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

Mike Wilking
Stony Brook University
6th Hyper-K Meeting
January 30th, 2015

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An Experimental Method to Remove Neutrino Interaction Uncertainties from Oscillation Experiments

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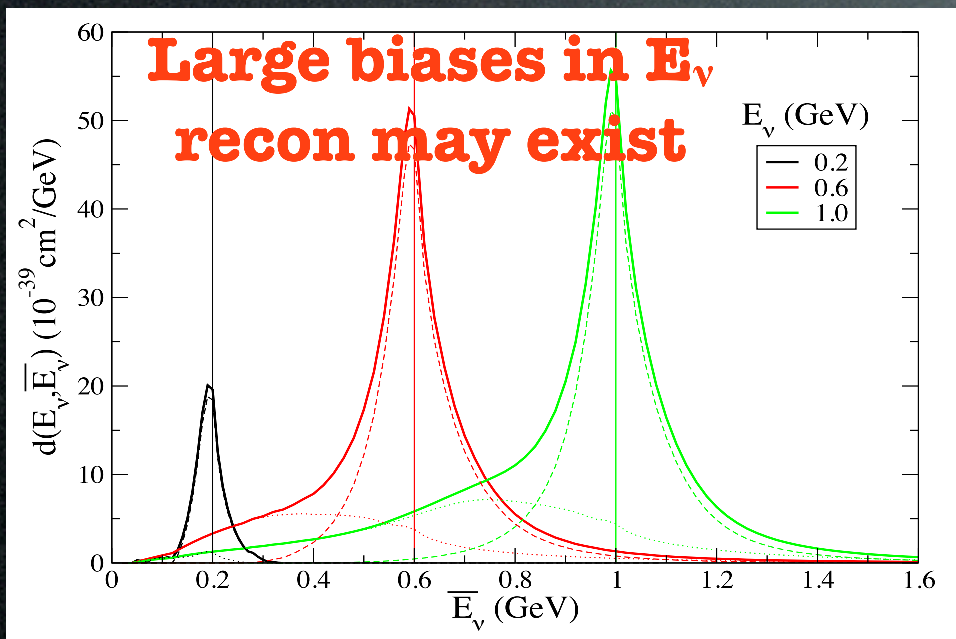
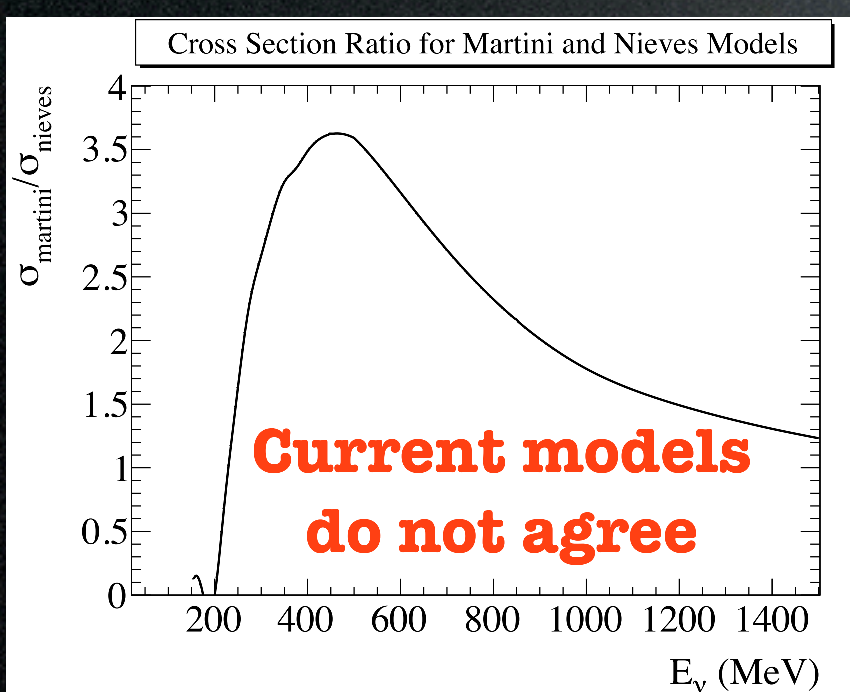
Overview

- Brief Reminder of NuPRISM Concept
  - E_ν Measurement Problem
  - Constraining E_ν with Linear Combinations
- Plans for other measurements
  - CPV & ν_e, sterile-ν, cross sections
- NuPRISM-Lite: Current Status
- Next Steps

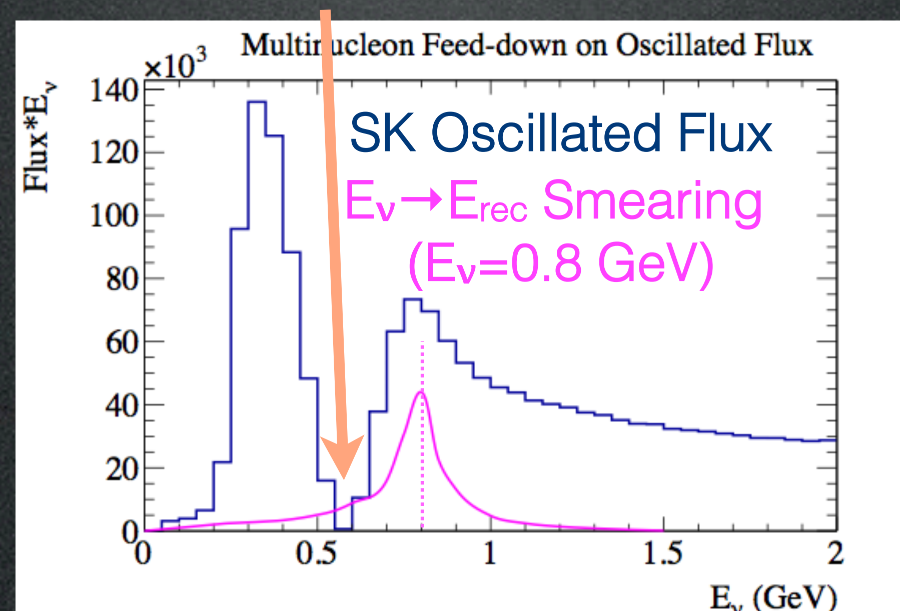
Why Hyper-K Needs NuPRISM:
The E_ν Measurement Problem



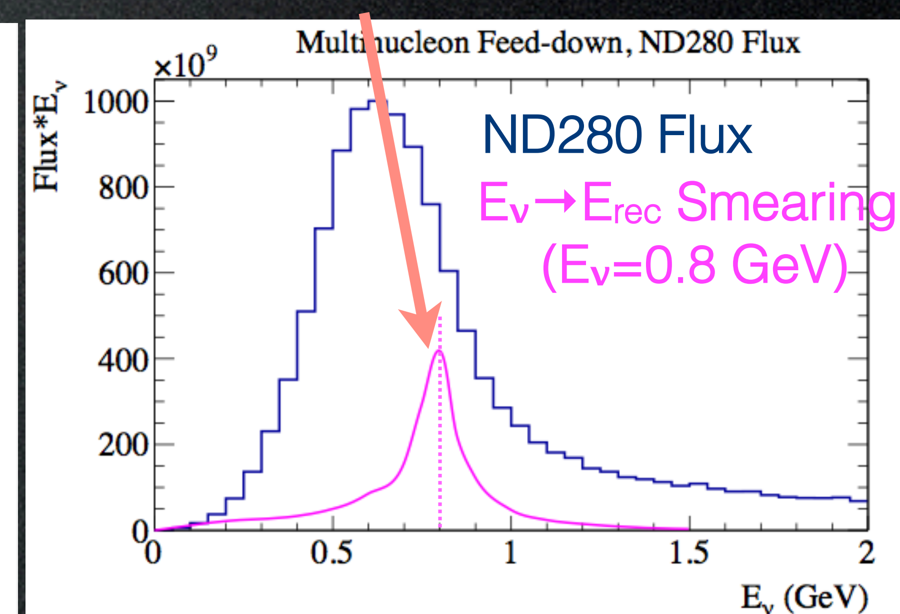


- It is now believed that large E biases can exists due to nuclear and non-nuclear effects (e.g. multinucleon interactions)
- Models are very difficult to produce and show large disagreements
- Without a data-driven constraint, this will likely be a dominant uncertainty for T2HK
- Typical near detectors likely cannot provide a sufficient constraint

Mixing Angle Bias!



Typical ND lacks sensitivity



- 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)

Reminder: NuPRISM Detector Concept

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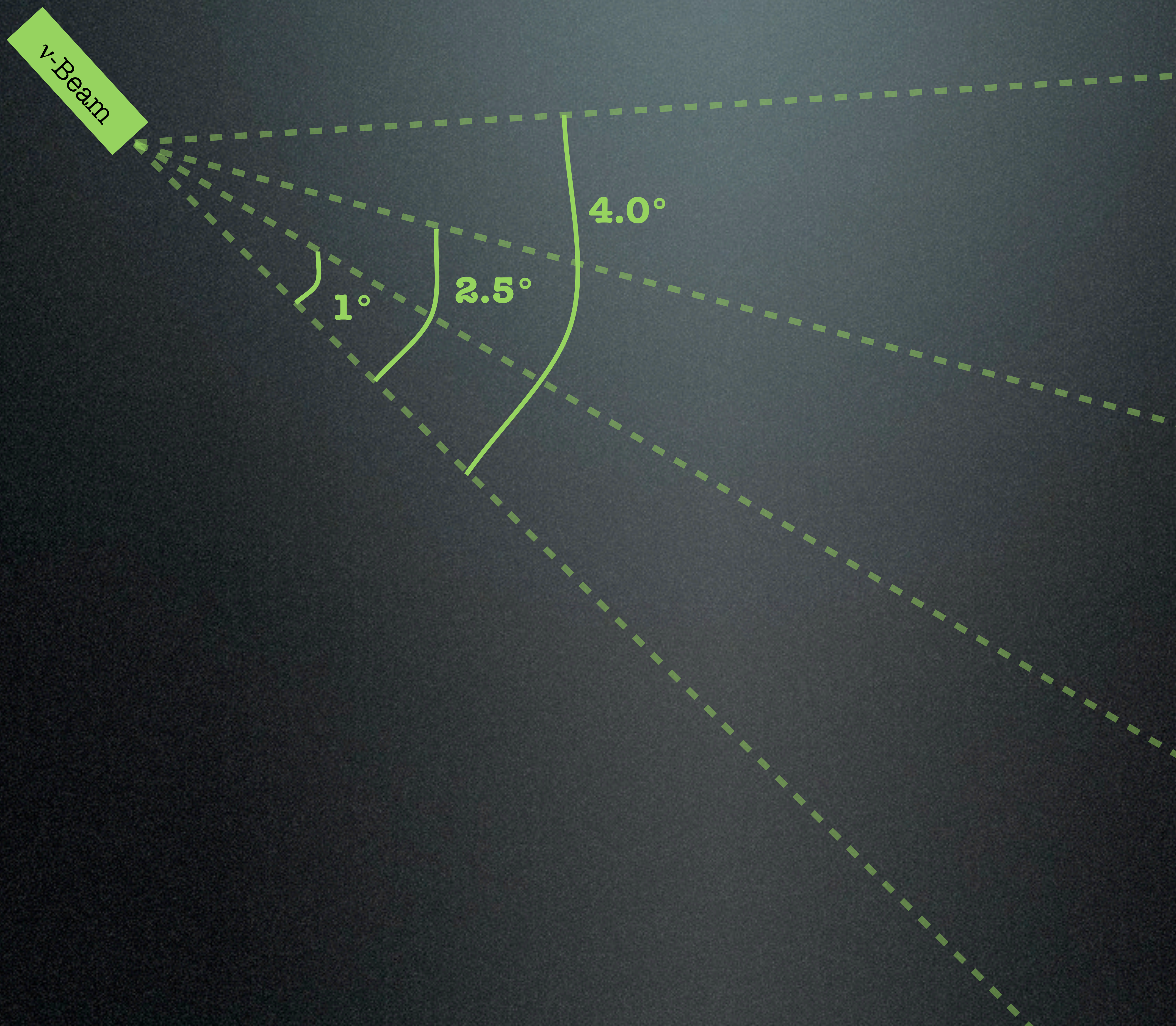
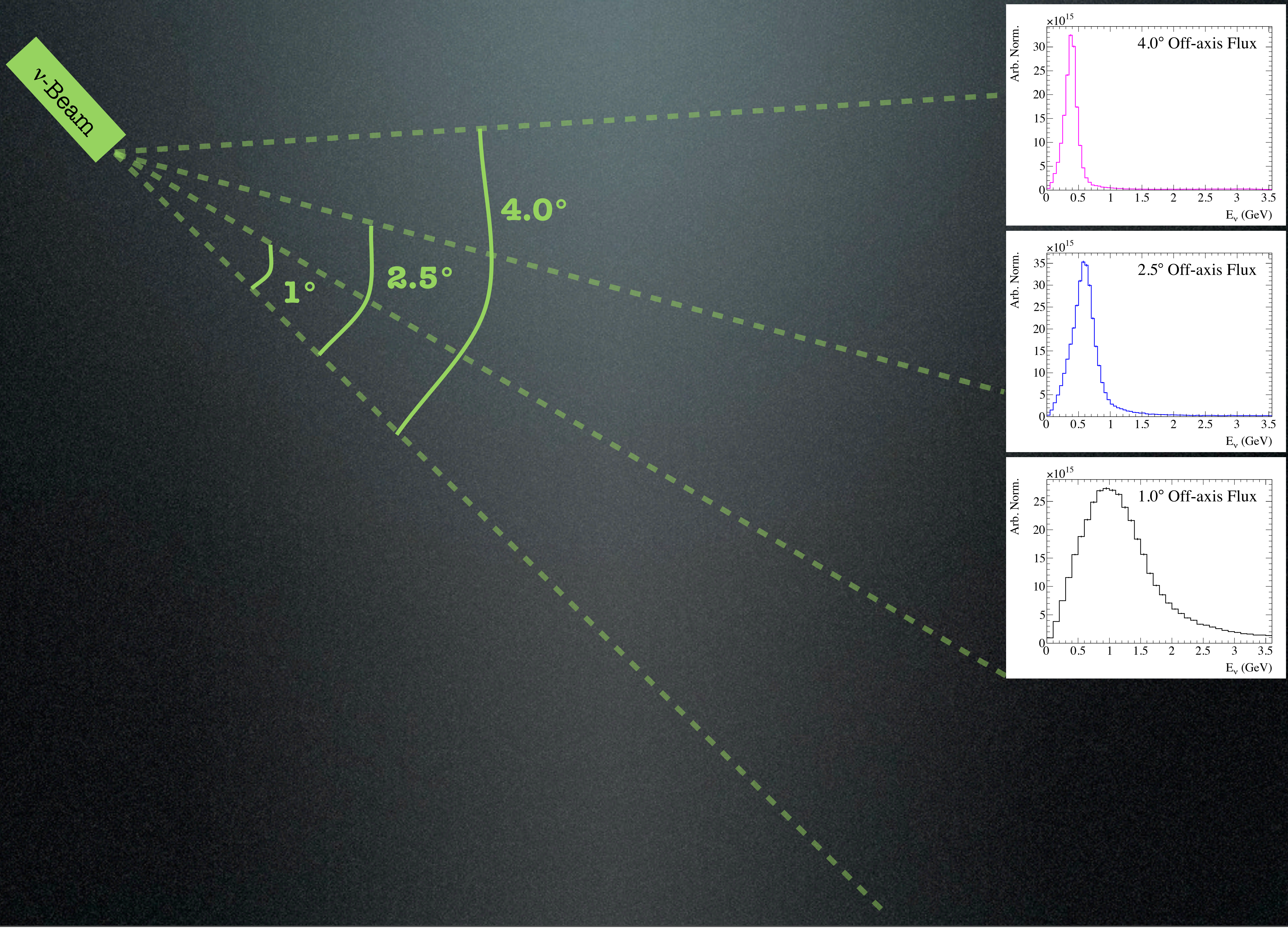


Reminder: NuPRISM Detector Concept



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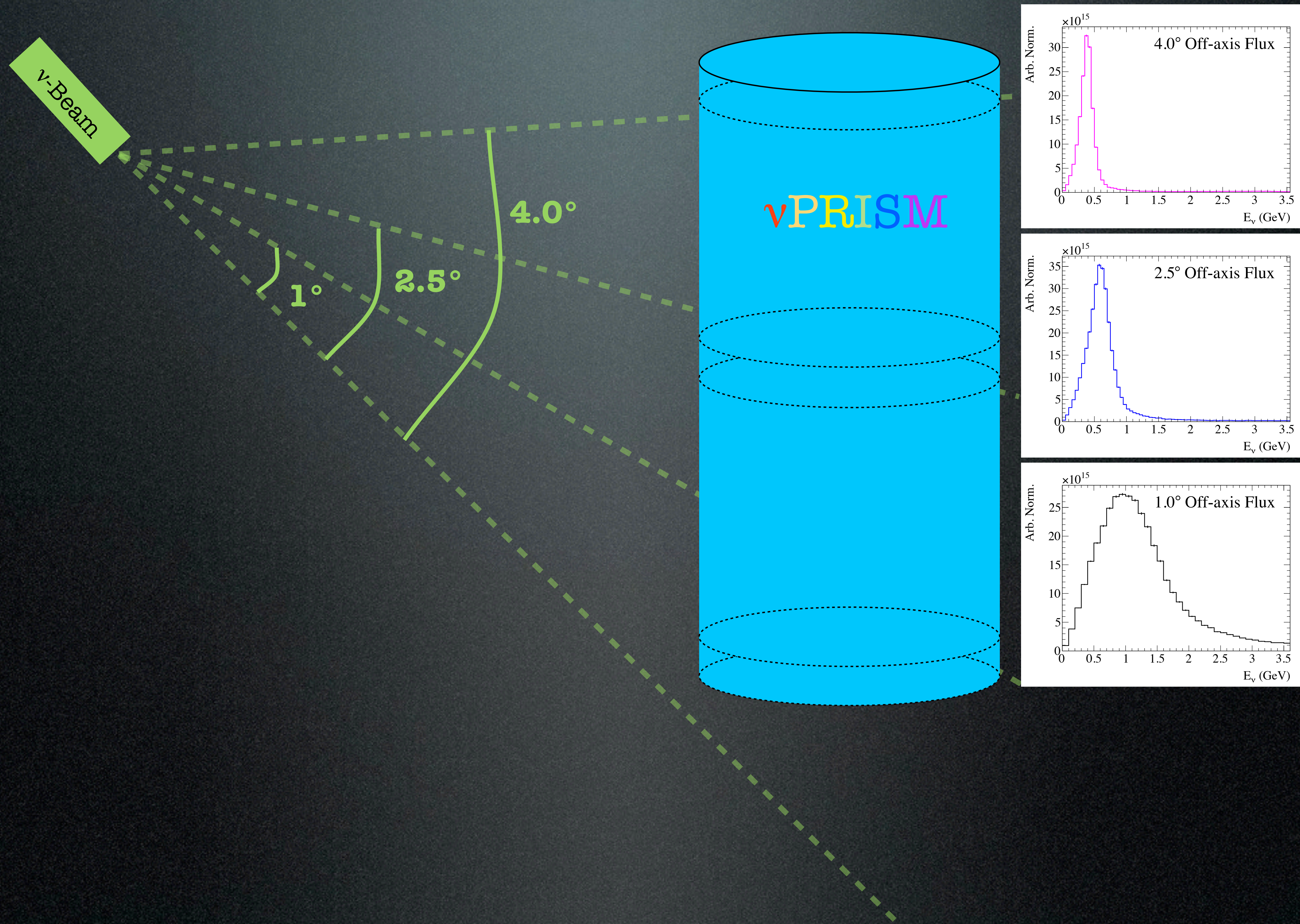

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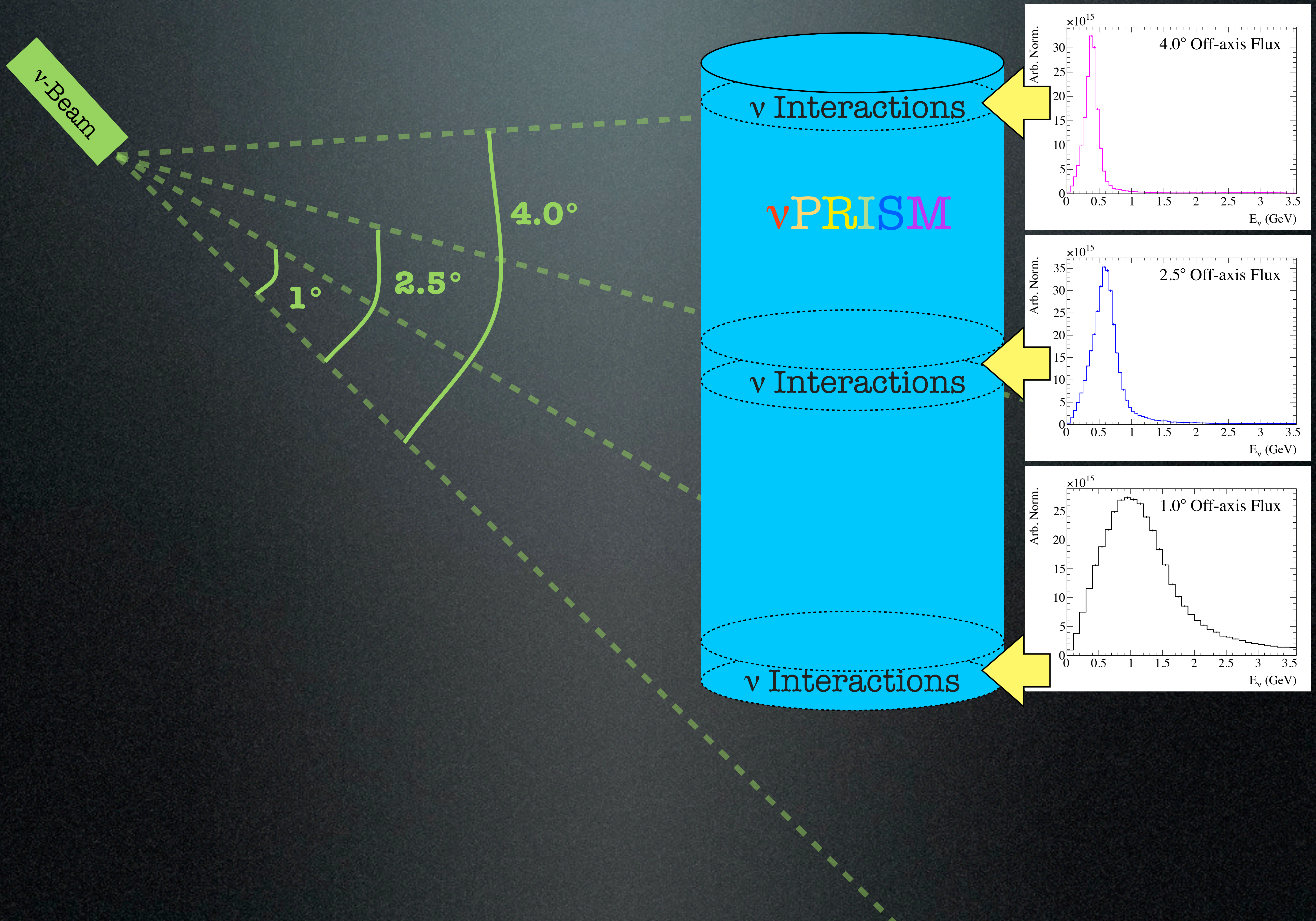

