



# Measurement of $\nu_e$ Charged-Current Interaction Cross Section on Water on T2K Pi-Zero Detector using Markov-Chain Monte Carlo Method

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Yue Wang

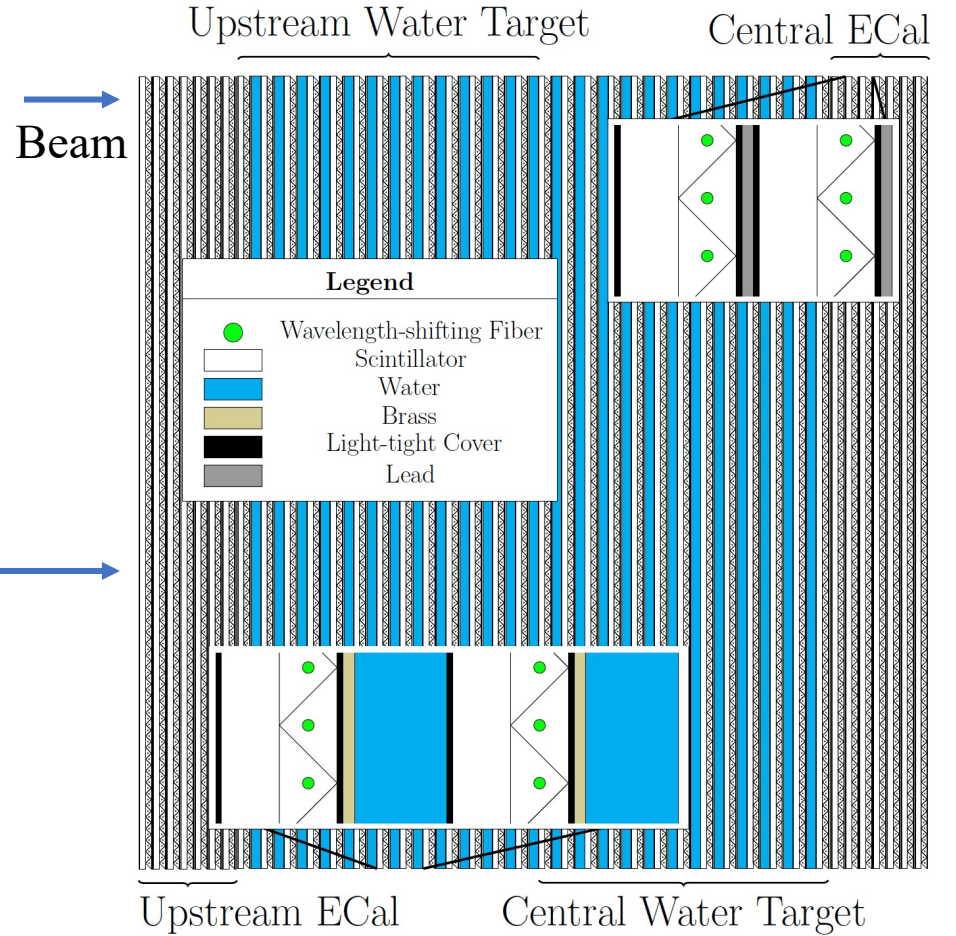
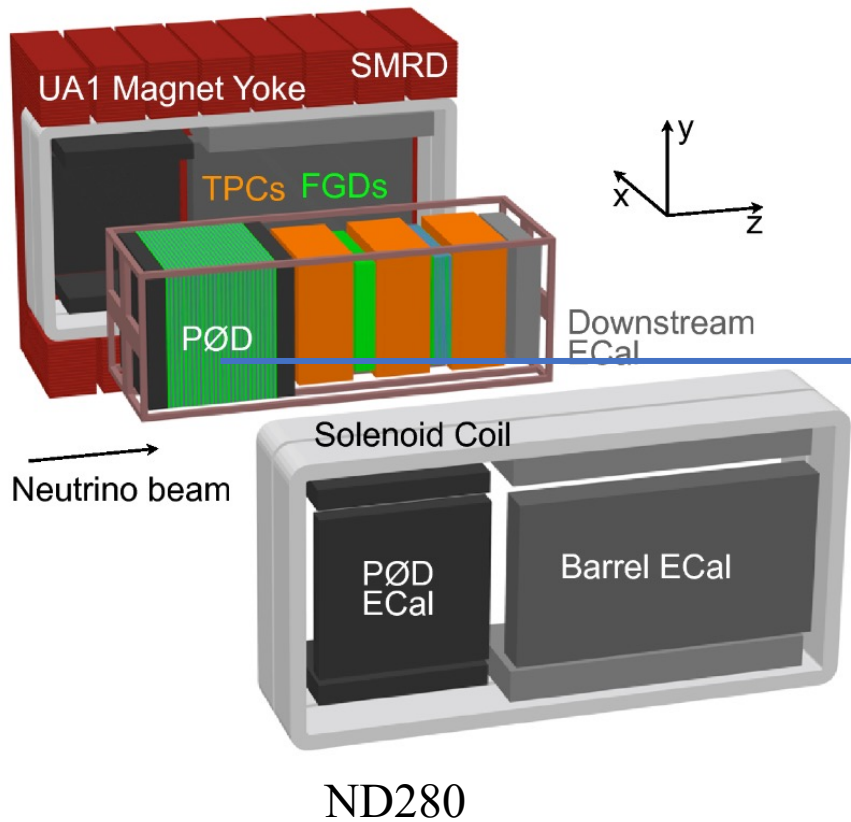
DPF 2021, on behalf of T2K Collaboration

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# Pi-Zero Detector (P0D)

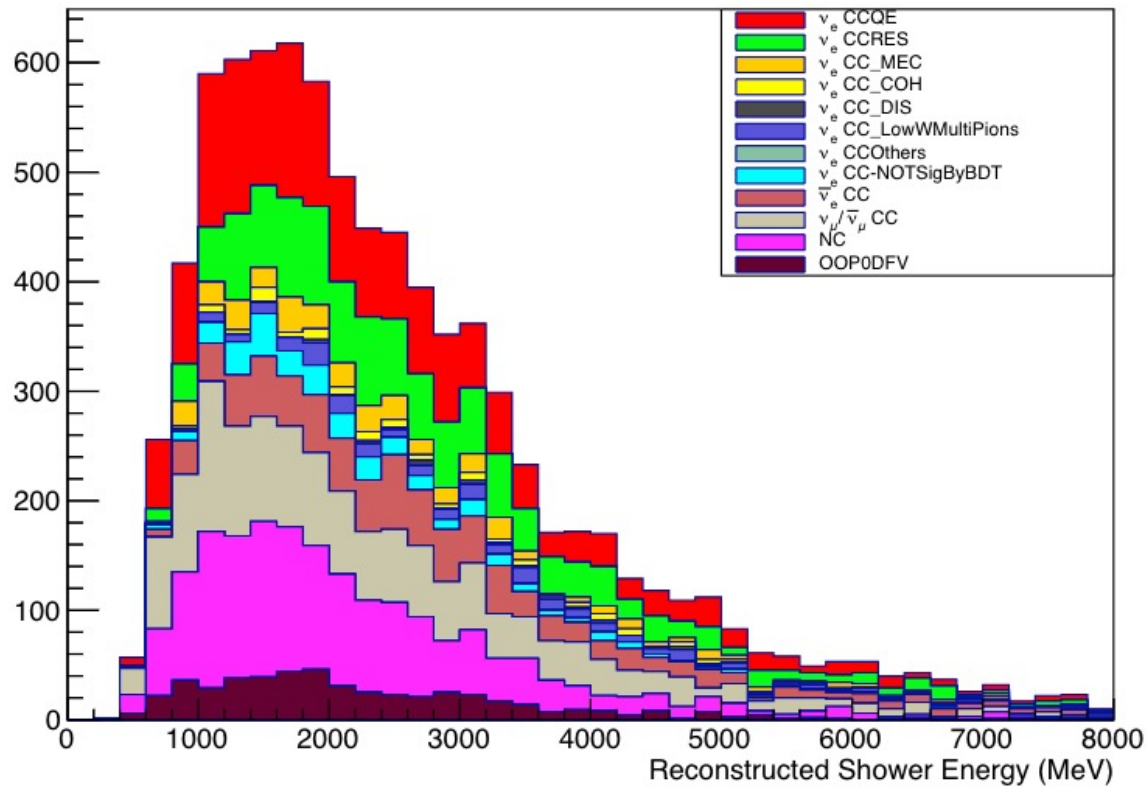
- P0D is part of T2K off-axis near detectors
- It consists of alternative scintillator layers and fillable water bags
- Water target mass in P0D is about 1910 kg



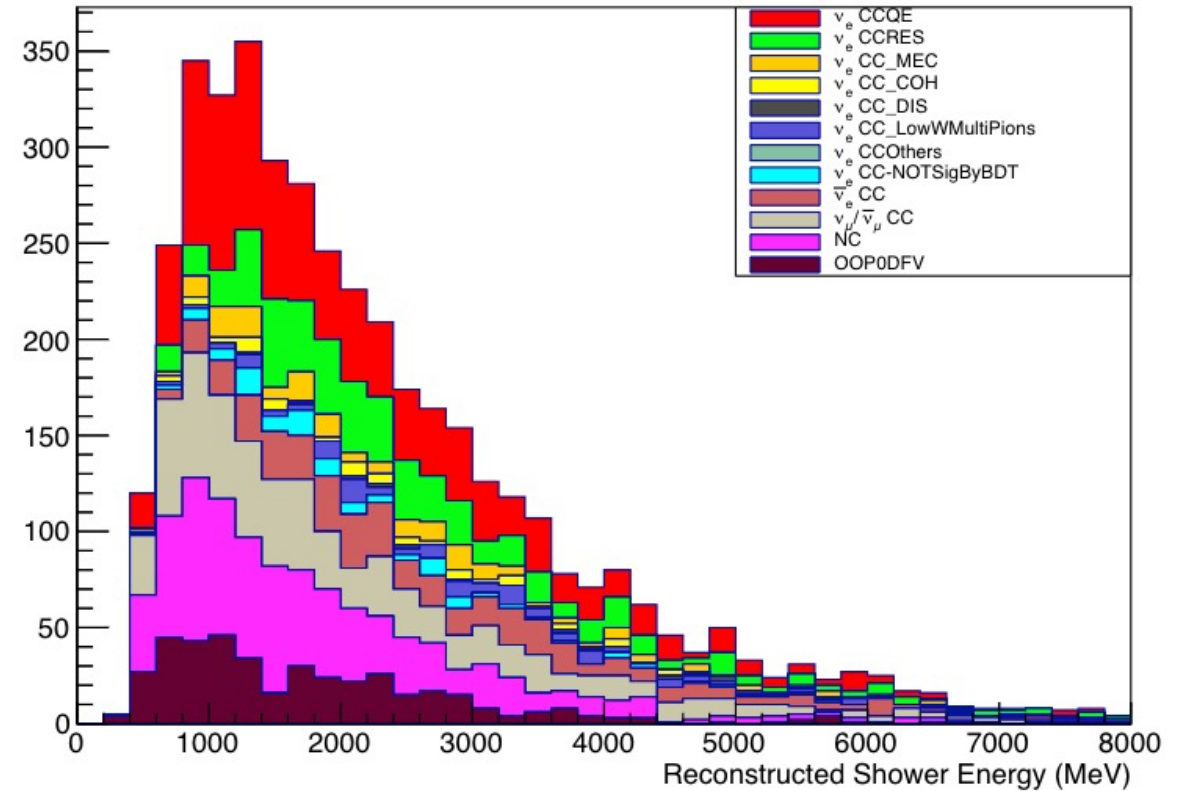
Schematic of P0D

- To measure  $\nu_e$  CC with **No Visible Proton and No Visible Charged pion** cross-section on water using FHC data
- T2K far detector (Super-Kamiokande) use water as target (water Cherenkov detector)
- There are few measurements on  $\nu_e$  interactions and this is the first measurement of  $\nu_e$  on water
- The intrinsic  $\nu_e$  component in the beam is a main background in the  $\nu_e$  appearance measurement
- A large systematic uncertainty in T2K  $\nu_e$  appearance observation comes from uncertainties related with the neutrino cross-section modeling
- The structure of fillable water bags in P0D allow us to do measurements under configurations that water is filled in (water-in) and drained out of (water-out) the detector  $\rightarrow$  on-water measurement

- $3e+21$  POT



Water-in configuration



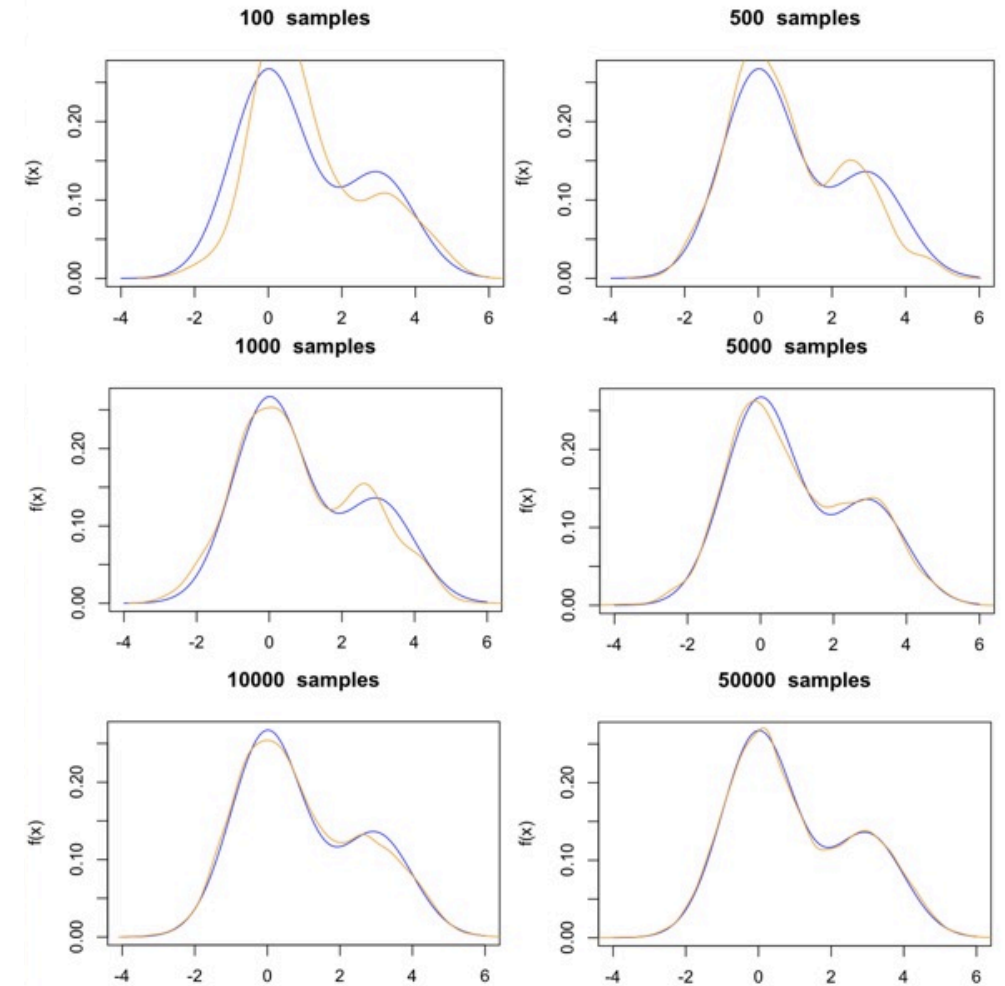
Water-out configuration

# Cross Section Extraction Strategy

- Joint-fit of water-in and water-out configuration
  - $N_{\text{waterin}} = N_{\text{onwater}} + N_{\text{notwater}}$
  - $N_{\text{waterout}} = N_{\text{notwater}}$
- Bayes Theorem  $P(\theta|x) = \frac{P(x|\theta)P(\theta)}{P(x)} \propto P(x|\theta)P(\theta)$ 
  - where  $P(\theta)$ : Prior distribution of  $\theta$
  - $P(x|\theta)$ : Likelihood function
  - $P(x) = \int P(x|\theta) P(\theta) d\theta$
  - $P(\theta|x)$ : Posterior distribution of  $\theta$  under the data  $x$  we measured
- Cross section  $\sigma(\theta)$  distribution  $P(\sigma(\theta|x))$

# Cross Section Extraction Strategy

- Use Markov-Chain Monte Carlo (MCMC) and estimate posterior distribution of cross section
- MCMC comprises a class of algorithms to sample from probability distributions
  - Use Metropolis-Hasting Algorithm to construct the chain in the current framework
- The desired distribution we want to sample is  $P(x|\theta)P(\theta)$



From wiki

# Cross Section Extraction Strategy with MCMC Fitter

- Define  $\log L = \log(P(x|\theta)P(\theta)) = \log(P(x|\theta)) + \log(P(\theta))$

$$\log L = \log L_{stat} + \log L_{prior}$$

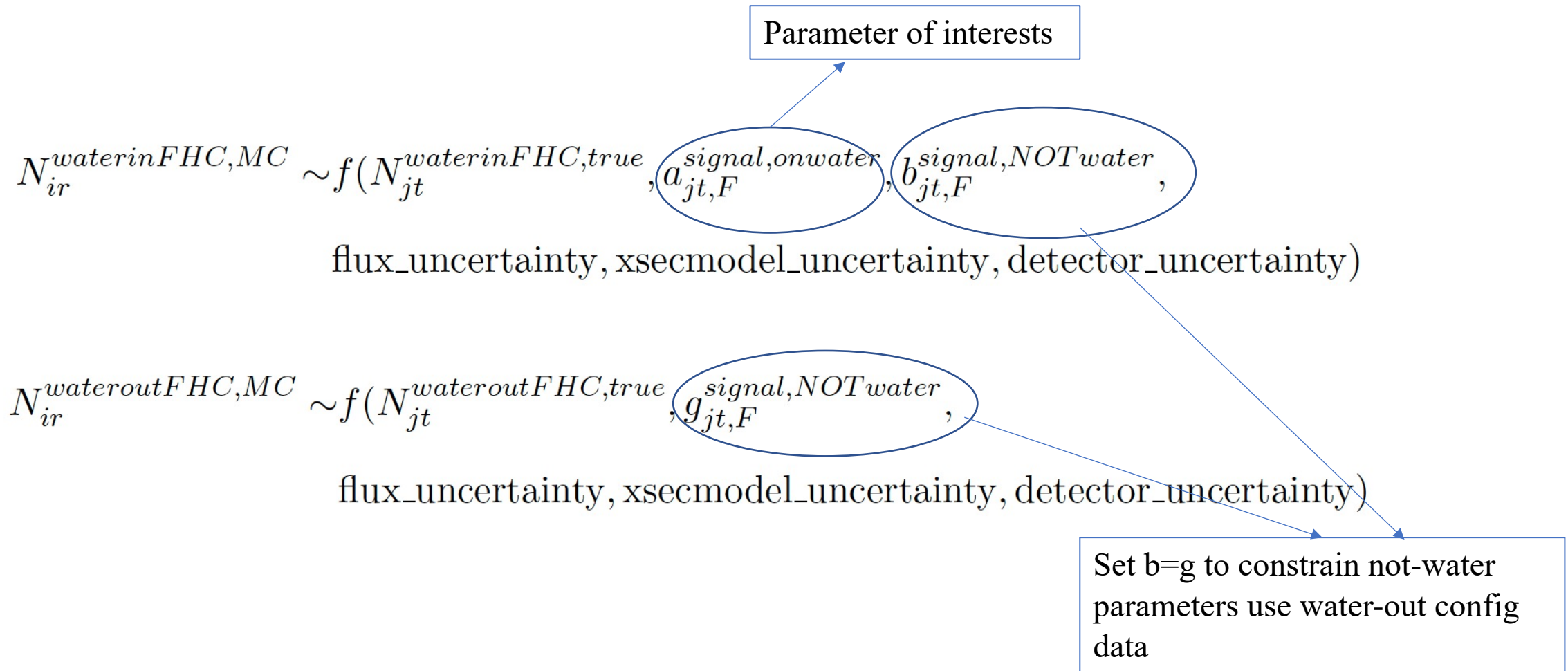
$$\log L_{stat} = \sum_{ir=1}^{RecoBin} N_{ir}^{data} - N_{ir}^{MC} + N_{ir}^{data} \log \frac{N_{ir}^{MC}}{N_{ir}^{data}}$$

$$\log L_{prior} = -\frac{1}{2} V^\dagger (cov)^{-1} V$$

	Signal Sample	NC1pi0 Sideband	$\nu_\mu/\bar{\nu}_\mu$ CC Sideband
Water-in	Y	Y	Y
Water-out	Y	Y	Y

where  $N_{ir}^{data}$  is the number of events in data in reco bin i,  $N_{ir}^{MC}$  is the number of events in MC in reco bin i, and  $V$  is the vector of nuisance parameters

# Cross-section Extraction with MCMC Fitter



# Cross-Section Extraction with MCMC Fitter

- When estimating xsec, at each step in MCMC fitter, a xsec value is calculated for each bin as below
- Then we can get a distribution of xsec in each bin after running MCMC fitter

$$\sigma_{jt} = \frac{a_{jt,F}^{signalonwater} N_{jt,afterSel,wSYS}^{\nu_e CC, onwater}}{\epsilon_{jt} \Phi N_{target}}$$

$$= \frac{a_{jt,F}^{signalonwater} \sum_k^{int\ type} \sum_n^{E_\nu} f_{n,jt}^{\nu_e} N_{jt}^{\nu_e CC, onwater}}{\epsilon_{jt} \Phi N_{target}} \cdot \prod_a^{models} \omega(a)_{jt,k}$$

Where jt means truth bin j  
int type means interaction type

where  $\epsilon_{jt} = \frac{N_{jt,afterSel,wSYS}^{\nu_e CC, onwater}}{N_{jt,beforeSel}^{\nu_e CC, onwater}}$  and wSYS means after take systematics into account.

