Proposal for a Hyper-K Near Detector

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3rd Open Hyper-K Meeting
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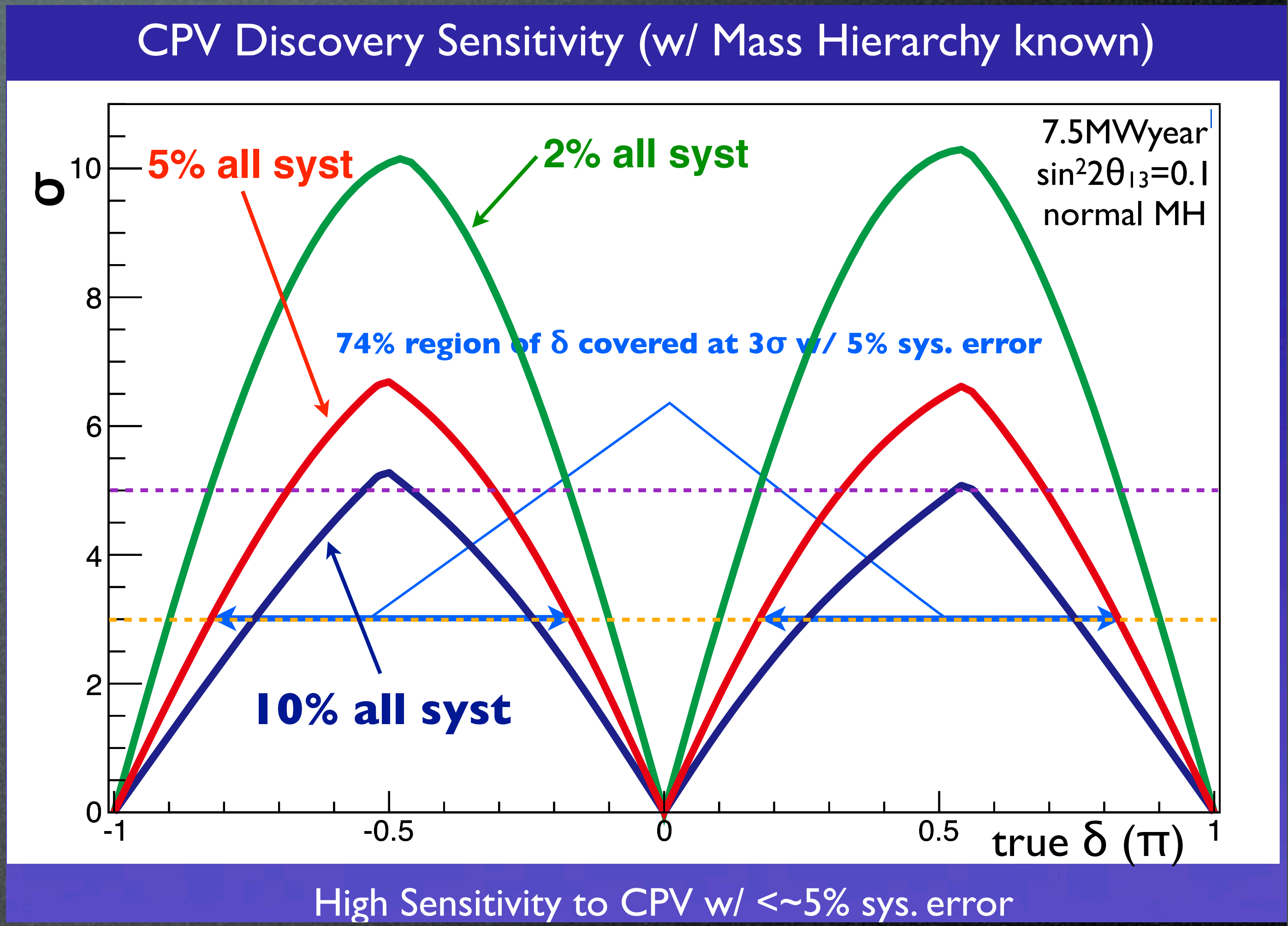
based on a conglomeration of ideas from
Mark Hartz, Akira Konaka, Kevin McFarland,
T2K 2km Detector Group, ...

Systematic Errors on δ_{CP}

- T2HK: 10 year run with a 750 kW beam
- With a 5% systematic error on the event rate, δ_{CP} measurement will be systematics limited
- To exploit the full physics potential of T2HK, need to reduce the systematic error to 2%



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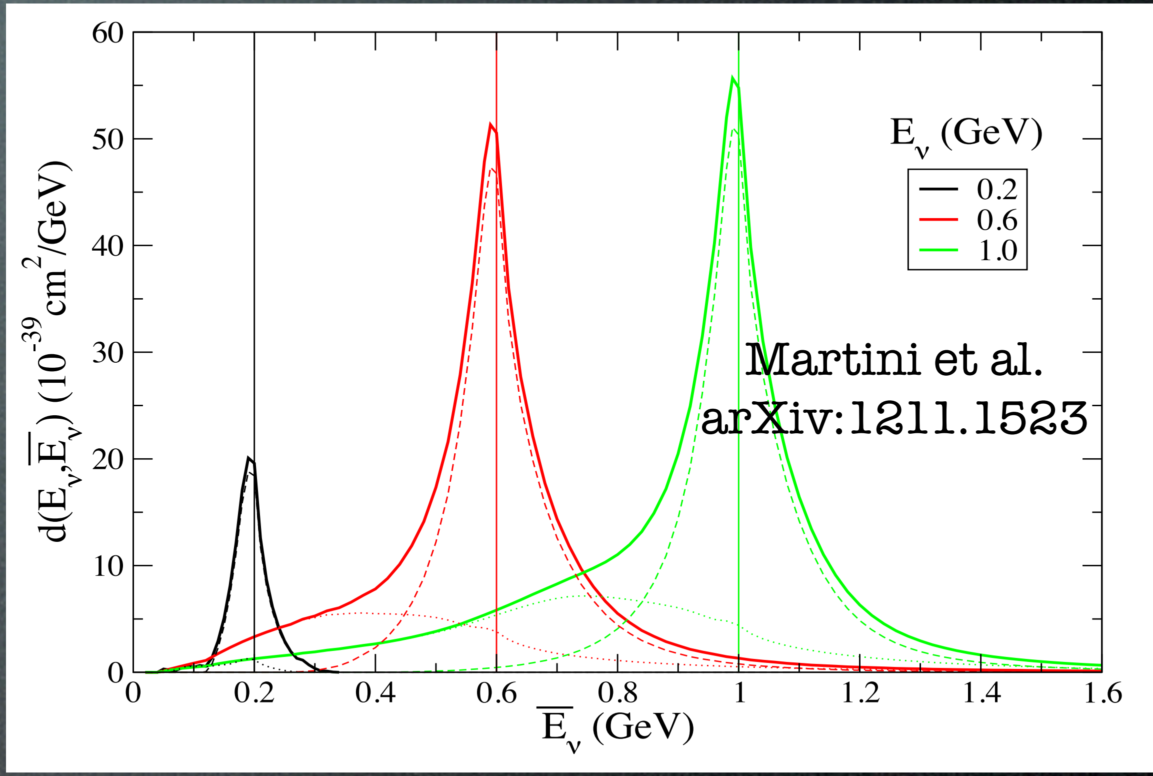
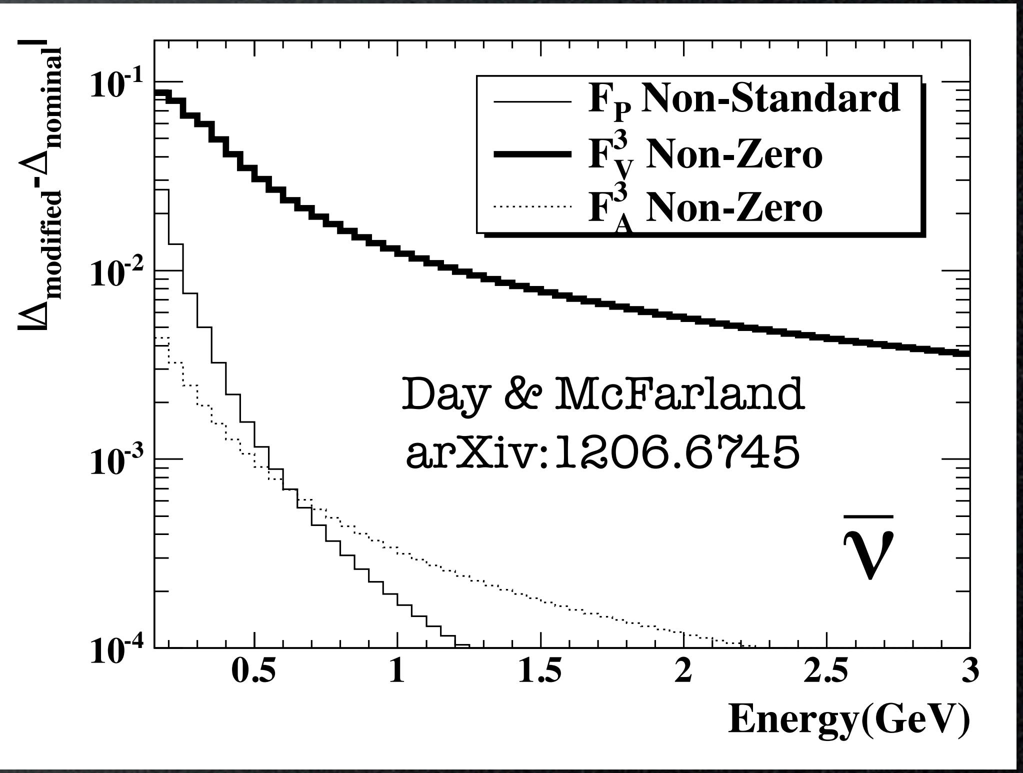
Challenges to Get to 2%

