Measurement of the ν_μ flux and inclusive charged current cross section at T2K's near detector

Melody Ravonel Salzgeber
for the T2K collaboration

Content and outline

- **The T2K experiment**
- **Rate measurement**
  - Method
  - Source of uncertainties
  - Results
- **Cross Section measurement**
  - Method
  - Source of uncertainties
  - Results

Used to constrain ***flux & cross section*** in T2K oscillation fits

Model independent method in momentum and angle ⇨ more useful for validating/improving models

The T2K experiment

Overview of the T2K experiment, where a high intensity beam of ν_μ is created at Tokai and sent 295 km under ground to Super-Kamiokande.

T2K: long baseline neutrino oscillation

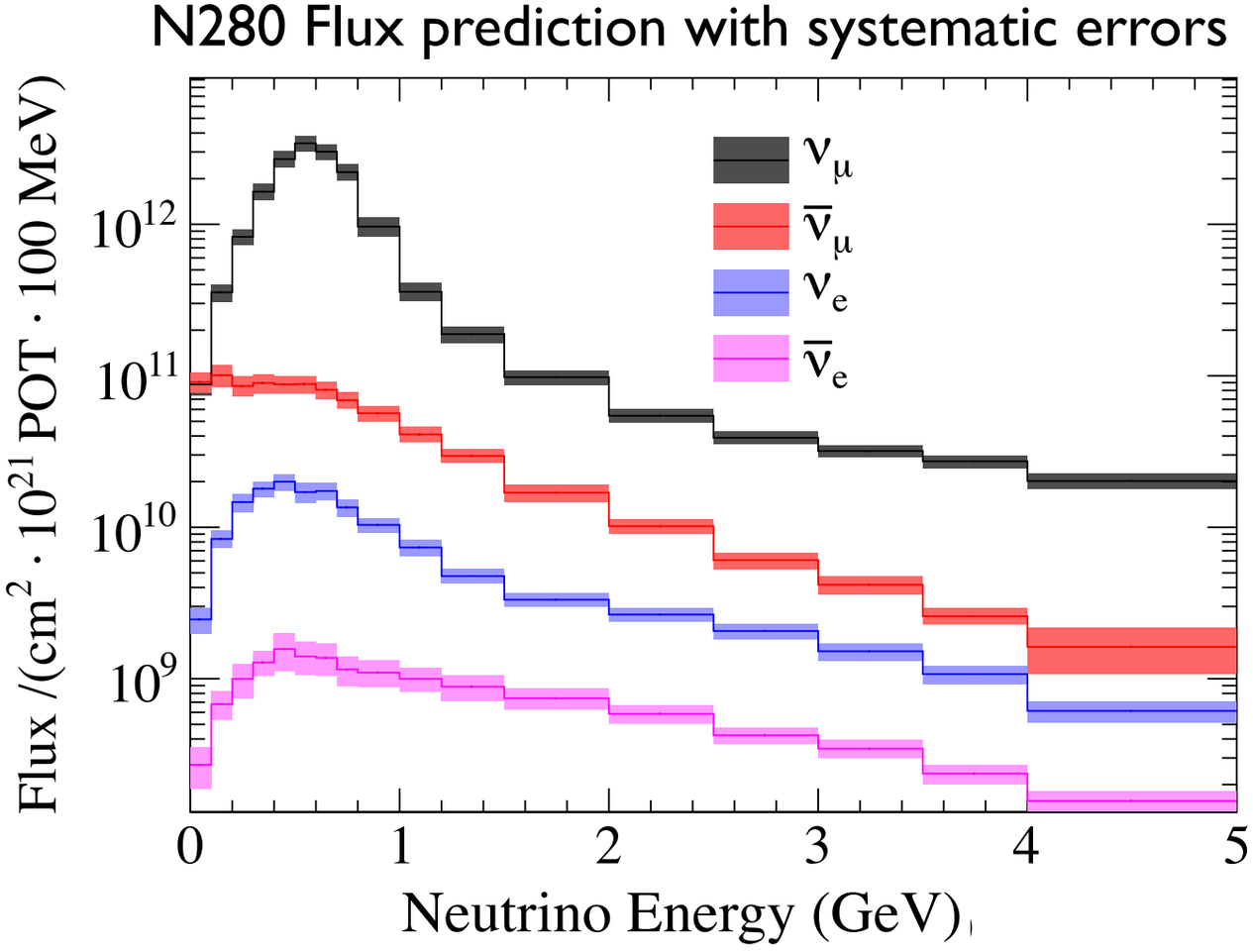
- ➡ high intensity neutrino beam (peak at 600 MeV)
- ➡ off-axis beam
- ➡ 30 GeV proton beam impinging on the 90 cm long graphite target.

Analysed POT (Jan 2010 - March 2011):

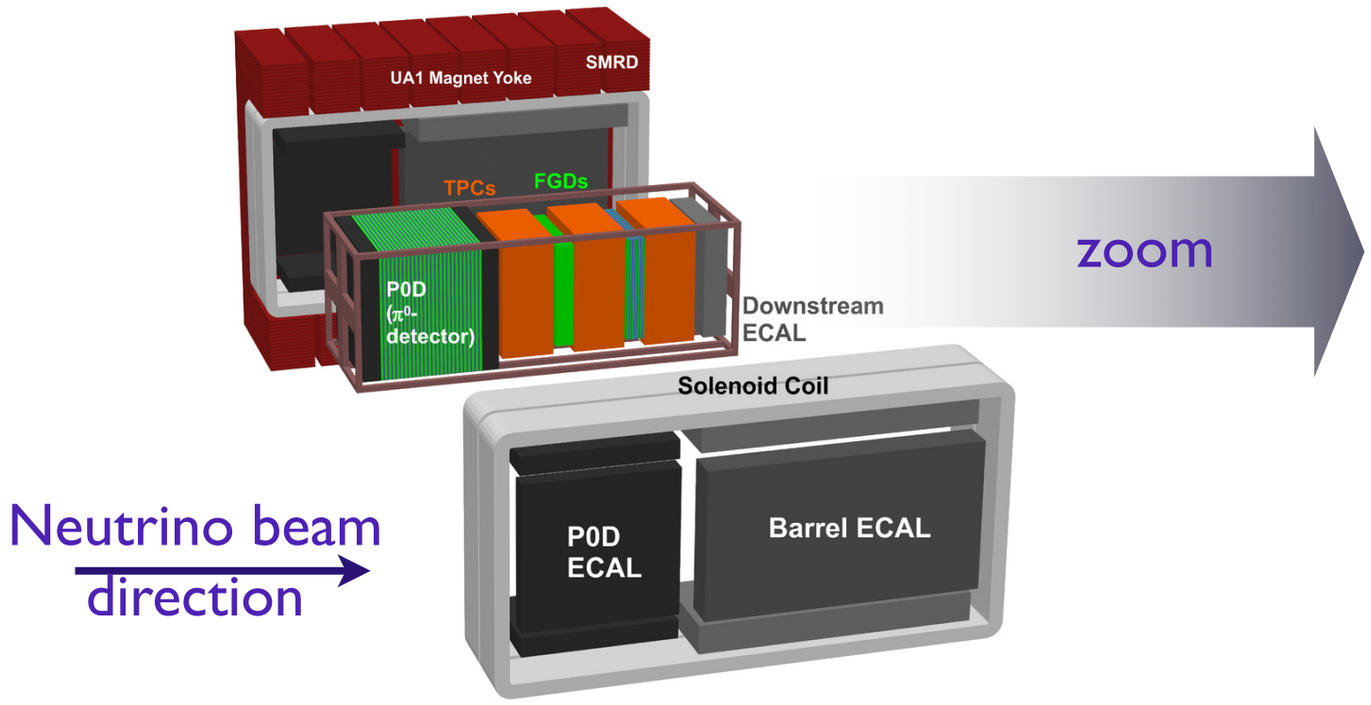
➡ POT = 10.796×10^{19}

Total Integrated ν_μ Flux

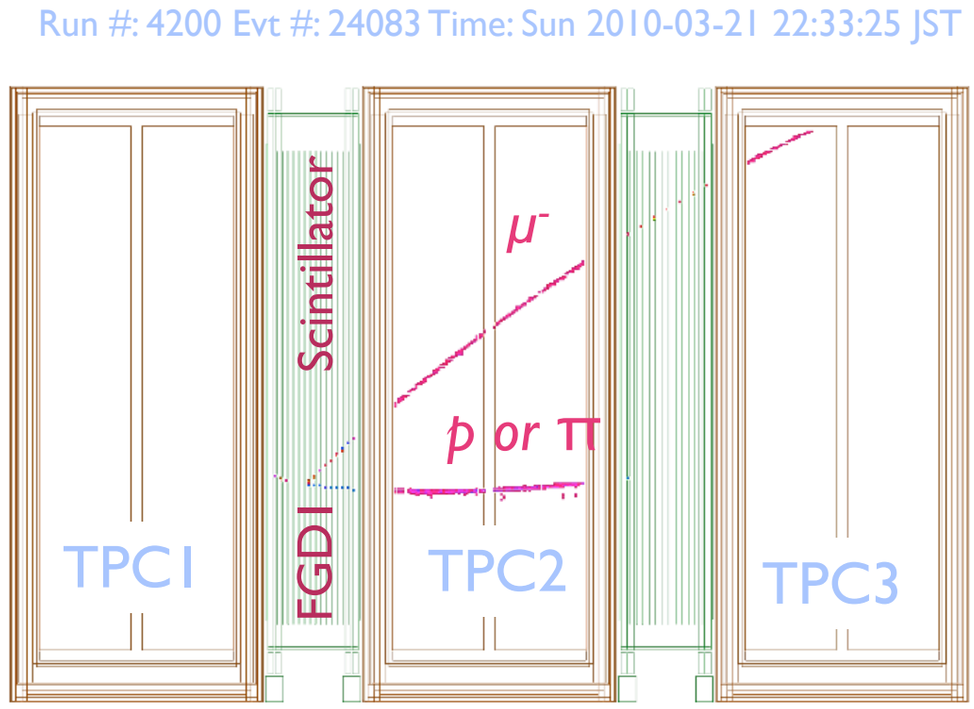
➡ 2.09×10^{12} cm^{-2}/POT



The off-axis near detector (ND280)



Overview of the off-axis Near Detector



Charged current event candidate in the tracker region of the near detector. Muon reconstructed angle 40° and reconstructed momentum: 566 MeV/c

Magnetized Detector (0.2 Tesla)

Time Projection Chambers (TPCs) & Fine Grain Detectors (FGDs) scintillators are the main detectors used for the analyses presented here

FGD1 scintillator (FV mass ~913 kg):

- Scintillator mainly composed of carbon
  C 86%, O 3.7%, H 7.4%, Ti 1.7%, Si 1%, N 0.1%
- Provides the target mass

Particle tracking with TPCs provides:

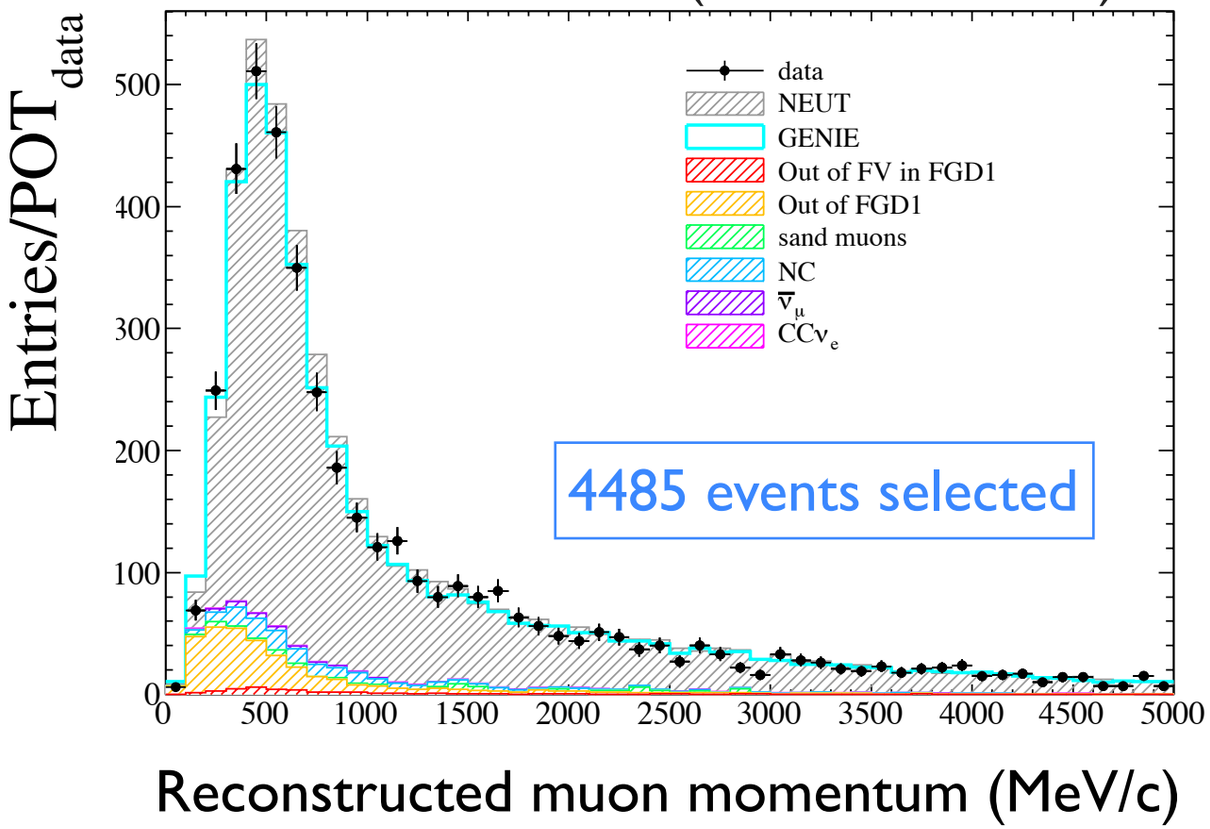
- Very low material density
- Excellent particle identification via dE/dx
- Momentum determination through deflection in a transversal 0.2T magnetic field

Event samples and selection

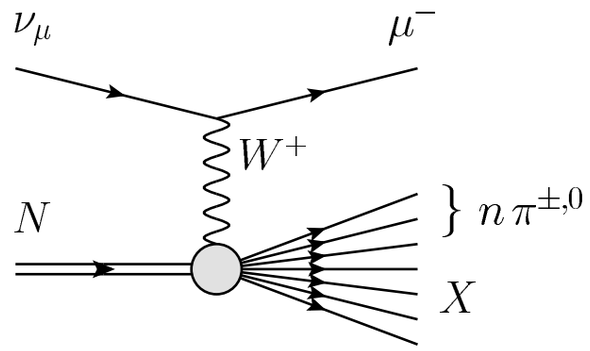
The CC selection at ND280

- At least one negative track in the TPC
- The track starts in fiducial volume of the FGD1
- dE/dx compatible with the muon hypothesis

