Recent developments on T2K flux and uncertainties

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On behalf of the T2K collaboration

NuInt 2015 - Osaka - Japan

Outline:

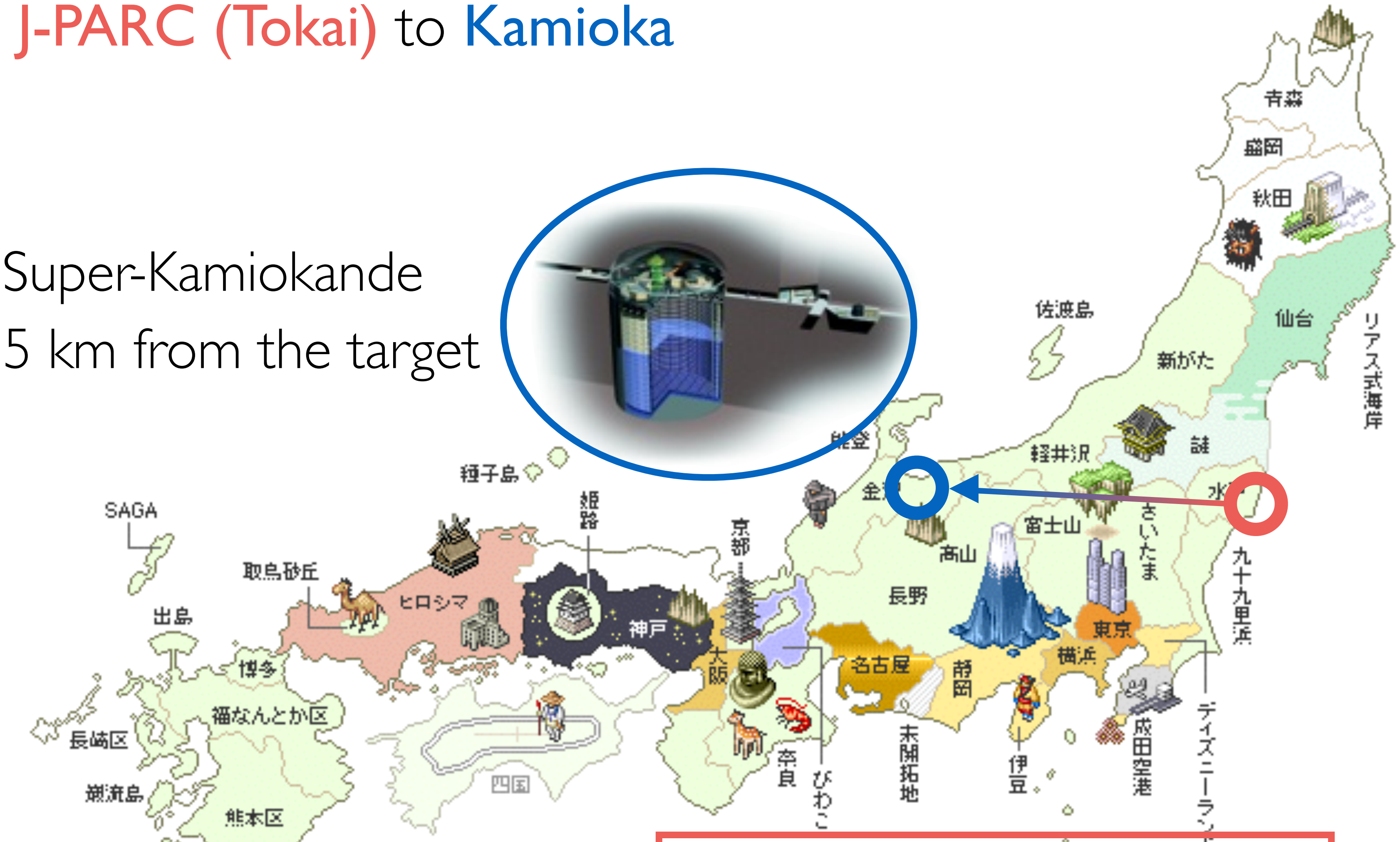
- The T2K experiment
- Generation of T2K flux tuned to hadroproduction data
- Flux uncertainties
- Prospects for the flux prediction

KEK-JAPAN

The T2K experiment

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

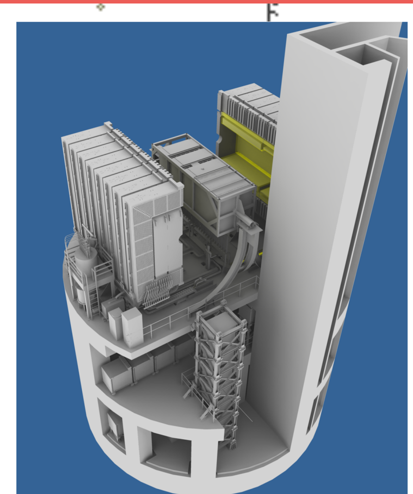
Super-Kamiokande
295 km from the target



T2K to-do list:

- Probe θ_{13} with $\nu_\mu \rightarrow \nu_e$
- Probe θ_{23} with $\nu_\mu \rightarrow \nu_\mu$
- Probe $\bar{\theta}_{13}$ with $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- Probe $\bar{\theta}_{23}$ with $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$
- Octant of θ_{23}
- Seek CP effect
- Various cross-section measurements

Neutrino source and near detectors at J-PARC



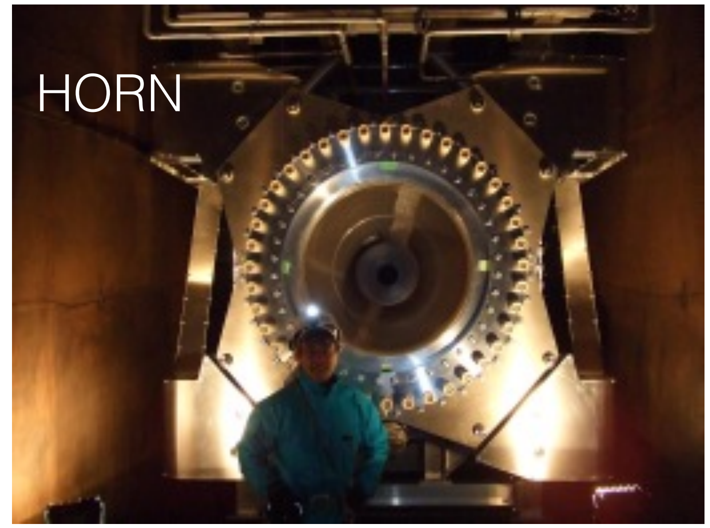
*NIM A**659**,106-135 (2011)*

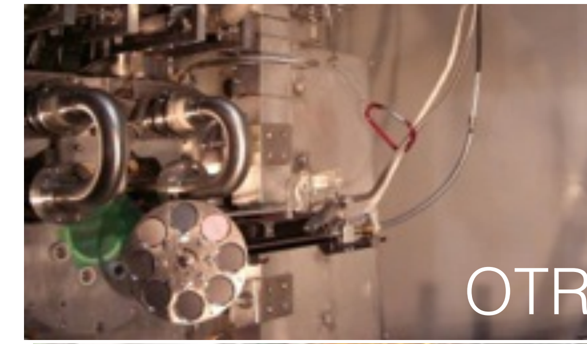
Generation of the flux

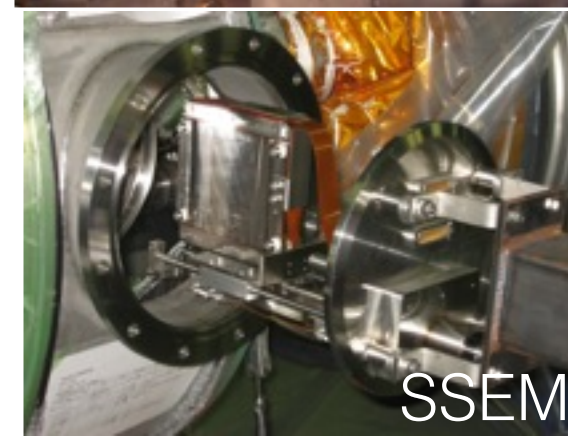
Beamline monitors measure the proton beam intensity, direction,…

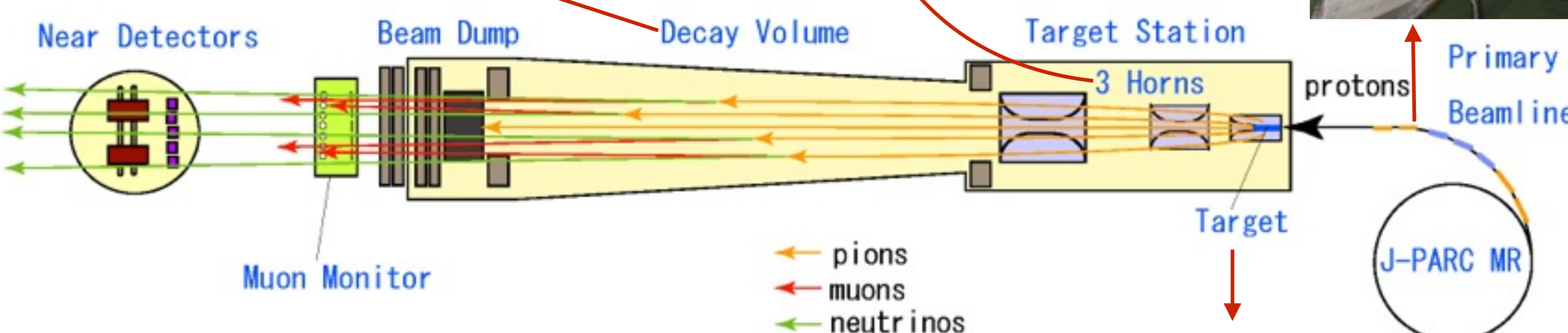
~96 m long

+250 kA → ν-enhanced flux
-250 kA → $\overline{\nu}$-enhanced flux









Graphite
90 cm long
2.6 cm diameter

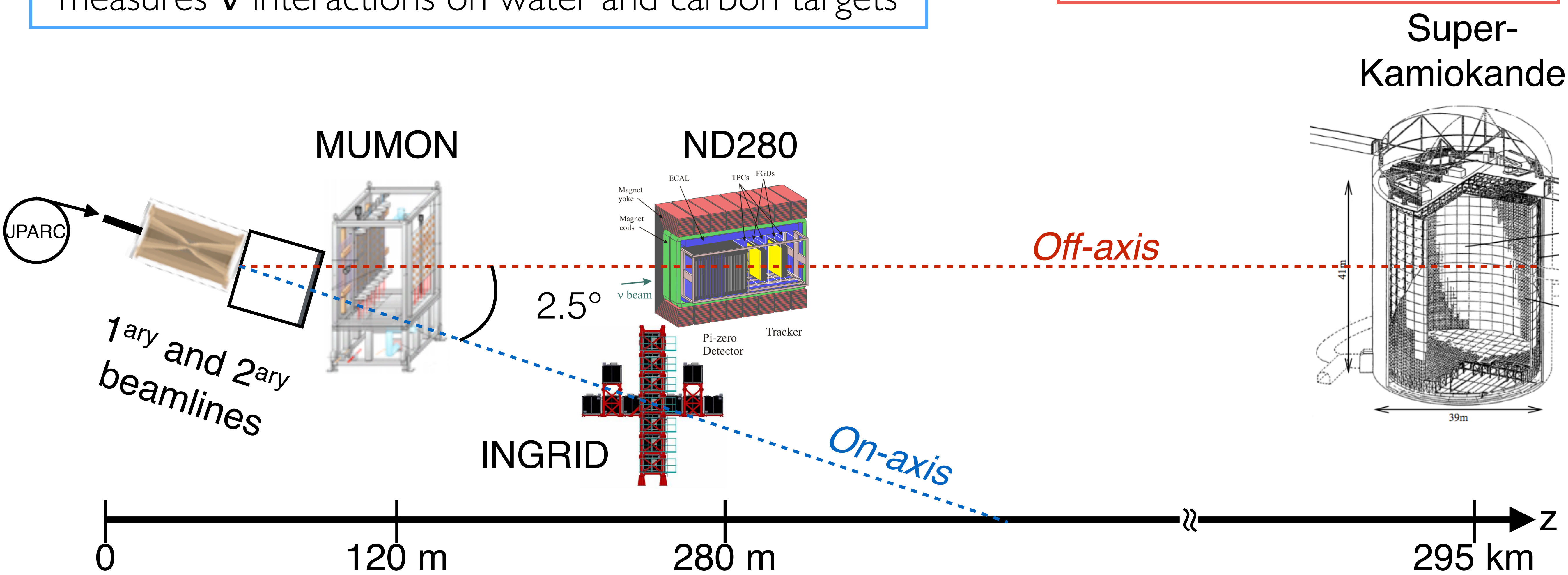
	Achieved	Goal, Design
Beam power	**371 kW**	750 kW
P.O.T. (total)	**11.04×10^{20}**	8×10^{21}
P.O.T. (ν)	7.00×10^{20}	
P.O.T. ($\overline{\nu}$)	4.04×10^{20}	
Horn current	$\pm$ 250 kA	$\pm$ 320 kA
Beam energy	30 GeV	

PRD 87 (2013) 012001

The T2K baseline

ND280 : constrains the spectrum before oscillations : measures ν interactions on water and carbon targets

SK : measures the spectrum after oscillations



MUMON : measures the muon flux after the beam dump

INGRID : monitors the stability of neutrino flux and direction Cross-section measurements are also performed

→ **Beam direction is stable within 1 mrad (ΔE = 2%)**

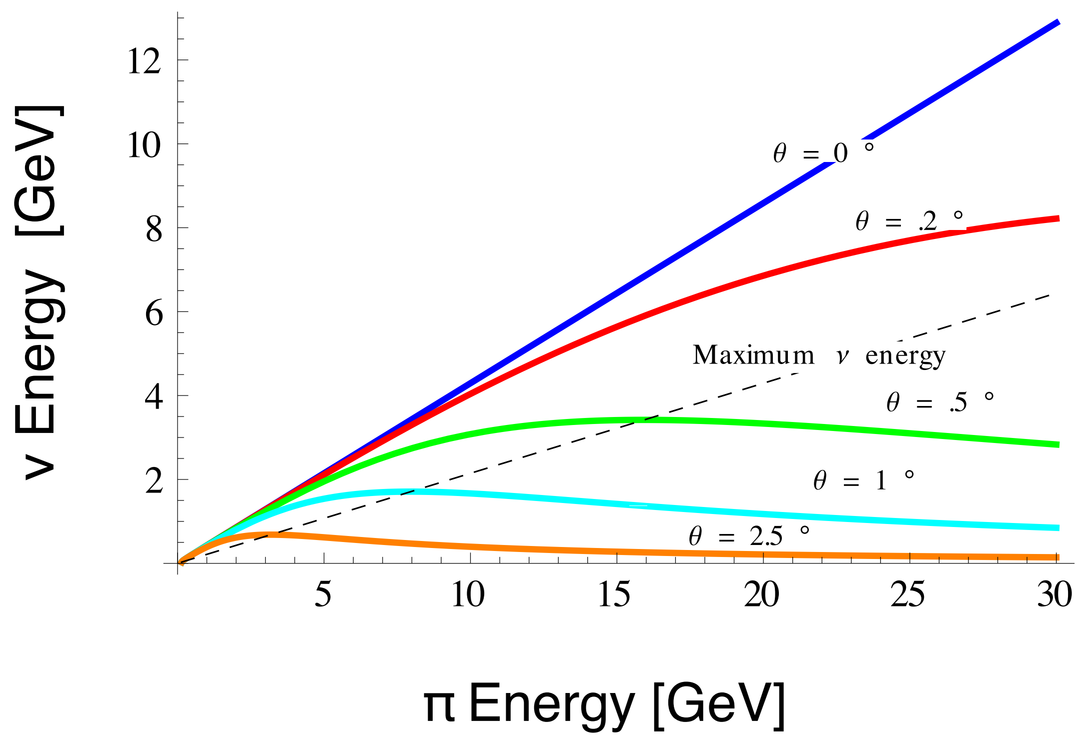
The Off-axis technique

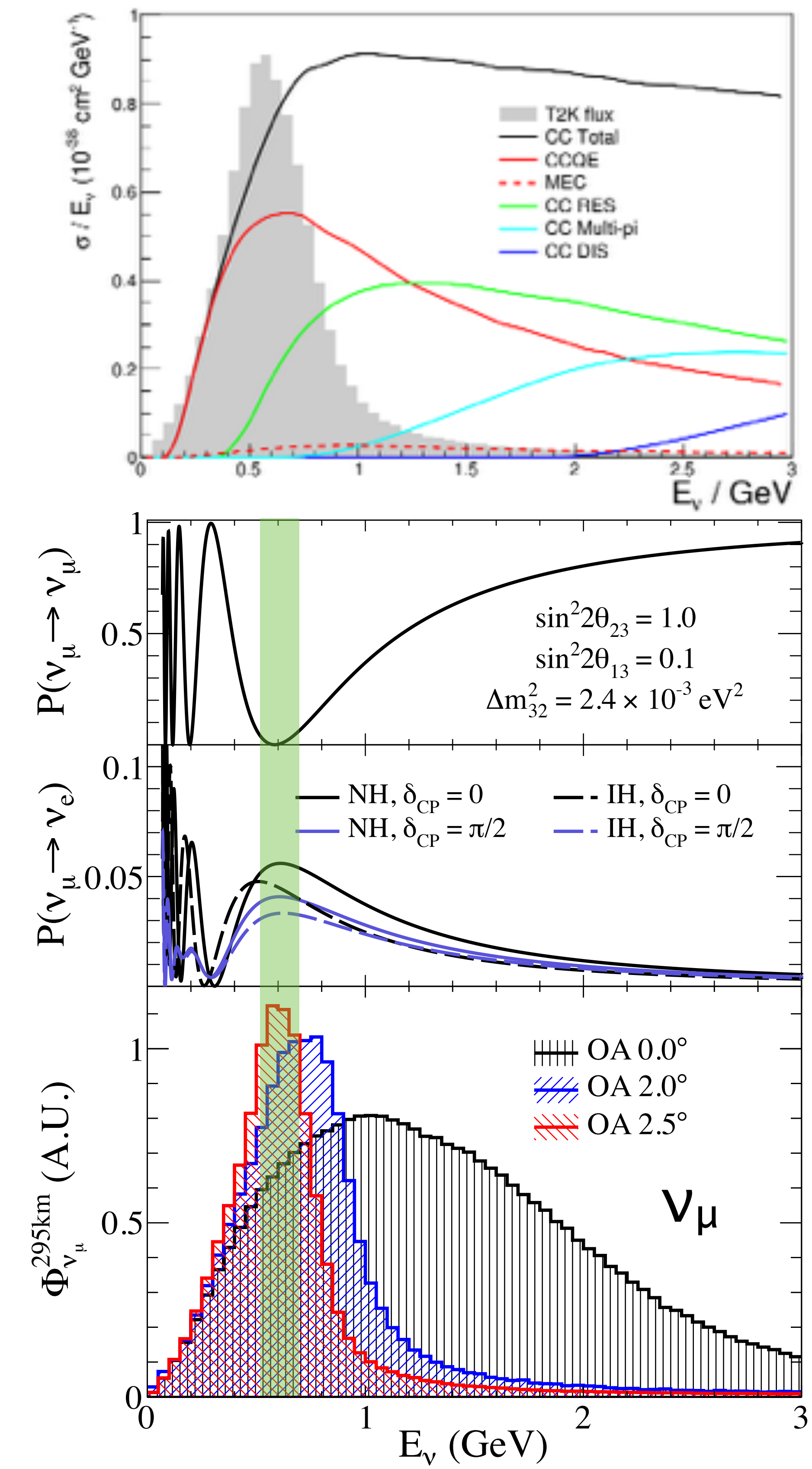
ND280 and Super-Kamiokande detectors are placed at a 2.5° angle off the target.

- Produces a narrow band neutrino beam at ~650 MeV, which maximize the $\nu_\mu \rightarrow \nu_e$ oscillation probability

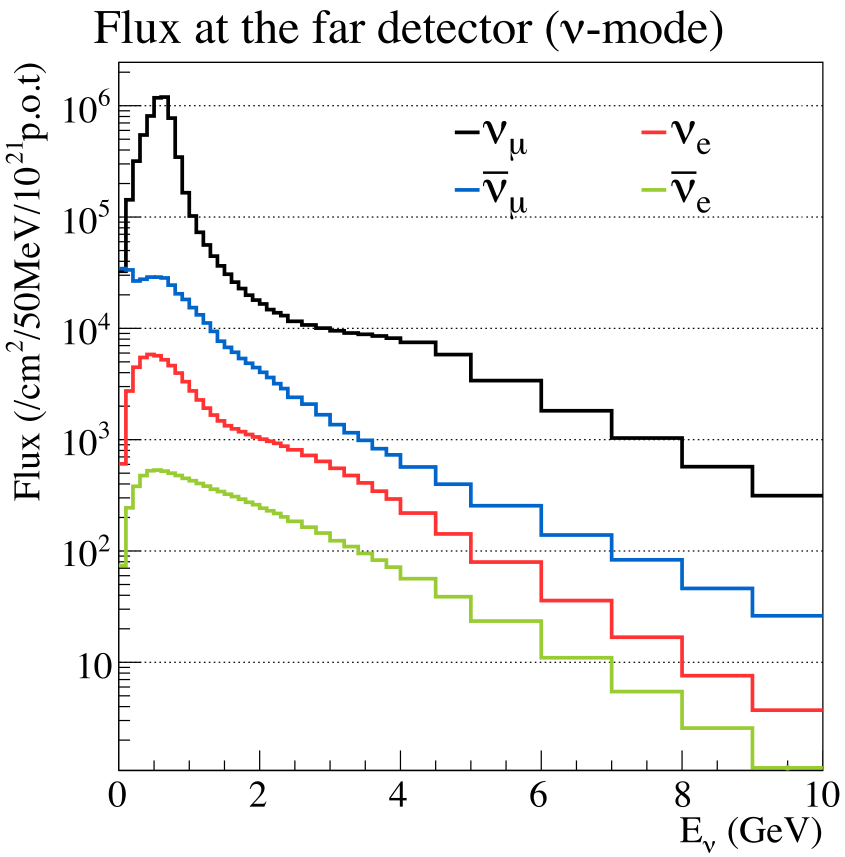
- As compared to the on-axis flux, the intensity is higher at the peak

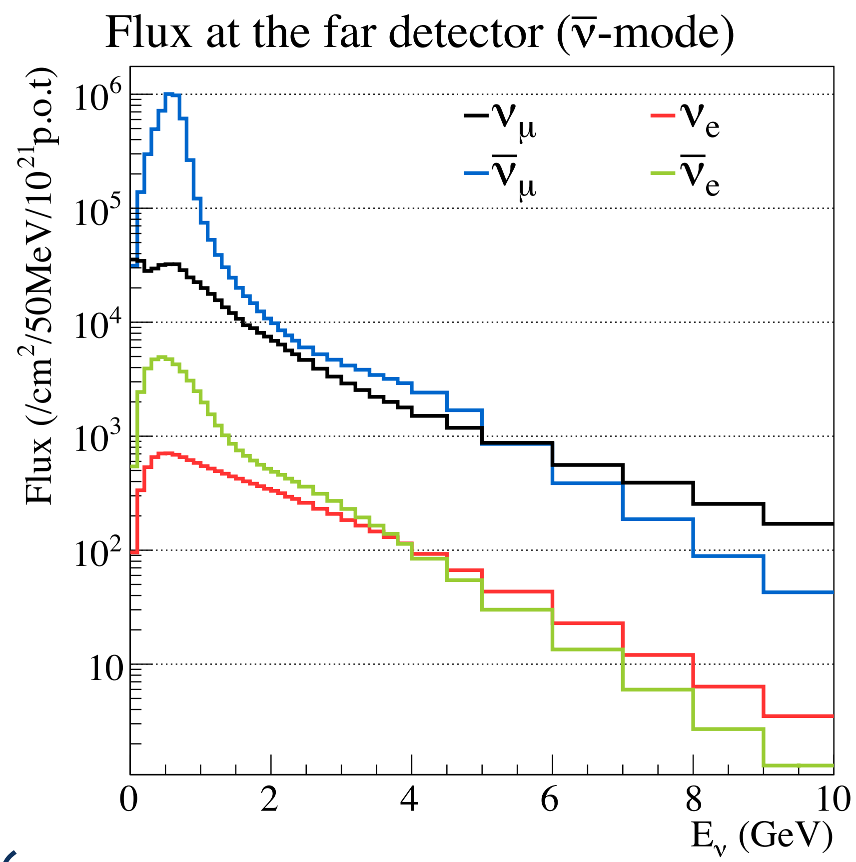
- Strongly suppress the high energy tail and favors neutrino interactions through the charged current quasi-elastic channel : $\nu_\mu + n \rightarrow p + \mu$





