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

Mike Wilking
Stony Brook University
NNN 2015
October 29th, 2015

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An Experimental Method to Remove Neutrino Interaction Uncertainties from Oscillation Experiments

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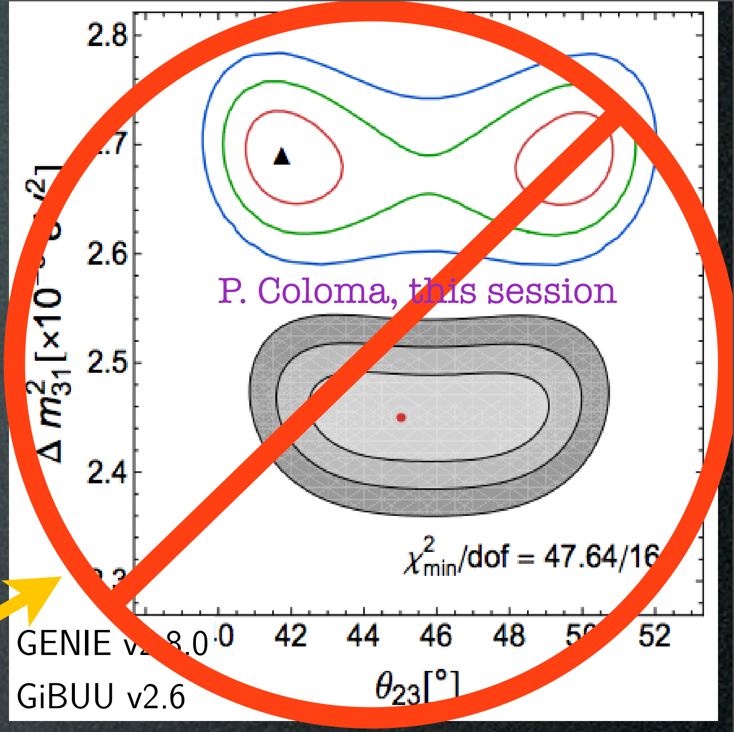
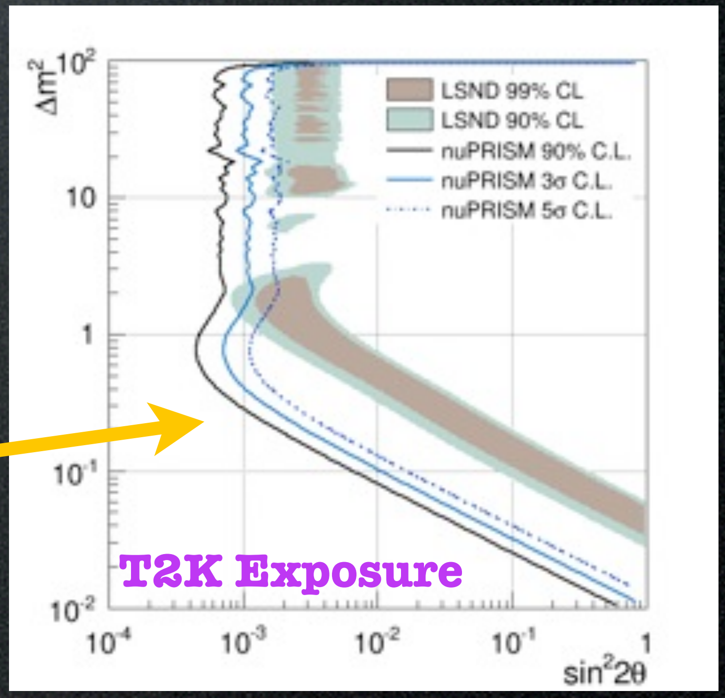
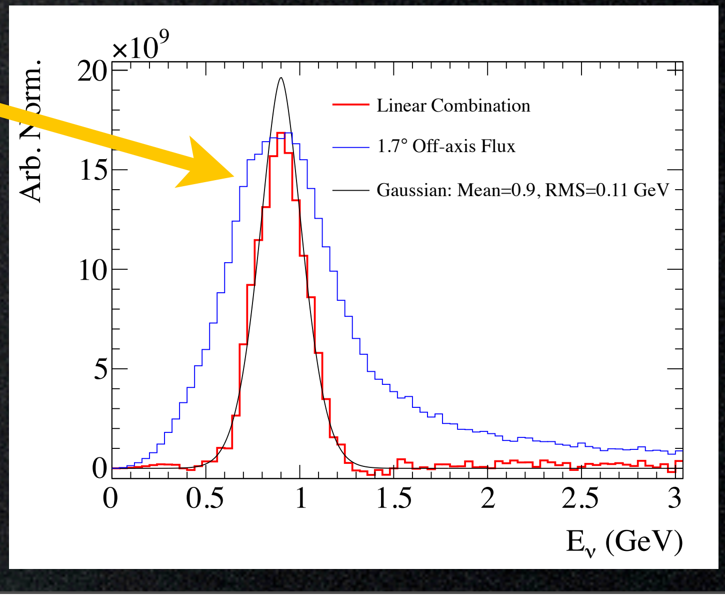
What is NuPRISM?

- NuPRISM is a near 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/Hyper-K/DUNE/…
   - These will be the largest uncertainties for the full T2K dataset (even more problematic for T2K2/HK/DUNE)
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

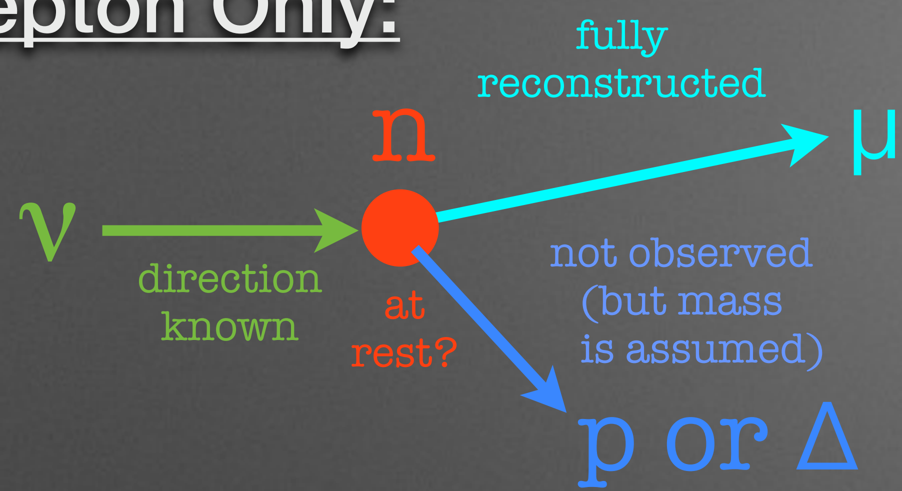






Measuring E_ν

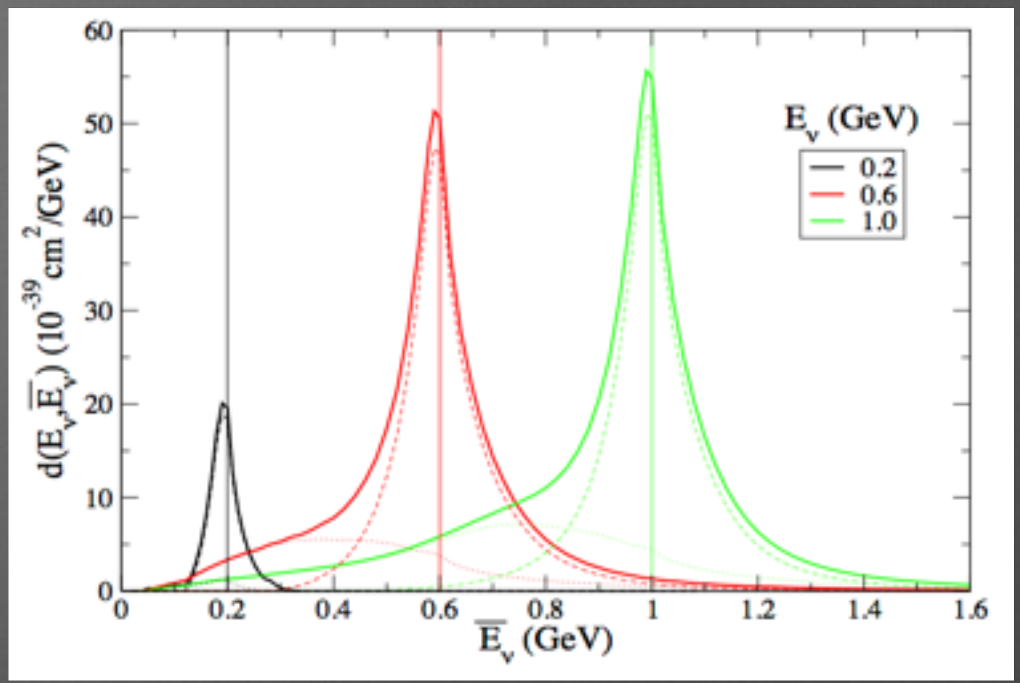
Lepton Only:



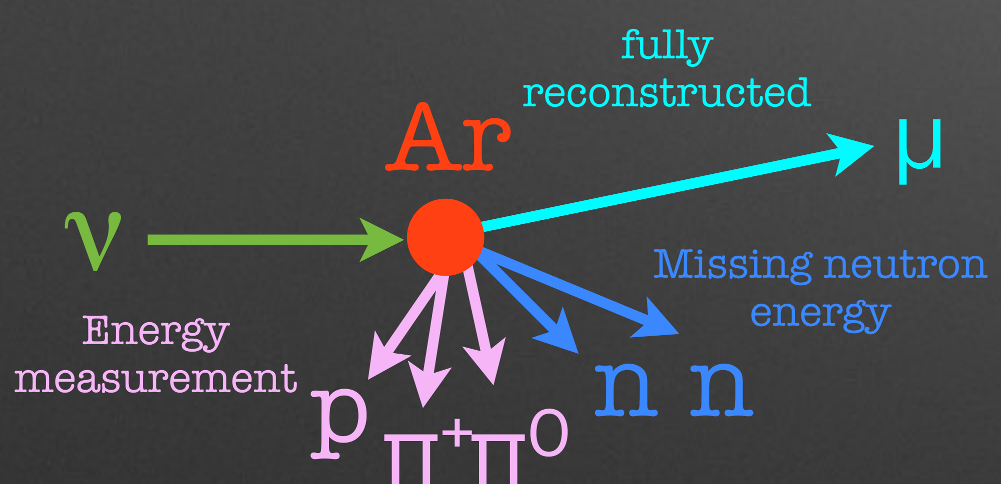
Must assume mass of recoiling hadron(s)

Problematic! due to Multi-nucleon interactions

Martini et al. arXiv:1211.1523



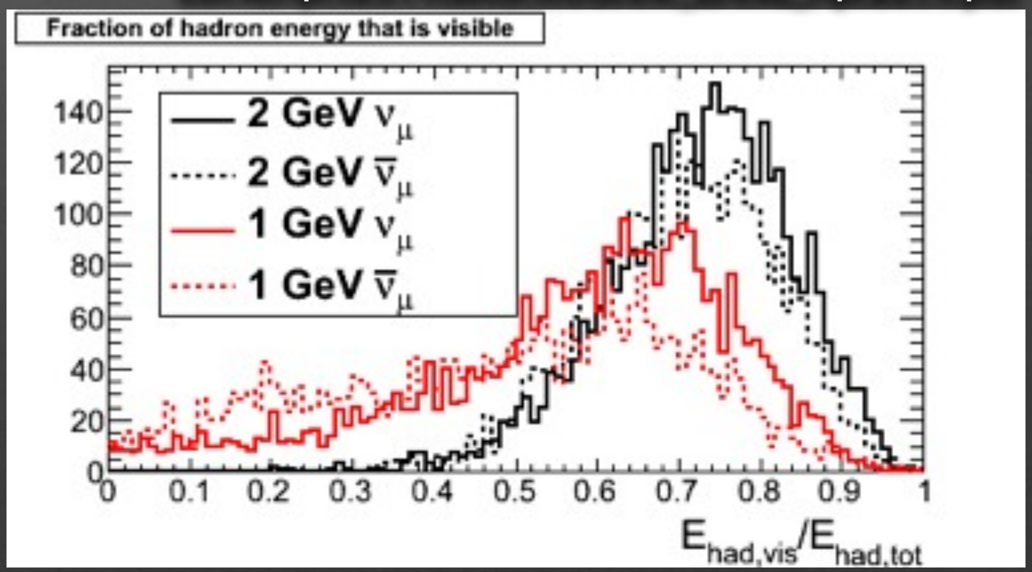
Lepton + Hadronic Energy:



Energy loss is worse at lower E_ν

Different for ν and anti-ν

http://public.lanl.gov/friedland/LBNEApril2014/
LBNEApril2014talks/McGrew_LANL_Apr2014.pdf



GEANT4 Simulation of a large LAr volume

(True deposited hadronic energy)/
(True initial hadronic energy)

- Both effects lead to underestimating the neutrino energy (feed down)
- Need to calibrate both leptonic (e & μ) & hadronic energy scales and energy tails (variance)

Measuring E_ν

Martini et al. arXiv:1211.1523

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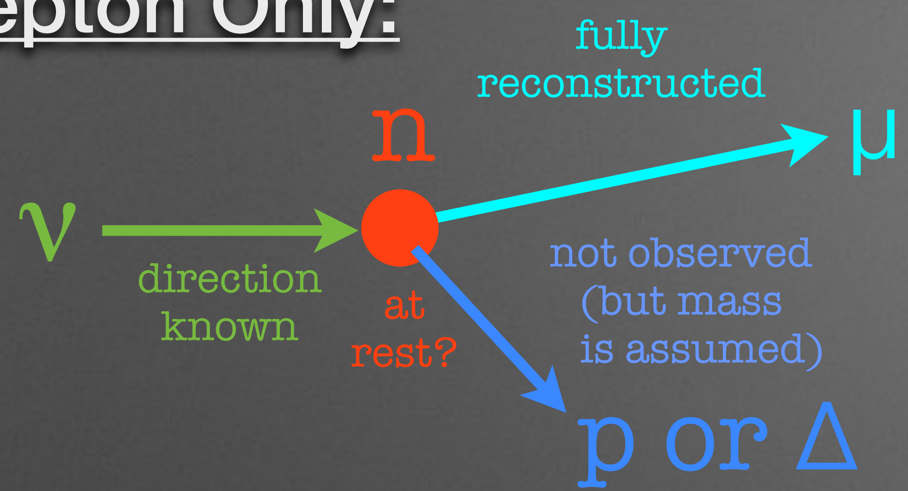

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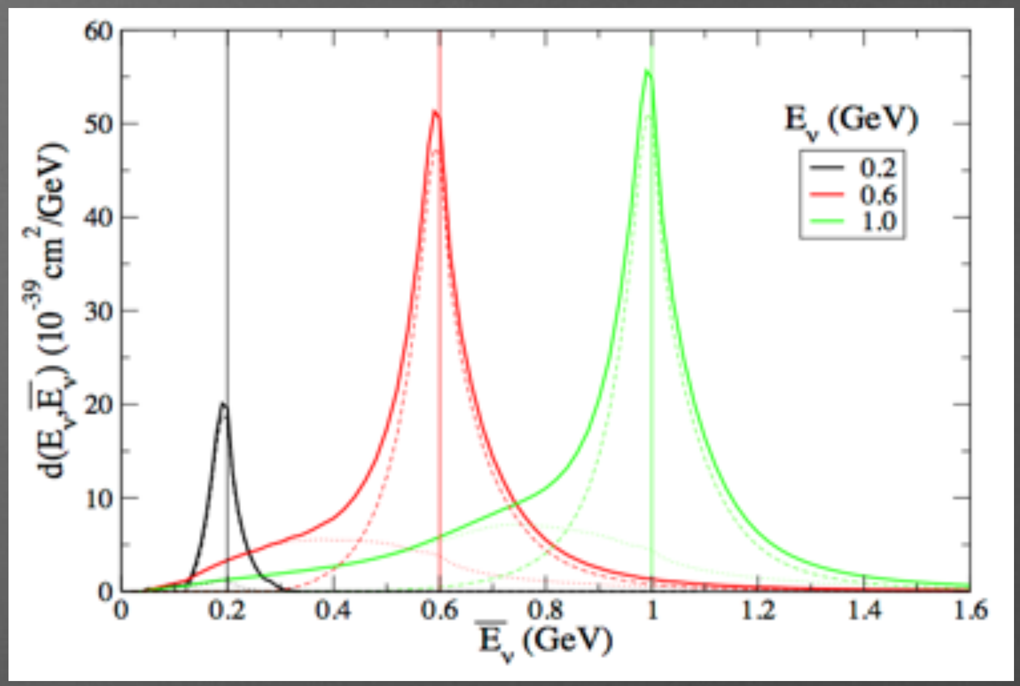

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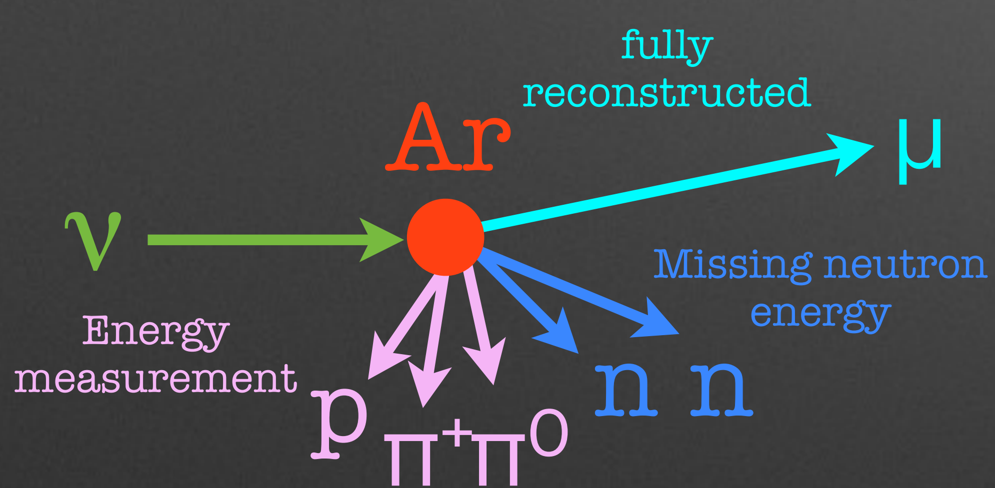

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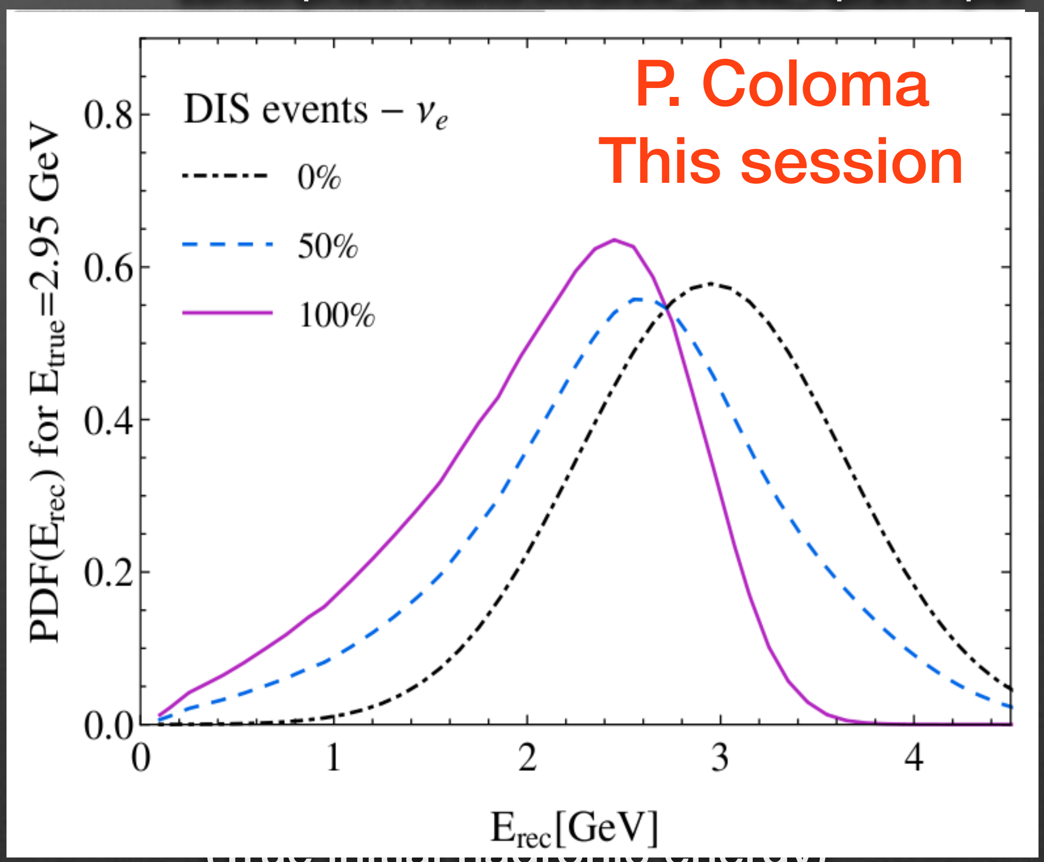
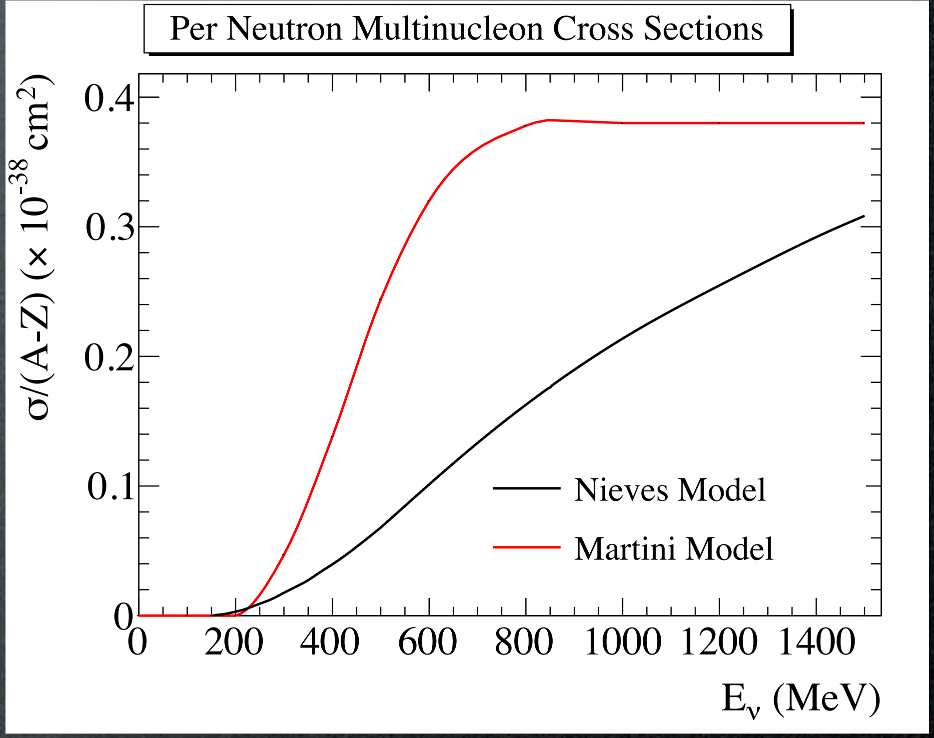
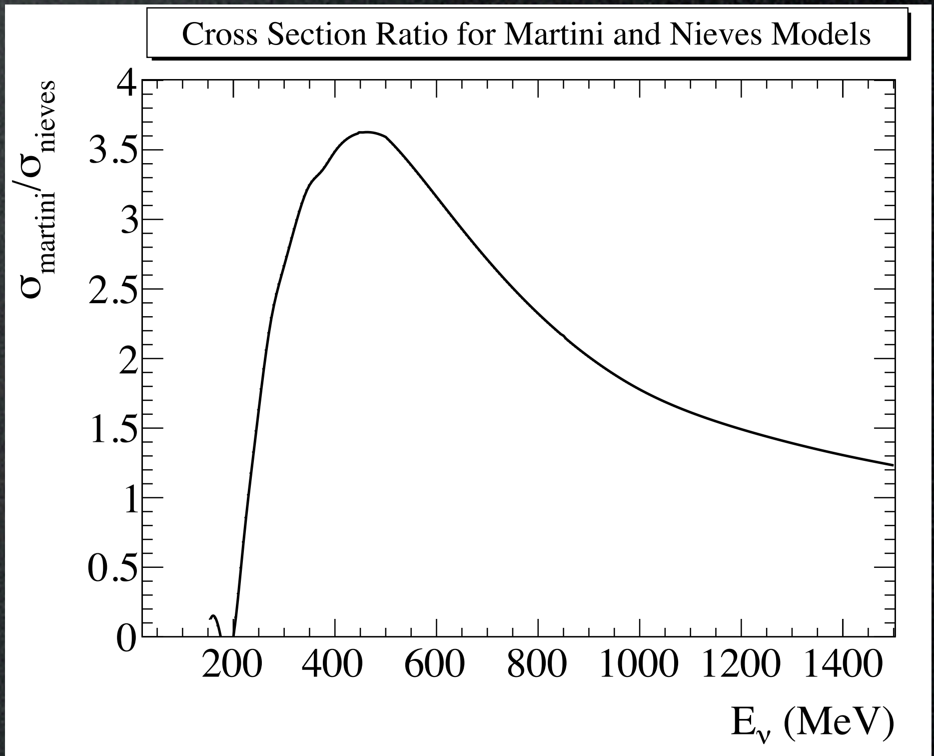


- Both effects lead to underestimating the neutrino energy (feed down)
- Need to calibrate both leptonic (e & μ) & hadronic energy scales and energy tails (variance)

