# Electron antineutrino appearance
## and our involvmenent in

T2K

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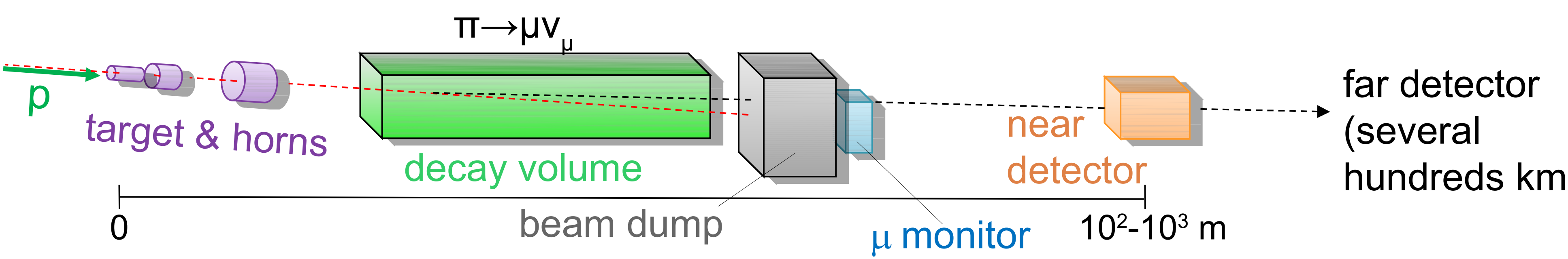
# T2K experiment

- long-baseline (295km) experiment
  - high intensity muon (anti)neutrino beam
  - peak energy 600 MeV


- relatively well controlled beam of neutrinos from (mostly) pion decays




- (anti)$\nu_\mu$ disappearance and (anti)$\nu_e$ appearance can be studied
  → ultimate goal: **CP violation**

- started to take data in 2010, $\nu_e$ appearance discovered in 2013

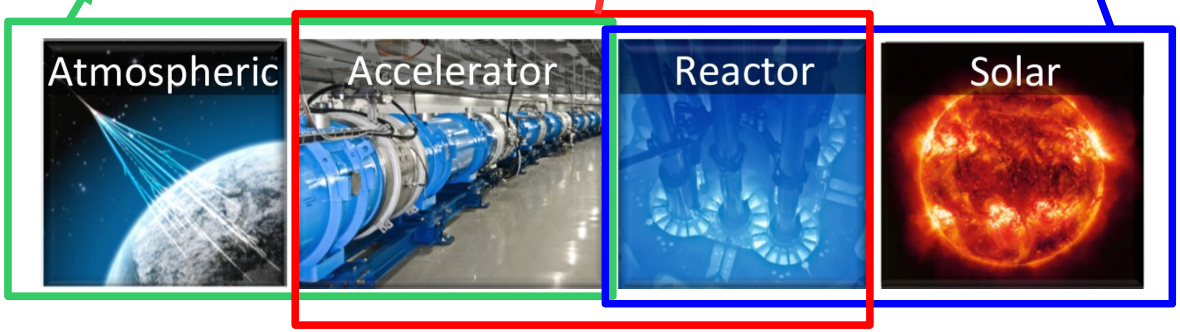
# Neutrino mixing and oscillations

mixing of flavor and mass eigenstates → PMNS matrix
parametrized as

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

$c_{xy} = \cos\theta_{xy}$
$s_{xy} = \sin\theta_{xy}$

**atmosphere**: $\nu_\mu$ disappearance
**accelerators**: $\nu_\mu$ disappearance and $\nu_\tau$ appearance




**Sun**: $\nu_e$ disappearance
**reactors**: $\bar{\nu}_e$ disappearance

**accelerators**: $\nu_e$ appearance
**reactors**: $\bar{\nu}_e$ disappearance

(in vacuum)

$$P_{\nu_\alpha\to\nu_\beta}=\delta_{\alpha\beta}-4\sum_{i>j}\Re\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin^2\Delta m^2_{ij}\frac{L}{4E}\pm2\sum_{i>j}\Im\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin^2\Delta m^2_{ij}\frac{L}{4E}$$

oscillation probabilities depend on 6 parameters – constants of nature: $\theta_{12}$, $\theta_{13}$, $\theta_{23}$, $\Delta m^2_{21} = m^2_2 - m^2_1$, $\Delta m^2_{32} = m^2_3 - m^2_2$, $\delta_{CP}$
and 2 specific for an experiment: baseline **L** and neutrino energy **E**

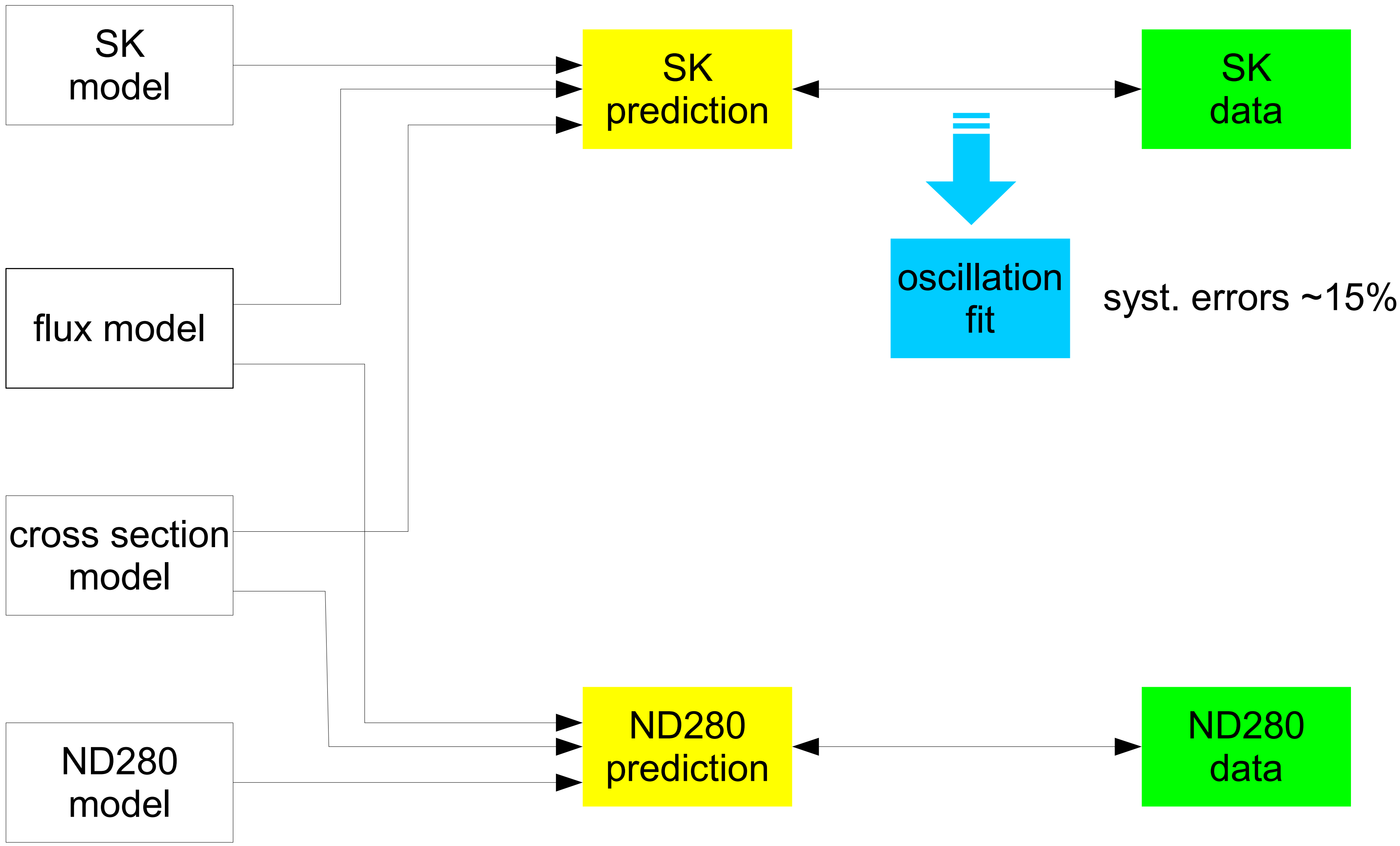
# Oscillations in T2K

- disappearance: $\nu_\mu \rightarrow \nu_\mu$ : $\theta_{23}$, $m^2_{32}$
  - comparison of $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ : CPT conservation
- appearance: $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ : $\theta_{13}$, $\theta_{23}$, $m^2_{32}$, $\delta_{CP}$
  - comparison of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ : CP conservation
- analysis method:
  comparison of <u>predicted</u> and <u>observed</u> rates and spectra of events

