TITUS Selection Study

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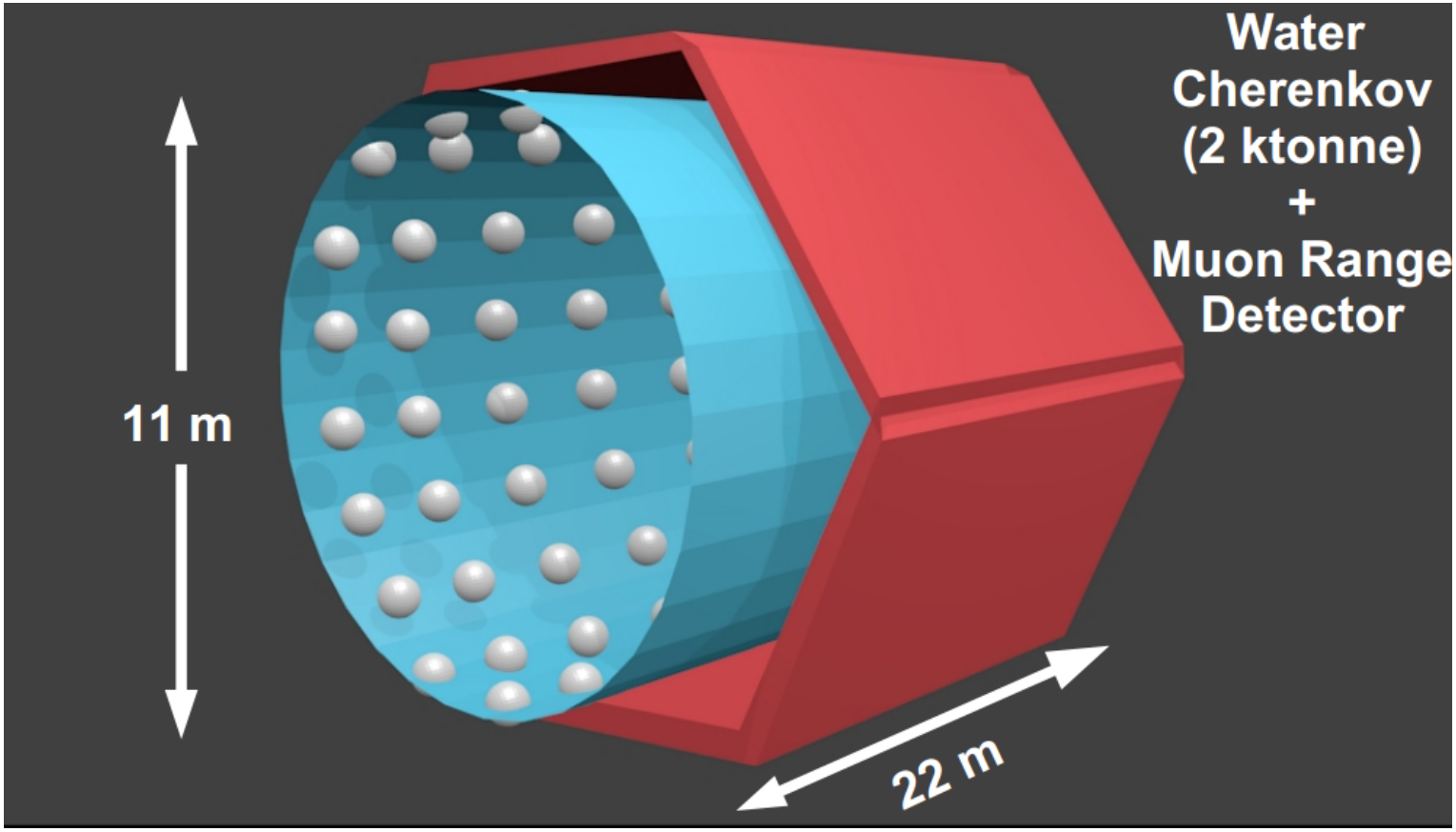
July 2014

The TITUS detector

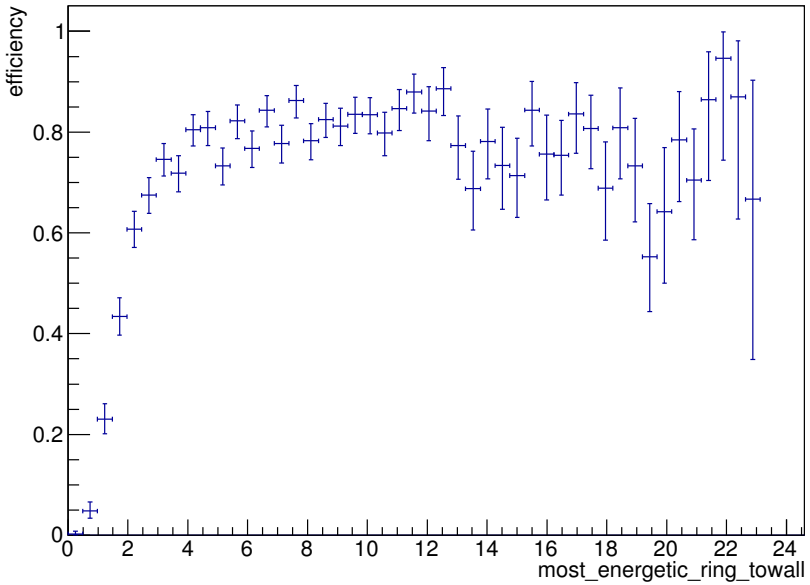
- Primary goal: maximize cancellation of uncertainties in near-far ratio.
  - Identical target nuclei.
  - At $\sim$2 km it is exposed to a similar total flux as the far detector
  - Gd doping allows neutron tagging (discriminate $\nu - \bar{\nu}$, multi-nucleon processes)
  - MRD to reconstruct escaping muons, sign-selection for $\nu - \bar{\nu}$ discrimination

