Systematic Uncertainties in Long Baseline Neutrino Oscillation Measurements

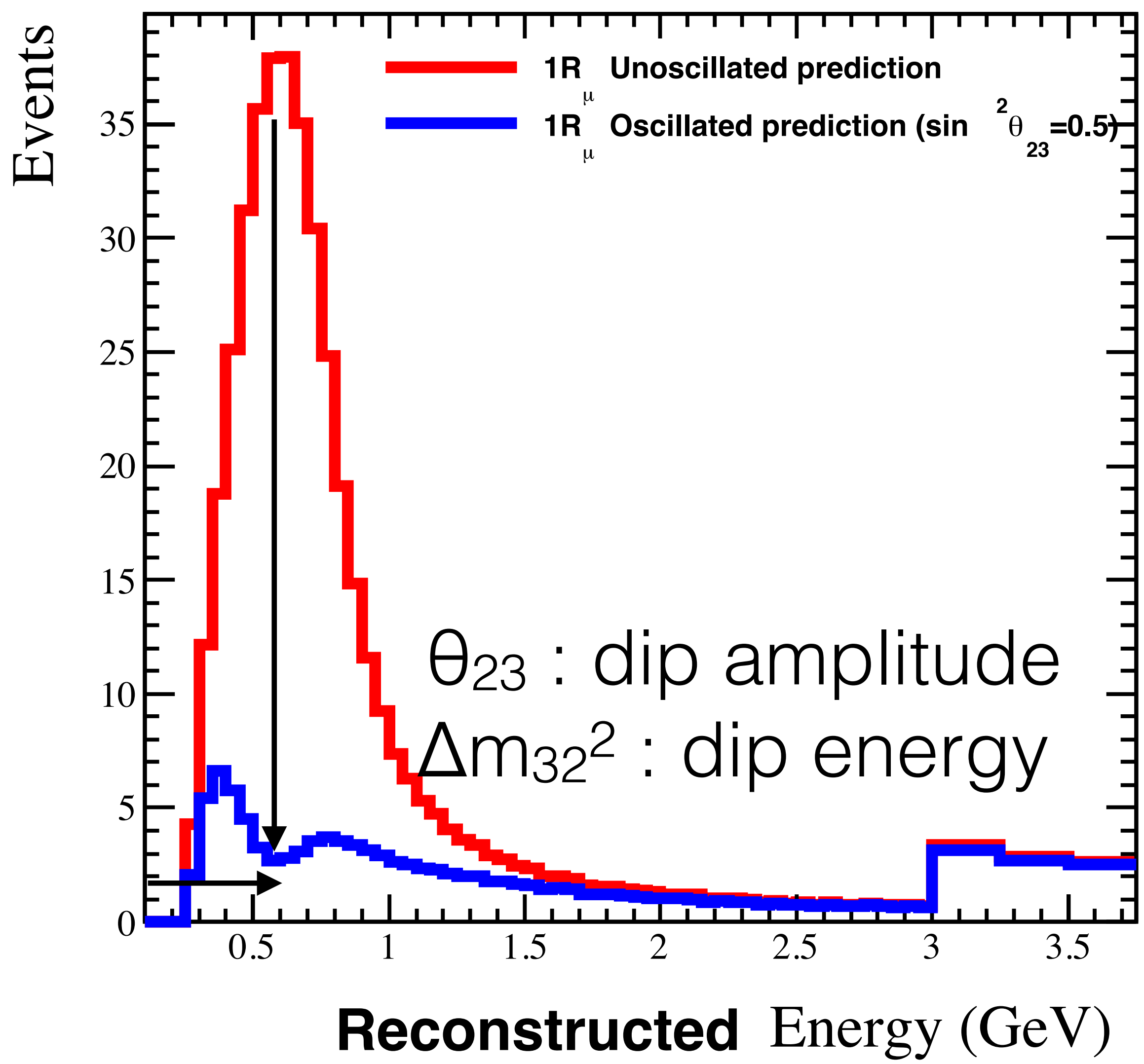
David Hadley

21st December 2017

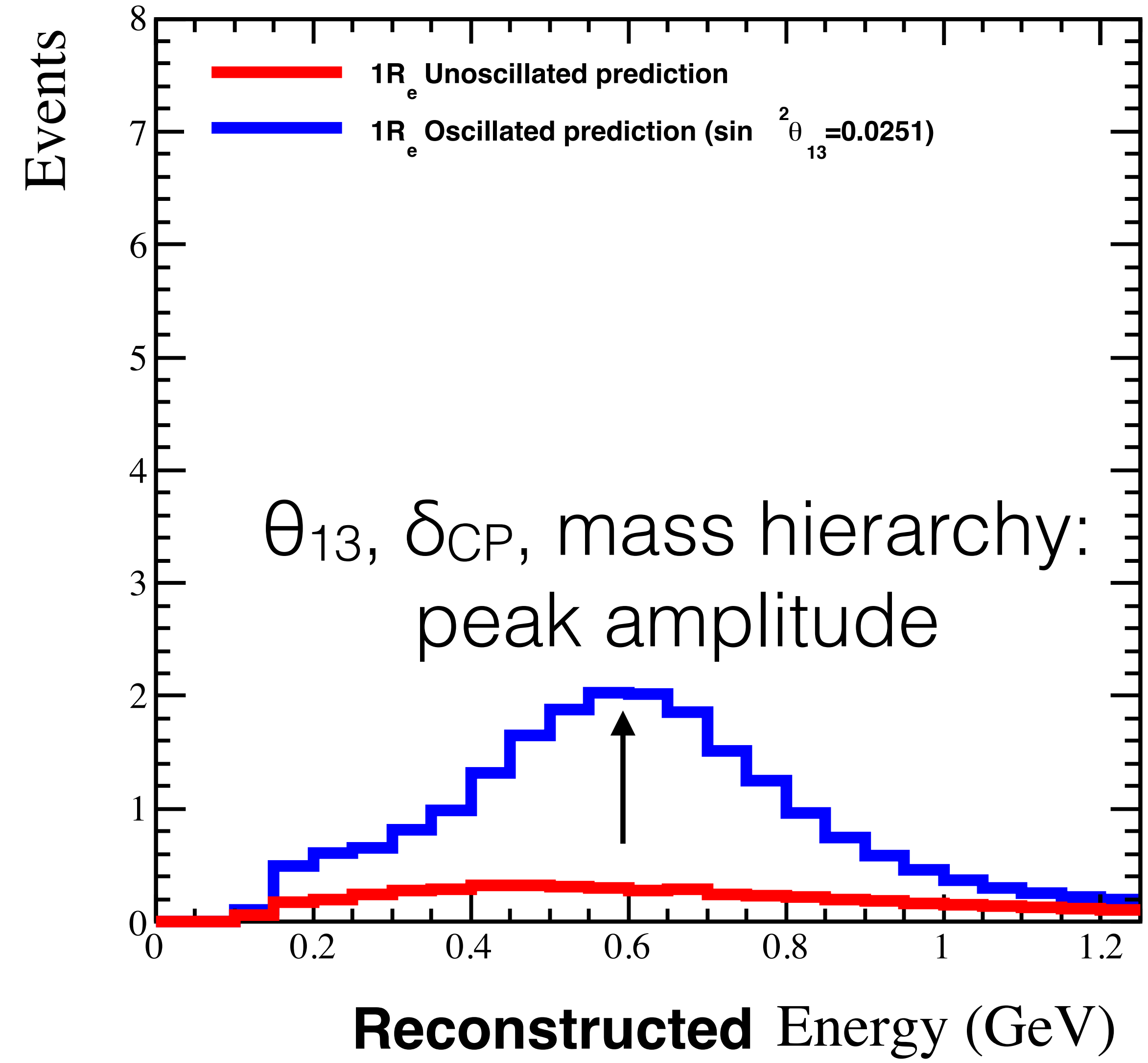
Prospects in Neutrino Physics, NuPhys2017

What is measured?

ν_μ disappearance



ν_e appearance



Measurement precision limited by:

- Statistics
- Neutrino energy reconstruction
- Knowledge of unoscillated spectrum and background contamination

Where do systematic uncertainties enter?

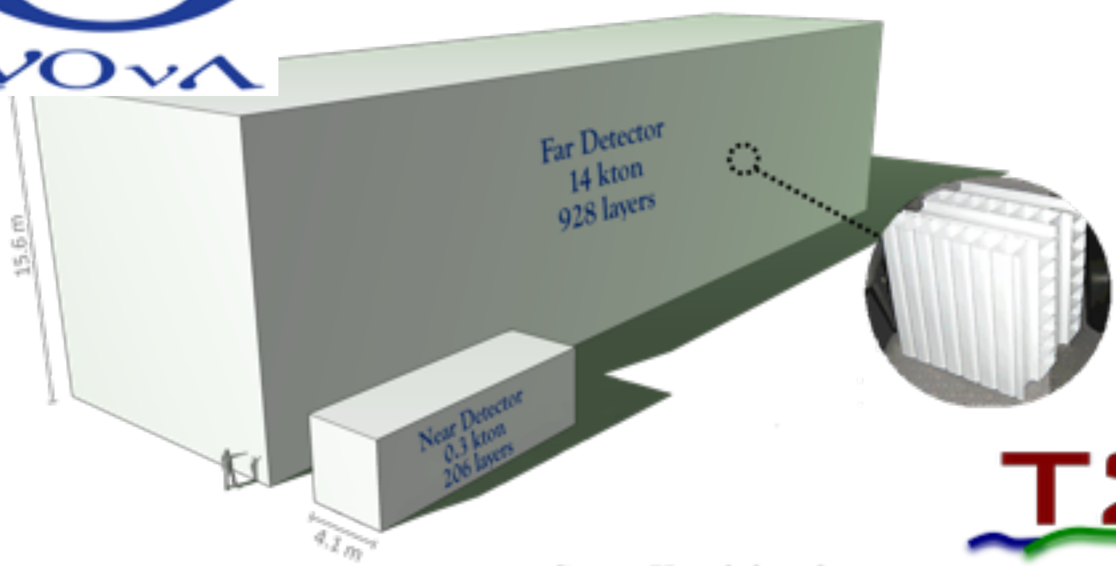
$$R(\vec{x}_{reco}) = \int \Phi(E_\nu) \times \sigma(E_\nu, \vec{x}_{true}) \times \varepsilon(\vec{x}_{true}, \vec{x}_{reco}) \times P(E_\nu, \vec{\theta})\, dE_\nu\, d\vec{x}_{true}$$

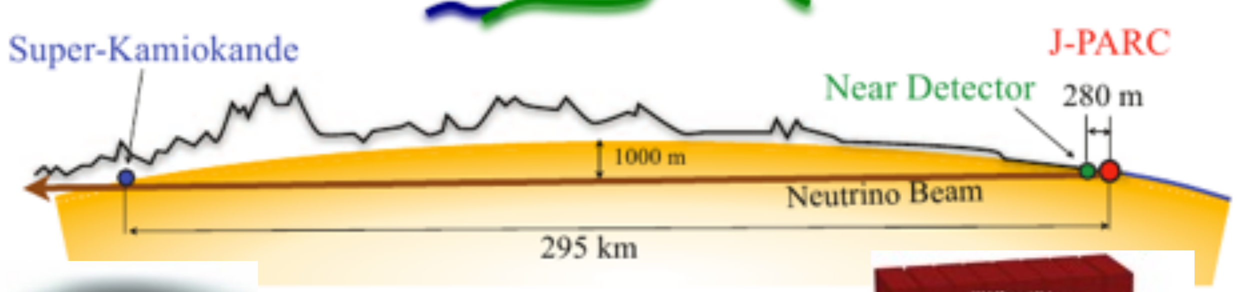
- $\Phi(E_\nu)$: Neutrino Flux
- $\sigma(E_\nu, \vec{x}_{true})$: Neutrino nucleus interaction model
- $\varepsilon(\vec{x}_{true}, \vec{x}_{reco})$: Detector efficiency and resolution
- $P(E_\nu, \vec{\theta})$: Oscillation Probability

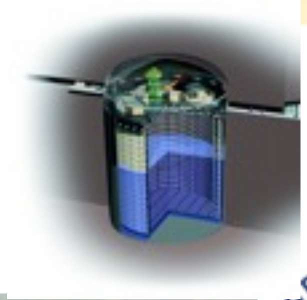
Use measurements at near detector to constrain $(\Phi \times \sigma \times \varepsilon)$

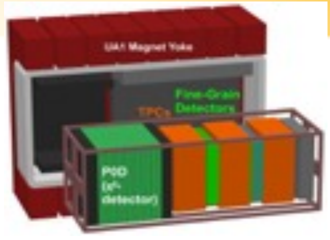
Cancellation of uncertainties is not perfect as no oscillation at the near detector and Φ and ε may differ

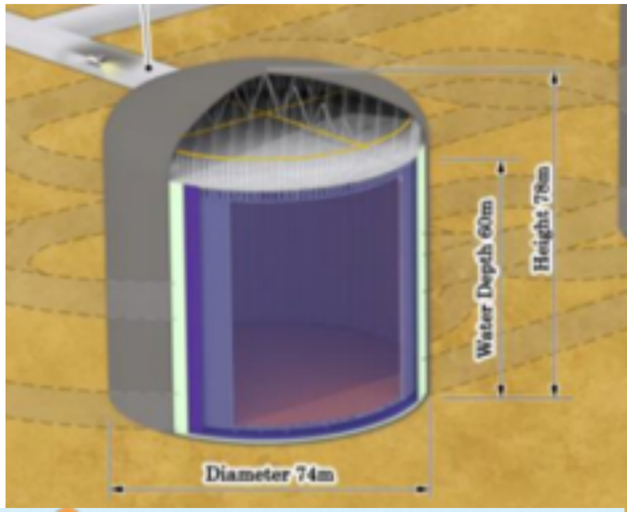
Accelerator based Neutrino Oscillation Experiments

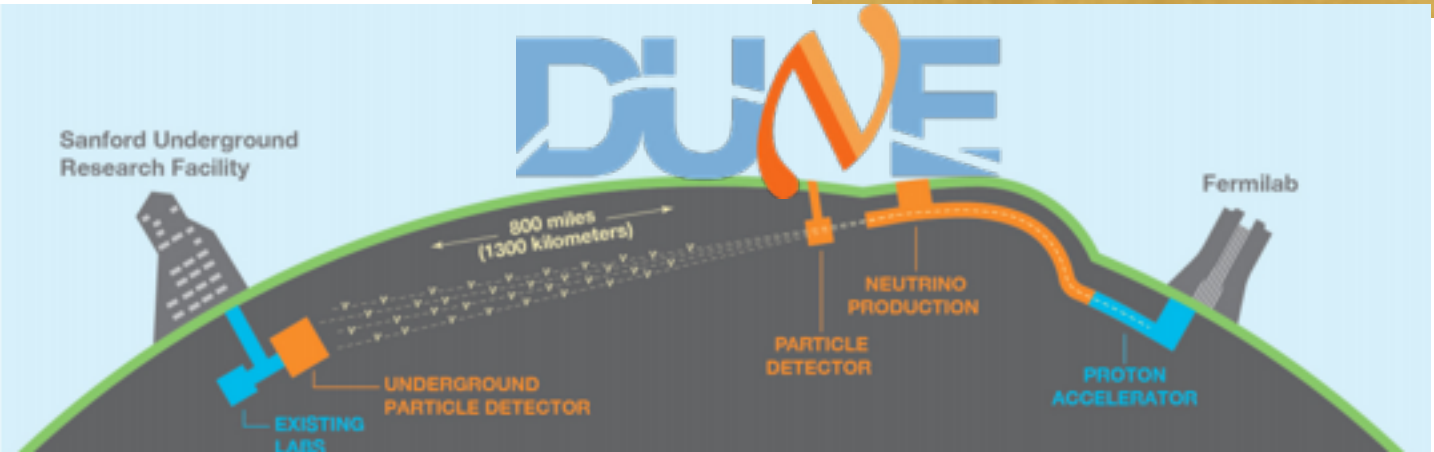












Accelerator based Neutrino Oscillation Experiments

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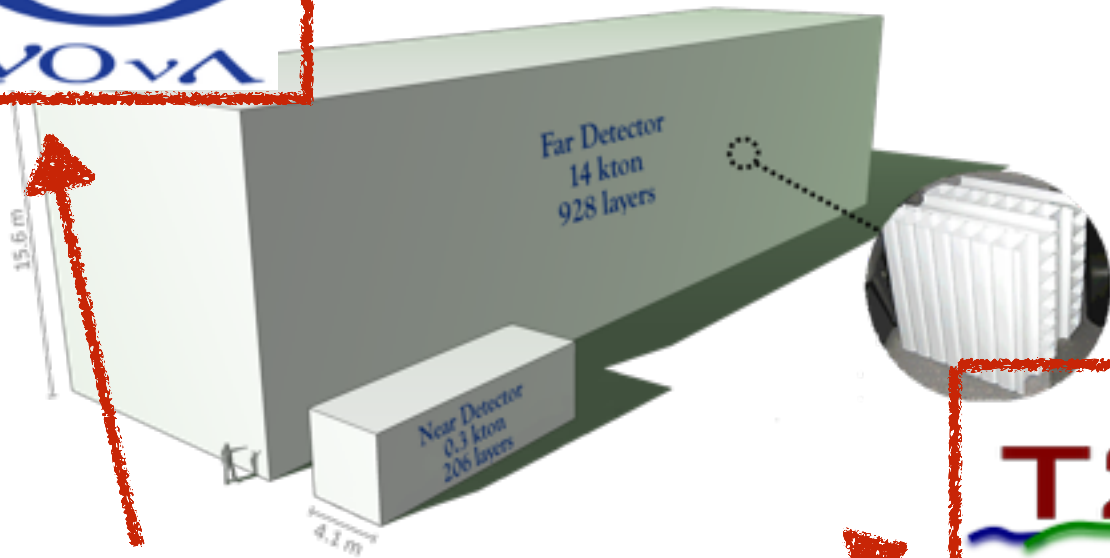
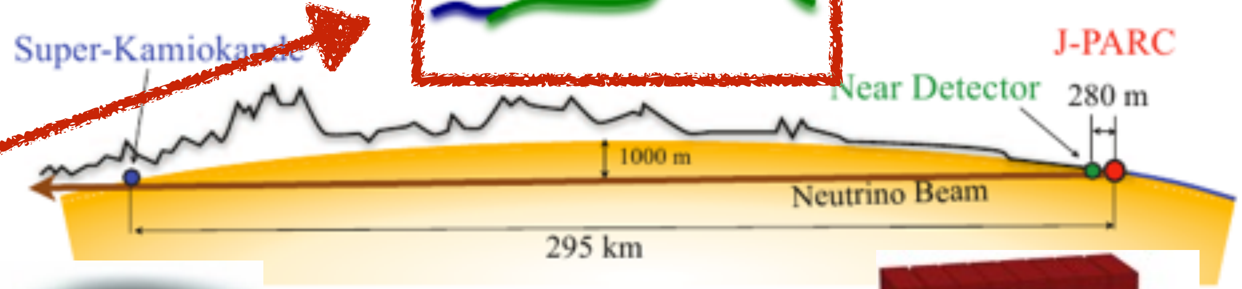
NOvA

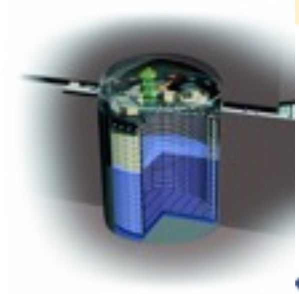


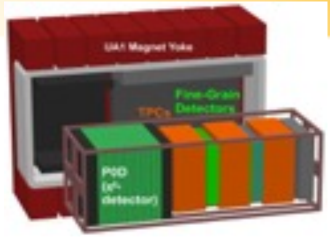
OPERA

MINOS

T2K

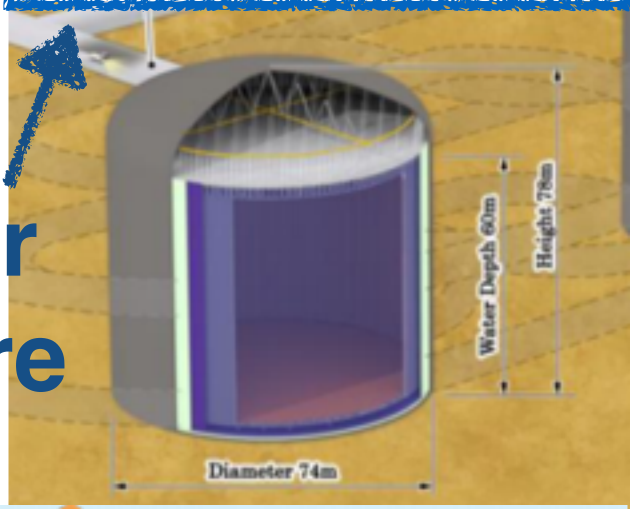






Currently running long baseline experiments

Hyper-Kamiokande



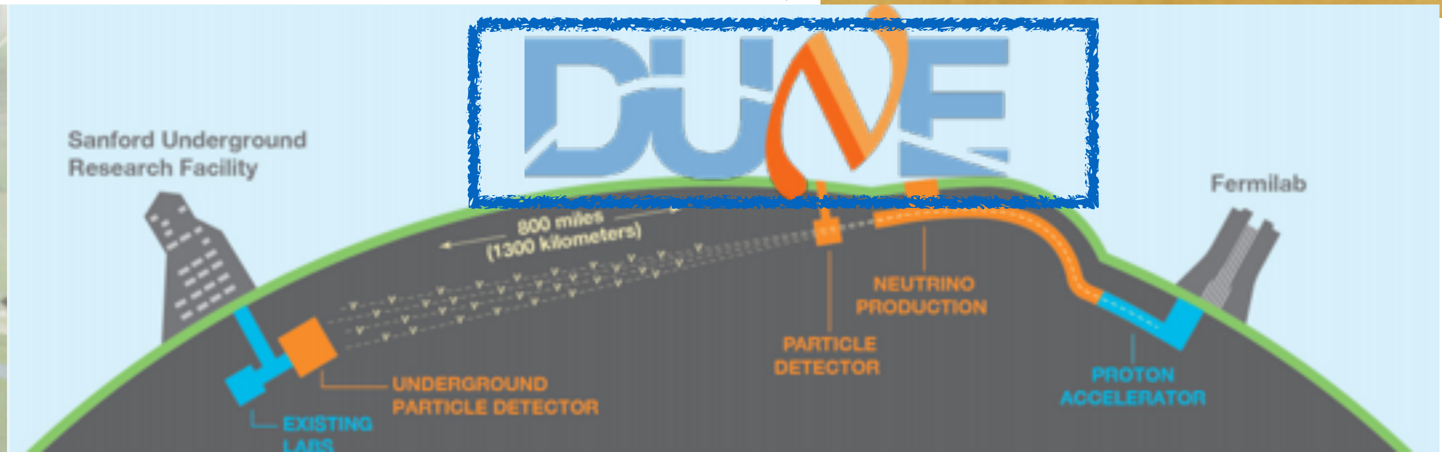
Near future

ICARUS

μBooNE

SBND
SHORT-BASELINE NEAR DETECTOR

DUNE



Statistics

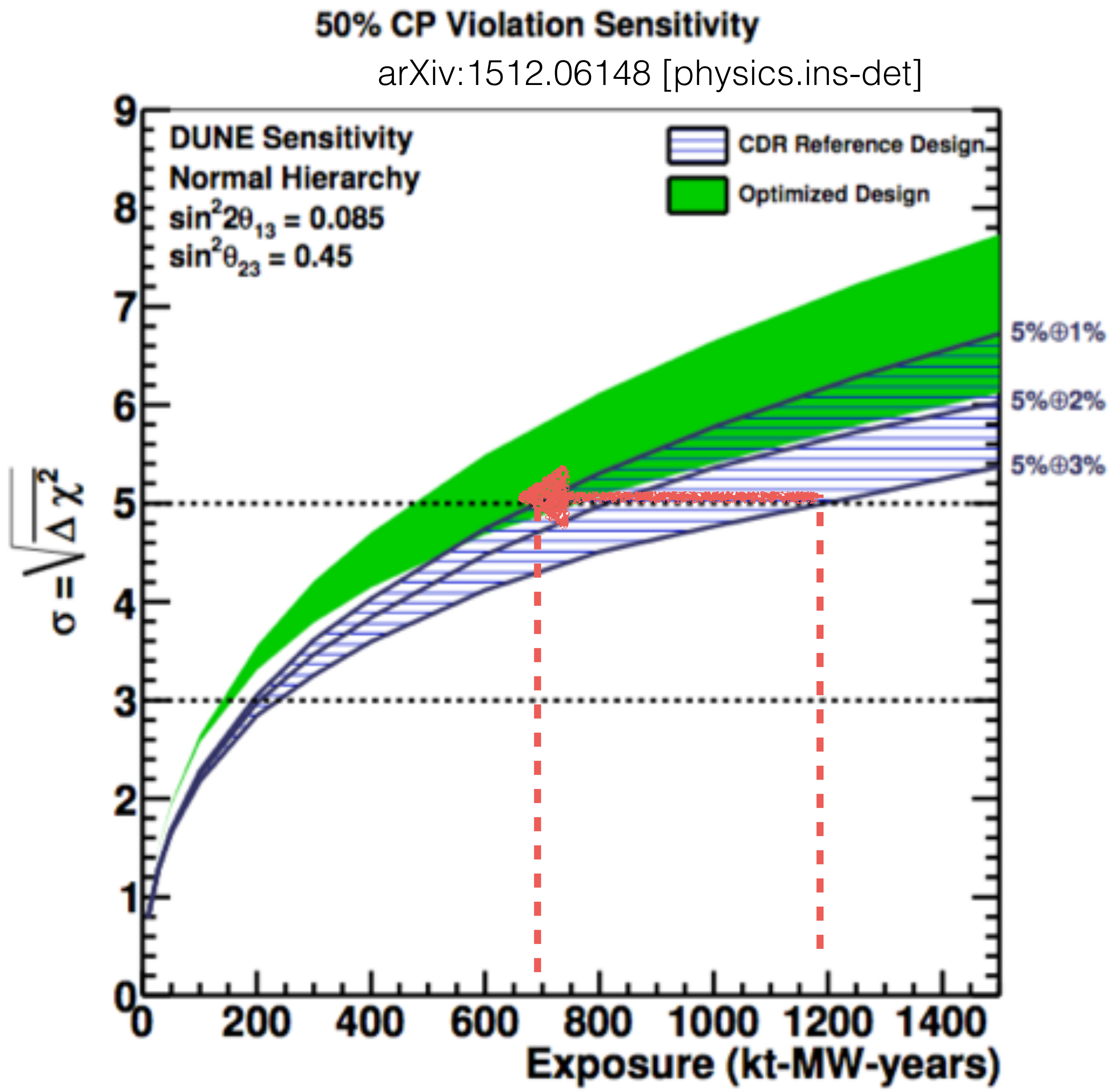
Experiment	$\nu_e + \bar{\nu}_e$	$1/\sqrt{N}$	Ref.
T2K (current)	74 + 7	12% + 40%	2.2×10^{21} POT
NOvA (current)	33	17%	FERMILAB-PUB-17-065-ND
NOvA (projected)	110 + 50	10% + 14%	arXiv:1409.7469 [hep-ex]
T2K-I (projected)	150 + 50	8% + 14%	7.8×10^{21} POT, arXiv:1409.7469 [hep-ex]
T2K-II	470 + 130	5% + 9%	20×10^{21} POT, arXiv1607.08004 [hep-ex]
Hyper-K	2900 + 2700	2% + 2%	10 yrs 2-tank staged KEK Preprint 2016-21
DUNE	1200 + 350	3% + 5%	3.5+3.5 yrs x 40kt @ 1.07 MW arXiv:1512.06148 [physics.ins-det]