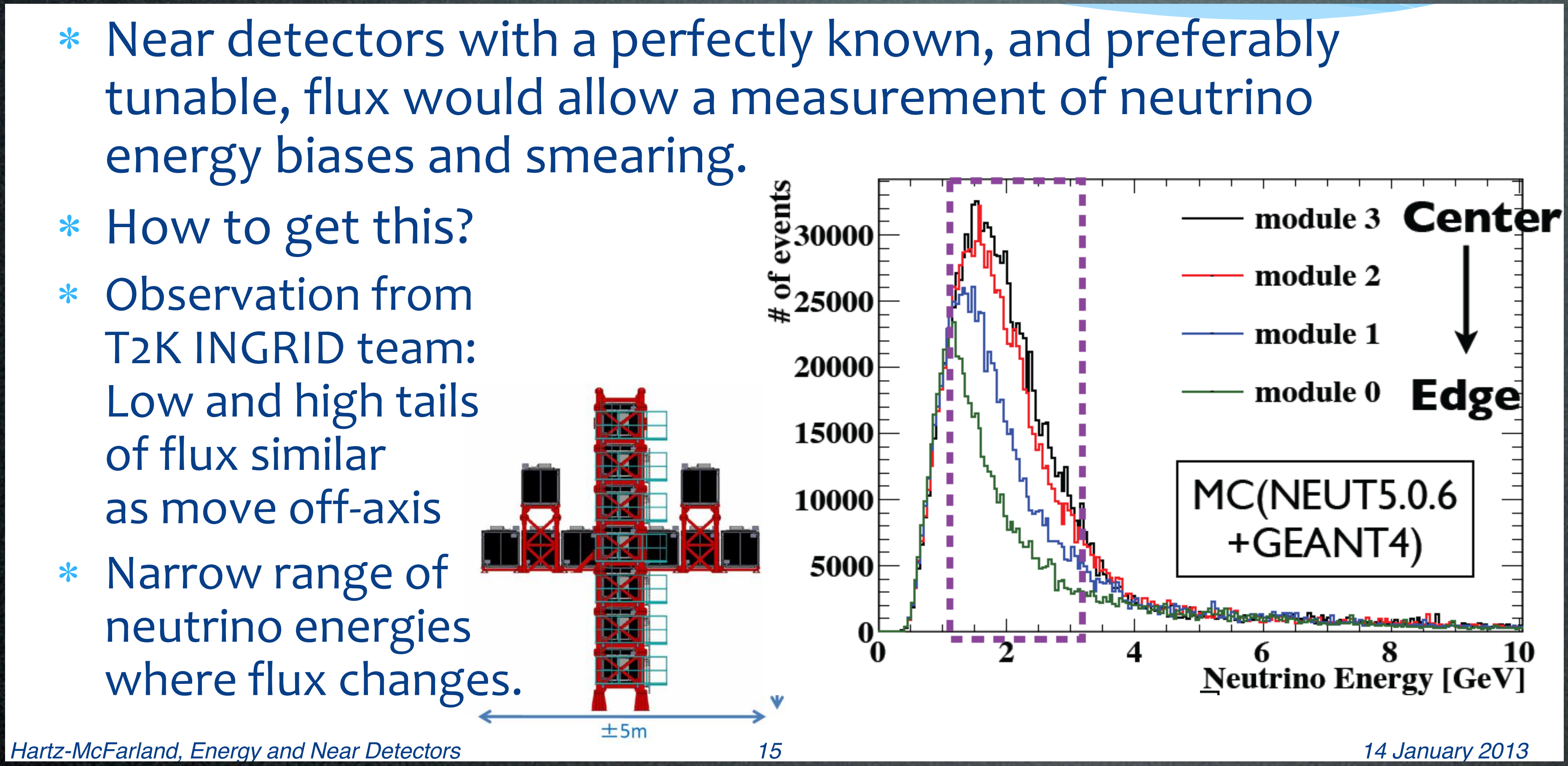
- **Relating lepton kinematics to neutrino energy**
  - **nuclear effects** (Fermi motion of target nucleons, off-shell effects, mixing of exclusive final states, multi-nucleon correlations)
  - **Relying on models** (with the help of external cross section measurements) **may not be sufficient to reach 2%**



- **Constraining ν_e cross sections**
  - ν_e cross section data is scarce
  - ν_μ and ν_e are impacted differently by nuclear form factors
    - Affects can be different for neutrinos and anti-neutrinos (and at 2% level)
    - **Could mimic CP violation**
    - May be able to constrain form factors with precise $\nu_\mu/\overline{\nu}_\mu$ measurements as well



Off-Axis Effect



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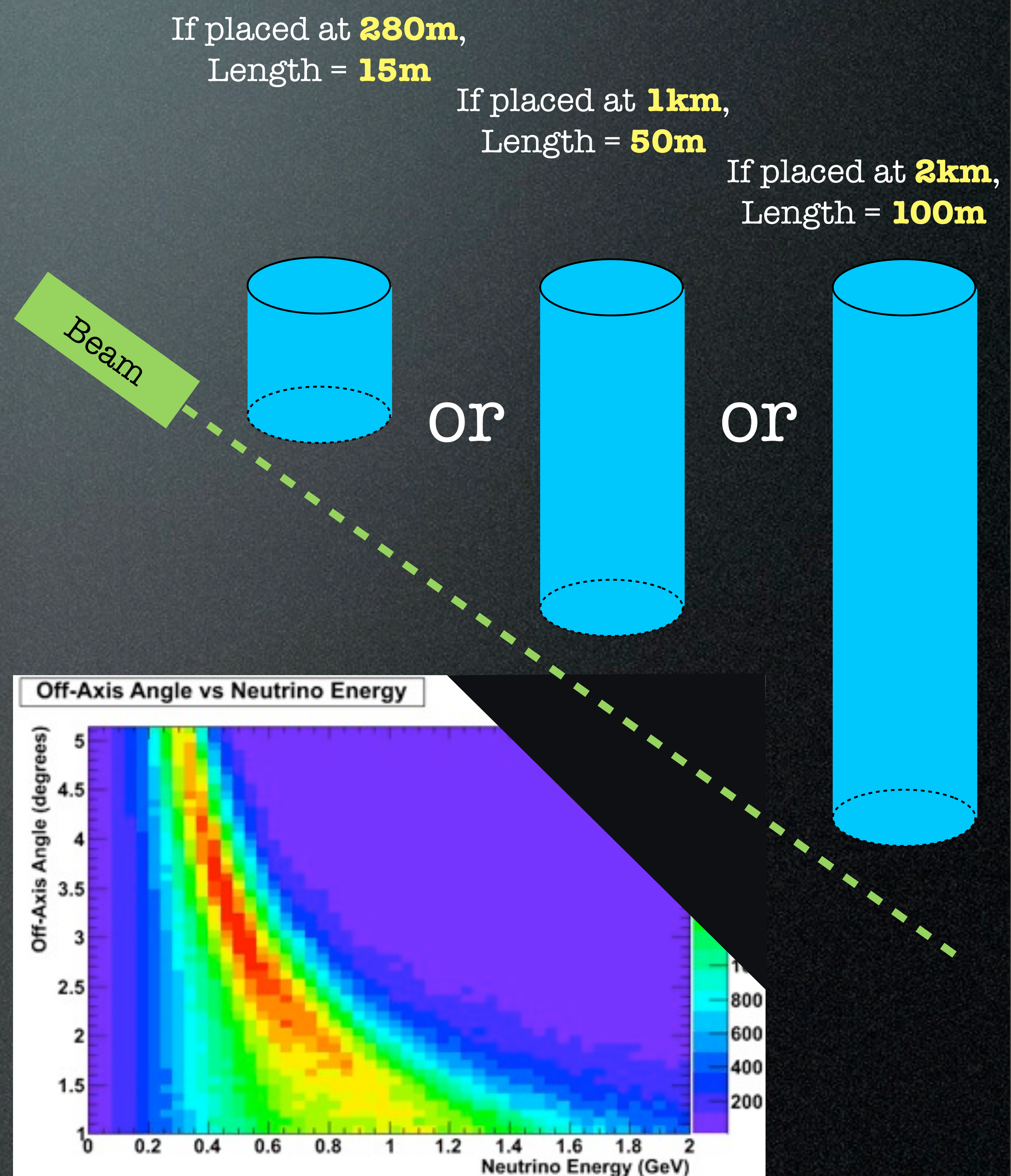
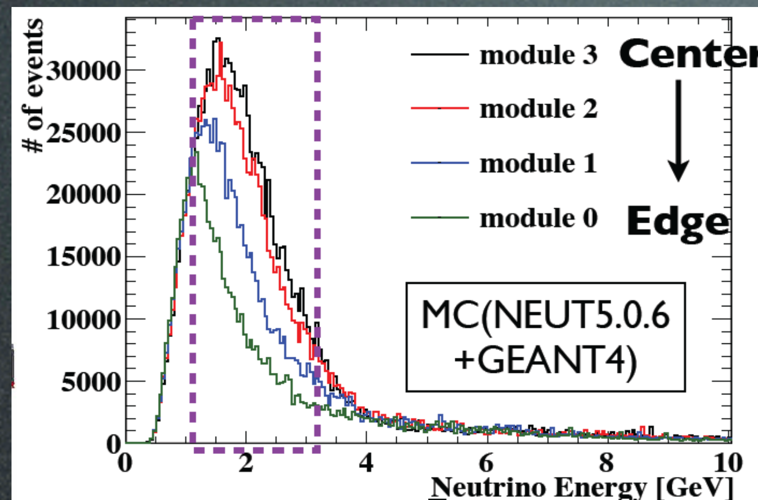
- As the off-axis angle changes, the neutrino energy spectrum is modified in a ver
- Measuring event properties at several different off-axis angles can provide information about E_ν without relying on neutrino interaction models