Current State of Multinucleon Interaction Modeling

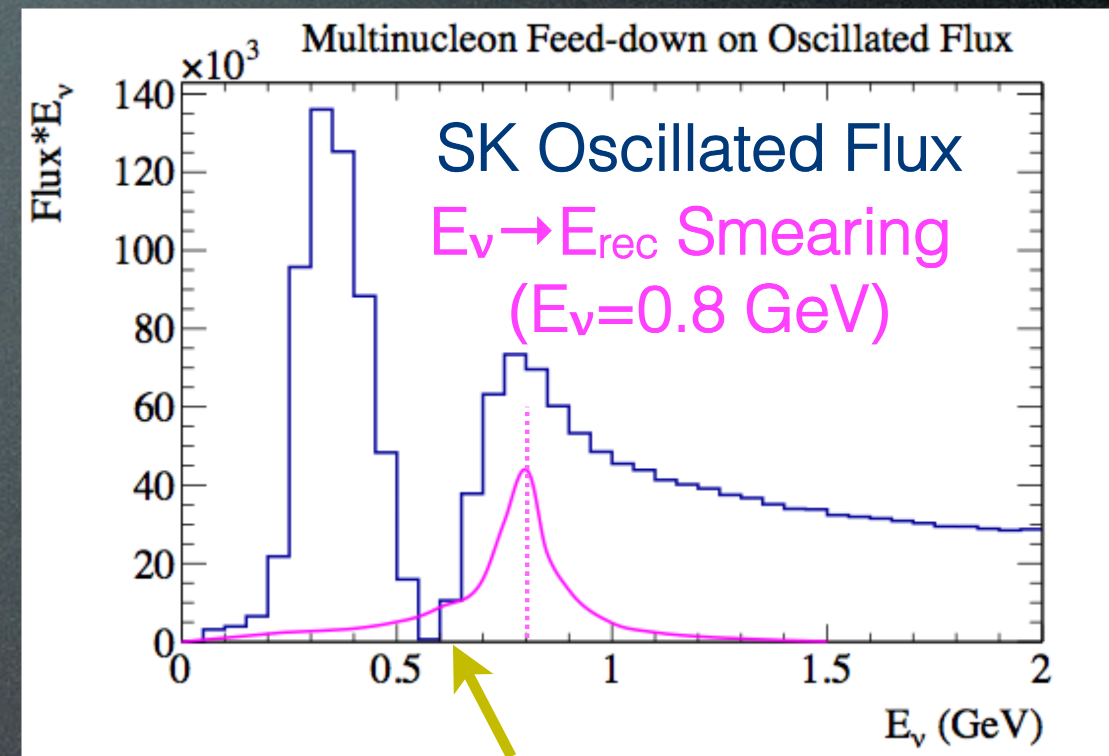
- The two most commonly used multi-nucleon models can be compared
  - J. Nieves, I. Ruiz Simo, and M. J. Vicente Vacas, PRC 83:045501 (2011)
  - M. Martini, M. Ericson, G. Chanfray, and J. Marteau, PRC 80:065501 (2009)
- Cross section differs by a **factor of 2 to 3** over a large range of neutrino energies
- A theoretical description of neutrino-nucleus interactions at 1 GeV is difficult
  - Will we ever be able to trust these models to the percent level?
  - A direct constraint from data is vital





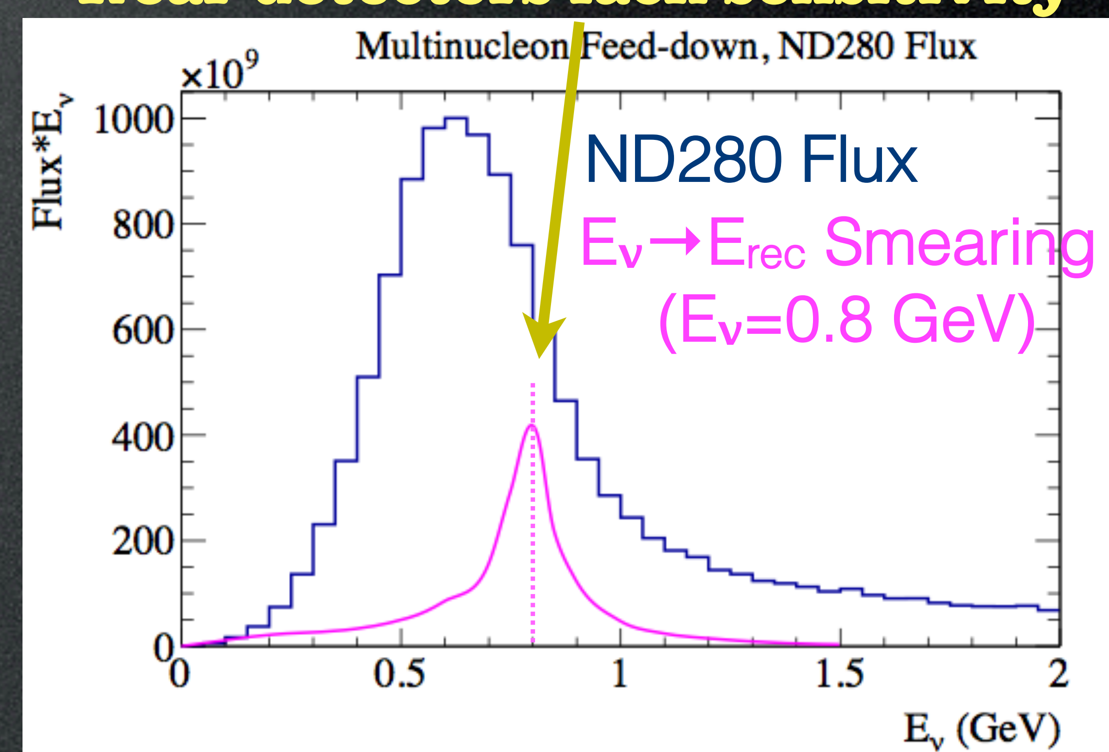
Constraints from Typical Near Detectors

- 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!**



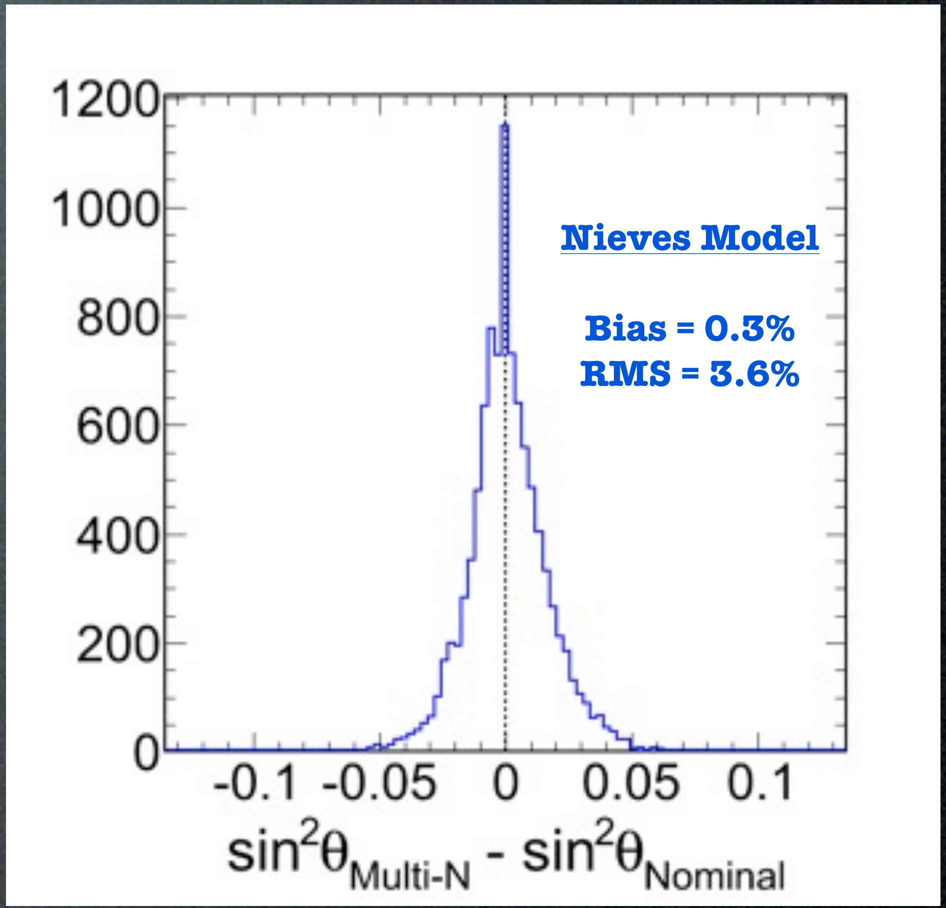
Mixing Angle Bias!

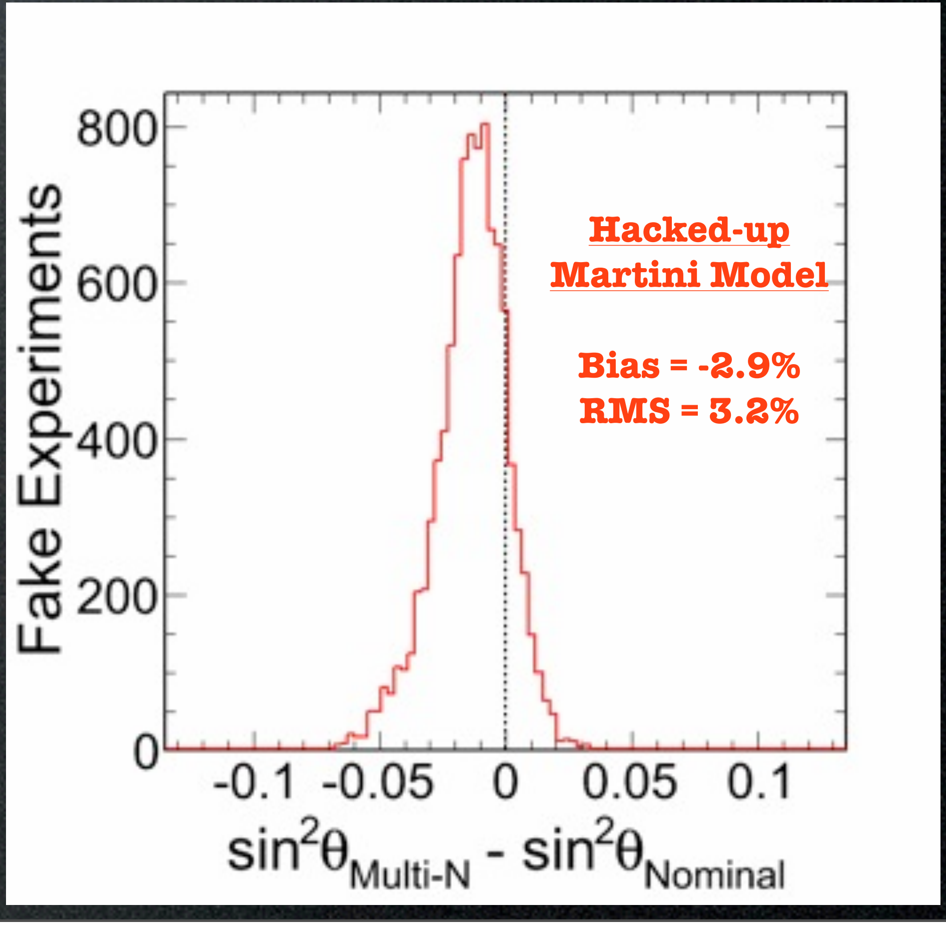
Near detectors lack sensitivity



Effect on T2K ν_μ Disappearance

- Create "fake data" samples with 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**

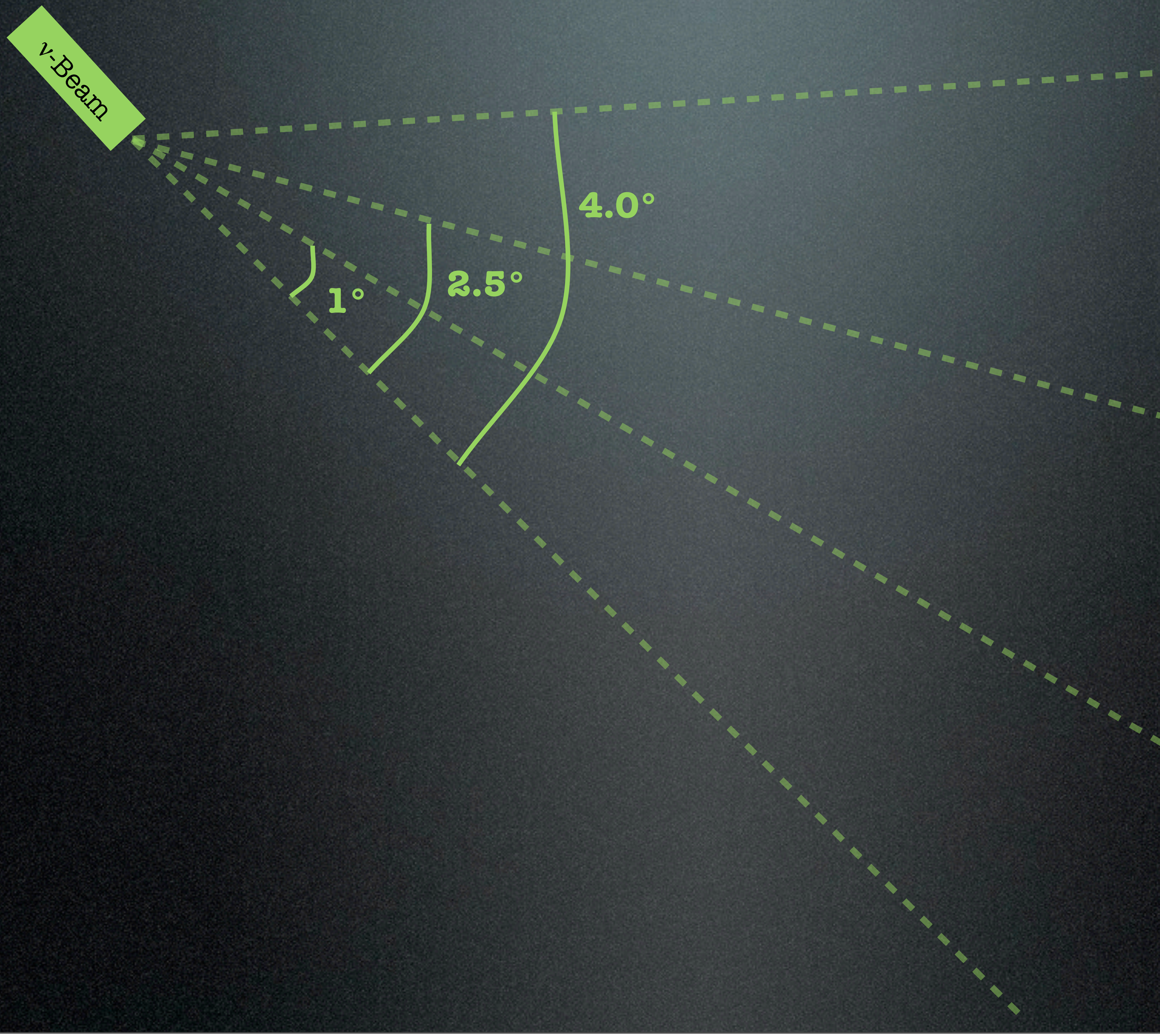




Can the E_ν problem be solved experimentally?

NuPRISM Detector Concept

NuPRISM Detector Concept



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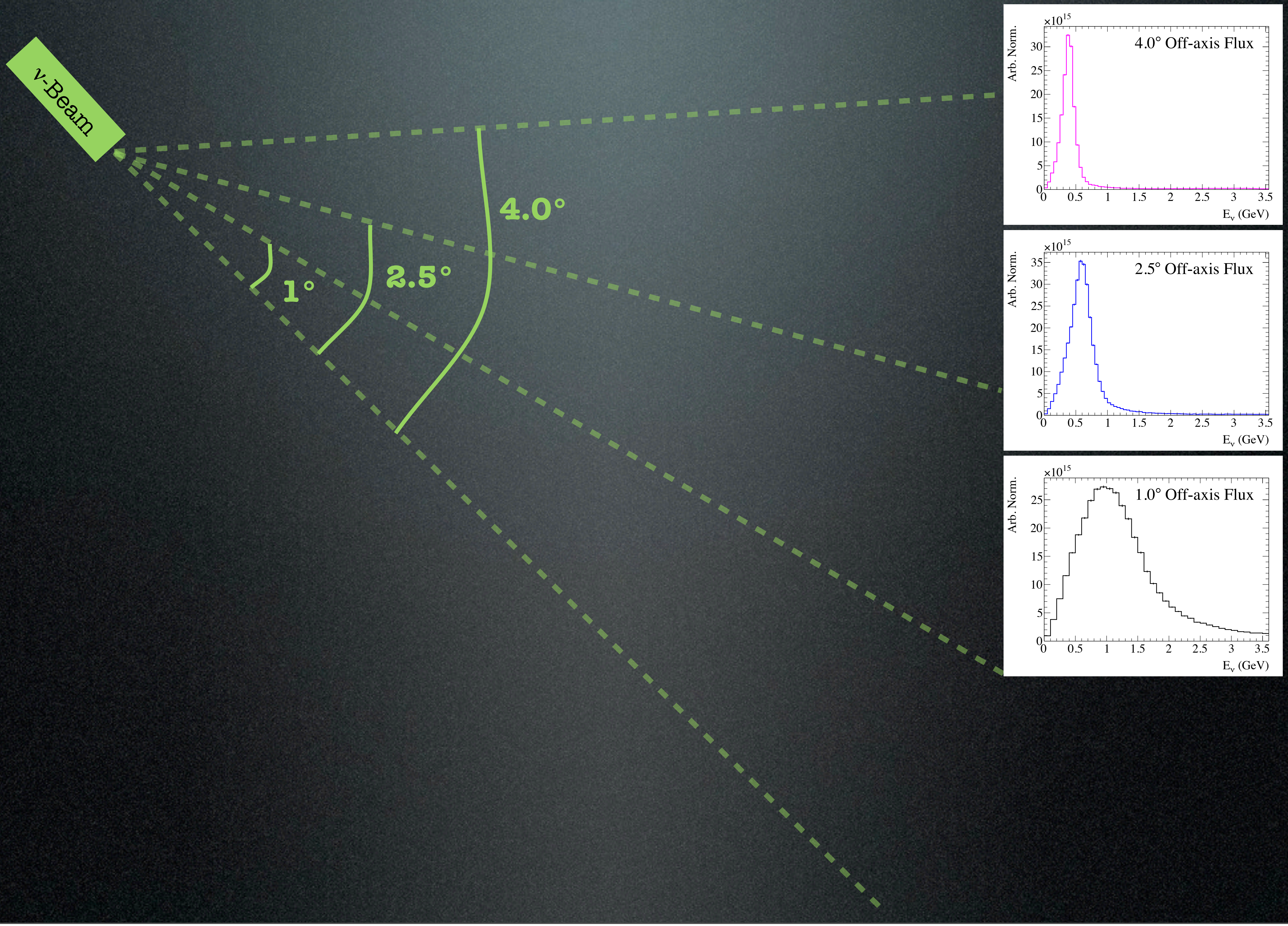

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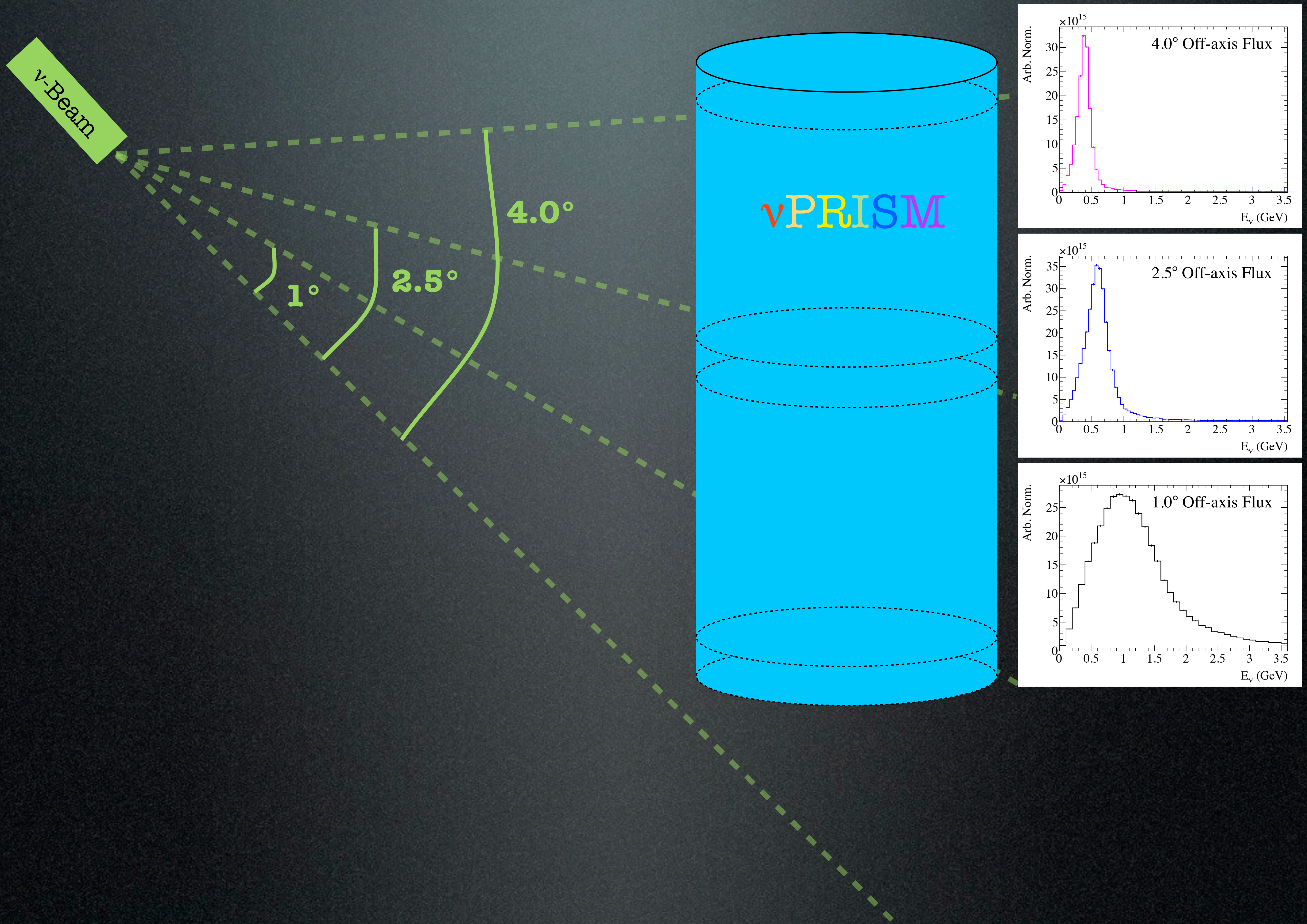

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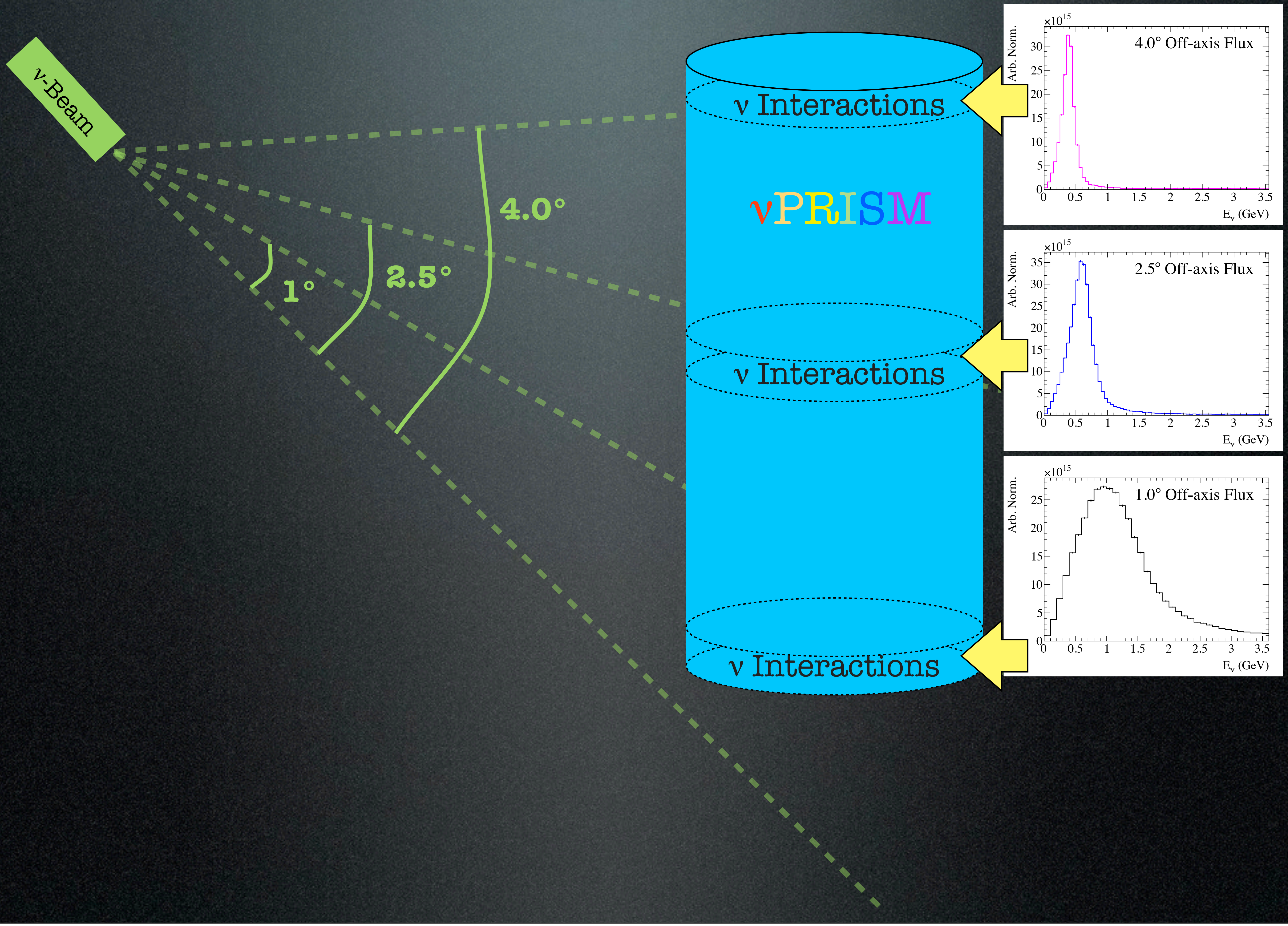