Current appearance measurements stats dominate

$O(10^3)$ ν_e at future experiments → demands ~2% systematics

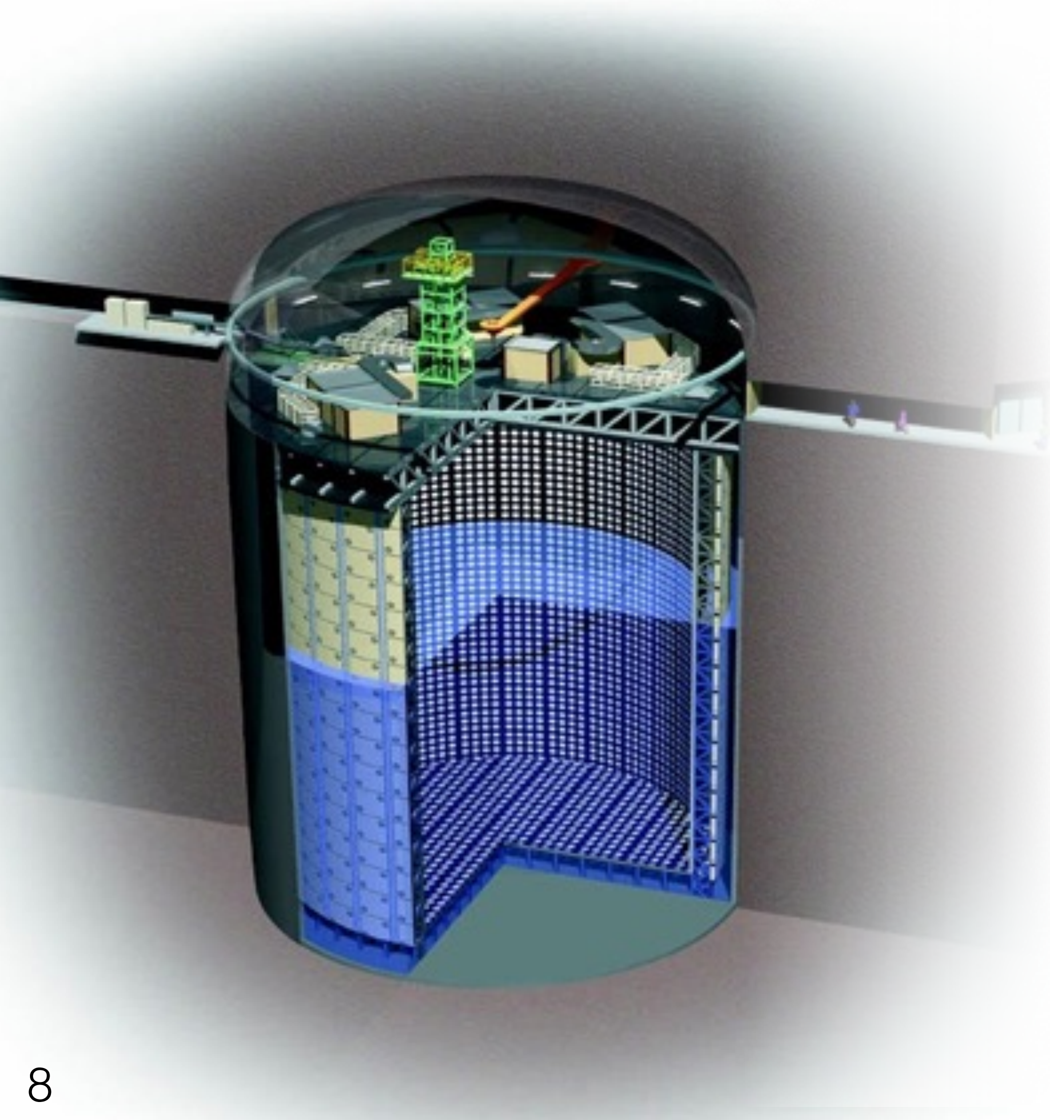
$O(10^4)$ ν_μ → need systematics as good as we can get!

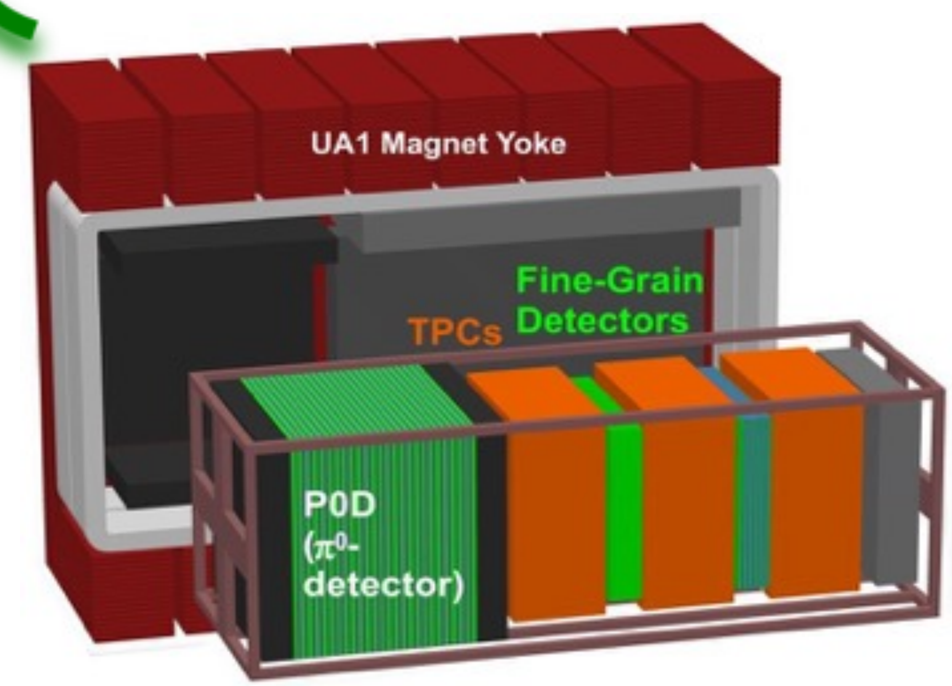
Systematic Uncertainties



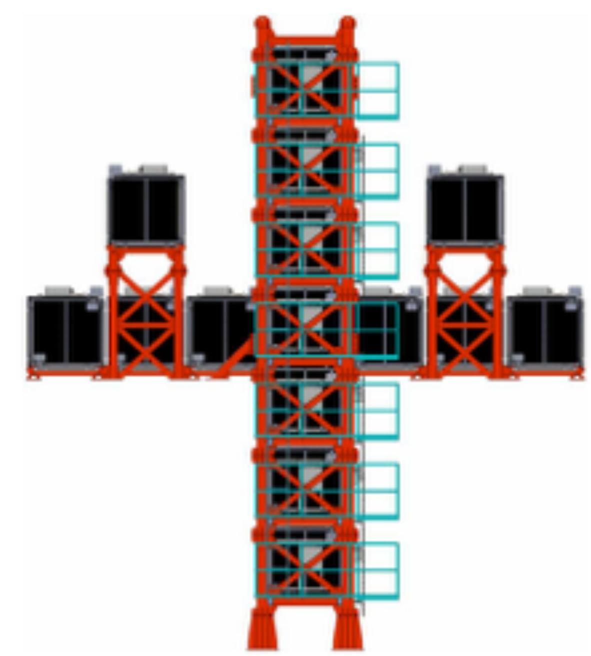
Reduction in systematic uncertainties can be equivalent to significant boost in exposure

Far Detector
(Super-K)

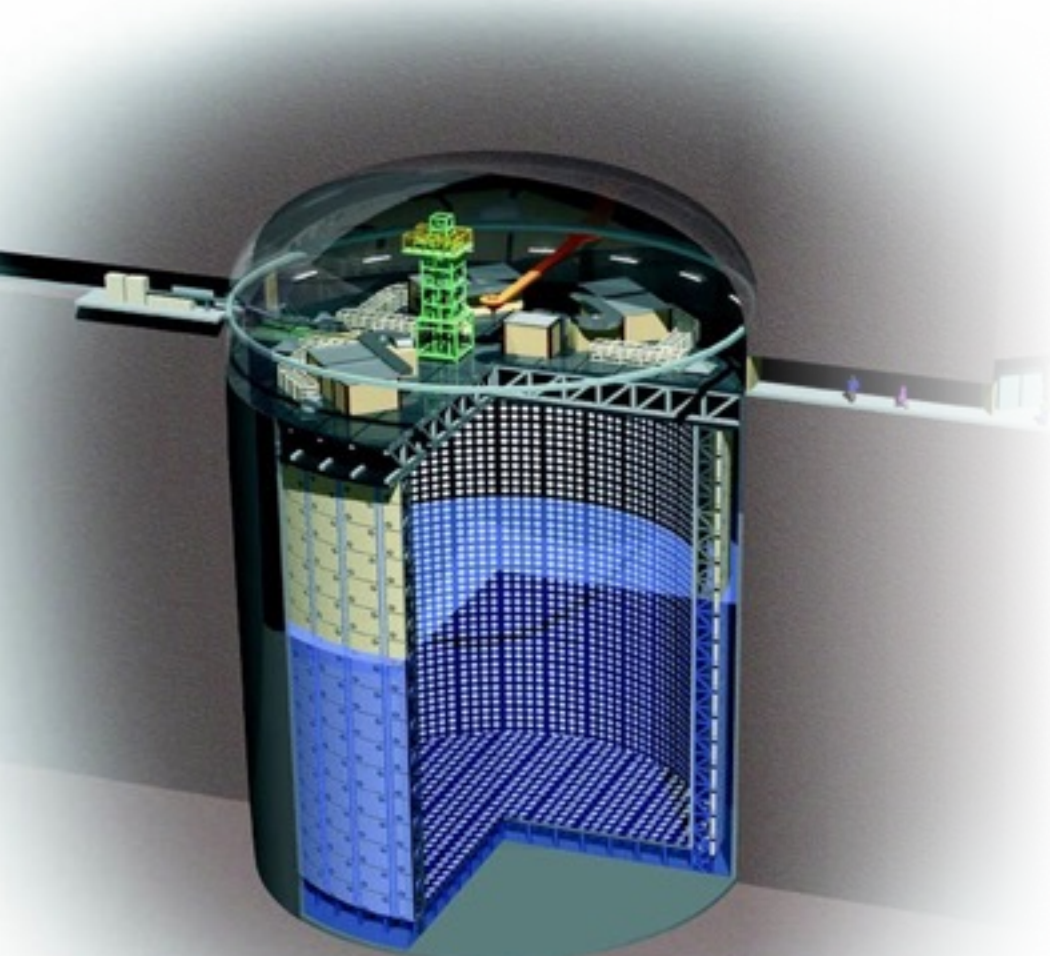




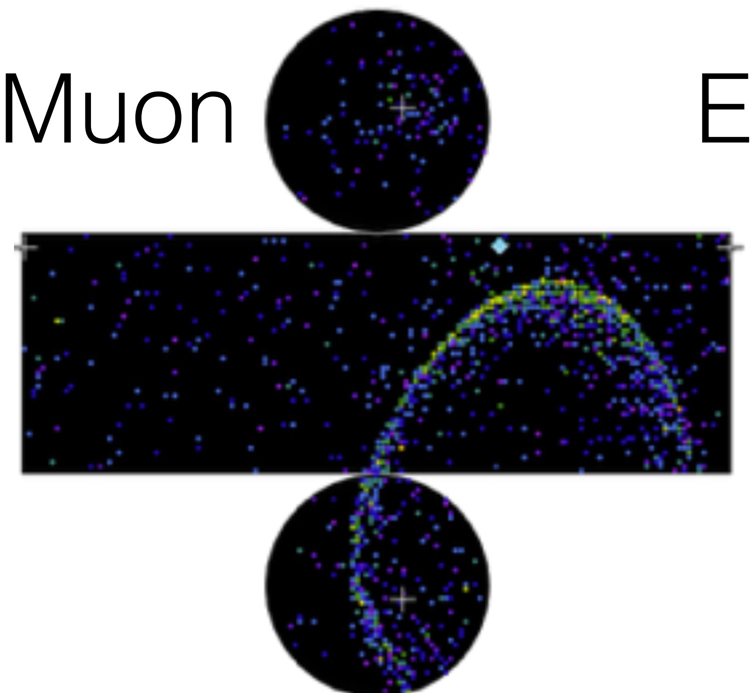
Near Detectors
(ND280+INGRID)



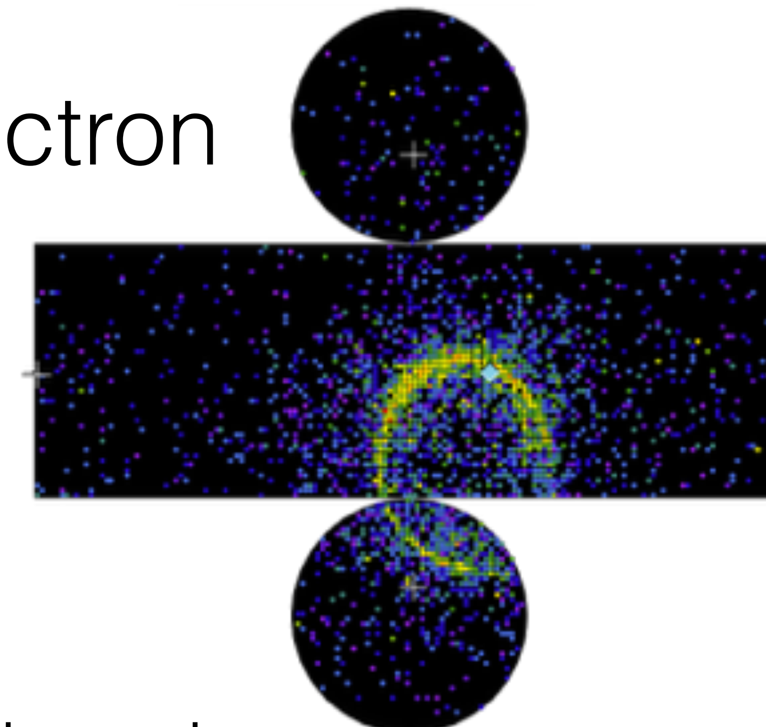
Water Cherenkov Far Detector
>22.5 kt fiducial mass



Muon



Electron



Oxygen target
4π acceptance

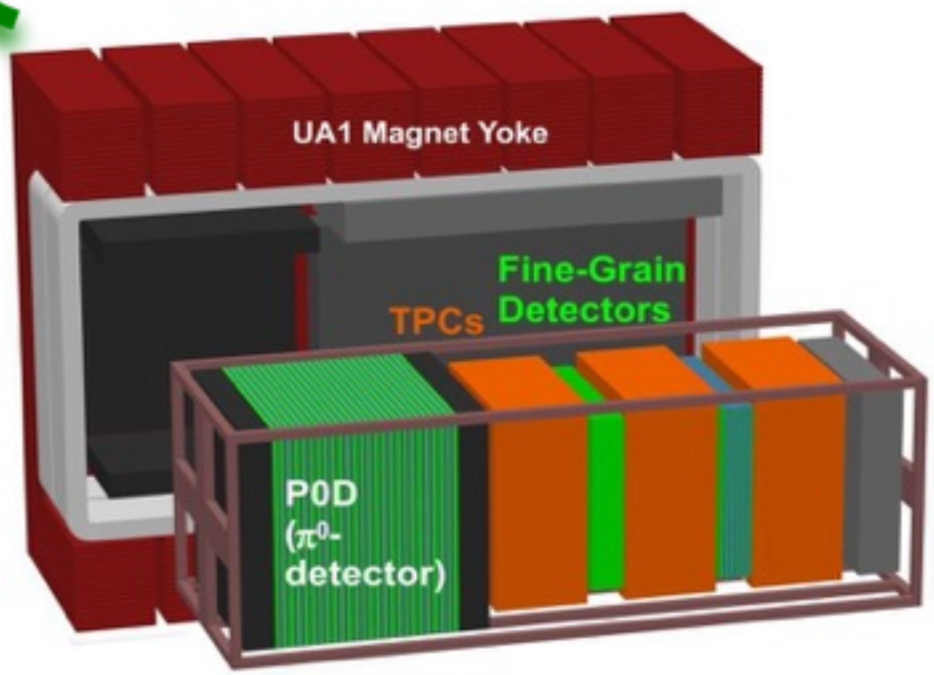
Energy reconstruction from lepton kinematics

Blind to particles below Cherenkov threshold
for protons < 1.1 GeV/c.
(neutron counting possible with SK-Gd)

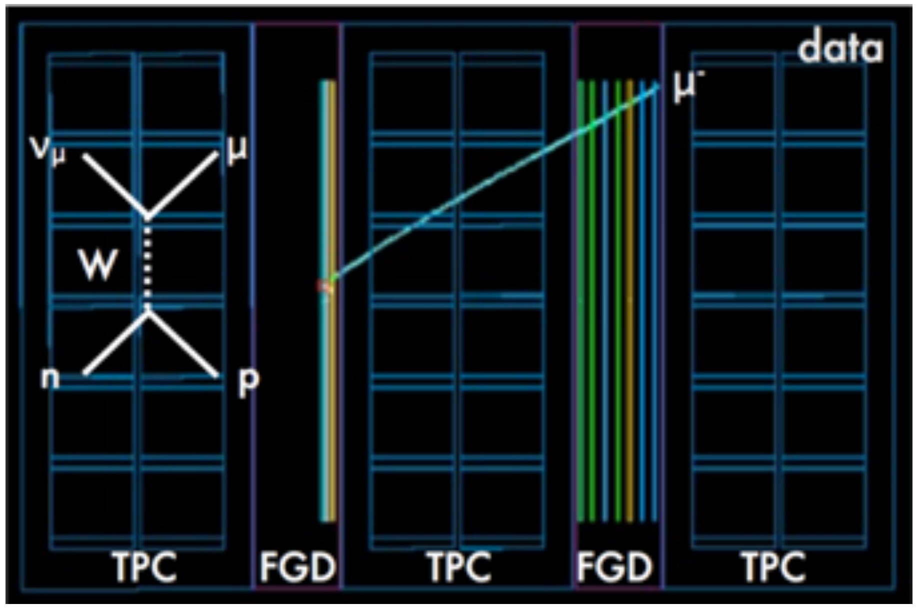
Carbon and Oxygen target materials

Acceptance differs from far detector

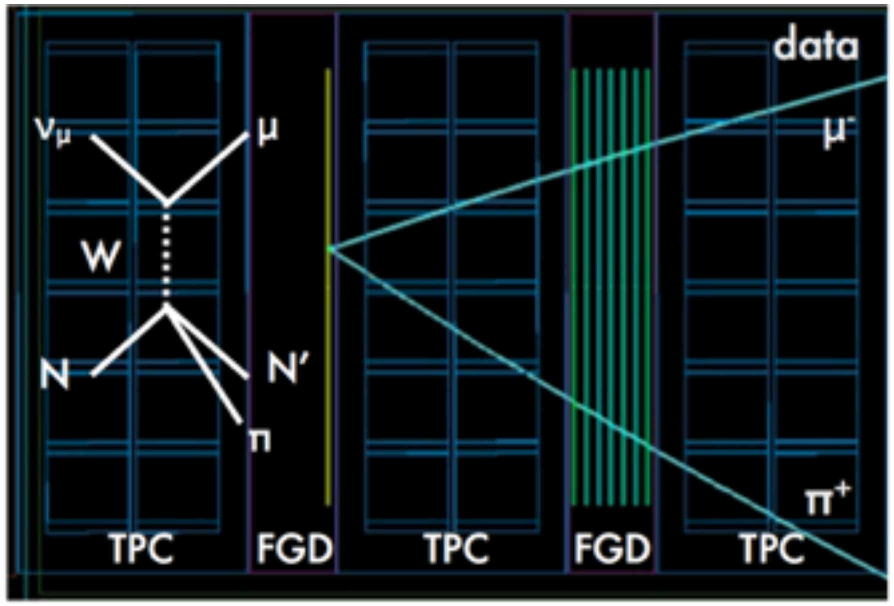
Magnetic field for sign selection



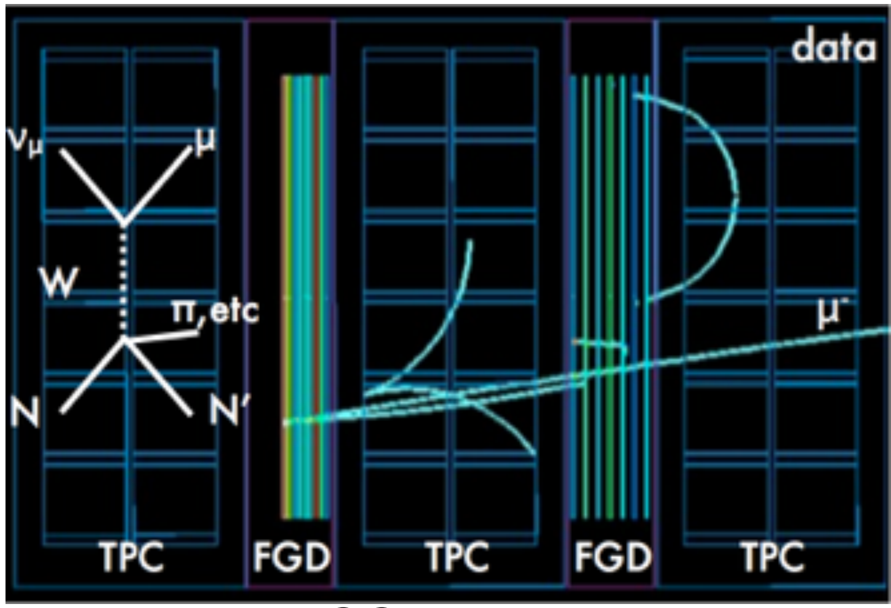
Near Detector (ND280)



CC 1μ + 0π + X



CC 1μ + 1π⁺ + X



CC other

NOvA Experiment

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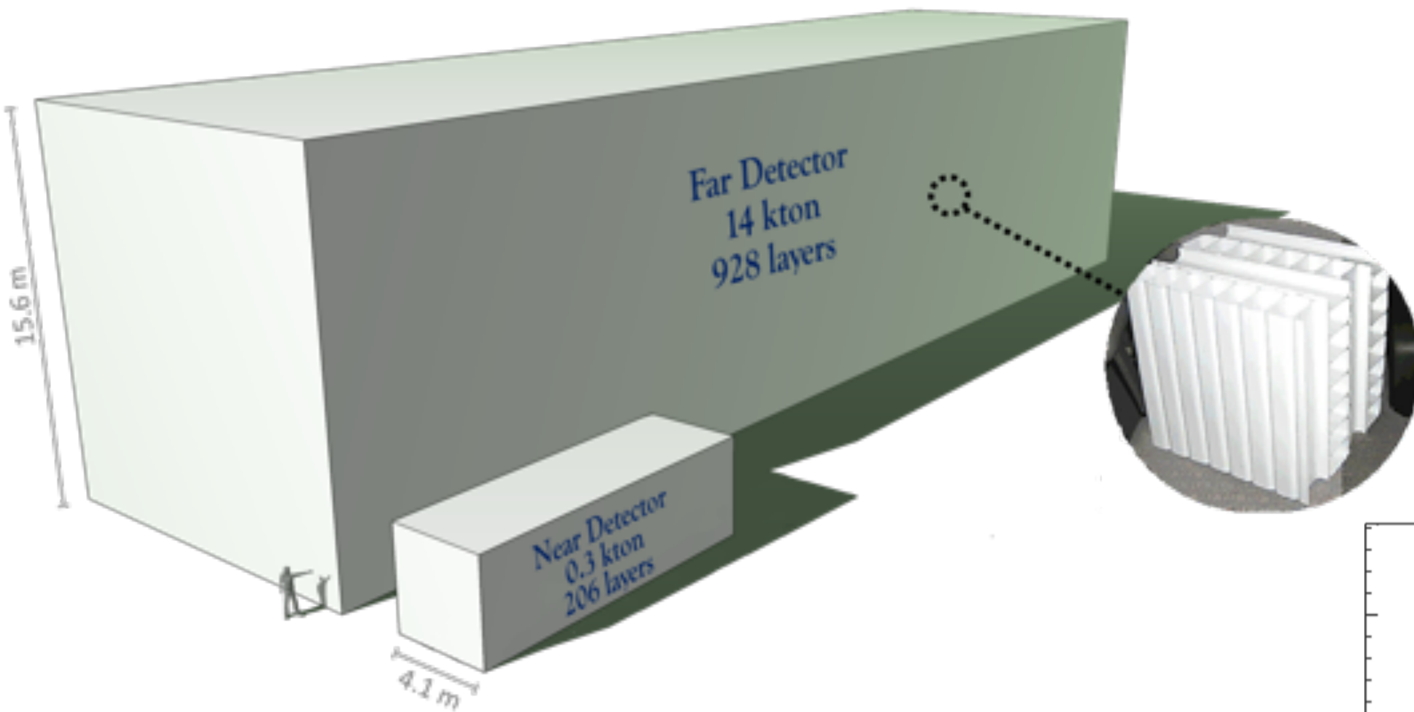


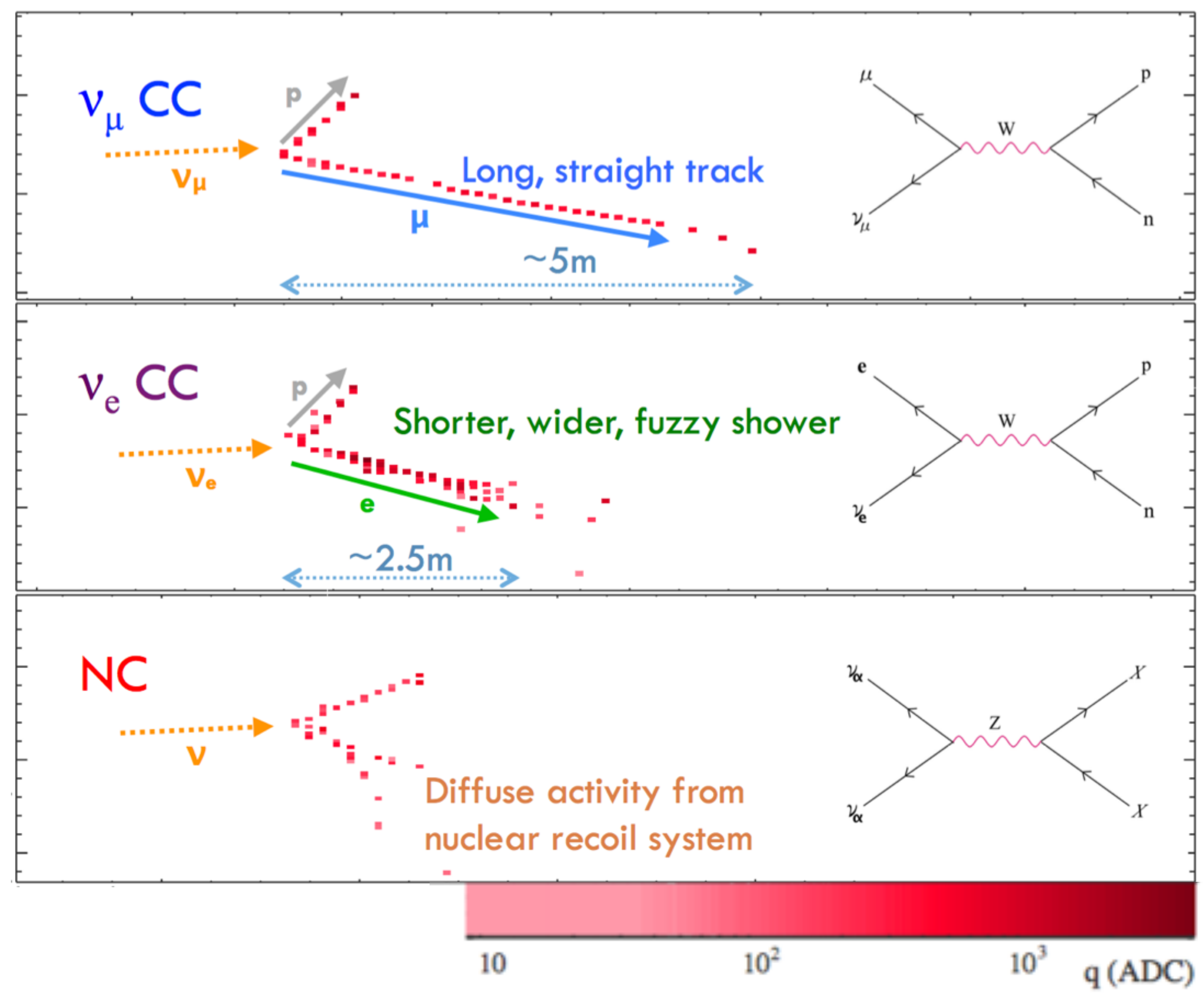
Liquid Scintillator tracking calorimeter

