HYPER-K SYSTEMATIC UNCERTAINTIES (BEAM RELATED)

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Neutrino Beams and Instrumentation Workshop (NBI)

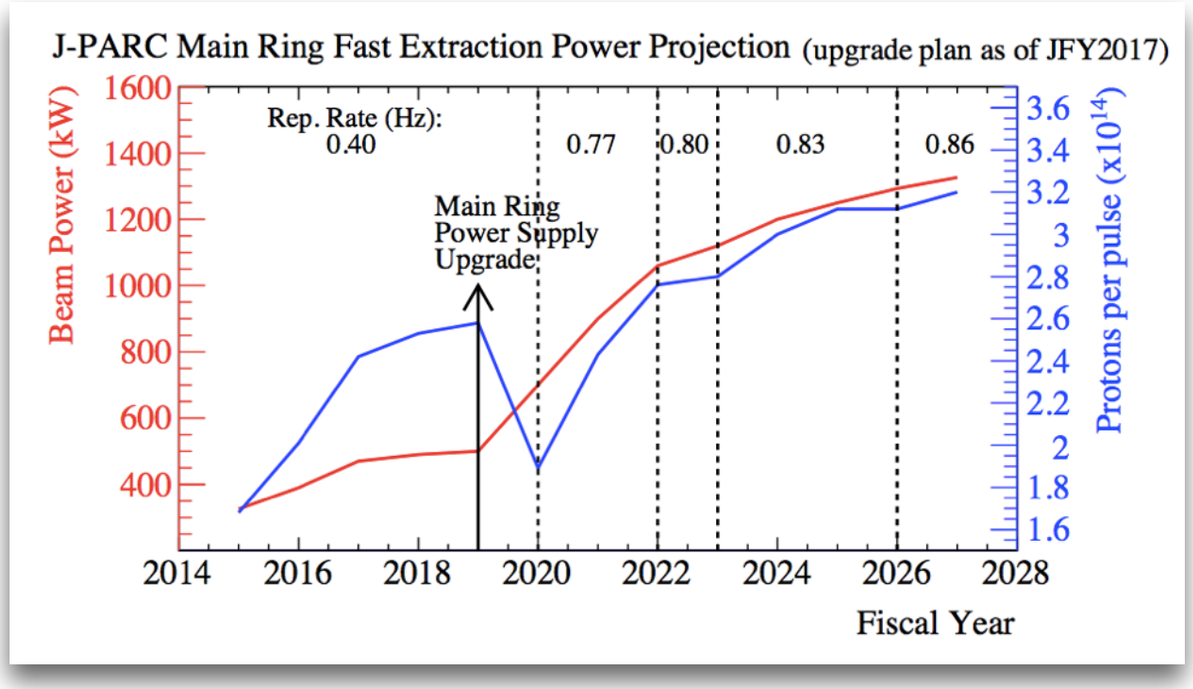
Fermilab, 2019/10/24

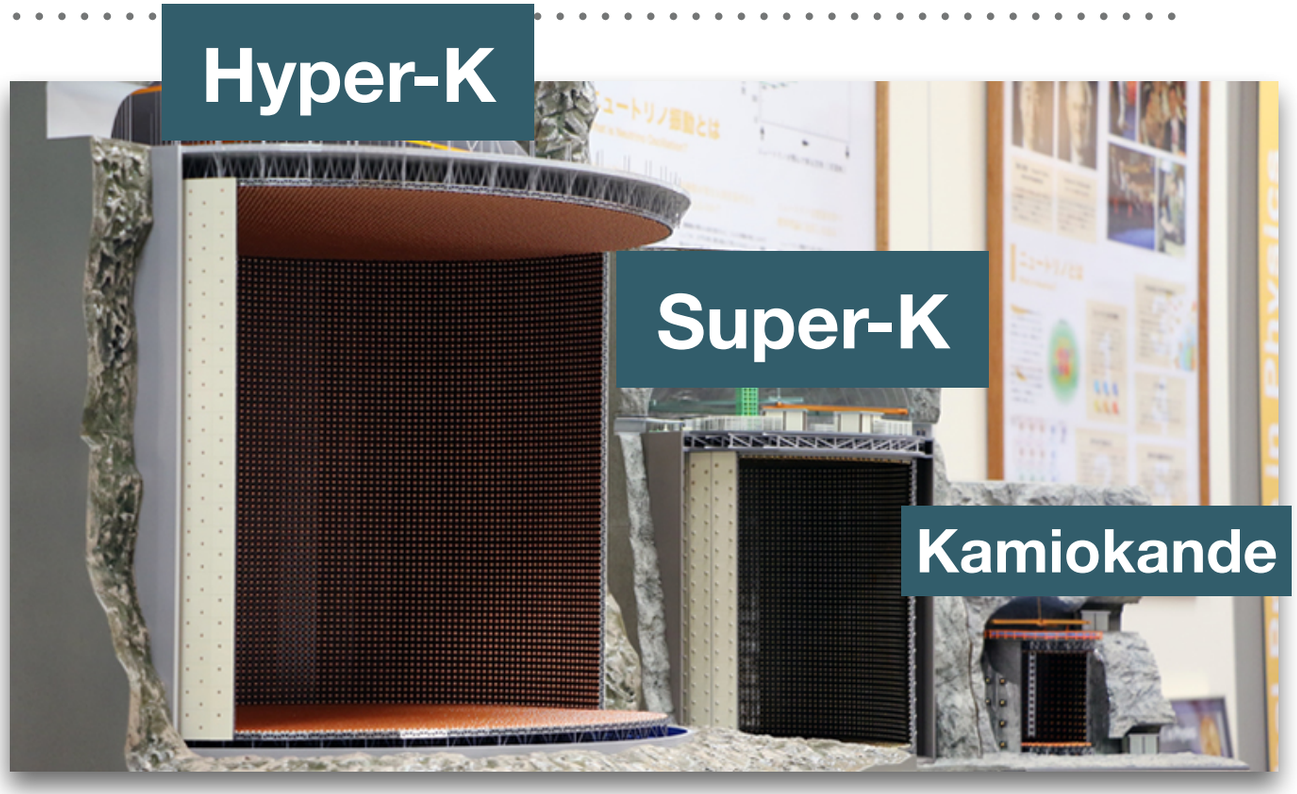
Hyper-Kamiokande

OVERVIEW OF THIS TALK

- Brief introduction to Hyper-K
- Overview of systematic uncertainties for Hyper-K
- Proposed near detector suite
- Systematic uncertainties and beam modeling

THE HYPER-K EXPERIMENT

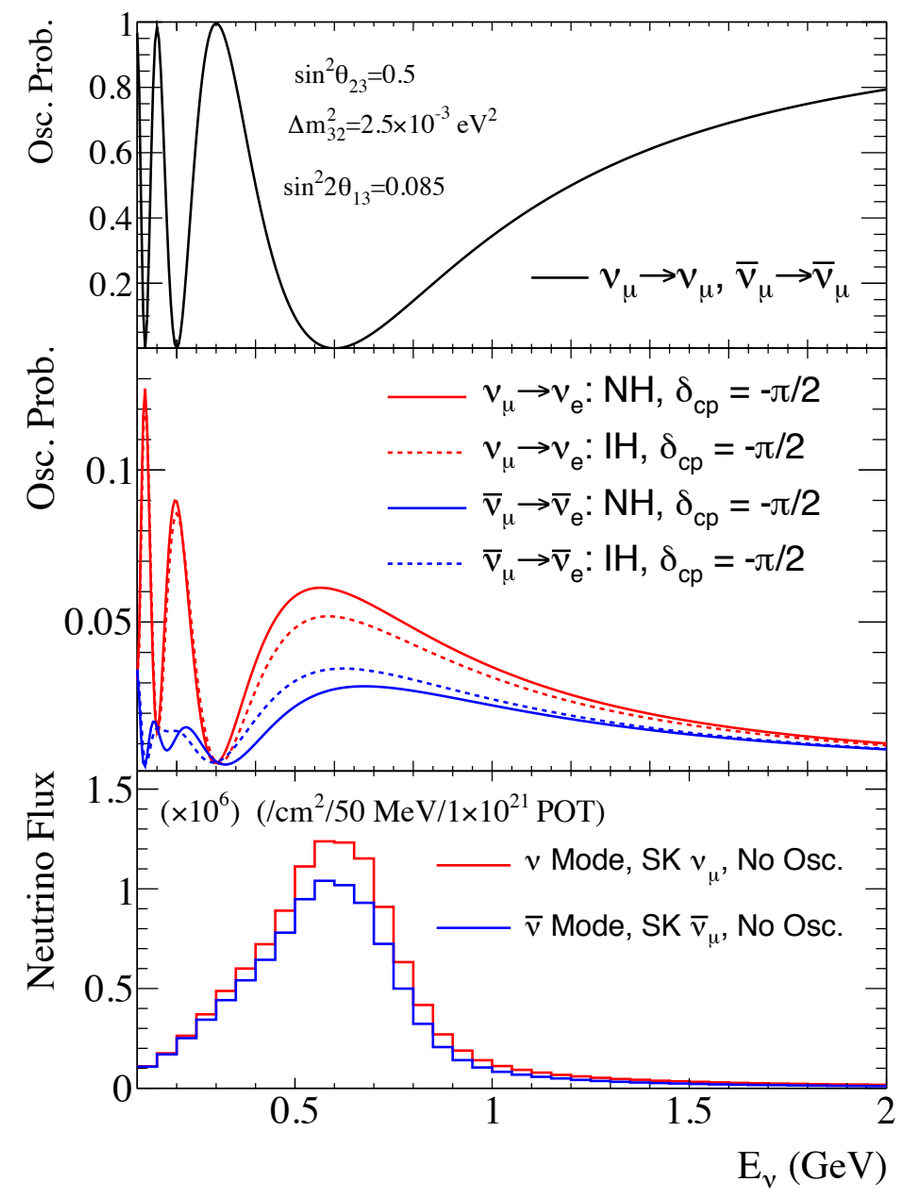




- Builds on the successful T2K and Super-Kamiokande experiments
- Beam will be upgraded from current power of ~500 kW to 1.3 MW
- Hyper-K will have an 8 times larger fiducial mass than Super-K
- New photo-detector technologies -> improved photon detection
- **New near and intermediate detectors**
- Hyper-K will accumulate statistics for accelerator based program 20x faster than T2K currently does

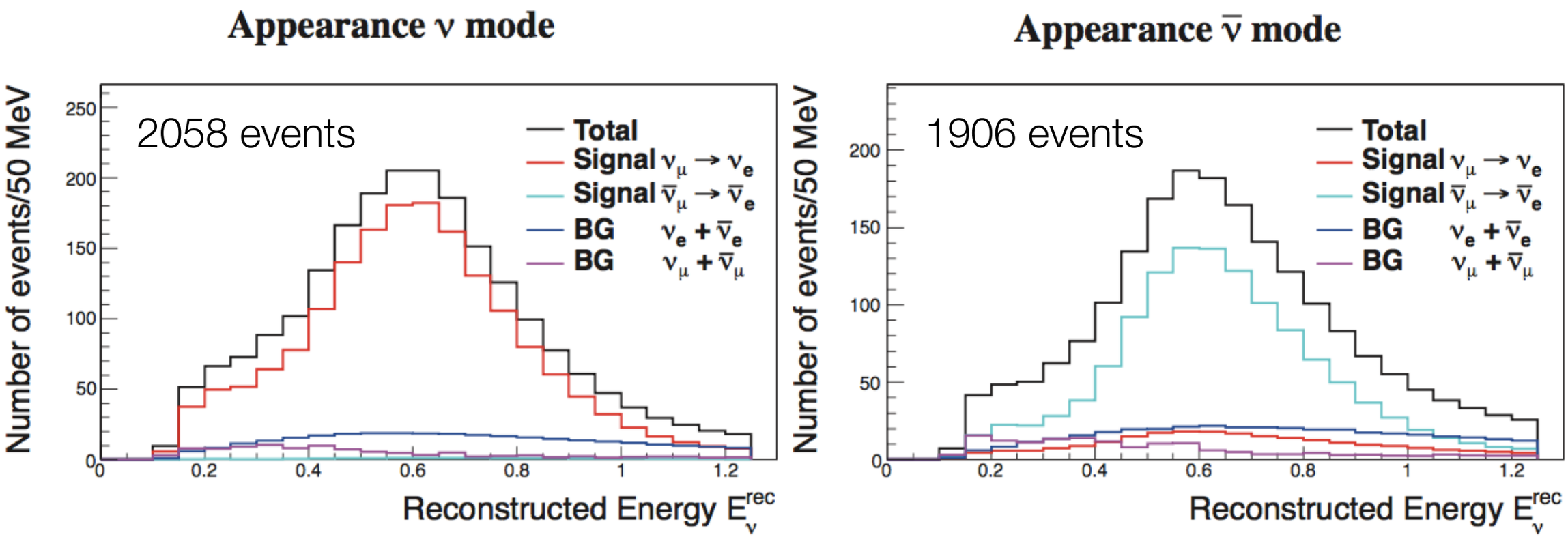
ACCELERATOR-BASED PHYSICS AT HYPER-K

- **Muon (anti)neutrino survival** sensitive to $\sin^2(2\theta_{23})$ and Δm^2_{32}
- **Electron (anti)neutrino appearance** sensitive to $\sin^2(\theta_{23})$, $\sin^2(2\theta_{13})$ and Δm^2_{32} in leading term, δ_{cp} in subleading terms, mass ordering through matter effect



