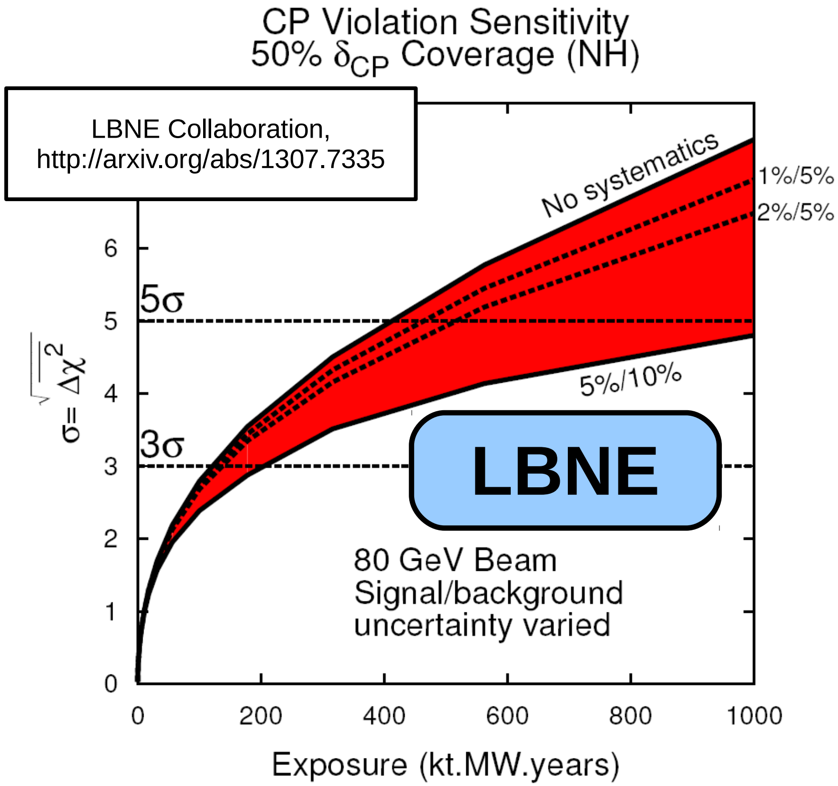
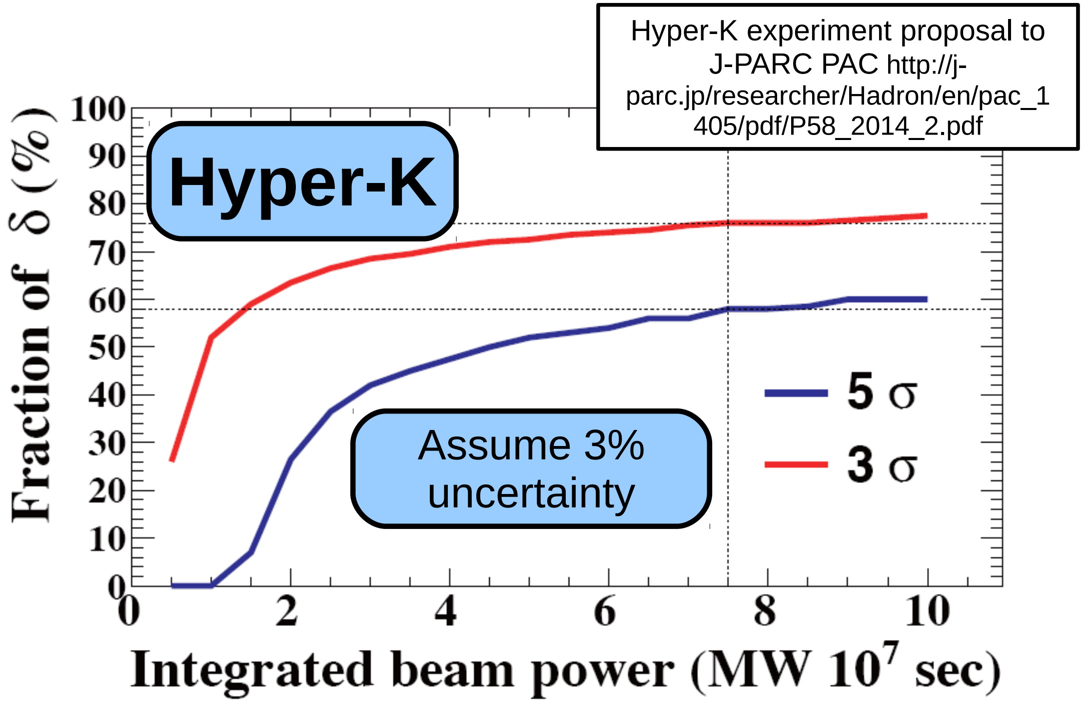
An Intermediate Water Cherenkov Detector at J-PARC

Mark Scott for the Hyper-K proto-collaboration
NuInt15
20th Nov 2015 – Osaka University

Discovering leptonic CP violation





- Hyper-K designed to measure CP violation
- Require 3% total uncertainty on neutrino events, 6% on anti-neutrino
- Experiment will be systematics limited!

Systematics at T2K

Source of uncertainty	ν_μ CC	ν_e CC
Flux and common cross sections		
(w/o ND280 constraint)	21.7%	26.0%
(w/ ND280 constraint)	2.7%	3.2%
Independent cross sections	5.0%	4.7%
SK	4.0%	2.7%
FSI + SI(+ PN)	3.0%	2.5%
Total		
(w/o ND280 constraint)	23.5%	26.8%
(w/ ND280 constraint)	7.7%	6.8%

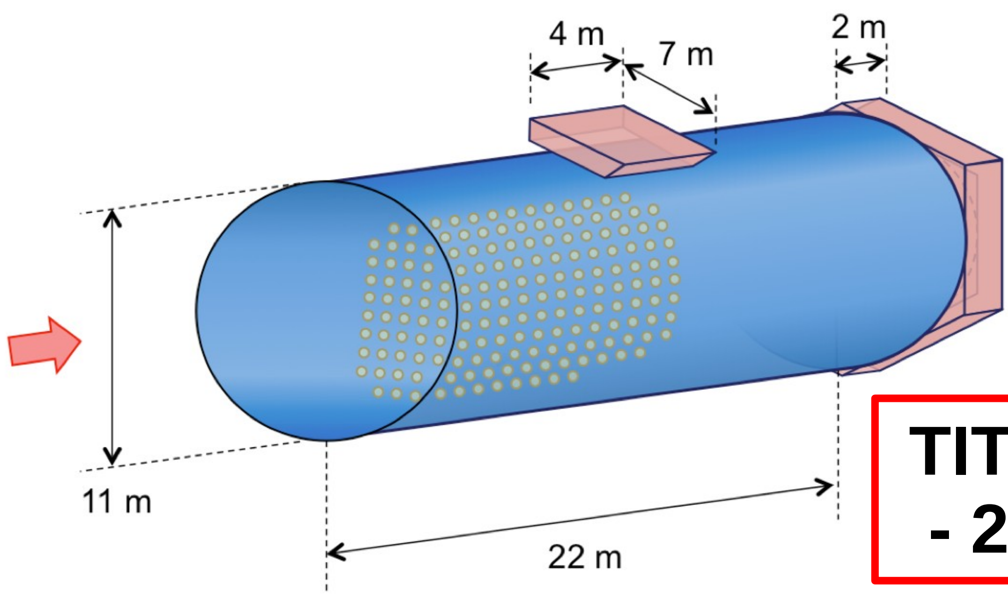
K. Abe et al. (T2K Collaboration) Phys. Rev. D 91, 072010

- Near detectors essential – 24% → 3%
- 5% independent cross section uncertainty:
  - Carbon → Oxygen extrapolation
  - No sample to constrain some interaction modes

- Fundamentally limited by
  - Low Oxygen/Carbon ratio
  - Insensitive to far detector backgrounds
  - Low reconstruction efficiency for particles perpendicular to beam

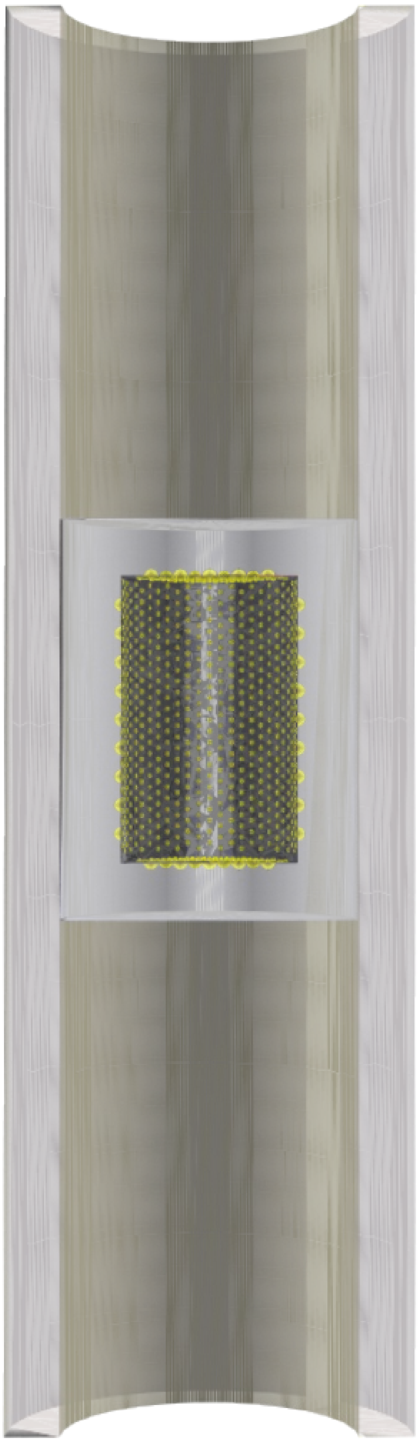
An intermediate detector

- Large (kiloton scale) water Cherenkov (WC) detector 1-2 km from beam target
  - Water target
  - 4π coverage
  - Same signal and background modes as far detector
  - Smaller near→far extrapolation systematic than T2K near detector



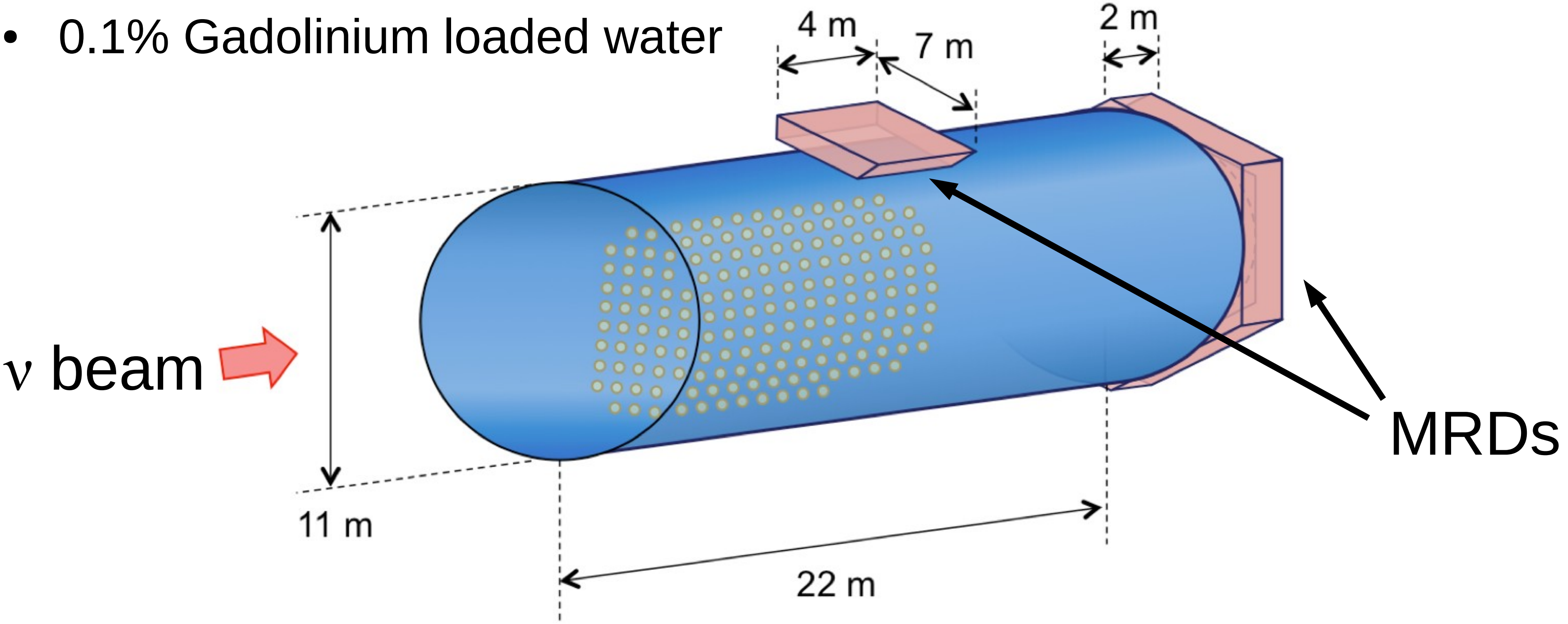
TITUS - 2km

NuPRISM - 1km

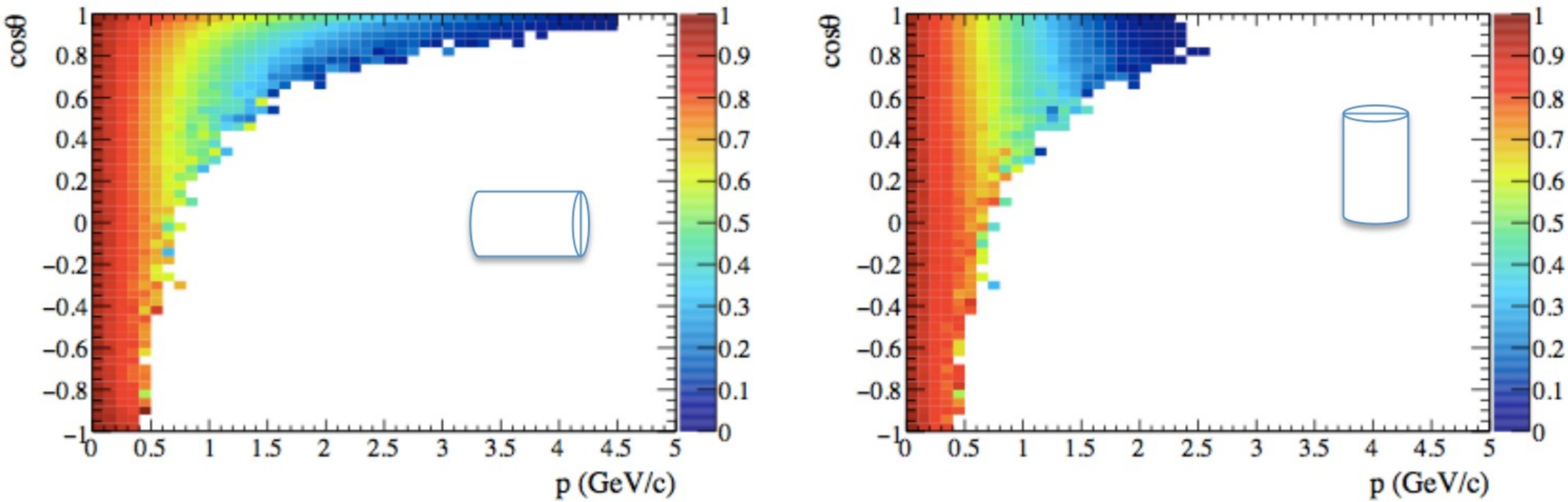


TITUS

- **T**okai **I**ntermediate **T**ank to measure the **U**noscillated **S**pectrum
- 2km from beam target
- Cylindrical WC with long axis parallel to beam
- PMTs interspersed with large area picosecond photo-detectors (LAPPDs) if available
- Magnetised muon range detector (MRD)
- 0.1% Gadolinium loaded water



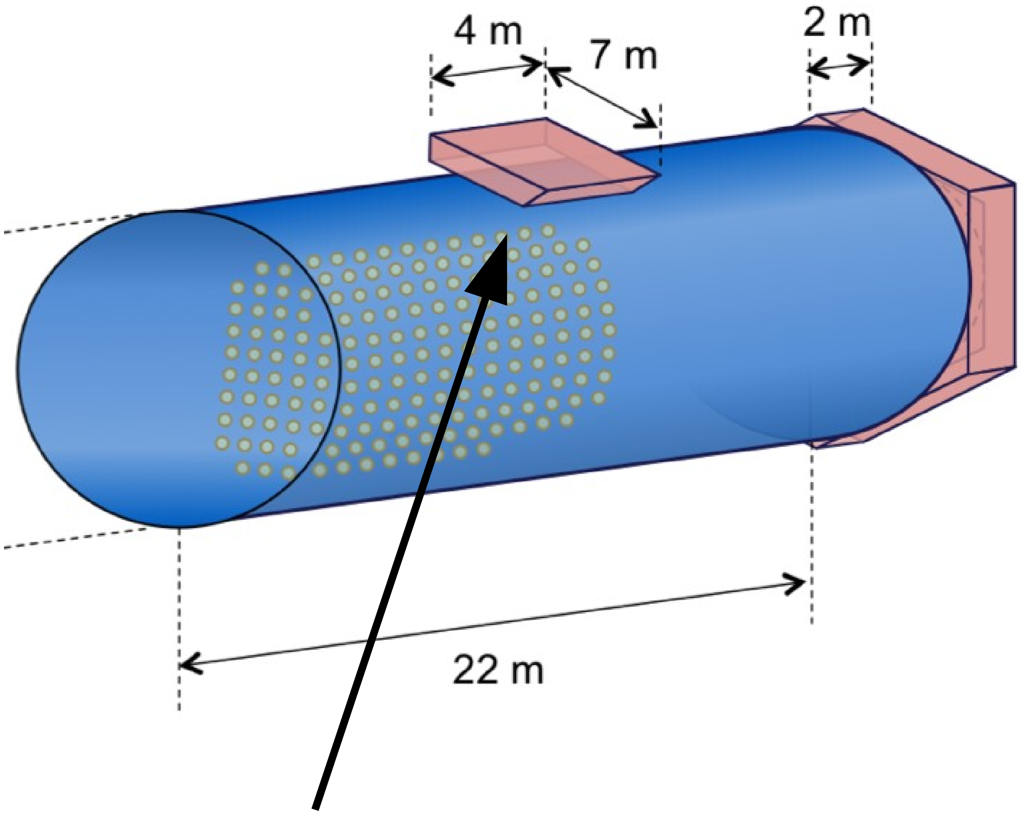
Detector acceptance



- Muon neutrino selection efficiency at TITUS for two orientations of detector
  - Vertical detector cannot reconstruct high momentum muons
  - Loses some of the flux ~ cos(θ) = 1

