Flux and Neutrino interaction model constraints using the T2K near detectors

Laura Zambelli (KEK)
On behalf of the T2K collaboration

Outline:

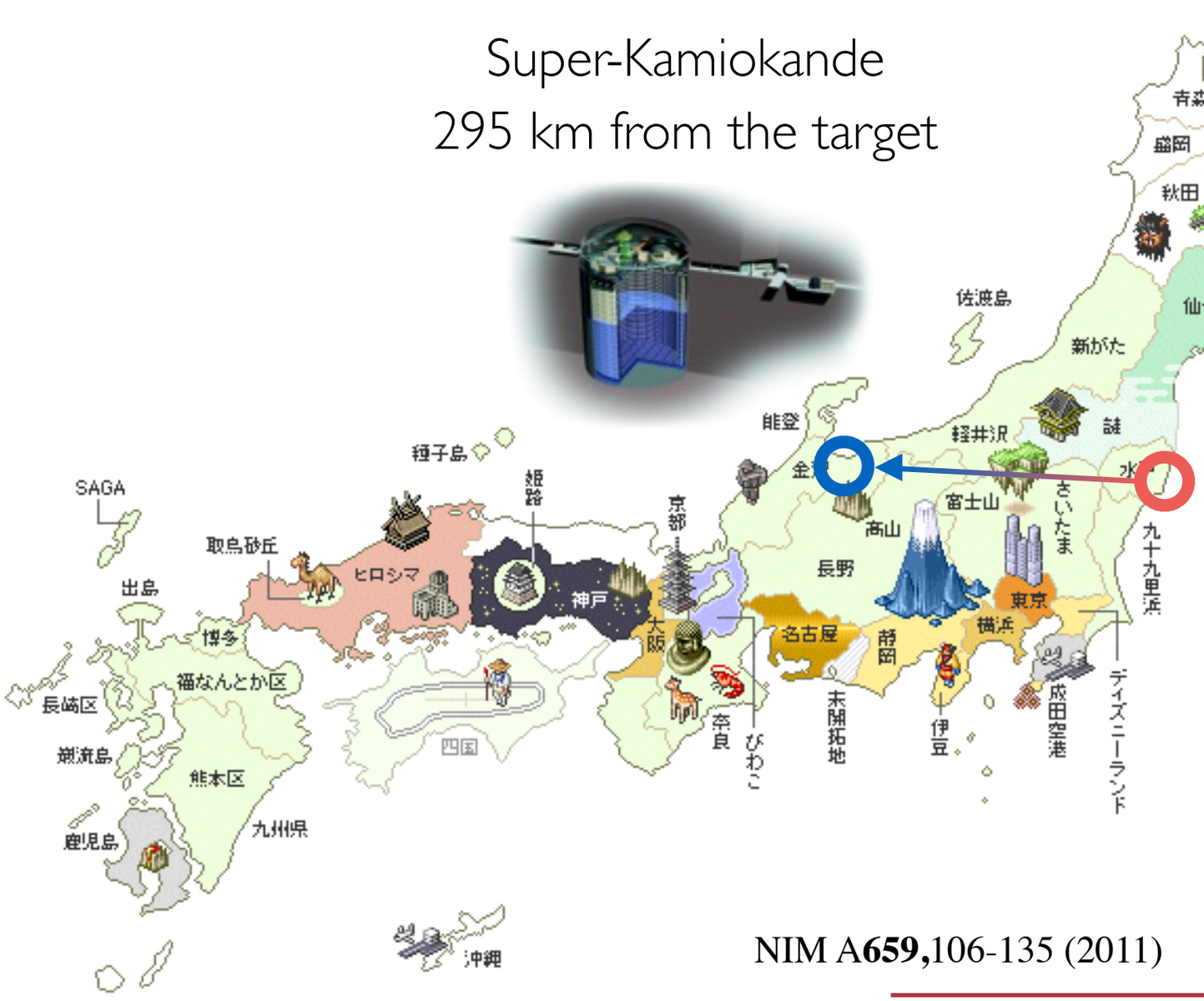
- The T2K experiment
- Generation of T2K flux tuned to hadroproduction data
- T2K near detectors cross section model and measurement
- Flux ⊗ cross section constraints to reduce uncertainties on neutrino oscillation measurement

KEK-JAPAN

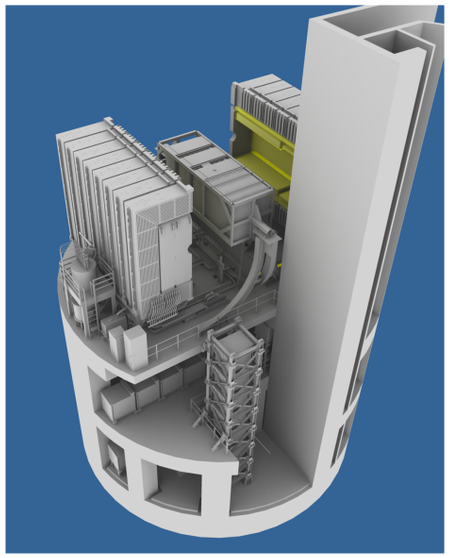
The T2K experiment

T2K is a long baseline neutrino experiment in Japan from J-PARC (Tokai) to Kamioka

Super-Kamiokande
295 km from the target

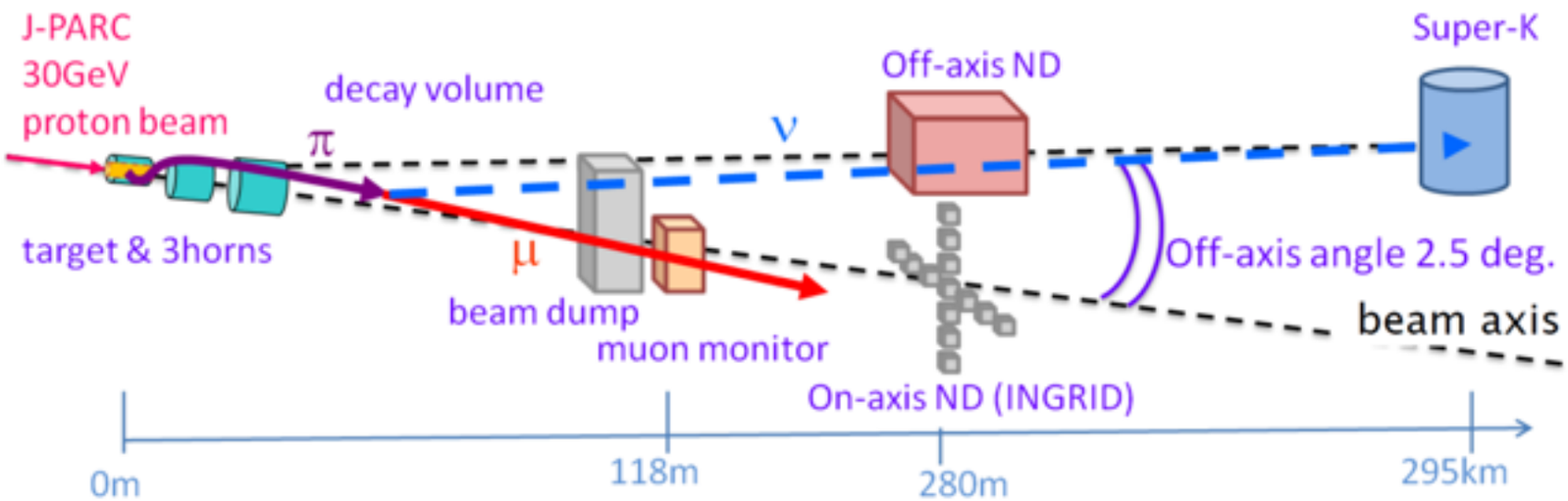


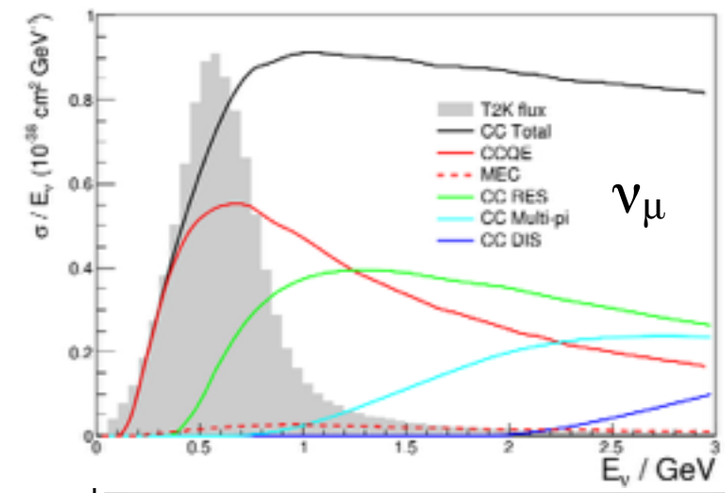
Neutrino source and near detectors at J-PARC



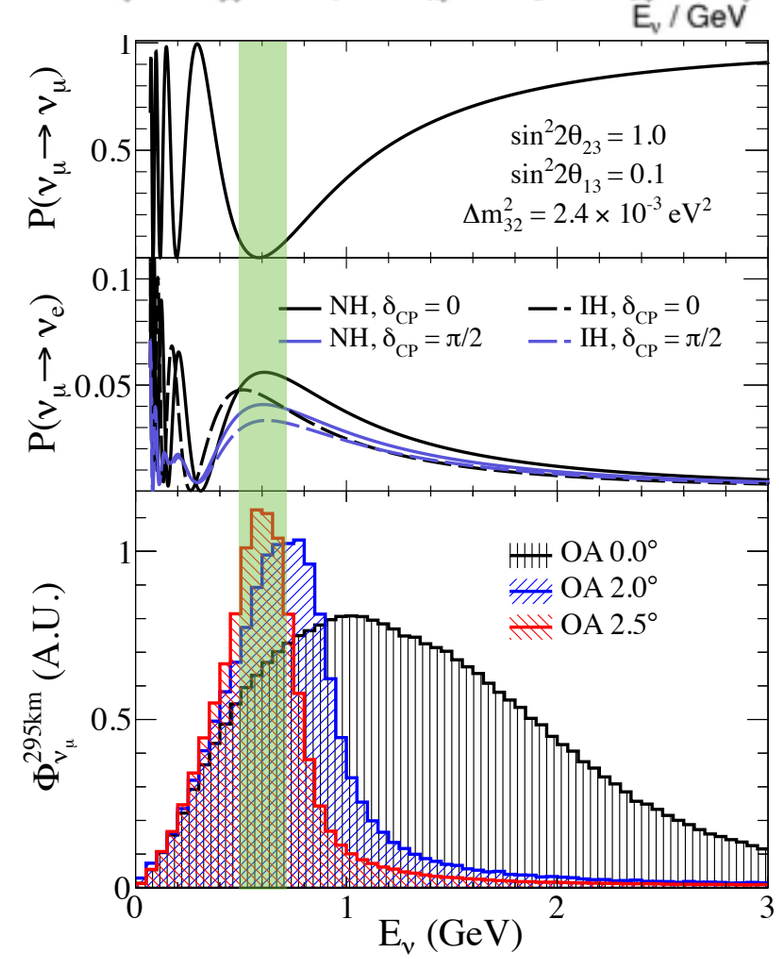
NIM A**659**,106-135 (2011)

Neutrino source and near detectors at J-PARC



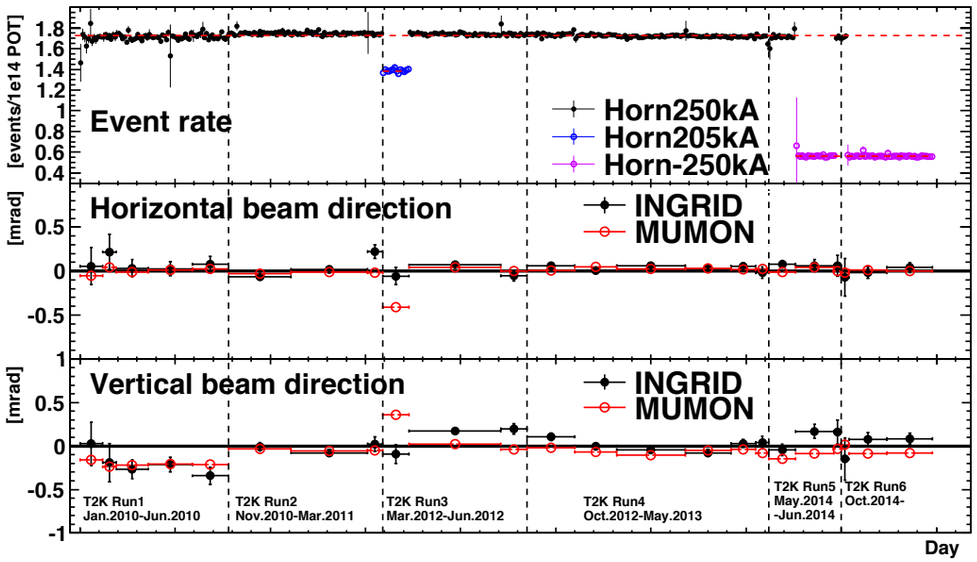


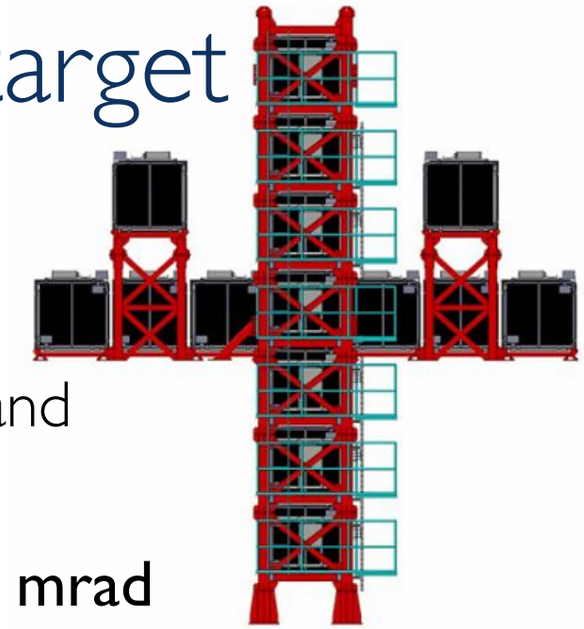
- J-PARC accelerator provides 30 GeV protons.
- Interactions in a 90 cm long graphite target produce hadrons, focussed by 3 horns running at ±250 kA.
- (anti)-**ν** beam is made from the decay in flight of **π**/K/**μ**.
- Muon neutrino beam is contaminated by wrong sign neutrinos and (anti)-ν_e.
- Off-axis beam technique allows us to have a neutrino beam peaked at the energy
  - maximizing the $\nu_\mu \rightarrow \nu_e$ oscillation channel
  - reducing the high energy **ν** interactions



PRD **87**, 012001 (2013)

Near detector complex at 280 m from the target





INGRID : On-axis

Monitors the stability neutrino flux and direction

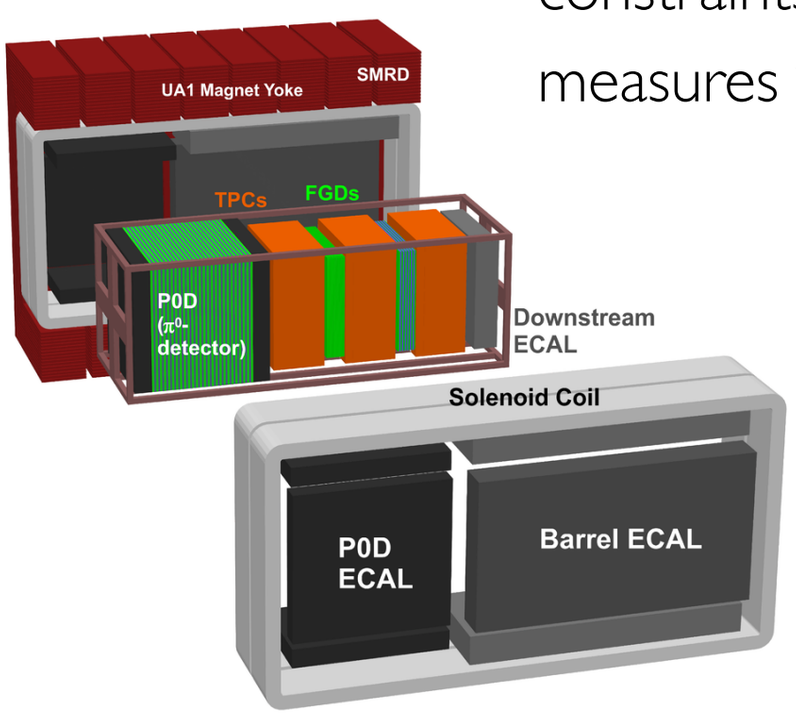
→**Beam direction is stable within 1 mrad**