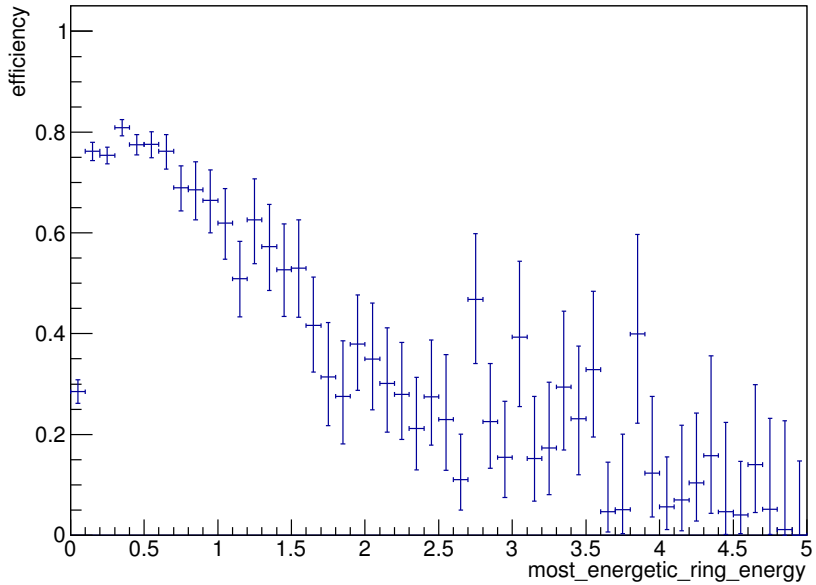


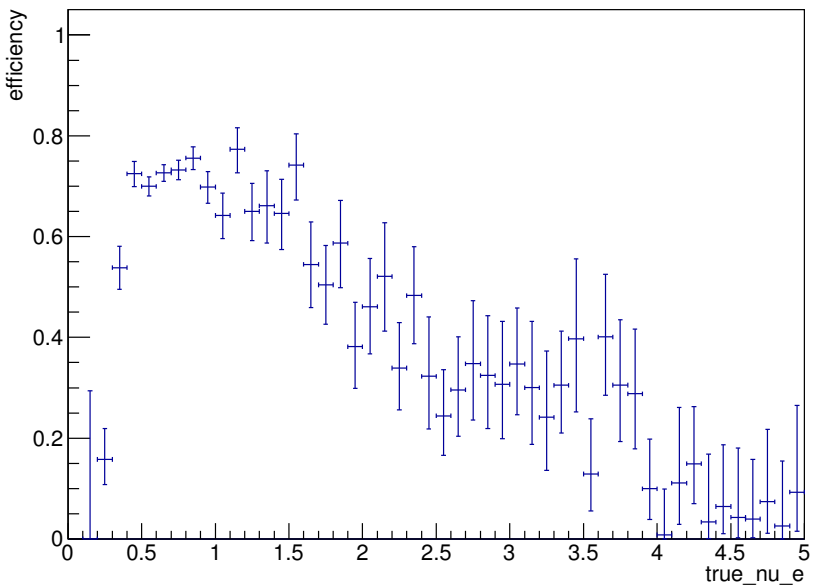
TITUS selection / reconstruction

- Vectors generated with NEUT.
- GEANT4 based detector simulation (ANNIE/WCsandbox).
- Super-K based reconstruction
  - Momentum and direction smeared.
  - Efficiency of 1Rmu and 1Re selection provided by tables
    - Distance to wall
    - E_ν
    - Most energetic ring energy
    - Final state topology
- Inflexible e.g. difficult to optimise cuts for smaller tank.
- But the best available until we have a TITUS reconstruction working.
  - on-going work to implement “real” reconstruction.

Selection Efficiency

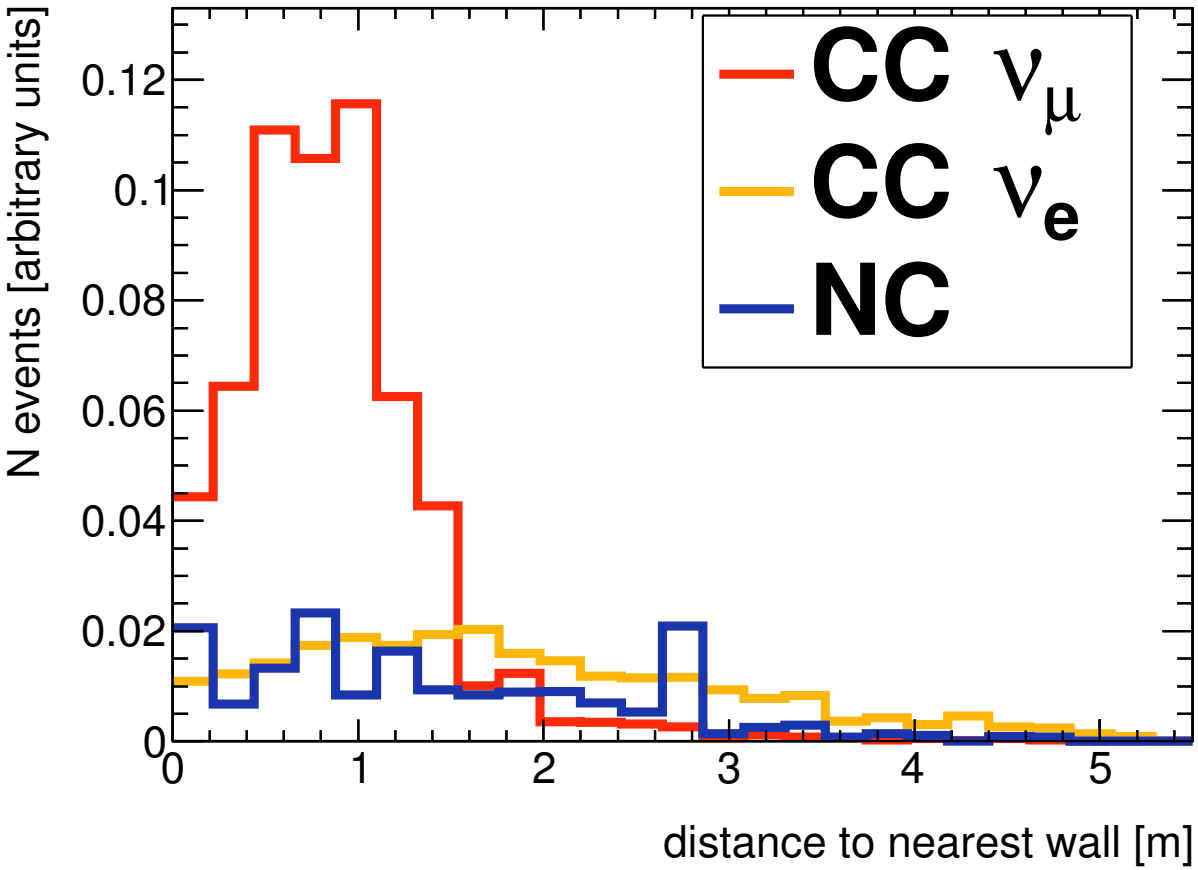






- Efficiencies for true CC1μ0π in TITUS.
- 80% plateau in "To wall" at 2m.
- Drop at high energy due to ranging out.