- Parallel orientation - 18% of muons escape tank

Magnetised Muon Range Detector



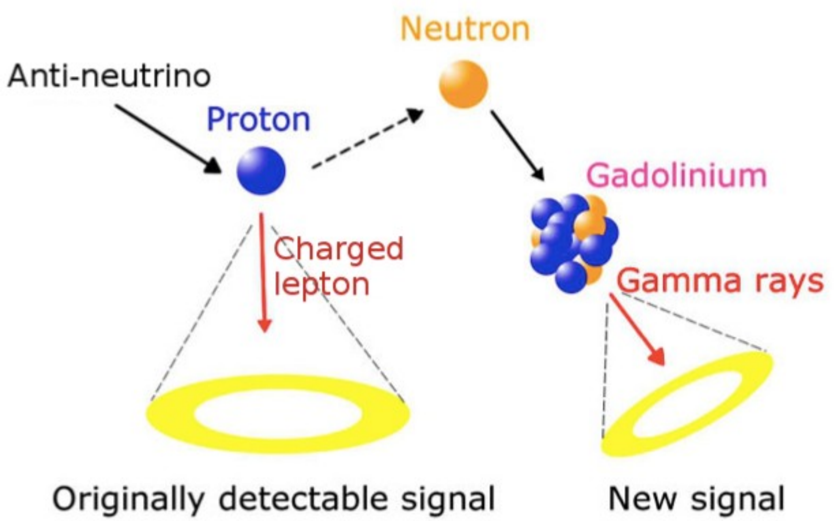
- 1.5T magnetised iron tracking detector
  - Iron interleaved with air gaps and scintillator
  - Measure lepton charge
    - 90% to 95% efficient for muons with momentum from 0.5 to 2 GeV
  - Complements Gd

- Side magnetised MRD – sample high Q^2 region
- Proof of principle: Baby-MIND detector (University of Geneva)
  - Will be used for Wagasci experiment at J-PARC
  - Use data to optimise design for T2HK

Gadolinium doping

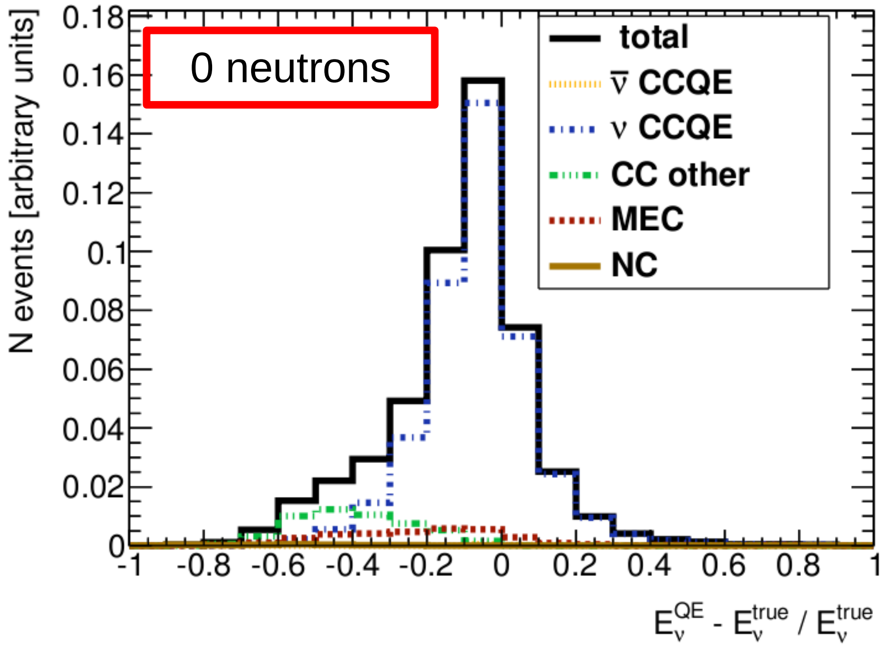
- Can be used by both TITUS and NuPRISM – studied at TITUS so far

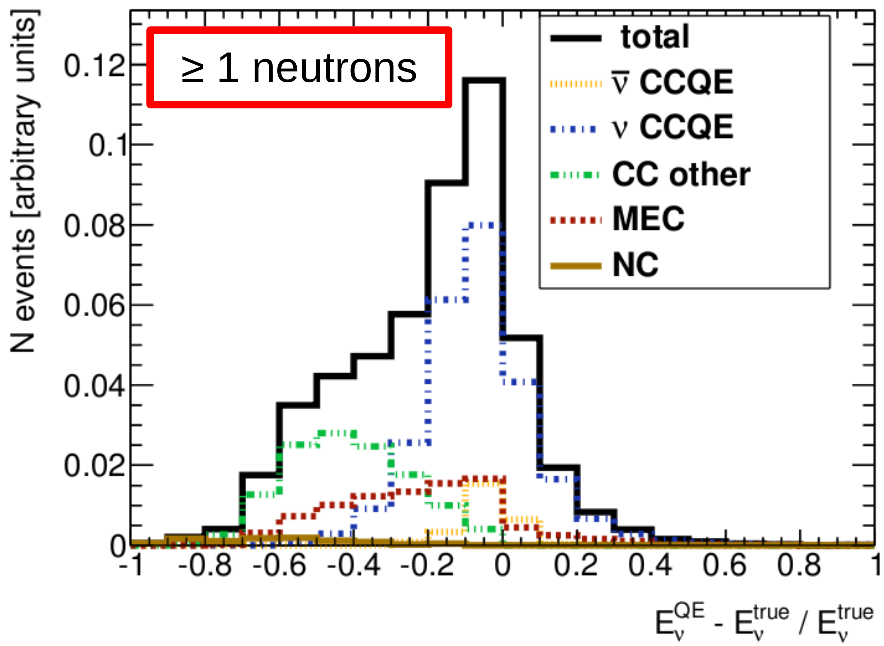
- Neutrons capture on Gd
  - 49,000b capture cross section
  - 8 MeV gamma cascade, 4-5 MeV visible
  - 0.1% doping → 90% neutrons capture on Gd



- Tag presence of neutron in final state – statistically separate neutrino CCQE interactions from others
  - ν_μ CCQE: $\nu_\mu + n \rightarrow \mu^- + p$ 0 neutrons
  - $\bar{\nu}_\mu$ CCQE: $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ 1 neutron
  - CCnQE backgrounds often produce neutrons

Gadolinium doping





- Neutrino energy resolution assuming CCQE kinematics in TITUS
  - 0 neutrons → higher CCQE purity
  - Improved energy resolution
  - Also improves anti-neutrino selection
- If NEUT model is correct, combination of MRD + Gd gives 96% pure ν_μ and $\bar{\nu}_\mu$ samples at T2HK neutrino flux peak

TITUS oscillation study

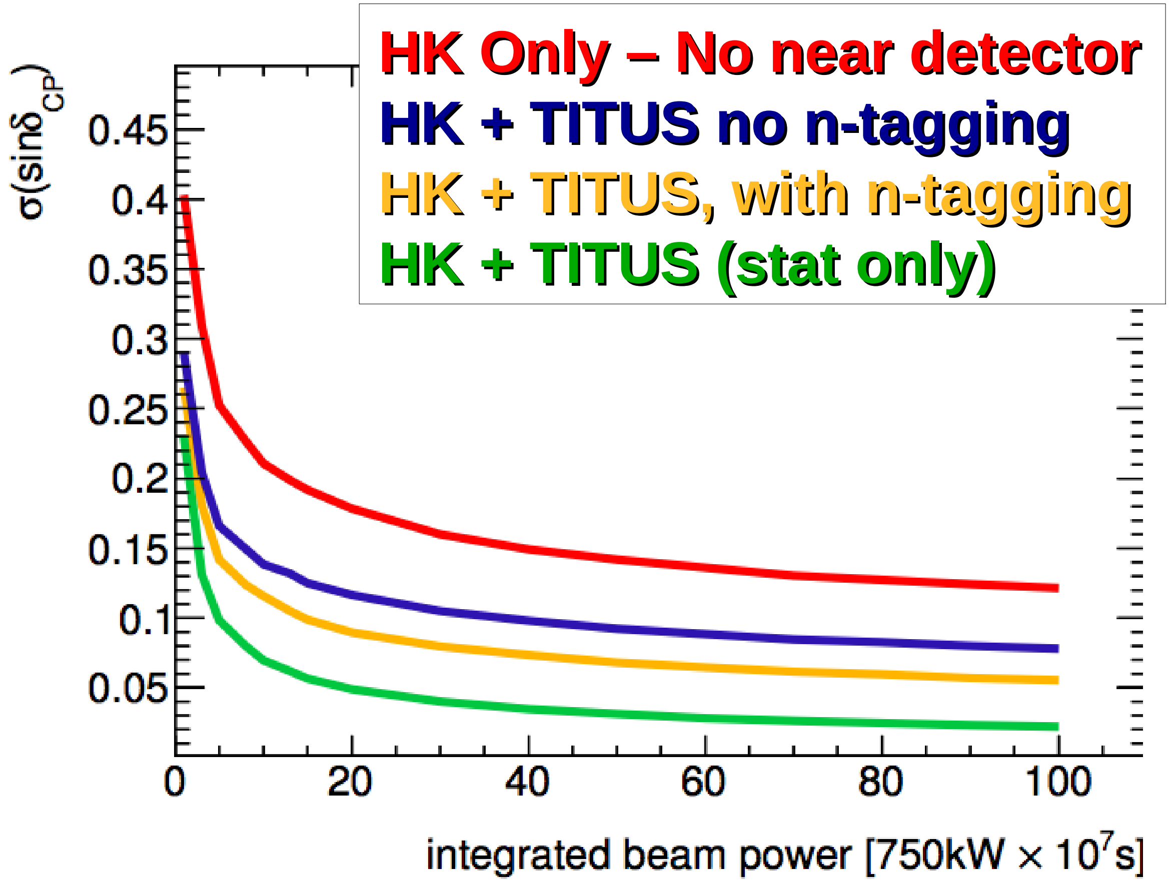
- Markov Chain MC analysis
  - 6% flux uncertainty, 100% correlated between TITUS and HK, 60% correlated between neutrino (FHC) and anti-neutrino (RHC) beams
  - Using T2K interaction model uncertainties
  - 10% neutron tag efficiency uncertainty
  - No near detector constraint
- Fit single ring, muon-like and electron-like samples in FHC and RHC beam
- Equal split of POT between FHC and RHC beams

Parameter	Nominal value and Prior Uncertainty
δ_{CP}	0.0, uniform in δ_{CP}
$\sin^2 2\theta_{13}$	0.095, uniform in $\sin^2 2\theta_{13}$
$\sin^2 2\theta_{23}$	1.0 ± 0.03 ($\approx \sin^2 2\theta_{23} > 0.95$ at 90% CL)
$\sin^2 2\theta_{12}$	0.857 ± 0.034
Δm^2_{32}	$2.32 \pm 0.10 \times 10^{-3}$ eV^2
Δm^2_{12}	$7.5 \pm 0.2 \times 10^{-5}$ eV^2

- Note, this is best case scenario:
  - Effect of Gd on event reconstruction not included – assume current SK selection efficiency at HK
  - Assumes nucleon final states predicted by NEUT are correct

δ_{CP} Precision

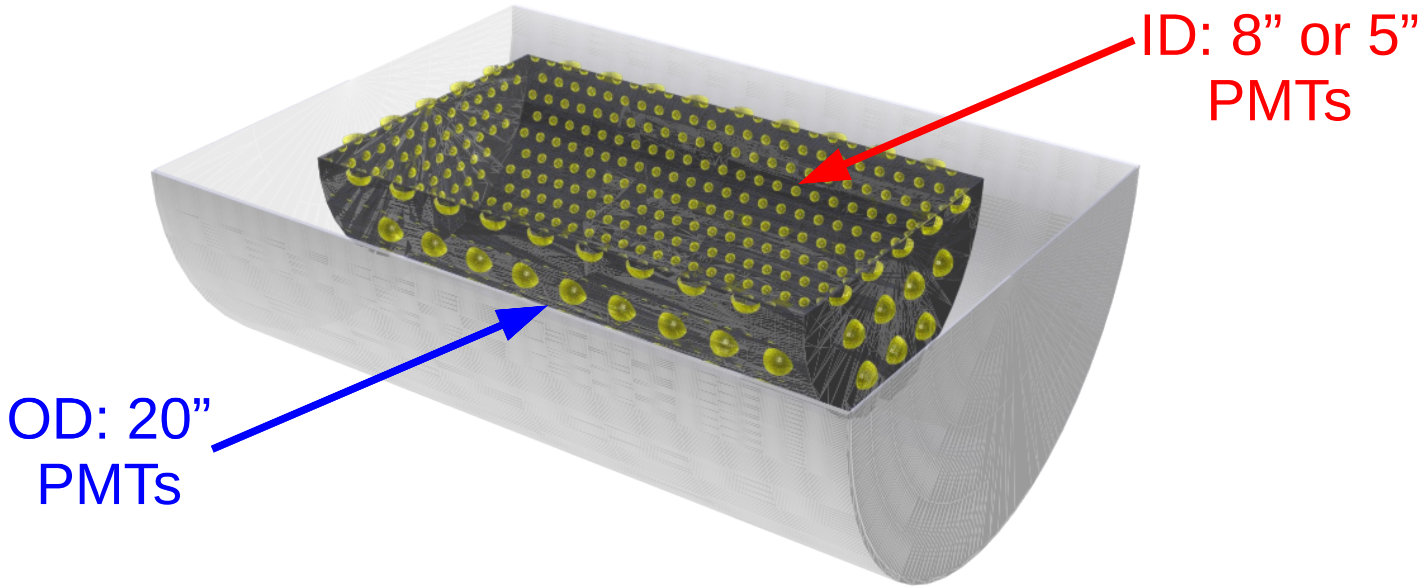
- Measurement precision at $\delta_{CP} = 0$
  - No constraint from ND280
  - NEUT nuclear model
  - SK selection efficiencies
- Binary neutron tag in near and far detectors - 17% improvement in precision

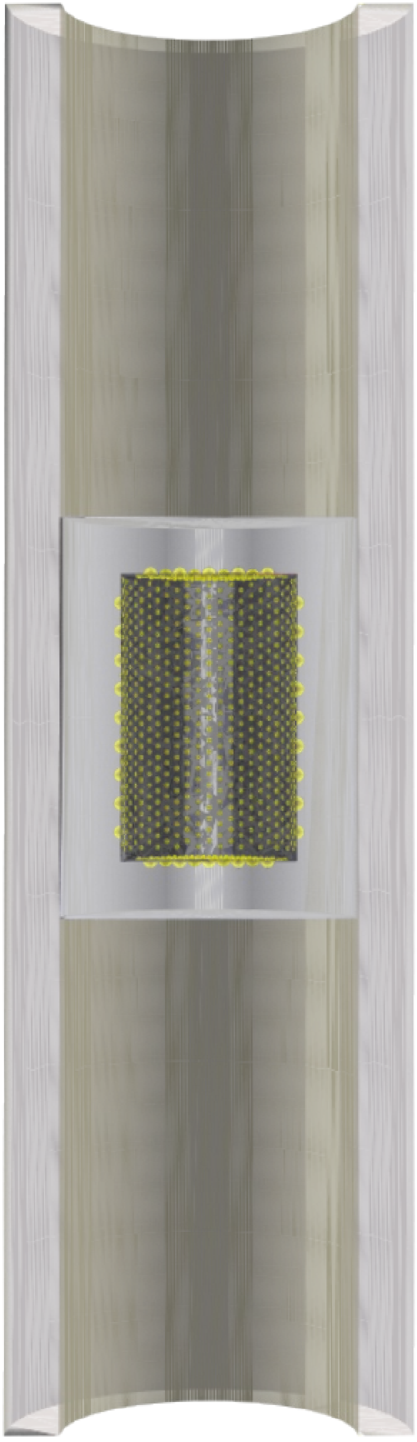


- Need to understand hadronic side of interactions to achieve this:
  - Predictions for hadronic side of interaction
  - Improved FSI models
  - Measurements at dedicated experiments

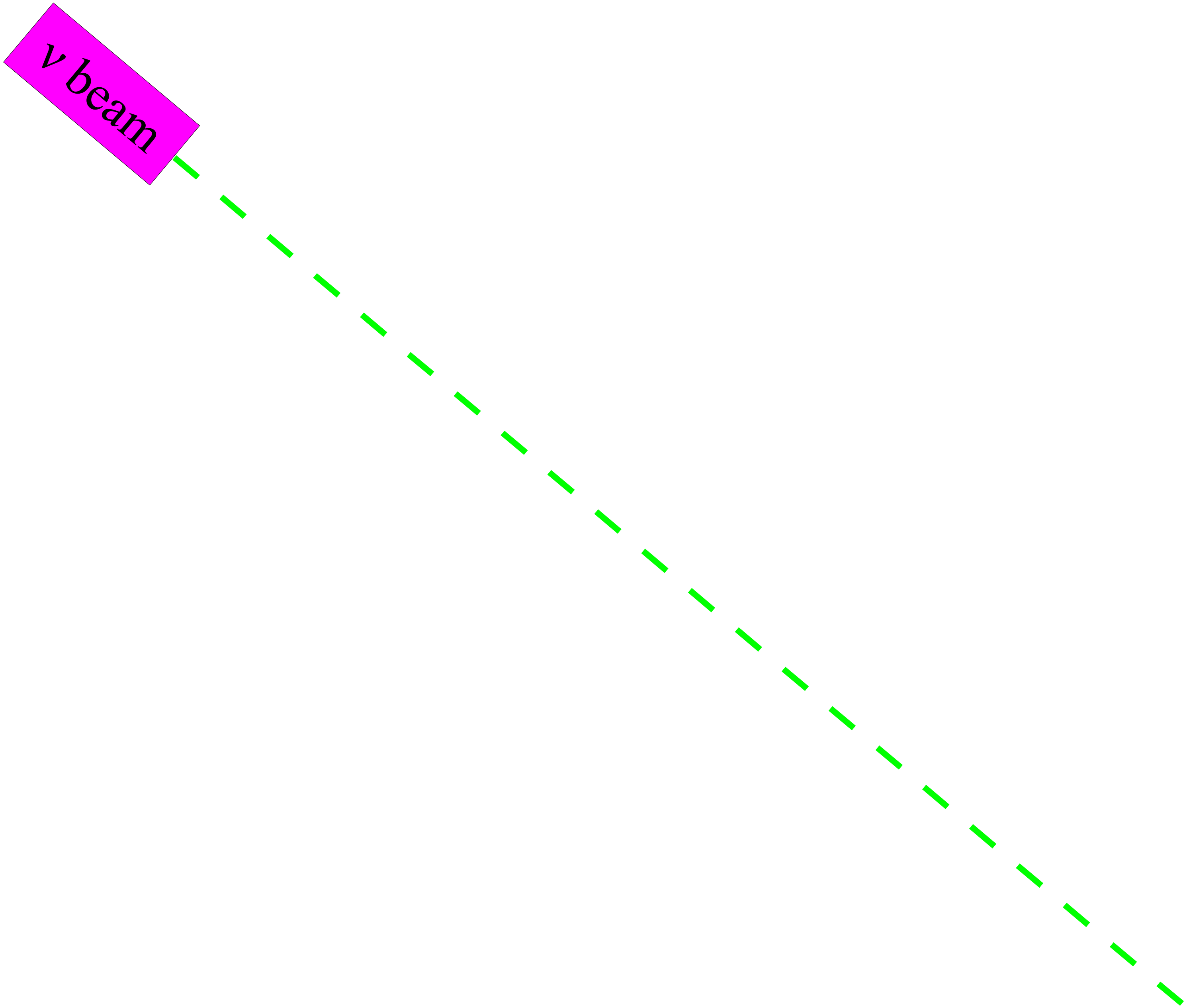
NuPRISM

- WC detector spanning 1° – 4° from the neutrino beam axis
  - 52.5m tall if 1km from neutrino production target
- Instrument movable cylinder:
  - Inner Detector (ID): 6 or 8m diameter, 10m tall
  - Outer Detector (OD): 10m diameter, 14m tall
- OD surrounded by scintillator panels
- All studies assume 2.2e^{21} POT exposure (0.5 * T2K)





