νPRISM: An Experimental Method to Remove Neutrino Interaction Uncertainties from Oscillation Experiments

Mike Wilking, Stony Brook University

Workshop on the Intermediate Neutrino Program

February 5th, 2015

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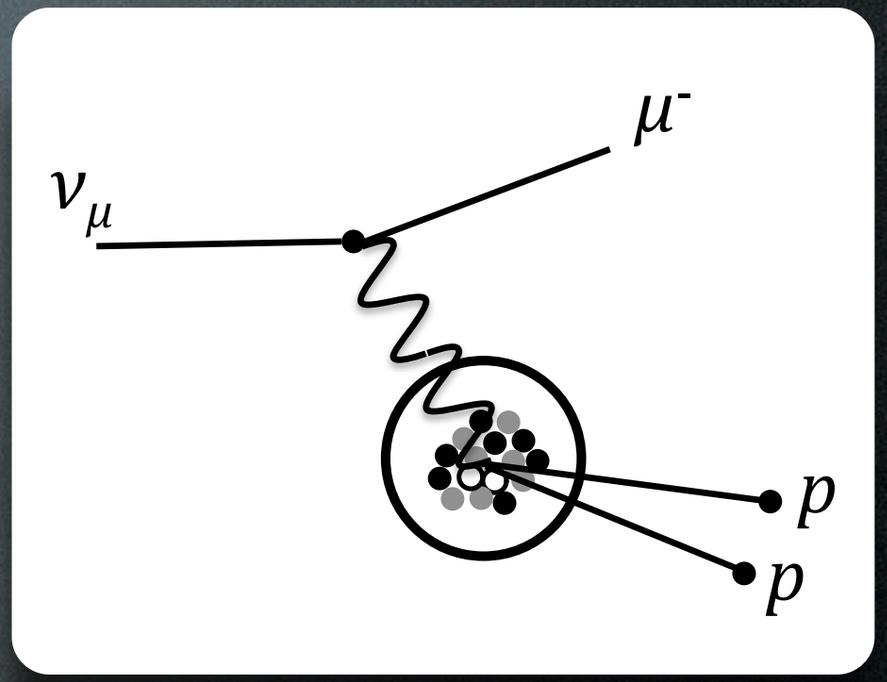
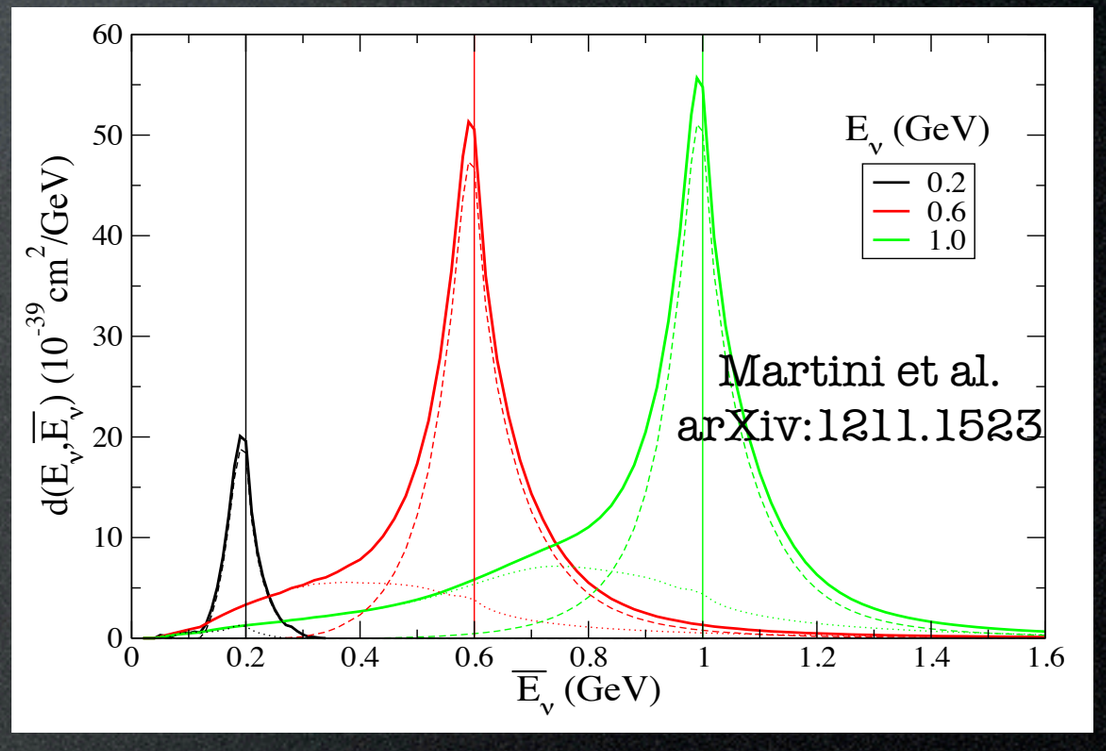
The E_ν Measurement Problem

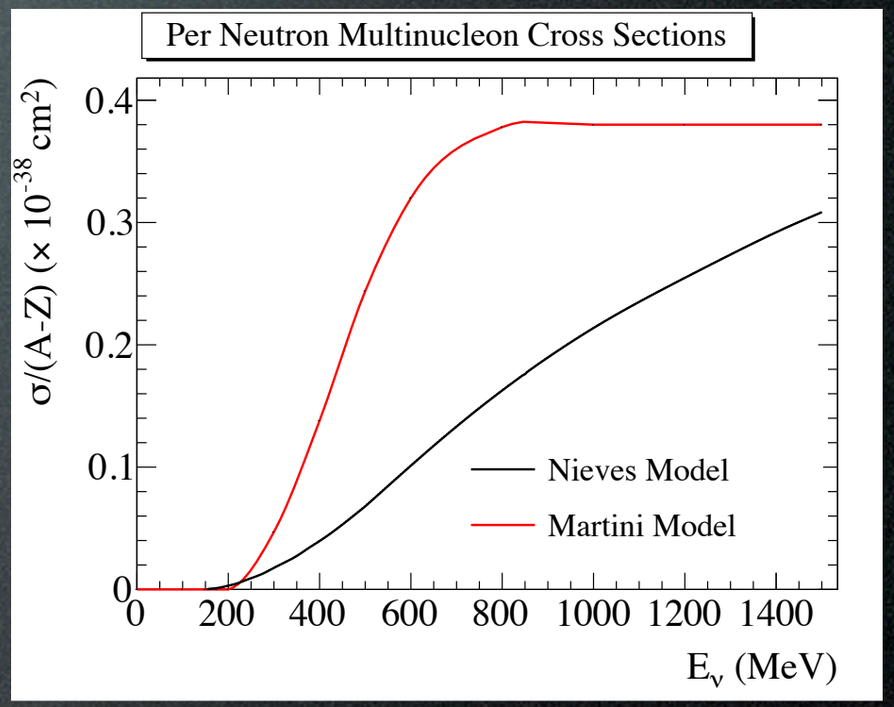
- Can experiments measure E_ν?
- Neutrino interaction models are now incorporating interactions with correlated nucleon pairs in the nucleus
  - This was not the case just a few years ago
  - If the current models are correct, a large fraction of events (~20-30%) can have a significant bias in reconstructed energy
- No direct data constraint exists
  - Oscillation experiments completely rely on models that were very different just 5 years ago

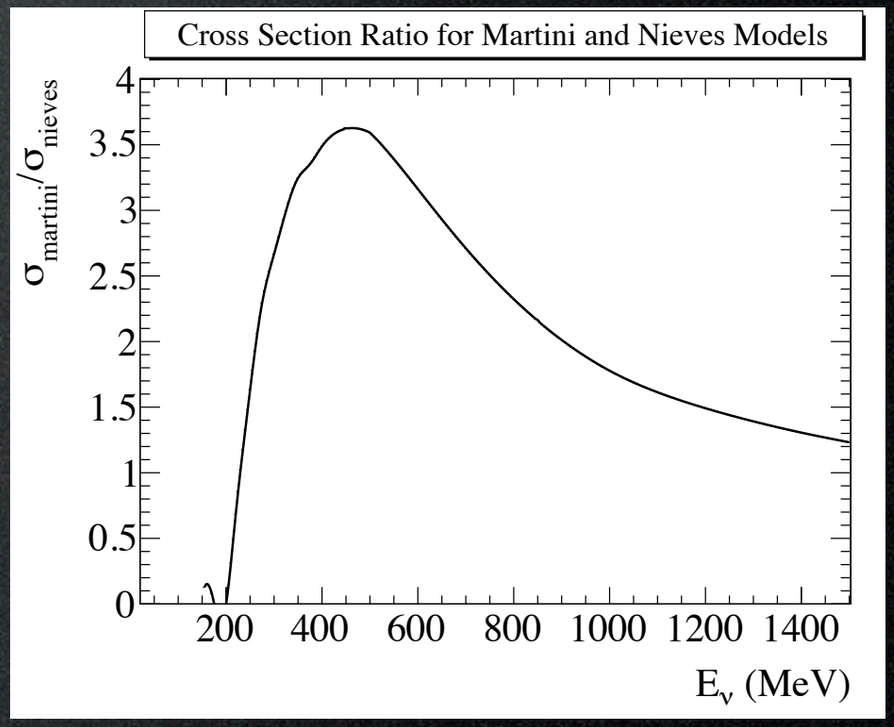




How Well are the New Models Understood?

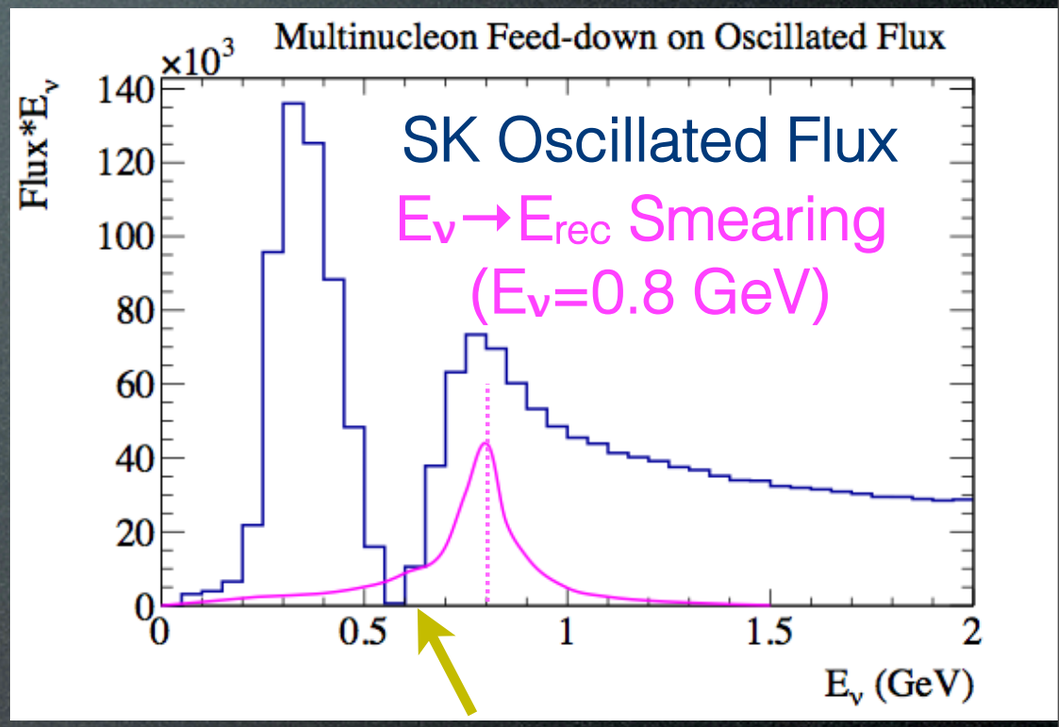
- It is very difficult to answer this question without a direct measurement
- However, the two most commonly used "new" models can be compared
  - J. Nieves, I. Ruiz Simo, and M. J. Vicente Vacas, PRC 83:045501 (2011)
  - M. Martini, M. Ericson, G. Chanfray, and J. Marteau, PRC 80:065501 (2009)
- Cross section differs by a factor of 2 to 3 over a large range of neutrino energies
- Which model is correct?
  - Is either model correct?
- How can we assign a systematic error to this process and trust that it is sufficient to cover the true model in nature?





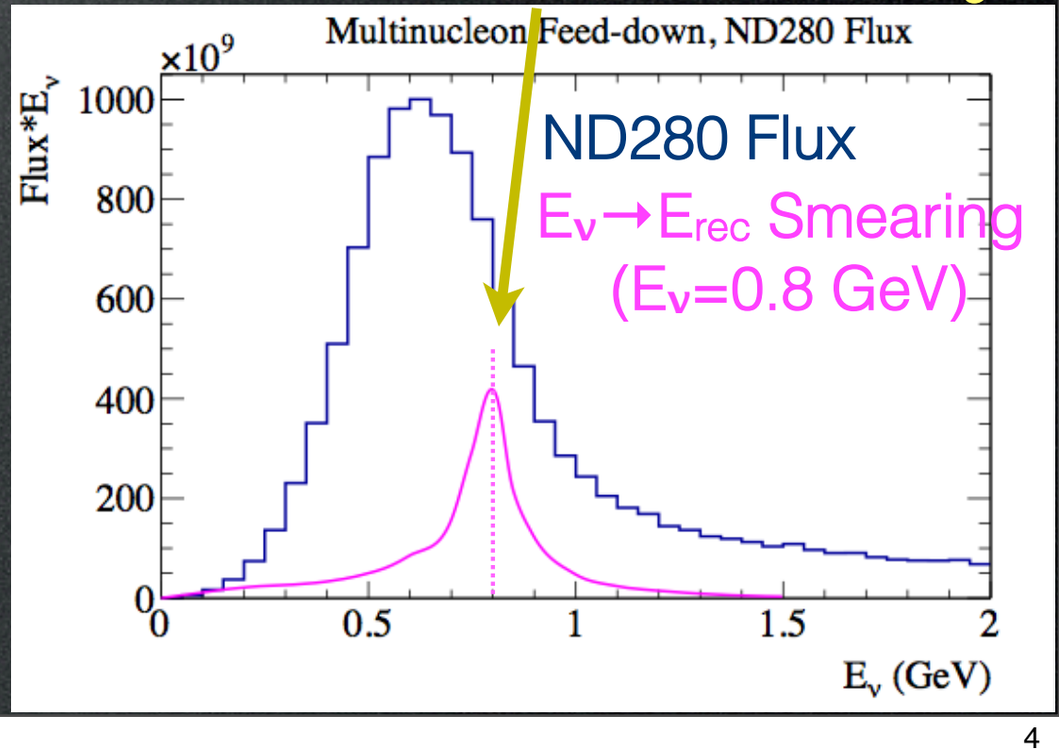
Isn't This is Why Oscillation Experiments Build Near Detectors?

- Shouldn't cross section systematics cancel in a near/far fit?
  - Some errors, like total normalization, will cancel
- However, multi-nucleon effect causes feed-down of events into oscillation dip
  - Cannot disentangle with near detectors
    - Energy spectrum is not oscillated
- More multi-nucleon = smaller dip
  - **Multi-nucleon effects are largely degenerate with mixing angle effect!**



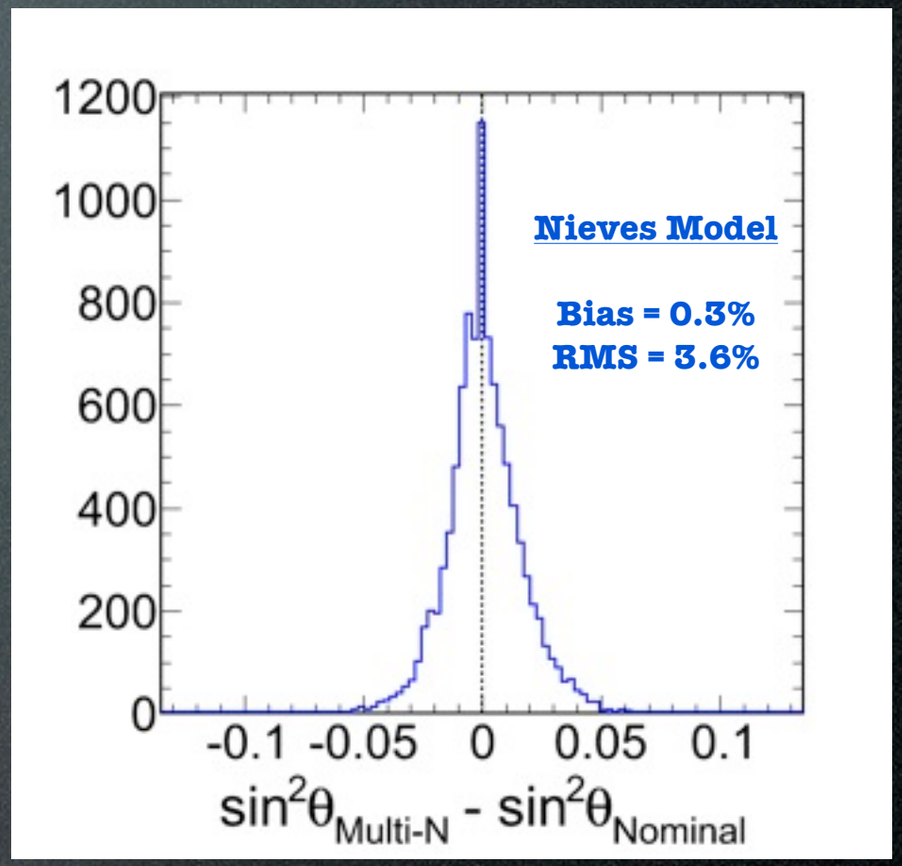
Mixing Angle Bias!

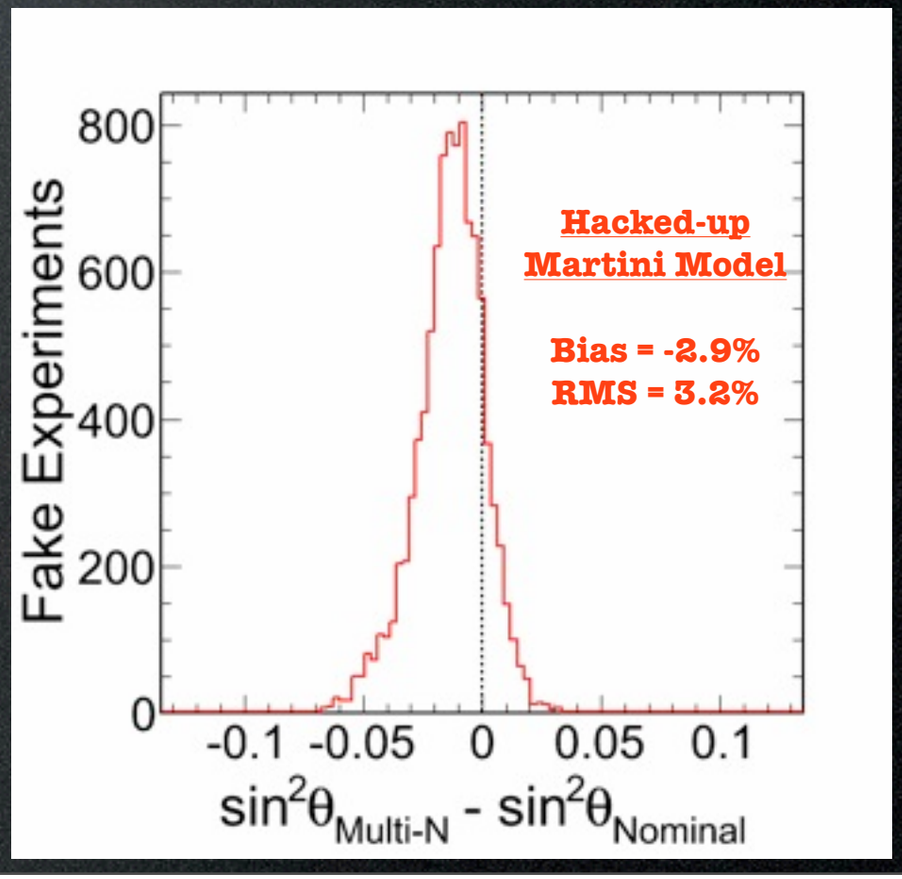
Near detectors lack sensitivity



Effect on T2K ν_μ Disappearance

- Create "fake data" samples with and without multi-nucleon events
  - Compare fitted θ_{23}
- For Nieves model, "average bias" (RMS) = **3.6%**
- For Martini model, mean bias = -2.9%, RMS = 3.2%
  - Full systematic = $\sqrt{(2.9\%^2+3.2\%^2)}$ = **4.3%**
  - **This would be an important systematic error at full T2K POT**
    - Not yet incorporated into official results
- But this is just a comparison of 2 models
  - How much larger could the actual systematic uncertainty be?
- A new detector to experimentally address this currently in the proposal stage
  - See the **NuPRISM** talk later in this session





Reminder: NuPRISM Detector Concept

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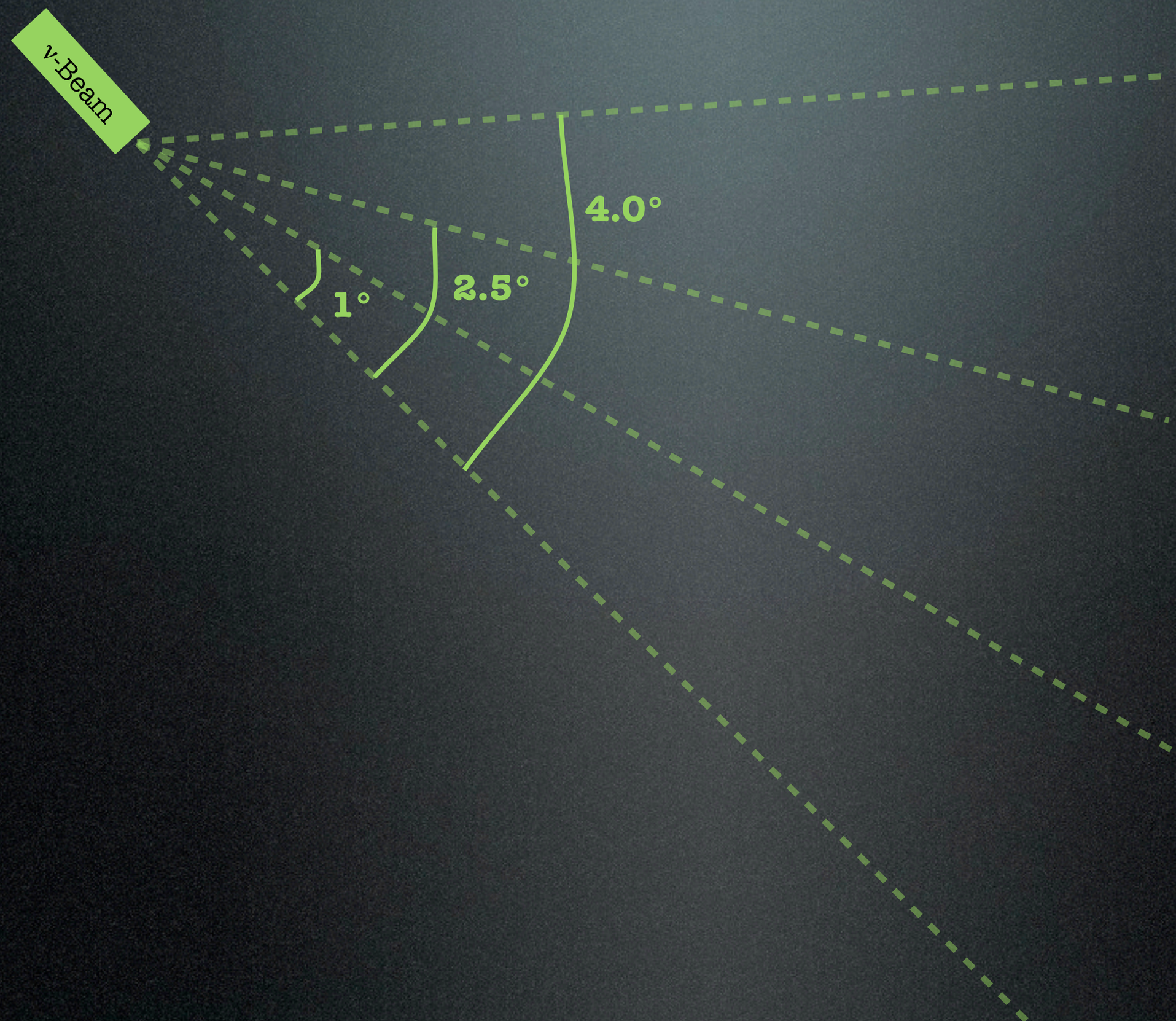

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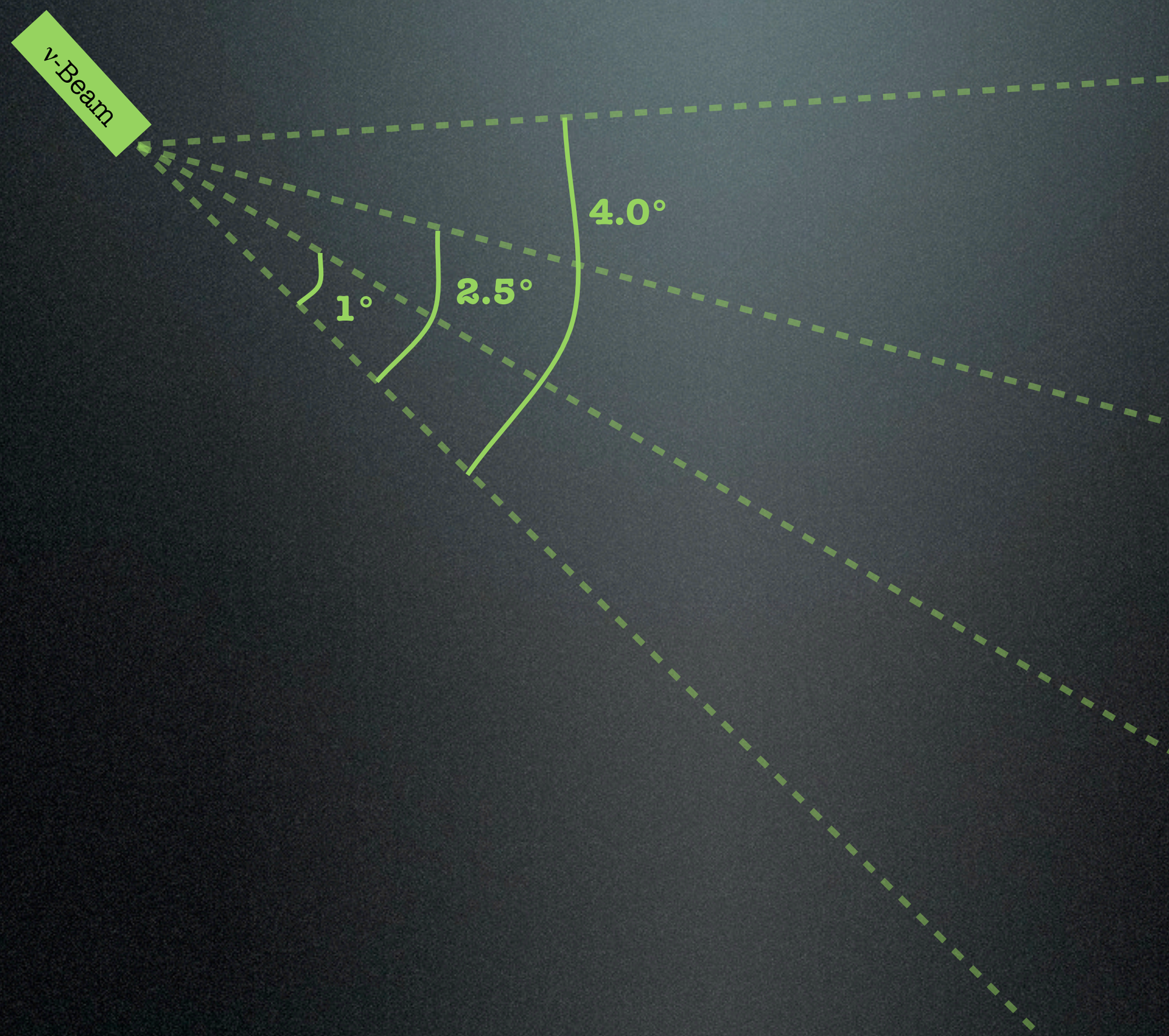

