nuPRISM

Constraining Neutrino Energy Using Multiple Off-Axis Angles

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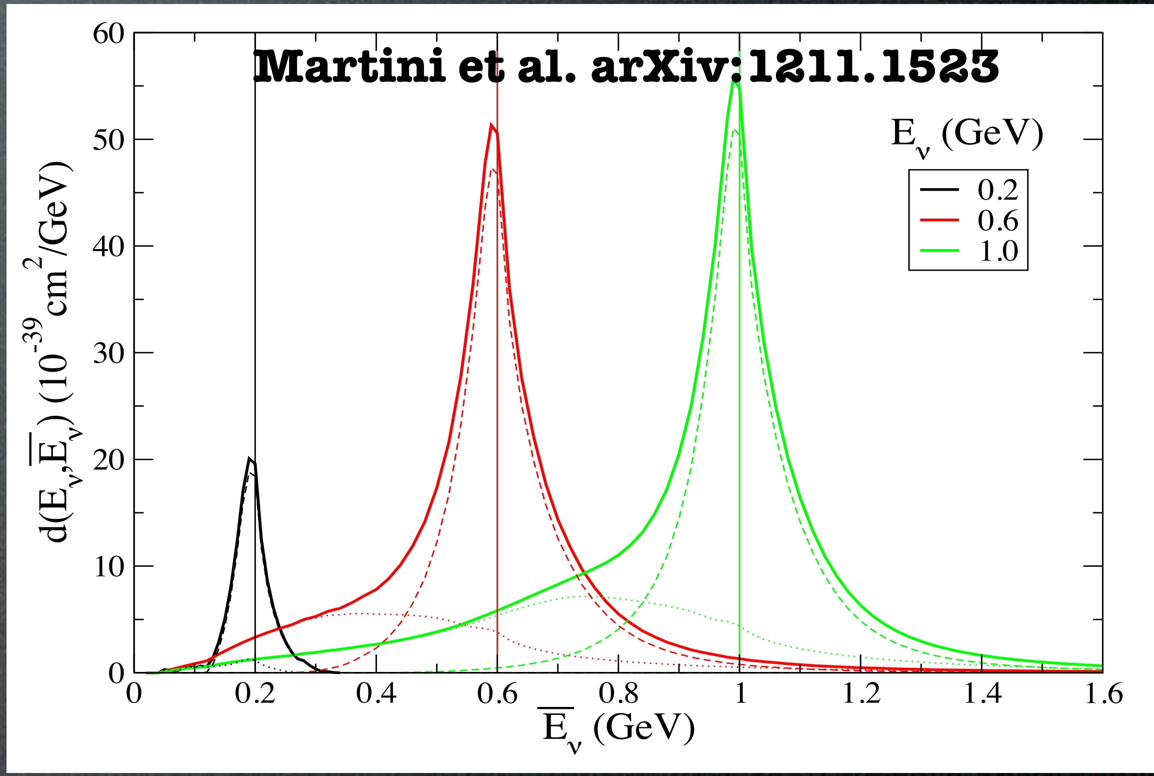
In collaboration with M. Hartz, T. Ishida, & A. Konaka

Requirements for a Hyper-K Near Detector

- 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
- A **water target** 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

Systematics of Energy Reconstruction

- 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 assumtions
  - Same near/far flux, same near/far detectors and performance
  - Since our actual situation is not as nice, these estimates are likely conservative

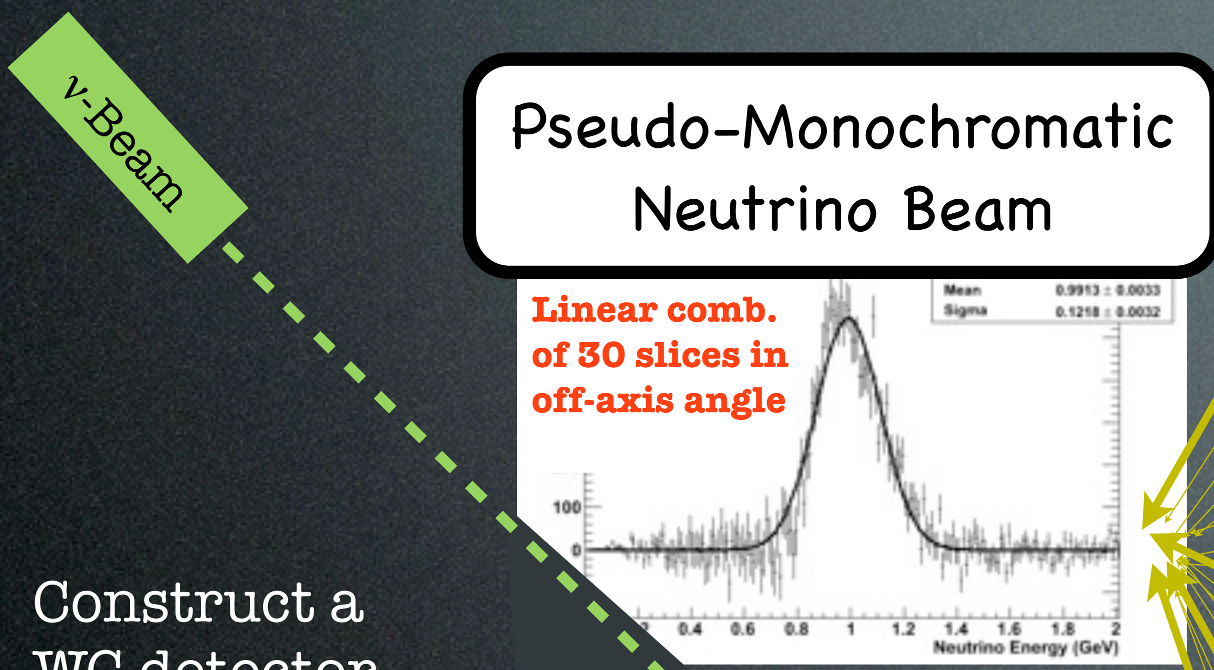
Fit results for true values **θ_{23}=45°** & **Δm^2_{31}= 2.45 * 10^{-3}**

