ND280 performances and limits

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Workshop on neutrino Near Detectors
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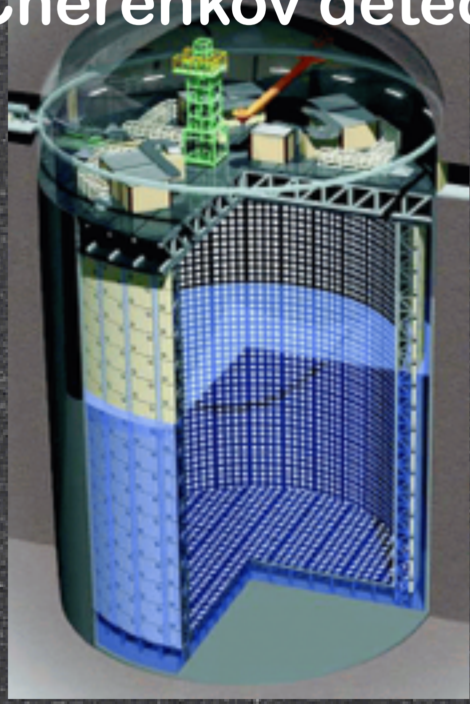
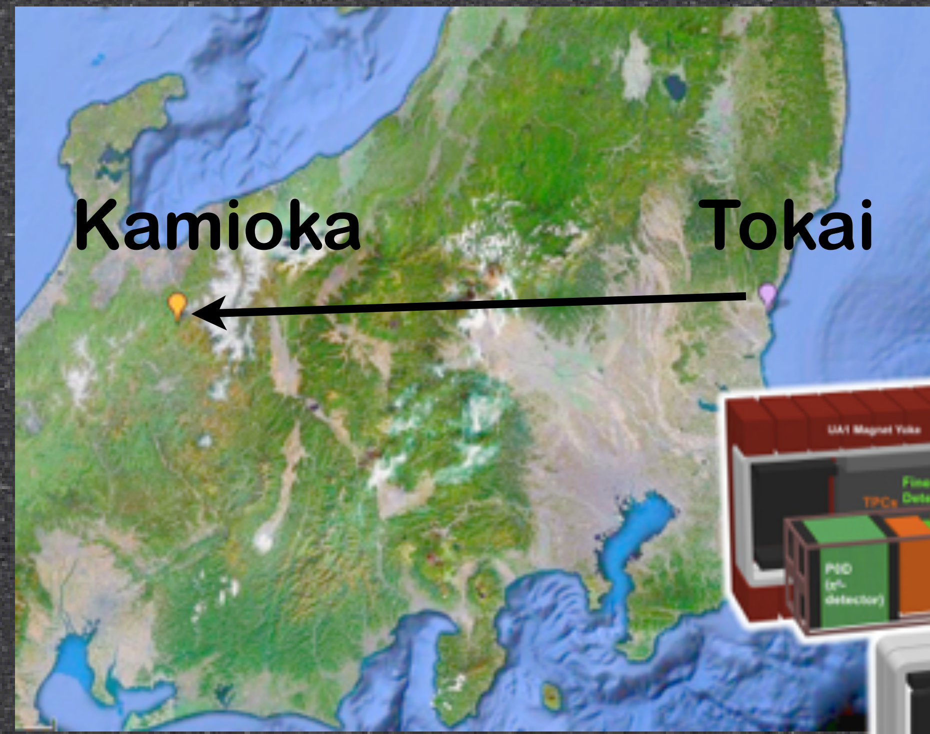
T2K experiment

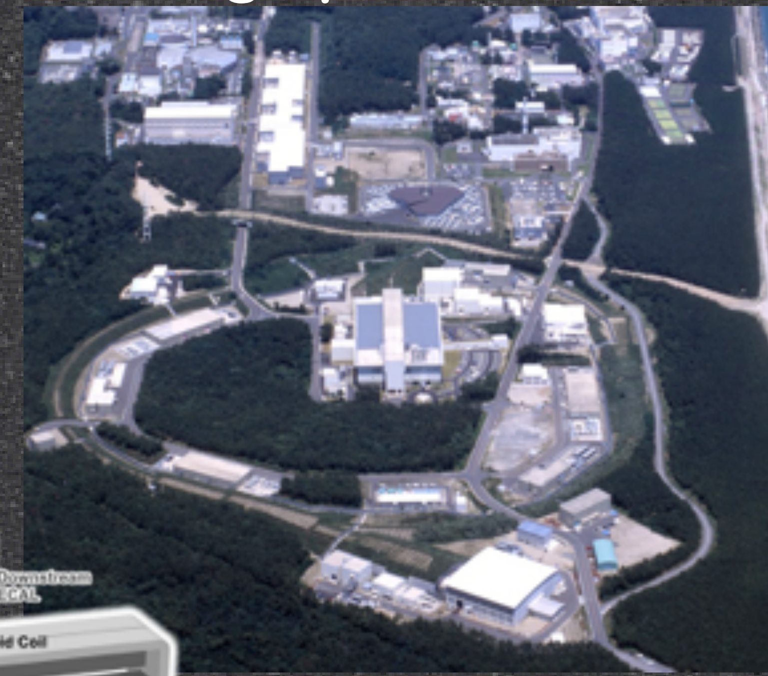
- High intensity ~600 MeV ν_μ beam produced at J-PARC (Tokai, Japan)
- Neutrinos detected at the Near Detector (ND280) and at the Far Detector (Super-Kamiokande) 295 km from J-PARC
- Main physics goals:
  - Observation of ν_e appearance → determine θ_{13} and δ_{CP}
  - Precise measurement of ν_μ disappearance → θ_{23} and Δm^2_{32}

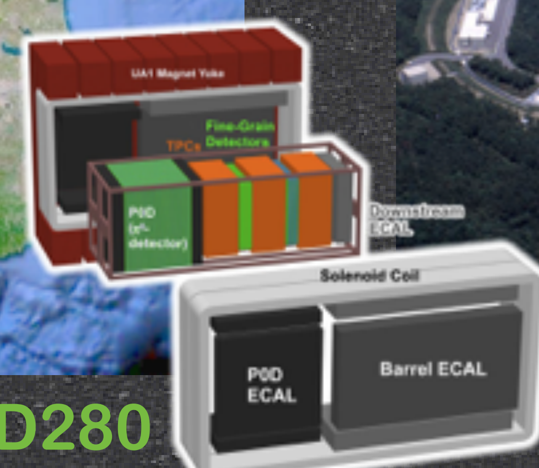
Super-Kamiokande: 22.5 kt fiducial volume water Cherenkov detector