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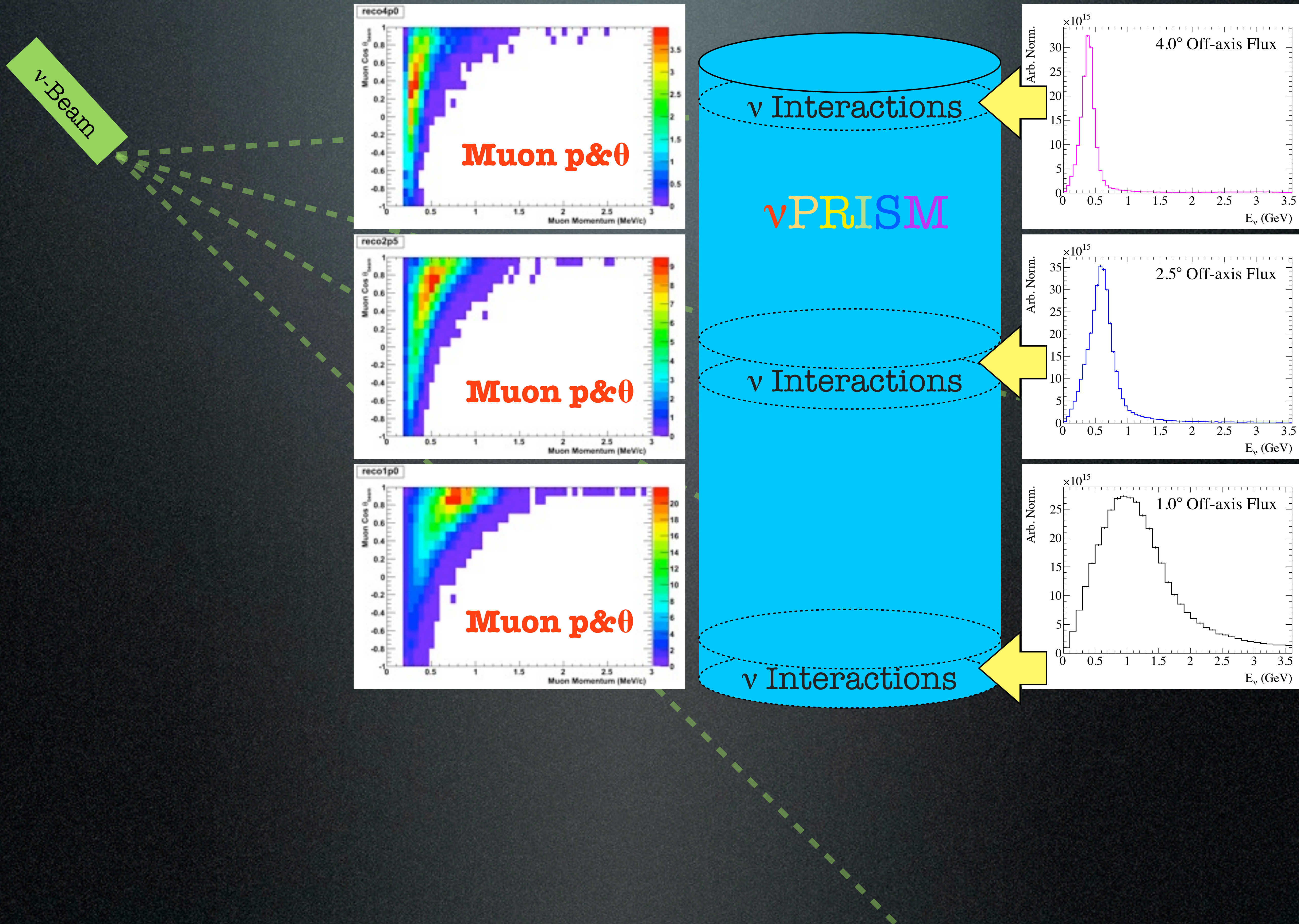

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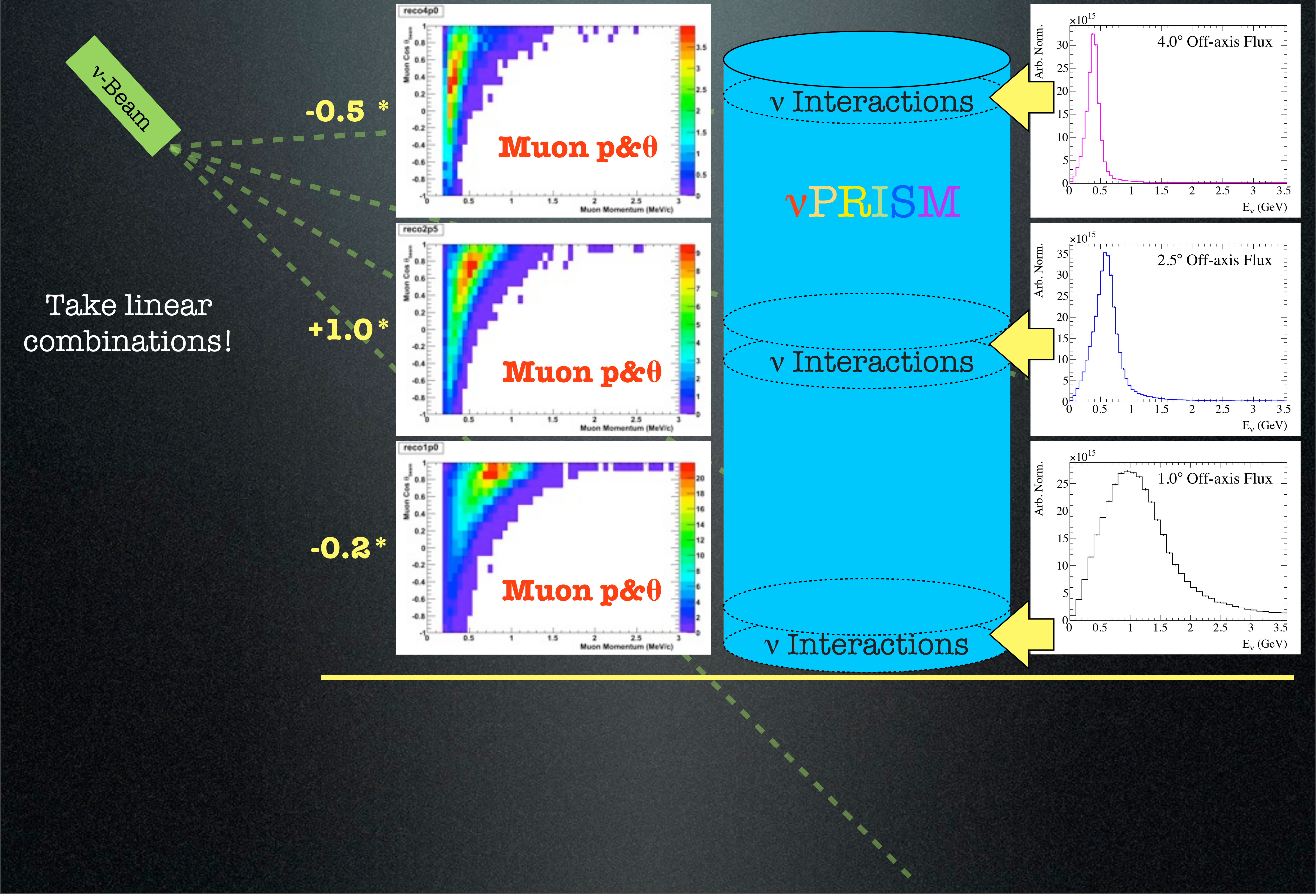

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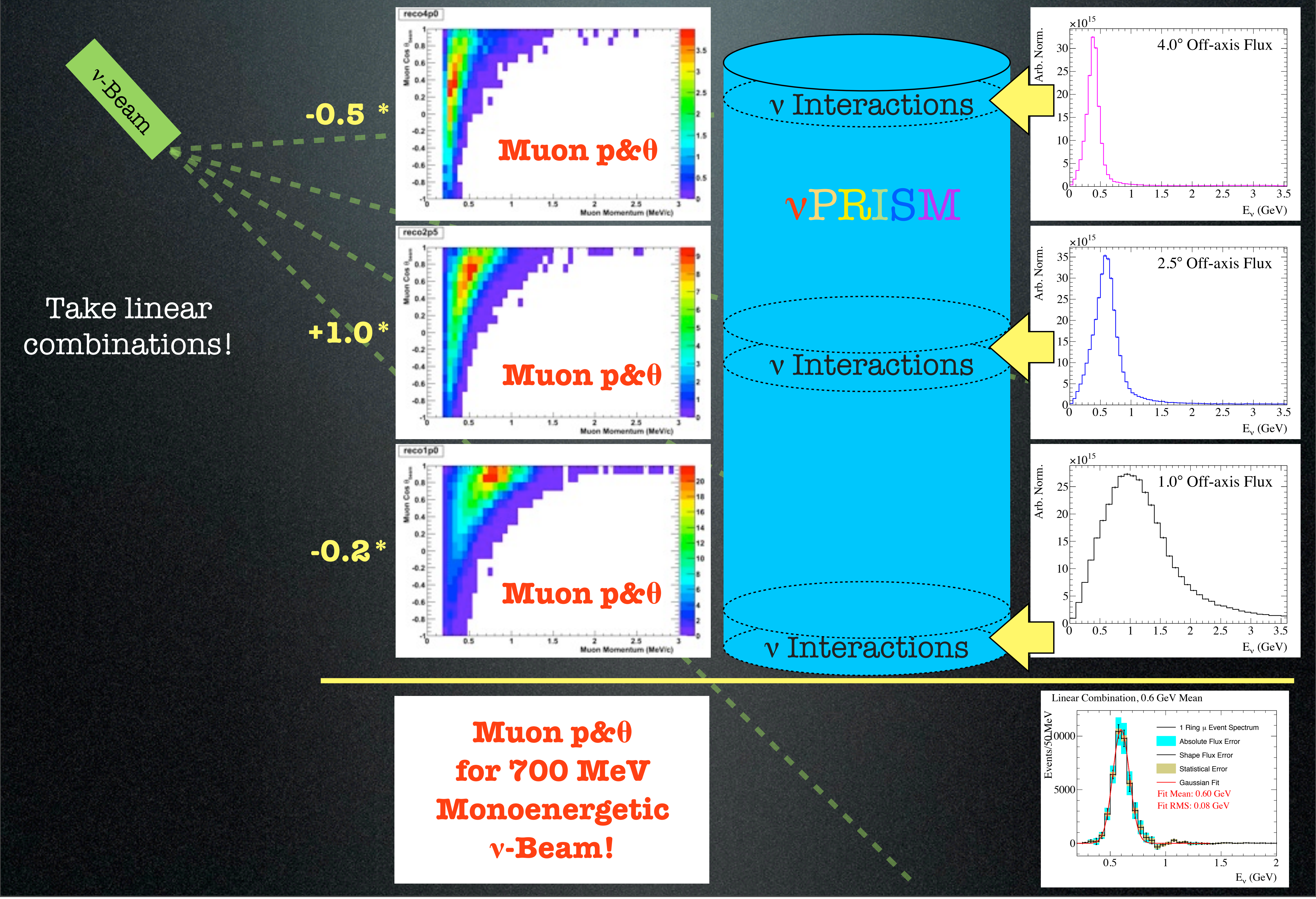

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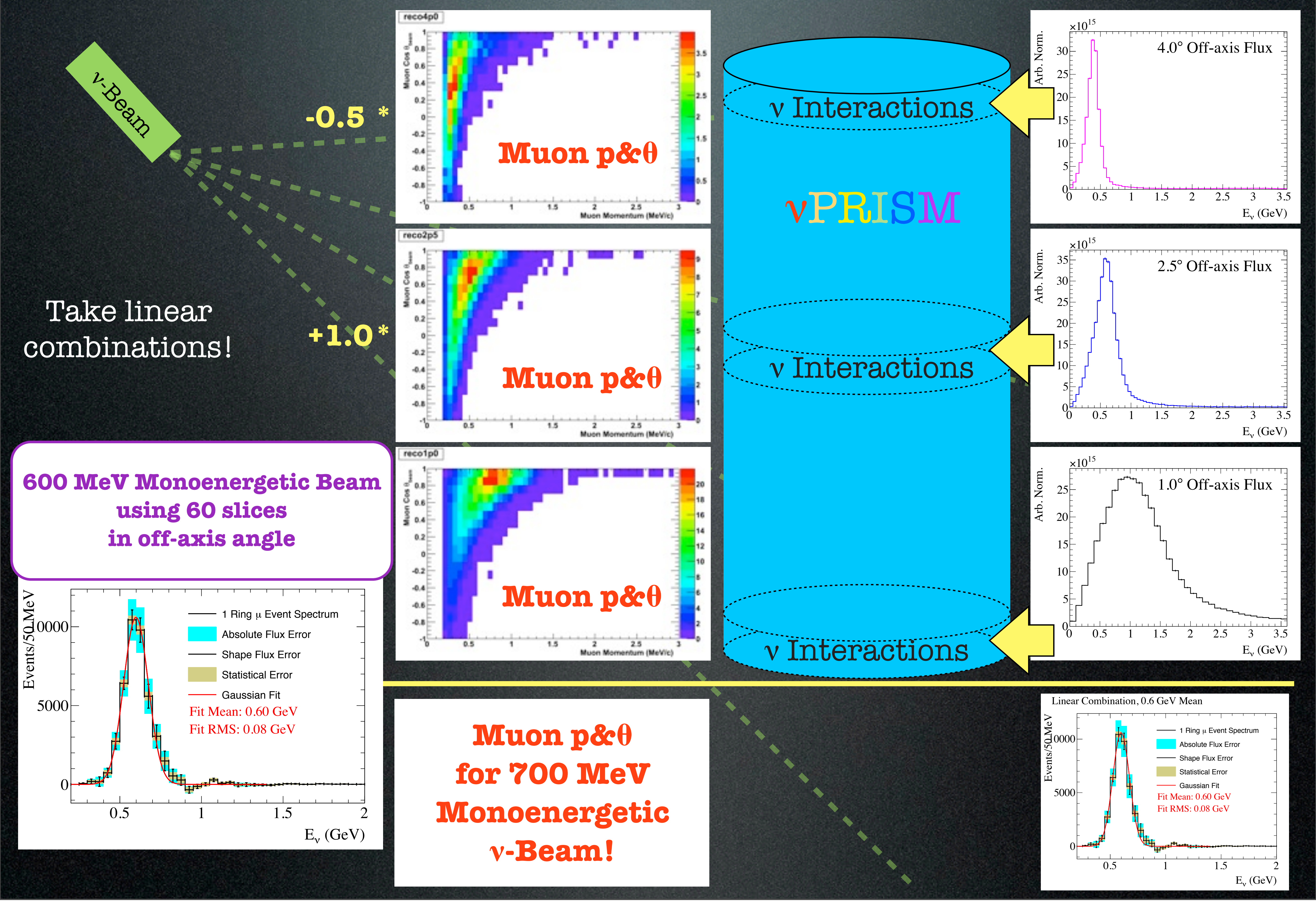
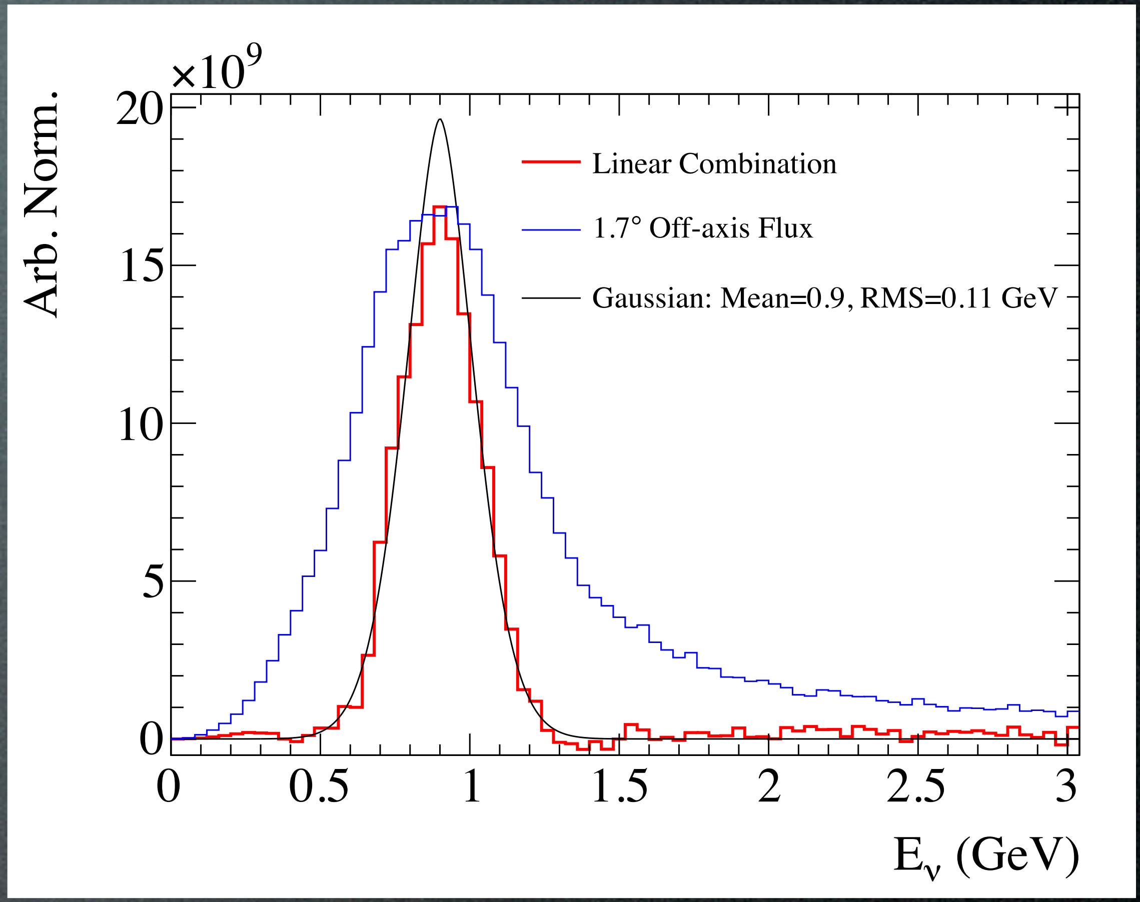
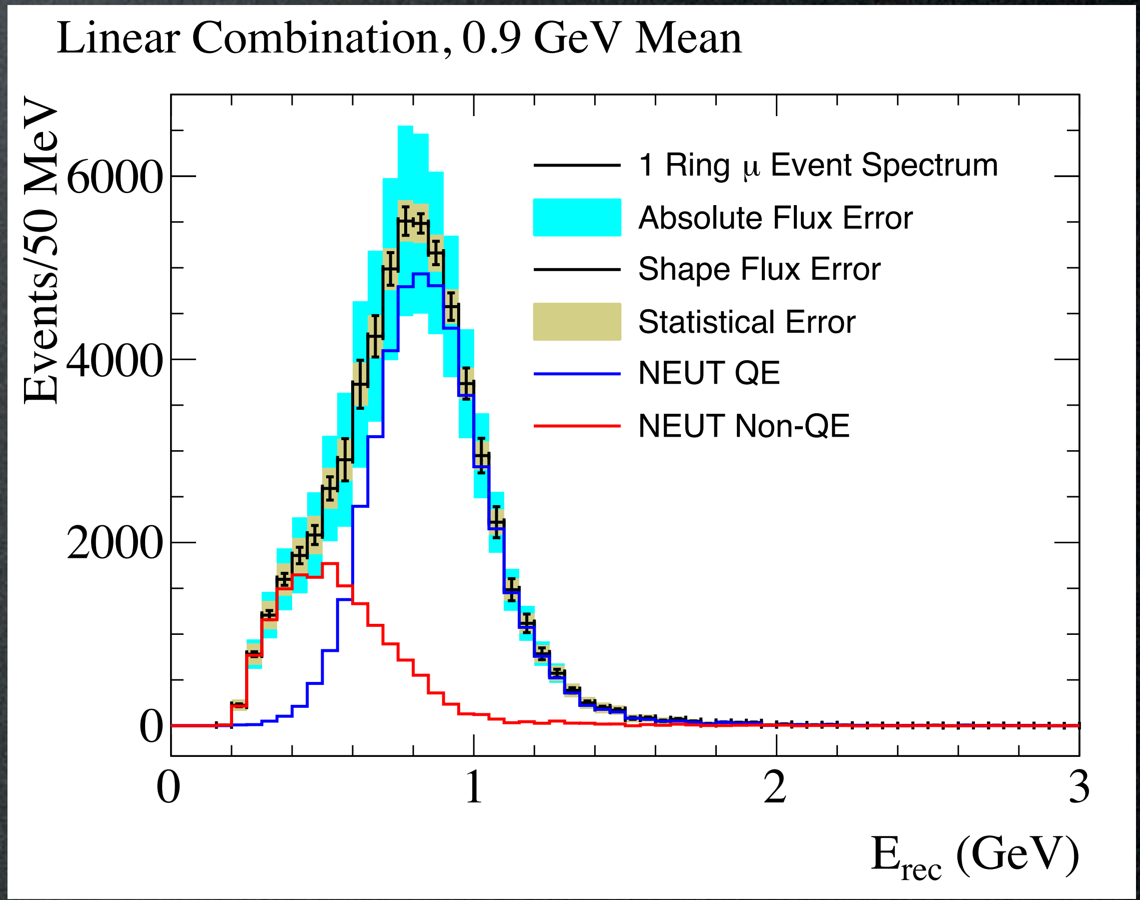


Benefits of a Monoenergetic Beam

- 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

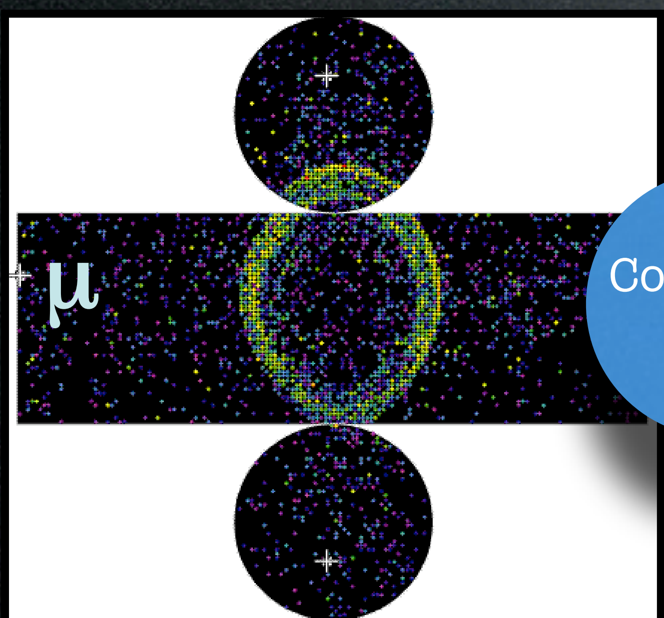




How We Typically Perform Oscillation Analyses

Observed far detector signal:

1-ring muon events



Composed Of:

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

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

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

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

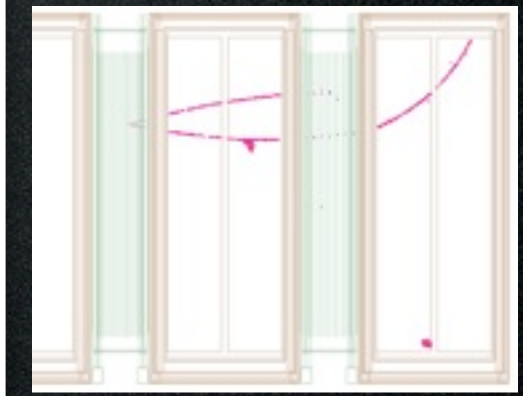
...

