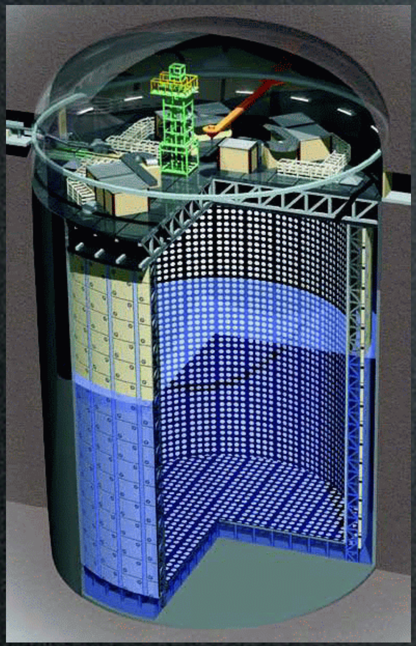
Potential Upgrades of T2K-ND280 and the νPRISM Detector

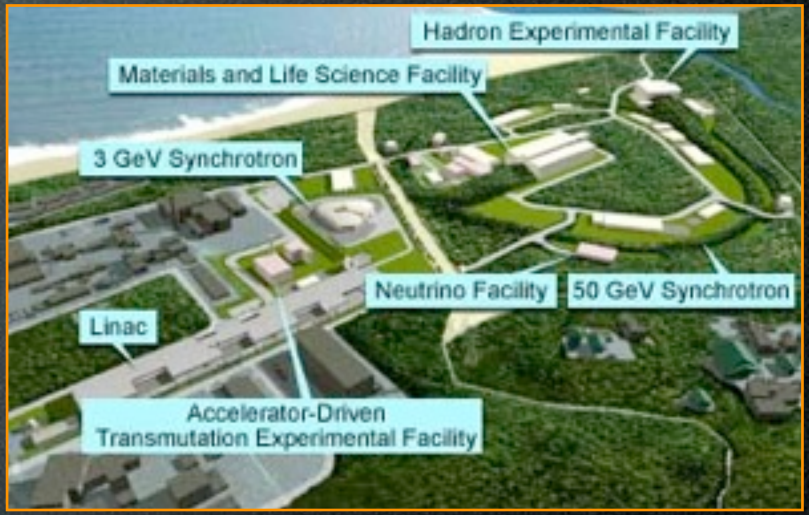
Mike Wilking, TRIUMF
NuInt Conference
22-May-2014

The T2K Experiment

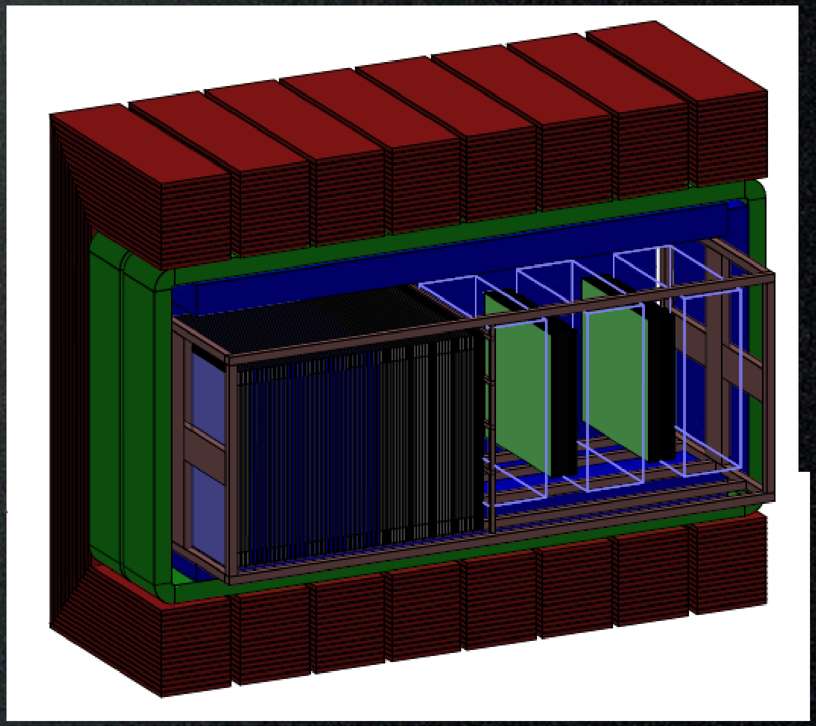
Super-K Detector



J-PARC Accelerator



Near Detector



- The T2K experiment searches for neutrino oscillations in a **high purity ν_μ beam**
- A **near detector** located 280 m downstream of the target measures the **unoscillated neutrino spectrum**
- The **neutrinos travel 295 km** to the Super-Kamiokande water Cherenkov detector
  - Search for **appearance of ν_e** (to measure θ_{13}, δ_{CP})
  - Search for **disappearance of ν_μ** (to measure θ_{23}, Δm^2_{32})

Near Detector Upgrade Goals

- The **largest systematic errors** for T2K oscillation analyses are from **neutrino interaction modeling**
    - These uncertainties will become important for the full T2K dataset (12x current statistics)
- The T2K collaboration is presently discussing **several potential near detector upgrades** to address neutrino cross section modeling
    - No final decisions have yet been made regarding any of these projects
- Two types of upgrades are being considered:
- **Improving model inputs**
    - Event rate measurements on D/H
    - Precision final state measurement on Ne
- **Direct measurements on H_2O**
    - Water-based liquid scintillator
    - **νPRISM**: an experimental method to remove neutrino model uncertainties from oscillation experiments

T2K ν_e Appearance PRL

TABLE II. The uncertainty (RMS/mean in %) on the predicted number of signal ν_e events for each group of systematic uncertainties for $\sin^2 2\theta_{13} = 0.1$ and 0.

Error source [%]	$\sin^2 2\theta_{13} = 0.1$	$\sin^2 2\theta_{13} = 0$
Beam flux and near detector	2.9	4.8
(w/o ND280 constraint)	(25.9)	(21.7)
ν interaction (external data)	7.5	6.8
Far detector and FSI+SI+PN	3.5	7.3
Total	8.8	11.1

The T2K near detector fit **constrains**:

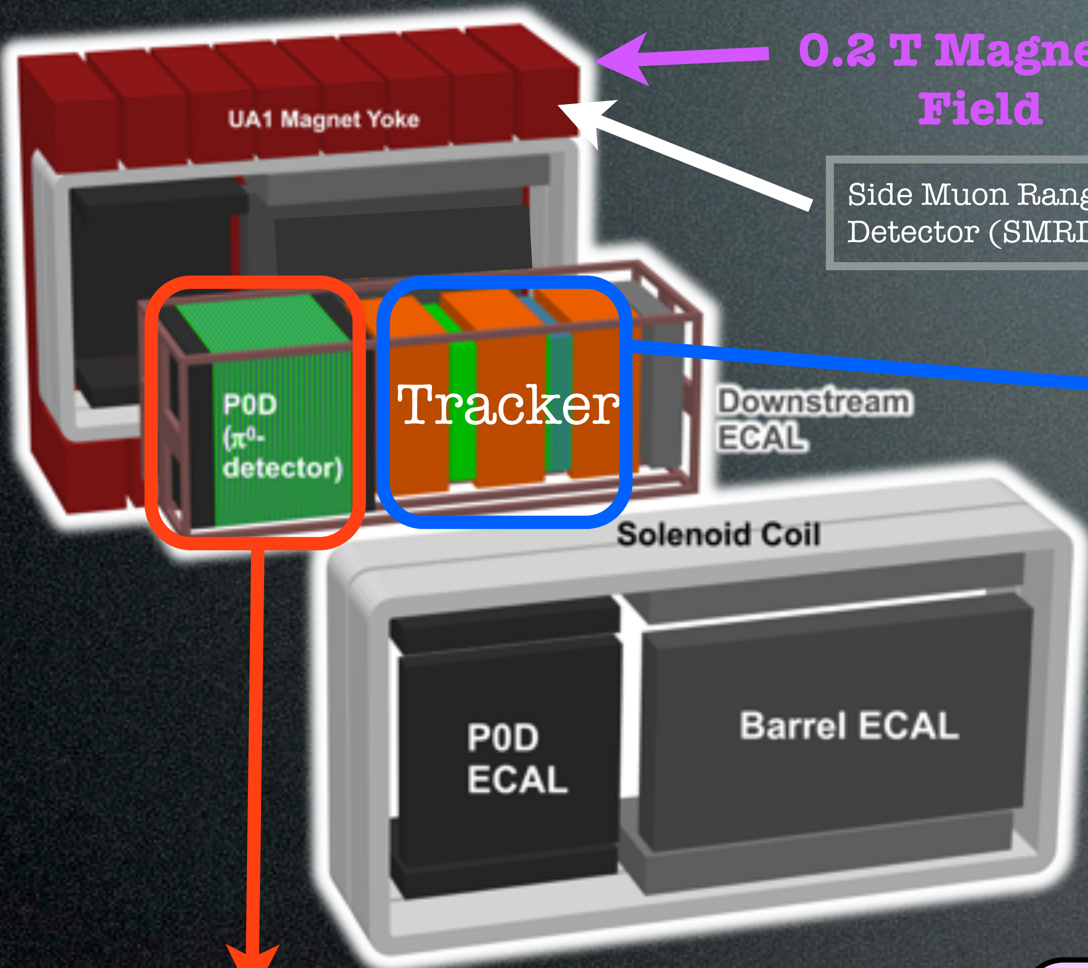
- Neutrino flux parameters
- CCQE (M_A^{QE} & norm.)
- CCπ^+ (M_A^{RES} & norm.)

2.9% combined error

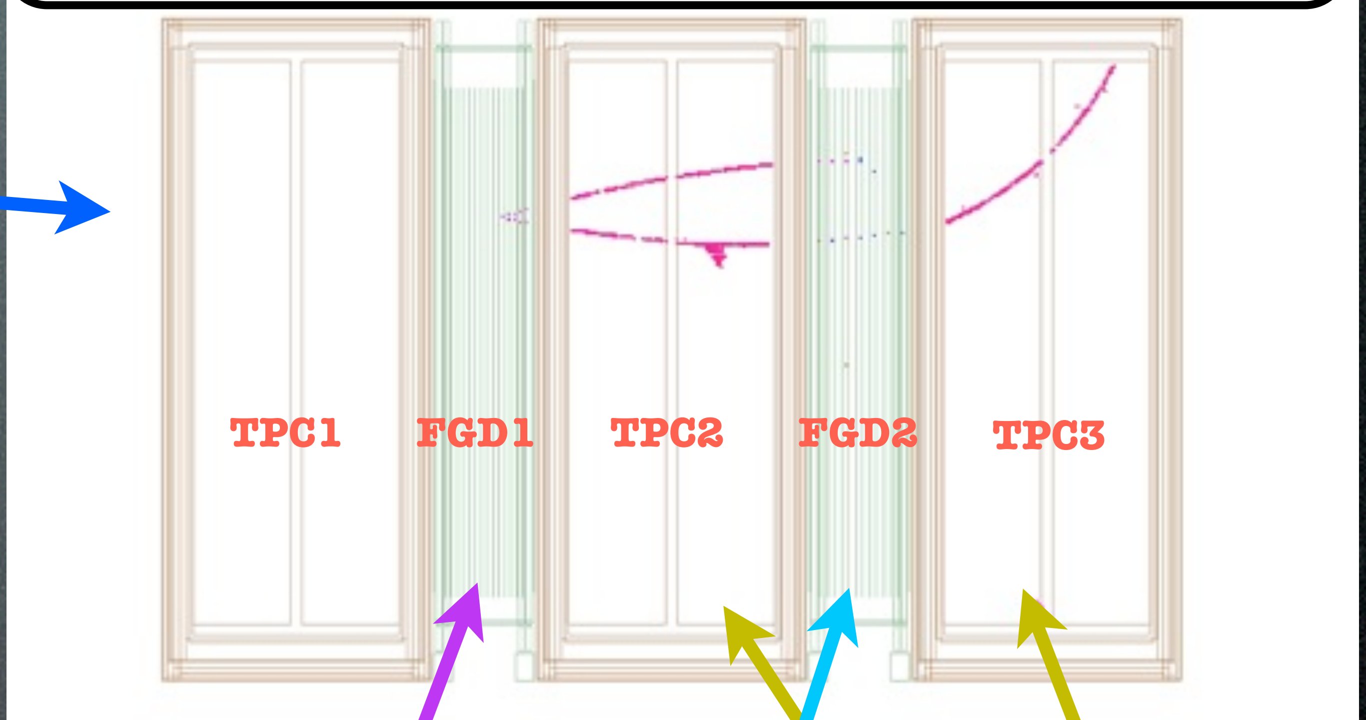
The T2K near detector fit **does NOT (yet) constrain**:

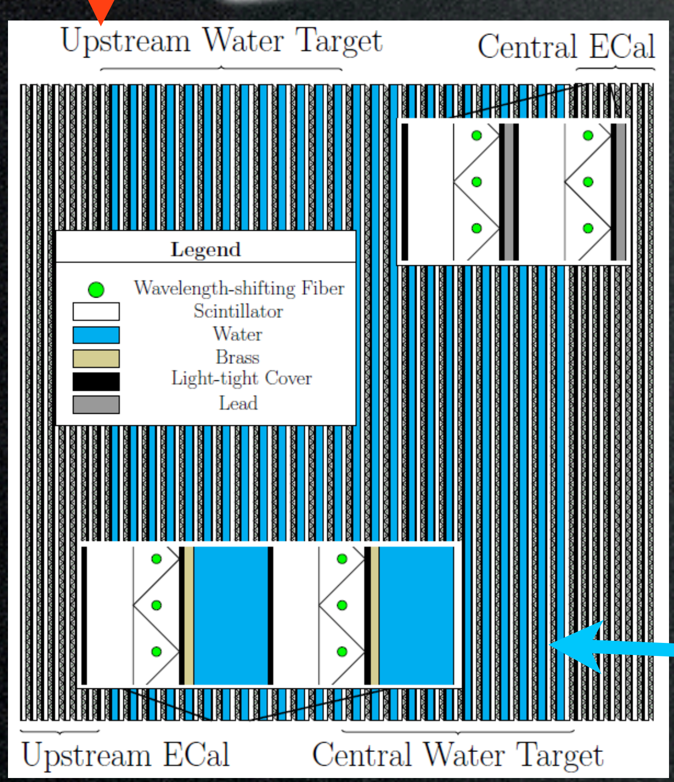
- Nuclear modeling **(5.9% error)**
- 0π Δ decay (2p2h) **(3.6% error)**
- $\sigma_{\nu e}/\sigma_{\nu\mu}$ **(2.8% error)**
- CC & NC multi-π & coherent processes **(< 1% error)**

T2K Near Detector (ND280)



CC Interaction in the Tracker





Fine-Grained Detectors (FGDs)

- Scintillator strips
- Provides neutrino target
- Detailed vertex information

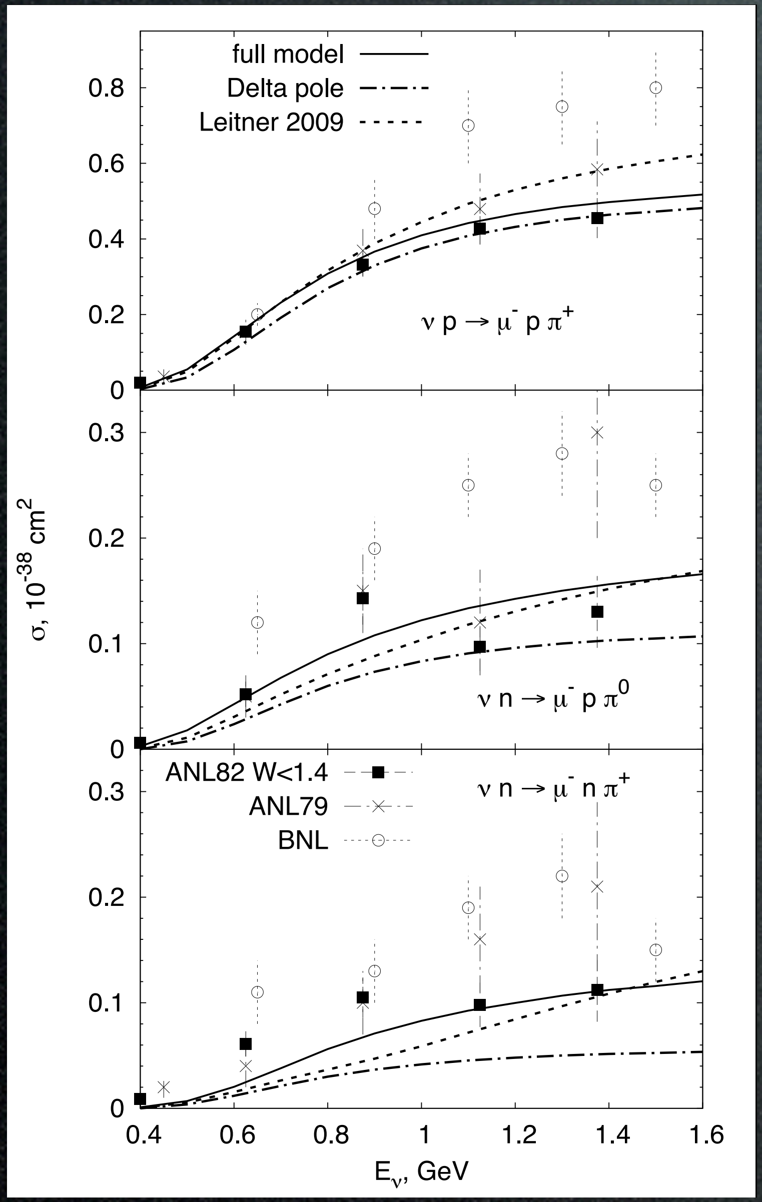
Time Projection Chambers (TPCs)

- Gas ionization chambers
- Track momentum from curvature
- Particle ID from dE/dx

FGD2 and the P0D have water layers to measure interactions on the same target as Super-K

Note: water layers are not instrumented

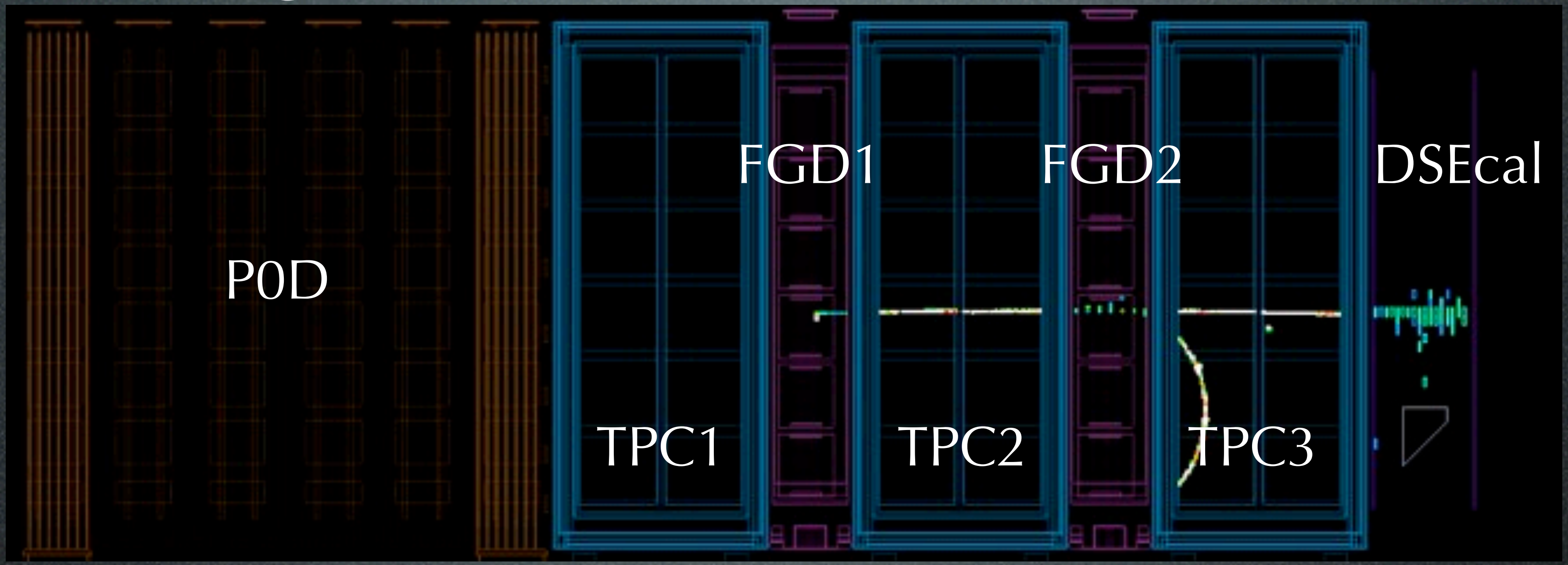
Measurements on D_2O



O. Lalakulich et al.
hep-ex/1007.0925v2

- **ν-nucleus** models are based on our knowledge of **ν-nucleon** interactions
  - Large disagreements exist in available experimental data
- Deuterium provides a **quasi-free neutron target** for CCQE interactions
  - A "standard candle" that is less dependent on nuclear effects
- Measurements of e.g. σ(C)/σ(D) & σ(O)/σ(D) can be very useful tools for model builders
  - Especially with more precise flux modeling, dedicated hadron production experiments, etc.

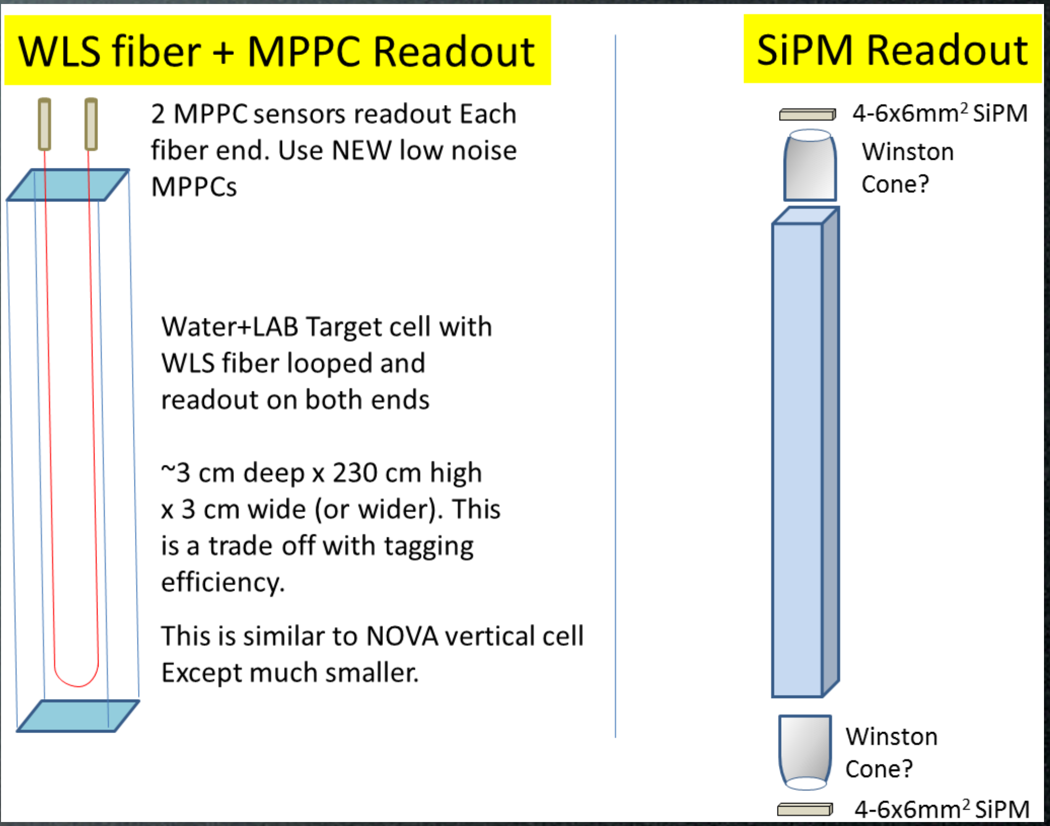
Depolying D_2O in ND280

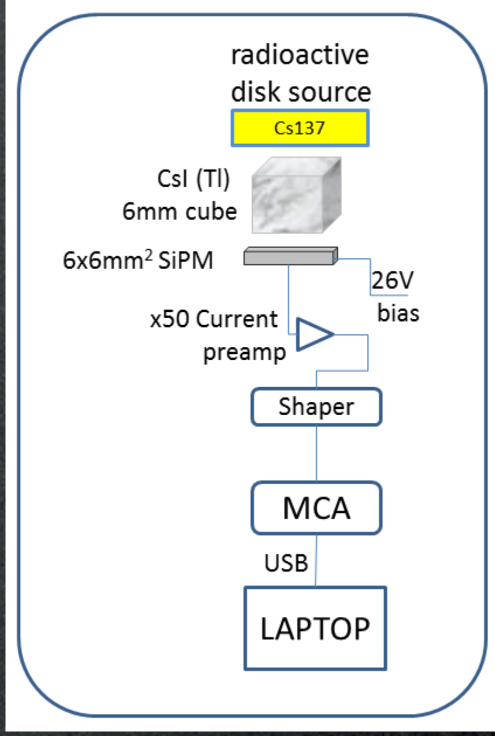


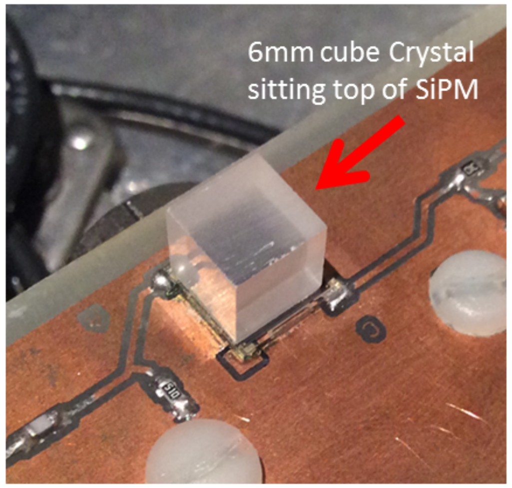
- **Simple solution**: replace the P0D and FGD2 water targets with D_2O
    - Compare event distributions with H_2O to those with D_2O
- **More complicated**: simultaneously circulate H_2O and D_2O in alternating layers
    - Measurements are less sensitive to changes in beam condition
- **Even more complicated**: replace scintillator layers entirely with active H_2O and D_2O layers
    - Reduces the required statistical subtraction (more precision)

Water-Based Liquid Scintillator

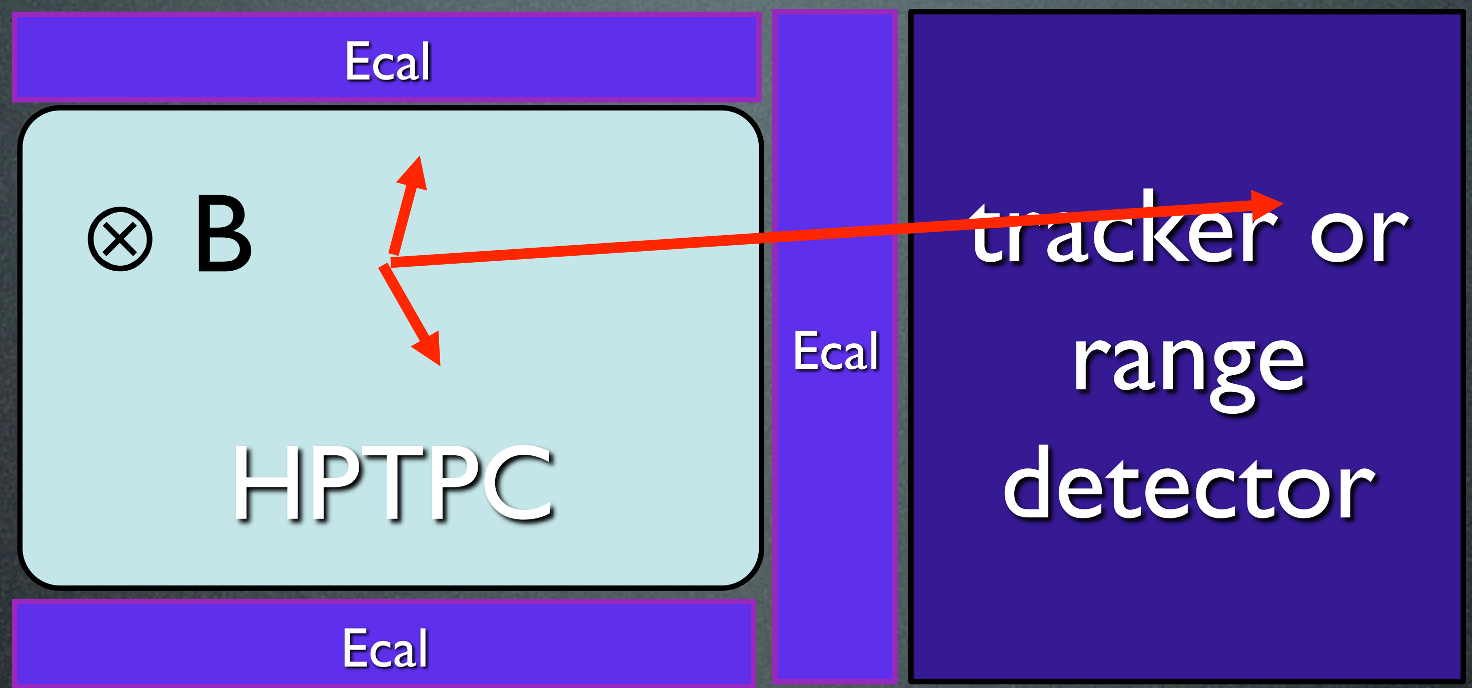
- When using either H_2O or D_2O targets, it is advantageous to measure deposited charge
  - **Sensitive to short tracks** exiting the nucleus (vertex activity)
  - Mitigates the need to perform a statistical subtraction to remove events on carbon
    - 2x reduction in statistical error is possible (**few % rate measurement**)
- Replacing plastic scintillator (CH) with fully active liquid targets requires WBLS
  - Possibility to make more finely segmented cells (e.g. $1cm^2 \rightarrow 0.1cm^2$)
- R&D is underway







High-Pressure Gas TPC



- The ND280 tracker and POD can be replaced with a high pressure time projection chamber
- Sensitive to <100 MeV/c protons
- High momentum particles are measured with a tracker or range detector
- Surrounded by a calorimeter for neutral particle containment
- Several different nuclear targets can be used/alternated:
  - He, Ne, Ar, CF_4 to study A-dependence of cross sections and FSI

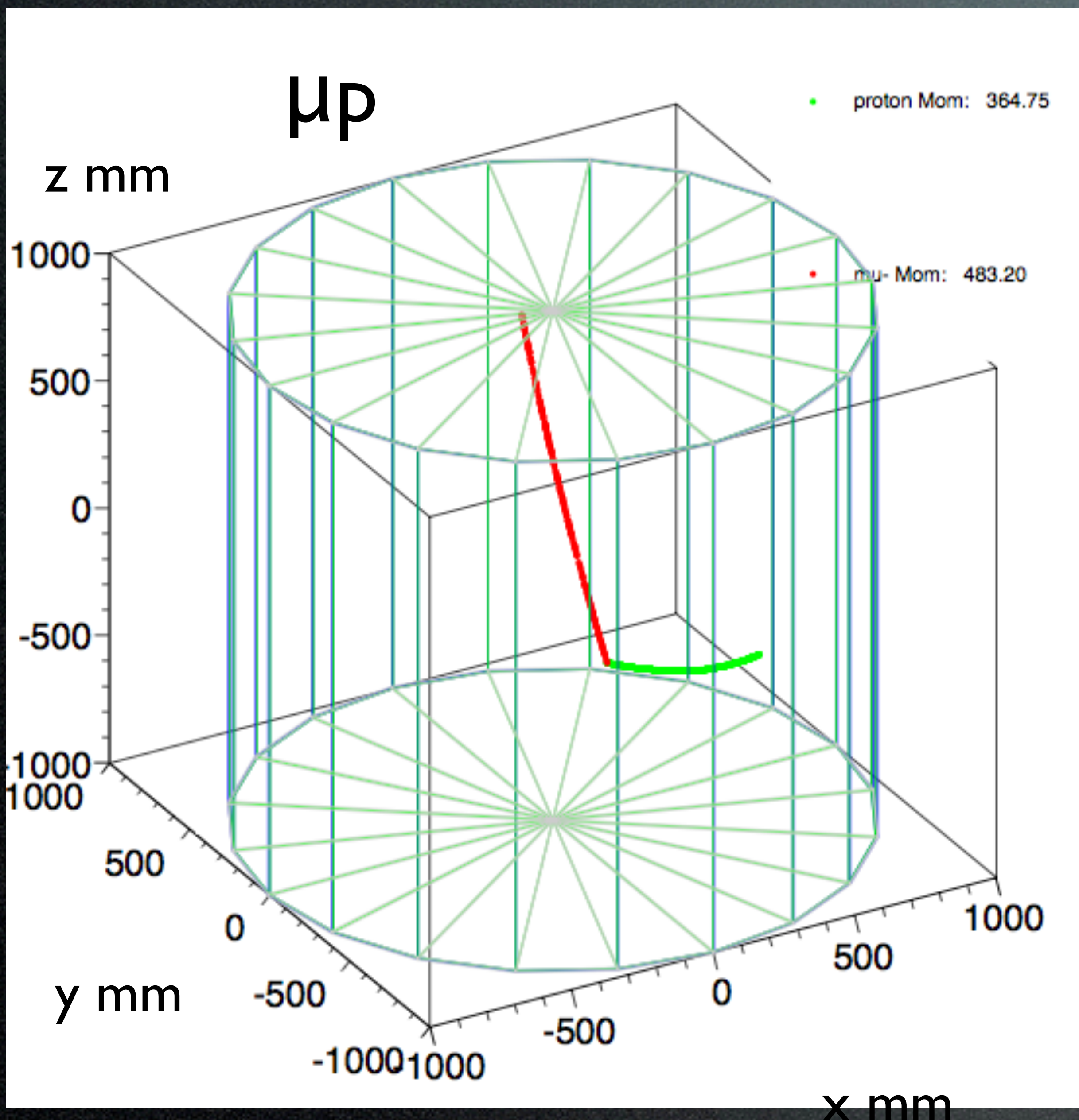
HPTPC Event Rates

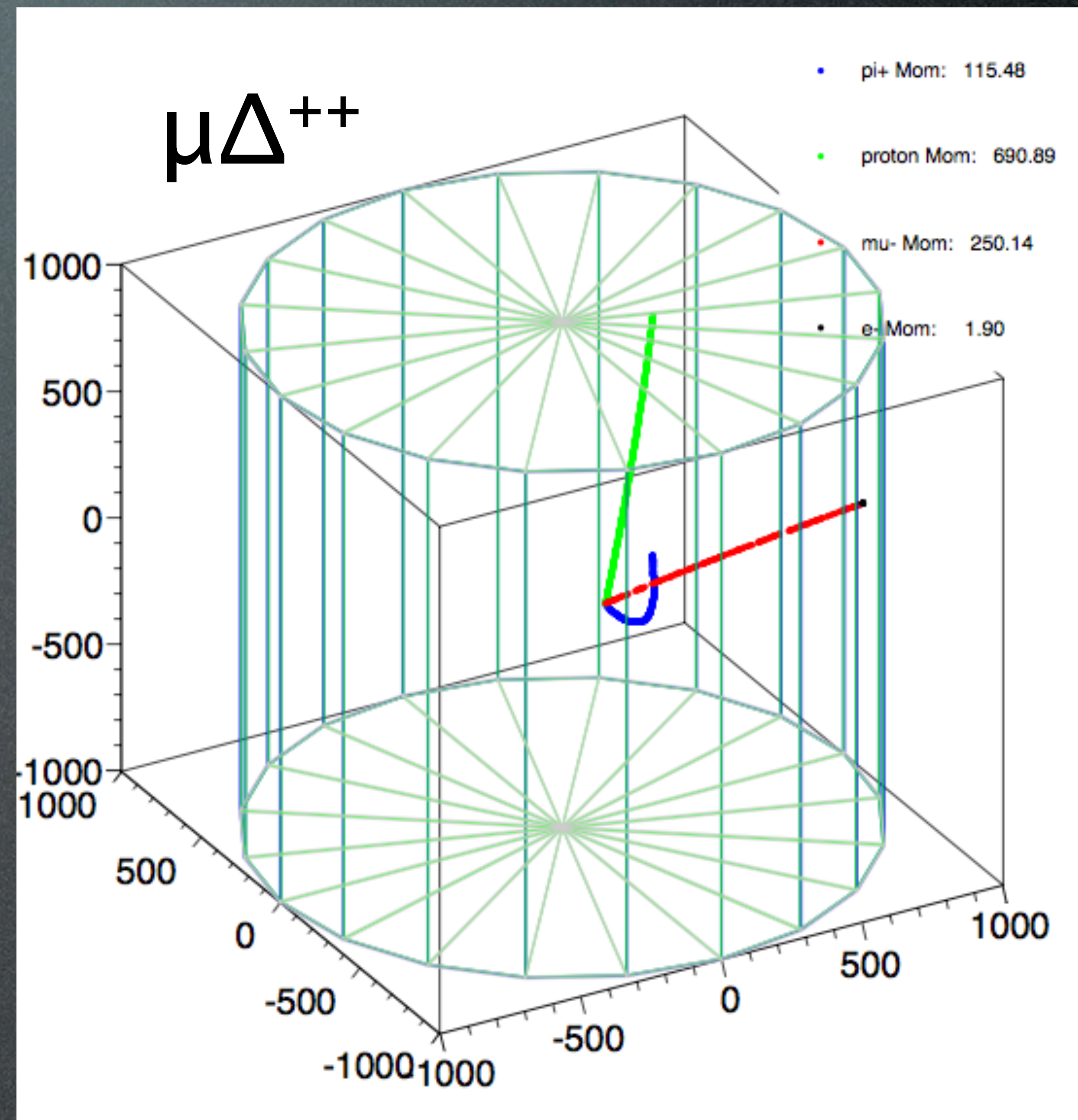
CC events assuming a $8m^3$ detector & full FV.

