

# T2K selection breakdowns

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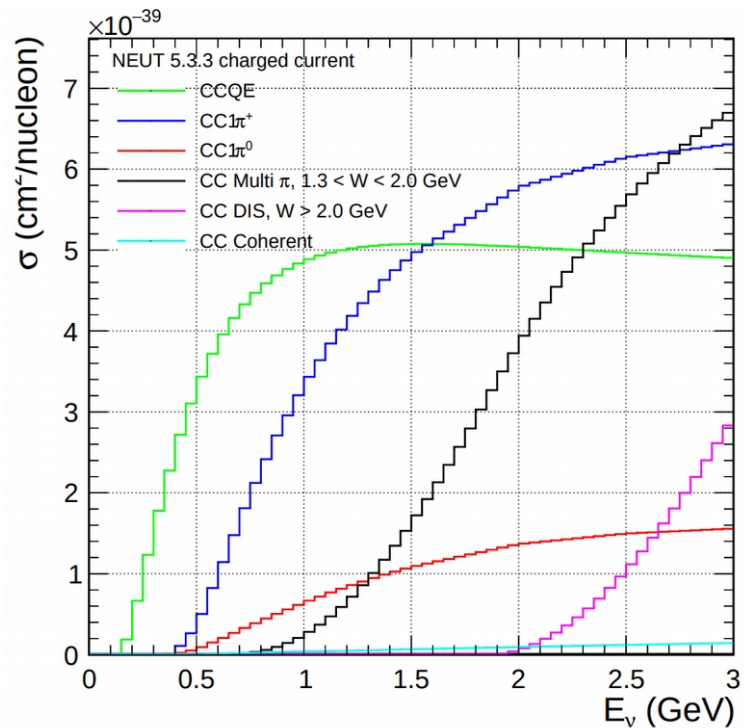
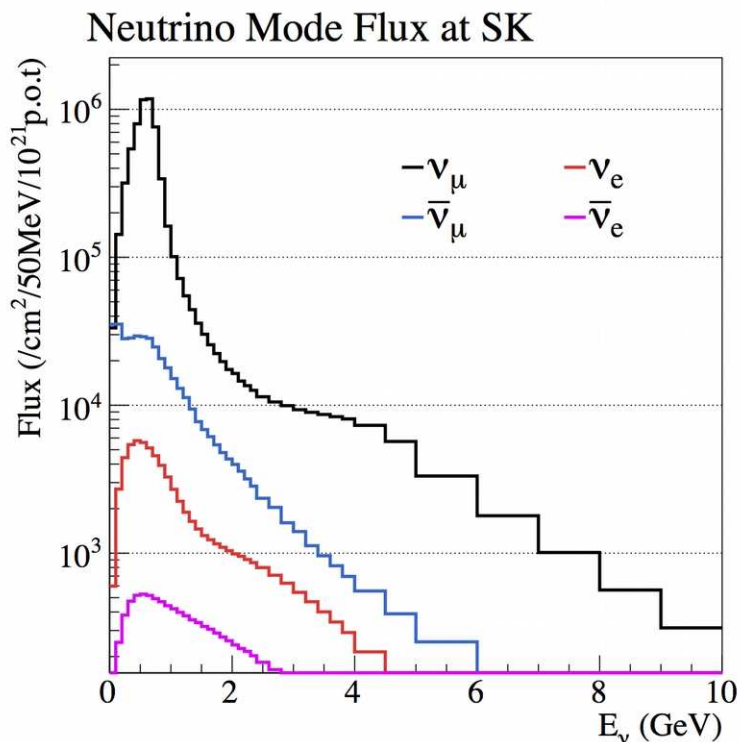
Work from Patrick Dunne, Simon Bienstock,  
Andy Chappell, Wing Ma and many others

NOvA-T2K Workshop, FNAL  
26 Feb 2019



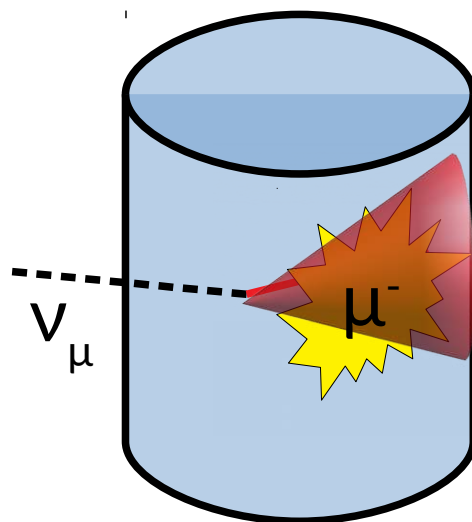
# Overview

- T2K uses a narrow band neutrino beam: dominated by CCQE



- “Background” to CCQE is 2p2h and single pion production+FSI
  - Selections are on observed topology
  - Largely irreducible because can’t undo FSI process
- How much of these true interaction modes are in our selections

# SK selections



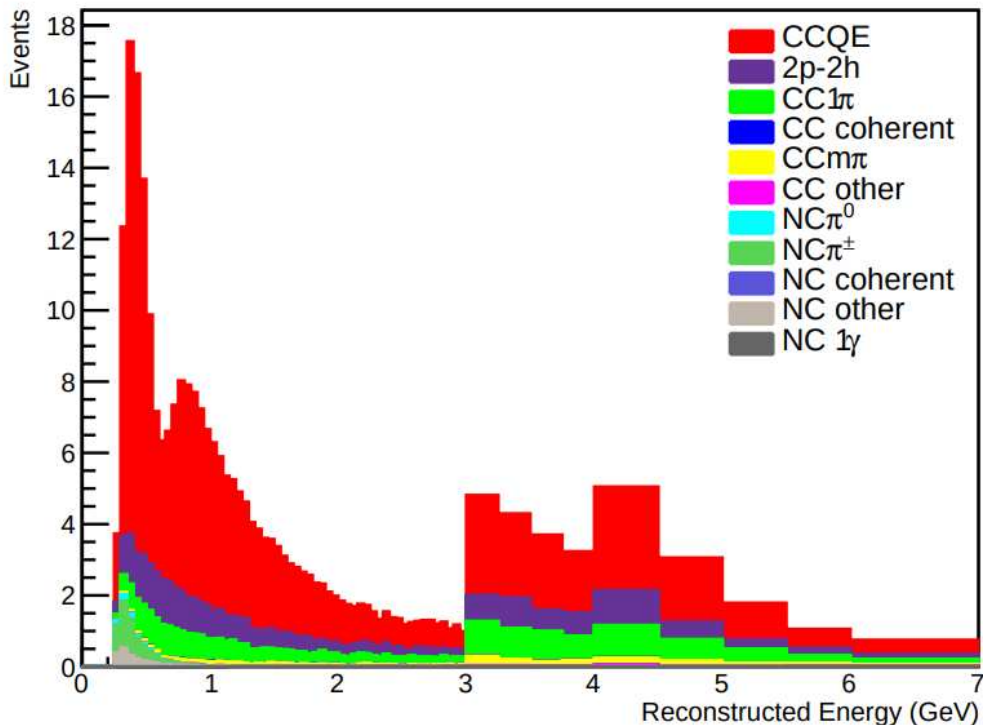
- Cylindrical Water Cherenkov detector
- $1R\mu$ ,  $1Re$ ,  $1Re1d.e.$  (only in FHC): 5 selections
  - Analysis proceeds using lepton variables and decay electron
- Containment, ring-counting, likelihood cuts (details in backup)
- $1R\mu$ : reconstructed  $p_\mu > 200$  MeV;  $1Re$ :  $E_{rec} < 1.25$  GeV
- For acceptance maps “signal” in  $1Re1de$  is defined as  $1e$ ,  $1\pi^+$