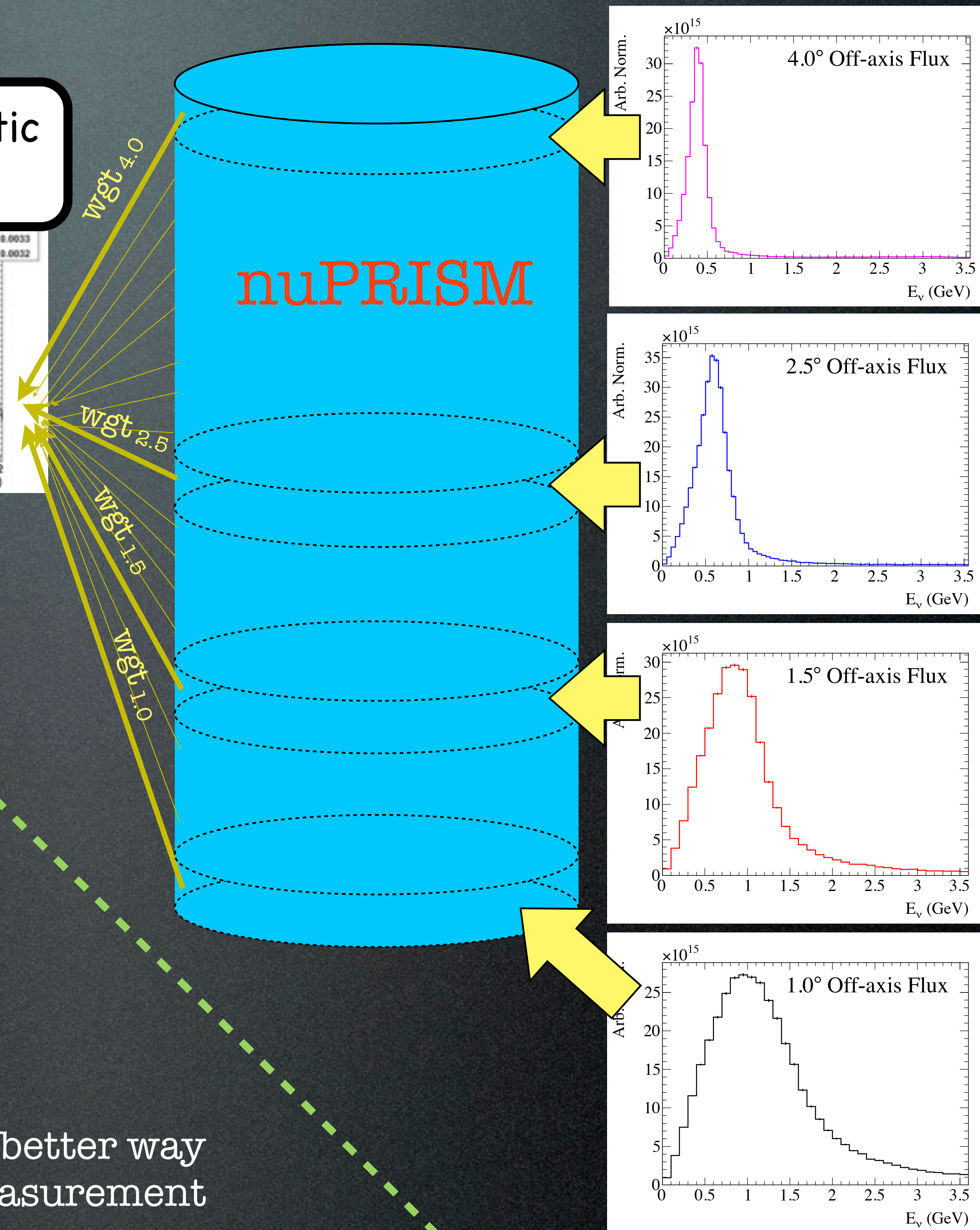
True	Fitted	$\theta_{23,min}$	$\Delta m^2_{31,min}[\mathrm{eV}^2]$	χ^2_{min}
GENIE (^{16}O)	GENIE (^{12}C)	44°	2.49×10^{-3}	2.28
GiBUU (^{16}O)	GENIE (^{16}O)	41.75°	2.69×10^{-3}	47.64
		47°	2.55×10^{-3}	20.95
GiBUU (^{16}O)	GiBUU (^{16}O) w/o MEC	42.5°	2.44×10^{-3}	22.38
GENIE (^{16}O)	GENIE (^{16}O)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

“Neutrino Prism” Detector Concept

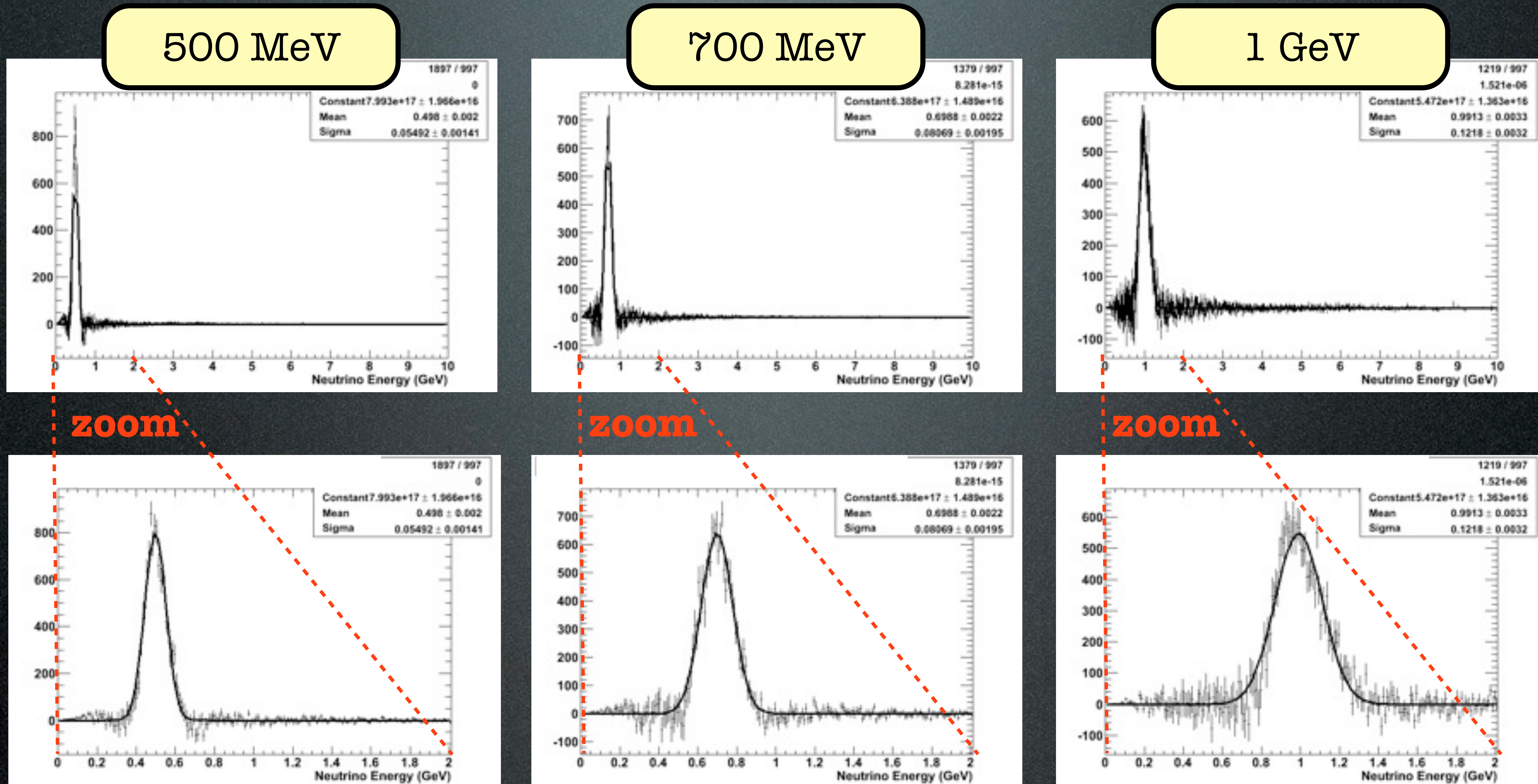




1. Construct a WC detector that spans 1° to 4° in off-axis angle
2. Logically divide the detector into 30 slices
3. Measure muon p,θ distribution in each slice
4. Take linear combinations of the measurements in each slice to get the p,θ distribution for a ~monochromatic neutrino beam

