Using proton information to constrain T2K fit

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T2K Experiment

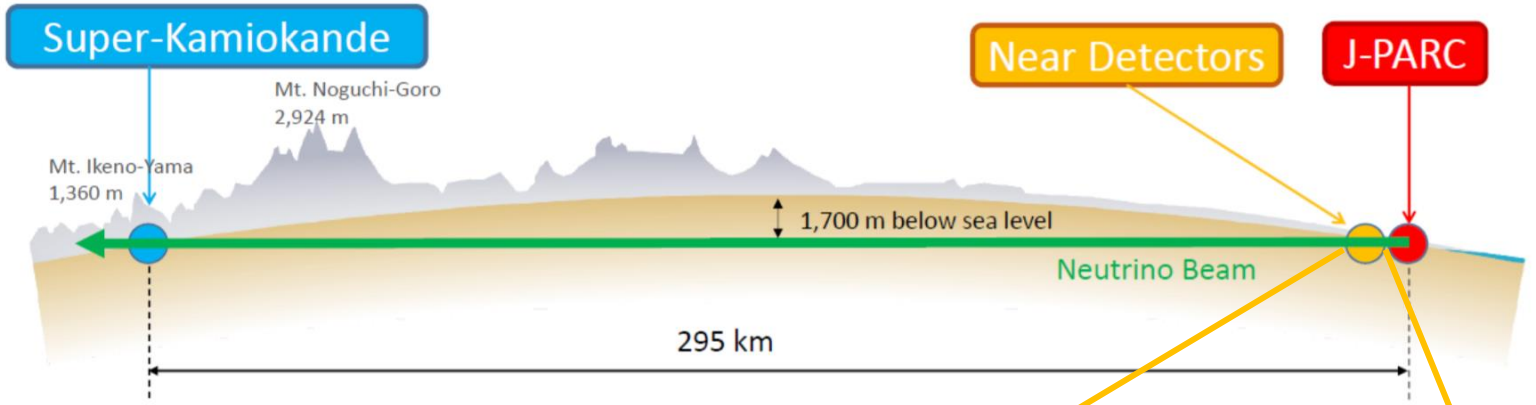
T2K is a long baseline experiment studying neutrino oscillations.

Beam production – J-PARC.

Near Detector – ND280.

Far Detector – Super-Kamiokande.

ND280 constrains cross-section and flux models which allow to obtain more precise measurements of oscillation parameters.

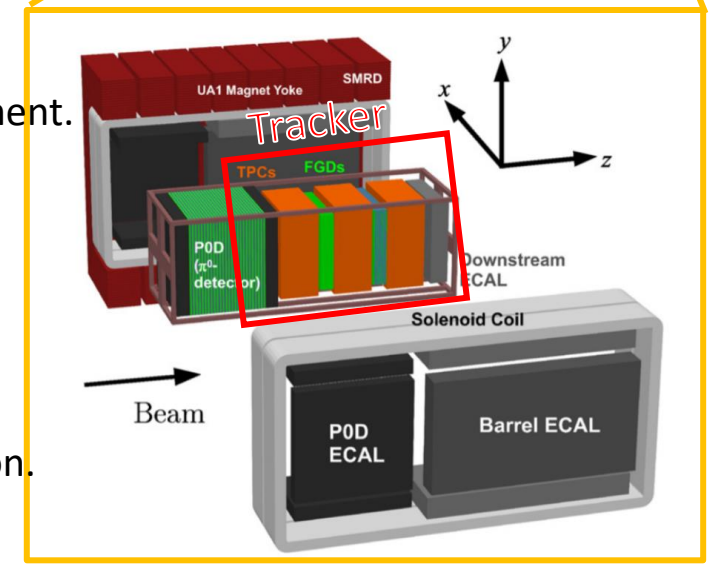


TPC

- Momentum measurement.
- particle identification (dE/dx measurement).

FGD

- target mass
- recoil proton detection.