Parents of neutrinos





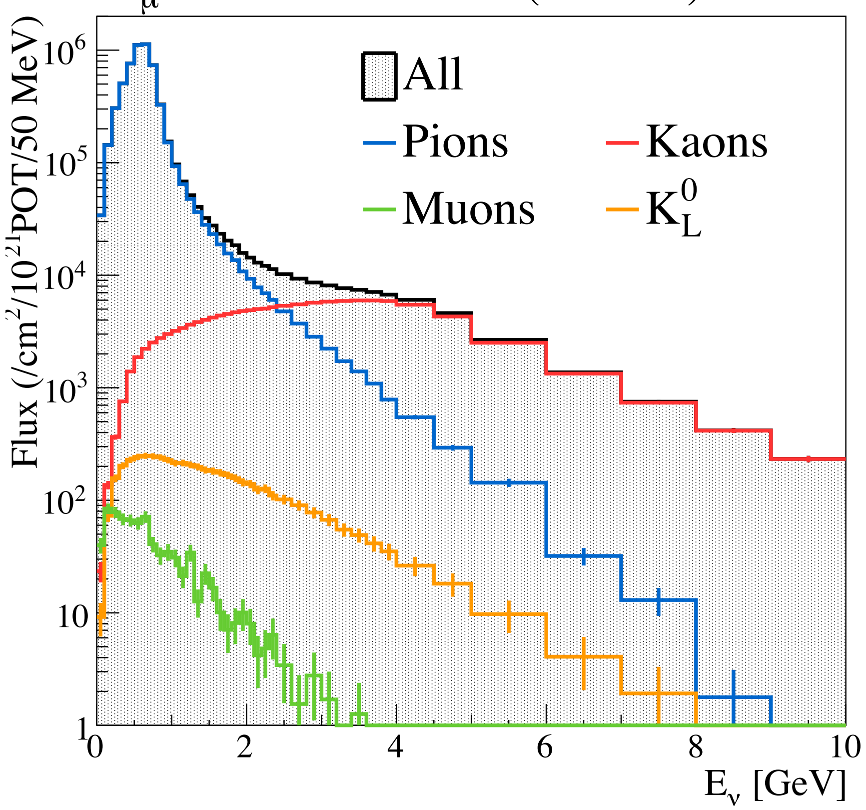
Not only pions are produced in the target.
Muons, charged and neutral kaons produce a background flux of electron neutrinos and « wrong-sign » neutrinos

- Electron neutrinos are a background for the appearance analysis
- As the far detector cannot distinguish the electric charge, wrong sign neutrinos are also a background
- Bigger contamination when running in anti-neutrino mode

channel			BR [%]
π	$\rightarrow$	$\mu\ \nu_\mu$	99.9
	$\rightarrow$	$e\ \nu_e$	10^{-4}
K	$\rightarrow$	$\mu\ \nu_\mu$	63.5
	$\rightarrow$	$\pi^0\ e\ \nu_e$	5.1
	$\rightarrow$	$\pi^0\ \mu\ \nu_\mu$	3.3
K^0_L	$\rightarrow$	$\pi\ e\ \nu_e$	40.5
	$\rightarrow$	$\pi\ \mu\ \nu_\mu$	27.0
μ	$\rightarrow$	$e\ \nu_e\ \nu_\mu$	100

The need for a hadroproduction measurement

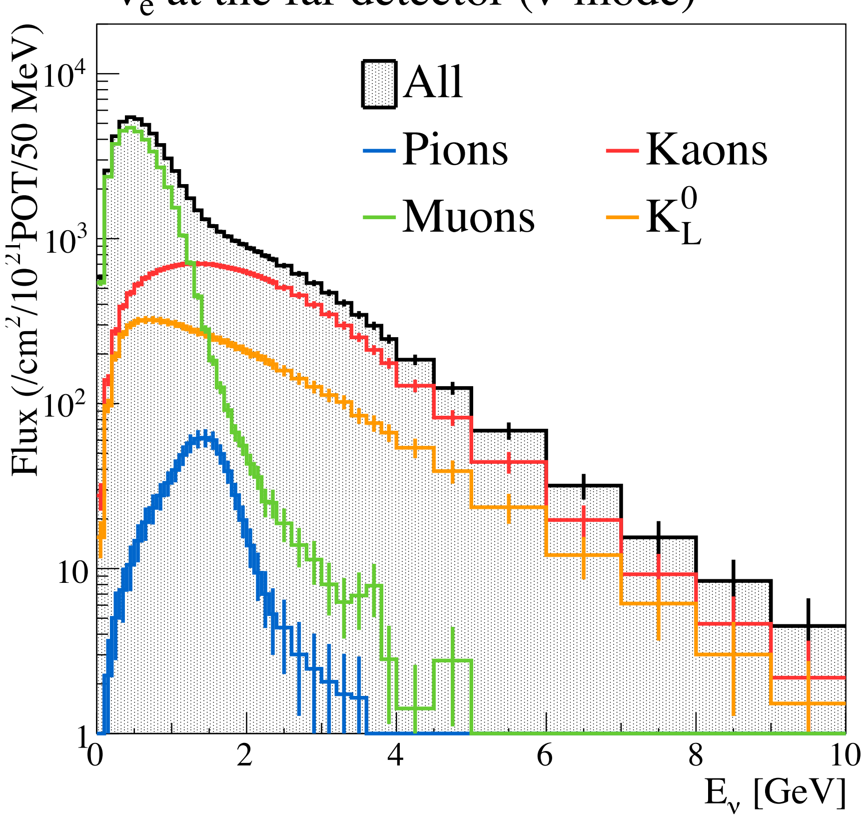
ν_μ at the far detector (ν-mode)



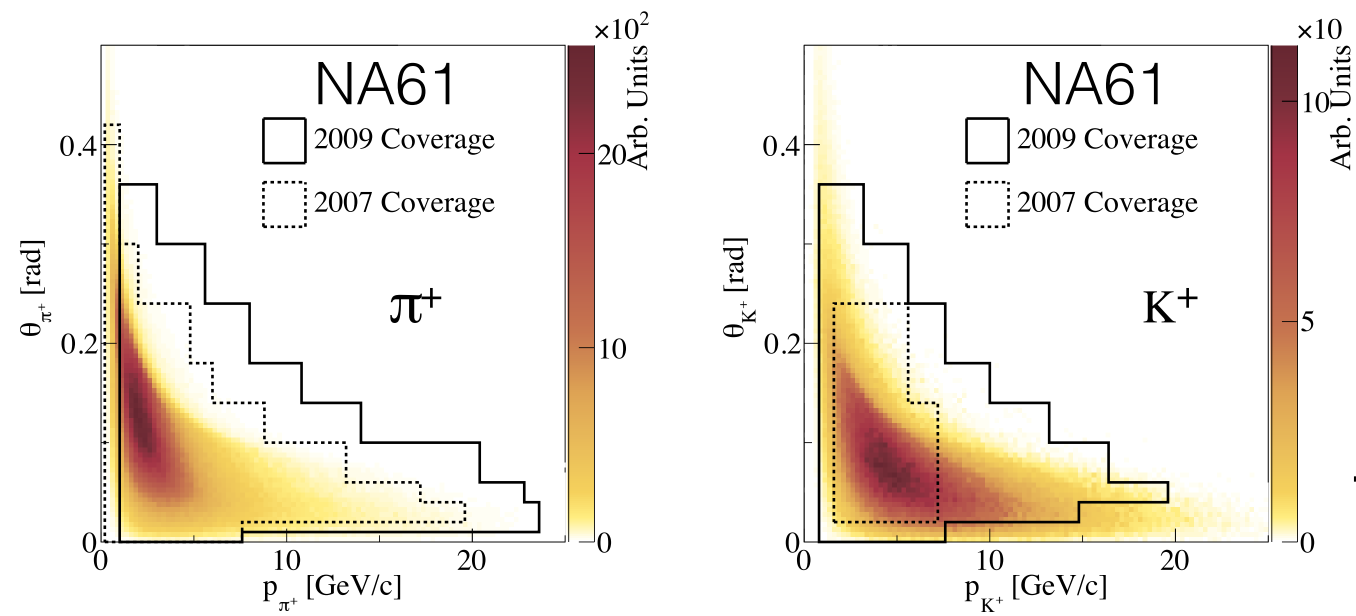
In order to predict the neutrino flux, one needs :

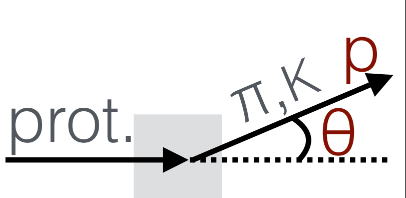
- An accurate description of the secondary beamline geometry in a Monte Carlo
  - ➞ We use Fluka and Geant3
- To reproduce the proton beam profile impinging the target
  - ➞ Beamline monitors data is parametrized
- A good knowledge of hadrons produced in p+C interactions
  - ➞ External experiment reproduces the T2K beam target conditions and measures the produced hadrons : NA61/SHINE at CERN

ν_e at the far detector (ν-mode)



{p,θ} of π^+ and K^+ producing ν at the far detector (ν-mode)



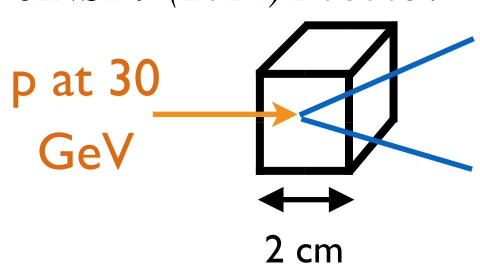


NA61/SHINE data for T2K

[1]: *PRC 84 (2011) 034604*, [2]: *PRC 85 (2012) 035210*,
[3]: *PRC 89 (2014) 025205*, [4]: *arXiv:1510.02703*
[5]: *NIM A701 (2013) 99-114*,
[6]: *A. Haesler's PHD (Geneva Uni., 2015)*.

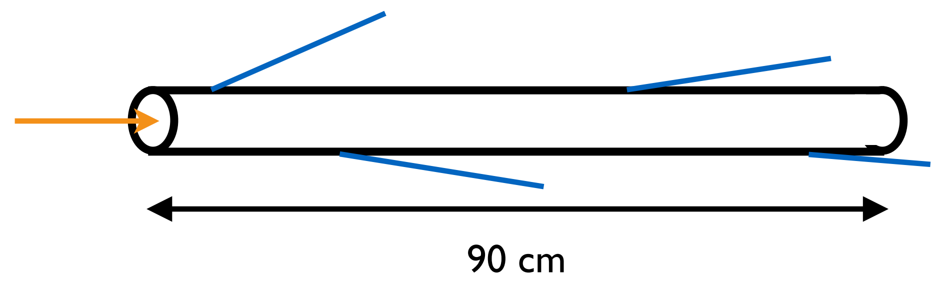
NA61/SHINE provides 2 types of datasets for T2K :

JINST 9 (2014) P06005.



thin target :

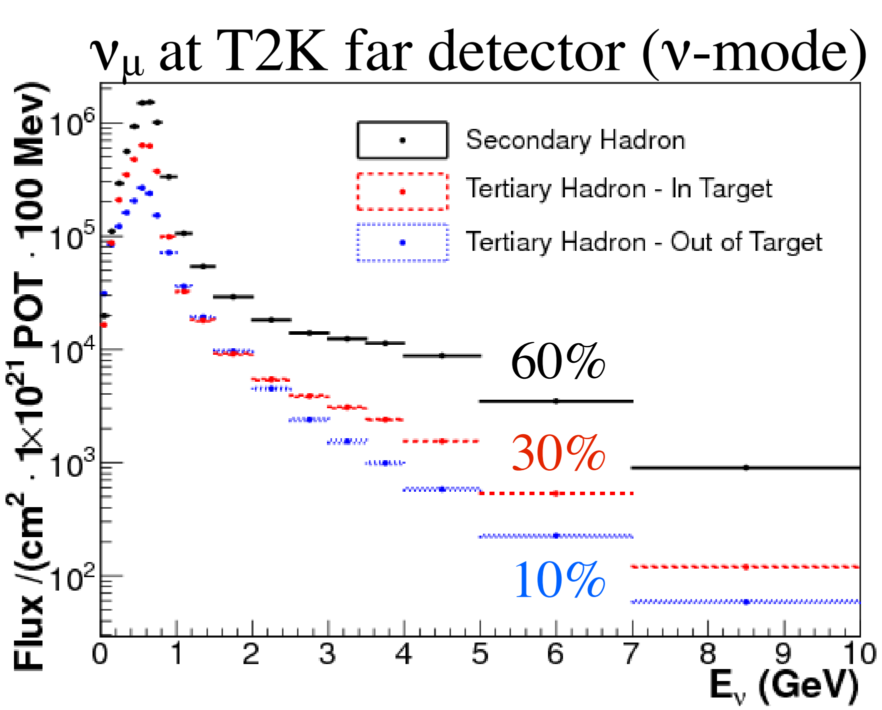
study the primary p+C interaction

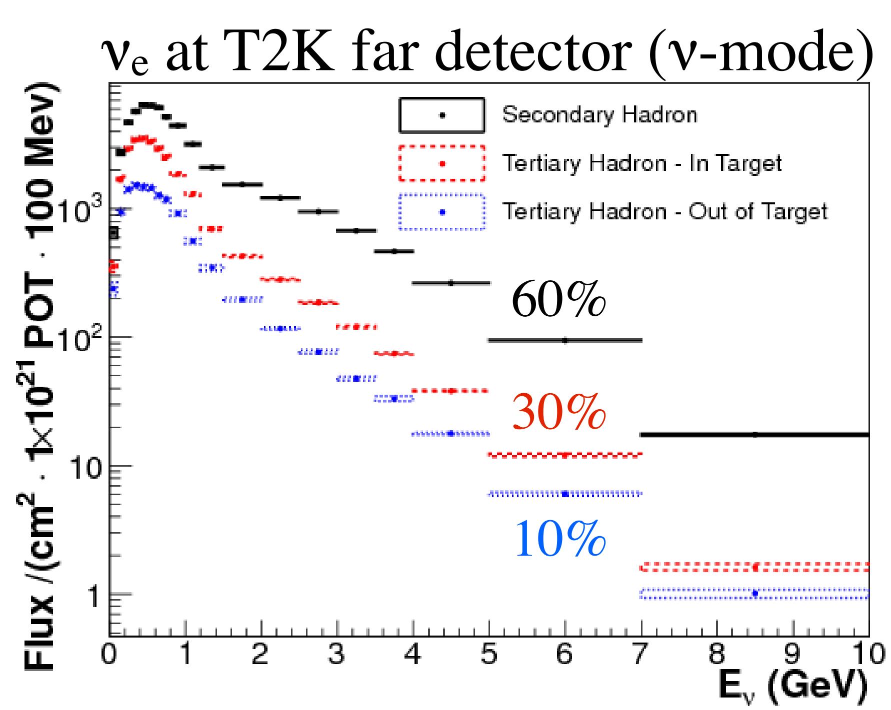


replica target :

accounts for the re-interactions in the target

Target	Year	Stat ($\times 10^6$)	NA61 status	T2K status
Thin	2007	0.7	published : $\pi^{\pm}$[1], K^{+}[2], K^0_S, Λ [3]	is used (prev. tuning)
	2009	5.4	submitted : $\pi^{\pm}$, $K^{\pm}$, p, K^0_S, Λ [4]	is used **(new tuning)**
Replica	2007	0.2	published : $\pi^{\pm}$ [5]	method developed
	2009	2.8	preliminary : $\pi^{\pm}$ [6]	work ongoing
	2010	$\sim$10	analysis started	-





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

NA61/SHINE thin target results

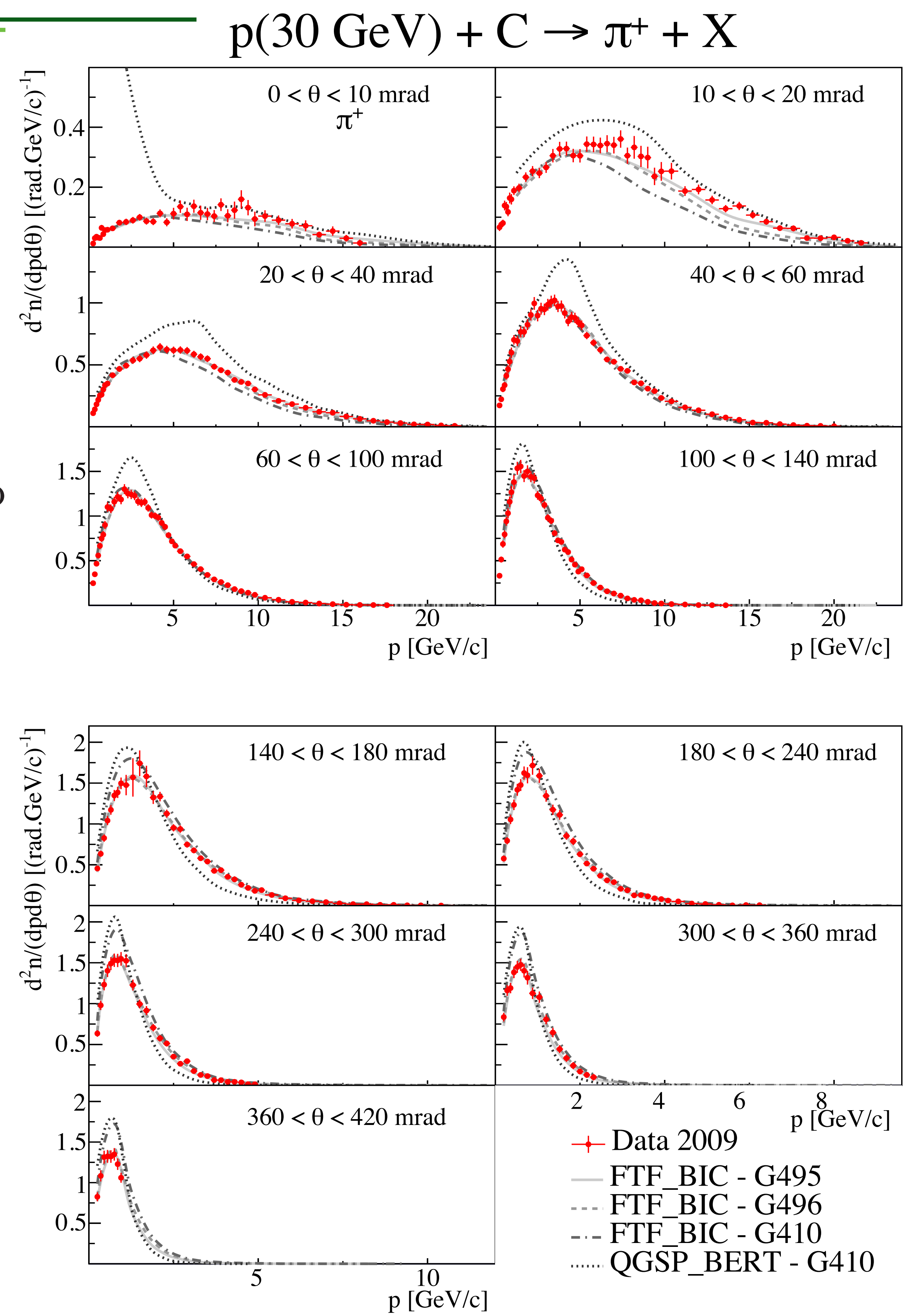
2009 NA61/SHINE data provides :

- the proton (30 GeV) carbon production cross section :

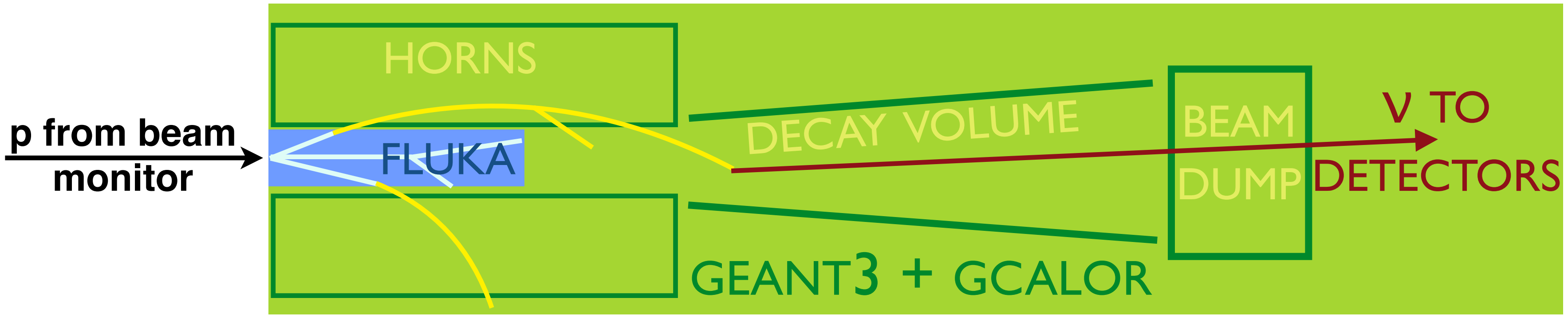
$$\sigma_{prod} = 230.7 \pm 2.7 \text{ (stat.) } \pm 1.2 \text{ (detector) } {}^{+6.3}_{-3.4} \text{ (model) mb}$$

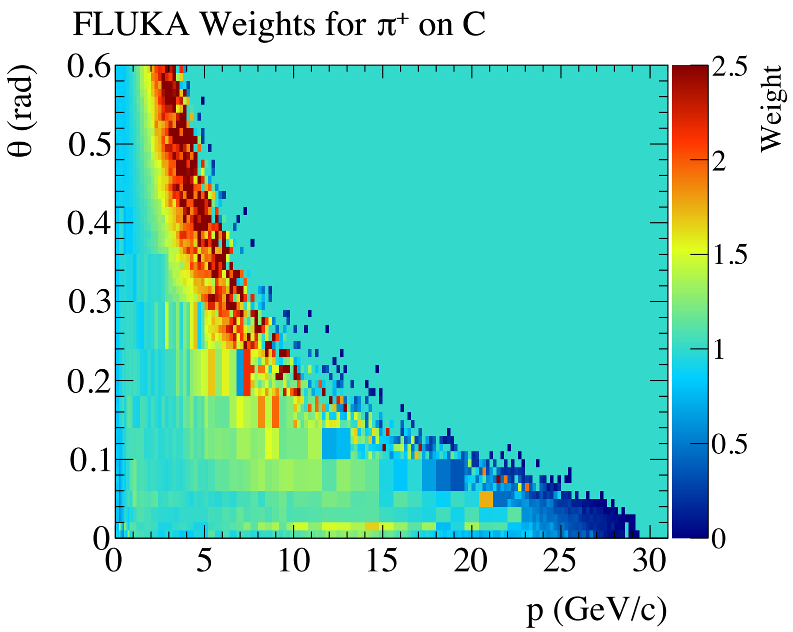
- the double differential multiplicity of $\pi^{\pm}$, $K^{\pm}$, K^0s, Λ and protons production (in bins of momentum and polar angle)

