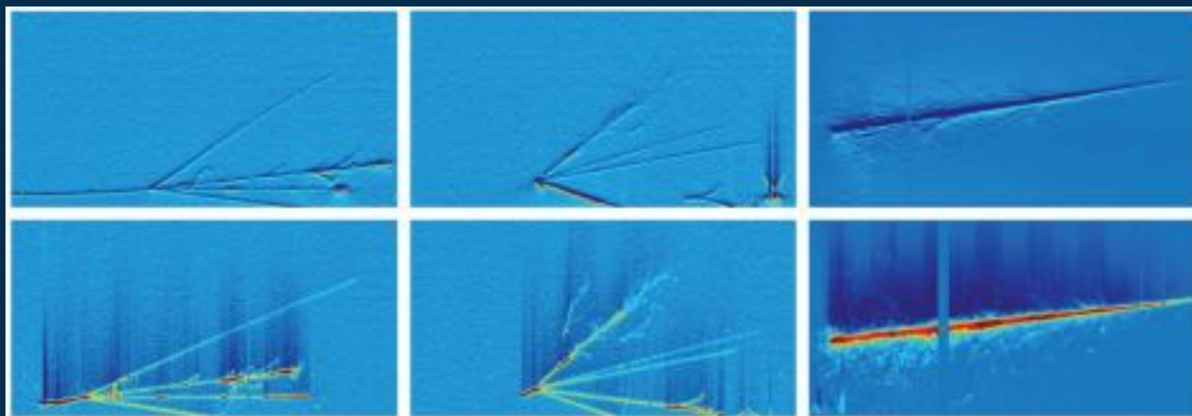
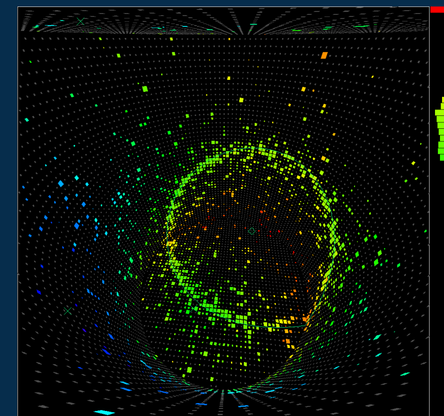




IMPACT OF SYSTEMATIC UNCERTAINTY ON FUTURE LONG-BASELINE OSCILLATION EXPERIMENTS

Elizabeth Worcester (Brookhaven National Lab)
Second International Meeting for Large Neutrino Infrastructures

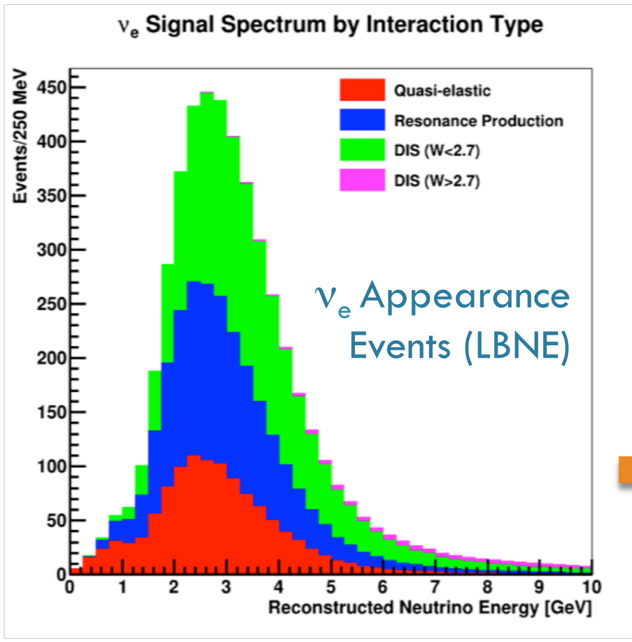
Overview

- Expectations for DUNE and HyperK
- Closer look at DUNE systematics studies
  - Sensitivity calculations
  - Analysis techniques
  - Constraining individual sources of systematic uncertainty
- Worldwide neutrino effort

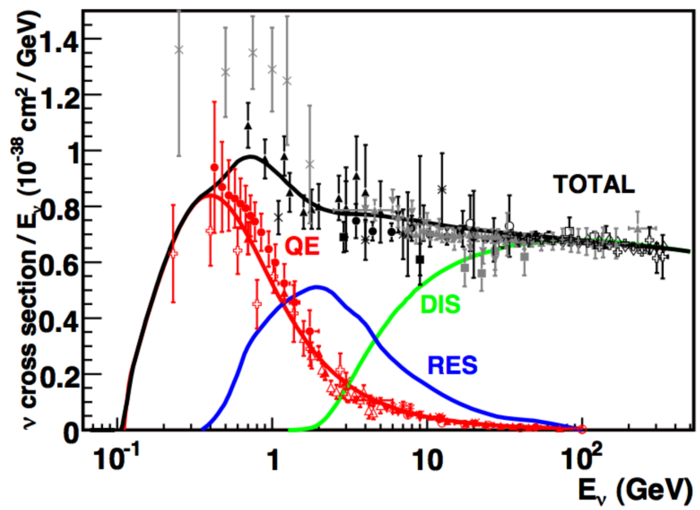
"The opinions expressed in this talk are not necessarily those of the DUNE collaboration…"

Info on HyperK taken from recent presentations by M. Shiozawa and M. Malek. Thank you!

Neutrino Events at DUNE



Significant contributions to event sample from QE, RES, DIS



DUNE LOI:

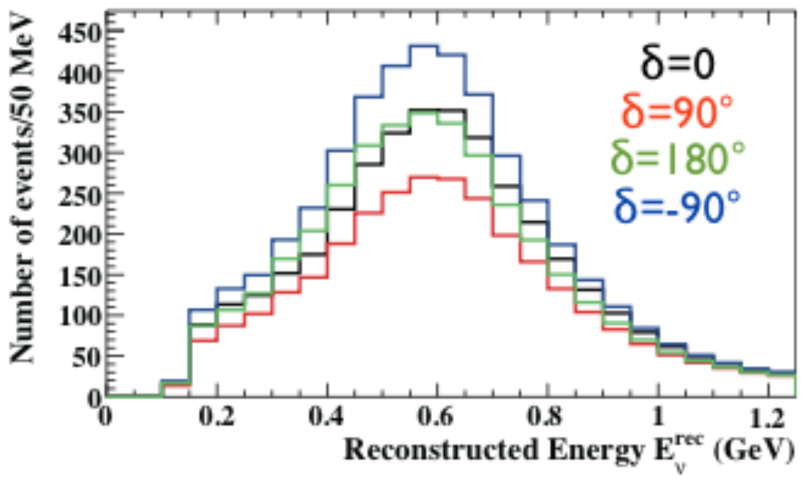
Run Mode	Signal Events			Background Events			
	δ_{CP}						
	$-\pi/2$	0	$\pi/2$	ν_μ NC	ν_μ CC	ν_e Beam	ν_τ CC
Neutrino	1068	864	649	72	83	182	55
Antineutrino	166	213	231	41	42	107	33

Exposure: 257 kt.MW.yr = 40 kt x 1.07 MW (80-GeV) x ($3\nu+3\bar{\nu}$) years

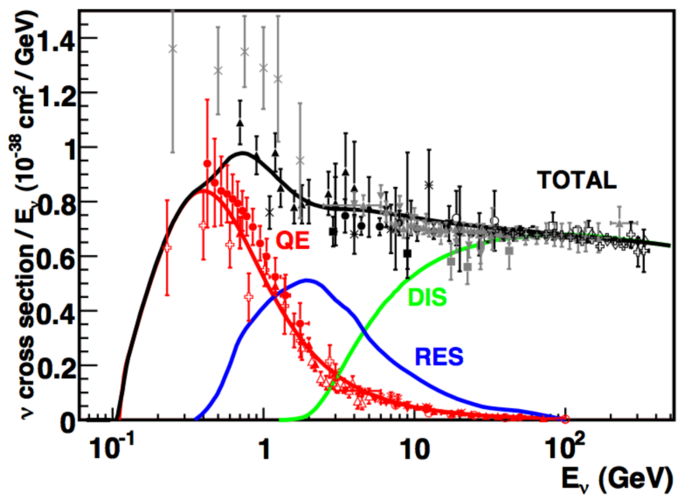
Note: depends on details of beam design!

