Imperial College London

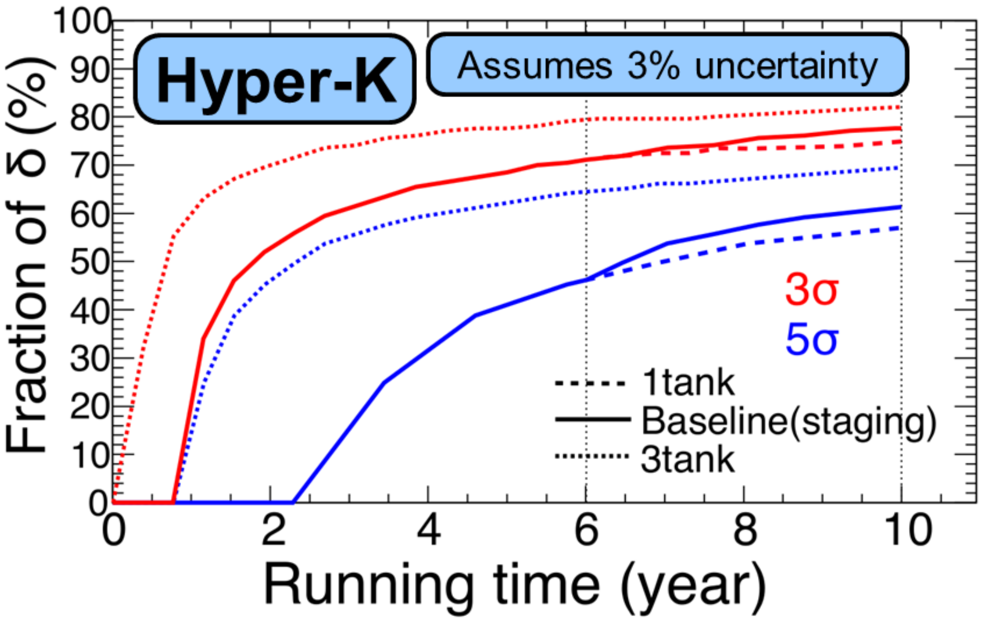
23rd October 2018

DUNE-PRISM and E61

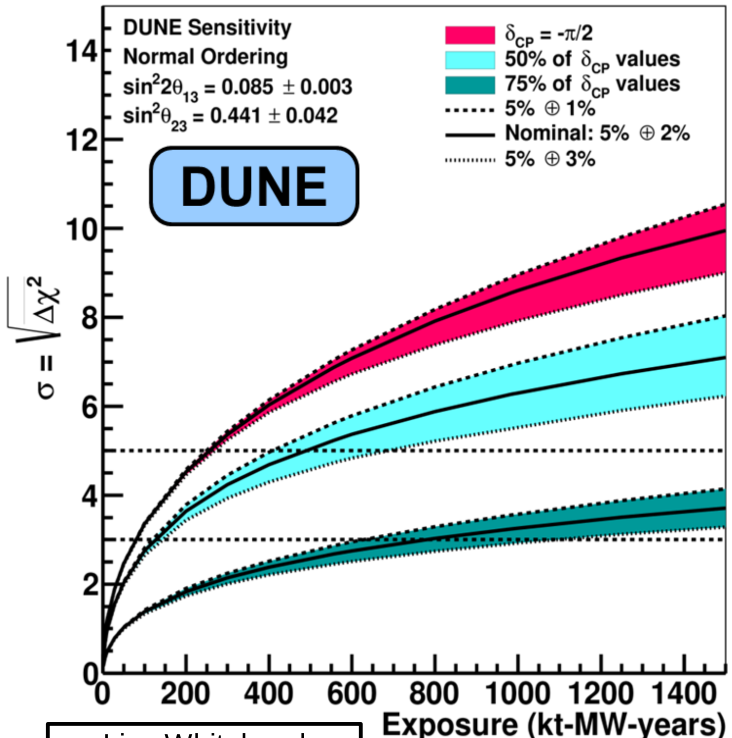
Physics with neutrinos over a range of off-axis angles

Mark Scott

Motivation



Hyper-K Design report



Lisa Whitehead
TAUP 2017
DUNE CP sensitivity

- Next-generation neutrino experiments will be systematics limited
- Goal is <3% total systematic on signal

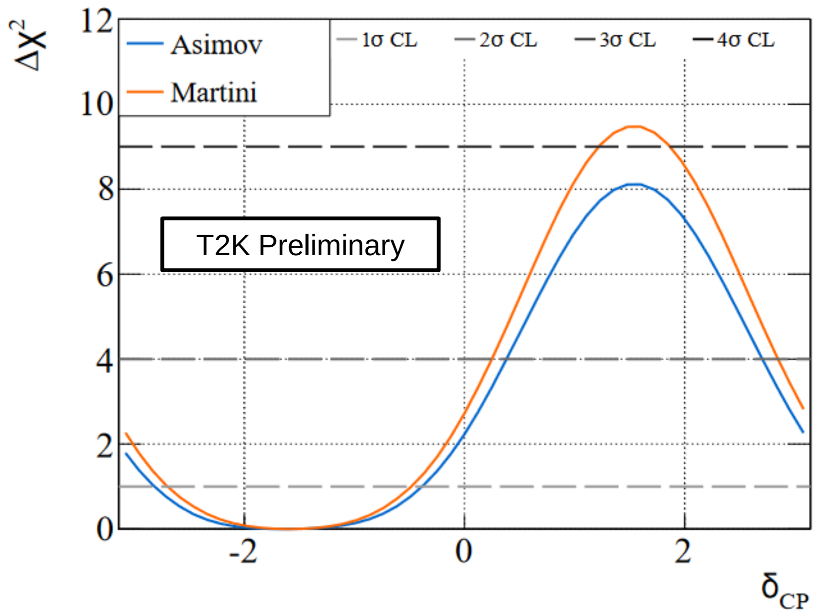
Current status

T2K Neutrino 2018

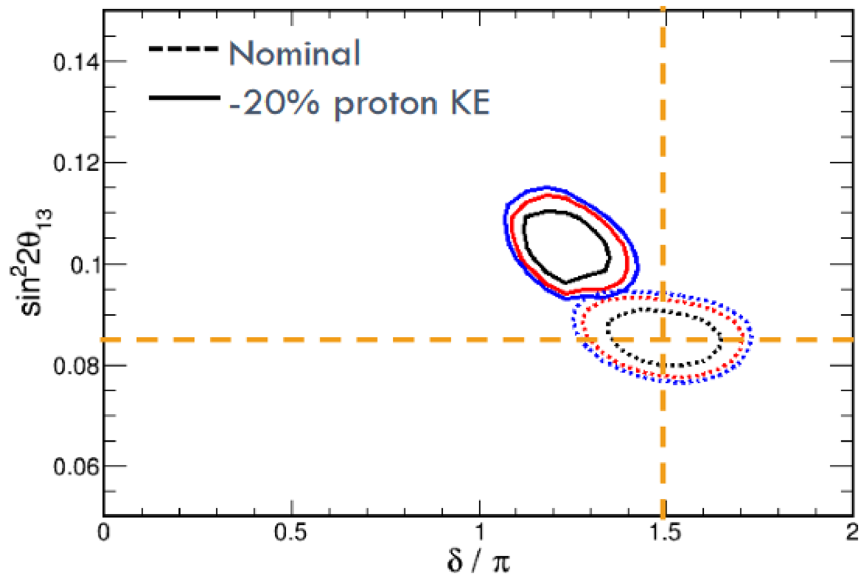
	1-Ring μ		1-Ring e			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	2.40	2.01	2.83	3.79	13.16	1.47
SK FSI+SI+PN	2.20	1.98	3.02	2.31	11.44	1.58
Flux + Xsec constrained	2.88	2.68	3.02	2.86	3.82	2.31
E_b	2.43	1.73	7.26	3.66	3.01	3.74
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1γ	0.00	0.00	1.07	2.58	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.99	0.18
Osc	0.03	0.03	3.86	3.60	3.77	0.79
All Systematics	4.91	4.28	8.81	7.03	18.32	5.87
All with osc	4.91	4.28	9.60	7.87	18.65	5.93

- Uncertainty on ratio of electron appearance to anti-electron appearance ~= uncertainty on δCP
- Cross-section uncertainties dominate
  - ~Identical near and far detectors, measure directly
  - Large near detector with excellent γ-e separation
  - Reduced by near detector fit, however…

Mock data studies



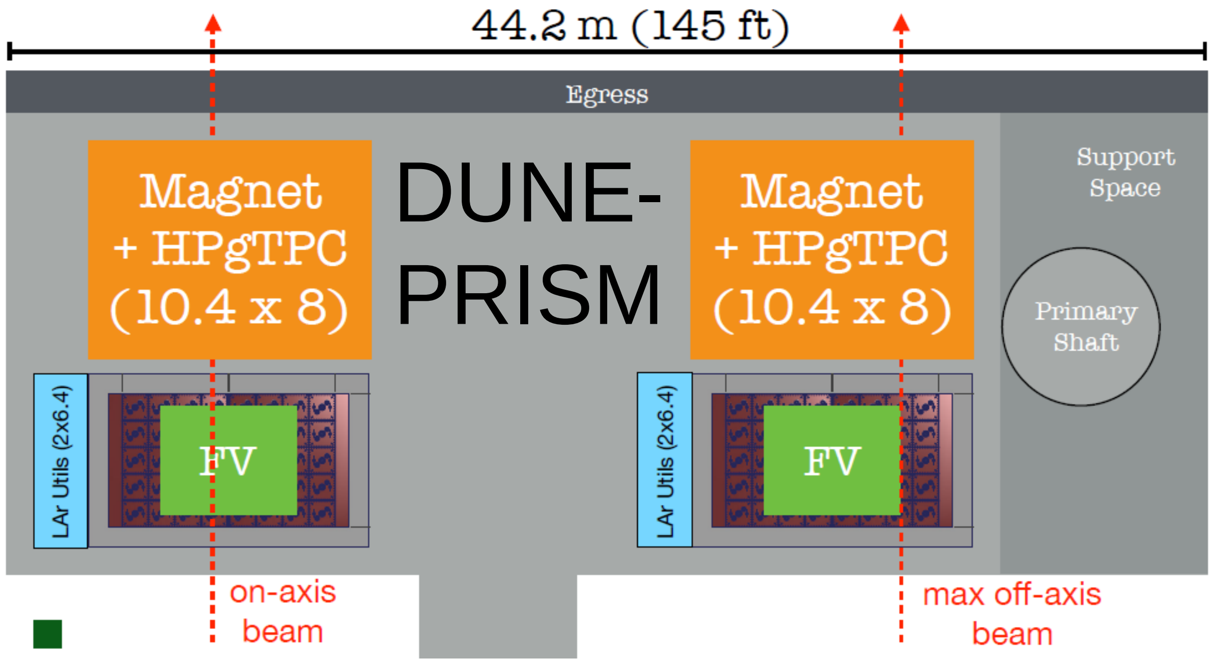
DUNE study - C. Vilela, G. Yang

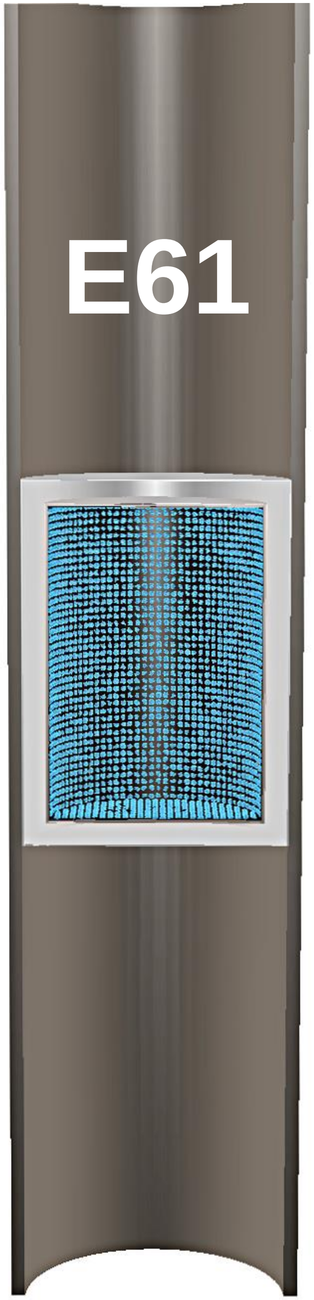


- Mock (fake) data studies – make simulated dataset by changing cross-section model
- Perform oscillation fit
- See change in oscillation contours compared to expectation – fitting to ND data can introduce biases in oscillation results

Imperial College London

DUNE-PRISM and E61



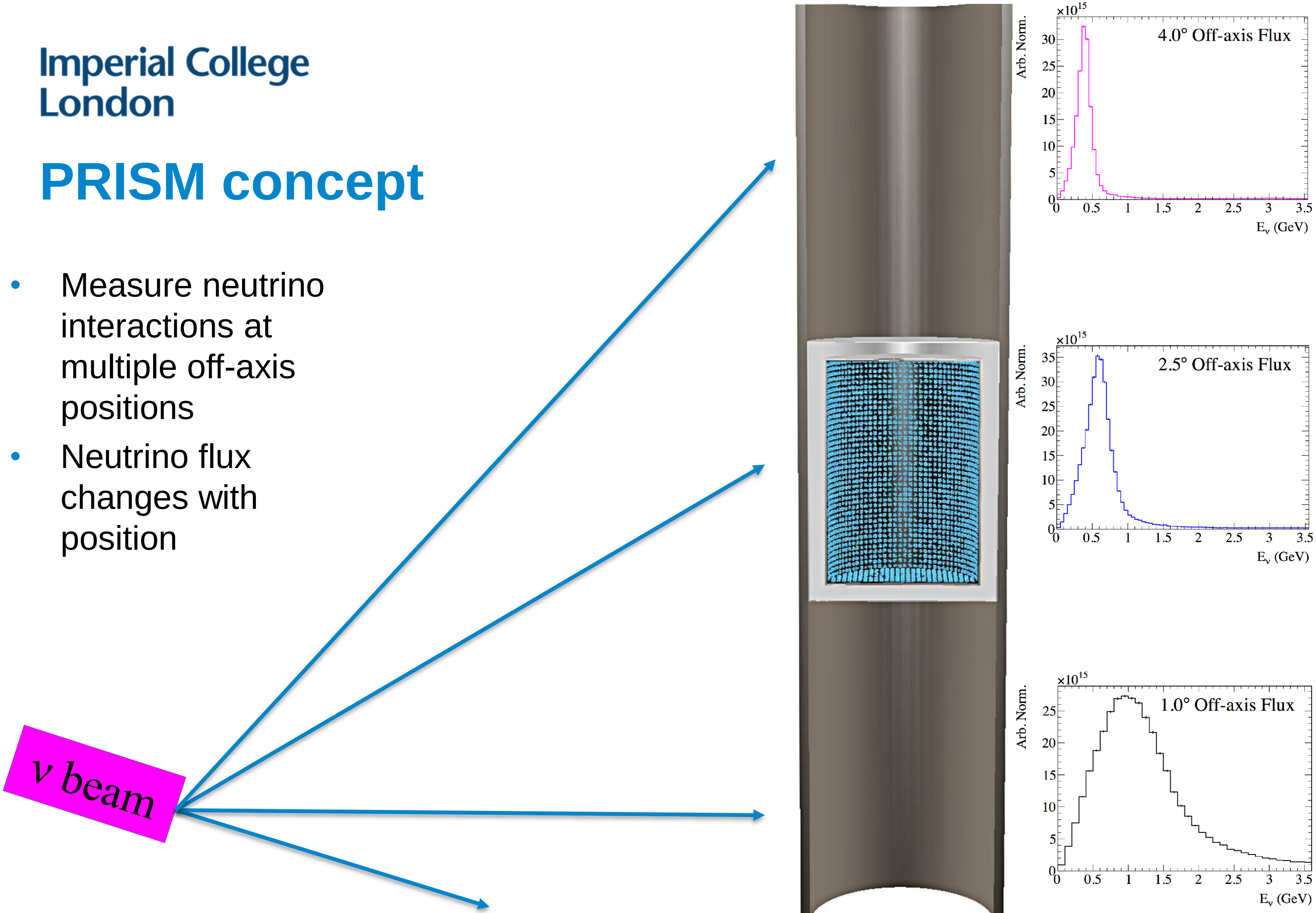


- Near / intermediated detectors for DUNE / HK
- Span a range of angles off the centre of the neutrino beam
  - DUNE-PRISM – horizontal, ~35m
  - E61 – vertical, ~50m