Thus,

$$\sigma_{jt} = \frac{a_{jt,F}^{signalonwater} N_{jt,beforeSel}^{\nu_e CC, onwater}}{\Phi N_{target}}$$

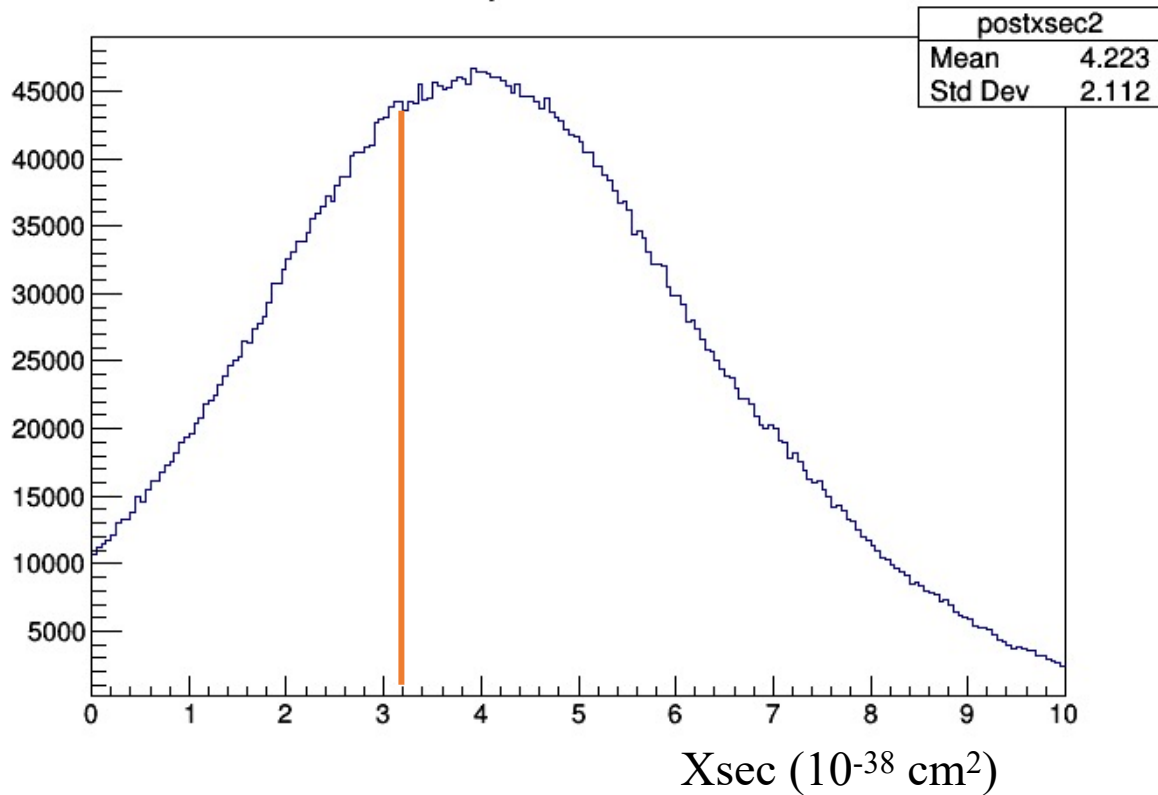
where

$$N_{beforeSel}^{\nu_e CC, onwater} = \sum_k^{int\ type} \sum_n^{E_\nu} f_{n,jt}^{\nu_e} N_{jt,beforeSel,fix}^{\nu_e CC, onwater} \cdot \prod_a^{models} \omega(a)_{jt,k}$$

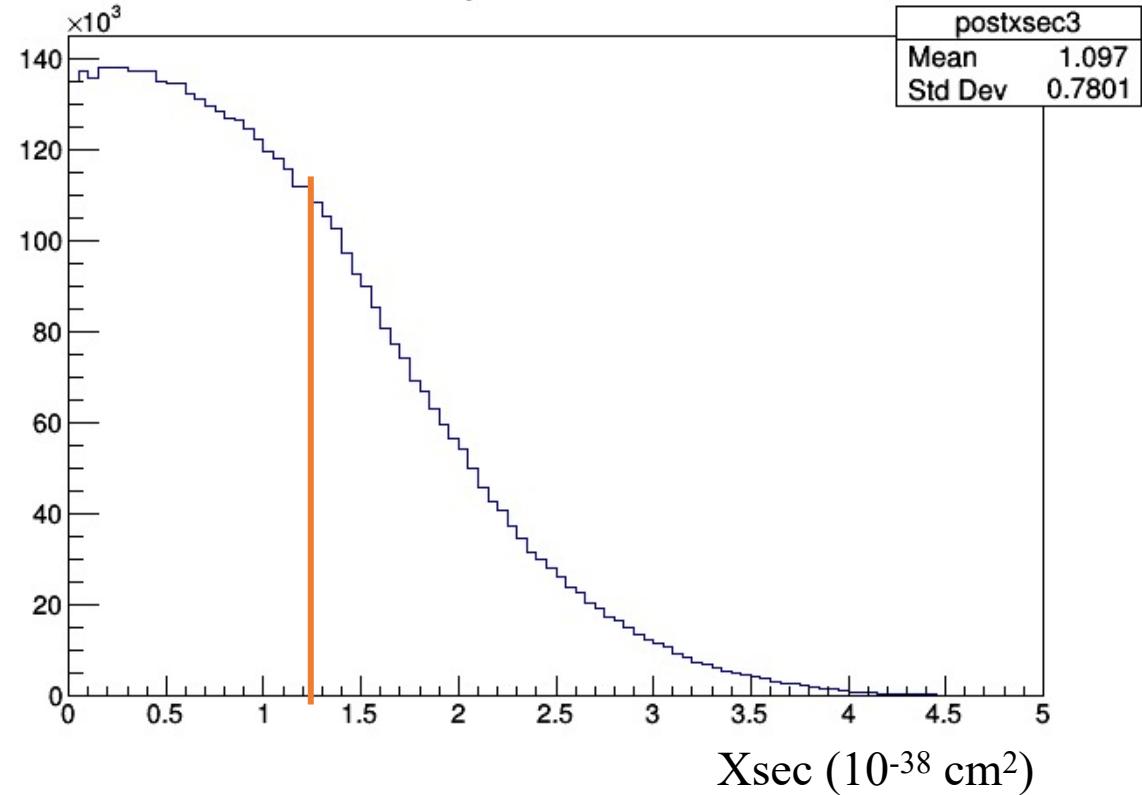
Just to emphasize that flux and xsec parameters are applied events by event NOT bin by bin. The formula is to show mathematically, which is not exactly how the implementation is in the program

# Fake Data Study Results

- Posterior Distribution of cross section at each bin



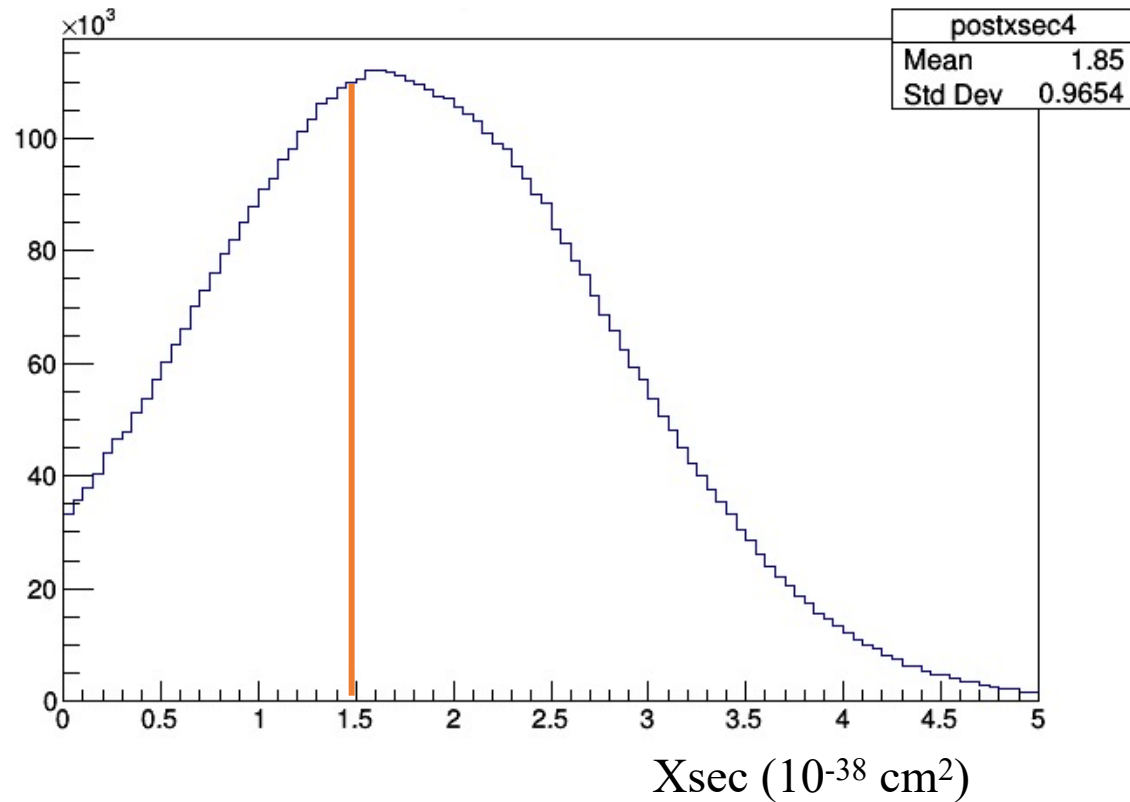
At bin 2 (600MeV – 1.5GeV)



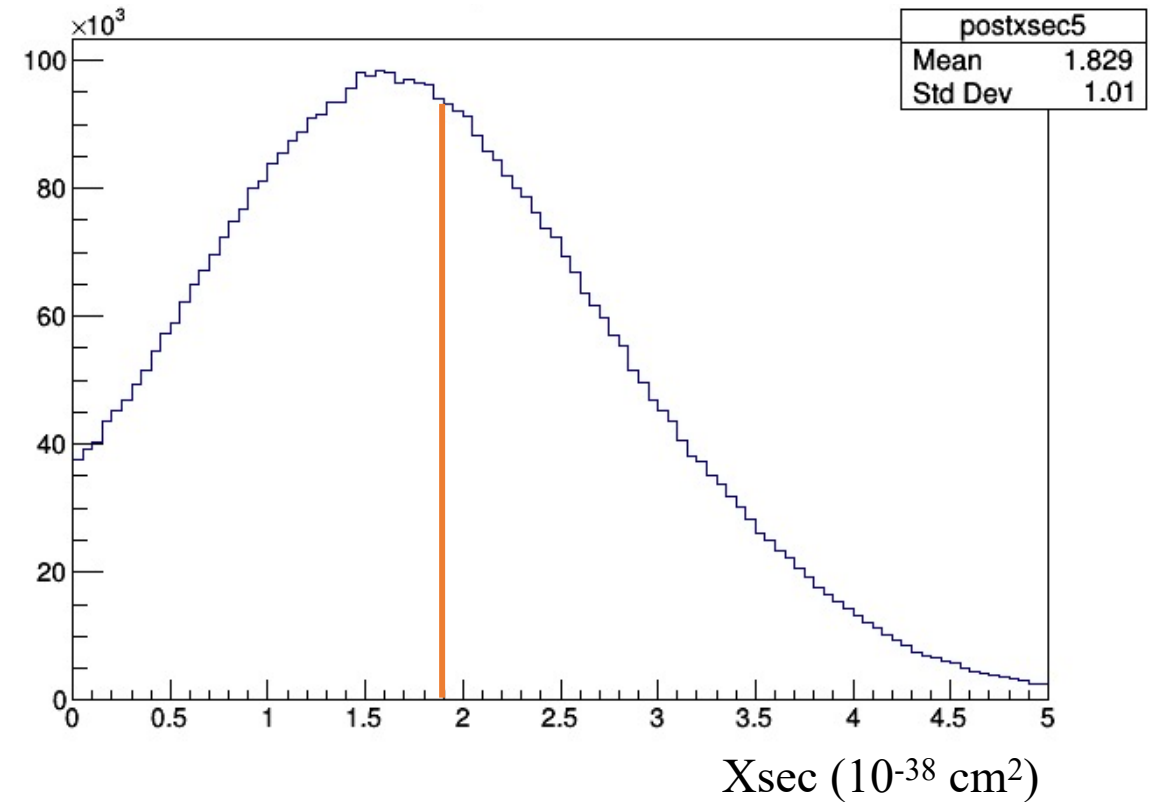
At bin 3 (1.5GeV – 2.3GeV)

# Fake Data Study Results

- Posterior Distribution of cross section at each bin



At bin 2 (600MeV – 1.5GeV)



At bin 3 (1.5GeV – 2.3GeV)

- We propose to use MCMC to do Bayesian inference on cross section
- Current fake data study results validate the method and framework
- We plan to release the results with real data soon

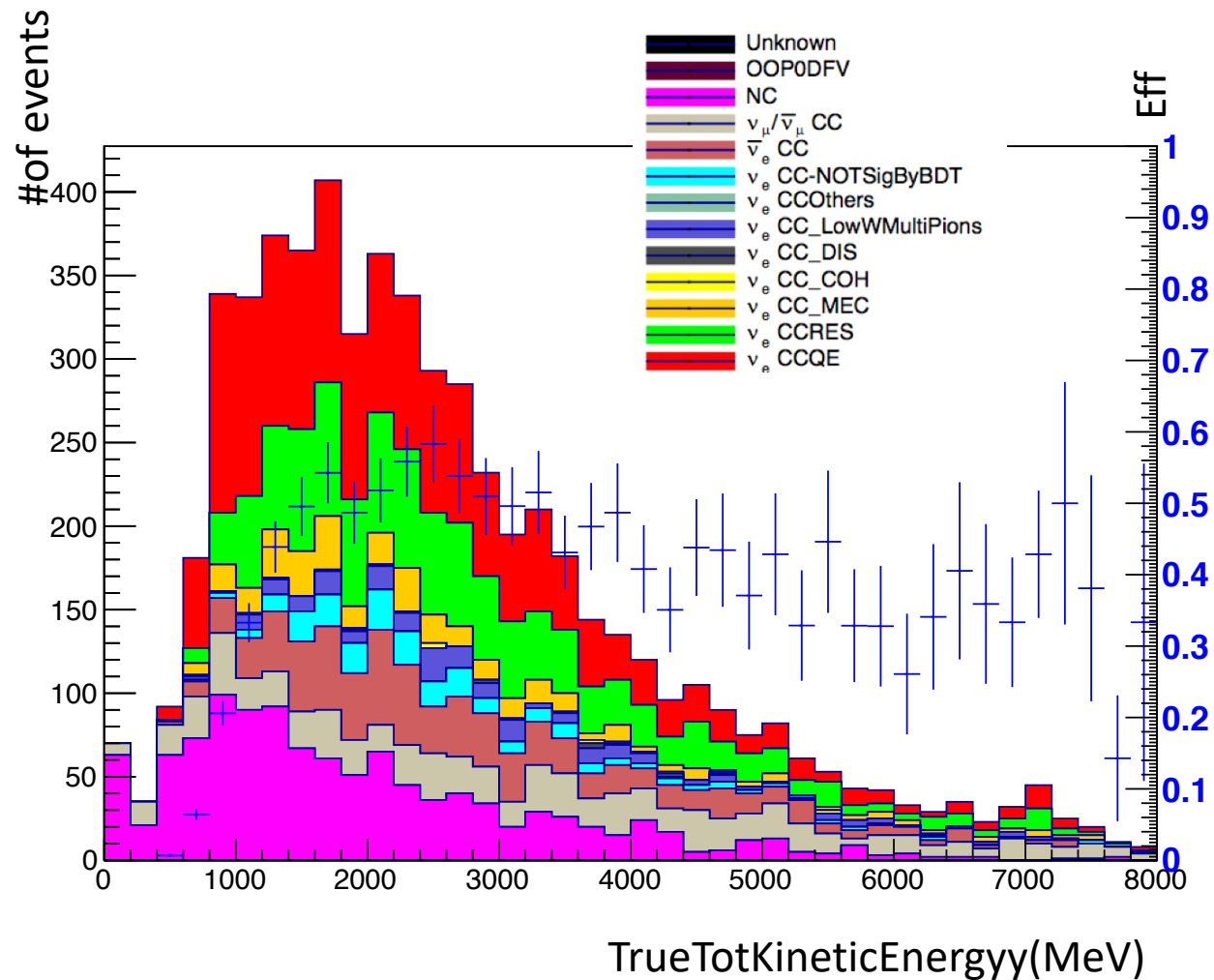
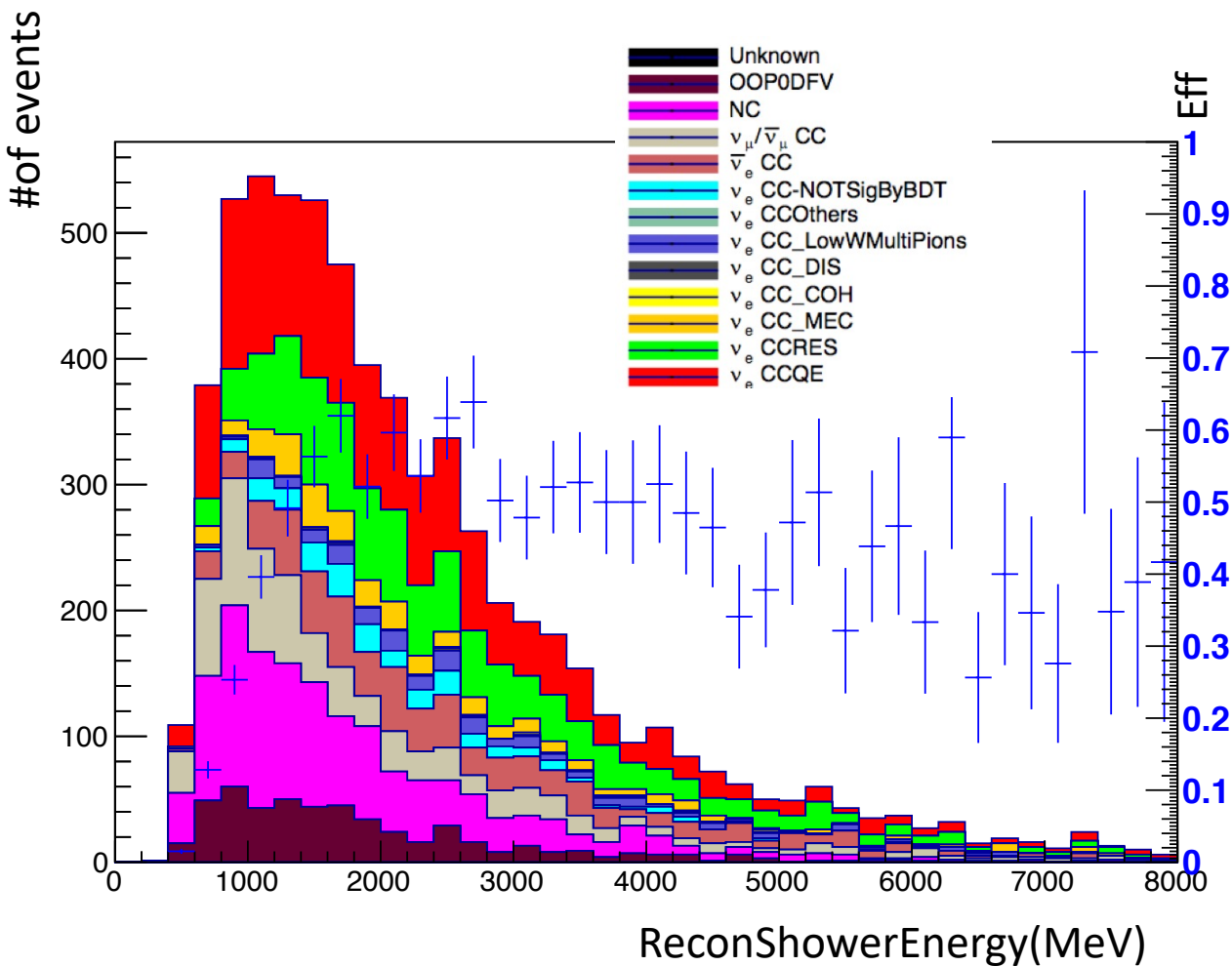


- Goal: measure  $1e-0$  Visible Proton-0 Visible Charged pion nue-CC xsec using POD data
  - Total xsec
  - 1d differential xsec w.r.t total kinetic energy of all primary outgoing charged particles, photons and pi0s
- Signal def: nueCC events passing Boosted Decision Tree(BDT) criteria for protons and pions, where the BDT is trained using particle gun simulations
  - BDT criteria for protons area function of true  $KE_p$ ,  $KE_e/KE_p$ ,  $\theta_p$ ,  $\theta_{ep}$  and similar to pions
  - Conceptually, BDT is similar to apply box cuts on particles true kinematics when defining signal

# Selected Signal Enriched Sample

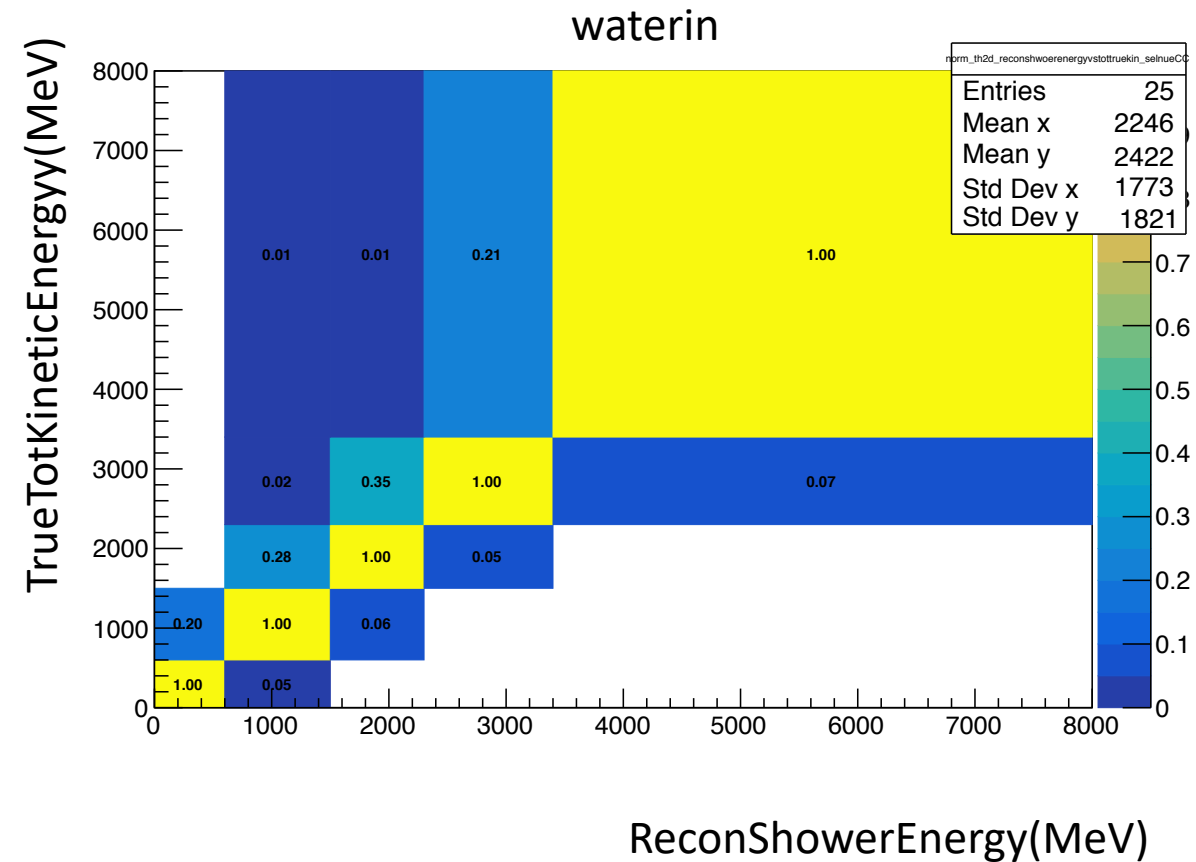
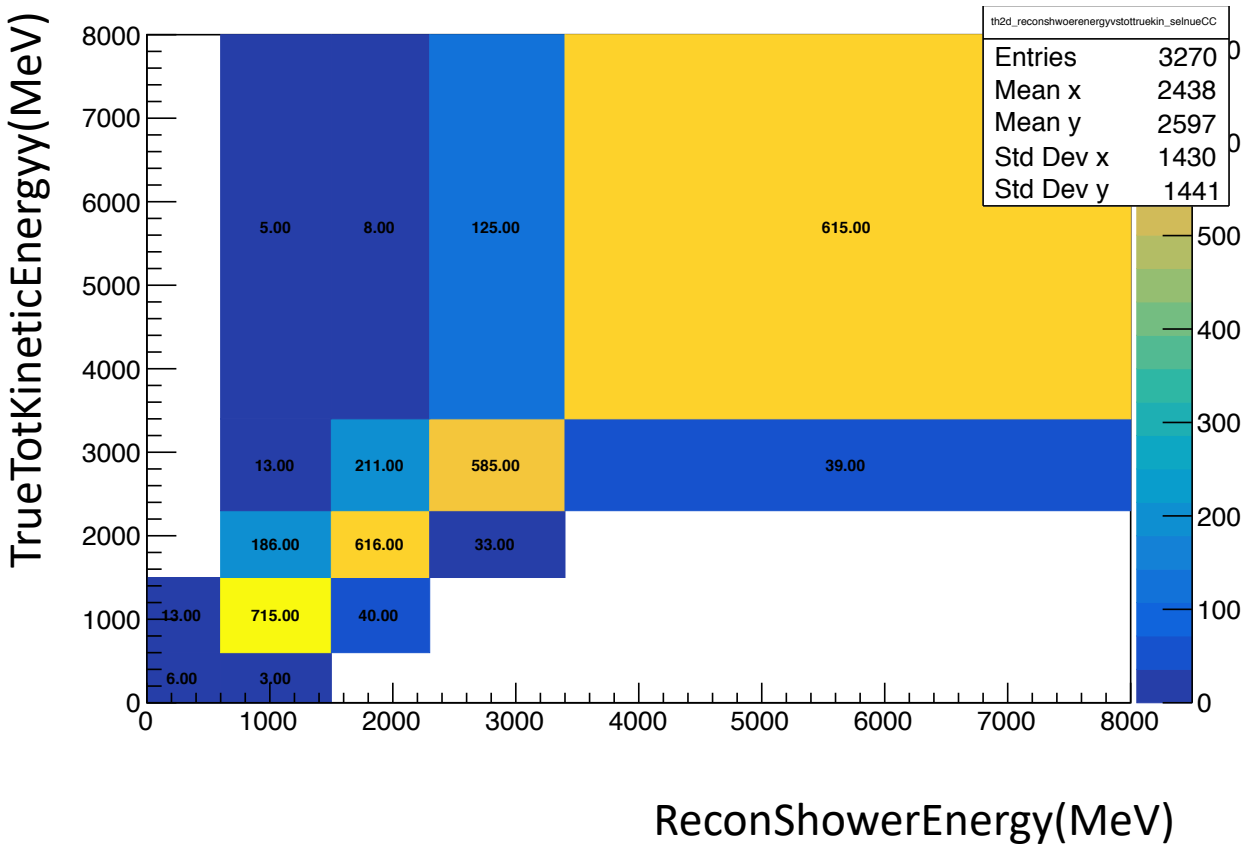
- waterin config

recon binning var in the fitter and truth binning var in the fitter for signal enriched sample



