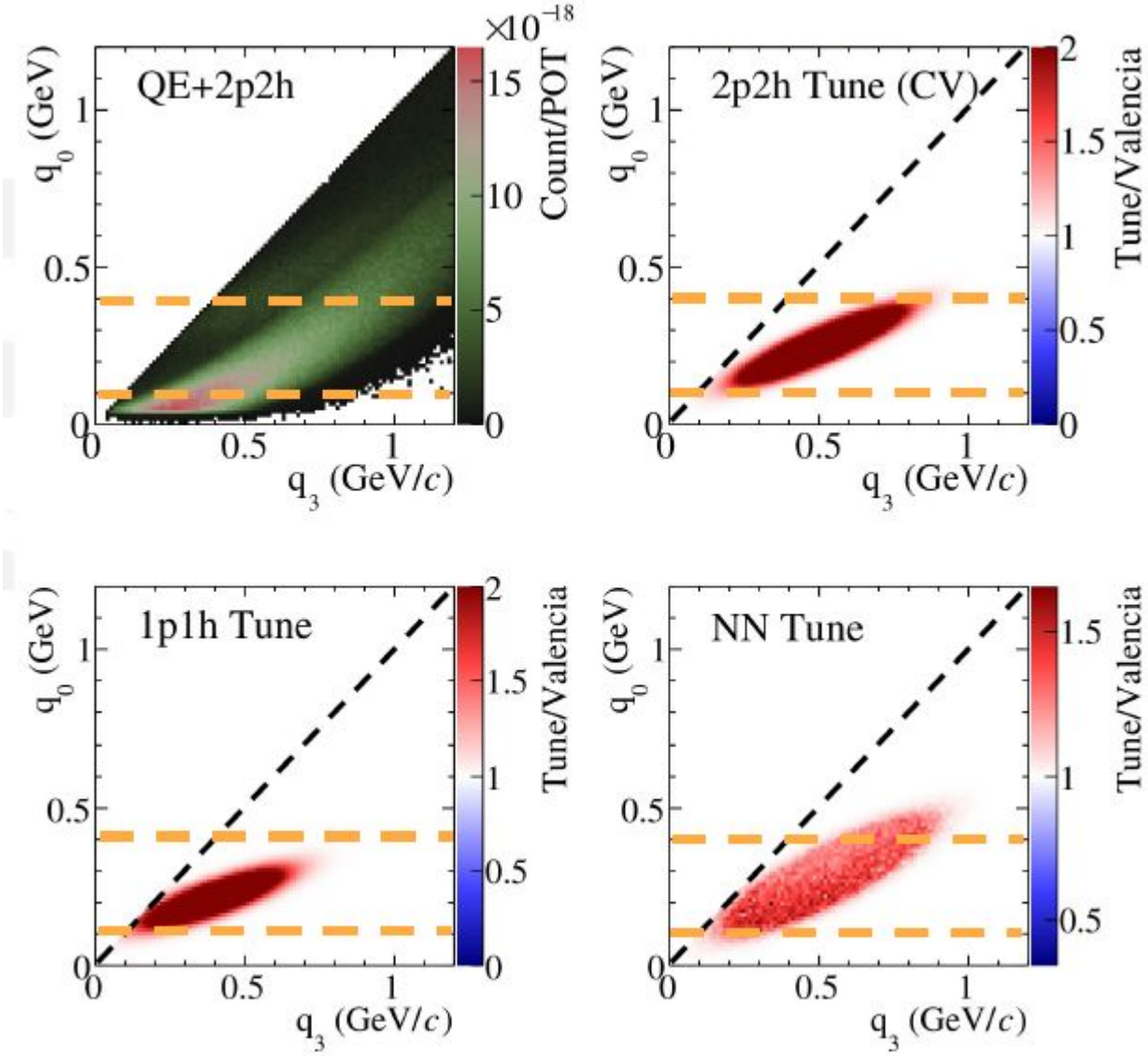
DUNEint not covered in GENIE

Additional parameters affecting non-resonant pion production

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

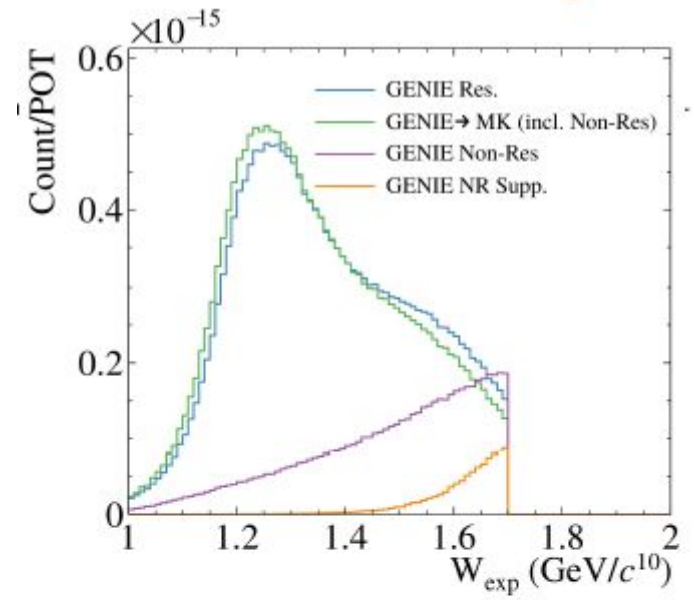
Example 1: uncertainty on "2-particle 2-hole" interactions

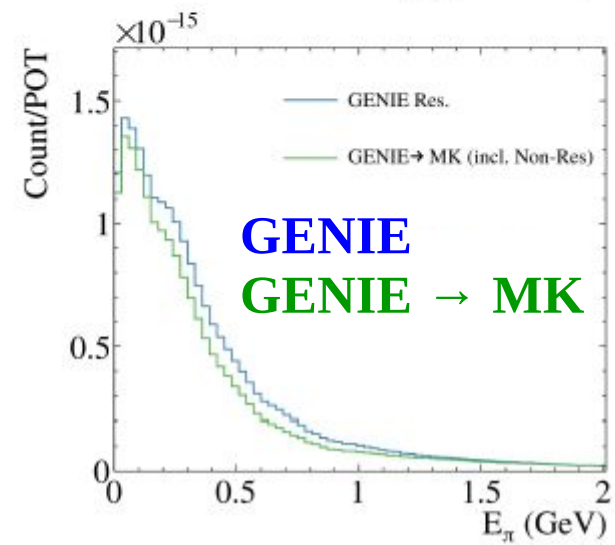
