Constraint on the CP symmetry-violating phase in neutrino oscillations in T2K experiment

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15.12.2020

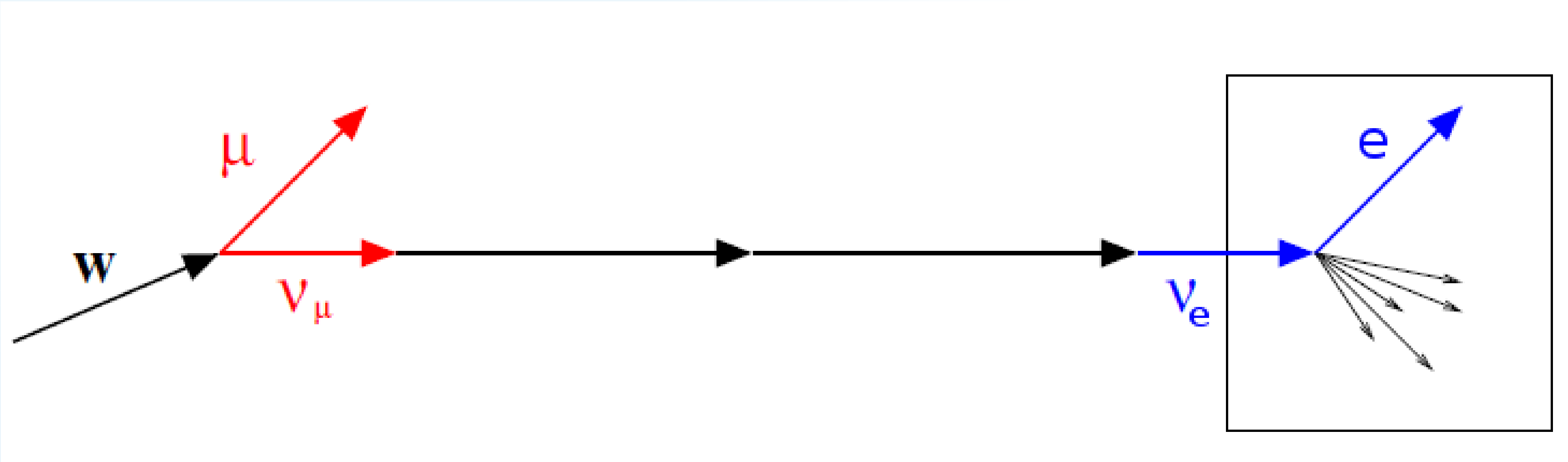
T2K

Outline

- T2K results on CP violation phase in neutrino oscillations.
  - T2K NCBJ group contribution to the result.

- Other activity of our group in 2020.
  - To be included in current and future oscillation analysis.

Neutrino oscillations: basic idea



- The flavour states ν_α, are superposition of mass states ν_i:

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

- ν_i are eigenstates of Hamiltonian and propagate for a time *t* as:

$$|\nu_i(t)\rangle = e^{-iE_i t} |\nu_i(0)\rangle$$

where $E_i = \sqrt{p^2 + m_i^2}$

(for vacuum)

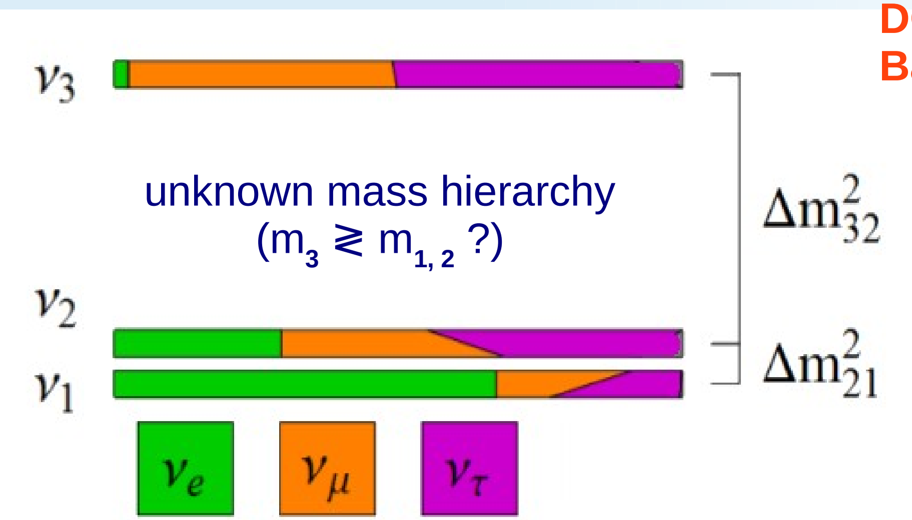
Neutrino oscillations: flavor-mass mixing

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

Super-K, K2K, MINOS, OPERA NOνA, T2K

Super-K, SNO, KamLAND

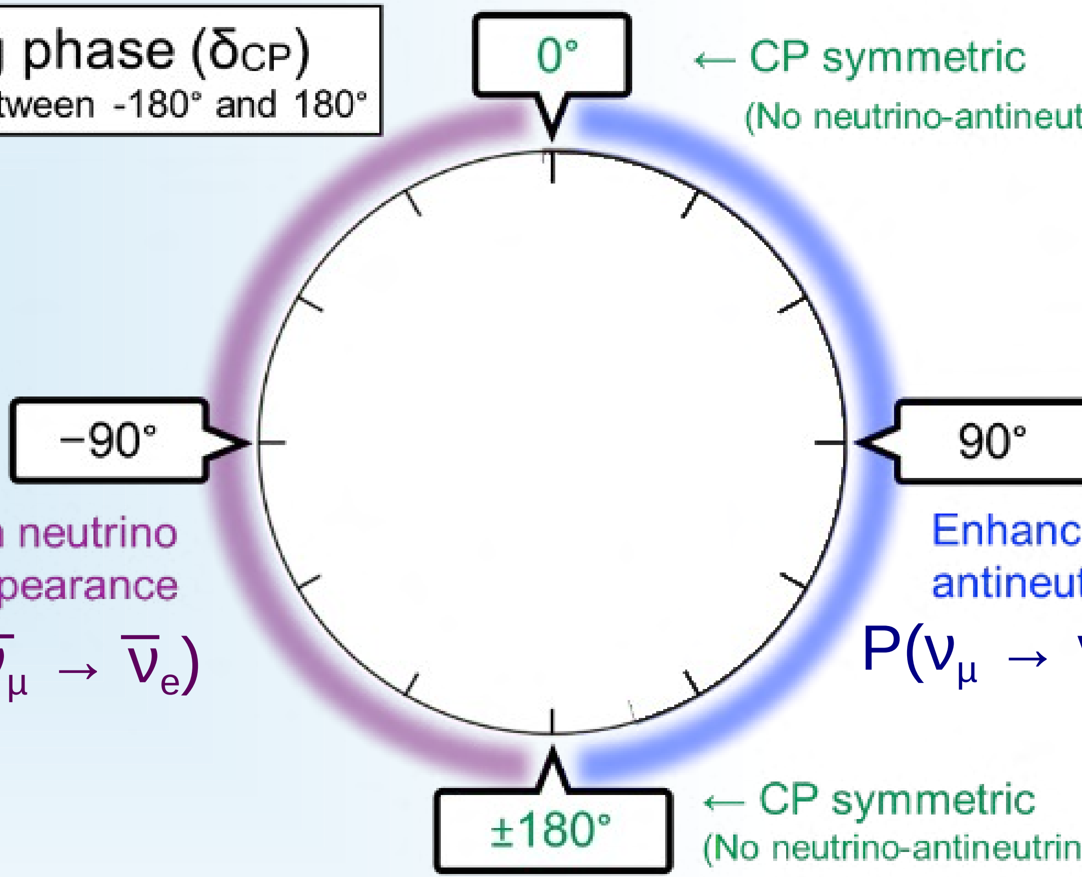
DChooz, RENO, Daya Bay, NOνA, T2K



- c_{ij}, s_{ij} – $\cos\theta_{ij}$, $\sin\theta_{ij}$
- θ_{ij} – mixing angles,
  δ_{CP} – CP violation (CPV) phase
- Long-baseline experiments are sensitive to Δm^2_{32}, θ_{23}, θ_{13} and δ_{CP}.

CP violation

CP violating phase (δ_{CP})
can take a value between -180° and 180°



← CP symmetric
(No neutrino-antineutrino difference)

Enhance electron neutrino appearance

$P(\nu_\mu \rightarrow \nu_e) > P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$

Enhance electron antineutrino appearance

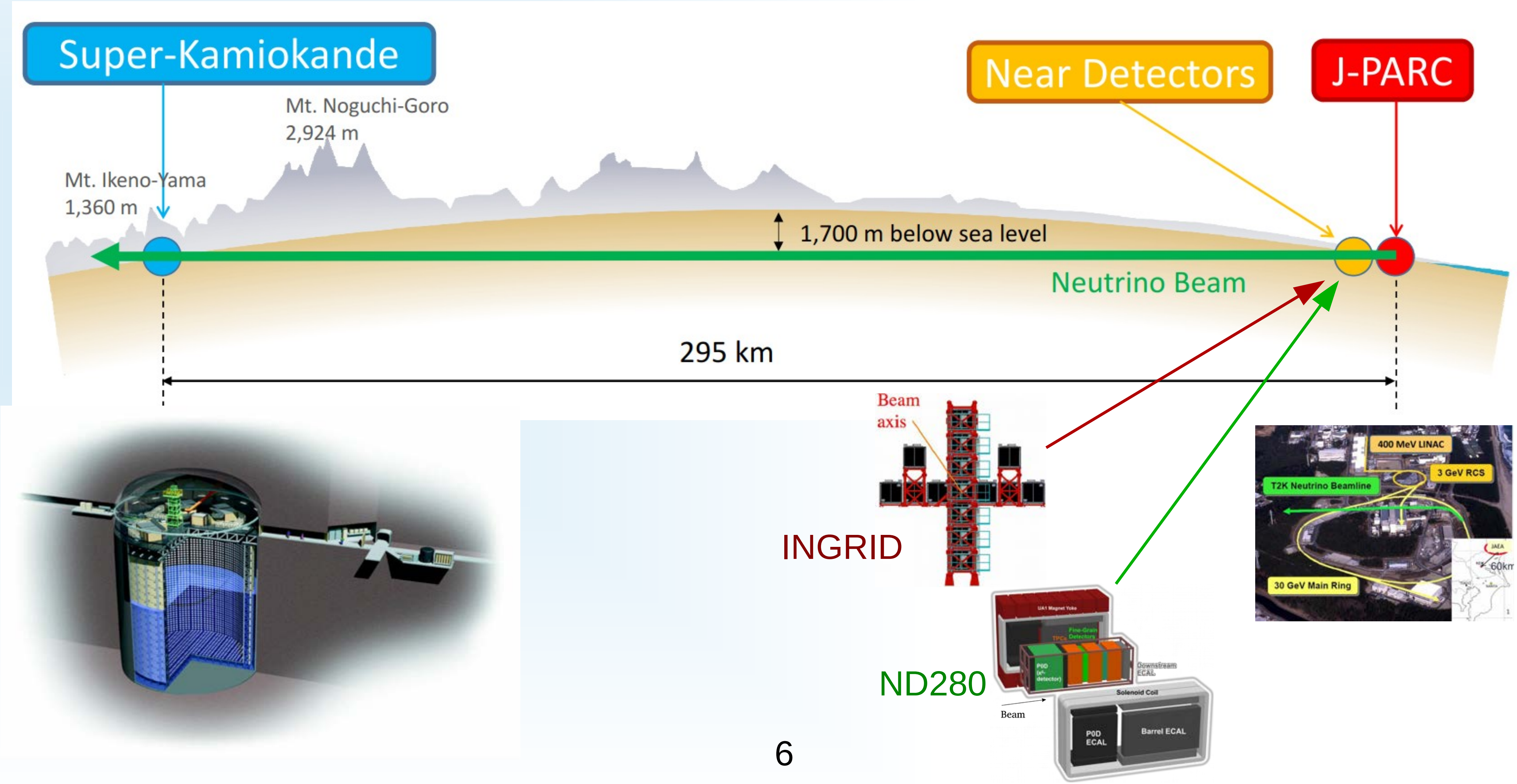
$P(\nu_\mu \rightarrow \nu_e) < P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$

← CP symmetric
(No neutrino-antineutrino difference)

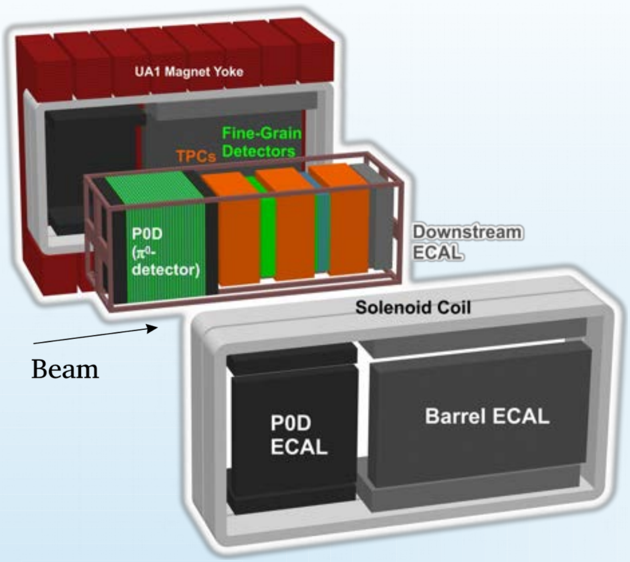
$P(\nu_\mu \rightarrow \nu_e) = P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$

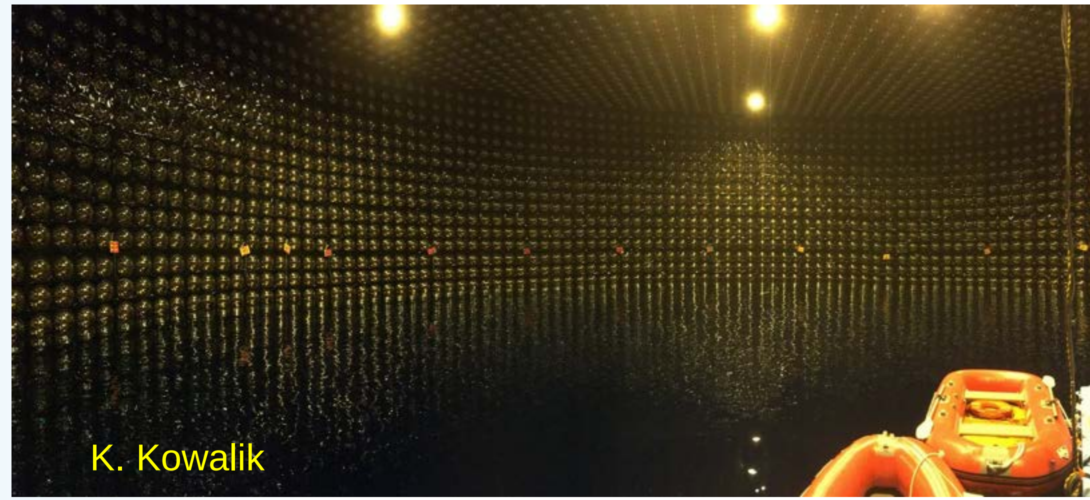
T2K experiment

- T2K is a long-baseline neutrino experiment in Japan.