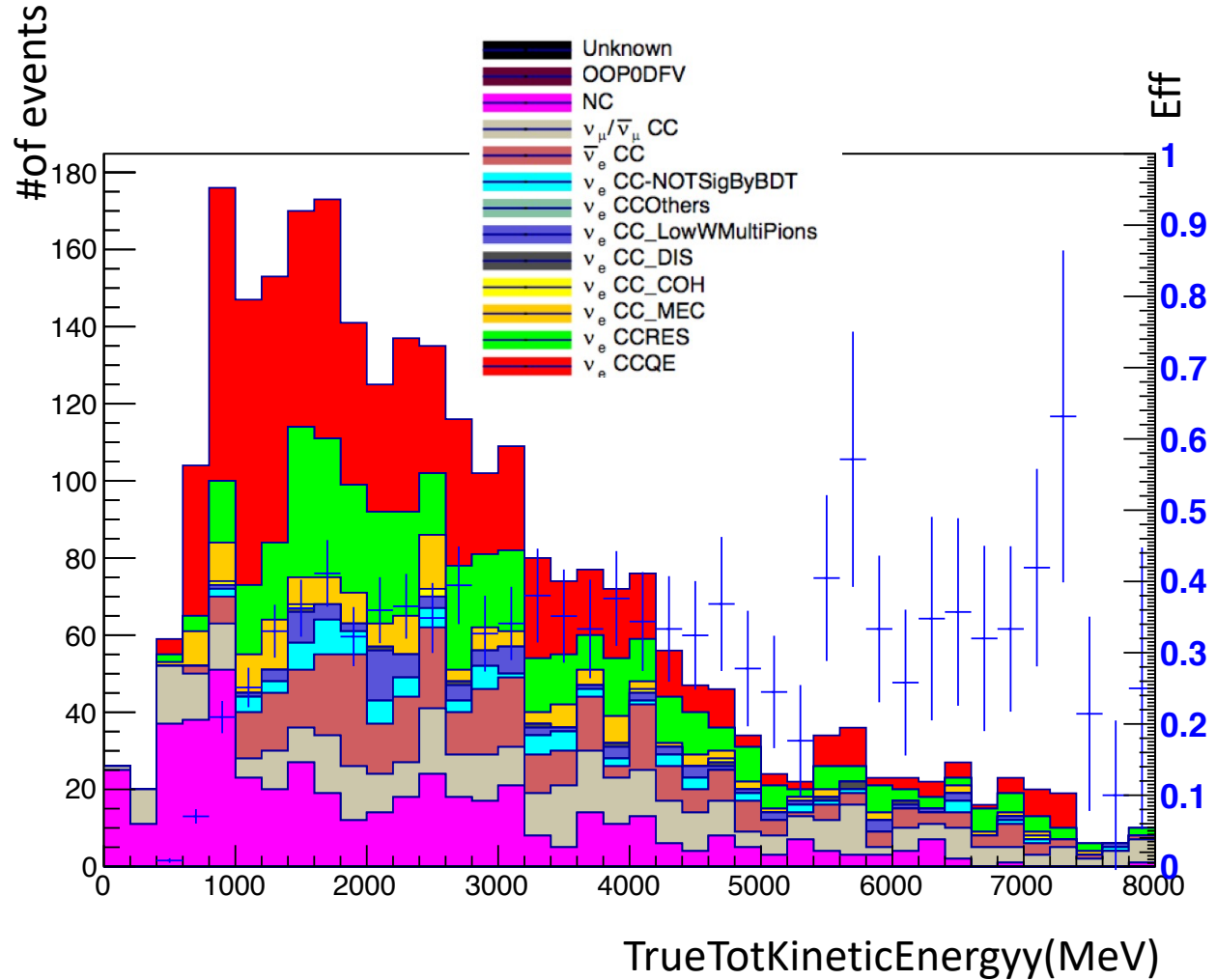
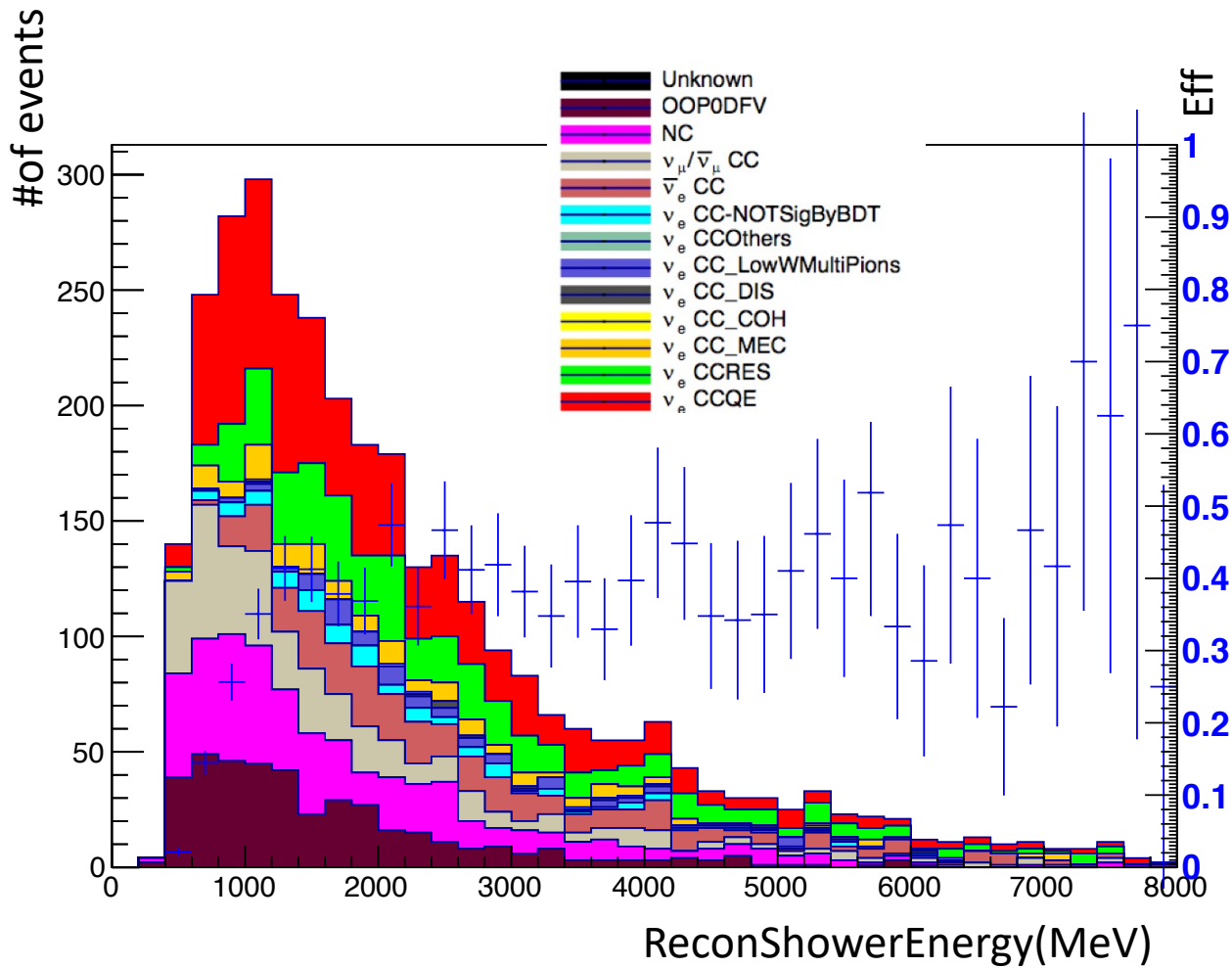
# Signal Enriched Sample Transfer matrix

- waterin config, in the binning used in the fitter ((last bin ends at 8000MeV in the plot but it actually extends to 30GeV)
- use events are selected nueCC signals after applying nue selection strategy



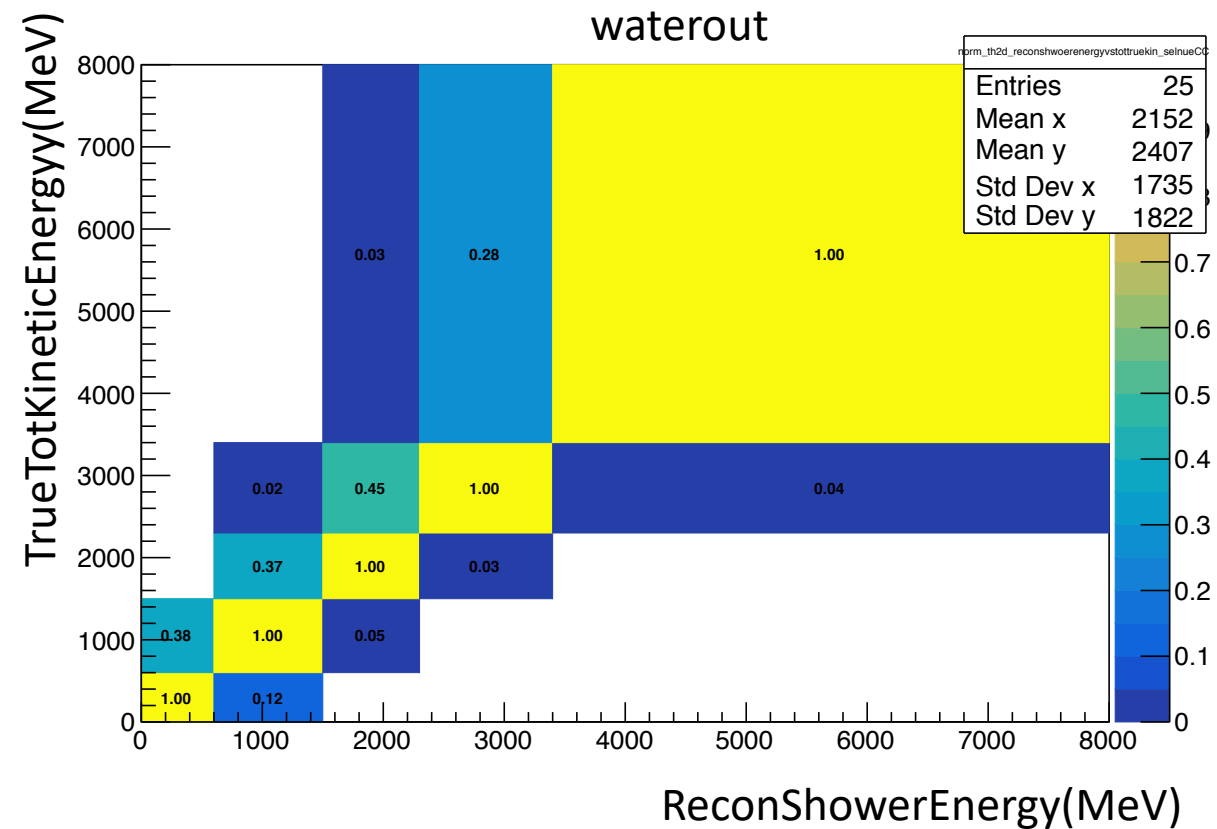
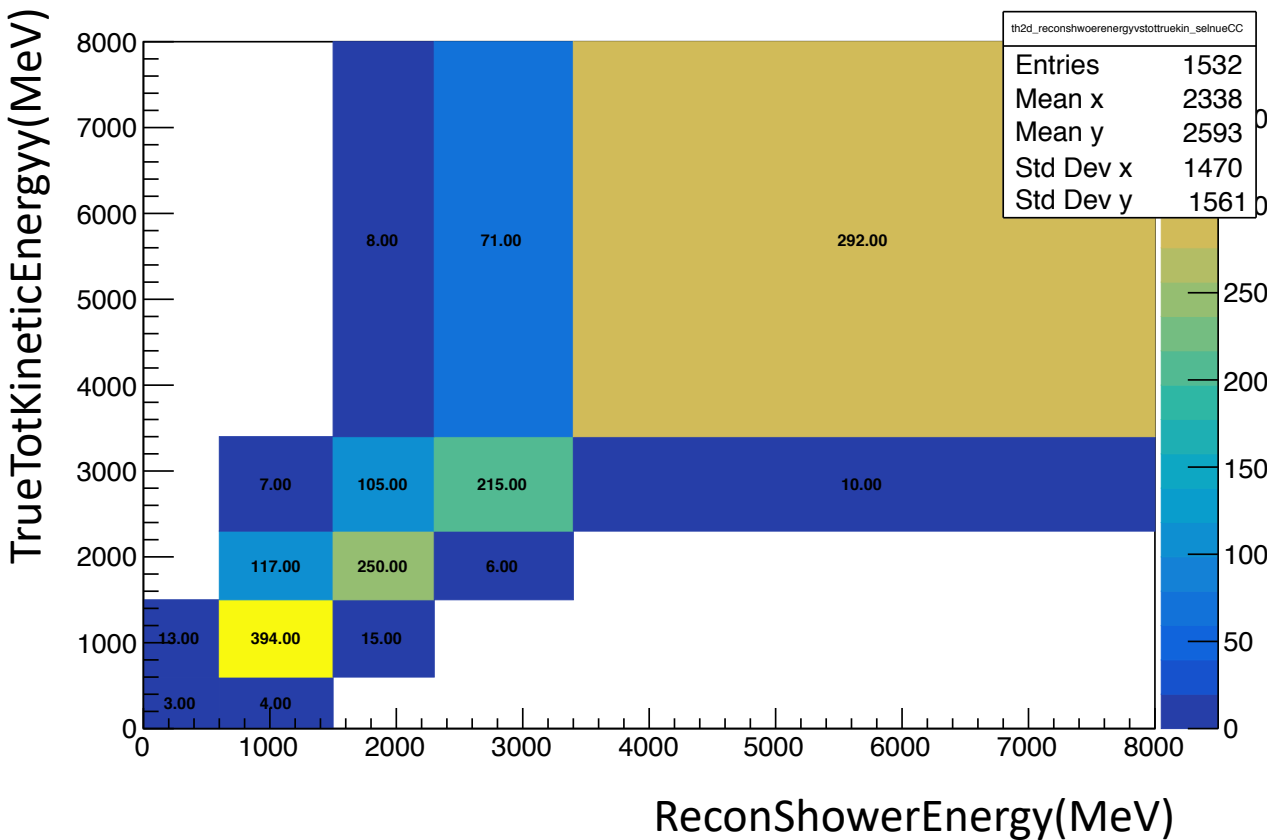
# Selected Signal Enriched Sample

- water-out config



# Signal Enriched Sample Transfer matrix

- waterout config, in the binning used in the fitter ((last bin ends at 8000MeV in the plot but it actually extends to 30GeV)
- use events are selected nueCC signals after applying nue selection strategy

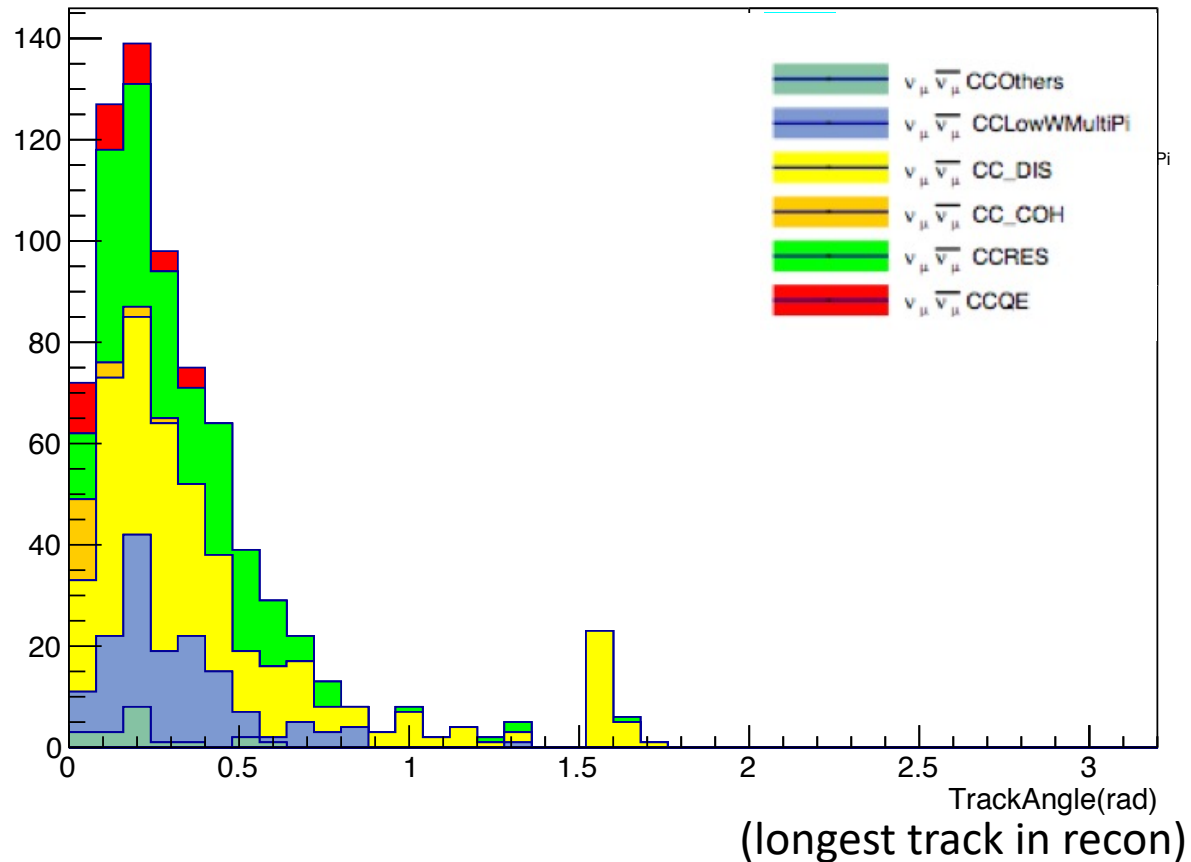


# $\nu_\mu(\bar{\nu}_\mu)$ CC (in FV) Backgrounds VS $\nu_\mu(\bar{\nu}_\mu)$ CC sidebands

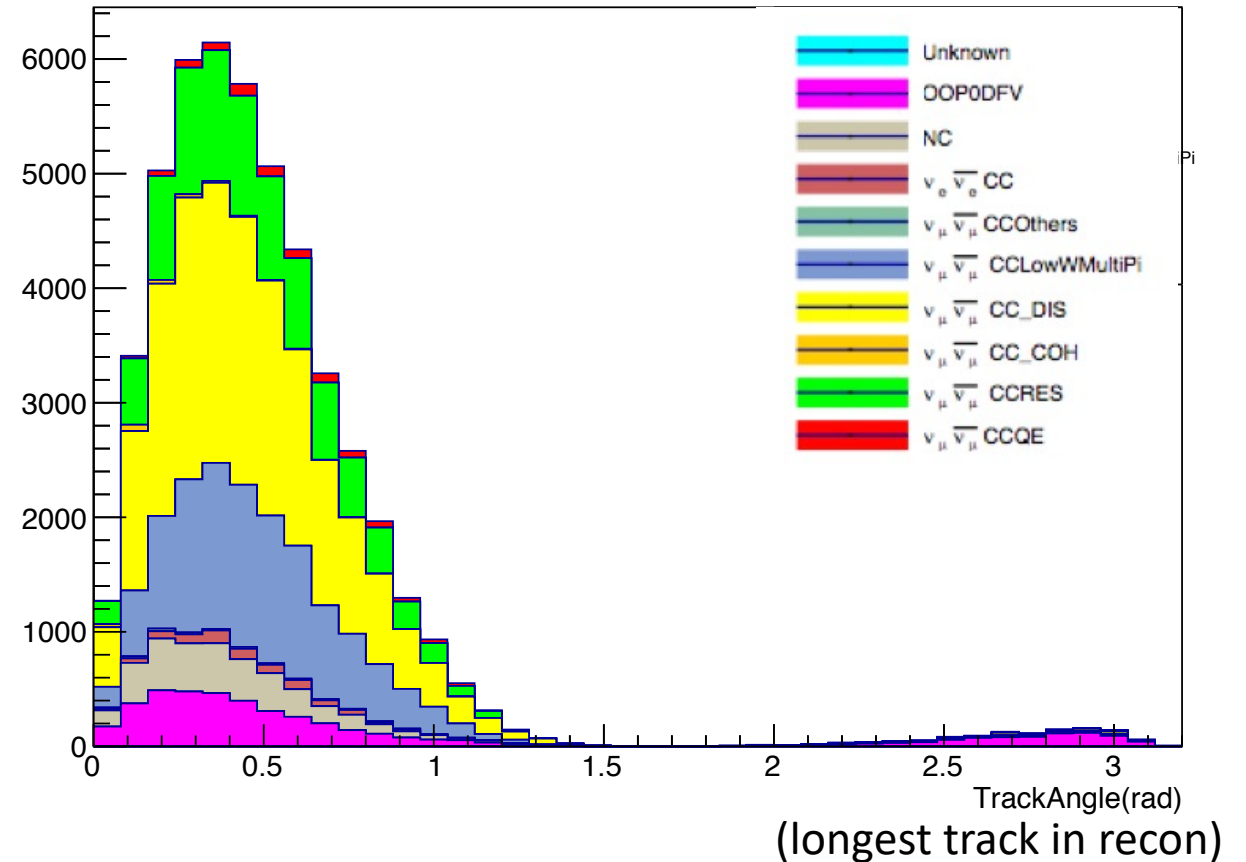
waterin config

Use the longest track's angle as the binning variable in the fitter for the  $\nu_\mu(\bar{\nu}_\mu)$  sidebands