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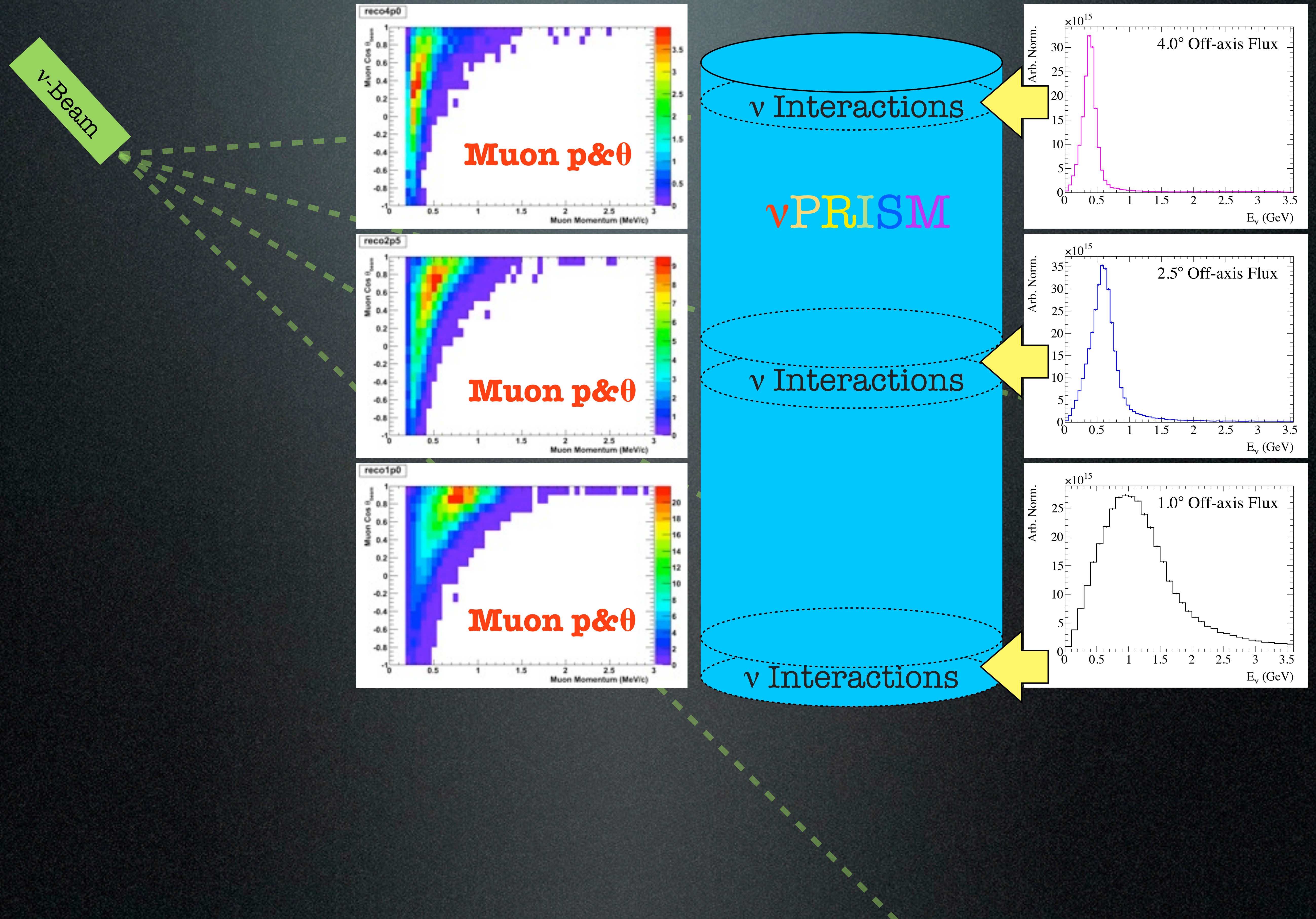

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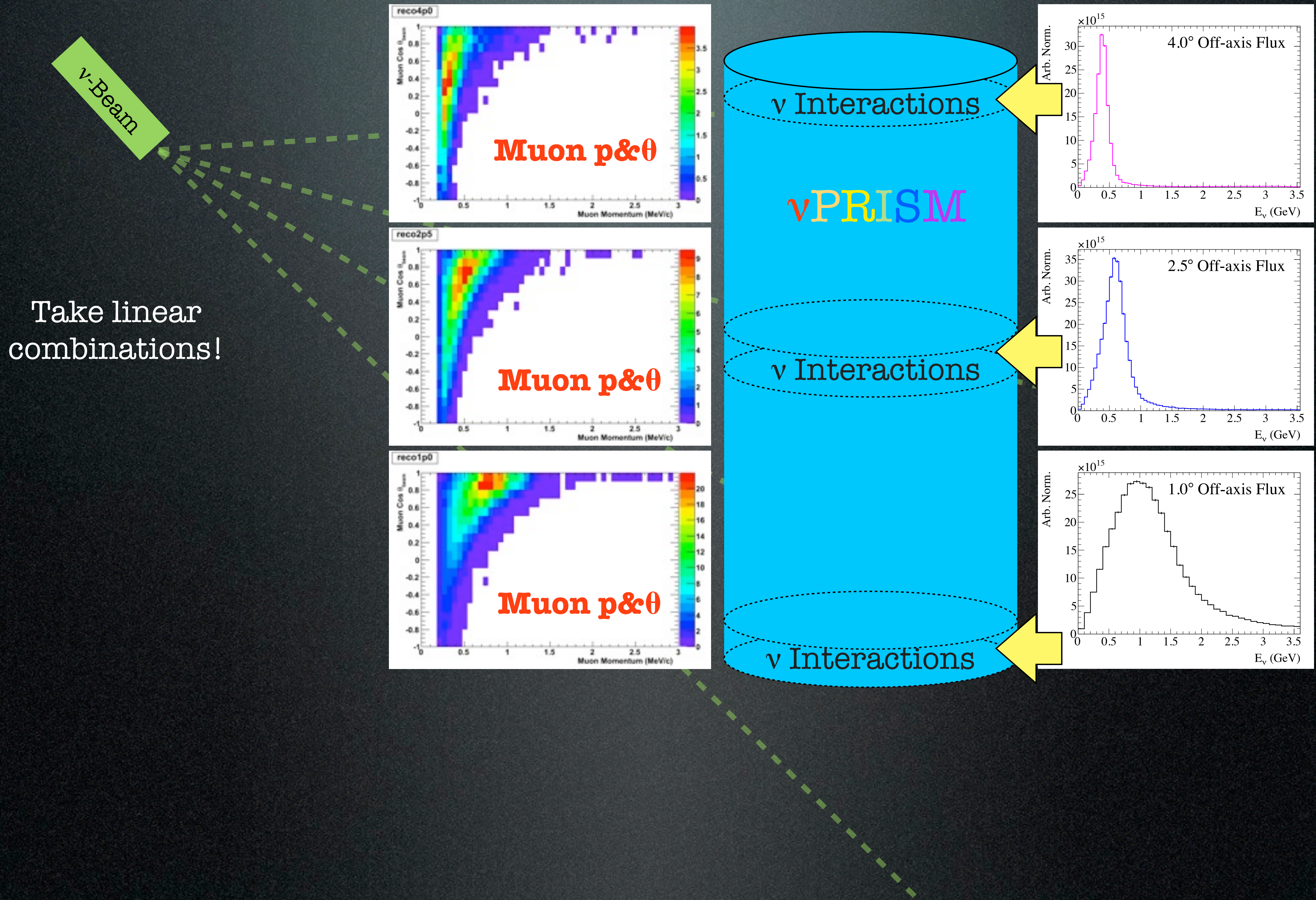

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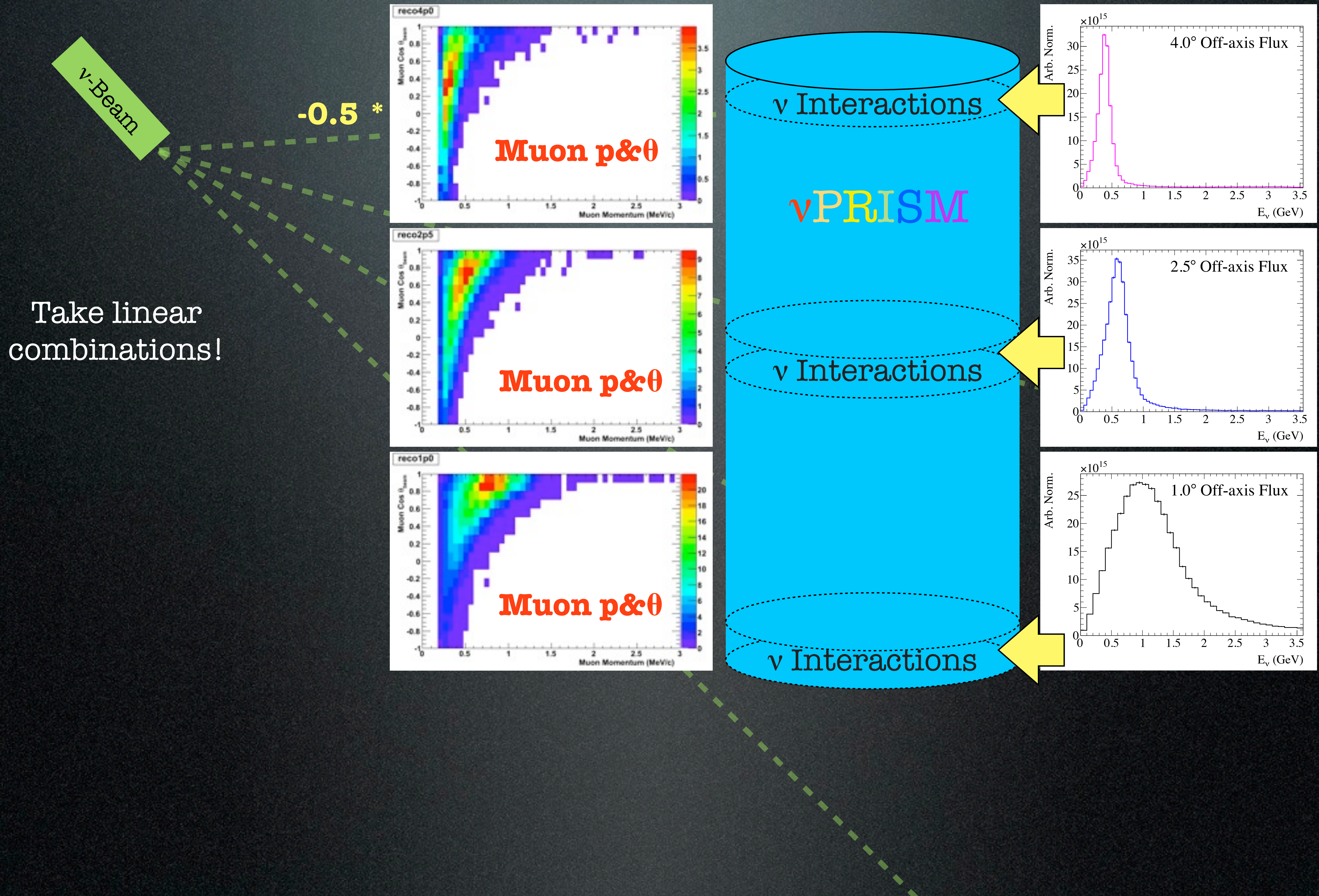

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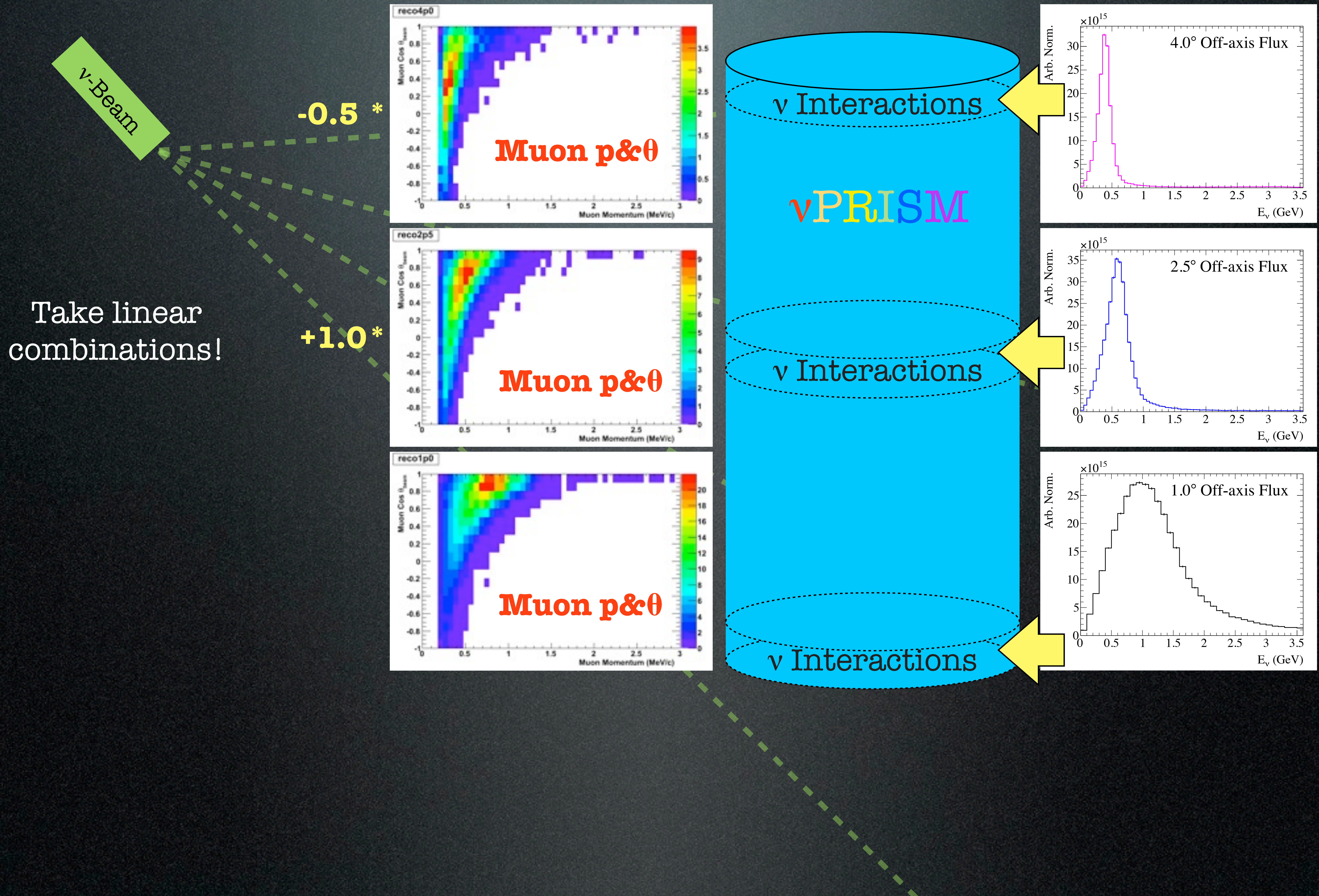

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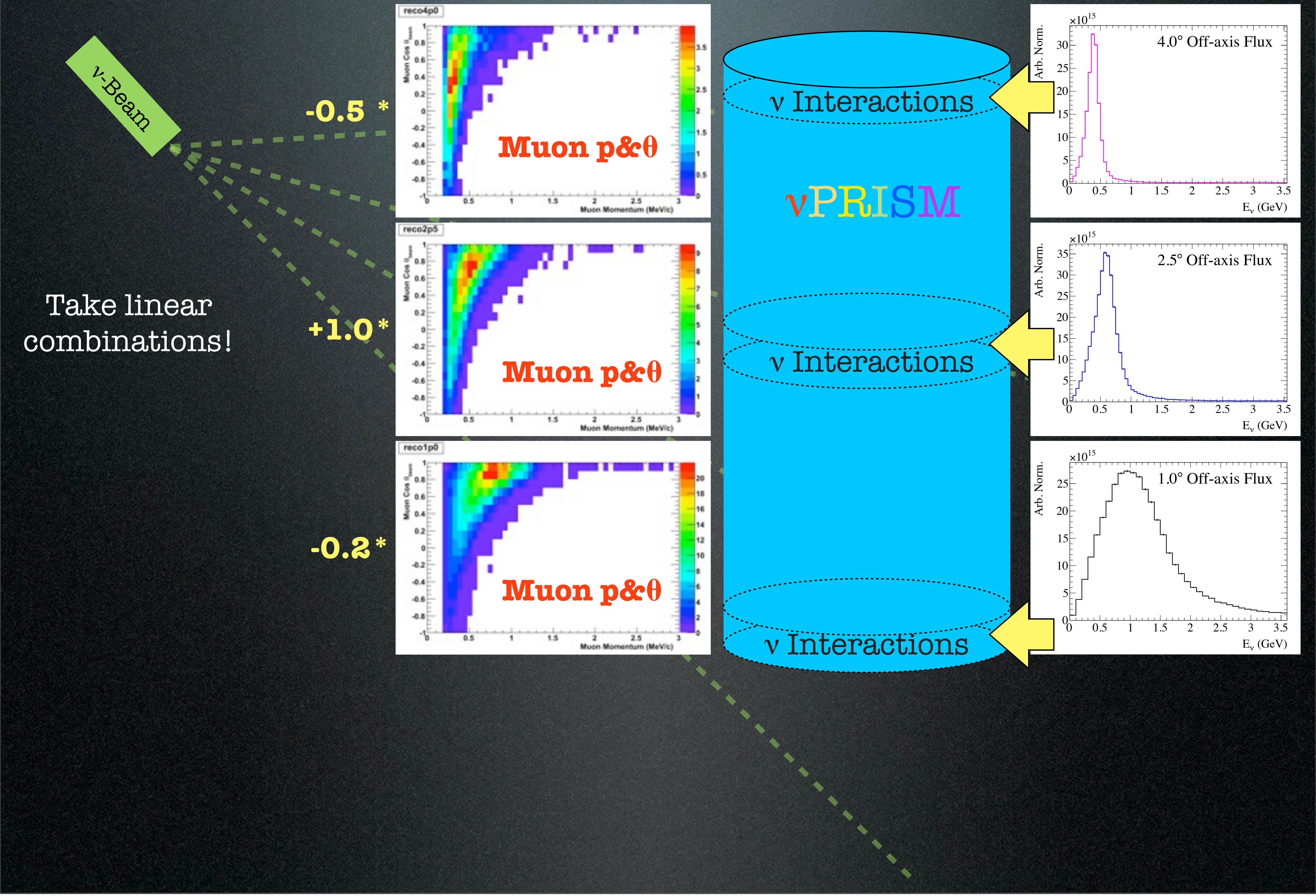

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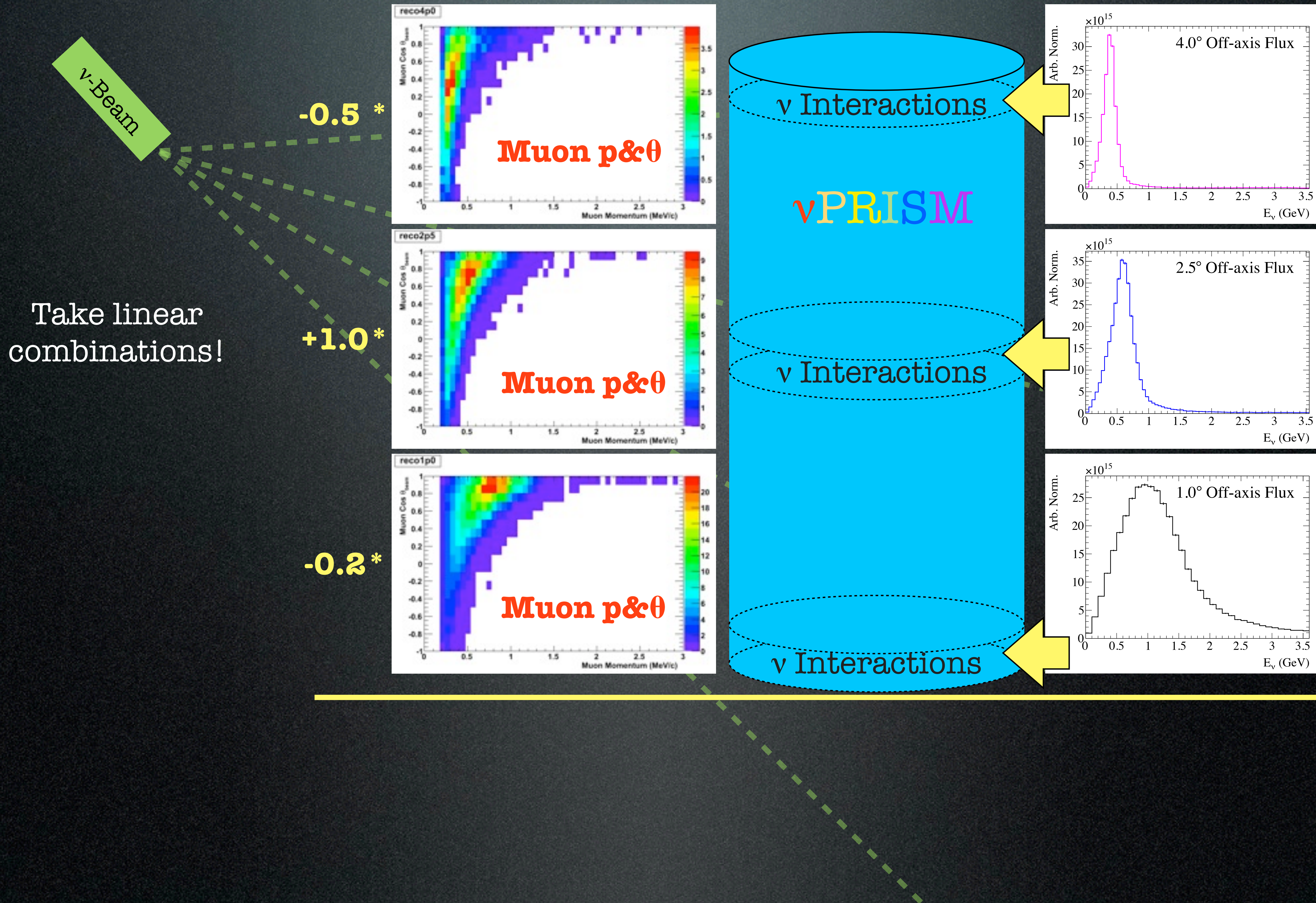

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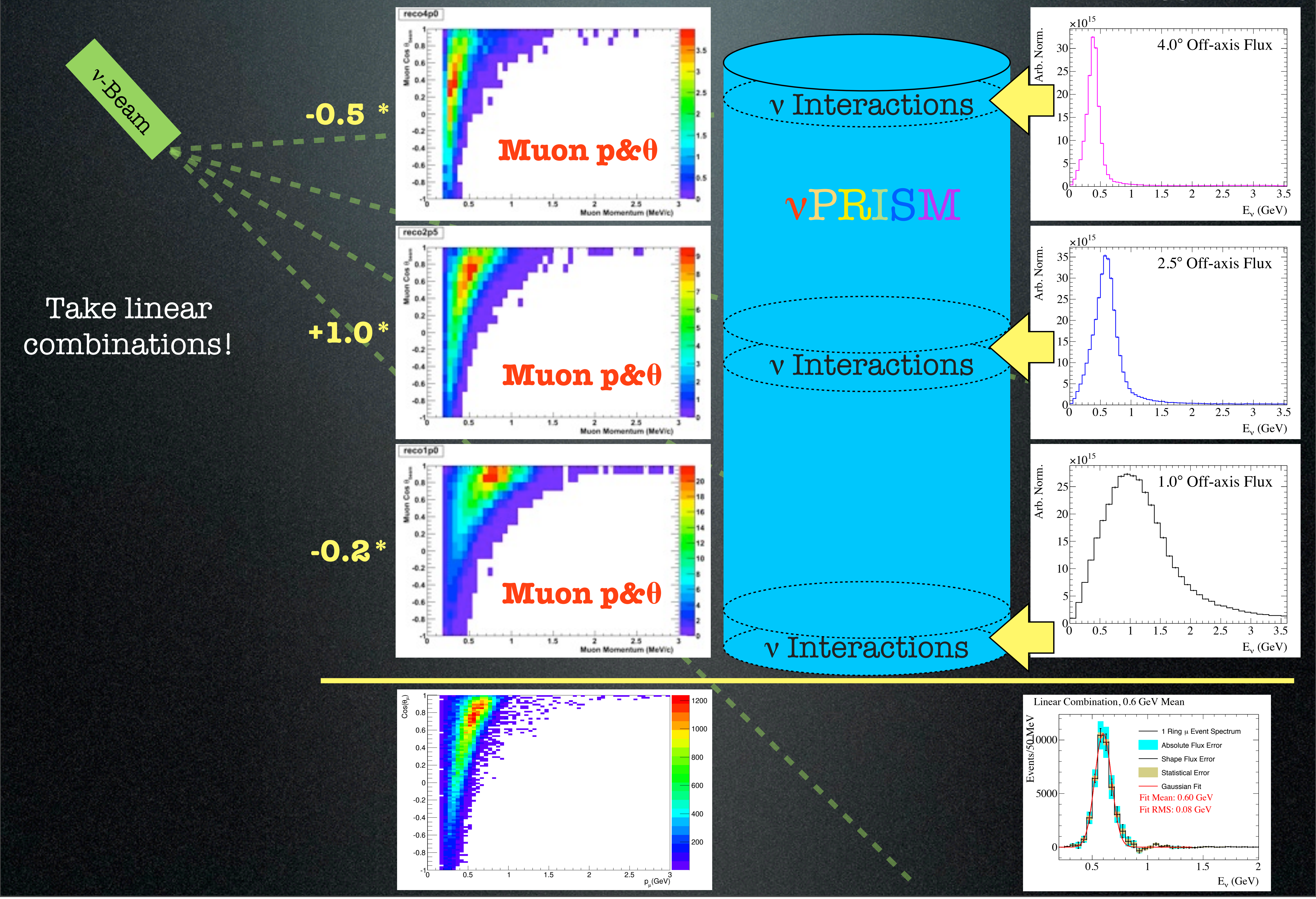