$2x2x2\ m^3$ 20°C	5 bars	10 bars
He	6.65 kg	13.3 kg
	520 evt/10^{21}pot	1040 evt/10^{21}pot
Ne	32.5 kg	67.1 kg
	2543 evt/10^{21}pot	5086 evt/10^{21}pot
Ar	66.5 kg	133 kg
	5203 evt/10^{21}pot	10406 evt/10^{21}pot
CF_4	146.3 kg	293 kg
	11450 evt/10^{21}pot	22893 evt/10^{21}pot

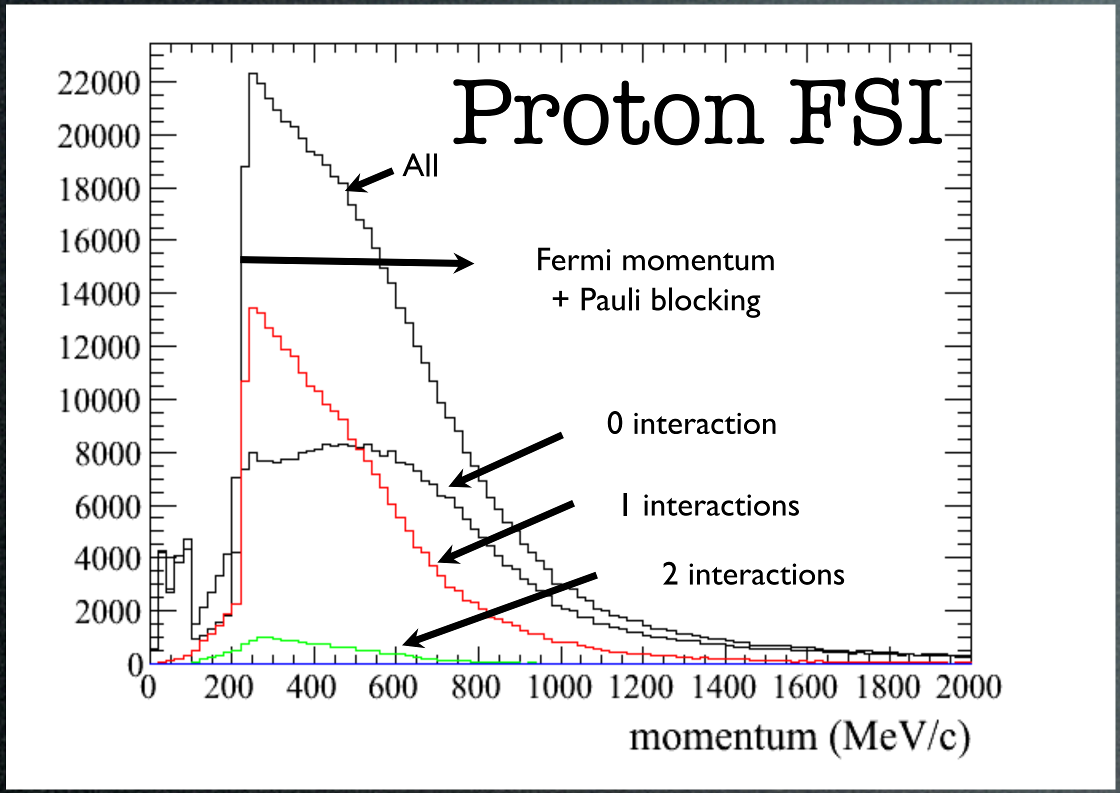
Expected ~1 x 10^{21} pot/year for ~4 years

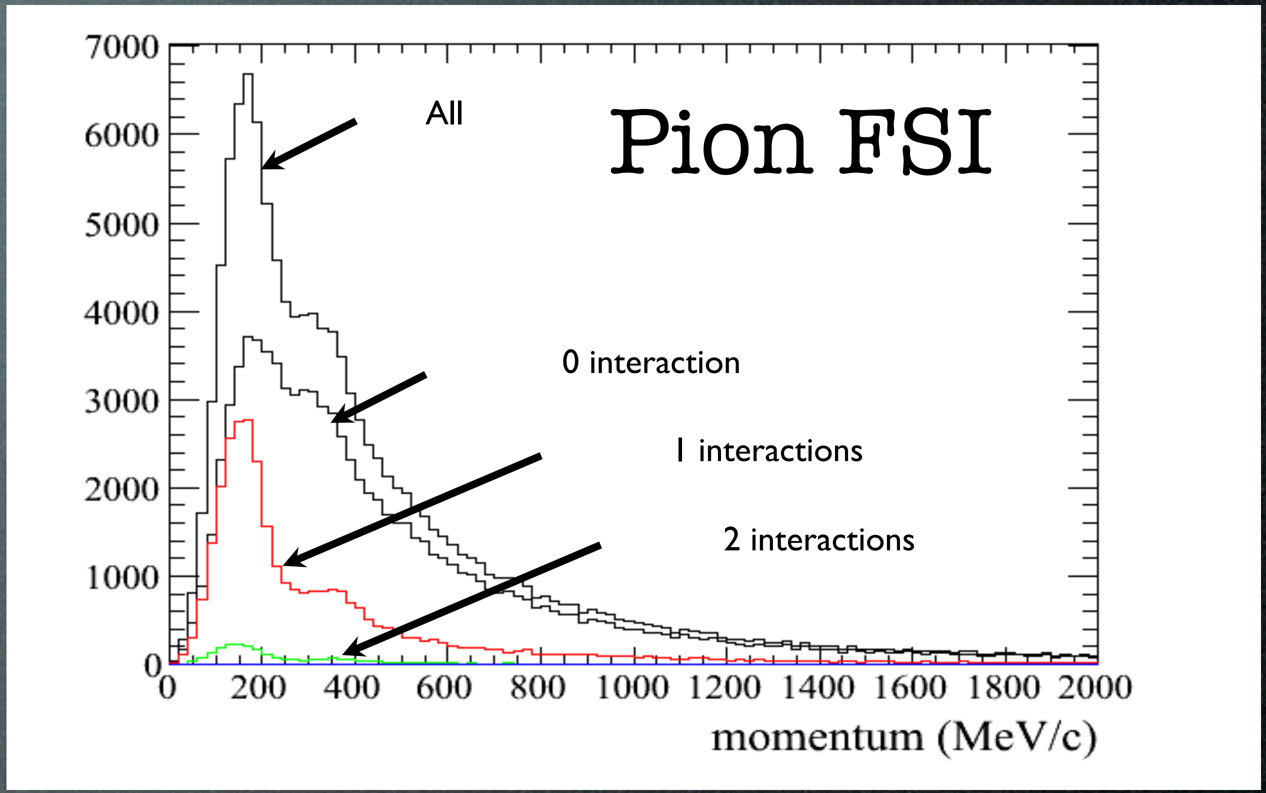
Simulated HPTPC Events



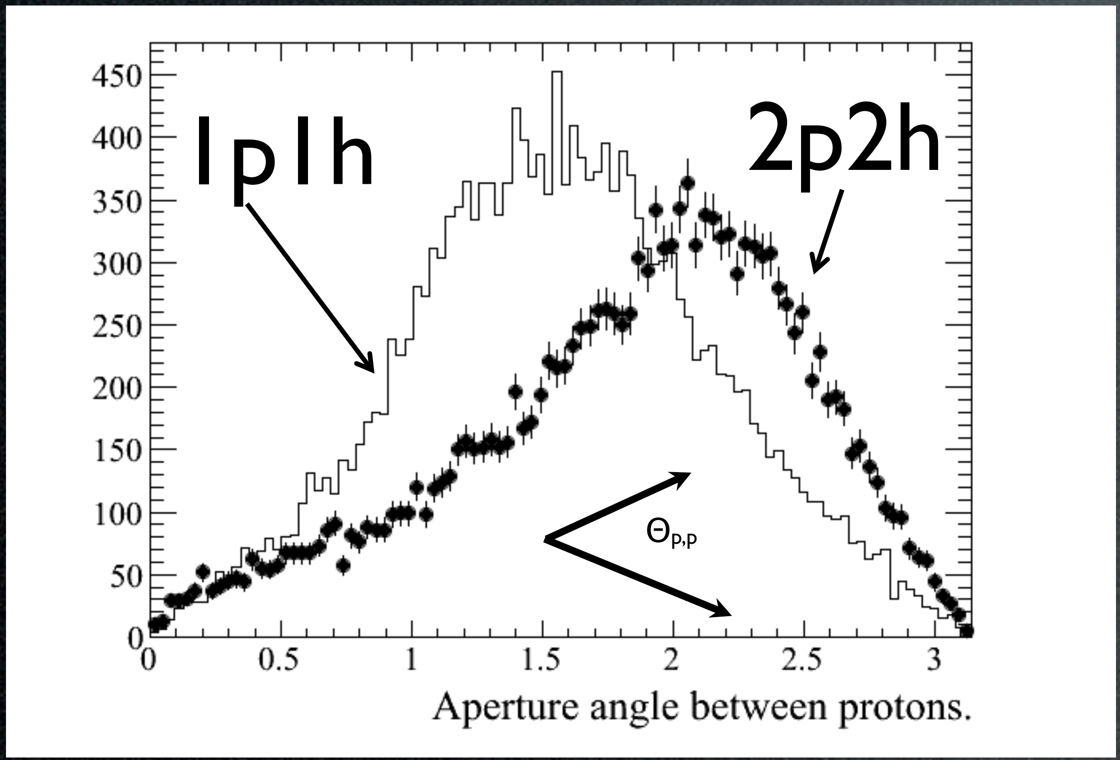


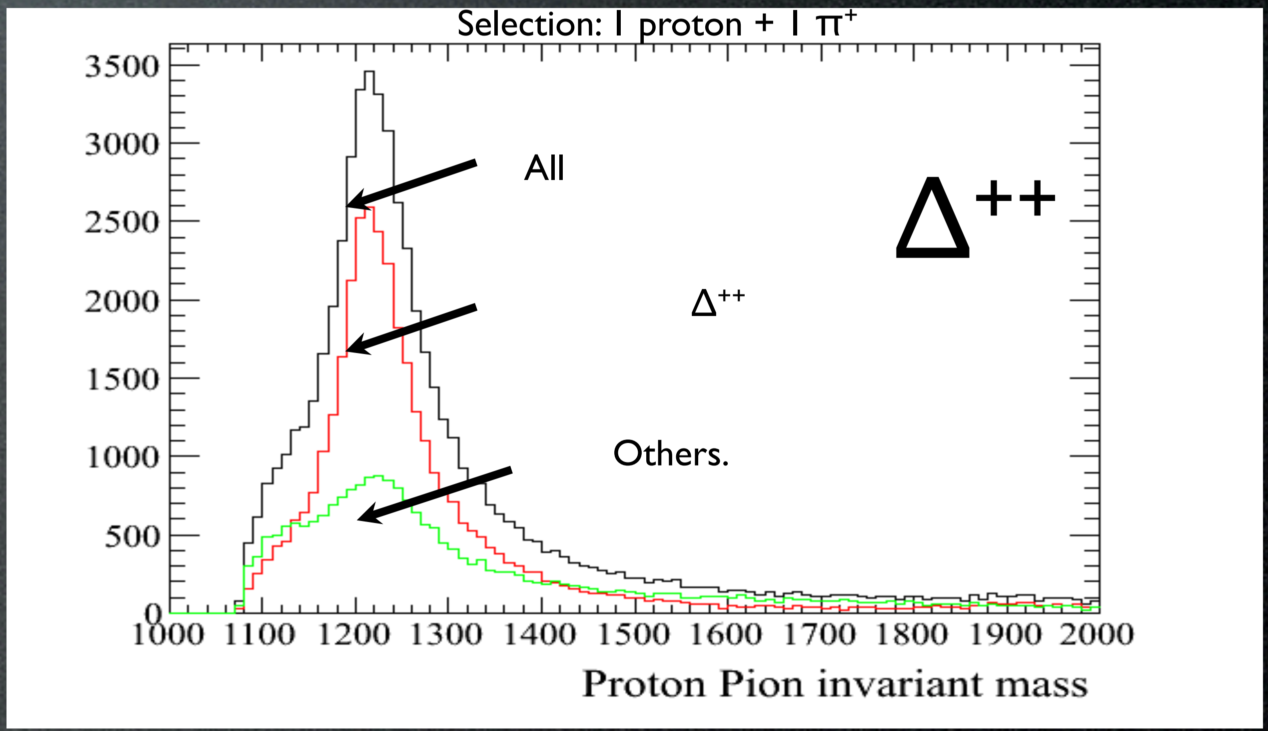
HPTPC Physics Goals





Neut + G4 simulation





- Much to learn from studying low momentum final state particles

νPRISM: An Experimental Method to Remove Neutrino Modeling Uncertainties from Osc. Experiments

For more detail, see νPRISM poster

(The poster session is over, but I would be happy to explain the details to anyone who is interested)

recision
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νPRISM:

An Experimental Method to Remove Neutrino Modeling Uncertainties from Osc. Experiments

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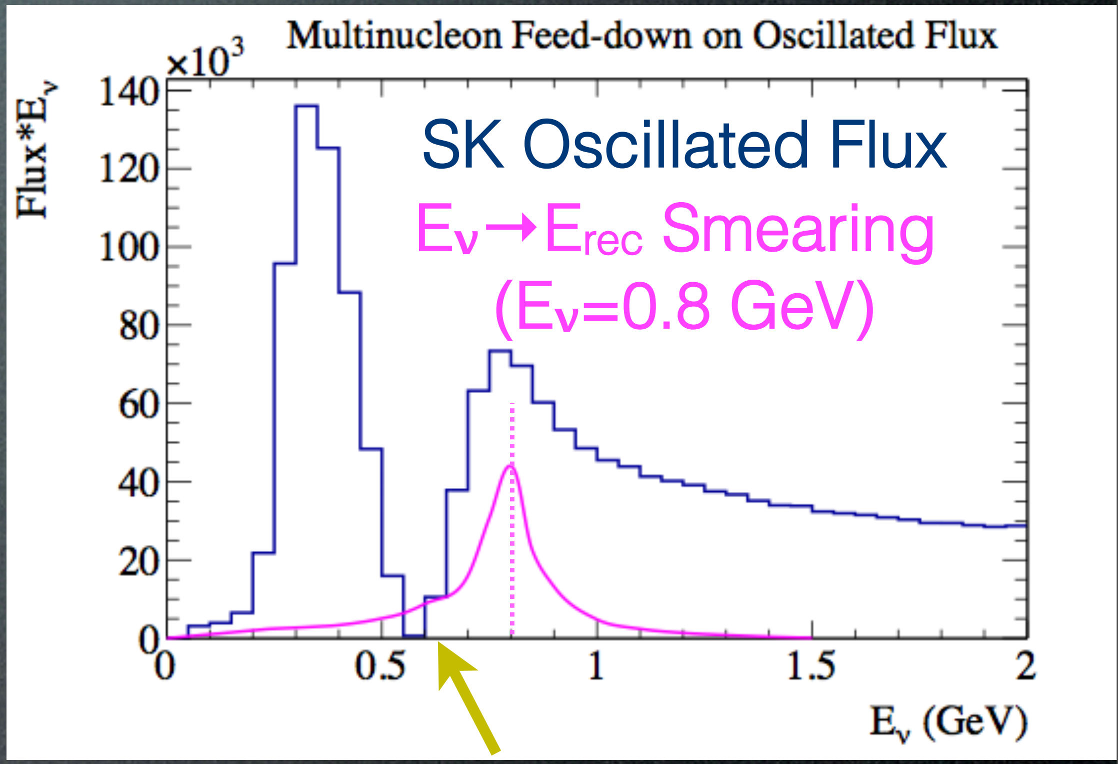
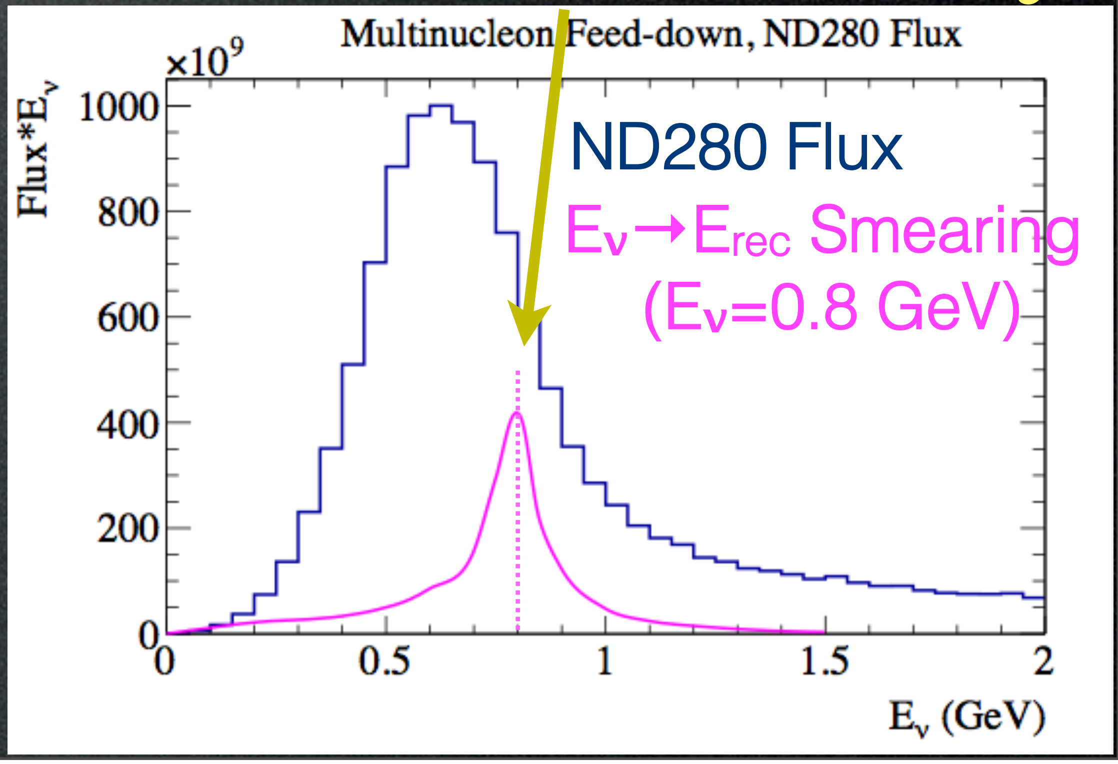
Multi-nucleon Effects in Oscillation Analyses

- 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!**
    (see Peter's talk from yesterday)
  - Near detector energy spectra are not oscillated
- More multi-nucleon = smaller dip
  - **Multi-nucleon effects are largely degenerate with mixing angle effect!**



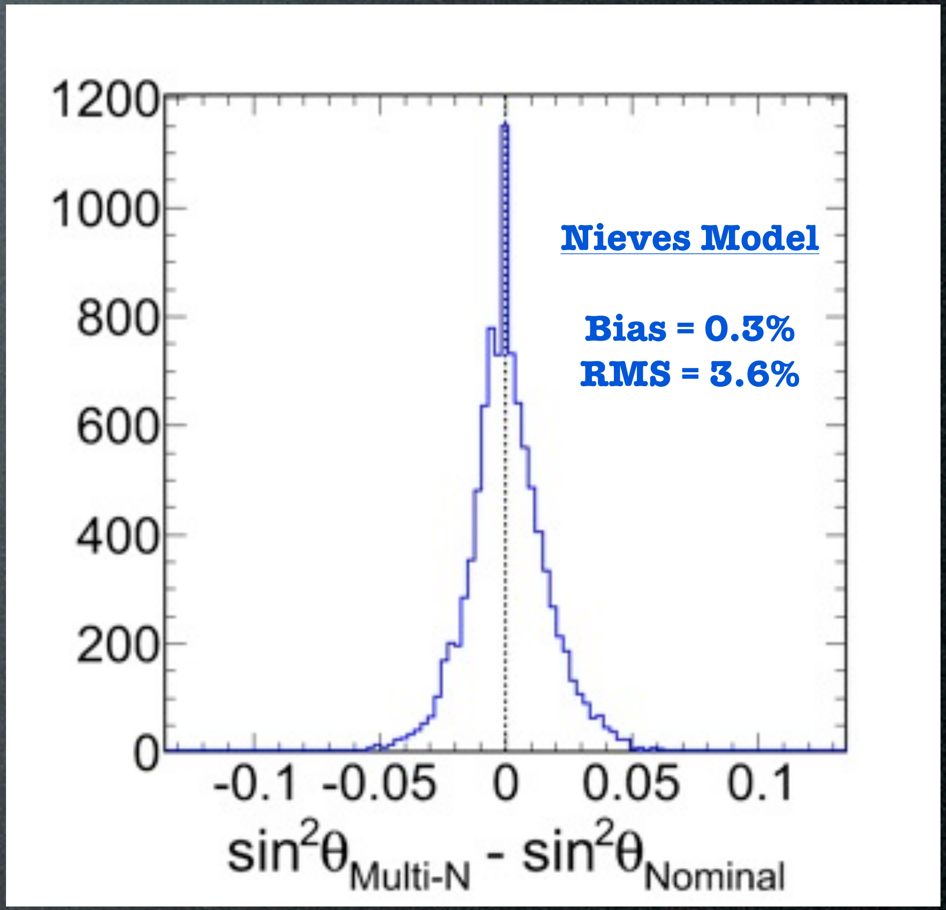
Mixing Angle Bias!

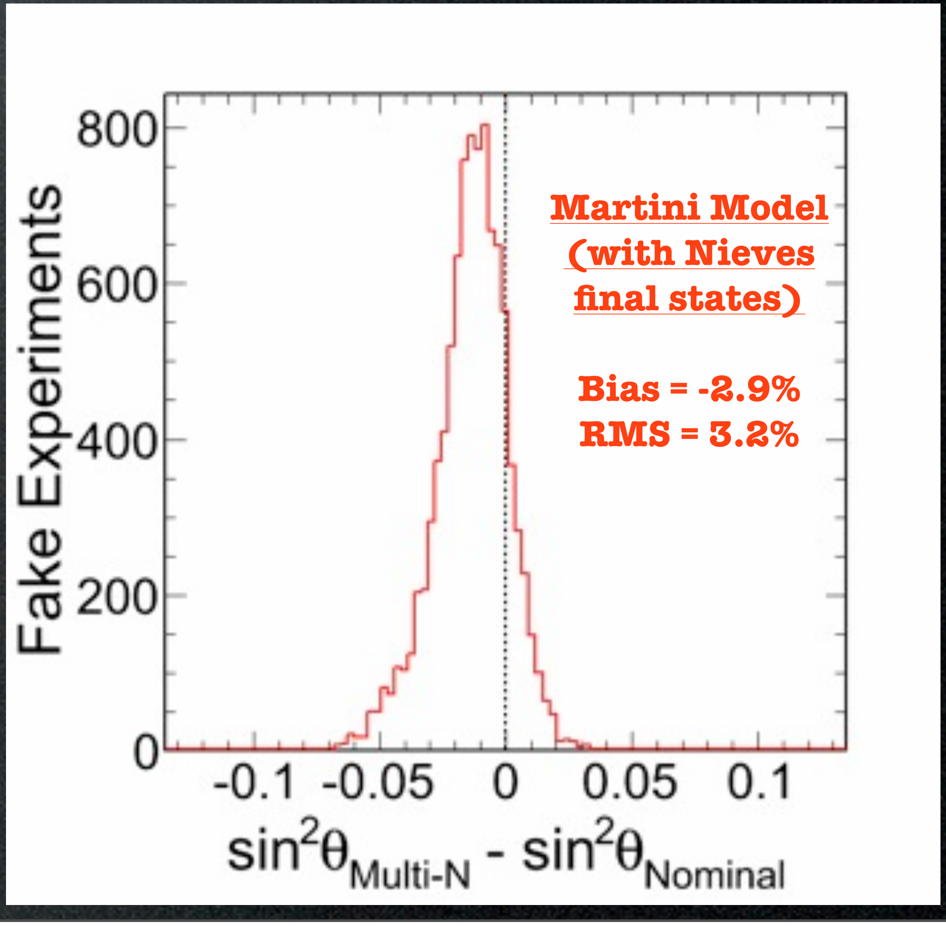
Near detectors lack sensitivity



Effect on T2K ν_μ Disappearance

- Default neut prediction is compared to the 2 multi-nucleon models
    - J. Nieves, I. Ruiz Simo, and M. J. Vicente Vacas, PRC 83:045501 (2011)
    - M. Martini, M. Ericson, and G. Chanfray, PRC 84:055502 (2011)
- Fit many "fake datasets" of each model (systematic throws of flux and cross section parameters)
    - In all cases, MC used in fit assumes default neut
- 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!**





νPRISM Detector Concept

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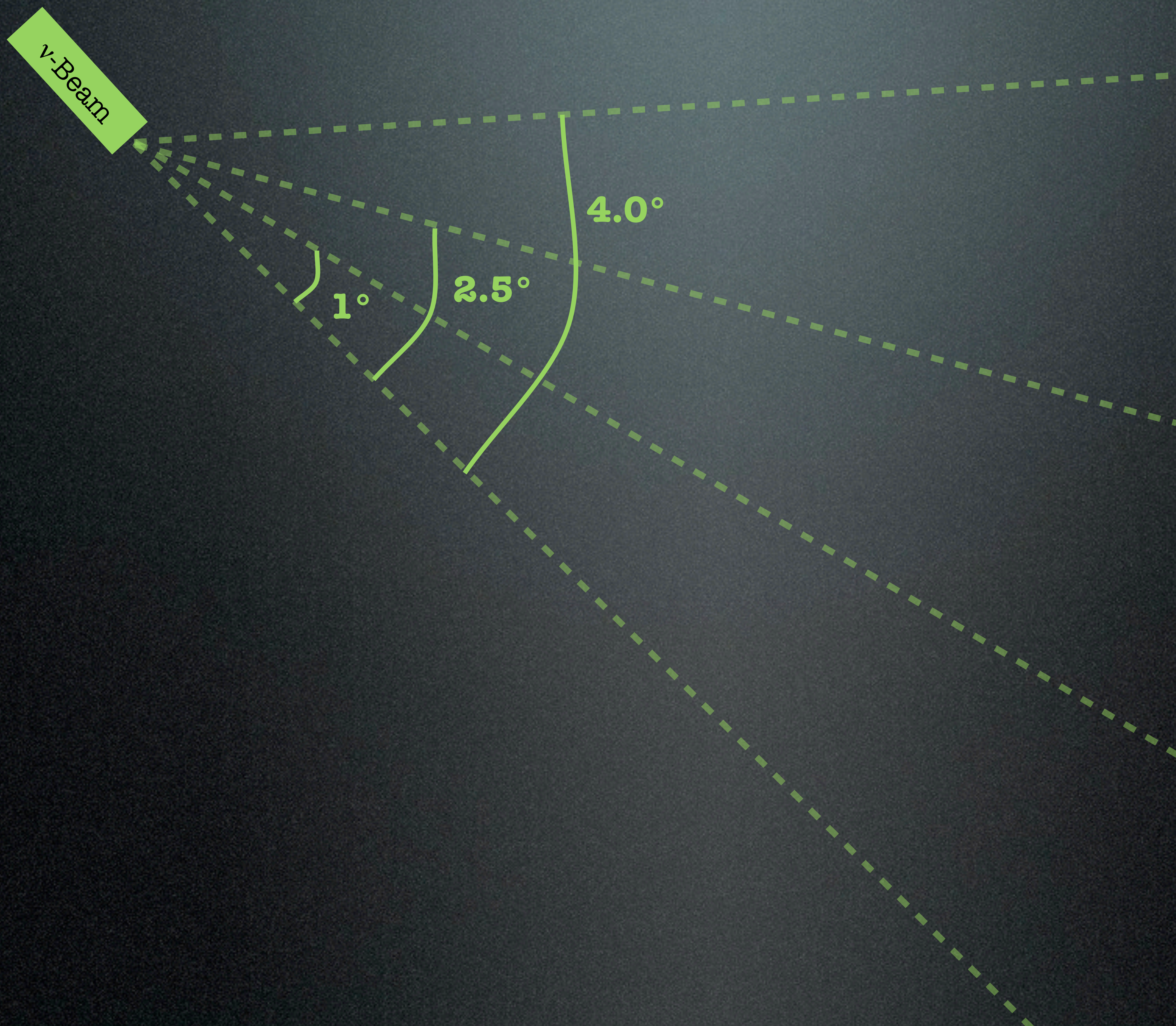

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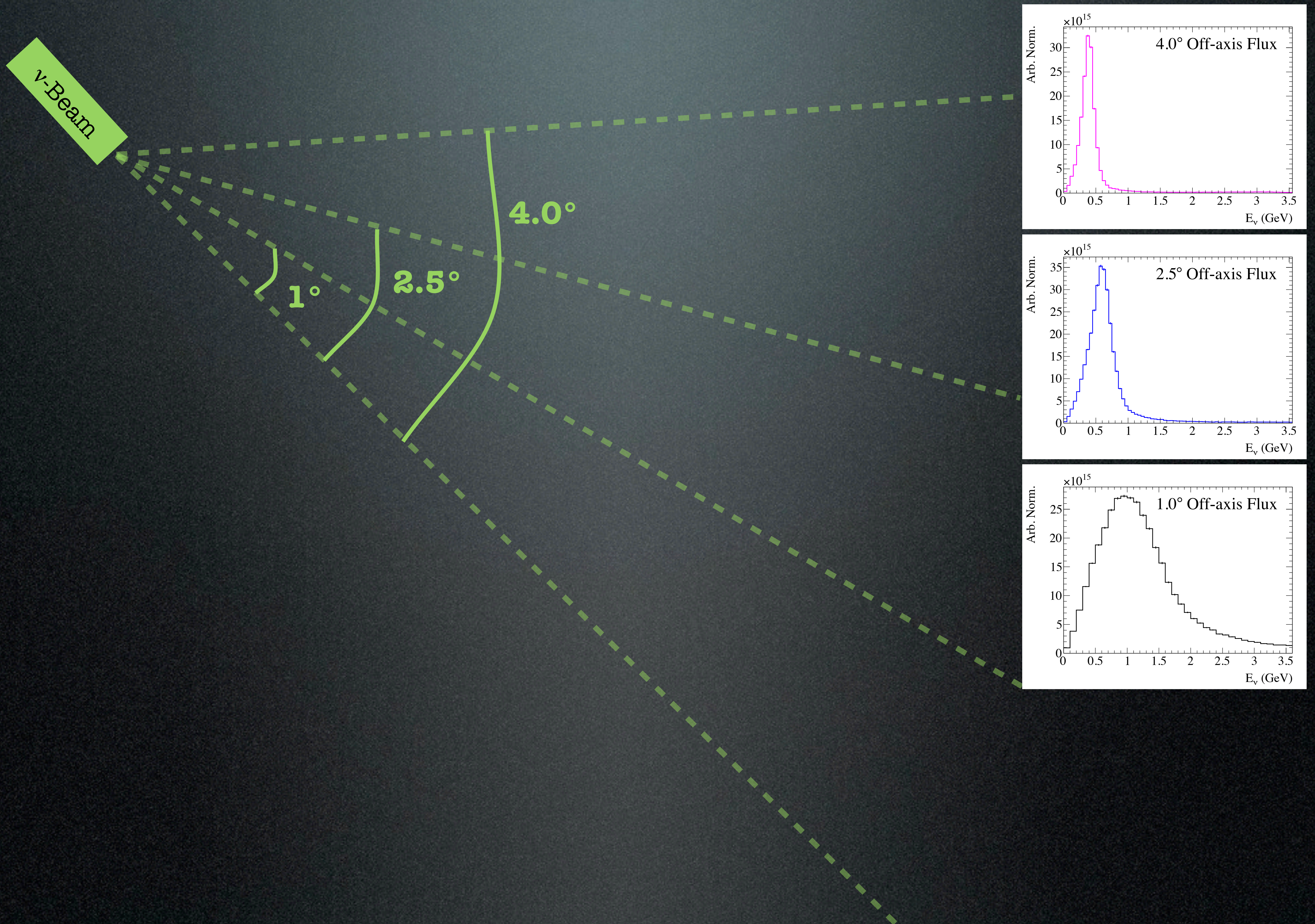

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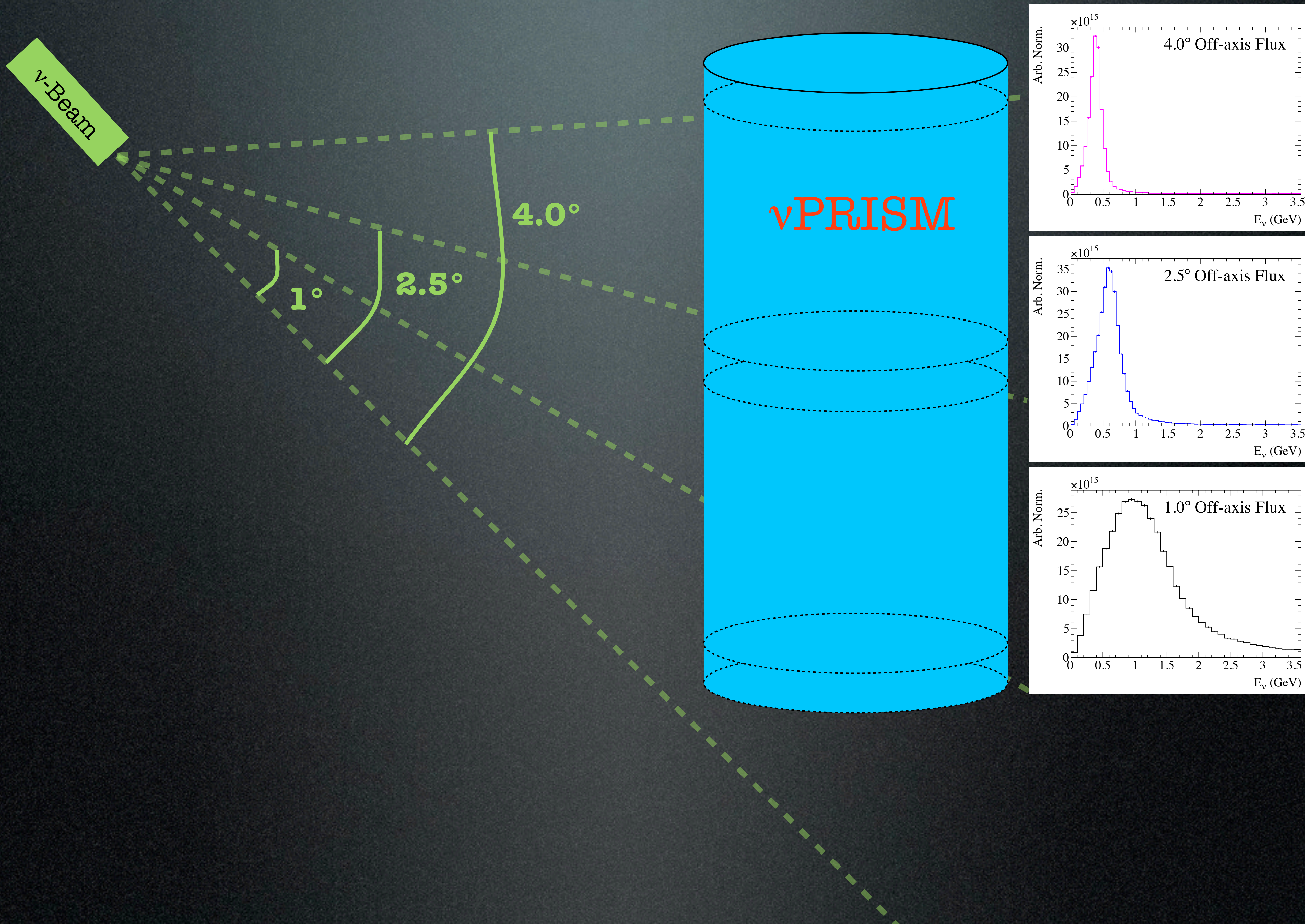