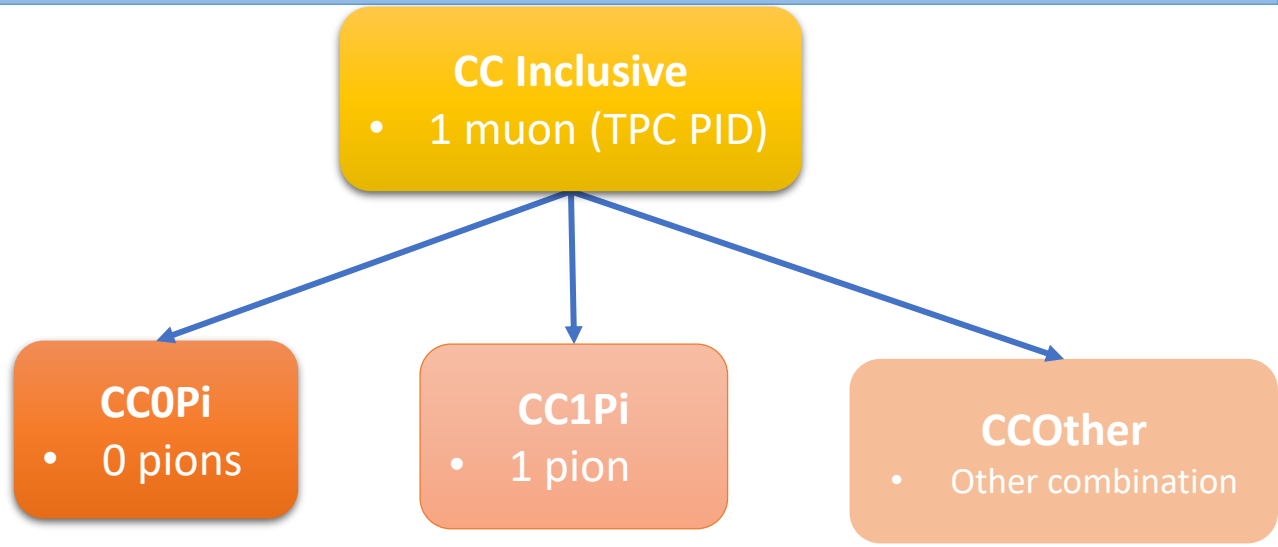
ND280 Fit

ND280 fit is important part of **T2K** oscillation analysis.

ND280 fit uses various samples (from FGD1 and FGD2), based on pion multiplicity.

Each sample has different physical properties and allows to probe different neutrino interactions.

Muon kinematics (momentum and emission angle) is used for fitting MC to data.



ND280 Fit - New Samples

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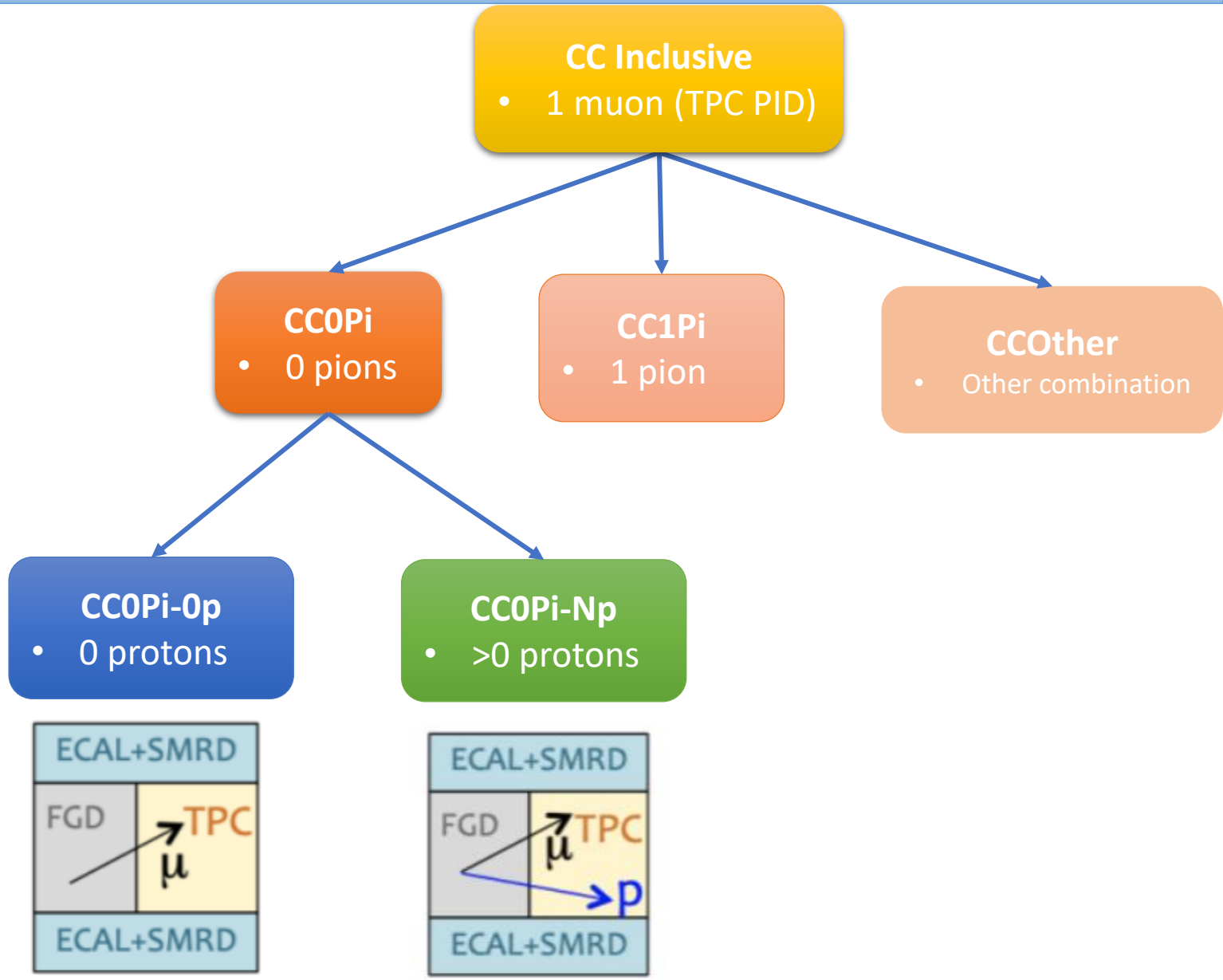
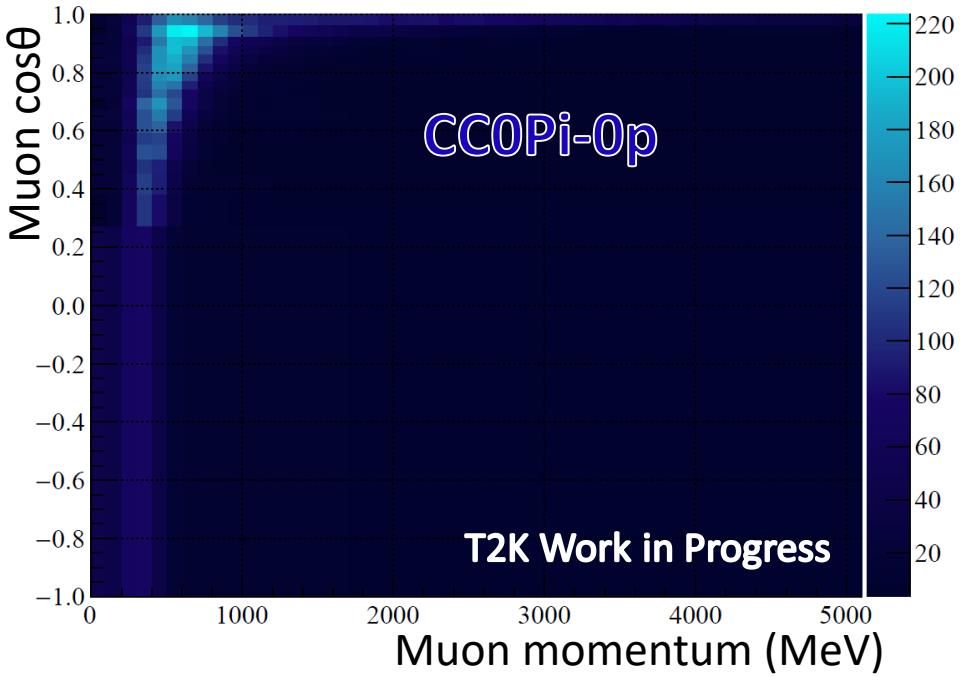
Proton samples: **CC0Pi-0p** and **CC0Pi-Np** originate from split of **CC0Pi** based on proton multiplicity (TPC and FGD PID).