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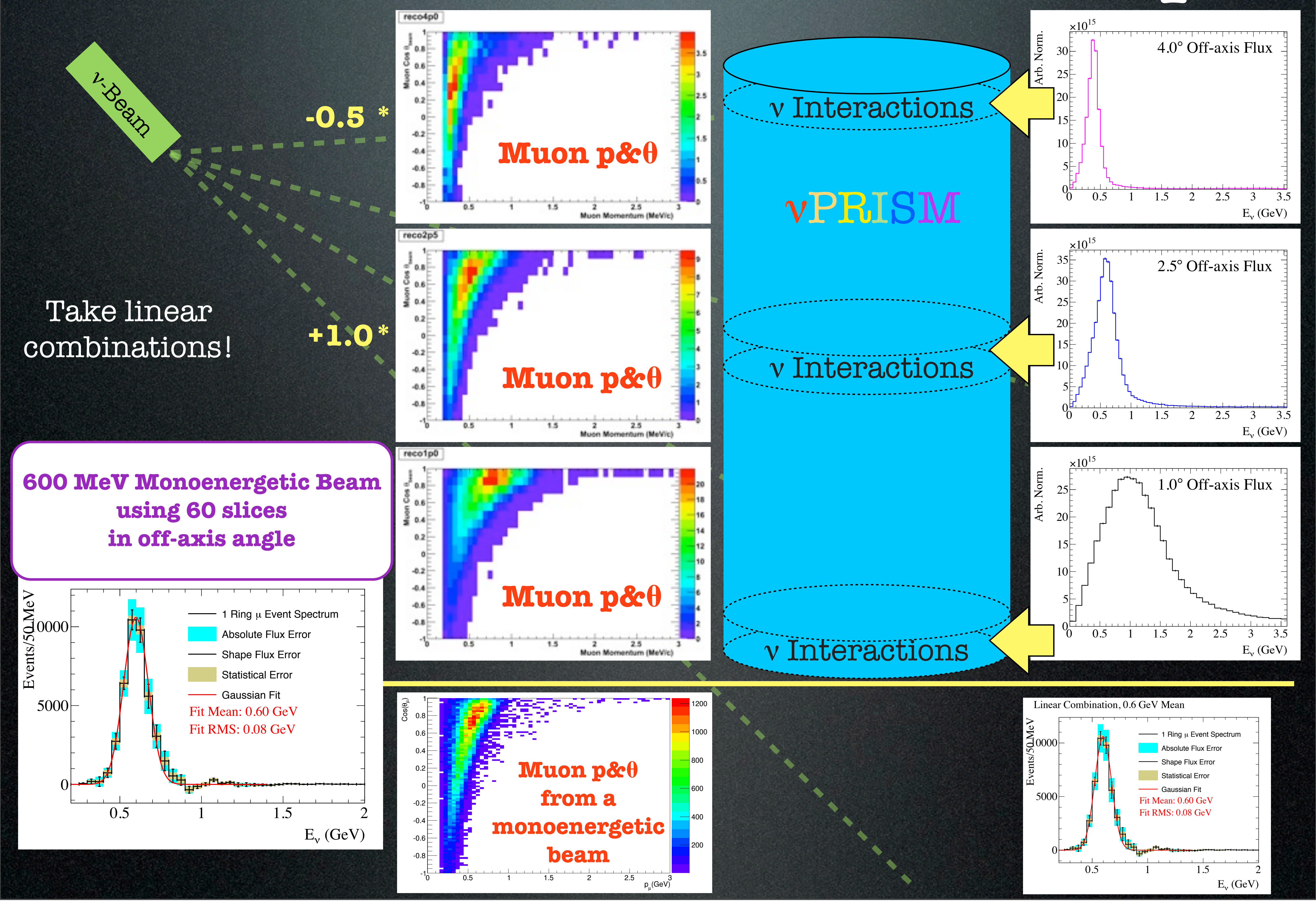
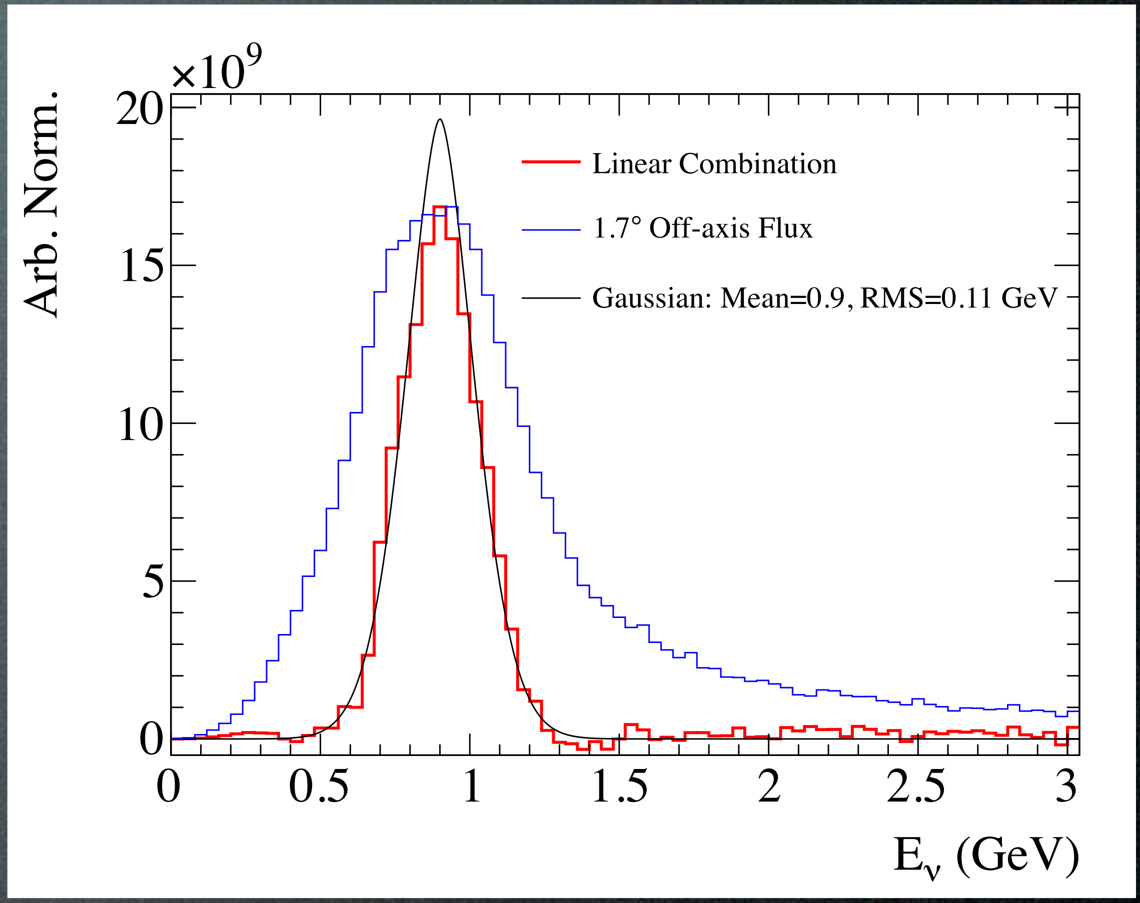
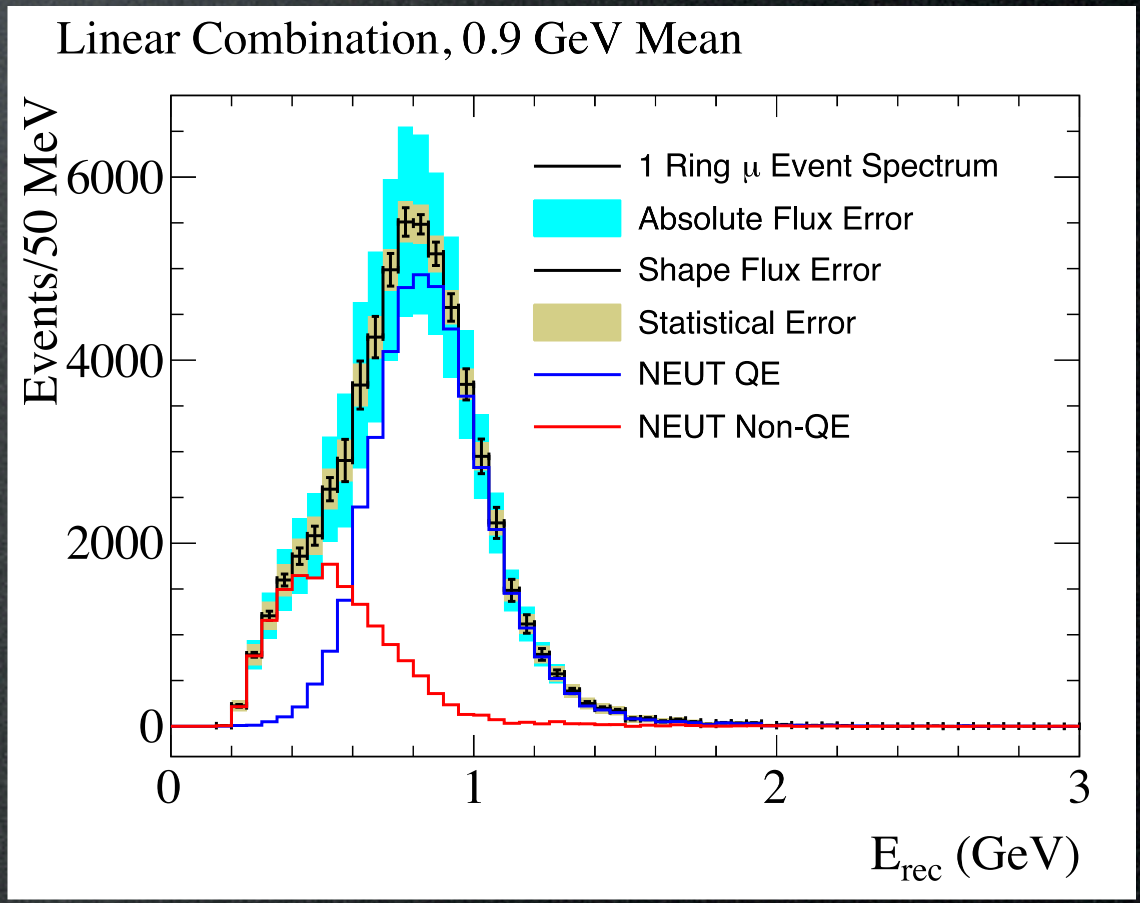


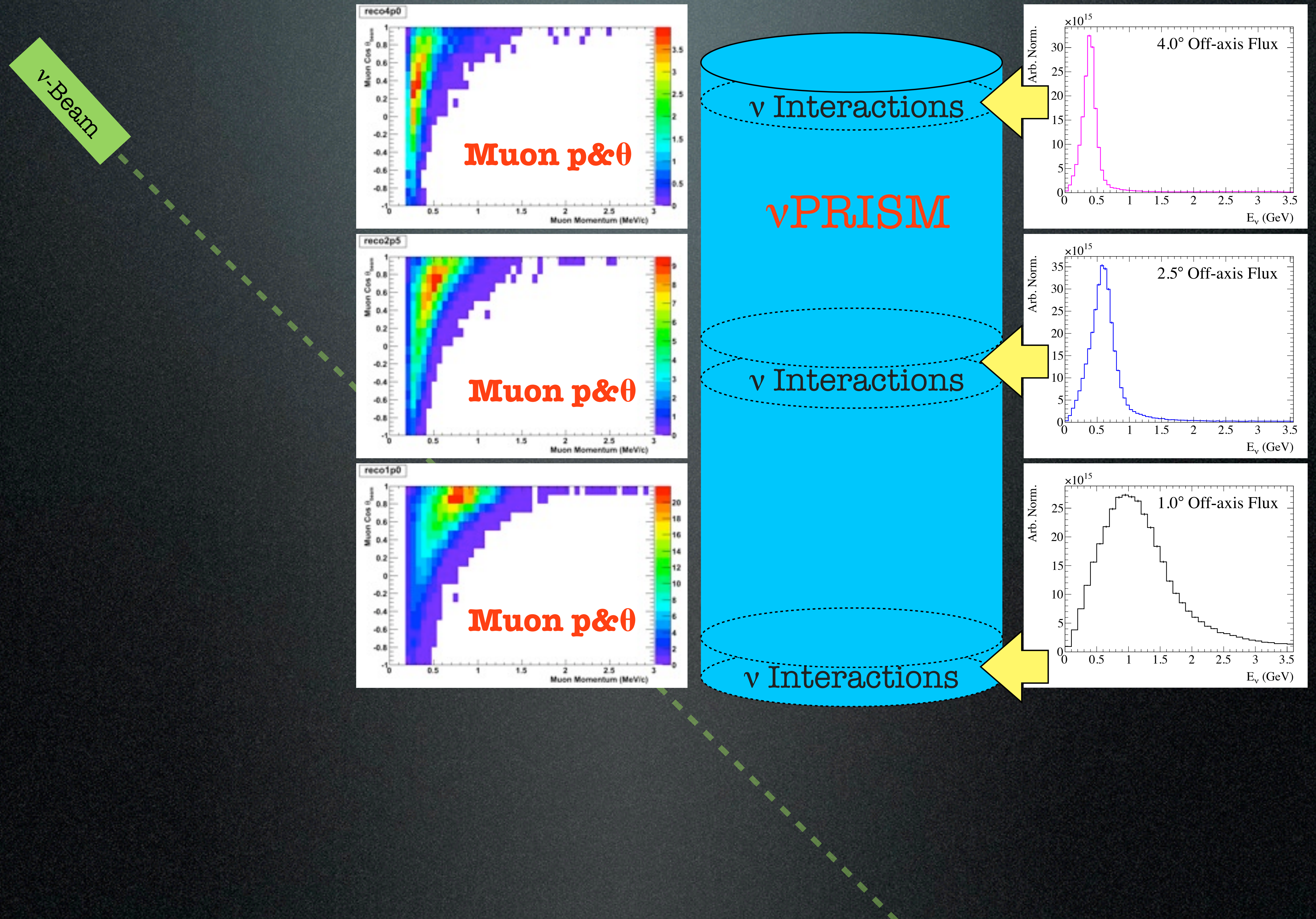
Benefits of a Monoenergetic Beam

- **Fully specified initial state!**
  - Electron-scattering-like measurements with neutrinos!
- First ever measurements of $\sigma^{NC}(E_\nu)$
  - Much better constraints on NC oscillation backgrounds
- First ever "**correct**" measurements of $\sigma^{CC}(E_\nu)$
  - No longer rely on final state particles to determine E_ν
- It is now possible to **separate the various components** of single-μ events!



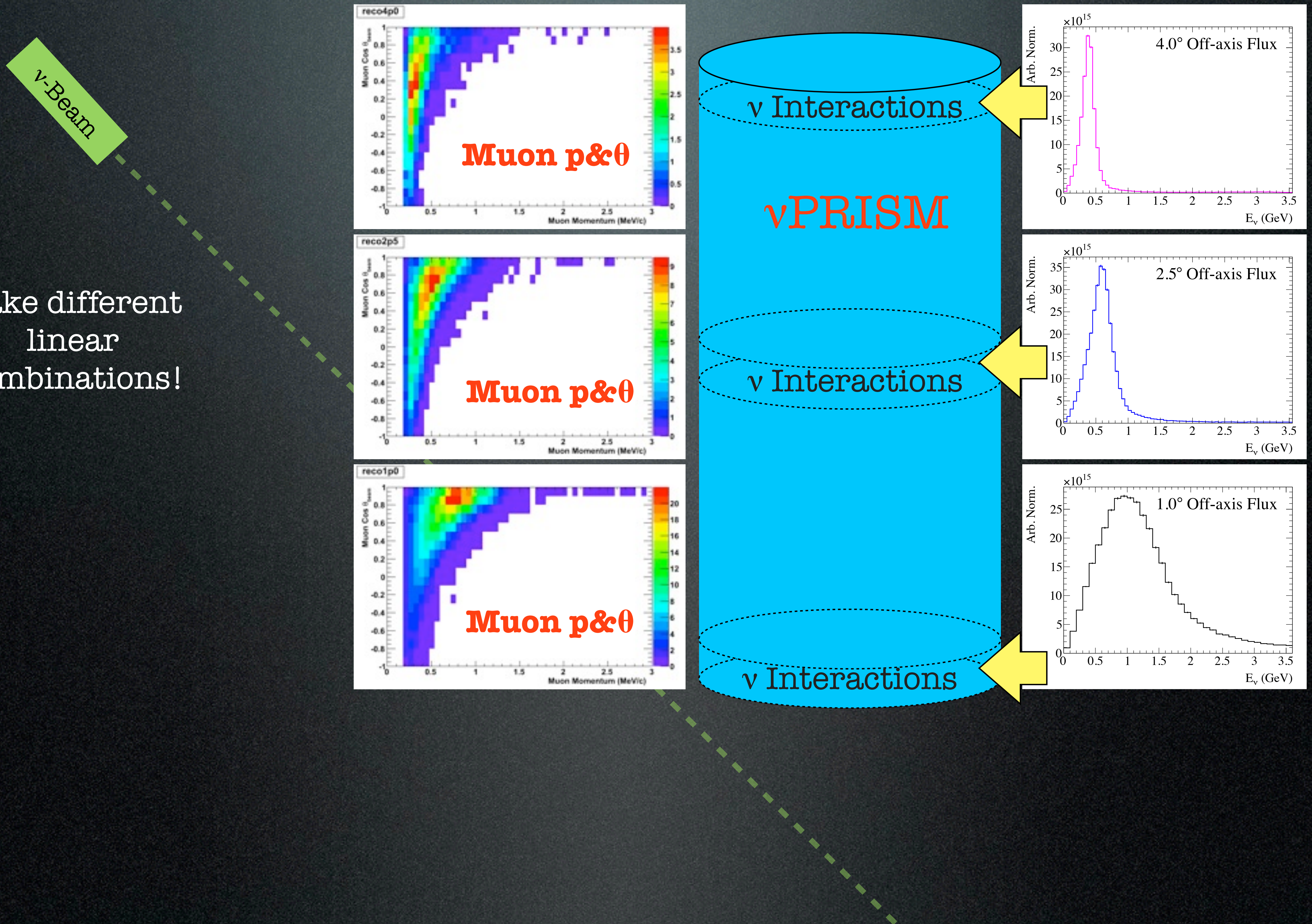


NuPRISM in Oscillation Experiments

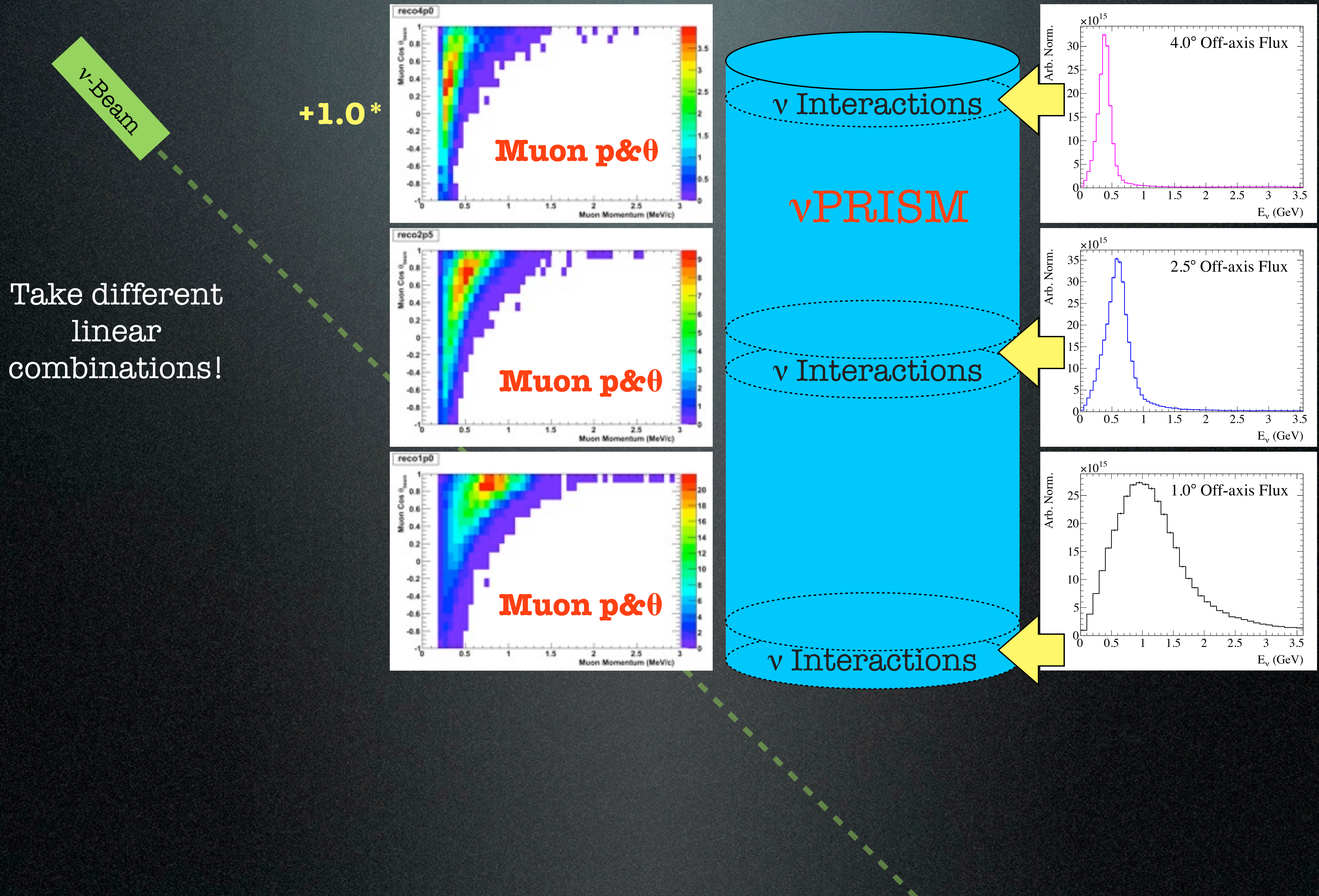


NuPRISM in Oscillation Experiments

Take different linear combinations!



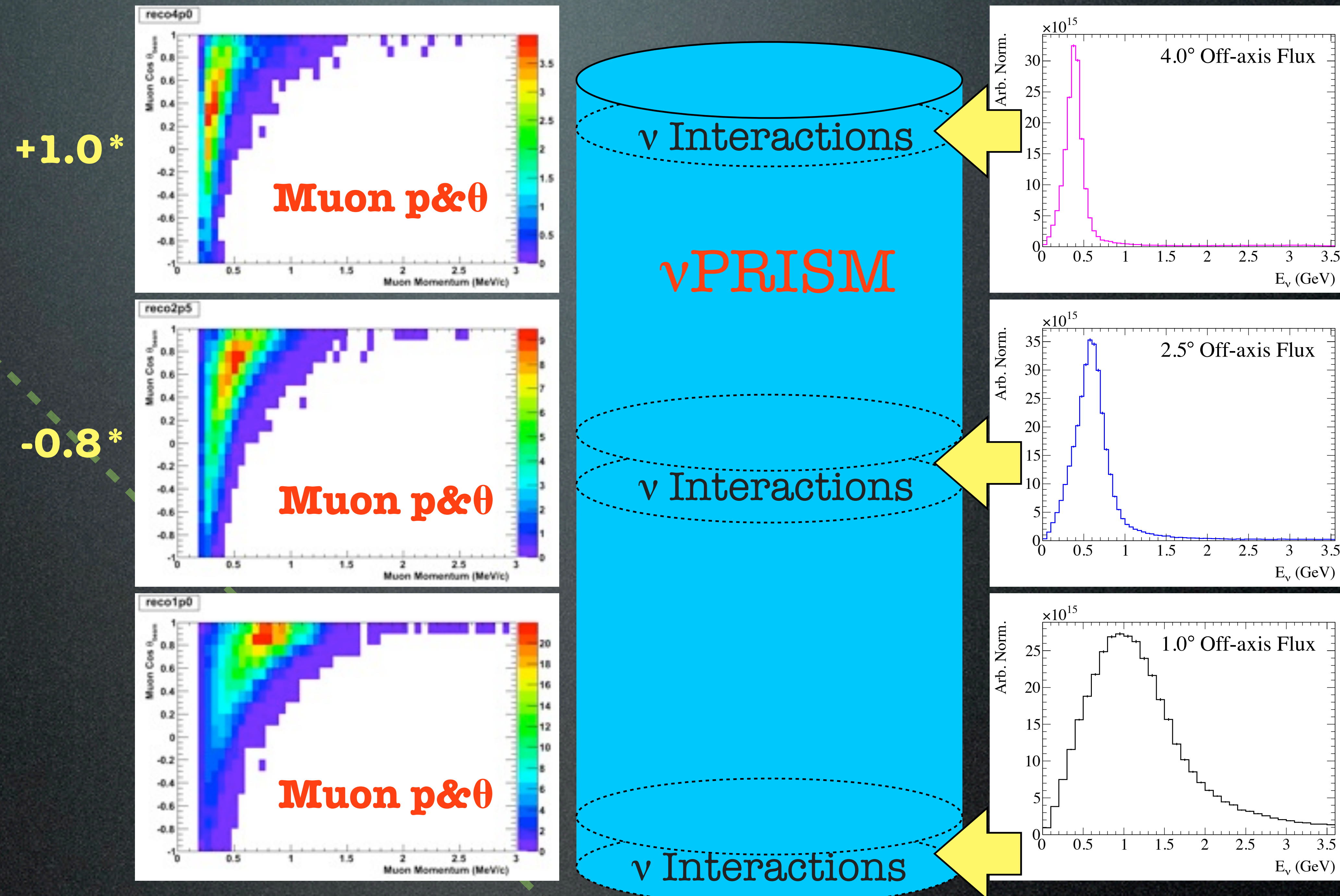
NuPRISM in Oscillation Experiments



NuPRISM in Oscillation Experiments

ν-Beam

Take different linear combinations!