Imperial College
London

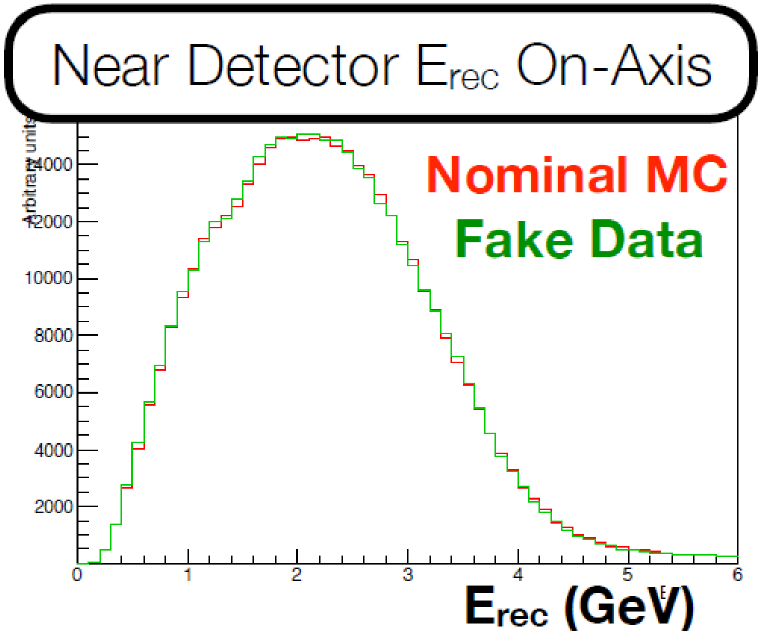
PRISM concept

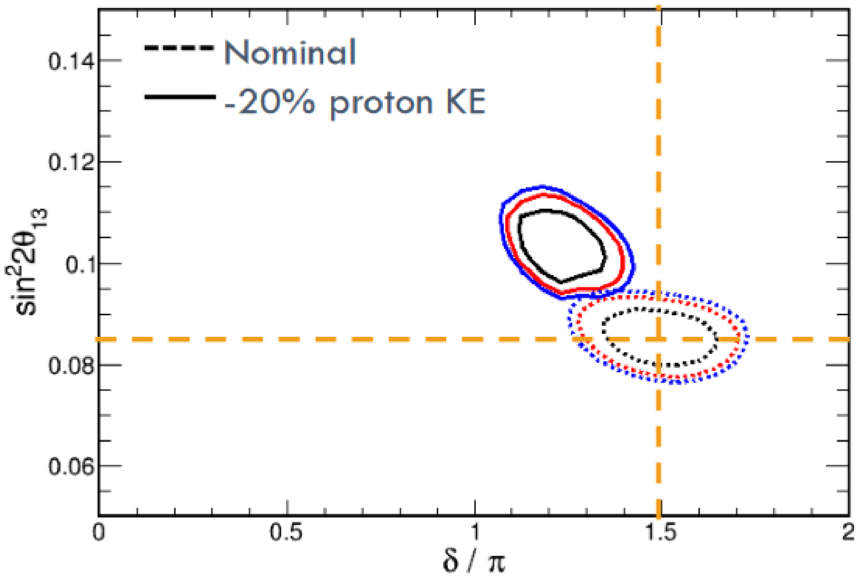
- Measure neutrino interactions at multiple off-axis positions
- Neutrino flux changes with position



PRISM benefits - 1

DUNE study - C. Vilela, G. Yang

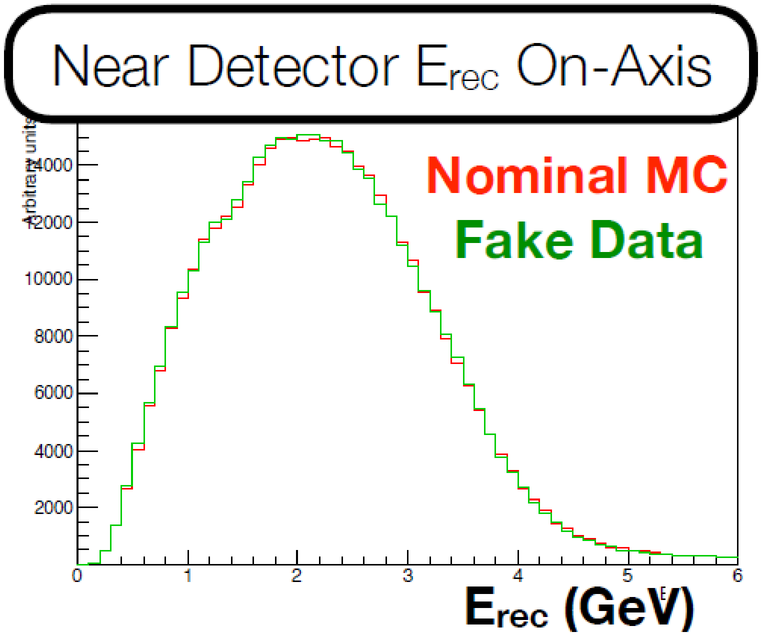


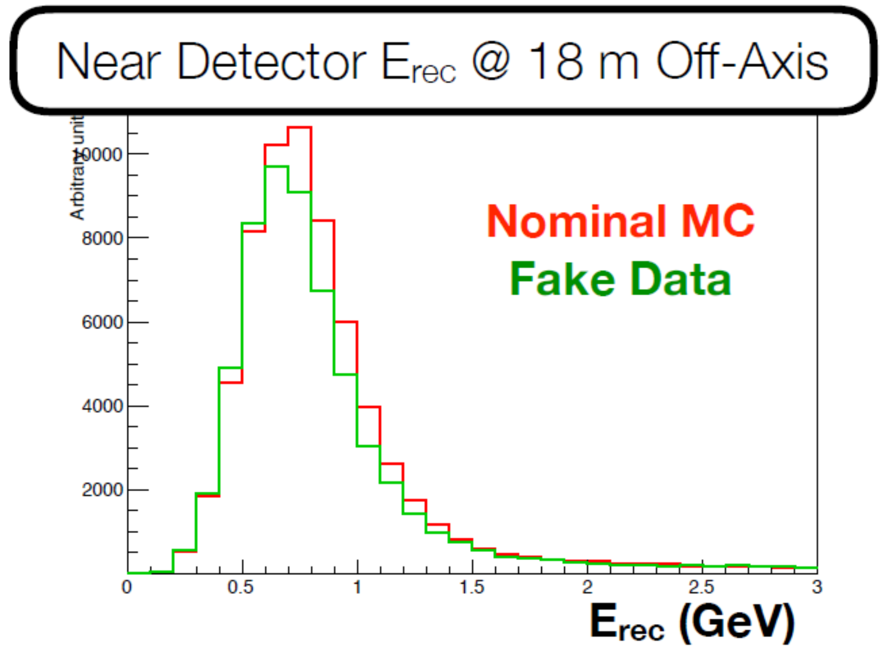


- Near detector along same axis as far detector tunes MC to match data - bias!

PRISM benefits - 1

DUNE study - C. Vilela, G. Yang



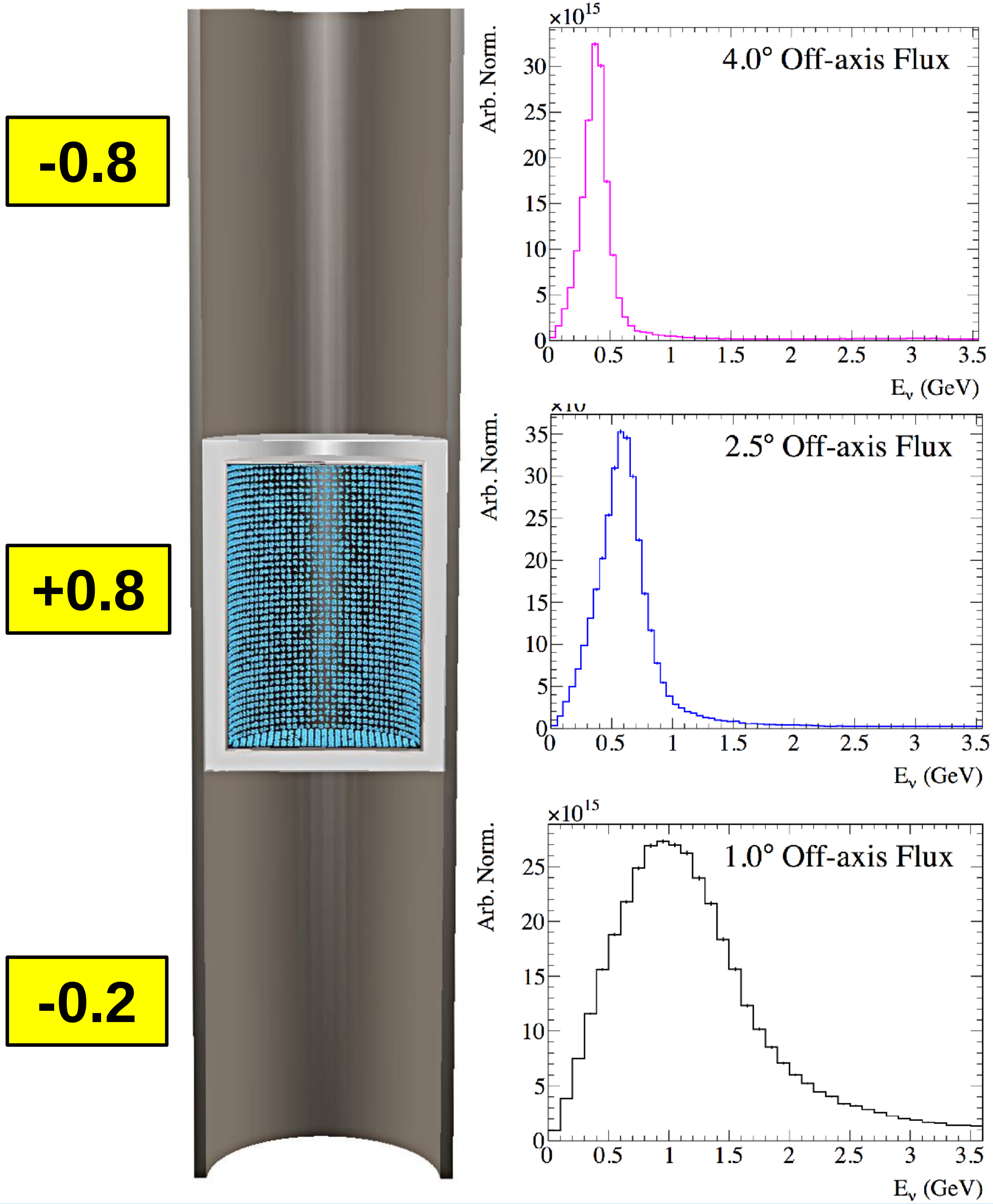


- Near detector along same axis as far detector tunes MC to match data - bias!
- Test tune ('Nominal MC' here) by comparing to data at point further off-axis
- Clearly see model does not agree – model tuning wrong / model incomplete

Imperial College London

PRISM benefits - 2

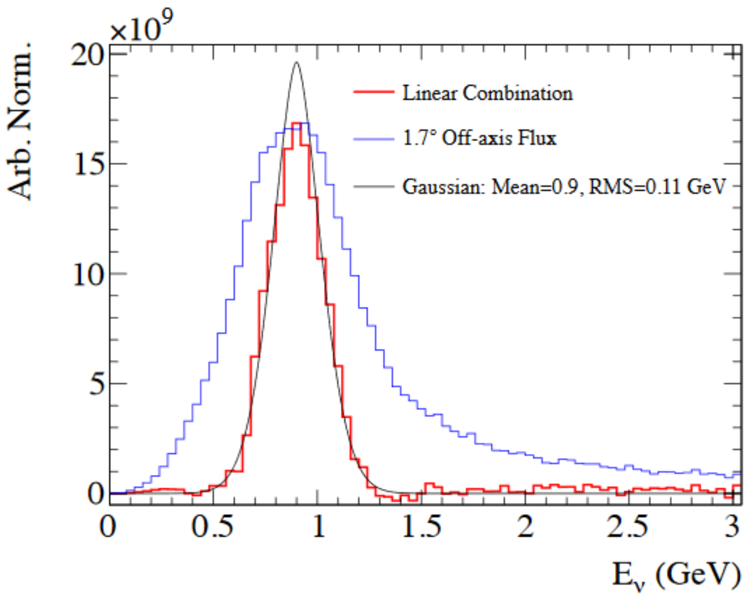
- Same detector measuring all off-axis fluxes
- Can weight and combine different off-axis ‘slices’

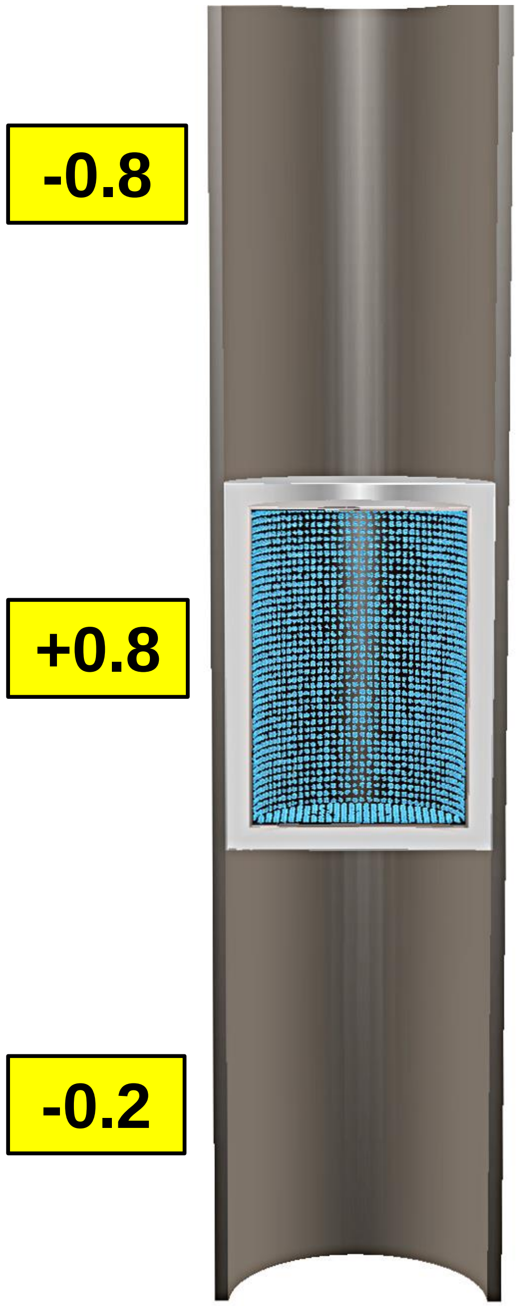


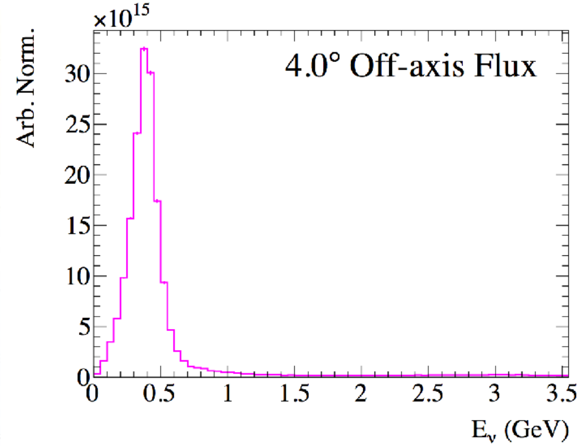
Imperial College London

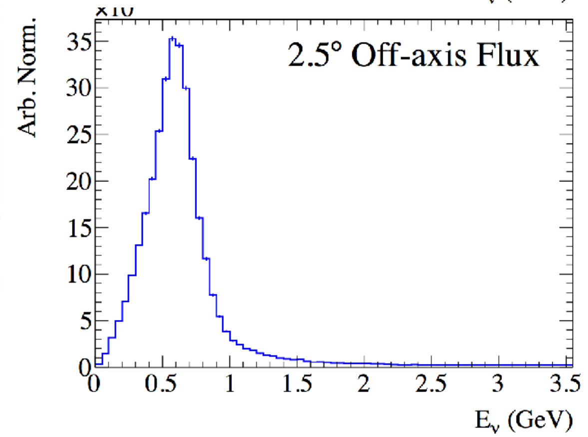
PRISM benefits - 2

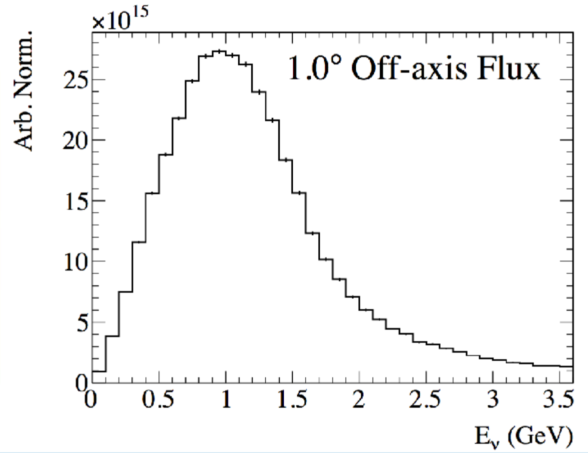
- Same detector measuring all off-axis fluxes
- Can weight and combine different off-axis ‘slices’
- Produce Gaussian energy distribution