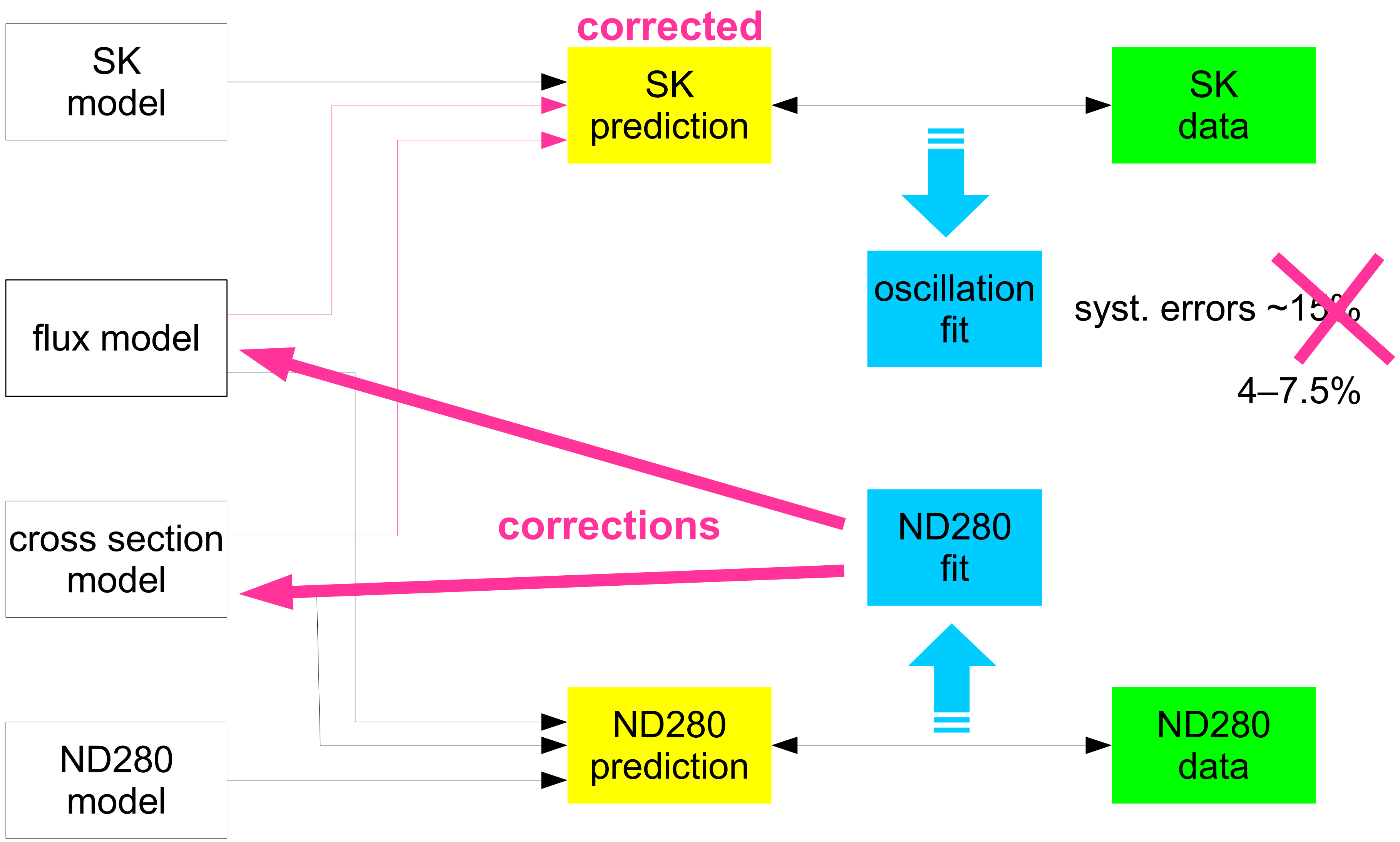
- neutrino flux modelling
- neutrino interaction modelling
- detector modelling
- oscillation probability formula

- detector calibration
- event reconstruction
- event selection
- systematic errors

# Analysis chain

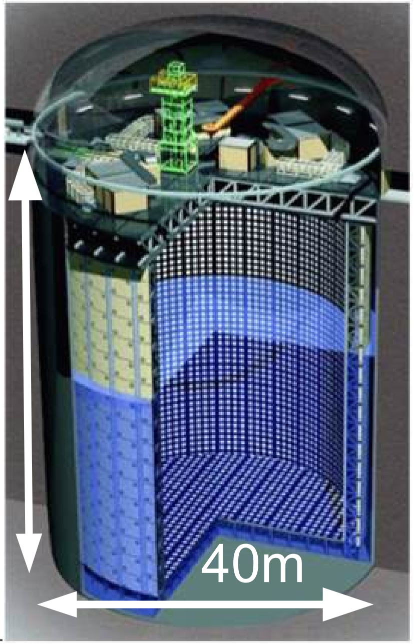


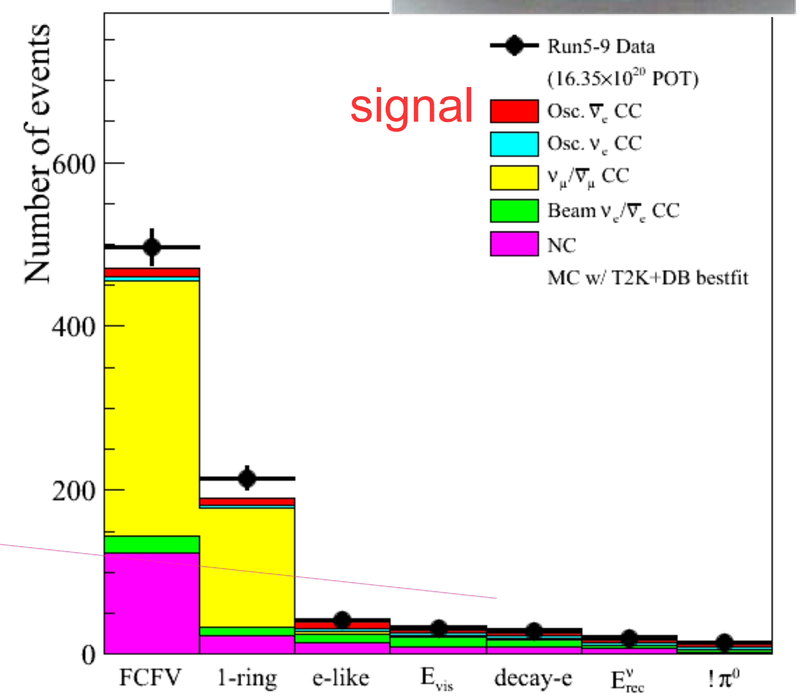
# Analysis chain

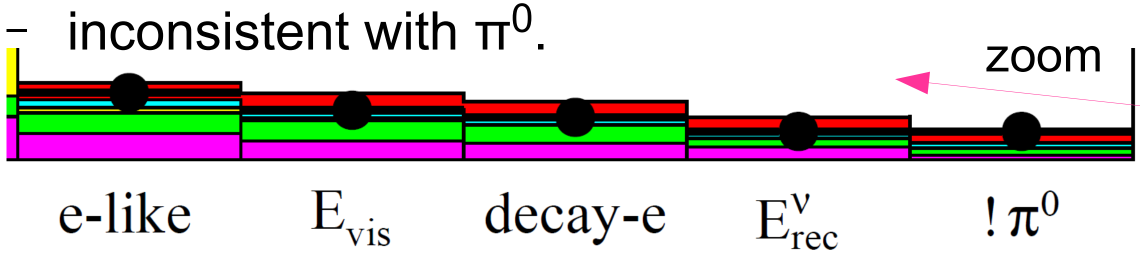


# T2K Far Detektor

- Water Cherenkov Super-Kamiokande
  - fiducial mass 22 kton, >11 000 PMTs in inner detector
  - $\Delta E/E$ ~10% for 2-body kinematics (QE-like)
  - very good $\mu/e$ separation
- interesting events:
  - CCQE candidates (for $\nu_\mu$, $\nu_e$, $\bar{\nu}_\mu$, $\bar{\nu}_e$) → $E_\nu$ reconstruction
  - sample enhanced in resonant pion production by $\nu_\mu$
- selection for $\bar{\nu}_e$ appearance
  - at beam time, fully contained, >80cm from wall
  - 1 Cherenkov ring, electron-like, >170cm from wall along electron direction
  - $E_{vis}$>100 MeV, no delayed activity,
  - $E_{\nu rec}$<1250 MeV,
  - inconsistent with $\pi^0$.