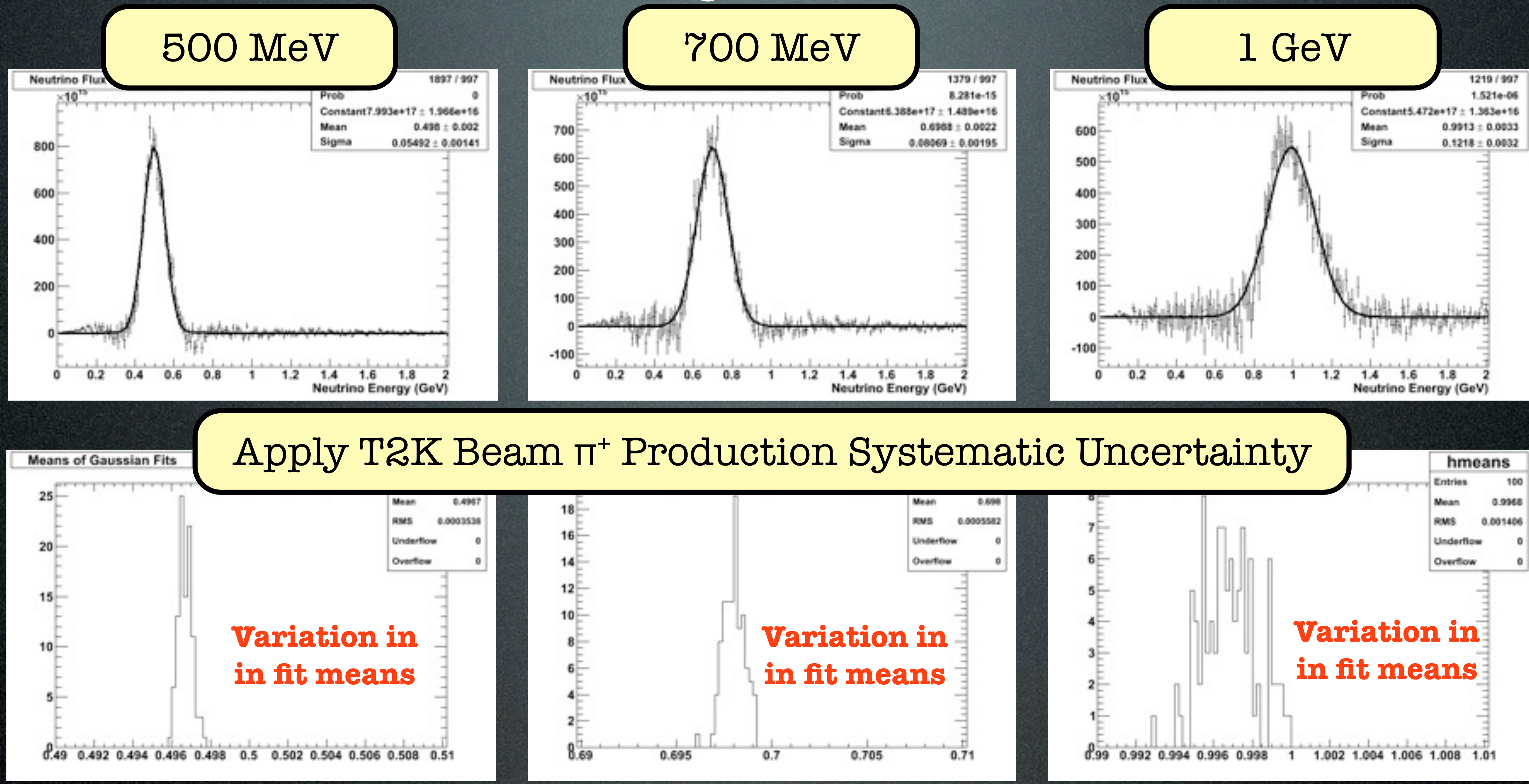
- This is just an example; there is likely better way to use the information from such a measurement

Neutrino Spectrometer



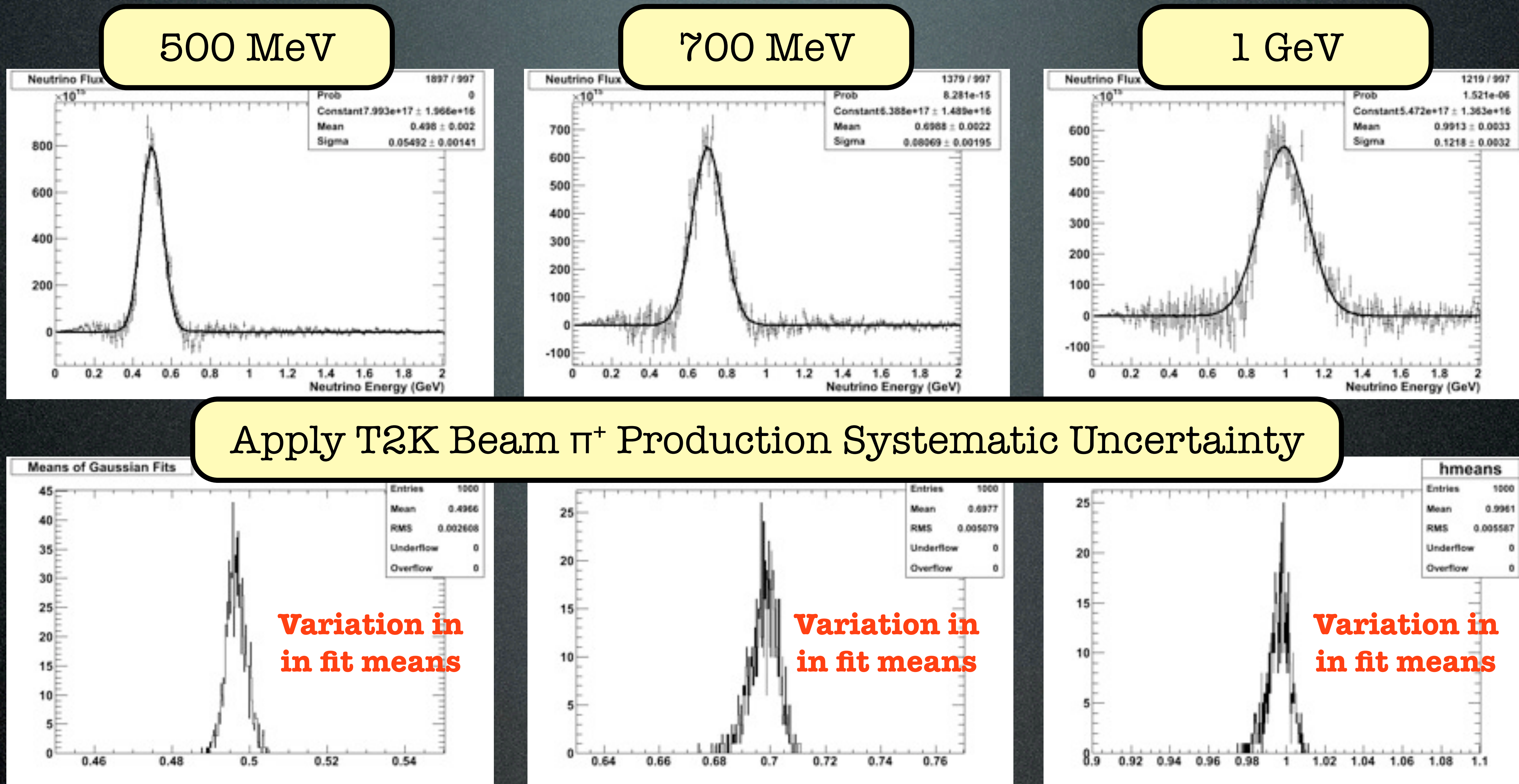
- Gaussian-like spectra can be produced for any choice of neutrino energy (between ~0.4 and ~1 GeV)
- High energy flux tail is canceled in all cases
  - The weights used for each of the 30 slices are given in the backups