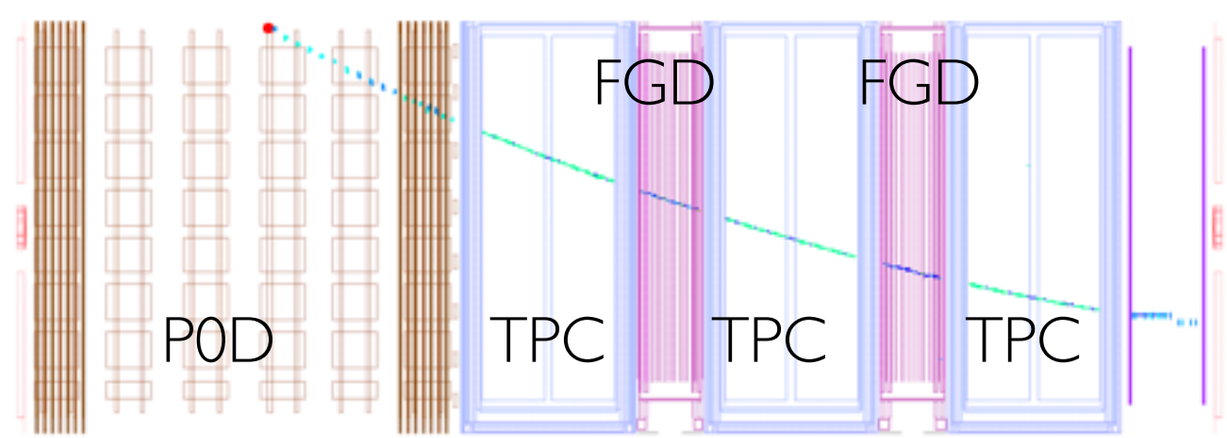
Cross section measurements are also performed

ND280 : Off-axis

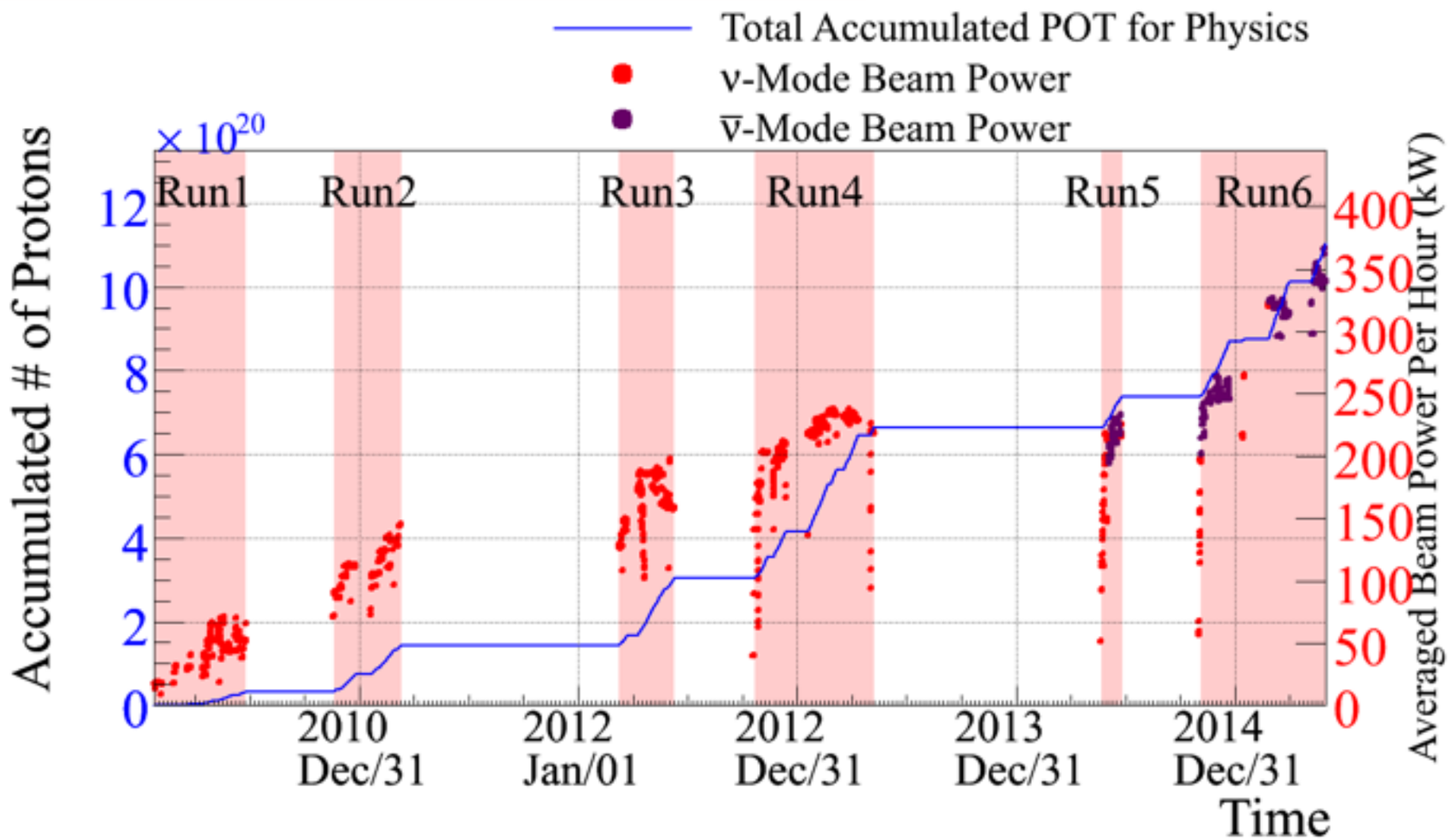
constraints the spectrum before oscillations

measures ν interactions on water and carbon targets





Data collected



Beam power reached **371 kW**

Accumulated protons on target :

11.04×10^{20} in total

7.00×10^{20} in ν mode

4.04×10^{20} in $\bar{\nu}$ mode

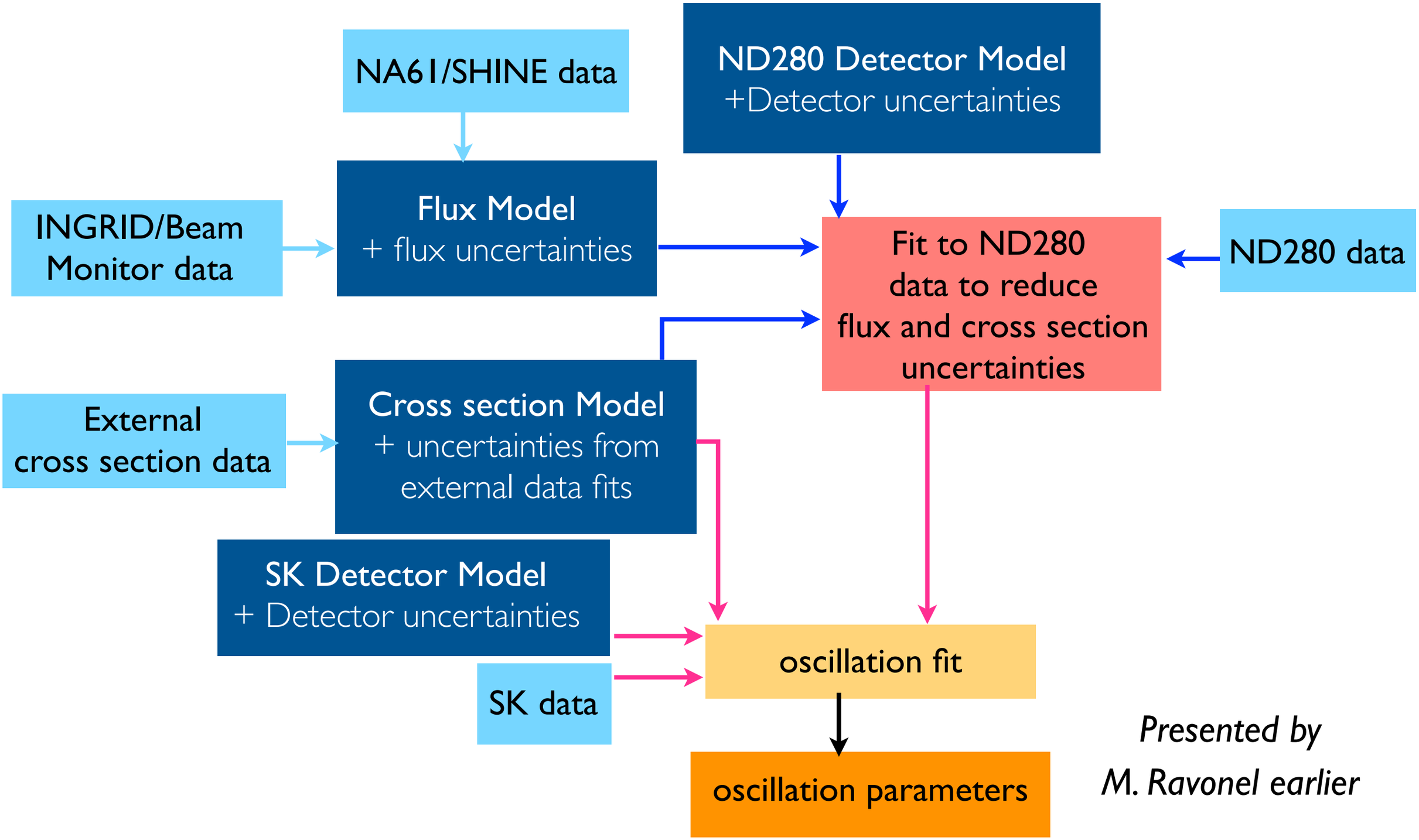
Analyzed protons on target for this presentation:

6.57×10^{20} in ν mode

4.30×10^{19} in $\bar{\nu}$ mode for ND280 constraints

4.04×10^{20} in $\bar{\nu}$ mode for INGRID and SK analysis

T2K strategy for oscillation parameters

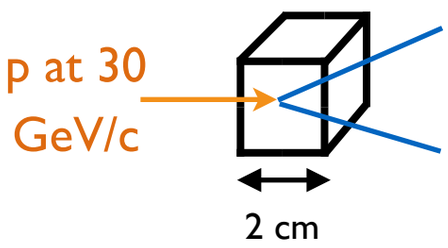


Presented by M. Ravonel earlier

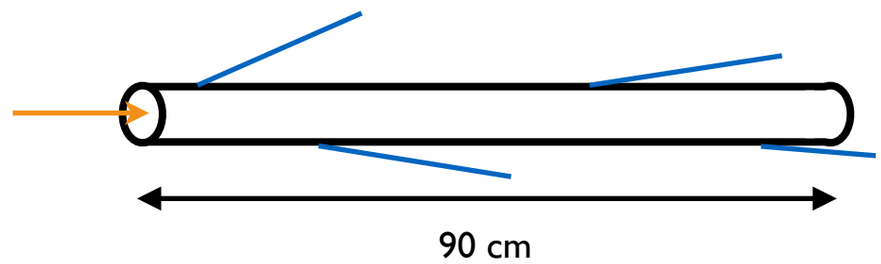
T2K flux strategy

Generate the un-oscillated flux by simulation. External hadroproduction data (mainly from NA61/SHINE experiment) are used to constrain the predictions from the generators.

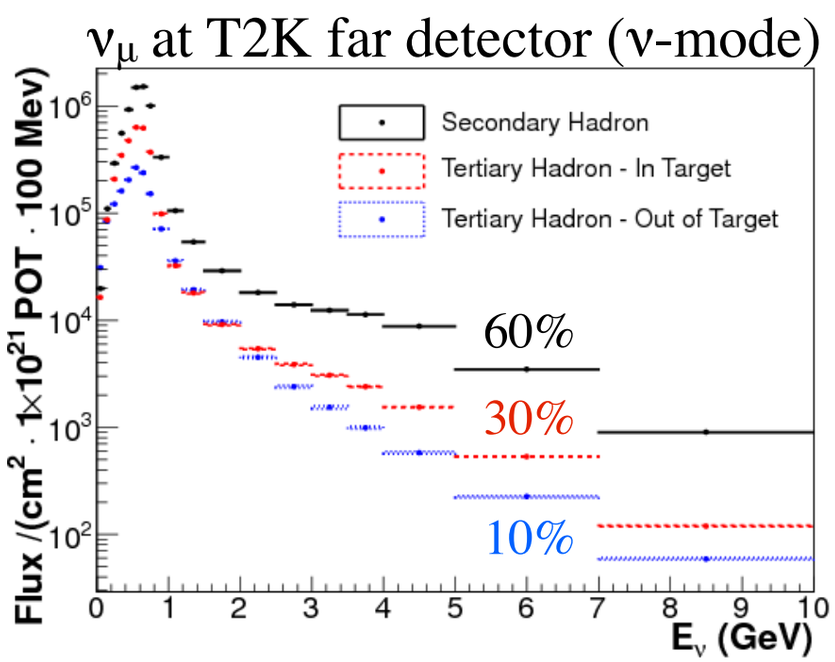
NA61/SHINE provides 2 types of datasets:



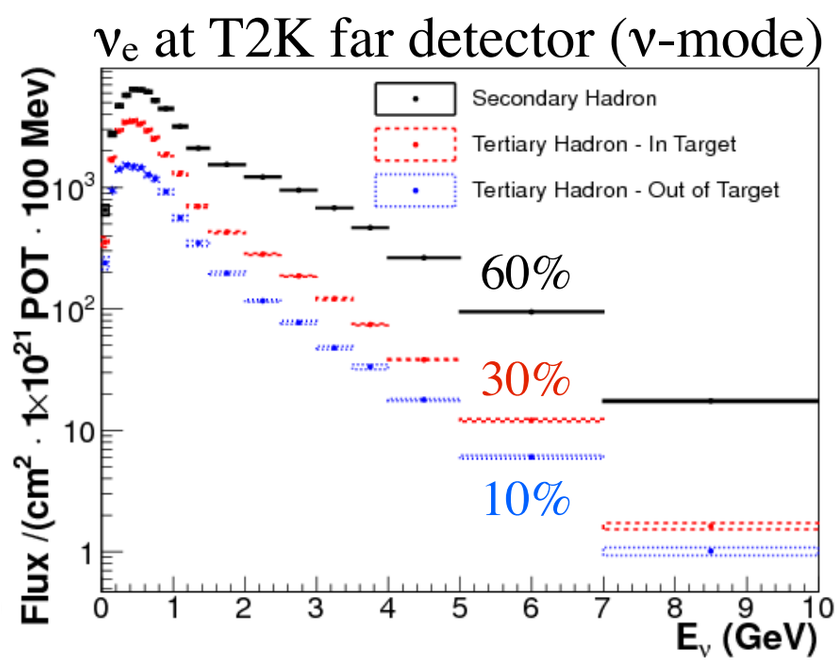
thin target :
study the primary p+C interaction



replica target :
accounts for the re-interactions in the target

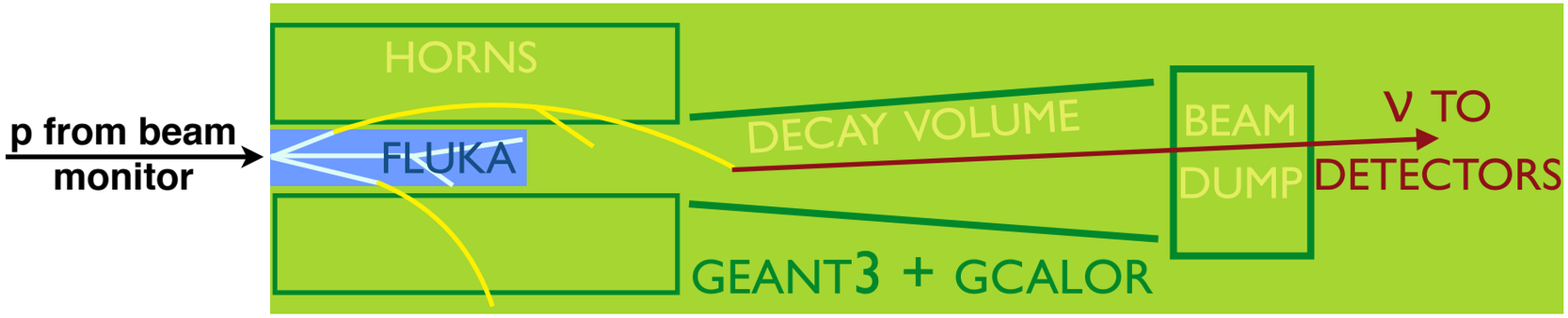


NIM A**701**, 99-114 (2013)