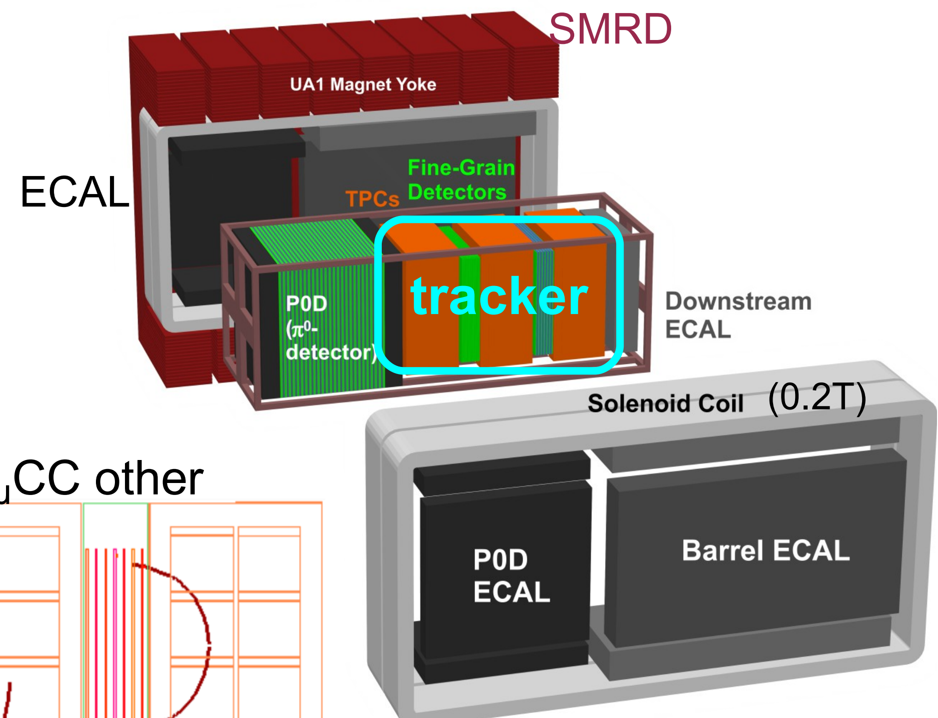


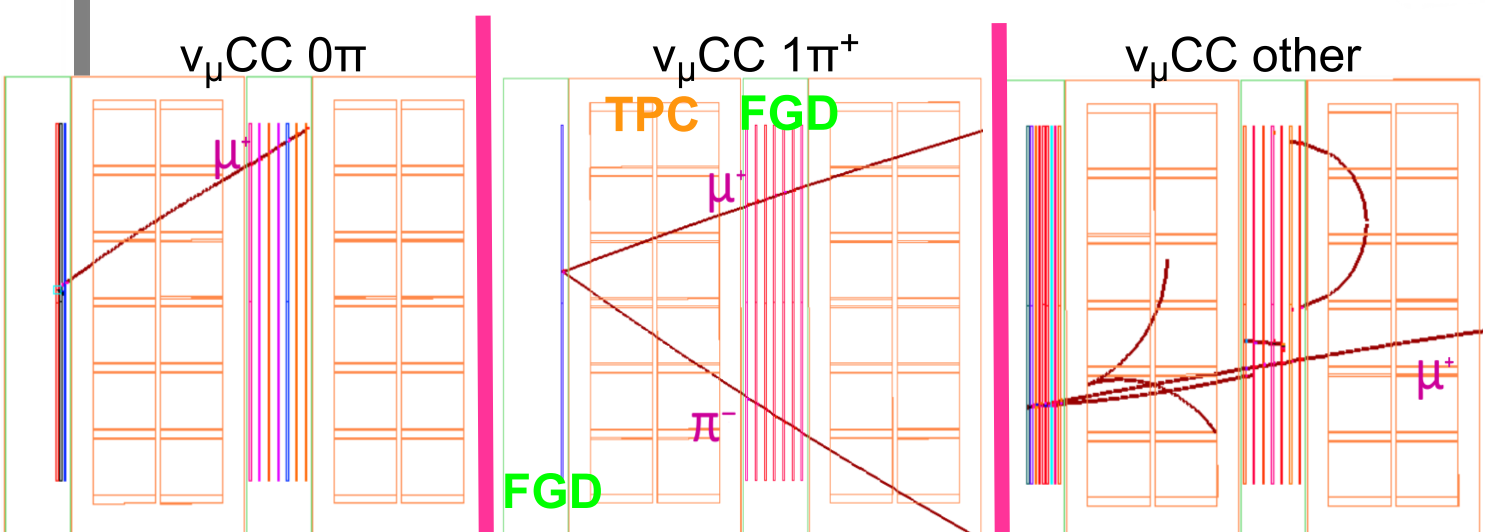



# T2K Near Detector

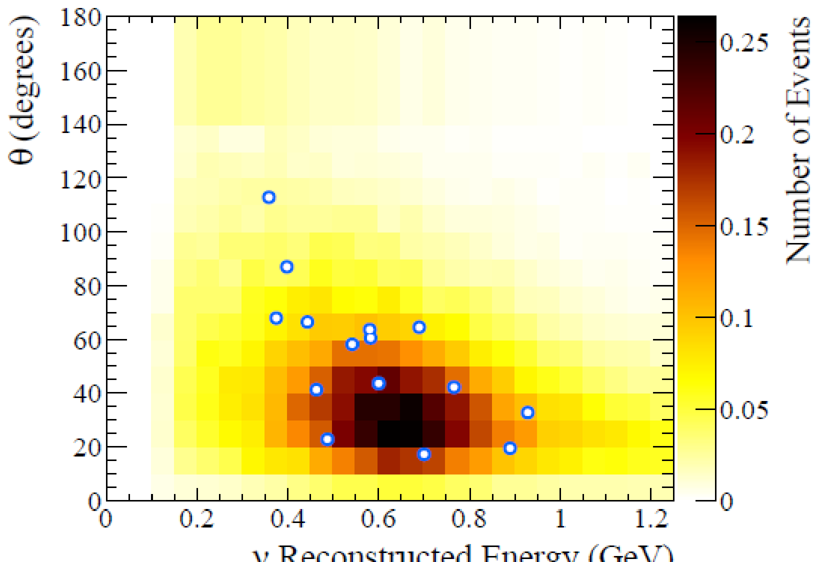
- set of **near detectors** at 280m
  - on-axis detector (INGRID) - controls beam direction and intensity
  - multi-purpose magnetized off-axis **ND280 -** used in oscillation analysis to suppress systematic errors and for cross-section measurements
- ND280 event samples
  - for neutrino beam mode:
    $\nu_\mu$CC 0π, 1$\pi^+$, other
  - for antineutrino beam mode:
    $\bar{\nu}_\mu$CC 1 track, N tracks,
    $\nu_\mu$CC 1 track, N tracks

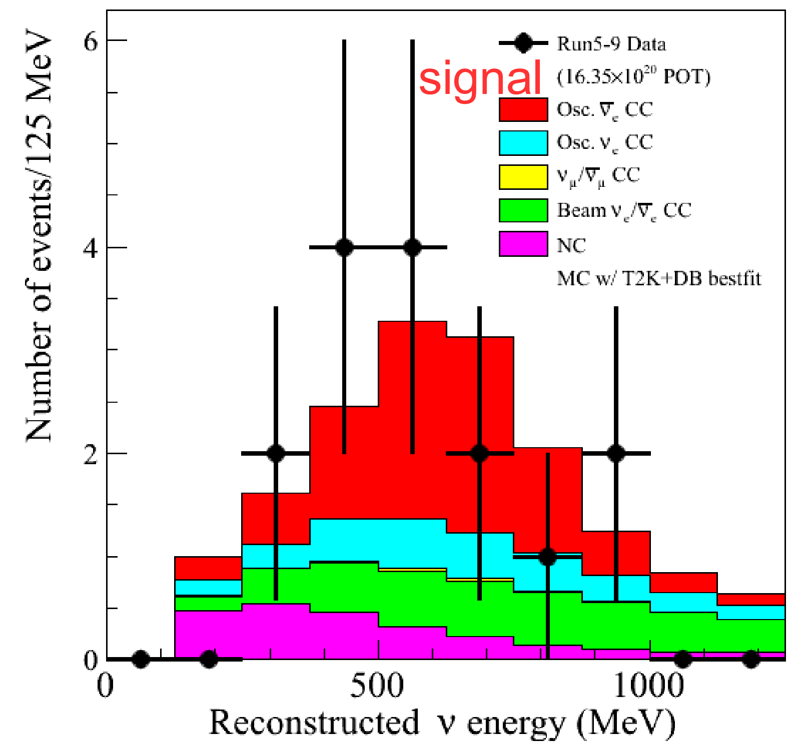


# $\bar{\nu}_e$ appearance: event rates

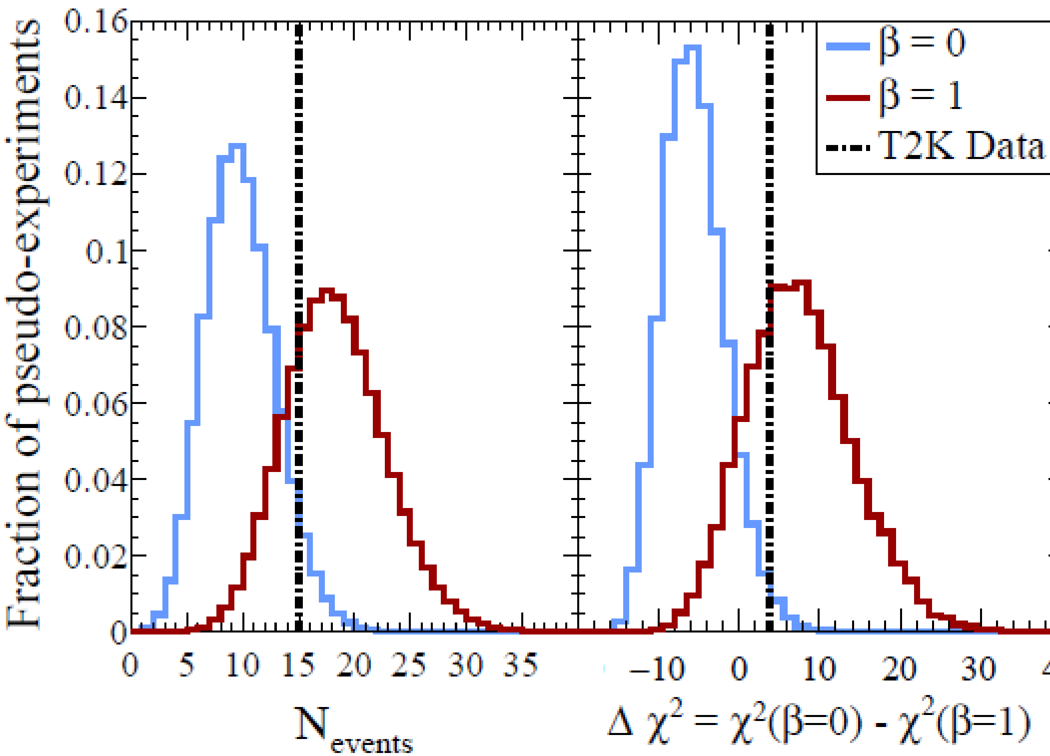
- joint analysis of all 5 samples from Far Detector
- expected values based on the previous T2K best fit point
  $\sin^2\theta_{23} = 0.528$, $\sin^2\theta_{13} = 0.0212$, $\sin^2\theta_{12} = 0.304$, $\Delta m^2_{32} = 2.509\cdot10^{-3}$ eV$^2$, $\Delta m^2_{21} = 7.53\cdot10^{-5}$ eV$^2$, $\delta_{CP} = -1.601$, normal hierarchy and $\beta = 1$
- expected background **9.3** events
  3.0 $\nu_\mu \rightarrow \nu_e$ events, 4.2 intrinsic $\nu_e$ and $\bar{\nu}_e$ events, 2.1 neutral-current interactions
- expected signal **7.4** events
- total prediction: **16.8** events
- observed: **15** events



# $\bar{\nu}_e$ appearance: results

- analysis method
  - β parameter:
    - 0 – no oscillations
    - 1 – PMNS oscillations
  - rate only and rate+shape
  - 10000 pseudo-experiments with randomized parameters and statistical fluctuations
  - 4 control samples to constrain oscillation parameters
  - binned Poisson likelihood and $\chi^2$ test statistics