J-PARC accelerator:
Design power: 750 kW

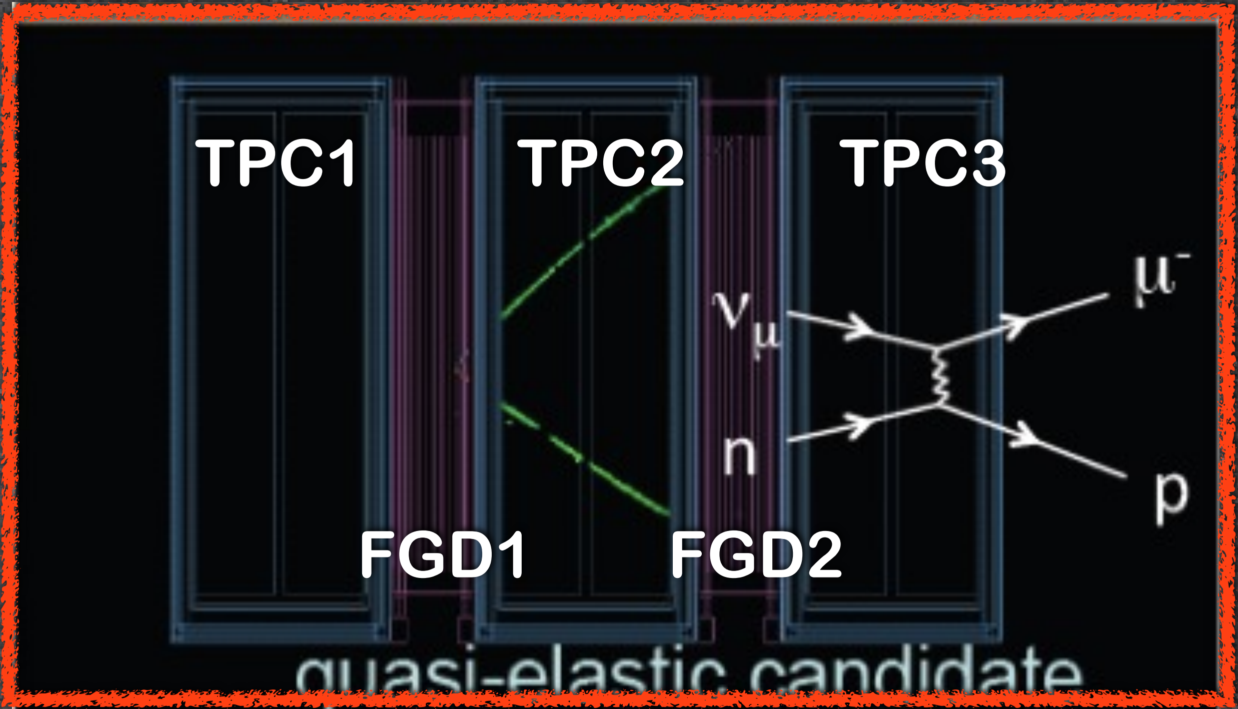


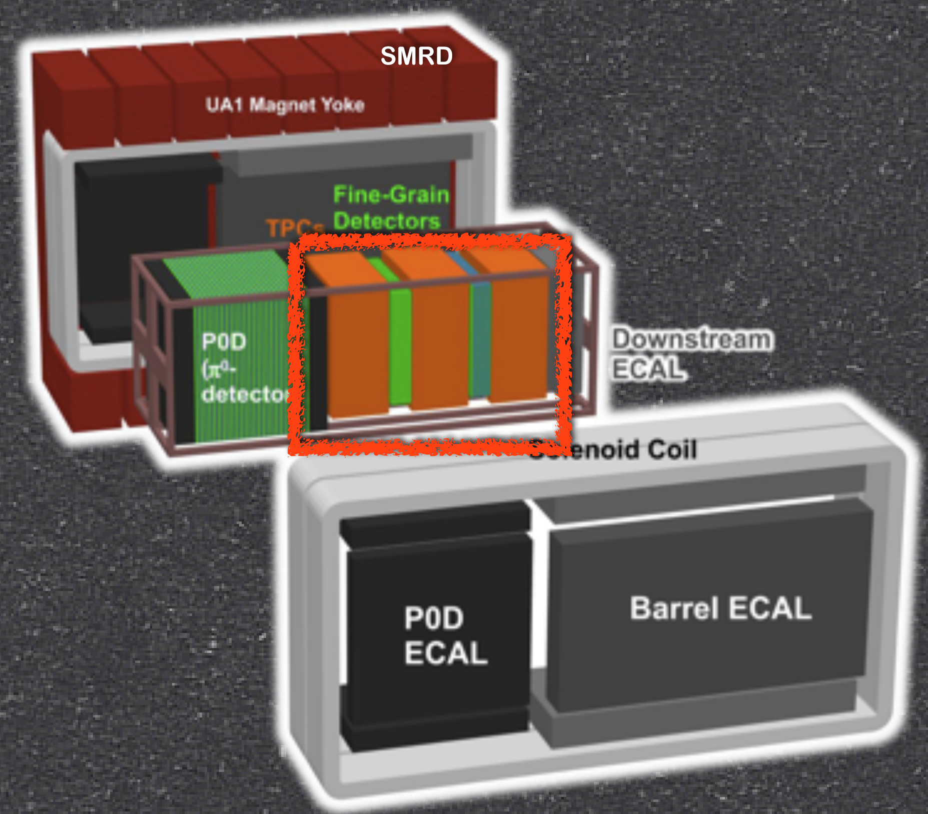


ND280

ND280

Tracker

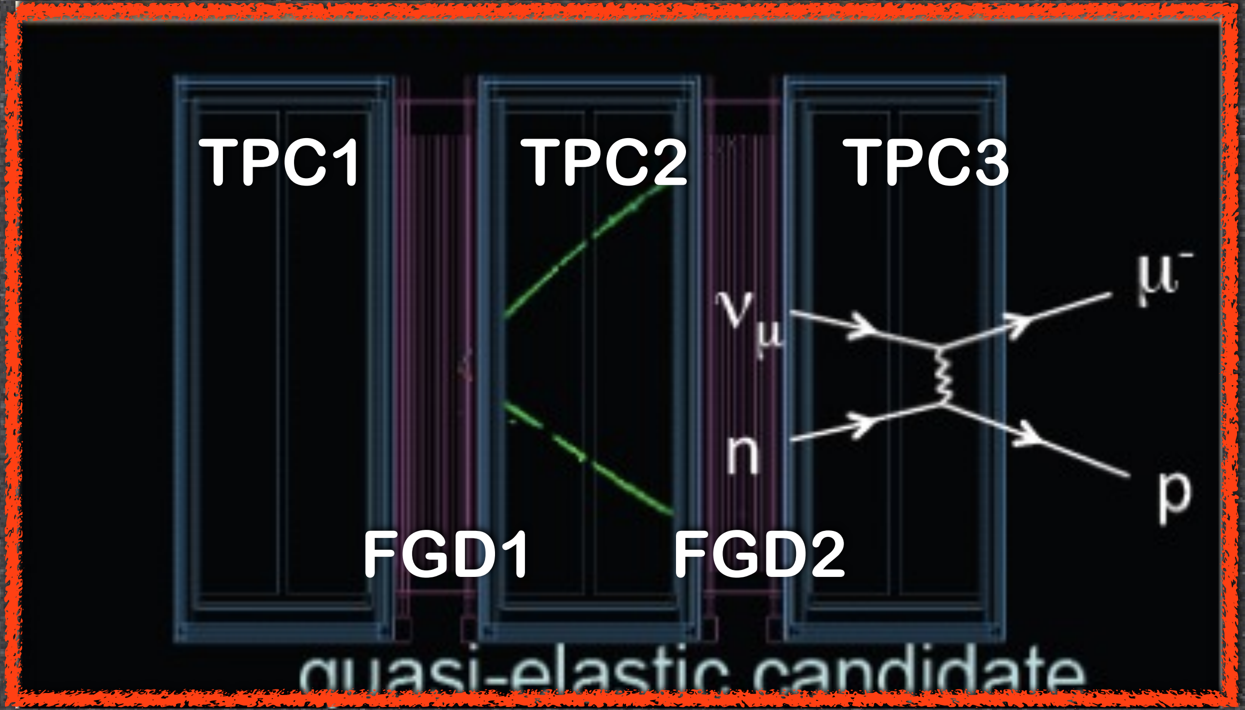


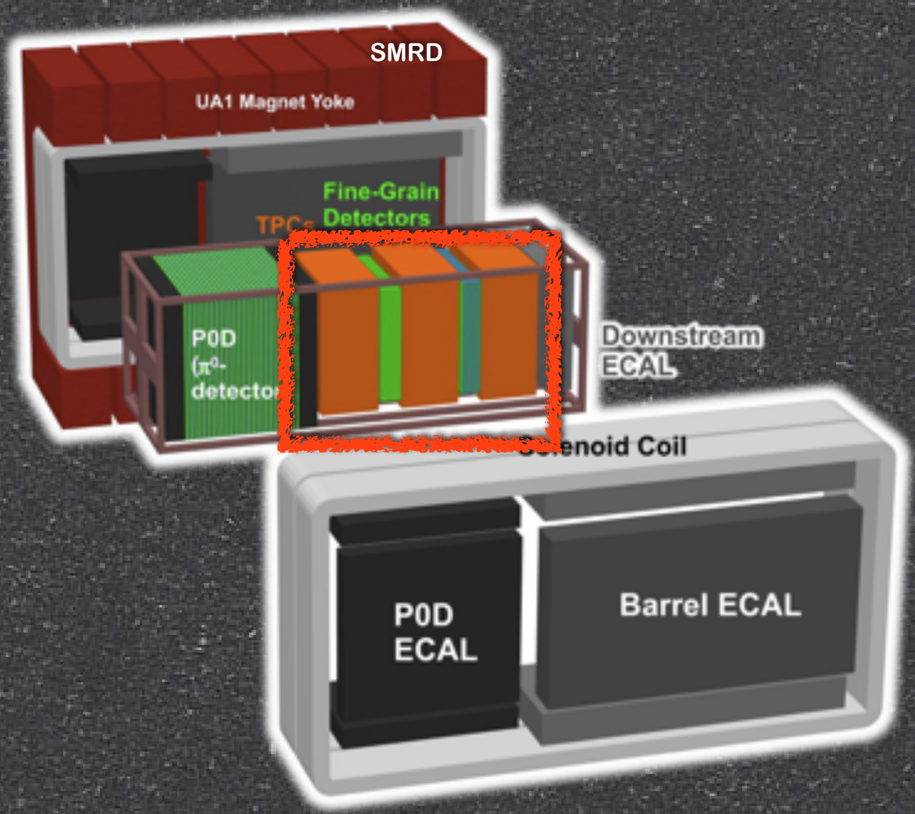


- Detector installed inside the UA1/NOMAD magnet (0.2 T magnetic field)
- A detector optimized to measure π^0 (P0D)
- A tracker system composed by:
  - 2 Fine Grained Detectors (target for ν interactions). FGD1 is pure scintillator, FGD2 has water layers interleaved with scintillator
  - 3 Time Projection Chambers: reconstruct momentum and charge of particles, PID based on measurement of ionization
  - Electromagnetic calorimeter to distinguish tracks from showers

Goals of ND280

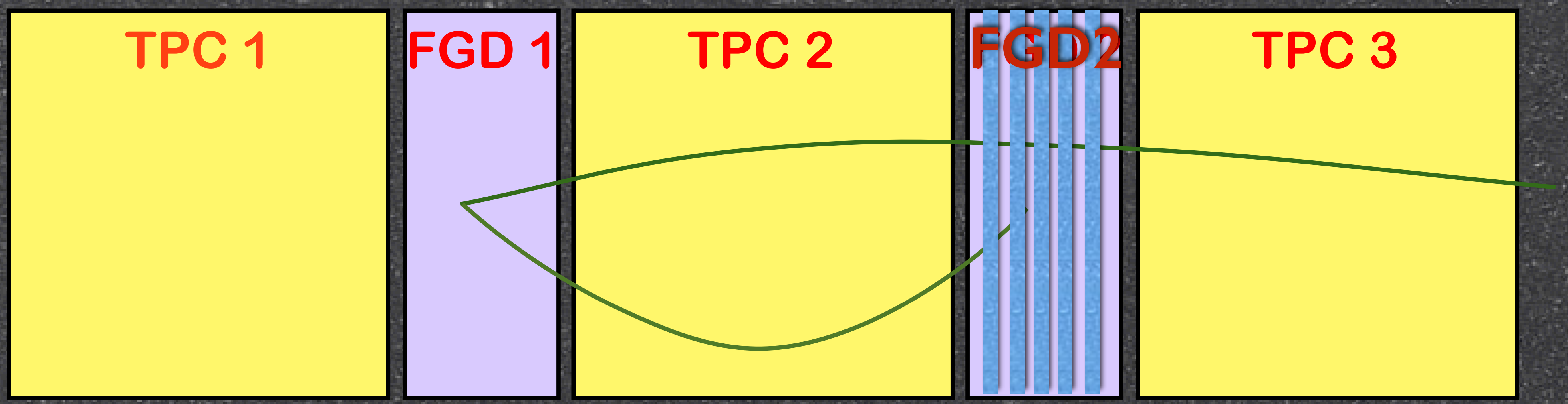
Tracker





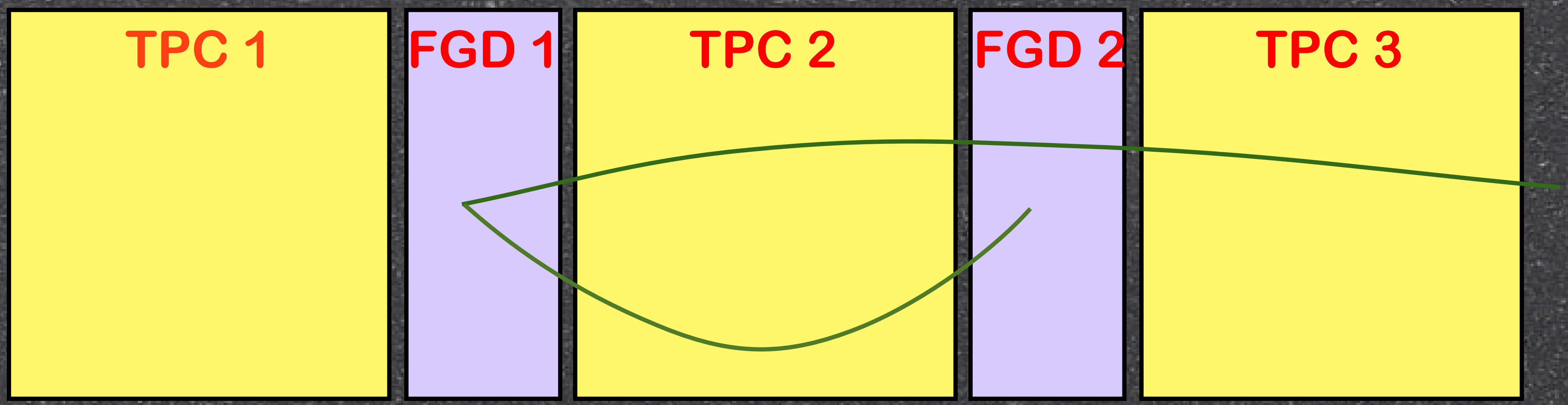
- Constraint the ν_μ and ν_e spectra before the oscillations
- Measure neutrino cross-sections
- Measure background processes to the oscillation analyses (π^0, CC1π, etc)

