Expanding T2K near detector fit by adding proton information

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1. T2K Experiment

T2K is a long baseline experiment studying neutrino oscillations in the appearance and disappearance channels.

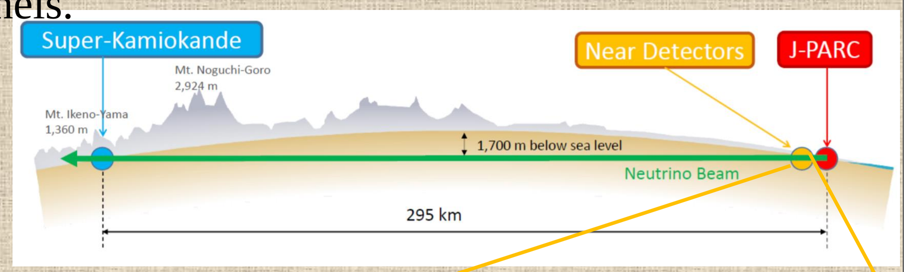
Neutrino or antineutrino beam production – J-PARC.

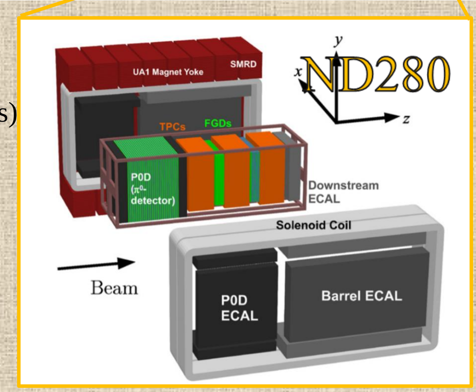
Near Detectors – ND280, INGRID, WAGASCI.

50 kt water Cherenkov detector– Super-Kamiokande.

ND280 is used to constrain cross-section and flux models which allows to obtain more precise measurements of oscillation parameters.

ND280 is also used in standalone cross-section measurements.





TPC (Time Projection Chambers)
- Momentum measurement.
- Particle identification (dE/dx measurement).

FGD (Fine Grained Detector)
- Target mass.
- Recoil proton detection.
- Contained pion tags.

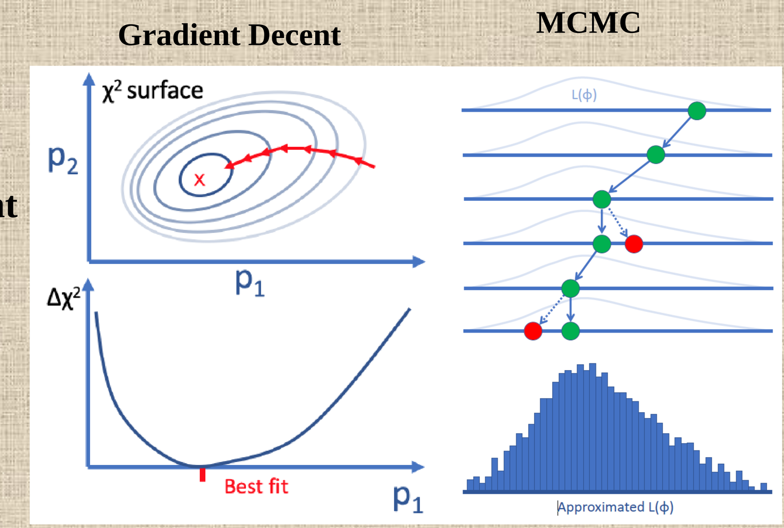
2. ND280 Fit

The ND280 fit is a crucial part of T2K oscillation analysis. Its main goal is to constrain the cross-section and flux model by fitting unoscillated MC predictions to ND280 data. Those constrains are passed to the T2K Far Detector, where fit with Super-Kamiokande samples takes place.

Two separate methods are used for ND280 fit: frequentist **Gradient Decent** and Bayesian Markov Chain Monte Carlo (**MCMC**). In both methods the Poissonian Log Likelihood (Eq. 1) (*), with Barlow-Beeston correction ($\beta_i, \sigma_{\beta_i}$) **[1]** and flux, cross-section, ND280 detector syst, is minimized.

The Likelihood considers muon kinematics (momentum and emission angle) for each ND280 event sample (there were 18 event samples used in 2020 analysis **[2]**).