- MINERvA and NOvA see an enhancement in cross section that is consistent with multi-nucleon 2p2h scattering, i.e. $\nu_\mu(np) \rightarrow \mu^- nn$
- MINERvA can fit in 4 different ways: as 1p1h, nn only, pp only, 2p2h
- Implemented parameter moves events between nn → 2p2h → 1p1h



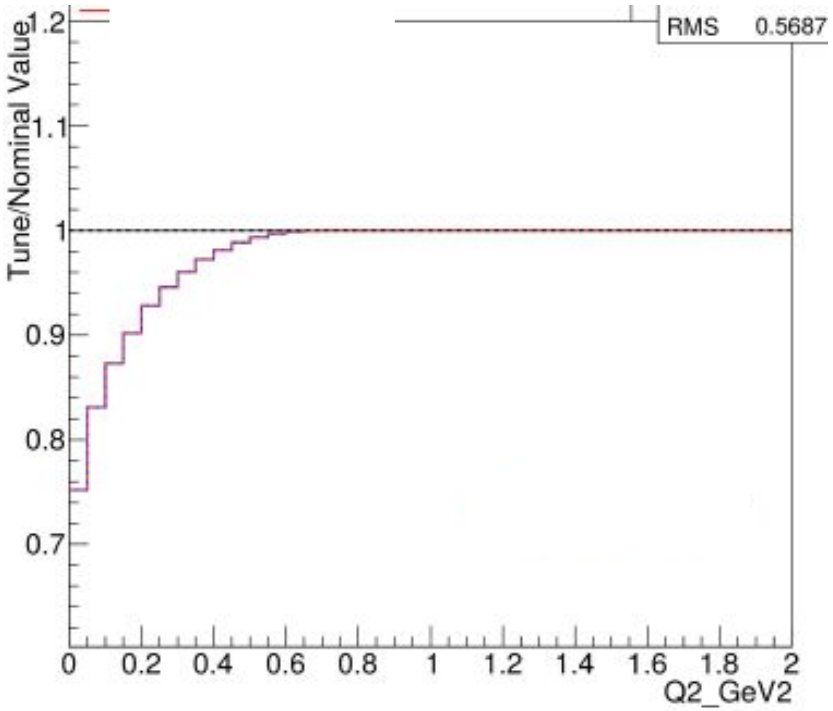
Example 2: Interference in single pion production

