Systematics Uncertainties in Future Neutrino Oscillation Experiments

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University of Medellin, November 8, 2019

Outline

- Introduction: oscillation measurements and near detectors
- Where systematic uncertainties enter measurements (cross section modeling uncertainties)
- Flux modeling and systematic uncertainties
- Detector modeling and systematic uncertainties

How to Approach This Problem?

List of cross section model systematic parameters in DUNE sensitivity studies:

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
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Mnv2p2hGaussEnhancement
MKSPP_ReWeight
E2p2h_A_nu
E2p2h_B_nu
E2p2h_A_nubar
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BeRPA_A
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BeRPA_D
C12ToAr40_2p2hScaling_nu
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nuenuebar_xsec_ratio
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SPPLowQ2Suppression

NR_nu_n_CC_2Pi
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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
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A Qualitative Approach

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

A Qualitative Approach

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What Will We Measure?

- Measurement of parameters describing neutrino oscillations

θ_{13}, θ_{23}, Δm^2_{32}, δ_{cp}
θ_{12}, Δm^2_{21}

- Answer a number of yes/no questions
  - Is $\sin(\delta_{cp}) \neq 0$ (is CP violation observed)?
  - Is the mass ordering "normal" or "inverted"?
  - Is $\theta_{23} = \pi/4, > \pi/4, < \pi/4$?
  - Are the neutrino oscillations observed consistent with mixing of 3 neutrino flavors?

$$P_{\mu\to\mu} = 1 - \left(\boxed{\sin^2 2\theta_{23}} - \sin^2\theta_{23}\cos 2\theta_{23}\sin^2 2\theta_{13}\right)\sin^2\left(\frac{\boxed{\Delta m^2_{32}}L}{4E_\nu}\right) + \ldots$$

Hyper-K, DUNE

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \boxed{\sin^2 2\theta_{12}} c^4_{13} \sin^2 \frac{\boxed{\Delta m^2_{21}}L}{4E} - \sin^2 2\theta_{13}\left[c^2_{12}\sin^2\frac{\boxed{\Delta m^2_{31}}L}{4E} + s^2_{12}\sin^2\frac{\boxed{\Delta m^2_{32}}L}{4E}\right]$$

JUNO

(Sorry, I will focus on DUNE and Hyper-K in this talk)

Appearance Probability

$$
\begin{aligned}
P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx{}& \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)^2}\Delta_{31}^2 \\
&+ \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\cos\theta_{13}\frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\Delta_{31}\frac{\sin(aL)}{aL}\Delta_{21}\cos(\Delta_{32})\cos\delta \\
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&+ \cos^2\theta_{13}\cos^2\theta_{23}\ \sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2. \qquad (2)
\end{aligned}
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$\Delta_{ji} = \frac{\Delta m^2_{ji} L}{4E}$ $\qquad aL/\Delta_{31} = 2\sqrt{2}G_F N_e E/\Delta m^2_{31}$

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Leading term probes mixing angle and mass splitting

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CP odd interference term can introduce CP violation (sign flips for neutrinos/antineutrinos)

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Matter effect introduces a dependence on the mass ordering

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Leading term probes mixing angle and mass splitting

CP odd interference term can introduce CP violation (sign flips for neutrinos/antineutrinos)

Matter effect introduces a dependence on the mass ordering

CP even term is relevant?

Where Systematic Uncertainties Enter

Predicting the far detector observations:

$$N_k(p_k,\theta_k) \propto \sum_i^{E^{true}\text{ bins}} \sum_j^{\text{flavors}} \Phi_j^{far}(E_i^{true})\, P_{\nu_j \to \nu_k}(E_i^{true})\, \sigma_k^A(E_i^{true}, p_k, \theta_k \ldots)\, \epsilon(p_k, \theta_k \ldots)\, M_{det}$$

Predicting the near detector observations:

$$N_j(p_j,\theta_j) \propto \sum_i^{E^{true}\text{ bins}} \Phi_j^{near}(E_i^{true})\, \sigma_j^A(E_i^{true}, p_j, \theta_j \ldots)\, \epsilon(p_j, \theta_j \ldots)\, M_{det}$$

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Neutrino production model

Where Systematic Uncertainties Enter

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Neutrino production model

Neutrino interaction model - relates neutrino energy/flavor to final-state particles

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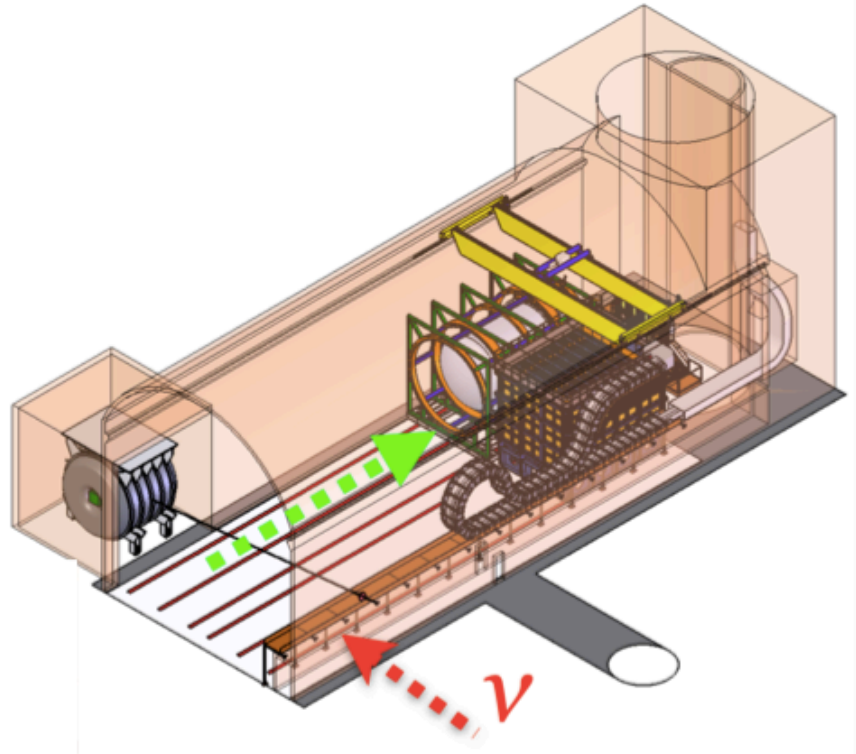
Neutrino production model

Neutrino interaction model - relates neutrino energy/flavor to final-state particles

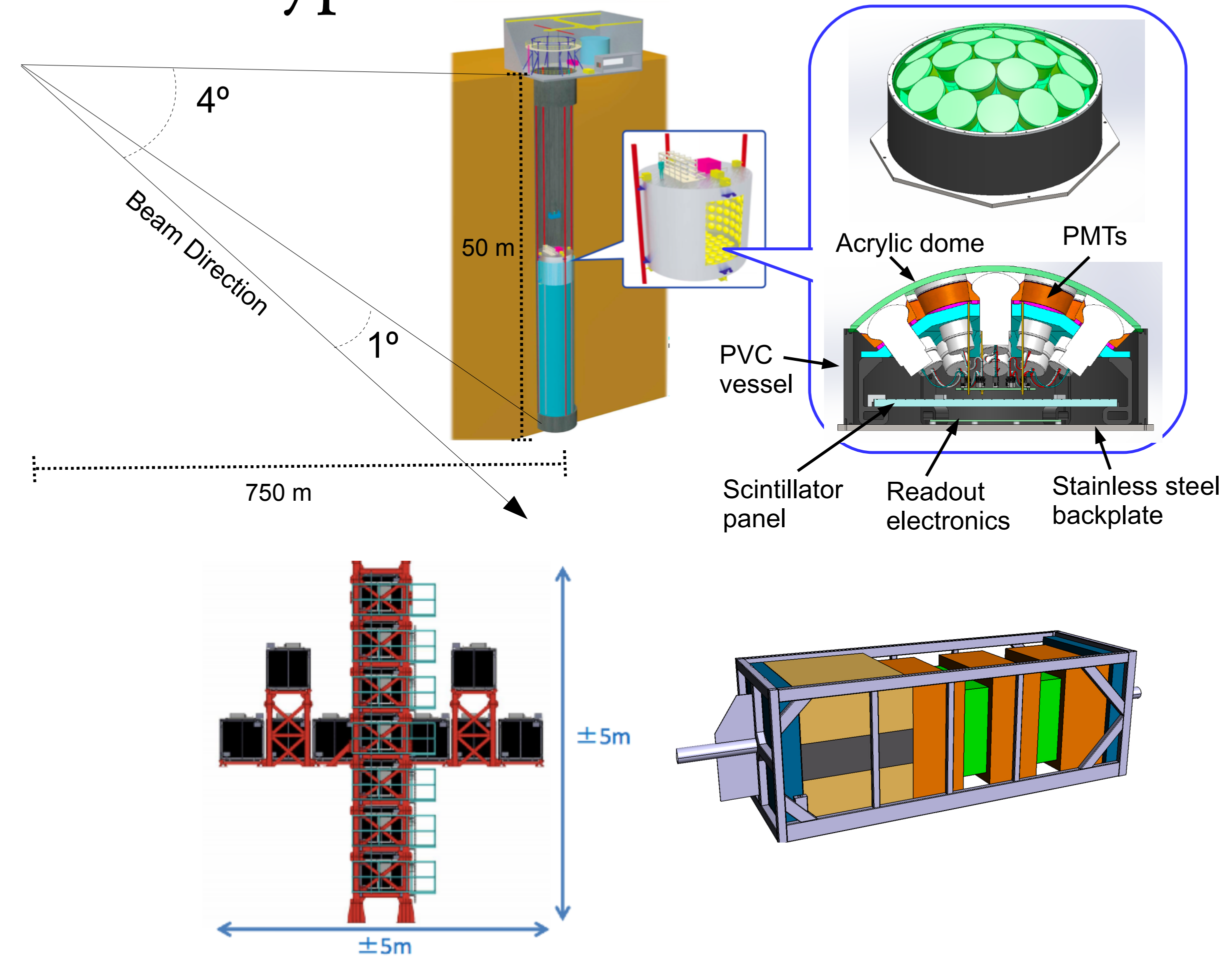
Detector response model - includes efficiency and resolution

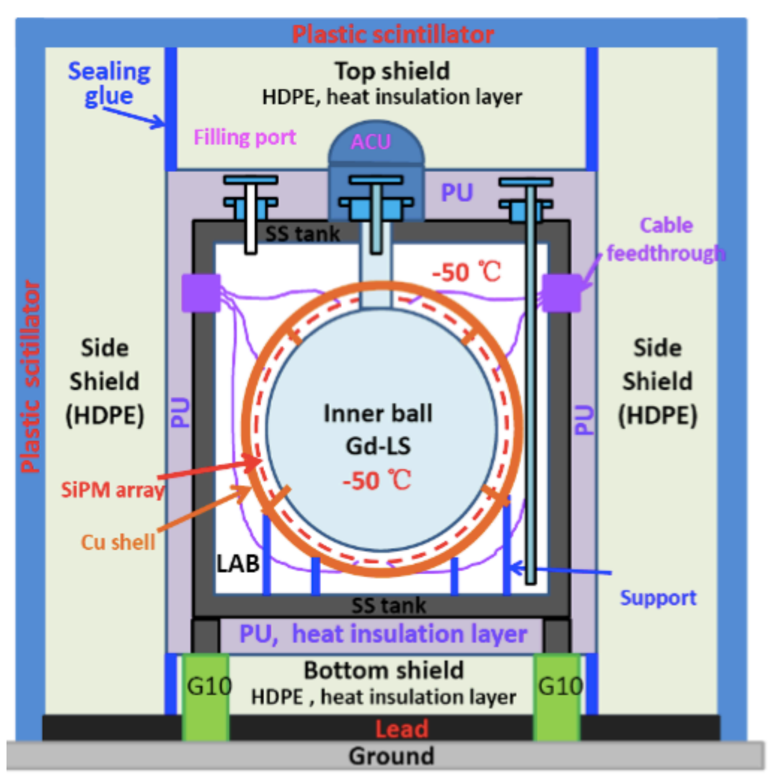
Near Detectors

DUNE Near Detectors



Hyper-K Near Detectors





TAO

Near detectors play central role on control of neutrino production and interaction model uncertainties

See talk in this session by J. Raaf

Limitations of Near Detectors

Do near detectors solve all problems?

Predicting the far detector observations:

$$N_k(p_k,\theta_k) \propto \sum_i^{E^{true}\text{ bins}} \sum_j^{\text{flavors}} \Phi_j^{far}(E_i^{true}) P_{\nu_j \to \nu_k}(E_i^{true}) \sigma_k^A(E_i^{true}, p_k, \theta_k \ldots) \epsilon(p_k, \theta_k \ldots) M_{det}$$

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Model uncertainties enter extrapolation due to differences in near and far detector rates:

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Different energy dependence of neutrino flux

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Model uncertainties enter extrapolation due to differences in near and far detector rates:

Different energy dependence of neutrino flux

Different flavor of neutrino flux

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Model uncertainties enter extrapolation due to differences in near and far detector rates:

- **Different energy dependence of neutrino flux**
- **Different flavor of neutrino flux**
- **Different nuclear target?**

Limitations of Near Detectors

Do near detectors solve all problems?

Predicting the far detector observations:

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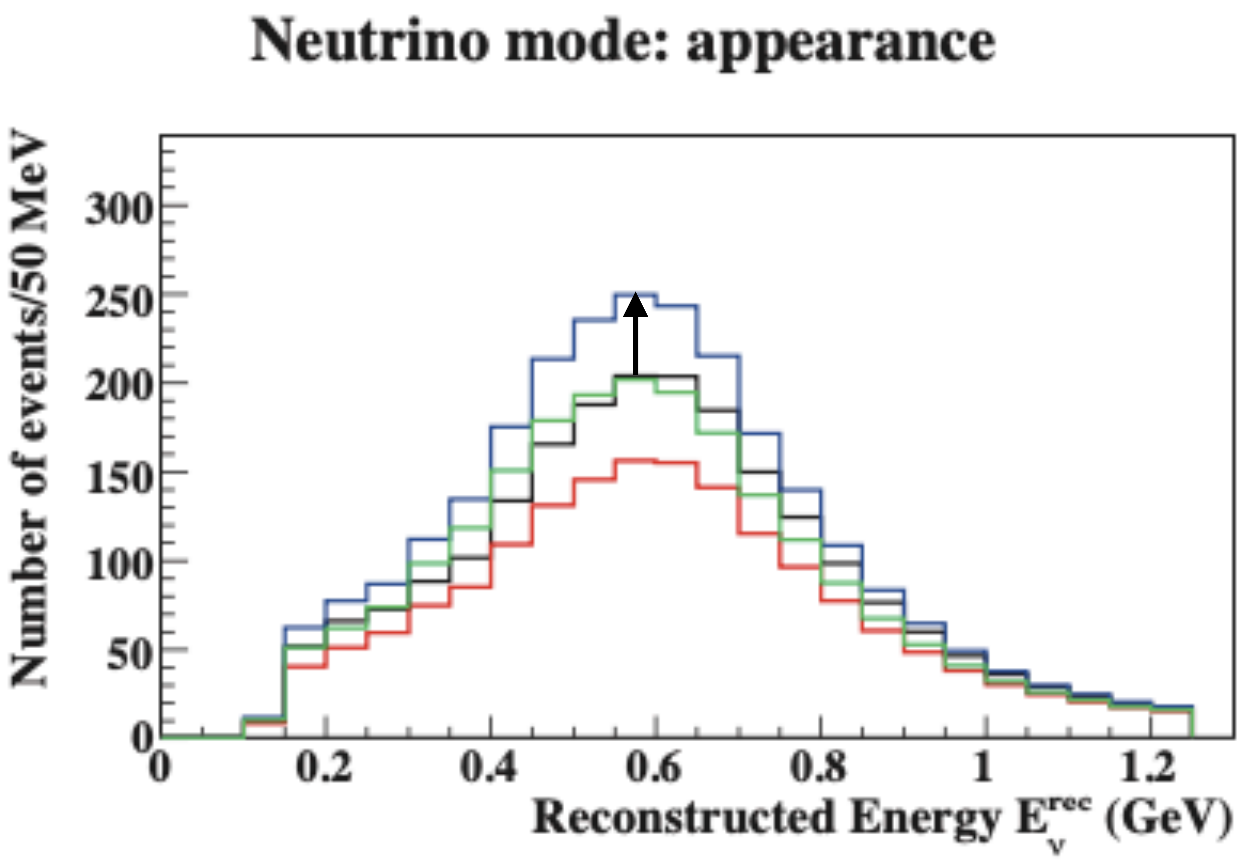
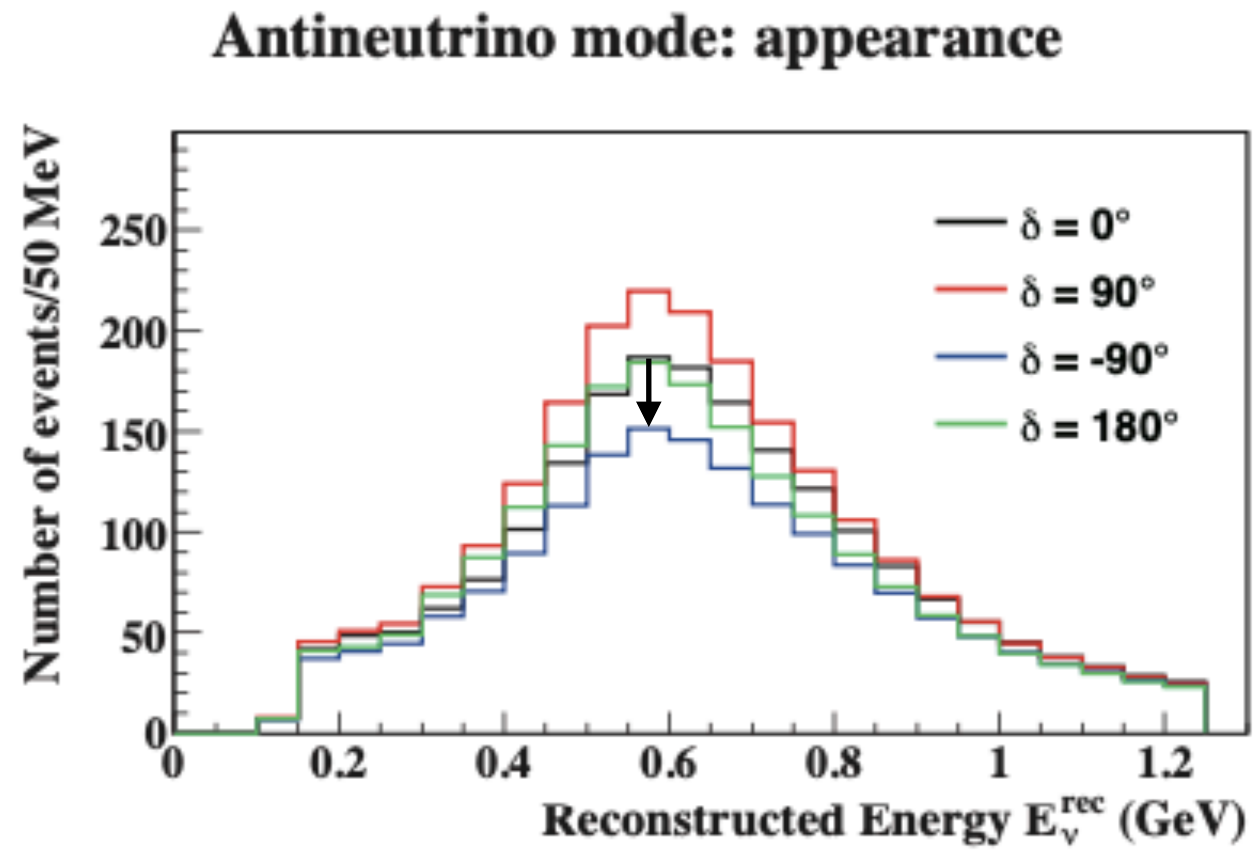
Model uncertainties enter extrapolation due to differences in near and far detector rates:

- **Different energy dependence of neutrino flux**
- **Different flavor of neutrino flux**
- **Different nuclear target?**
- **Different detection efficiency**

CP Violation Discovery

Hyper-K Design Report: arXiv:1805.04163





Signature is asymmetric deviation in electron neutrino and electron antineutrino candidates

Neutrino and antineutrino interaction rates must be be constrained by near detectors

In DUNE, sensitivity to $\sin(\delta_{cp})$ can also manifest as spectrum distortions

Electron (anti)Neutrino Cross Section

Different flavor of neutrino flux

We are measuring muon neutrino and muon antineutrino interactions in near detectors

Sensitive to uncertainties on $\sigma(\nu_e)/\sigma(\nu_\mu)$ relative to $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$

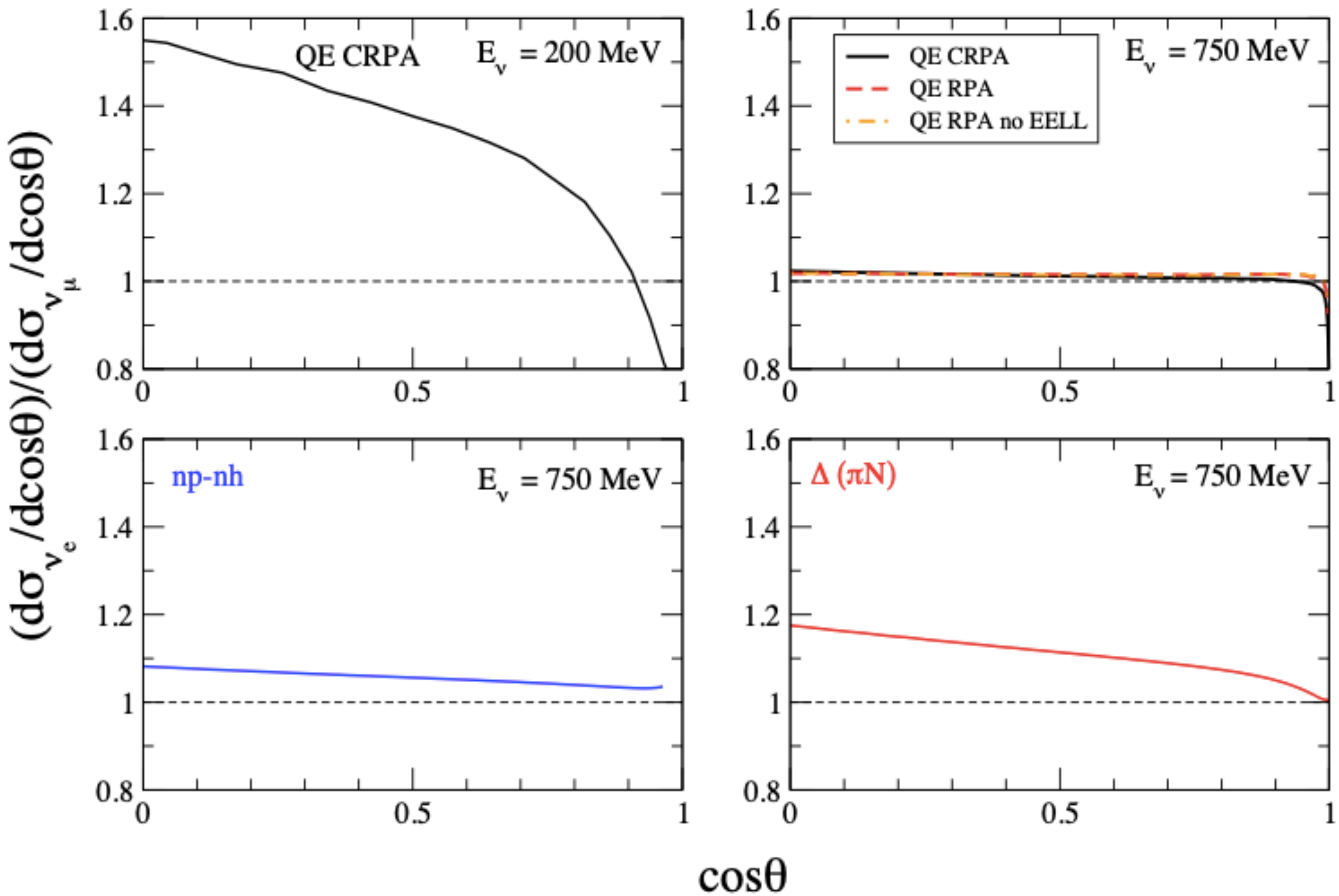
In T2K systematic error assigned based on paper of Day and McFarland (Phys. Rev. D86 (2012) 053003) on QE cross sections

- Form factor uncertainties in mass dependent terms
- Phase space differences
- Investigation of radiative corrections

T2K % error on $N(\nu_e)/N(\bar{\nu}_e)$

Error source	FHC/RHC
SK Detector	1.47
SK FSI+SI+PN	1.57
Flux + Xsec constrained	2.67
E_b	3.62
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	3.03
NC1γ	1.50
NC Other	0.18
Osc	0.77
All Systematics	5.96
All with osc	6.03

Extending to Other Channels



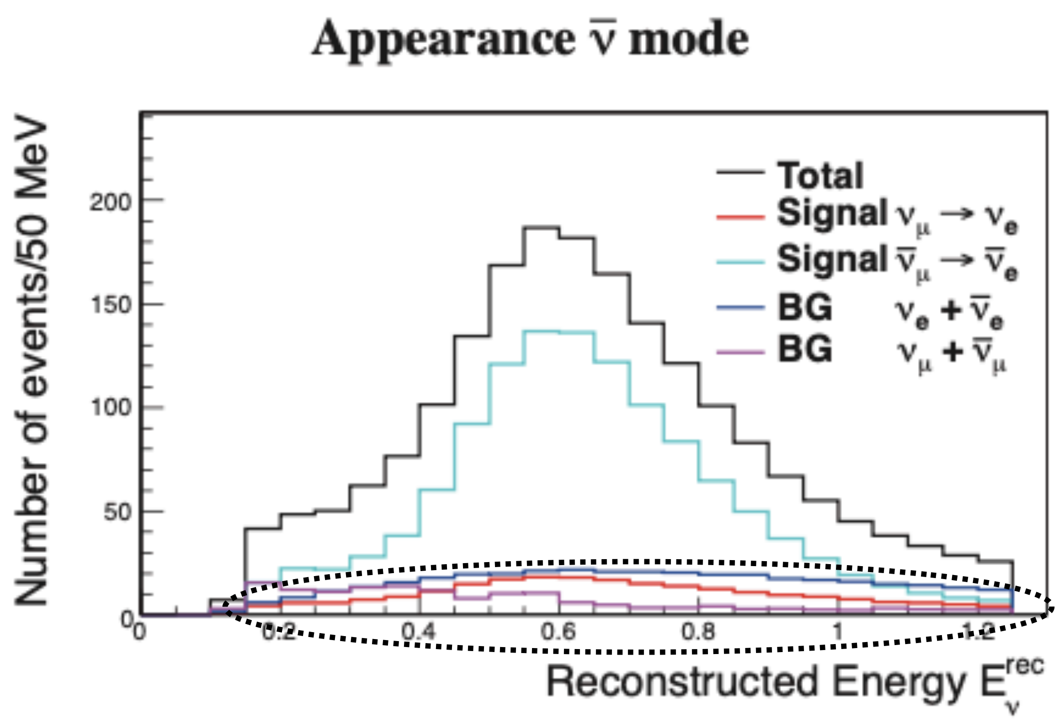
M. Martini et. al., Phys.Rev. C94 (2016) no.1, 015501

Investigations of the cross section ratios do exist in the literature

A complete survey of predictions for neutrinos and antineutrinos in all interaction modes for all effective models?

Wrong-Sign Background

Hyper-K Design Report: arXiv:1805.04163



Wrong-sign oscillations are 10-20% of the oscillation signal in antineutrino mode

Far detectors are not magnetized, so separation relies on hadron system

T. Vladisavljevic, T2K Flux Prediction, NuINT 2018

	Number of Interactions in Hadronic Ancestry		
	1 Interaction	≥2 Interactions	≥ 1 Out-of-target Interaction
ND280 ν_μ flux	63.2%	36.8%	12.6%
ND280 $\bar{\nu}_\mu$ flux	39.5%	60.5%	49.8%

For neutrino mode flux, but similar fractions for antineutrino mode

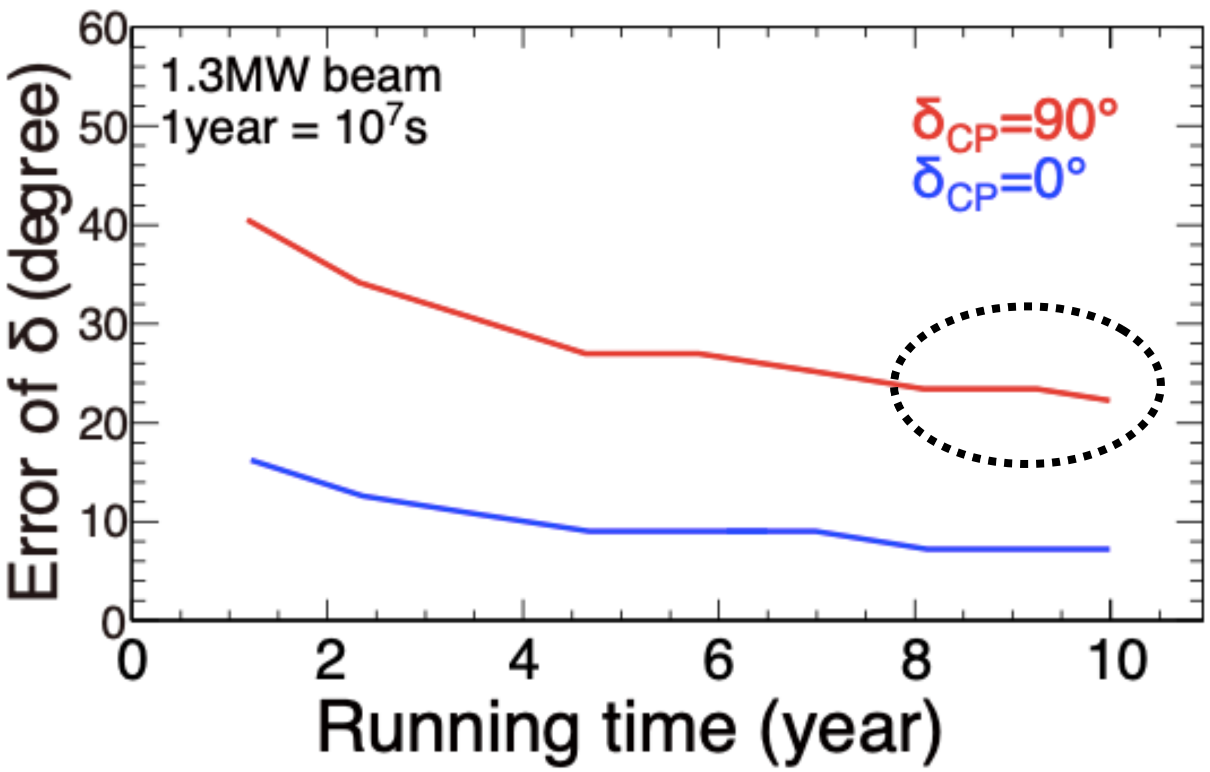
Up to 50% of the wrong-sign flux comes from hadrons interaction outside of the target