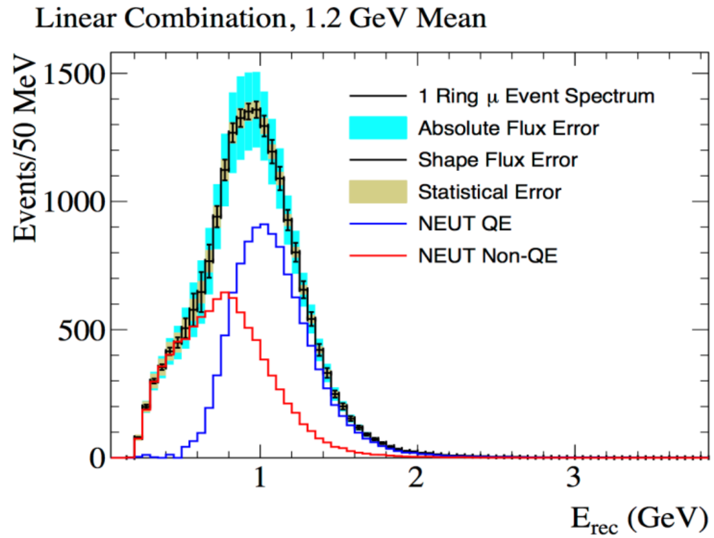


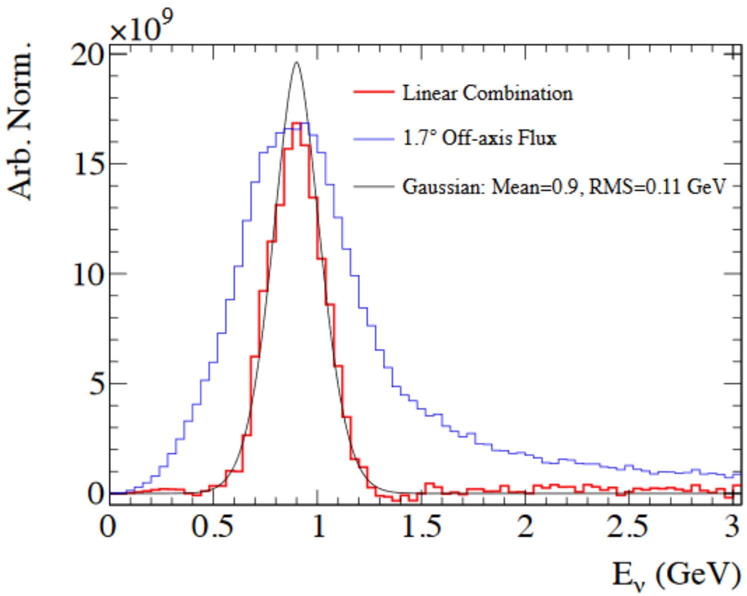


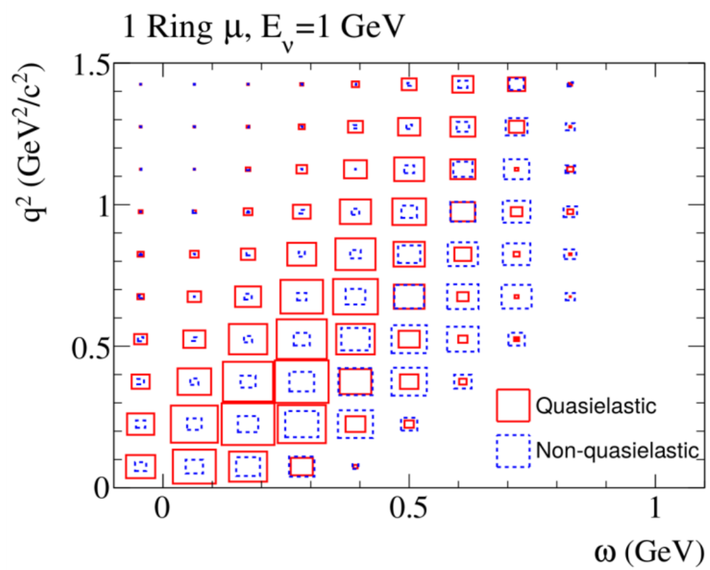


PRISM benefits - 2

- Same detector measuring all off-axis fluxes
- Can weight and combine different off-axis ‘slices’
- Produce Gaussian energy distribution





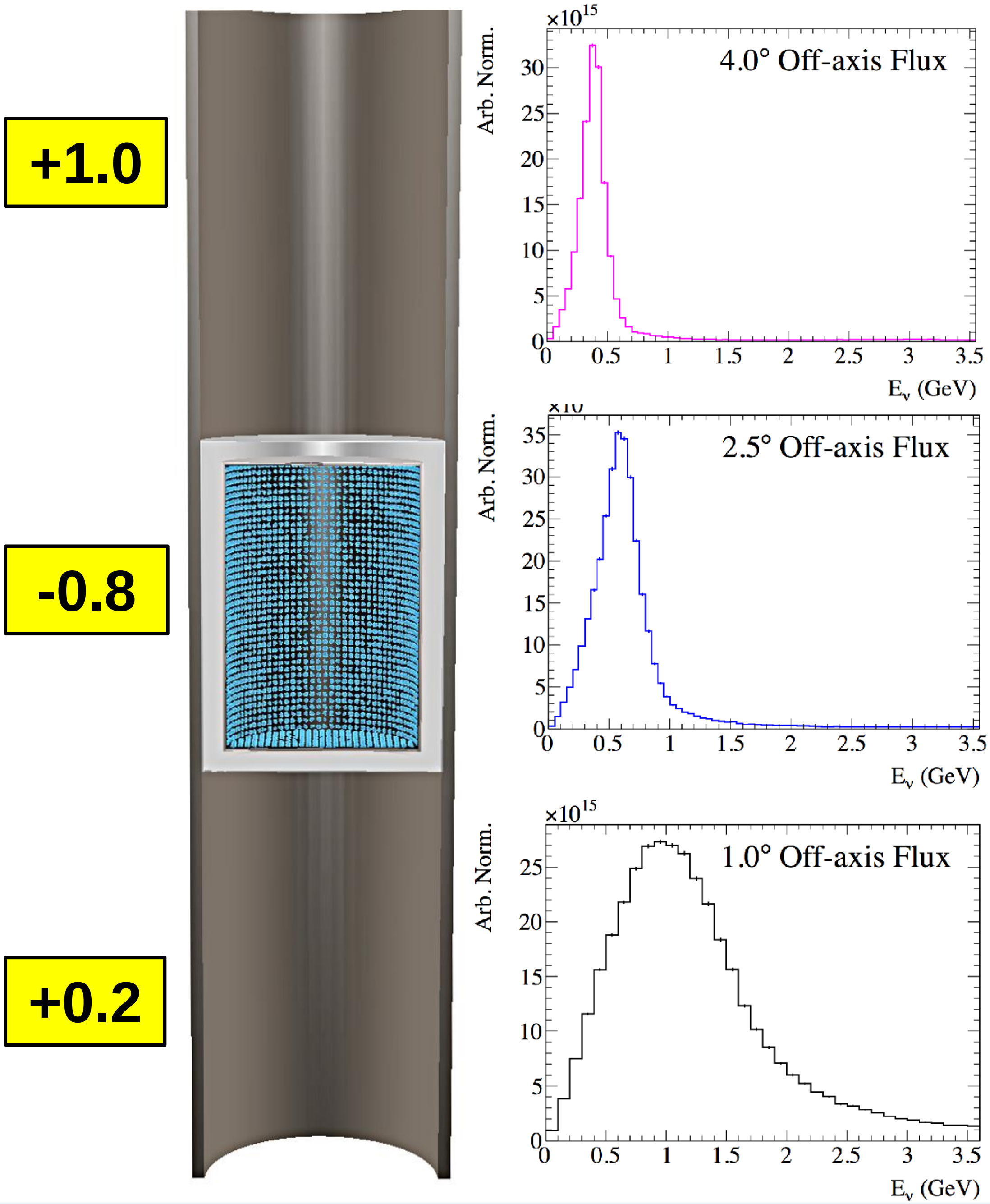


- Measure at a known energy
- Map out true-reco relationship
- Energy range determined by off-axis range

Imperial College London

PRISM benefits - 3

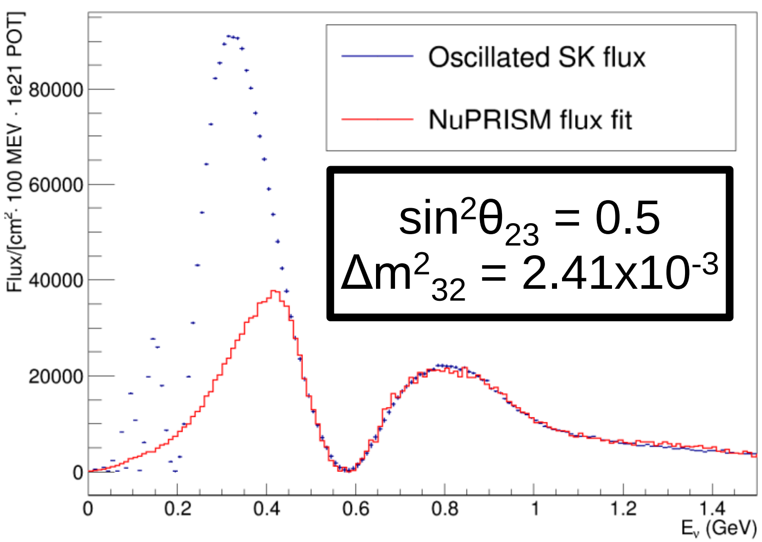
- Can have different linear combination

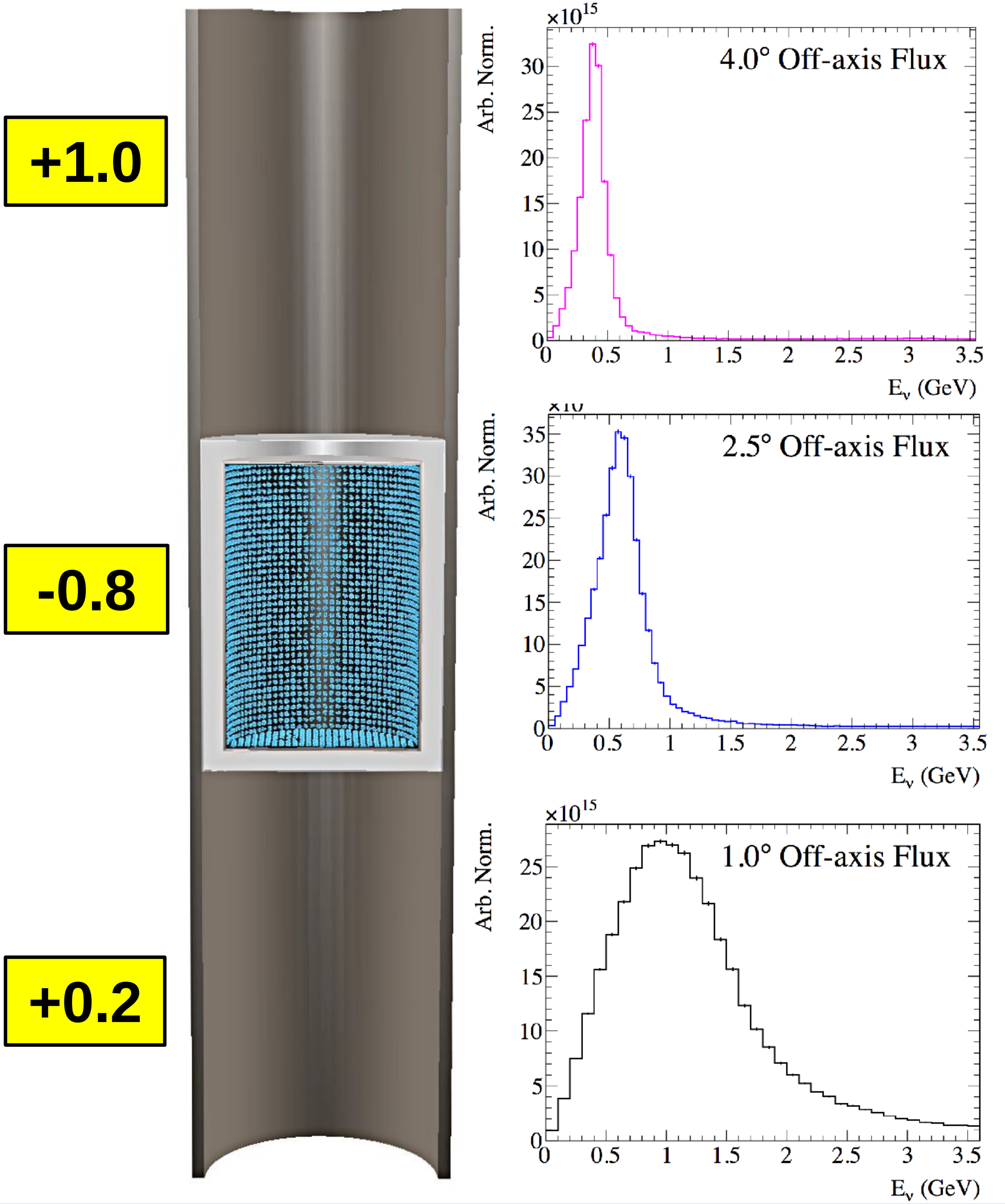


Imperial College London

PRISM benefits - 3

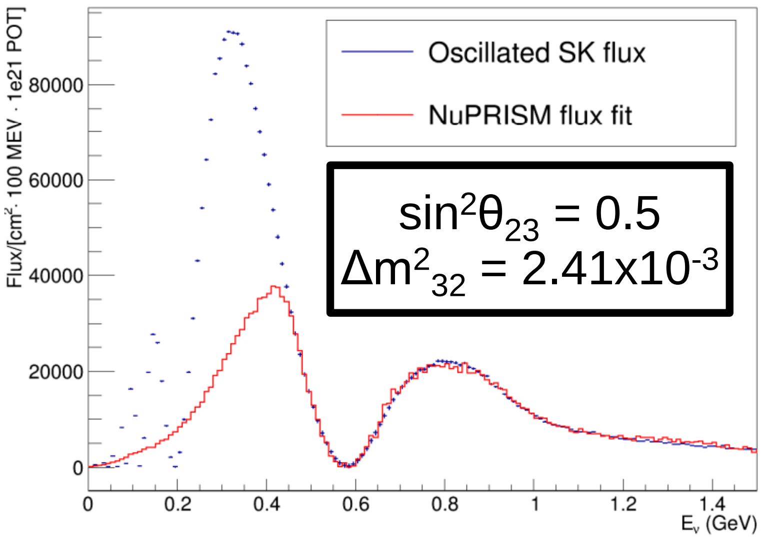
- Can have different linear combination
- Recreate oscillated flux using near detector data