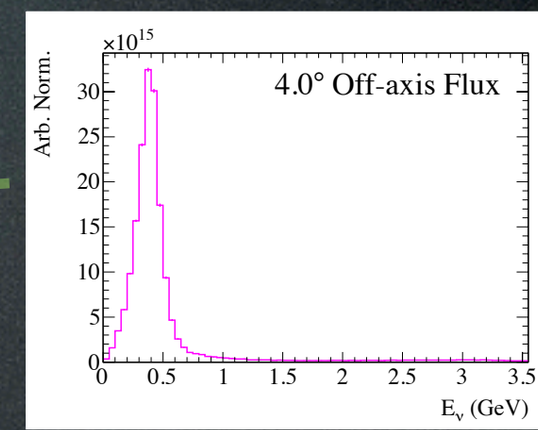

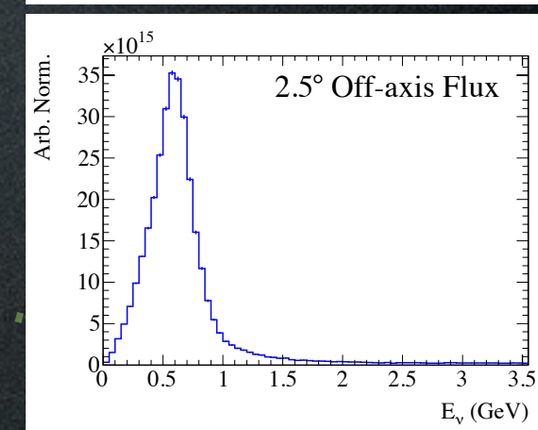

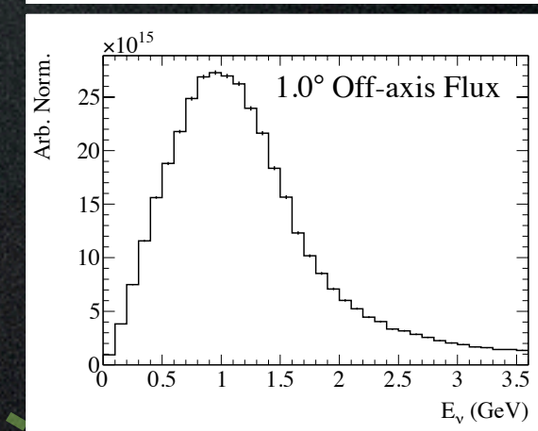

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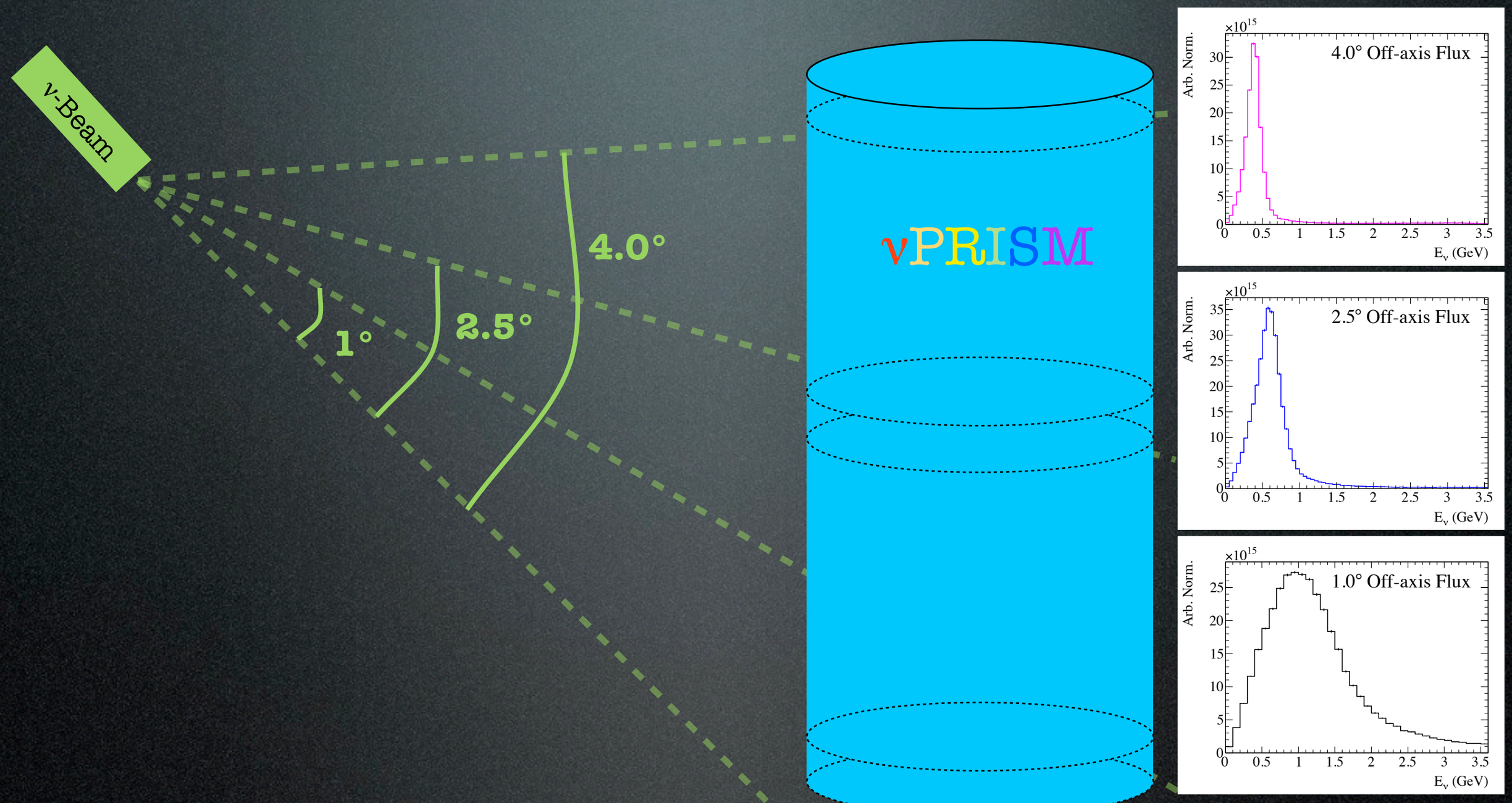

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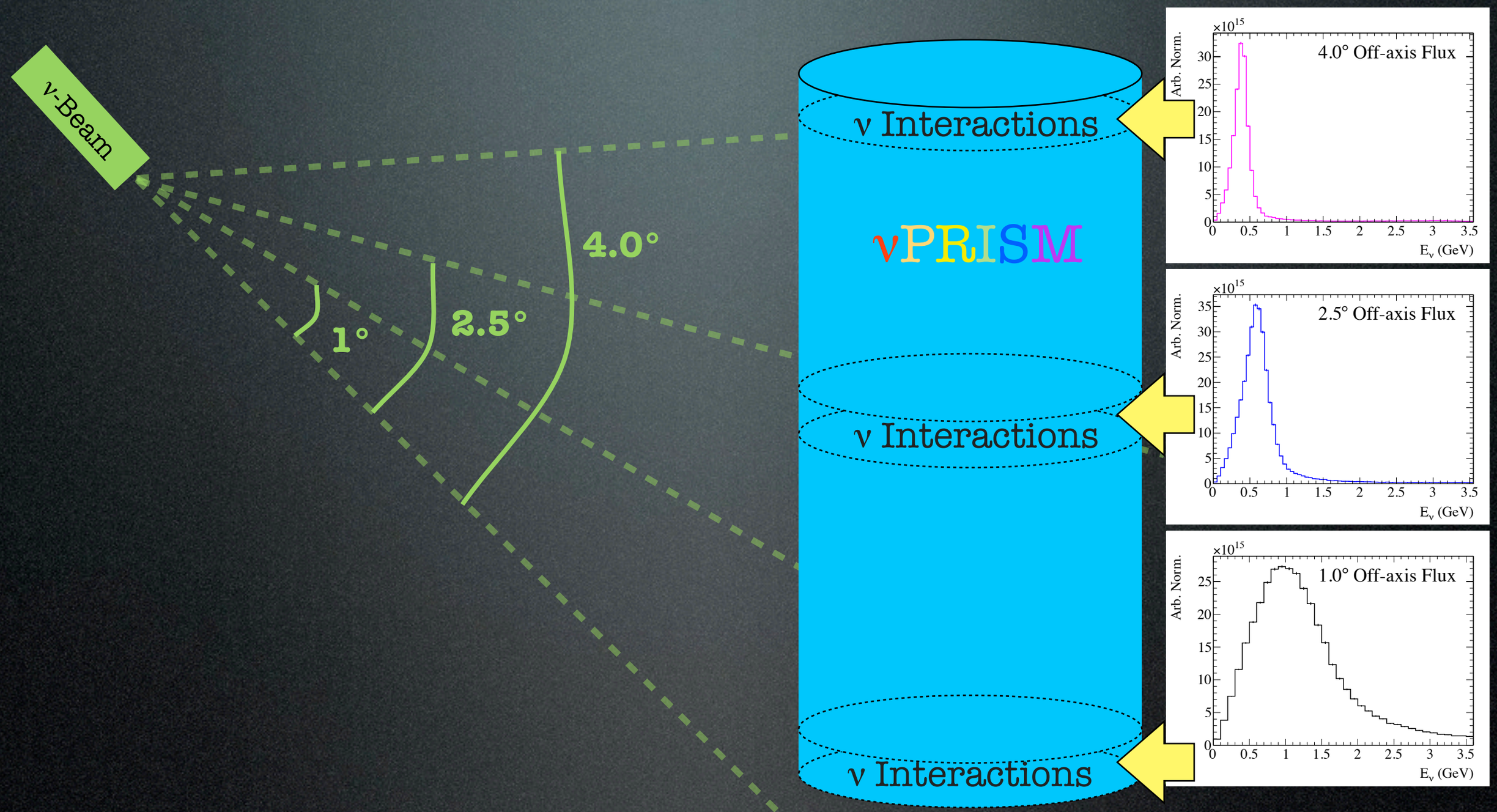

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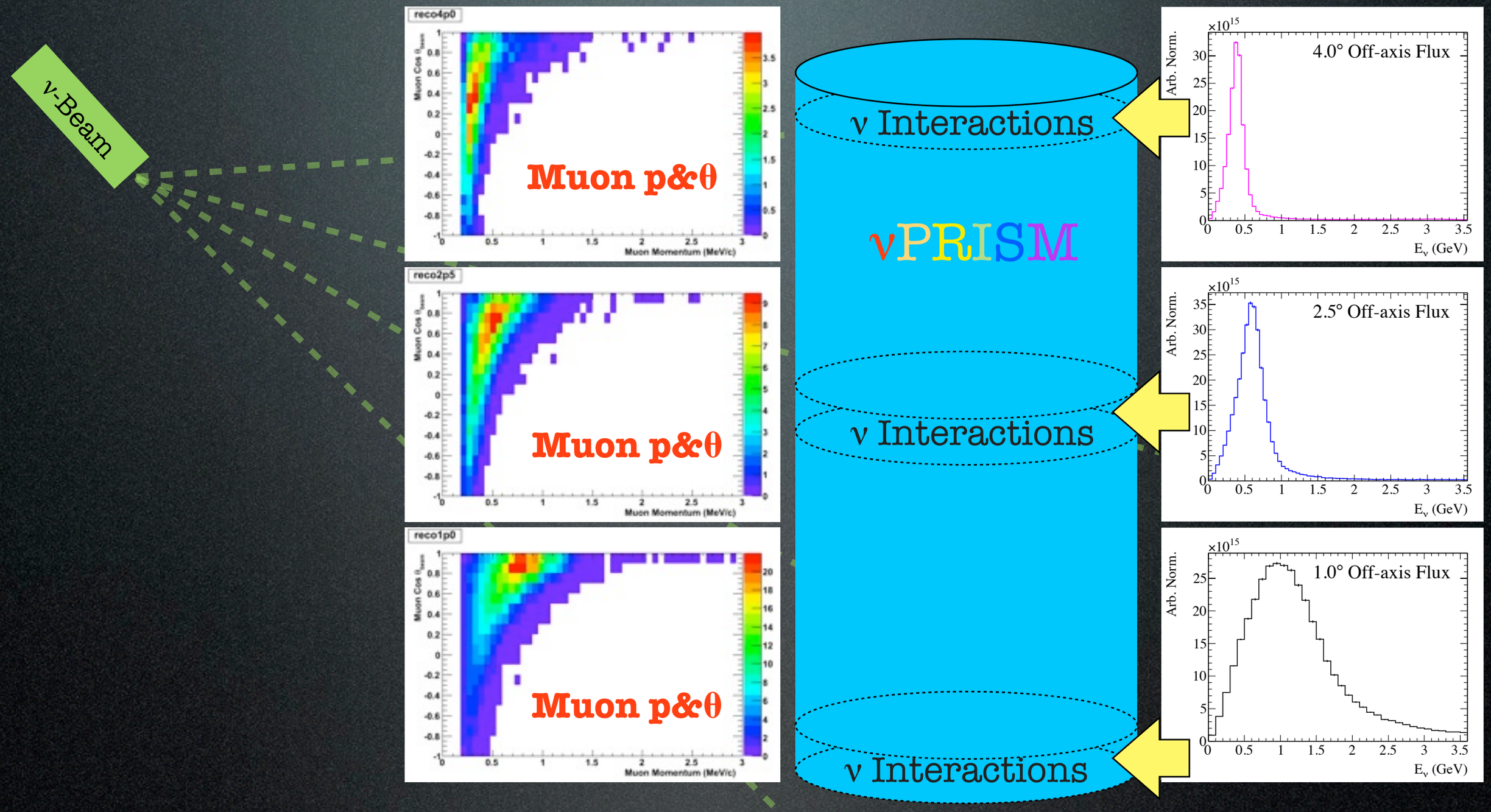

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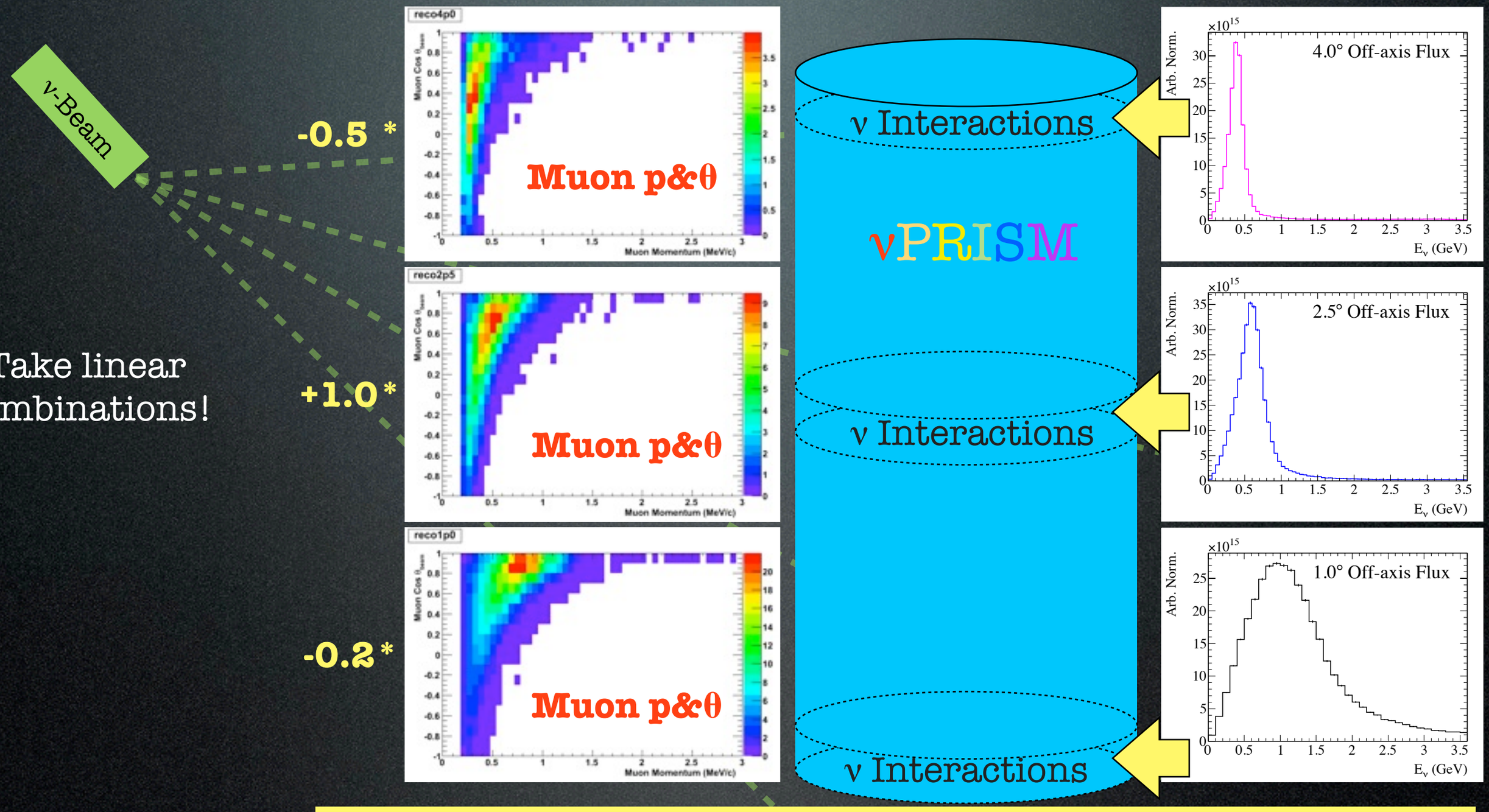
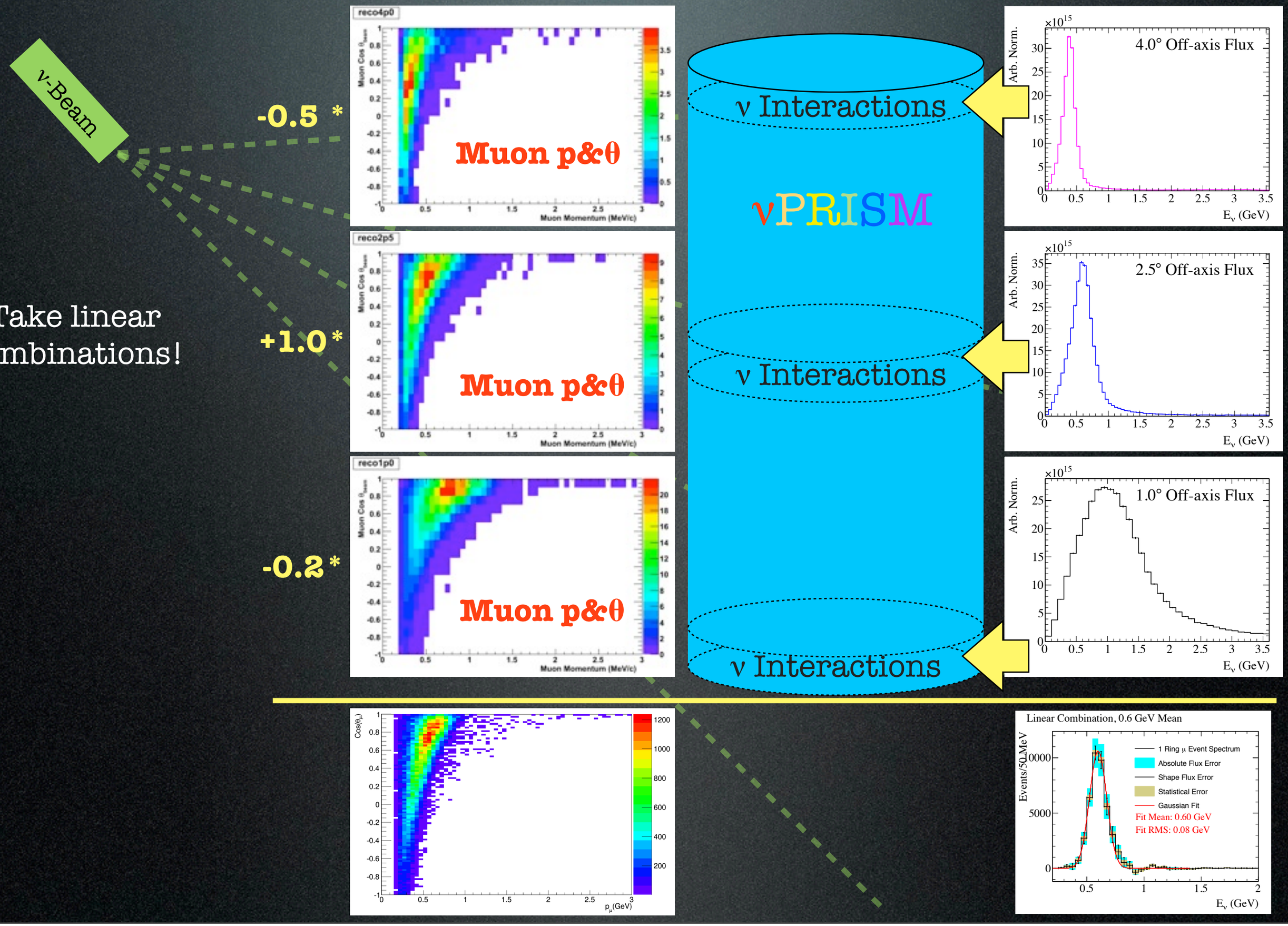


Take linear combinations!

Reminder: NuPRISM Detector Concept



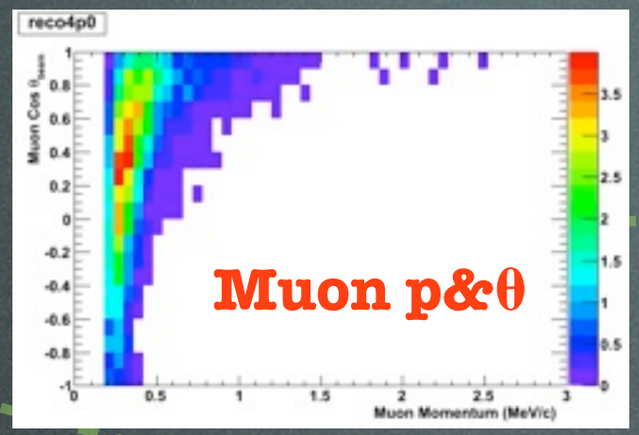
Take linear combinations!

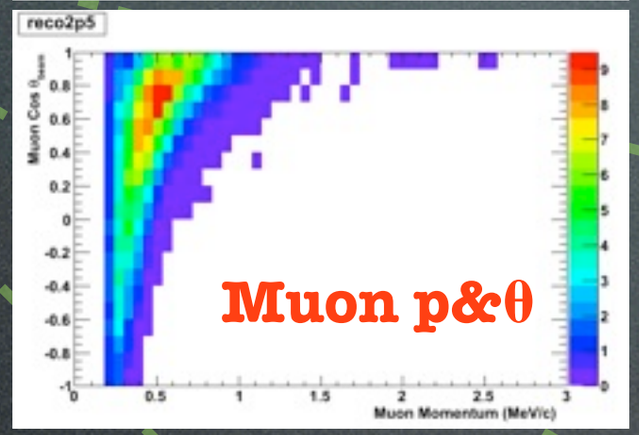
Reminder: NuPRISM Detector Concept

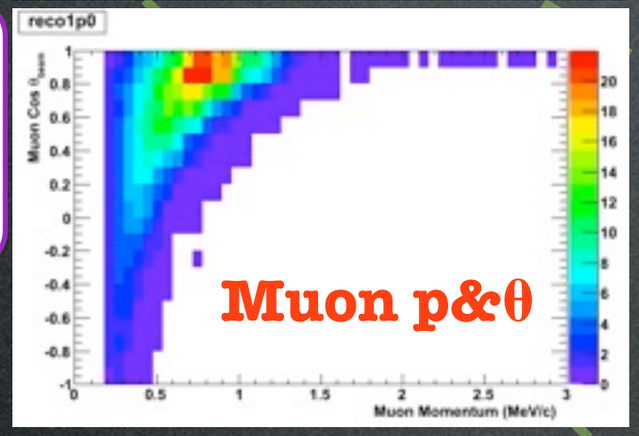
-0.5 *

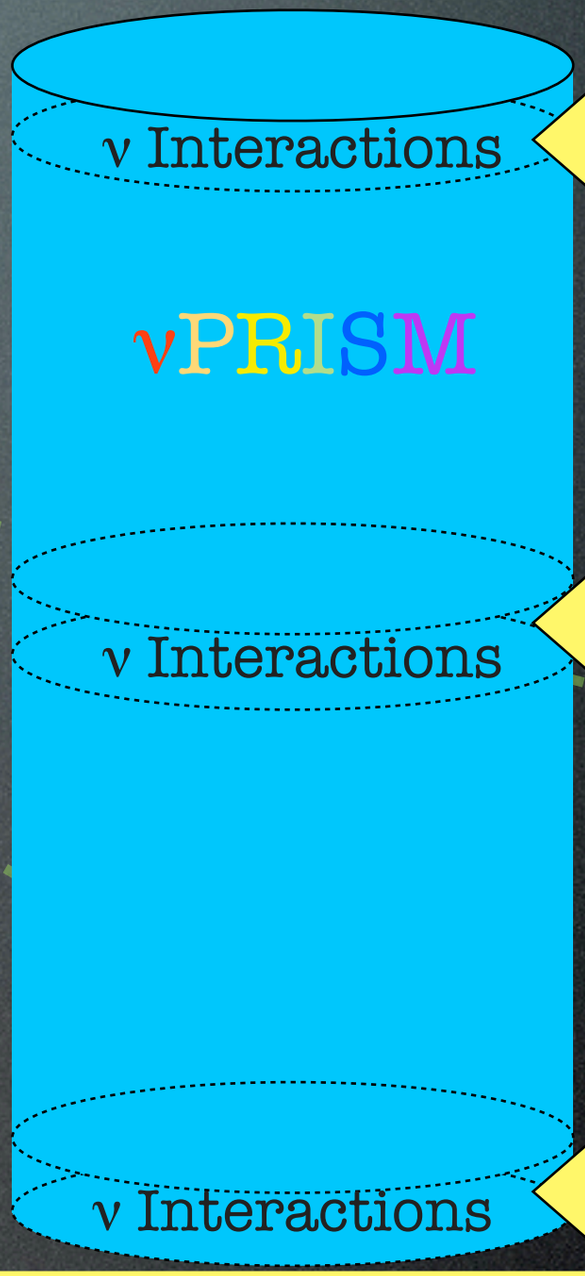
+1.0 *

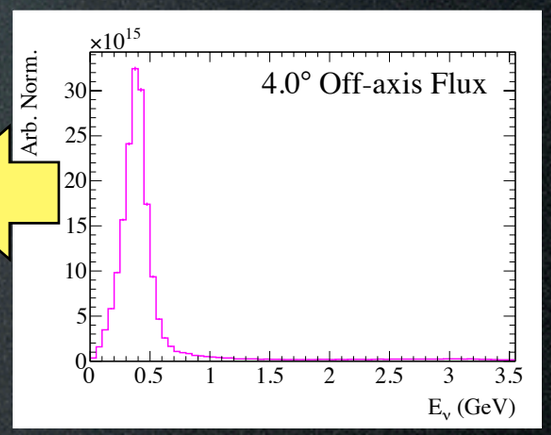
Take linear combinations!