Detectors





Off-axis near detector: ND280

- ND280 is a multipurpose detector used to constrain the off-axis flux and neutrino interaction model.
- Neutrino CC interactions are measured in the tracker.
- Magnetic field allows for charge and momentum measurement.
- Several samples of events:
  - For neutrino and antineutrino modes
  - Different reaction types (pion/track multiplicity)

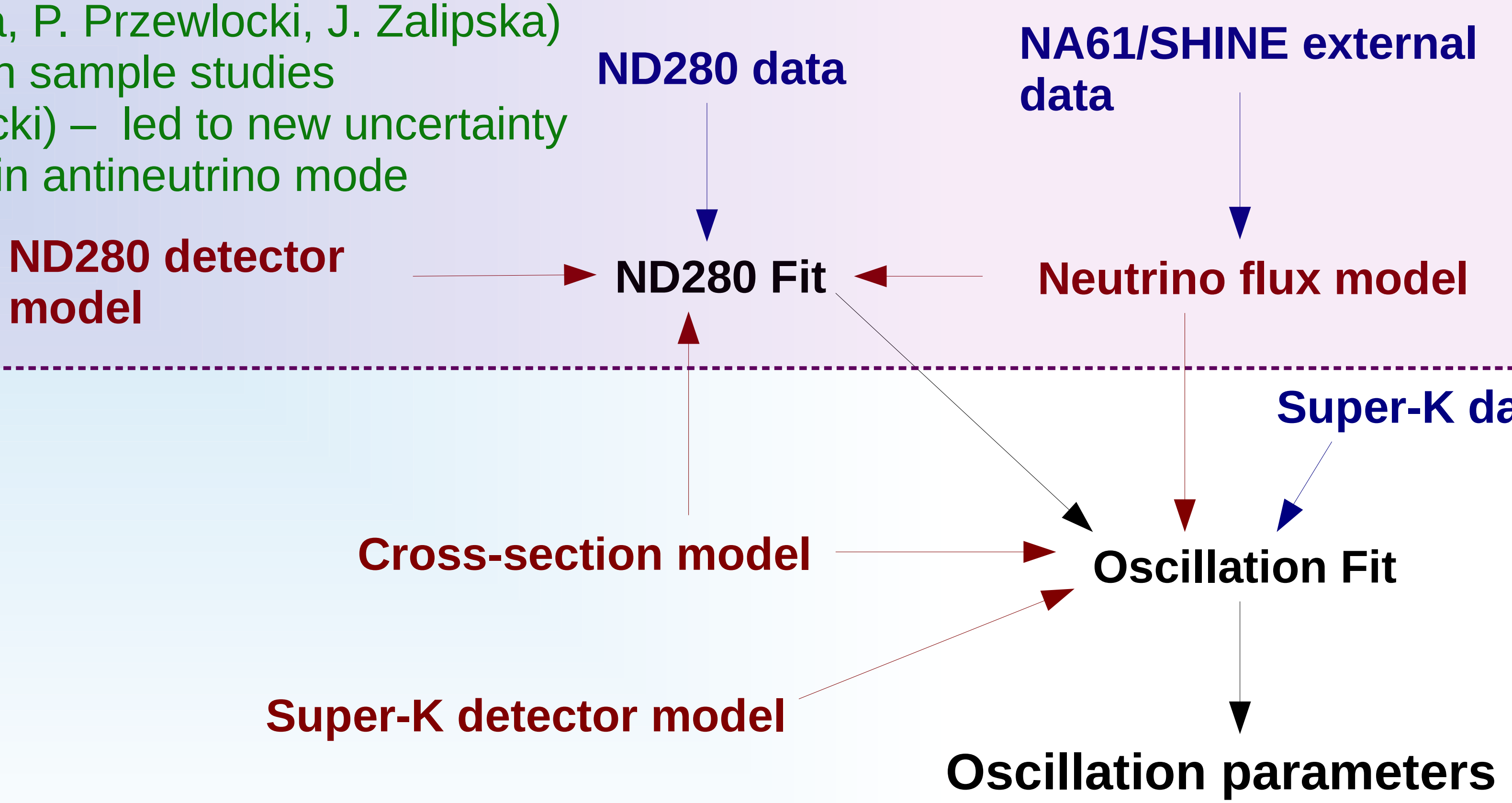
Far detector: Super-Kamiokande

- 50 kton water Cherenkov detector
- 39 m in diameter, 41 m in height
- Over 10000 PMTs measure the Cherenkov light inside the tank.
- Super-K samples:
  - Neutrino and antineutrino modes
  - All samples based on single e/μ ring

Analysis strategy and our contribution

- External background and cosmics studies (J. Lagoda).
- Event migration and estimation of the detector systematic errors. (J. Lagoda, P. Przewlocki, J. Zalipska)
- Single pion sample studies (G. Zarnecki) – led to new uncertainty on CC1pi in antineutrino mode

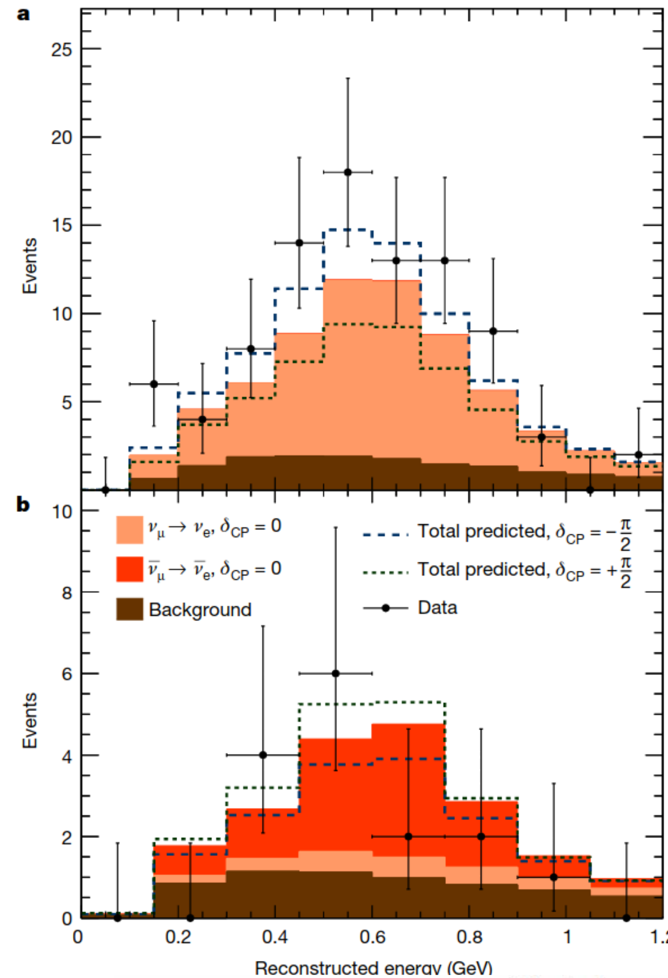
- Cross-section measurement of pi-production in p+C interaction. Reduction of neutrino flux systematic uncertainty (K. Kowalik).



Super-K fit to data

Plots: The reconstructed neutrino energy spectra for the SK samples with electron-like events in neutrino/antineutrino beam mode.

Table: The predicted number of events for the δ_{CP} = -π/2 and the measured number of events for the three e-like samples at SK.

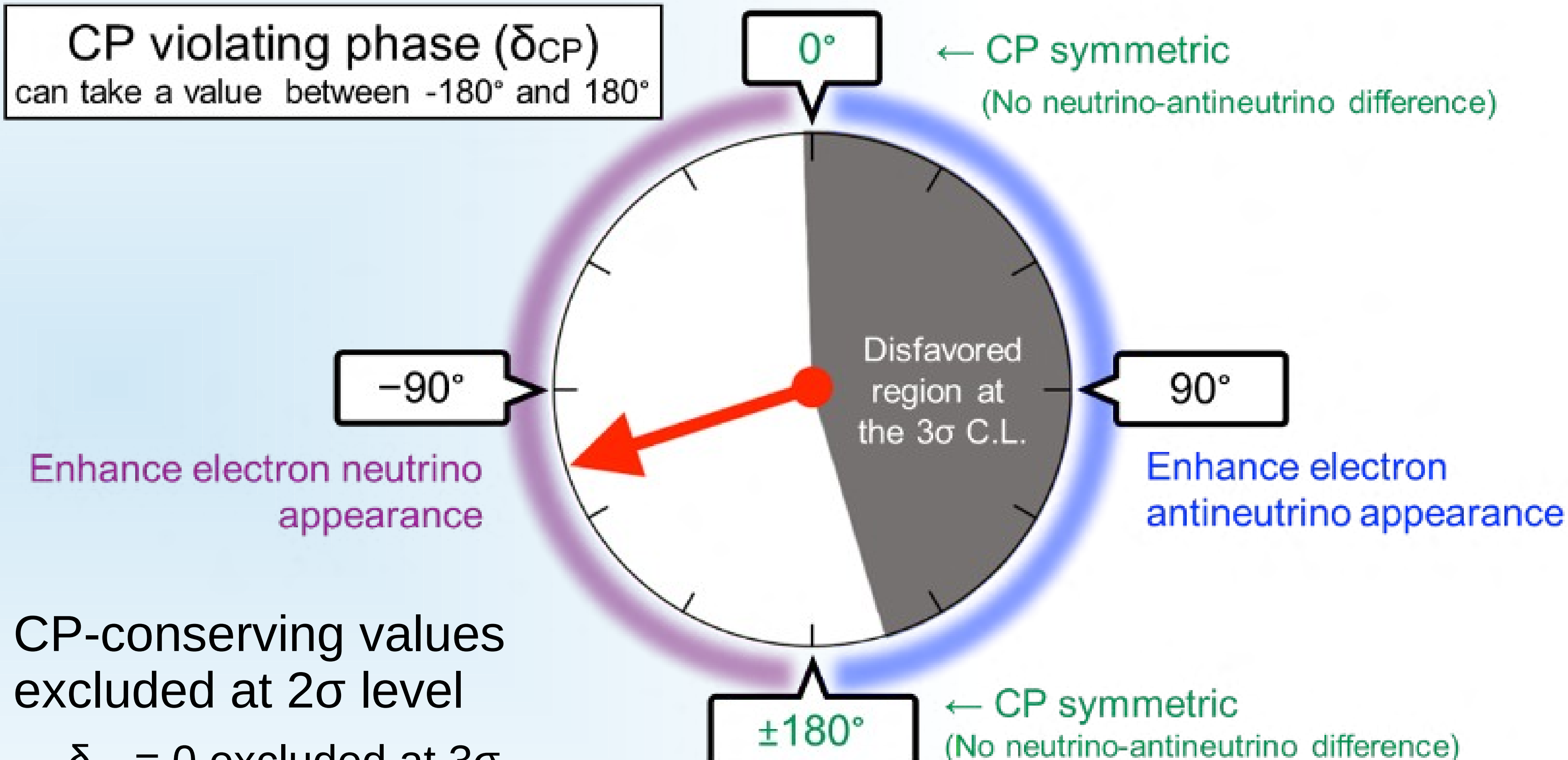


c	1e0de ν-mode	1e0de $\bar{\nu}$-mode	1e1de ν-mode
$\nu_\mu \to \nu_e$	59.0	3.0	5.4
$\bar{\nu}_\mu \to \bar{\nu}_e$	0.4	7.5	0.0
Background	13.8	6.4	1.5
Total predicted	73.2	16.9	6.9
Systematic uncertainty	8.8%	7.1%	18.4%
Data	75	15	15

Selection	Total syst. error (%) Pre	Post
ν-mode		
1-ring-μ	15	5
1-ring-e	17	9
1-ring-e + 1π^+	22	18
$\overline{\nu}$-mode		
1-ring-μ	13	4
1-ring-e	14	7

ND280 fit impact on syst. error

Results: δ_{CP}



- CP-conserving values excluded at 2σ level
  - $\delta_{CP} = 0$ excluded at 3σ level
- Best fit: $\delta_{CP} = -1.885$ (-0.6π)

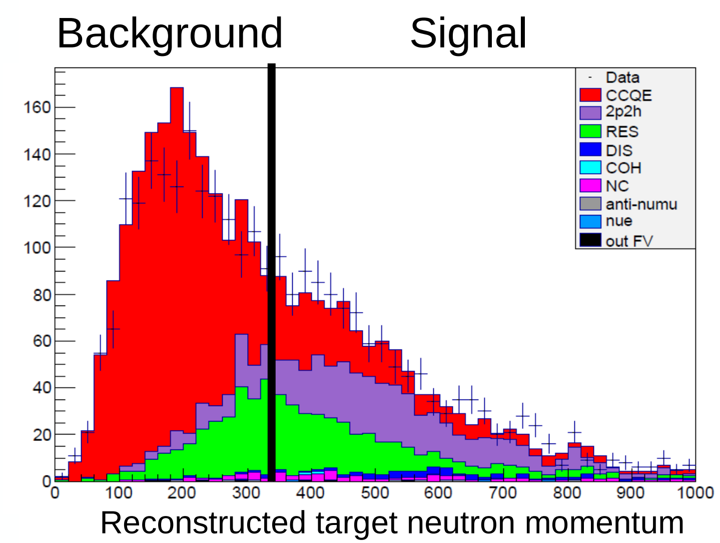
Mid-Summary

- CP violation is one of Sakharov's conditions for an explanation of the observed imbalance of matter and antimatter in the Universe.
- The CP symmetry in neutrino sector can be studied by comparing the oscillation probabilities for neutrinos and anti-neutrinos.
- **Current T2K data indicates CP violation at the 2σ confidence level.**
  δ_{CP} = 0 excluded at 3σ level.
  Result published in ***Nature*** **580 (2020) 7803, 339-344**.

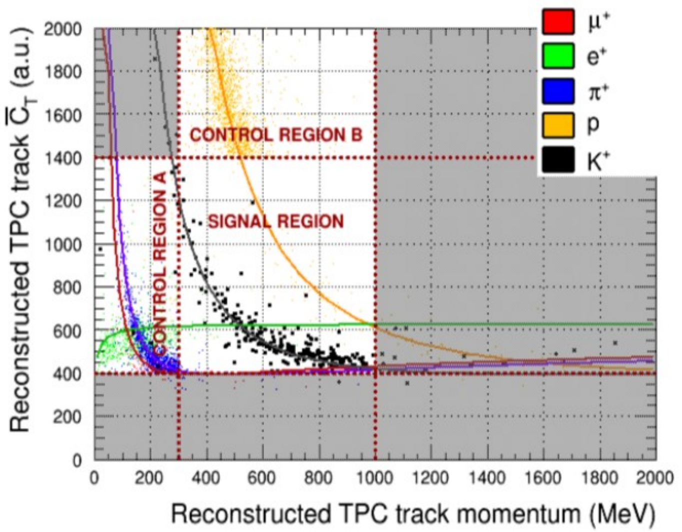
Other analyses and tasks in 2020

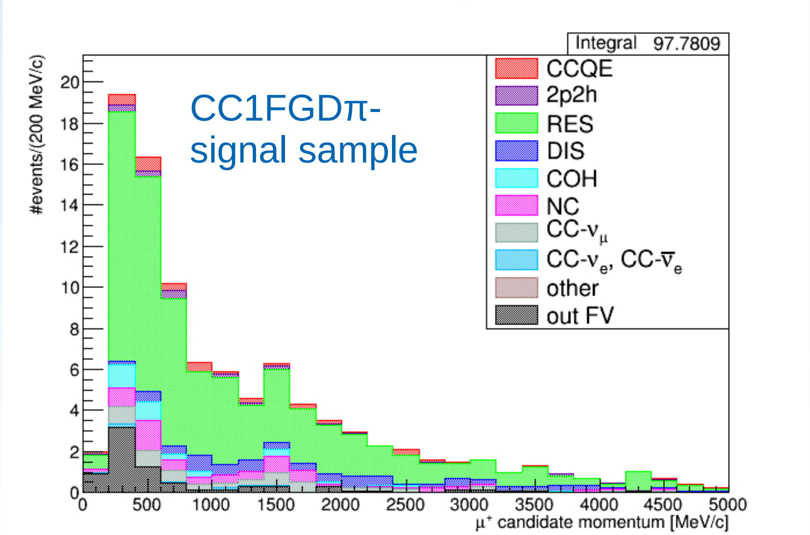
Off-axis near detector: ND280

- **Polish groups involved in FGD subdetector data quality checks and expert shifts.**
- **MEC interaction studies (J. Zalipska).**