Almost identical near far detectors

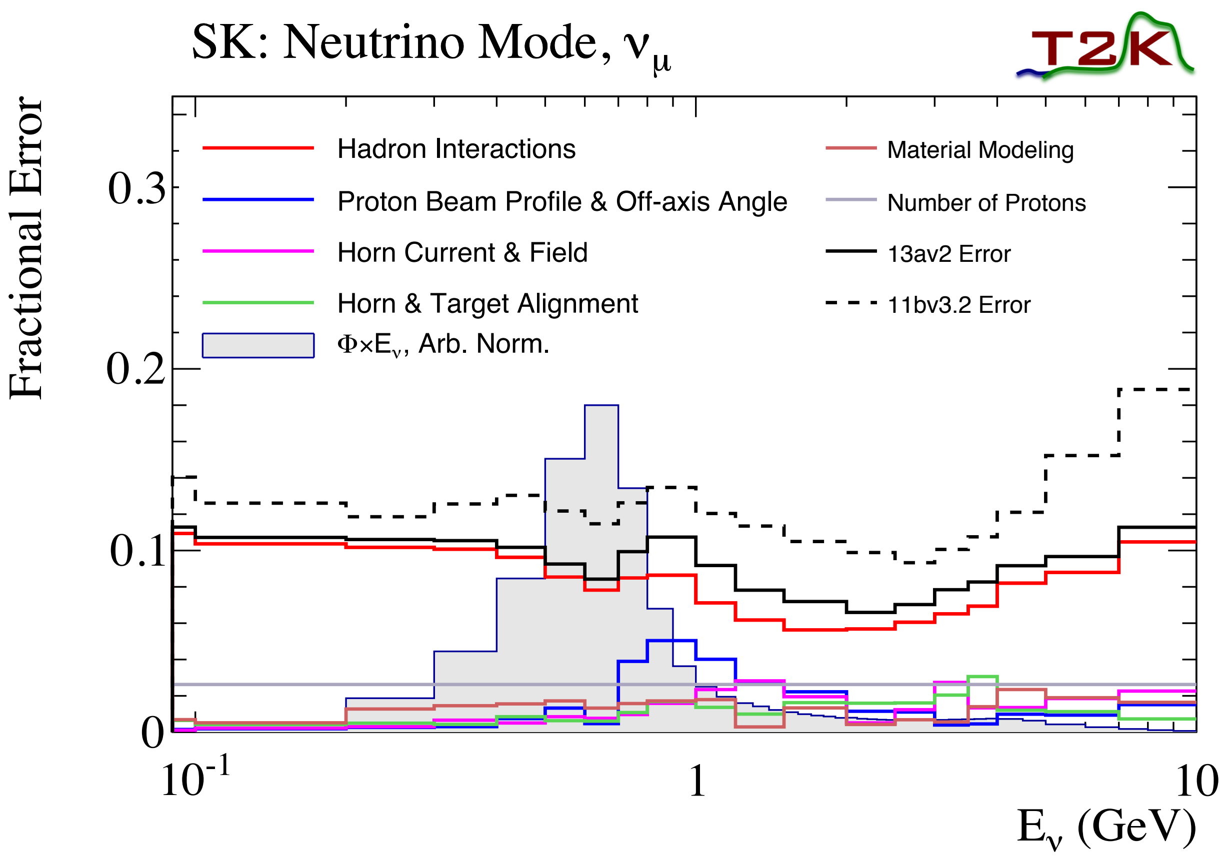
Calorimetric Energy Reconstruction

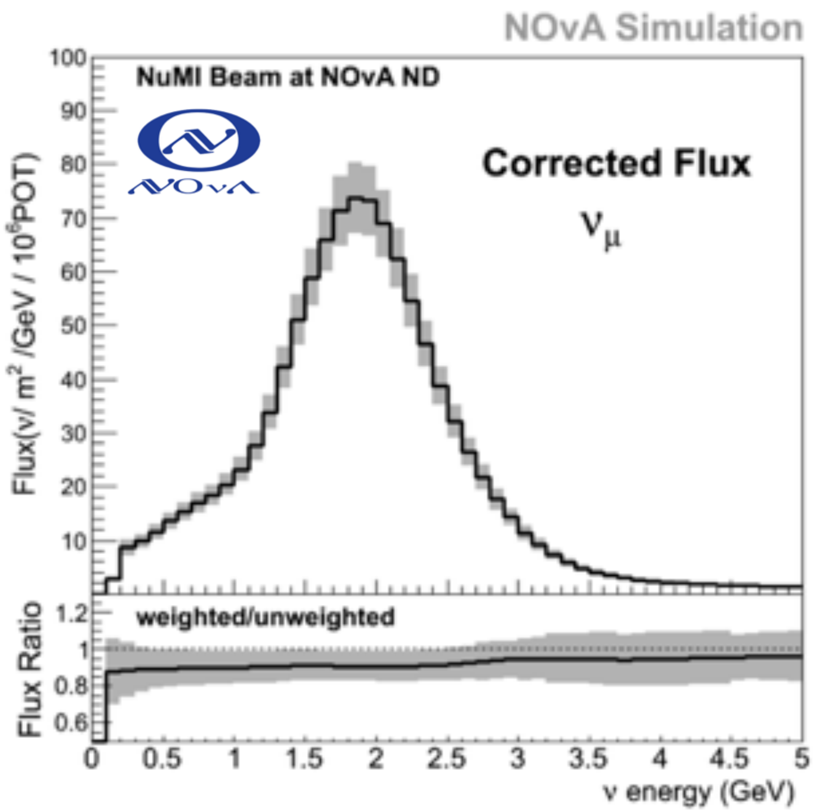
$E_{\nu\, reco} = E_{lep} + E_{had}$

P Vahle Neutrino 2016



Flux Uncertainties





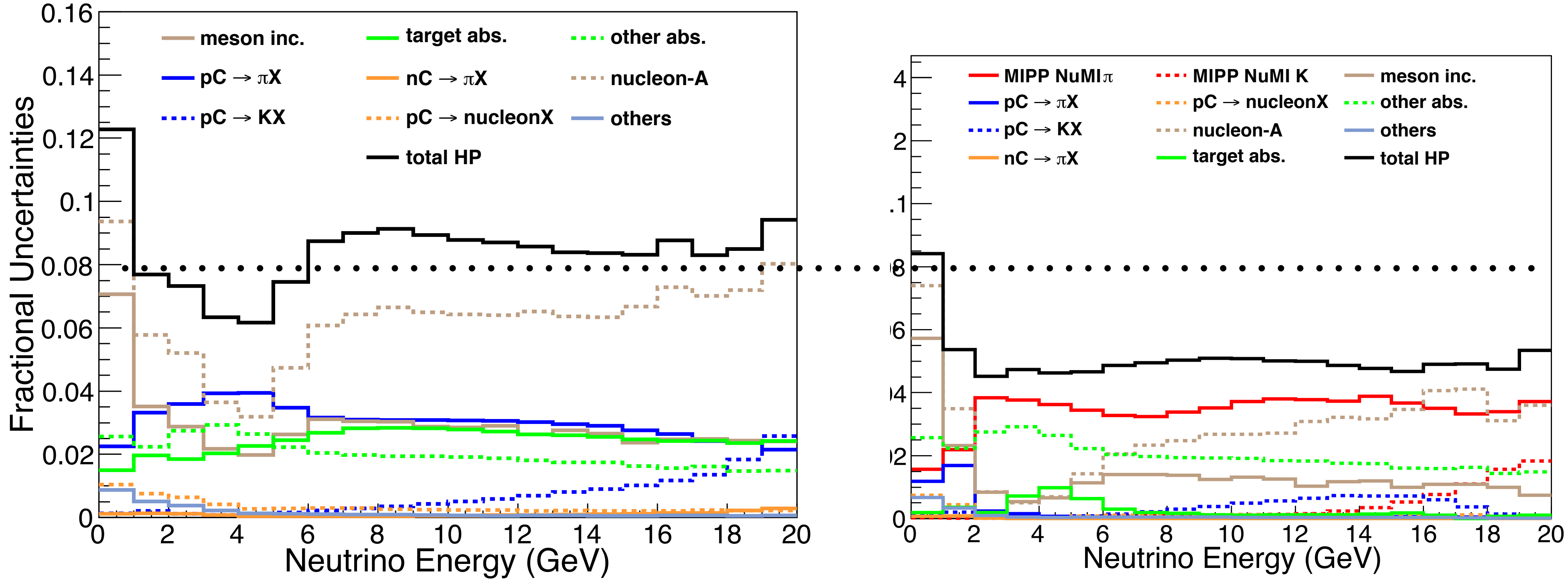
T2K ~ 8-12% (based on thin target tuning)

Dominated by hadron interaction modelling

Alignment/focussing uncertainties are also important (especially for near to far extrapolation)

Flux Uncertainties

Thin Target → Thick Target



MINERvA Low E NuMI Flux Uncertainties, Phys. Rev. D 95, 039903 (2017)

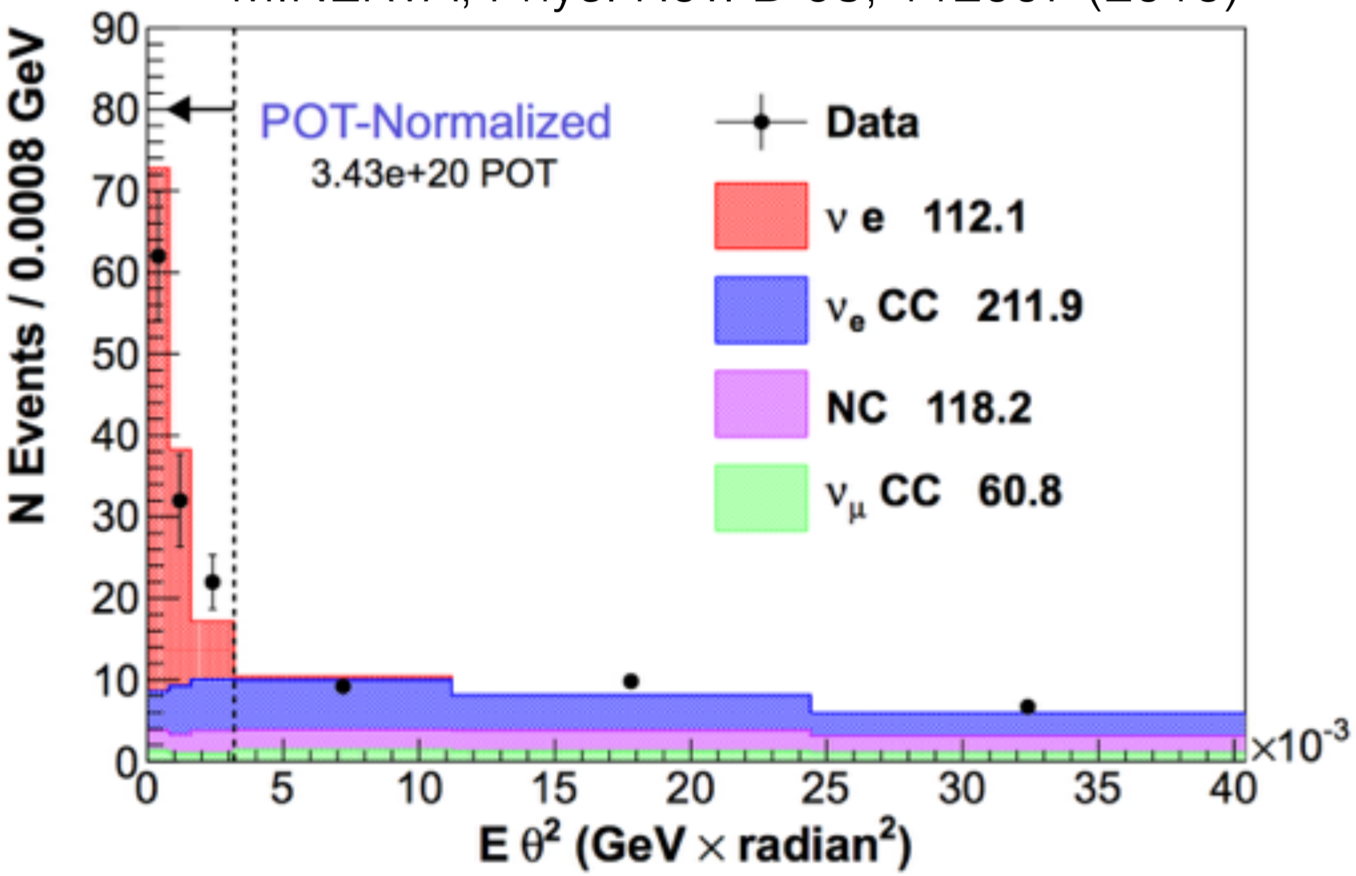
Significant reductions from thick/replica target
(See Tomislav Vladisavljevic poster for latest T2K tuning)

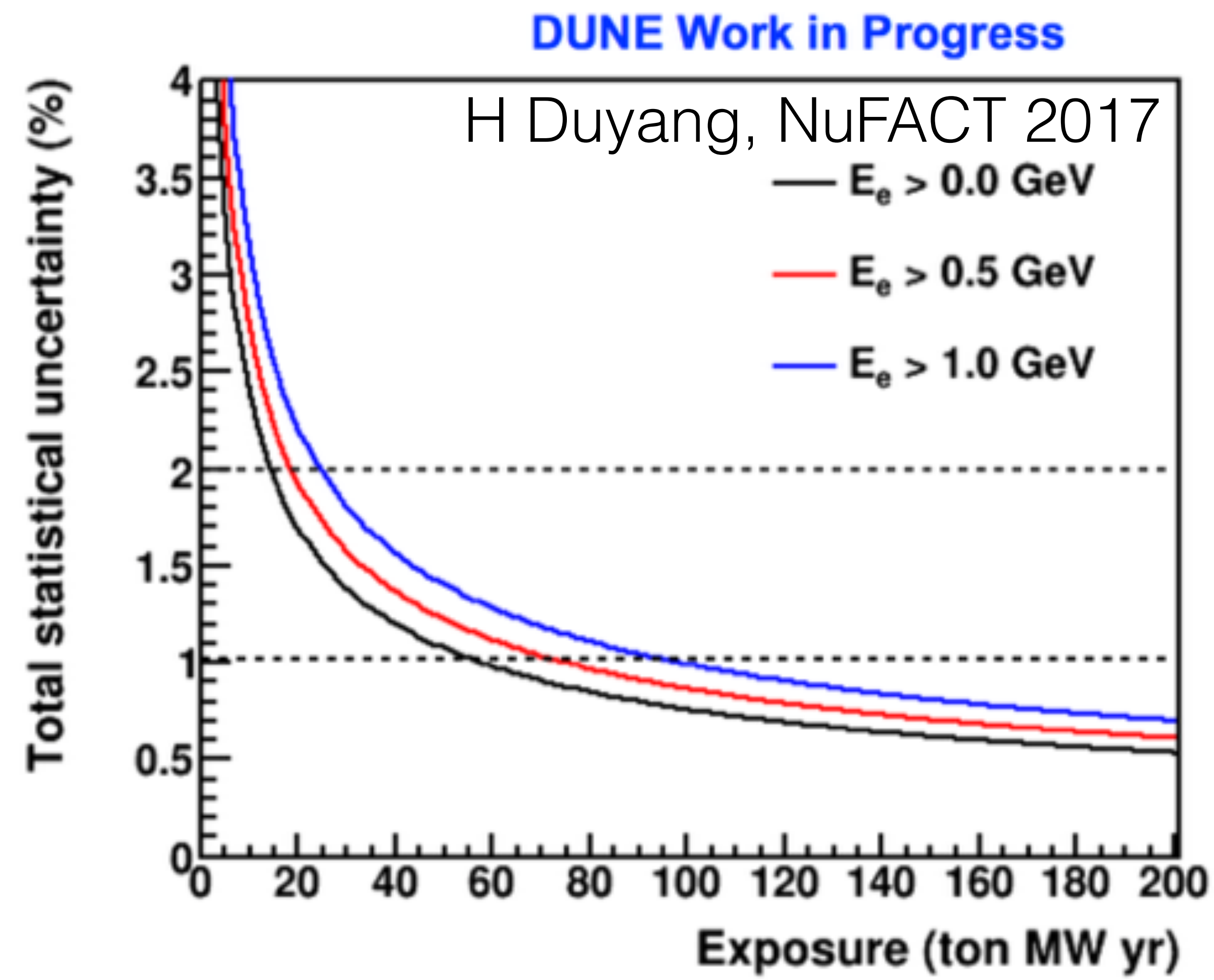
Future high beam power experiments may have different target material/geometry requiring dedicated hadron production measurements

Flux Uncertainties

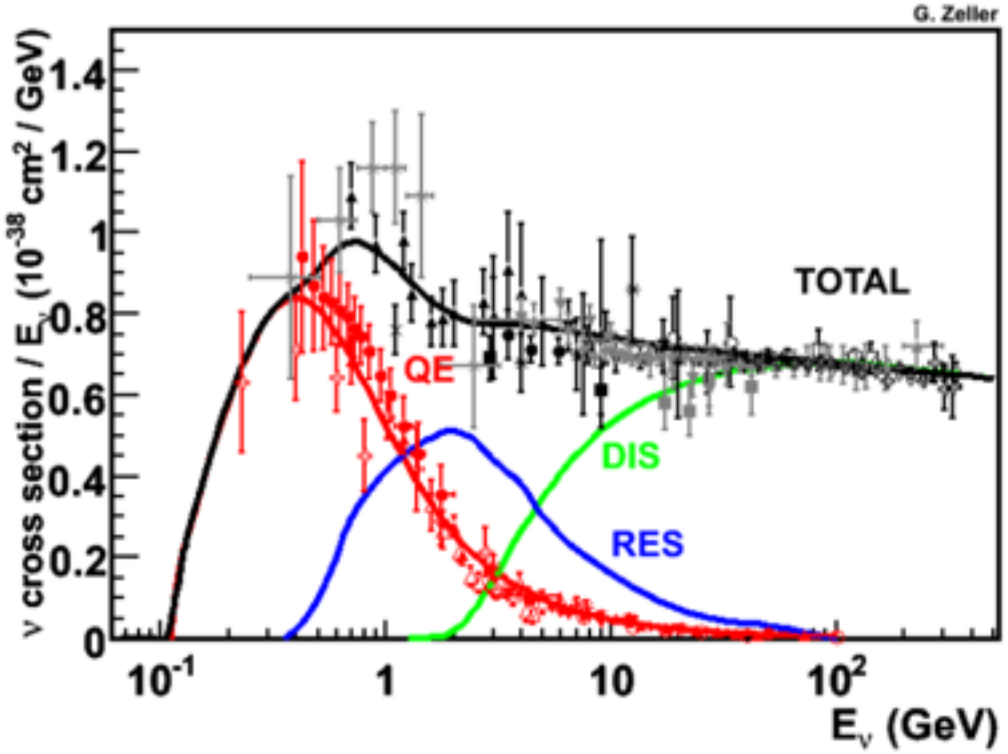
In situ flux measurements possible
eg neutrino-electron elastic scattering

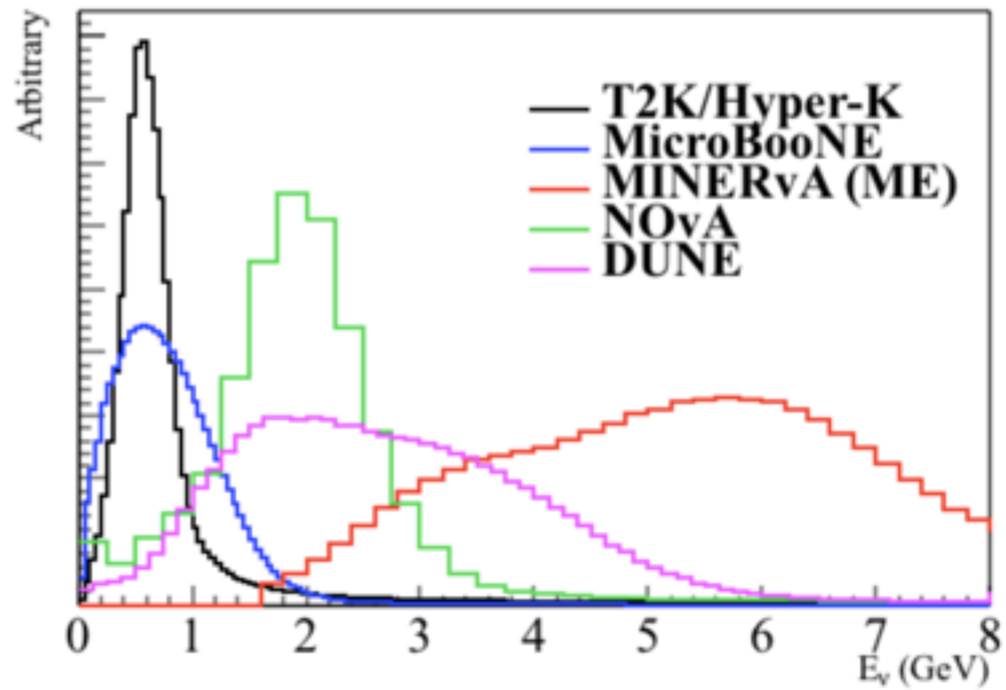
MINERvA, Phys. Rev. D 93, 112007 (2016)





Neutrino Interaction Model Uncertainties





Wide range of processes need to be simulated
Require both lepton and hadronic side of the interaction

Nuclear effects important in the relevant energy regime

Experiments rely on MC generators
for $E_{visible} \rightarrow E_{\nu}$ extrapolation

Model parameter uncertainties from fits to external datasets
Sometimes parameter error must be inflated or ad-hoc parameters to account for discrepancies between model and data or known flaws in the model

T2K Cross-Section Model

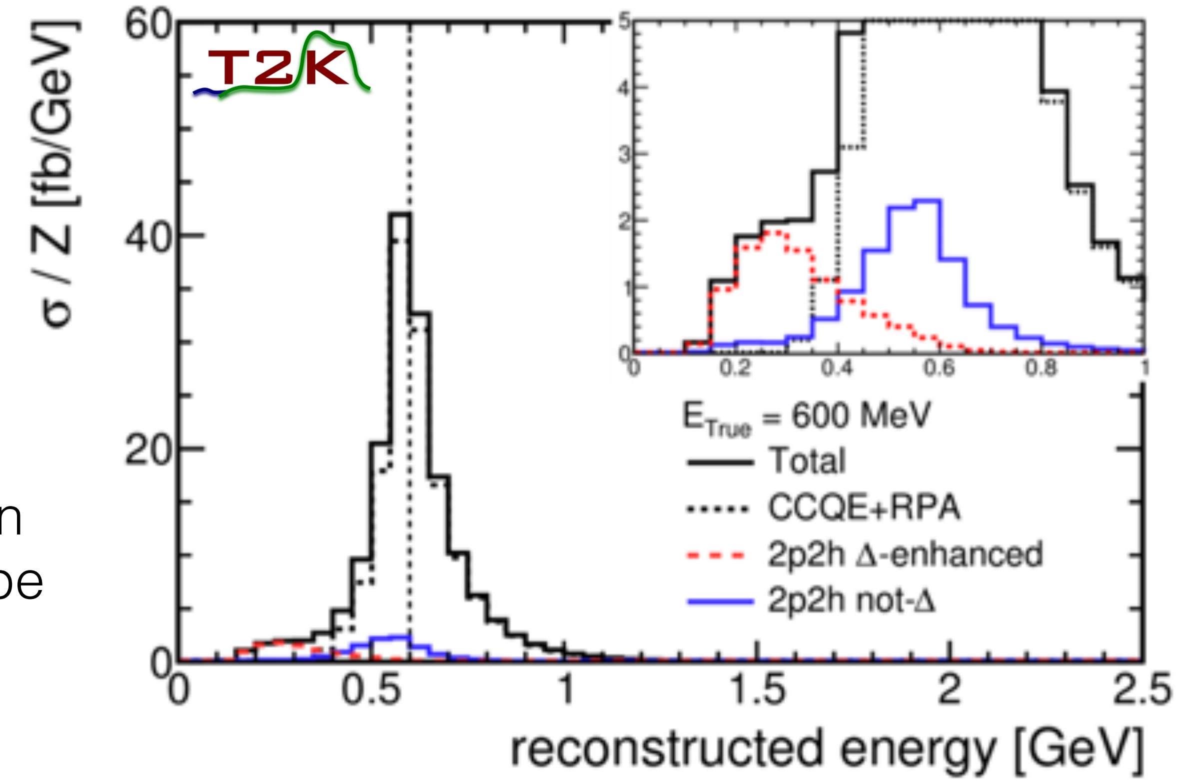
Implemented in NEUT MC generator

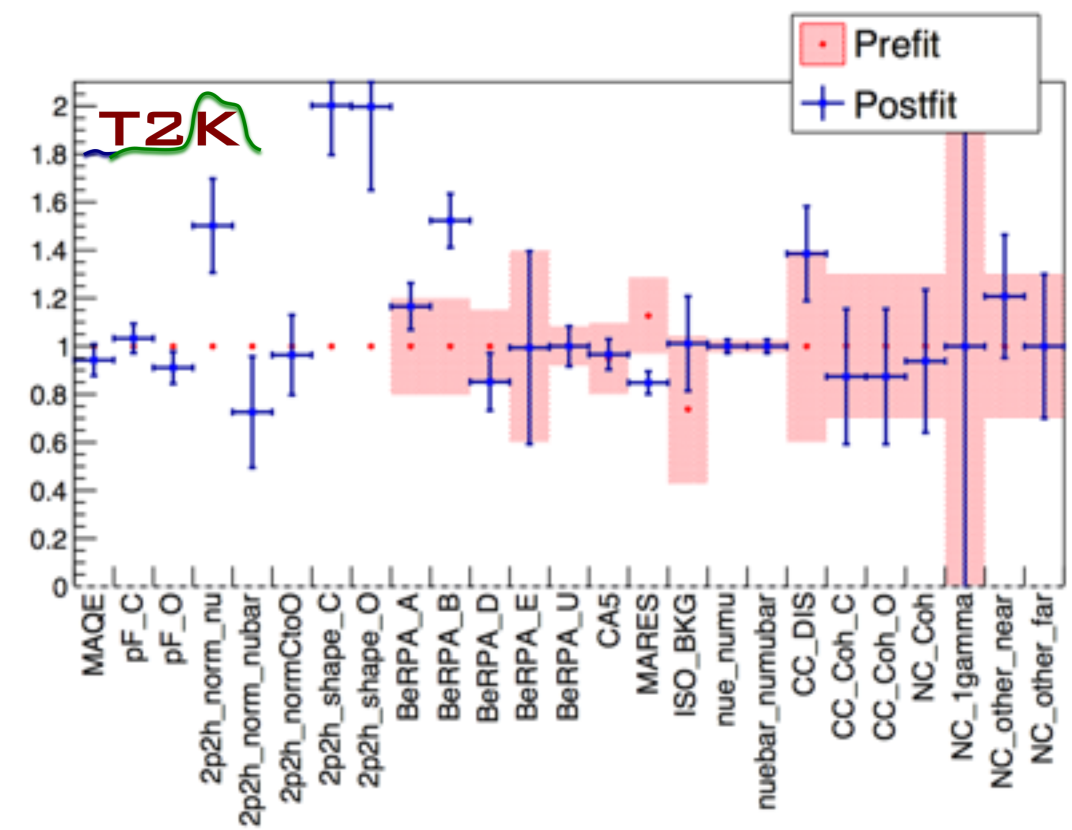
Quasi-elastic scattering most important process at T2K energies