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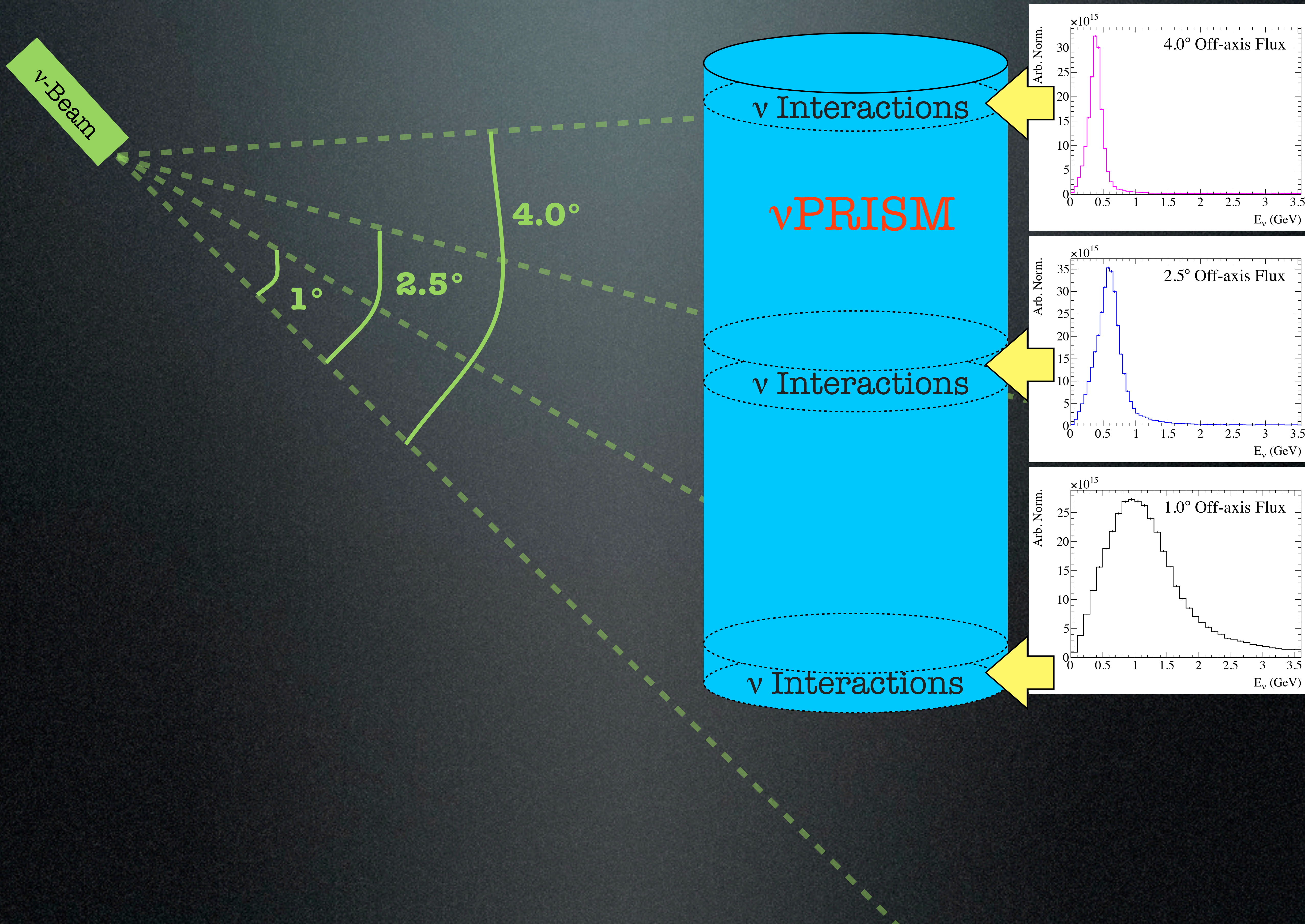

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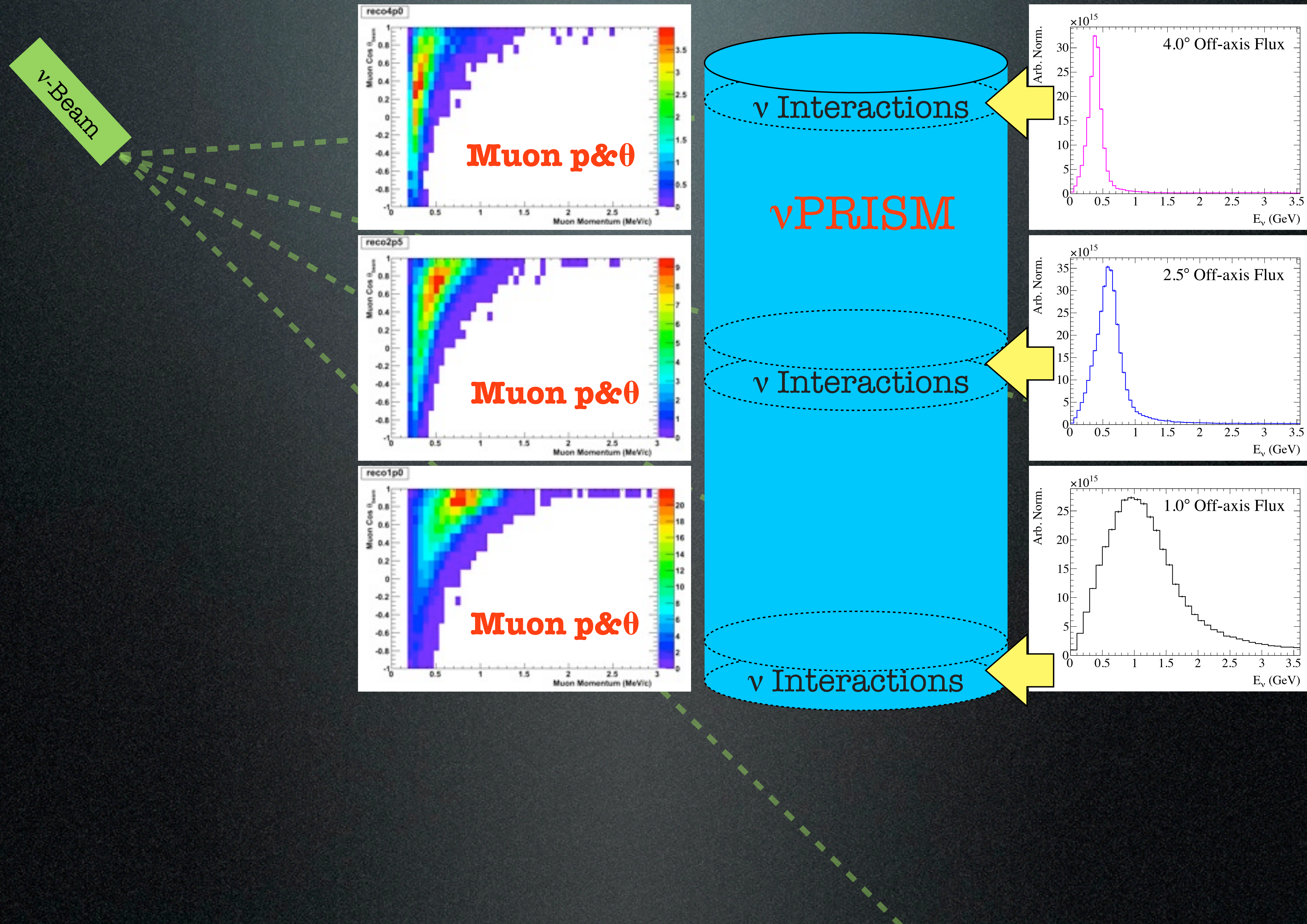

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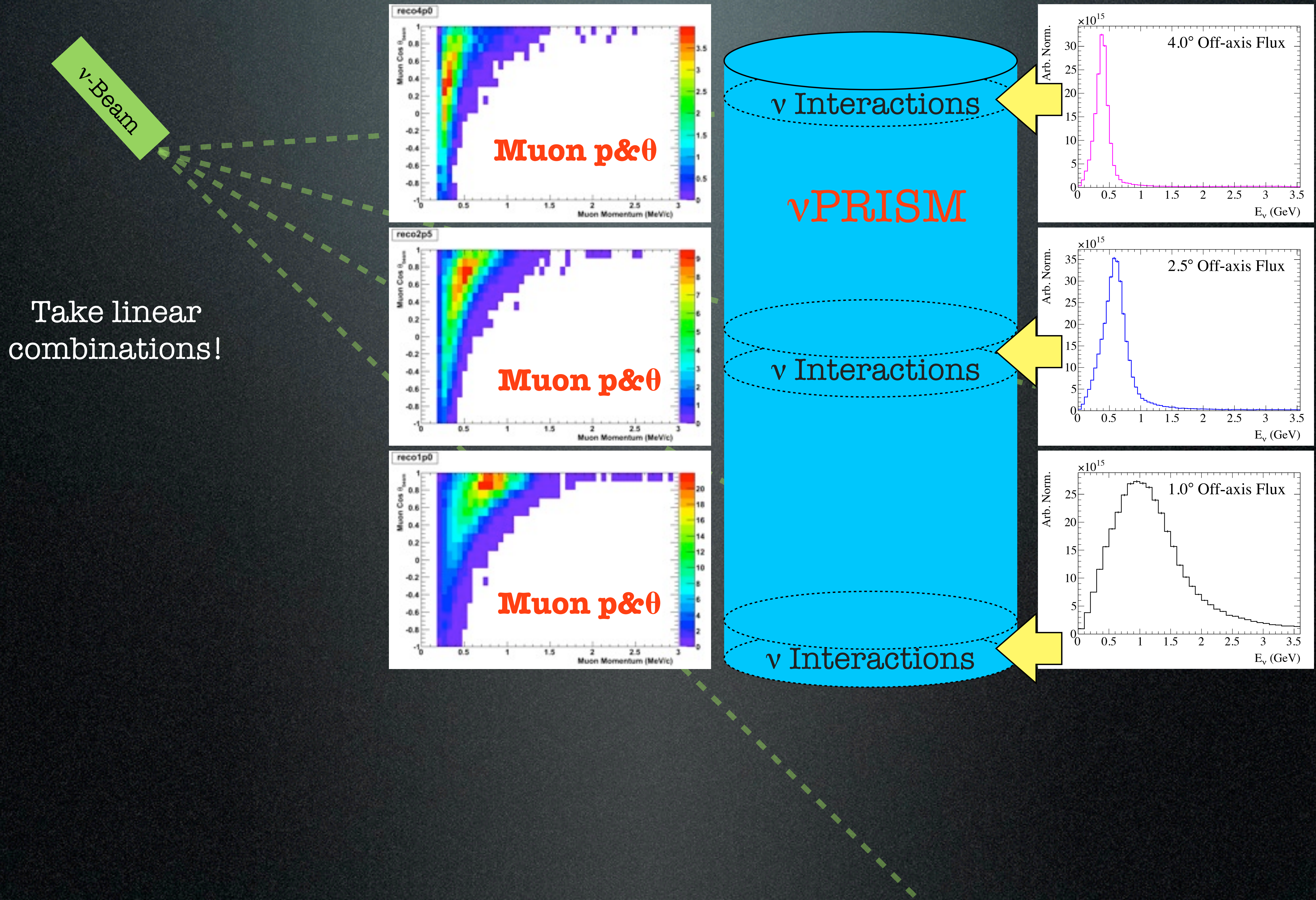

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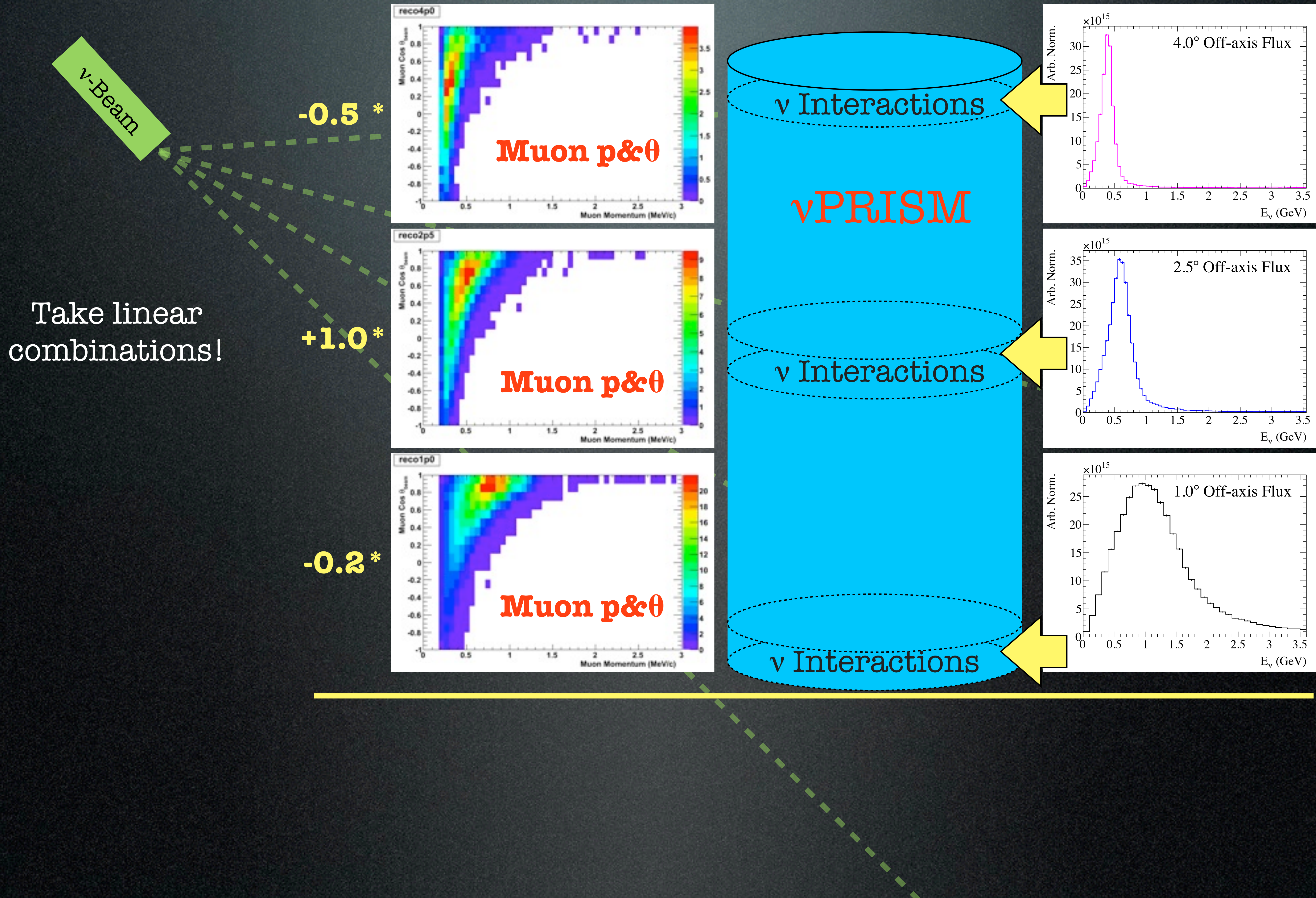

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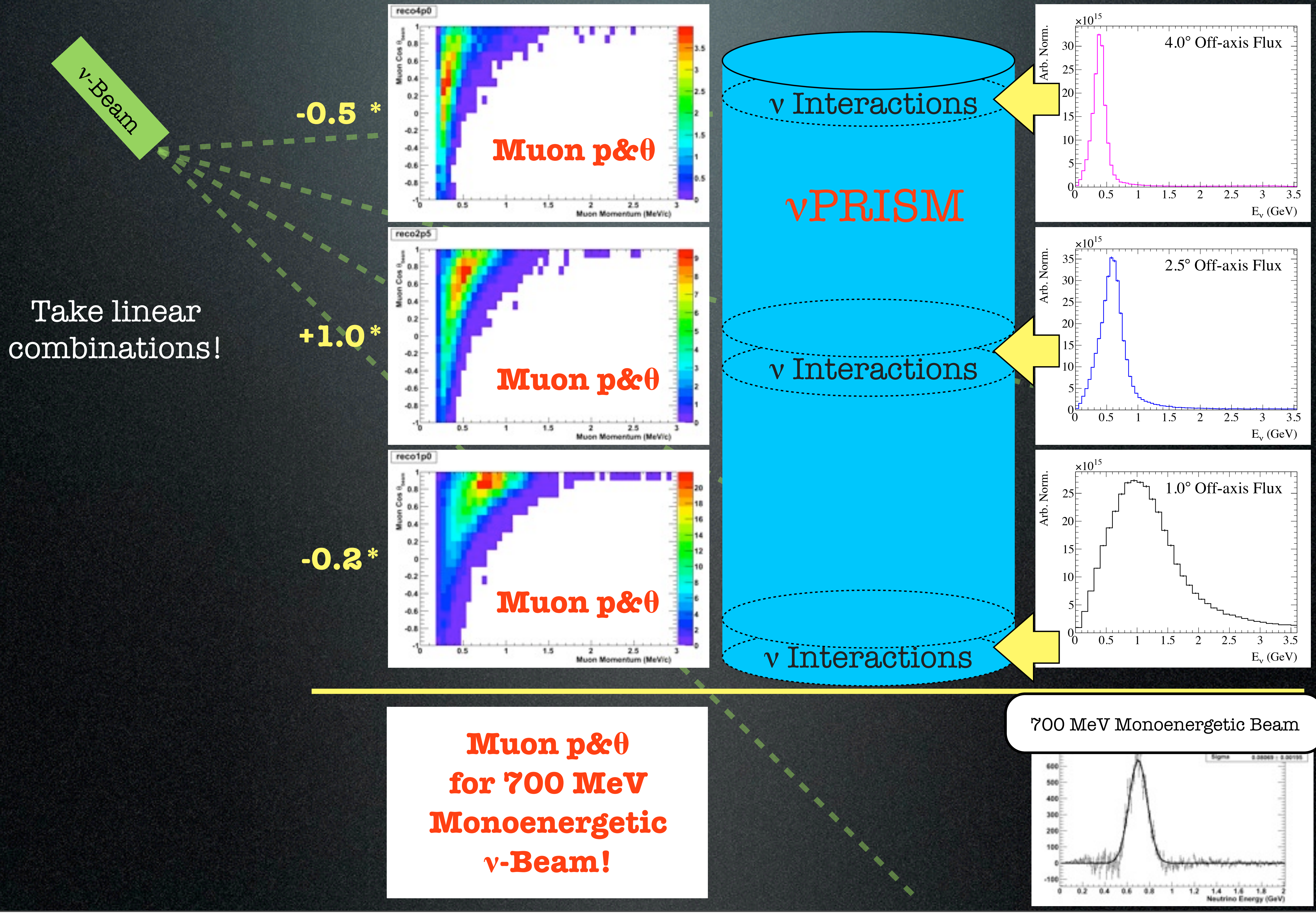

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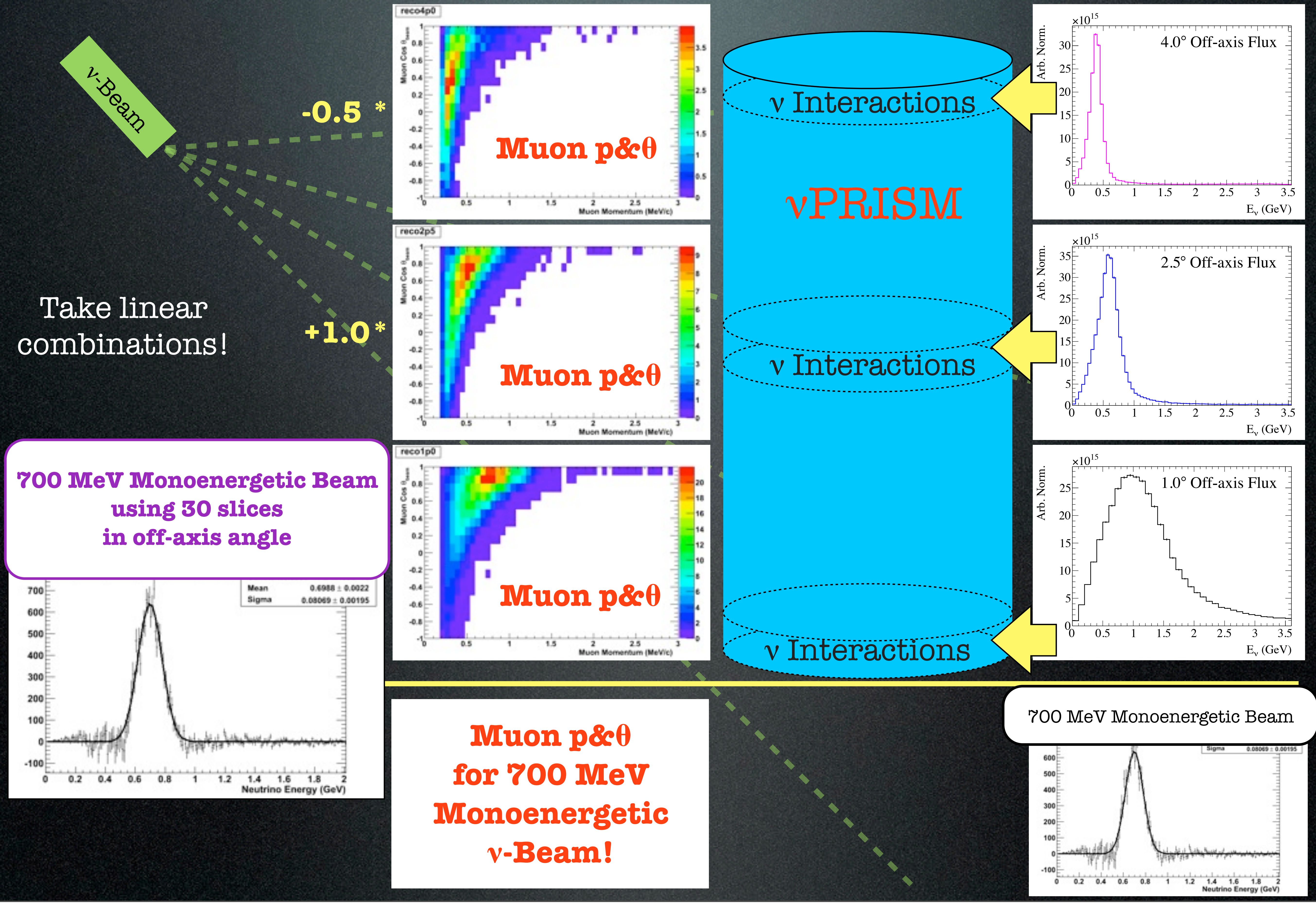
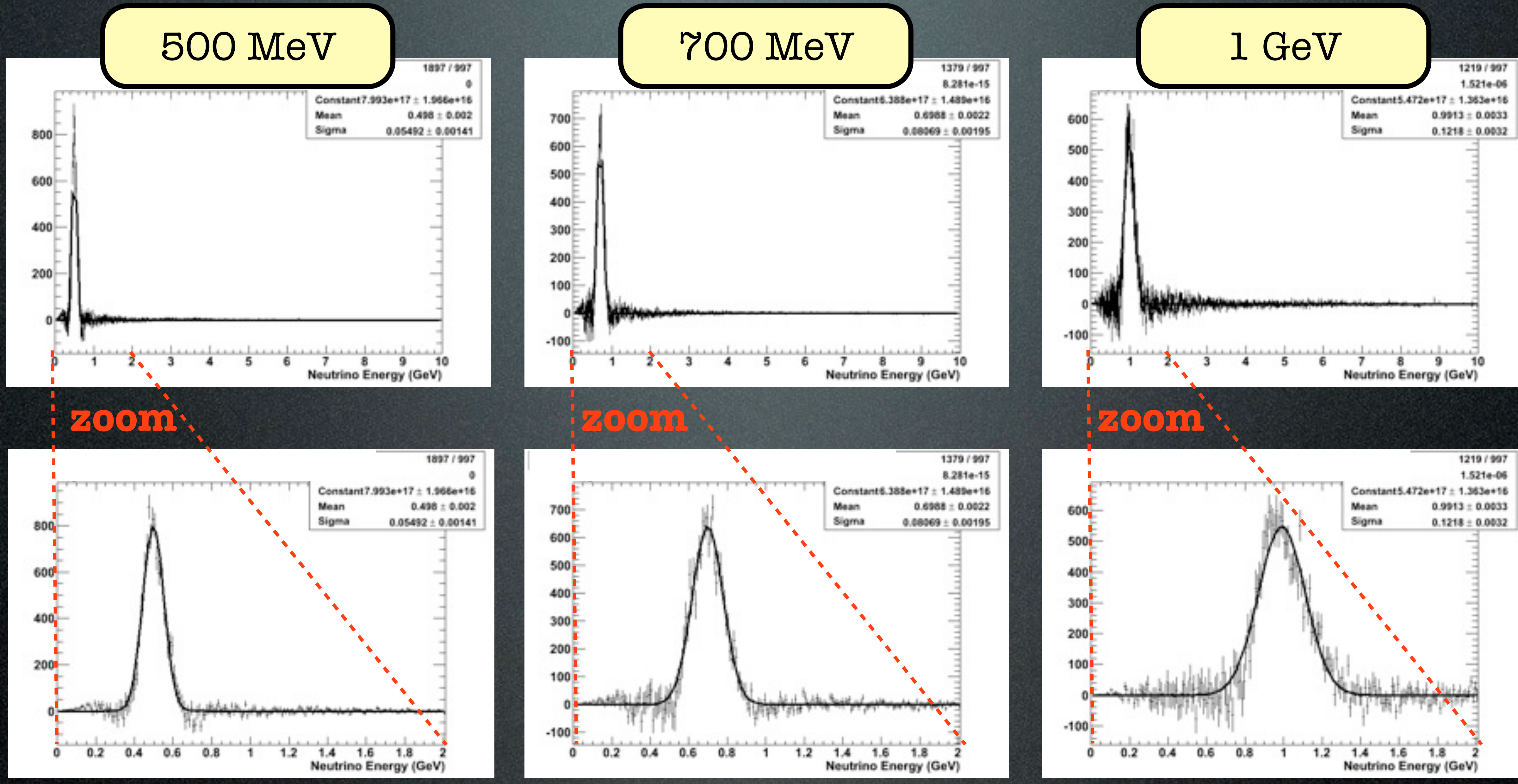
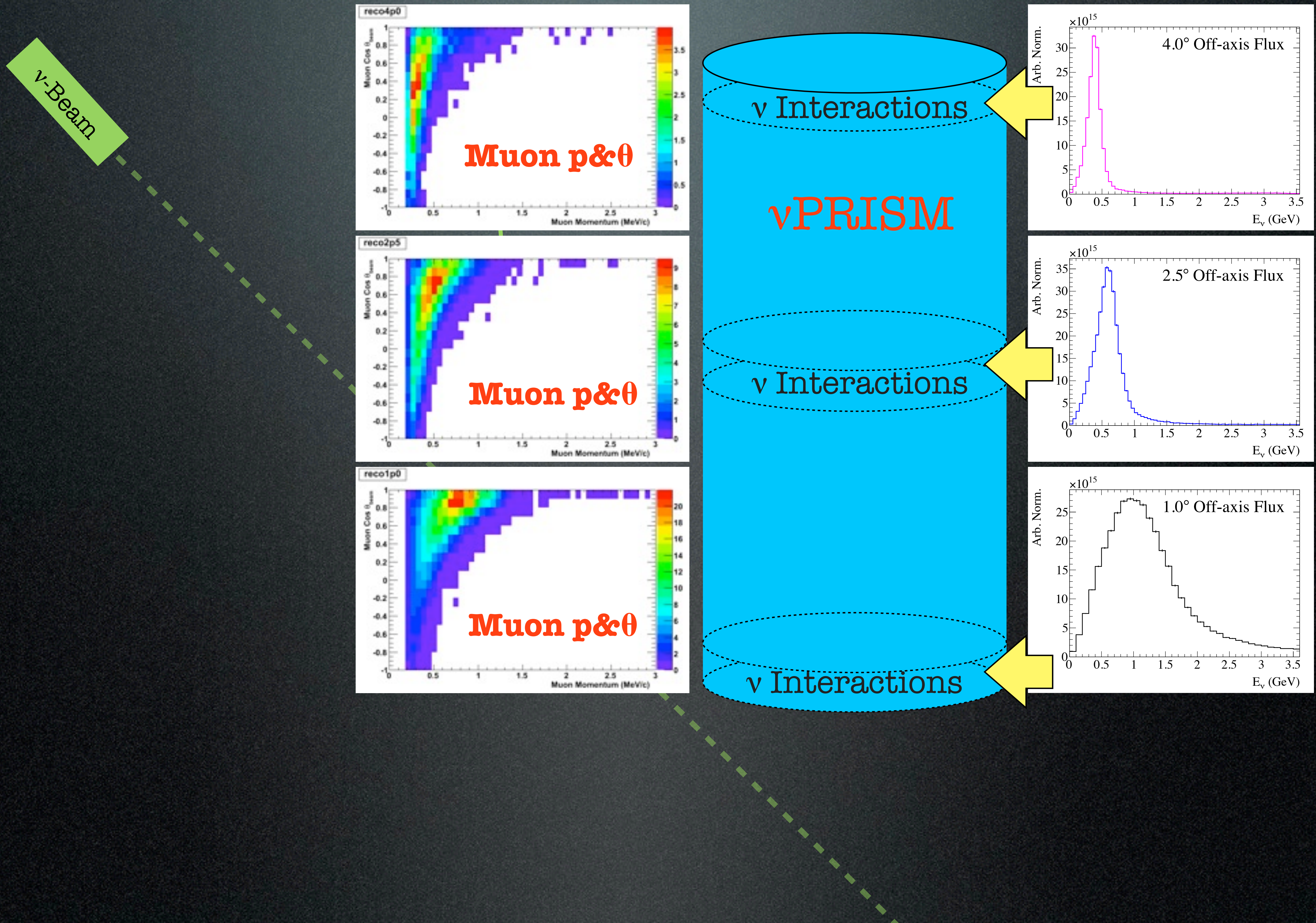


Neutrino Spectrometer



- Gaussian-like spectra can be produced for any choice of neutrino energy (between ~0.4 and ~1 GeV)
  - Depends on off axis angle range (6°→ 0.25 GeV, 0°→ 1.2 GeV)
- High energy flux tail is canceled in all cases

Removing Near/Far Flux Differences



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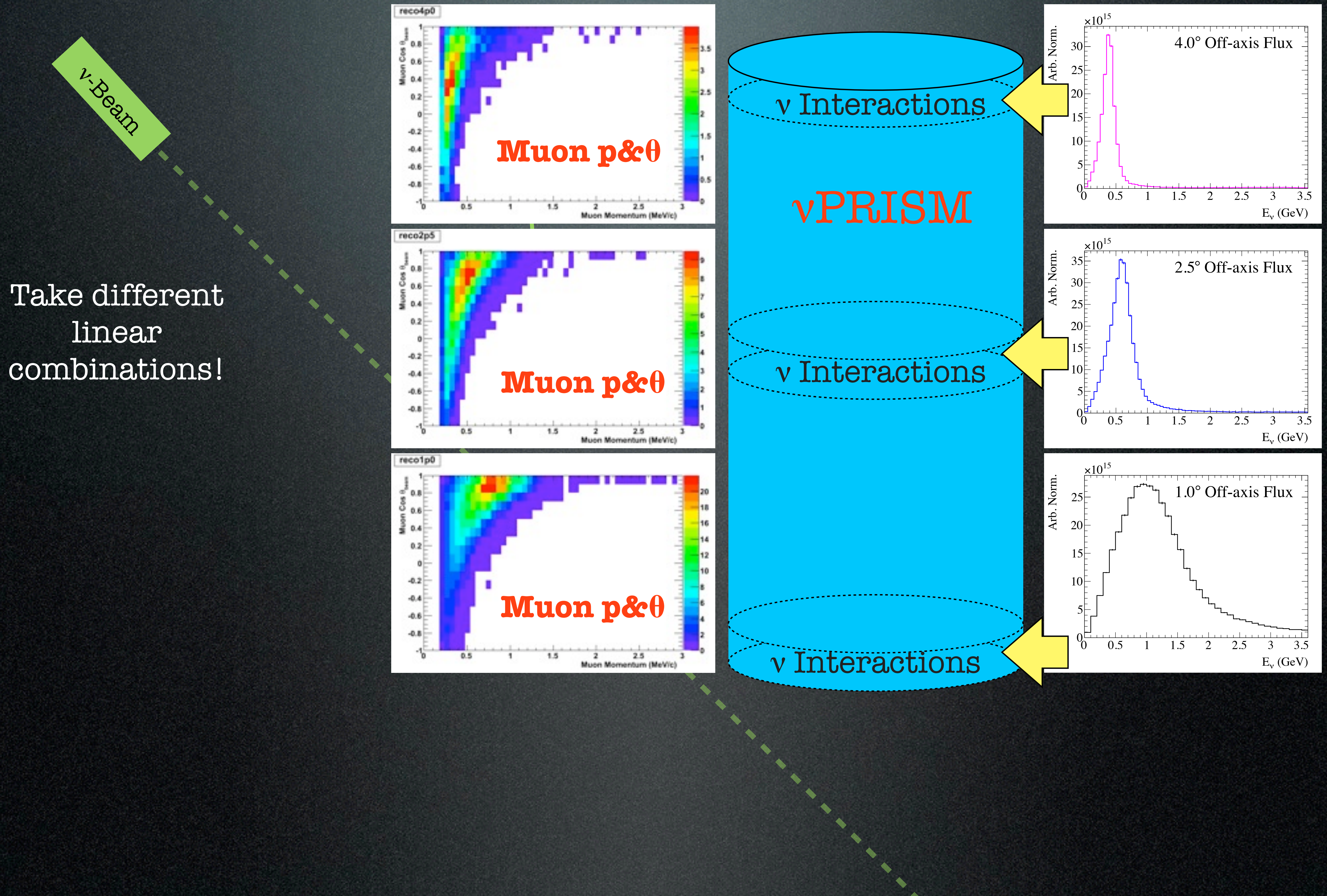