Material modeling and interaction modeling are important

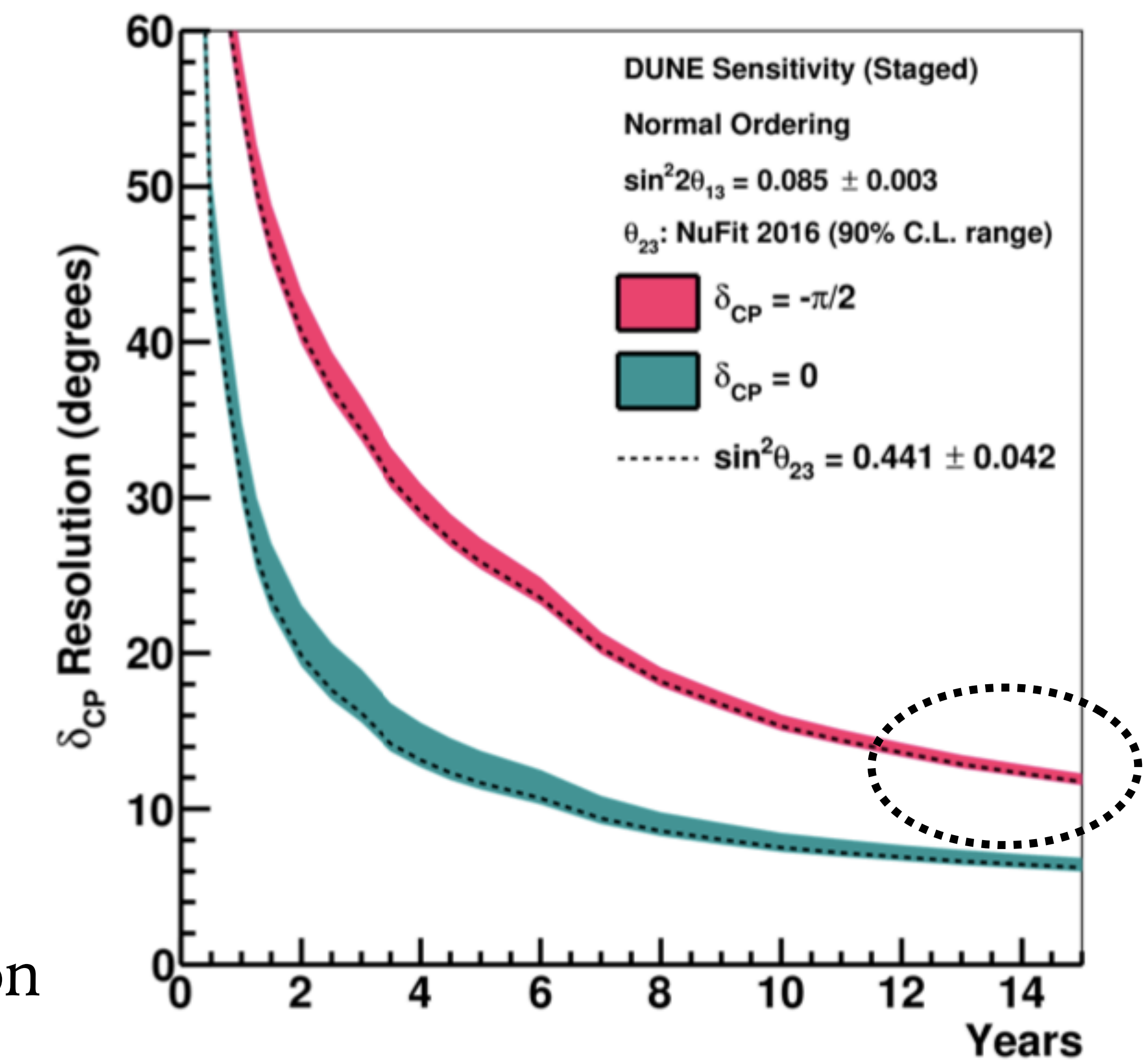
Motivation for magnetized near detectors

CP Phase Precision Measurement

Hyper-K Design Report: arXiv:1805.04163



DUNE Interim Design Report: arXiv:1807.10334



As pointed out by M. Bishai yesterday, precision worse near maximal mixing

$d(\sin\delta_{cp})/d\delta_{cp} \to 0$ as $|\sin\delta_{cp}| \to 1$

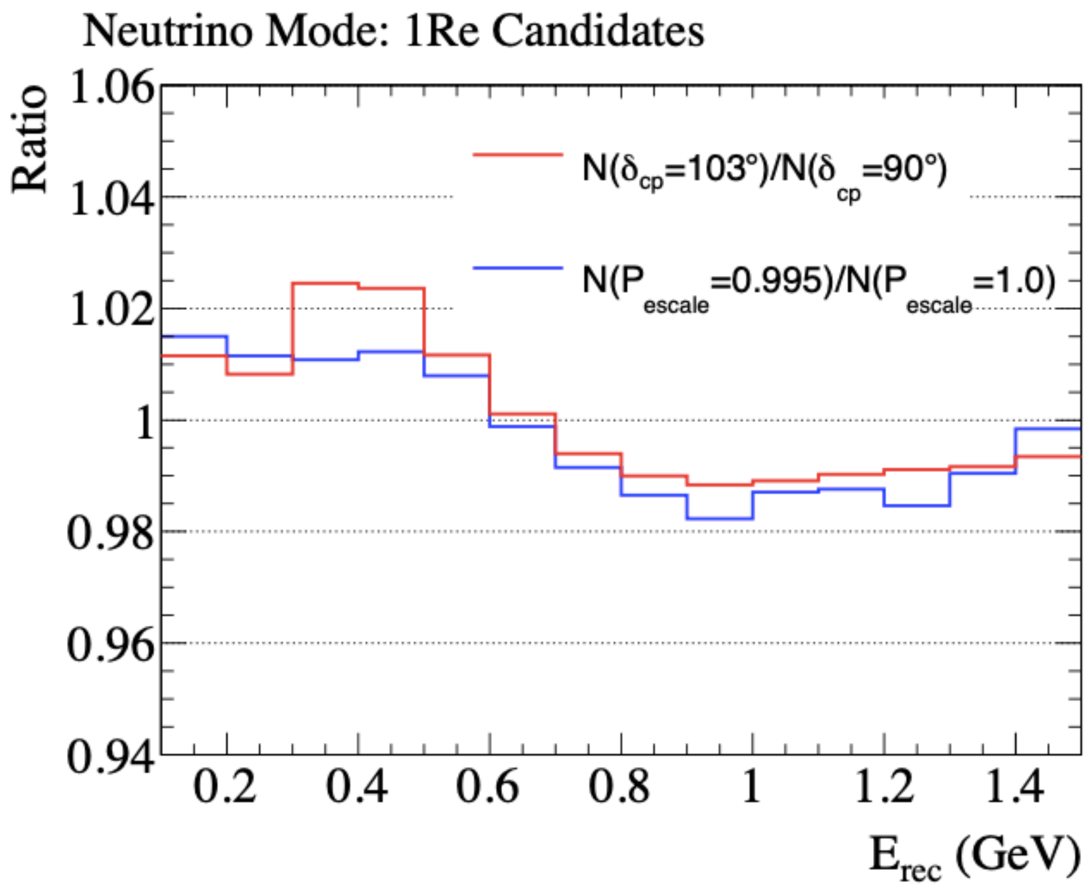
CP Even: $$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\cos\theta_{13}\frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\Delta_{31}\frac{\sin(aL)}{aL}\Delta_{21}\boxed{\cos(\Delta_{32})}\cos\delta$$

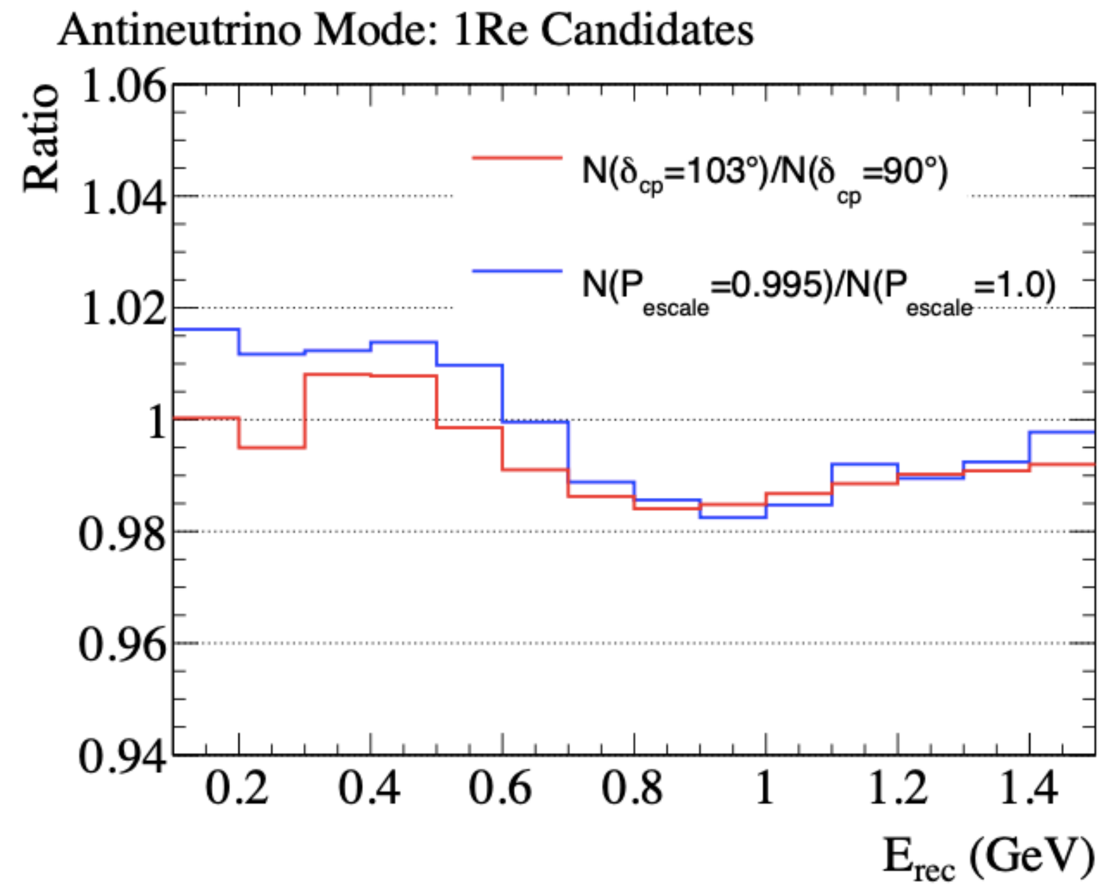
Increases or decreases prediction away from oscillation maximum

CP Phase Precision Measurement

T2HKK White Paper: arXiv:1611.06118

Ratio to nominal spectrum at Hyper-K





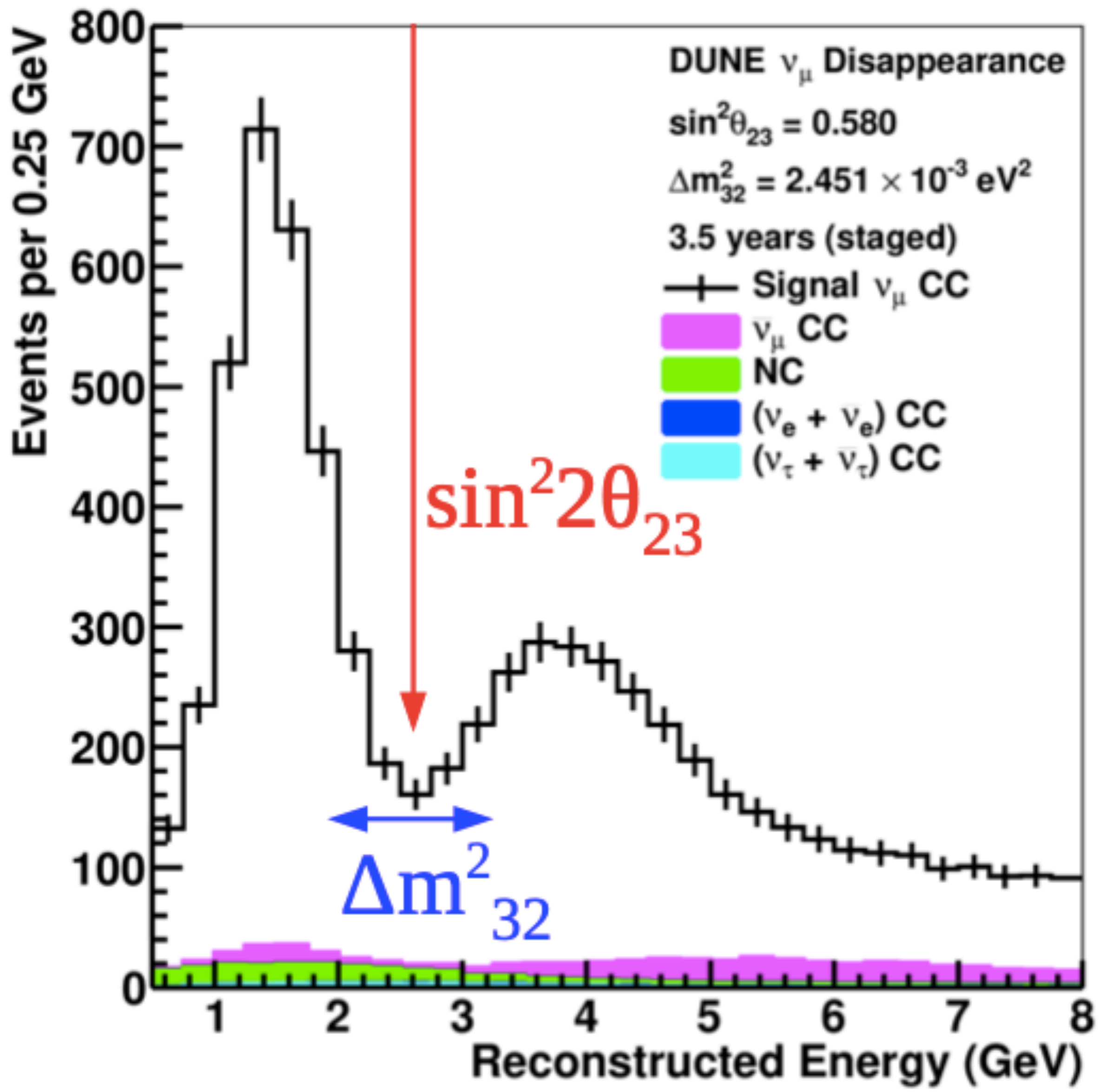
Enhancement of the predicted rate away from the oscillation maximum

Most sensitivity between first and second oscillation maximum

Magnitude of effect is equivalent to 0.5% energy scale shift at first oscillation maximum

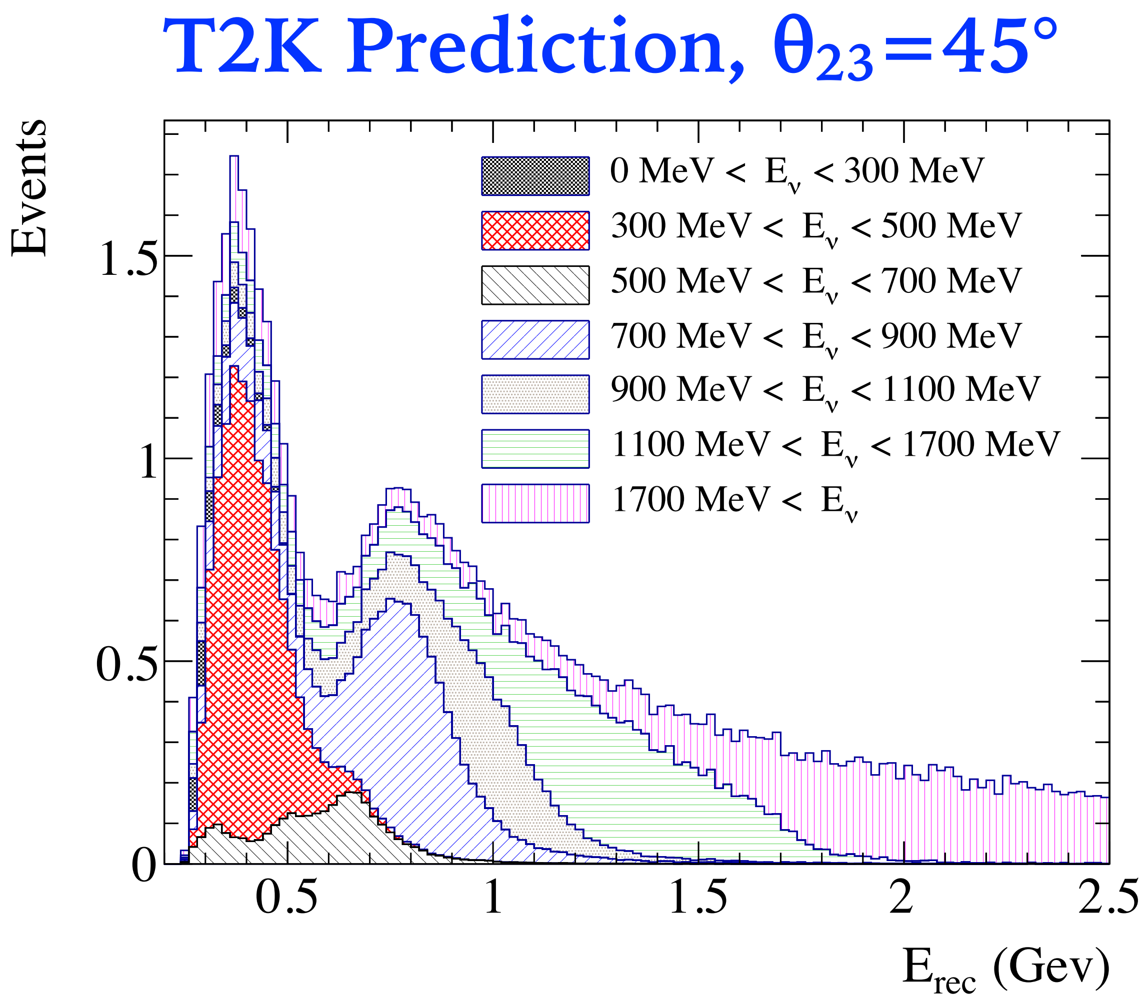
Sensitive to systematic effects on reconstructed energy