Beam Systematics



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

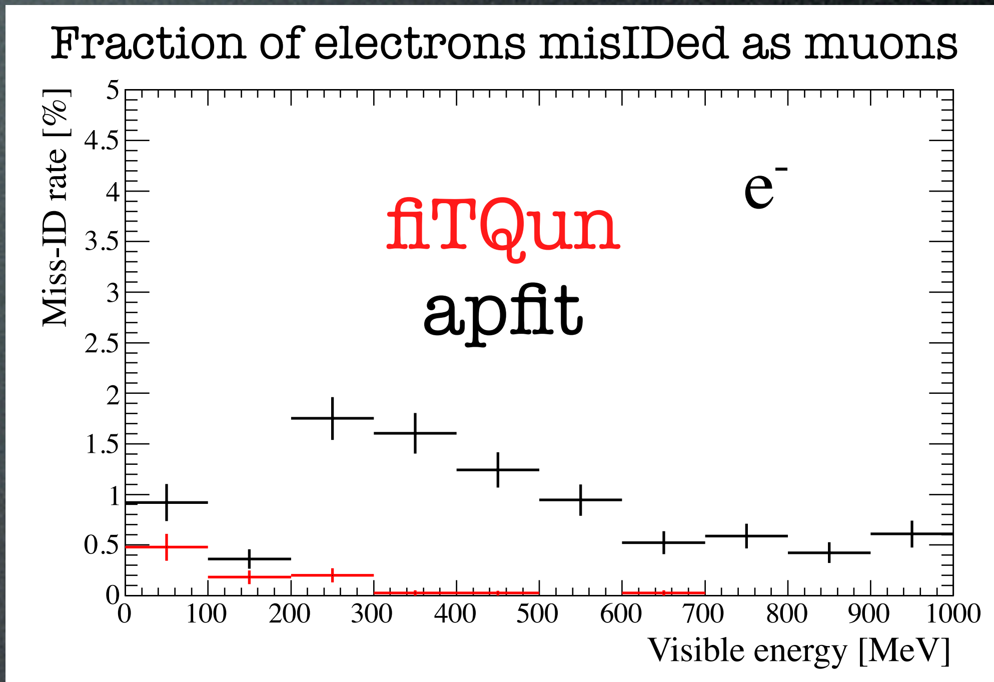
Detector Systematics

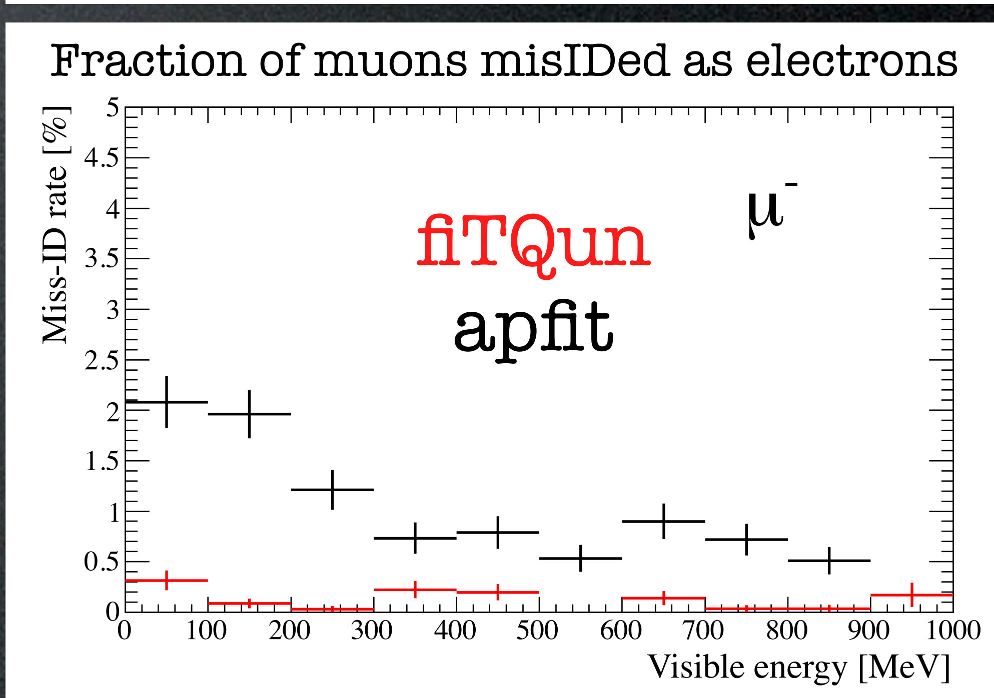


- Efficiency was randomly varied by 5% in each slice
  - The resulting variations in the fit means are still all below 1%
- Continuous variations across the detector can cause problems
  - Need homogeneous detector, and good monitoring & calibration