- Valencia 2p-2h model Phys. Rev. C83 (2011) 045501
- Long-range effects with Random Phase Approximation
- Parameters introduced to vary normalisation and shape
- Relativistic Fermi Gas (RFG) nuclear model
- Uncertainties from RFG ↔ Local Fermi Gas
- Final state interactions with cascade model

No priors on most CCQE parameters
Constraint from near detector

Impact of alternative models not implemented in oscillation analysis evaluated with fake data studies





NOvA Cross-section Model

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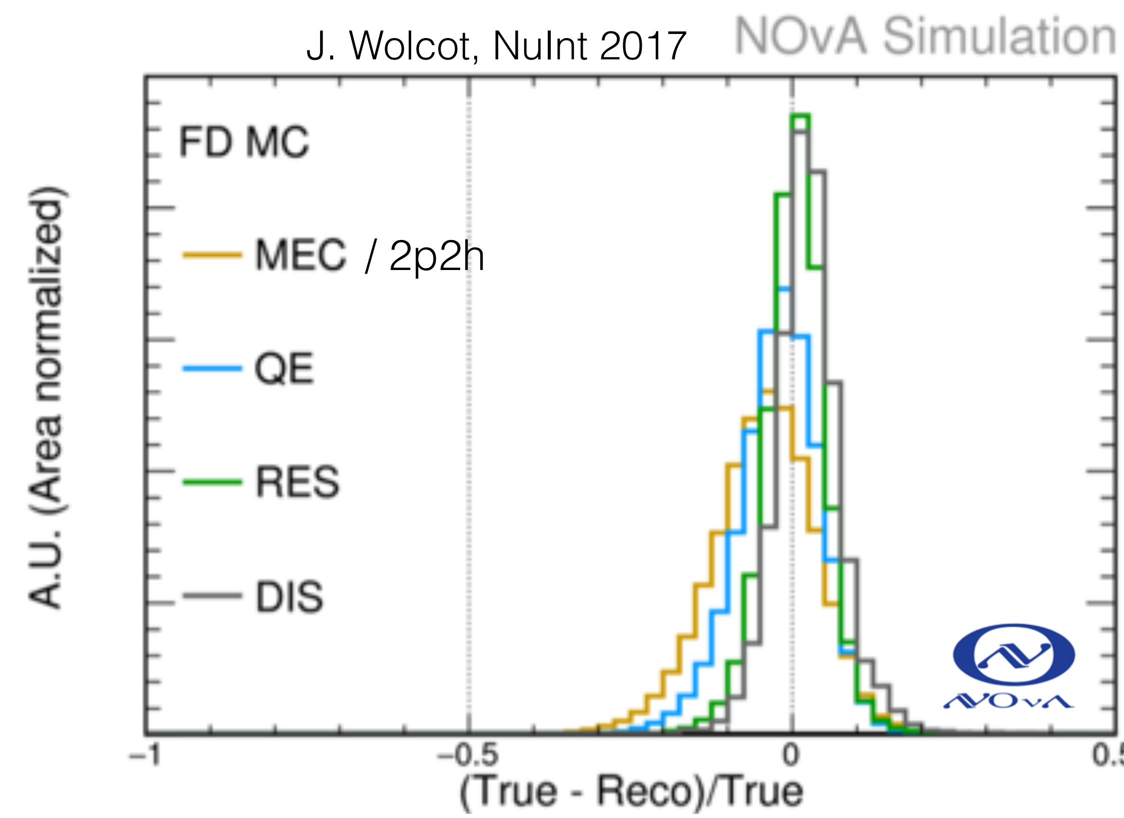
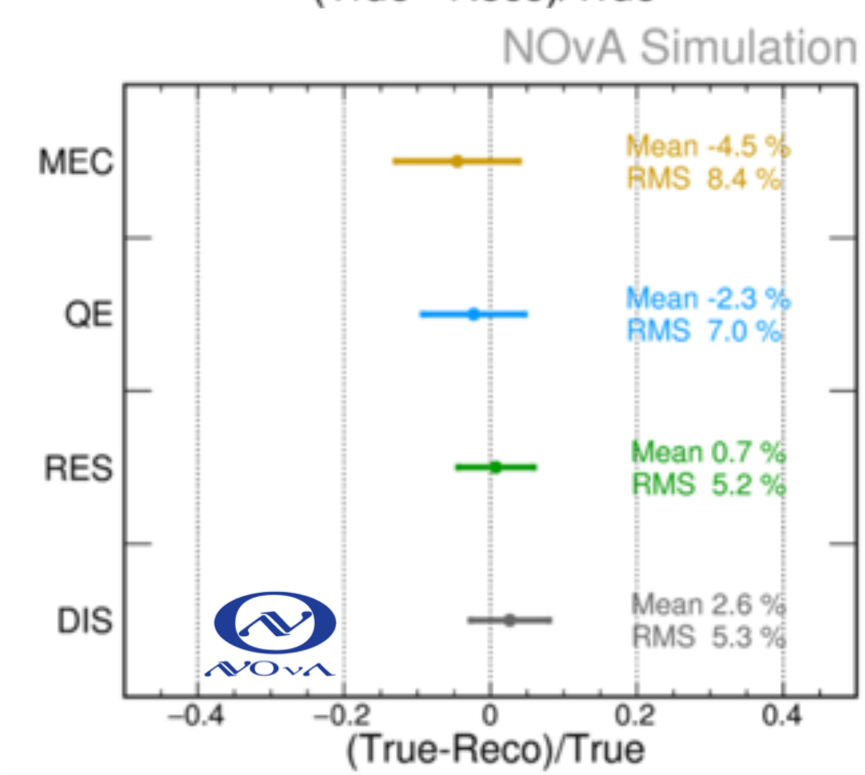
Use GENIE MC generator and uncertainties

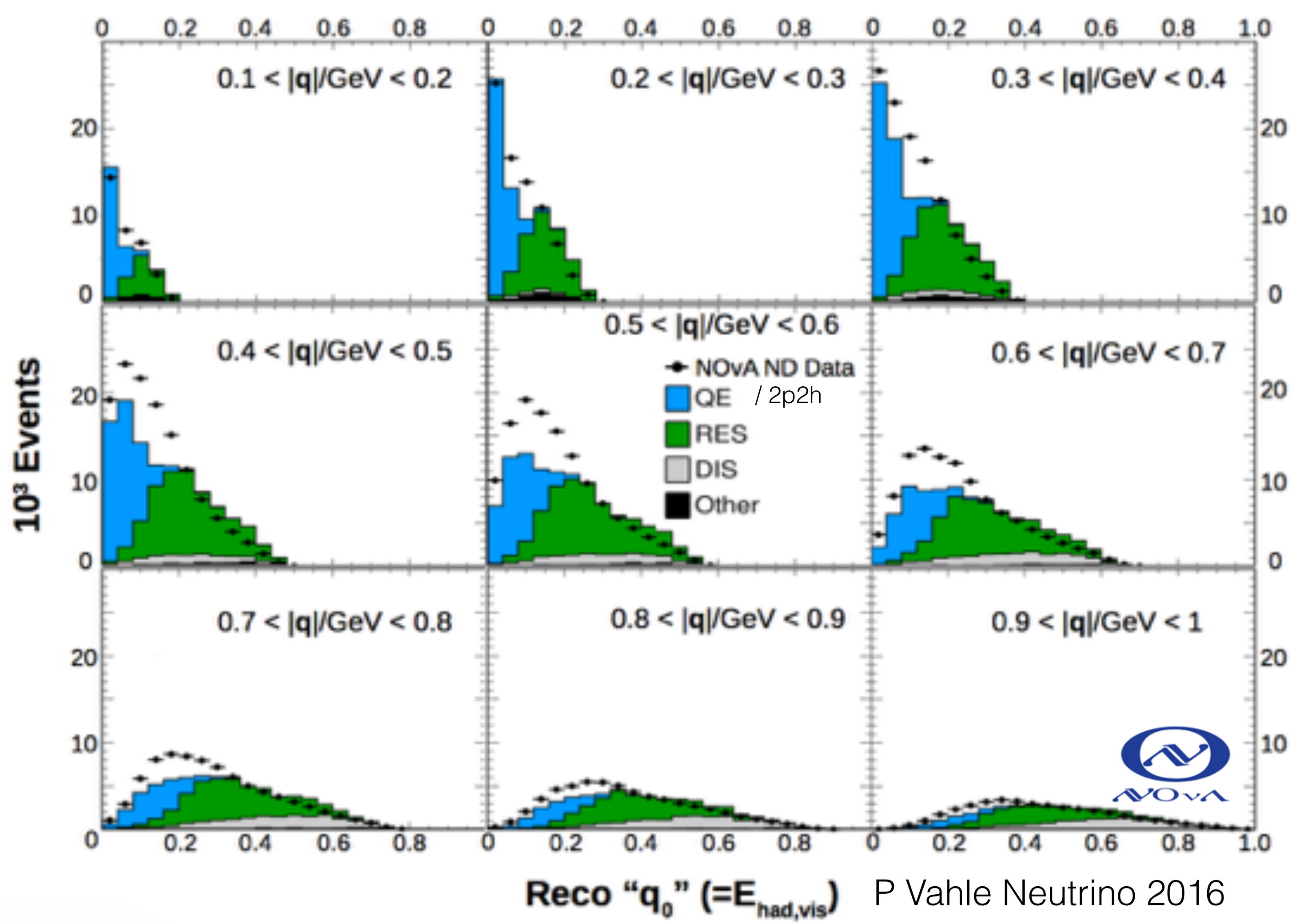
Some additions/modifications

- Empirical 2p2h model, tuned to match ND data
- Parameters to cover RPA uncertainties
- Alternative tuning of CC1π model [Eur. Phys. J. C 76, 474 (2016)]

J. Wolcot, NuInt 2017







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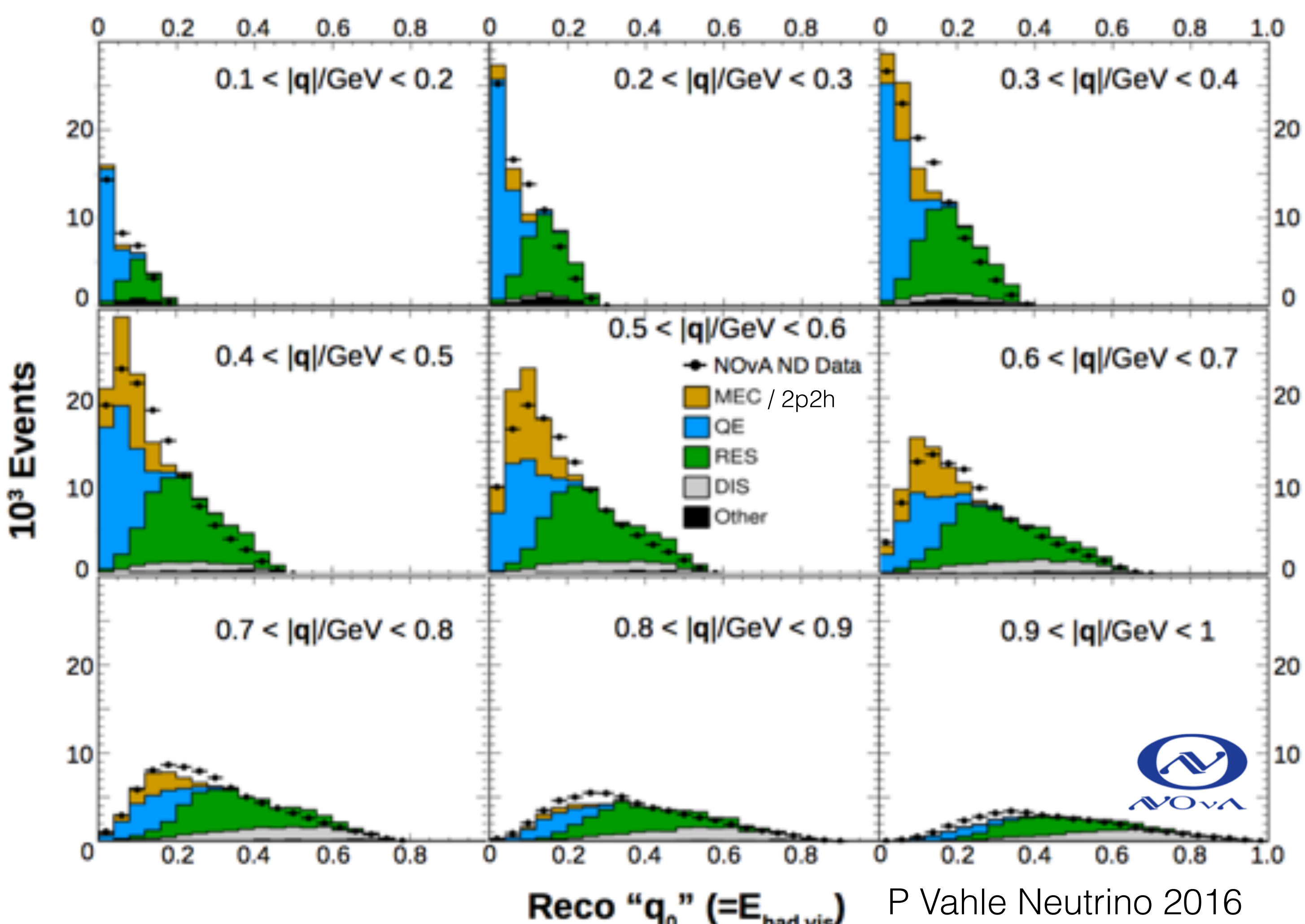

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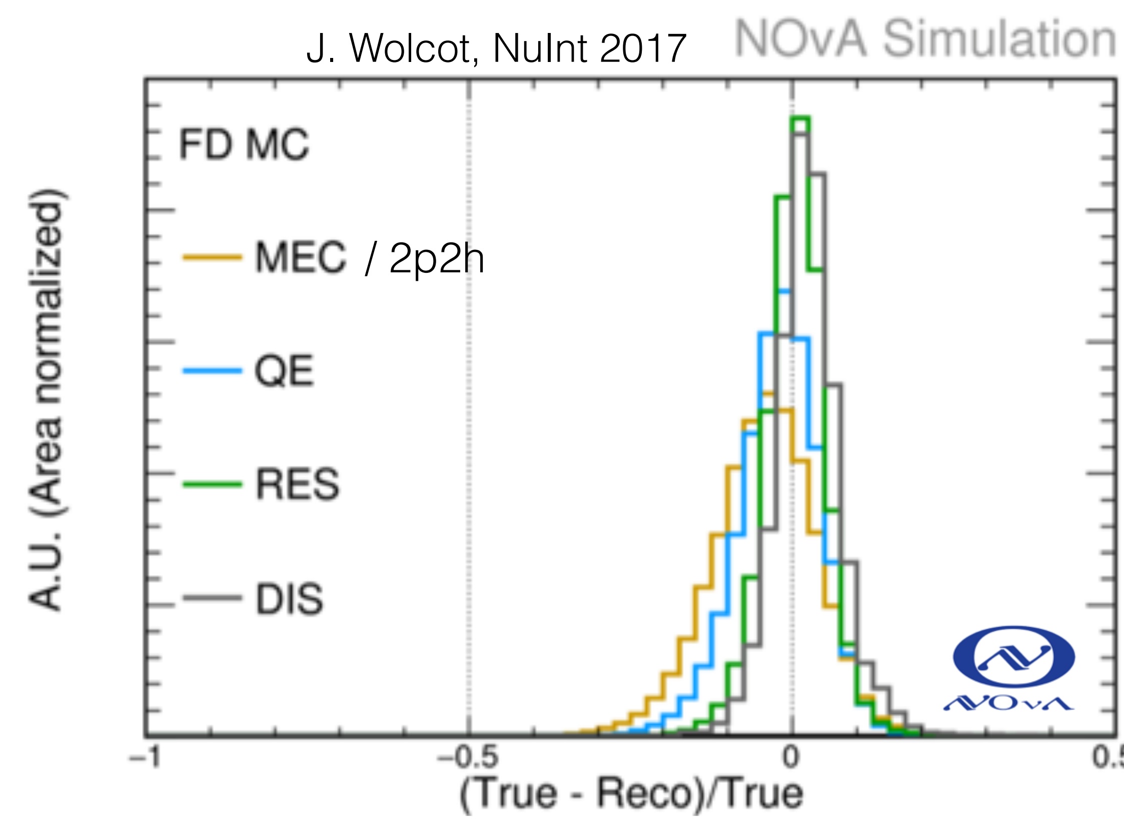

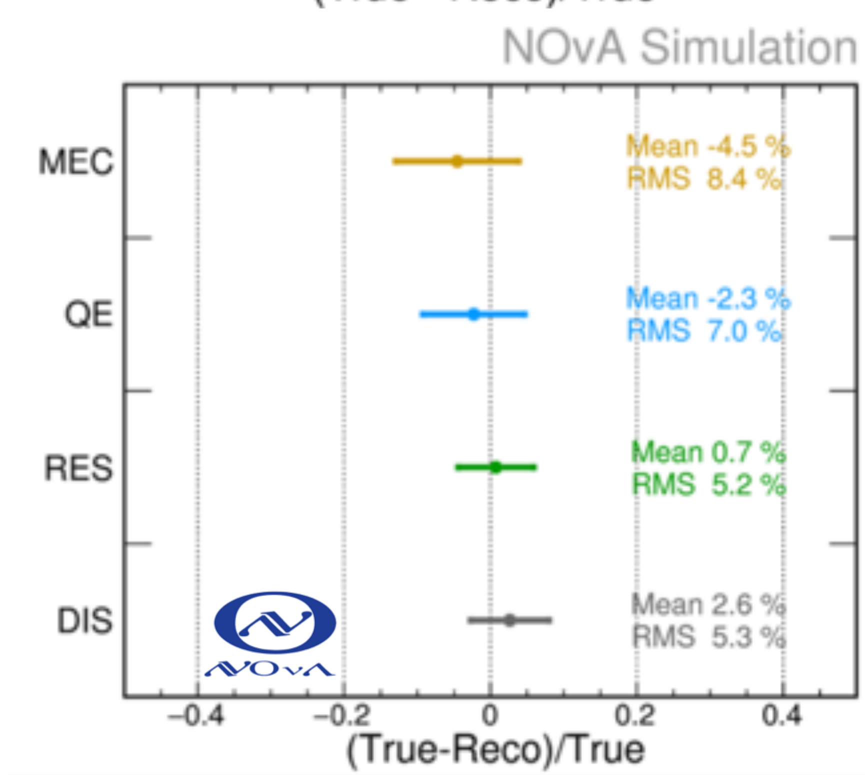

Detector Modelling Uncertainties

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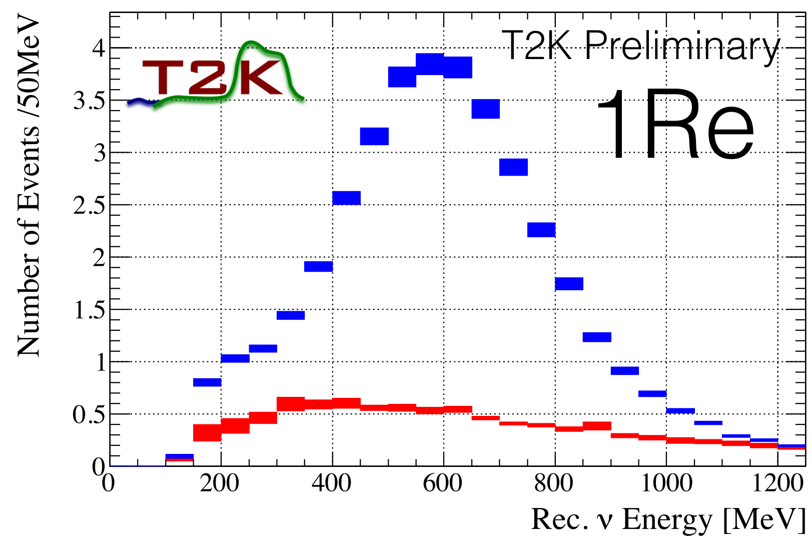
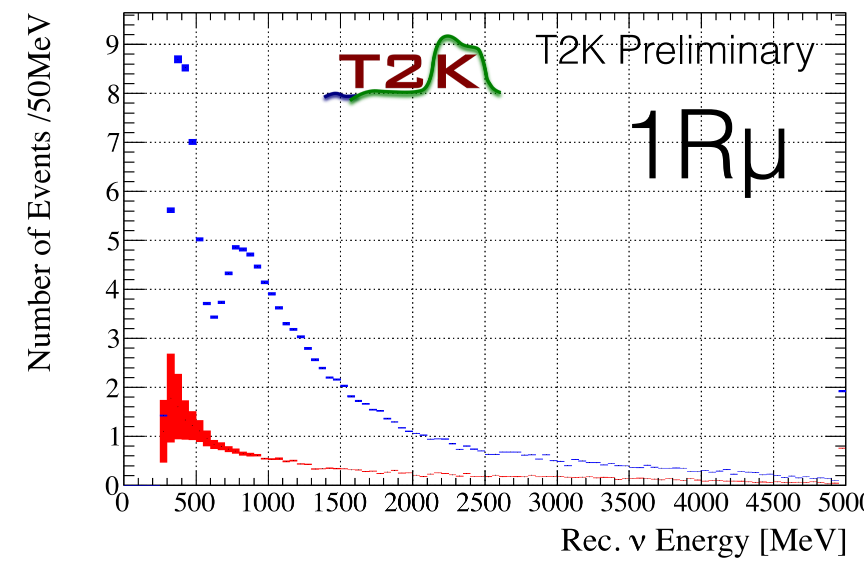
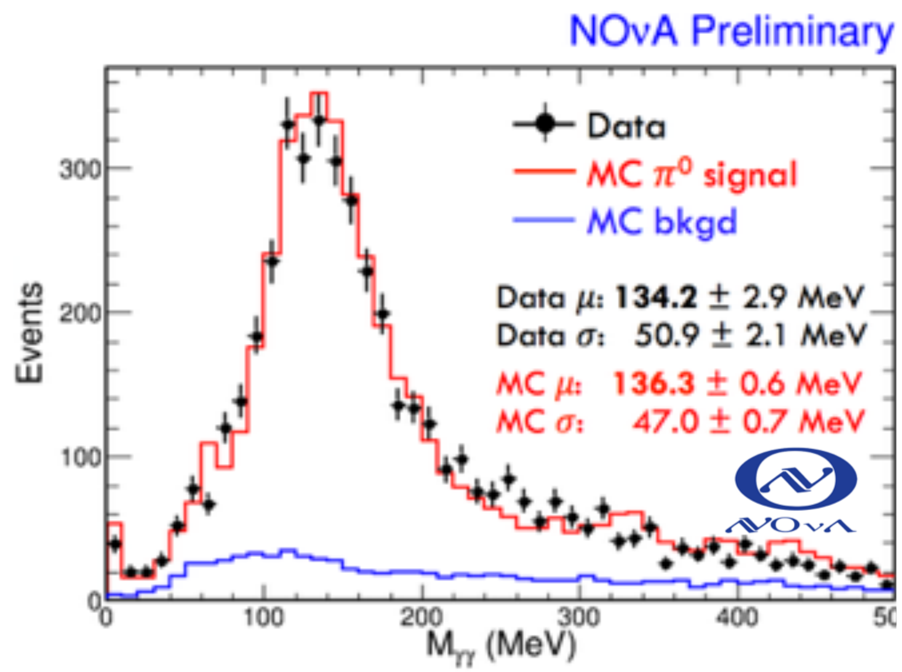
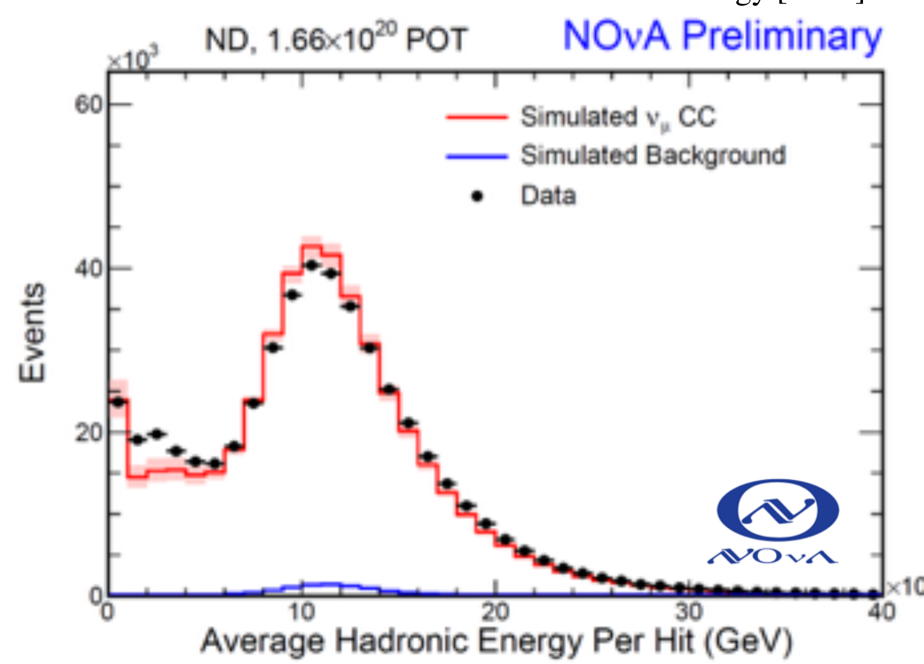
SK detector response evaluated with atmospheric sample





NOvA detector response evaluated with beam and cosmic muon samples in both ND and FD





Detector modelling uncertainties typically from data MC comparisons in control samples
May be limited by control sample statistics

T2K Systematic Uncertainties

Error Source	μ sample [%] ν	μ sample [%] $\bar{\nu}$	e sample [%] ν	e sample [%] $\bar{\nu}$
SK Detector	1.9	1.6	3.0	4.2
SK FSI+SI+PN	2.2	2.0	2.9	2.5
ND280 Constraint (Flux + Cross Section)	3.3	2.7	3.2	2.9
$\sigma(\nu_e)/\sigma(\nu_\mu)$	-	-	2.6	1.5
NC 1γ	-	-	1.1	2.6
NC other	0.3	0.1	0.1	0.3
Total Systematic	4.4	3.8	6.3	6.4
Statistical	6.5	12	12	40

T2K preliminary (final systematics pending)

Total systematic uncertainty
~4 - 6%
Smaller than stats. uncertainty
(for now!)