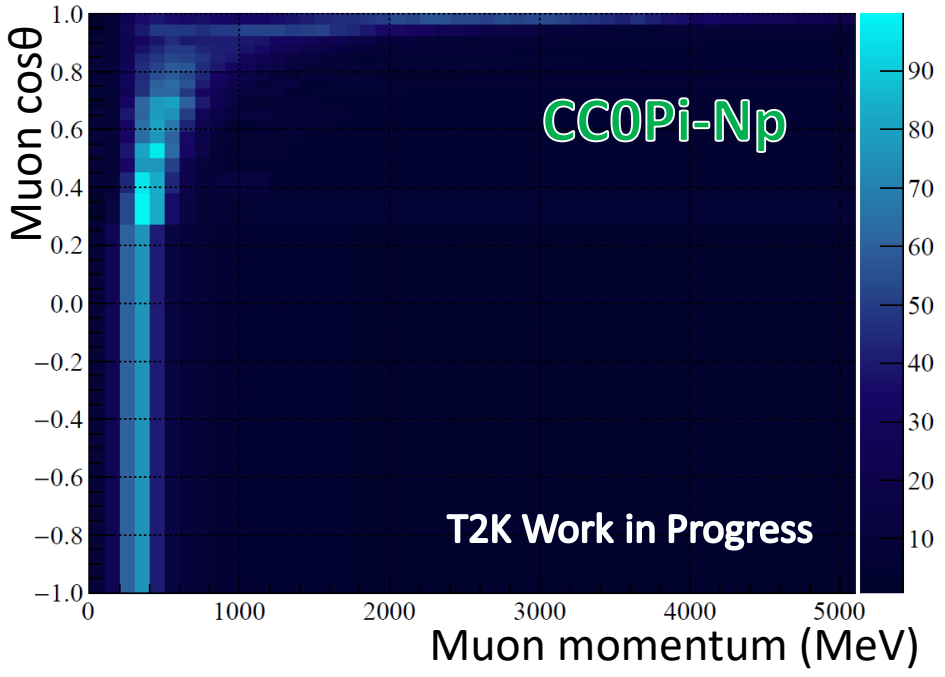
Properties of Proton Samples



Both samples have different phase space of muon kinematics.