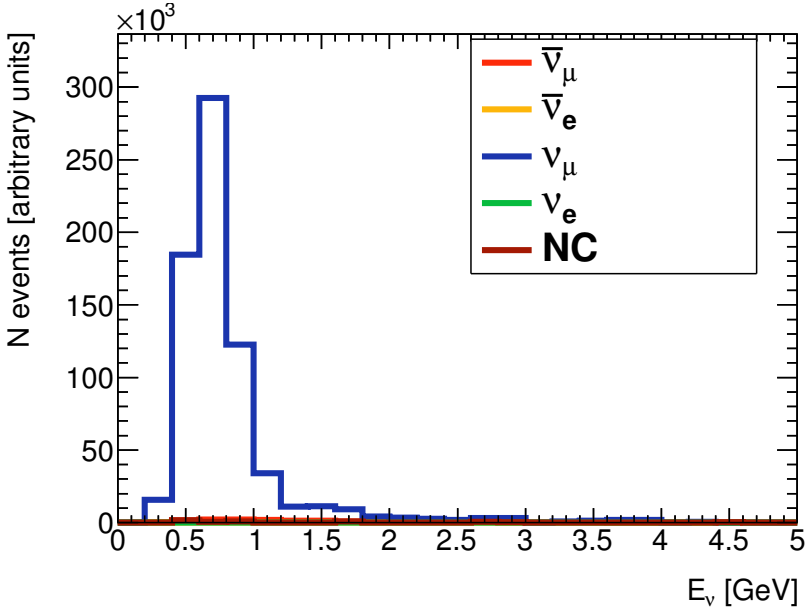
Fiducial Volume



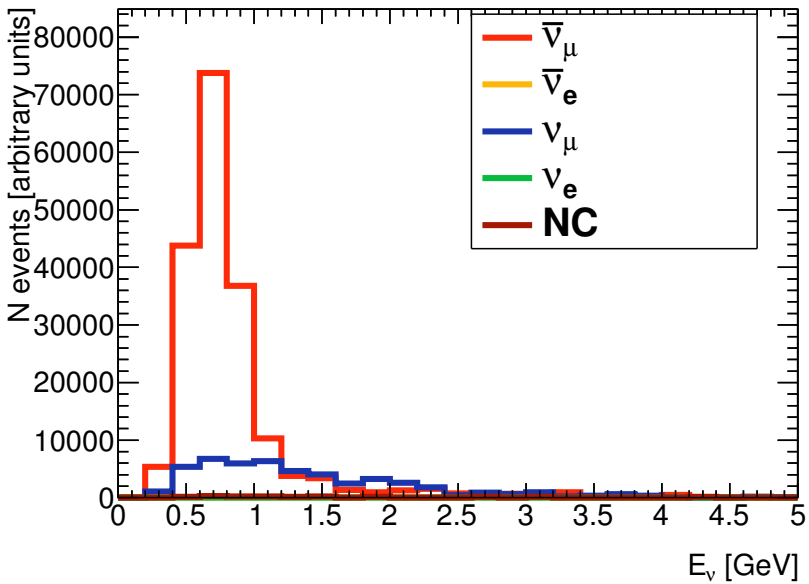
- Large muon contamination in electron sample at dwall$<$ 2.0m
- Low efficiency at towall $<$ 2m
- Choose 2m fiducial volume
- Cuts to be re-optimised when real reconstruction available.