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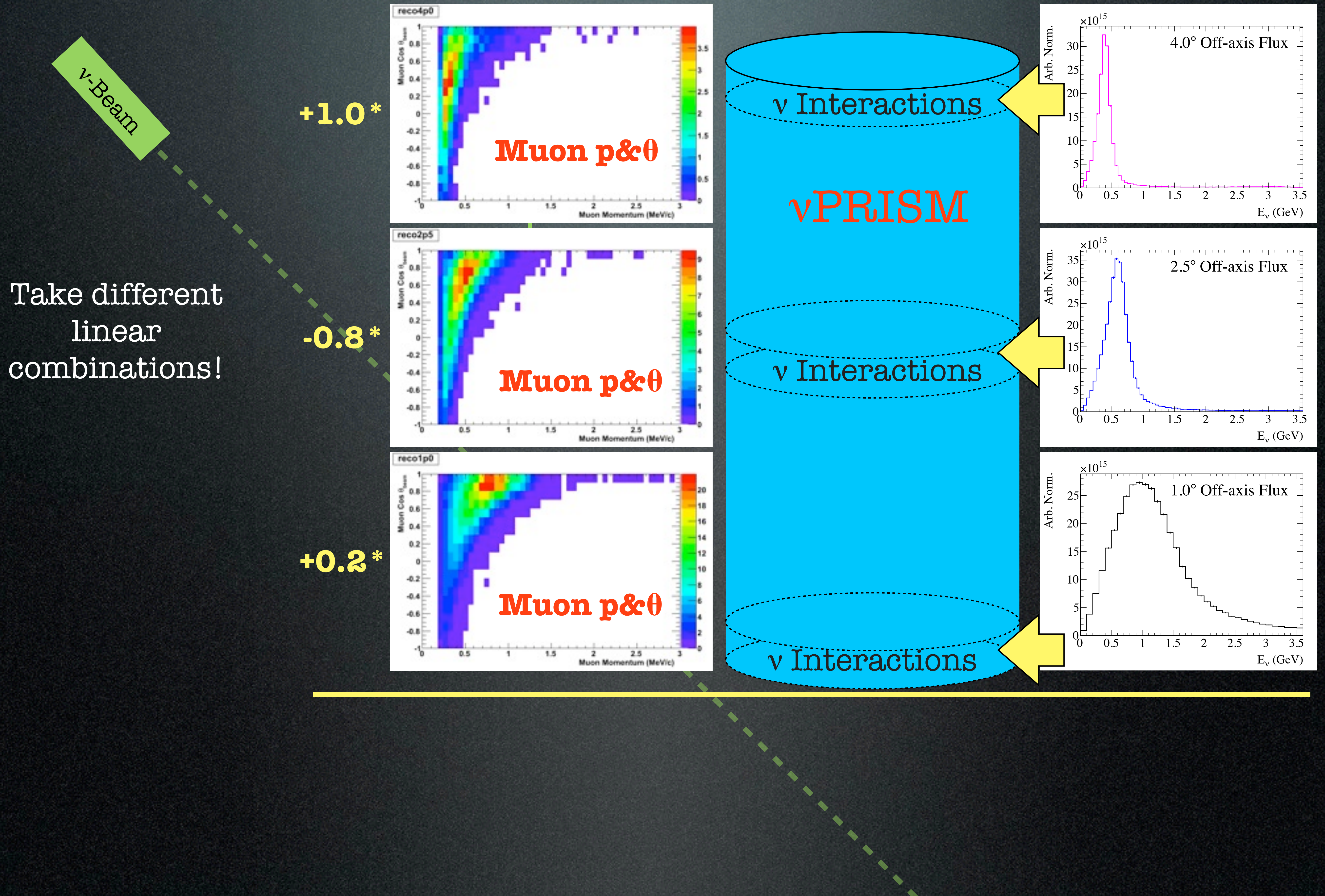
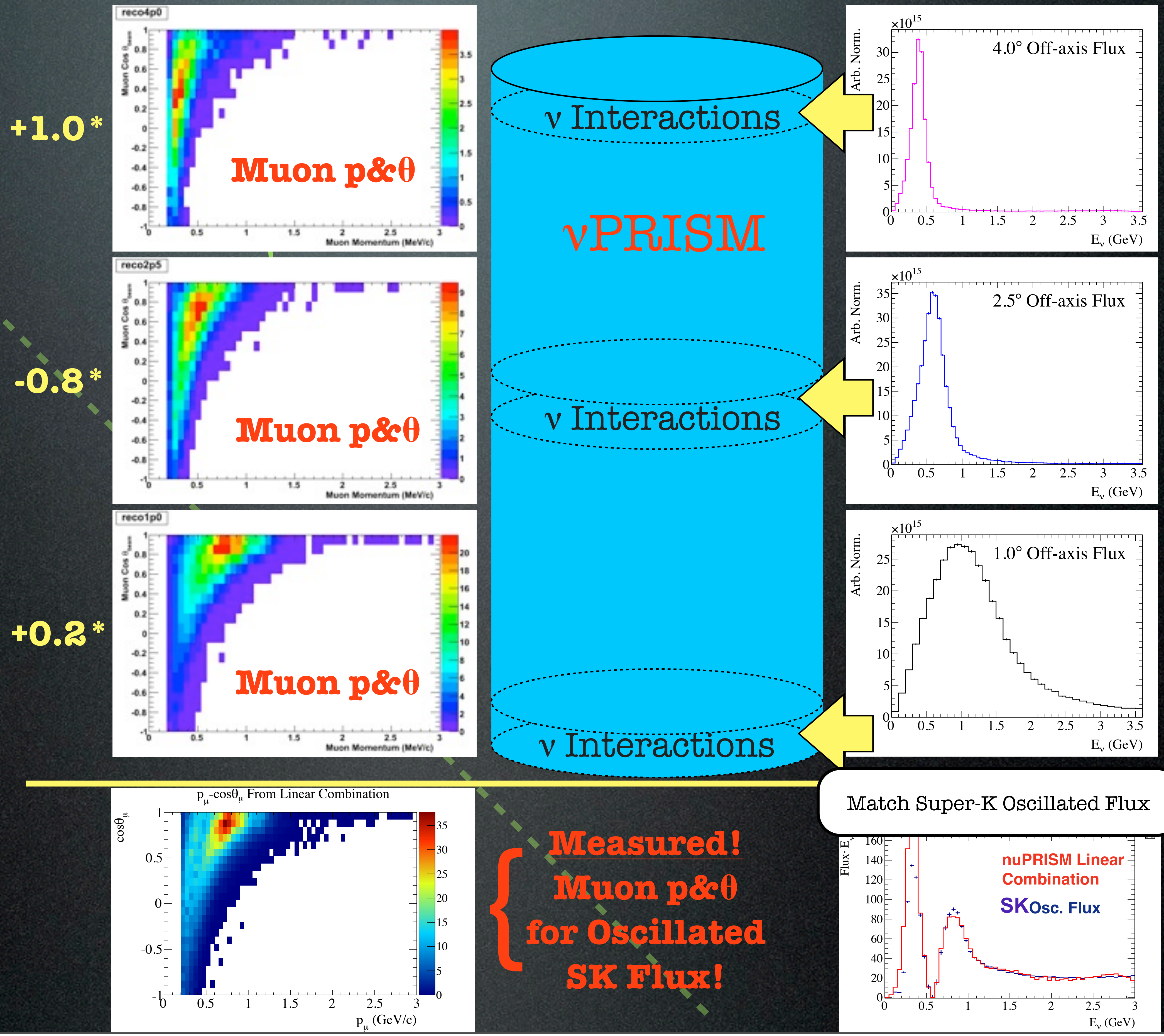


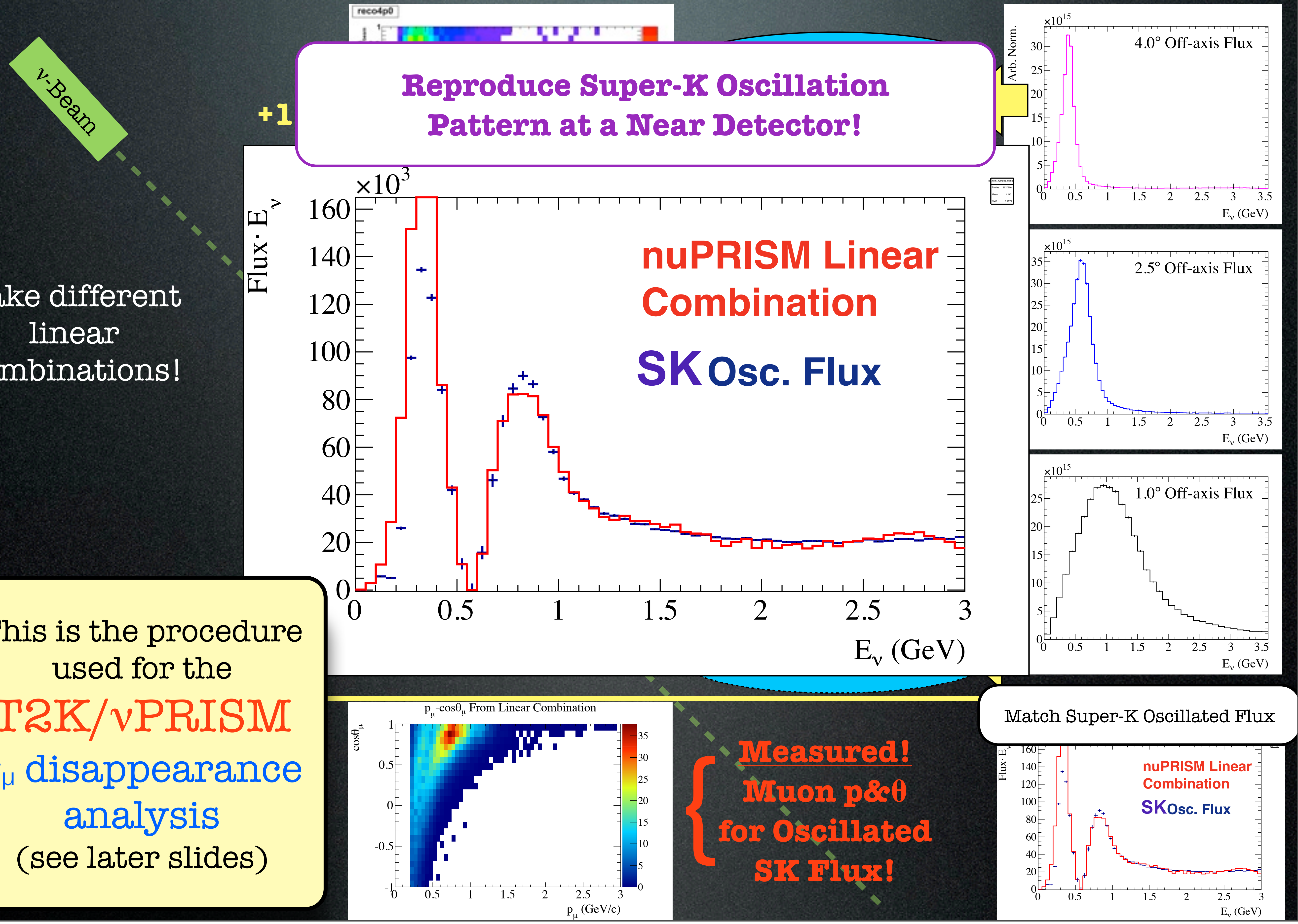
Removing Near/Far Flux Differences

ν-Beam

Take different linear combinations!



Removing Near/Far Flux Differences



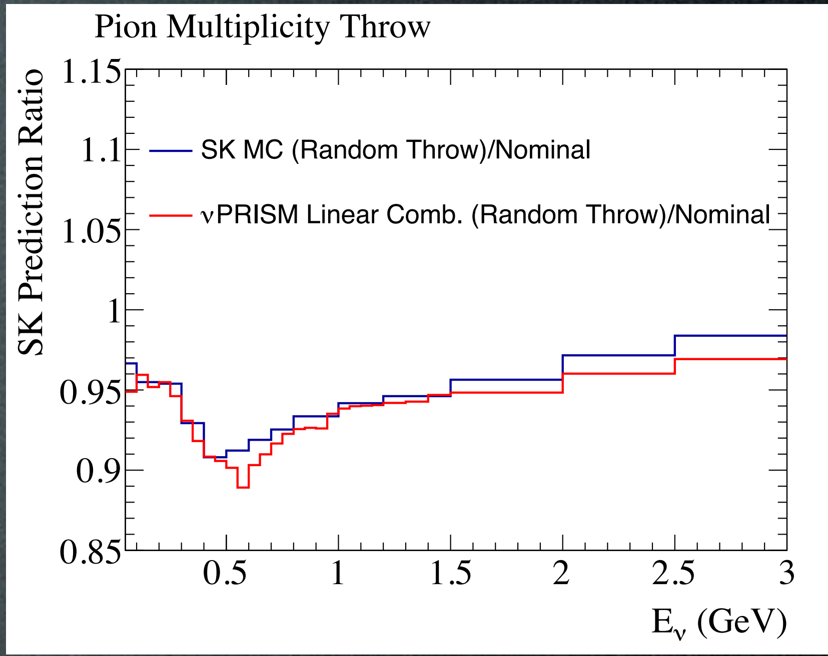
Take different linear combinations!

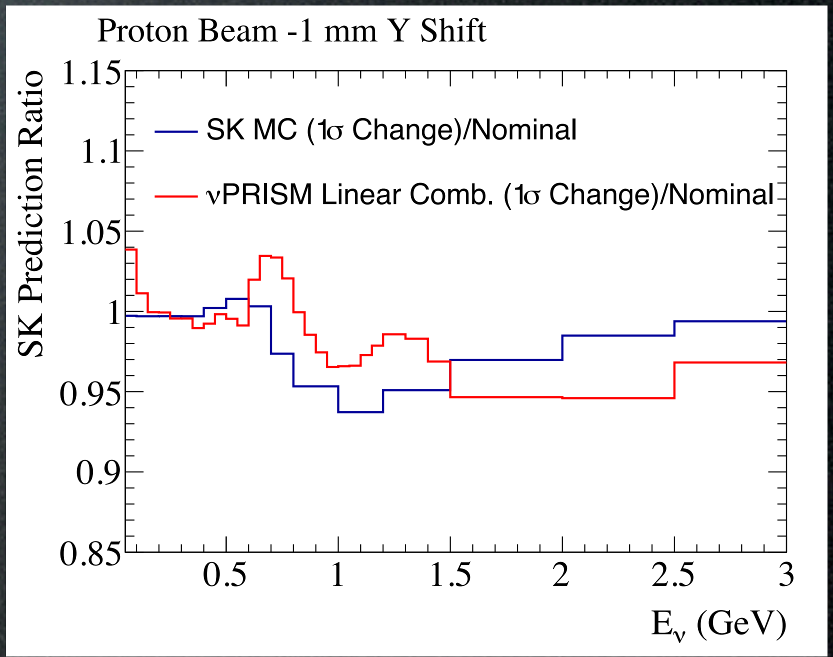
This is the procedure used for the T2K/νPRISM ν_μ disappearance analysis (see later slides)

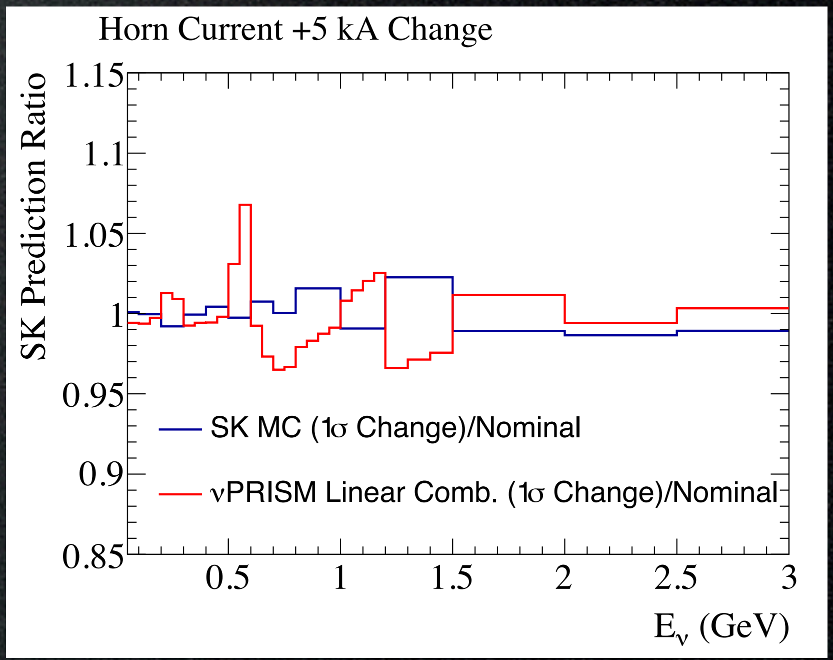
Measured! Muon p&θ for Oscillated SK Flux!

Beam Uncertainties

- Haven't we just replaced **unknown cross section errors** with **unknown flux errors**?
  - Yes! But only relative flux errors are important!
  - Cancelation exist between νPRISM 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 already reasonable!
  - No constraint used (yet) from existing near detectors
    - Uncertainties set by NA61 and T2K beam data



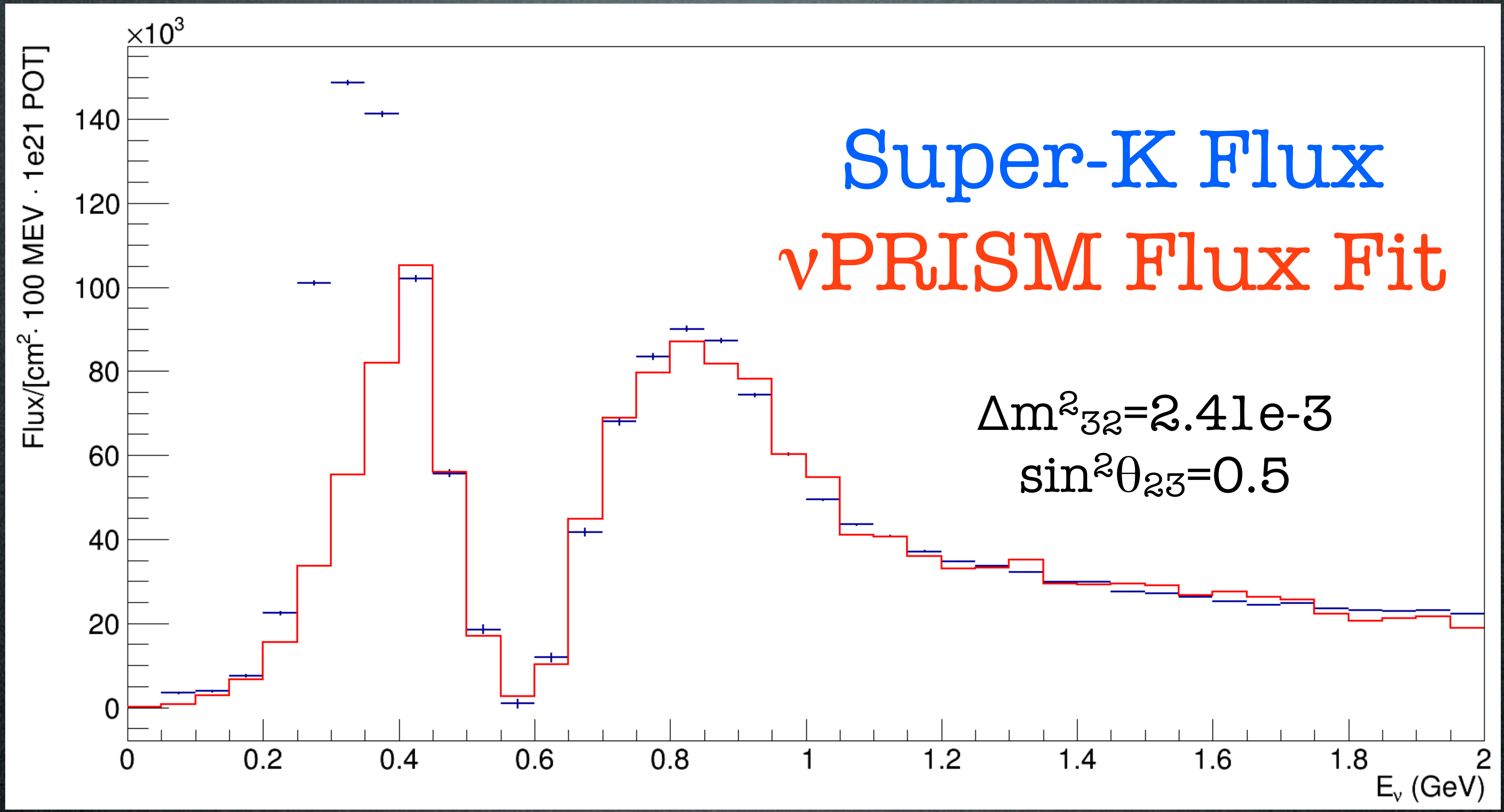




The T2K-νPRISM ν_μ Disappearance Analysis

Most straightforward to perform, and directly impacts sensitivity to CP violation

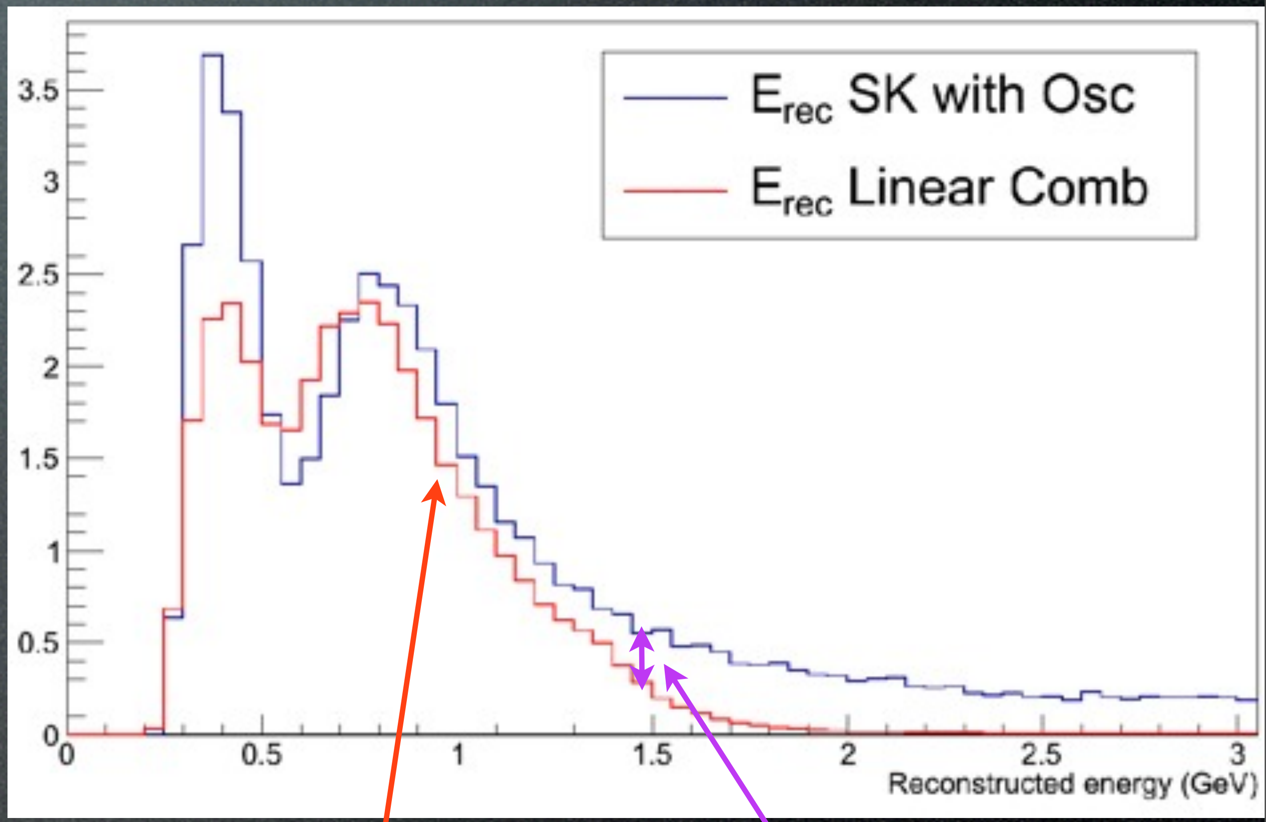
Flux Fit



- Fit for coefficients of 30 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_{rec} Distribution

- **For now, collapse 2D muon p,θ distribution into 1D E_{rec} plot**
  - Use CCQE formula
    - Arbitrary choice! This introduces negligible model dependence
  - Eventually, we will just use p,θ bins directly
- **Notice the νPRISM and SK distributions disagree**
  - If they didn't, we would have no cross section systematic errors (modulo previously discussed flux variations)
  - Differences are from detector acceptance & resolution, and imperfect flux fit
- **Super-K prediction is now given by directly-measured νPRISM spectrum!**
  - T2K measurements are now largely independent of cross section modeling!

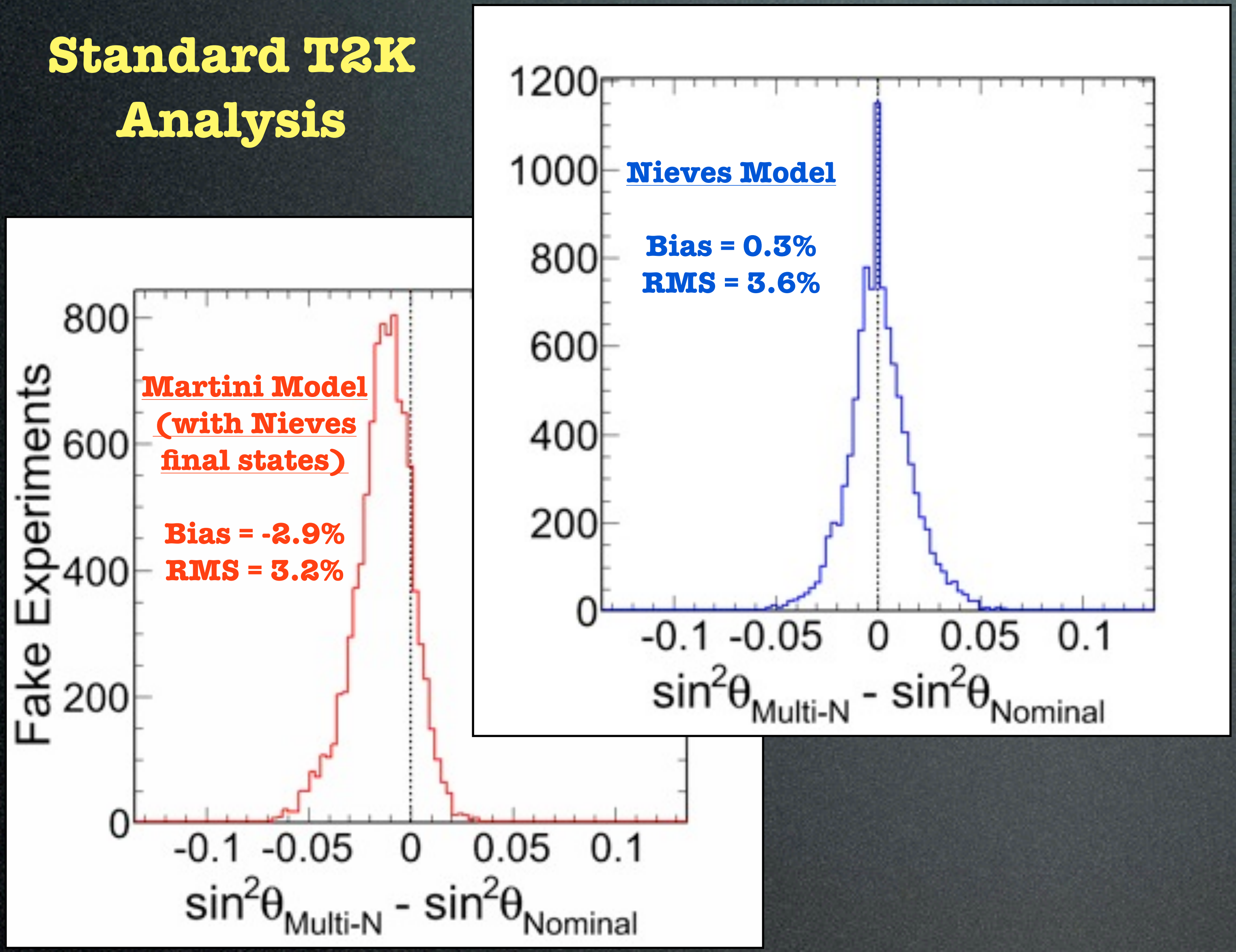


directly measured component

model-dependent correction factor (systematic uncertainty)

νPRISM ν_μ Disappearance Constraint

Standard T2K Analysis



νPRISM ν_μ Disappearance Constraint

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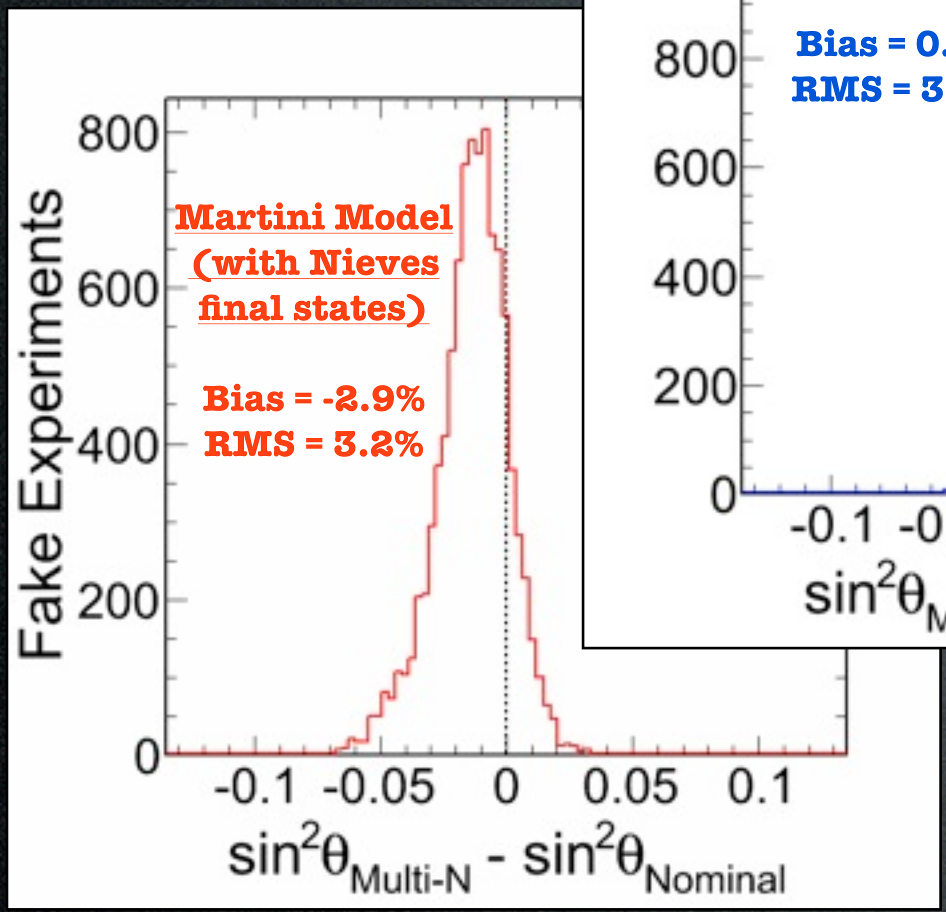

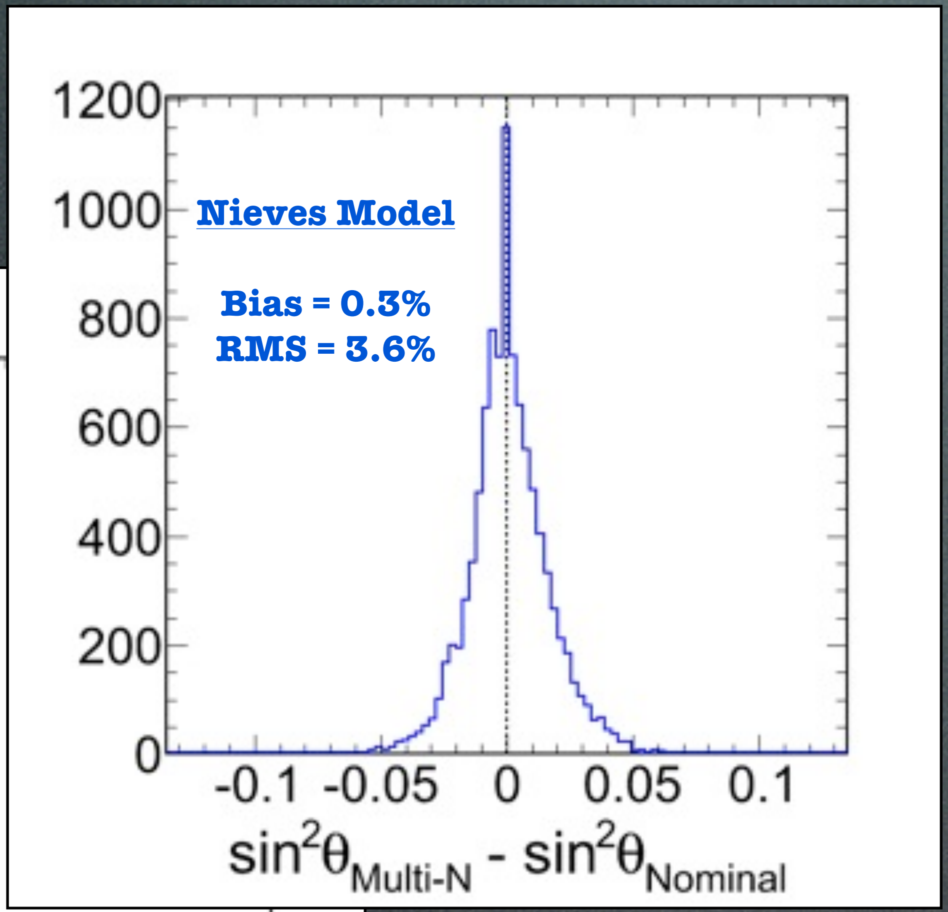

νPRISM Analysis

νPRISM ν_μ Disappearance Constraint

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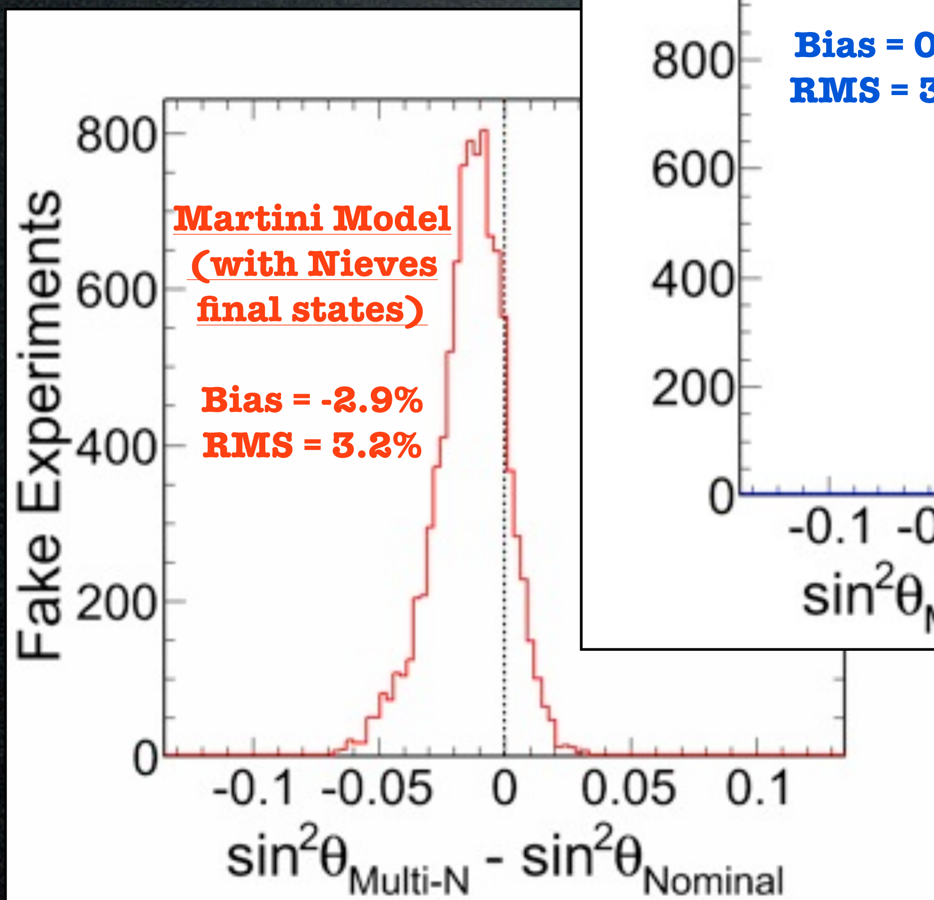