$\nu_\mu(\bar{\nu}_\mu)$ CC background in signal sample



$\nu_\mu(\bar{\nu}_\mu)$ CC sidebands

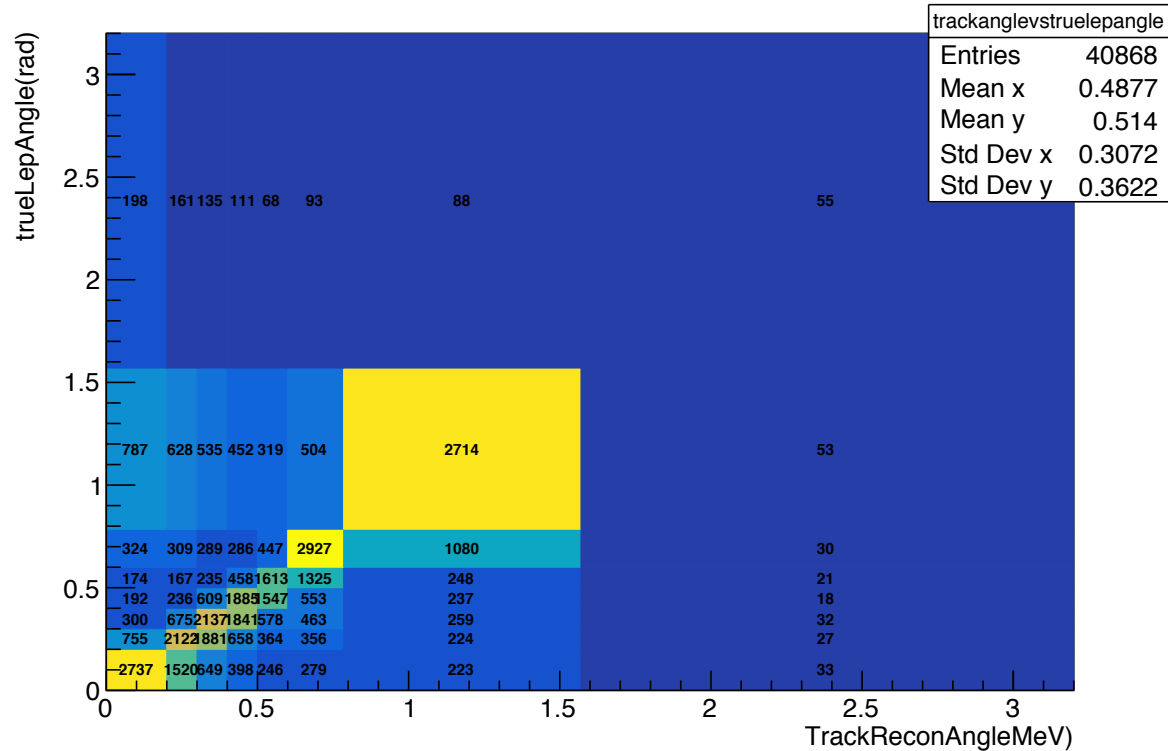


# $\nu_\mu(\bar{\nu}_\mu)$ CC sidebands Transfer matrix

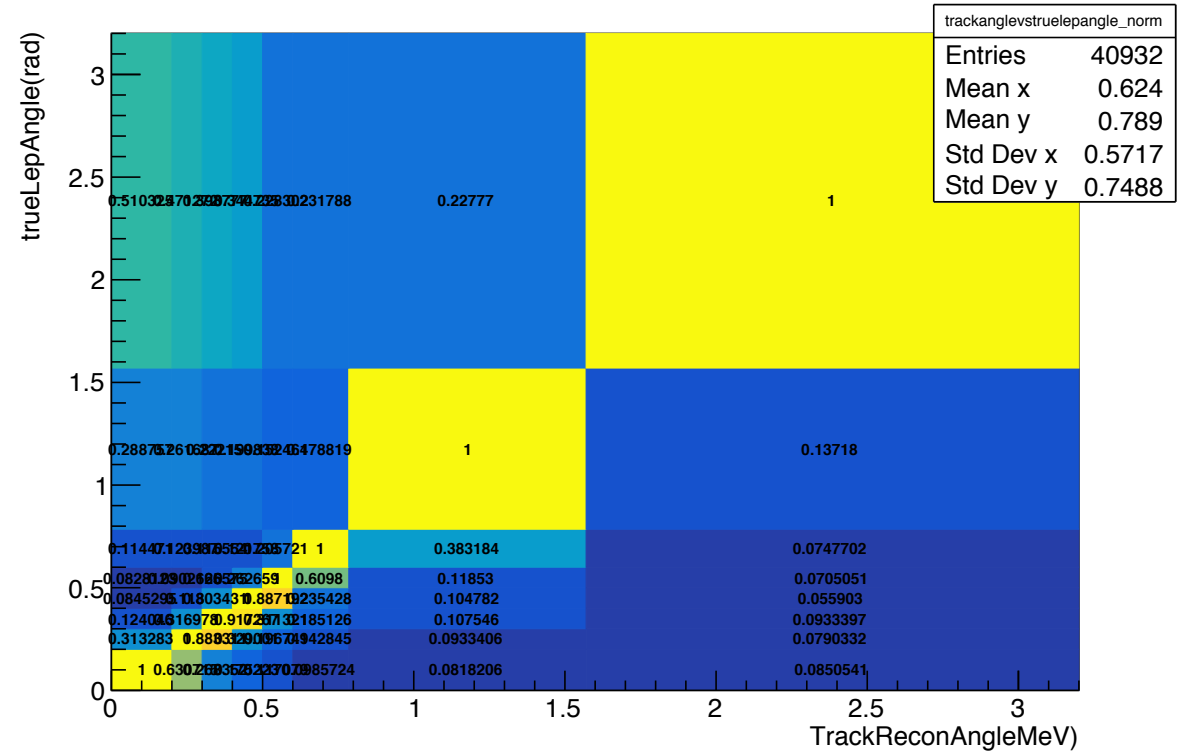
waterin config

Transfer Matrix of longest angle and true muon angle in the selected  $\nu_\mu(\bar{\nu}_\mu)$  CC sidebands  
 Binning here is the binning used in the fitter. previous page shows a finer binning than this one.

trackanglevstruelepangle



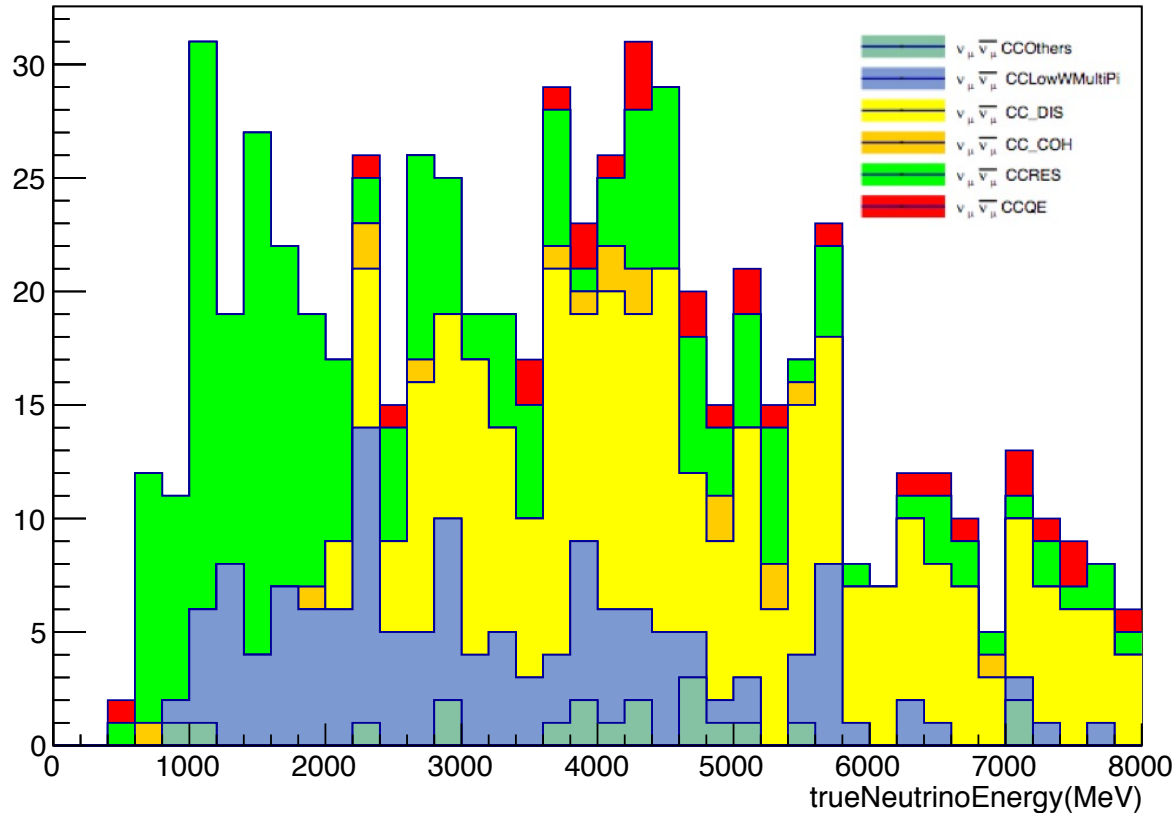
trackanglevstruelepangle



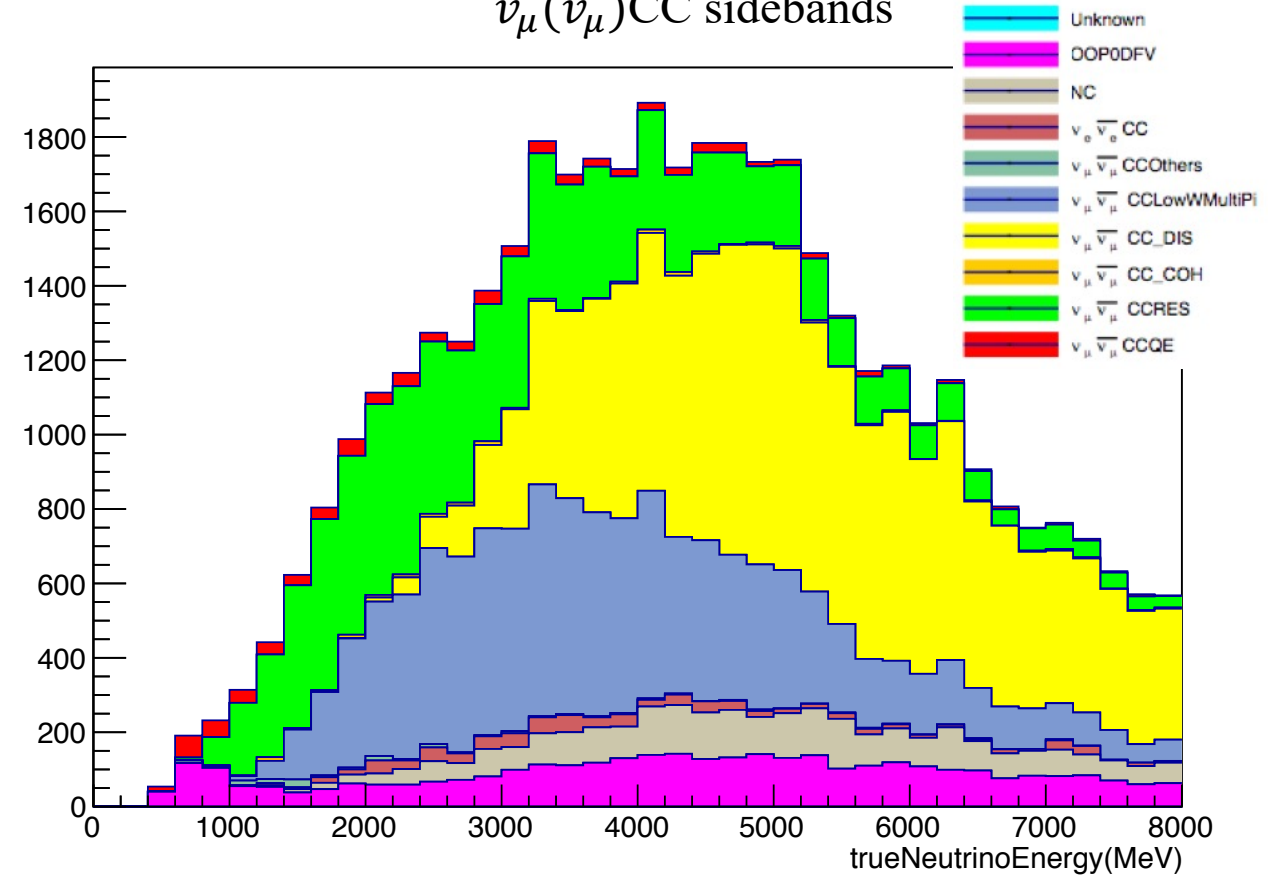
# $\nu_\mu(\bar{\nu}_\mu)$ CC (in FV) Backgrounds VS $\nu_\mu(\bar{\nu}_\mu)$ CC sidebands

waterin config

$\nu_\mu(\bar{\nu}_\mu)$ CC background in signal sample



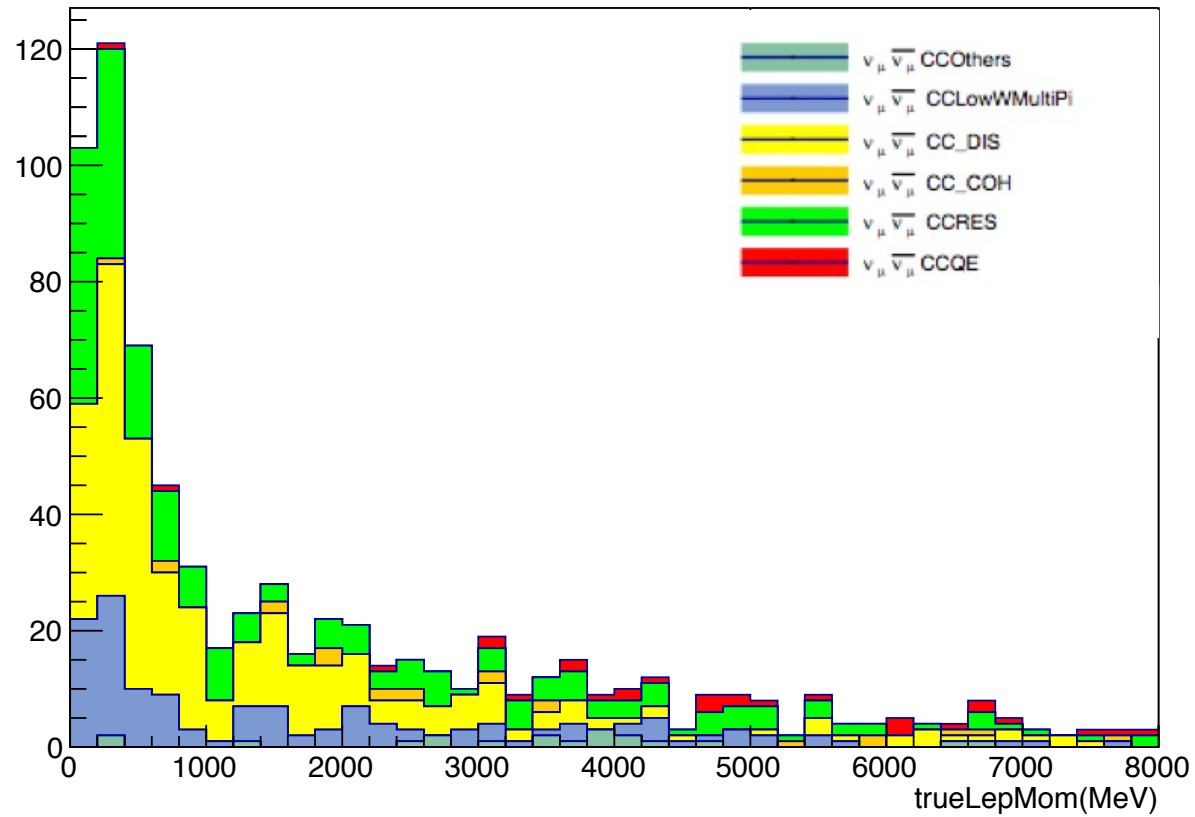
$\nu_\mu(\bar{\nu}_\mu)$ CC sidebands



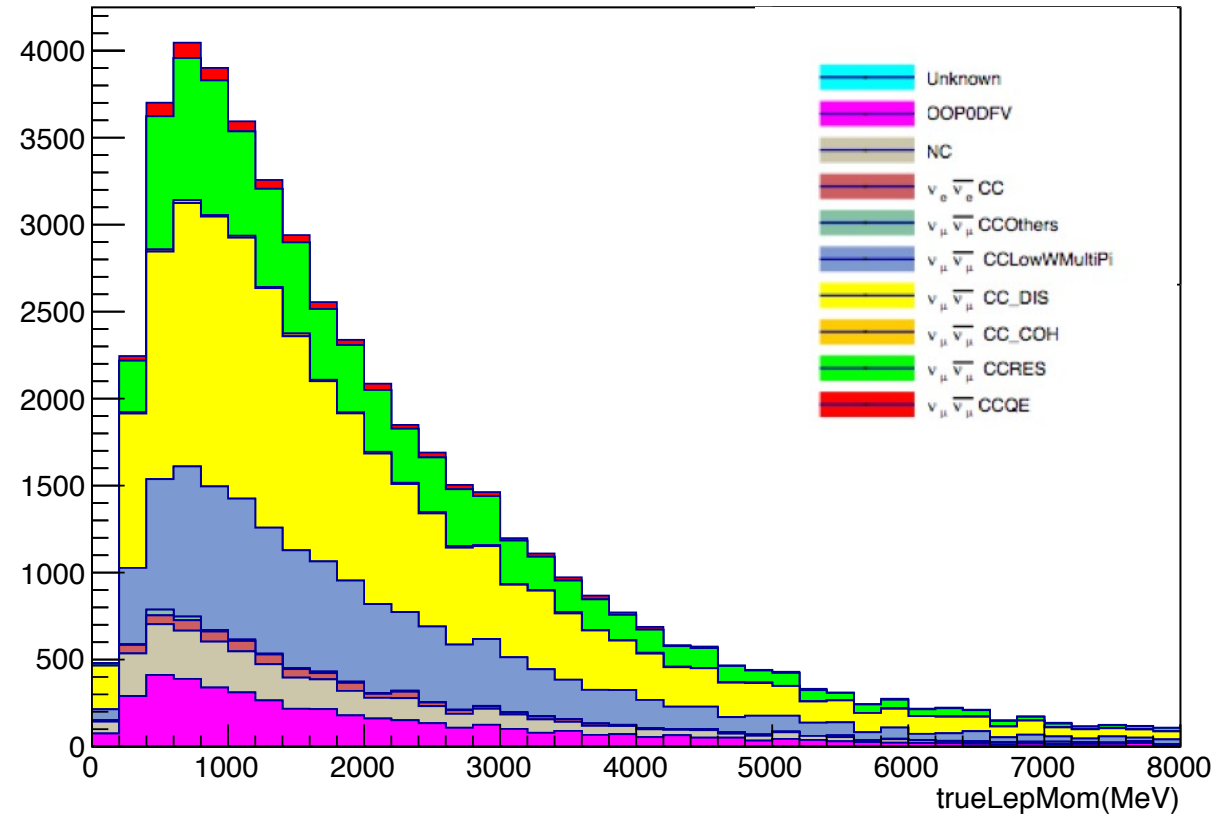
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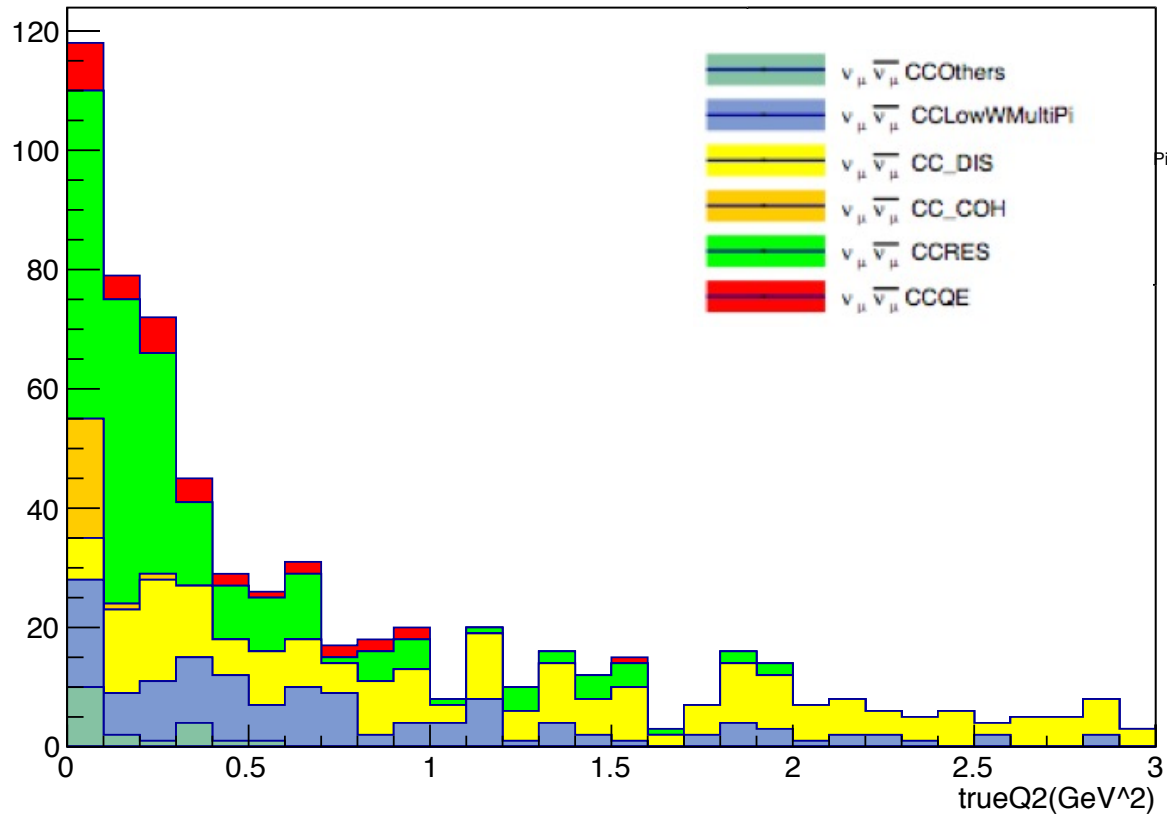
$\nu_\mu(\bar{\nu}_\mu)$ CC sidebands



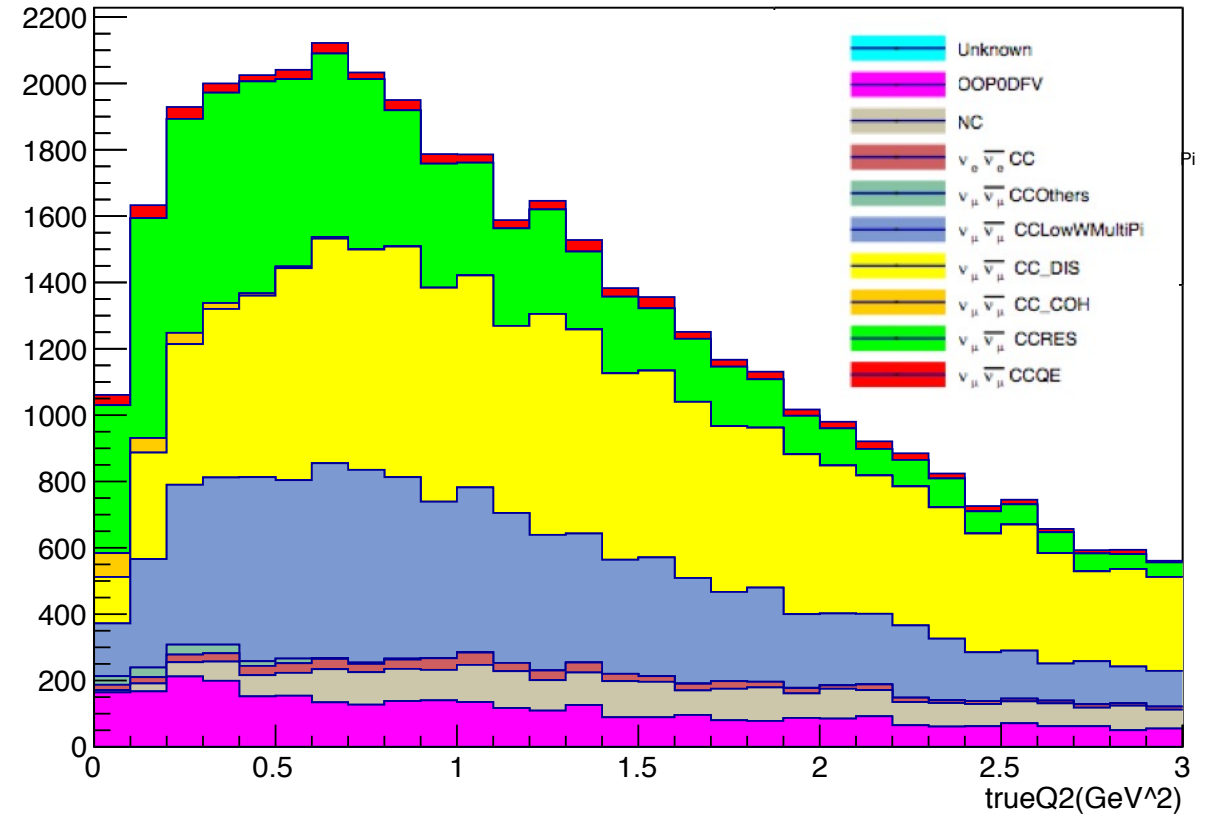
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waterin config