→ See A. Bravar's talk later today



T2K flux predictions with NA61 - multiplicities

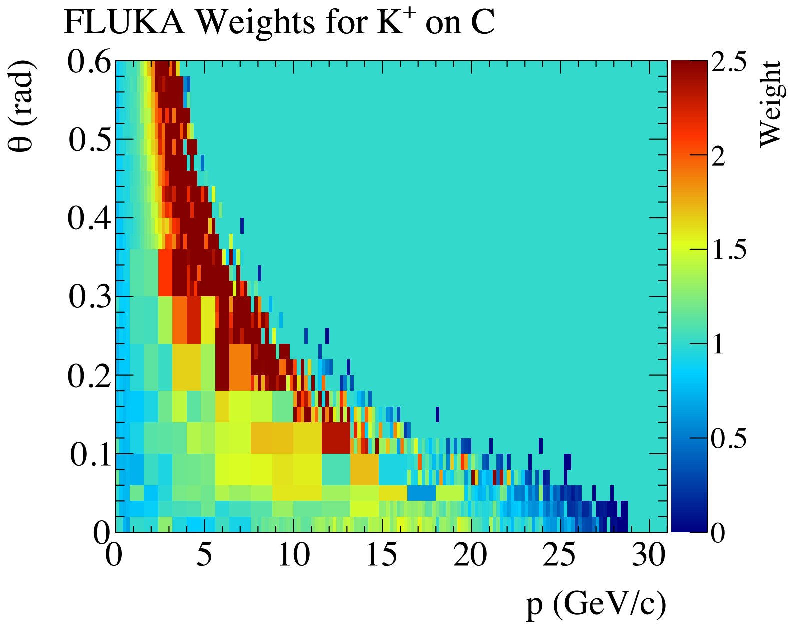


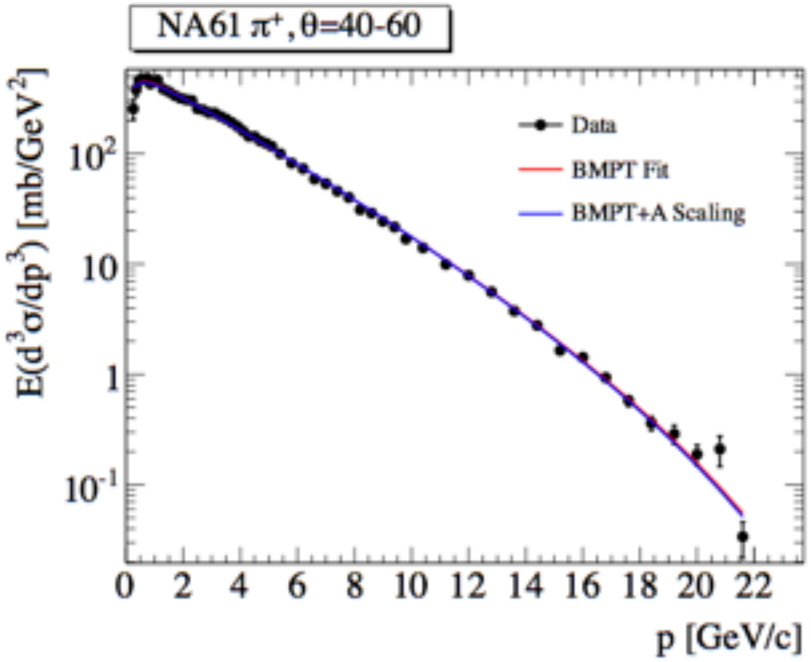


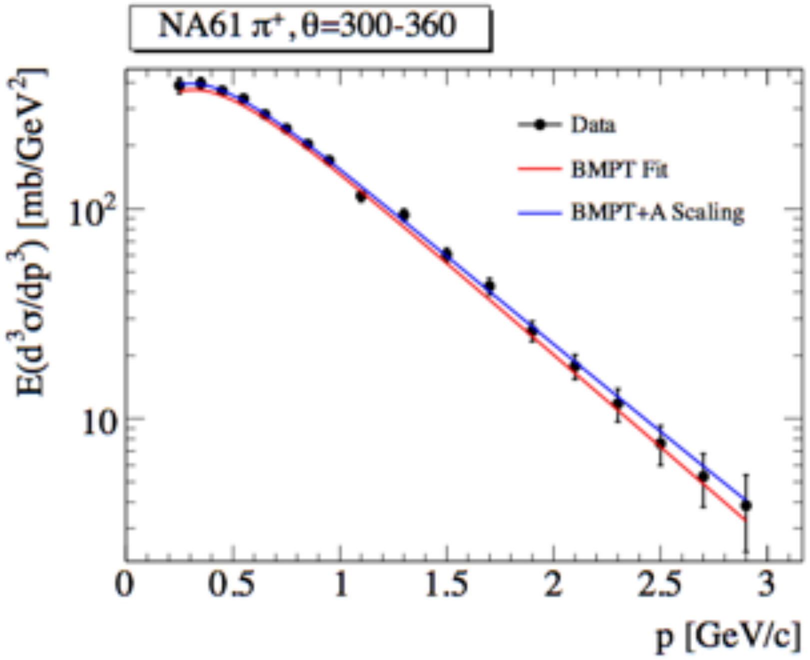
For each neutrino produced, we re-weight most of the inelastic interactions leading to its production to external data :

$$W = \frac{\left(\frac{d^2 n}{dp d\theta}\right)_{data}}{\left(\frac{d^2 n}{dp d\theta}\right)_{MC}}$$

Where MC stands for
Fluka if the interaction is in the target
GCALOR if it's in the 2ary beamline



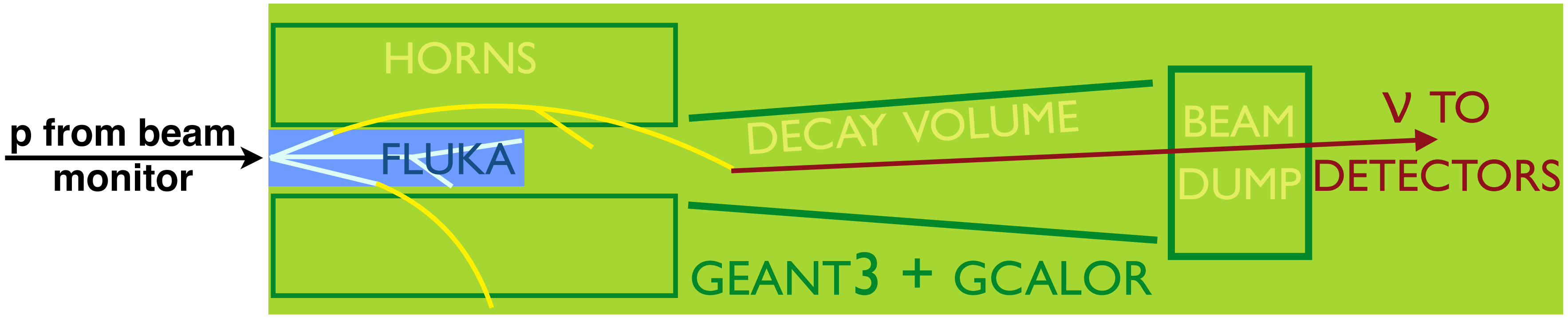


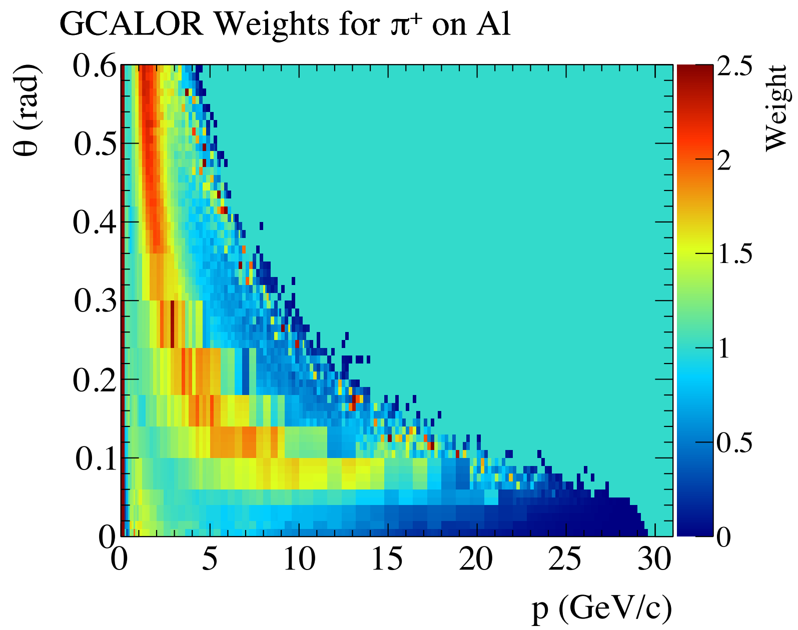


NA61 data are fitted with the BMPT parametrization to extend the {p, θ} coverage

M. Bonesini, et al, EPJ. C20 (2001) 13–27

T2K flux predictions with NA61 - scalings





We scale NA61 data to be able to re-weight re-interactions :

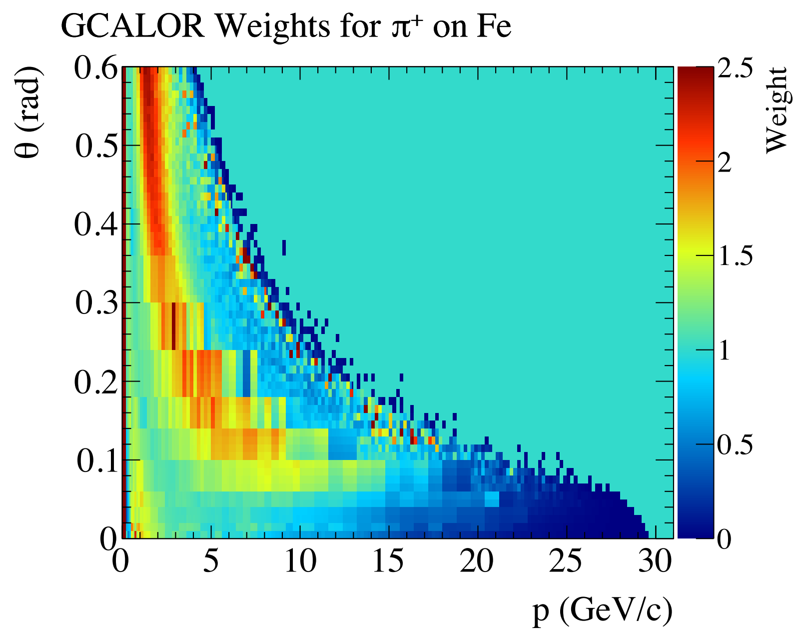
- Rescale NA61 data in target for interactions in the beamline
Eg : p[31 GeV/c] + Al→ π/K/p + X

We consider interactions on C, Al, Ti, Fe

The target scaling uses a parametrization with

$$\frac{d^2\sigma}{dpd\theta}(A_1) = \left[\frac{A_1}{A_0}\right]^{\alpha(x_F,p_T)} \frac{d^2\sigma}{dpd\theta}(A_0)$$

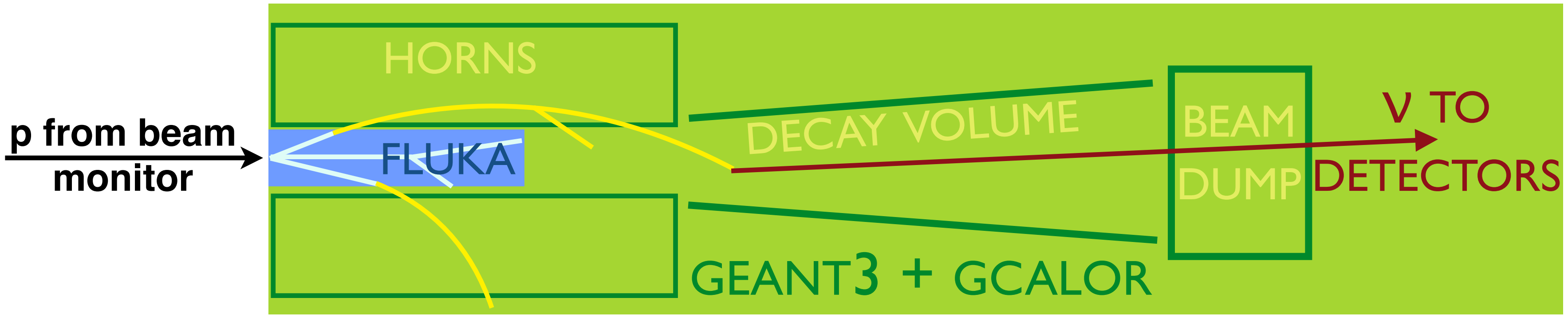
Where the parameters of the α function are fitted to data

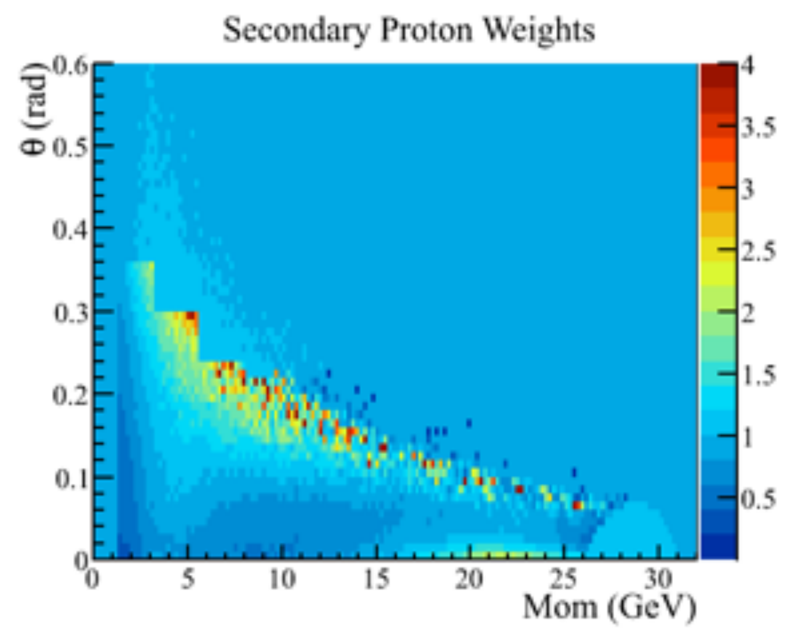


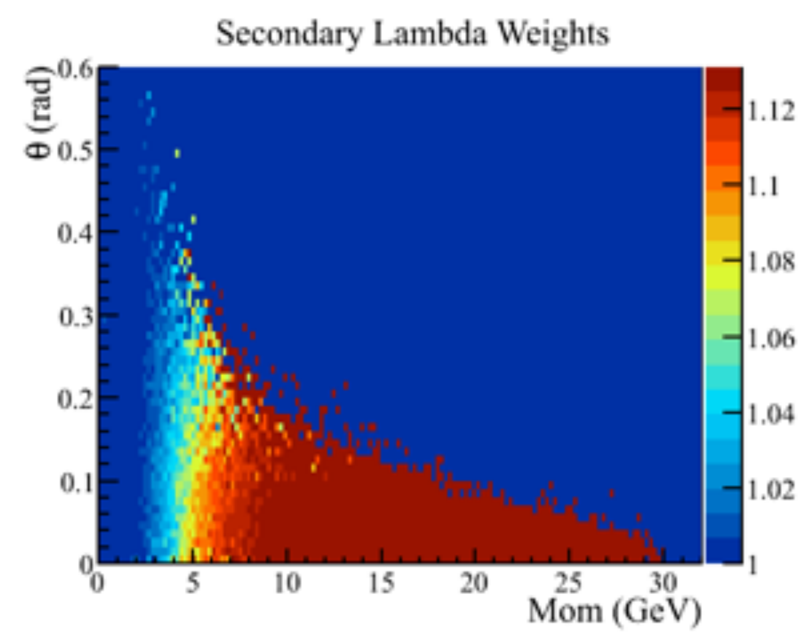
- Rescale NA61 data in center of mass:
Eg : p[20 GeV/c] + C → π/K/p + X

The scaling in center of mass uses the Feynman-scaling hypothesis (the invariant cross section is constant when expressed in terms of x_F and p_T).

T2K flux predictions with NA61 - secondary nucleons





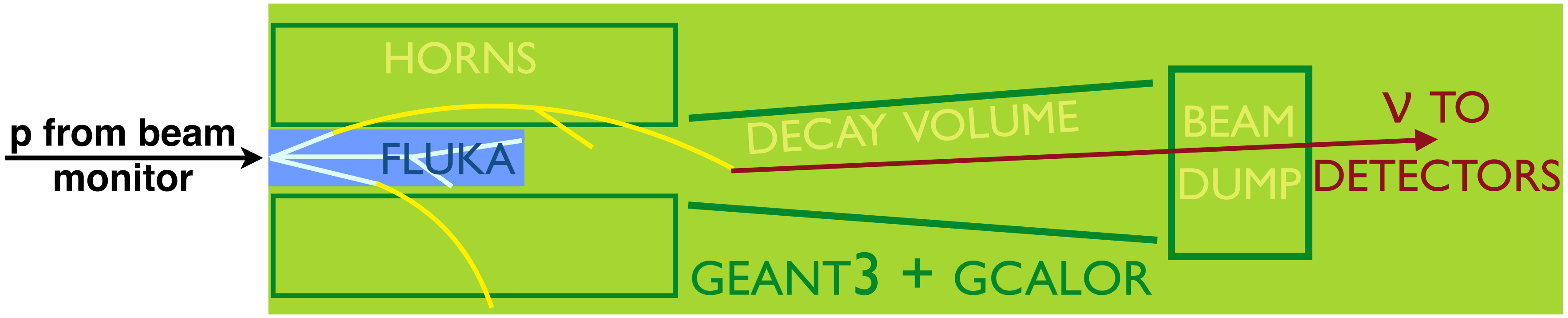


p+C→p/n/Λ/Σ + X is also re-weighted

Now, we use only proton production data from NA61 and Allaby [p+Be at 19.2 GeV → p + X]

Using the baryon number conservation constraint, the weights for n, Λ and Σ are computed from large MC statistics :
the leading baryon is re-weighted to data, the other ones are compensated to holds the baryon conservation.

T2K flux predictions with NA61 - cross sections

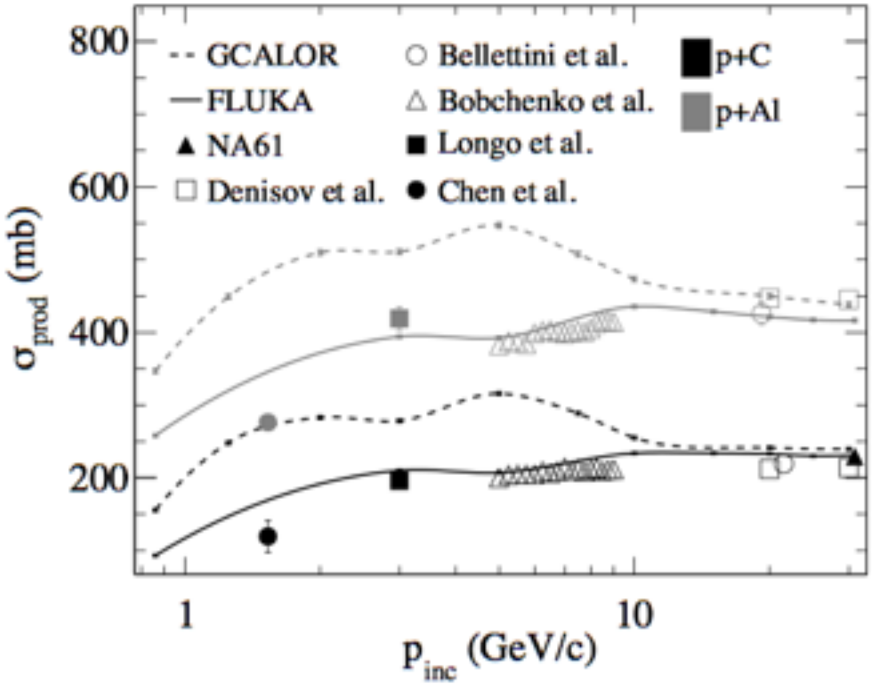


We also re-weight the production cross-section for each interaction as follows:

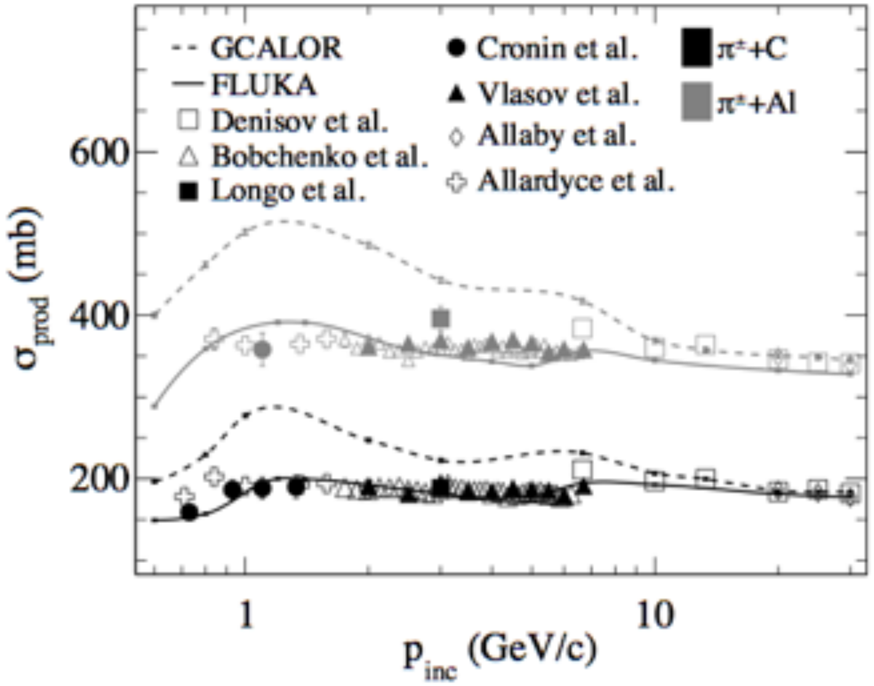
$$W = \frac{\sigma_{data}}{\sigma_{MC}} \times \exp(-\rho d[\sigma_{data} - \sigma_{MC}])$$

MC : Fluka, GCALOR
ρ is the material density
d is the length of crossed material

proton interactions

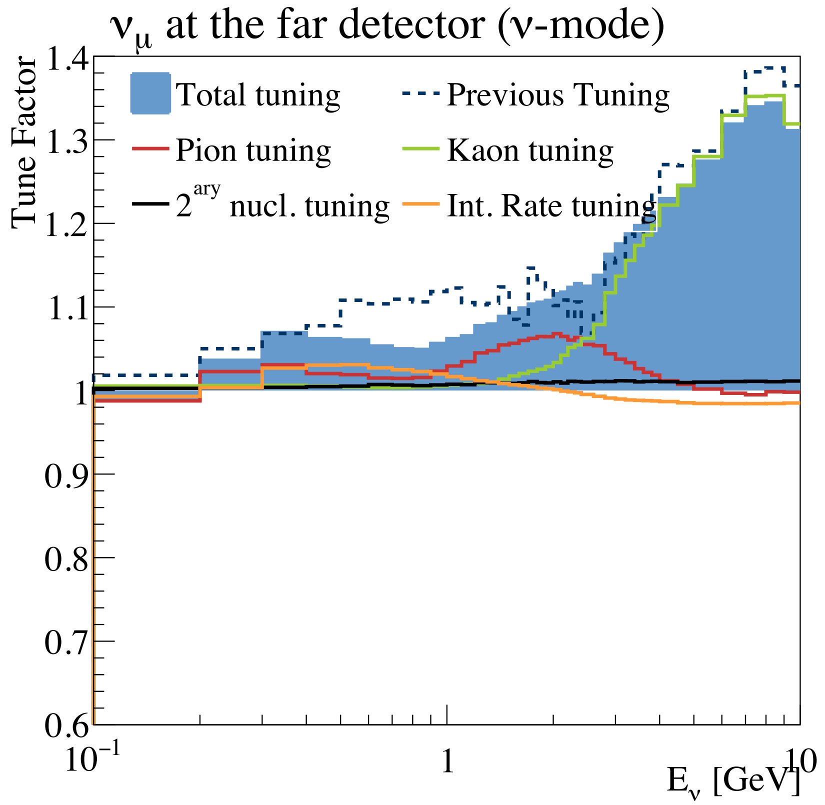


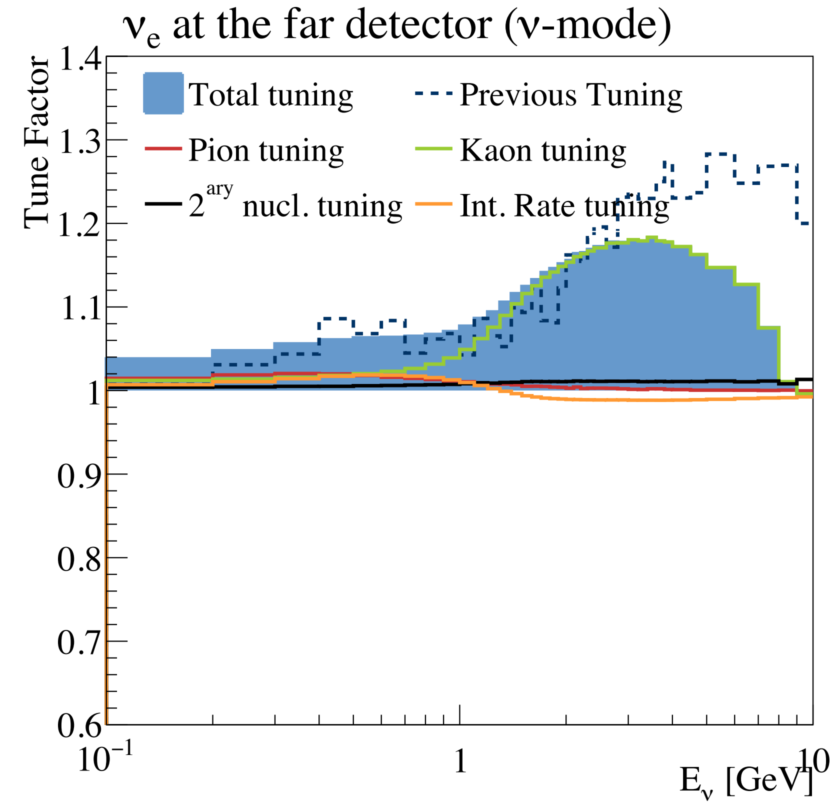
pion interactions

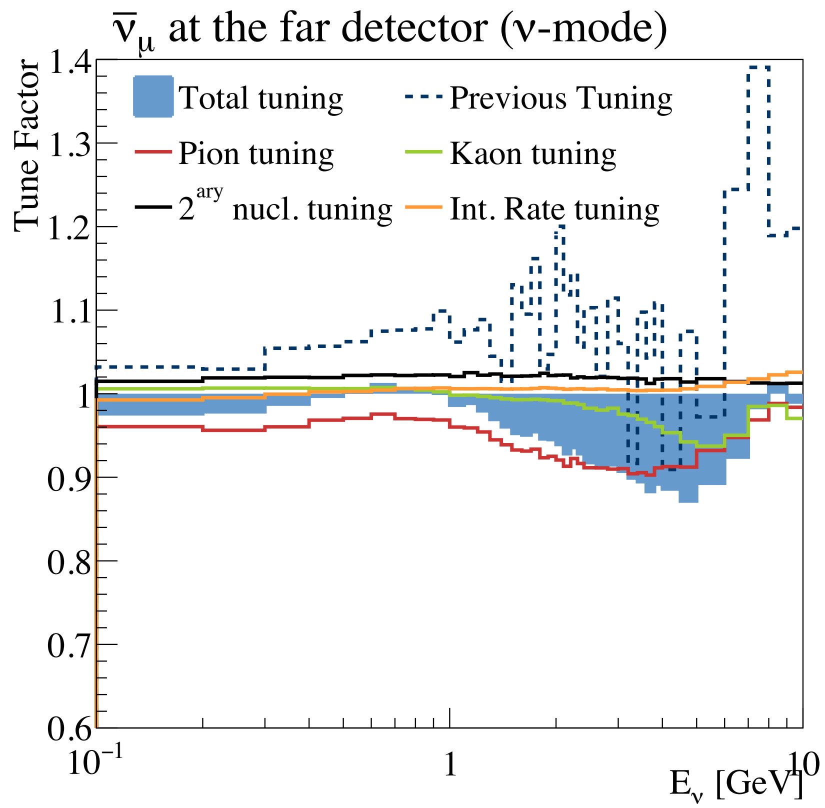


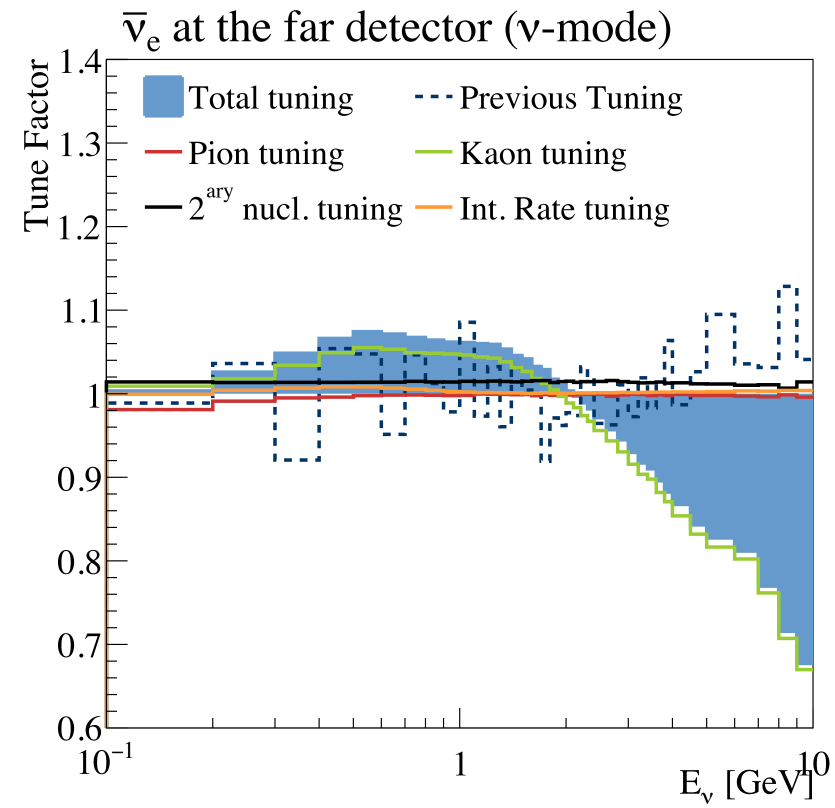
For the time being, Fluka production cross-sections are not tuned to data, only re-interactions in the beamline are tuned (handled by GCALOR).

