ν P R I S M:
An **Experimental** Method to **Remove** Neutrino Interaction Uncertainties from Oscilation Experiments

Mike Wilking, TRIUMF

5th Hyper-Kamiokande ND Premeeting

19-July-2014

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νPRISM:

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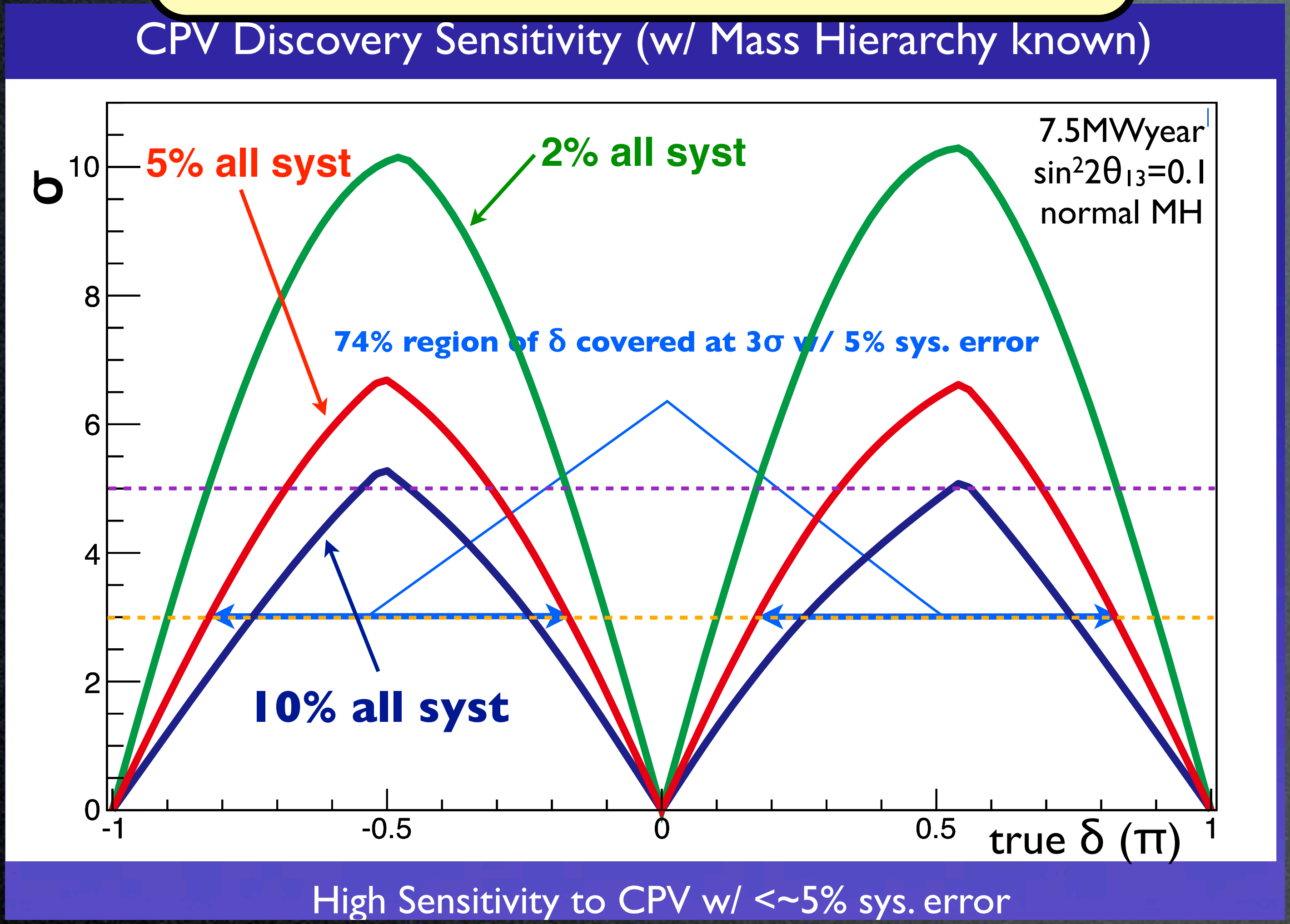
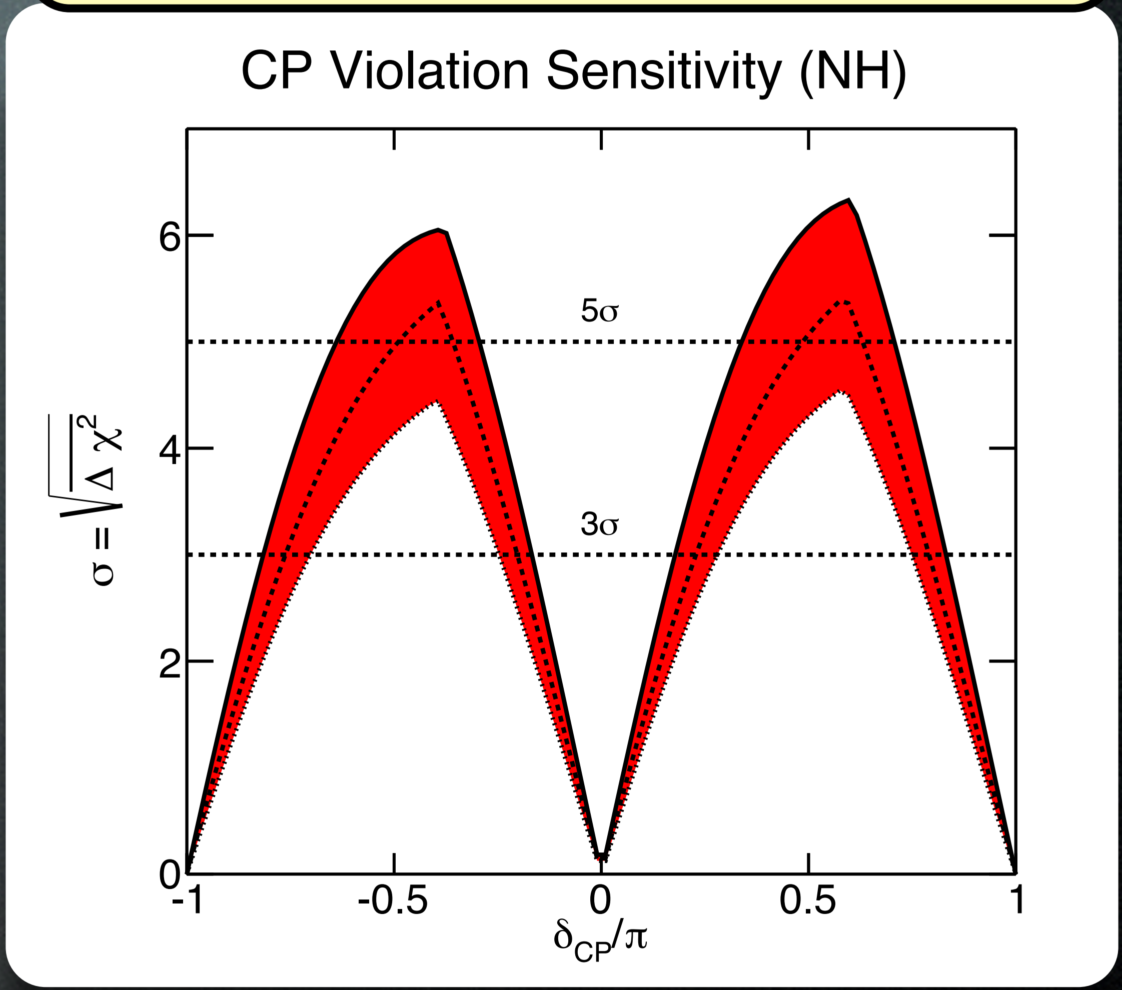
Defining "Precision δ_{CP} Measurements"

Hyper-Kamiokande



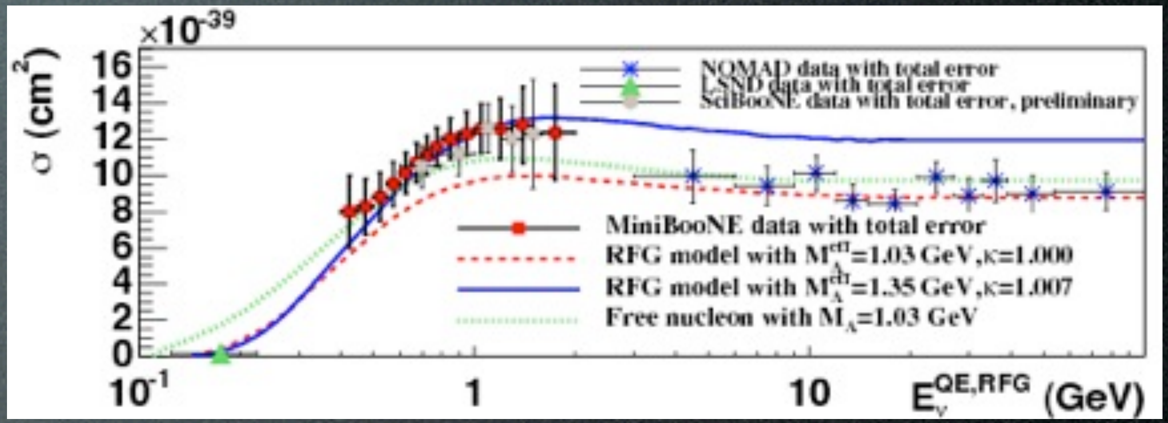
LBNE

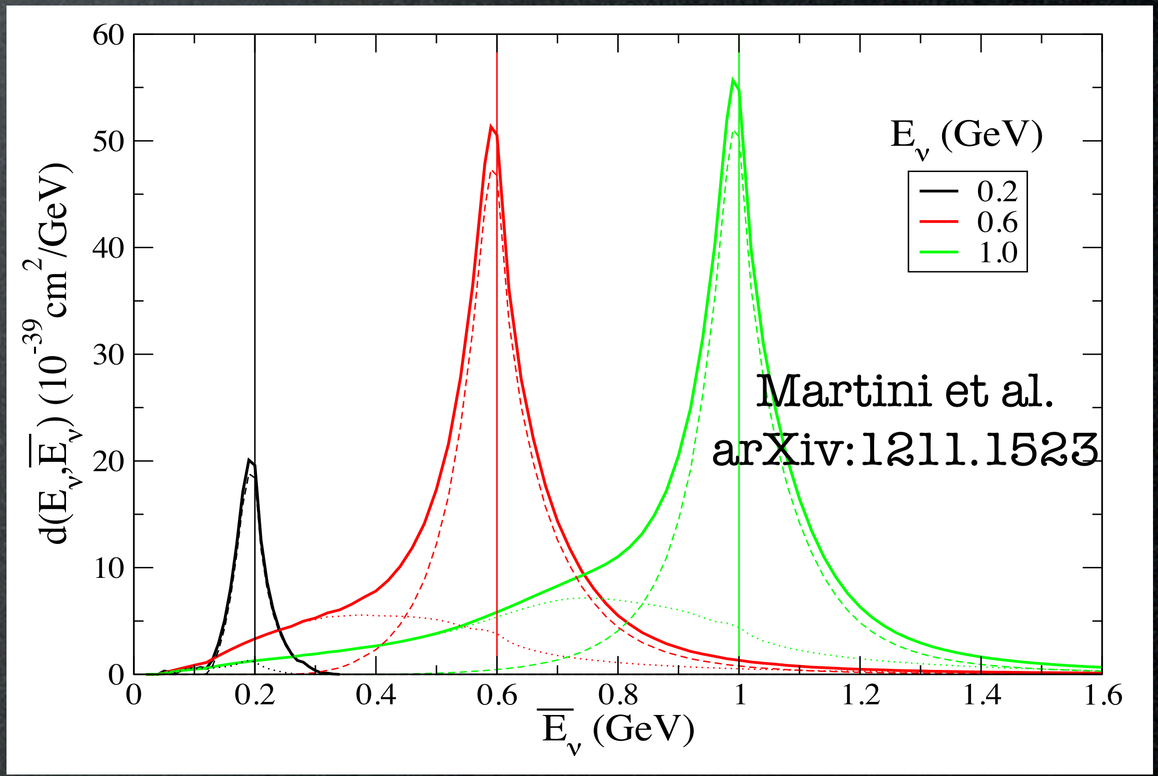


- Old sensitivity plots (somewhat out of date)
    - Normalization uncertainties only
- Takeaway message: CP violation experiments will likely be systematics limited
    - Largely due to neutrino interaction uncertainties

Can Experiments Measure E_ν?

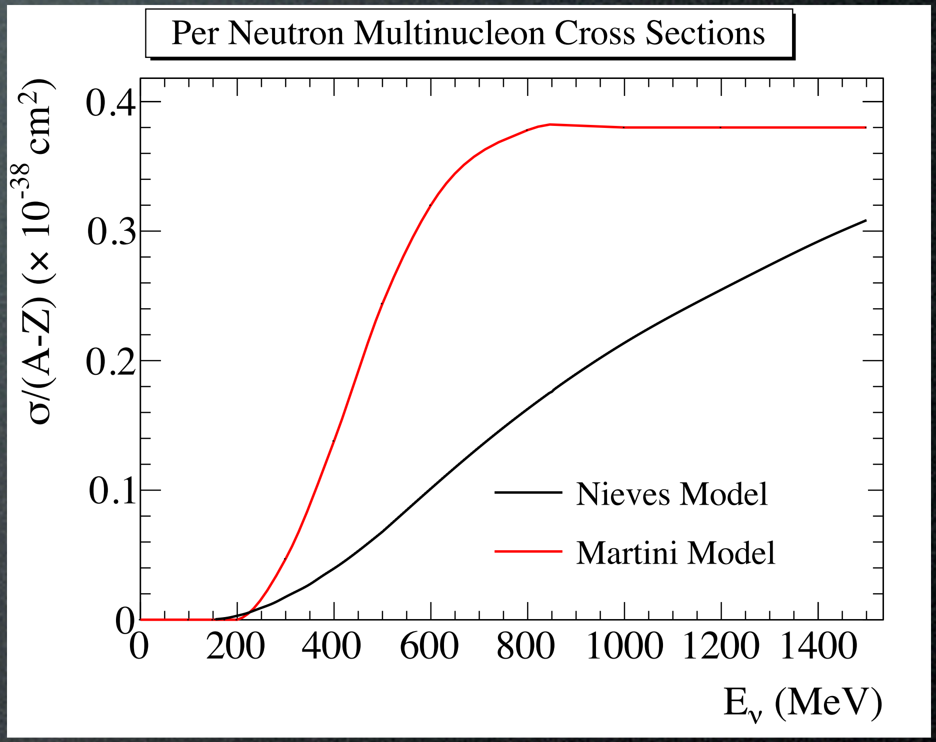
- In 2009, MiniBooNE CCQE data showed an excess not predicted by any existing neutrino cross section model
  - ...and inconsistent with NOMAD CCQE data at higher energies
- This is now believed to be caused by nucleon correlations (and other nuclear and even non-nuclear effects)
  - If correct, a large fraction of events (~20-30%) can have a significant bias in reconstructed energy
- No direct data constraint exists
  - Oscillation experiments completely rely on models that were very different just 5 years ago

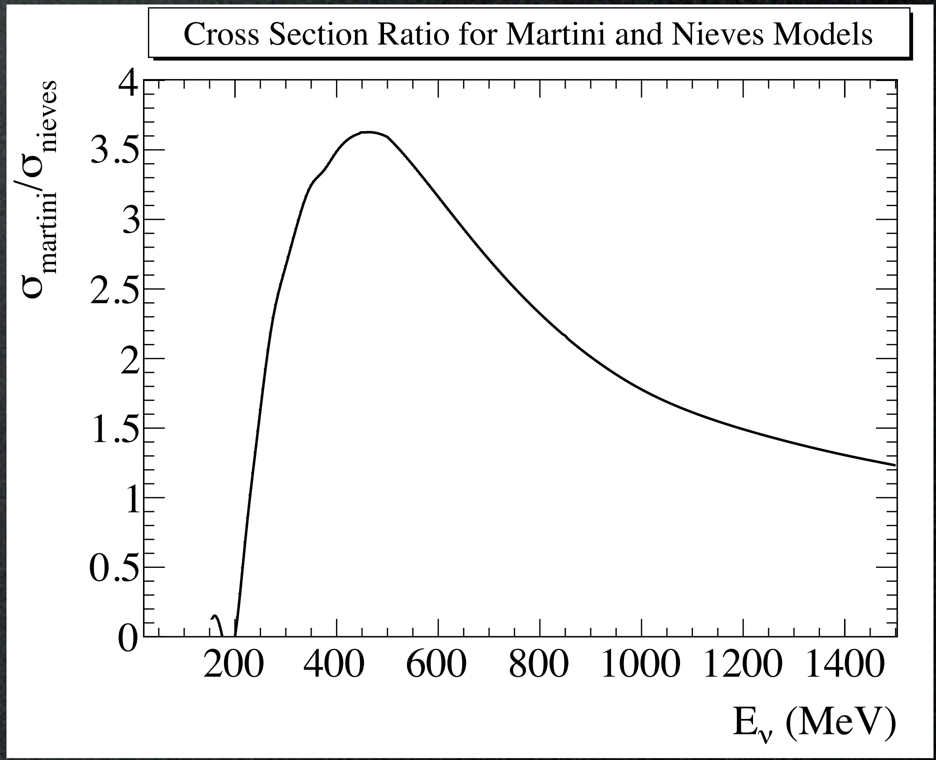




How Well are the New Models Understood?

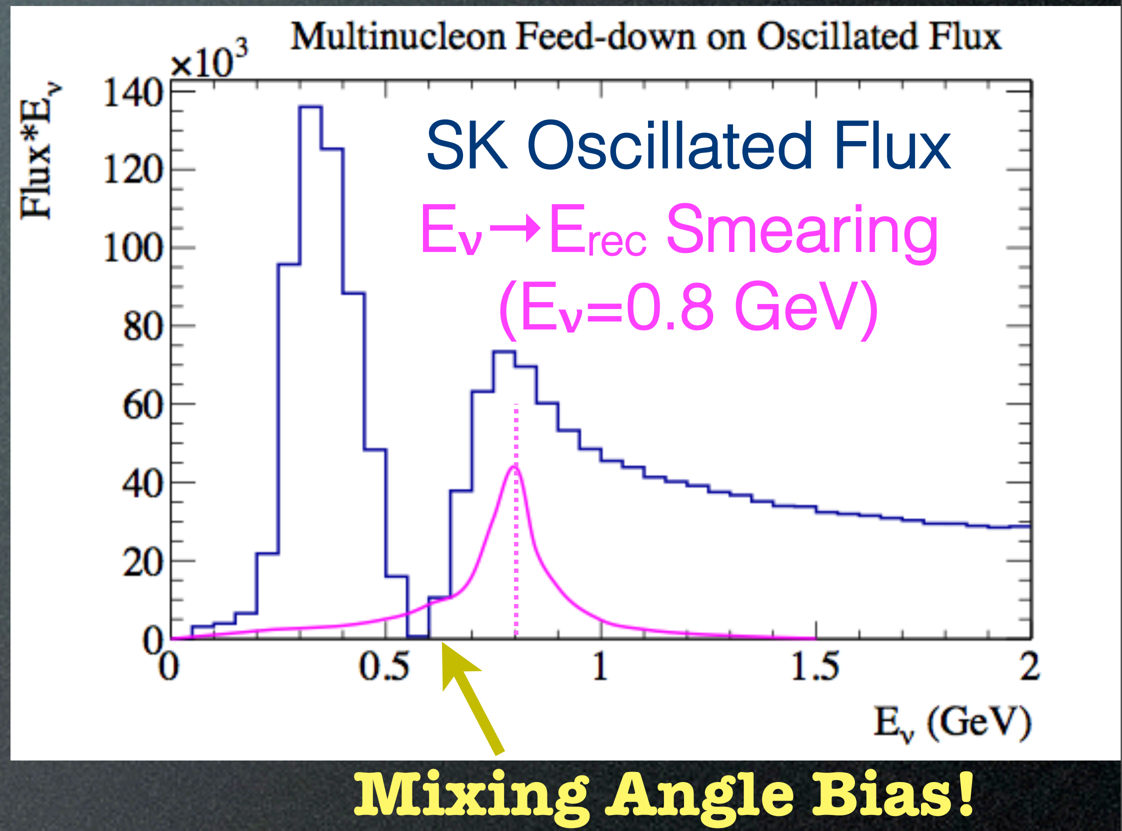
- It is very difficult to answer this question without a direct measurement
- However, the two most commonly used “new” models can be compared
    - J. Nieves, I. Ruiz Simo, and M. J. Vicente Vacas, PRC 83:045501 (2011)
    - M. Martini, M. Ericson, G. Chanfray, and J. Marteau, PRC 80:065501 (2009)
- Cross section differs by a factor of 2 to 3 over a large range of neutrino energies
- Which model is correct?
    - Is either model correct?
- Nuclear physics at 1 GeV is difficult

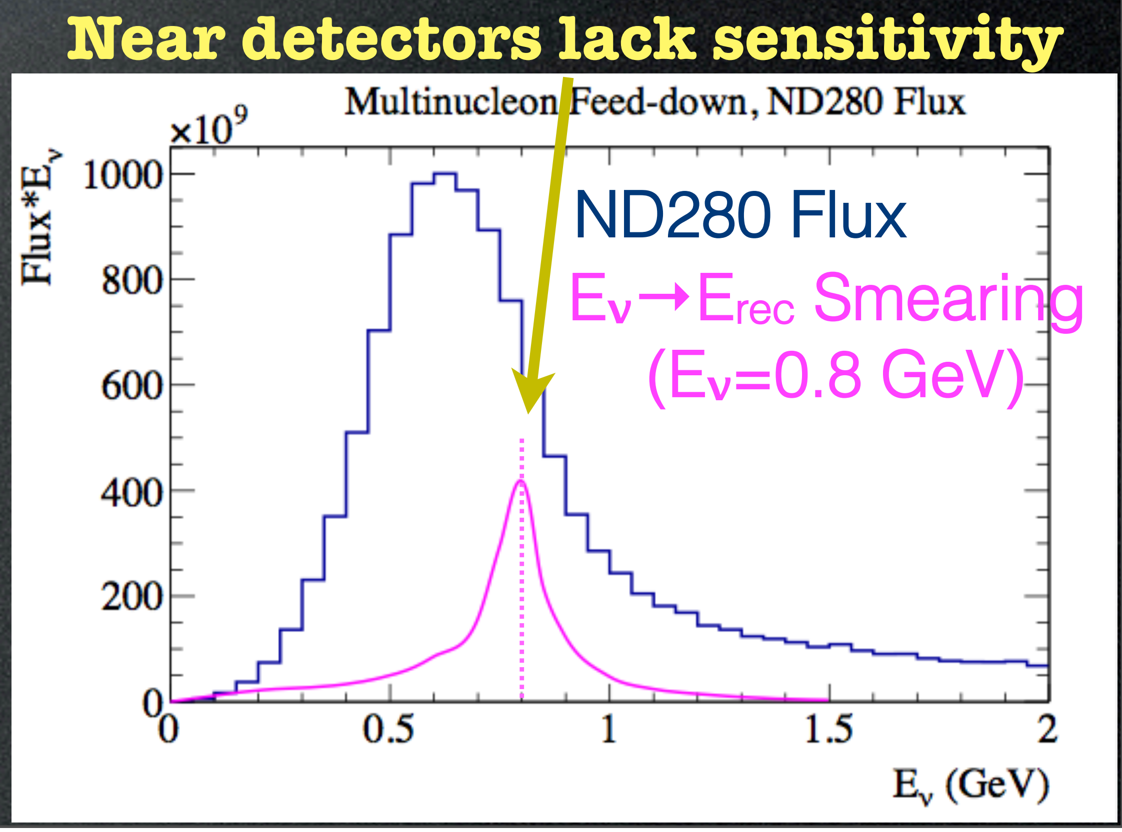




Isn't This is Why Oscillation Experiments Build Near Detectors?

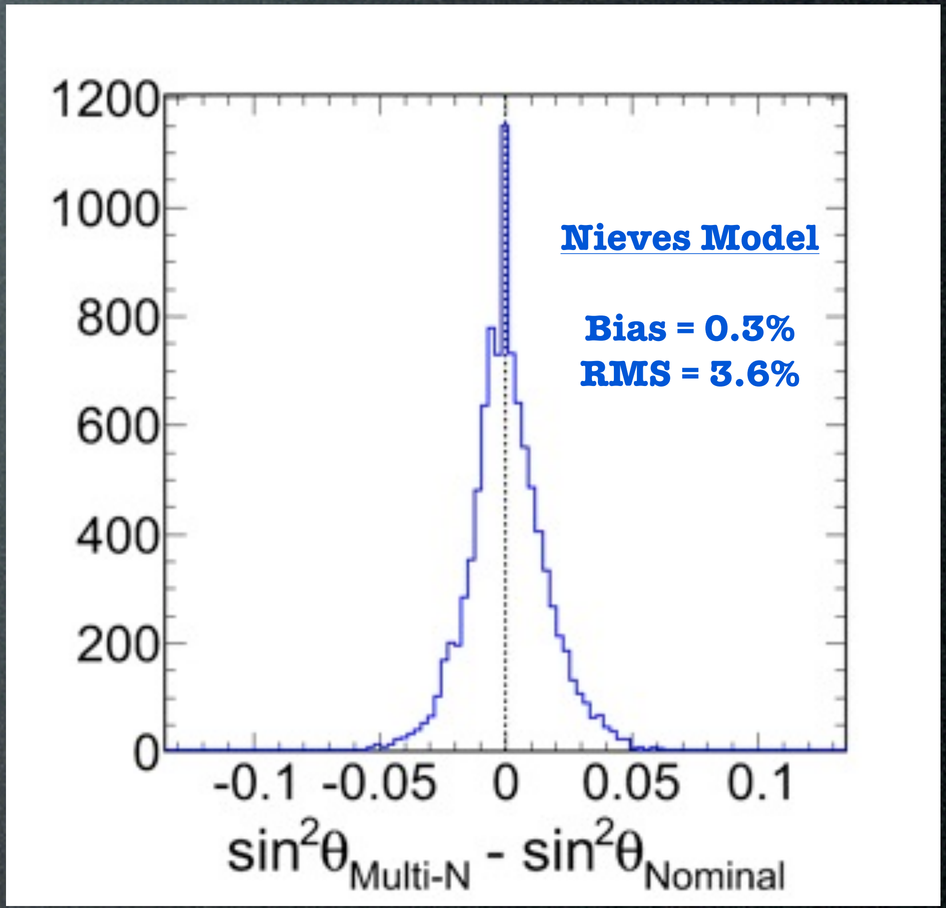
- Shouldn't cross section systematics cancel in a near/far fit?
  - Some errors, like total normalization, will cancel
- However, multi-nucleon effect causes feed-down of events into oscillation dip
  - Cannot disentangle with near detectors
    - Energy spectrum is not oscillated
- More multi-nucleon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

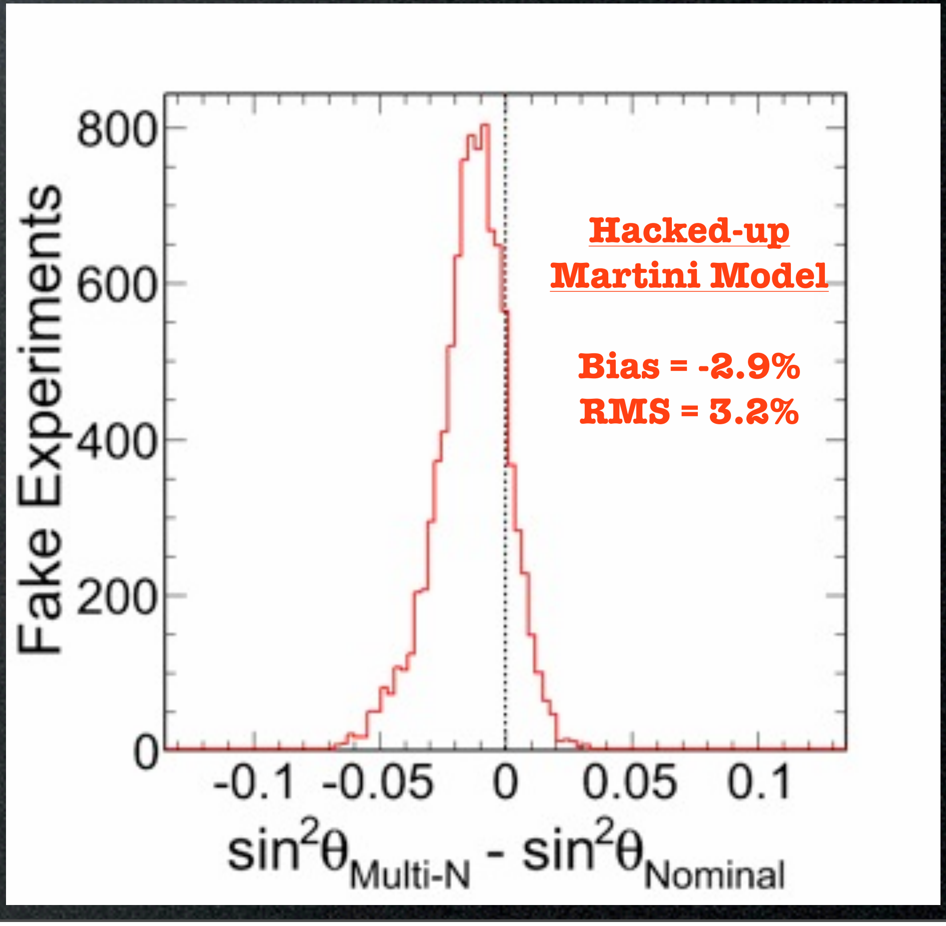




Effect on T2K ν_μ Disappearance

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

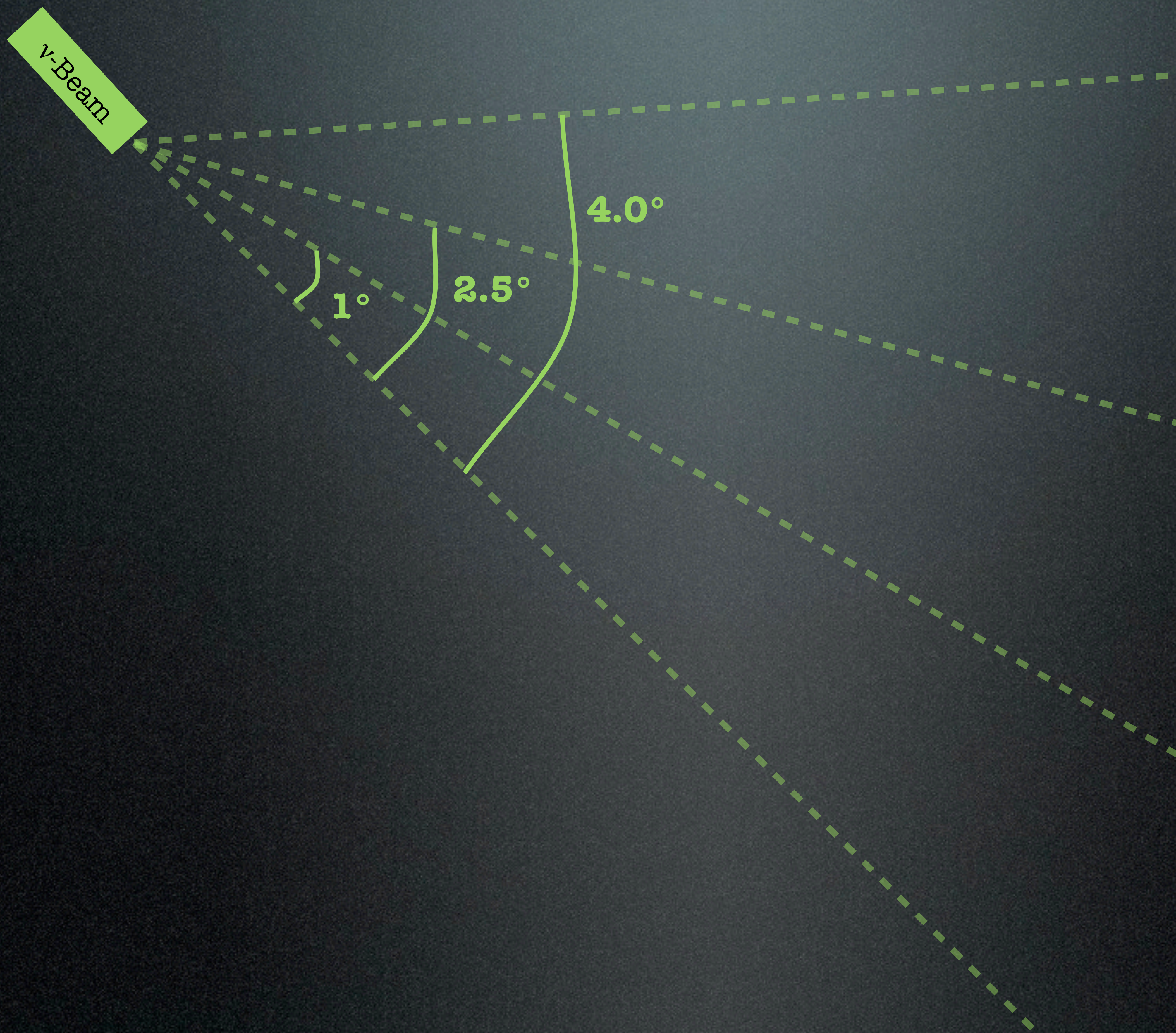




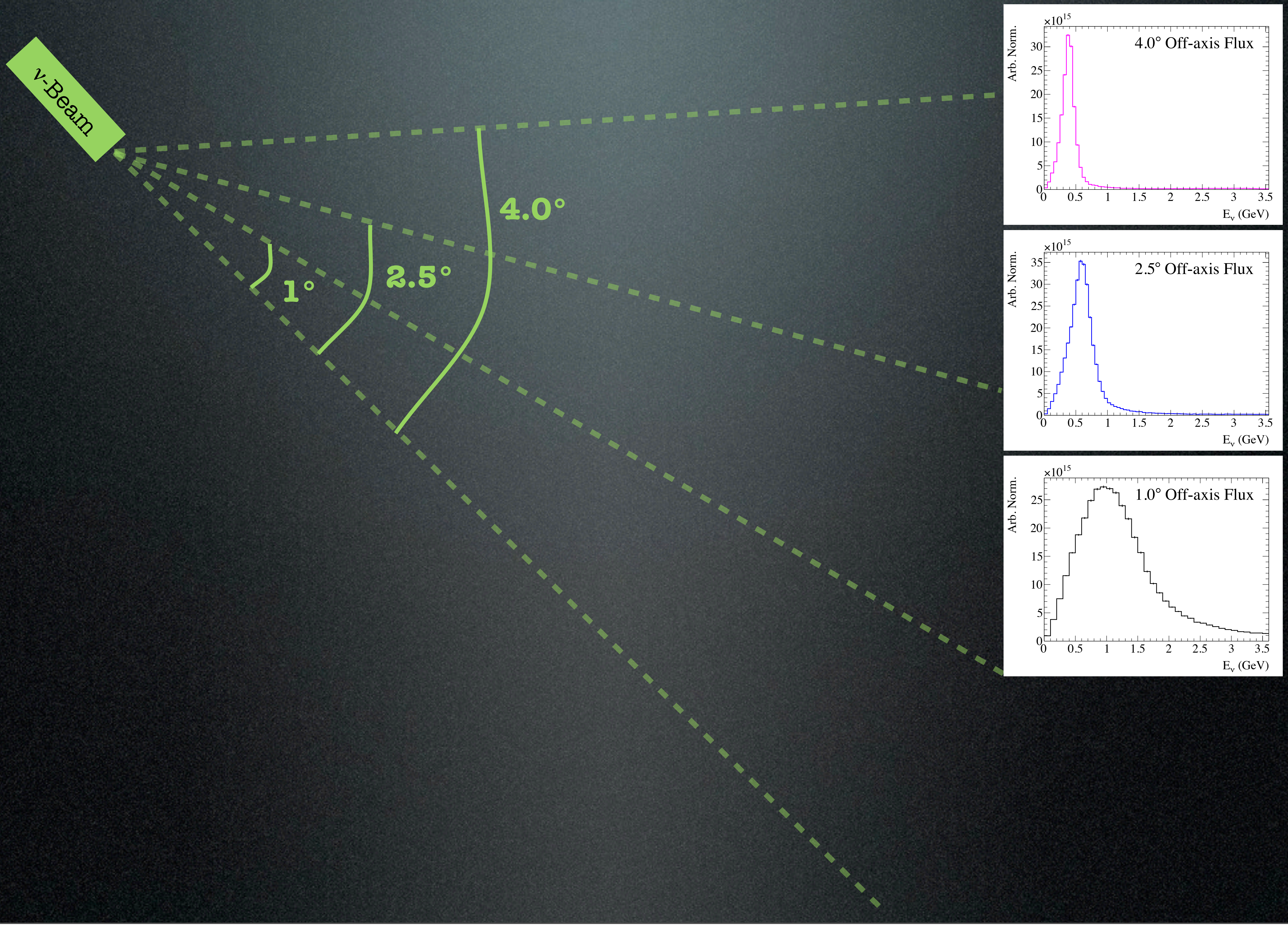
Can the E_ν problem be solved experimentally?