Adding a new samples may improve T2K sensitivity , however it requires also rethinking systematic error.



$$-2\log\mathcal{L}_{stat} = 2\sum_{j}^{\text{samples}}\sum_{i}^{\text{bins}}\left[\left(N_{\text{MC}} - N_{\text{Data}} + N_{\text{Data}}\log\frac{N_{\text{Data}}}{N_{\text{MC}}}\right) + \frac{(\beta_i - 1)^2}{2\sigma_{\beta_i}^2}\right] \quad (1)$$

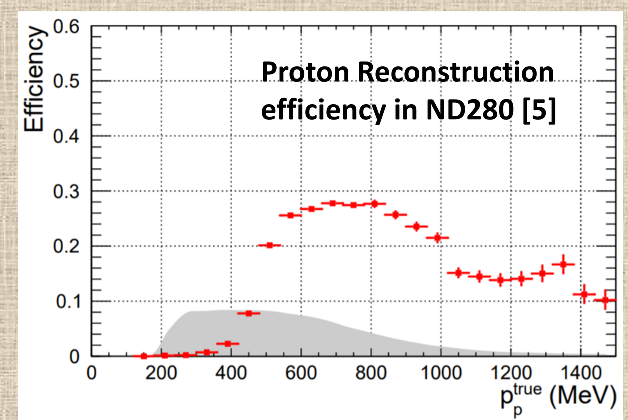
(*) Full formula also includes penalty terms.

3. Proton Tagged Samples

T2K has been using ND280 event samples based on pion tagging in a recent analysis **[2]**. Since samples based on proton multiplicity have shown interesting sensitivities in the recent T2K cross section measurements **[3, 4]** there is ongoing work on adding new samples, based on proton tagging, to the ND280 fit.

Proton tagged samples: **CC0Pi-0p** and **CC0Pi-Np** originate from split of CC0Pi (events without reconstructed pions) based on proton multiplicity reconstructed in TPC and FGD.

The reconstruction threshold for protons in ND280 is around 450 MeV. This means more than half of protons remain undetected. The imminent upgrade will dramatically improve this.