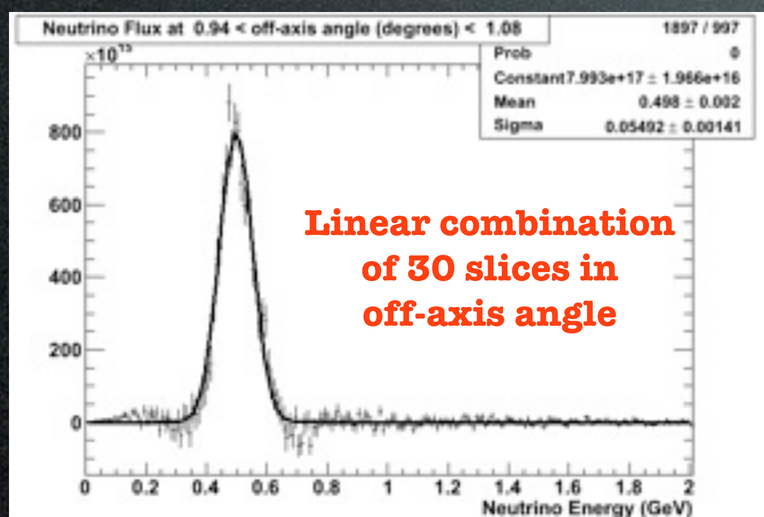
Detector Concept

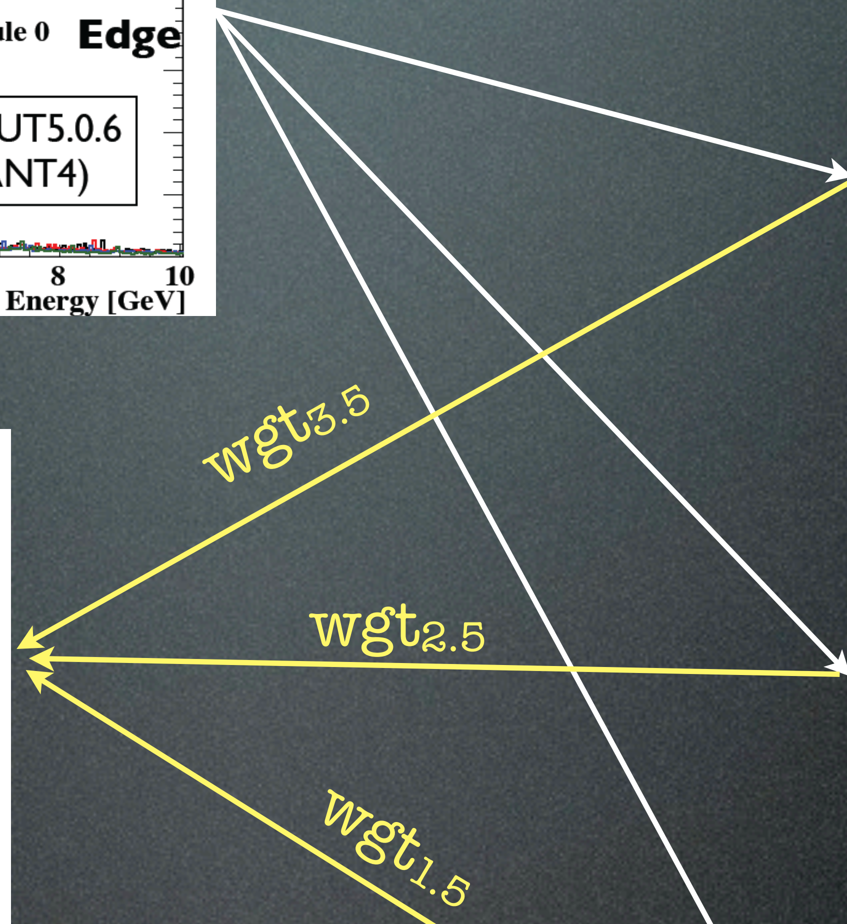
- A long-tube water Cherenkov detector
  - Tube height depends on the distance from the beam target
- Continuous mapping of off-axis angle from **1°** to **4°**
- Same target (water) as the far detector
  - T2K uses different targets at the near and far detector
  - Many non-canceling uncertainties
    - Nucleon initial state model
    - Pionless delta decay
    - Final state interactions
    - Nuclear modifications to the Delta resonance