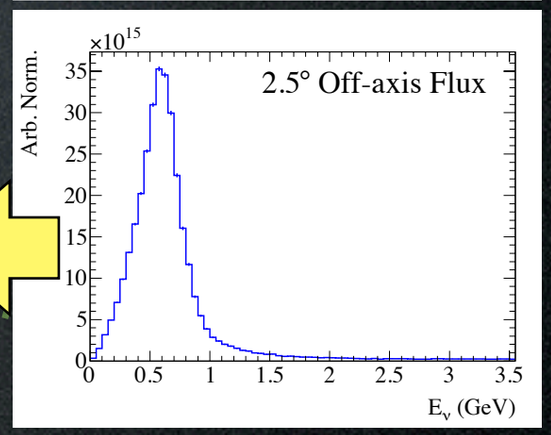


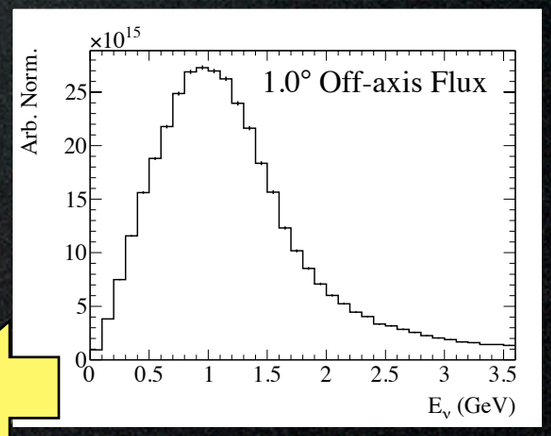




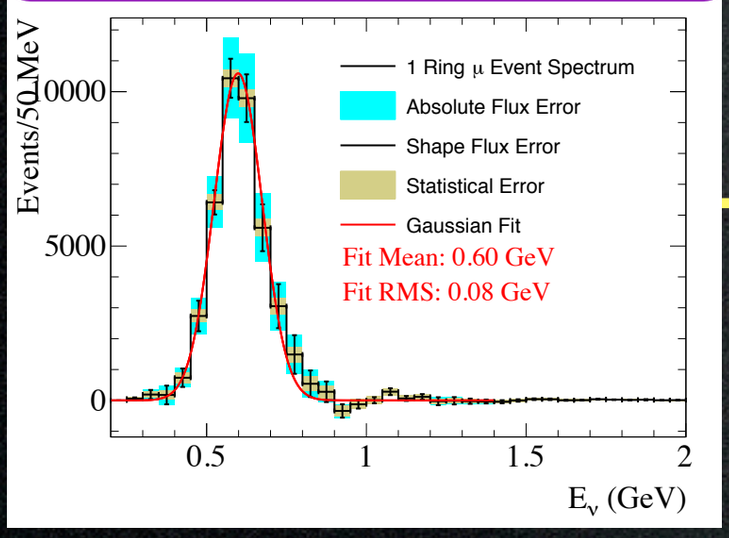


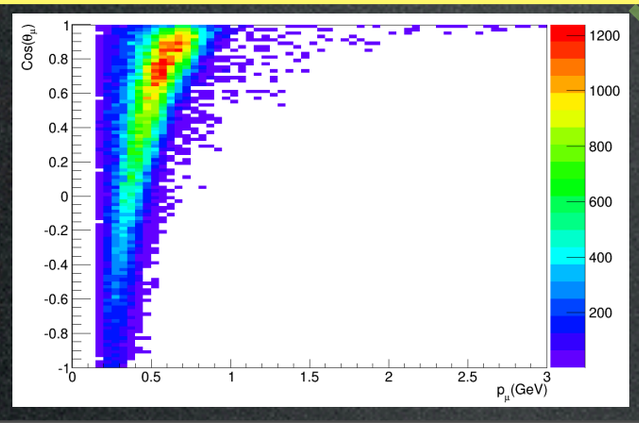


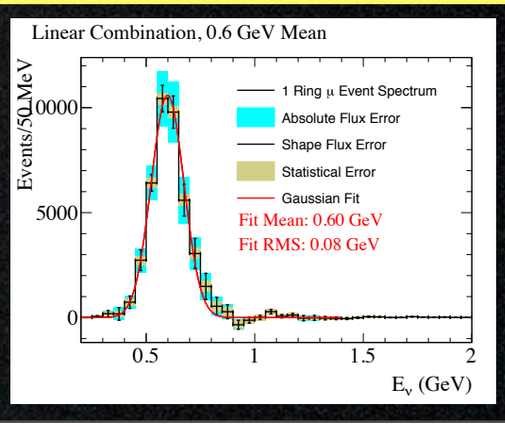




600 MeV Monoenergetic Beam using 60 slices in off-axis angle

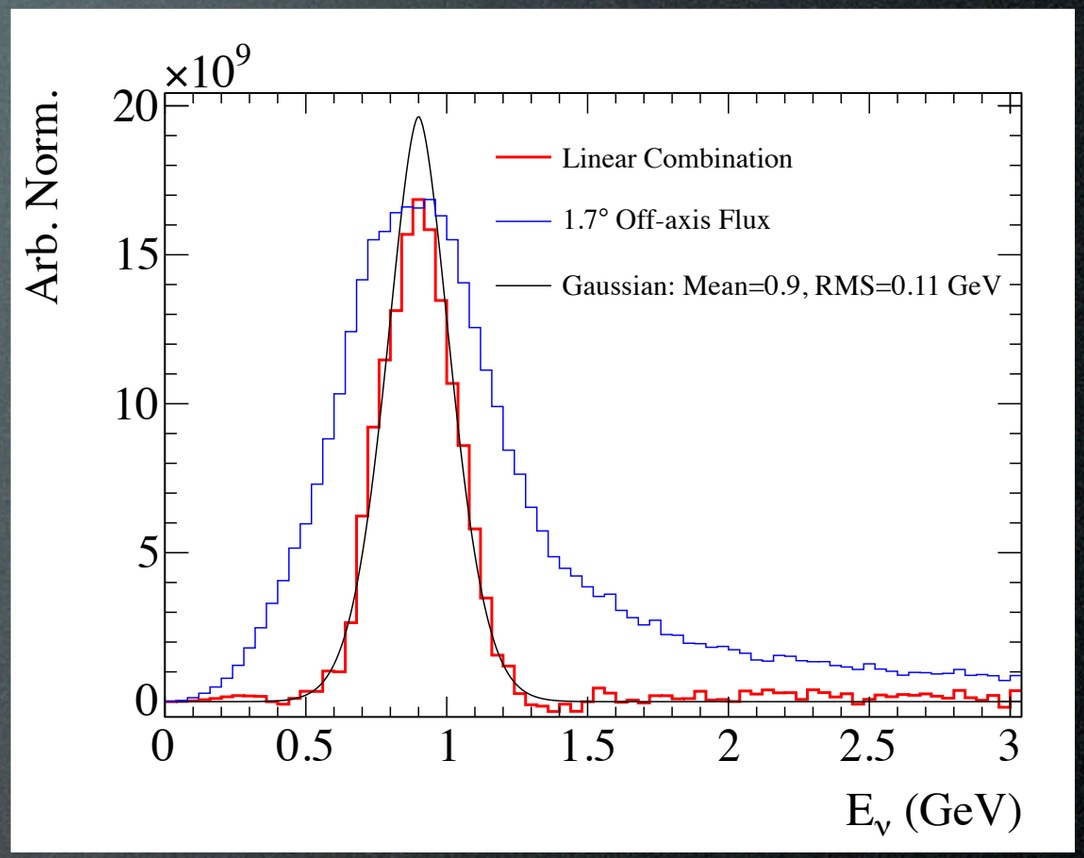


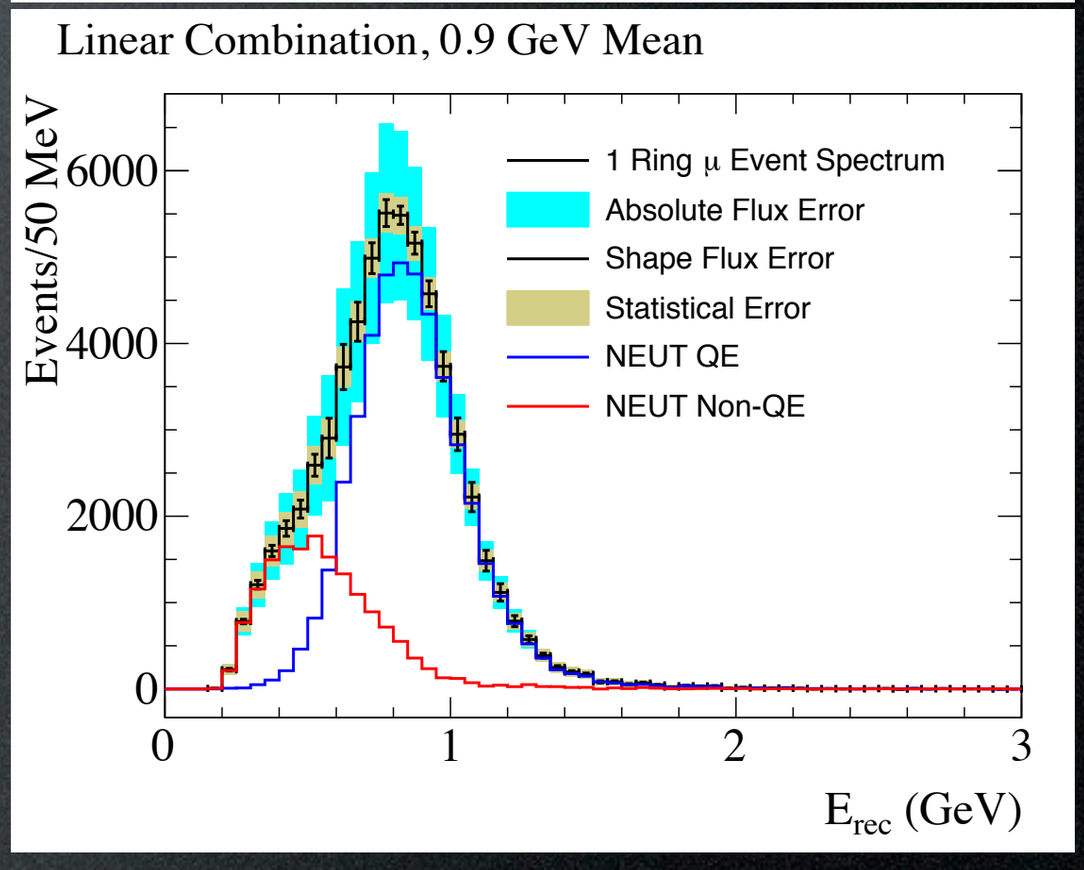




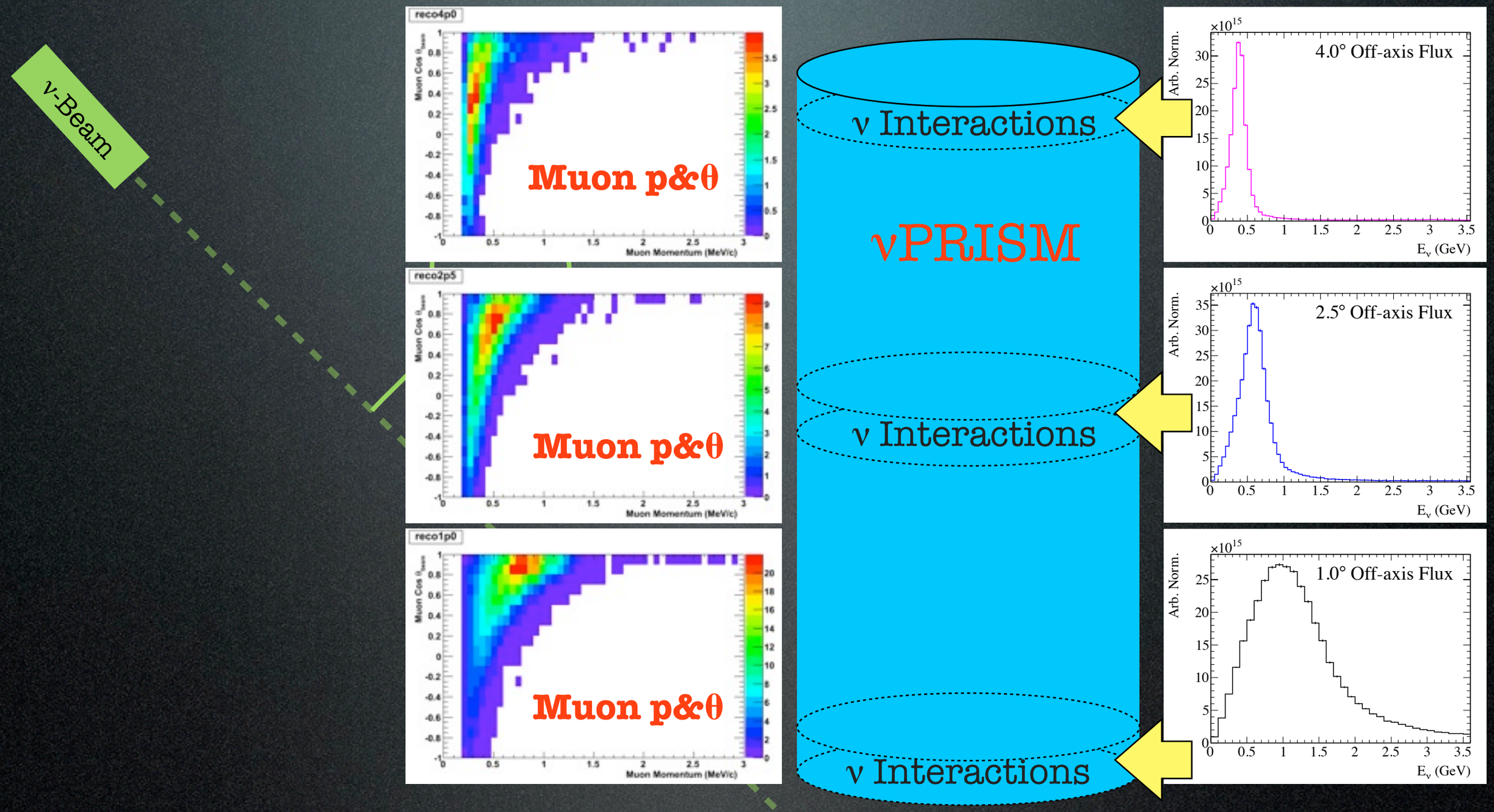
Benefits of a Monoenergetic Beam

- First ever measurements of NC events with E_ν
  - Much better constraints on NC oscillation backgrounds
- First ever "correct" measurements of CC events with E_ν
  - No longer rely on final state particles to determine E_ν
- It is now possible to separate the various components of single-μ events!
- This is also very interesting to the nuclear physics community

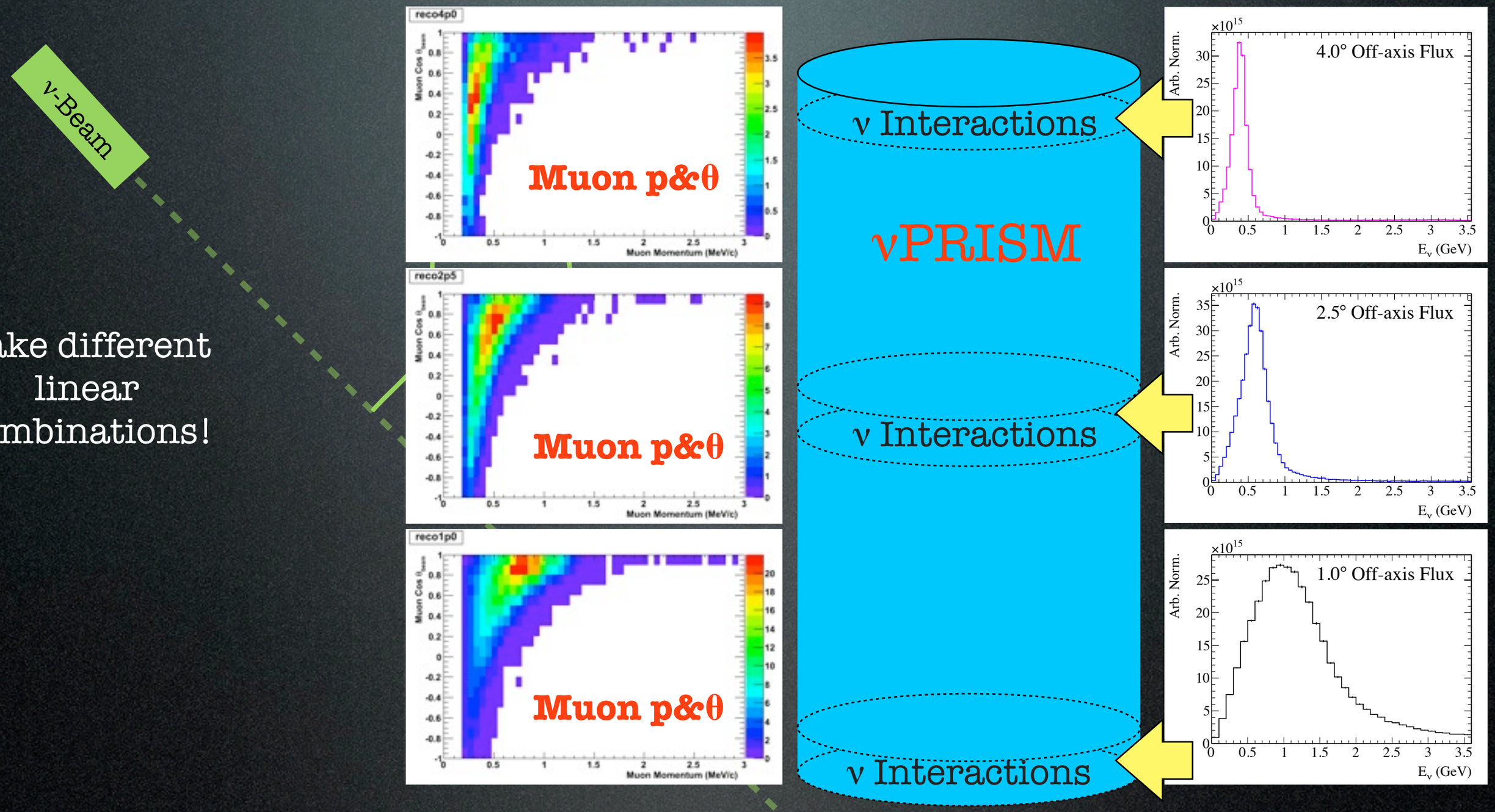




NuPRISM in Oscillation Analyses

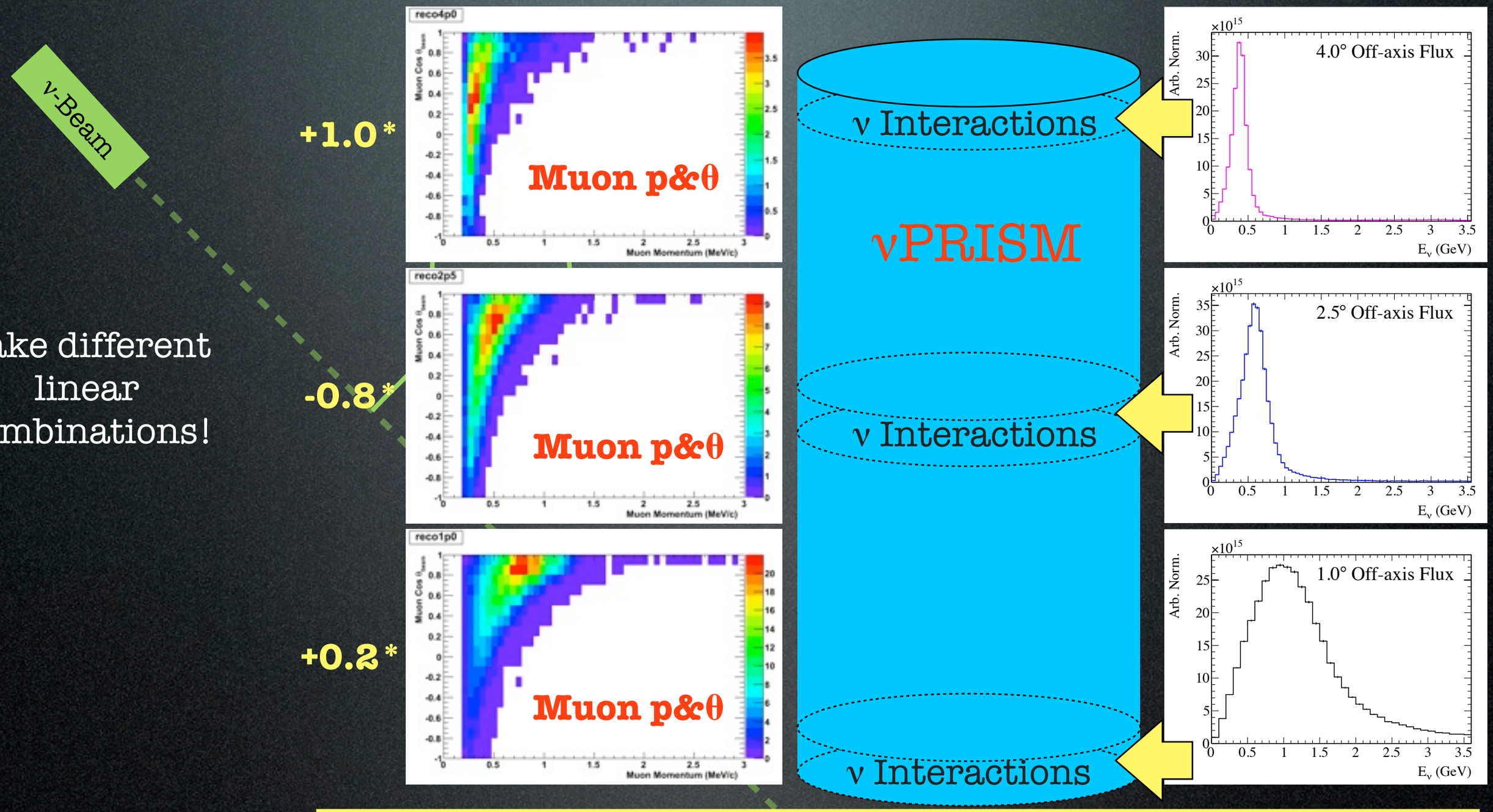


NuPRISM in Oscillation Analyses



Take different linear combinations!

NuPRISM in Oscillation Analyses

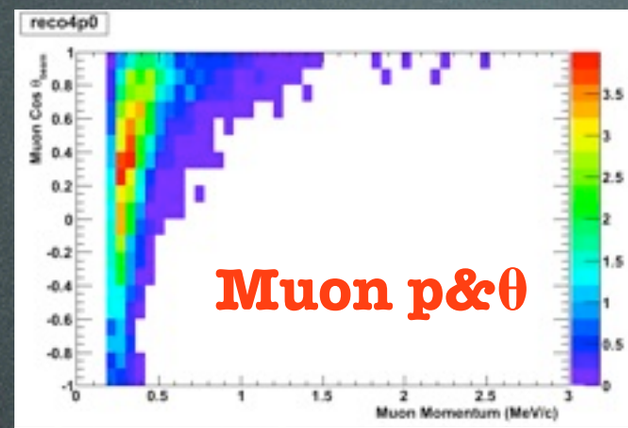


Take different linear combinations!

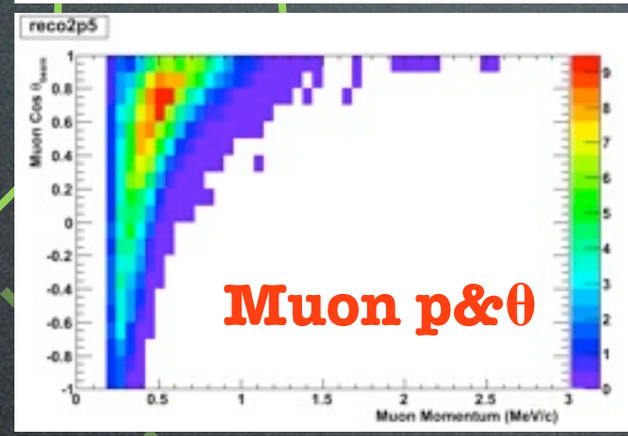
NuPRISM in Oscillation Analyses

Take different linear combinations!