$\nu_\mu(\bar{\nu}_\mu)$ CC background in signal sample



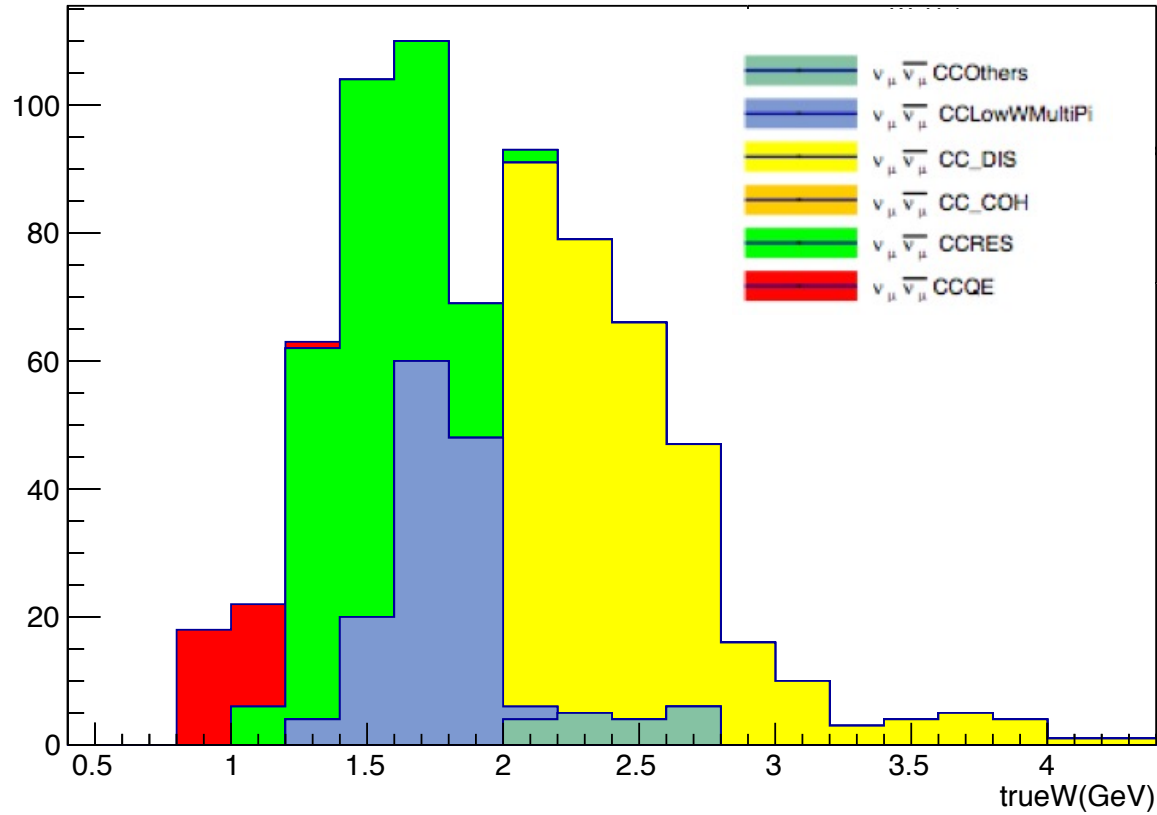
$\nu_\mu(\bar{\nu}_\mu)$ CC sidebands



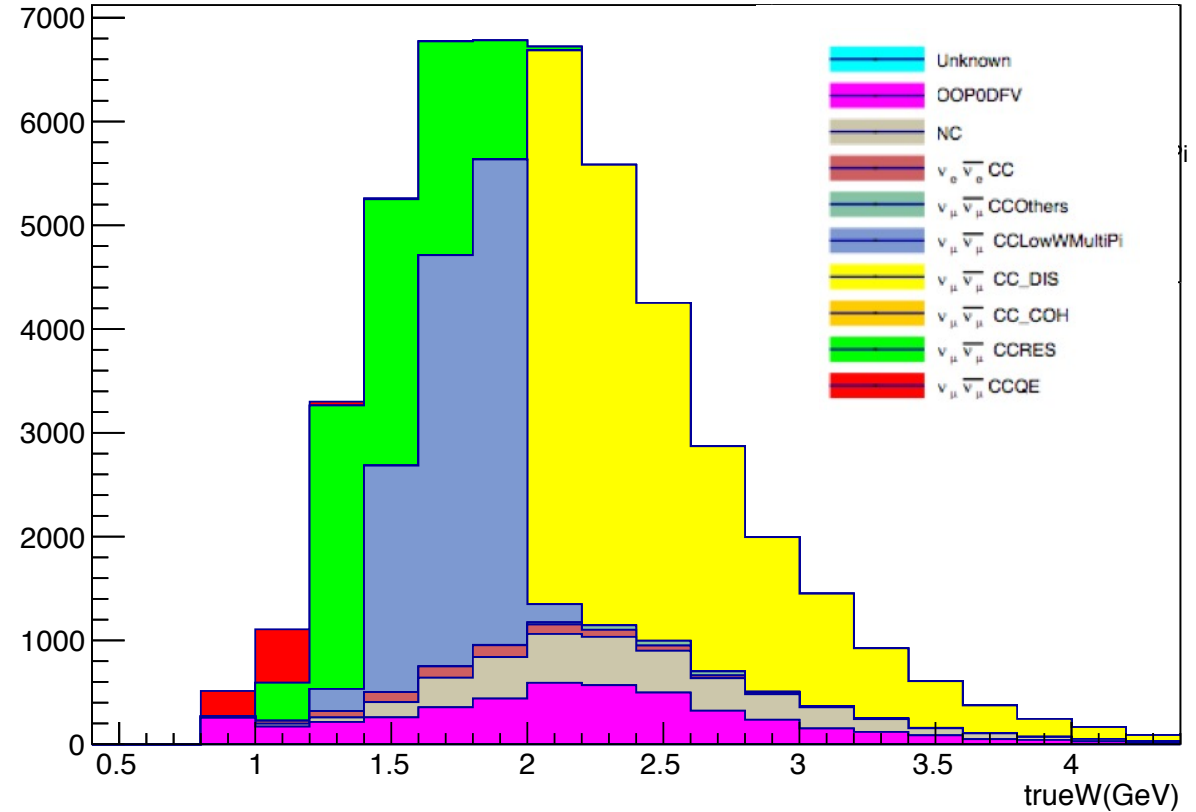
# $\nu_\mu(\bar{\nu}_\mu)$ CC (in FV) Backgrounds VS $\nu_\mu(\bar{\nu}_\mu)$ CC sidebands

waterin config

$\nu_\mu(\bar{\nu}_\mu)$ CC background in signal sample



$\nu_\mu(\bar{\nu}_\mu)$ CC sidebands

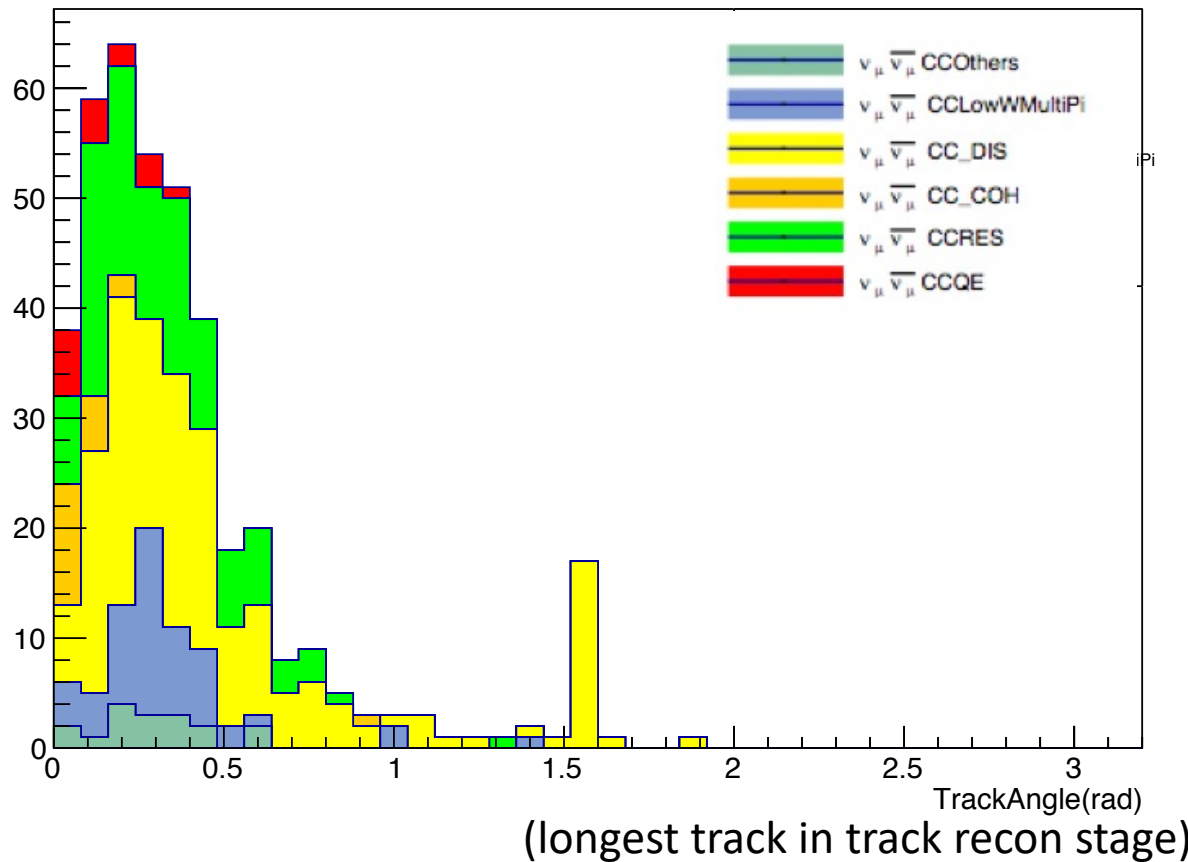


# $\nu_\mu(\bar{\nu}_\mu)$ CC (in FV) Backgrounds VS $\nu_\mu(\bar{\nu}_\mu)$ CC sidebands

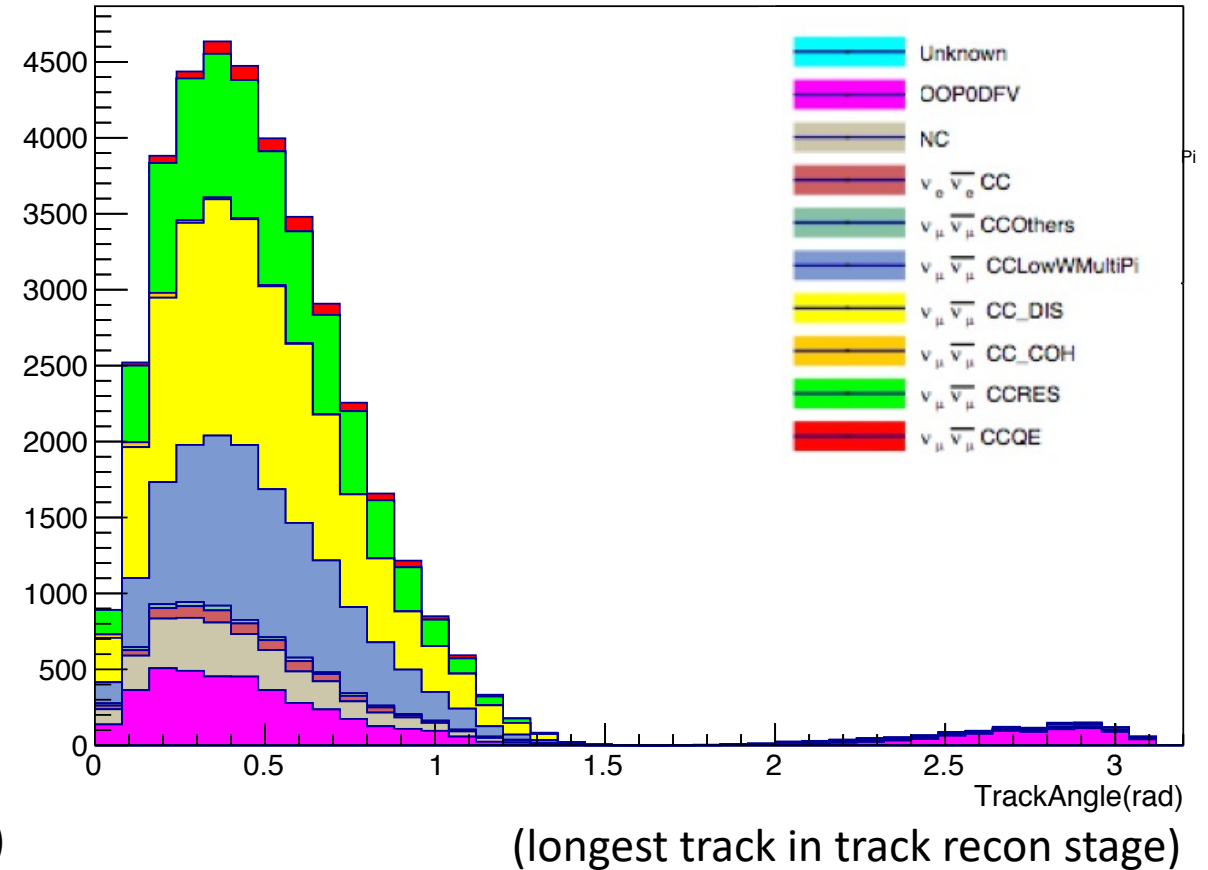
waterout config

Use the longest track's angle as the binning variable in the fitter for the  $\nu_\mu(\bar{\nu}_\mu)$  sidebands

$\nu_\mu(\bar{\nu}_\mu)$ CC background in signal sample



$\nu_\mu(\bar{\nu}_\mu)$ CC sidebands

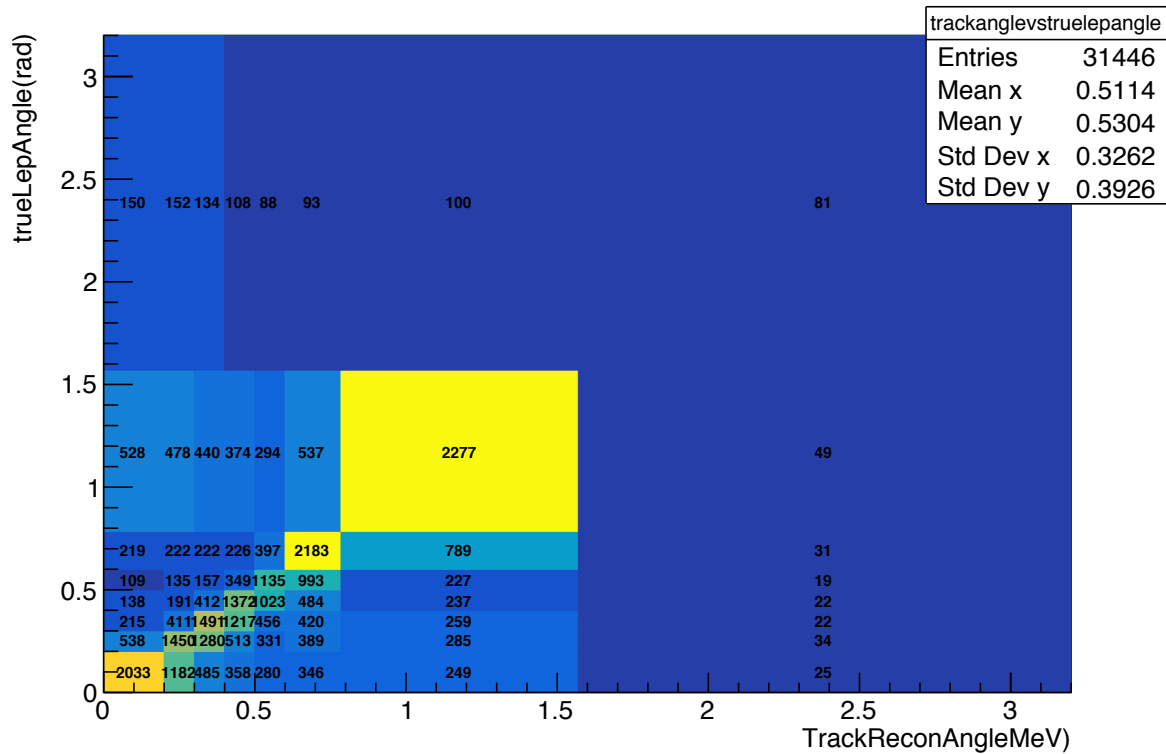


# $\nu_\mu (\bar{\nu}_\mu)$ CC sidebands Transfer matrix

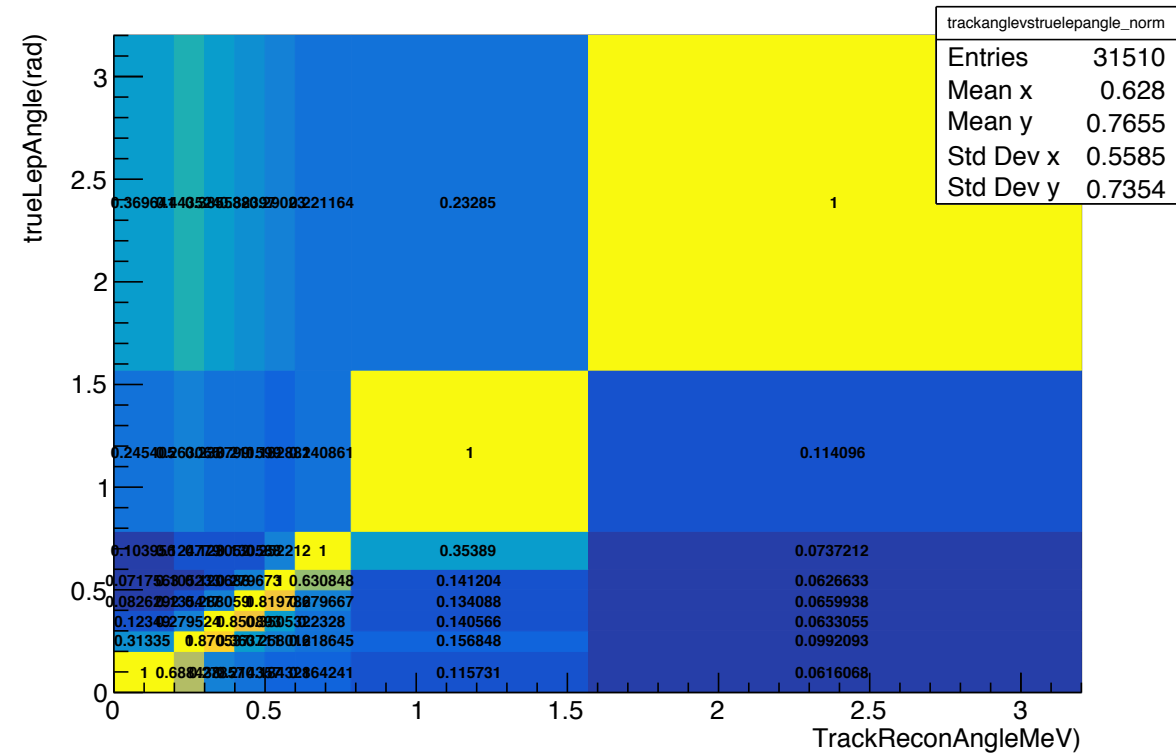
waterout config

Transfer Matrix of longest angle and true muon angle in the selected numuCC sidebands.

trackanglevstruelepangle



trackanglevstruelepangle

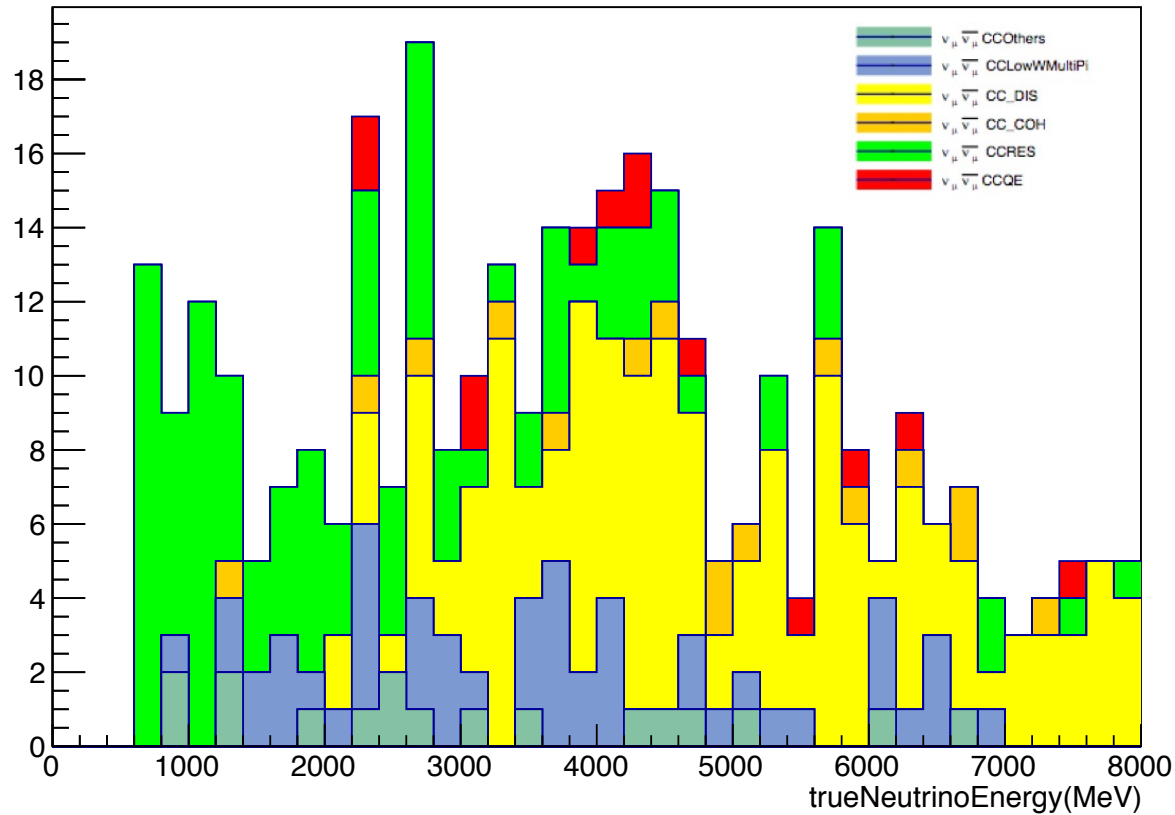


Normalized

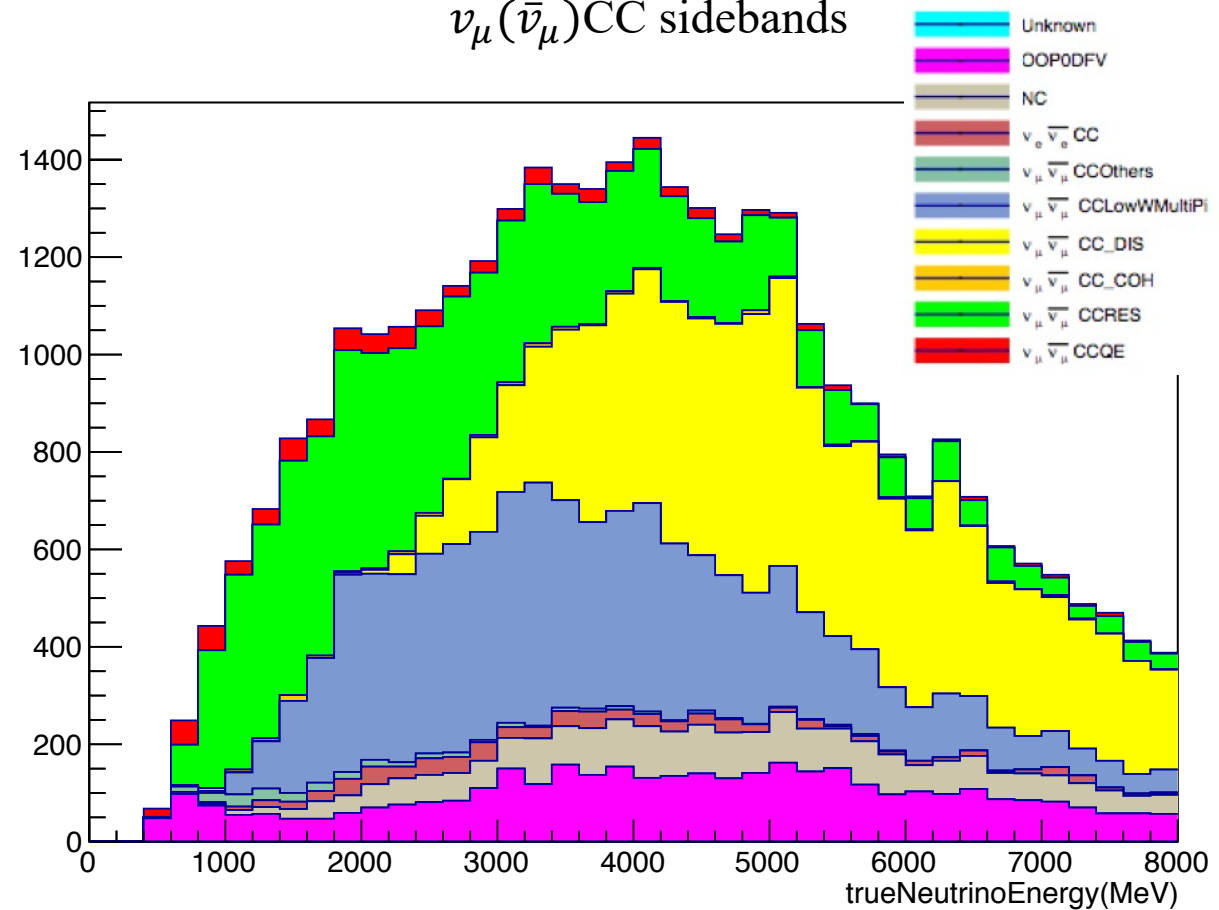
# $\nu_\mu(\bar{\nu}_\mu)$ CC (in FV) Backgrounds VS $\nu_\mu(\bar{\nu}_\mu)$ CC sidebands