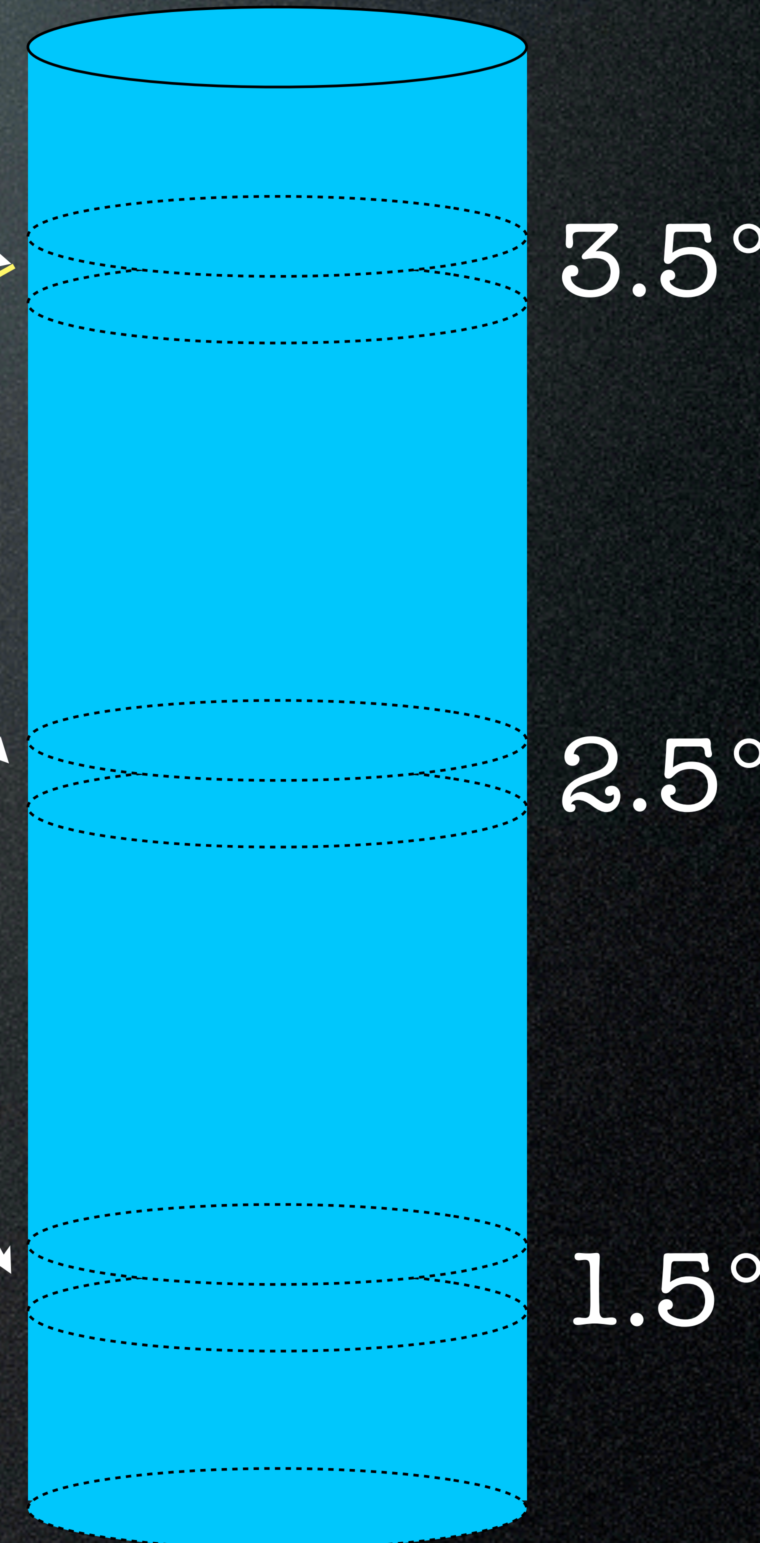


Neutrino Spectrometer I



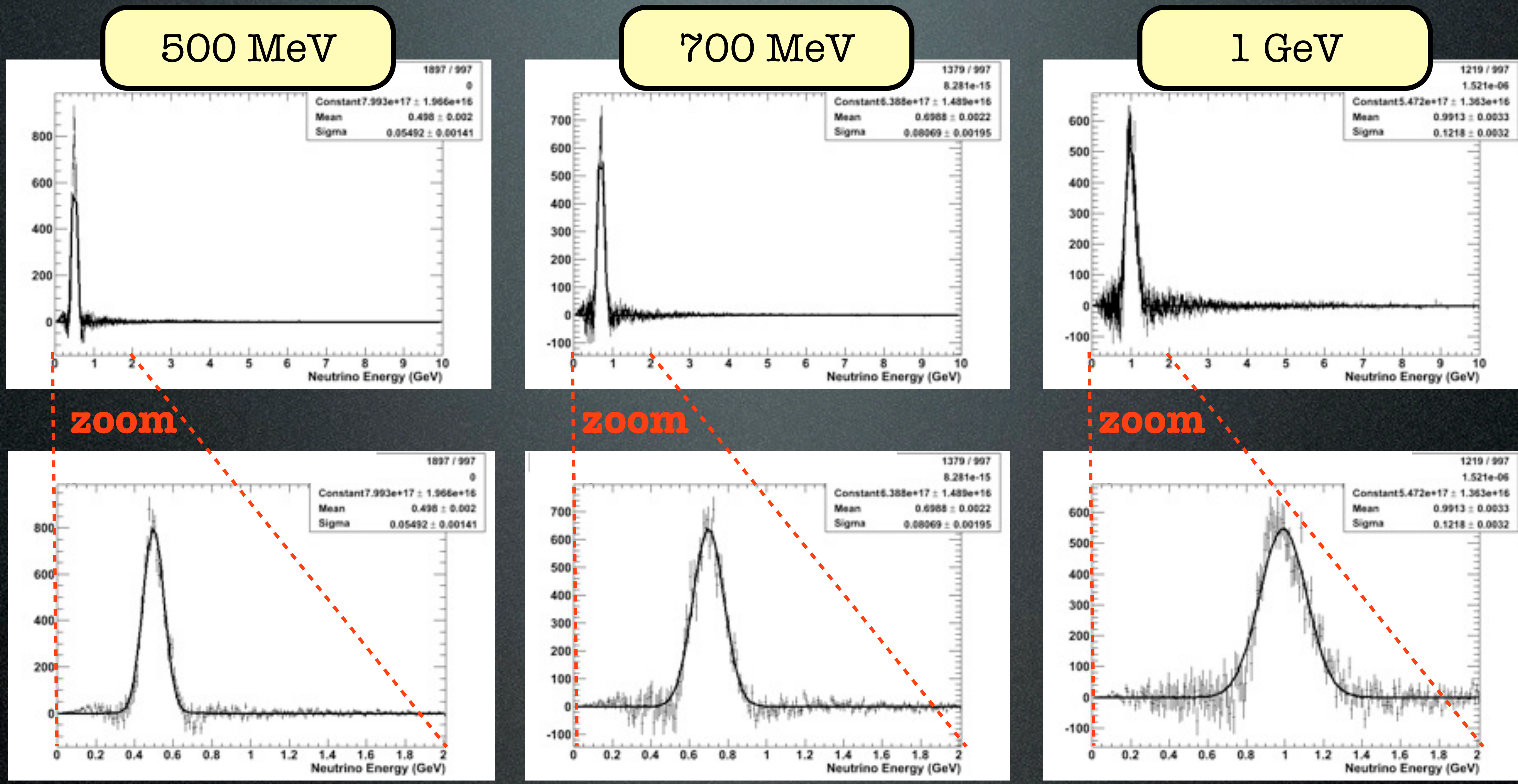






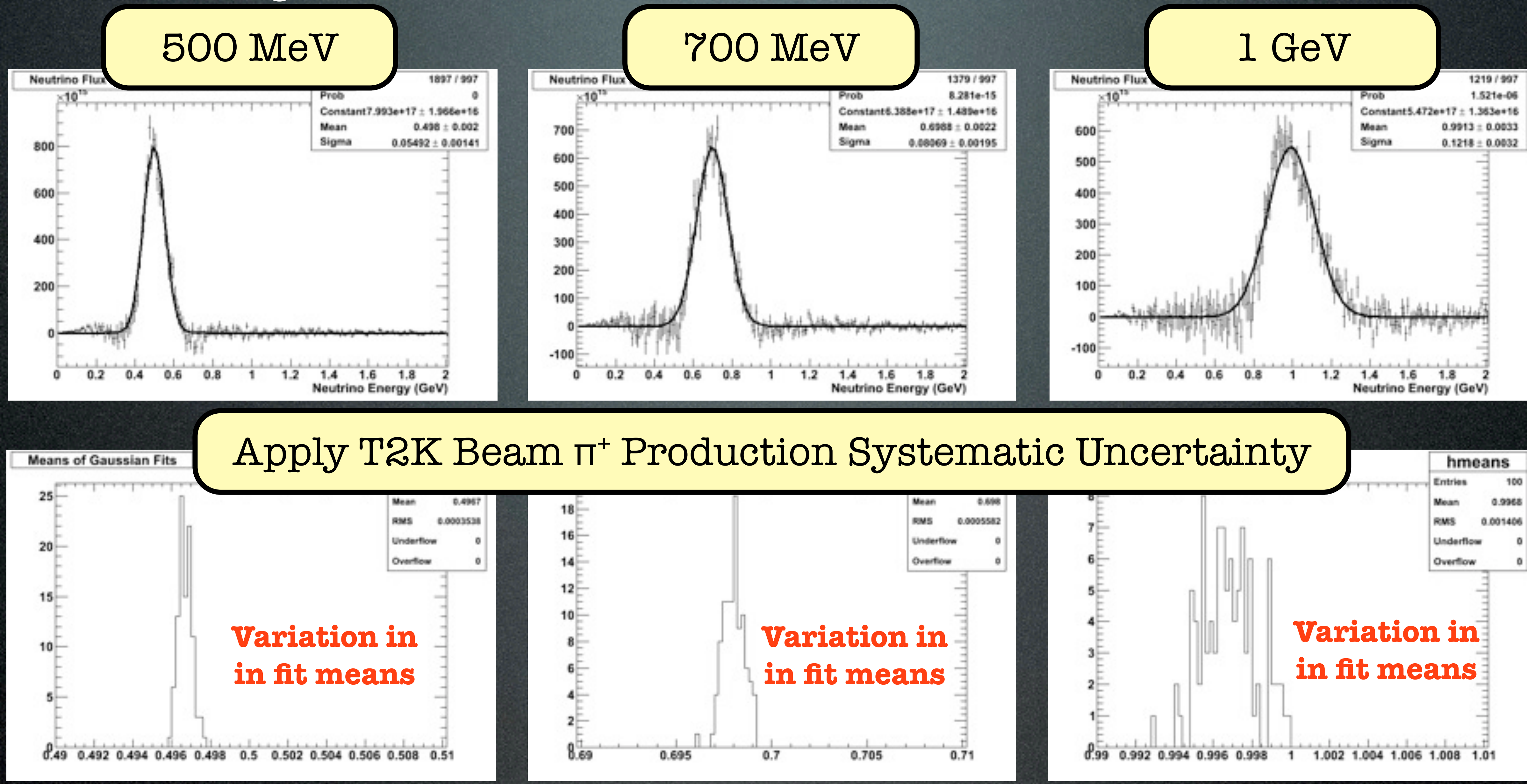
- Muon p/theta distribution is measured in each detector slice
- By taking linear combinations of many different slices, can make Gaussian neutrino spectra at various energies
- Just for illustration purposes; actual analysis to extract muon p/θ vs E_ν will be more sophisticated