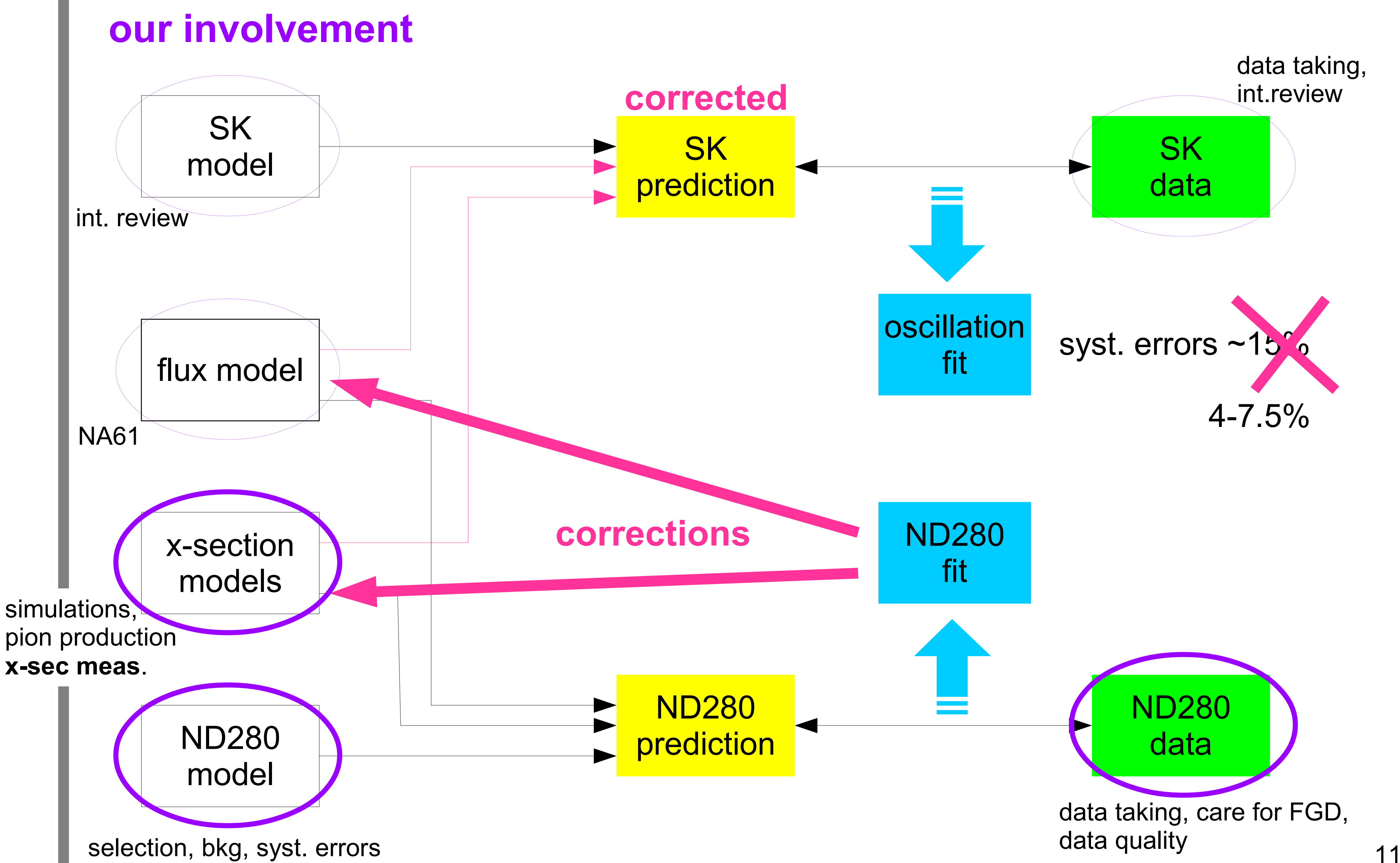



| $\beta$ | Analysis | p-value | $\sigma$ |
|---|---|---|---|
| 0 | rate-only | $0.059 \pm 0.002$ | $1.89^{+0.02}_{-0.01}$ |
| | rate+shape | $0.0163 \pm 0.0009$ | $2.40 \pm 0.02$ |
| 1 | rate-only | $0.321 \pm 0.003$ | $0.99 \pm 0.01$ |
| | rate+shape | $0.300 \pm 0.004$ | $1.04 \pm 0.01$ |

2.4σ exclusion of no-oscillations hypothesis

(reminder: first indication of $\nu_e$ appearance in 2011: 2.5σ)

# Analysis chain and our group

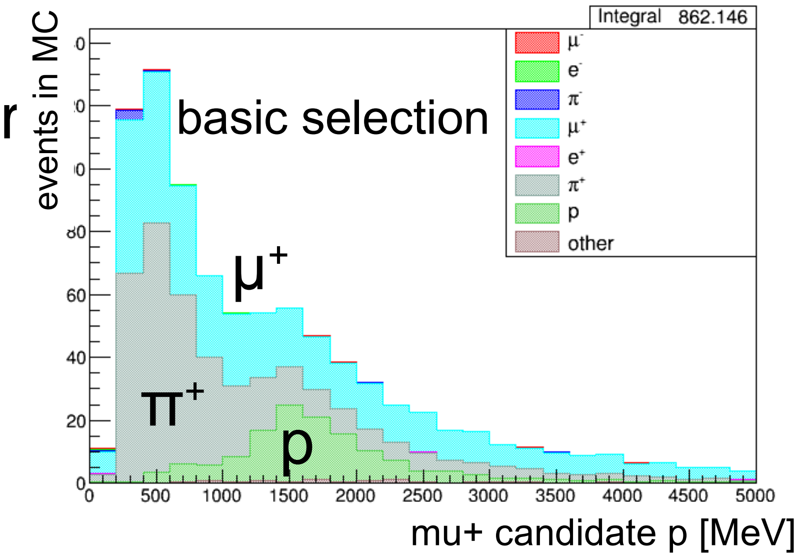


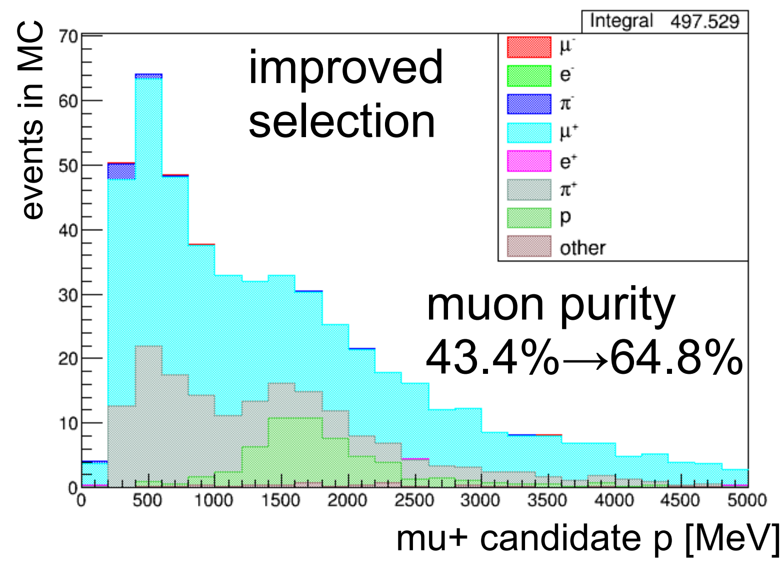
# Cross-section measurements

- measurements → better interactions models → better predictions for the oscillation studies

- continuation of activities reported last year
  - well advanced, the final results expected next year

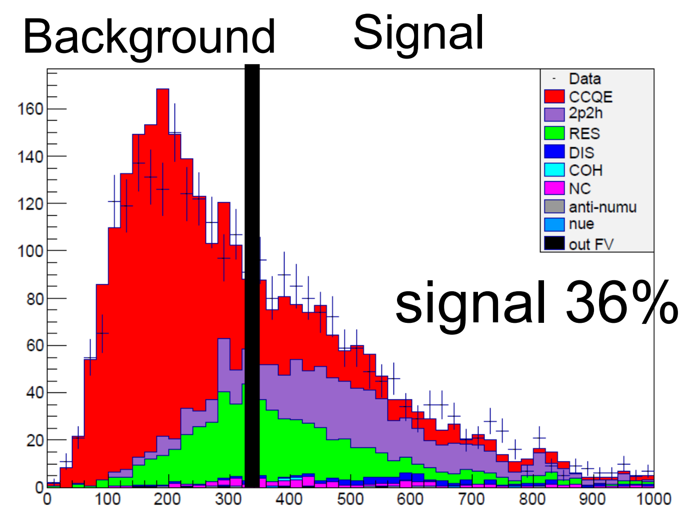
- **single pion production** by antineutrinos
  $\nu_\mu$+N → $\mu^+$ + $\pi^-$ +N'
  (G.Żarnecki supervised by JŁ)
  - large background from neutrino contamination
  - selection and control samples approved
  - systematics almost ready
  - fake data studies ongoing
  - waiting for permission to look 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

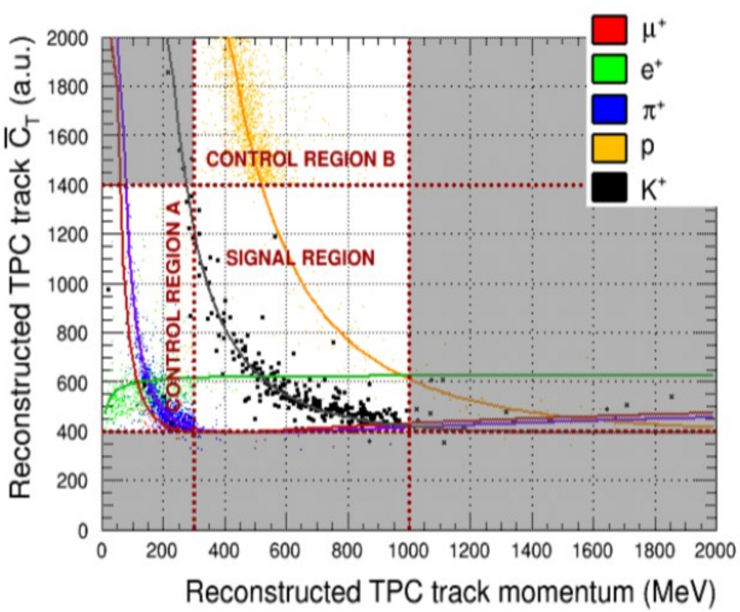



- **strangeness production** by neutrinos (K.Kowalik)