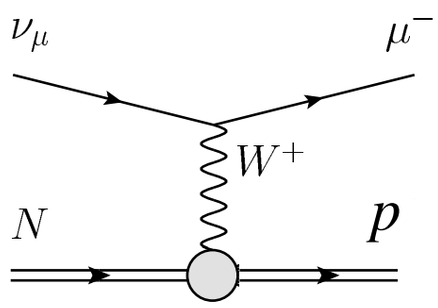
After CC selection (with default MC)



Charge Current (CC) interaction

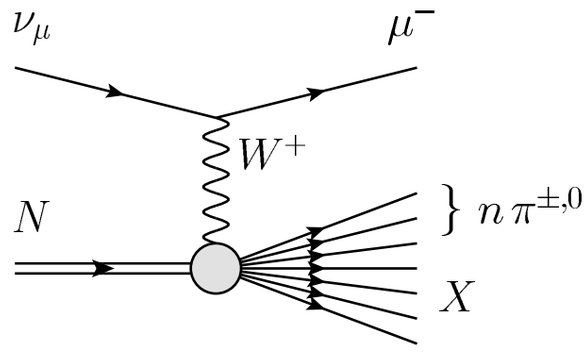


CC-Quasi Elastic (CCQE)



CC-nonQE (CCnQE)

= all CC that is not QE



CCnQE sub-sample

= all CC selected that is not QE

CCQE sub-sample

- Only one TPC-FGD track
- No Michel electron

2354 events selected

The Generators used (references)

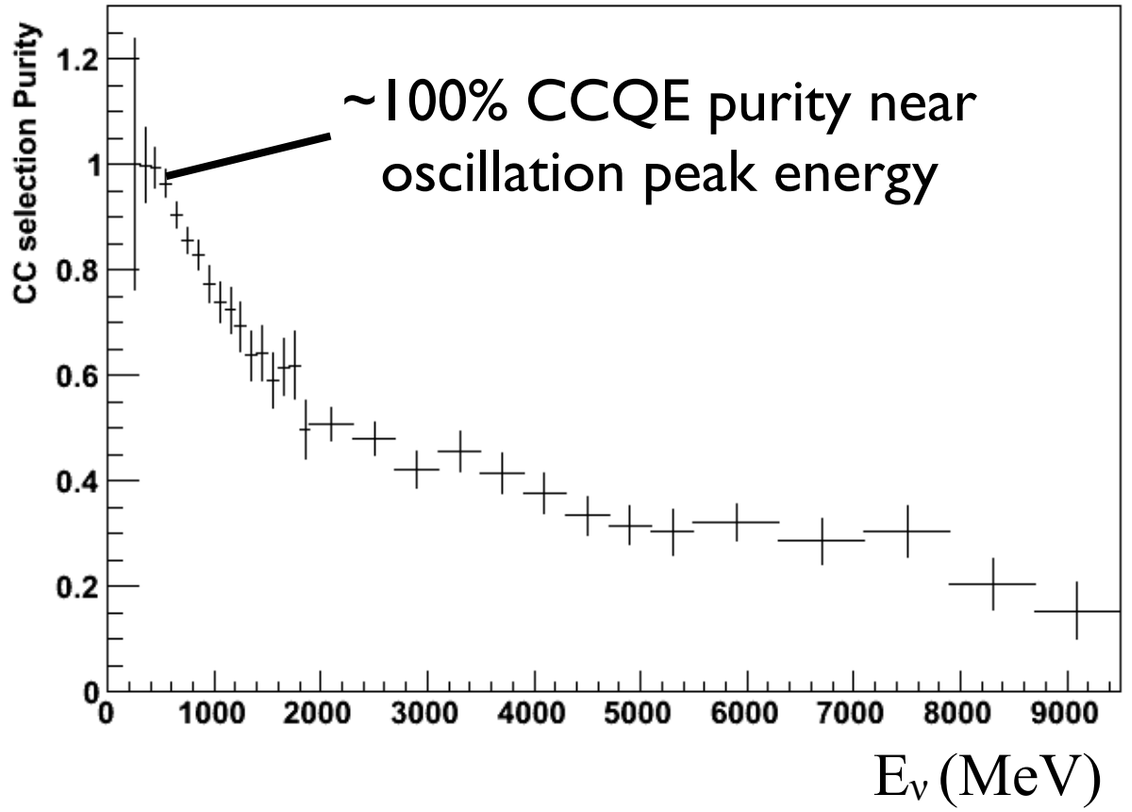
NEUT: http://www.actaphys.u j.edu.pl/vol40/pdf/v40p2477.pdf.

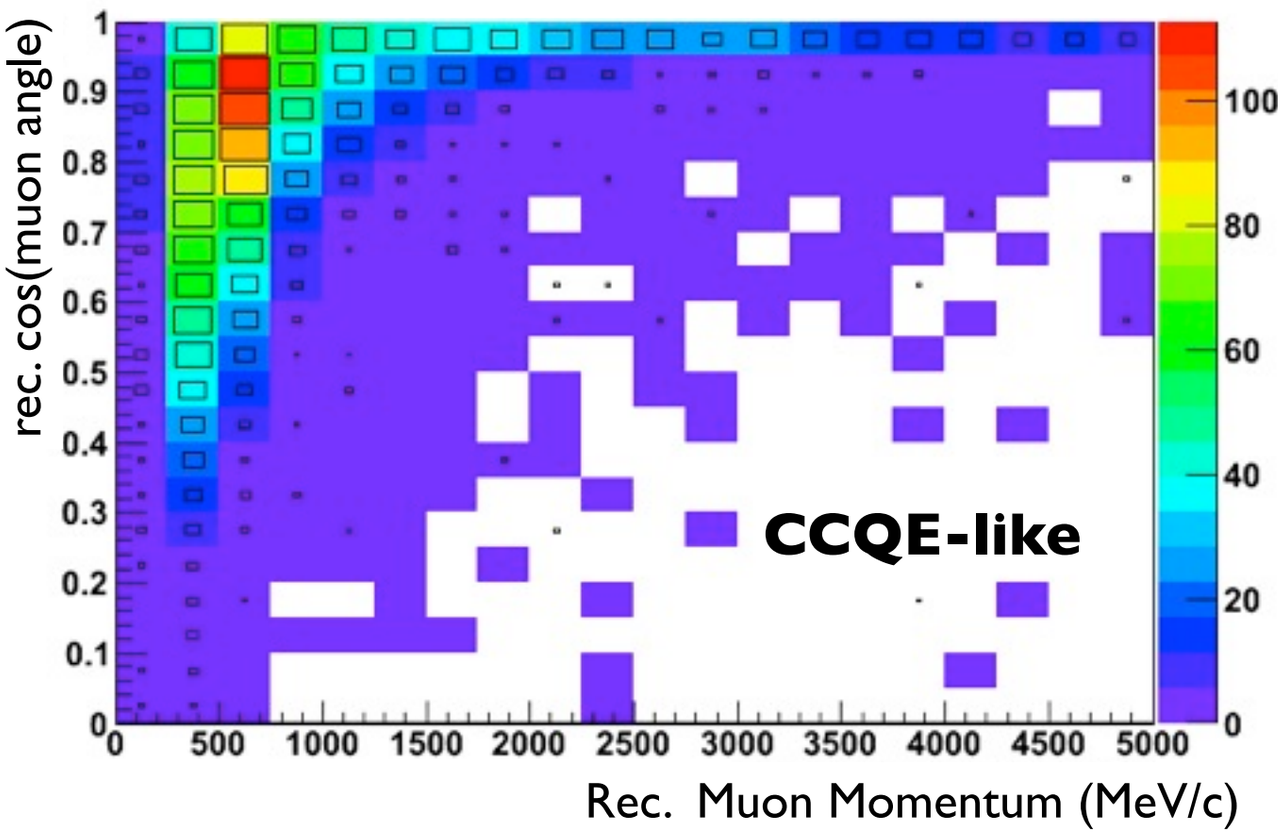
GENIE: http://www.genie-mc.org/

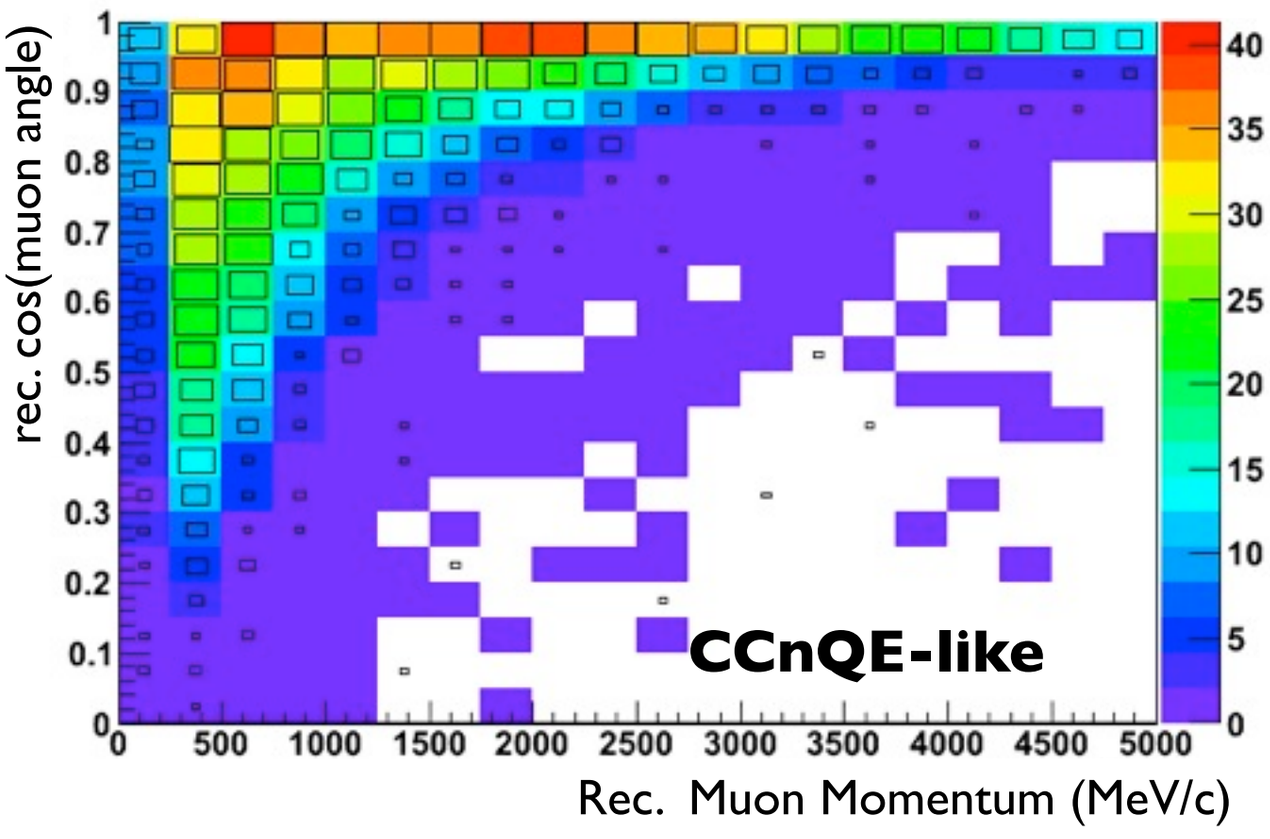
NuWro: http://th-www.if.uj.edu.pl/acta/vol40/pdf/v40p2507.pdf

Selection performance

	Efficiency	Purity
CCQE	40%	72%
CC	50%	88%







Rate Measurement Method

Likelihood Fit at ND280

$$-2\ \ln(\mathcal{L}_{ND280}) = f(N_j^{data}, V_x, V_b, V_d, \vec{s})$$

INPUT
ND280 events

# of reconstructed events at the near detector in the (p-θ) plane

INPUT
covariances

Uncertainties from

Cross-Section (V_x)

Flux (V_b)
(from Na61, proton beam monitors, etc)

Detector (V_d)
(FSI included here)

Parameters to be fitted

RESULTS

used to constrain
flux & cross section
parameters in T2K
oscillation fits

Cross Section uncertainty (input for rate and xsec-meas.)

normalization uncertainties

Parameters	Energy range (GeV)	Nominal value	Error
CCQE	$0.0 < E_\nu < 1.5$	1	11 %
CCQE	$1.5 < E_\nu < 3.5$	1	30 %
CCQE	$3.5 < E_\nu$	1	30 %
CC-1π	$0.0 < E_\nu < 2.5$	1.63	43 %
CC-1π	$2.5 < E_\nu$	1	40 %
CC-COH	$0.0 < E_\nu$	1	100 %
NC-oth	$0.0 < E_\nu$	1	30 %
NC-1π^0	$0.0 < E_\nu$	1.18	43 %

uncertainties coming from comparison of our generator (NEUT) with external data

Parameters	Nominal value	Error
M_A^{CCQE}	1.21 GeV	37.2 %
M_A^{RES}	1.16 GeV	9.5 %
CC-oth shape	0	40 %
p_F	217 MeV/c	13.8 %
W_{shape}	87.7	51.7 %
pionless Δ decay	0.2	20 %

Parameters	Nominal value	Error
Spectral Function	Off (0)	100 %
1π E_ν shape	Off (0)	50 %

Energy dependent uncertainty for CC-nπ and CC deep inelatic (40%/E_ν)