Neutrino Events at HyperK

Neutrino mode: Appearance



Event sample dominated by QE, single pion production

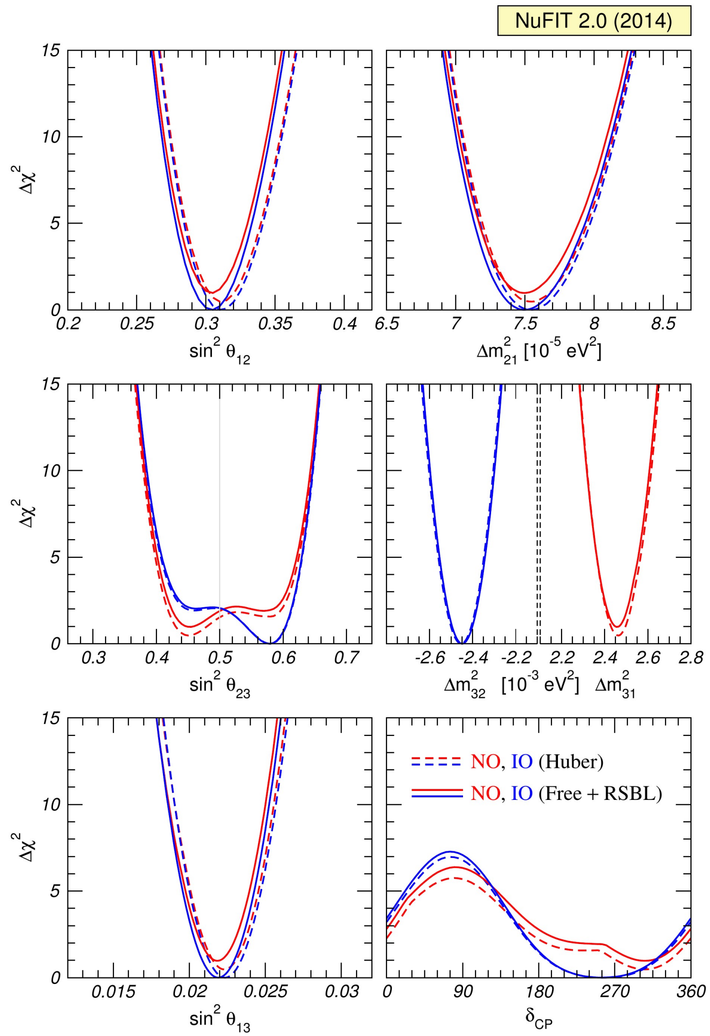


- Expected # of events for $\sin^2 2\theta_{13} = 0.1$, $\delta = 0$ and NH

(7.5 x 10⁷ MW·sec)

	Signal (νμ→νe CC)	Wrong sign appearance	νμ/ν̄μ CC	beam νe/ν̄e contamination	NC
ν	3,016	28	11	523	172
ν̄	2,110	396	9	618	265

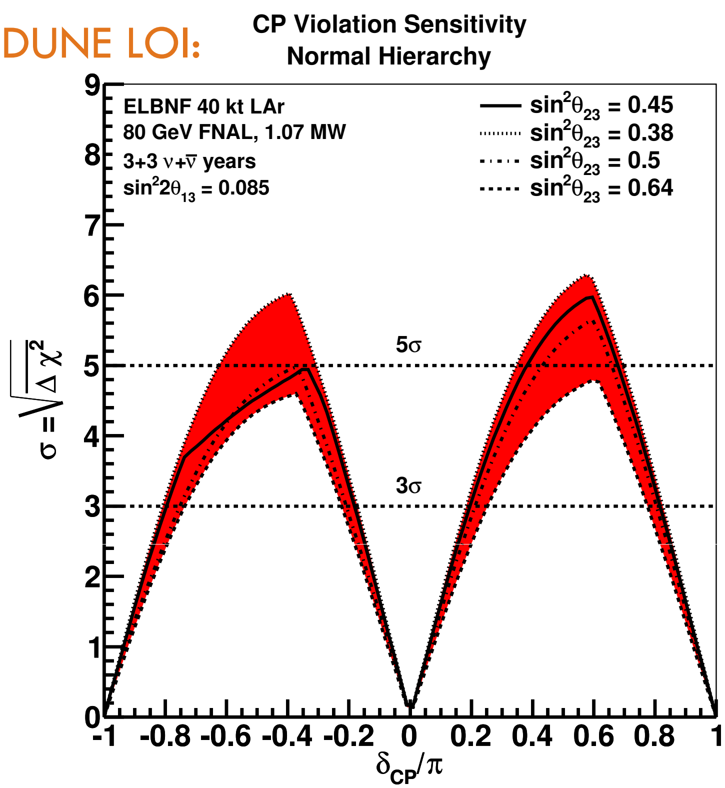
Neutrino Oscillation Parameters



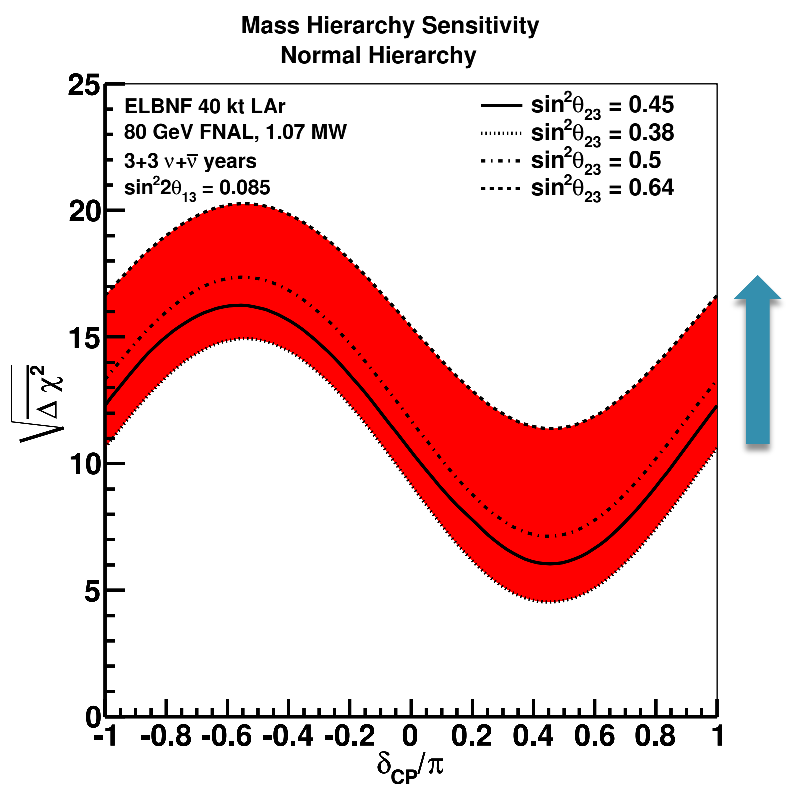
- NuFit 2014
  - http://www.nu-fit.org/
  - Includes results through Neutrino 2014
- Some preference for δ_{CP} near $-\pi/2$
- θ_{23} octant unknown
- IH slightly preferred (<1σ significance)
- Further constraints expected from existing and planned experiments:
  - External constraints on mixing angles improve early sensitivity
  - Measurement of neutrino MH critical for HyperK CPV sensitivity
  - Measurements or even hints of MH or δ_{CP} value could influence run plans