Selected Samples in TITUS

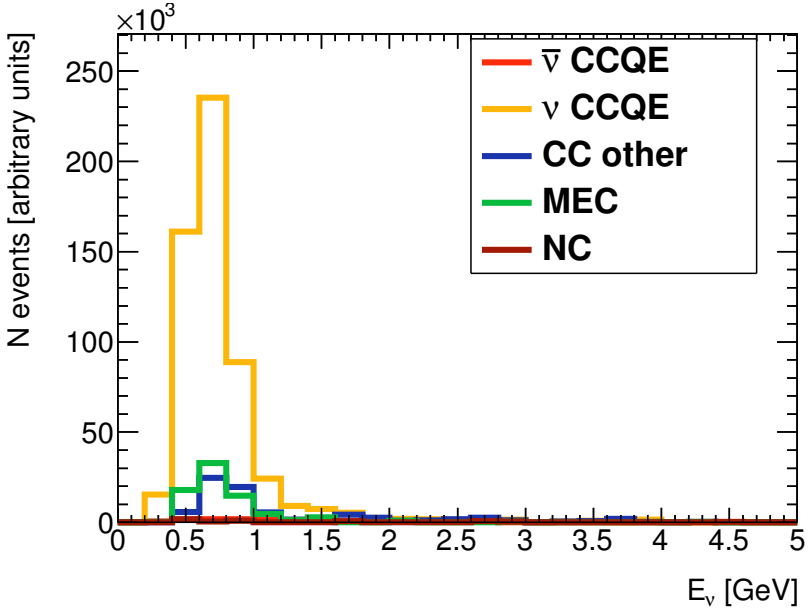
TITUS 1Rmu FHC



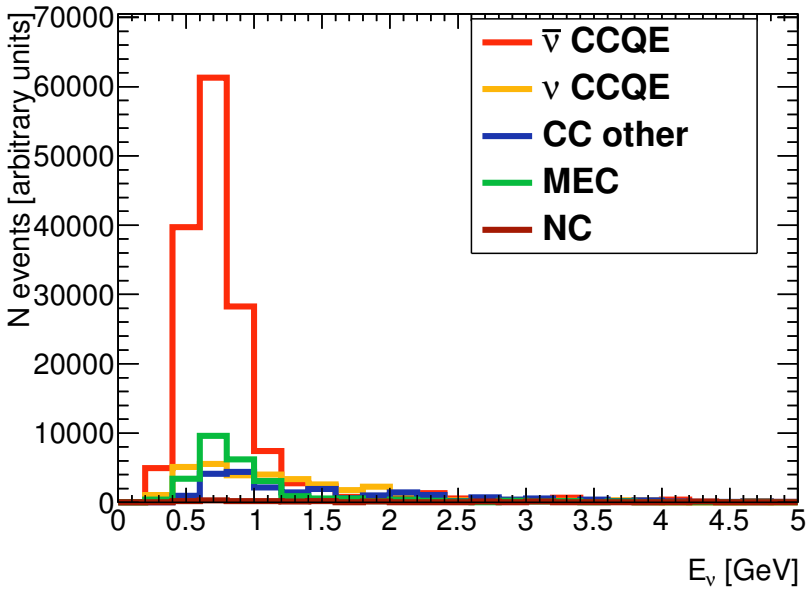
TITUS 1Rmu RHC



TITUS 1Rmu FHC

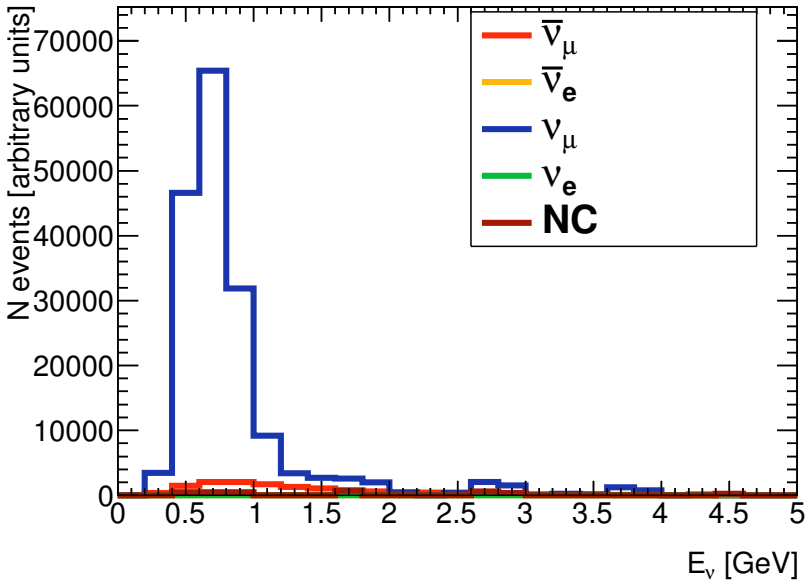


TITUS 1Rmu RHC

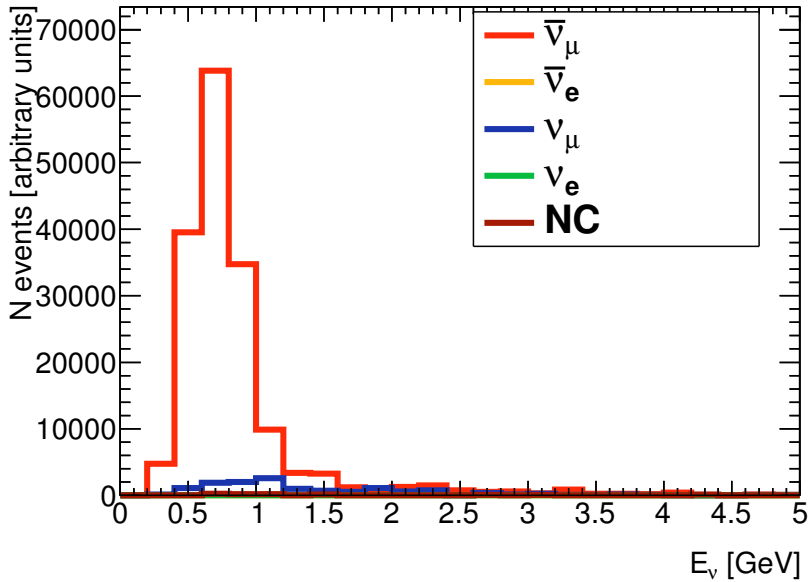


Selected Samples in TITUS

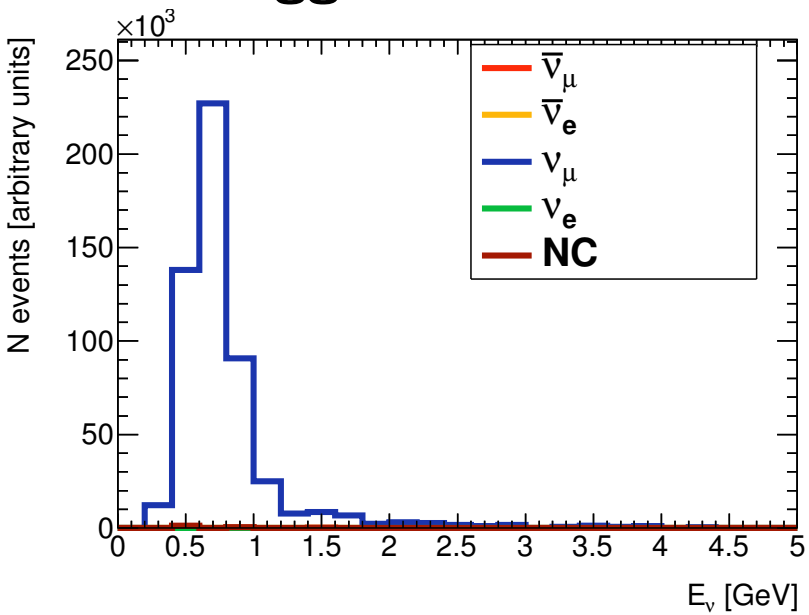
FHC with tagged neutron



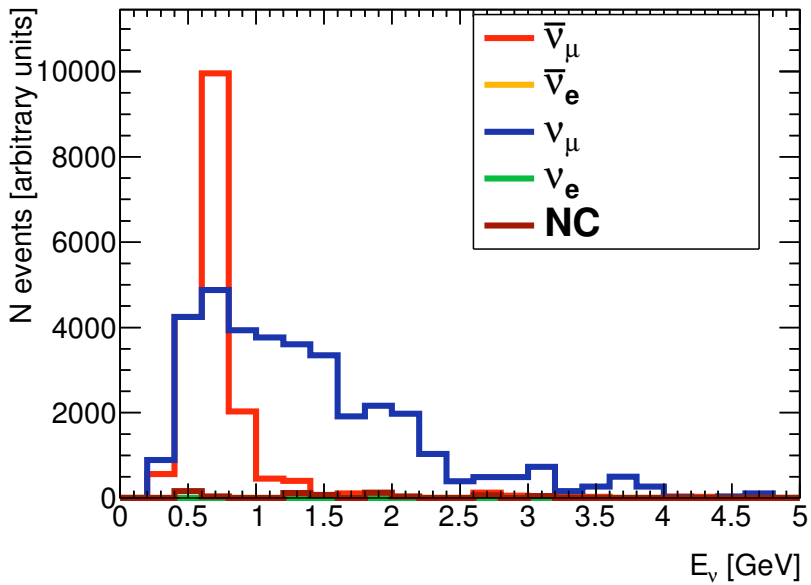
RHC with tagged neutron



FHC no tagged neutron

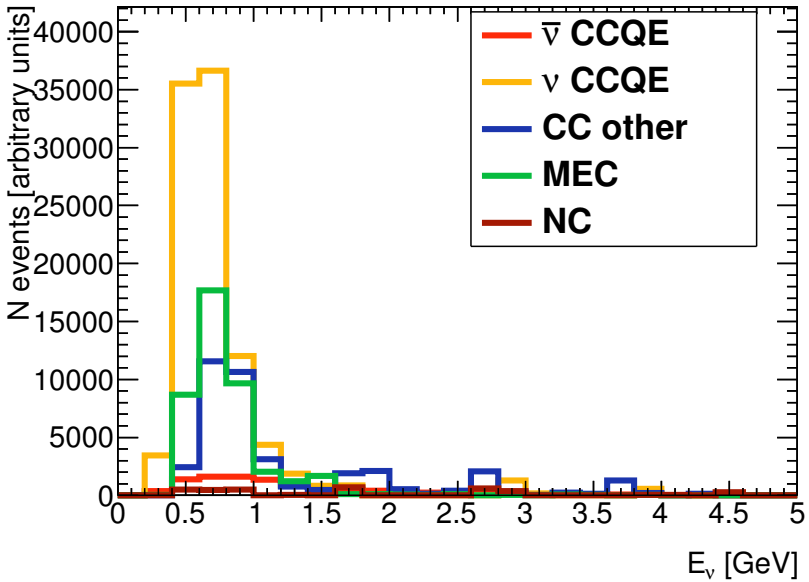


RHC no tagged neutron