NuPRISM concept



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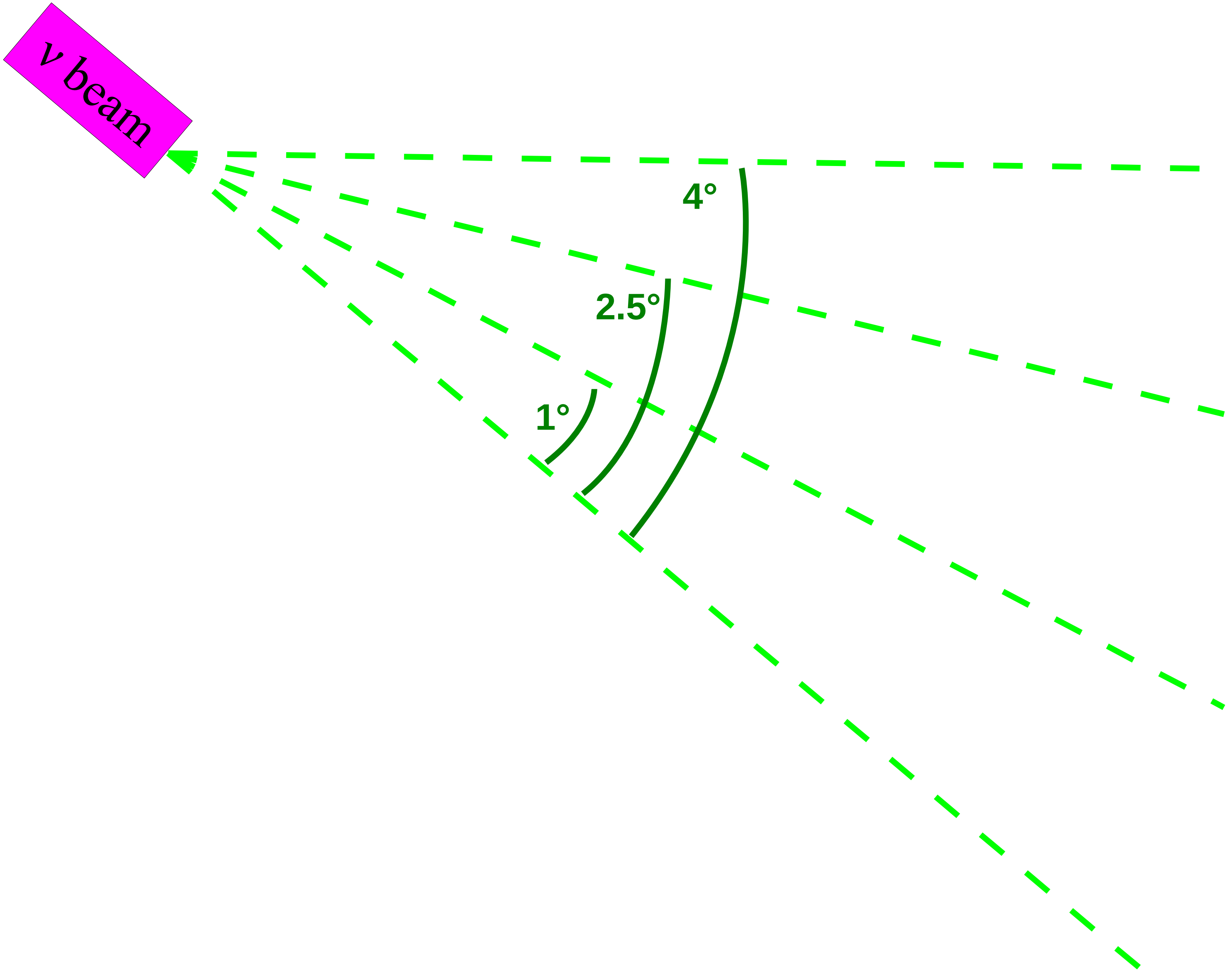
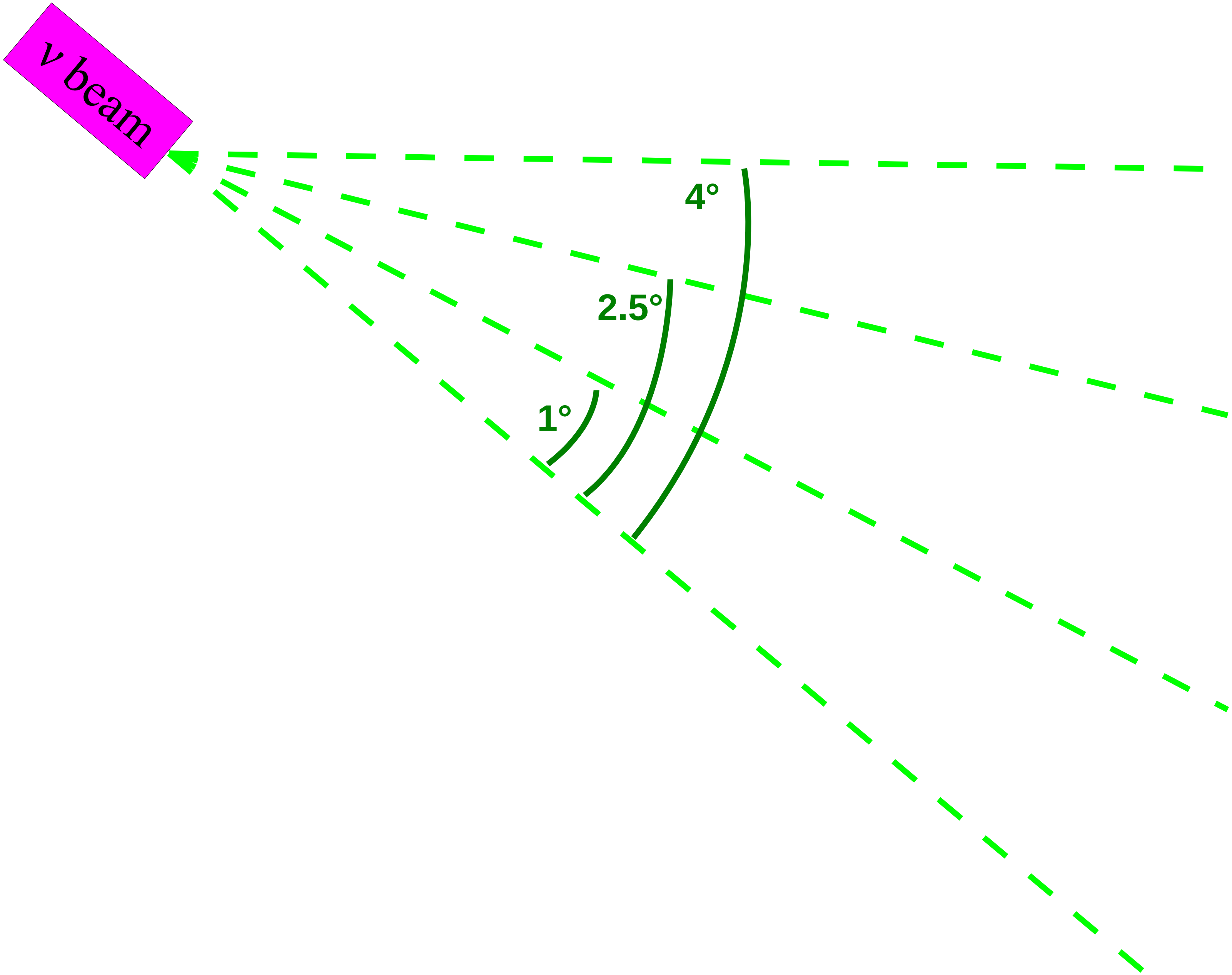
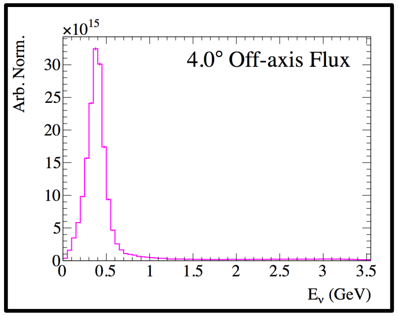
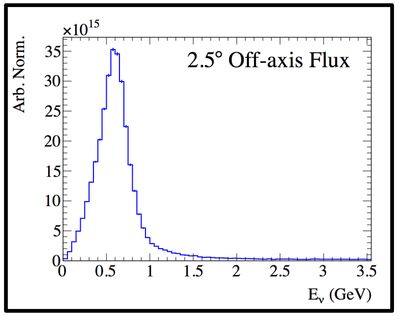
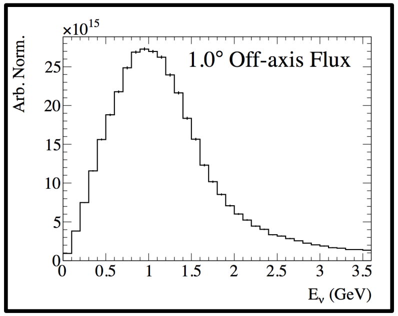


NuPRISM concept









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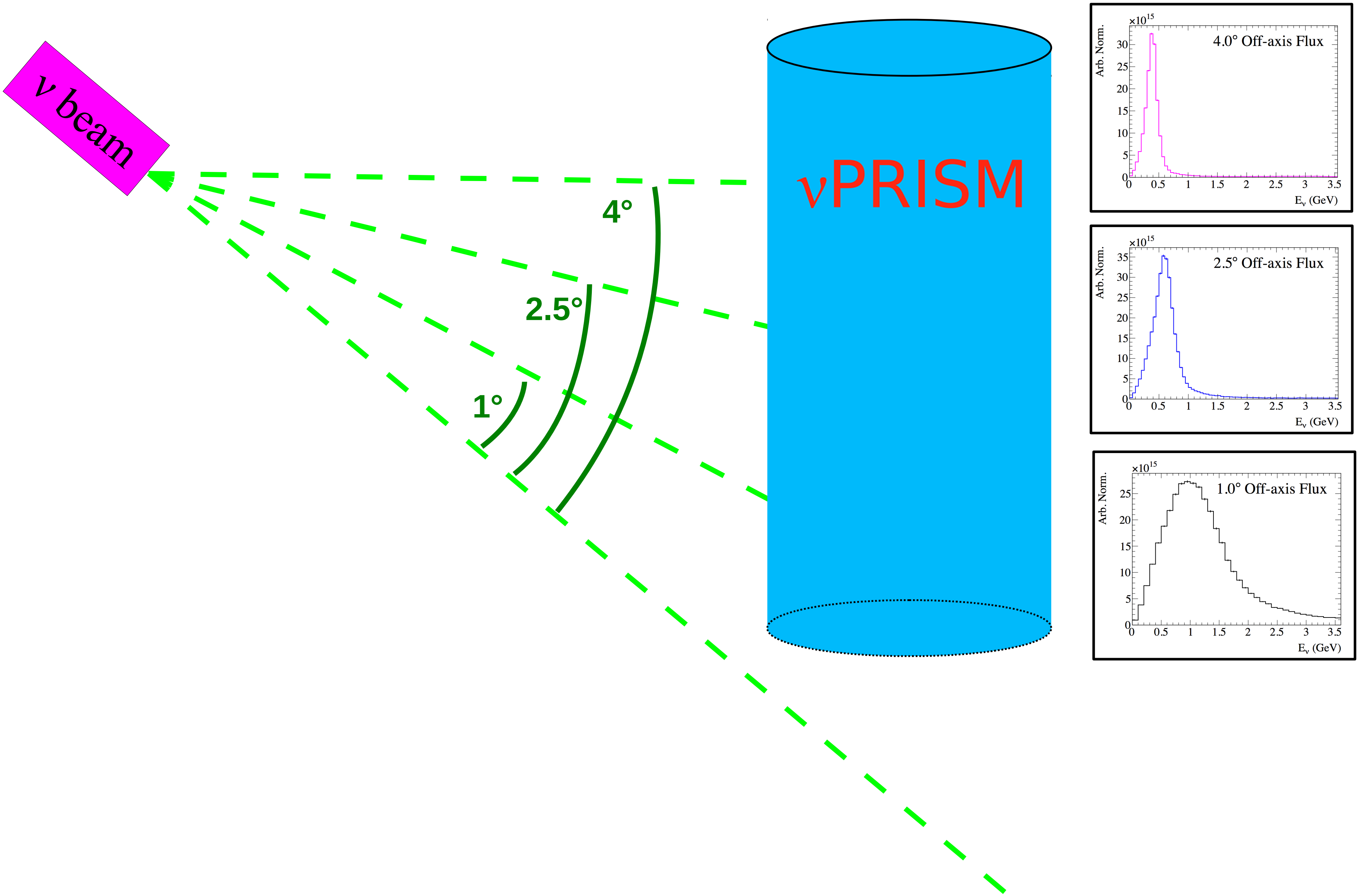

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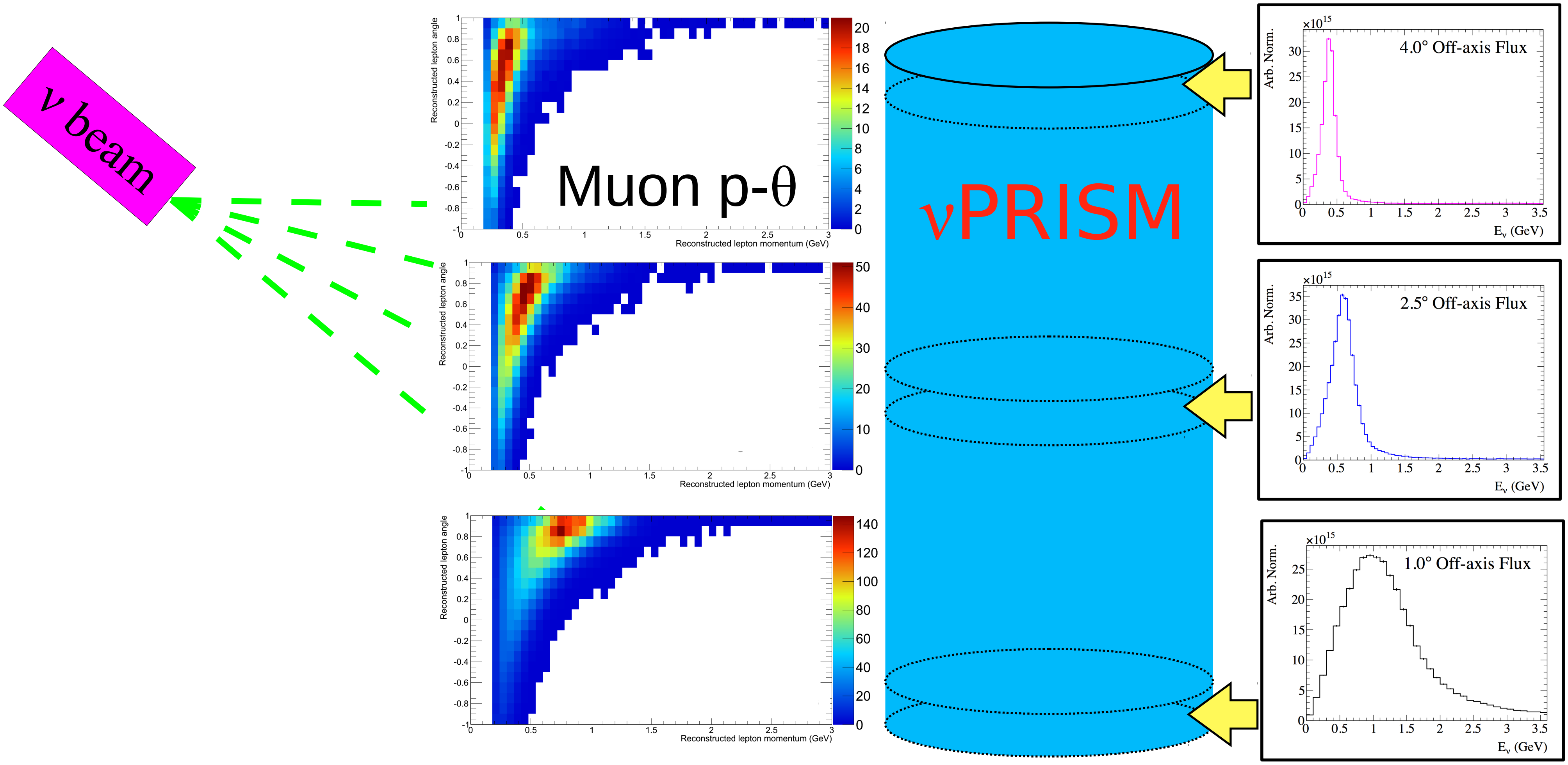