ND280 proton tracking threshold is about 450-500 MeV/c.

Different fraction of reactions.



CC0Pi-0p - lower muon momentum, mostly forward going muons.

Better purity for CCQE.

	CC0Pi	CC0Pi-0p	CC0Pi-Np
	Fraction %	Fraction %	Fraction %
CCQE	51	58	38
2p2h	11	10	11
RES	23	19	30
Other	15	13	21

CC0Pi-Np - higher muon momentum, more muons going at higher angle.

Better purity for non-CCQE contributions.

Energy and momentum transfer (2p2h)

Nieves et. al. model **[1]** describing 2p2h interactions has two peak structure.

CC0Pi-0p - mostly lower q_0/q_3 region.

CC0Pi-Np - higher q_0/q_3 region.

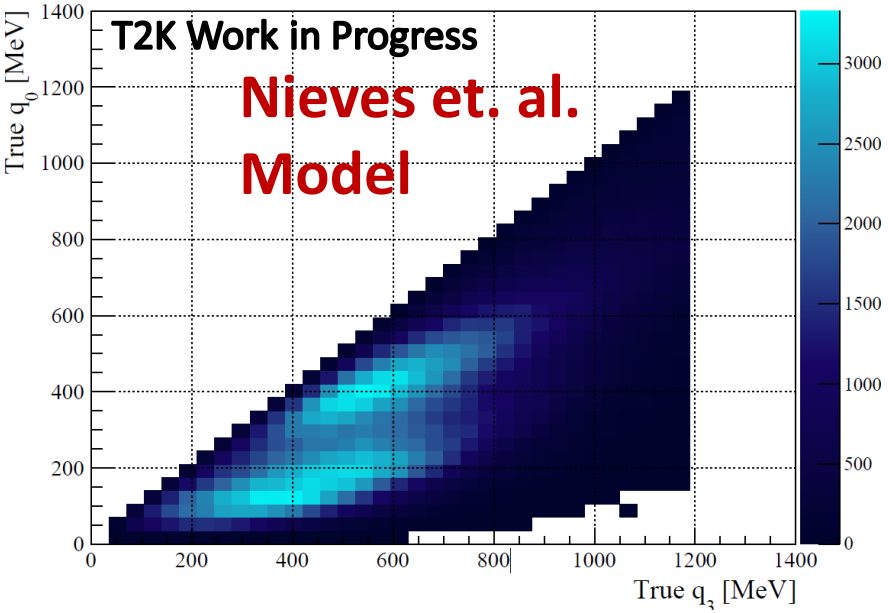
We can probe different regions of 2p2h phase-space.

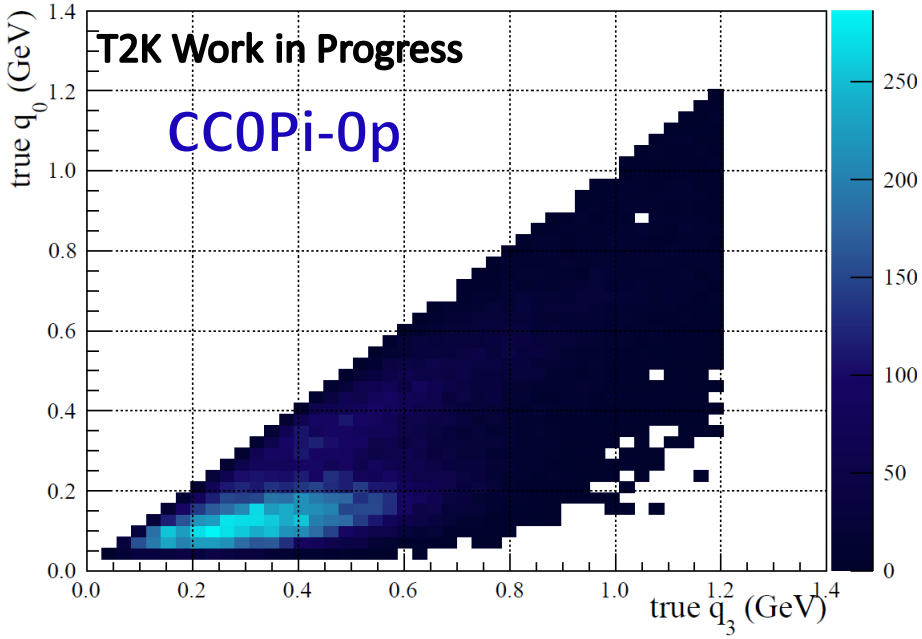
Energy transfer:

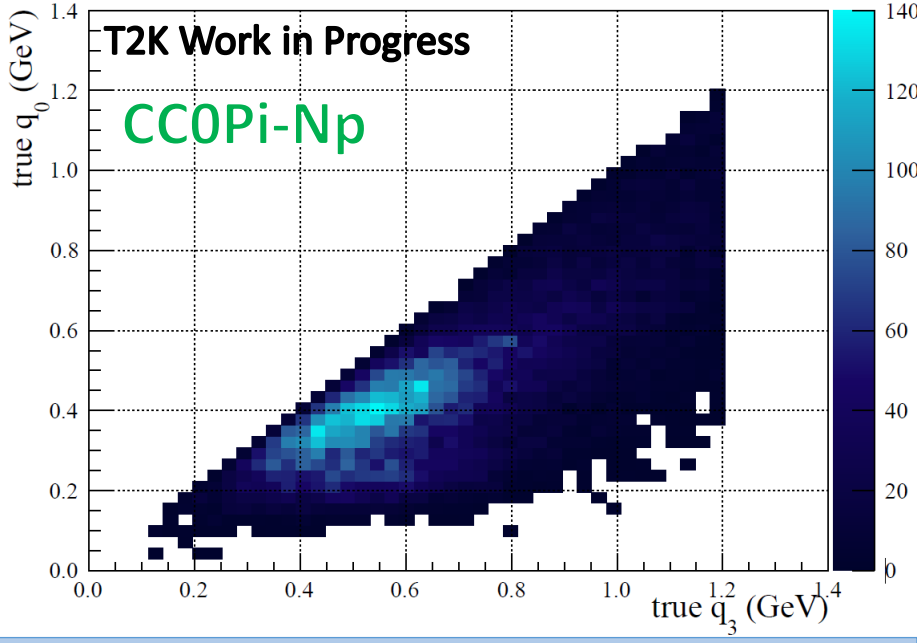
$$\boldsymbol{q_0} = E_\upsilon - E_\mu$$

Momentum transfer:

$$\boldsymbol{q_3} = p_\upsilon - p_\mu$$







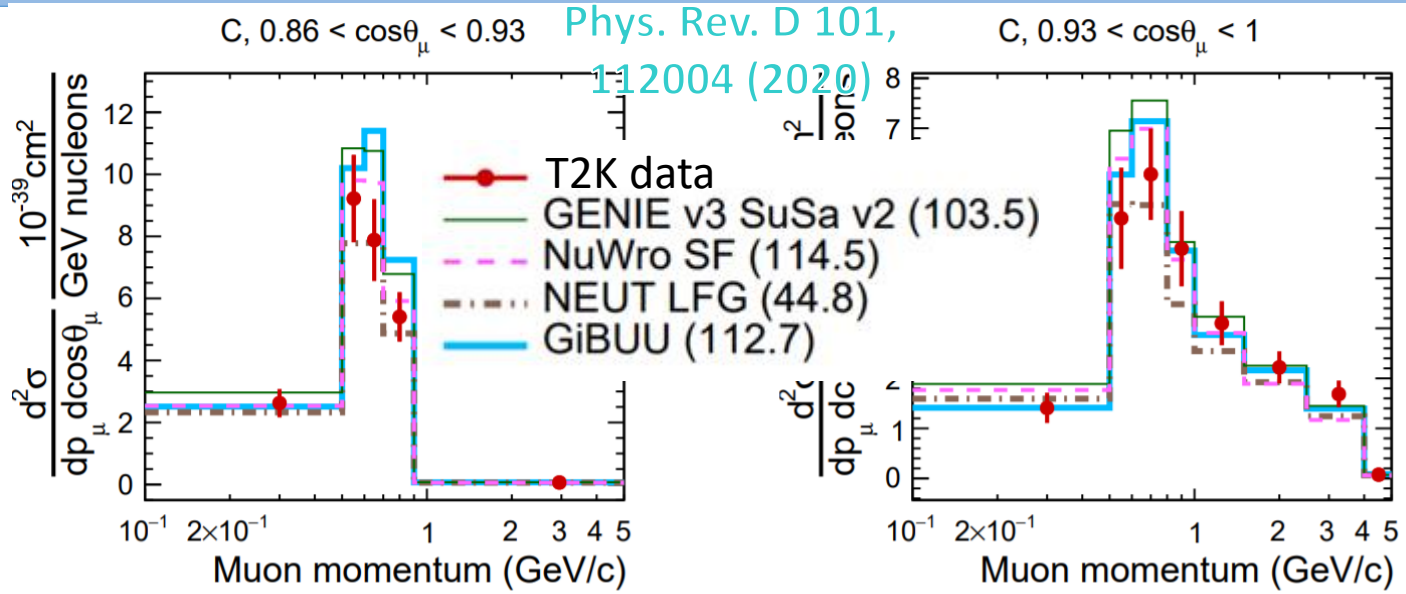
[1] Phys. Lett., B 707:72-75, 2012.