4. Selection Flow in ND280 Fit

CC Inclusive
- 1 muon
- Quality cuts

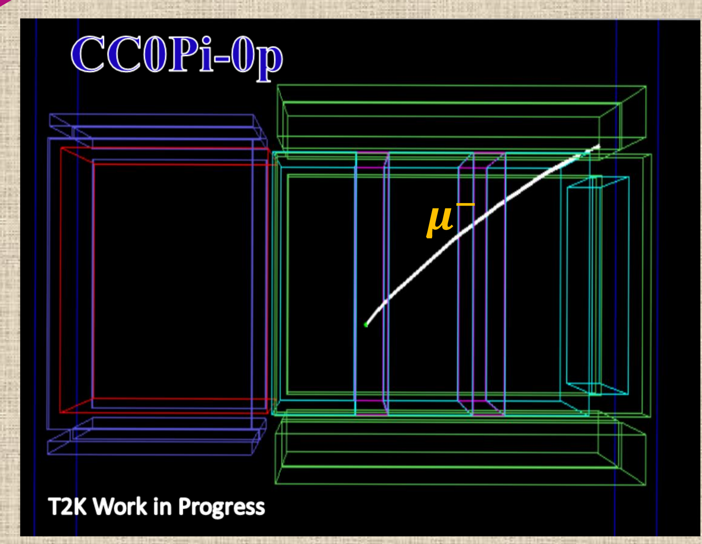
CC1Pi
- 1 pion

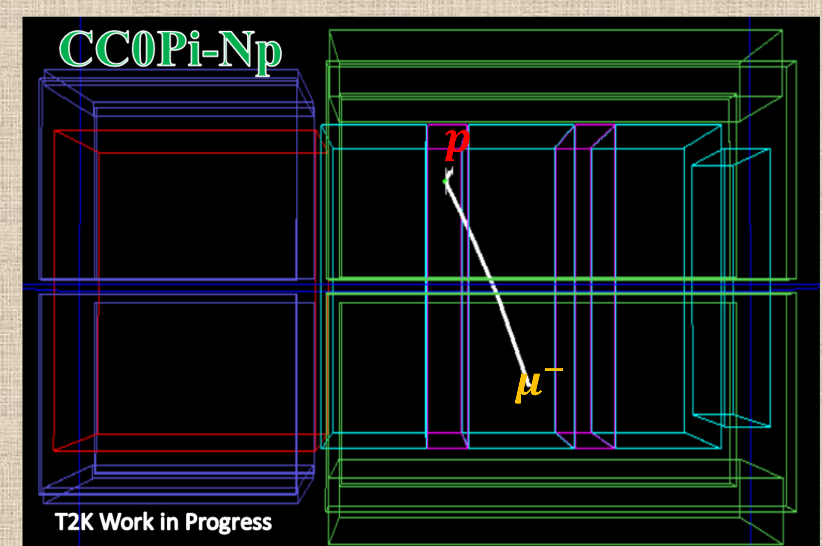
CC0Pi
- 0 pions

CCOther
- Other combinations

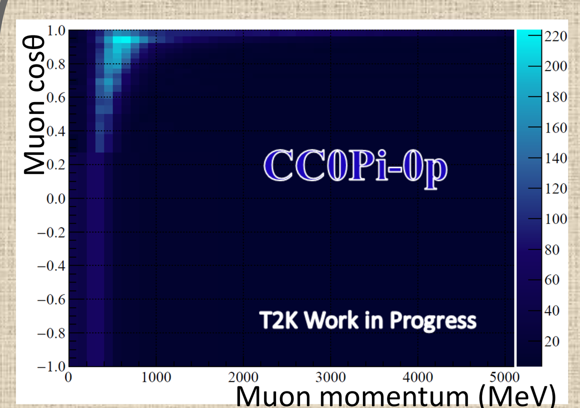
CC0Pi-0p
- 0 protons

CC0Pi-Np
- >0 protons





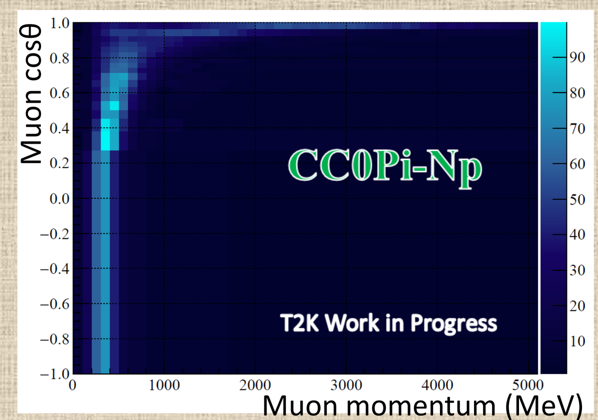
5. Properties of Proton Tagged Samples



Both samples occupy different phase space of muon kinematics.

In case of **CC0Pi-0p** most of neutrino momentum is taken by the muon, which is going forward.

CC0Pi-Np events contain a high momentum proton to conserve momentum the muon has to travel at a higher angle.



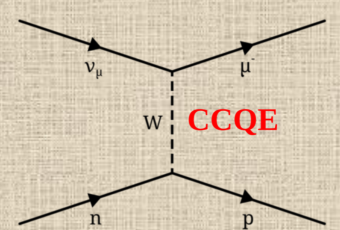
CC0Pi-0p - lower muon momentum, mostly forward going muons.

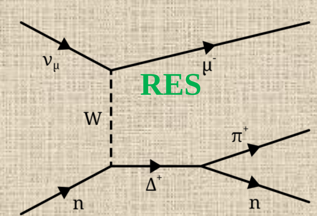
CC0Pi-Np - higher muon momentum, more muons going at higher angle.

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

Better purity for non-CCQE contributions.