Strength and limits of ND280

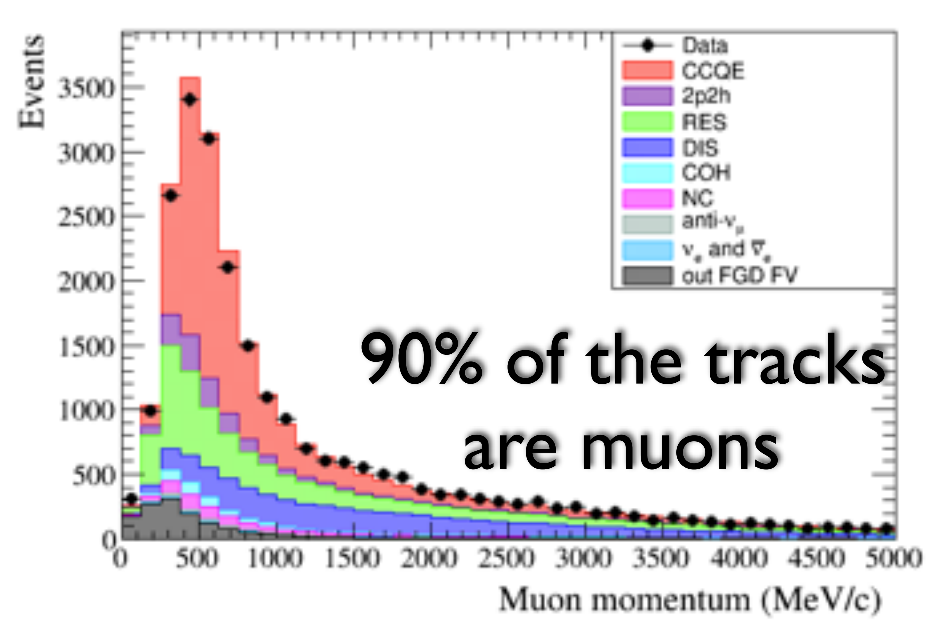


- Magnet + TPCs → reconstruct the charge of the particles, precise measurement of their momenta
- Fully active target for vertex reconstruction
- FGD2 has water and carbon layers → allow to constraint cross-section systematic uncertainties on both targets
- Designed to have excellent efficiency for forward going tracks but not for high angle tracks
  - Efficiency drops below ~600 MeV
- The tracker mass is not huge (~2 ton) so the statistics for νe interactions is limited

ND280 analyses

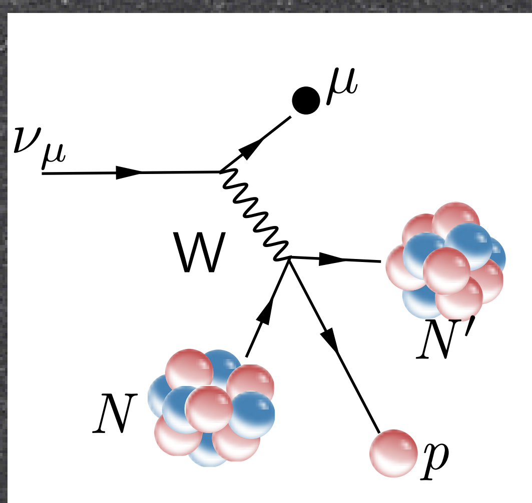


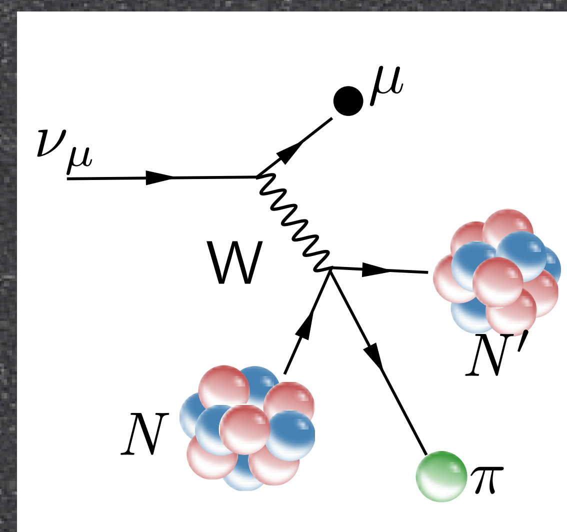
- The main use of ND280 is to constrain flux and cross-section uncertainties in the T2K oscillation analyses
- Neutrino interactions are selected in the FGD and the charged particles produced are tracked in the TPC
- The most energetic forward going negative track is selected as the lepton candidate
  - Positive track if we are taking data in $\overline{\nu}$ mode
- Precise measurement of momentum and angle of the muon

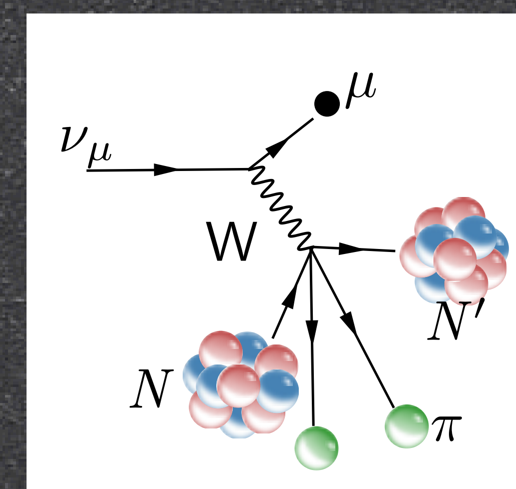


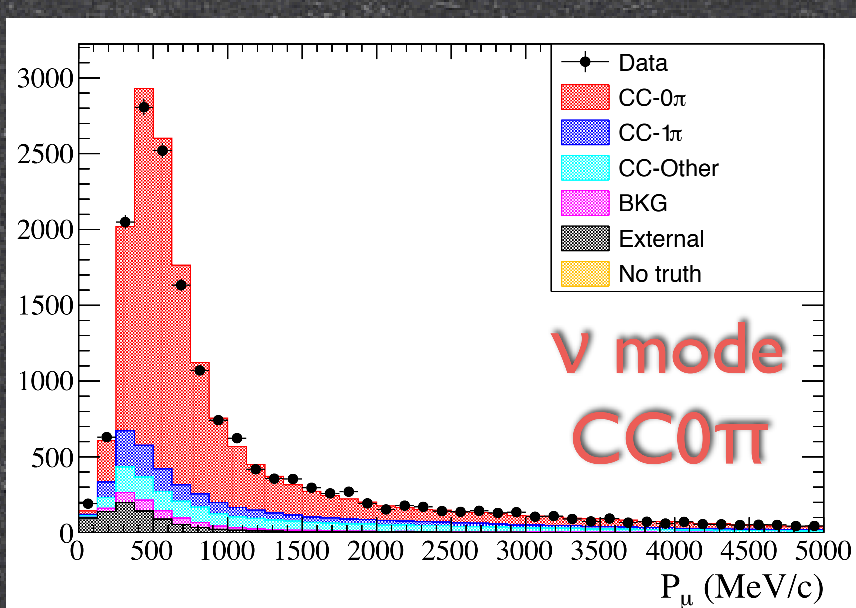
ND280 ν_μ analyses

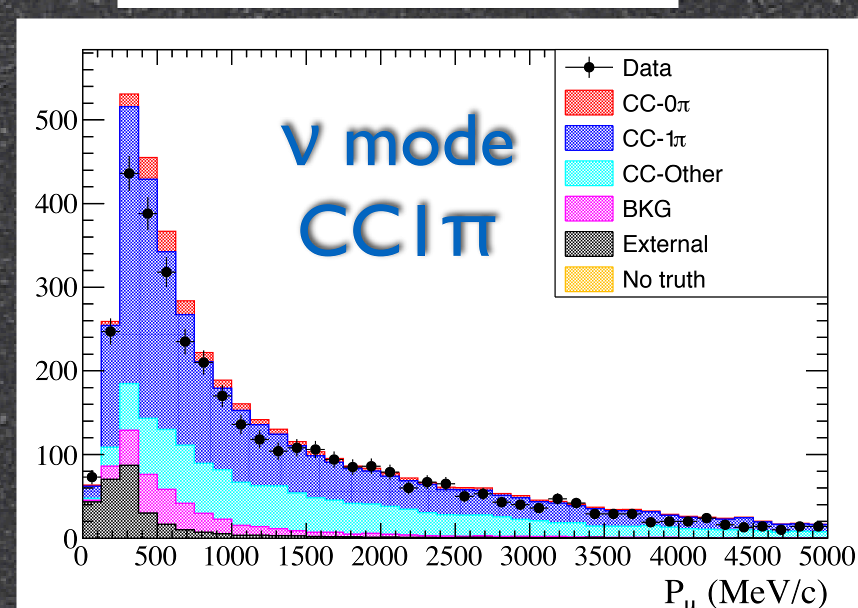
- The inclusive sample is sub-divided according to the number of observed pions (0π, 1π, $N\pi$) using TPC and FGD reconstruction