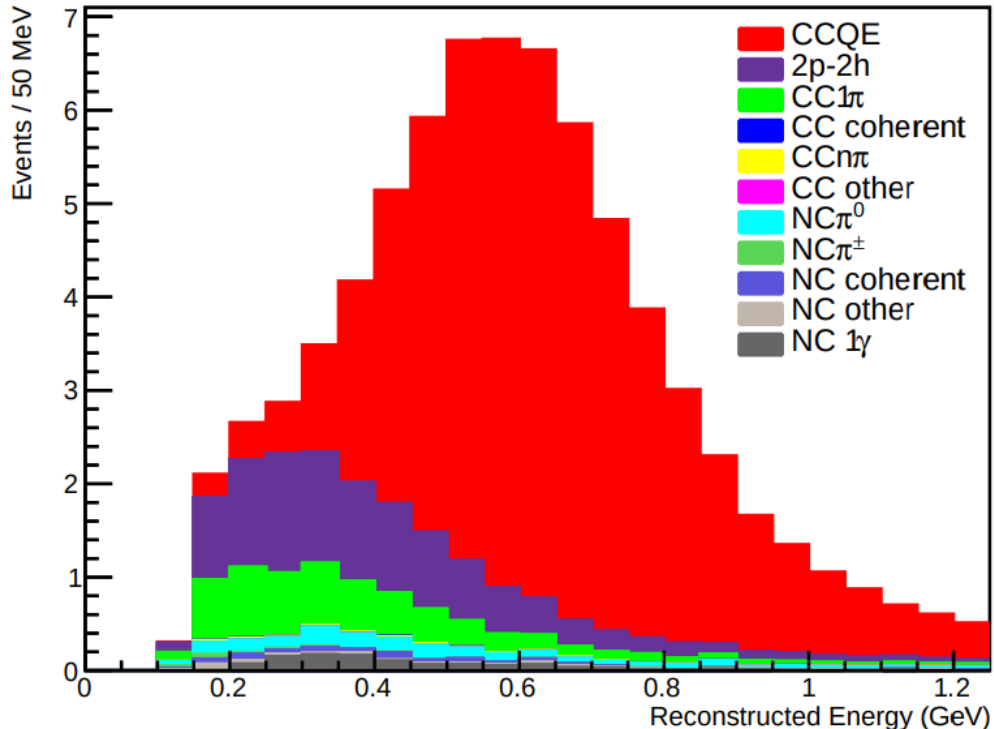
# SK selections FHC

- Mode breakdown of 1R $\mu$  and 1Re selections in FHC

### 1R $\mu$ FHC



### 1Re FHC



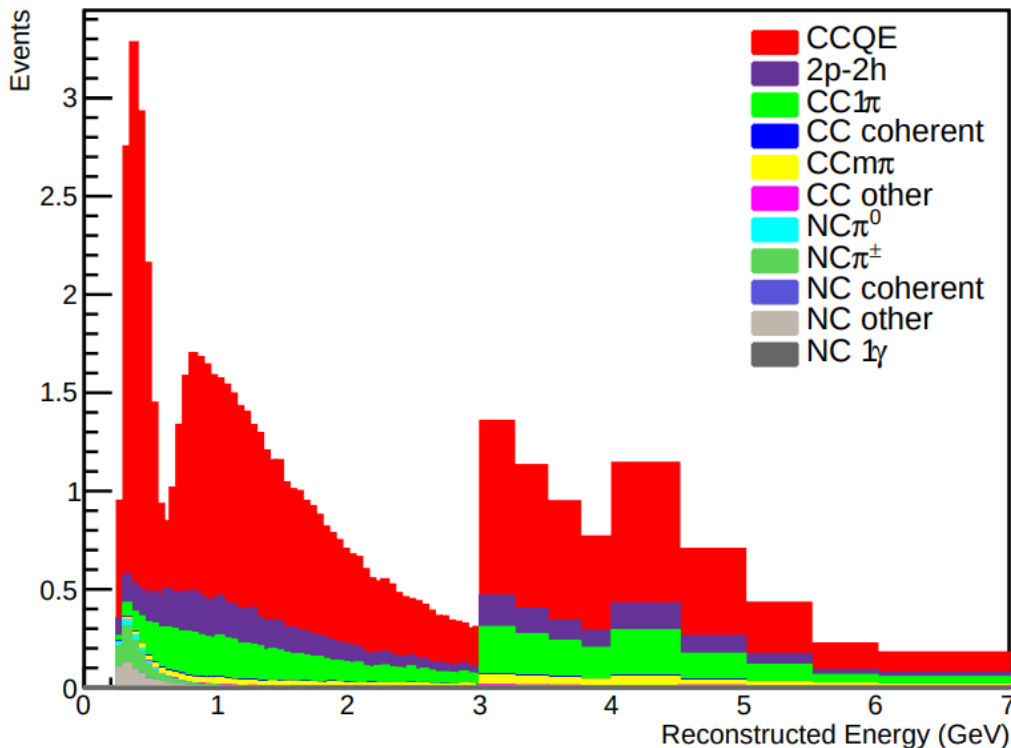
- CCQE (70%, 73%) and 2p2h (14%, 14%) dominant
- CC1 $\pi^\pm$  present for both (11%, 8%)
- NC1 $\pi^\pm$  for 1R $\mu$  (2%), NC1 $\pi^0$  for 1Re (3%)