Results : tuning factor









Uncertainties

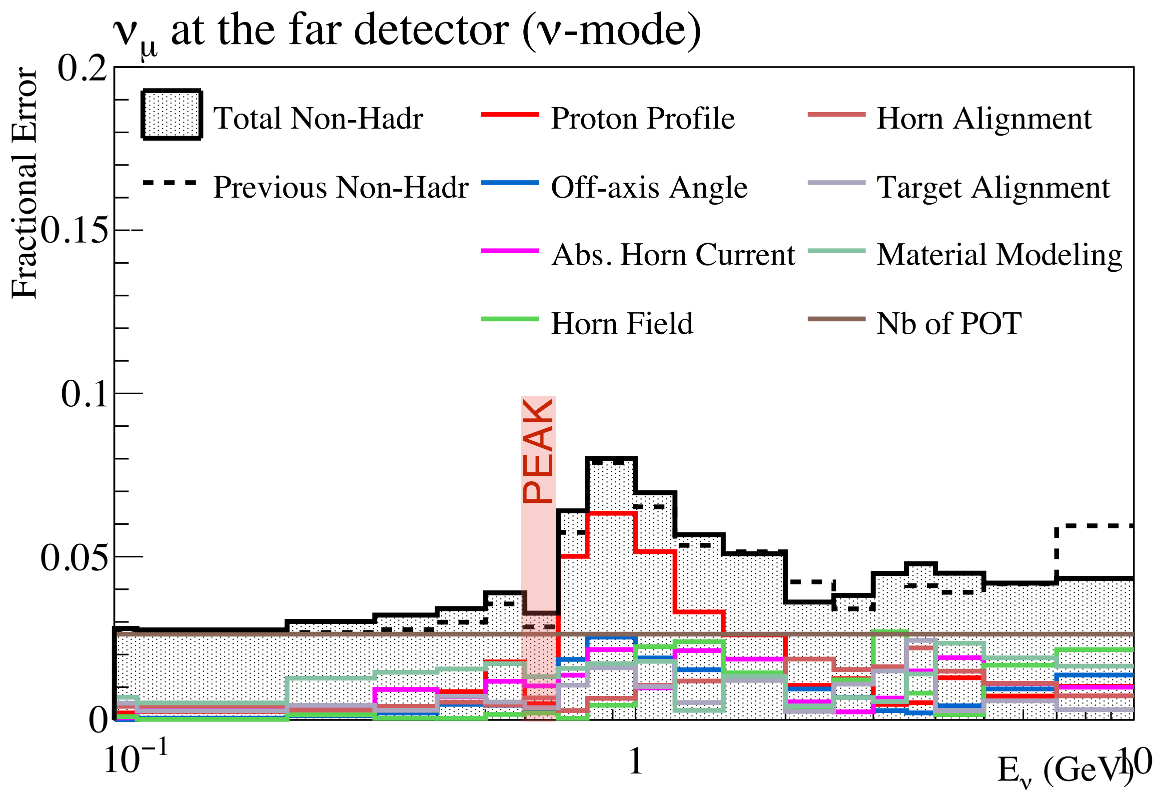
Uncertainty evaluated:

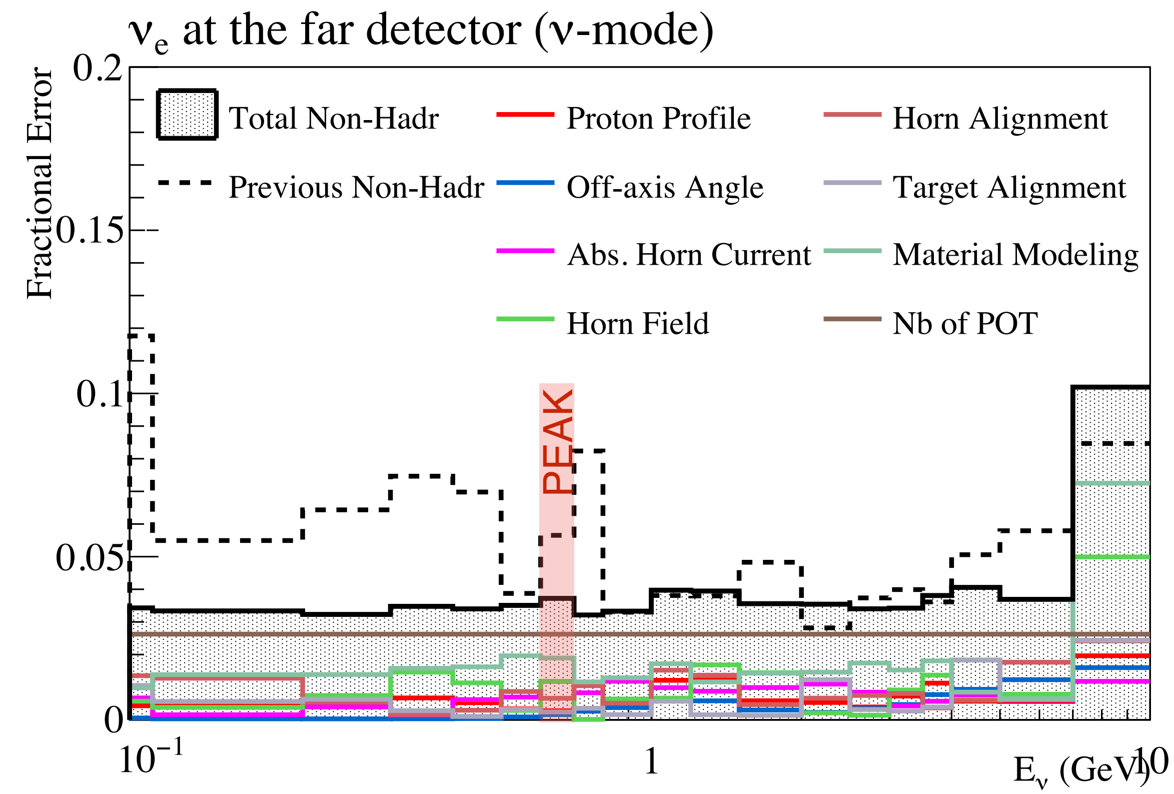
Non-Hadronic part :
- Horn current
- Target and horn alignment
- Off-axis angle
- Proton beam parameters
- Horn field asymmetry
- Material simulation
- Proton On Target (POT)

Hadronic-part :
- Meson multiplicity
- Pion re-scattering
- Secondary nucleon production
- Interaction length

→Previous tuning and error estimate used the NA61 2007 thin target data only

Uncertainties - non hadronic

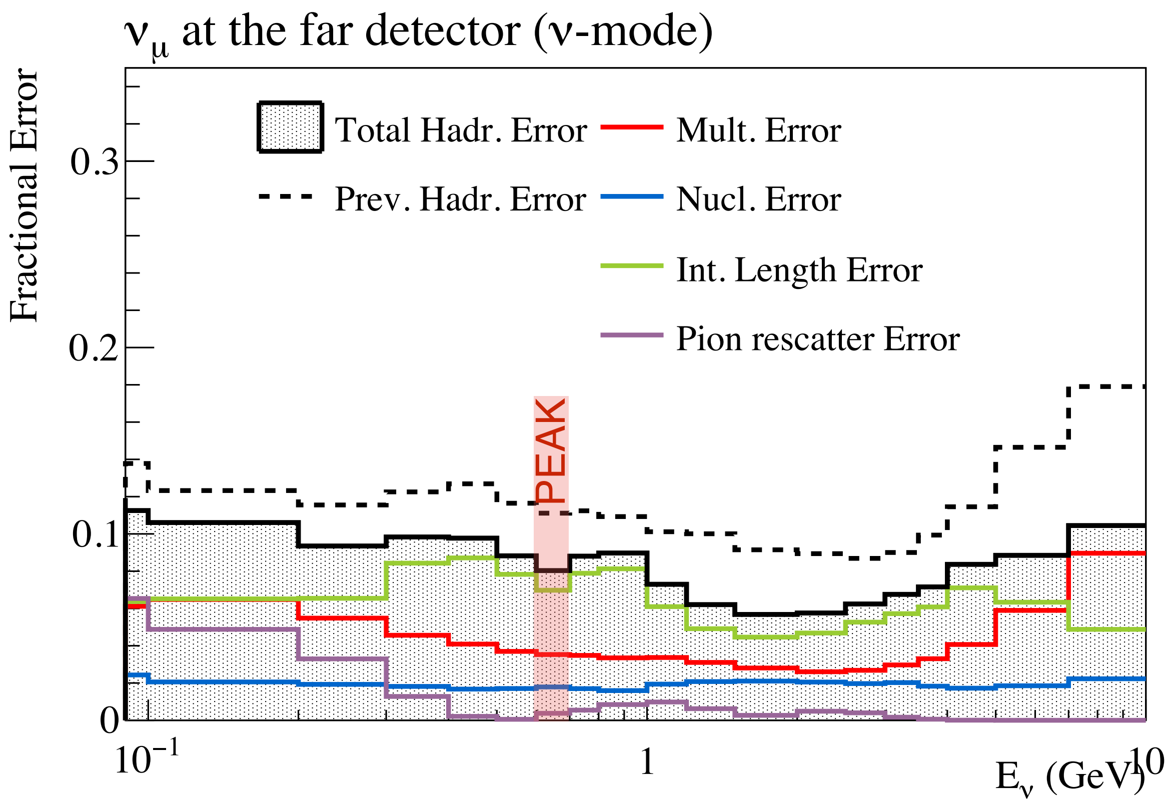


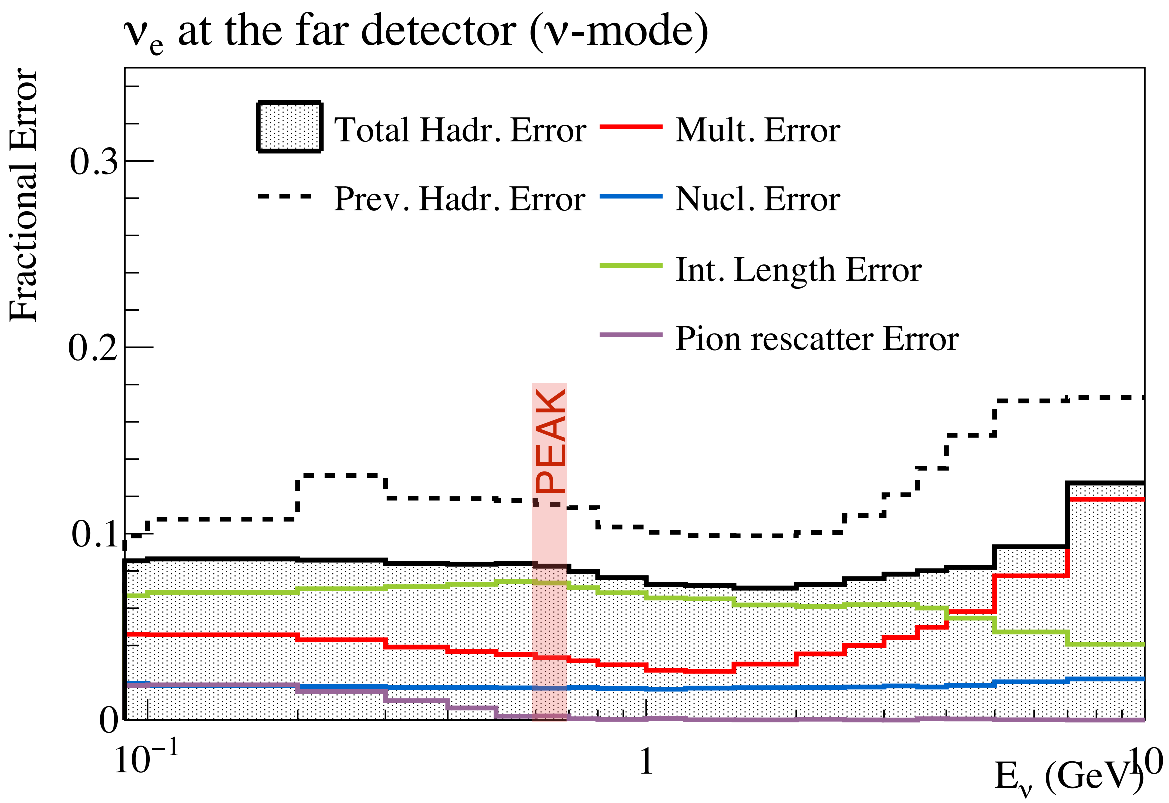


All sources have been re-estimated.

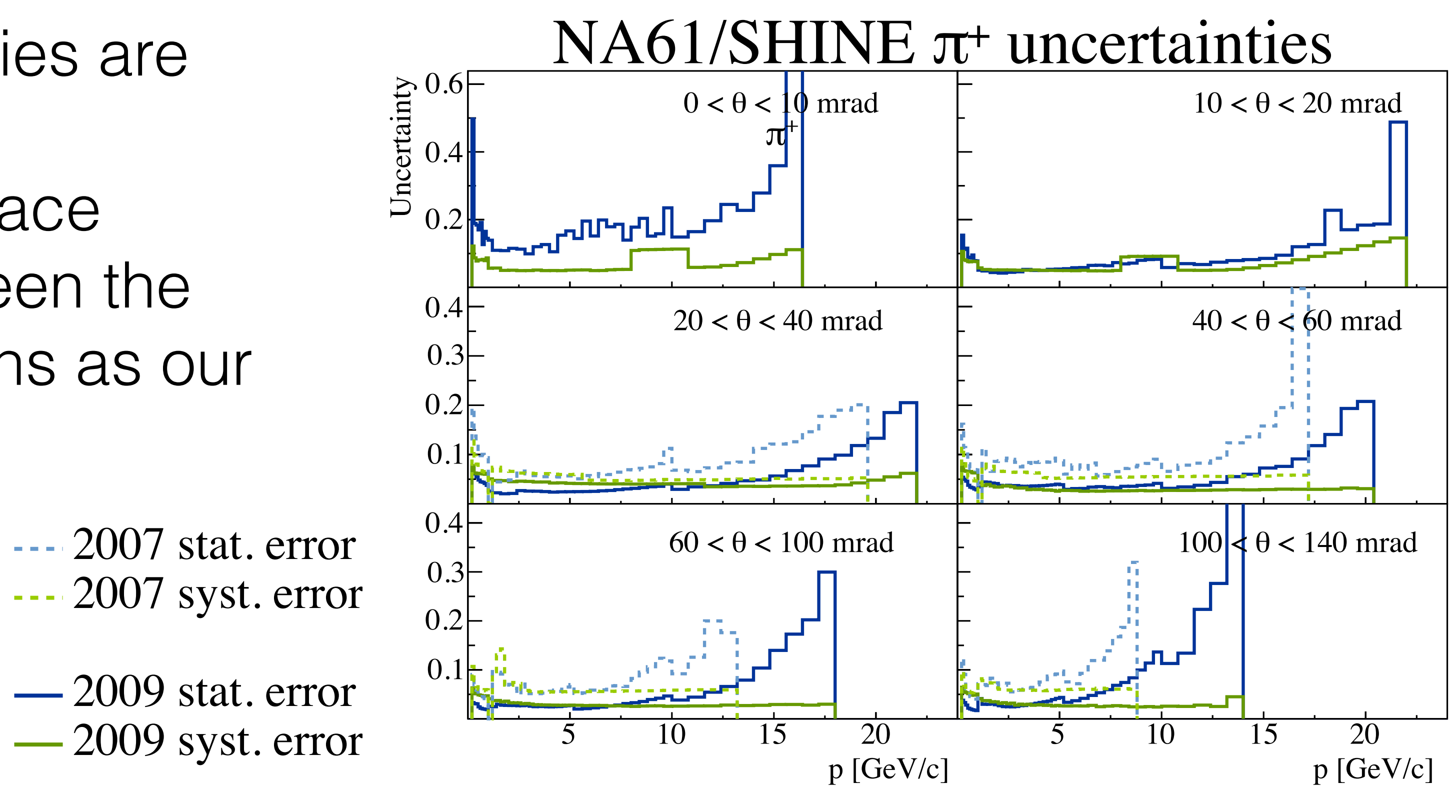
The proton beam profile affects the off peak region. We are investigating on ways to reduce it (mostly driven by fit uncertainties)
On-going analysis aims at reducing the error on the number of proton on target (only affect cross-section analysis though)
The error reduction on the ν_e is mostly due to greater Monte Carlo statistics

Uncertainties - hadronic - multiplicity & cross section

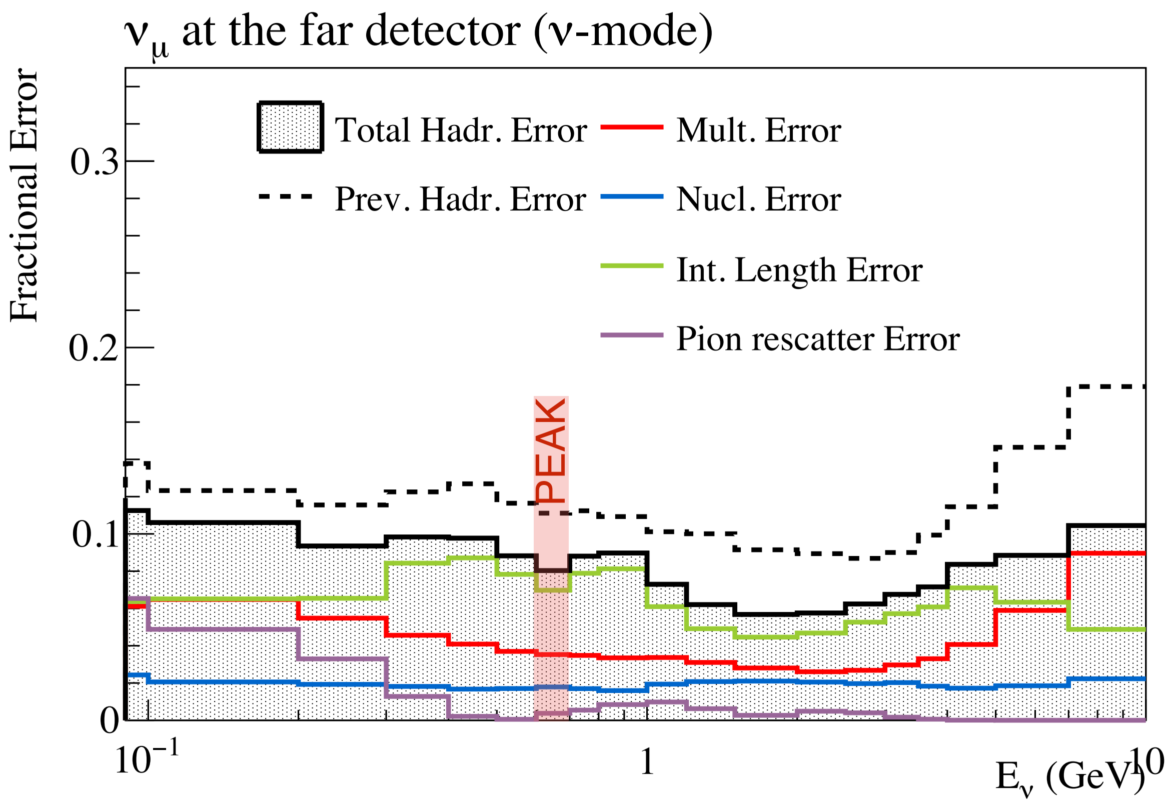


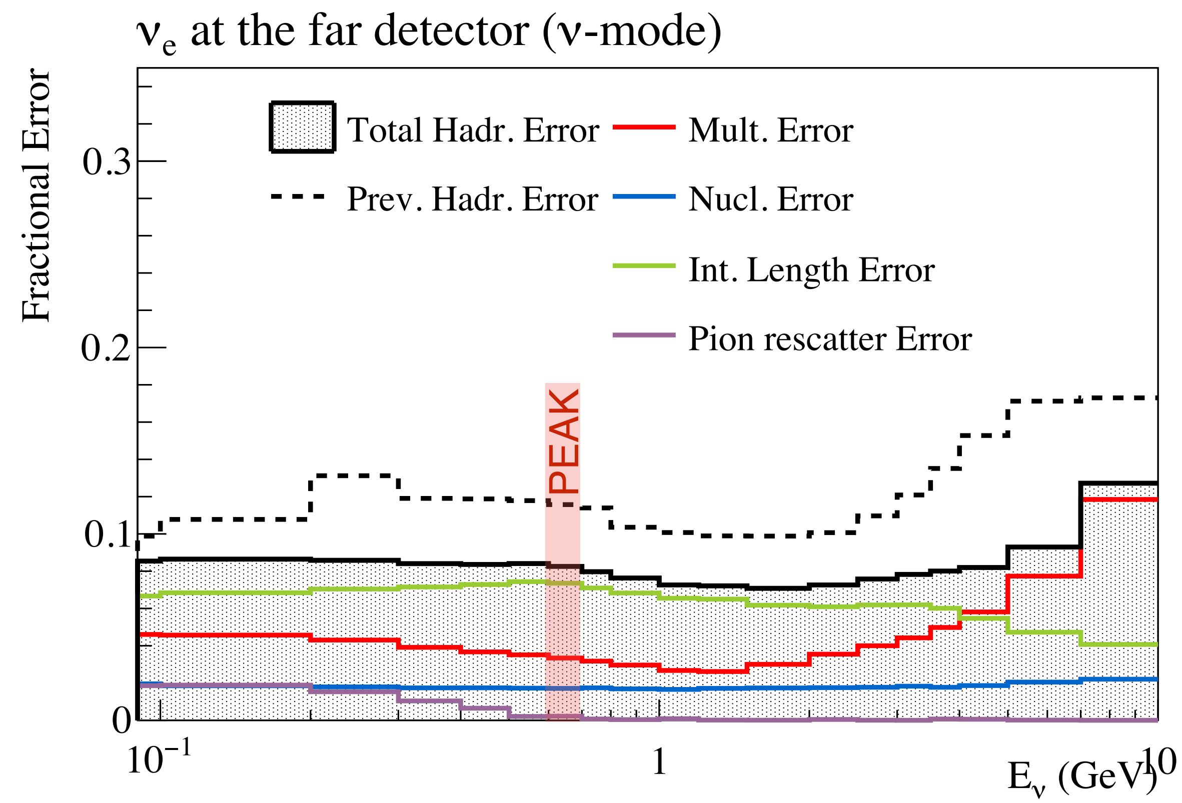


NA61 2009 thin target results uncertainties are reduced as compared to 2007.
For interactions outside NA61 phase space coverage, we used the difference between the BMPT extrapolation and Fluka predictions as our uncertainty.