Probing low Q2 region with Proton Samples (CCQE)

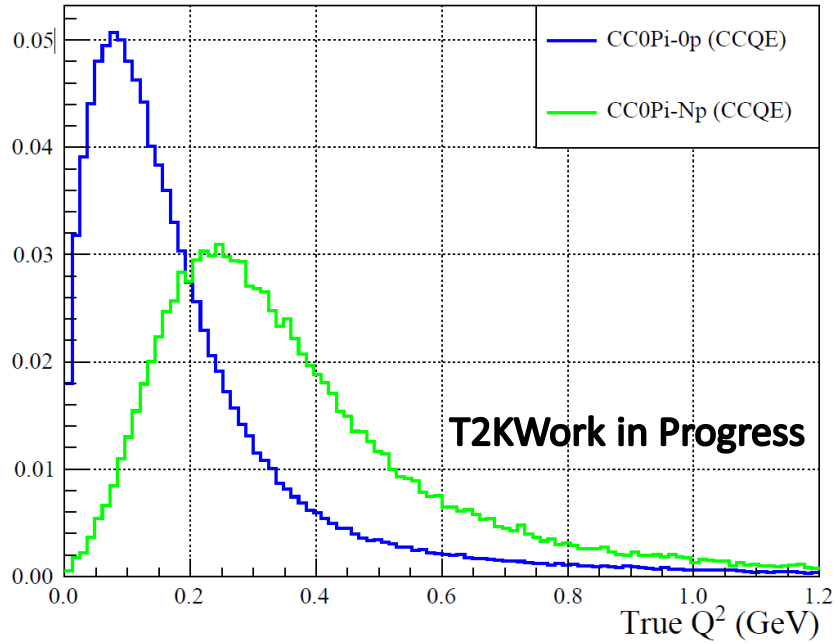
Since 2020 T2K uses **Spectral Function (SF)** to describe state of initial nucleon in nucleus.

Spectral Function model overpredicts CCQE interaction for lower values of Q^2.

Proton samples have distinctive distributions of Q^2 and can help to better probe lower and higher regions of Q^2.



NEUT MC with Spectral Function (SF)



Summary

Proton samples: **CC0Pi-0p** and **CC0Pi-Np**

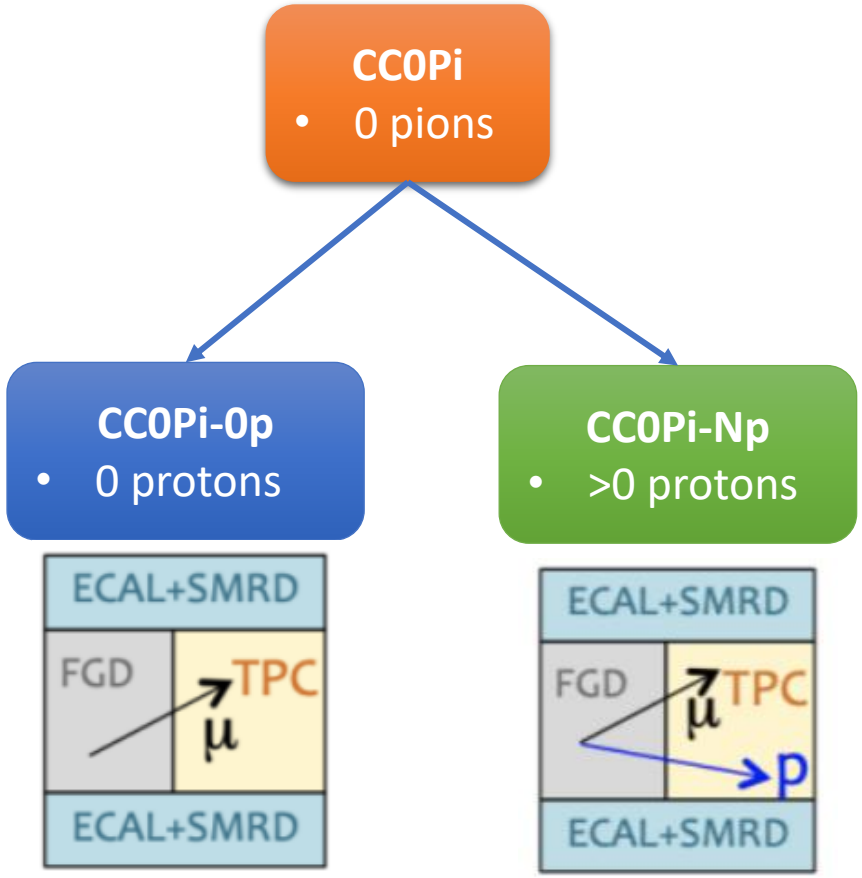
CC0Pi-0p - lower muon momentum, mostly forward going muons. Better purity for CCQE.