- **Cross-section analysis ongoing.**
  - **Single kaon production (K. Kowalik)**
  - **Single pion production (G. Zarnecki)**



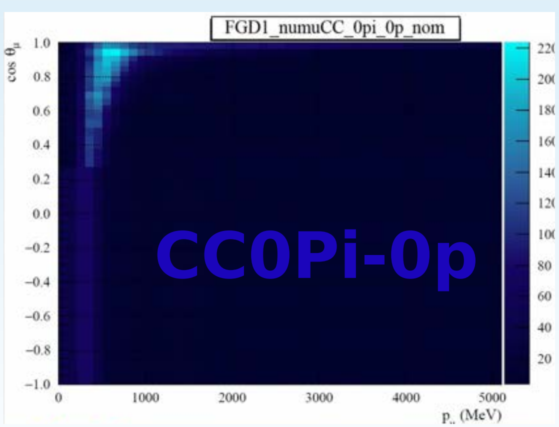


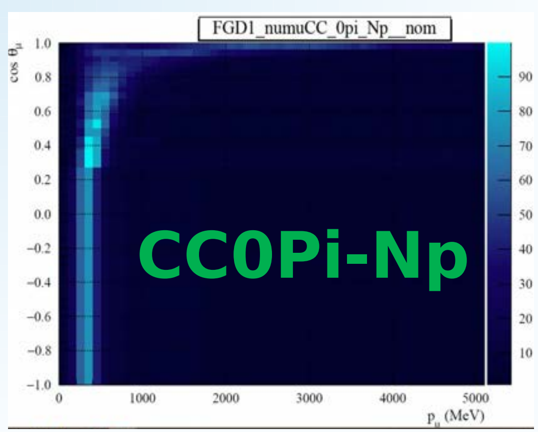
Analysis samples

New group members

ND280

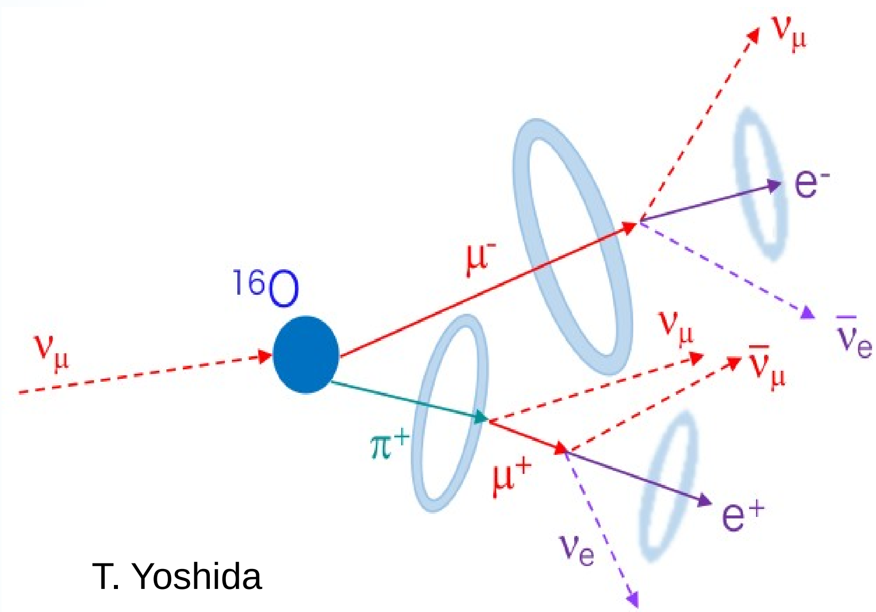
- **Antineutrino multipion analysis (J. Lagoda, G. Zarnecki)**
- **Ongoing analysis on extended ND280 samples (proton multiplicity) (K. Skwarczynski)**





Super-K

- **Vertex distribution studies (L. Mohan)**
- **Multiring samples (L. Mohan, Y. Prabhu)**

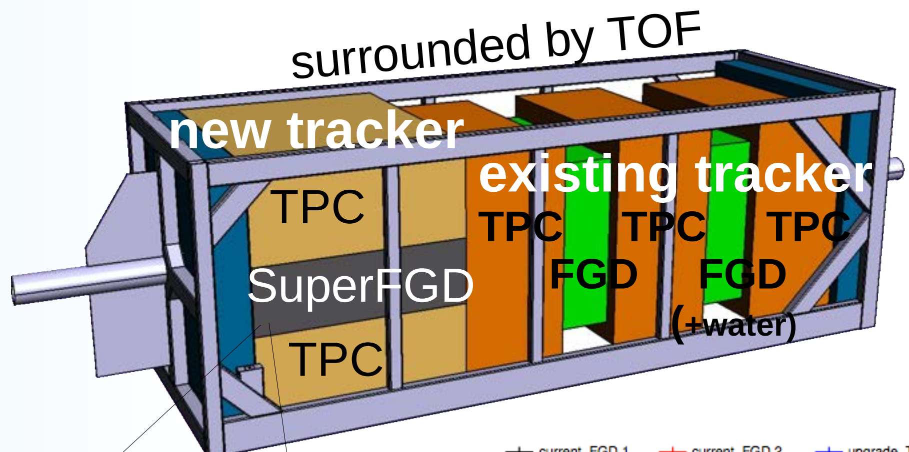


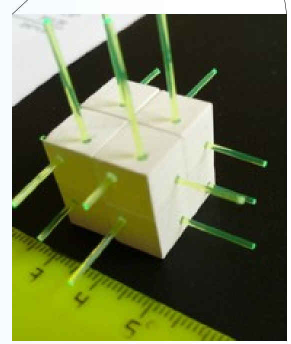
T. Yoshida

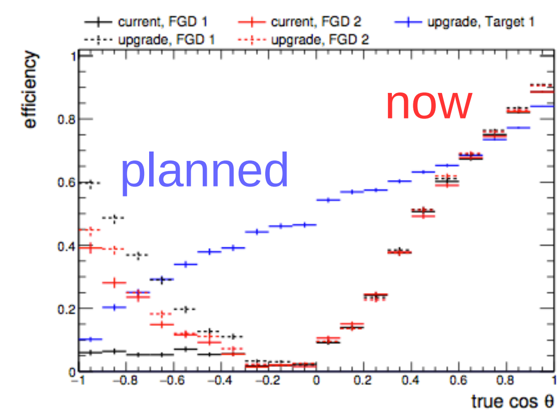
Figure 5.1: Schematic illustration of a ν_μ CC1π^+ event in SK.

T2K II

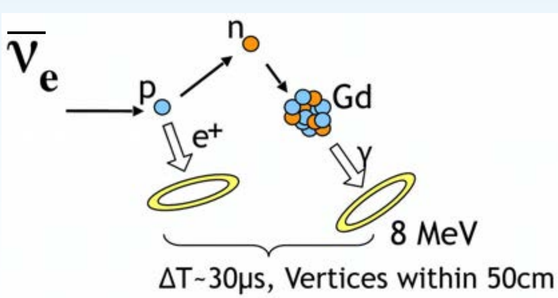
- **Upgrade of ND280 for T2K Phase-II**
  - **SuperFGD (J. Zalipska, K. Skwarczynski, W. Zurek, N. Panchal)**
    - **Test results published in J. of Instr.**
  - High angle TPCs
- Upgrade of Super-K
  - Gadolinium dissolved
  - **Neutron capture studies (M. Mandal)**







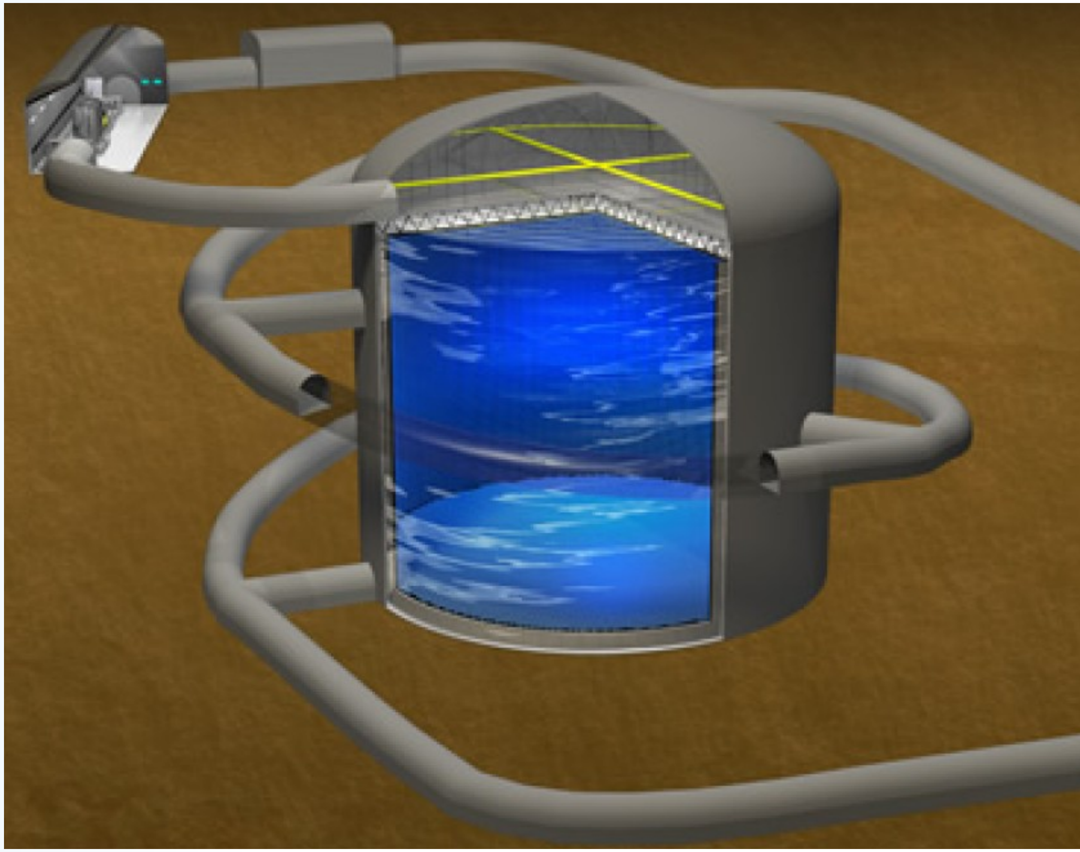
angular efficiency



New group members

Hyper-Kamiokande

- Next generation underground water Cherenkov detector. It will serve as a far detector of a long baseline experiment (with the same baseline of 295 km) for the upgraded J-PARC beam.
  - 260 kton
  - 74 m in diameter, 60 m in height
  - High sensitivity PMTs
- Approved this year and expected to start in 2027.
- **Warsaw T2K Group is a co-founder of the collaboration.**



Summary

- T2K Warsaw Group is involved in near detector ND280 operation, data analysis and upgrade, and extends activity from Near also to Far detector.
- 4 new members joined in 2020
- The T2K collaboration is preparing for T2K phase-II
(2022?-2026)

Current T2K Group in NCBJ

- Ewa Rondio (professor)
- Justyna Lagoda (associate professor)
- Katarzyna Kowalik (assistant professor)
- Joanna Zalipska (assistant professor)
- **Lakshmi Mohan (assistant professor)**
- **Neha Panchal (assistant professor)**
- **Maitrayee Mandal (PhD student)**
- **Yashwanth S Prabhu (PhD student)**
- Kamil Skwarczynski (PhD student)
- Grzegorz Zarnecki (PhD student)

Grants

- Finansowanie wkładu krajowego wnoszonego na rzecz udziału we wspólnym międzynarodowym przedsięwzięciu pt. "Eksperyment T2K (Tokai to Kamioka)" – MNiSW Financing of national contribution paid to international activity named "Experiment T2K (Tokai to Kamioka)"
  - started October 1st, 2017, planned for 5 years
- Japan and Europe Network for Neutrino and Intensity Frontier Experimental Research 2 (JENNIFER 2), H2020-MSCA-RISE-2018 + “Premia na Horyzoncie”
  - started April 1st, 2019, planned for 4 years
- OPUS “Badanie skorelowanych par nukleonów w oddziaływaniach neutrin”
  - started March 16 2017, finished summer 2020
- SONATA BIS “Precise measurements of neutrino oscillations in the improved T2K experiment“
  - started in April 2019, planned for 4 years
- Super-Kamiokande to Hyper-Kamiokande (SK2HK), H2020-MSCA-RISE-2019 + “Premia na Horyzoncie”
  - started November 1st, 2019, planned for 4 years

CP symmetry

- Parity operator: $P\Psi(x) = \Psi(-x)$
  - In particular, left-handed particle becomes right-handed particle.
  - $P|\nu_L\rangle \rightarrow |\nu_R\rangle$ **State doesn't exist!**

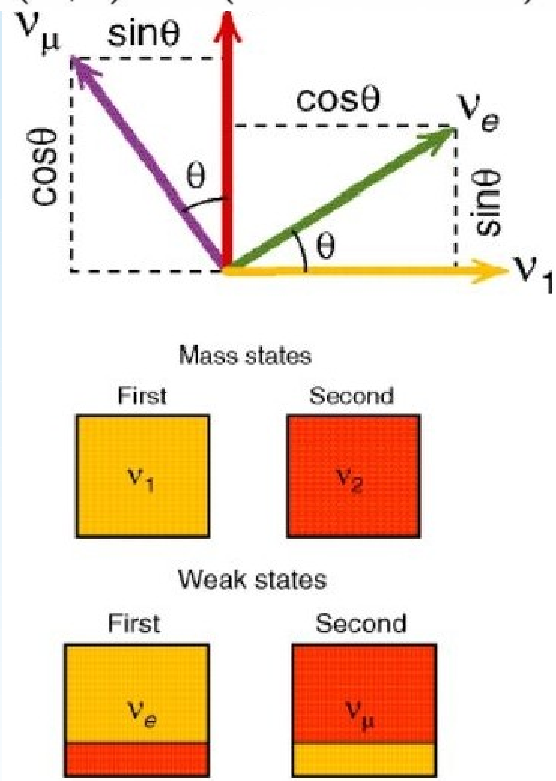
- Charge conjugation C:
  particles → anti-particles
  - $C|\nu_L\rangle \rightarrow |\bar{\nu}_L\rangle$ **State doesn't exist!**

- $CP|\nu_L\rangle \rightarrow |\bar{\nu}_R\rangle$ State exists. Neutrinos are always left-handed, anti-neutrinos – right-handed.