Neutrino Spectrometer II



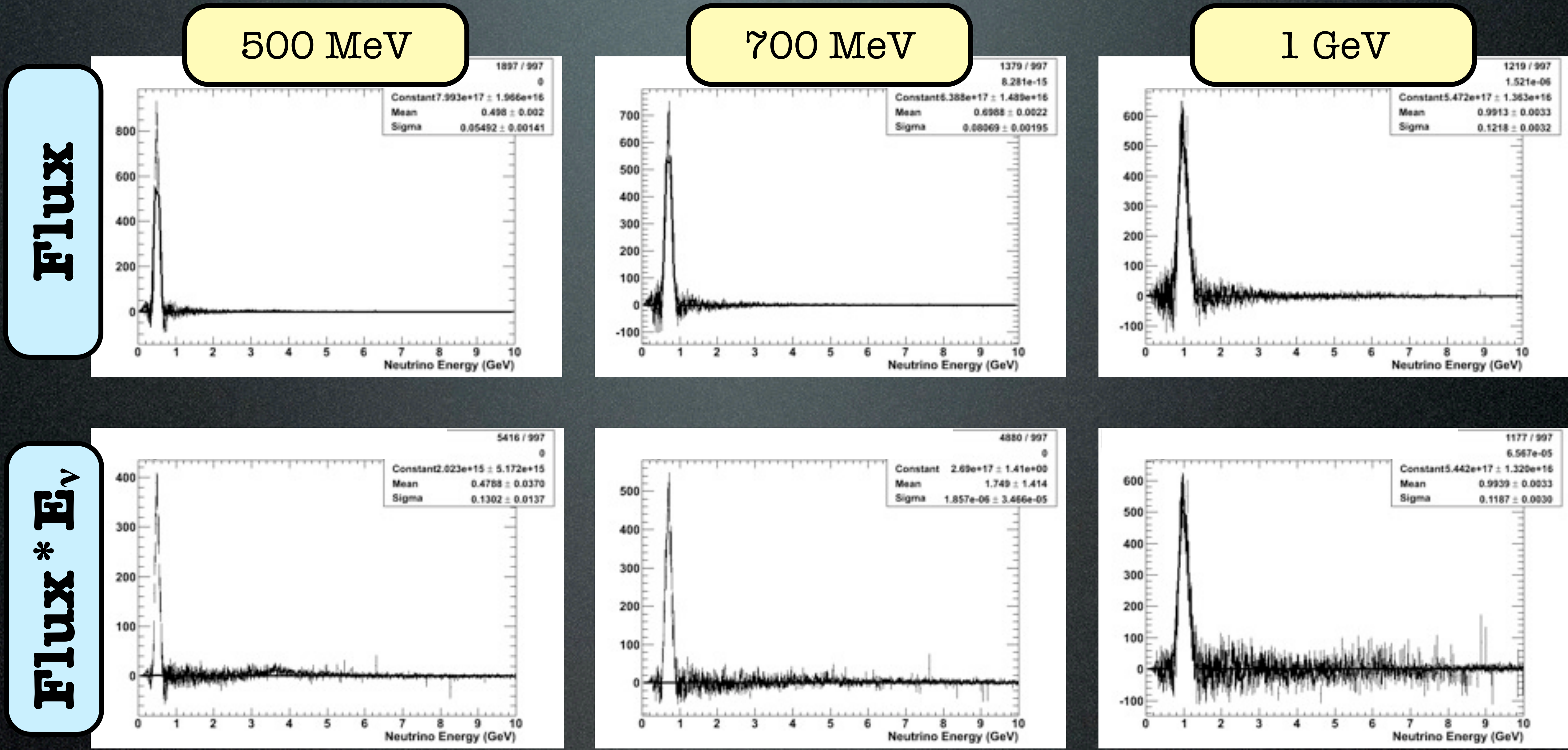
- Gaussian spectra can be produced for any choice of neutrino energy (between ~0.25 and ~1 GeV)
- High energy flux tail is canceled in all cases

Systematic Uncertainties



- Question: How do beam uncertainties affect ability to use off-axis angle to determine neutrino energy?
- 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 + production **uncertainty is ~0.1%**
  - More detailed study needed, but first look is promising!

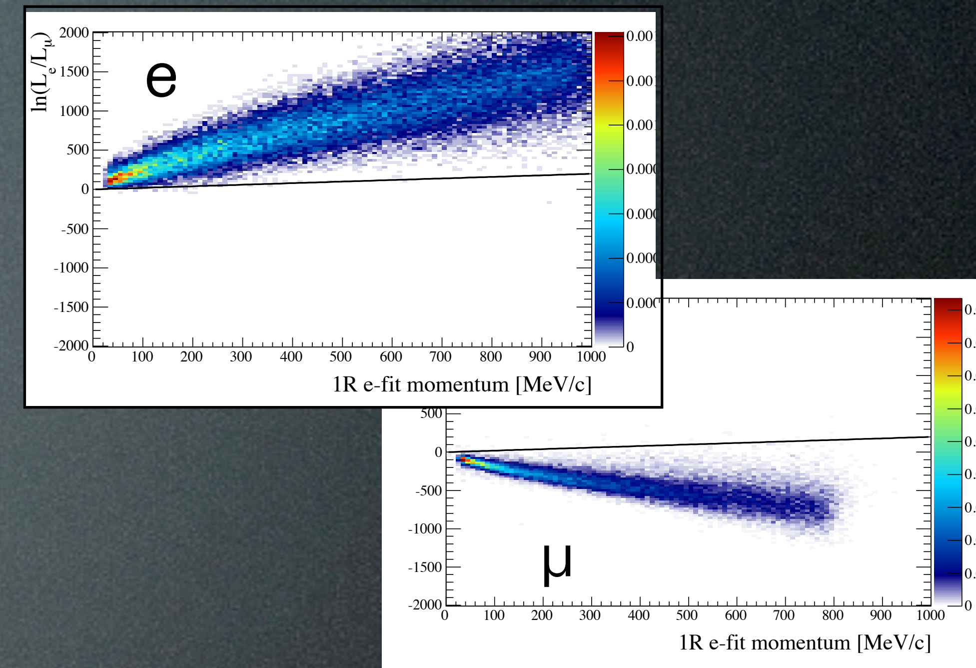
High Energy Flux Cancelation

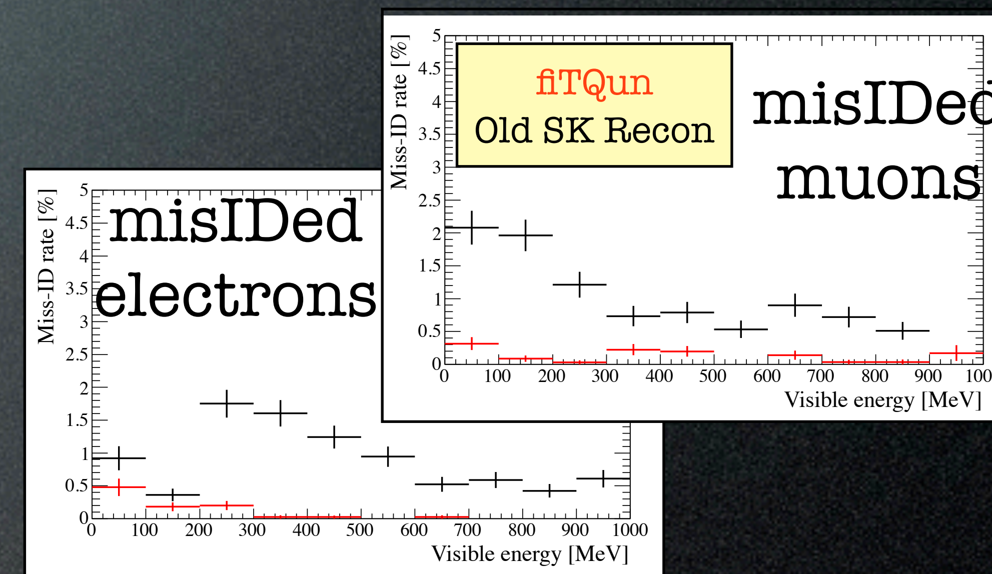


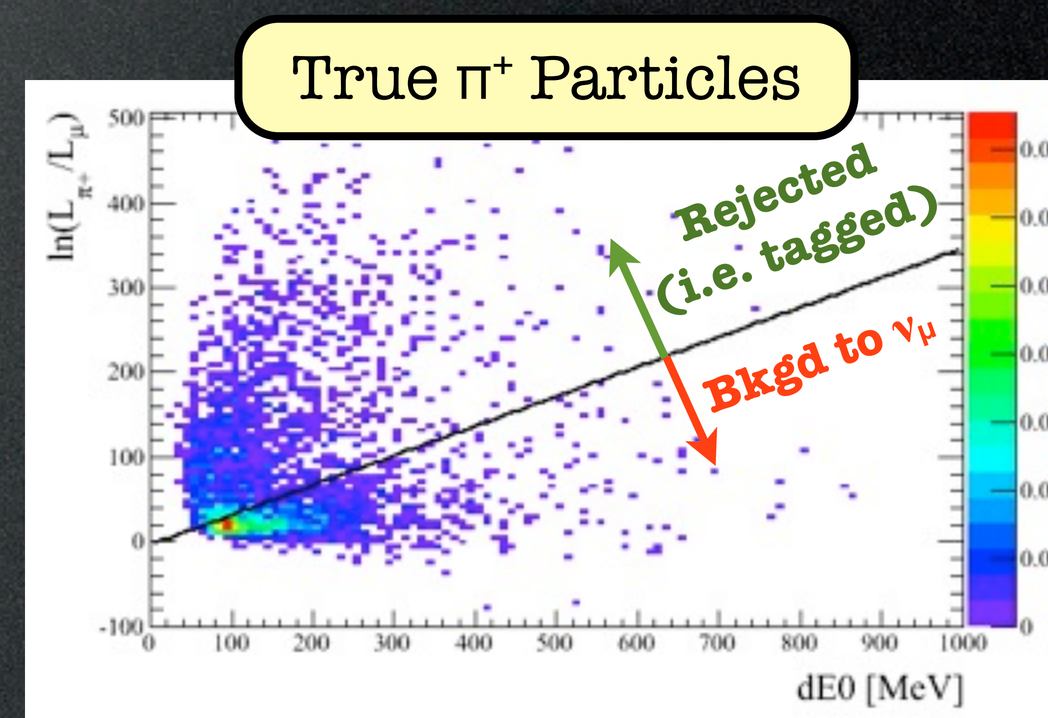
- It may be more important to precisely cancel the high energy flux, since ν cross sections grow vs E_ν
- Can weight flux by E_ν to get a rough idea
  - Still able to remove almost all contribution from high energy