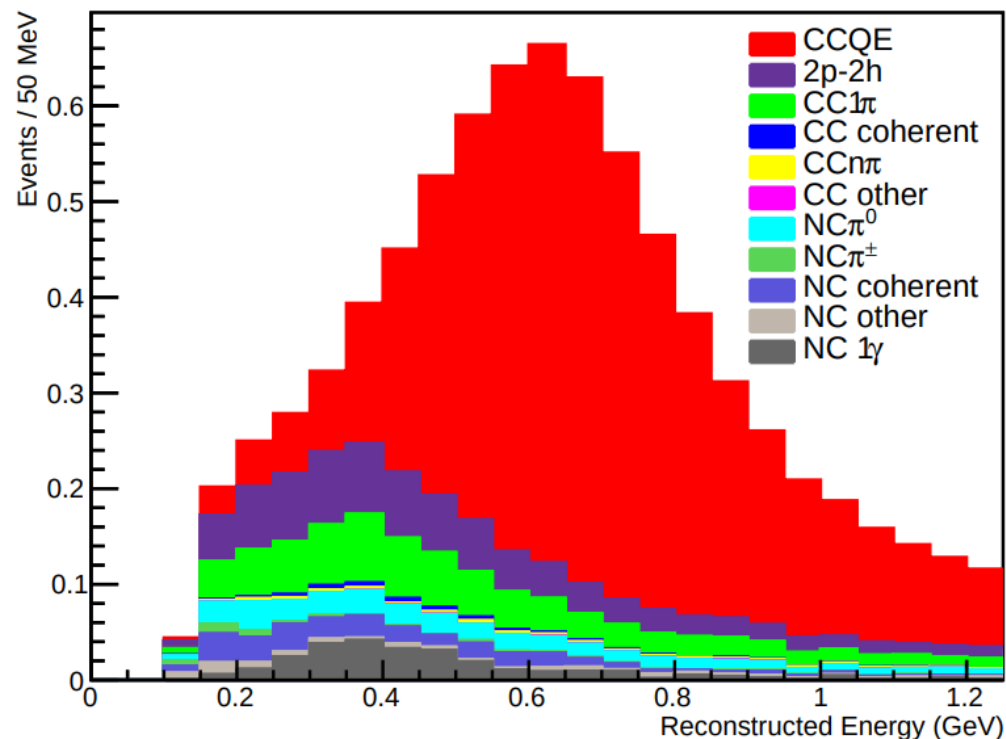
# SK selections RHC

- Mode breakdown of 1R $\mu$  and 1Re selections in RHC

1R $\mu$  RHC



1Re RHC

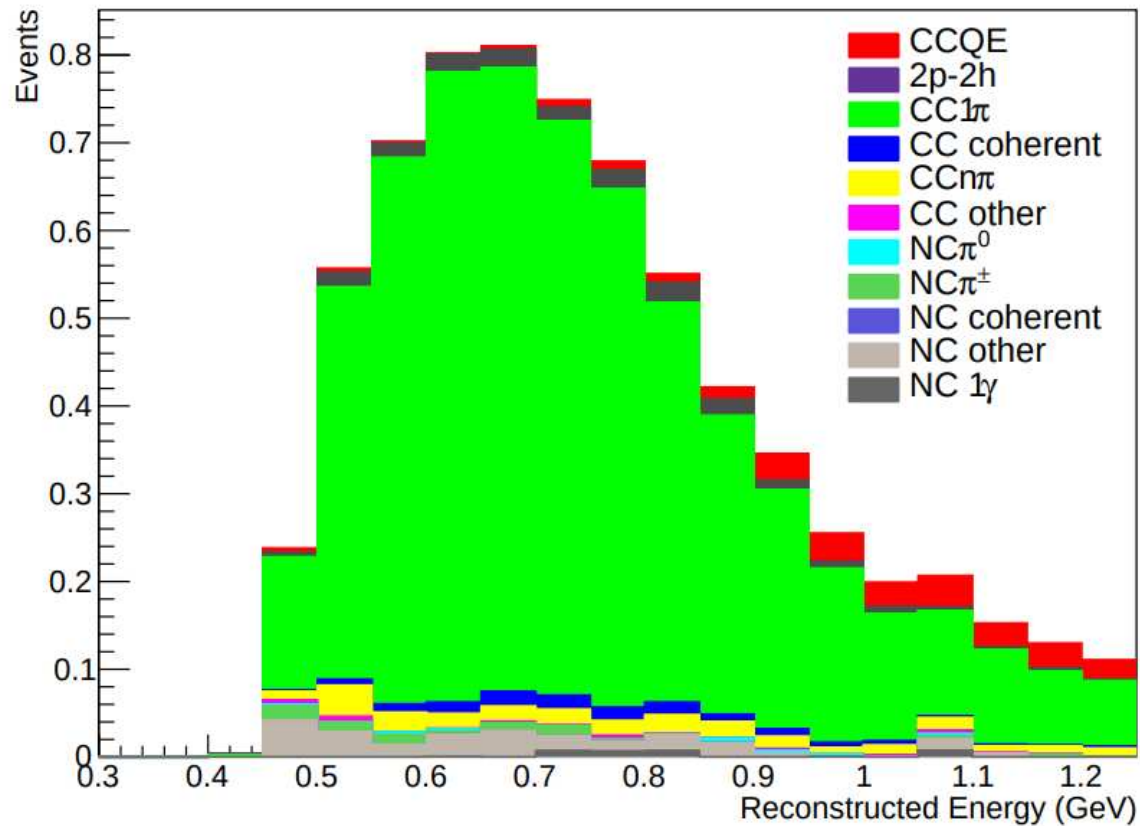


- CCQE (70%, 67%) and 2p2h (11%, 10%) dominant
- CC1 $\pi^\pm$  present for both (13%, 9%)
- NC1 $\pi^\pm$  and CCOther for 1R $\mu$  (1%, 2%), NC1 $\pi^0$  for 1Re (5%)