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

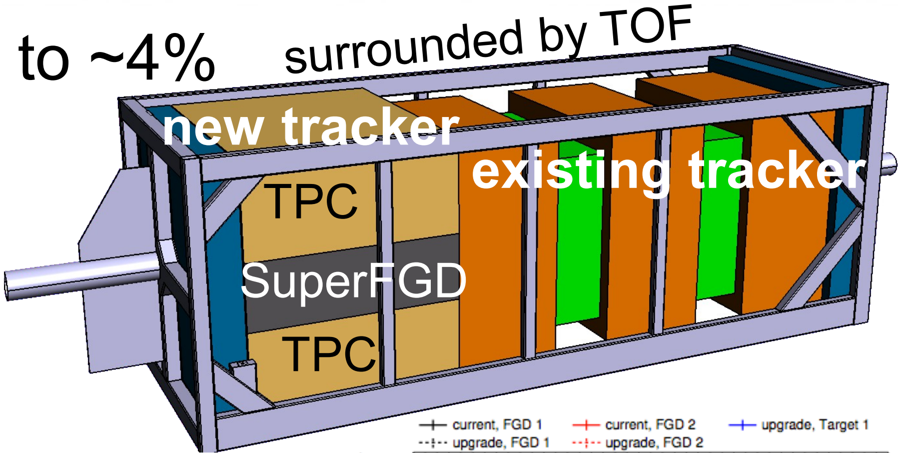
single particle production $\nu_\mu + p \rightarrow \mu^- + p + K^+$

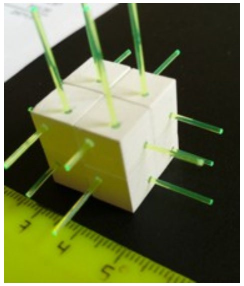
  - efficiency study done
  - systematic errors estimated
  - final checks of background control samples
  - models of final and secondary state interactions under investigation (not well known)

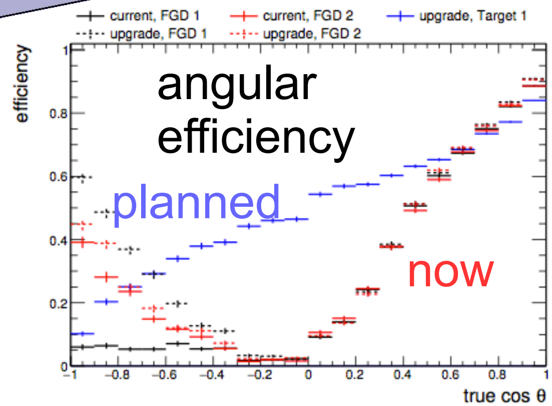


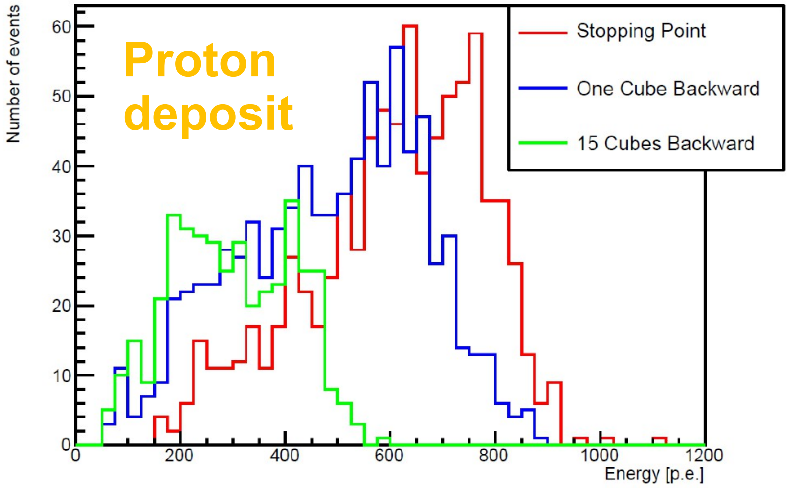
# More improvements to come

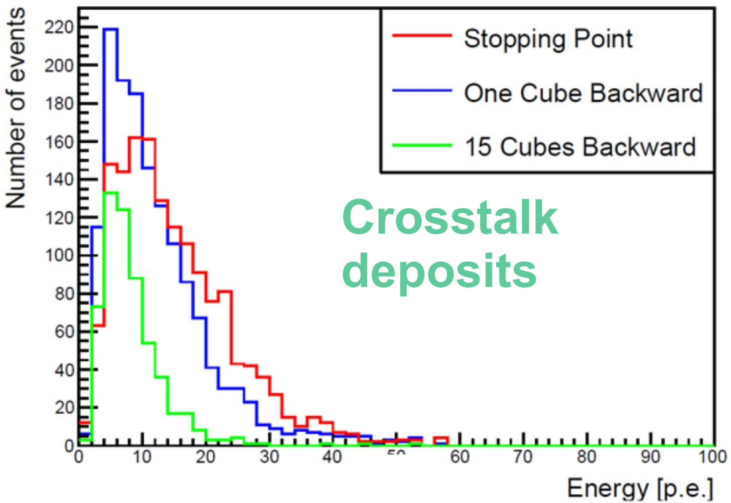
- T2K phase 2 goal: reduce systematics to ~4%
- features of upgraded detector:
  - full polar angle acceptance
  - high efficiency for short tracks
  - → better constraints for nucleus models
- SuperFGD and TPC prototypes tested with beams at CERN in summer 2018
  (J.Zalipska, K.Skwarczyński, W.Żurek)
  - effect of cross talk was studied
  - results being prepared for publication





# Summary

- T2K aim: search for **CP violation**, measurements of other **oscillation parameters** and the **cross sections**
- NCBJ group is still mostly involved in the ND280-related activities
  - contribution to oscillation analysis
  - cross-section measurements
  - also “service tasks” (data quality assessment, expert shifts, MC production etc.)
- plan to be more involved in non-ND280 activities
  - two new post-docs will join us soon
  - increasing interest in Water Cherenkov activities
  - in future the experience may be used for Hyper-Kamiokande project
    - NCBJ may be selected to build a calibration linac for H-K
- close cooperation with FUW and co-supervising of their students
  - 1 MSc defended 2019
  - 1 expected 2020

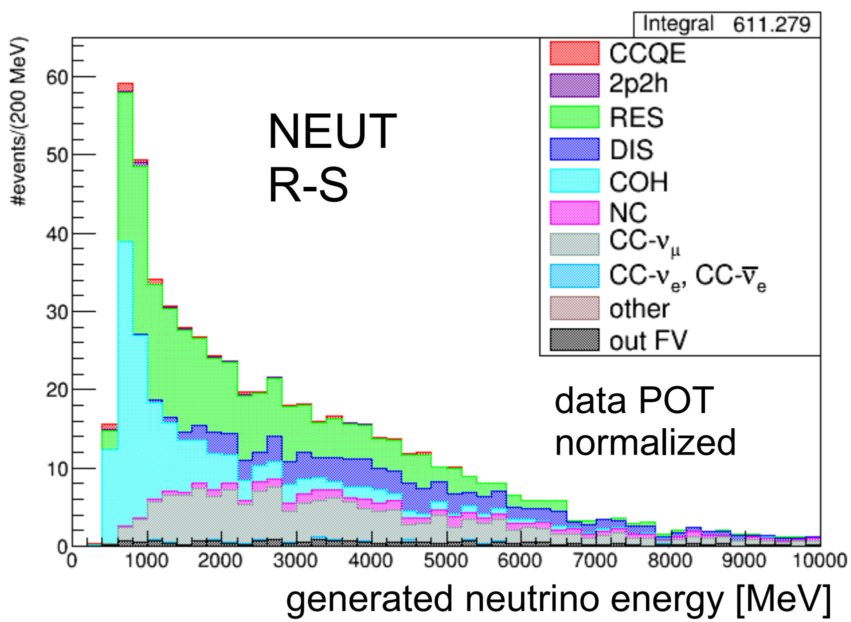
# Backup

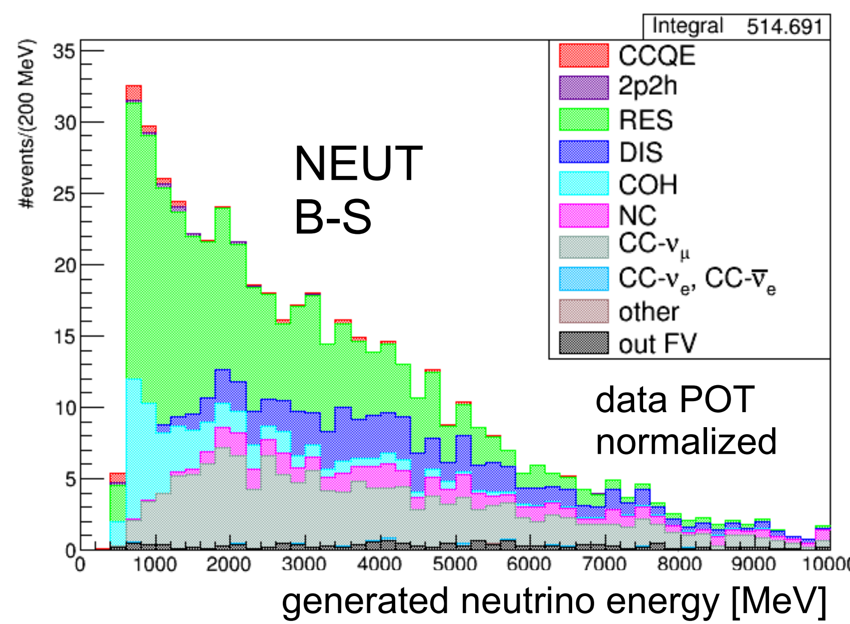
# Grants

- 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 (JENNIFER), H2020-MSCA-RISE-2014 + "Premia na Horyzoncie" + additional MNiSW funding
  - ended March 31st, 2019
- continuation: JENNIFER II + "Premia na Horyzoncie"
  - started April 1st, 2019, planned for 4 years
- OPUS "Badanie skorelowanych par nukleonów w oddziaływaniach neutrin"
  - started March 16 2017, planned for 3 years
- SONATA BIS "Precise measurements of neutrino oscillations in the improved T2K experiment"
  - started in April, planned for 4 years
- Super-Kamiokande to Hyper-Kamiokande (SK2HK), H2020-MSCA-RISE-2019
  - started November 1st, 2019, planned for 4 years

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

- The basic goal of the analysis is measuring x-section for muon antineutrino CC interaction with single $\pi^-$ production on carbon target.
- Selection tested in many ways (efficiency, $Q^2$, W, phase space, $E_\nu$)
- Recently the selection was compared for Monte Carlo samples based on different models (Rein-Sehgal vs. Berger-Sehgal).



