NuPRISM in the T2K Era

Mike Wilking

Workshop for Neutrino Programs with Facilities in Japan

August 5th, 2015

Overview

- NuPRISM is a water Cherenkov detector that spans a wide angular range (~1°-4°) off-axis from the neutrino beam direction
- This type of detector can perform a wide variety of interesting neutrino physics measurements

1. NuPRISM can greatly **reduce neutrino interaction uncertainties** in T2K and Hyper-K
   - These may be the largest uncertainties for the full T2K dataset
2. NuPRISM can perform a high precision search for **sterile neutrino** oscillations
3. NuPRISM can determine neutrino interaction final states from **mono-energetic neutrino beams**
   - Electron-scattering-like measurements are now possible
   - Very interesting probe for nuclear physics, and to constrain the relationship between neutrino energy and observable lepton kinematics
4. NuPRISM is expected to provide a unique and precise constraint on $\sigma_{\nu e}/\sigma_{\nu\mu}$

The NuPRISM Collaboration

- NuPRISM has 56 members (primarily physicists) from 10 countries
- In addition, the proposal submitted to the J-PARC PAC in June includes letters of support from several nuclear theorists:

  J. Carlson (LANL)
  T.W. Donnelly (MIT)
  M. Ericson (IPN Lyon, CERN)
  S. Gandolfi (LANL)
  A. Lovato (ANL)
  M. Martini (Ghent)
  S.C. Pieper (ANL)
  R. Schiavilla (JLAB/ODU)
  R.B. Wiringa (ANL)

Proposal for the NuPRISM Experiment in the J-PARC Neutrino Beamline

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(The NuPRISM Collaboration)

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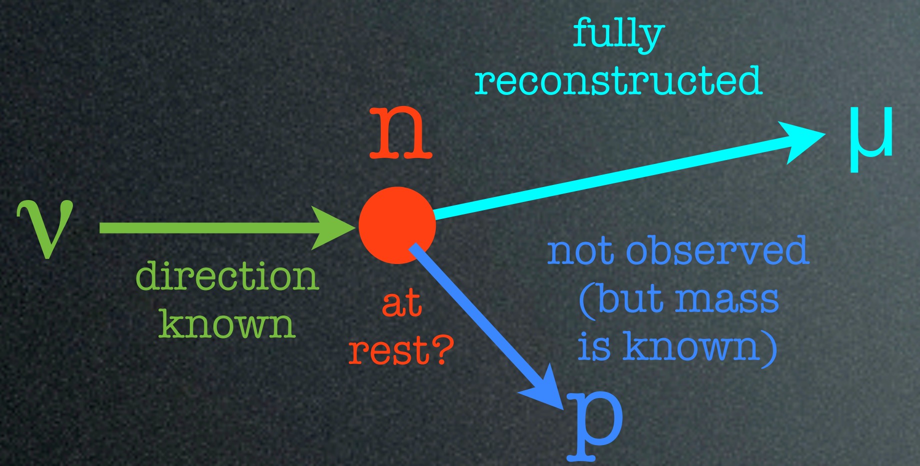
(Dated: June 16, 2015)

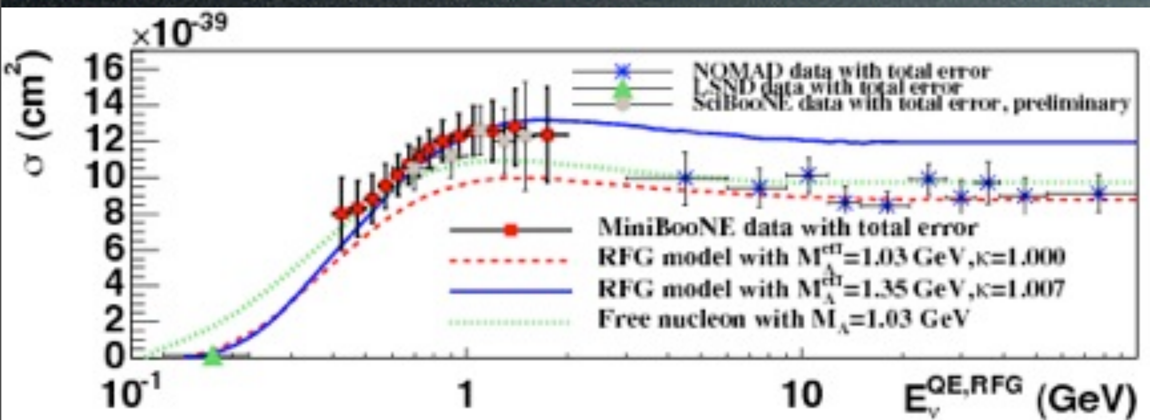
Measuring E_ν

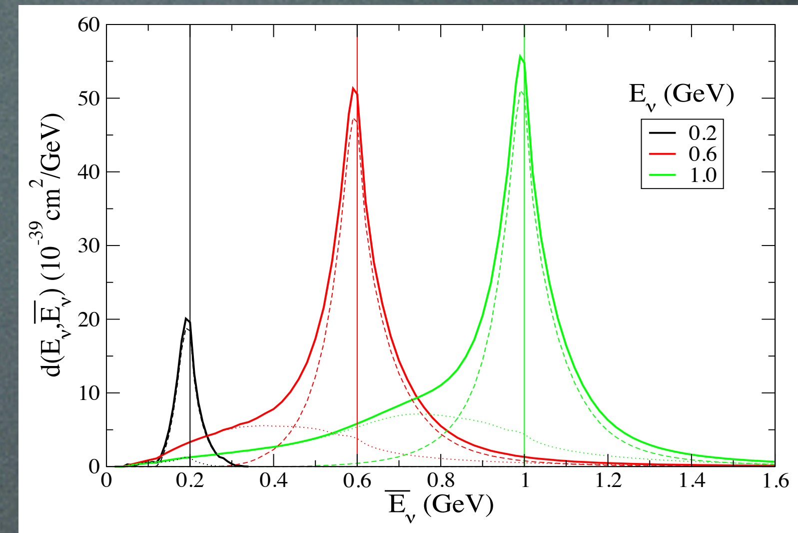


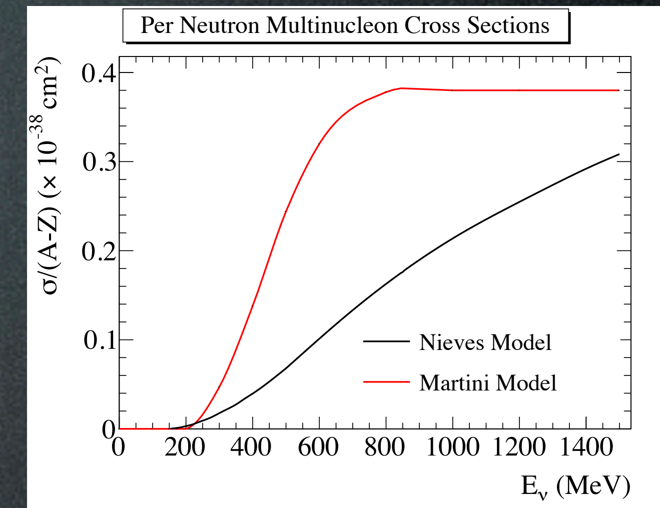
$$E_\nu^{QE} = \frac{2(M_n')E_\mu - ((M_n')^2 + m_\mu^2 - M_p^2)}{2 \cdot [(M_n') - E_\mu + \sqrt{E_\mu^2 - m_\mu^2} \cos\theta_\mu]}$$

- Neutrino oscillations are a function of neutrino energy
  - However, **E_ν cannot be directly measured** from final state particle kinematics
- If only the outgoing muon 4-momentum is measured, E_ν is determined assuming:
  - **The neutrino direction is known (good assumption)**
    - Detectors are far from the beam source
  - **The target nucleon is at rest (marginal assumption)**
    - Adds an irreducible smearing to the neutrino energy resolution
  - **The recoiling nucleon mass is known (problematic assumption)**
    - This is only correct for interactions with a single nucleon
- Some experiments (e.g. LAr) attempt to measure the energy of the outgoing hadrons
  - **Requires knowledge of neutron kinematics (problematic assumption)**

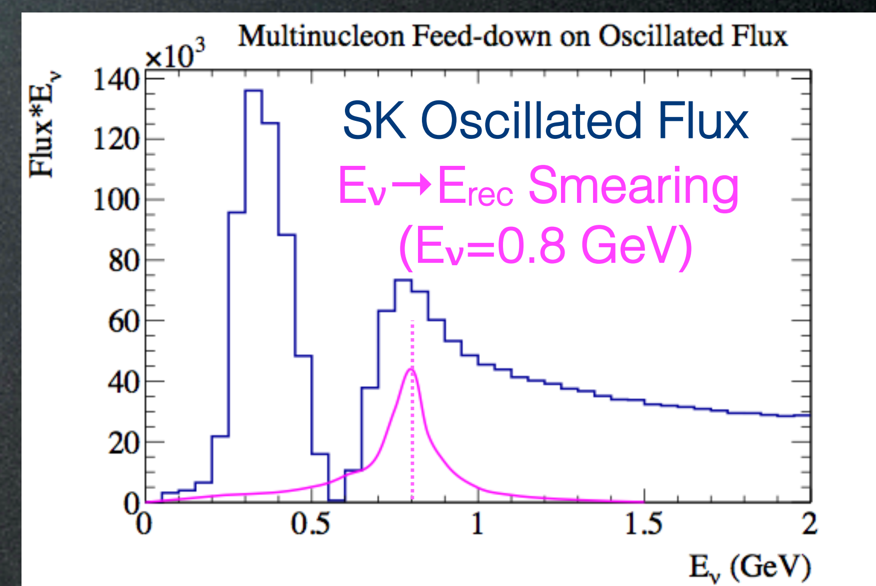
The E_ν Measurement Problem

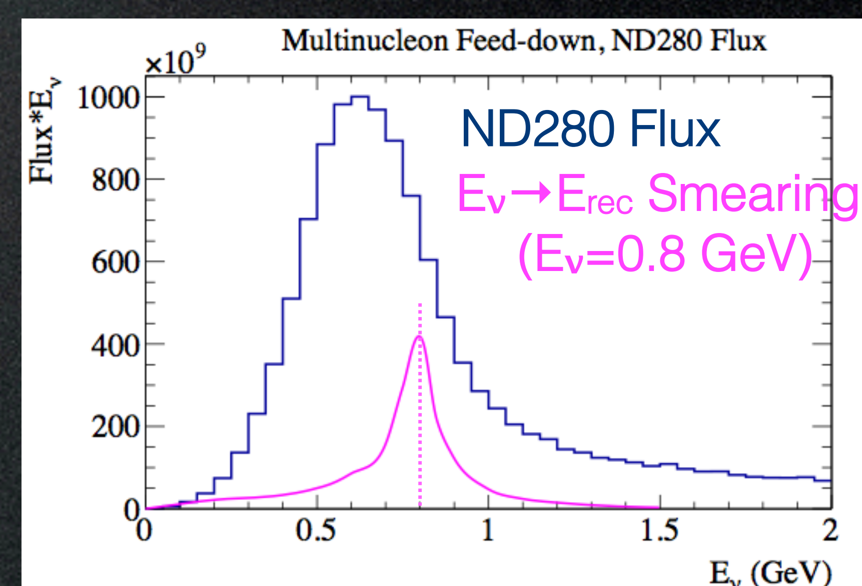






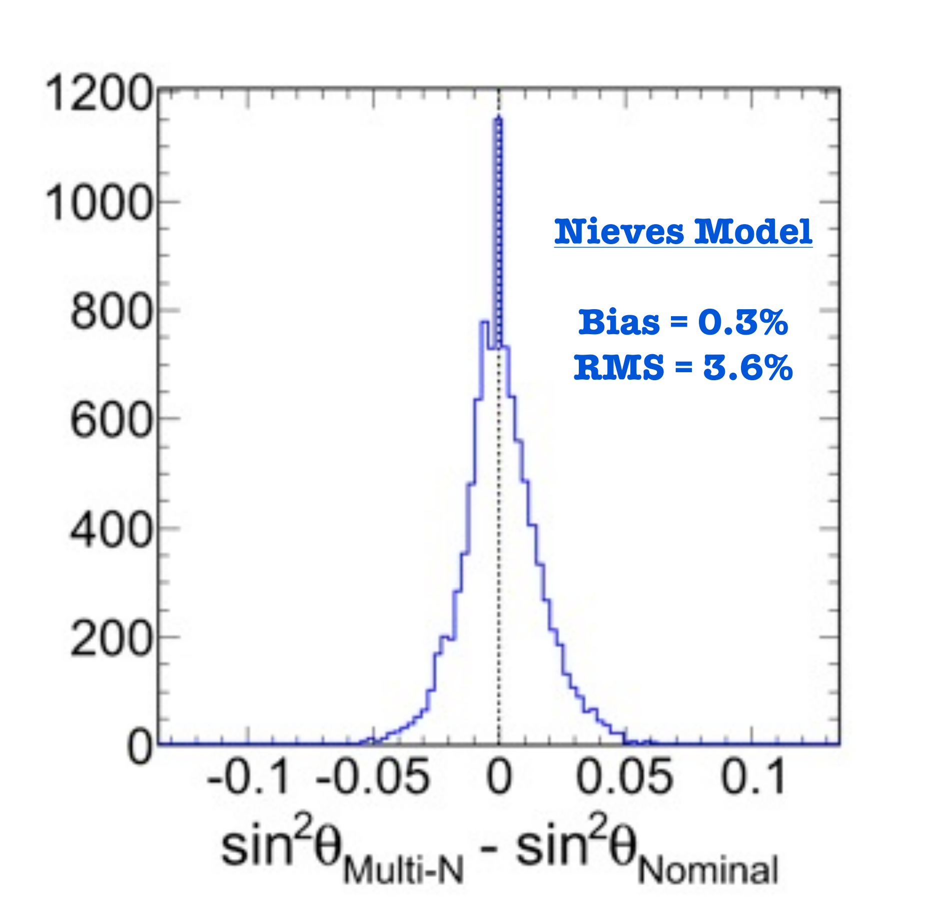
- Large inconsistencies in σ vs "E_ν" measurements led to a reexamination of ν-nucleus interactions
- Correlations between nucleons causes a "feed down" in reconstructed E_ν
  - This feed down directly impacts the sensitivity to oscillation parameters
  - Modeling this feed down is very difficult, and current models have large disagreements
- ND280 is largely insensitive to this effect

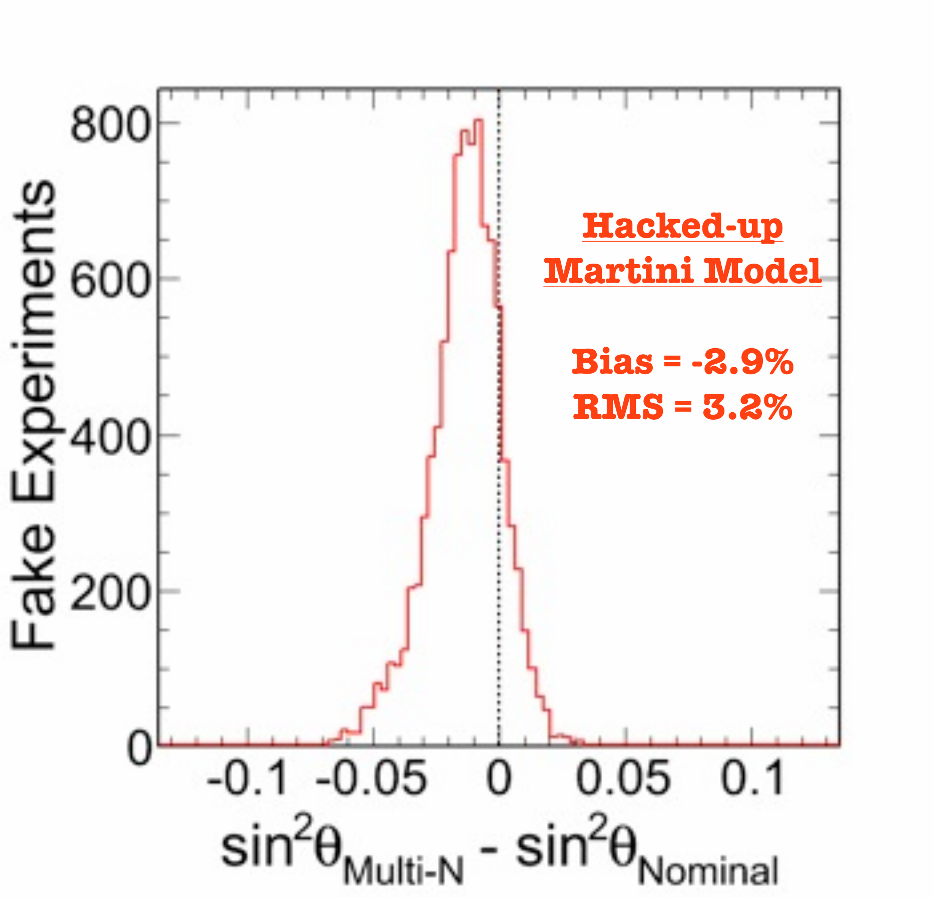




Effect on T2K ν_μ Disappearance

- 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 is expected to be one of the largest systematic uncertainties for the full T2K run**
- But this is just a comparison of 2 models
  - How much larger could the actual systematic uncertainty be?
- **A data-driven constraint is needed**





T2K Systematic Uncertainties

From Ichikawa-san's talk yesterday

Fractional error on # of events		ν_μ sample	ν_e sample		$\bar{\nu}_\mu$ sample	$\bar{\nu}_e$ sample
ν flux		16%	11%		7.1%	8%
ν flux and cross section	w/o ND measurement	21.8%	26.0%		9.2%	9.4%
	w/ ND measurement	2.7%	3.1%		3.4%	3.0%
ν cross section due to difference of nuclear target btw. near and far		5.0%	4.7%		10%	9.8%
Final or Secondary Hadronic Interaction		3.0%	2.4%		2.1%	2.2%
Super-K detector		4.0%	2.7%		3.8%	3.0%
total	w/o ND measurement	23.5%	26.8%		14.4%	13.5%
	w/ ND measurement	7.7%	6.8%		11.6%	11.0%

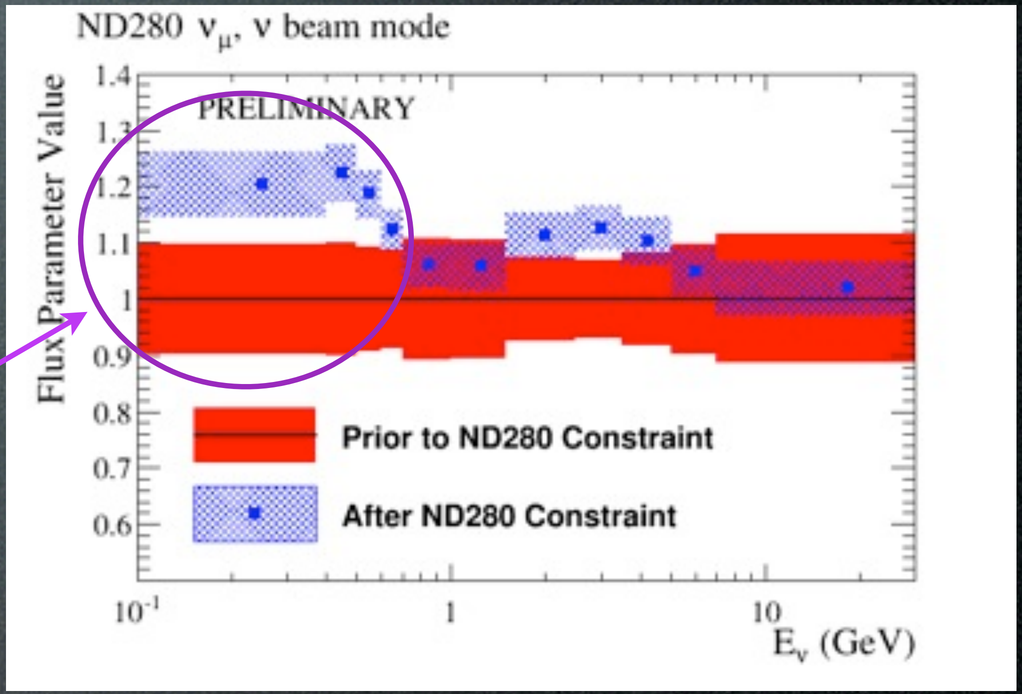
2014 2015

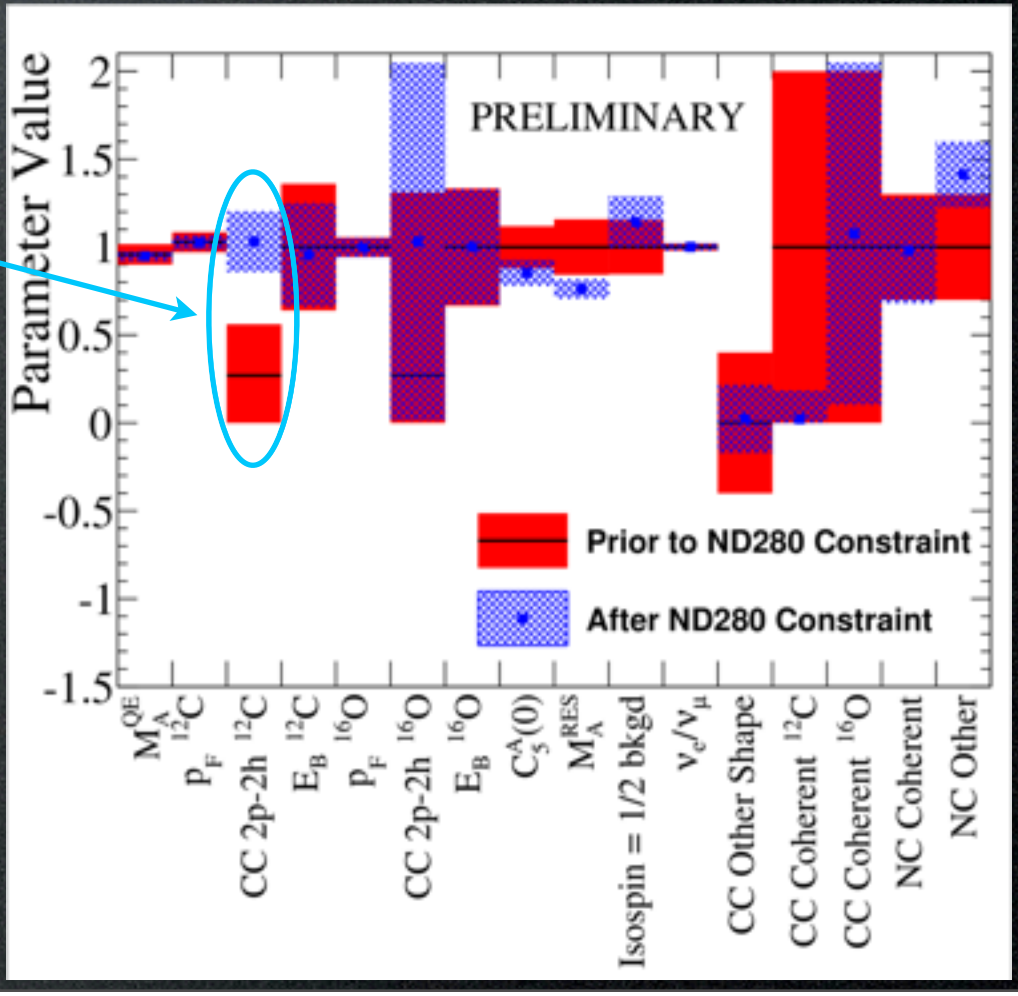
- For T2K*3, the goal is to reduce these errors to the 2-3% level
- The largest systematic errors are due to neutrino interactions
  - However, the O vs C errors shown above will be somewhat reduced when ND280 water targets are incorporated
    - This may appear to suggest that we have a chance to reach few percent errors with the current near detectors
- But these errors rely on the current model (and just a normalization uncertainty on multinucleon events)

Will We Ever Have a Reliable Model?

("Ever" = before everyone at this workshop retires)

- The 3% flux & cross section uncertainties on the previous page are derived from the ND280 fit
    - The results of this fit push important flux and cross section uncertainties well outside of their prior errors
- 20% flux variations in the oscillation region are concerning, given our knowledge of the flux (see Sekiguchi-san's talk from yesterday)
    - If a 20% flux change is too large, the current cross section model does not describe ND280 data
- MEC normalization moves from 0.27 ± 0.29 to 1.03 ± 0.17
    - If no prior constraints on single-μ parameters are used, MEC normalization moves to 1.56 ± 0.26
- Have we already reached a systematic limit?
- While it is certainly true that we need to understand ν_e & anti-ν_e cross sections to measure δ_{CP} (more on this later), we cannot do precision oscillation physics without a much more precise understanding of ν-nucleus interactions

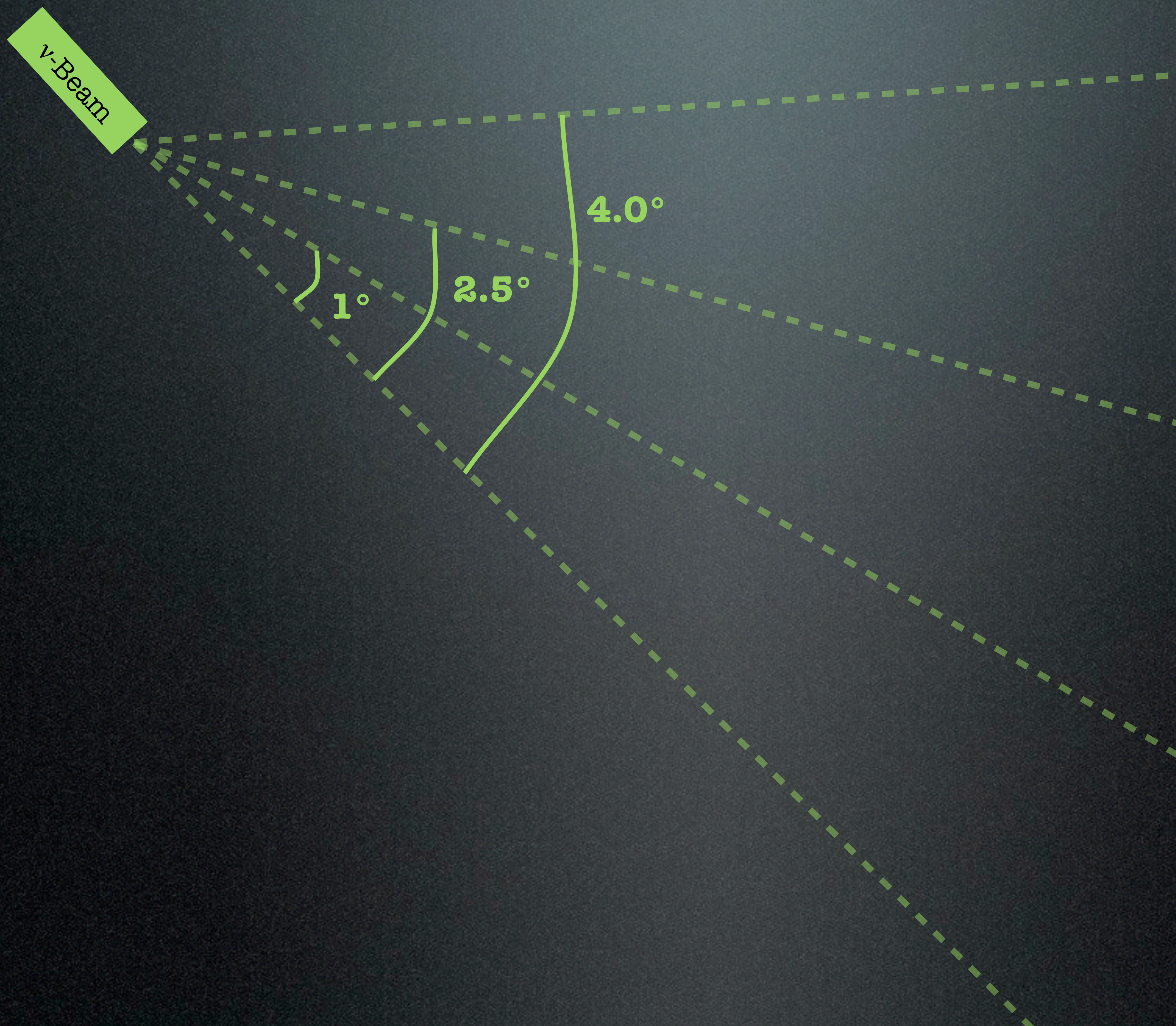




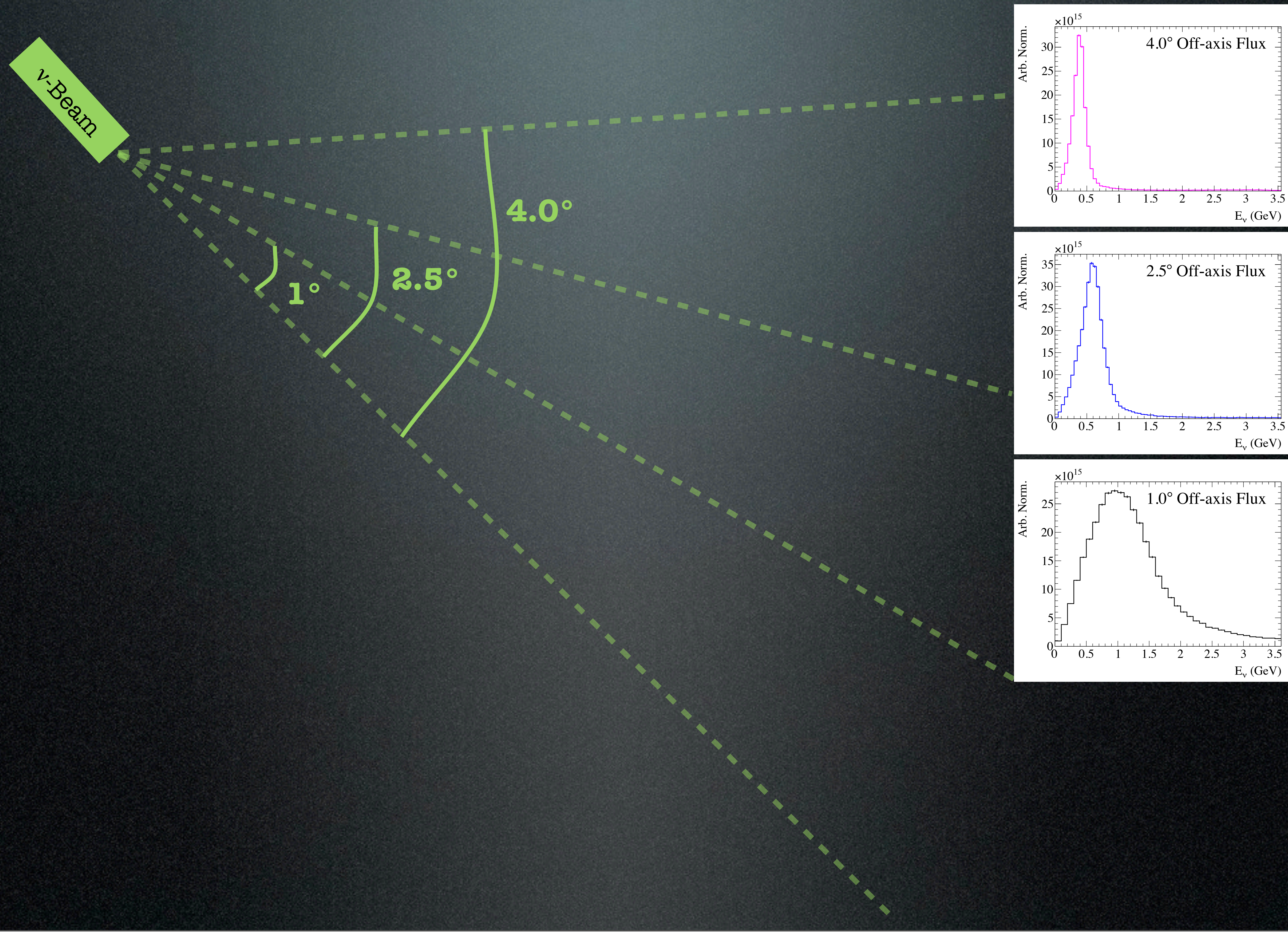
Can the E_ν problem be solved experimentally?