νPRISM Detector Concept

νPRISM Detector Concept



νPRISM Detector Concept



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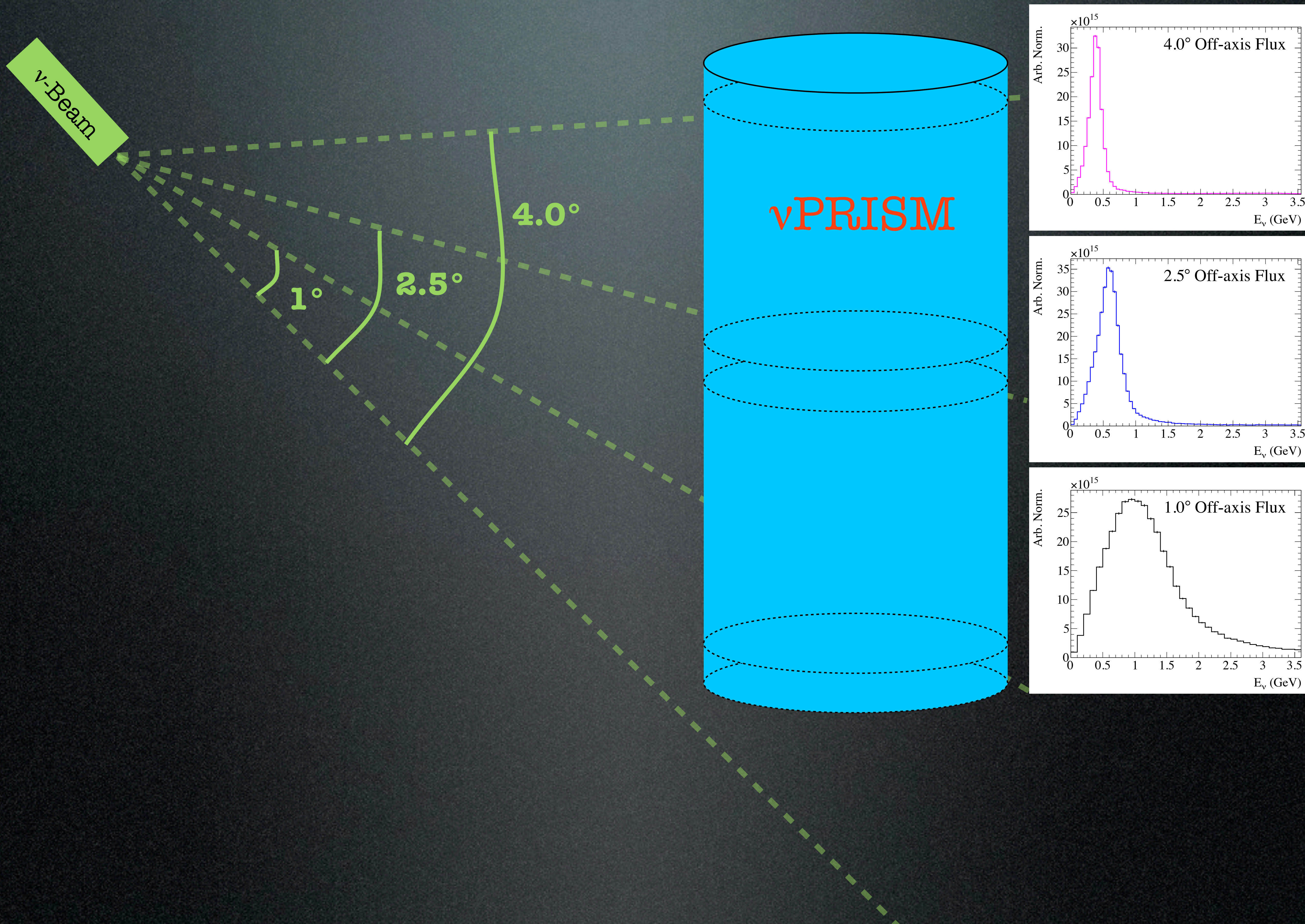

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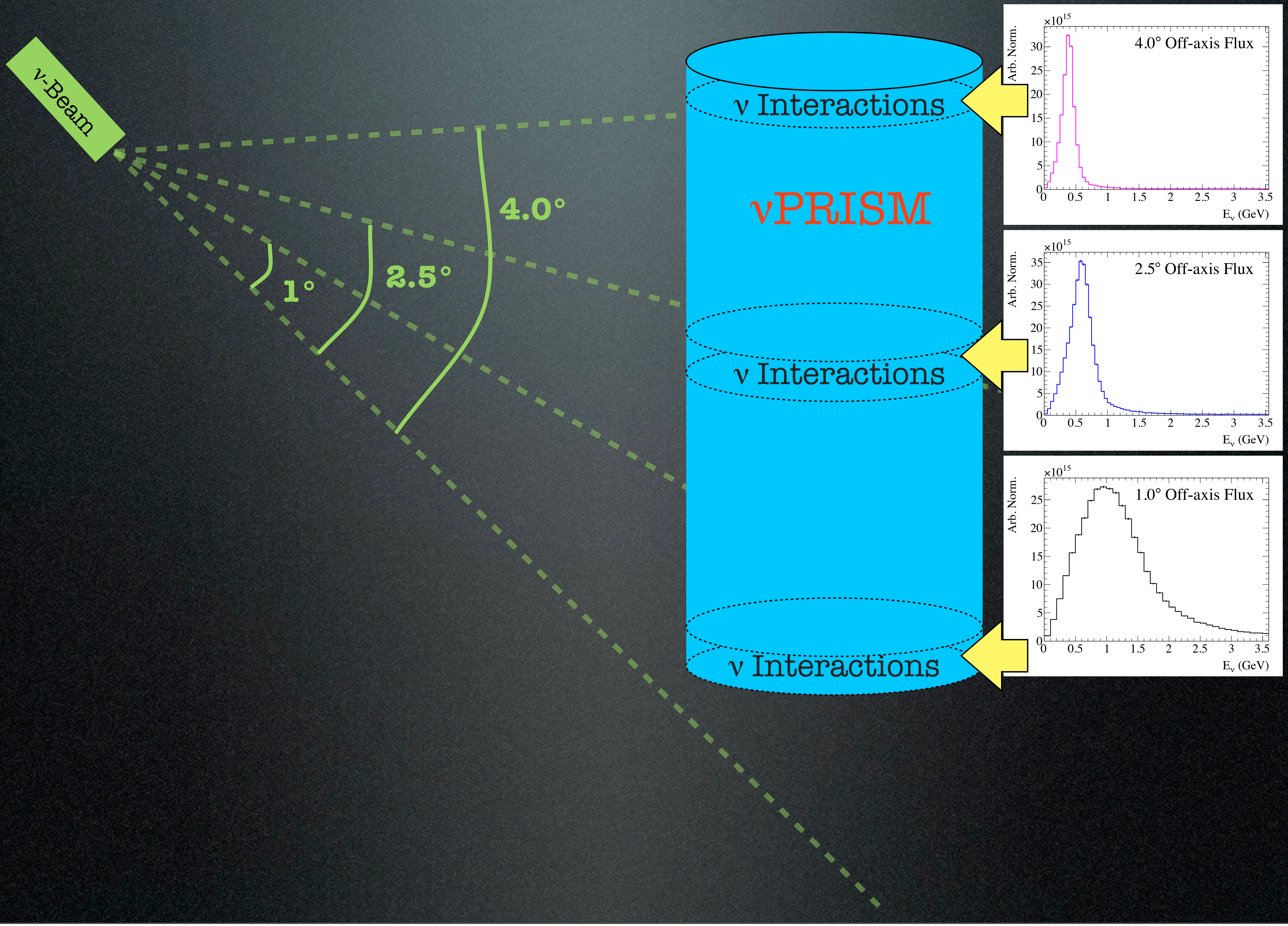

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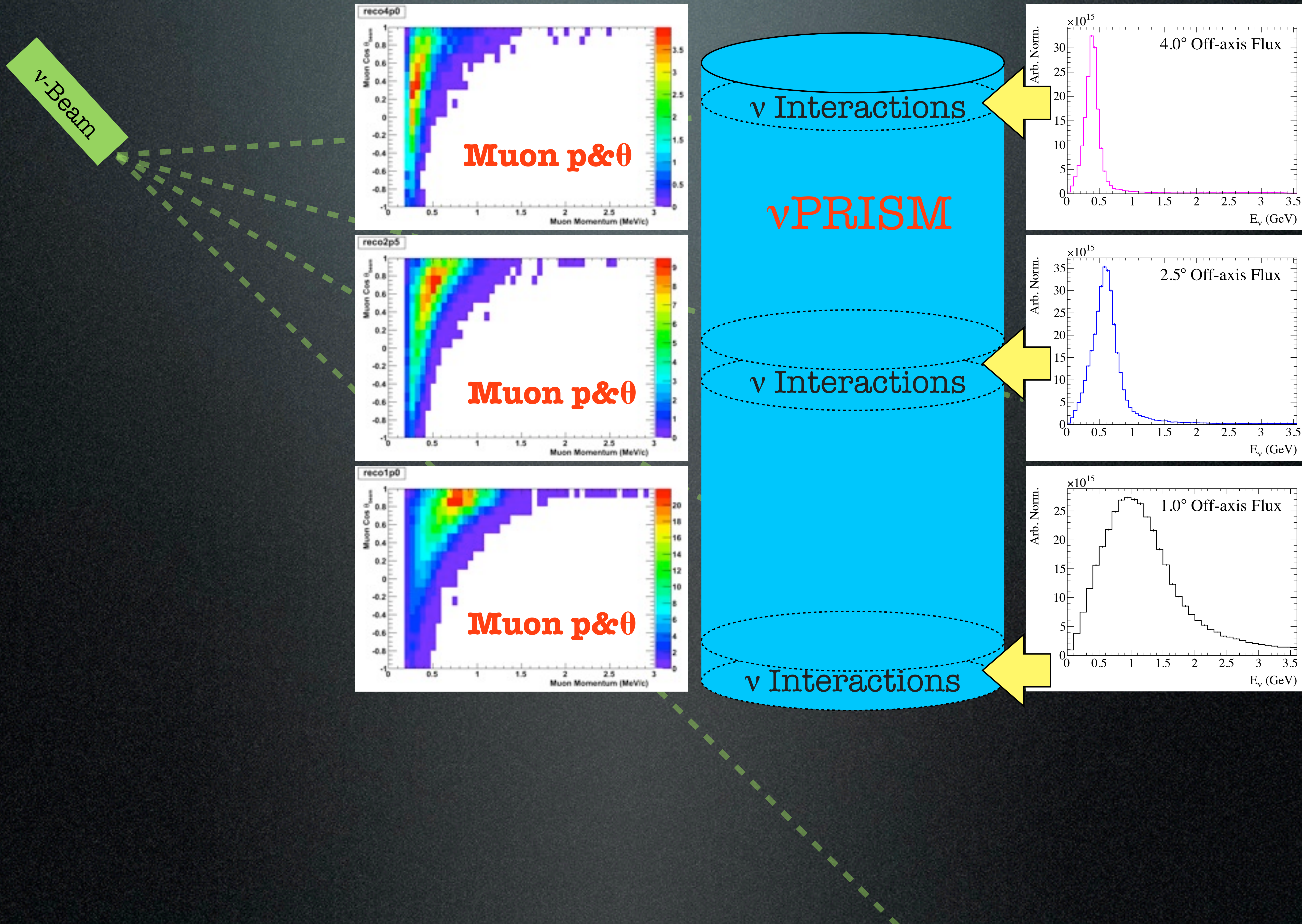

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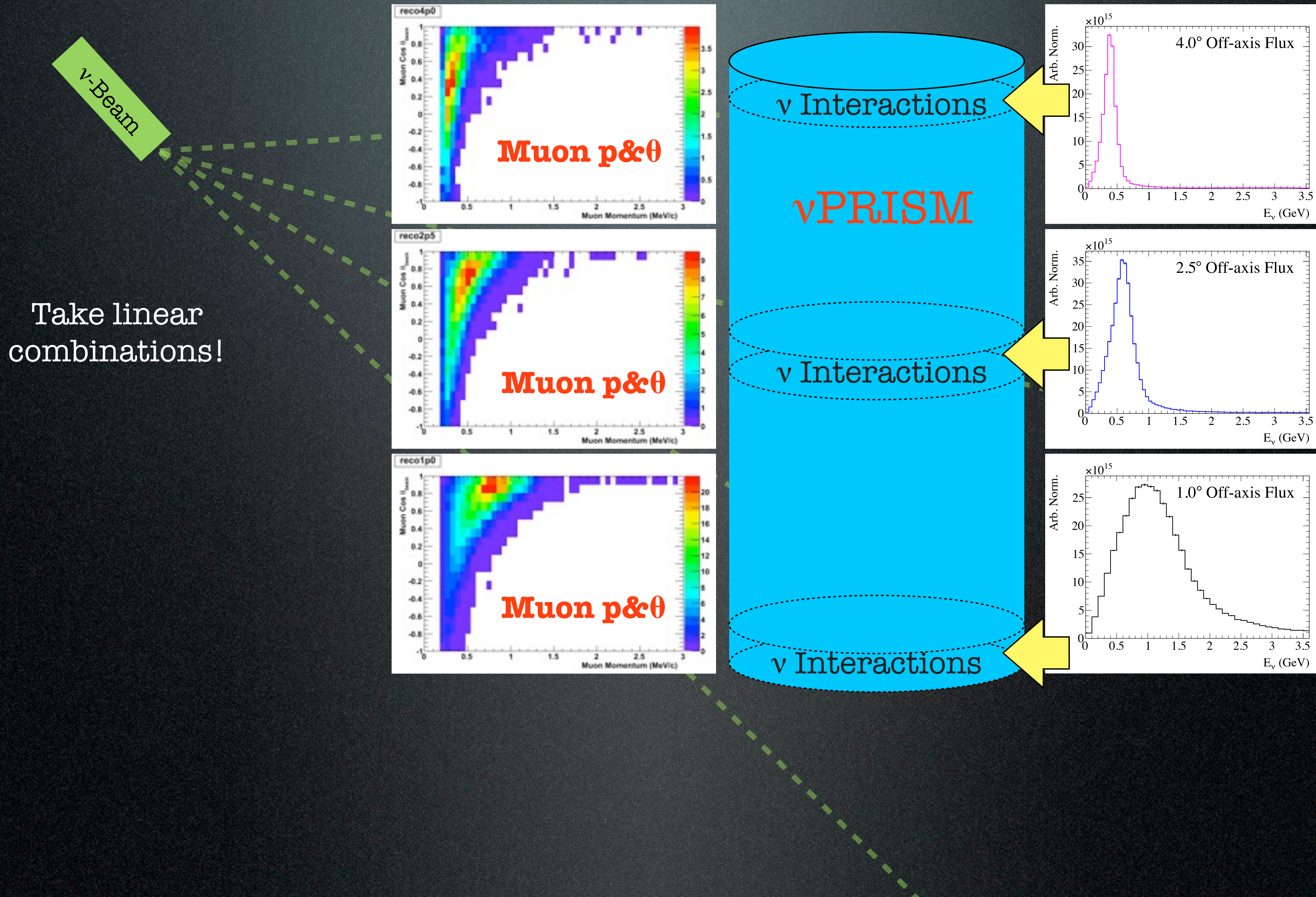
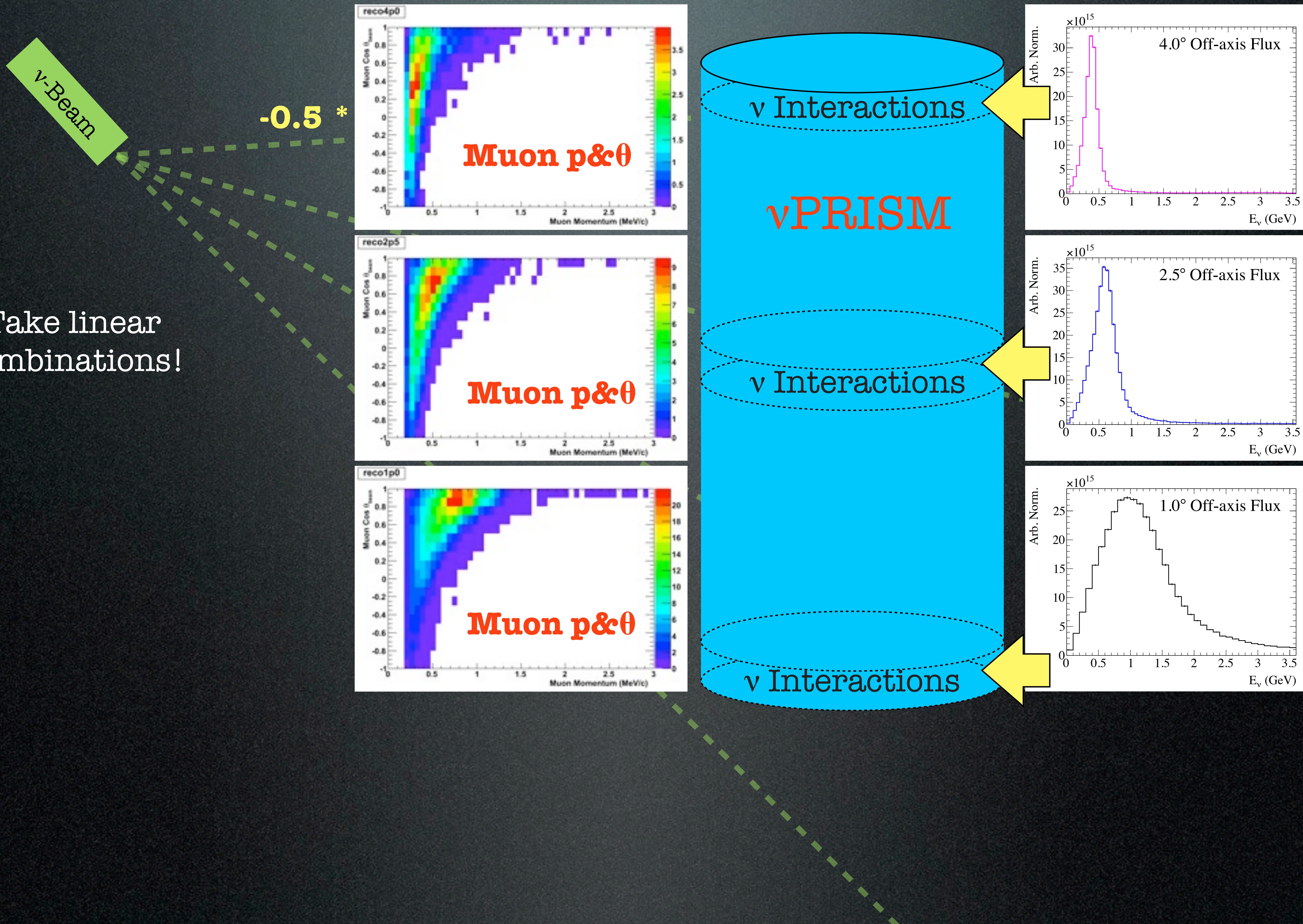


νPRISM Detector Concept

Take linear combinations!



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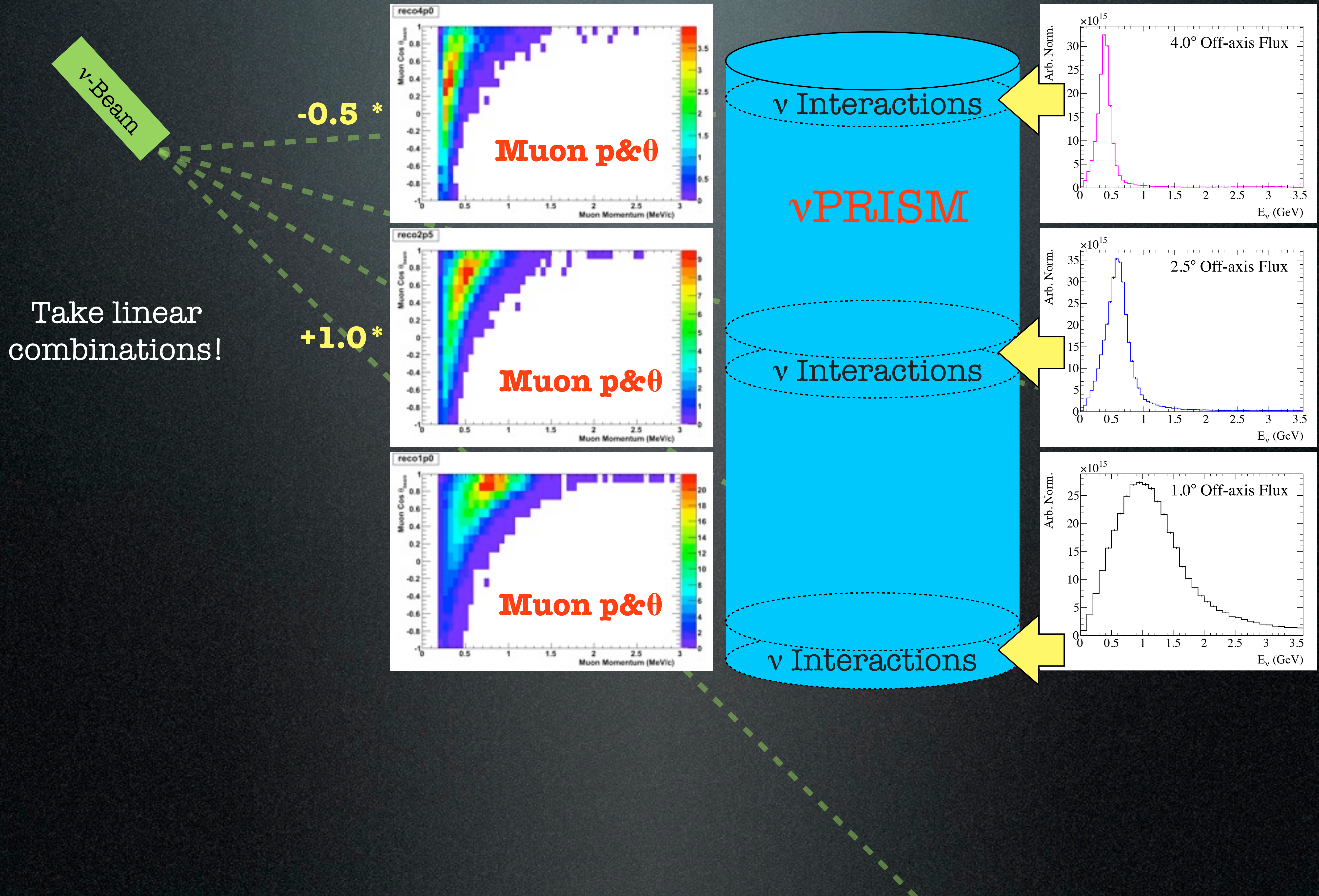

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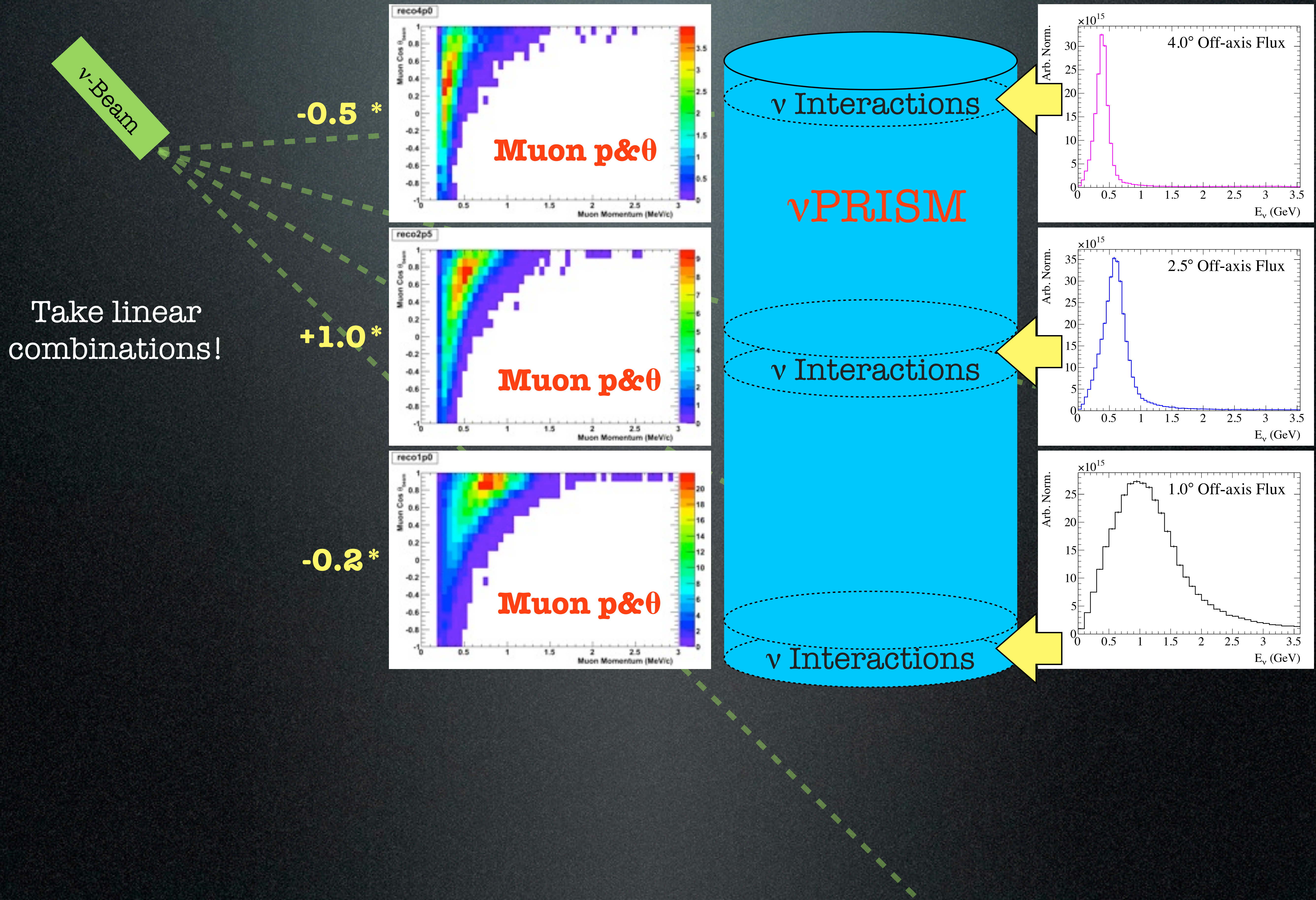

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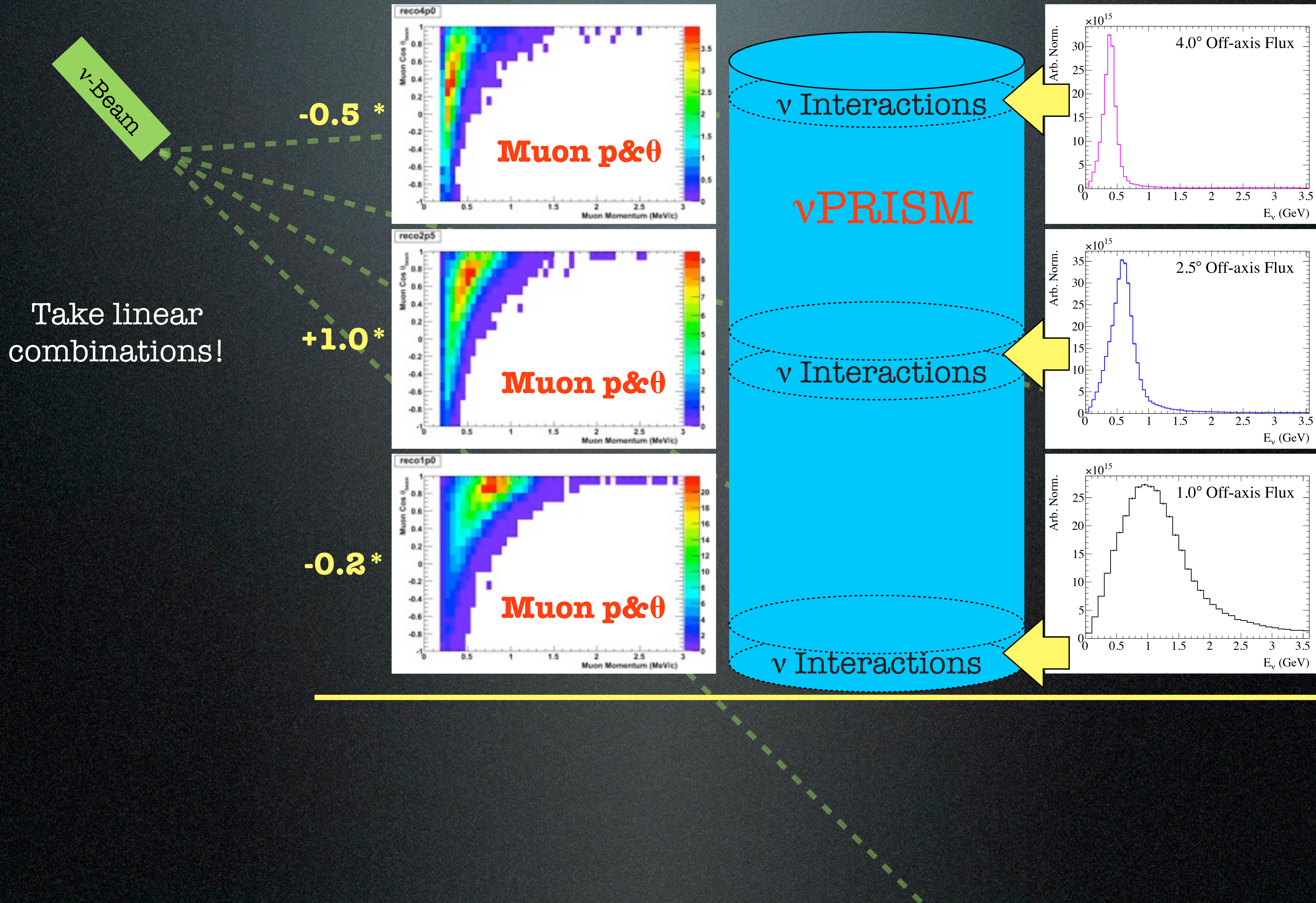

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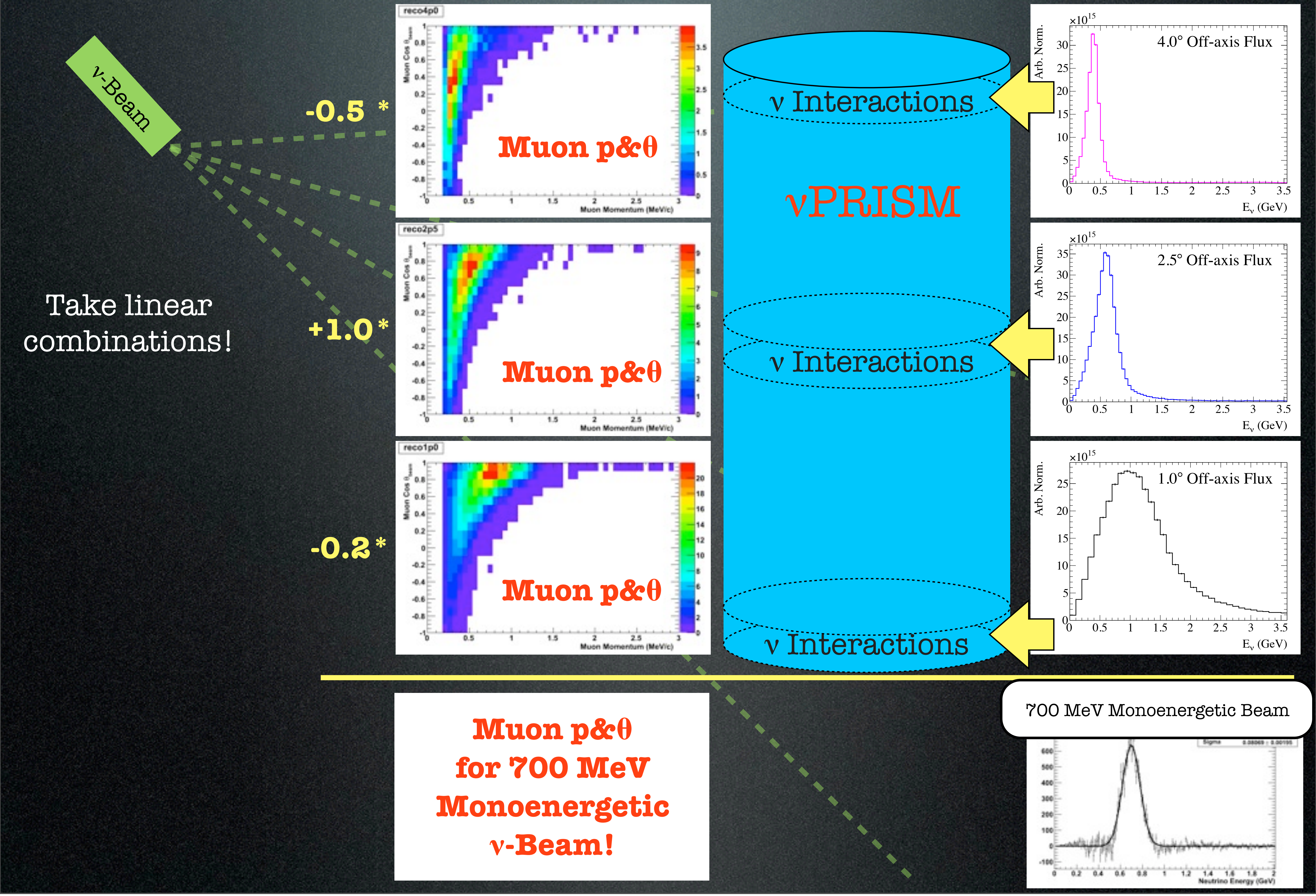

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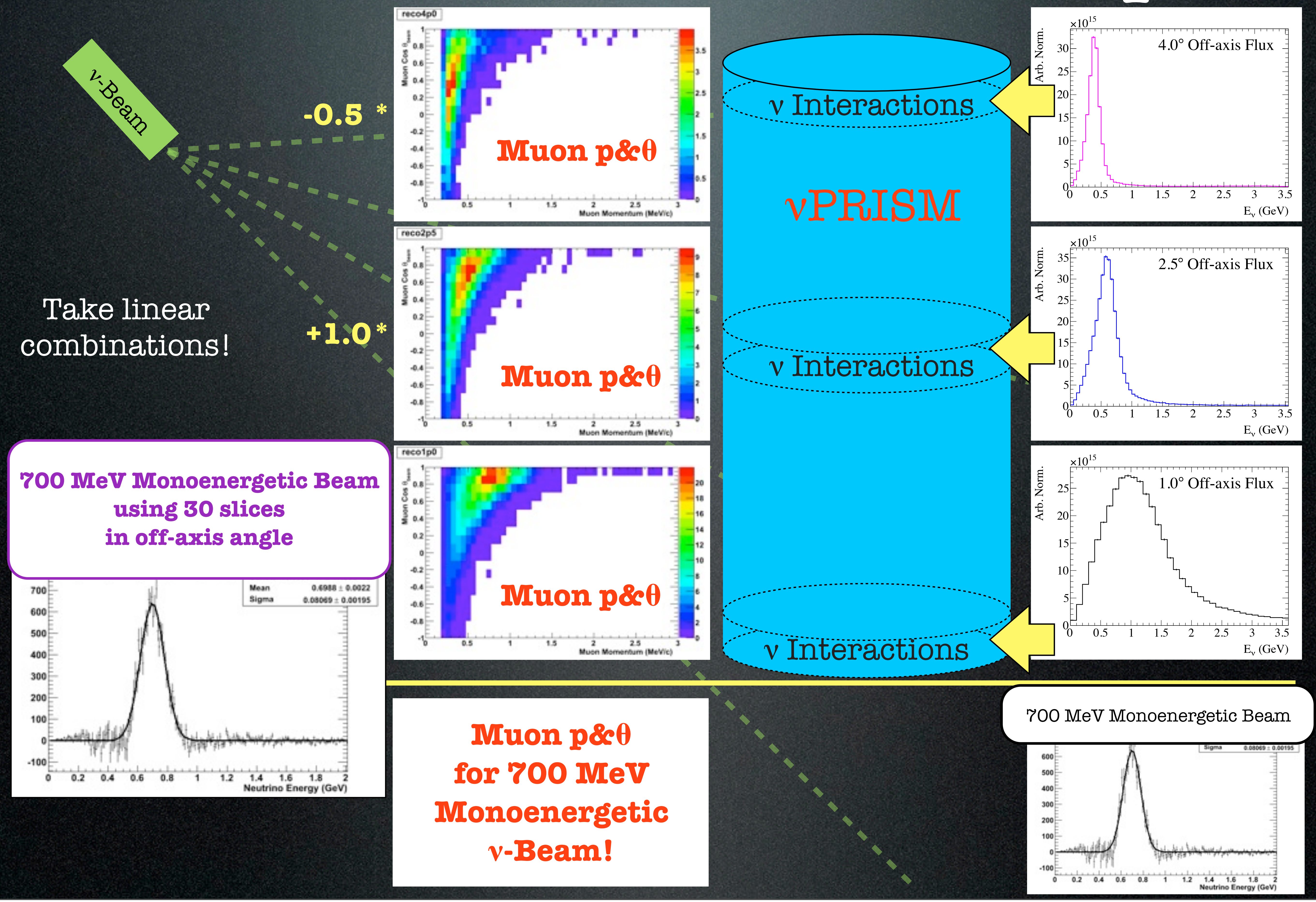
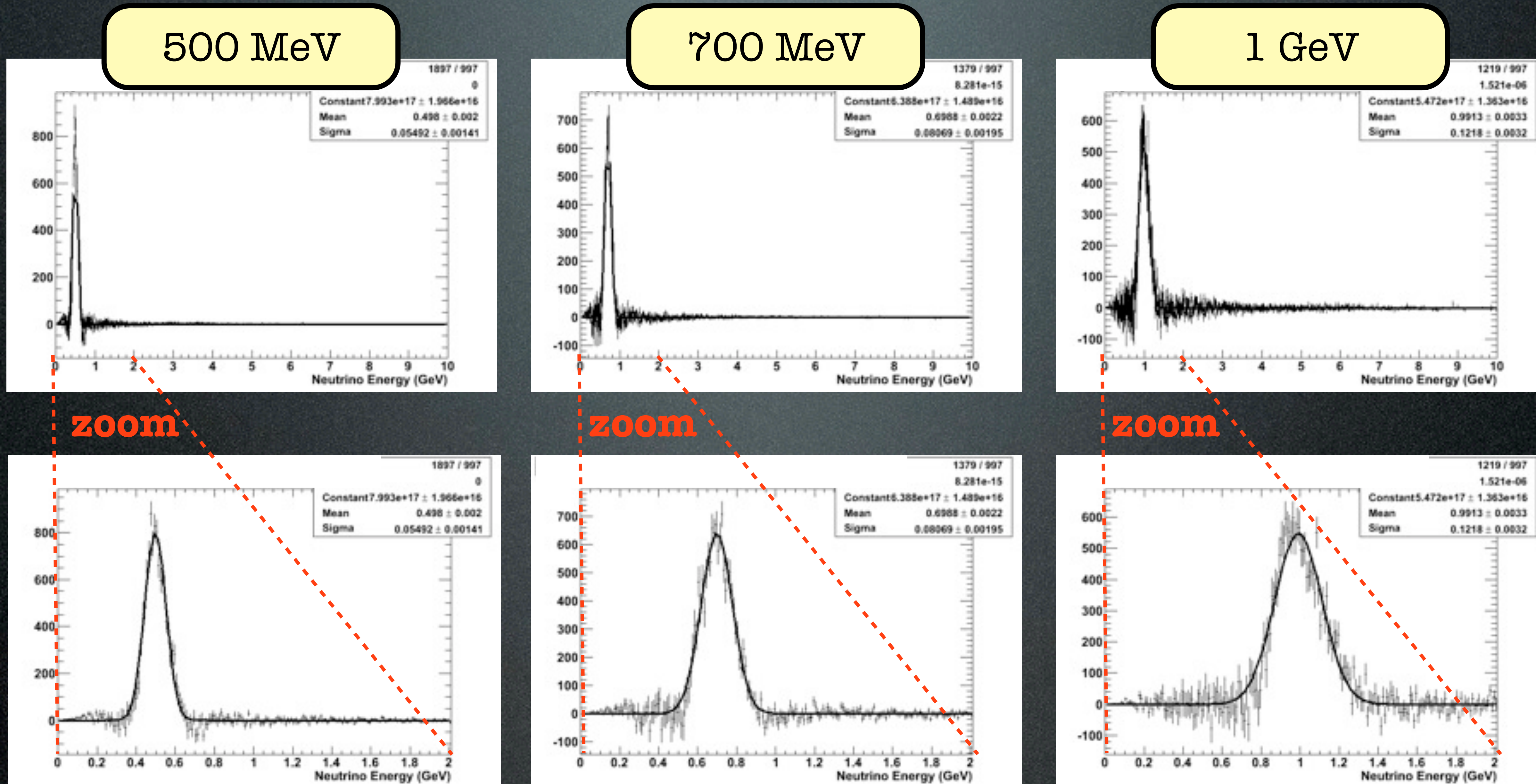