- CC1π is important contribution to DUNE oscillation signal
- GENIE's Rein-Sehgal resonant pion model lacks interference with non-resonant processes
- Our model includes this effect using the "MK model," which includes resonant, non-resonant, and interference terms
- Result in different W distribution and different hadron ejection
- Difference is treated as uncertainty



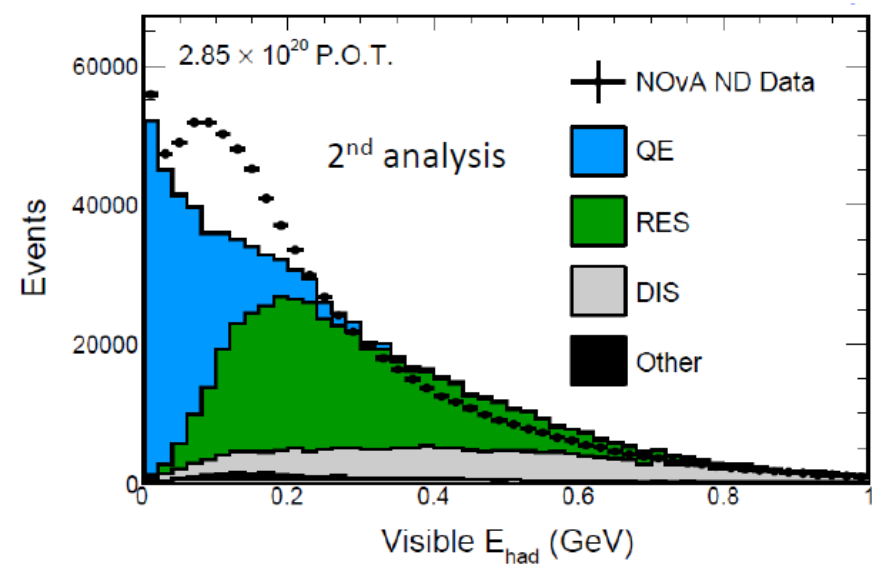


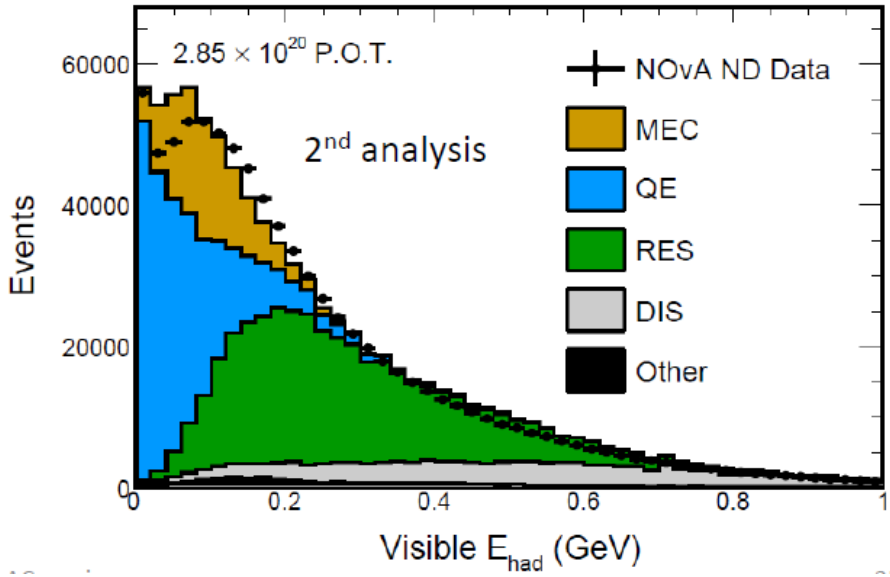
Example 3: Suppression in CC1π at low momentum transfer