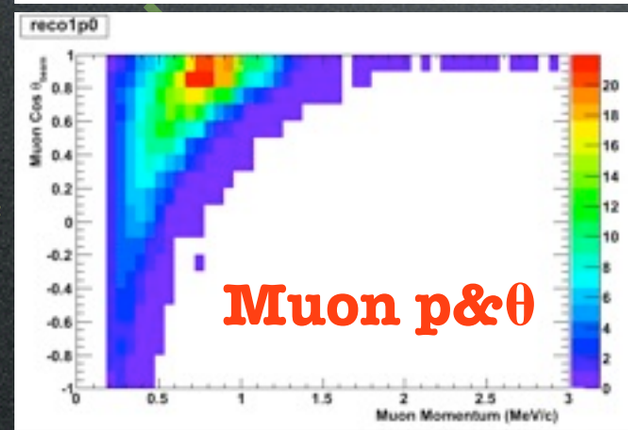
+1.0 *

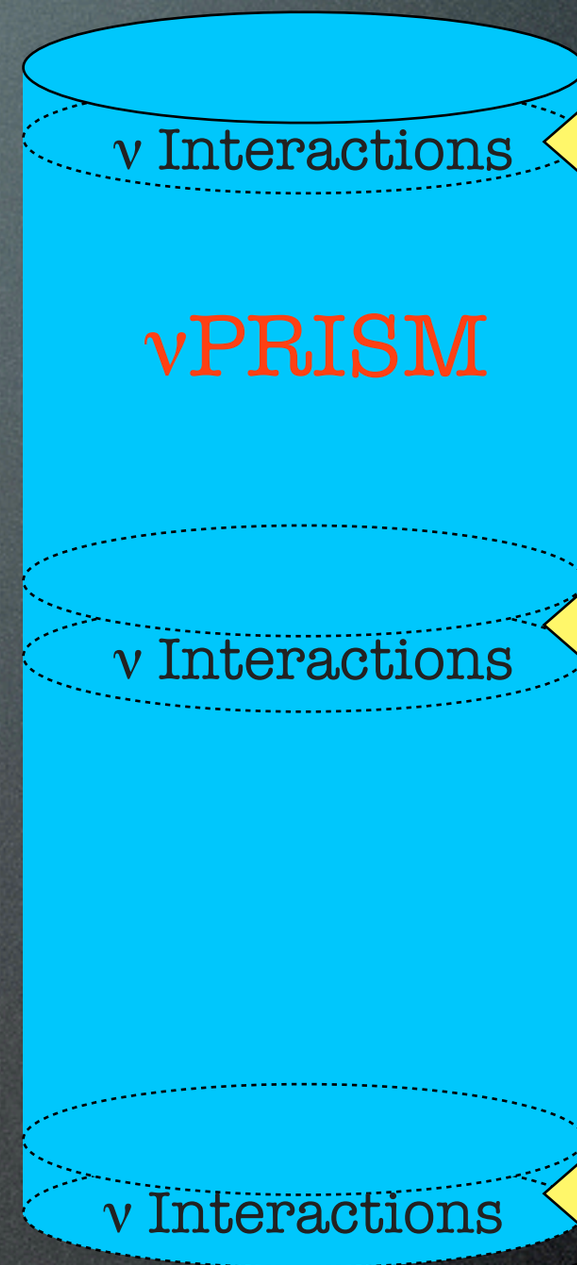


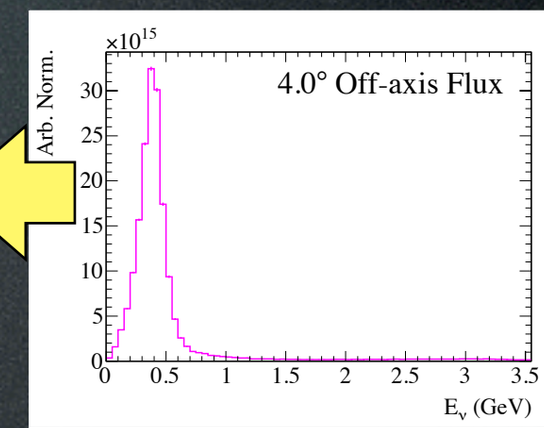
-0.8 *

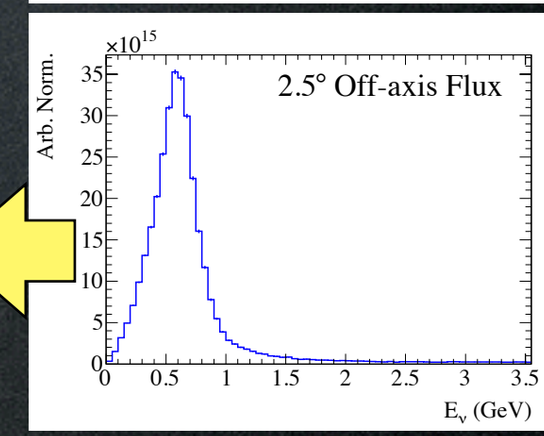


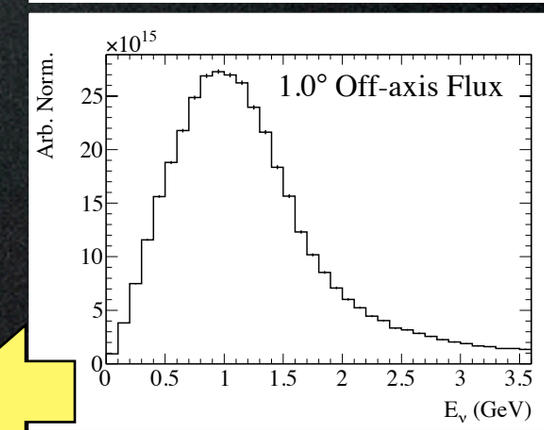
+0.2 *

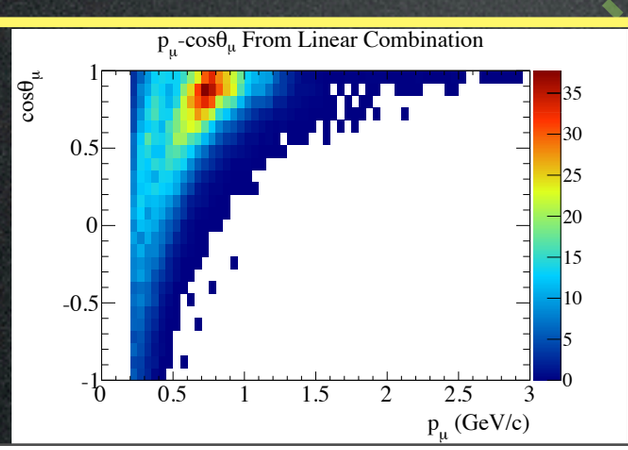






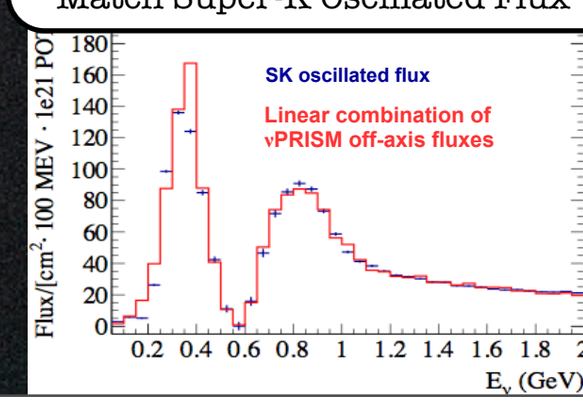






Measured! Muon p&θ for Oscillated SK Flux!

Match Super-K Oscillated Flux

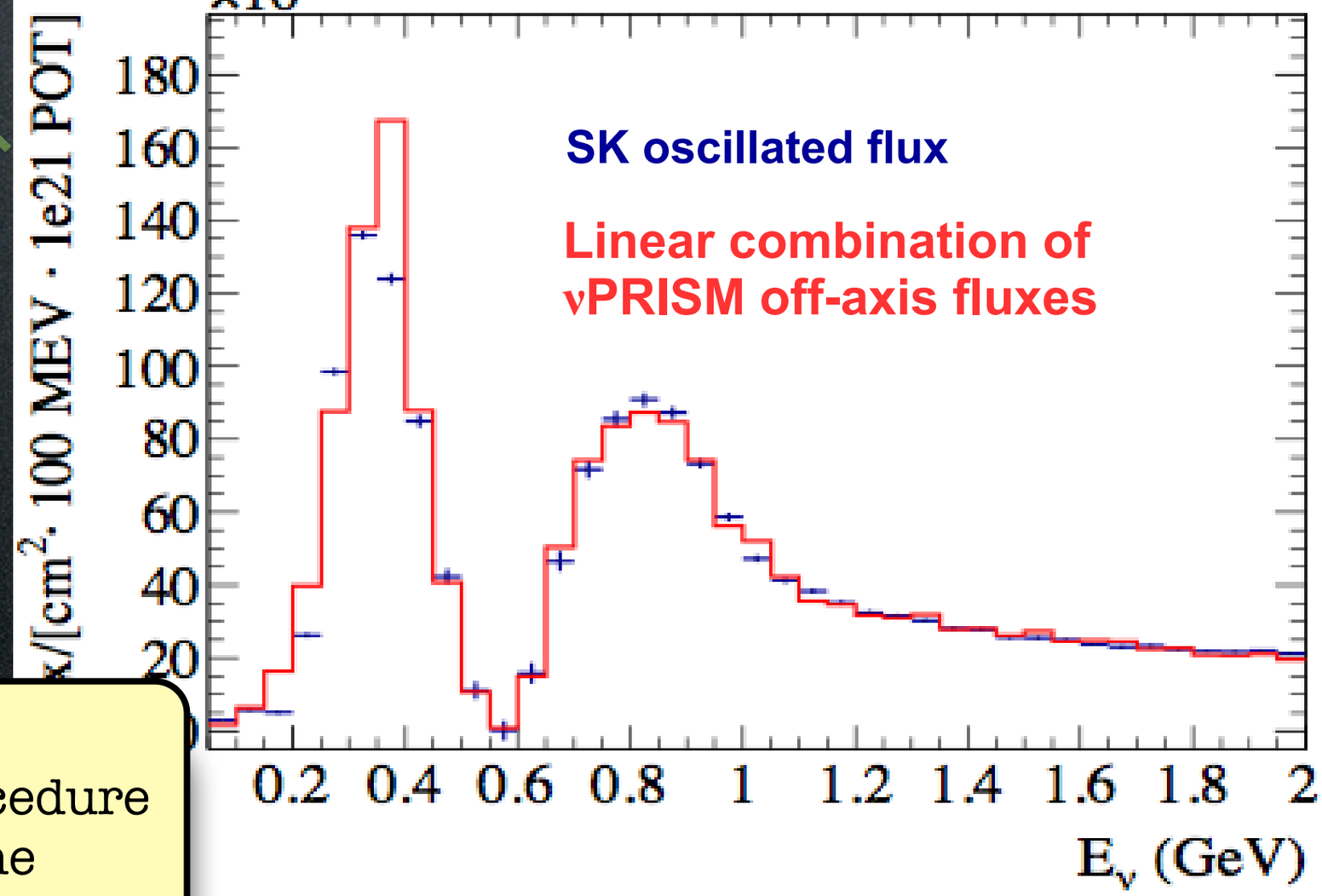


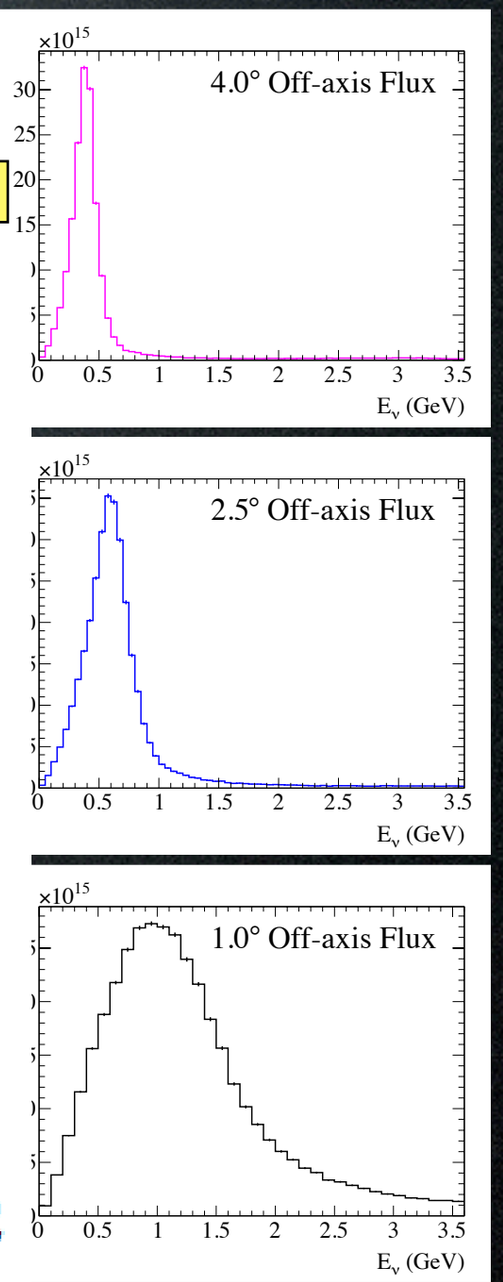
NuPRISM in Oscillation Analyses

Reproduce Super-K Oscillation Pattern at a Near Detector!

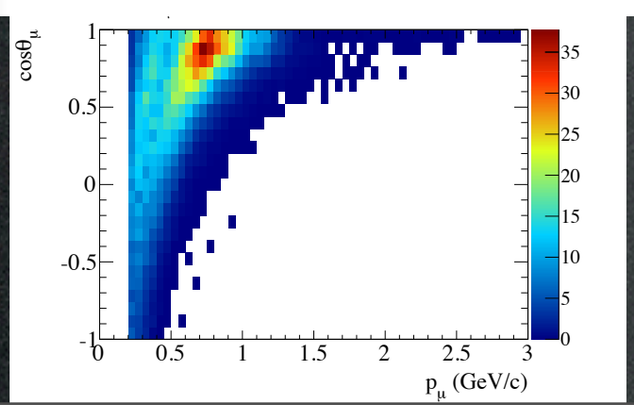
ν-Beam

Take different linear combinations!

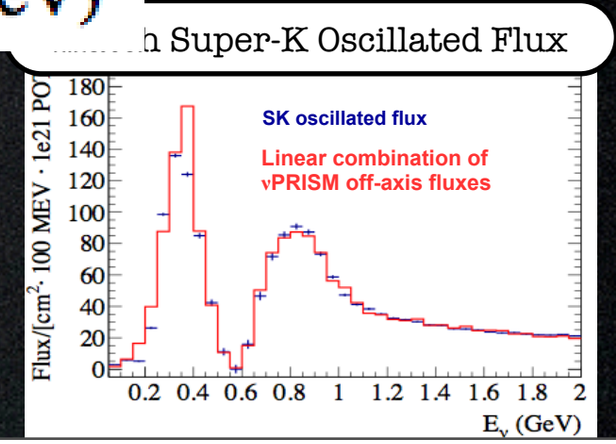




This is the procedure used for the T2K/nuPRISM ν_μ disappearance analysis

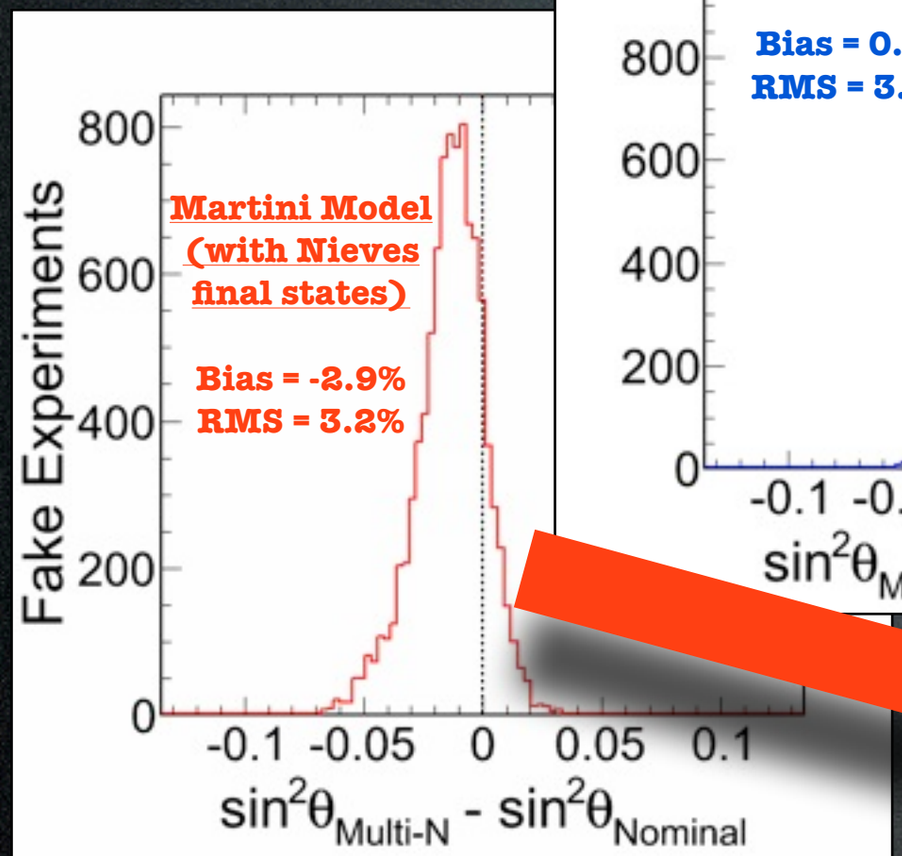


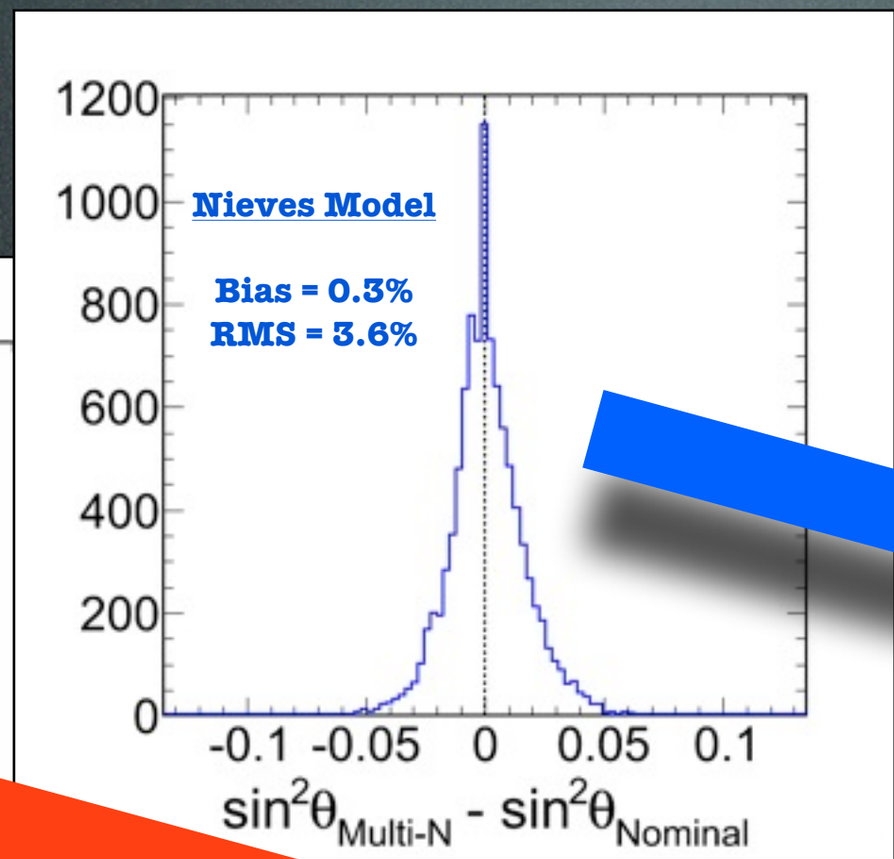
Measured! Muon p&θ for Oscillated SK Flux!



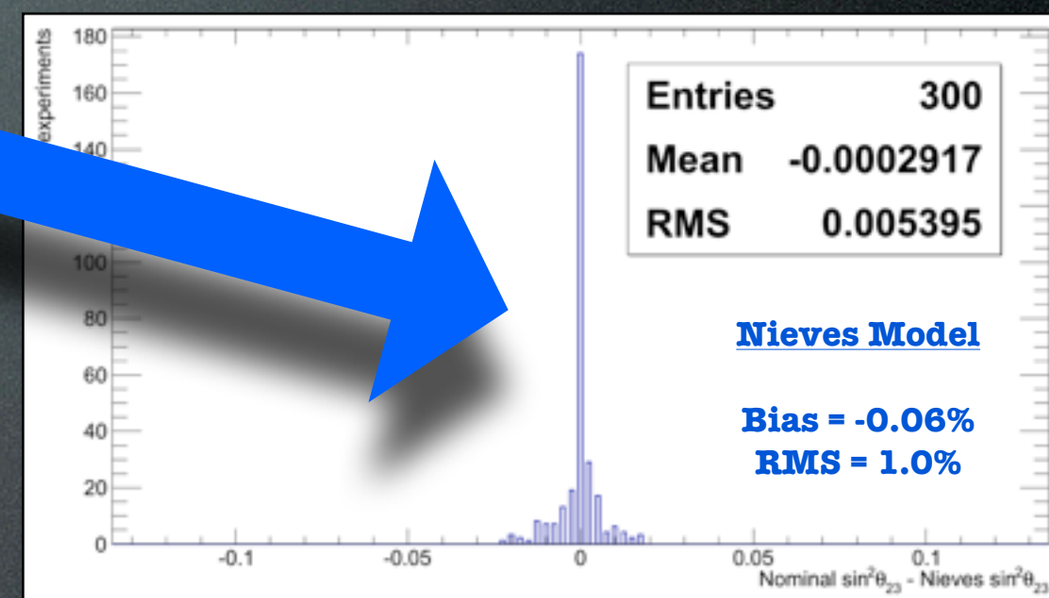
νPRISM ν_μ Disappearance Constraint

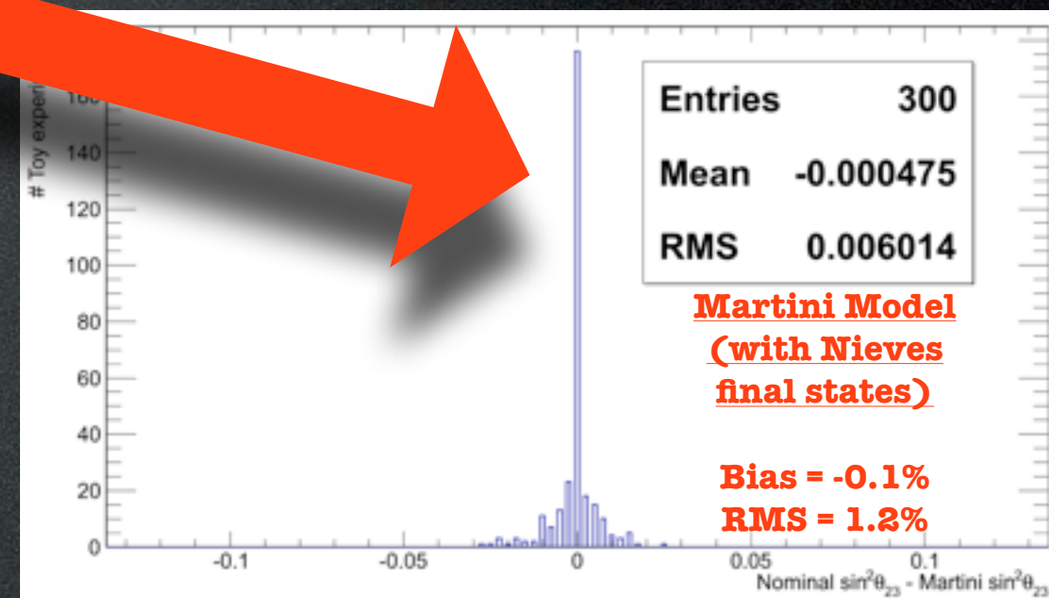
Standard T2K Analysis





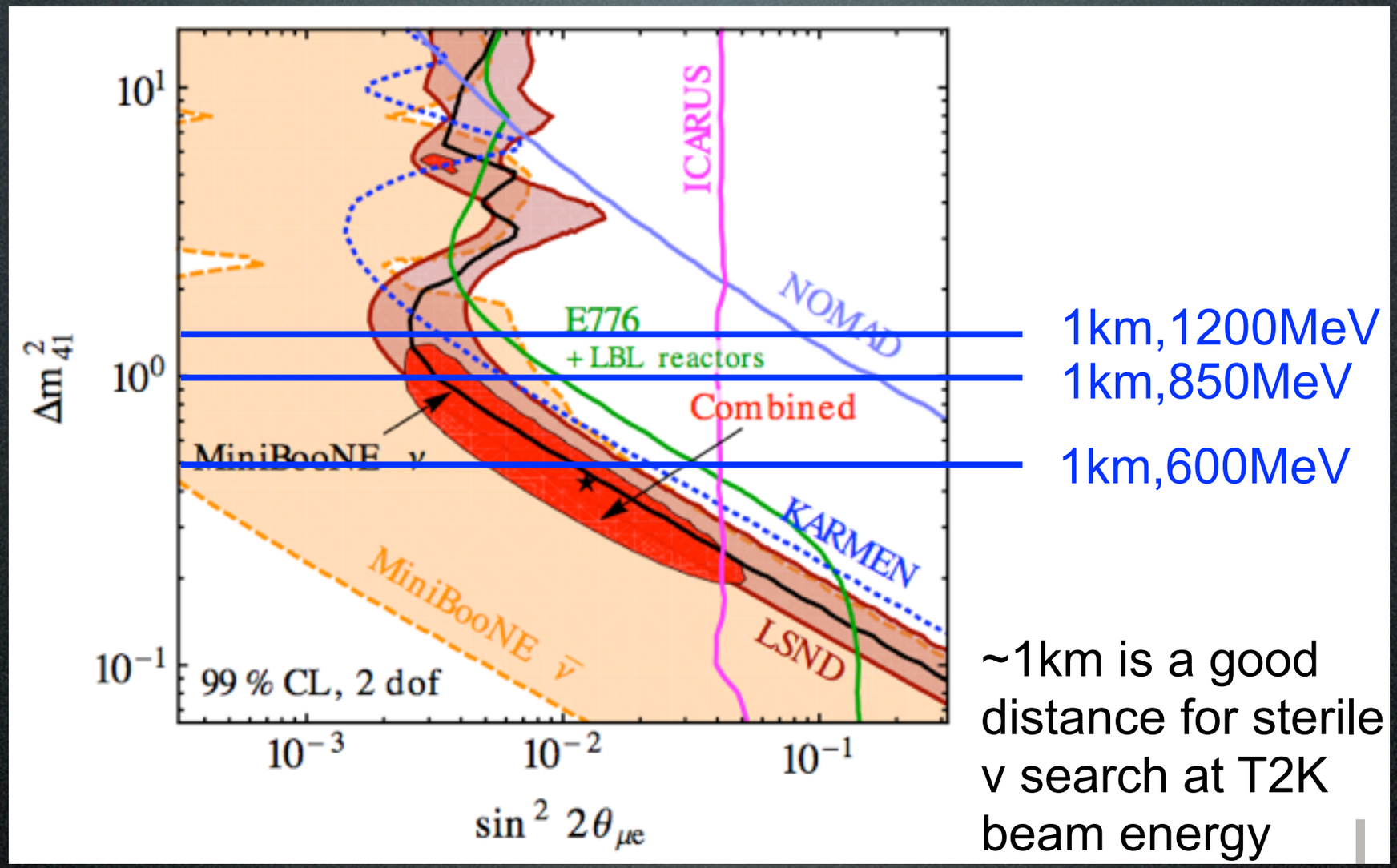
νPRISM Analysis





- Fake data studies show the bias in θ_{23} is reduced from **4.3%/3.6%** to **1.2%/1.0%**
- More importantly, this is now based on a **data constraint**, rather than a model-based guess
- Expect the NuPRISM constraints to get significantly better as additional constraints are implemented (very conservative errors)

Sterile Neutrinos

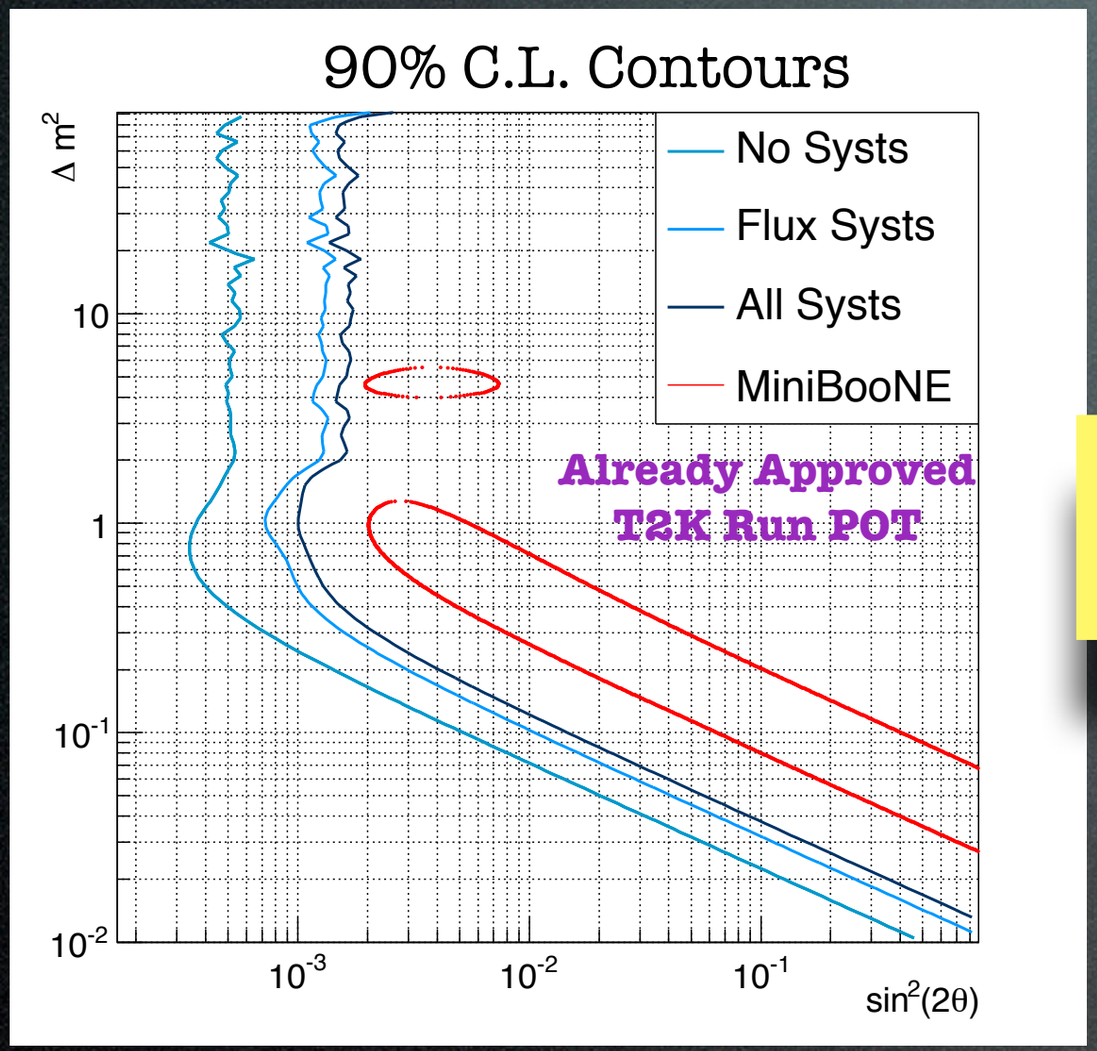


- The 1 km baseline is ideal for sterile neutrinos
  - Like Fermilab SB, but with a much bigger detector (5kt vs 0.6kt)
- Many repeated measurements for varying energy spectra (several L/E)
  - Signal and background events vary differently across the detector