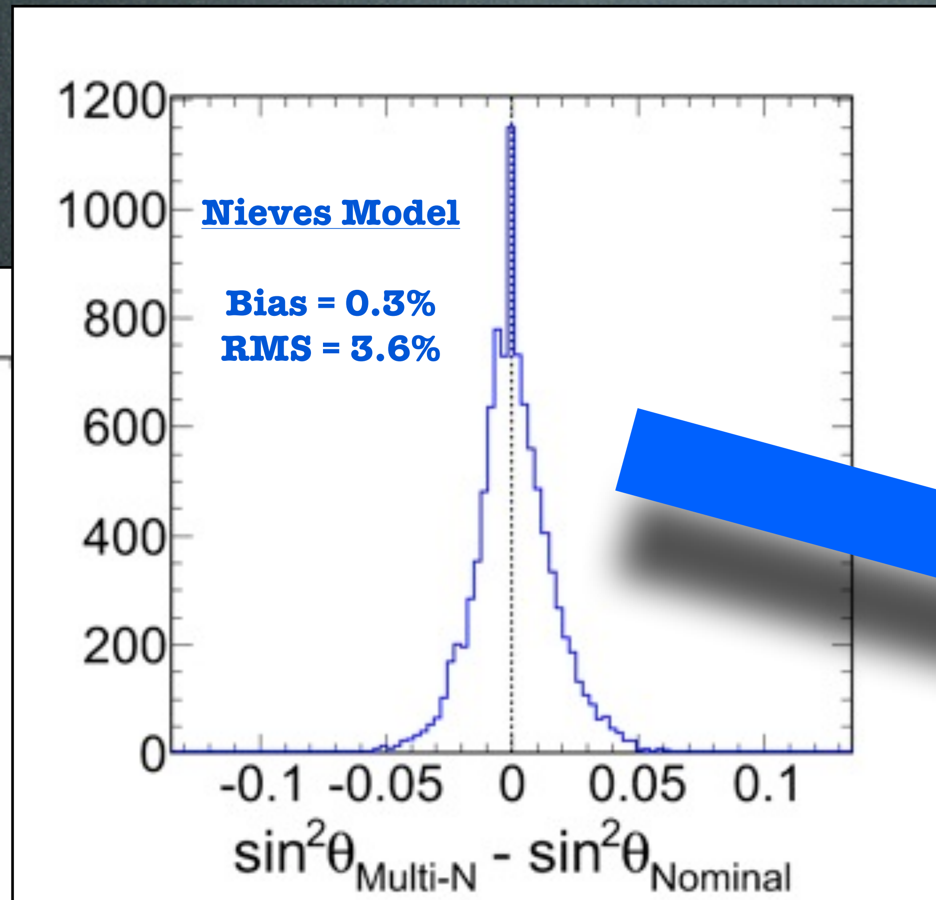

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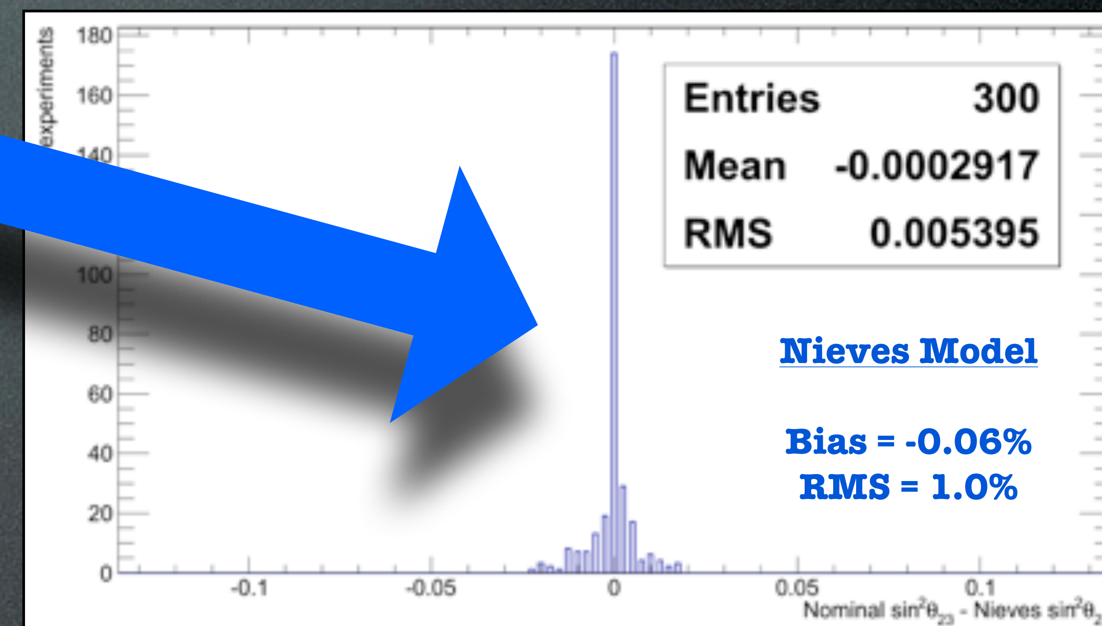

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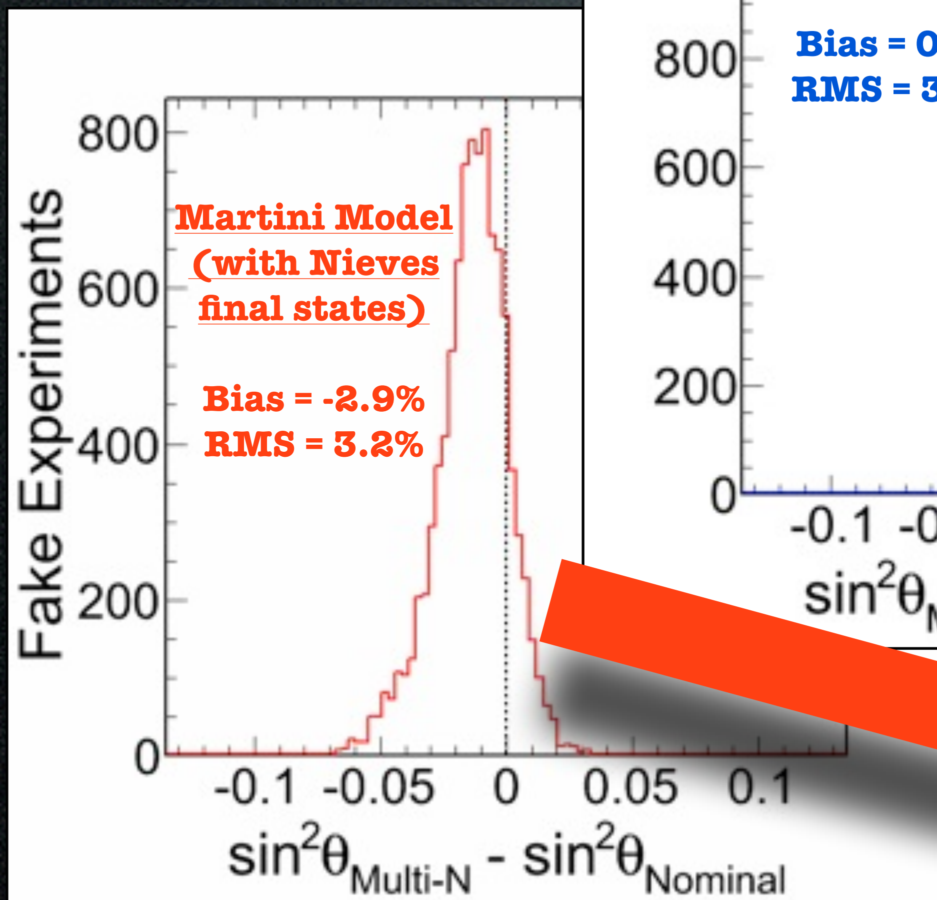
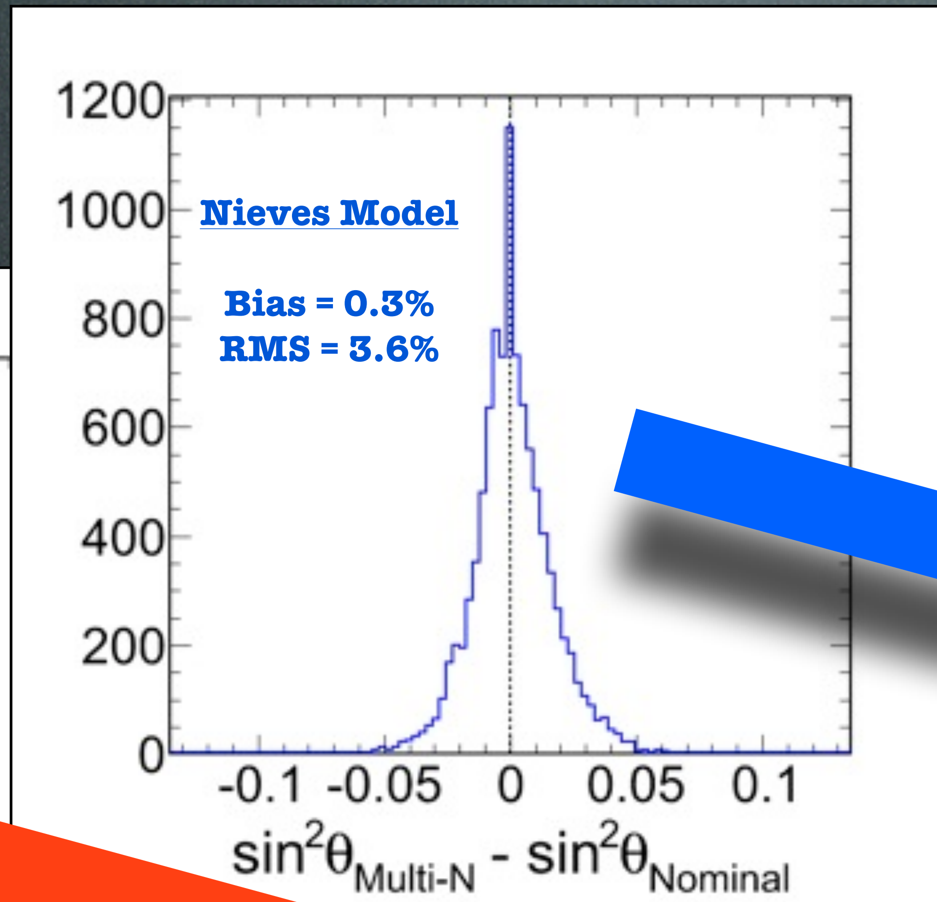
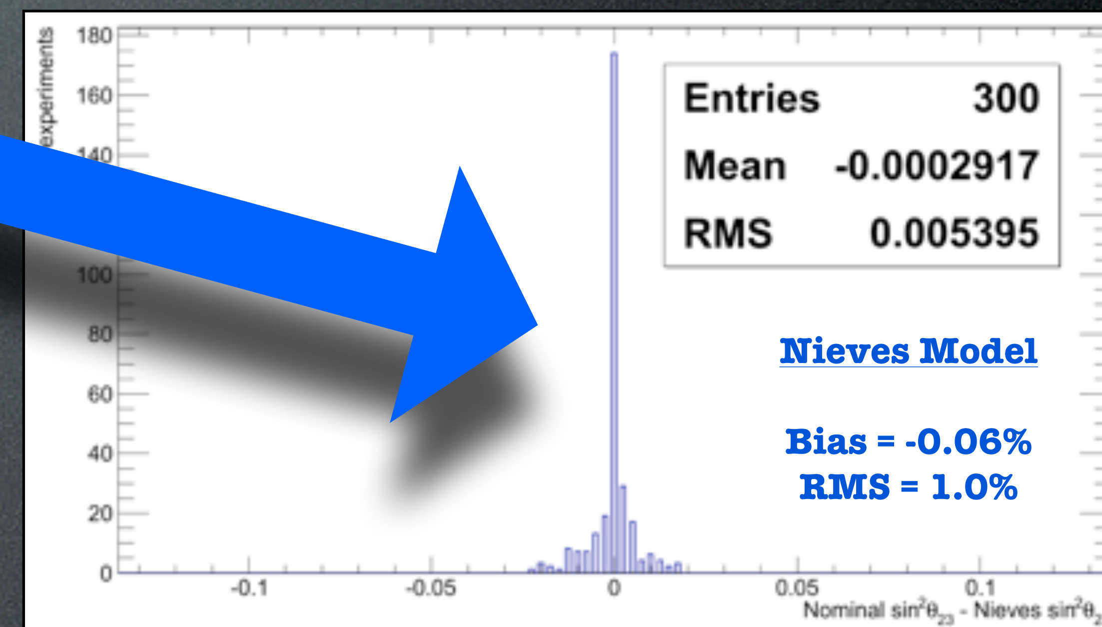
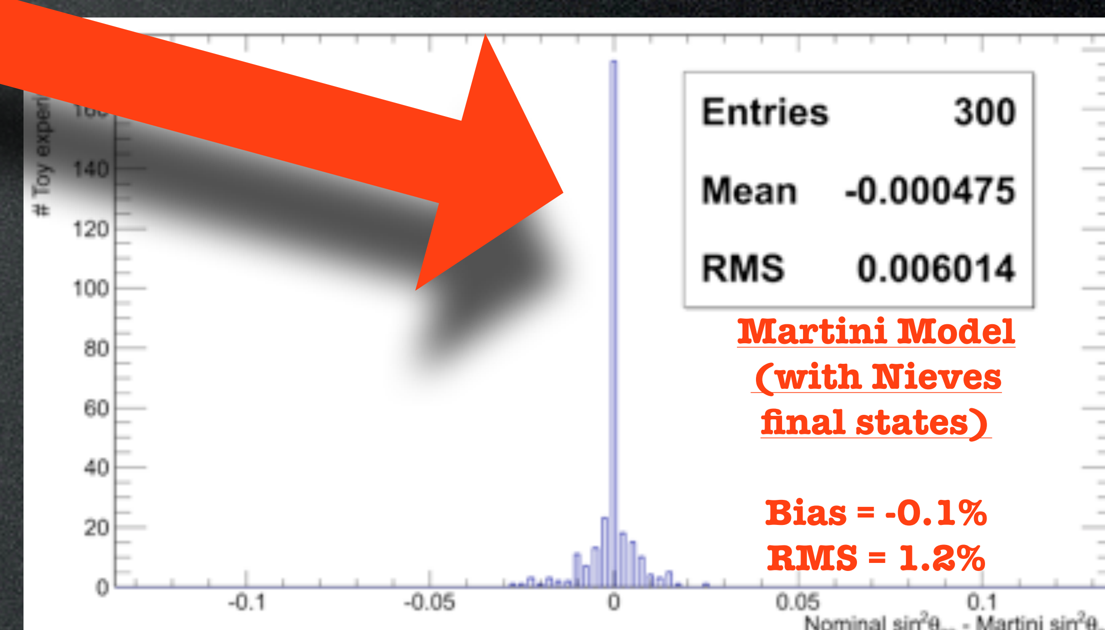
Standard T2K Analysis





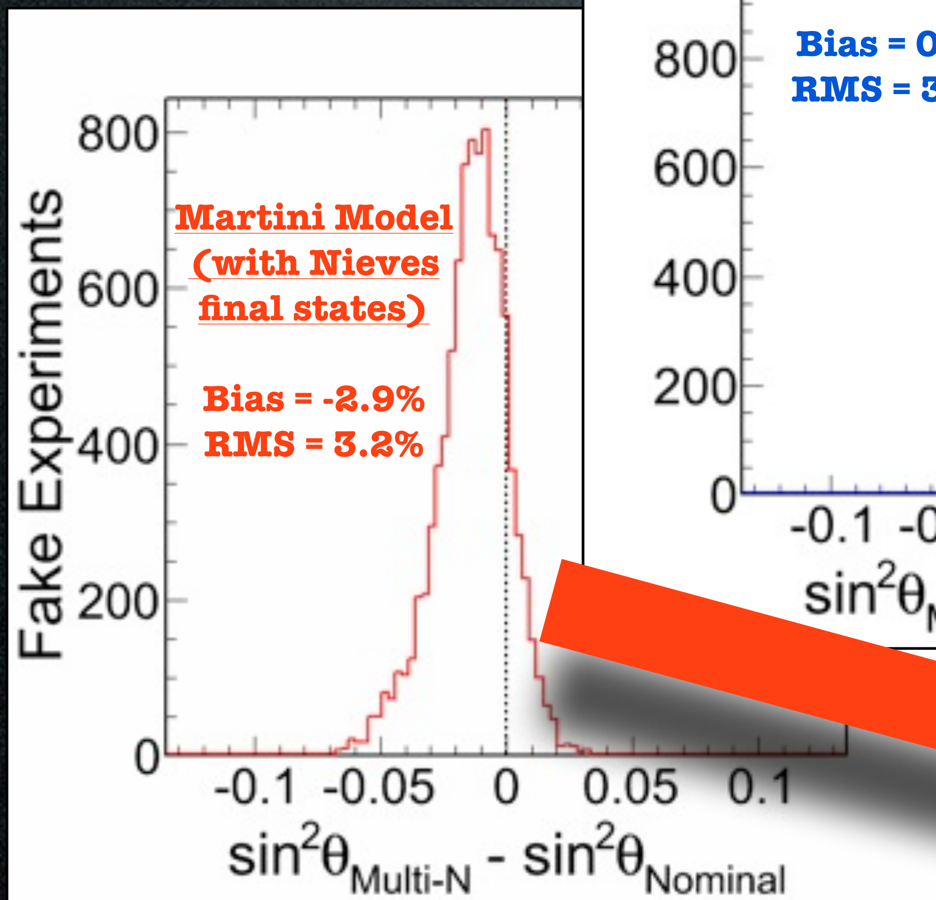
νPRISM Analysis

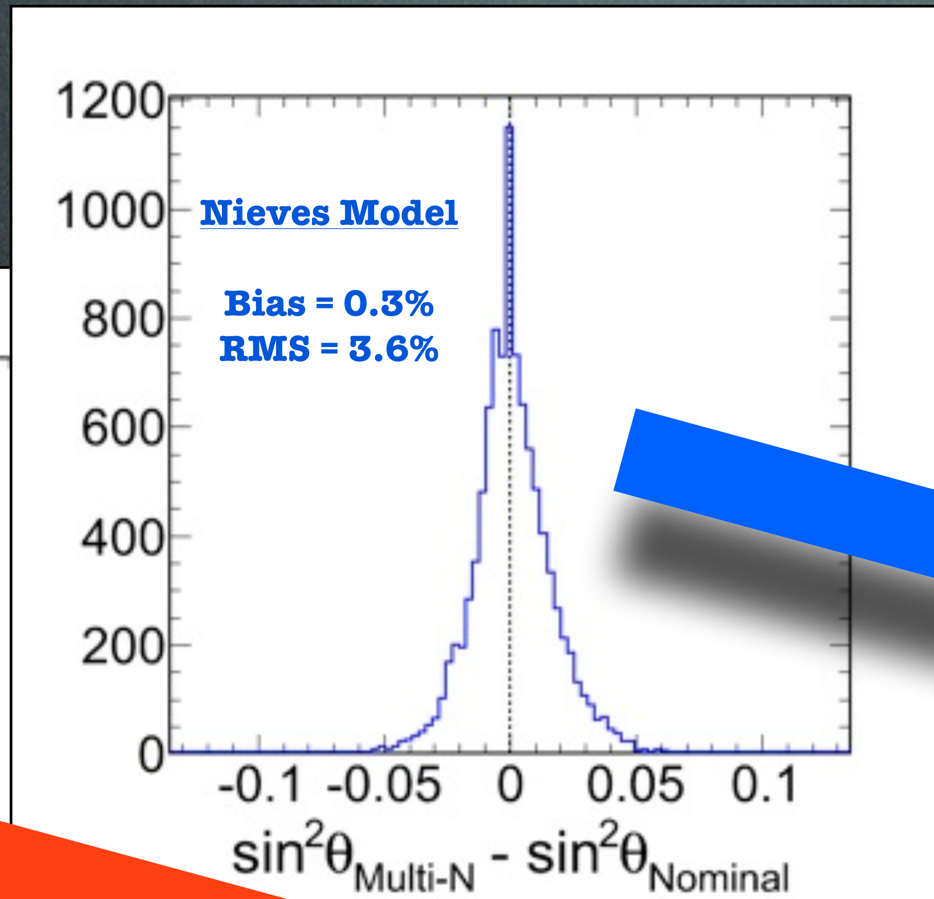




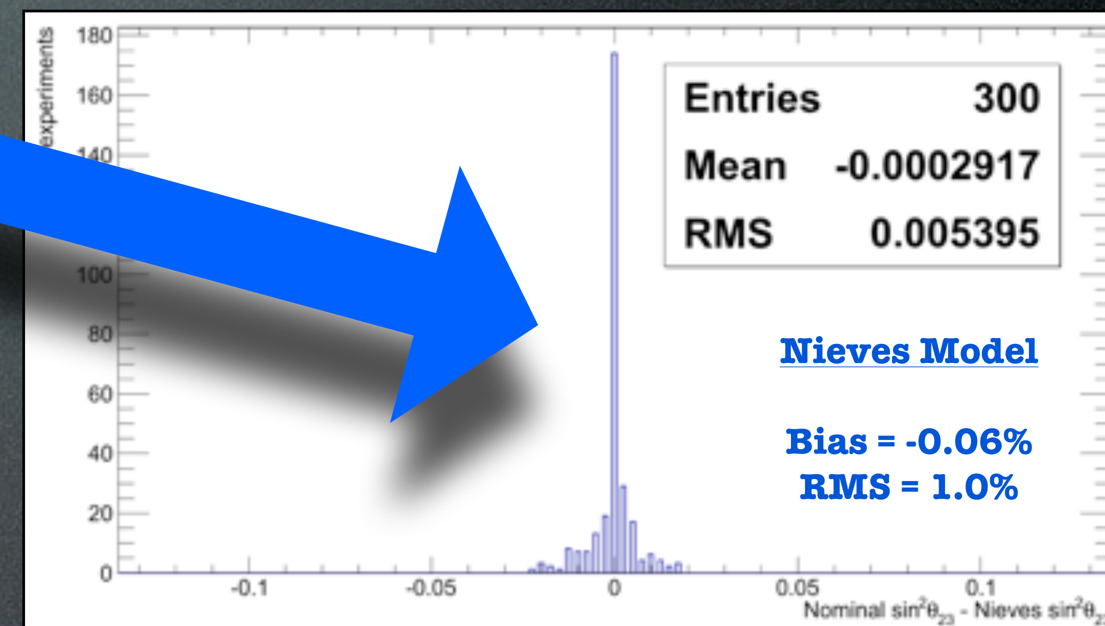
νPRISM ν_μ Disappearance Constraint

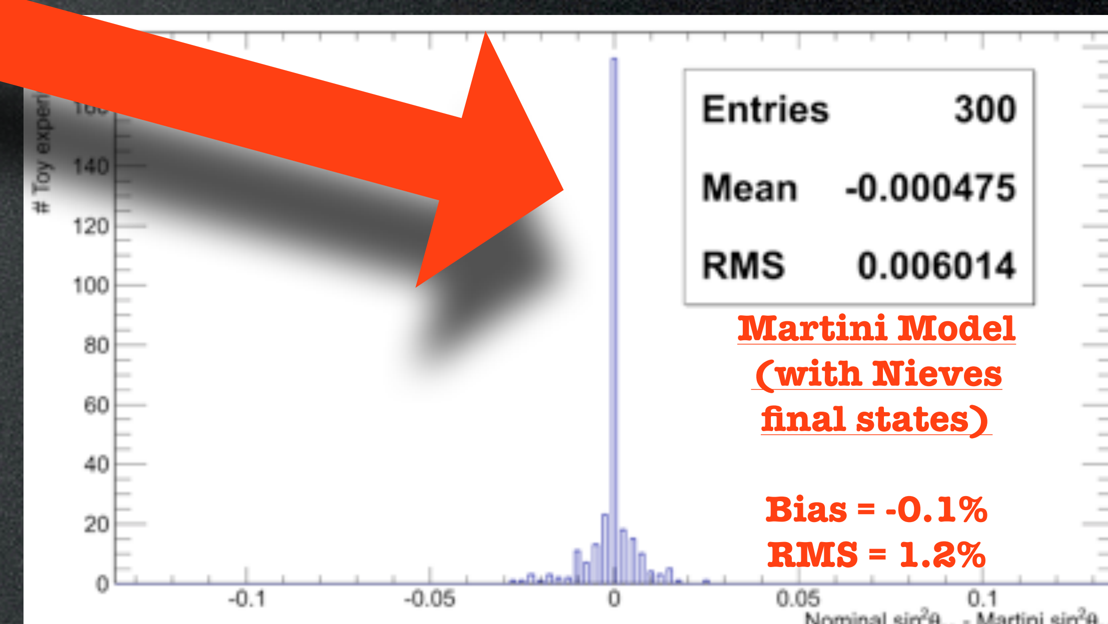
Standard T2K Analysis





νPRISM Analysis

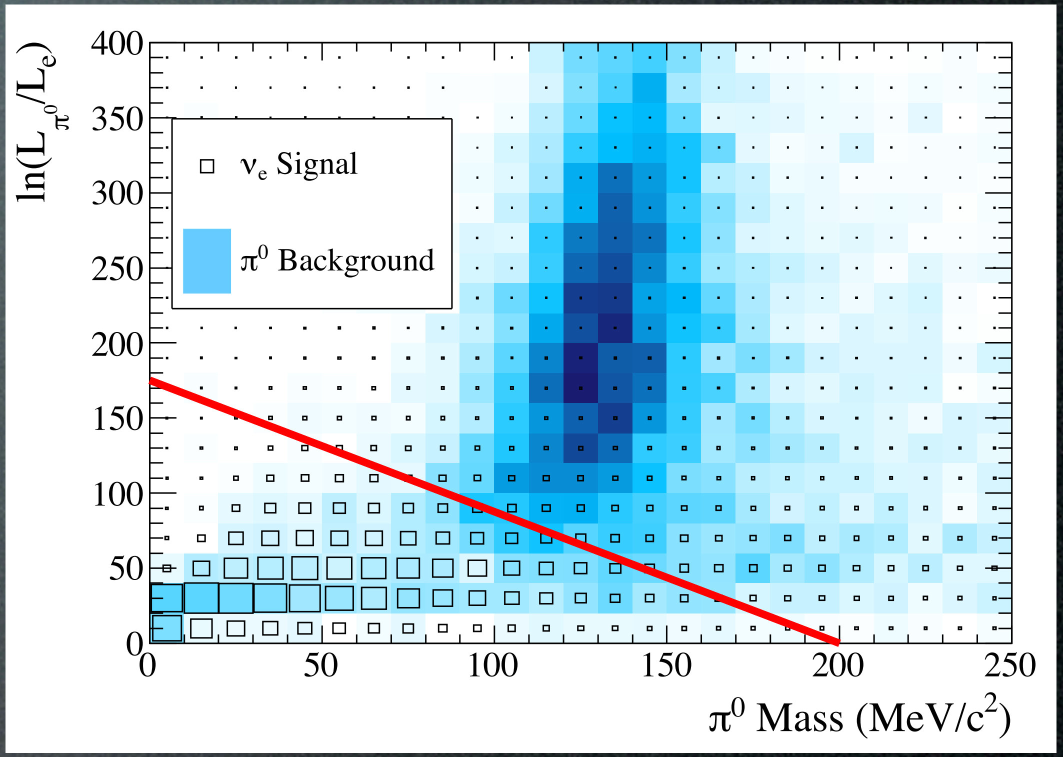


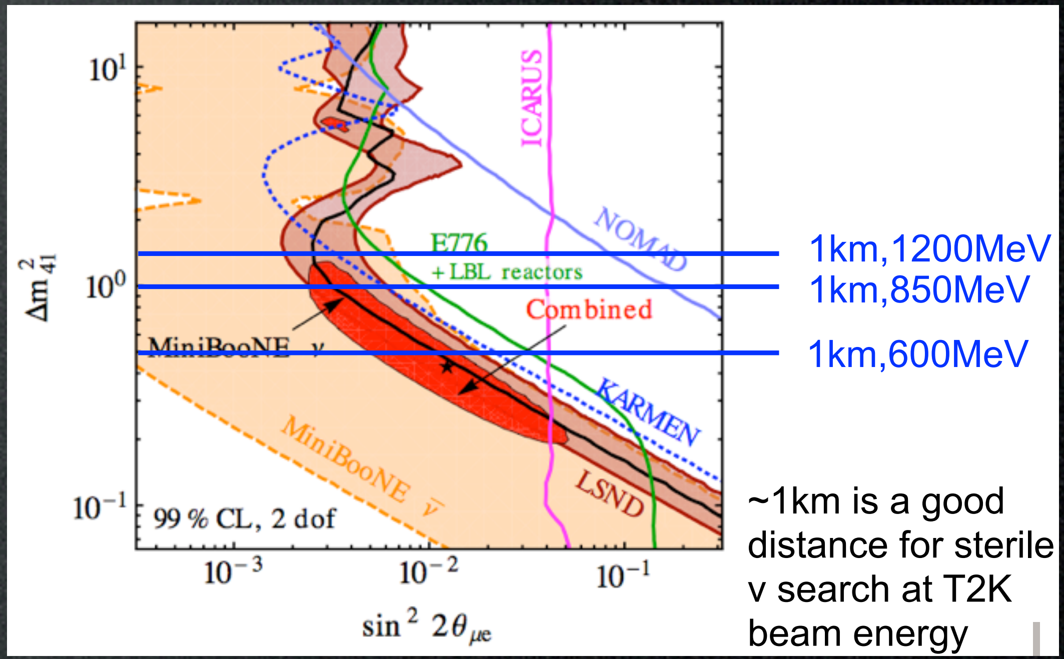


- νPRISM analysis is largely independent of assumed cross section model
  - Using conservative systematics
  - Without using any information from the existing near detector
- Data-driven constraint is possible!

Other νPRISM Capabilities

- Measurement of $\sigma(\nu_e)/\sigma(\nu_\mu)$
  - Reproduce νPRISM ν_e flux with νPRISM ν_μ combinations
  - Flux cancels in p,θ ratio
  - Recently, large improvements in π^0 detection in WC detectors
- Unique, redundant sterile neutrino measurements
  - Good coverage of MiniBooNE region
  - One "L" but many "E"!
- Much more to come!





Upgrade Timescales

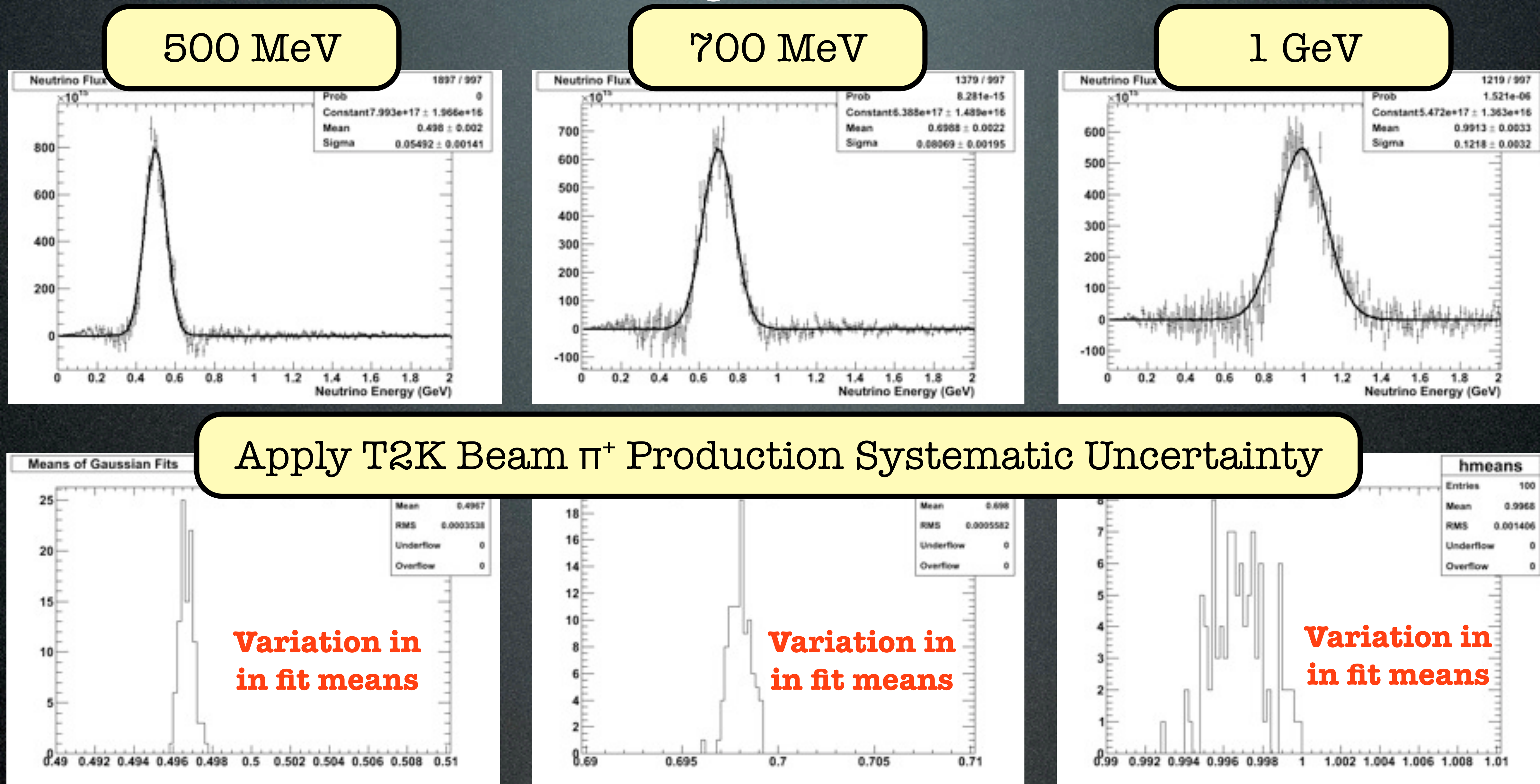
- **Short term: ~1-2 years**
(upgrades that utilize existing hardware)
    - Replacing water targets with D_2O
- **Mid term: ~2-3 years**
(upgrades that require significant modifications to existing hardware)
    - Instrumenting liquid volumes for use with water-based liquid scintillator
- **Longer term: ~4-5 years**
(upgrades that require new detectors or significant R&D)
    - Replacing scintillator bars with bars of finely segmented scintillator-doped water
    - High pressure Neon TPC
    - νPRISM
- J-PARC beam upgrade from 300 kW to 700 kW is **expected in 2018**
    - Any chosen project would aim to be ready for the upgraded beam

Summary

- Several near detector upgrades are currently being considered within the T2K collaboration
  - Addition of deuterium targets
  - Water-based liquid scintillator to measure vertex activity in water targets
  - High pressure neon TPC
  - νPRISM: an experimental method to remove neutrino model uncertainties
- Decisions regarding which upgrades will go ahead will be made in the next ~1 year

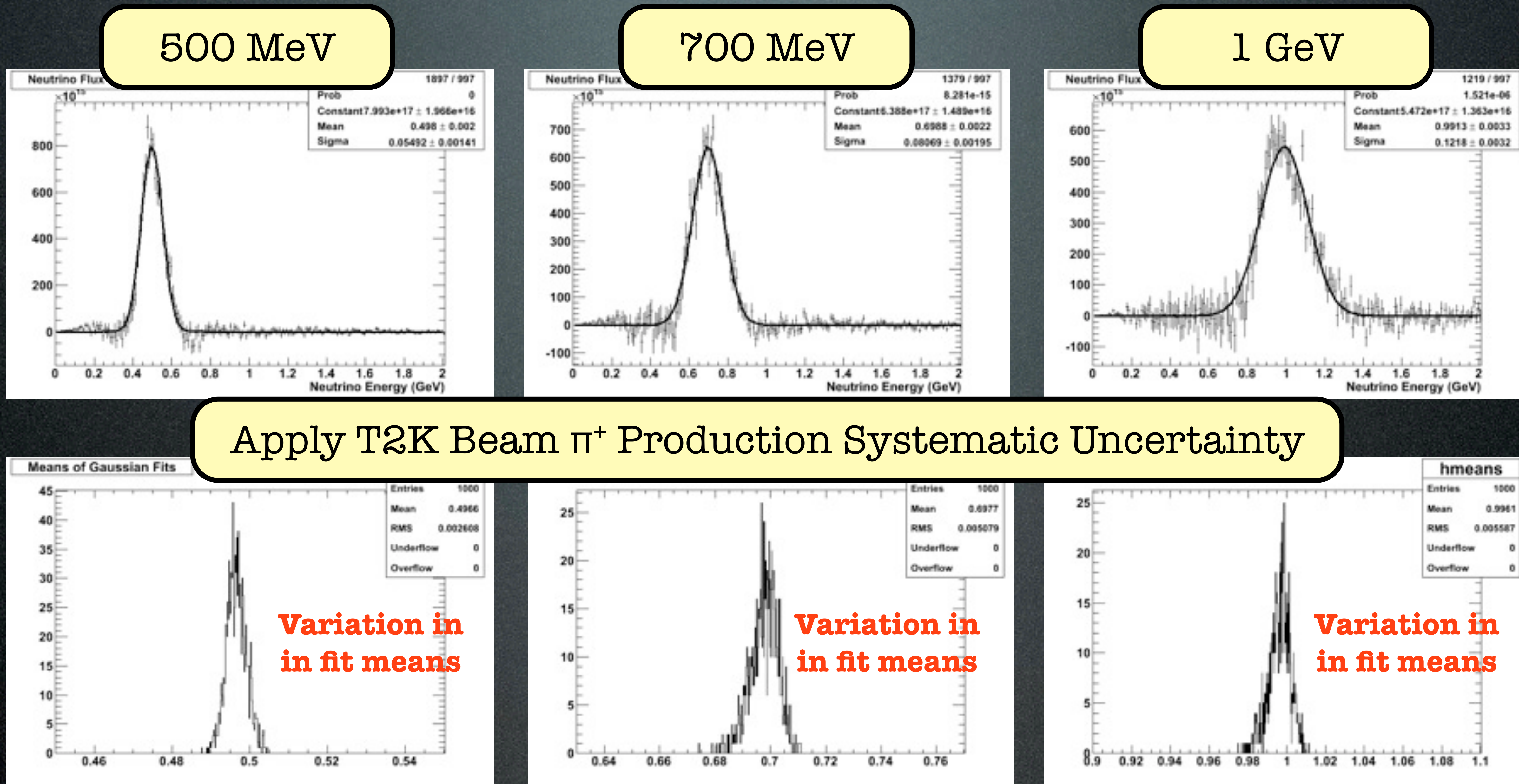
Supplement

Beam Systematics



- Apply **T2K π^+ production variations** to flux linear combinations
  - This is expected to be the dominant normalization uncertainty for T2HK
- Spread in neutrino energy due to π^+ production **uncertainty is $\mathcal{O}$(0.1%)**
  - More detailed study needed, but so far looks promising