Atmospheric Mixing Parameters



- The depth of the oscillation "dip" depends on $\sin^2 2\theta_{23}$
  - Modeling of events that populate this region is critical
- Energy where the oscillation "dips" depends on Δm^2_{23}
  - Systematic uncertainties for energy scale should be controlled well enough for desired precision on Δm^2_{23}

Energy Reconstruction



Events with “wrong” reconstructed energy fill the oscillation maximum region

Energy Reconstruction in Hyper-K based on lepton kinematics:

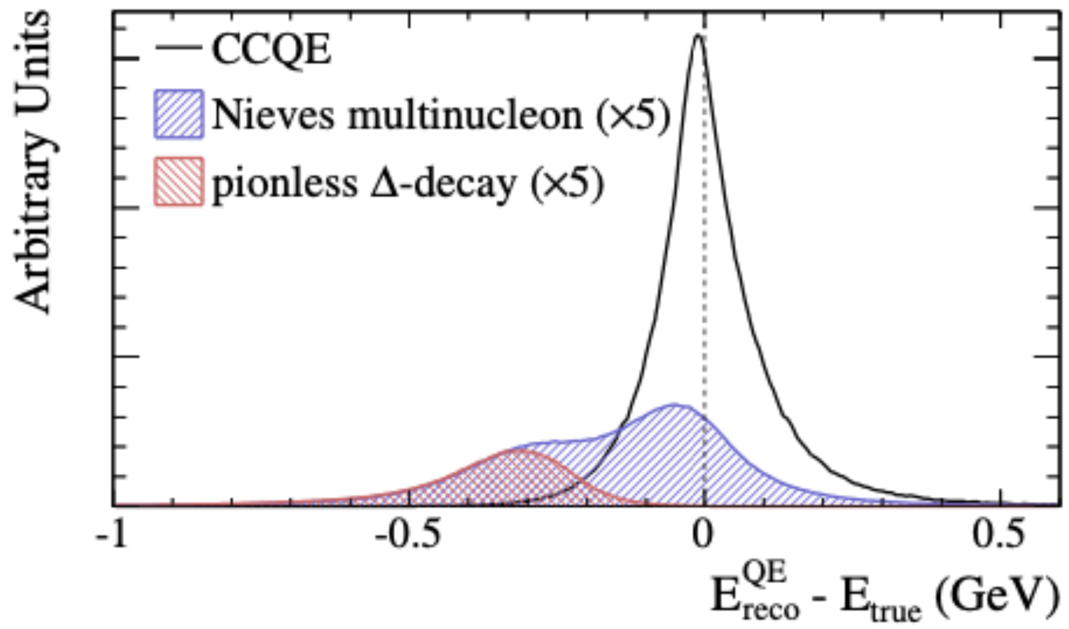
$$E_\nu^{\text{rec}} = \frac{2(M_n - E_B)E_\mu - (E_B^2 - 2M_nE_B + m_\mu^2 + \Delta M^2)}{2\left[M_n - E_B - E_\mu + \quad p_\mu \cos\theta_\mu\right]}$$

Energy Reconstruction in DUNE based on calorimetric reconstruction

$$E_\nu = E_\mu + E_{\pi\pm} + E_{\pi 0} + E_p + \ldots$$

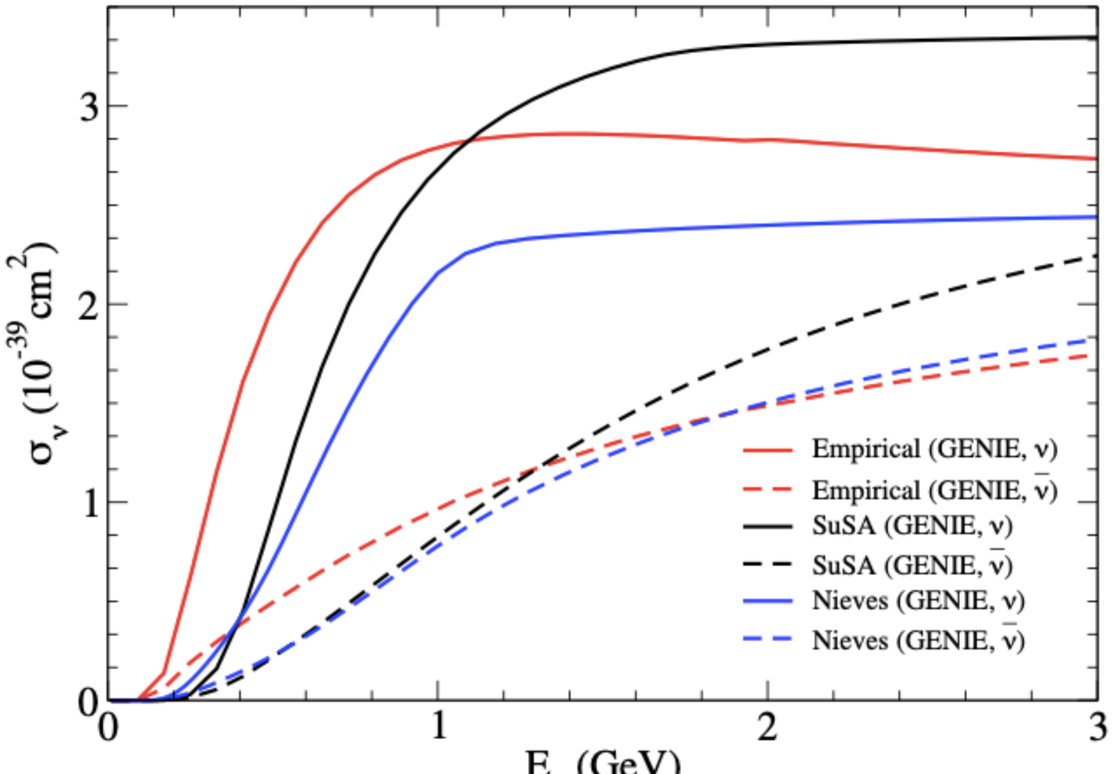
Non-QE Processes

T2K: Phys. Rev. Lett. 112 (2014)



- For reconstruction on QE assumption, large energy bias possible for non-QE processes
  - Multi-nulceon (np-nh) process
  - Pion production and absorption

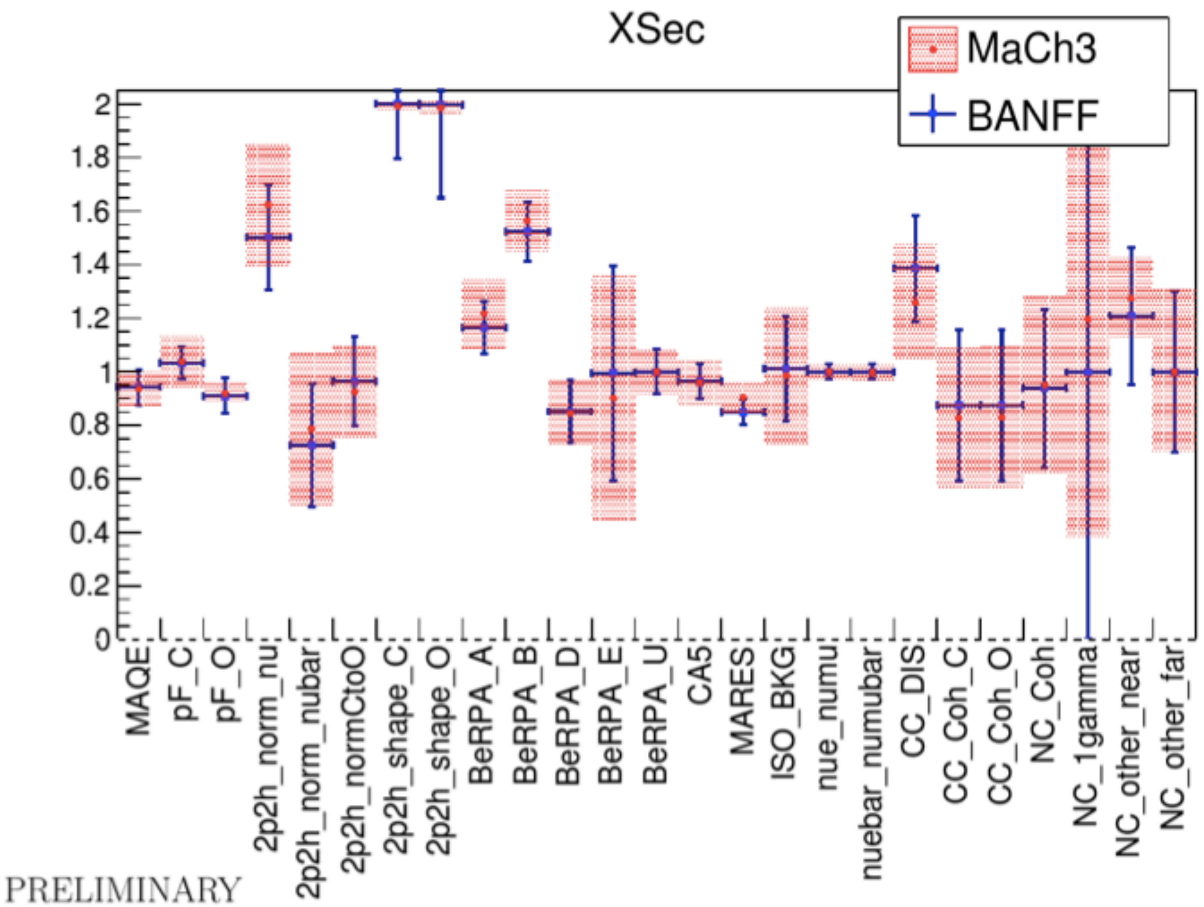
Dolan, Megias, Bolognesi: arXiv:1905.08556



2p-2h models implemented in GENIE

- Range of effective models on the market for 2p-2h, pion production/absorption
- No consistent picture at the moment

Confronting Data (T2K)



T2K, C. Bronner, NuFact 2019

T2K fits a model to near detector data including parameters that vary kinematics and normalization of 2p-2h

2p-2h model of Nieves et al., Phys. Rev. C83, 045501 (2011)

Many parameters pulled far from nominal values

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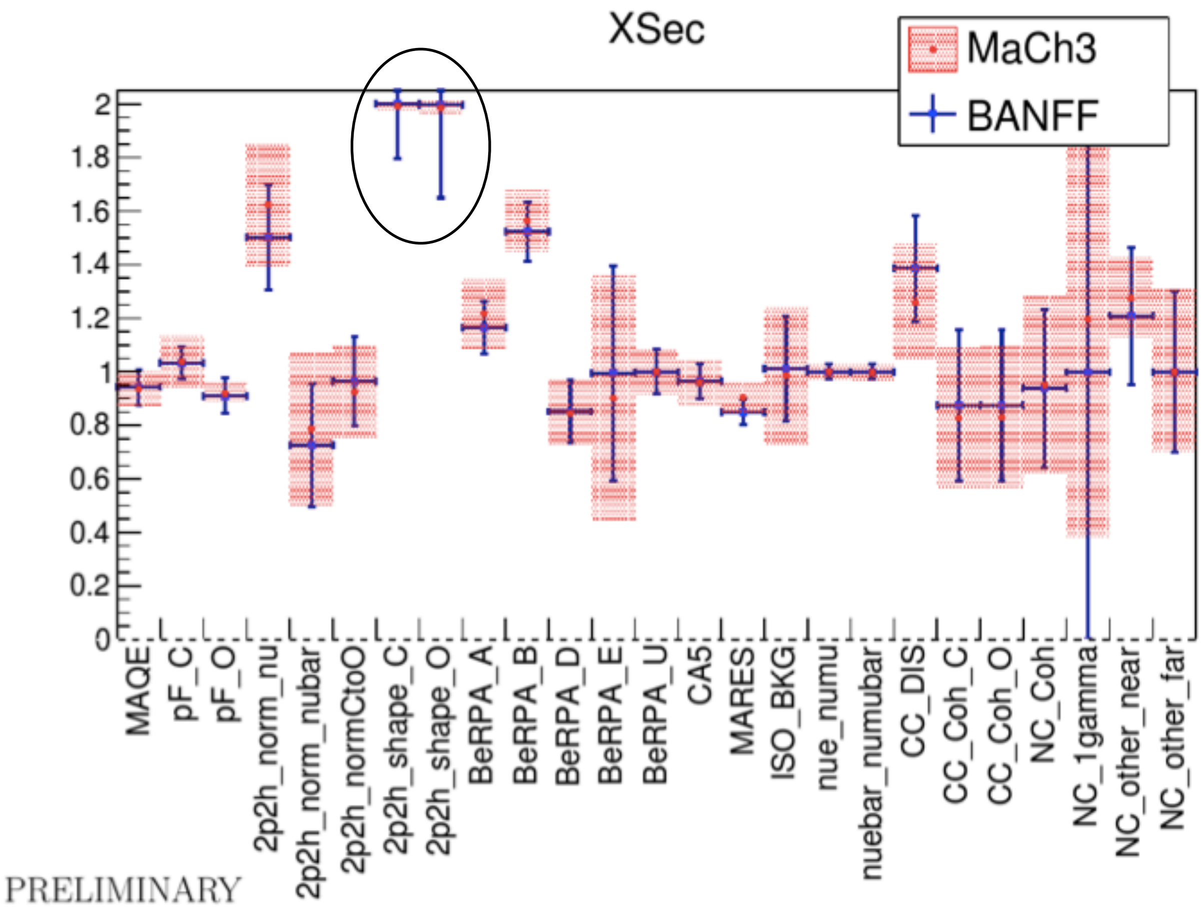

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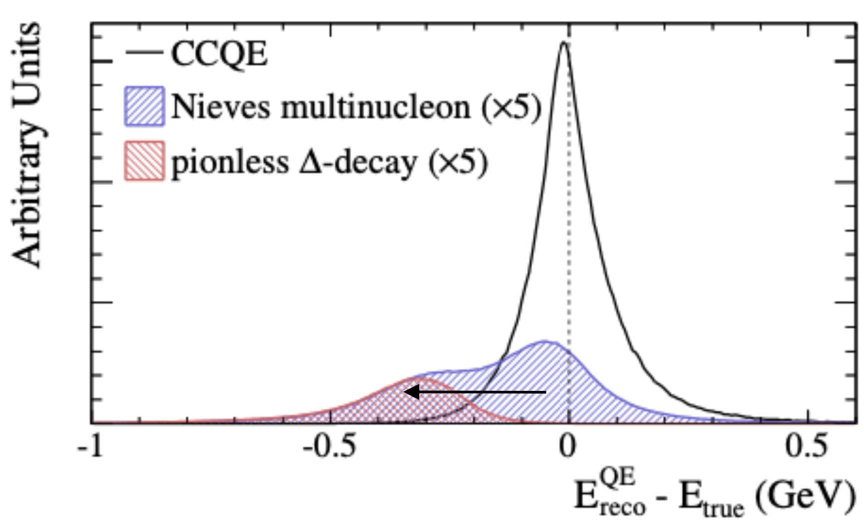
Move the strength to larger energy reconstruction bias