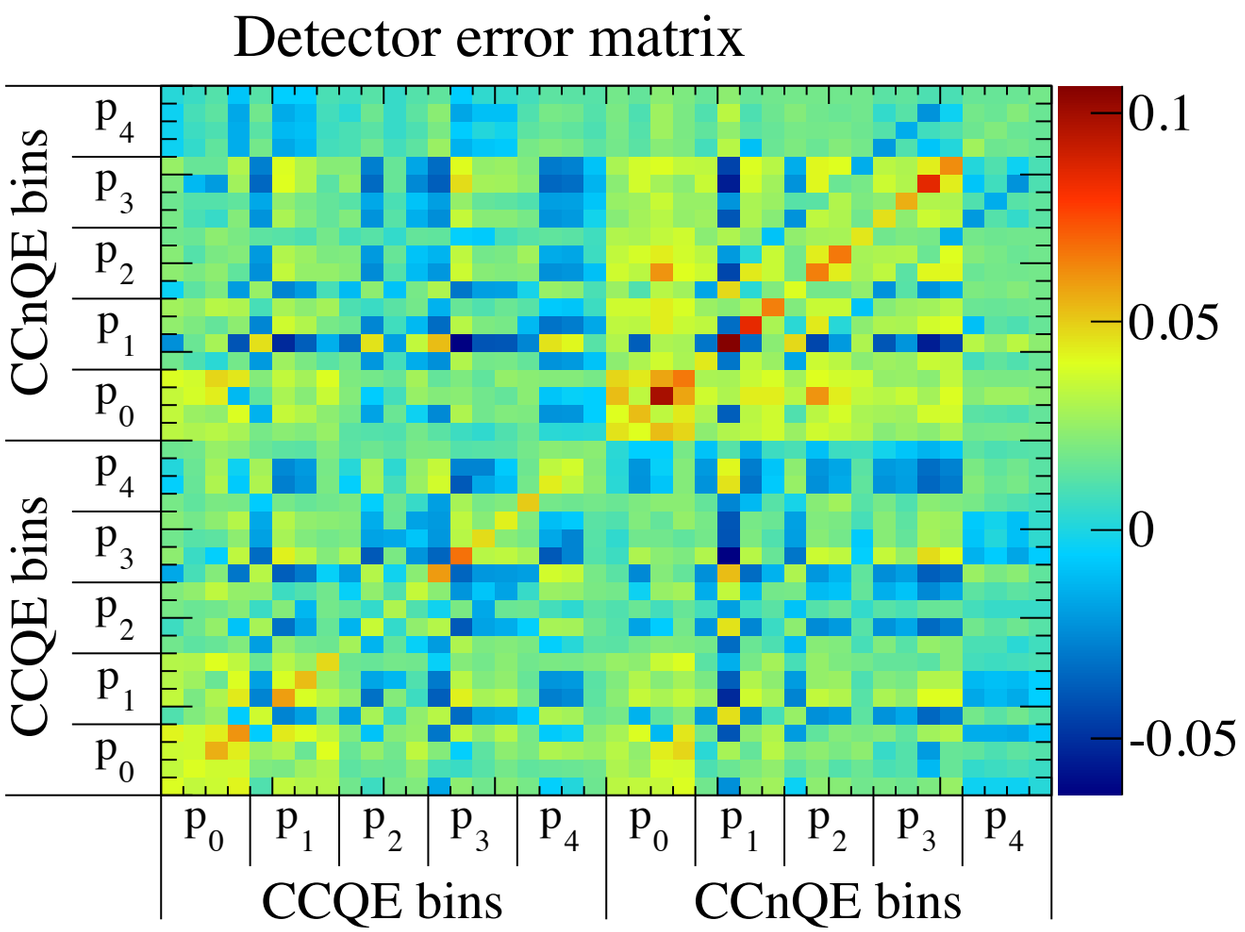
Decay width of the resonance allowing the modification of the shape of the pion momentum in resonance interactions

20% of all Δ may decay to produce no pions in NEUT generator

Replace relativistic Fermi gas by NuWro generator spectral function

Parameter changing the shape of 1π channel below 1GeV

Systematics and results



Detector

- dominated by statistic
- main systematic uncertainty coming from out of fiducial volume background (OOFV) and momentum distortions due to magnetic field

Flux

Systematic on the flux is about 10%
- comes mainly from cross-section production and secondary interactions

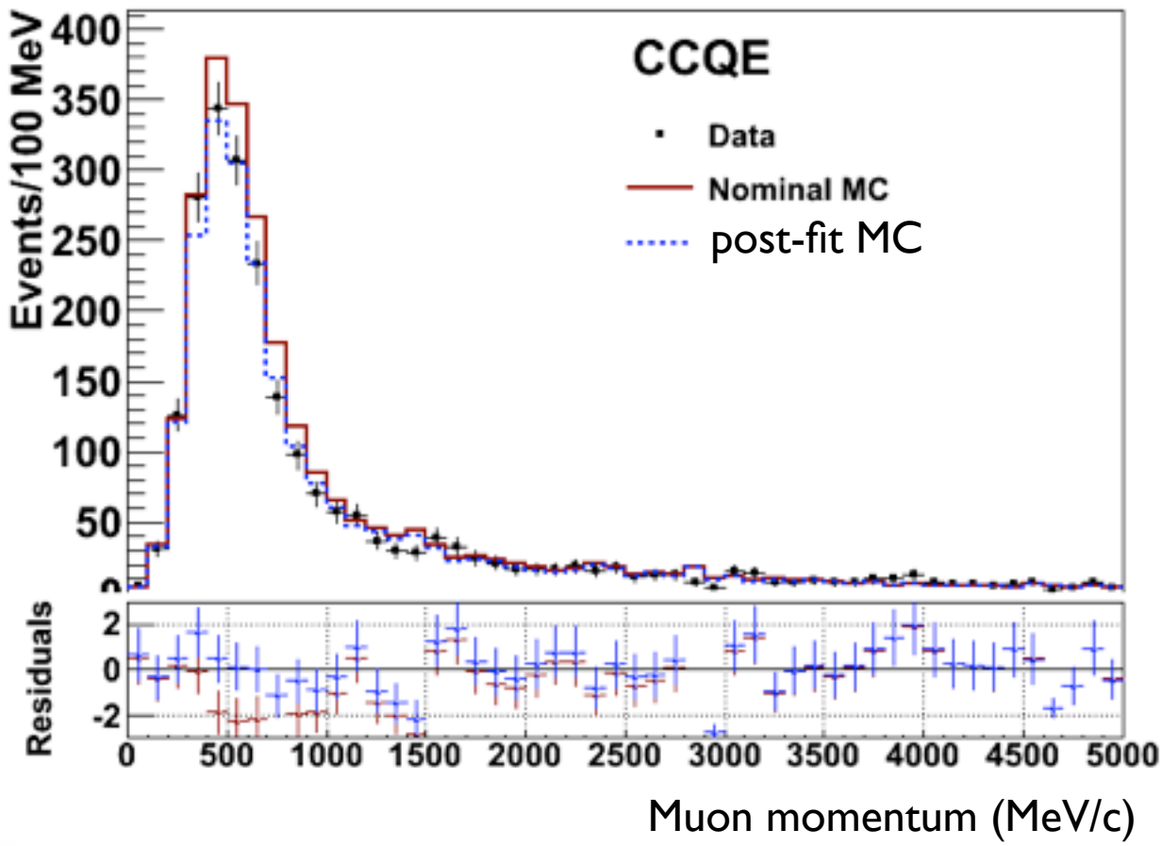
The Results

Much better agreement of the data with the MC

CC selection
Data/MC$_{nom}$ = 95.5%
Data/MC$_{refit}$ = 99.5%

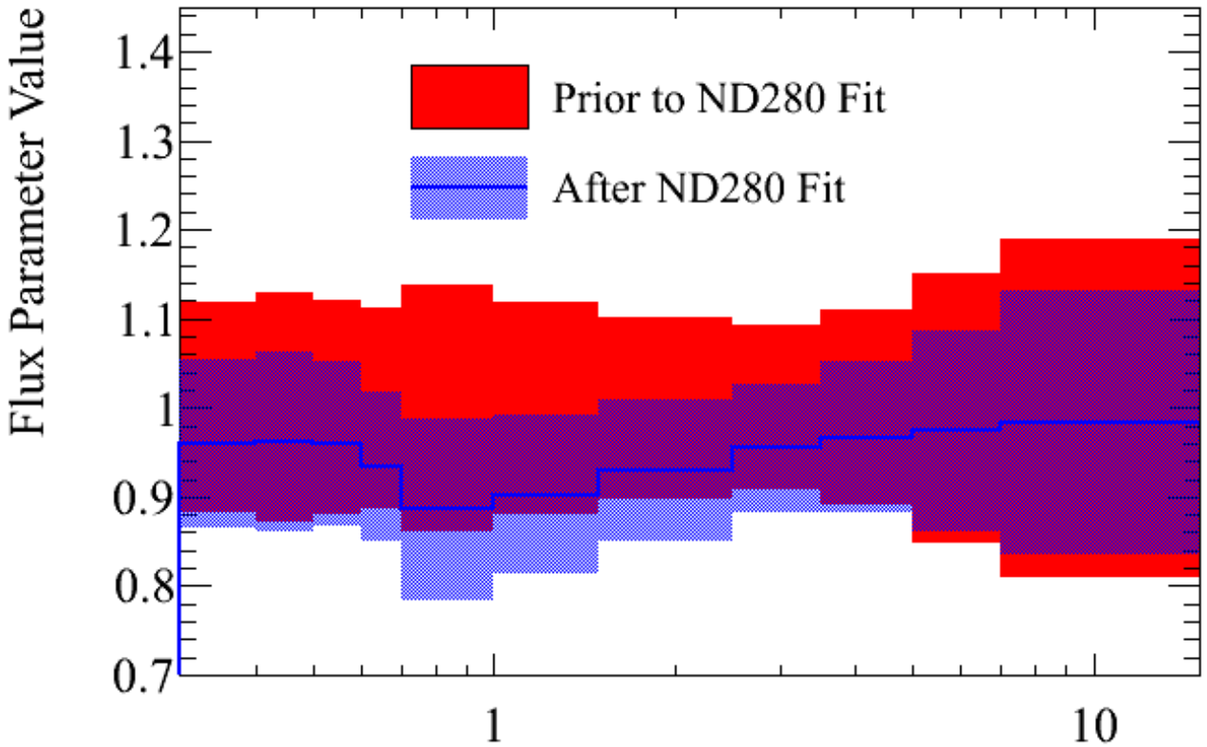
CCQE selection
Data/MC$_{nom}$ = 95.0%
Data/MC$_{refit}$ = 99.9%

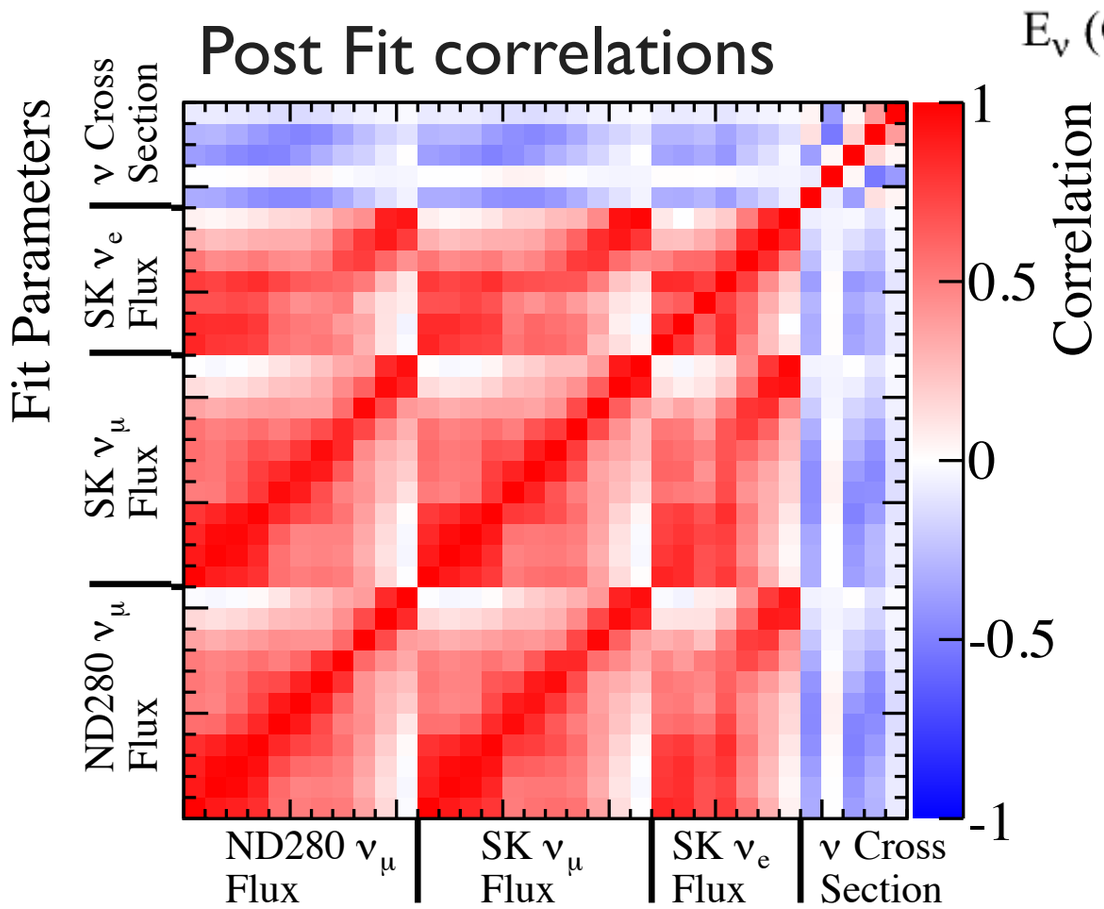
CCnQE selection
Data/MC$_{nom}$ = 98.7%
Data/MC$_{refit}$ = 99.4%



Far detector prediction

T2K Far Detector (FD) ν_μ flux parameters





Reduction of the systematic errors of the neutrino flux at the far detector due to the ND280 measurements:

20% ➡ 10% error

Cross section parameters are constrained from fit
(see result in backup)

ND280 can also do other kinds of measurements... (cross section,...)

Flux averaged cross Section Measurement Method

Flux averaged differential cross section:

$$\left\langle \frac{\partial^2\sigma}{\partial p_\mu \partial \cos\theta_\mu} \right\rangle_{kl} = \frac{N_{kl}^{\text{int}}}{T\phi \Delta p_{\mu,k} \Delta \cos\theta_{\mu,l}}$$