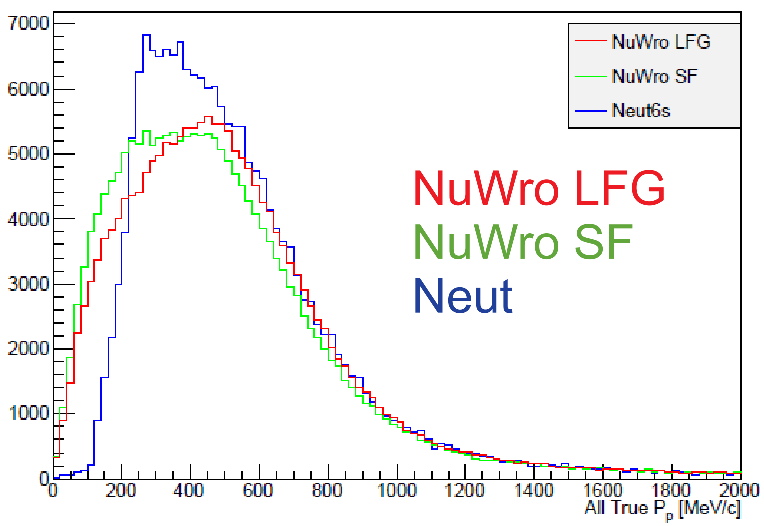




- Currently the fake data studies with cross-section extraction tools are being done.

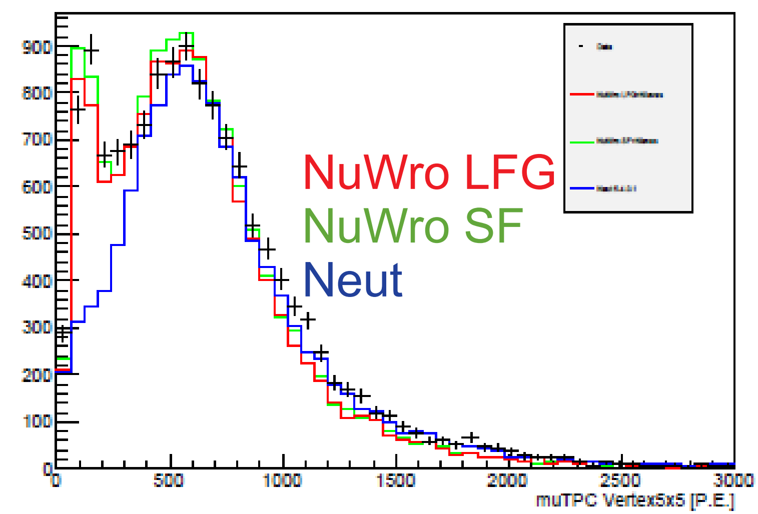
# Low momentum protons

- 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]



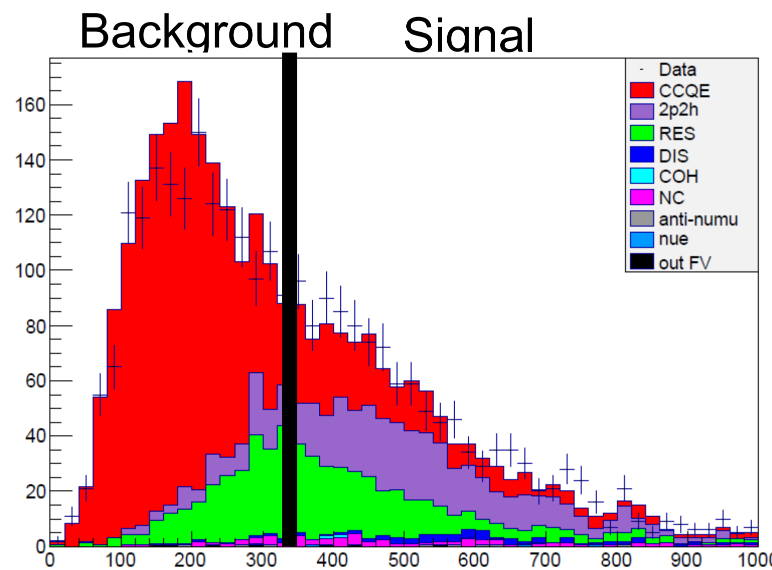

Vertex in 5x5 box [P.E.]

**NuWro Spectral Function agree with data**

# Search for MEC signal

For sample with reconstructed muon and proton tracks

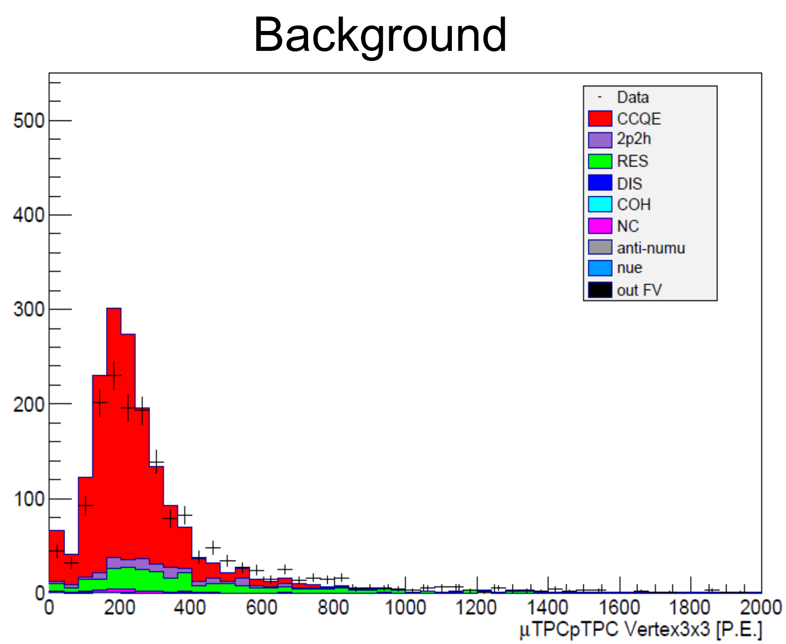
**Reconstructed target neutron momentum** helps to discriminate between CCQE-enhanced (Background) and MEC-enhanced (Signal) sub-samples.