Neutrino oscillations: two flavors approximation

- For two flavor approximation the probability of flavor conservation may be expressed as:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

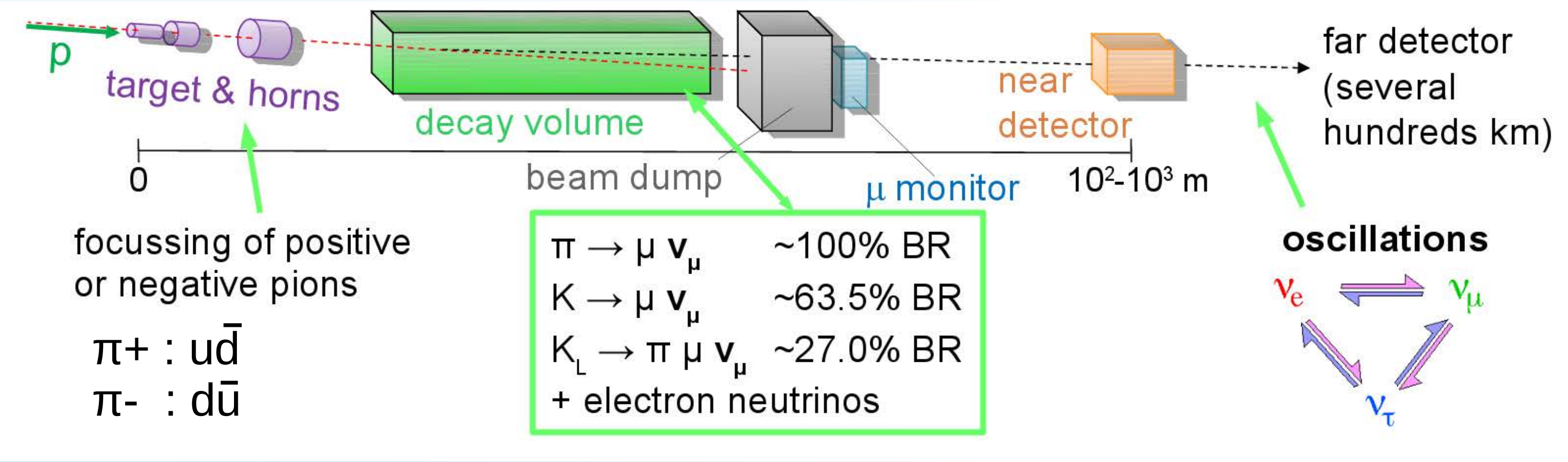


$$P(\nu_\mu \to \nu_\mu) = |\langle \nu_\mu(t) | \nu_\mu(0) \rangle|^2$$

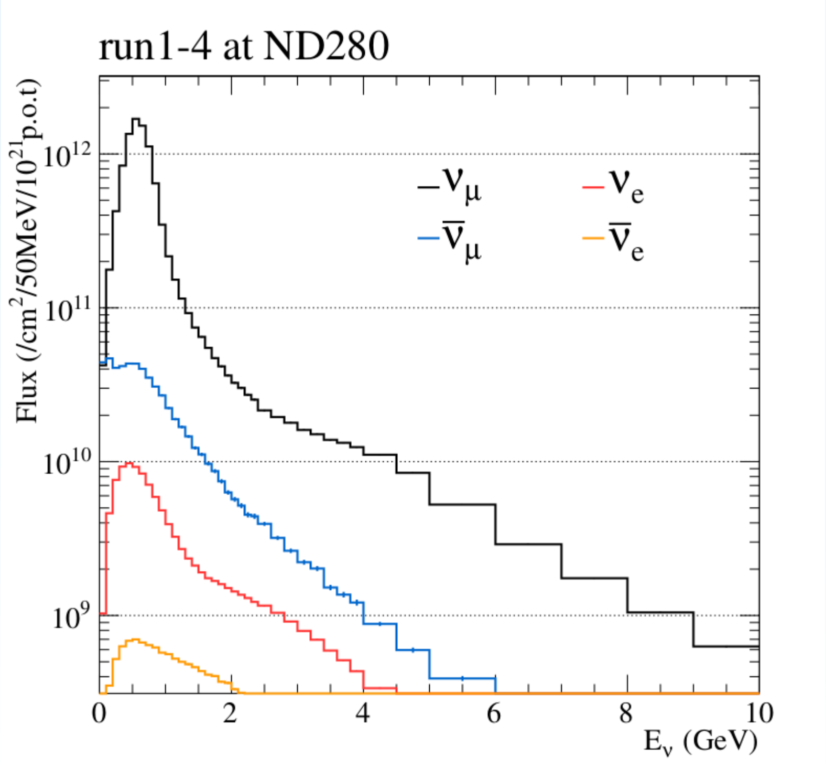
$$= 1 - \sin^2 2\theta \sin^2 \left(\frac{E_2 - E_1}{2} t \right)$$

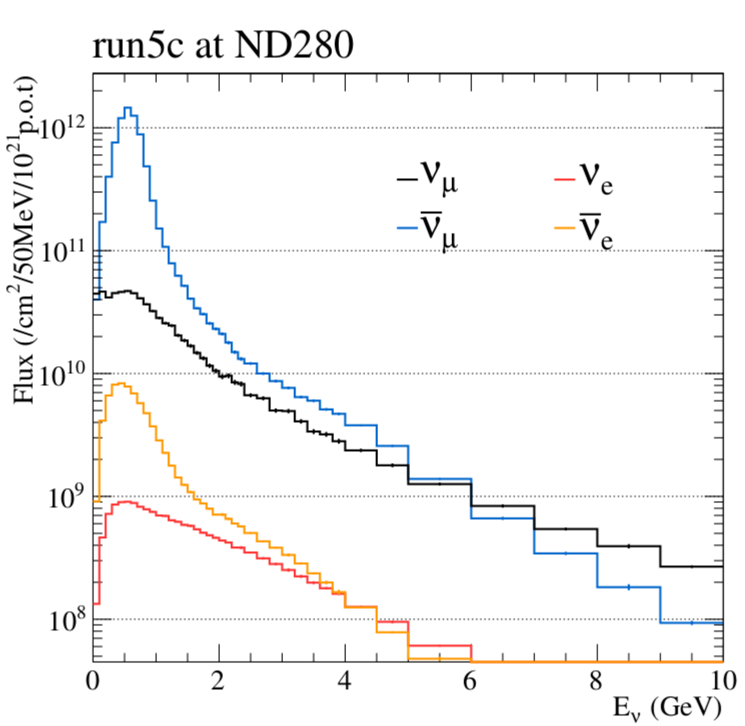
$$\approx 1 - \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2_{21} L}{4E} \right)$$

T2K beam

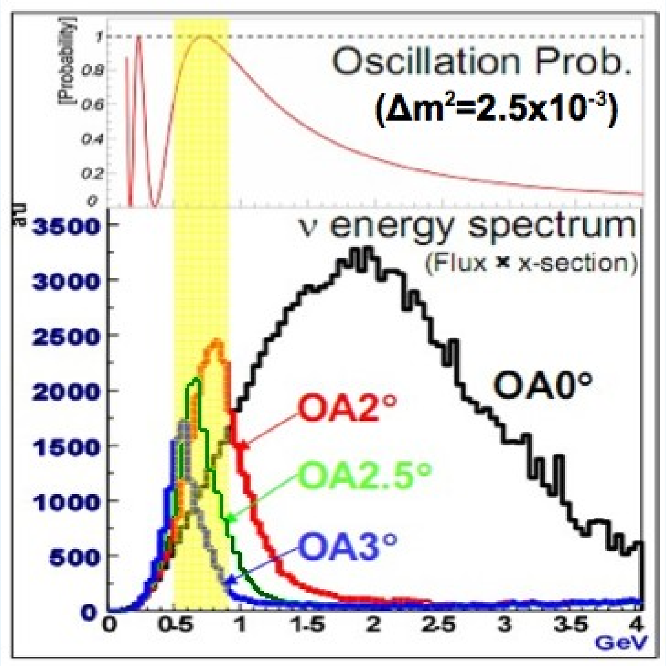


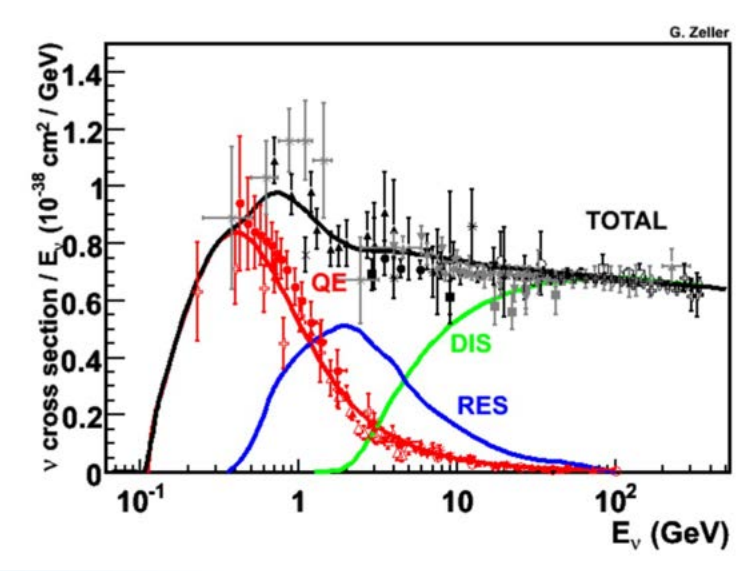
Beam may be used in FHC (neutrino) mode or RHC (anti-neutrino) mode.





Neutrino charged current interactions at T2K

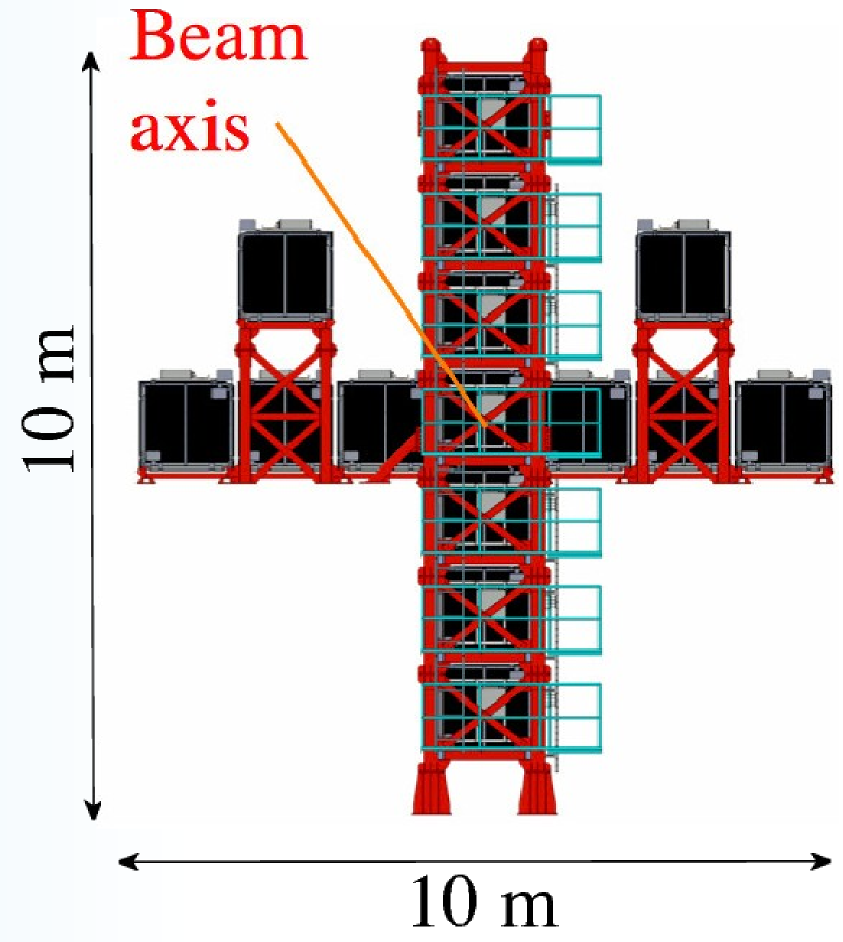




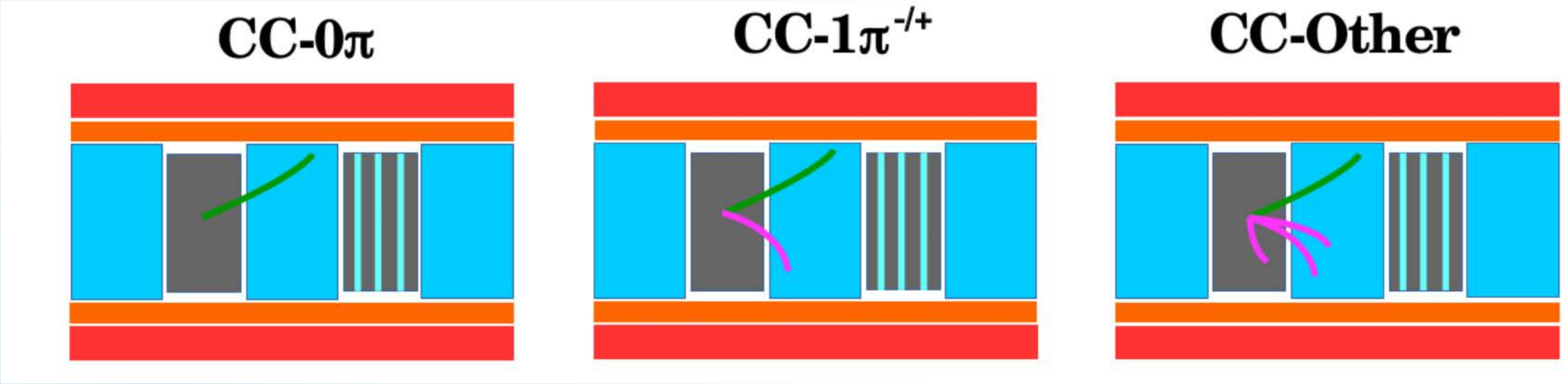
- Around T2K beam peak (~600 MeV), mostly CCQE and resonant reactions occur.
- Off-axis strategy enhances oscillation effect and CCQE interactions.

On-axis near detector: INGRID

- Cross-shaped detector composed of 16 Fe/scintillator modules and 1 only-scintillator.
- Monitors beam's direction, profile and intensity.

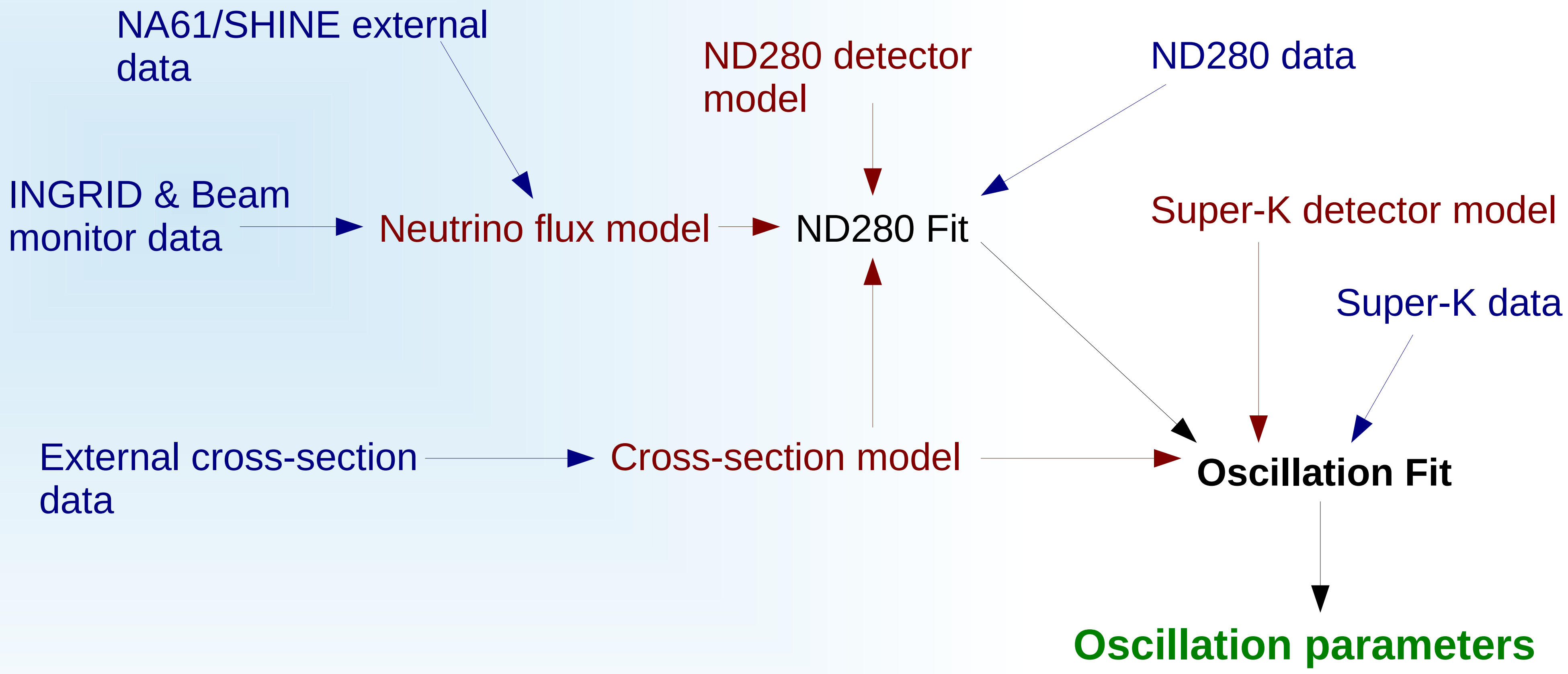


ND280 data samples

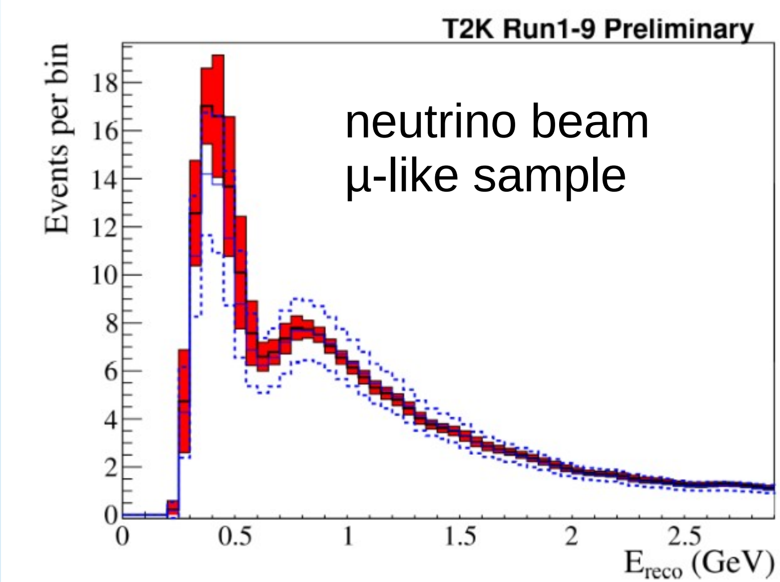


- We can't measure directly certain type of reaction. We classify event with respect to the pion multiplicity:
  - CC0π sample – enhanced with CCQE interactions
  - CC1π – enhanced with resonant interactions
  - CCother