# of interactions in true bin

# of target nucleons

flux

2D binning: (k,l) $\Longleftrightarrow$ $(p_k, \cos\theta_l)$

1D binning: k $\Longleftrightarrow$ $(p, \cos\theta)_k$

Method

Unfolding

$$N_k^{\text{int}} \approx \widehat{N}_k = \frac{U_{kj}}{\epsilon_k}\left(N_j^{sel} - B_j\right)$$

unfolding matrix

efficiency

# of sel. events

background in rec. bin

unfolding based on Bayes' theorem

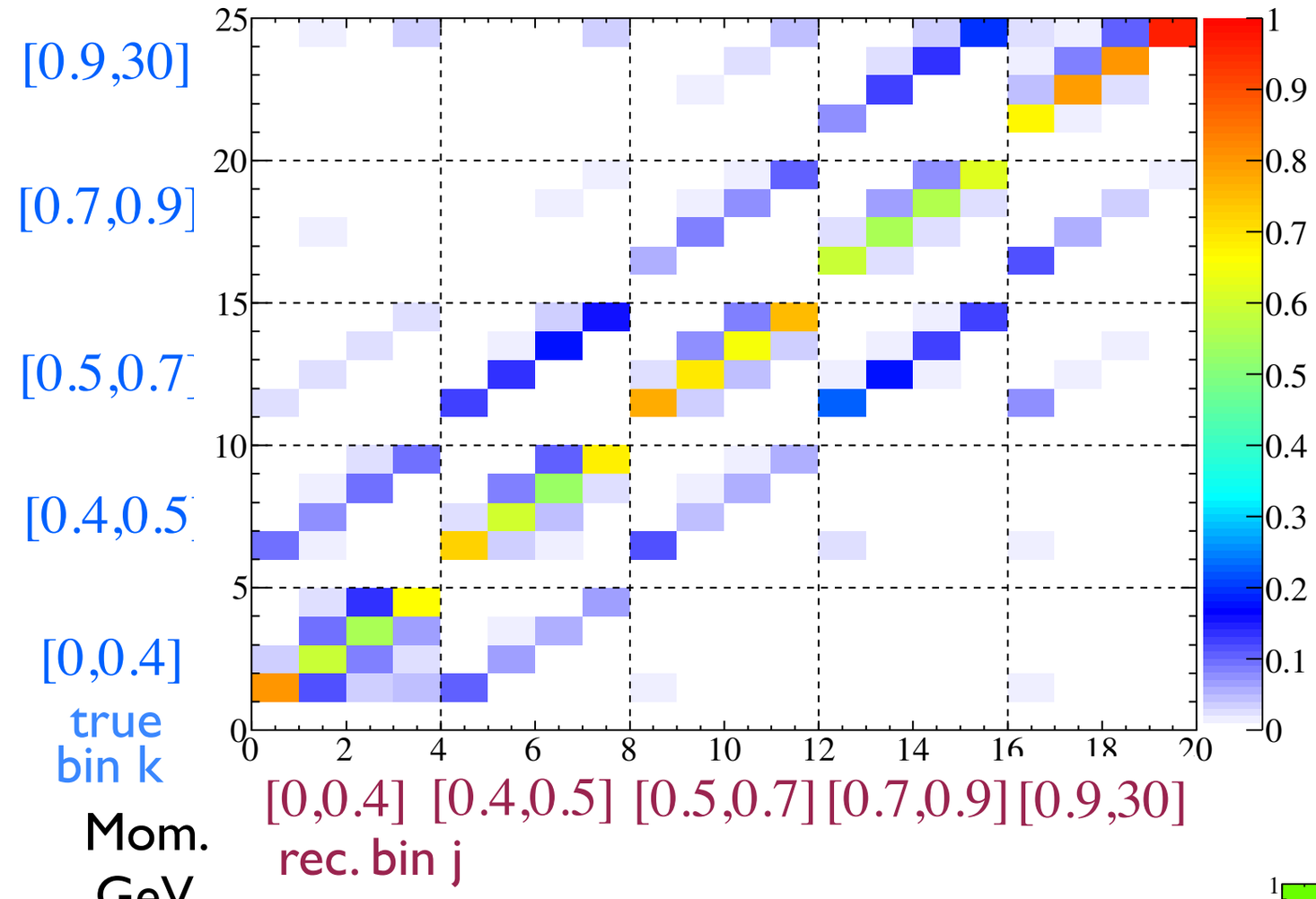
$$U_{kj} = P(k|j) = \frac{P(j|k)P(k)}{\sum_\alpha P(j|\alpha)}$$

U_{kj} = probability to have an interaction in bin k, when having reconstructed the event in bin j

reco. (j index)

true (k index)

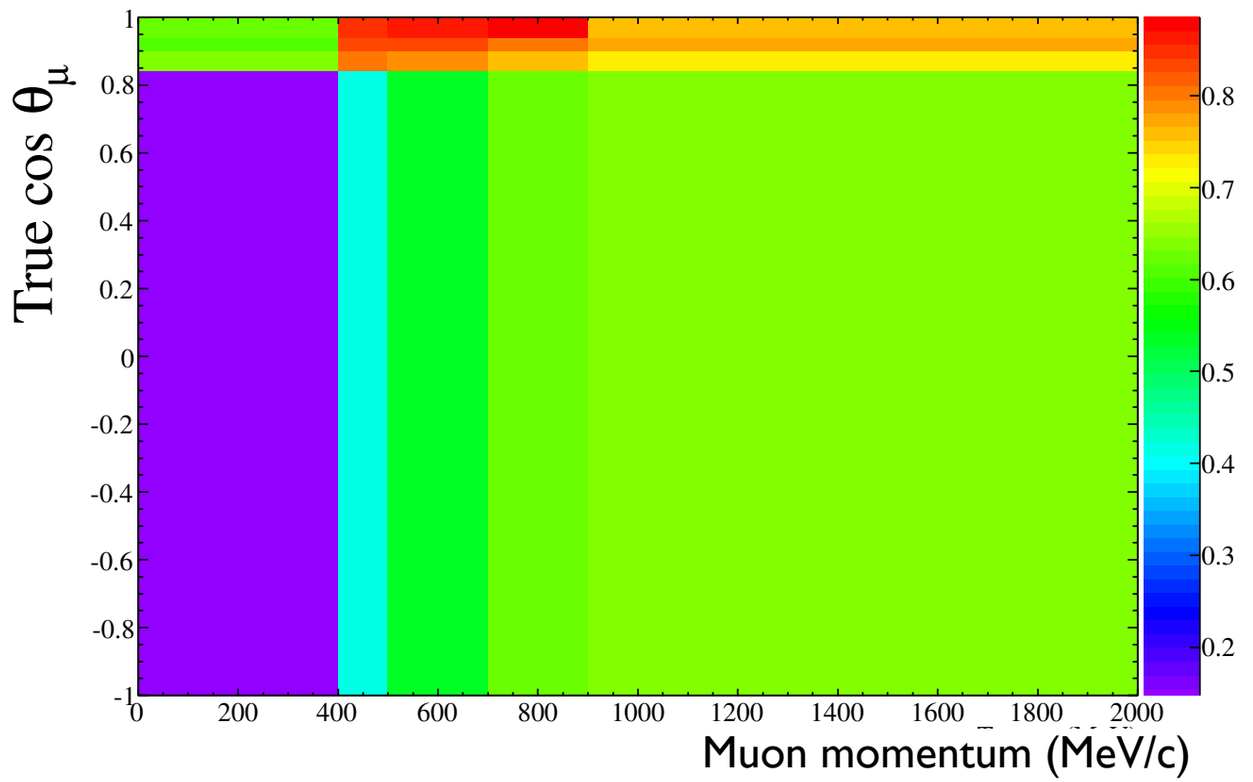
Unfolding matrix and efficiency



Unfolding matrix: mostly diagonal

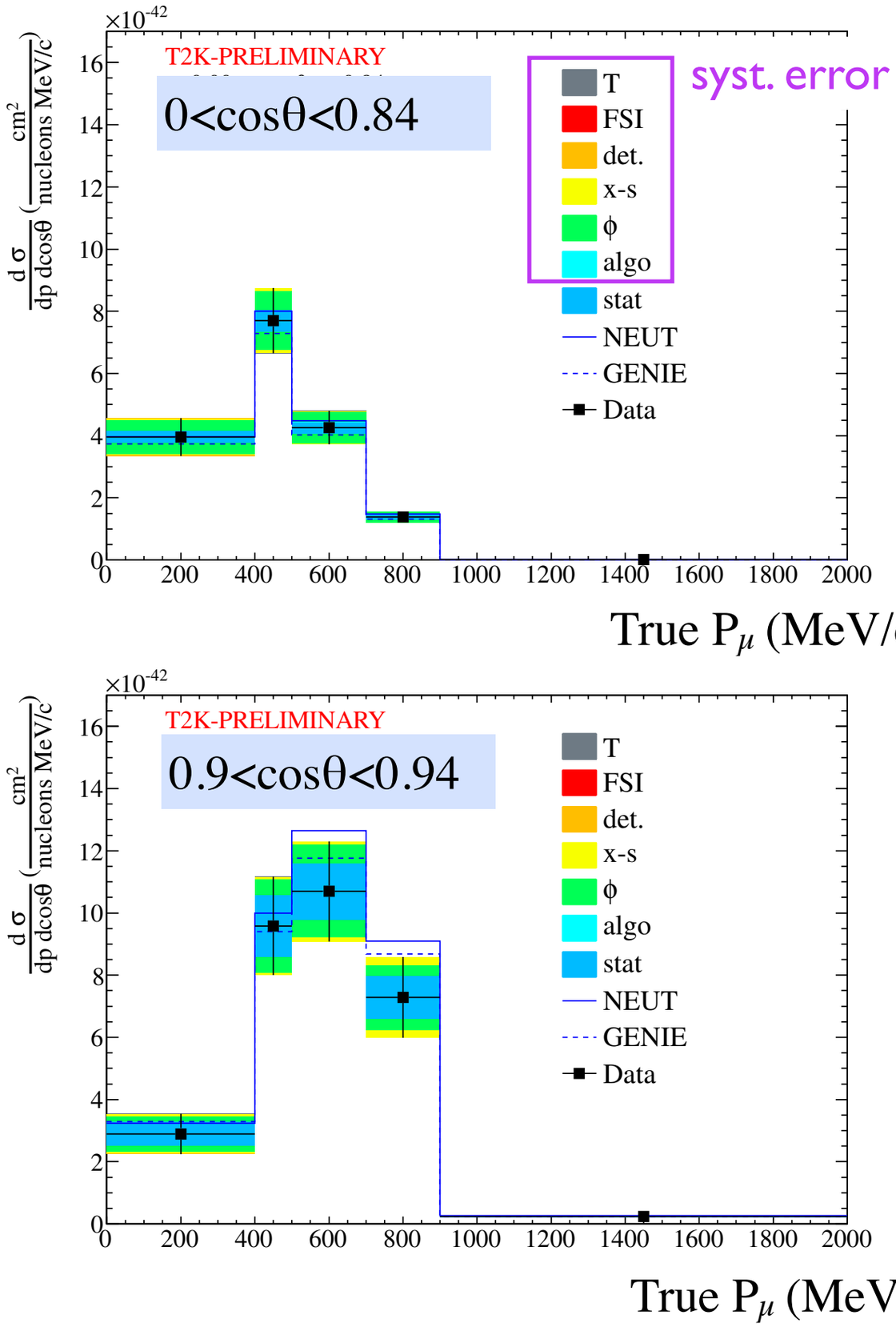
Efficiency very low in the backward going region

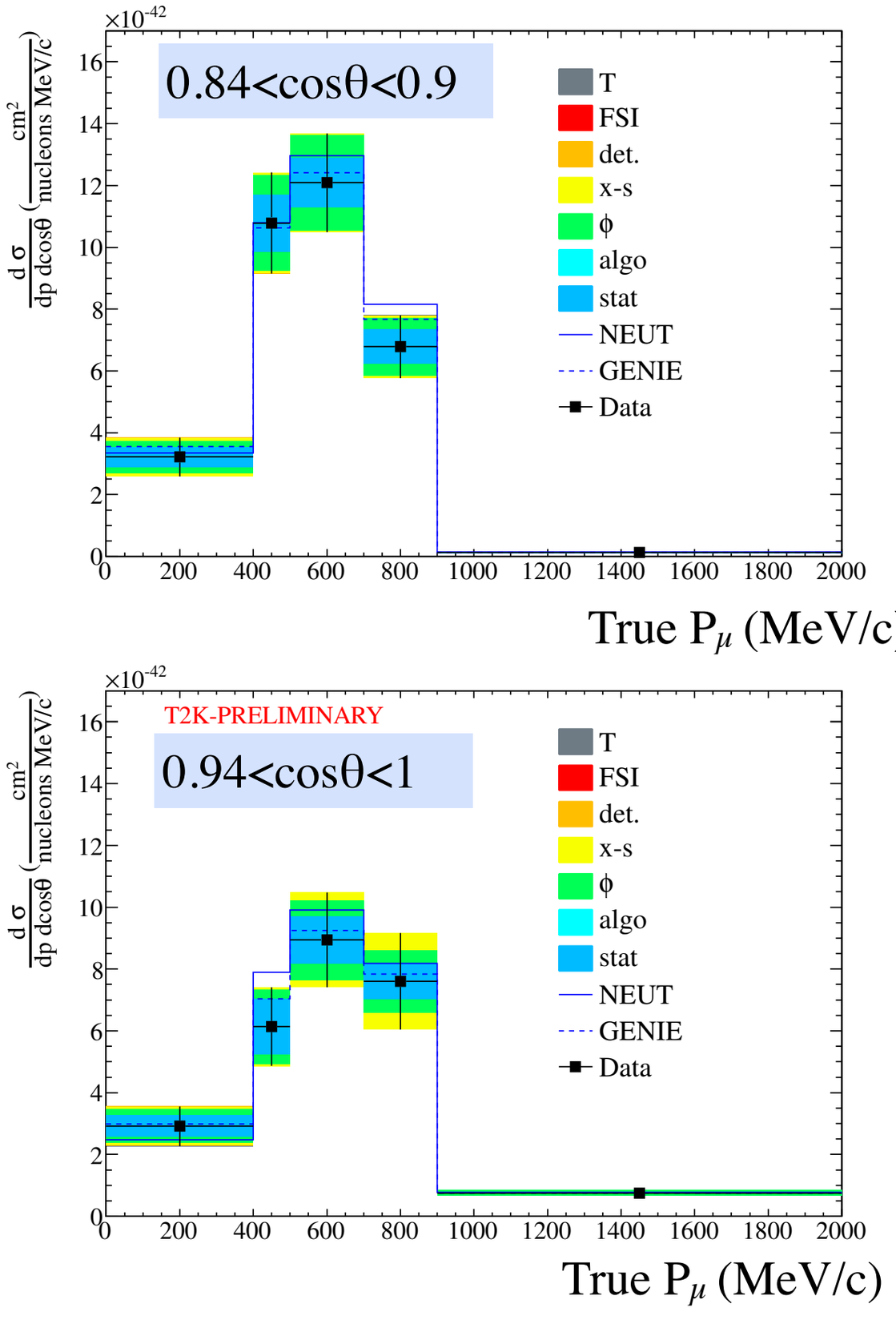
CC signal efficiency



Differential Cross section Results / per nucleon

*T: Target, **FSI**: Final State Interaction **det.**: detector, **x-s**: cross-section, **algo**: unfolding algorithm*