Broad physics program, see talk by A. Konaka on Monday

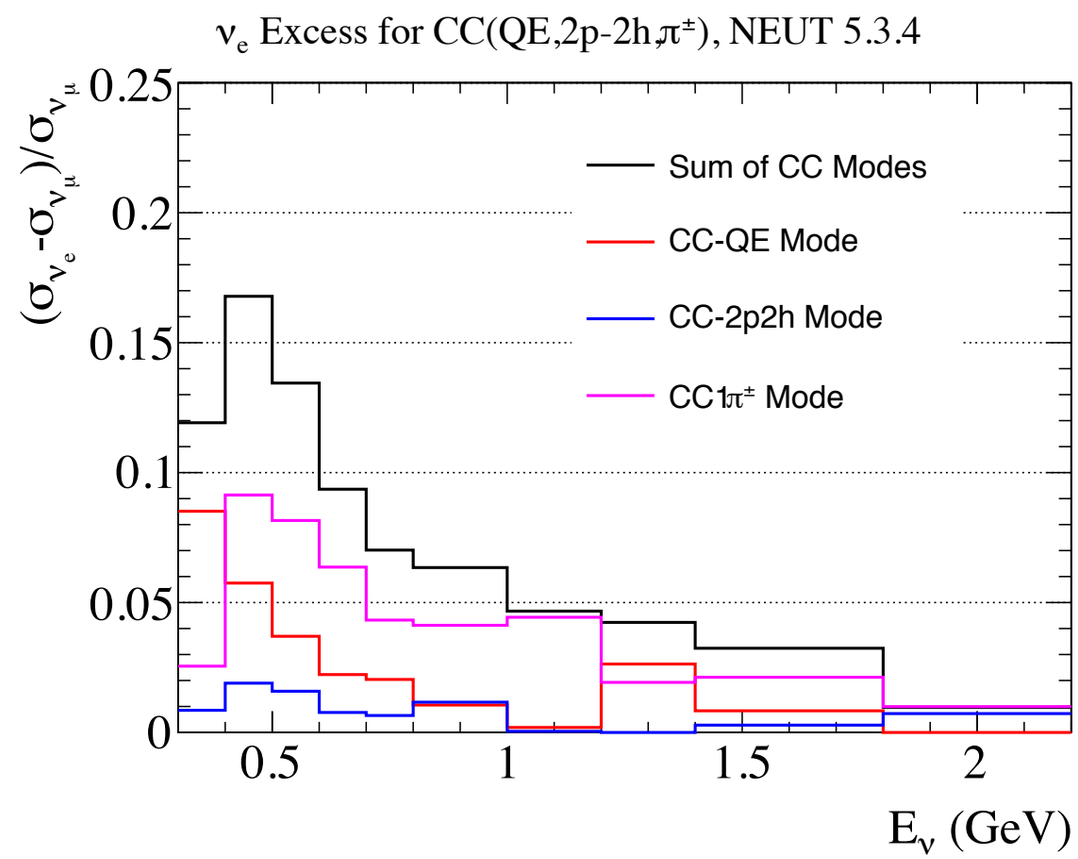
CP VIOLATION REQUIREMENT



- To first order, Hyper-K CP violation search is a counting experiment
- ~2000 events in neutrino and antineutrino mode
  - Statistical uncertainty on asymmetry measurement is ~3% after 10 years
- Need systematic error reduction to this level

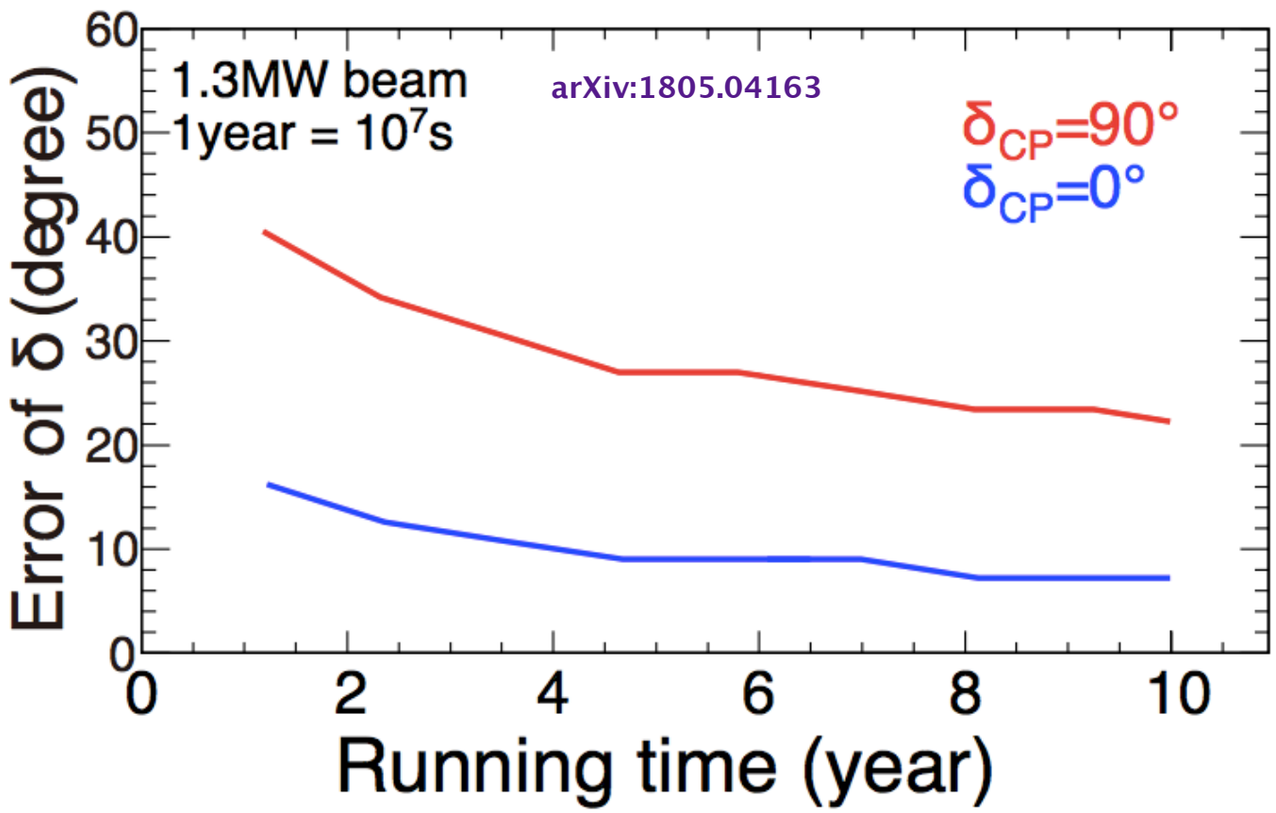
T2K SYSTEMATIC ERRORS

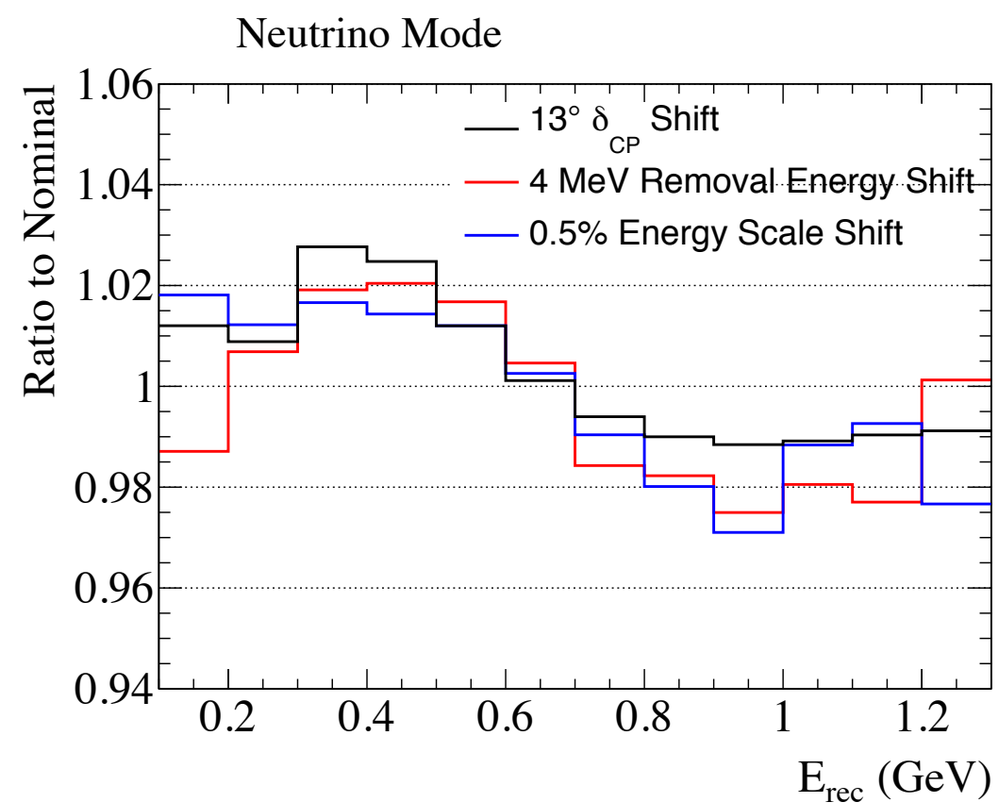
Error Source	% Error on neutrino/ antineutrino rate
Pion Interactions	1.58
Neutral Current Background	1.50
Electron (anti)neutrino cross section	3.03
Extrapolation from near detector	2.31
Removal Energy	3.74
Far Detector model	1.47
Total	5.87



- T2K systematic error primarily dominated by neutrino (or pion) interaction systematic uncertainties (red box)
- Largest is uncertainty on relative cross sections of ν_e and ν_e-bar (blue box)
  - T2K error is only theoretical error on CCQE interactions
- Hyper-K should measure the cross section ratios: $\sigma(\nu_e)/\sigma(\nu_\mu)$ and $\sigma(\overline{\nu}_e)/\sigma(\overline{\nu}_\mu)$