NuPRISM Detector Concept

NuPRISM Detector Concept



NuPRISM Detector Concept



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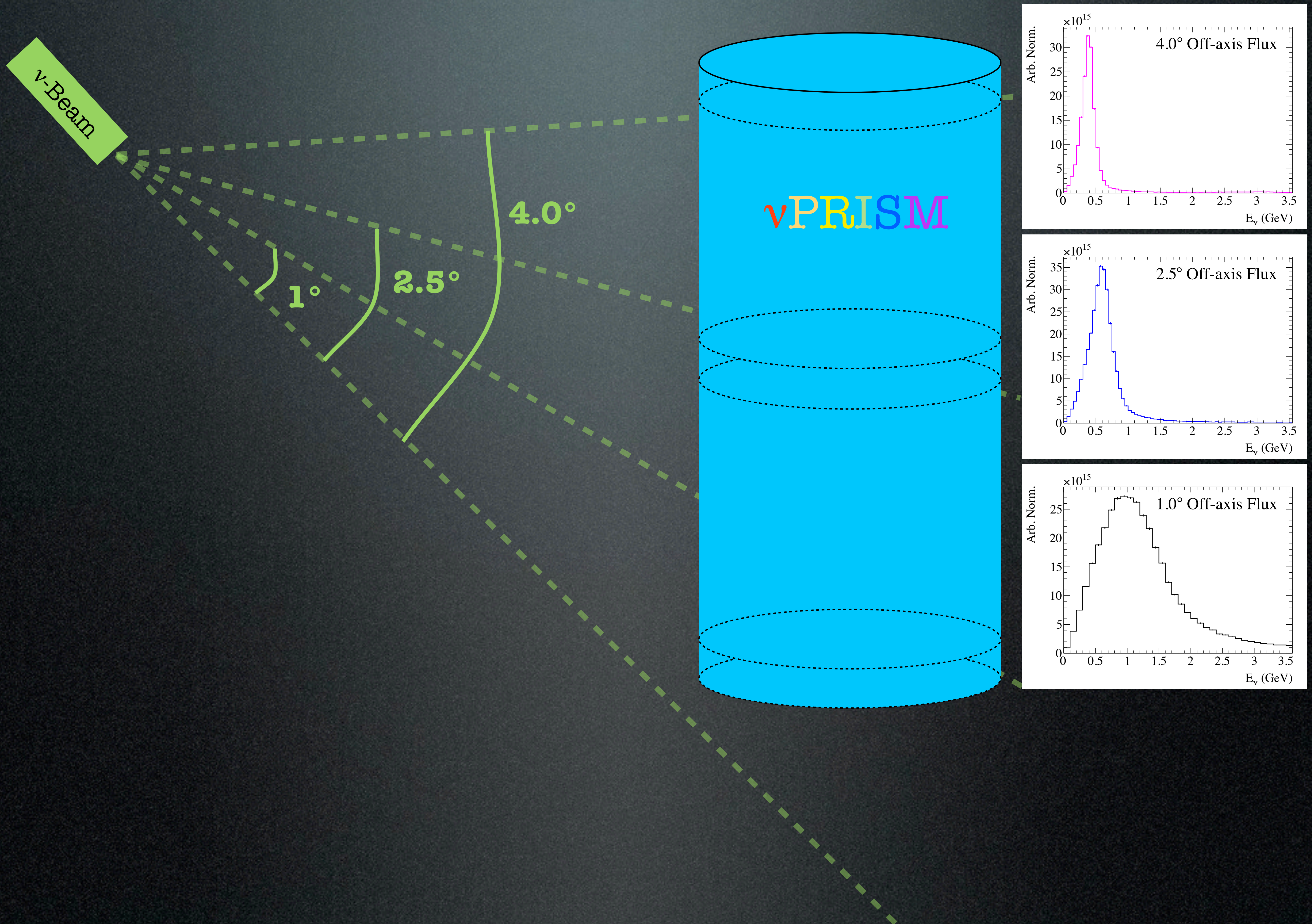

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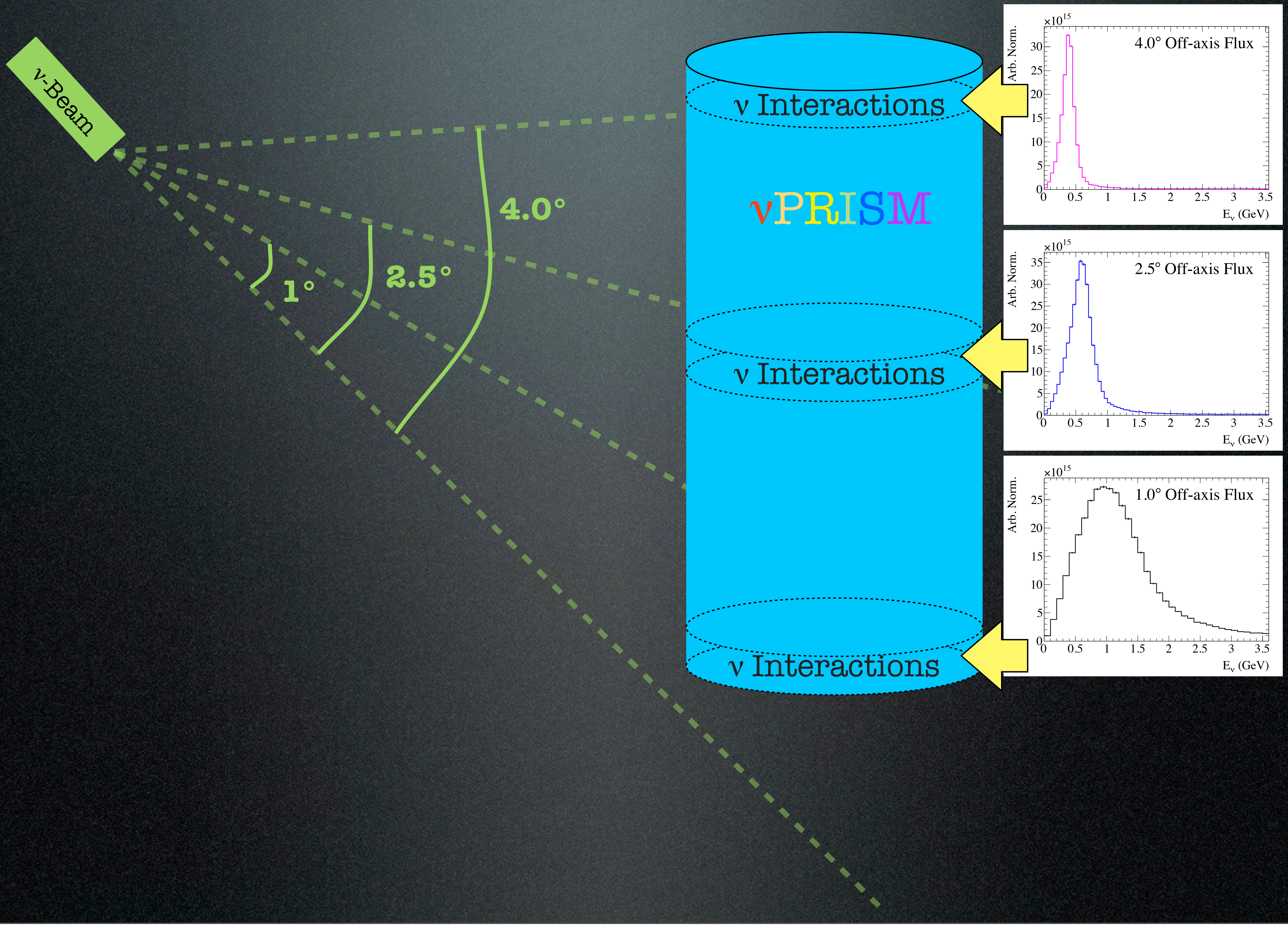

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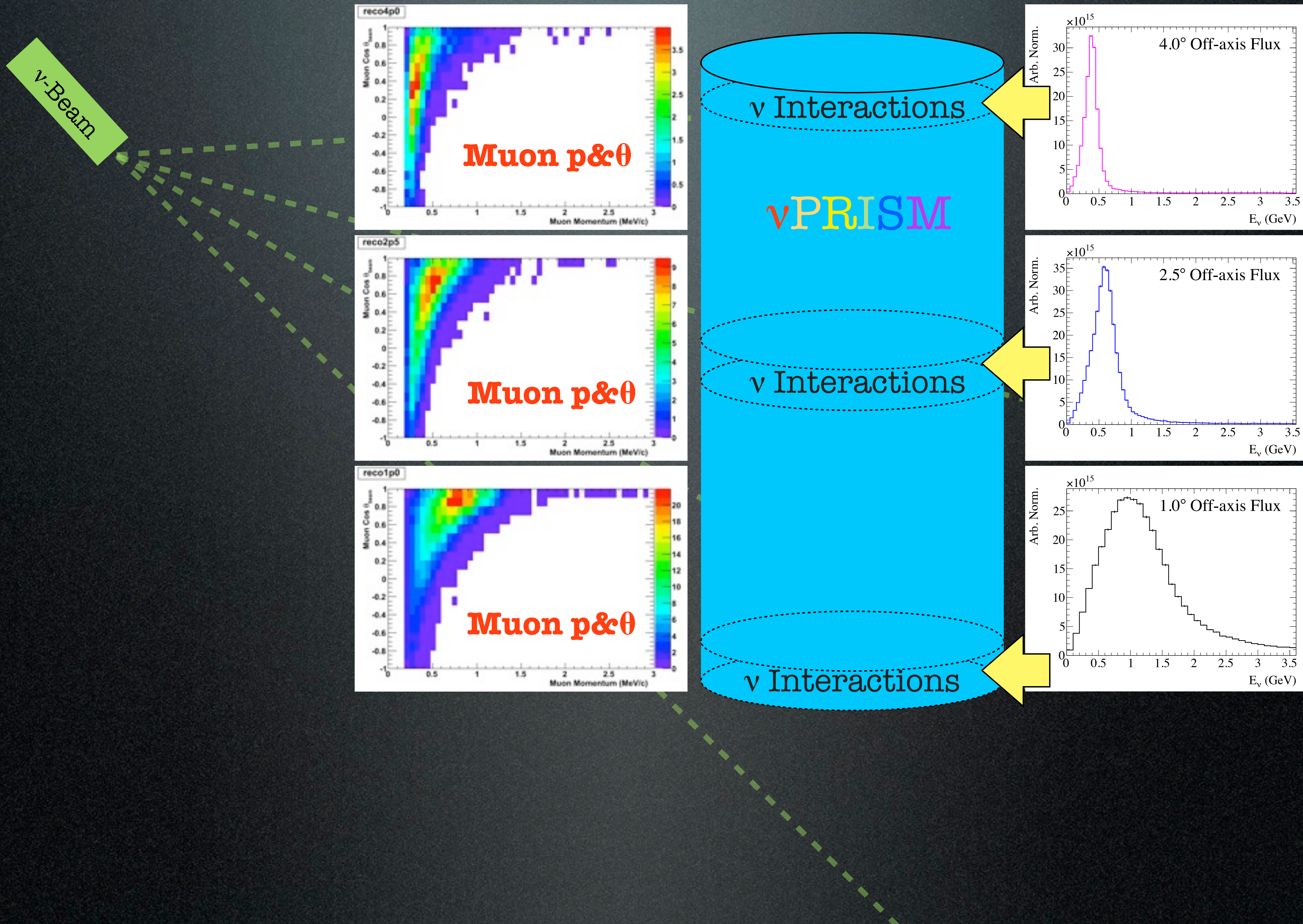

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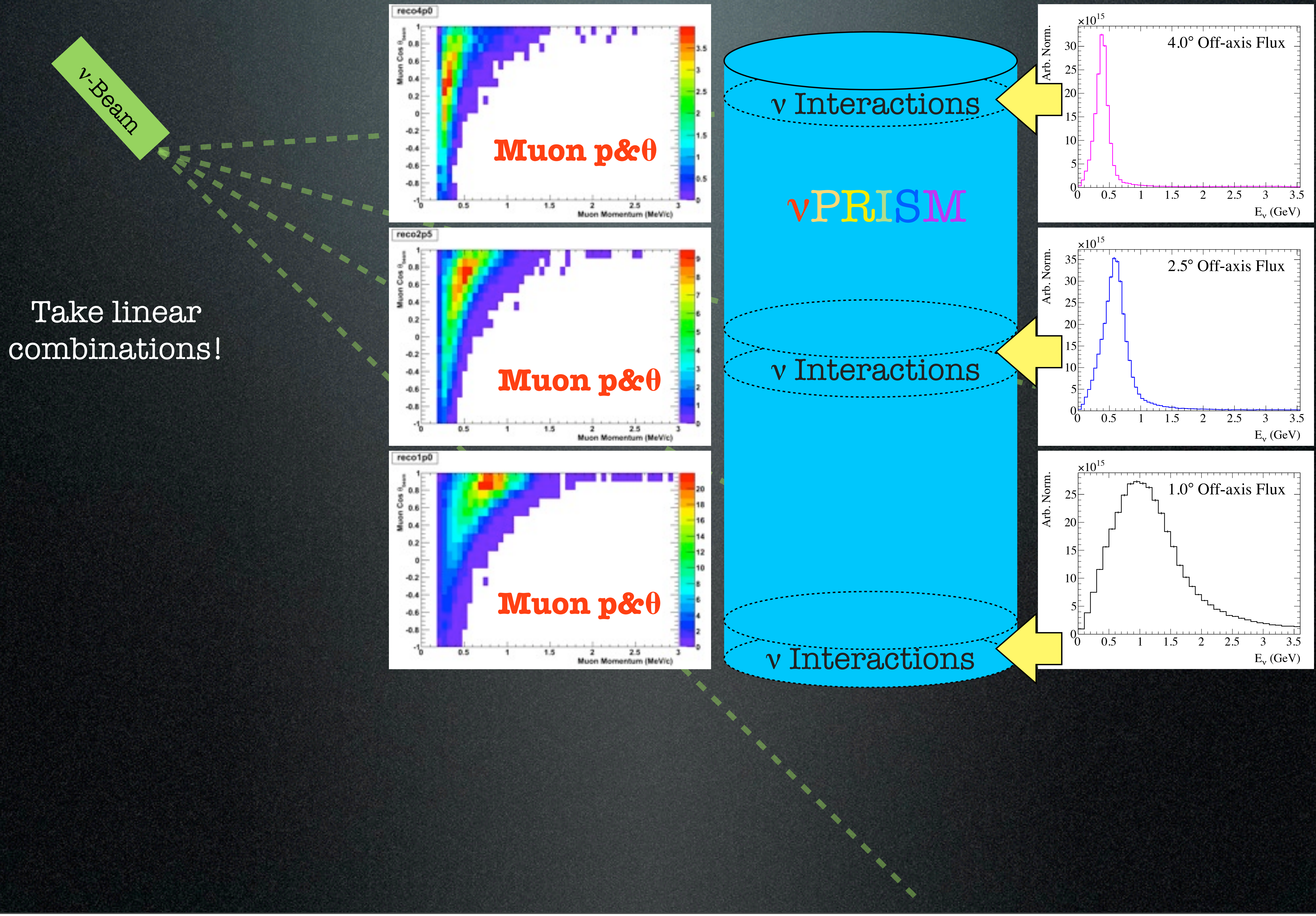
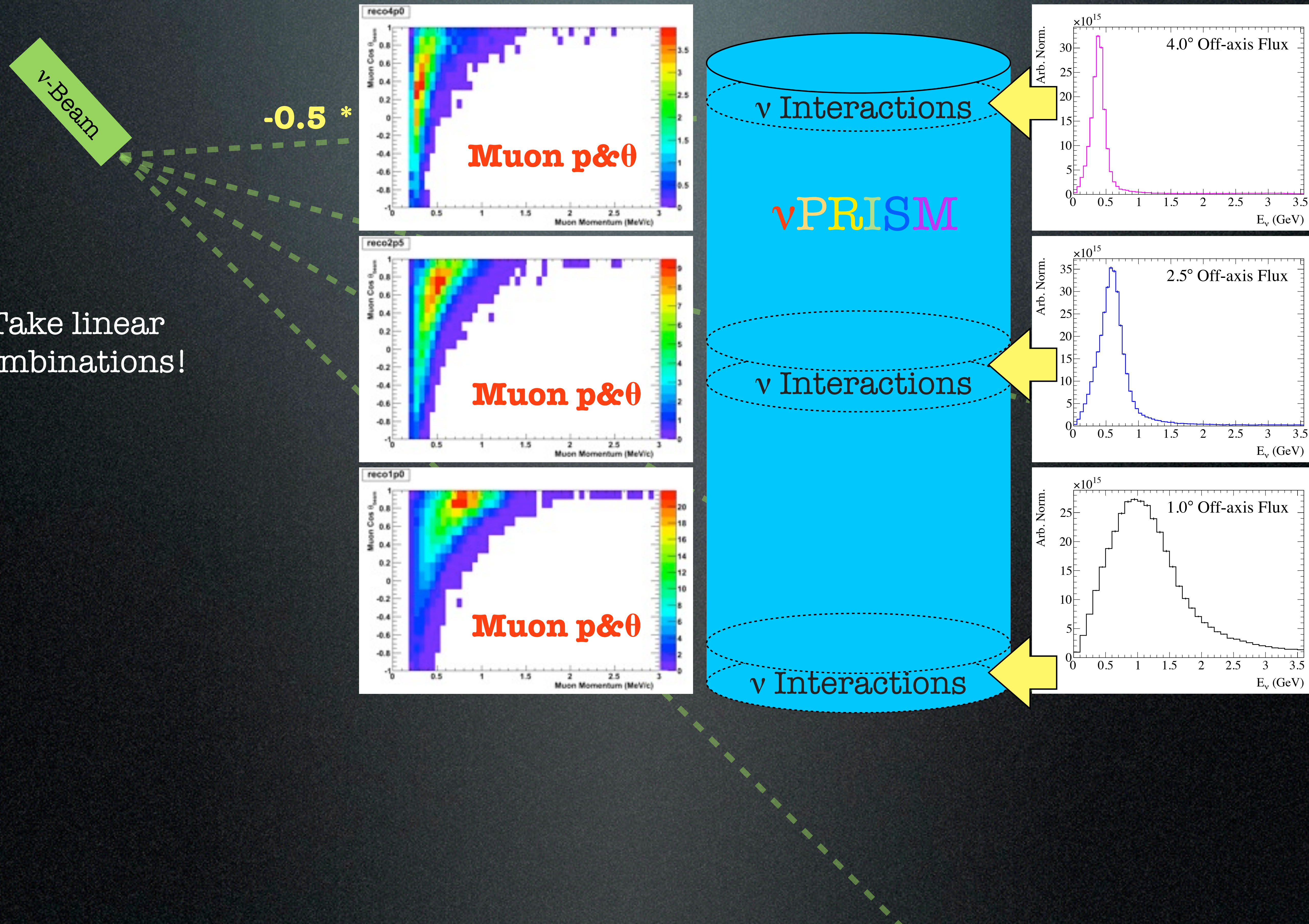


NuPRISM Detector Concept

Take linear combinations!



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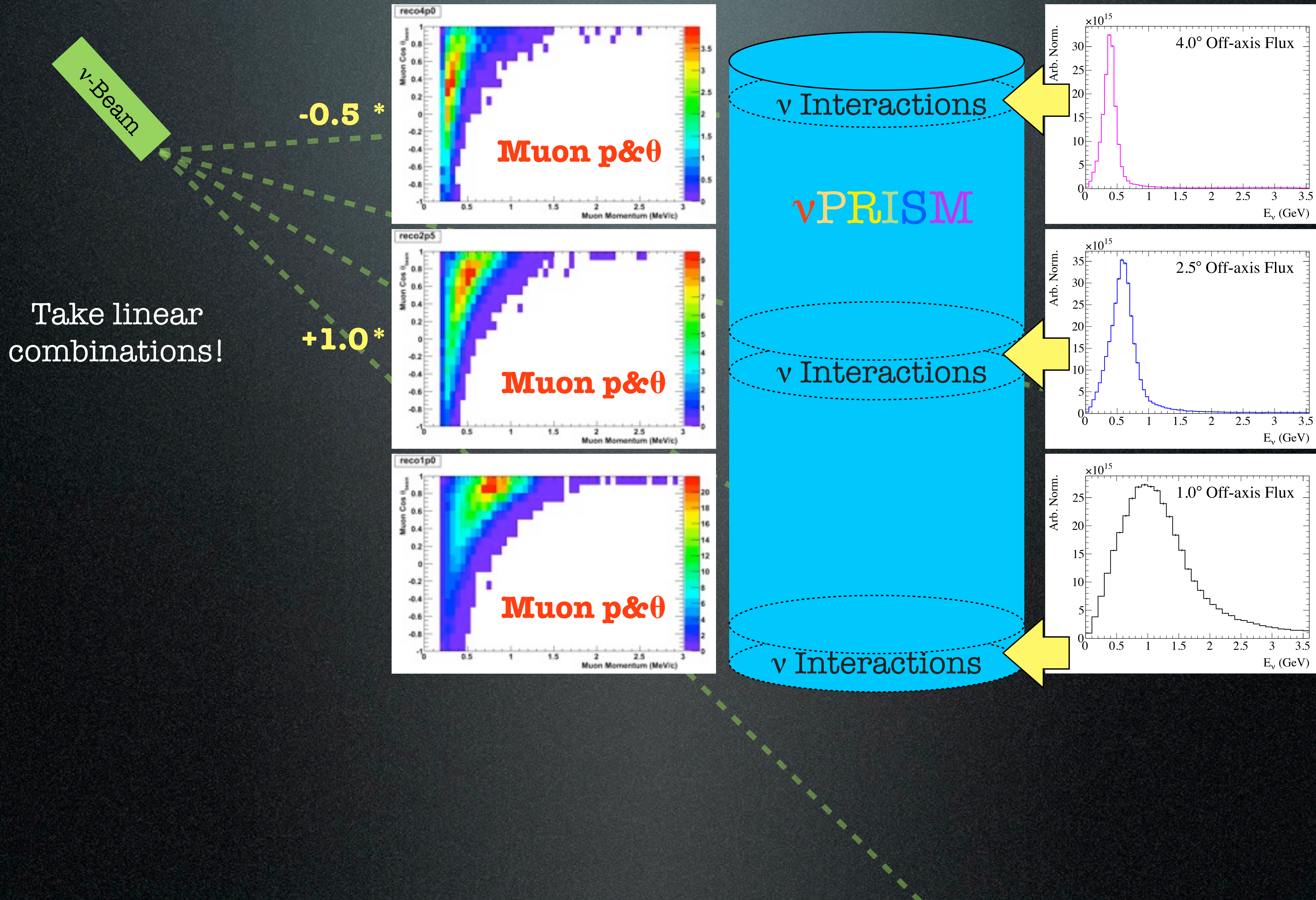

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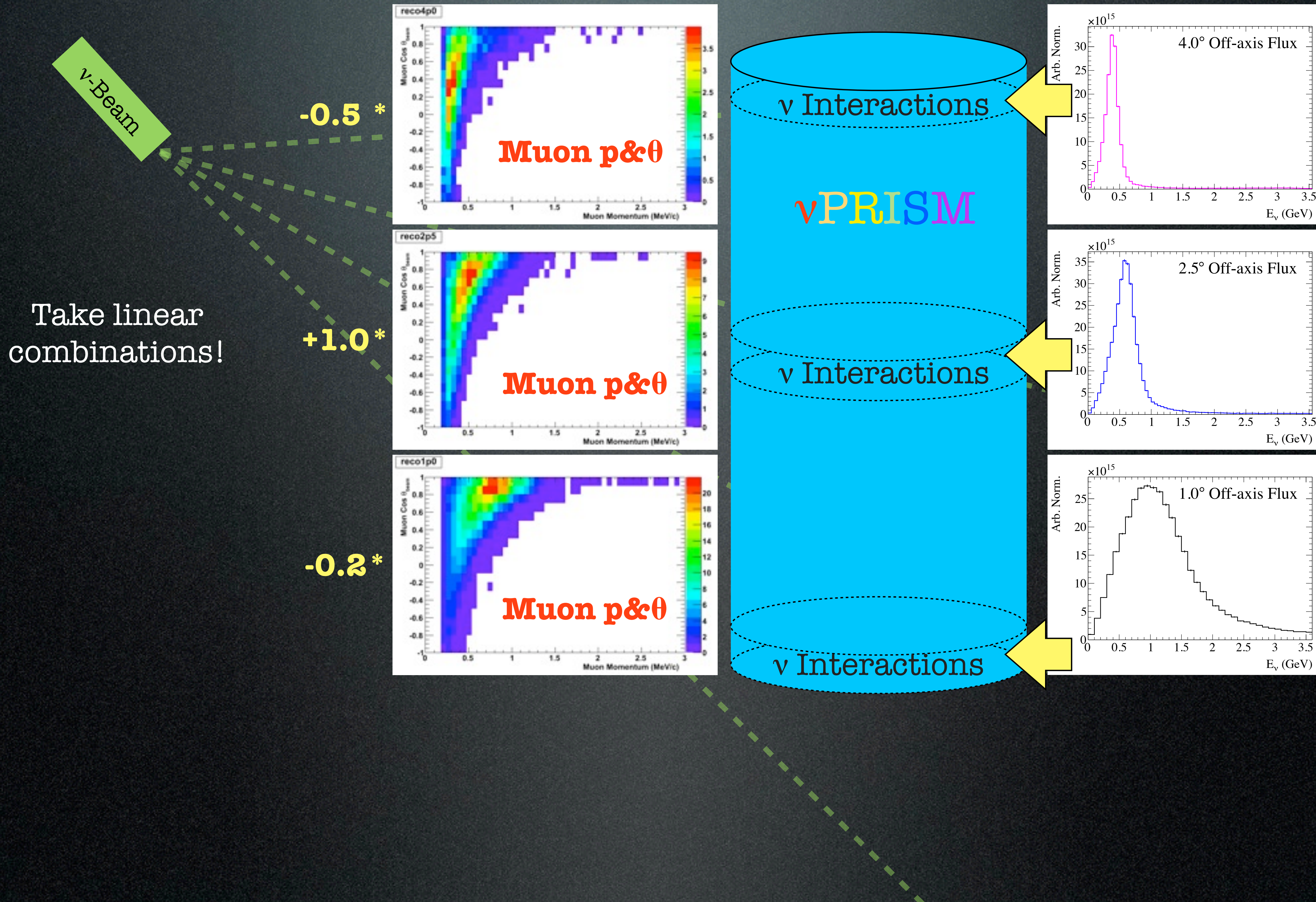