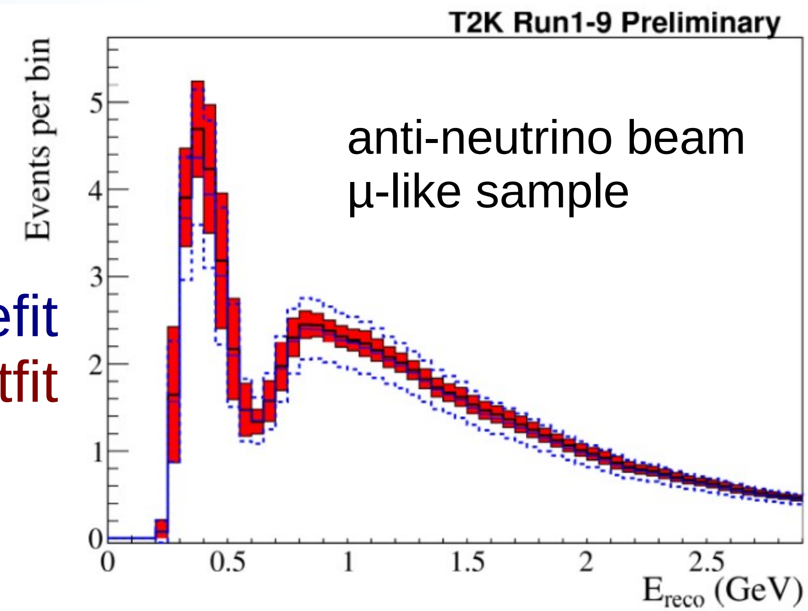
Analysis strategy

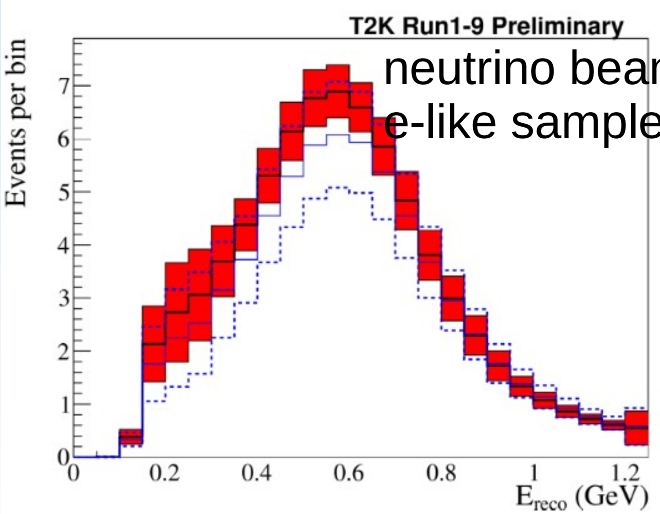


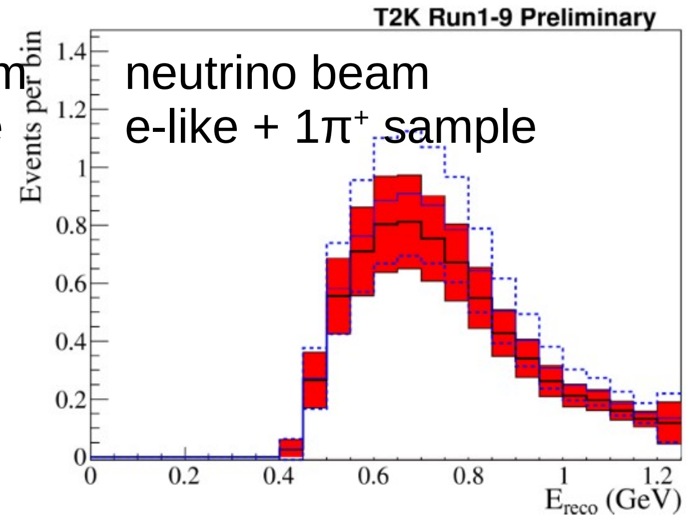
ND280 constraints for Super-K

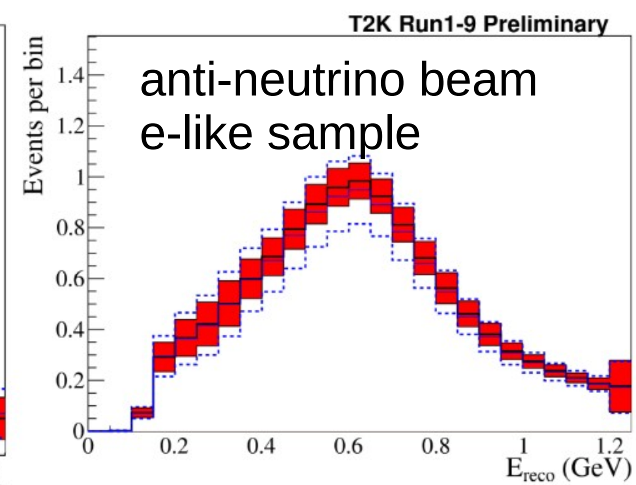


blue – prefit
red – postfit

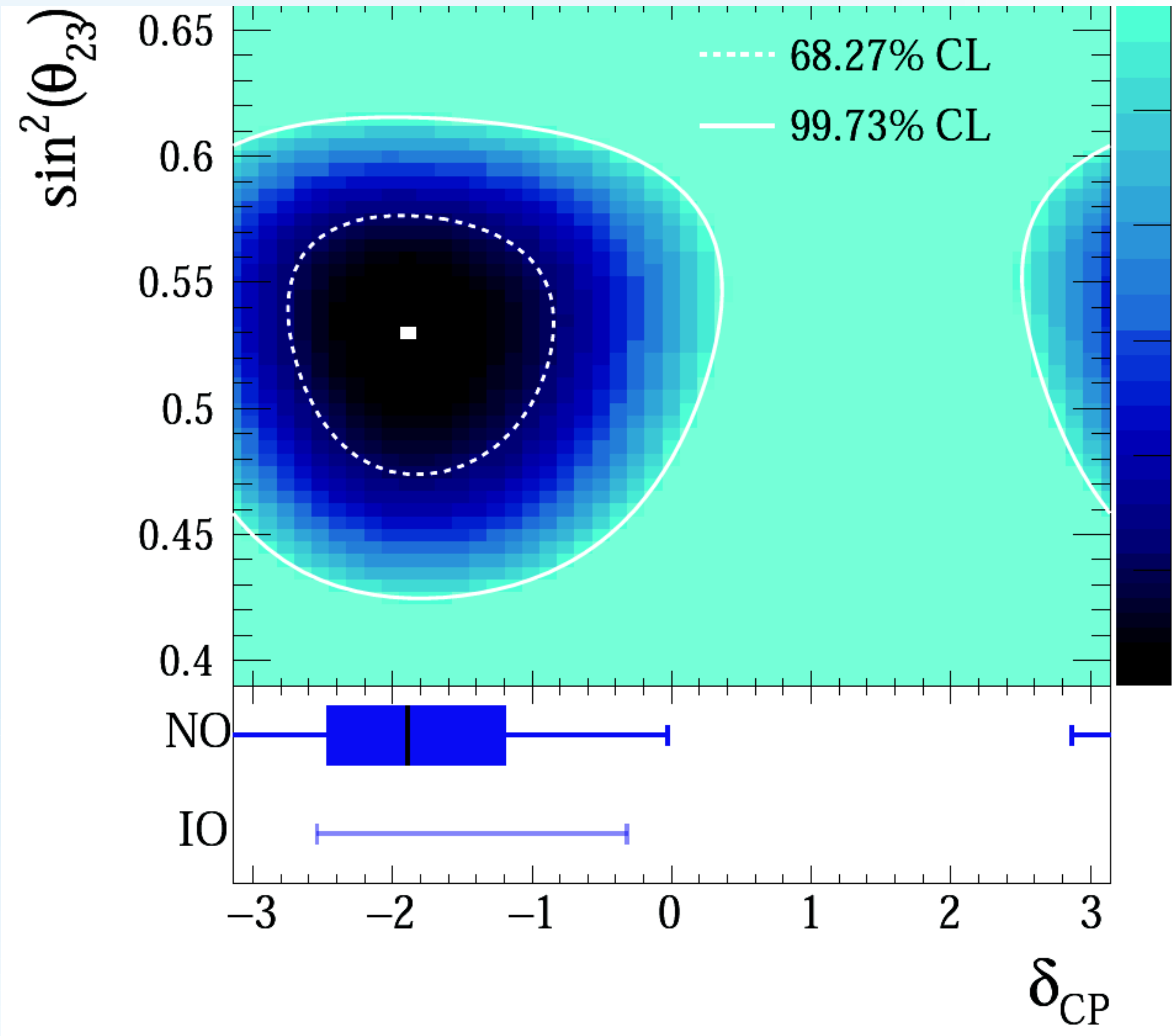








Results: $\sin^2(\Theta_{23})$ vs δ_{CP}

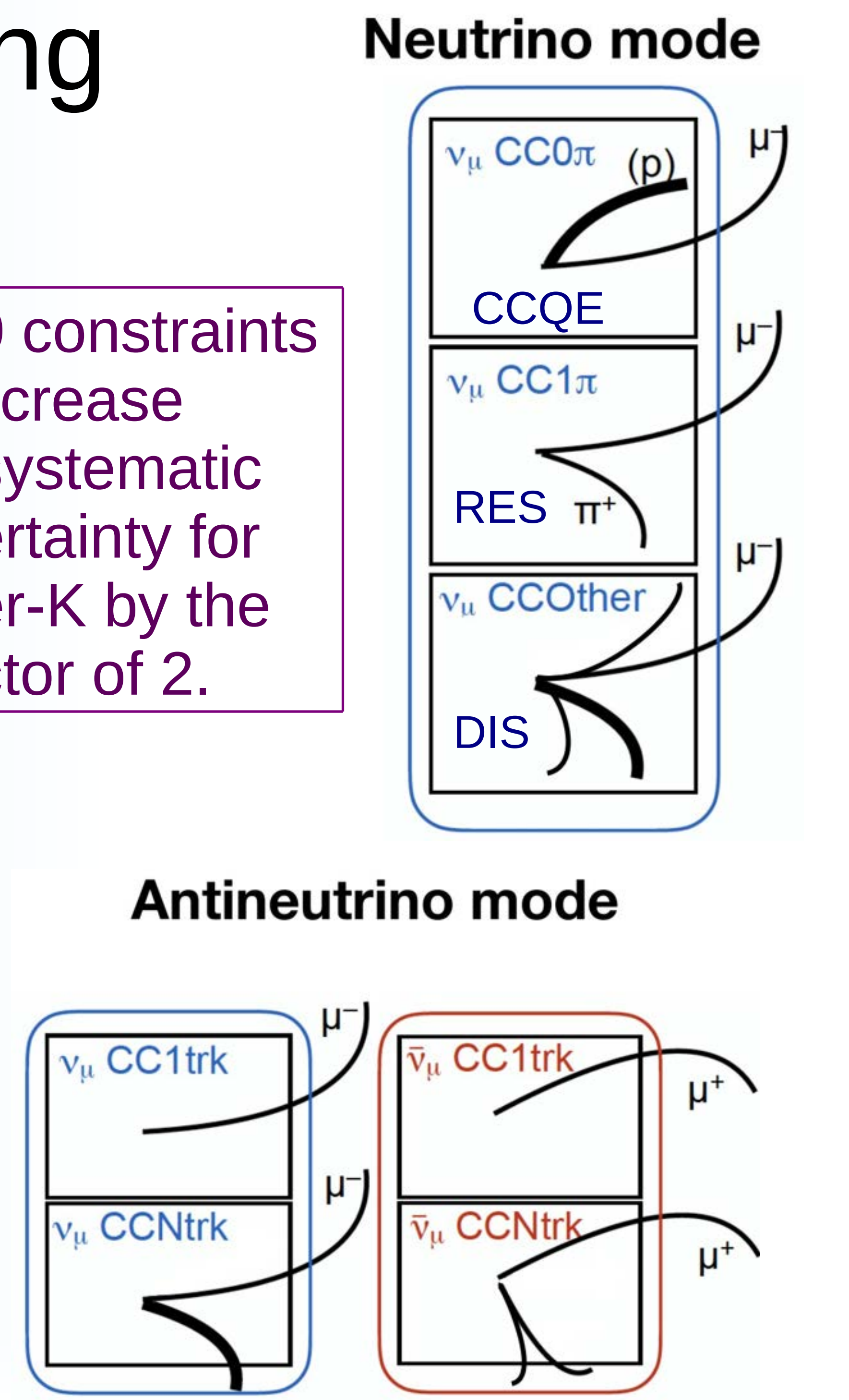


- CP-conserving values excluded at 2σ level
  - $\delta_{CP} = 0$ excluded at 3σ level
- Normal Hierarchy preferred (89%)
  - Best fit:
    δ_{CP} = -1.885 (-0.6π)
    for NH

ND280 data fitting

- Several samples of events:
  - For neutrino and antineutrino modes
  - Different reaction types (pion/track multiplicity)
  - C and O target nuclei
- **Ongoing analysis on extended ND280 samples (K. Skwarczynski)**

ND280 constraints decrease the systematic uncertainty for Super-K by the factor of 2.



Splitting **CC0Pi** based on proton multiplicity we can gain two samples with distinctive physical properties.