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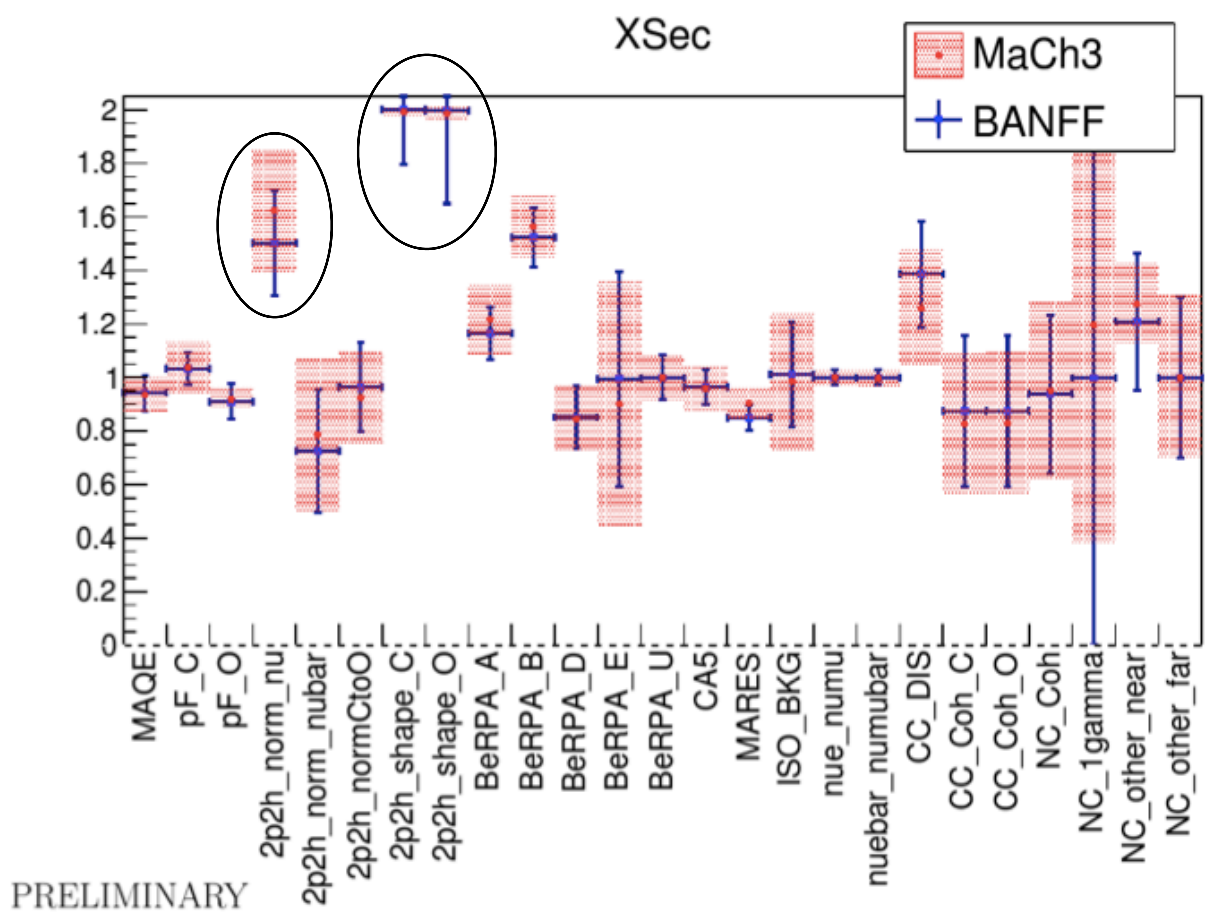

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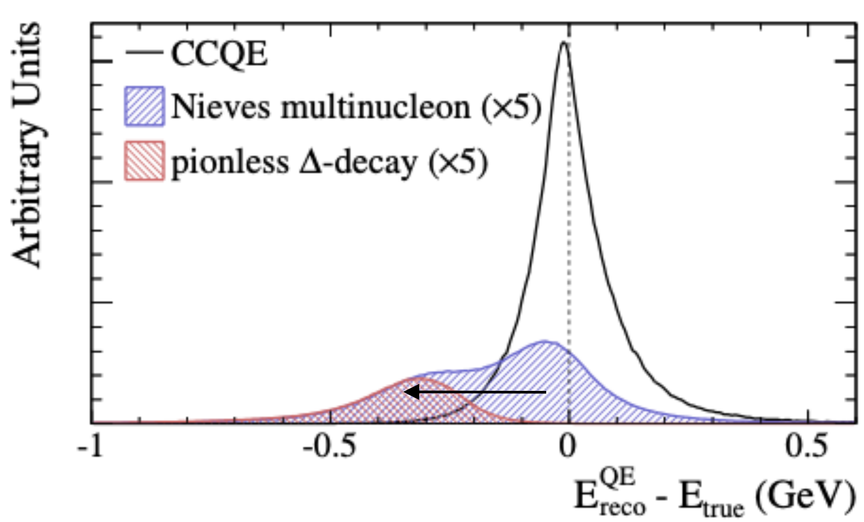
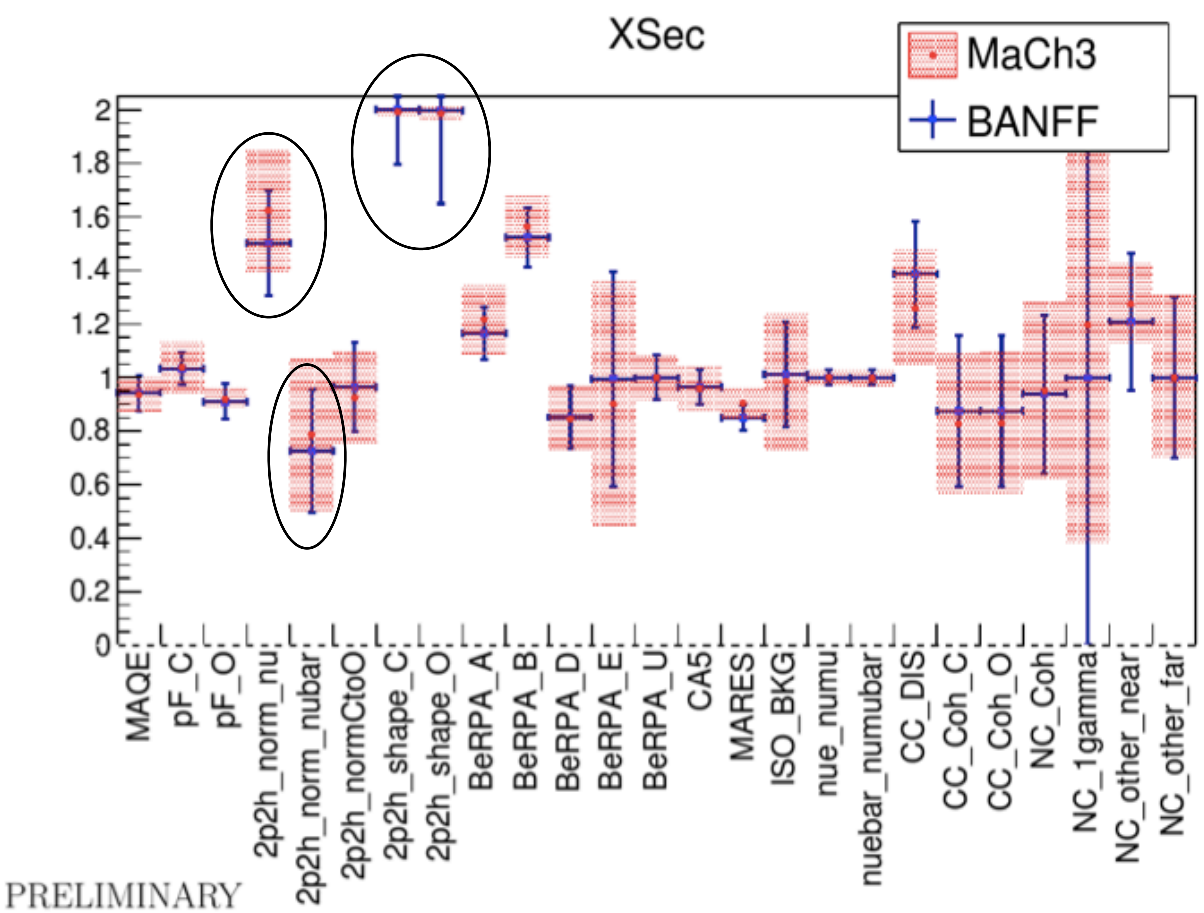


Enhance 2p-2h in neutrino interactions by ~50%

Confronting Data (T2K)



T2K, C. Bronner, NuFact 2019

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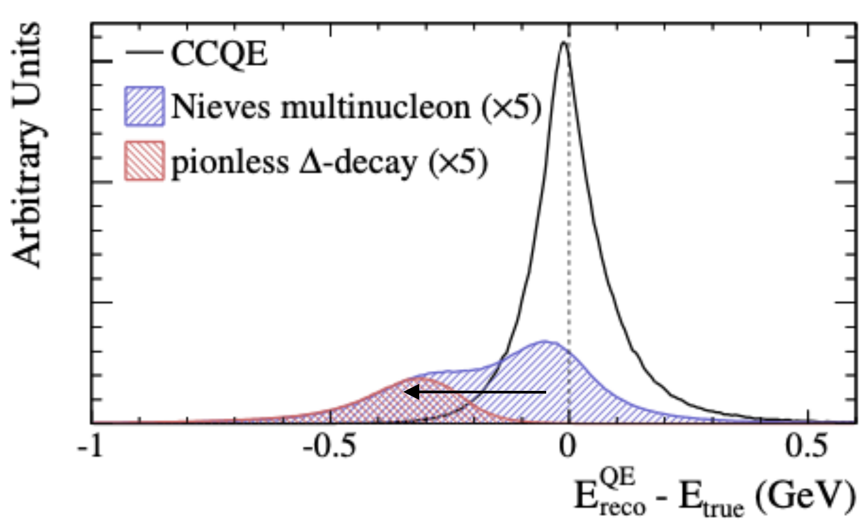
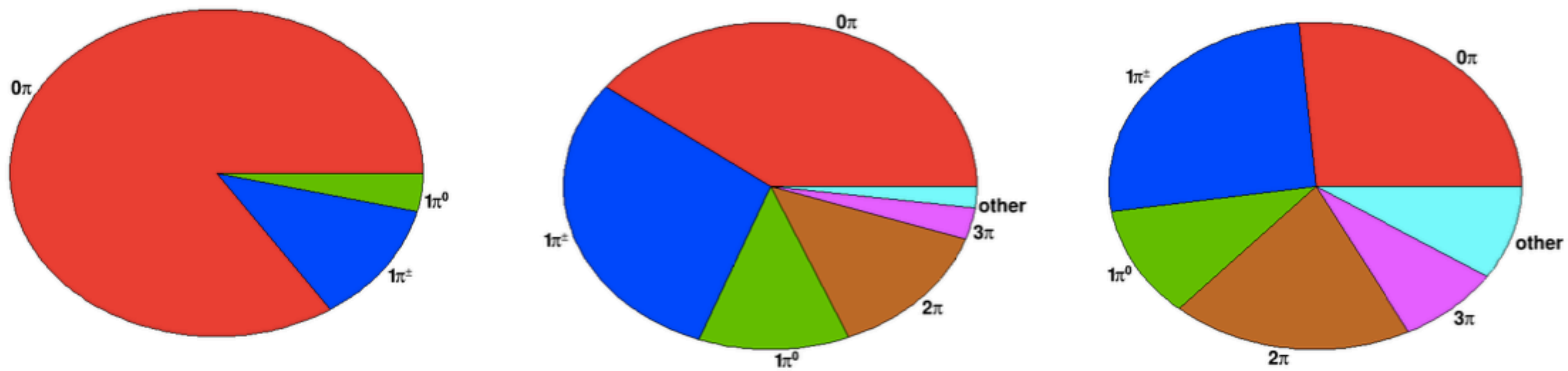


Enhance 2p-2h in neutrino interactions by ∼50%

Decrease the 2p-2h in antineutrino interactions by ∼20%

Calorimetric Energy Reconstruction

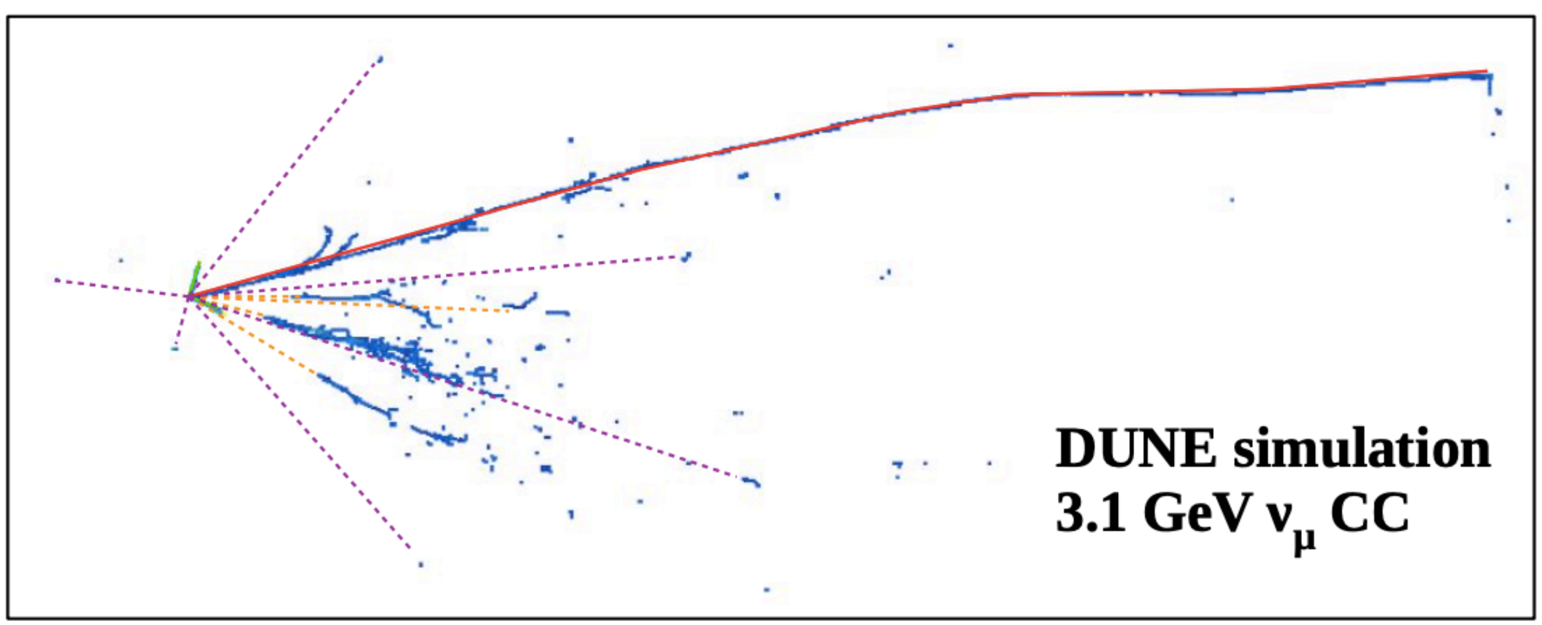
C. Marshall



$0.4 < E_\nu < 0.8$ GeV $2.3 < E_\nu < 2.7$ GeV $4.0 < E_\nu < 4.5$ GeV

DUNE covers QE, 2p-2h, single pion production, multi-pion production/DIS

Accurately identified particles can be have energy inferred calorimetrically



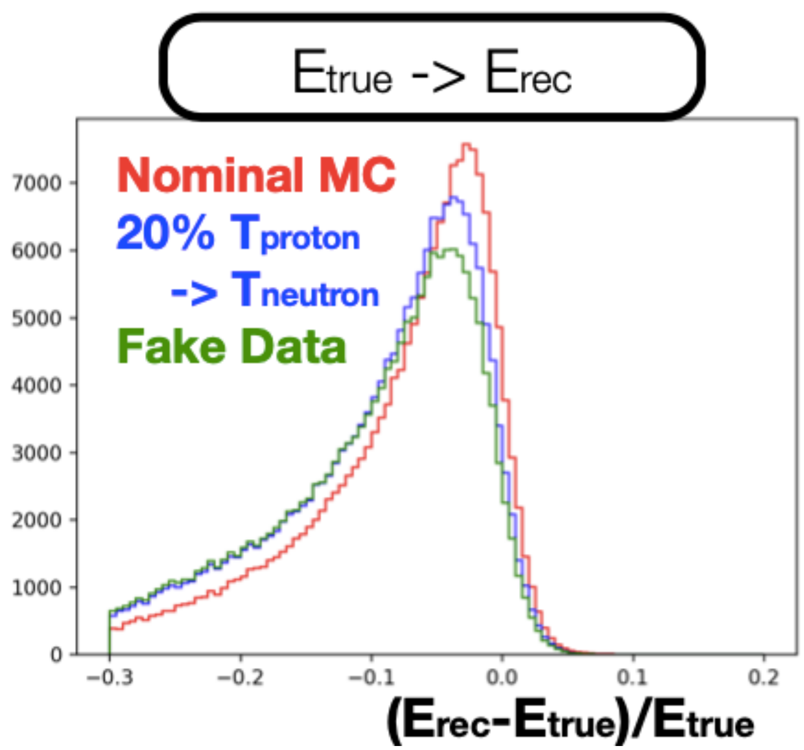
Neutrons are small blips of charge in the detector: missing energy