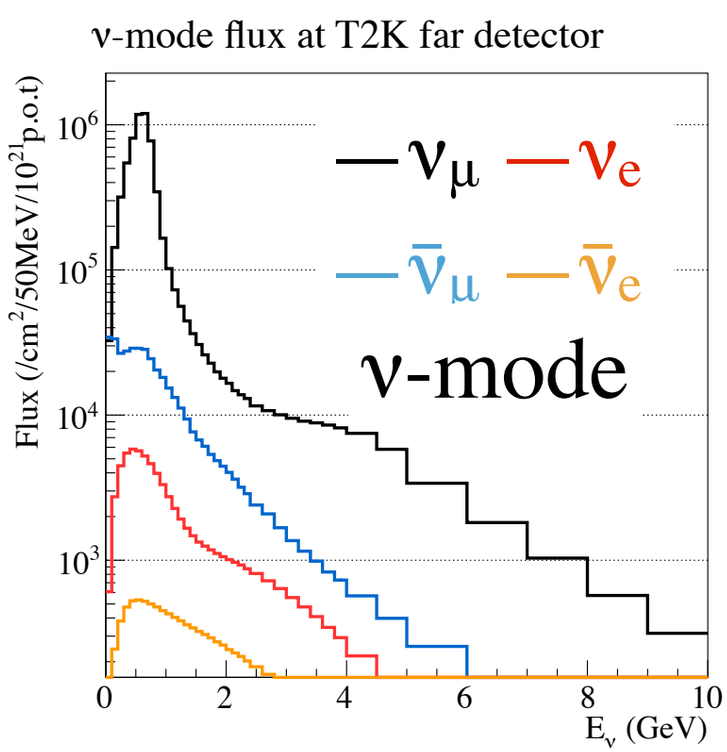
60% of the flux (at peak energy) is directly tunable with the thin target data. Up to 90% once the replica target data will be implemented in the tuning.

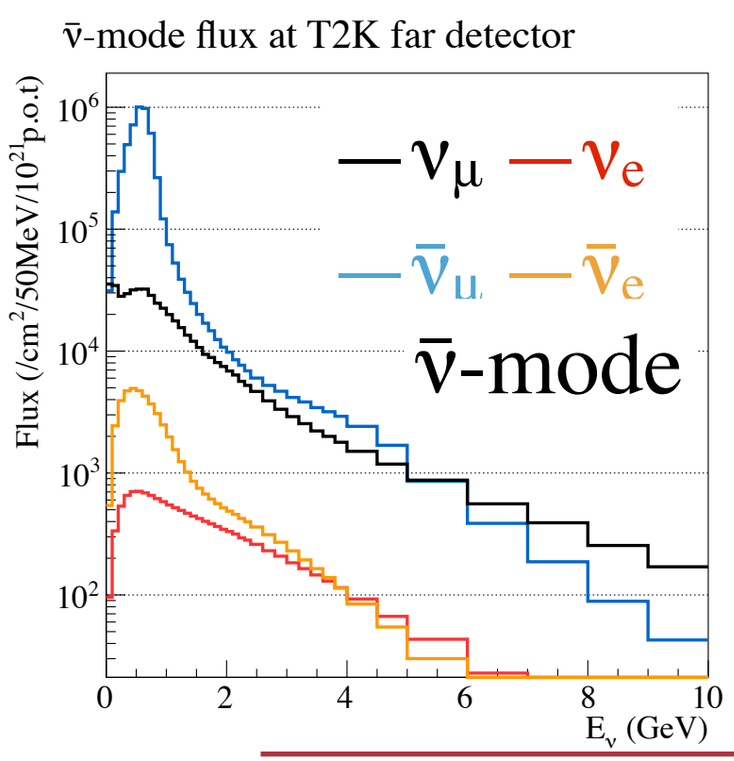
Neutrino flux predictions tuned to external data



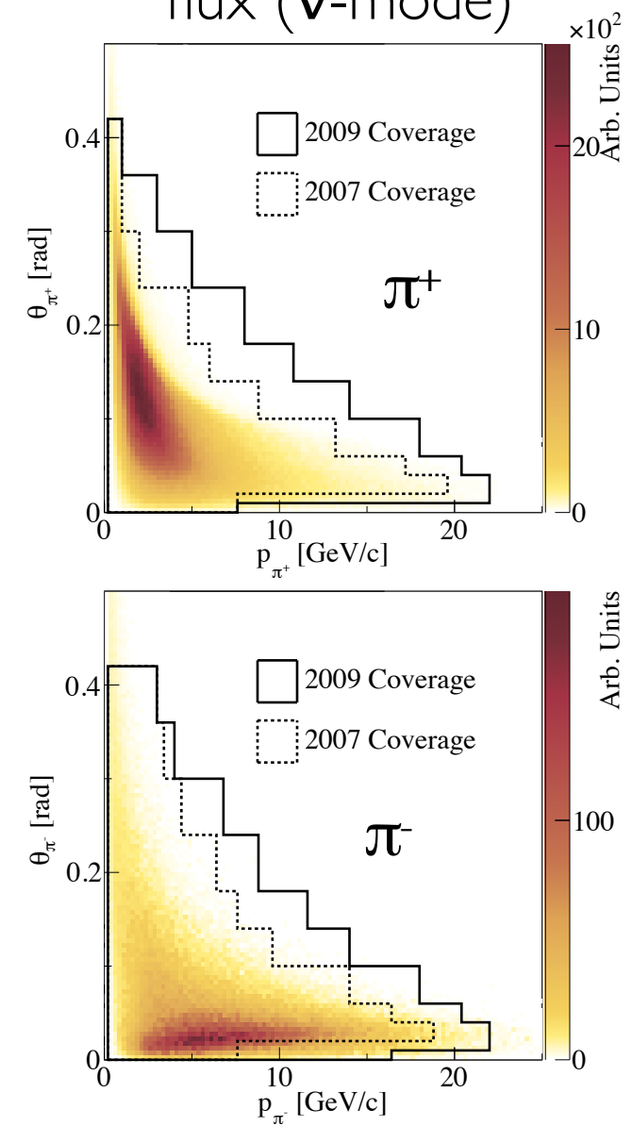
Most interactions leading to the production of a neutrino are tuned according to hadroproduction data. The multiplicity and the production cross section are taken into account.

NA61/SHINE has recently released the production of $\pi^{\pm}$, $K^{\pm}$, $K^{0}s$ and Λ from the **2009** thin target dataset. *See A. Korzenev talk*

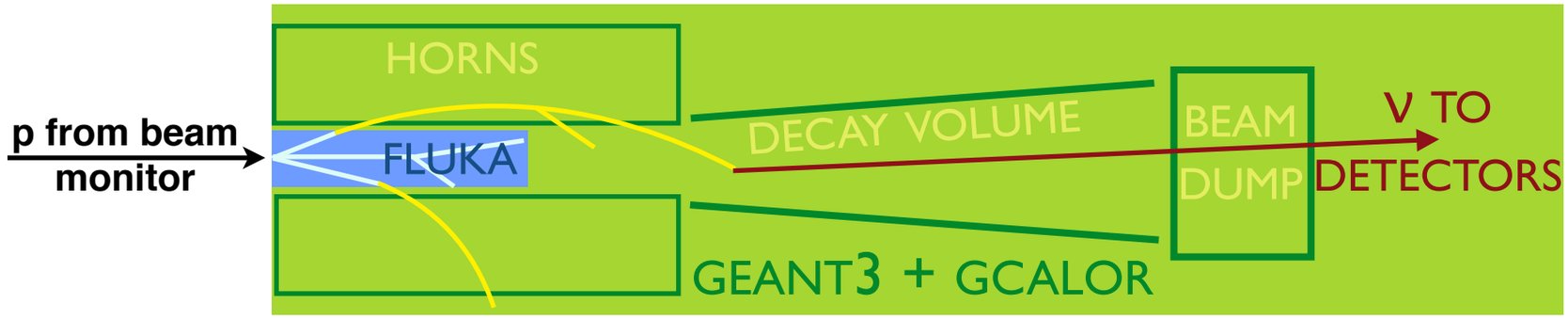




p-θ phase space of hadrons contributing to T2K far detector flux (ν-mode)



Neutrino flux uncertainties

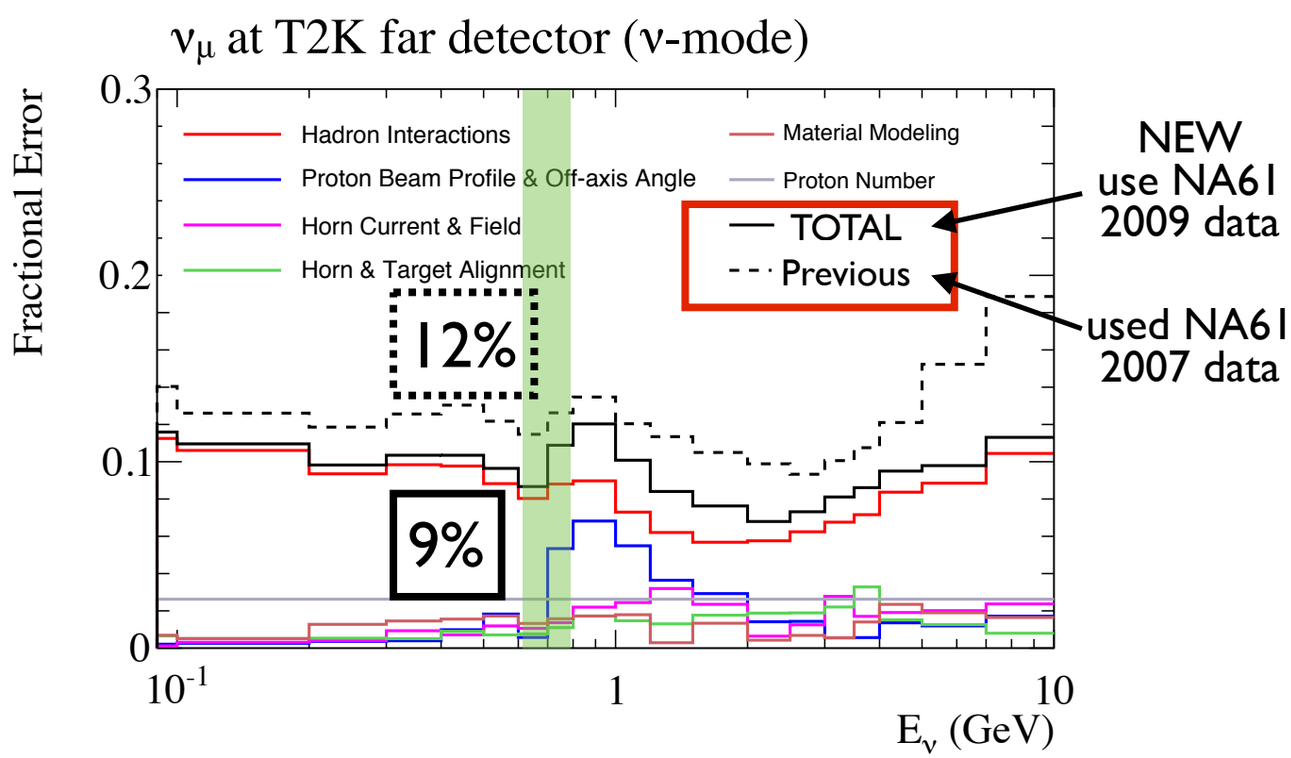


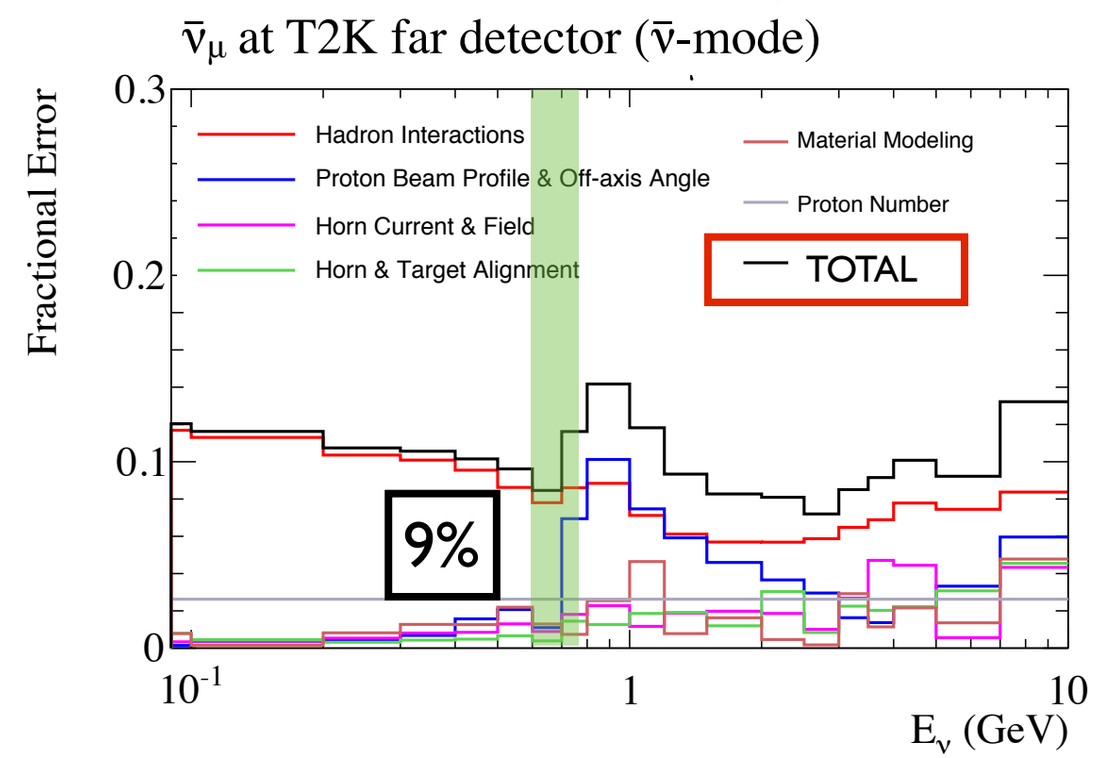
<u>beamline related uncertainties</u> :
proton beam profile, off-axis angle,
horn current & field, alignment

<u>hadron interactions related uncertainties</u> :
NA61 uncertainties, re-scattering
secondary nucleon production tuned

At T2K peak energy, flux uncertainty has now decreased to a level of ~10%!