ν_μ Backgrounds

- For the T2HK δ_{CP} measurement, we wish to measure momentum vs angle distribution of **single-ring muon events** for each neutrino energy
  - Including, e.g., CCπ^+ events where the π^+ is below Cherenkov threshold
    - (some additional separation based on decay electrons may also be useful)
  - This relationship can then be inverted at Hyper-K to produce energy spectrum
- Electrons are rarely misidentified as muons in Super-K (~0.1%)
- Main background is from pion rings
  - At Super-K, we now have a method to separate some π^+ background from μ signal
  - We can also now select a pure π^+ sample to constrain this background
  - (These same tools can also be applied to single-proton backgrounds)
- More details in the fiTQun reconstruction talk tomorrow

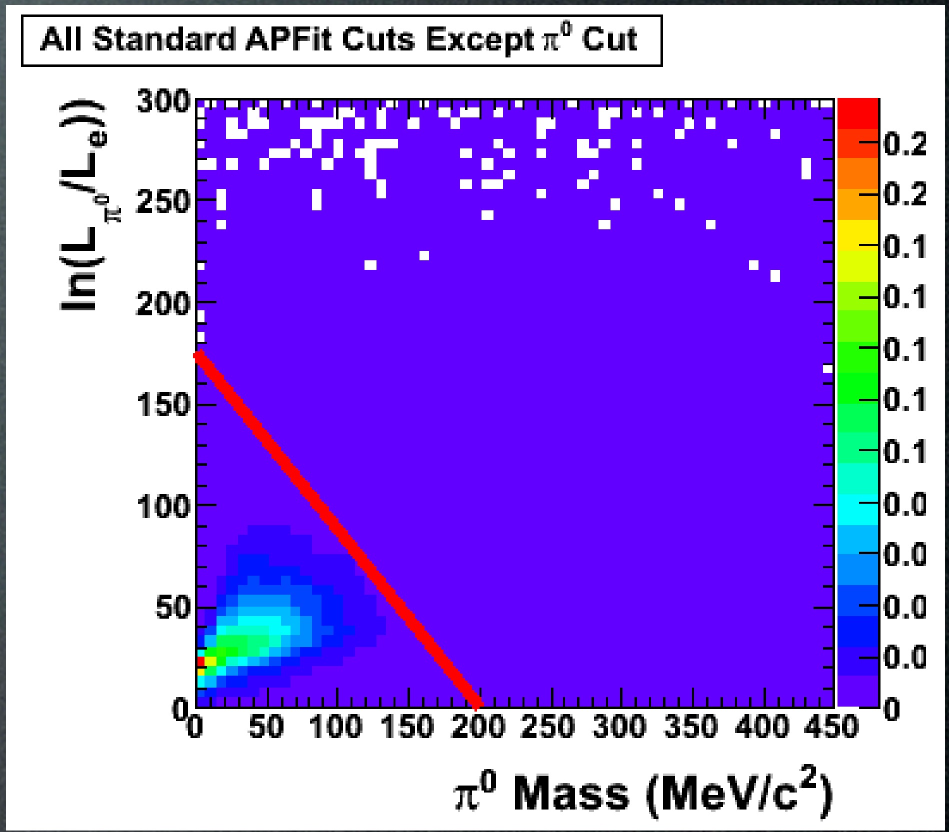


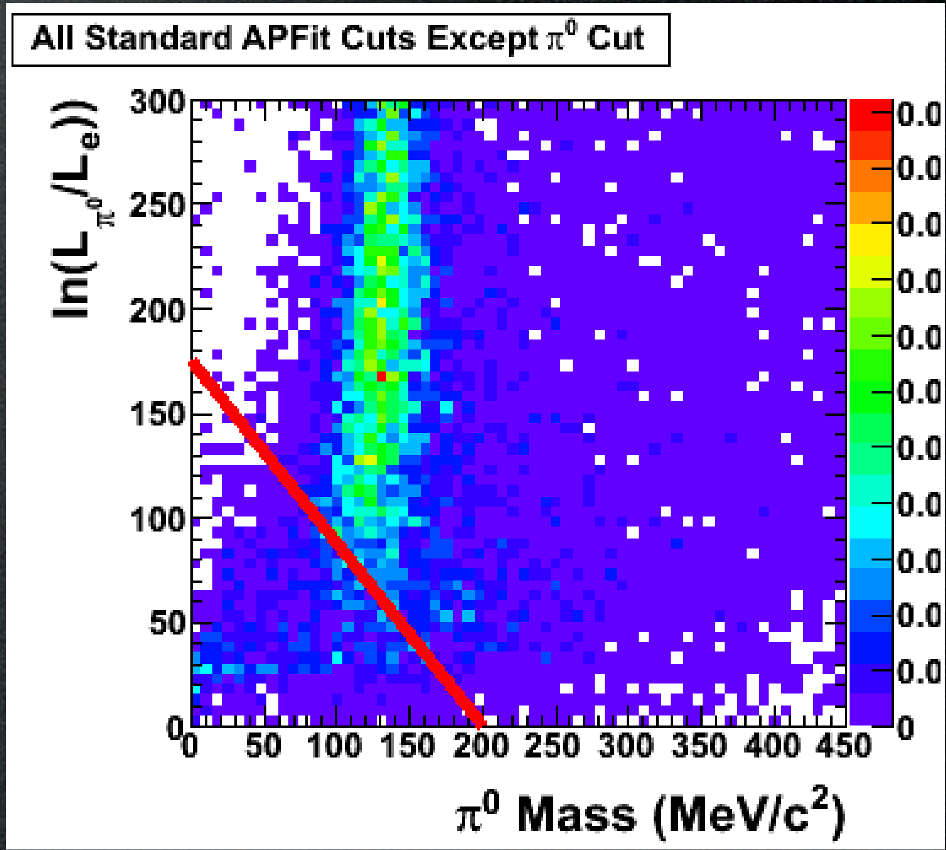




ν_e Backgrounds

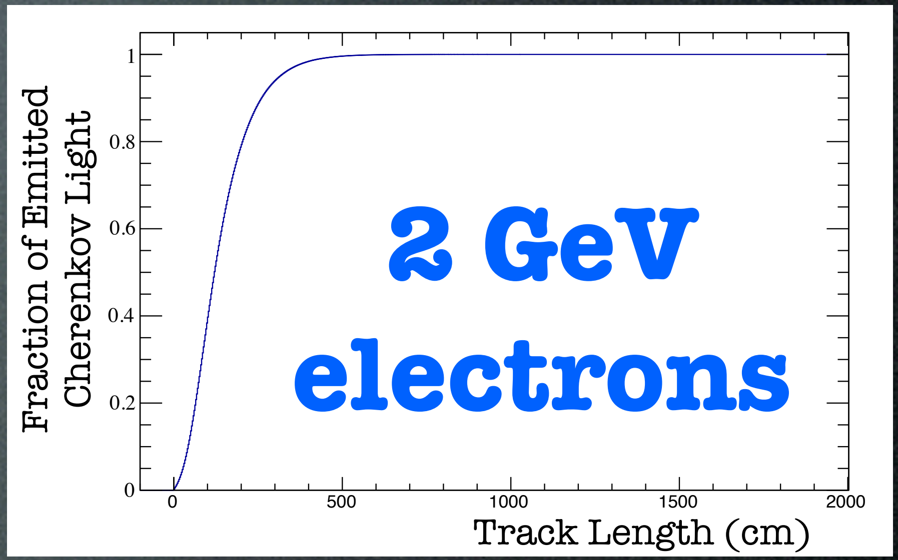
- Good separation of electrons from muons
- Recent significant improvement to e/π^0 separation
  - 70% reduction in T2K π^0 background
- Water Cherenkov detectors are a very good technology for measuring and constraining NC π^0 production
- More susceptible to entering neutral particles than the ν_μ measurement
  - Significant distance between the upstream wall and the FV may be required