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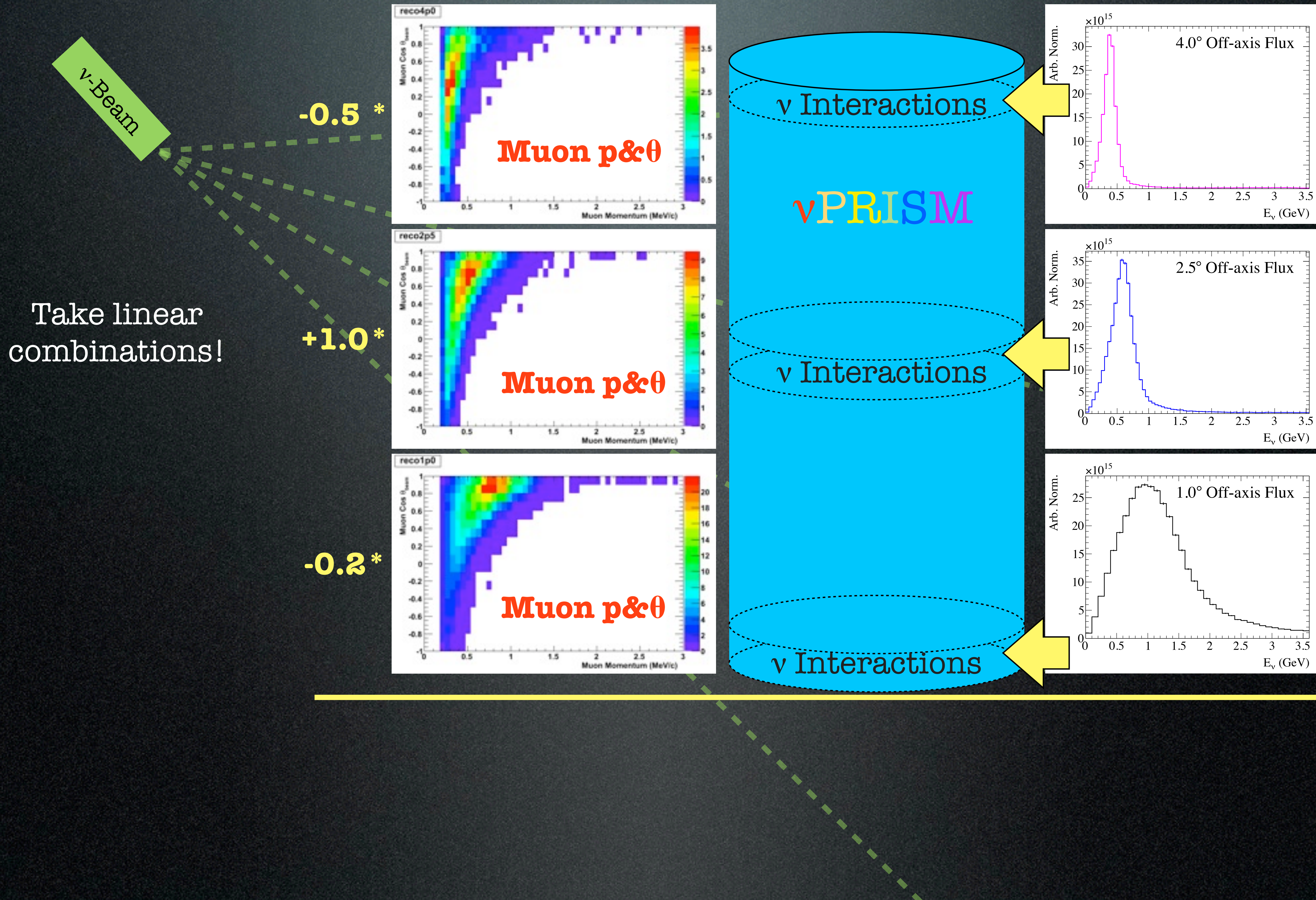

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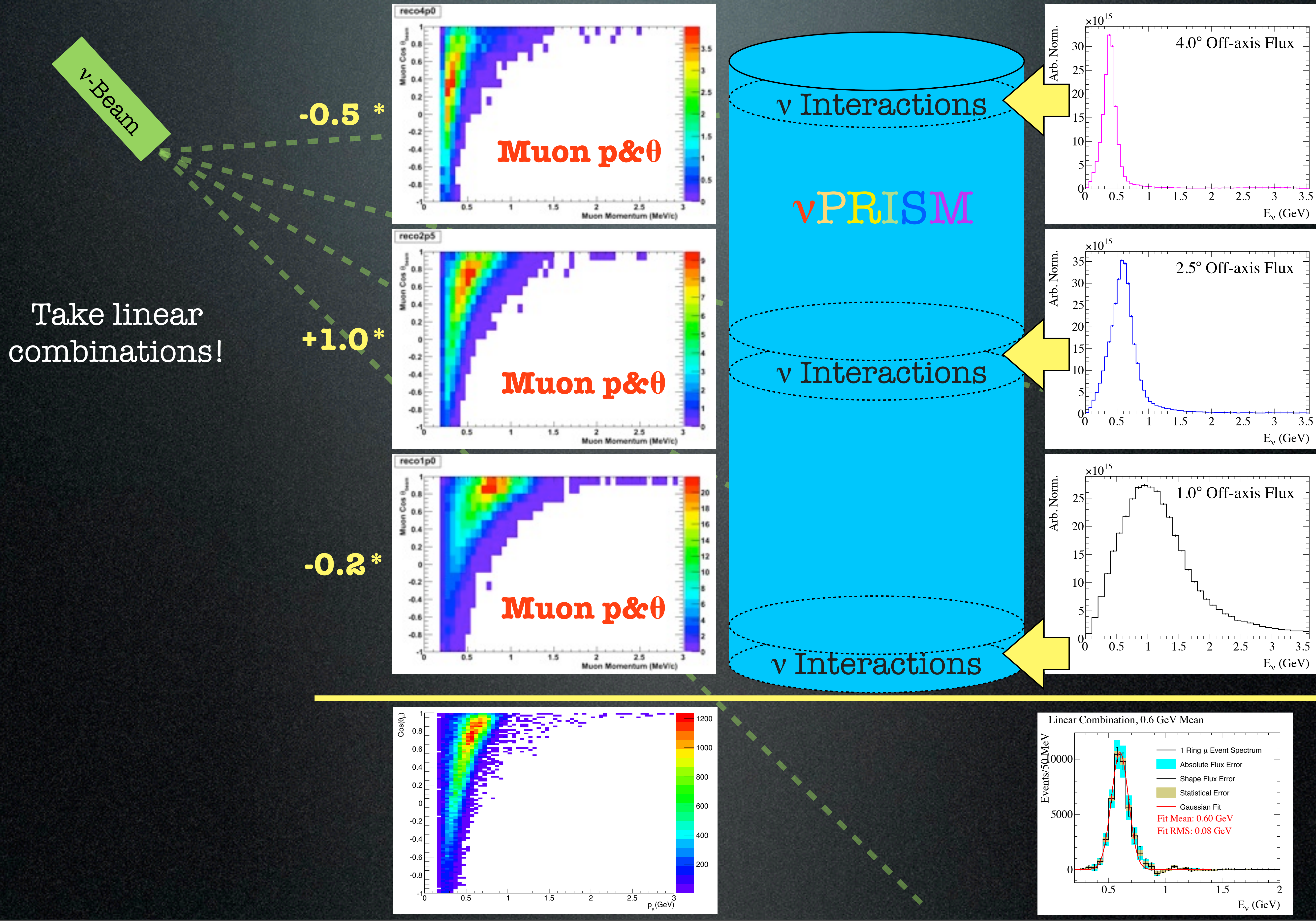

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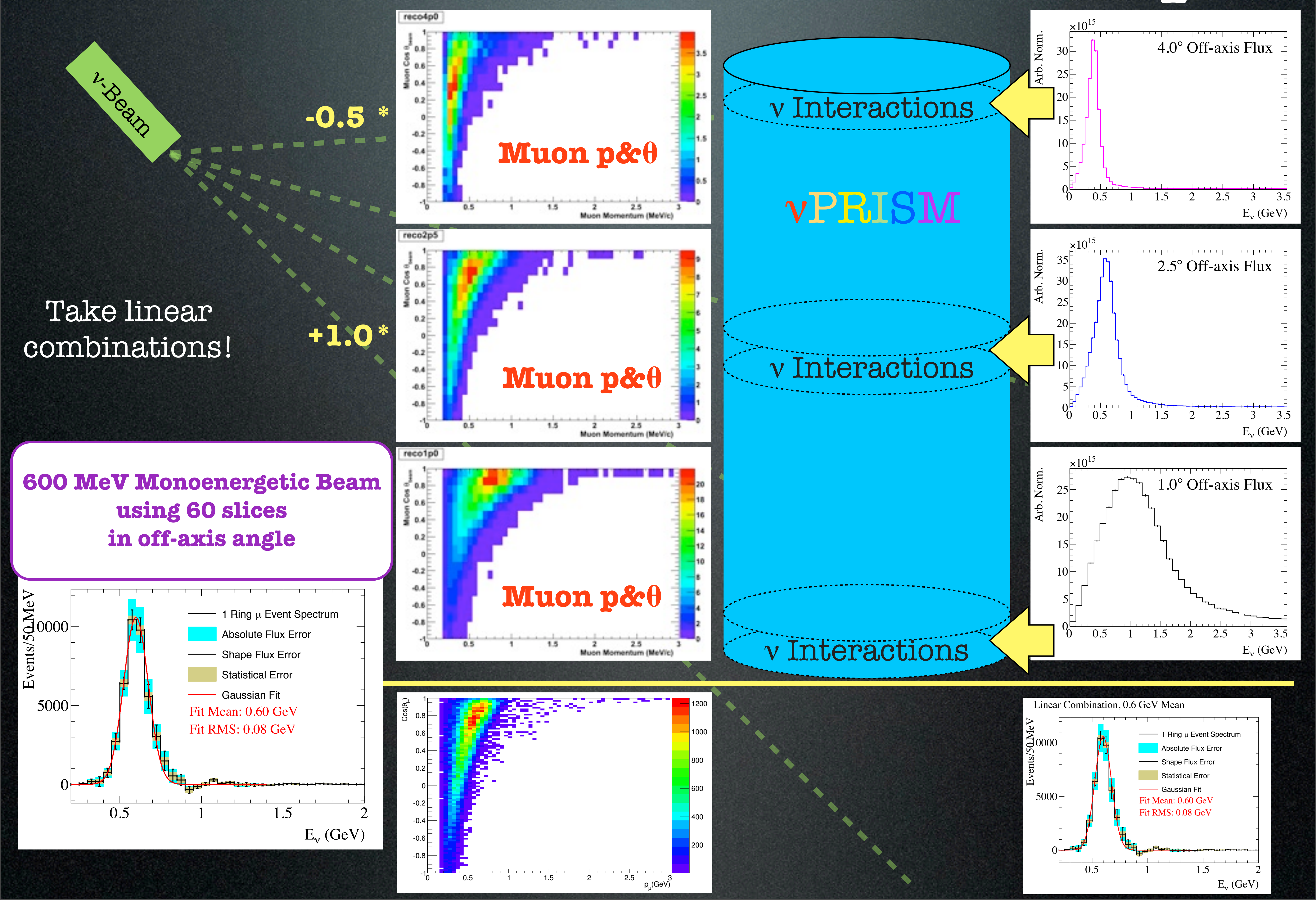
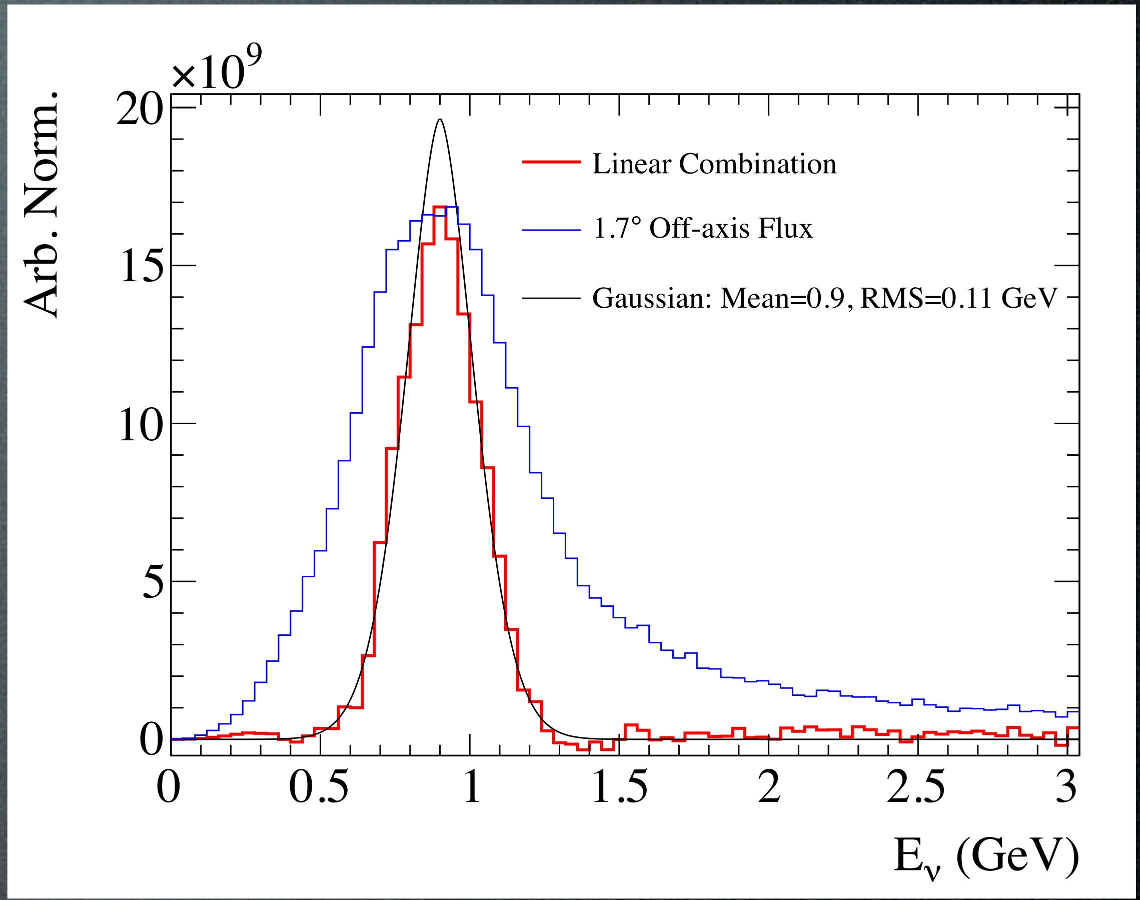
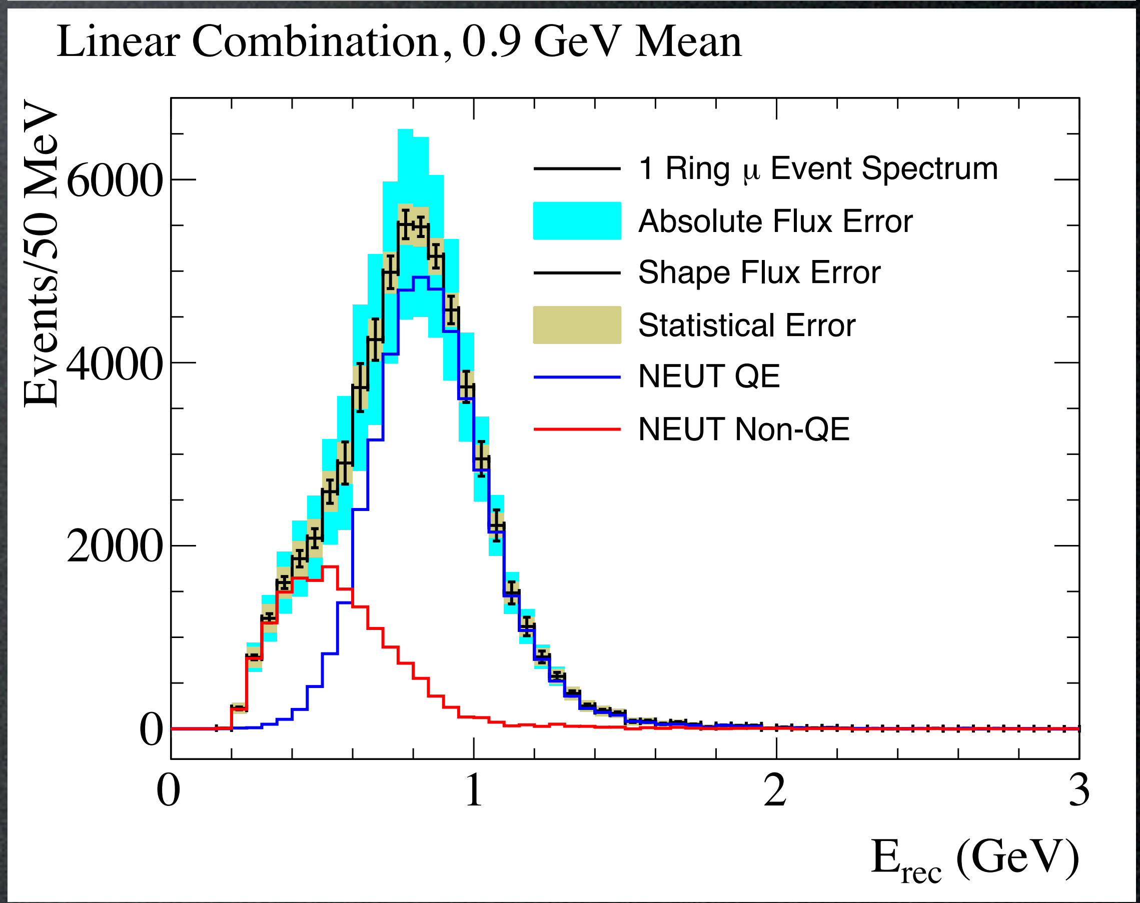


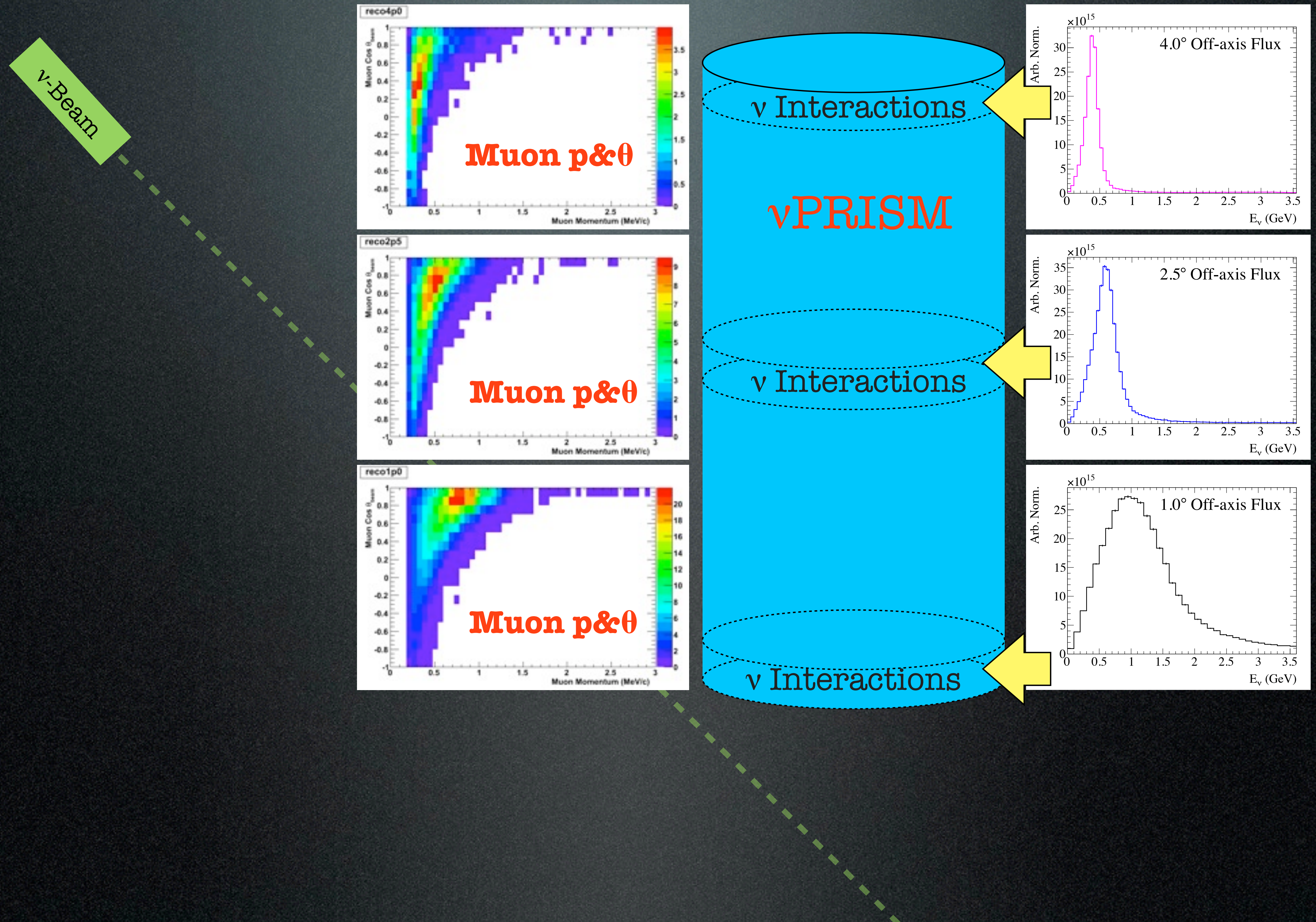
Benefits of a Monoenergetic Beam

- 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!



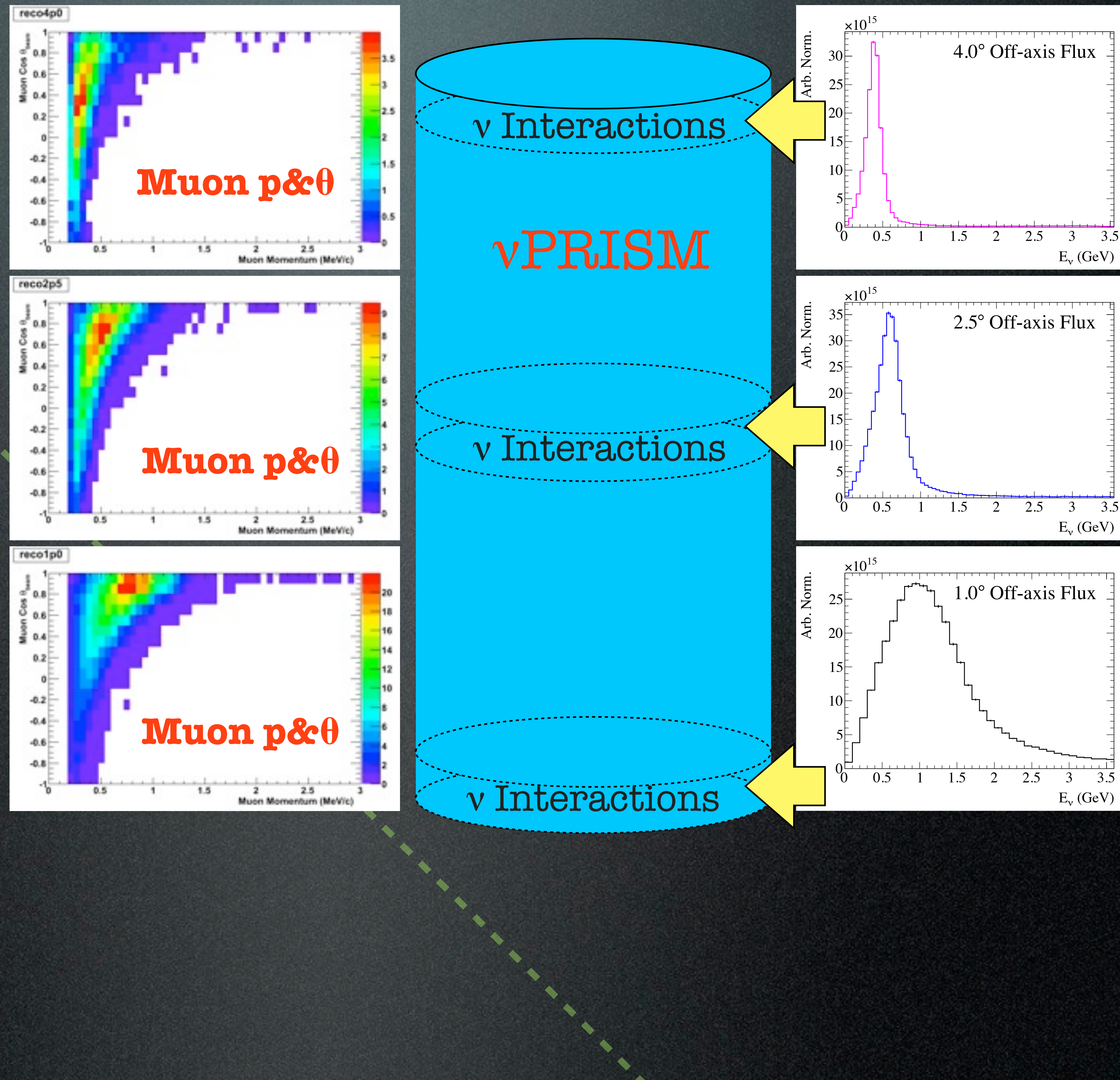


NuPRISM in Oscillation Experiments



NuPRISM in Oscillation Experiments

Take different linear combinations!



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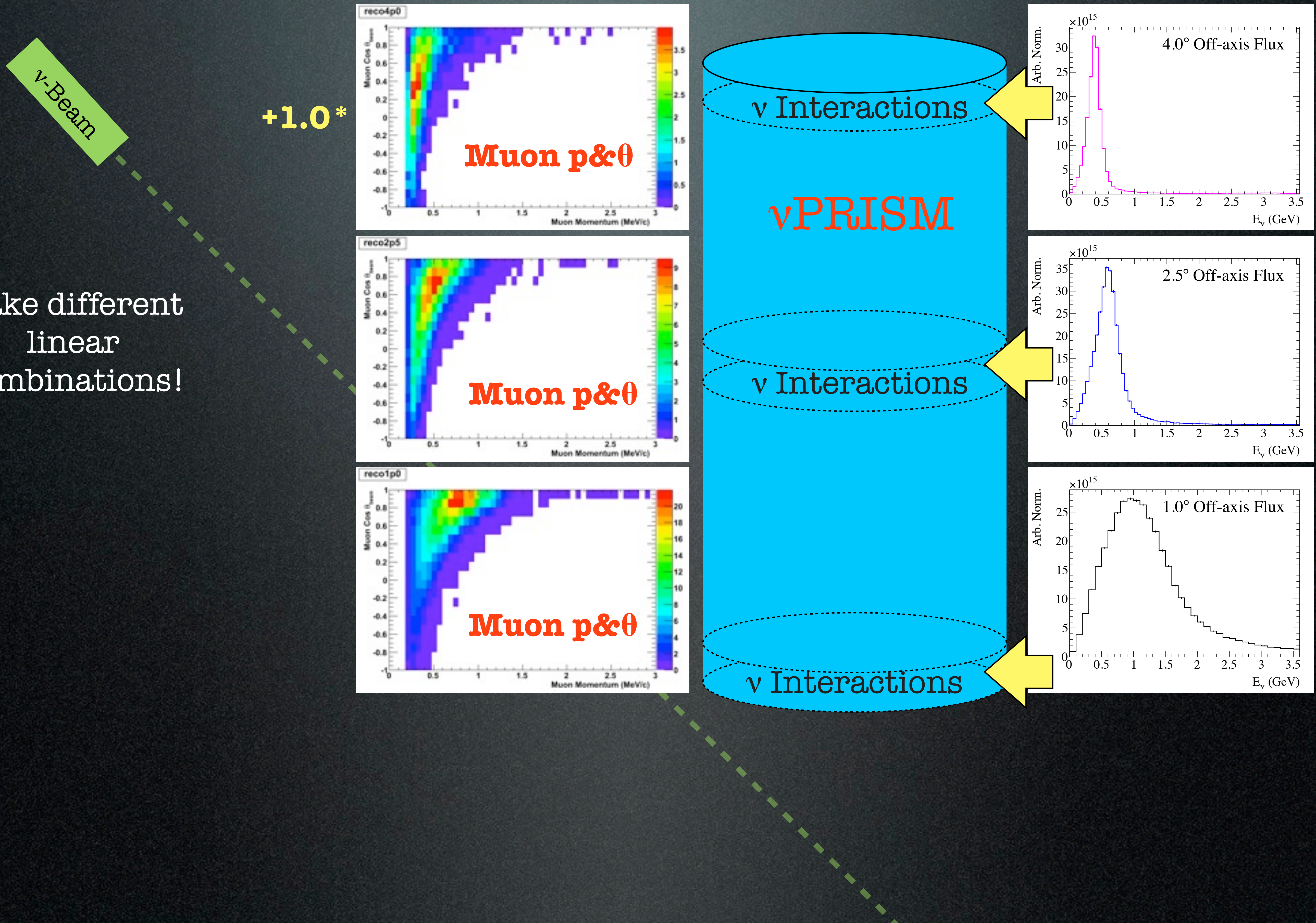

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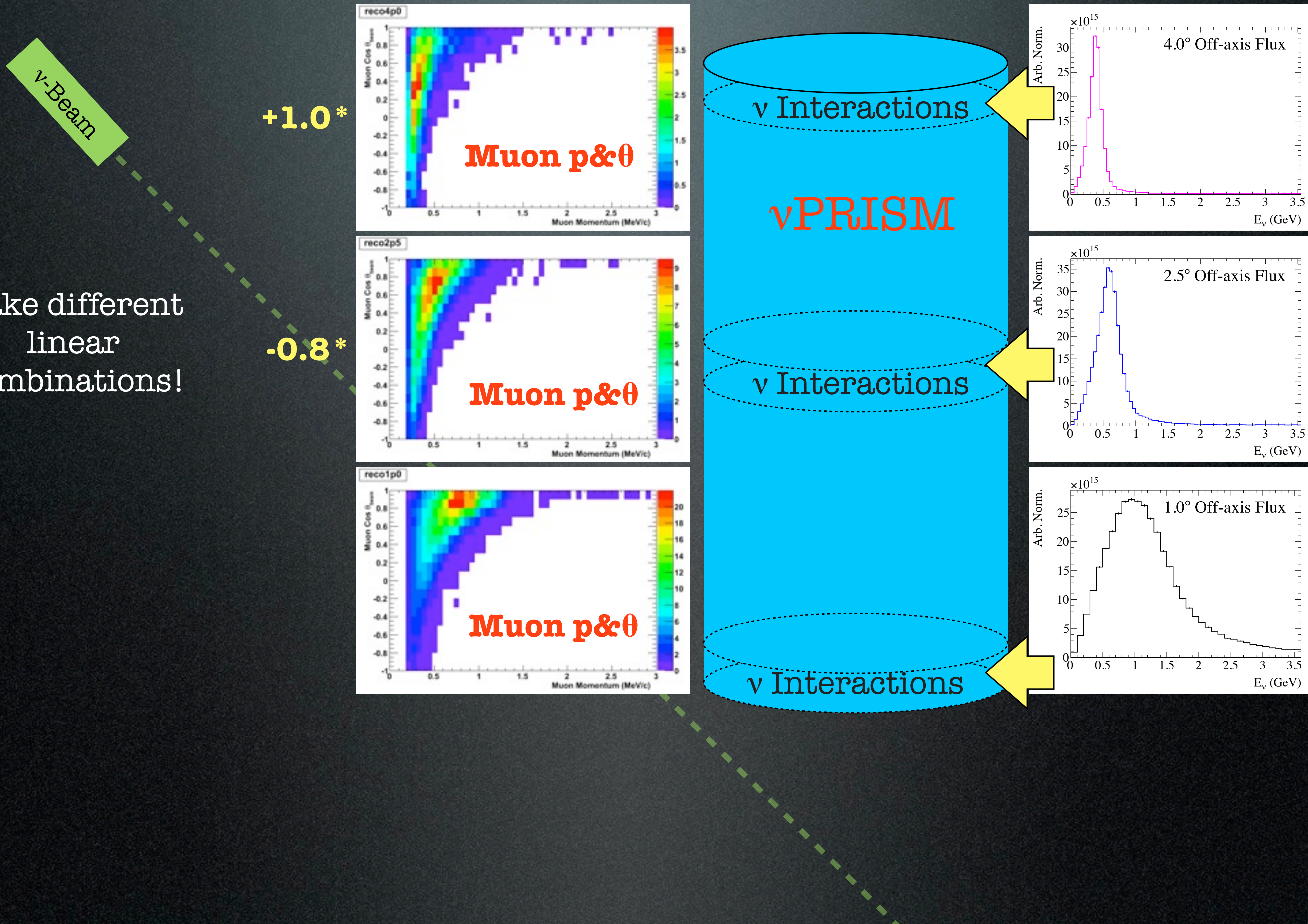