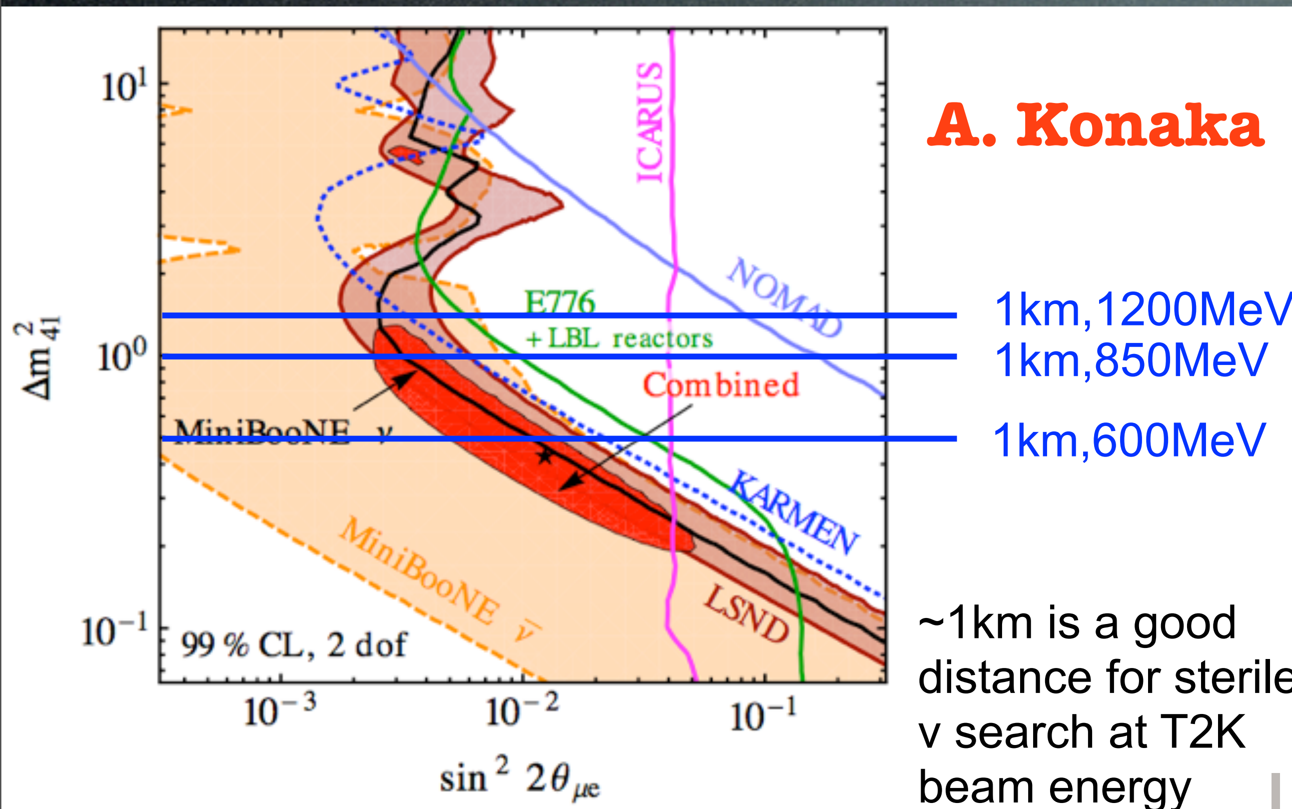
Physics Overview

- Direct measurement of the relationship between lepton kinematics and neutrino energy
  - No longer rely solely on models
- 4π detector (like HK)
- Target material is water (like HK)
  - Can directly measure NC backgrounds
- Very good e/μ separation
- Can make a precise measurement of beam ν_e
  - π^0 background can be well separated
  - May also be able to constrain ν_e cross sections
- Short baseline with multiple energy spectra provide a unique environment for sterile neutrino measurements





Sterile Neutrinos



~1km is a good distance for sterile ν search at T2K beam energy

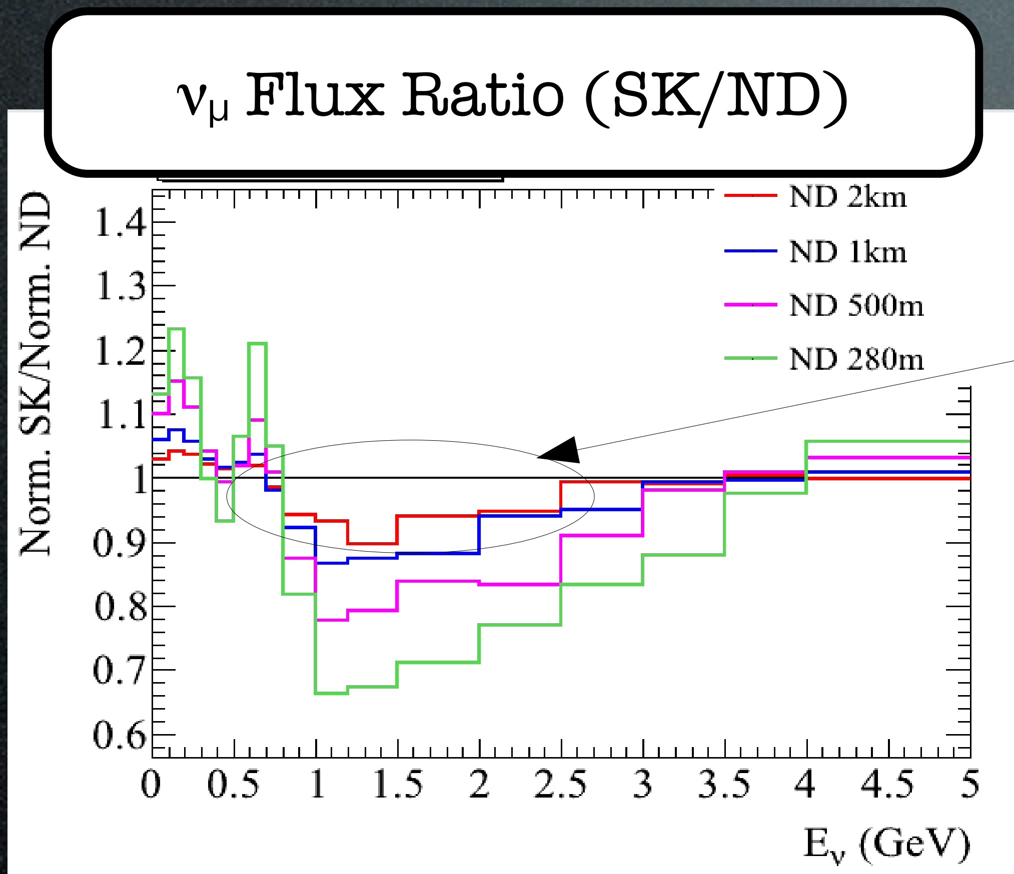
- Expected number of ν_μ CCQE:
  - 3×10^{20} POT (200kWx1year) at SK: 200 ν_μ evts
  - 1km detector with 100ton fiducial (per degree): $N\nu_\mu=200\times(295/1)^2\times(0.1/22.5)=80$k events

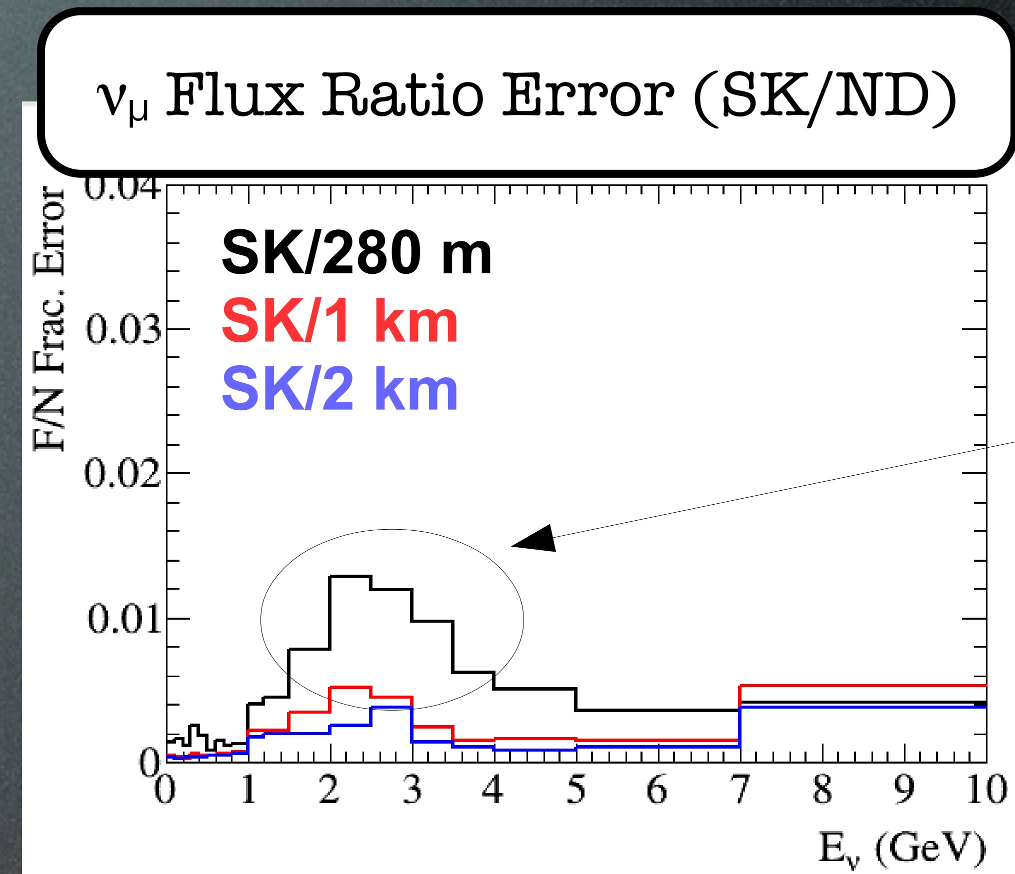
  4 m diameter fiducial
- For sterile mixing $\sin^2 2\theta_{\mu e}=10^{-3}$ at oscillation max.
  - signal: 80k x 10^{-3} = 80 events
  - beam ν_e BG: 80k x 0.5% = 400 evts [off-axis helps!]
  - sensitivity: 80/sqrt(400)=4σ for 1 year @ 200kW