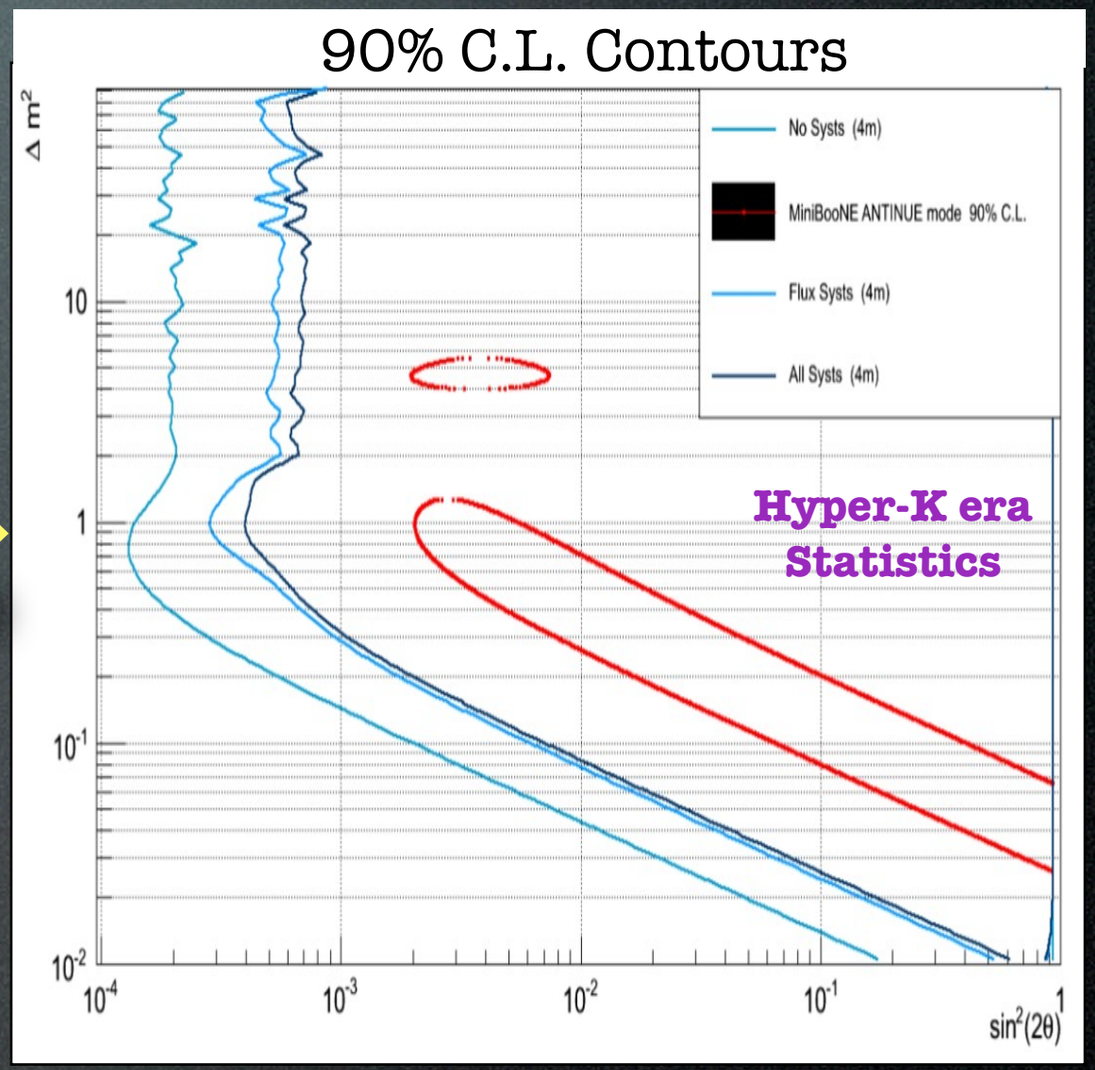
Sterile Neutrino Analysis

- To compute first sensitivities, make several conservative assumptions
- **No constraint from the existing near detector (ND280)**
  - Eventually, a powerful 2-detector constraint will be incorporated
- **No constraints on background processes**
  - nuPRISM should provide control samples for all of the major backgrounds to impose strong data-driven constraints
- **No combined $\nu_\mu + \nu_e$ fit**
  - MiniBooNE results would not have been possible without normalizing the ν_e signal to the observed ν_μ spectrum
- **Assume Super-K detector efficiencies and resolutions**
  - nuPRISM has smaller phototubes, and should perform better closer to the wall (which is important, since the diameter is much smaller)
  - Significant increase in ν_e statistics is expected
- With such conservative assumptions, is a measurement still possible?

(Very) Conservative Sterile-ν Sensitivities

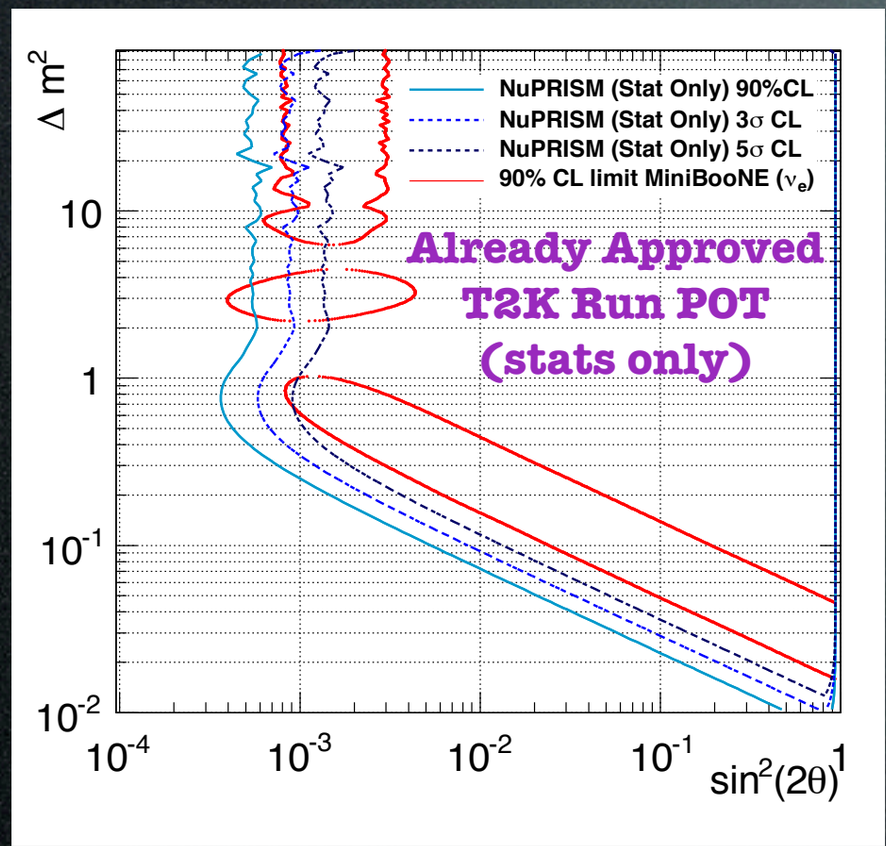


Increase Statistics

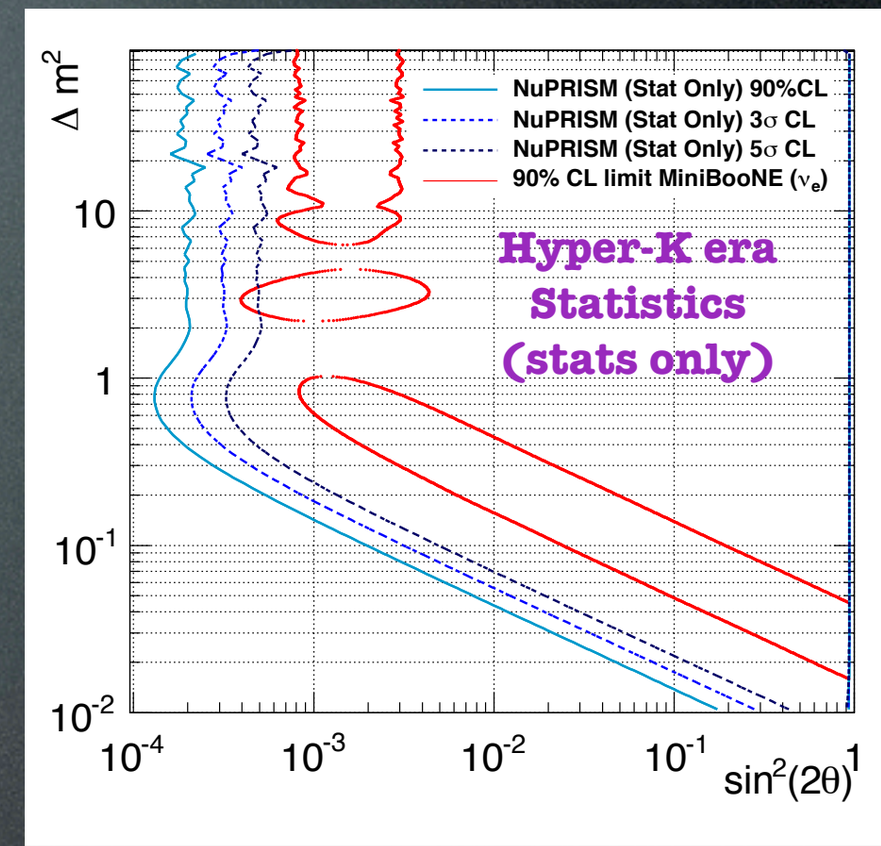


- Exclude currently allowed MiniBooNE anti-ν regions at 90% C.L.
- Much better limits expected as the analysis improves
  - Expect to be statistics limited, and for the statistics to increase
    - Better FV, better PID, better pi0 rejection, ...

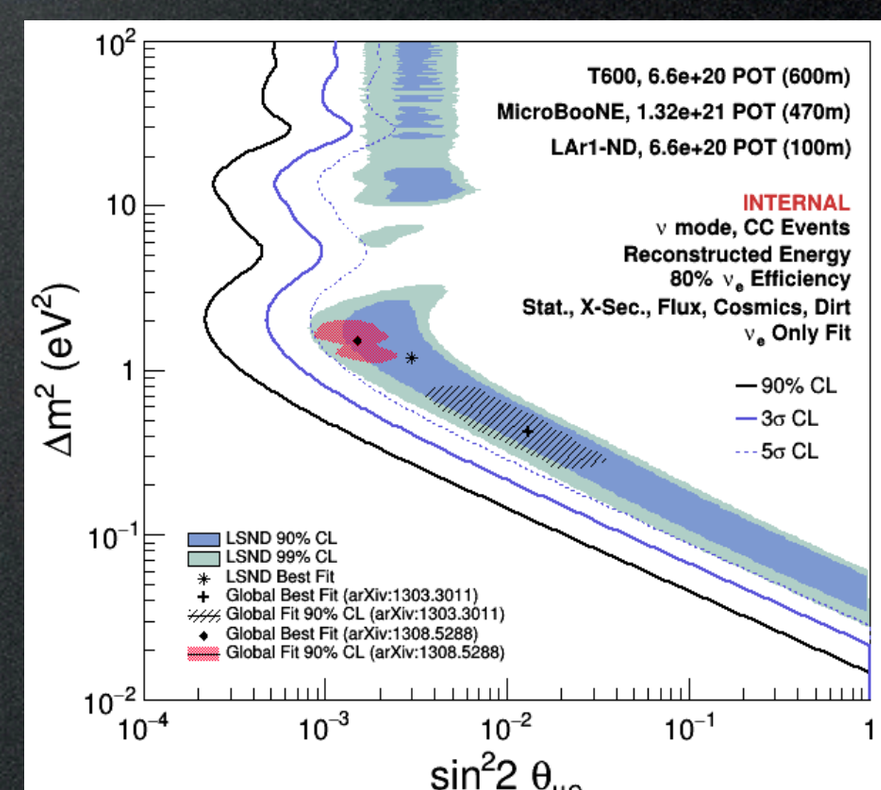
How Well Might NuPRISM Do?



Increase Statistics



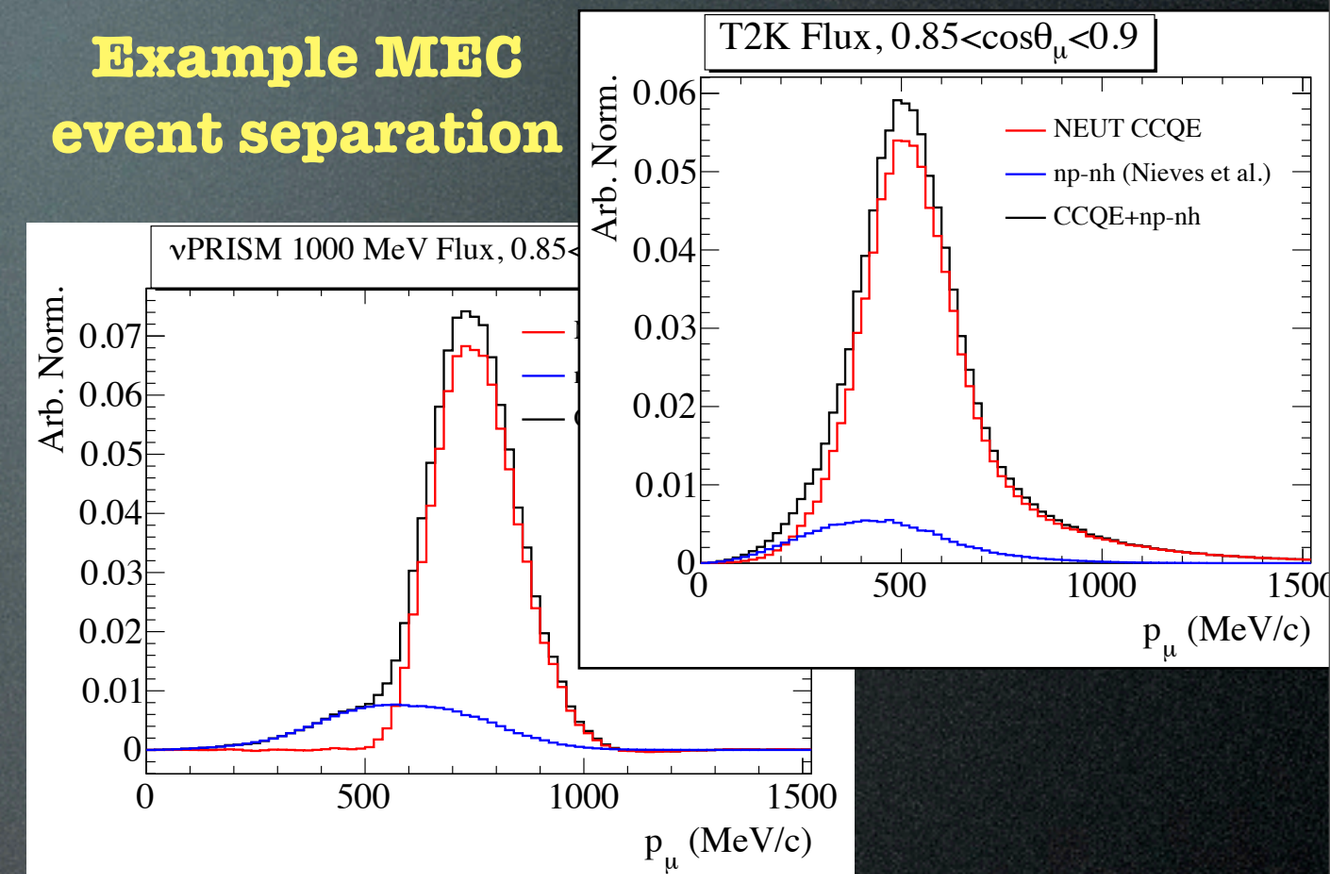
- For now, just focus on statistics-only contours
  - Expect big improvements in the currently assumed conservative systematics
- More realistic studies are underway



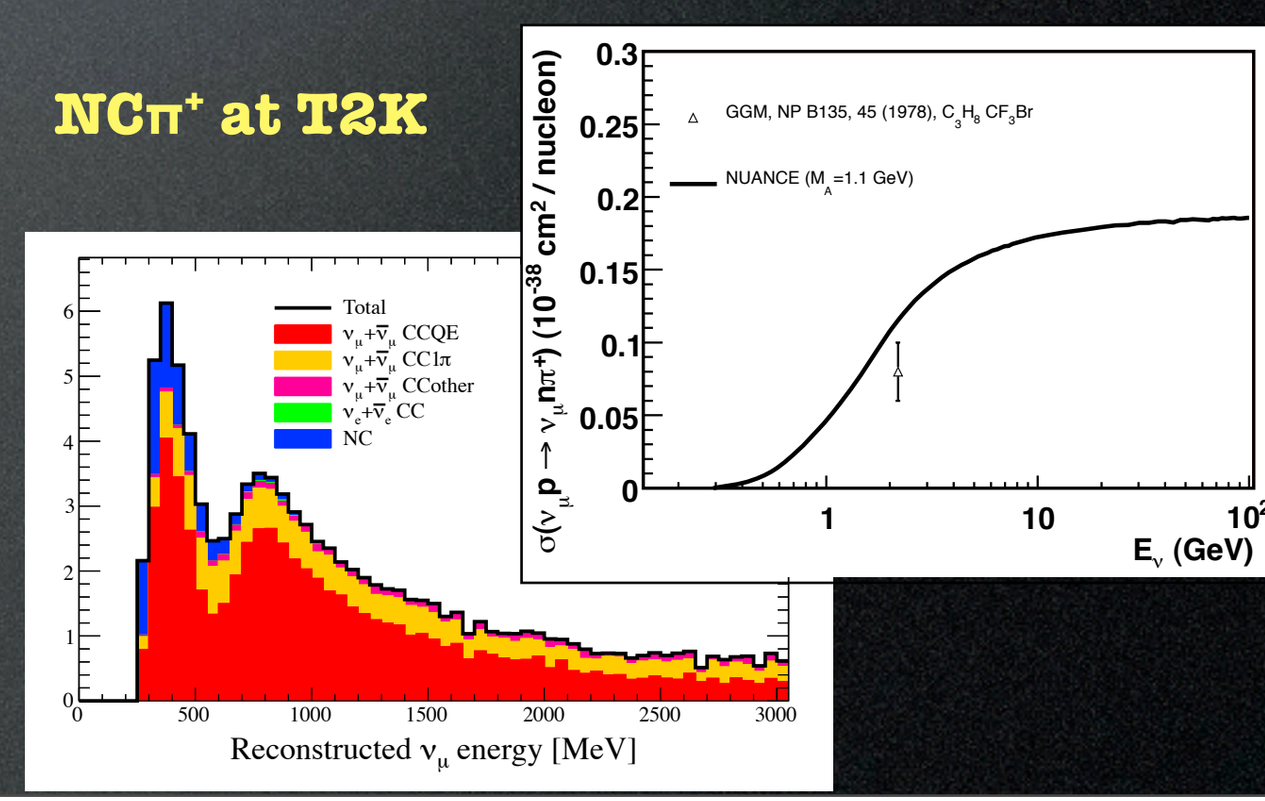
ν Cross Section Measurements

- Mono-energetic neutrino beams are ideal for measuring neutrino cross sections
  - Can provide a strong constraint on new models
- T2K ν_μ disappearance is subject to large NCπ^+ uncertainties
  - 1 existing measurement
  - NuPRISM can place a strong constraint on this process vs E_ν

Example MEC event separation

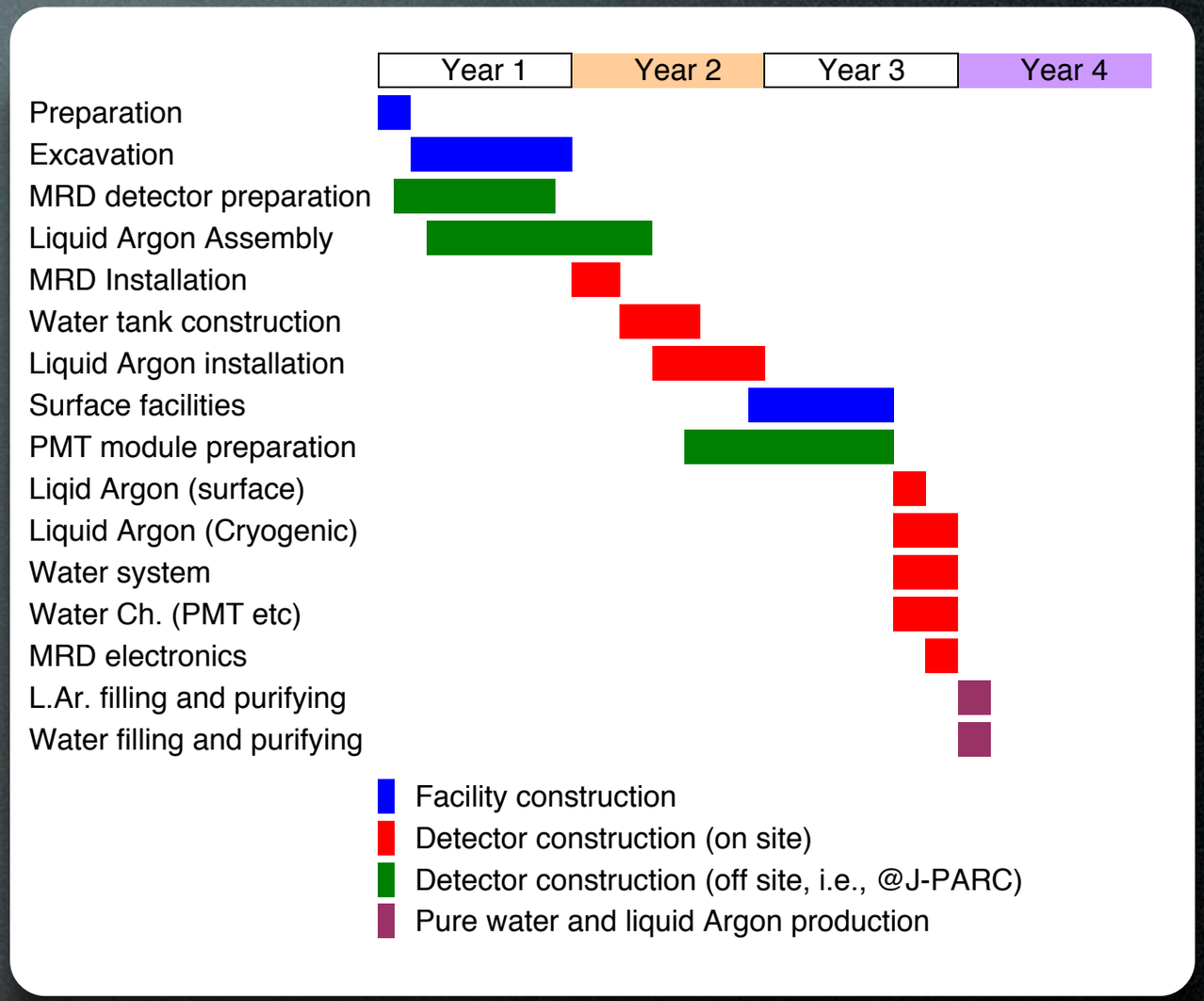


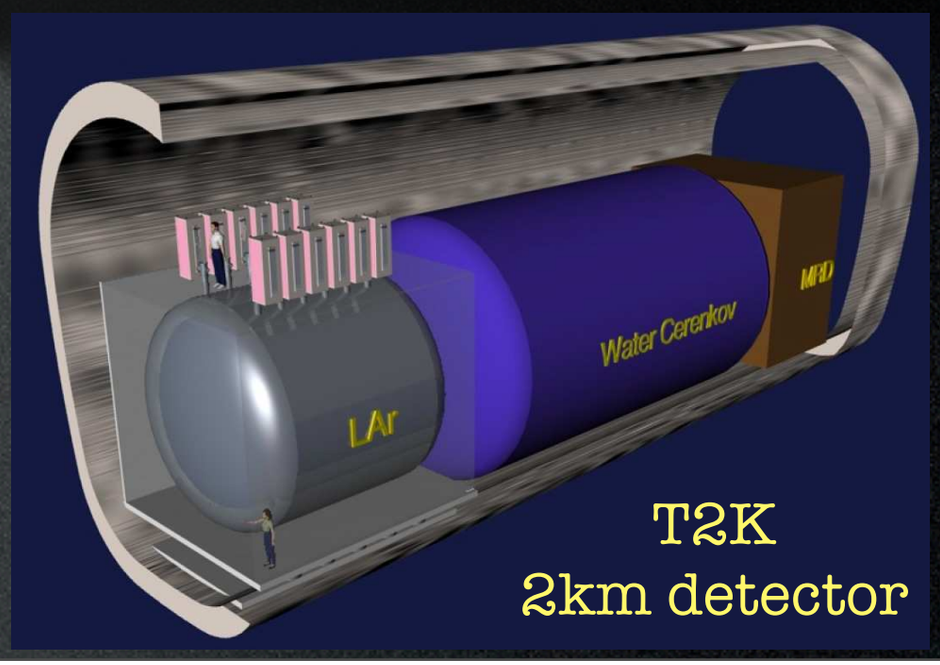
NCπ^+ at T2K



Timescales

- The T2K 2 km detector provides a
- NuPRISM construction time is faster
  - Same pit depth as the 2km detector, but no excavation of a large cavern at the bottom of the pit
  - Smaller instrumented volume
  - No LAr or MRD detector
- < 3 year timescale from approval to data taking
- Goal is to start data taking in time for the J-PARC 700kW beam (2018?)
  - Ideally, ground breaking would start in 2016





Current Status

- A Letter of Interest (LoI) was submitted to the J-PARC PAC in November 2014
  - arXiv:1412.3086
  - Full proposal to be submitted in June
- 50 physicists (and growing)
  - Several non-T2K members have joined
  - Room for many more
- Total cost is $15-$20M
  - US can make a big impact for <10% of the total project cost
  - US contributions can also include PMTs from MiniBooNE or Daya Bay

Spokespeople

Letter of Intent to Construct a nuPRISM Detector in the J-PARC Neutrino Beamline

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(The nuPRISM Collaboration)

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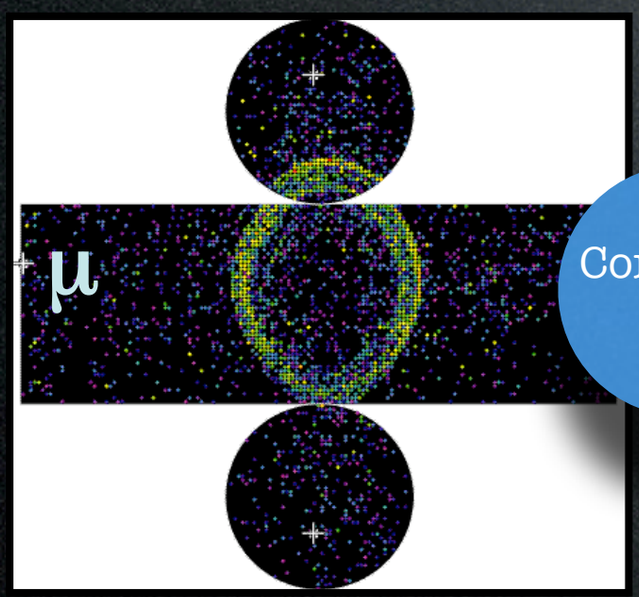
Summary

- NuPRISM is the only experimental mechanism that can largely remove neutrino interaction uncertainties from oscillation measurements
  - An experimental solution to the neutrino energy measurement problem!
  - Important for T2K
  - Essential for next generation experiments
- Many other important measurements (sterile-ν, unique cross sections)
- NuPRISM is a stand-alone experimental collaboration of >50 physicists
  - Several members that are not T2K members
- Full proposal will be submitted to the J-PARC PAC in June
  - With stage-1 approval, Japanese funding can be sought
    - Collaborators from KEK, ICRR, and several other Japanese institutions will host the project
- US can play a large role with a relatively modest (< 10%) contribution to the project

Supplement

How We Typically Perform Oscillation Analyses

Observed far detector signal:
1-ring muon events



Composed Of:

Nuclear model

CCQE: $\mu^- + p$ (p unobserved)

CCπ^+: $\mu^- + N + \pi^+$ (p, π^+ unobserved)

CCDIS: $\mu^- + X$ (X unobserved)

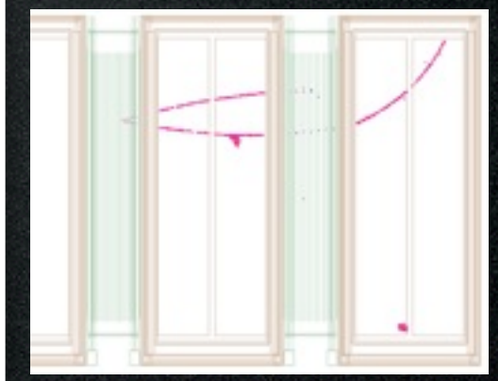
NCπ^+: $\pi^+ + n$ (π^+ misidentified, n unobserved)

...