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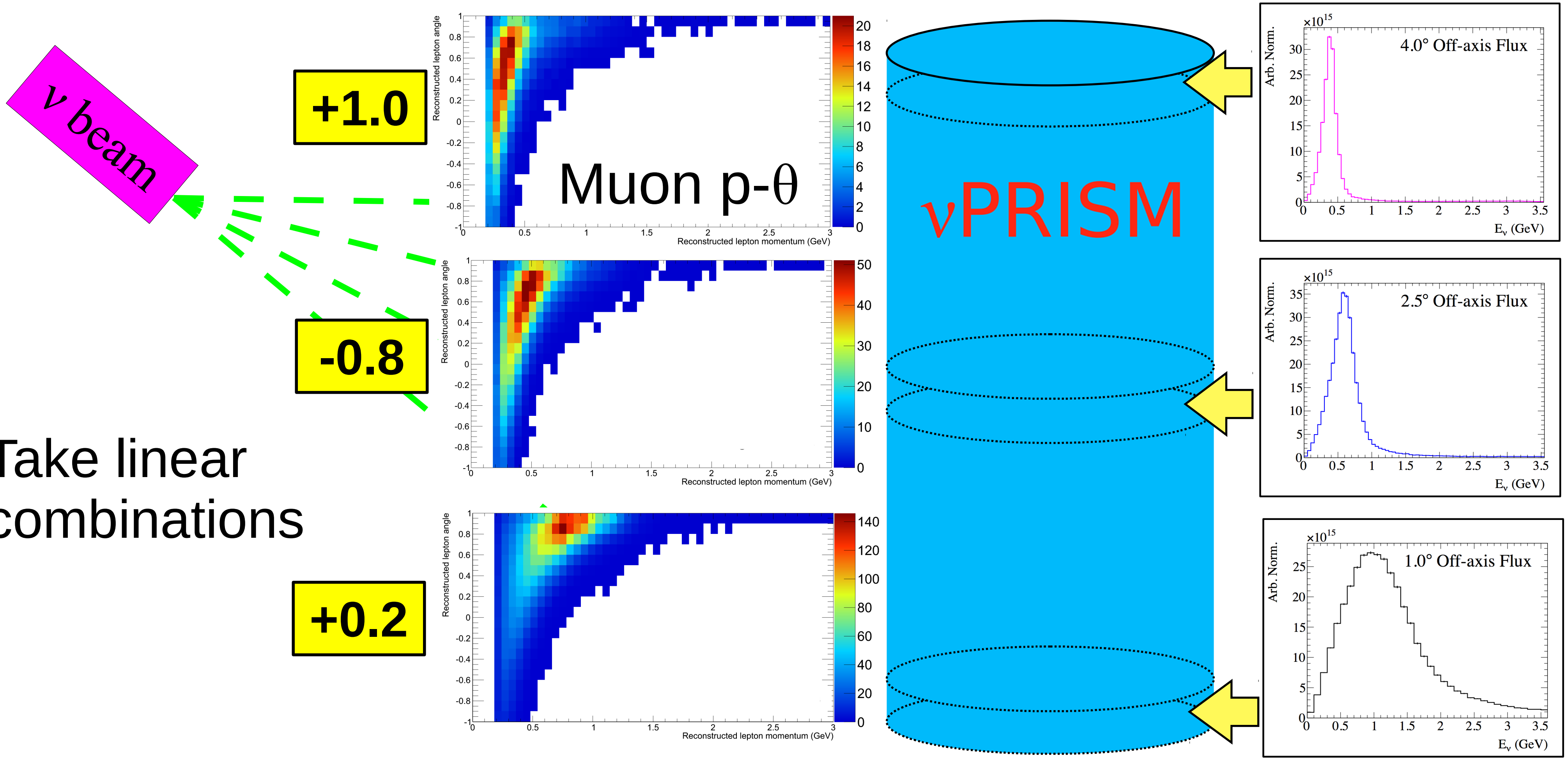
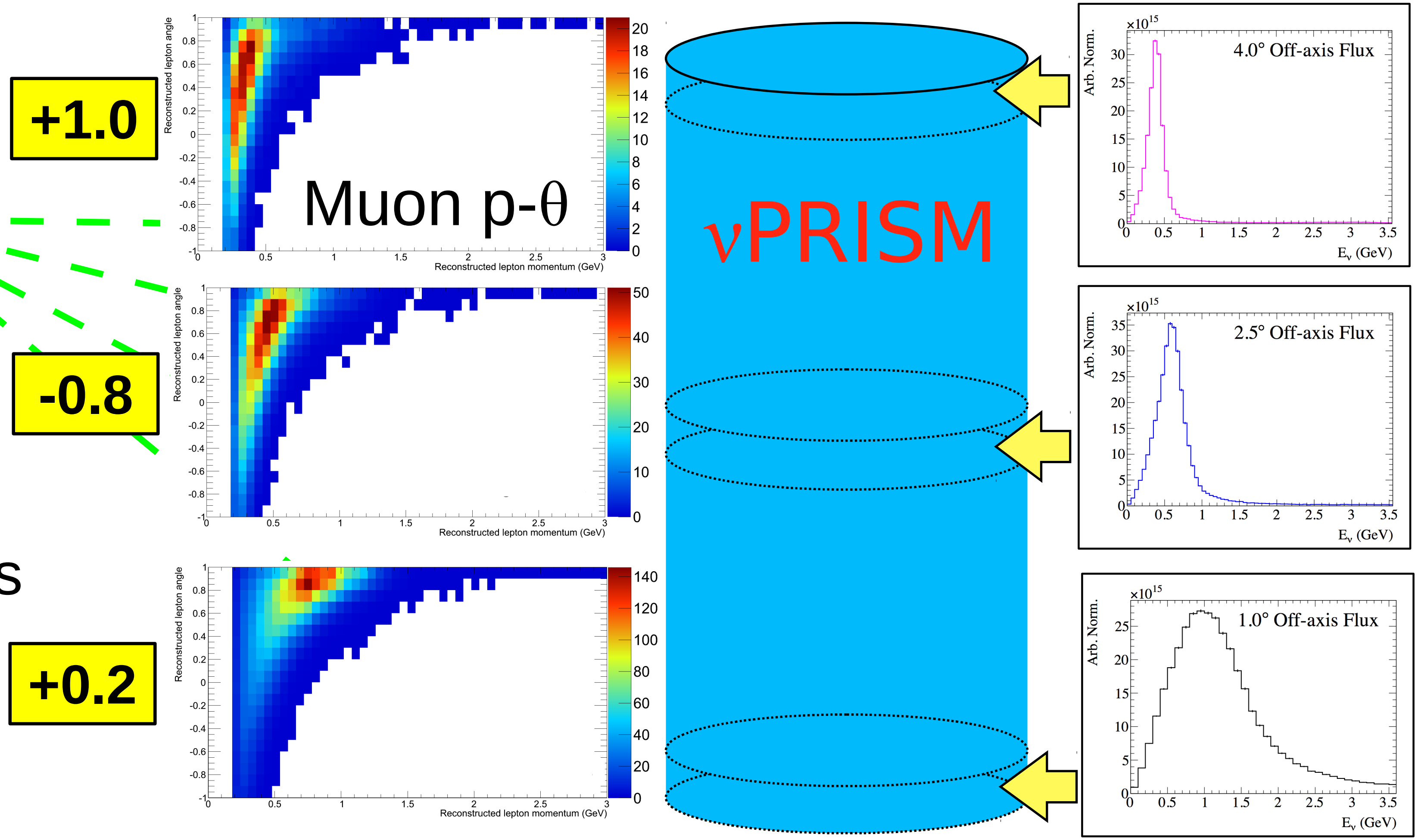


Take linear combinations

NuPRISM concept



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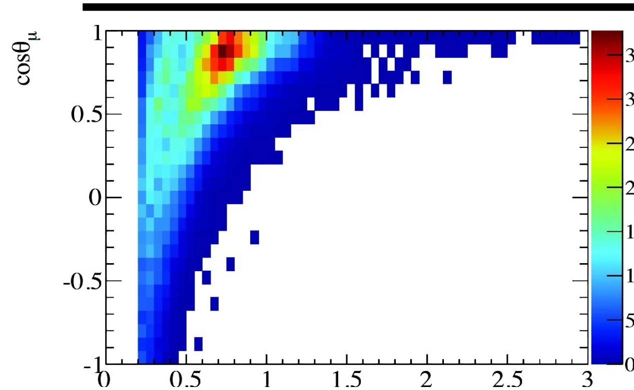
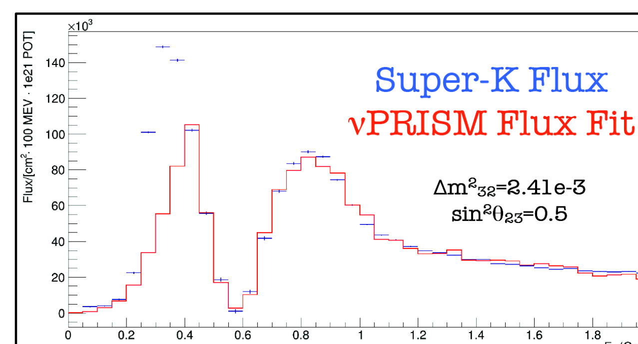
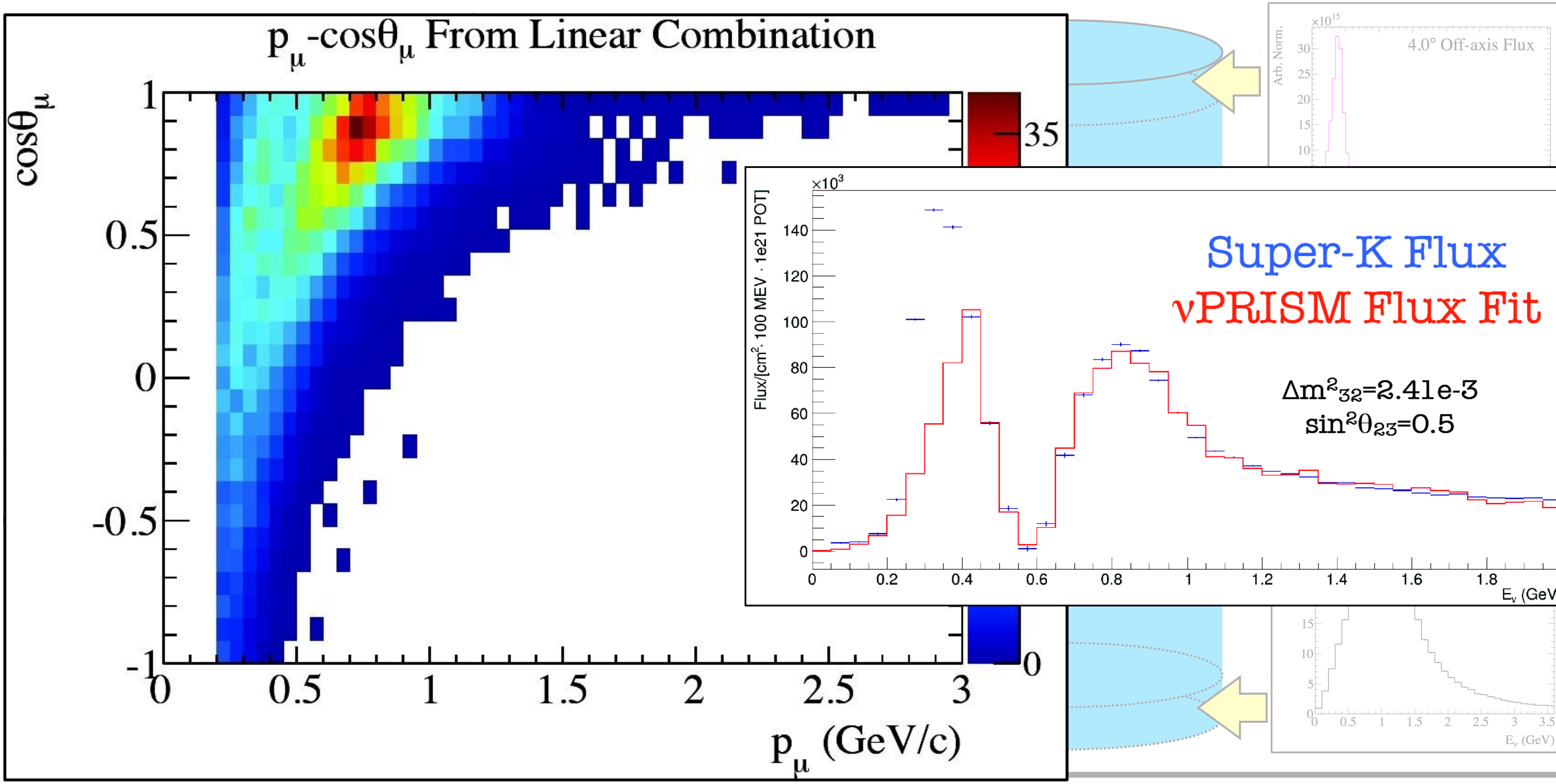
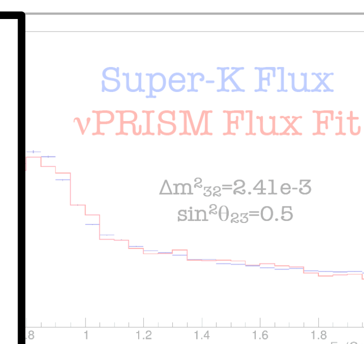




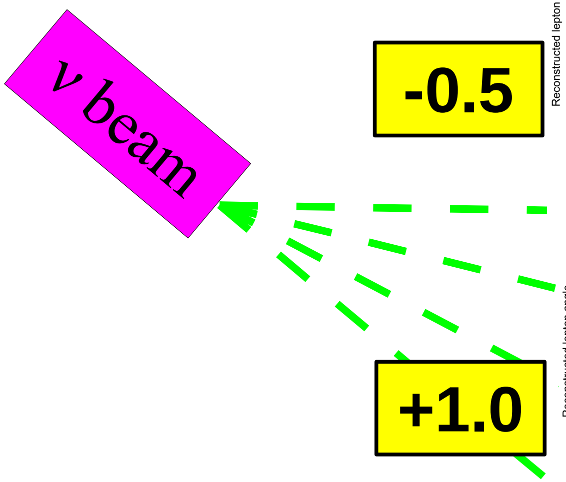
ν Oscillation with NuPRISM

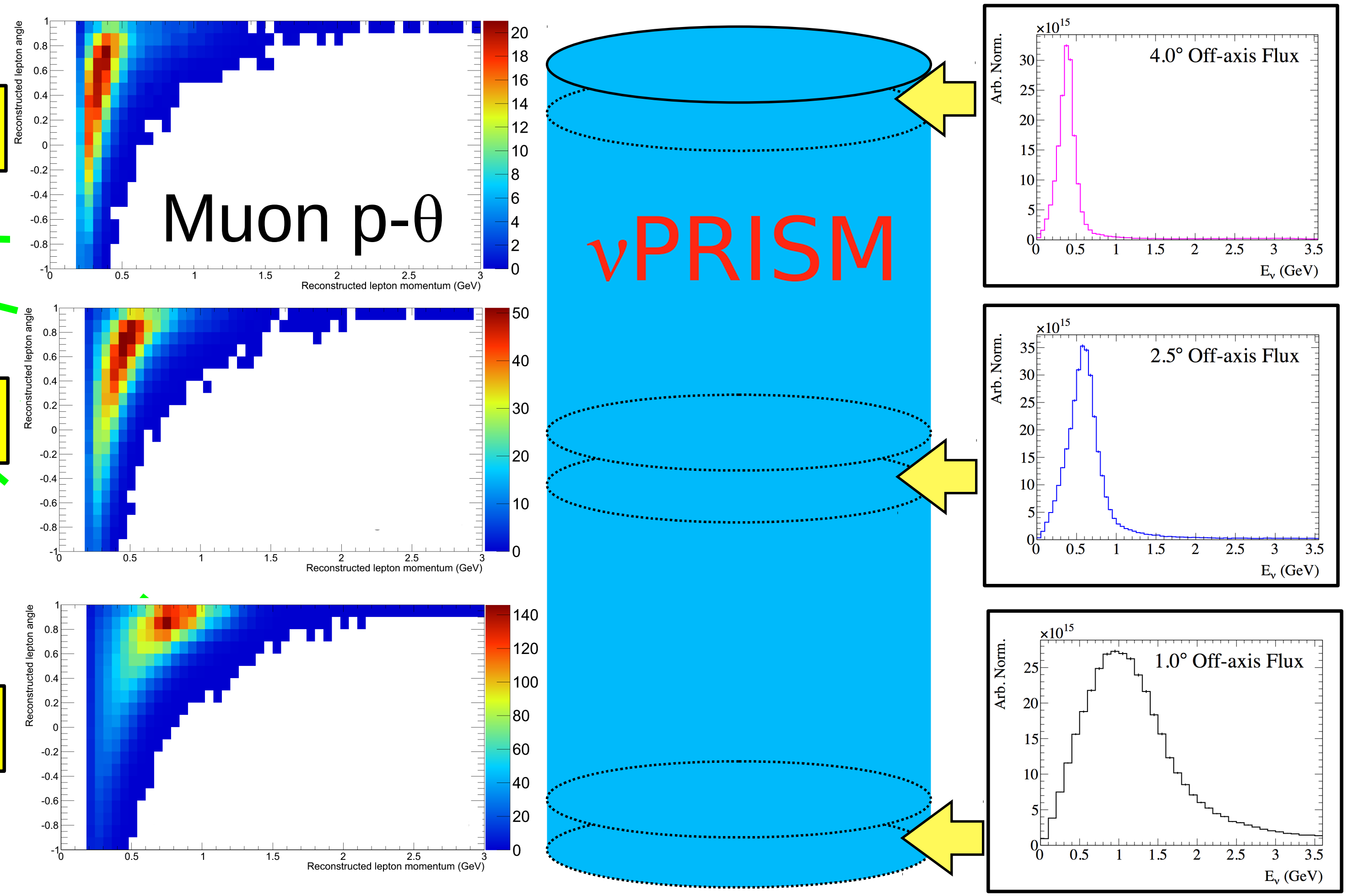




- Recreate oscillated neutrino flux at HK using near detector
- Directly measure muon p-θ for given value of oscillation parameters