CC0Pi-Np - higher muon momentum, more muons going at higher angle. Better purity for non-CCQE contributions.

Proton samples can help probe two peaks of 2p2h Nieves et. al. model.

Better constrain low Q2 region of CCQE.

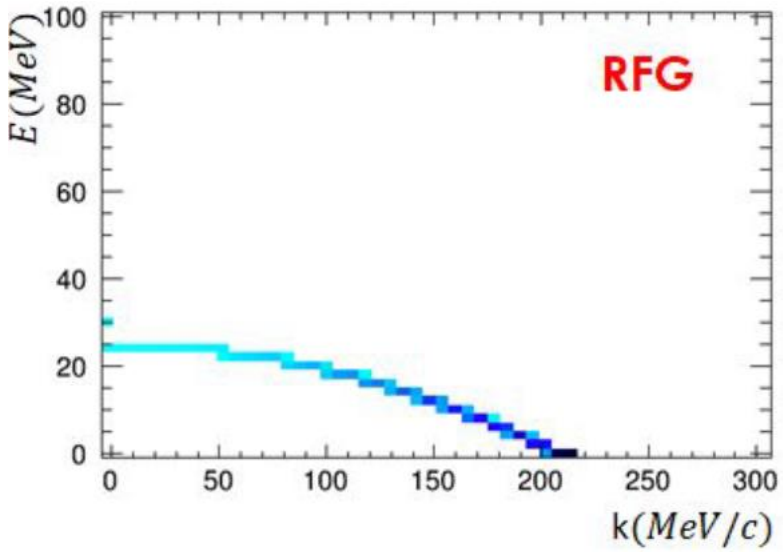
T2K is also considering adding proton kinematics into **ND280 fit** in future.