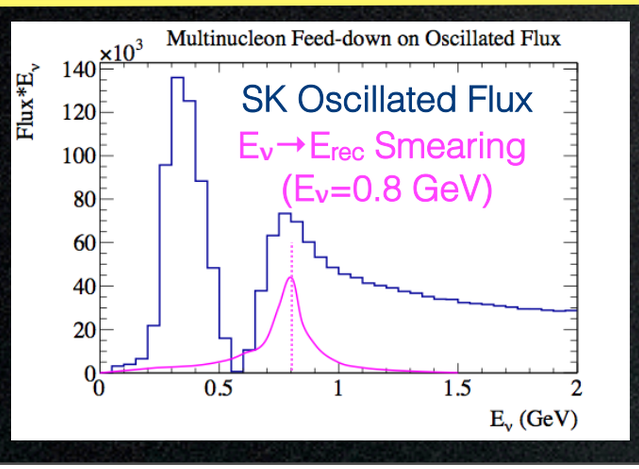
Predicted by poorly understood models

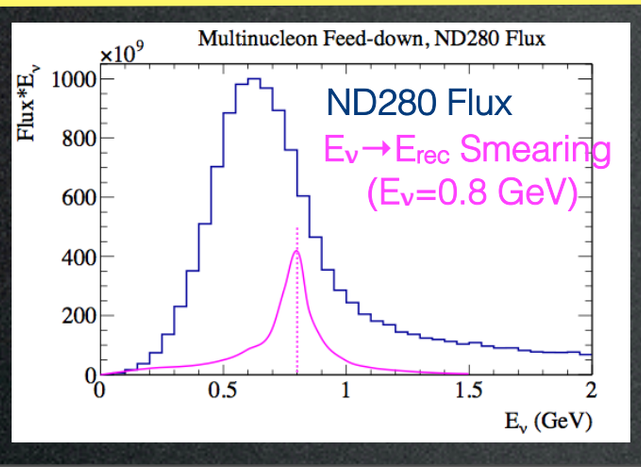
Parameter	E_ν Range	Nominal	Error	Class
M_A^{QE}	all	1.21 GeV/c^2	0.45	shape
M_A^{RES}	all	1.41 GeV/c^2	0.11	shape
p_F ^{12}C	all	217 MeV/c	30	shape
E_B ^{12}C	all	25 MeV	9	shape
SF ^{12}C	all	0 (off)	1 (on)	shape
CC Other shape ND280	all	0.0	0.40	shape
Pion-less Δ Decay	all	0.0	0.2	shape
CCQE E1	$0 < E_\nu < 1.5$	1.0	0.11	norm
CCQE E2	$1.5 < E_\nu < 3.5$	1.0	0.30	norm
CCQE E3	$E_\nu > 3.5$	1.0	0.30	norm
CC1π E1	$0 < E_\nu < 2.5$	1.15	0.43	norm
CC1π E2	$E_\nu > 2.5$	1.0	0.40	norm
CC Coh	all	1.0	1.0	norm
NC1π^0	all	0.96	0.43	norm
NC 1$\pi^\pm$	all	1.0	0.3	norm
NC Coh	all	1.0	0.3	norm
NC other	all	1.0	0.30	norm
ν_μ/ν_e	all	1.0	0.03	norm
$\nu/\bar{\nu}$	all	1.0	0.40	norm

Simultaneously constrain flux and cross section parameters with a near detector



But the near and far fluxes are different!



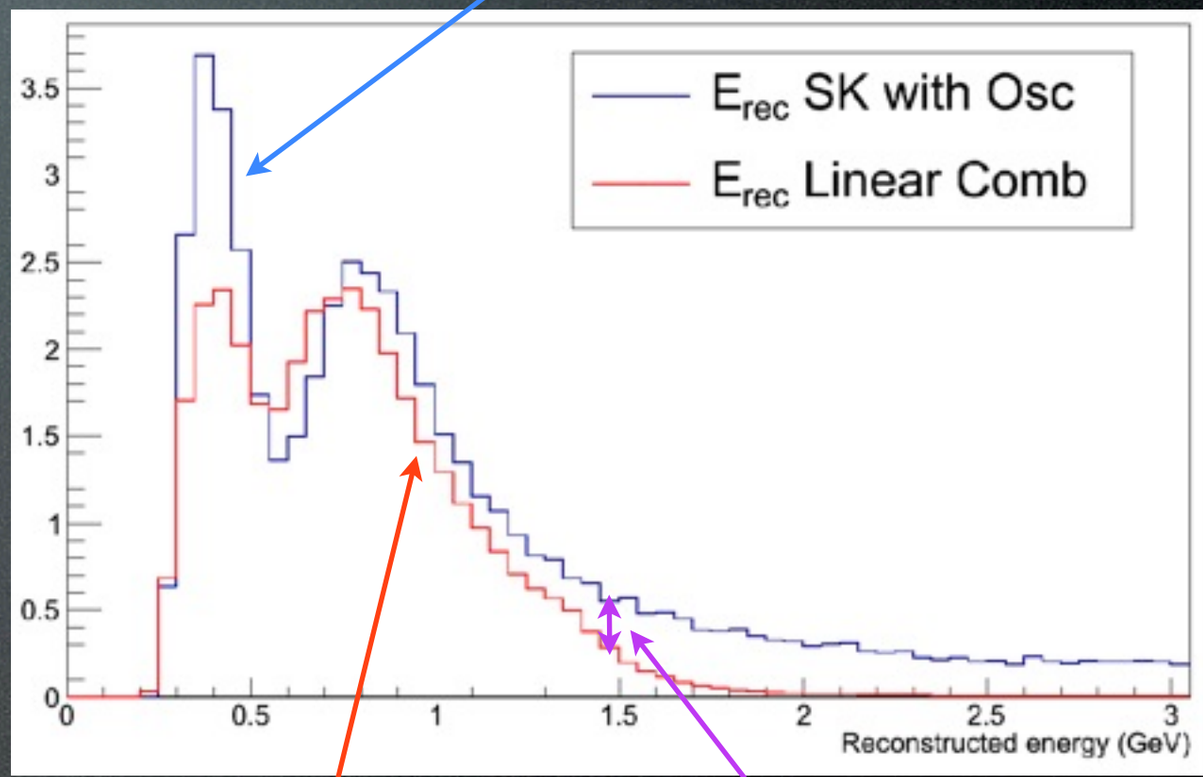


Goal of NuPRISM is to replace this procedure with a data measurement (to first order)

E_{rec} Distribution

- **For now, collapse 2D muon p,θ distribution into 1D E_{rec} plot**
- **Notice the NuPRISM and SK distributions disagree**
  - If they didn't, we would have no cross section systematic errors (modulo variations in the flux)
  - Differences are from detector acceptance & resolution, and imperfect flux fit
- **Super-K prediction is largely based on the directly-measured NuPRISM muon kinematics!**
  - Now, only a small amount of model extrapolation is needed
  - T2K measurements are now largely independent of cross section modeling!

Previously, the entire predicted E_{rec} distribution at Super-K was based on model extrapolation



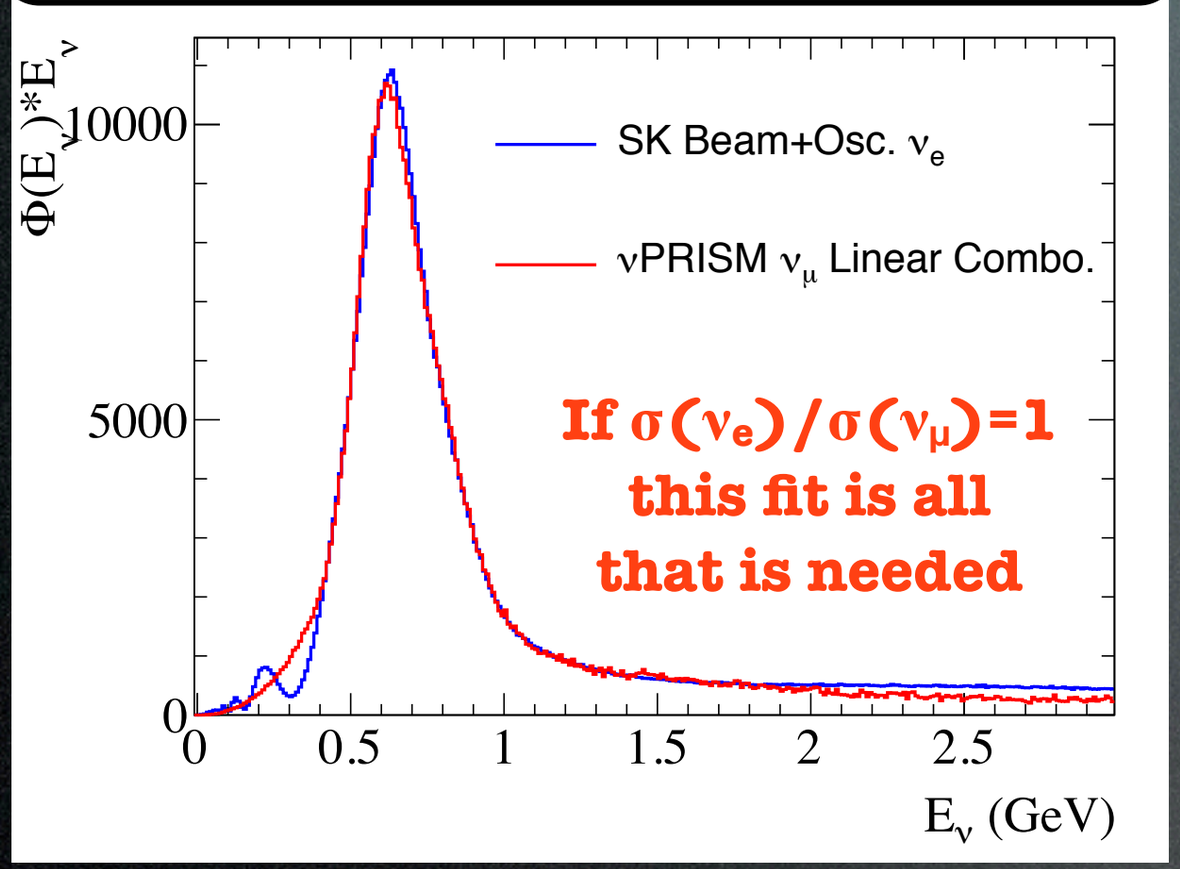
Now, NuPRISM directly measures most of this distribution

The remaining model-dependent correction factor (i.e. systematic uncertainty) is relatively small

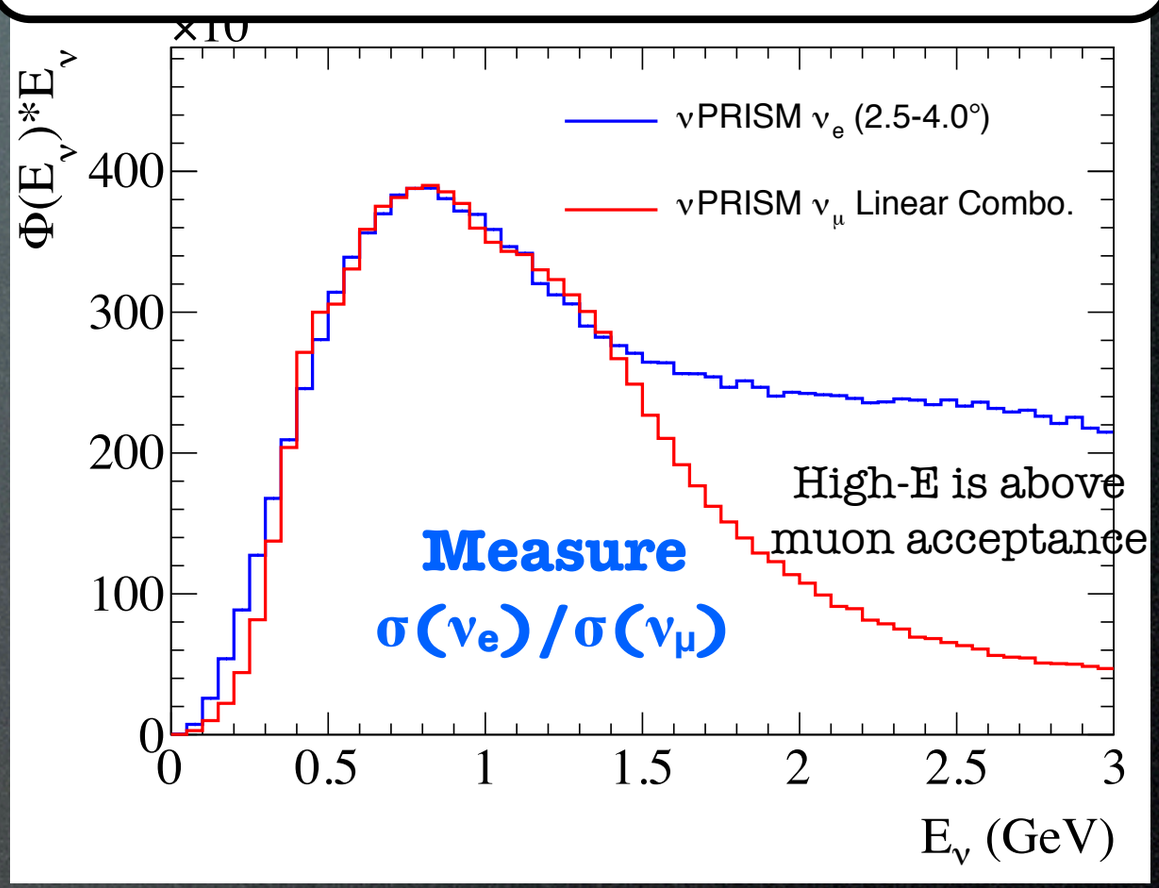
nuPRISM CPV (ν_e Appearance)

2 step approach:

Step 1: Measure **Super-K** ν_e response with nuPRISM ν_μ



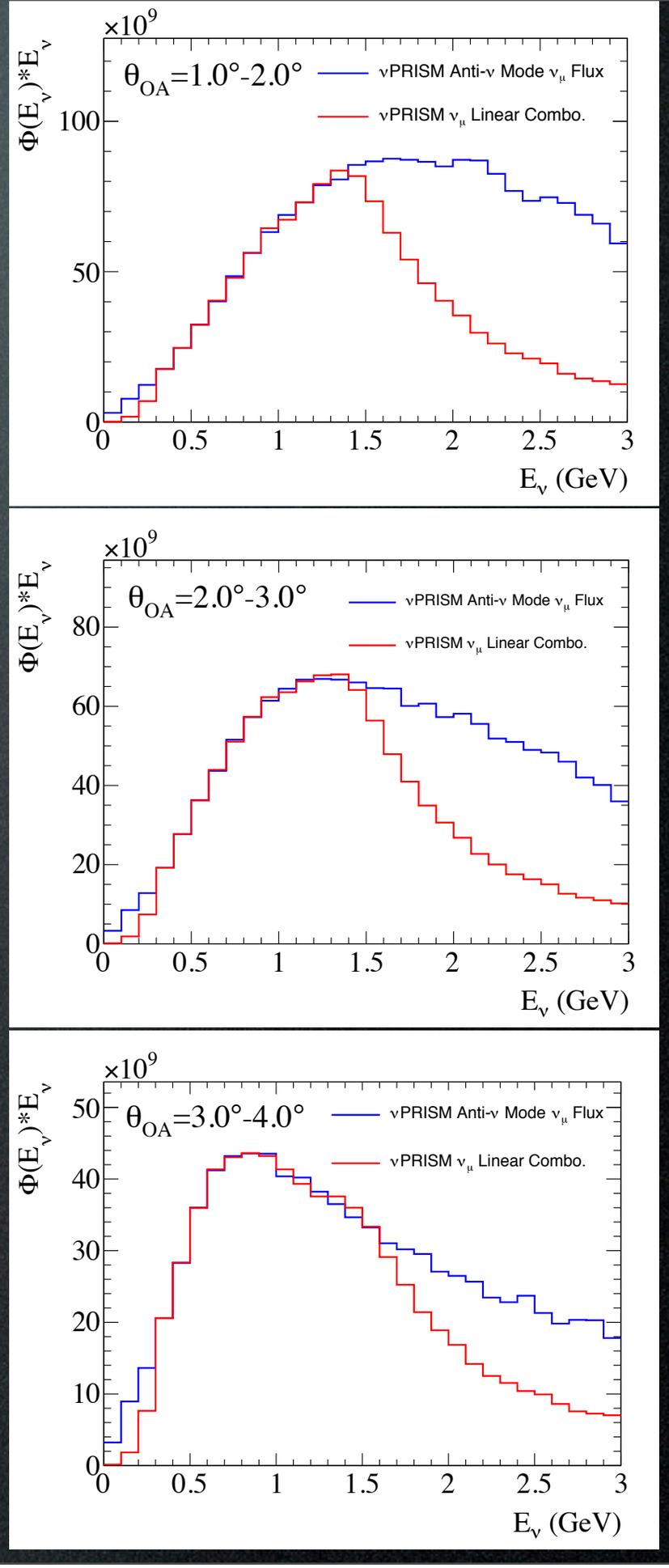
Step 2: Measure **nuPRISM** ν_e response with nuPRISM ν_μ



- Step 1 is the ν_e version of the ν_μ disappearance analysis
- Step 2 uses only nuPRISM to measure $\sigma(\nu_e)/\sigma(\nu_\mu)$
  - High energy disagreement is above muon acceptance
  - These plots show flux*E_ν, so difference is 1-ring μ events is smaller

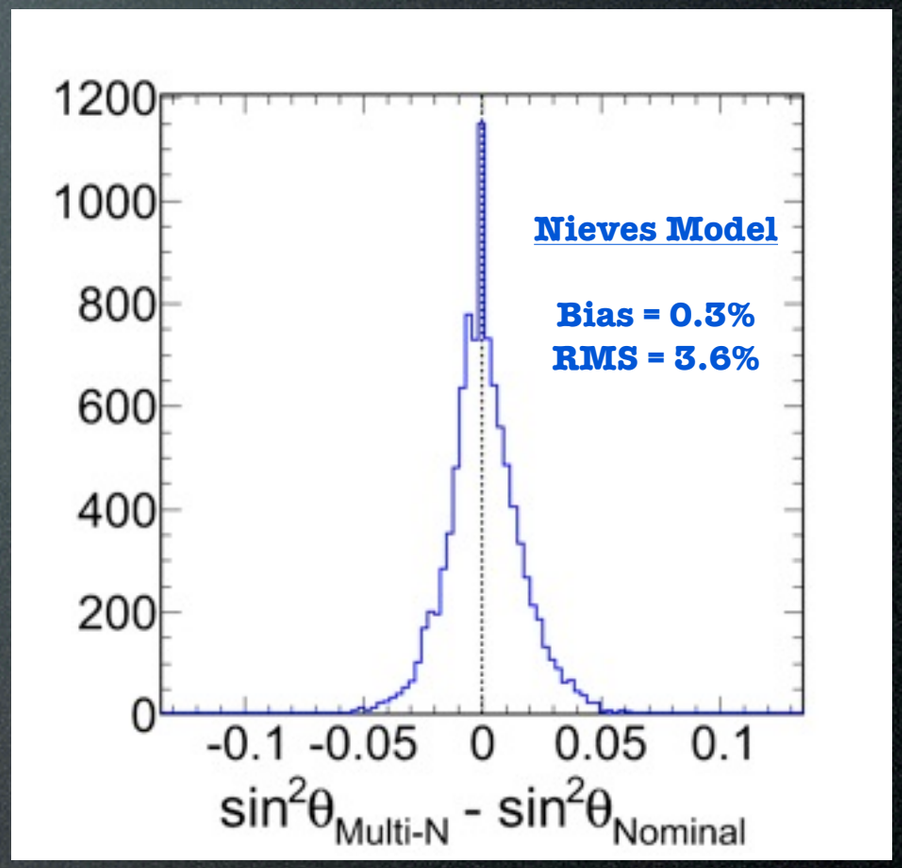
Anti-neutrinos

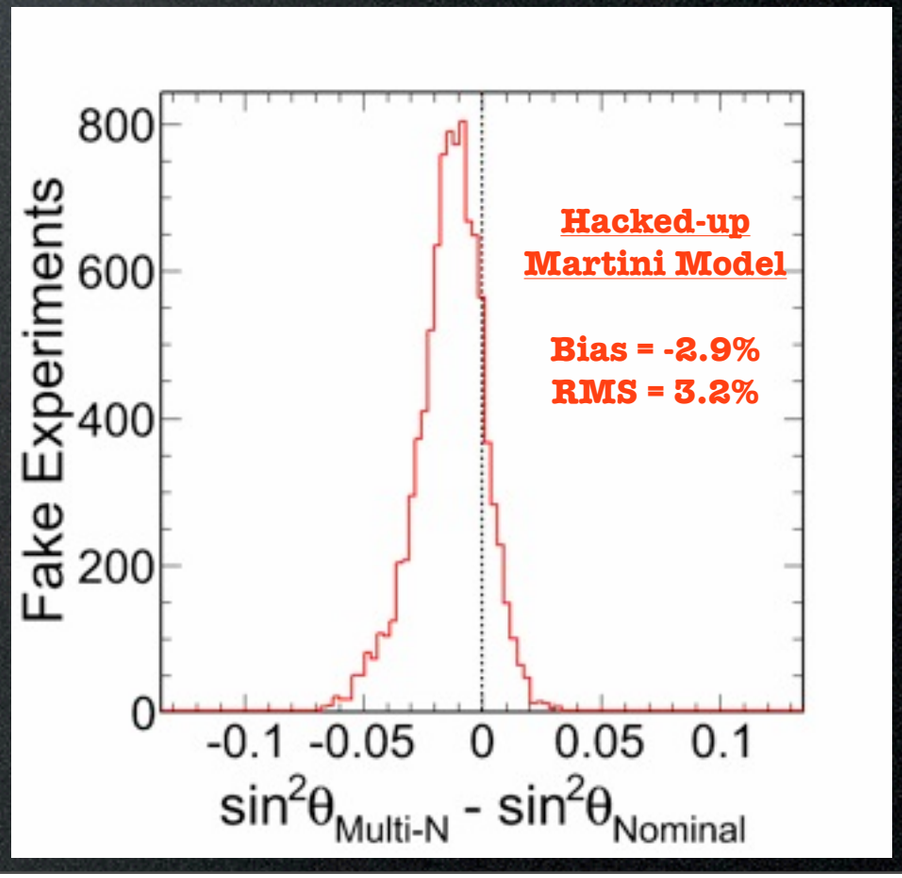
- T2K can switch between ν-mode and anti-ν-mode running by switching the beam focusing
- Anti-ν-mode analysis is the same as for neutrinos
  - Except with a much larger neutrino contamination
- Can use **ν-mode ν_μ data** to construct the **ν_μ background** in the **anti-ν-mode anti-ν_μ** data
  - Statistical separation of neutrinos from anti-neutrinos, rather than event-by-event sign selection
- After subtracting neutrino background, standard NuPRISM oscillation analyses can be applied to anti-neutrinos



Effect on T2K ν_μ Disappearance

- Create "fake data" samples with flux and cross section variations
  - With and without multi-nucleon events
- For each fake data set, full T2K near/far oscillation fit is performed
  - For each variation, plot difference with and without multi-nucleon events
- For Nieves model, "average bias" (RMS) = **3.6%**
- For Martini model, mean bias = -2.9%, RMS = 3.2%
  - Full systematic = $\sqrt{(2.9\%^2+3.2\%^2)}$ = **4.3%**
  - **This would be one of the largest systematic uncertainties**
- But this is just a comparison of 2 models
  - How much larger could the actual systematic uncertainty be?
- **We need a data-driven constraint!**





Interpreting Linear Combinations

- After νPRISM linear combination:
  - CC-ν_μ spectrum should reproduce oscillated far detector spectrum: **Good!**
  - NC-ν_μ backgrounds will also appear "oscillated": **Bad!**
    - NC events are unaffected by oscillations at Super-K
- **NC events must be subtracted** at both Super-K and nuPRISM
  - Introduces cross section model dependence
- However, **NC backgrounds can be very well measured** using mono-energetic beams
  - Significantly reduces cross section model dependence
- In current analysis (see later slides), NC constraint has not yet been applied
  - **Conservative errors**