Flux av. Total Cross section of CC $<\sigma>_\phi = \frac{N_{tot}}{T\phi}$

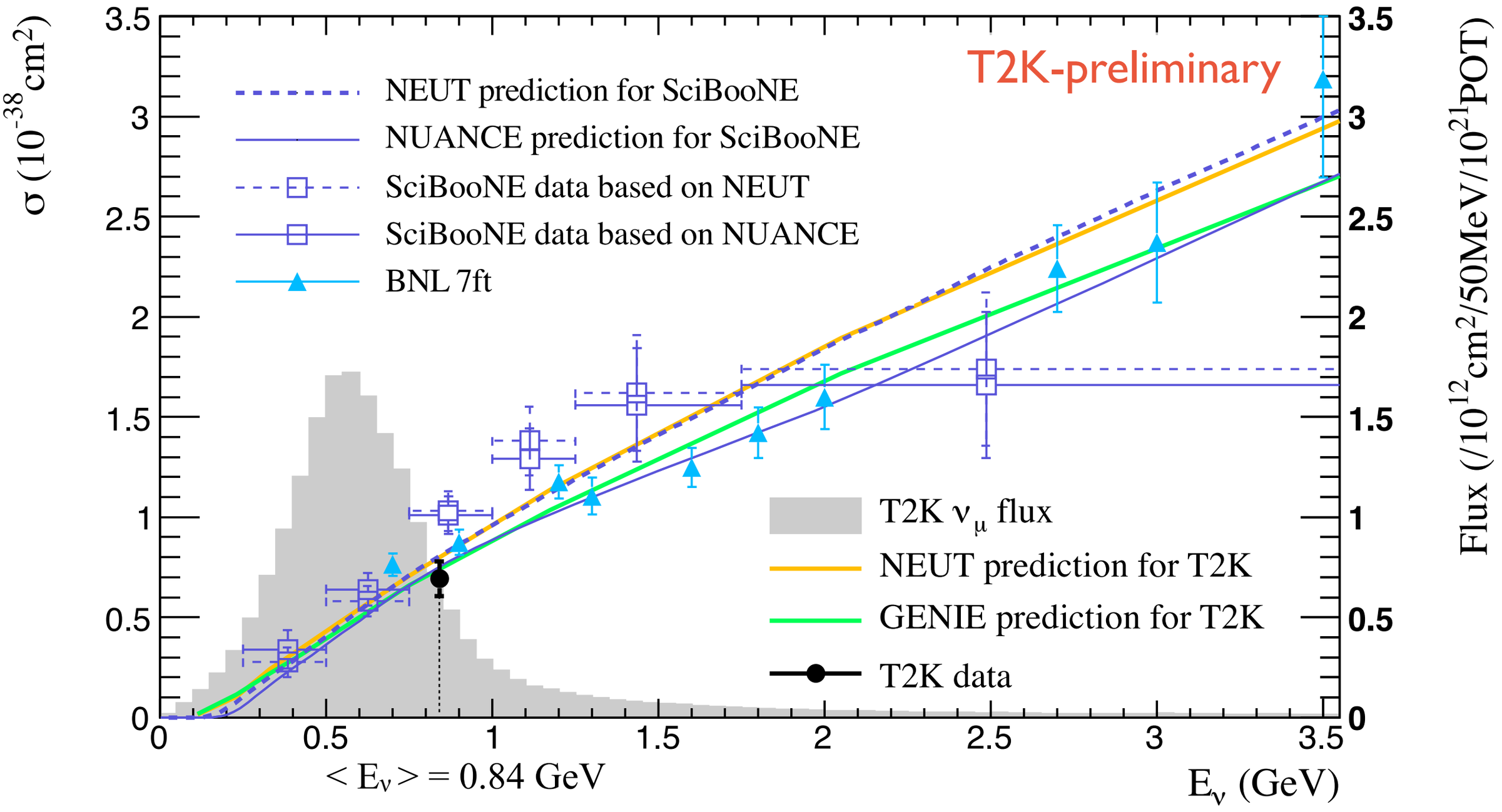
data

$$\langle\sigma_{\rm CC}\rangle_\phi = (6.93 \pm 0.13(stat) \pm 0.85(syst)) \times 10^{-39} \frac{\rm cm^2}{\rm nucleons}$$

predicted from generators

$$\langle\sigma_{\rm CC}^{\rm NEUT}\rangle_\phi = 7.26 \times 10^{-39} \frac{\rm cm^2}{\rm nucleons}$$

$$\langle\sigma_{\rm CC}^{\rm GENIE}\rangle_\phi = 6.68 \times 10^{-39} \frac{\rm cm^2}{\rm nucleons}$$



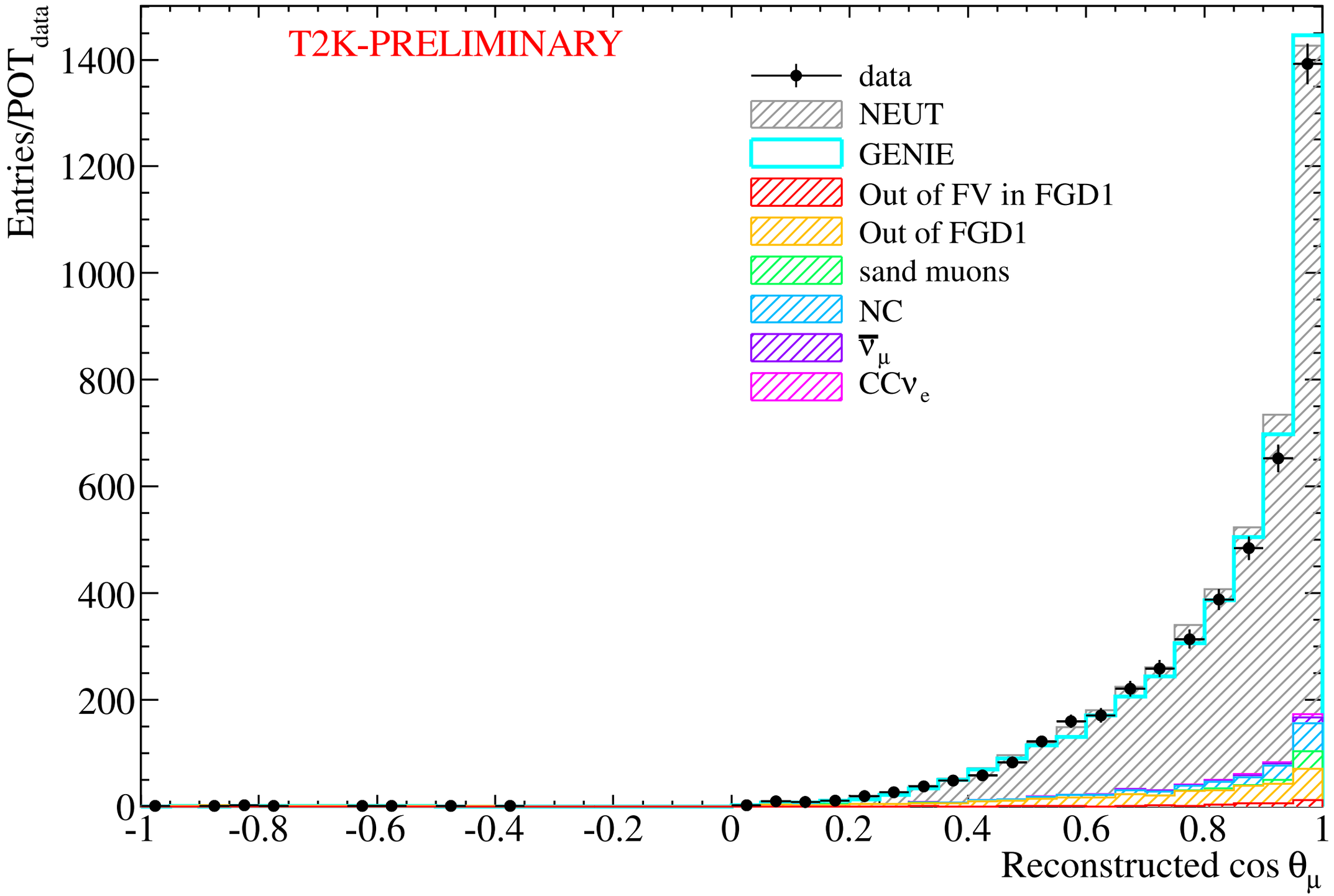
Conclusions

- **Notable improvement of the flux prediction at the T2K far detector due to the measurement at ND280**
  - 20% to 10% error reduction of the predicted flux at the far detector
- **The cross section results are compatible with the MC and experiments**
  - The total cross section result is:

$$\langle \sigma_{\mathrm{CC}} \rangle_{\phi} = (6.93 \pm 0.13(stat) \pm 0.85(syst)) \times 10^{-39} \frac{\mathrm{cm}^2}{\mathrm{nucleons}}$$

  - More results on cross-sections in preparation
- **Preliminary results presented, publication in preparation**

- BACK UP


T2K-PRELIMINARY
Entries/POT$_{data}$
1400
1200
1000
800
600
400
200
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Reconstructed cos θ_μ
data
NEUT
GENIE
Out of FV in FGD1
Out of FGD1
sand muons
NC
$\overline{\nu}_\mu$
CCν_e

Fraction of each element

Component	C	O	H	Ti	Si	N	Total
Scintillator bars	1.7651 ± 0.0067	0.0248 ± 0.0039	0.1468 ± 0.0006	0.0355 ± 0.0059	0	0.0010 ± 0.00004	1.973 ± 0.0104
G10	0.0196 ± 0.0015	0.0331 ± 0.0001	0.0034 ± 0.0018	0	0.0218 ± 0.0043	0.0013 ± 0.0013	0.079
Plexus MA590	0.0484 ± 0.0060	0.0215 ± 0.0027	0.0065 ± 0.0008	0	0	0.0009 ± 0.0001	0.0774 ± 0.0096
fiber	0.0155	0.00002	0.0013	0	0	0.00002	0.0169
XY module	1.849 ± 0.0092	0.0794 ± 0.0048	0.1579 ± 0.0021	0.0355 ± 0.0059	0.0218 ± 0.0043	0.0031 ± 0.0012	2.147 ± 0.0144

Table 12.12: Elemental composition of the components of a typical XY layer, in g/cm^2 of each element [136]

Flux systematic sources (summary)

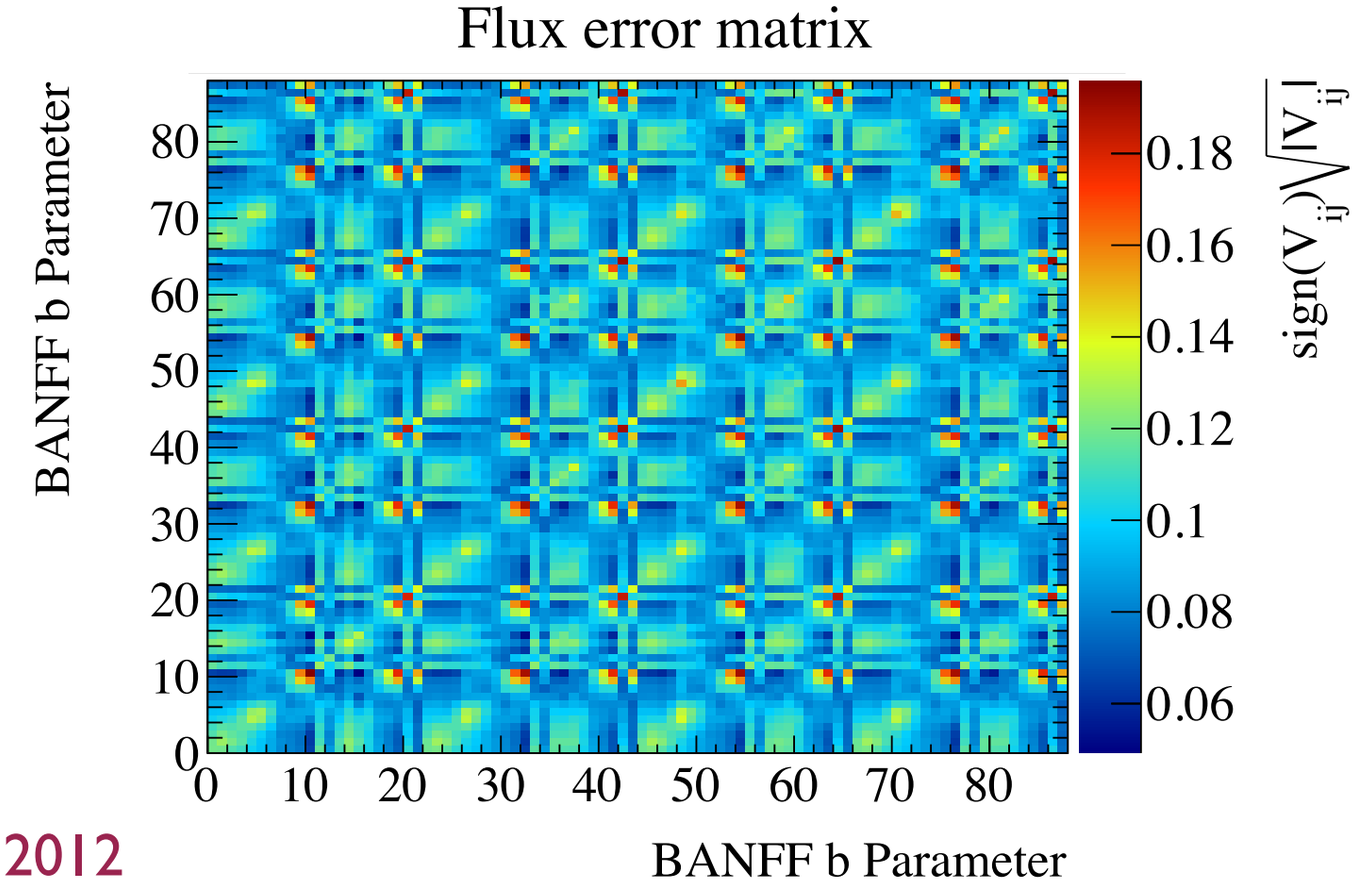
sources	Max. Error (%)	Min. Error (%)	Norm. Error (%)
Kaon	16.7	0.4	0.8
Pion	6.1	0.6	5.0
Proton beam	5.1	0.2	1.1
Off-axis angle	5.4	0.1	1.6
Horn ang. align.	1.0	0.2	0.5
Horn field assym.	6.7	0.01	0.3
Cross-sec. production	7.8	4.5	6.4
Horn abs. current	1.9	0.4	0.9
Target align.	2.6	0.05	0.2
Sec. nucl. production	8.5	2.9	6.9
Total	19.6	8.9	10.9