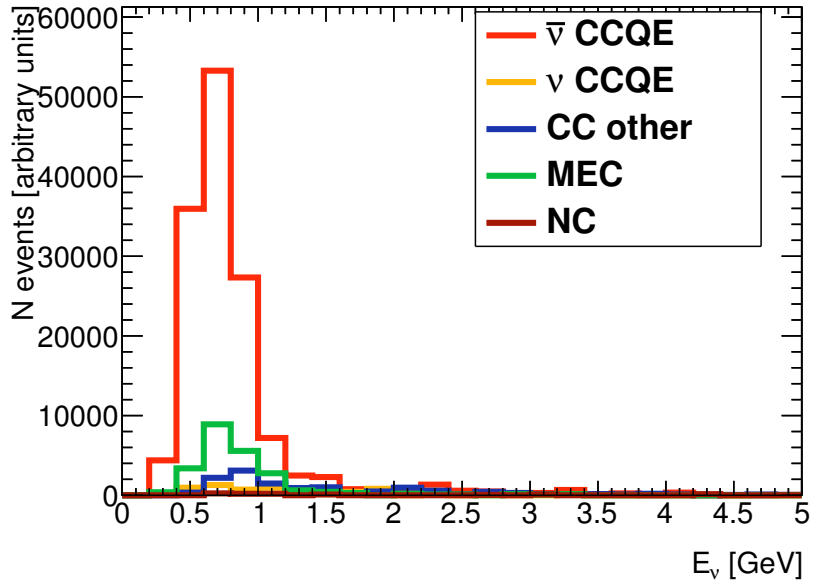


Selected Samples in TITUS

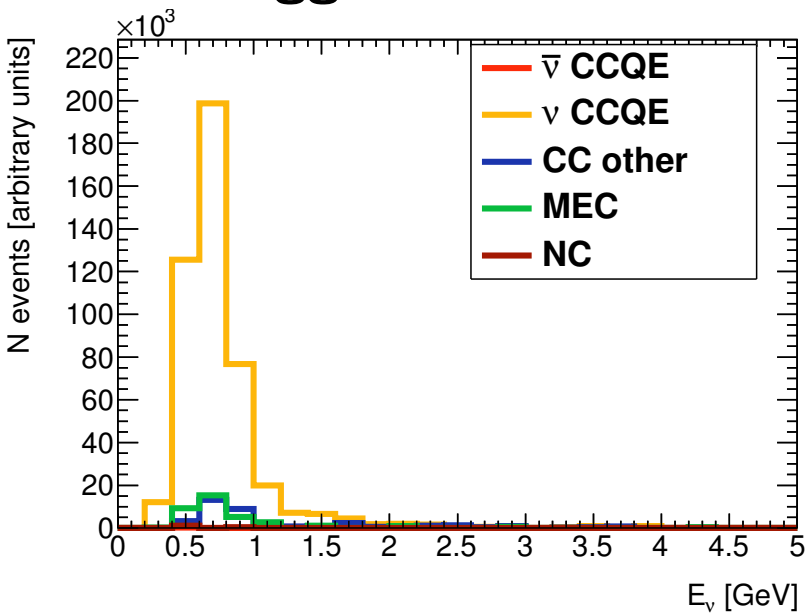
FHC with tagged neutron



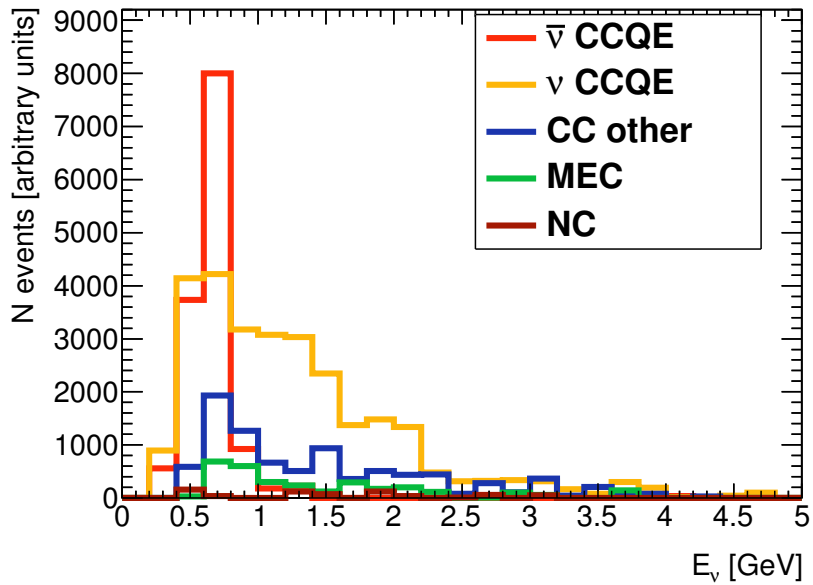
RHC with tagged neutron



FHC no tagged neutron

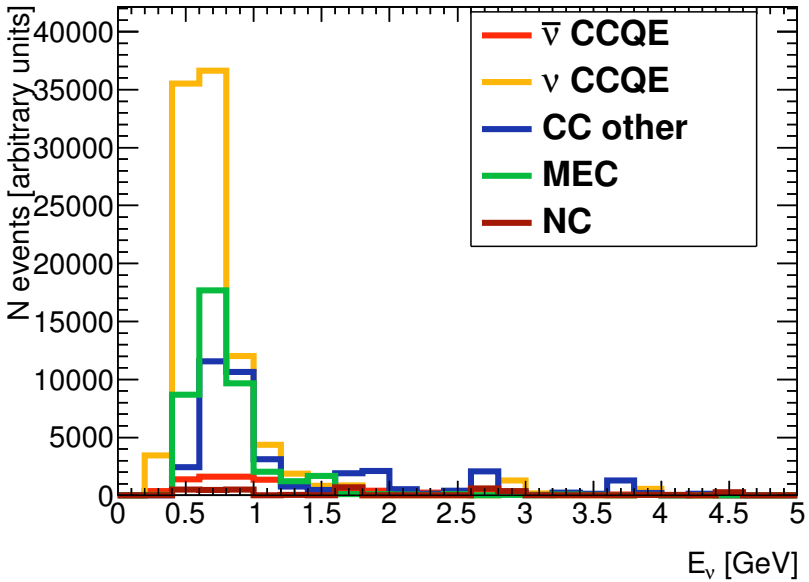


RHC no tagged neutron

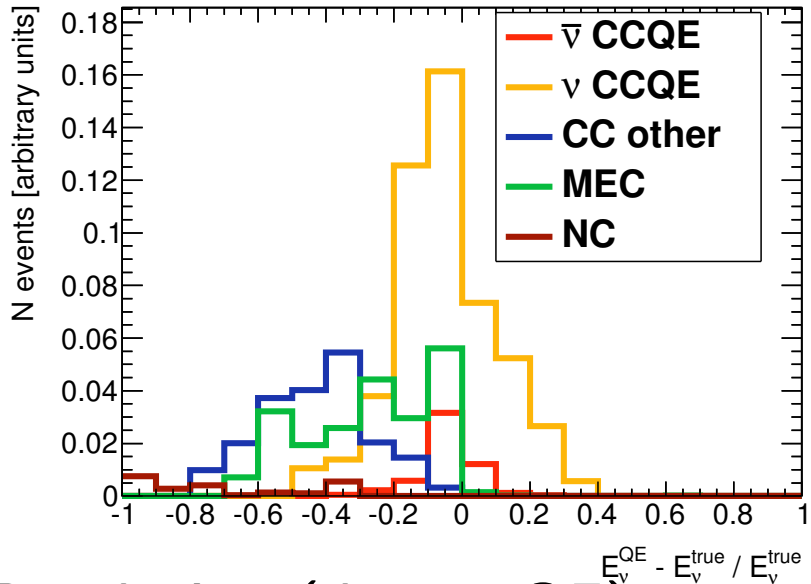


Selected Samples in TITUS

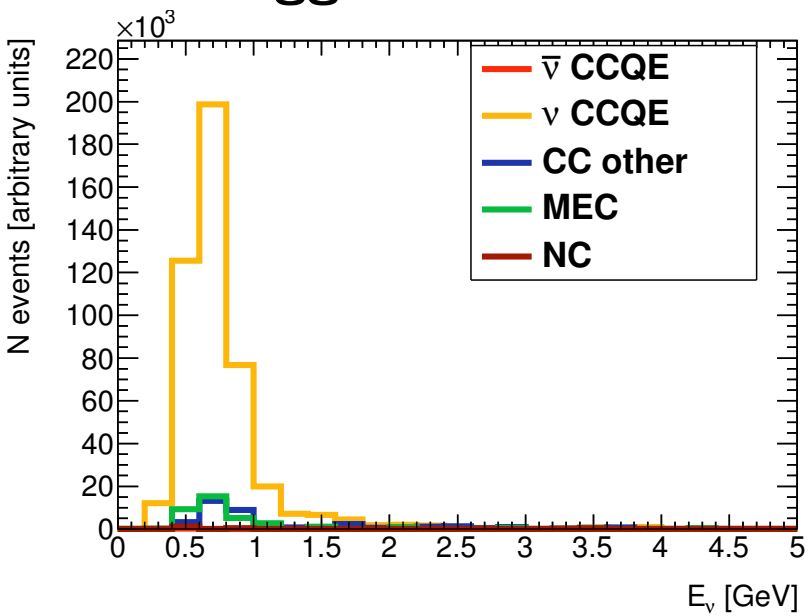
FHC with tagged neutron



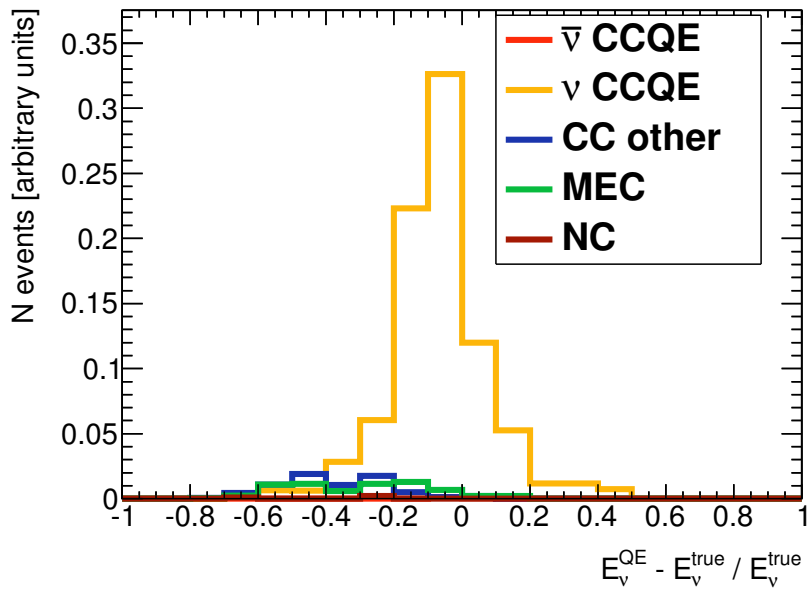
Resolution (due to QE)



FHC no tagged neutron