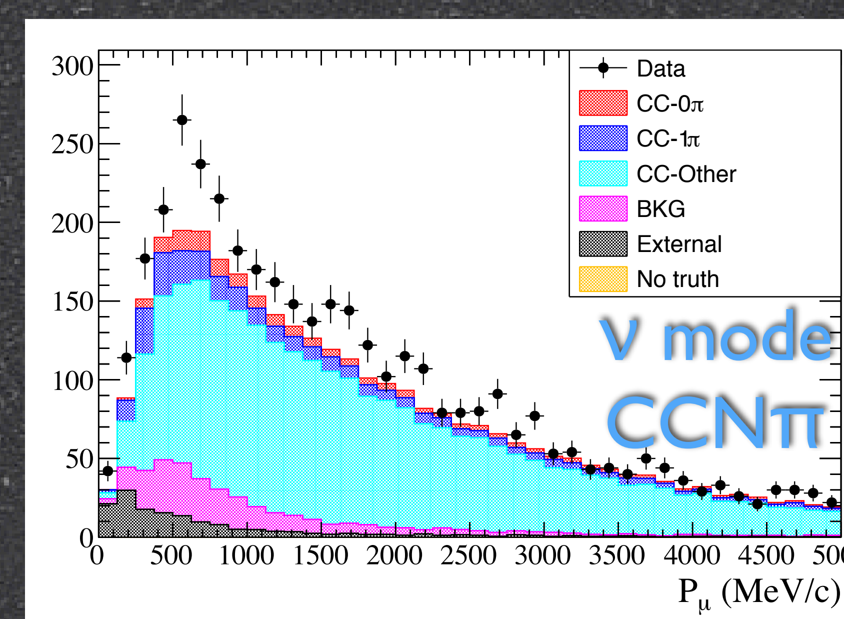






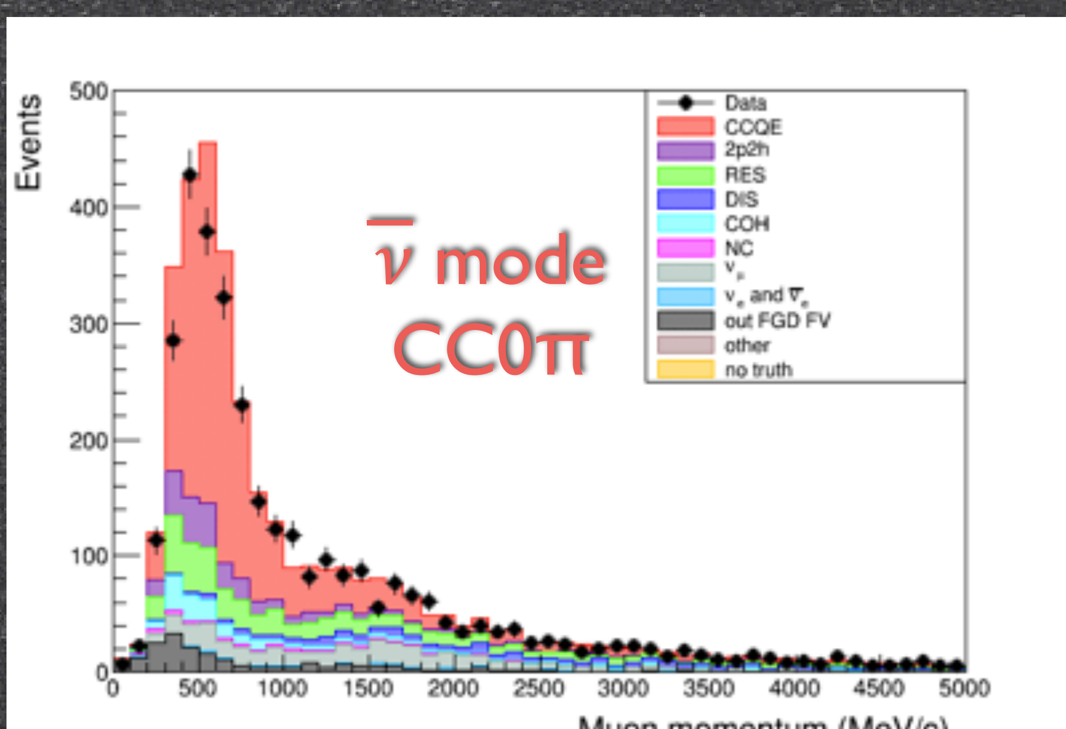


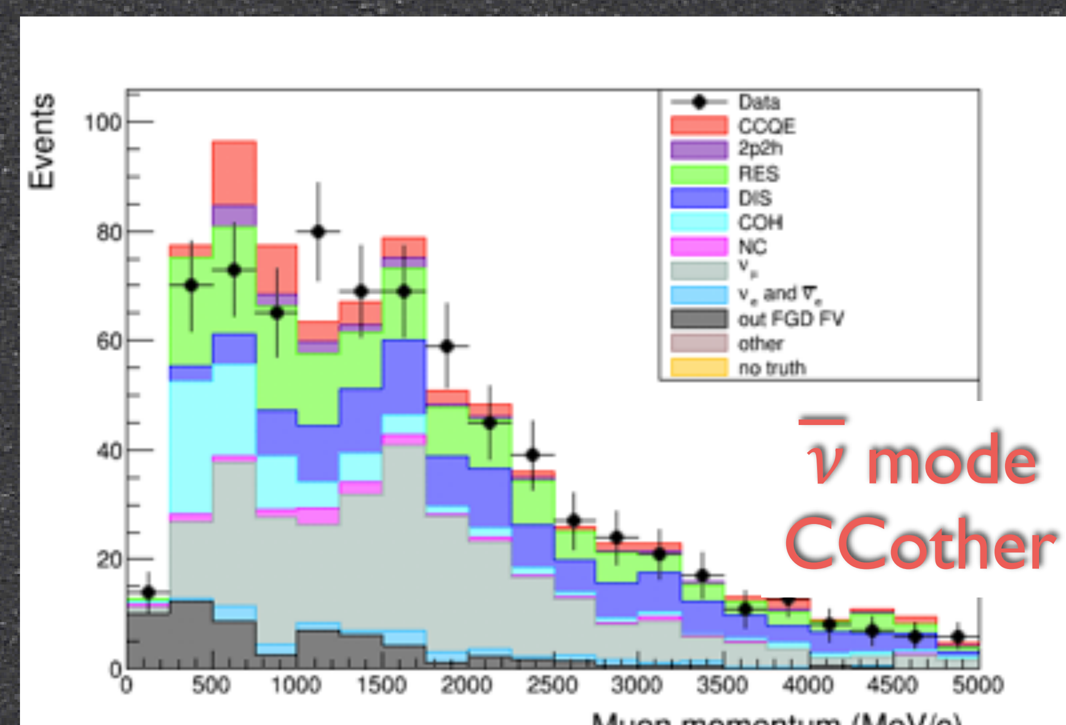




ND280 $\bar{\nu}_\mu$ analyses

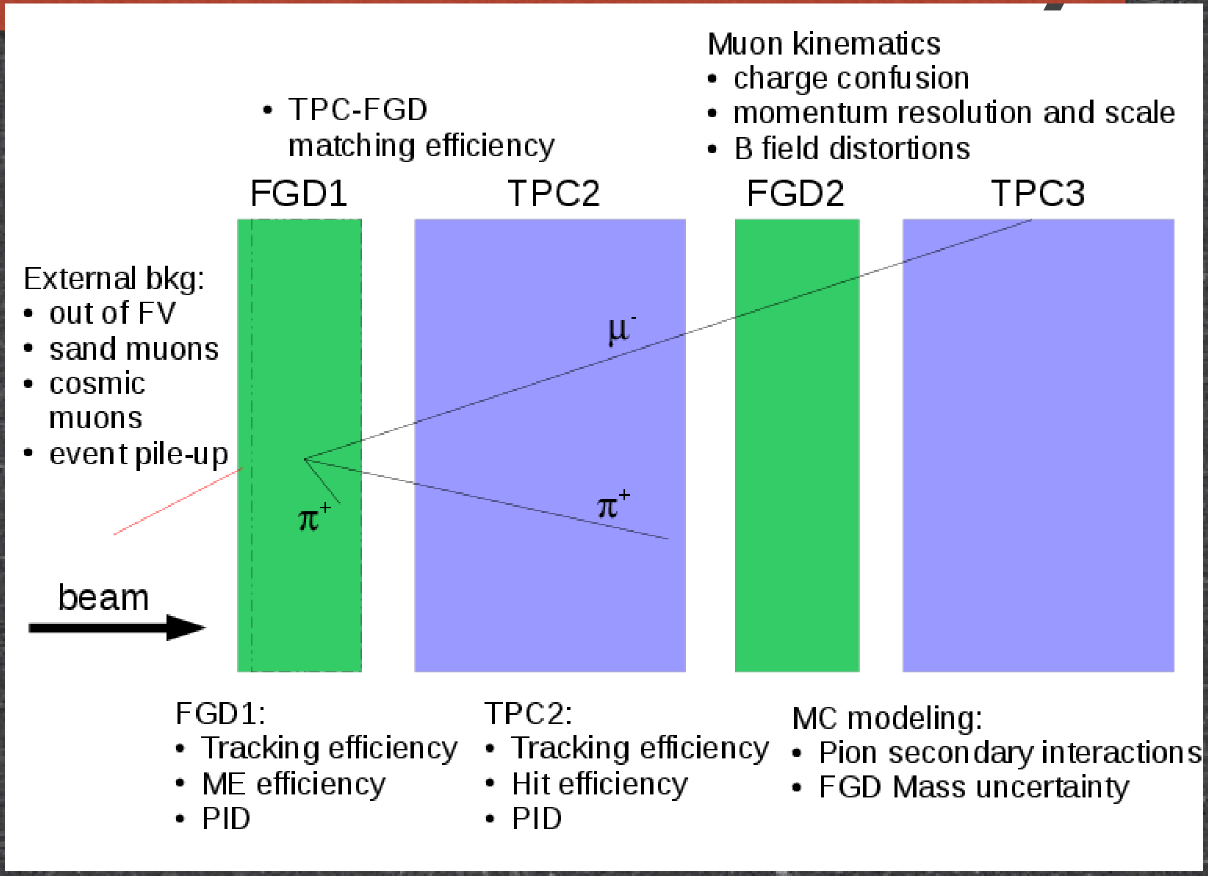
- Similar analysis but selecting positive muons
  - $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$
- Thanks to the magnetic field the contamination of ν in the selection is <5%
- Divide the sample in 1 track (mainly CC0π) and N tracks



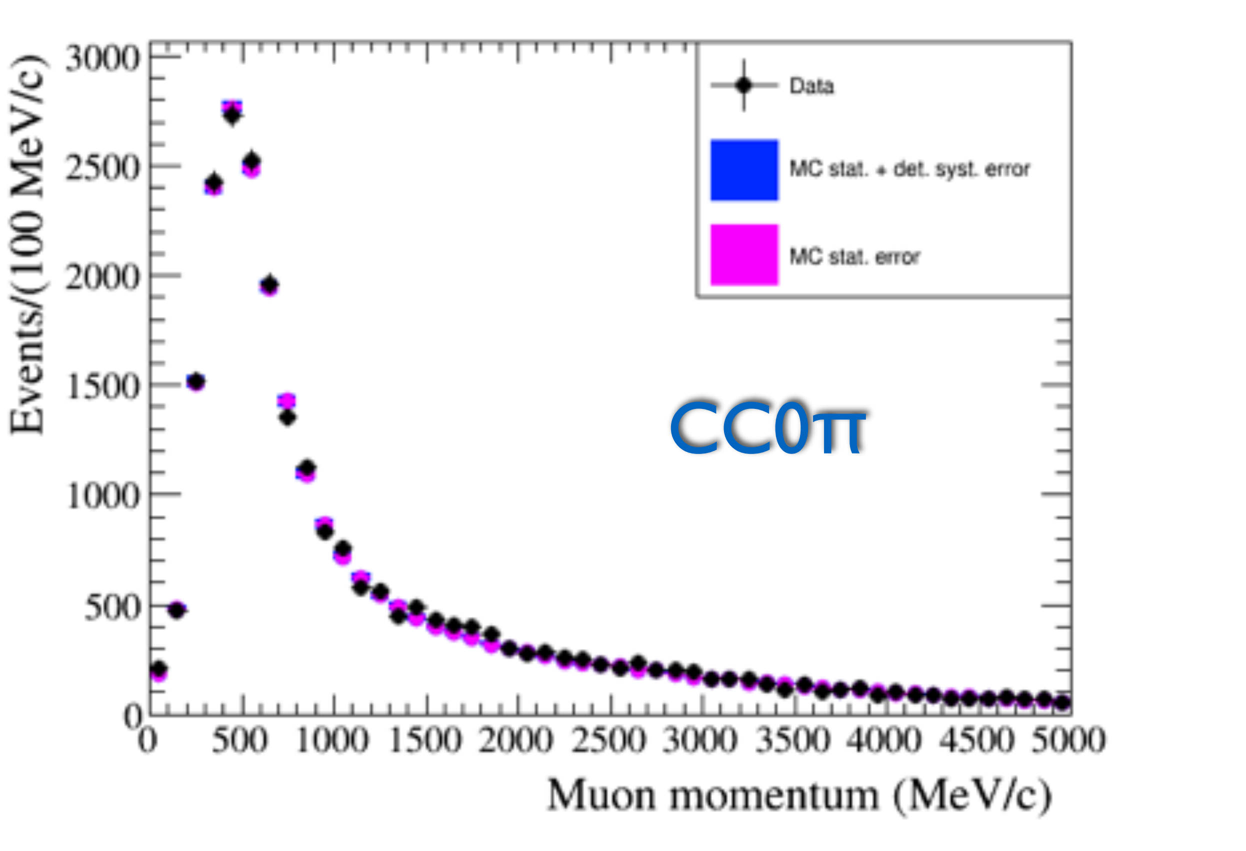


Detector systematic errors

- Detector systematic uncertainties are small in the ND280 analysis
  - 1.7% for the CC0π sample, 3.9% for the CC1π
- The dominant systematics is due to the pion secondary interactions → work is on-going to use ND280 data to reduce this source of systematic uncertainty