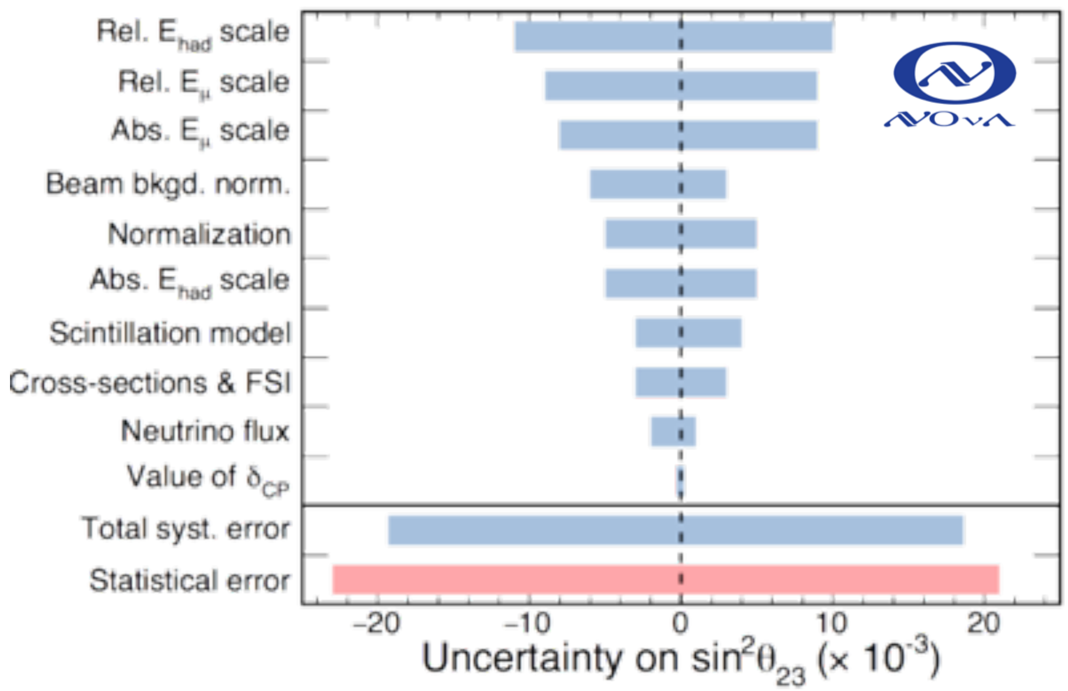
ND280 constraint
13%→3%

Pion Final State Interactions (FSI) and Secondary Interactions (SI) modelling important

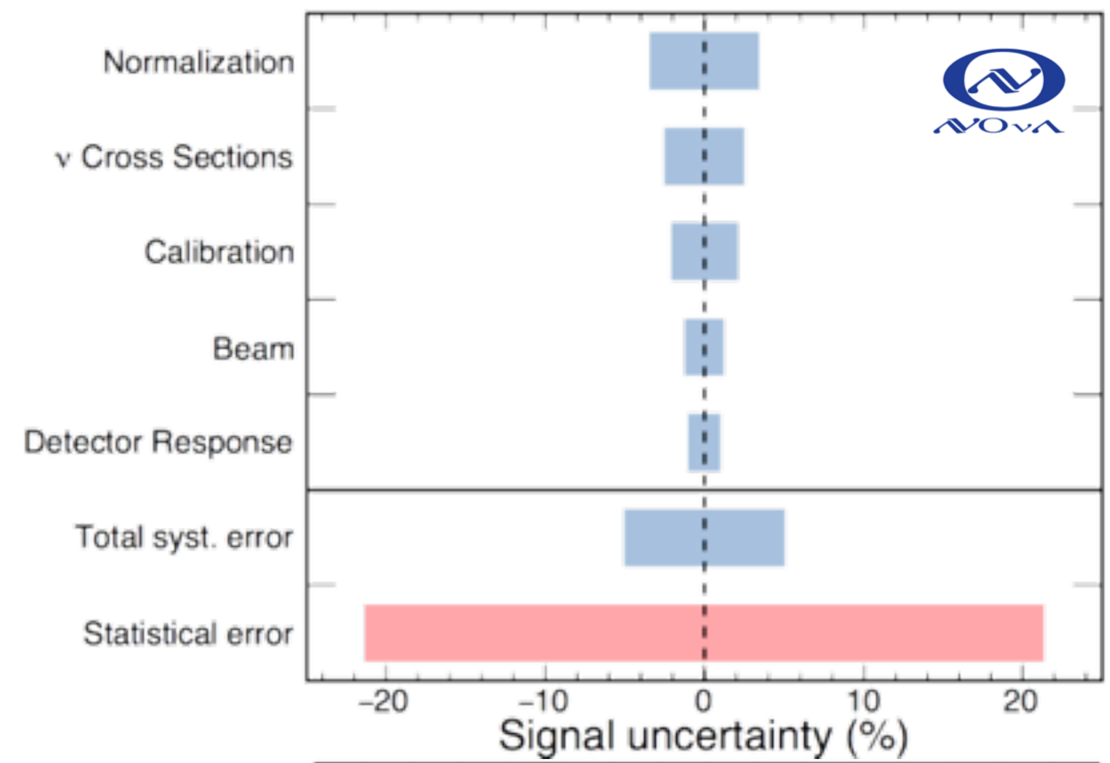
Theoretical uncertainty
ν_e to ν_μ
Difficult to constrain with near detector

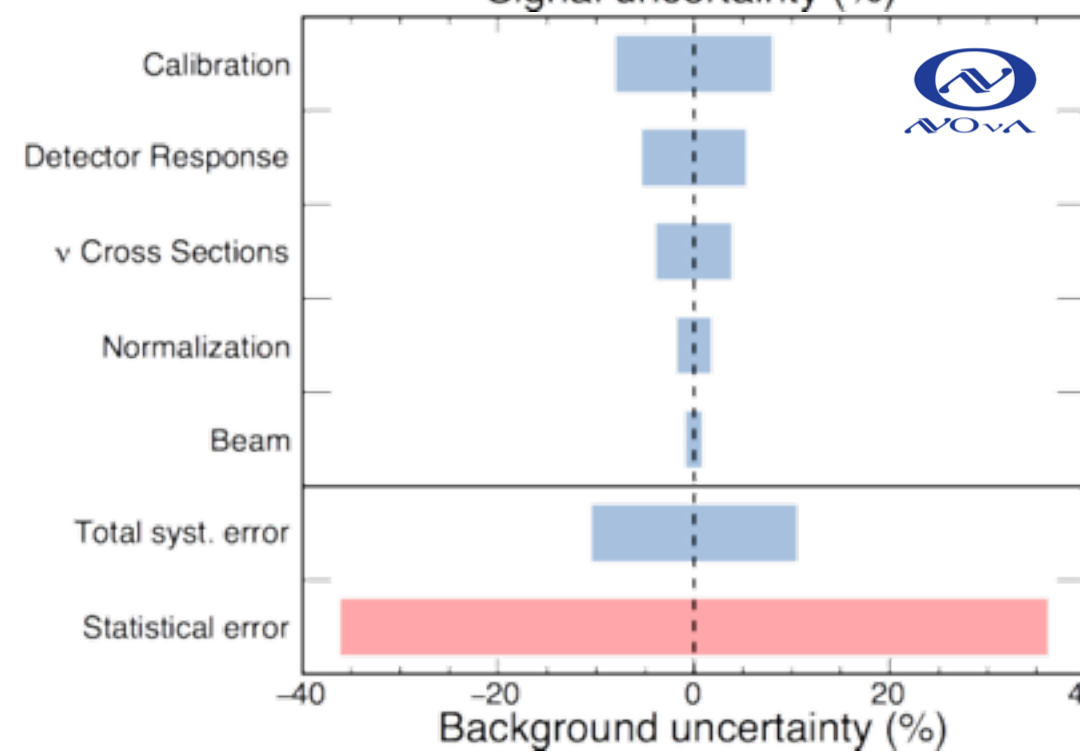
NOvA Systematic Uncertainties

ν_μ



ν_e





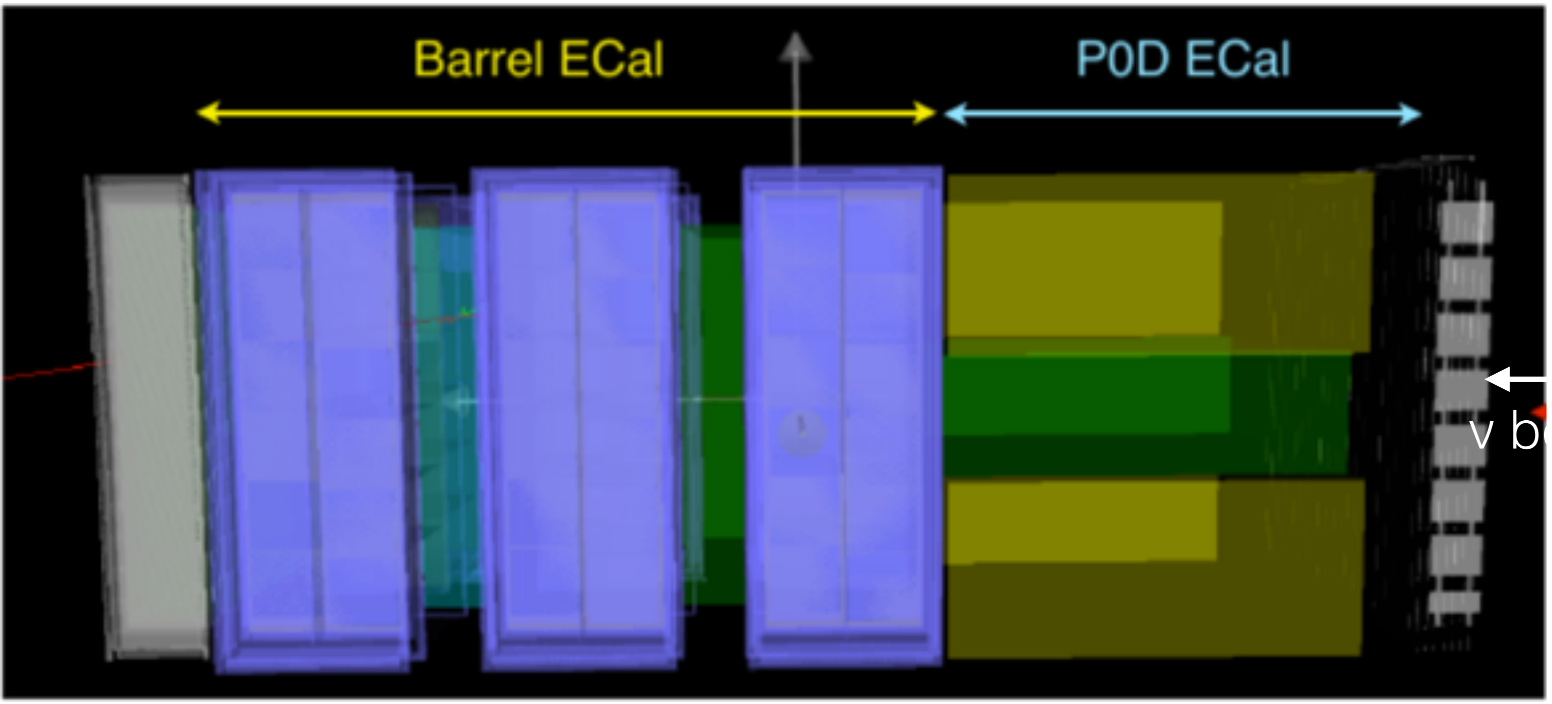
ν_e ~ 5-10%

ν_μ ~ 3-4%

Energy scale uncertainties dominate ν_μ

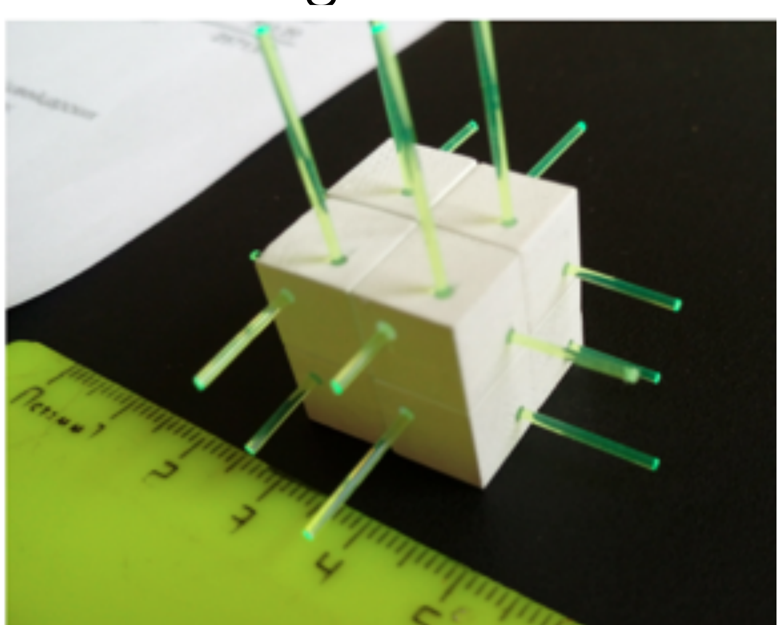
Near Detector Development

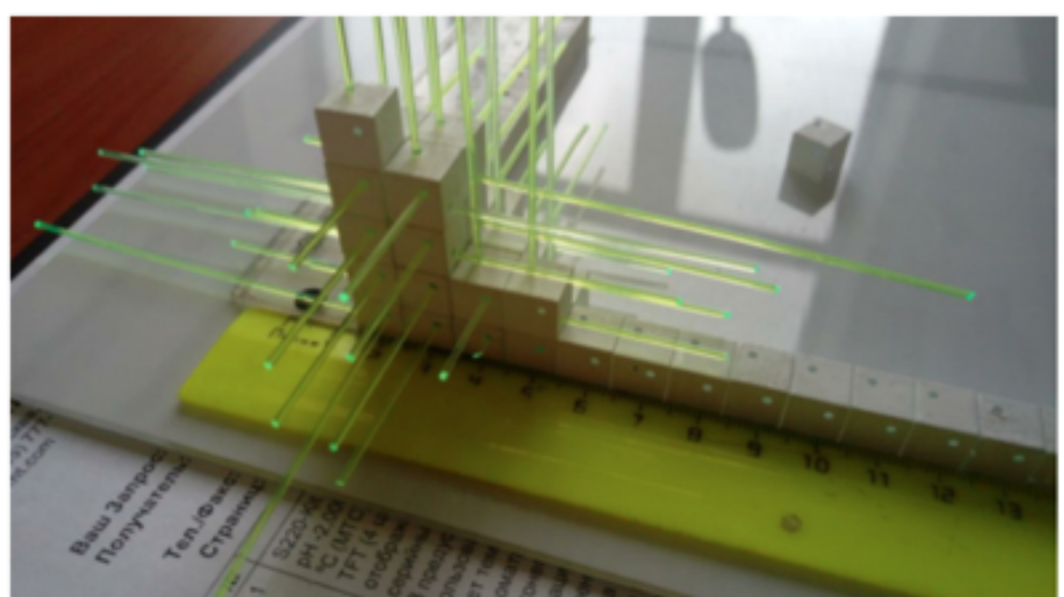
Planned ND280 Near Detector Upgrade



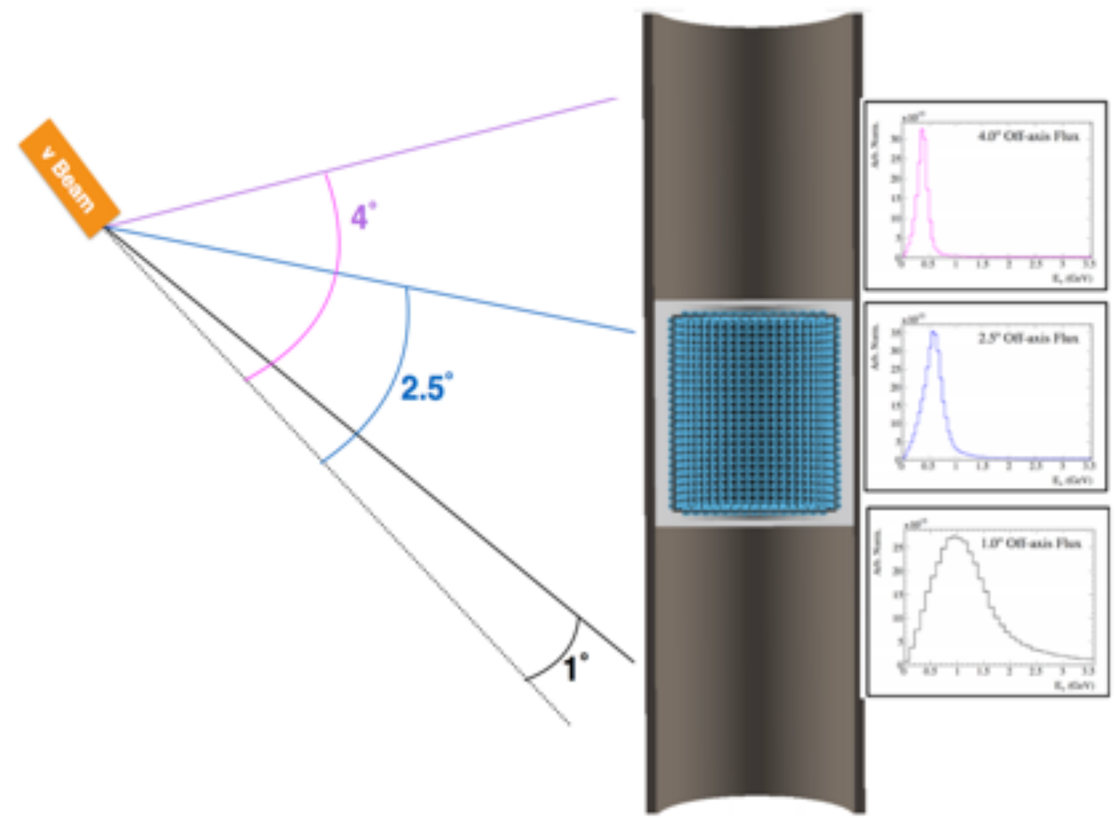
Near detector upgrades for T2K-II and T2HK era

New target with increased angular acceptance





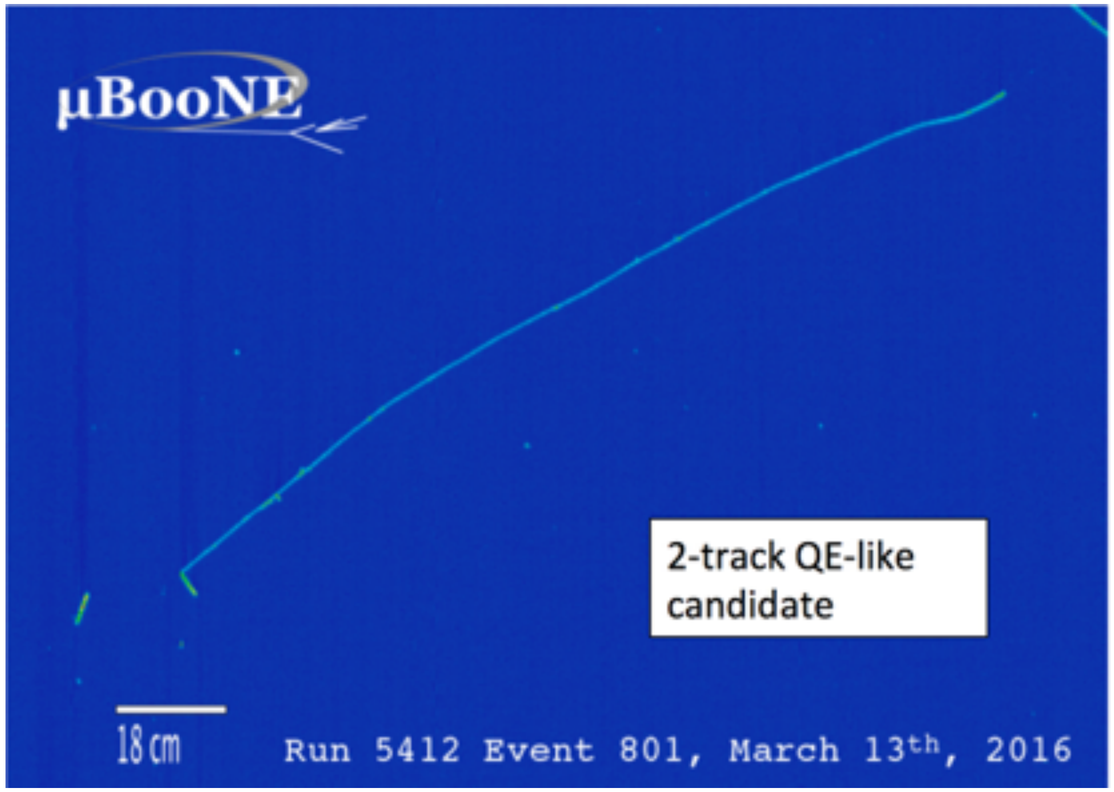
E61 Experiment

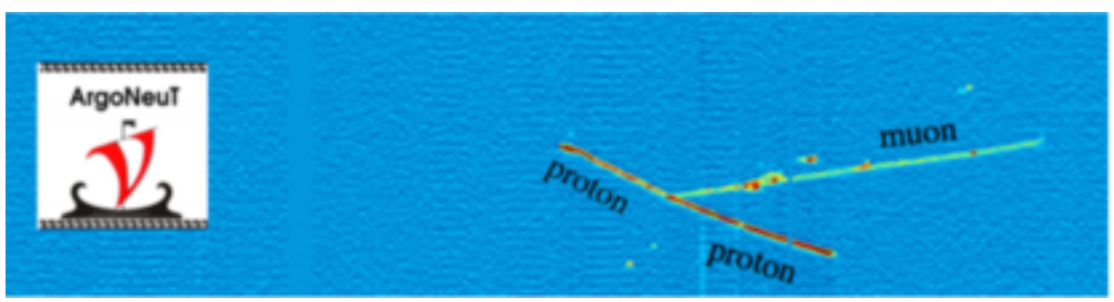


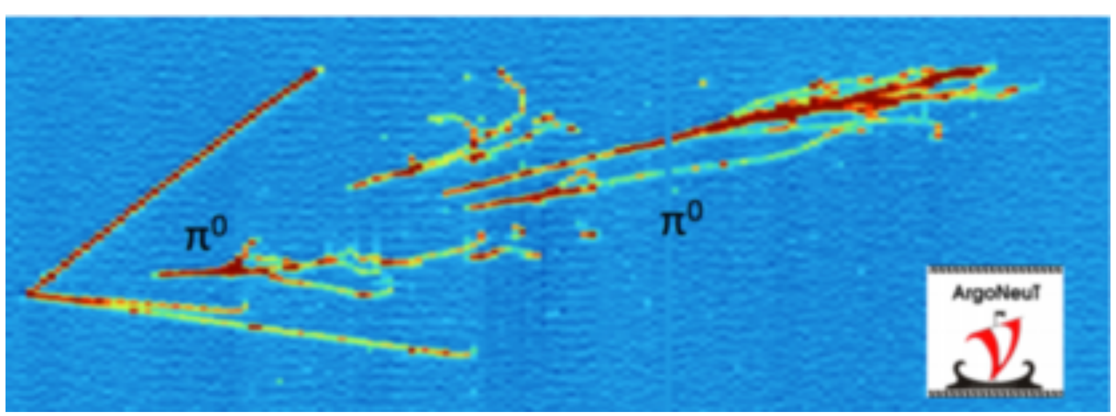
Intermediate Water-Cherenkov detector

Map detector response using multiple off-axis angles

Near Detector Development



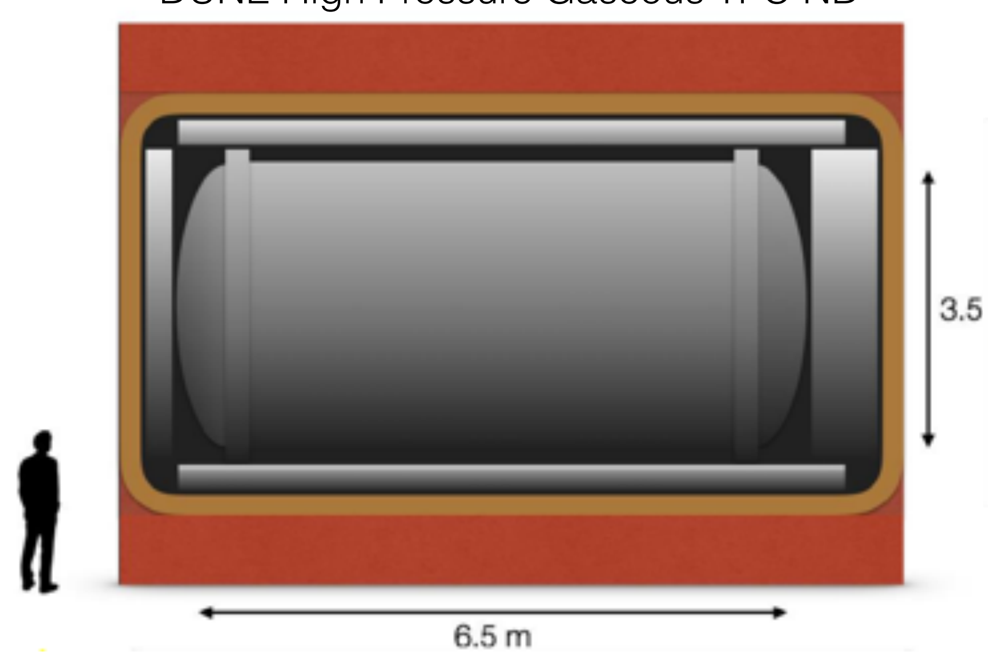


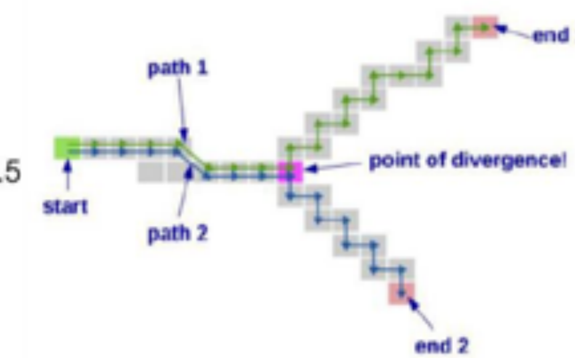


Several Argon TPC experiments
Natural ND candidates for DUNE

Precisely image the neutrino interaction vertex (better constraints on neutrino-nucleus interaction models → better energy measurement)