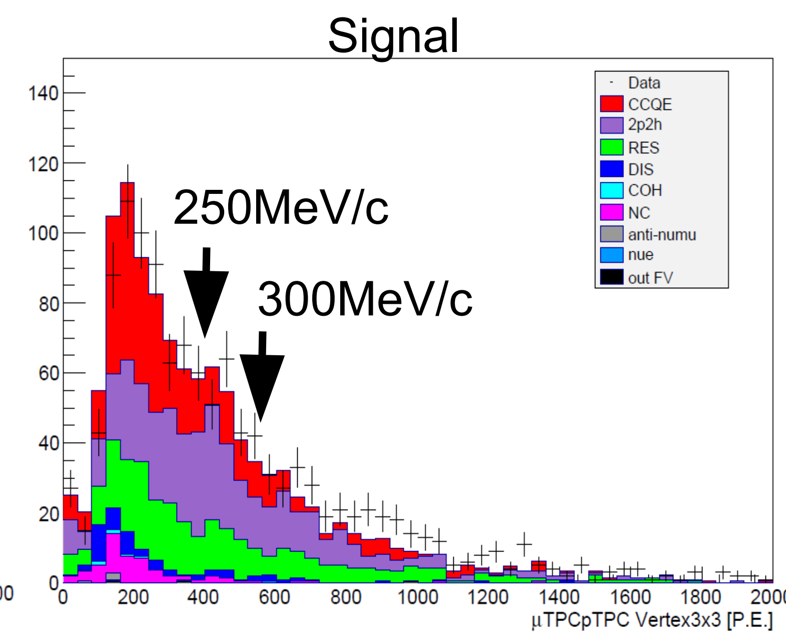



**VA after Pn cut**

Background:
CCQE 78%
MEC 6%

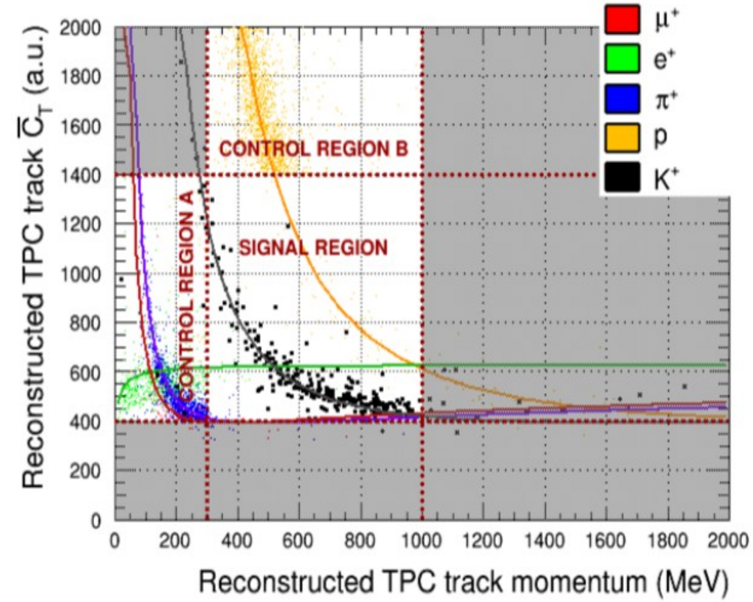
Signal:
CCQE 31%
MEC 36%

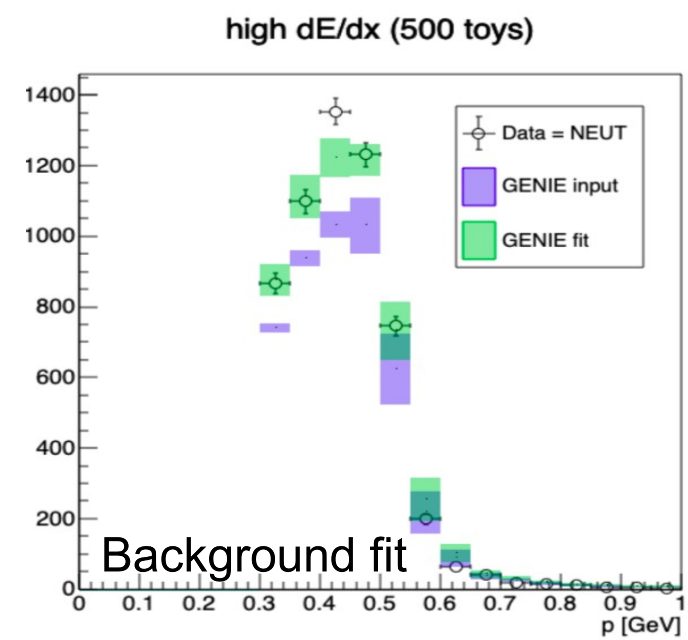


# Measurement of Strangeness Production

- $K^+$ 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



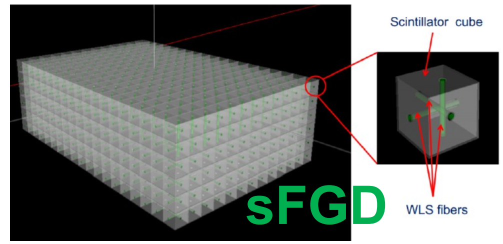



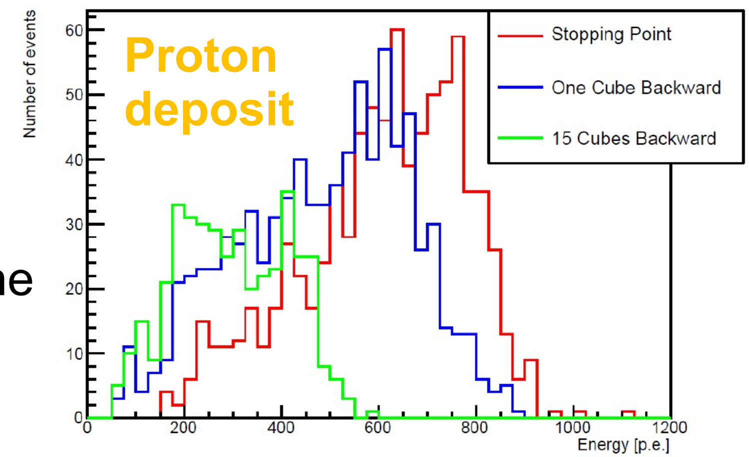
# Crosstalk study in Super FGD protoype

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

Prototype was tested at CERN in 2018.

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.

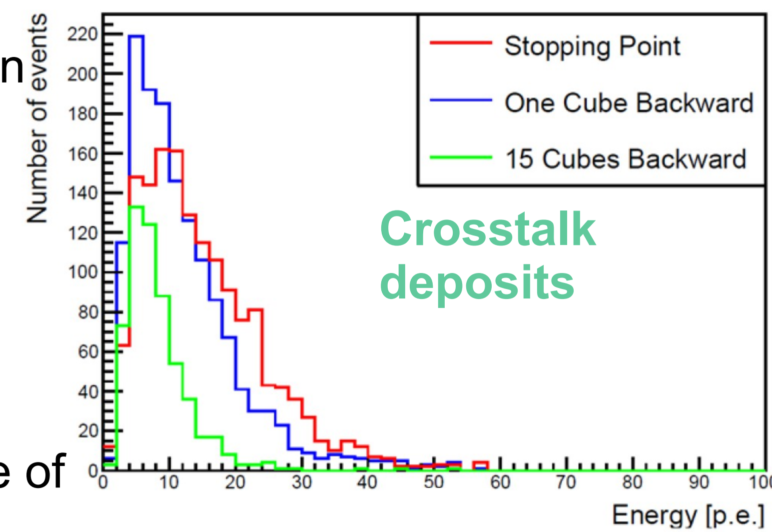


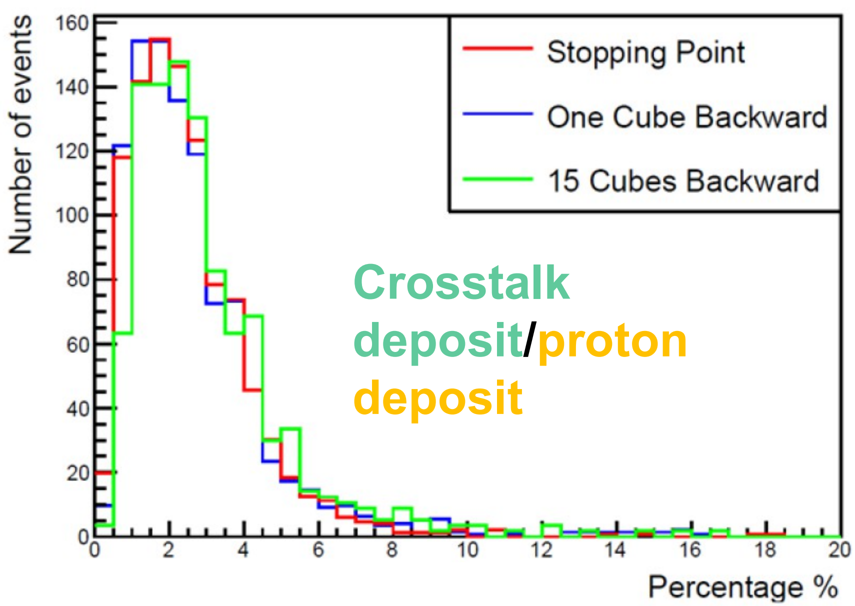

Compare cubes with the proton deposit with surrounding cubes.

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.

# Effect of ND280 fit

**BEFORE**

| Error source | 1-Ring $\mu$ FHC | 1-Ring $\mu$ RHC | 1-Ring $e$ FHC | 1-Ring $e$ RHC | 1-Ring $e$ FHC CC1$\pi$ |
|---|---|---|---|---|---|
| Beam | 8.0% | 7.3% | 8.0% | 8.1% | 8.9% |
| Cross-section (all) | 12.3% | 10.3% | 12.3% | 10.1% | 8.7% |
| Beam + Cross-section (all) | 14.5% | 12.6% | 14.5% | 13.0% | 12.6% |
| **Total** | 15.0% | 13.0% | 15.0% | 13.7% | 20.1% |

**AFTER**

| Error source | FHC | RHC | FHC | RHC | FHC CC1$\pi$ |
|---|---|---|---|---|---|
| Beam | 4.3% | 4.1% | 4.4% | 4.2% | 4.4% |
| Cross-section (constr. by ND280) | 4.7% | 4.0% | 4.8% | 4.1% | 4.1% |
| Cross-section (all) | 5.6% | 4.4% | 8.4% | 6.2% | 5.6% |
| Beam + Cross-section (constr. by ND280) | 3.3% | 3.3% | 3.3% | 3.1% | 4.0% |
| Beam + Cross-section (all) | 4.4% | 2.9% | 7.7% | 5.7% | 5.6% |
| New $E_b$ fake data parameter | 3.2% | 1.3% | 7.2% | 4.1% | 2.8% |
| SK+FSI+SI | 3.3% | 2.9% | 4.1% | 4.3% | 16.6% |
| **Total** | 5.5% | 4.4% | 8.8% | 7.3% | 17.8% |

# What so special about $\nu_\mu \to \nu_e$ channel?

- allows for CP violation studies

$$P(\nu_\mu \to \nu_e) = 4 c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31}$$ **dominant term**

$$+8 c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta_{CP} - s_{12} s_{13} s_{23}) \cos\Delta_{32} \sin\Delta_{31} \sin\Delta_{21}$$

$$-8 c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \boxed{\sin\delta_{CP}} \sin\Delta_{32} \sin\Delta_{31} \sin\Delta_{21}$$ **CP violation**

$$+4 s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2 c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta_{CP}) \sin^2\Delta_{21}$$

$$-8 c_{13}^2 s_{13}^2 s_{23}^2 \frac{aL}{4E_\nu} (1-2s_{13}^2) \cos\Delta_{32} \sin\Delta_{31} + 8 c_{13}^2 s_{13}^2 s_{23}^2 \frac{a}{\Delta m_{31}^2} (1-2s_{13}^2) \sin^2\Delta_{31}$$ **matter**