Flux error matrix

bin 0-10 : ND280 ν_μ
bin 11-12: ND280 anti-ν_μ
bin 13-19: ND280 ν_e
bin 20-21: ND280 anti-ν_e

bin 22-32: SK ν_μ
bin 33-34: SK anti-ν_μ
bin 35-41: SK ν_e
bin 42-43: SK anti-ν_e

bin 44-87: SK latest data in 2012

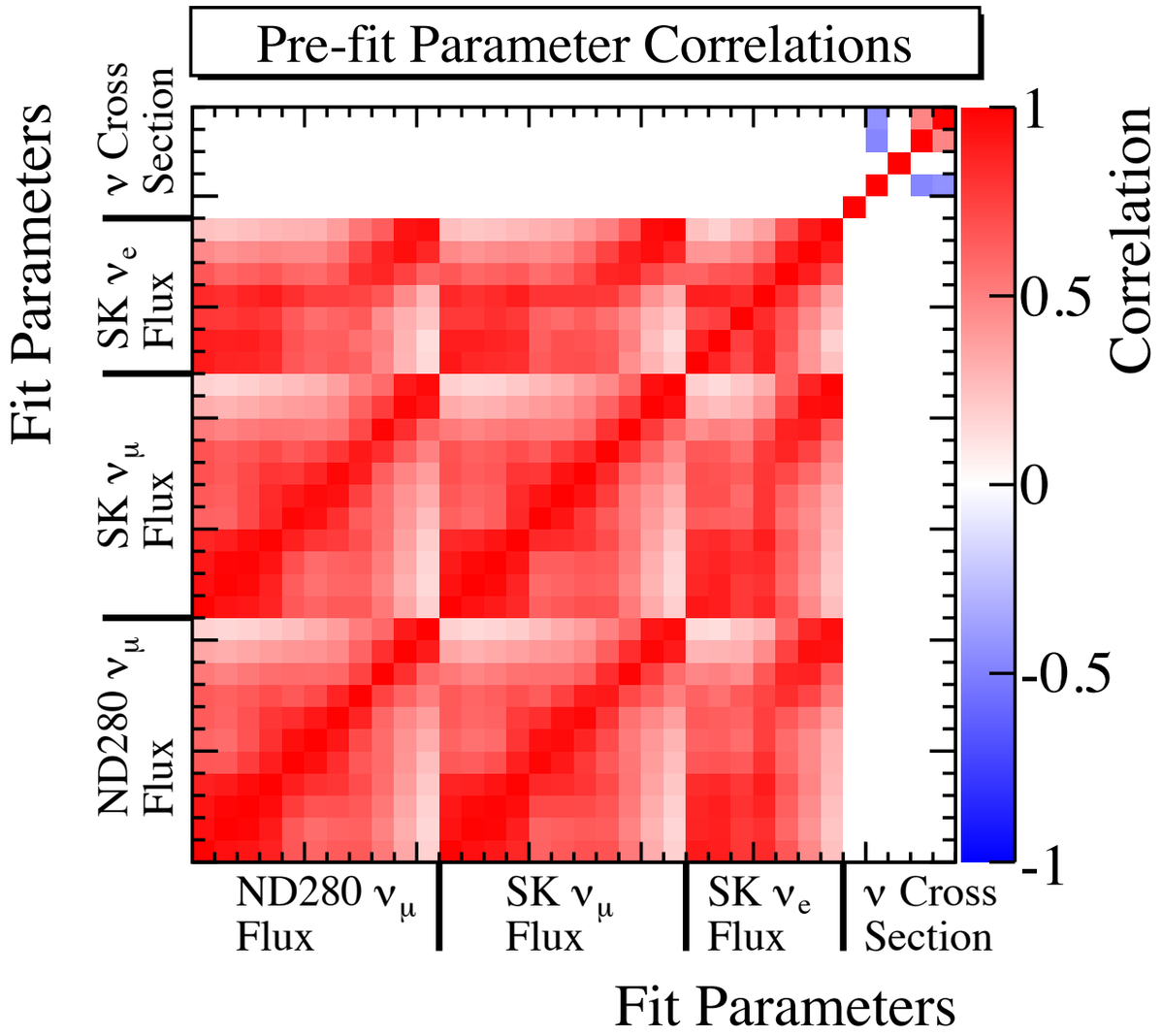


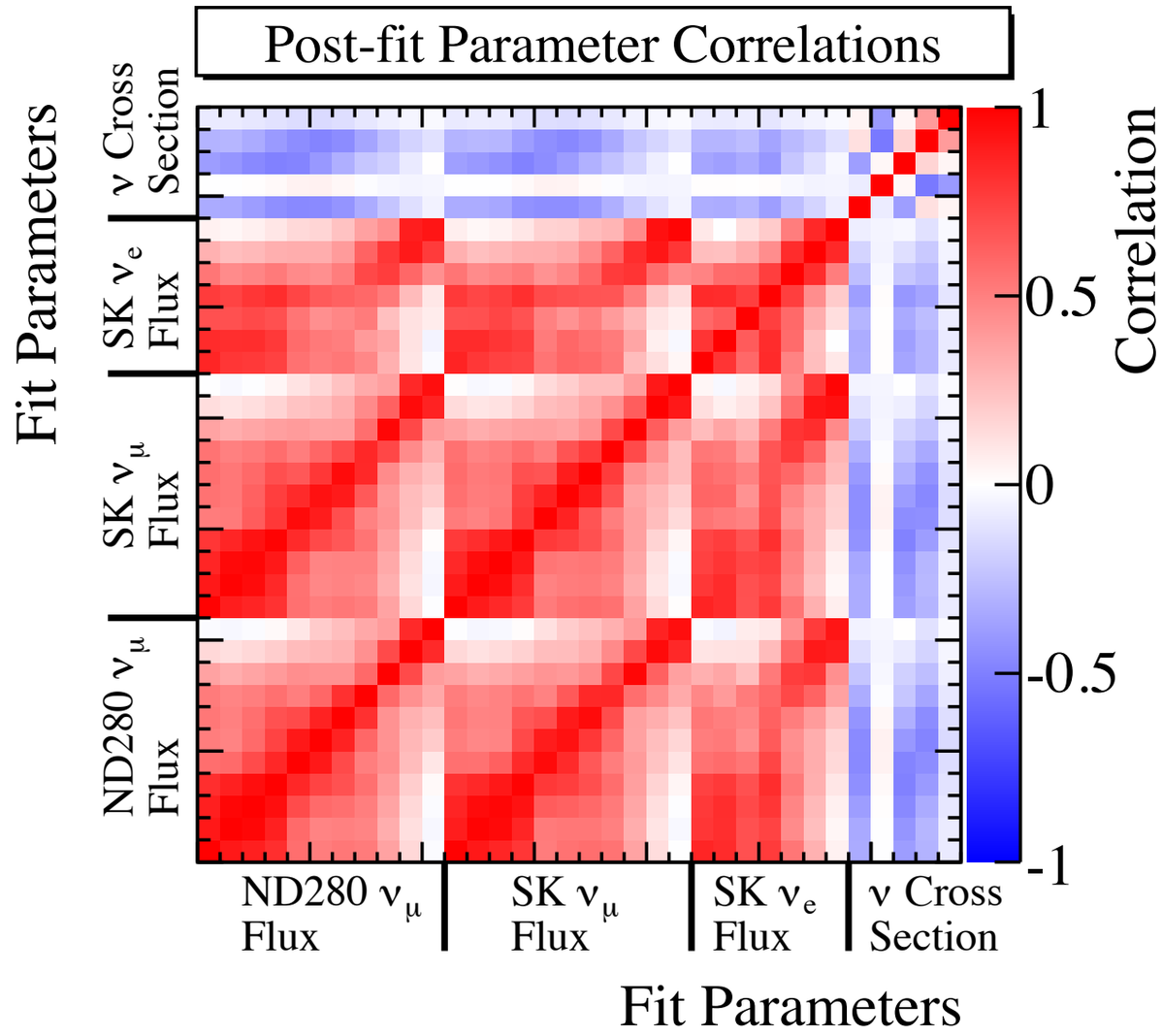
Detector response systematic sources (summary)

Systematic Error	Data Sample	Error size (%)
TPC track quality cut	Beam data/MC	0.1
TPC track efficiency	Beam data/MC	0.5
TPC *broken track* tracking efficiency	Beam data/MC	0.6
TPC Particle ID (PID)	Beam data/MC	0.1
TPC momentum scale	external data	0.51
TPC momentum distortion	special MC	$1-7$
TPC momentum resolution	Beam data/MC	2.0
TPC-FGD matching efficiency	sand muon + cosmics	< 1
Fiducial Mass	external measurement	0.67
Charge mis-ID	Beam data/MC	< 0.3
Michel electron tagging	cosmics	0.49
Cosmic rays	special MC	0.1
Sand muons	special MC	1.5
Out-of-fiducial volume (OOFV) background	several samples	$1-9$
Pion reinteractions	Beam data/MC	$1-4$
Pileup	data/MC	0.24

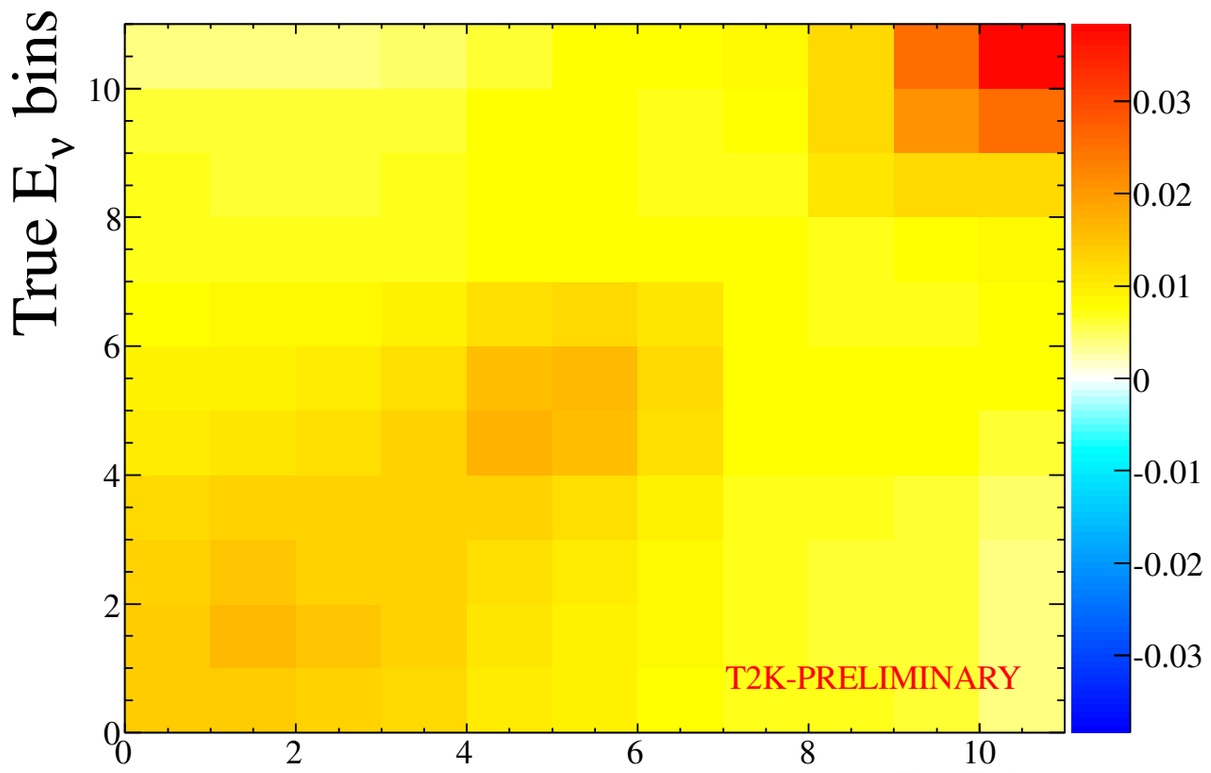
Fitted Neutrino Interaction Model Parameters

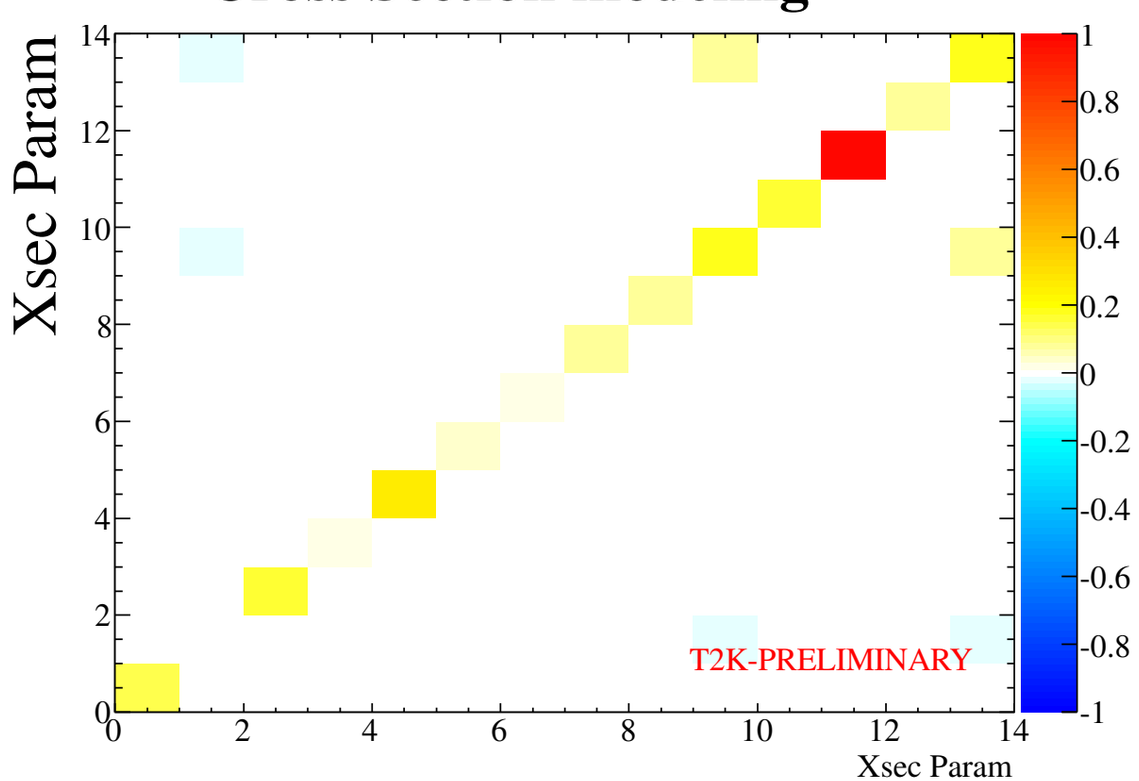
Parameter	Prior Value	Fitted Value
M_A^{QE} (GeV)	1.21 ± 0.45	1.19 ± 0.19
M_A^{RES} (GeV)	1.162 ± 0.110	1.137 ± 0.095
CCQE Norm. < 1.5 GeV	1.0 ± 0.11	0.941 ± 0.087
CCQE Norm. 1.5-3.5 GeV	1.0 ± 0.30	0.92 ± 0.23
CCQE Norm. > 3.5 GeV	1.0 ± 0.30	1.18 ± 0.25
CC1π Norm. < 2.5 GeV	1.63 ± 0.43	1.67 ± 0.28
CC1π Norm. > 2.5 GeV	1.0 ± 0.40	1.10 ± 0.30
NC1π^0 Norm.	1.19 ± 0.43	1.22 ± 0.40
Spectral Function	0 (off) ± 1 (on)	0.04 ± 0.21
p_F (MeV/c)	217 ± 30	224 ± 24
CC Other Shape (GeV)	0.0 ± 0.4	-0.05 ± 0.35