NuPRISM in Oscillation Experiments

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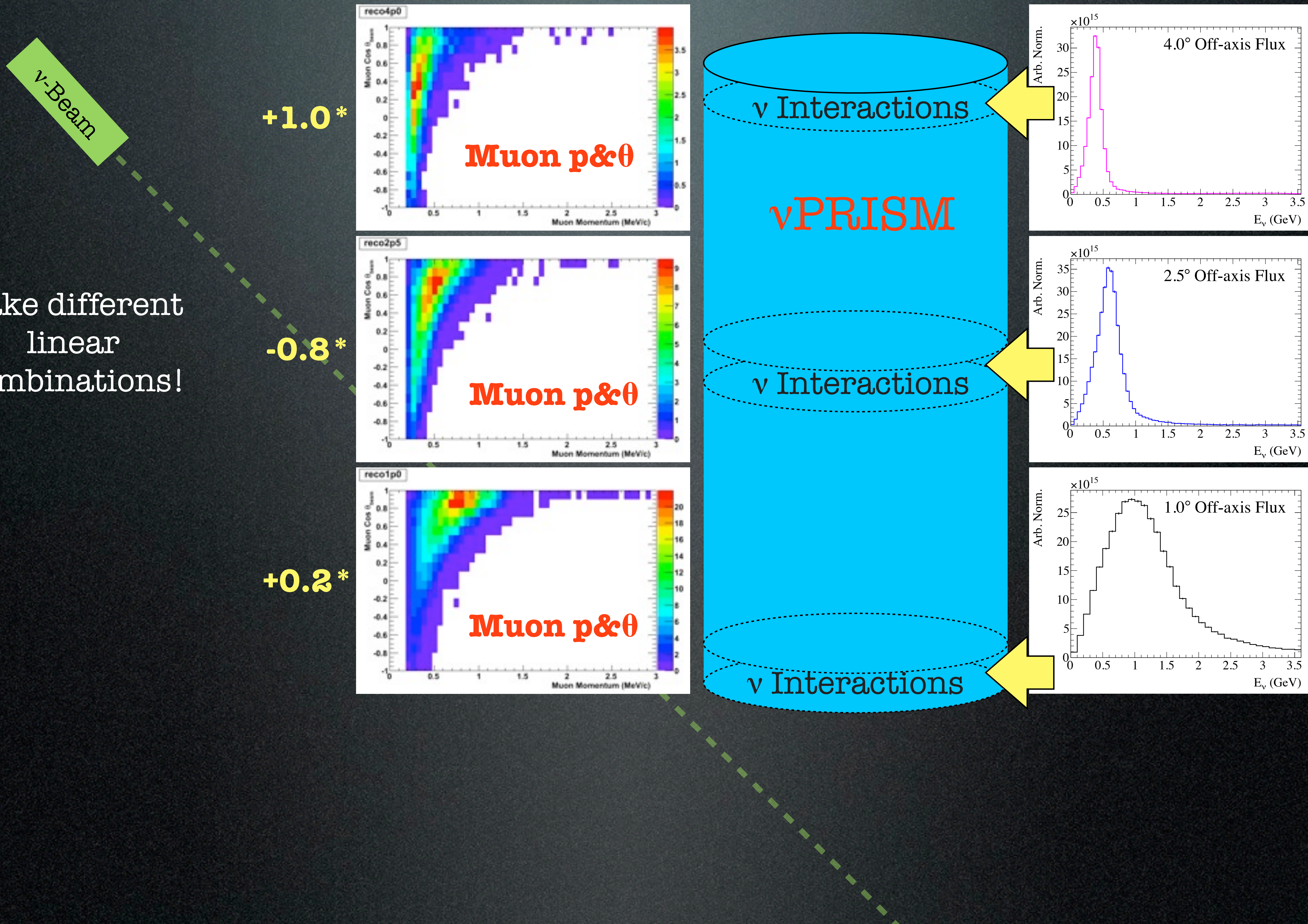
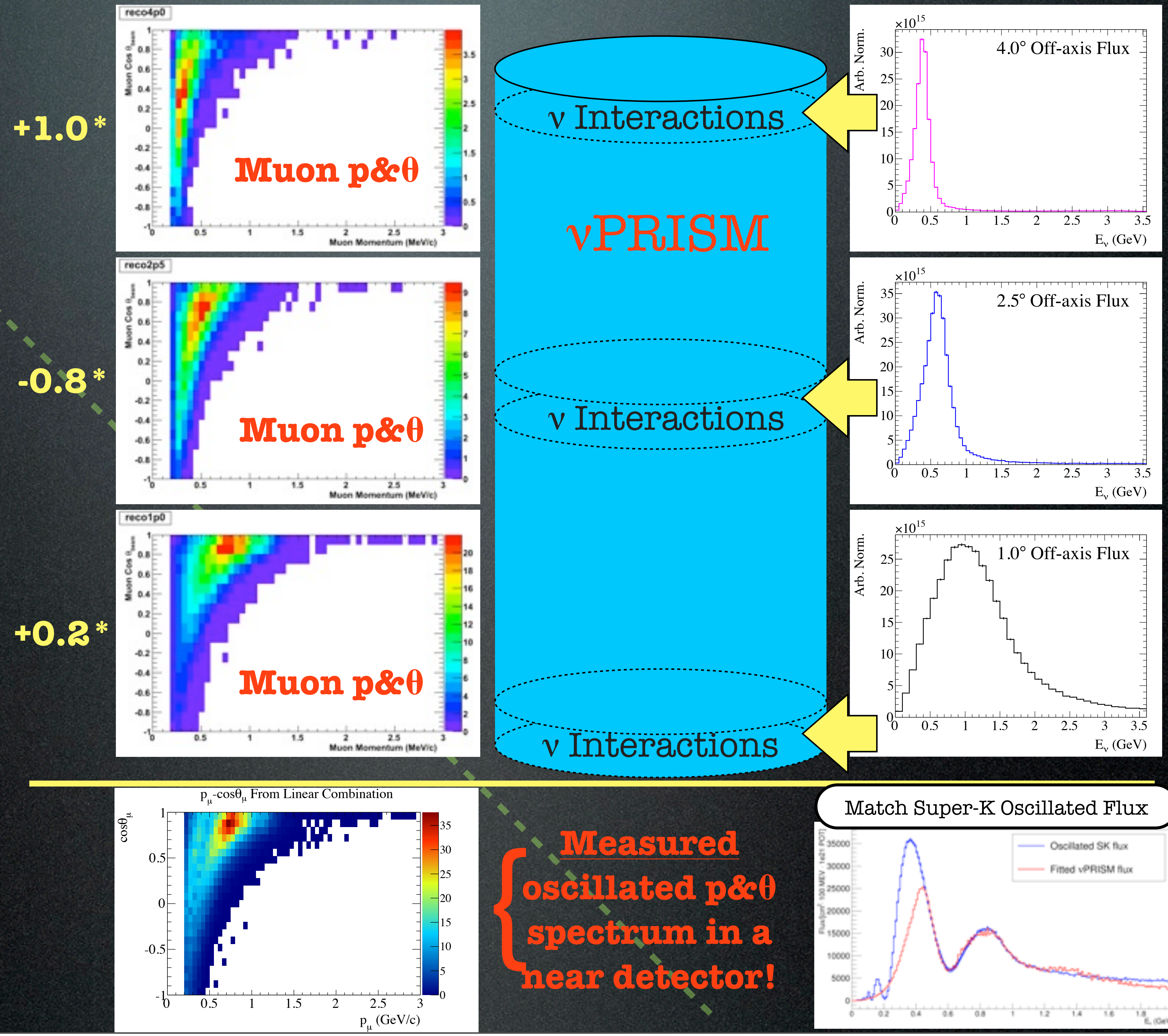


NuPRISM in Oscillation Experiments



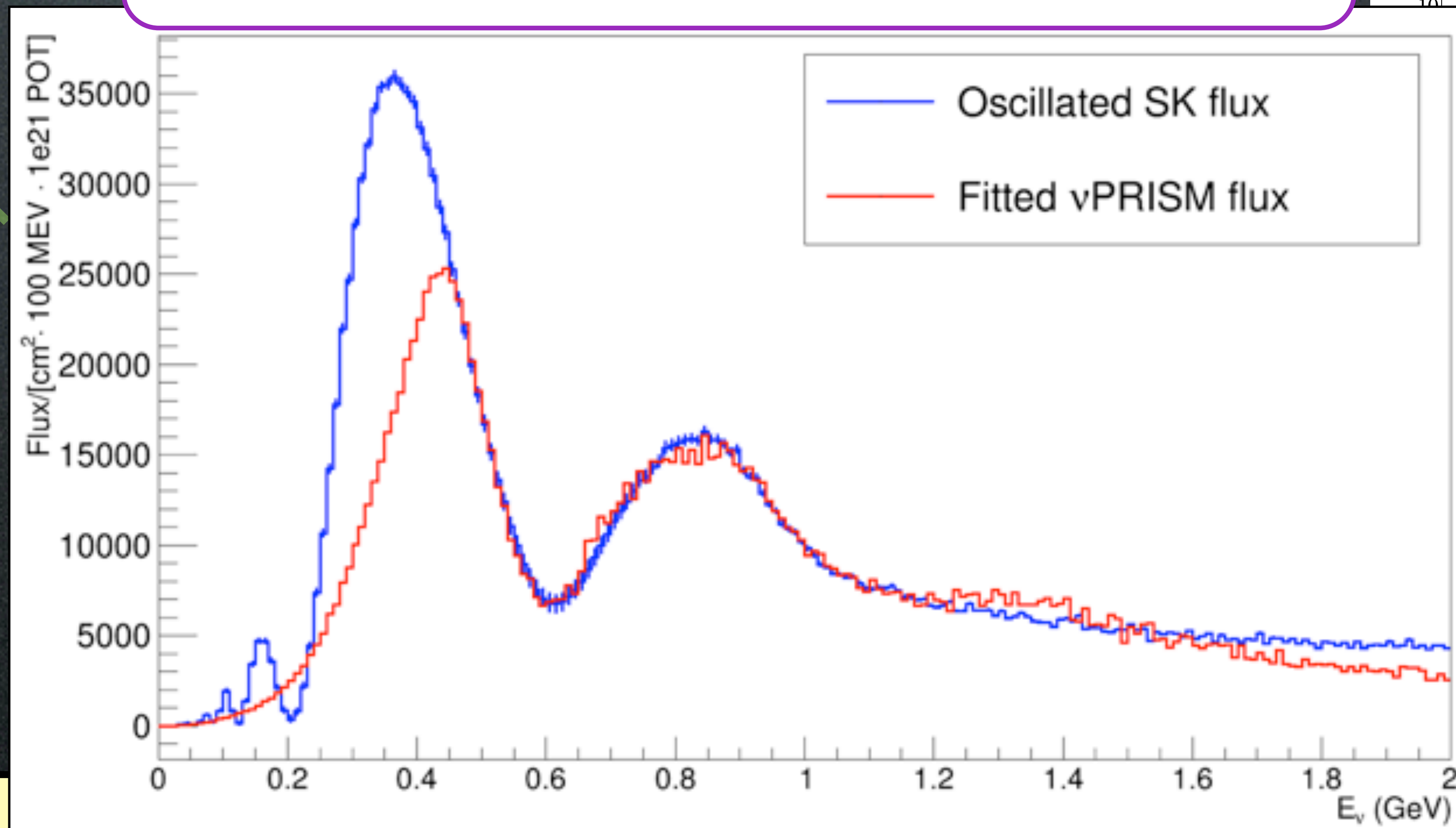
Take different linear combinations!

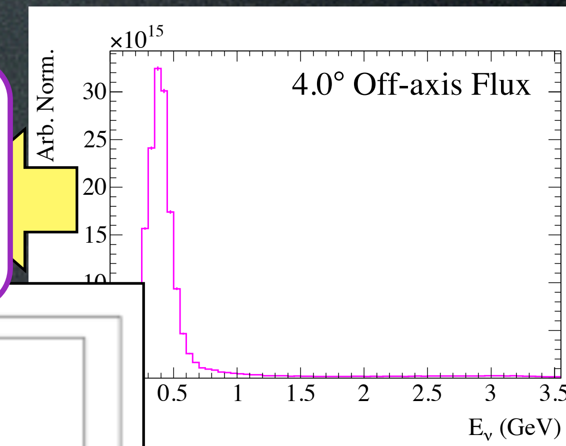
Measured oscillated p&θ spectrum in a near detector!

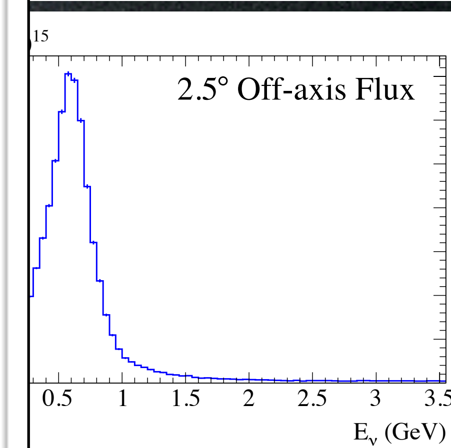
NuPRISM in Oscillation Experiments

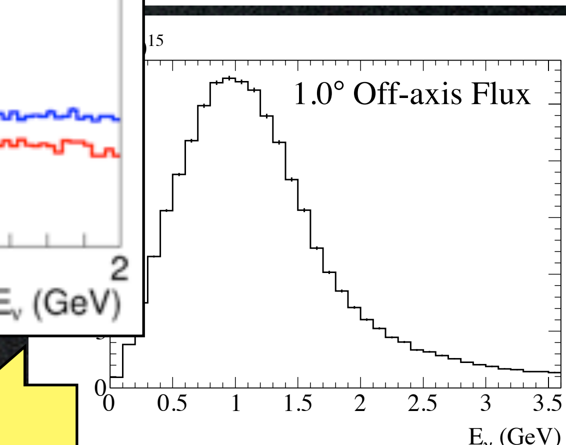
Take different linear combinations!

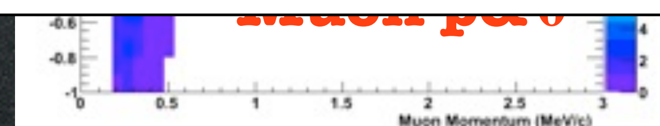
Reproduce Super-K Oscillation Pattern at a Near Detector!









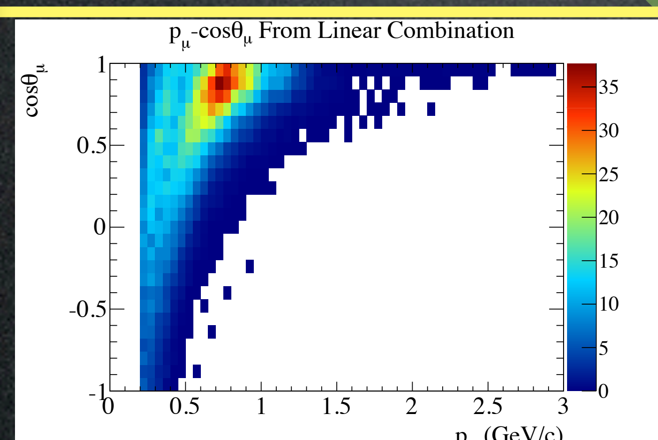


This is the procedure used for the

T2K/nuPRISM

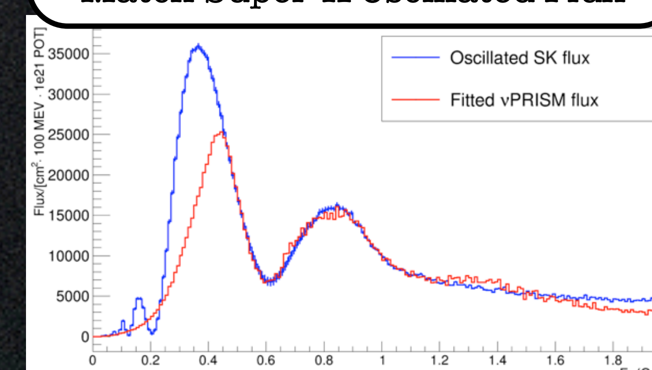
ν_μ disappearance analysis

(next slides)



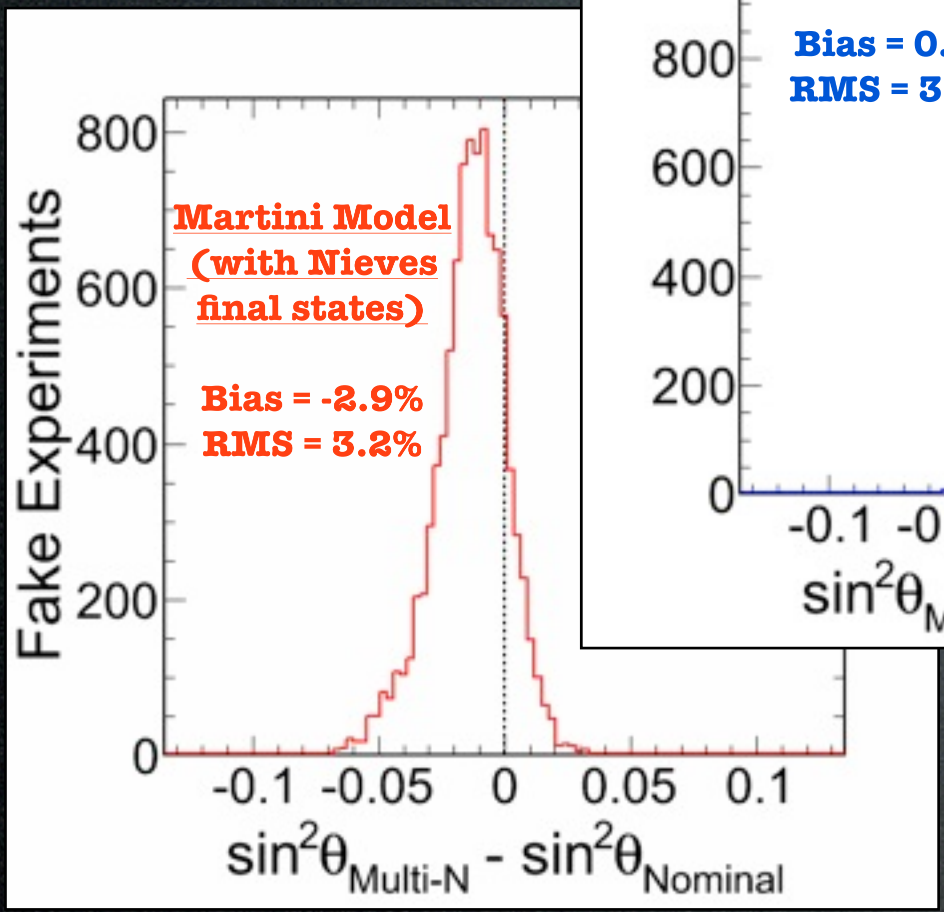
Measured oscillated p&θ spectrum in a near detector!

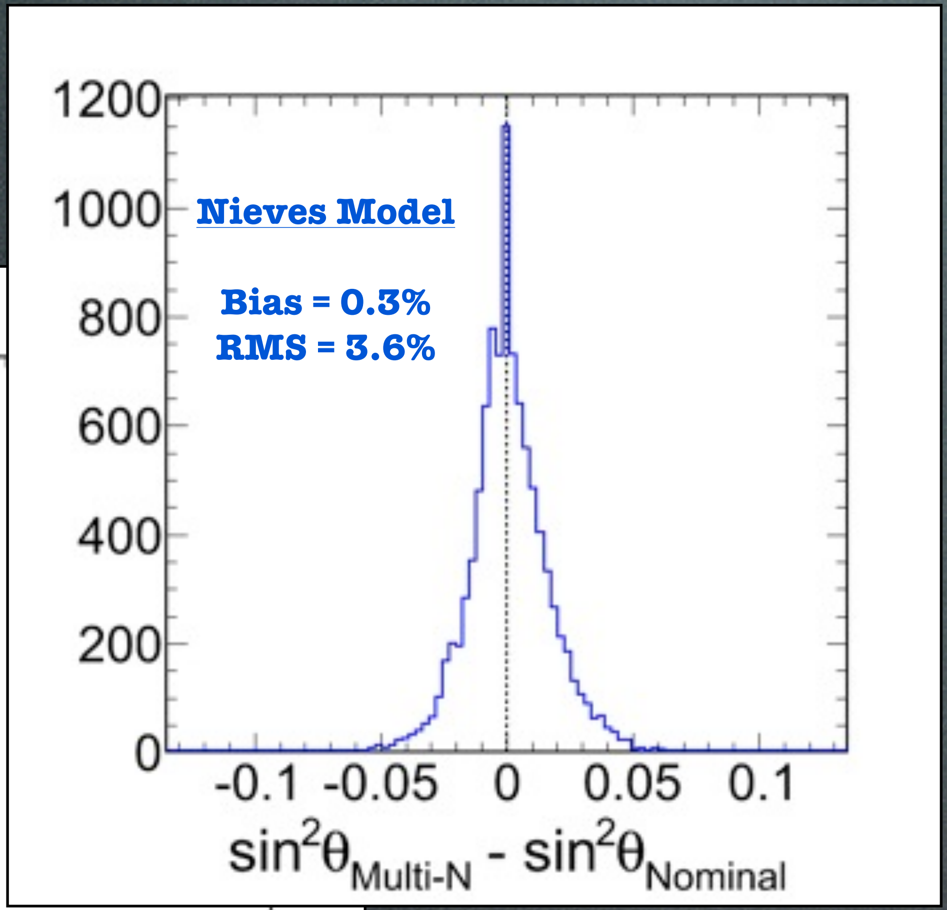
Match Super-K Oscillated Flux



NuPRISM ν_μ Disappearance Constraint

Standard T2K Analysis





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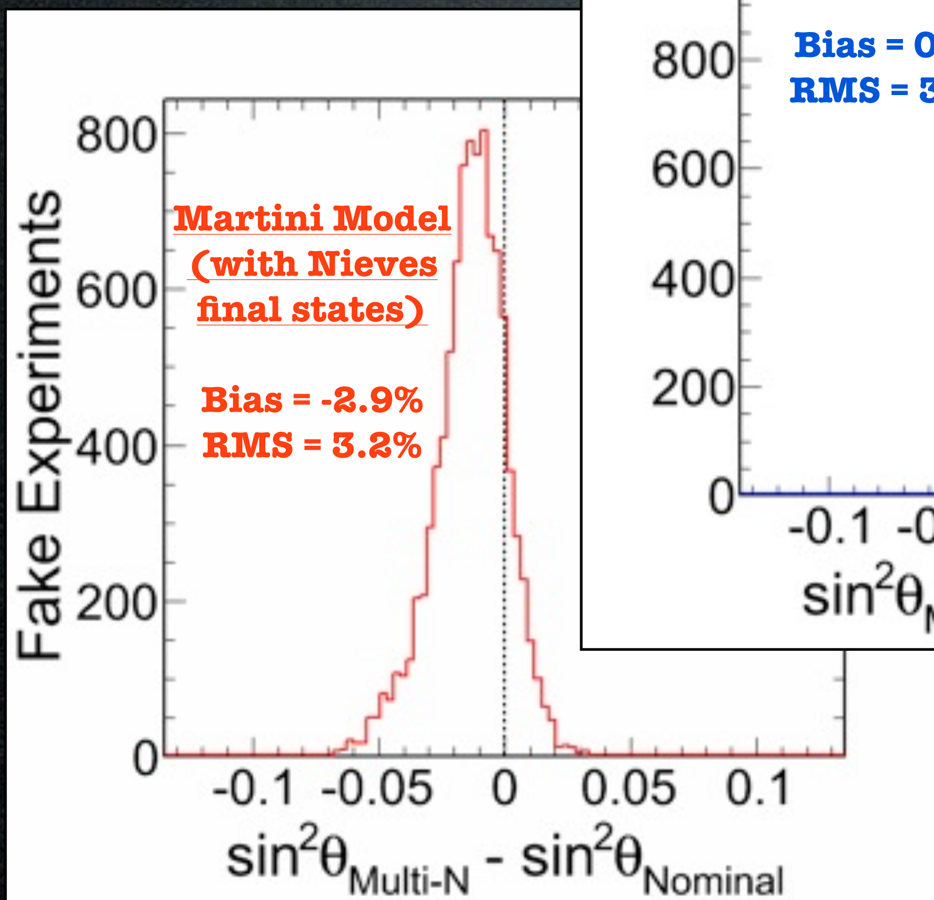