Covariance matrix between detectors, ν flavor and run modes is computed





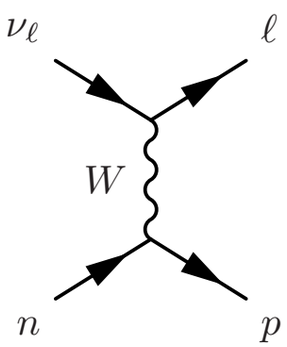
T2K cross section strategy

Uses most recent NEUT generator predictions :

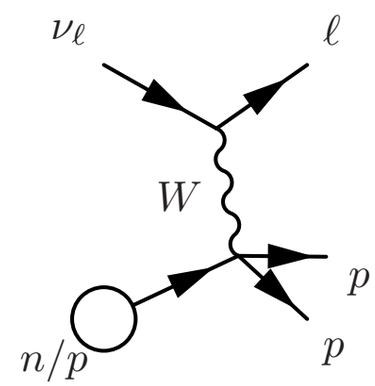
Acta Phys.Polon. **B40**, 2477-2489 (2009)

- Improved charged current quasi elastic (CCQE) description with Relativistic Fermi Gas + Random Phase Approximation
- Multi-nucleon ejection channel based on Nieves et al model implemented

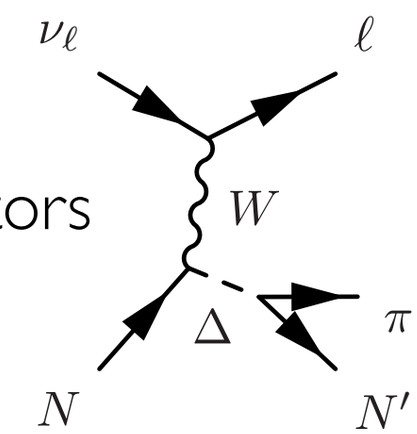
PRC **83**, 045501 (2011)



classic CCQE process, dominant at T2K energies



MEC model allows ν to interact with a pair of nucleons



- Resonant π production model retuned with Graczyk & Sobczyk form factors

PRD **77**, 053001, (2008) PRD **90**, 112017, (2014)

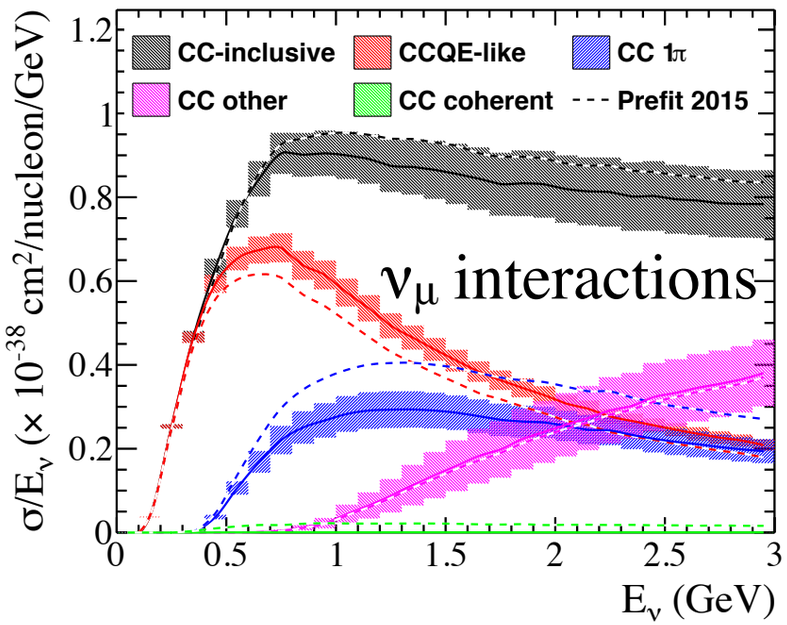
- Deep inelastic scattering, multi-π production, other resonant production and other neutral current interactions are mostly unchanged from the previous NEUT version

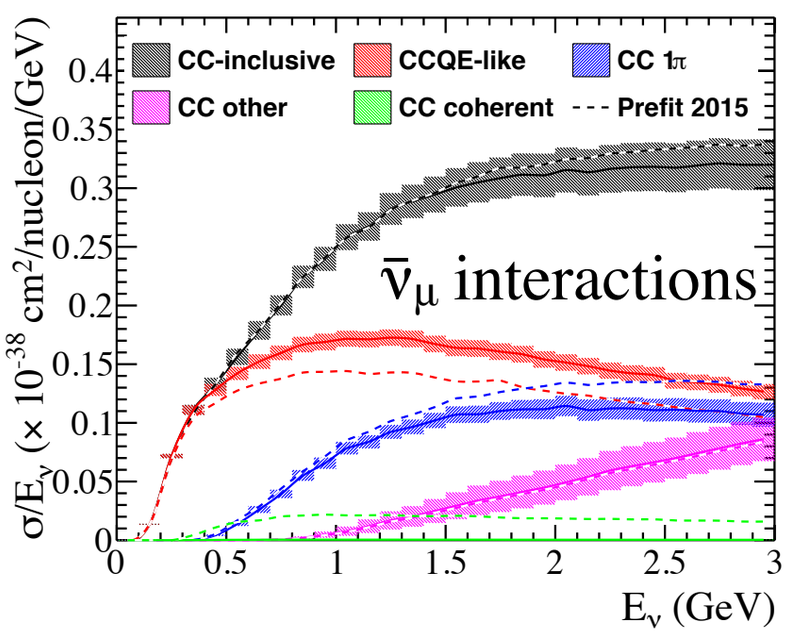
T2K cross section strategy

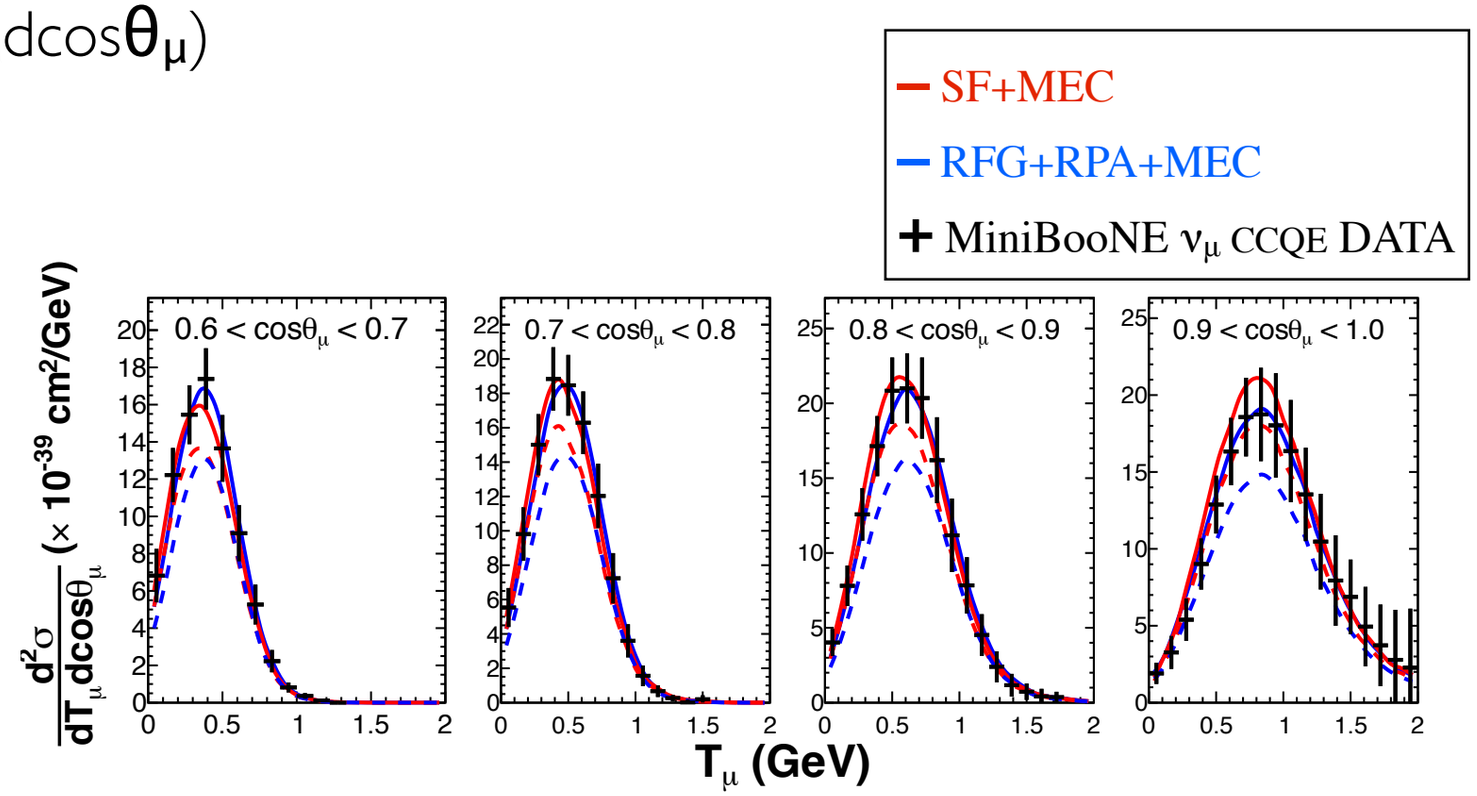
NEUT cross section default parameters are tuned to external data:

MiniBooNE $\nu_\mu/\bar{\nu}_\mu$ CCQE (in $d^2\sigma/dT_\mu d\cos\theta_\mu$)

Minerva $\nu_\mu/\bar{\nu}_\mu$ CCQE (in $d\sigma/dQ^2$)





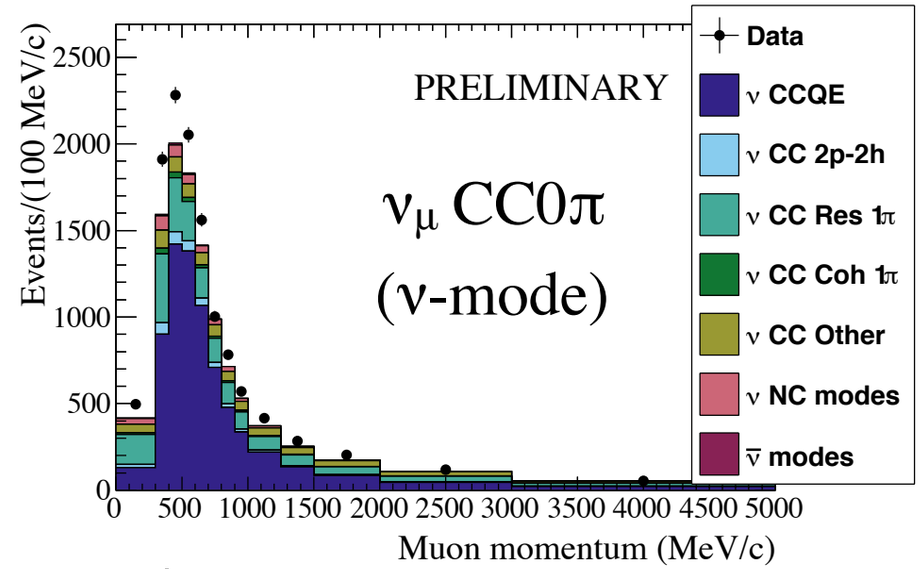


Cross section model uncertainties come from underlying model parameters and normalizations.
As tensions appeared with some data, we also inflated the errors to take it into account.

Near detector constraints strategy

See L. Magaletti poster to learn more on cross section measurements at ND280

A binned Likelihood is adjusted to ND280 data (in bins of muon momentum and angle) taking into account the variation of the flux, cross section model and near detector model within their systematic uncertainties and correlations.



<u>ν-mode data</u> :

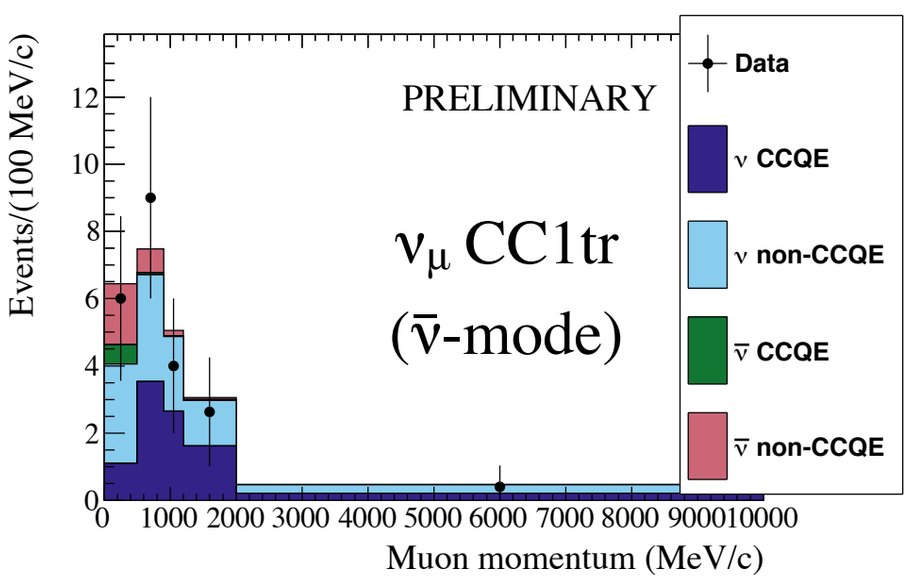
ν_μ interactions divided into 3 samples :

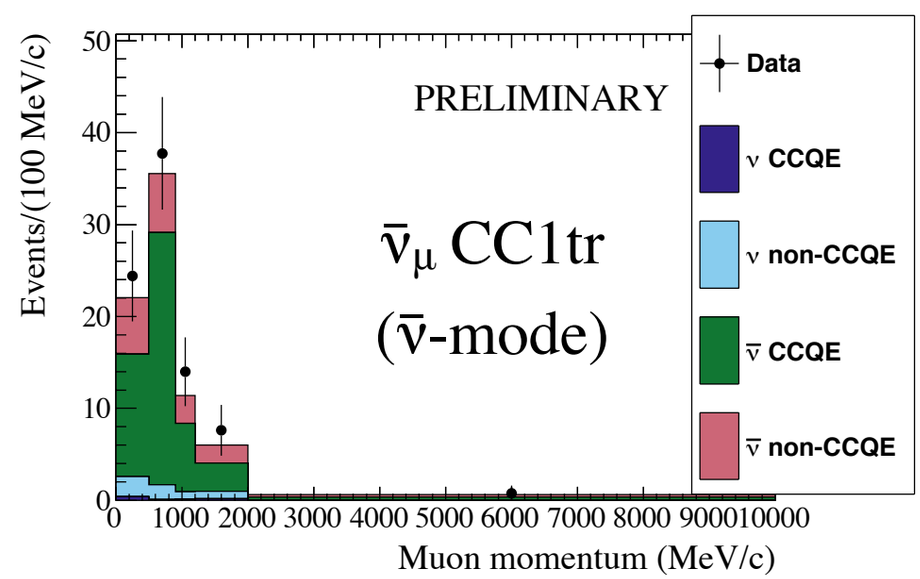
CC0π, CC1π and CCother

<u>$\bar{\nu}$-mode data</u> :