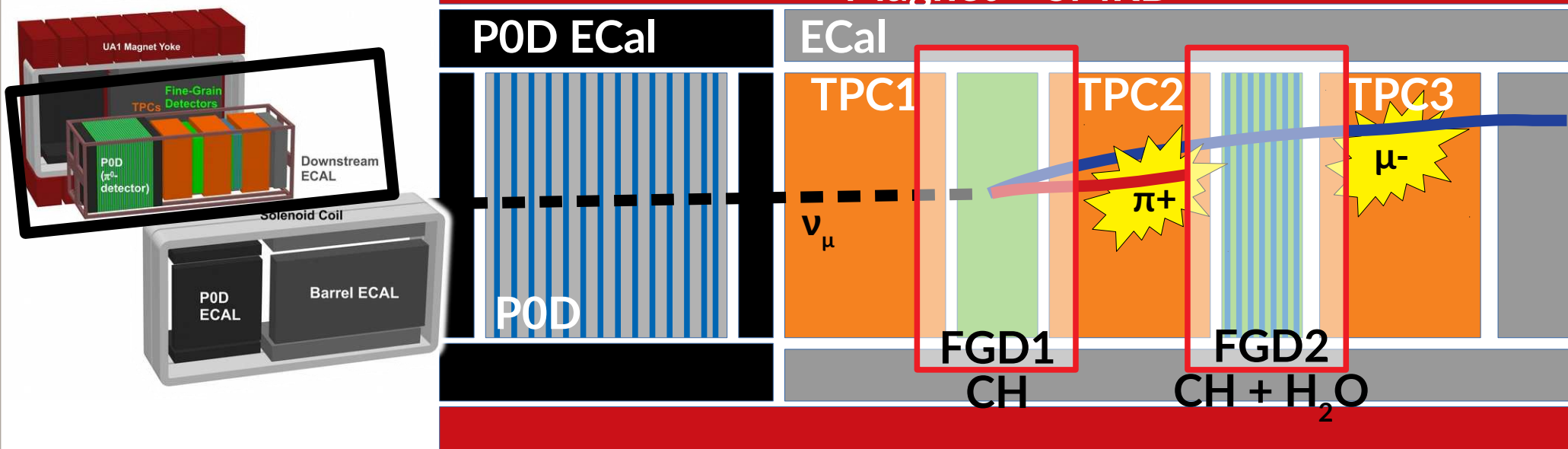
# SK selections

- Mode breakdown of 1Re 1d.e. selections in FHC



- CC1 $\pi^{\pm}$  dominant (82%)
- CCQE (4%), CCOther (4%), NCOther (3%)

# ND280 selections



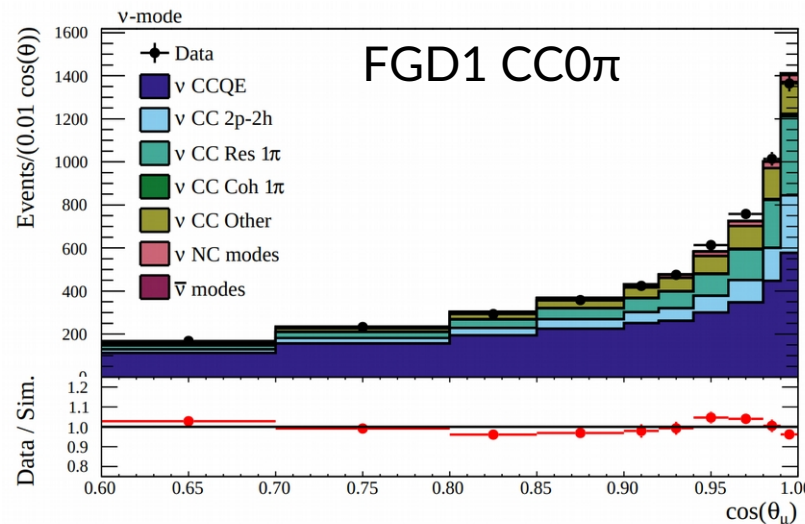
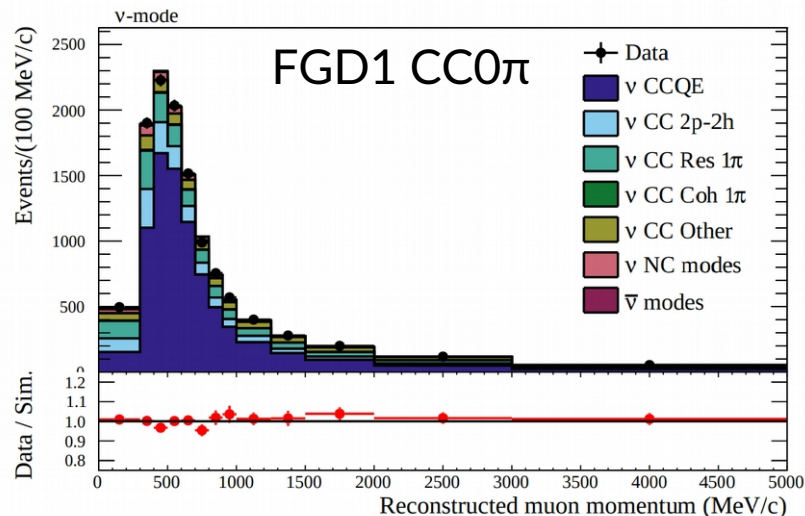
- All selections are CC-only: select muon as high momentum negative(positive) track with muon PID
- Selection splits on reconstructed pion multiplicity
- CC0 $\pi$ , CC1 $\pi$ , CCOther: constrain signal and background model
- CCOther soaks up  $N(\pi^\pm) > 1$ ,  $N(\pi^0) > 0$
- Split by FGD1/2, FHC/RHC, Pion mult., Neutrino/anti-neutrino (for RHC): 18 selections



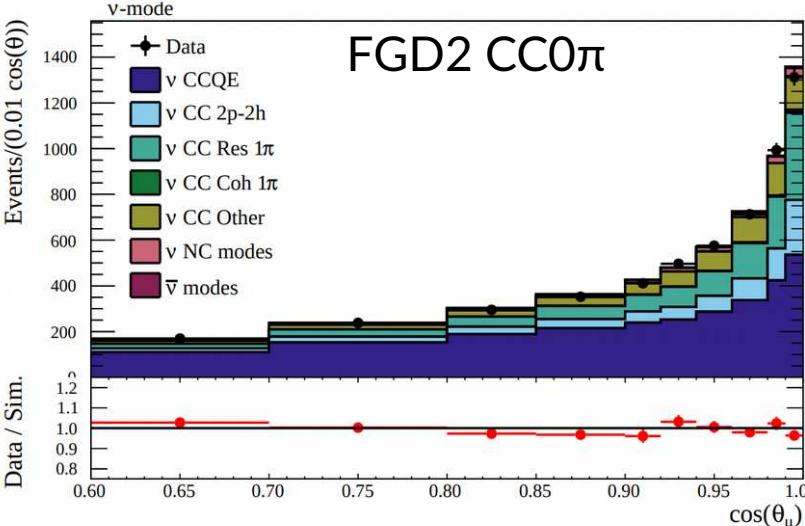
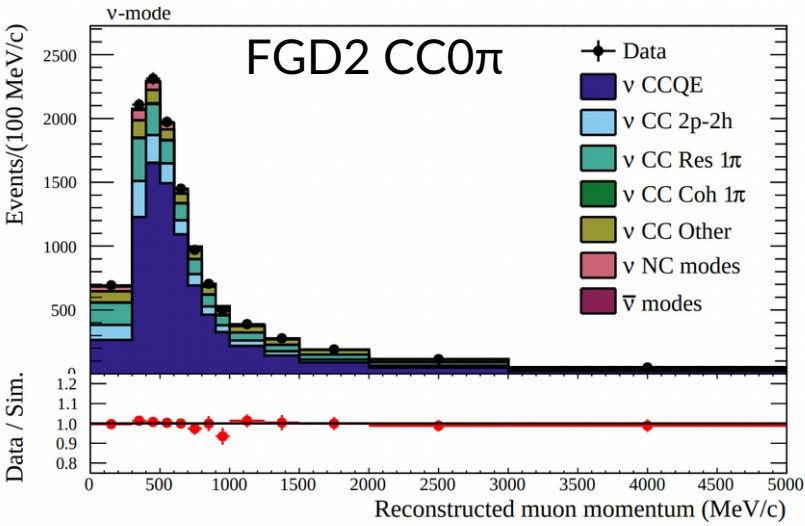