Nuclear model

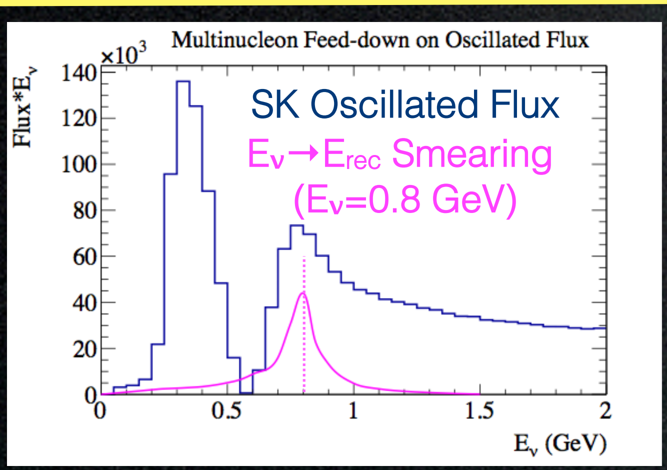
Predicted by poorly understood models

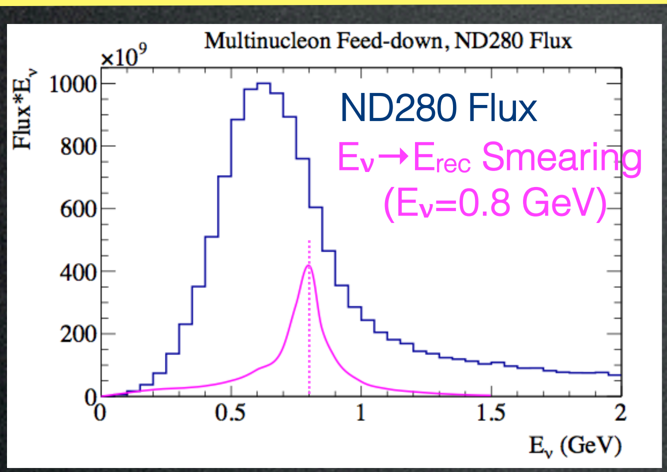
Parameter	E_ν Range	Nominal	Error	Class
M_A^{QE}	all	1.21 GeV/c^2	0.45	shape
M_A^{RES}	all	1.41 GeV/c^2	0.11	shape
p_F ^{12}C	all	217 MeV/c	30	shape
E_B ^{12}C	all	25 MeV	9	shape
SF ^{12}C	all	0 (off)	1 (on)	shape
CC Other shape ND280	all	0.0	0.40	shape
Pion-less Δ Decay	all	0.0	0.2	shape
CCQE E1	$0 < E_\nu < 1.5$	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



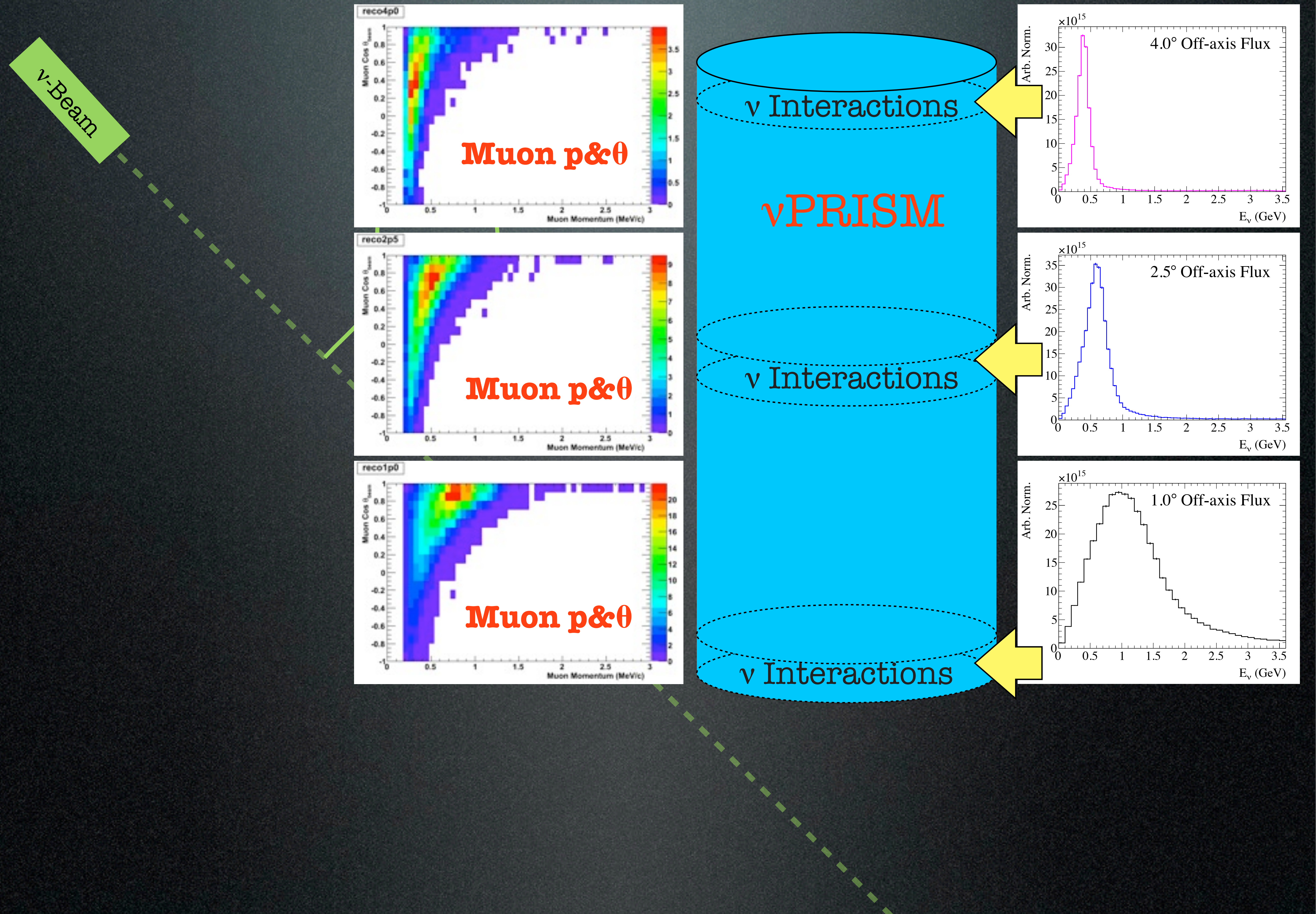
But the near and far fluxes are different!





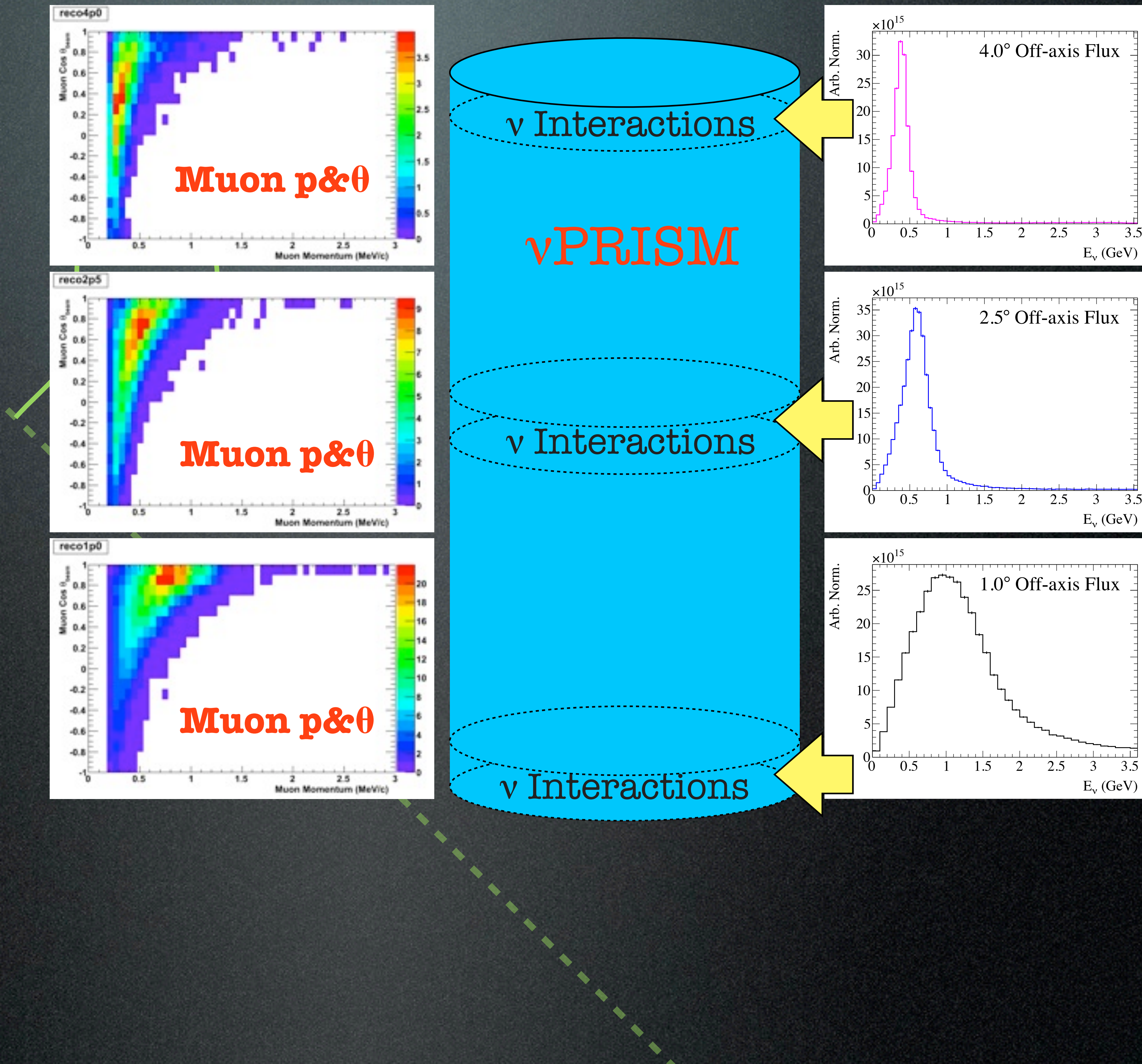
Goal of NuPRISM is to replace this procedure with a data measurement (to first order)

NuPRISM in Oscillation Analyses

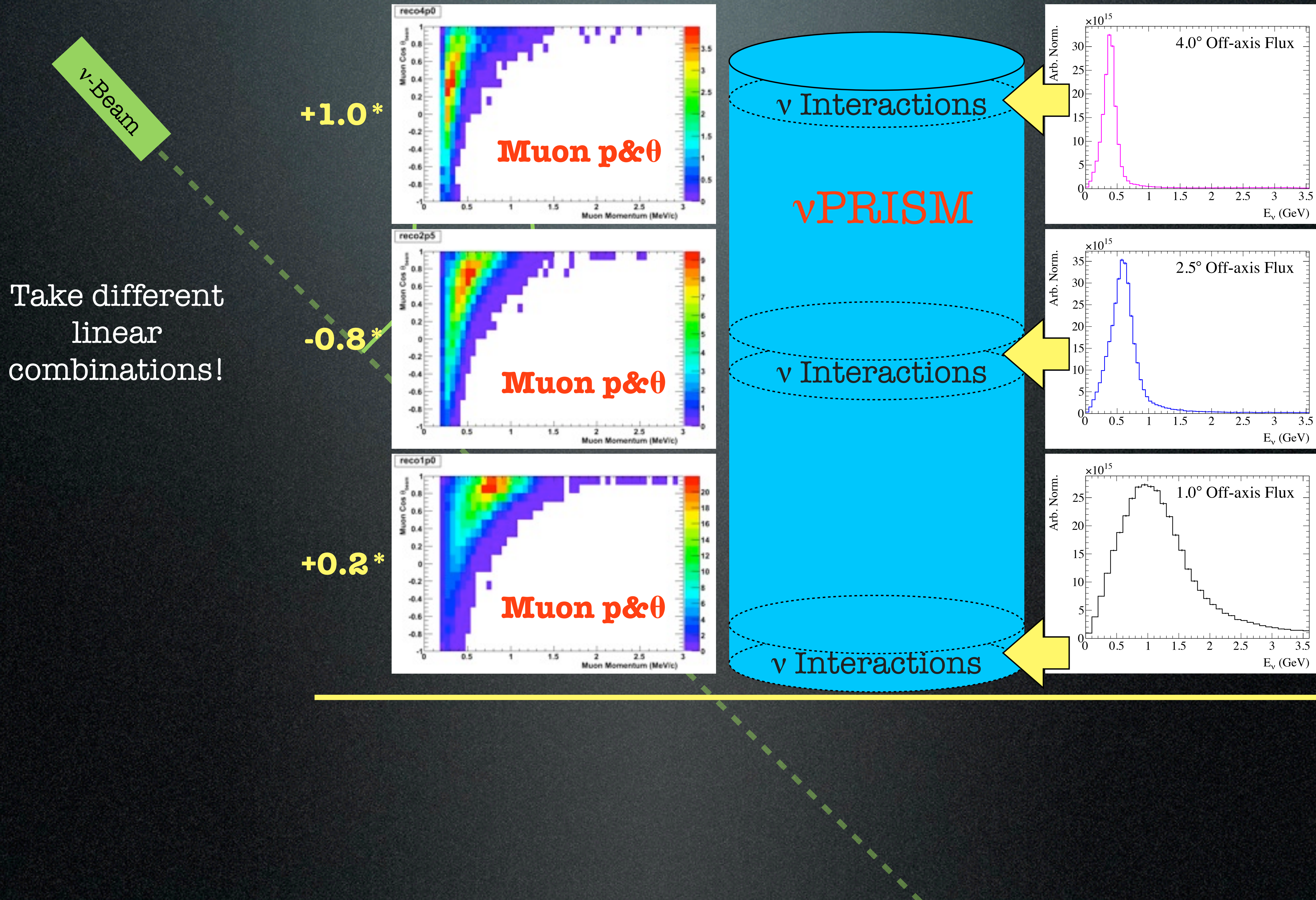


NuPRISM in Oscillation Analyses

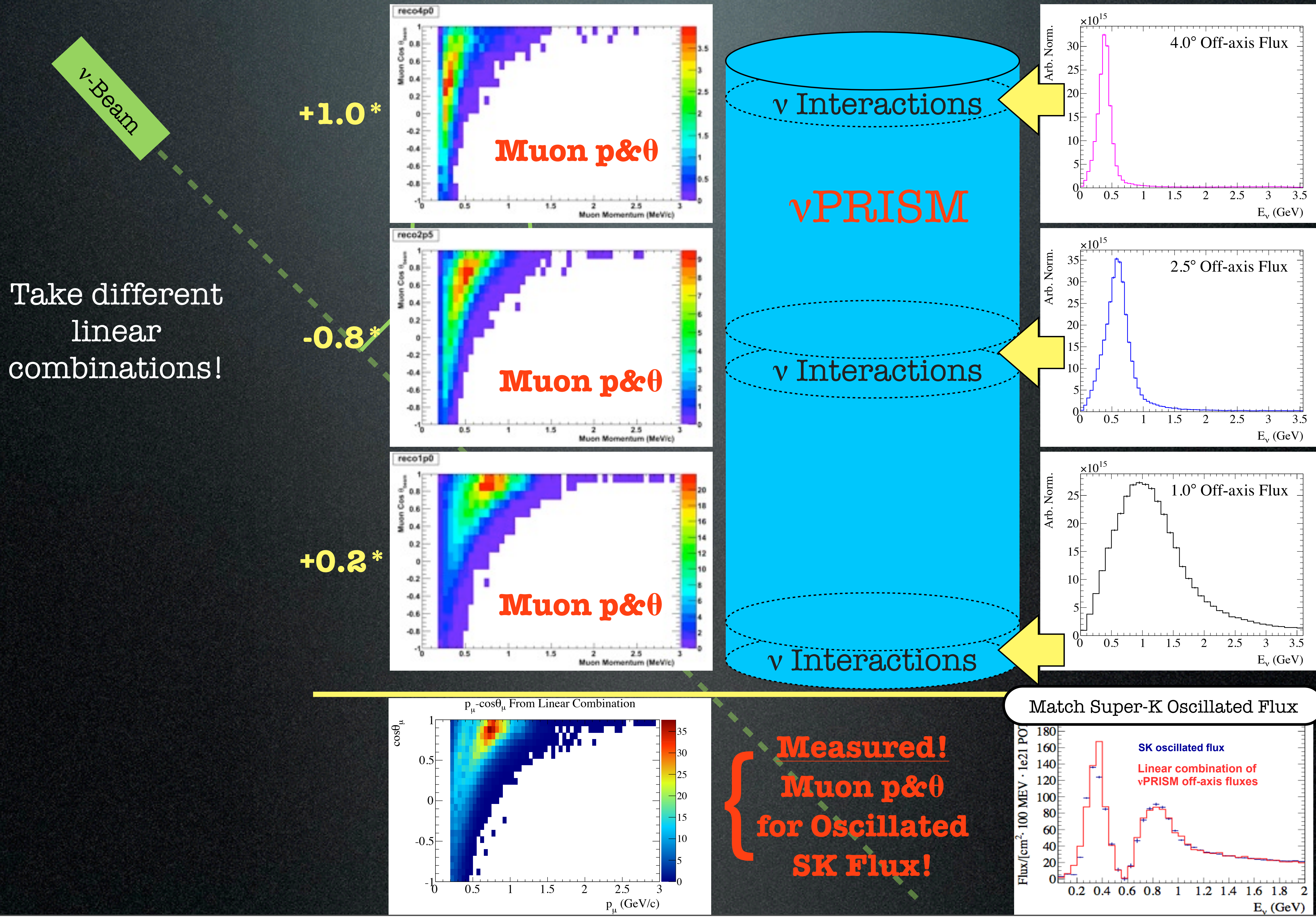
Take different linear combinations!



NuPRISM in Oscillation Analyses



NuPRISM in Oscillation Analyses

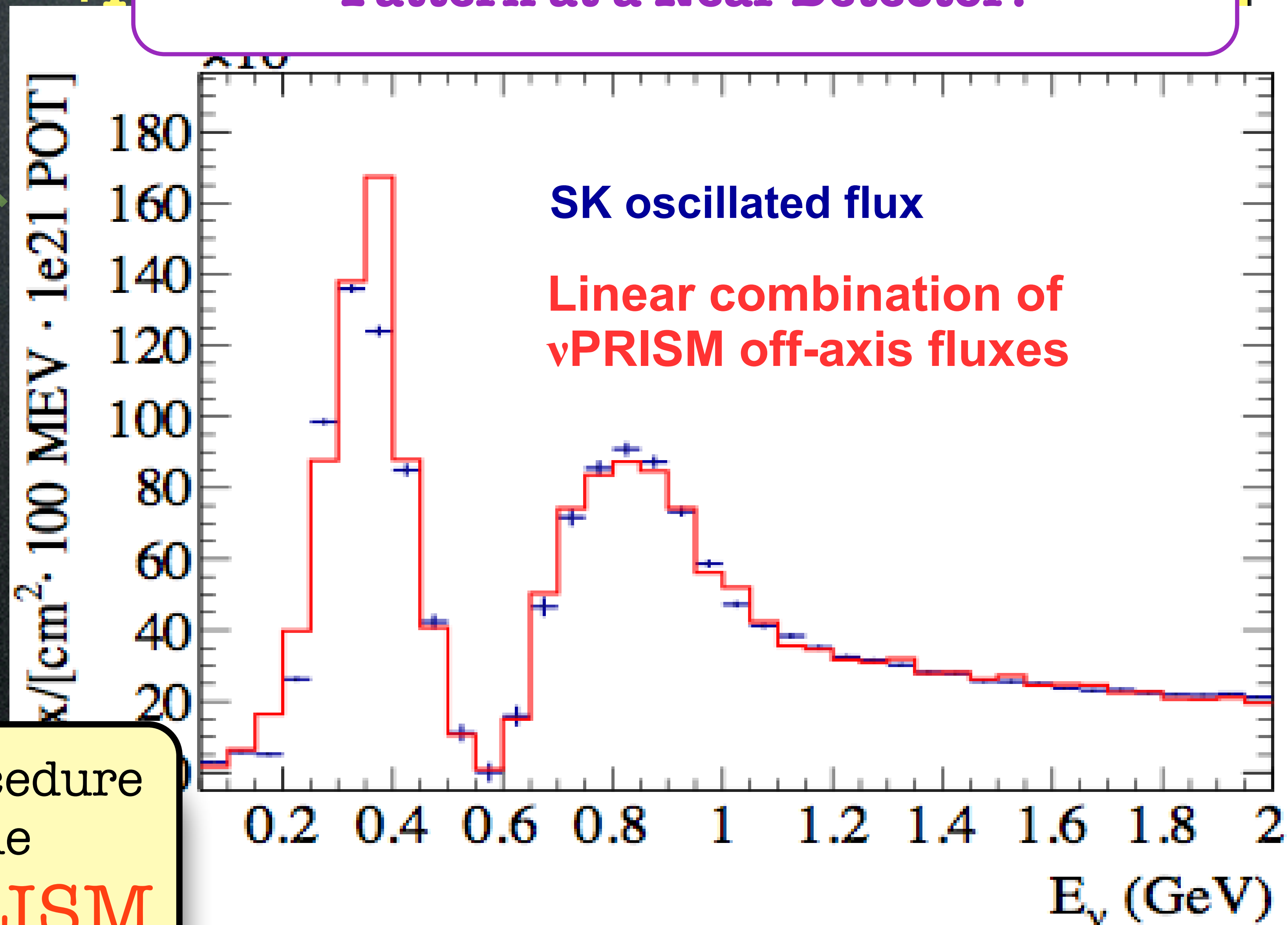


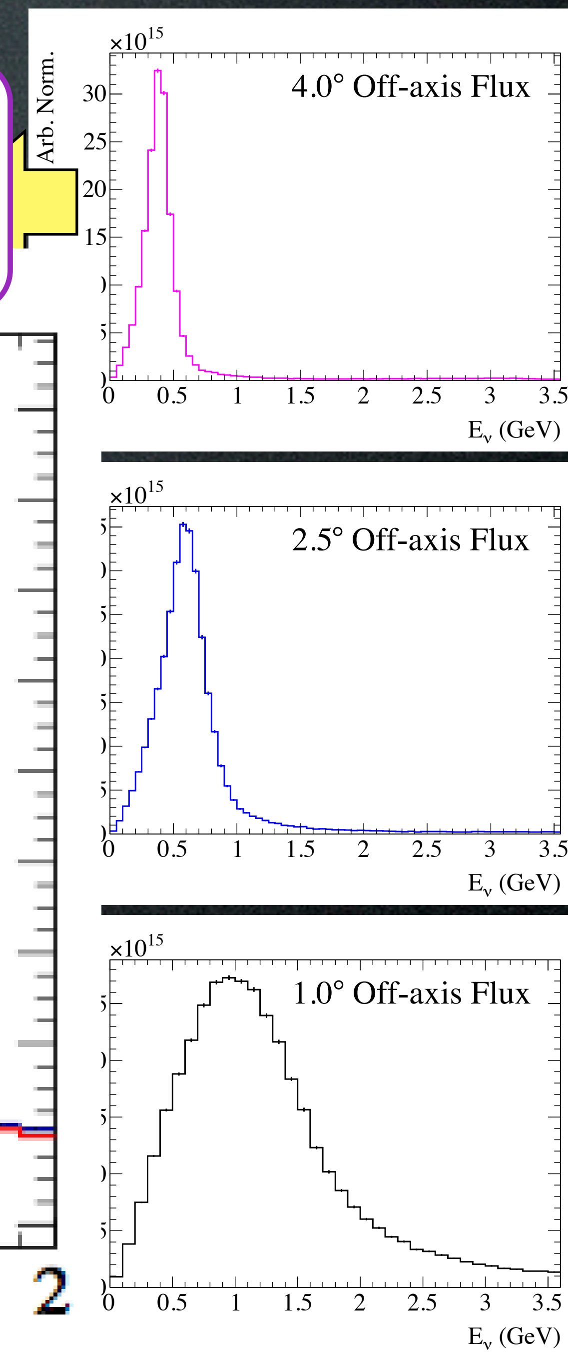
NuPRISM in Oscillation Analyses

ν-Beam

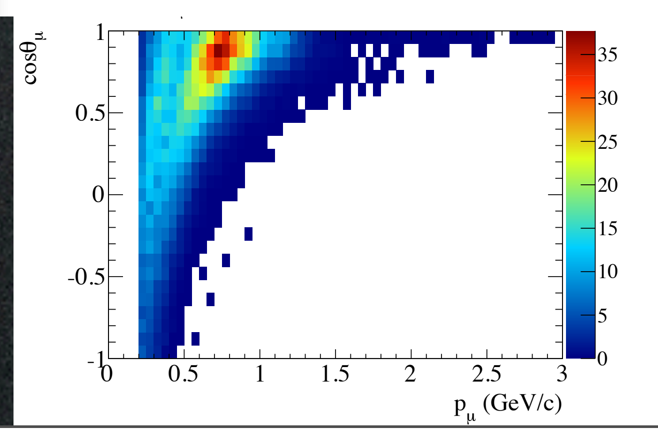
Reproduce Super-K Oscillation Pattern at a Near Detector!