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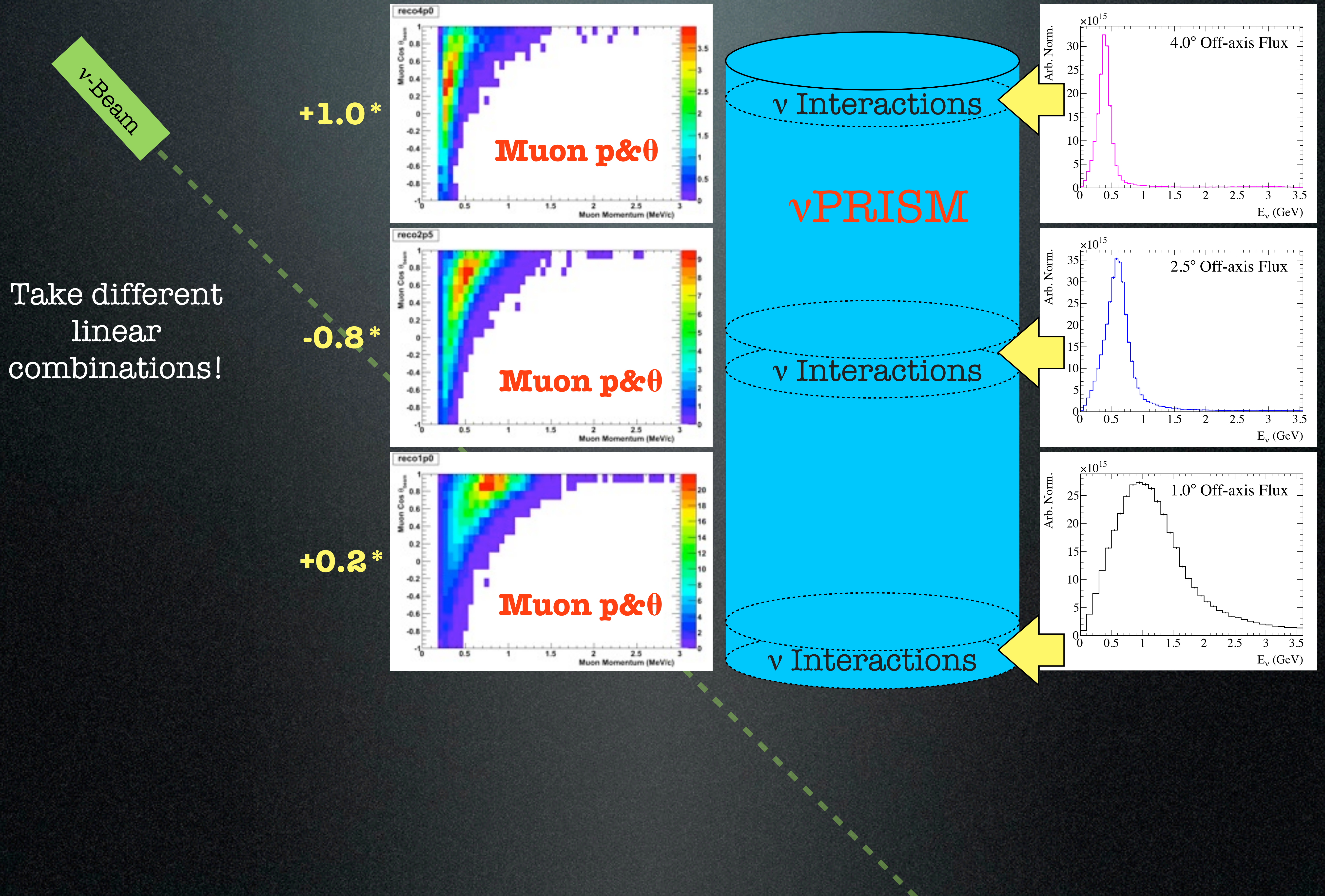
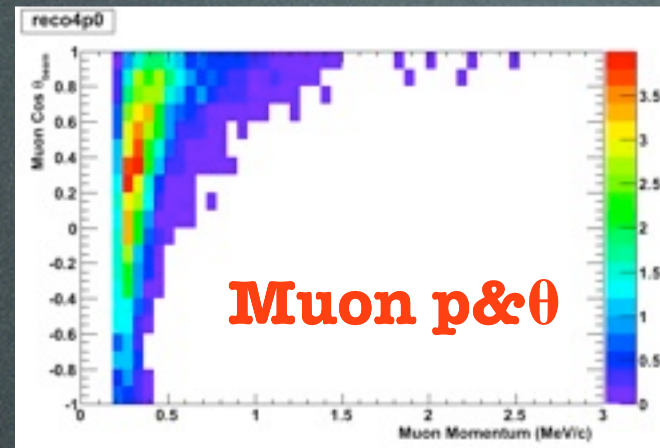


NuPRISM in Oscillation Experiments

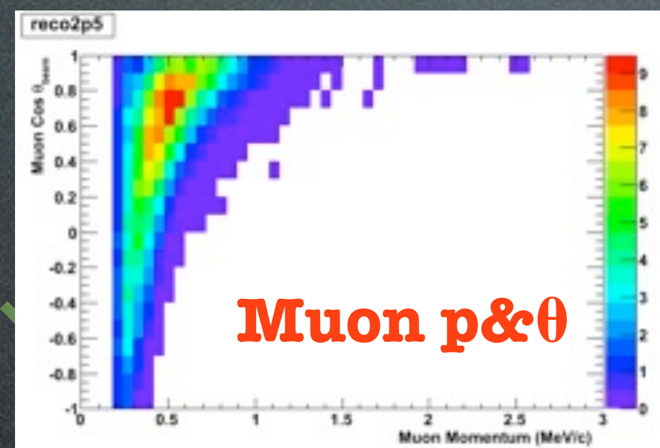
ν-Beam

Take different linear combinations!

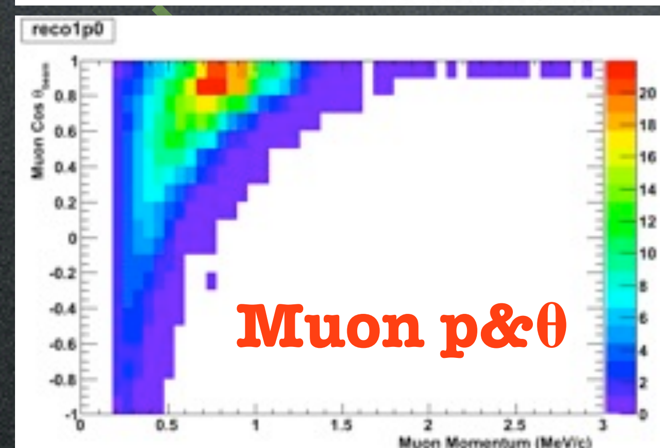
+1.0 *

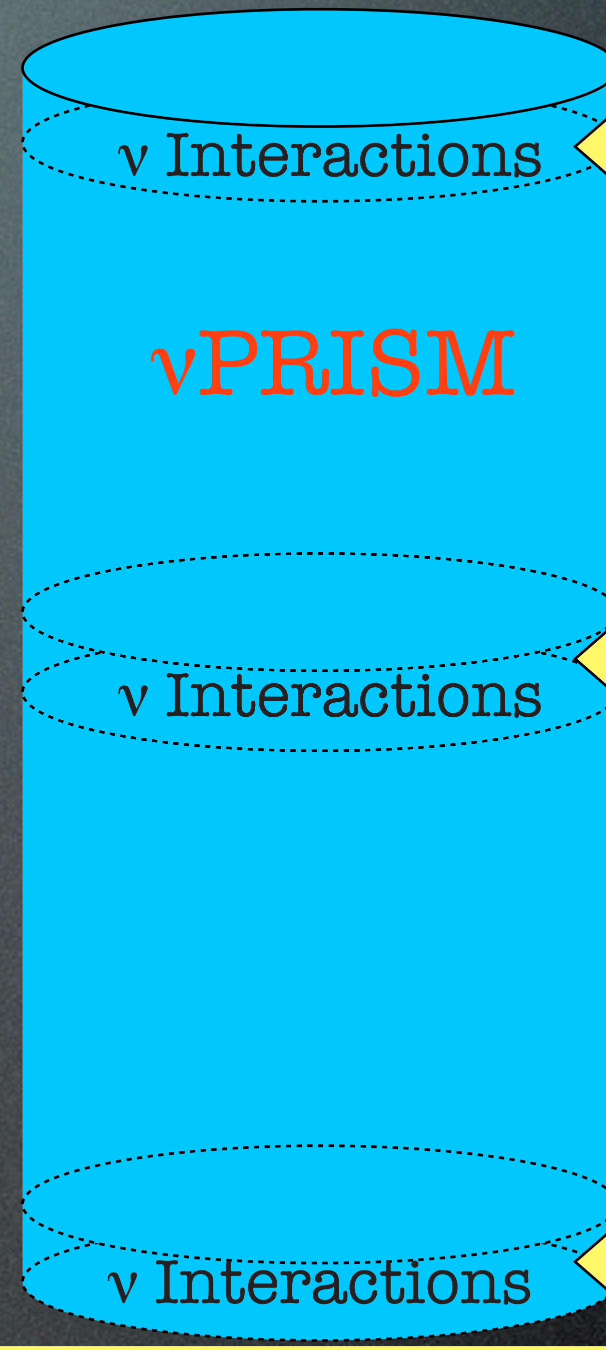


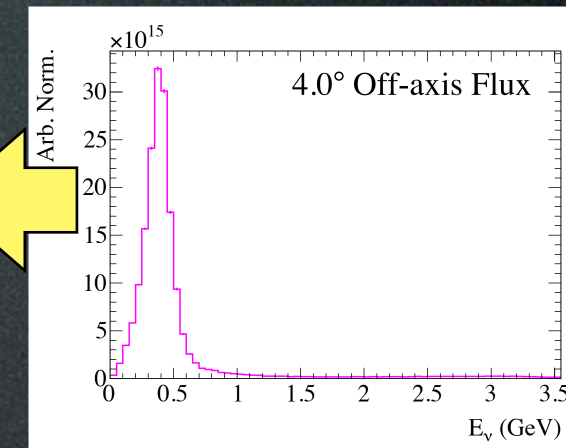
-0.8 *

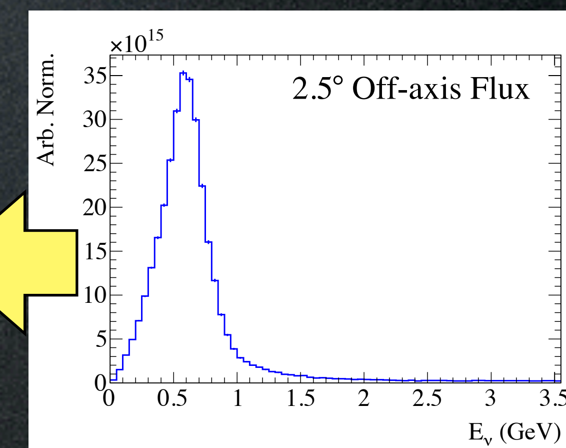


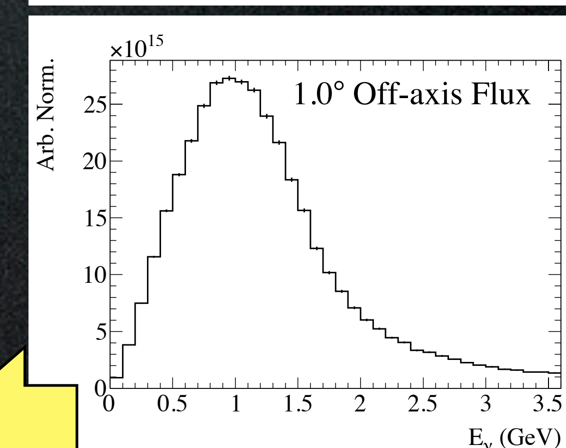
+0.2 *

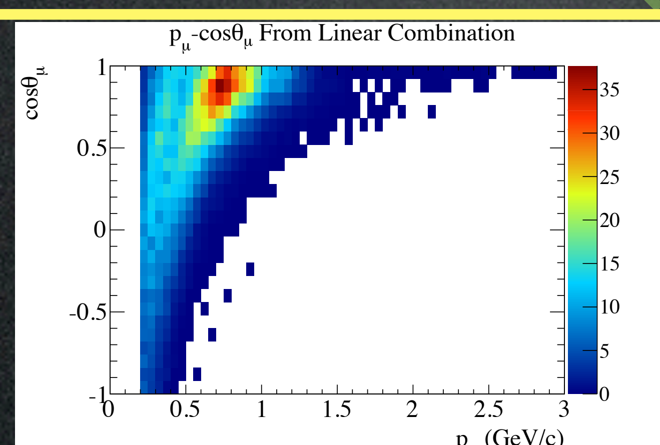






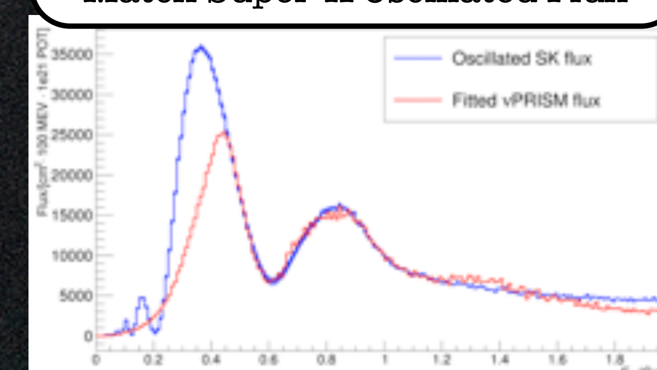






Measured! Muon p&θ for Oscillated SK Flux!

Match Super-K Oscillated Flux

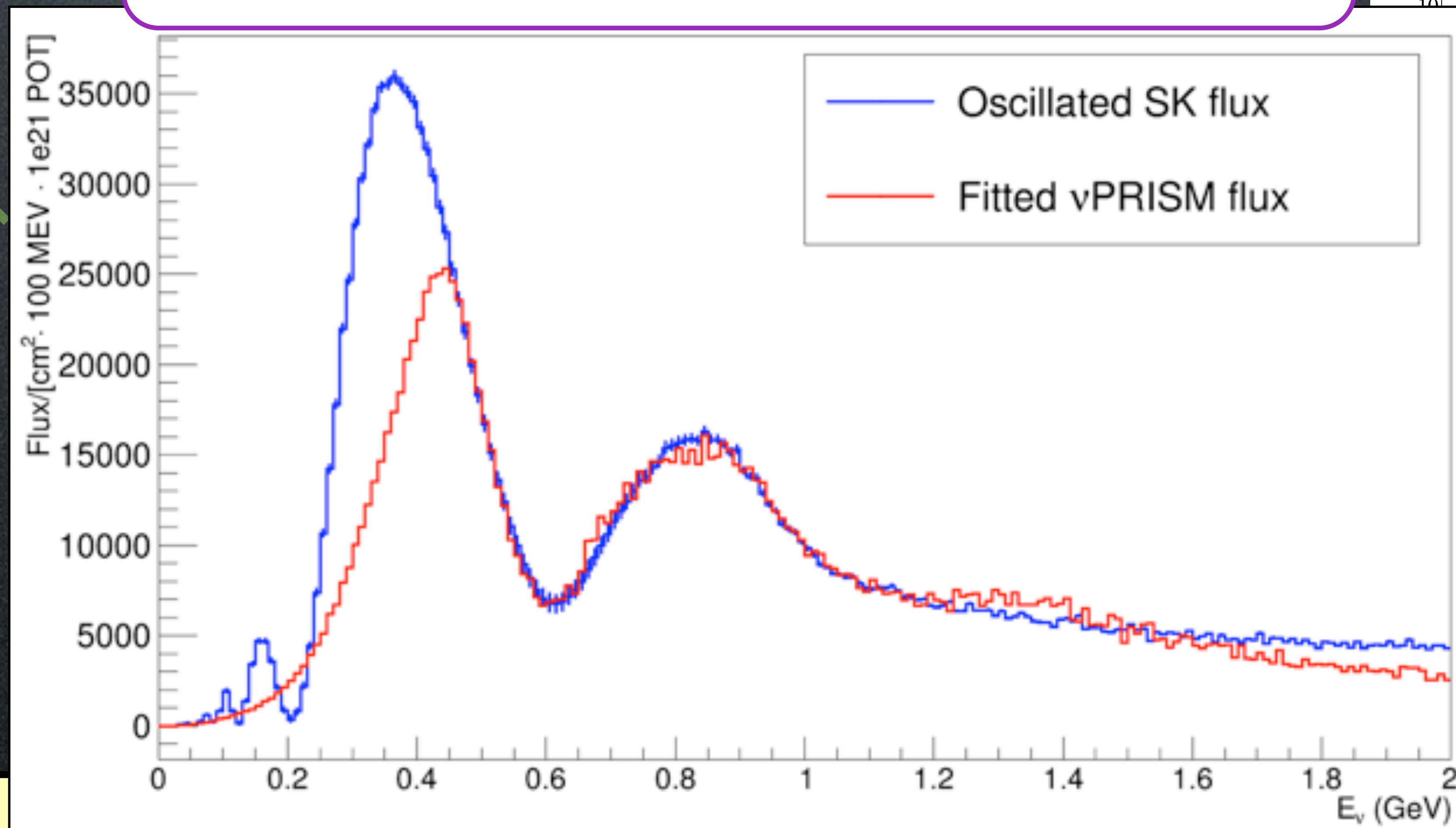


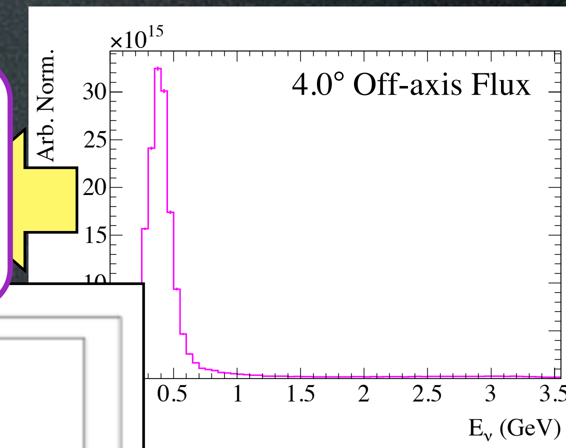
NuPRISM in Oscillation Experiments

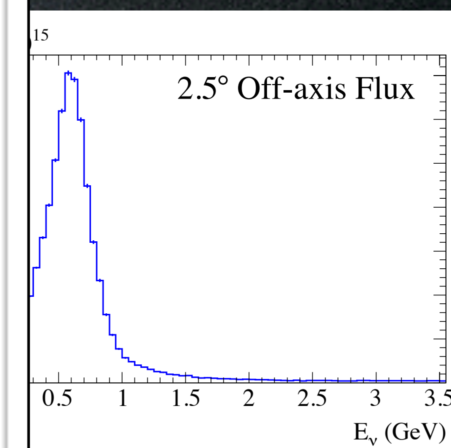
ν-Beam

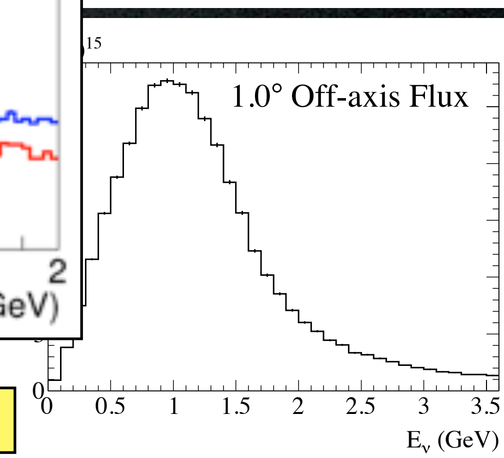
+1

Reproduce Super-K Oscillation Pattern at a Near Detector!





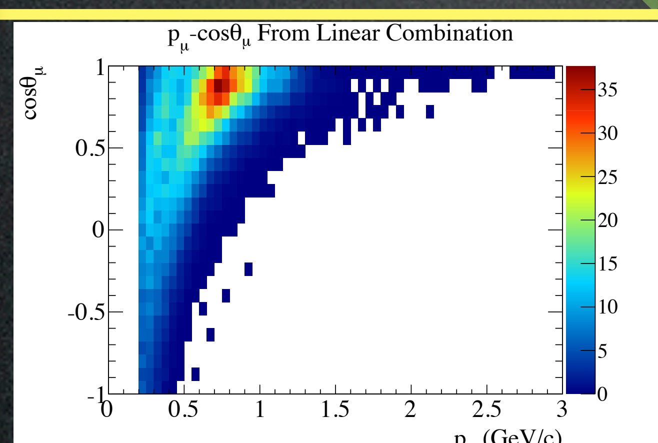




Take different linear combinations!

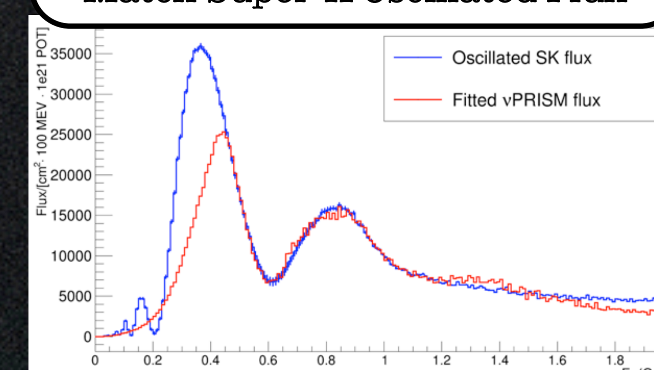
ν Interactions

This is the procedure used for the
T2K/nuPRISM
ν_μ disappearance analysis
(next slides)



Measured! Muon p&θ for Oscillated SK Flux!