Resolution (due to QE)



Question

- Given measurements at TITUS, how much is the uncertainty in event rate at Hyper-K reduced?

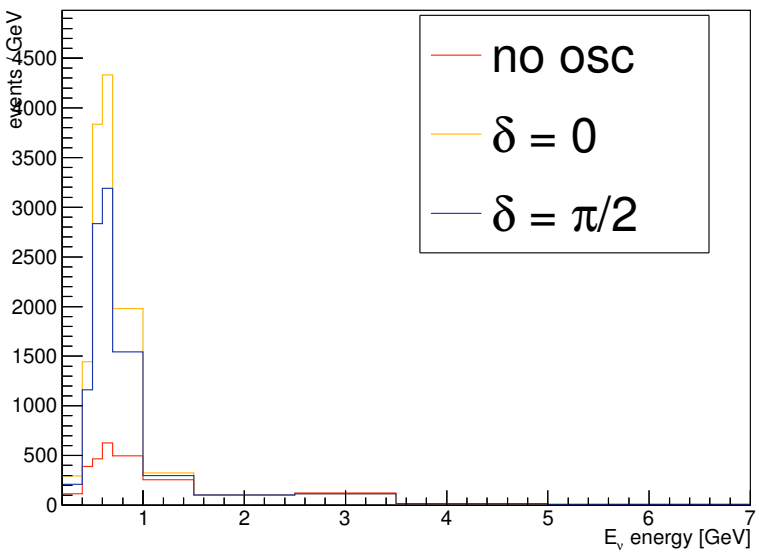
Method

- Used a two step procedure.
- Start with the prior constraints on flux and cross section parameters currently used by T2K.
- Fit these parameters to the predicted TITUS event rate.
- Apply the updated prior uncertainty to the far detector prediction.
- NB fit only uses total number of selected events (without neutron tagging, no shape information).