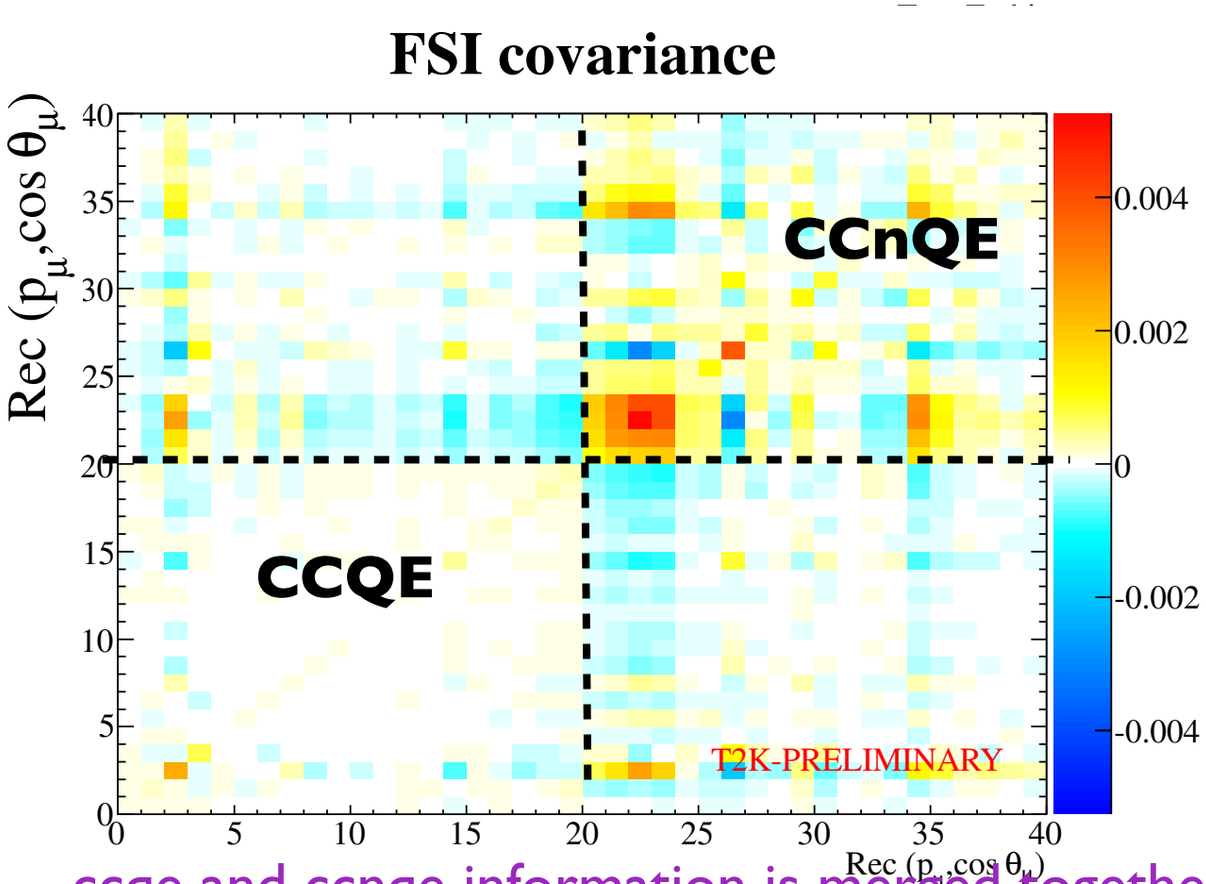

Pre-fit Parameter Correlations
Fit Parameters
ν Cross Section
SK νe Flux
SK νμ Flux
ND280 νμ Flux
ND280 νμ Flux
SK νμ Flux
SK νe Flux
ν Cross Section
Fit Parameters
1
0.5
0
-0.5
-1
Correlation

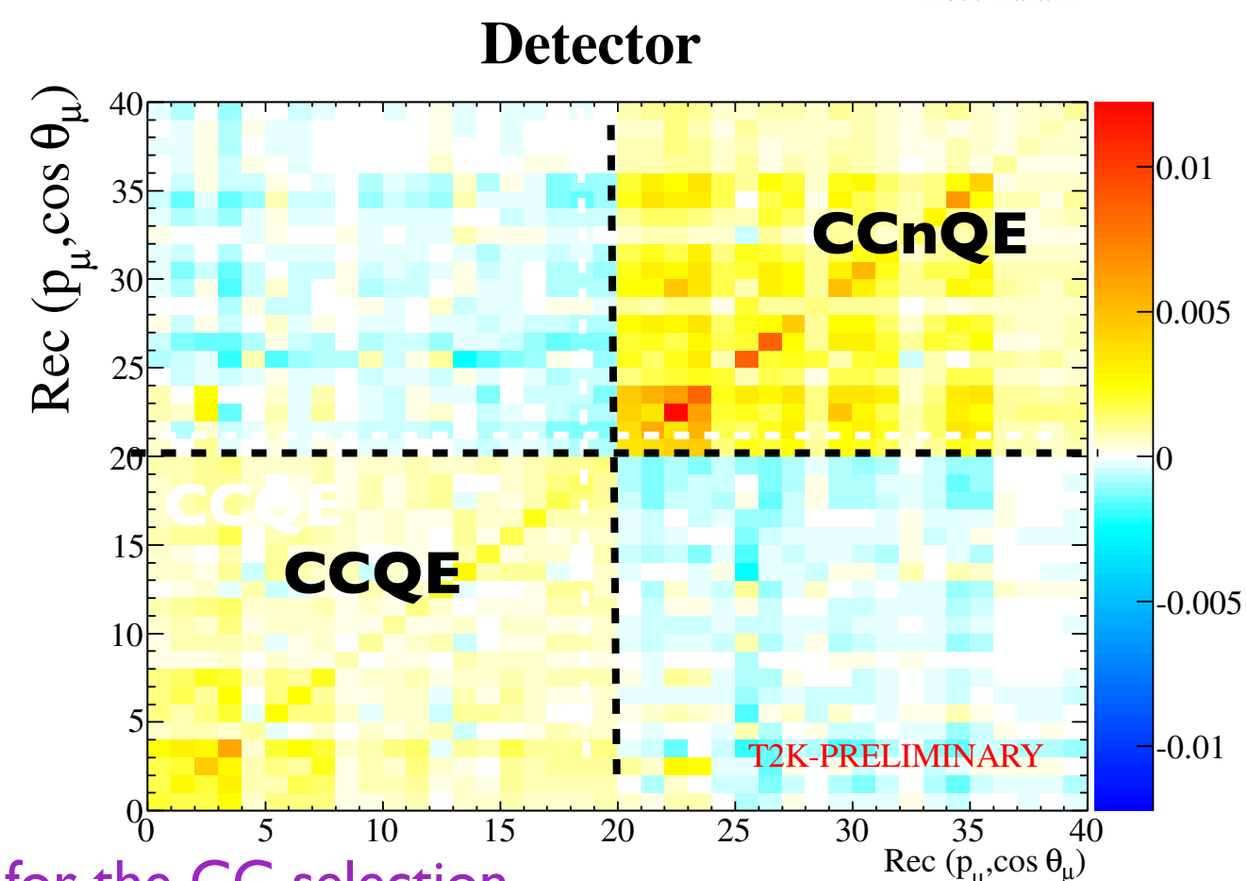

Post-fit Parameter Correlations
Fit Parameters
ν Cross Section
SK νe Flux
SK νμ Flux
ND280 νμ Flux
ND280 νμ Flux
SK νμ Flux
SK νe Flux
ν Cross Section
Fit Parameters
1
0.5
0
-0.5
-1
Correlation

Covariances matrices (input sources)









ccqe and ccnqe information is merged together for the CC selection

Systematic errors

The sources

How

same input as before

FSI
Detector
Cross-Section

Flux

is obtained by
- reweighting the MC 200x decomposing the cov. matrices (Cholesky decomposition)
- the **data** is unfolded with the reweighted MC

$$\text{error} = \text{RMS}\left(\widehat{N}^{\text{rw}}_{t_k} - \widehat{N}^{(nom)}_{t_k}\right)$$

$$\text{error} = \text{RMS}\left(\frac{\widehat{N}^{\text{rw}}_{t_k}}{\phi^{\text{rw}}} - \frac{\widehat{N}^{(nom)}_{t_k}}{\phi^{(nom)}}\right)$$

algorithm

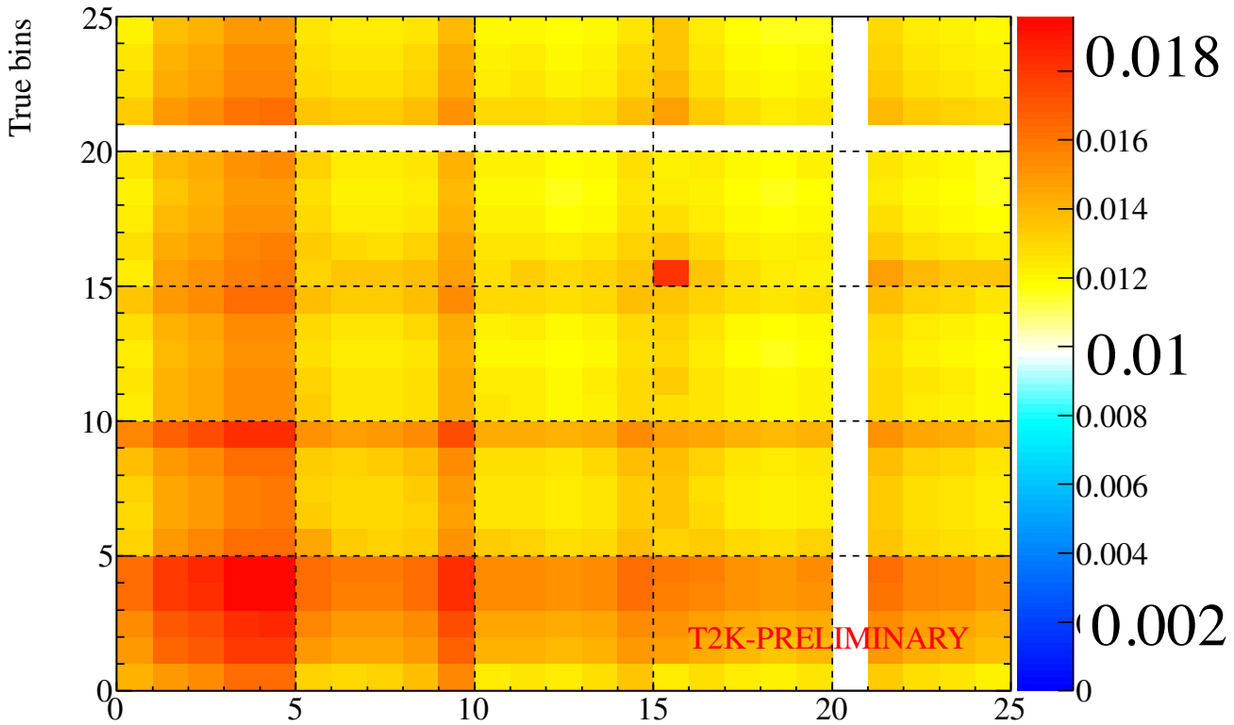
is obtained by unfolding a 1000 data size MC with the nominal MC

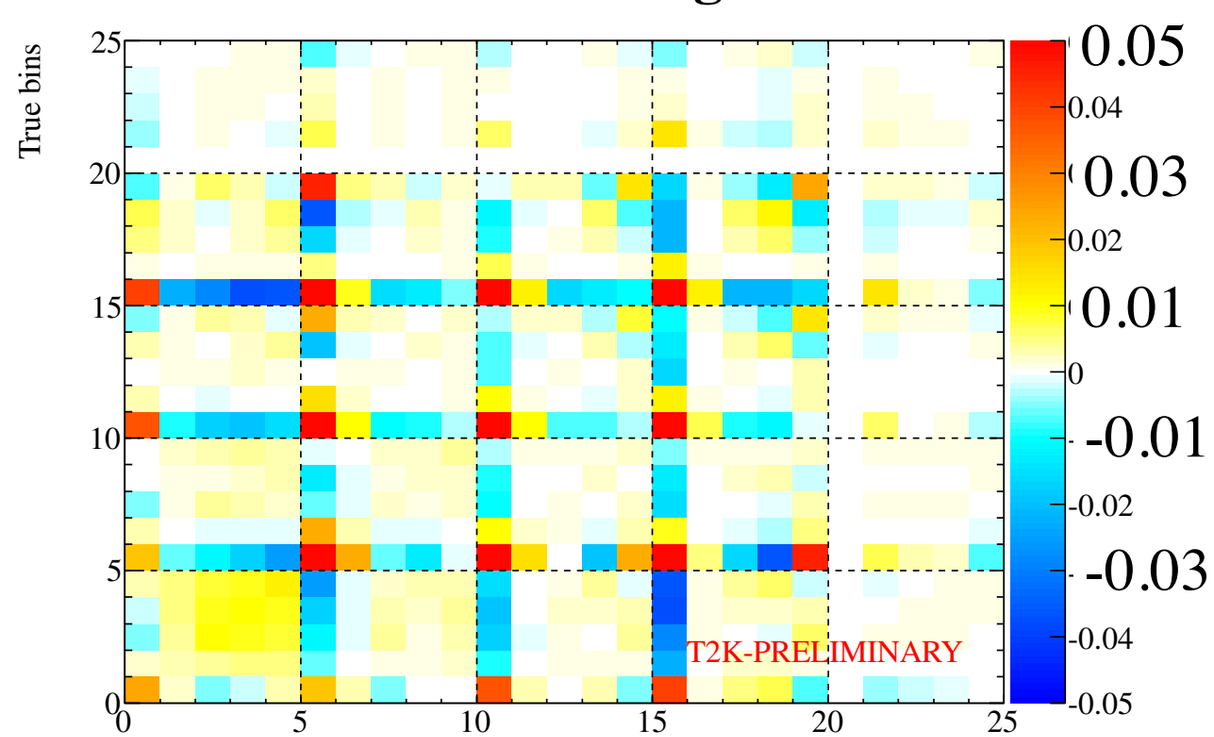
$$\text{error} = \text{MEAN}\left(\widehat{N}^{(nom)}_{t_k} - N^{truth}_{t_k}\right)$$