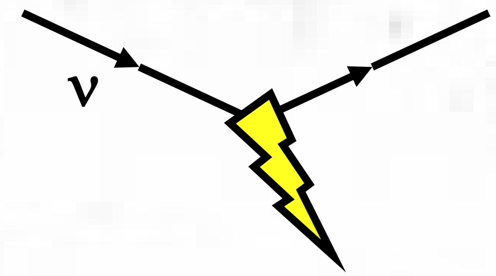
Neutrino Spectrometer



- 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

Other Uses of νPRISM data

Limitations of Near Detectors

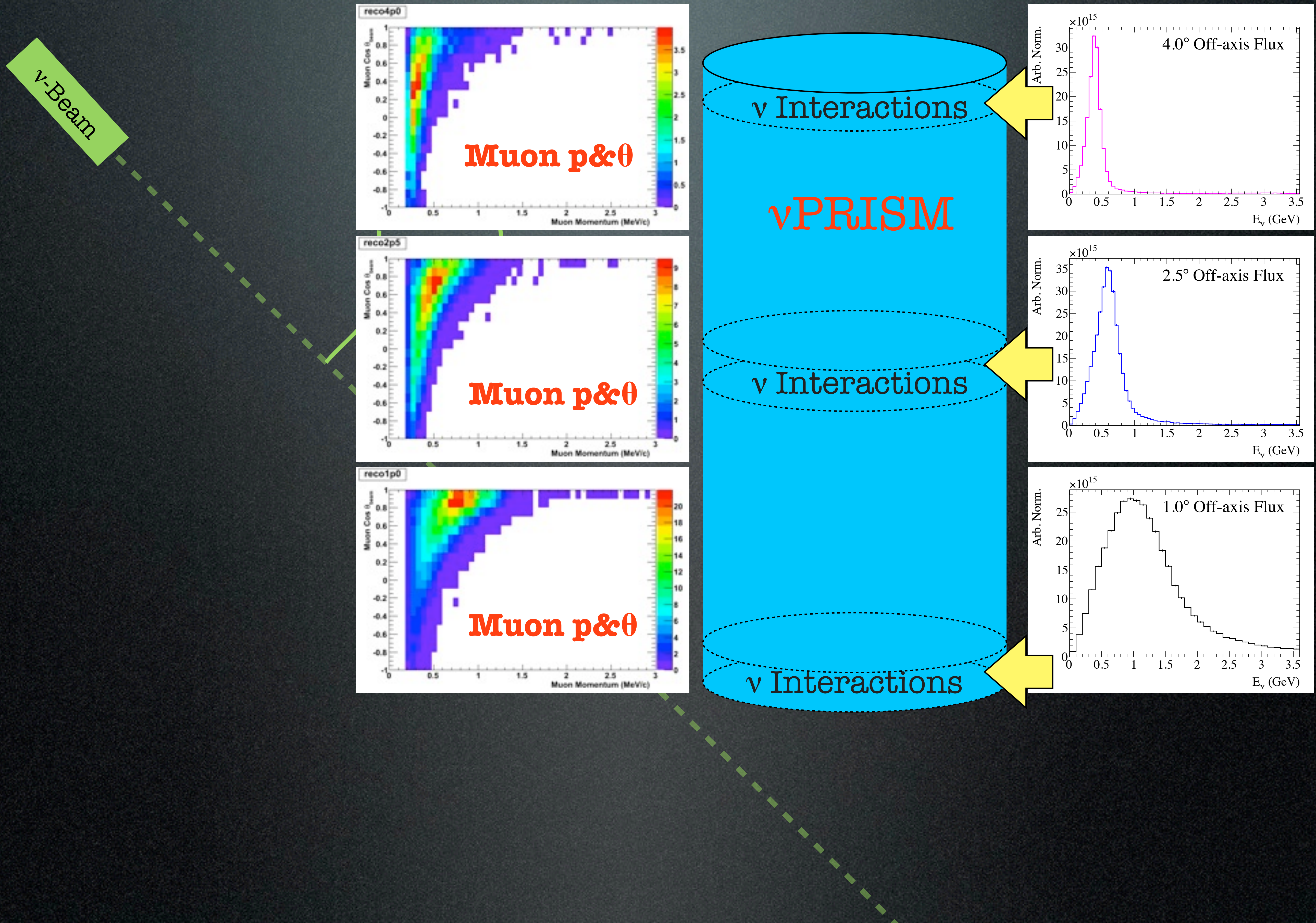


- Limitations of even "perfect" near detectors:
  1. Flux is never identical near and far, because of oscillations if for no other reason.
  2. Near detector has backgrounds to reactions of interest which may not be identical to far detector (see #1).

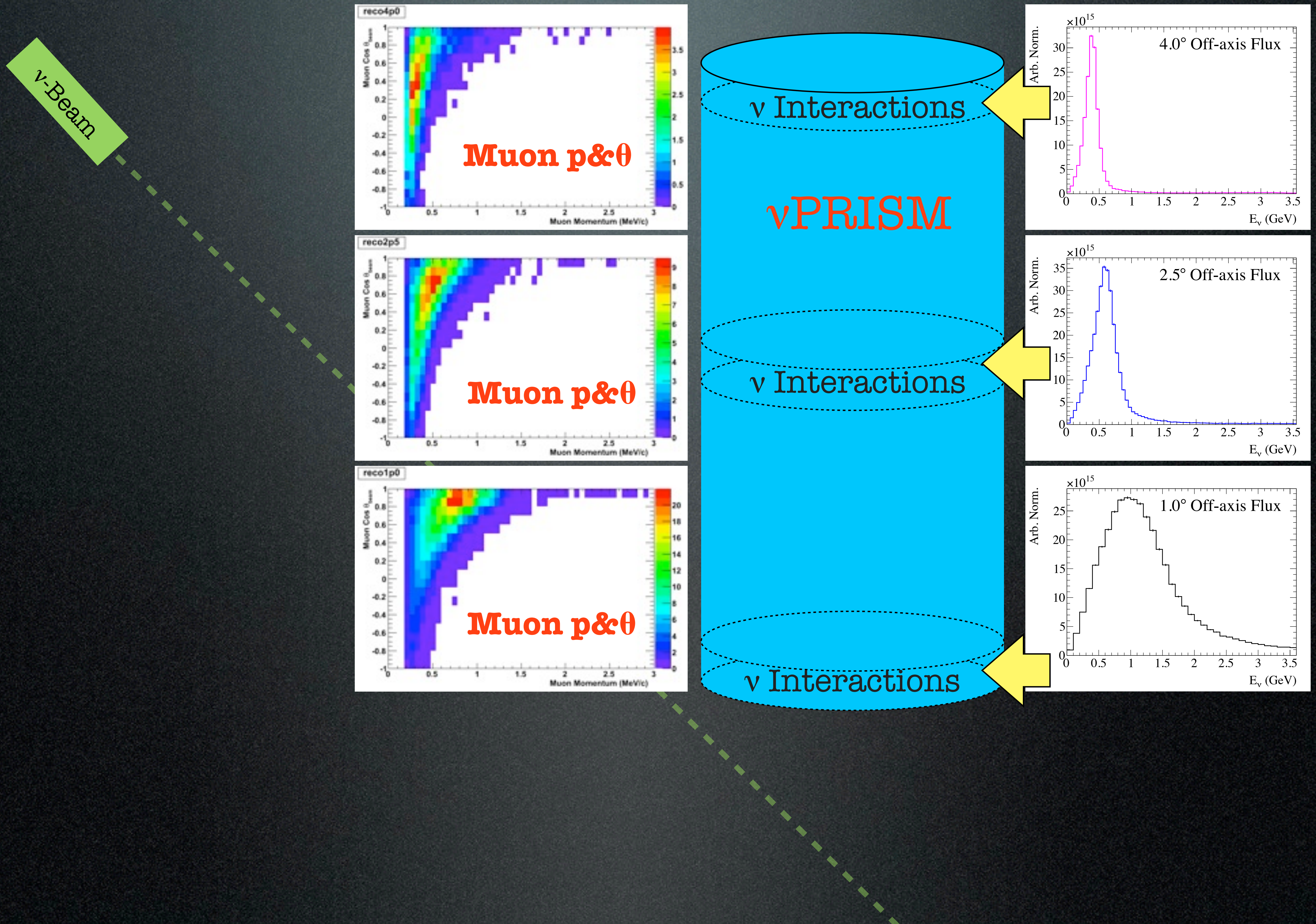
K. McFarland, Aspen Conference (2013)

Can νPRISM address this issue as well?

Removing Near/Far Flux Differences

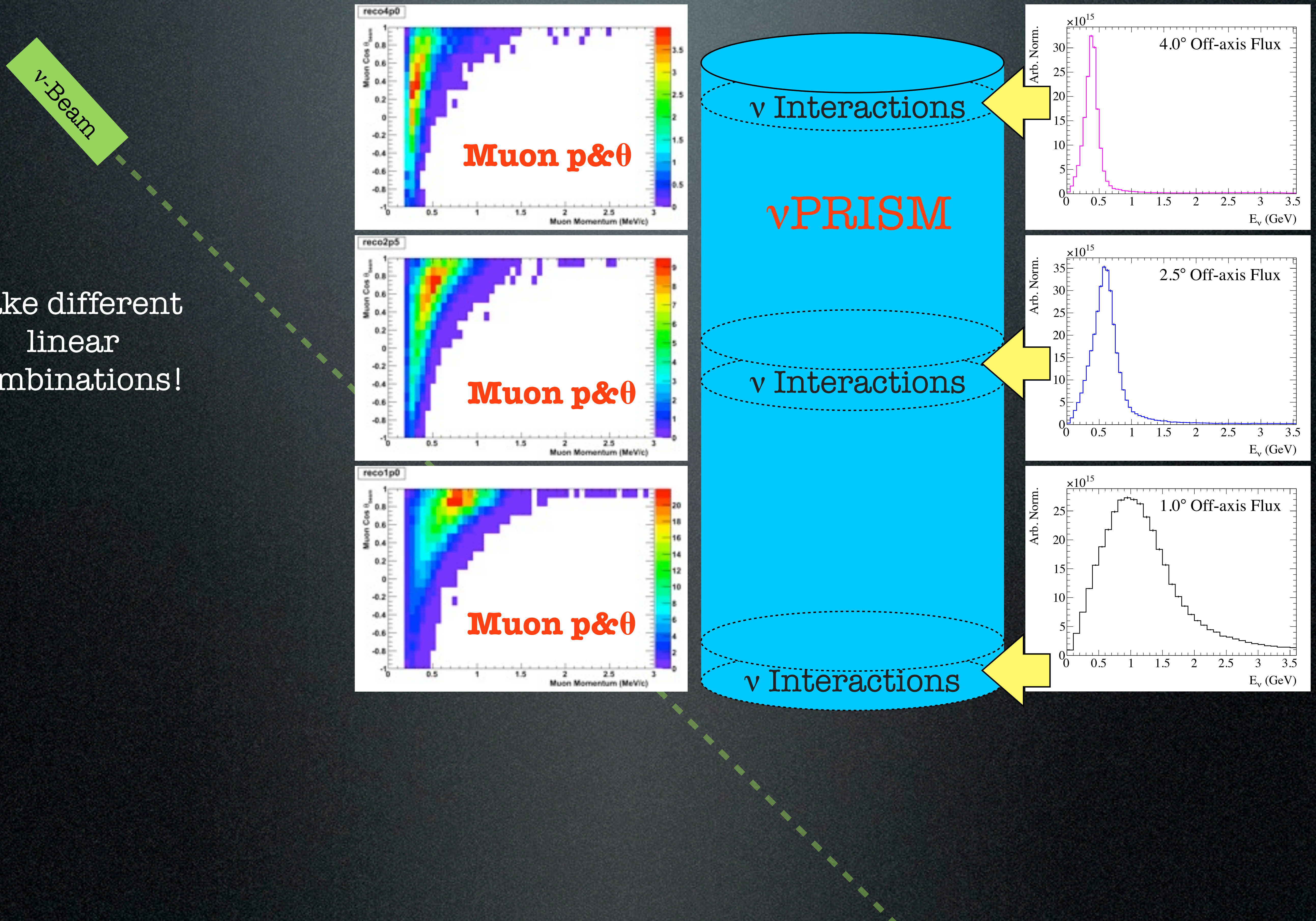


Removing Near/Far Flux Differences



Removing Near/Far Flux Differences

Take different linear combinations!



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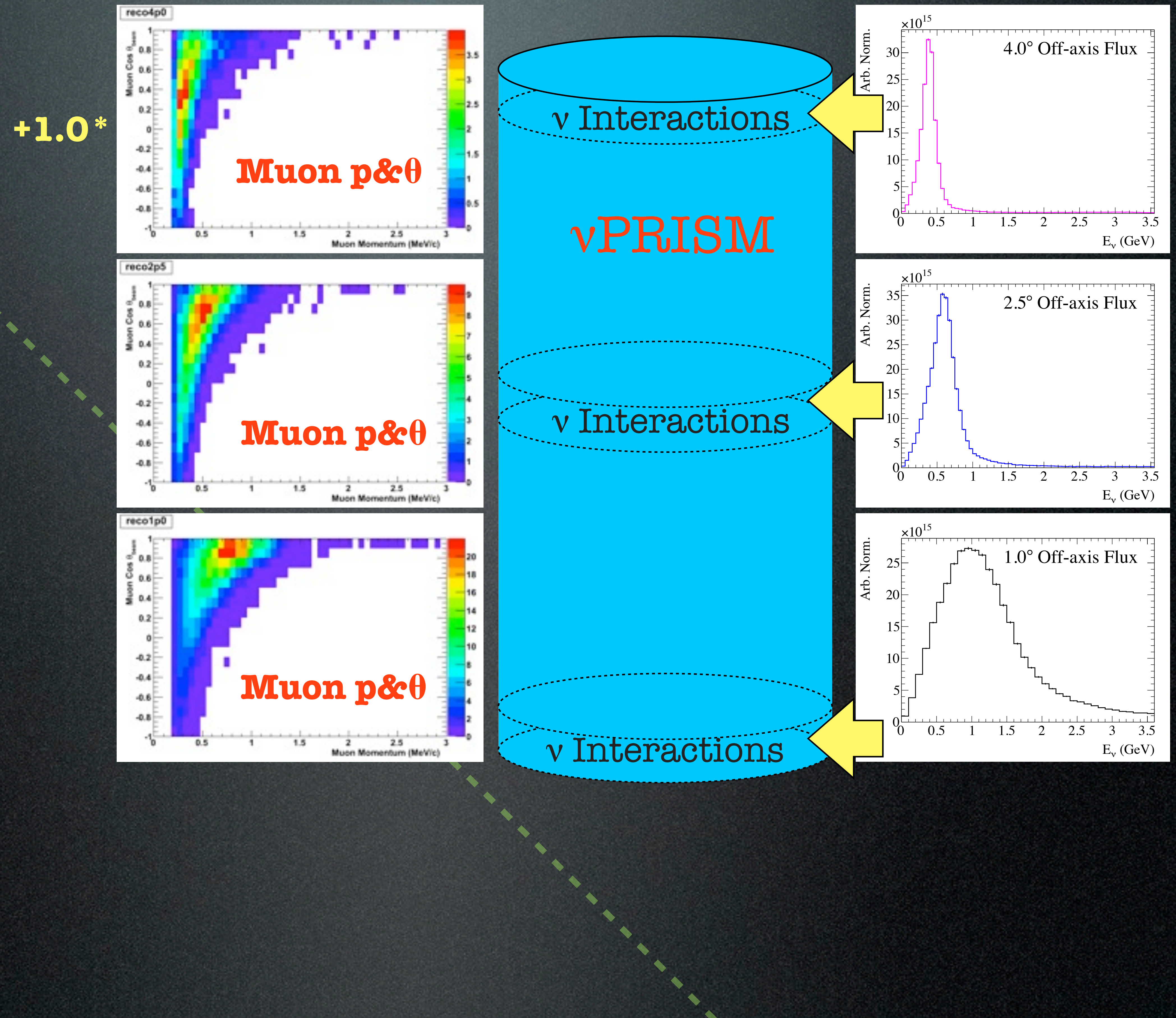
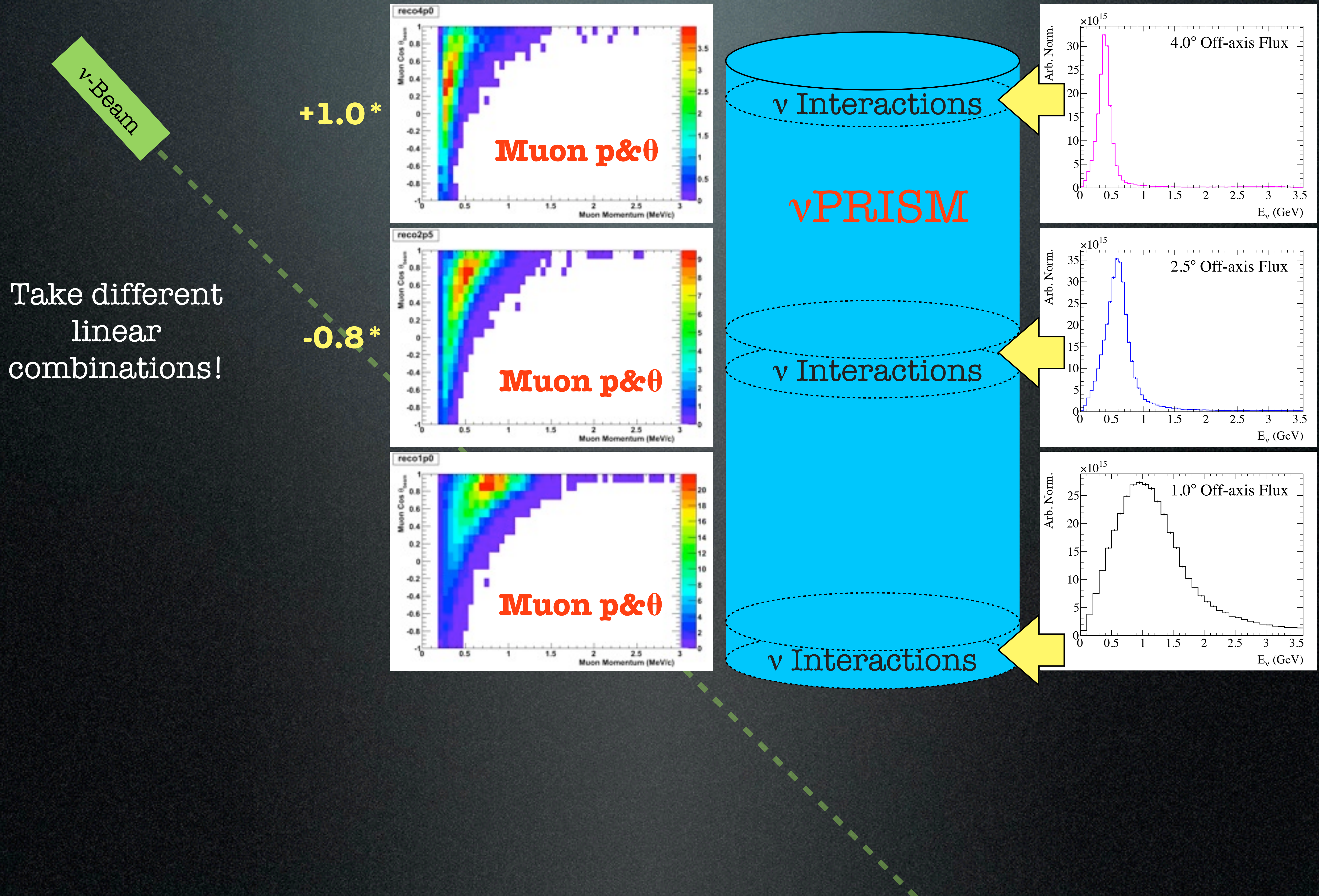


Removing Near/Far Flux Differences



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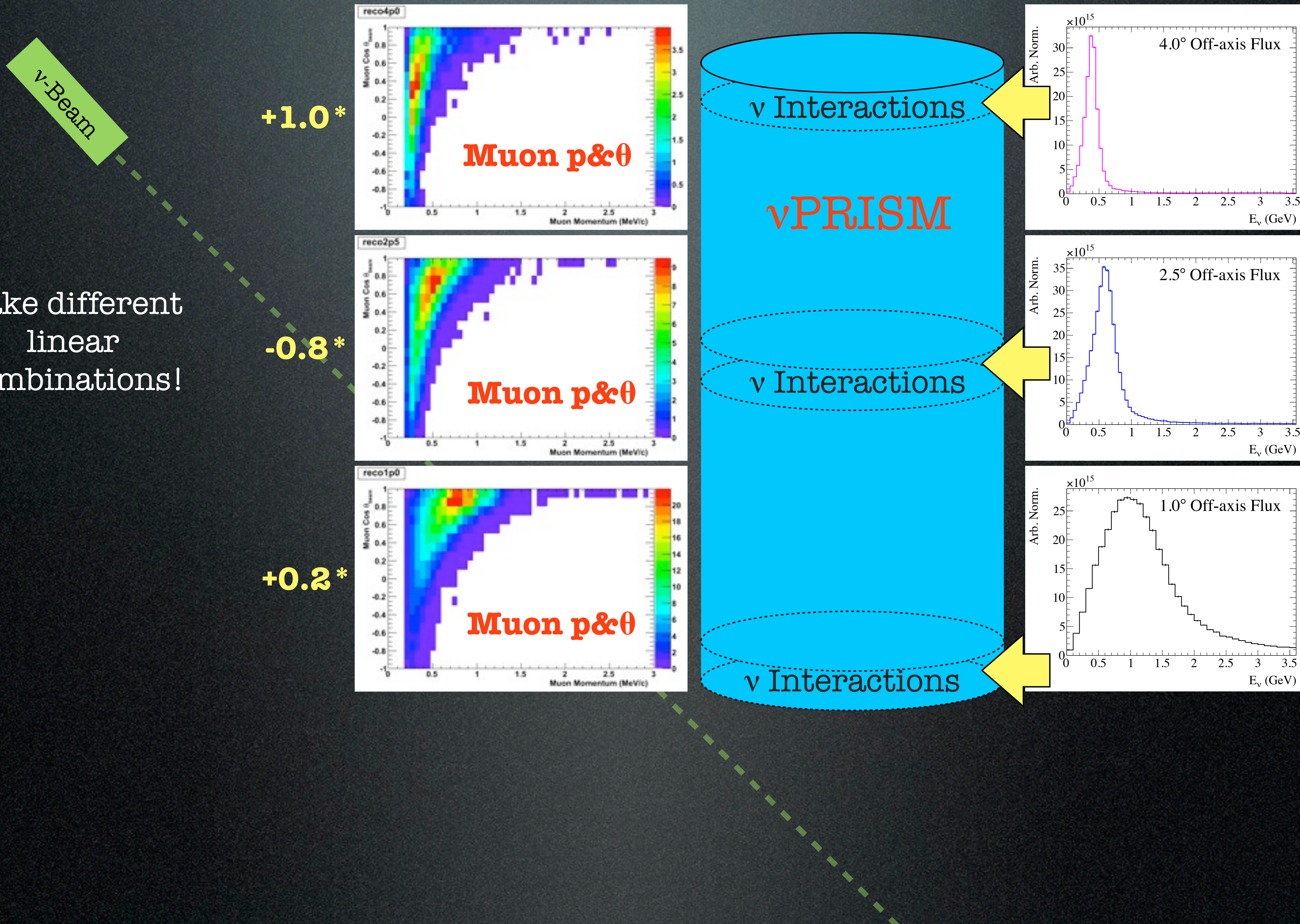
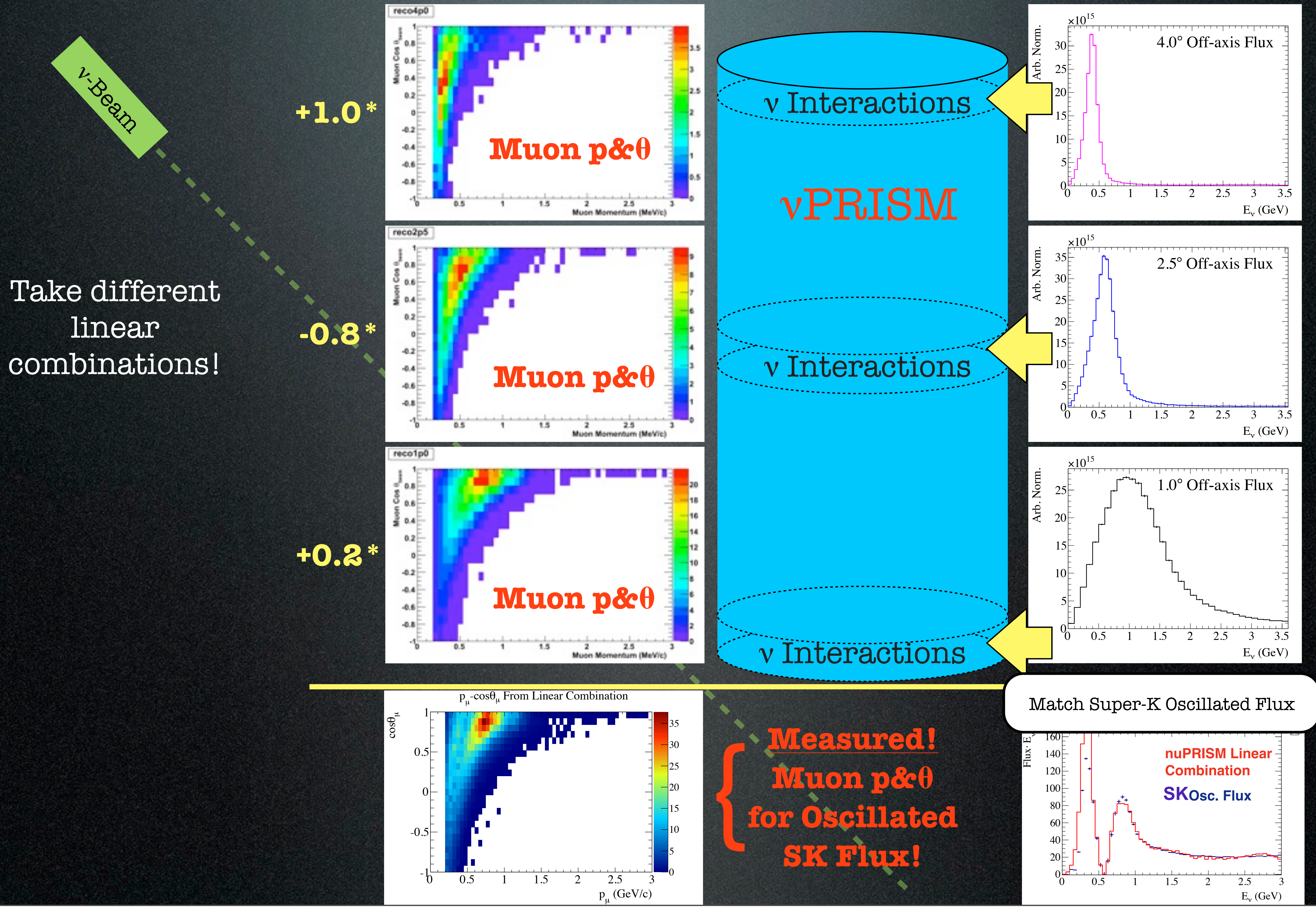


Removing Near/Far Flux Differences



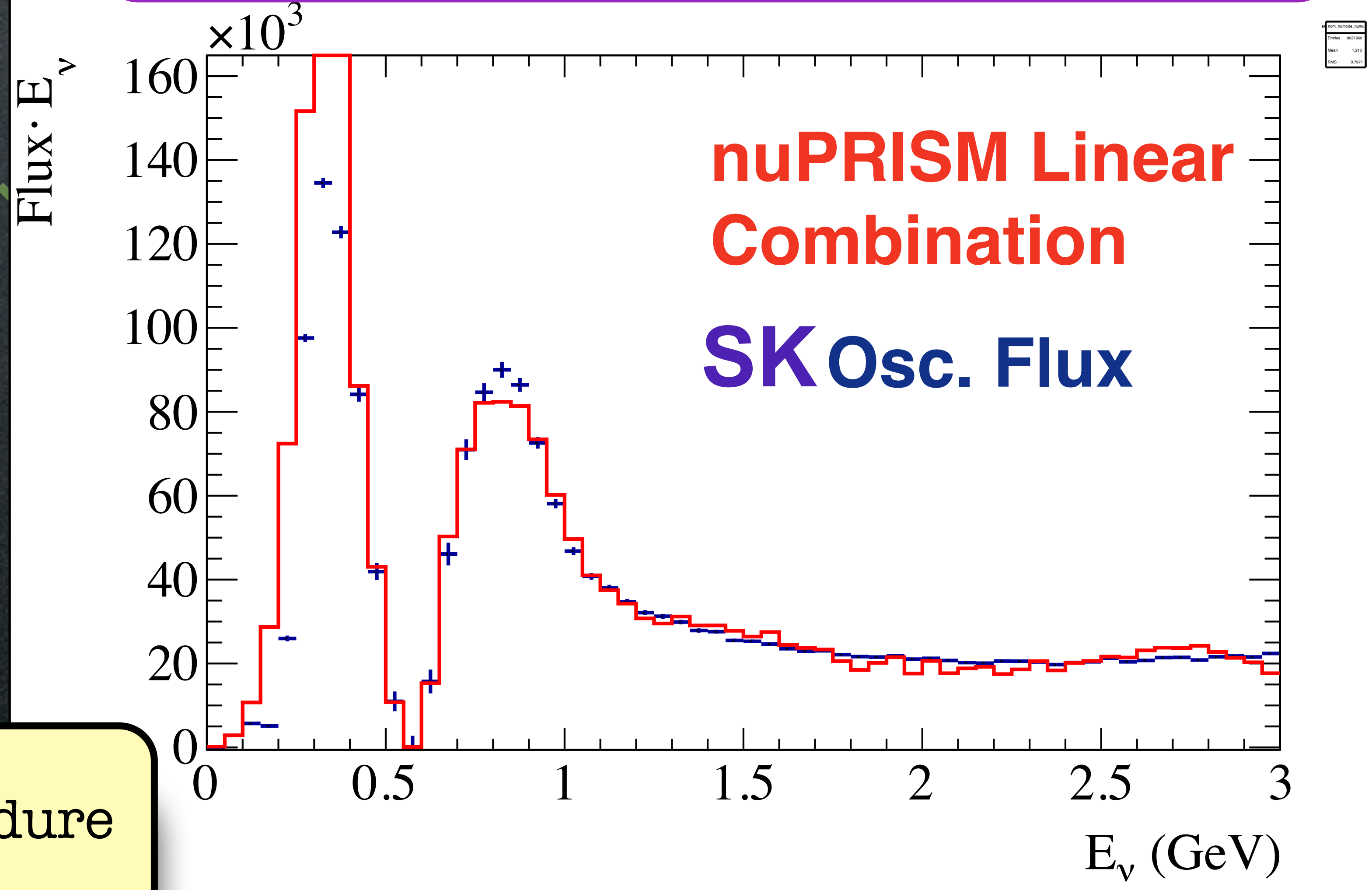
Removing Near/Far Flux Differences

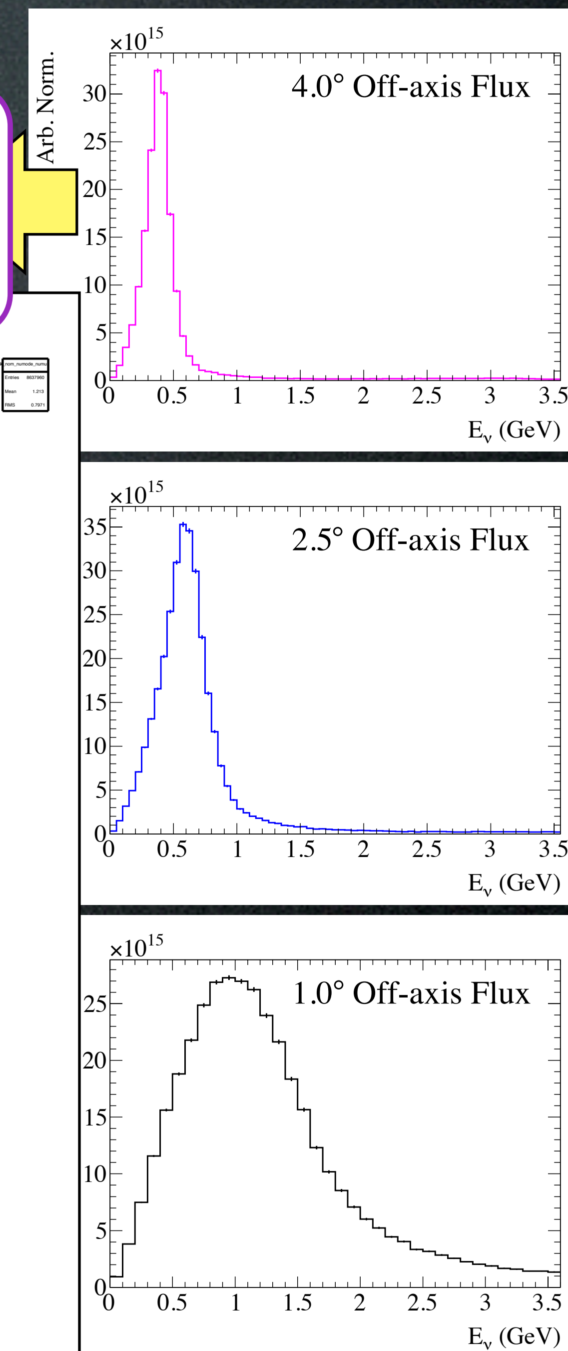
ν-Beam

+1

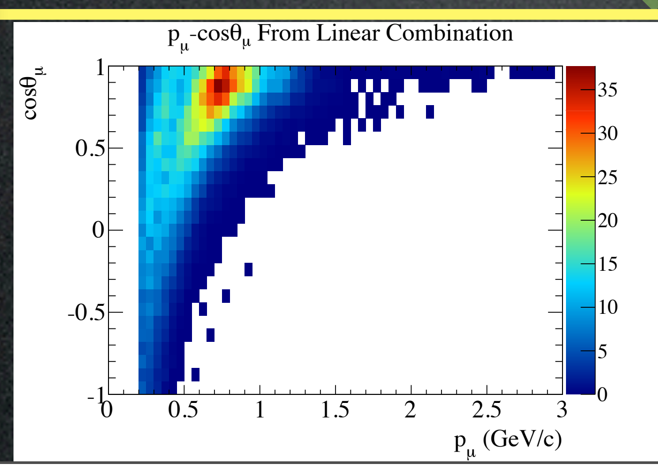
Reproduce Super-K Oscillation Pattern at a Near Detector!

Take different linear combinations!



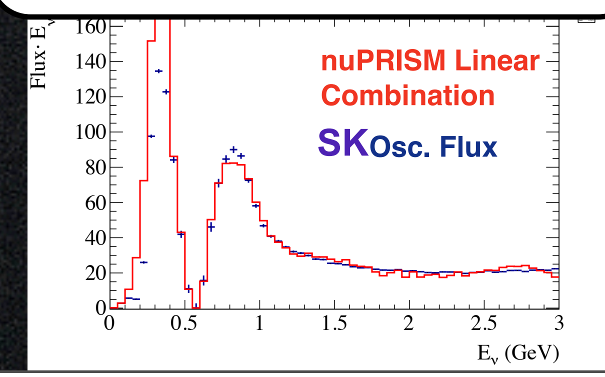


This is the procedure used for the T2K/νPRISM ν_μ disappearance analysis (see later slides)



Measured! Muon p&θ for Oscillated SK Flux!