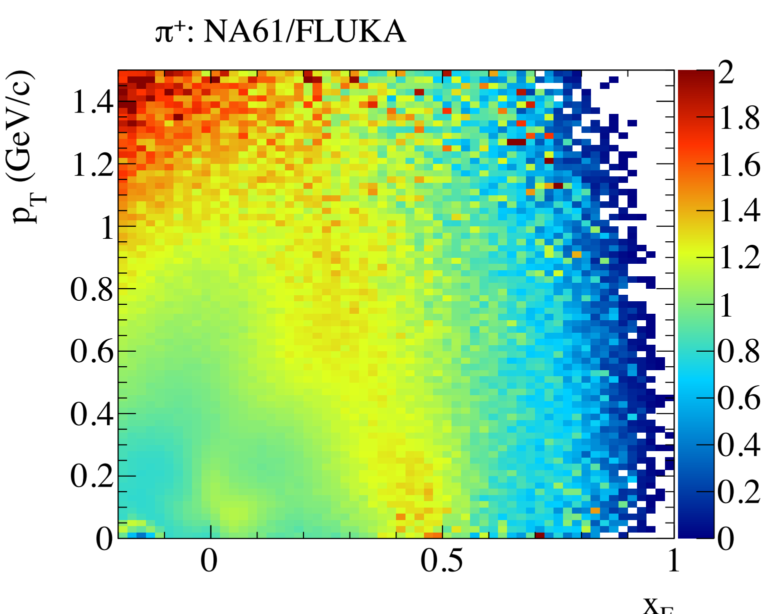
Uncertainties - hadronic - multiplicity & cross section



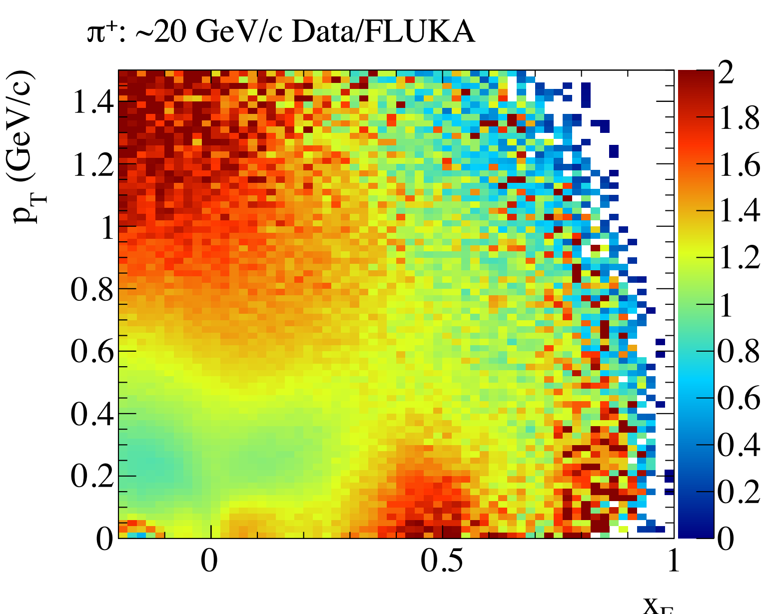


We tested our scaling hypothesis with external data to estimate our uncertainties

x_F-p_T phase space of π^+ production (invariant cross section)



NA61 (pC at 31 GeV)

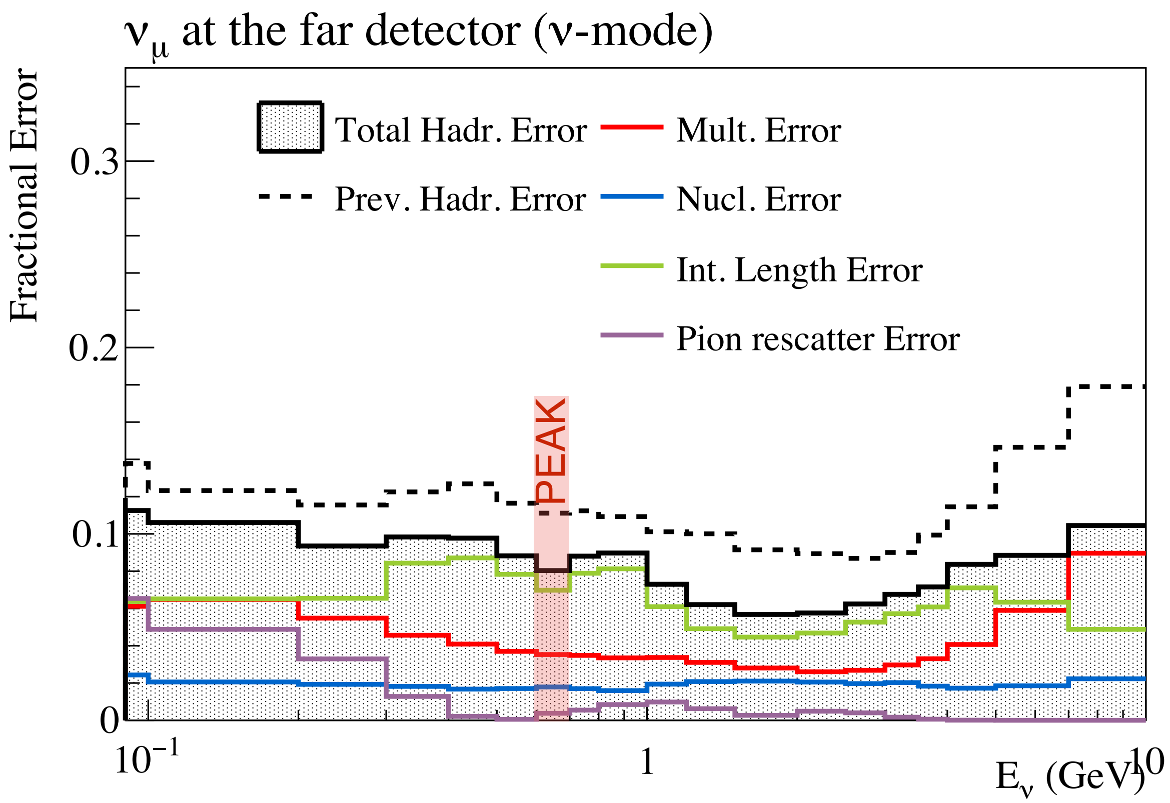


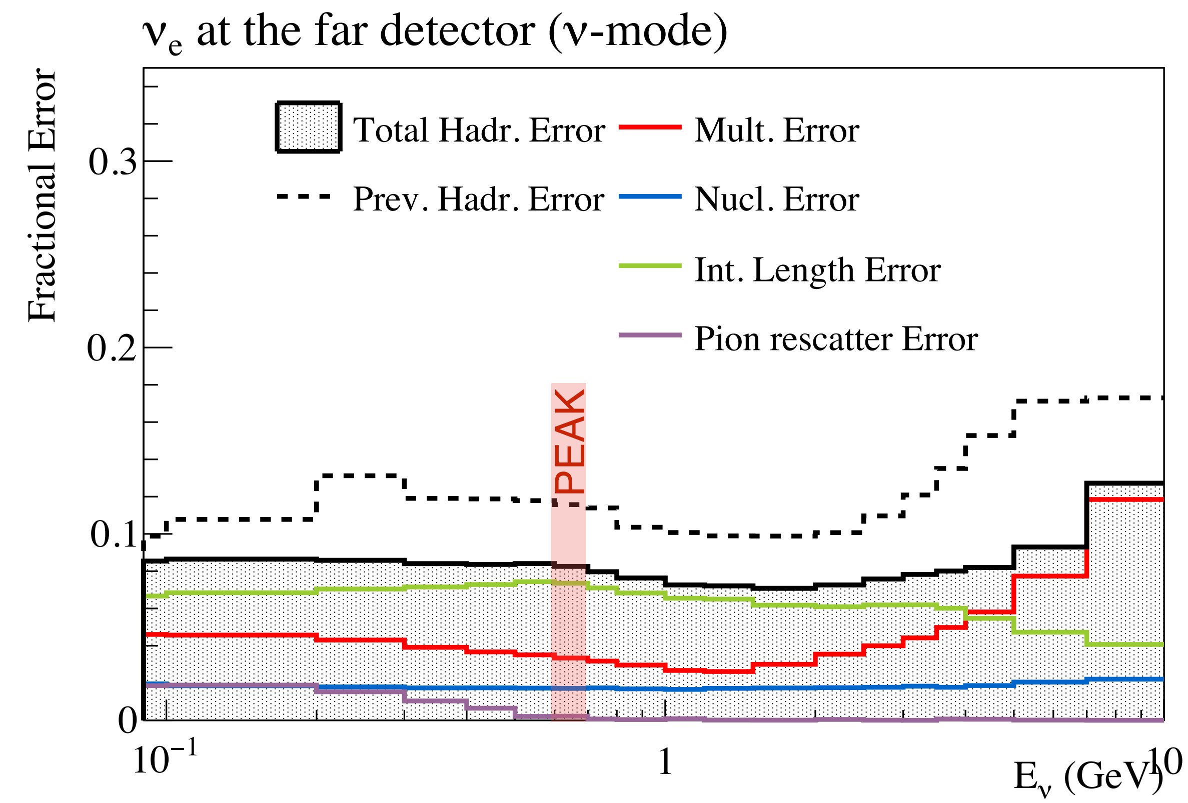
Allaby (pC at 20 GeV)

The uncertainty from the interaction length is conservatively estimated as the size of the quasi-elastic cross-section :

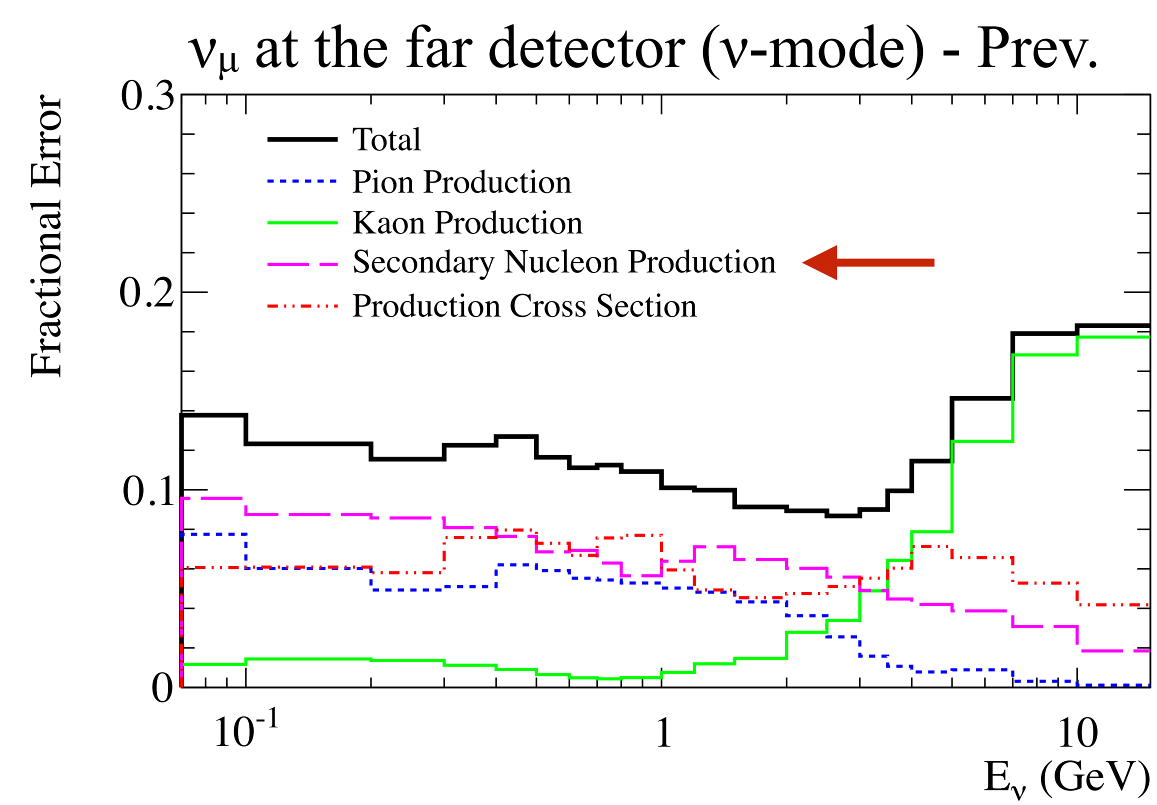
$$\sigma_{\mathrm{QE}}(31\ \mathrm{GeV}) = 27.70 \pm 0.10(\mathrm{stat})\ ^{+4.30}_{-0.10}(\mathrm{mod})\ \mathrm{mb}$$

Uncertainties - hadronic - secondary nucleon

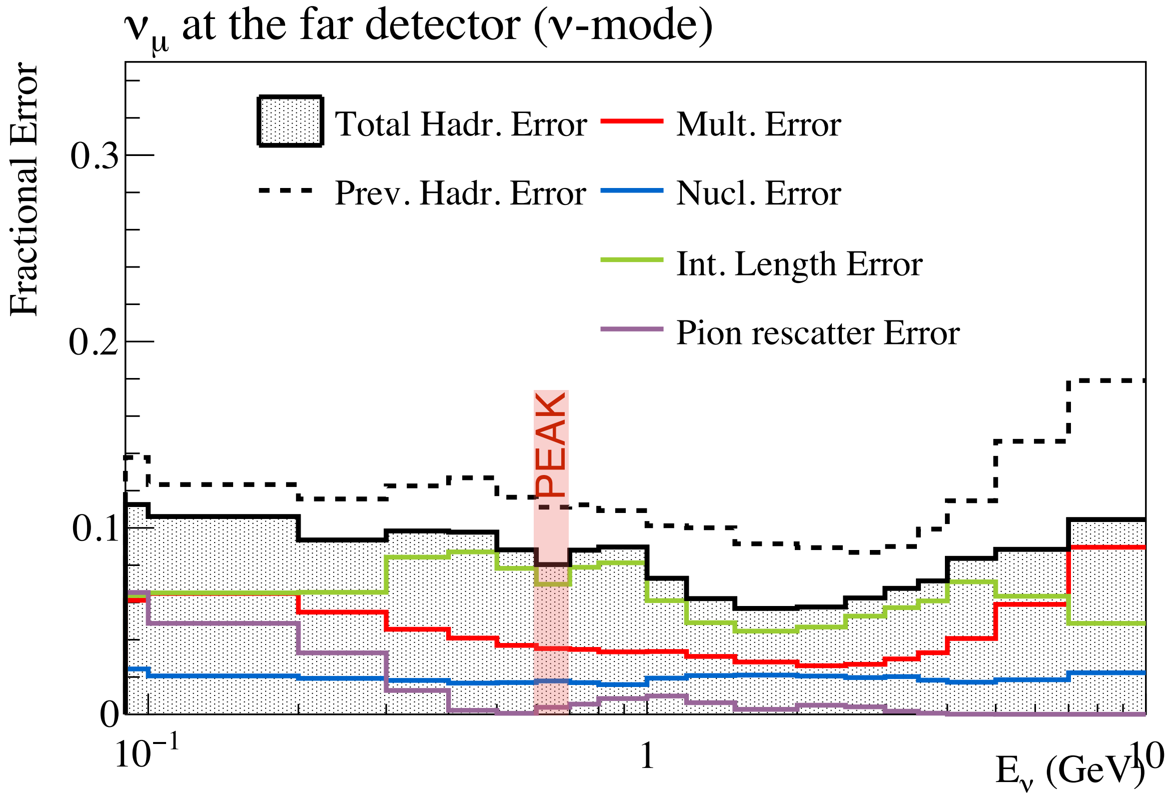


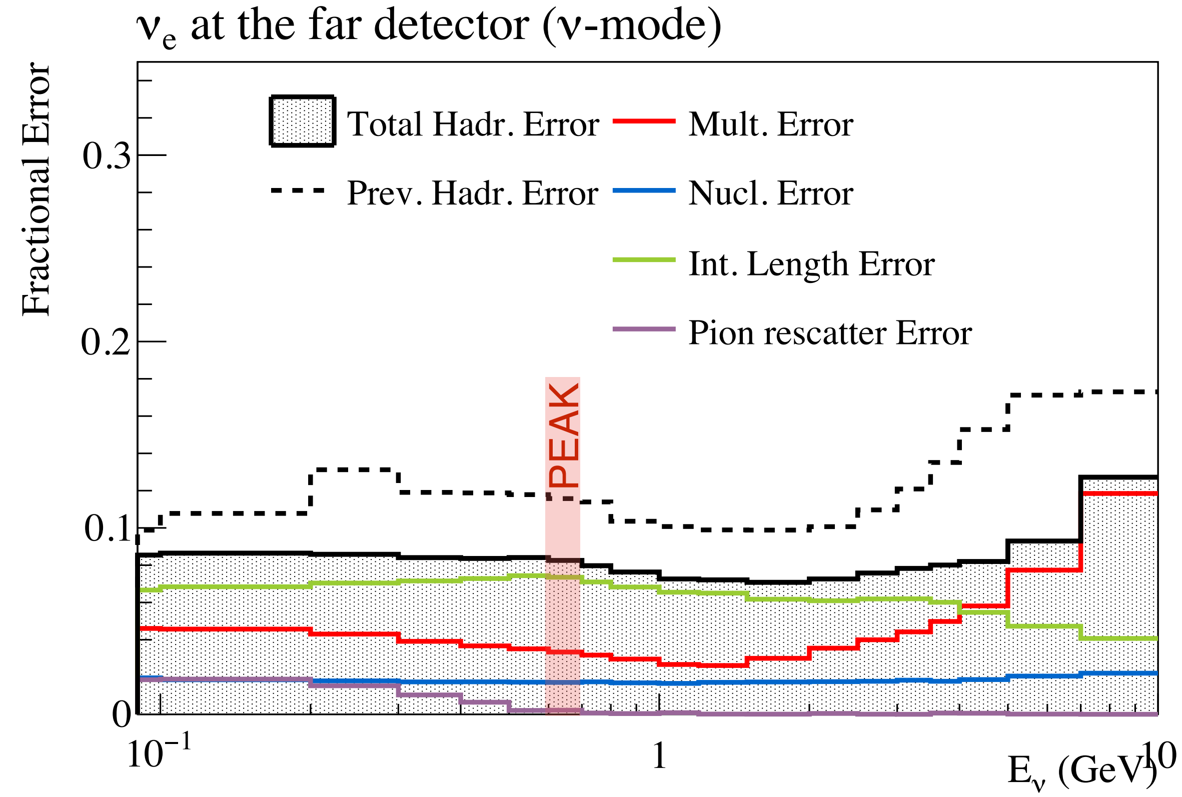


The total secondary baryon production uncertainty is significantly lowered compared to the previous estimate, as for example the ν_μ error is currently about 2% [10% previously]
It is estimated by comparing tuned flux with difference inputs:
lambda weights computed with NA61 data, neutron weights from NA49 data,…



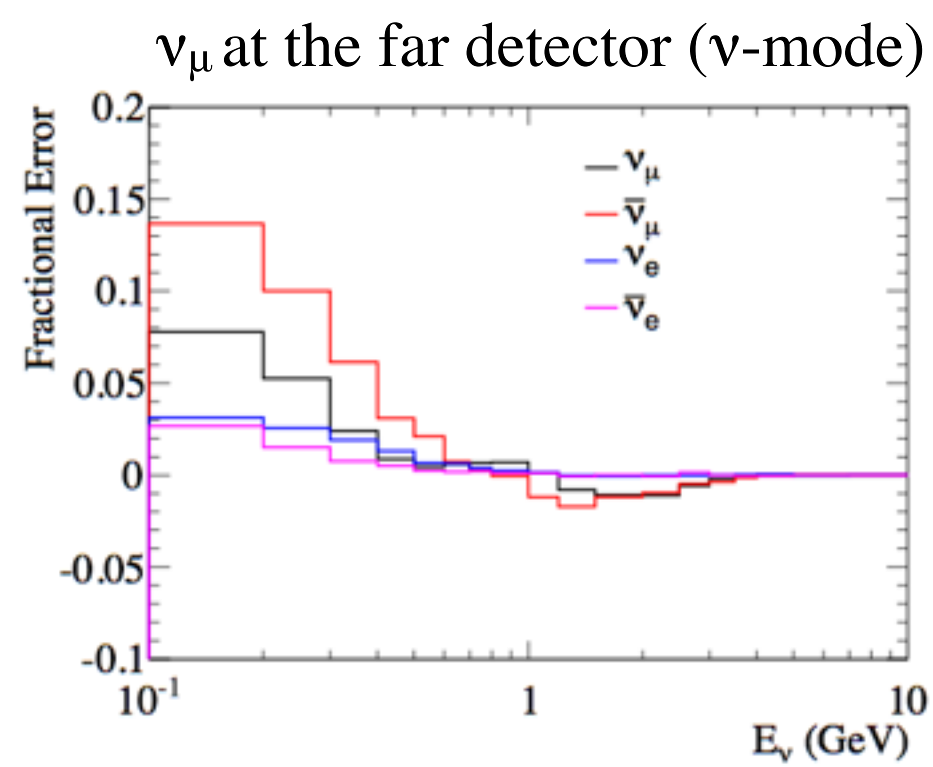
Uncertainties - hadronic - pion scattering



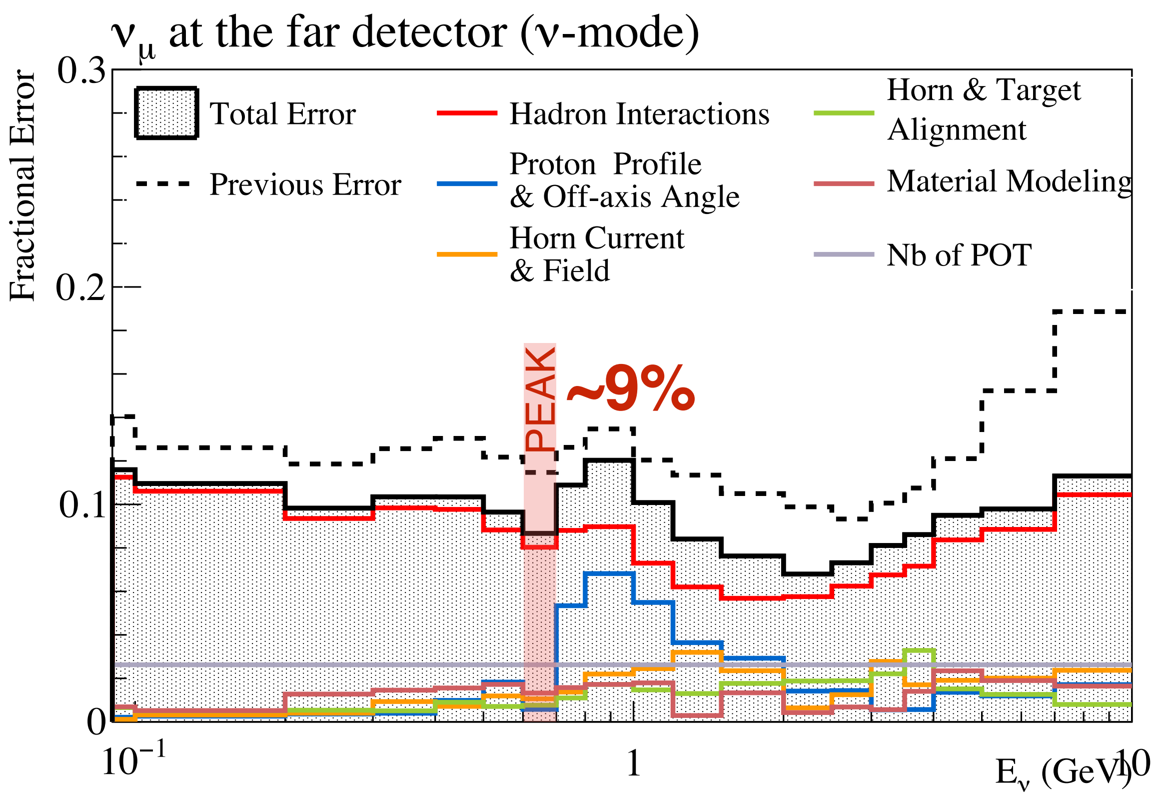


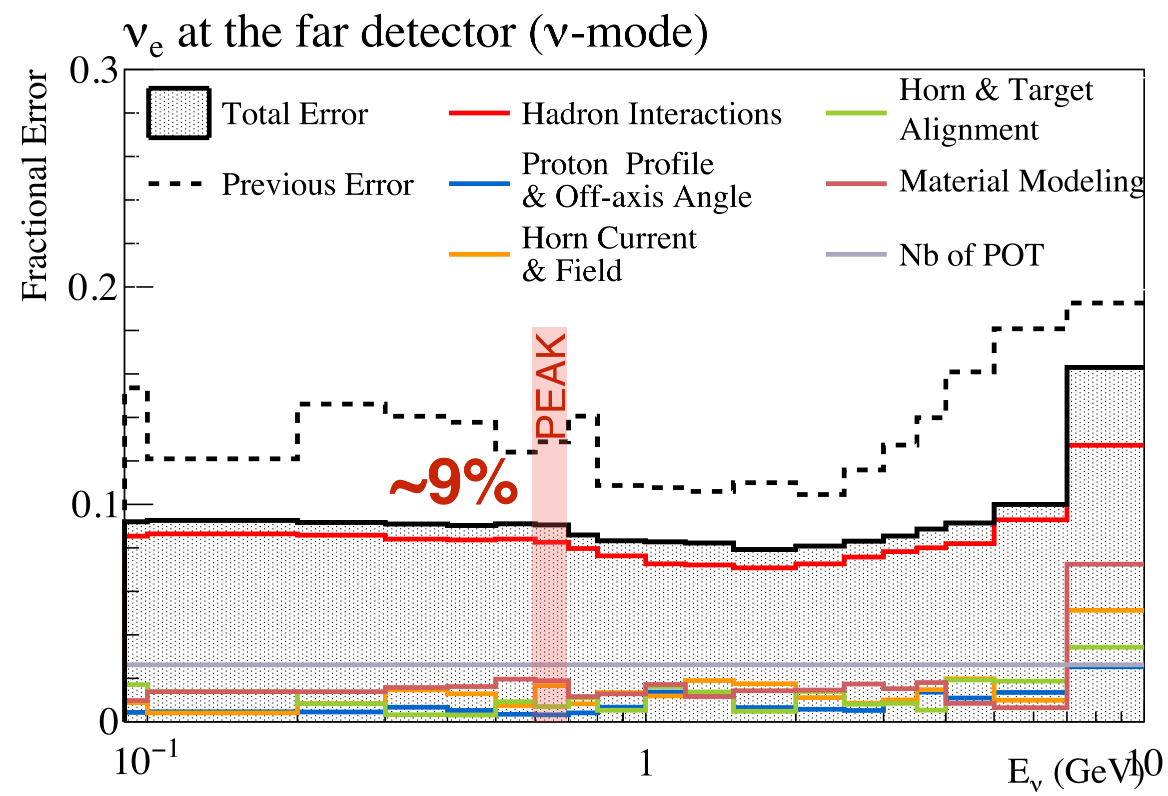
Pion scattering affects mostly ν_μ flux
It is estimated with HARP $\pi^\pm$+[C/Al]→$\pi^\pm$+X data at 3, 5, 8 and 12 GeV/c