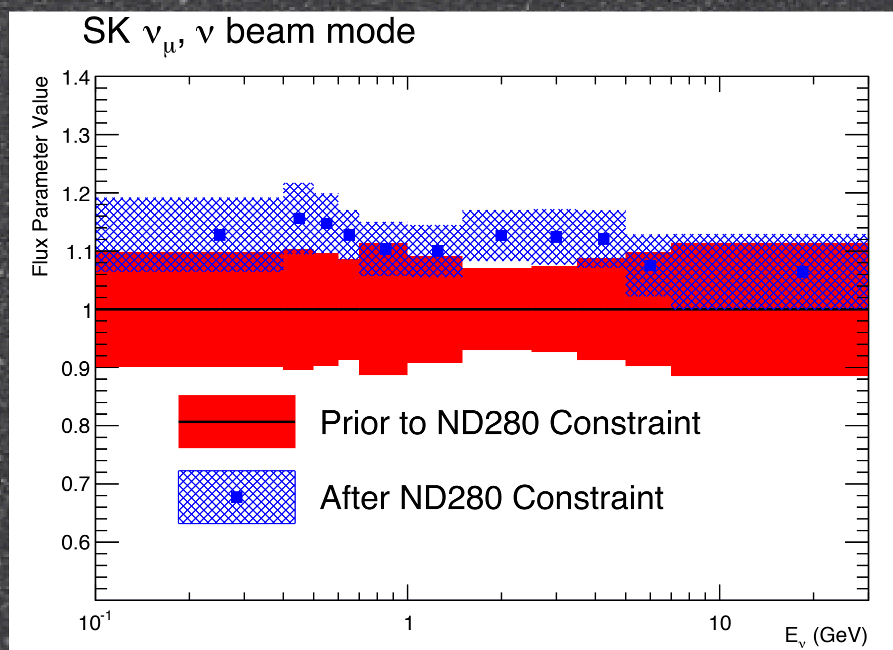


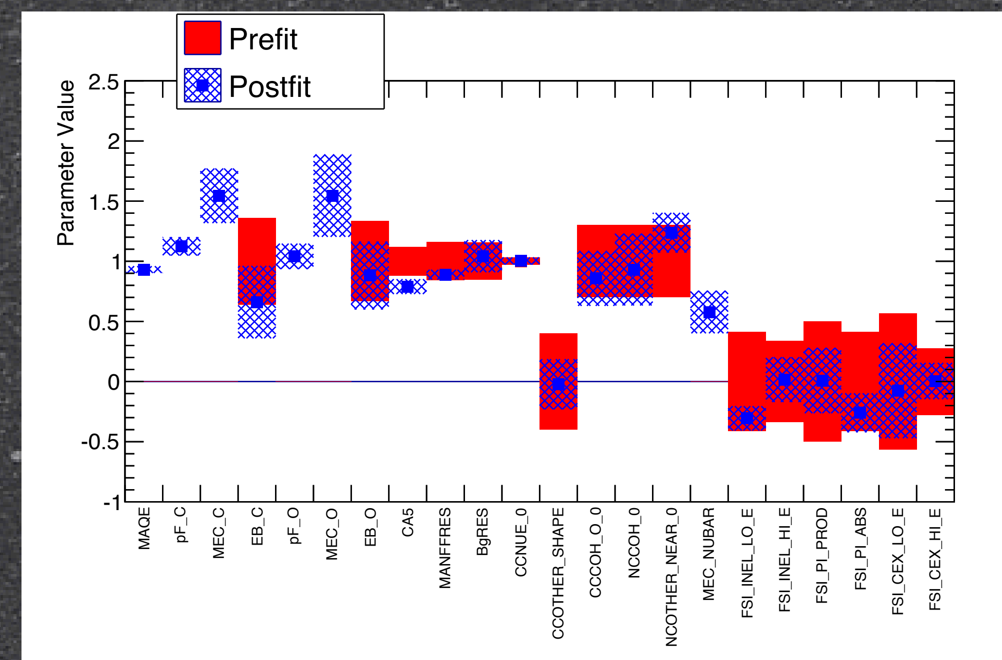
systematic error source	*prod6B total error in (%)*			
	CC	*CC0Pi*	*CC1Pi*	*CCOther*
Observable-variation systematics				
Field distortions	0.0971	0.0822	0.1581	0.0989
Momentum resolution	0.1082	0.0786	0.1354	0.3404
Momentum scale	0.0791	0.0478	0.0780	0.2343
TPC PID	0.4538	0.4273	1.2179	0.7854
FGD PID	0.0003	0.0088	0.0322	0.0185
Time of flight	0.0783	0.0735	0.0721	0.1130
Efficiency-like systematics				
Charge ID efficiency	0.0935	0.1220	0.0766	0.0777
TPC cluster efficiency	0.0006	0.0004	0.0005	0.0014
TPC track efficiency	0.5231	0.4624	0.6984	0.6801
FGD track efficiency	0.0030	0.0084	0.0320	0.0864
TPC-FGD matching efficiency	0.2850	0.2213	0.3186	0.6063
Michel electron	0.0043	0.0916	0.4294	0.0065
Normalization systematics				
OOFV background	0.4699	0.5255	0.4508	0.2053
Pile-up	0.1219	0.1219	0.1218	0.1218
FGD mass	0.3893	0.3879	0.3888	0.3984
Pion secondary interactions	2.0518	1.4350	3.6126	5.5949
ALL				
All magnet	2.2734	1.6909	3.8818	5.9080
Sand muon background	0.0332	0.0364	0.0211	0.0281
TOTAL	2.2737	1.6913	3.8818	5.9081



Systematic reduction in Oscillation

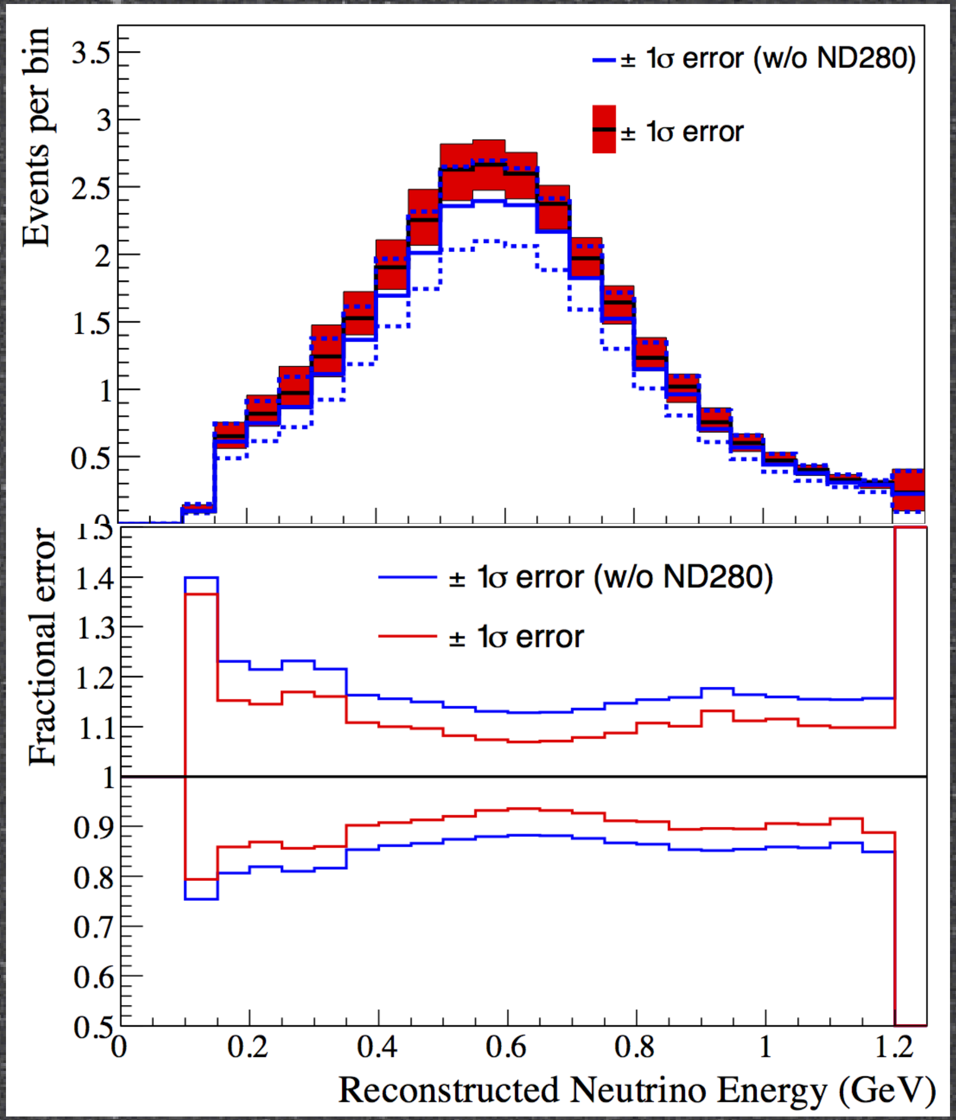
$$\Delta\chi^2_{ND280} = 2\sum_{j}^{reco\ bins} N_j^{pred}(\vec{f},\vec{x},\vec{d}) - N_j^{obs} + N_j^{obs} ln\left(\frac{N_j^{obs}}{N_j^{pred}(\vec{f},\vec{x},\vec{d})}\right)$$
$$+ \Delta\vec{f}^{\,t}\, V_{flux}^{-1}\Delta\vec{f} + \Delta\vec{x}^{\,t}\, V_{xsec}^{-1}\Delta\vec{x} + \Delta\vec{d}^{\,t}\, V_{det}^{-1}\Delta\vec{d}$$

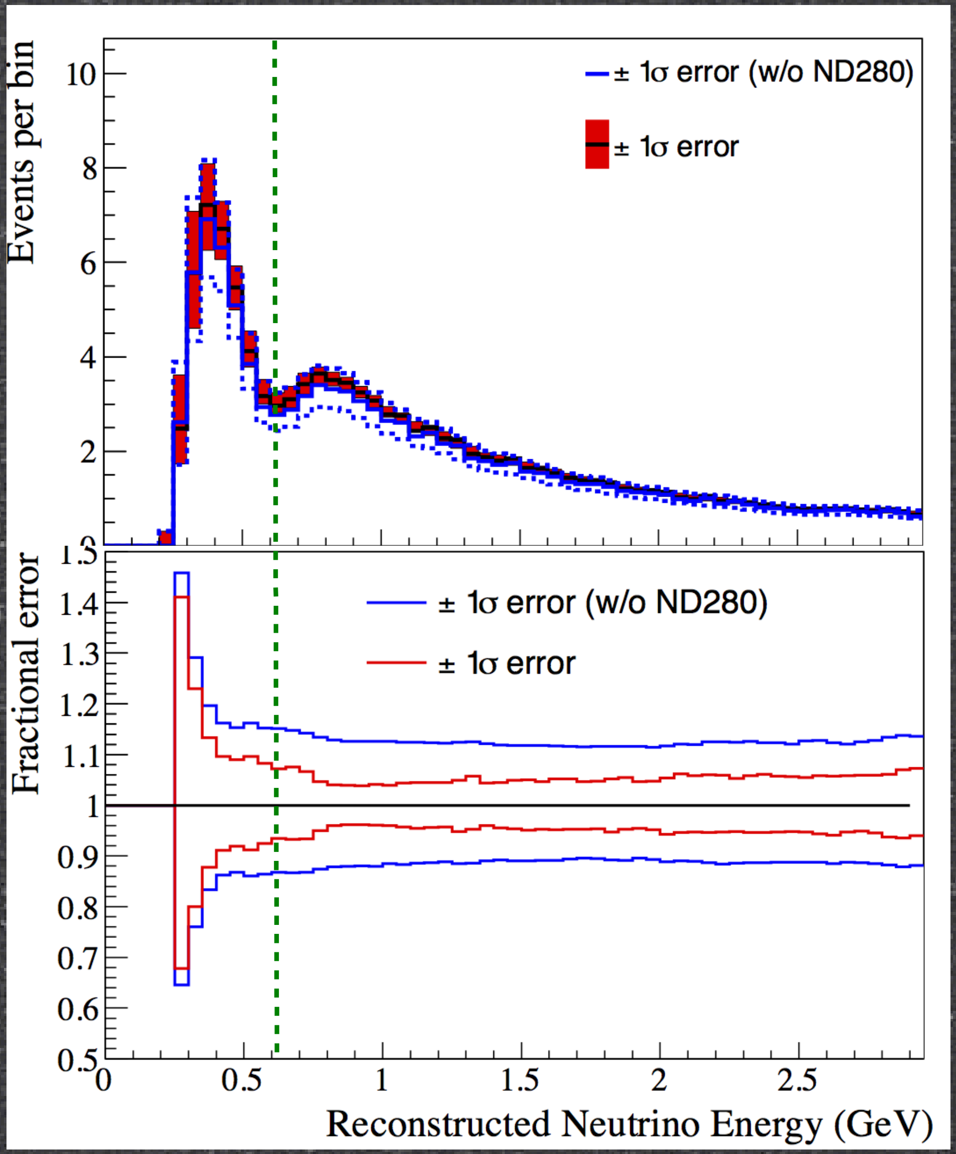




- For the T2K oscillation analyses we model flux and cross-section systematic uncertainties
  - Flux: mainly based on NA61/SHINE data (currently 10-15% uncertainties)
  - Cross-section: use external data to constraint the neutrino interaction model based on NEUT