Match Super-K Oscillated Flux



Interpreting Linear Combinations

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

ν Energy Spectrum

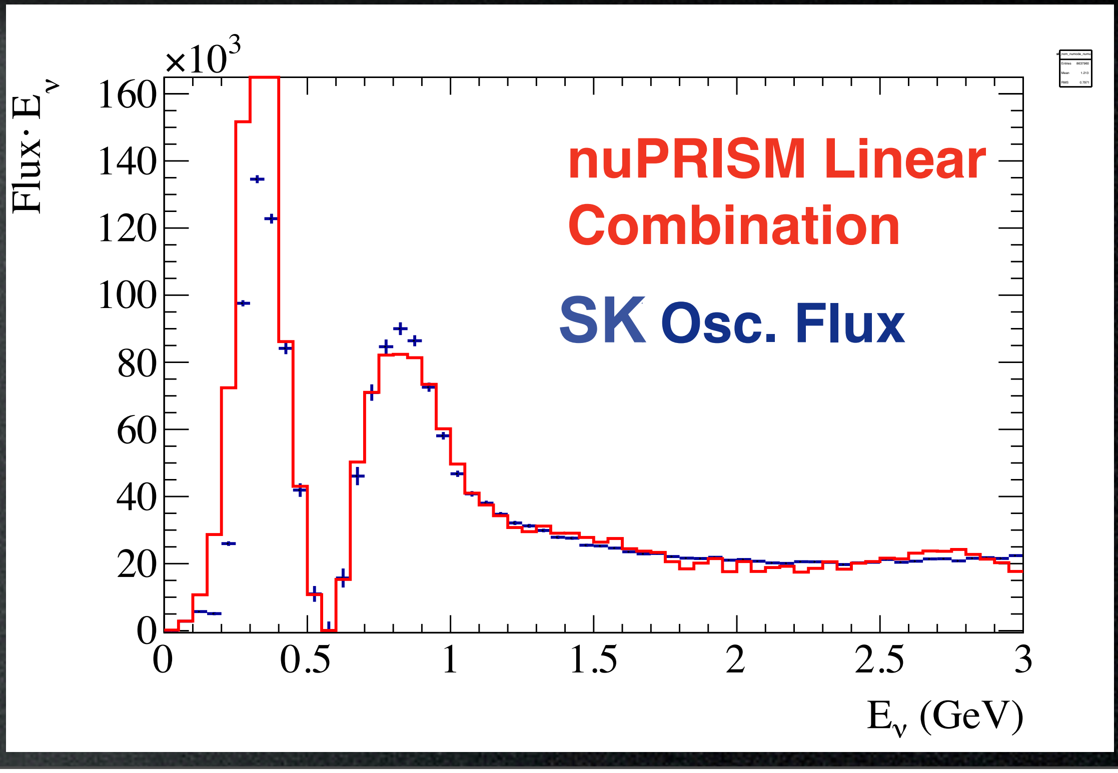
Flux < 1 GeV is dominated by π^+ decay

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

ν_μ produced in 2-body decay

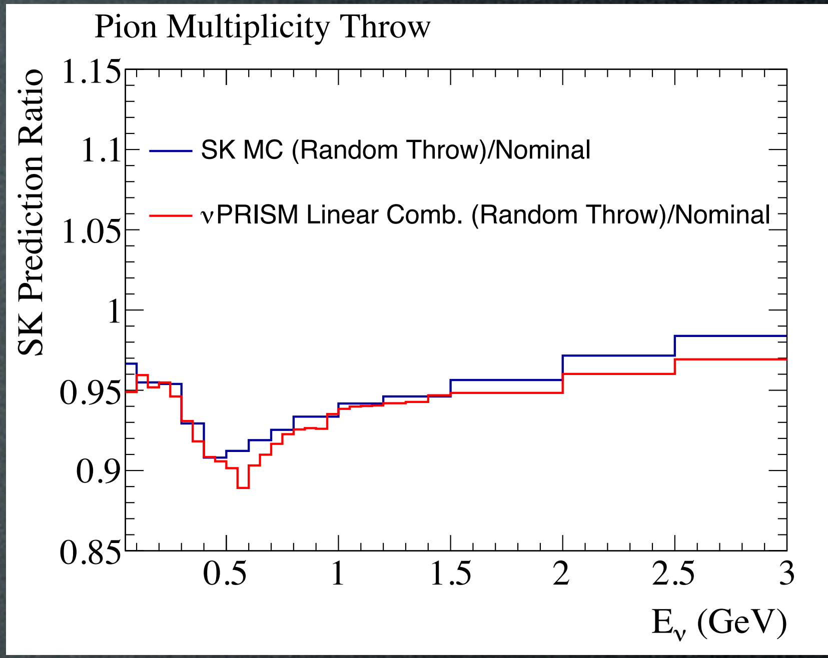
ν_e produced in 3-body decay

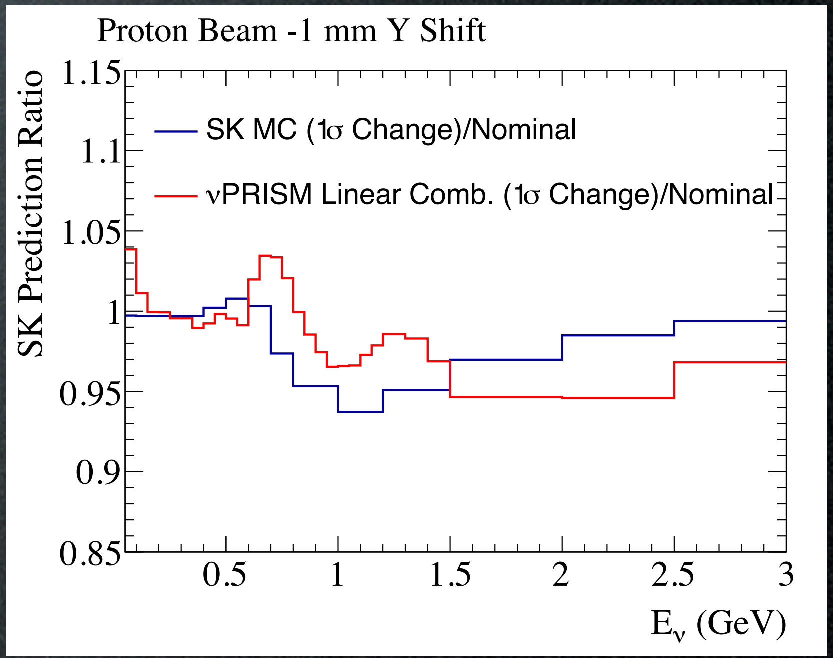
☞ Only ν_μ are subject to off-axis affect

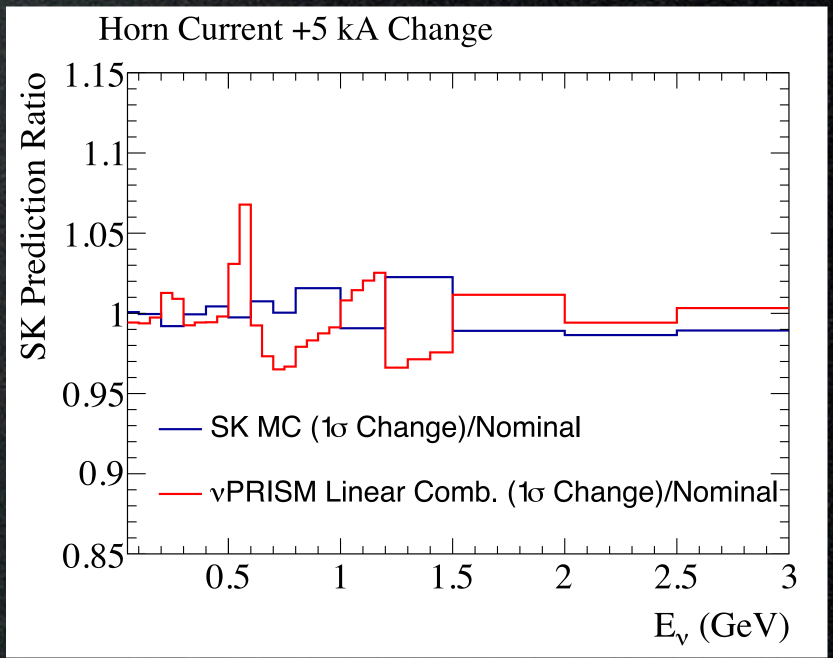


More on Beam Errors

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



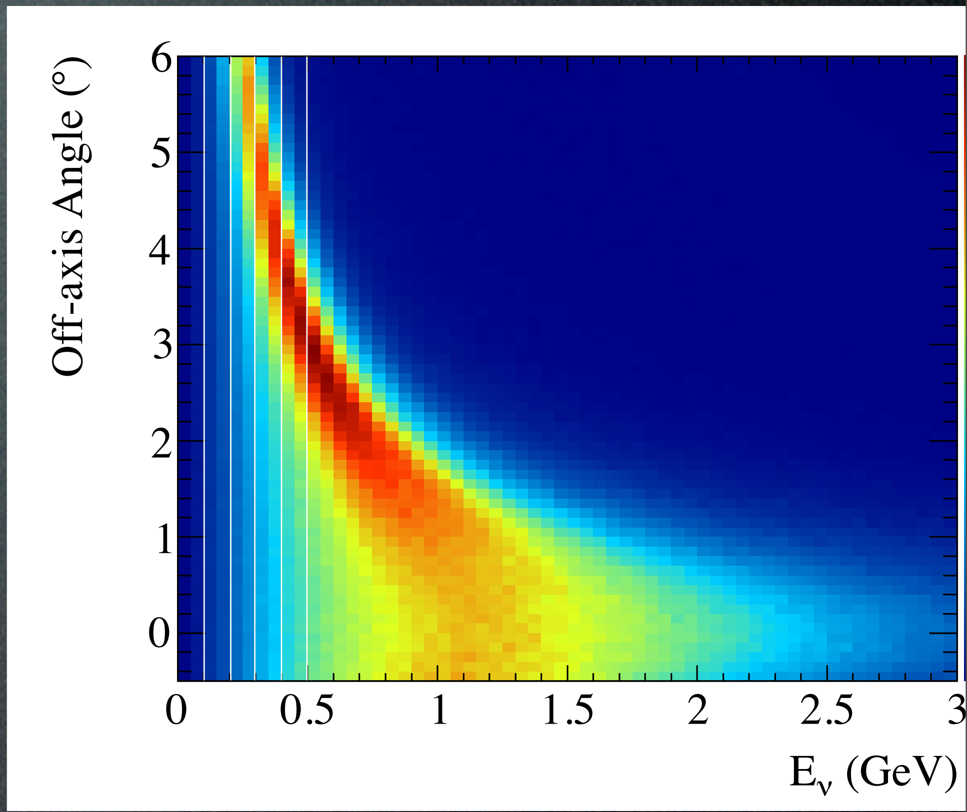




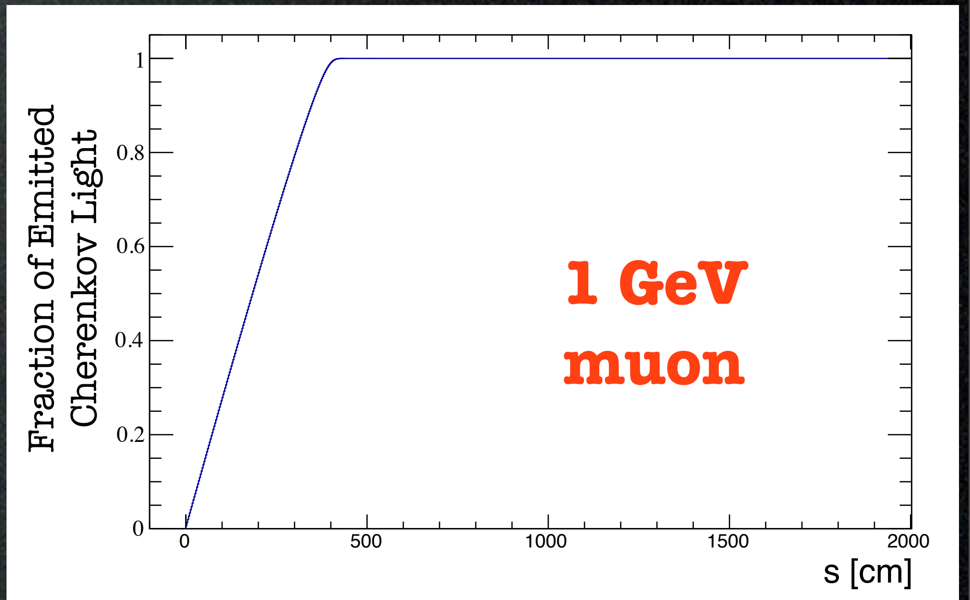
Design Considerations

- **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
  - How much outer detector is necessary?

Off-axis Fluxes



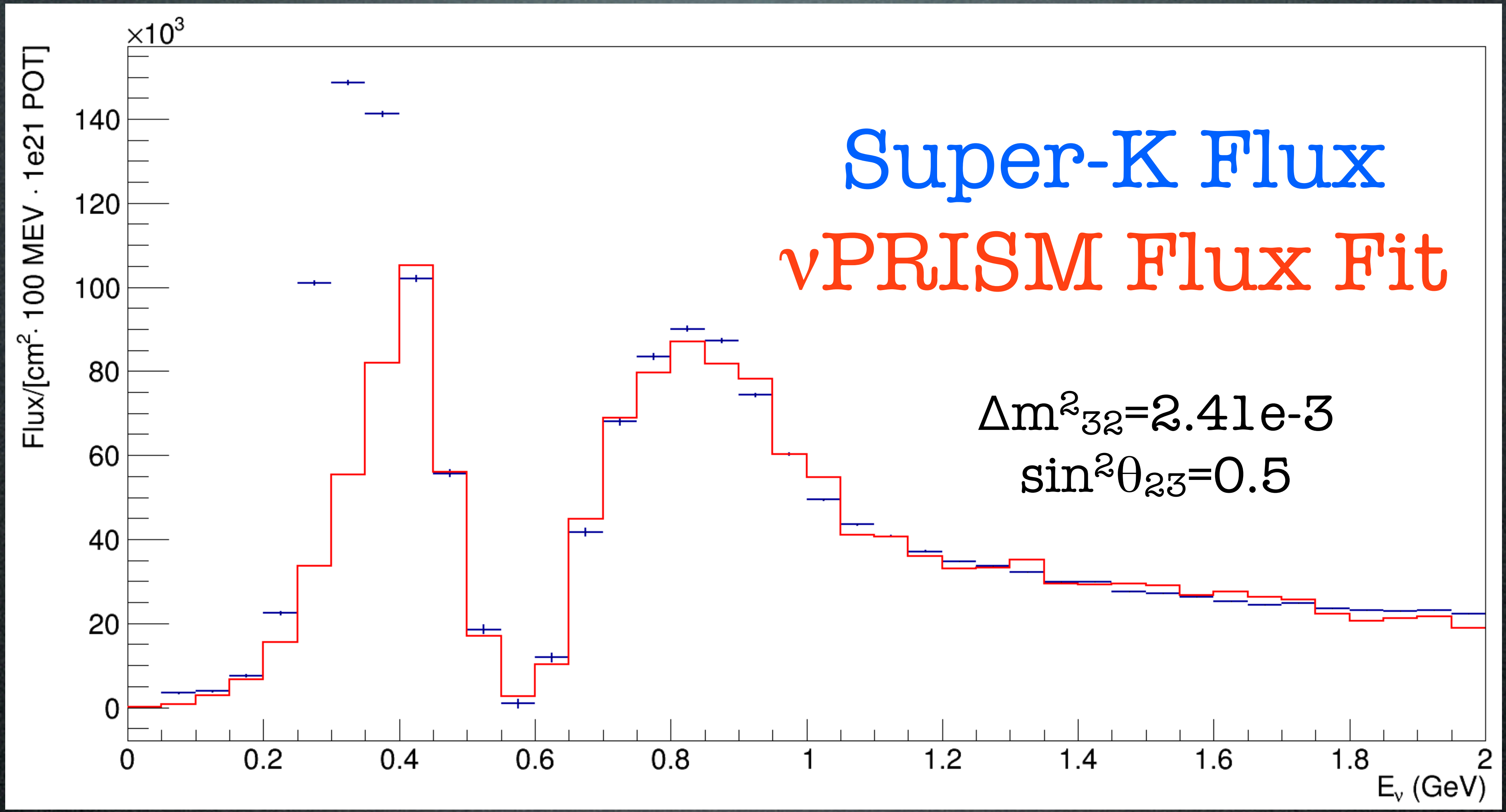
Muon Range



The νPRISM ν_μ Disappearance Analysis

Details to be presented in the next talk
by Mark Scott

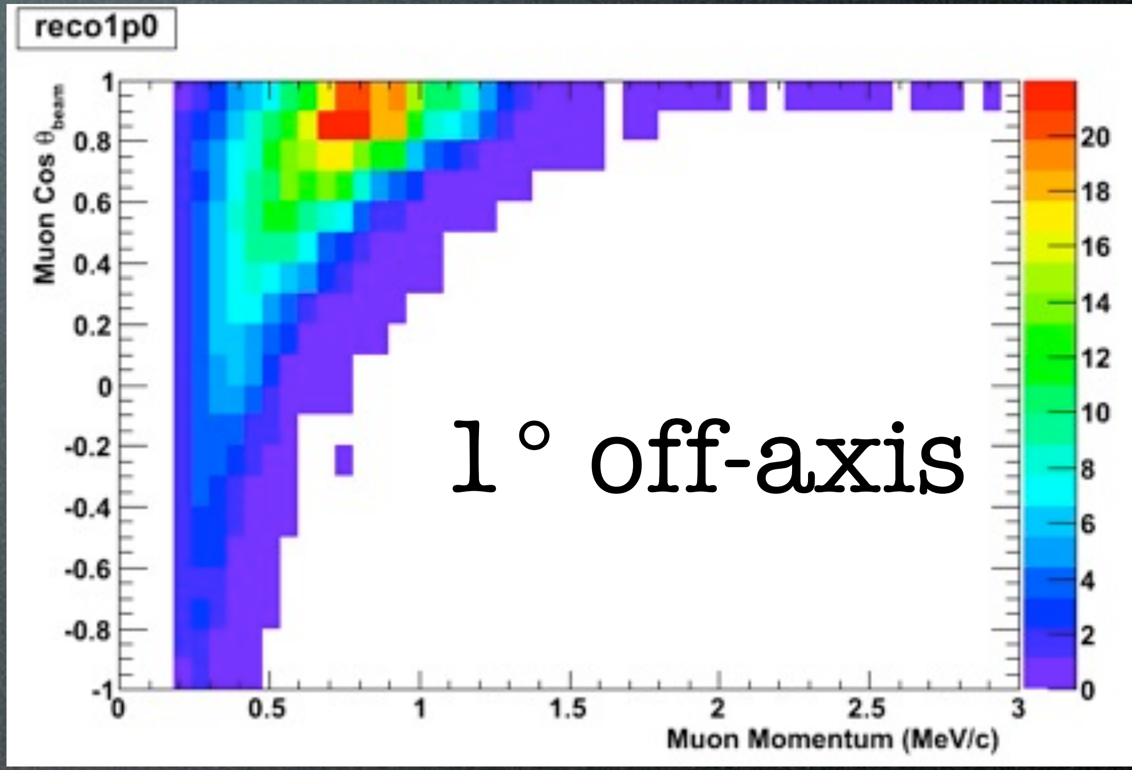
Flux Fit



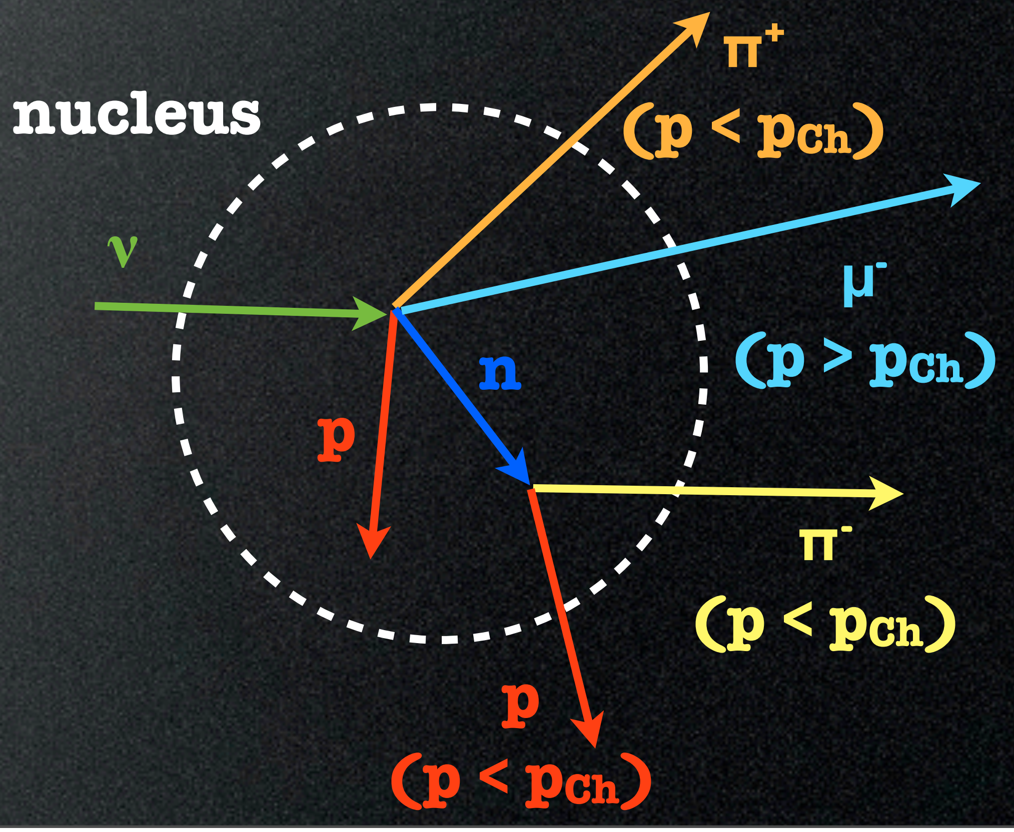
- Fit for coefficients of 30 off-axis νPRISM slices to match a chosen Super-K oscillated spectrum
  - Fit between 400 MeV and 2 GeV
  - **Repeat this fit for every set of oscillation parameters**
- Notice disagreement at low energy
  - The most off-axis flux (4°) peaks at 380 MeV, so difficult to fit lower energies
  - Could extend detector further off-axis, but the low energy region is not very important to extract oscillation physics

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

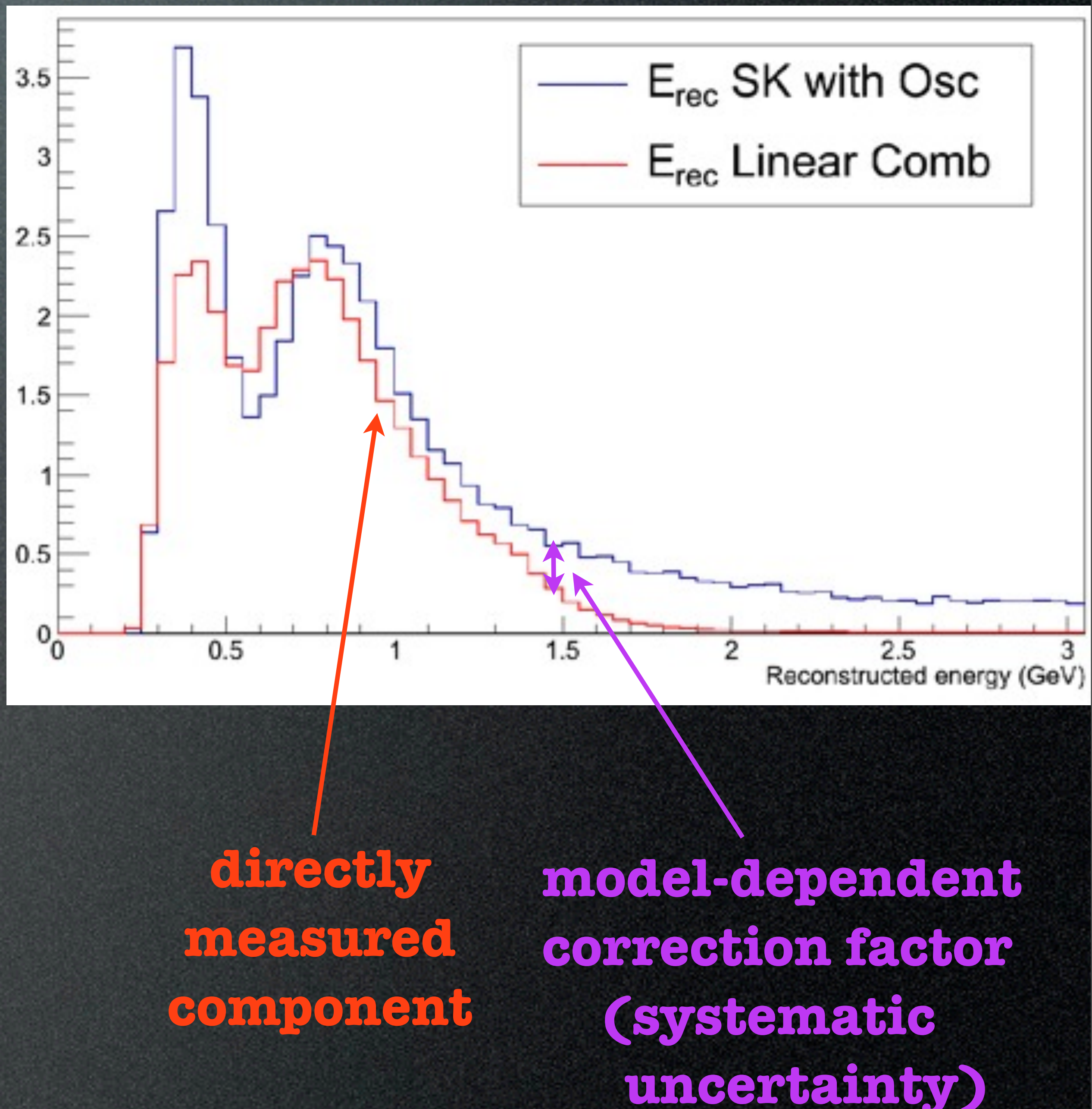


Example Signal Event



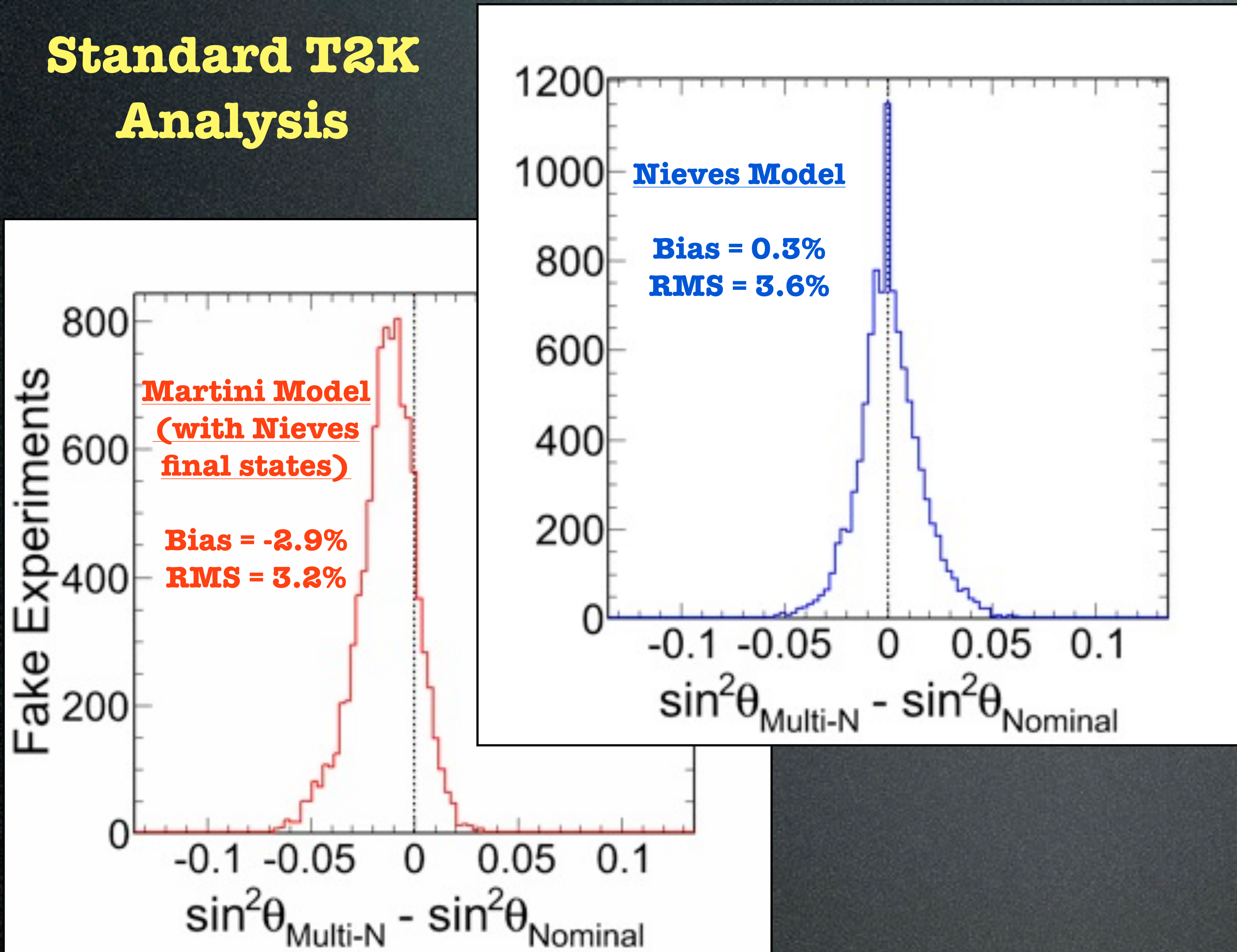
E_{rec} Distribution

- **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!



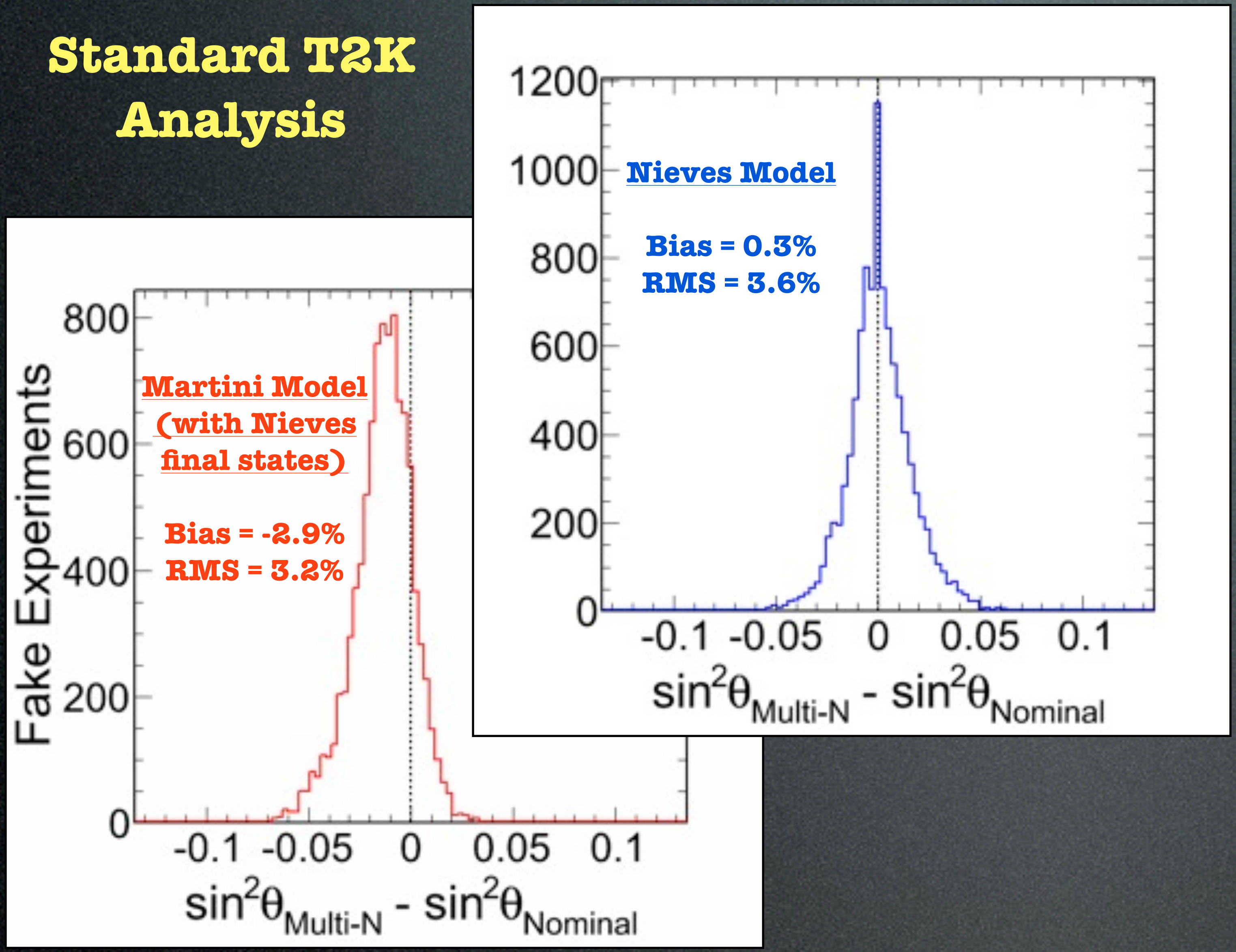
ν_μ Disappearance Bias

Standard T2K Analysis



νPRISM ν_μ Disappearance Bias

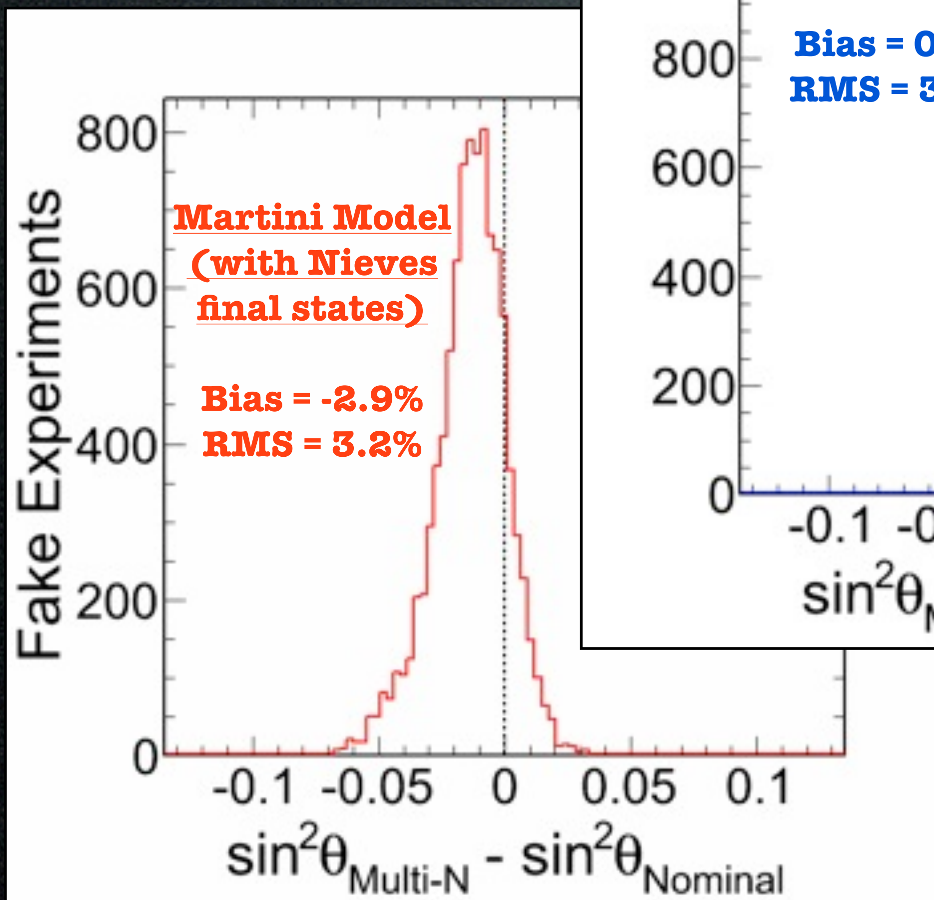
Standard T2K Analysis

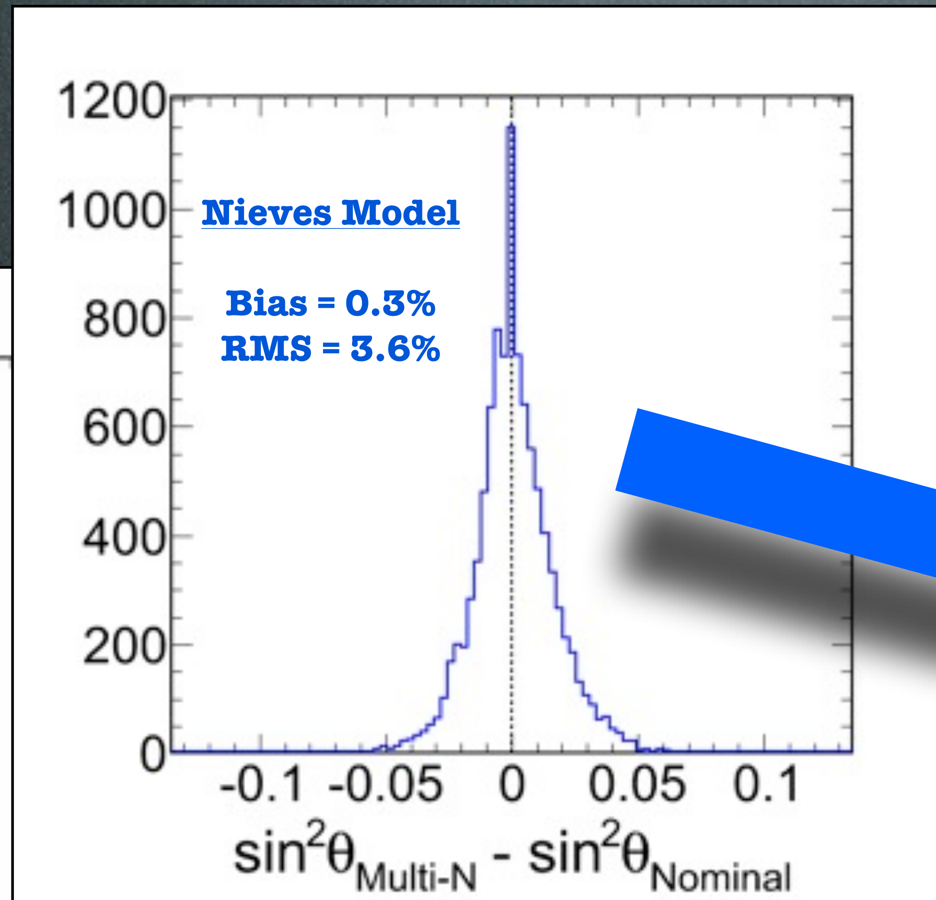


νPRISM Analysis

νPRISM ν_μ Disappearance Bias

Standard T2K Analysis





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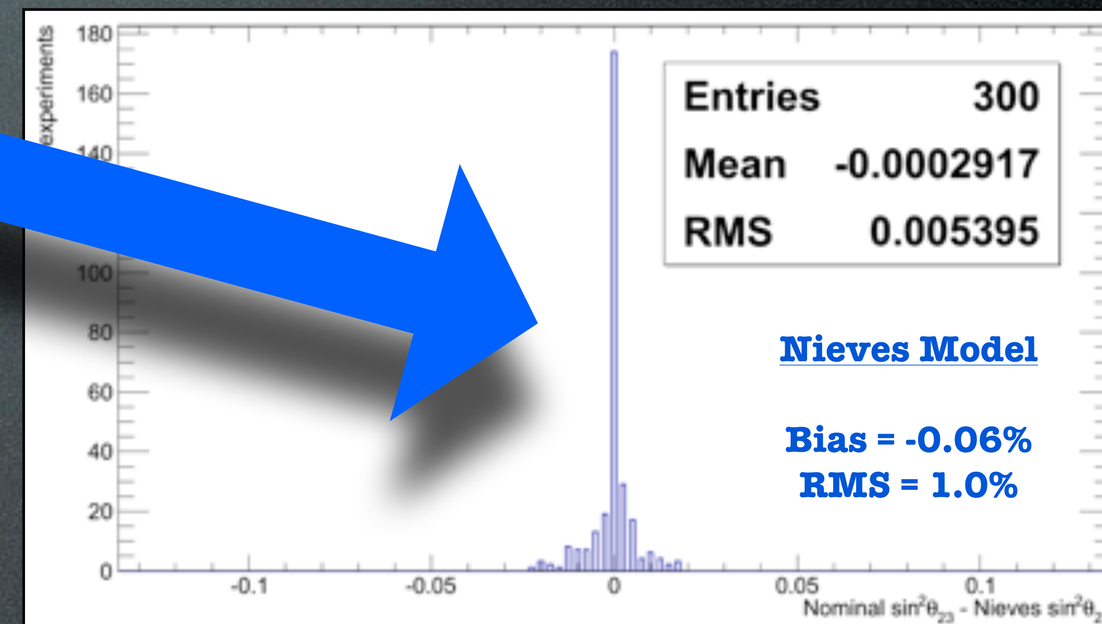