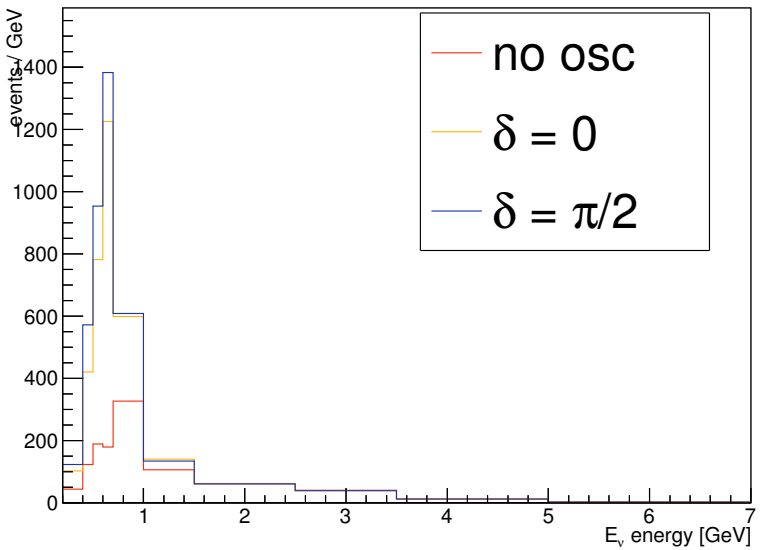
Input Data

- 4 input data samples
  - TITUS 1Rμ FHC
  - TITUS 1Re RHC
  - Hyper-K 1Re FHC
  - Hyper-K 1Re RHC
- No Hyper-K MC
  - Split TITUS MC in half.
  - Apply oscillation probability (calculated with globes).
  - Table-based efficiency applied with towall scaled to Hyper-K size.

HK $1R\mu$ selection, FHC



HK $1Re$ selection, RHC



Fit Method

- Maximum likelihood fit to the TITUS detector 1Rμ samples.

$$
\begin{aligned}
-2\ln\lambda(\theta) &= 2\sum_{i}^{\text{samples}}\left(E_i(\theta) - N_i + N_i\ln\frac{N_i}{E_i(\theta)}\right) \\
&\quad +\ln\frac{\pi(\theta)}{\pi(\theta_0)} \qquad (1)
\end{aligned}
$$

$$
\pi(\theta) \propto e^{-\frac{1}{2}\Delta\theta V^{-1}\Delta\theta}
$$

- where θ are the parameters modelling the flux and cross section uncertainties.
- π is a multi-variate Gaussian constraining the input parameters.
- For speed and simplicity, only include total number of events in each sample in the fit.
- Fit the Asimov dataset (i.e. fake data generated with all parameters set to their nominal values, and no statistical variation).

Cross Systematic Uncertainties

- Systematic uncertainties are based on T2K NIWG errors with some additions.
- MEC
  - NEUT implements NIEVES MEC model.
  - Assign a 50% normalisation uncertainty.
- $\nu - \bar{\nu}$
  - Selected 20%
- Nucleon FSI uncertainty.
  - Still to be evaluated.
  - Plan to take this from GENIE.
  - Important for nucleon tagging studies.

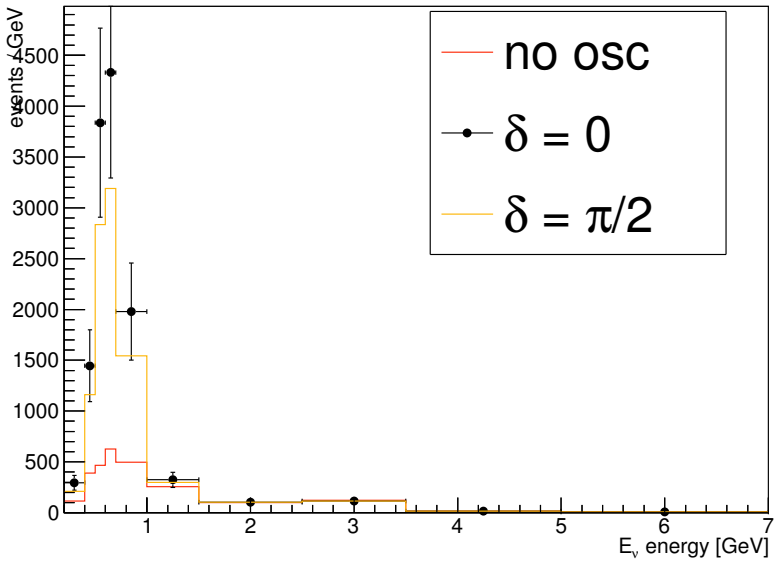
Parameter	Initial Value
CC1π E1	1.15 ± 0.43
CC1PI_E2	1.00 ± 0.40
CC coherent	1.00 ± 1.00
CCQE E1	1.00 ± 0.11
CCQE E2	1.00 ± 0.30
CCQE E3	1.00 ± 0.30
MEC	1.00 ± 0.50
NC $1\pi^0$	1.00 ± 0.30
CC other shape	0.00 ± 0.40
p_F	217.00 ± 30.00
SF	0.00 ± 1.00
M_A^{QE}	1.21 ± 0.10
M_A^{RES}	1.41 ± 0.11
$\nu - \bar{\nu}$ ratio	1.00 ± 0.20
$\nu_e - \nu_\mu$ ratio	1.00 ± 0.03

Flux Systematic Uncertainties

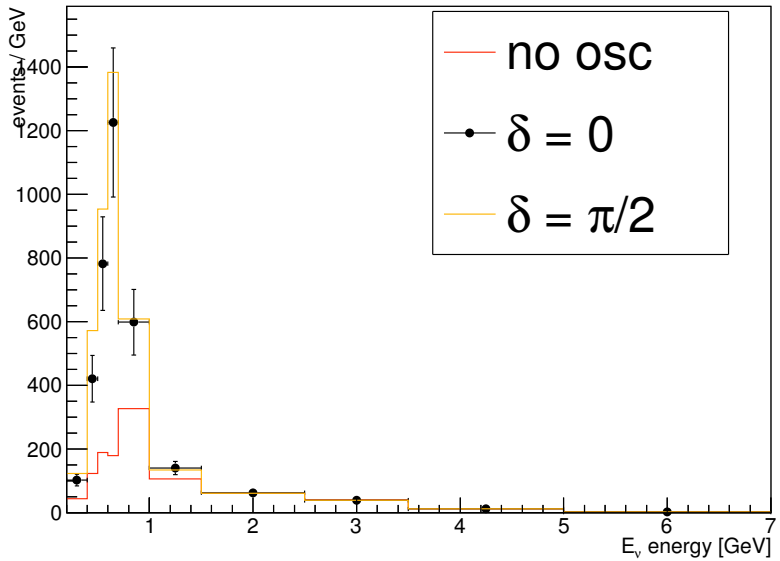
- As a placeholder I am using the current T2K (ND280-SK) matrix.
- Overestimates uncertainty as ND280-T2K has a relatively large uncertainty on the near-to-far extrapolation.
  - Use the same flux covariance matrix for both FHC and RHC.
  - No FHC/RHC correlation included
    - Used independent flux parameters.
    - All off-diagonal elements in the covariance matrix correlating FHC and RHC parameters set to zero.
    - This represents the worst case scenario.