Effect of θ_{23} Uncertainty

DUNE LOI:



Increasing θ_{23}

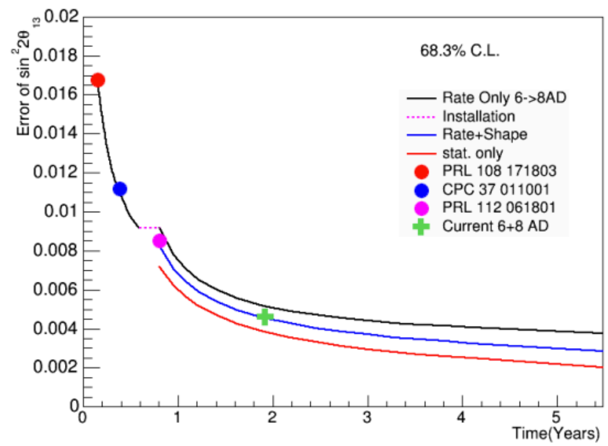


$$\mathcal{A}_{CP} \sim \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta_{\rm CP}}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right) + \text{matter effects}$$

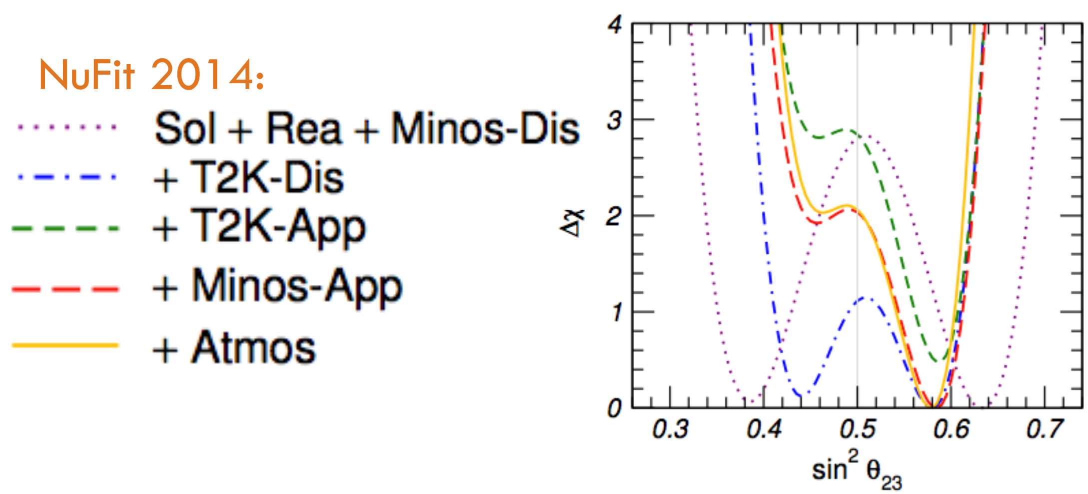
Prospects for Improved Oscillation Parameter Measurements

- Daya Bay measurement of θ_{13} projected to reach ~1.5% precision (currently 2.5%)
- JUNO measurement of $|\Delta m^2_{32}|$ predicted to have <1% precision (currently ~2%)
- NOvA, T2K, SuperK, & PINGU data all expected to improve precision on θ_{23}

Daya Bay projected sensitivity:



NuFit 2014:



Systematic Uncertainty in HyperK

Uncertainty on the expected number of events at Hyper-K (%)

	ν mode		anti-ν mode		(T2K 2014)	
	νe	νμ	$\bar{\nu}$e	$\bar{\nu}$μ	νe	νμ
Flux&ND	3.0	2.8	5.6	4.2	3.1	2.7
XSEC model	1.2	1.5	2.0	1.4	4.7	5.0
Far Det. +FSI	0.7	1.0	1.7	1.1	3.7	5.0
Total	3.3	3.3	6.2	4.5	6.8	7.6

- Flux uncertainty similar to T2K
- Cross-section modeling uncertainty from nuclear difference reduced by water measurements in ND
- FD uncertainty reduced by larger control samples

Systematic Uncertainty in DUNE

- Goals for individual sources of systematic uncertainty determined based on previous experience: compare to MINOS & T2K
- DUNE will be like MINOS in some ways and like T2K in other ways
- For each case, DUNE will do a bit better than the experiment that it is most like
- Expect some significant cancellation in 4-sample fit
- This only an educated guess at reasonable goals – detailed DUNE-specific studies are required and in progress

DUNE LOI:

Source of Uncertainty	MINOS ν_e	T2K ν_e	ELBNF ν_e	Comments
Beam Flux after N/F extrapolation	0.3%	2.9%	2%	MINOS is normalization only. ELBNF normalization and shape highly correlated between ν_μ/ν_e.
Neutrino interaction modeling				
Simulation includes: Hadronization Cross sections Nuclear models	2.7%	7.5%	~2%	Hadronization models are better constrained in the ELBNF LArTPC. N/F cancellation is larger in MINOS/ELBNF. Cross-section uncertainties are larger at T2K energies. Spectral analysis in ELBNF provides extra constraint.
Detector effects				
Energy scale (ν_μ)	3.5%	included above	(2%)	Included in ELBNF ν_μ sample uncertainty only in 3-flavor fit. MINOS dominated by hadronic scale.
Energy scale (ν_e)	2.7%	3.4% Includes all FD effects	2%	Totally active LArTPC with calibration and test beam data lowers uncertainty.
Fiducial volume	2.4%	1%	1%	Larger detectors = smaller uncertainty.
Total	5.7%	8.8%	3.6 %	Uncorrelated ν_e uncertainty in full ELBNF 3-flavor fit = 1-2%.