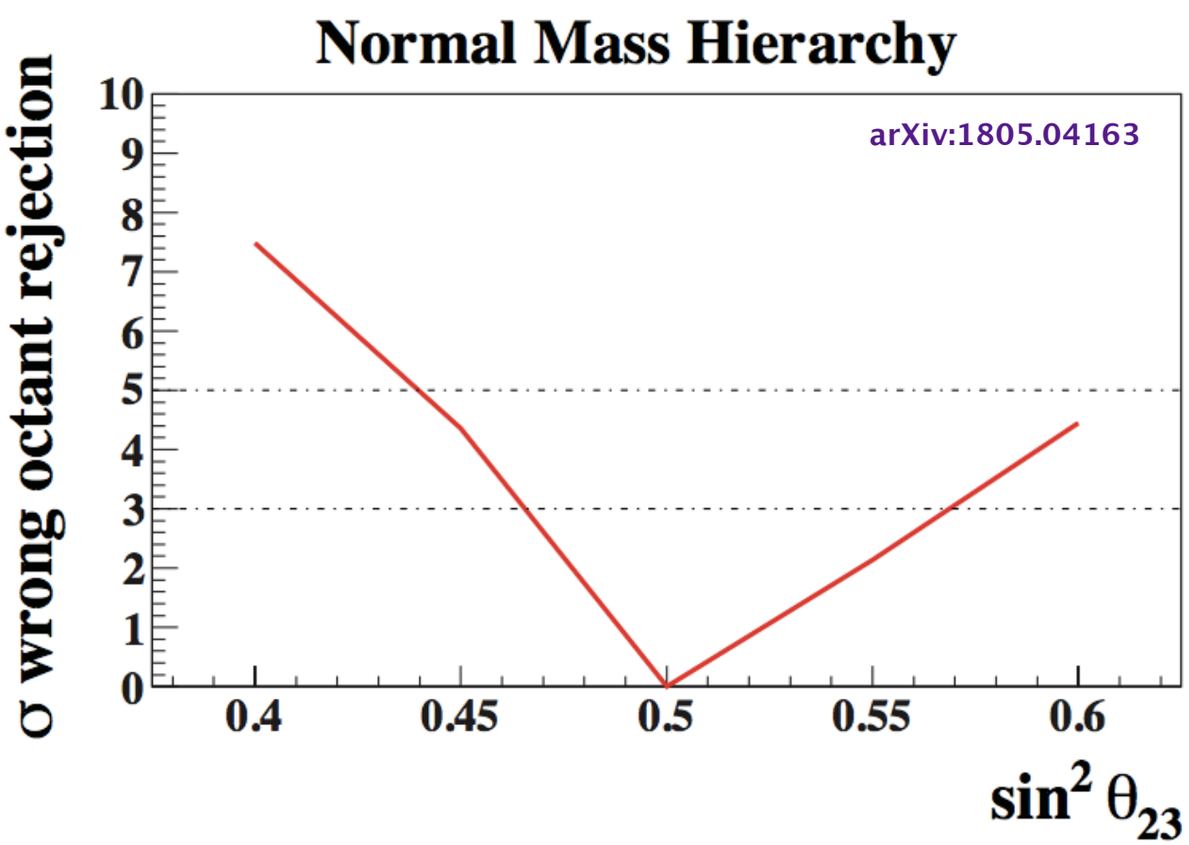
PRECISION CP PHASE – SYSTEMATIC EFFECTS

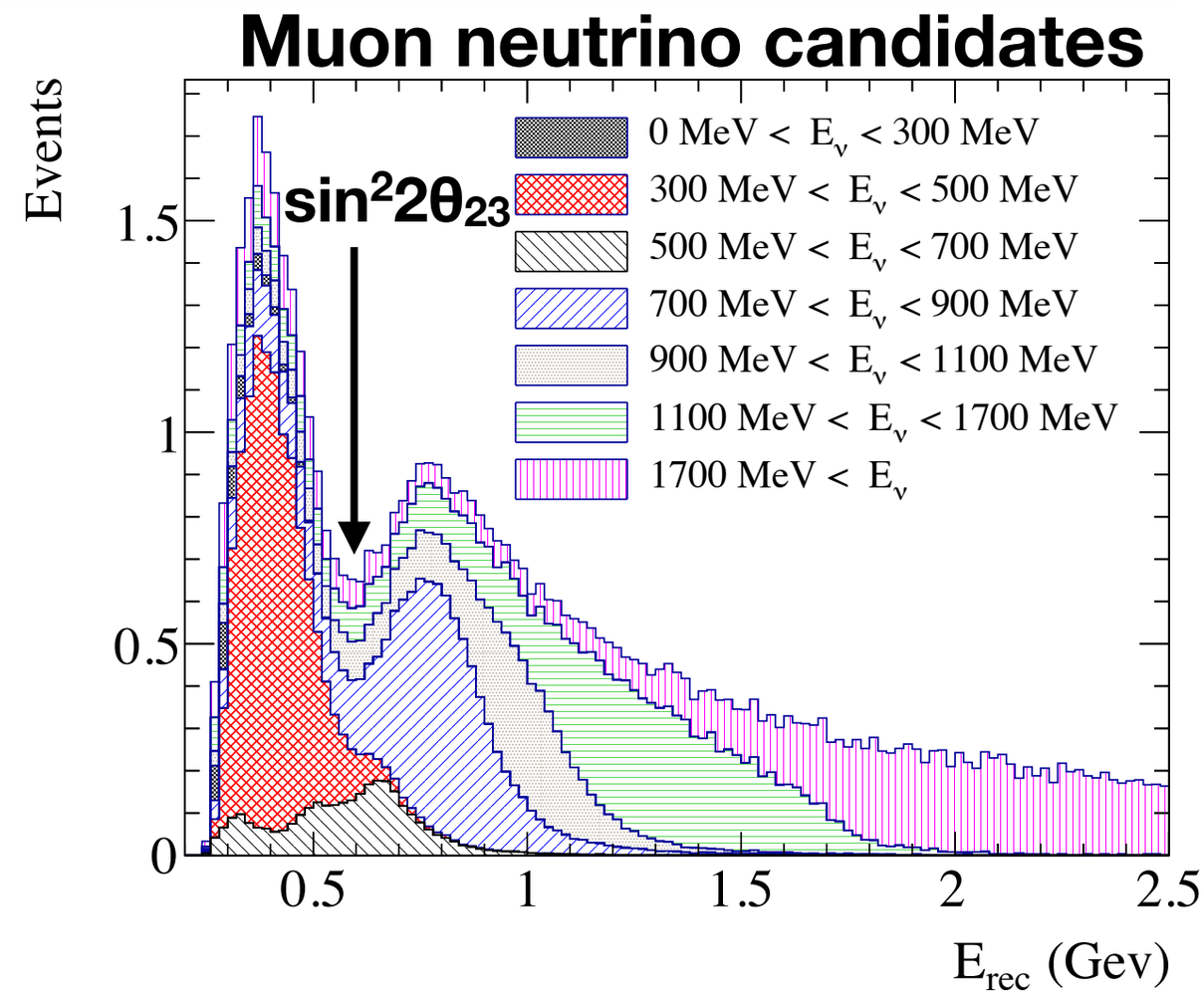




- Near the true value of δ_{cp} = ±90°, the measurement of δ_{cp} is less precise
- Because CP-conserving term dominates and effect is equivalent to energy scale shift in observed spectrum
- Energy scale uncertainties should be controlled at the 0.5% level
  - Off-axis angle uncertainty should be <0.3 mrad

Atmospheric Parameters





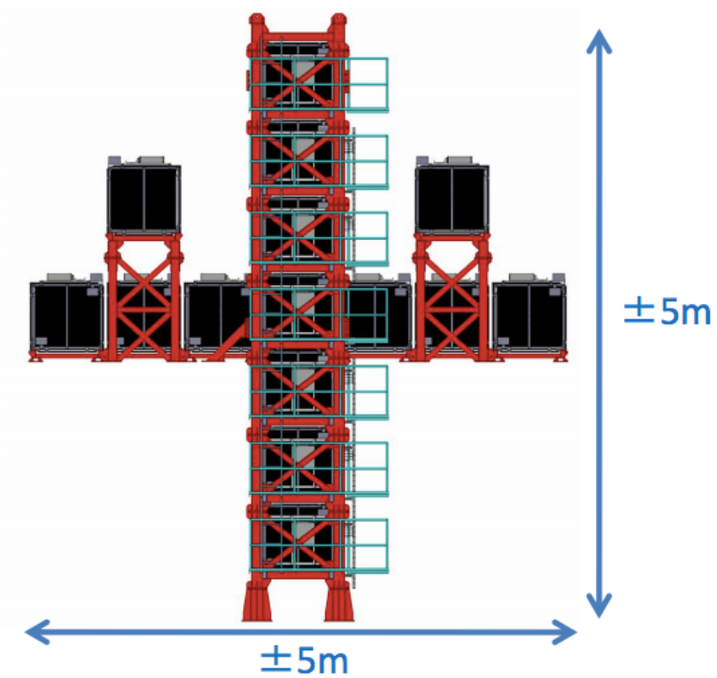
- We are interested in whether θ_{23} is consistent with maximal mixing (θ_{23}=45°)
- Need a good understanding of events with reconstructed energies that feed down into the oscillation maximum region

Systematic Uncertainties

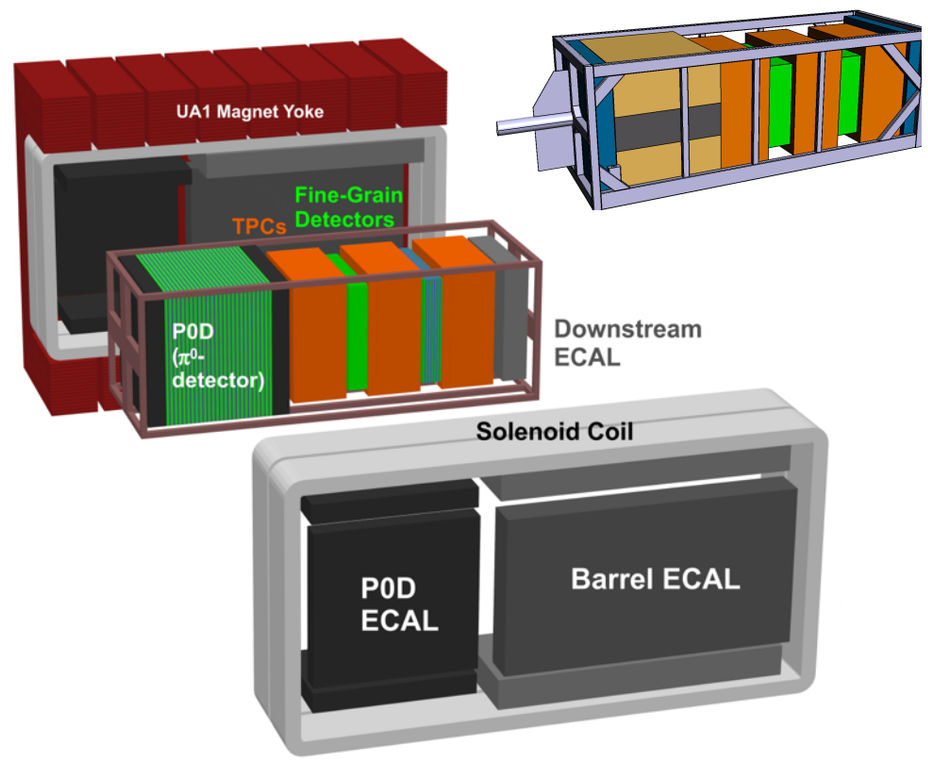
- Dominant systematic uncertainties in Hyper-K are generally from the interaction cross section modeling
- The extrapolation errors on the flux model are generally small
- However, flux uncertainties can enter into the measurements in a manner that does not allow for simple cancellation in the near/far ratio
- Will show a few near detector measurements and these types of flux uncertainties

BASELINE DESIGN FOR NEAR/INTERMEDIATE DETECTORS

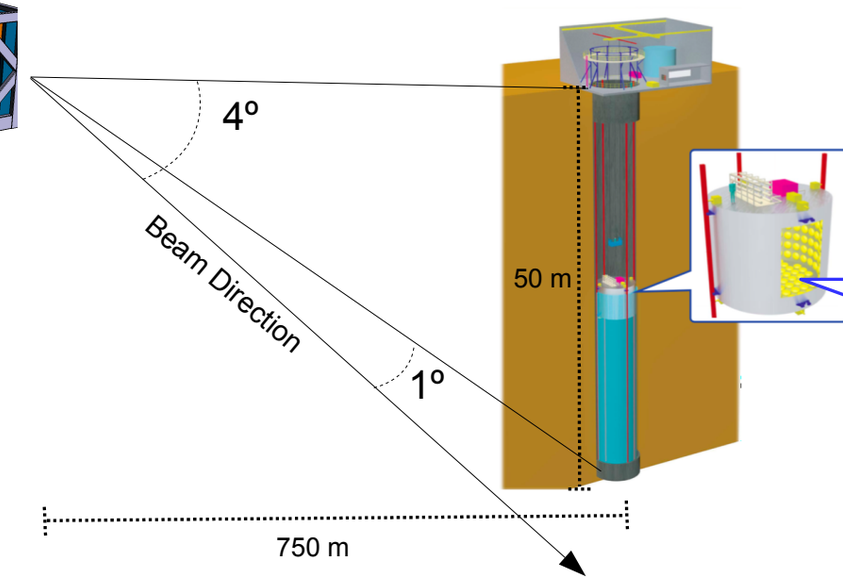
On-axis Detector (INGRID)



Off-axis Magnetized Tracker (ND280→ND280 Upgrade→??)