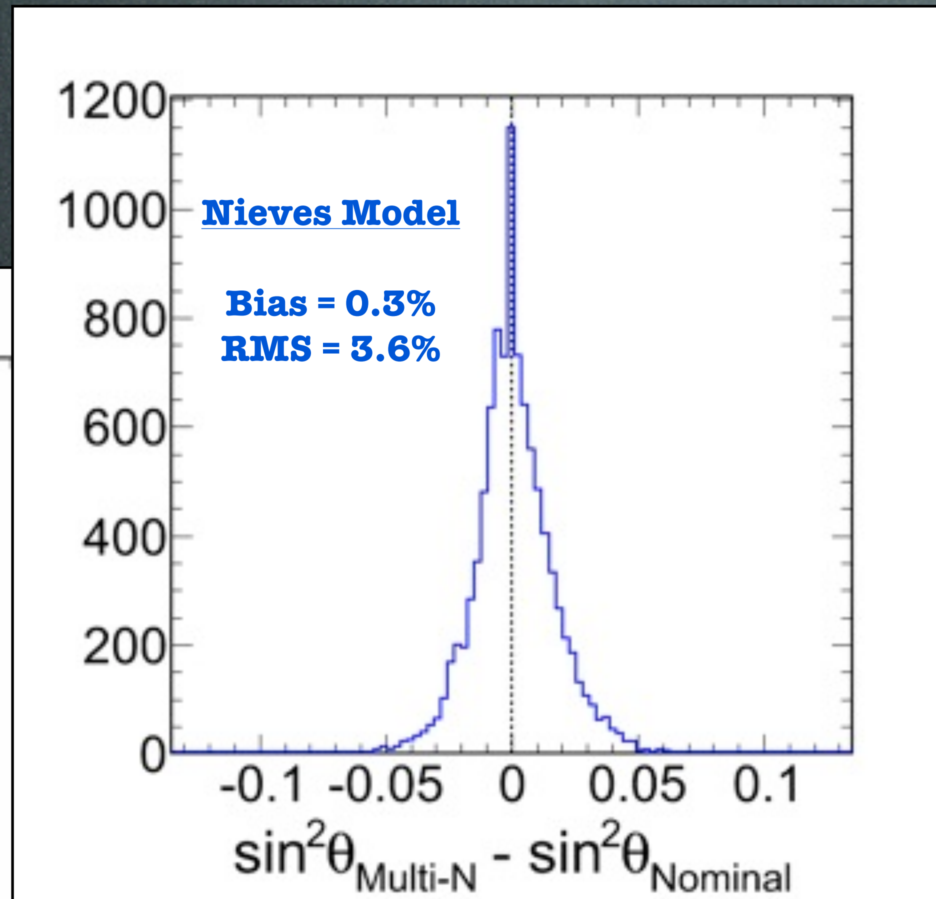

νPRISM Analysis

NuPRISM ν_μ Disappearance Constraint

Standard T2K Analysis

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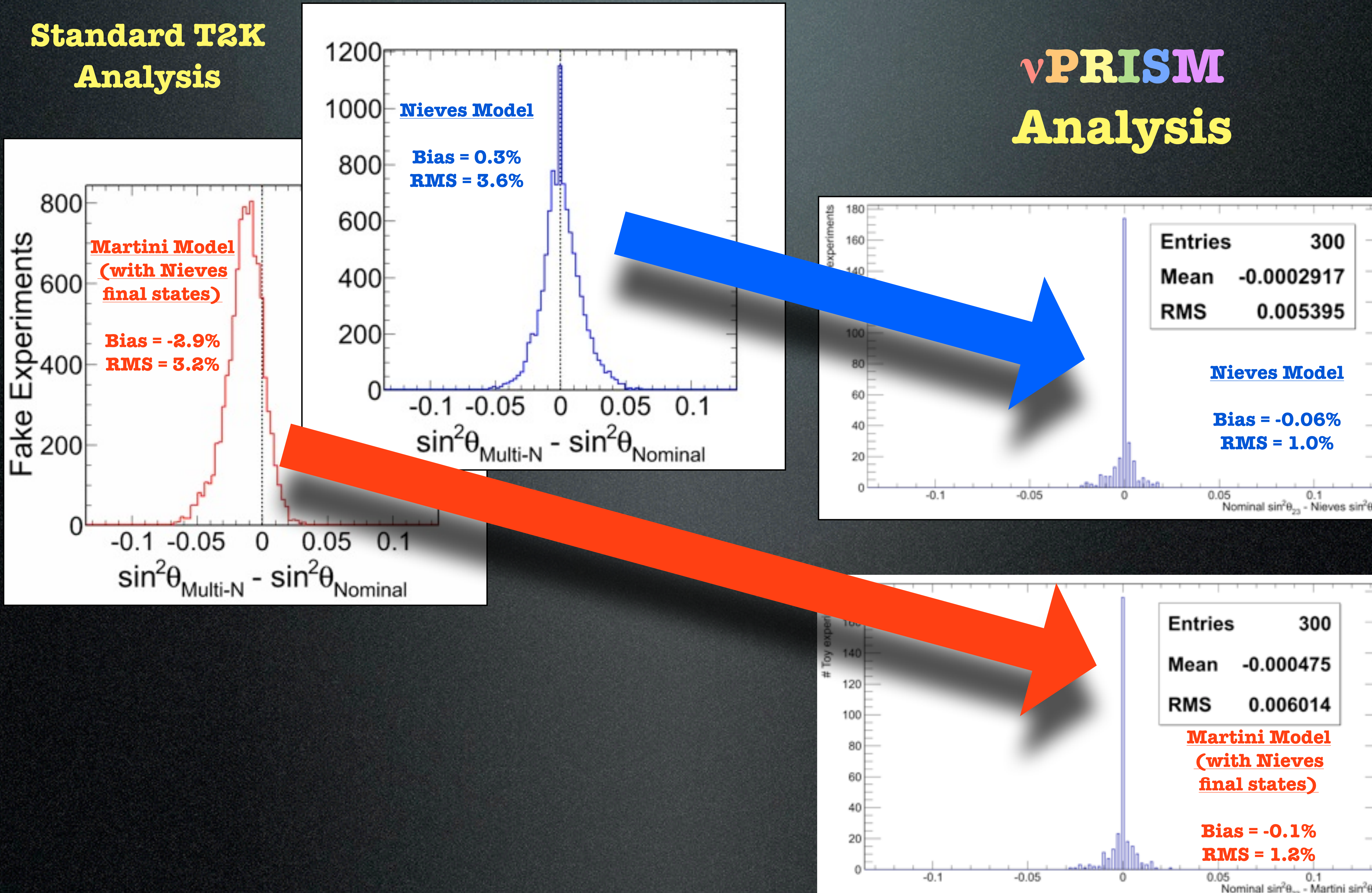

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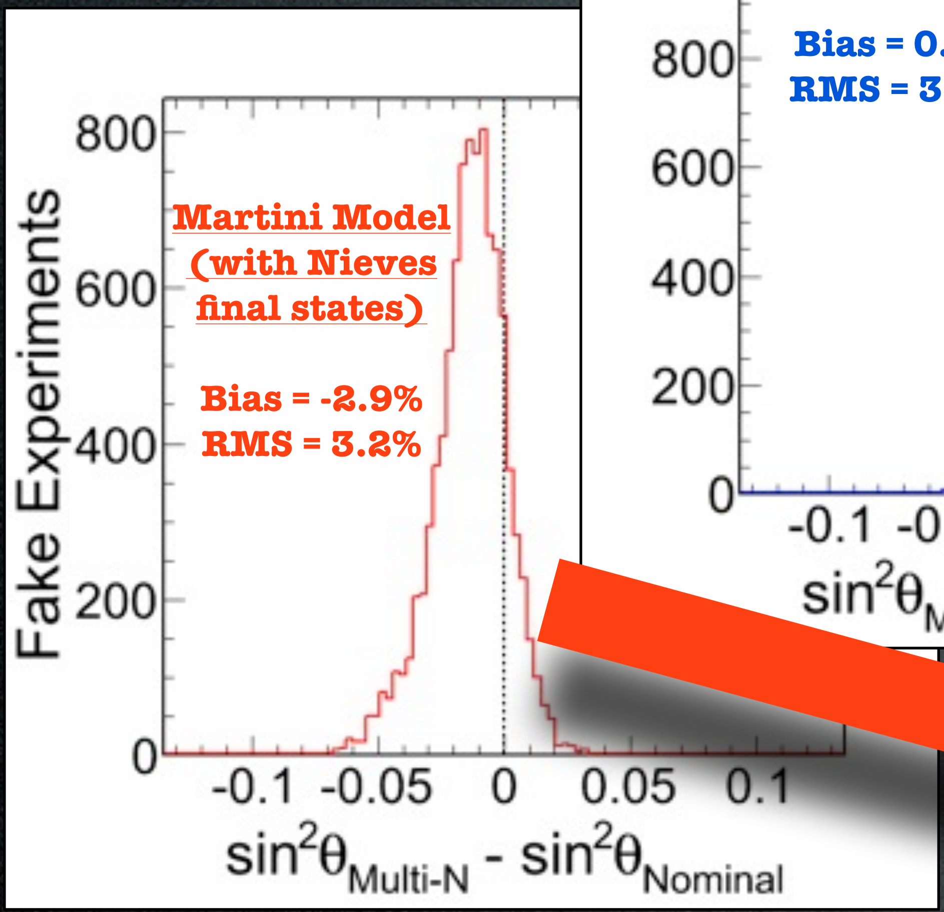

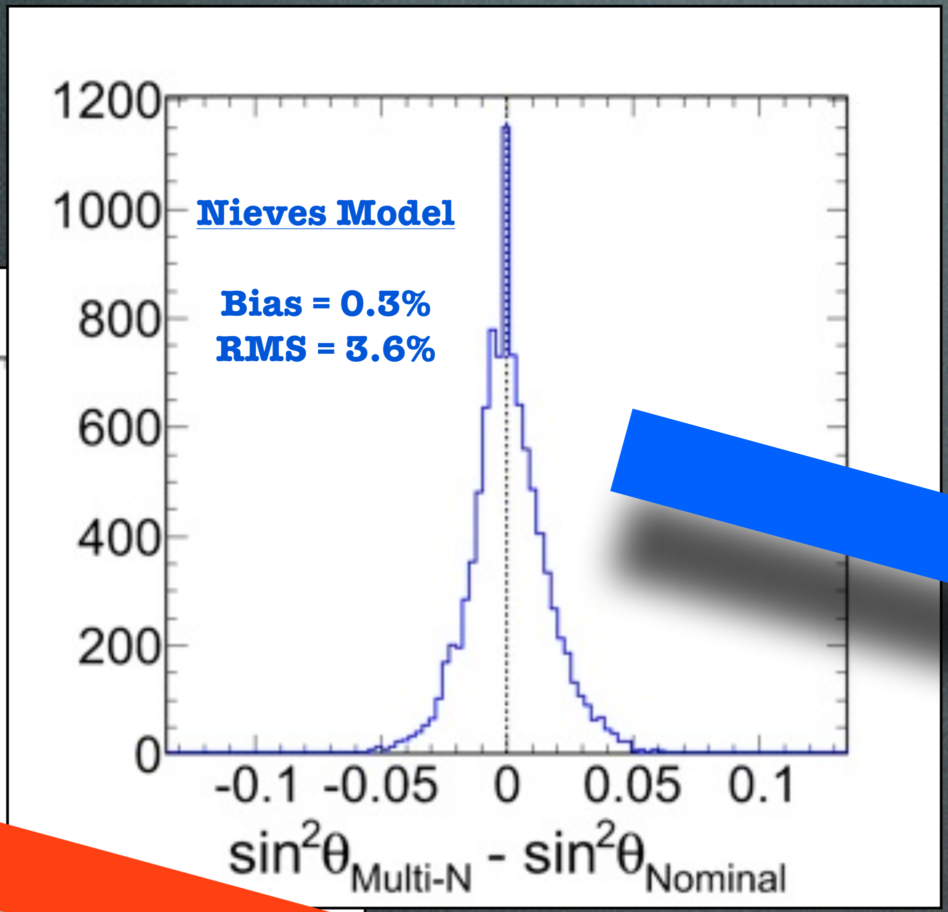

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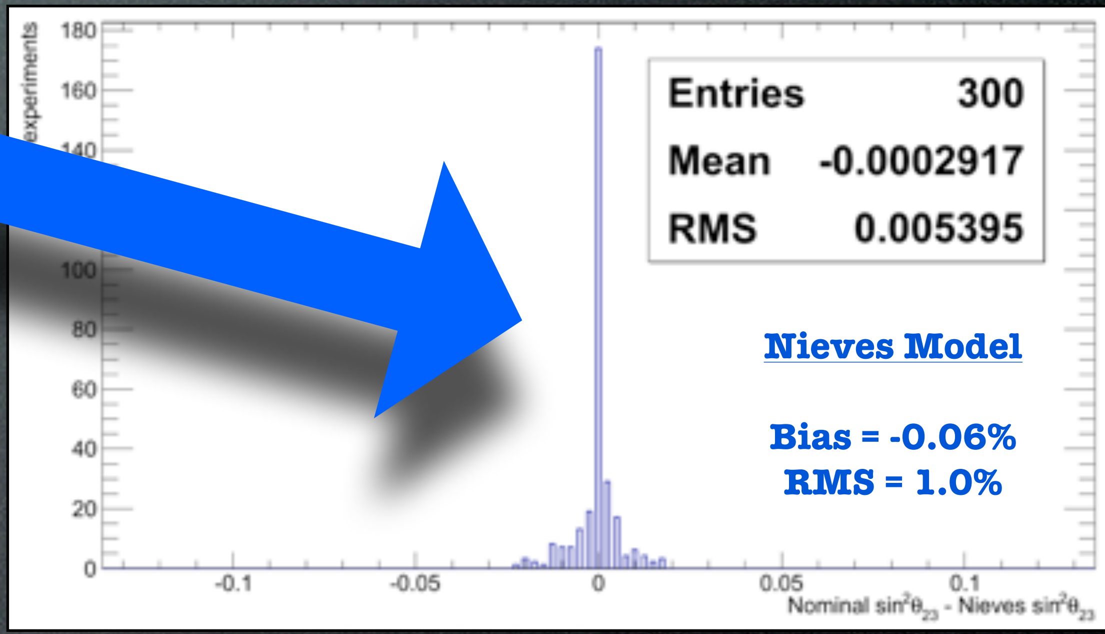

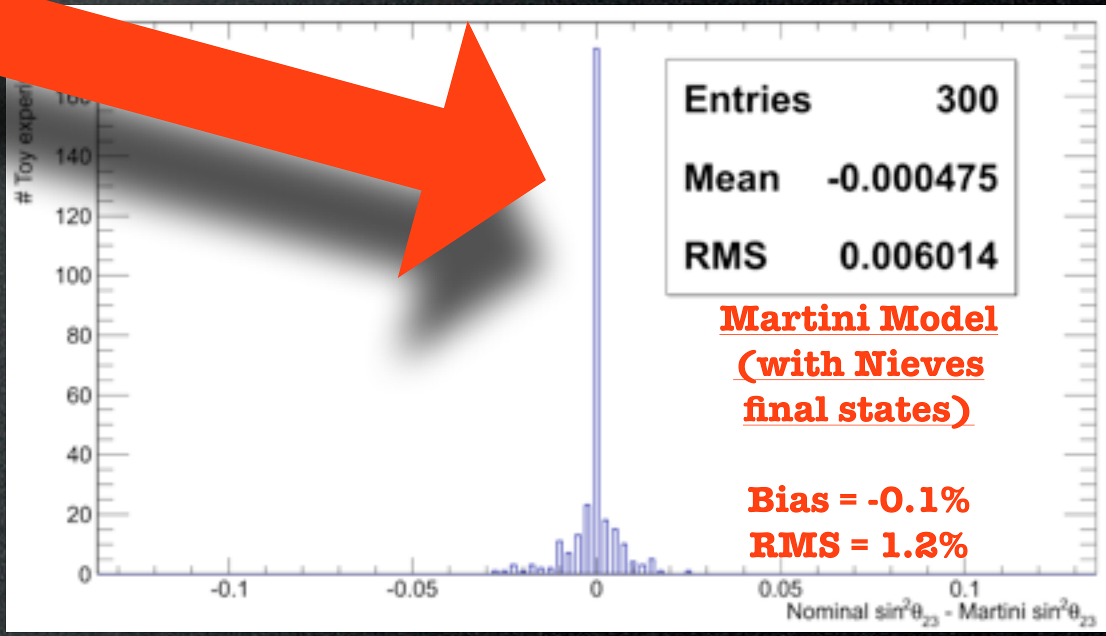

- Fake data studies show the bias in θ_{13} is reduced from **4.3%**/**3.6%** to **1.2%**/**1.0%**

NuPRISM ν_μ Disappearance Constraint

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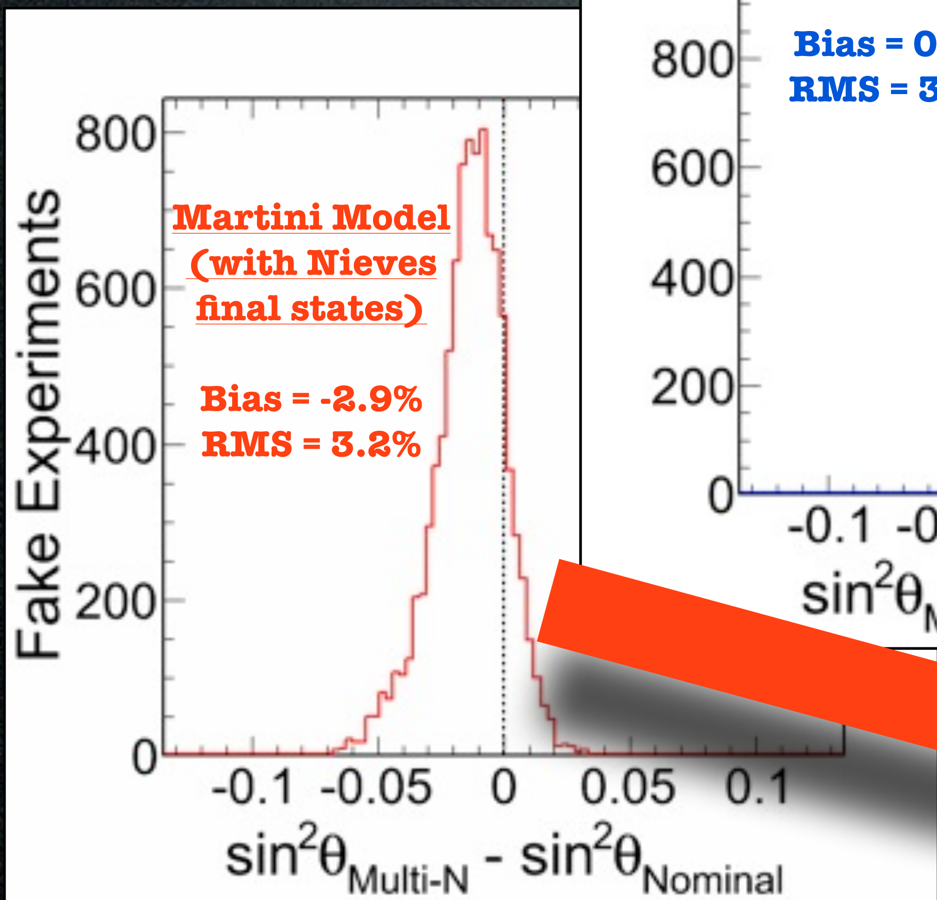

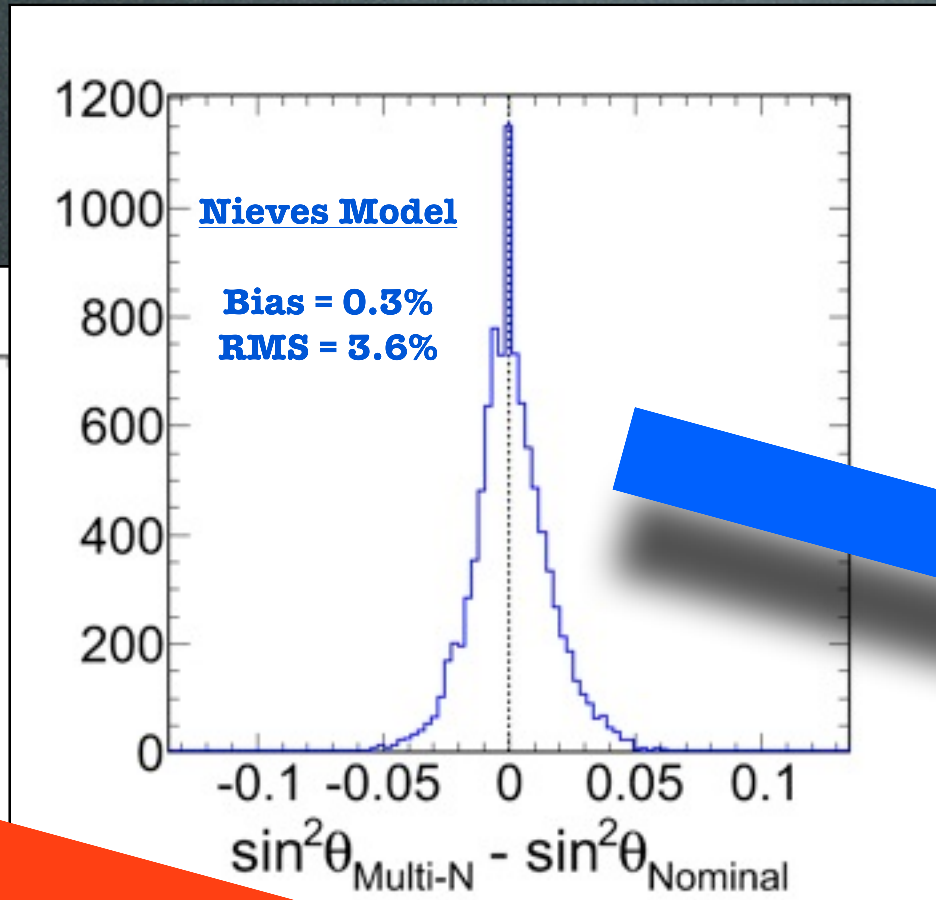

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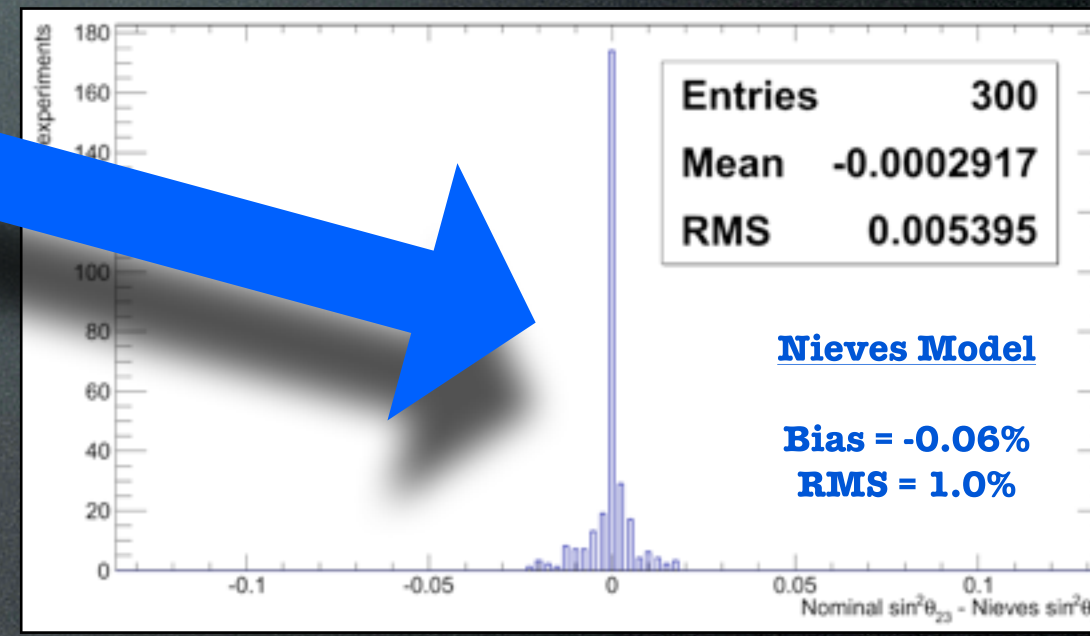
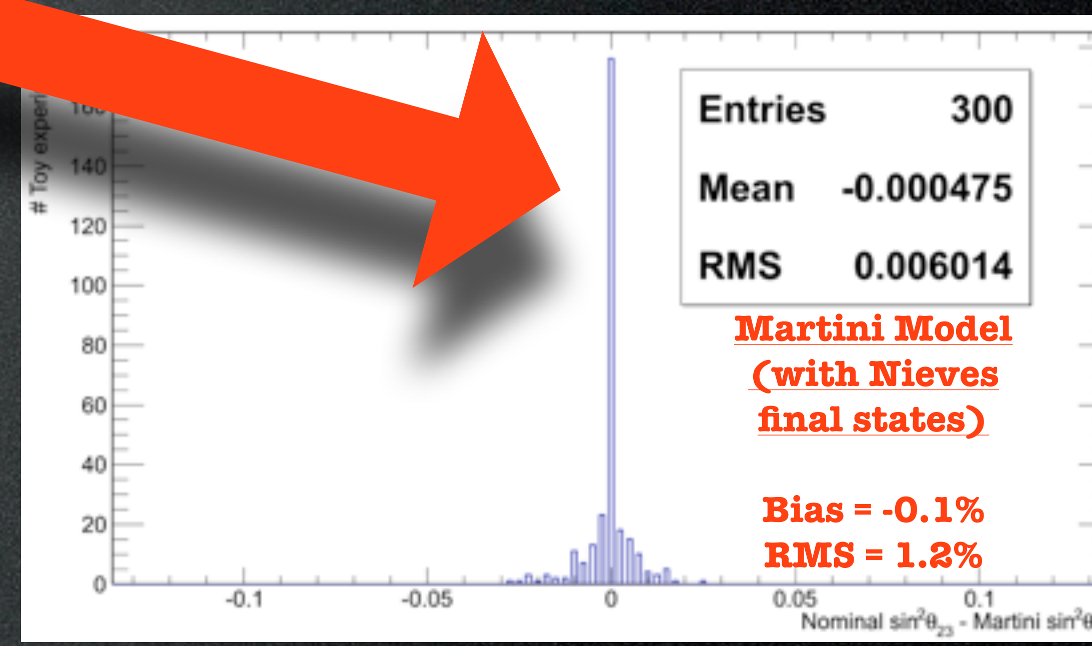
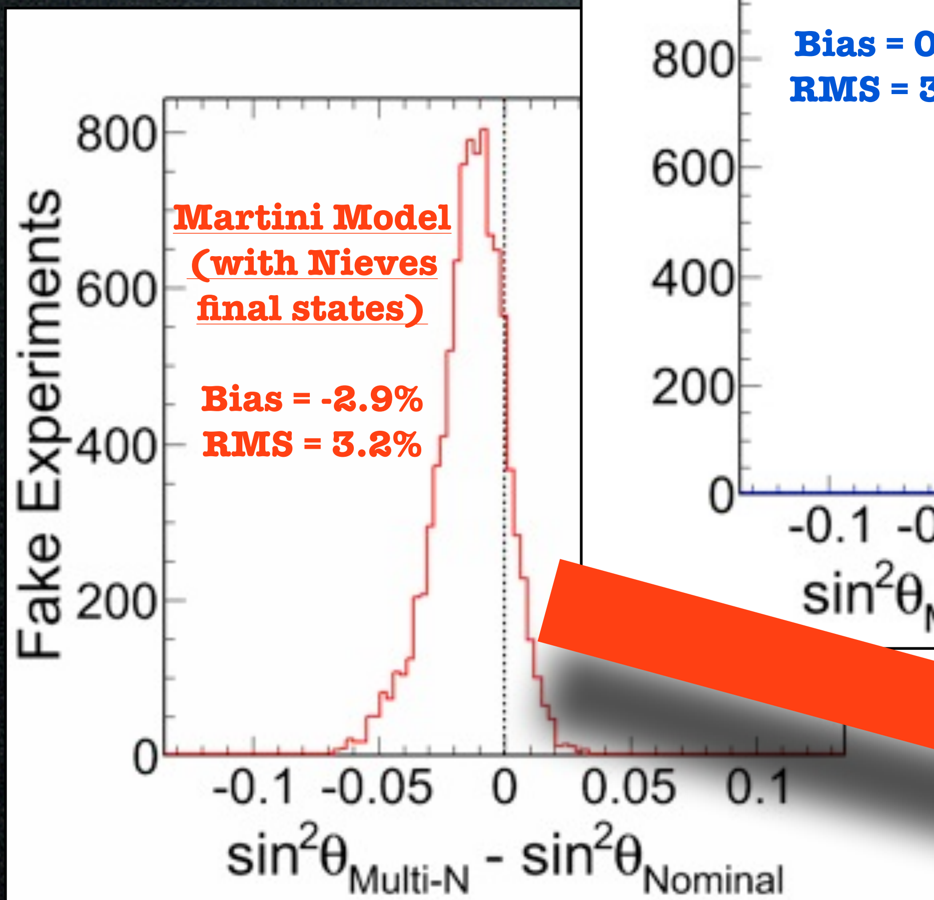