νPRISM ν_μ Disappearance Bias

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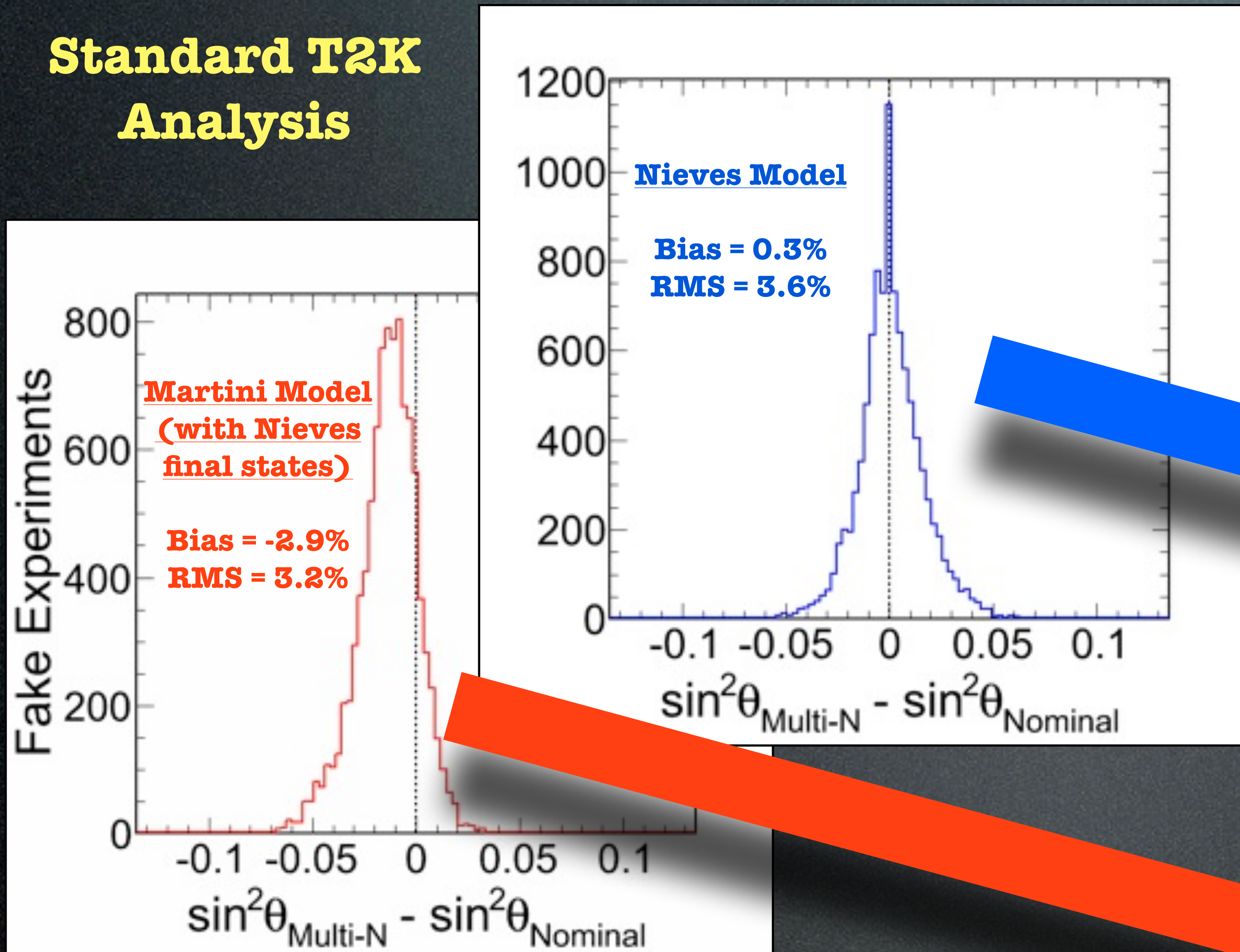
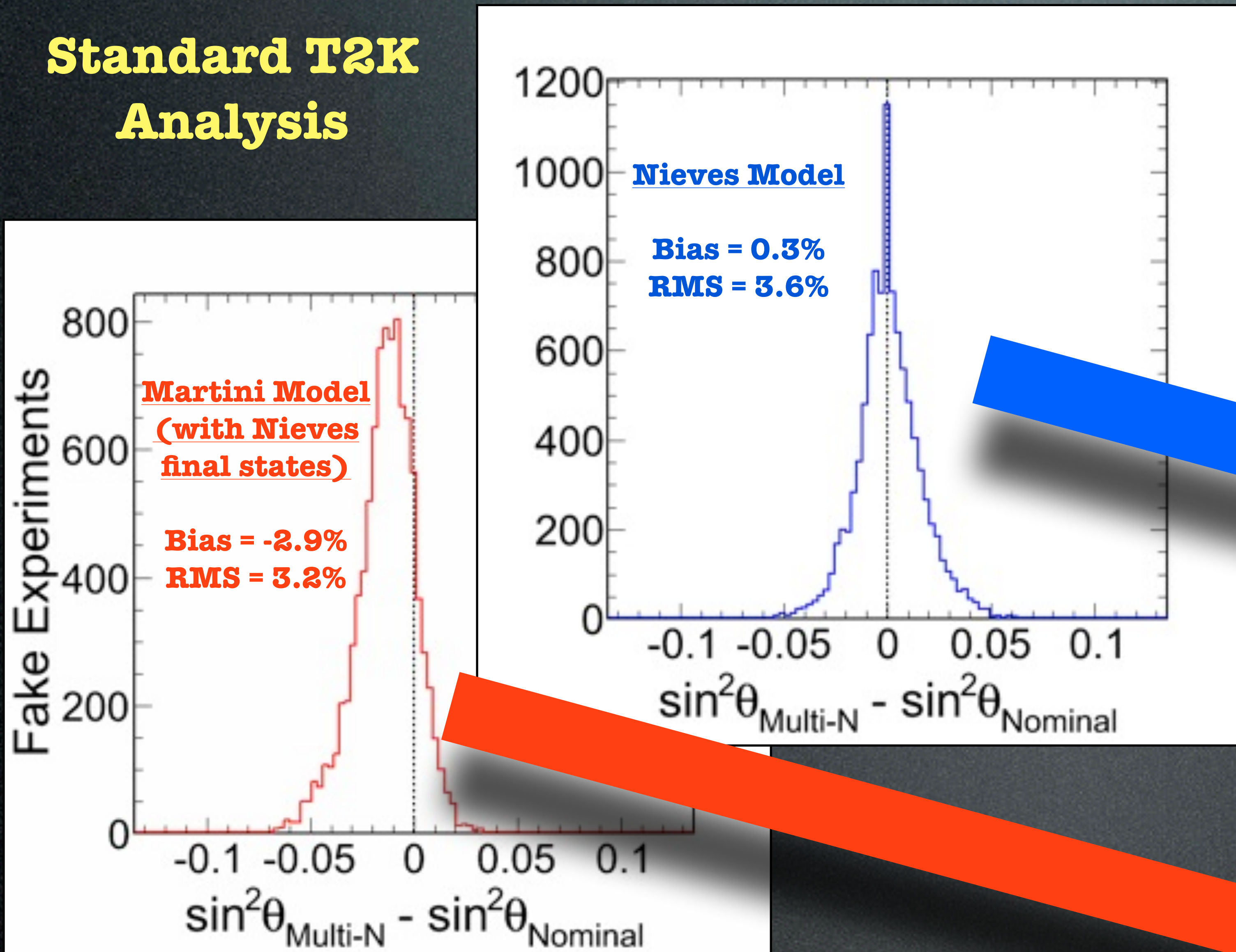


νPRISM Analysis

νPRISM ν_μ Disappearance Bias

Standard T2K Analysis



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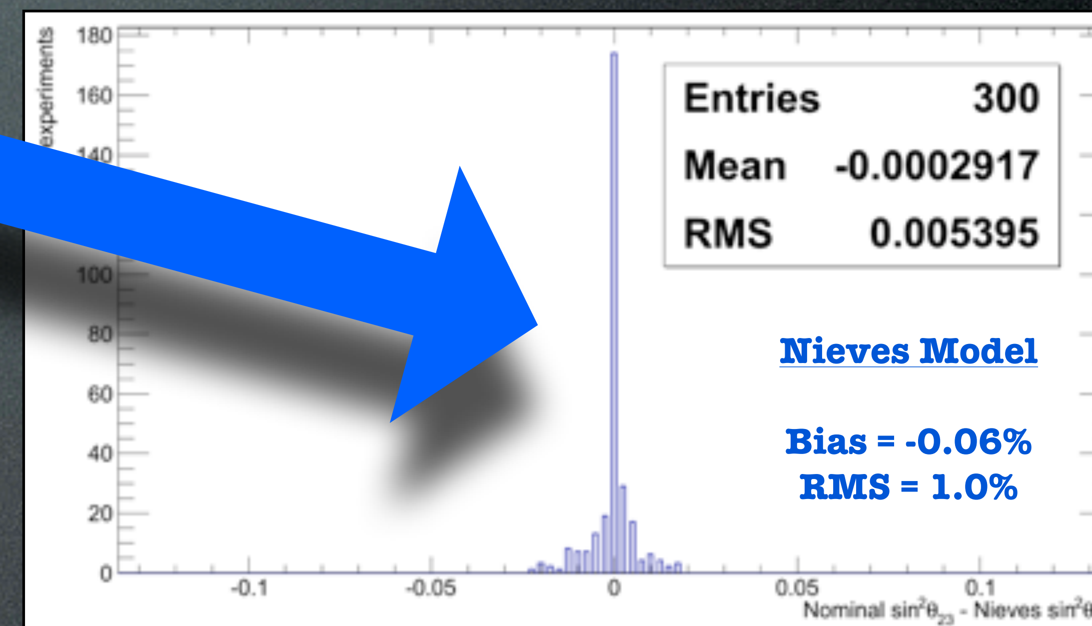
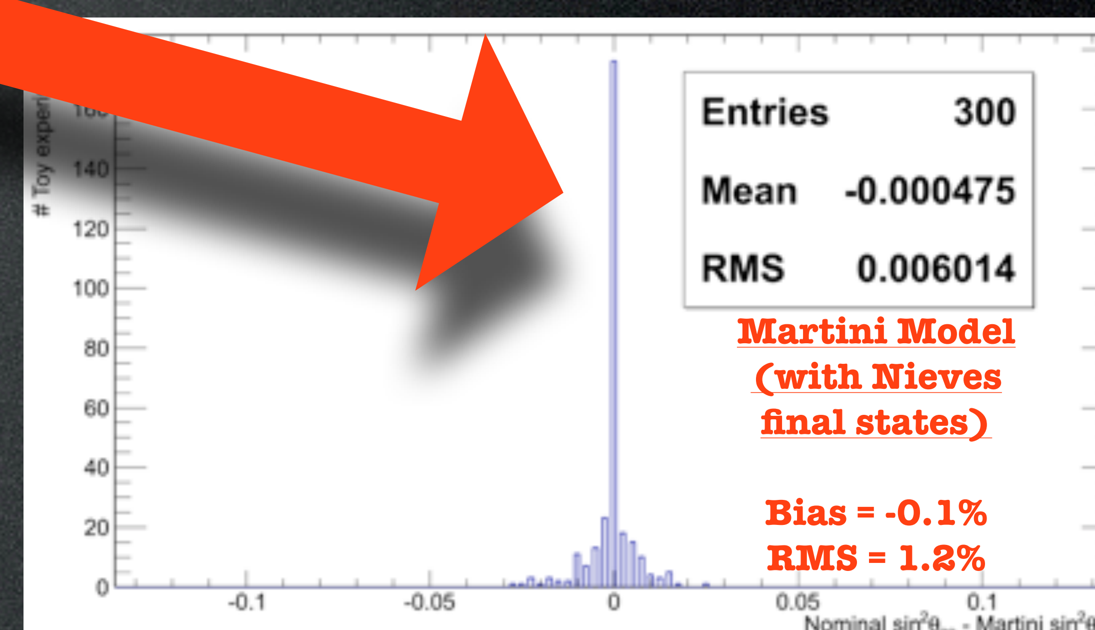
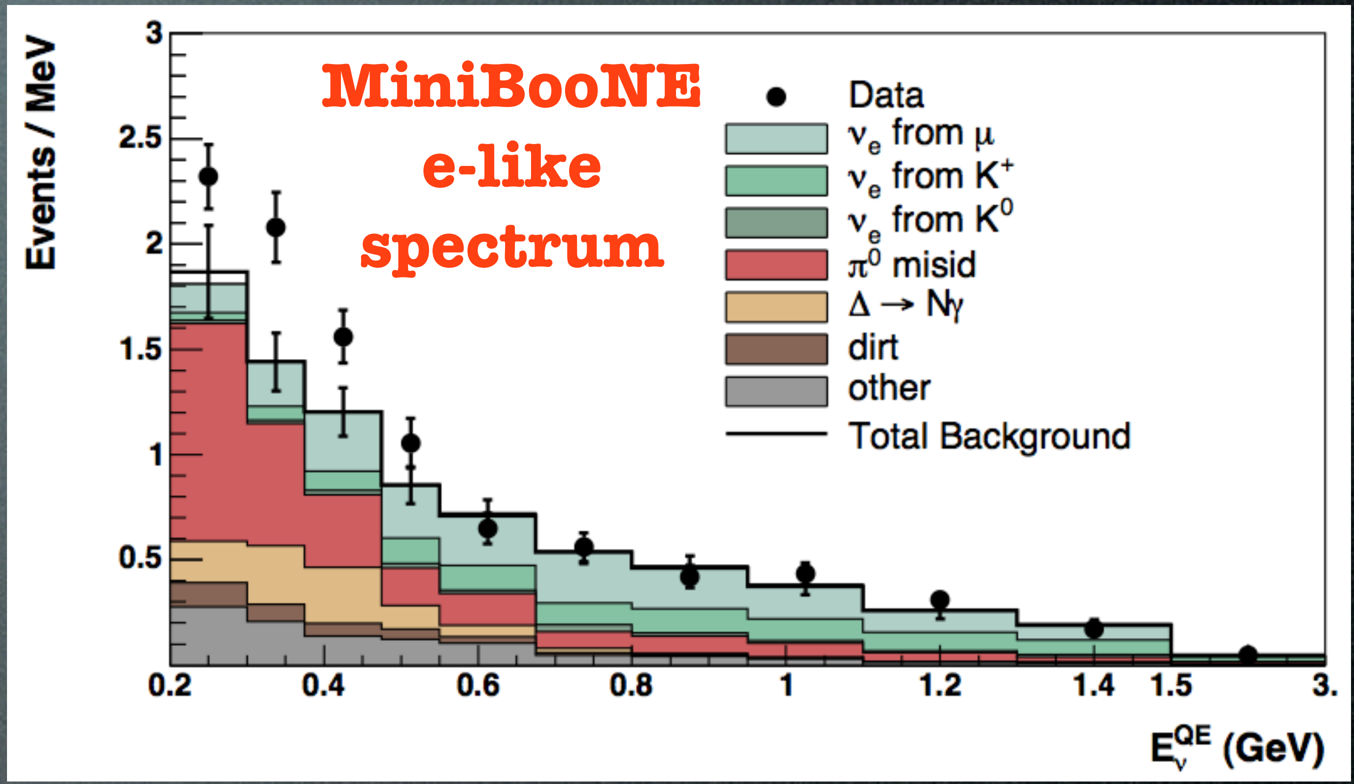


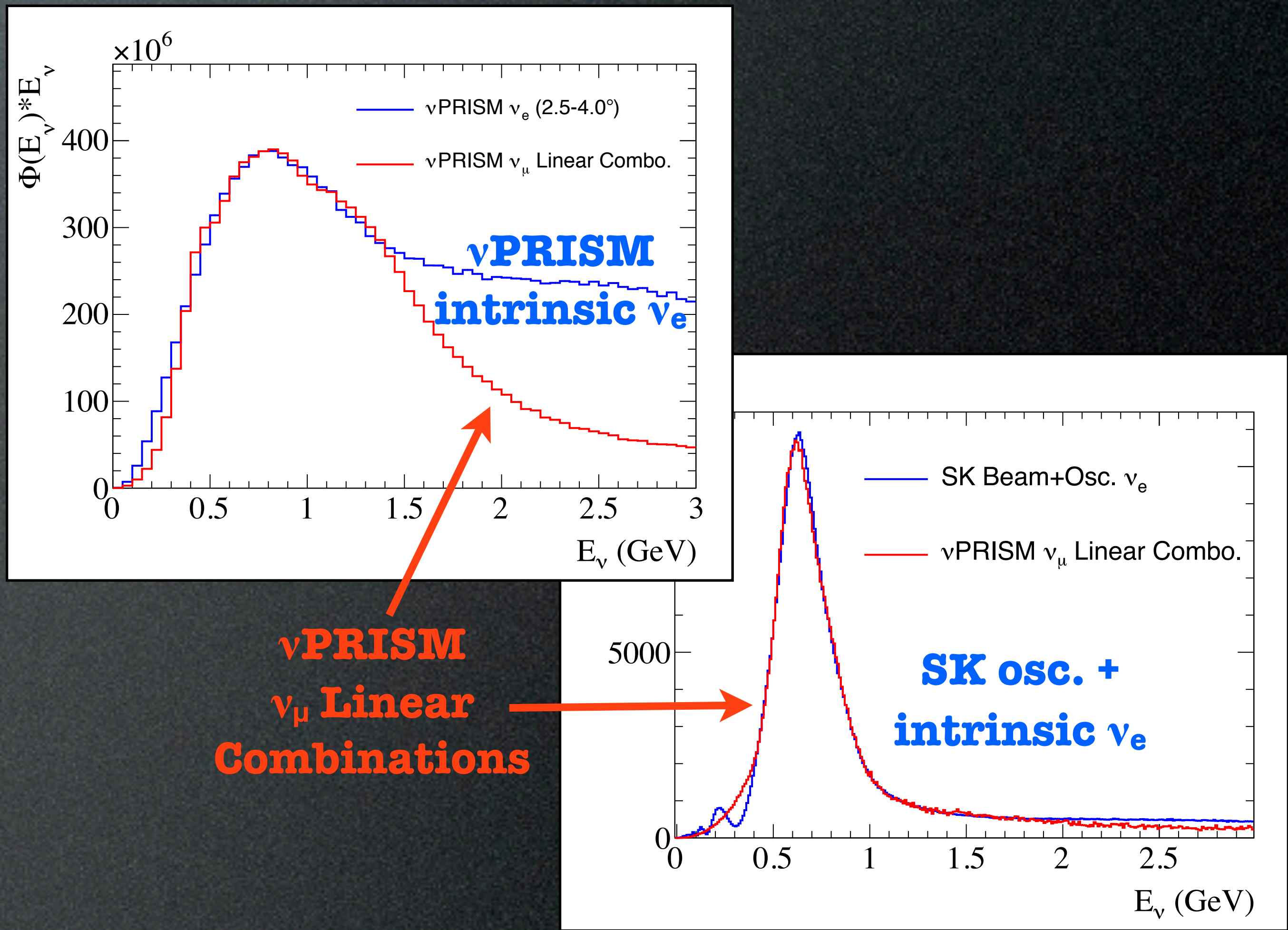


- νPRISM analysis is largely independent of assumed cross section model
  - Using conservative systematics
  - Without using any information from the existing near detector
- Data-driven constraint is possible!

Electron-like Measurements

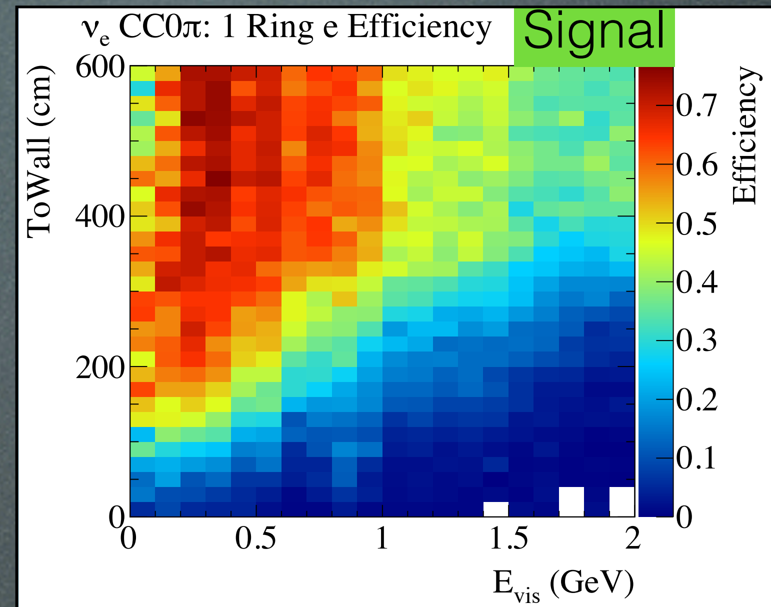
- MiniBooNE sees a large excess of electron-like events from?
  - NCπ^0
  - Single-γ production
  - External γ
  - Beam ν_e
  - muon misID
  - sterile neutrinos
- This must be understood for a precision CP violation measurement
- Linear combination of ν_μ fluxes can be used to reproduce **BOTH:**
  - The SK ν_e signal+background
    - Direct measurement of far detector ν_e response (excluding $\sigma(\nu_e)/\sigma(\nu_\mu)$ uncertainty)
  - The νPRISM ν_e flux
    - This will allow direct comparison of ν_μ and ν_e double-differential xsec

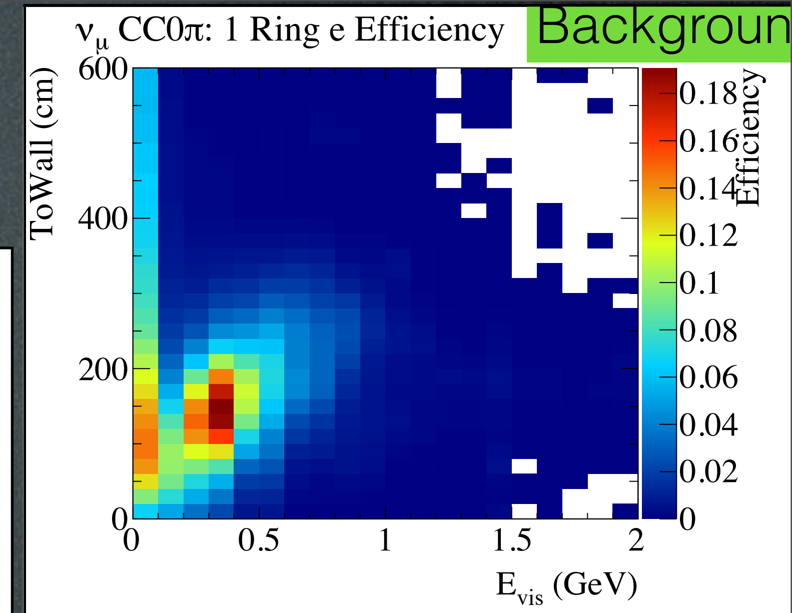


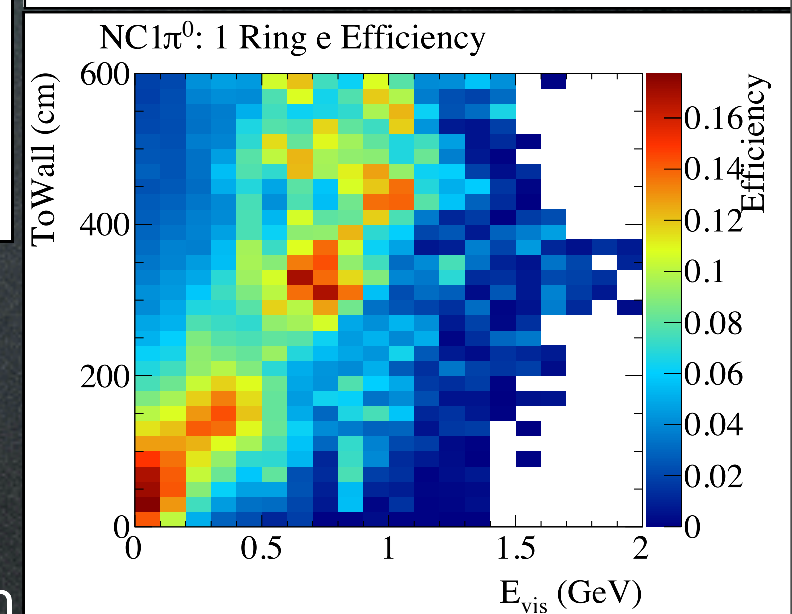


ν_e Event Selection

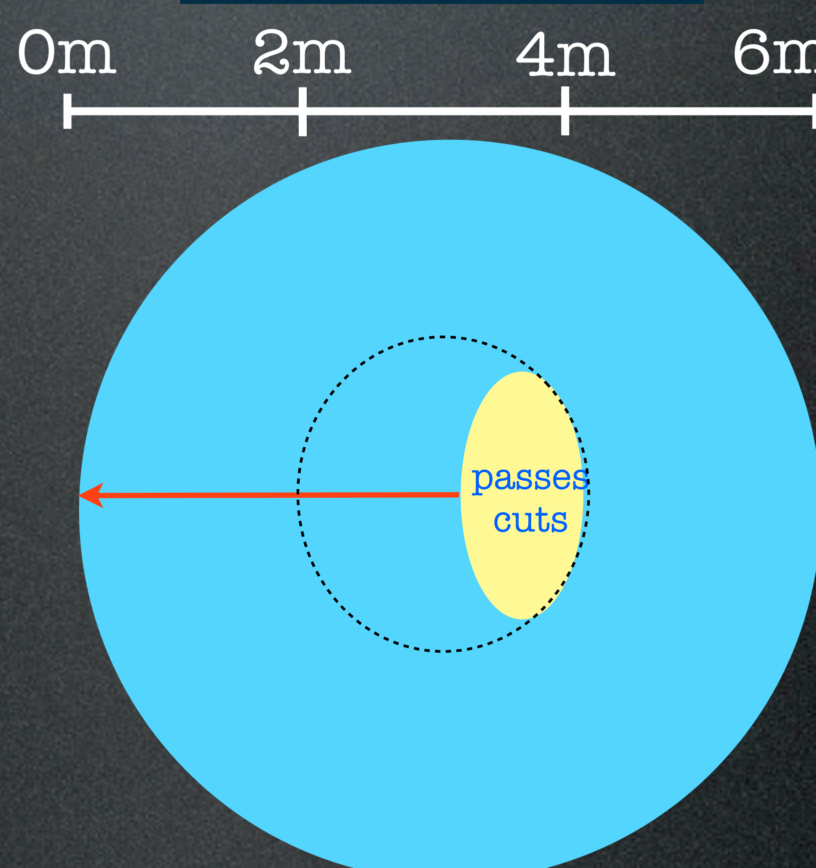
- ν_e's are more sensitive to the tank diameter than ν_μ's
- Large ν_μ background requires good PID
    - PID degrades as particles approach the tank wall
- 6m diameter may be too small
    - 8m diameter is also being investigated
    - (with 10m OD diameter kept fixed)







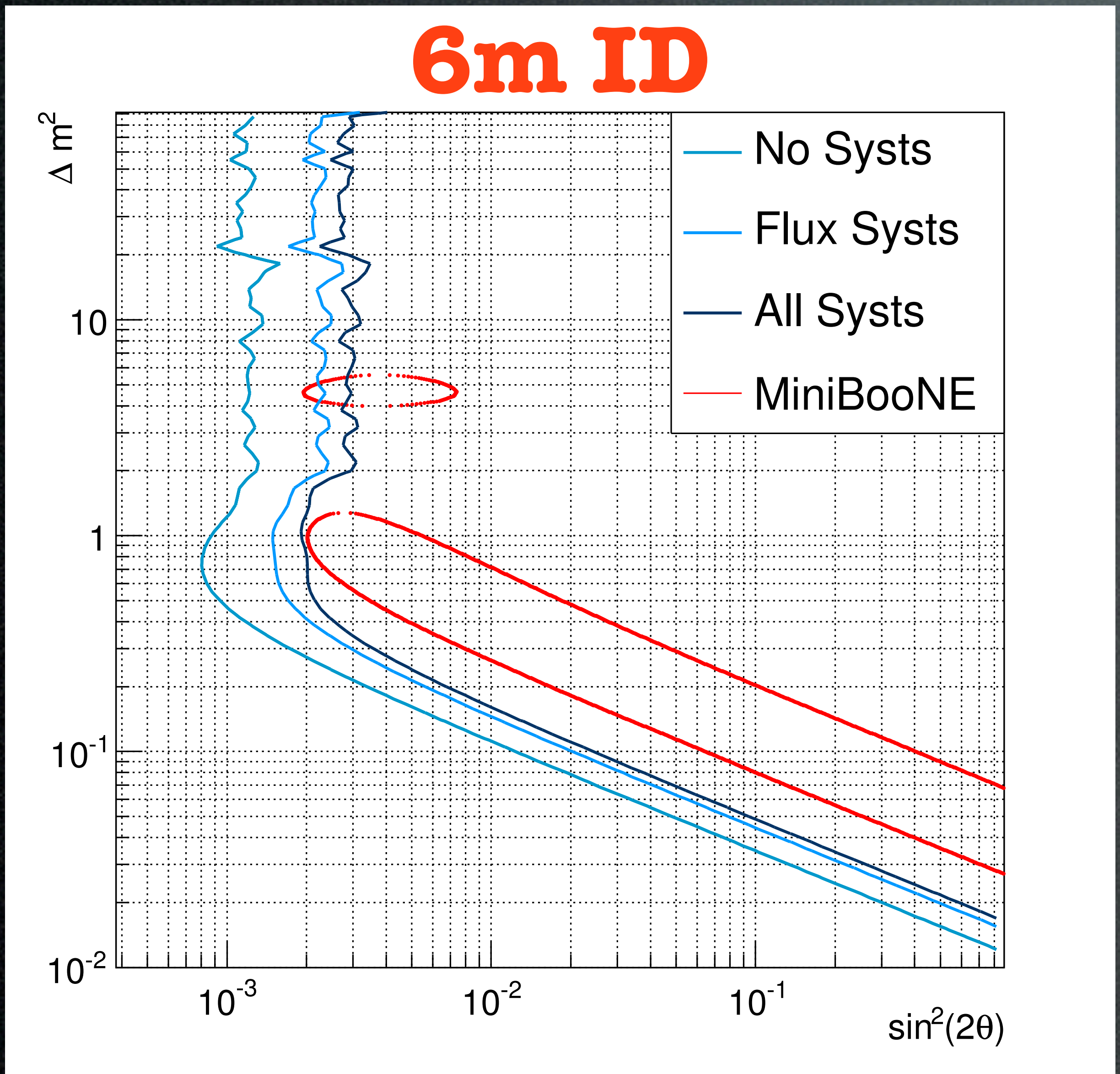
1 Ring e selection:
E_{vis}>200 MeV
DWall>200 cm
ToWall>320 cm

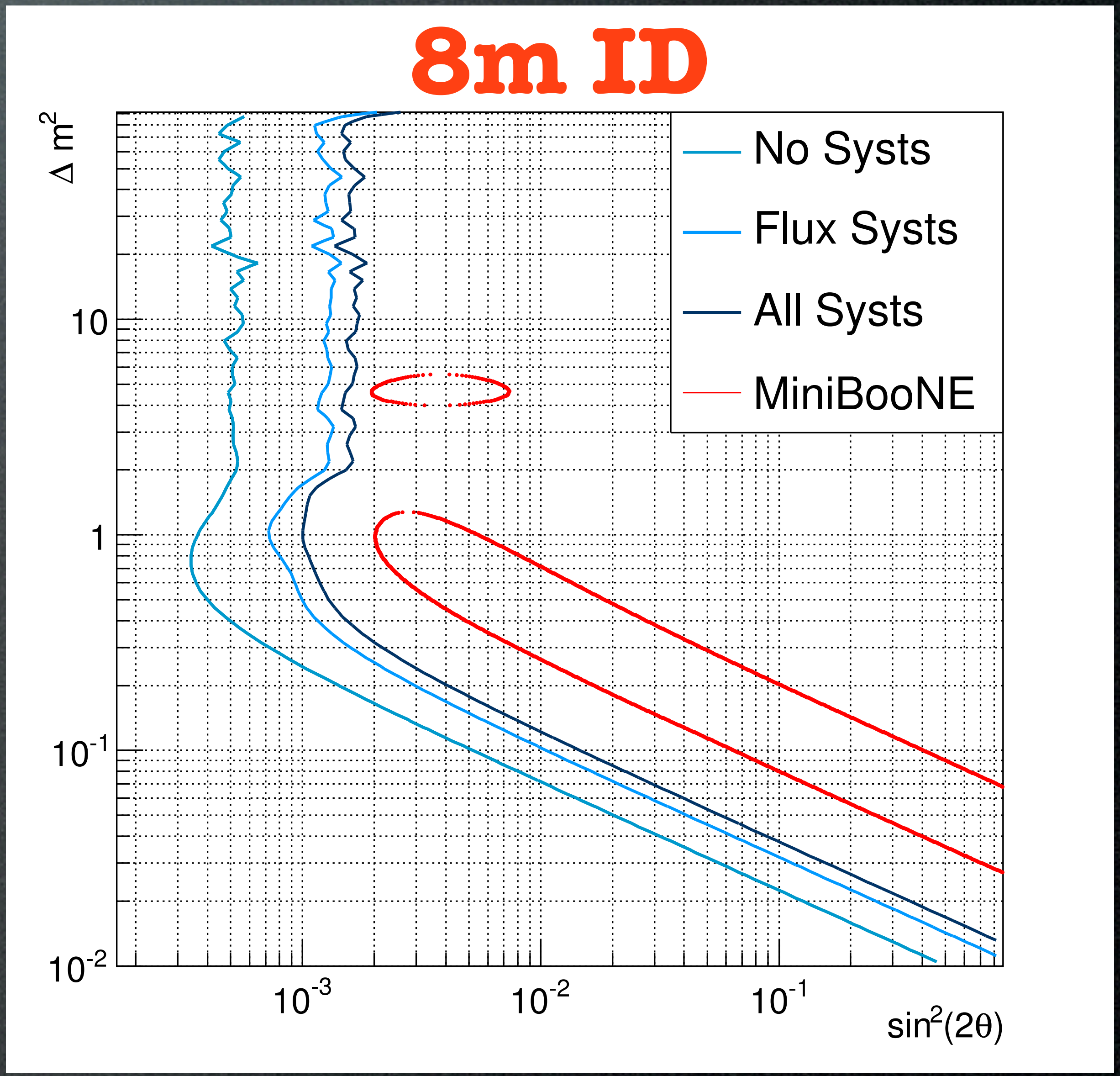


Tank Diameter Strongly Impacts ν_e Fiducial Volume

Preliminary Sterile-ν Sensitivity

- Based on half the total T2K statistics (expected after beam upgrade)
- Conservative estimates
  - MiniBooNE-style $\nu_e+\nu_\mu$ fit not yet used (strong flux correlations)
  - ND280 not yet used (2 detector fit can add significant sensitivity)