DUNE Neutron Toy Study

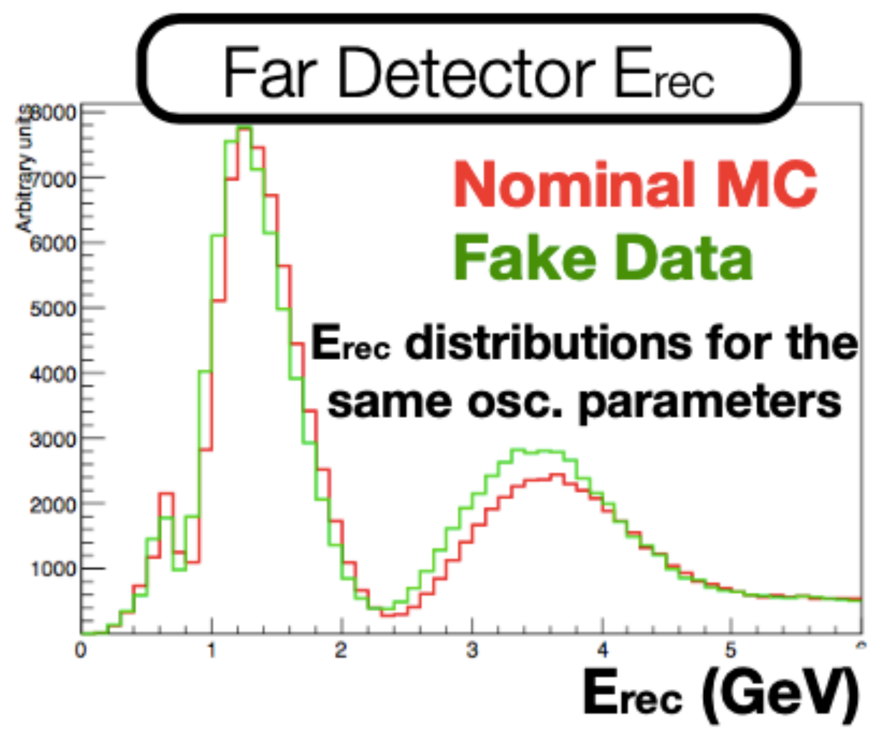
DUNE collaborators performed a toy study of the impact of uncertainties on energy carried by neutrons

- 20% of proton kinetic energy transferred to neutrons
- Incorrect model adjustments are made to fit the near detector data assuming only an on-axis measurement

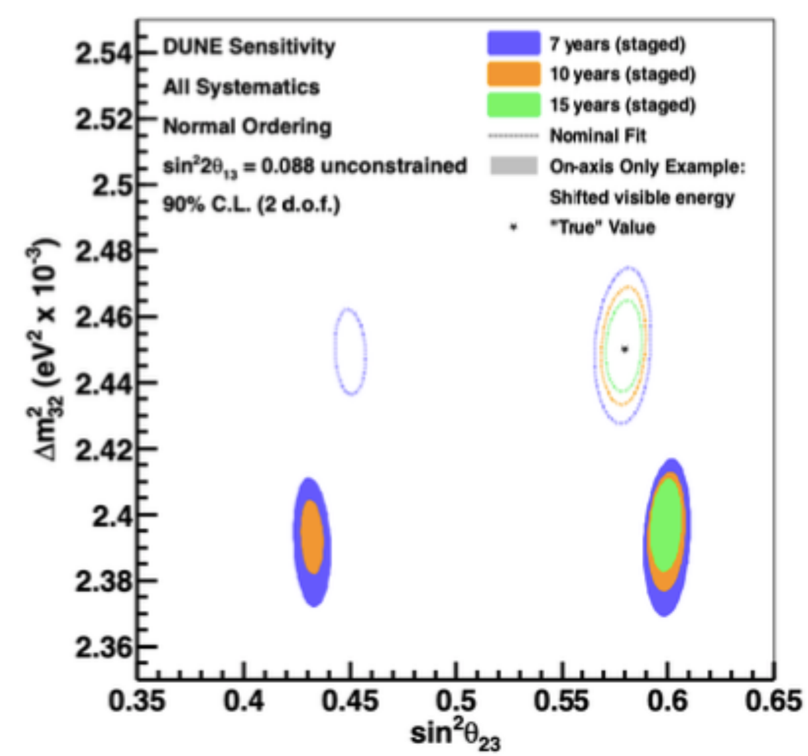
Biased energy reconstruction



Leads to biased prediction at far detector

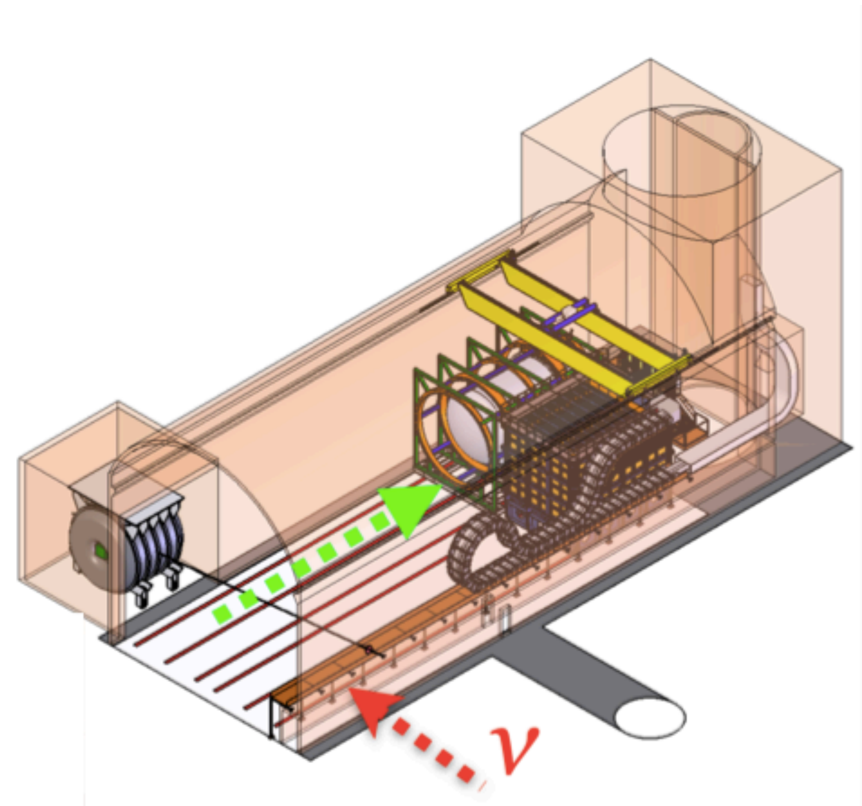


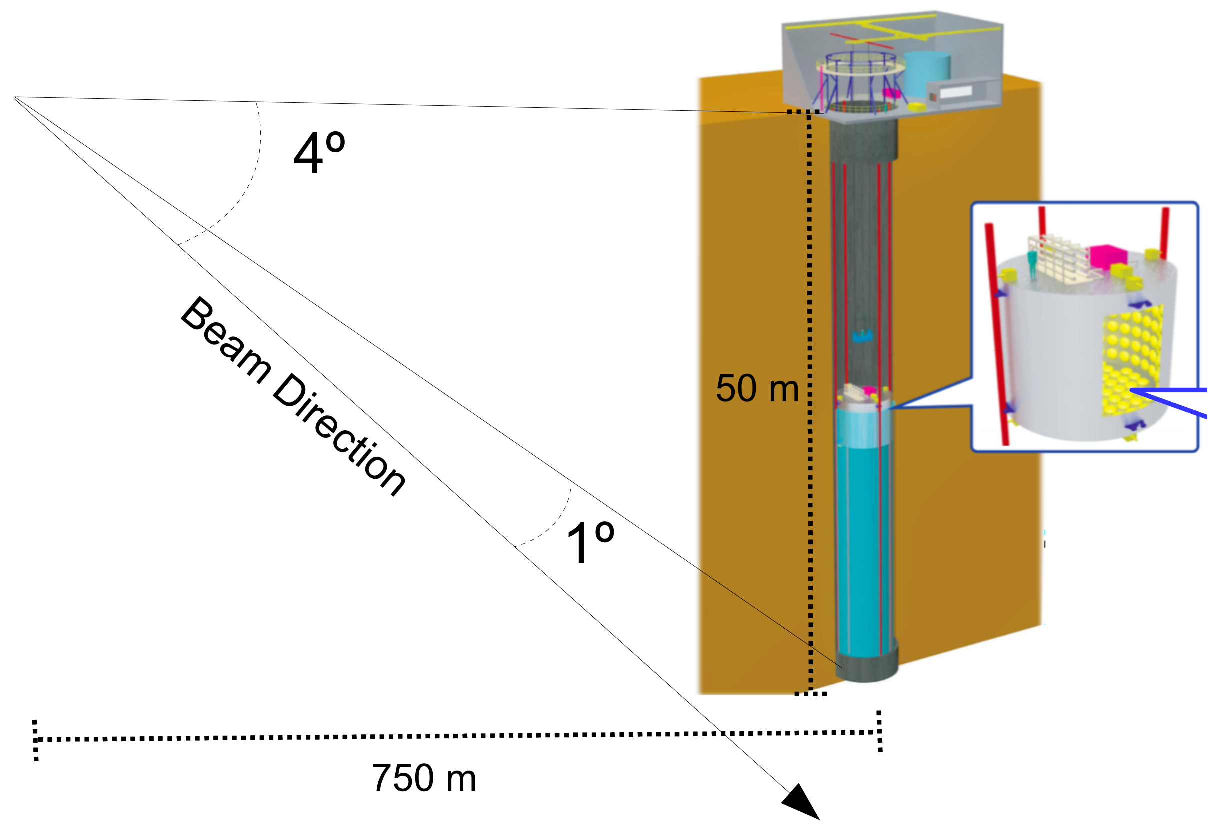
Leads to biased oscillation parameters

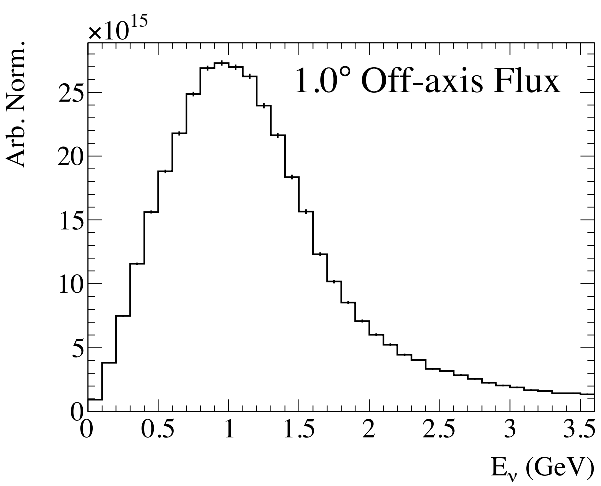


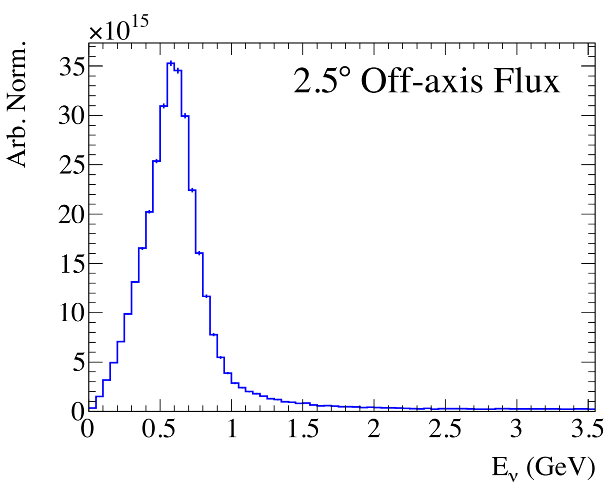
PRISM Detectors

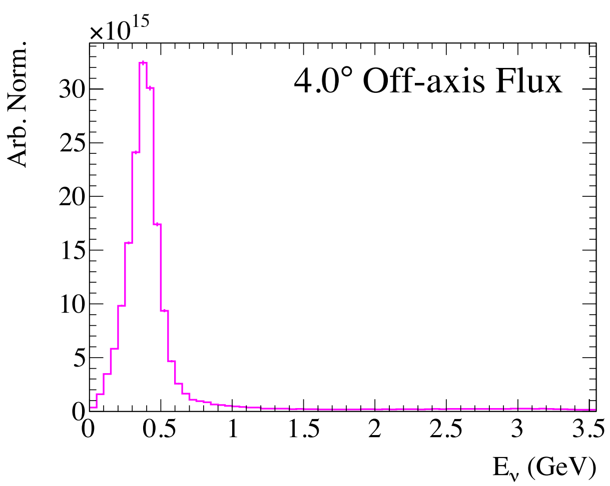
Energy reconstruction is challenging, motivating measurements at a range of off-axis angles (PRISM concept)