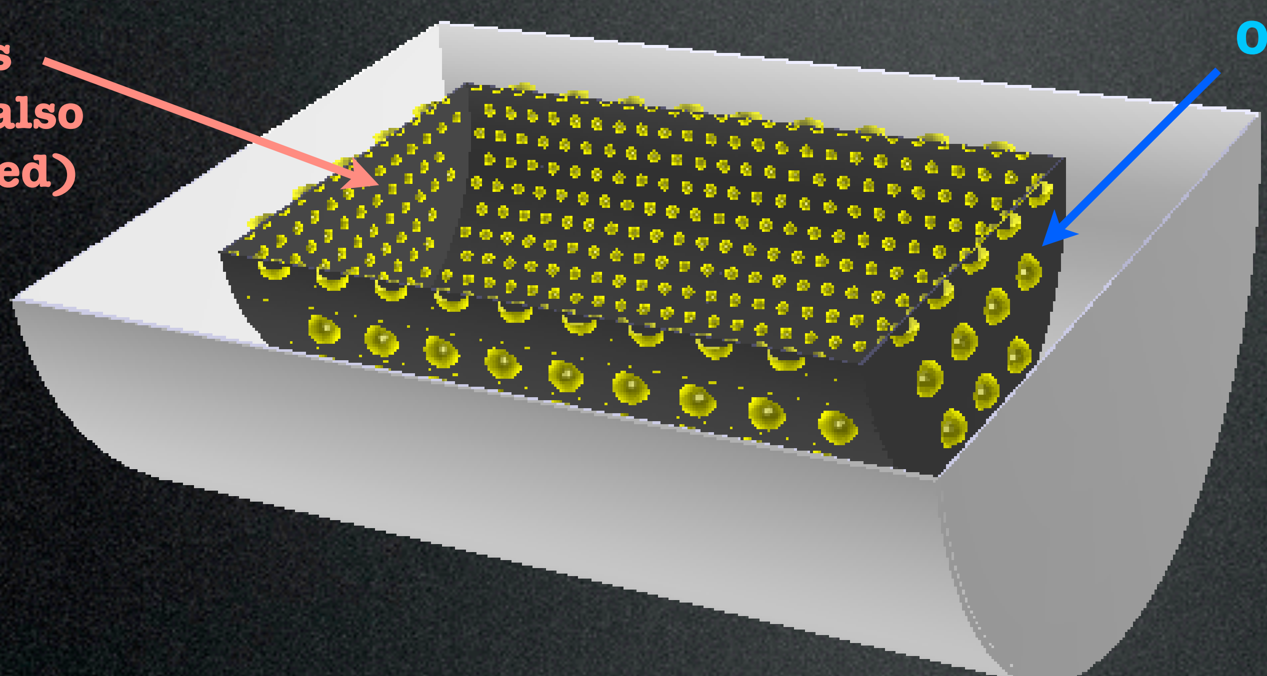
Detector Systematics

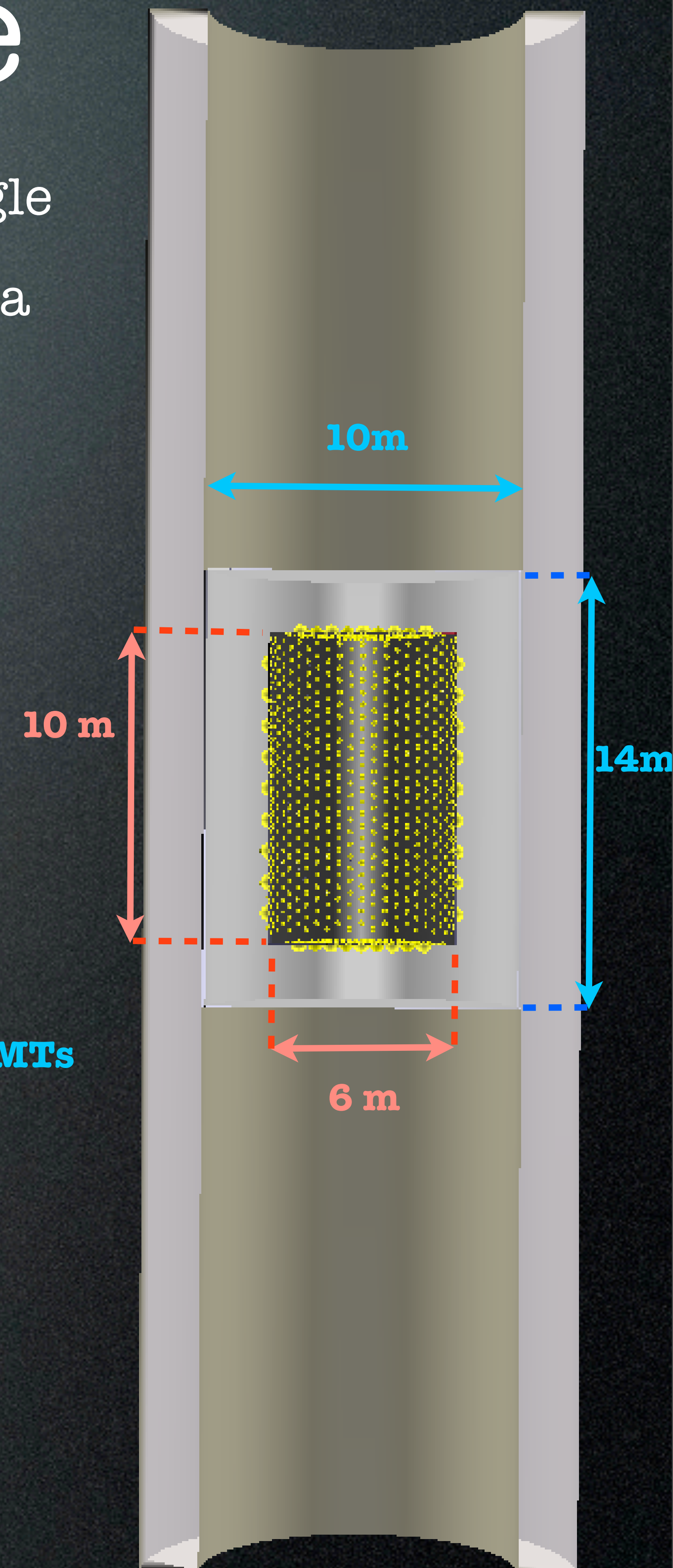


- Efficiency was randomly varied by 5% in each slice
    - The resulting variations in the fit means are still all below 1%
- Continuous variations across the detector can cause problems
    - Need homogeneous detector, and good monitoring & calibration

νPRISM-Lite

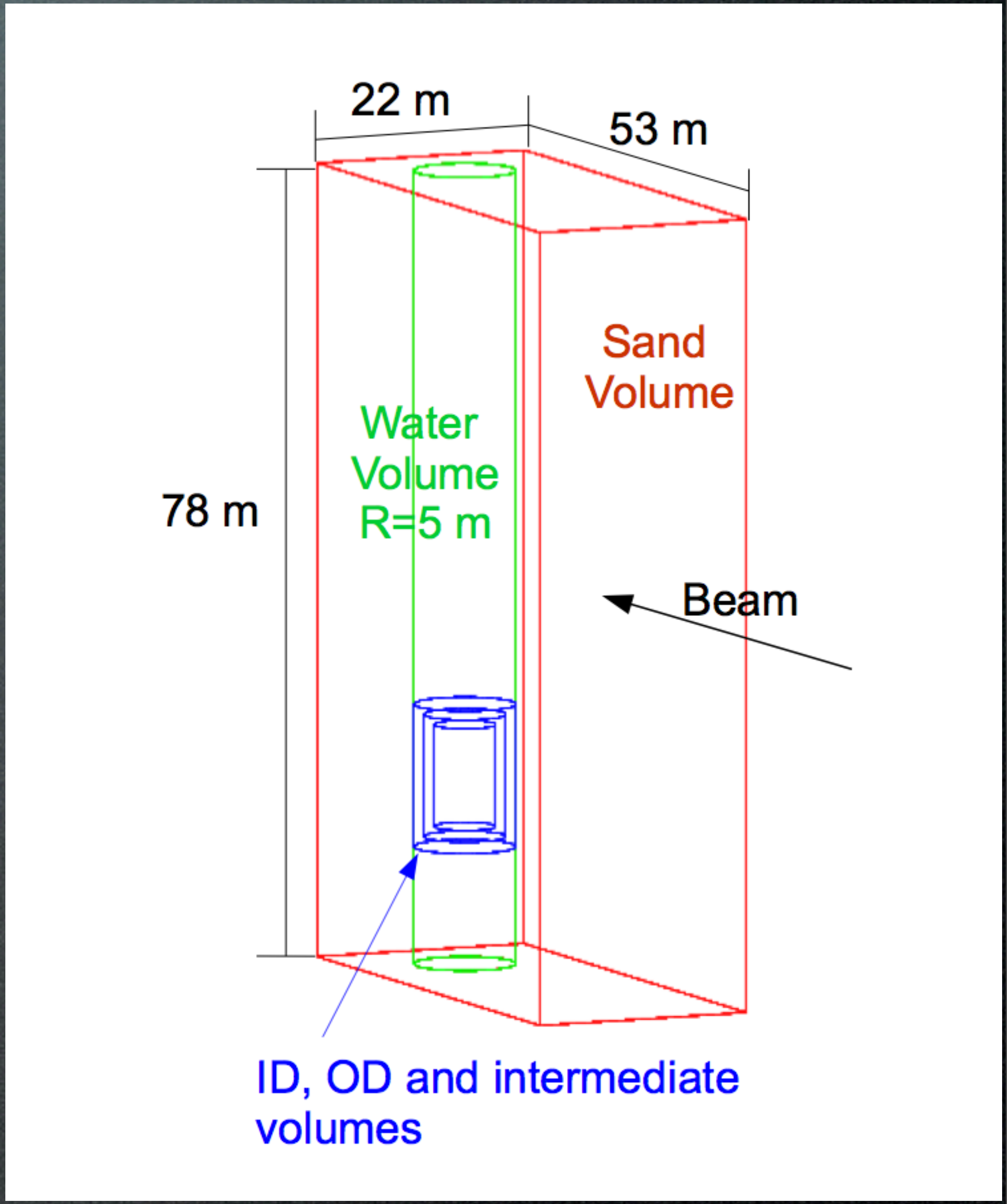
- At 1 km, need 50 m tall tank to span 1-4° off-axis angle
- Instrument one subsection of the tank at a time with a moveable detector
- Baseline design:
    - Inner Detector (ID): 6m diameter, 10m tall
    - Outer Detector (OD): 10m diameter, 14m tall
- To improve sand muon tagging (precise entering position and time), OD is surrounded by scintillator panels (not pictured)





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!

νPRISM Prediction for Super-K

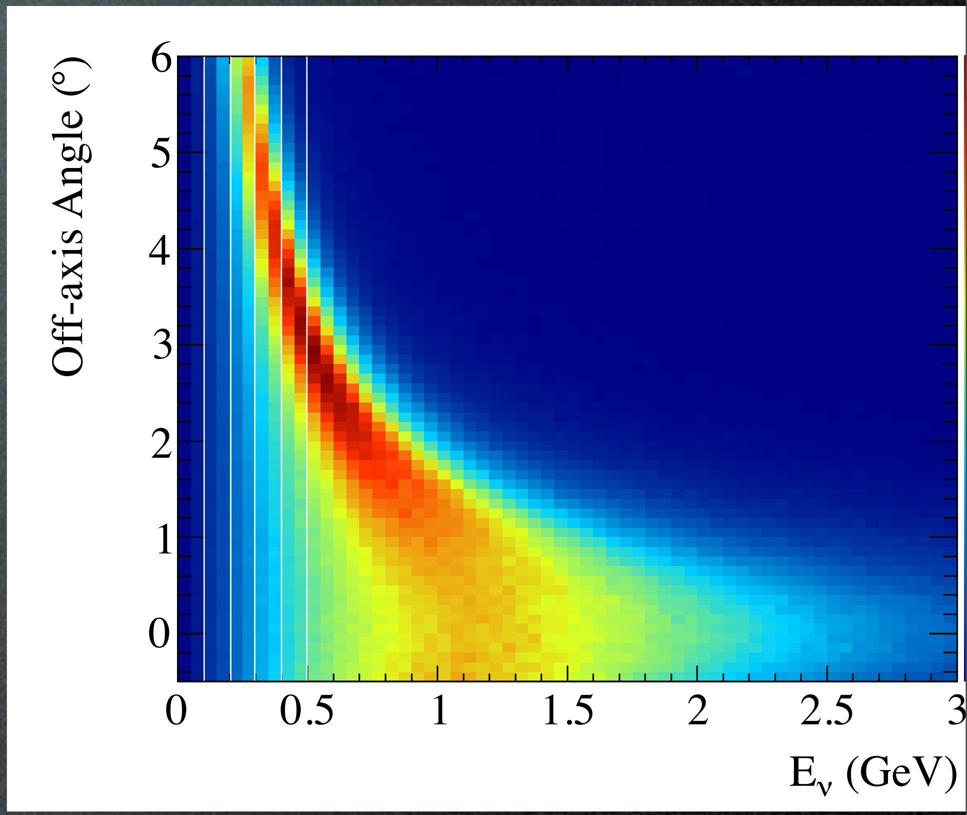
- **Efficiency correction** is still needed for both νPRISM and Super-K
- νPRISM and Super-K have **different detector geometries**
  - Particles penetrate ID wall (and get vetoed) more often in νPRISM
  - Particle ID degrades near the tank wall
- The efficiency correction is performed in **muon momentum 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)

$$\underbrace{E^{SK}_{rec,j}}_{\text{predicted Super-K } E_{rec} \text{ distribution}}(\Delta m^2_{32}, \theta_{23}) = \sum_{p,\theta} \left[\sum_{i}^{OAangles} \underbrace{c_i}_{\text{weight for off-axis slice, i}}(\Delta m^2_{32}, \theta_{23}) \left(\underbrace{N^{obs}_{p\theta i}}_{\text{\# events in muon p,}\theta\text{ bin in slice, i}} - \underbrace{B_{p\theta i}}_{\text{background subtraction}} \right) \underbrace{\frac{\epsilon^{SK}_{p\theta}}{\epsilon^{\nu\mathrm{PRISM}}_{p\theta i}}}_{\text{efficiency ratio}} \right] * \underbrace{M_{p\theta j}}_{\text{translation matrix p,}\theta \to E_{rec}}$$

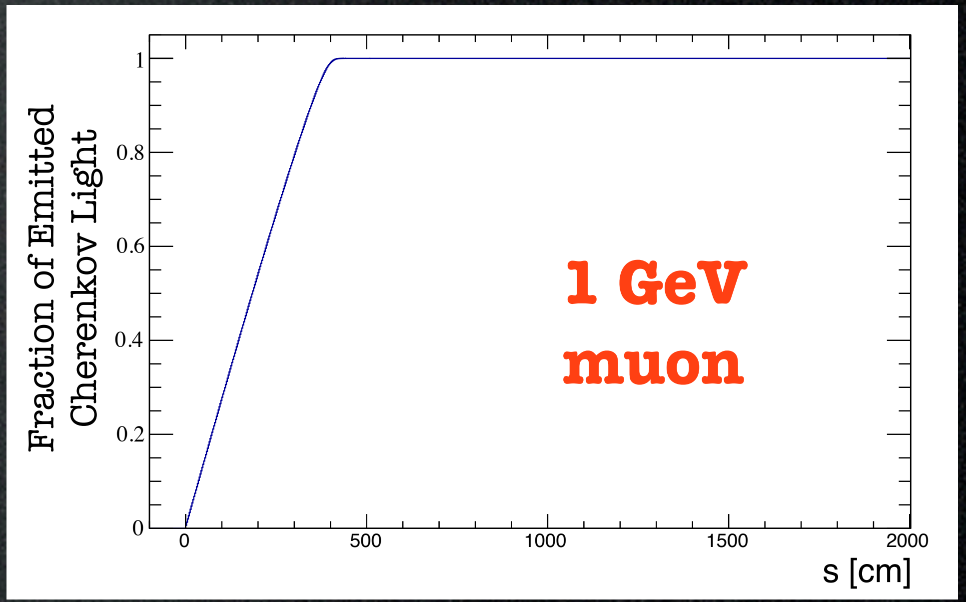
Other Design Considerations

- **Civil construction is expensive!**
  - Smaller hole = More affordable
- **Off-axis angle 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?

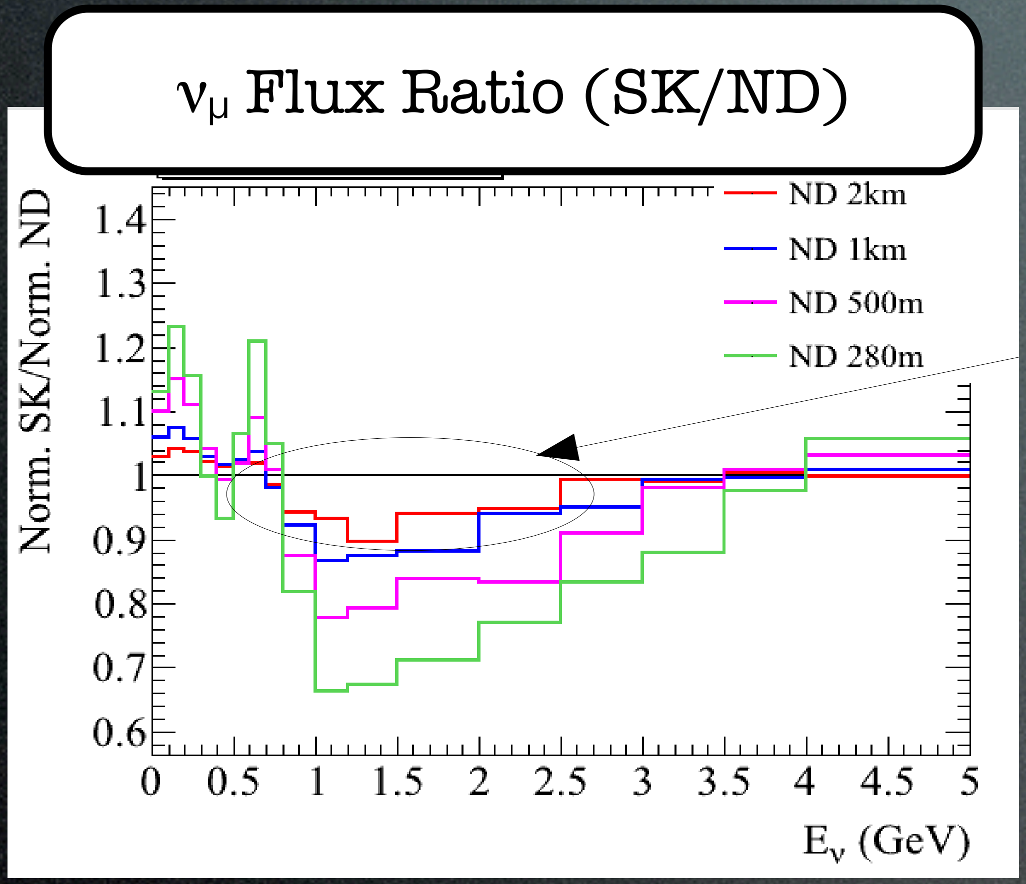
Off-axis Fluxes

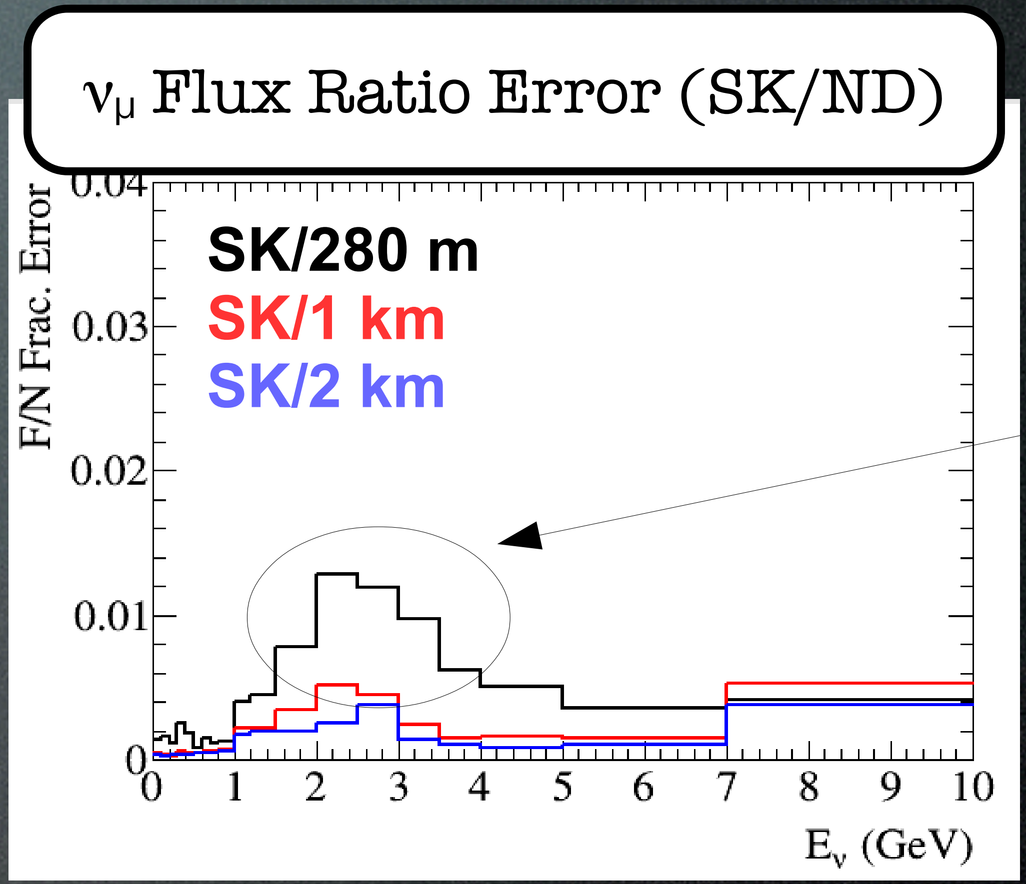


Muon Range



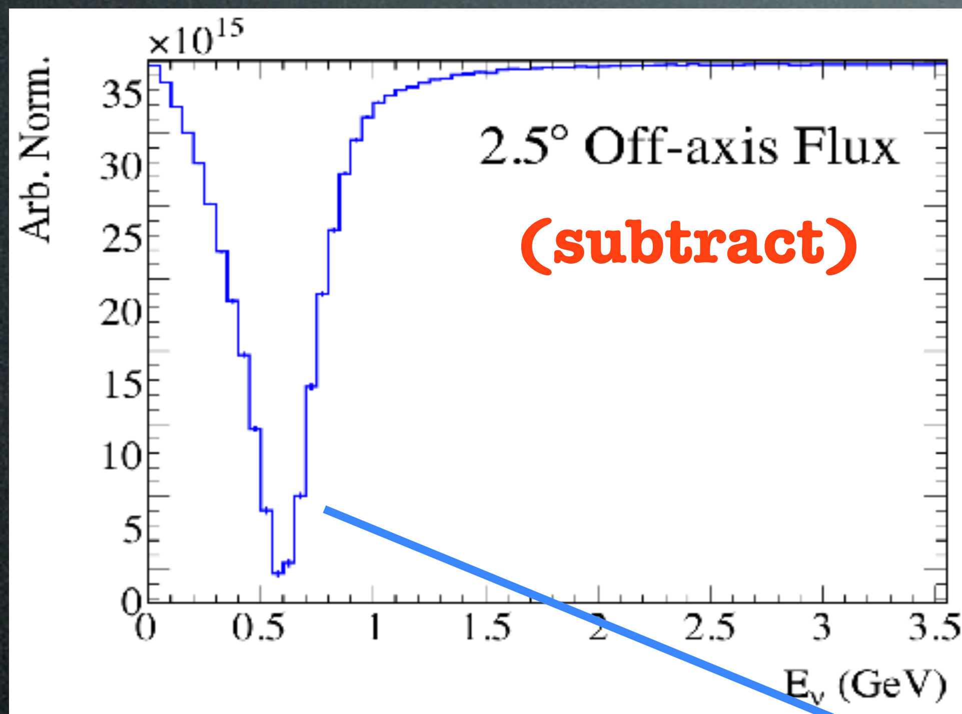
Design Considerations: Energy Spectrum Ratio

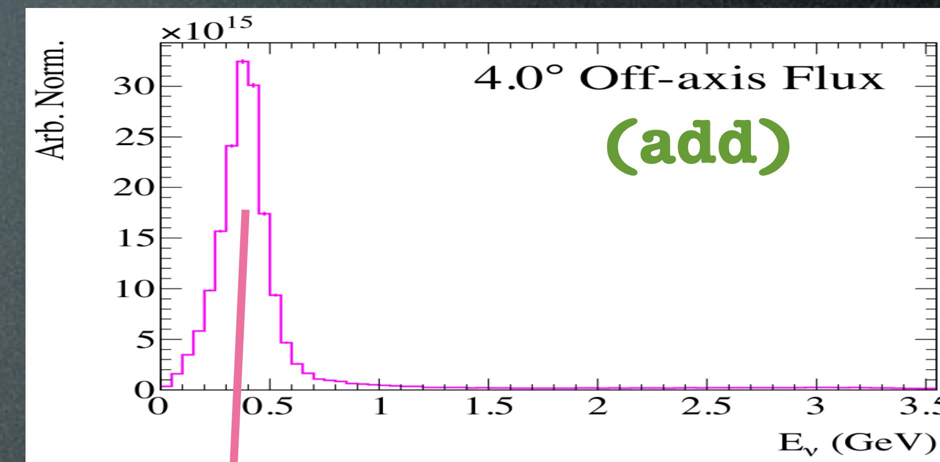


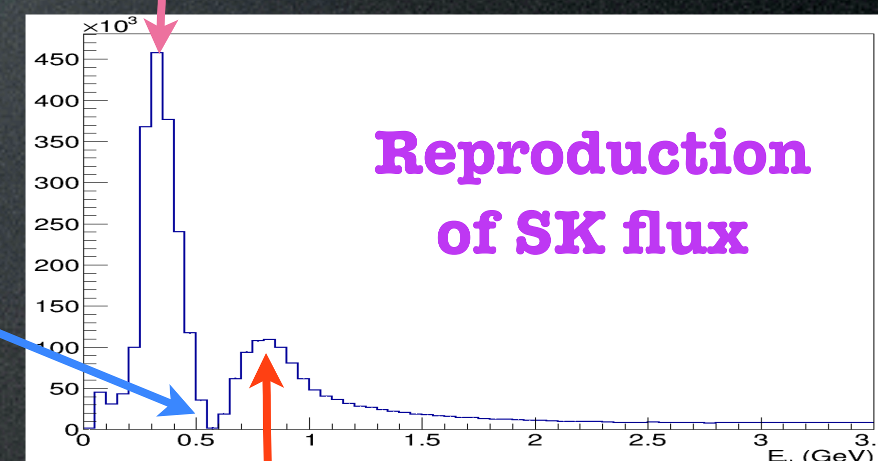


- At 280 m, the flux shape has 20-30% differences below 1 GeV
  - Uncertainty in the ratio is noticeably larger, but mostly above 1 GeV
- The difference between 1km and 2km is small in both shape and shape uncertainty

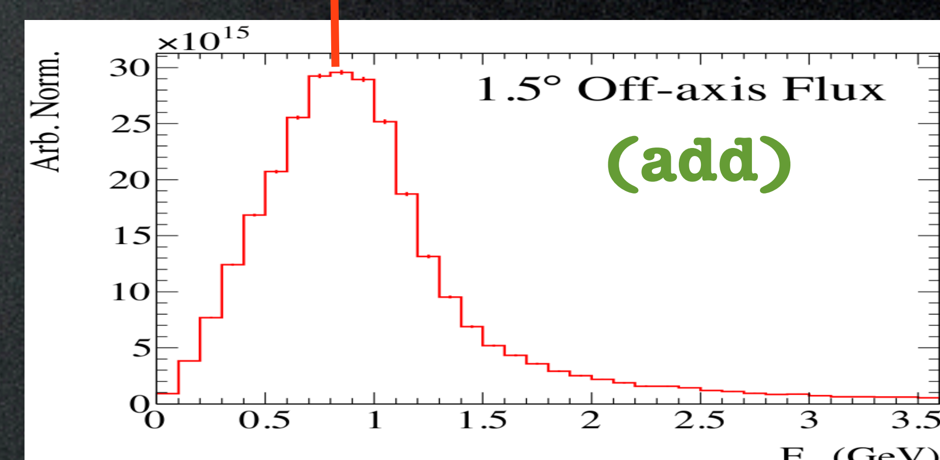
Reminder: Analysis Concept





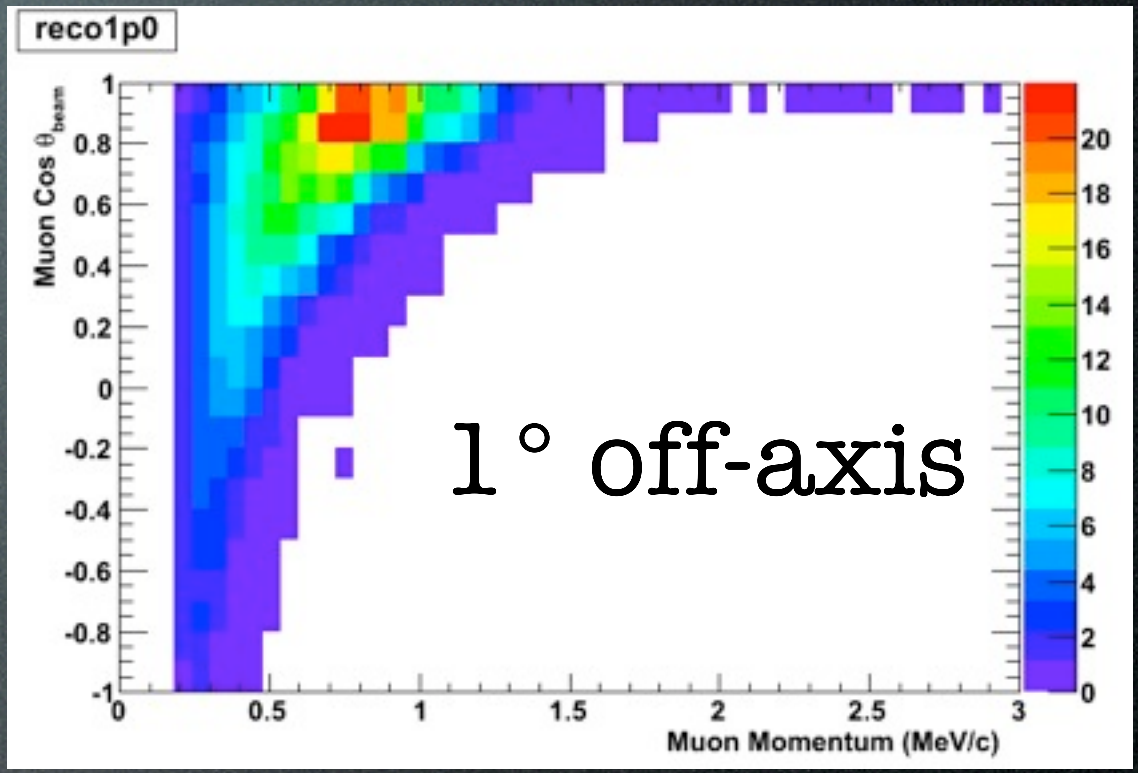


- Different slices of νPRISM are combined to reproduce an oscillated SK flux
    - **Flux only!** No cross sections or detector response at this point
- For simplicity, only 3 slices are shown here
    - The default analysis **uses 30 slices**

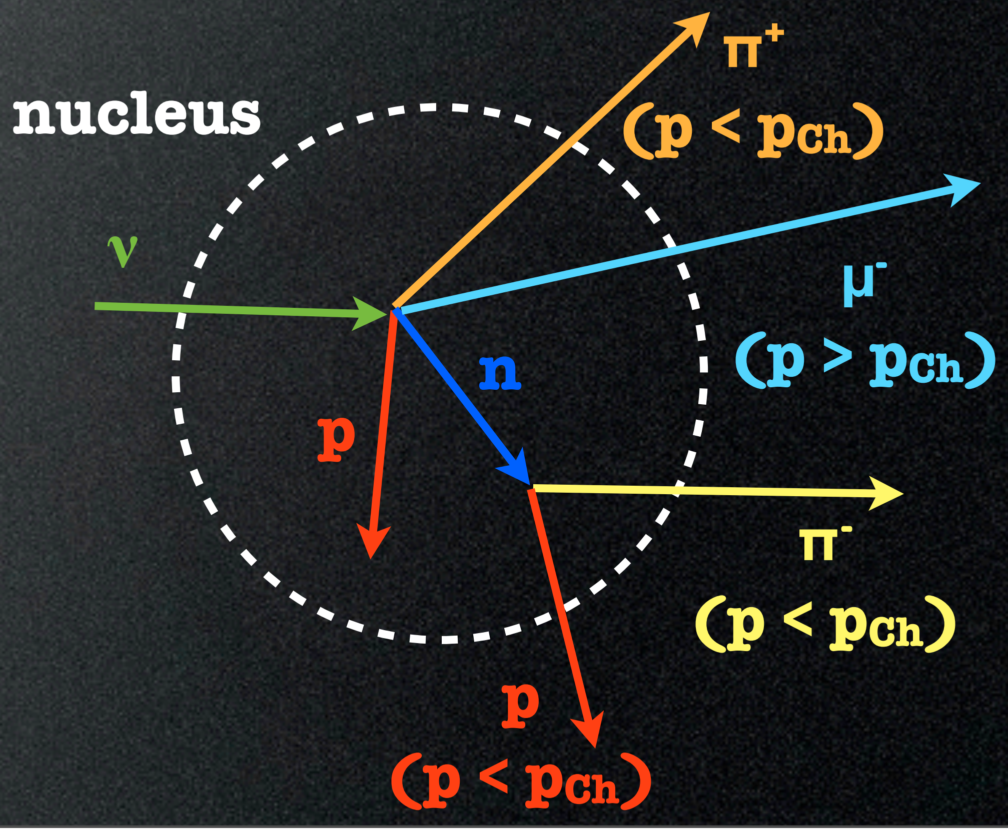


Signal Selection/Definition

- **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
- νPRISM can measure **single muon response** for a given E_ν spectrum
  - Signal includes CCQE, multi-nucleon, CCπ⁺, etc.
  - No need to make individual measurements of each process and extrapolate to T2K flux