# ND280 selections

- $CC0\pi$  constrains most of the signal model at SK



68% of all FHC events are  $CC0\pi$



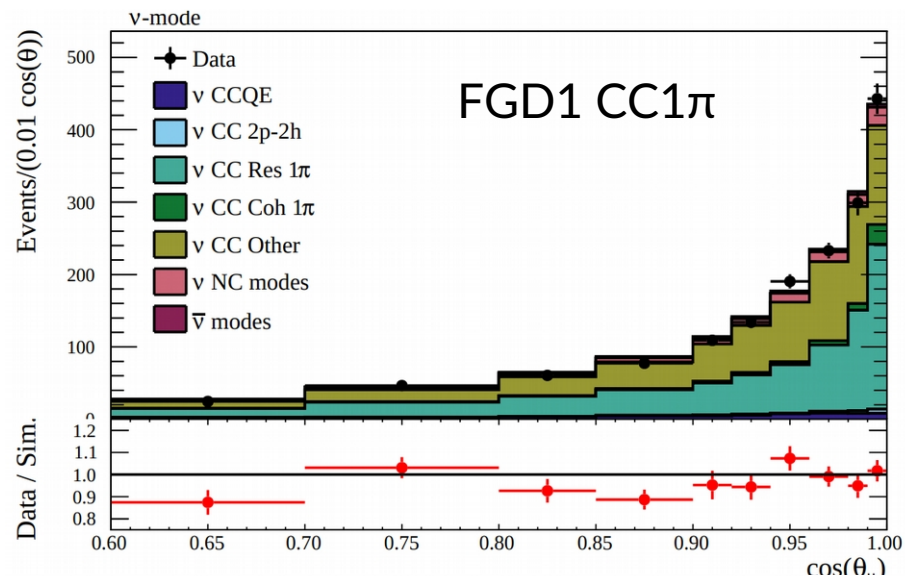
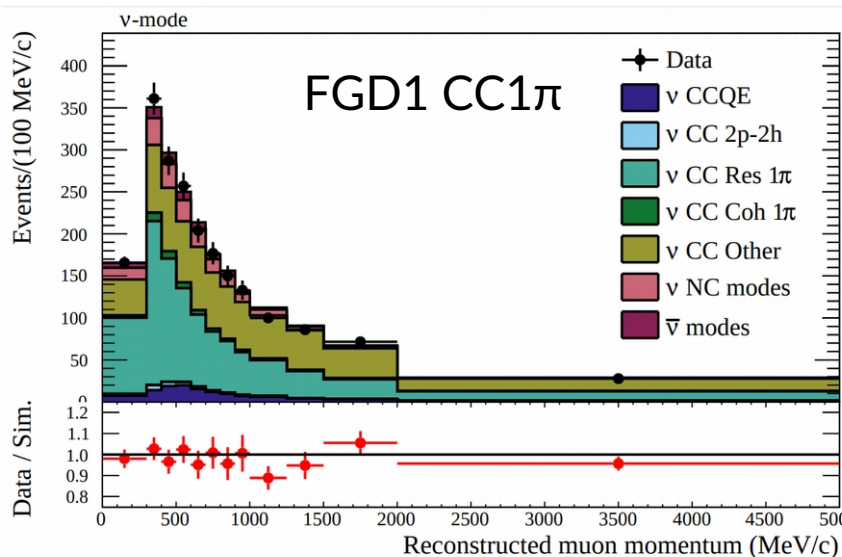
- $CCQE$  (57%),  $2p2h$  (10%),  $CC1\pi$  (20%)



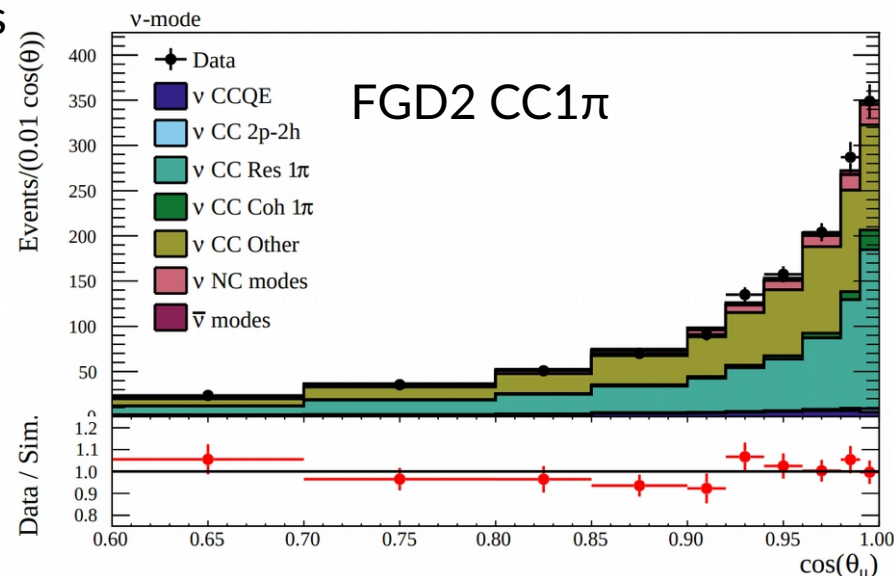
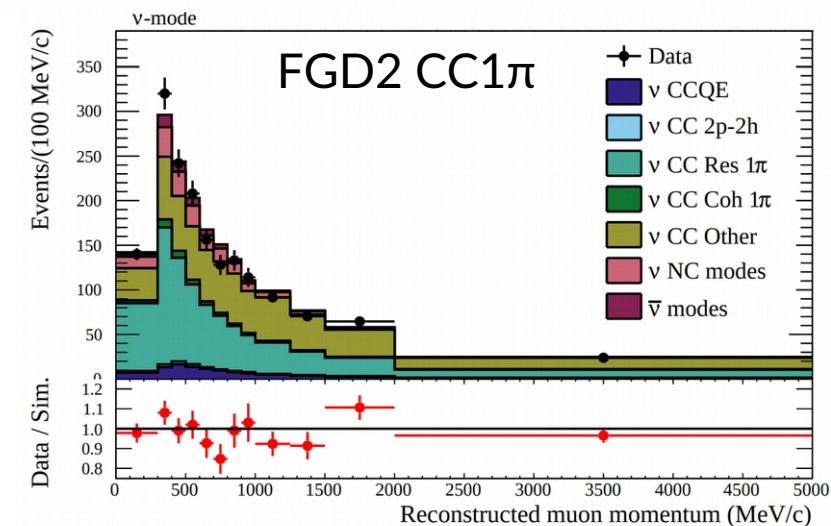