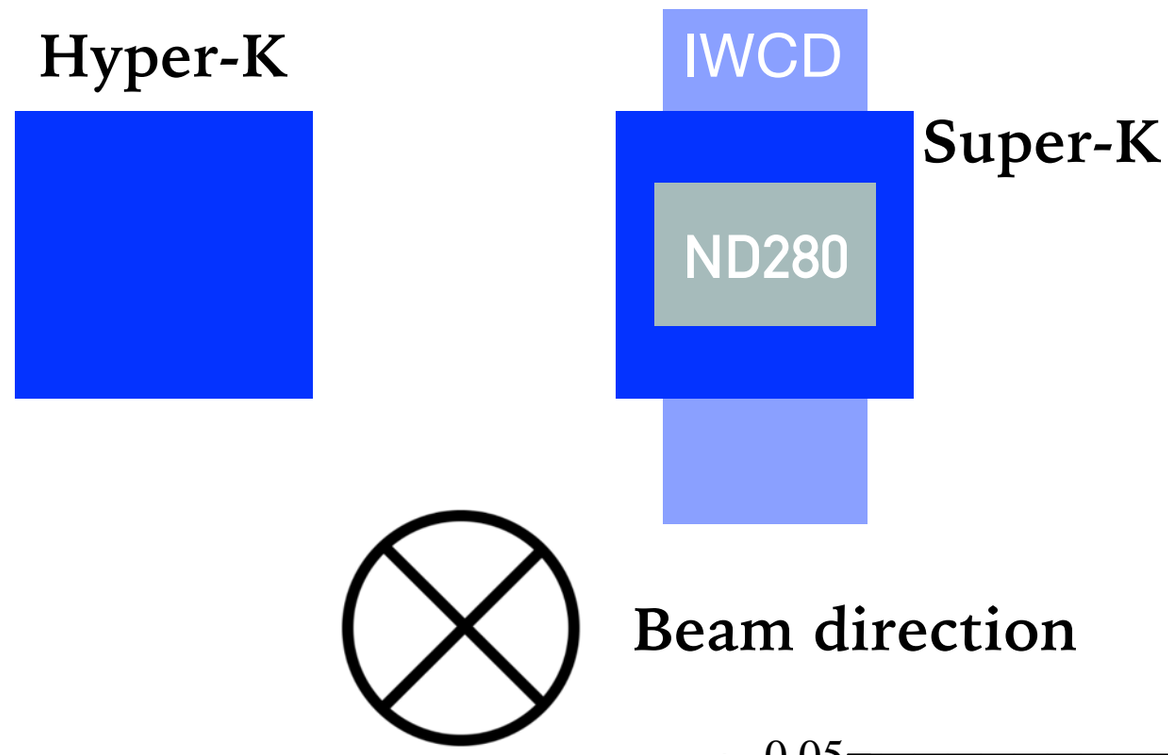
Off-axis spanning intermediate water Cherenkov detector (IWCD)



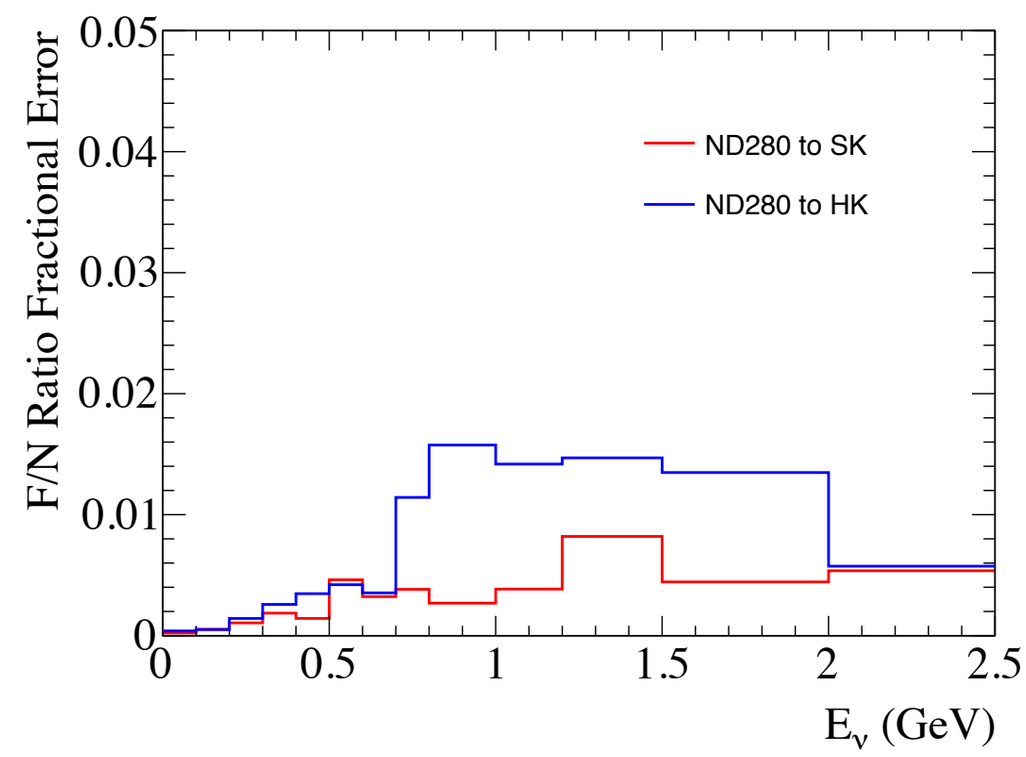
- On-axis detector: measure beam direction, monitor event rate
- Off-axis magnetized tracker: charge separation (measurement of wrong-sign background), study of recoil system
  - Expect upgrades of detector inherited from T2K will be necessary
- Off-axis spanning water Cherenkov detector: intrinsic backgrounds, electron (anti)neutrino cross-sections, neutrino energy vs. observables, H_2O target, neutron multiplicity measurement

BEAM DIRECTION MEASUREMENT

- For Hyper-K, ND280 and IWCD are not along same direction as far detector

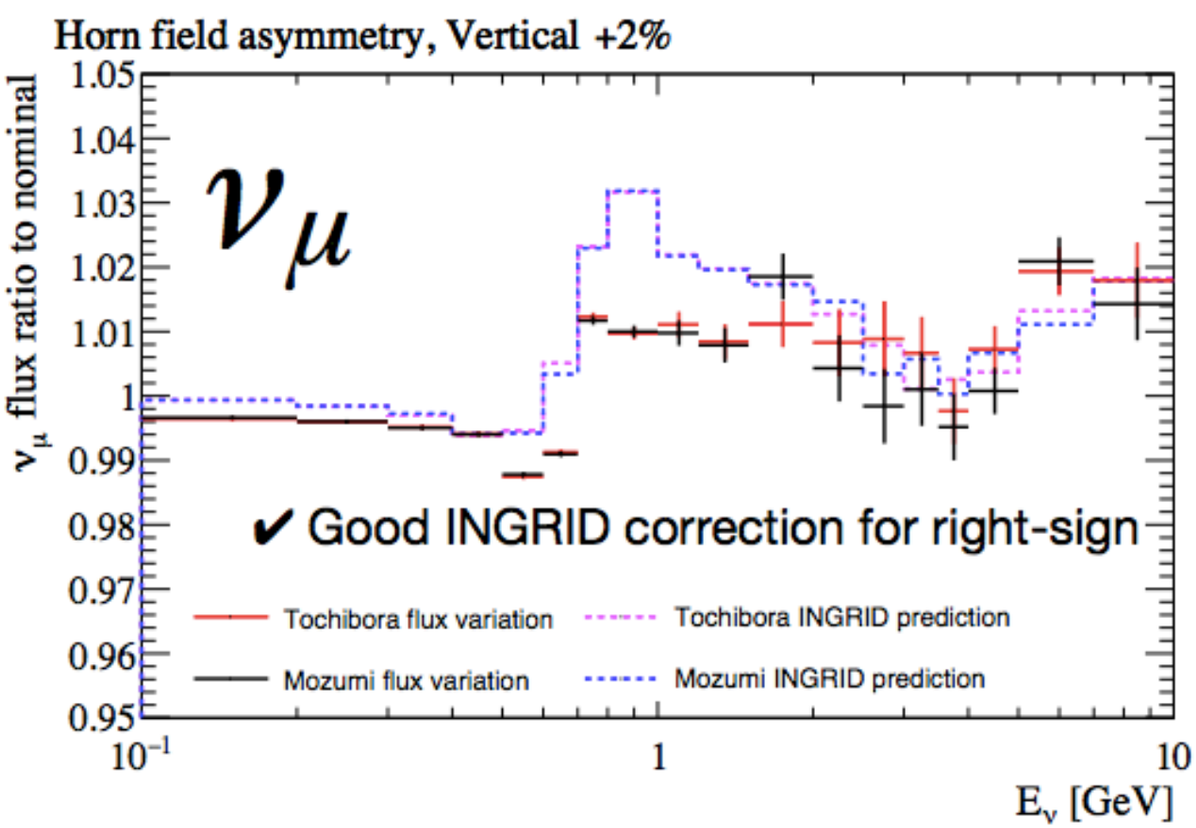


- Can introduce additional direction uncertainty that doesn't cancel in far/near ratio
- Corresponds to a <2 MeV peak energy shift of spectrum when considering simple off-axis angle uncertainty, assuming INGRID constraint
  - What about second-order effects?



RESIDUAL ERRORS WITH INGRID CONSTRAINT

- There are a number of systematic effects that to first order correspond to a shift of the beam direction
  - Proton beam transverse position at target, horn and target alignment, horn field or material asymmetries…
- At second order, these systematic effects may not have the exact same signature at INGRID and Hyper-K
- An INGRID measurement of the off-axis angle will leave residual errors at Hyper-K

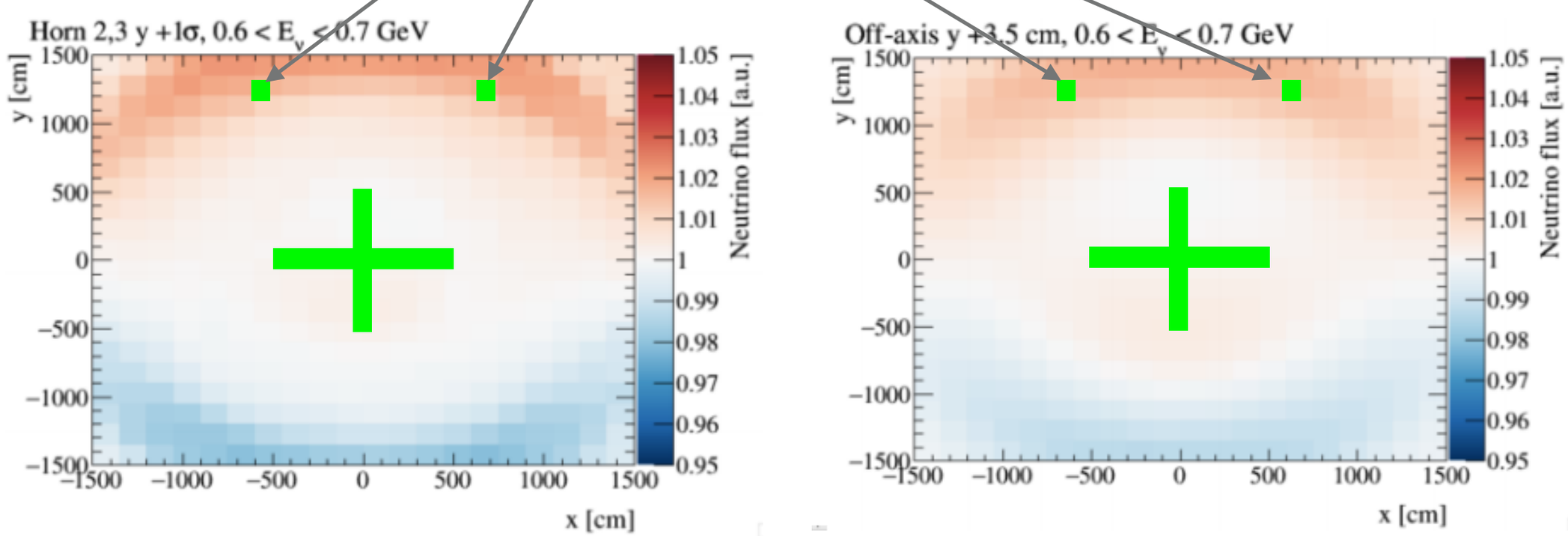


The fit to the beam direction at INGRID predicts the first-order change to the spectrum