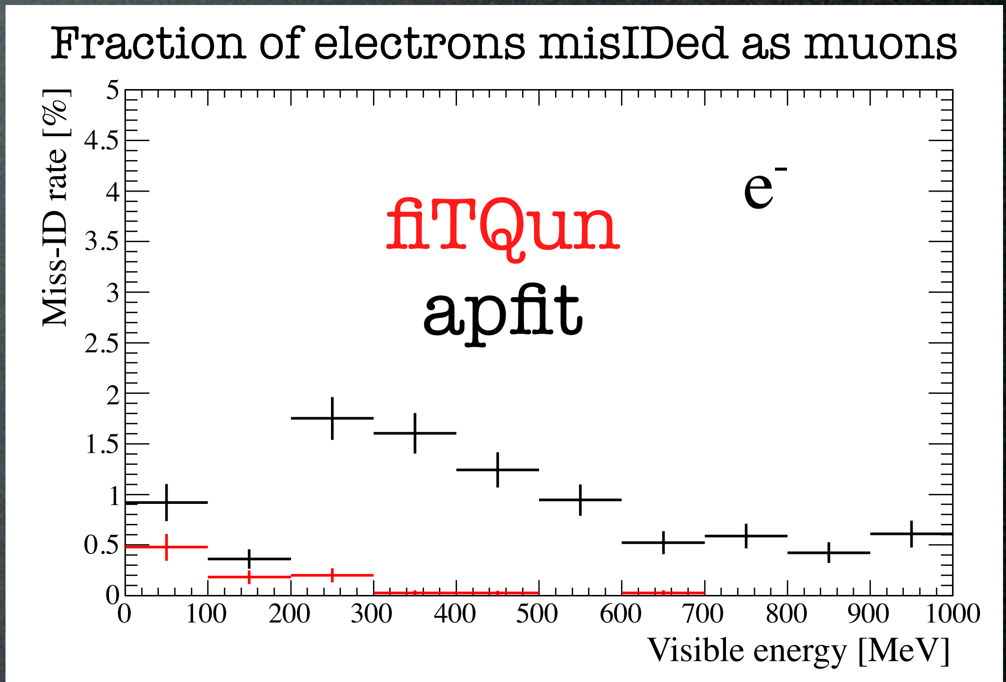


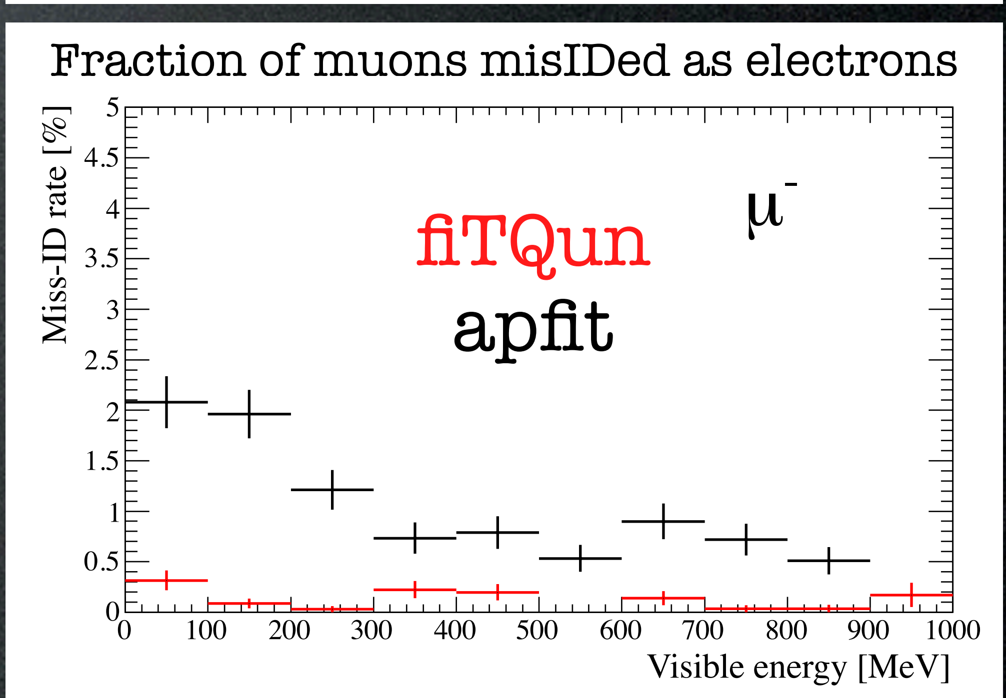
Example Signal Event



Physics Capabilities

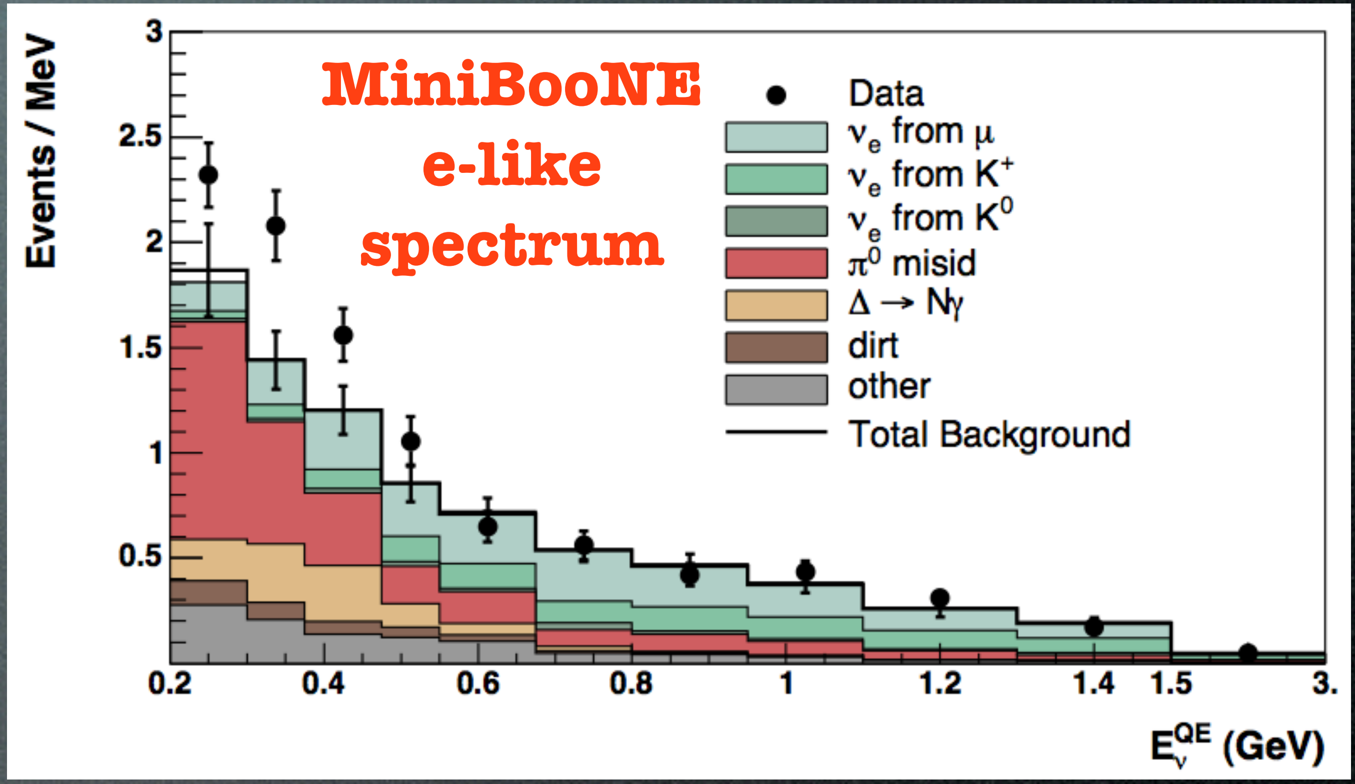
- Direct measurement of the relationship between lepton kinematics and neutrino energy
  - No longer rely solely on models
- 4π detector (like Super-K)
- Target material is water (like Super-K)
  - Can directly measure NC backgrounds
- Very good e/μ separation
- Can make a precise measurement of beam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

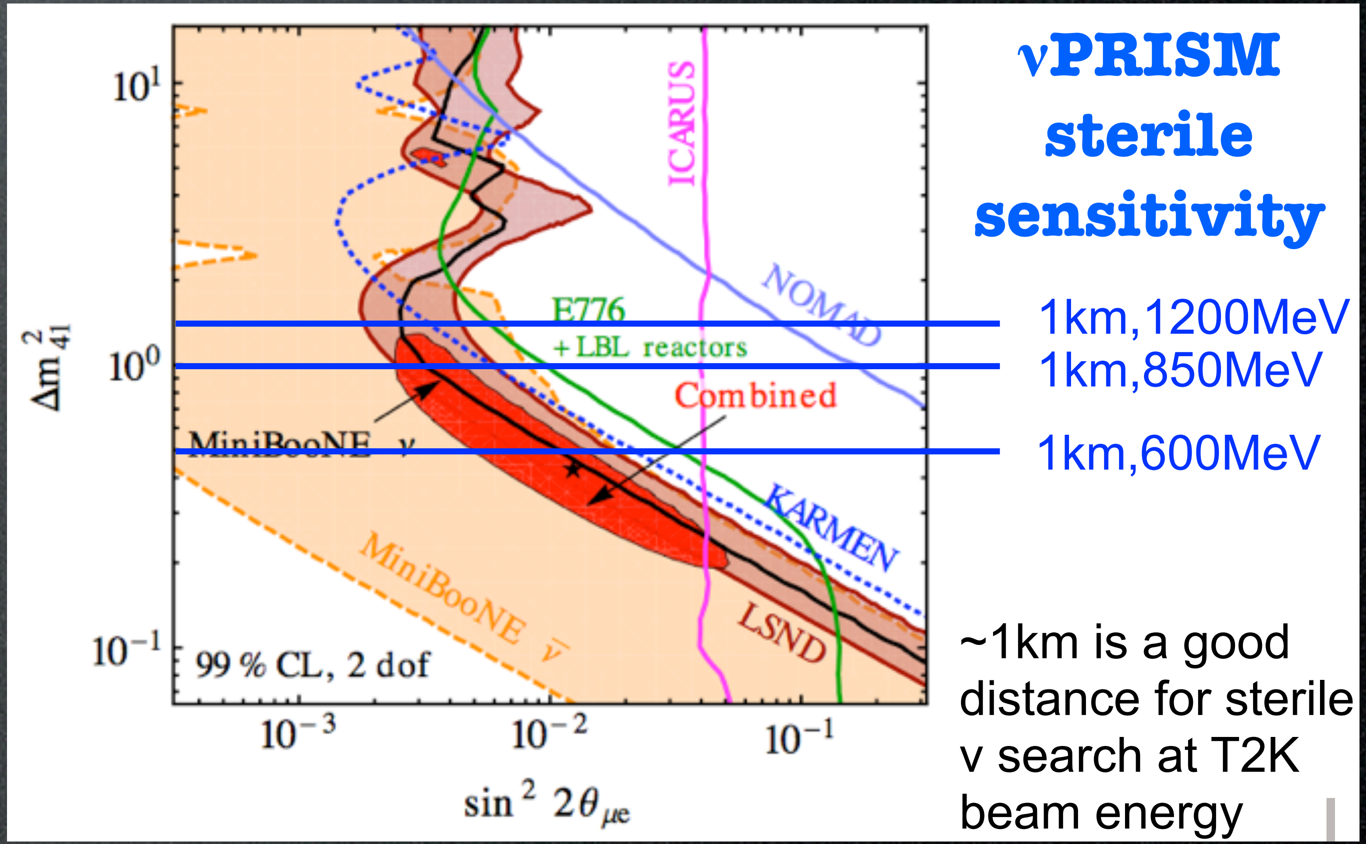




Electron-like Measurements

- MiniBooNE sees a large excess of electron-like events
  - Sources: NCπ^0, single-γ production, external γ, beam ν_e, sterile neutrinos, muon misID
  - This must be understood for precision CP violation measurement
- Linear combination of ν_μ fluxes can be used to reproduce ν_e flux
  - This will allow direct comparison of ν_μ and ν_e cross section
  - At large off-axis angle, ν_μ background to ν_e is reduced
- A large detector with a 1 km baseline can give a strong constraint on MiniBooNE sterile interpretation
  - Sterile neutrino sensitivity studies are underway!

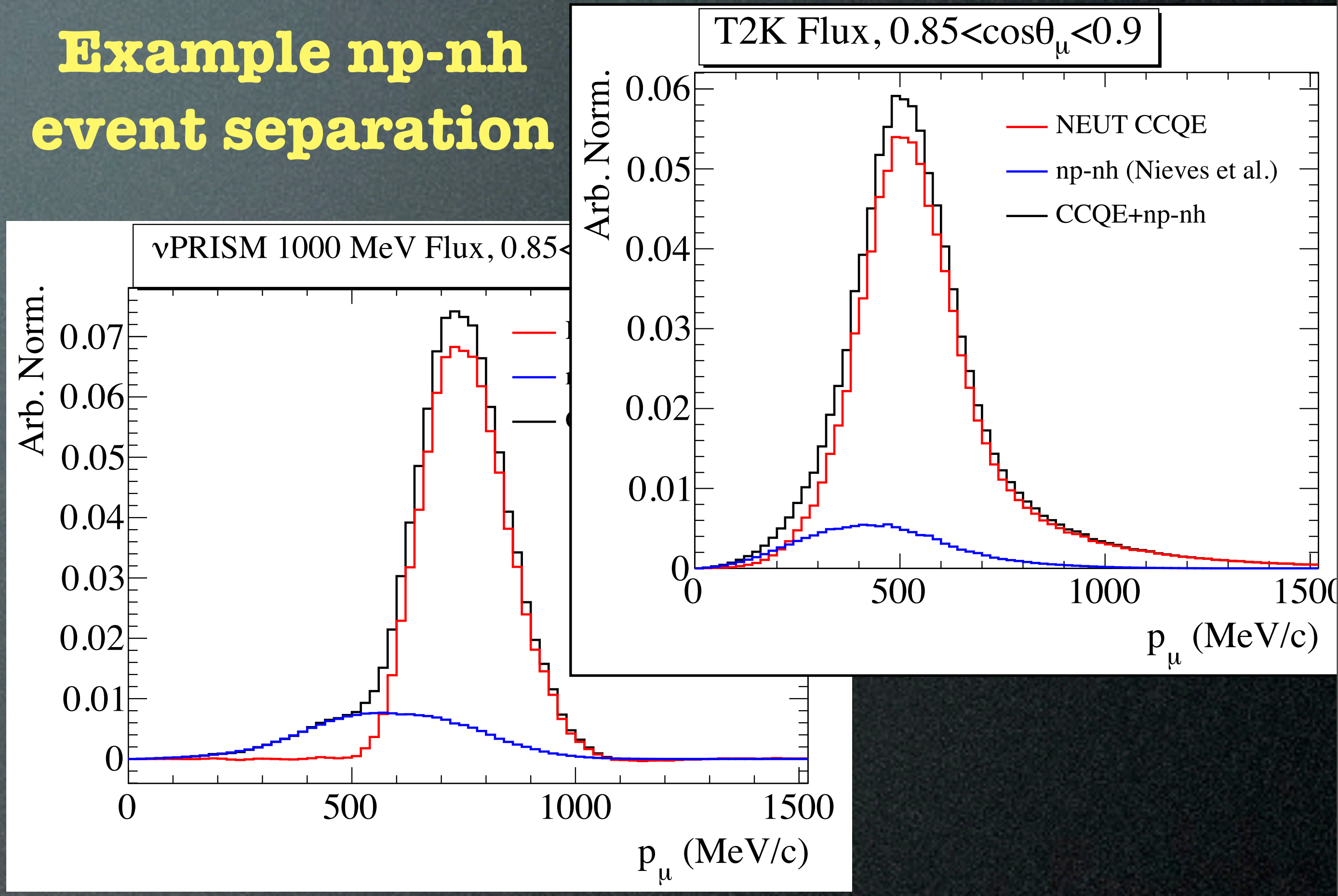




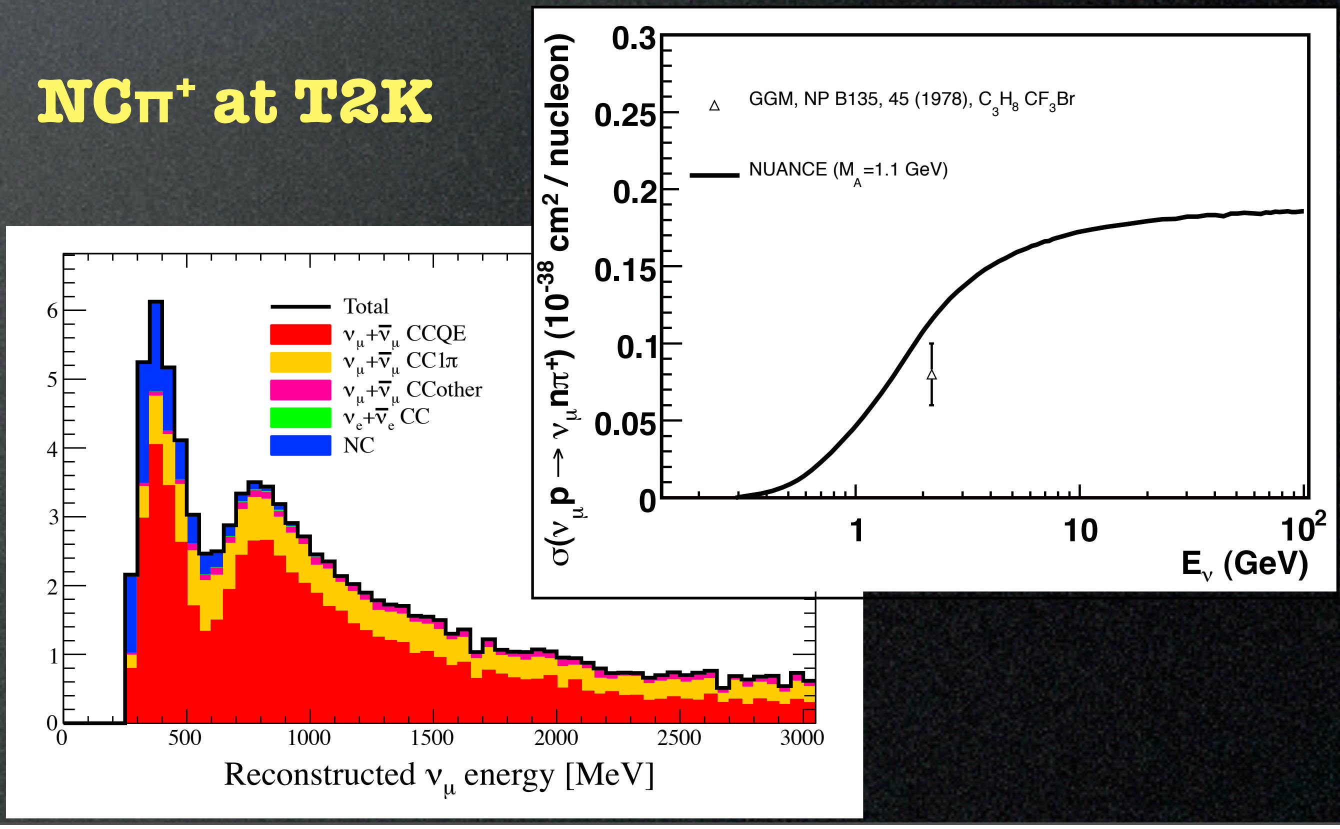
ν Cross Section Measurements

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

Example np-nh event separation

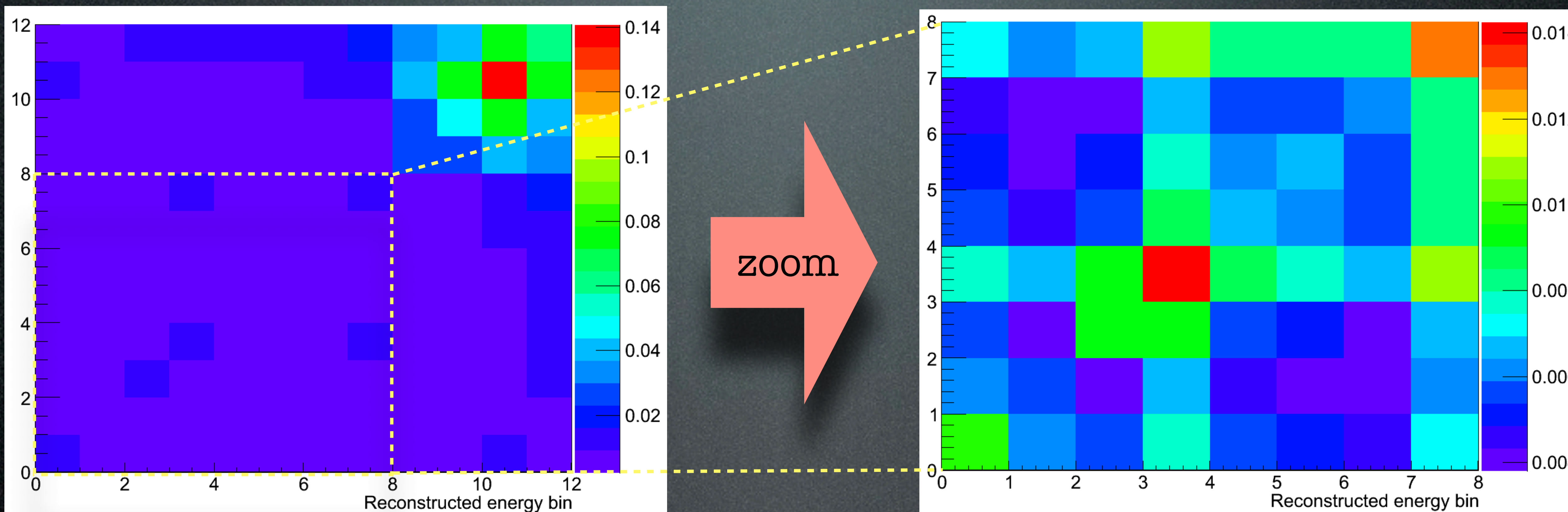


$NC\pi^+$ at T2K



Systematic Covariance Matrices

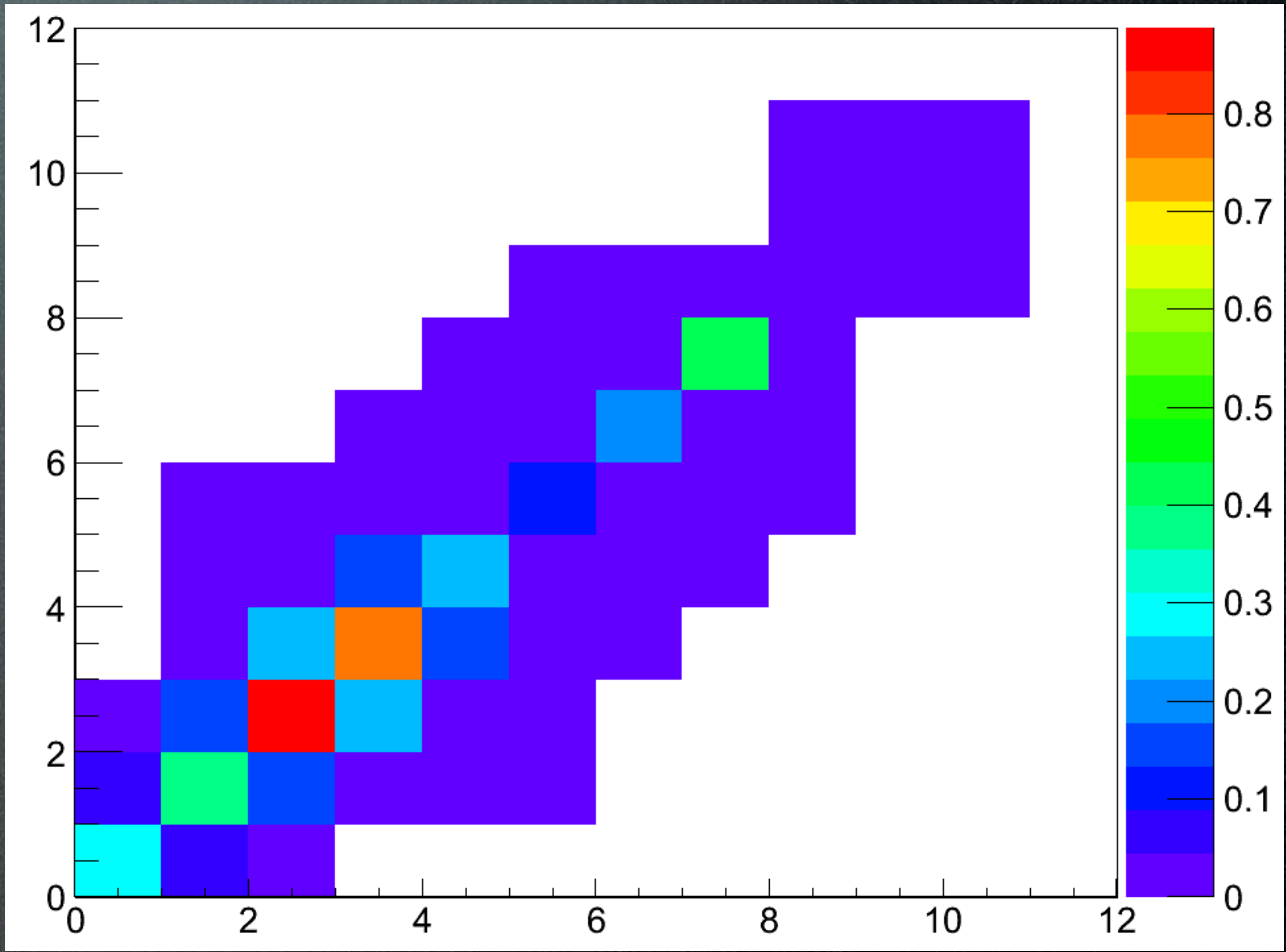
Analysis is performed in 12 unequal-sized E_{rec} bins



- Matrices show fractional uncertainties (normalized to bin content)
- At high energies, νPRISM provides no constraint
  - Detector acceptance: all muons exit the ID
  - Subject to full flux & cross section uncertainties
- Bin 3 (600-700 MeV) has a 11.8% uncertainty (~1.2% on $\sin^2 2\theta_{23}$)

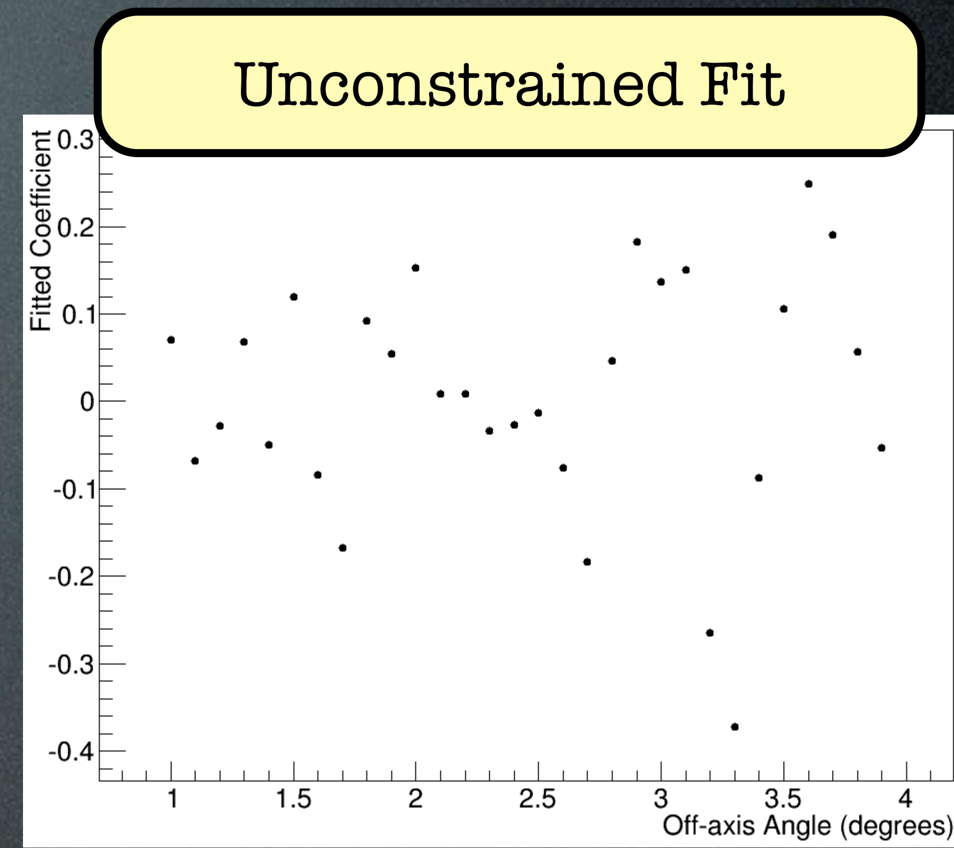
Statistical Uncertainties

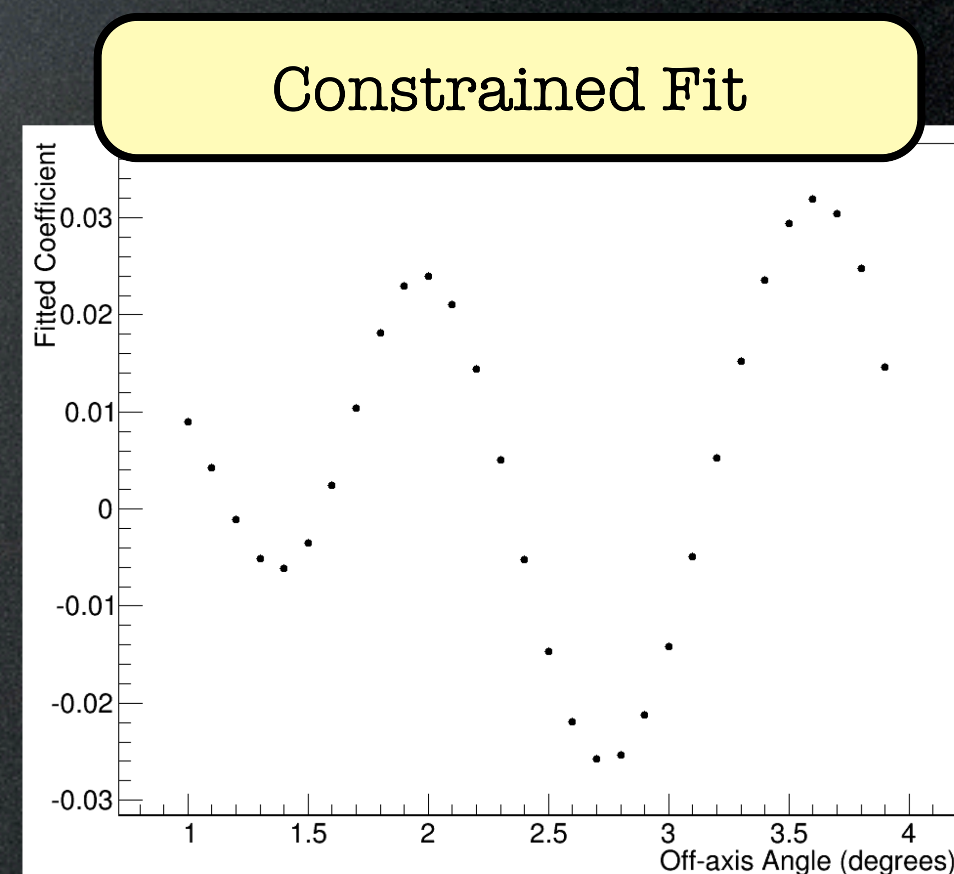
- Linear combinations can cause very large fractional uncertainties
  - e.g. a simple statistical subtraction
  - $\sqrt{(N_1+N_2)} / (N_1-N_2)$
- A naive fit of 30 νPRISM slices to an SK flux gives **nearly 100% errors!**
- But, many non-unique solutions exist for νPRISM flux weights



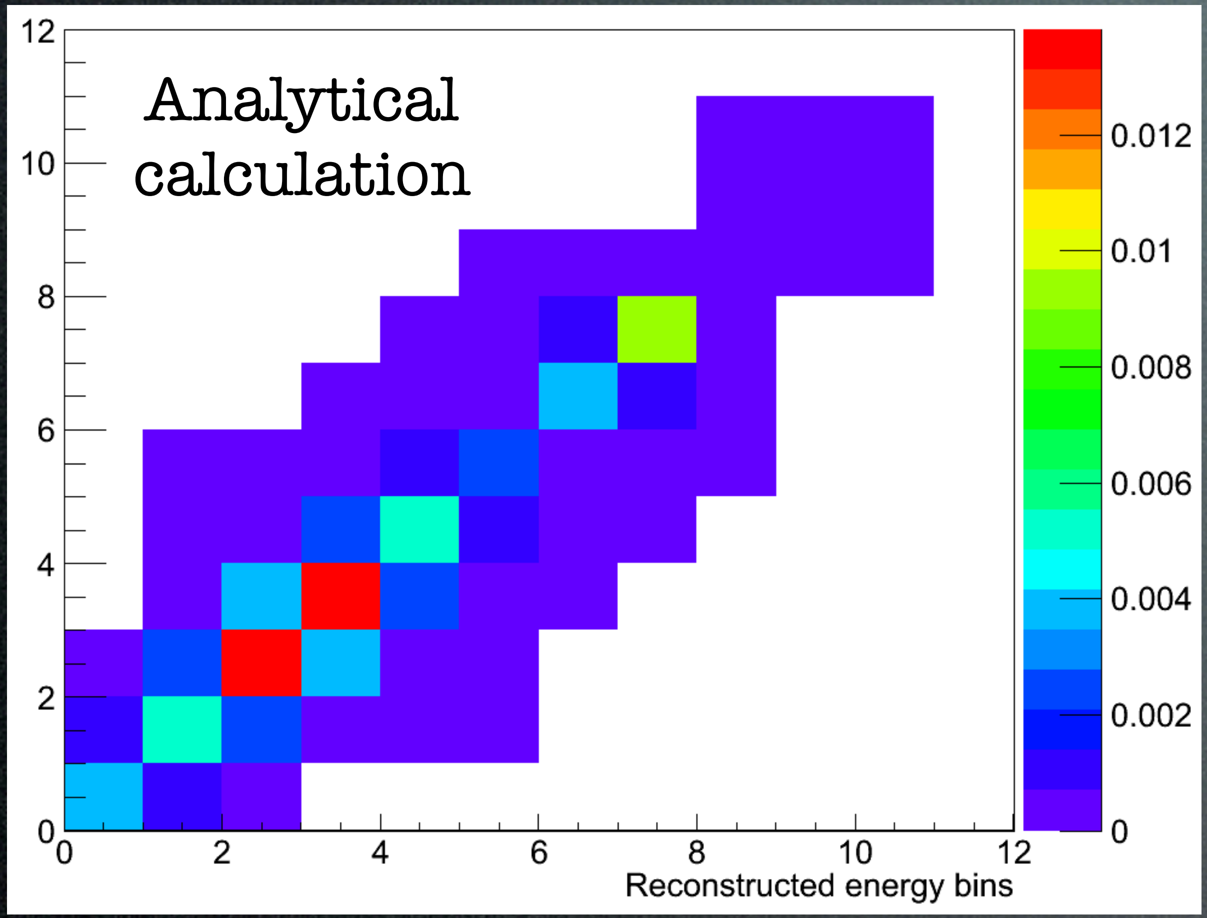
Reducing Statistical Errors

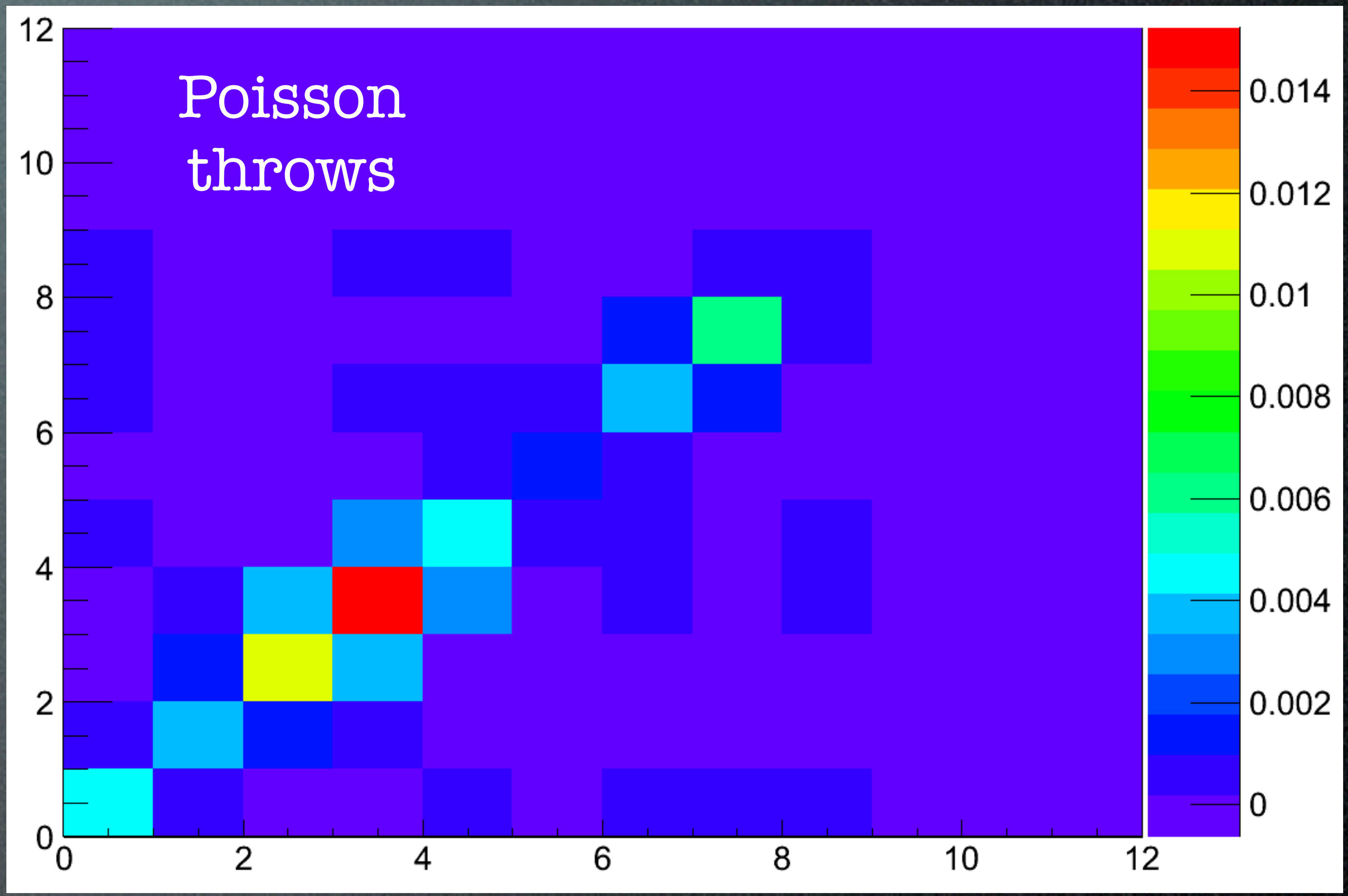
- Flux predictions contain Monte Carlo statistical uncertainties
  - Strongly affect fit results
- Instead, can enforce that neighboring bins must have similar weights
  - Results in smooth variation of weights across off-axis angles
- Variance of weights is reduced by an order of magnitude
  - Significant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