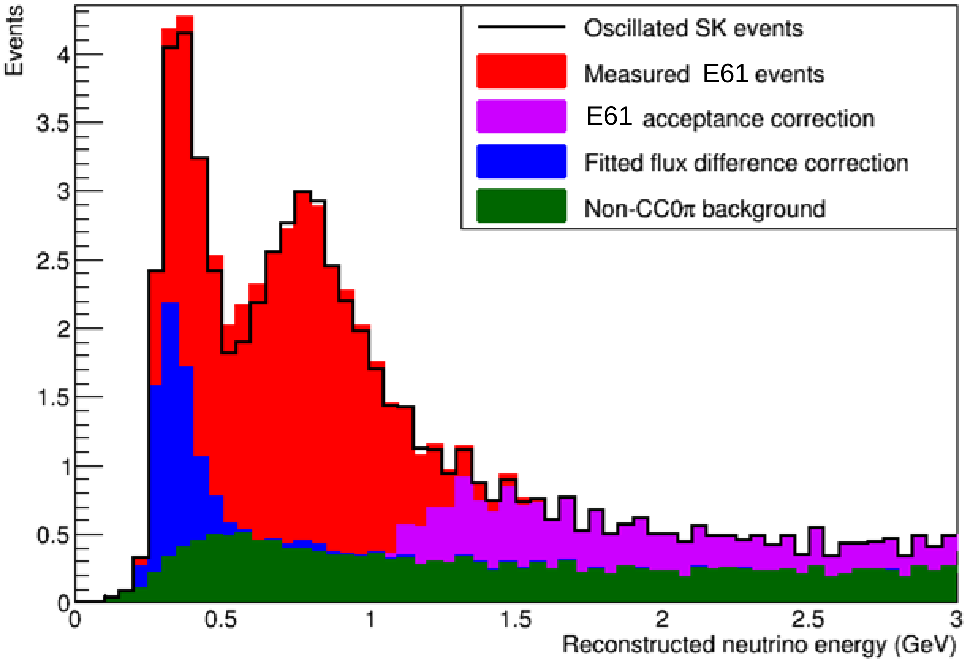




PRISM benefits - 3

- Can have different linear combination
- Recreate oscillated flux using near detector data



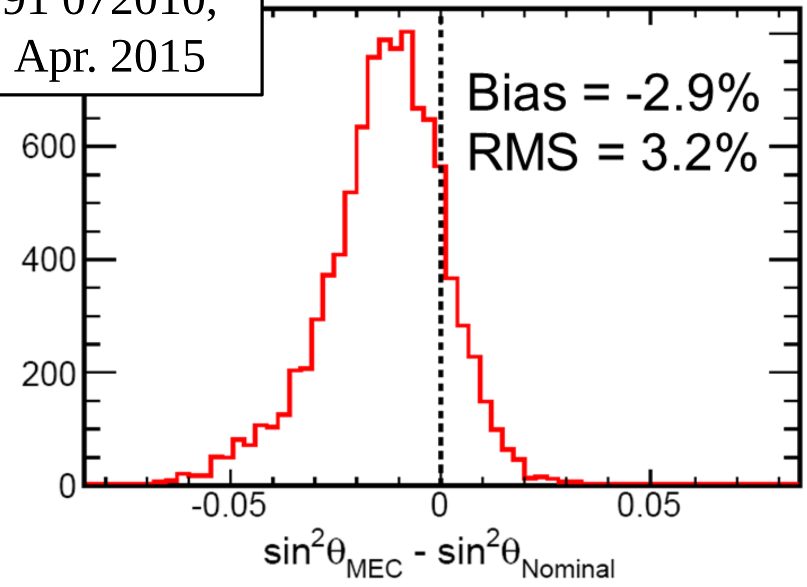


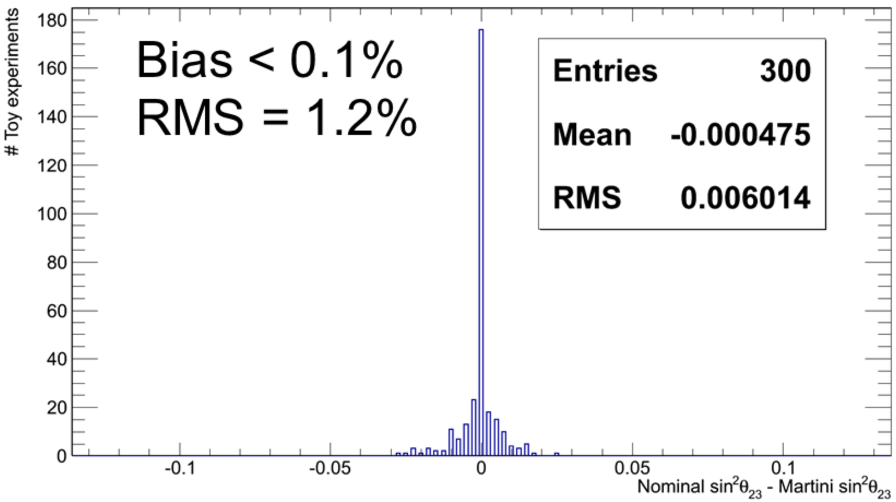
- Use data to directly predict oscillated spectrum (red)
- Backgrounds (green) can be measured in-situ
- Biases due to ND fit will only affect corrections (blue, magenta)

PRISM benefits - 3

- Mock data analysis at T2K
  - Addition of multi-nucleon events to mock data
  - Analysis MC without multi-nucleon events
  - Biased values of θ_{23} measured

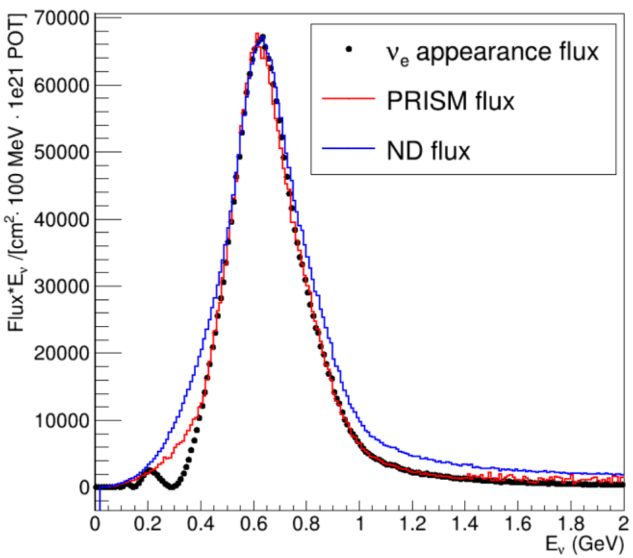
K. Abe *et al*, *Phys. Rev. D*, 91 072010, Apr. 2015

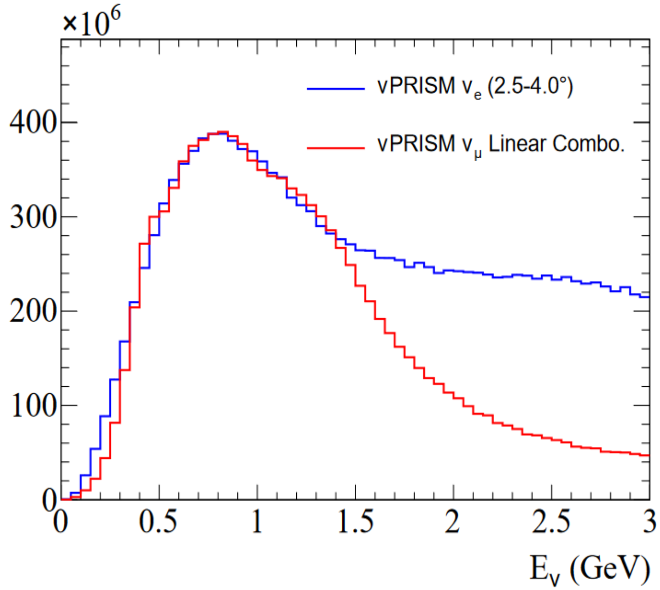


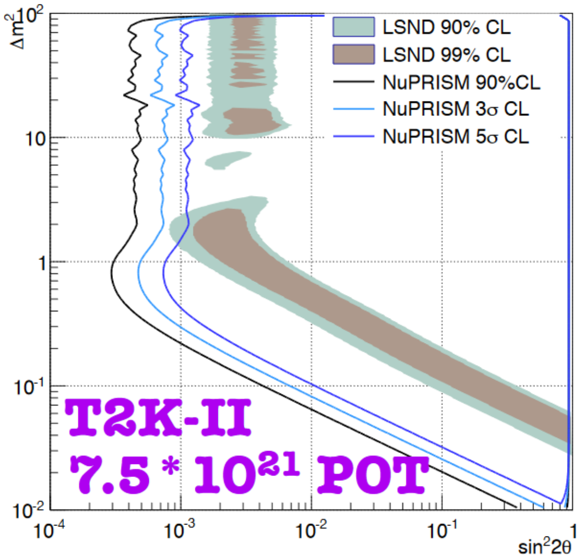


- Identical analysis with E61
  - Multi-nucleon events added to mock data
    - Not MC
  - Linear combination applied
  - Measured θ_{23} unbiased

PRISM benefits - 4







- Fit appearance flux
  - Removes tails seen at ND
- Fit ND ν_e flux
  - Directly measure electron/muon cross-section ratio
- Sterile searches
  - 5σ exclusion of LSND
  - Oscillation vs off-axis angle

E61 and DUNE-PRISM status

- DUNE Near Detector Concept Study group recommended:
  - The design of a DUNE ND to be mobile and able to make measurements at one or more off-axis positions should go forward
  - The ND experimental hall should be 35m x 17m, with the long-axis perpendicular to the beam axis to allow for off-axis measurements

- E61
  - Stage 1 approval from J-PARC
  - Two-stage approach, test beam planned for 2021
  - Proposed as intermediate detector for HK, official adoption by collaboration expected in near future
  - Site surveys and engineering consultation ongoing

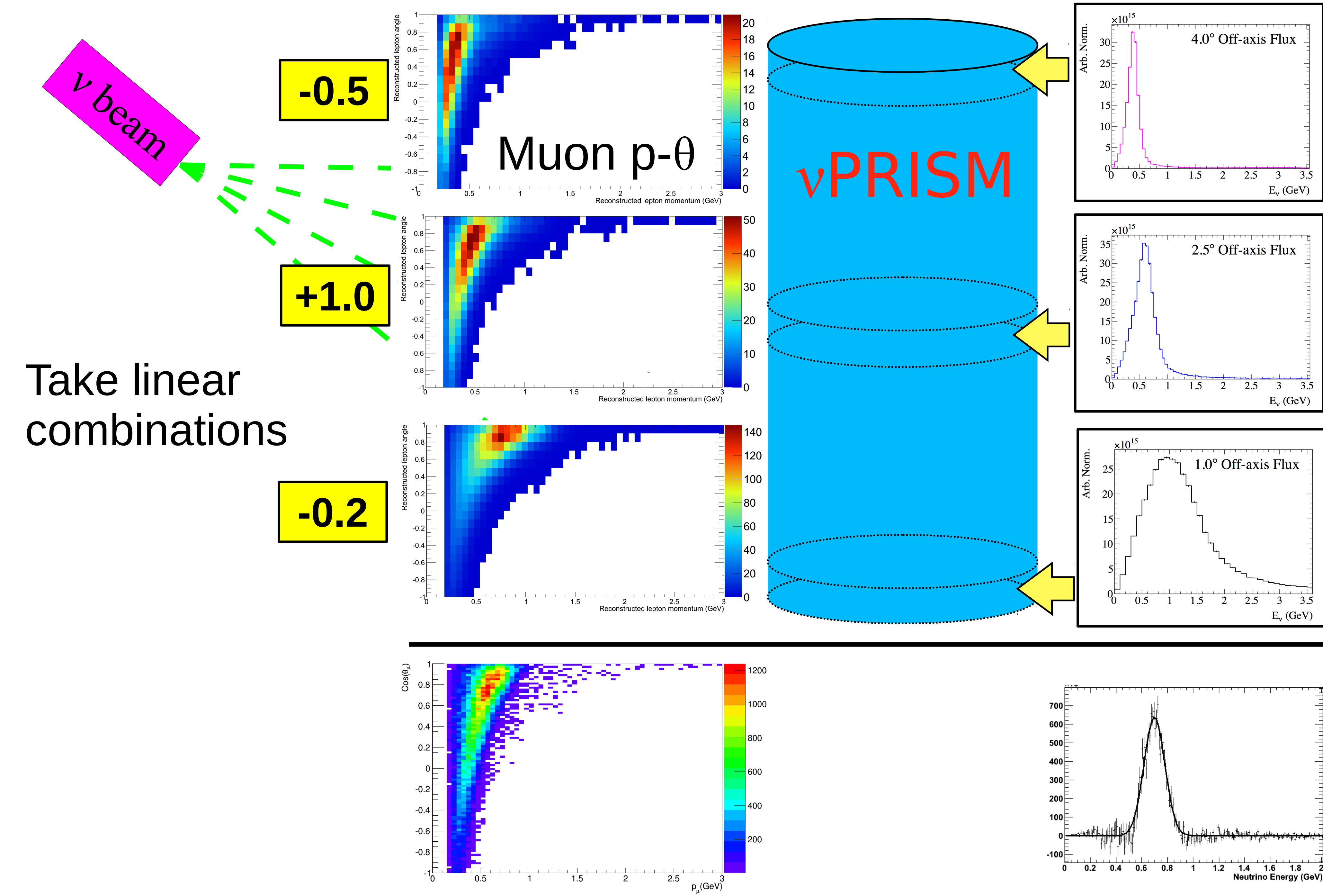
Summary

- Future long-baseline experiments will be systematics dominated
  - Controlling these will be challenging
  - Tuning models to near detector data can produce biases in oscillation parameters
- Measuring multiple off-axis fluxes can reduce or remove these difficulties
  - Cross-check of tuned model
  - Gaussian fluxes for cross-section measurements at known energy
  - Matched, oscillated fluxes to protect against bias from incomplete / inaccurate models
- Development of a movable, off-axis detector being pursued by DUNE and HK
  - Technical feasibility, ultimate sensitivities to oscillation parameters
  - Calibration, detector systematics