But bin-by-bin changes can be off by as much as 1-2% in the right-sign flux

STRATEGY FOR RESIDUAL SPECTRUM ERRORS

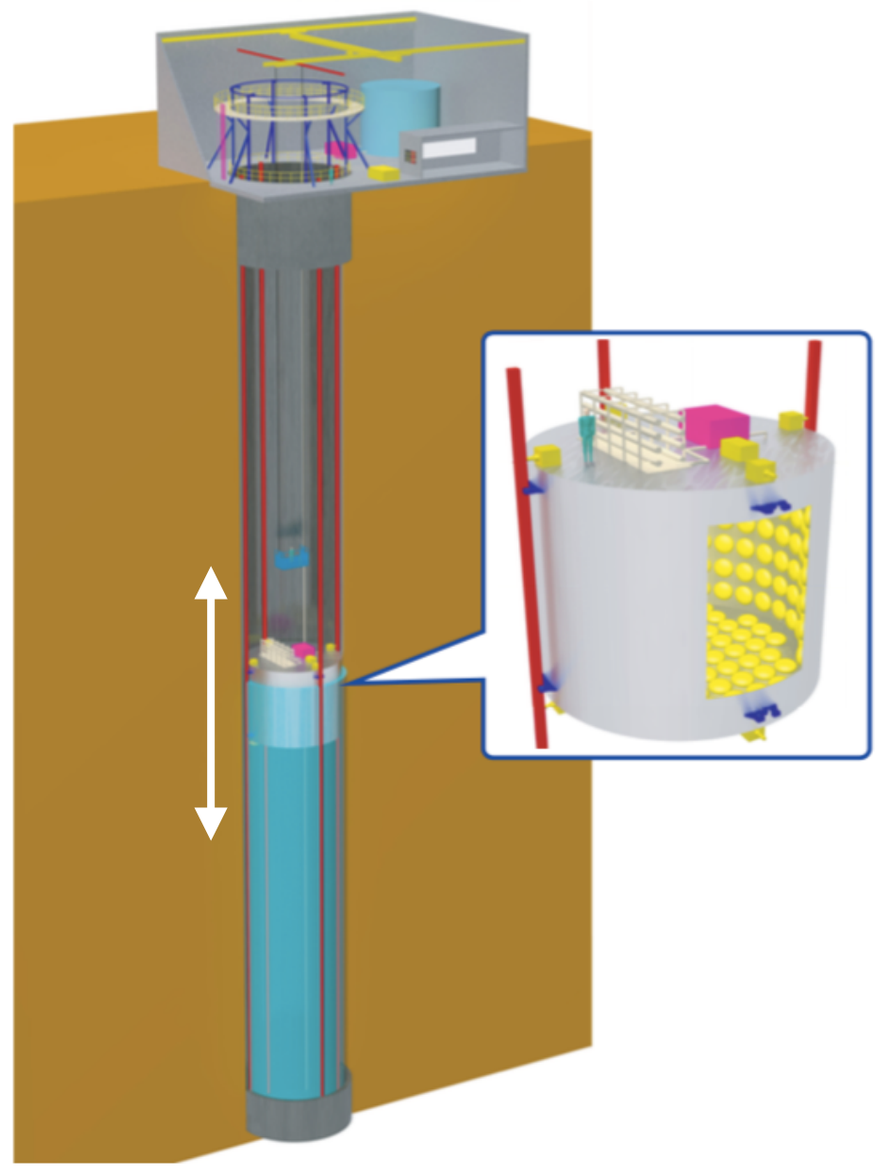
- We are making a full evaluation of these residual errors and their impact on the Hyper-K physics measurements
- If they need further constraint, there are two approaches
  - Reduce the systematic error sources: better alignment, beam position measurement, horn field measurements, material modeling, etc.
  - Consider additional beam profile monitors located away from the cross configuration of INGRID

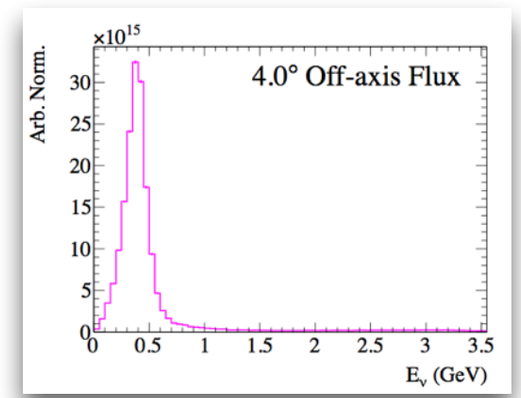


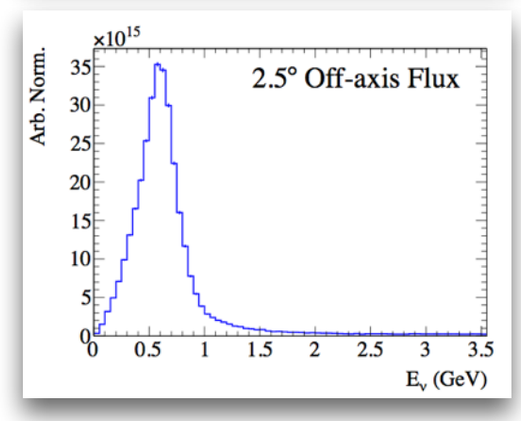
THE IWCD

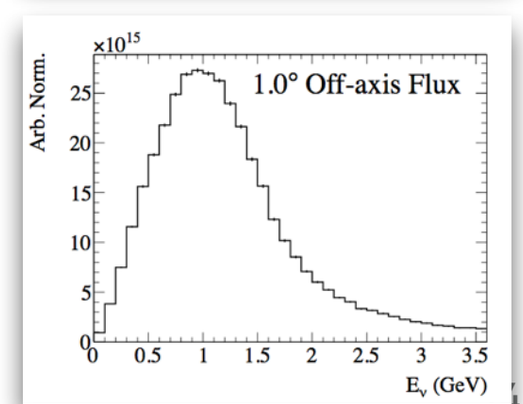
- The IWCD is 8 m tall, 10 m diameter water Cherenkov detector in a vertical pit
- Detector vertical position controlled with external water level (see below)

- Changing the vertical position changes the off-axis angle
- Neutrino spectrum varies with off-axis angle
- Can probe relationship between neutrino energy and observed final states in water Cherenkov detector