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

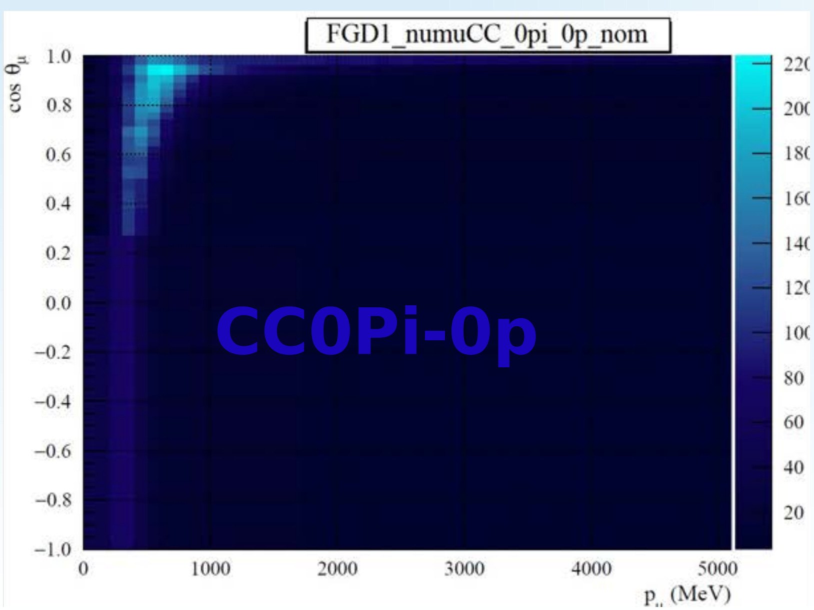
CC0Pi-Np - higher muon momentum, more muons going under higher angle.
Better purity for RES and DIS.

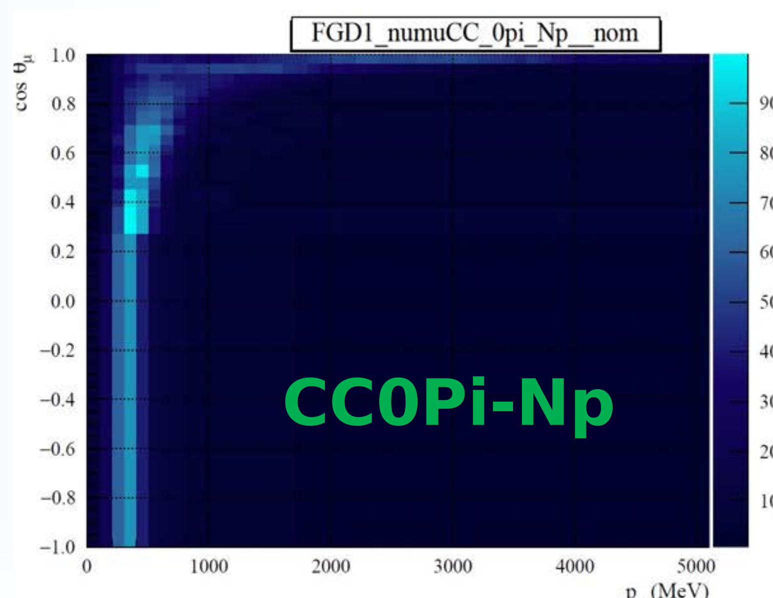
CC0Pi
0 reconstructed pions

CC0Pi-0p
0 reconstructed protons

CC0Pi-Np
>0 reconstructed protons

	CC0Pi	CC0Pi-0p	CC0Pi-Np
reaction	purity	purity	purity
CCQE	51	58	38
2p2h	11	10	11
RES	23	19	30
DIS	5	4	7

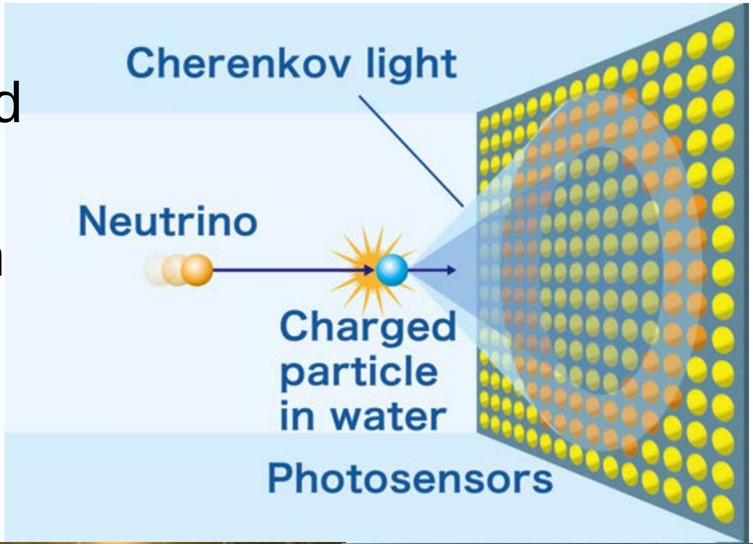


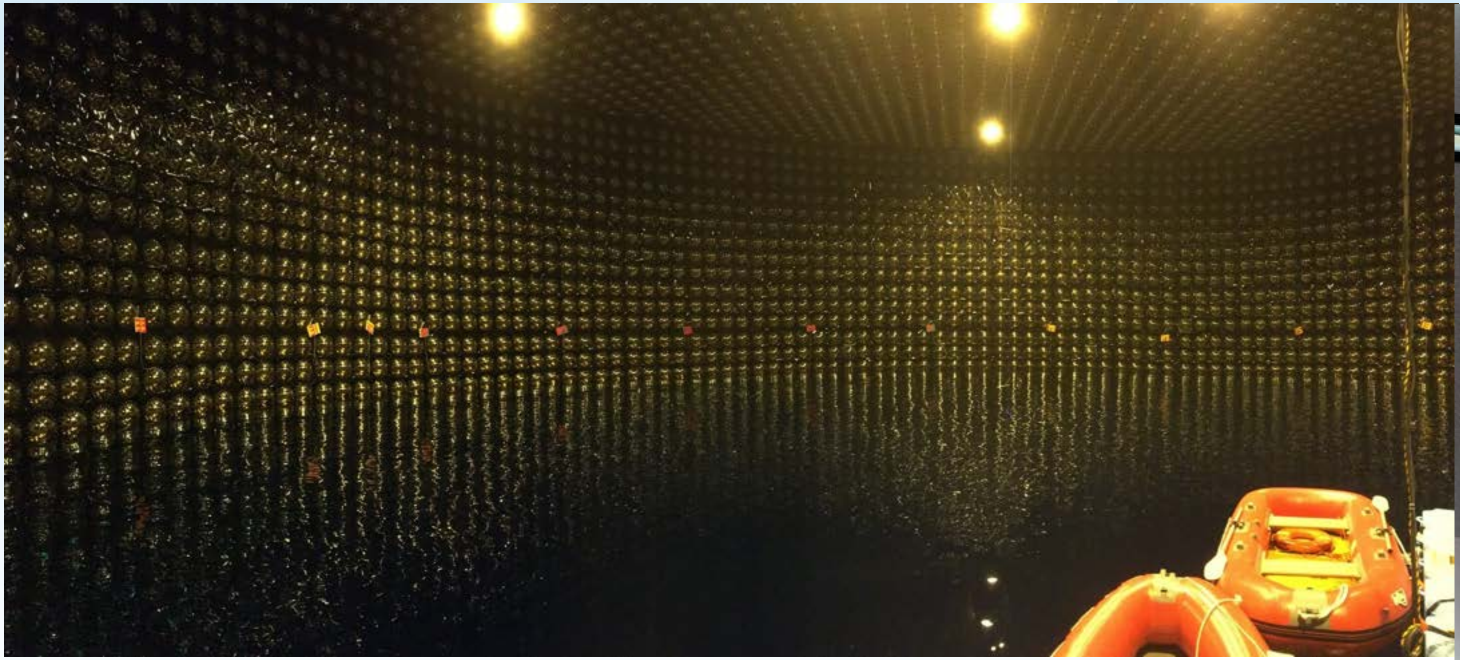


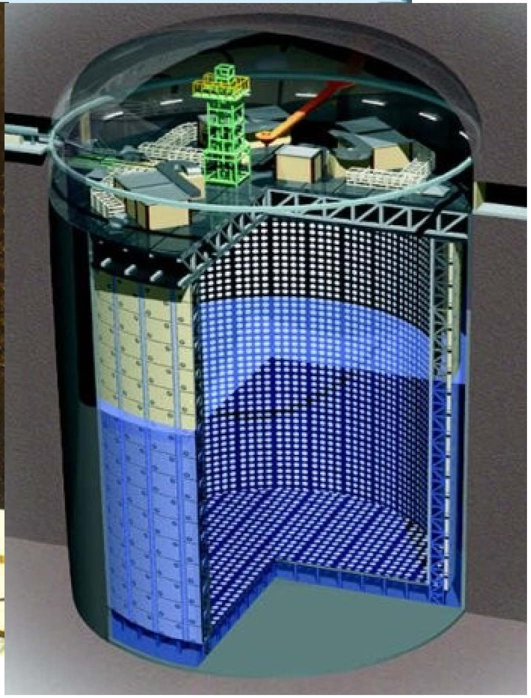
Far detector: Super-Kamiokande

- Cherenkov radiation appears when charged particle propagates with velocity v > c/n
- Single ring – signature of CCQE interaction
- **Vertex distribution studies (L. Mohan)**
- **Multiring samples (L. Mohan, Y. Prabhu)**

New group members







ν_μ CC $1\pi^+$ event selection

- Second largest sample after CCQE
- Inclusion in oscillation analysis is expected increase sensitivity to θ_{23} and $|\Delta m^2_{32}|$.

Software	Version
NEUT	5.3.2
SK software	14c library
fiTQun	v4r0
Flux tune	13av3
BANFF	20170614
T2KReWeight	v1r27p3

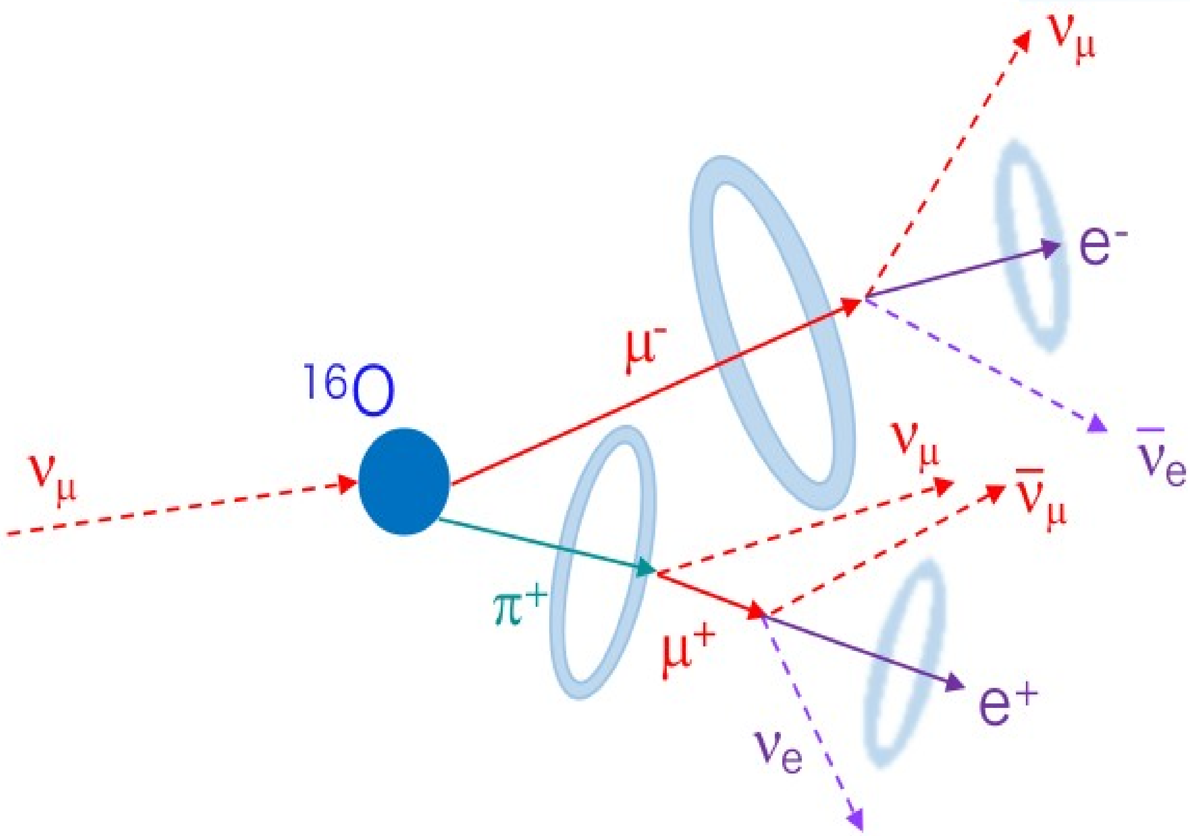


Figure 5.1: Schematic illustration of a ν_μ CC$1\pi^+$ event in SK.

Asimov A oscillation parameter set assumed

Parameter	Value
$\sin^2 2\theta_{12}$	0.806336
$\sin^2 2\theta_{13}$	0.0856816
$\sin^2 2\theta_{23}$	0.996864
Δm^2_{21}	$7.53 \times 10^{-5}\,\mathrm{eV}^2$
Δm^2_{32}	$2.509 \times 10^{-3}\,\mathrm{eV}^2$
δ_{CP}	-1.601

"A study of single charged-pion production events at Super-Kamiokande induced by charged-current interaction of T2K-beam muon neutrinos" – Thesis of Dr. Tomoyo Yoshida

Event Selection Criteria

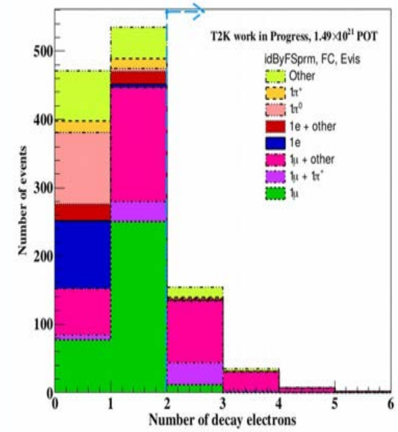
- Fully contained events: $evclass == 1$ and $nhitac < 16$, where $nhitac$ = PMT hits in the outer detector
- Visible energy cut: $evisible > 30$ MeV
- FV: $fqdwall > 80$ cm for 1 decay electron sample and $fqdwall > 50$ cm for 2 decay electron sample
- Ndecay e cut: Number of fiTQun sub–events = 2 (3) for 1 (2) decay electron sample.

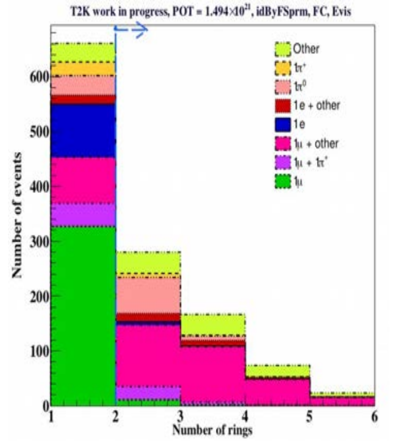
- Masking cut to avoid double counting 1 ring events: i.e, don't count as multi–ring event if the number of rings from multi–ring fitter = 1 and number of fiTQun sub–events < 3.

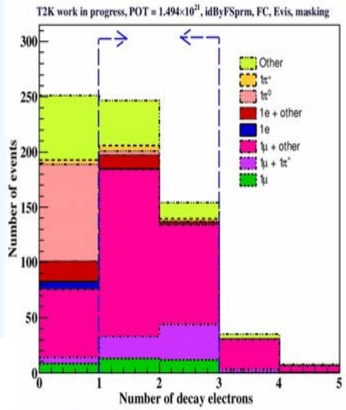
- $ln(L_{\pi\pi}/L_e) > 400 + 1.2p^{min}_{\pi\pi}$ for 1 decay e; $ln(L_{\pi\pi}/L_e) > 400 + 1.0p^{min}_{\pi\pi}$ for 1 decay e.