Note: T2K uncertainties from 2013

DUNE Systematics

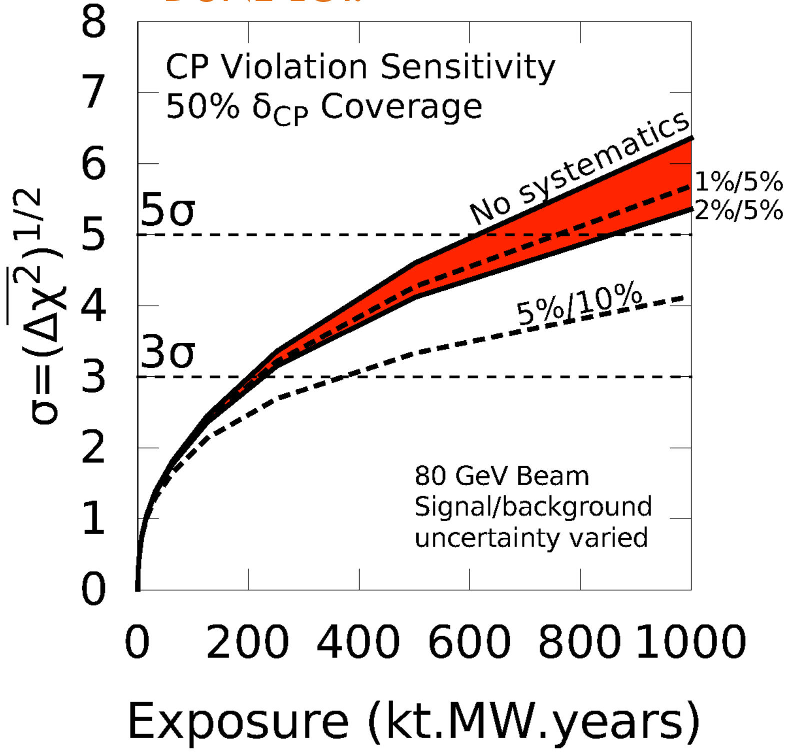
A closer look

Treatment of Uncertainty in DUNE Sensitivity Calculations

- DUNE long-baseline physics sensitivities are based on GLoBES calculations
  - Inputs from G4LBNE (beam simulation), GENIE (neutrino interactions), Fast MC (energy smearing & efficiencies)
  - Oscillation parameters from NuFIT
  - Educated guess about expected level of systematic uncertainty
- Effect of systematic uncertainty approximated using signal and background normalization uncertainties
- Signal normalization uncertainties are treated as *uncorrelated* among the modes (ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$) and represent the residual uncertainty expected after constraints from the near detector and the four-sample fit are applied
  - $\nu_\mu = \bar{\nu}_\mu = 5\%$ → Flux uncertainty after ND constraint
  - $\nu_e = \bar{\nu}_e = 2\%$ → Residual uncertainty after ν_μ and $\nu/\bar{\nu}$ constraint
- Individual background normalization uncertainties have appropriate correlations (eg: NC and ν_μ background normalization is correlated)

Effect of Normalization Uncertainty

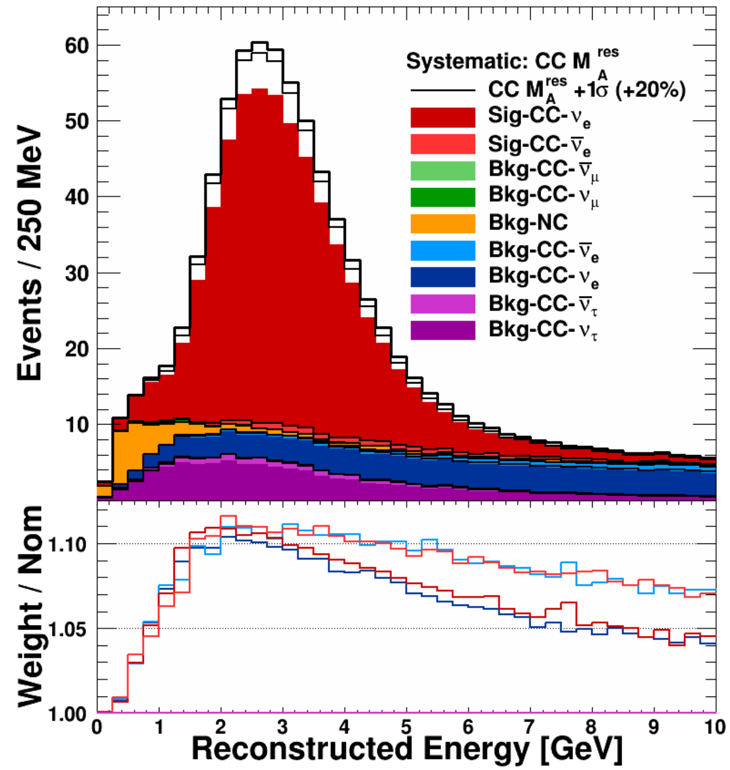
DUNE LOI:



- Actual experimental sensitivity to systematic uncertainty will depend on details of the neutrino beam and detector performance and will include both normalization and shape uncertainty
- Example shown here demonstrates:
  - Statistically limited for early stages of the experiment up to ~100 kt-MW-years
  - Control of normalization uncertainty at the few % level may be needed for discovery of CP violation at the 5σ level
  - Much work to do, but some time in which to do it!

Analysis Tool: Fast MC

- Fast MC = Flux simulations + GENIE + parameterized detector response
  - Detector response parameterization based on inputs from LArSoft simulations, GEANT4, and ICARUS
- Reconstructed quantities and selection criteria based on realistic kinematics
- Reweighting technique will provide ability to study sensitivity to uncertainties in cross-sections, hadronization model, FSI, beam line optics, beam design choices, and energy scale/resolution
- GLoBES-based sensitivity calculations using Fast MC inputs

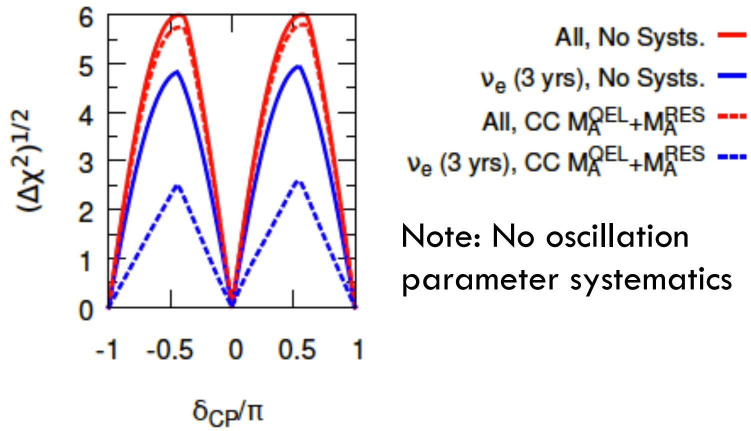


Example: ν_e appearance spectrum showing variation that is induced by changing the value of M_A^{RES} by $+1\sigma$ in the simulation

Example: Constraining Cross Sections with Far Detector

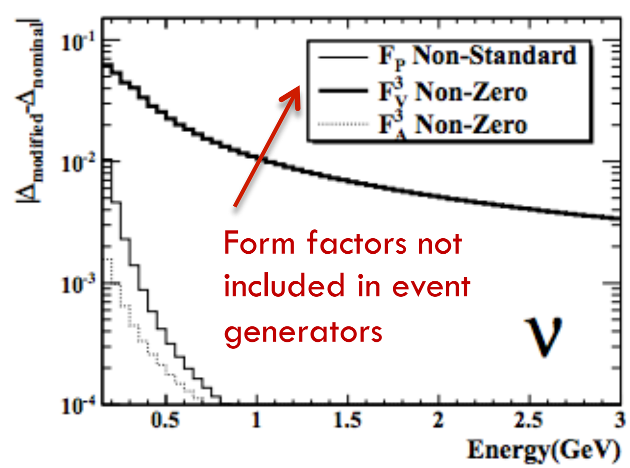
- FastMC with **no** ND constraints
  - Vary cross-section parameters within GENIE uncertainties, eg: M_A^{QE} and M_A^{RES}
- Significant degradation in sensitivity for fit to only ν_e appearance sample for a single cross-section systematic uncertainty
- Fit to all four FD samples significantly constrains cross-section variations leading to very little degradation in sensitivity for same cross-section uncertainty
- Includes uncertainty in cross-section ratios: $\nu/\bar{\nu}$ (10%) and ν_e/ν_μ (2.5%)
  - Theory input needed
  - Cross-section measurements needed