Match Super-K Oscillated Flux

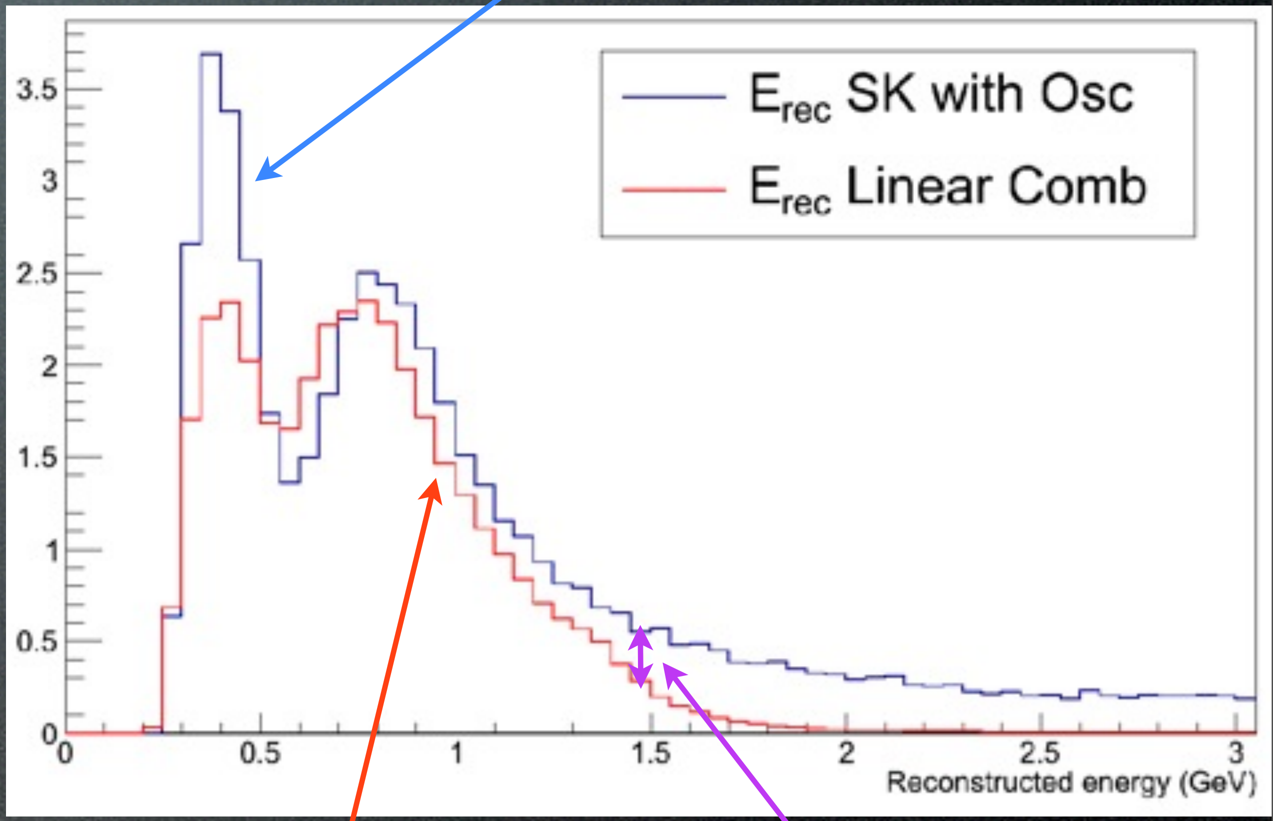


The nuPRISM ν_μ Disappearance Analysis

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

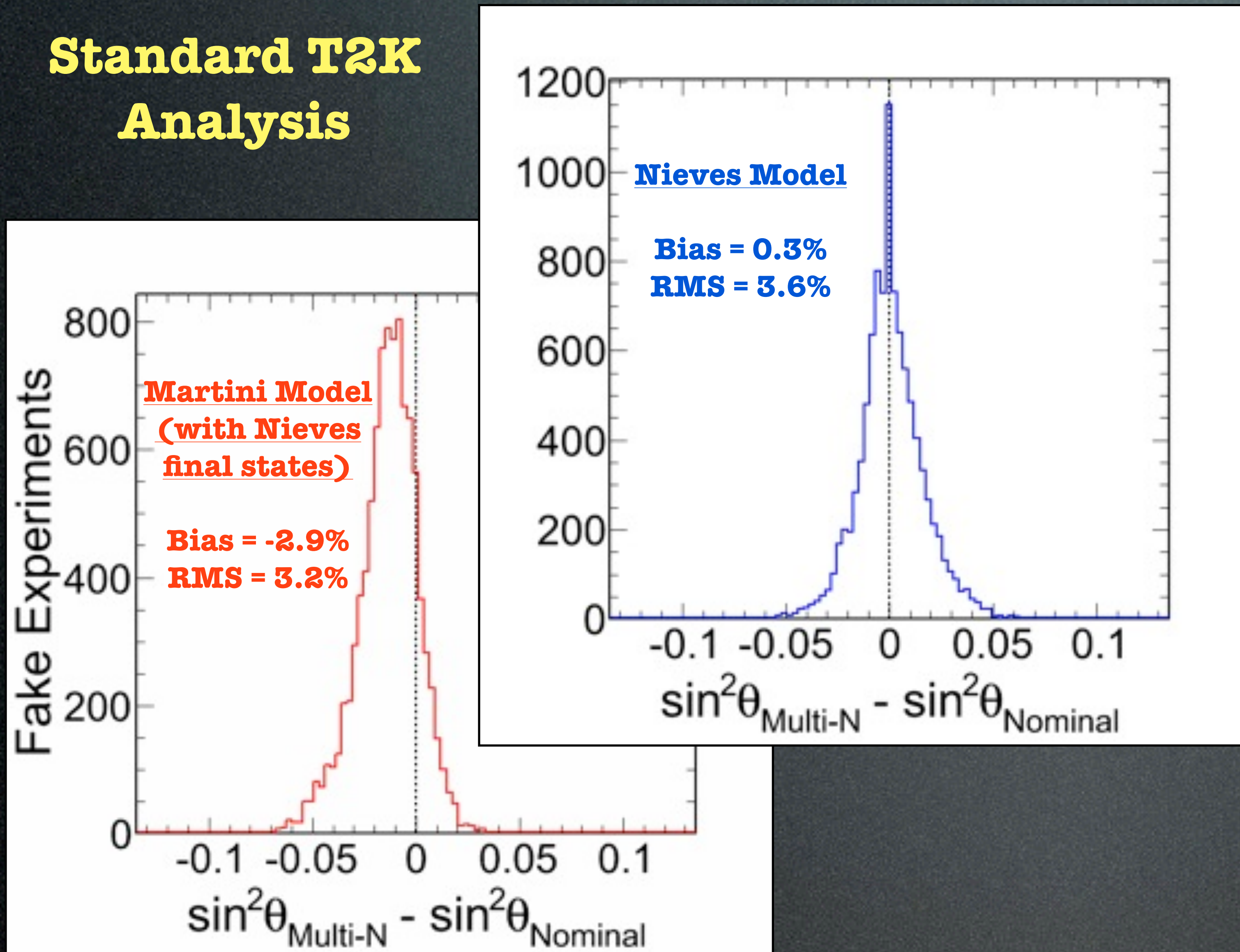


Now, NuPRISM directly measures most of this distribution

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

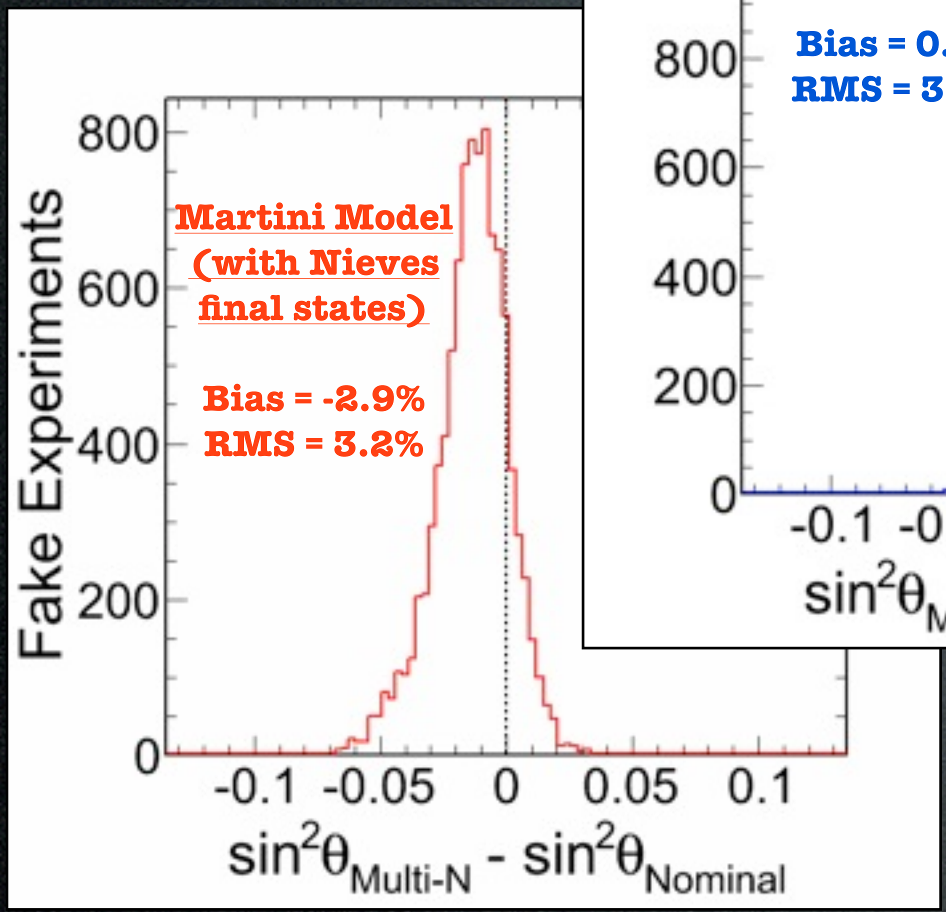
NuPRISM ν_μ Disappearance Constraint

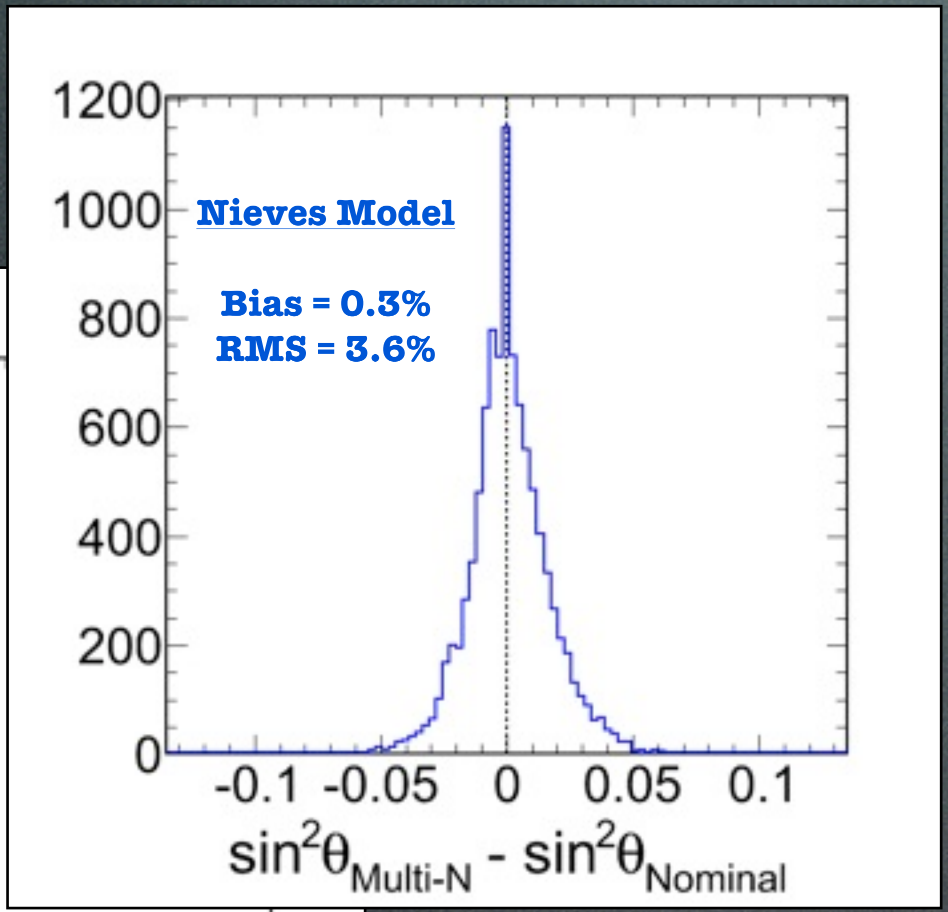
Standard T2K Analysis



NuPRISM ν_μ Disappearance Constraint

Standard T2K Analysis

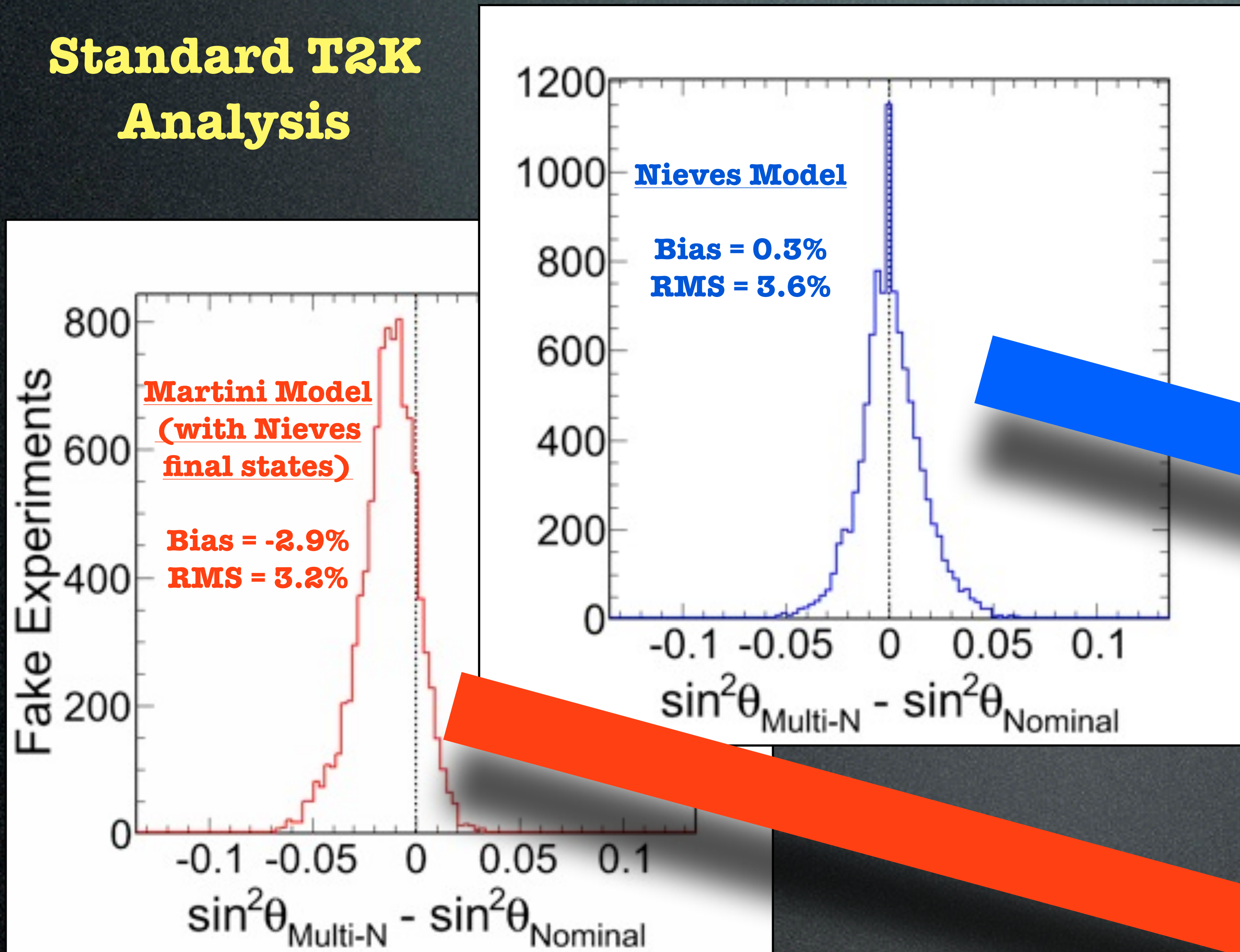




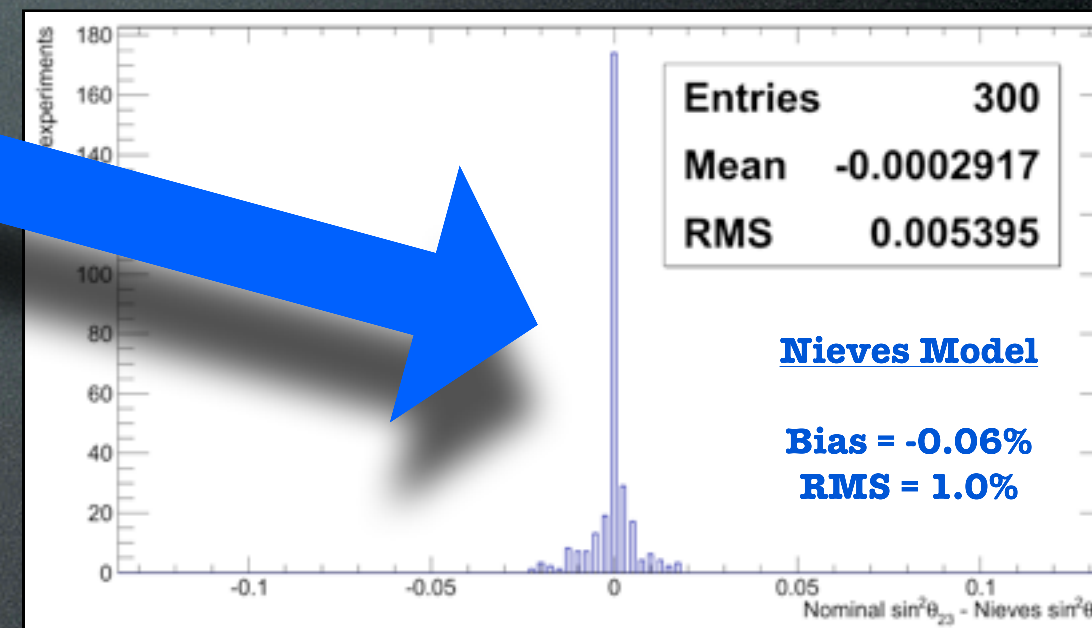
νPRISM Analysis

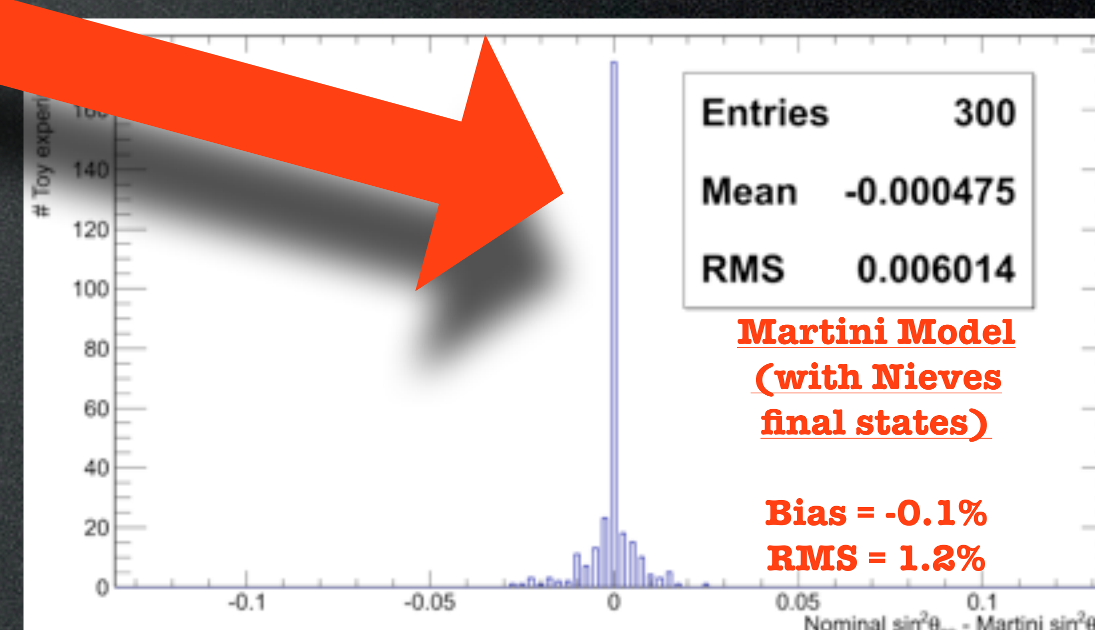
NuPRISM ν_μ Disappearance Constraint

Standard T2K Analysis



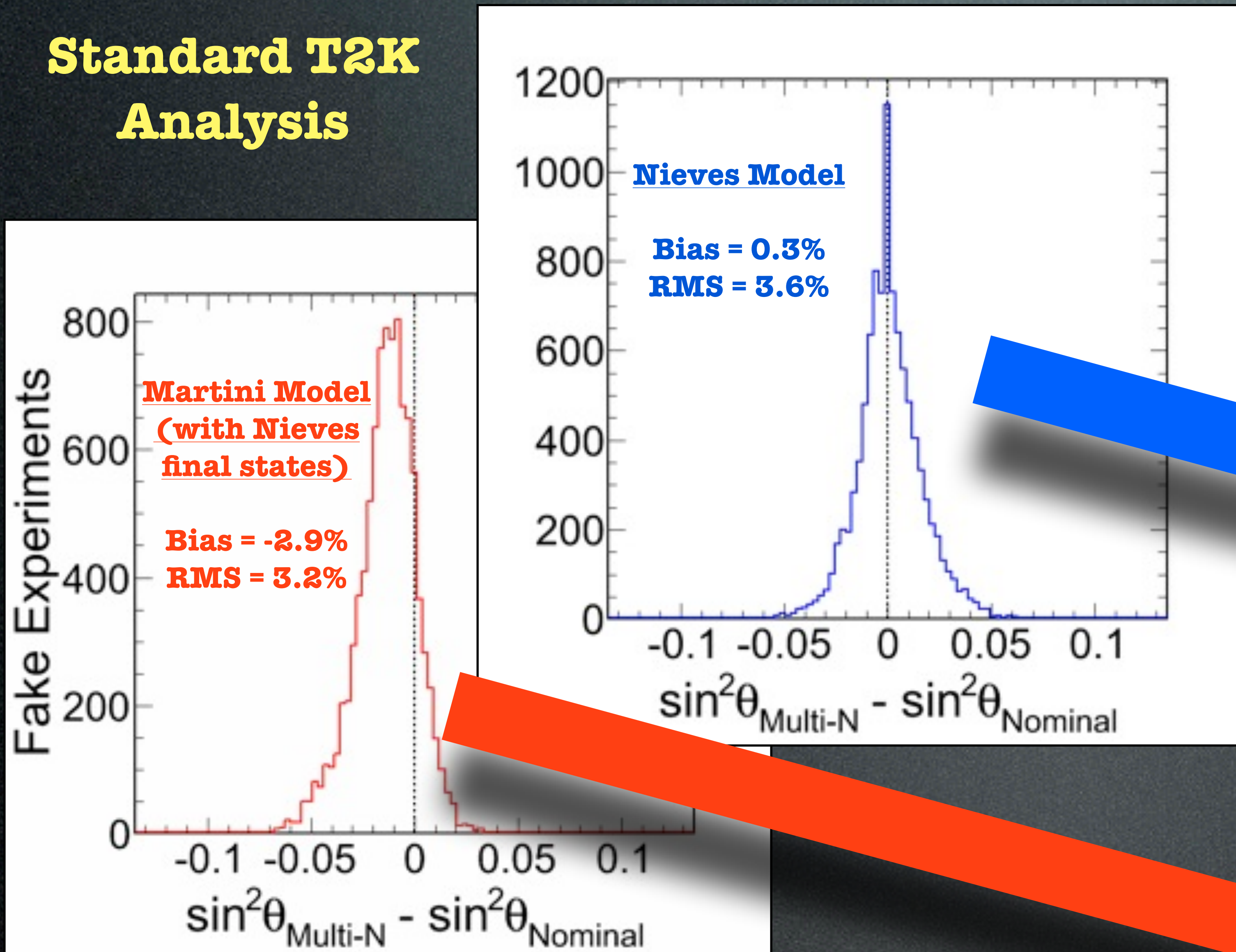
νPRISM Analysis





NuPRISM ν_μ Disappearance Constraint

Standard T2K Analysis

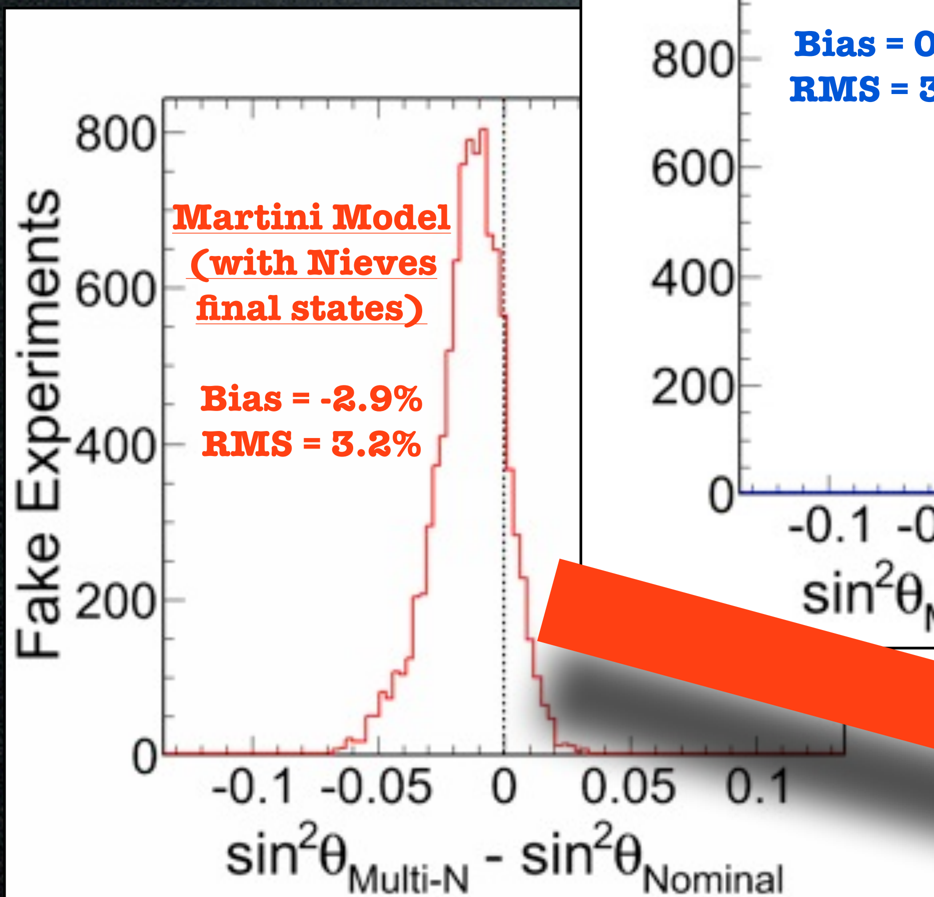


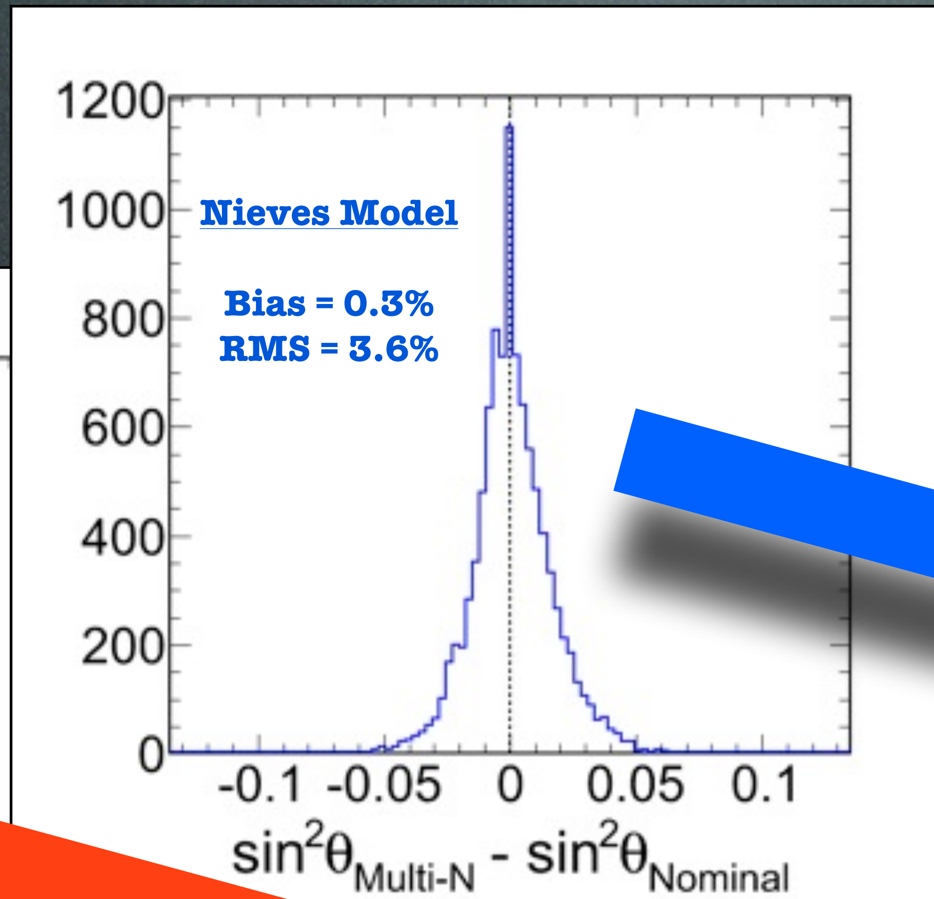
νPRISM Analysis

- Fake data studies show the bias in θ_{13} is reduced from **4.3%**/**3.6%** to **1.2%**/**1.0%**

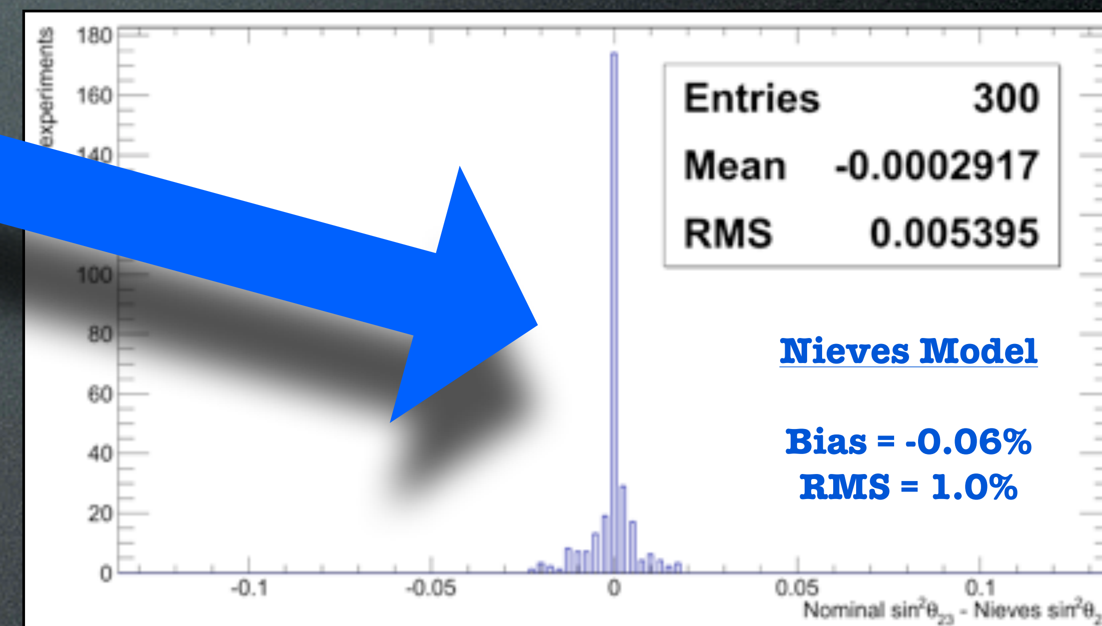
NuPRISM ν_μ Disappearance Constraint

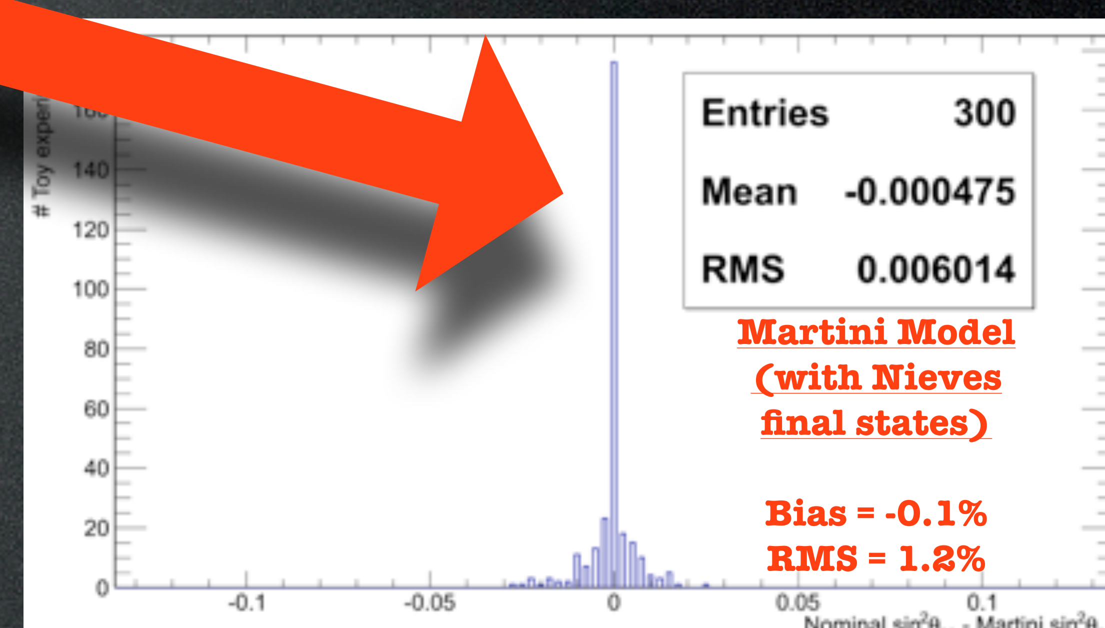
Standard T2K Analysis





νPRISM Analysis

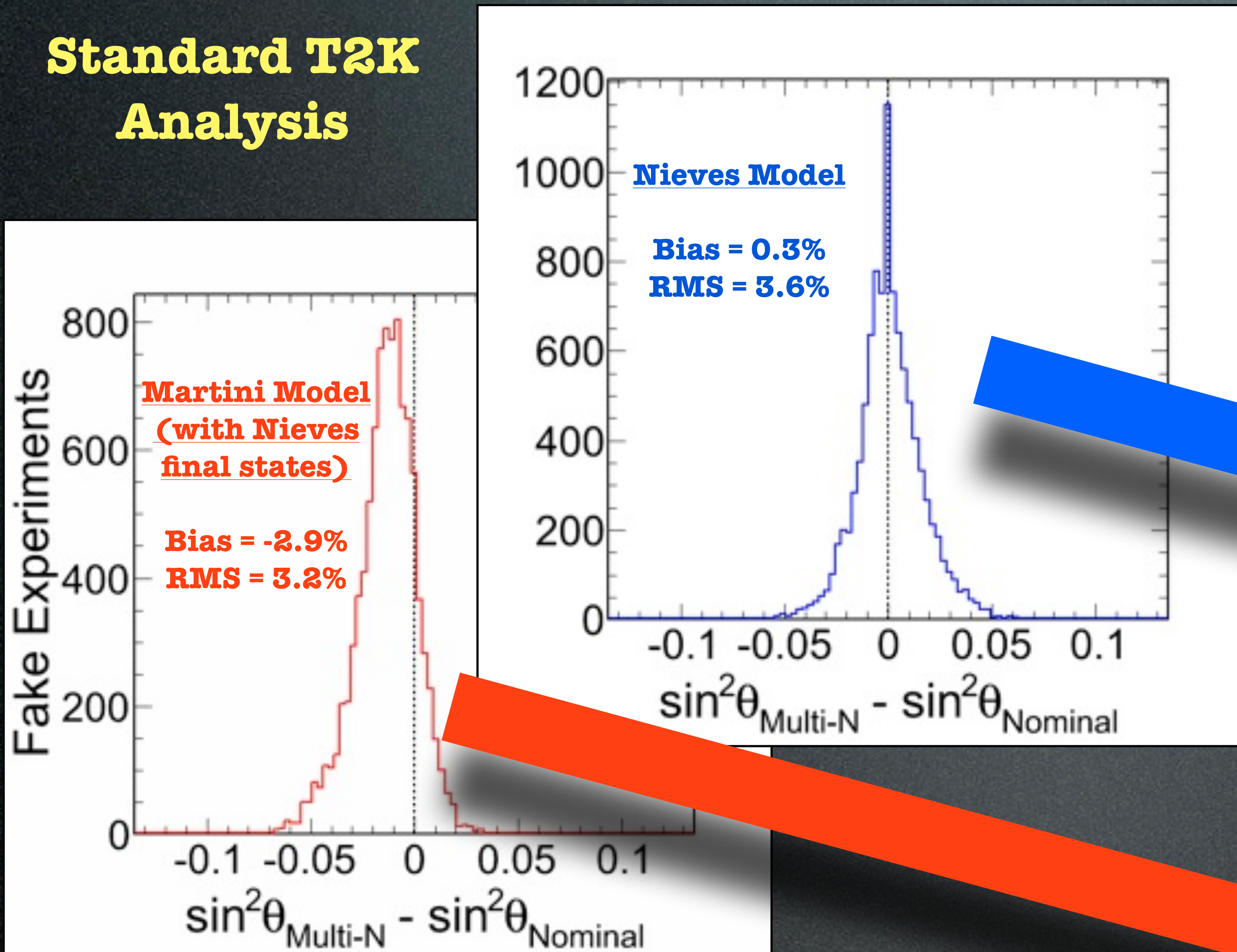




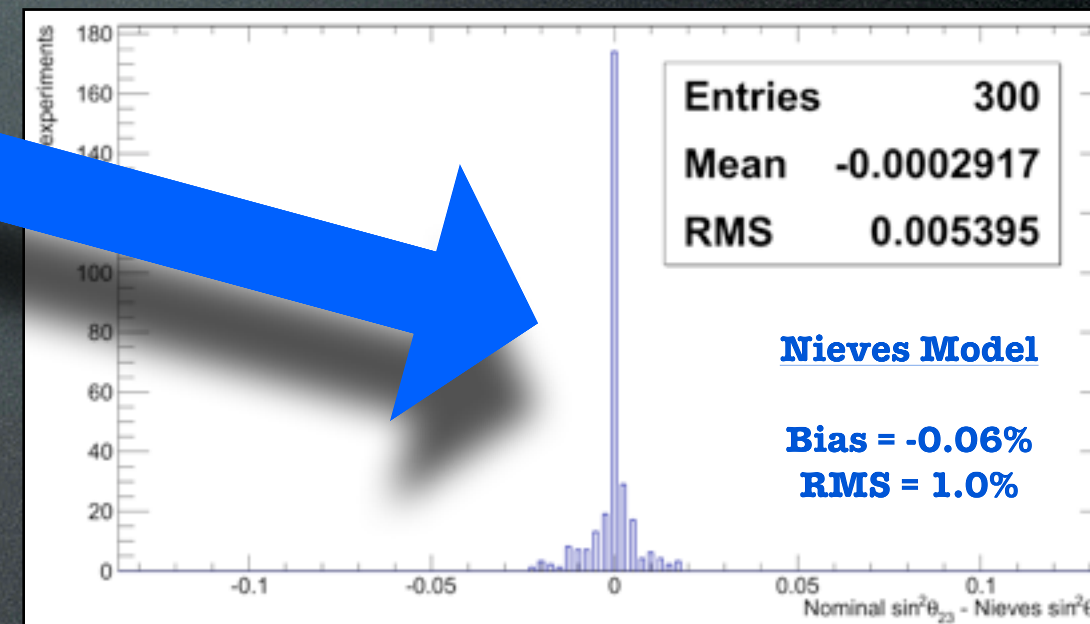
- Fake data studies show the bias in θ_{13} is reduced from **4.3%**/**3.6%** to **1.2%**/**1.0%**
- More importantly, this is now based on a **data constraint**, rather than a model-based guess