  Current Beam Power
- Advantage of this approach:
  - Better S/N by tuning into oscillation max. off-axis angle
  - Redundancy: neutrino beam energy E_ν

- Back of the envelope calculations look very promising
  - Many repeated measurements for varying energy spectra
- Need to produce sensitivity contours with basic assumptions about detector performance

Design Considerations: Flux Ratio

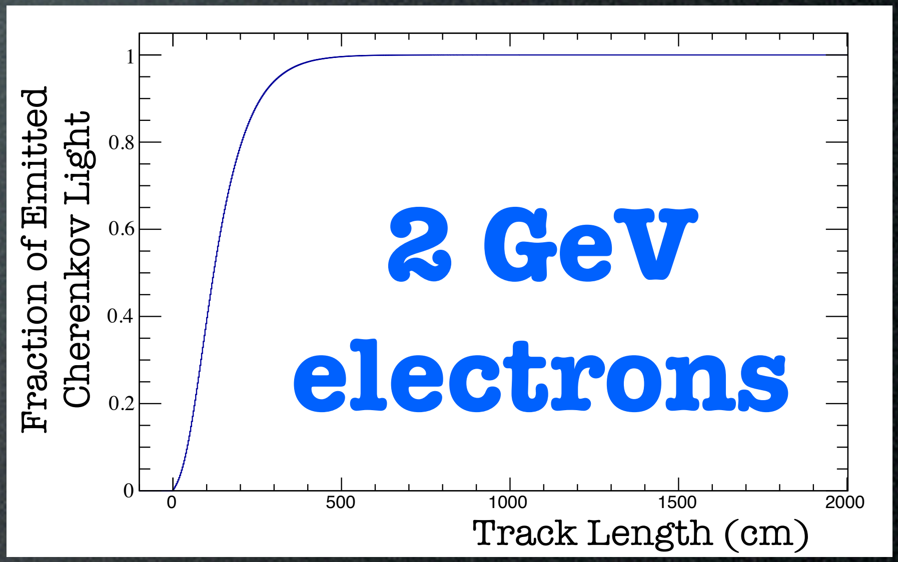


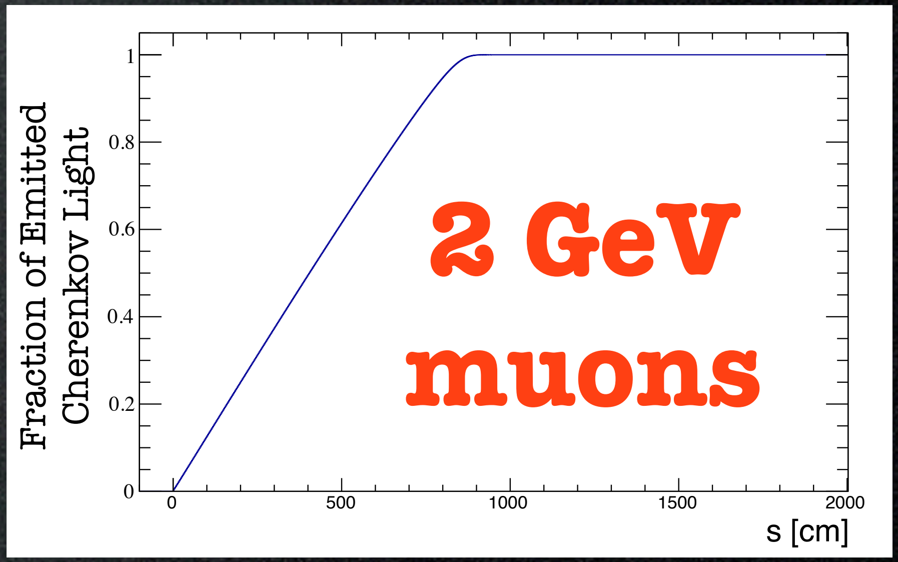


- At 280 m, both the flux shape has 20-30% differences below 1 GeV
  - Uncertainty in the ratio is noticeably larger, but mostly above 1 GeV
- The difference between 1km and 2km is small in both shape and shape uncertainty

Design Considerations: Tank Size

- The tank height is proportional to the distance from the target (off-axis angle range is fixed)
  - D = **280 m** ⇒ H = **15 m**
  - D = **1 km** ⇒ H = **50 m**
  - D = **2 km** ⇒ H = **100 m**
- Beam points 3.62° downward (target elevation = -1.955m), so detector may extend a few meters above ground depending on the site elevation
- Tank diameter is determined by the maximum muon momentum we wish to measure (in the forward direction)
  - **2.0 GeV/c** muons => 9 m (+ FV cut)
  - **1.5 GeV/c** muons => 6.5 m (+ FV cut)
  - **1.0 GeV/c** muons => 4 m (+ FV cut)
  - Electron range does not vary much with momentum