ν Energy Spectrum

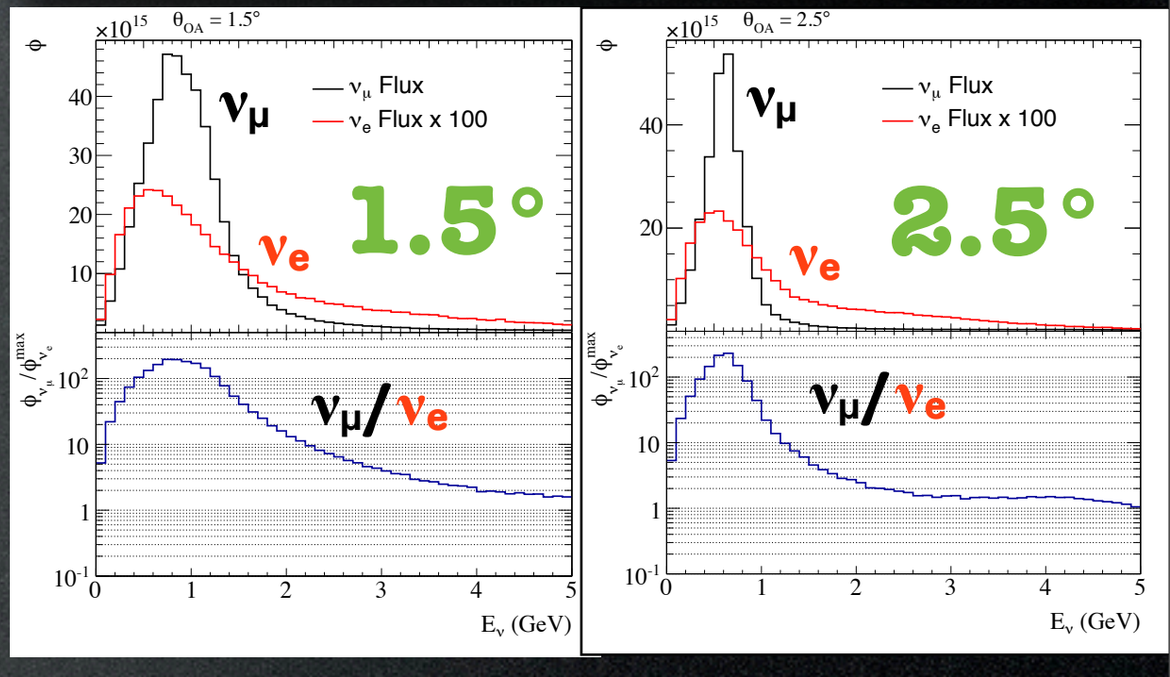
Flux < 1 GeV is dominated by π^+ decay

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

ν_μ produced in 2-body decay

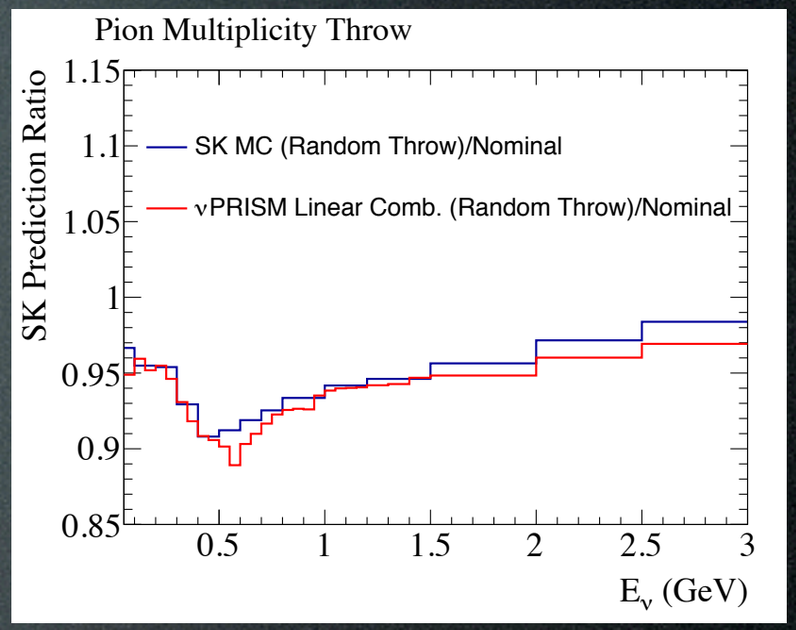
ν_e produced in 3-body decay

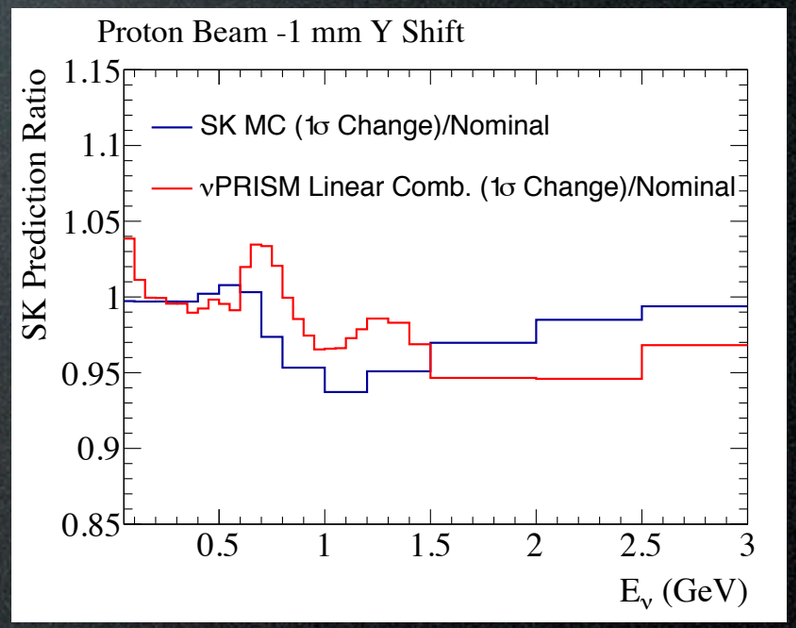
☞ ν_μ experience more off-axis affect

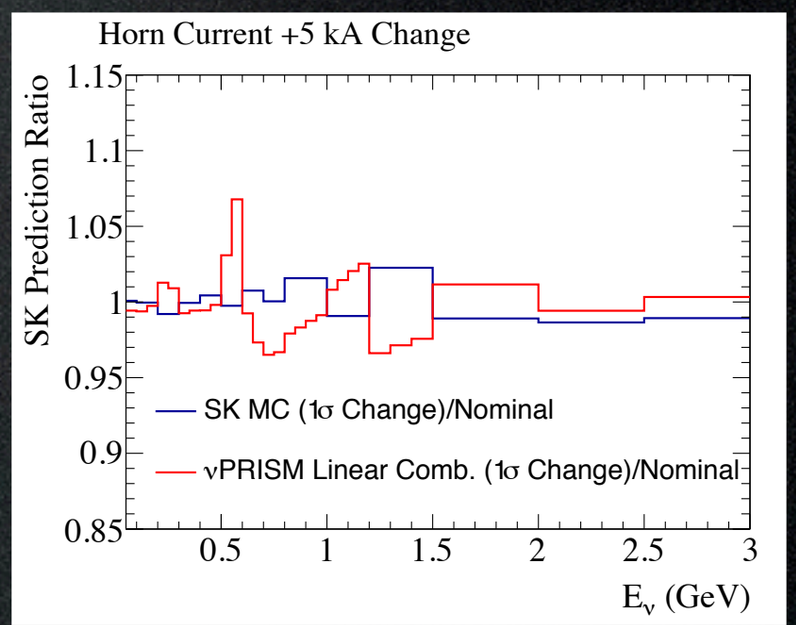


More on Beam Errors

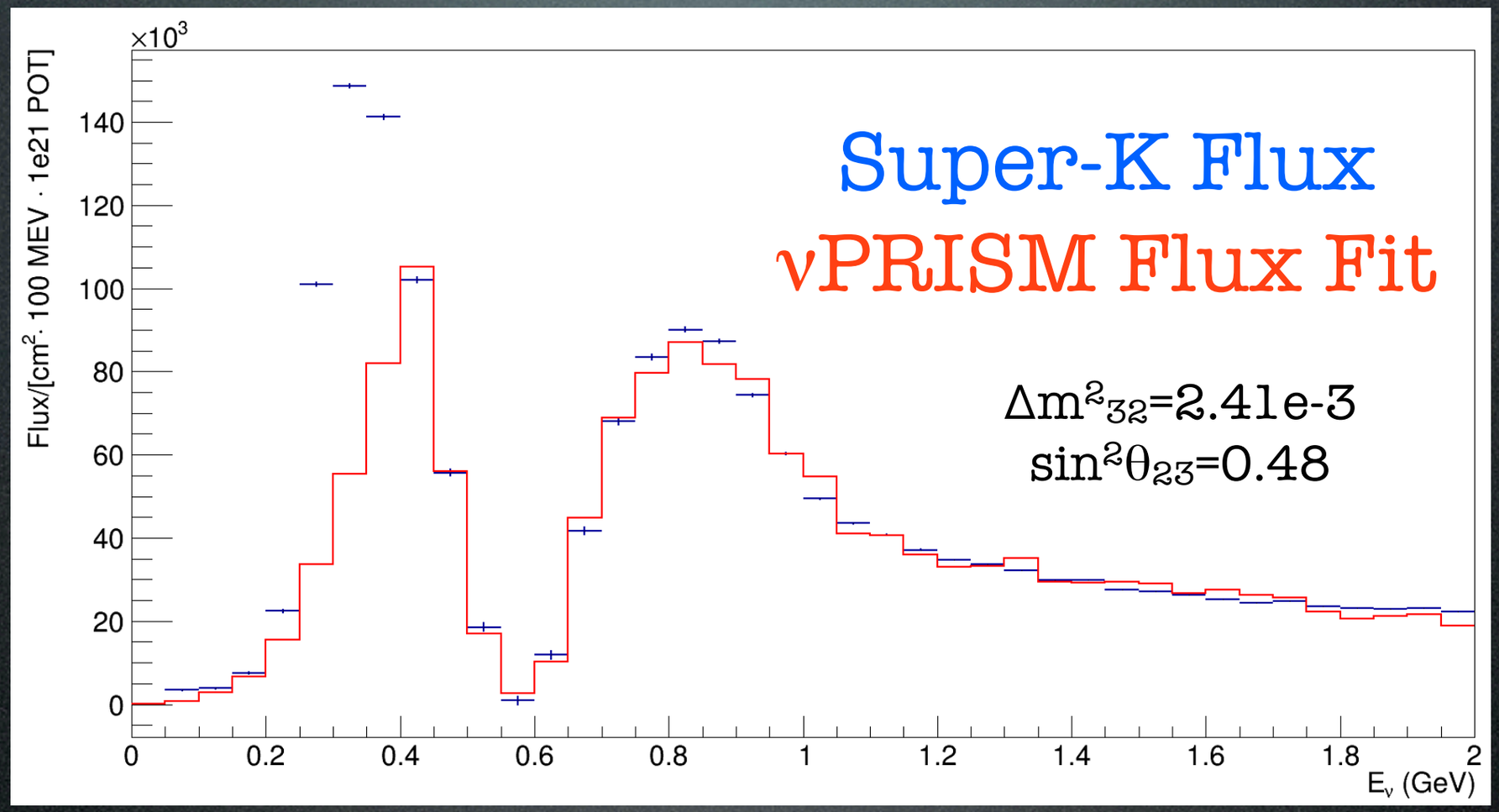
- Haven't we just replaced **unknown cross section errors** with **unknown flux errors**?
  - Yes! But only relative flux errors are important!
  - Cancelation exist between nuPRISM and far detector variations
- **Normalization uncertainties will cancel** in the νPRISM analysis
  - Cancelations persist, even for the νPRISM linear combination
  - Shape errors are most important
- For scale, **10% variation** near the dip means **~1% variation** in $\sin^2 2\theta_{23}$
  - Although this region is dominated by feed down
- Full flux variations are reasonable
  - No constraint used (yet) from existing near detector!







Flux Fit



- Fit for coefficients of 60 off-axis νPRISM slices to match a chosen Super-K oscillated spectrum
  - Fit between 400 MeV and 2 GeV
  - **Repeat this fit for every set of oscillation parameters**
- Notice disagreement at low energy
  - The most off-axis flux (4°) peaks at 380 MeV, so difficult to fit lower energies
  - Could extend detector further off-axis, but the low energy region is not very important to extract oscillation physics (e.g. nuclear feed-down not an issue)

nuPRISM Prediction for Super-K

- **Efficiency correction** is still needed for both νPRISM and Super-K
- νPRISM and Super-K have **different detector geometries**
  - Particles penetrate ID wall (and get vetoed) more often in nuPRISM
  - Particle ID degrades near the tank wall
- The efficiency correction is performed in **muon momentum and angle** to be as **model independent** as possible
  - This should be nearly a pure geometry correction
- For now, fit in Super-K E_{rec} distribution (in future, just use muon p,θ)

$$E^{SK}_{rec,j}(\Delta m^2_{32}, \theta_{23}) = \sum_{p,\theta} \left[\sum_{i}^{OAangles} c_i(\Delta m^2_{32}, \theta_{23}) \left(N^{obs}_{p\theta i} - B_{p\theta i}\right) \frac{\epsilon^{SK}_{p\theta}}{\epsilon^{\nu\mathrm{PRISM}}_{p\theta i}} \right] * M_{p\theta j}$$

predicted Super-K E_{rec} distribution

weight for off-axis slice, i

events in muon p,θ bin in slice, i

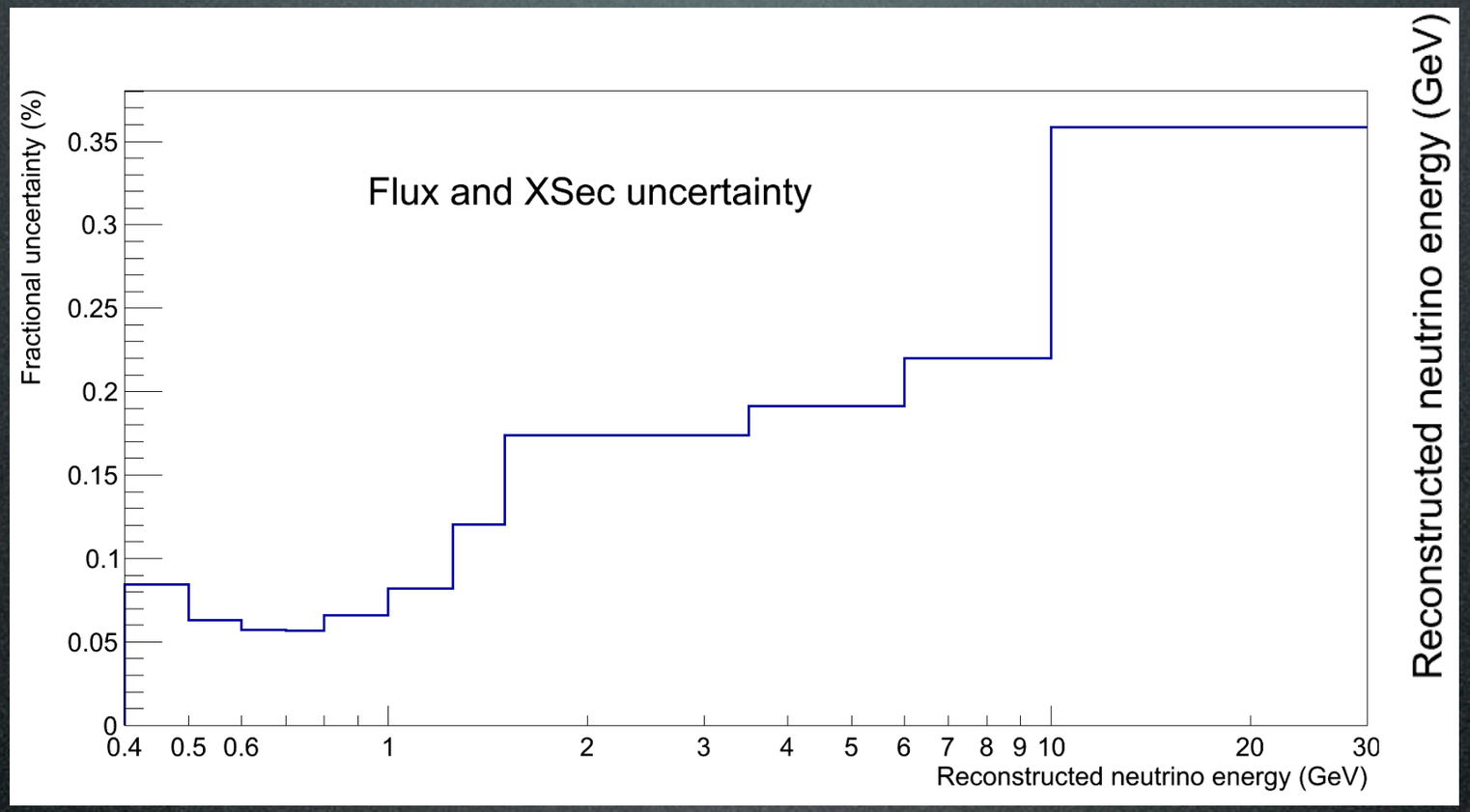
background subtraction

efficiency ratio

translation matrix p,θ → E_{rec}

Systematic Covariance Matrices

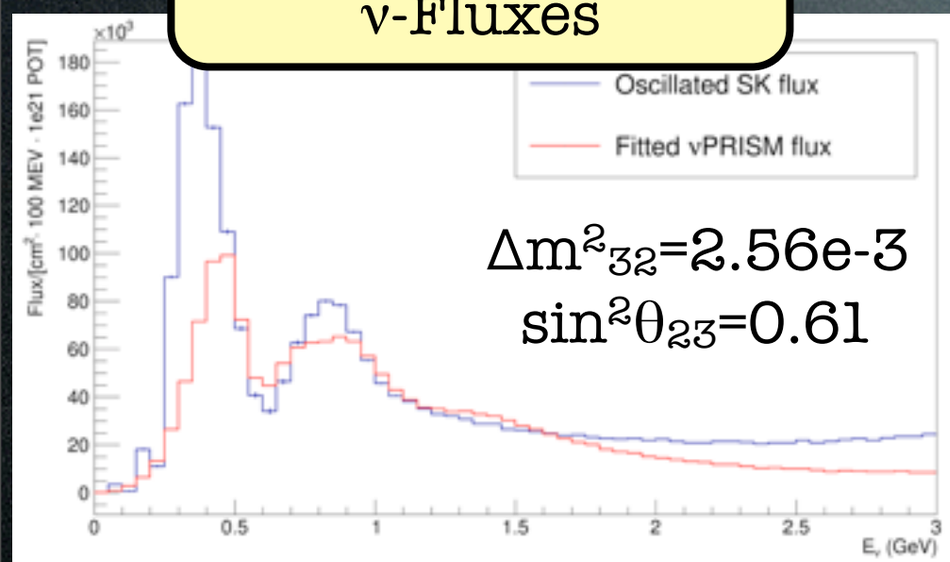
Analysis is performed in unequal-sized E_{rec} bins

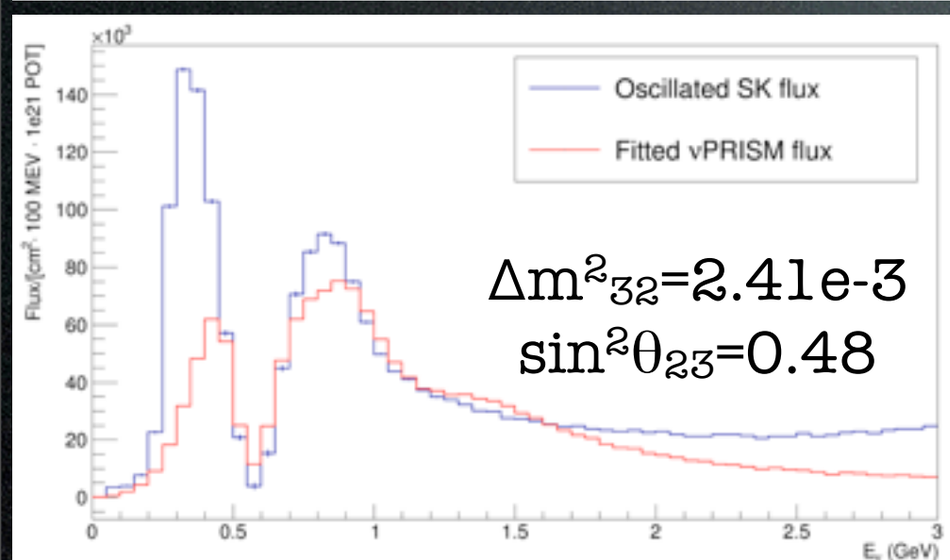


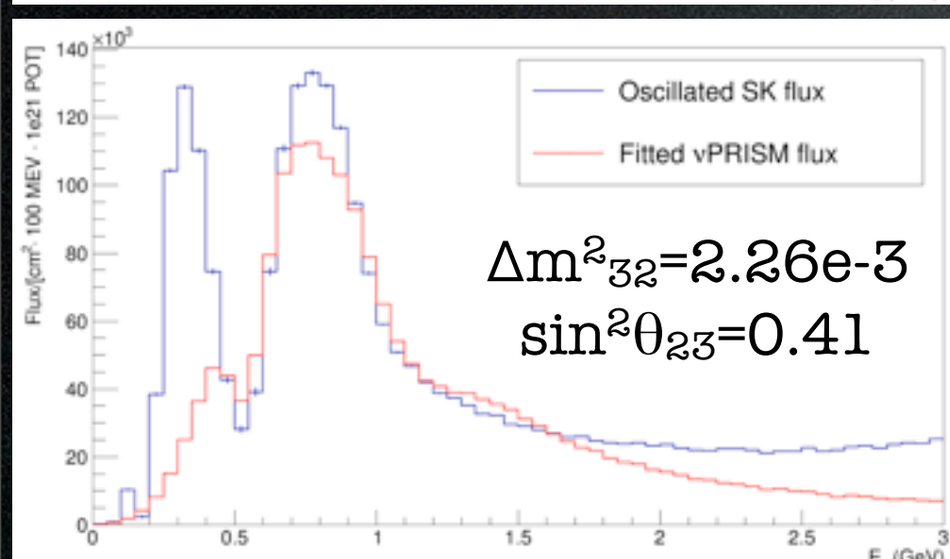
- Fractional uncertainties are shown (normalized to bin content)
- At high energies, νPRISM provides no constraint
  - Detector acceptance: all muons exit the inner detector
  - Subject to full flux & cross section uncertainties
- Bin 3 (600-700 MeV) has a 6% uncertainty

Smoothed ν-Flux Fits

ν-Fluxes

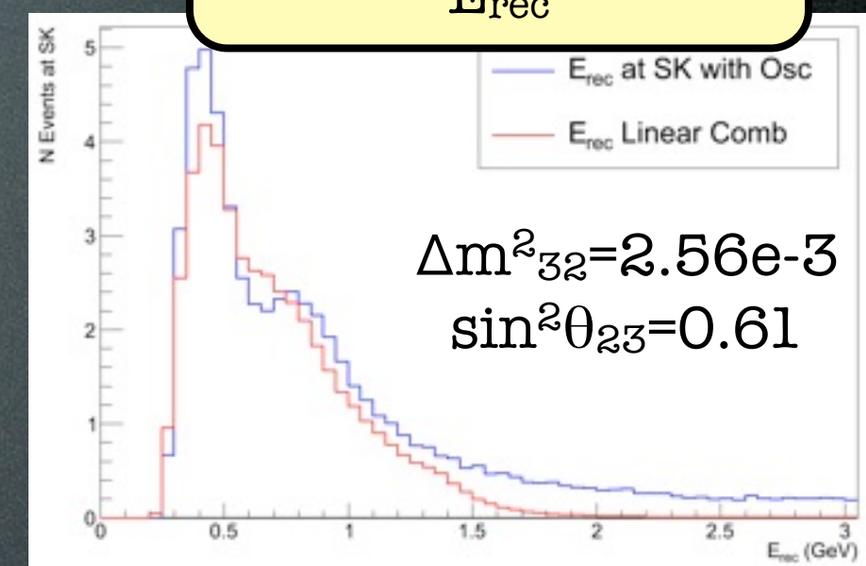


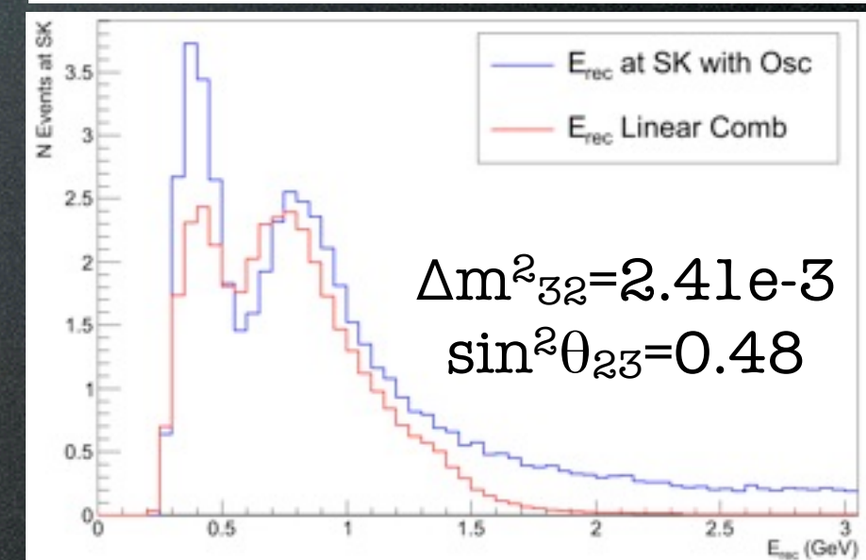


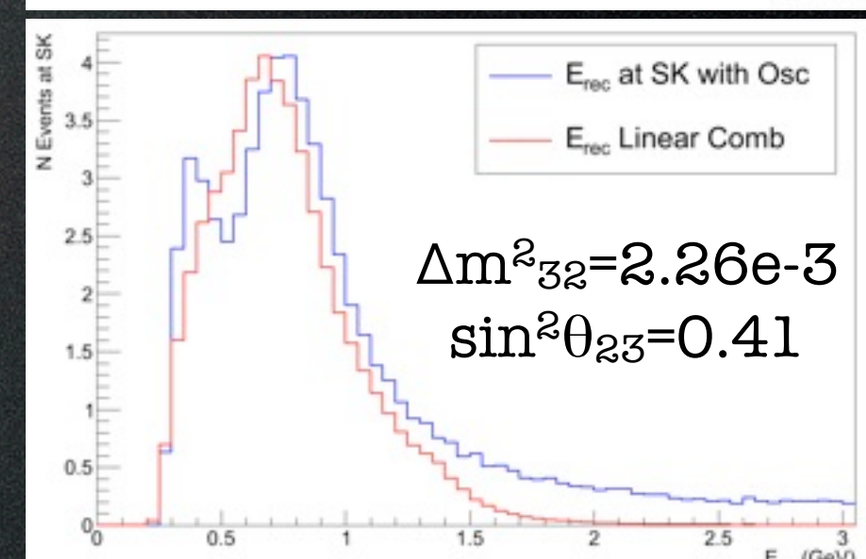


- Smoothed flux fits do not match as well
  - Easy to improve, if necessary
- However, very small increase to systematic uncertainties
  - Flux systematic variations are large
- Fits can be improved
  - Smoothness can be relaxed near fast-changing features
  - Off-axis angle bins need not be equal size