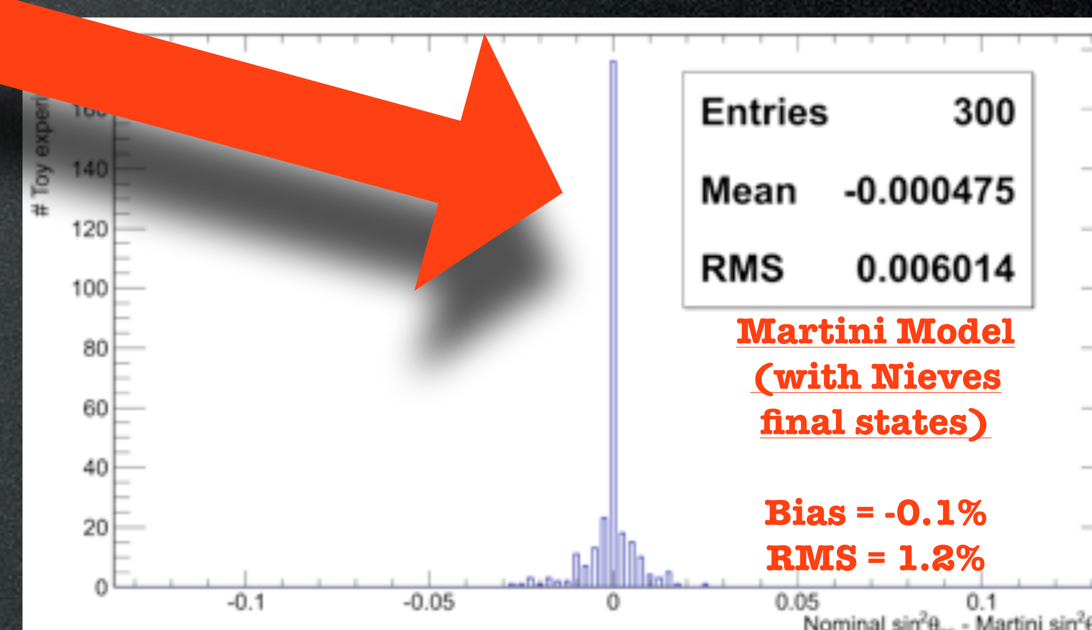
NuPRISM ν_μ Disappearance Constraint

Standard T2K Analysis



νPRISM Analysis



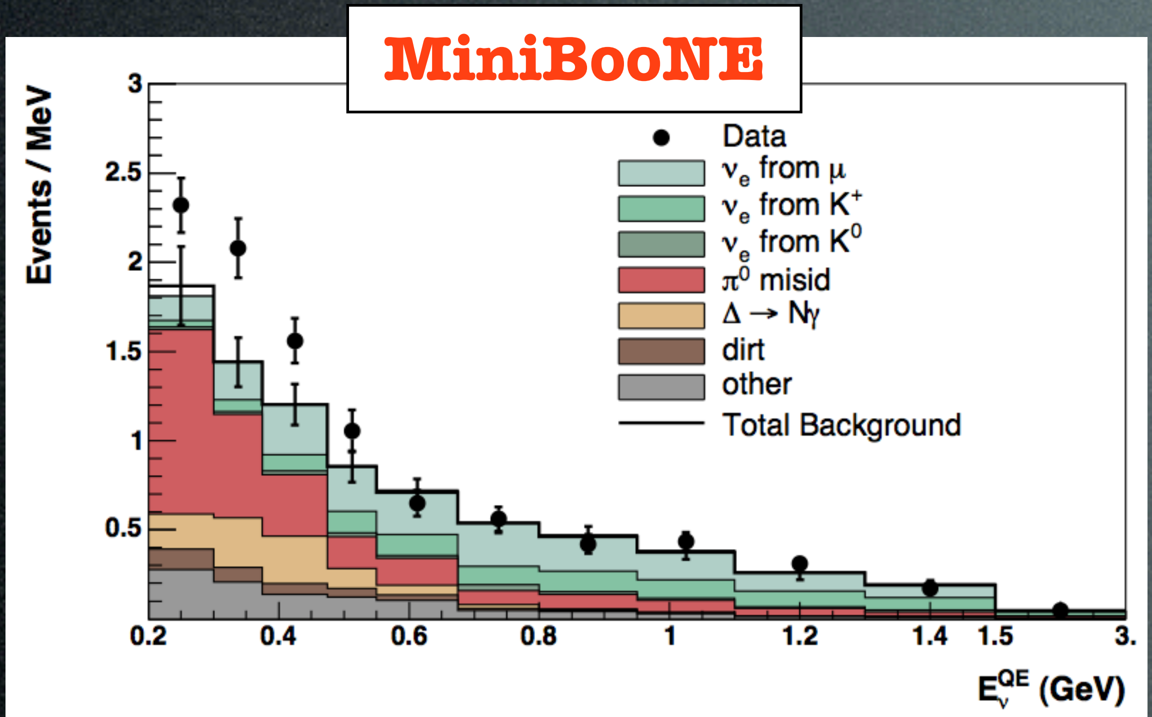


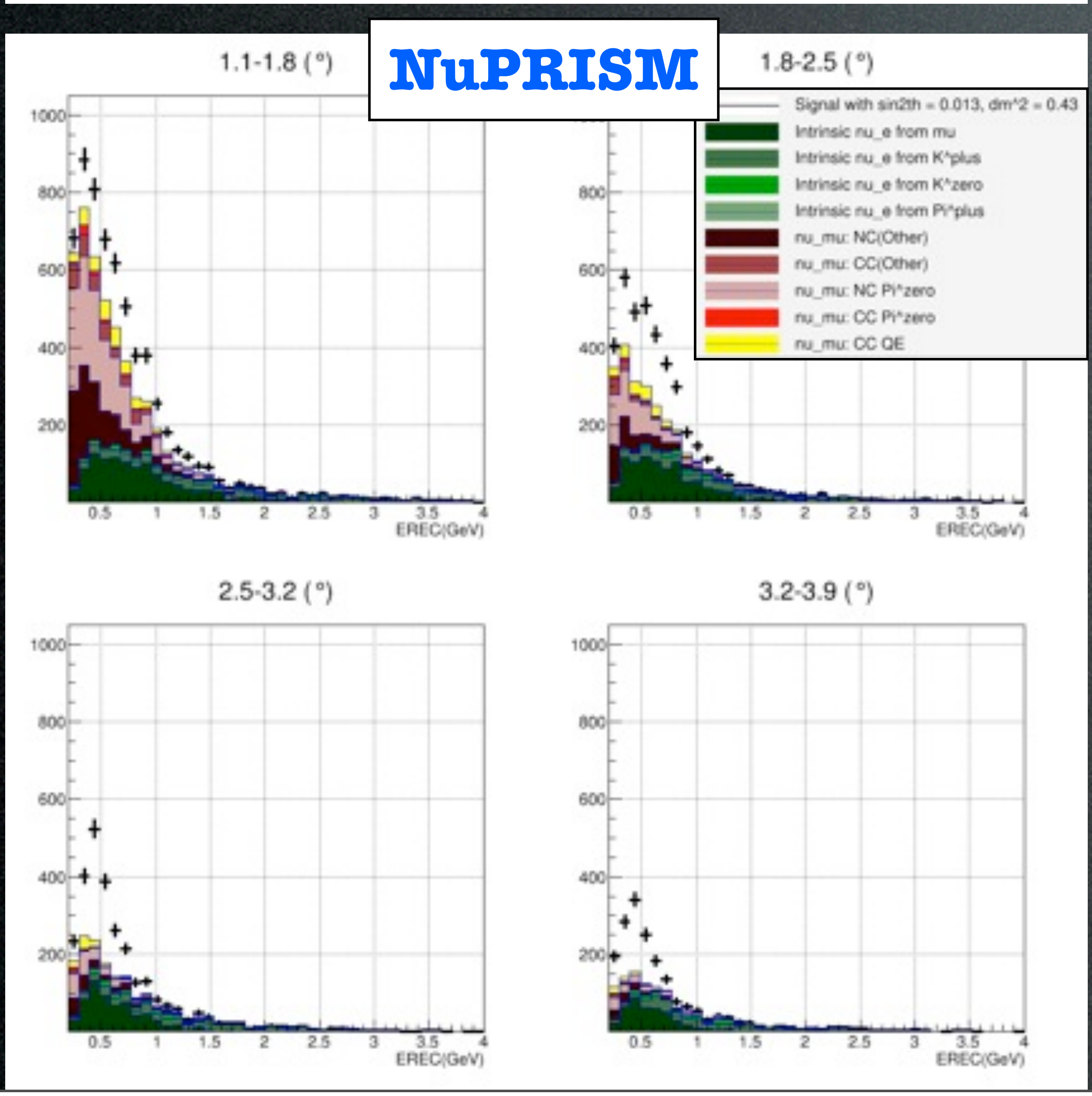
- Fake data studies show the bias in θ_{13} is reduced from **4.3%**/**3.6%** to **1.2%**/**1.0%**
- More importantly, this is now based on a **data constraint**, rather than a model-based guess
- Expect the NuPRISM constraints to get significantly better as additional constraints are implemented (very conservative errors)

More Physics!

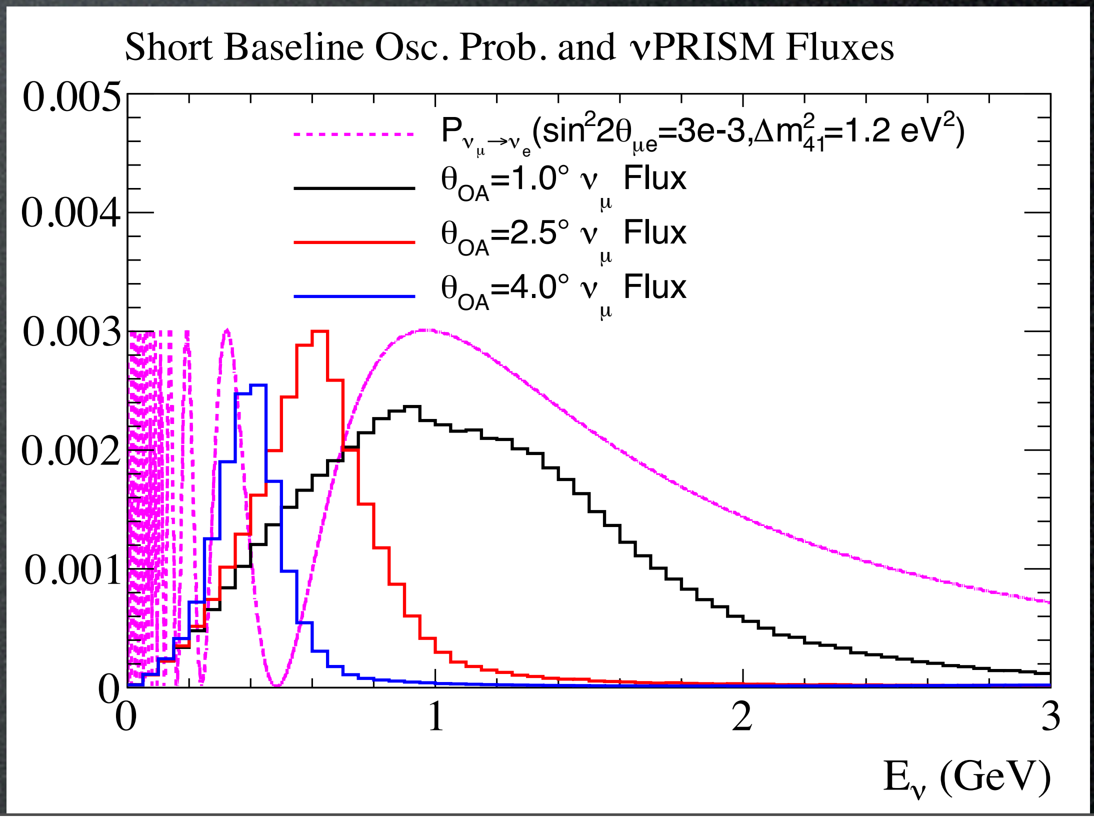
NuPRISM can do more than just improve long-baseline measurements

Sterile Neutrinos





- A multi-kton detector, ~1 km from a 600 MeV neutrino beam is well suited to confirm or refute the MiniBooNE/LSND event excesses
- NuPRISM has the additional benefit of continuously sampling a variety of L/E values
  - Oscillation signal and backgrounds vary differently vs off-axis angle
  - This provides an additional handle on many uncertain backgrounds (e.g. NC single-photon production)

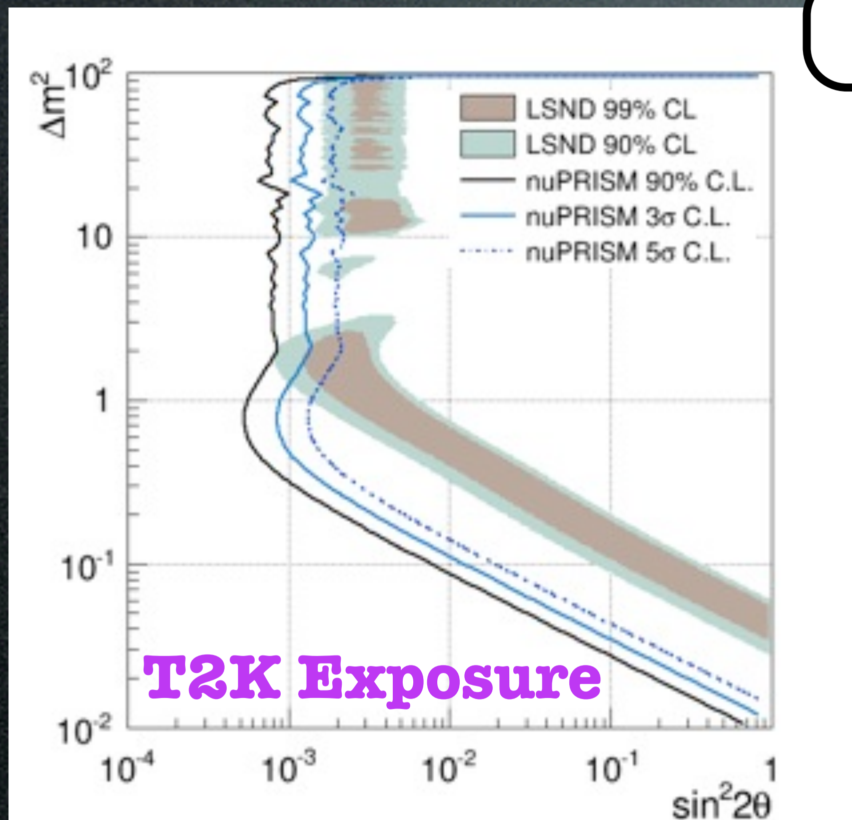


Sterile Neutrino Analysis

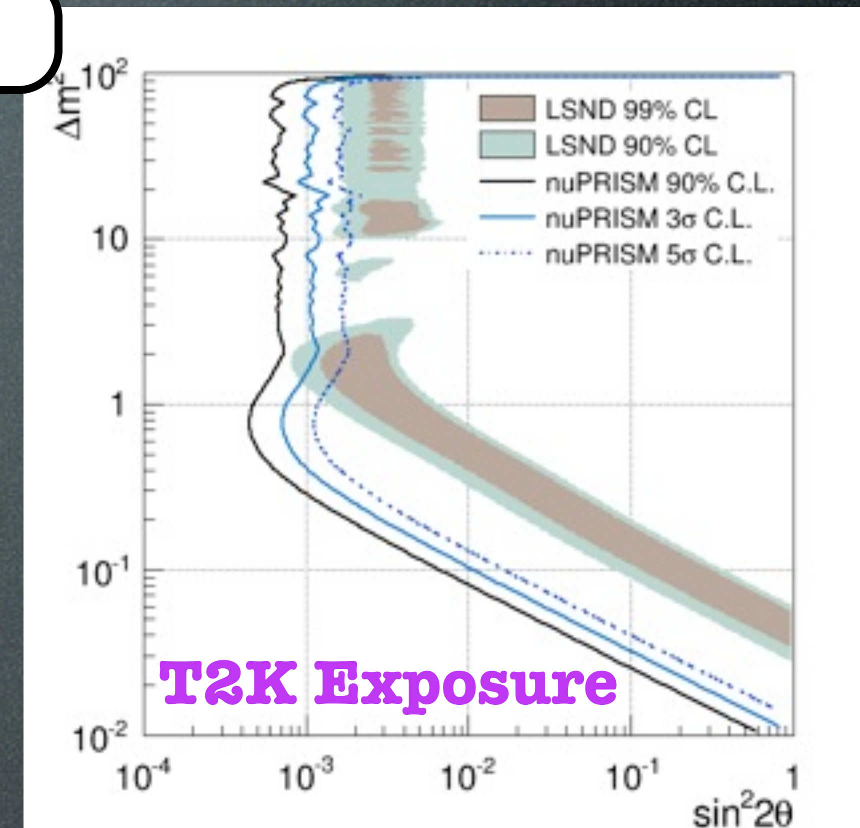
- To compute first sensitivities, make several conservative assumptions
- **No constraint from the existing near detector (ND280)**
  - Eventually, a powerful 2-detector constraint will be incorporated
- **No constraints on background processes**
  - nuPRISM should provide control samples for all of the major backgrounds to impose strong data-driven constraints
- **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
- Since this analysis is still statistics limited, any additional T2K (or eventually Hyper-K) running will improve the sensitivity

Current Sterile-ν Sensitivities

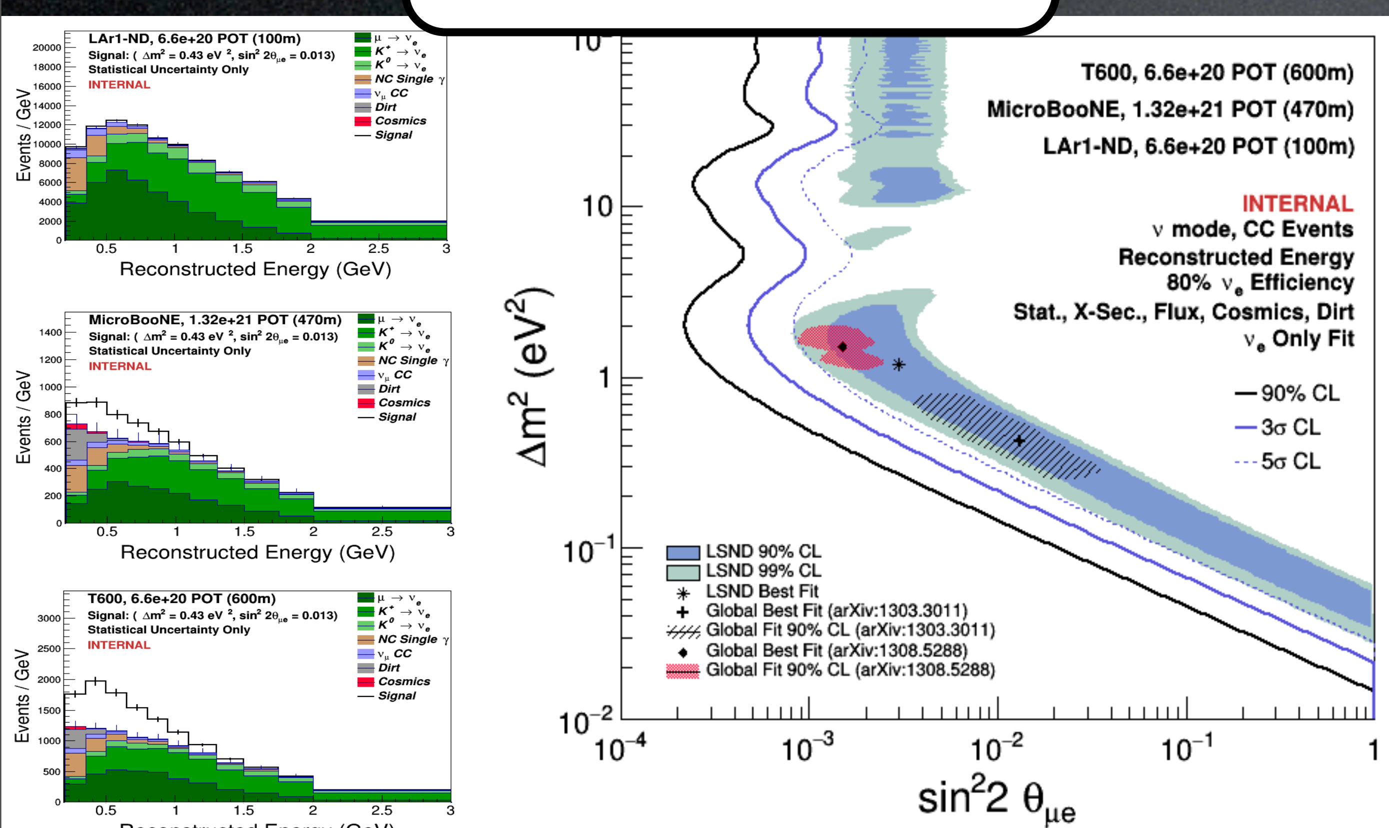
NuPRISM



30% reduction in π^0 background or π^0 uncertainty



Fermilab SBN

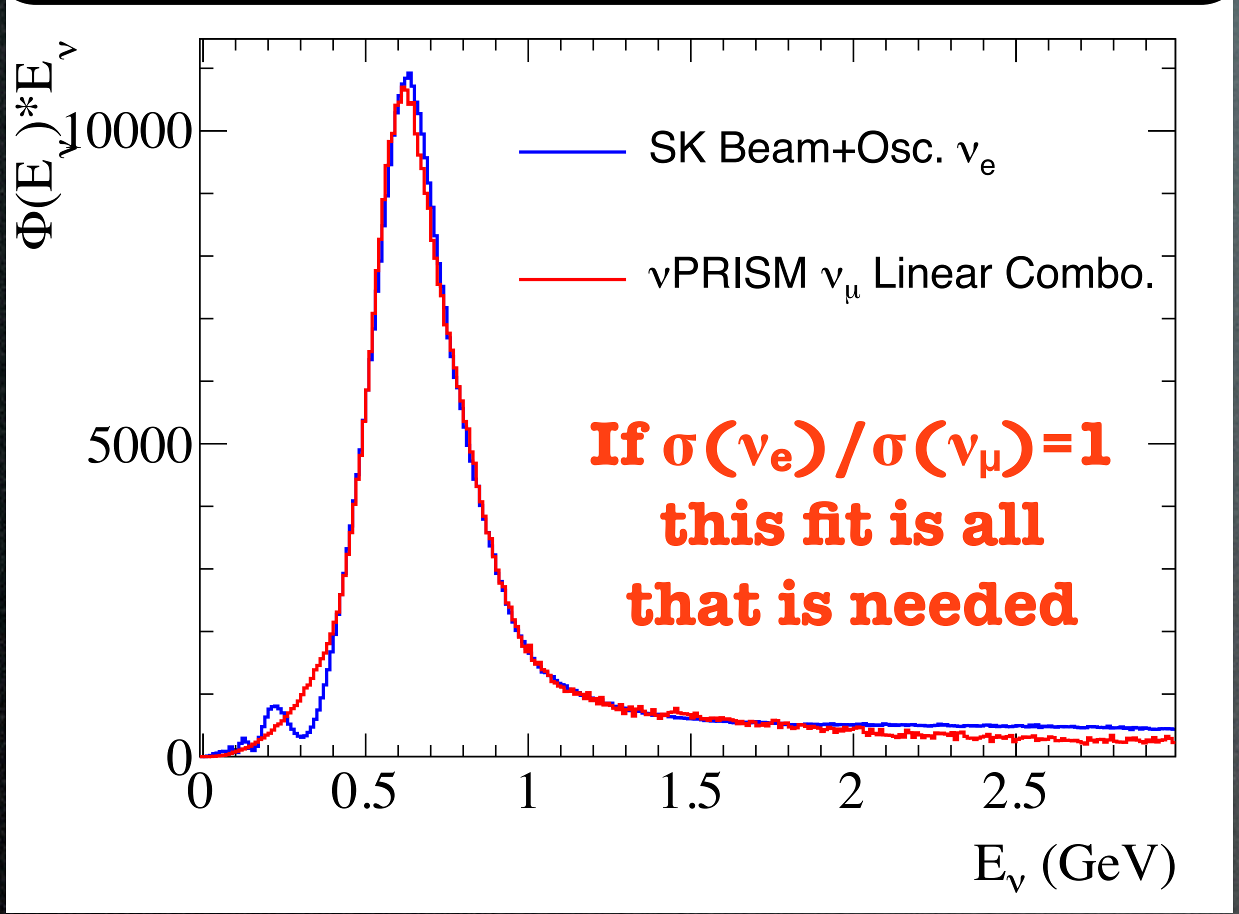


- Much of the LSND allowed region is already excluded at 3-5σ
  - Much better limits expected as the analysis improves
- Current sensitivity is comparable to Fermilab short-baseline program
  - More importantly, Fermilab SBN has less power to rule out background explanations than NuPRISM