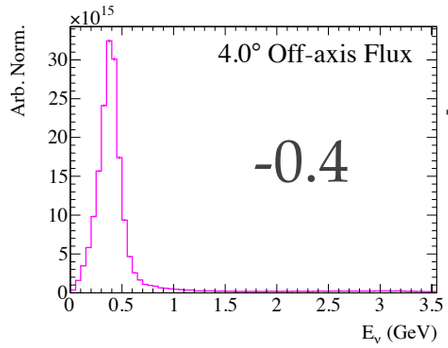


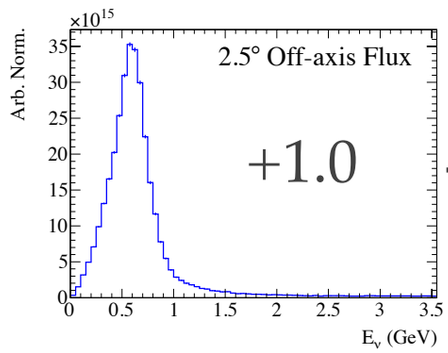


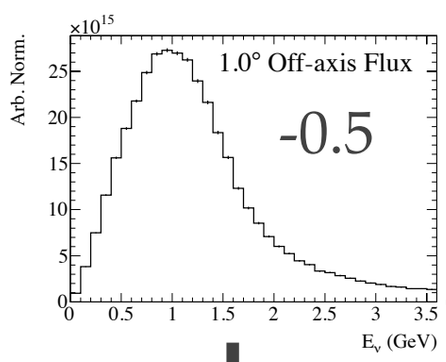




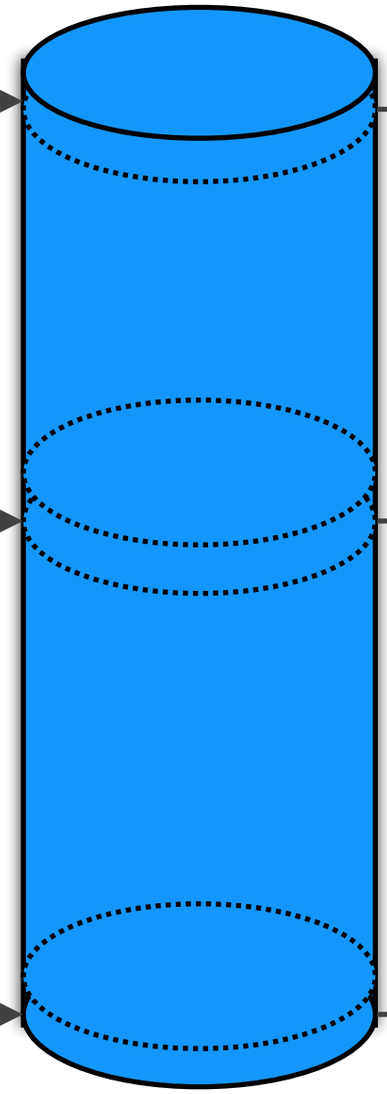
USING THE OFF-AXIS DATA



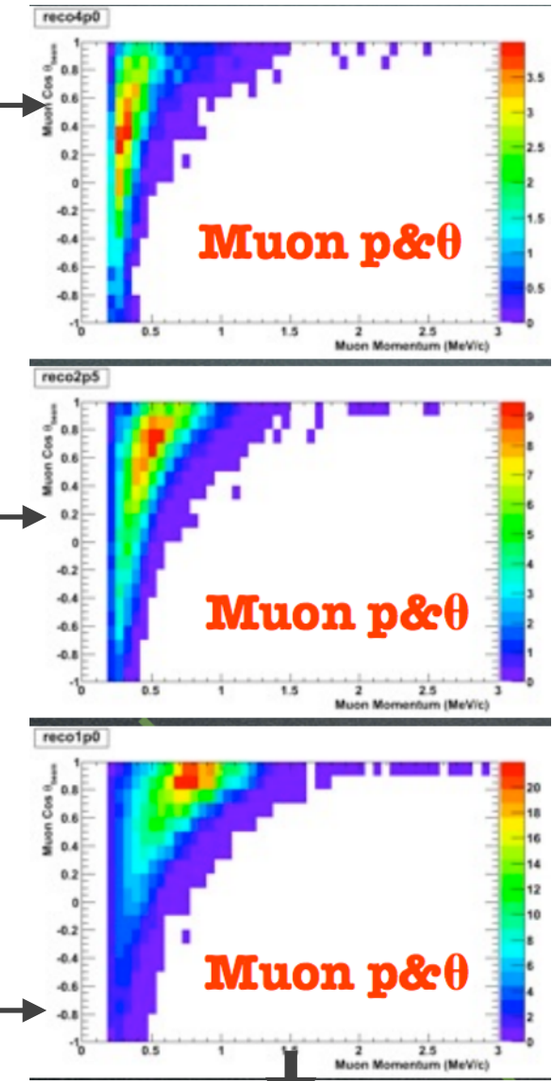


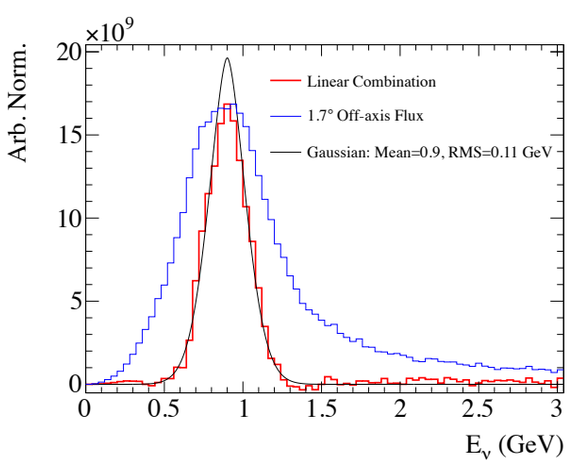


Spectra at at each off-axis bin

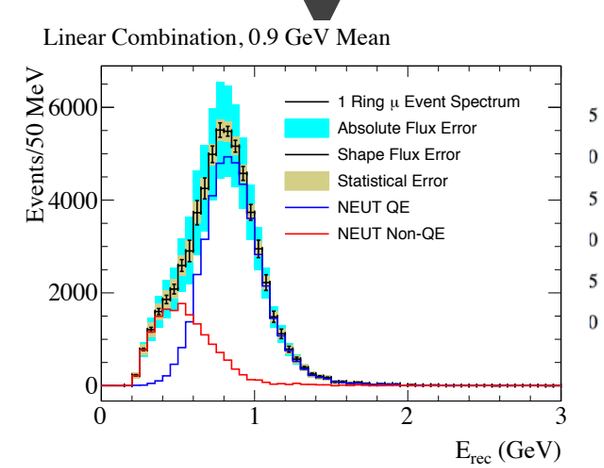


Observed muon kinematic distributions



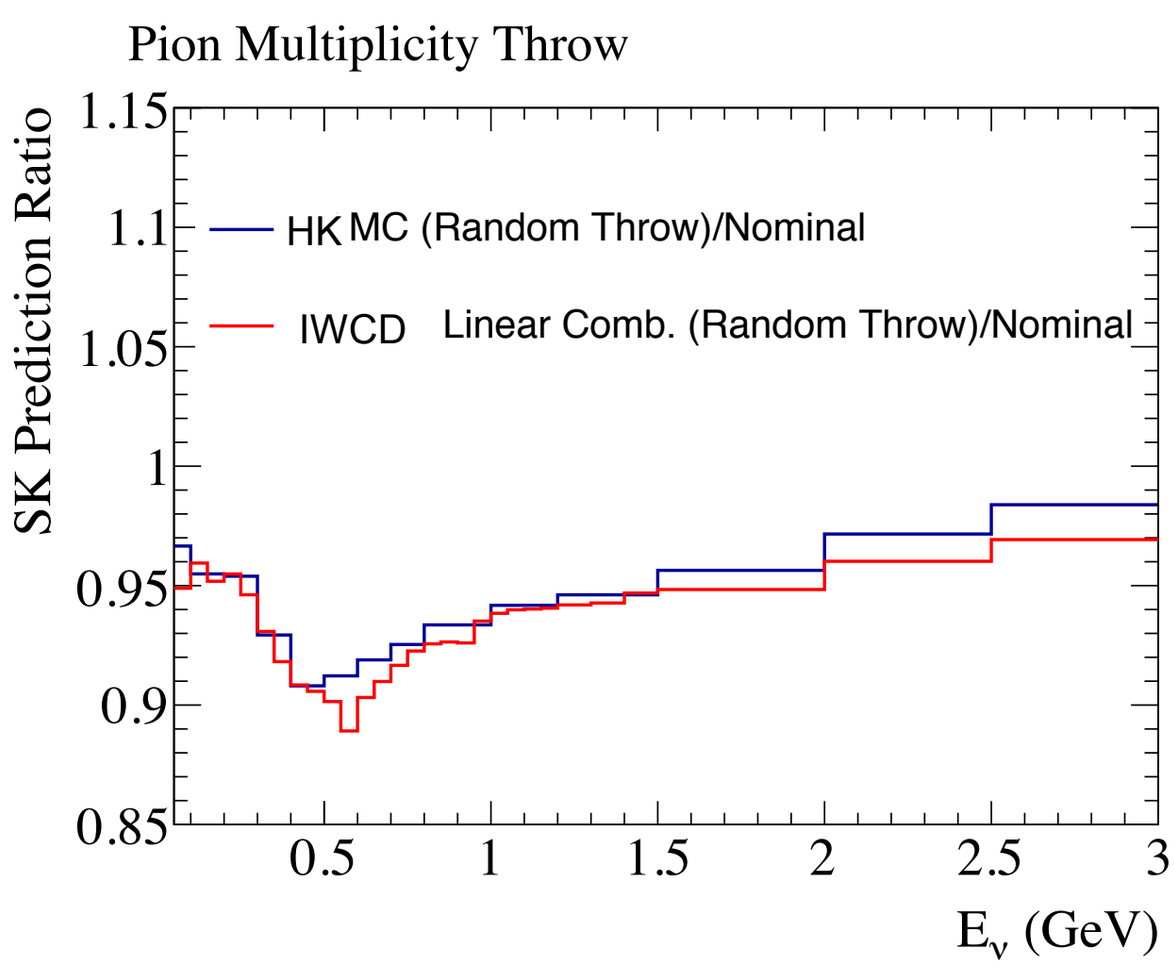


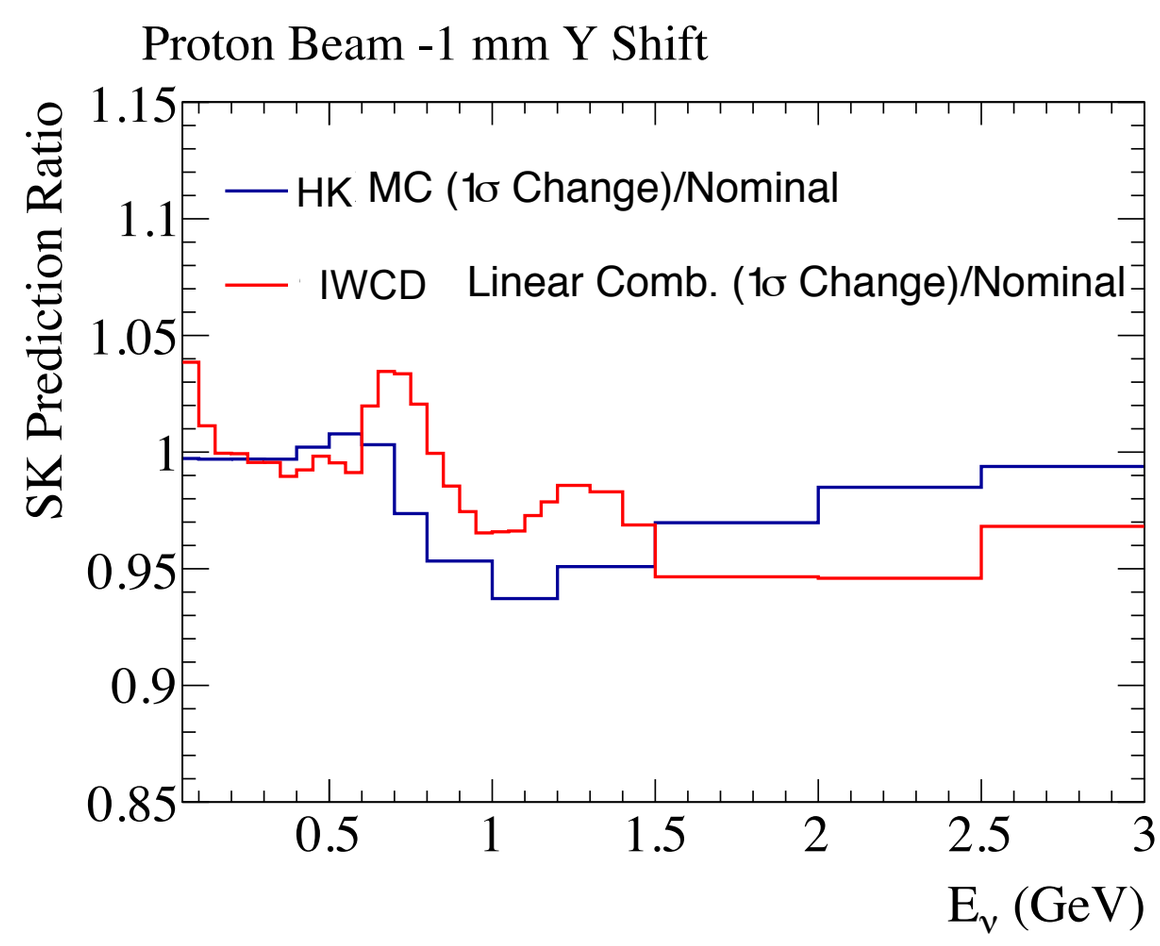
Subtract off low energy and high energy tails of flux → produce very narrow beam to measure energy response.



FLUX UNCERTAINTIES IN IWCD ANALYSIS

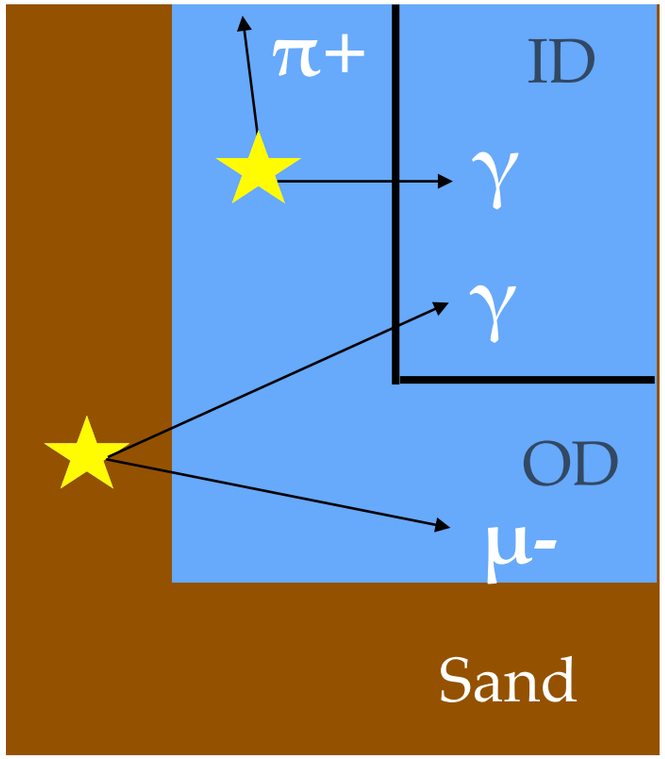
- We study flux errors for the case where the linear combinations are used to reproduce the muon neutrino spectrum after disappearance
- Hadron production errors cancel well between linear combination IWCD flux and Hyper-K flux
- Errors that affect the beam profile (such as off-axis angle) don't cancel as well
  - We can benefit from strategies to reduce these