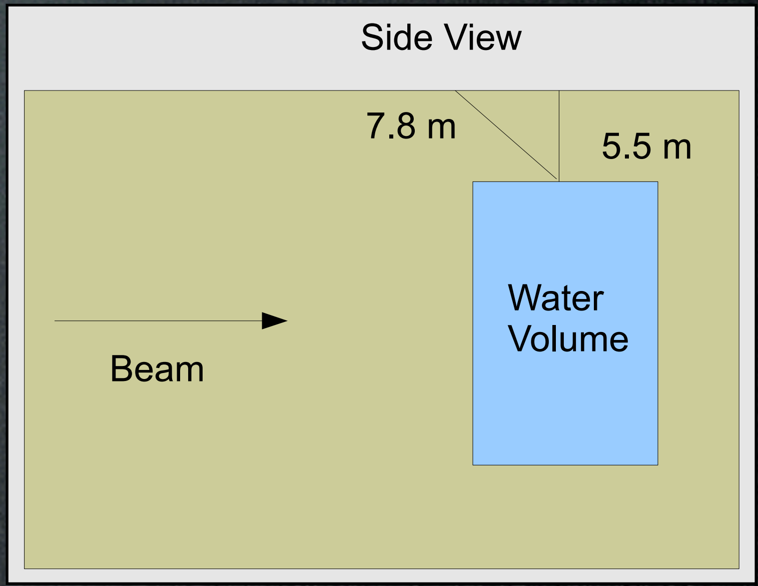


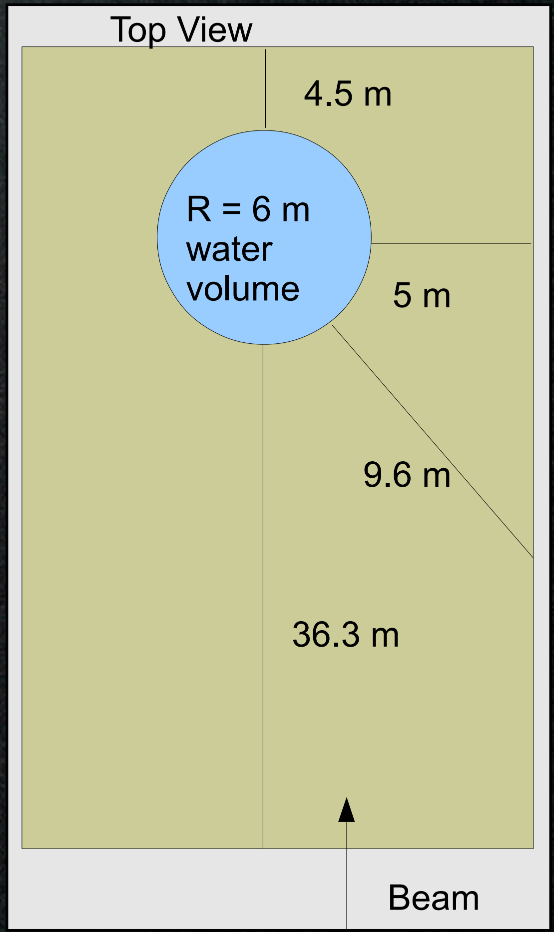


Design Considerations: Event Pileup

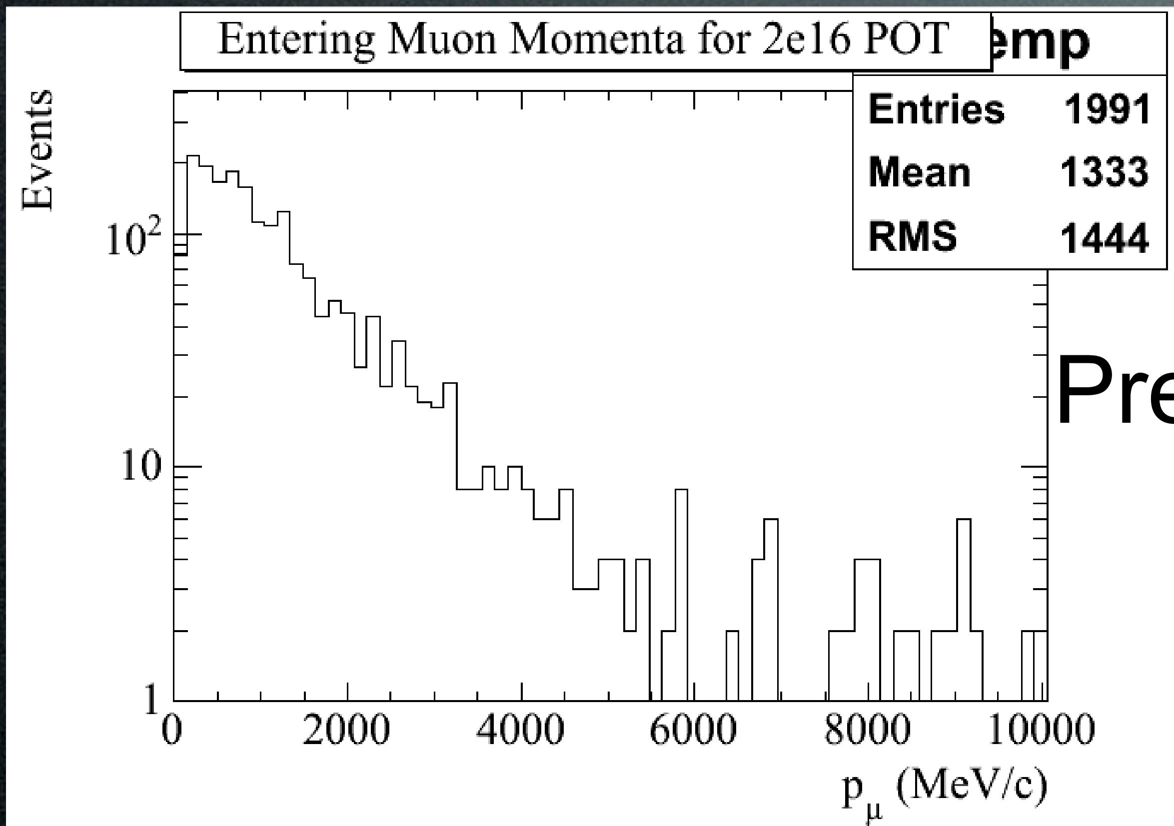
M. Hartz

- T2K flux calculation and neutgeom have been extended to produce neutrino vectors in nuPRISM geometry
- Simple GEANT4 simulation of water volume and surrounding sand
    - SiO_2 (1.5 g/cm3) and H_2O
- First simulation at 1 km, spanning -0.5° to 0.8° (22m high) and 6m diameter
- 1e8 ν-interactions in water per 1e21 POT