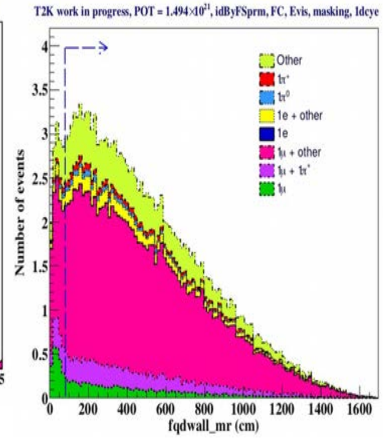
- $ln(L_{the\ best\ of\ other\ 2R\ hypotheses}/L_{\pi\pi}) < 340$ for decay e; $ln(L_{the\ best\ of\ other\ 2R\ hypotheses}/L_{\pi\pi}) < 310$ for decay e.

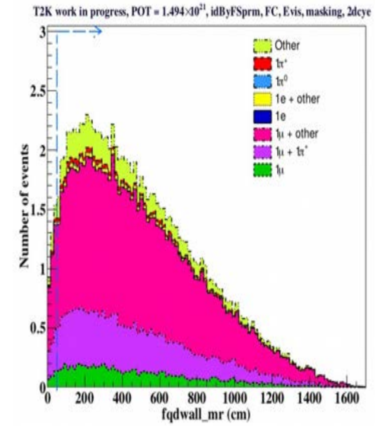
- E_{loss} cut $fqmreloss[i][0] + fqmreloss[i][1] > 300$ with $fqmrifit[i] = 20000033$ for 1 decay e sample only

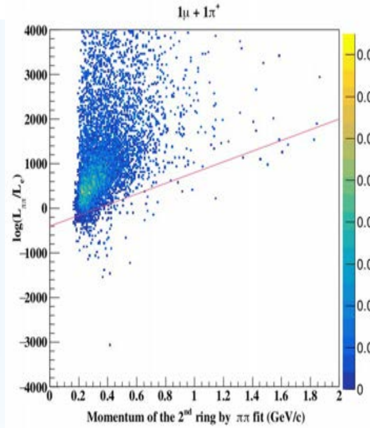


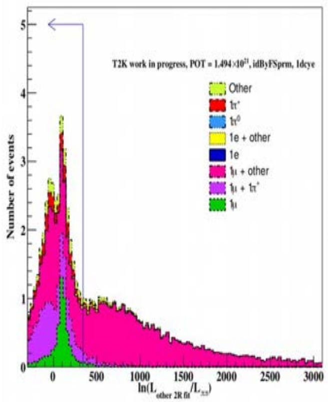


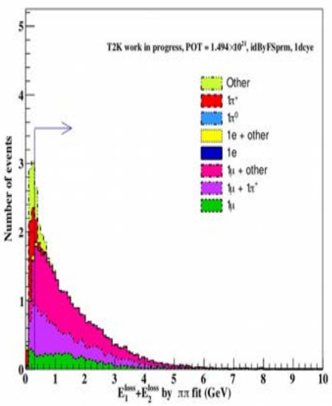








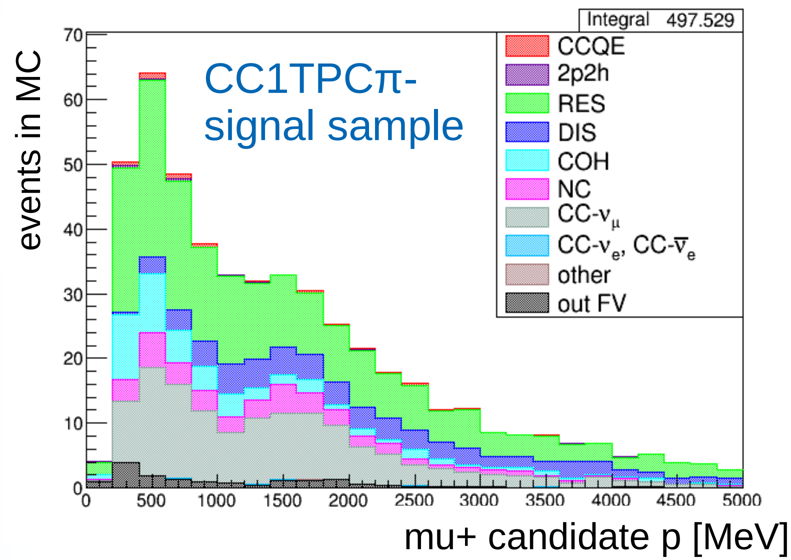


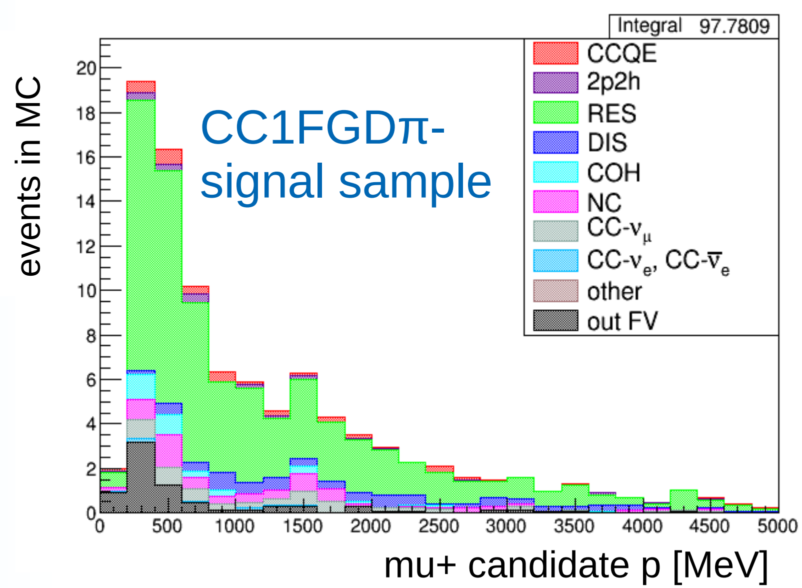


14b MC

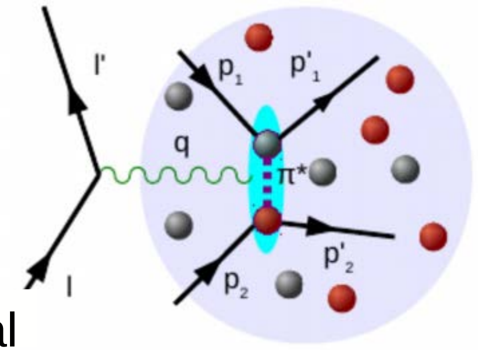
Cross-section measurements

- measurements → better interactions models → better predictions for the oscillation studies
- continuation of activities reported last year
  - well advanced, the final results expected soon
- **single pion production** by antineutrinos
  $\bar{\nu}_\mu + N \rightarrow \mu^+ + \pi^- + N'$
  (G. Żarnecki supervised by JŁ)
  - large background from neutrino contamination
  - selection and control samples approved
  - systematics ready
  - fake data studies ongoing
  - waiting for permission to look at real data

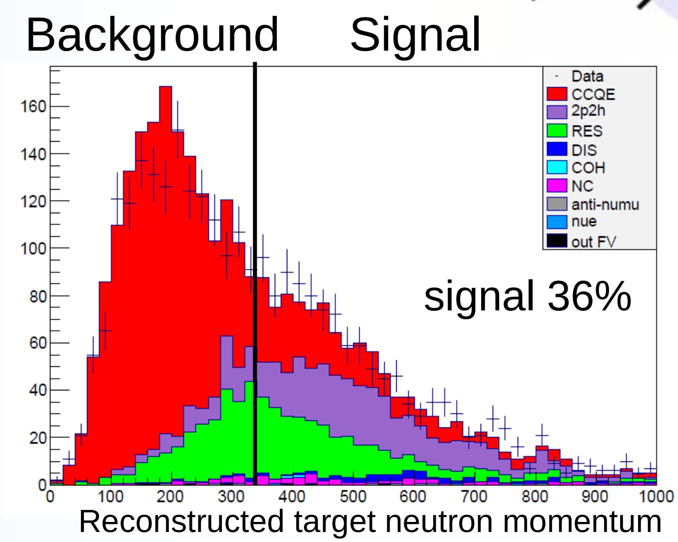




Cross-section measurements



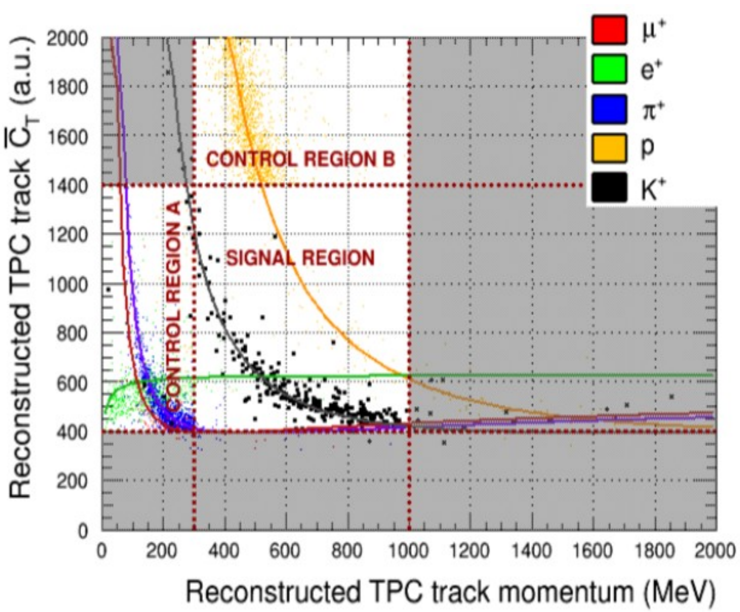
- **searches for Meson Exchange Current** (J.Zalipska)
  - low energy nucleons expected in an event
  - big differences in the models
  - discriminating variable:
    reconstructed target neutron momentum
  - studies of detector systematics
    in progress



- **strangeness production** by neutrinos (K.Kowalik)

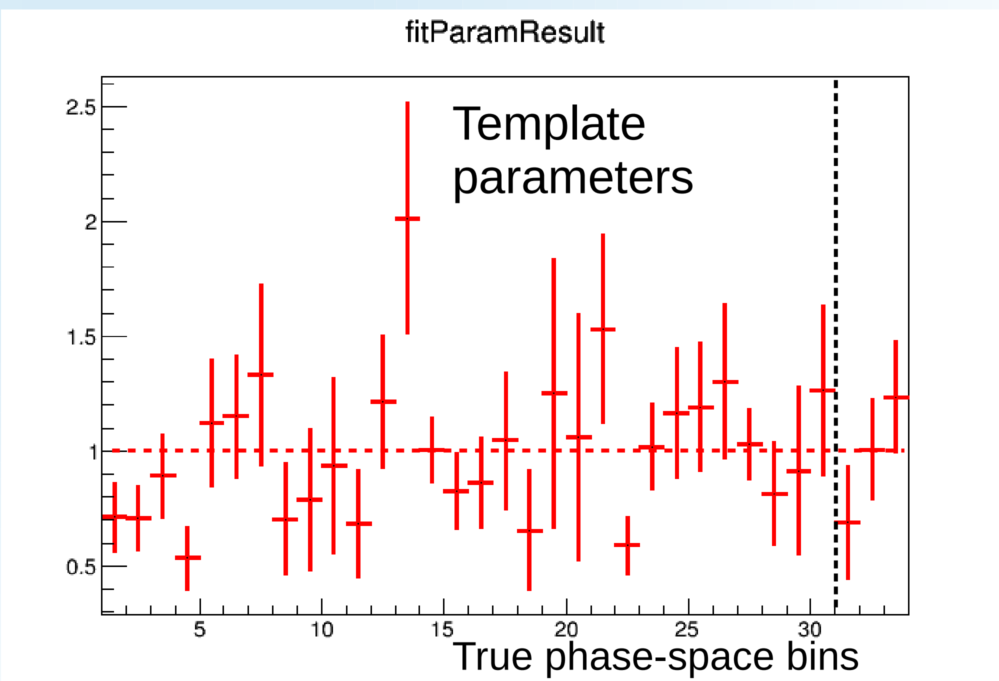
  associated production $\nu_\mu + n \rightarrow \mu^- + K^+ + \Lambda^0$
  single particle production $\nu_\mu + p \rightarrow \mu^- + p + K^+$

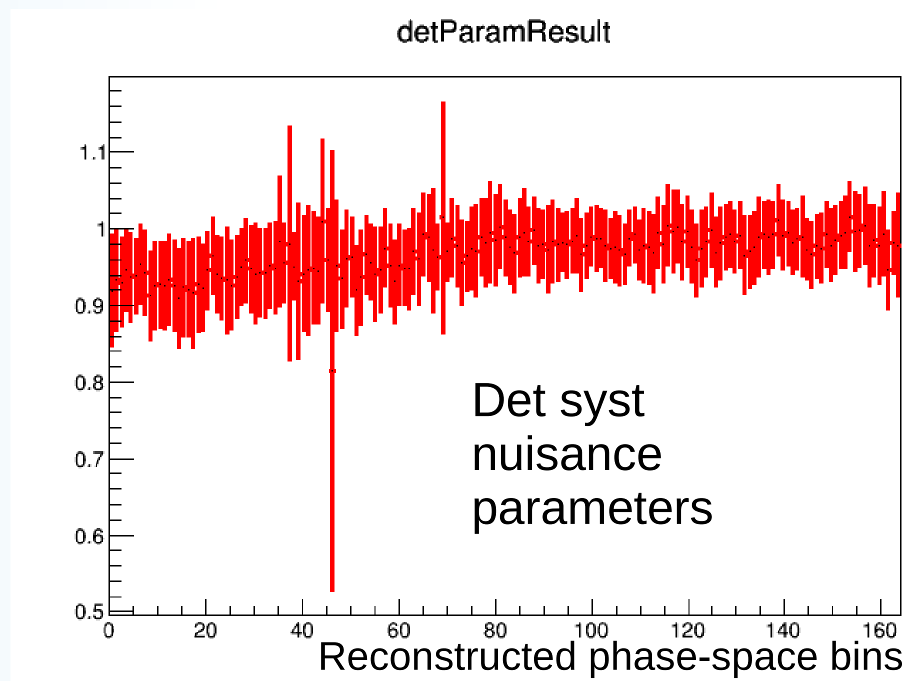
  - efficiency study done
  - systematic errors estimated
  - final checks of background control samples
  - models of final and secondary state interactions under investigation (not well known)



$\bar{\nu}_\mu$ CC1π- cross section measurement

- The basic goal of the analysis is measuring x-section for muon antineutrino CC interaction with single π^- production on carbon target.
- Selection tested in many ways (efficiency, Q^2, W, phase space, E_ν)
- Cross-section will be extracted via likelihood fit method.



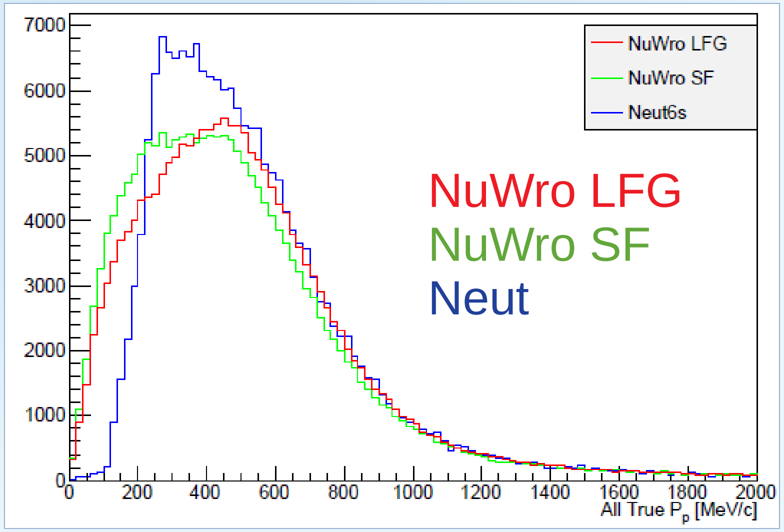


- Currently the fake data studies with cross-section extraction tools are being done.