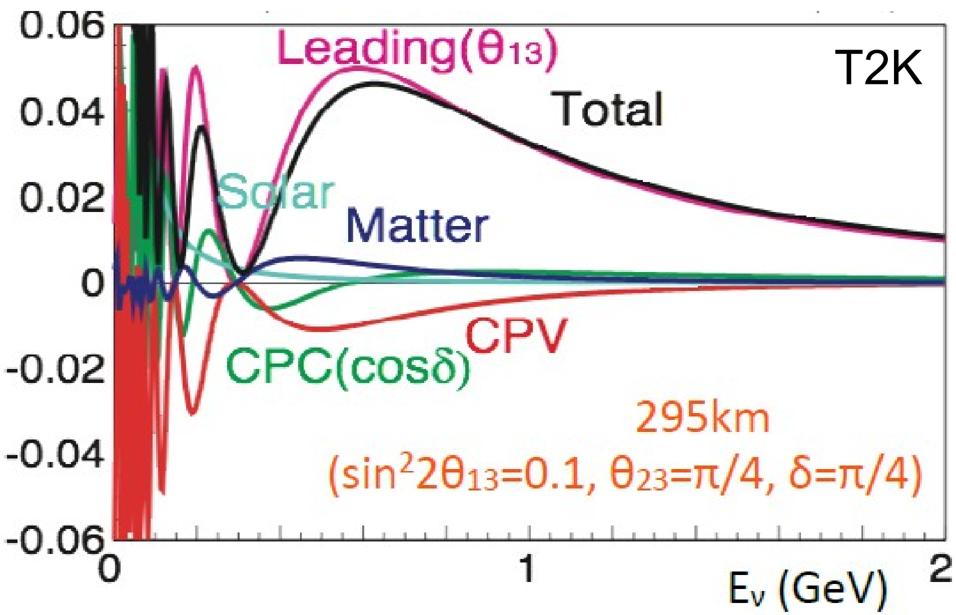
for $\bar{\nu}$

$$\delta_{CP} \to -\delta_{CP}$$

$$a \to -a \qquad a = 2\sqrt{2} G_F n_e E_\nu$$

$n_e$ related to matter density

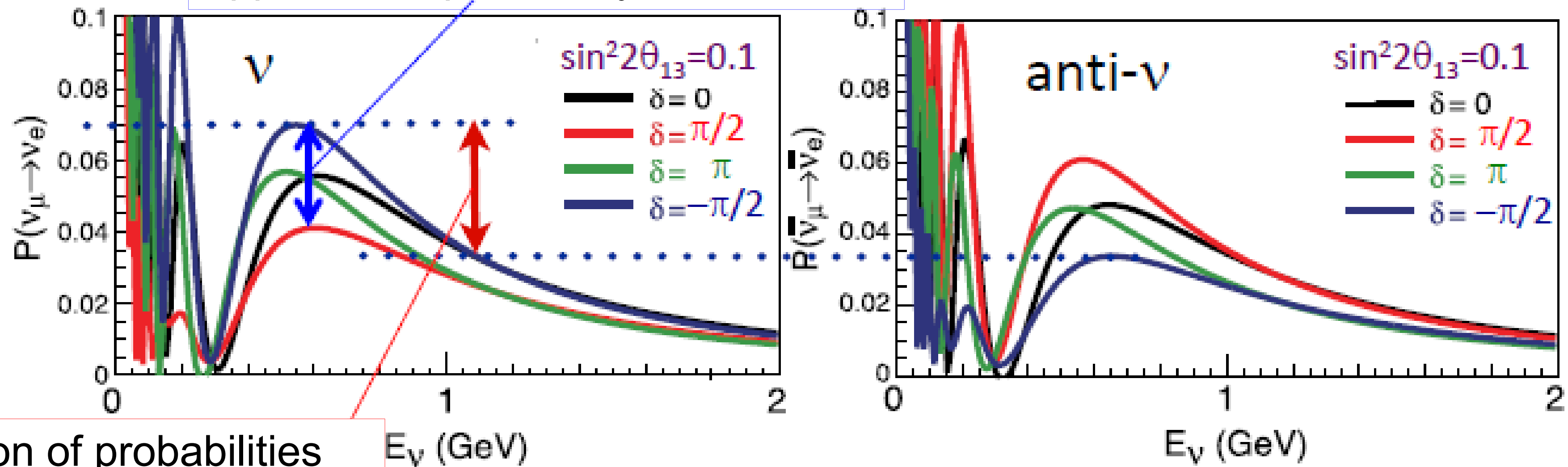
subleading effect,
can be as large as 30%
of dominant



# $\nu_e$ appearance

- discovered by T2K in 2013
  - probability depends on $\theta_{13}$, $\theta_{23}$ – and $\delta_{CP}$

appearance probability for neutrinos

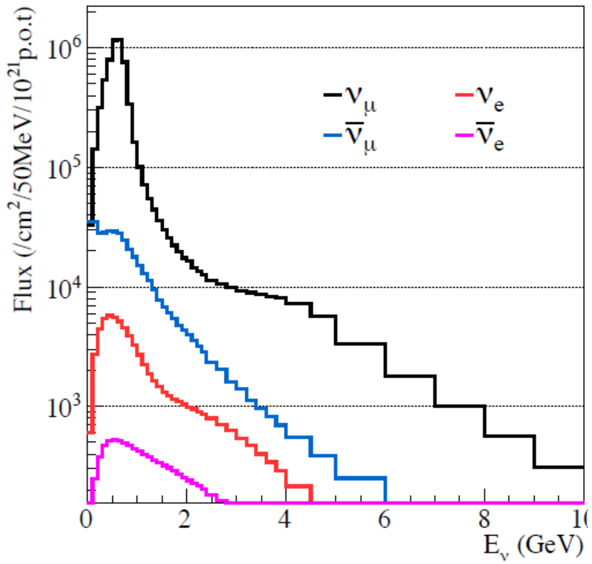



comparison of probabilities
for netrinos and antineutrinos

  - due to matter effect different probabilities for ν and $\bar{\nu}$ even if CP is not violated
  - parameter degeneracies to disentagle: effects from mass hierarchy, CP violation, octant of $\theta_{23}$ – more effects to study
  - combination of experiment with different baseline increase sensitivity

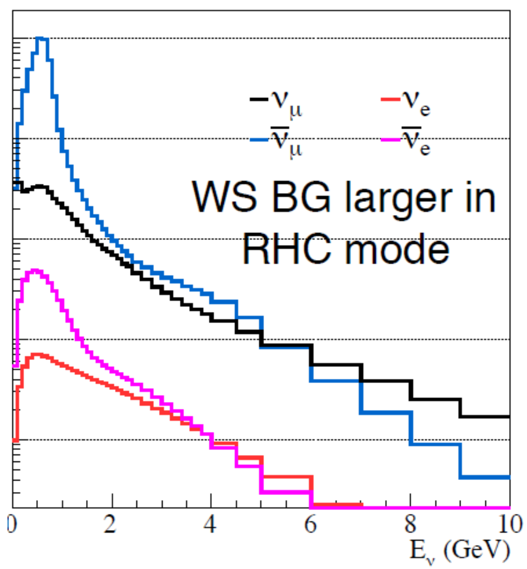
# Fluxes

- T2K




$\nu$

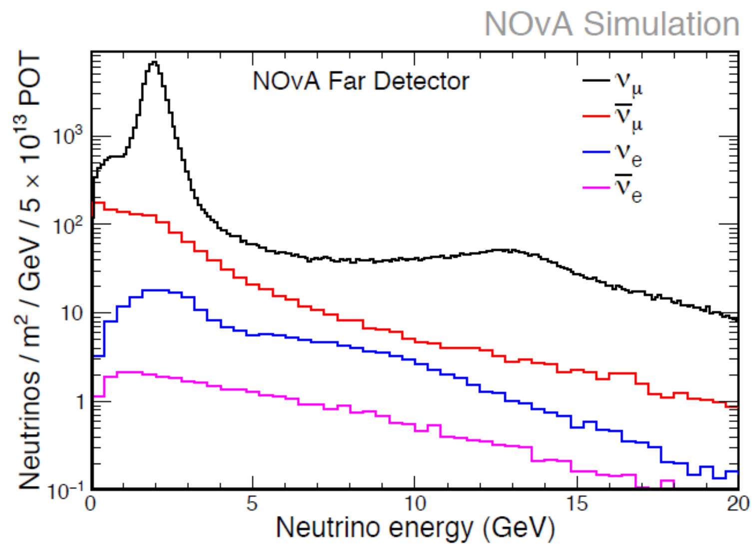
FHC

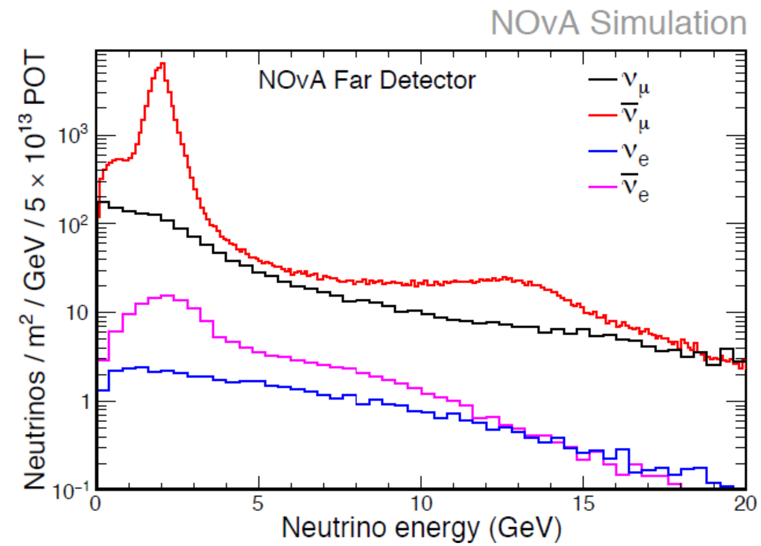



$\bar{\nu}$

RHC

- NOvA




Small wrong sign component for both beams

# Disappearance: results