Systematic errors in OA





- Change the expected rate of events at SK
- Reduce the systematic uncertainties → from ~15% to ~5%

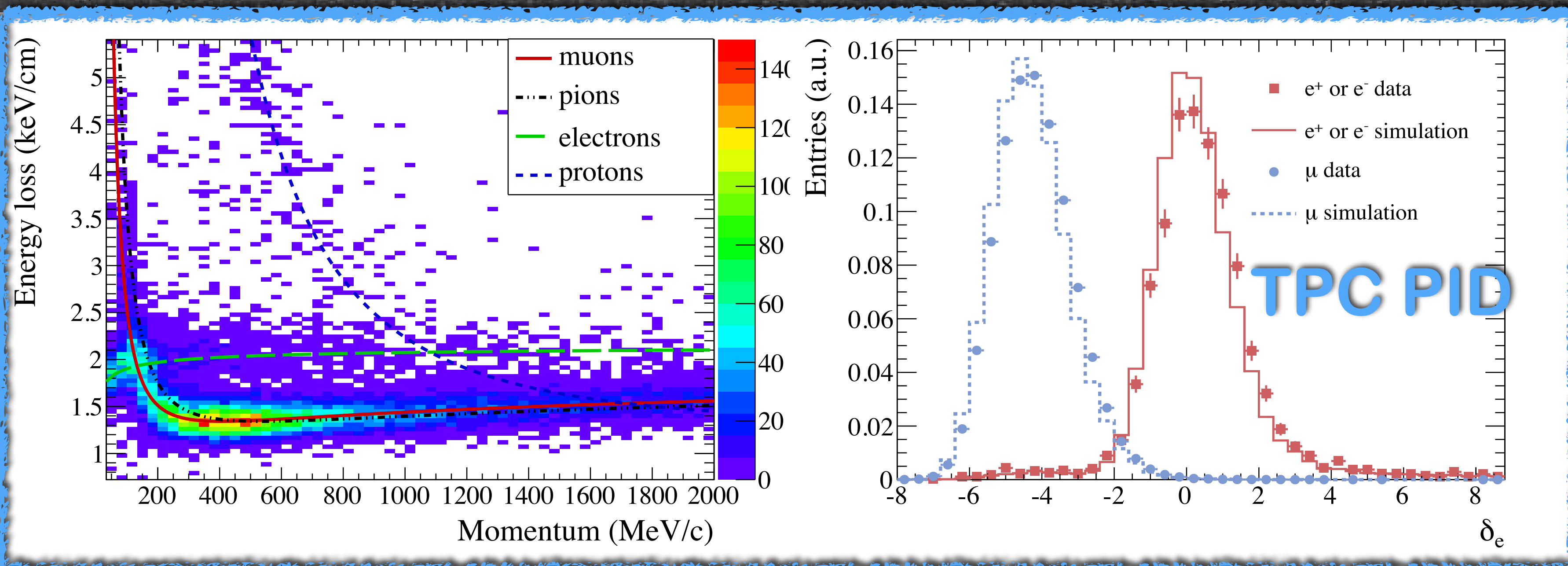
Systematic errors in OA

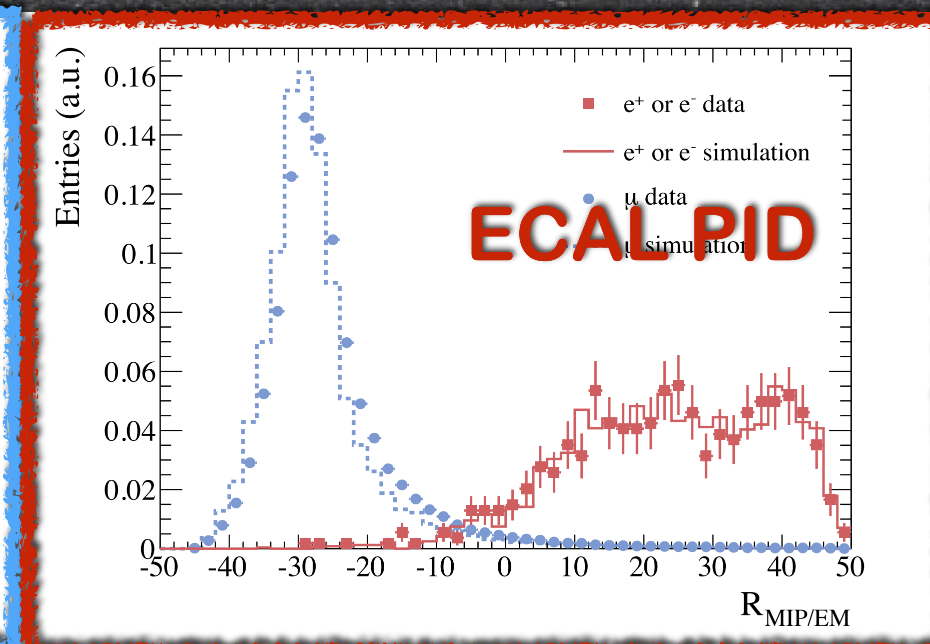
	ν_μ sample $1R_\mu$ FHC	ν_e sample $1R_e$ FHC	$\bar{\nu}_\mu$ sample $1R_\mu$ RHC	$\bar{\nu}_e$ sample $1R_e$ RHC	$1R_e$ FHC/RHC
ν flux+cross-section constrained by ND280	2,8%	2,9%	3,3%	3,2%	2,2%
ν_e/ν_μ and $\bar{\nu}_e/\bar{\nu}_\mu$ cross-sections	0,0%	2,7%	0,0%	1,5%	3,1%
NC γ	0,0%	1,4%	0,0%	3,0%	1,5%
NC other	0,8%	0,2%	0,8%	0,3%	0,2%
Final or secondary hadron int.	1,5%	2,5%	2,1%	2,5%	3,6%
Super-K detector	3,9%	2,4%	3,3%	3,1%	1,6%
Total	**5,0%**	**5,4%**	**5,2%**	**6,2%**	**5,8%**

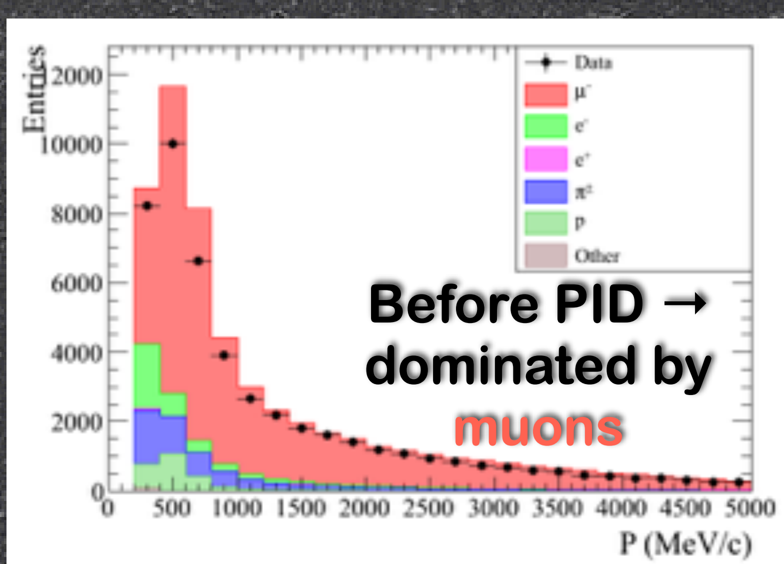
- Flux and cross-section systematics within the model used for the ND280 fit are reduced to the 3% level
  - We also implemented fake data studies to study the effect of different cross-section models on the extraction of oscillation parameters
- The other main systematic uncertainty for δ_{CP} is due to the ν_e/ν_μ cross-section difference → can we do something with ND280?

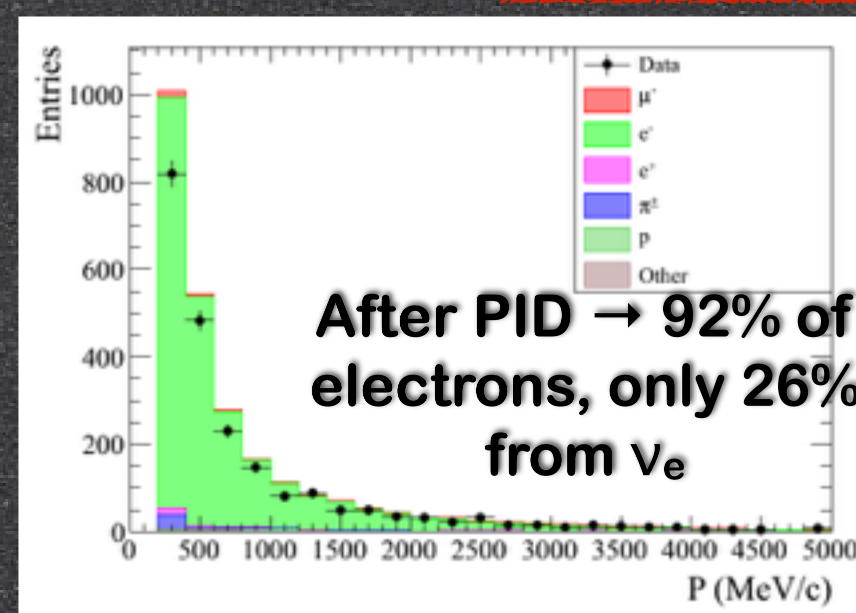
ν_e analysis: ND280 PID capabilities

- In T2K beam there is a residual beam νe component of ~1% of the total flux → main background to νe appearance at SK
- To select them we need to reject the dominant muon signal