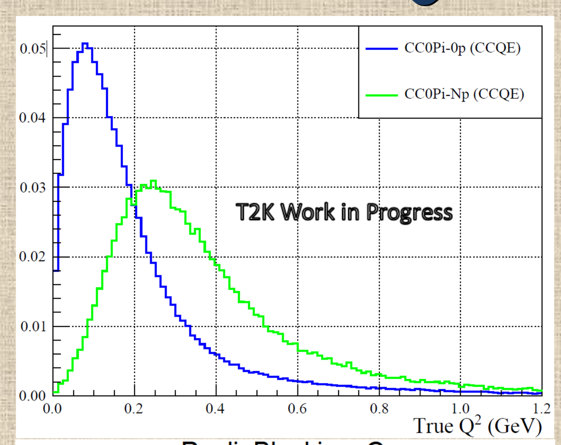
6. Enhanced ability to constrain CCQE

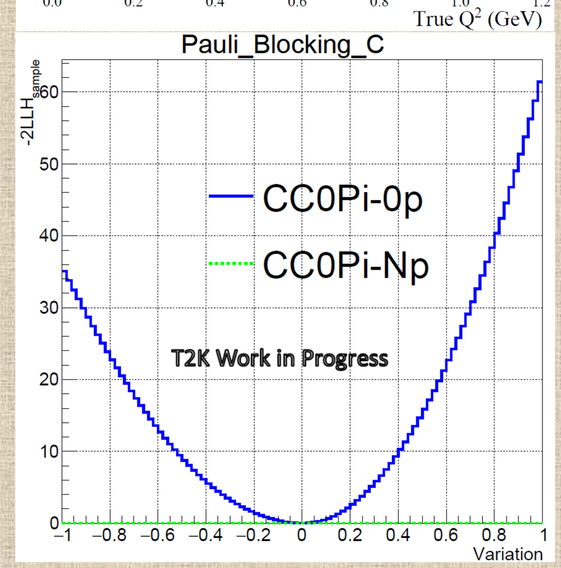
Proton tagged samples have distinctive distributions of Q^2 and can help to better probe lower and higher regions of Q^2.

Low Q^2 events can be suppressed by Pauli Blocking **[7]** or other nuclear effects. Pauli Blocking and binding energy involves releasing the nucleon after it has a certain momentum, which translates to Pauli Blocking cutting into low Q^2 in this case.

Most of the protons that are reconstructed in the ND280 have high momentum, so aren't affected by nucleon correlations, and the events that don't have a visible proton will often have a proton of relatively low momentum, so it is more affected by the Pauli Blocking.

By looking at the parameter which affects Pauli Blocking in T2K MC, we can see that most of sensitivity to this effect on T2K MC comes from the **CC0Pi-0p** sample.





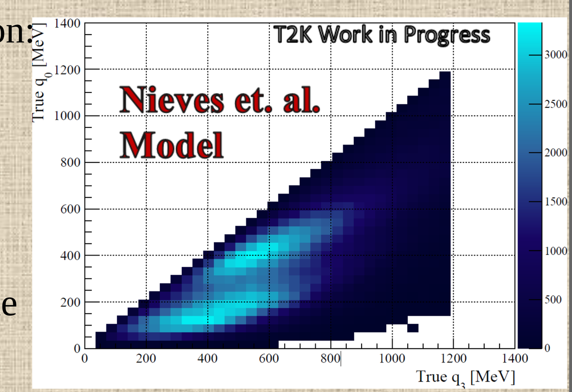
7. Ability to constrain 2p2h models

Nieves et. al. model **[6]** describing 2p2h interactions has very characteristic two peak structure in phase space of energy and momentum transfer. Proton tagged events have a distinctive distribution.

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

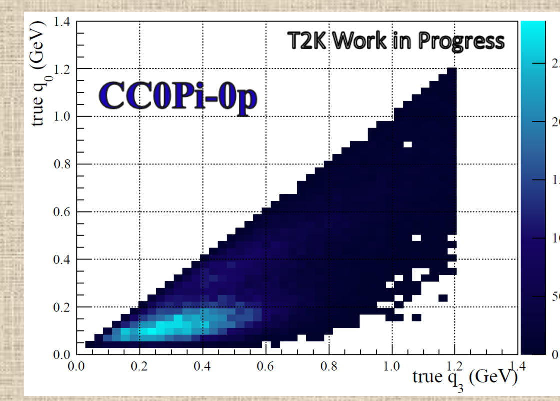
CC0Pi-Np - higher q_0/q_3 region.

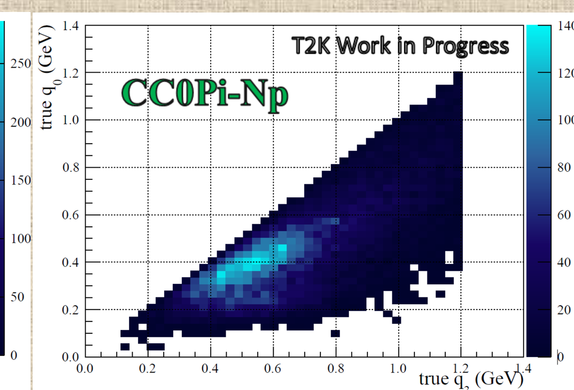
In ND280 fit there is a parameter which allows for shifting between the two q_0/q_3 regions in the analysis. With proton tagged samples we can better probe this parameter.