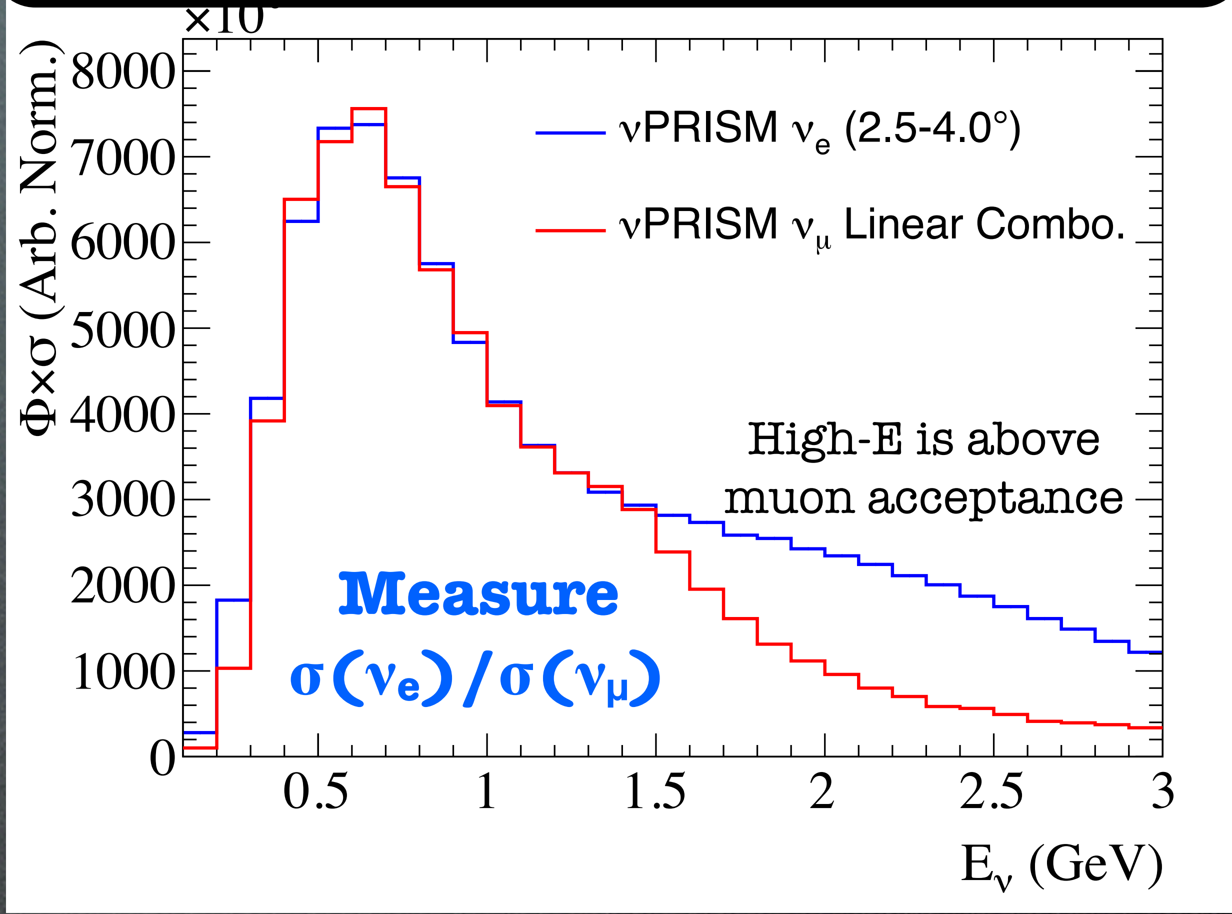
NuPRISM ν_e Appearance (CPV)

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
- Need large mass near detector to make a few percent measurement of $\sigma(\nu_e)/\sigma(\nu_\mu)$ (ND280 target is a few ton, NuPRISM target is a few kton)

Constraining the ν_e Cross Section

- Water Cherenkov detectors can achieve high ν_e purities
  - In T2K, 3.50 intrinsic ν_e events vs 0.96 NC events ➜ **77% ν_e purity**
- Studies to optimize PMT size/granularity to maximize ν_e purity in NuPRISM are ongoing
- NuPRISM can also make use of higher off-axis angles:

50% increase in ν_e fraction from 2.5° to 4.0° off-axis

Off-axis angle (°)	ve Flux 0.3-0.9 GeV	vμ Flux 0.3-5.0 GeV	Ratio ve/vμ
2.5	1.24E+15	2.46E+17	0.507%
3.0	1.14E+15	1.90E+17	0.600%
3.5	1.00E+15	1.47E+17	0.679%
4.0	8.65E+14	1.14E+17	0.760%

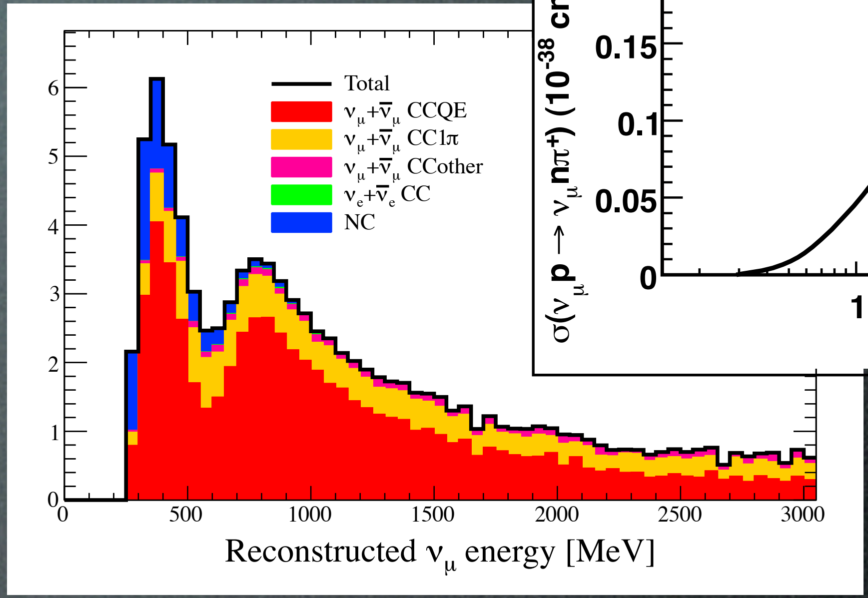
ν_e Cross Section Precision

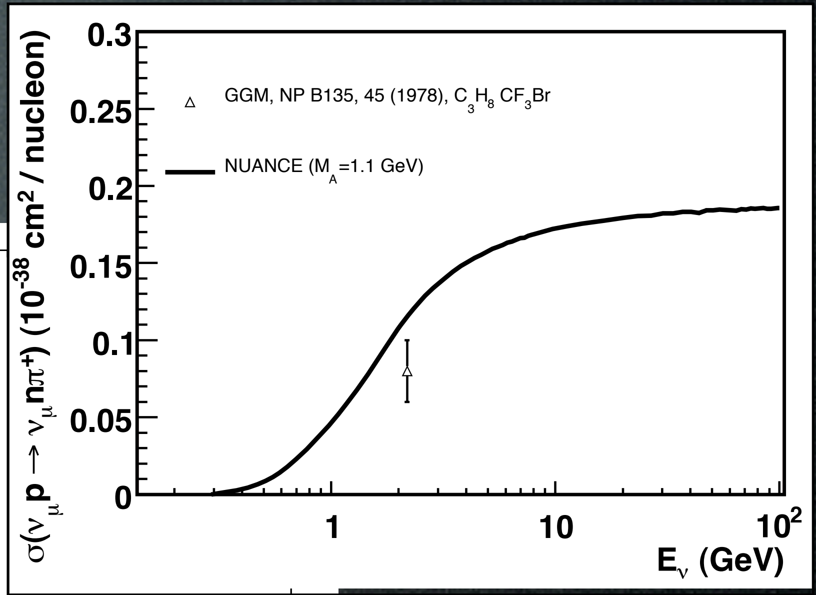
- For 10^{22} POT, expect 9340 ν_e single-e (i.e. CCQE-like) interactions
  - 2.5° - 4.0° range
  - $0.3 < E_\nu < 0.9$ MeV
  - 2 m fiducial volume
- Assuming Super-K efficiency, this would provide a 1.3% statistical error on $N_{\nu e}/N_{\nu\mu}$
  - Backgrounds will dilute the sensitivity, but NuPRISM can make very precise in-situ measurements of the backgrounds
- ν_e/ν_μ flux uncertainty is 3.2% (5.2%) in the 300-600 (600-900) MeV range
  - If hadron production uncertainties are reduced by half, ν_e/ν_μ flux uncertainty is reduced to 1.7% (3.4%)
- 3% uncertainty may be achievable
  - NuPRISM ν_e/ν_μ flux matching technique provides a unique measurement of $(d^2\sigma_{\nu e}/dpd\theta)$ / $(d^2\sigma_{\nu\mu}/dpd\theta)$

ν Cross Section Measurements

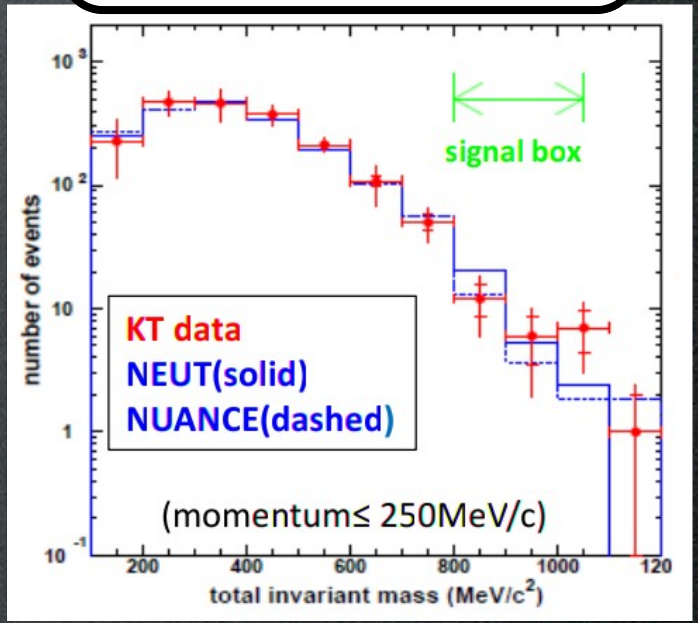
- T2K ν_μ disappearance is subject to large NCπ^+ uncertainties
    - 1 existing measurement
    - νPRISM can place a strong constraint on this process vs E_ν
- NuPRISM is an ideal setup to measure proton decay backgrounds
    - Repeat $p \to e^+\pi^0$ background measurement from K2K 1 kton detector
    - 50% of the $p \to K^+\nu$ background is from ν-induced K+ production
        - Production rate has large uncertainties
- Hyper-K proton decay measurements are background limited, so these measurements are crucial

NCπ^+ at T2K



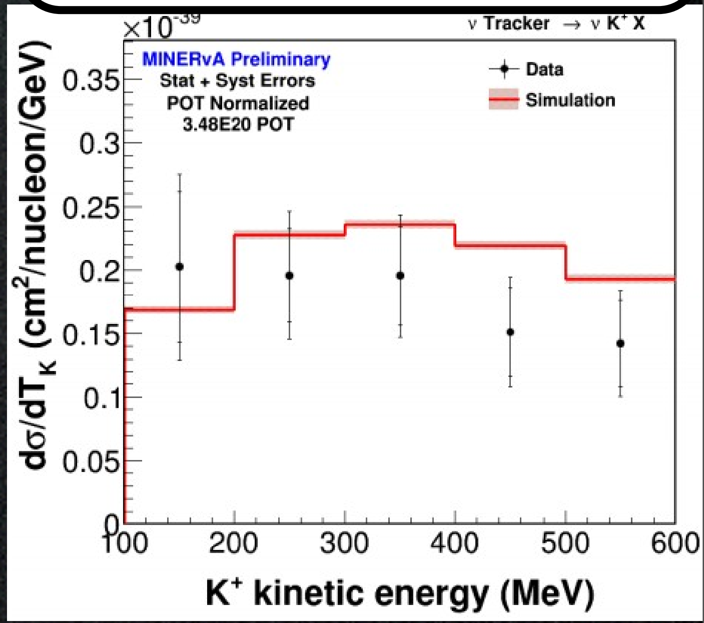


K2K $e^+\pi^0$ Bkgd Measurement



$$N(\mathrm{Mtyr}^{-1}) = 1.63^{+0.42}_{-0.33}(\mathrm{stat})^{+0.45}_{-0.51}(\mathrm{syst}).$$

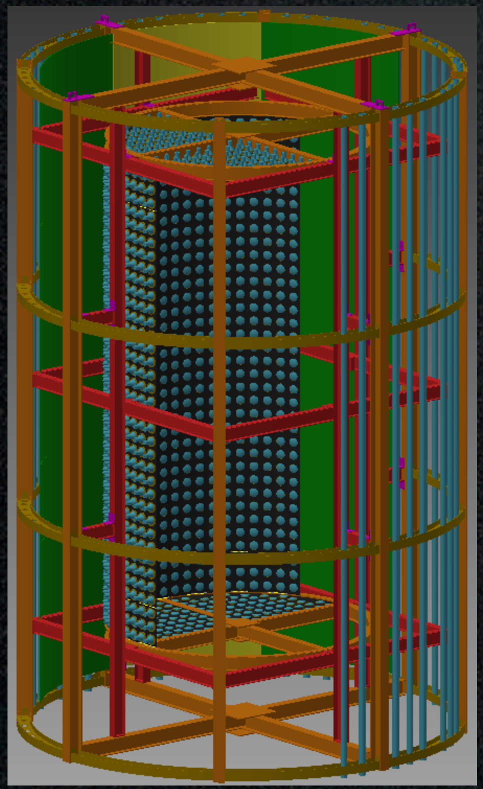
MINERvA K^+ Prod. Measurement

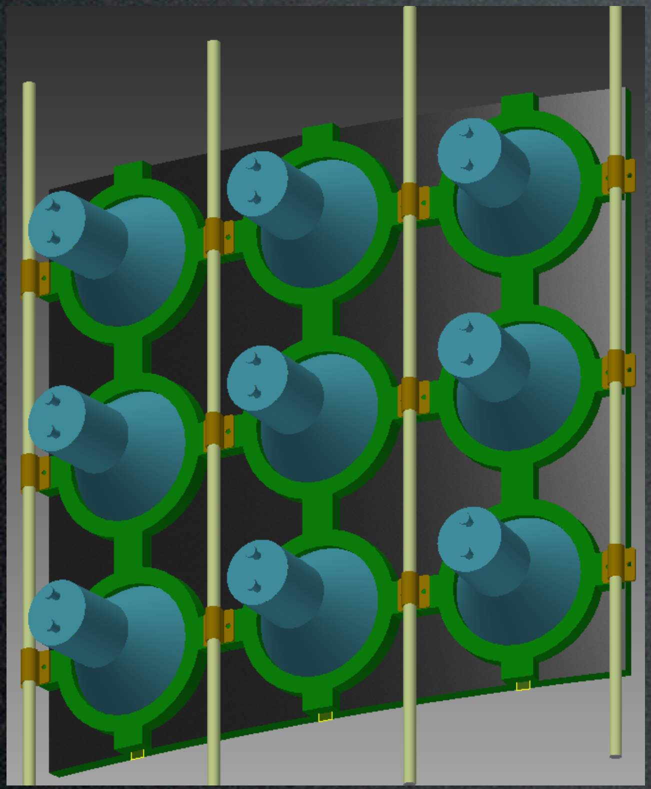


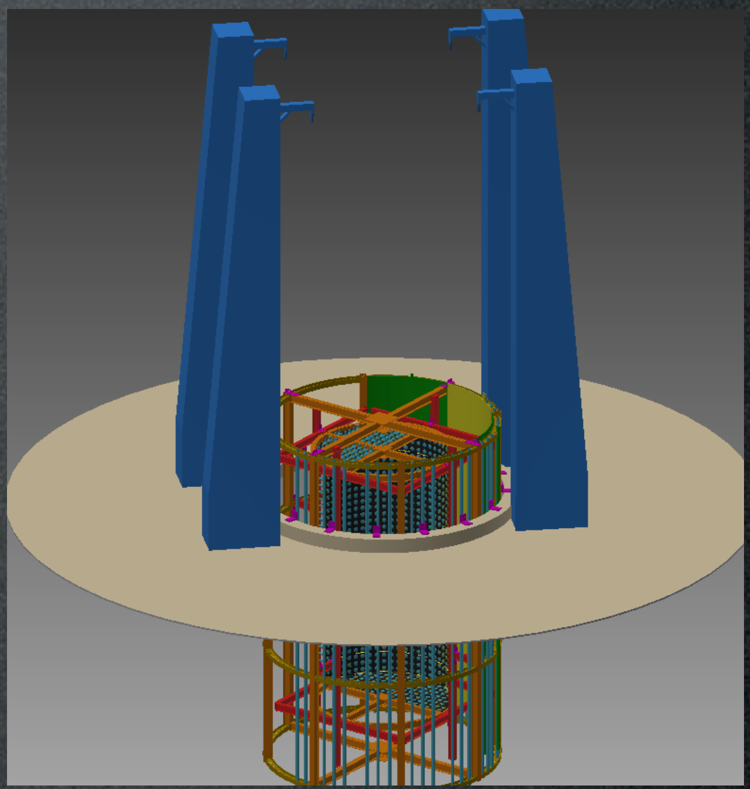
Design Considerations

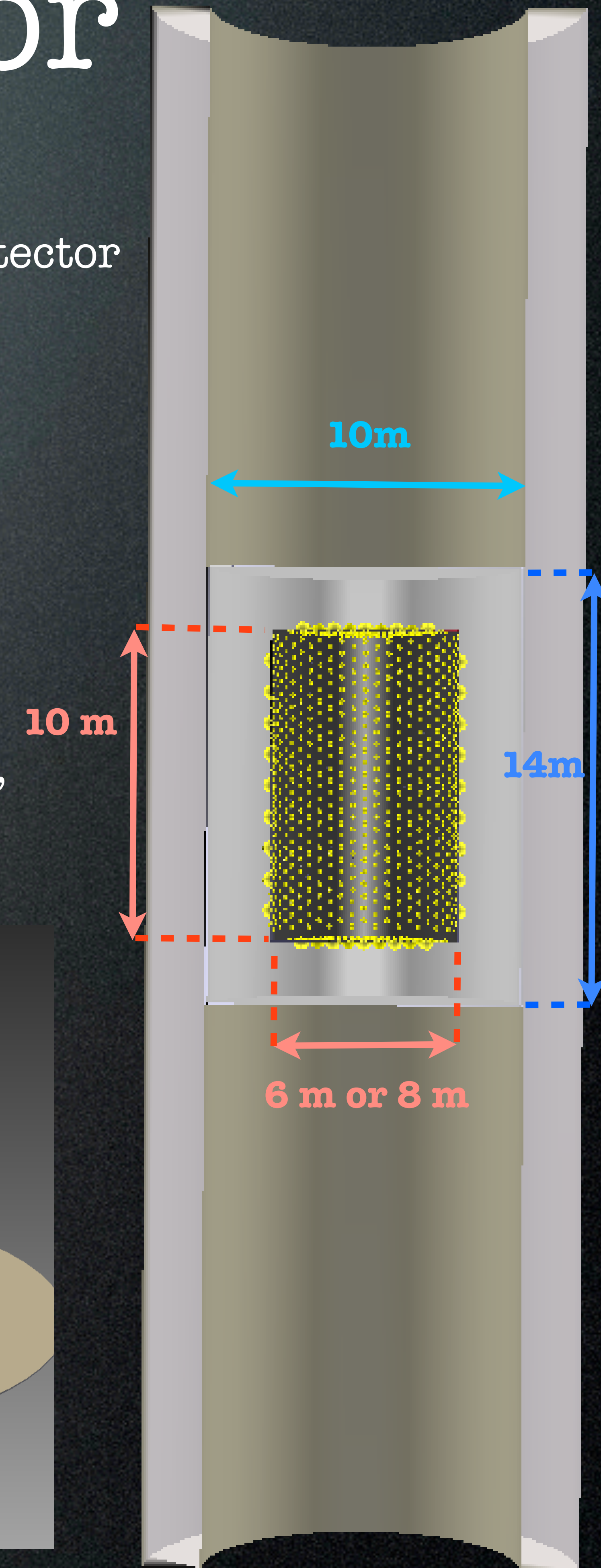
NuPRISM Detector

- At 1 km, need 50 m tall tank to span 1-4° off-axis angle
- Instrument one subsection of the tank at a time with a moveable detector
- Baseline design:
    - Inner Detector (ID): 6 m or 8 m diameter, 10 m tall
        - 8" and 5" PMTs are both under study
    - Outer Detector (OD): 10m diameter, 14m tall
        - Default plan is to use HK prototype 20" PMTs
- To improve sand muon tagging (precise entering position and time), OD is surrounded by scintillator panels





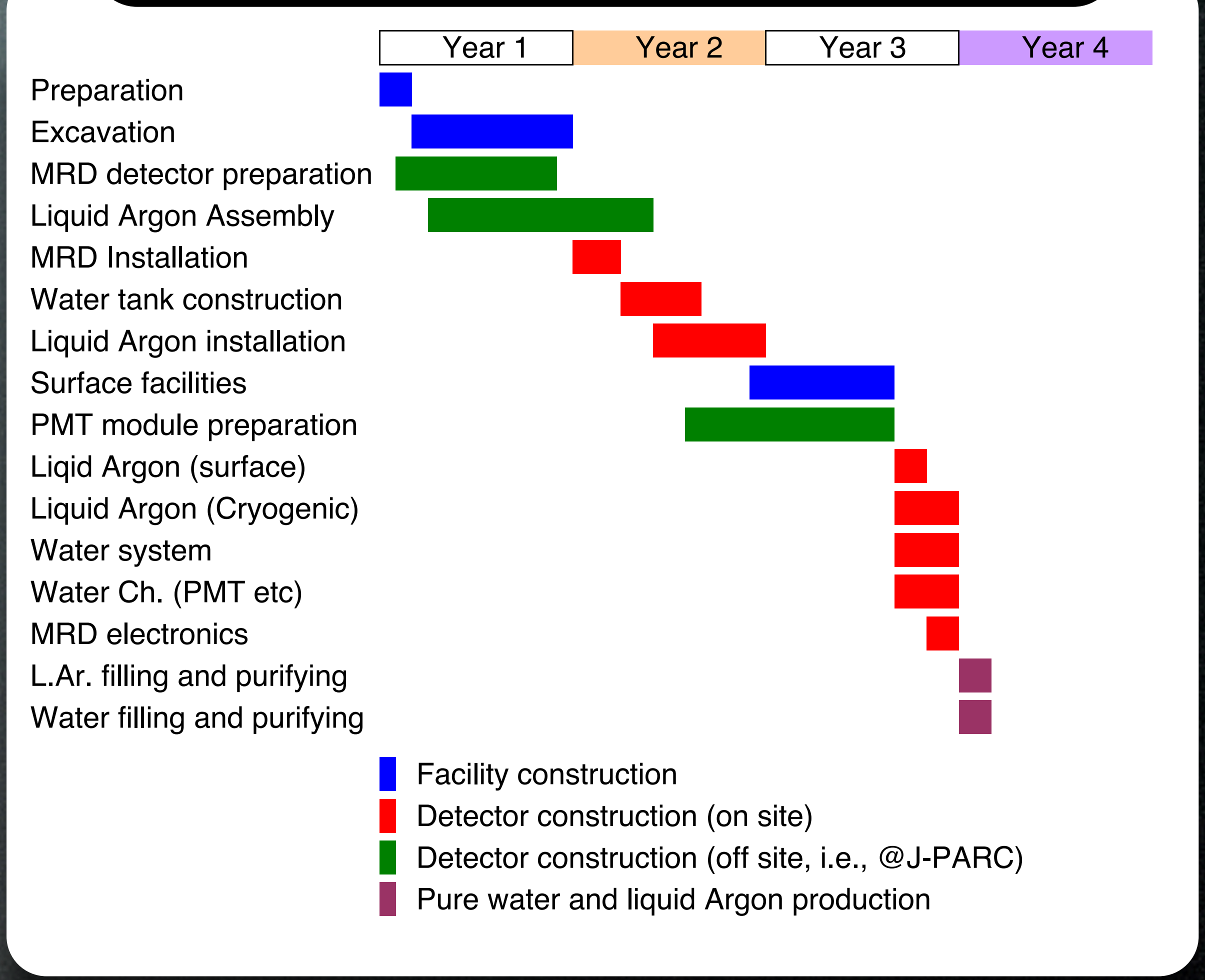


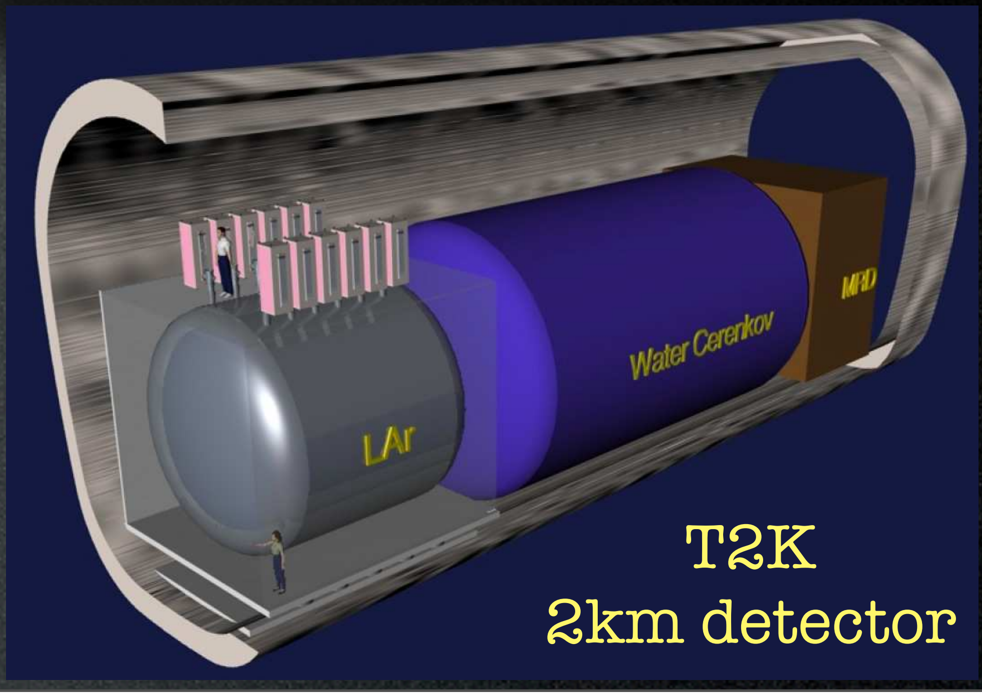


Timescales

- Water Cherenkov construction was studied for the T2K 2 km detector proposed in 2005
- 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 MRD or LAr detector
- < 3 year timescale from ground breaking to data taking
- Goal is to start data taking soon after the J-PARC 700kW beam upgrade expected in 2018
  - More than half of the T2K POT will be taken after the beam upgrade
  - Aiming for ground breaking in 2016

Old T2K 2 km Schedule





Project Costs

- Current estimates of the project cost come from:
  - Direct consultations with manufacturers
  - The T2K 2km detector proposal (*)
- Company estimates have been obtained for cost drivers (civil construction and PMTs)
  - Civil construction cost could increase after geological survey of the chosen site
  - For PMTs, both high quantum efficiency (HQE) and hybrid photodetectors (HPD) are under consideration

Cost Summary

Item	Cost (US M$)
Cavity Construction, Including HDPE Liner	6.00
*Surface Buildings	0.77
*Air-Conditioning, Water, and Services	0.50
*Power Facilities	0.68
*Cranes and Elevator	0.31
*PMT Support Structure	1.27
3,215 8-inch PMTs	4.30
PMT Electronics	1.45
*PMT Cables and Connectors	0.13
Scintillator Panels	0.36
Water System	0.35
Gd Water Option	0.15
*GPS System	0.04
Total	16.31

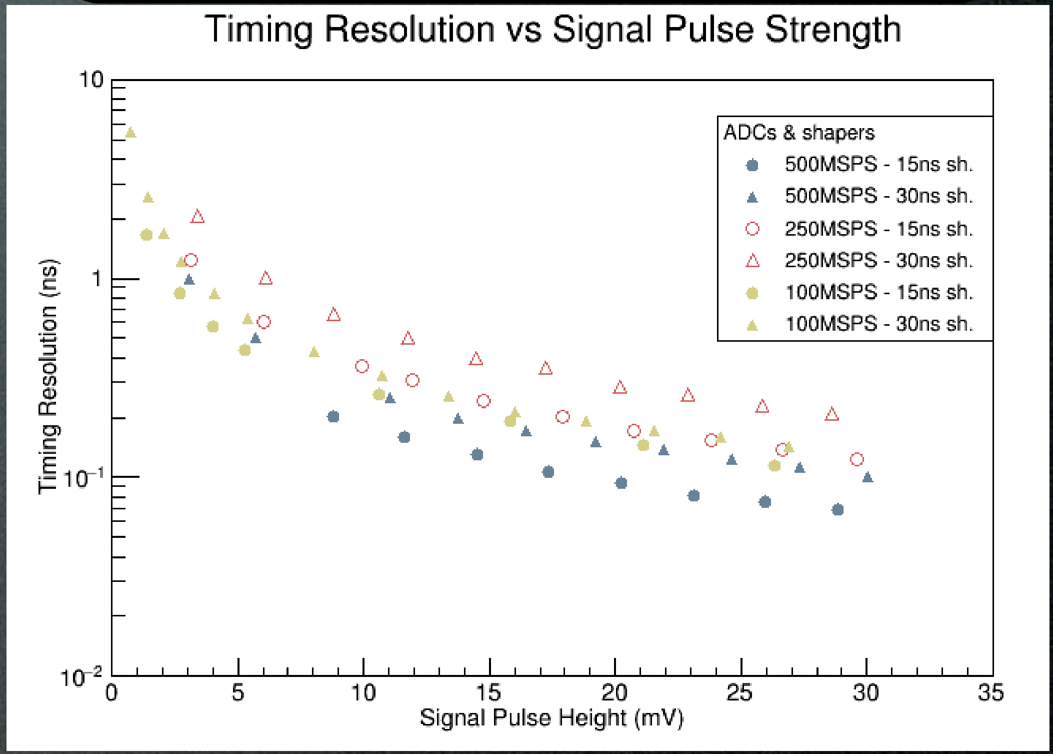
Hamamatsu PMT Quotes

Name	QE%	Quantity	Price/PMT	Cost	Delivery
5" PMT	25	8,000	103,500	828M	any
5" PMT HQE	35	5,714	123,700	707M	any
8" PMT	25	3,215	143,000	460M	any
8" PMT HQE	35	2,296	170,500	391M	any
8" HPD HQE	35	2,296	264,000	606M	2014
	35	2,296	236,500	543M	2015
	35	2,296	209,000	480M	2016
20" PMT HQE	30	508	604,500	307M	2014
	30	508	572,000	291M	2015
	30	508	539,500	274M	2016
20" HPD HQE	30	508	715,000	363M	2014
	30	508	617,500	314M	2015
	30	508	520,000	264M	2016

Synergies with Hyper-K

- The systematic error constraints provided by NuPRISM will be required in the Hyper-K era
  - NuPRISM will become a Hyper-K near detector
  - Need to understand whether NuPRISM can control cross section systematics before Hyper-K starts taking data
- Hyper-K is considering in-water electronics
  - NuPRISM allows in-water electronics to be tested, and provides unique accessibility due to its ability to move out of the water
- A large scale PMT water tank test for Hyper-K PMTs is being planned, and NuPRISM can fill this role
  - Even if NuPRISM is not ready for the start of this test, it can be coordinated to make use of the detector hardware when it is ready to operate
    - This may fund a useful portion of the experiment
- NuPRISM provides new physics and a cohesive program between T2K and Hyper-K
  - Analogous to the Fermilab SBN program