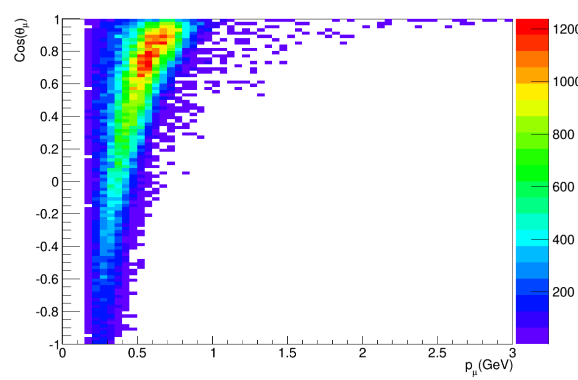
Mono-energetic beams

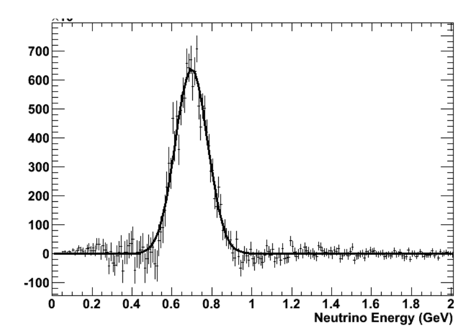




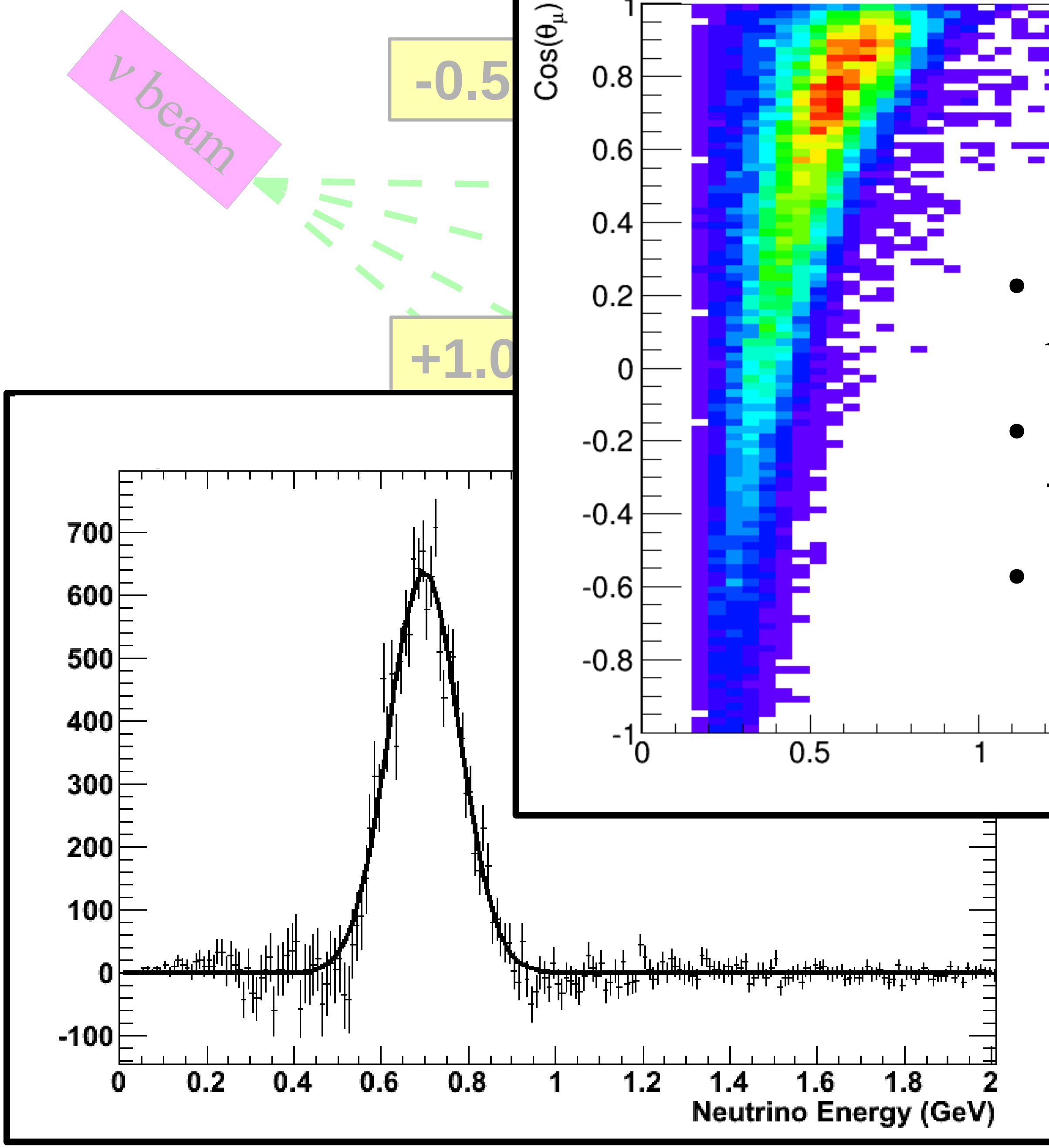
Or take different combinations

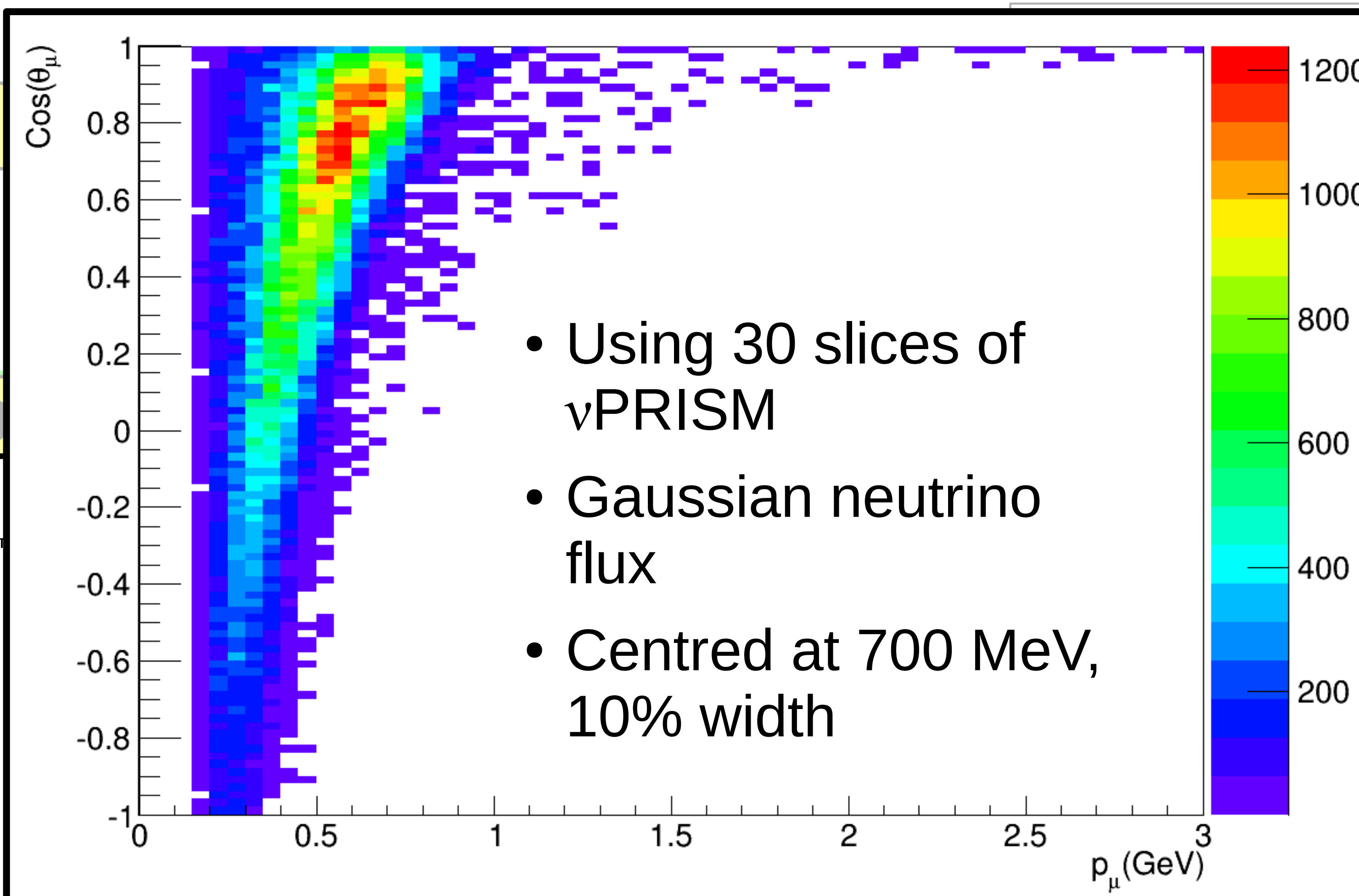
-0.2



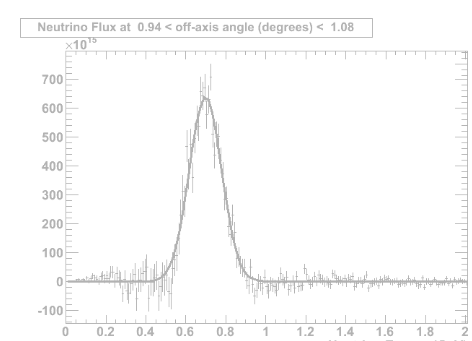


Mono-energetic beams

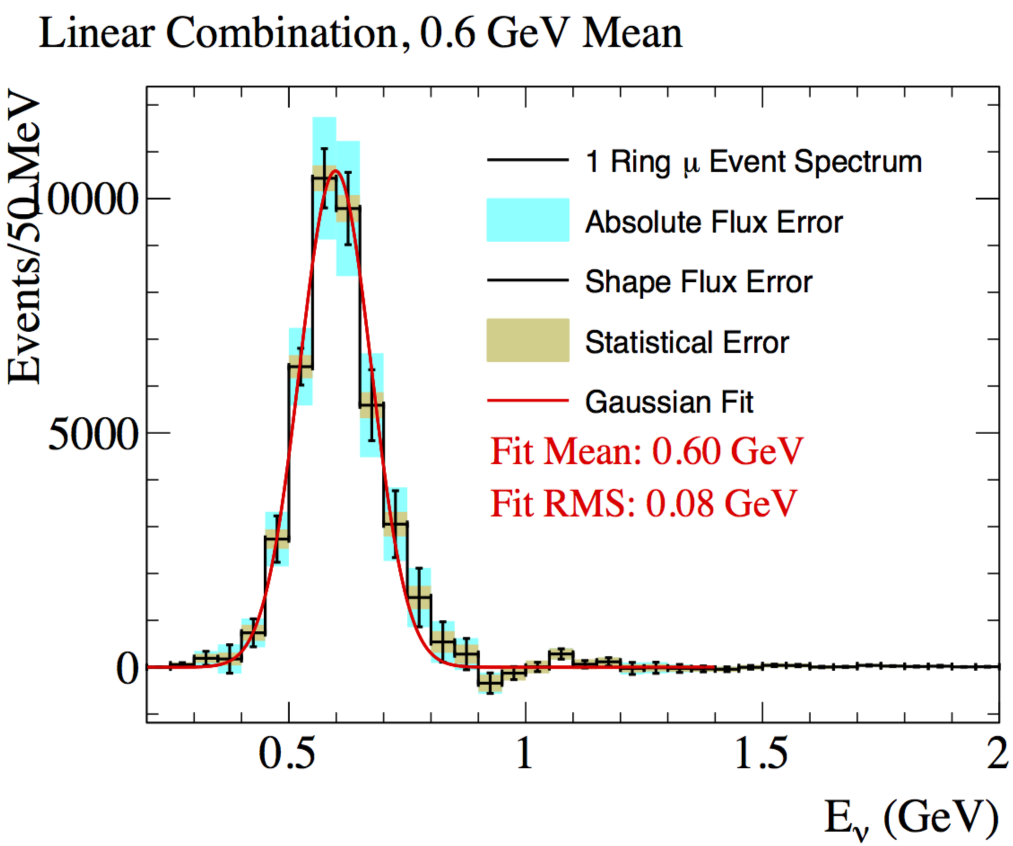


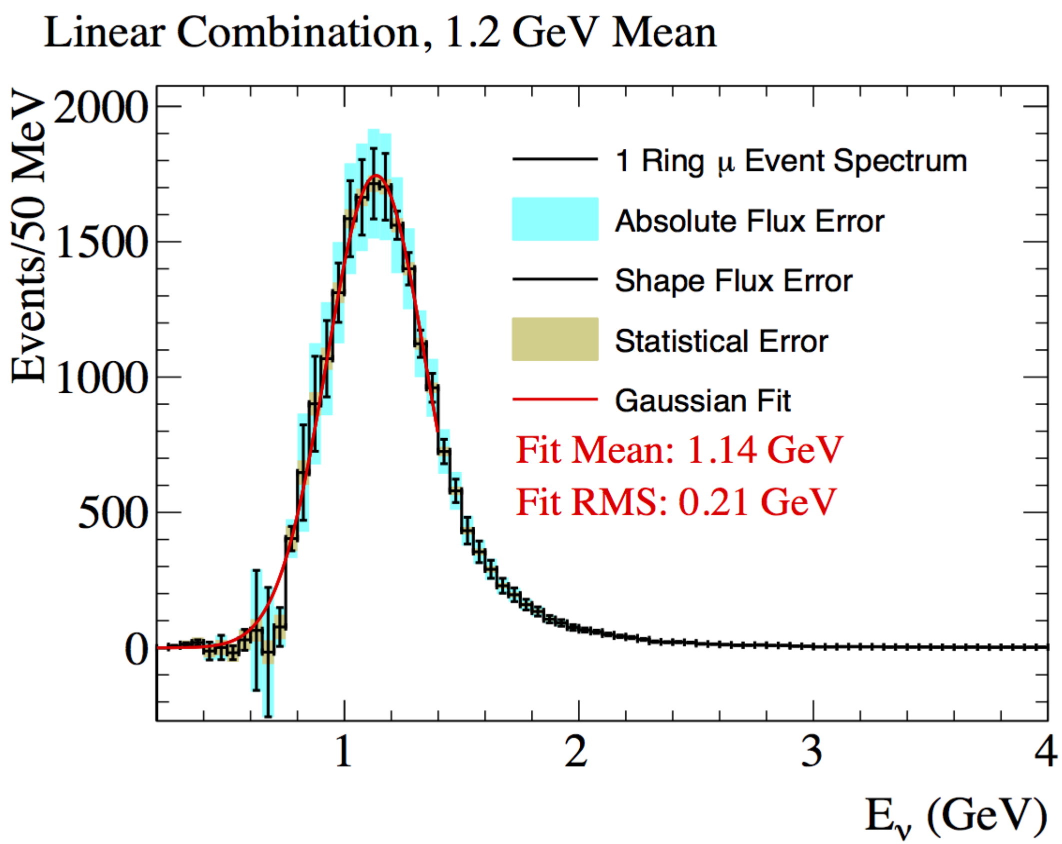


- Using 30 slices of νPRISM
- Gaussian neutrino flux
- Centred at 700 MeV, 10% width



Mono-energetic beams in practice

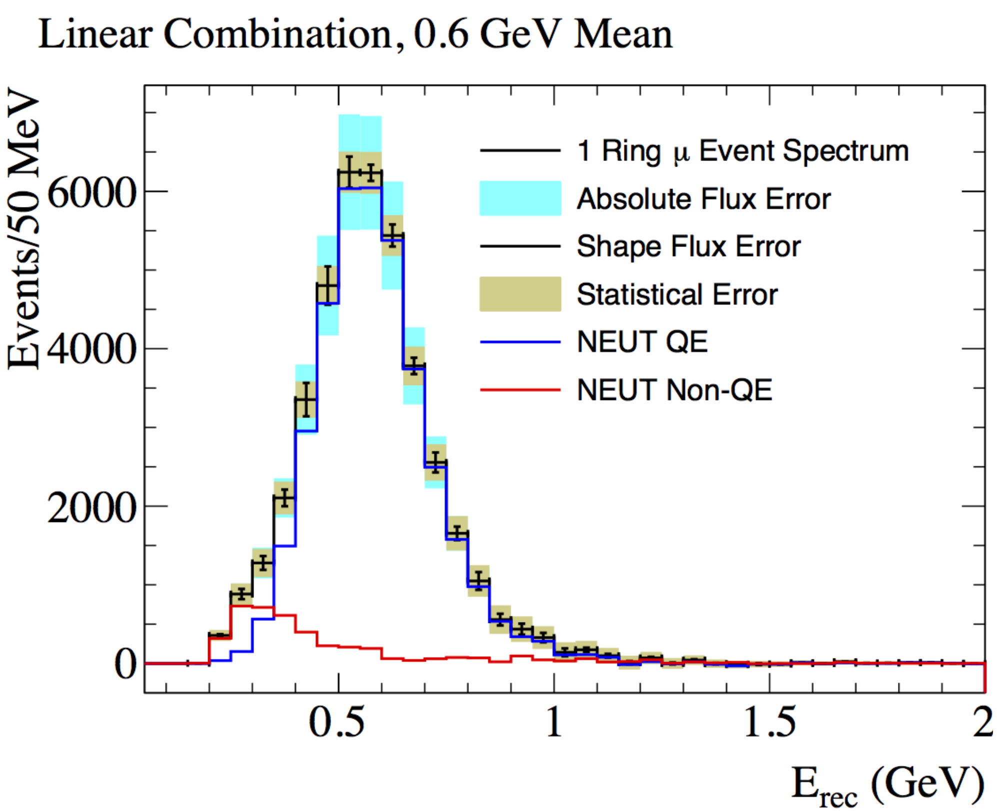


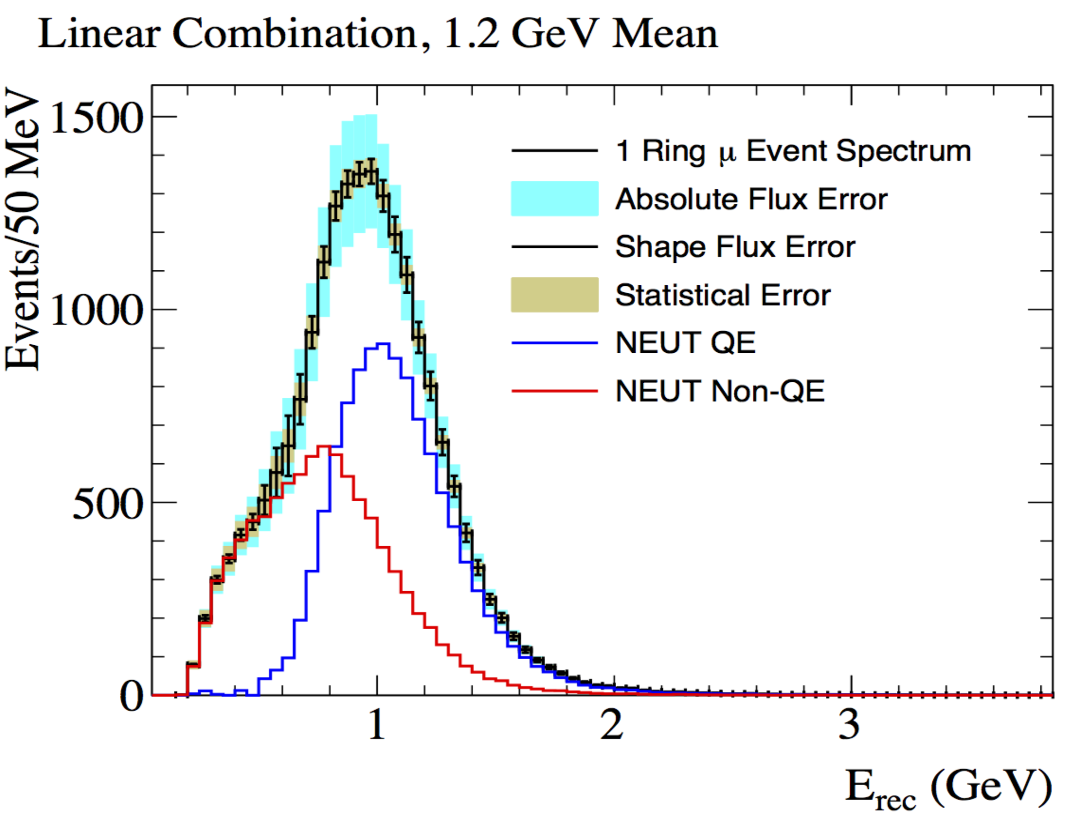


- Gaussian neutrino beams with neutrino energy from 400 MeV → 1200 MeV
  - Determined by off-axis angular span of detector
- Full T2K flux error shown
- High energy tail almost completely cancelled

How can we use them?