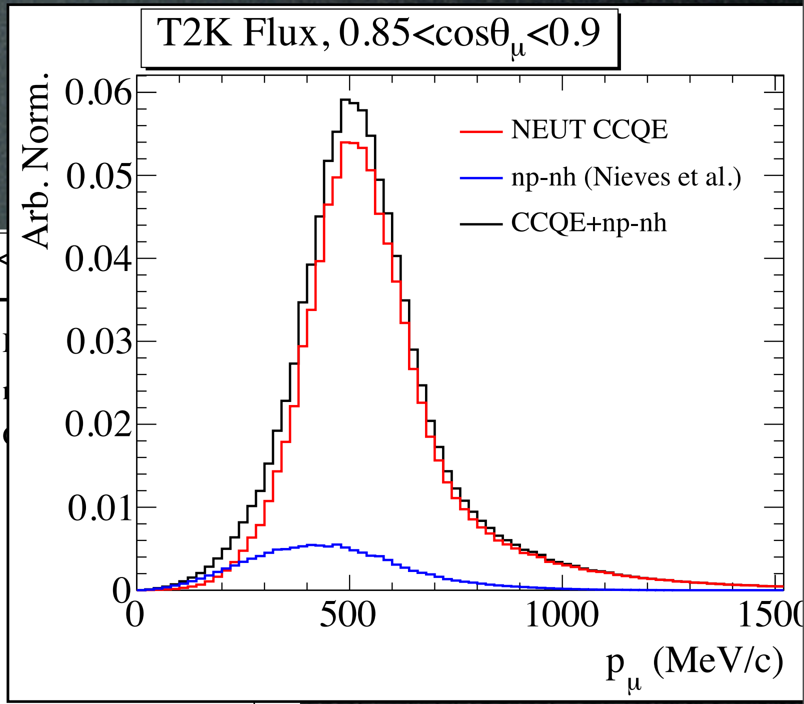


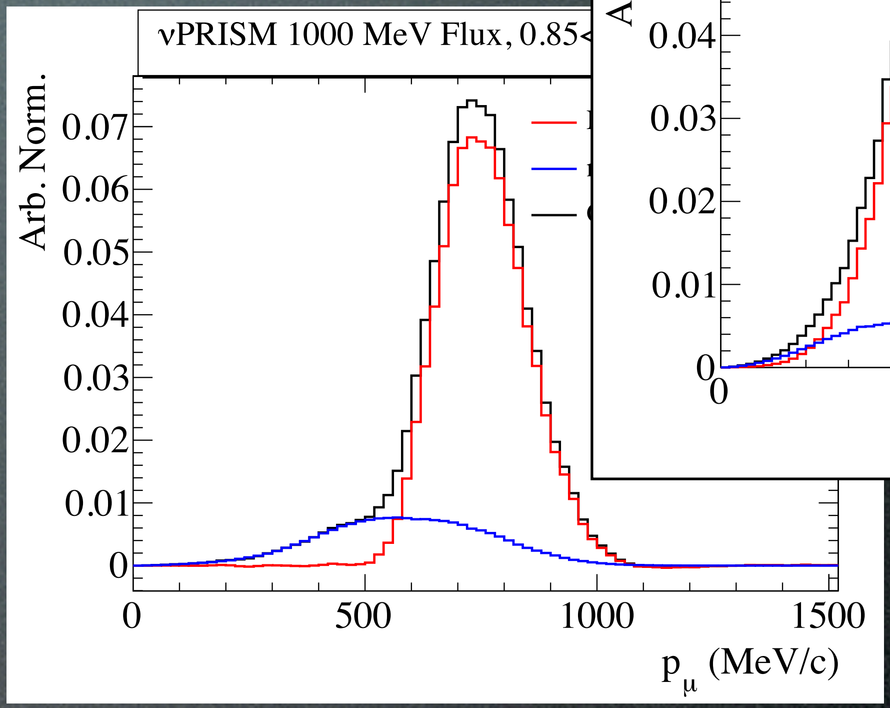


ν Cross Section Measurements

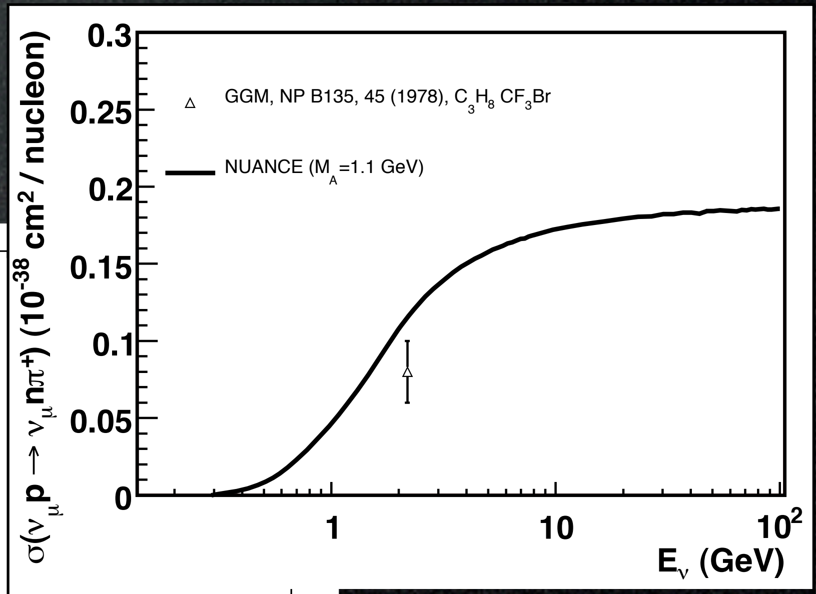
- Mono-energetic neutrino beams are ideal for measuring neutrino cross sections
    - Can provide a strong constraint on new models
- T2K ν_μ disappearance is subject to large $NC\pi^+$ uncertainties
    - 1 existing measurement
    - νPRISM can place a strong constraint on this process vs E_ν

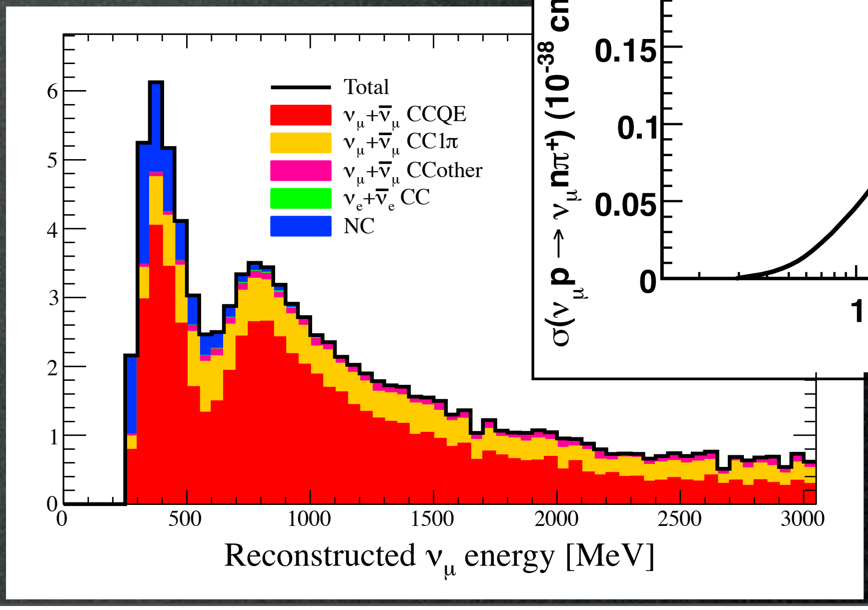
Example MEC event separation





NCπ⁺ at T2K





Can We Build This Detector Now?

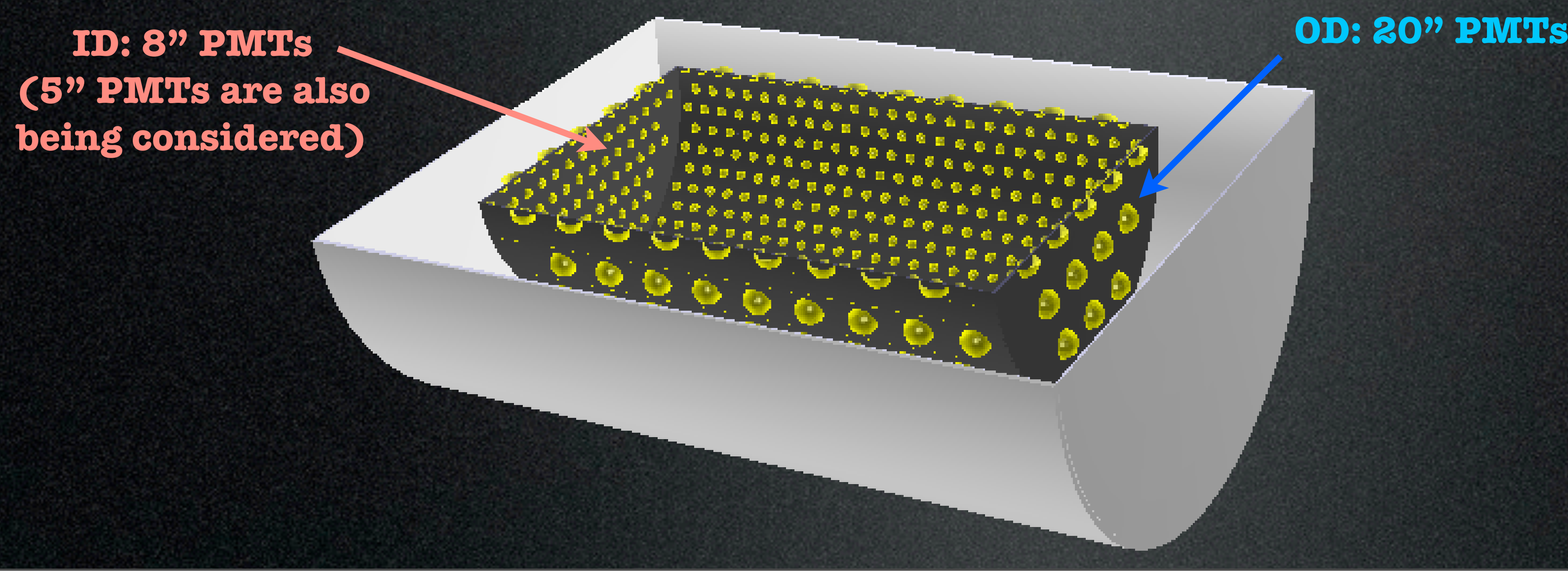
Smaller scale version is currently being considered for a T2K upgrade:

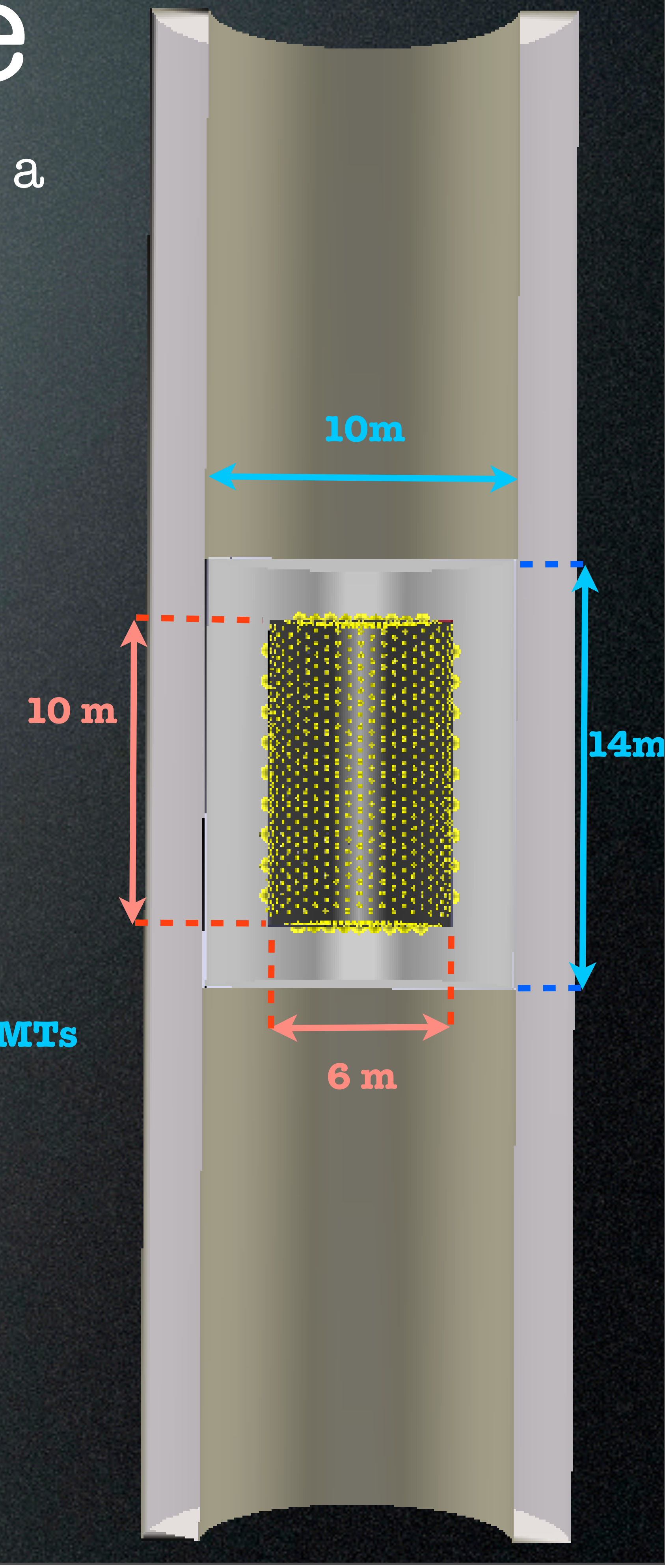
νPRISM-Lite

- Improve T2K physics program
  - Better oscillation measurements
  - Sterile neutrino program
  - Bridge project between T2K & Hyper-K to keep continuity in Japanese neutrino physics program
- Can provide proof-of-principle before Hyper-K is built
  - Upgraded T2K beamline = Hyper-K beamline

νPRISM-Lite

- Instrument one subsection of the tank at a time with a moveable detector
  - Cost difference?
- Baseline design:
  - Inner Detector (ID): 6 or 8m 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)



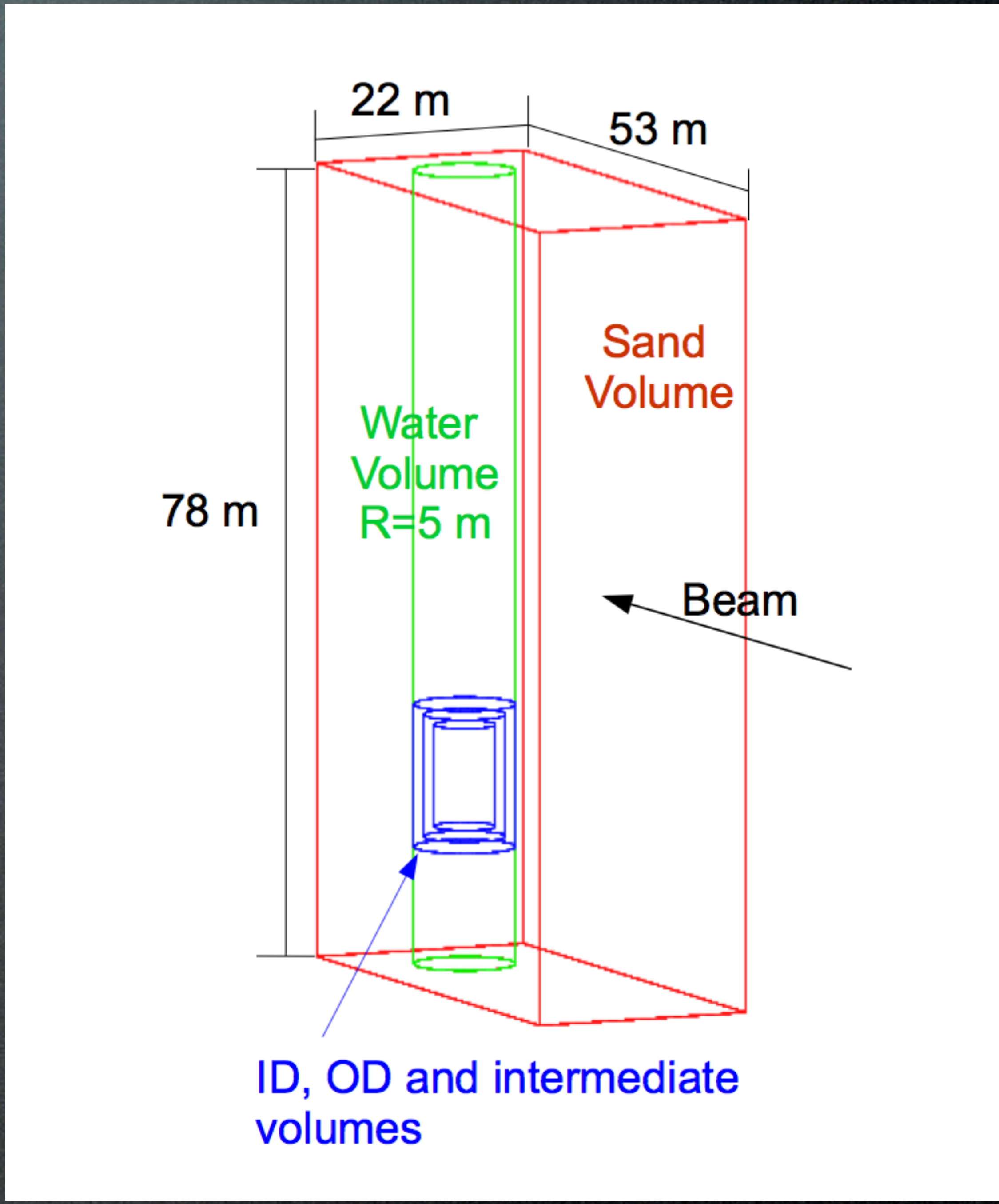


Potential Detector Locations

- Non-rice-field locations at 750m, 1km, and 1.2km
  - Many additional sites if rice fields are also considered
- Site acquisition will rely on J-PARC & KEK
  - Significant lead time is required

Event Pileup at 1 km

- 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!

Civil Construction

- Estimates have been acquired for various construction methods (see table below)
- Initial estimates are for a 50m deep, 10m diameter pit
  - Final options will depend on detailed geological survey performed at the chosen site
- Current estimates range from US $5M to $8M

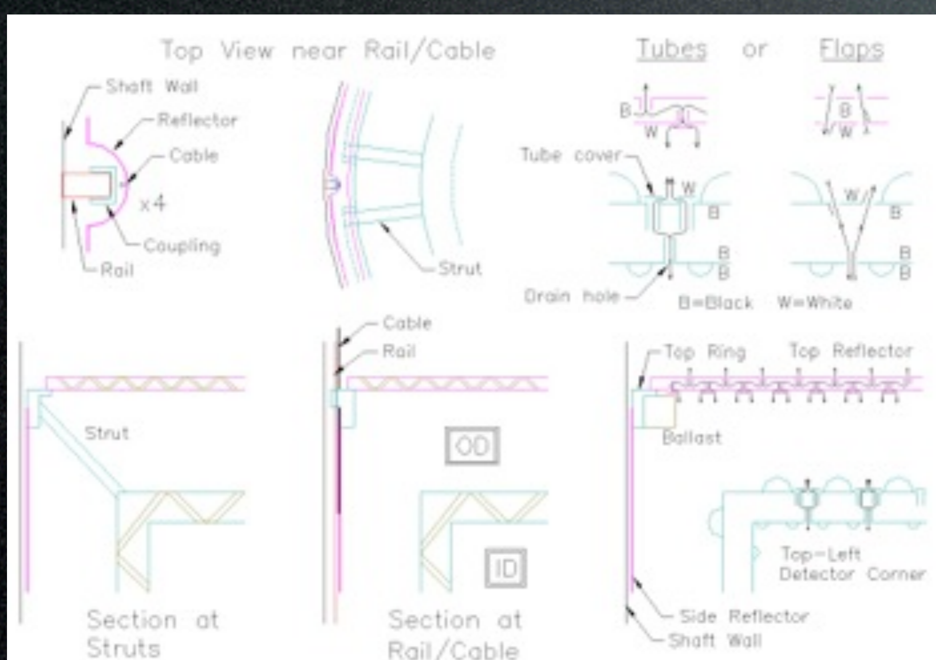
Table 1: Summary of initial cost estimation for civil construction.

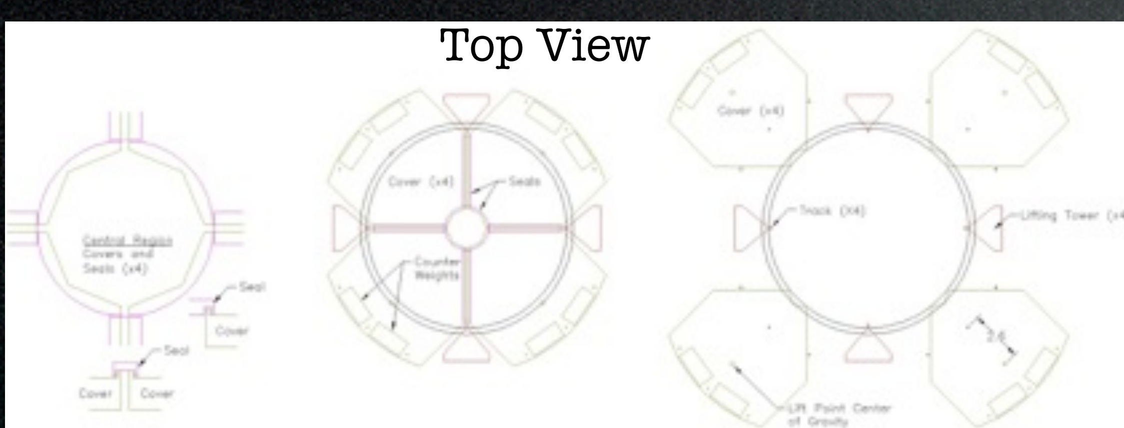
(Unit: Oku JPY, roughly corresponds to Million USD)

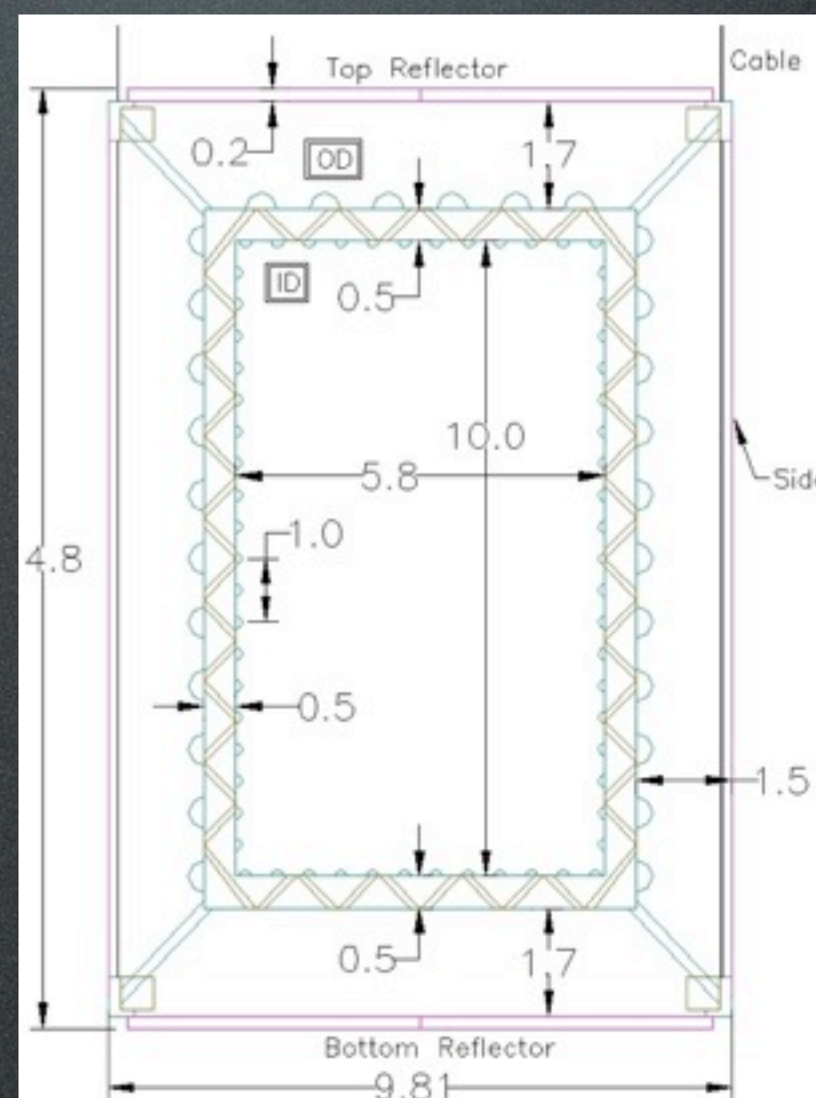
Method	Pneumatic Caisson	Soil Mixing Wall	New Austrian Tunneling	Urban Ring
Survey	0.1 (assume 70 m deep boring survey)			
Designing	0.15			
Land preparation	0.15			
Construction	7.7	5.9	5.3∼6.1	7.5

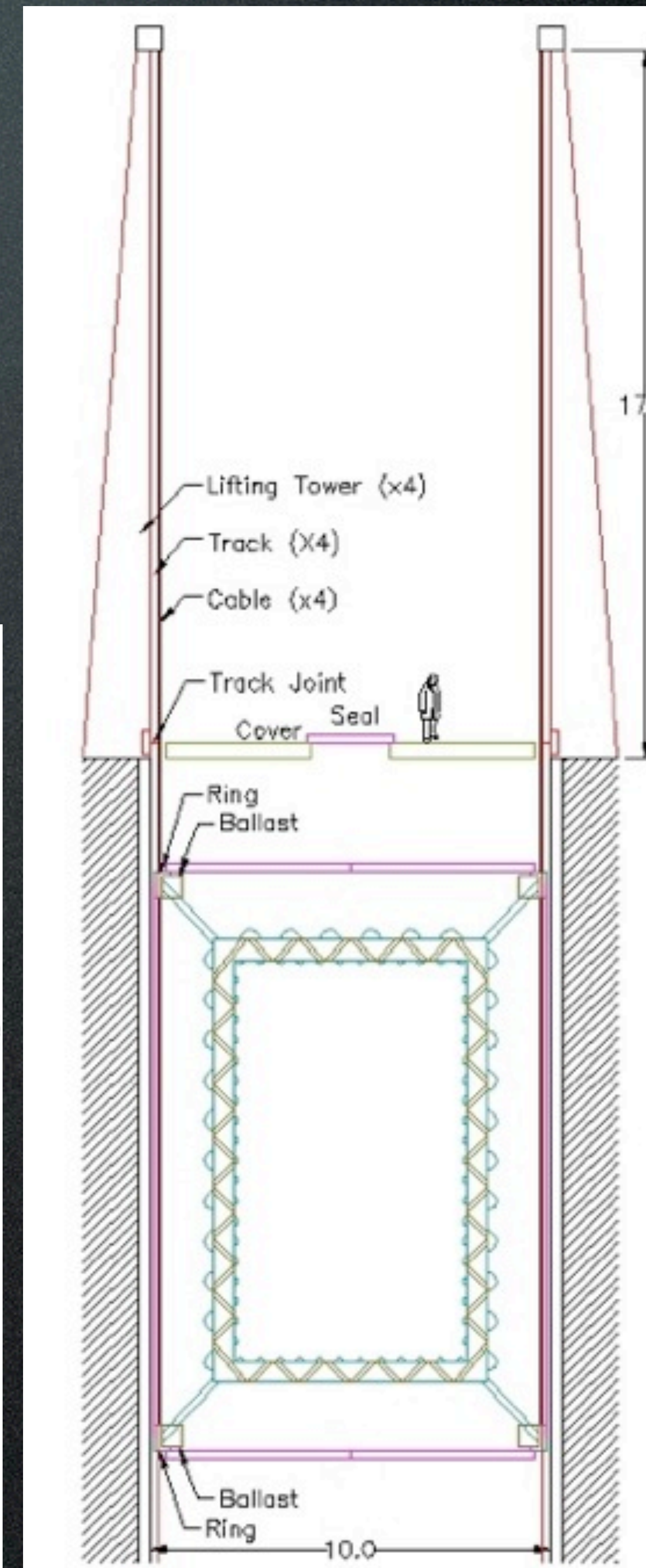
Detector Frame

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









PMTs

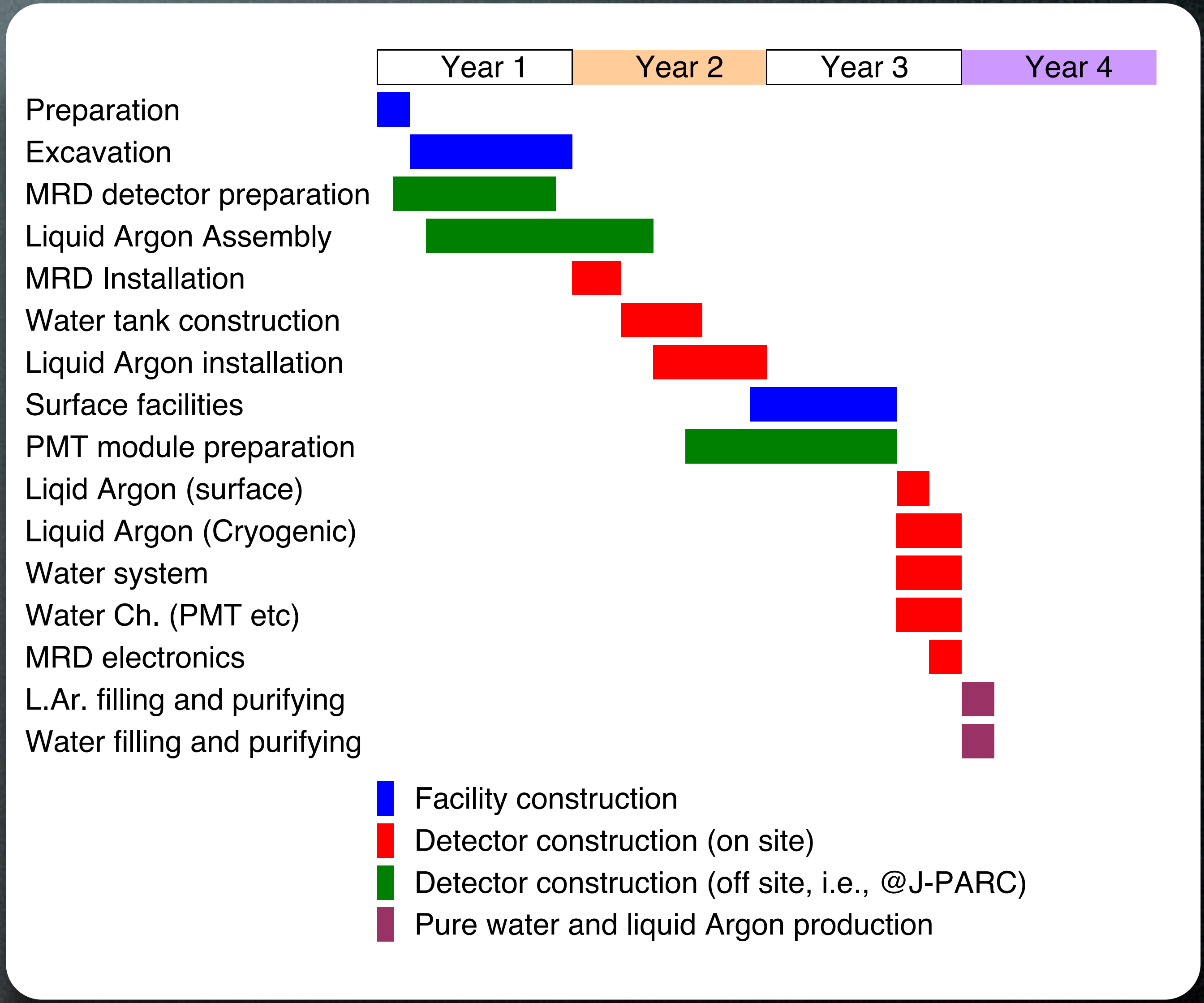
- For the ID, both 8” and 5” PMTs are being considered
  - Perhaps with high-quantum-efficiency (HQE) coating
  - Also considering Hyper-K-style hybrid photodetectors (HPD)
- Initial Hamamatsu estimate for basic 8” R5912 PMT is much more expensive that assumed for 2km detector
  - **US $4.3M for 3,000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

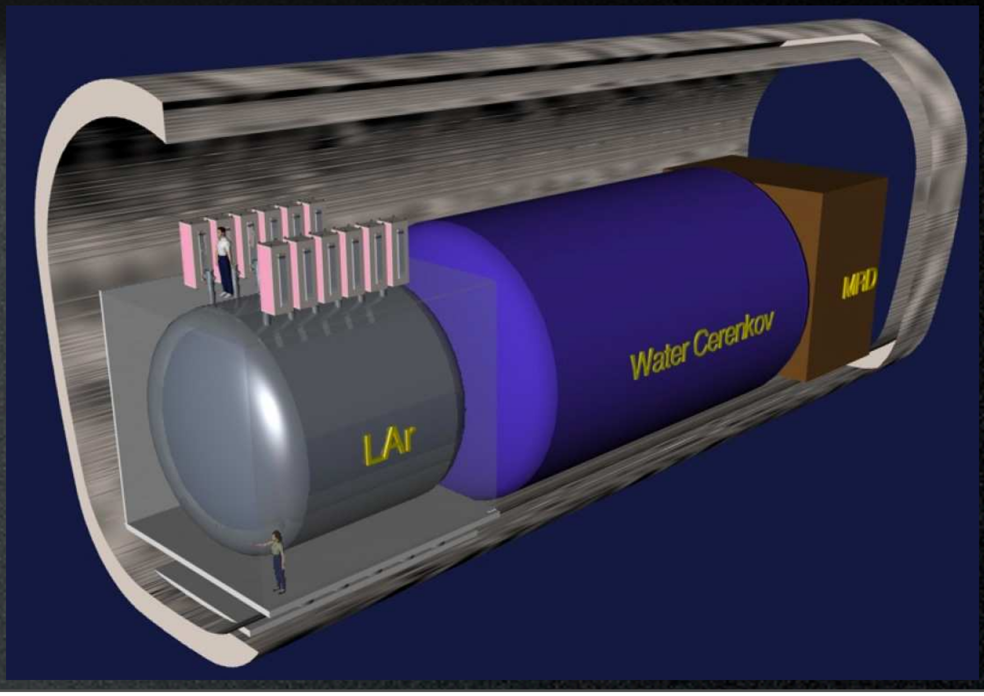
Hamamatsu Estimates

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

νPRISM-Lite Timescales

- Water Cherenkov construction was studies for a T2K near detector proposed in 2005
- νPRISM could perhaps be built faster
  - Same pit depth as the 2km detector, but no excavation of a large cavern at the bottom of the pit
  - Smaller instrumented volume
  - No LAr or MRD detector
- ~3 year timescale from approval to completion
- Goal is to start data taking in time for the J-PARC 700kW beam upgrade expected in 2019
  - Ground breaking in 2016





Current Status

- A detailed Expression of Interest (EoI) document has been written
  - Detailed ν_μ disappearance results
  - Discussion of other physics applications (CP violation, anti-nu, sterile neutrinos, etc.)
  - Preliminary detector design
- First step is formal approval from T2K
- Next step is to gain support from J-PARC/KEK & international funding agencies
- νPRISM can provide a mechanism by which new collaborations can join T2K to perform CP violation and sterile neutrino measurements

Expression of Interest: The νPRISM-Lite T2K Near Detector

Sampa Bhadra[14], Christophe Bronner[7], Javier Caravaca[2], Michal Dziewiecki[13], Guillermo Fiorentini-Aguirre[14], Megan Friend[5], Mark Hartz[6], Robert Henderson[8], Taku Ishida[5], Asher Kaboth[3], Akira Konaka[8], Yury Kudenko[4], Thomas Lindner[8], Kendall Mahn[8], John Martin[12], Kevin McFarland[11], Shoei Nakayama[1], Kimihiro Okumura[1], Andrzej Rychter[13], Federico Sanchez[2], Mark Scott[8], Tetsuro Sekiguchi[5], Masato Shiozawa[1], Roman Tacik[10], Hide-Kazu Tanaka[1], Hirohisa Tanaka[9], Shimpei Tobayama[9], Mark Vagins[6], John Vo[2], Morgan Wascko[3], Michael Wilking[8], Stan Yen[8], and Marcin Ziembicki[13]

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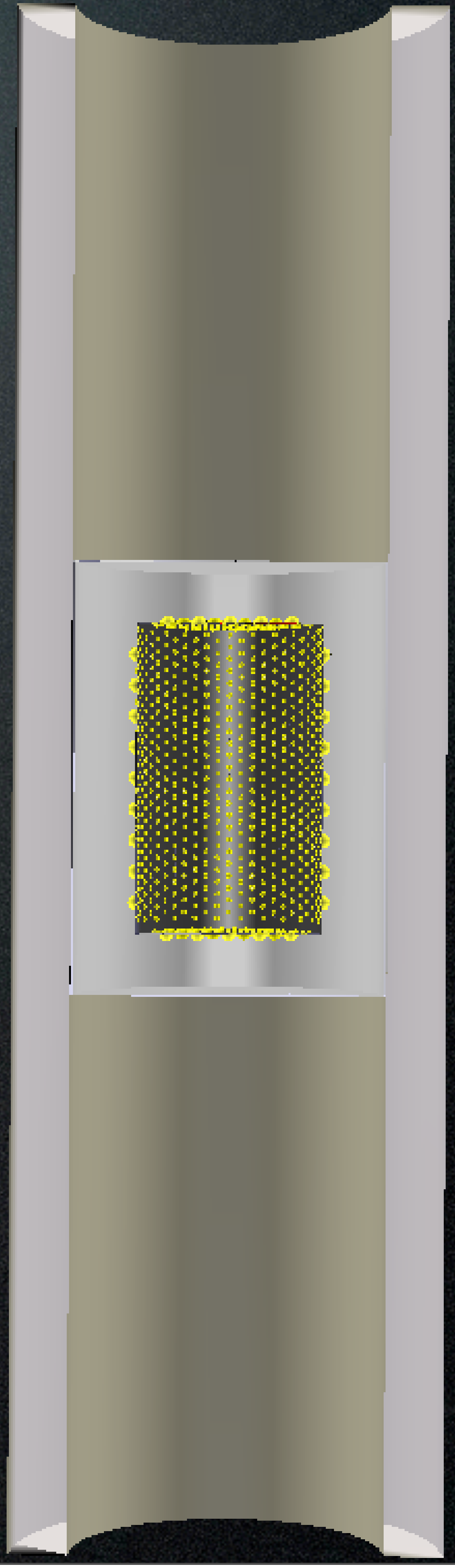
[6]Kavli IPMU
[7]Kyoto University
[8]TRIUMF
[9]University of British Columbia
[10]University of Regina
[11]University of Rochester
[12]University of Toronto
[13]Warsaw University of Technology, Institute of Radioelectronics
[14]York University

Next Steps

- **Need to extend physics studies beyond ν_μ disappearance**
  - ν_e measurements & CP violation sensitivity
  - Anti-neutrinos (w/ wrong-sign background)
  - Joint analyses using ND280
- **Detailed detector MC development is underway**
  - Much of this work has already been done for Hyper-K
    - Full MC and reconstruction software are available
- **More detailed design and engineering work is needed**
  - Full cost estimates for all detector components are underway
- **Plan to submit a full proposal at the end of the summer**

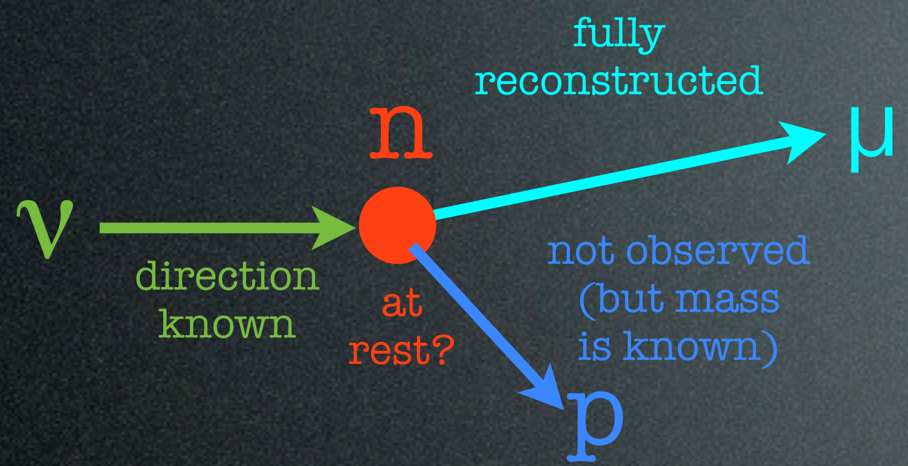
Summary

- Accelerator-based neutrino oscillation experiments require precision measurements of E_ν
  - Currently, must rely on models to related E_ν to experimental observables
  - Models are rapidly evolving, and large disagreements exist between available models
- The νPRISM detector concept can provide a direct, data-driven constraint on E_ν reconstruction
  - Far detector response is measured for any oscillated spectrum
- Hope to have a working example for T2K in 2019
- This concept should be useful for any accelerator-based neutrino experiment



Supplement

Measuring E_ν



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

- The neutrino energy is determined from the 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 on a single nucleon (next slide)
- LBNE will attempt to measure the energy of the outgoing hadrons
  - **Requires knowledge of neutron production (problematic assumption)**

More Model Comparisons!