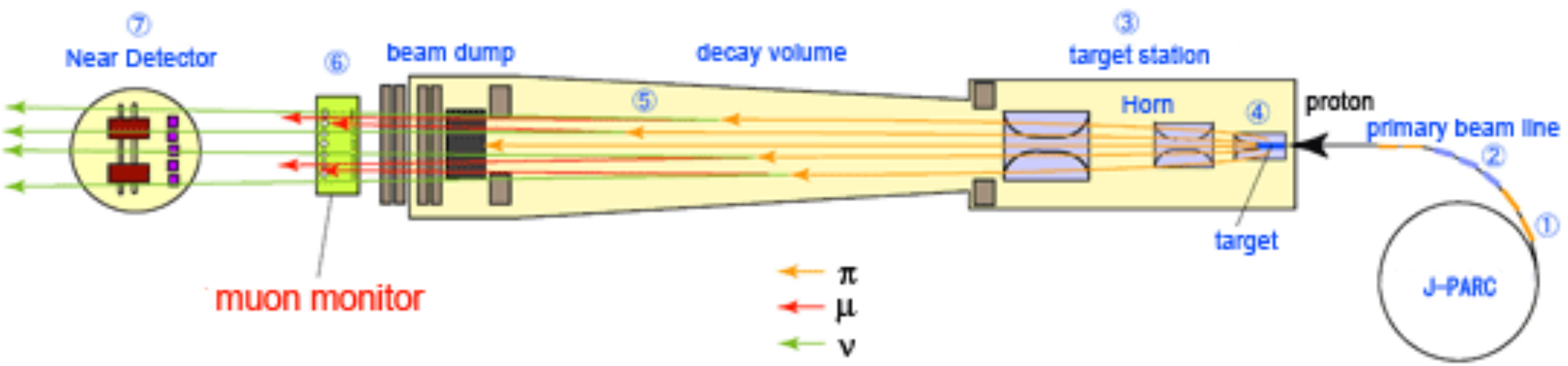






Probe range of spectra to map out energy response

Flux Model Uncertainties



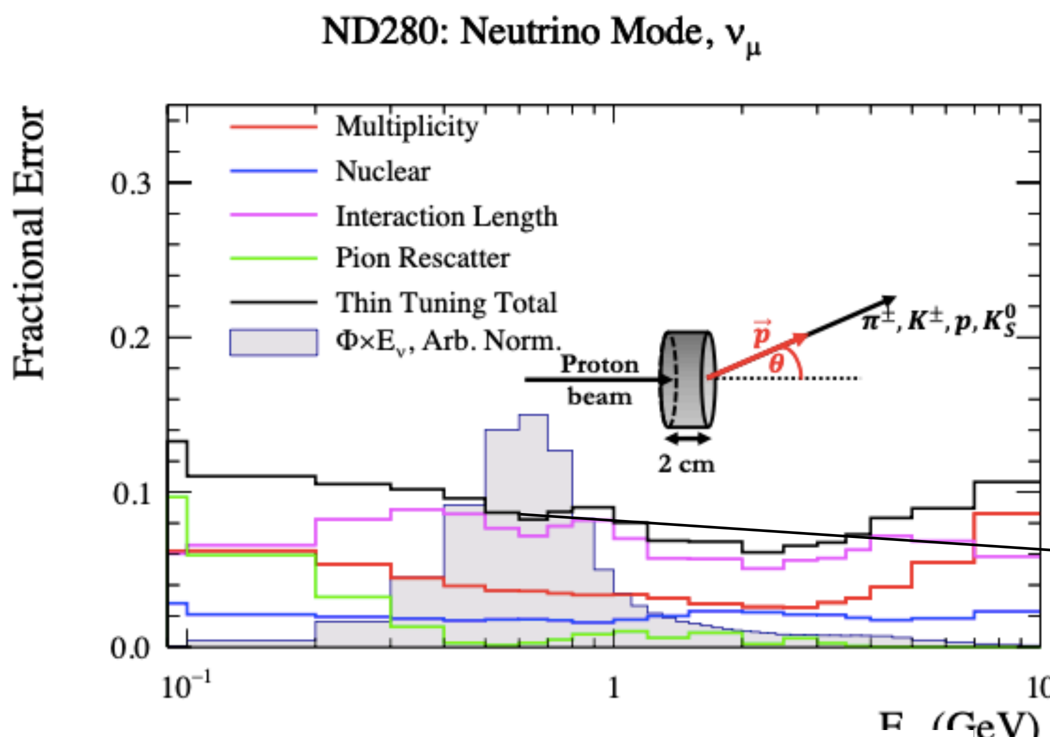
Neutrino flux predictions are based on simulations of the proton beam, production target, focussing horns, target hall, decay volume and beam dump

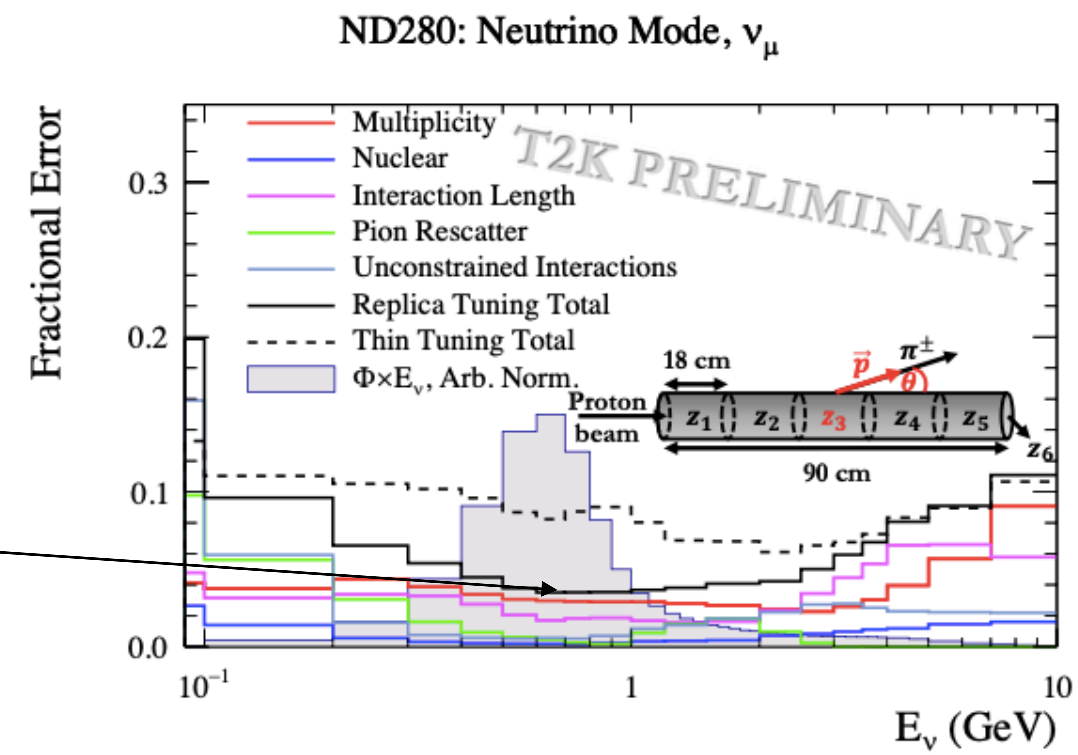
Sources of uncertainties include:

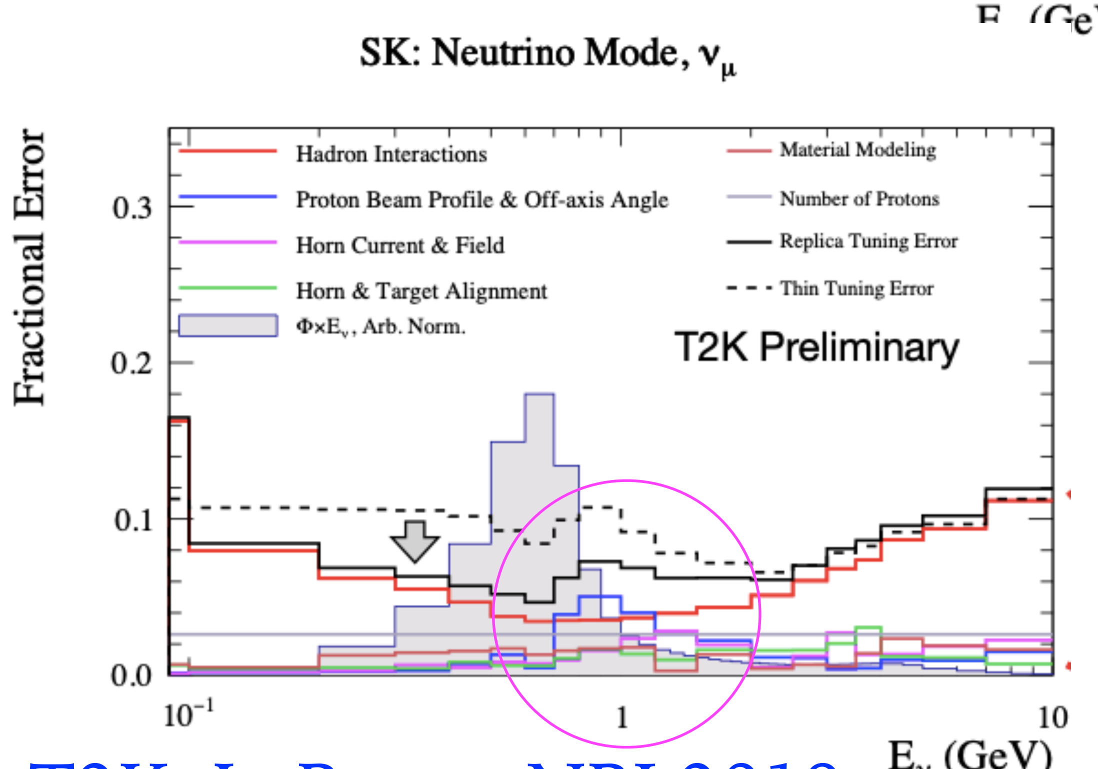
- Modeling of hadronic interactions in target and other materials
- Intensity and transverse profile of the proton beam
- Alignment of the beam line elements including the target and horns
- Accuracy of material modeling in the simulation
- Accuracy of modeling of the magnetic horn field strength and uniformity

Absolute Flux Uncertainties

As shown by T2K, the use of replica target data (from NA61/SHINE) can reduced flux model uncertainties from hadron interactions to ∼5%







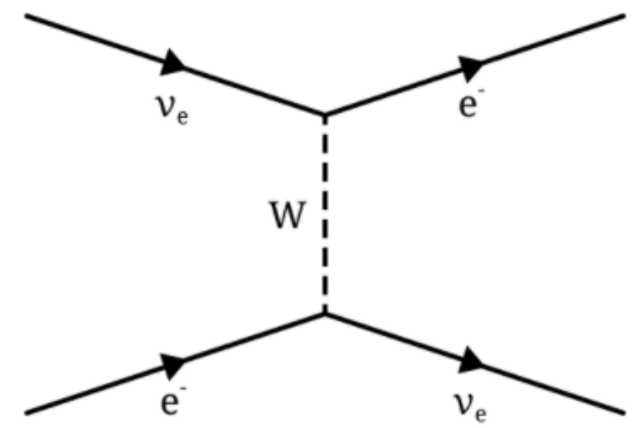
Contributions of from error sources other than hadron interactions start to dominate in some energy ranges

T2K, L. Berns, NBI 2019

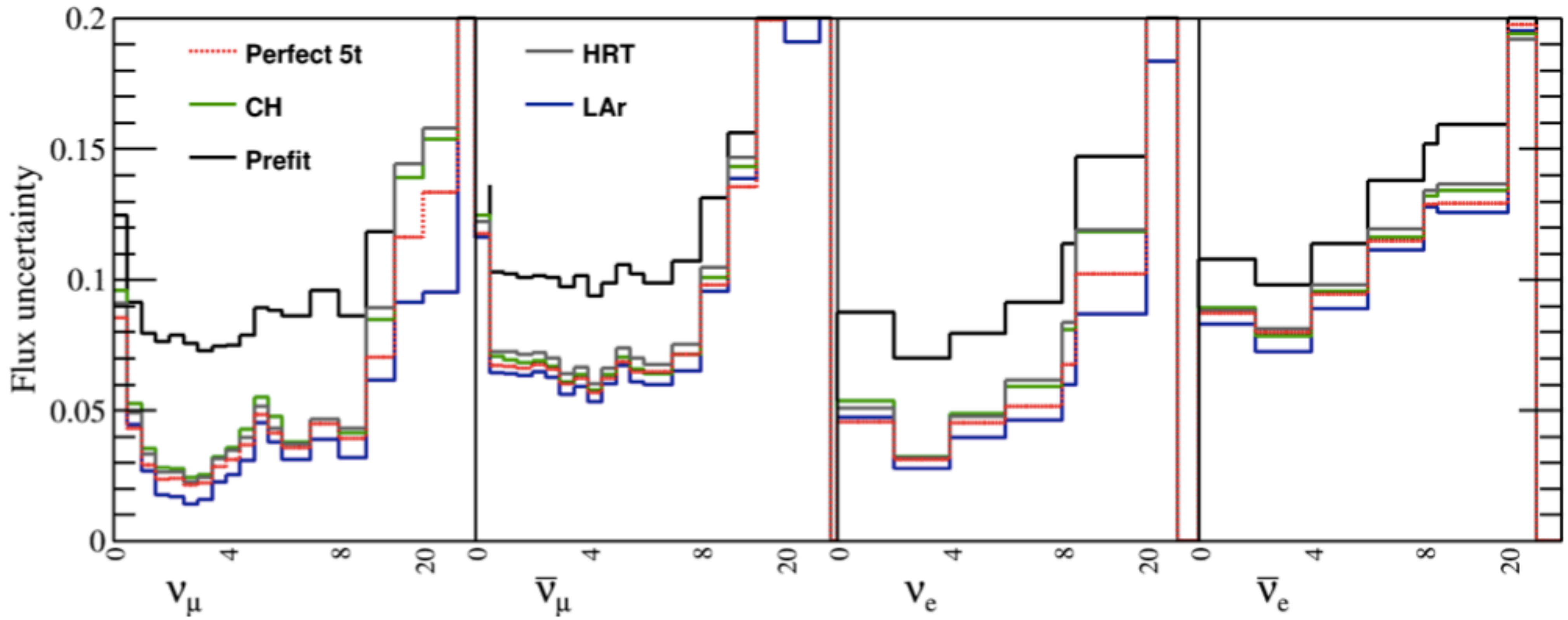
Direct Measurement of Neutrino Flux

Neutrino-electron scattering has known interaction cross section

Selection of these events can be used to normalize the flux with few percent accuracy



Impact in DUNE: Marshall, McFarland and Wilkinson arXiv:1910.10996



(a) FHC

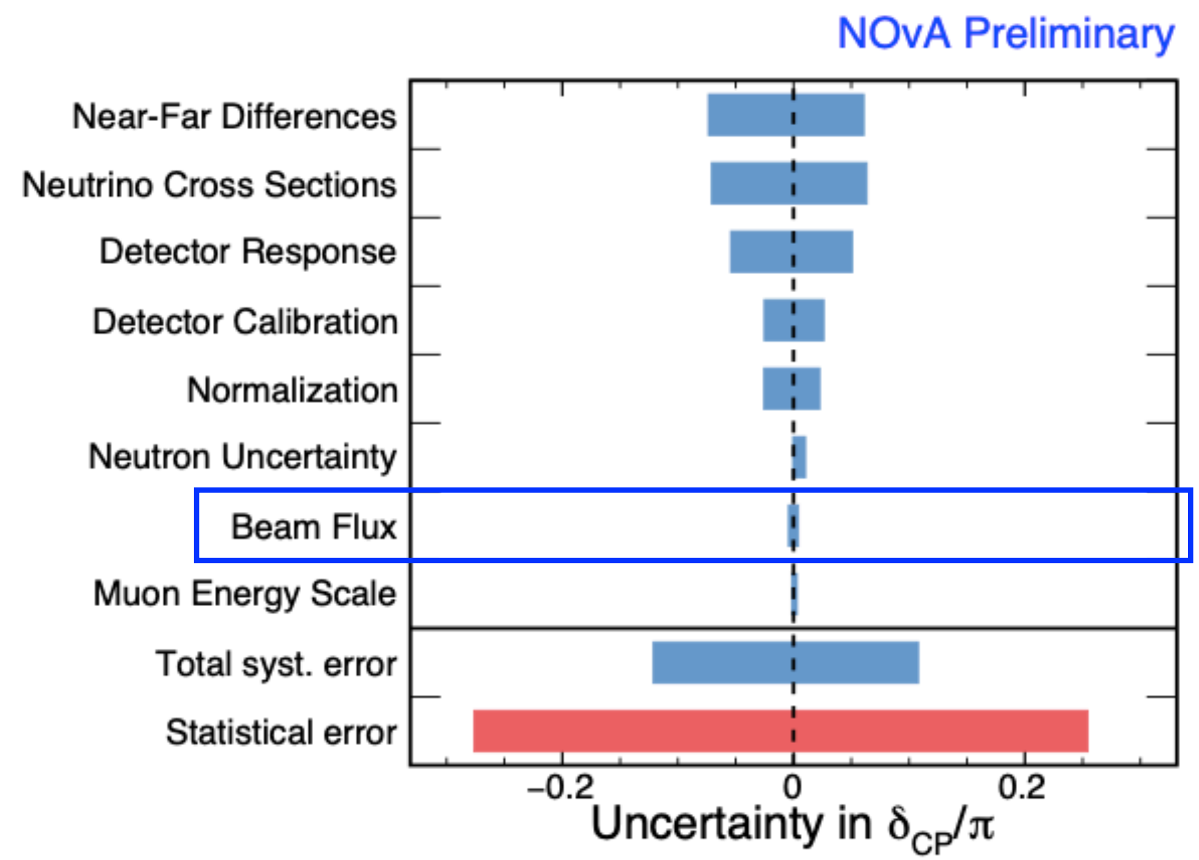
Neutrino-electron scattering processes does not differentiate flavors. Rely on relationship of neutrino flavors in flux model.