DUNE High Pressure Gaseous TPC ND





Ultra-low thresholds with gaseous TPC

Summary

Statistical precision promised by future high beam power and high mass experiments place high demands on the systematic uncertainties that experiments must reach

T2K and NOvA have reported systematics uncertainties in the range ~ 3 - 10% level

Reductions are needed today to make best use of the increasing statistical precision in the T2K and NOvA disappearance measurements

Improved flux determination, ν-nucleus interaction modelling and understanding of detector response will all play a role

Systematic Uncertainties in Long Baseline Neutrino Oscillation Measurements

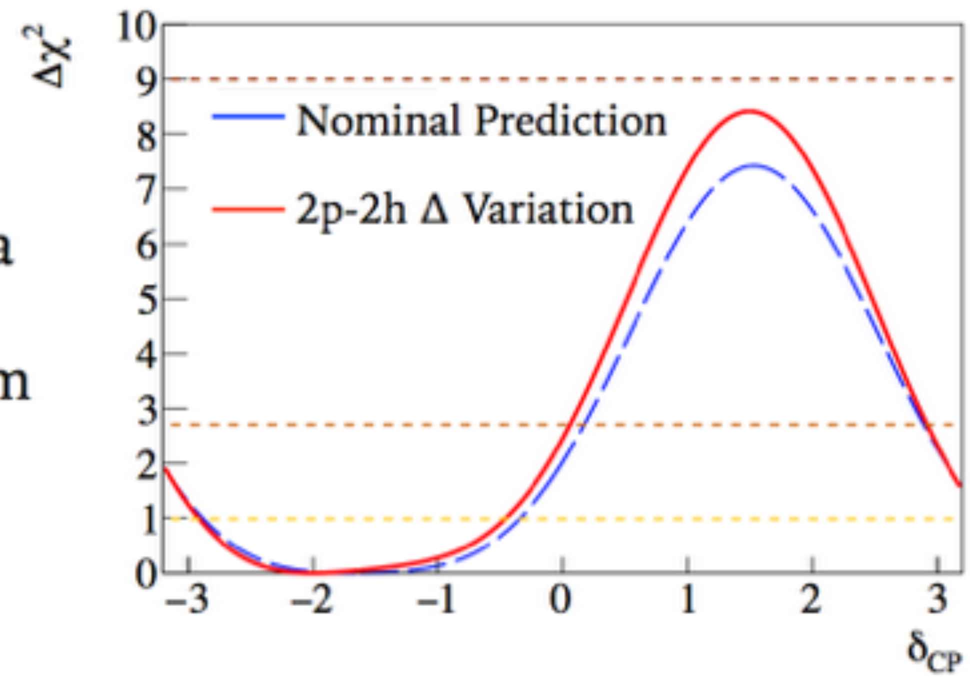
David Hadley

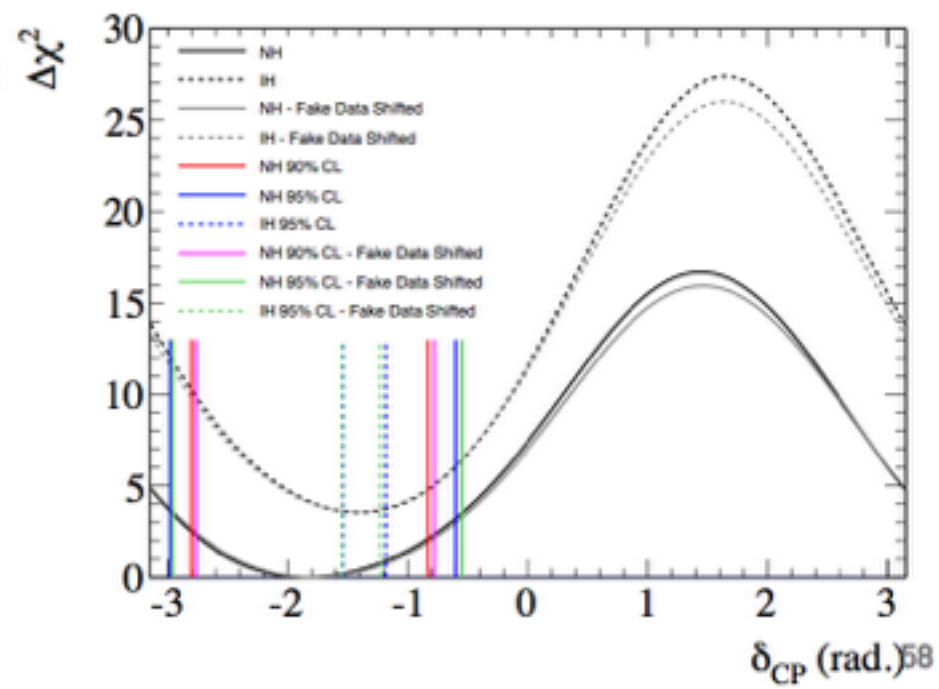
21st December 2017
Prospects in Neutrino Physics, NuPhys2017

Fake Data Studies

IMPACT ON CP PHASE

- Consider how changes to the $\Delta\chi^2$ impact intervals calculated from data
  - Shift $\Delta\chi^2$ observed in data (bottom plot) by difference observed in systematic study (top plot)
- **Maximum shift in the NH 2σ confidence interval mid-point was 1.7%**
- **Maximum change to the NH 2σ confidence interval was 2.3%**
- **Impact on δ_{cp} intervals is small**





Fake Data Studies

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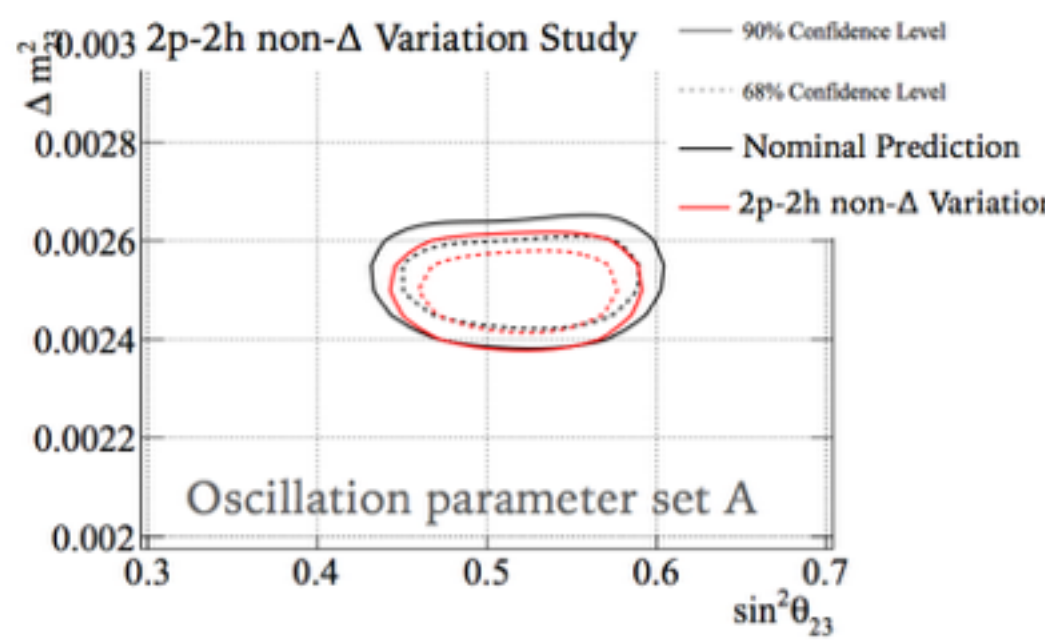
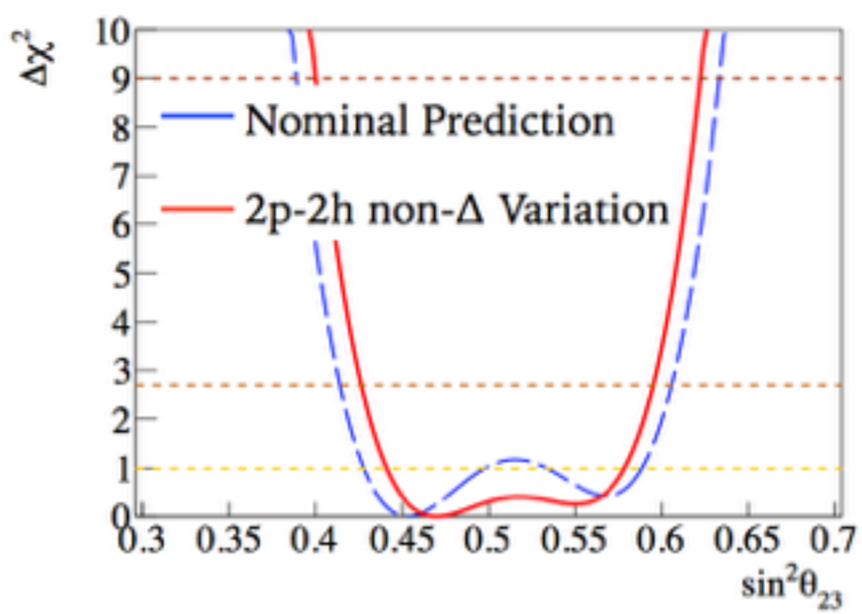
IMPACT ON ATMOSPHERIC PARAMETERS

T2K

- In this study, Δm^2_{32} is biased to lower values
- $\sin^2\theta_{23}$ is biased towards maximal disappearance
  - Leads to narrower contour than fit to nominal prediction
- Shift towards maximal also seen in 1-D contour for oscillation parameter set B (bottom)





Fake Data Studies

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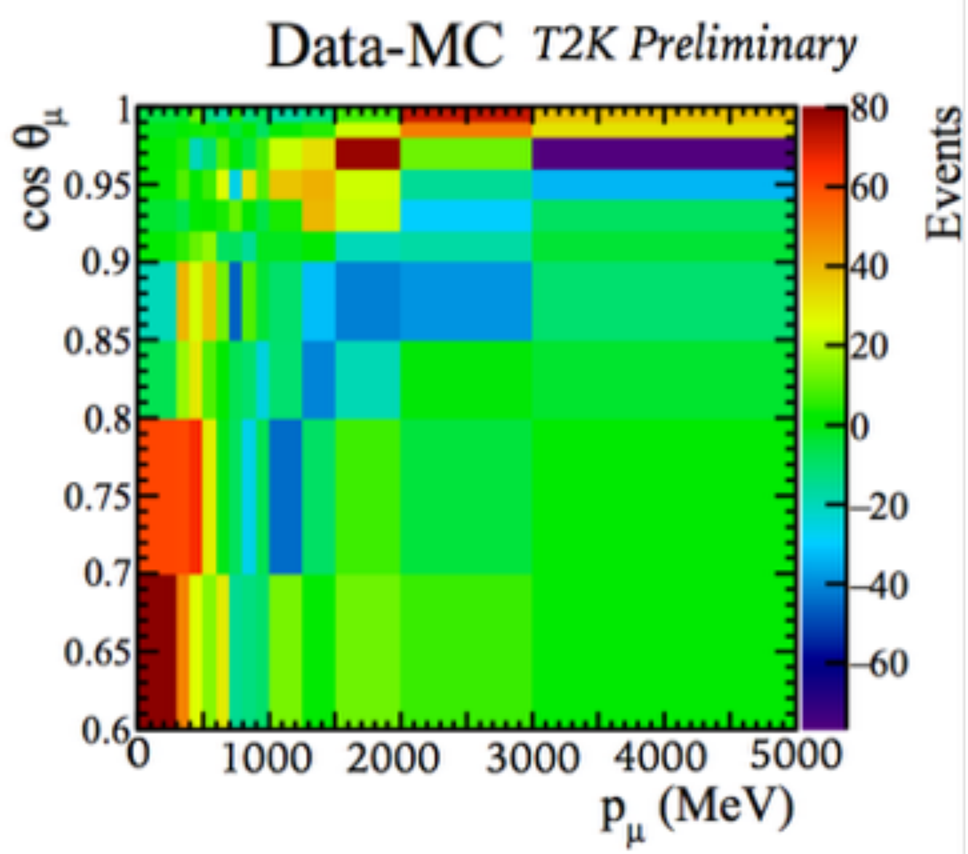
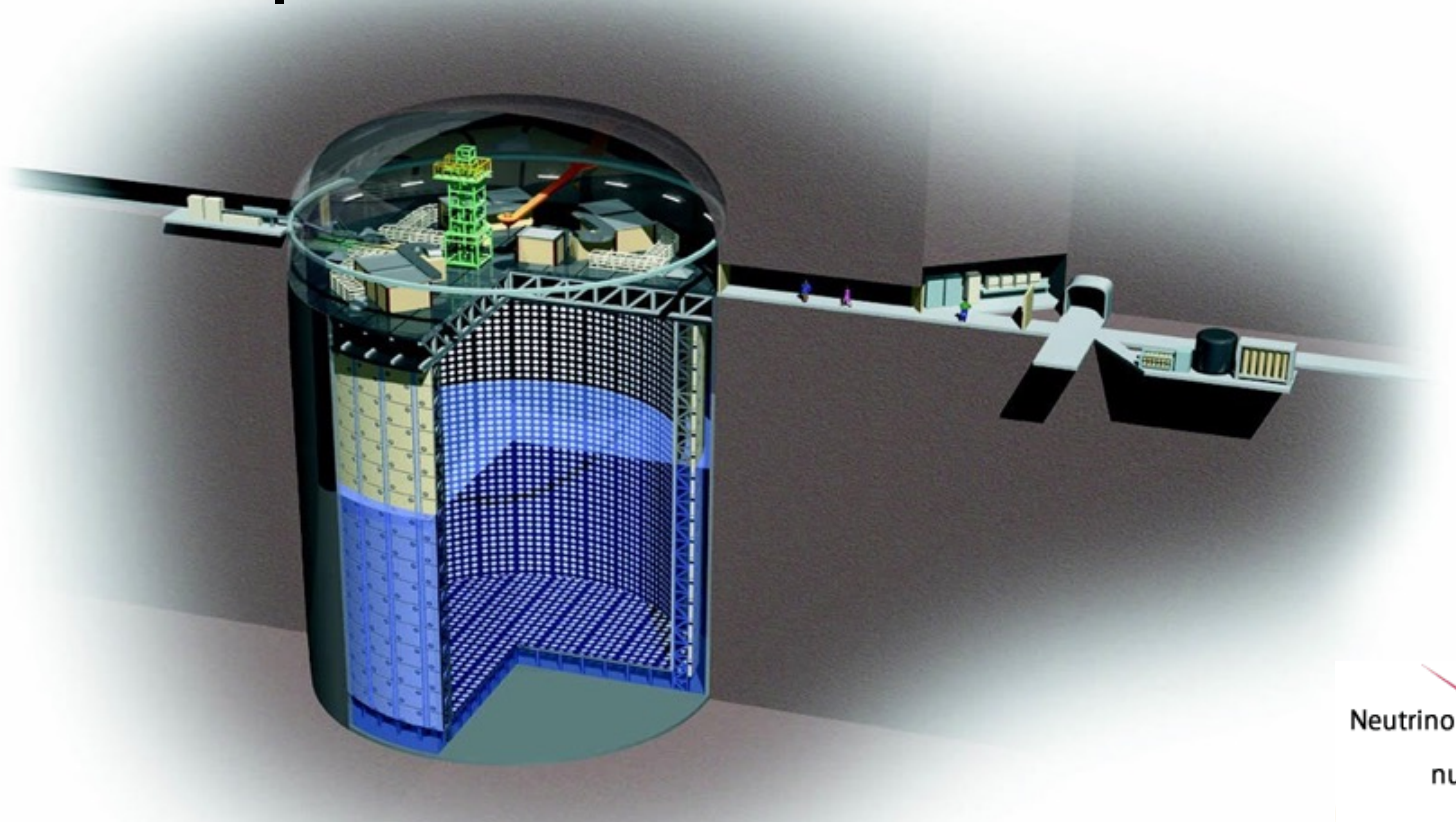
ND280 DATA-DRIVEN VARIATION

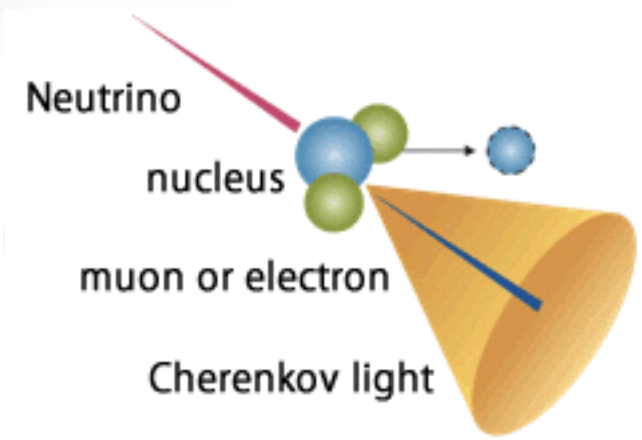
T2K

- Take excess of data over prediction prior to ND280 fitting
- Assign excess to 1 of 3 types of interactions:
  - CCQE
  - 2p-2h Δ-enhanced
  - 2p-2h non-Δ-enhanced
- Apply modeled excess to predict rates ND280 and SK
- Run fits
- Effect seen on $\sin^2\theta_{23}$ and Δm^2_{32}
- No significant impact on the measured intervals for δ_{cp}