- Provides more information on neutrino interactions
- Clear separation between quasi-elastic (QE) and non-QE events
- Measure quatities of interest (neutron multiplicities, cross sections):
  - As function of true neutrino energy
  - In same detector → highly correlated flux and detector systematics





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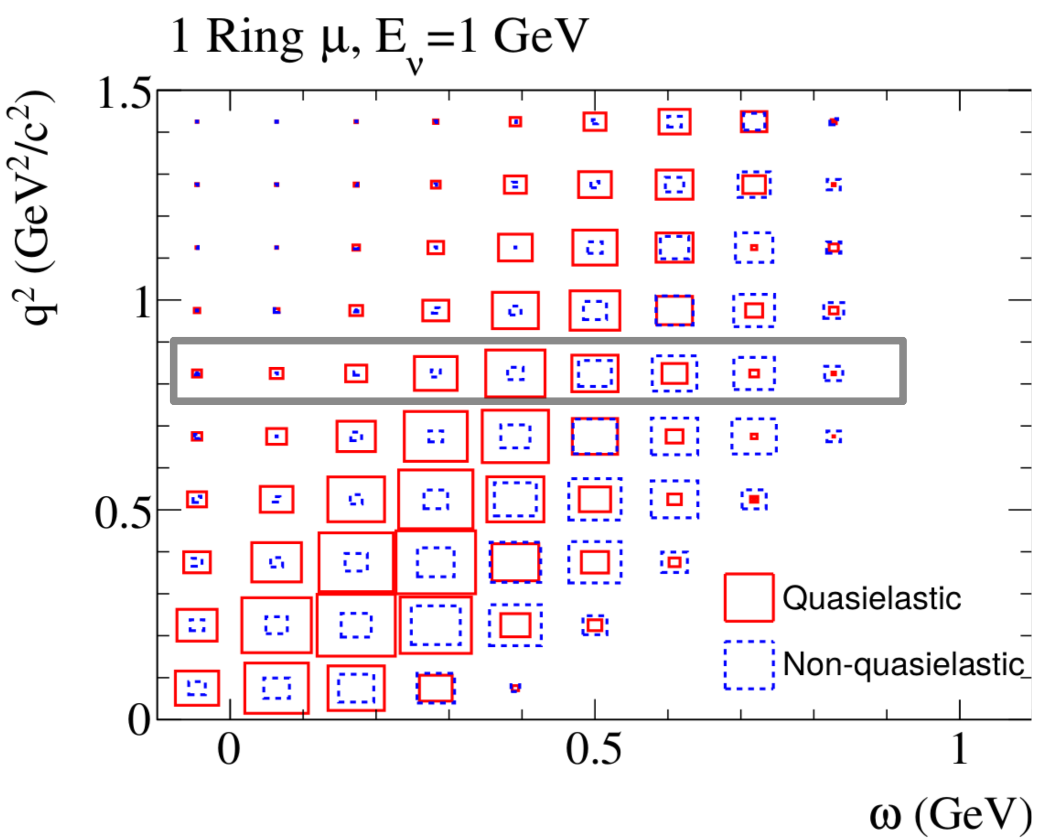
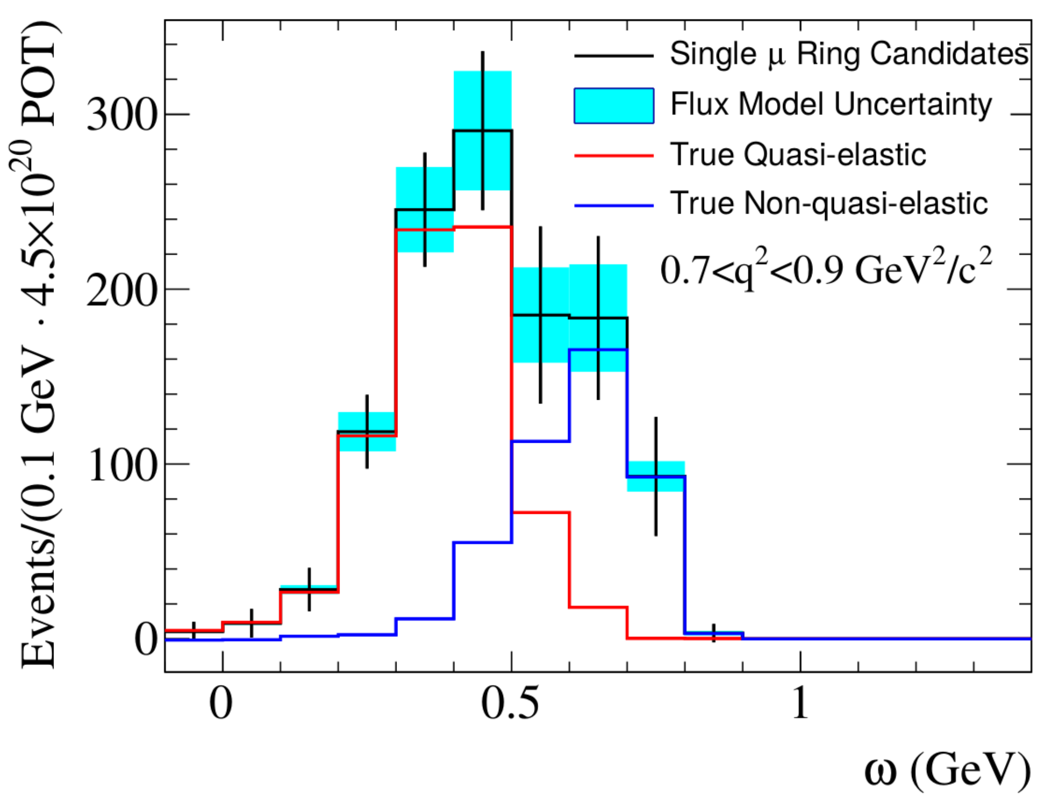
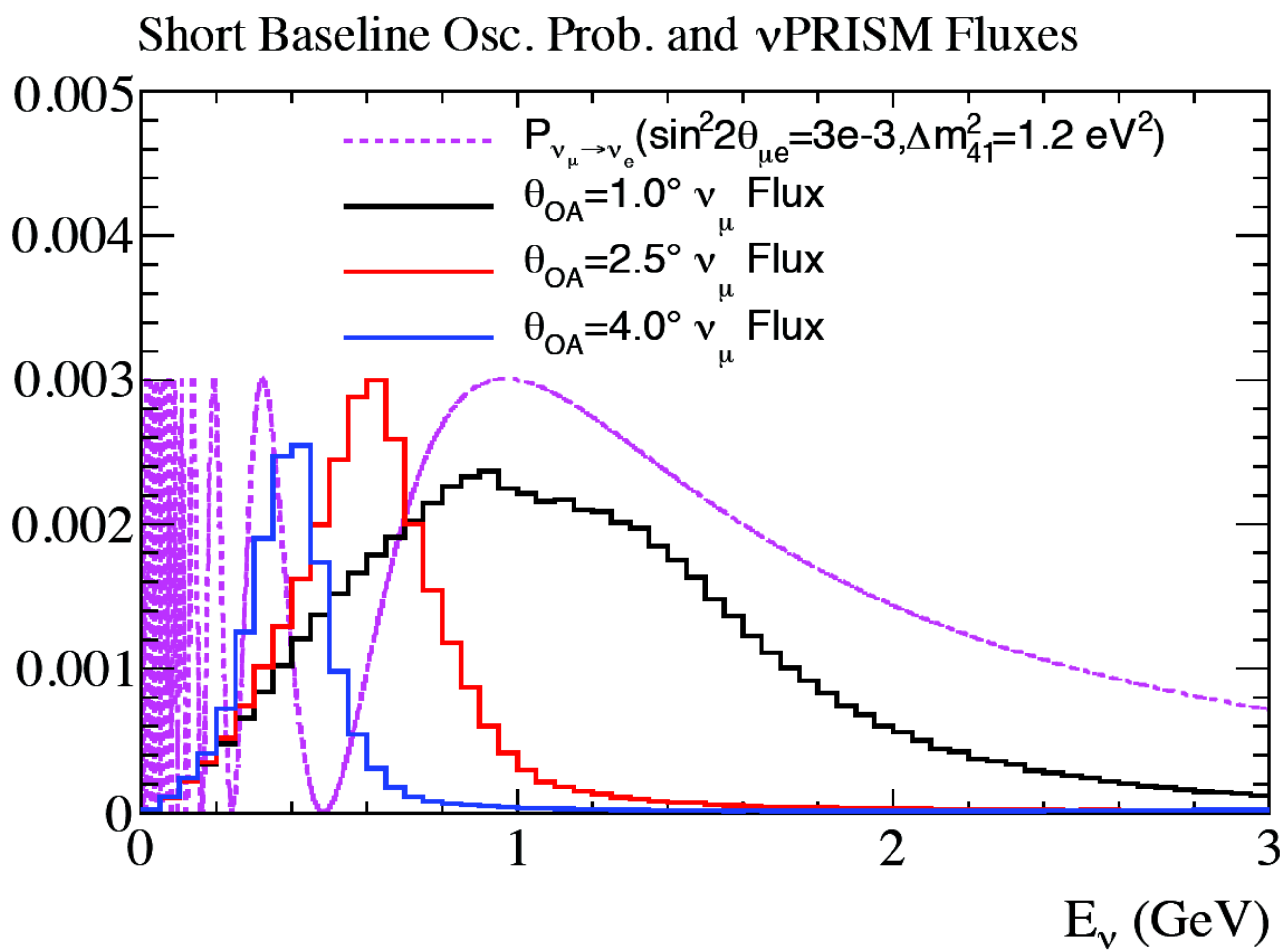
  - In same detector → highly correlated flux and detector systematics
  - Can also calculate Q^2 or ω

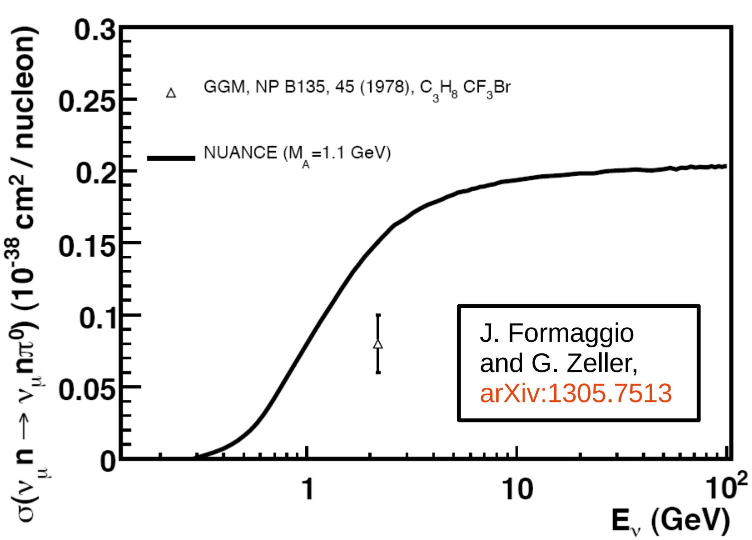




Short baseline oscillations

- NuPRISM (TITUS) – same L/E range as LSND and MiniBooNE sterile results
- Neutrino flux variation across NuPRISM provides unique capabilities
  - Directly probe oscillation curve
  - Constrain backgrounds
    - Energy dependence
    - Direct measurements



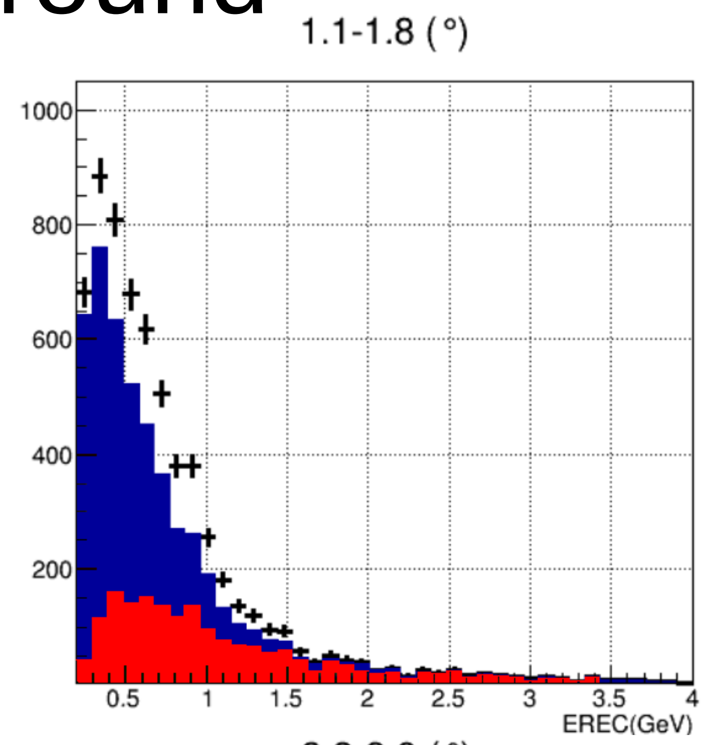


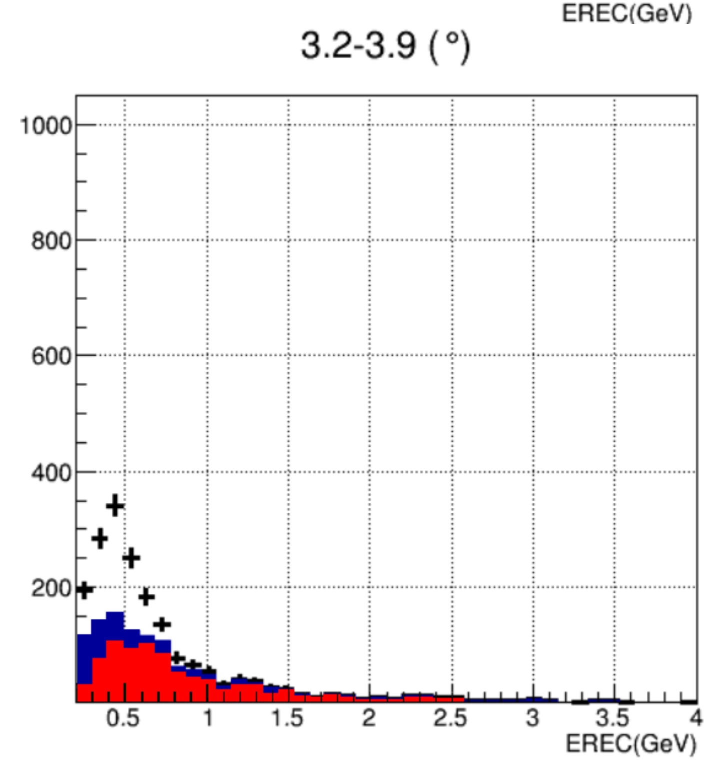
Signal and background

- Search for ν_e appearance using ν_μ events to constrain flux
- Full T2K flux and cross section uncertainties included

Points = Appearance signal
Red = Intrinsic ν_e bkgd
Blue = ν_μ bkgd

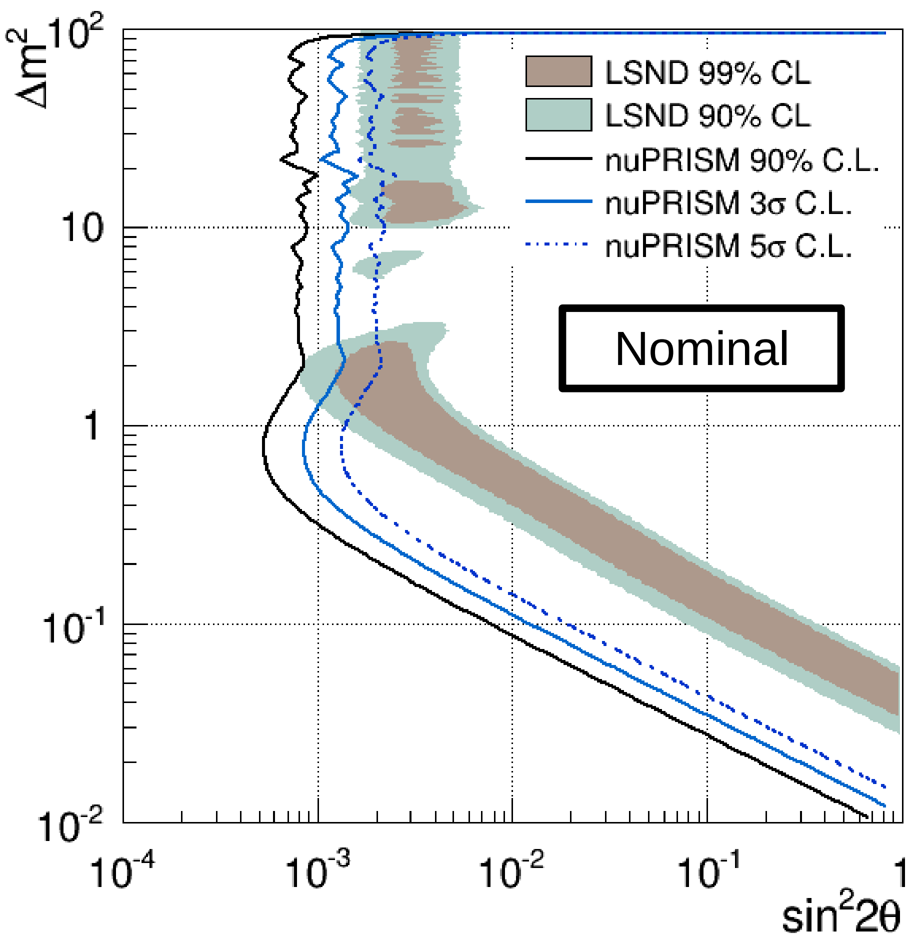
- On-axis (top)
  - High ν_μ contamination
  - Broad signal distribution
- Off-axis (bottom)
  - Very little ν_μ contamination
  - Signal peaked at low reconstructed energy

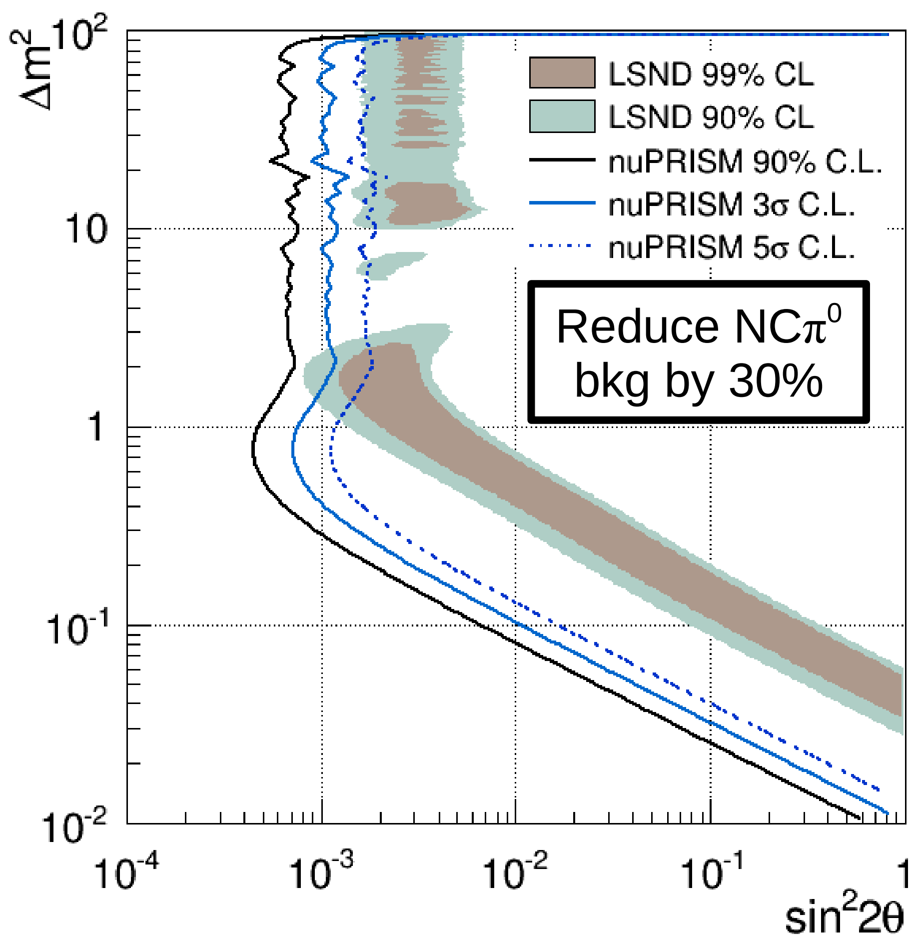




Sterile sensitivity

- Excludes entire LSND allowed region at 90%, most of it at 5σ
- Expect results to improve:
  - Full reconstruction and selection
  - Direct constraint of backgrounds
  - Include T2K near detector