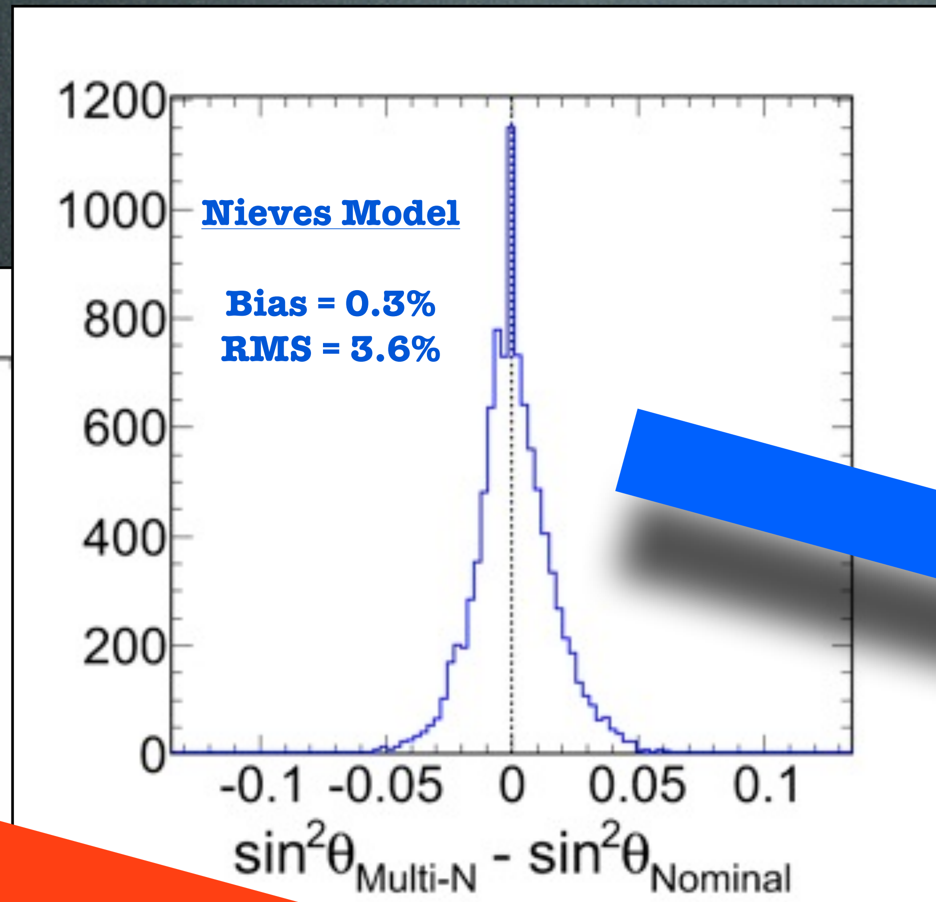


- Fake data studies show the bias in θ_{13} is reduced from **4.3%**/**3.6%** to **1.2%**/**1.0%**
- More importantly, this is now based on a **data constraint**, rather than a model-based guess

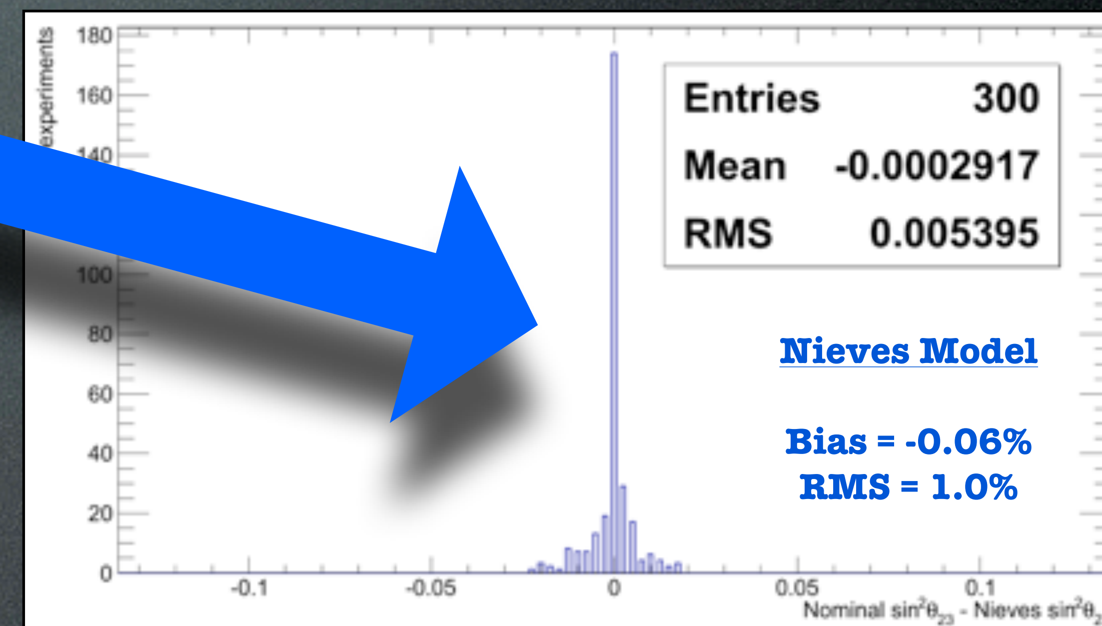
NuPRISM ν_μ Disappearance Constraint

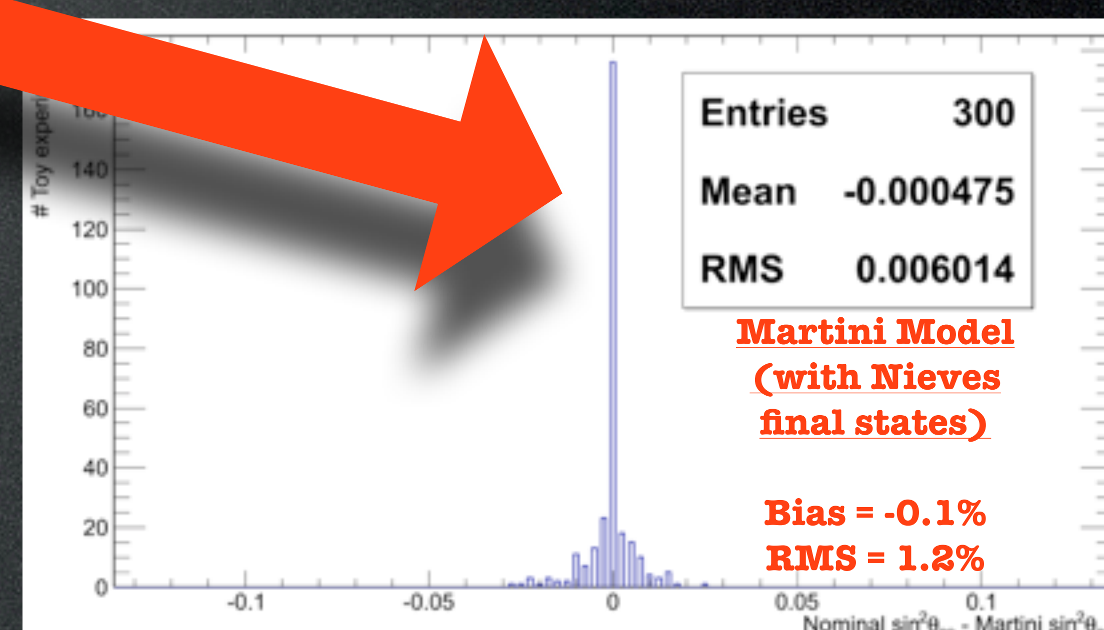
Standard T2K Analysis





νPRISM Analysis



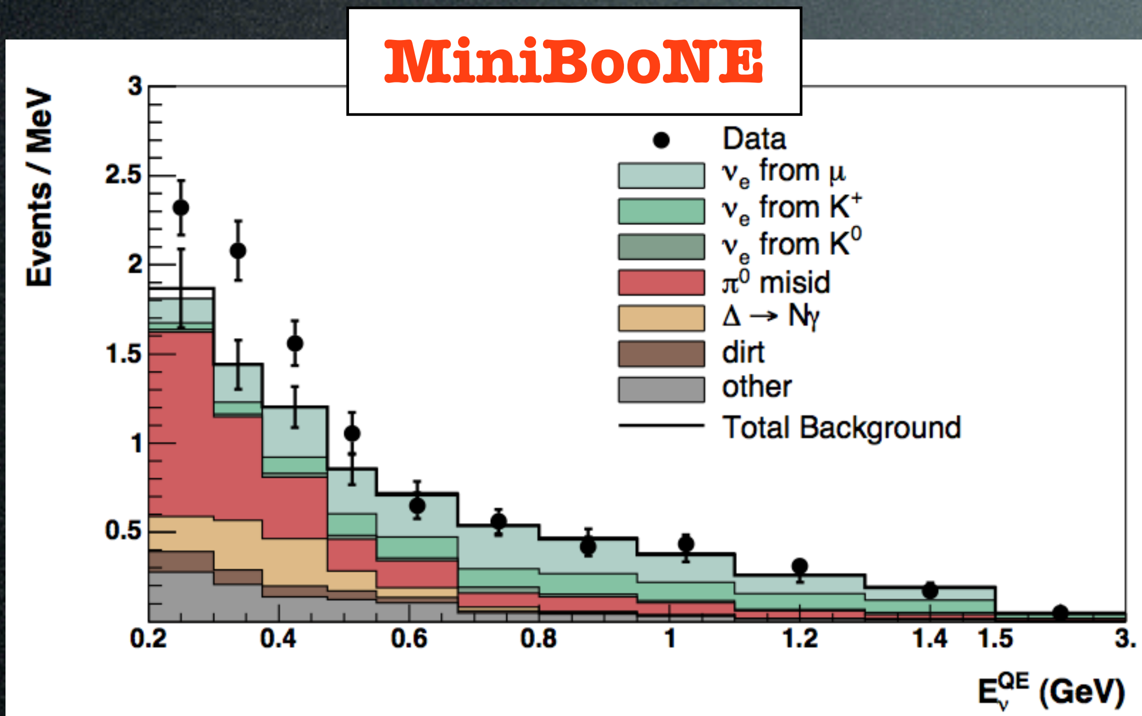


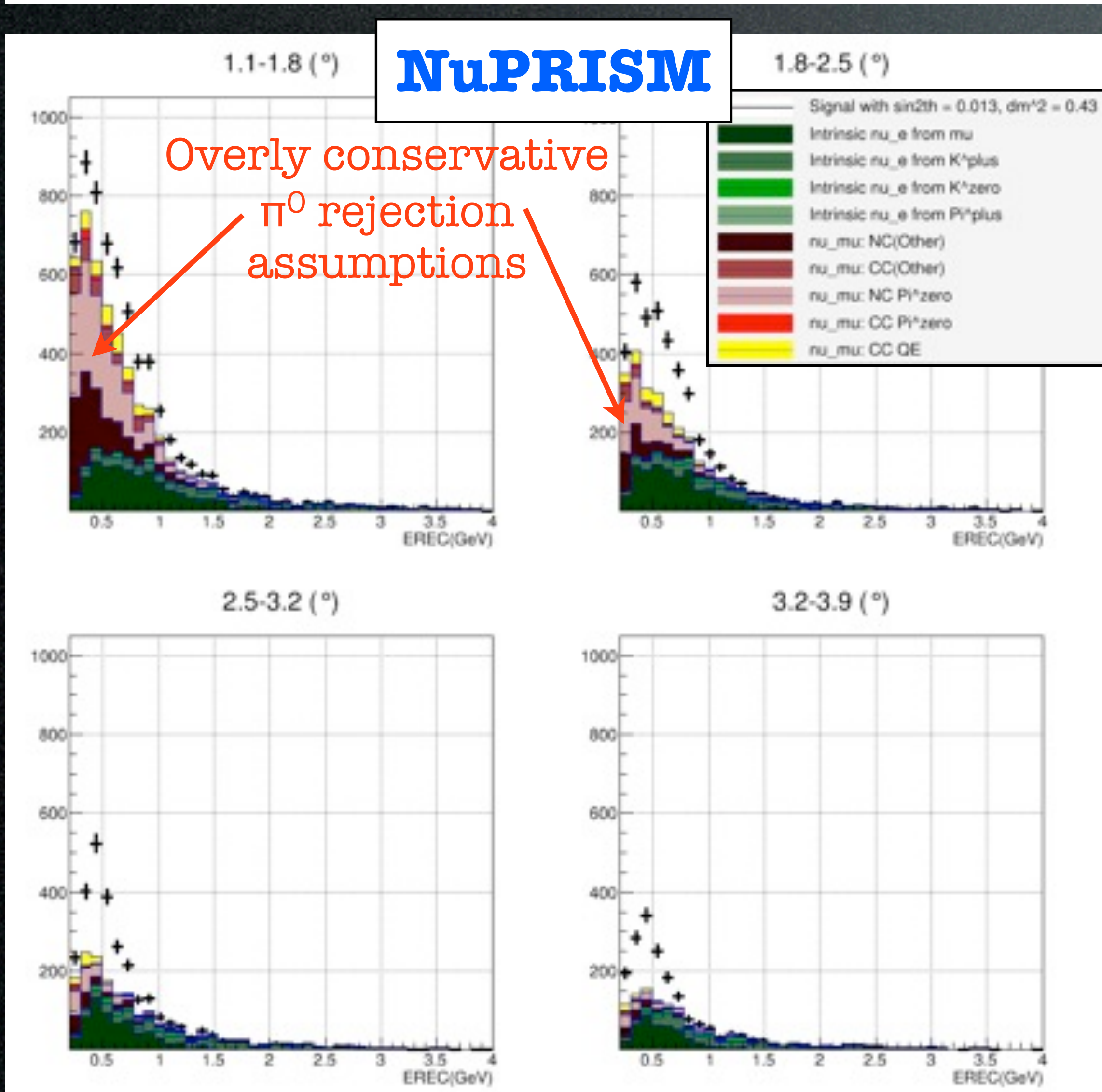
- Fake data studies show the bias in θ_{13} is reduced from **4.3%**/**3.6%** to **1.2%**/**1.0%**
- More importantly, this is now based on a **data constraint**, rather than a model-based guess
- Expect the NuPRISM constraints to get significantly better as additional constraints are implemented (very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

More Physics!

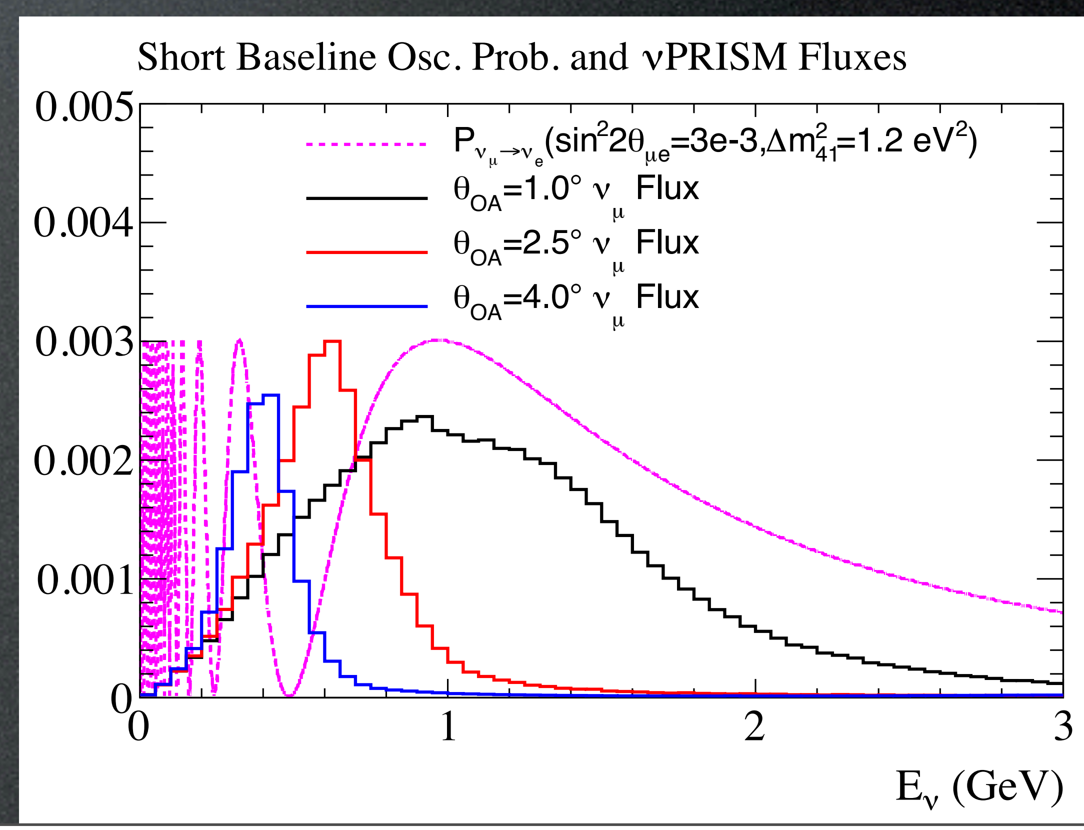
NuPRISM can do more than just improve long-baseline measurements

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)

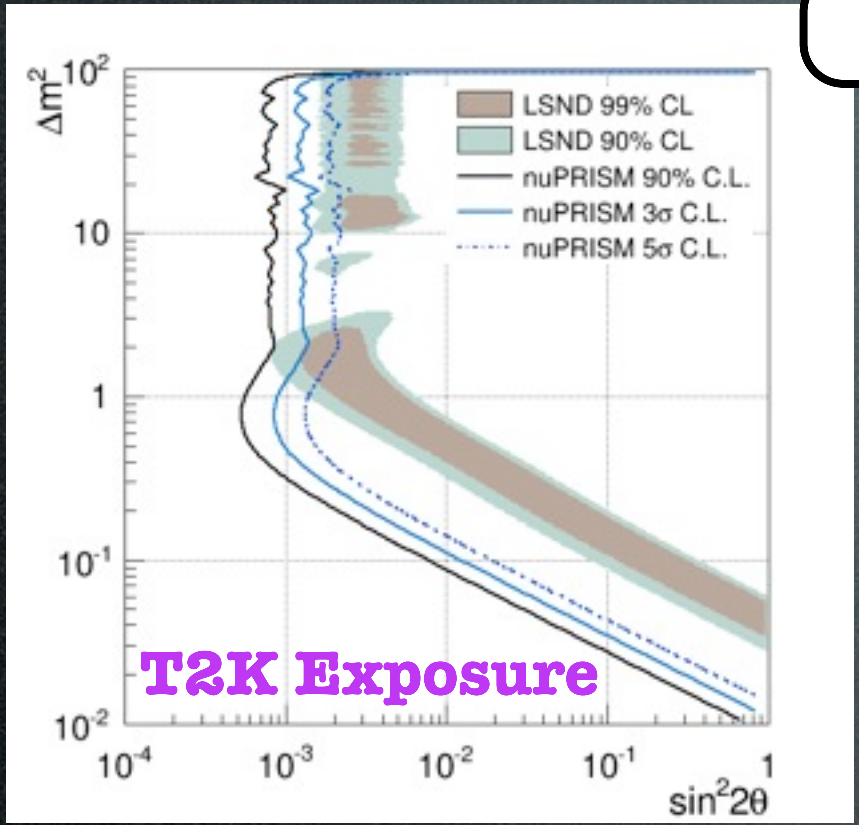


Sterile Neutrino Analysis

- 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 running (T2K2 and/or Hyper-K) will improve the sensitivity