Take different linear combinations!

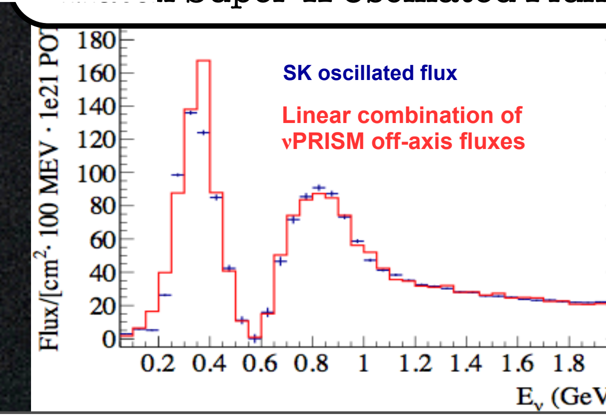




This is the procedure used for the T2K/nuPRISM ν_μ disappearance analysis (Details in the Next Talk by Mark Scott)



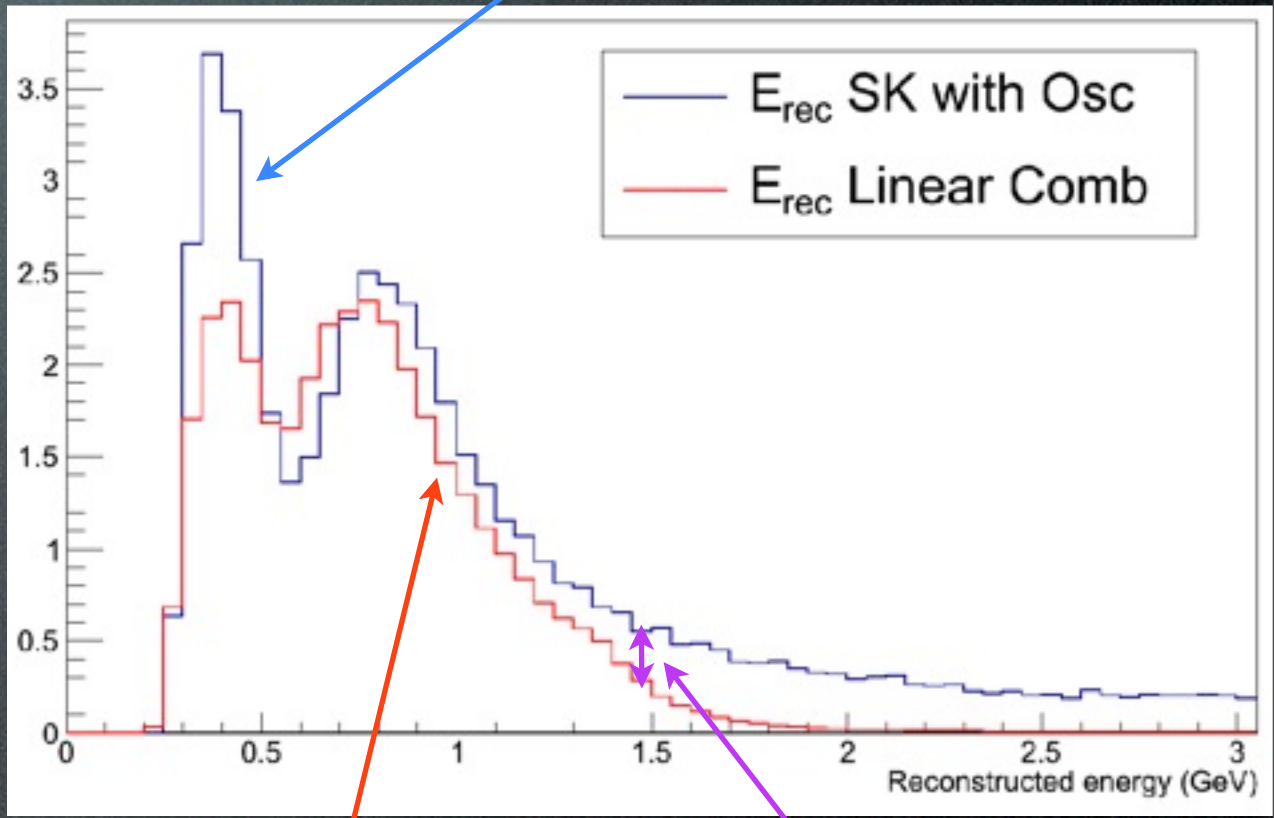
Measured! Muon p&θ for Oscillated SK Flux!



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

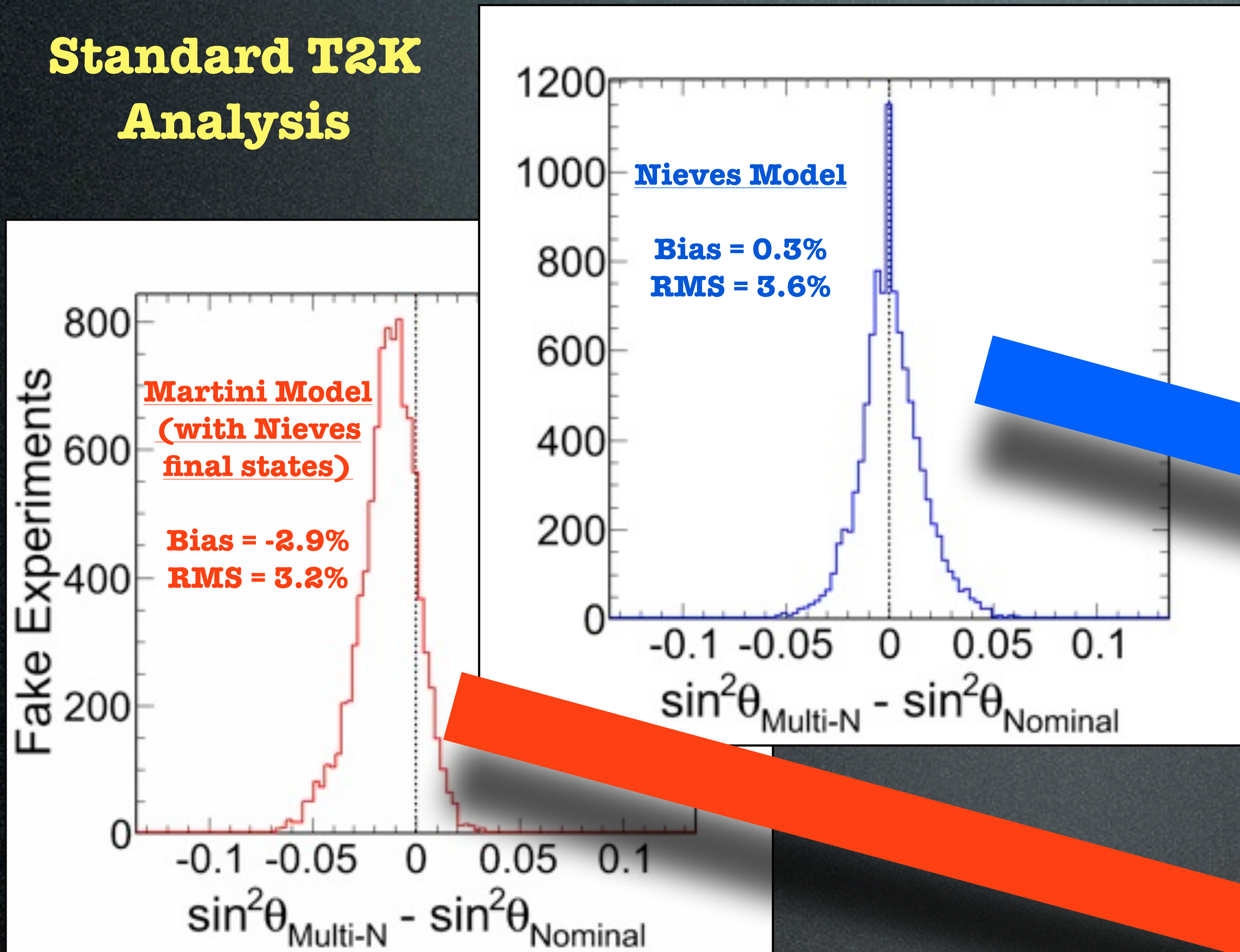


Now, NuPRISM directly measures most of this distribution

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

νPRISM ν_μ Disappearance Constraint

Standard T2K Analysis



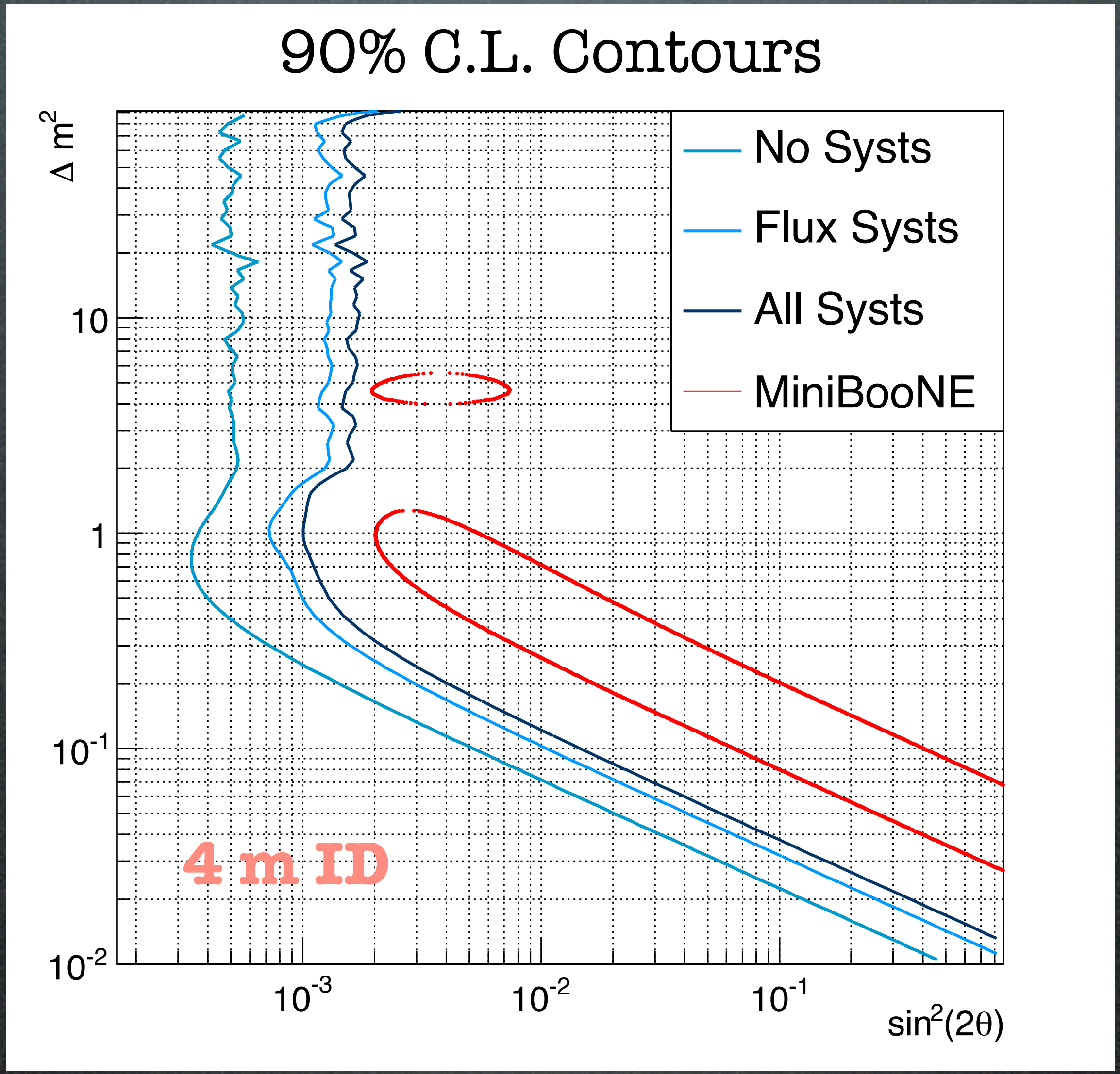
νPRISM Analysis

- Fake data studies show the bias in θ_{13} 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 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



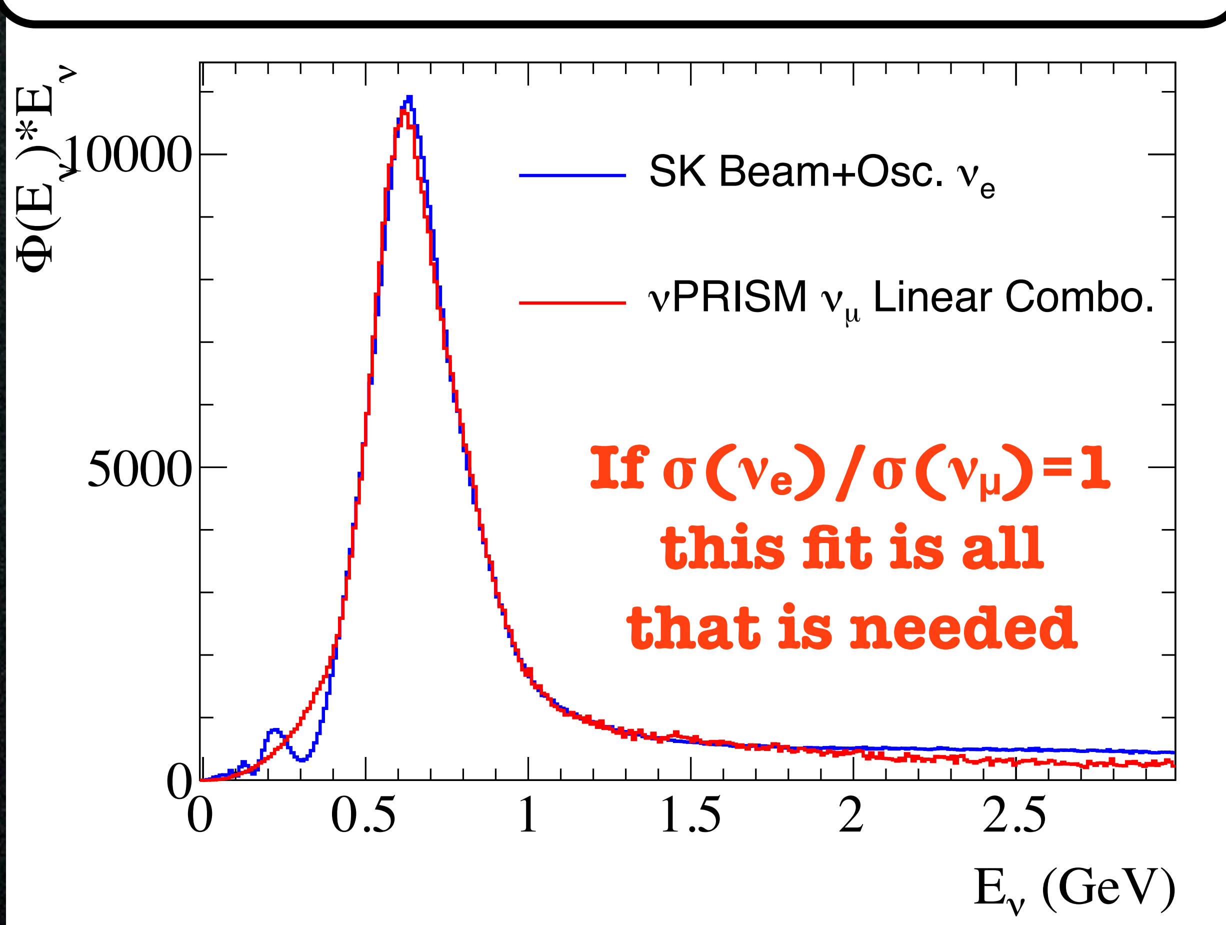
- Can already exclude currently allowed MiniBooNE regions at 90% C.L.
- Much better limits expected as the analysis improves

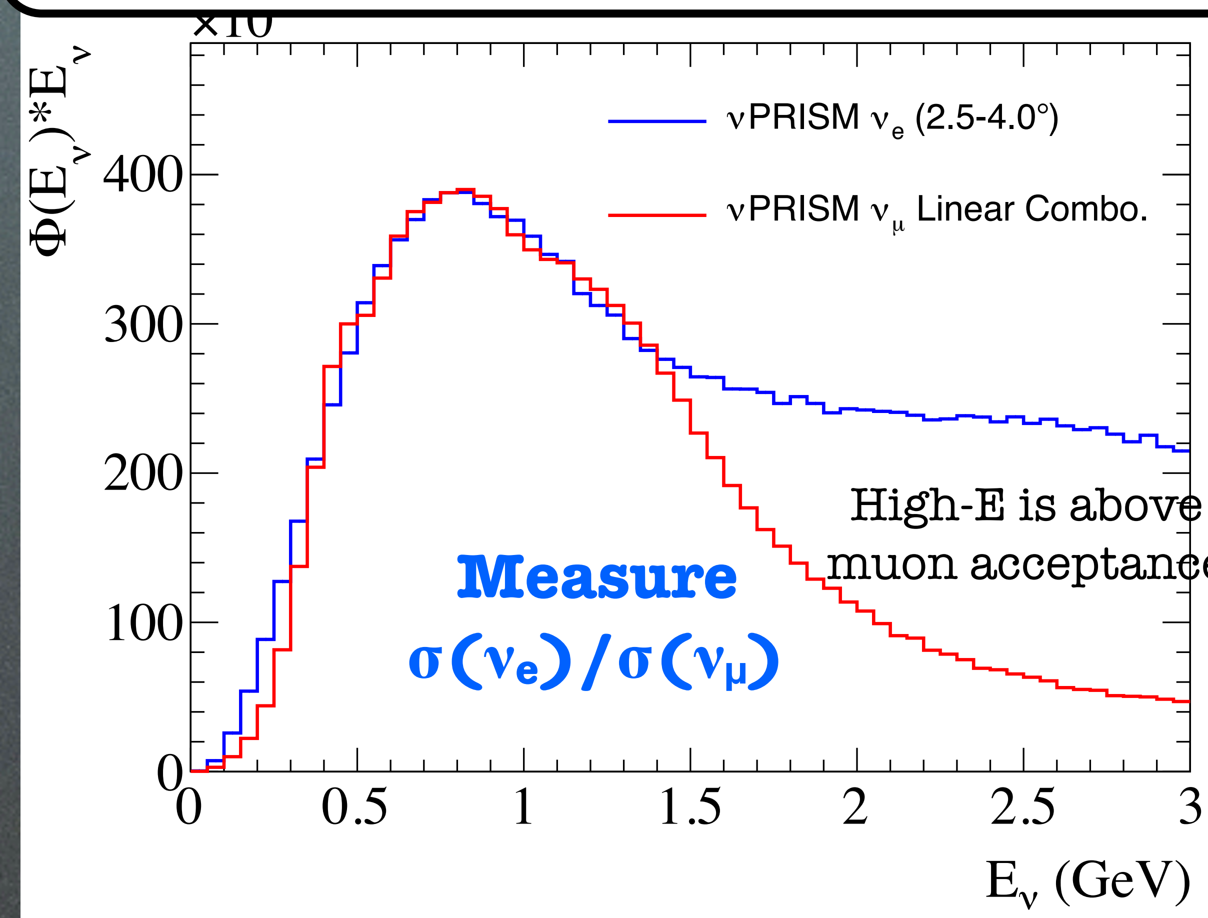
nuPRISM CPV (ν_e Appearance)

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

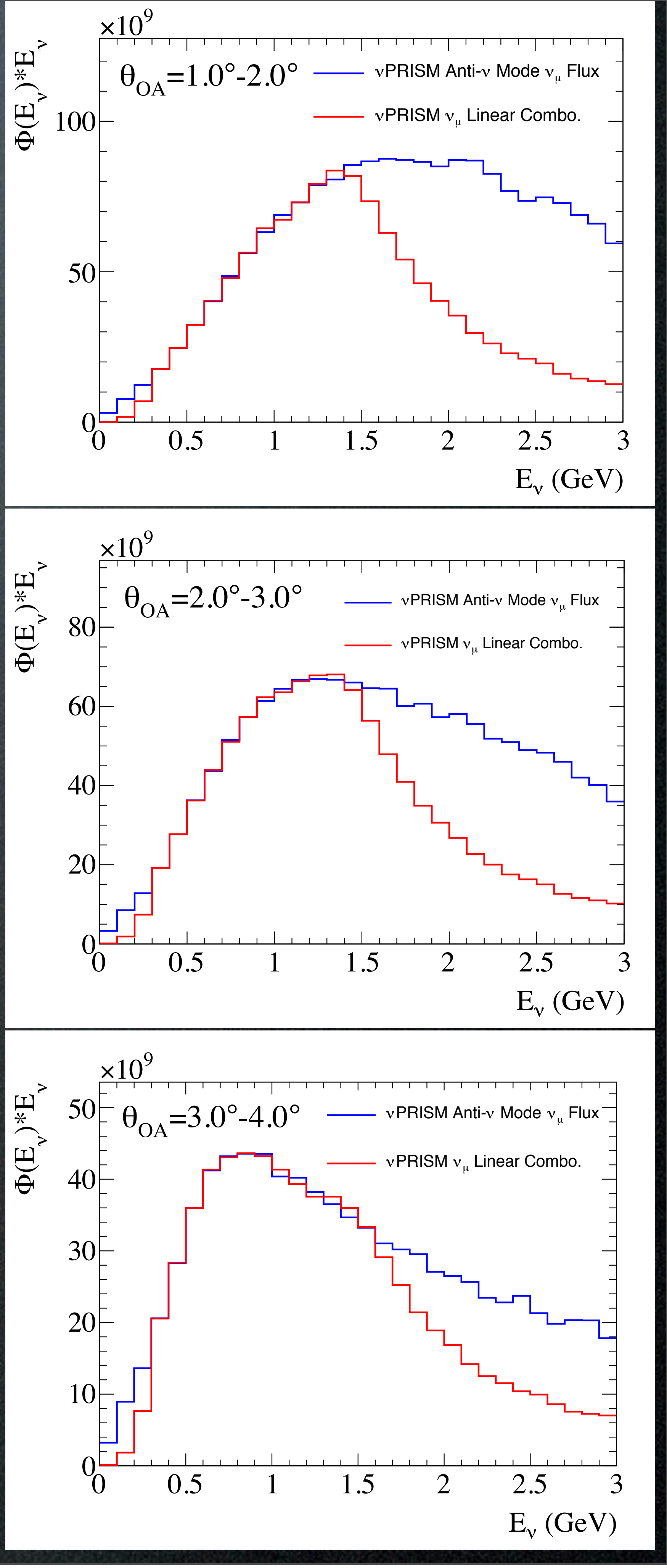




- Step 1 is the ν_e version of the ν_μ disappearance analysis
- Step 2 uses only nuPRISM to measure $\sigma(\nu_e)/\sigma(\nu_\mu)$
  - High energy disagreement is above muon acceptance
  - These plots show flux*E_ν, so difference is 1-ring μ events is smaller