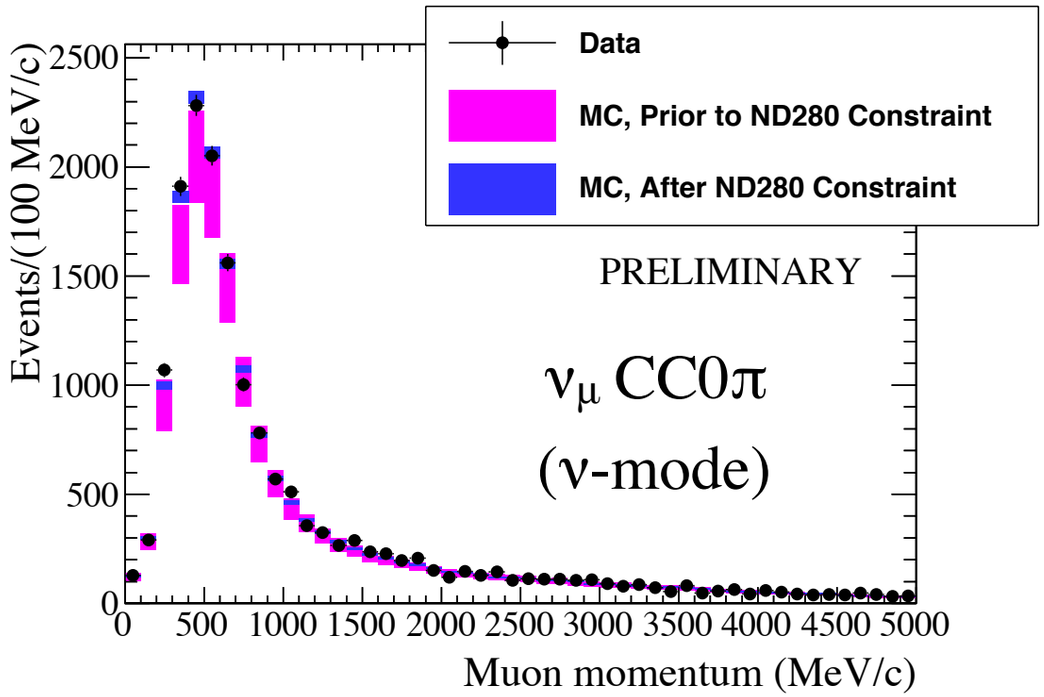
ν_μ interaction and $\bar{\nu}_\mu$ interactions are separated into 2 samples:

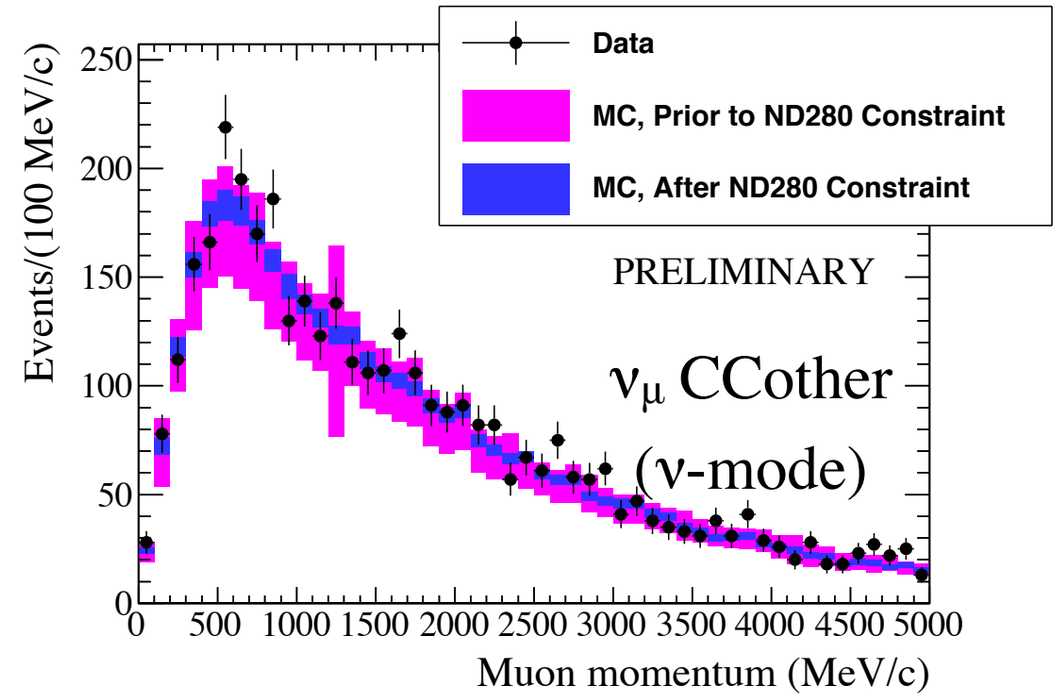
1 tracks (CC1tr) and >1 tracks (CCNtr).

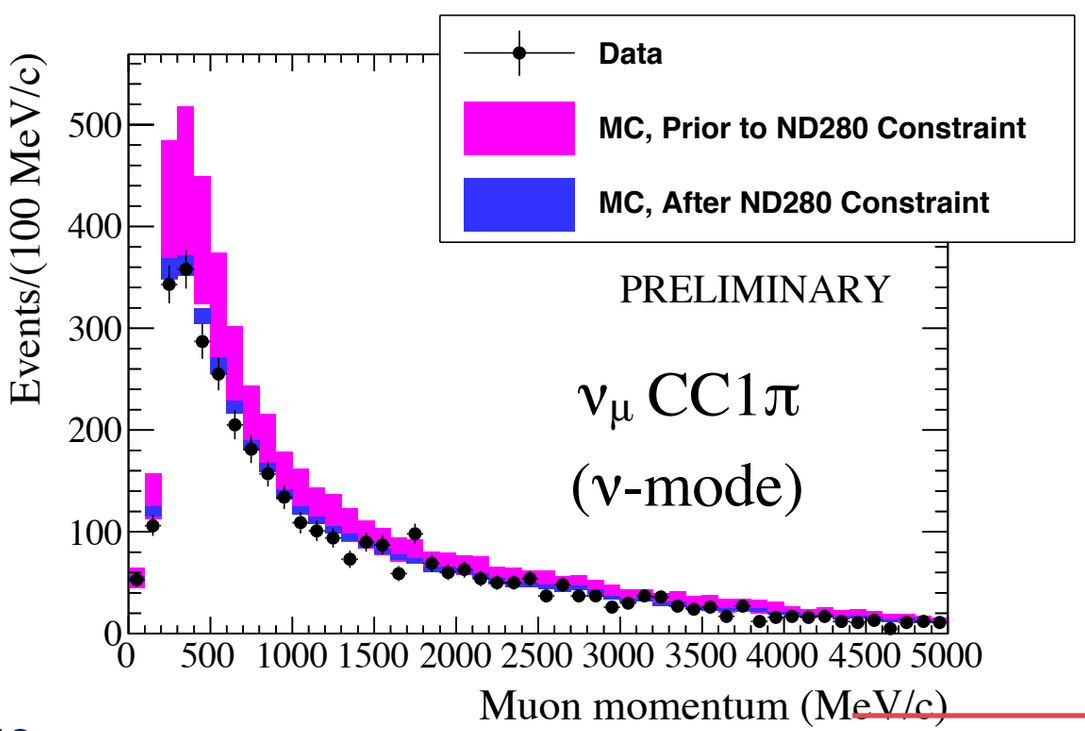




T2K near detector constraints : ν-mode







The adjusted parameters are :

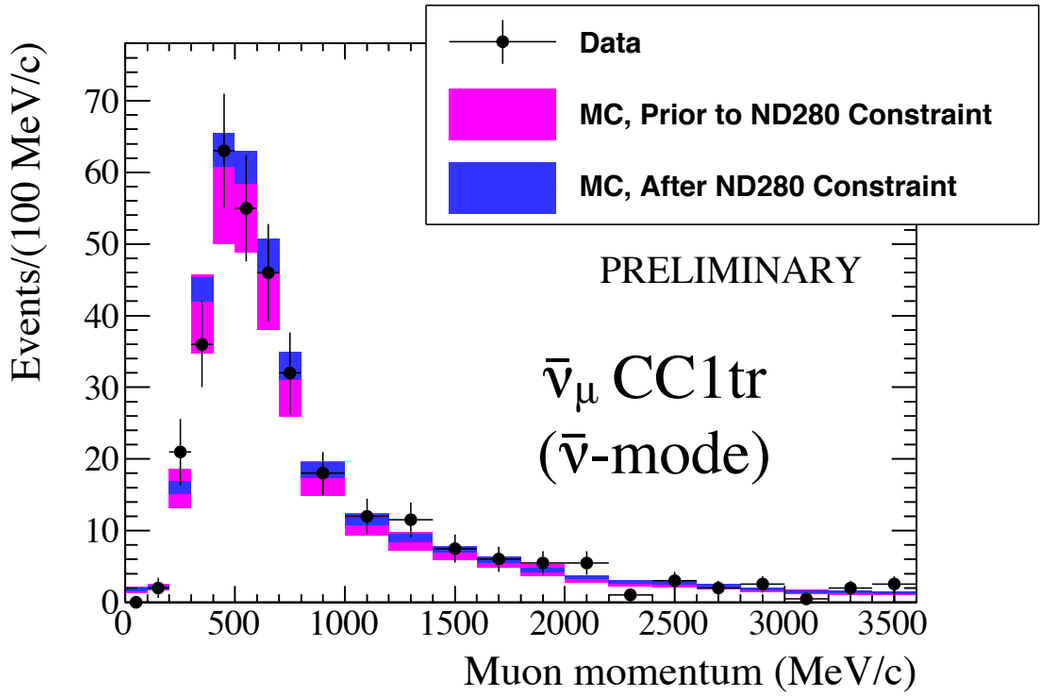
one per flux bin

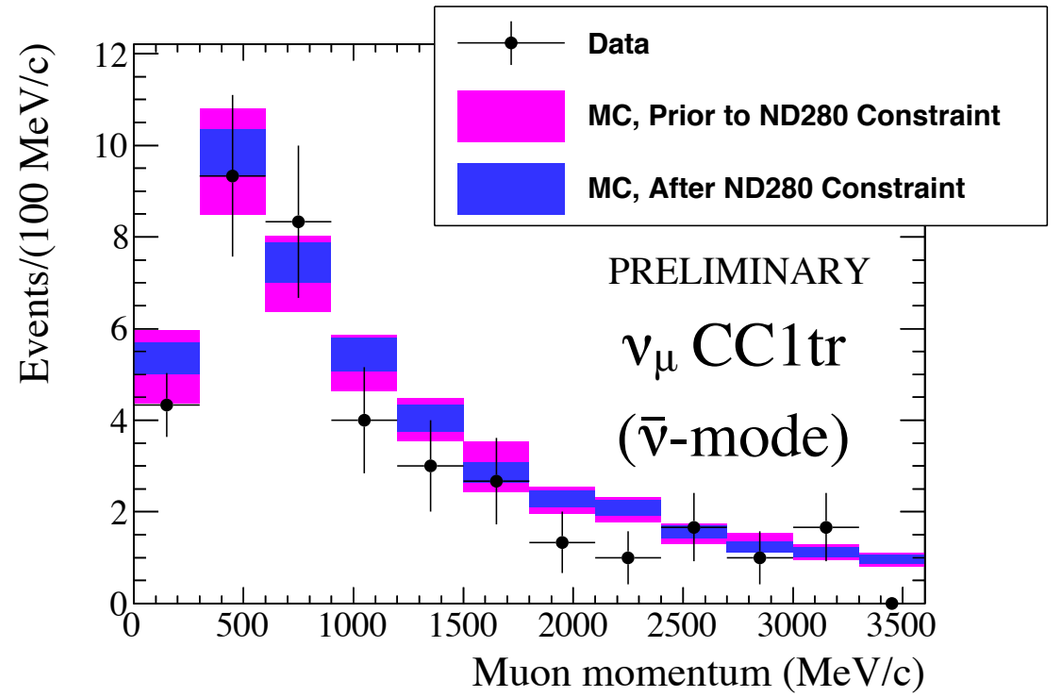
cross section parameters like $M_A^{QE/RES}$,

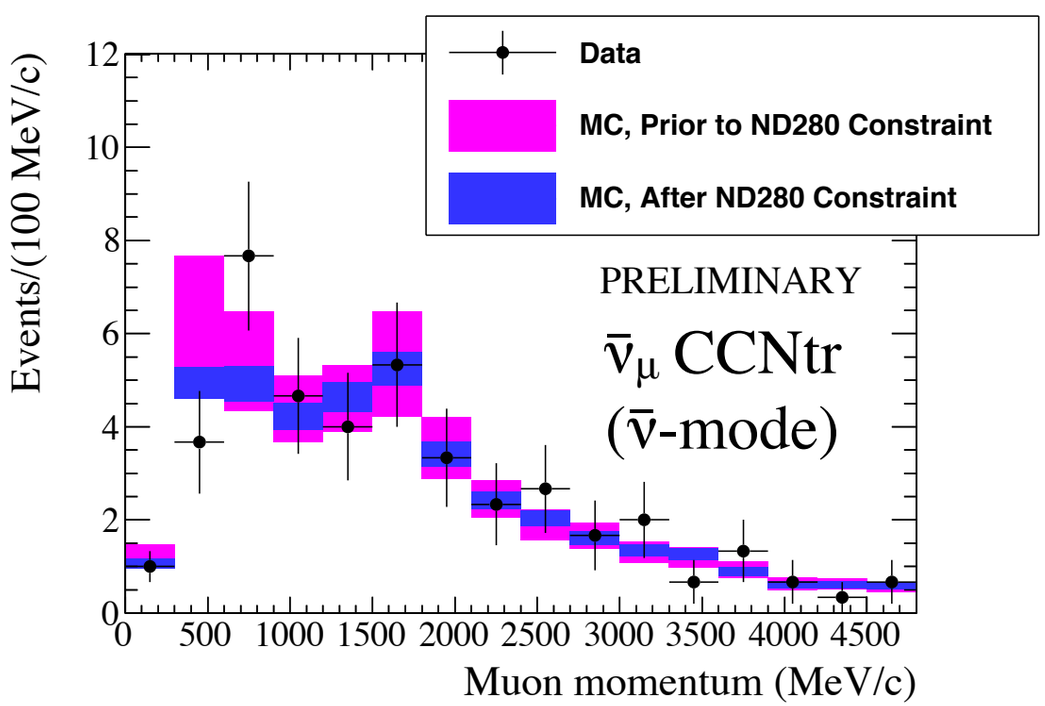
Fermi momentum, MEC normalization,…

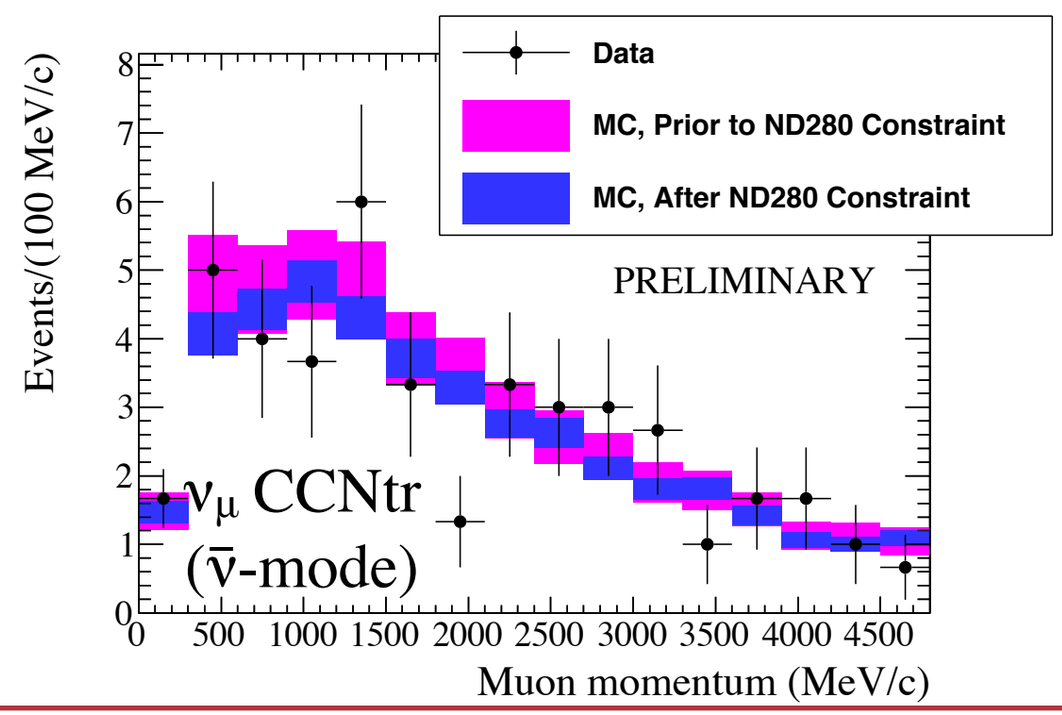
Clearly the data is in better agreement after the constraints