# ND280 selections

- CC1 $\pi$  constrains background model at SK



17% of all FHC events are CC1 $\pi$

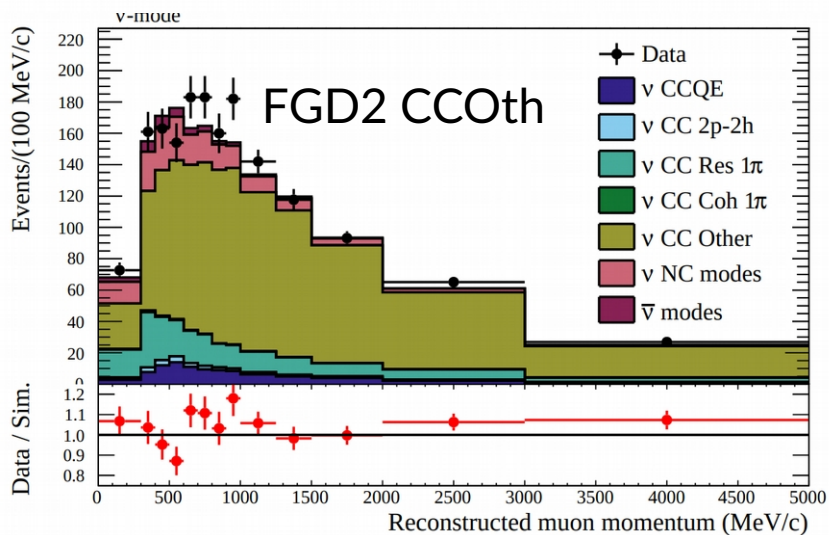
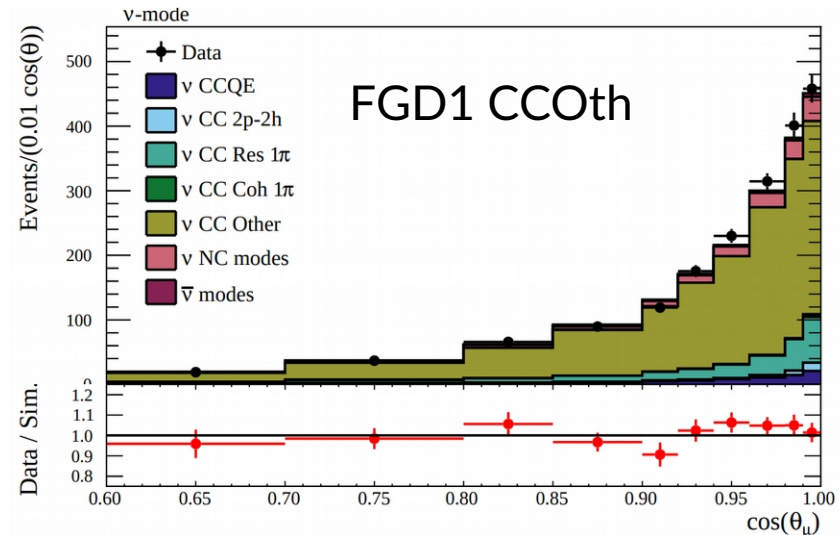
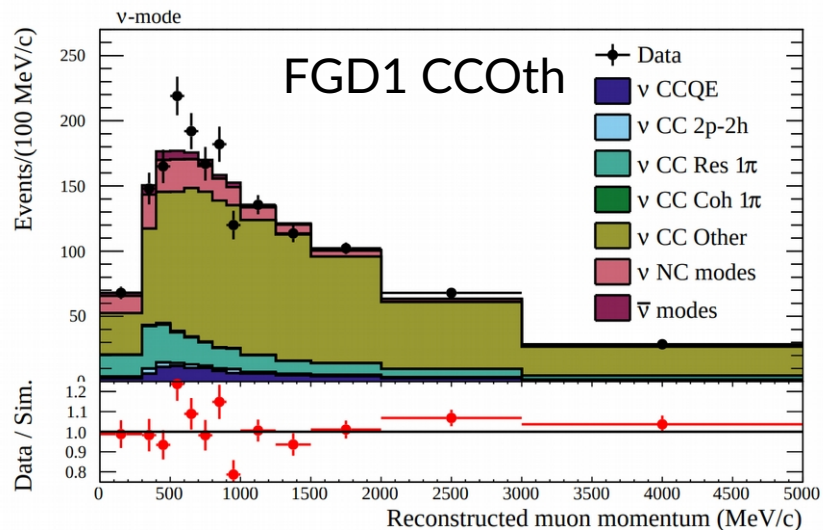


- CC1 $\pi$ <sub>res</sub> (50%), CCMulti- $\pi$  (18%), CC DIS (17%)

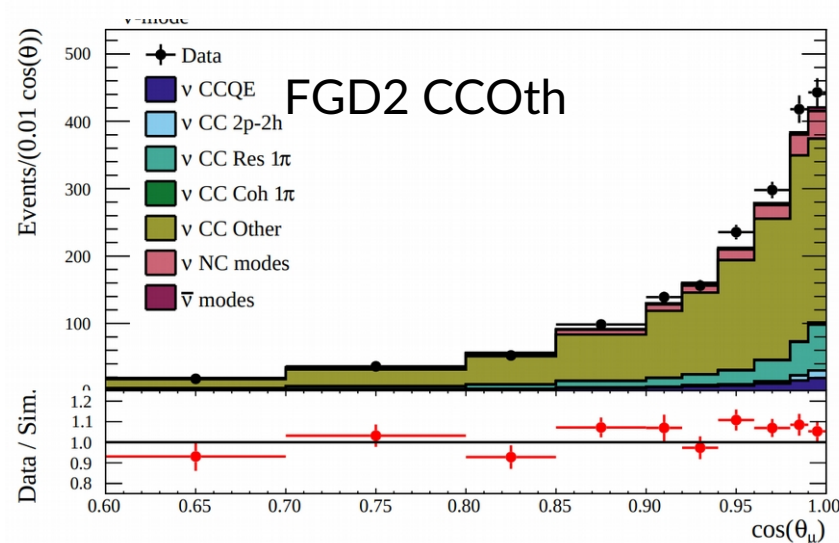


# ND280 selections

- CCOther constrains background model at SK



15% of all FHC events are CCOther



- CC DIS (45%), CCMulti- $\pi$  (26%), CC $1\pi_{res}$  (15%)