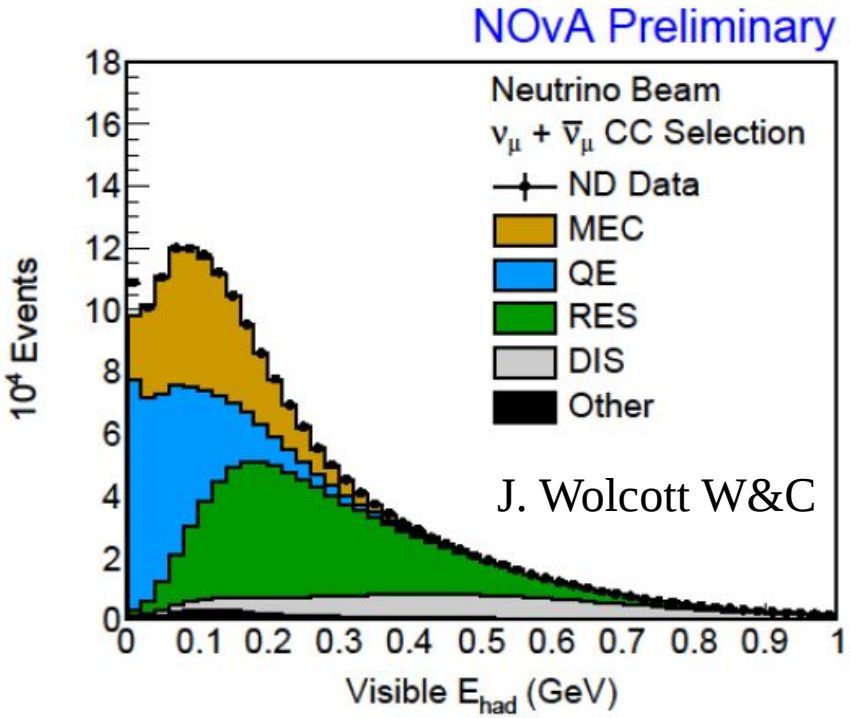
- MiniBooNE, MINERvA, NOvA, MINOS see a suppression at low Q^2 for single pion production
- Evaluated from a fit to MINERvA data compared to our version of GENIE
- DUNE cross section uncertainty includes physics beyond GENIE