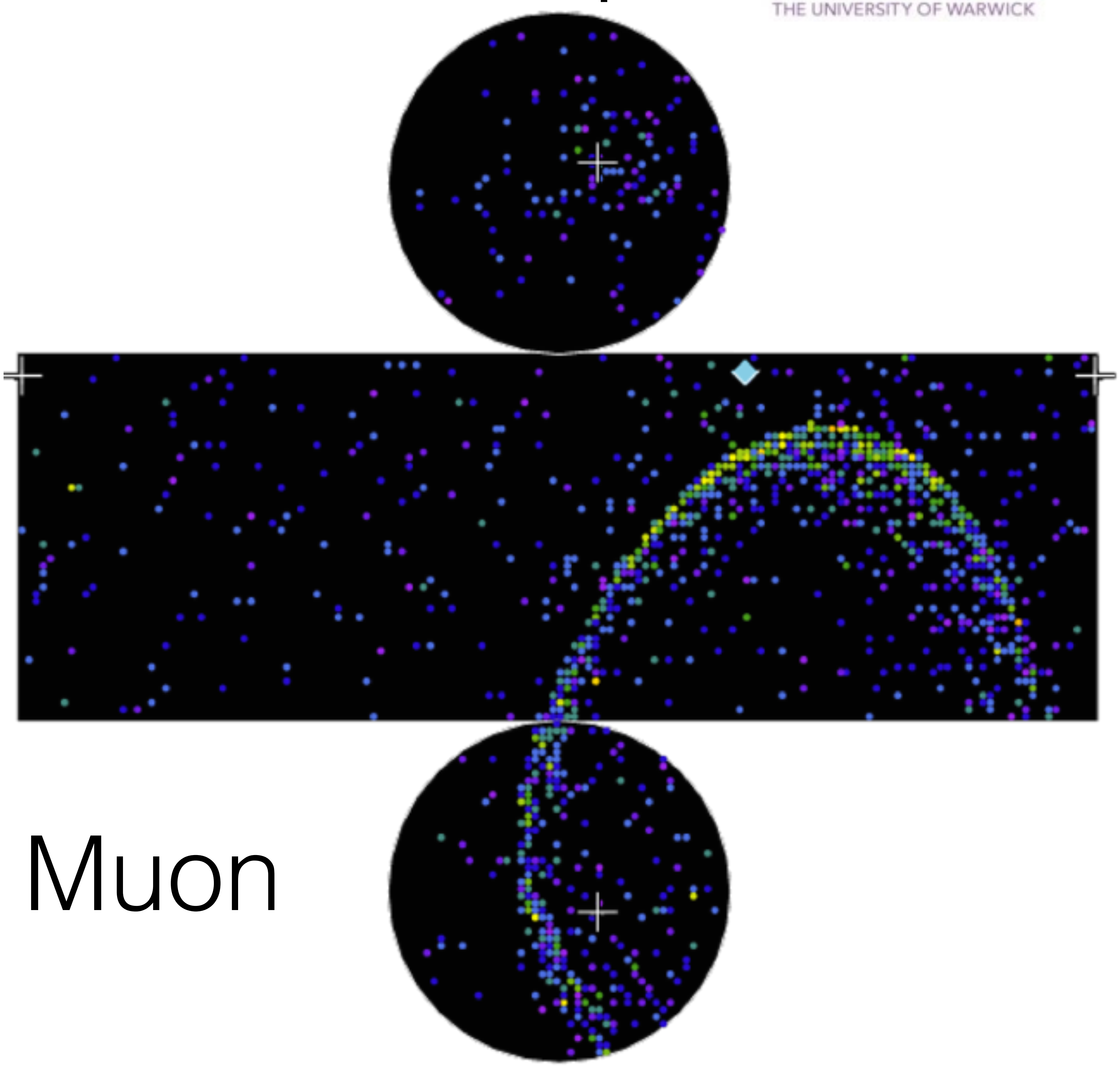
Super-Kamiokande





Water Cherenkov Detector
>22.5 kt fiducial mass

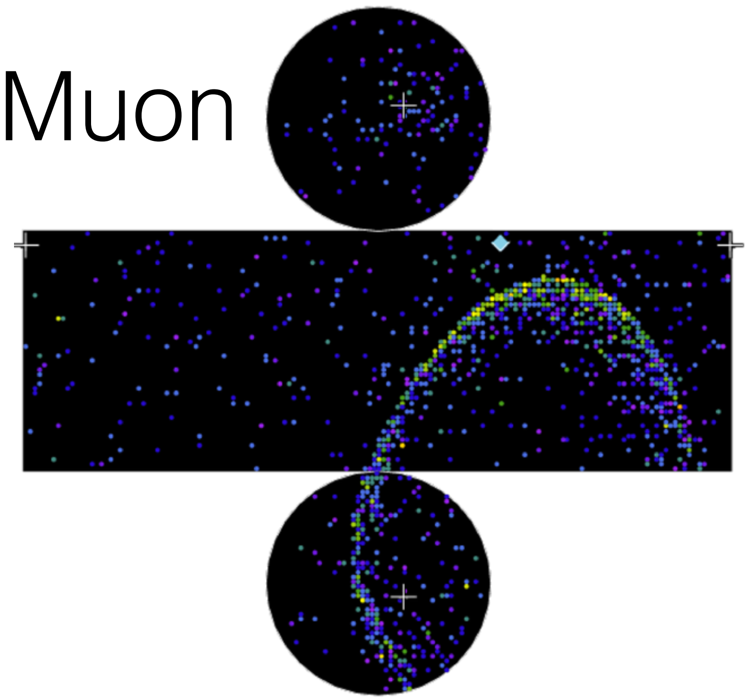
Water Cherenkov Technique

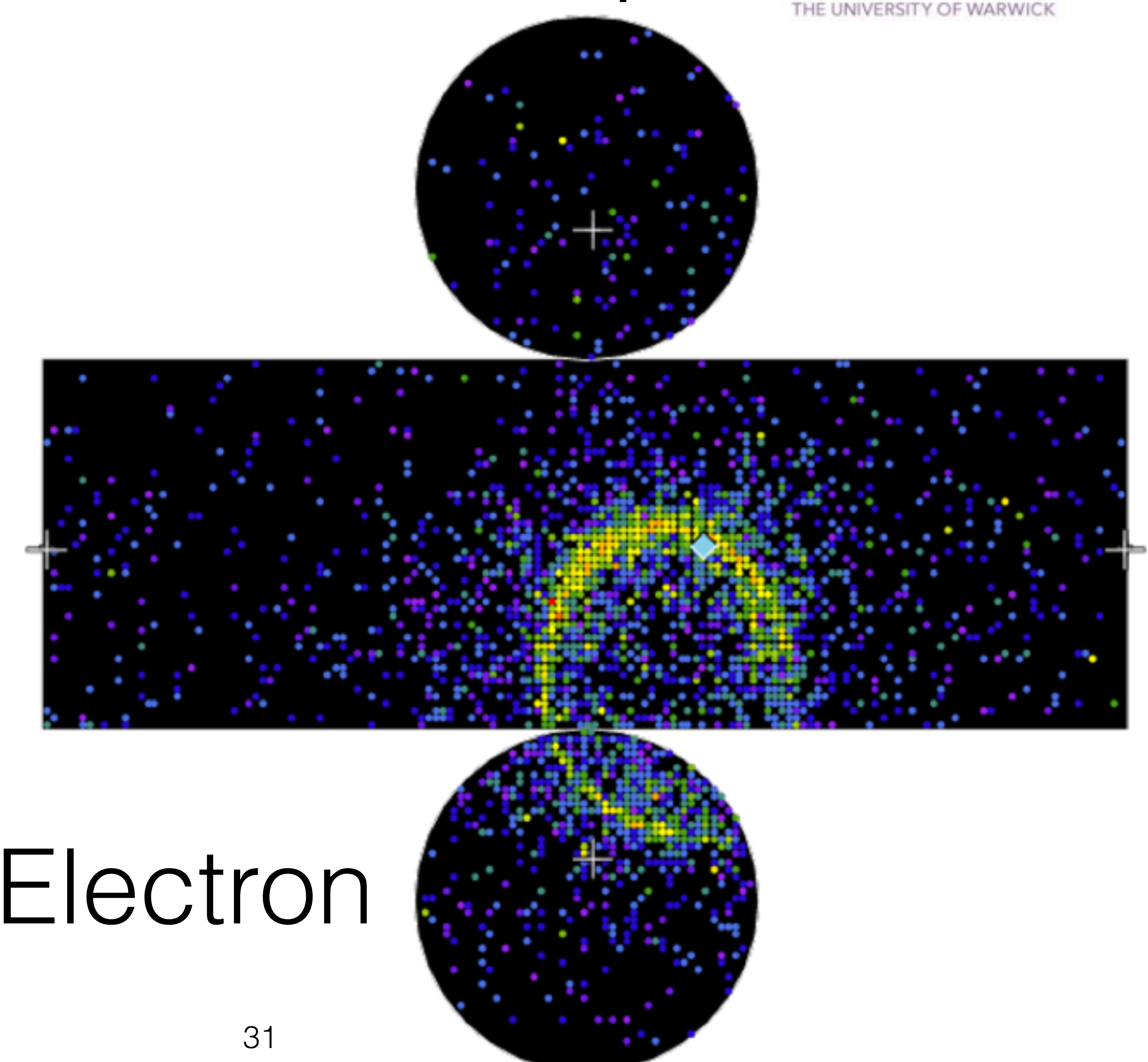


Muon

Water Cherenkov Technique

Muon

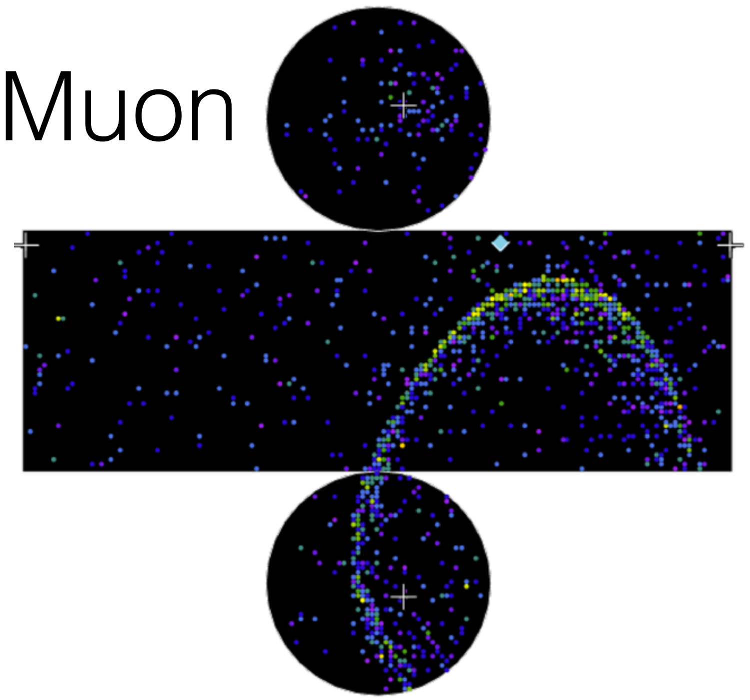




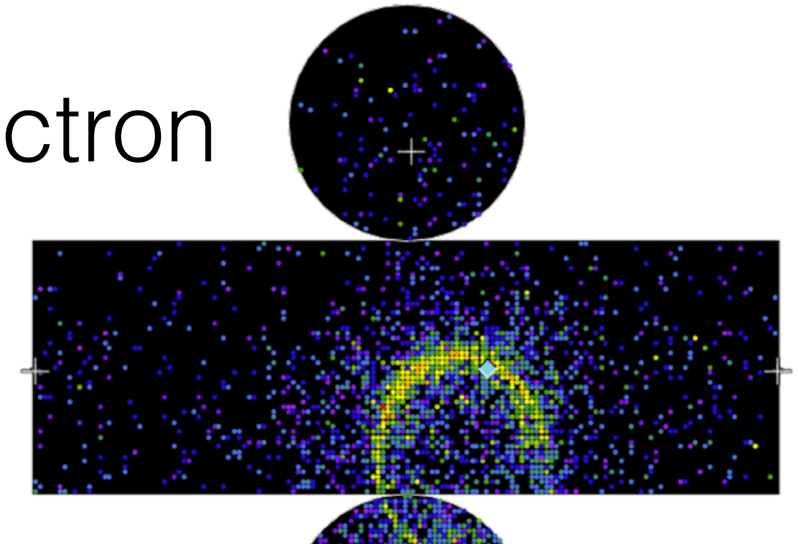
Electron

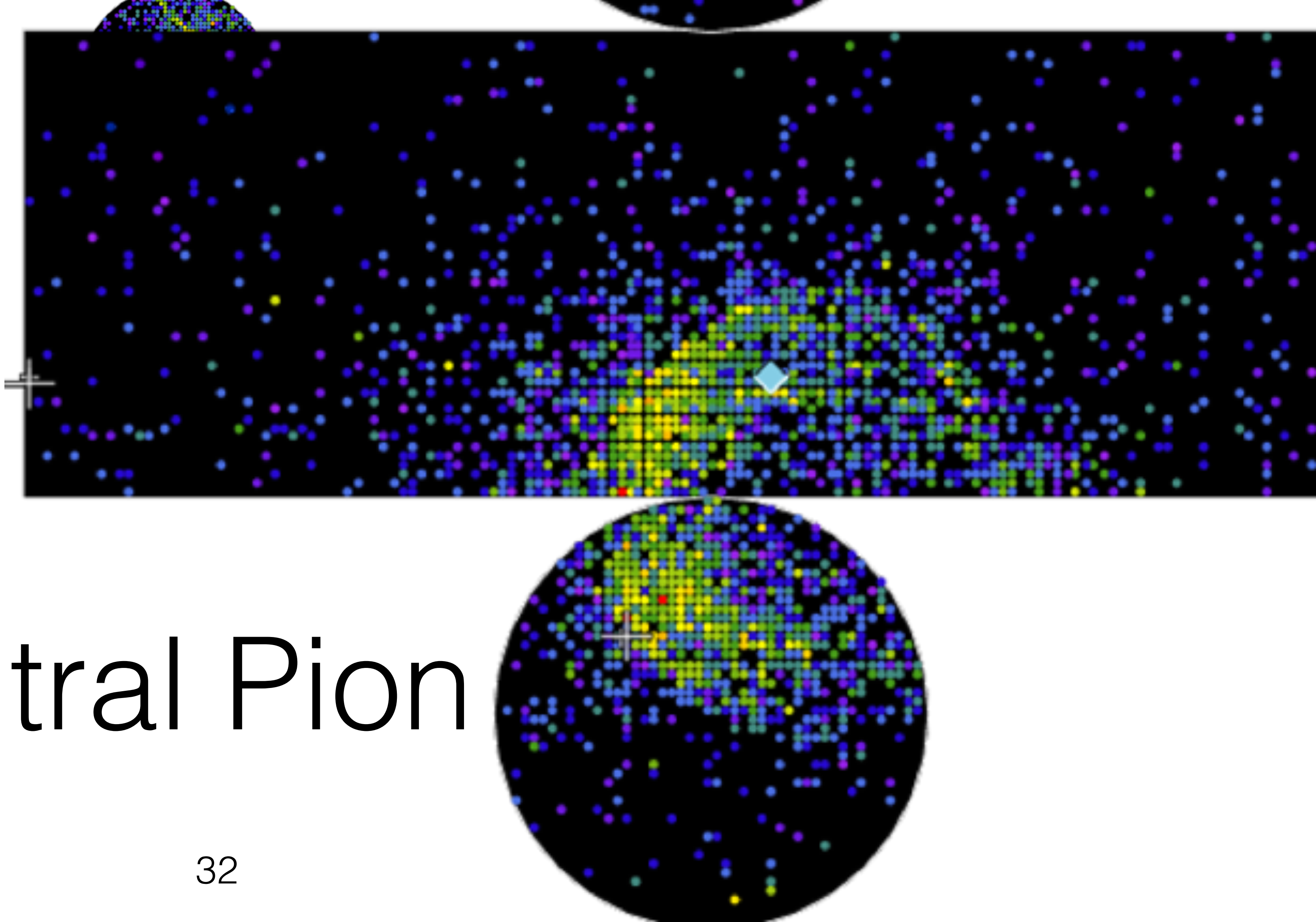
Water Cherenkov Technique

Muon



Electron

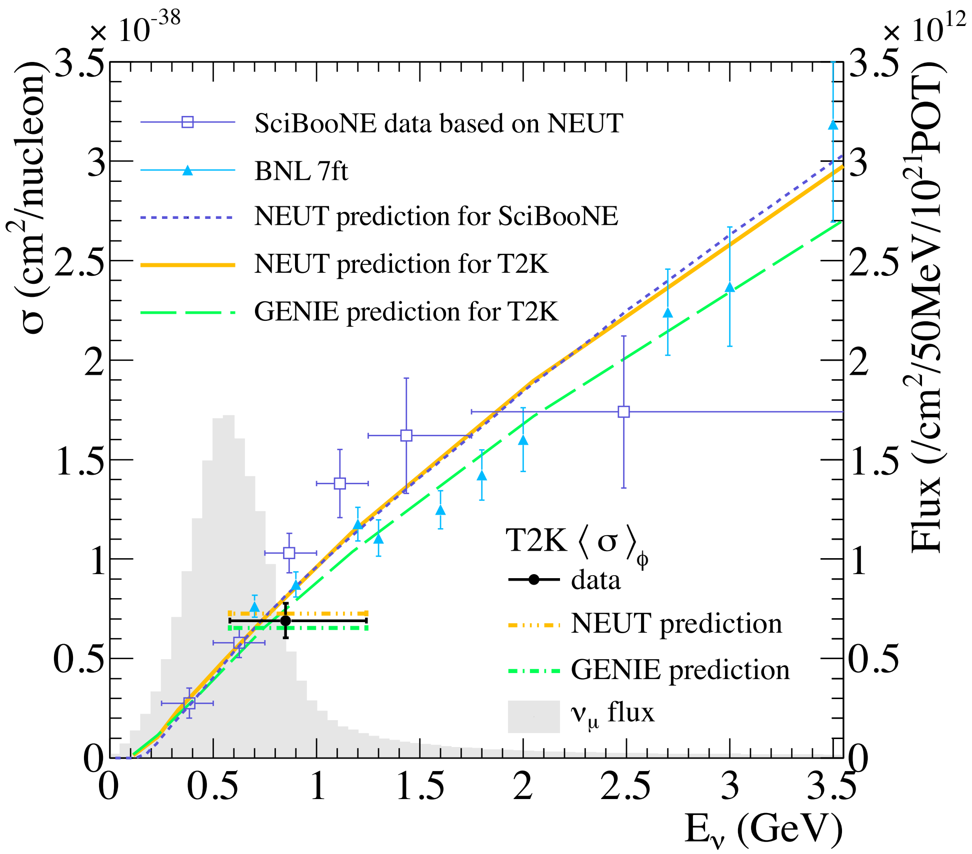




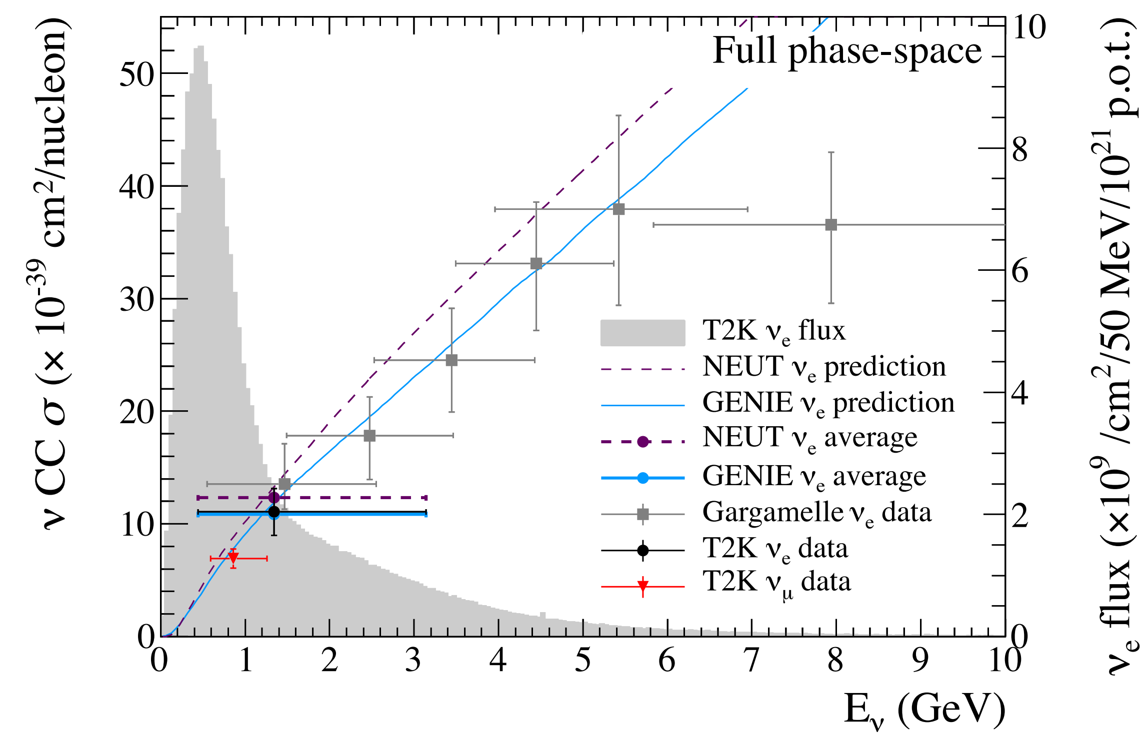
Neutral Pion

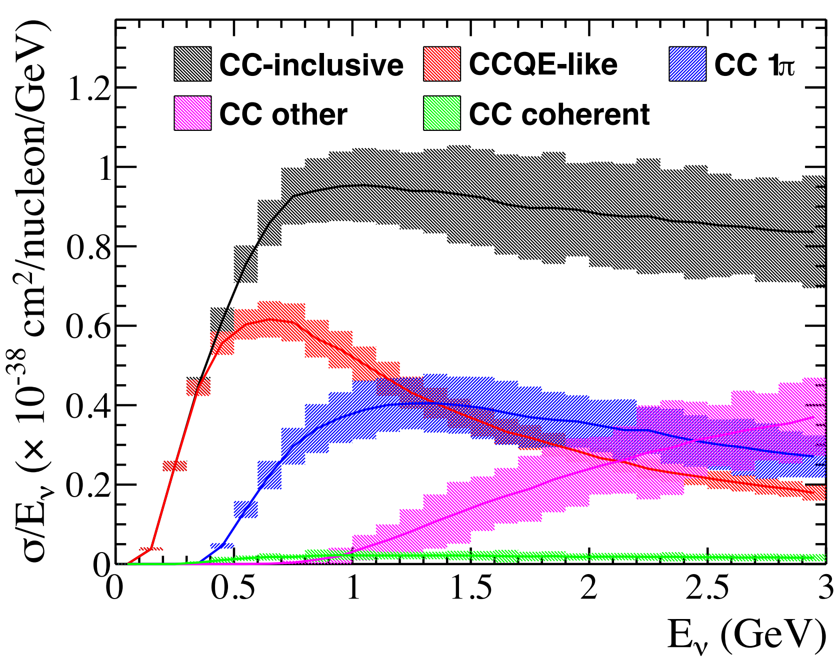
ND280 Flux

Phys. Rev. D 87, 092003 (2013)



Phys. Rev. Lett. 113, 241803 (2014)





In neutrino-mode

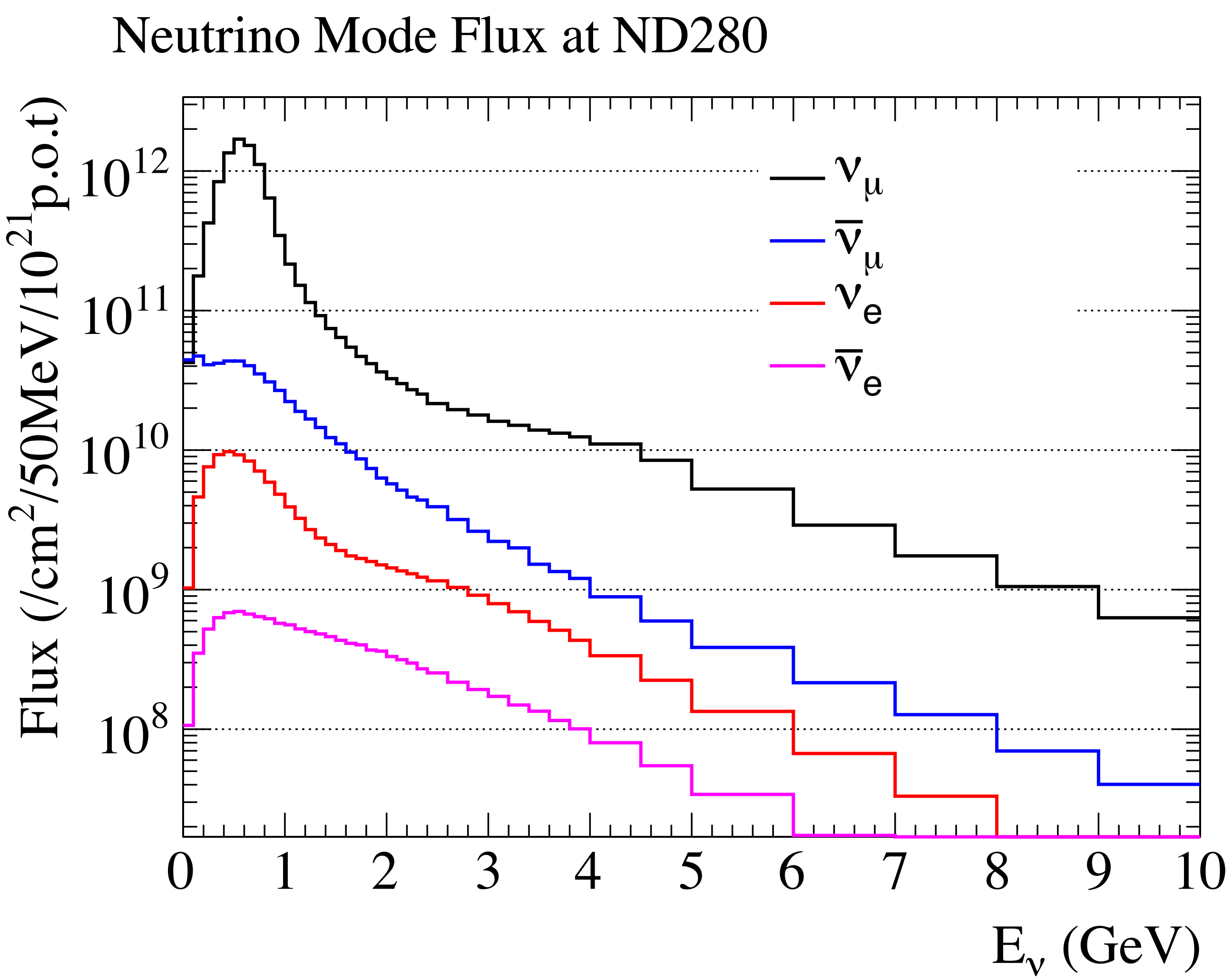
ν_μ : ⟨E⟩ = 0.85 GeV, (~90%)

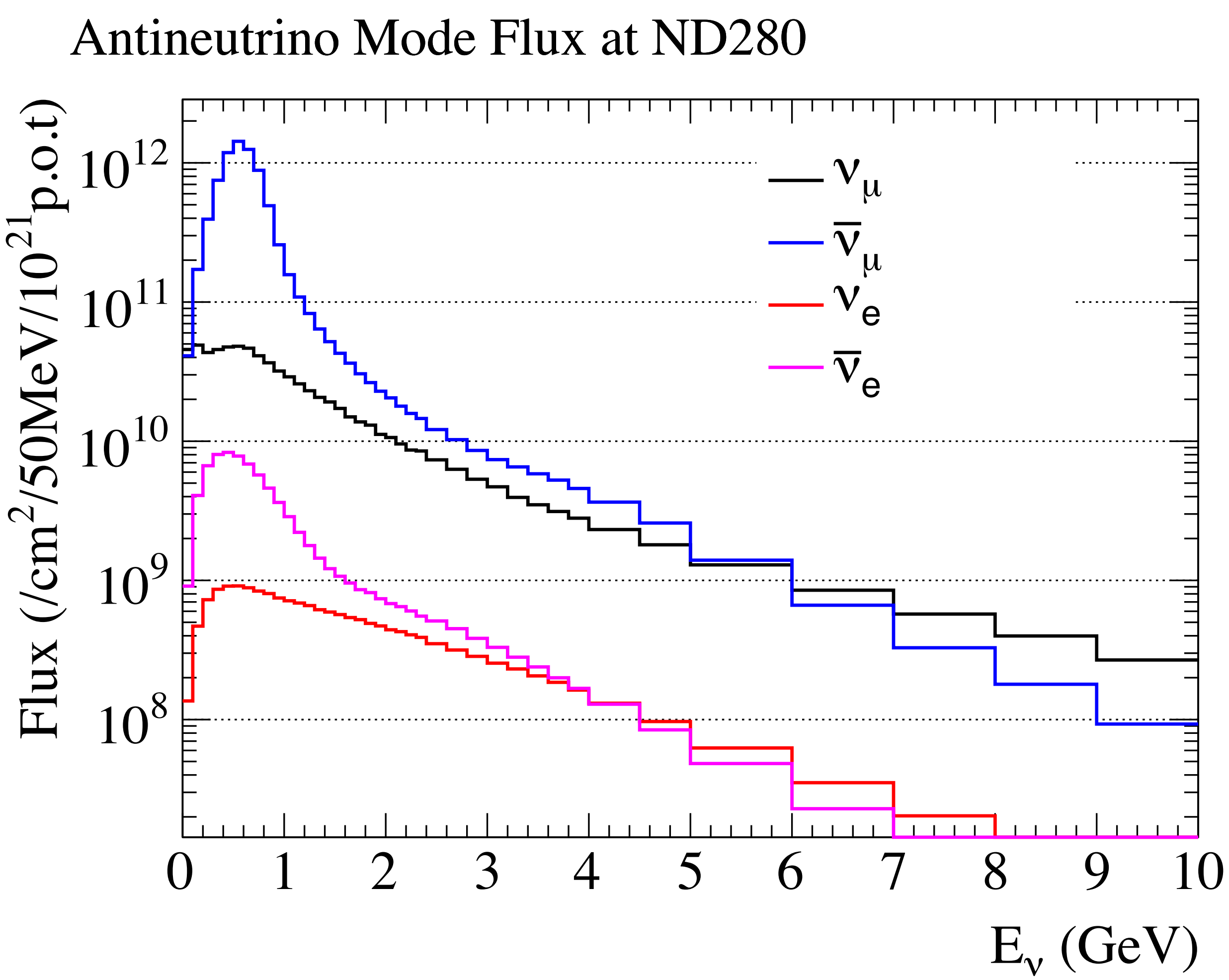
ν_e : ⟨E⟩ = 1.3 GeV,(~1%)

Dominant Reaction: CCQE

Single Pion Production

Flux at ND280





In neutrino-mode

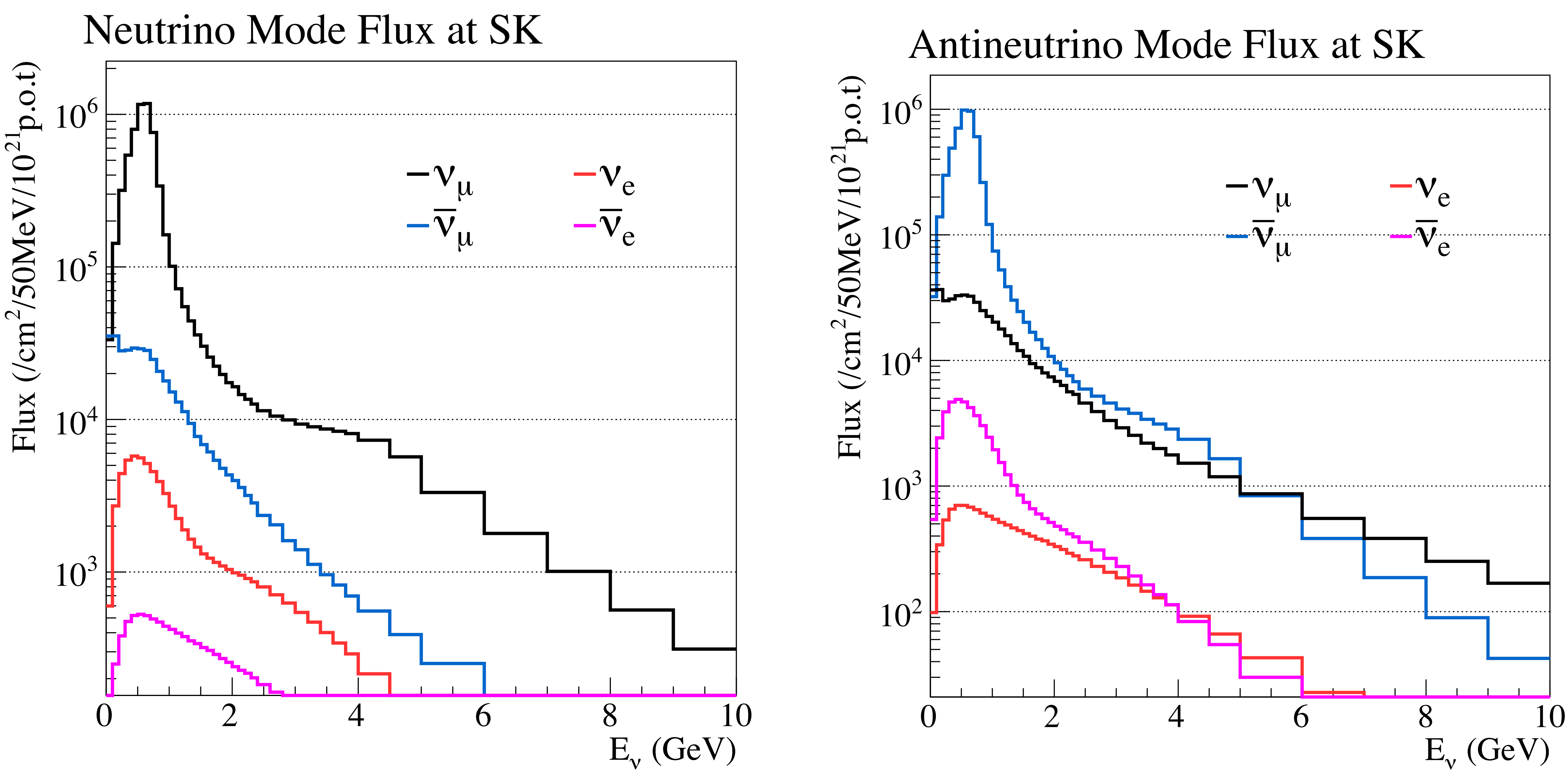
ν_μ : ⟨E⟩ = 0.85 GeV, (~90%)

ν_e : ⟨E⟩ = 1.3 GeV,(~1%)