# Future

- Both ND280 and SK are developing more selections to go into official analyses
- ND280:
  - Possibility of adding in proton candidate tracks
  - Dedicated  $\nu_e$  and  $\gamma$  control samples
  - Improved backwards and high-angle reconstruction using the ECal and SMRD PID and matching
- SK:
  - 2 ring selection in development
  - Will include much more single pion production events
  - Although these events constrain oscillations less (higher  $E_\nu$ ), it's complimentary to 1Re 1d.e.
  - Investigations into decay electron cuts too



# Summary

- ND280 and SK selection breakdowns shown
- T2K neutrino flux ( $\sim 0.6$  GeV) means CCQE dominant
- SK 1R selections dominated by CCQE (70%) and 2p2h (15%)
  - 1Re 1de dominated by  $CC1\pi^\pm$  (82%)
- ND280 uses recon. pion multiplicity to split selections
  - Fit signal and background samples for  $0\pi$  physics
  - $CC0\pi$ : 50% CCQE, 2p2h (10%),  $CC1\pi$  (20%)
  - Different to SK primarily due to acceptance and reconstruction
  - 68% of selected FHC events are  $0\pi$  selected



# Thanks



# ND280 event counts

T2K run 2-6, 2017-18 analyses, pre-tune

Sample	Nominal MC
FGD1 CC0 $\pi$ $\nu_\mu$	16723.80
FGD1 CC1 $\pi$ $\nu_\mu$	4381.47
FGD1 CCOther $\nu_\mu$	3943.95
FGD2 CC0 $\pi$ $\nu_\mu$	16959.30
FGD2 CC1 $\pi$ $\nu_\mu$	3564.23
FGD2 CCOther $\nu_\mu$	3570.94
FGD1 CC1Track $\bar{\nu}_\mu$	3587.77
FGD1 CCNTrack $\bar{\nu}_\mu$	1066.91
FGD2 CC1Track $\bar{\nu}_\mu$	3618.29
FGD2 CCNTrack $\bar{\nu}_\mu$	1077.24
FGD1 CC1Track $\nu_\mu$ in RHC	1272.17
FGD1 CCNTrack $\nu_\mu$ in RHC	1357.45
FGD2 CC1Track $\nu_\mu$ in RHC	1262.63
FGD2 CCNTrack $\nu_\mu$ in RHC	1246.71
Total	63632.86

T2K run 2-8, 2018- analyses, pre-tune

Sample	Nominal MC
FGD1 0 $\pi$	31529.3
FGD1 1 $\pi$	7998.1
FGD1 other	6793.68
FGD2 0 $\pi$	31734
FGD2 1 $\pi$	6419.04
FGD2 other	6562.75
FGD1 $\bar{\nu}_\mu$ 0 $\pi$	6371.34
FGD1 $\bar{\nu}_\mu$ 1 $\pi$	533.253
FGD1 $\bar{\nu}_\mu$ other	1023.36
FGD2 $\bar{\nu}_\mu$ 0 $\pi$	6283.35
FGD2 $\bar{\nu}_\mu$ 1 $\pi$	483.508
FGD2 $\bar{\nu}_\mu$ other	943.956
FGD1 $\nu_\mu$ RHC 0 $\pi$	2485.51
FGD1 $\nu_\mu$ RHC 1 $\pi$	855.911
FGD1 $\nu_\mu$ RHC other	804.647
FGD2 $\nu_\mu$ RHC 0 $\pi$	2553.51
FGD2 $\nu_\mu$ RHC 1 $\pi$	679.99
FGD2 $\nu_\mu$ RHC other	792.166
Total	114847

**N.B. MC subject to model parameters: these are just meant to be indicative!**





# SK event counts

T2K run 2-8, 2018- analyses, pre-tune

SK sample		$\nu_\mu$	$\nu_e$	$\bar{\nu}_\mu$	$\bar{\nu}_e$	$\nu_e$ signal	$\bar{\nu}_e$ signal	Total
FHC 1R $_\mu$	Unosc.	1032.20133	0.22571	29.27574	0.02277	0.00000	0.00000	1061.72555
	Osc. A	226.32063	0.22530	15.09567	0.02275	0.05801	0.00028	241.72264
	Osc. B	236.96139	0.22530	15.23470	0.02275	0.03979	0.00036	252.48428
FHC 1R $_e$	Unosc.	5.53636	8.06040	0.24202	0.37171	0.00000	0.00000	14.21050
	Osc. A	4.54691	7.50513	0.22423	0.35192	50.37052	0.34829	63.34700
	Osc. B	4.55877	7.50513	0.22439	0.35192	34.75386	0.41848	47.81254
FHC CC-1 $\pi^+$	Unosc.	1.44498	1.09939	0.03577	0.01001	0.00000	0.00000	2.59015
	Osc. A	0.50014	1.02353	0.02400	0.00960	6.13047	0.00695	7.69469
	Osc. B	0.51191	1.02353	0.02413	0.00960	4.42335	0.00840	6.00092
RHC 1R $_\mu$	Unosc.	47.05223	0.03926	146.83759	0.02617	0.00000	0.00000	193.95525
	Osc. A	22.70539	0.03920	36.51955	0.02612	0.00152	0.00207	59.29385
	Osc. B	22.97233	0.03920	37.82922	0.02612	0.00115	0.00258	60.87061
RHC 1R $_e$	Unosc.	0.46046	0.69453	0.83340	1.10271	0.00000	0.00000	3.09109
	Osc. A	0.42091	0.65028	0.70965	1.03854	1.20541	3.27052	7.29531
	Osc. B	0.42130	0.65028	0.71097	1.03854	0.87909	3.88051	7.58068

**N.B. MC subject to model parameters: these are just meant to be indicative!**



# SK mode event counts

T2K run 2-8, 2018- analyses, pre-tune

Table 14: Event rate table for 1R $\mu$ , SKMC 14a with tuned RUN1-8 FHC flux 13av2 and with BANFF/NIWG postfit reweight,  $1.4938 \times 10^{21}$  POT.