T2K near detector constraints : $\bar{\nu}$-mode

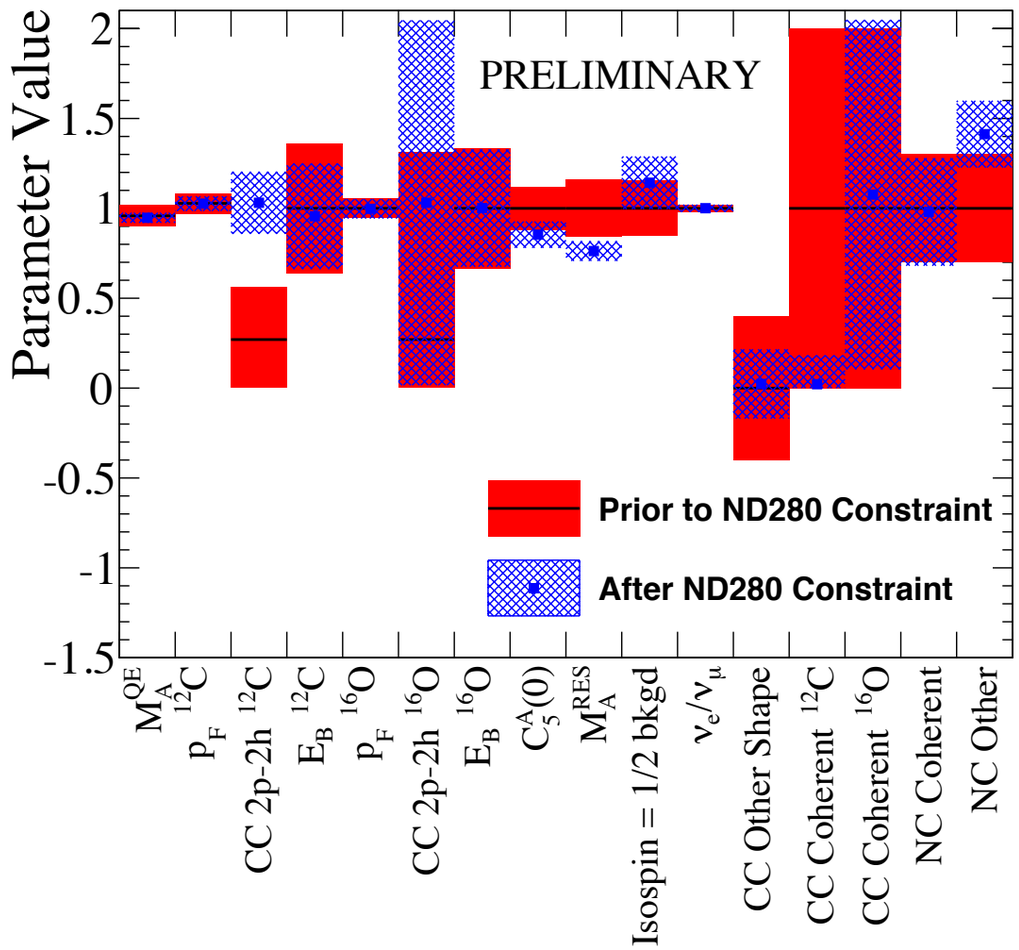


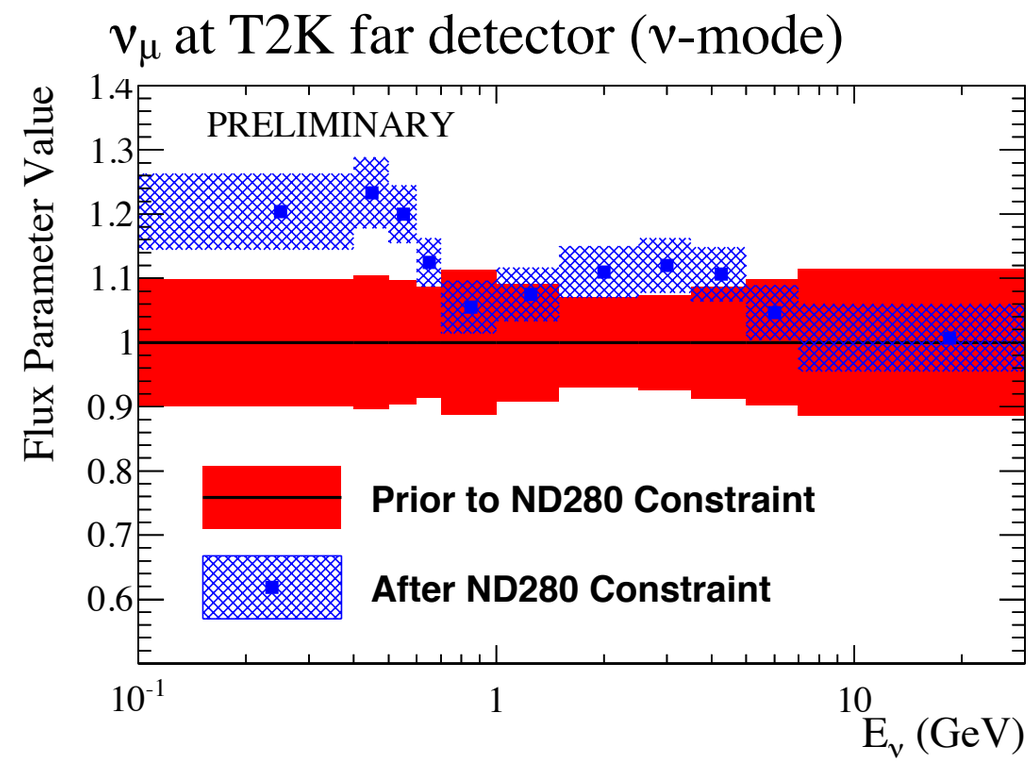


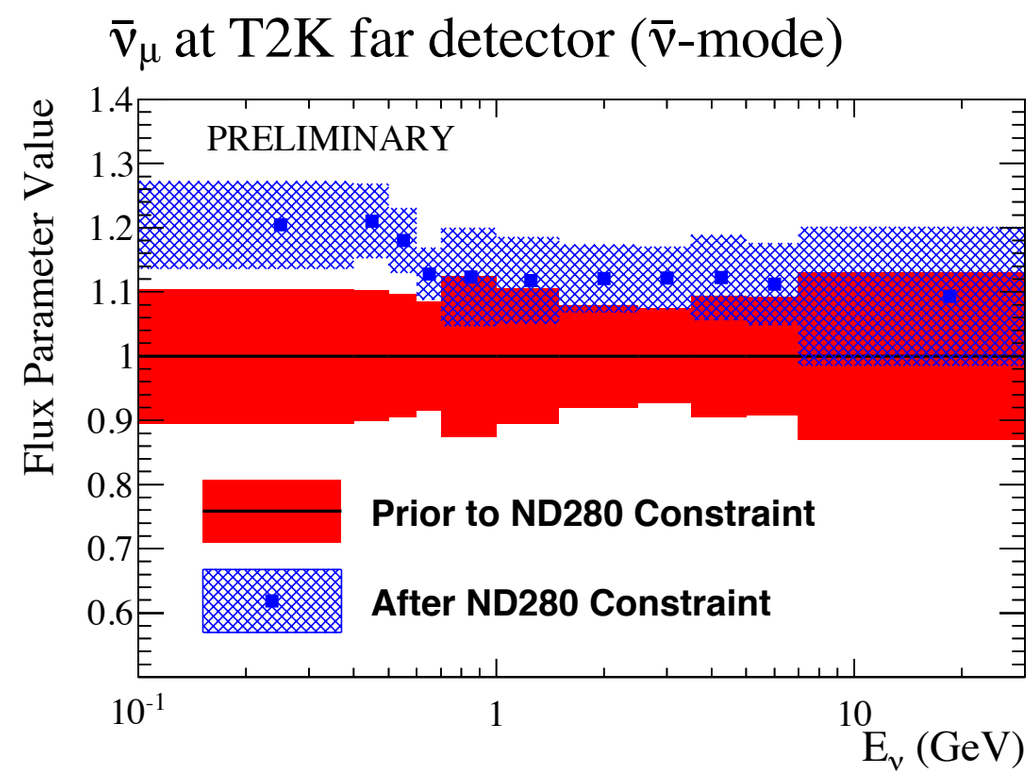




T2K near detector constraints







	$\bar{\nu}_\mu$ disappearance	w/o near detector constraints	w/ near detector constraints
ν flux and cross section	flux	7.1%	3.5%
	cross section (common to ND280)	5.8%	1.4%
	flux ⊗ cross section (common to ND280)	**9.2%**	**3.4%**
	cross section (far detector only)	10 %	
	multi-nucleon effect on oxygen	9.5%	
final or secondary hadronic interaction		2.1%	
far detector		3.8%	
Total		**14.4%**	**11.6%**

Conclusions

Flux :

- With the contribution of latest NA61 results, T2K flux uncertainties decreased to the level of 10%
- Implementation of NA61 replica target is ongoing and will contribute to a significant reduction of the T2K systematic uncertainties.

Cross Section :

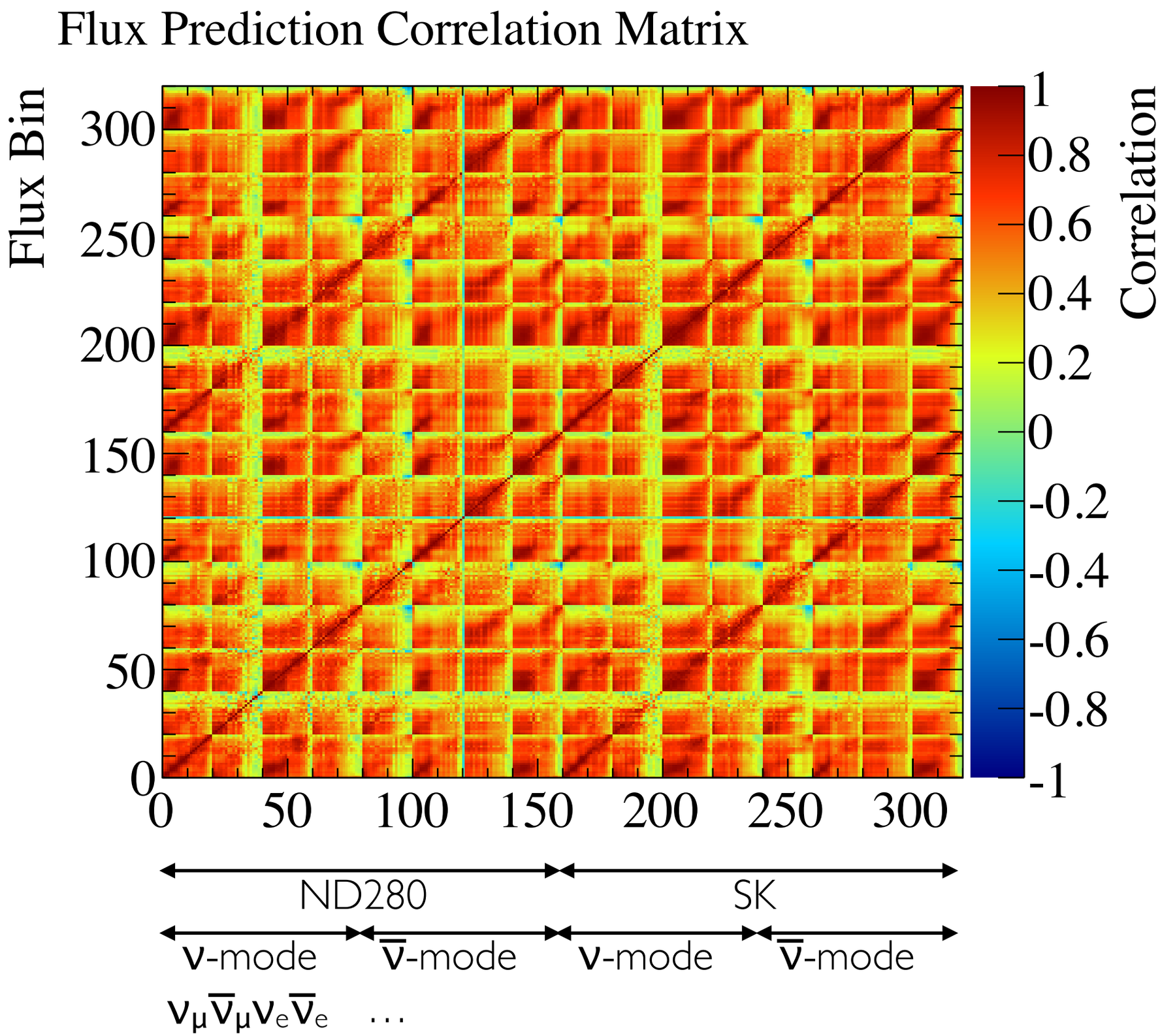
- NEUT includes improved CCQE and CCRES models, as well as multi-nucleon interactions.

Nominal NEUT parameters are tuned to external data (MiniBooNE, Minerva)

T2K near detector constraints :

- Taking all the available informations, in both neutrino and anti-neutrino modes, the constraints on flux⊗cross section uncertainties decrease to ~3%
- CC interactions on water will be added to the samples
- Near detector measurement uncertainties are still statistically dominated

Flux correlation matrix

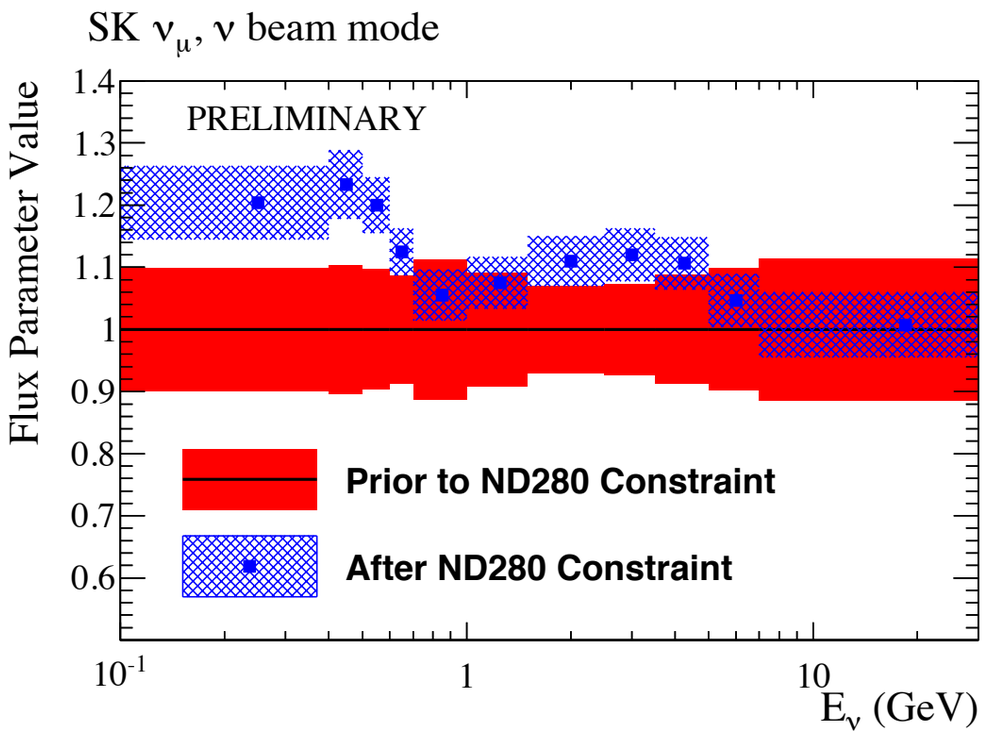


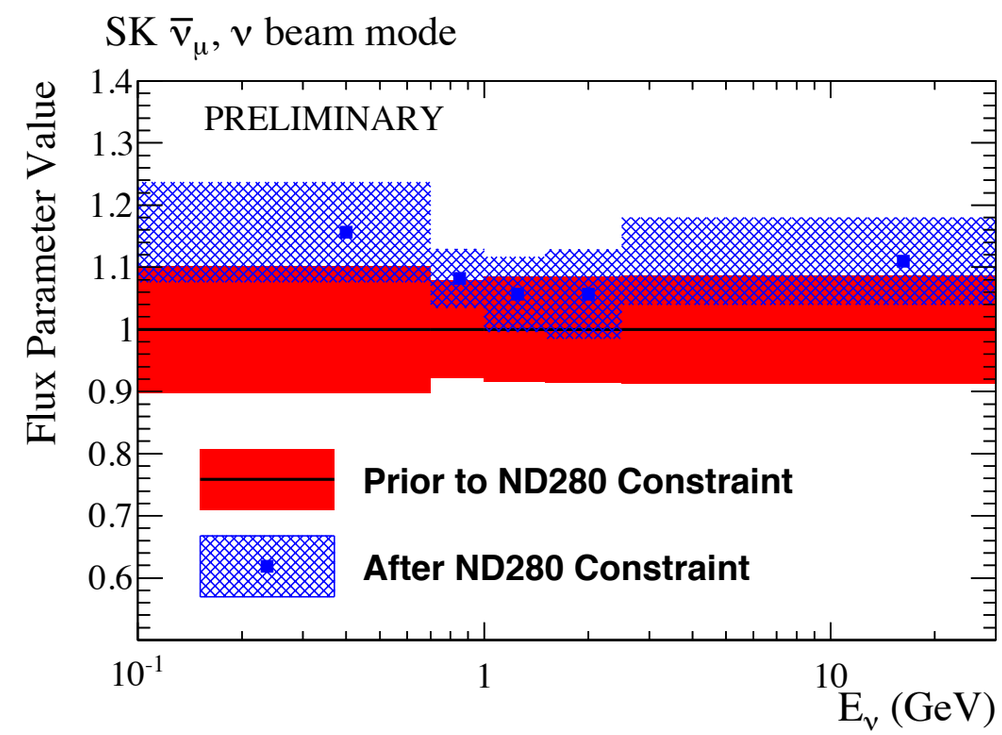
ND280 fit : effect on cross section parameters