waterout config

$\nu_\mu(\bar{\nu}_\mu)$ CC background in signal sample



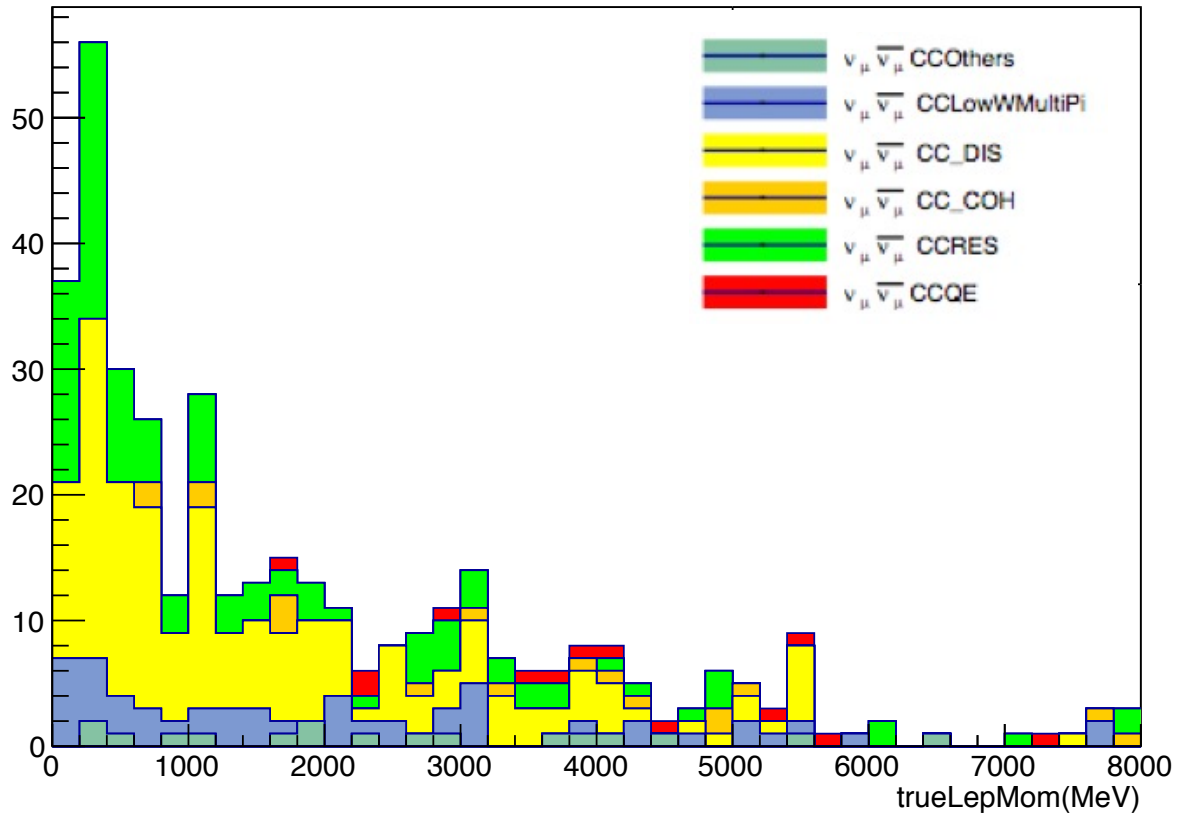
$\nu_\mu(\bar{\nu}_\mu)$ CC sidebands



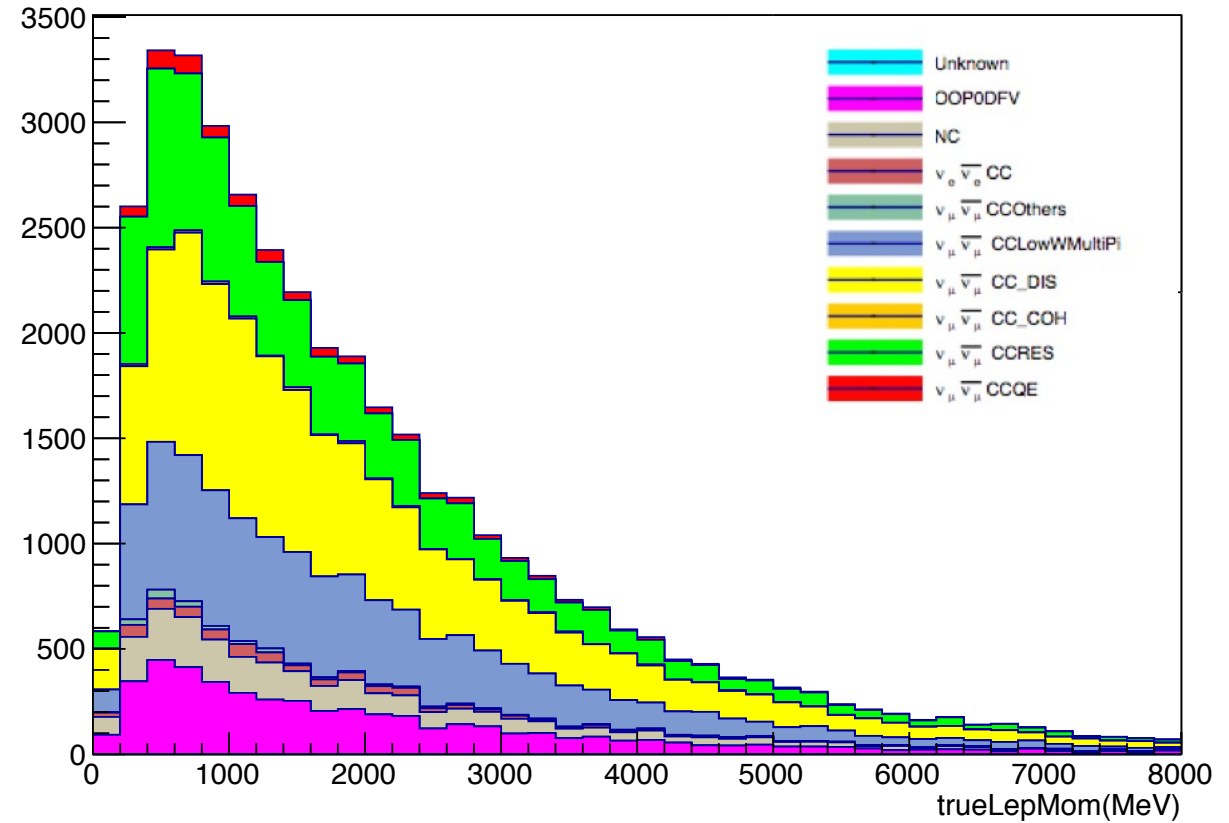
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waterout config

$\nu_\mu(\bar{\nu}_\mu)$ CC background in signal sample



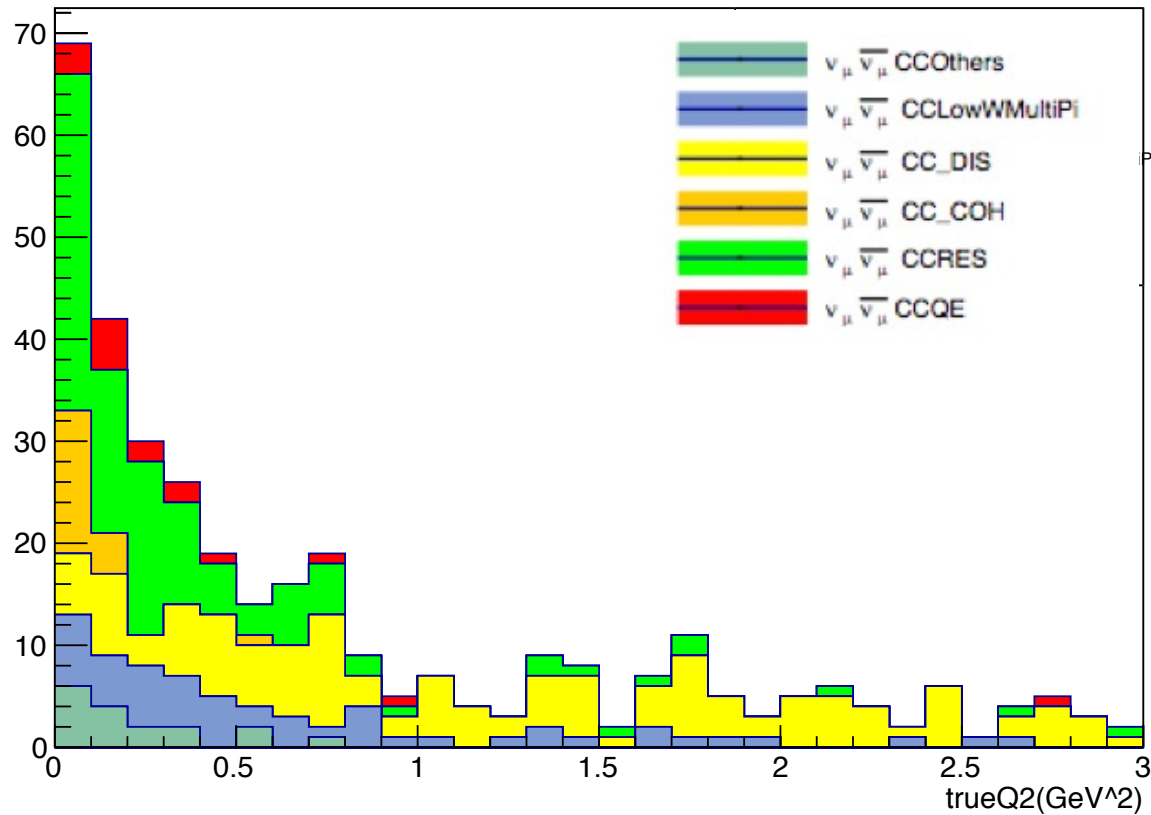
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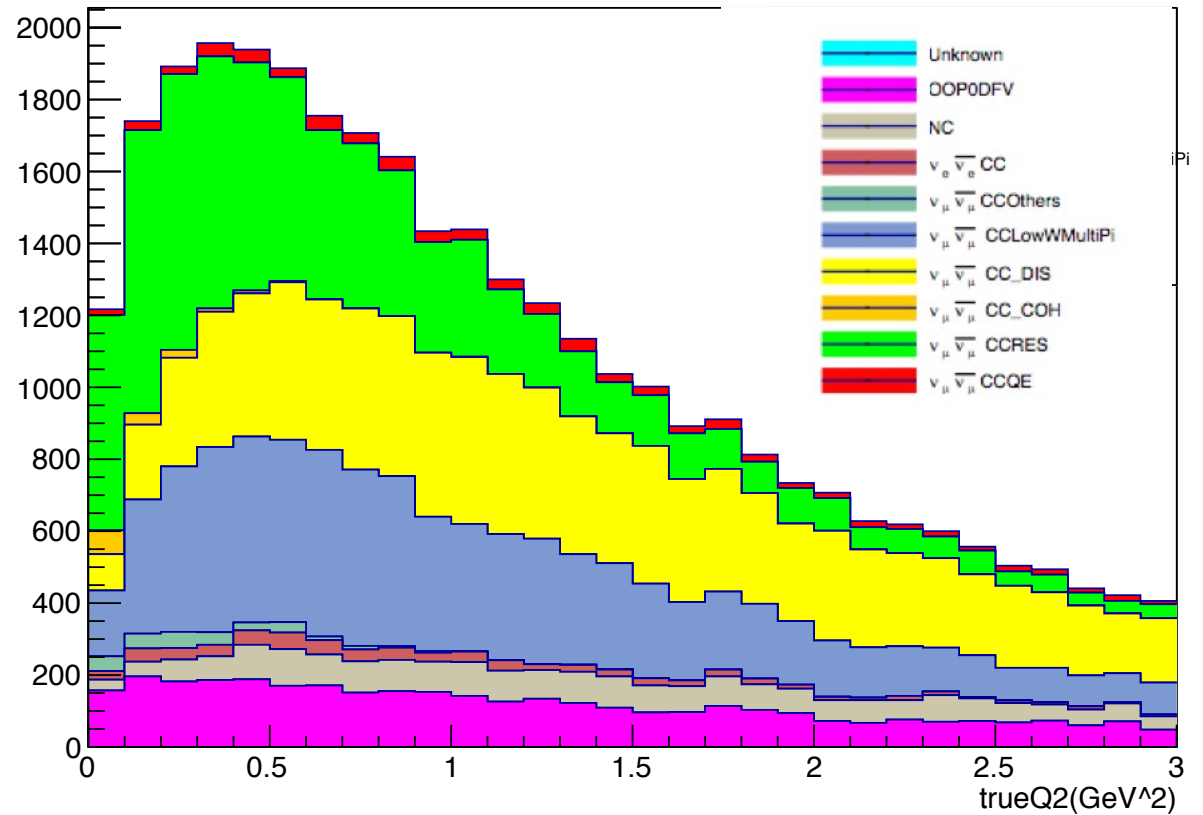
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waterout config

$\nu_\mu(\bar{\nu}_\mu)$ CC background in signal sample



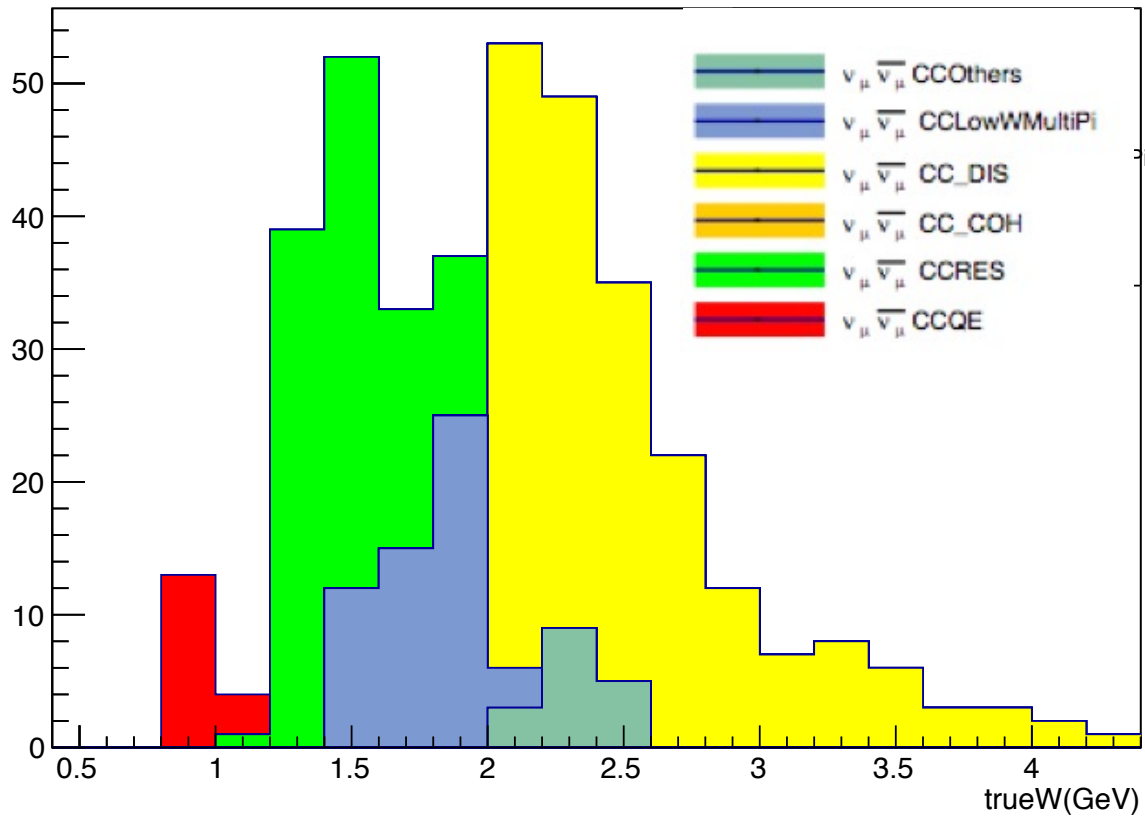
$\nu_\mu(\bar{\nu}_\mu)$ CC sidebands



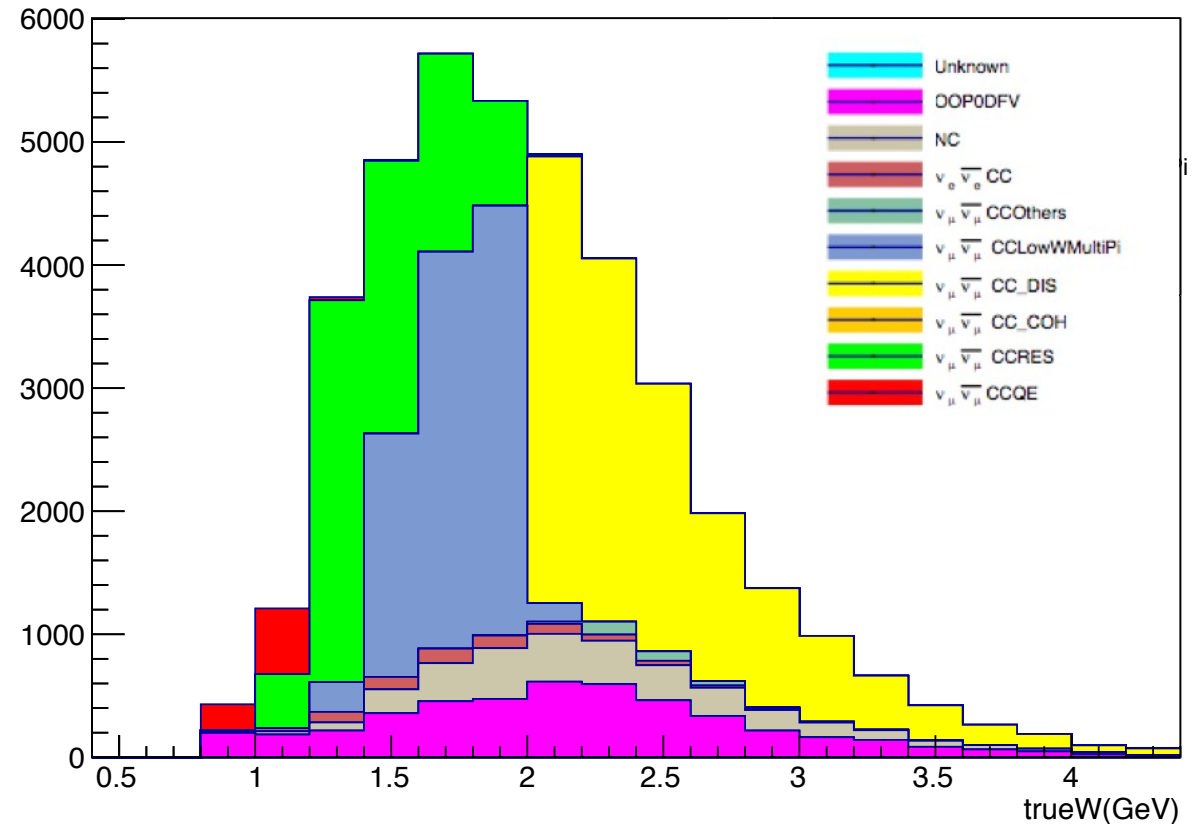
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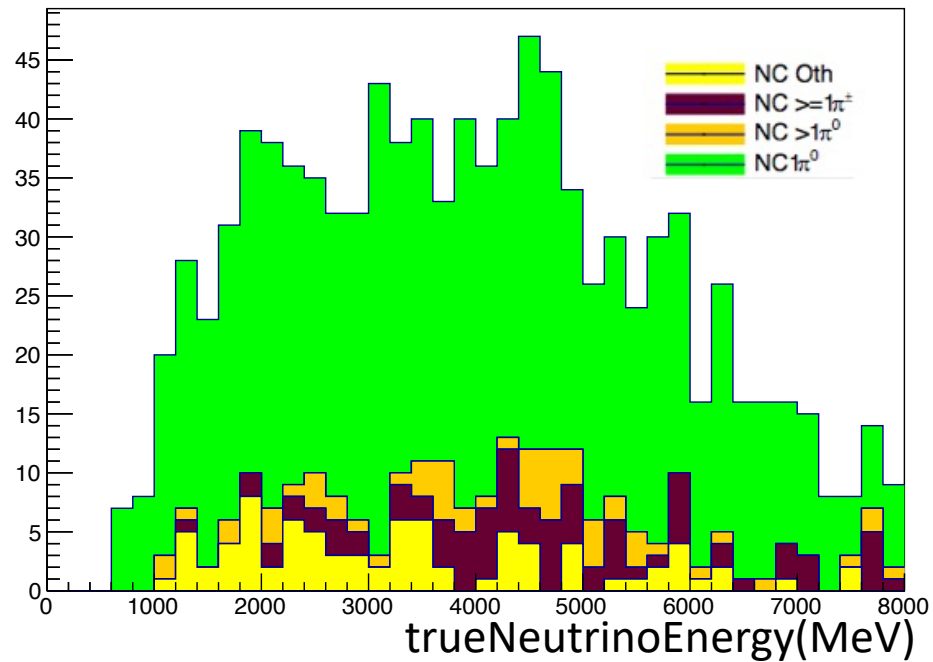
$\nu_\mu(\bar{\nu}_\mu)$ CC background in signal sample