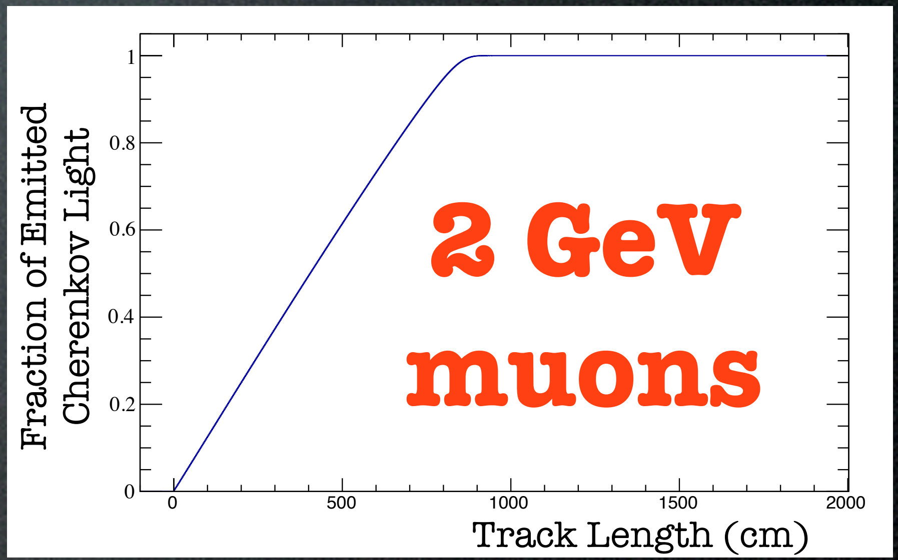


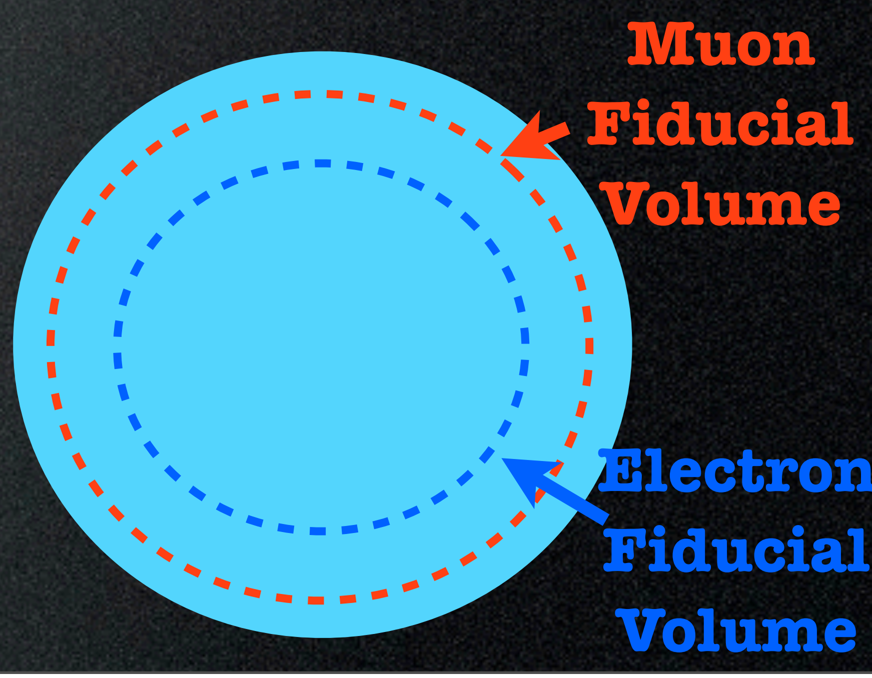


Setting the Tube Diameter

- Main requirement is the maximum muon momentum that can be measured (fiducial volume
  - Tube Diameter > Muon range (i.e. max mom.) + Distance between FV and wall
  - Main upstream FV requirement is to separate fully contained muons from entering muons
    - Driven by the vertex resolution
  - Particle ID also degrades if the particle is to close to the wall at which it is pointing (need a "to wall" cut)
- Electrons are more sensitive to entering backgrounds
  - For the electron measurement, the fiducial volume can begin further downstream because electron path length is shorter
    - A 2 GeV electron emits all of its light within 4-5 m

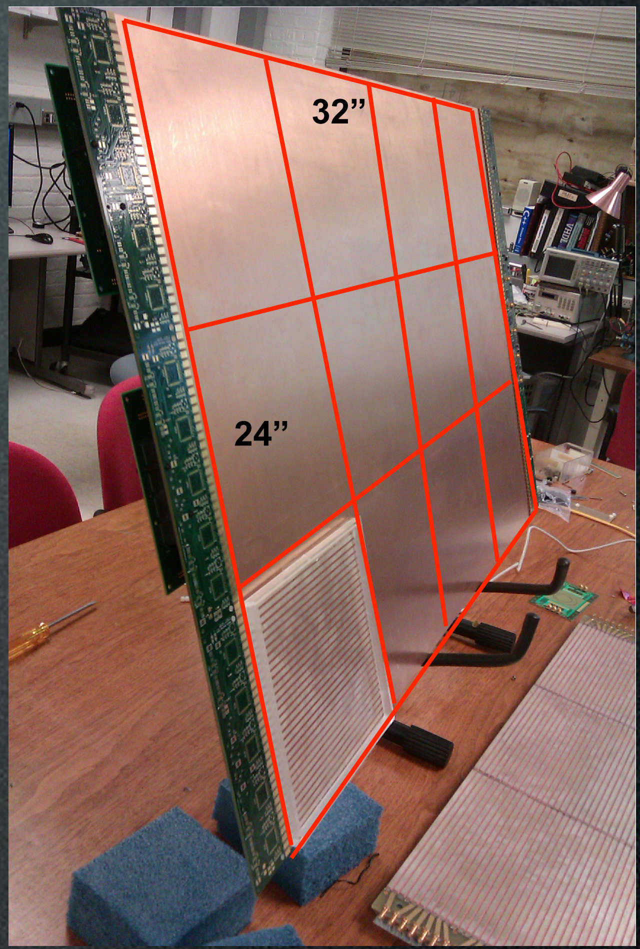


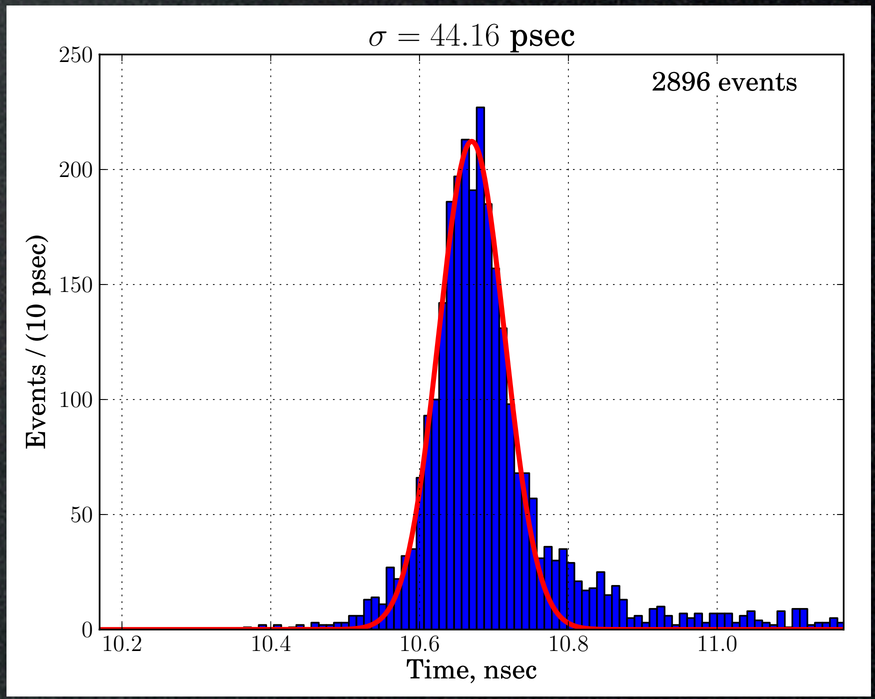




Multi-Channel Plates

- **Better timing resolution = better vertex resolution**
  - With better vertex resolution, the muon fiducial volume can be expanded closer to the tank wall
- Large area picosecond photon detectors (LAPPDs) can provide single photon hit time **resolution of ~50 psec**
  - See talk tomorrow by Mayly Sanchez
- Vertex resolution of few centimeters
  - Can use almost the **whole tube volume as FV**
- Also **see substructure in rings**
  - Time and position of every photon is recorded
  - More information than just adding total charge





Detector Size

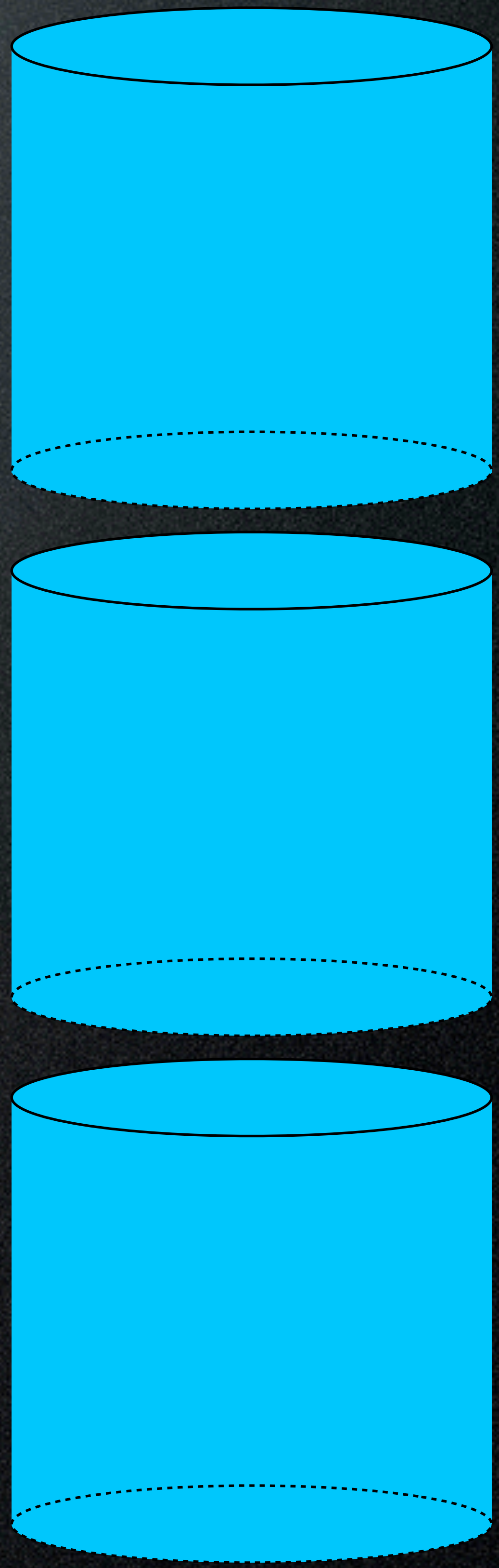
The table gives the mass of water in kton