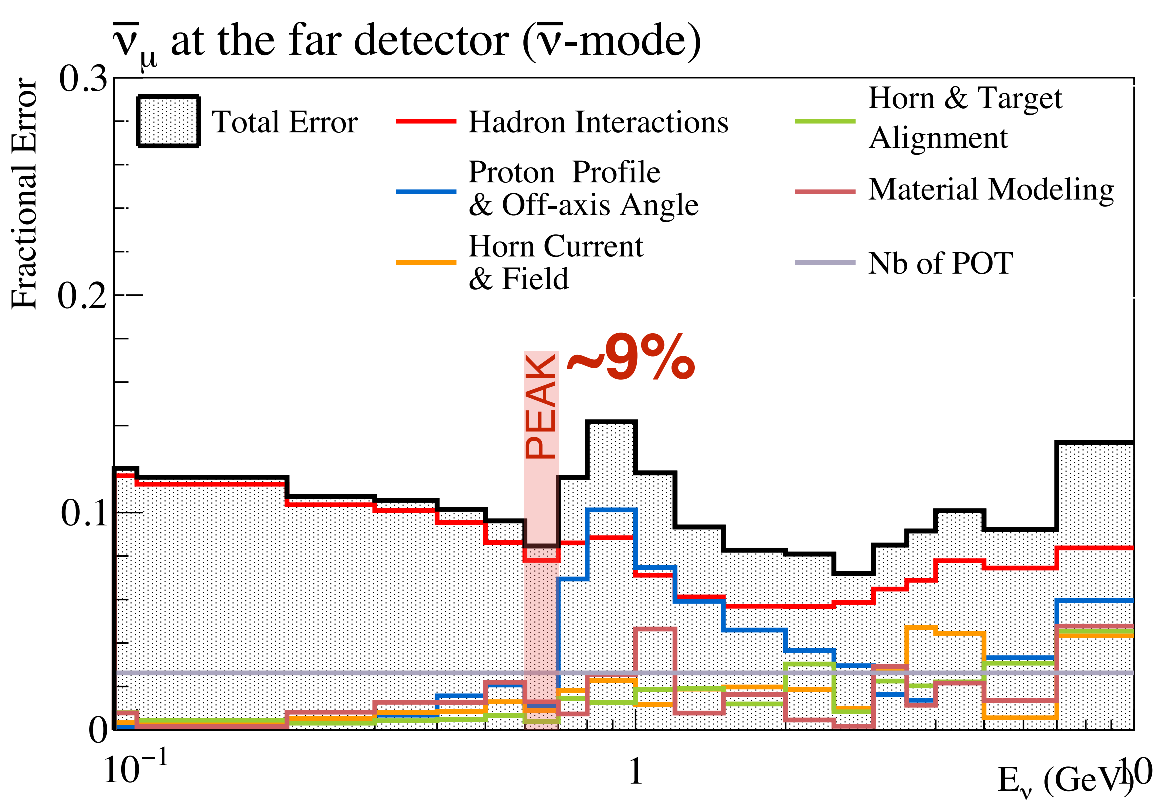
The error on pion scattering is taken as the difference between flux tuned with and without pion scattering tuning.

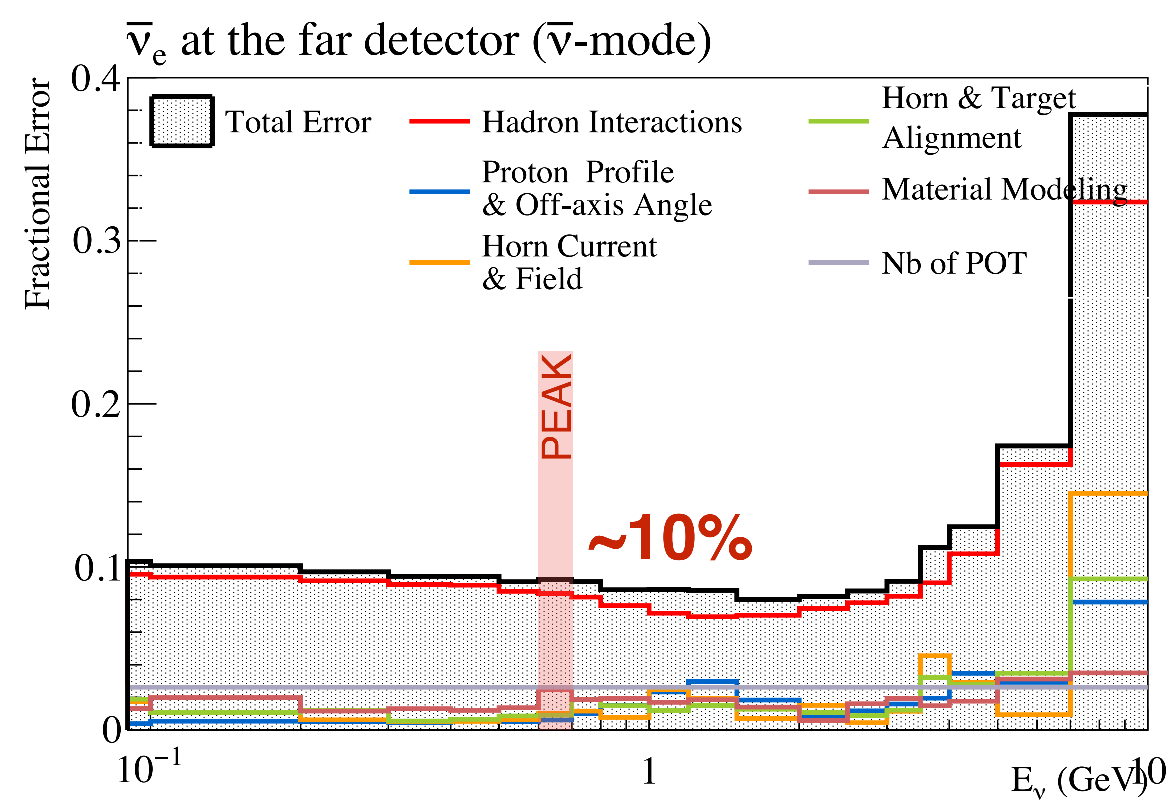


Final uncertainty

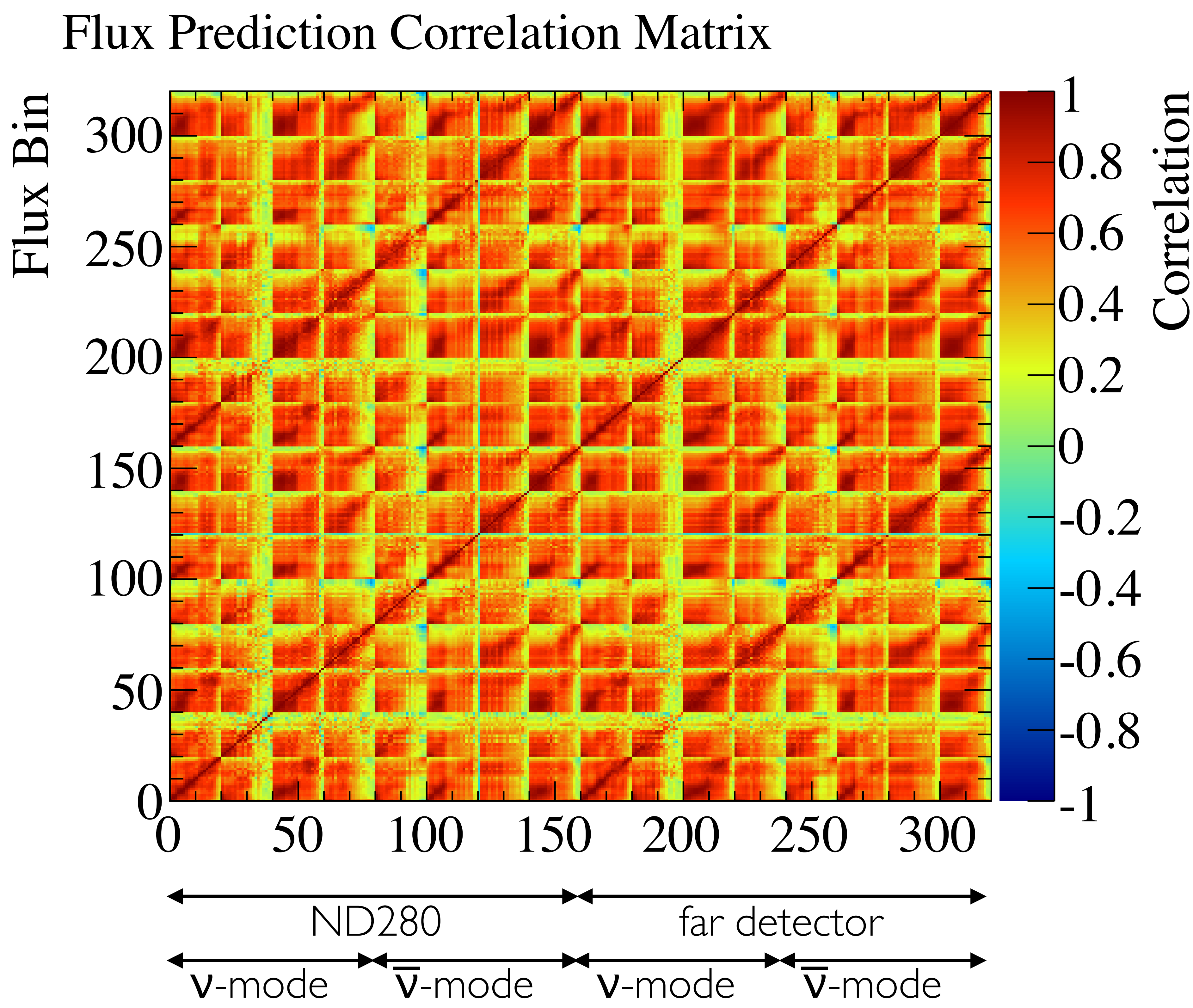








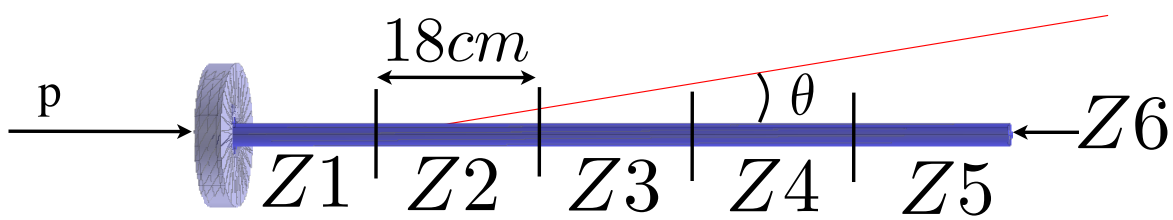
Correlation matrix



$\nu_\mu \bar{\nu}_\mu \nu_e \bar{\nu}_e$ …

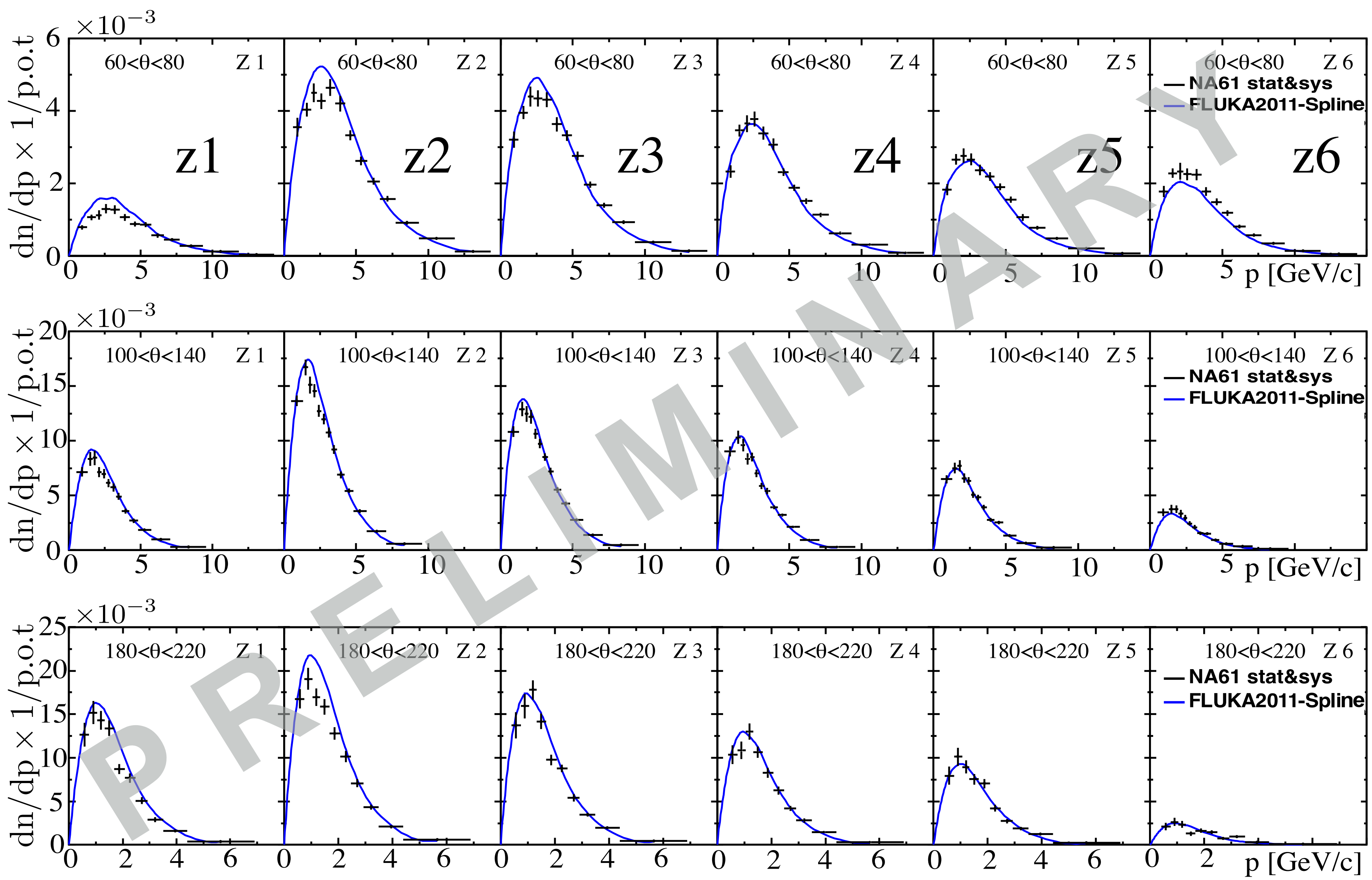
NA61/SHINE long target results

Preliminary results have been released recently
The target is divided into 6 bins : 5 bins of 18 cm
+ the downstream face of the target



$\pi^{\pm}$ differential spectra in {p,θ,z} bins extracted at the surface of the target :

+ data
(stat + syst)
—Fluka

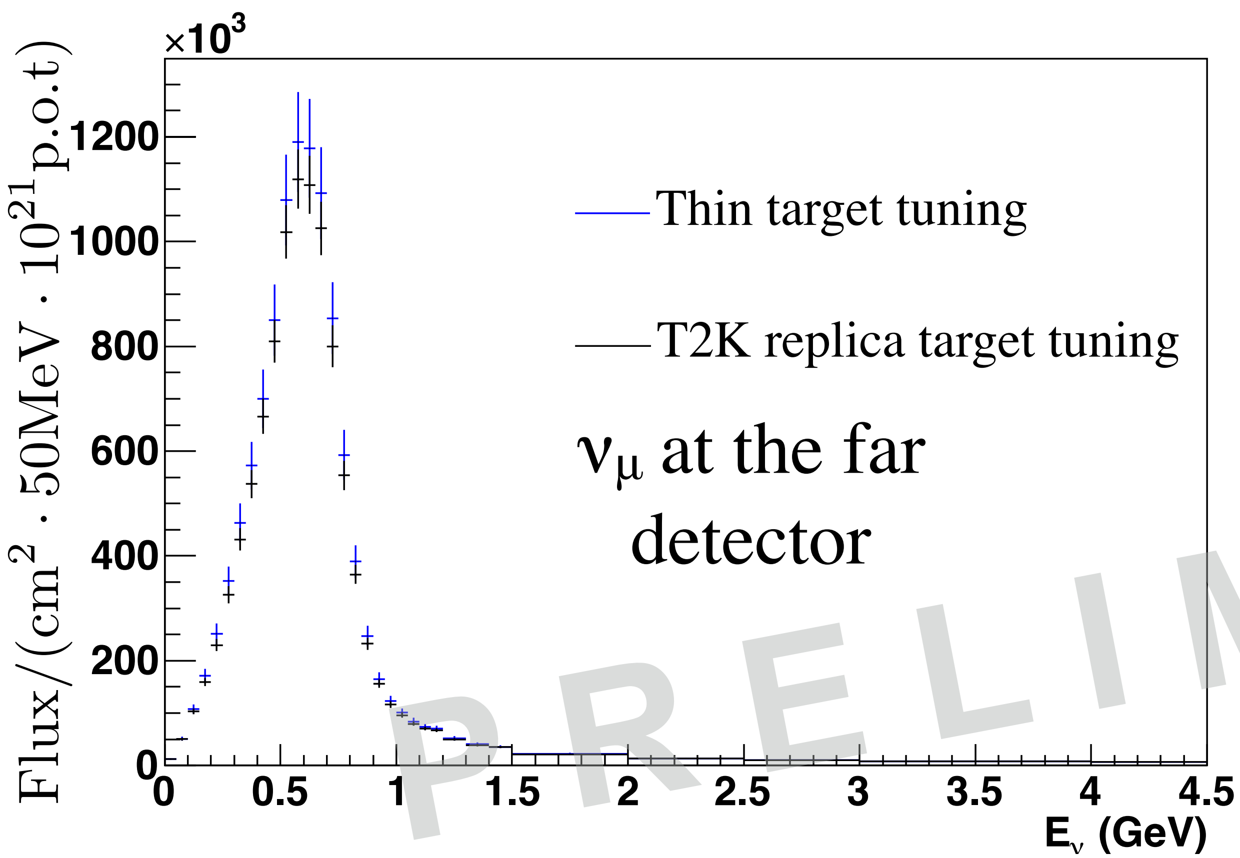


A. Haesler's PHD (Geneva Uni., 2015).

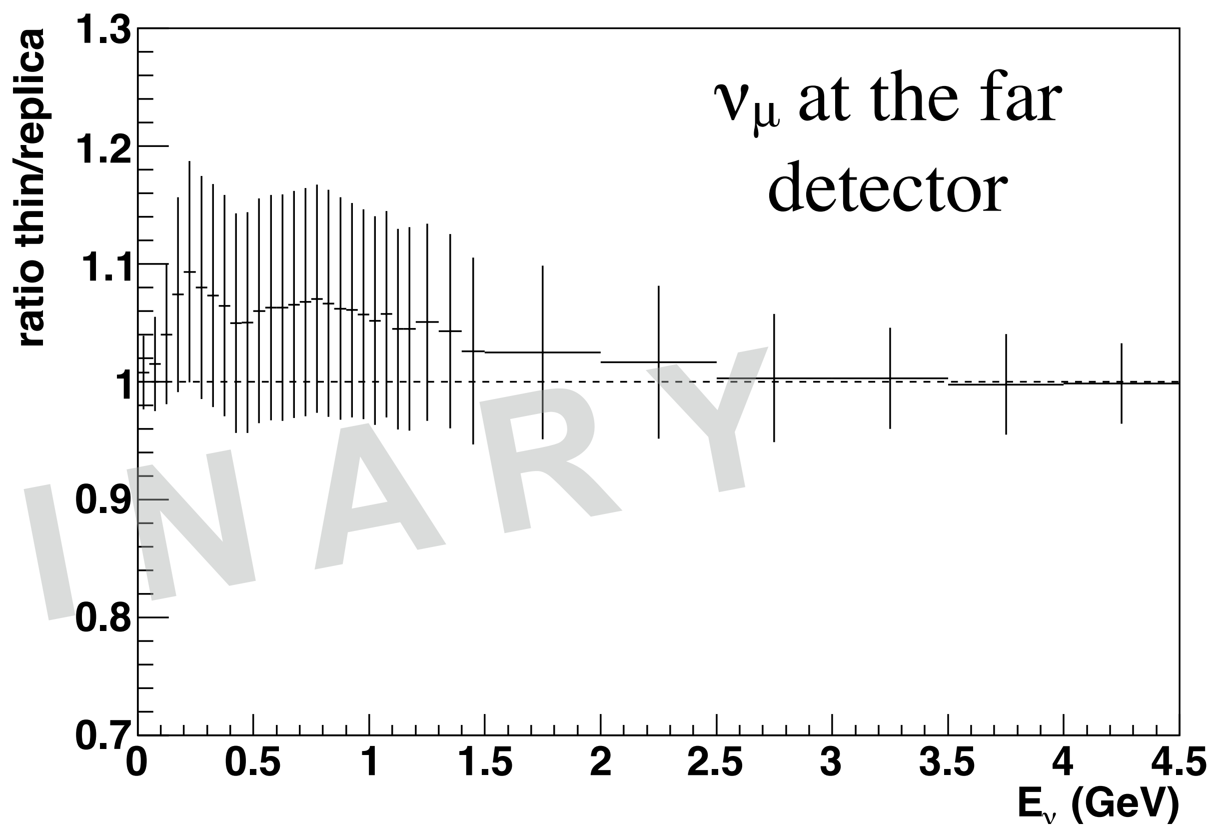
Prospect for T2K flux prediction

Preliminary work has been done to include the replica target data in the T2K flux tuning process.

pion escaping the target → tune to NA61 replica target data
all other particles → use the standard tuning (with the thin target)



ν_μ flux predictions at SK with the thin target and replica target re-weightings



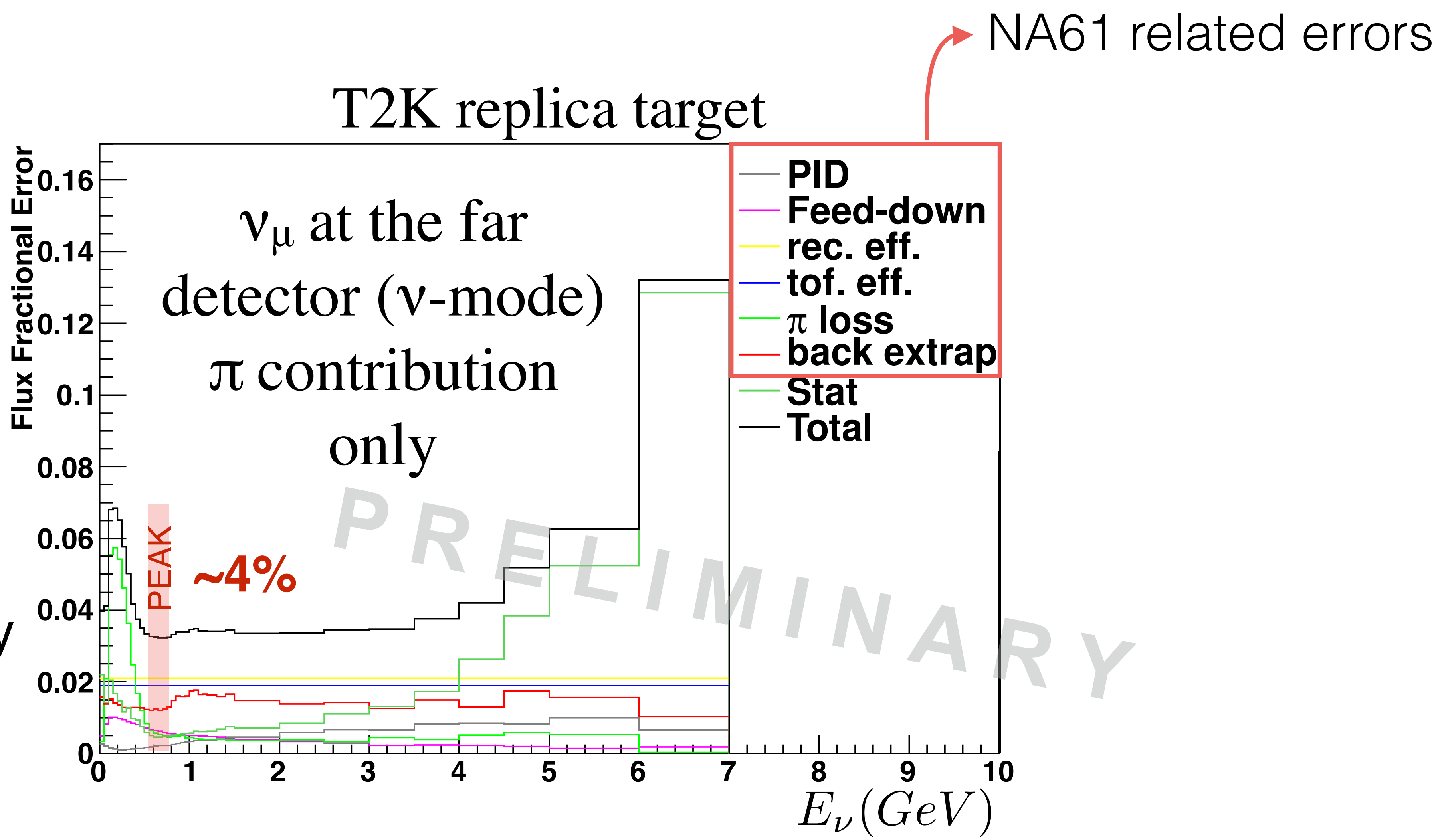
ratio of thin target over T2K replica target re-weightings for the ν_μ flux predictions at SK

Prospect for T2K flux prediction

Preliminary work has been done to include the replica target data in the T2K flux tuning process.