Summary

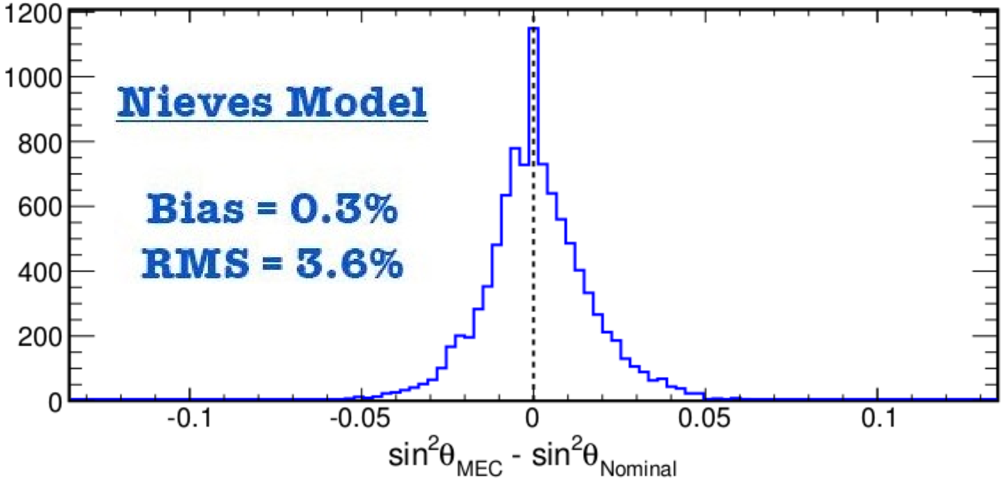
- Experiments becoming systematics limited
- T2K experience has shown intermediate detector must have:
  - Same nuclear target
  - Same acceptance
  - Same signal + background
    - Kiloton scale WC detector 1-2km from neutrino production target

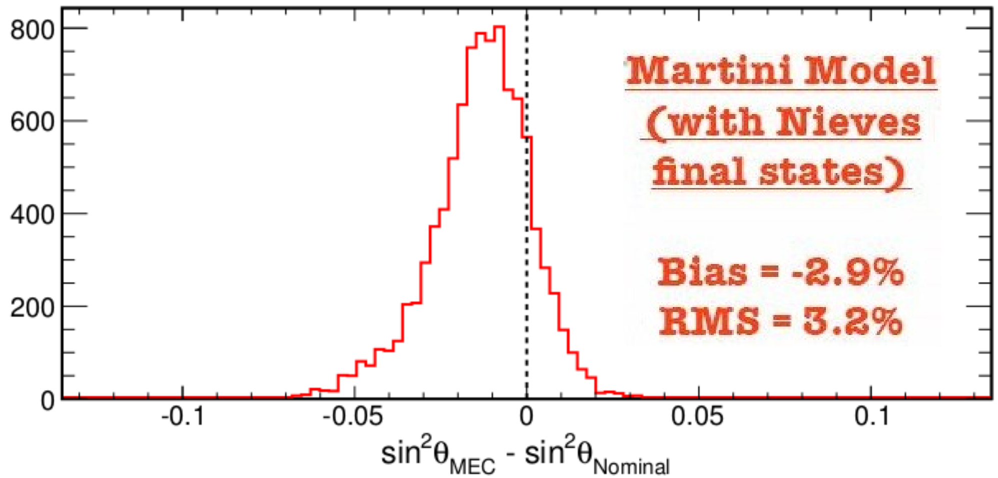
- Two proposals – TITUS and NuPRISM
  - TITUS – 2km from target
    - Novel MRD + Gd increase acceptance and sign-select lepton
  - NuPRISM – 1km from target, large off-axis angle coverage
    - Unique probe of cross-sections and sterile neutrinos
    - Oscillation analyses largely independent of interaction model

Backup slides

T2K multi-nucleon study

- MC-based analysis using full detector simulation, full systematics etc.
- Three fake datasets
  - Nominal NEUT MC
  - NEUT + meson exchange current (MEC) events from Nieves' model - Phys. Rev. C, 83:045501, Apr 2011
  - NEUT + MEC events based on Martini's model - Phys. Rev. C, 81:045502, Apr 2010
- Perform disappearance fit to extract θ_{23} in each case and compare

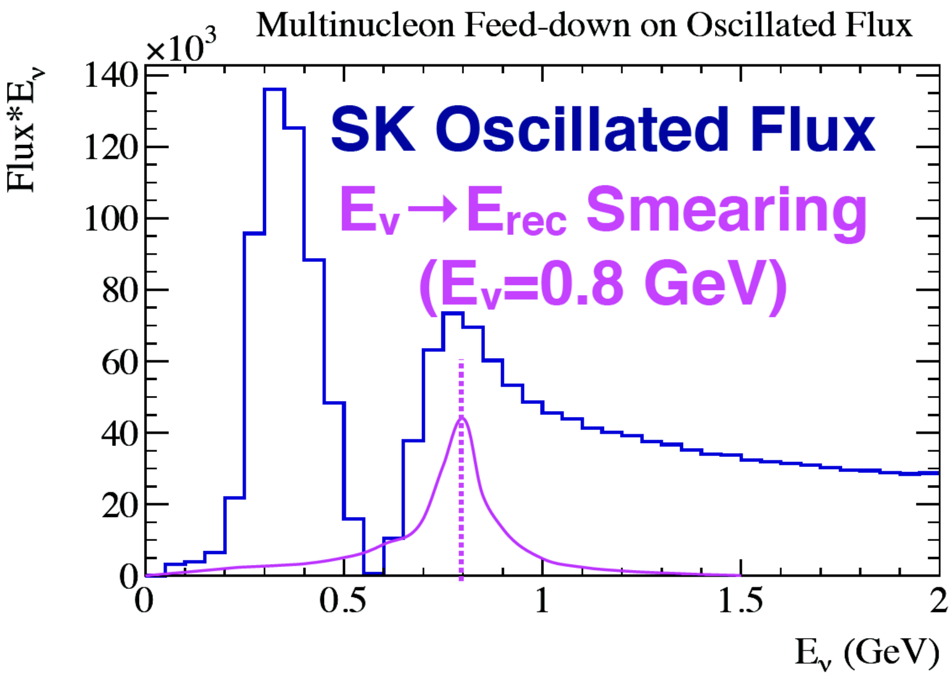


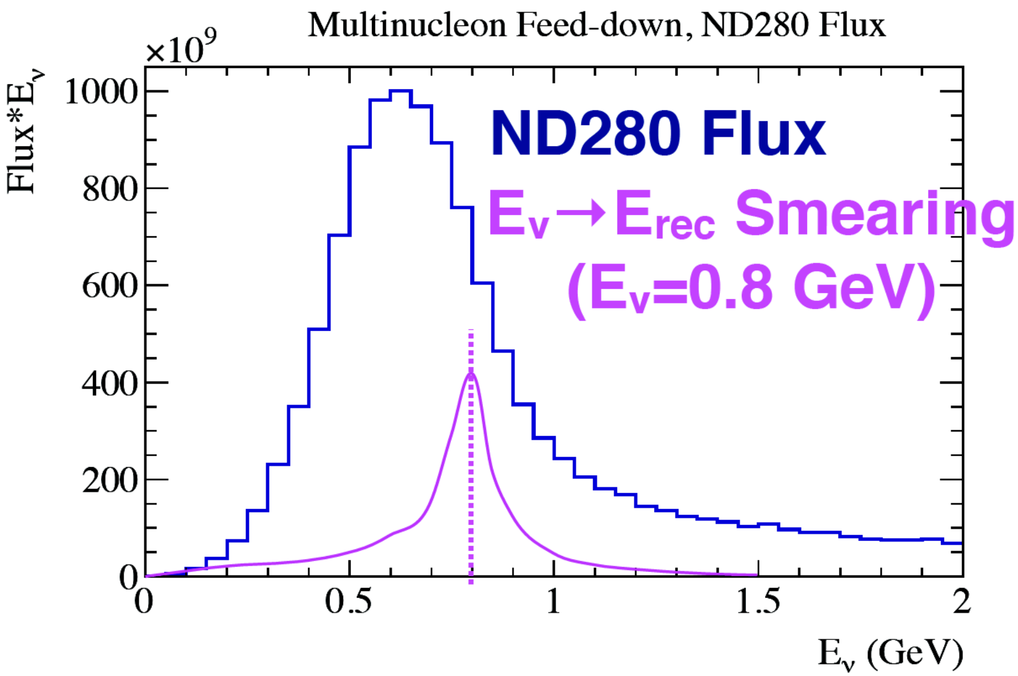


- Both models give ~3.5% RMS in $\sin^2\theta_{23}$, Martini model introduces ~3% bias
- Effects much smaller than current statistical uncertainty, but maybe large for future analyses

What about near detectors?

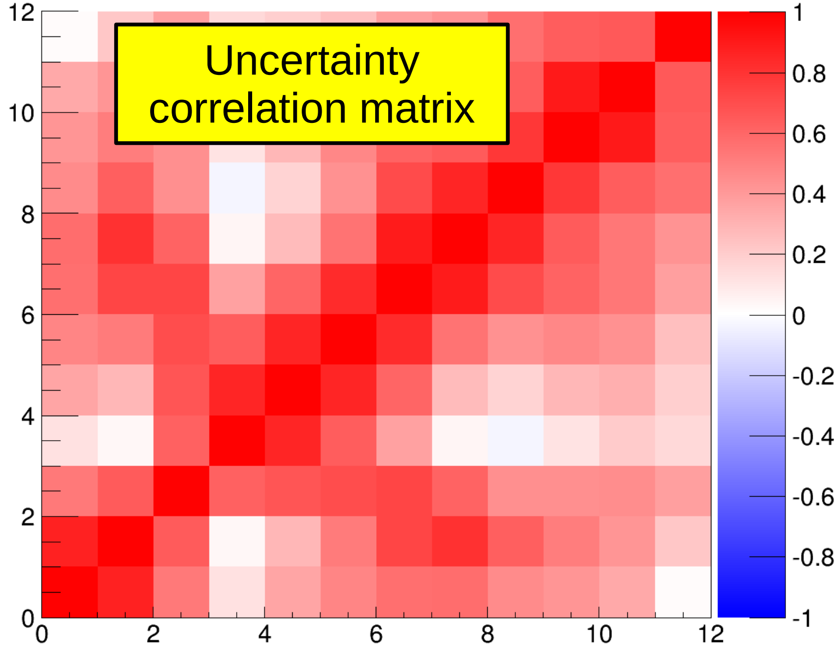
- Can't near detectors precisely measure the expected event rate?
  - Only if they see the same flux as the far detector
- We study neutrino oscillations – near and far detector fluxes are different



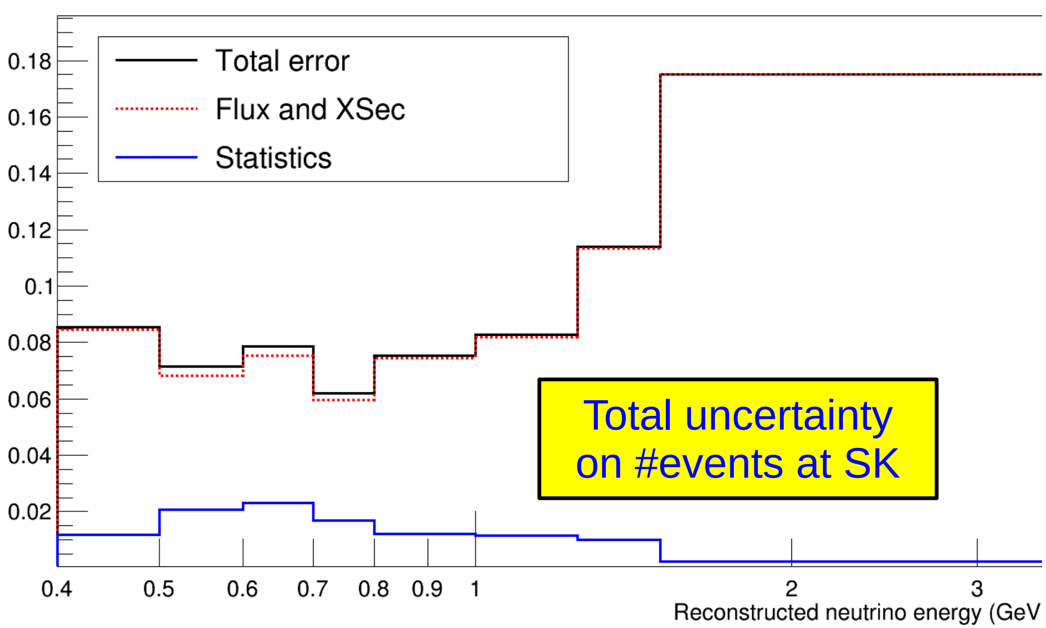


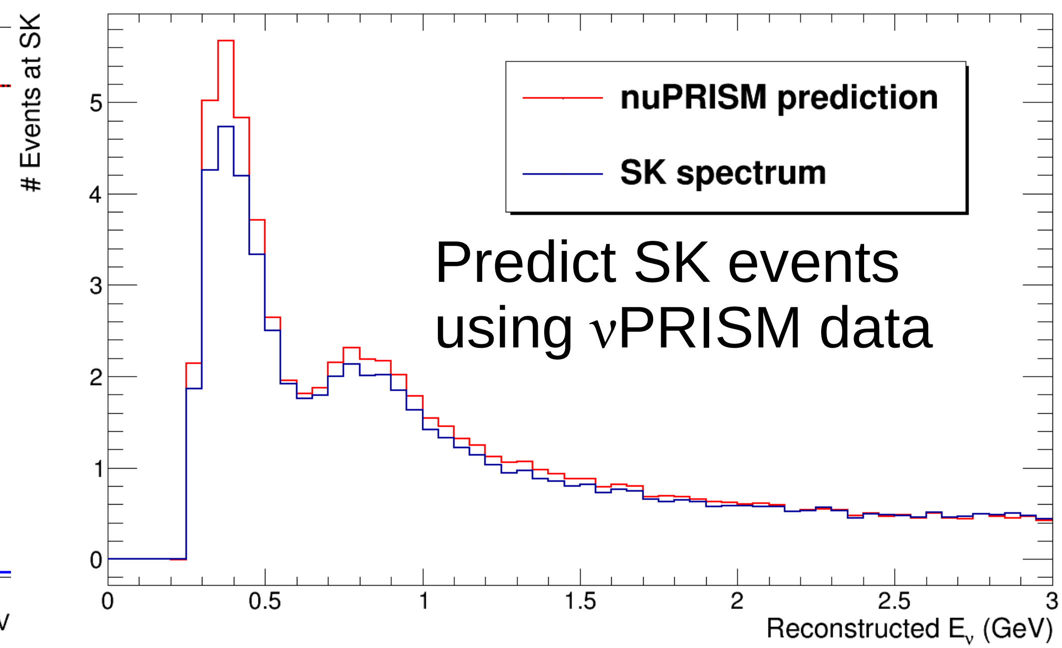
- Nuclear effects cause feed-down of reconstructed events into oscillation dip
- These events are hidden by flux peak at near detector

νPRISM disappearance analysis



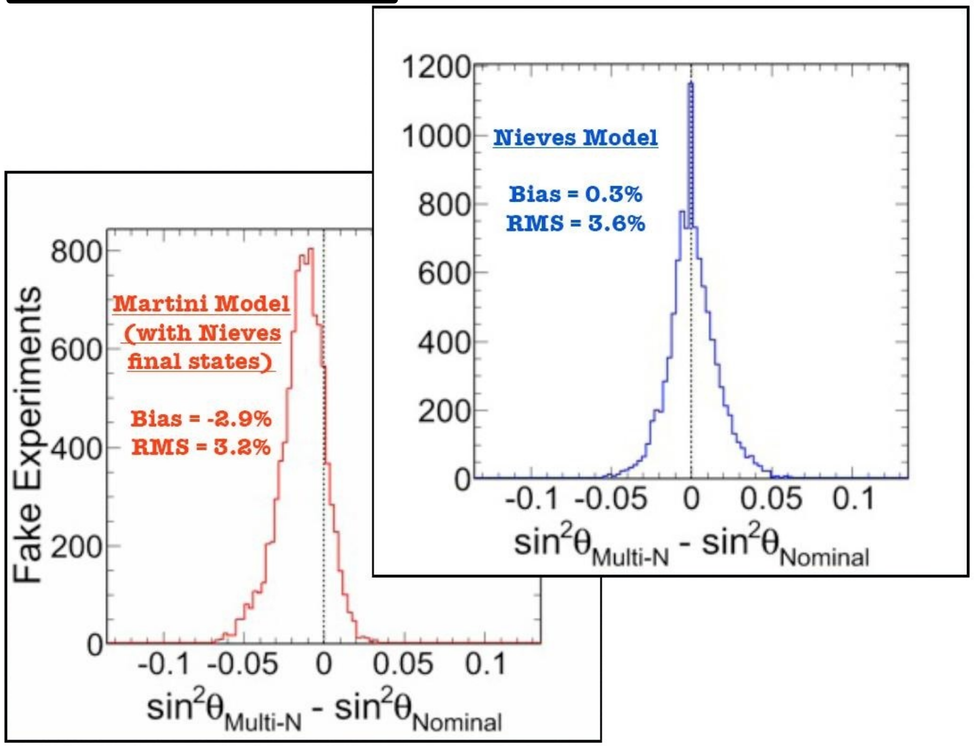
- Full analysis using νPRISM as near detector for T2K
- Take into account:
  - Statistical error from linear combinations
  - Neutrino beam uncertainties – direction, flux etc.
  - Interaction model uncertainties