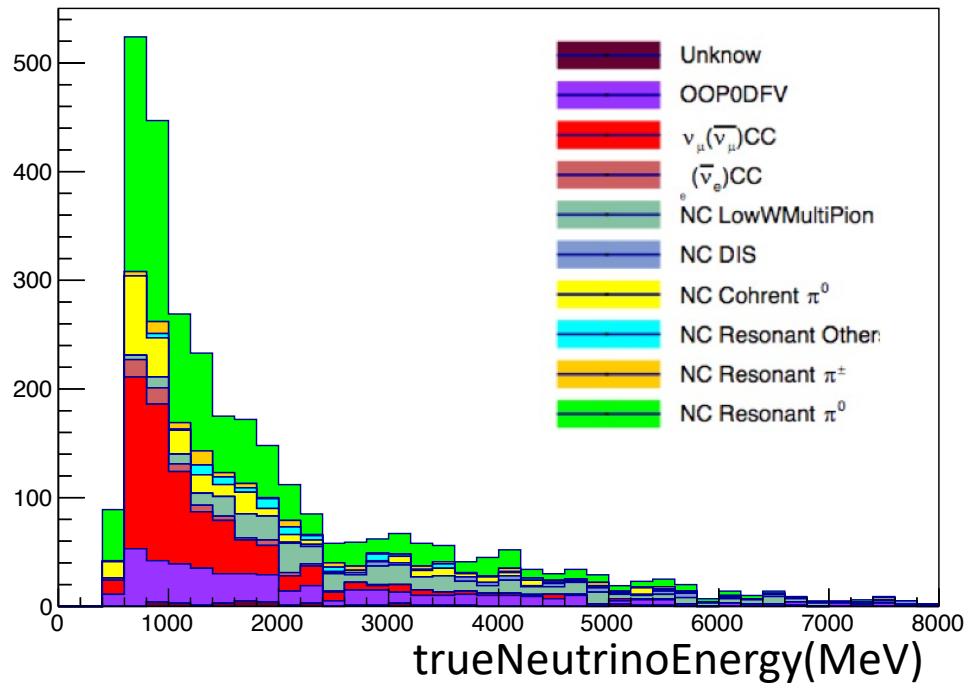
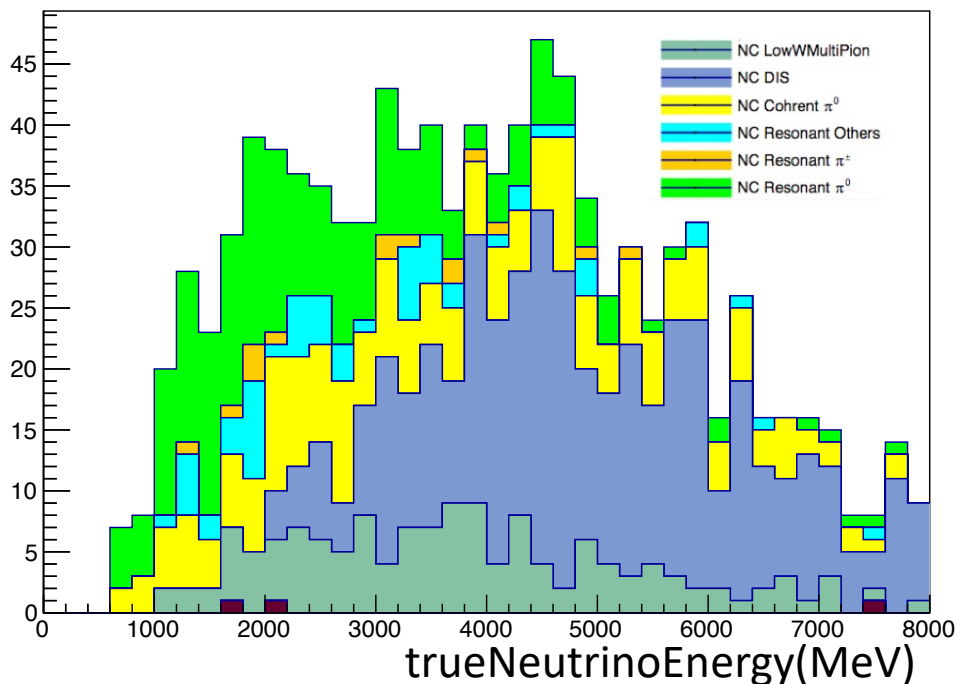
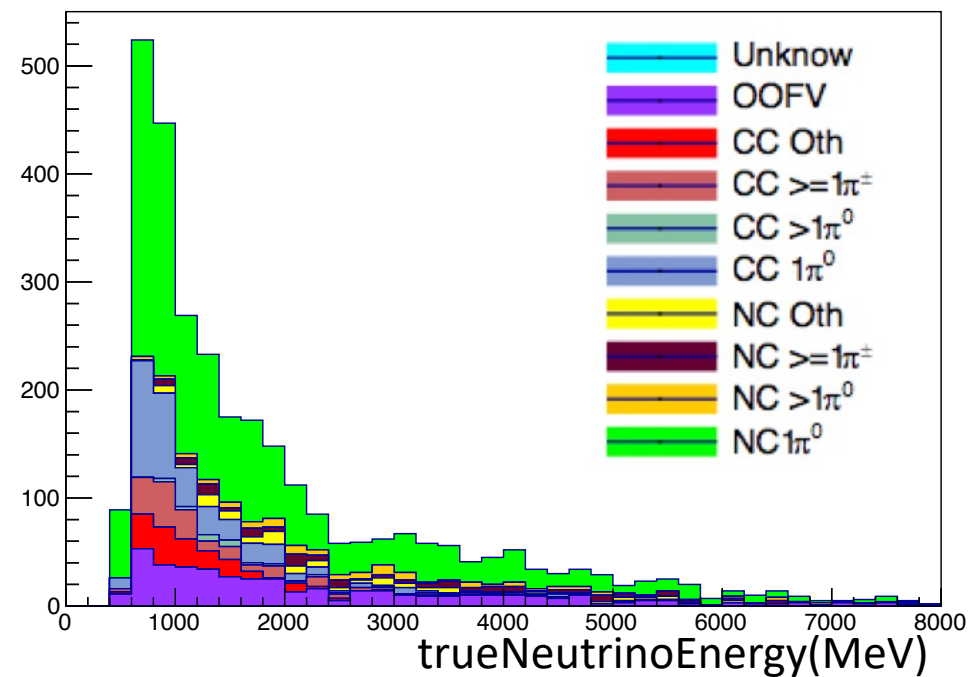
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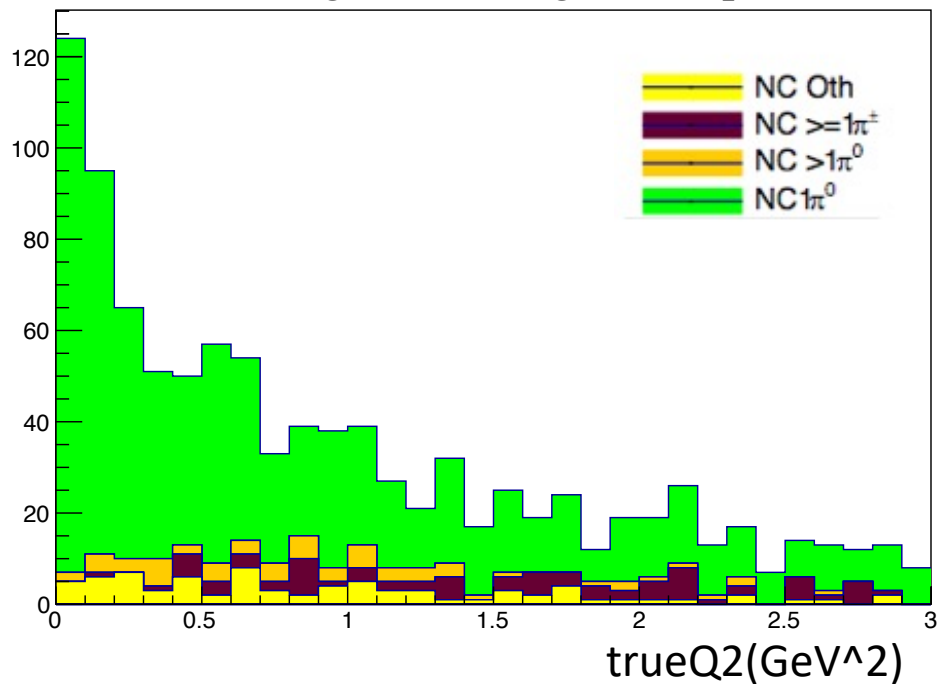
NC background in signal sample



NC sidebands

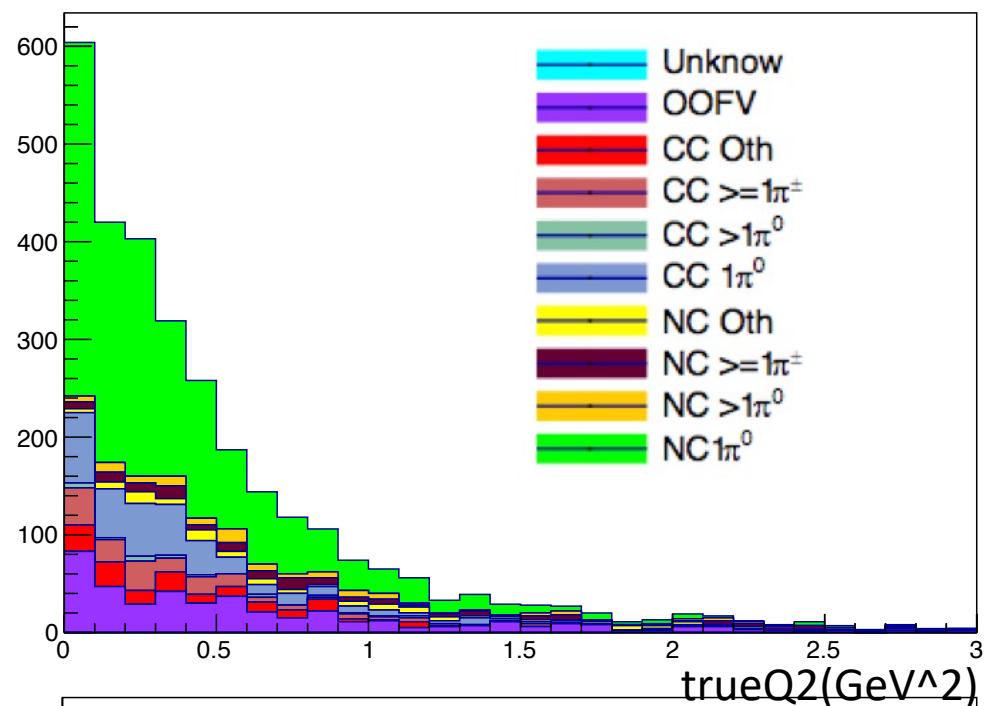


NC background in signal sample

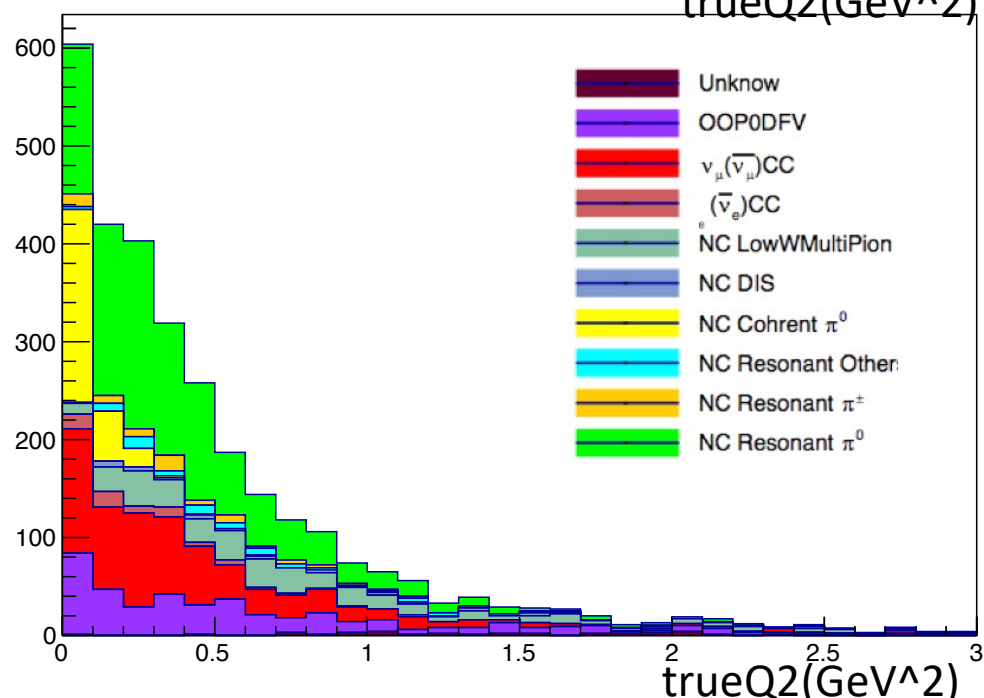
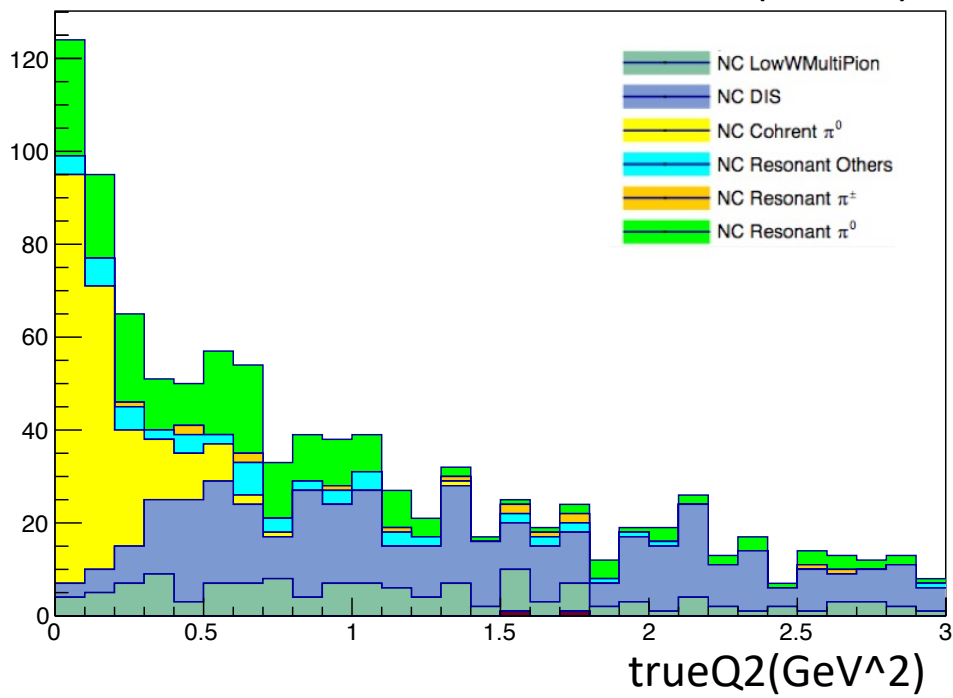


In topology

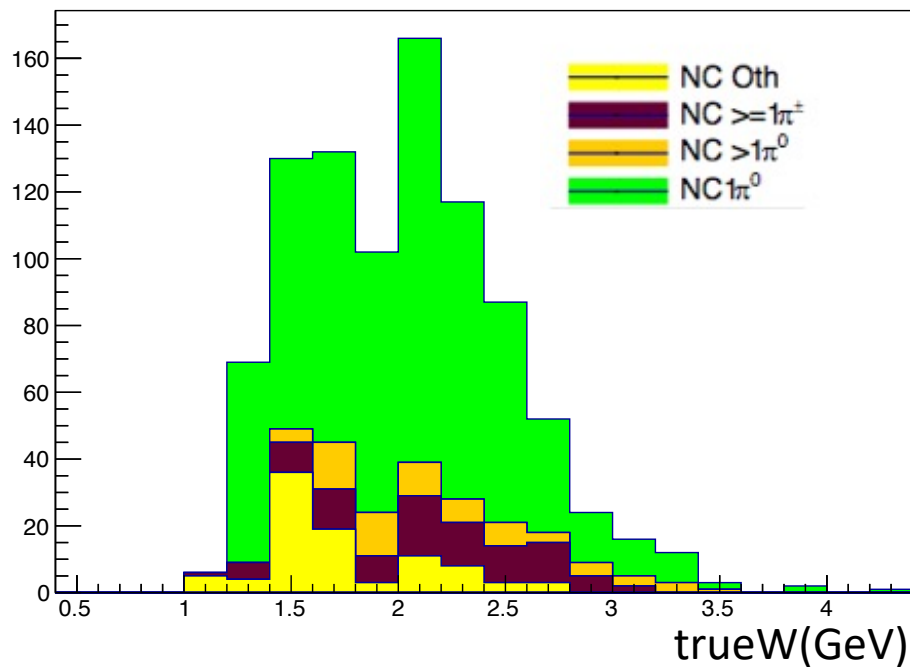
NC sidebands



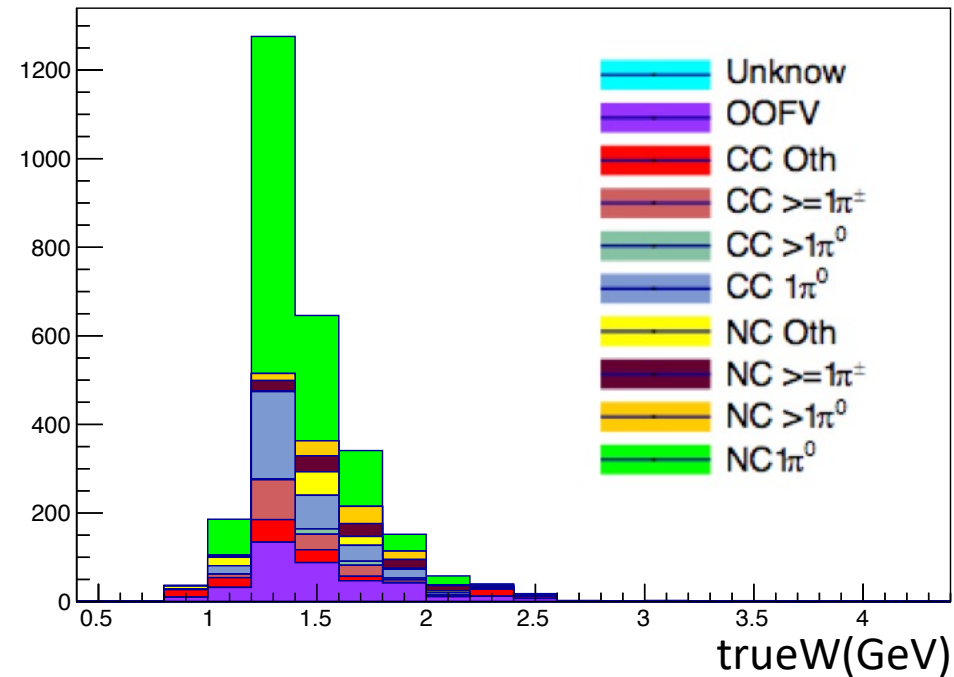
In reaction



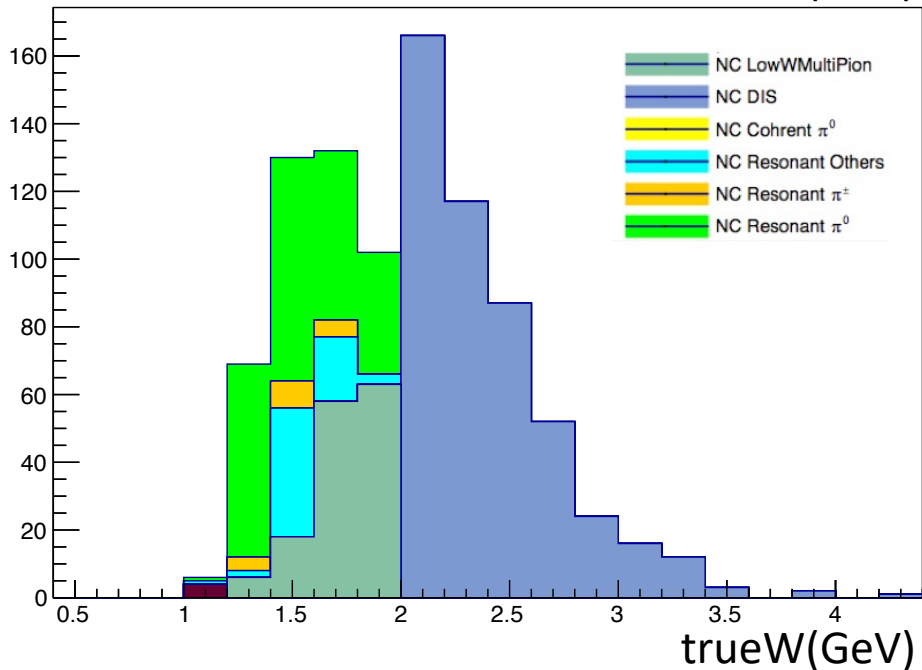
NC background in signal sample



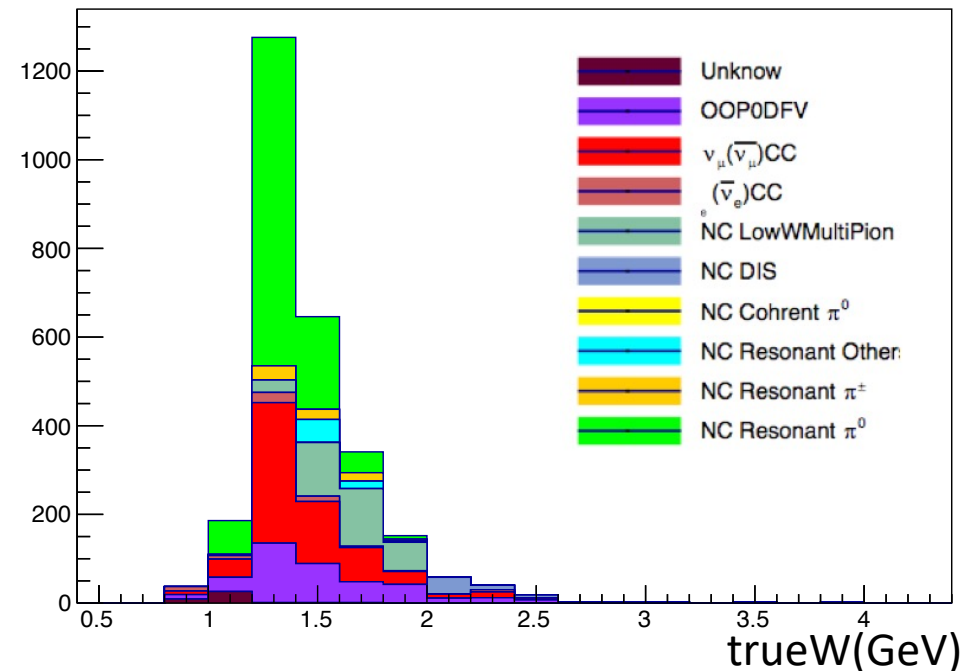
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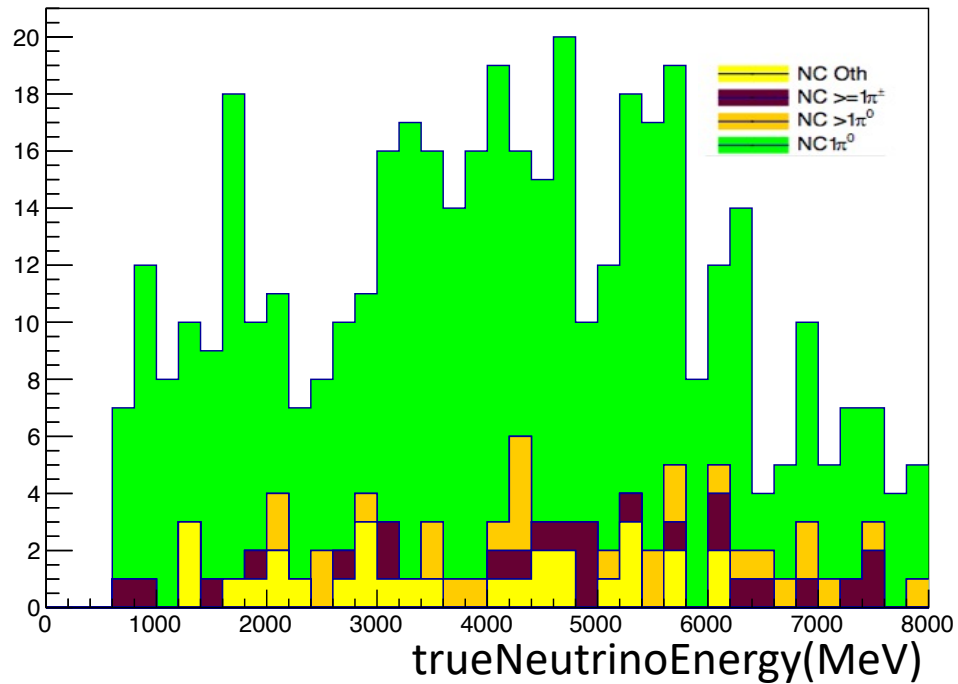
In topology