M. Bass, D. Cherdack, R. Gran



Note: No oscillation parameter systematics

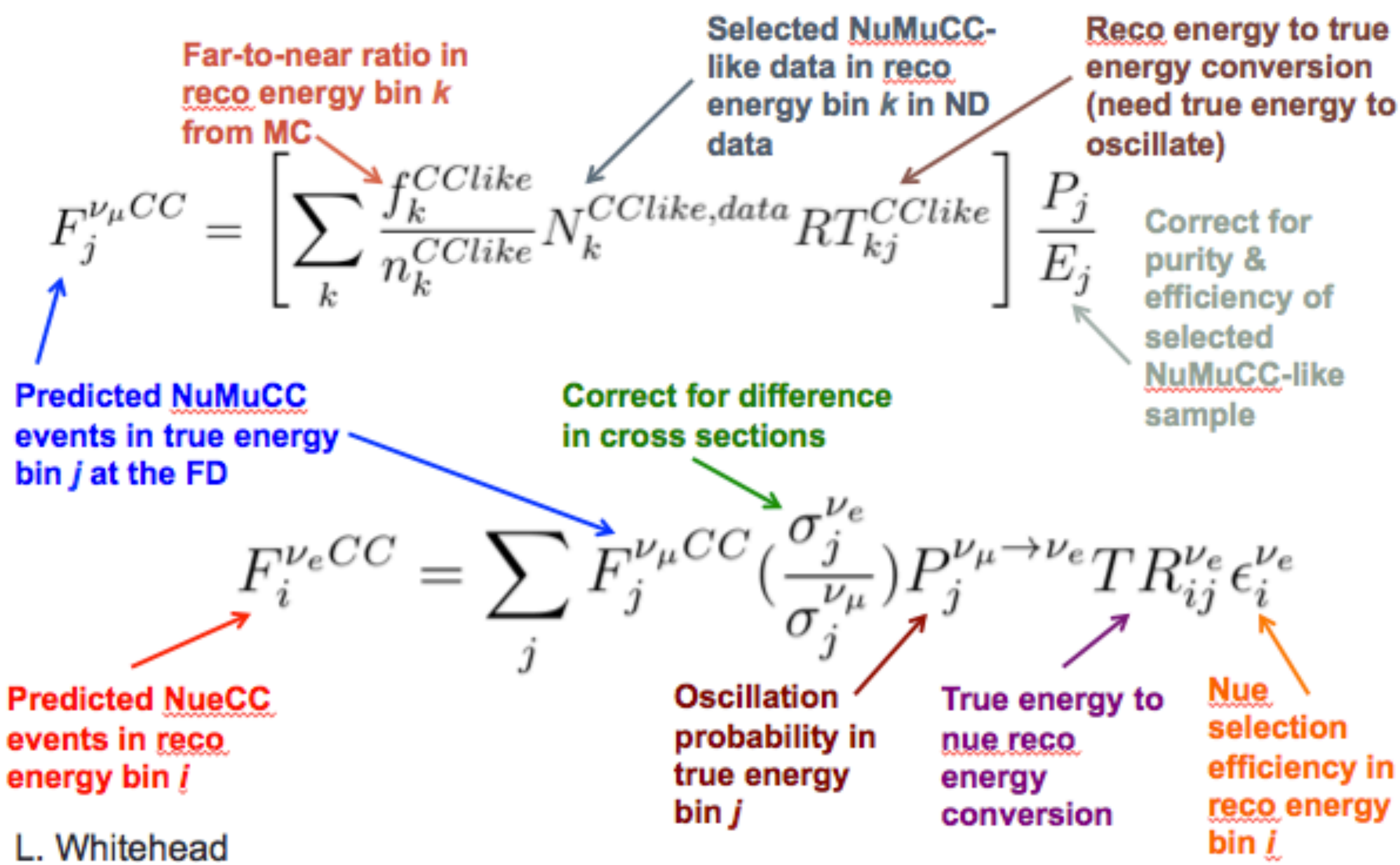
arXiv:1206.6745



Form factors not included in event generators

Constraints from Near Detector

- MINOS-like strategy: Direct ND to FD extrapolation

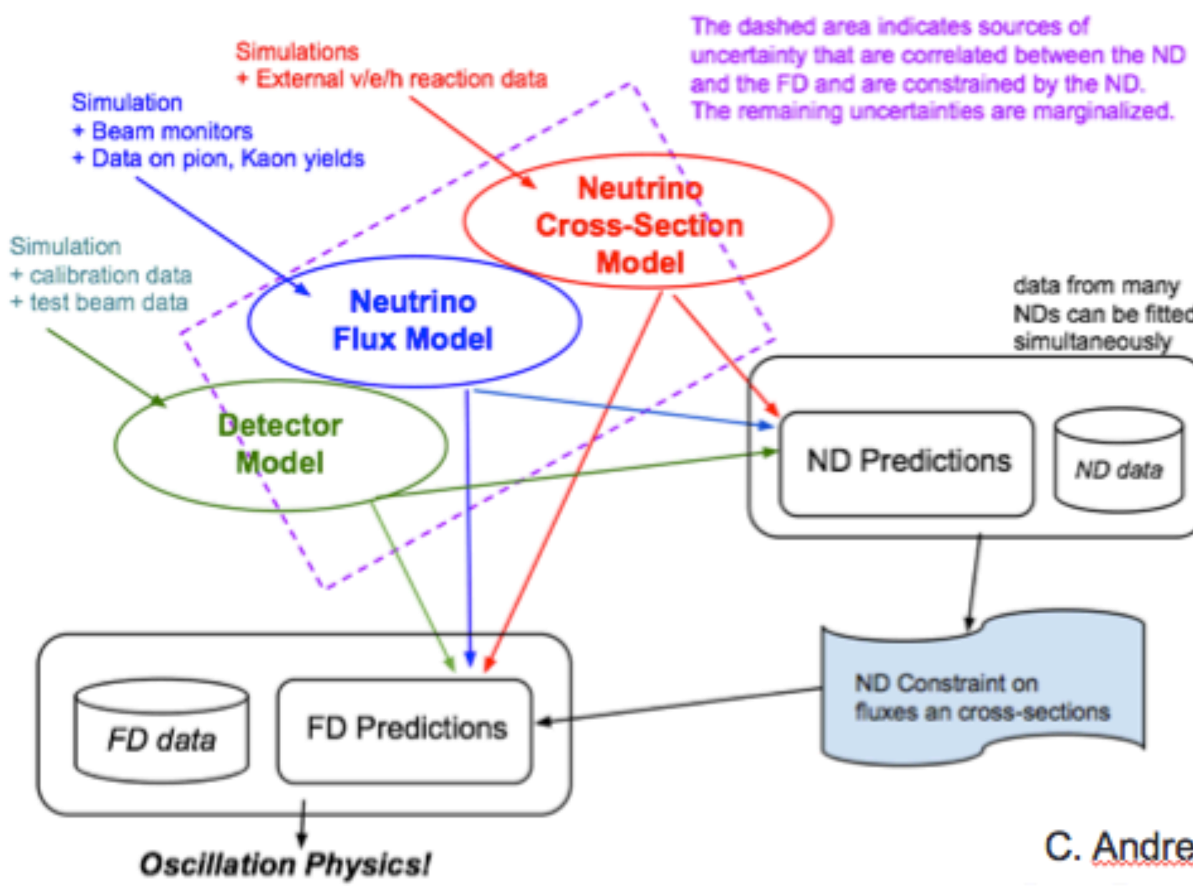


$$F_j^{\nu_\mu CC} = \left[\sum_k \frac{f_k^{CClike}}{n_k^{CClike}} N_k^{CClike,data} RT_{kj}^{CClike} \right] \frac{P_j}{E_j}$$

$$F_i^{\nu_e CC} = \sum_j F_j^{\nu_\mu CC} \left(\frac{\sigma_j^{\nu_e}}{\sigma_j^{\nu_\mu}}\right) P_j^{\nu_\mu \to \nu_e} TR_{ij}^{\nu_e} \epsilon_i^{\nu_e}$$

Constraints from Near Detector

- T2K-like strategy:

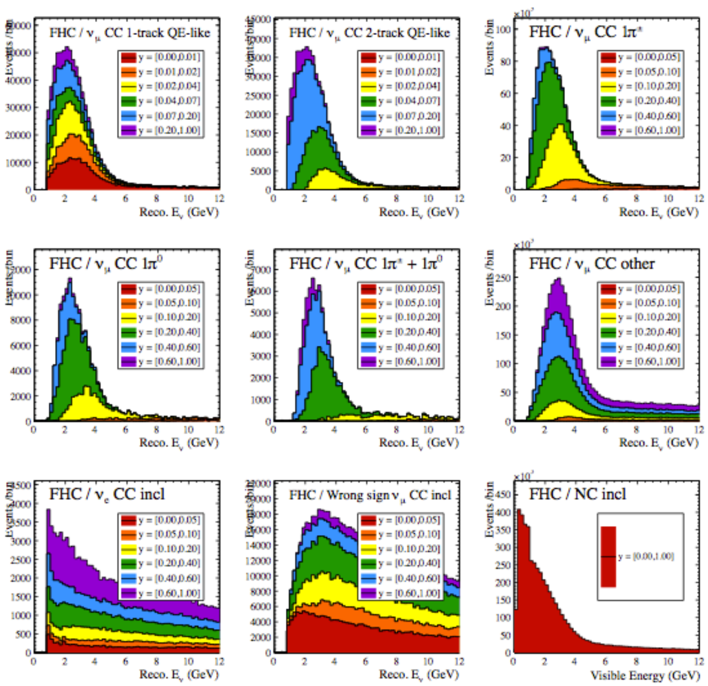


C. Andreopoulos

Analysis Tool: VALOR

- Adapted from T2K for DUNE ND analysis:
  - 9 x 2 near detector samples based on FastMC-ND
  - Fit 2D (E_{reco}, y_{reco}) distributions for most samples
  - 51 systematics parameters (flux, cross-section, efficiency)

ND Samples:

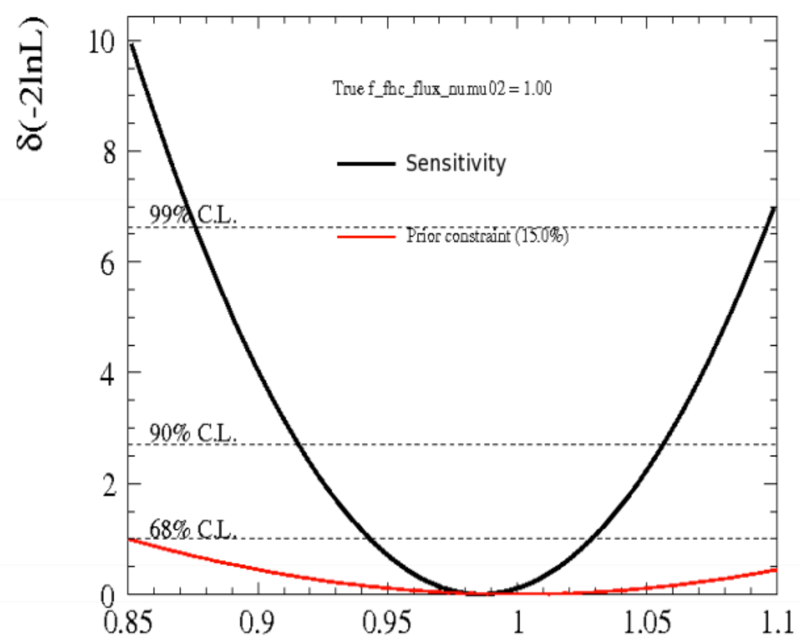


- ν_μ CC inclusive
  - ν_μCC 1-track QE enhanced (FHC: μ^- only)
  - ν_μCC 2-track QE enhanced (FHC: $\mu^- + \text{p}$)
  - ν_μCC $1\pi^\pm$ (FHC: $\mu^- + 1\pi^\pm + \text{X}$)
  - ν_μCC $1\pi^0$ (FHC: $\mu^- + 1\pi^0 + \text{X}$)
  - ν_μCC $1\pi^\pm + 1\pi^0$ (FHC: $\mu^- + 1\pi^\pm + 1\pi^0 + \text{X}$)
  - ν_μCC other
    - $\rightarrow$ in future, subdivide further
- Wrong-sign ν_μCC inclusive (FHC: $\mu^+ + \text{X}$)
  $\rightarrow$ in future, subdivide further
- ν_eCC inclusive (FHC: $e^- + \text{X}$)
  $\rightarrow$ in future, subdivide further
- NC inclusive
  $\rightarrow$ in future, subdivide further (NCEL, NC $1\pi^\pm$, NC $1\pi^0$)

Constraining Flux Uncertainty

Constraining flux with ND in VALOR:

FHC ν_μ flux in 2.5-3 GeV

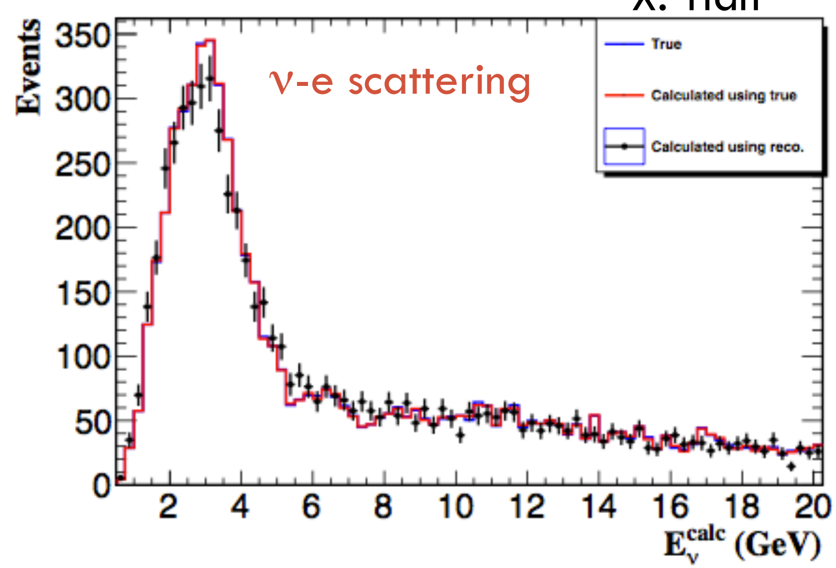


No surprise that ND provides significant flux constraint!

Constraining flux with specific ND samples:

- Preliminary study of flux determination using Fast MC simulation of FGT near detector
  - Absolute normalization based on fully leptonic neutrino interactions (2-3%)
  - Flux shape determination based on low ν_0 method (1-2%)

X. Tian



Cross-section and nuclear models: Beyond current uncertainties

- Basic strategy is to compare observables among alternative cross-section and nuclear-interaction models in GENIE
  - Long- and short-range correlations among nucleons
  - Effect of random phase approximations
  - Meson exchange currents
  - 2p-2h effects in CCQE
  - Effective spectral functions
  - Coherent pion production
  - Alternative model of DIS interactions
  - Variation of tunable parameters within existing models

  } In various stages of implementation in GENIE.
- Comparison with data (ArgoNeuT,MINERvA, NOvA-ND, T2K-ND280, μBooNE, SBN-ND, ICARUS, …)
- Comparison with alternative generators (NuWro, GiBUU)
- Requires support for and close collaboration among model builders, developers of event generators, cross-section experiments, and long-baseline experiments.