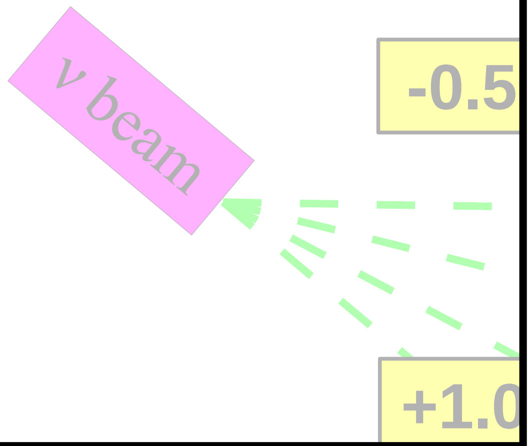
Imperial College London

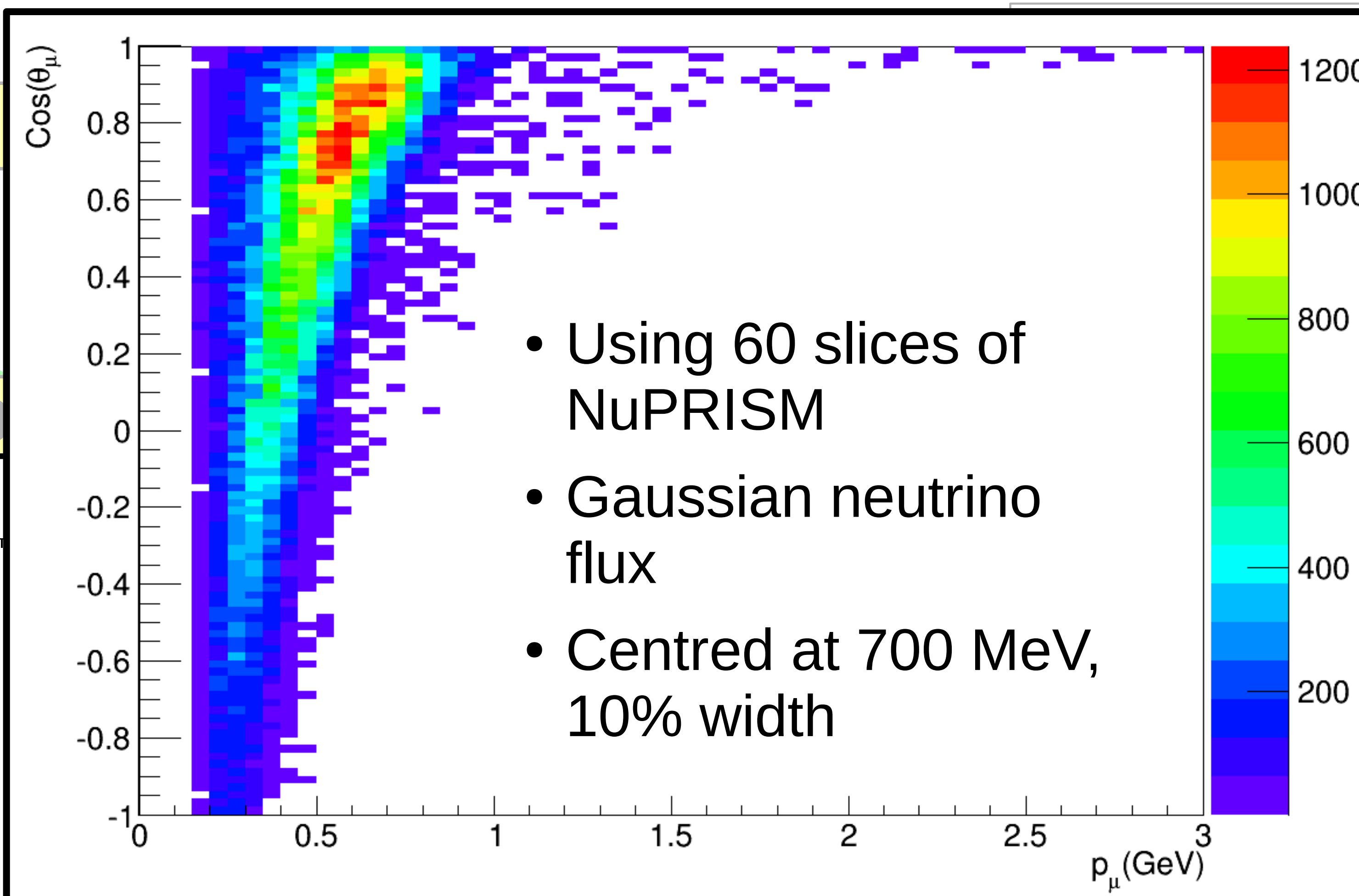
Backups

Mono-energetic beams

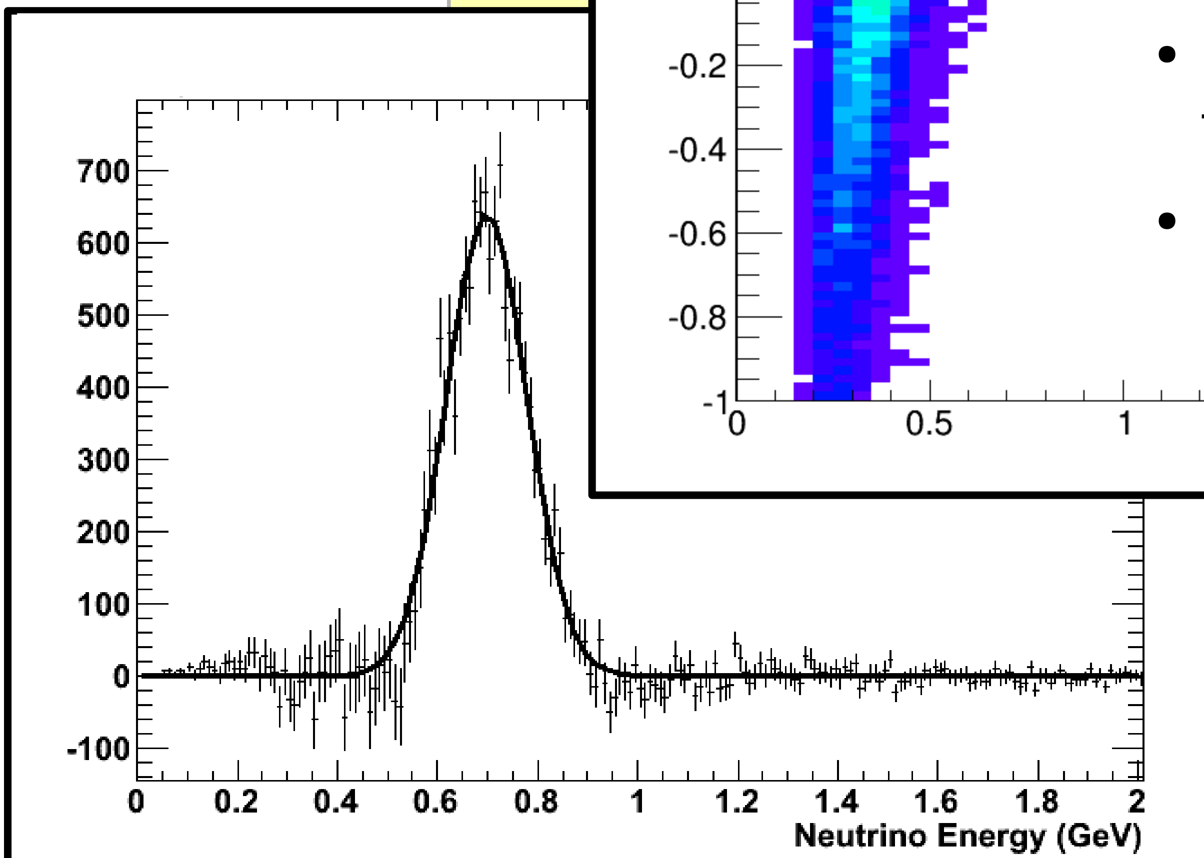


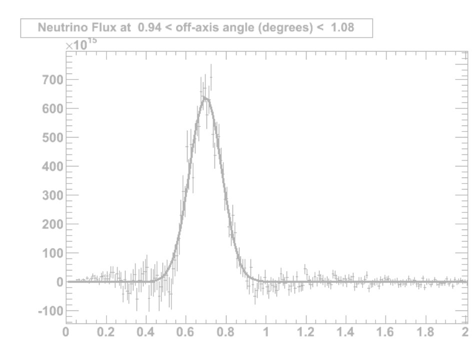
Mono-energetic beams





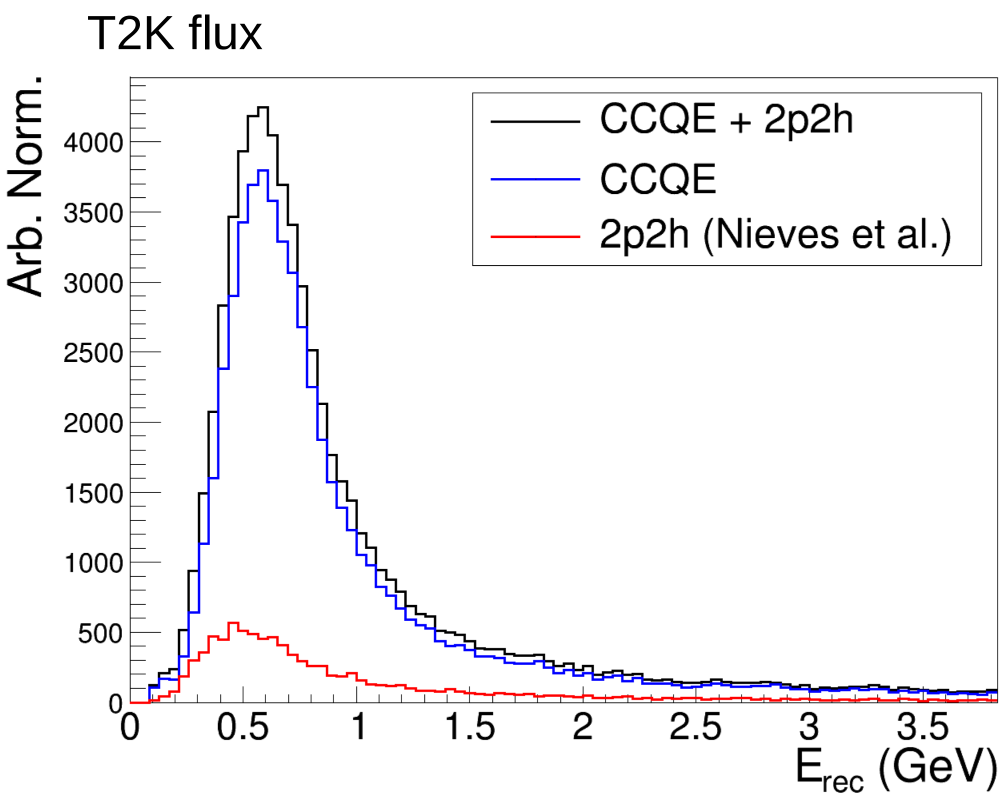
- Using 60 slices of NuPRISM
- Gaussian neutrino flux
- Centred at 700 MeV, 10% width

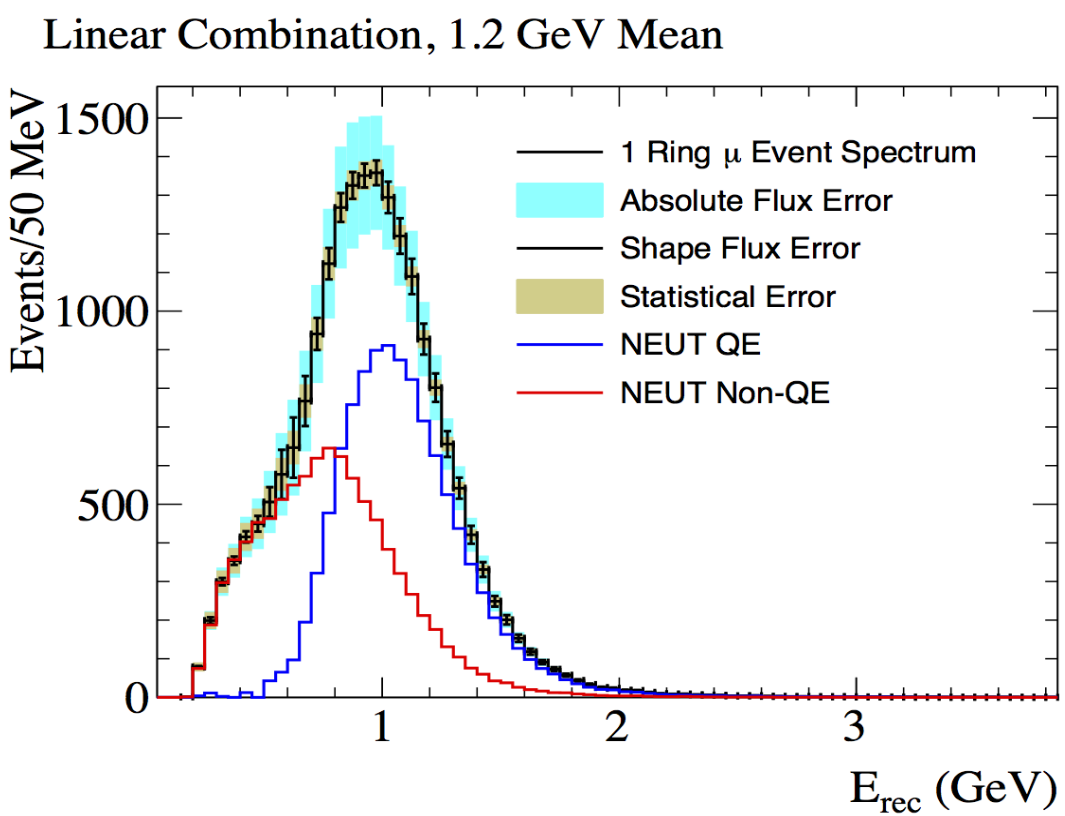




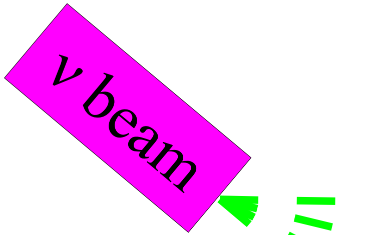
How can we use them?

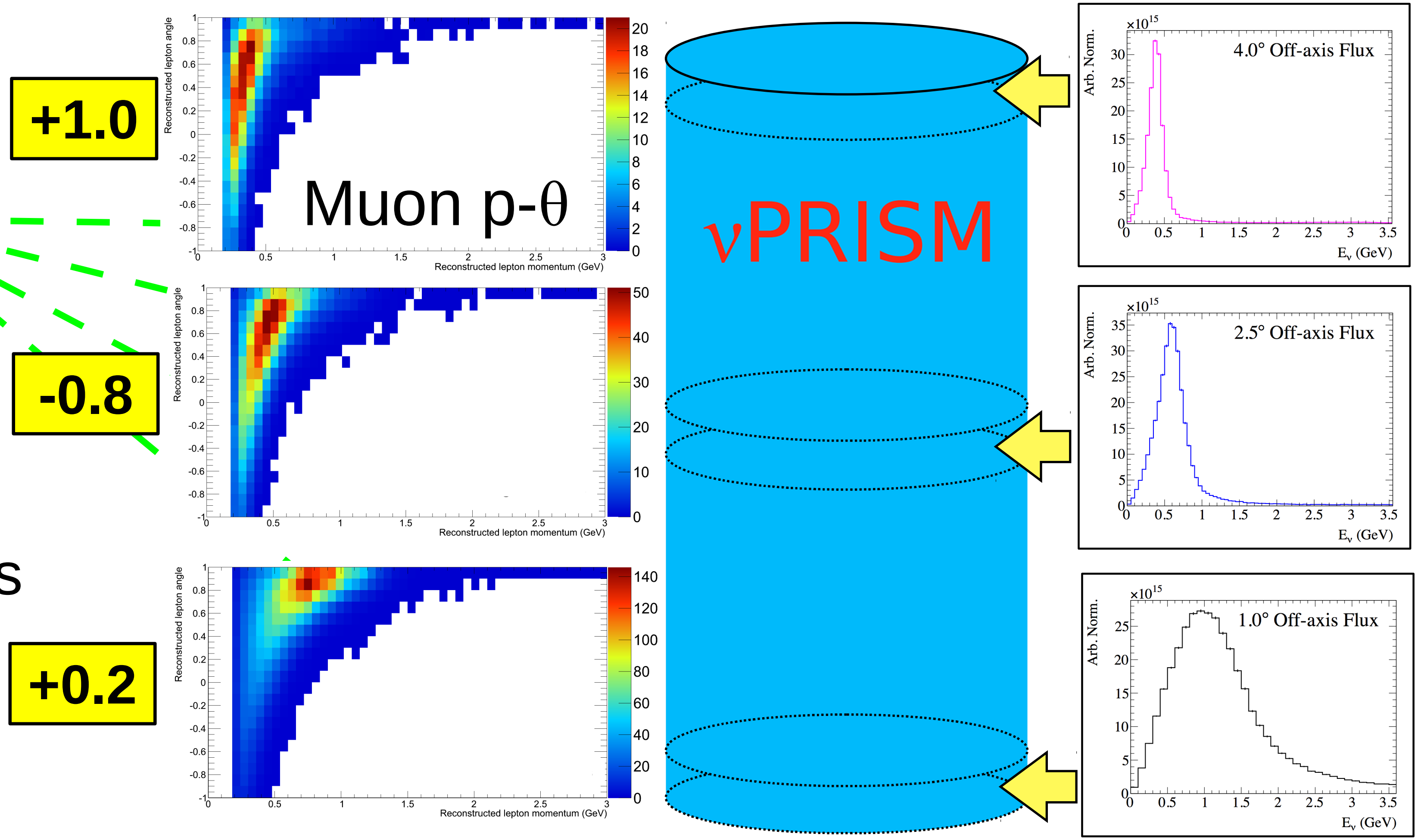
- Provides more information on neutrino interactions
- Separate quasi-elastic (QE) and multi-nucleon (np-nh) events
- Measure in data:
  - Cross-sections (inc. NC) as function of true neutrino energy
  - In same detector → highly correlated flux and detector systematics
  - Measure vs true Q^2 or ω – variables controlling interaction mode