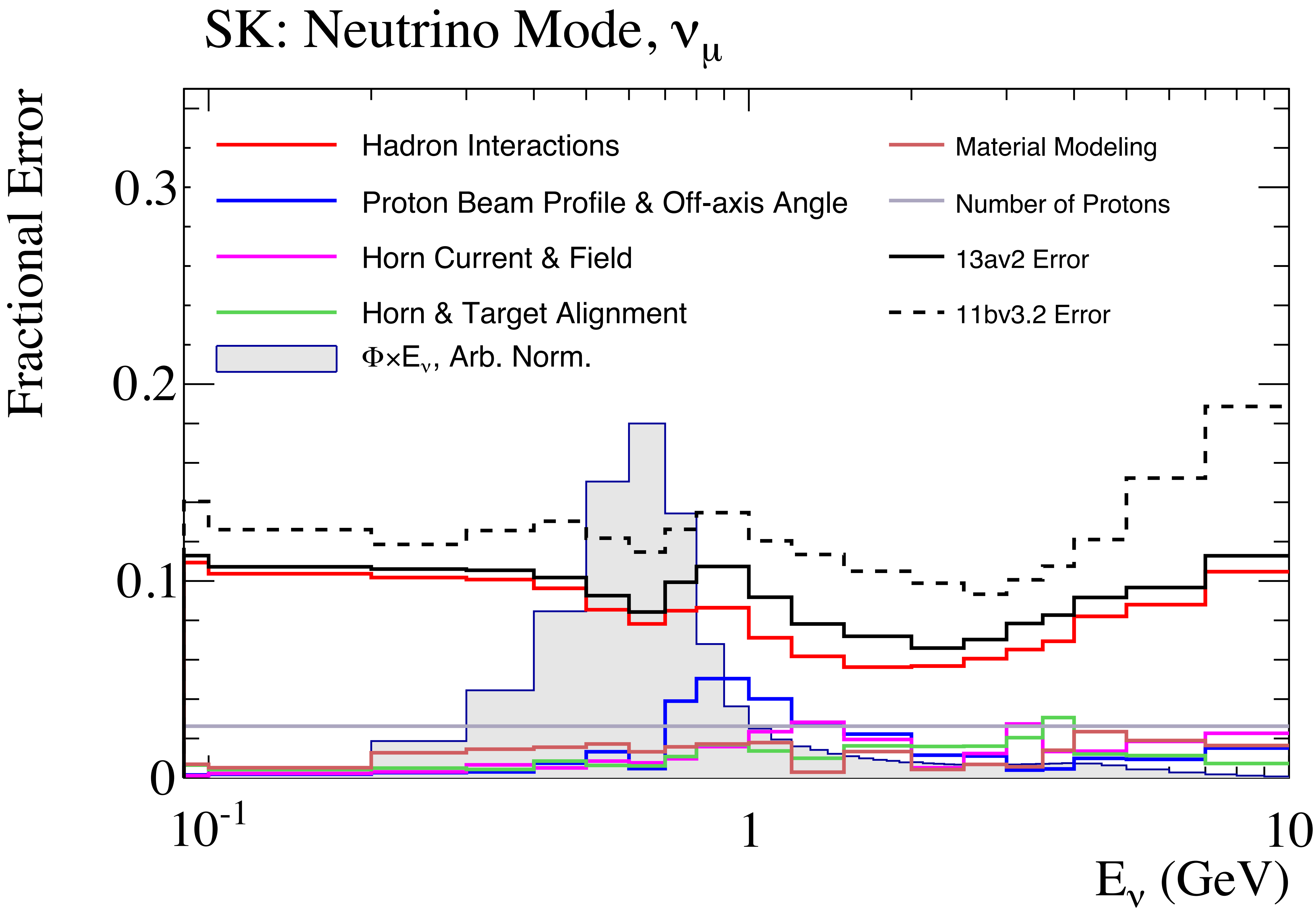
Dominant Reaction: CCQE

Single Pion Production

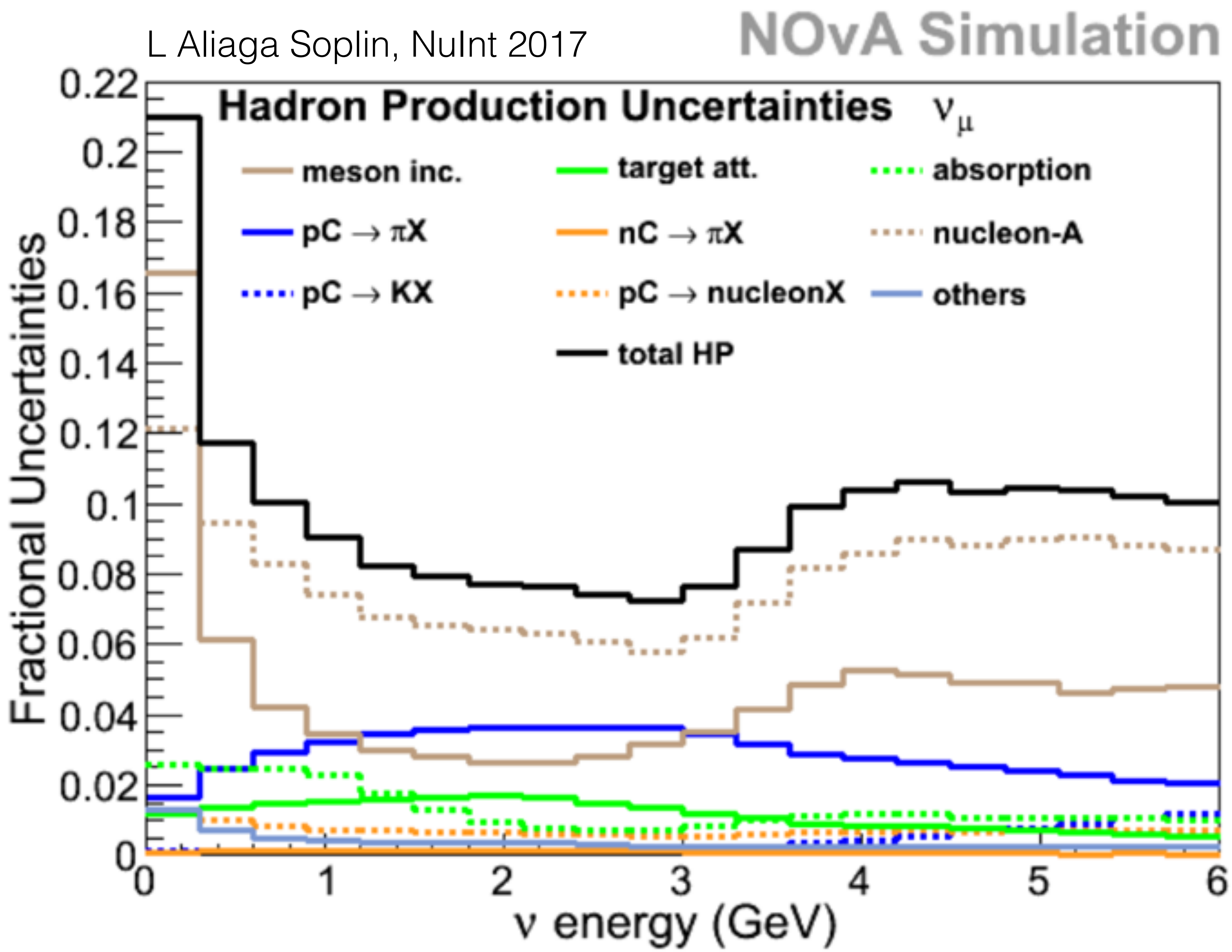
Flux at Super-K



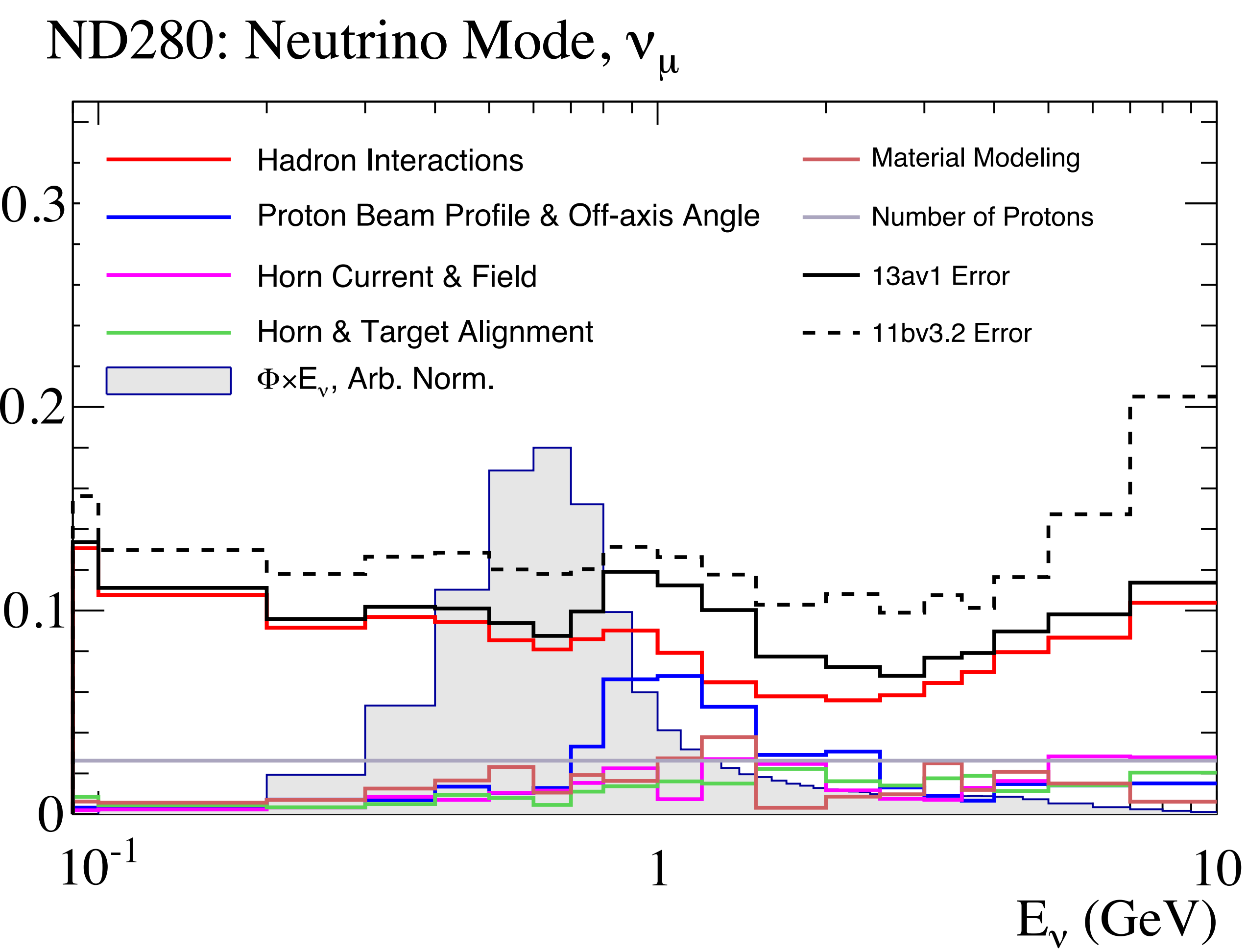
Flux Uncertainty

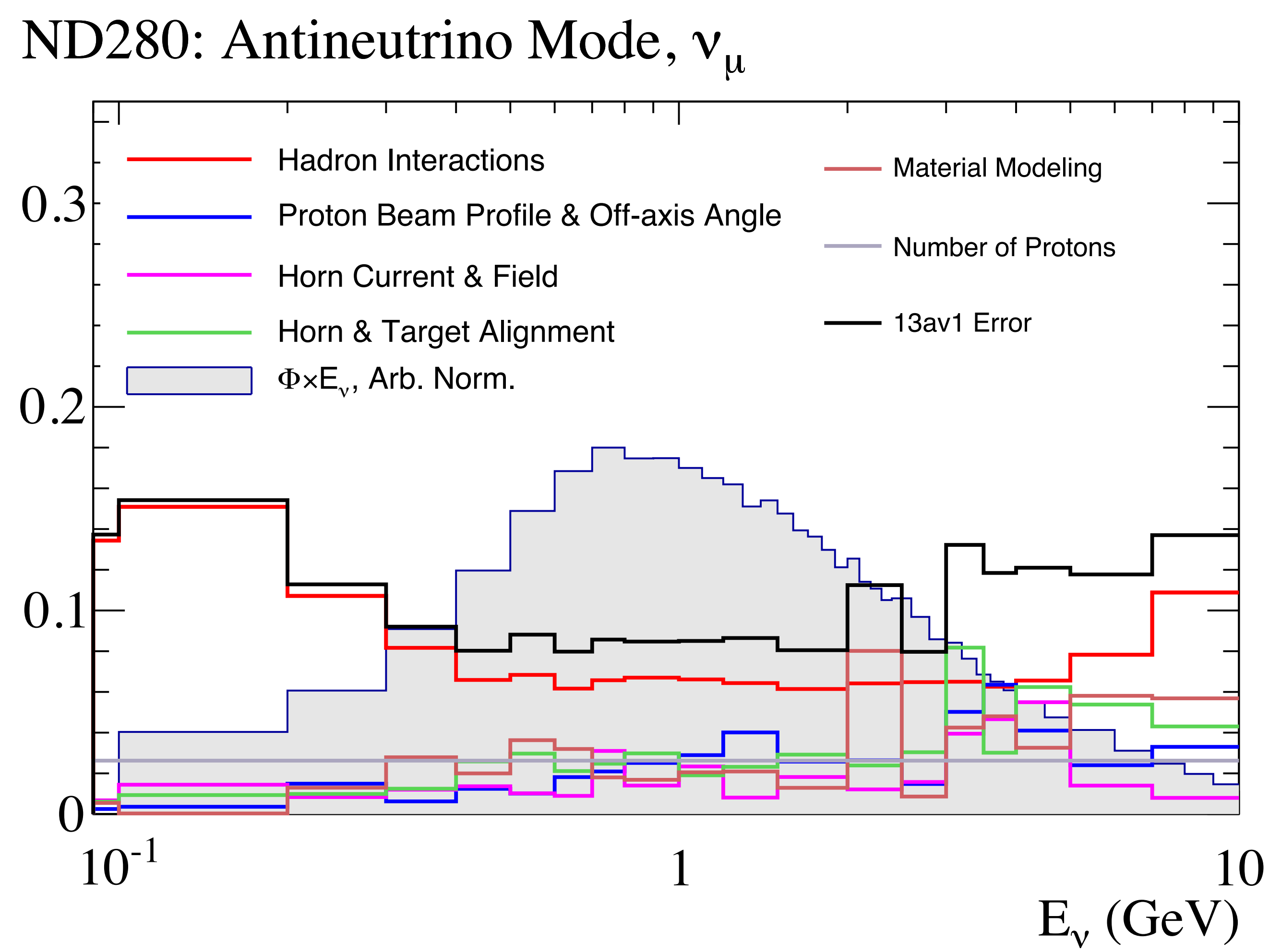


Flux Uncertainty

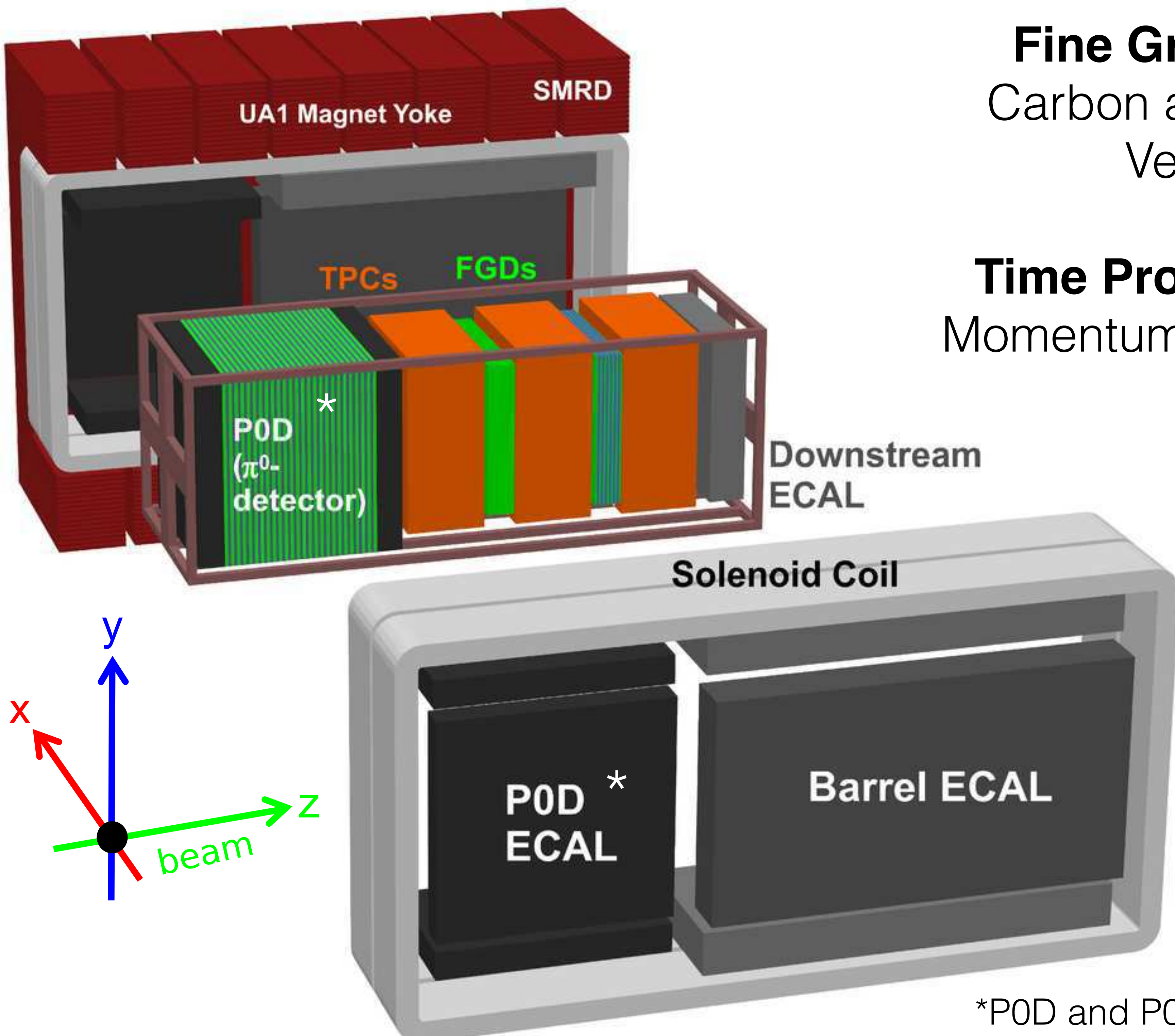


Flux at ND280





ND280 Detector



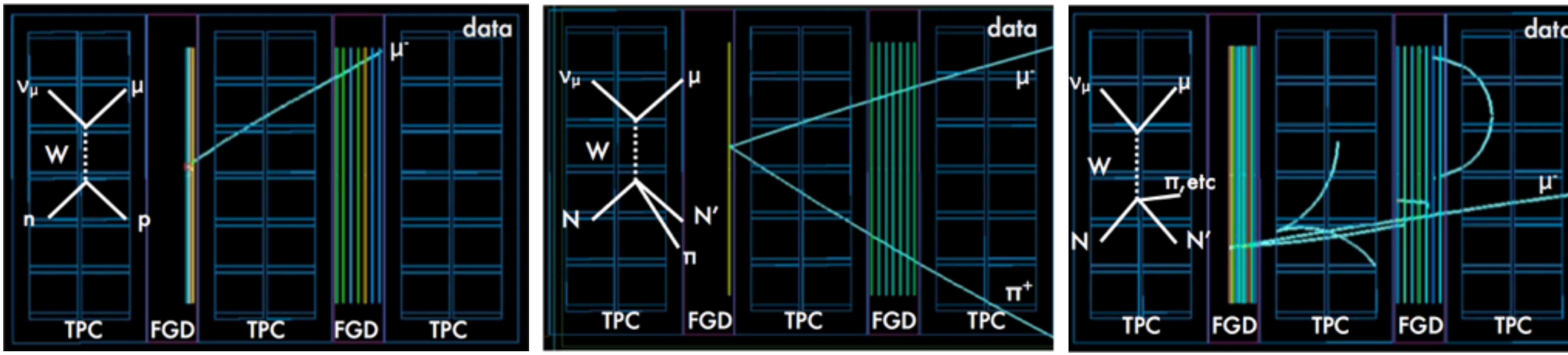
Fine Grained Detectors (FGD)
Carbon and Oxygen Target Mass,
Vertex reconstruction

Time Projection Chambers (TPC)
Momentum and Charge Measurement
Particle ID

EM Calorimeters
Neutral Particle Reconstruction
Additional PID and
energy measurement
Tag entering backgrounds

*P0D and P0D ECal detectors not be discussed here.
See arXiv:1111.5030 and arXiv:1308.3445 for information on these detectors.

ND280 Input to T2K Oscillation Analysis



ND280 data split based on reconstructed topology enhanced in different interaction types

Fit flux + interaction model and propagate to far detector

As statistics increase and analysis becomes more sophisticated incorporate more channels

T2K Analysis Strategy

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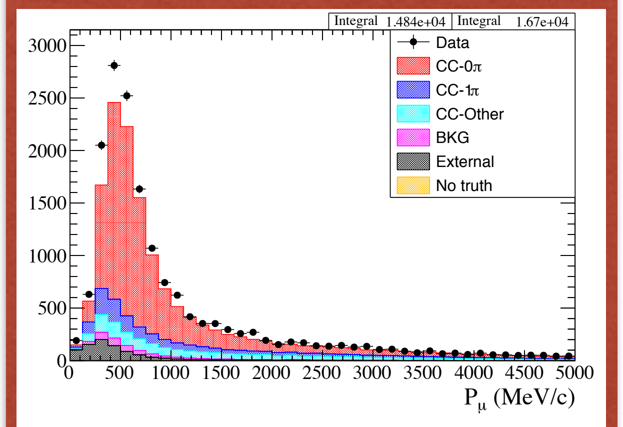
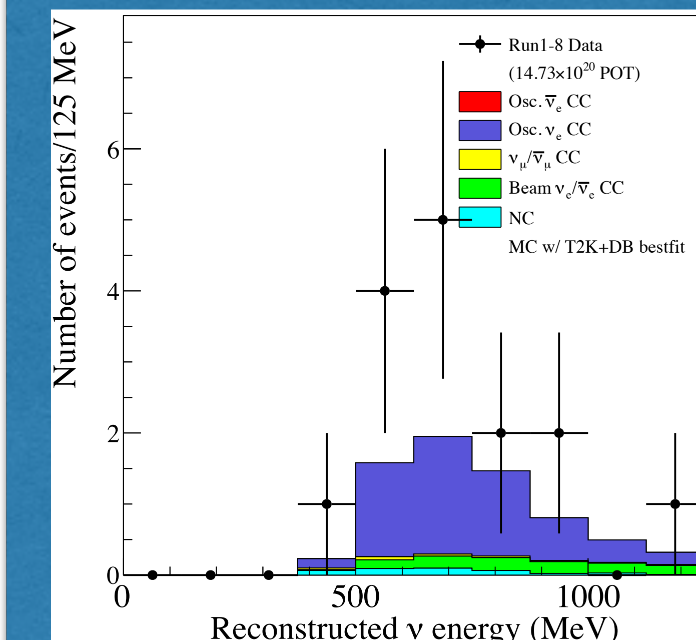
Near Detector Data



Far Detector Data



Theoretical Predictions

External Cross Section Measurements

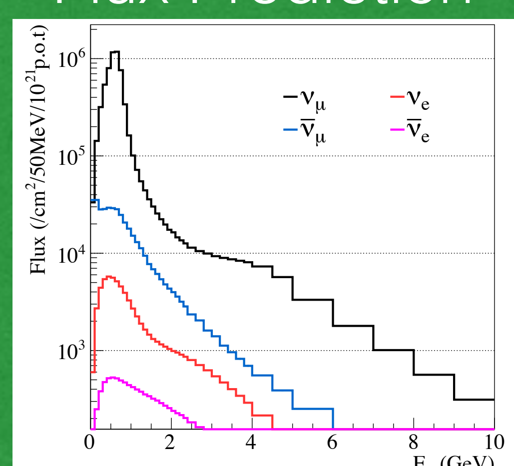
ν-Nucleus Interaction Model

Updated Flux + ν-Nucleus Interaction Model

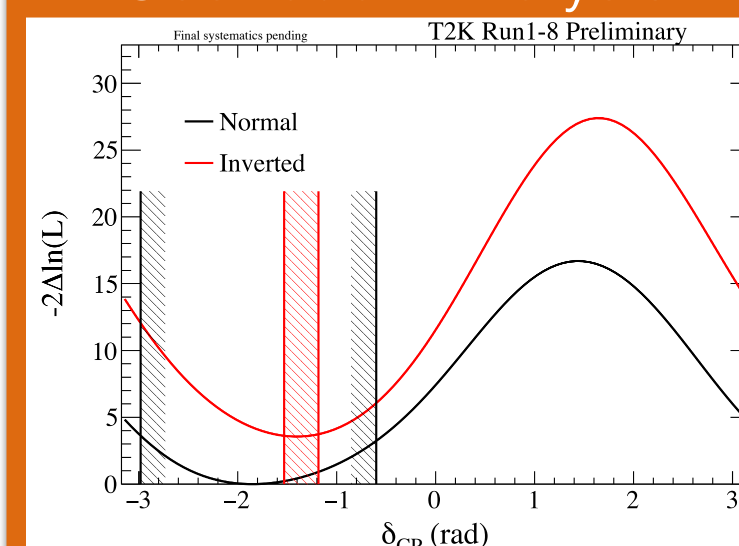
NA61/SHINE

INGRID and Beam Monitors

Flux Prediction



Oscillation Analysis



NOvA Analysis Strategy

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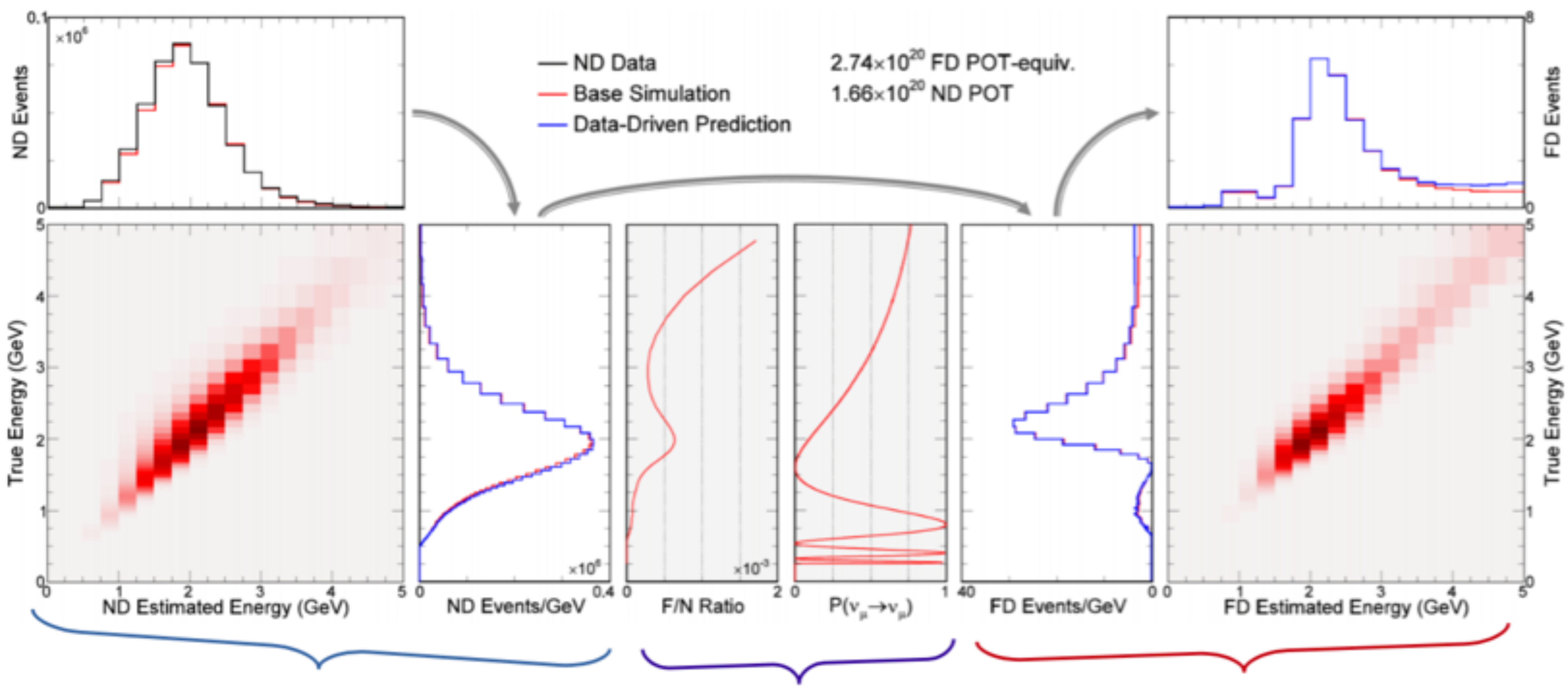
To produce a data-driven prediction at FD, based on ND:

J. Wolcot, NuInt 2017



True energy distribution is corrected so that reconstructed data & MC agree at the ND...

...modified true energy distribution is propagated through predicted geometric beam dispersion & acceptance ratio, oscillations...

... and "extrapolated" reconstructed energy distribution computed to compare to data