Lesson from NOvA: significant MC tuning will be required to match ND

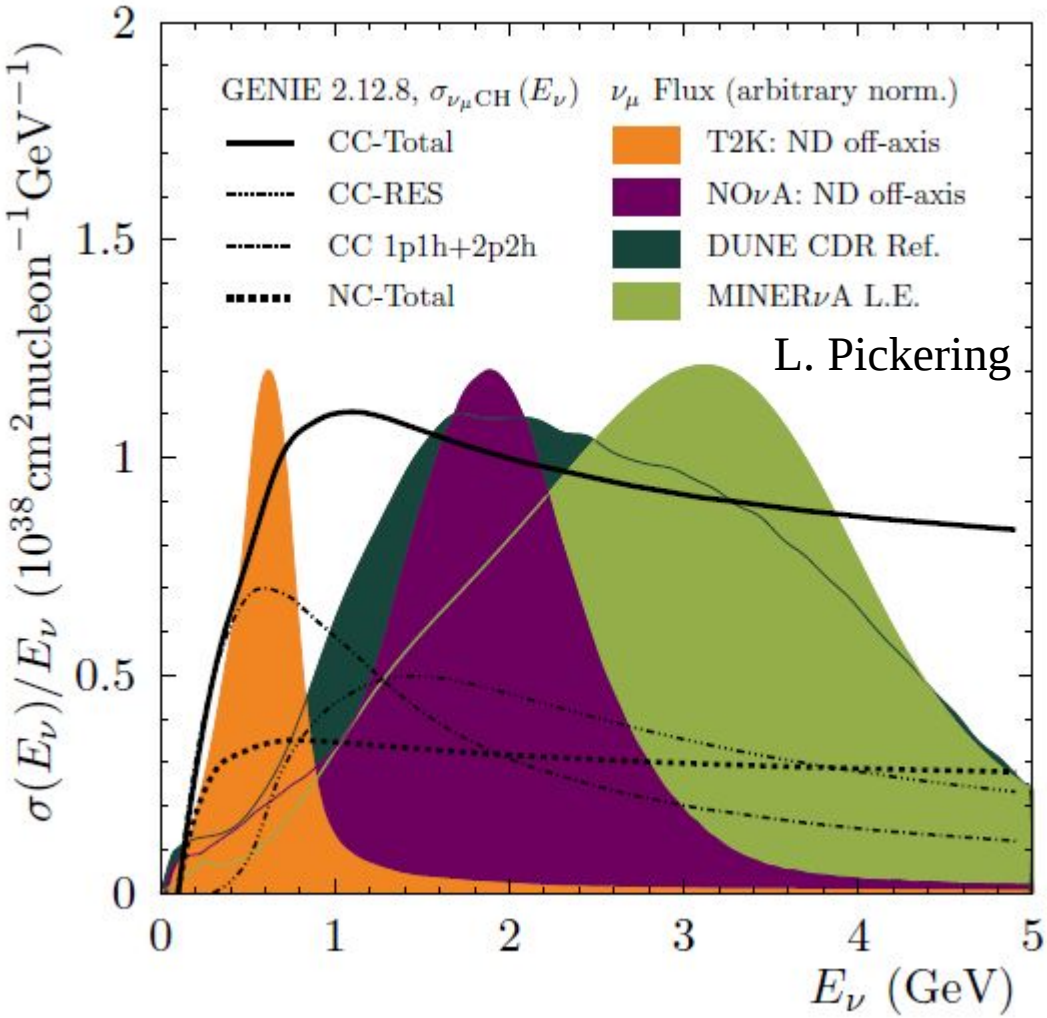




- Out-of-the-box GENIE RFG (top-left), with empirical 2p2h added (bottom left)
- Improved models and extensive cross section model tuning (right)