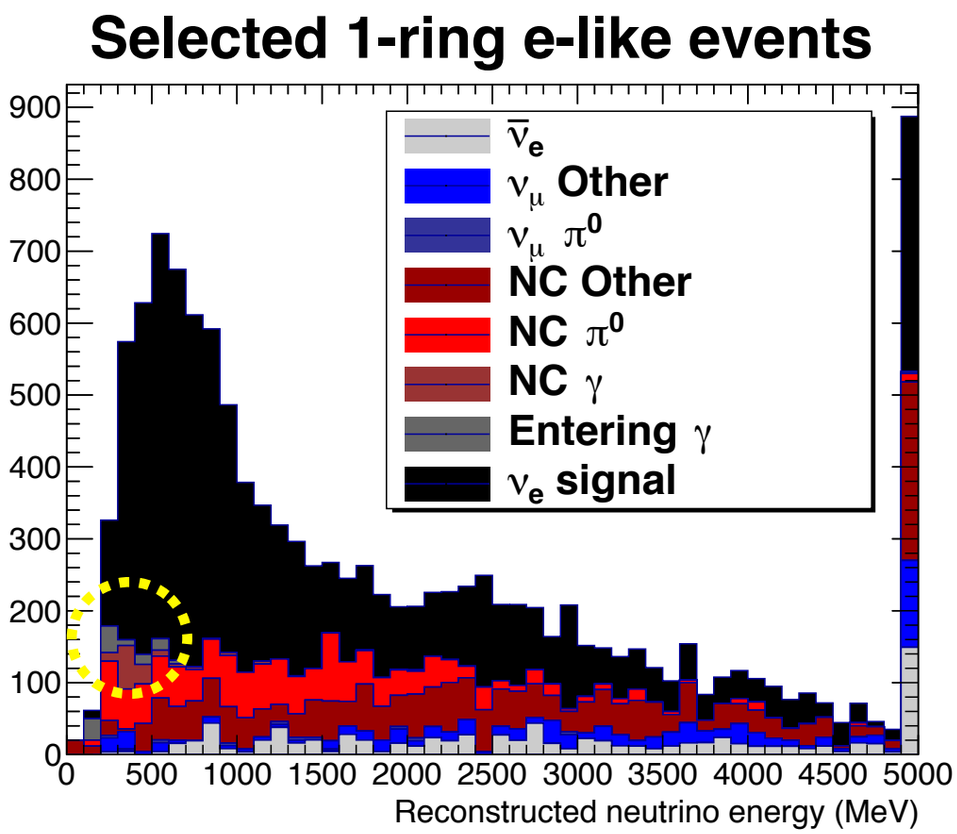




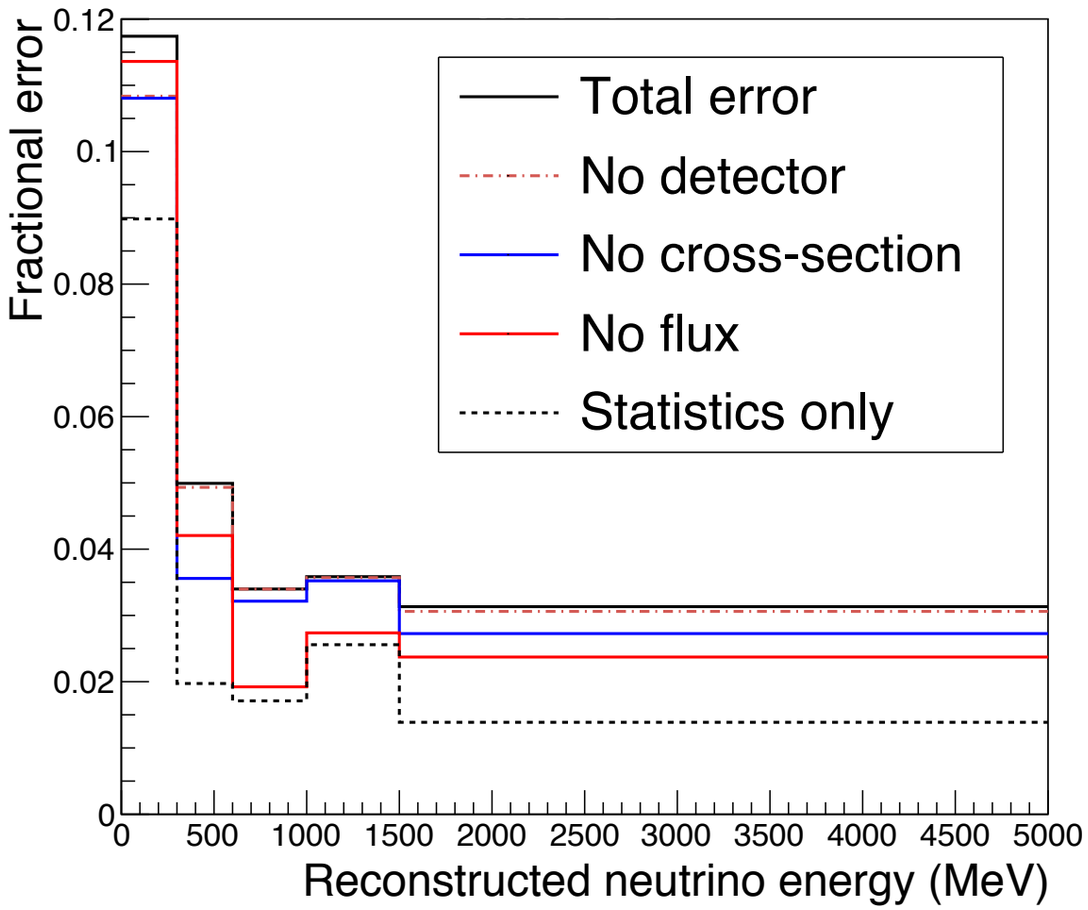
ELECTRON (ANTI) NEUTRINO CROSS SECTION IN IWCD

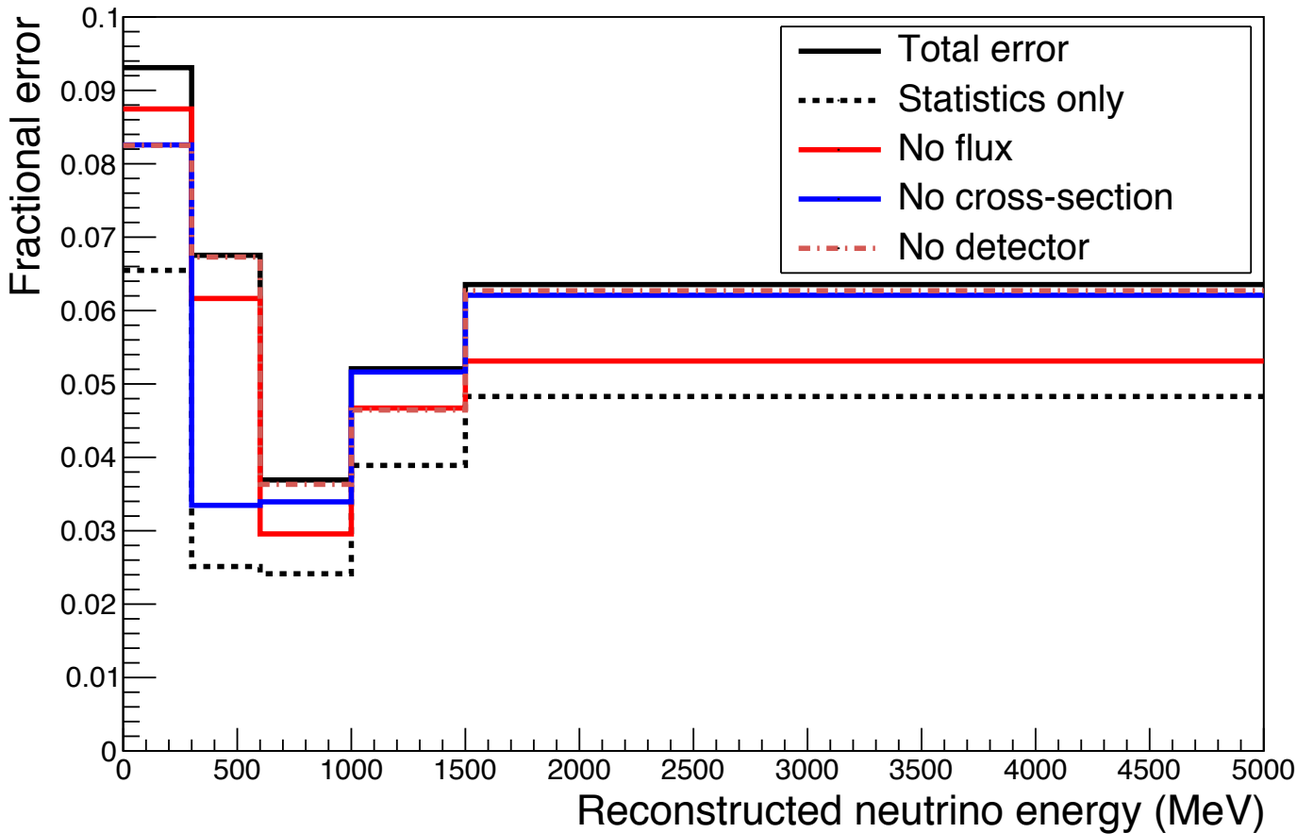
- Use intrinsic electron (anti)neutrinos in beam to measure their cross section
- Advantages in IWCD
  - Active shielding minimizing high energy external gamma background
  - The fraction of electron (anti)neutrino flux increases with off-axis angle
- Measurements are made relative to the muon (anti)neutrinos
- >70% pure samples of a few thousand candidates can be achieved
- Statistics at low energy are important





ELECTRON (ANTI) NEUTRINO CROSS SECTION



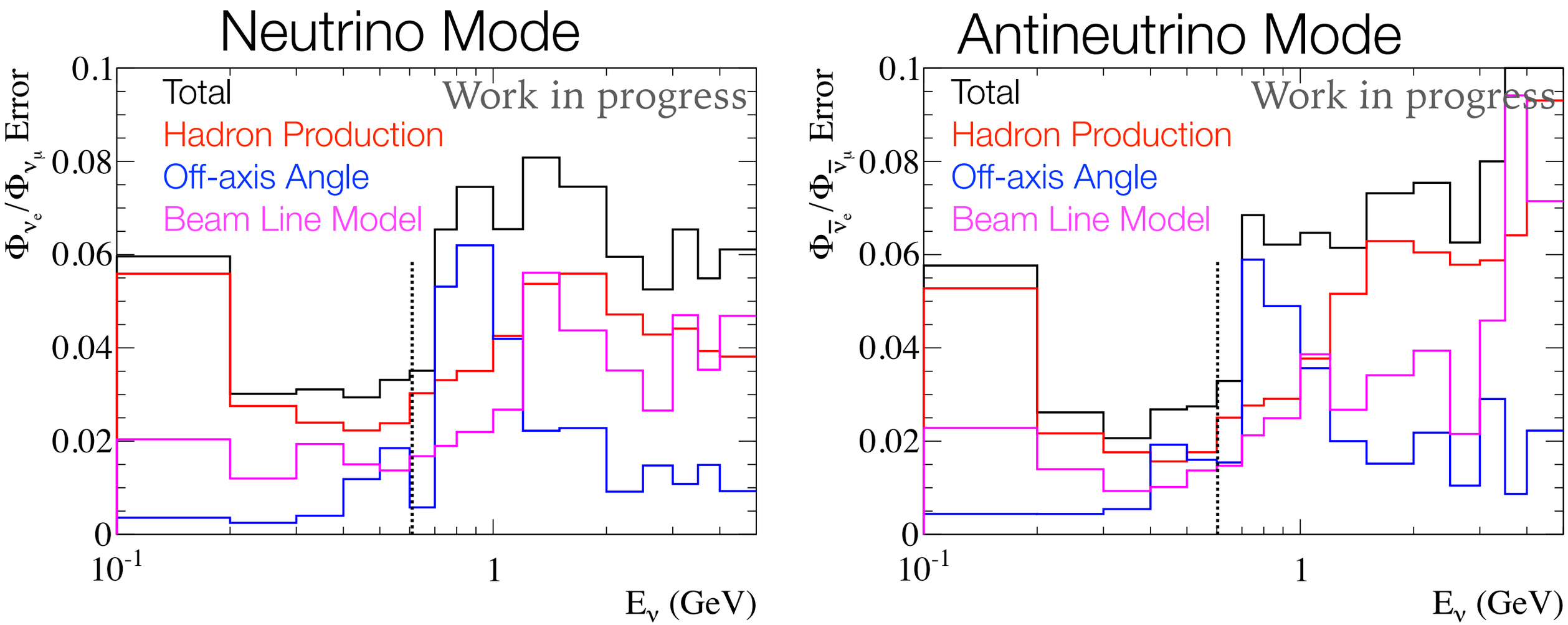


- Statistical errors are at the 2-4% level for bins of primary importances
- Controlling uncertainties on the flux and backgrounds will be important for achieving this level of precision
- Calibration is also important. Relative error on fiducial volume for muon neutrino and electron neutrino candidates must be controlled.