Do Flux Model Uncertainties Matter?

Flux model uncertainties are not dominant in analyses of current experiments, T2K and NOvA

T2K % error on $N(\nu_e)/N(\bar{\nu}_e)$

Error source	FHC/RHC
SK Detector	1.47
SK FSI+SI+PN	1.57
Flux + Xsec constrained	2.67
E_b	3.62
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	3.03
NC1γ	1.50
NC Other	0.18
Osc	0.77
All Systematics	5.96
All with osc	6.03



NOvA, L. Kolupaeva, EPS-HEP 2019

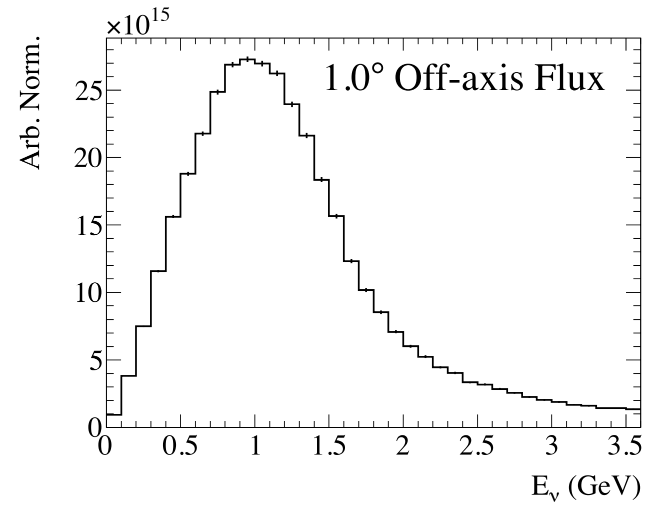
Do we need to worry about flux model uncertainties for Hyper-K and DUNE?

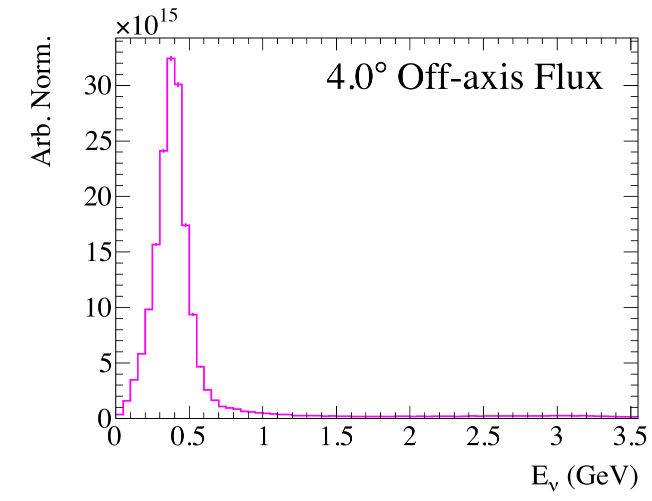
Accurate flux predictions are necessary to make neutrino interaction cross section measurements

New Uses of Neutrino Flux Models

The PRISM method requires an accurate understanding of the neutrino flux prediction as a function of off-axis angle

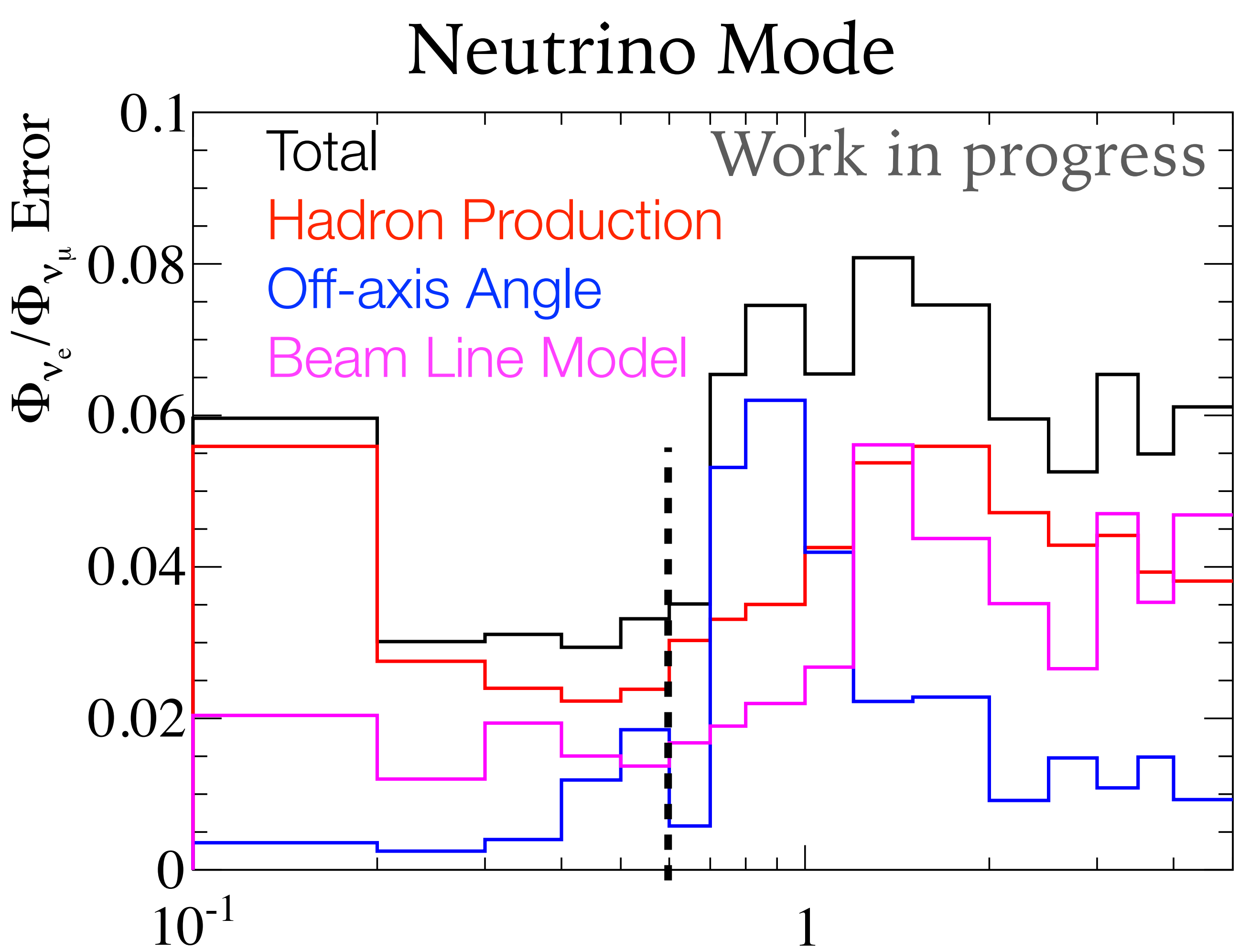
Are uncertainties on off-axis angle dependence of flux small enough?





May use electron (anti)neutrino contamination of beam from muon and kaon decays to measure $\sigma(\nu_e)/\sigma(\nu_\mu)$ and $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$

Need to control uncertainties on $\Phi(\nu_e)/\Phi(\nu_\mu)$ and $\Phi(\bar{\nu}_e)/\Phi(\bar{\nu}_\mu)$



M. Hartz, NBI 2019

Detector Modeling

Detector modeling uncertainties impact the oscillation measurements directly

DUNE Interim Design Report (arXiv:1807.10334) lists general requirements:

- ✦1-2% understanding of normalization, energy and position resolution (similar goals for Hyper-K)
- ✦1% energy scale uncertainty on lepton
- ✦3% energy scale uncertainty on hadrons

Both experiments will aim to measure low-level properties of the detectors:

DUNE: electric field, drift velocity, electron lifetime, etc.

Hyper-K: photon scattering and absorption lengths, photodetector gain and efficiency, etc.

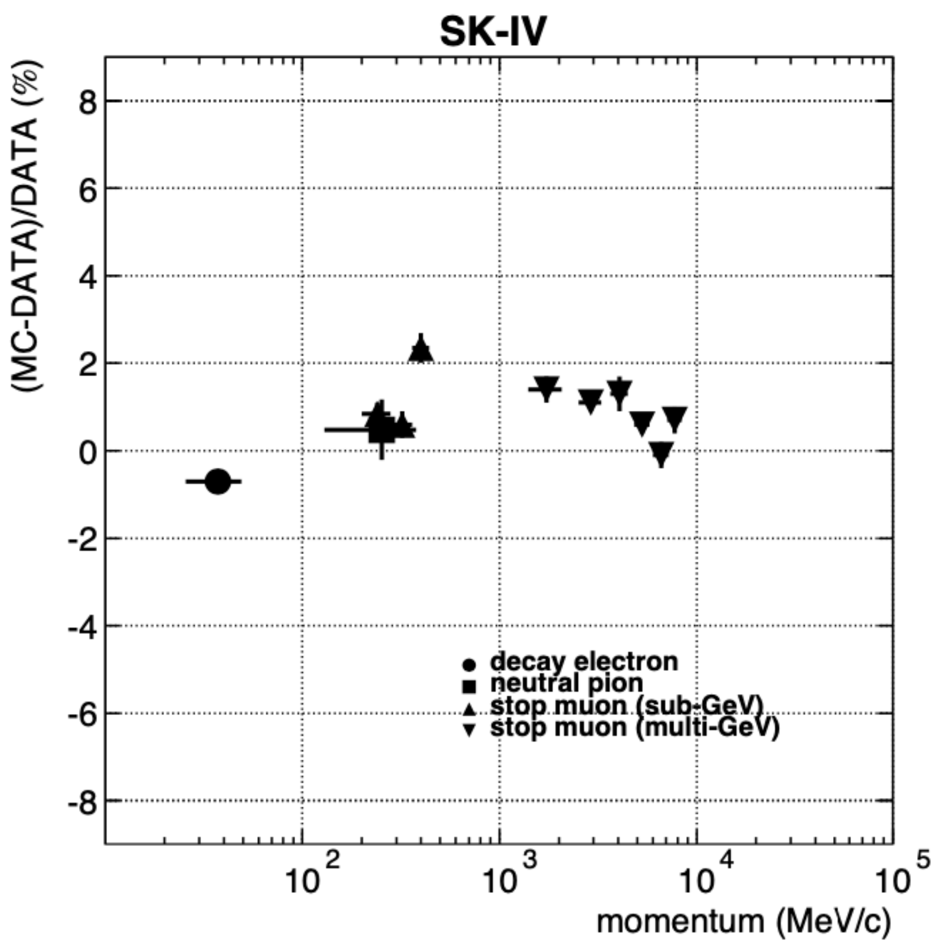
Radioactive calibration sources and control samples such as cosmic muons, Michel electrons and π^0 are used

Detector Modeling Example

Hyper-K builds on Super-K methods for energy scale calibration in high energy analyses:

- ✦ PMT properties such as efficiency, 1 p.e. response, linearity are calibrated with sources including a 9 MeV gamma source (neutron capture on ^{58}Ni) and Nitrogen-dye laser
- ✦ Global correction to the photo-electron yield made using through-going cosmic muons

Hyper-K Design Report: arXiv:1805.04163



2.4% energy scale uncertainty in Super-K

Based on maximum data/MC discrepancy in physics control samples

Conservative evaluation (RMS of points is less than 2.4%)

Test Beam Measurements

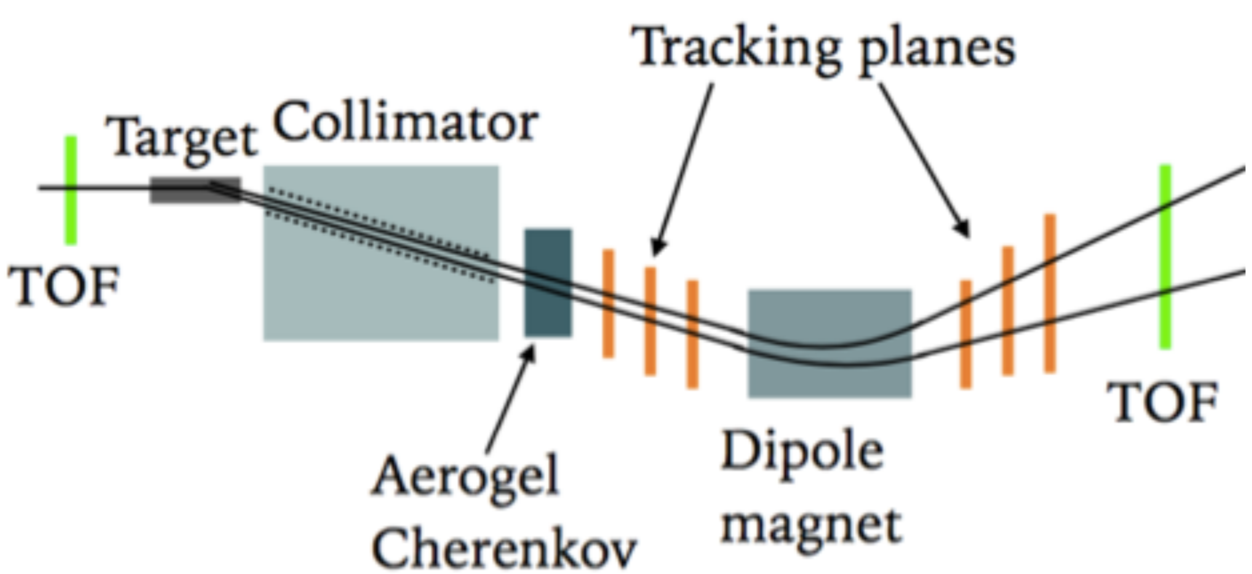
Measurements of prototypes or full modules in test beams must play a role in detector modeling, e.g. ProtoDUNES, upcoming Super-FGD neutron measurements, etc.

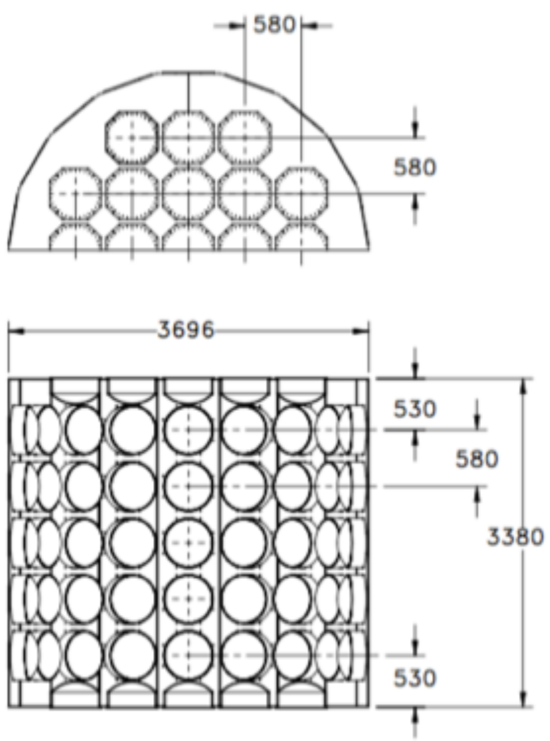
A water Cherenkov test beam experiment:

50-ton water Cherenkov detector prototype at CERN

Tertiary particle production near the detector to achieve low energies

LOI submitted to CERN SPSC (CERN-SPSC-2019-042)





Summary

- Control of systematic uncertainties will be critical for next-generation oscillation experiments
- Near detectors help, but traditional measurements at one off-axis position are not sufficient
- Energy reconstruction and energy scale must be well-constrained
    - PRISM concept is new approach to measure the energy reconstruction
- Flux model uncertainty reduction must also focus on off-axis angle dependence and flavor ratios
- We should expect more detailed plans for detector modeling and calibration from collaborations in the future

Thank You