TITUS Fit Results

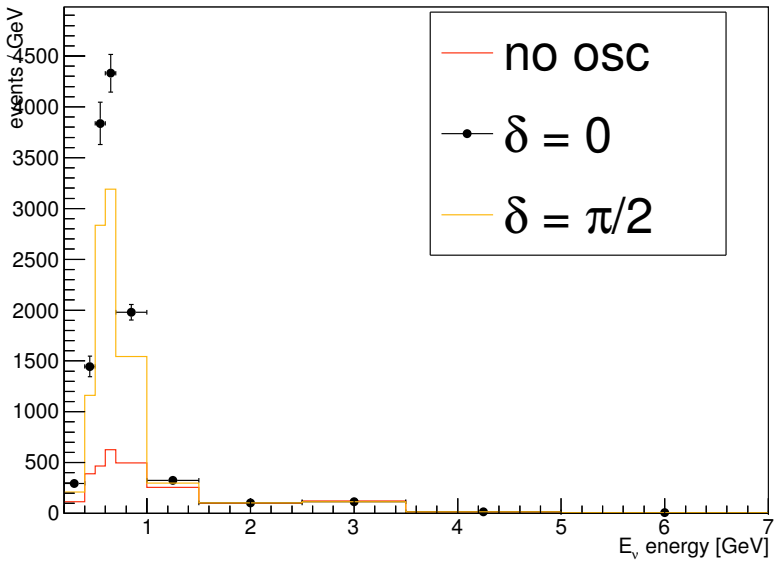
FHC before fit



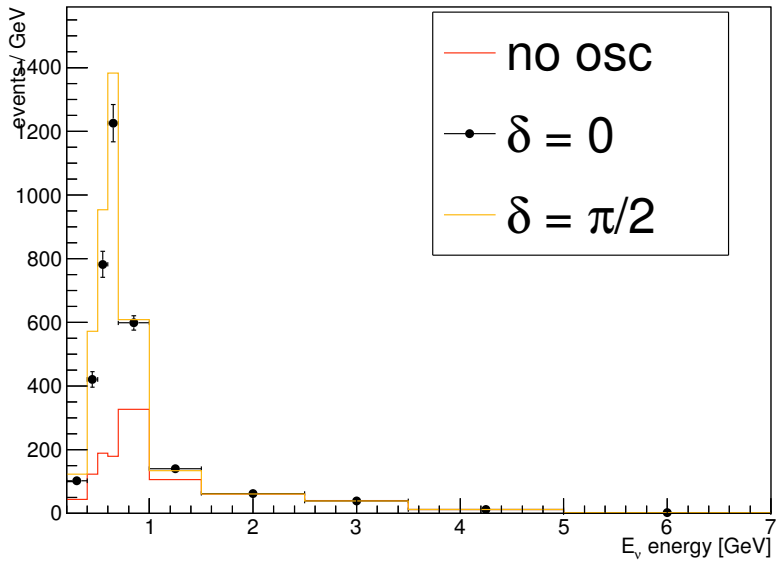
RHC before fit



FHC after fit



RHC after fit



No TITUS constraint

	TITUS FHC	TITUS RHC	HK FHC	HK RHC
CC1PI E1	0.040	0.028	0.038	0.032
CC1PI E2	0.003	0.004	0.011	0.016
CC coherent	0.004	0.010	0.003	0.007
CCQE E1	0.041	0.039	0.066	0.059
CCQE E2	0.004	0.010	0.007	0.013
CCQE E3	0.002	0.003	0.003	0.005
MEC	0.029	0.028	0.039	0.041
NC 1pi0	0.017	0.020	0.013	0.024
CC other	0.002	0.002	0.003	0.004
pf	0.000	0.000	0.002	0.001
sf	0.003	0.000	0.005	0.001
MACCQE	0.000	0.000	0.000	0.000
MARES	0.008	0.009	0.011	0.015
$\nu/\bar{\nu}$	0.186	0.114	0.184	0.092
ν_μ/ν_e	0.028	0.028	0.018	0.015
flux	0.106	0.103	0.103	0.103
xsec	0.199	0.137	0.203	0.133
total	0.249	0.172	0.253	0.164

After TITUS constraint

	TITUS FHC	TITUS RHC	HK FHC	HK RHC
CC1PI E1	0.039	0.028	0.037	0.031
CC1PI E2	0.003	0.004	0.011	0.015
CC coherent	0.004	0.010	0.003	0.007
CCQE E1	0.034	0.032	0.054	0.048
CCQE E2	0.004	0.010	0.007	0.012
CCQE E3	0.002	0.003	0.003	0.004
MEC	0.018	0.018	0.024	0.025
NC 1pi0	0.017	0.021	0.013	0.025
CC other	0.002	0.002	0.003	0.004
pf	0.000	0.000	0.002	0.001
sf	0.003	0.000	0.005	0.001
MACCQE	0.000	0.000	0.000	0.000
MARES	0.008	0.009	0.011	0.015
$\nu/\bar{\nu}$	0.089	0.054	0.088	0.044
ν_μ/ν_e	0.028	0.028	0.018	0.015
flux	0.096	0.070	0.092	0.072
xsec	0.085	0.081	0.088	0.087
total	0.009	0.007	0.030	0.035

Summary

- Applied SK-based 1-ring selections to TITUS simulated events.
- Implemented a fit a to the near + far event rates.
- Great reduction in total systematic error when including TITUS

	HK FFC error	HK RHC error
No TITUS	0.253	0.164
With TITUS	0.030	0.035

Next steps

- Flux extrapolation may be a limiting factor.
  - Currently using the ND280+SK matrix as a placeholder.
  - Need to update to a more appropriate matrix for TITUS.
- Investigate effects of additional selection
  - with neutron tagging
  - with MRD
- Implement missing systematic errors (in particular nucleon FSI).
- Include shape information, and fit for oscillation parameters.

Backup