Reduced Statistical Uncertainties

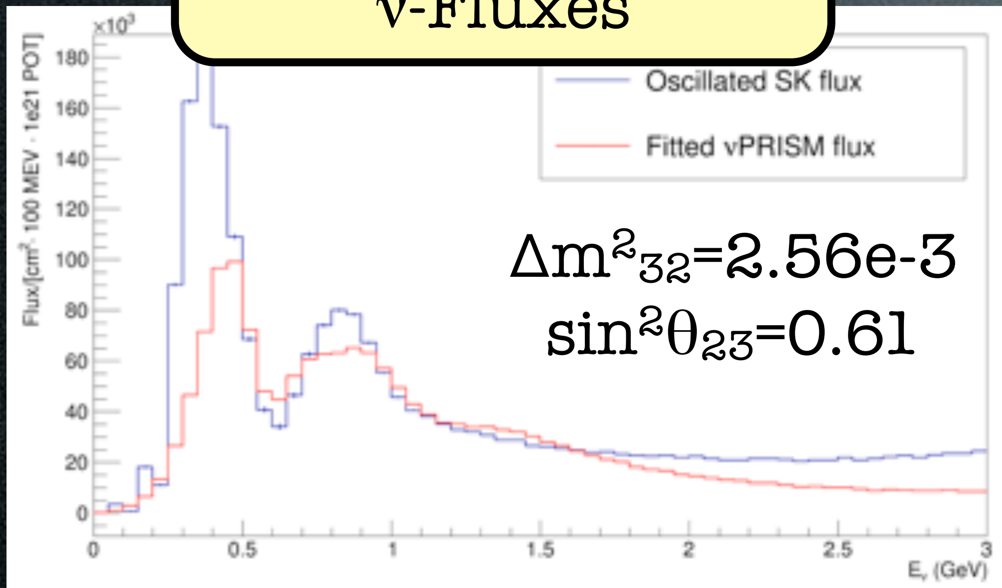


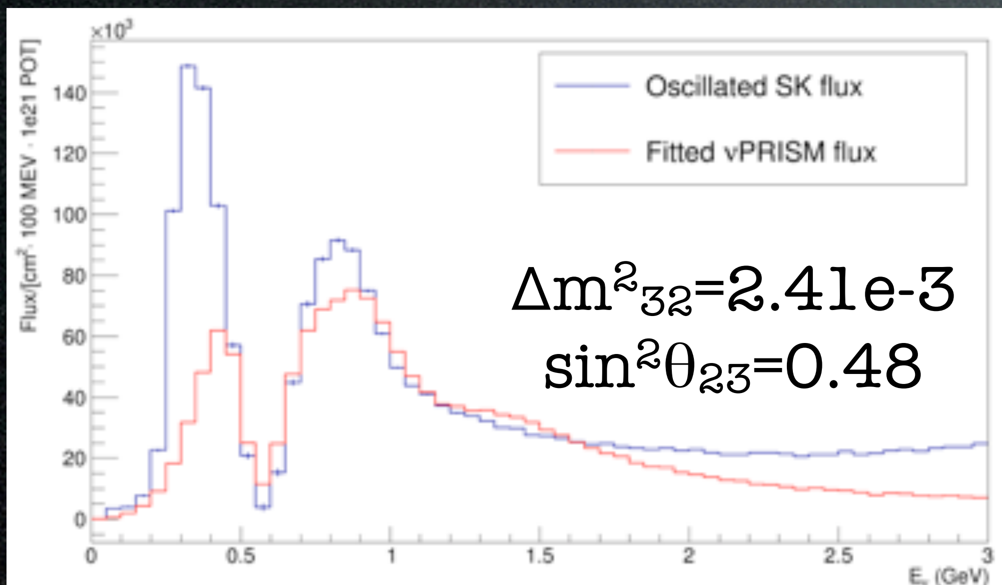


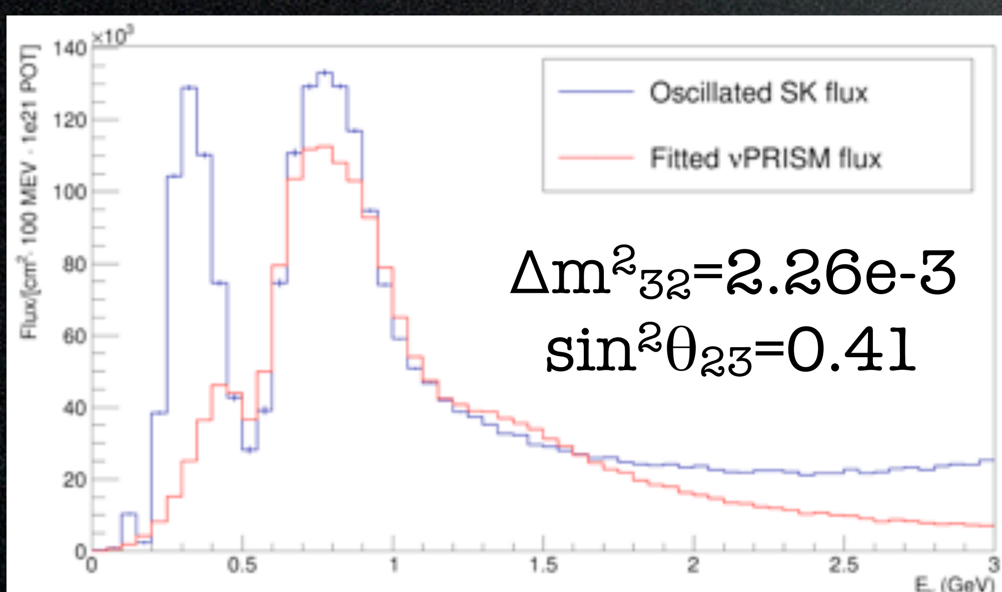
- Statistical errors have been reduced to 10-12%
  - Current level of systematic errors
  - These can be significantly reduced with slightly larger ID
- Cross checked analytical calculation with 100 Poisson throws of each muon p,θ bin → consistent result

New ν-Flux Fits

ν-Fluxes

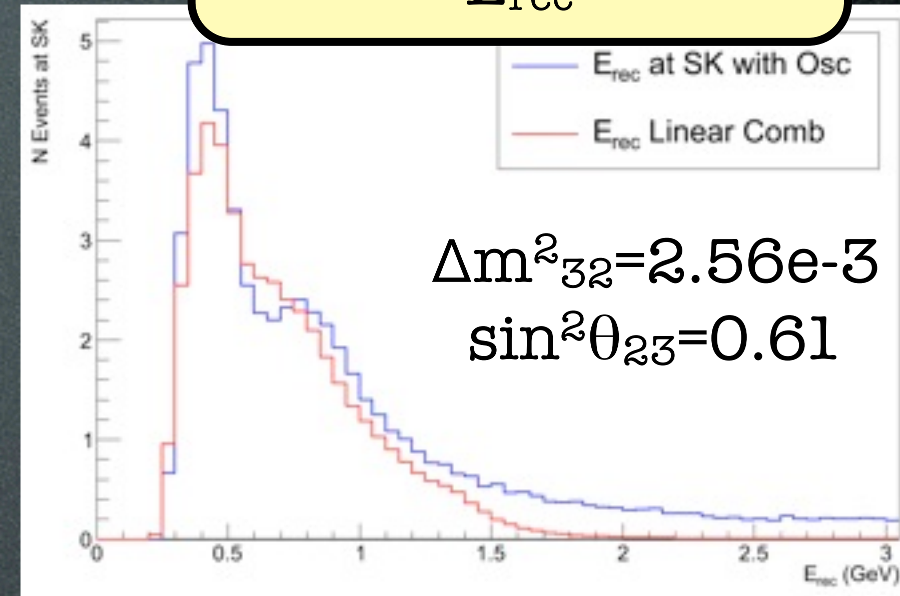


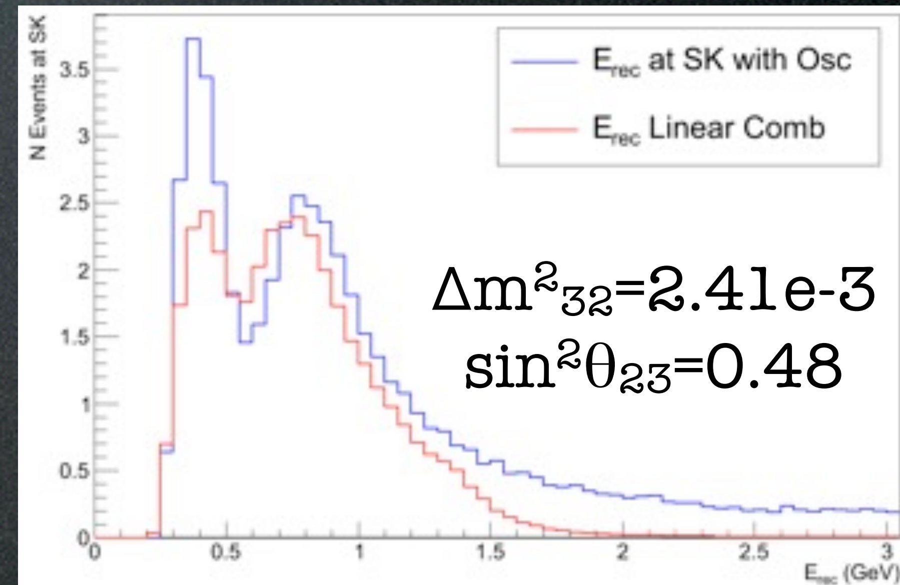


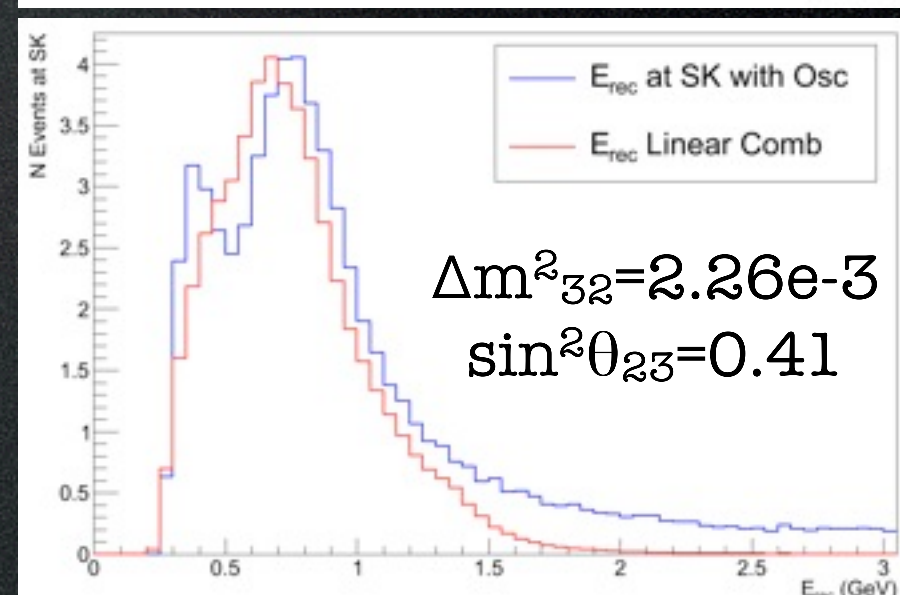


- Fits are not perfect
- However, very small increase to systematic uncertainties
  - Flux systematic variations are large
- Fits can be improved
  - Smoothness can be relaxed near fast-changing features
  - Off-axis angle bins need not be equal size

E_{rec}

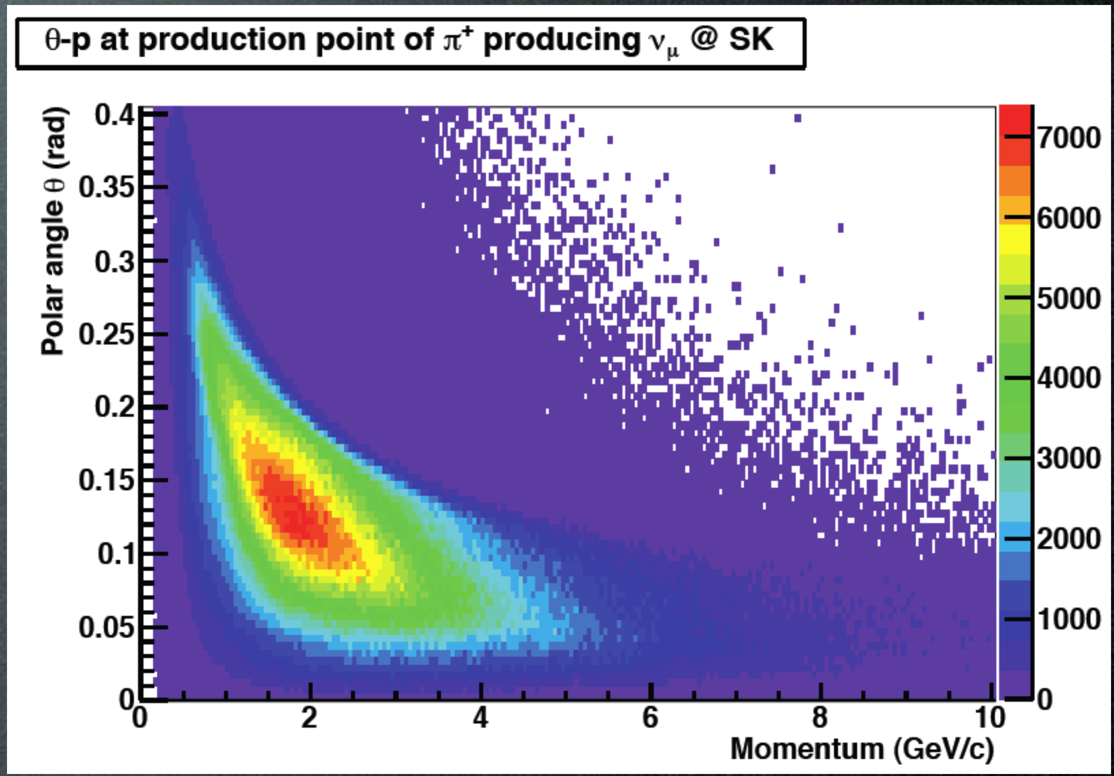




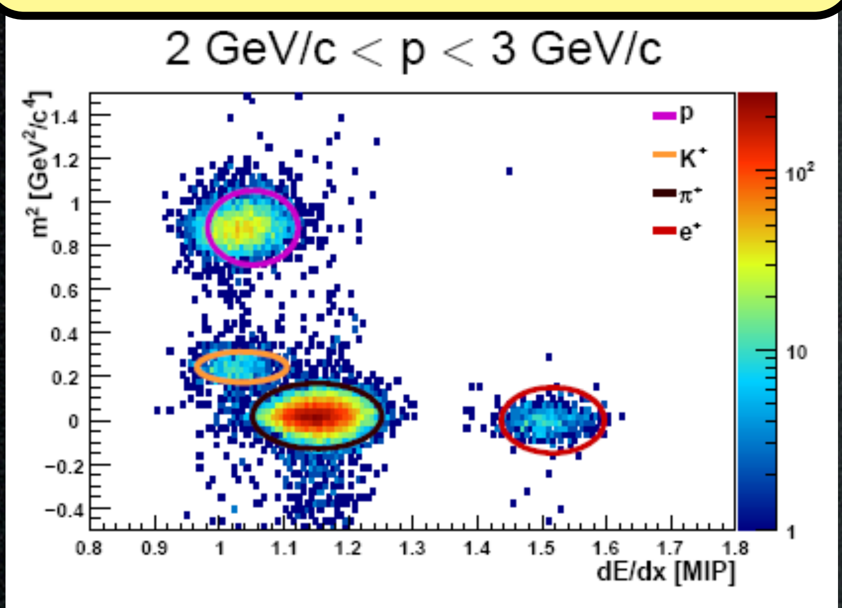


Constraining the ν Flux

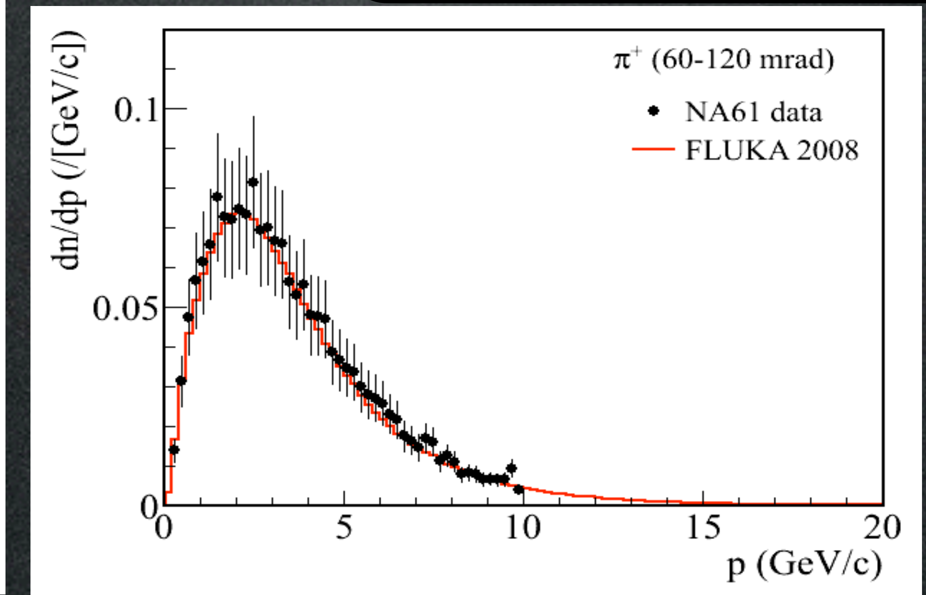
- The dominant flux uncertainties are in π/K production from p+C interactions
- “Sweet spot” for producing neutrinos at Super K (due to horn focusing)
- The NA61 experiment at CERN has taken data on a thin C target and a T2K replica target
    - Good particle separation from combined time-of-flight and dE/dx measurements
    - T2K flux has been tuned to match differential pion production cross sections

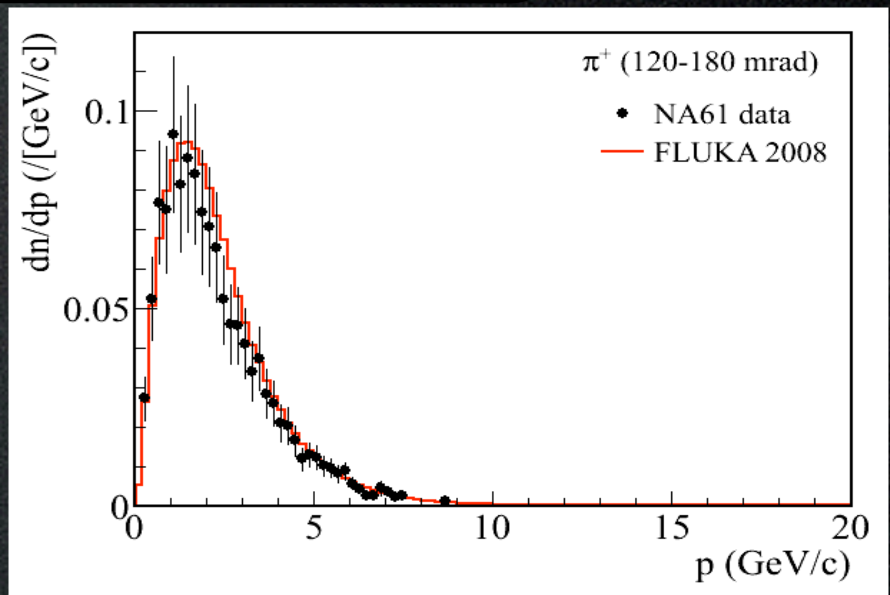


NA61 Particle ID



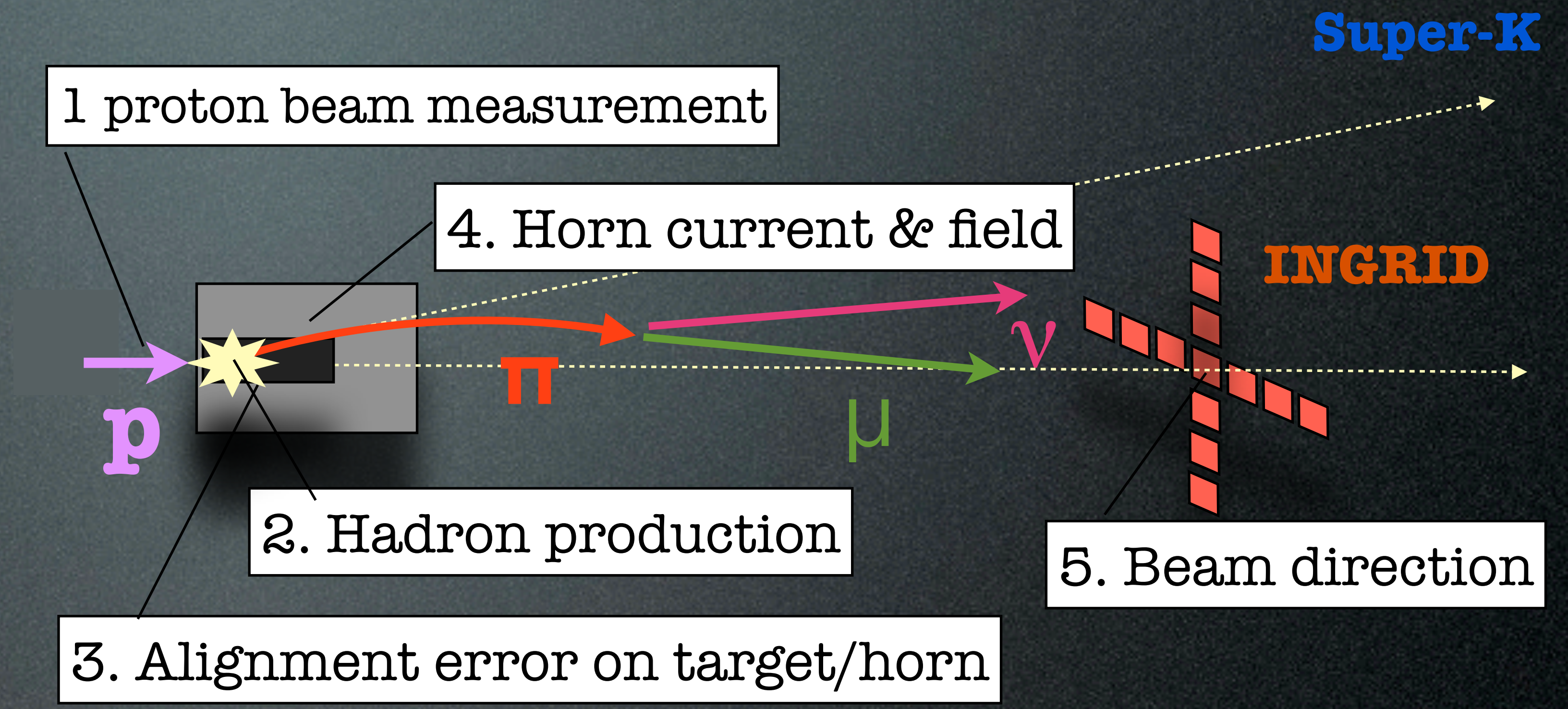
NA61 Data vs FLUKA

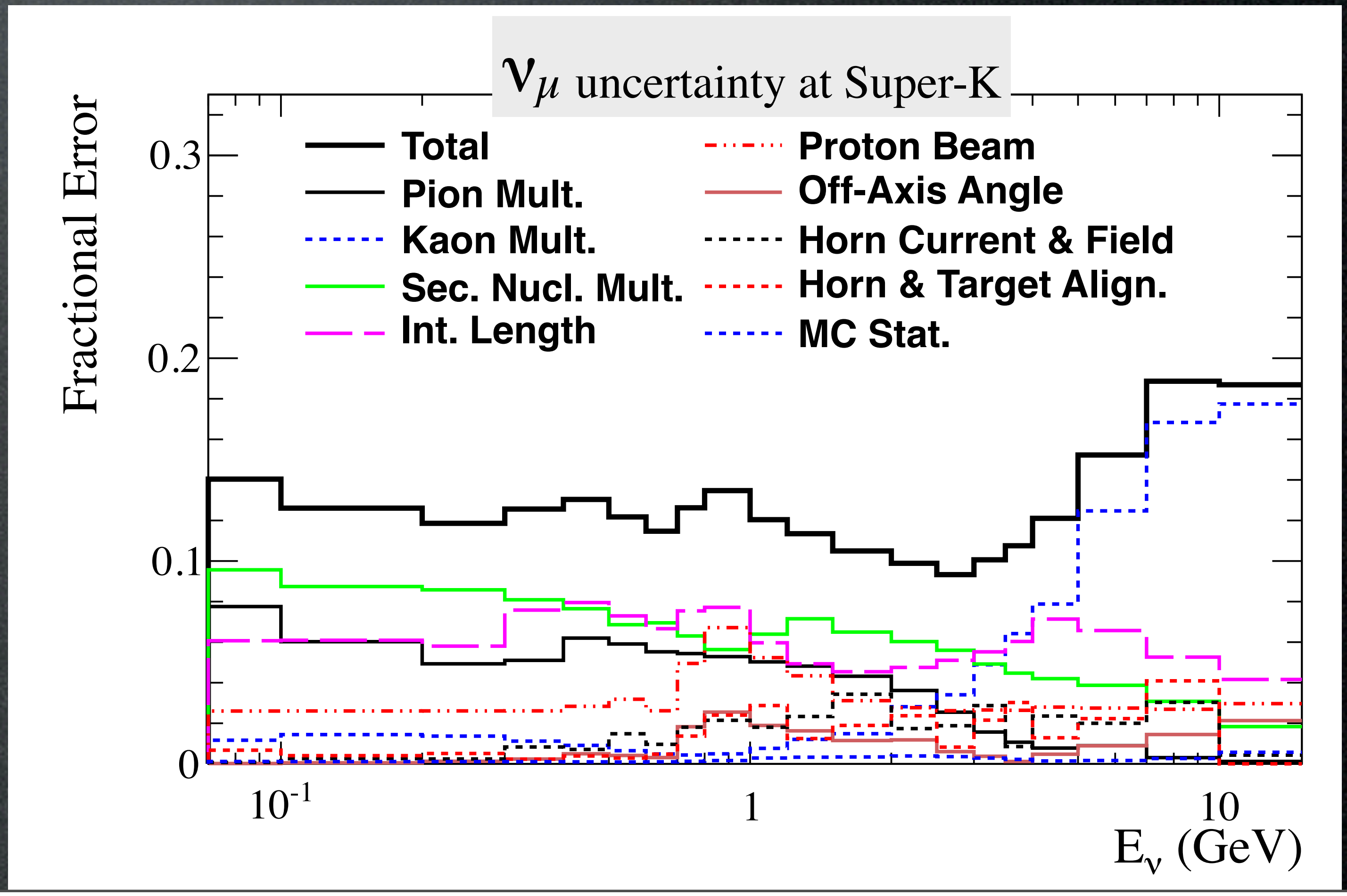




ν Flux Uncertainties

1. Measurement error on monitoring proton beam
2. Hadron production
3. Alignment error on the target and the horn
4. Horn current & field
5. Neutrino beam direction (Off-axis angle)





Near Detector Constraints

Goal: Constrain ν-flux and cross section parameters (used for T2K far detector MC prediction)

ν-Flux

ν_μ and ν_e fluxes are correlated

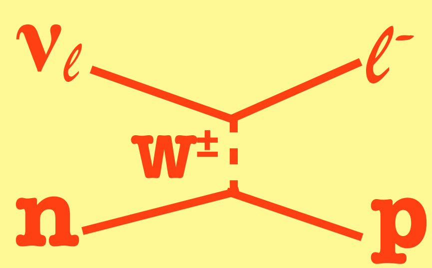
$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

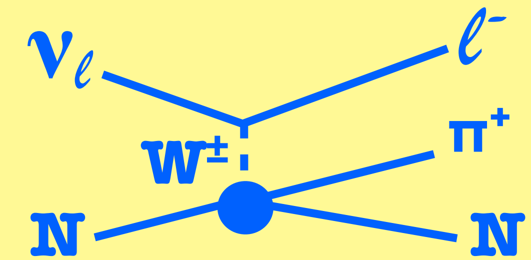
Can use ν_μ measurement to constrain the ν_e flux

External constraints from **NA61**

Cross Sections

Main CC interactions relevant to T2K are **CCQE** and **CCπ$^+$**





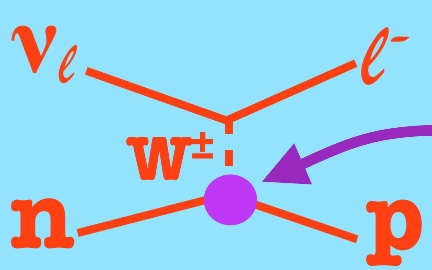
Need to constrain the parameters of these interactions: M_A^{QE}, M_A^{RES}, etc.

External constraints from **MiniBooNE**

The ν_μ spectrum at the near detector is fit to extract flux and cross section constraints at the far detector

T2K Cross Section Model (2013)

CCQE



Main difficulty is in understanding the hadronic current

However, the vector form factors are known from electron scattering!

- Remaining axial vector form factor has 2 parameters
- $F_A(0)$ is known from beta decay experiments
- M_A is the only free parameter

$$F_A(Q^2) = \frac{F_A(0)}{(1 + \frac{Q^2}{M_A^2})^2}$$

CCπ^+

- More complicated (and ad hoc)
- Has its own M_A parameter
- Pion-less Δ decay added by hand

Nuclear Model

- Relativistic Fermi Gas (binding energy + p_{Fermi})
- Can also reweight to a spectral function treatment

Other

- Norm. factors are varied for other processes

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

Near Detector Requirements for Future ν-Osc. Experiments

- The relationship between **lepton kinematics** (what you measure) and **neutrino energy** (what you want to constrain) has an **unknown** and **potentially large** systematic uncertainty
  - A data-driven constraint is required for a precision CP violation measurement
- **Same target** as far detector is required
  - Nuclear effects are not understood at the few percent level, even for C vs O
- Must be able to **precisely measure ν_e**
  - Constrain beam ν_e background
  - Perhaps a ν_e cross section constraint
- Must constrain other backgrounds
  - $CC\pi^+$, $NC\pi^+$, multi-π, ...

T2K ν_e Appearance PRL

TABLE II. The uncertainty (RMS/mean in %) on the predicted number of signal ν_e events for each group of systematic uncertainties for $\sin^2 2\theta_{13} = 0.1$ and 0.

Error source [%]	$\sin^2 2\theta_{13} = 0.1$	$\sin^2 2\theta_{13} = 0$
Beam flux and near detector	2.9	4.8
(w/o ND280 constraint)	(25.9)	(21.7)
ν interaction (external data)	7.5	6.8
Far detector and FSI+SI+PN	3.5	7.3
Total	8.8	11.1

T2K ν_μ Disappearance

Table 13: Uncertainty (r.m.s./mean in %) on the N_{exp}^{SK} distribution from each group of systematic error source. Systematic parameters refined by the ND280 fit represent "ND280 fit". Mean systematic parameter values after the ND280 fit are used for the both systematic error sets before/after the ND280 fit.

Error source	$(\sin^2\theta_{23}, \Delta m^2_{32}) = (0.5, 2.4\times10^{-3})$ Before ND280 fit	After ND280 fit
BANFF-constrained Flux and ν interactions	21.6	2.7
Unconstrained ν interactions	5.9	4.9
SK detector + FSI-SI	6.3	5.6
$\sin^2(\theta_{13})$, $\sin^2(\theta_{12})$, Δm^2_{12}, δ_{CP}	0.2	0.2
Total	23.4	8.1

ν_μ Disappearance Systematics

- From KDI Technote
- "MEC-like" pionless delta decay is the largest systematic uncertainty
- νPRISM measures 1-ring μ-like events
  - Same as SK ν_μ selection
  - Reduced dependence on FSI-SI Uncertainties

Total Errors (%N_{SK})

Table 13: Uncertainty (r.m.s./mean in %) on the N^{SK}_{exp} distribution from each group of systematic error source. Systematic parameters refined by the ND280 fit represent "ND280 fit". Mean systematic parameter values after the ND280 fit are used for the both systematic error sets before/after the ND280 fit.

Error source	$(\sin^2\theta_{23}, \Delta m^2_{32}) = (0.5, 2.4\times10^{-3})$ Before ND280 fit	After ND280 fit
BANFF-constrained Flux and ν interactions	21.6	2.7
Unconstrained ν interactions	5.9	4.9
SK detector + FSI-SI	6.3	5.6
$\sin^2(\theta_{13})$, $\sin^2(\theta_{12})$, Δm^2_{12}, δ_{CP}	0.2	0.2
Total	23.4	8.1

Detailed Error Table (%N_{SK})

Table 12: Summary of the fractional change (in %) of the number of ν_μ candidate events under a change to each systematic parameter by $\pm1\sigma$ error size of before or after ND280 fit at $(\sin^2\theta_{23}, \Delta m^2_{32}) = (0.5, 2.4\times10^{-3})$. Mean systematic parameter values after ND280 fit are used for the both error cases.

Systematic uncertainty	$(\sin^2\theta_{23}, \Delta m^2_{32}) = (0.5, 2.4\times10^{-3})$ Before ND280 fit	After ND280 fit
Beam flux	±15.9	± 7.2
M_A^{QE}	+14.8/-17.9	+2.7/-2.8
M_A^{RES}	+6.7/-6.6	+2.4/-2.3
CCQE norm (E^{true} <1.5 GeV)	±4.2	±3.3
CCQE norm (E^{true}=1.5∼3.5 GeV)	±3.9	±1.6
CCQE norm (E^{true} >3.5 GeV)	±1.2	±0.5
CC1π norm (E^{true} <3.5 GeV)	±4.9	±2.0
CC1π norm (E^{true} >3.5 GeV)	±5.4	±1.6
CC other shape	±0.8	(same as before fit)
Spectral function	-0.9/+0.9	(same as before fit)
E_b	0.1/+0.3	(same as before fit)
p_F	+0.15/0.03	(same as before fit)
CCCoh norm	±0.8	(same as before fit)
NCπ norm	±1.1	(same as before fit)
¡NCOth norm	±0.9	(same as before fit)
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$	±0.01	(same as before fit)
W-shape	+0.38/-0.43	(same as before fit)
Pi-less delta decay	±6.3	(same as before fit)
$\sigma_{\bar\nu}/\sigma_\nu$	±1.2	(same as before fit)
SK eff. & FSI-SI for $\nu_\mu,\bar\nu_\mu$ CCQE (E^{rec} <0.4 GeV)	±0.2	(same as before fit)
SK eff. & FSI-SI for $\nu_\mu,\bar\nu_\mu$ CCQE (E^{rec}=0.4∼1.1 GeV)	±0.7	(same as before fit)
SK eff. & FSI-SI for $\nu_\mu,\bar\nu_\mu$ CCQE (E^{rec} >1.1 GeV)	±0.9	(same as before fit)
SK eff. & FSI-SI for $\nu_\mu,\bar\nu_\mu$ CCnonQE	±4.6	(same as before fit)
SK eff. & FSI-SI for ν_e CC	±0.3	(same as before fit)
SK eff. & FSI-SI for All NC	±3.8	(same as before fit)
SK energy scale	(unchanged)	(same as before fit)

Correlated

Total Error = 2.7%

PDD phase space is similar to MEC

Effect of FSI-SI is significant