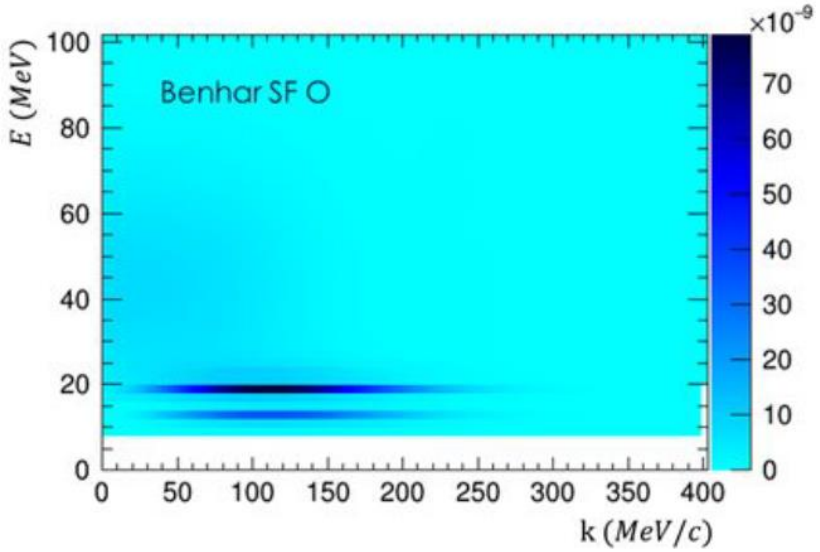
Backup

RFG vs SF

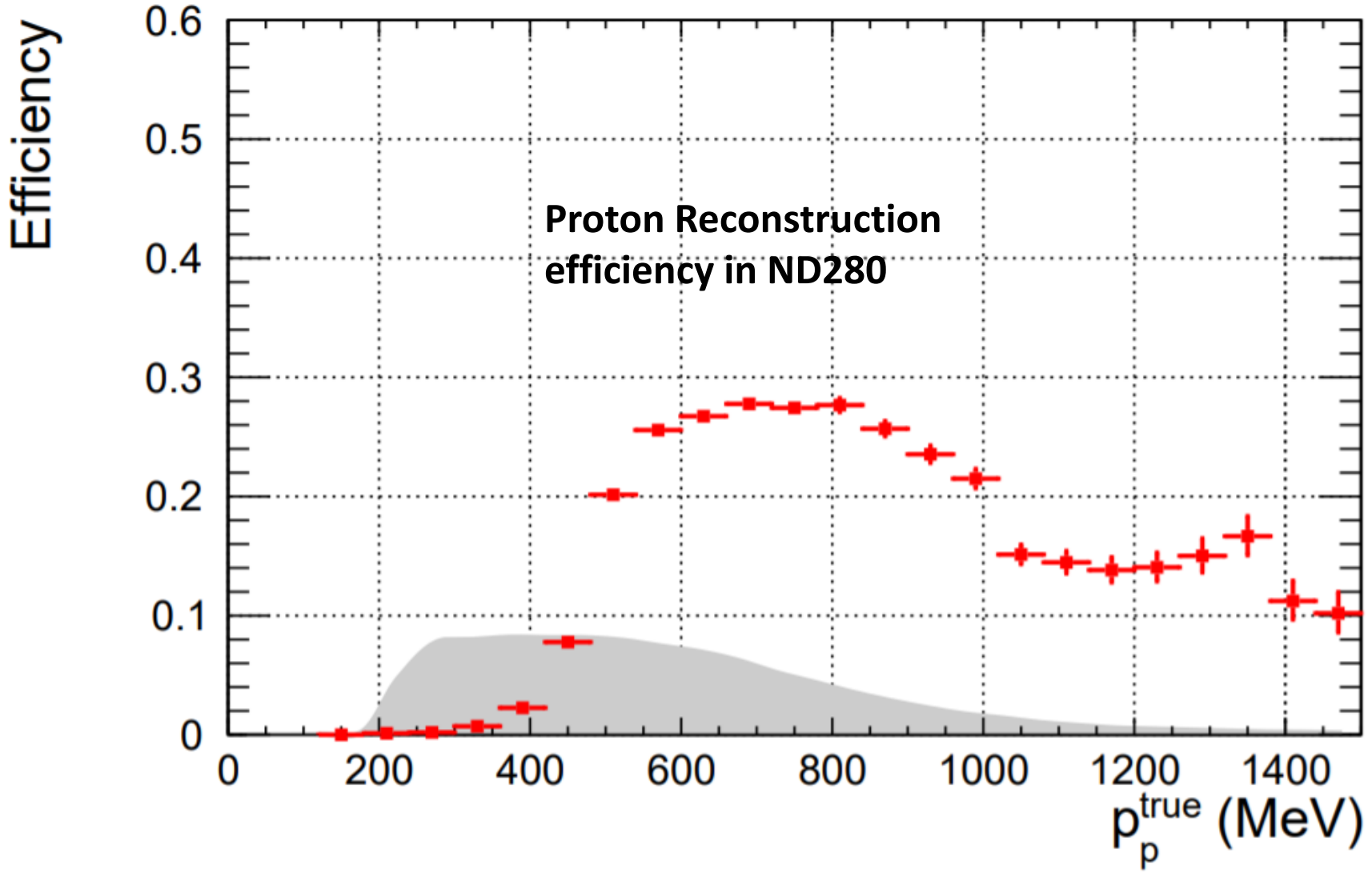
Relativistic Fermi Gas



Spectral Funciton



Reconstruction Threshold for Protons



Effects of ND280 fit

Before ND280 fit

Table 21: Uncertainty on the number of event in each SK sample broken by error source before the BANFF fit.

Error source	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+	FHC/RHC
Flux	5.1%	4.7%	4.8%	4.7%	4.9%	2.7%
Cross-section (all)	10.1%	10.1%	11.9%	10.3%	12.0%	10.4%
SK+SI+PN	2.9%	2.5%	3.3%	4.4%	13.4%	1.4%
Total	11.1%	11.3%	13.0%	12.1%	18.7%	10.7%

After ND280 fit

Table 20: Uncertainty on the number of event in each SK sample broken by error source after the BANFF fit. To obtain error rates comparable with the "Flux+Xsec (ND constrained)" presented by MaCh3 [22], square sum the "Flux+Xsec (ND constr)", "$\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$", "NC γ".

Error source	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+	FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
2p2h Edep	0.4	0.4	0.2	0.2	0.0	0.2
BG_A^{RES} low-p_π	0.4	2.5	0.1	2.2	0.1	2.1
$\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$	0.0	0.0	2.6	1.5	2.7	3.0
NC γ	0.0	0.0	1.4	2.4	0.0	1.0
NC Other	0.2	0.2	0.2	0.4	0.8	0.2
SK	2.1	1.9	3.1	3.9	13.4	1.2
Total	3.0	4.0	4.7	5.9	14.3	4.3

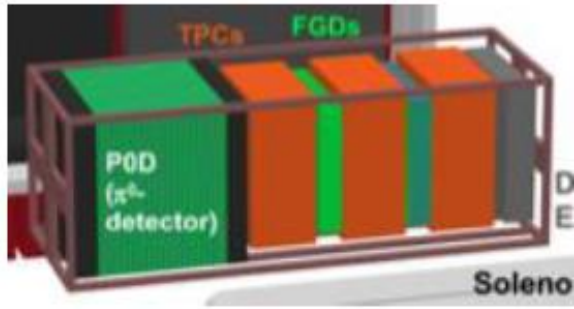
ND280 Samples

Used samples for 2020 analysis.

	FGD1			FGD2		
ν in FHC	CC0π	CC1π	CCNπ	CC0π	CC1π	CCNπ
$\bar{\nu}$ in RHC	CC0π	CC1π	CCNπ	CC0π	CC1π	CCNπ
ν in RHC	CC0π	CC1π	CCNπ	CC0π	CC1π	CCNπ

FHC – Neutrino mode

RHC – Antineutrino mode



Oscillation Analysis - OA