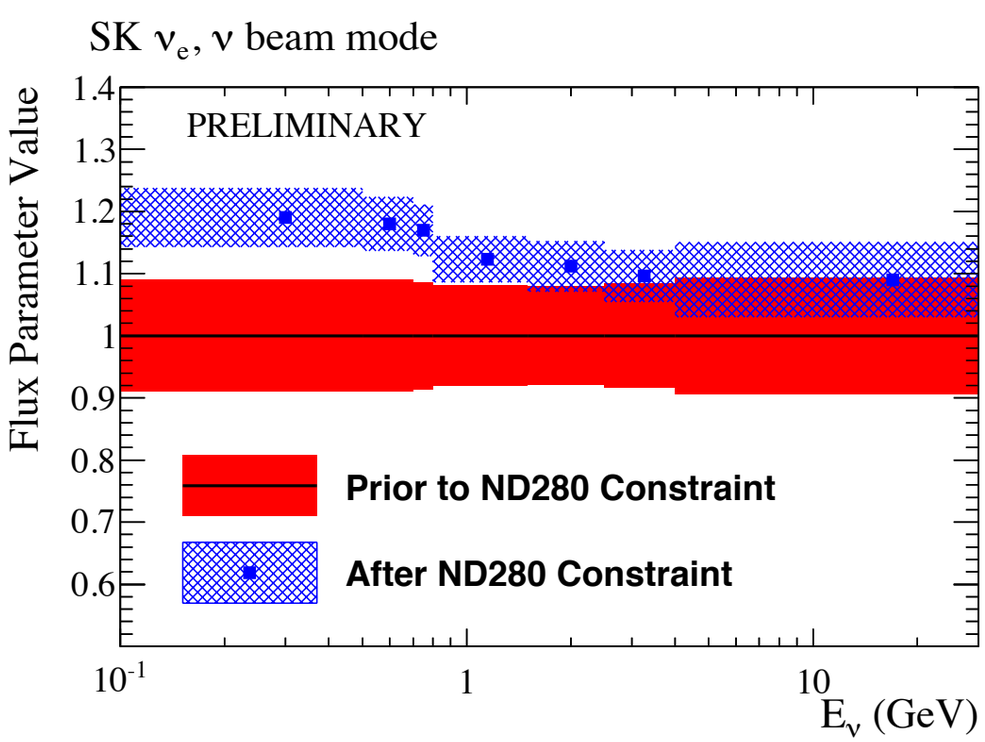
T2K Preliminary

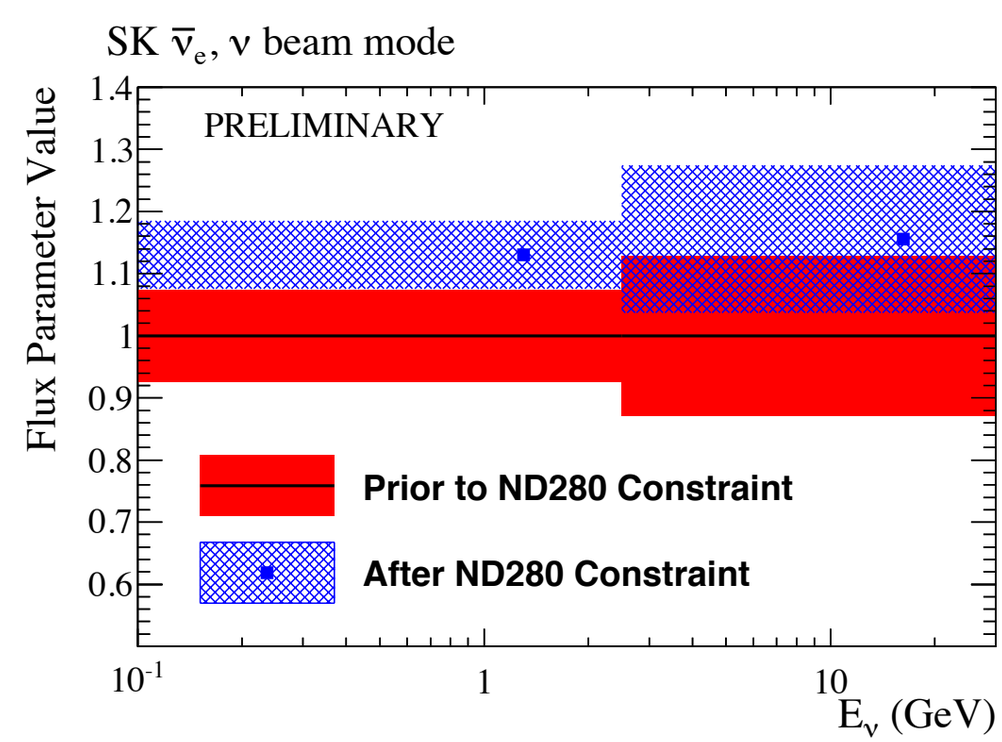
Cross-section Model Parameter	Prior to ND280 Constraint	After ND280 Constraint
M_A^{QE} (GeV/c^2)	1.150 ± 0.070	1.137 ± 0.034
CC 2p-2h ^{12}C	0.27 ± 0.29	1.03 ± 0.17
CC 2p-2h ^{16}O	0.27 ± 1.04	1.03 ± 1.01
p_F ^{12}C (MeV/c)	223.0 ± 12.3	222.7 ± 8.8
E_B ^{12}C (MeV)	25.0 ± 9.0	23.9 ± 7.3
$C^A_5(0)$	1.01 ± 0.12	0.862 ± 0.074
M_A^{RES} (GeV/c^2)	0.95 ± 0.15	0.724 ± 0.052
I=1/2 Background	1.3 ± 0.2	1.49 ± 0.19
CC Coherent ^{12}C	1.0 ± 1.0	0.02 ± 0.16
CC Other Shape	0.0 ± 0.4	0.02 ± 0.19