Event Type	$\nu_\mu \rightarrow \nu_\mu$	$\nu_e \rightarrow \nu_e$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	$\nu_\mu \rightarrow \nu_e$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Total
CCQE	175.703	0.00416552	11.13	0.00019653	0.0225969	0.000146672	186.86
CCMEC	35.4338	0.00154277	1.4228	7.97633e-05	0.0257846	3.9511e-05	36.884
CC 1 $\pi$	27.6407	0.00200534	2.64209	9.17424e-05	0.0241803	7.41611e-05	30.3091
CC coh.	0.288823	0	0.0930526	0	0	4.40042e-06	0.38188
CC other	5.49932	0.000869576	0.411229	8.04633e-05	0.000114636	5.58696e-06	5.91162
NC 1 $\pi$	5.51246	0.117377	0.198492	0.0113567	0	0	5.83969
NC coh.	0	0	0.000437836	3.54443e-05	0	0	0.000473281
NC 1 $\gamma$	0	0	0	0	0	0	0
NC other	2.06264	0.0744108	0.132049	0.00926371	0	0	2.27837
Subtotal	252.14	0.200371	16.0301	0.0211044	0.0726763	0.000270332	
Total	268.465						

**N.B. MC  
subject to  
model  
parameters:  
these are  
just meant  
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indicative!**

Table 15: Event rate table for 1Re, SKMC 14a with tuned RUN1-8 FHC flux 13av2 and with BANFF/NIWG postfit reweight,  $1.4938 \times 10^{21}$  POT.

Event Type	$\nu_\mu \rightarrow \nu_\mu$	$\nu_e \rightarrow \nu_e$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	$\nu_\mu \rightarrow \nu_e$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Total
CCQE	0.159522	6.36547	0.00638335	0.259222	46.5074	0.280765	53.5788
CCMEC	0.029832	1.60953	0.00118712	0.0433937	8.70183	0.0392179	10.425
CC 1 $\pi$	0.0465275	0.93865	0.00281785	0.0685006	4.48405	0.0477212	5.58826
CC coh.	0.000111774	0.0083635	0.000176312	0.00402802	0.034421	0.00330043	0.050401
CC other	0.0133688	0.12913	0.000345135	0.00956688	0.0876432	0.00328056	0.243335
NC 1 $\pi$	1.86545	0.0421363	0.0710173	0.00419691	0	0	1.98281
NC coh.	0.529064	0.00720666	0.0483747	0.00298199	0	0	0.587627
NC 1 $\gamma$	0.940606	0.0170139	0.0502942	0.00236797	0	0	1.01028
NC other	0.319026	0.0171028	0.021453	0.00129939	0	0	0.358881
Subtotal	3.90351	9.13461	0.202049	0.395558	59.8154	0.374285	
Total	73.8254						

# SK mode event counts

T2K run 2-8, 2018- analyses, pre-tune

Table 16: Event rate table for  $1R\mu$ , SKMC 14a with tuned RUN5c-9 RHC flux 13av2 and with BANFF/NIWG postfit reweight,  $1.12355 \times 10^{21}$  POT.

Event Type	$\nu_\mu \rightarrow \nu_\mu$	$\nu_e \rightarrow \nu_e$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	$\nu_\mu \rightarrow \nu_e$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Total
CCQE	22.7191	0.00124192	44.4006	0.00138171	0.00138629	0.00203299	67.1257
CCMEC	6.64252	0.000384022	4.22572	0.000397061	0.00050176	0.000308271	10.8698
CC $1\pi$	5.87701	0.000495874	6.7402	0.00037396	0.000886564	0.000911669	12.6199
CC coh.	0.069952	0	0.261113	6.90872e-05	0	9.48097e-05	0.331229
CC other	1.40172	0.00017524	0.901933	0	0	0	2.30383
NC $1\pi$	0.623499	0.0259974	0.774878	0.0208673	0	0	1.44524
NC coh.	0	0	0.00299151	0	0	0	0.00299151
NC $1\gamma$	0	0	0	0	0	0	0
NC other	0.469519	0.0243994	0.298727	0.0117317	0	0	0.804377
Subtotal	37.8033	0.0526939	57.6061	0.0348208	0.00277461	0.00334774	
Total	95.5031						

Table 17: Event rate table for  $1Re$ , SKMC 14a with tuned RUN5c-9 RHC flux 13av2 and with BANFF/NIWG postfit reweight,  $1.12355 \times 10^{21}$  POT.

Event Type	$\nu_\mu \rightarrow \nu_\mu$	$\nu_e \rightarrow \nu_e$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	$\nu_\mu \rightarrow \nu_e$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Total
CCQE	0.0191374	0.75772	0.0355391	1.26076	1.52497	4.24592	7.84404
CCMEC	0.00436565	0.213633	0.00326523	0.167941	0.345621	0.490633	1.22546
CC $1\pi$	0.0113179	0.150281	0.0108895	0.214338	0.212844	0.496713	1.09638
CC coh.	3.51809e-05	0.00147703	0.000624046	0.0158532	0.00169465	0.0465097	0.0661938
CC other	0.00578346	0.0314615	0.00177536	0.0171618	0.0154815	0.00993159	0.0815953
NC $1\pi$	0.242593	0.00993186	0.291907	0.008146	0	0	0.552578
NC coh.	0.0710557	0.00328891	0.300962	0.00471667	0	0	0.380023
NC $1\gamma$	0.11798	0.00653189	0.259715	0.00569703	0	0	0.389923
NC other	0.0842232	0.00327448	0.0396883	0.00146572	0	0	0.128652
Subtotal	0.556491	1.1776	0.944365	1.69608	2.10061	5.28971	
Total	11.7649						

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# SK mode event counts

T2K run 2-8, 2018- analyses, pre-tune

Table 18: Event rate table for 1R  $\nu_e$  CC $1\pi^+$ , SKMC 14a with tuned RUN1-8 FHC flux 13av2 and with BANFF/NIWG postfit reweight,  $1.4938 \times 10^{21}$  POT.

Event Type	$\nu_\mu \rightarrow \nu_\mu$	$\nu_e \rightarrow \nu_e$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	$\nu_\mu \rightarrow \nu_e$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Total
CCQE	0.0284456	0.0247056	0.00118382	0.00176561	0.212471	0.00267771	0.27125
CCMEC	0.00999485	0.0221372	0.000491648	0.000962066	0.158864	0.0010558	0.193506
CC $1\pi$	0.0748465	0.766678	0.0025816	0.00388938	4.85236	0.00228791	5.70265
CC coh.	0.000261504	0.0178076	7.87933e-05	7.2905e-05	0.111576	0.000108294	0.129905
CC other	0.0376334	0.113125	0.00116559	0.0028351	0.119542	0.00151032	0.275811
NC $1\pi$	0.0854134	0.00242449	0.00470547	0.000416685	0	0	0.09296
NC coh.	0	0	0	0	0	0	0
NC $1\gamma$	0.0285274	0	0.000681434	7.18958e-05	0	0	0.0292807
NC other	0.206987	0.00837641	0.0131914	0.000898777	0	0	0.229454
Subtotal	0.47211	0.955254	0.0240797	0.0109124	5.45482	0.00764003	
Total				6.92481			

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