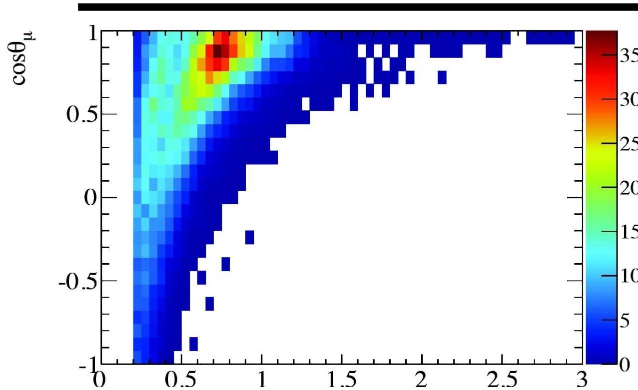


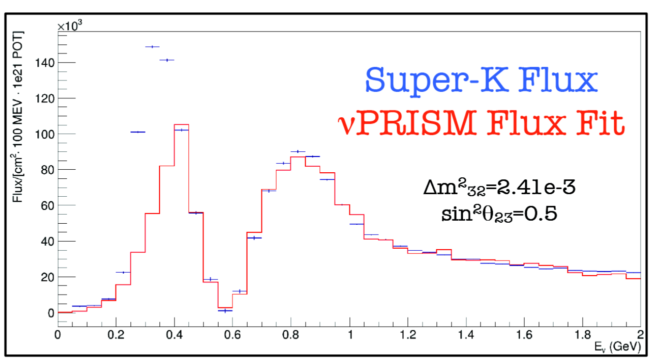
ν Oscillation with NuPRISM



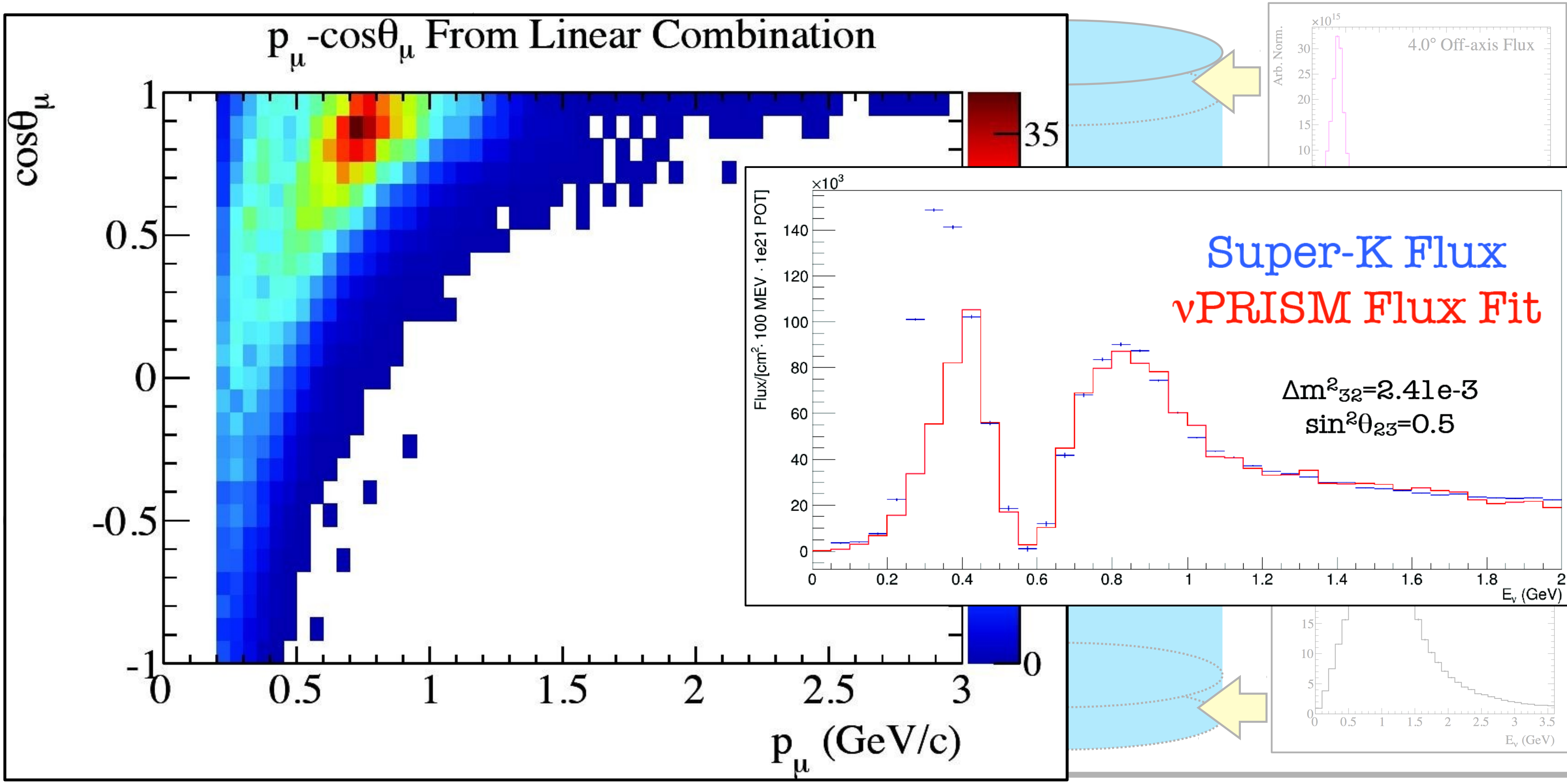


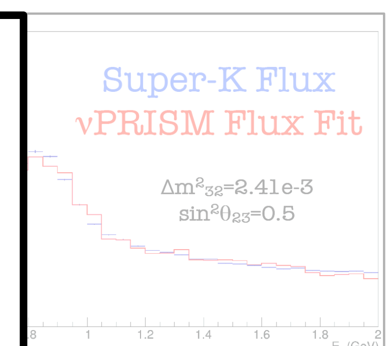
Take linear combinations





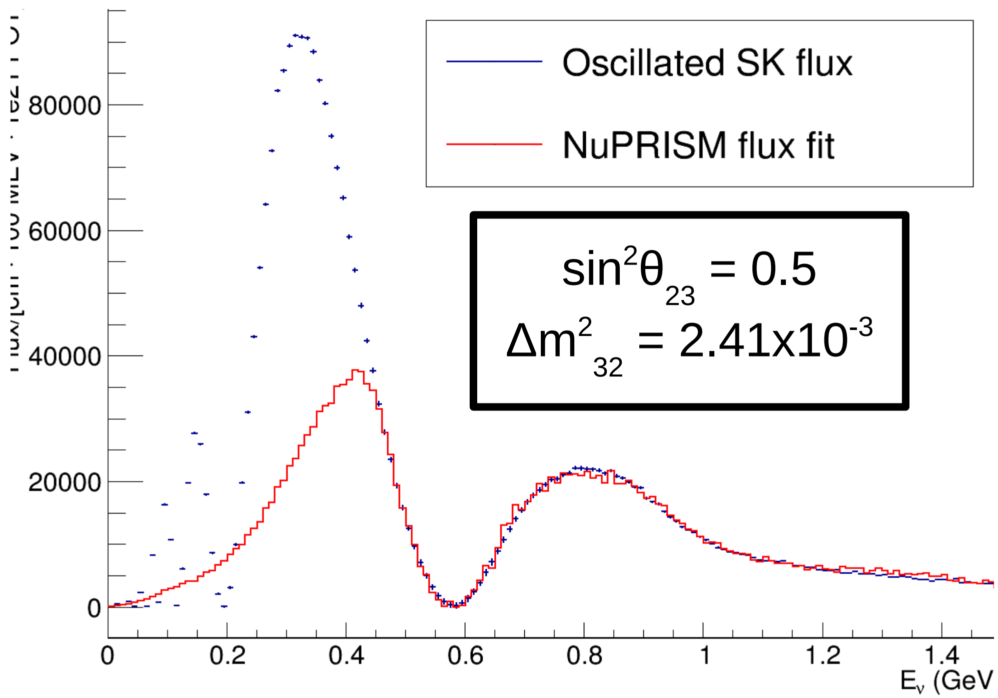
ν Oscillation with NuPRISM

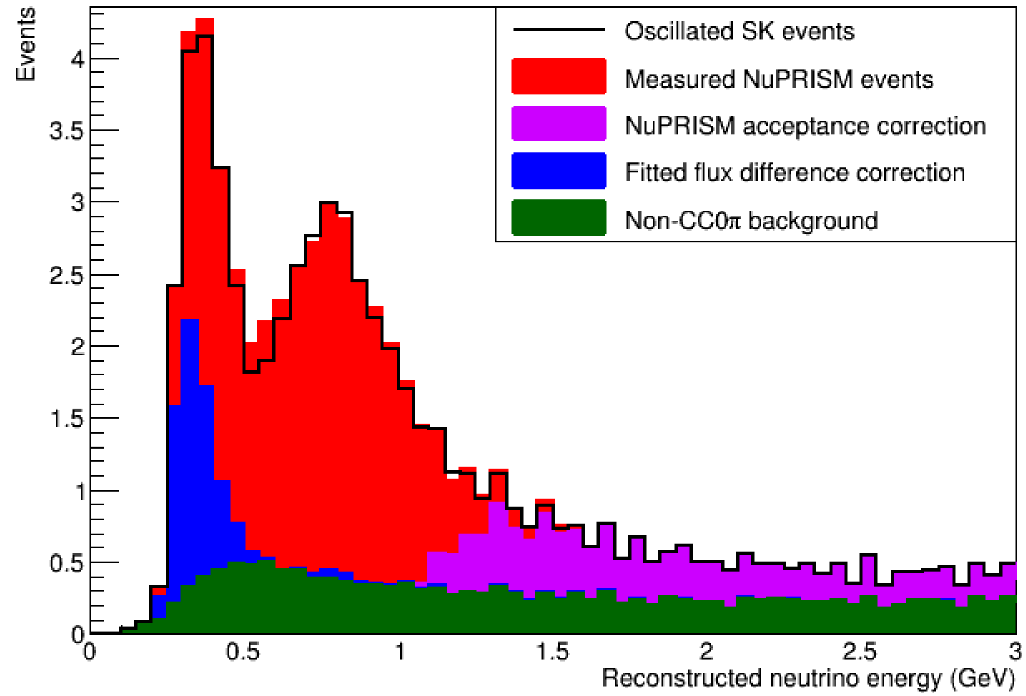




- Recreate oscillated neutrino flux at SK using near detector
- Directly measure muon p-θ for given value of oscillation parameters

NuPRISM ν Oscillation with NuPRISM TRIUMF

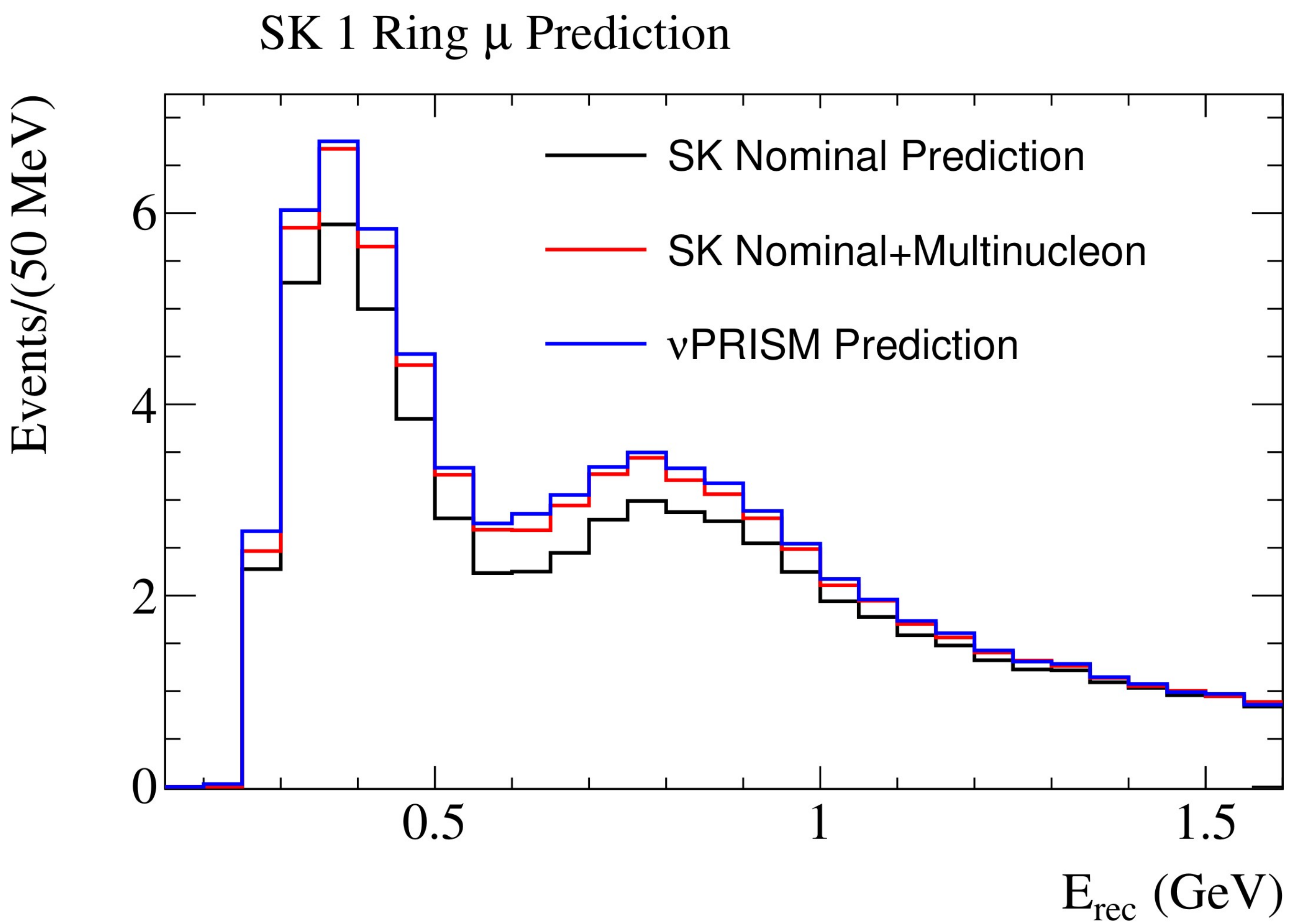




- Event rate = Flux(E_ν) * Cross-section(E_ν) * Efficiency
- NuPRISM and SK have water target – same cross-section
- If fluxes (and efficiency) match:
  - NuPRISM linear combination event rate == **oscillated** SK event rate
  - No cross-section model, no effect from wrong model choice, FSI, SI...
  - Directly compare to SK data to get oscillation parameters
- Corrections for different detector acceptances (magenta) and flux fit differences (blue) still use interaction model

Multi-Nucleon example

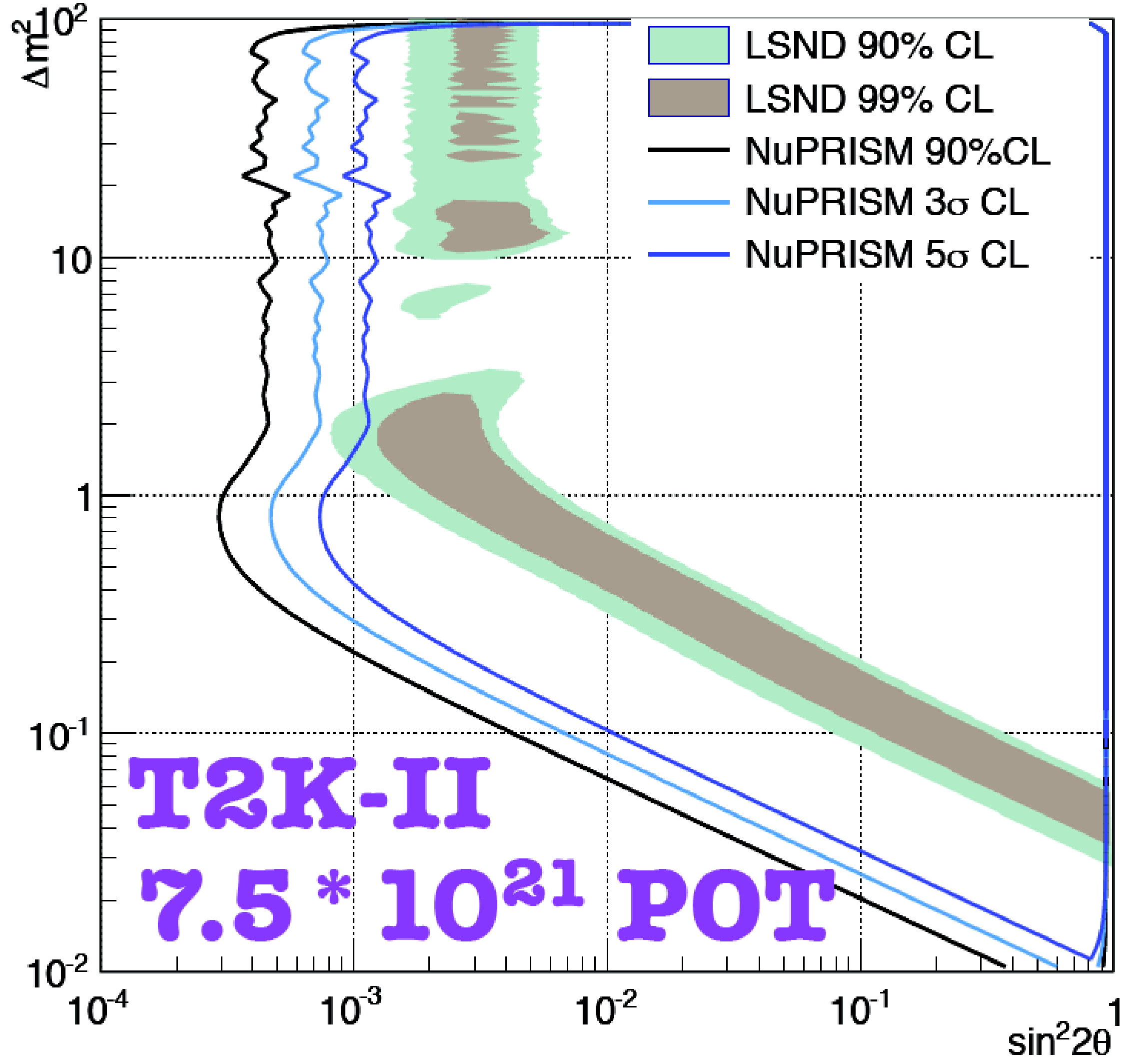
- Add multi-nucleon events to SK and NuPRISM MC to create fake dataset
  - Neutrino interaction model does not include these events
- Redo linear combinations using fake data
- NuPRISM correctly predicts SK event rate!