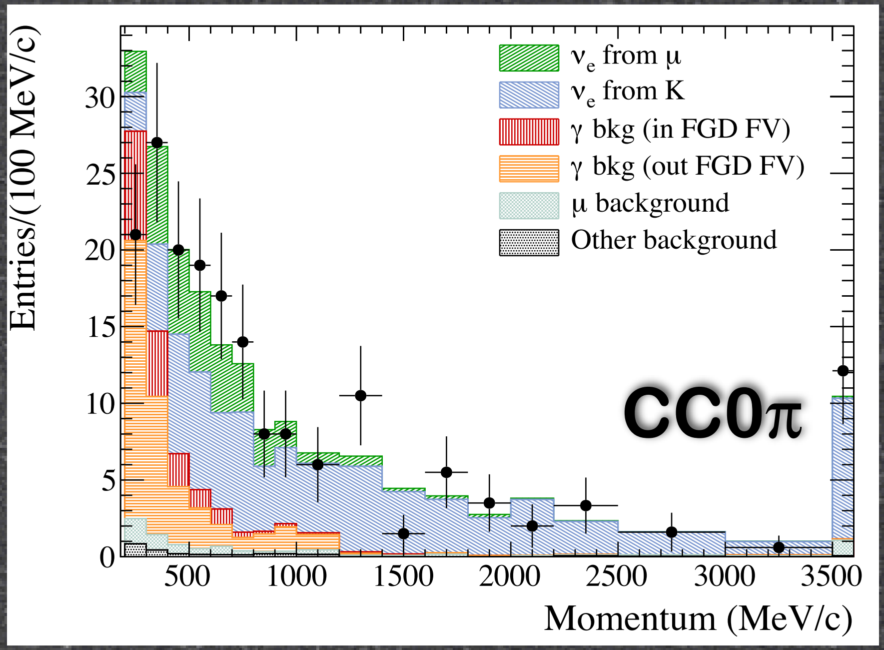


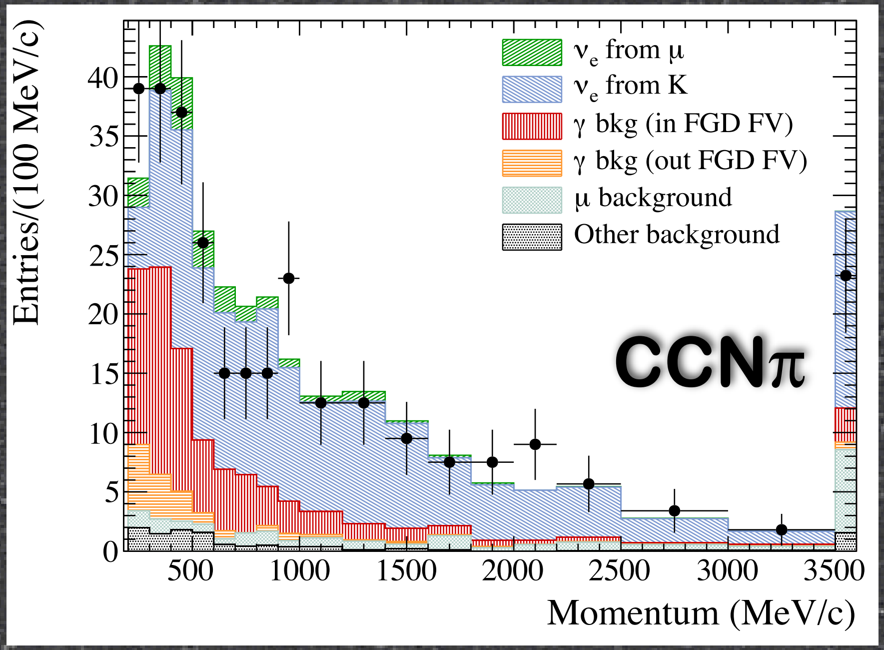






CC ν_e measurement





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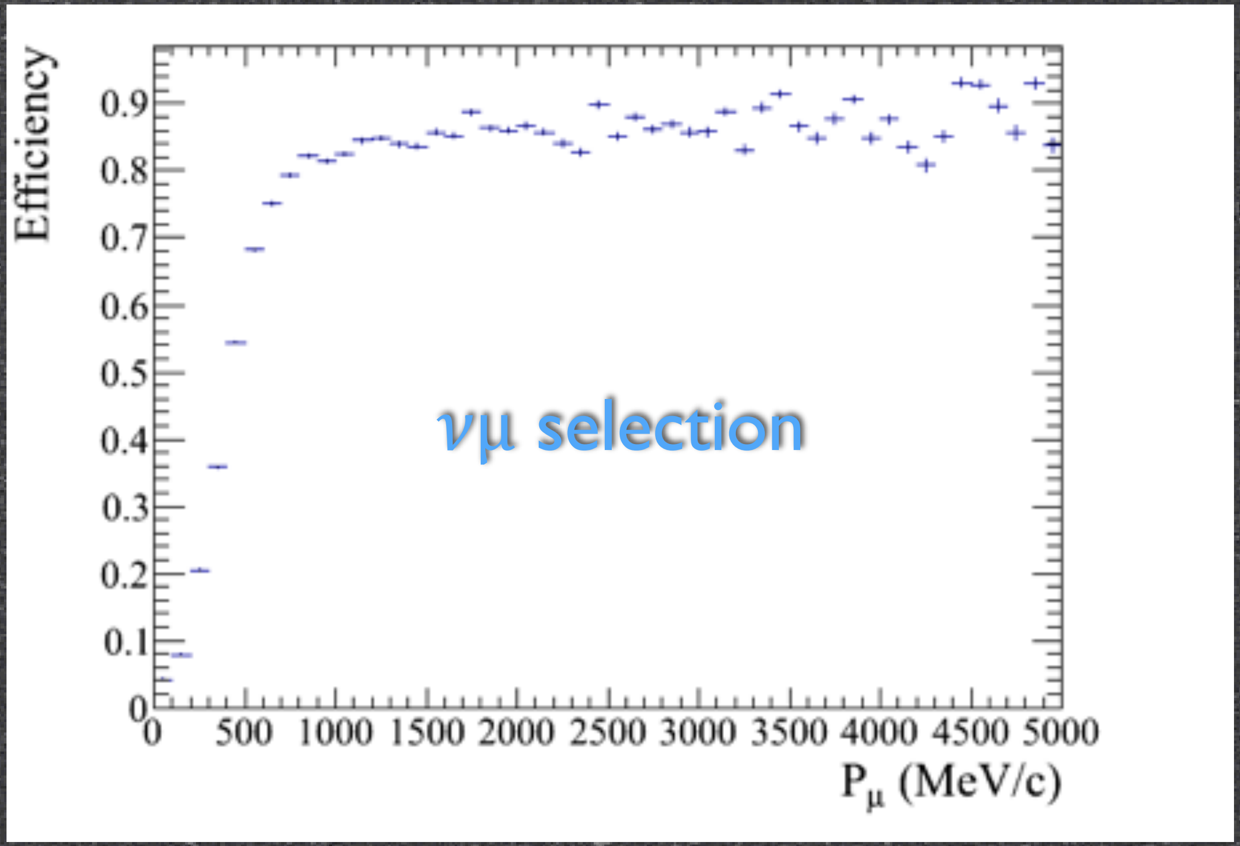
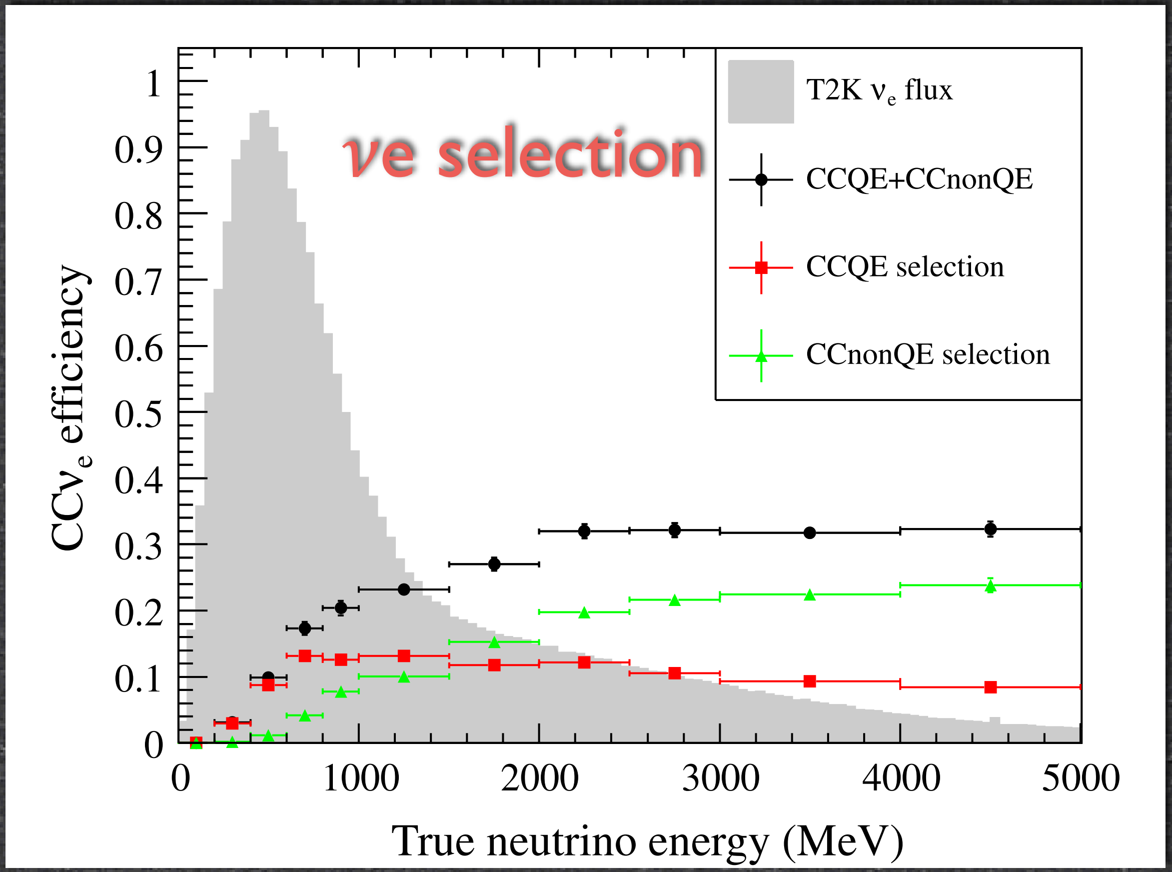
- Inclusive beam ν_e component
  - R(ν_e) = 1.01 ± 0.06 (stat.) ± 0.06 (flux + x-sec) ± 0.05 (detector) → 1.01 ± 0.10
- Separate ν_e from μ and from K decays
  - R(ν_e from μ) = 0.68 ± 0.30 → mostly at low energy
  - R(ν_e from K) = 1.10 ± 0.14 → mostly at high energy
- Even with more POT it will be difficult to constraint the νe cross-section at low energy at the level due to the low ND280 efficiency at this energy