Anti-neutrinos

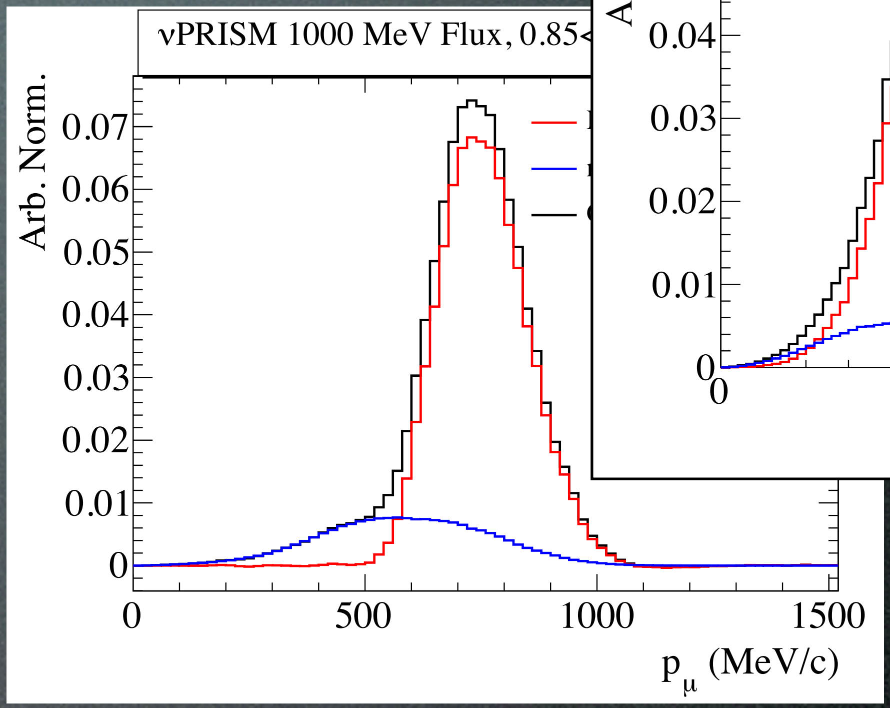
- T2K can switch between ν-mode and anti-ν-mode running by switching the beam focusing
- Anti-ν-mode analysis is the same as for neutrinos
    - Except with a much larger neutrino contamination
- Can use **ν-mode ν_μ data** to construct the **ν_μ background** in the **anti-ν-mode anti-ν_μ** data
    - 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

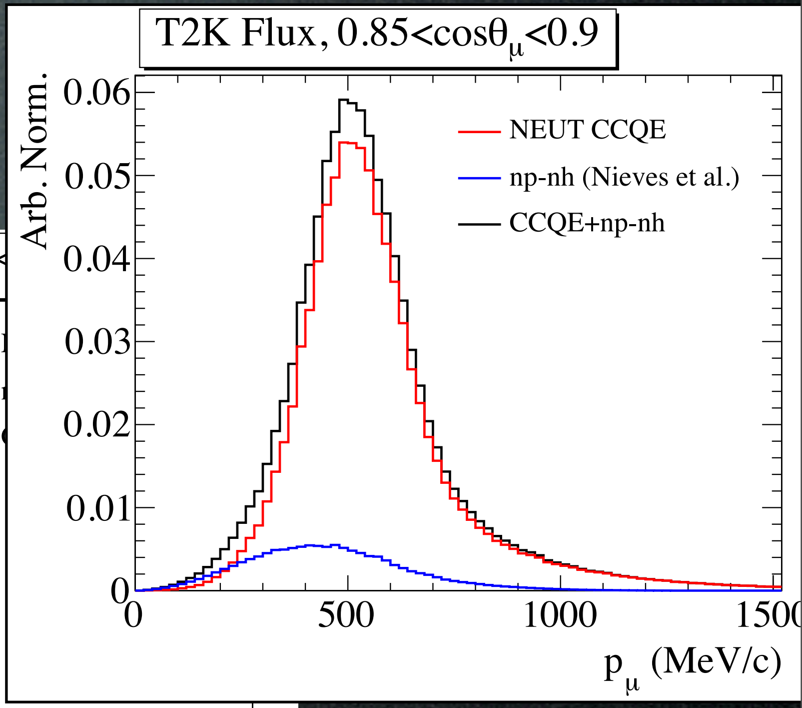


ν Cross Section Measurements

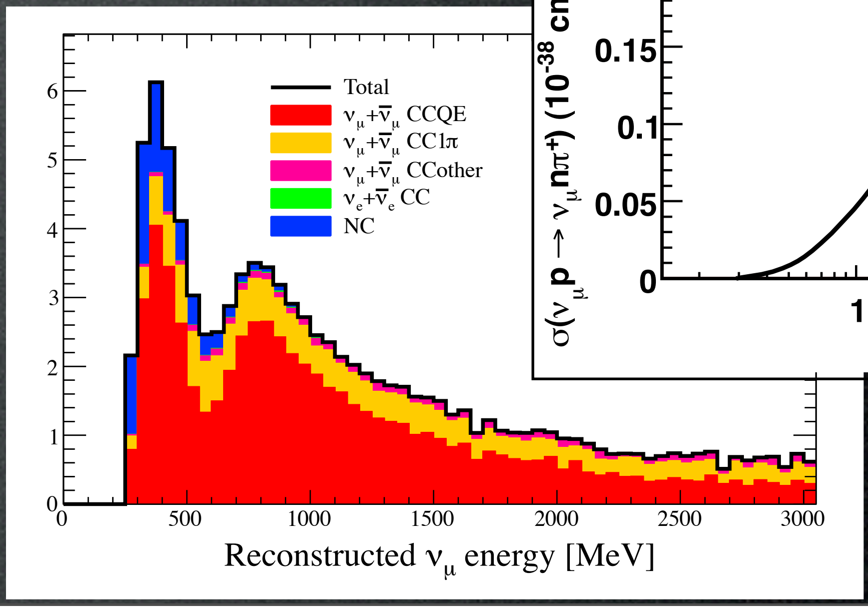
- Mono-energetic neutrino beams are ideal for measuring neutrino cross sections
  - Can provide a strong constraint on new models
- T2K ν_μ disappearance is subject to large $NC\pi^+$ uncertainties
  - 1 existing measurement
  - NuPRISM can place a strong constraint on this process vs E_ν

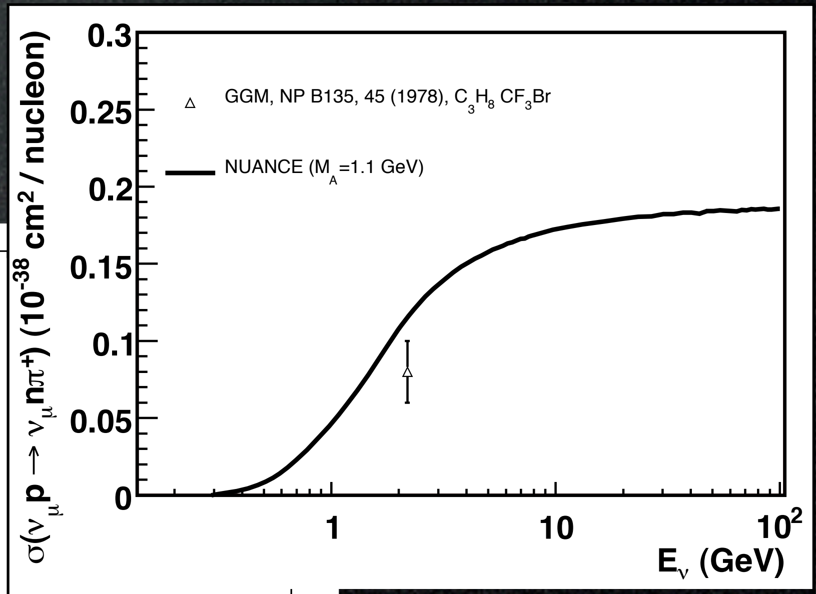
Example MEC event separation





$NC\pi^+$ at T2K

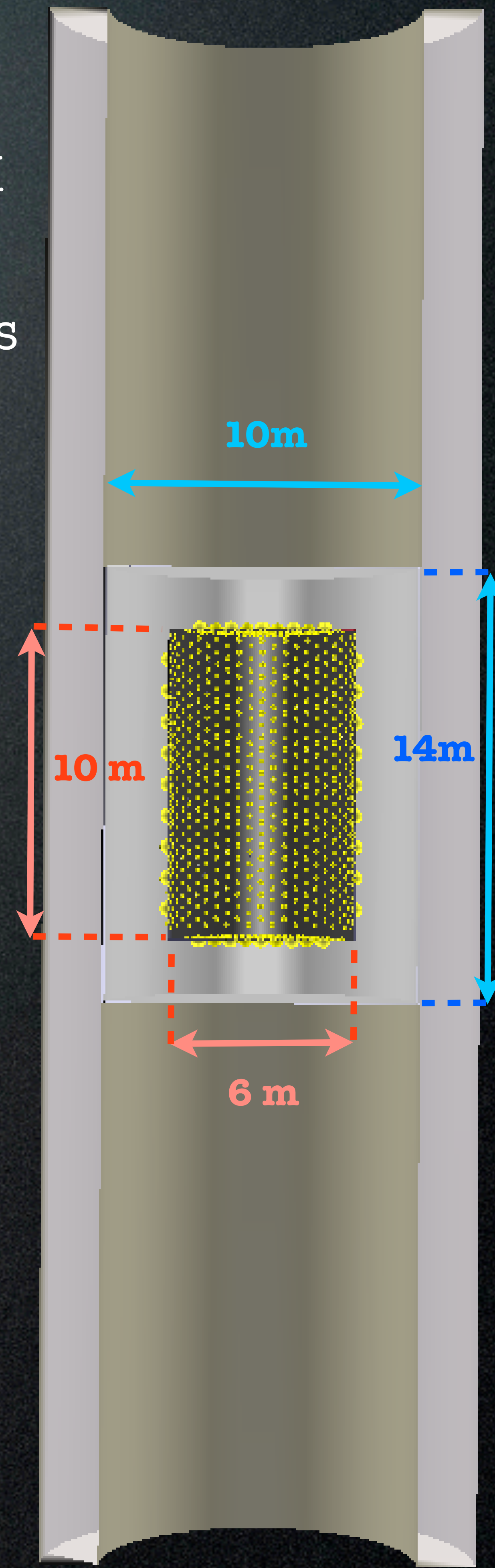




NuPRISM-Lite

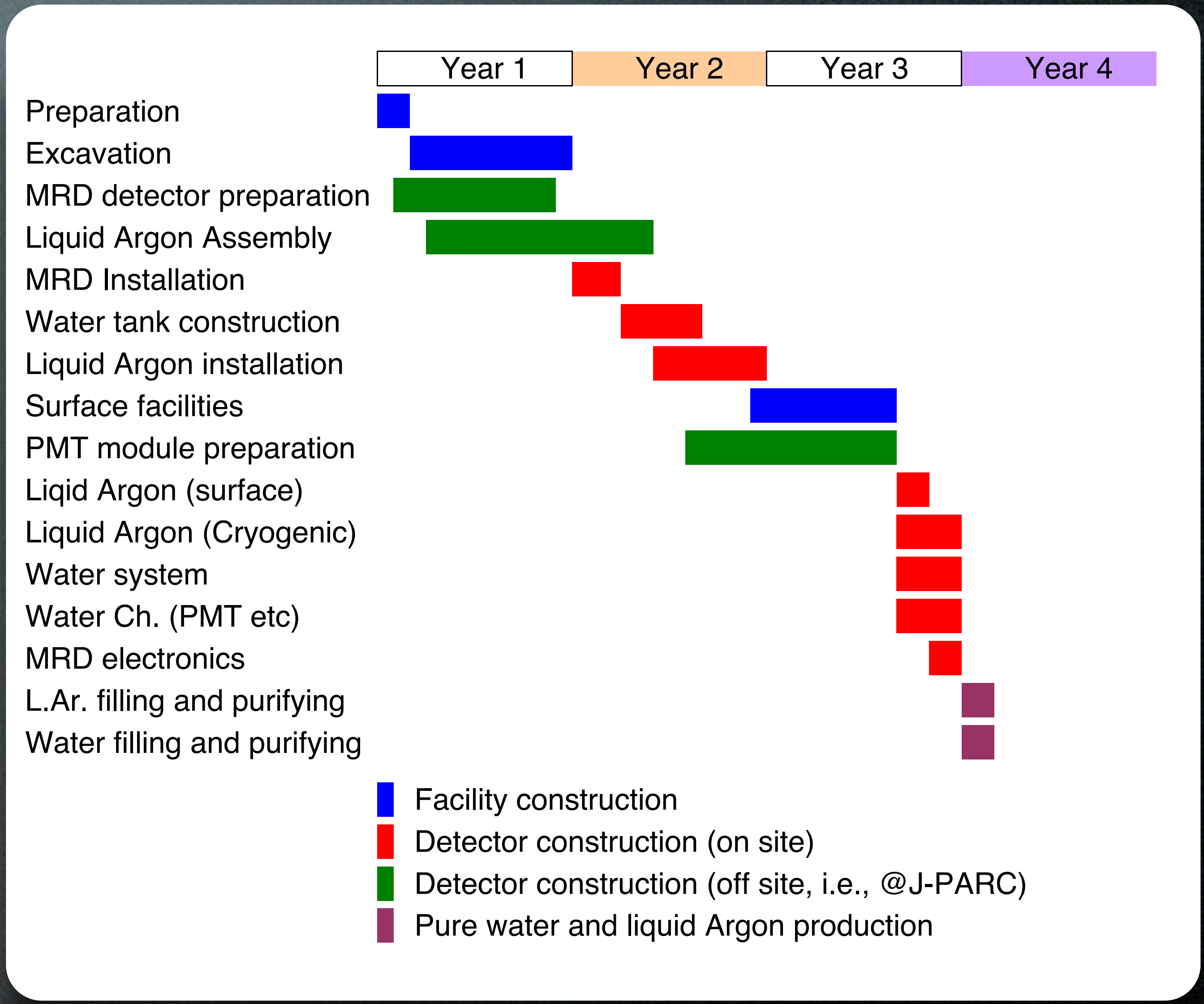
- Goal is to construct the first NuPRISM detector during the T2K era
  - Moveable detector that samples full off axis range in 5 steps
  - After J-PARC beam upgrade (2019?) T2K will double its POT
- Provides an ideal environment for Hyper-K detector R&D
  - Detector can be lifted out of the water for maintenance or replacements
- Provides a mechanism to grow the Japanese neutrino physics community toward Hyper-K
  - Large, engaged, international user base will be needed

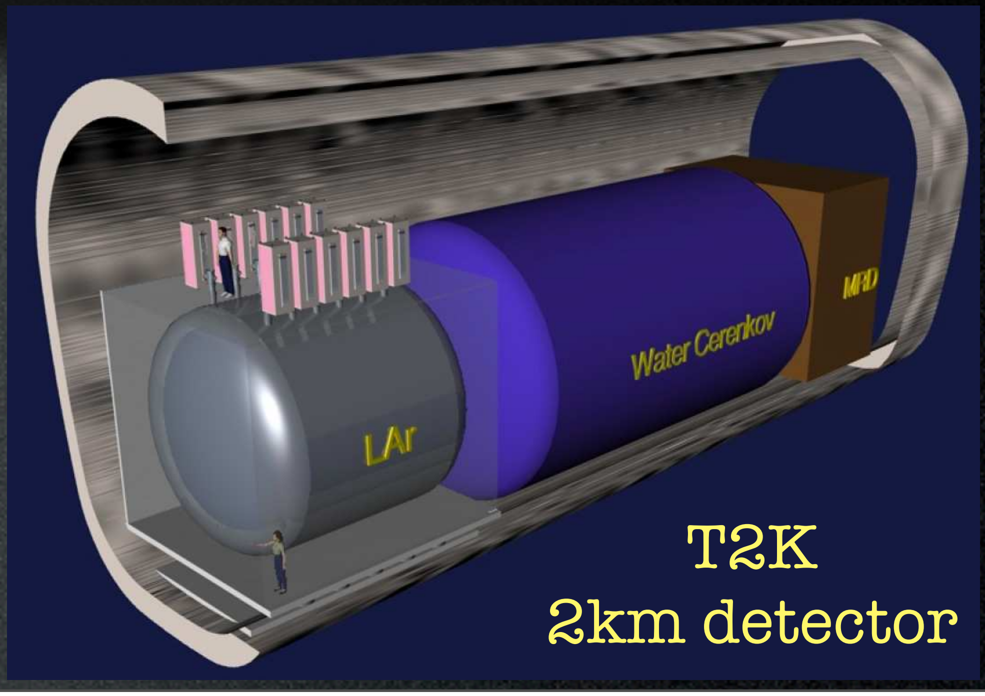
	Current	Transition Project	Future
Fermilab	NOvA	Short-baseline LAr	LBNF
J-PARC	T2K	??? NuPRISM?	Hyper-K



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 (2019?)
  - 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
- Total cost is $15-$20M
  - Cheaper than Fermilab short-baseline program
  - Will need to spend this eventually to build a Hyper-K ND anyway
- Several sources of money already exist to build a WC detector for Hyper-K R&D
  - If timescales are compatible; this money can be used for NuPRISM
  - Even if initial testing is done elsewhere (e.g. EGADs), can transfer to NuPRISM later

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

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Next Steps

- Full proposal will be submitted to the J-PARC PAC, July 15-17
- Significant progress has been made in detector simulation (next talk)
- However, reconstruction is not yet available
  - Simple tuning of PMT QE and water attenuation was not sufficient for 8" PMTs
  - Full tuning of PMT pulse shape, angular acceptance, and time PDFs are now underway
    - Same procedure as for Hyper-K (see fiTQun talk)
- Aiming for significant progress in physics analyses for the full proposal
  - Full ν_μ disappearance analysis with estimate of all systematic errors
  - Complete ν_e appearance analysis with CP violation constraint
    - Including anti-neutrinos if wrong-sign background constraint can be finished
- Planning a weeklong workshop in mid-March
  - Intensive week of analysis work (very few talks)

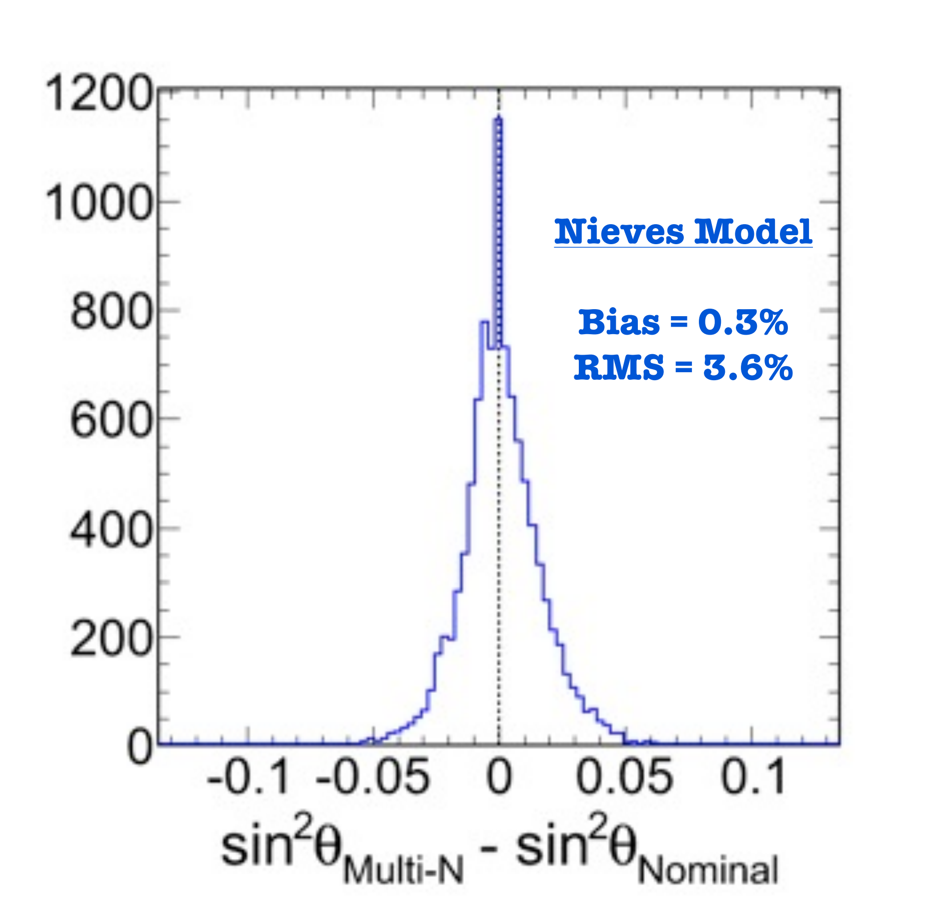
Summary

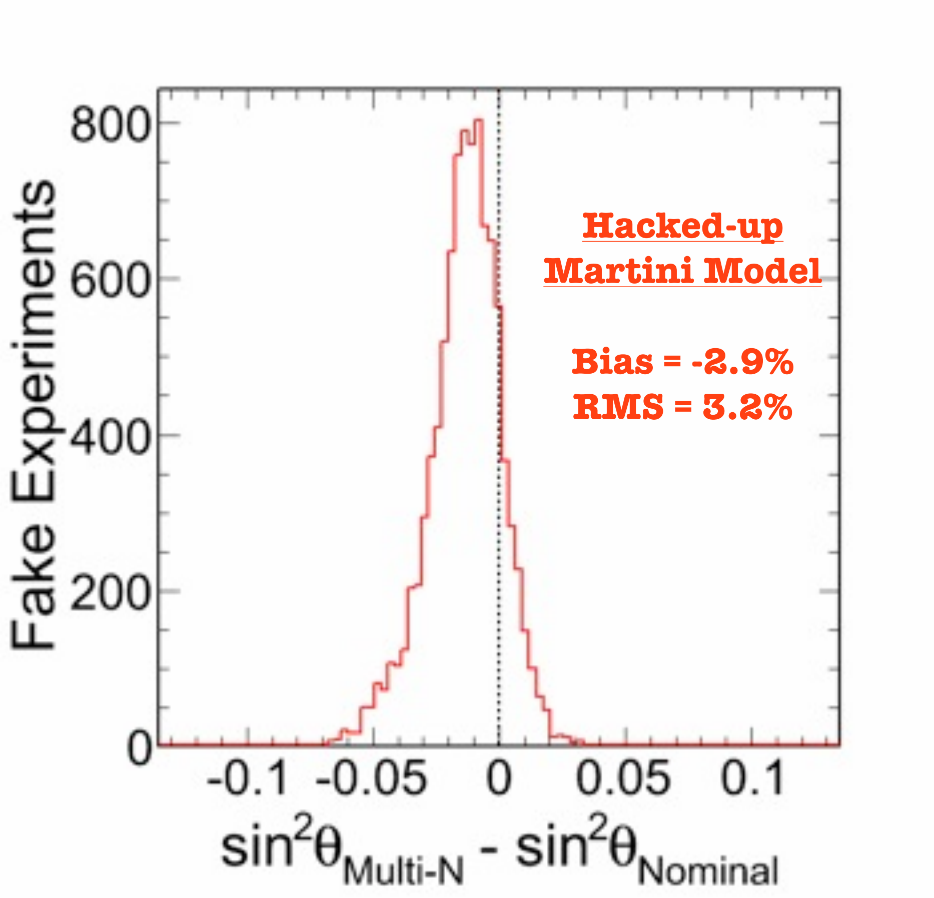
- To reach ultimate Hyper-K precision, it will be necessary to constrain E_ν reconstruction
  - NuPRISM provides the only data-driven mechanism for achieving this
- NuPRISM can also measure many other important physical processes
  - Sterile neutrinos and a variety of unique cross section measurements
- It is important to build the first version now! (NuPRISM-Lite)
  - A lot of interesting physics in the next 5 years!
  - Ideal tool for Hyper-K R&D
  - Intermediate project to expand Hyper-K involvement
  - We need a detailed understanding of NuPRISM to ensure it will achieve Hyper-K goals (calibration requirements, etc.)
- A full proposal will be submitted to J-PARC in June
- Additional collaborators are welcome!
  - Consider attending the NuPRISM meeting on Sunday and/or the week-long workshop in March