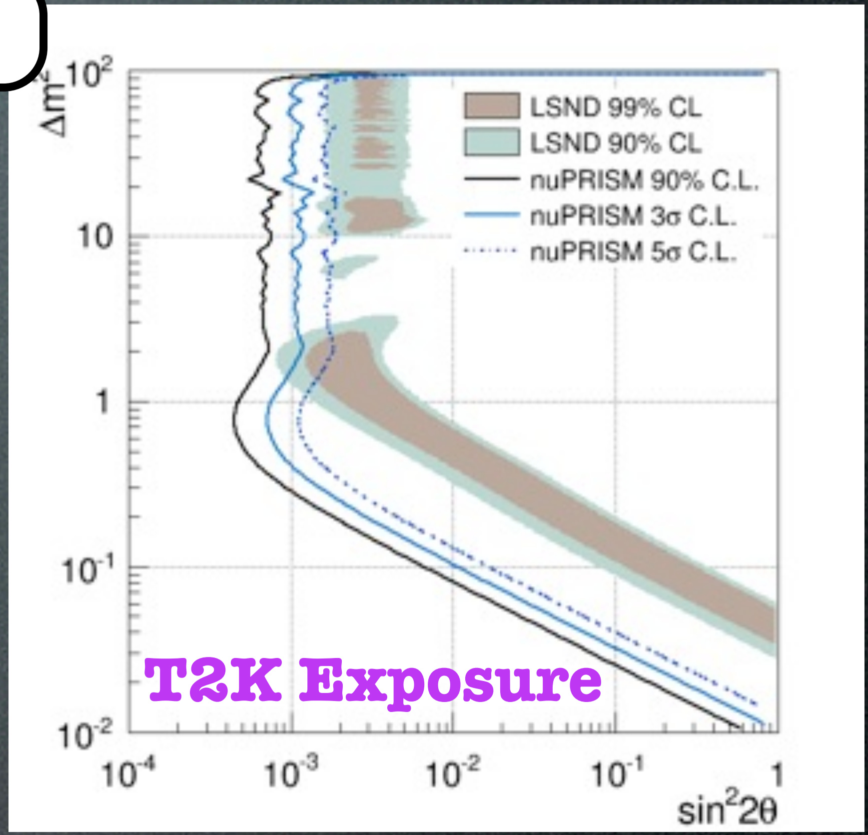
Current Sterile-ν Sensitivities

NuPRISM

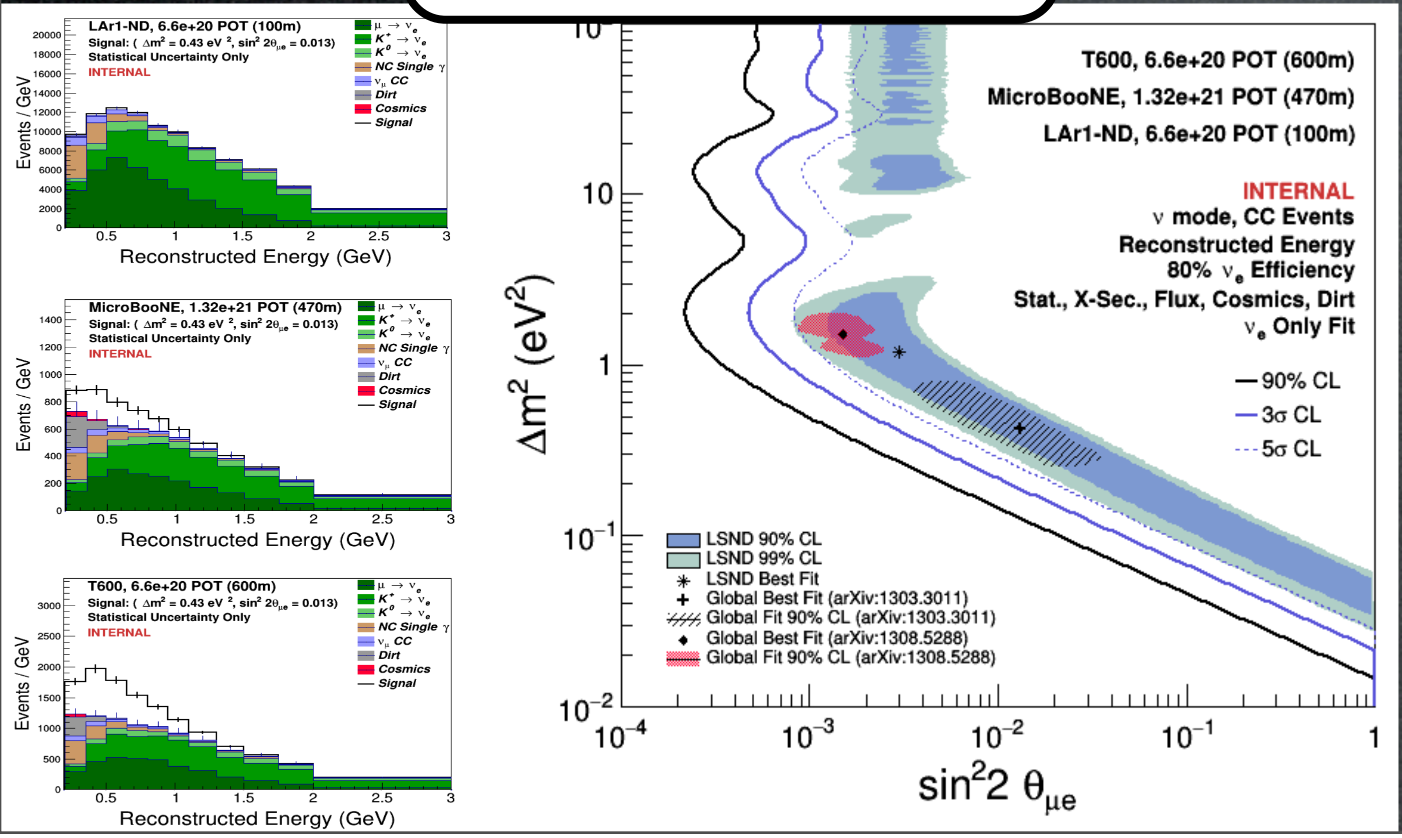


30% reduction in π^0 background or π^0 uncertainty

Should be easily achievable



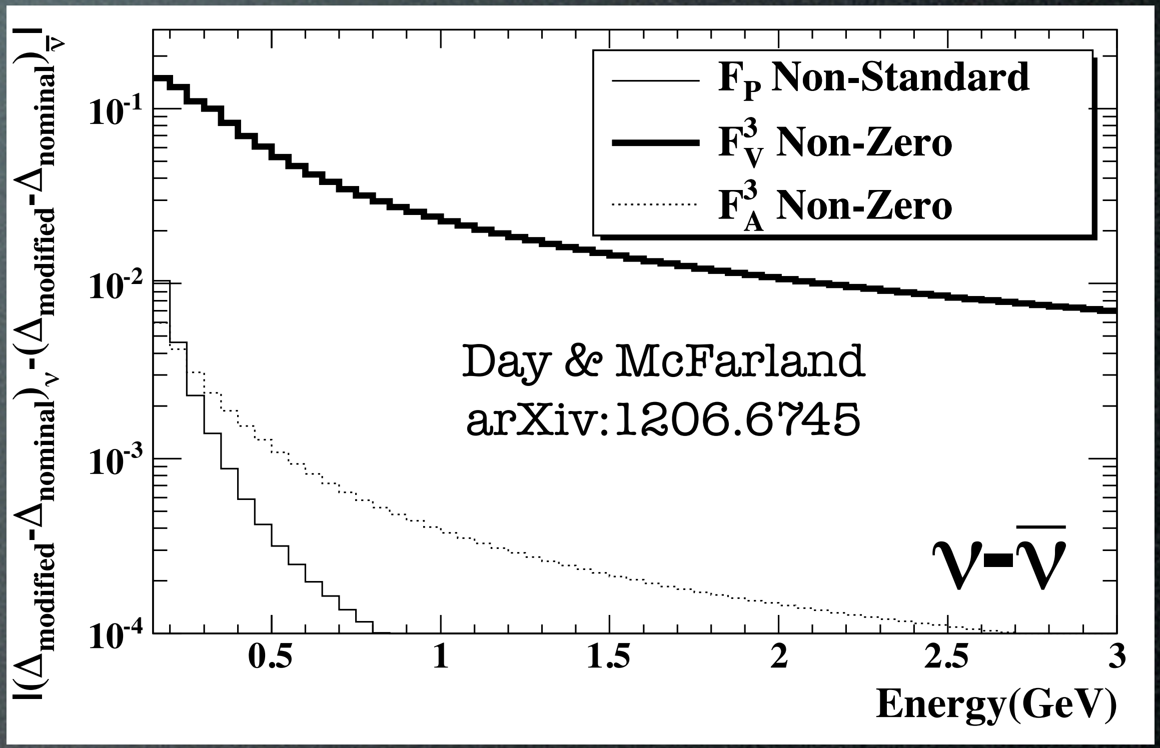
Fermilab SBN



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

Constraining δ_{CP}

- The **strong constraints on ν_μ** interactions provided by NuPRISM will provide a lot of information about nuclear effects in ν_e interactions
- However, there may still be some differences between ν_e and ν_μ cross sections (e.g. 2nd class currents?)
- How do we constrain ν_e events?
  - Intrinsic ν_e in beam
    - Requires a large detector with the same nucleus and acceptance as the far detector
    - **NuPRISM**!
  - Otherwise, we may have to build **NuSTORM**



Need to measure:

$\sigma(\nu_\mu)/\sigma(\bar{\nu}_\mu)$

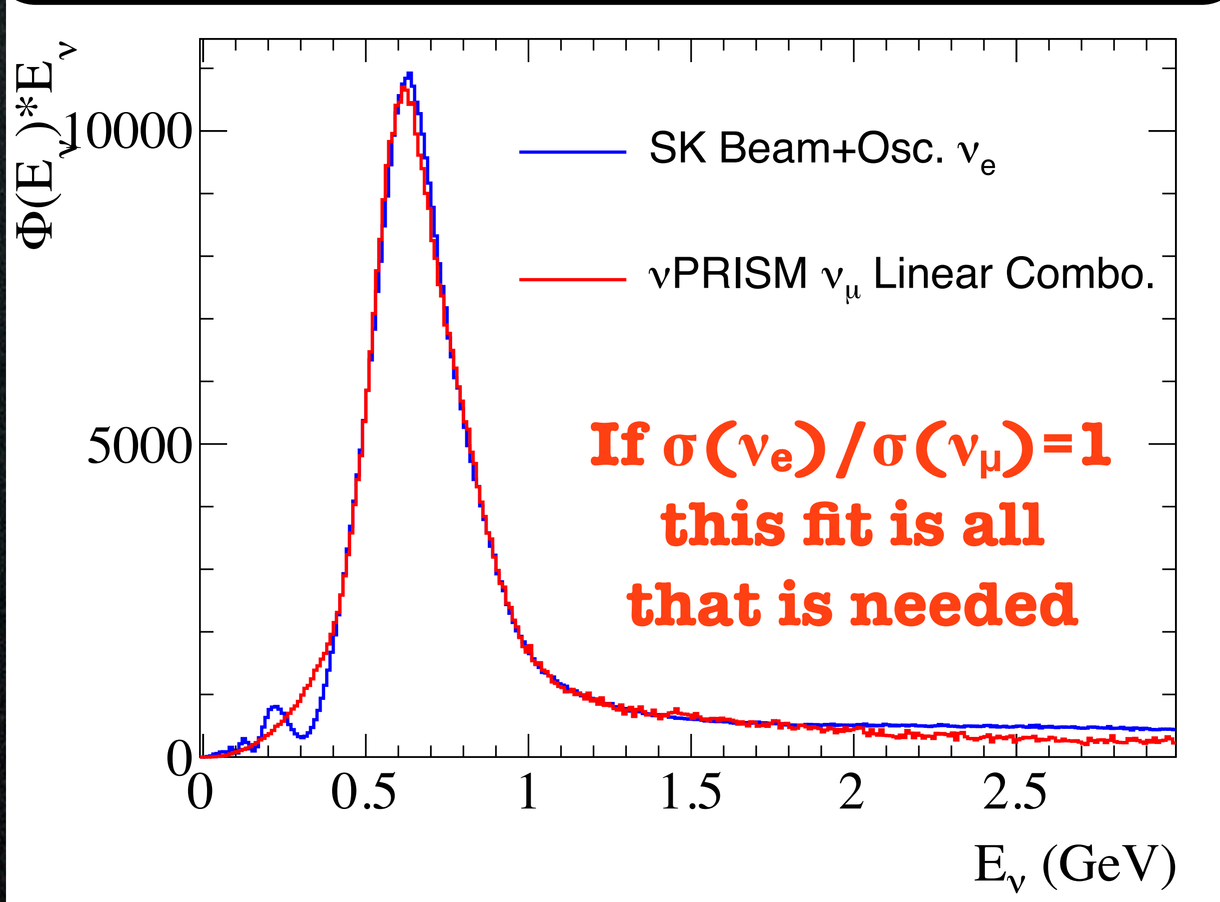
$\sigma(\nu_e)/\sigma(\nu_\mu)$

$\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$

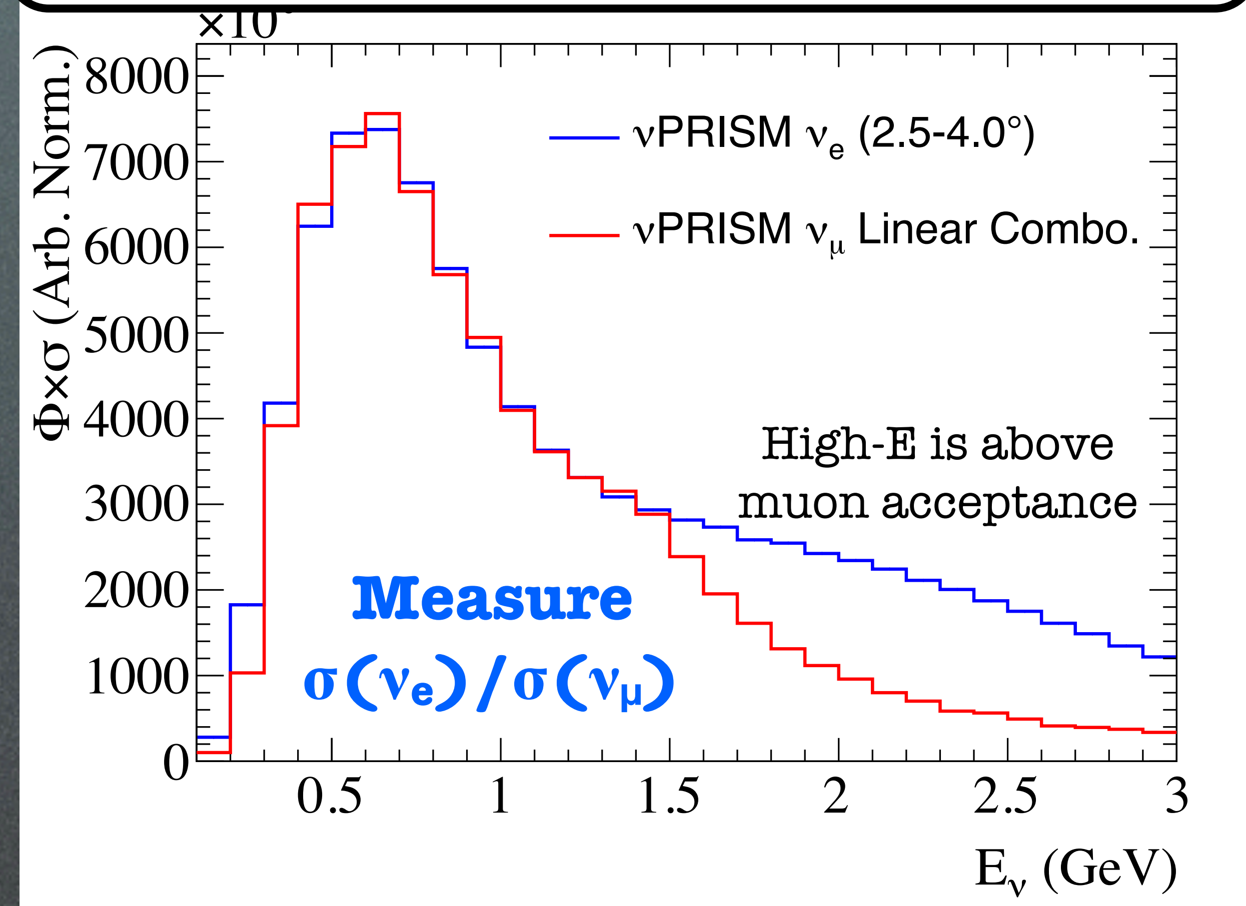
NuPRISM ν_e Appearance (CPV)

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 (º)	νe Flux 0.3-0.9 GeV	νμ Flux 0.3-5.0 GeV	Ratio νe/νμ
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%

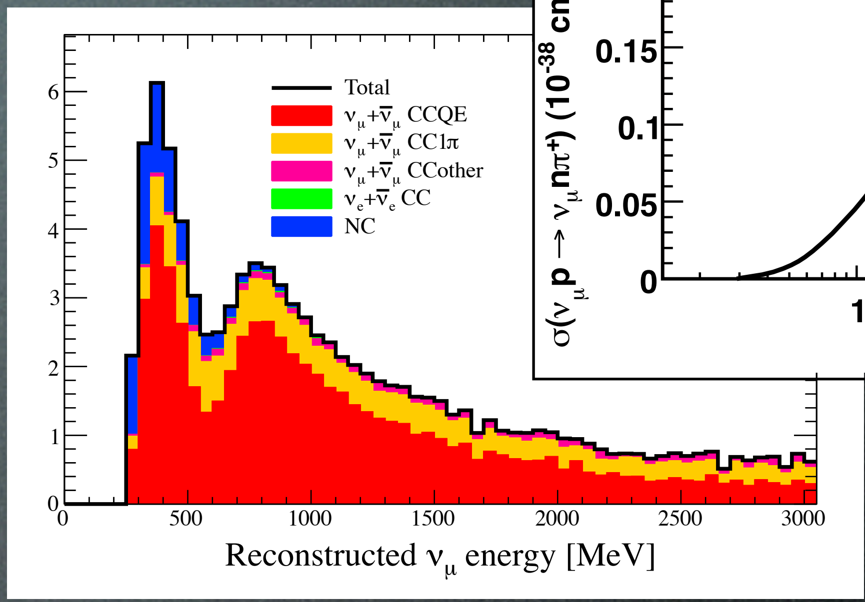
ν_e Cross Section Precision

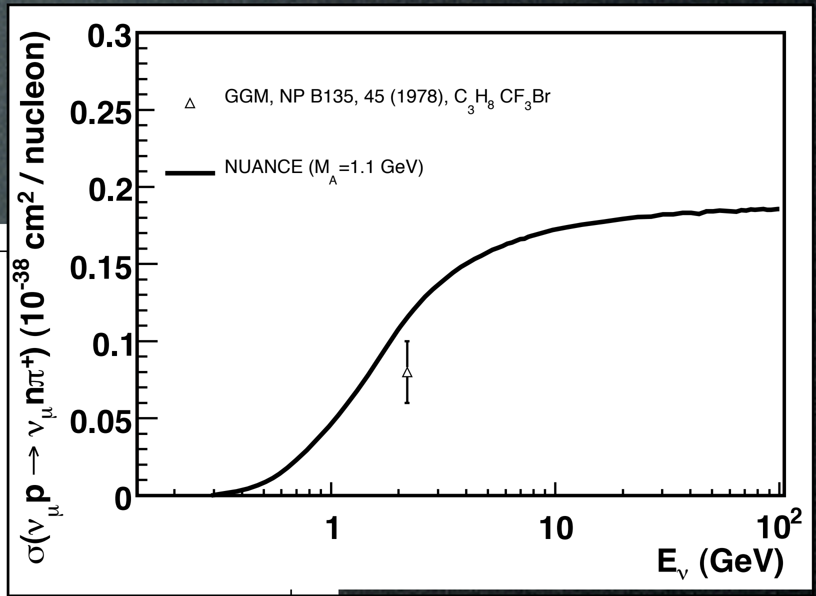
- For 10^{22} POT, expect **9340 ν_e single-e** (i.e. CCQE-like) interactions
    - 2.5° - 4.0° range
    - $0.3 < E_\nu < 0.9$ MeV
    - 2 m fiducial volume
- Assuming Super-K efficiency, this would provide a **1.3% statistical error** on **$N_{\nu e}/N_{\nu\mu}$**
    - Backgrounds will dilute the 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**
    - In addition, 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

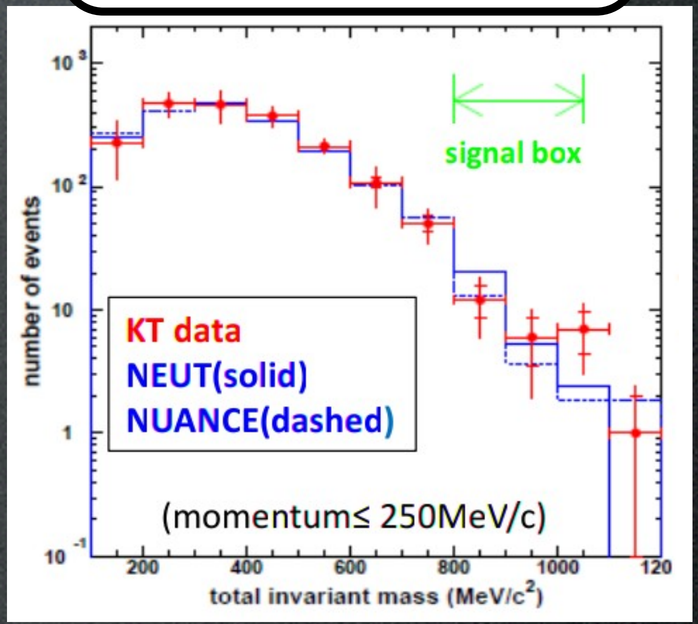
- T2K ν_μ disappearance is subject to large $NC\pi^+$ uncertainties
  - 1 existing measurement
  - νPRISM can place a strong constraint on this process vs E_ν
- NuPRISM is an ideal setup to measure proton decay backgrounds
  - Repeat $p \rightarrow e^+\pi^0$ background measurement from K2K 1 kton detector
  - 50% of the $p \rightarrow K^+\nu$ 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

$NC\pi^+$ at T2K



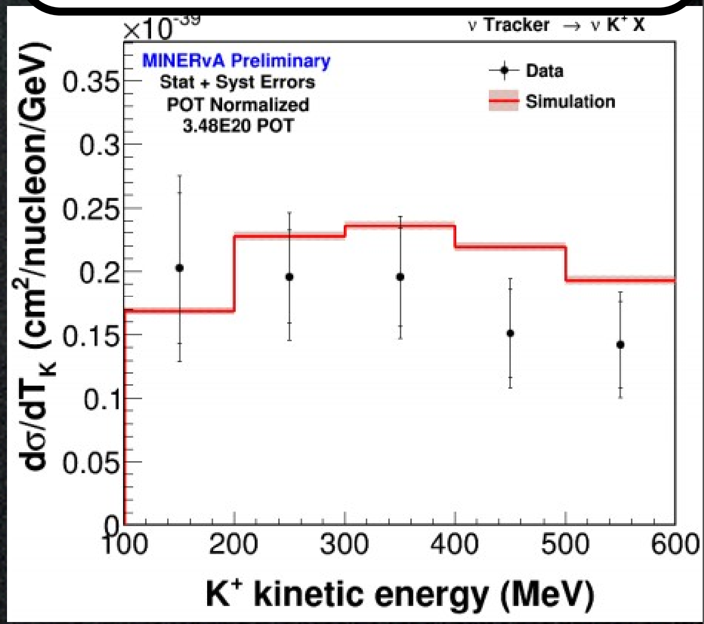


K2K $e^+\pi^0$ Bkgd Measurement



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

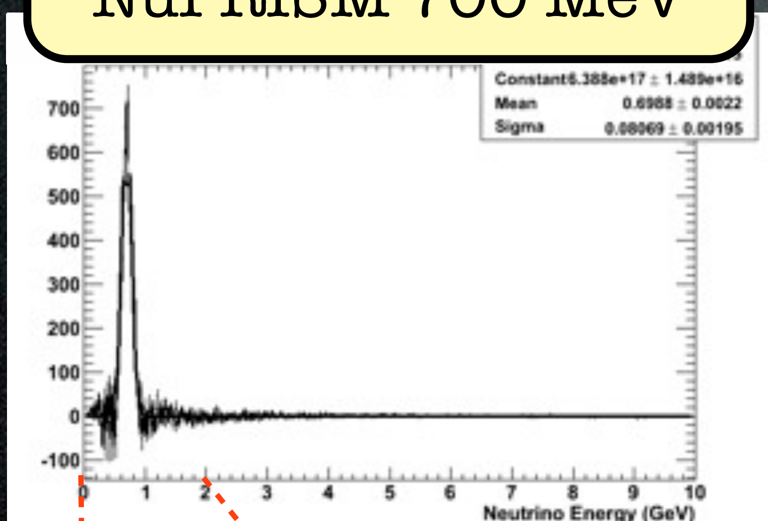
MINERvA K^+ Prod. Measurement



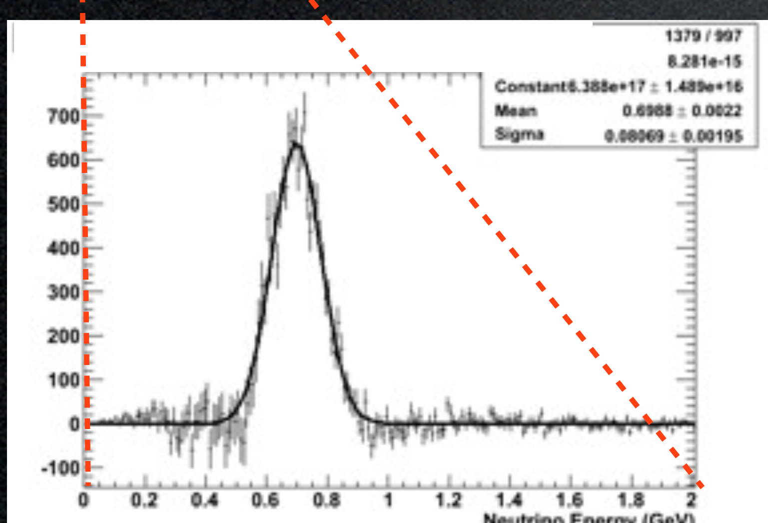
DUNE-PRISM

- NuPRISM technique also works for DUNE (or NuSTORM)
  - Main drawback: on-axis flux limits high-E_ν reach
  - Can only make mono-energetic beams up to the first osc. max (~2.5 GeV)
    - However, 2nd oscillation maximum can be very well constrained

NuPRISM 700 MeV



zoom

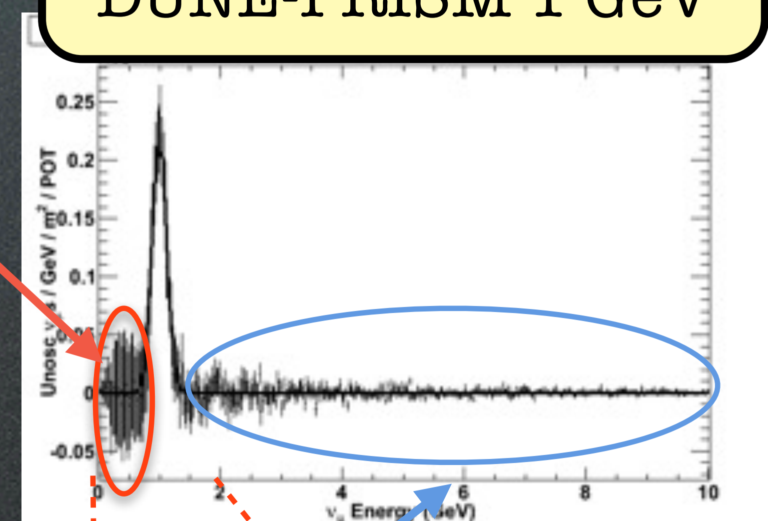


(Larger errors at low E are due to more off-axis slices & no flux-weight smoothing)

Easy to fix

Good cancelation of high energy flux tail

DUNE-PRISM 1 GeV



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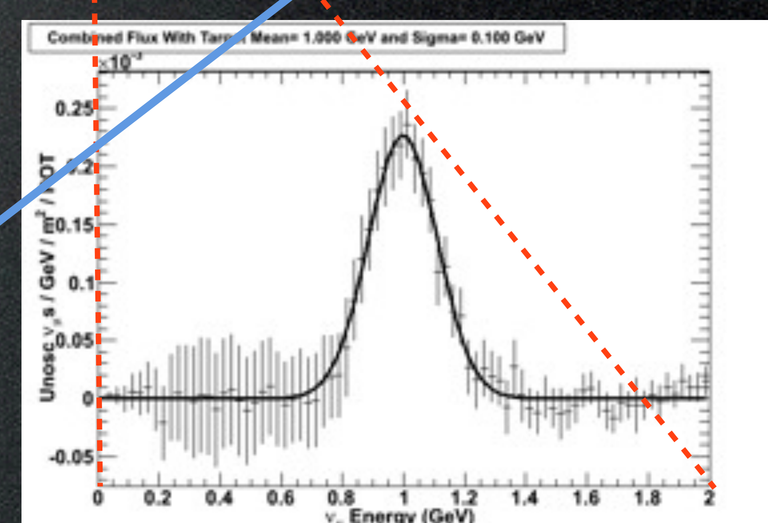

Summary

- 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
    - 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
    - Plans for an extended run will enhance sensitivity for sterile neutrinos and $\sigma(\nu_e)$ measurements
- The NuPRISM concept can be applied to any long-baseline neutrino experiment (e.g. DUNE)