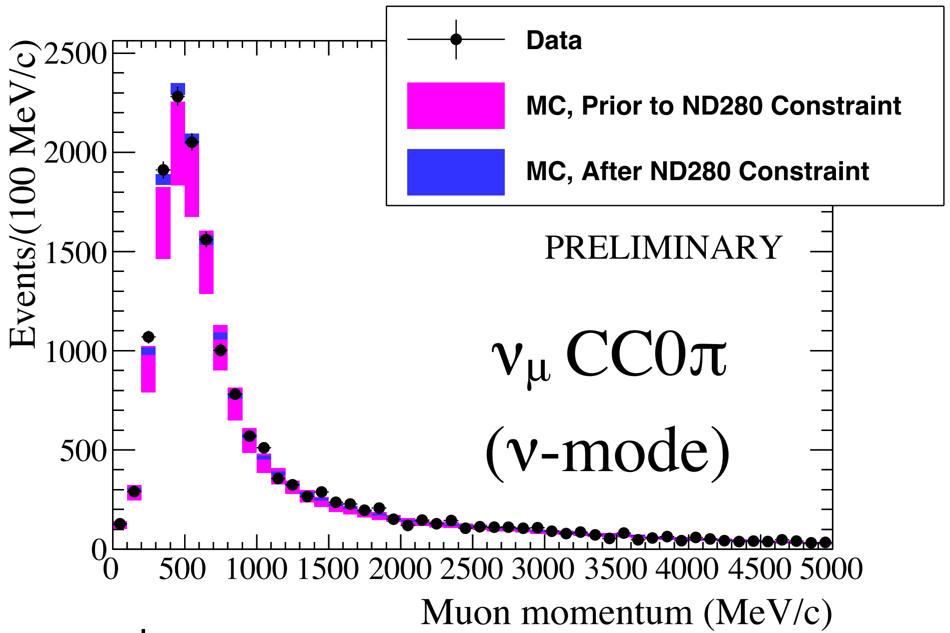
First estimation of the flux error when using the replica target data : only the multiplicity error is propagated (not the interaction cross section)

4% is a low limit!
To be compared with the current multiplicity error



Flux & cross-section constraints for the oscillation analysis

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> :

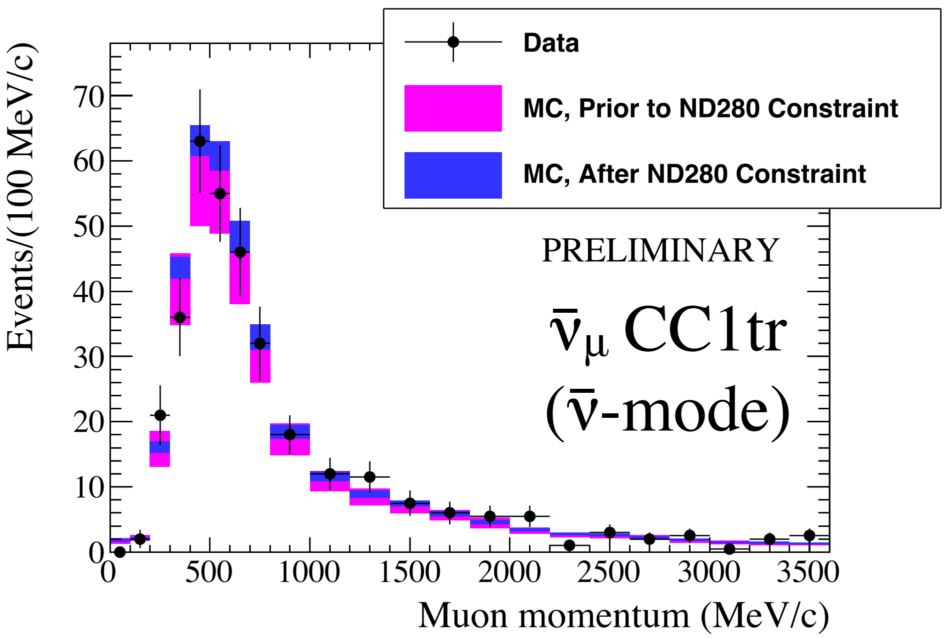
ν_μ interactions divided into 3 samples :

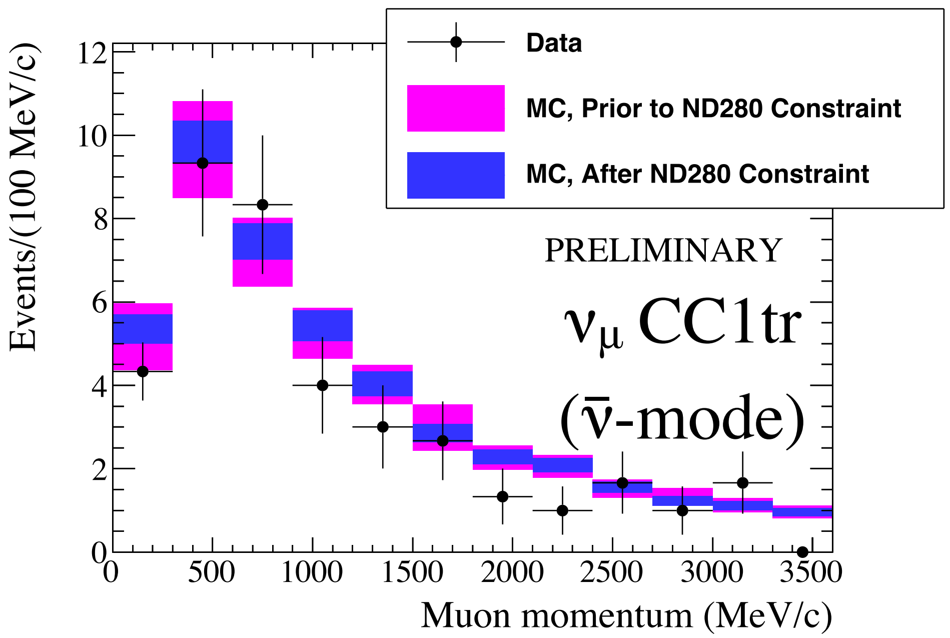
CC0π, CC1π and CCother

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

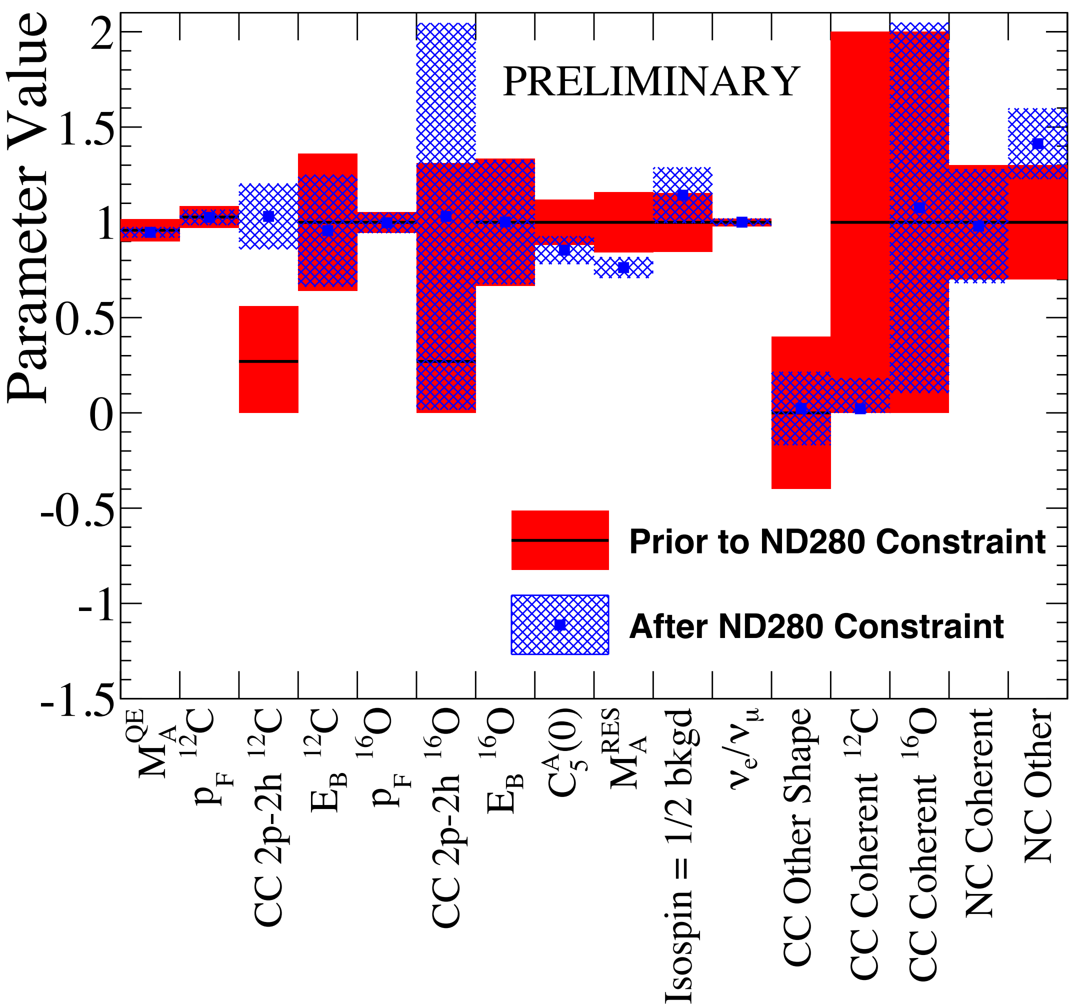
ν_μ interaction and $\bar{\nu}_\mu$ interactions are separated into 2 samples:

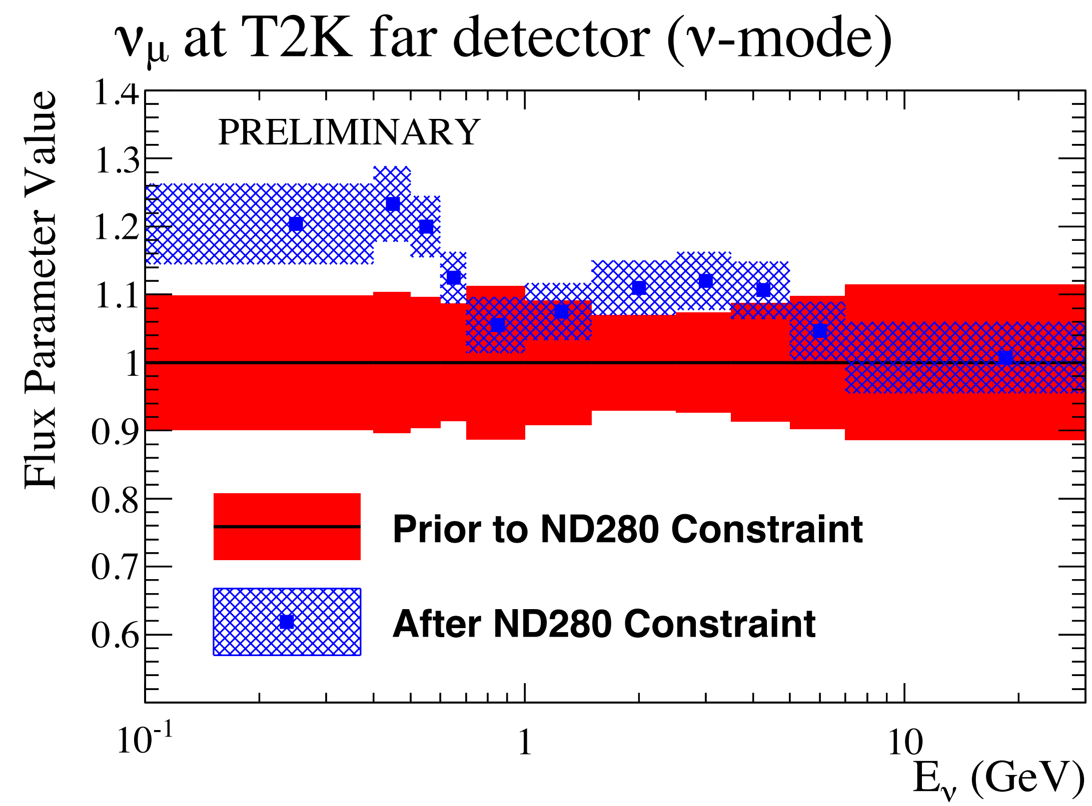
1 track (CC1tr) and >1 tracks (CCNtr).

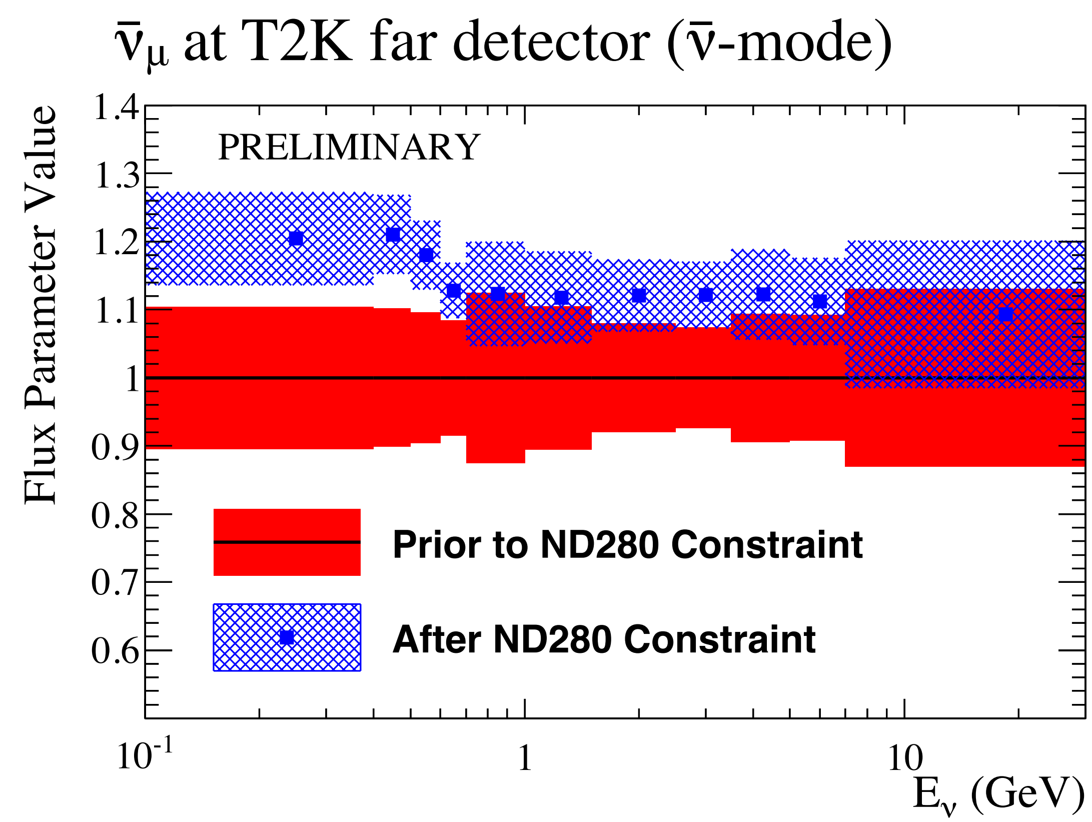




Flux & cross-section constraints for the oscillation analysis







$\bar{\nu}_\mu$ 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

T2K flux is predicted with the help of the latest NA61/SHINE thin target data.
The uncertainty on the flux is now around ~9% at the peak energy

The replica target data is in the process of being included in the analysis.
The flux uncertainty is expected to be further reduced.
2 methods are developed :

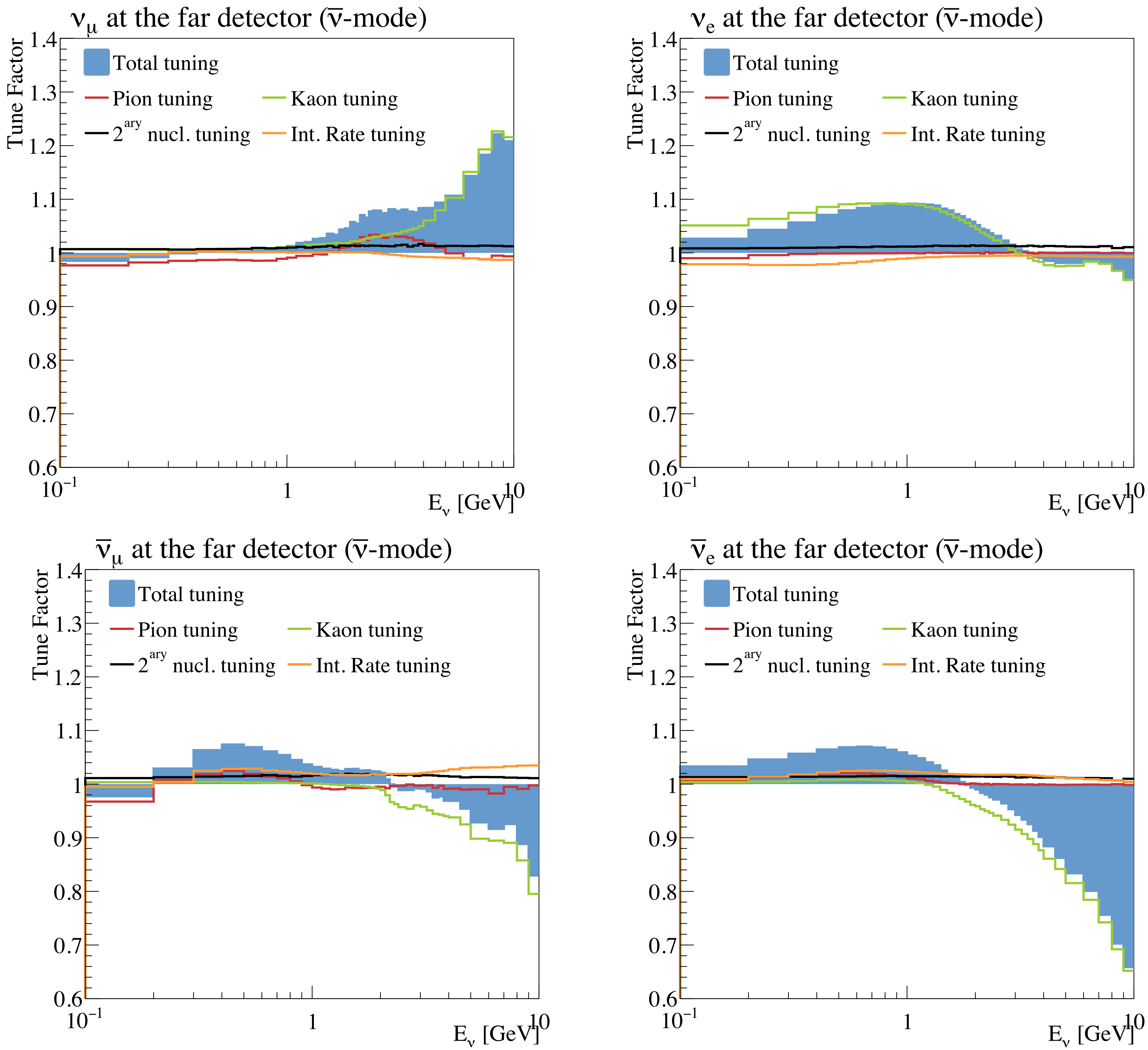
- Compute tuning factors for each {p,θ,z} bins of escaping pions, as for the thin target
- Construct a likelihood including cross-section and multiplicity parameters

For the oscillation analysis, the flux and cross-sections parameters are constrained by the measurements from the ND280 detector.

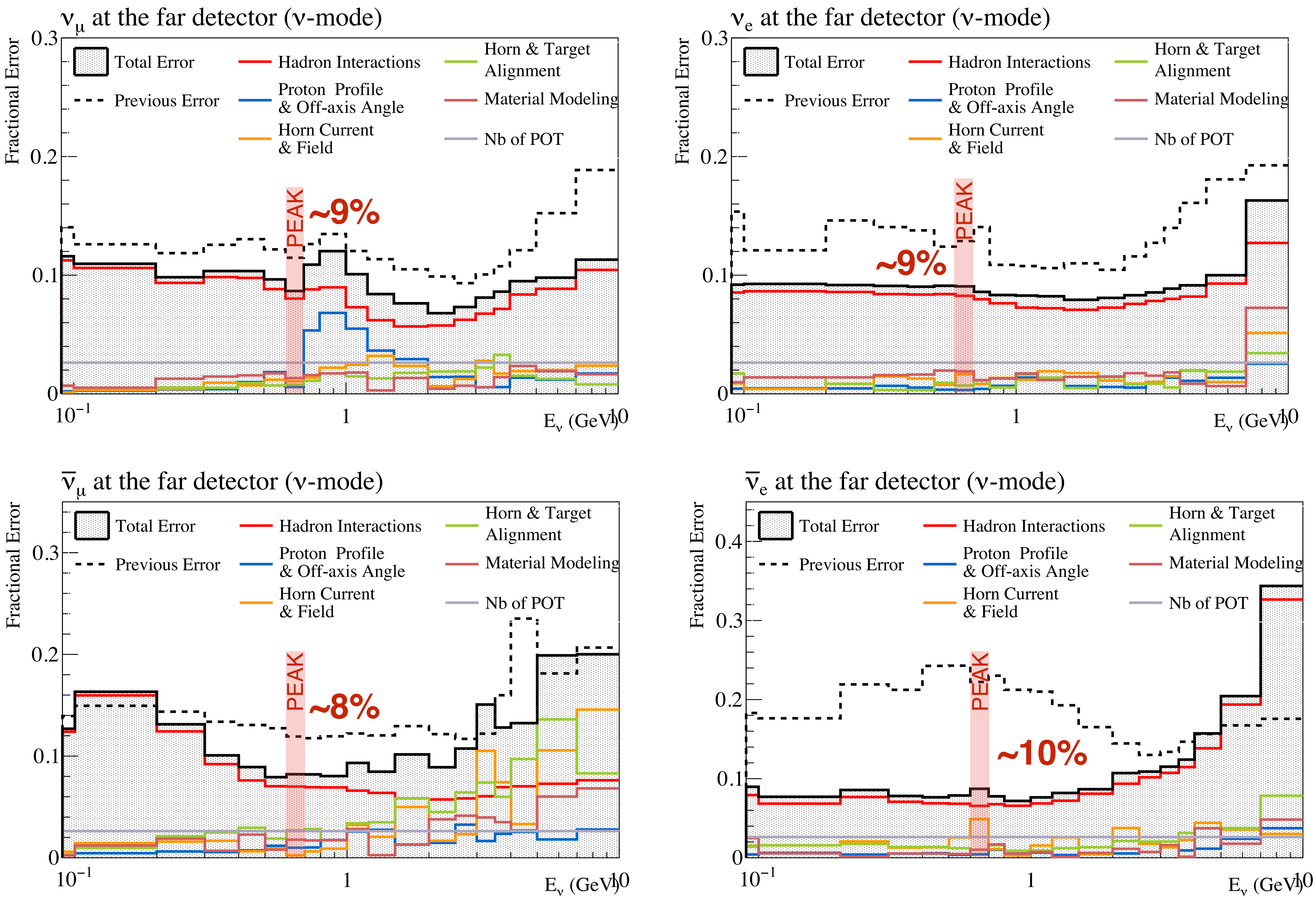
The absolute flux prediction is used for the cross-section measurements in the T2K near detectors.