ND280 efficiency

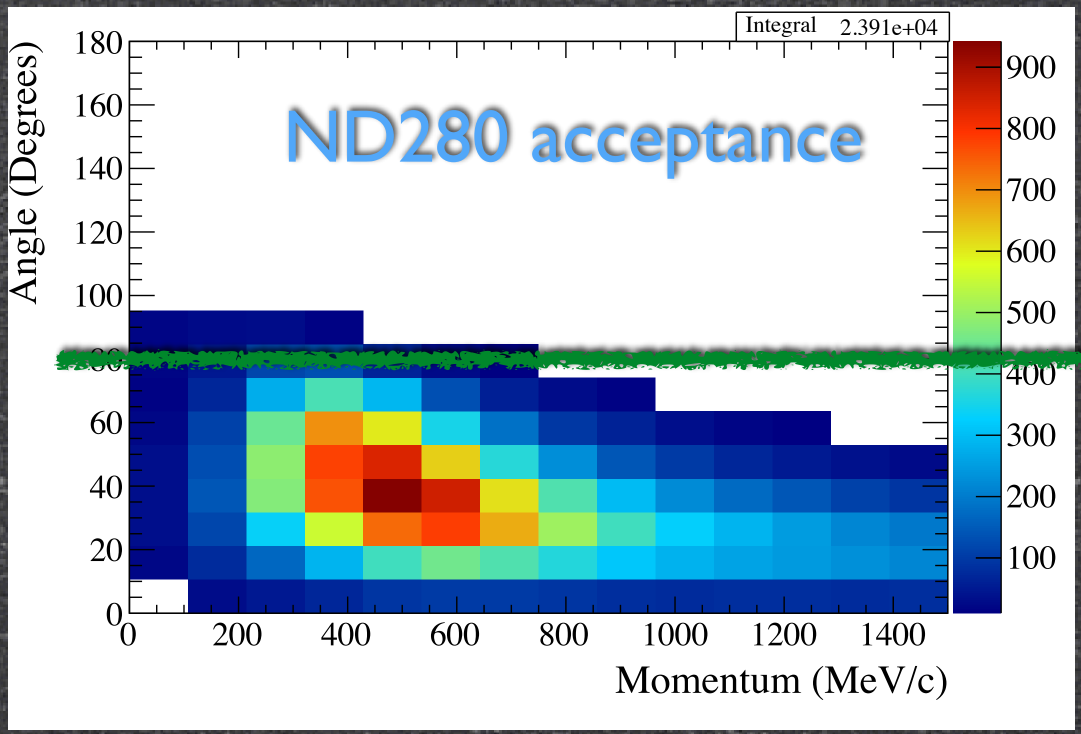
- The efficiency of ND280 is flat at high energy but it goes down rapidly for E<600 MeV
- This is mainly due to the requirement of having tracks entering the TPC
  - Low momentum leptons are often emitted at high angle and do not reach the TPC

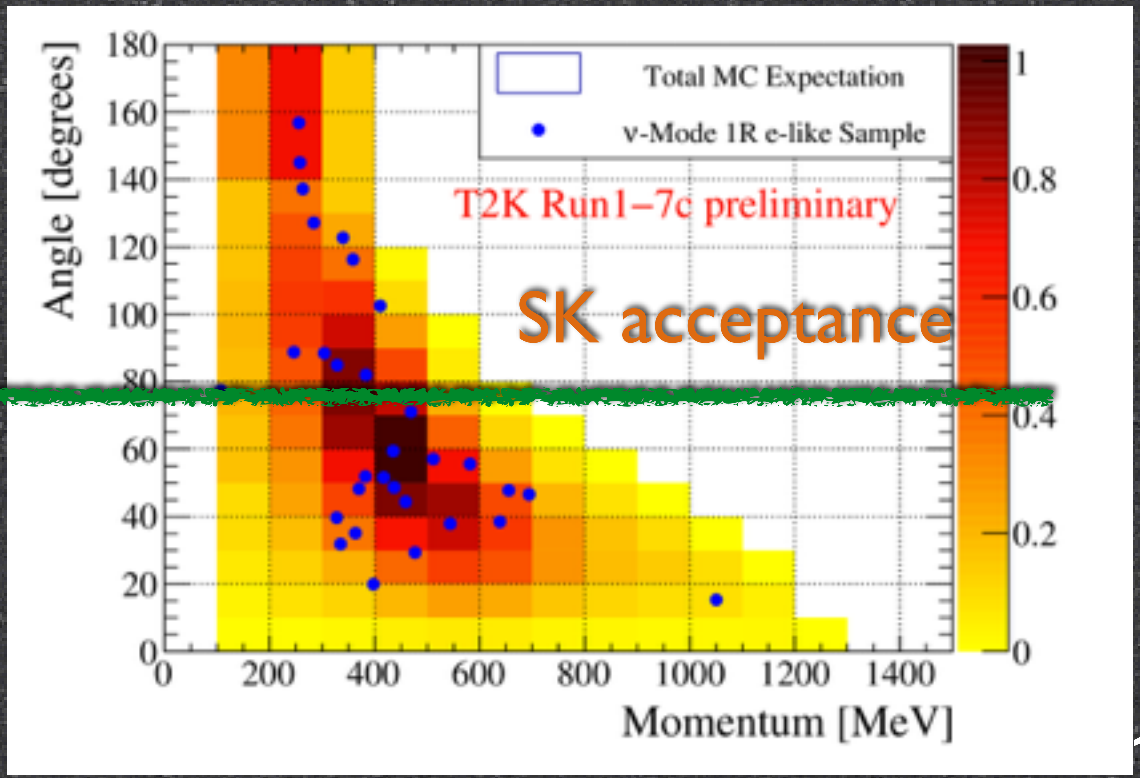




Angular acceptance

- One of the main limitation of current ND280 analyses is that it only select forward-going muons
- In SK the acceptance is flat with respect to the lepton angle and events with backward leptons are also selected
- Currently we constraint the models in the forward region and we let the model constraint the backward region → model dependent

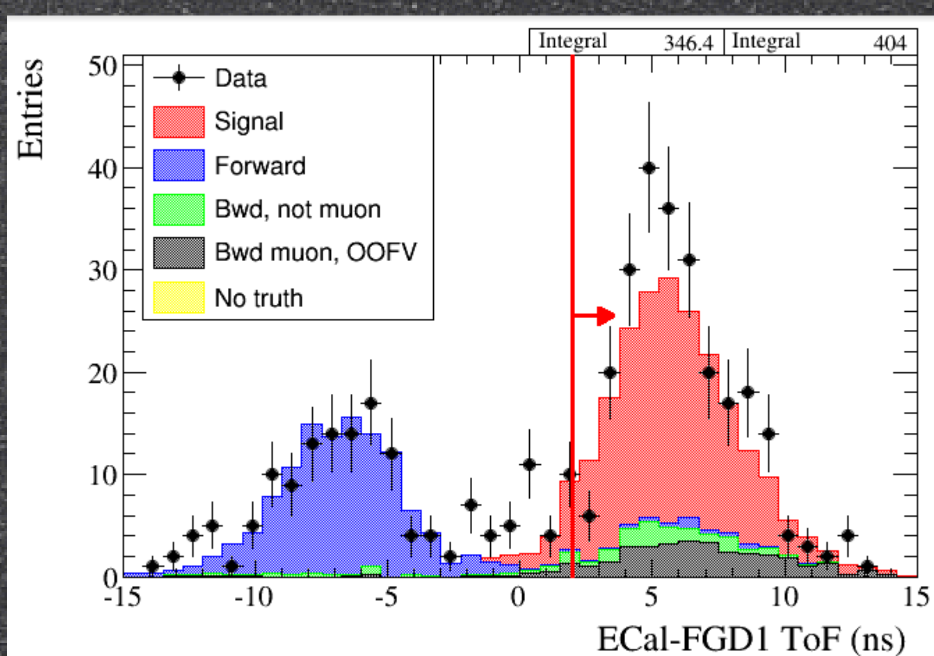


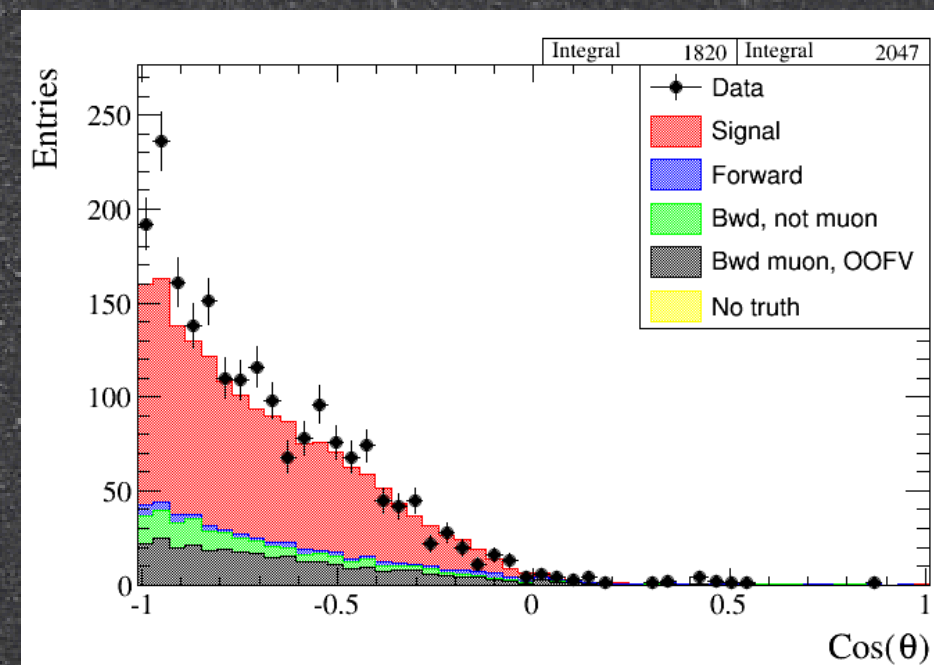


Increasing angular efficiency

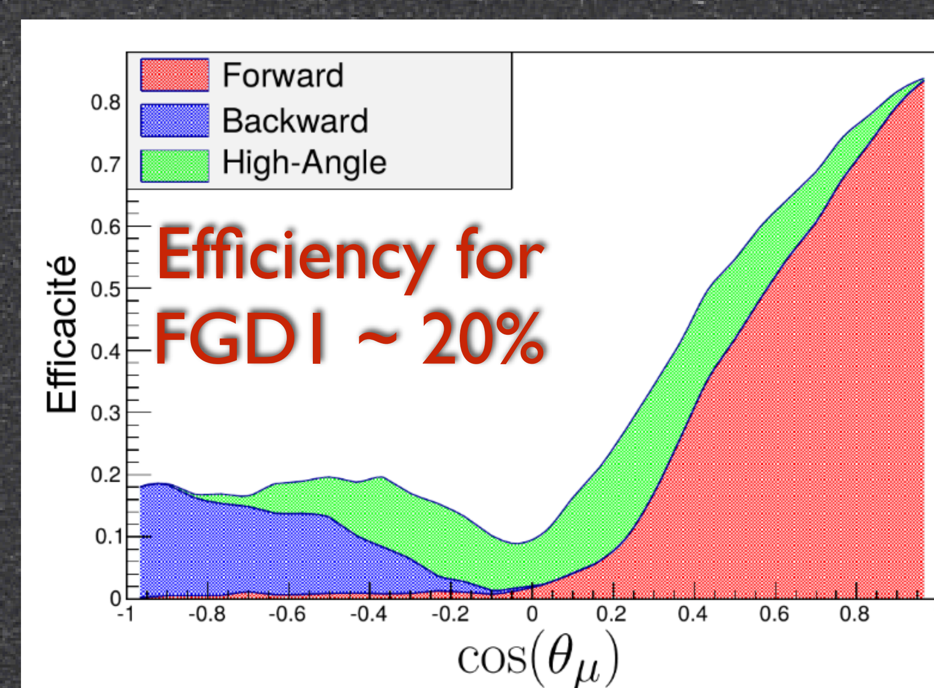
- Working to increase the angular acceptance by selecting high angle and backward going tracks

Backward tracks: use ToF between FGD and ECAL or P0D → not optimized for ToF, low efficiency





High angle → no TPC tracks, larger systematic uncertainties are expected



Conclusions

- ND280 is stably running and contributing in a decisive way to the results of T2K
  - Excellent detector to reconstruct the momentum of the leptons produced in neutrino interactions
  - The magnetic field allows excellent separation between ν and $\bar{\nu}$
- Thanks to the ND280 inputs the systematic uncertainties on the oscillation analysis are reduced from ~15 to ~5%
- After some years of running some limitations have been identified and might be fixed with an upgraded version of ND280
  - Low efficiency for low momentum and high angle tracks
  - The number of reconstructed ν_e is not enough to effectively constraint ν_e/ν_μ cross-section below 1 GeV