Far Detector Systematics

- Detector performance inputs to Fast MC
  - Lepton resolutions
  - Hadron resolutions
  - Energy scale
  - Signal efficiency
  - e-γ separation
  - Background rejection

Based on:
- GENIE kinematics
- ICARUS results
- LArSoft hand scans
- μBooNE LArSoft studies

- Implementation of energy resolution and scale variations in DUNE sensitivity calculations in progress
  - Will set requirements for detector performance
- Data-MC comparisons are critical
  - 35t prototype and μBooNE data coming soon
  - LArIAT, CAPTAIN, SBN-ND, CERN neutrino platform prototypes…

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Worldwide Effort

Some highlights

GENIE Upgrades

GENIE Release Roadmap: 2.12

- GENIE 2.12.0 - likely this Summer/Fall
  - QEL Lambda production (J. Poage and H. Gallagher)
  - Berger-Sehgal coherent pion production (PRD 79, 053003 (2009)) (G. Perdue, H. Gallagher, D. Cherdack)
  - Local Fermi Gas & Nieves et al CCQE with RPA (J. Johnston and S. Dytman)
  - Valencia Model Meson Exchange-Currents (J. Schwer and R. Gran)
  - Alvarez-Ruso et al microscopic coherent pion production (PRC 75, 055501 (2007) and PRC 76, 068501 (2007)) (S. Dennis and S. Boyd)
  - Oset FSI model (T. Golan)
  - Kaon FSI (F. de Maria Blaszczyk, S. Dytman)
  - Z expansion of QEL form factor (Hill et al, PRD 84, 073006) (A. Meyer)
  - Benhar Spectral Functions (C. Mariani, M. Jen, and A. Furmanski)
    - Ambitious to get it all… (and I may have forgotten something)
- GENIE 3.0 - likely early 2016
  - New default physics tune incorporating all of these models and recent neutrino-nucleus cross section data, plus many tuning and data comparison tools.

Fermilab

11 Gabriel Perdue I DUNE Collaboration Meeting April 16, 2015

NA61/SHINE

- Hadron production measurements on a variety of materials and neutrino production targets, including T2K replica target
- Similar efforts planned for FNAL target designs

K. Abe, et. al, PRD87 (2013) 012001:

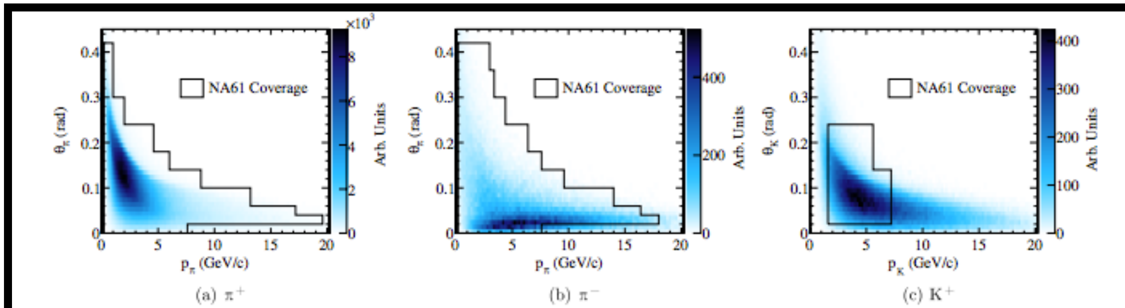


FIG. 15 (color online). The phase space of pions and kaons contributing to the predicted neutrino flux at SK, and the regions covered by NA61/SHINE measurements.

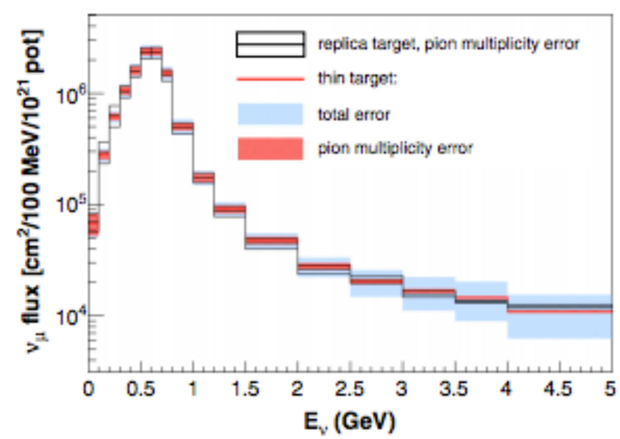
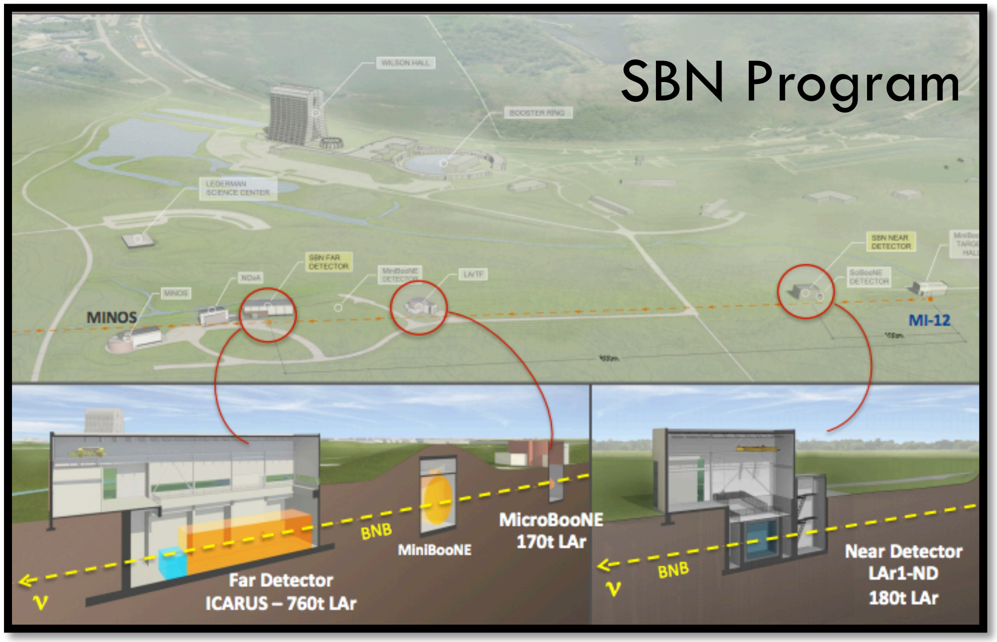


FIG. 39 (color online). Reweighted ν_μ flux at the far detector based on the NA61/SHINE thin target and replica target measurements.

Intermediate Neutrino Program

- See talks from: C. Rubbia, P. Wilson, S. Kettell



Large neutrino event samples:

- ~1.2M CC interactions per year (~7000 ν_e) in SBN-ND
- Large samples in uBooNE and ICARUS

ν-Ar cross-section measurements

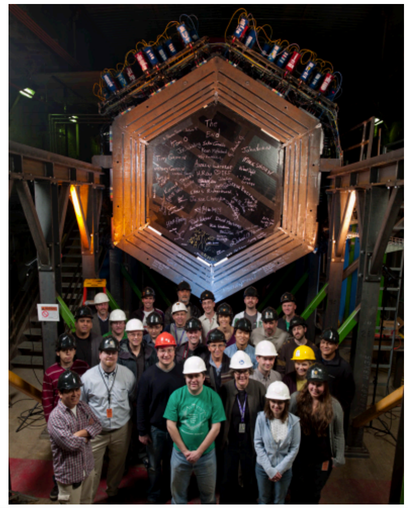
Development of simulation/analysis techniques:

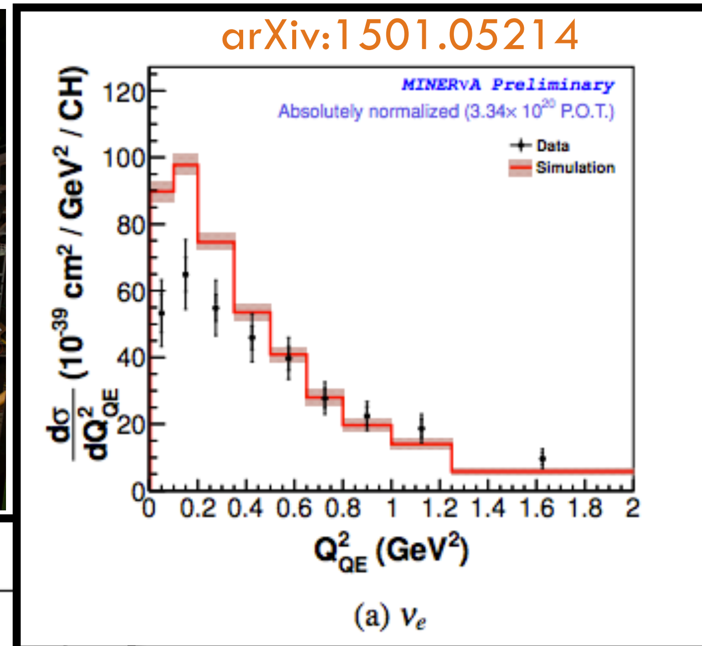
- High statistics validation of simulation
- Fully automated reconstruction
- Refined analysis techniques including opportunity to test near-far cross-calibration and extrapolation

Interaction Measurements

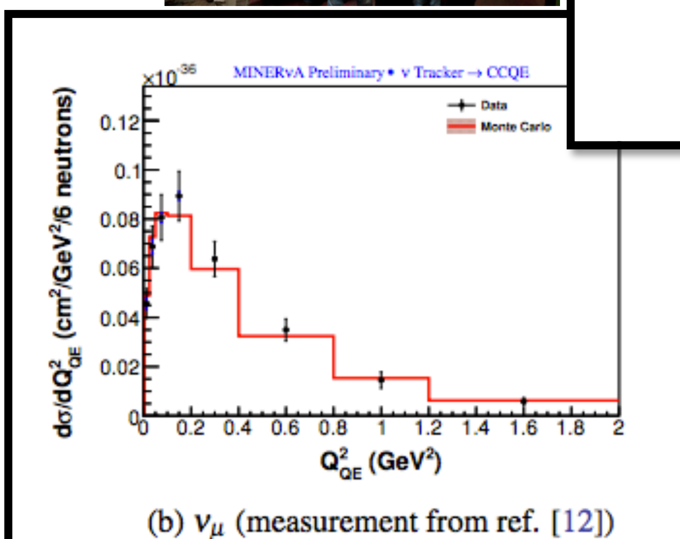
- Critical for making progress on cross-section and nuclear modeling uncertainties
- Many current and planned experiments:
  - ArgoNeuT
  - MINERvA
  - NOvA-ND
  - T2K-ND280
  - μBooNE
  - SBN-ND
  - ICARUS
  - JLab e-Ar scattering

MINERvA





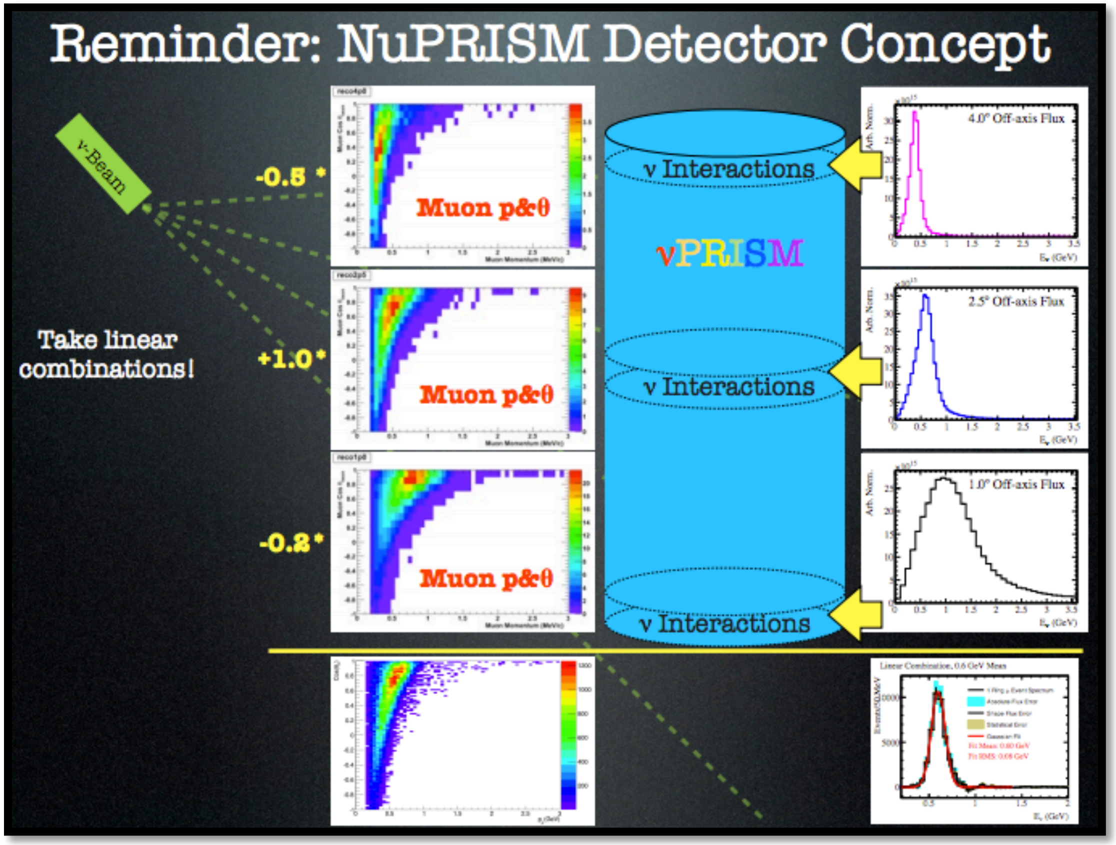
(a) ν_e



(b) ν_μ (measurement from ref. [12])

nuPRISM

M. Wilking:



- Proposal for data-driven method to reduce modeling uncertainty in reconstructed neutrino kinematics
- Use linear combinations of measured kinematics from different off-axis angles to simulate a desired spectrum (eg: mono-energetic beam or oscillated FD spectrum)
- MC studies show significant reduction in bias of reconstructed quantities

Sociology

- The neutrino community consists of a large number of collaborations
  - Many have common hardware/software
  - Many shared sources of systematic uncertainty
- How to facilitate effective communication?
  - Timely propagation of information suggests that in many cases this may need to occur outside of the formal publication process
  - Process for releasing information to another collaboration needs to be simple and clear-cut
  - Interests of individual collaborations must also be respected
- Leadership needed to establish procedures for and a culture of effective communication. This physics is hard - let's help each other as much as we can.

Summary

- DUNE and HyperK need and expect to collect large event samples – will ultimately require control of systematic uncertainty at the level of a few percent.
- Effort underway to address systematic uncertainties from flux, cross-section and nuclear models, and detector effects requires worldwide cooperation:
  - Experience gained from past and present experiments
  - Experiment-specific evaluation of expected systematics and associated detector performance requirements
  - Oscillation parameter measurements
  - Hadron production and cross-section measurements
  - Neutrino interaction models and event generators
  - Detector simulation and reconstruction techniques
  - Test-beam data
  - Support for new ideas