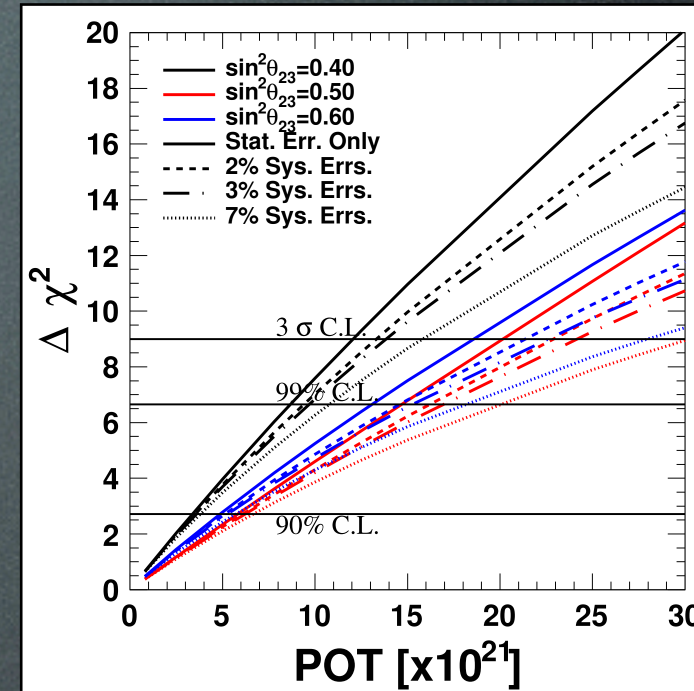
Joint NuPRISM/Hyper-K
Electronics Development Tests



Requirements for T2K*3

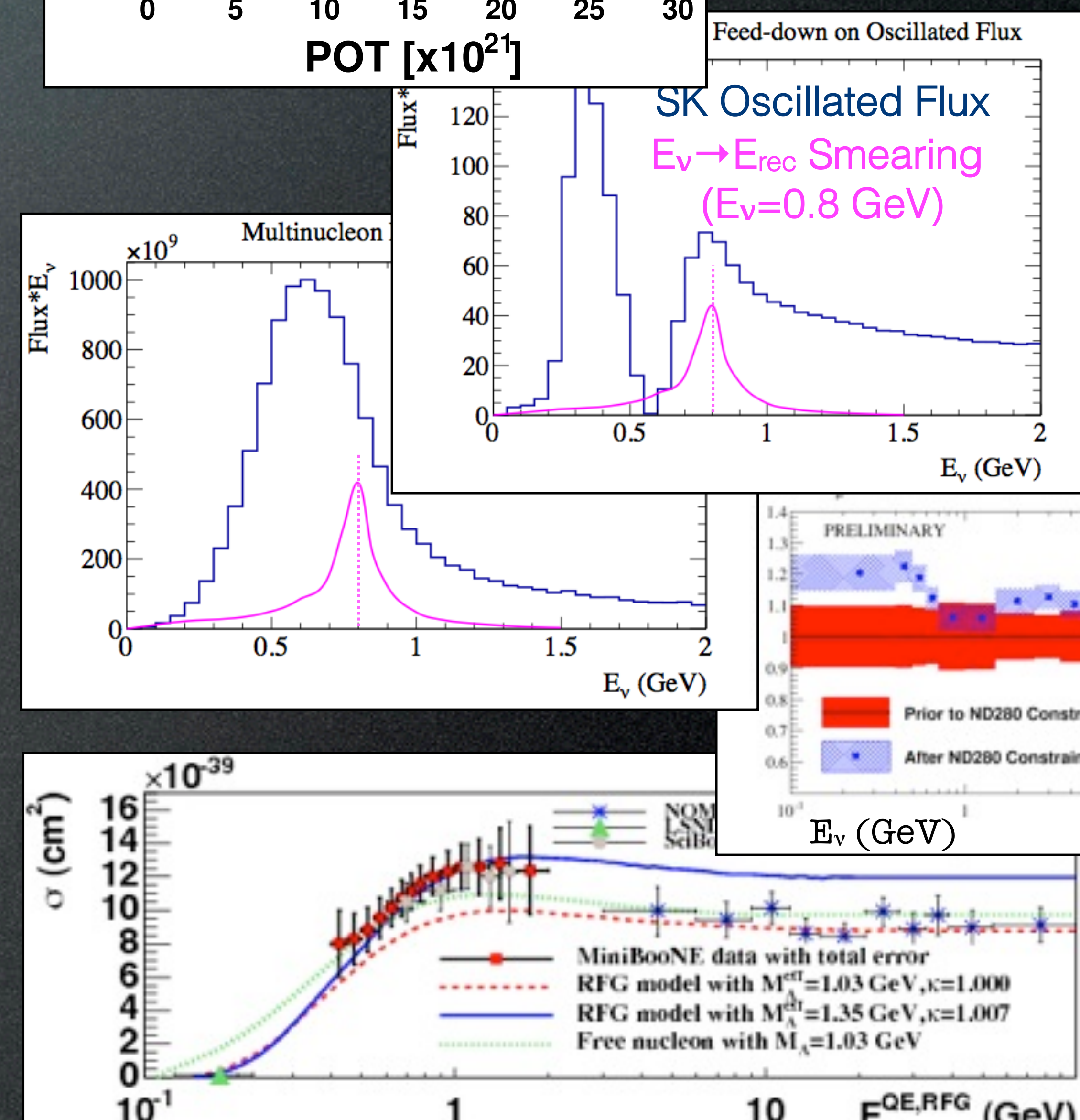
Fractional error on # of events		ν_μ sample	ν_e sample		$\bar{\nu}_\mu$ sample	$\bar{\nu}_e$ sample
ν flux		16%	11%		7.1%	8%
ν flux and cross section	w/o ND measurement	21.8%	26.0%		9.2%	9.4%
	w/ ND measurement	2.7%	3.1%		3.4%	3.0%
ν cross section due to difference of nuclear target btw. near and far		5.0%	4.7%		10%	9.8%
Final or Secondary Hadronic Interaction		3.0%	2.4%		2.1%	2.2%
Super-K detector		4.0%	2.7%		3.8%	3.0%
total	w/o ND measurement	23.5%	26.8%		14.4%	13.5%
	w/ ND measurement	7.7%	6.8%		11.6%	11.0%

2014 2015



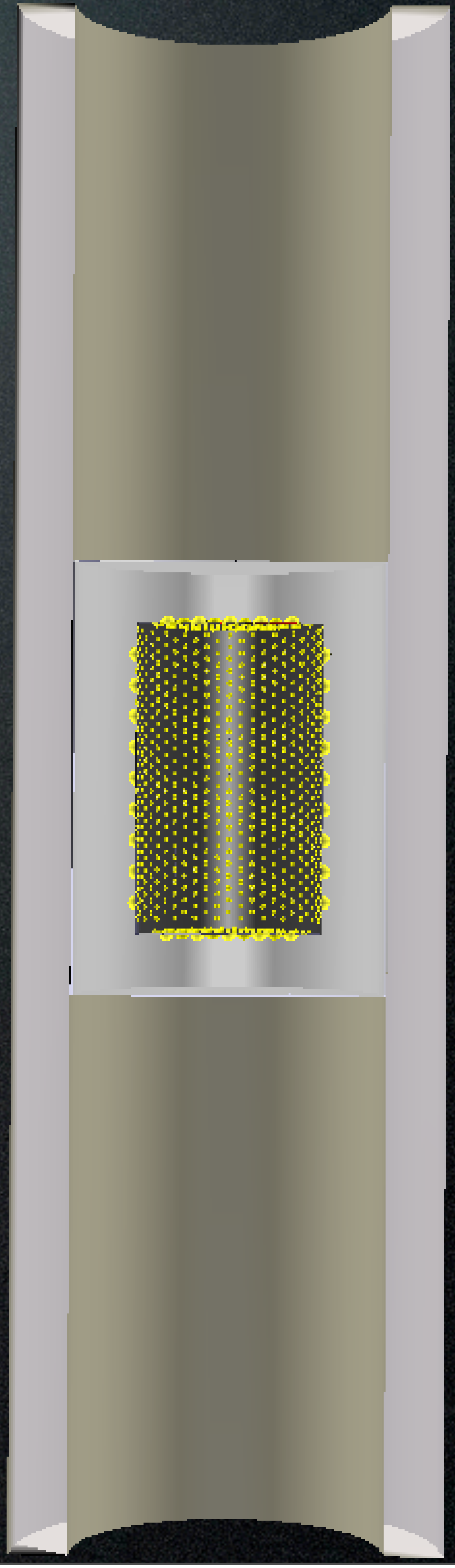
M. Friend Talk Yesterday

- If θ_{23} is close to maximal, it will not be possible to measure δ_{CP} at 3σ without 2-3% uncertainties
- It is quite possible that we will not understand ν-nucleus interactions with that precision with ND280 alone
    - A direct experimental constraint is needed
- A new, large water detector is needed to constrain ν_e cross sections at the few percent level



Summary

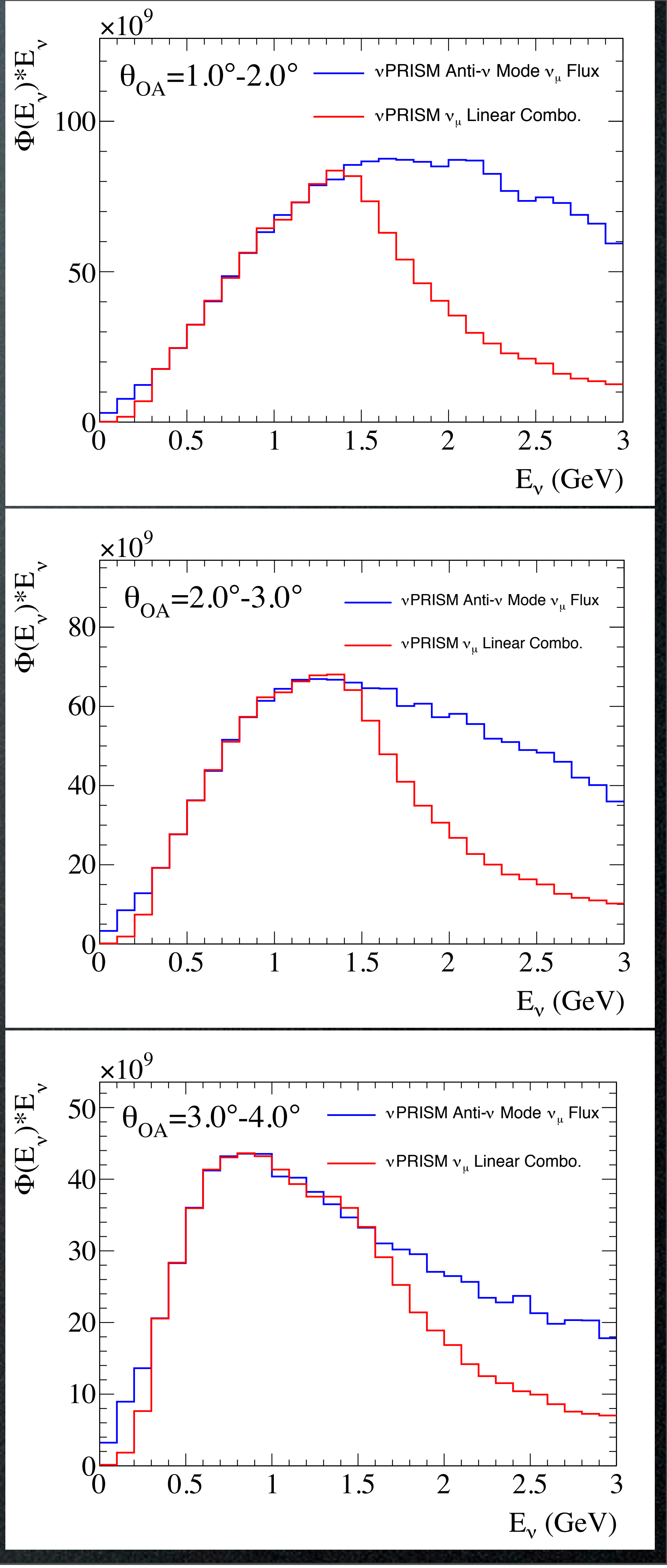
- We are entering an era where the largest uncertainties in neutrino oscillation experiments will be determined by poorly understood models
  - NuPRISM provides an experimental solution to the neutrino energy measurement problem
- NuPRISM will produce a wide variety of other interesting measurements
  - A unique sterile neutrino search
  - Nuclear physics from mono-energetic beams
  - Enhanced measurements from existing Super-K data (e.g. ATM sub-GeV CPV)
  - A wide variety of unique cross section measurements and model constraints
- These physics goals can be achieve within the currently allocated beam time for T2K (no additional beam time is required)
- NuPRISM can supply an exciting physics program that bridges the gap between T2K and Hyper-K



Supplement

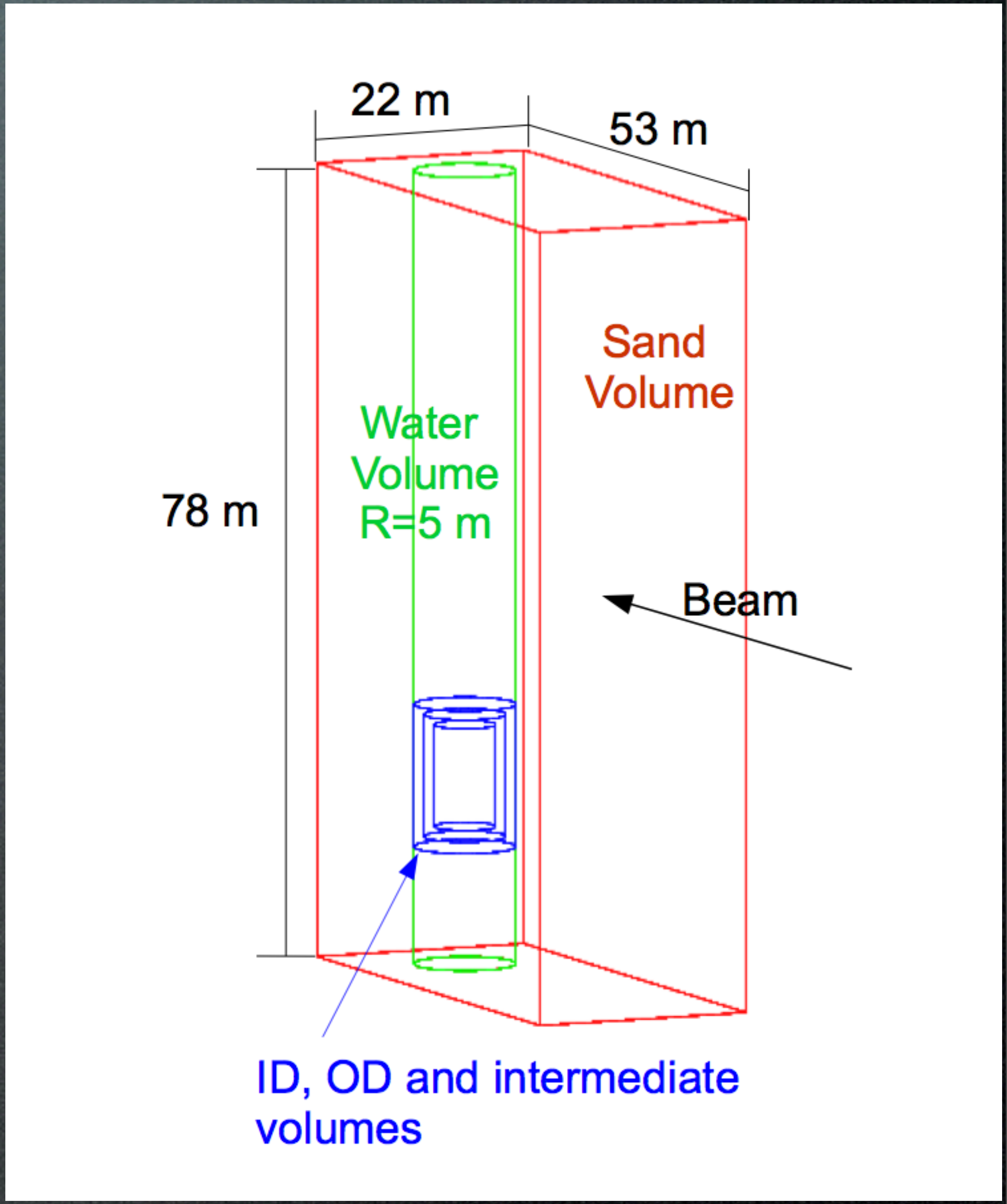
Anti-neutrinos

- T2K can switch between ν-mode and anti-ν-mode running by switching the beam focusing
- Anti-ν-mode NuPRISM 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
- After subtracting neutrino background, standard nuPRISM oscillation analyses can be applied to anti-neutrinos



Event Pileup

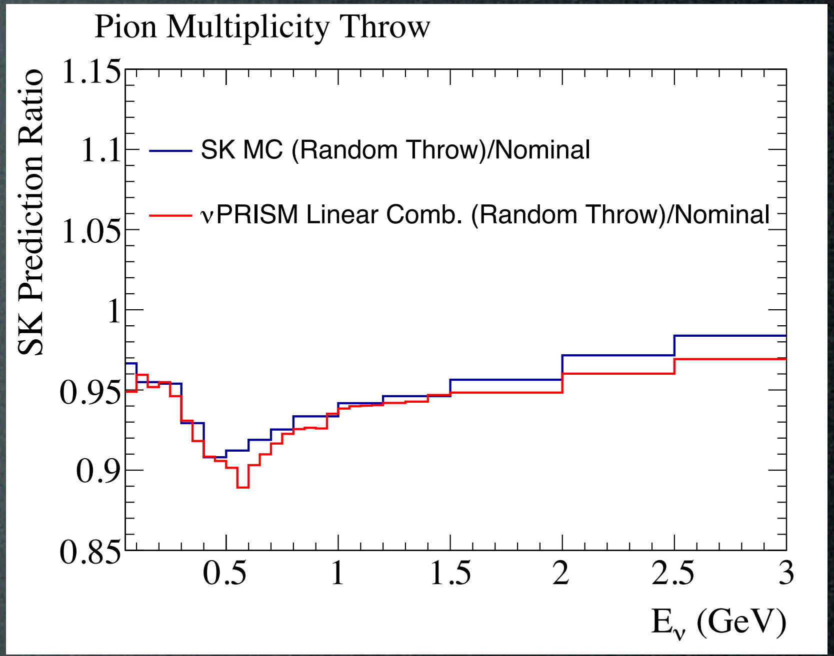
- Full GEANT4 simulation of water and surrounding sand
  - Using T2K flux and neut cross section model
- 8 beam bunches per spill, separated by 670 ns with a width of 27 ns (FWHM)
- **92%/26%/11% chance of OD light in a bunch at 1.3°/2.3°/3.3° degrees off axis**
  - Simple cut on OD light may be too crude
    - Can use the scintillator panels to tag entering particle locations
- **4.6%/1.7%/0.8% of bunches have ID activity from more than 1 interaction**
  - Use the reconstruction to either veto multiple vertices (or multiple rings), or just reconstruct each vertex
    - Significant advances in multi-ring reconstruction are now available

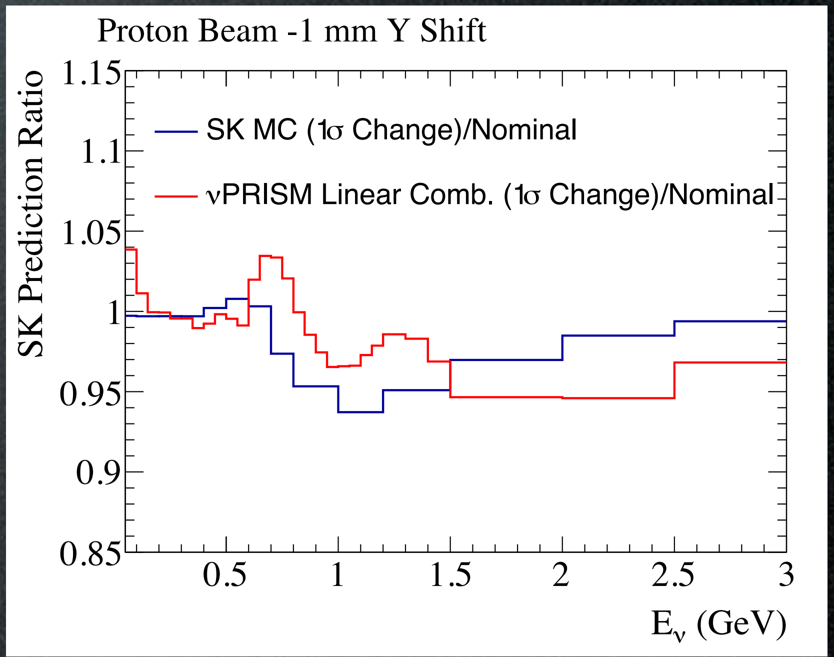


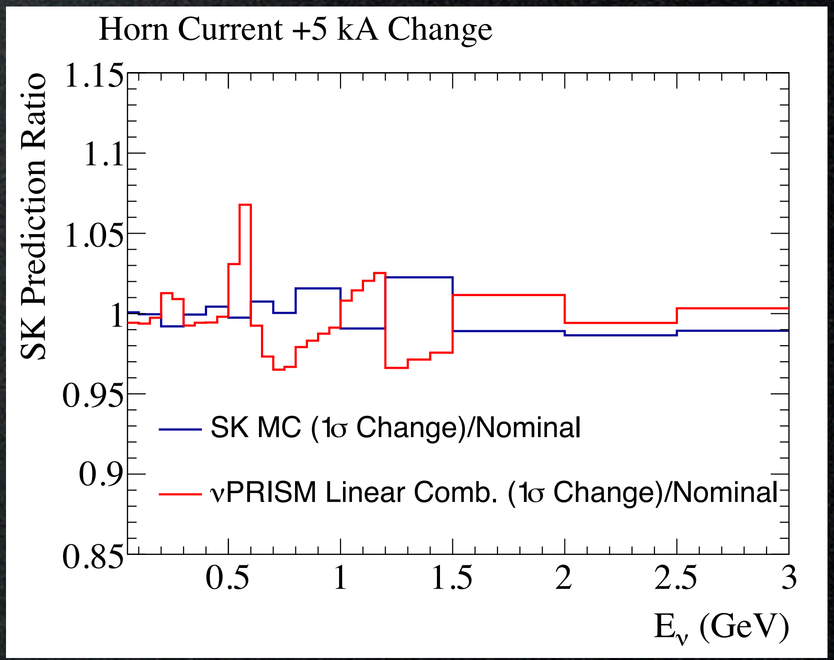
Pileup Rates at 1 km Look Acceptable!

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!

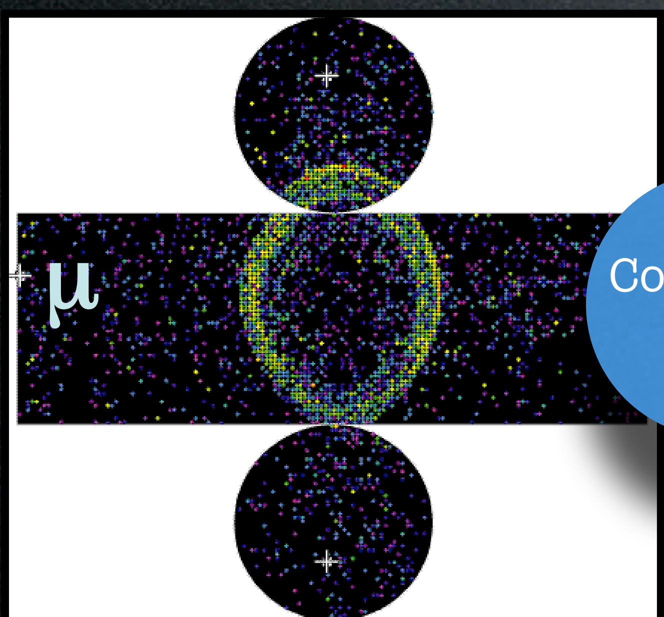






Reminder: Standard Oscillation Experiment Technique

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)

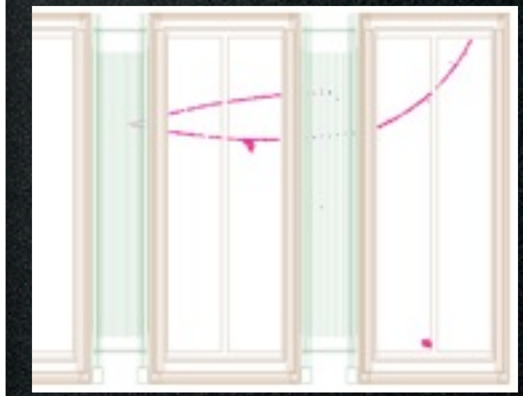
...

Nuclear model

Predicted by poorly understood models

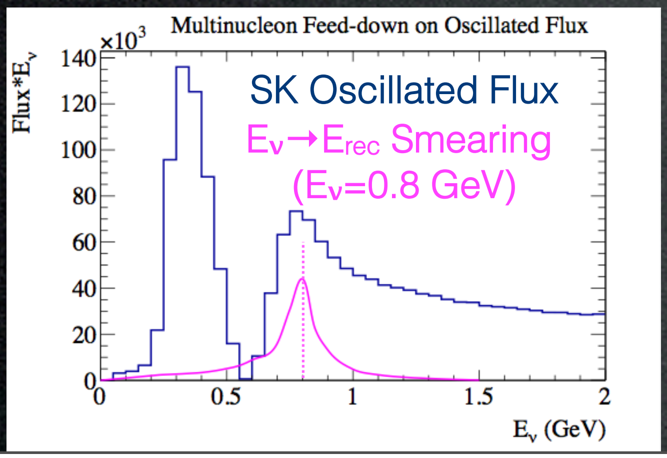
Parameter	E_ν Range	Nominal	Error	Class
M_A^{QE}	all	1.21 GeV/c^2	0.45	shape
M_A^{RES}	all	1.41 GeV/c^2	0.11	shape
p_F ^{12}C	all	217 MeV/c	30	shape
E_B ^{12}C	all	25 MeV	9	shape
SF ^{12}C	all	0 (off)	1 (on)	shape
CC Other shape ND280	all	0.0	0.40	shape
Pion-less Δ Decay	all	0.0	0.2	shape
CCQE E1	$0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

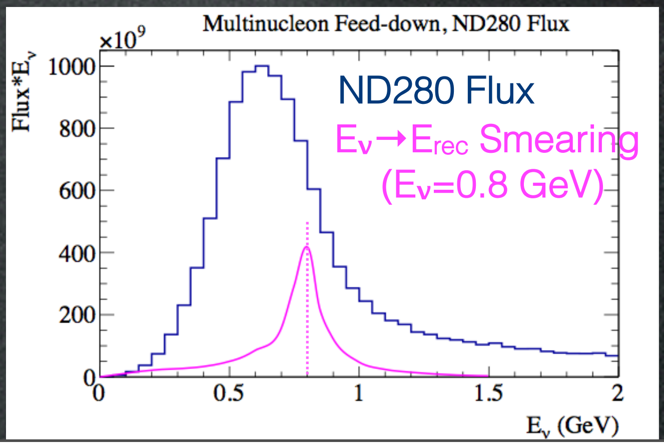
Simultaneously constrain flux and cross section parameters with a near detector



Often with a different nuclear target and phase space

Fluxes are also quite different:



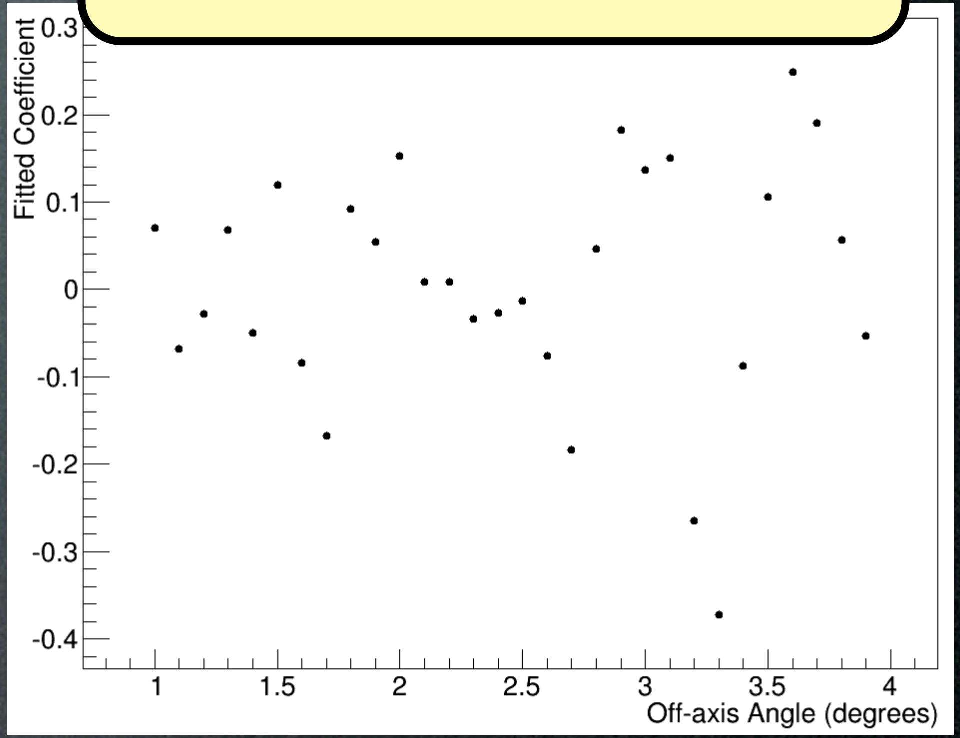


Very difficult to deconvolve!

Reducing Statistical Errors

- Flux predictions contain Monte Carlo statistical uncertainties
  - Strongly affect fit results
- Instead, can enforce that **neighboring bins must have similar weights**
  - Results in smooth variation of weights across off-axis angles
- Variance of weights is reduced by an order of magnitude
  - Significant reduction in statistical uncertainties

Unconstrained Fit



Constrained Fit