Sterile neutrinos

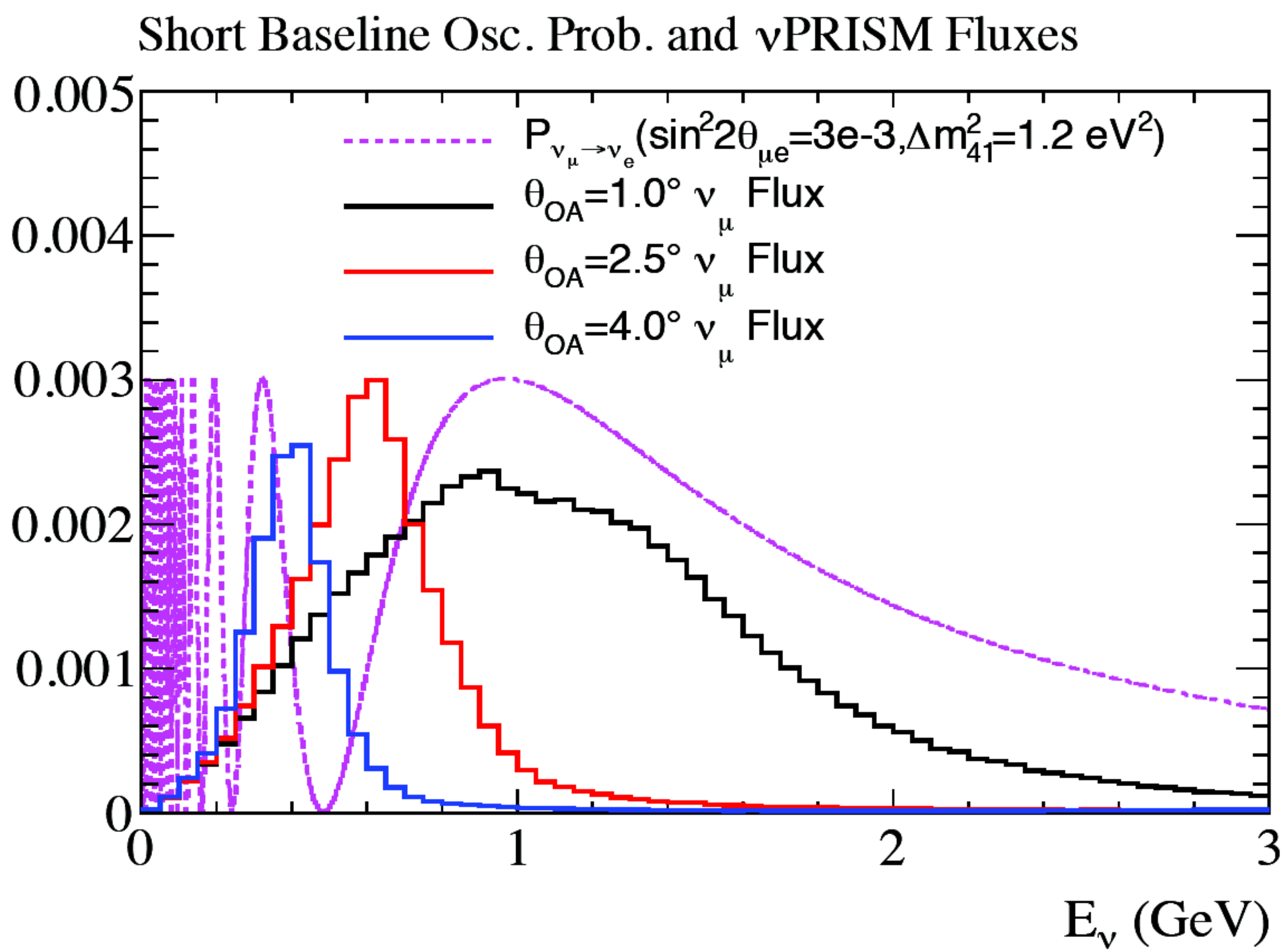
- NuPRISM neutrino fluxes peak at different energies for a given baseline
- Sterile oscillation has different energy dependency than background cross-sections → can separate them

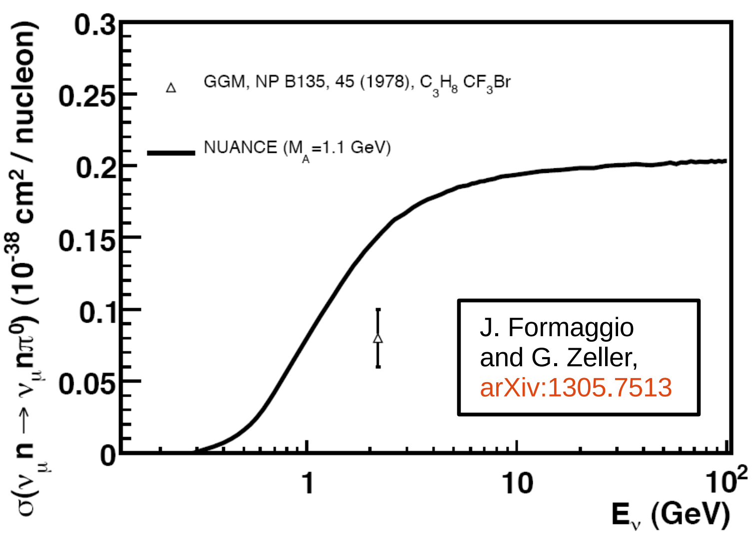
- Excludes (almost) entire LSND allowed region at 5σ
  - Comparable to Fermilab SBN
- Statistics limited!
  - Expect results to improve:
    - Full reconstruction and selection
    - Direct constraint of backgrounds
    - Include T2K near detector



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





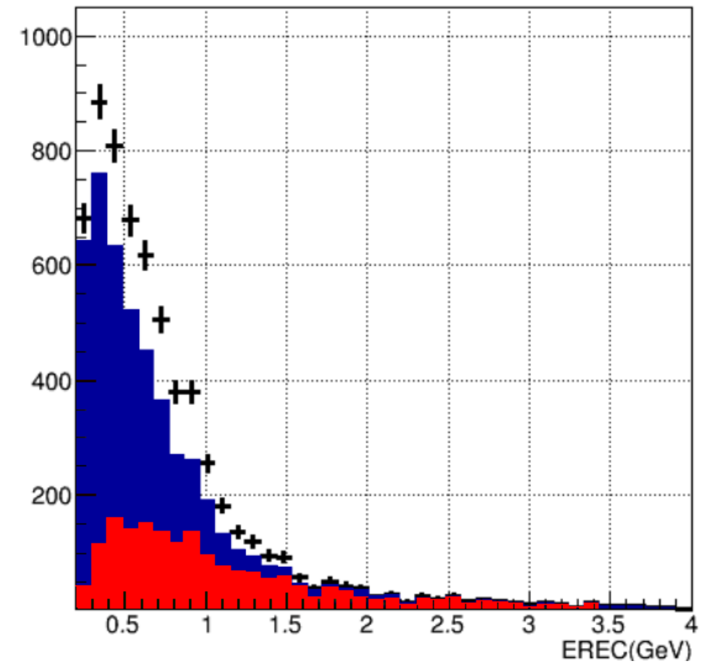
Signal and background

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

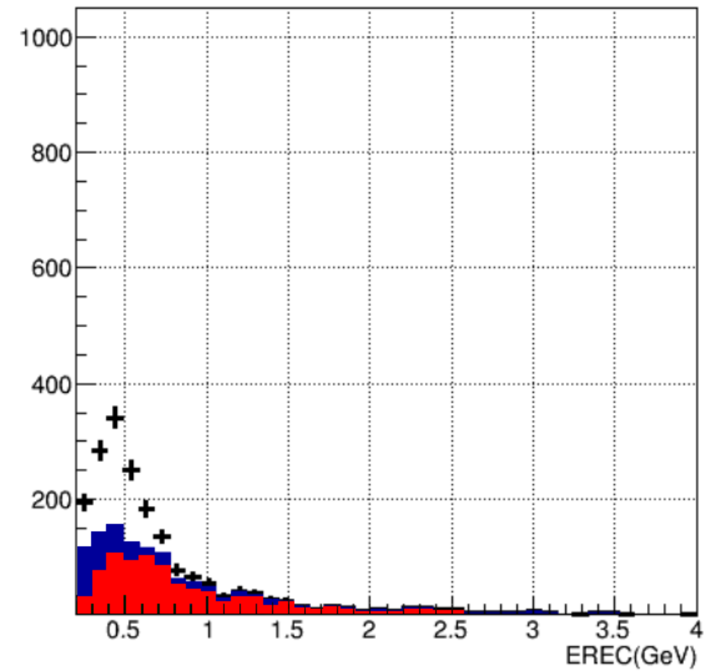
Points = Appearance signal
Red = Intrinsic ν_e bkgd
Blue = ν_μ bkgd

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

1.1-1.8 (°)

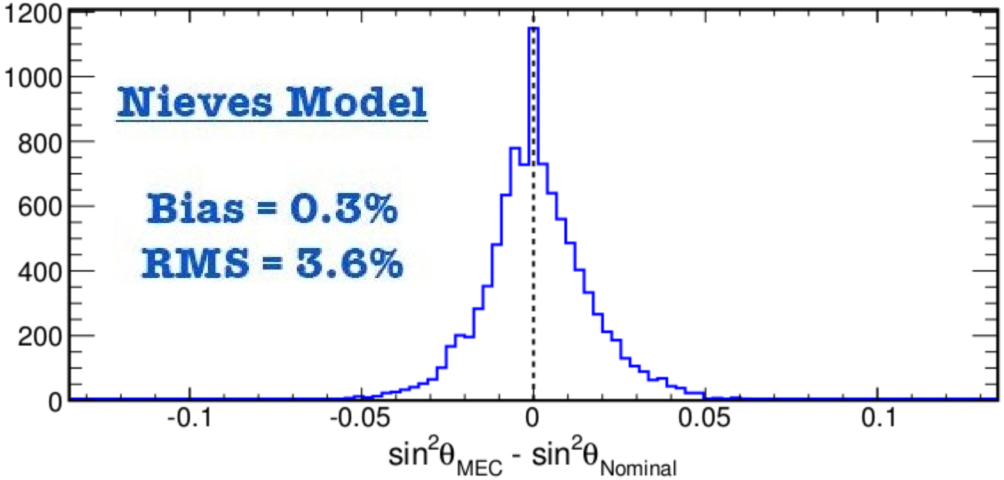


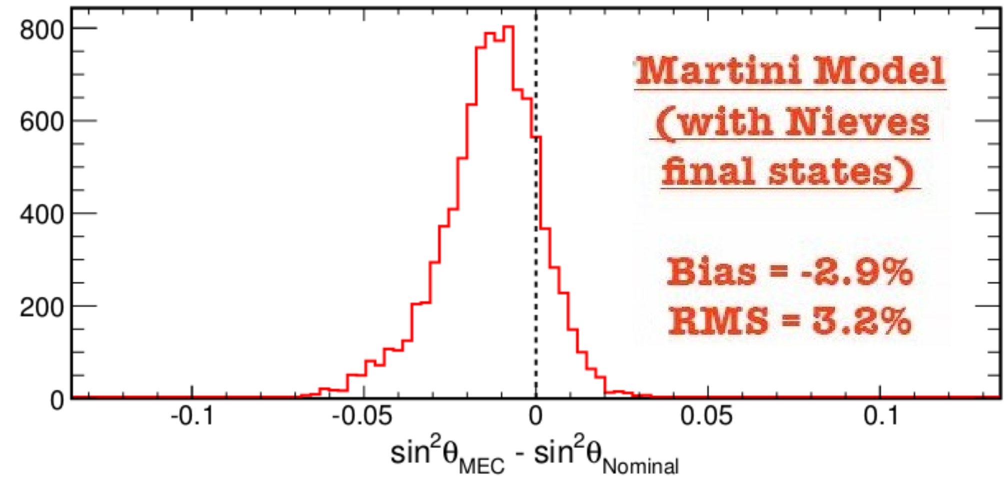
3.2-3.9 (°)



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



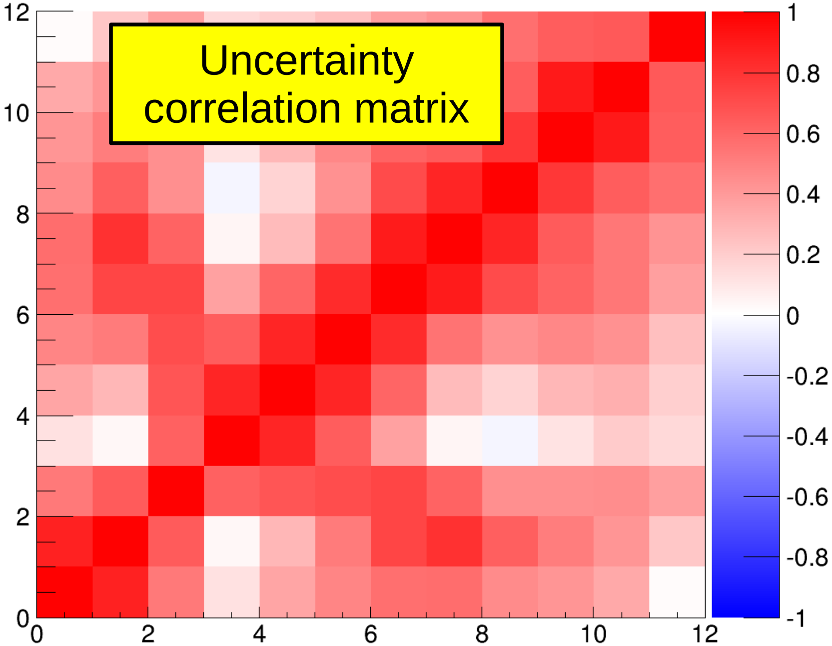


- Both models give ~3.5% RMS in $\sin^2\theta_{23}$, Martini model introduces ~3% bias
- Effects much smaller than current statistical uncertainty, but maybe large for future analyses