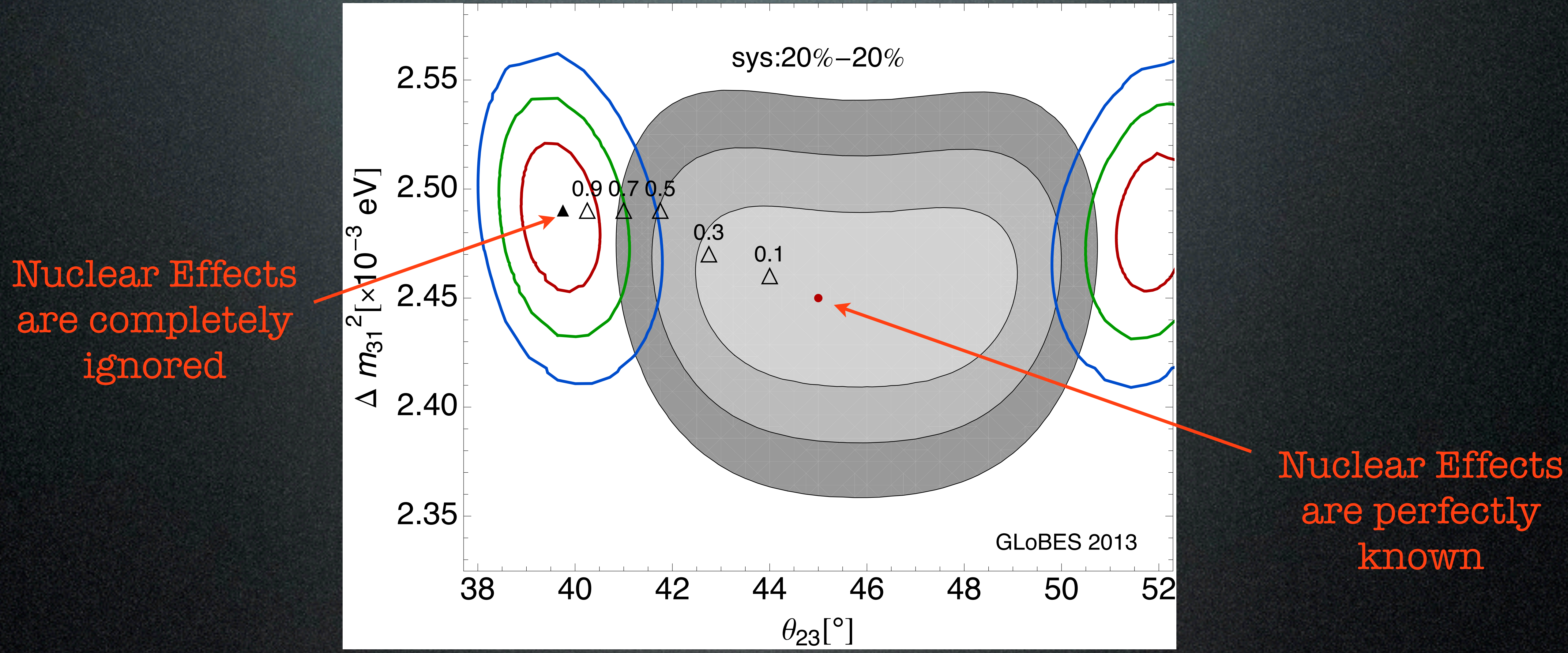
- P. Coloma, P. Huber, C.-M. Jen, and C. Mariani, arXiv: 1311.4506 (Dec, 2013)
- Goal was to understand biases in oscillation parameters from neutrino event generators
  - Try to approximate the T2K near/far setup
- Uses two well-established generators: GENIE & GiBUU
  - Treat one model as true, and fit with the other
- Full near + far fit with some simplifying assumptions
  - Same near/far flux, same near/far detectors and performance
  - Since the actual situation is not as nice, these estimates are likely conservative

Fit results for true values **θ_{23}=45°** & **Δm^2_{31}= 2.45 * 10^{-3}**

True	Fitted	$\theta_{23,min}$	$\Delta m^2_{31,min}[\mathrm{eV}^2]$	χ^2_{min}
GENIE (^{16}O)	GENIE (^{12}C)	44°	2.49×10^{-3}	2.28
GiBUU (^{16}O)	GENIE (^{16}O)	41.75°	2.69×10^{-3}	47.64
		47°	2.55×10^{-3}	20.95
GiBUU (^{16}O)	GiBUU (^{16}O) w/o MEC	42.5°	2.44×10^{-3}	22.38
GENIE (^{16}O)	GENIE (^{16}O) w/o MEC	44.5°	2.36×10^{-3}	19.54

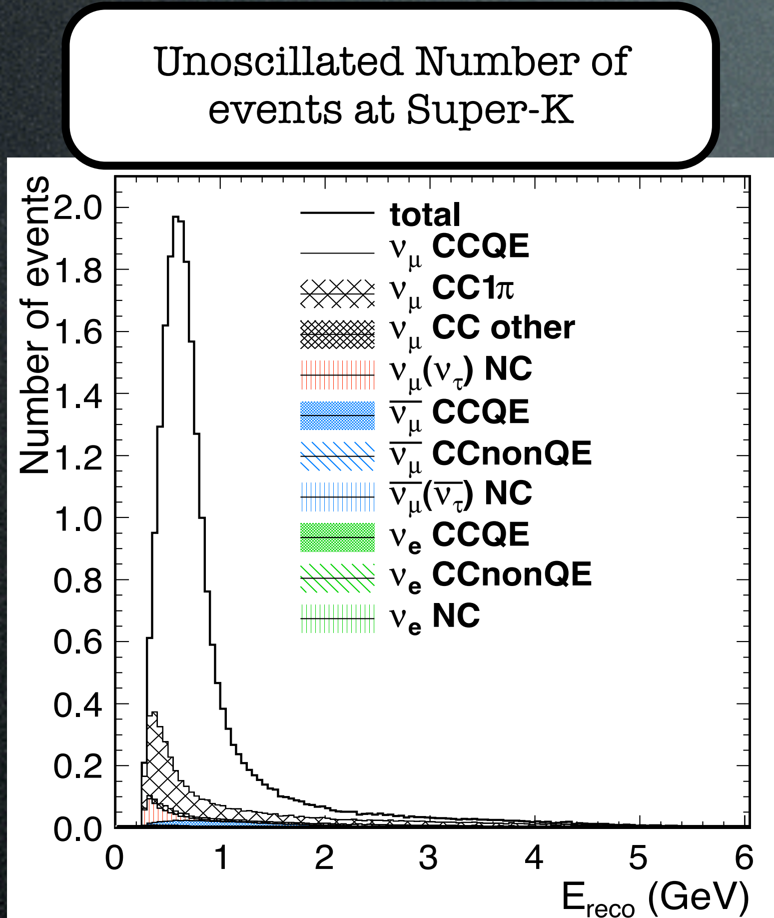
Fit has 16 d.o.f.

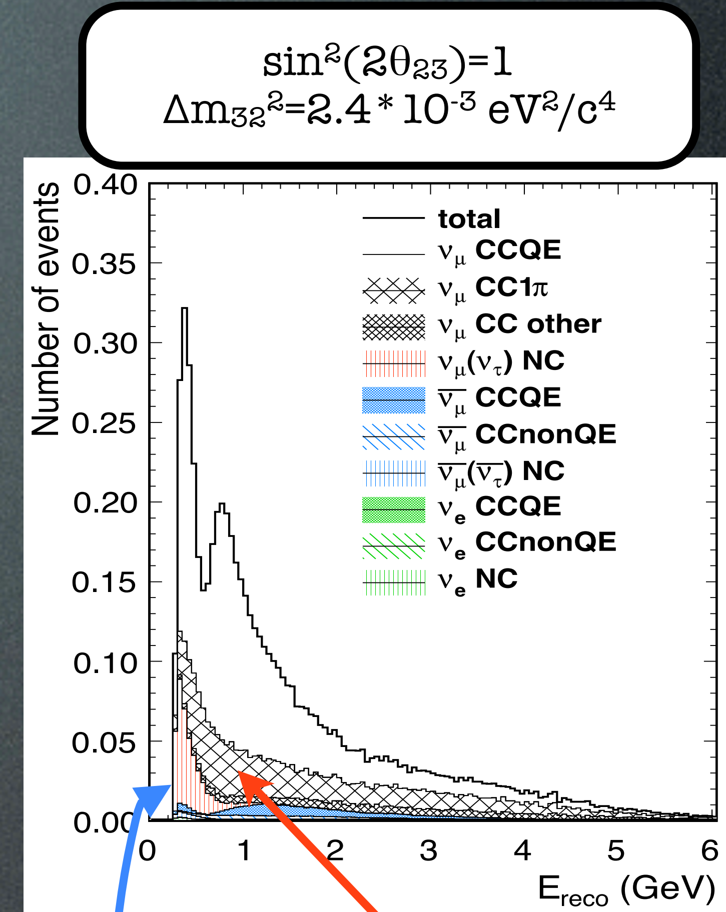
Biases due to cross section modeling can be significant!



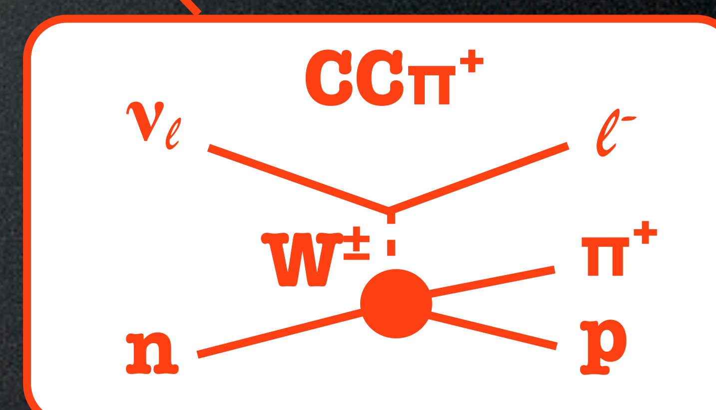
- P. Coloma, P. Huber, arXiv:1307.1243
-

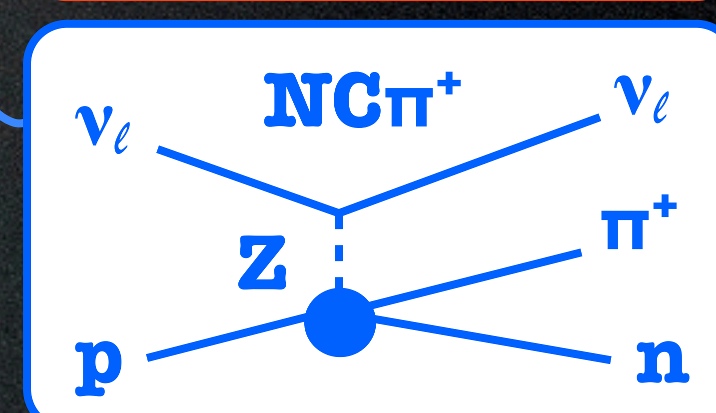
T2K ν_μ Disappearance



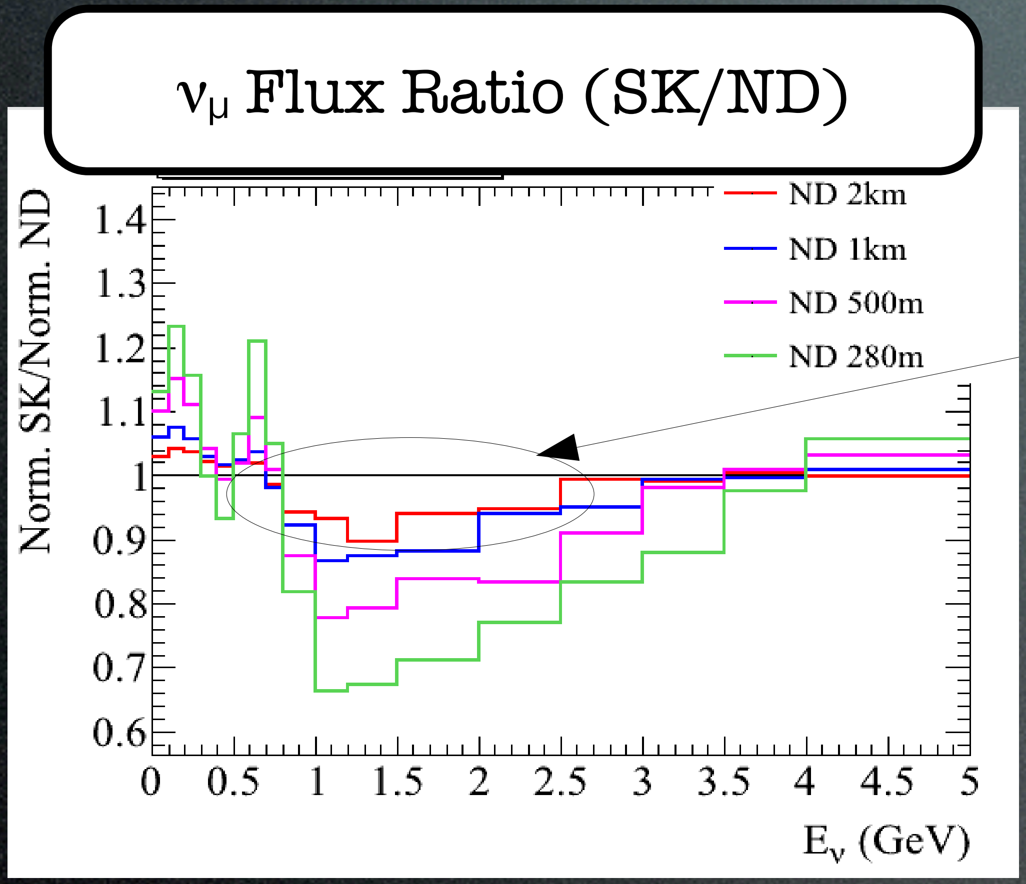


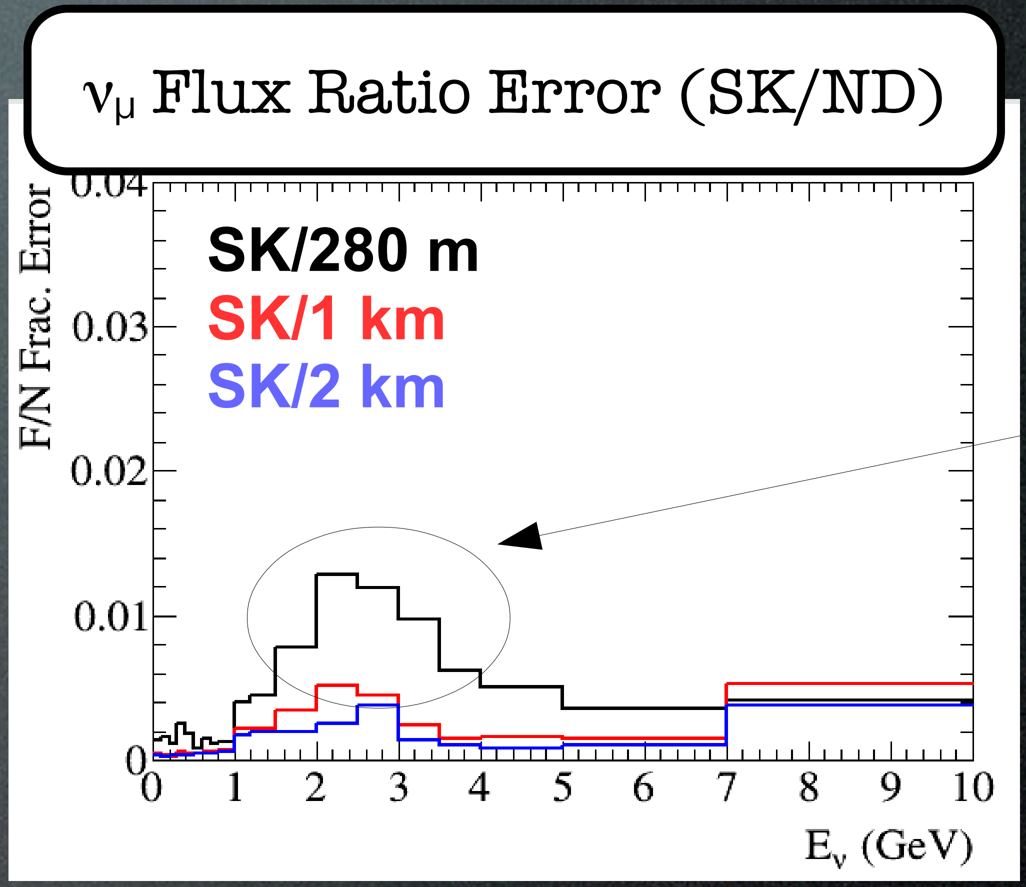
- Largest backgrounds are from CCπ^+ and NCπ^+
- **NCπ^+**: pion is misidentified as a muon
  - **Uncertainty on NCπ^+ is large (>100%)**
- **CCπ^+**: pion is unobserved
  - Neutrino energy is misreconstructed
  - Fills in the oscillation "dip" (big impact on θ_{23} measurement)





Design Considerations: Energy Spectrum Ratio

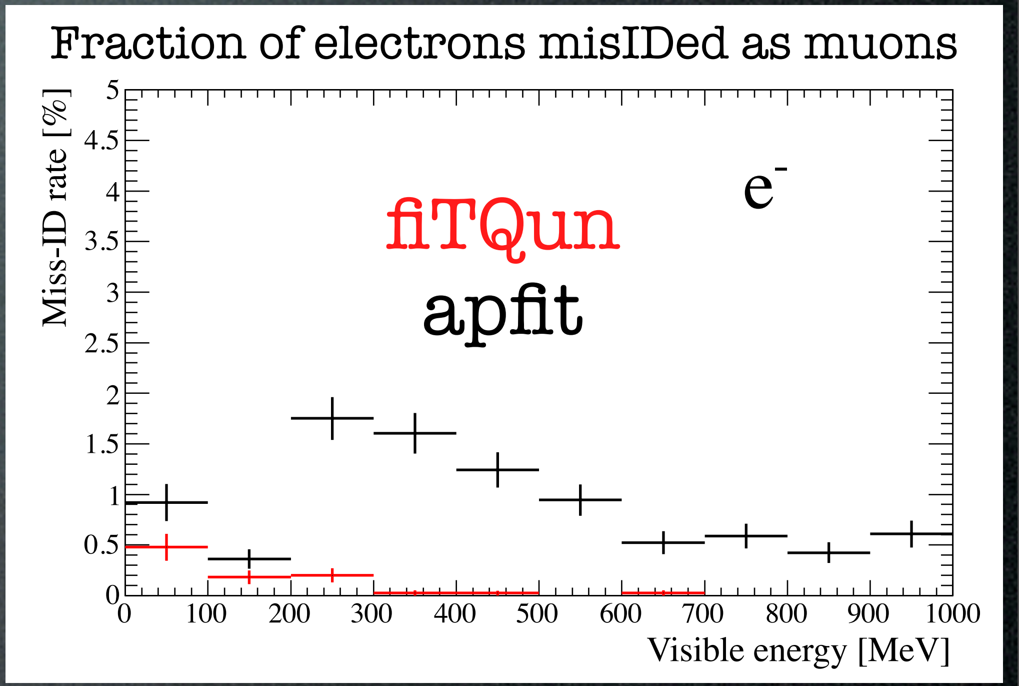


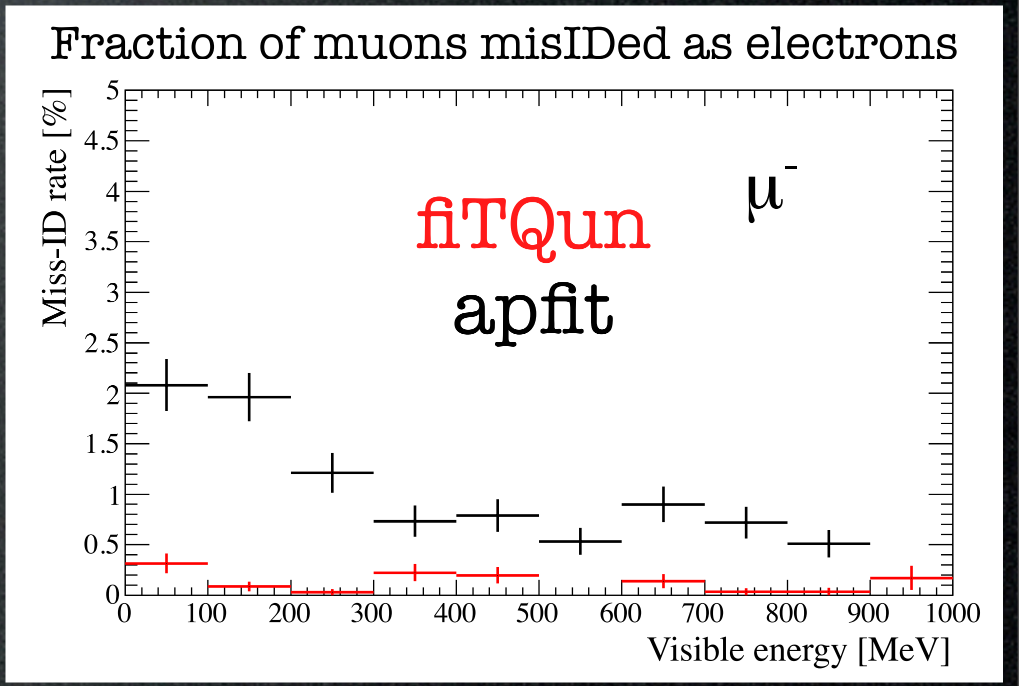


- At 280 m, the flux shape has 20-30% differences below 1 GeV
  - Uncertainty in the ratio is noticeably larger, but mostly above 1 GeV
- The difference between 1km and 2km is small in both shape and shape uncertainty

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





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)

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

predicted Super-K E_{rec} distribution

weight for off-axis slice, i

events in muon p,θ bin in slice, i

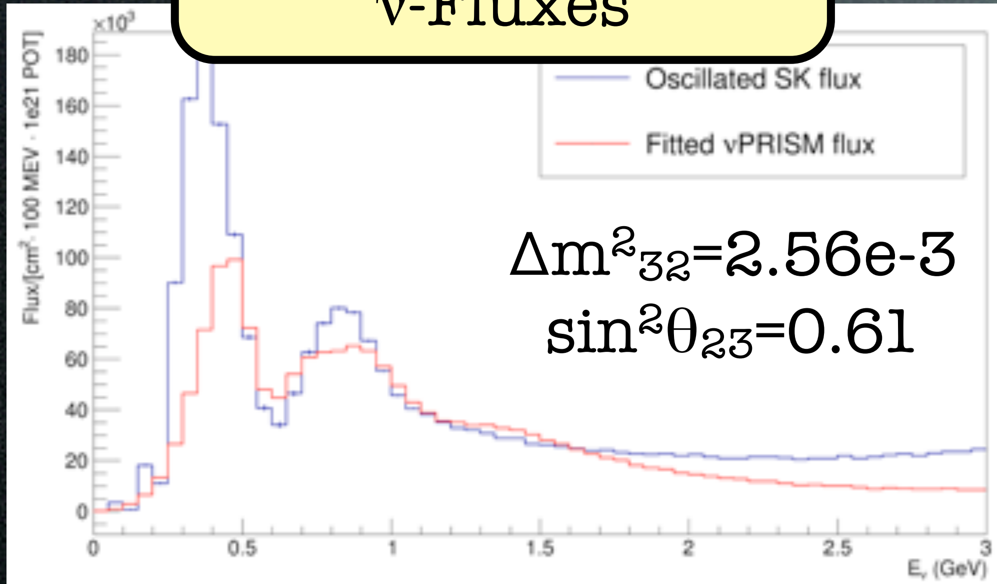
background subtraction

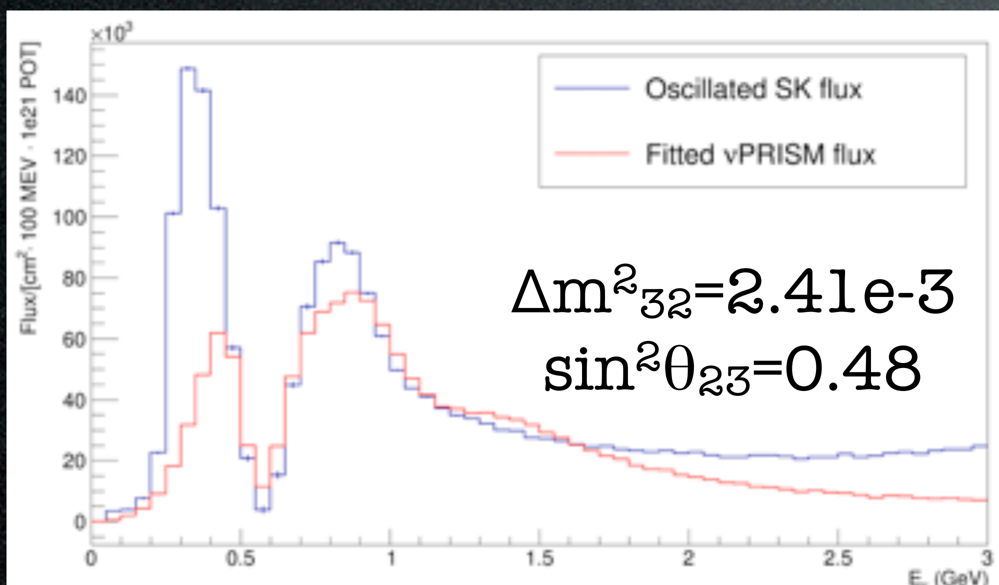
efficiency ratio

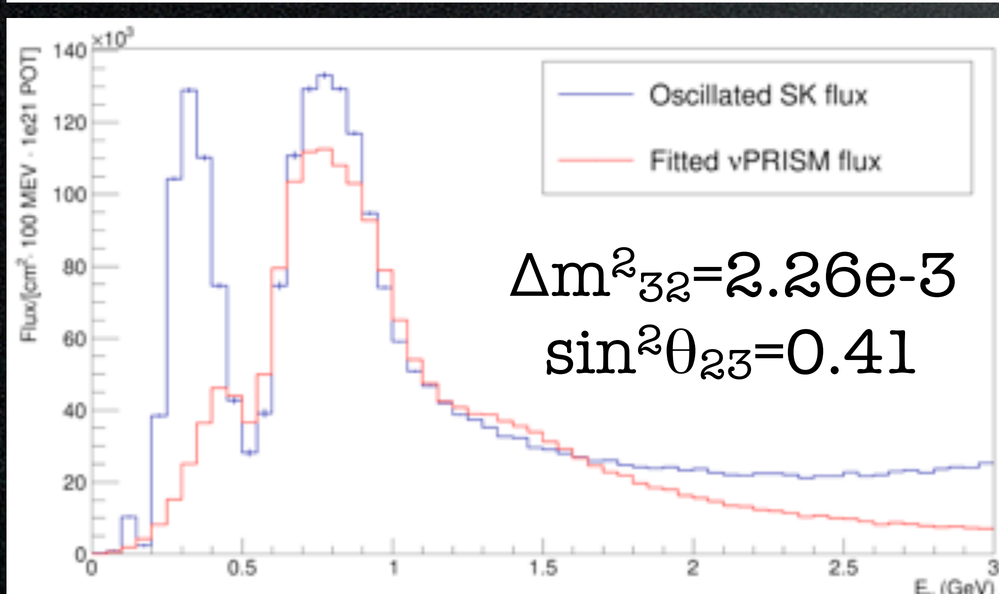
translation matrix p,θ → E_{rec}

New ν-Flux Fits

ν-Fluxes

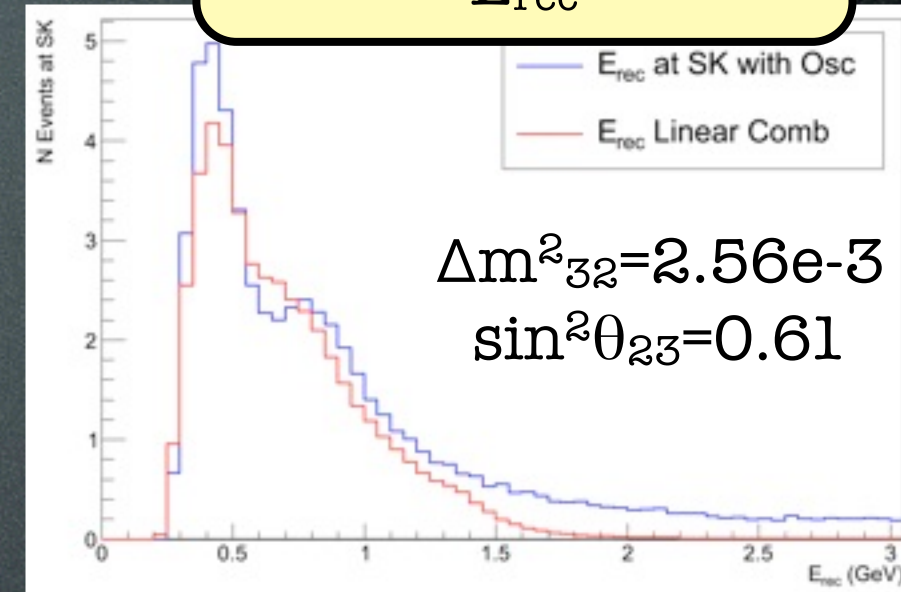


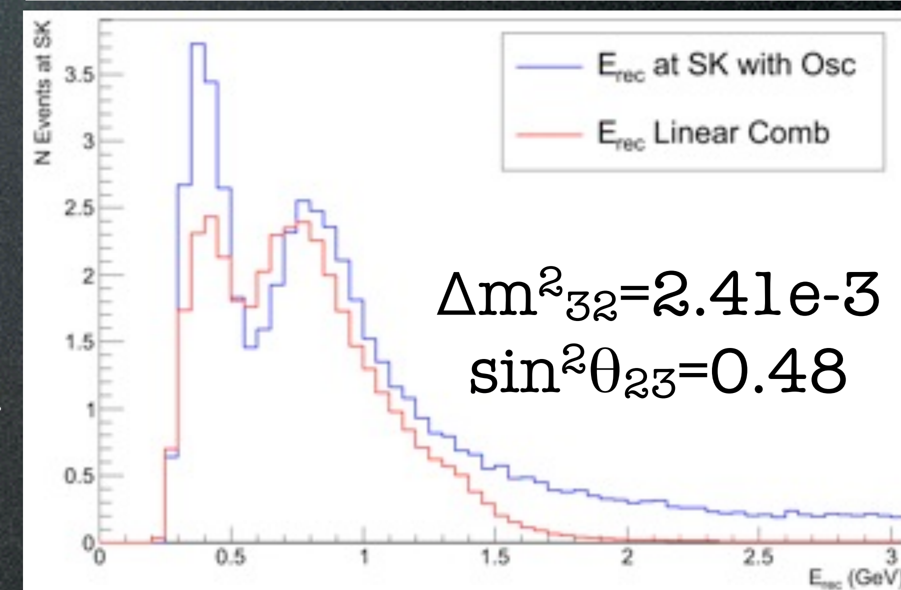


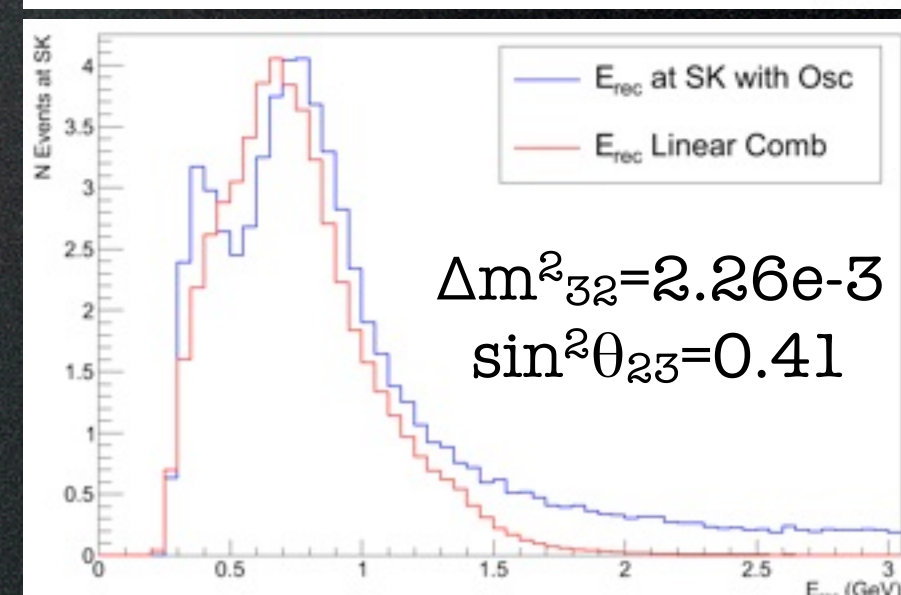


- Fits are not perfect
- However, very small increase to systematic uncertainties
  - Flux systematic variations are large
- Fits can be improved
  - Smoothness can be relaxed near fast-changing features
  - Off-axis angle bins need not be equal size