FLUX ERRORS FOR ELECTRON (ANTI)NEUTRINO MEASUREMENTS

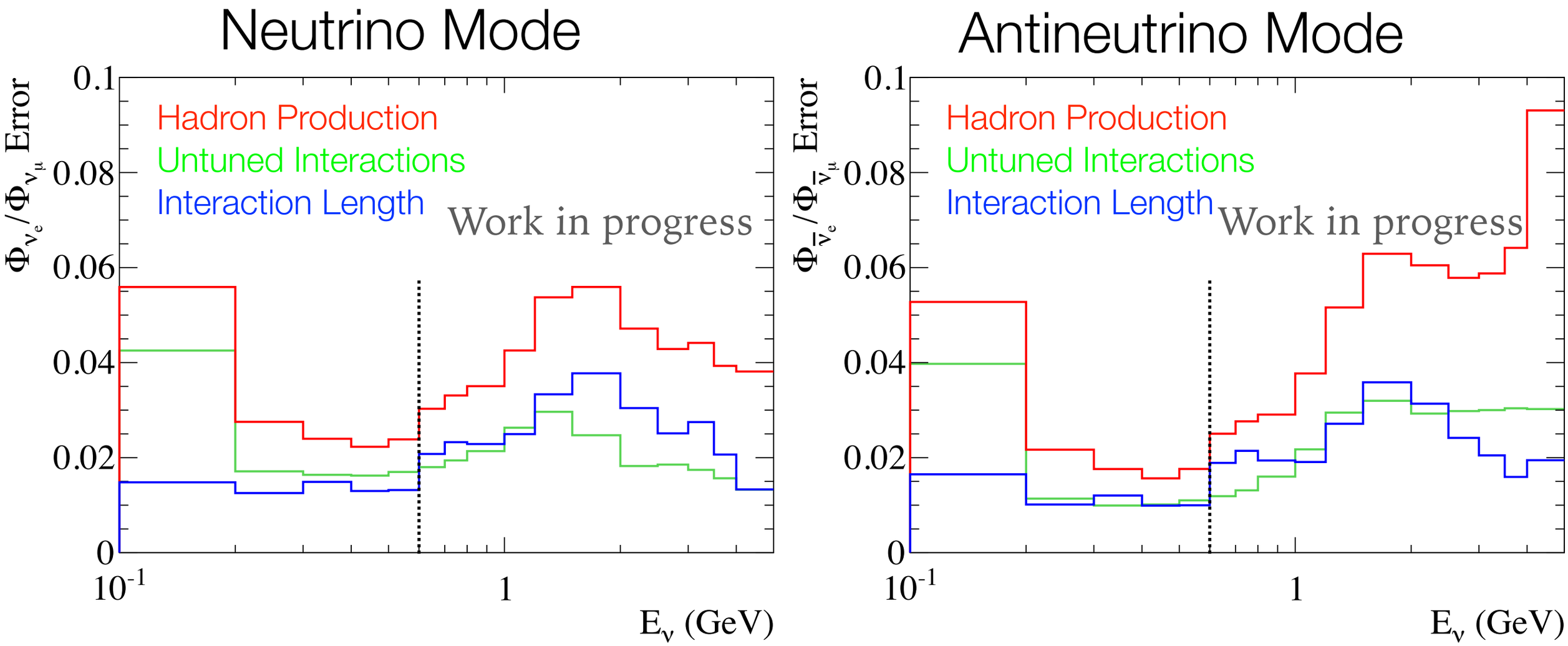
- Measuring the cross section ratios $\sigma(\nu_e)/\sigma(\nu_\mu)$ and $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$
- Depend on the flux ratios $\Phi(\nu_e)/\Phi(\nu_\mu)$ and $\Phi(\bar{\nu}_e)/\Phi(\bar{\nu}_\mu)$
- IWCD studies are carried out with an older version of the flux uncertainties based on NA61/SHINE thin target data
- Have done preliminary investigation into errors with NA61/SHINE 2009 replica target data **Eur. Phys. J. C76 (2016) no.11, 617**
  - Based on T2K flux error calculations (only at 2.5° off-axis)
  - NA61/SHINE 2009 replica target data only for pion production
  - Future T2K flux releases will be based on NA61/SHINE 2010 replica target data that includes kaon production measurements
    Eur. Phys. J. C79 (2019) no.2, 100

FLUX RATIO UNCERTAINTIES



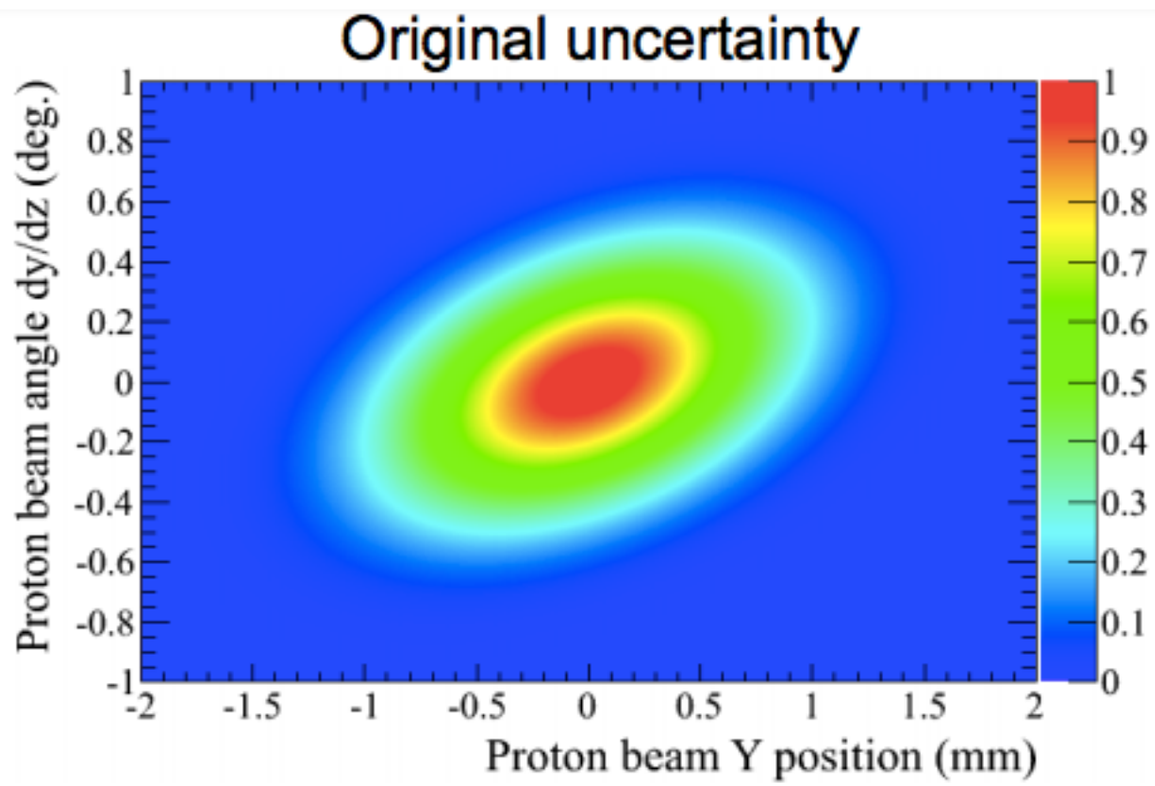
- Uncertainty just above flux peak is dominated by off-axis angle uncertainty
- No dominant source of beam line modeling errors.
  - Would benefit from reduction of error on: horn current measurement, horn field measurement, beam line alignment, material modeling etc.

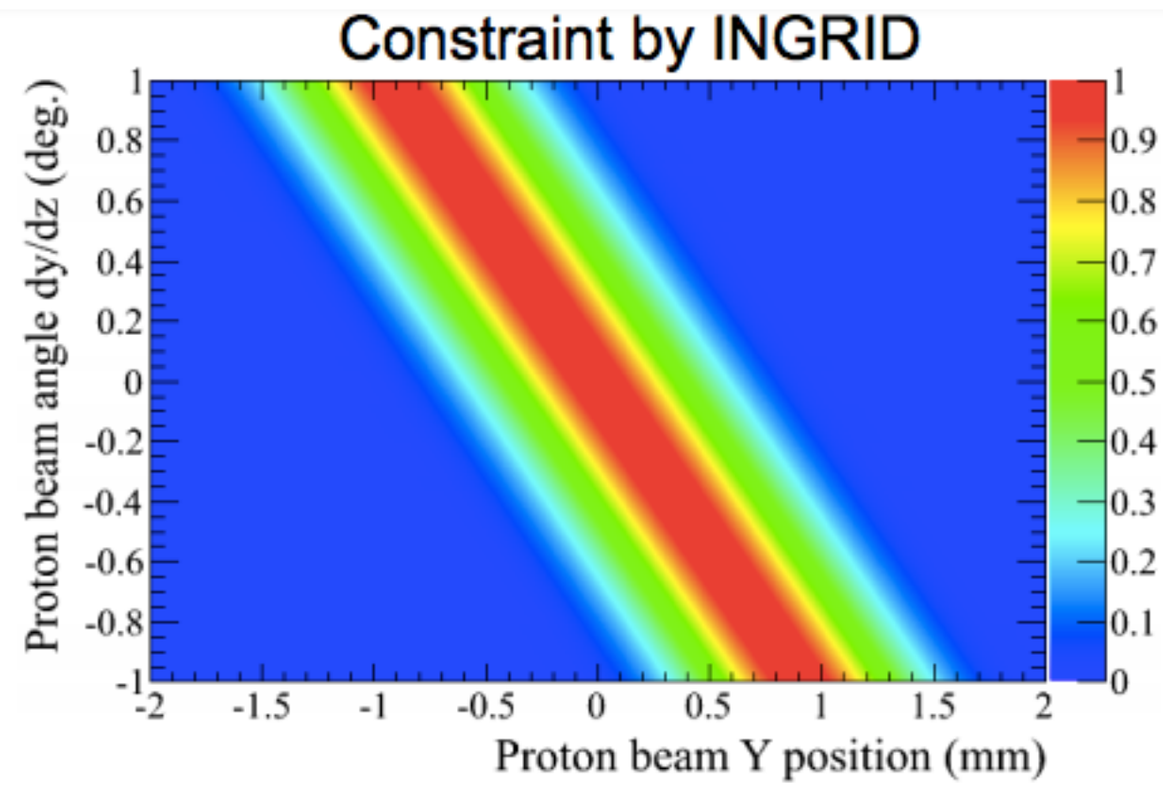
HADRON ERRORS



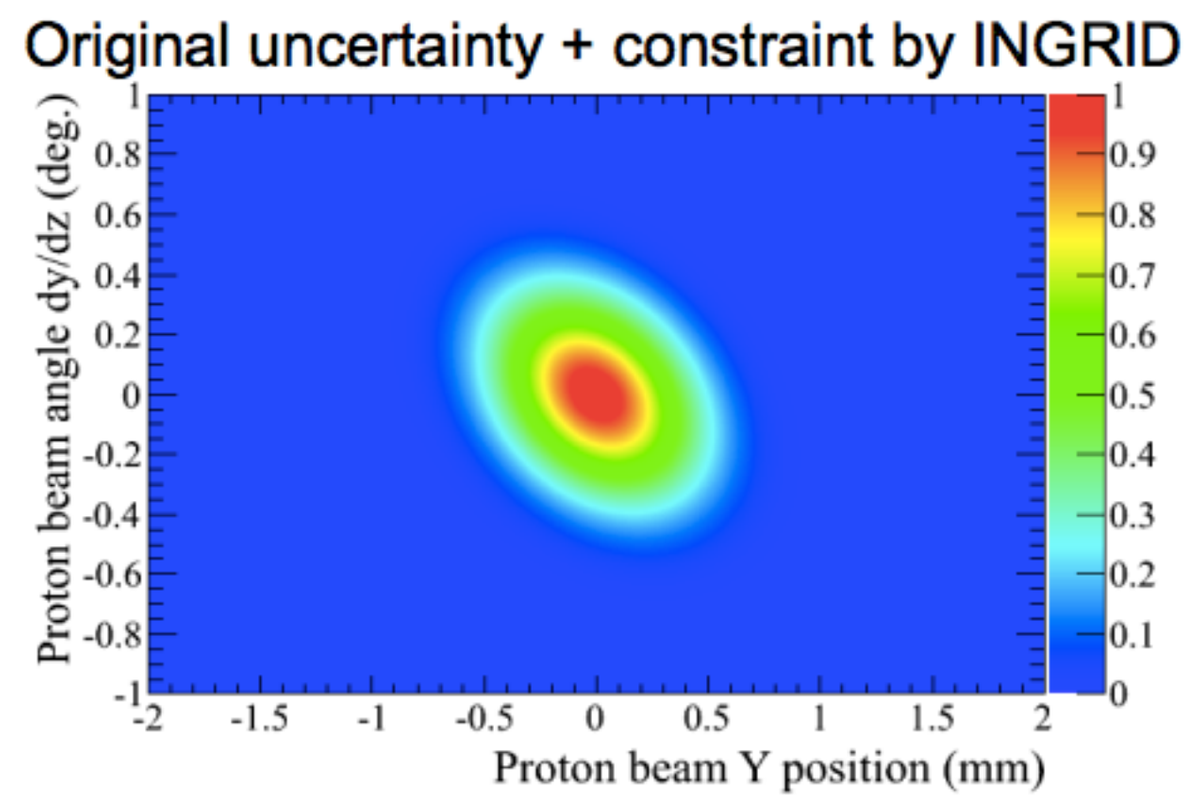
- Uncertainties on the interaction length and un-tuned interactions dominate the hadron production errors
- Some of these are related to kaon production and kaon re-scattering
  - Should revisit after 2010 replica target data is used

OFF-AXIS ANGLE ERROR





- Dominant source of error on beam direction is from beam vertical position/angle at the target
- Can be constrained by the INGRID measurement



CONCLUSION

- Controlling systematic errors is important for the Hyper-K physics program
- Standard flux errors on the near to far extrapolation aren't dominant
- We consider other sources of errors
  - Flux profile errors with left/right asymmetry
  - Errors as a function of off-axis angle
  - Errors on the $\Phi(\nu_e)/\Phi(\nu_\mu)$ and $\Phi(\bar{\nu}_e)/\Phi(\bar{\nu}_\mu)$ ratios
- Hyper-K is considering improved beam monitor and additional hadron production measurements to reduce these errors

THANK YOU