In reaction

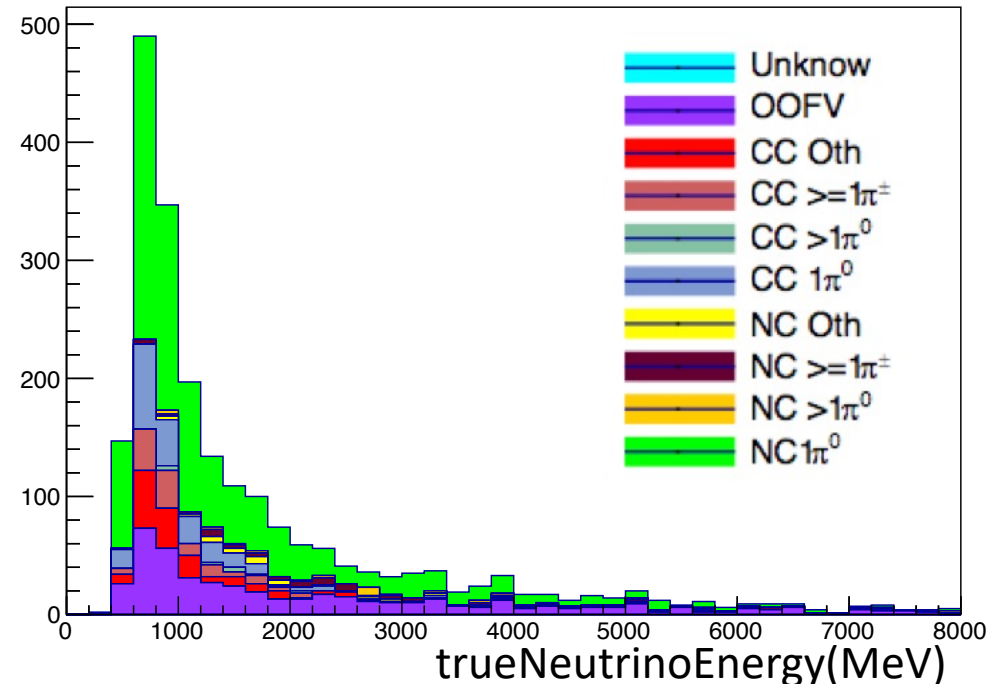


NC background in signal sample

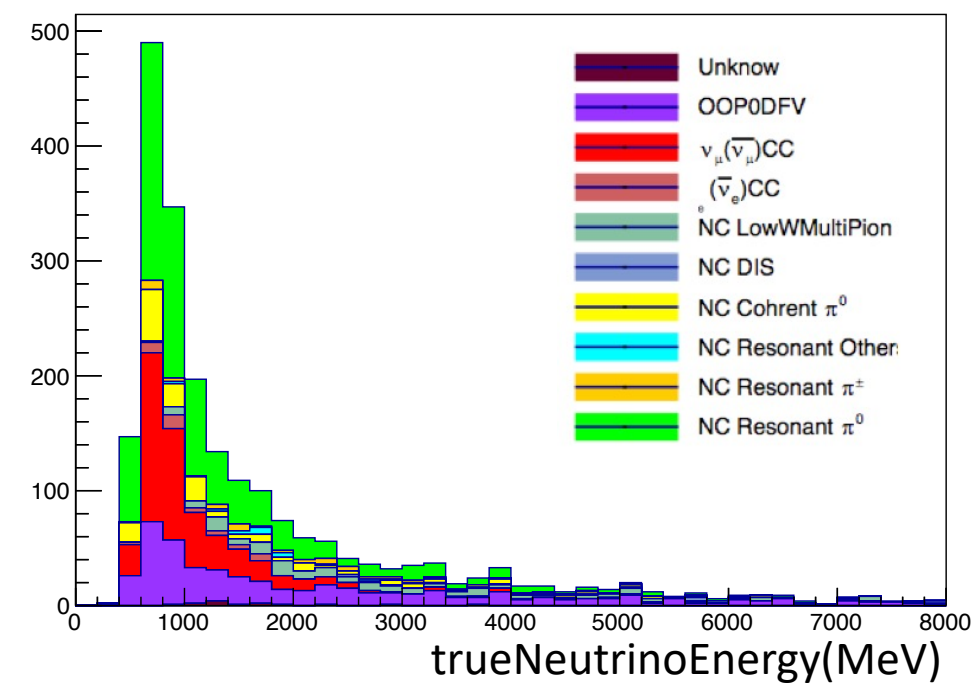
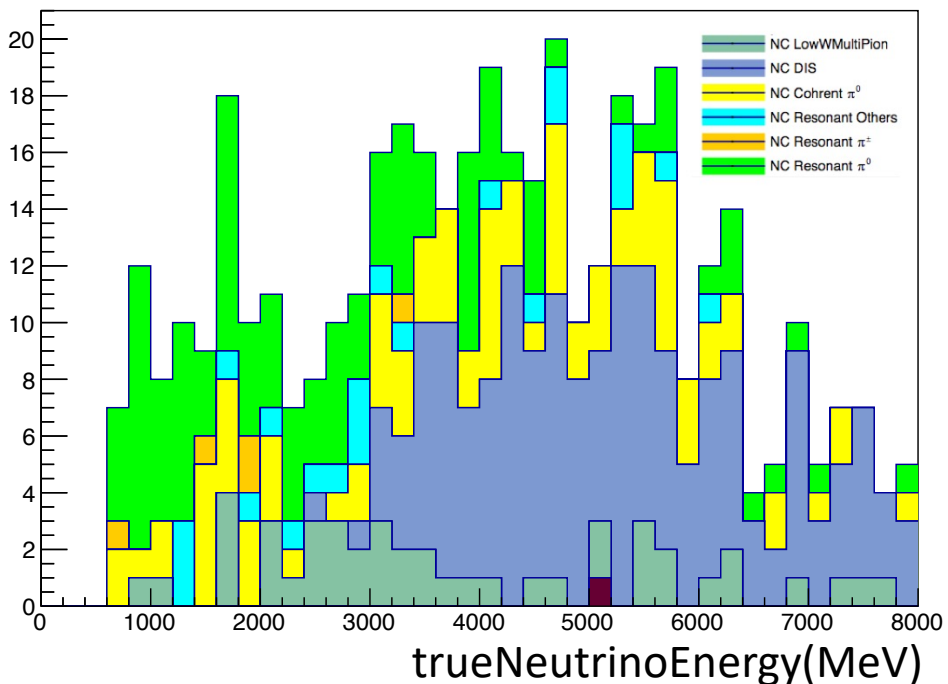


In topology

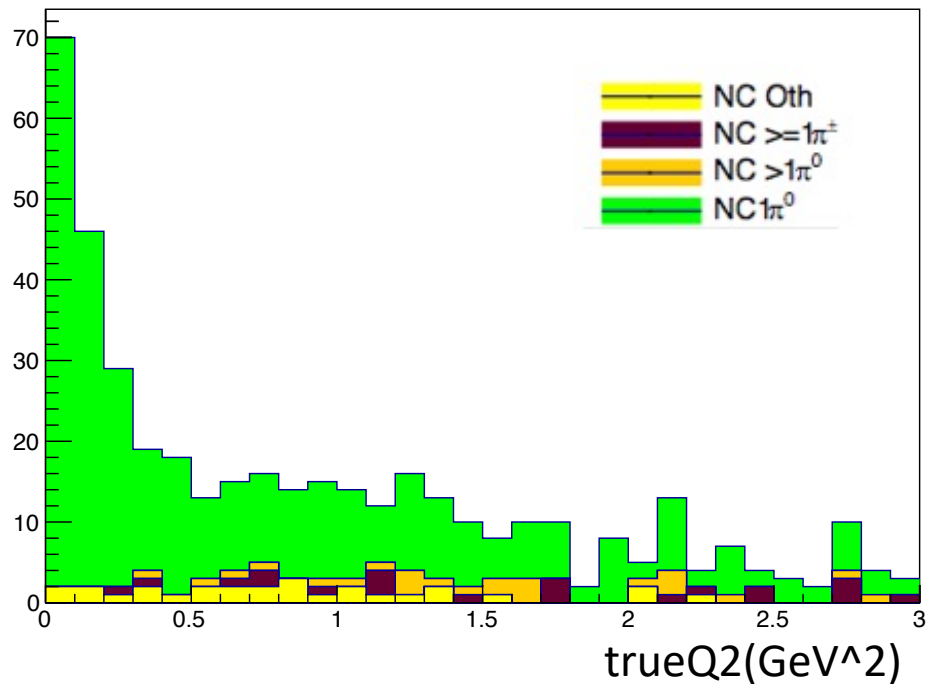
NC sidebands



In reaction

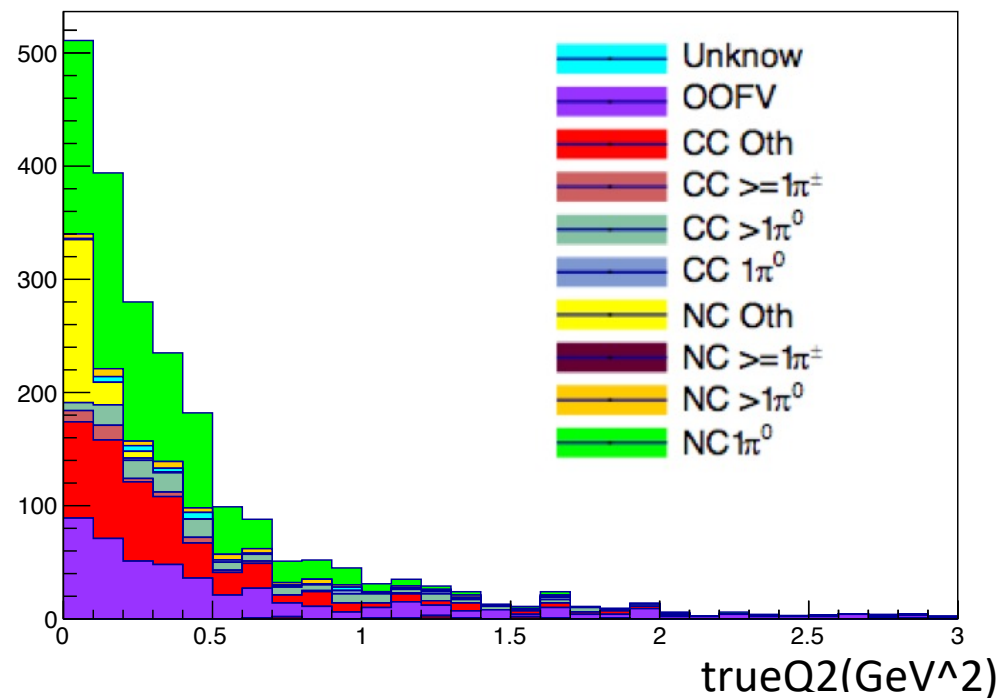


NC background in signal sample

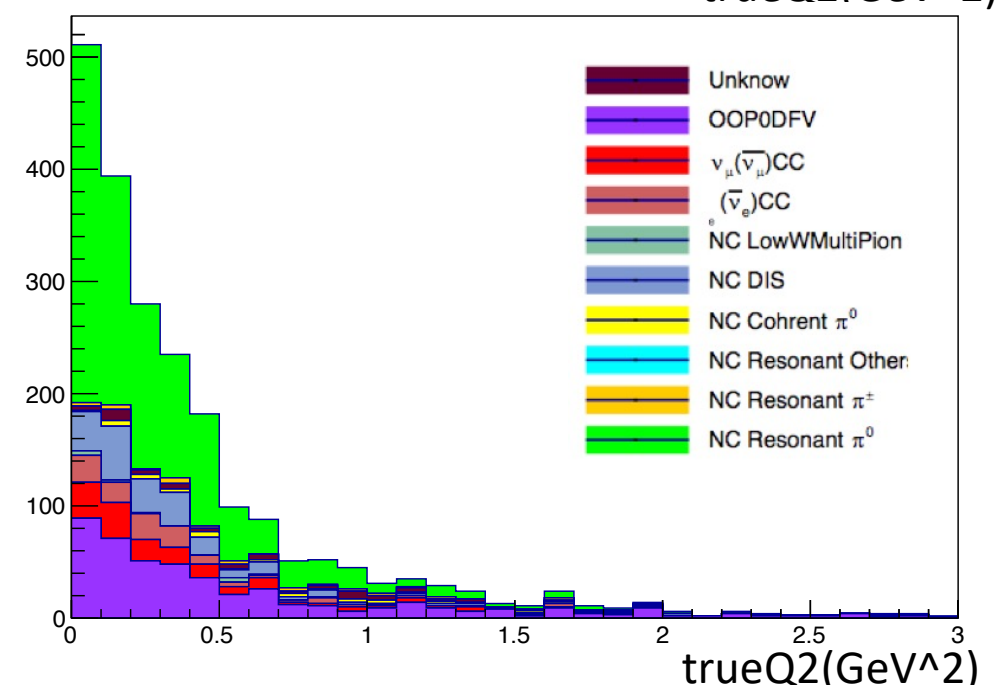
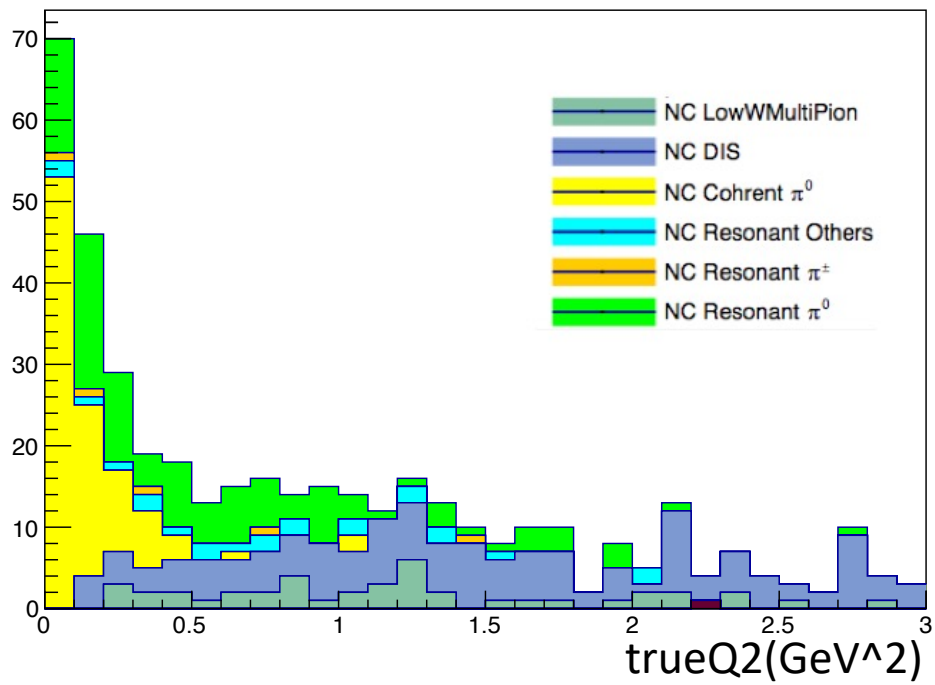


In topology

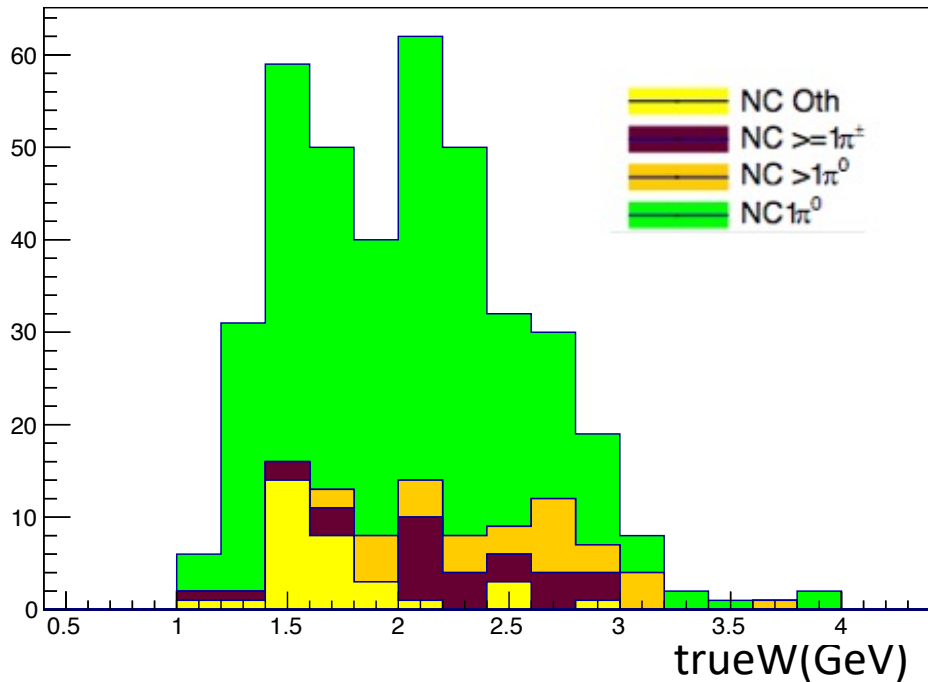
NC sidebands



In reaction

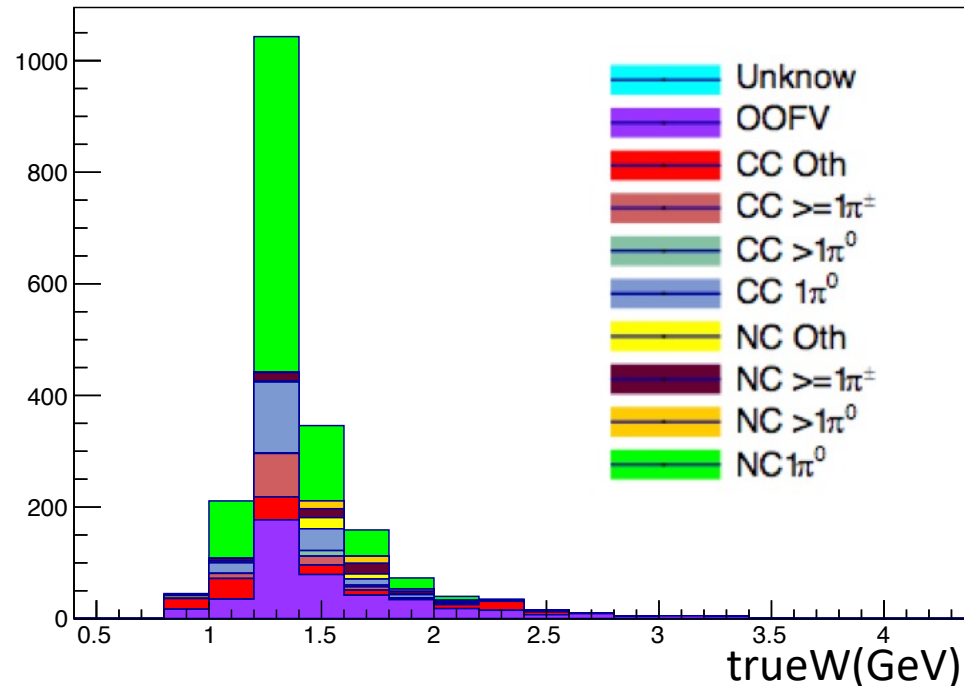


NC background in signal sample

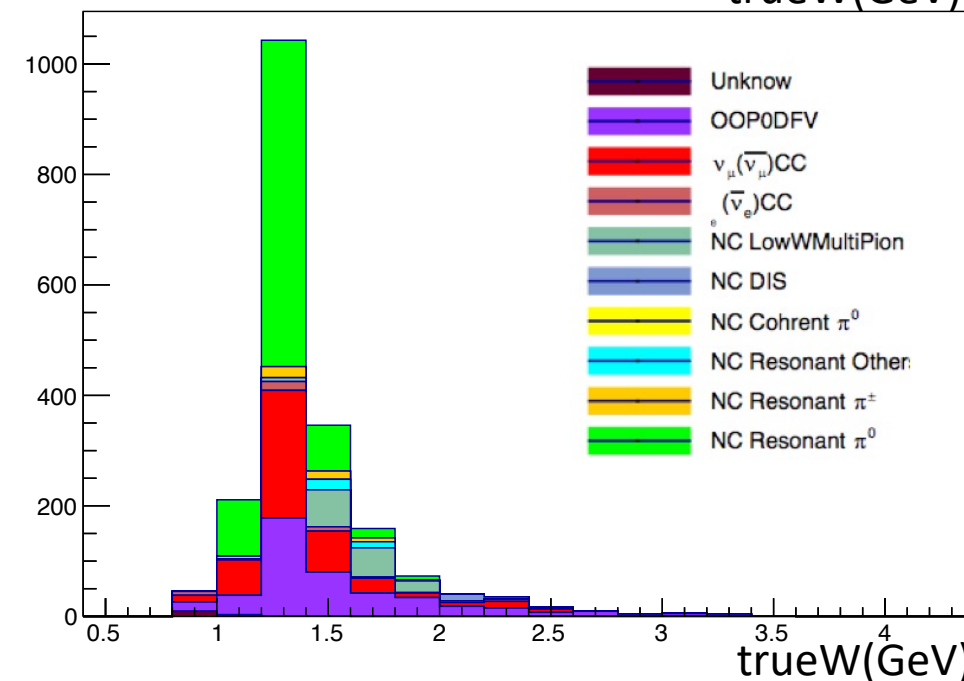
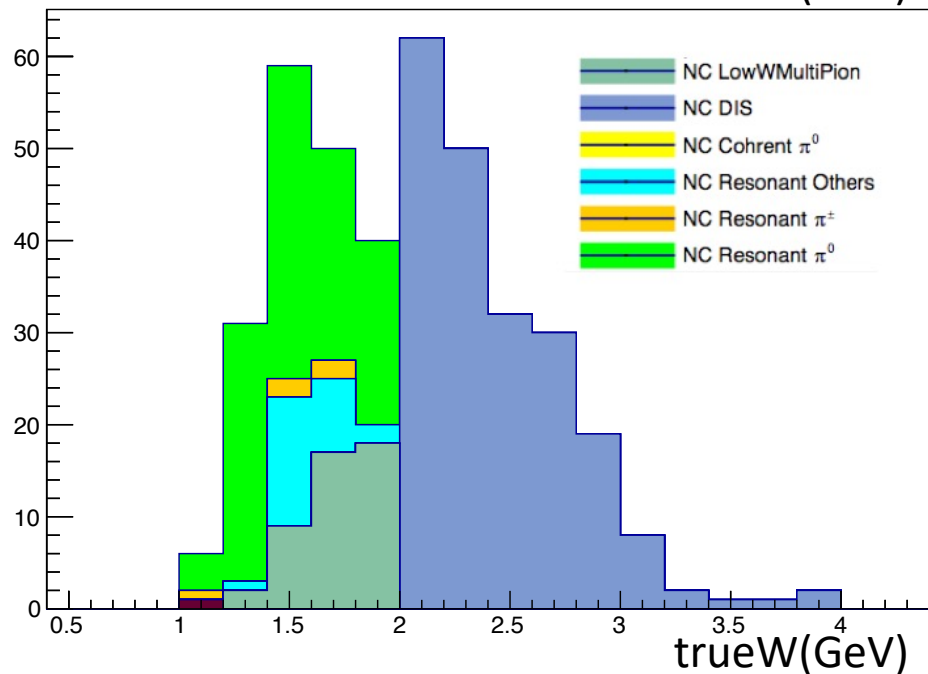


In topology

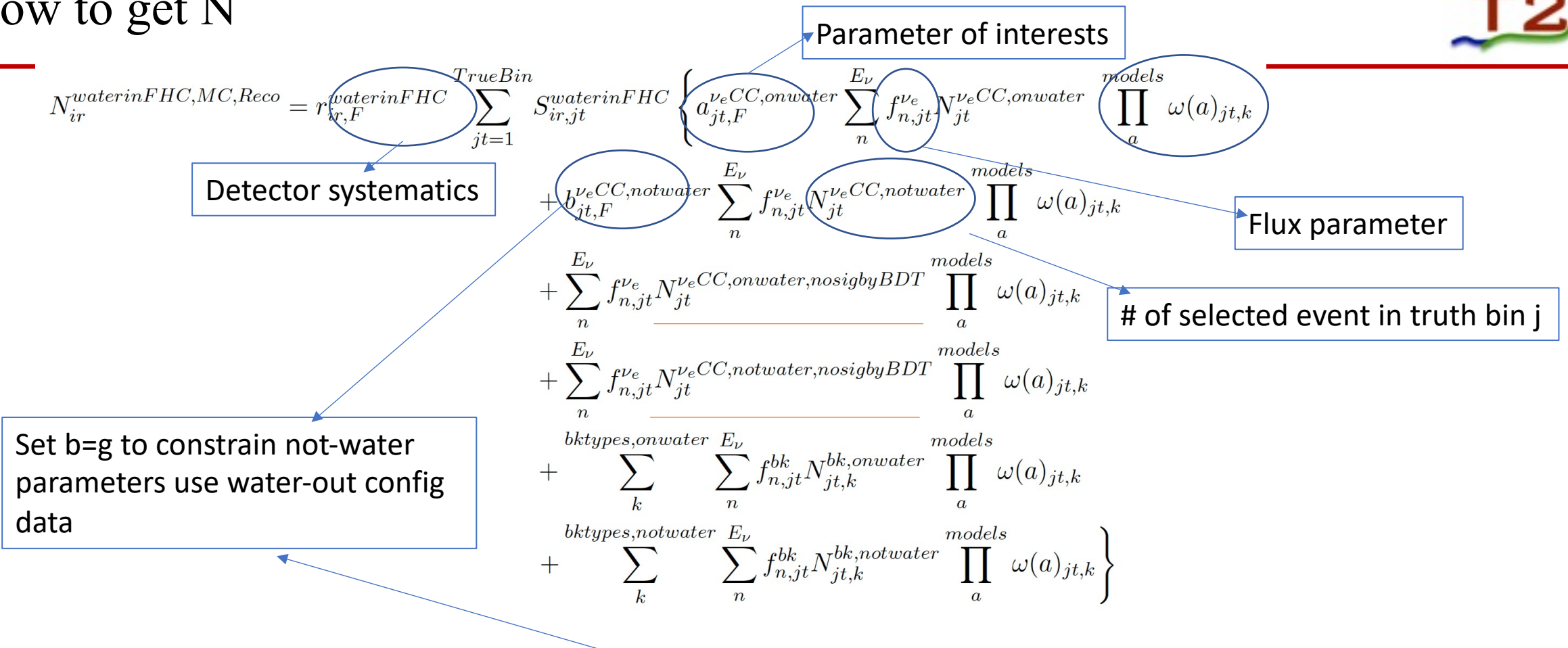
NC sidebands



In reaction



# How to get N



$$N_{ir}^{wateroutFHC,MC,Reco} = r_{ir,F}^{wateroutFHC} \sum_{jt=1}^{TrueBin} S_{ir,jt}^{wateroutFHC} \left\{ g_{jt,F}^{\nu_e CC, notwater} \sum_n^{E_\nu} f_{n,jt}^{\nu_e} N_{jt}^{\nu_e CC, notwater} \prod_a^{models} \omega(a)_{jt,k} \right.$$

$$+ \sum_n^{E_\nu} f_{n,jt}^{\nu_e} N_{jt}^{\nu_e CC, notwater, nosigbyBDT} \prod_a^{models} \omega(a)_{jt,k}$$

$$+ \left. \sum_k^{bktypes, notwater} \sum_n^{E_\nu} f_{n,jt}^{bk} N_{jt,k}^{bk, notwater} \prod_a^{models} \omega(a)_{jt,k} \right\}$$