Supplement

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

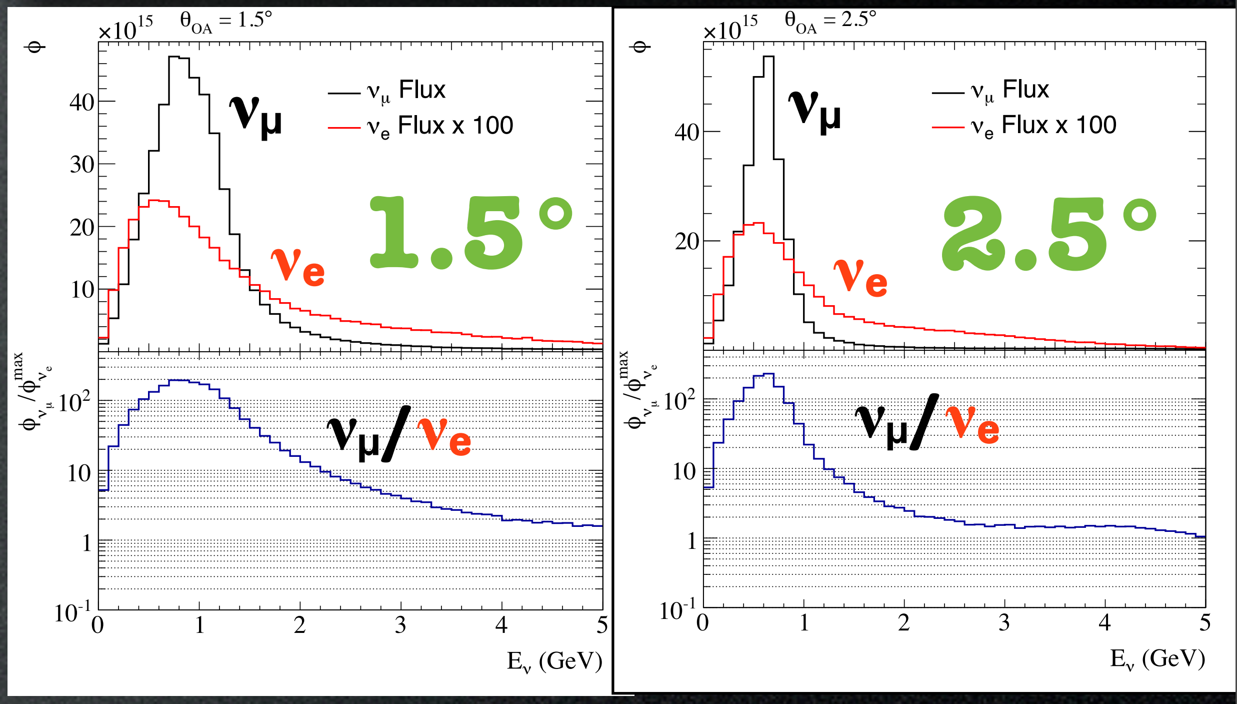
Flux < 1 GeV is dominated by π^+ decay

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

ν_μ produced in 2-body decay

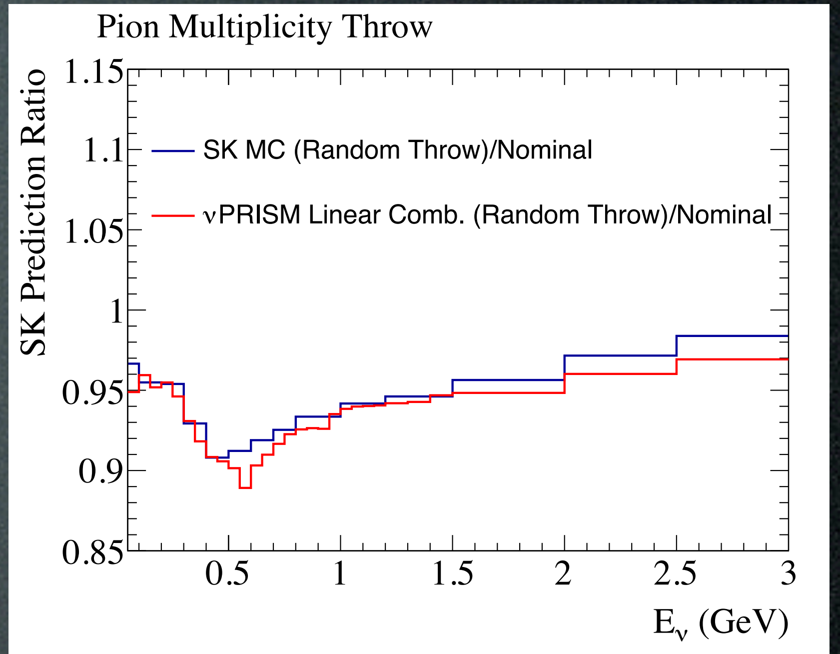
ν_e produced in 3-body decay

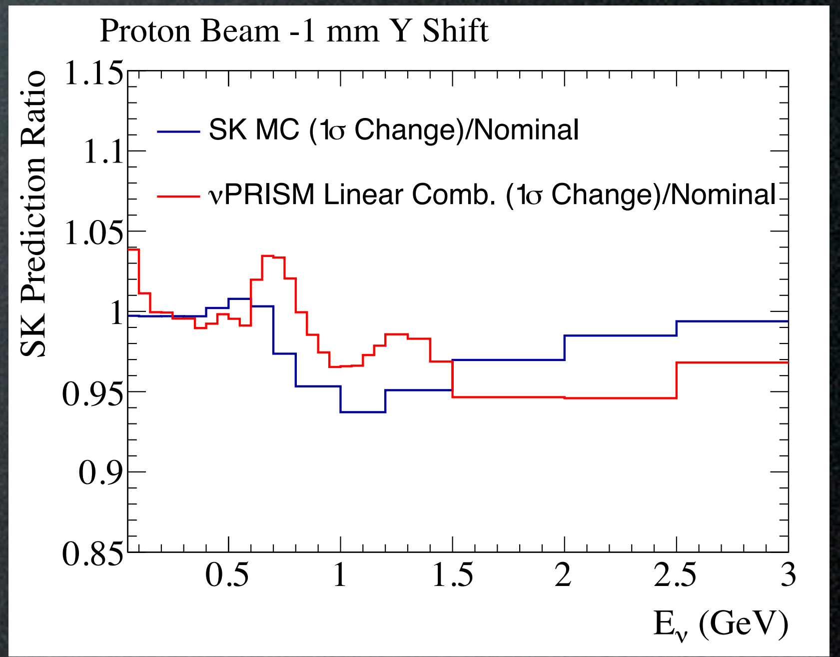
☞ ν_μ experience more off-axis affect

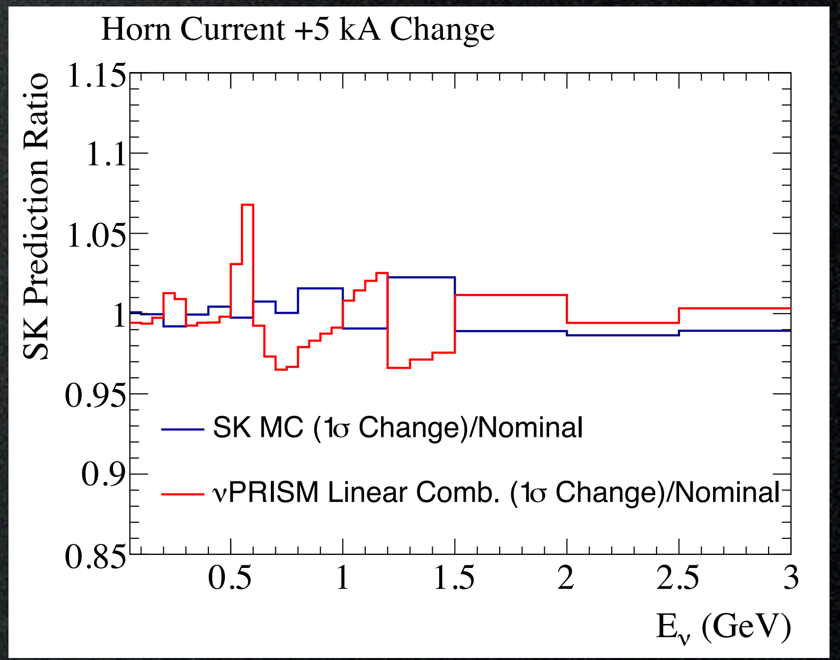


More on Beam Errors

- 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!

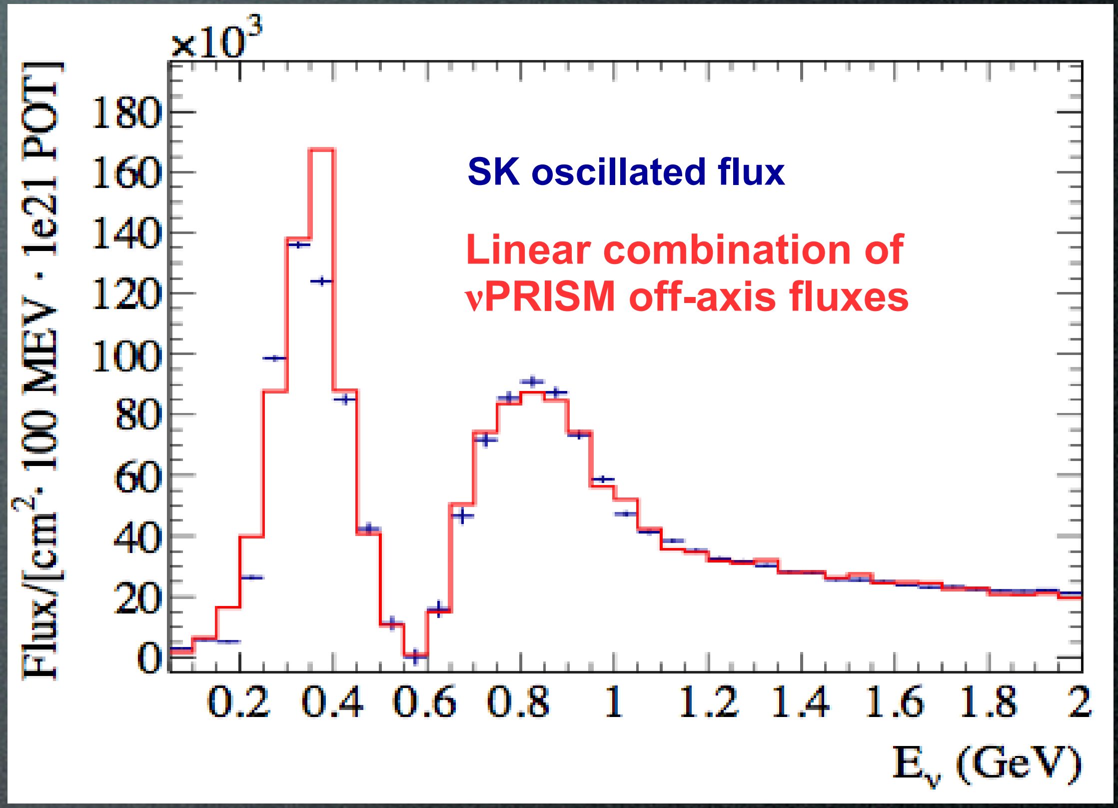


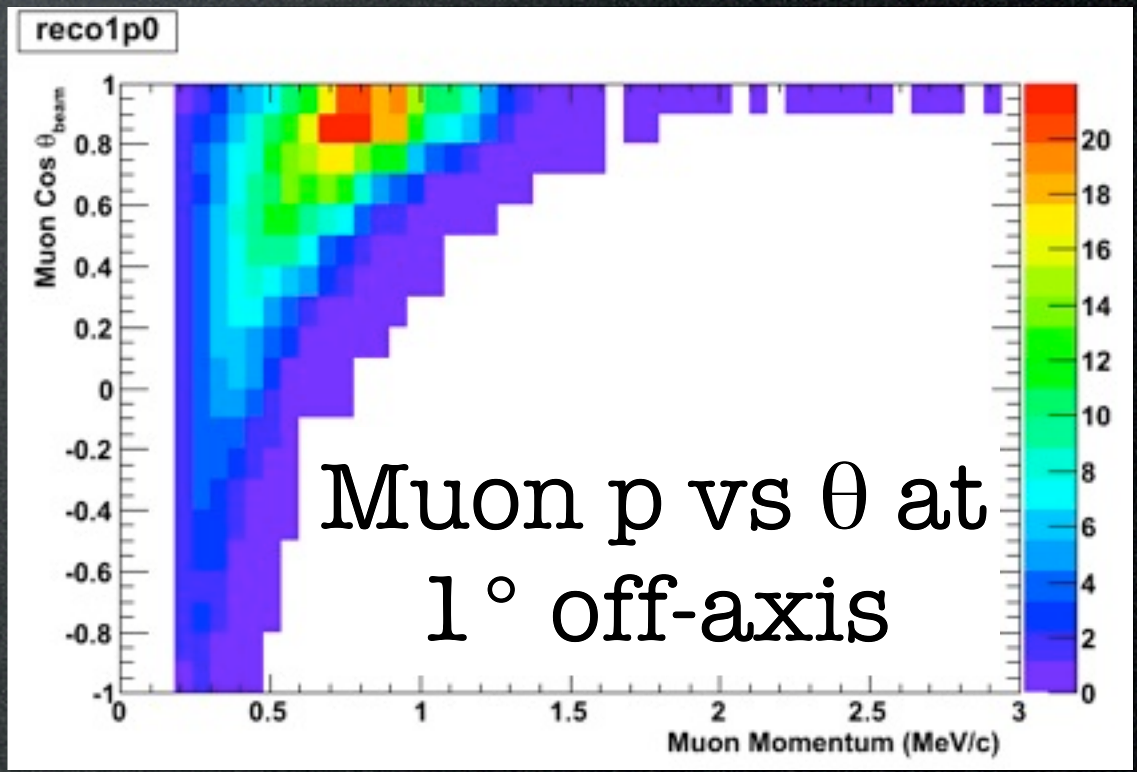




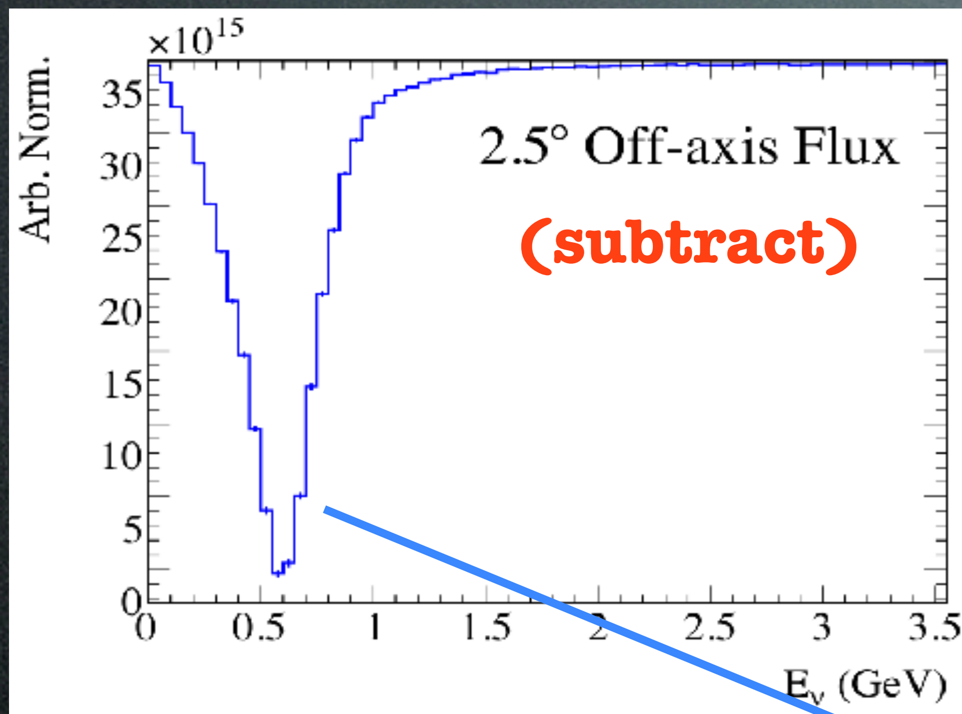
nuPRISM Technique

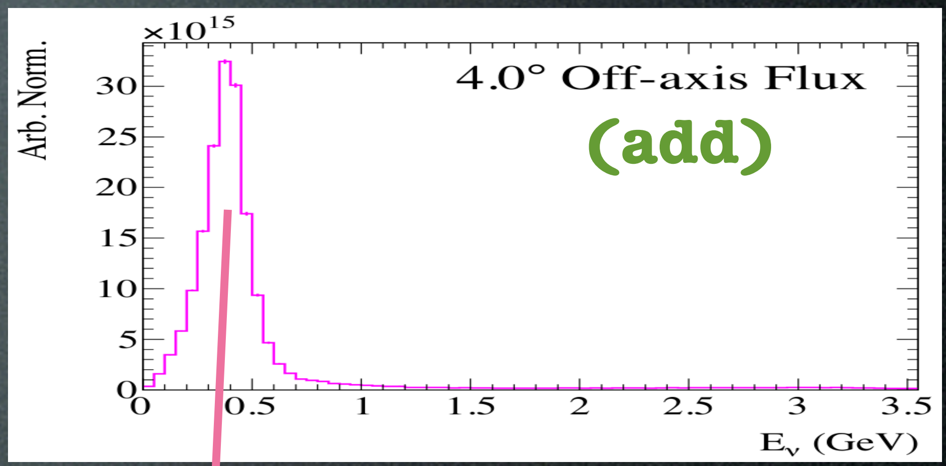
- Flux is now the same at the near and far detector
  - **Can just measure observed muon p vs θ for any oscillated flux**
- Same signal selection as used at Super-K
  - Single, muon-like ring
- **Signal events** are defined as **all true single-ring, muon-like events**
  - A muon above Cherenkov threshold
  - All other particles below Cherenkov threshold
  - Signal includes CCQE, multi-nucleon, $CC\pi^+$, etc.
- **No need to make individual measurements of each process and extrapolate to T2K flux**

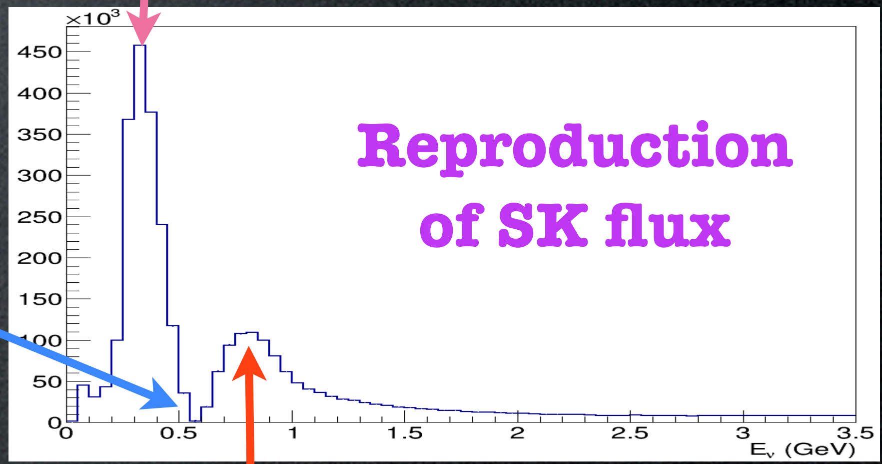


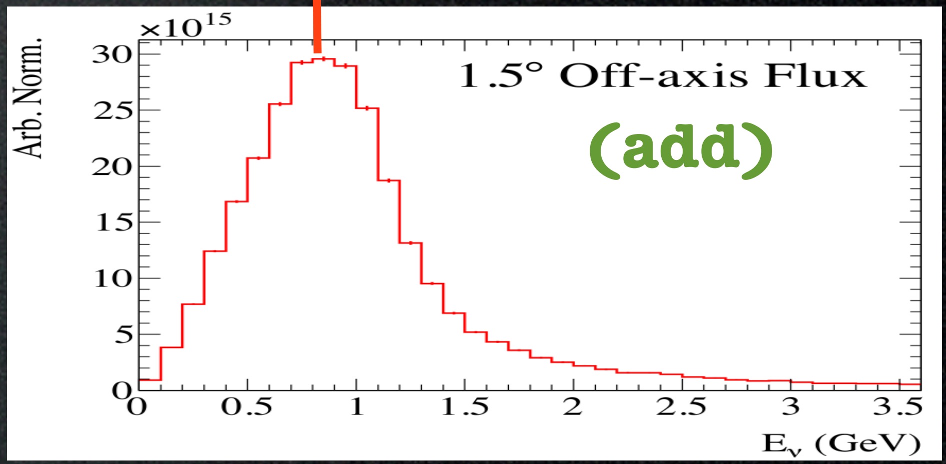


Reminder: Analysis Concept



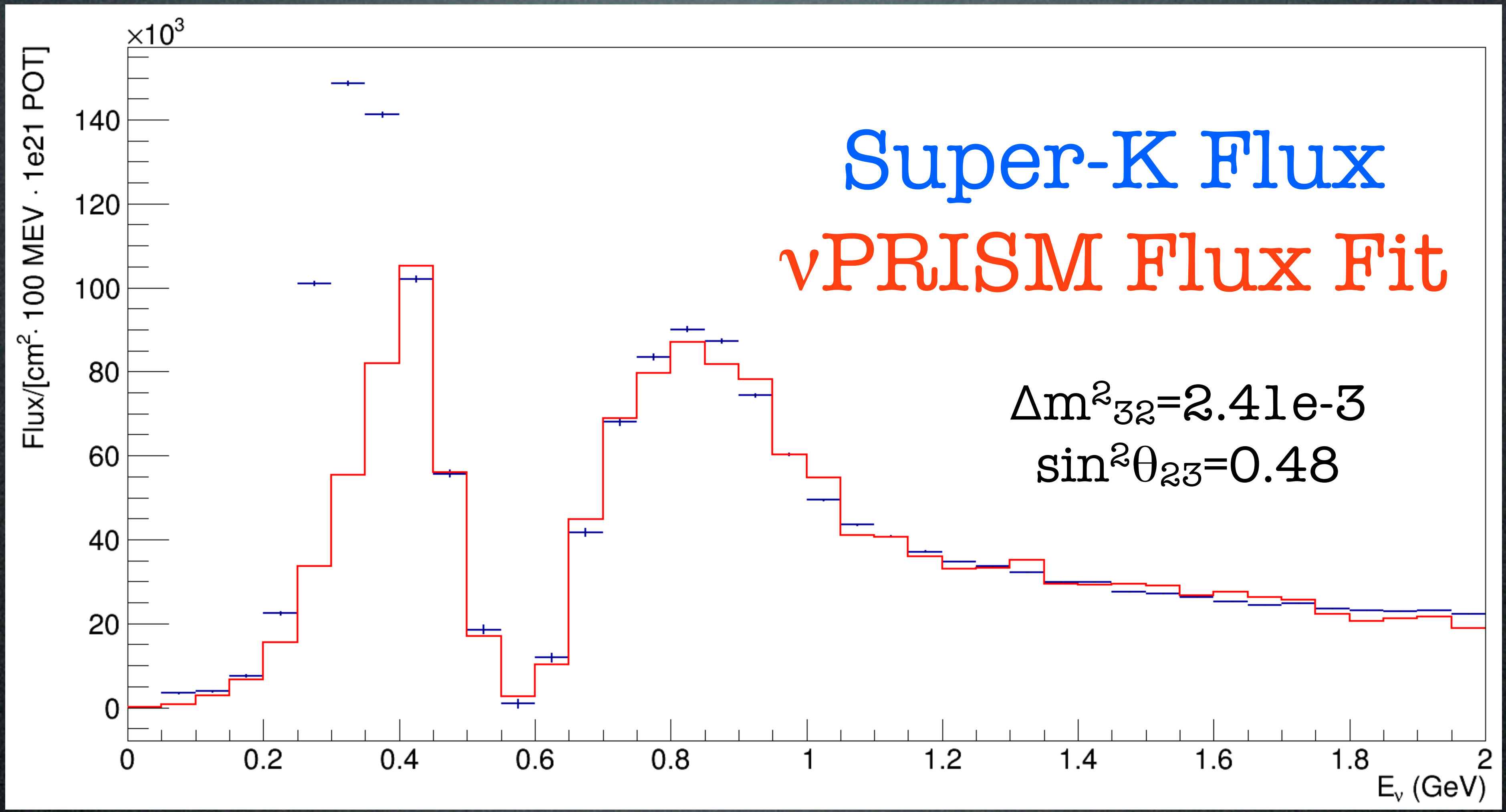






- Different slices of nuPRISM are combined to reproduce an oscillated SK flux
  - **Flux only!** No cross sections or detector response at this point
- For simplicity, only 3 slices are shown here
  - The default analysis **uses 60 slices**