Energy transfer:
$\boldsymbol{q_0} = E_\nu - E_\mu$

Momentum transfer:
$|\vec{\boldsymbol{q}}_3| = |\vec{p}_\nu| - |\vec{p}_\mu|$



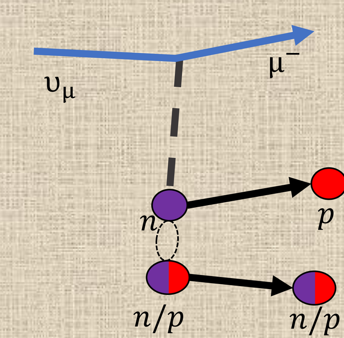


8. 2p2h Interactions: Nucleon Pairs

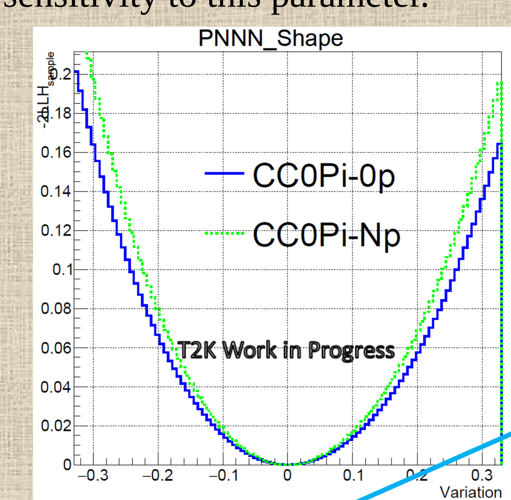
2p2h interactions of neutrinos can happen on proton-neutron (**pn**) pair or neutron-neutron (**nn**) pair.

Both **Nieves et. al.** and **SUSAv2** **[8]** model predicts different kinematic properties of proton coming from **pn** or **nn** pair.

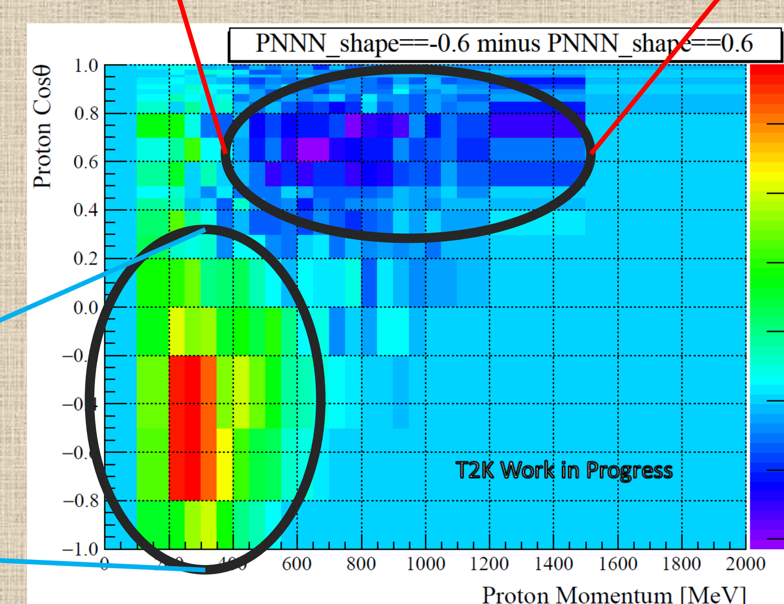
By constructing a parameter which changes the ratio of such pairs we can try to estimate the sensitivity of proton samples to this effect.



Both proton tagged samples have similar sensitivity to this parameter.



Increase of **pn** shifts events to higher momentum, forward going protons.



Increase of **nn** shifts events to lower momentum, higher angles.

9. Summary

Proton tagged samples due to different properties can help to better constrain several cross-section effects:

- Pauli blocking due to better separation of low Q^2.
- **CC0Pi-0p** higher purity for CCQE, **CC0Pi-Np** better purity for non-CCQE contributions.
- **Nieves et. al.** model of 2p2h as a consequence of better $\boldsymbol{q_0}$ and $\boldsymbol{q_3}$ separation.
- Sensitivity in separation of **pn** and **nn** pair in 2p2h model.

References
[1] Comput. Phys. Commun. (1993)
[2] arXiv:2101.03779
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Supported by NCN grant no:
UMO-2018/30/E/ST2/00441