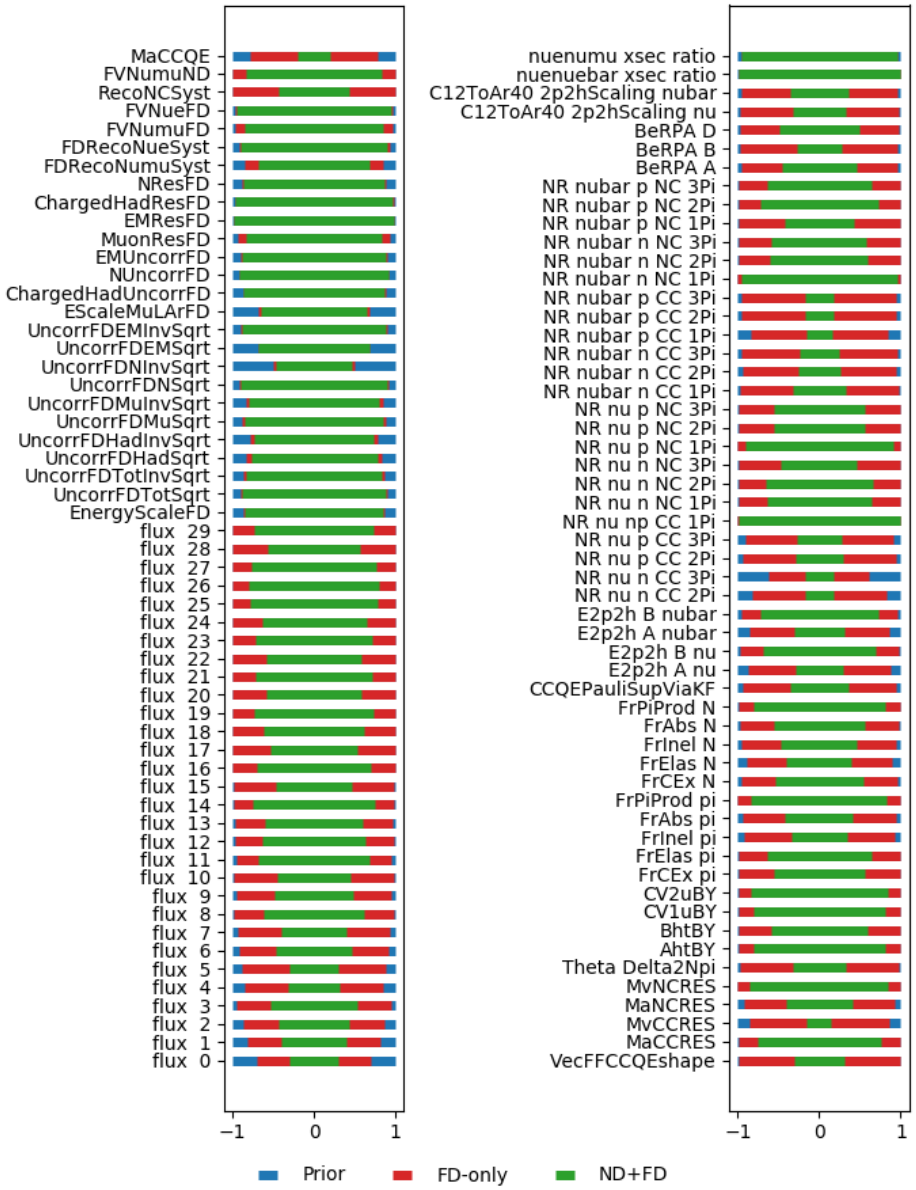


Event mixture in DUNE oscillation sample is different from T2K, NOvA



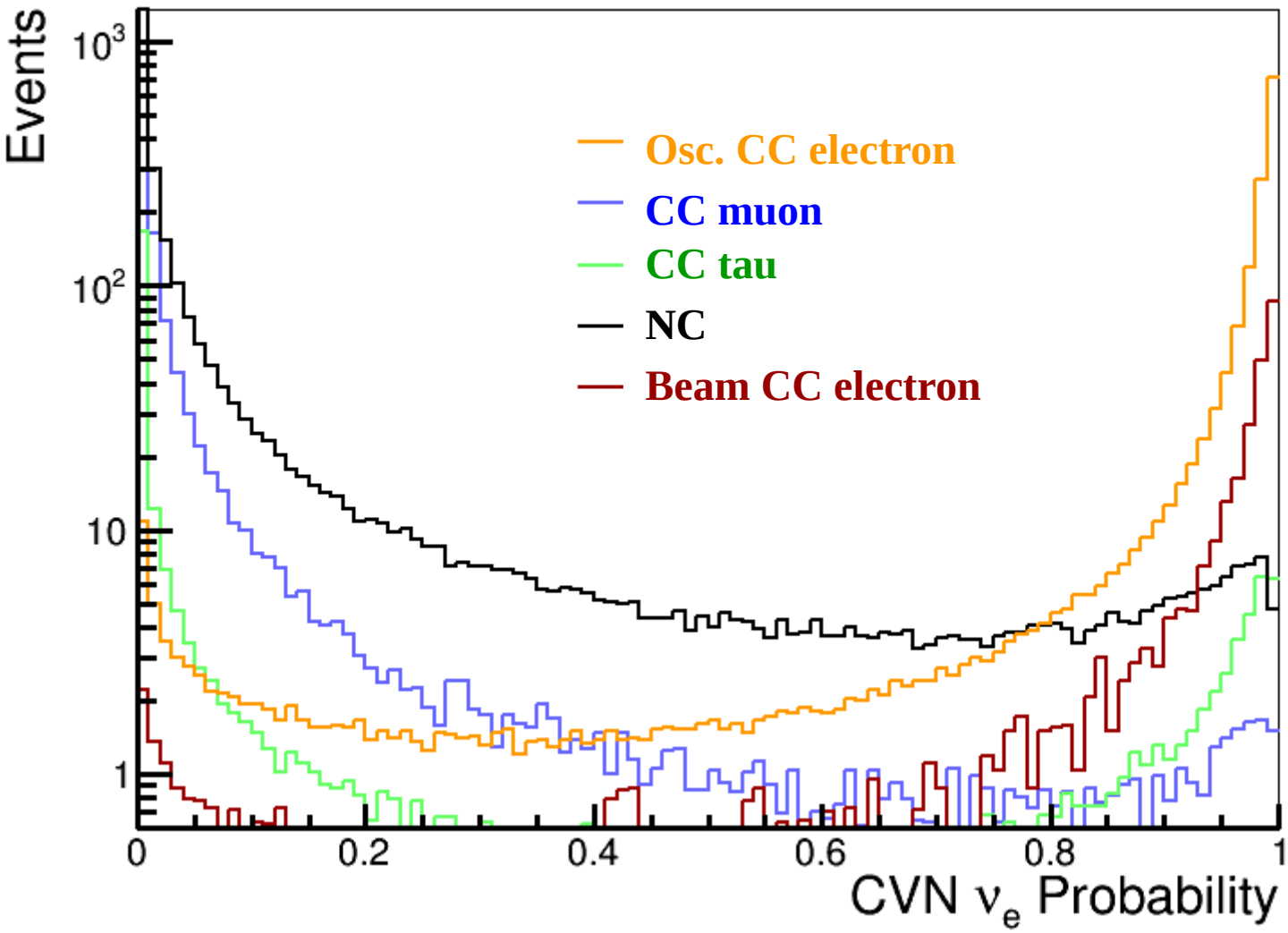
- DUNE oscillation maximum occurs where QE, resonant, and DIS interactions are all significant

Post-fit systematics in TDR



- Left panel is flux & FD detector effects, right panel is cross sections
- Generally very weakly constrained by FD alone, but become very constrained by ND

Far detector event selection: FHC ν_e CVN probability



- FHC event probabilities from CVN
- Cut at 0.85 for this analysis
- Selects oscillated and intrinsic electrons