ND280 fit : effect on flux parameters

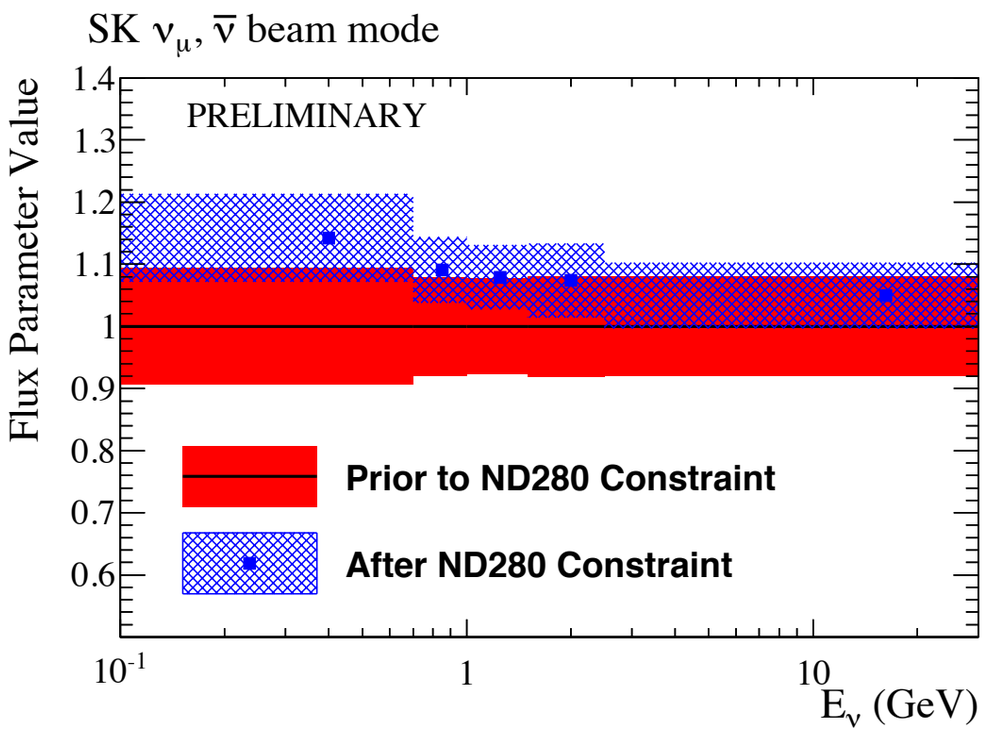


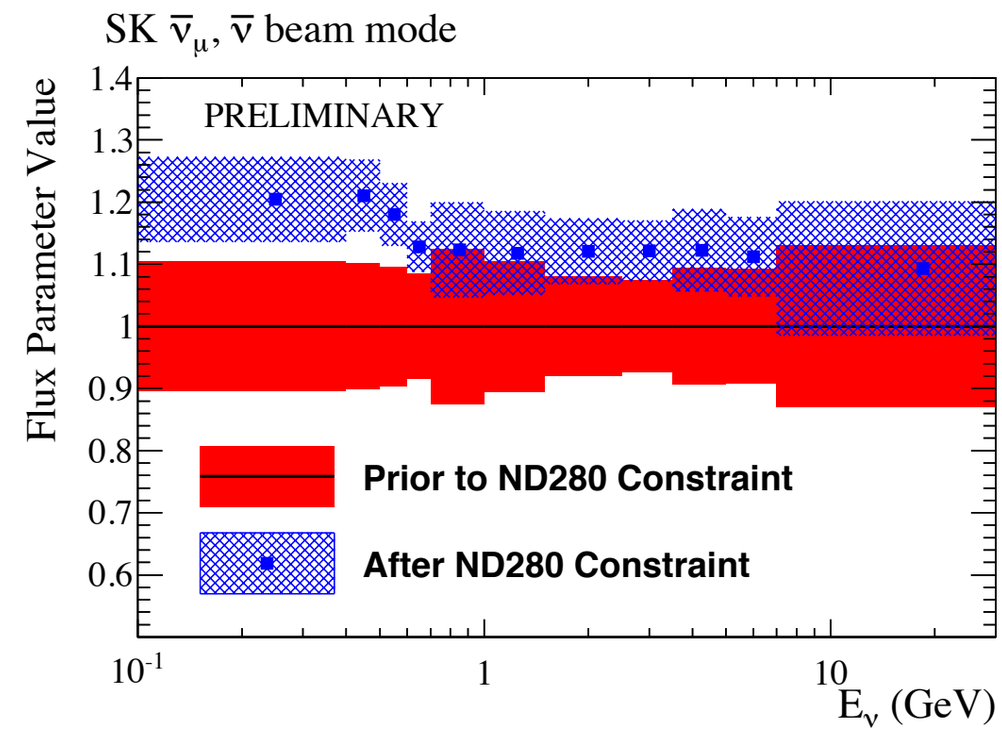


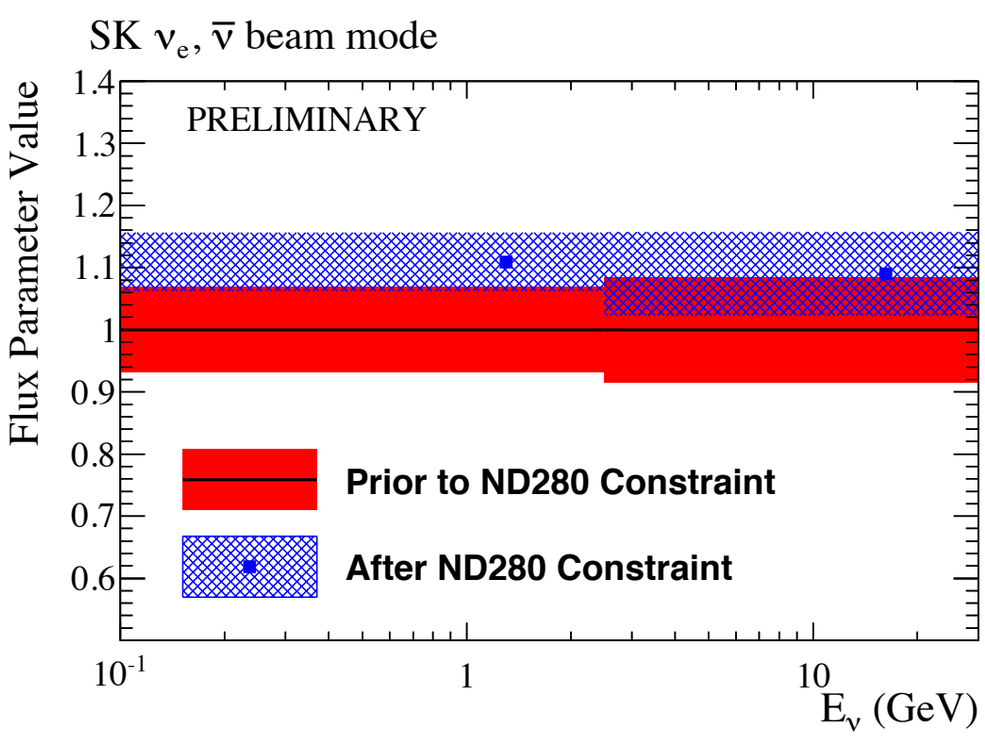


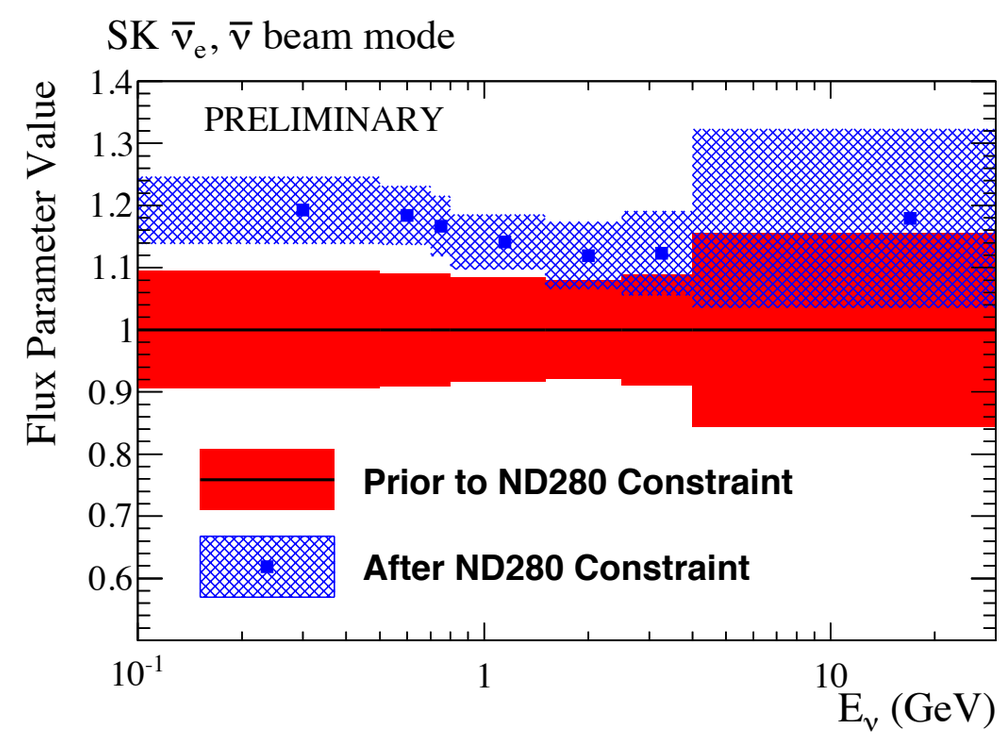


ND280 fit : effect on flux parameters



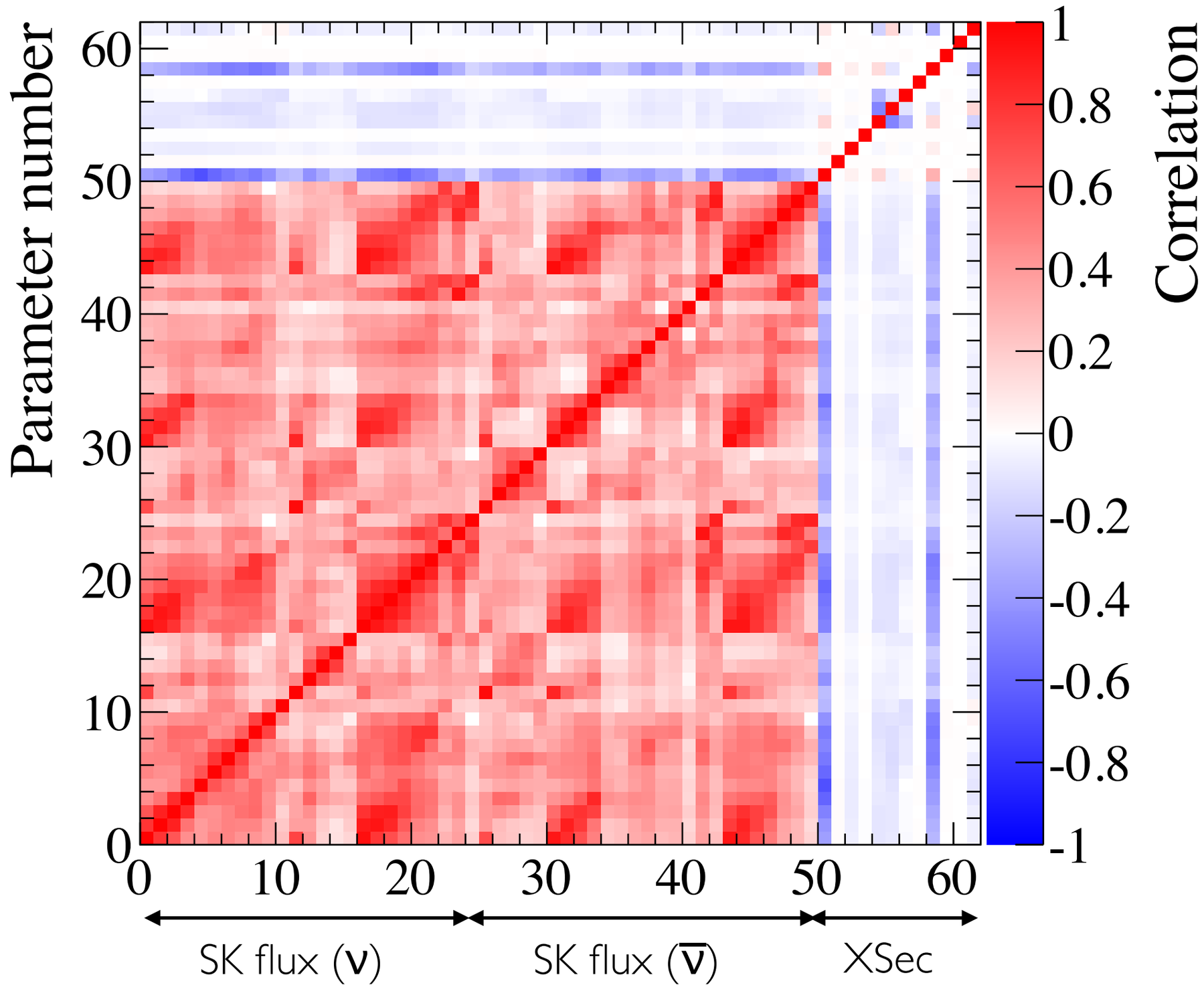




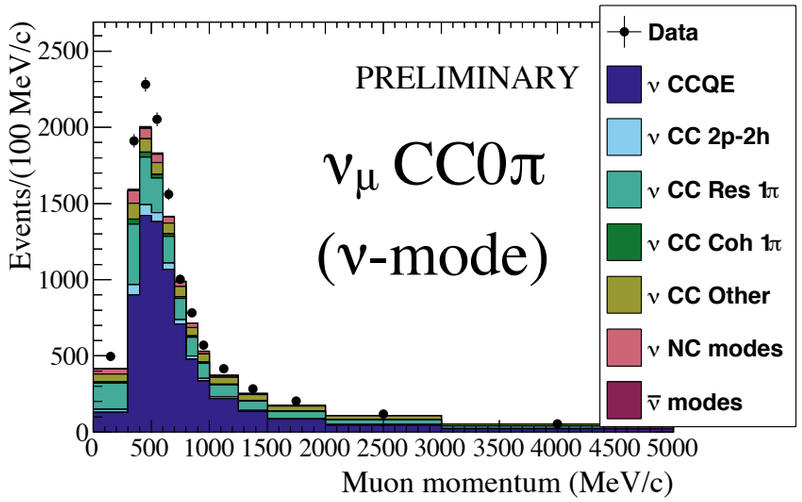


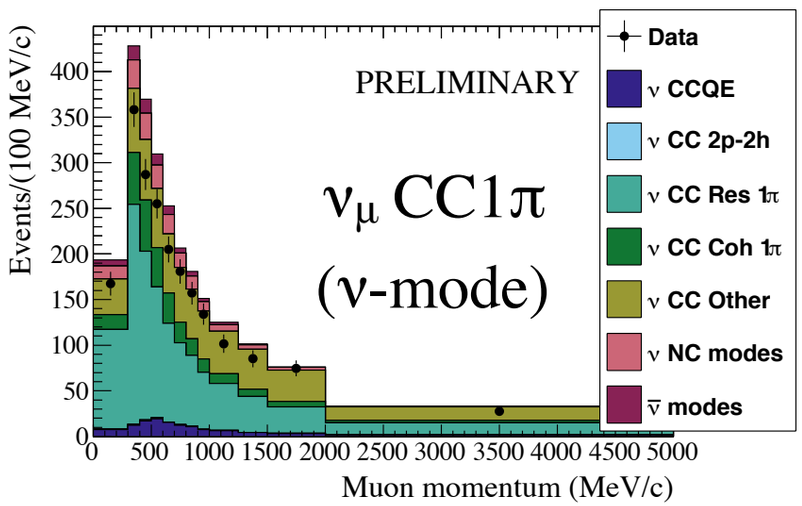
Flux and cross section parameters correlations

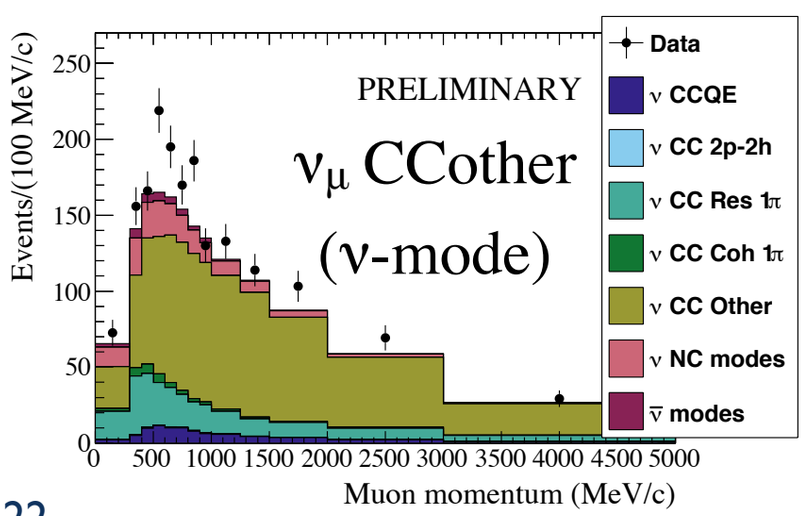
Parameters	Parameter number(s)
SK, Positive Focusing, ν_μ	0 – 10
SK, Positive Focusing, $\bar{\nu}_\mu$	11 – 15
SK, Positive Focusing, ν_e	16 – 22
SK, Positive Focusing, $\bar{\nu}_e$	23 – 24
SK, Negative Focusing, ν_μ	25 – 29
SK, Negative Focusing, $\bar{\nu}_\mu$	30 – 40
SK, Negative Focusing, ν_e	41 – 42
SK, Negative Focusing, $\bar{\nu}_e$	43 – 49
M_A^{QE} (GeV/c^2)	50
p_F ^{16}O (MeV/c)	51
CC 2p-2h ^{16}O	52
E_B ^{16}O (MeV)	53
$C_5^A(0)$	54
M_A^{RES} (GeV/c^2)	55
Isospin=$\frac{1}{2}$ Background	56
ν_e/ν_μ	57
CC Other Shape	58
CC Coherent ^{16}O	59
NC Coherent	60
NC Other	61

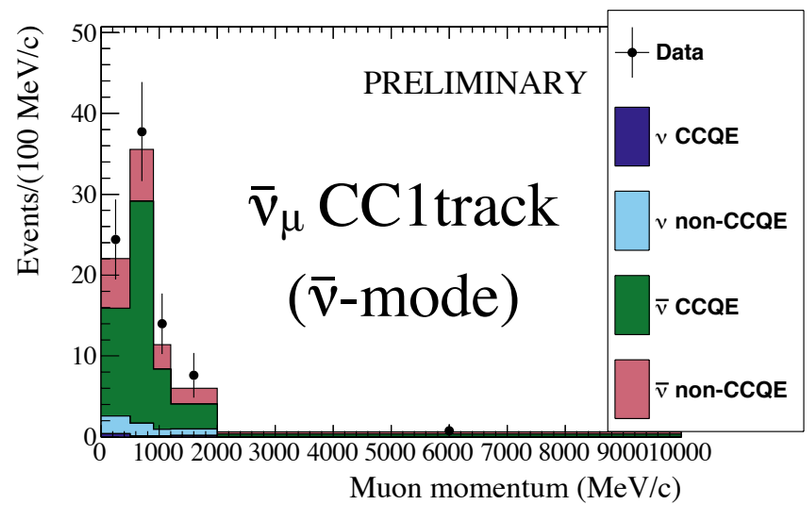


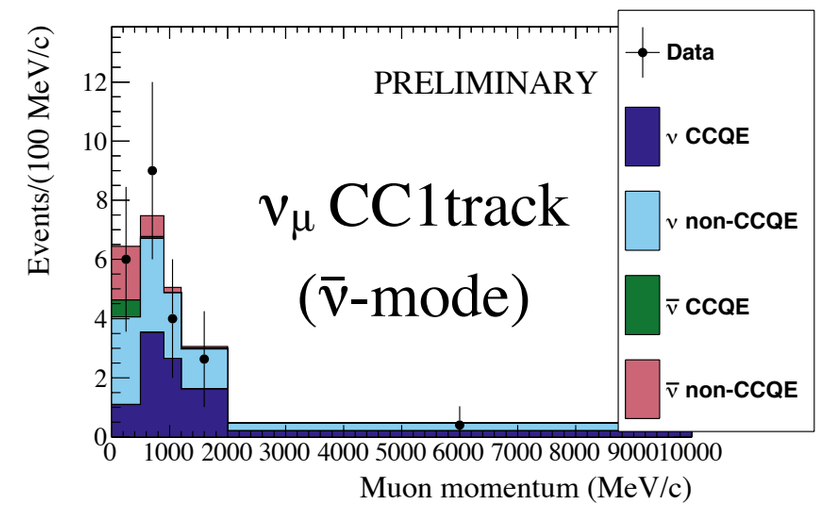
Near detector cross section measurement - pre-fit

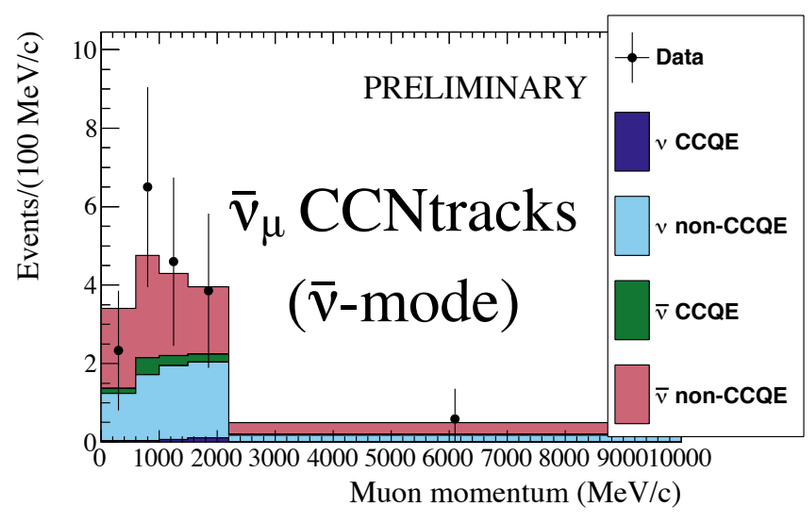


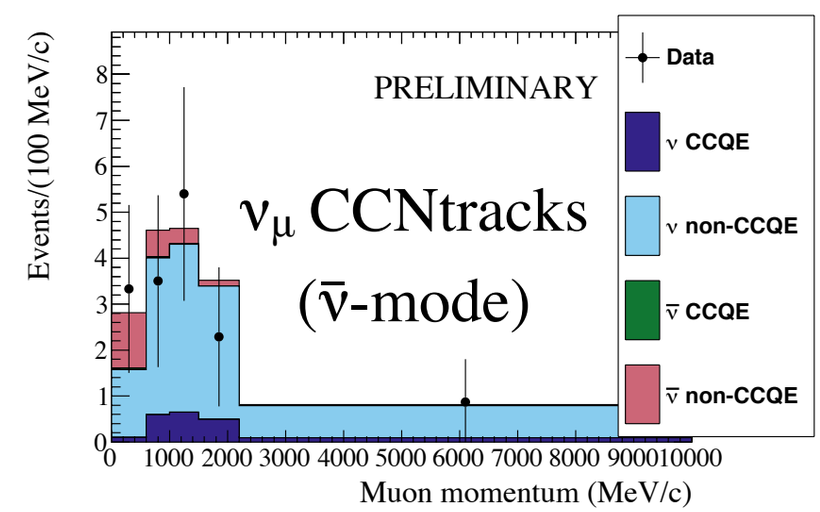












Near detector cross section measurement - post-fit