Effect of multi-nucleon events at νPRISM

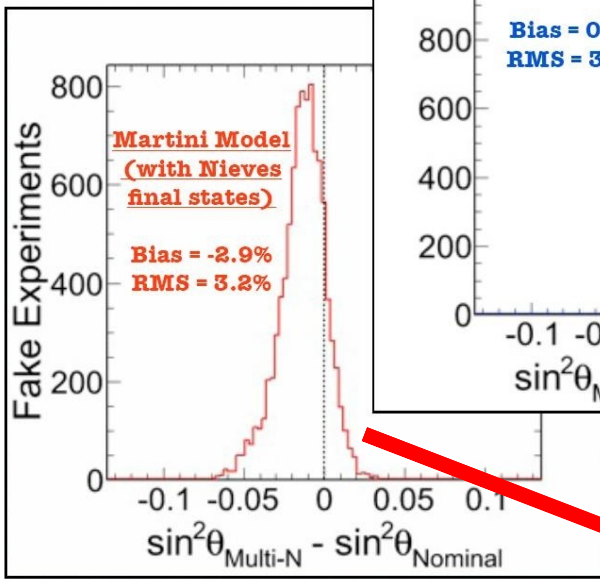
T2K analysis

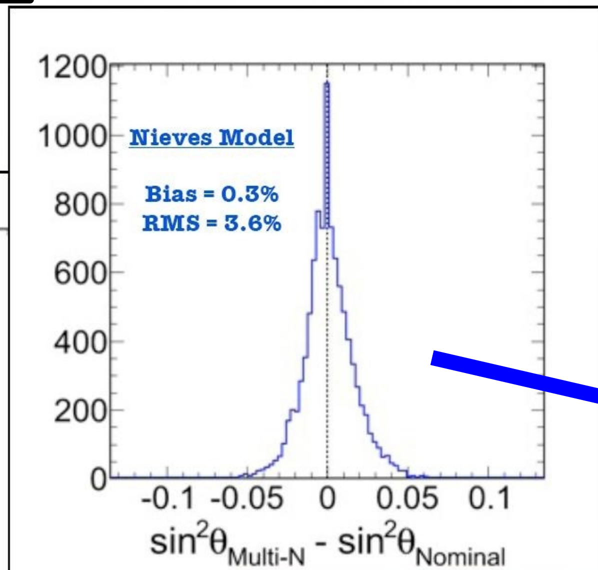


- Add np-nh events (Nieves and Martini models) to T2K fake data
- Perform disappearance fit to extract θ_{23}
- Compare to result from fit to nominal fake data

Effect of multi-nucleon events at νPRISM

T2K analysis





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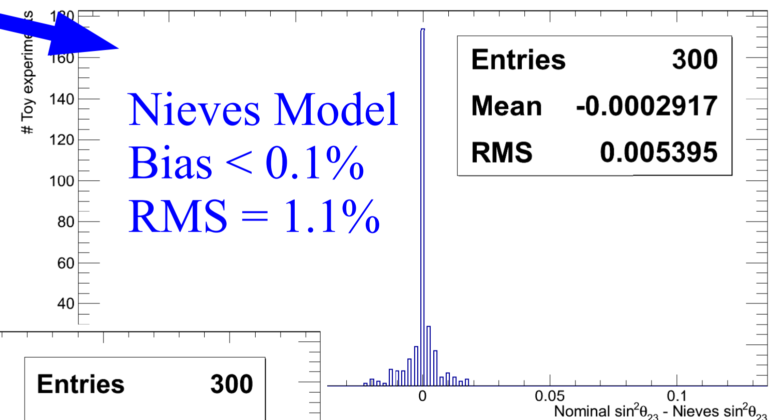
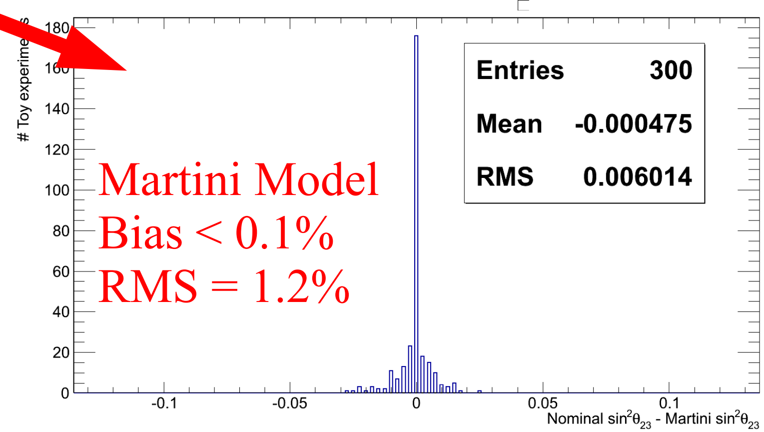


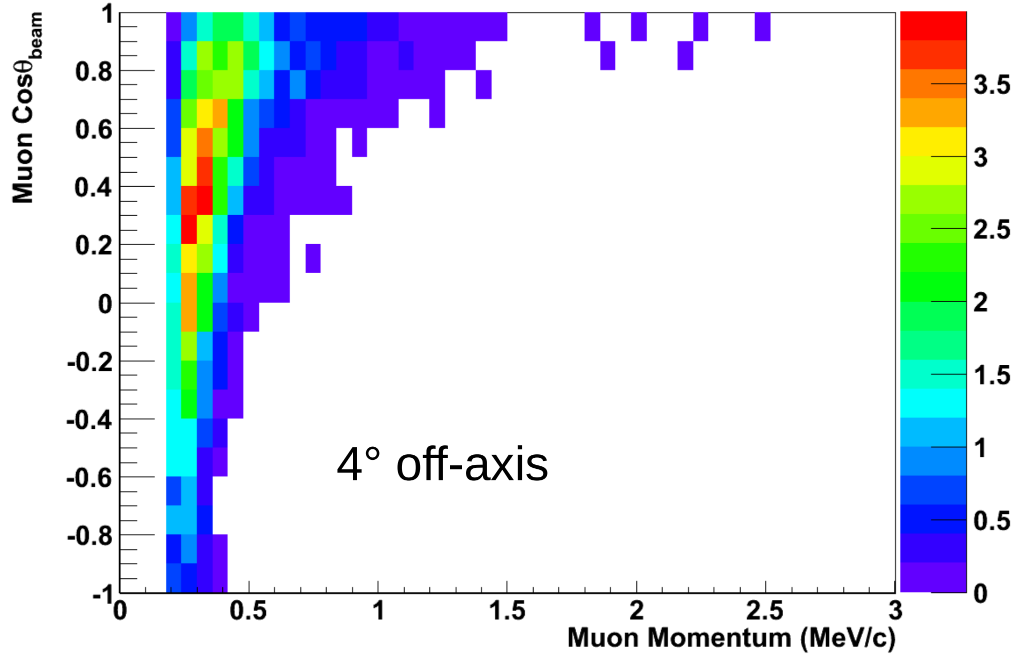


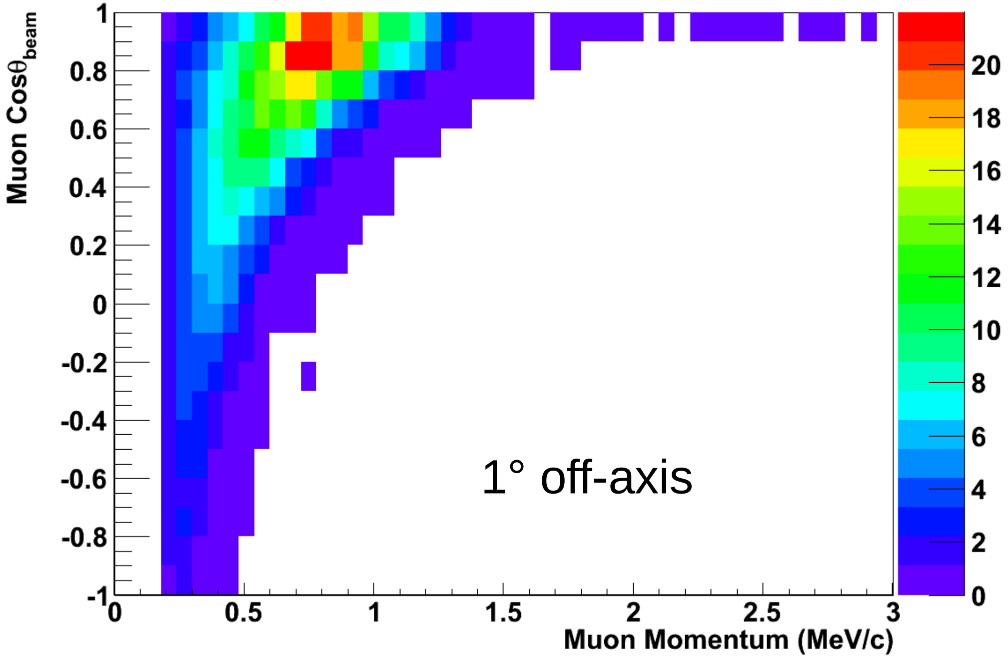
- Bias and RMS greatly reduced
- νPRISM analysis largely independent of cross section model

νPRISM analysis

Event Selection

- Same event selection as at SK:
  - Single ring
  - Muon-like
  - Fully contained in fiducial volume

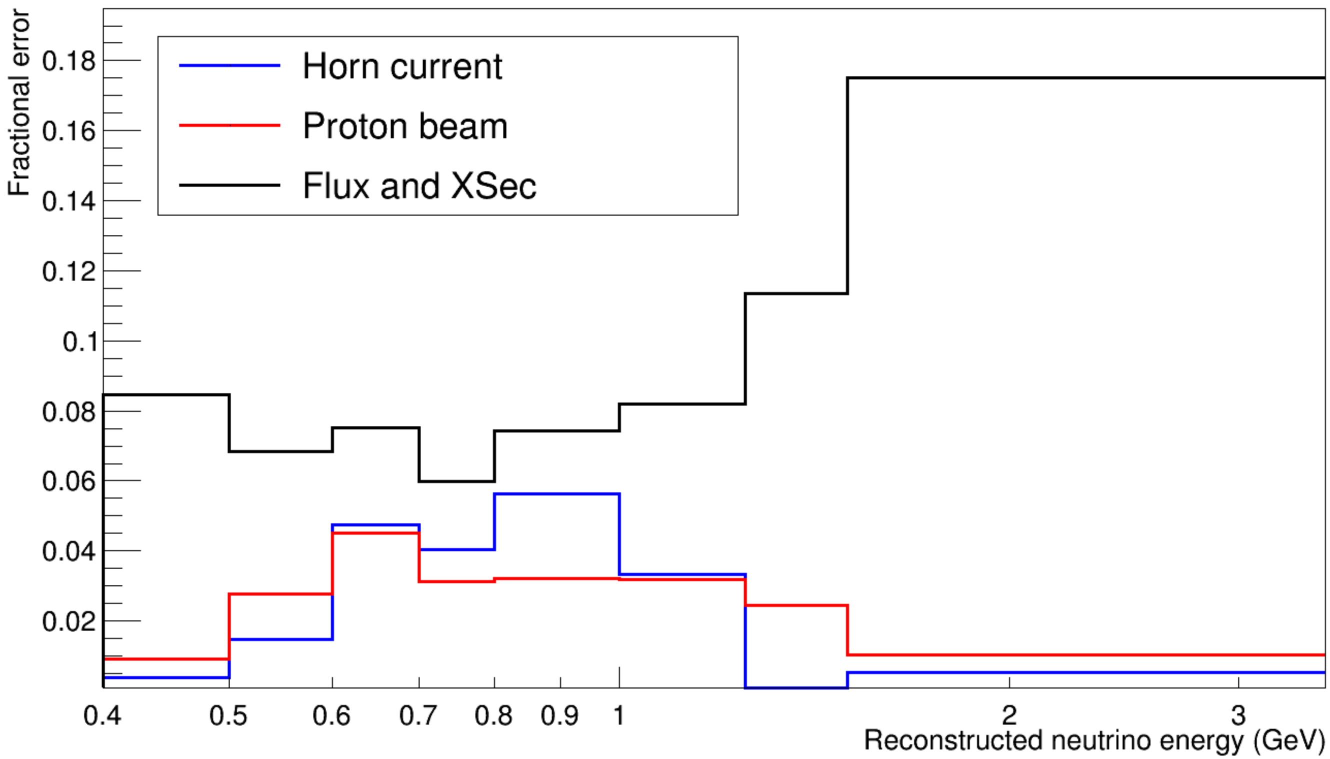




- Record the off-axis angle of the interaction, using the reconstructed vertex position

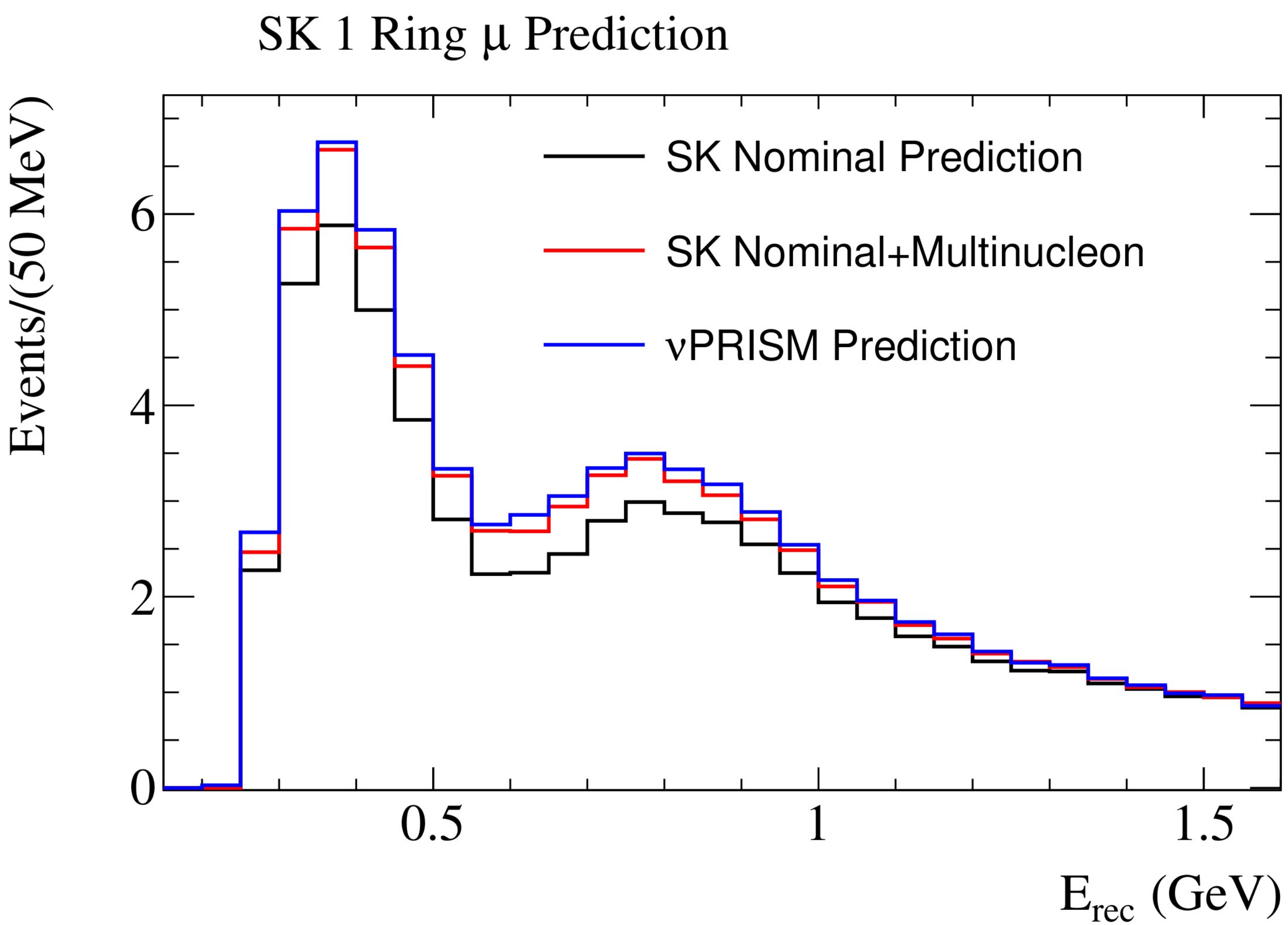
Flux systematics

- Flux uncertainty ~7% at oscillation dip
- Largely driven by proton beam and horn current uncertainties
  - Can be constrained by better beamline measurements



Multi-Nucleon example

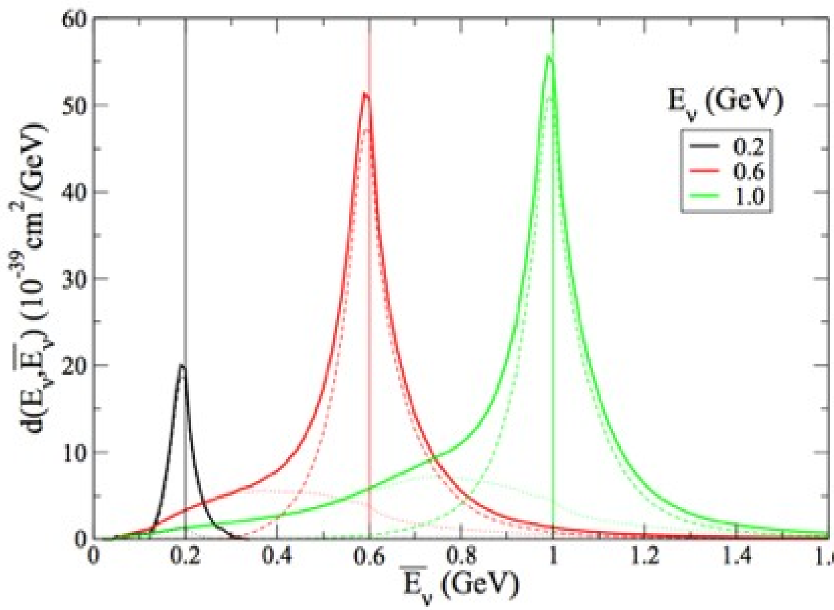
- Add multi-nucleon events to the nominal MC to make fake data



- See νPRISM prediction still reproduces oscillated SK spectrum when multi-nucleon events are present

Motivation for Gaussian Beams

- The modelling of multi-nucleon reactions, pion absorption, the nuclear initial state, etc., introduce uncertainties on:
  - The absolute normalization of the cross section for CC events with only visible leptons
  - The relationship between the lepton (or other final state) kinematics and the neutrino energy (important for oscillation measurements)
- Measuring the effect of nuclear effects on the final state kinematics is challenging in a conventional beams due to the width of the neutrino spectrum
- Ideally, a monochromatic neutrino beam would allow one to study how nuclear effects contribute to the final state particle distributions
- We can make "mono-chromatic" neutrino beams in nuPRISM



Martini et. al.
Phys.Rev. D87 (2013) 013009

Mono-chromatic Beams with NuPRISM

- Using the linear combination method, we can produce Gaussian beams with widths significantly less than an off-axis spectrum peaked at the same energy

$$G(E_\nu;\mu,\sigma)=\sum_{i=1}^{\#\text{ of Off-axis bins}} c_i\varphi_i(E_\nu)$$

- Here the c_i are chose to give the desired mean μ and width σ of the Gaussian
- In practice, the range of μ that can be achieved is limited by the range of peak energies in the off-axis fluxes that nuPRISM observed, ~0.4-1.2 GeV
- The width of the mono-chromatic beam, σ, is limited by the level of statistical and systematic error that can be propagated in the linear combination