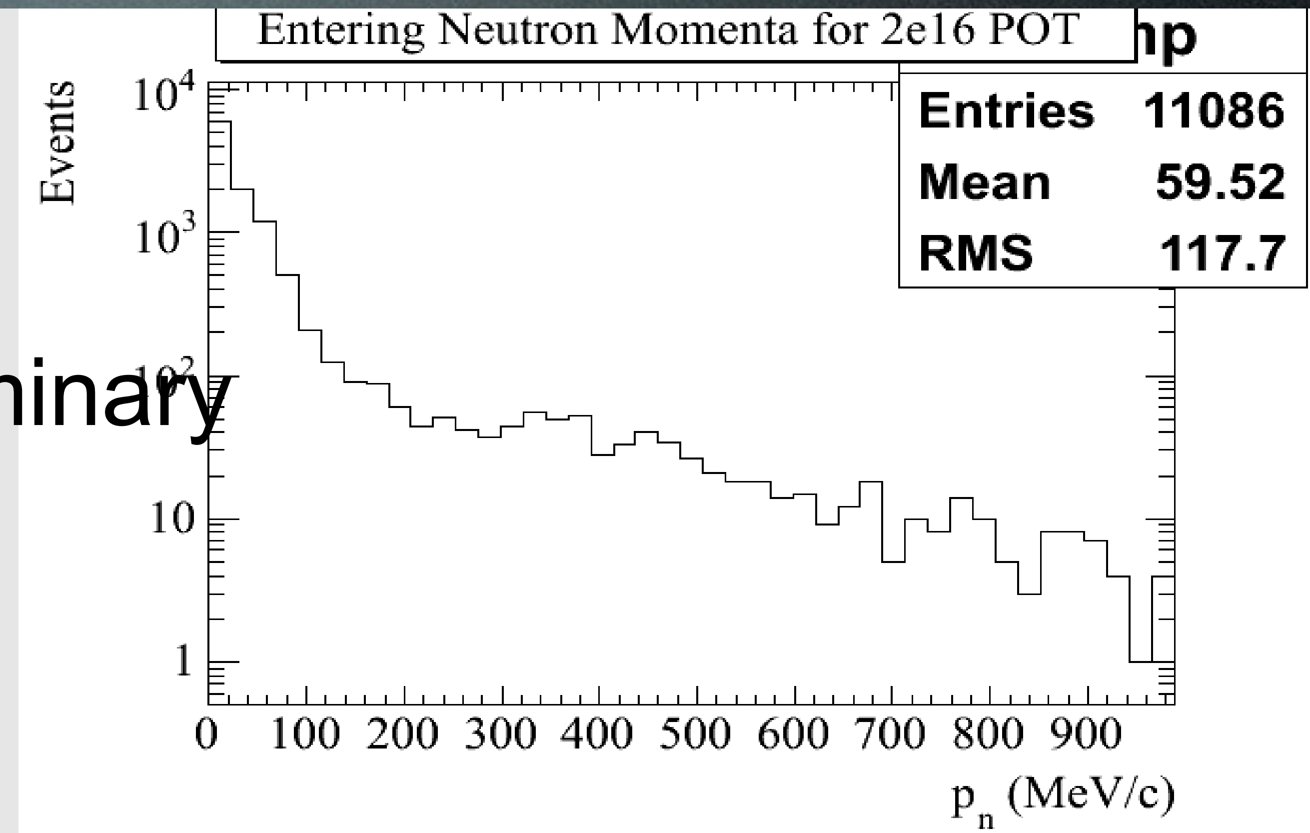




Simulation Results

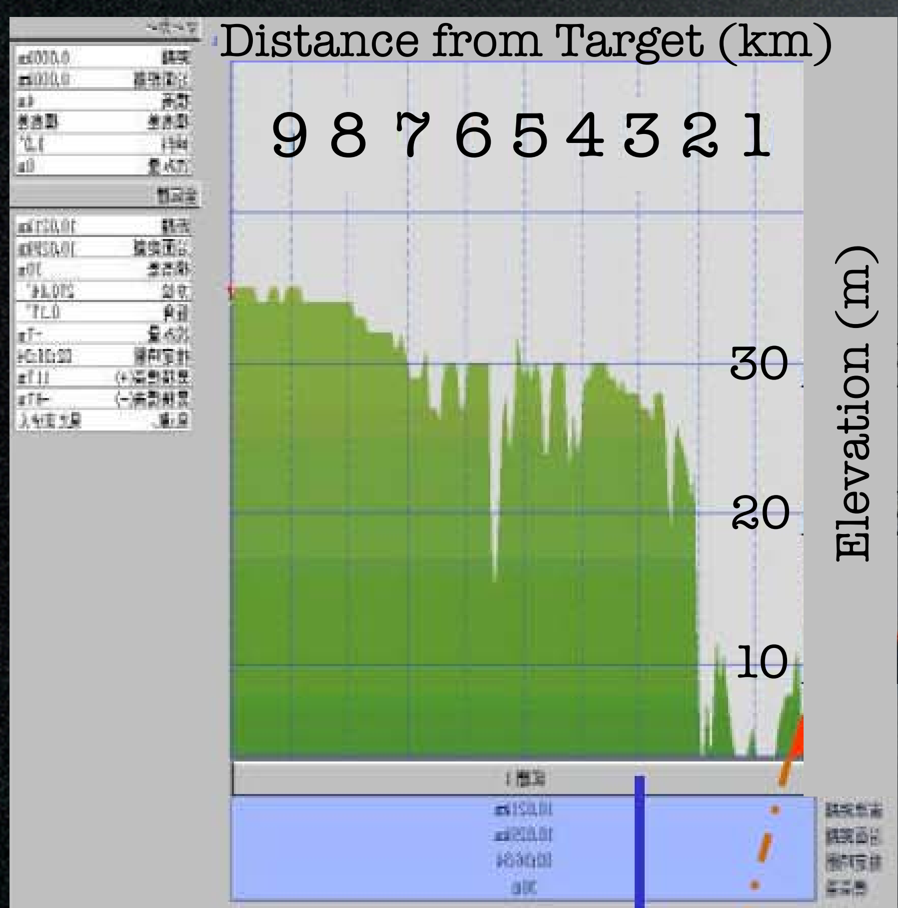


Preliminary



- At 700 kW (2e13 p/bunch), 2 sand muons per bunch enter the water volume
  - 10-15% of bunches have no sand muons
  - On axis rate (-0.5° to 0.8°) is higher than we expect at (1° to 4°)
  - Overlapping rings can likely be disentangled
  - Could consider a cylindrical tank to further reduce the rate
- 11 neutrons per bunch reach the water
  - Very low energy; will not produce rings
  - Nearly all will be stopped in an outer detector

Potential Detector Locations



- Non-rice-field locations at 750m, 1km, and 1.2km
  - Although, for the original 2km detector, Kajita-san considered rice fields as well
- Beyond 2km, the elevation spikes
  - Would need 30m deeper hole

Near Detector Site Slideshow

Cost Considerations

- Original T2K 2km proposal gives a very good reference for initial cost estimates (from 2005)
- Civil construction for nuPRISM should be cheaper
  - Similar pit depth
  - No need to excavate an underground cavern
  - Cheaper pit digging techniques are now available
- $1,000 per 8-inch PMT, including electronics
  - H=60m, D=6m, 40% coverage = ~15,000 PMTs
  - Different photodetectors and electronics should be explored (LAPPDs?)

2km detector

ITEM/SYSTEM	TOTAL COST
Hall Excavation/Construction	9.63 US M$
Surface Buildings	0.77
Air-Conditioning, Water and Services	0.50
Power Facilities	0.68
Cranes	0.08
Elevator	0.23
TOTAL	11.9 US M$

ITEM/SYSTEM	TOTAL COST
5660 8" PMTs	3.79 US M$
5660 25m cables	0.10
5660/2 SHV connectors	0.13
TOTAL	4.02 US M$

Qty	Description	Unit Cost	Total cost
4	HV Mainframe (16 slots each)	$12,760	$51,000
45	HV Module (12 channels each)	1,895	85,300
27	9U VME crate (20 cards each)	200	5,400
520	Paddle Card	345	179,400
14	Power supply for paddle cards	490	6,900
27	remote controller card (1/crate)	400	10,800
14	19" electronics rack (1/2 crates)	1,000	14,000
520	20' HV cable with SHV	60	31,200
520	12-channel custom data cables	70	36,400
1	Linux PC for control	1,500	1,500
–	Mobilization, shipping	–	2,500
5660	Custom Readout Electronics	200	1,132,000
	Total (including spares)		1.56 US M$

ITEM/SYSTEM	TOTAL COST
25 gpm Reverse Osmosis Unit	$ 25,500
Pre Treatment Equipment	15,500
Post Filters	15,000
Ultraviolet Sterilizers	5,000
Make up Tank System	5,000
Chiller and Heat Exchanger	50,000
Monitors and Controls	45,000
PLC Control	30,000
Install materials	60,000
Install Labor	50,000
Engineering	5,000
Estimated freight to Japan	15,000
TOTAL	0.32 US M$

Next Steps

- Simulation of nuPRISM flux + neut integration are already available
- Need a to perform a complete toy analysis with realistic statistical errors
  - Ultimate uncertainties with the linear combination method need to be better understood
- Real reconstruction tools are needed to understand whether sand muon pileup can be disentangled from signal rings (or whether we must veto all events with entering muons)
  - Luckily, the current version of fiTQun can be easily adapted if the detector geometry is cylindrical
- The linear combination method may not be the best way to extract the relationship between muon momentum and neutrino energy
- Need to study how well this procedure works for anti-neutrino running when the wrong-sign background is large

Conclusions

- T2HK physics goals require a better understanding of neutrino interaction cross sections than is currently available
  - We need a direct measurement of the relationship between lepton kinematics and E_ν
- nuPRISM can produce a direct, data-driven constraint on this relationship
- nuPRISM also provides measurements of many important backgrounds on water
  - Beam ν_e flux (and some cross section constraint)
  - $CC\pi^+$, $NC\pi^+$, $NC\pi^0$, ...
  - Even measurements of NC interactions as a function of E_ν are possible
- R&D has begun concerning detector design, facility acquisition, and physics sensitivities
  - However, many areas for new people to contribute