Title

Tuning factor in $\overline{\nu}$-mode

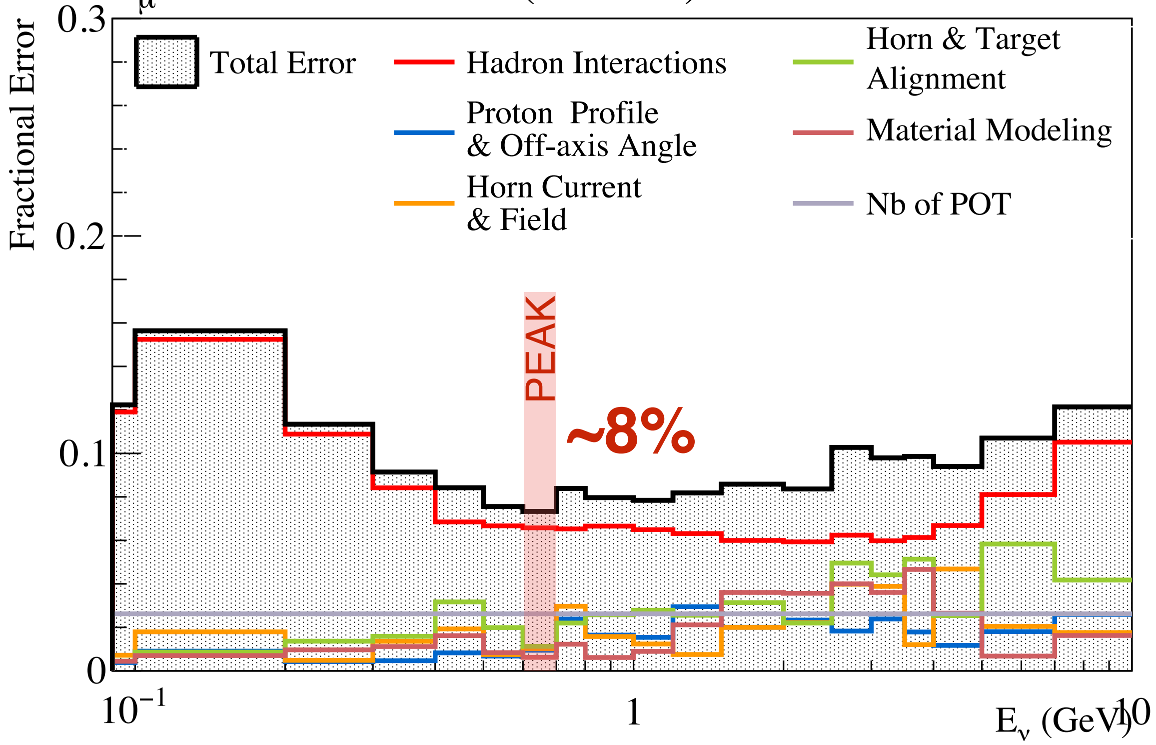


Flux error ($\boldsymbol{\nu}$-mode)

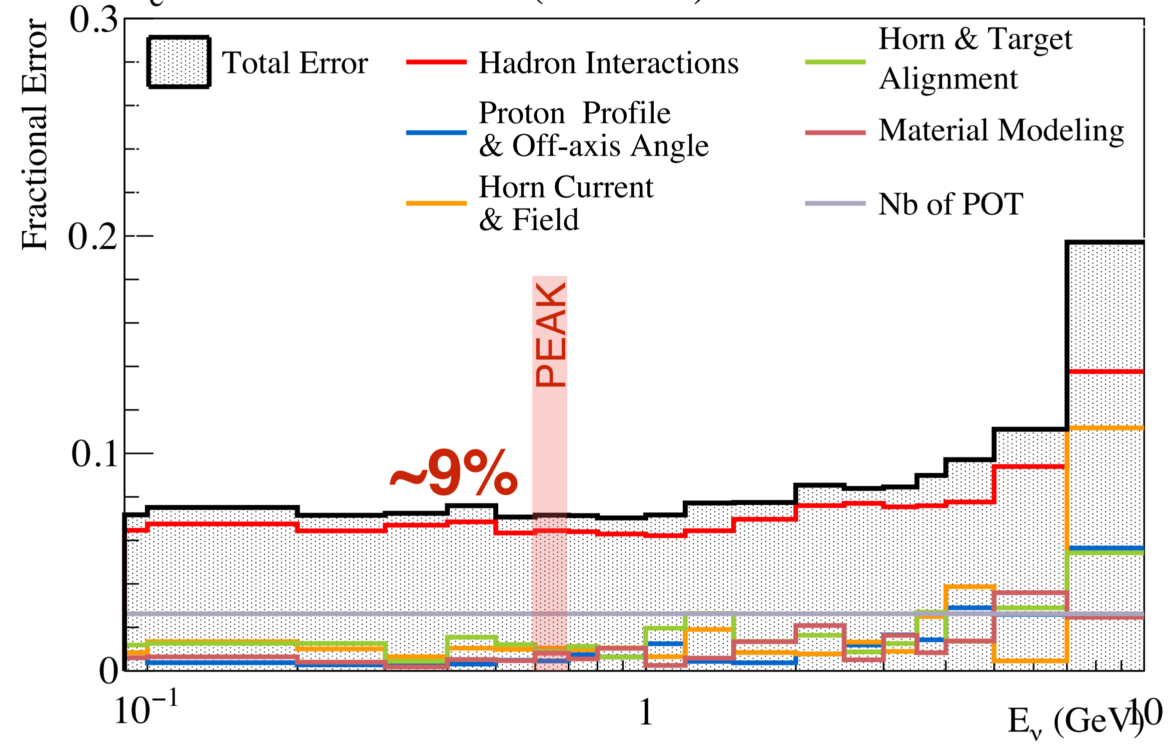


Flux error ($\overline{\nu}$-mode)

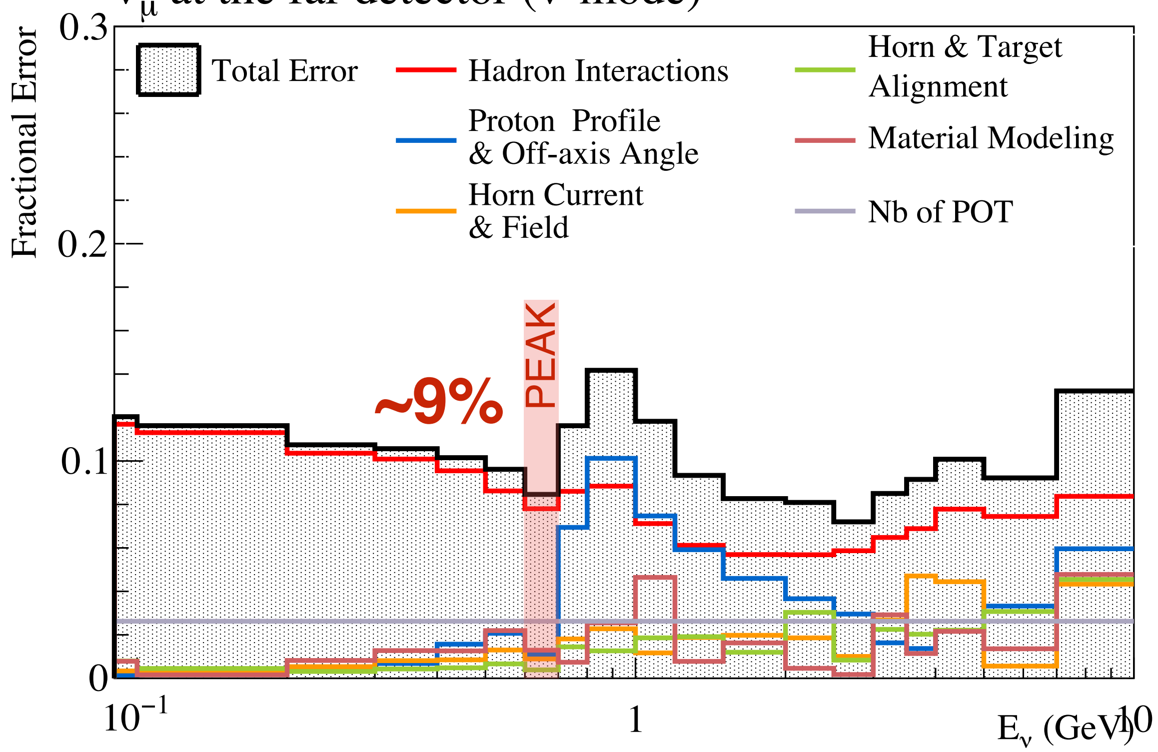
ν_μ at the far detector ($\overline{\nu}$-mode)



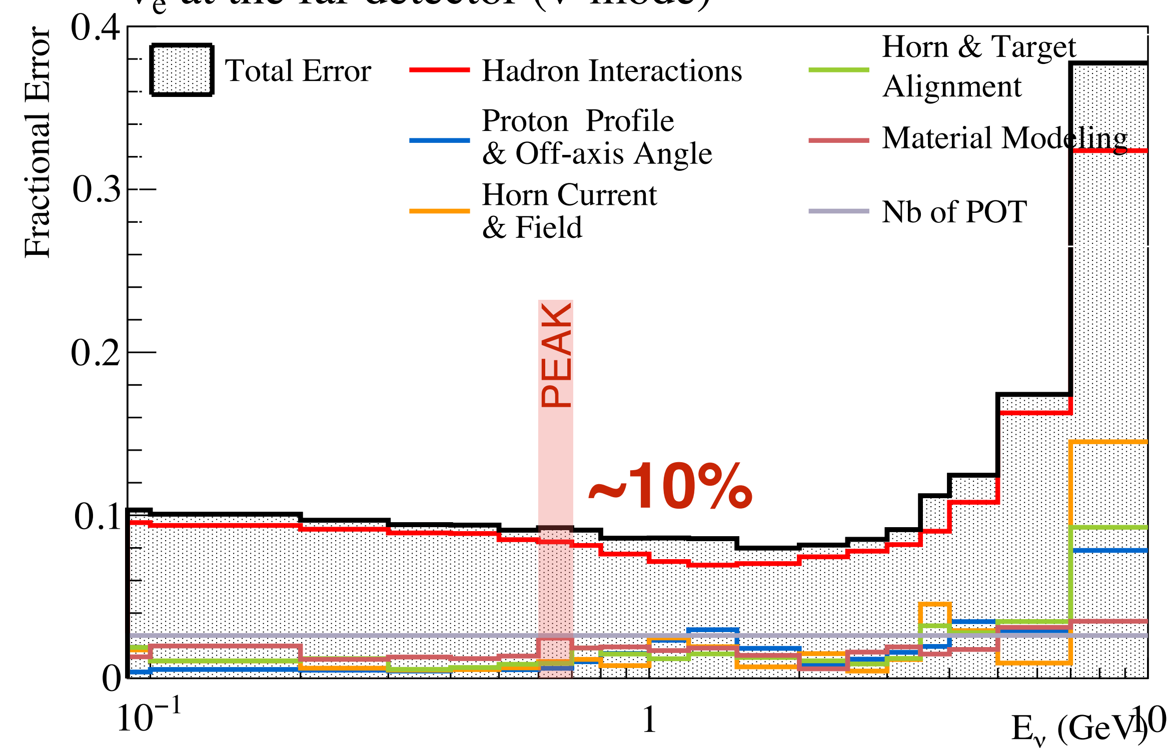
ν_e at the far detector ($\overline{\nu}$-mode)



$\overline{\nu}_\mu$ at the far detector ($\overline{\nu}$-mode)



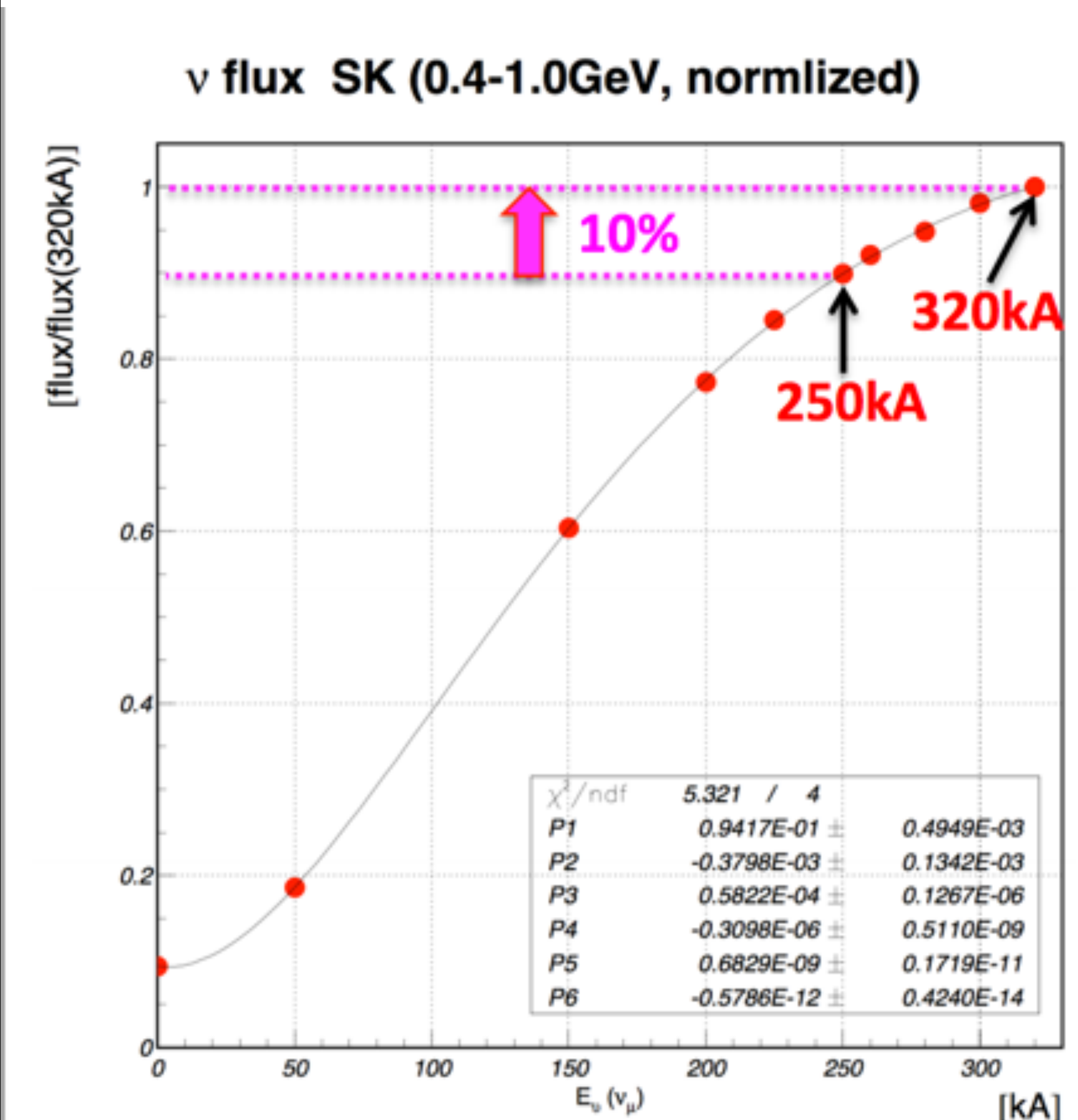
$\overline{\nu}_e$ at the far detector ($\overline{\nu}$-mode)

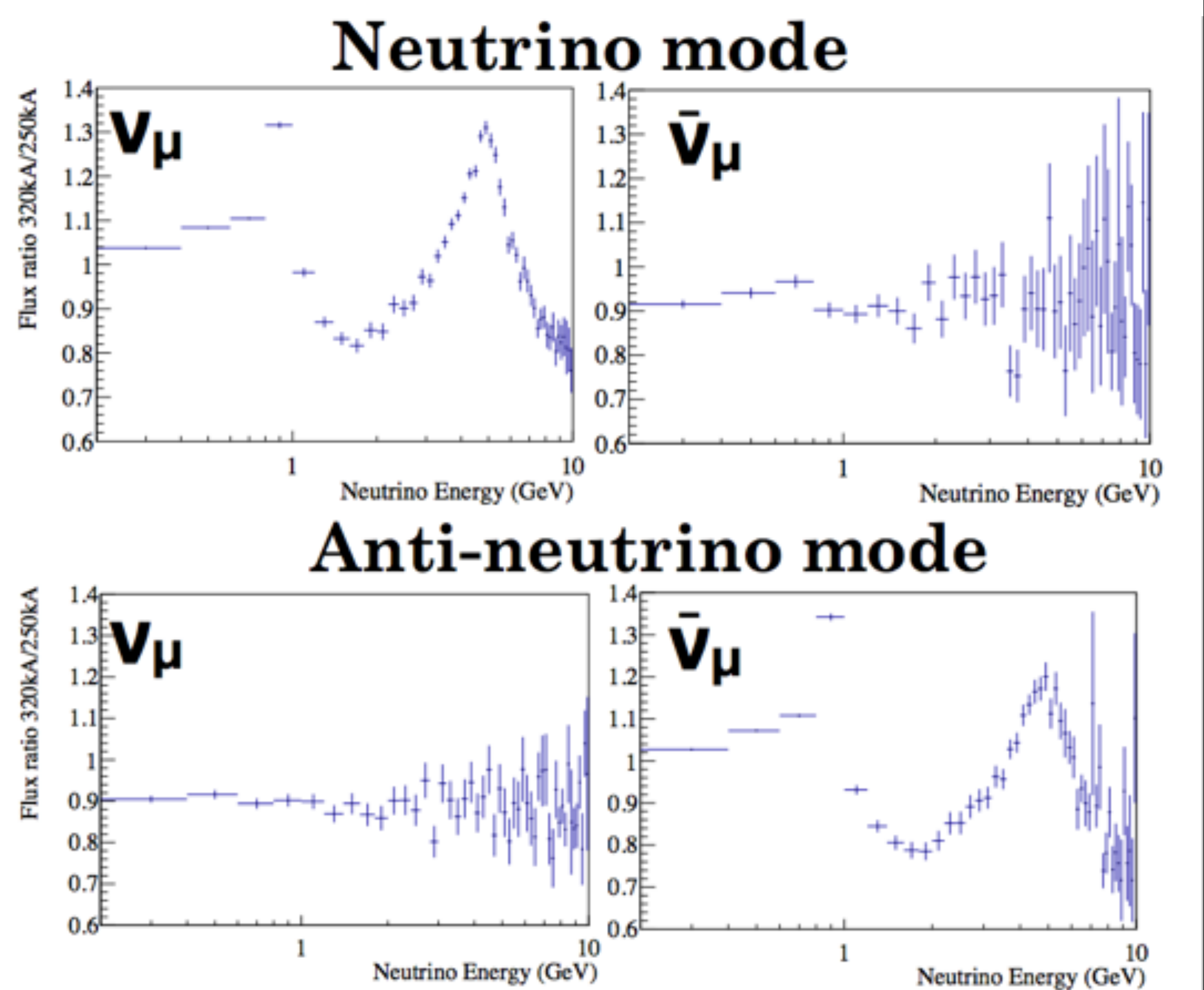


Beam prospects for T2K2

Increase the horn current ±250 kA → ±320 kA

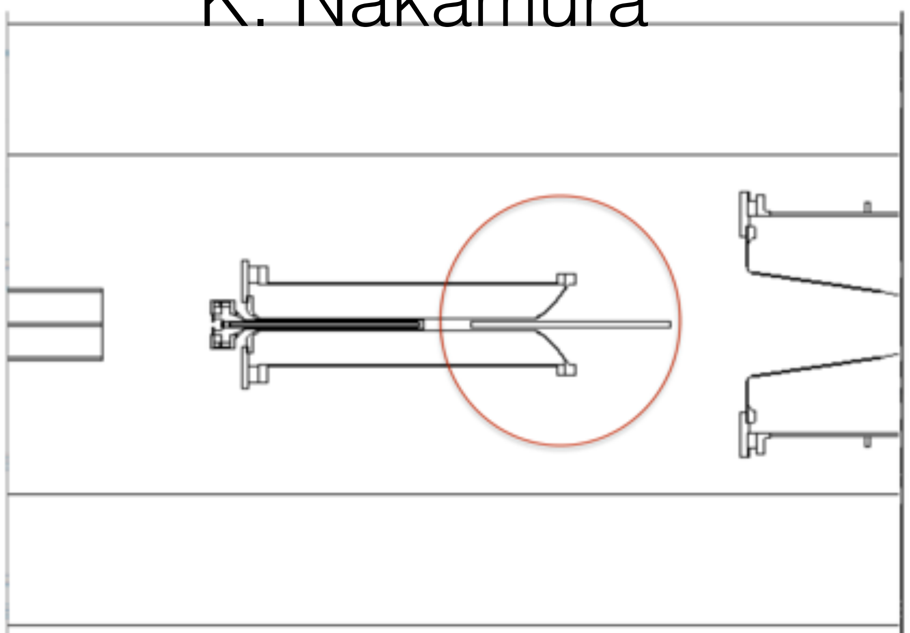
- +10% improvement of the flux at the far detector
- 5~10 % reduction of the 'wrong-sign' neutrinos at the peak

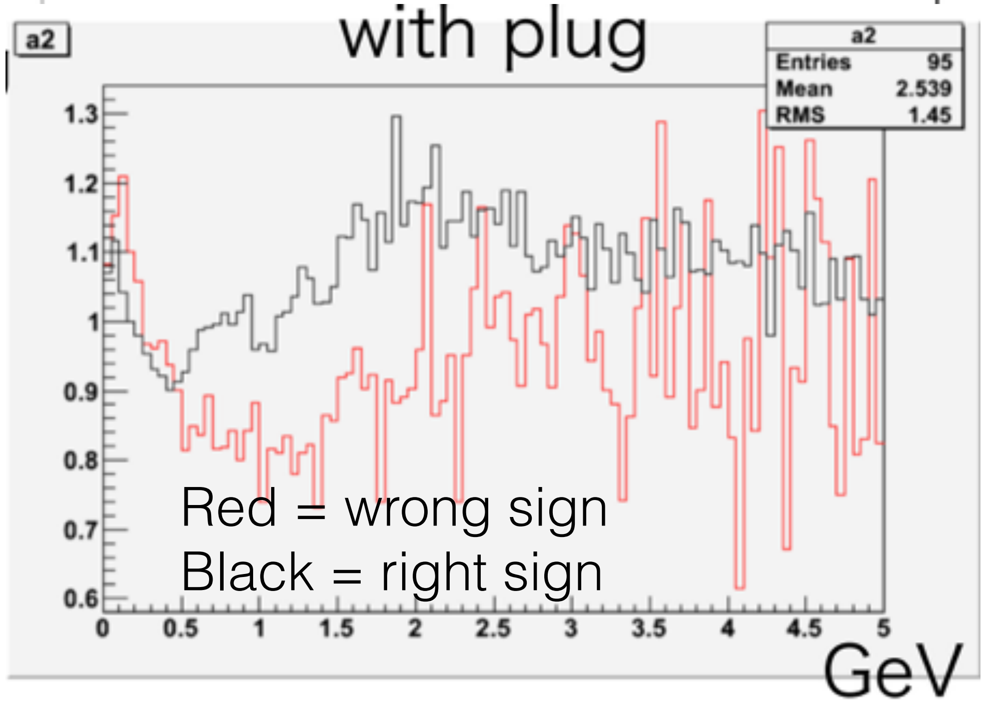




Beam Plug for Wrong Sign Background

K. Nakamura





- A larger fraction of the wrong sign background originates from forward produced hadrons
- These may be reduced by placing an absorber downstream of the target
- Nakamura-san has started to study this
- Preliminary study showed reduction of the wrong sign above 400 MeV
- Also some reduction of the right sign flux
- Maybe no conclusion for near-term T2K-II discussion

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