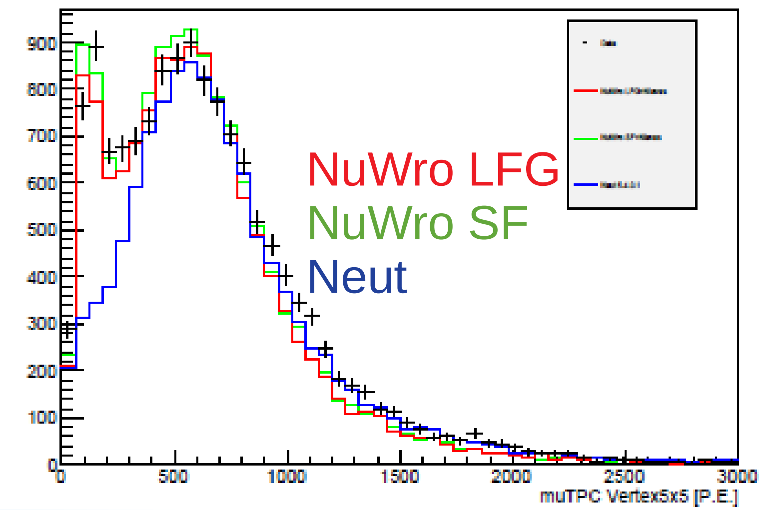
Low momentum protons

- Low momentum protons are simulated differently by NEUT and NuWro neutrino Monte Carlo generators

Vertex Activity for CC0π sub-sample with reconstructed muon track only, low momentum proton is not reconstructed, but visible in VA



True proton momentum [MeV/c]



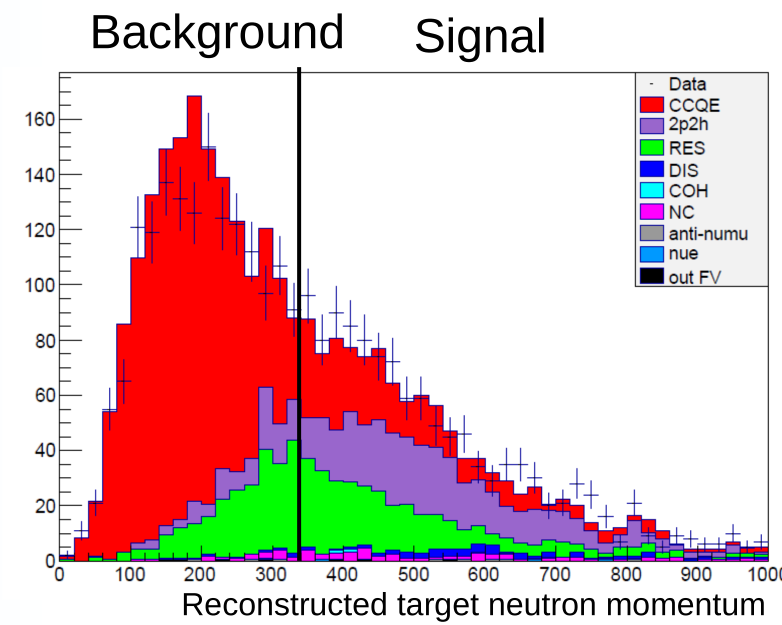
Vertex in 5x5 box [P.E.]

NuWro Spectral Function agrees with data

Search for MEC signal

For sample with reconstructed muon and proton tracks

Reconstructed target neutron momentum helps to discriminate between CCQE-enhanced (Background) and MEC-enhanced (Signal) sub-samples.

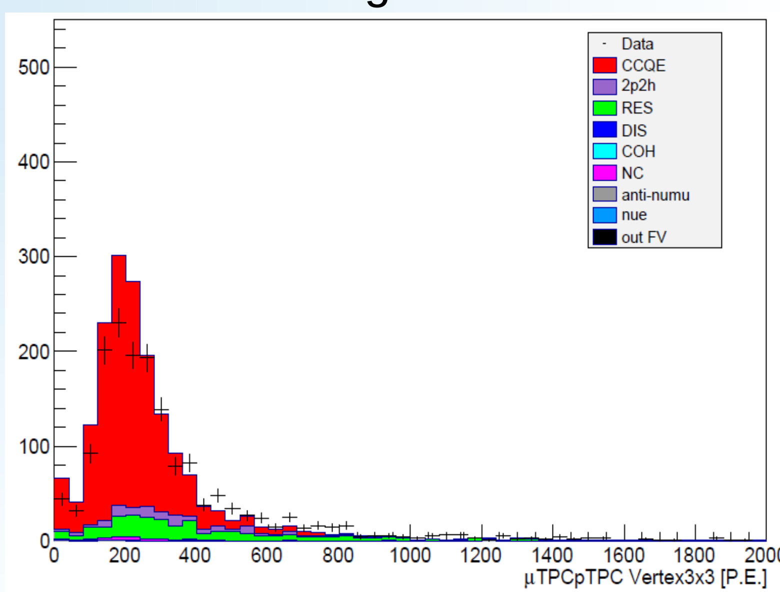


VA after Pn cut

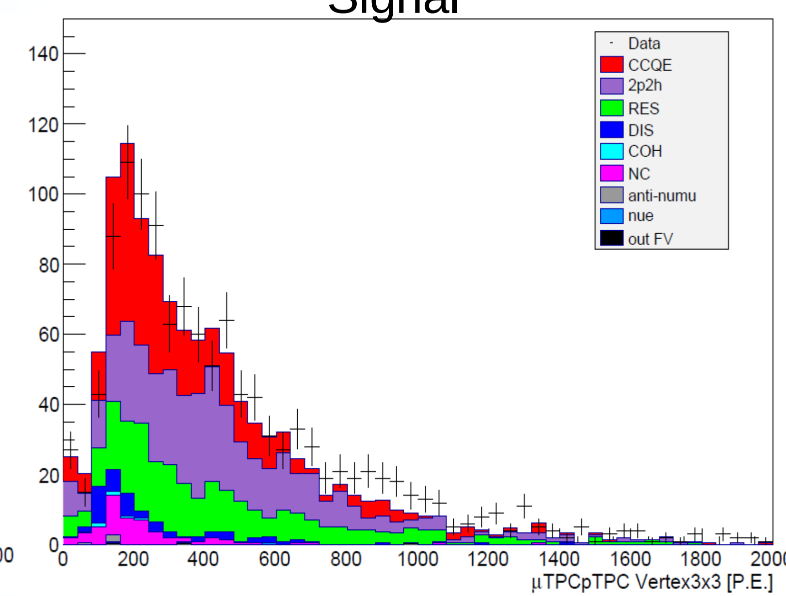
Background:
CCQE 78%
MEC 6%

Signal:
CCQE 31%
MEC 36%

Background

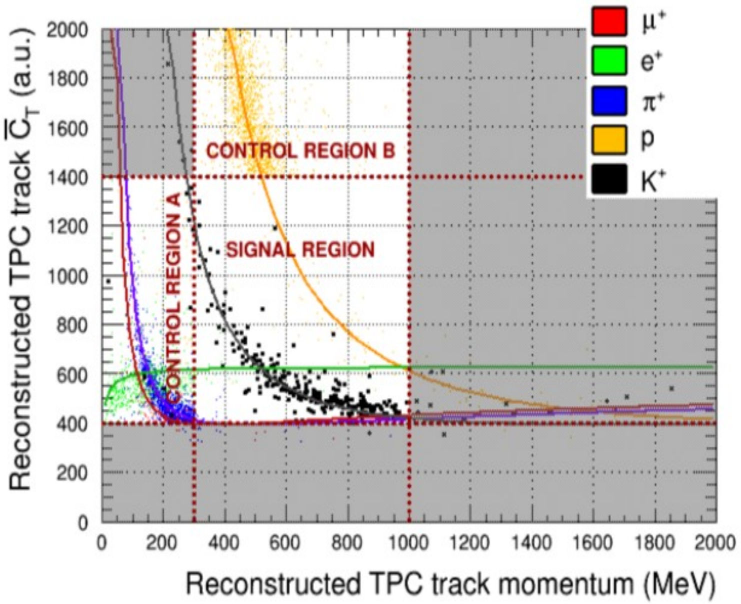


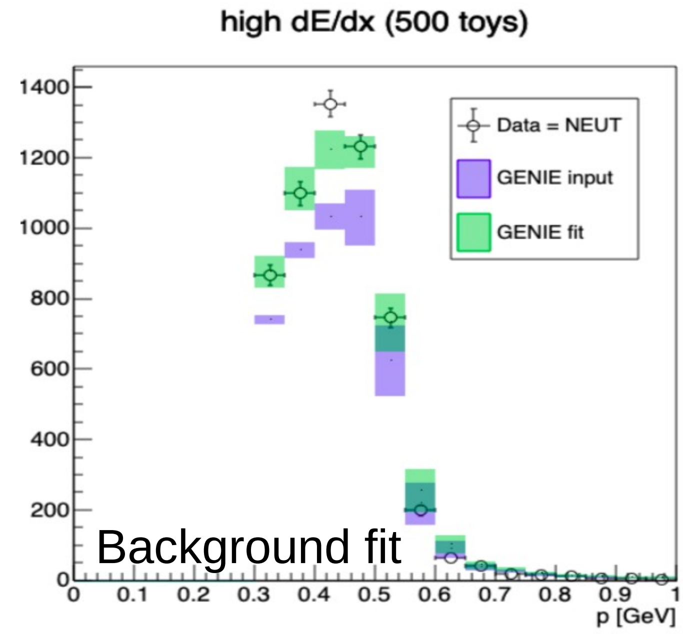
Signal



Measurement of Strangeness Production

- K^+ production by neutrinos (K.Kowalik)
  - associated production $\nu_\mu + n \rightarrow \mu^- + K^+ + \Lambda^0$
  - single particle production $\nu_\mu + p \rightarrow \mu^- + p + K^+$
- Cross section for $\nu_\mu CC1K^+$ on carbon
  - First measurement, limited statistics, inputs ready or nearly finished
  - Both K+ and μ selected in TPC with PID cuts
  - Efficiency study performed for different MC/ production models
  - Systematic errors dominated by K^+ PID and secondary interactions
  - Background estimated from MC fit to data for control samples (final checks)
  - Modeling of final and secondary state interactions under investigation (not well known)
  - Under internal review, publication expected

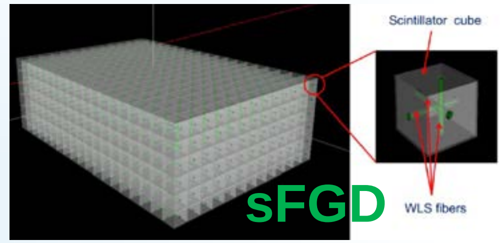


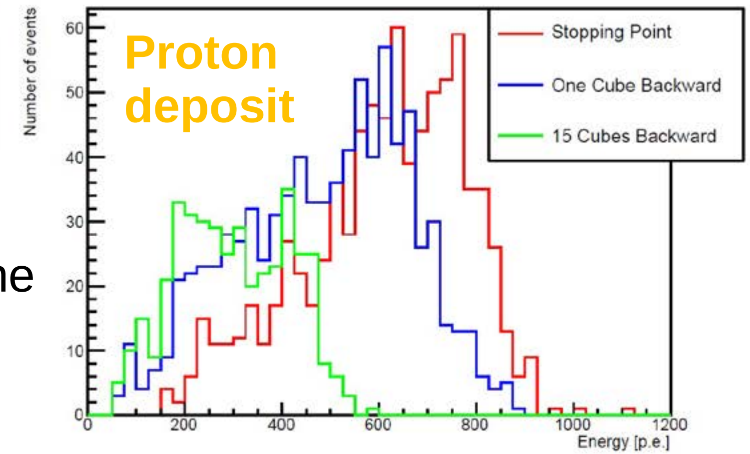


Crosstalk study in Super FGD prototype

Super FGD (sFGD)–new scintillation detector for ND280 consisting of scintillation **cubes**.

Prototype was tested at CERN in 2018.





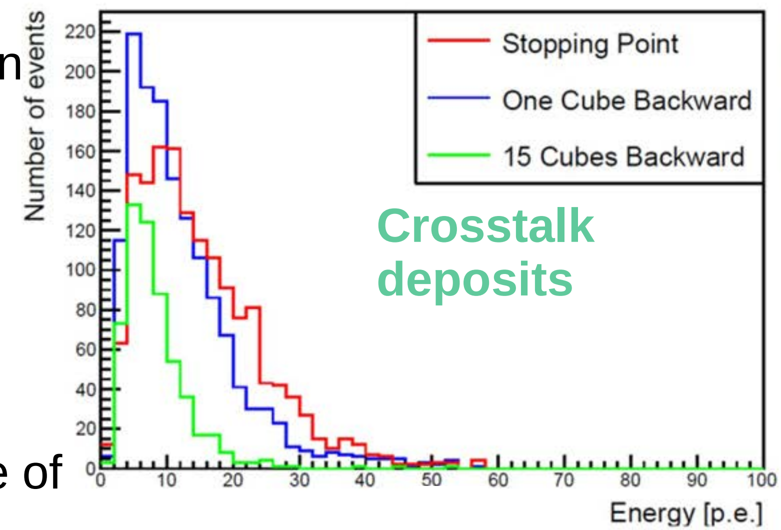
Compare cubes with the proton deposit with surrounding cubes.

Cube where proton „stops" was studied (stopping point).

Results were compared with crosstalk one cube backward,

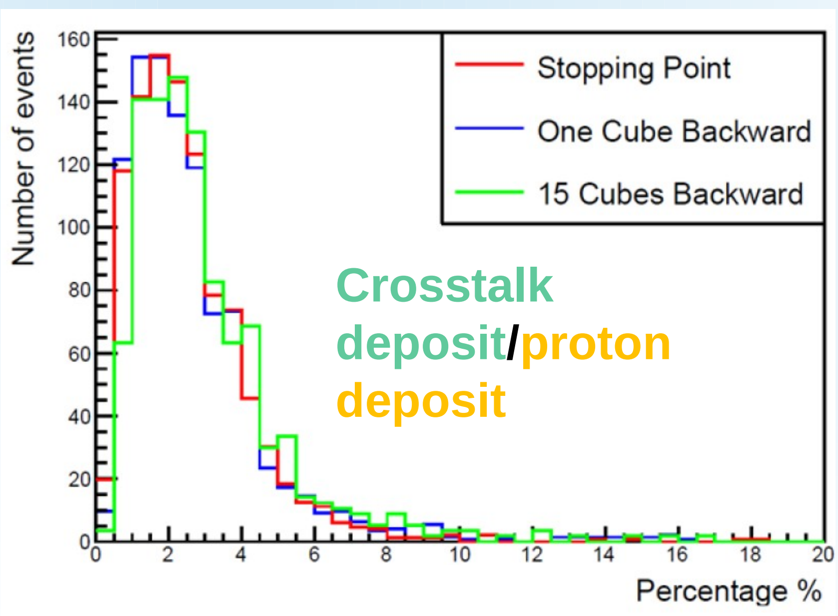
and with crosstalk 15 cubes backward from stopping point.

Proton deposits changes depending on the position from stopping point.



Crosstalk deposits behaves similarly.

Crosstalk deposits depends on the value of proton deposit.



We take crosstalk deposit and divide it by proton deposit event by event.

Crosstalk deposit is proportional to proton deposit.

Results published in J. of Instr.