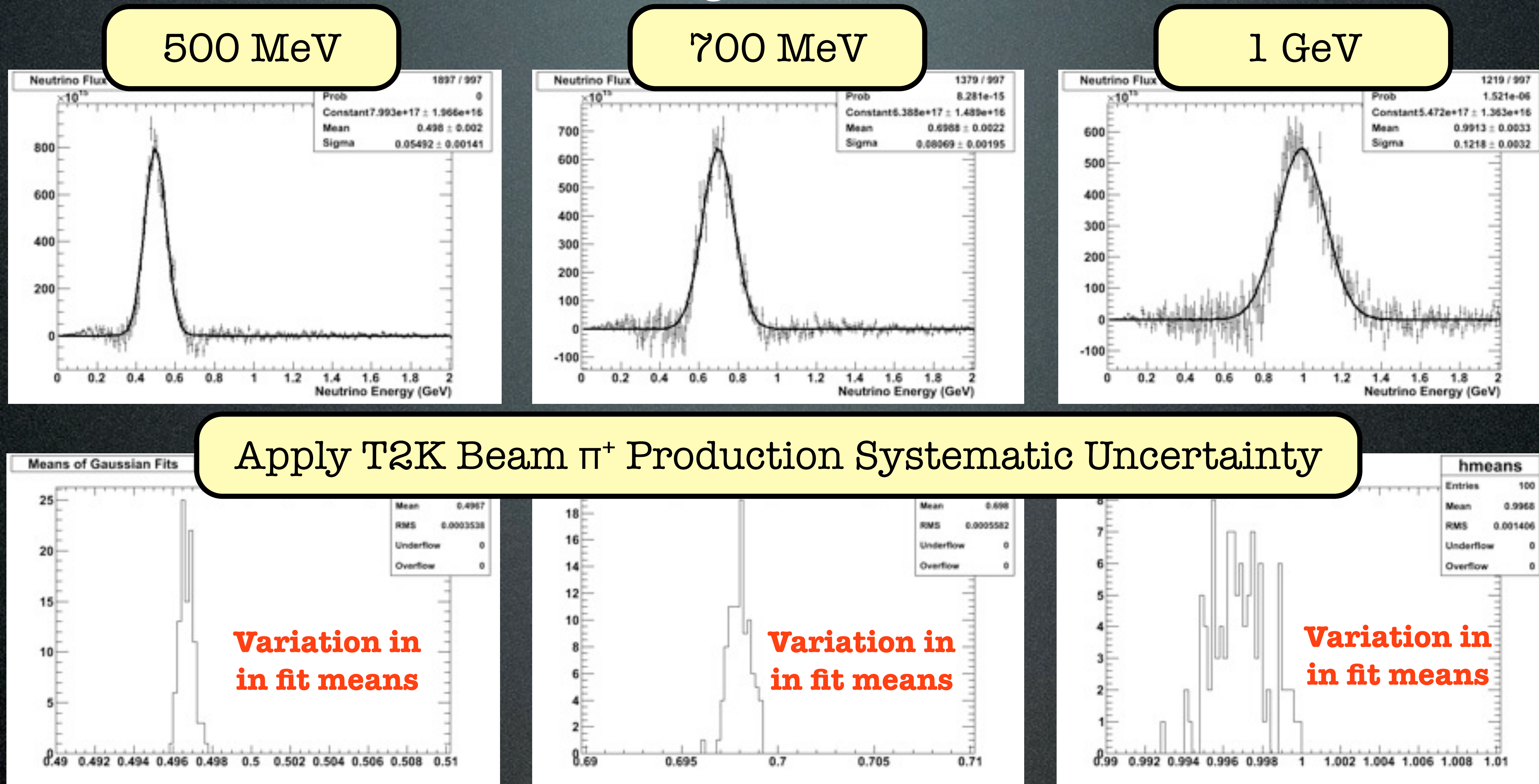
E_{rec}





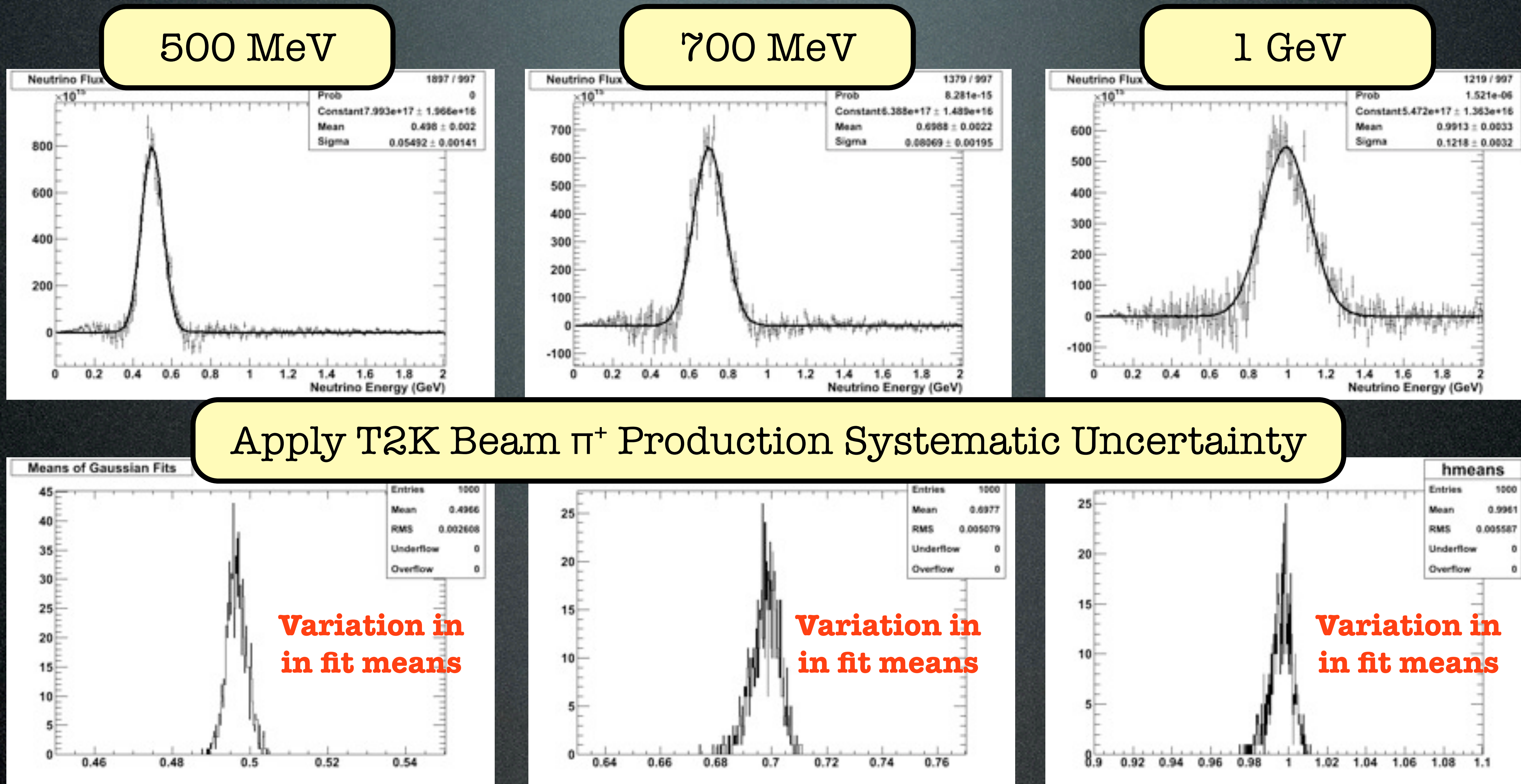


Beam Systematics



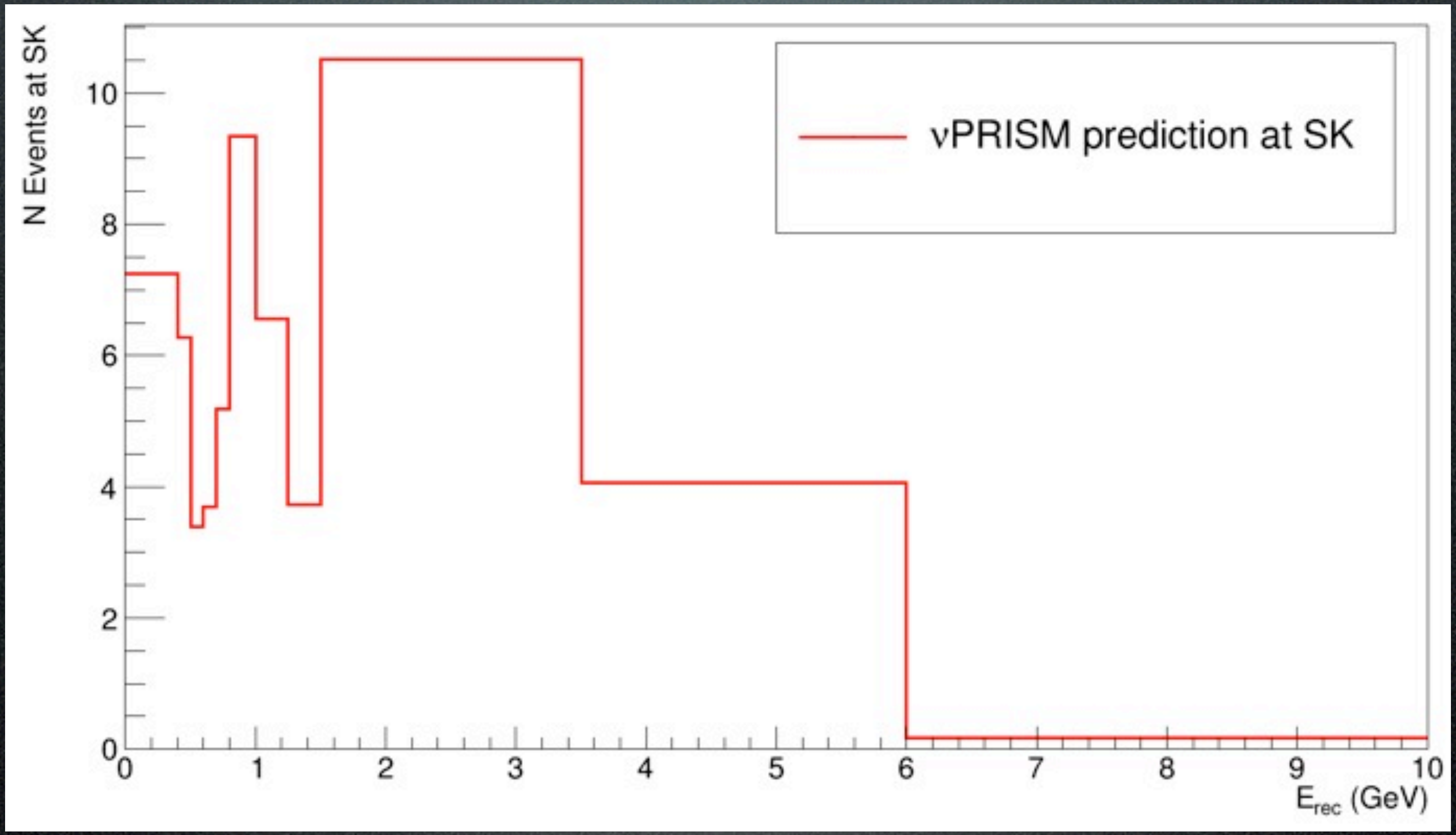
- Apply **T2K π^+ production variations** to flux linear combinations
  - This is expected to be the dominant normalization uncertainty for T2HK
- Spread in neutrino energy due to π^+ production **uncertainty is $\mathcal{O}$(0.1%)**
  - More detailed study needed, but so far looks promising

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

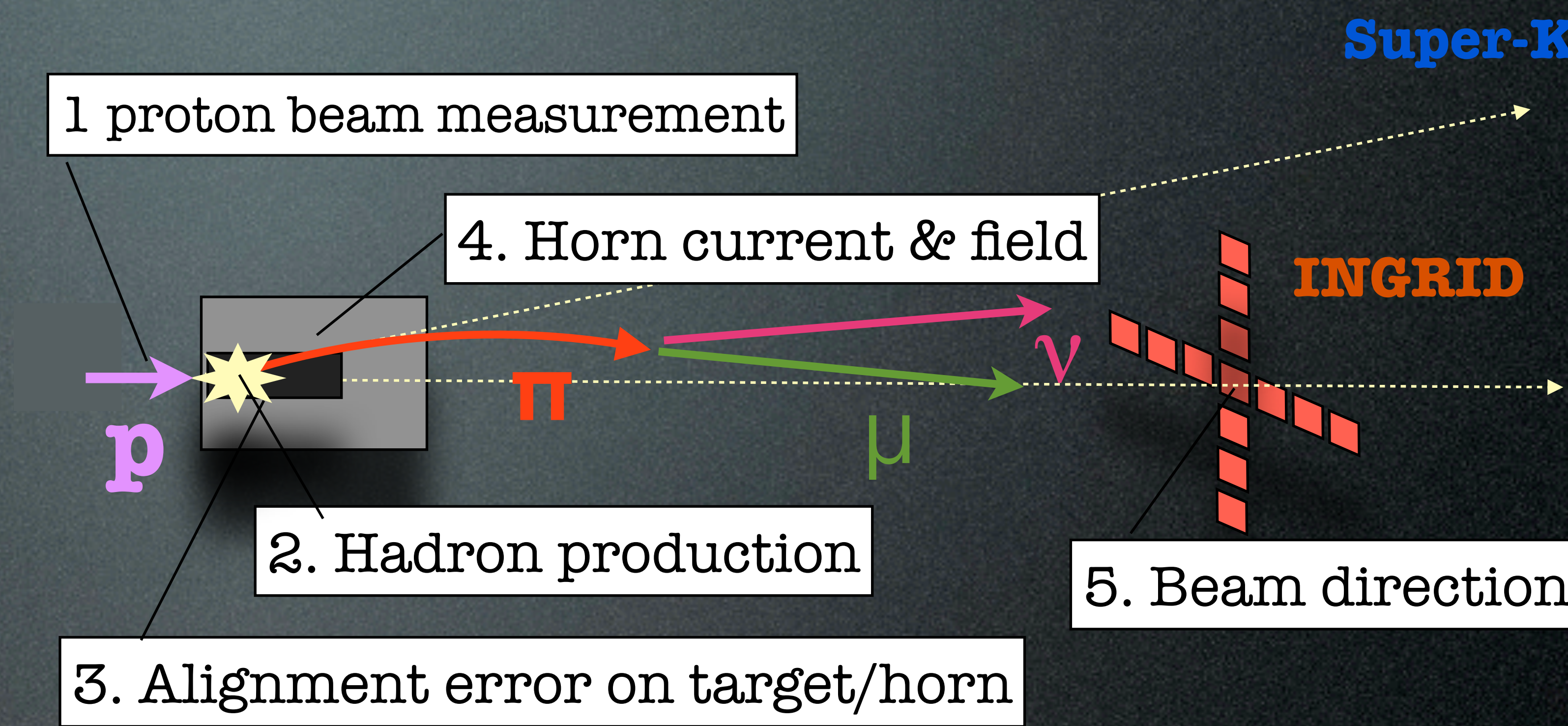
E_{rec} Binning

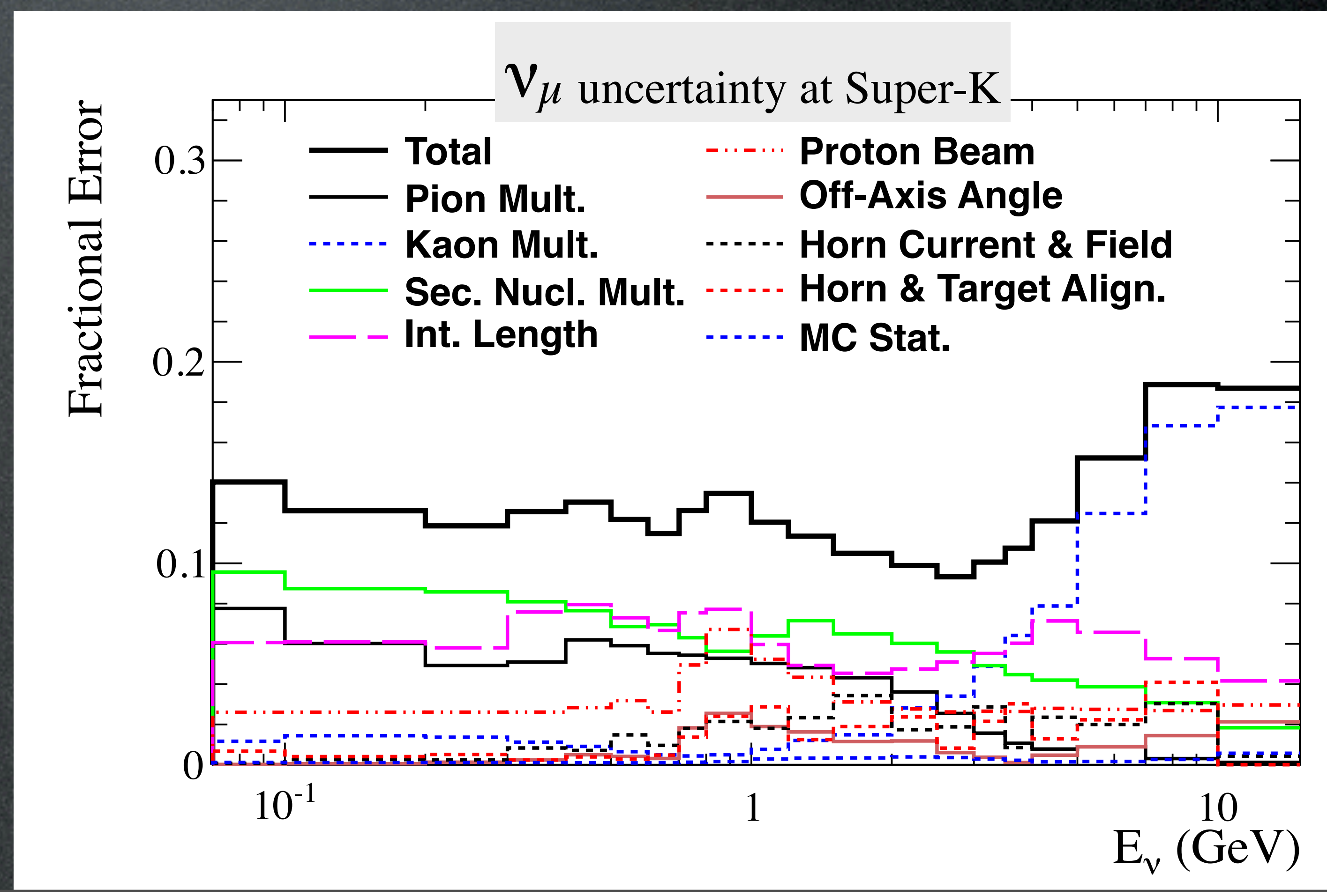


- Last bin (10-30 GeV) is not shown

ν Flux Uncertainties

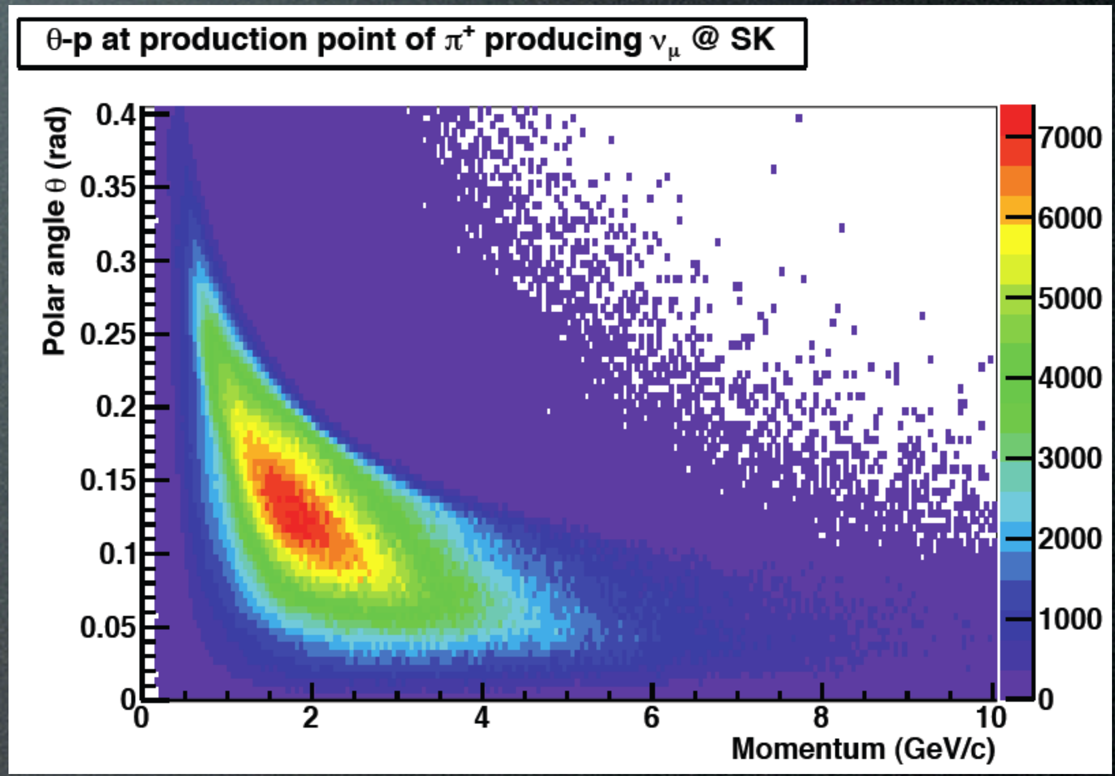
1. **Measurement error on monitoring proton beam**
2. **Hadron production**
3. **Alignment error on the target and the horn**
4. **Horn current & field**
5. **Neutrino beam direction (Off-axis angle)**



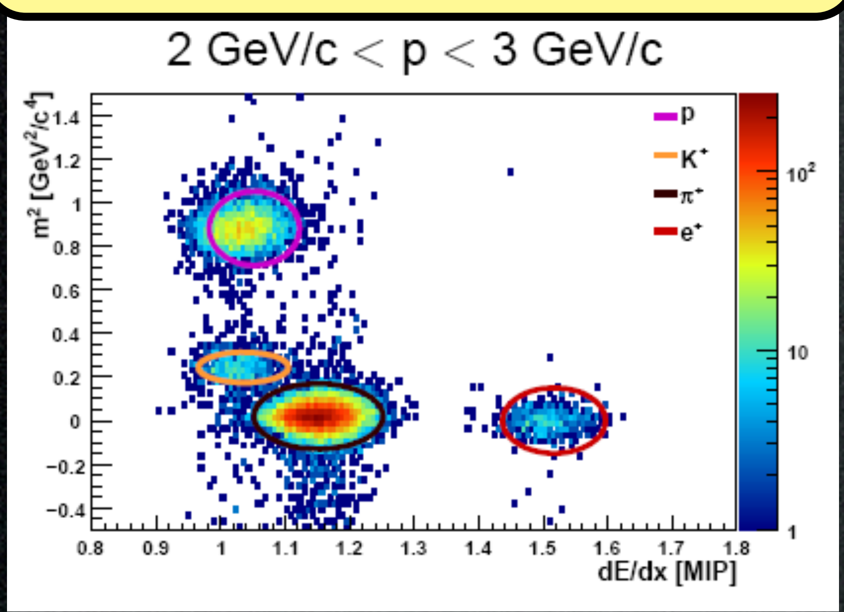


Constraining the ν Flux

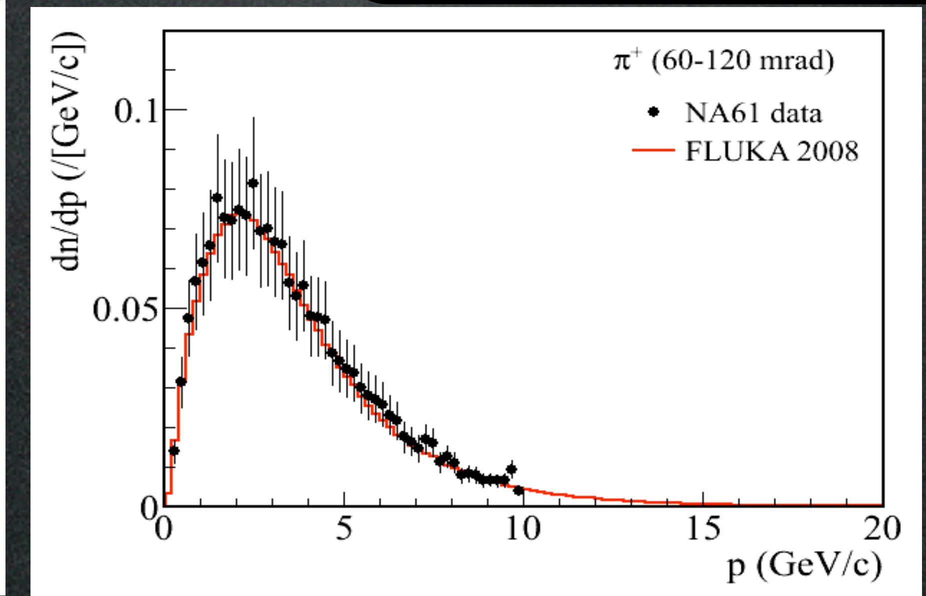
- The dominant flux uncertainties are in π/K production from p+C interactions
- "Sweet spot" for producing neutrinos at Super K (due to horn focusing)
- The NA61 experiment at CERN has taken data on a thin C target and a T2K replica target
  - Good particle separation from combined time-of-flight and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

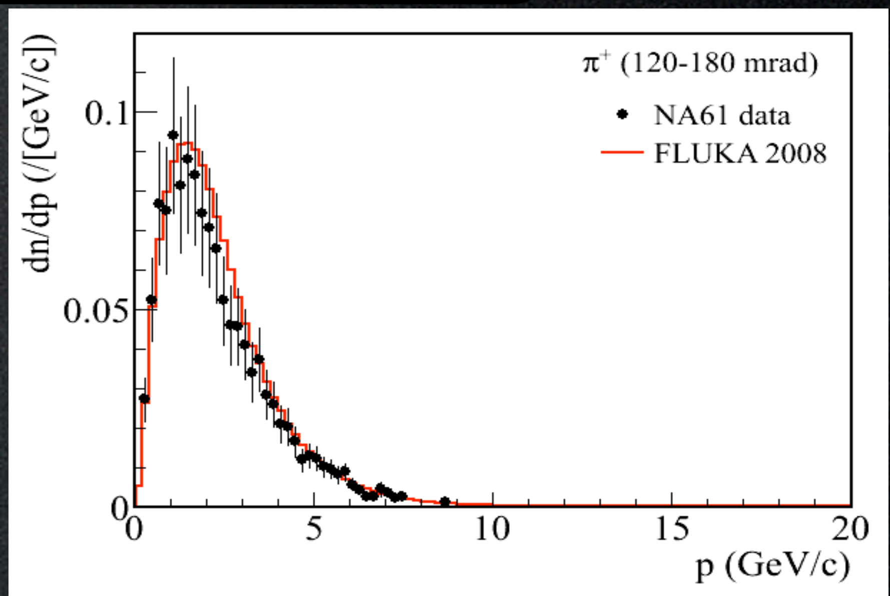


NA61 Particle ID

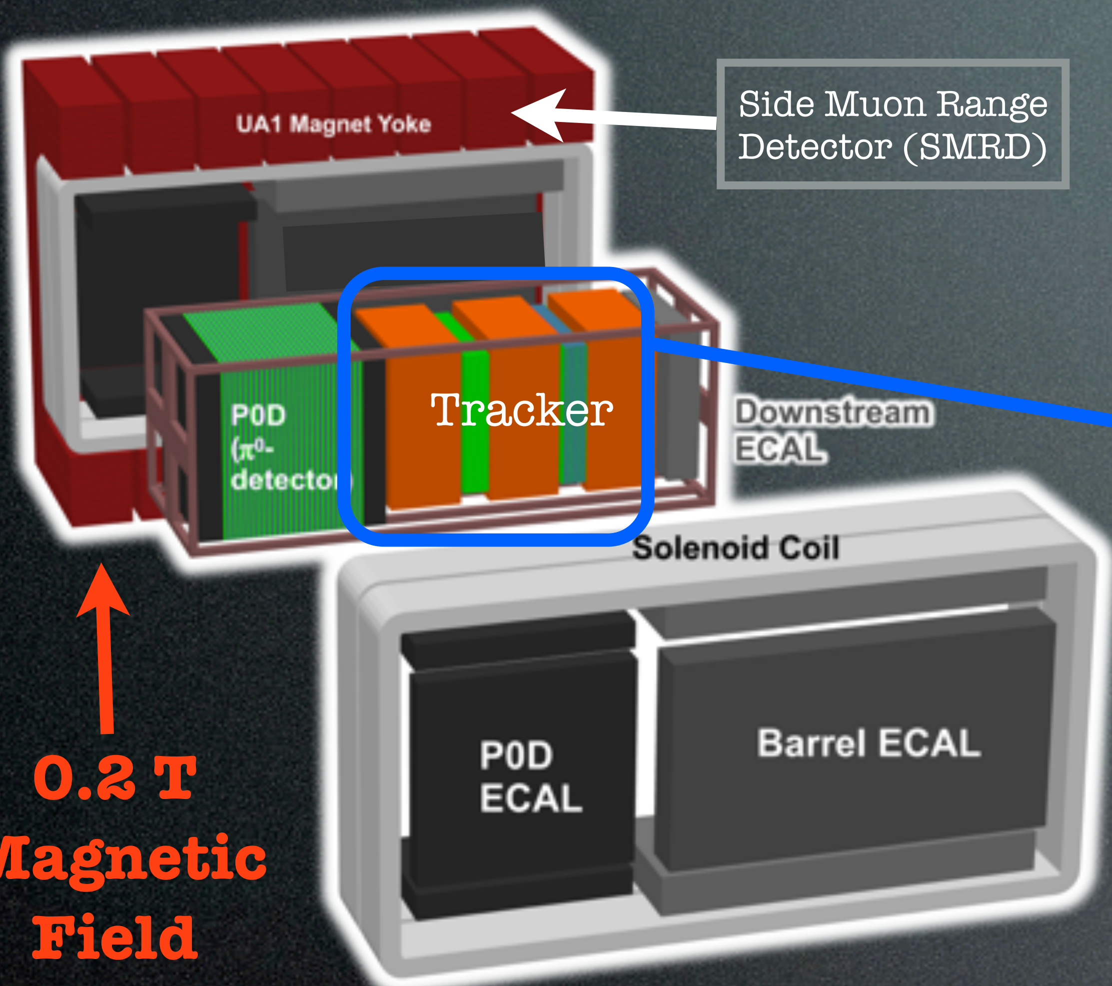


NA61 Data vs FLUKA

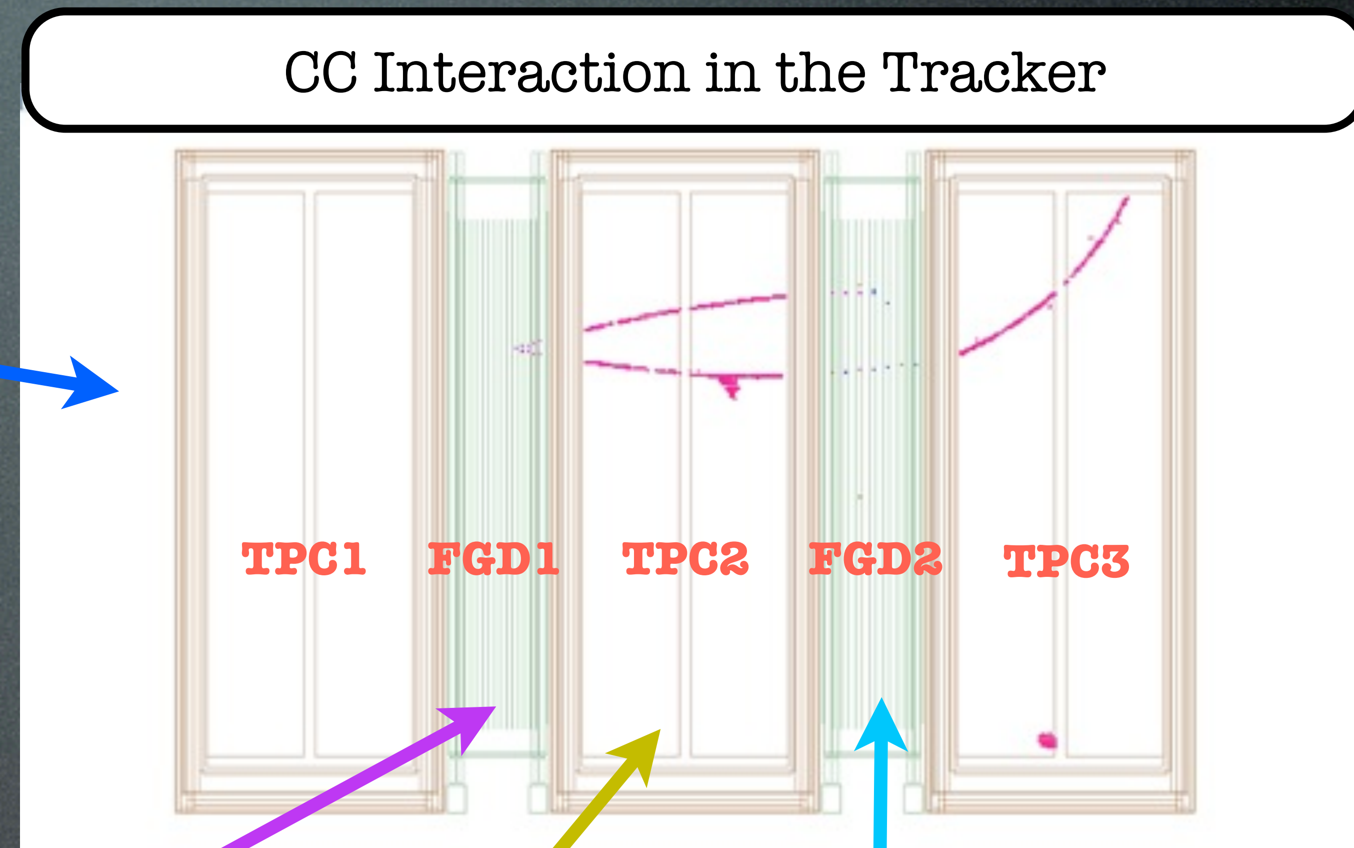




T2K Near Detector Constraints



0.2 T Magnetic Field



FGD2 has water layers to constrain interactions on same target as Super-K

Not yet used; planned 2014 analysis improvement

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

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

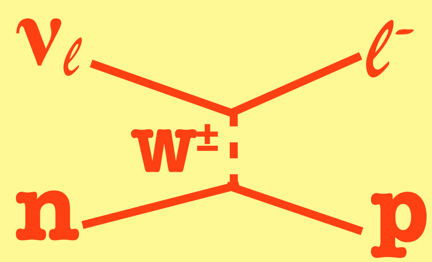
$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

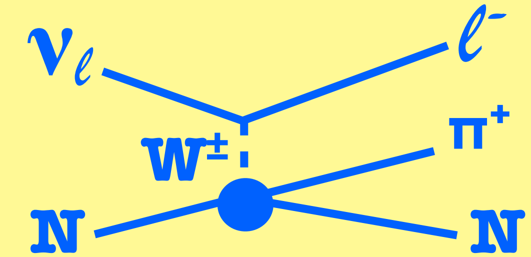
Can use ν_μ measurement to constrain the ν_e flux

External constraints from **NA61**

Cross Sections

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





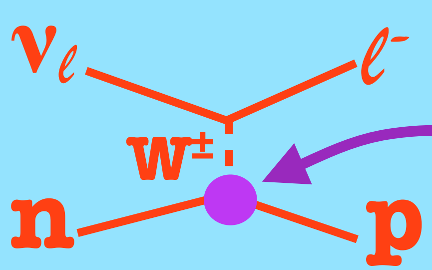
Need to constrain the parameters of these interactions: M_A^{QE}, M_A^{RES}, etc.

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

Summary of Improvements

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

Factor 2.4 more ND280 POT

Improved SK π^0 rejection

New ND280 reconstruction, selection, binning

Factor 2.2 more ND280 POT

*Results presented at Neutrino 2012 conference

**Published results, arXiv:1304.0841v2

***Update to NEUT tuning with MiniBooNE data

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

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^{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

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
-

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

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
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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

Scintillator Panels

Panel Layout

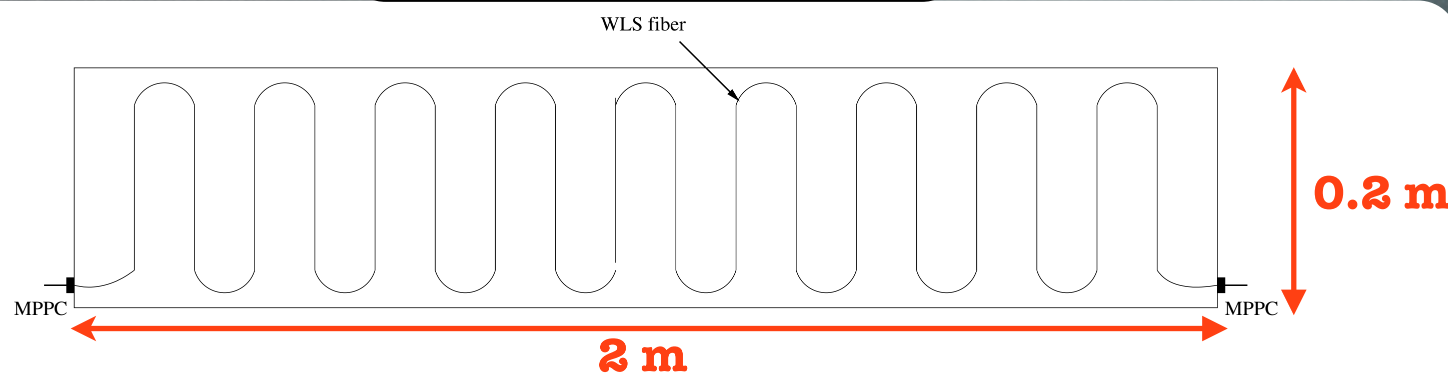

Figure 16: Drawing view of a scintillator counter for the νPRISM-Lite veto system.

Cost per Panel

Material/labor	cost in $US
One extruded slab covered by a reflector	70
WLS fiber Y11, 6 m long, 2$/m	12
Optical glue, 2 g/m, 0.3$/g	3.6
Optical connectors $2times0.25$	0.5
MPPC 2 × 10$	20
Labor	14
Total	~ 120

- To improve the effectiveness of vetoing entering sand muons, SMRD-style scintillator panels are being considered
  - The presence of light in the OD need not veto an event if the track does not enter the ID
  - Scintillator provides entering & exiting positions in time and space
- 3,000 panels are required to surround the entire OD
  - Total cost = US $360,000