Tube Length \ Tube Diameter	5 m	7 m	8 m	10 m
15 m	0.3	0.6	0.8	1.2
50 m	1.0	1.9	2.5	3.9
100 m	2.0	3.8	5.0	7.8

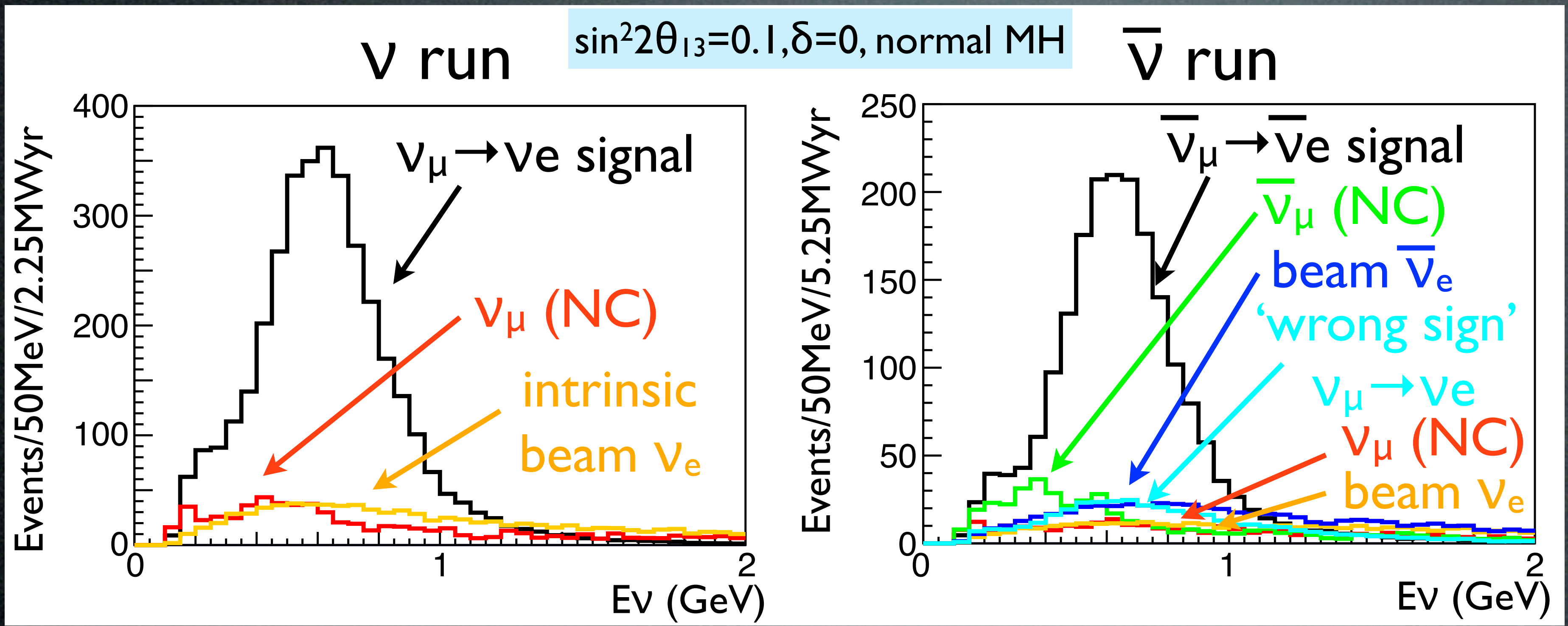
Typical size = few kton

Other Design Considerations

- Water pressure
  - If the water pressure is too high at 100 m, it is possible to break the detector into pieces
- Water quality
  - No need for a Super-K caliber water filtration system
    - Super-K has 80m optical transparency
  - This detector has typical photon transmission distances of ~10-15m
- Event pile-up
  - May be able to reconstruct 2 simultaneous events, especially if the vertices are well separated
  - Michel-tagging efficiency/accuracy is reduced as pile up increases
  - Both problems are helped by moving to the 2 km site



Detector Limitations



ν & anti-ν backgrounds for T2HK

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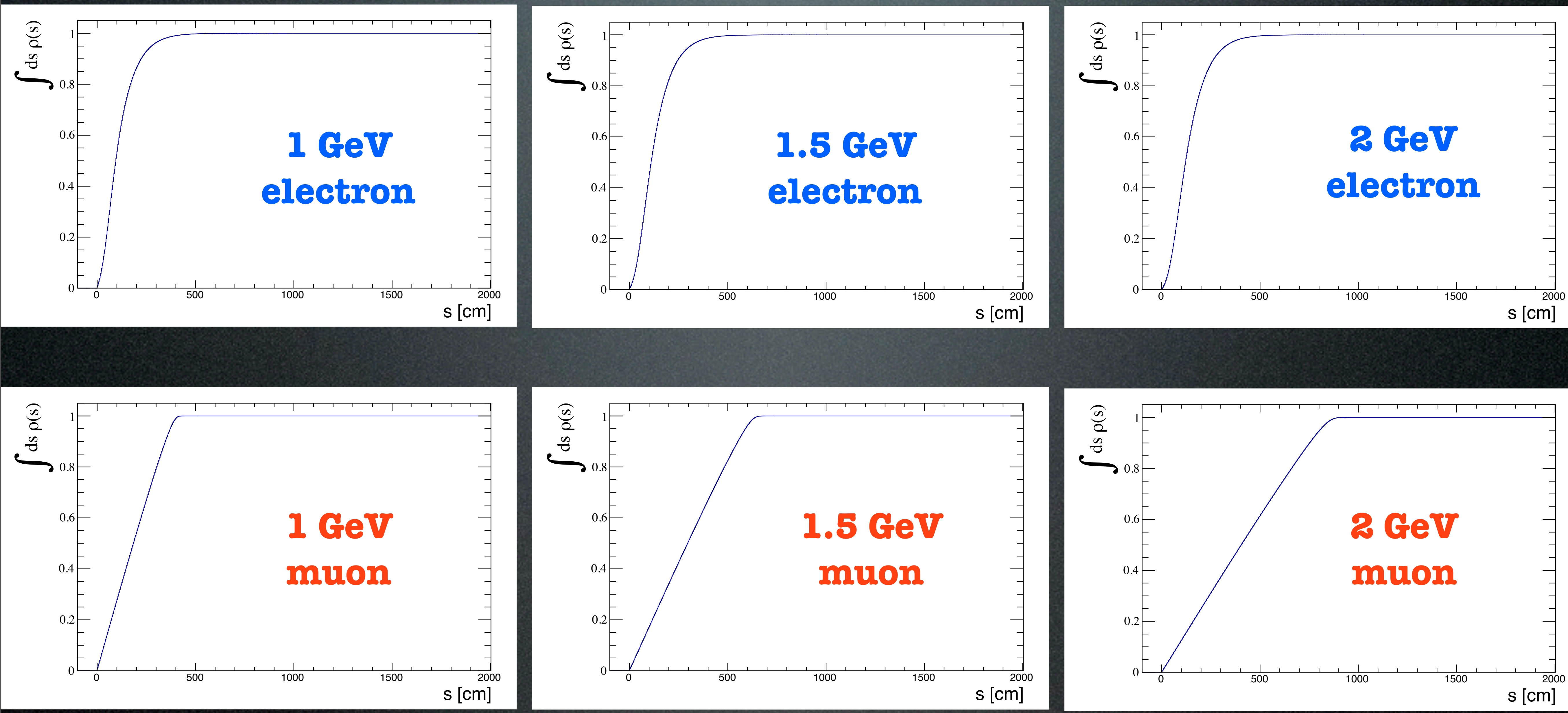
- The proposed detector does not provide lepton sign selection
  - Cannot separate the wrong-sign background in the anti-ν beam
  - Measurements from ND280 to separate these components will be useful
  - Some separation power may be available by looking at μ + π events with and without a Michel tag
- Little information is provided about low energy hadrons exiting the nucleus
  - Not required for the δ_{CP} measurement (this is main principle motivating this detector design)
  - However, more information could, in principle, better constrain residual effects from cross section models

Summary

- Neutrino interaction cross section uncertainties may be the dominant error in a T2HK δ_{CP} measurement
  - Need 2% uncertainty on event rate to match statistical precision
  - Our understanding of neutrino interactions may not reach this level in time for Hyper-K
- A tall water Cherenkov detector that spans ~1° to ~4° off-axis angles can be used to measure muon kinematics vs E_ν without relying on a neutrino cross section model
  - Initial look at systematics suggests this method may be robust to beam uncertainties
- Water Cherenkov detectors are also very good at measuring pure samples of electrons
  - Can constrain ν_e/ν_μ cross section ratio

Backups

Electron and Muon Ranges in Water



- Muon range has ~linear dependence on momentum
- Electron range does not strongly depend on momentum above 1 GeV