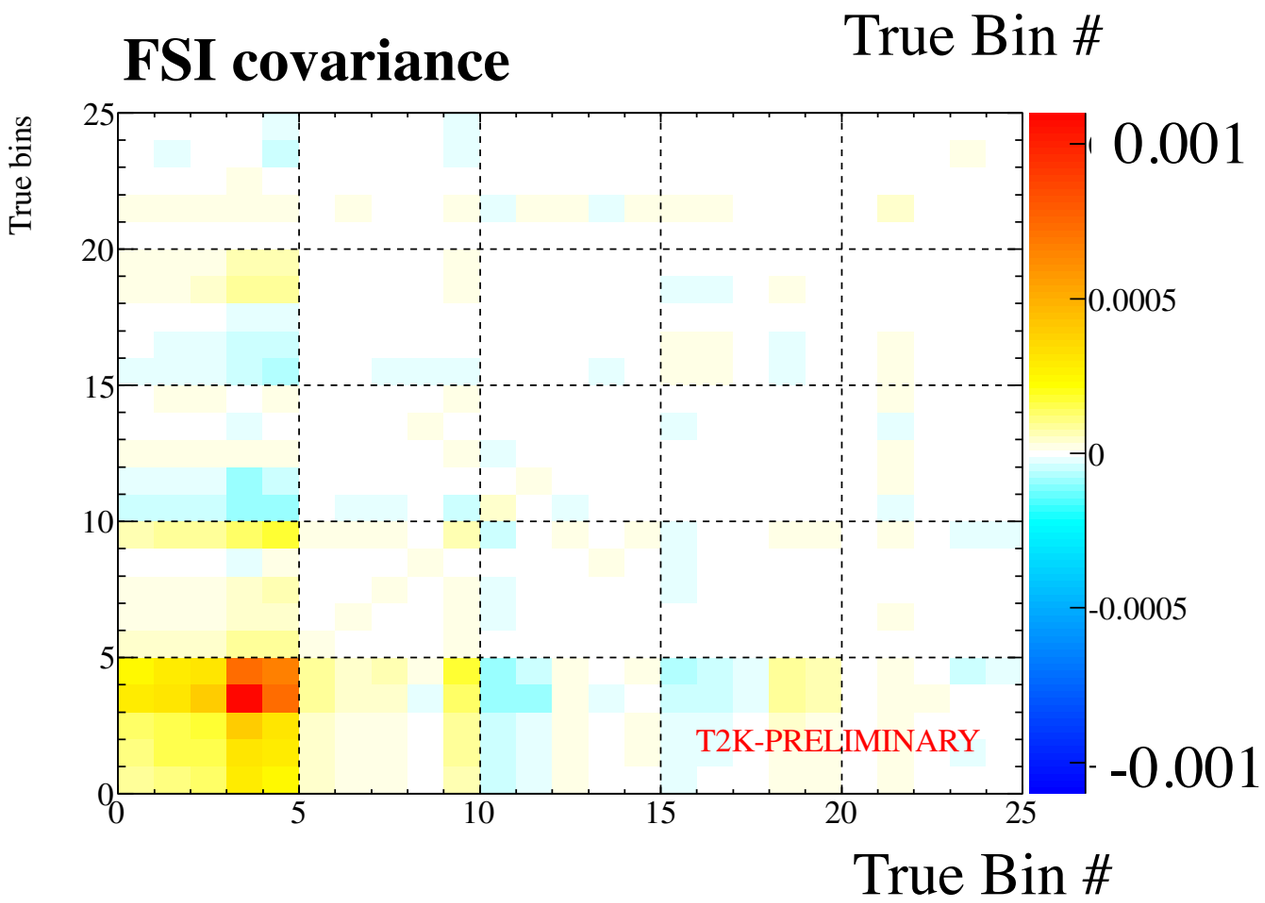
Target

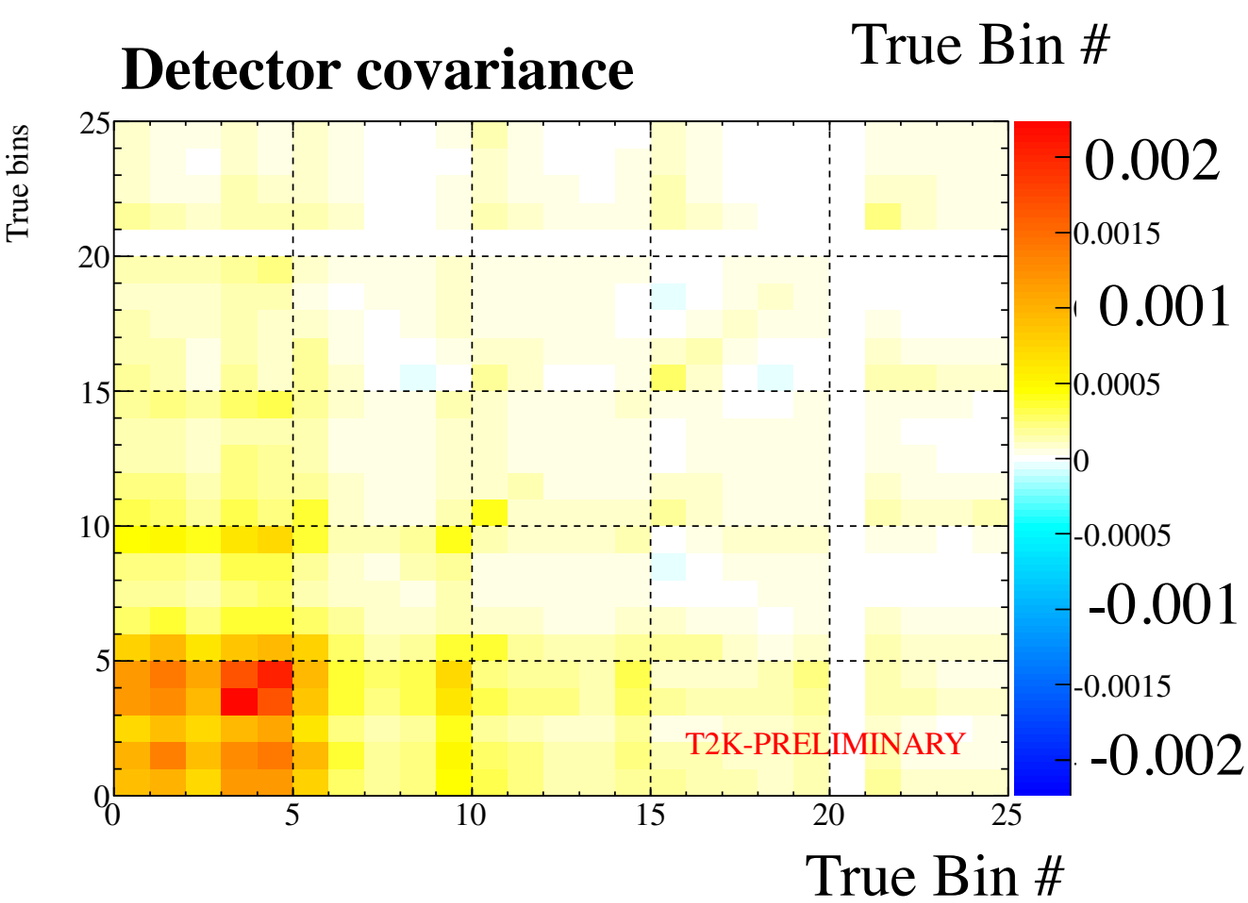
$$\text{error} = \frac{\delta T}{T} = 0.67\%$$ from measurements

Systematic errors

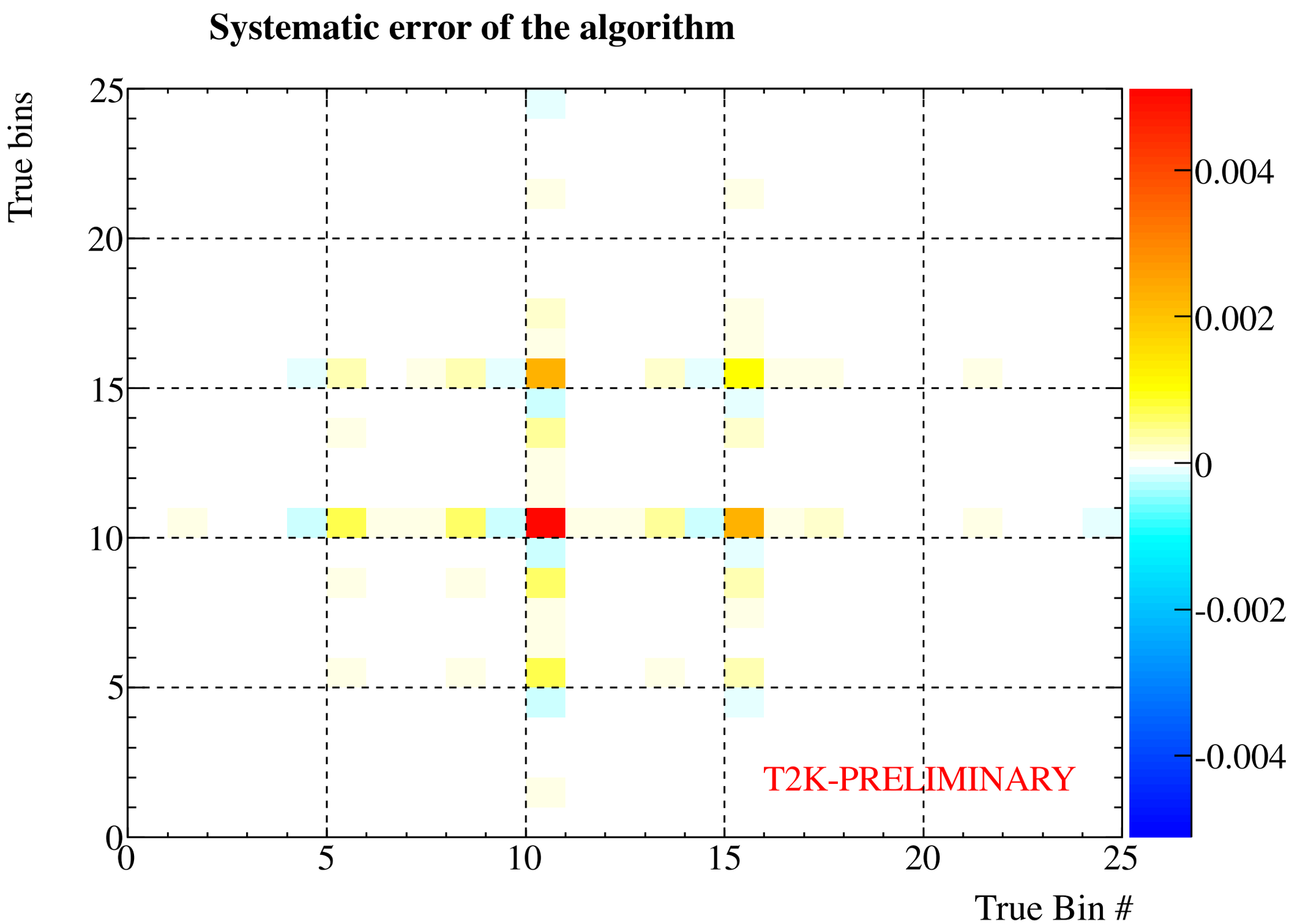








Systematic errors



systematic error (all)

Table 17: Summary of the systematic errors. The error on the number of target (0.67 %) have been added in quadrature to the total systematic error. ϕ, *det.*, *FSI* label the systematic uncertainty of the beam flux, detector response and FSI changed systematically following the covariance matrix showed in Fig. 9,11,10,12, x-s design the influence of the change of all the cross-section modeling parameter and channel rate.

P_μ (GeV/c)	$\cos\theta_\mu$	algo. (%)	ϕ (%)	x-s (%)	det. (%)	FSI (%)	syst (%)	stat (%)	tot (%)
[0.0, 0.4]	[−1, 0]	0.03	11.92	15.45	2.97	0.96	19.78	2.86	19.98
	[0, 0.84]	0.10	12.82	5.44	3.70	1.23	14.49	5.03	15.34
	[0.84, 0.9]	0.06	13.17	10.25	2.67	1.35	16.98	9.37	19.39
	[0.9, 0.94]	0.06	13.95	10.02	4.73	3.32	18.14	11.82	21.65
	[0.94, 1]	0.24	14.00	11.09	4.49	2.57	18.61	13.78	23.16
[0.4, 0.5]	[−1, 0]	0.98	12.05	48.06	2.79	0.47	49.64	3.52	49.77
	[0, 0.84]	0.13	11.39	5.68	1.31	0.34	12.83	4.27	13.52
	[0.84, 0.9]	0.18	11.41	4.96	0.94	0.38	12.51	8.55	15.15
	[0.9, 0.94]	0.90	11.71	4.90	1.19	0.44	12.82	9.97	16.24
	[0.94, 1]	0.34	13.12	6.25	2.06	0.83	14.73	11.42	18.64
[0.5, 0.7]	[−1, 0]	7.15	11.22	47.37	1.97	0.63	49.25	30.30	57.83
	[0, 0.84]	0.10	11.12	3.76	1.10	0.37	11.83	3.86	12.44
	[0.84, 0.9]	0.10	10.87	3.25	0.79	0.29	11.41	6.18	12.98
	[0.9, 0.94]	0.55	11.06	5.62	0.76	0.32	12.48	7.18	14.39
	[0.94, 1]	0.22	11.71	9.15	0.98	0.24	14.92	7.67	16.77
[0.7, 0.9]	[−1, 0]	3.18	13.48	101.82	1.59	0.48	102.77	28.89	106.75
	[0, 0.84]	0.19	11.35	2.93	1.14	0.41	11.81	5.23	12.92
	[0.84, 0.9]	0.23	10.93	5.84	0.83	0.19	12.45	6.85	14.21
	[0.9, 0.94]	0.04	10.75	10.59	0.95	0.40	15.15	7.57	16.94
	[0.94, 1]	0.03	11.01	15.59	0.79	0.30	19.13	6.90	20.34
[0.9, 30.0]	[−1, 0]	-	-	-	-	-	-	-	-
	[0, 0.84]	0.20	11.83	4.97	1.46	0.69	12.97	5.88	14.24
	[0.84, 0.9]	0.07	11.30	2.31	0.89	0.26	11.60	6.05	13.09
	[0.9, 0.94]	0.05	11.09	2.08	0.72	0.36	11.34	5.33	12.53
	[0.94, 1]	0.09	10.90	2.25	0.75	0.26	11.19	2.97	11.58

highest contribution

highest contribution

Run I			
Event type	CC Inclusive	CCQE enhanced	CCnQE enhanced
CCQE	0.450 ± 0.014	0.716 ± 0.017	0.145 ± 0.015
RES	0.212 ± 0.012	0.141 ± 0.013	0.294 ± 0.019
DIS	0.191 ± 0.011	0.0418 ± 0.0077	0.361 ± 0.020
COH	0.0297 ± 0.0047	0.0175 ± 0.0051	0.0438 ± 0.0084
NC	0.0319 ± 0.0049	0.0131 ± 0.0044	0.0534 ± 0.0093
anti-numu	0.0110 ± 0.0029	0.0010 ± 0.0012	0.0225 ± 0.0061
out of FGD	0.0646 ± 0.0069	0.0606 ± 0.0092	0.069 ± 0.010
out FGD FV	0.0099 ± 0.0028	0.0091 ± 0.0037	0.0107 ± 0.0042

Run II			
Event type	CC Inclusive	CCQE enhanced	CCnQE enhanced
CCQE	0.4491 ± 0.0085	0.708 ± 0.011	0.1455 ± 0.0089
RES	0.2138 ± 0.0070	0.1458 ± 0.0082	0.293 ± 0.011
DIS	0.1927 ± 0.0067	0.0374 ± 0.0044	0.375 ± 0.012
COH	0.0282 ± 0.0028	0.0176 ± 0.0031	0.0406 ± 0.0050
NC	0.0323 ± 0.0030	0.0144 ± 0.0028	0.0534 ± 0.0057
anti-numu	0.0073 ± 0.0015	0.0027 ± 0.0012	0.0127 ± 0.0028
out of FGD	0.0668 ± 0.0043	0.0644 ± 0.0057	0.0696 ± 0.0064
out FGD FV	0.0098 ± 0.0017	0.0096 ± 0.0023	0.0099 ± 0.0025

Table 4: Composition of the selected events for Run II for the CC-inclusive, CCQE and CCnQE enhanced samples.