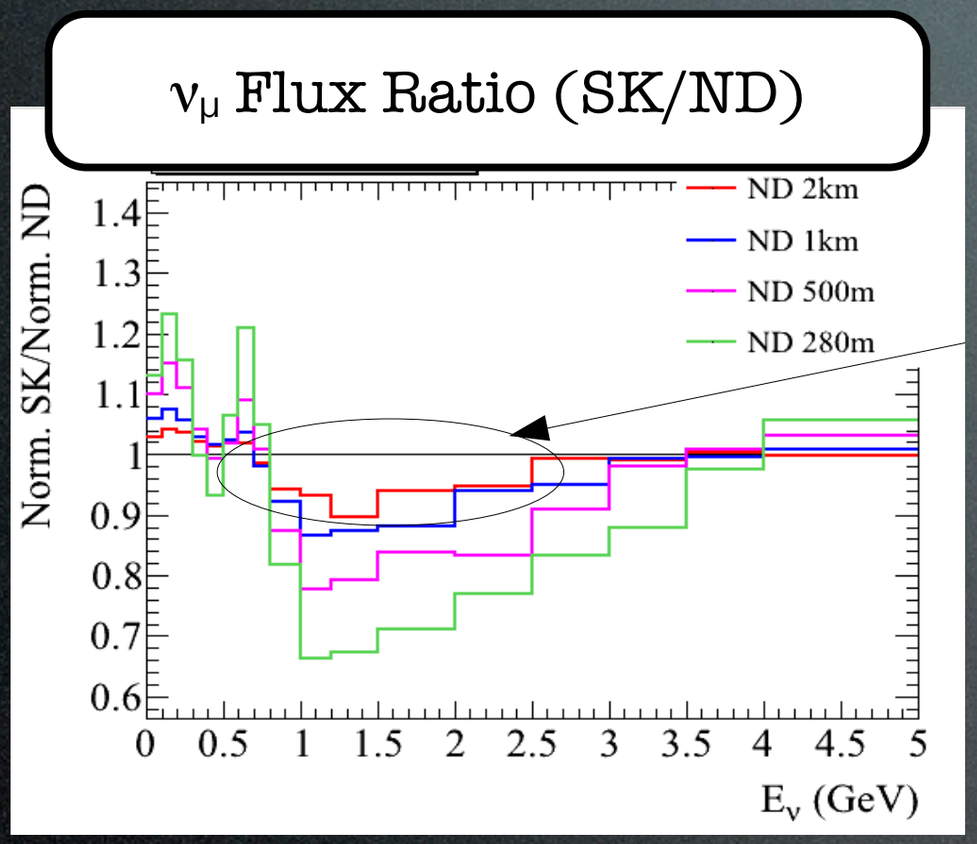
E_{rec}

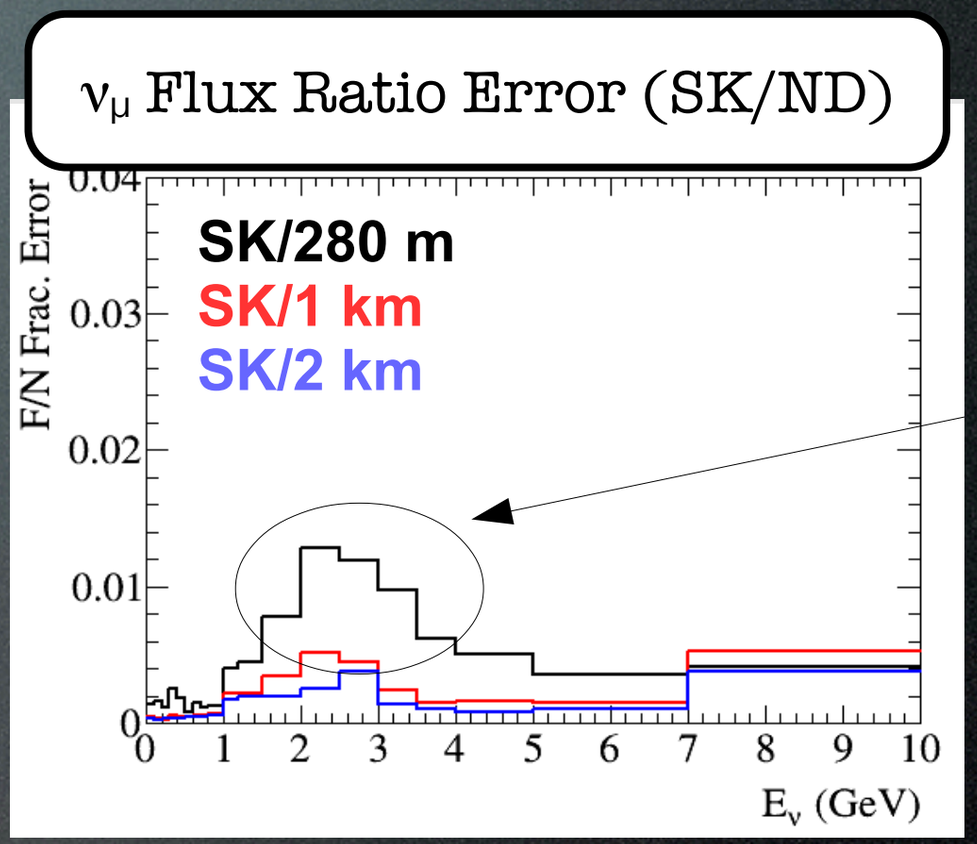






Detector Location: Energy Spectrum Ratio



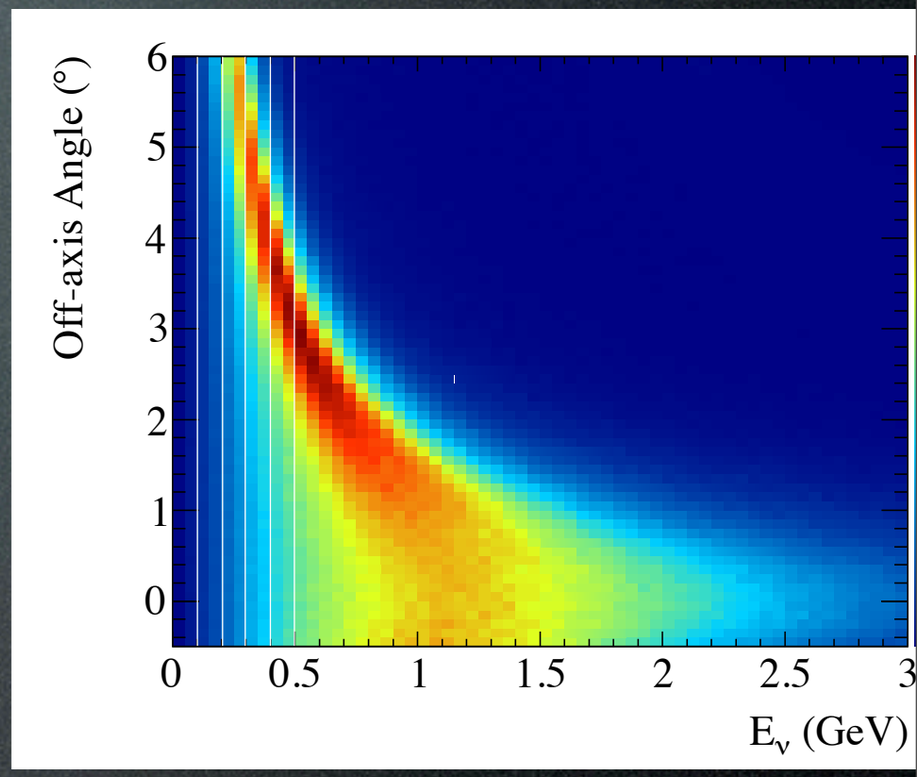


- At 280 m, the flux shape has 20-30% differences below 1 GeV
  - Uncertainty in the ratio is noticeably larger, but mostly above 1 GeV
- The difference between 1km and 2km is small in both shape and shape uncertainty

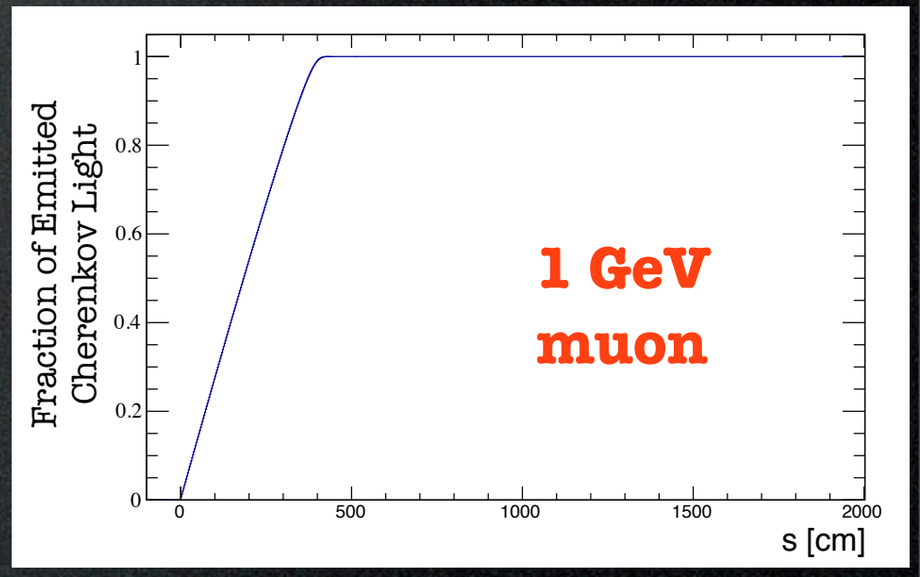
Other Design Considerations

- **Civil construction is expensive!**
  - Smaller hole = More affordable
- **Off-axis angle range (i.e. E_ν range)**
  - On-axis flux peaks at 1.2 GeV
  - 4° (6°) off-axis peaks at ~380 (~260) MeV
  - Beam points 3.63° below horizon, so get ~4° for free
- **Distance to target**
  - At 1 (1.2) km , need 54 (65) m deep pit to span 1°-4°
  - Event pileup must be manageable (see later slides)
- **Tank diameter**
  - Determines maximum muon contained
    - 4 m (+ FV cut) for 1 GeV/c muon
  - PID degrades near the wall
    - Important for selecting e-like events
  - Larger = more stats, but also more pileup
  - Larger = more PMTs = more expensive
  - How much outer detector is necessary?

Off-axis Fluxes

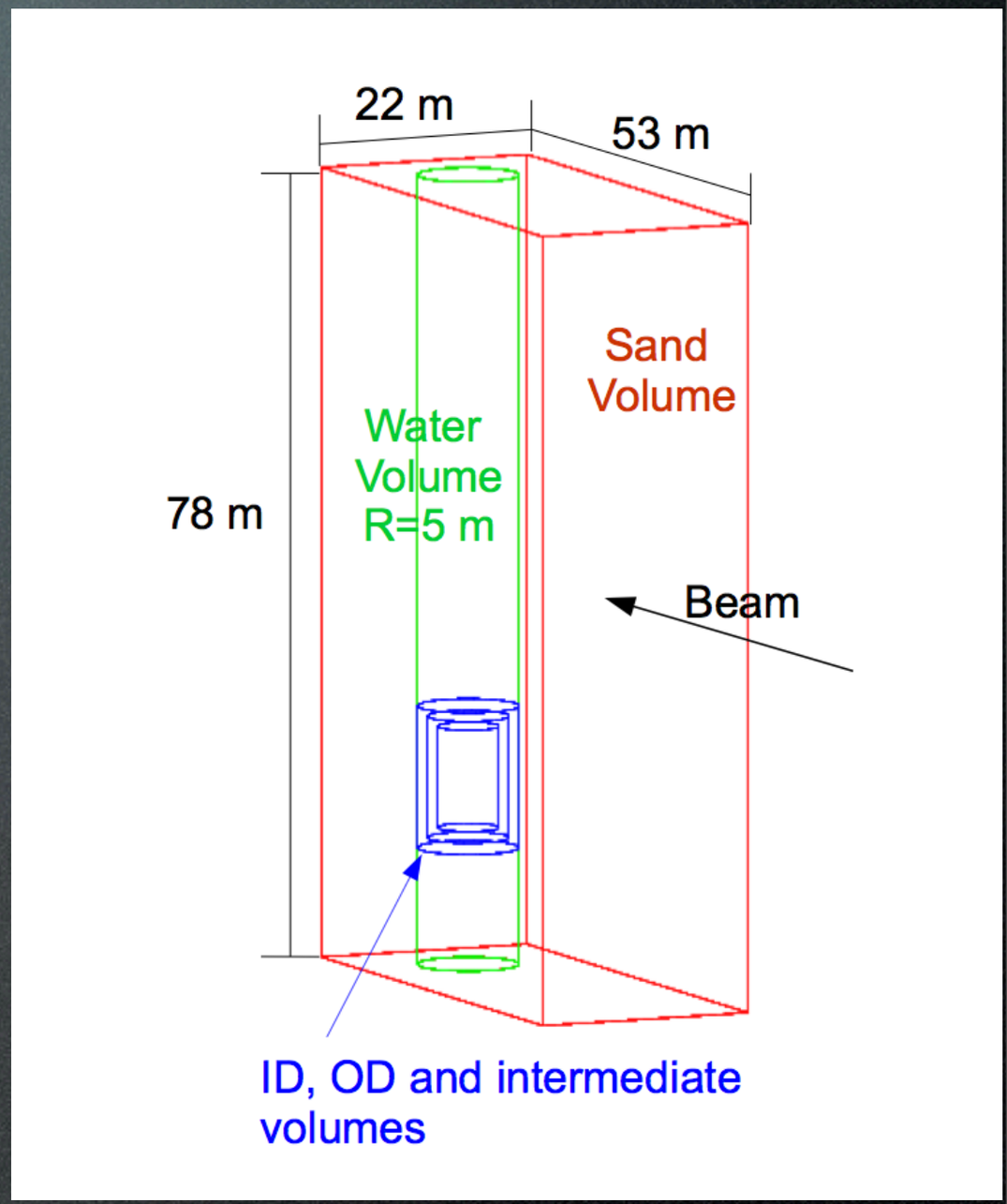


Muon Range



Event Pileup

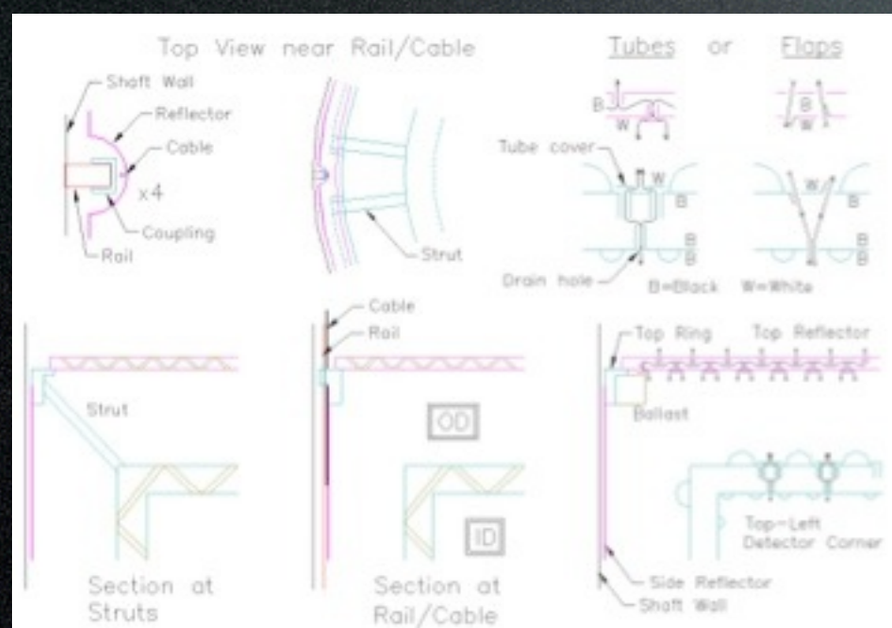
- Full GEANT4 simulation of water and surrounding sand
  - Using T2K flux and neut cross section model
- 8 beam bunches per spill, separated by 670 ns with a width of 27 ns (FWHM)
- **41% chance of in-bunch OD activity during an ID-contained event**
  - Want to avoid vetoing only on OD light (i.e. using scintillator panels)
- **17% of bunches have ID activity from more than 1 interaction**
  - 10% of these have no OD activity
  - Need careful reconstruction studies
    - (but multi-ring reconstruction at Super-K works very well)

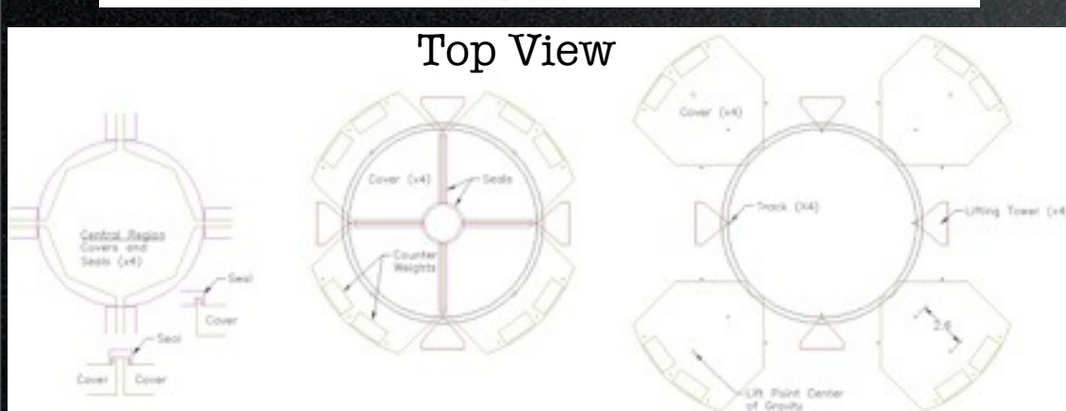


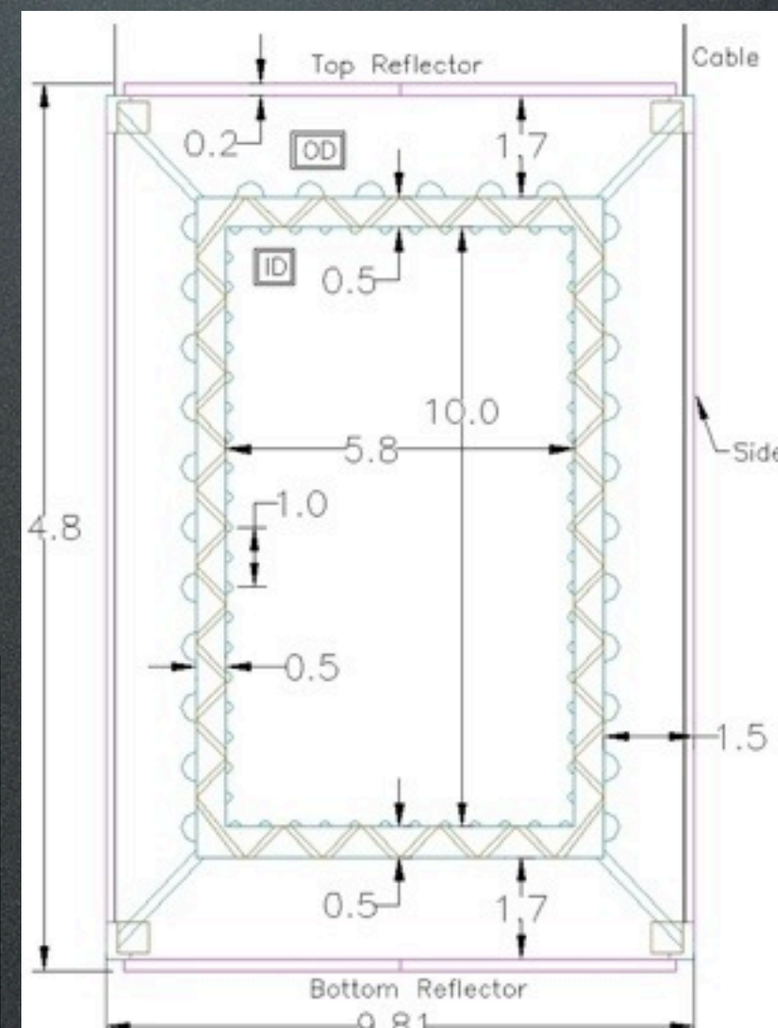
Pileup Rates at 1 km Look Acceptable!

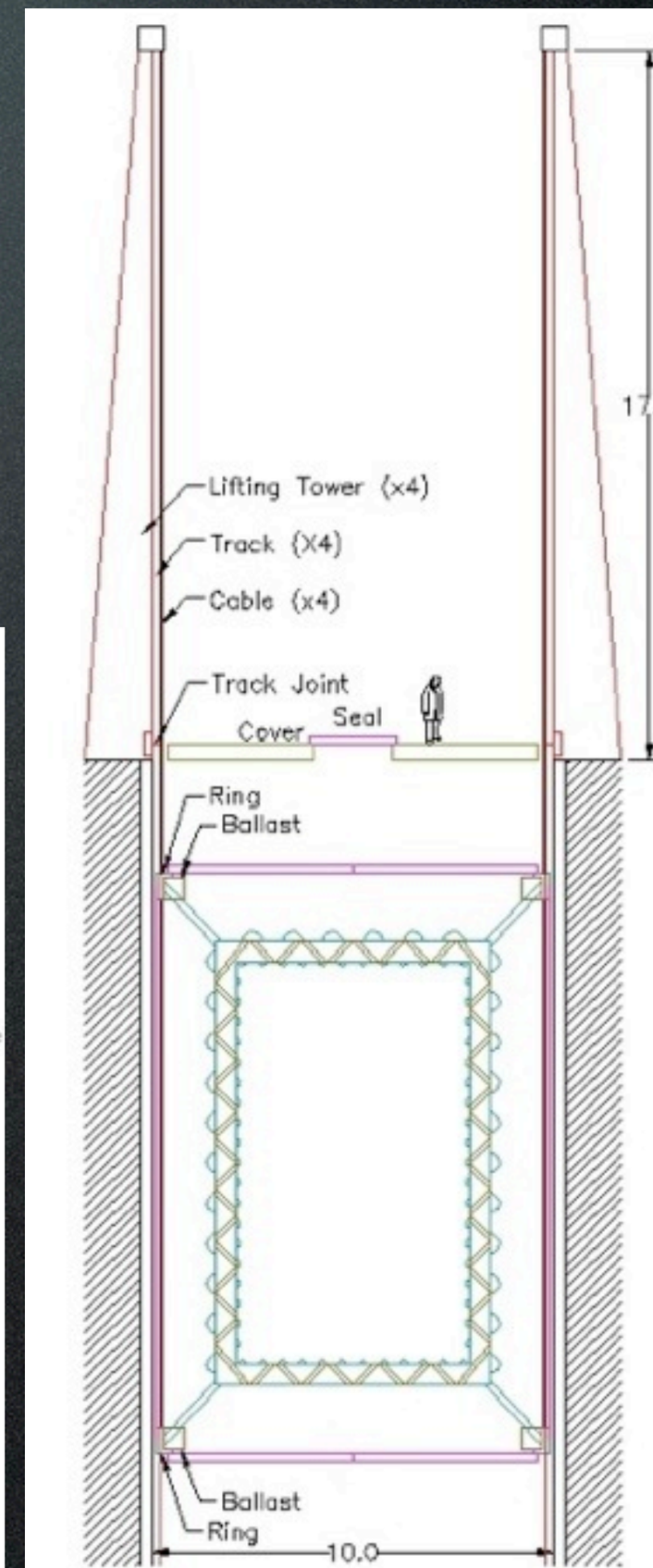
Detector Frame

- Initial proposal for ID/OD frame and lifting mechanism has been produced
- Careful consideration given to water flow rate while in motion
- 4 towers allow the entire detector to be lifted out of the water tank for maintenance



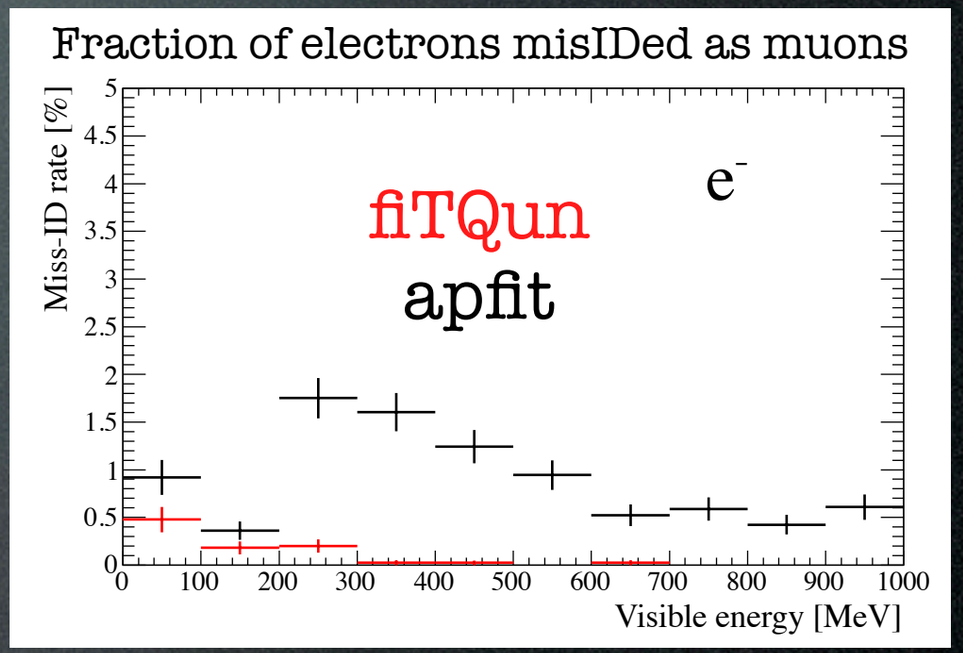


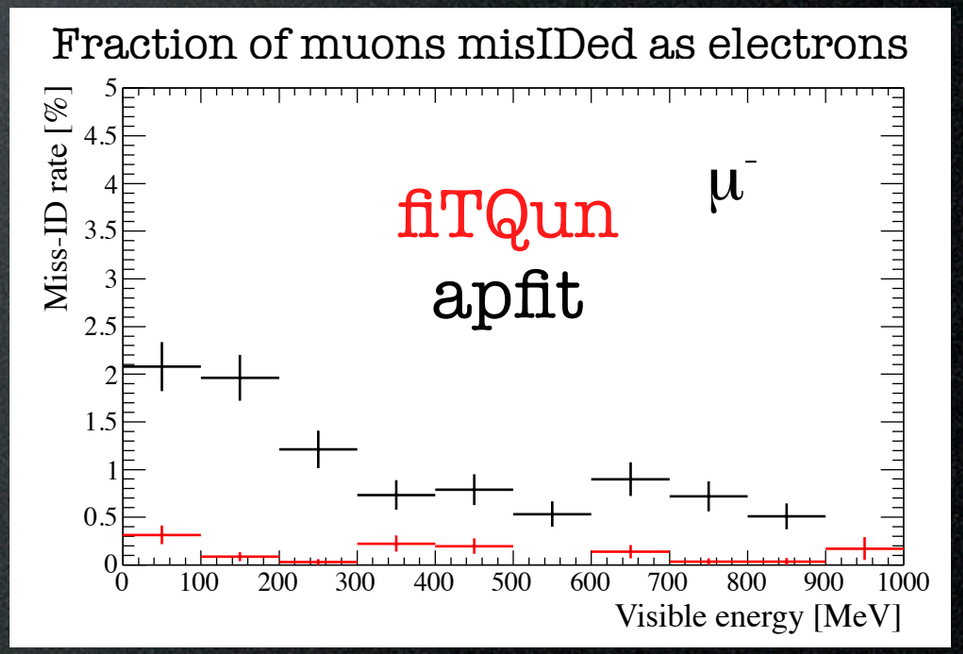




Physics Capabilities

- Direct measurement of the relationship between lepton kinematics and neutrino energy
  - No longer rely solely on models
- 4π detector (like Super-K)
- Target material is water (like Super-K)
  - Can directly measure NC backgrounds
- Very good e/μ separation
- Can make a precise measurement of beam ν_e
  - π^0 background is well separated
  - Can also constrain ν_e cross sections





T2K Uncertainties

ND280 Analysis	ND280 Data	SK Selection	$\sin^2 2\theta_{13}=0.1$	$\sin^2 2\theta_{13}=0.0$
No Constraint	--	Old	22.6%	18.3%
No Constraint	--	New	26.9%	22.2%
2012 method*	Runs 1-2	Old	5.7%	8.7%
2012 method**	Runs 1-3	Old	5.0%	8.5%
2012 method	Runs 1-3	New	4.9%	6.5%
2012 method***	Runs 1-3	New	4.7%	6.1%
2013 method	Runs 1-3	New	3.5%	5.2%
2013 method	Runs 1-4	New	3.0%	4.9%

Factor 2.4 more ND280 POT

Improved SK π^0 rejection

New ND280 reconstruction, selection, binning

Factor 2.2 more ND280 POT

*Results presented at Neutrino 2012 conference

**Published results, arXiv:1304.0841v2

***Update to NEUT tuning with MiniBooNE data

These are very nice constraints!
(if the current parametrization is to be believed)