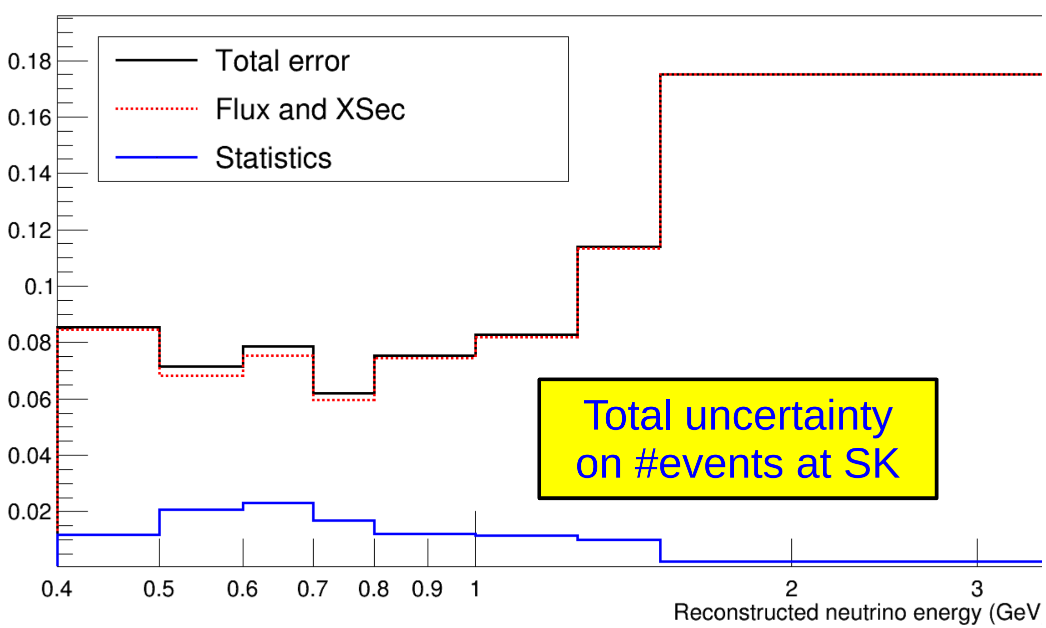
NuPRISM

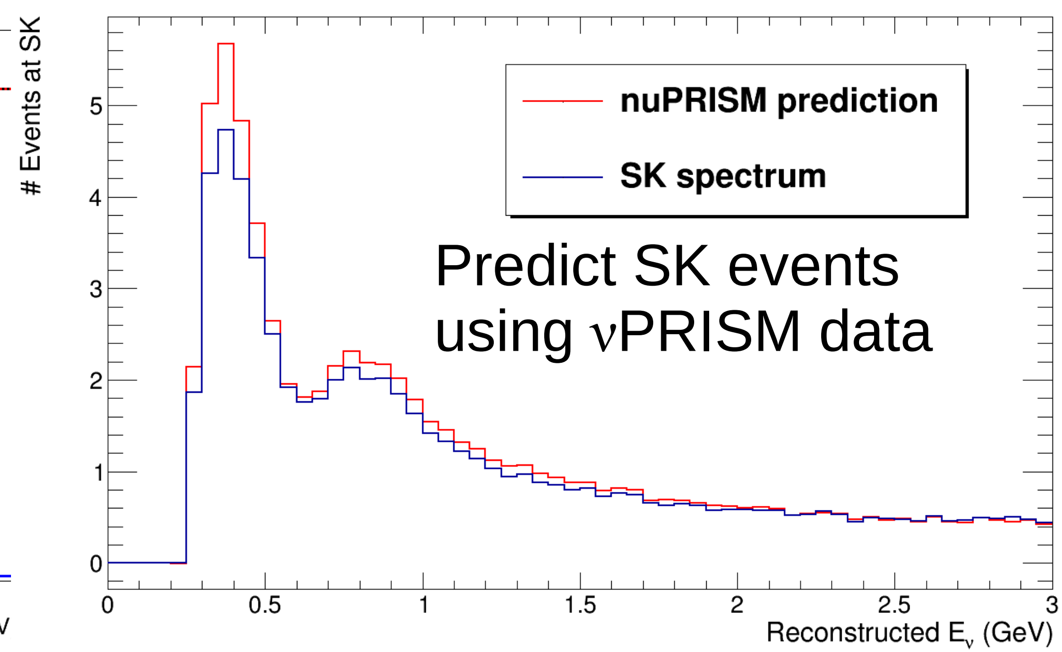
νPRISM disappearance analysis

TRIUMF



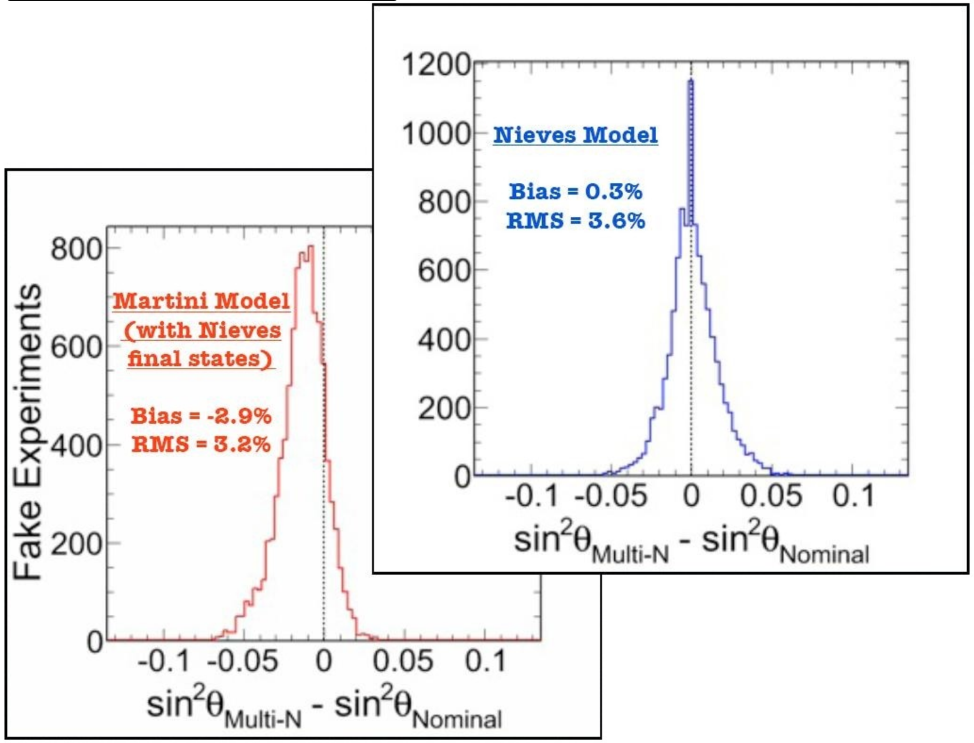
- Full analysis using νPRISM as near detector for T2K
- Take into account:
  - Statistical error from linear combinations
  - Neutrino beam uncertainties – direction, flux etc.
  - Interaction model uncertainties





Effect of multi-nucleon events at νPRISM

T2K analysis



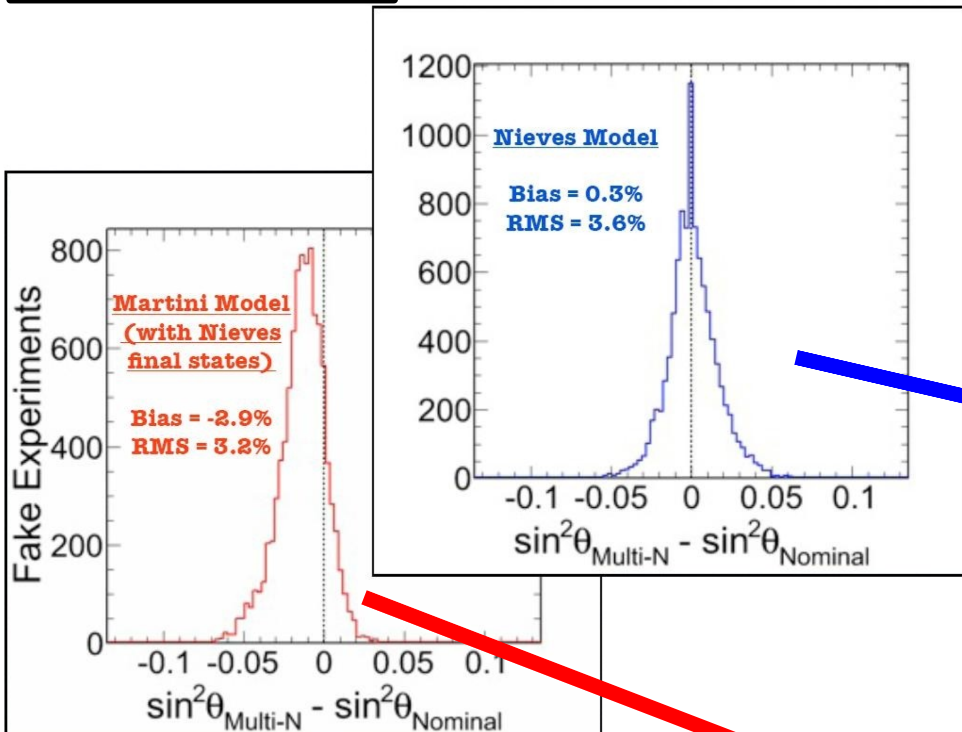
- Add np-nh events (Nieves and Martini models) to T2K fake data
- Perform disappearance fit to extract θ_{23}
- Compare to result from fit to nominal fake data

NuPRISM

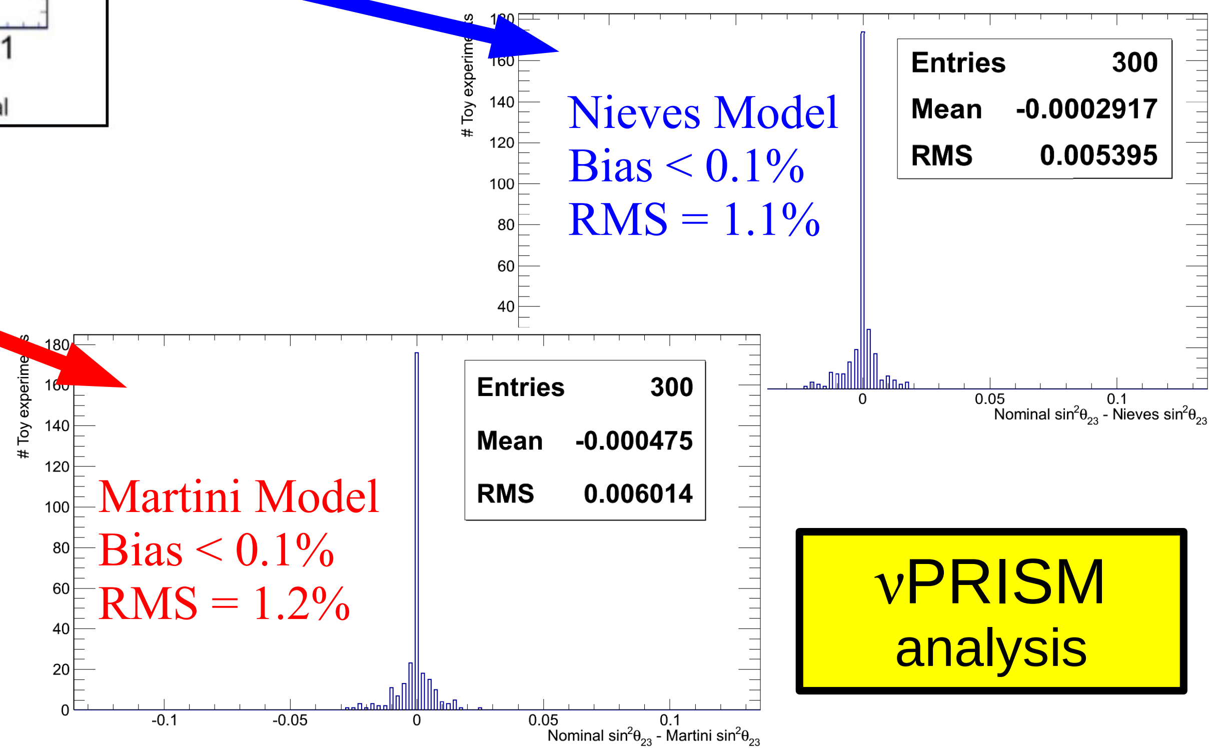
Effect of multi-nucleon events at νPRISM

TRIUMF

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

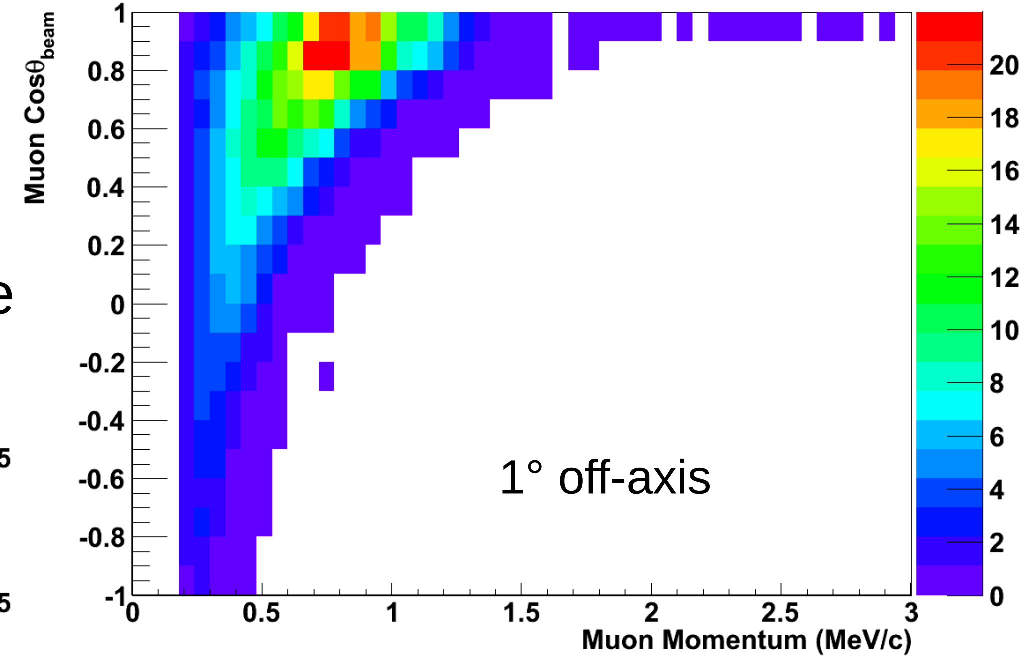


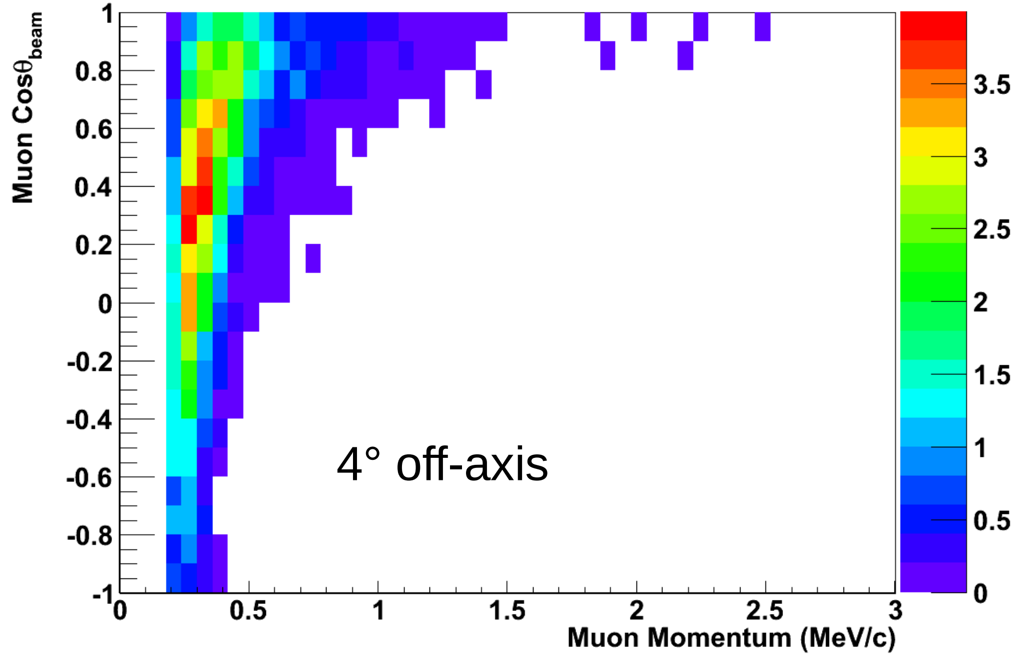
- Bias and RMS greatly reduced
- νPRISM analysis largely independent of cross section model

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