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)

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

predicted Super-K E_{rec} distribution

weight for off-axis slice, i

events in muon p,θ bin in slice, i

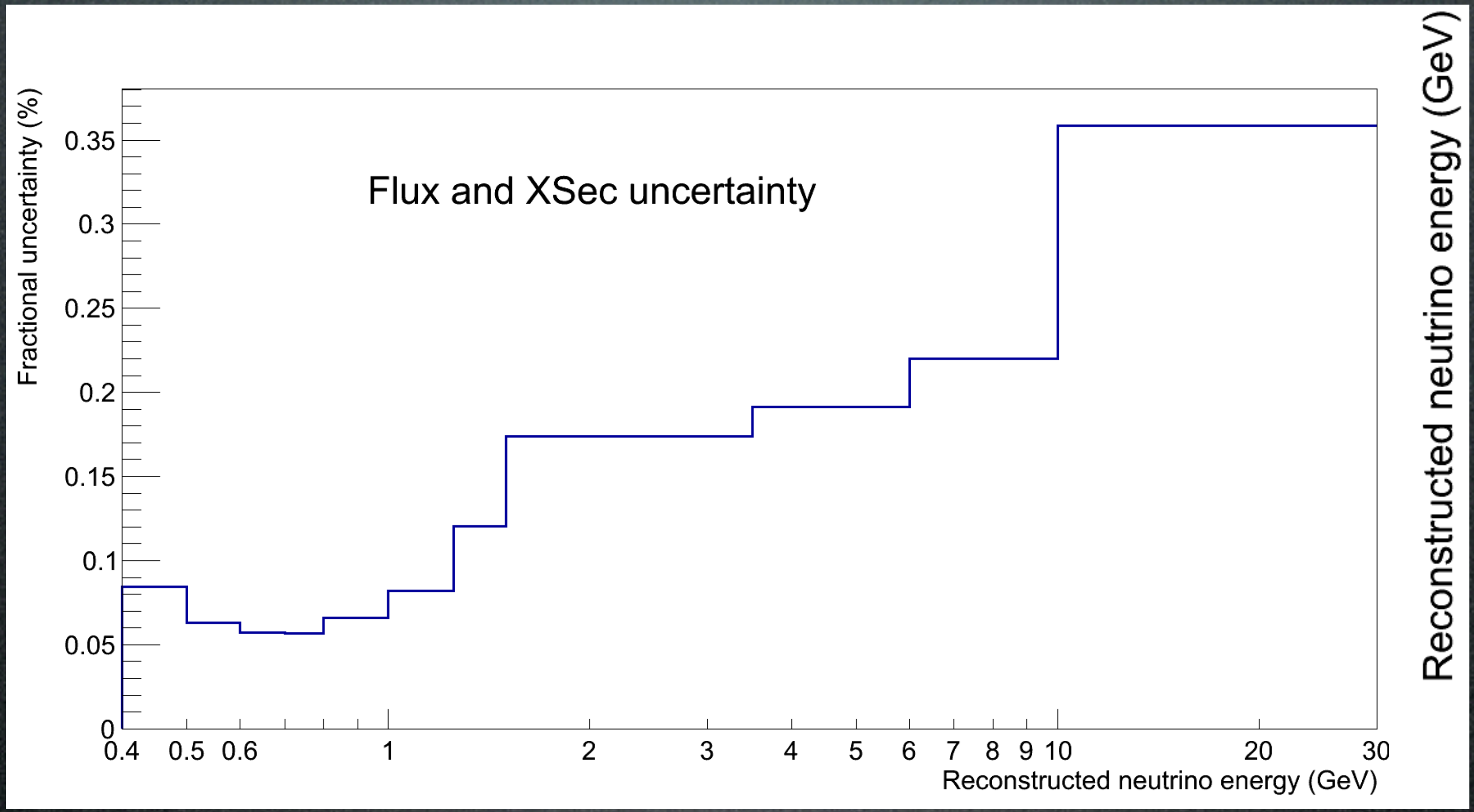
background subtraction

efficiency ratio

translation matrix p,θ → E_{rec}

Systematic Covariance Matrices

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

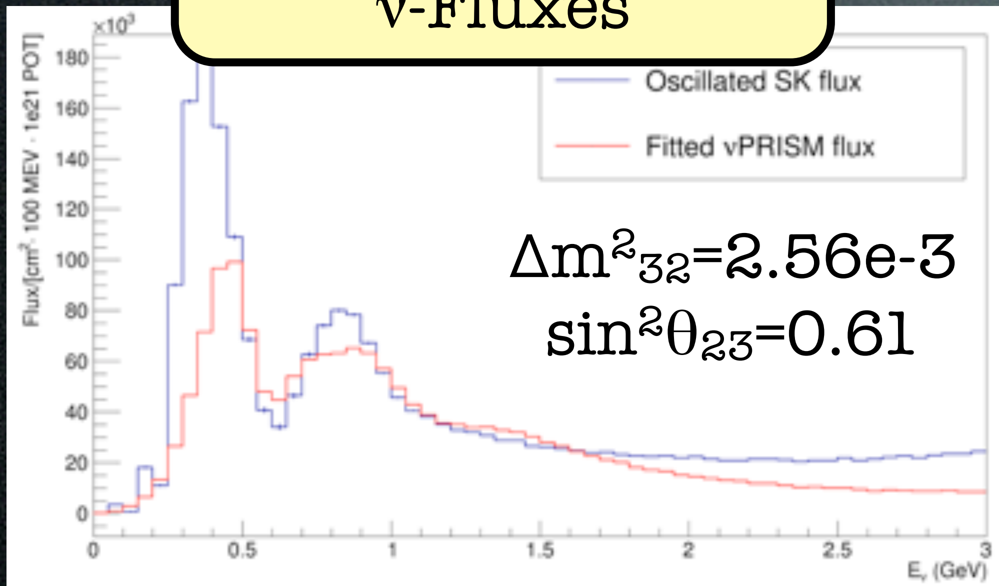


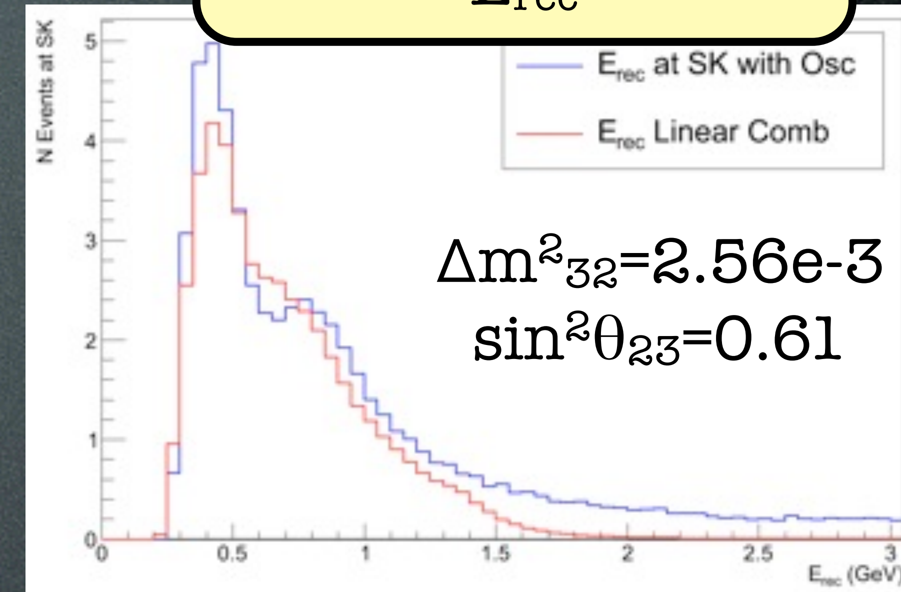
- Fractional uncertainties are shown (normalized to bin content)
- At high energies, νPRISM provides no constraint
  - Detector acceptance: all muons exit the inner detector
  - Subject to full flux & cross section uncertainties
- Bin 3 (600-700 MeV) has a 6% uncertainty

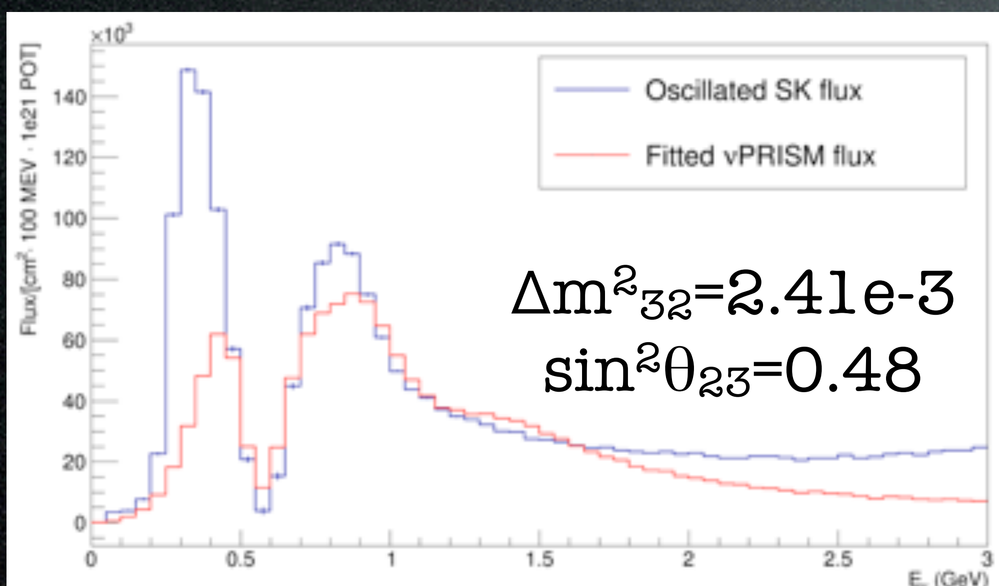
Smoothed ν-Flux Fits

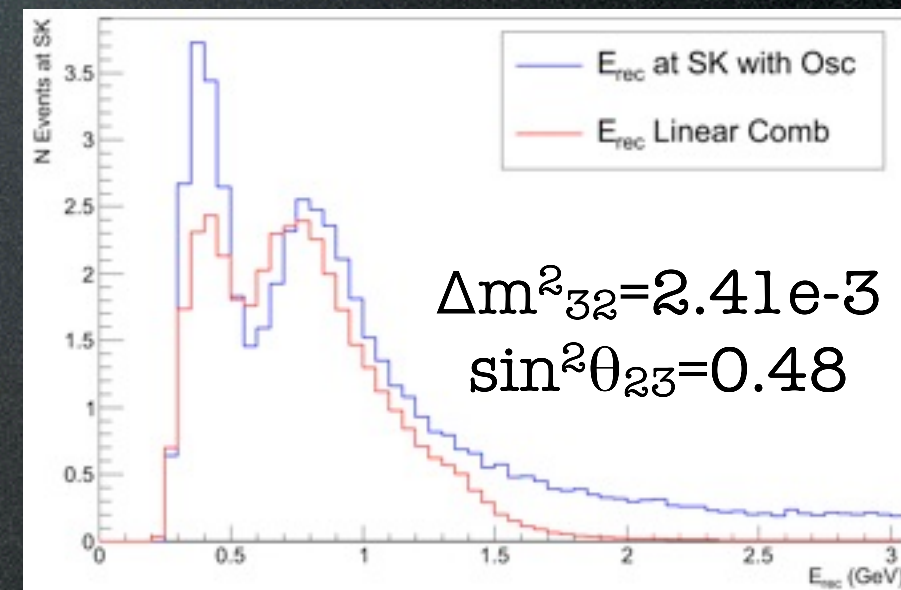
ν-Fluxes

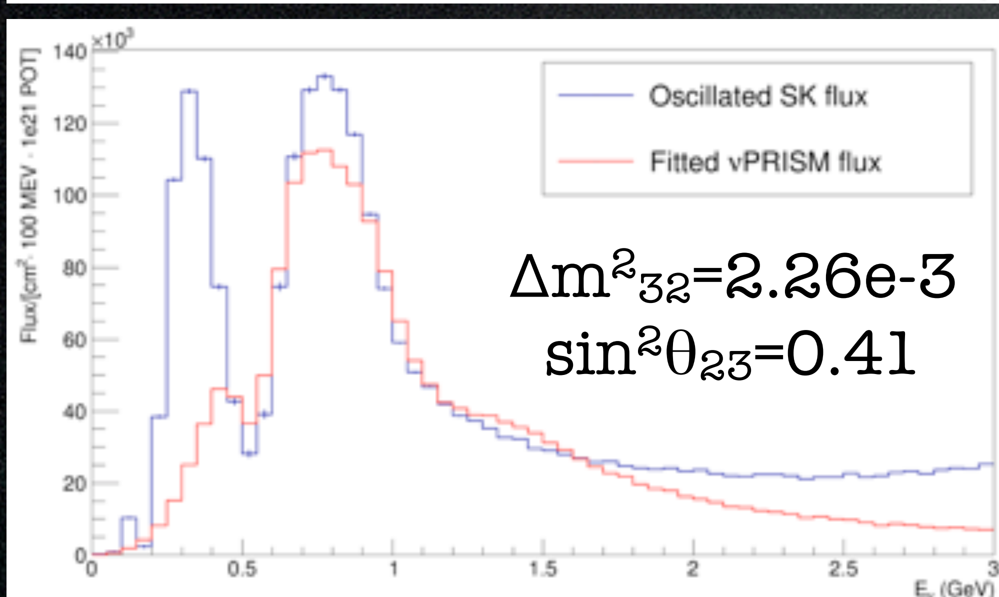
E_{rec}

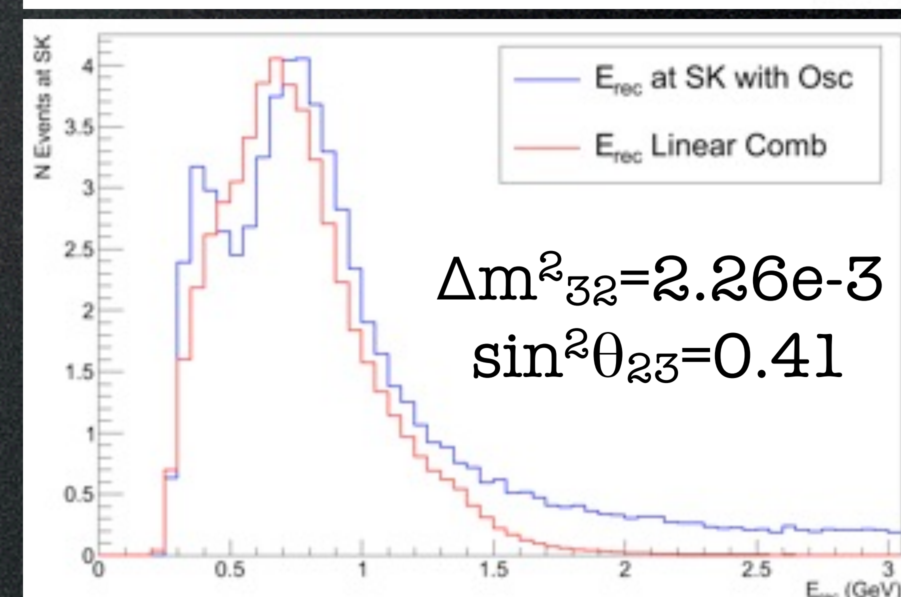






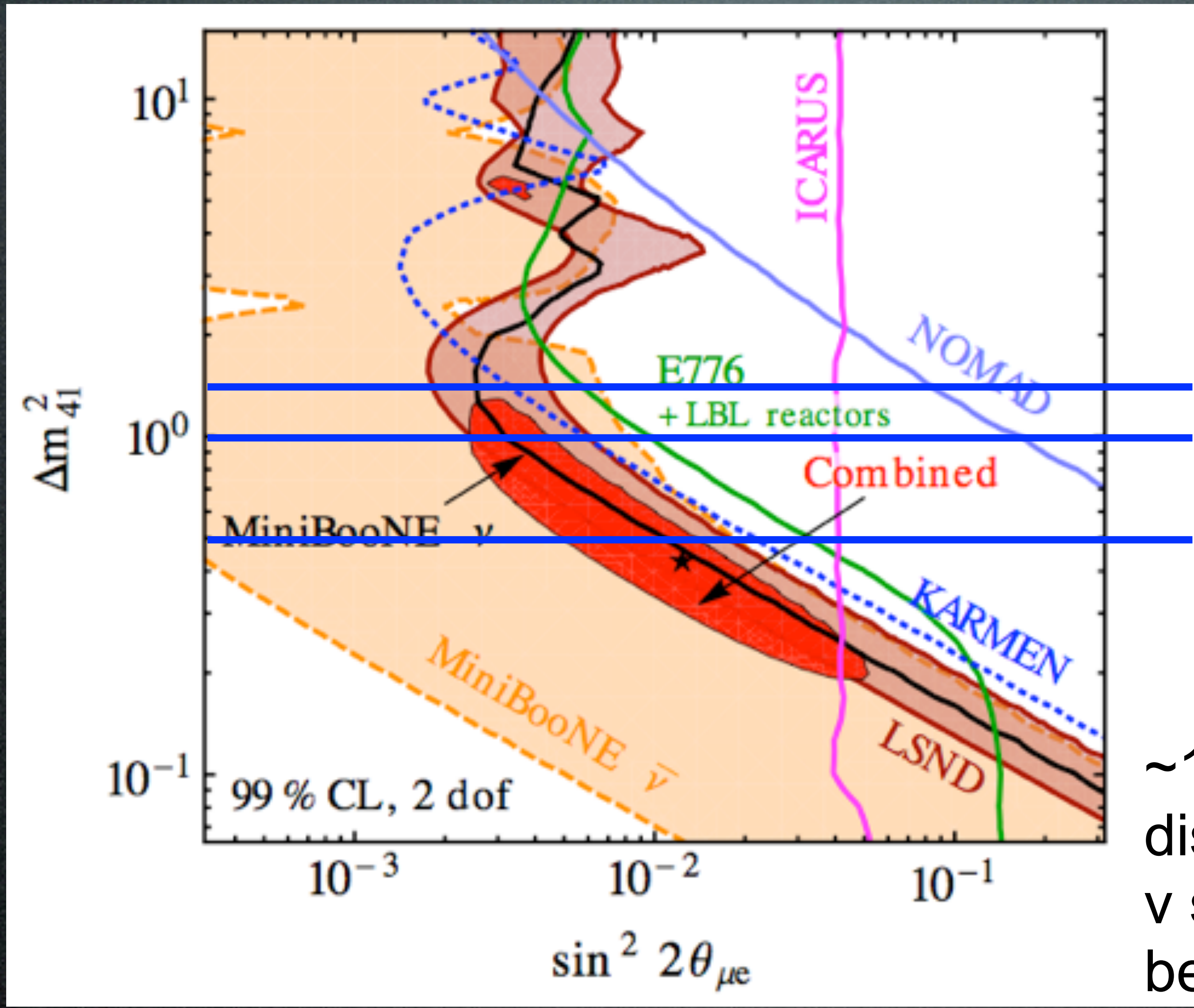






- Smoothed flux fits do not match as well
  - Easy to improve, if necessary
- However, very small increase to systematic uncertainties
  - Flux systematic variations are large
- Fits can be improved
  - Smoothness can be relaxed near fast-changing features
  - Off-axis angle bins need not be equal size

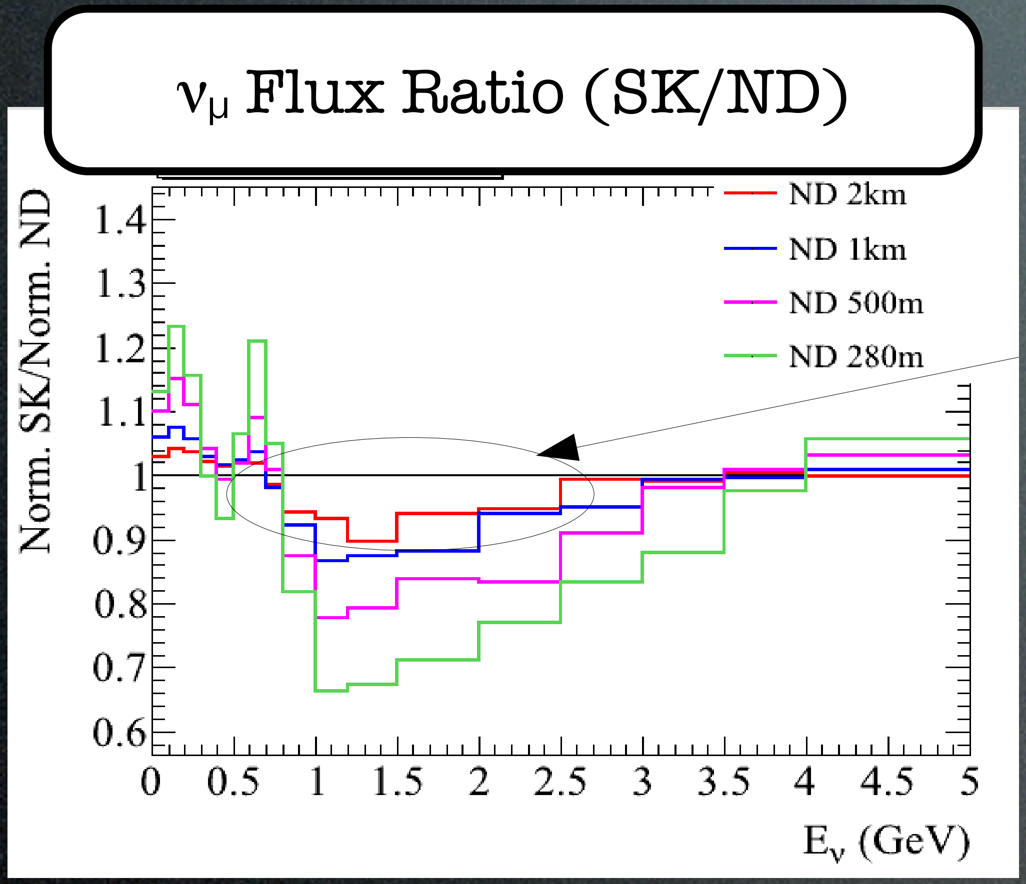
Sterile Neutrinos

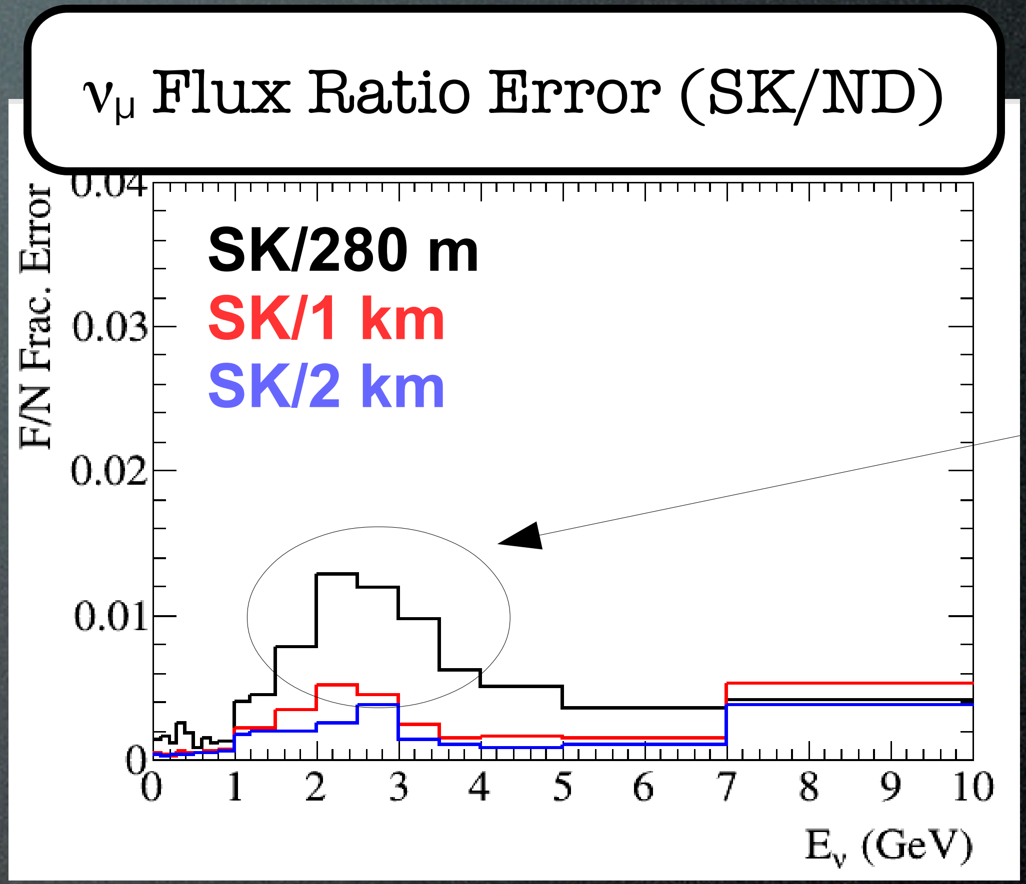


~1km is a good distance for sterile v search at T2K beam energy

- The 1 km baseline is ideal for sterile neutrinos
  - Many repeated measurements for varying energy spectra
  - Continuously sample a variety of L/E values

Detector Location: Energy Spectrum Ratio



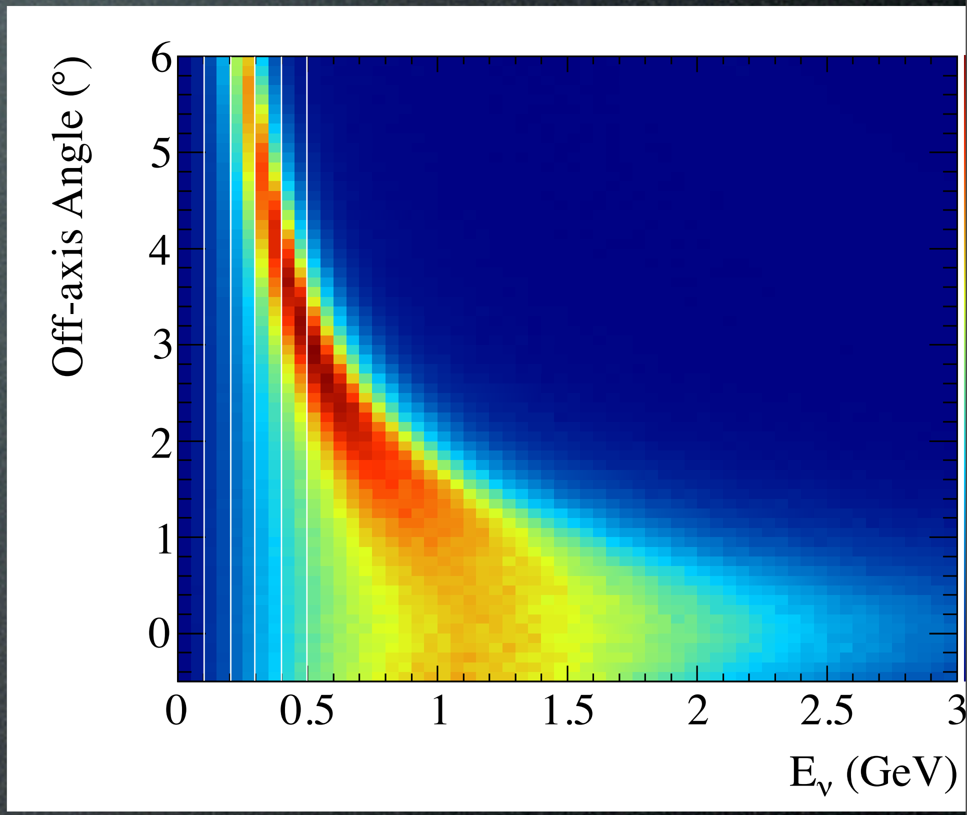


- At 280 m, the flux shape has 20-30% differences below 1 GeV
  - Uncertainty in the ratio is noticeably larger, but mostly above 1 GeV
- The difference between 1km and 2km is small in both shape and shape uncertainty

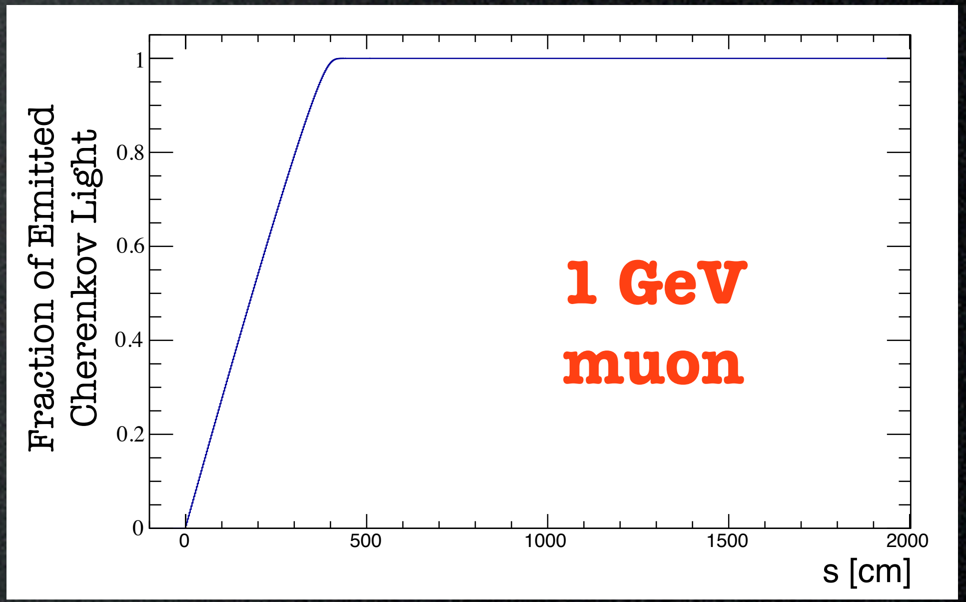
Other Design Considerations

- **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

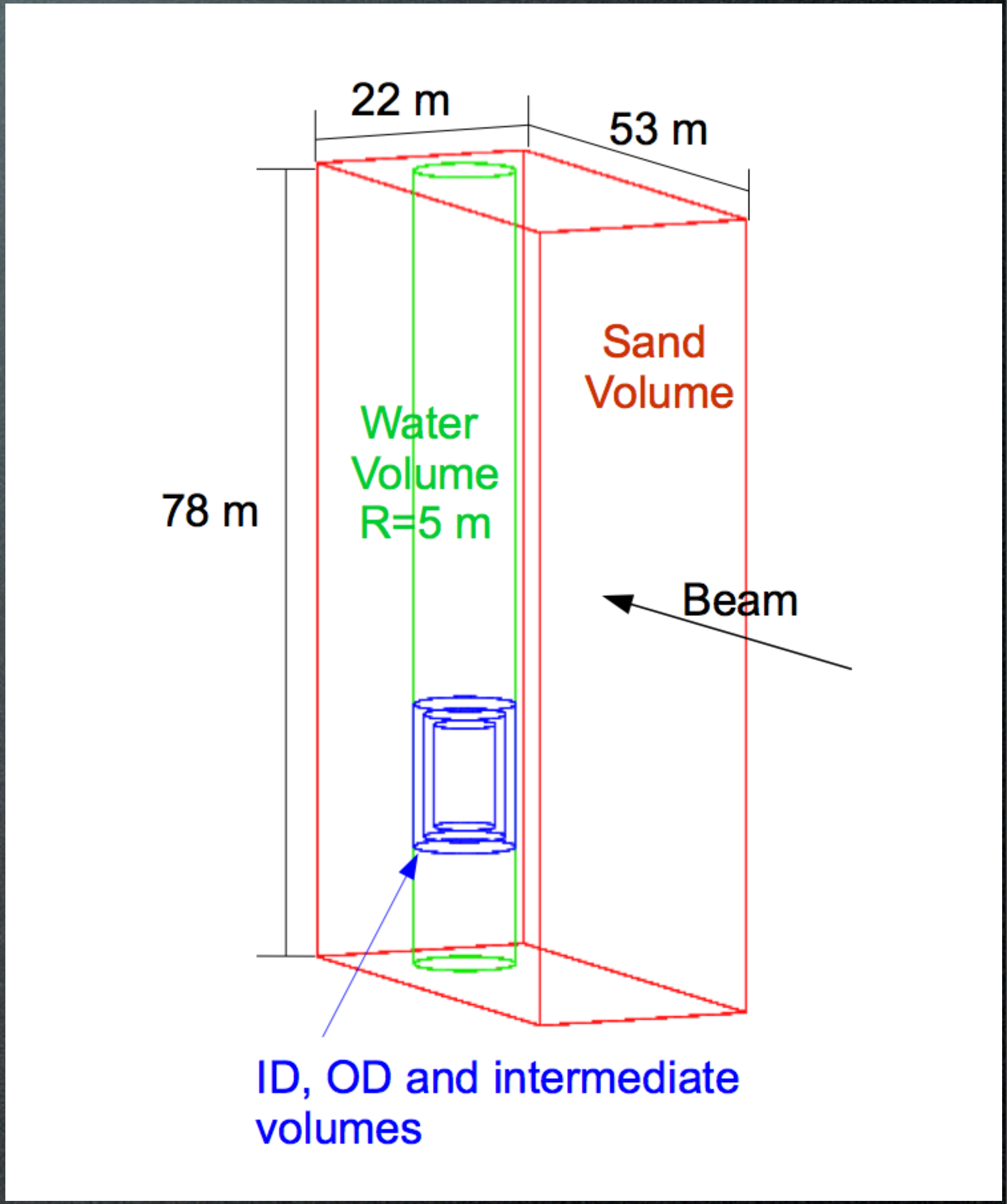


Muon Range



Event Pileup

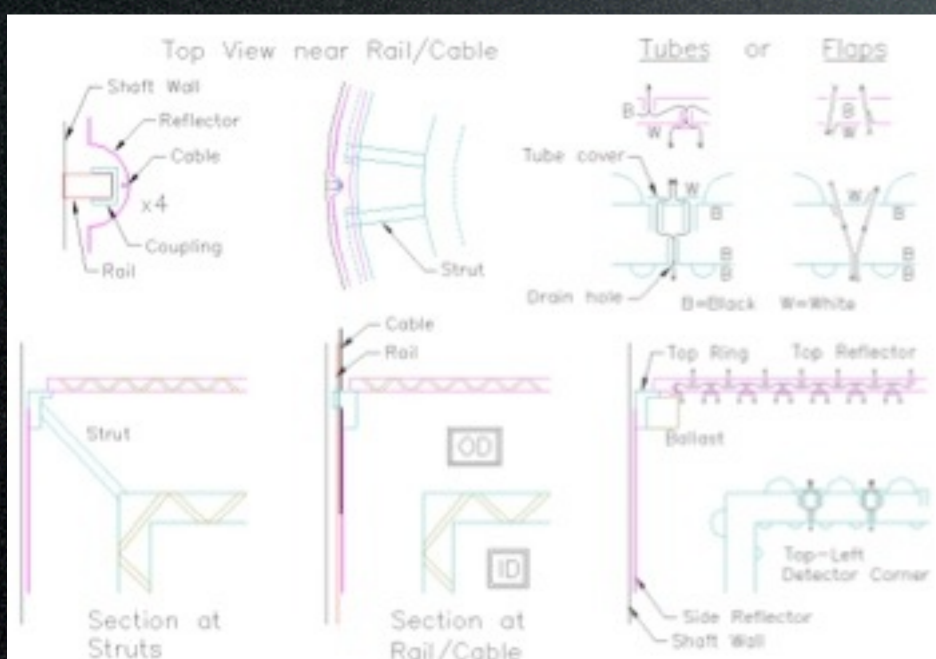
- Full GEANT4 simulation of water and surrounding sand
    - Using T2K flux and neut cross section model
- 8 beam bunches per spill, separated by 670 ns with a width of 27 ns (FWHM)
- **41% chance of in-bunch OD activity during an ID-contained event**
    - Want to avoid vetoing only on OD light (i.e. 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)



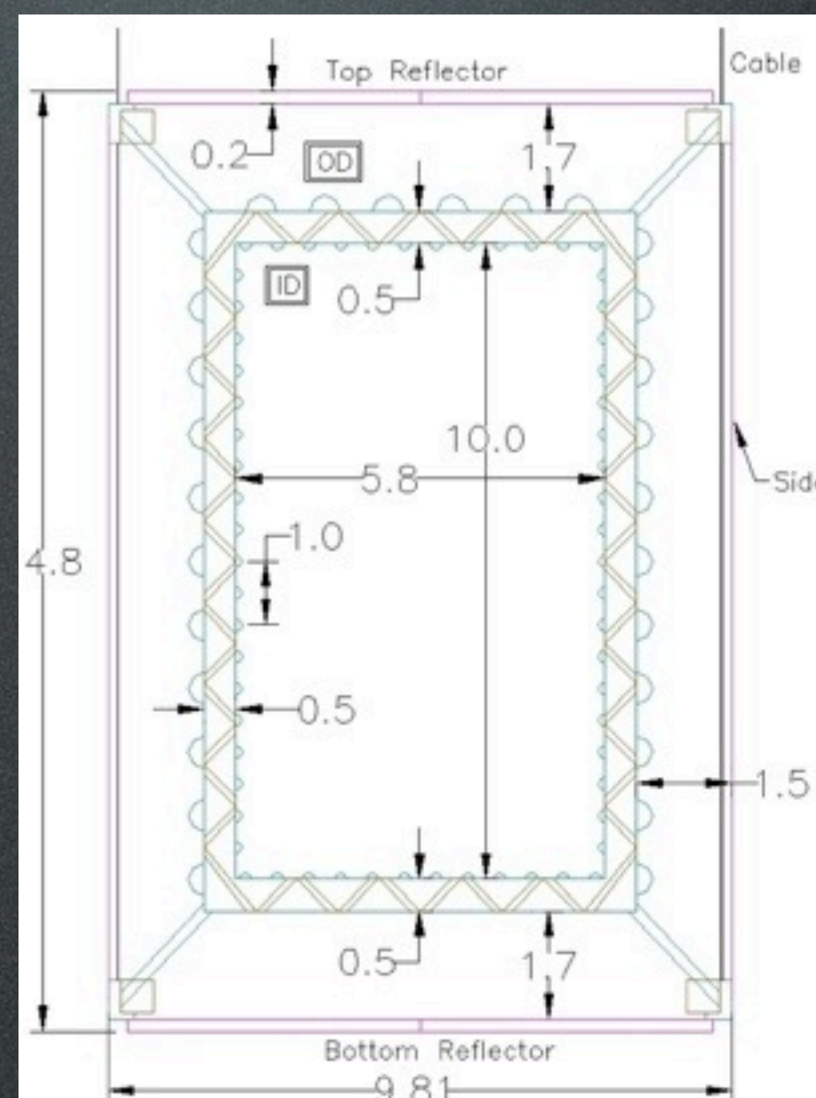
Pileup Rates at 1 km Look Acceptable!

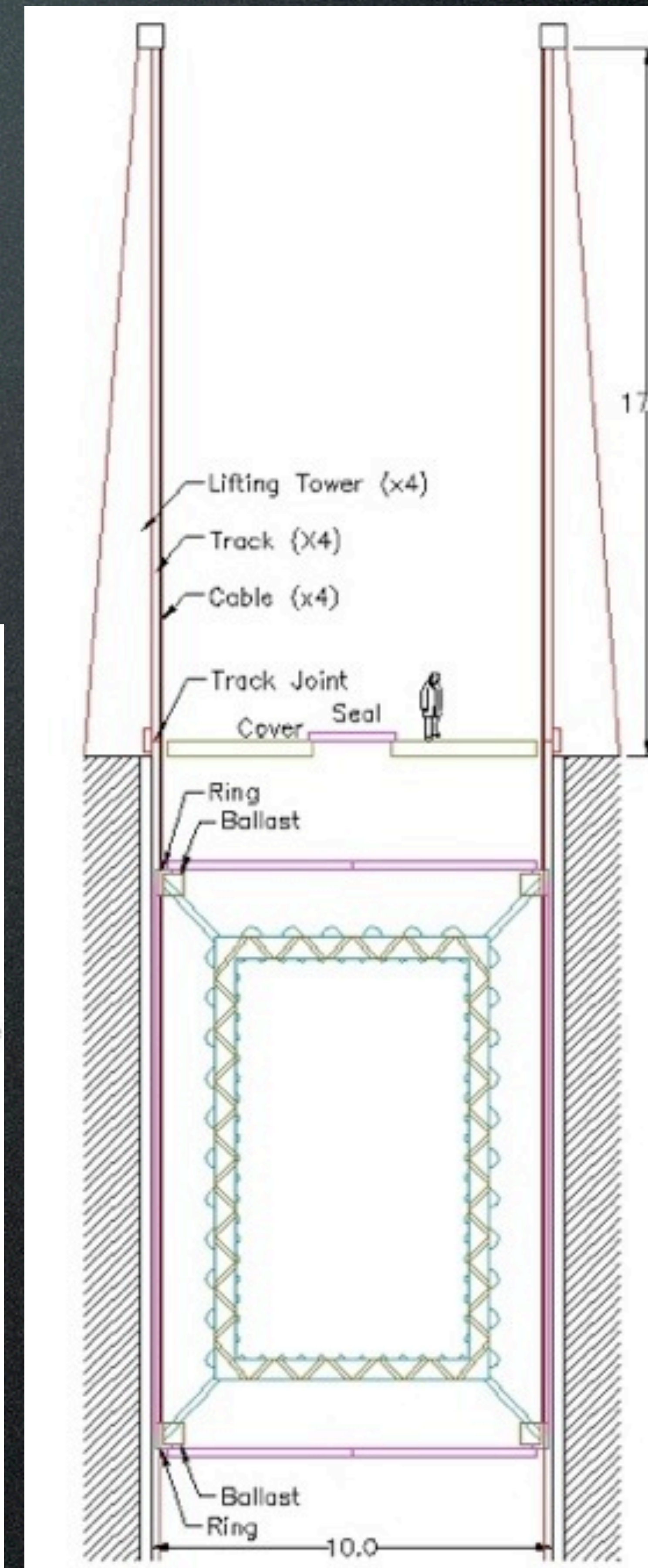
Detector Frame

- 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



Top View





PMTs

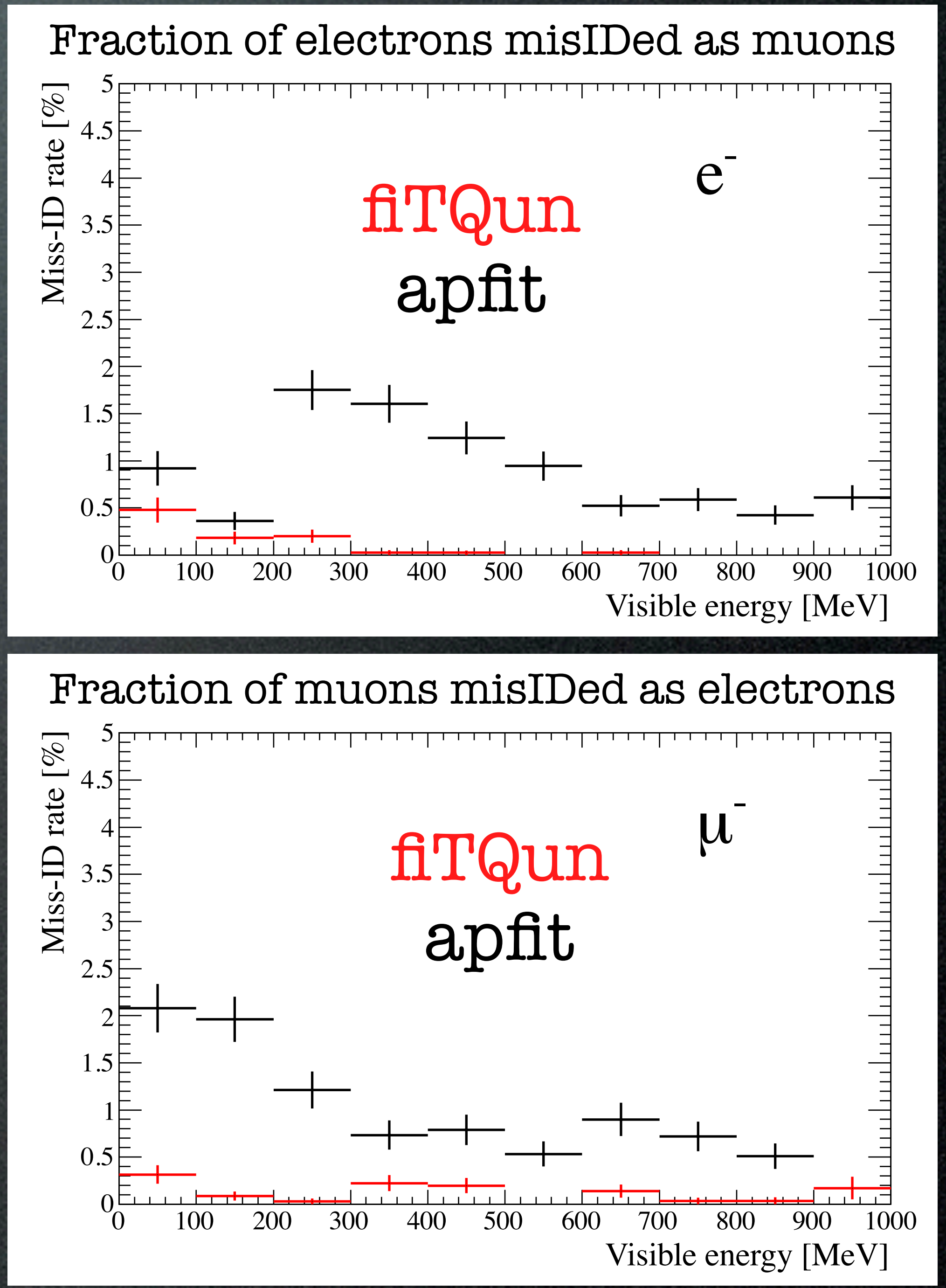
- For the ID, both 8” and 5” PMTs are being considered
  - Perhaps with high-quantum-efficiency (HQE) coating
  - Also considering Hyper-K-style hybrid photodetectors (HPD)
- Initial Hamamatsu estimate for basic 8” R5912 PMT is much more expensive that assumed for 2km detector
  - **US $4.3M for 3,000 PMTs**
- UK/Texas company ETEL/ADIT has also been consulted
  - Basic 8” PMT is $1775
  - No HQE or HPD option available

Hamamatsu Estimates

Name	Type	QE%	Quantity	Price/PMT	Total Cost	Delivery Year
5” PMT	R6594-WPassy	25	8000	103,500	828M	
5” PMT HQE		35	5714	123,700	707M	
8” PMT	R5912-WPassy	25	3215	143,000	460M	
8” PMT HQE		35	2296	170,500	391M	
8” HPD HQE	R12112-WPmodule	35	2296	264,000	606M	2014
		35	2296	236,500	543M	2015
		35	2296	209,000	480M	2016
20” PMT HQE	R12860-WPassy	30	508	604,500	307M	2014
		30	508	572,000	291M	2015
		30	508	539,500	274M	2016
20” HPD HQE	R12850-WPmodule	30	508	715,000	363M	2014
		30	508	617,500	314M	2015
		30	508	520,000	264M	2016
20” HPD HQE	R12850-WPmodule	30	140	770,000	108M	2014
		30	140	665,000	93M	2015
		30	140	560,000	78M	2016
20” PMT	R12860-WPassy	30	140	651,000	91M	2014
		30	140	616,000	86M	2015
		30	140	581,000	81M	2016

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)