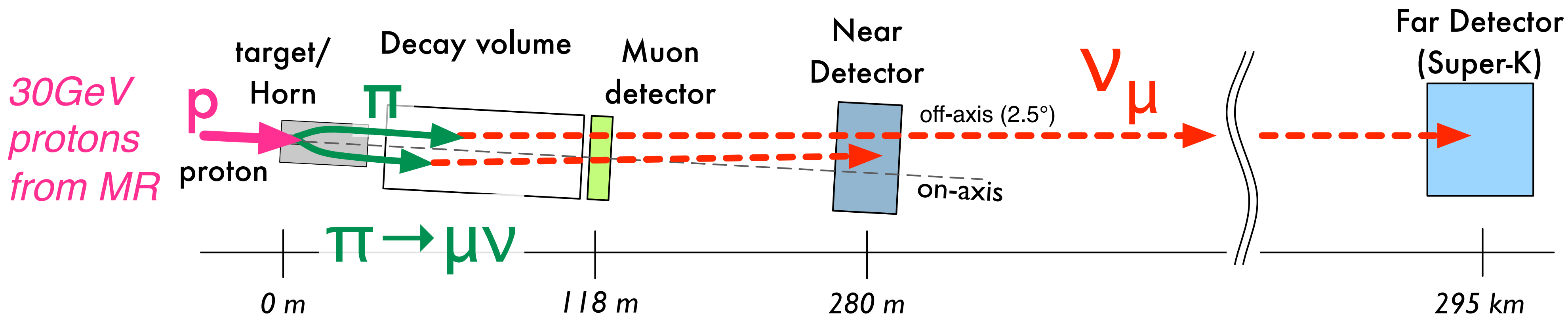
T2K flux prediction with NA61

NA61/SHINE Beyond 2020 Workshop, 2017/July/28

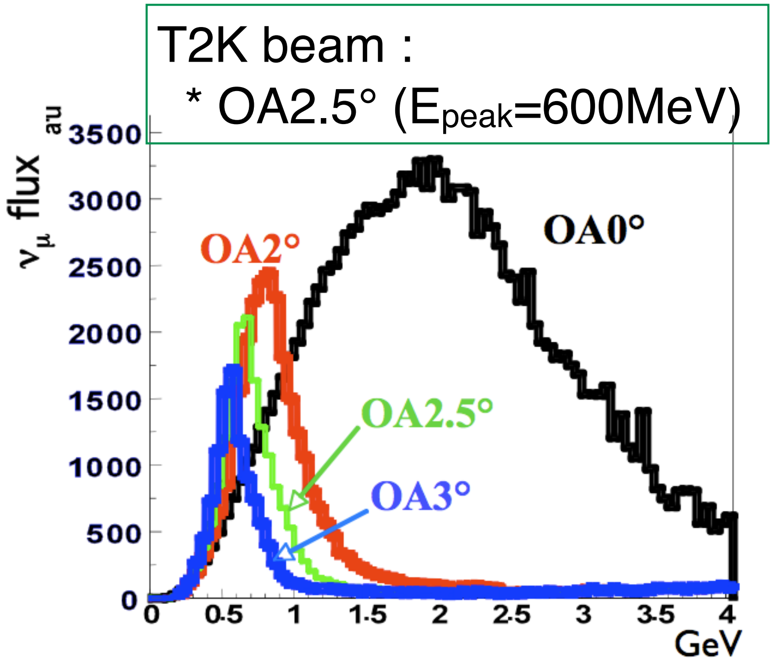
Ken Sakashita (J-PARC/KEK)
for T2K/J-PARC neutrino facility

T2K neutrino beam



- Accelerator-based ν beam
- ν / $\overline{\nu}$ can be switched by flipping horn polarity
- ν energy is narrow with off-axis method

  L = 295km → oscillation peak at 0.6GeV



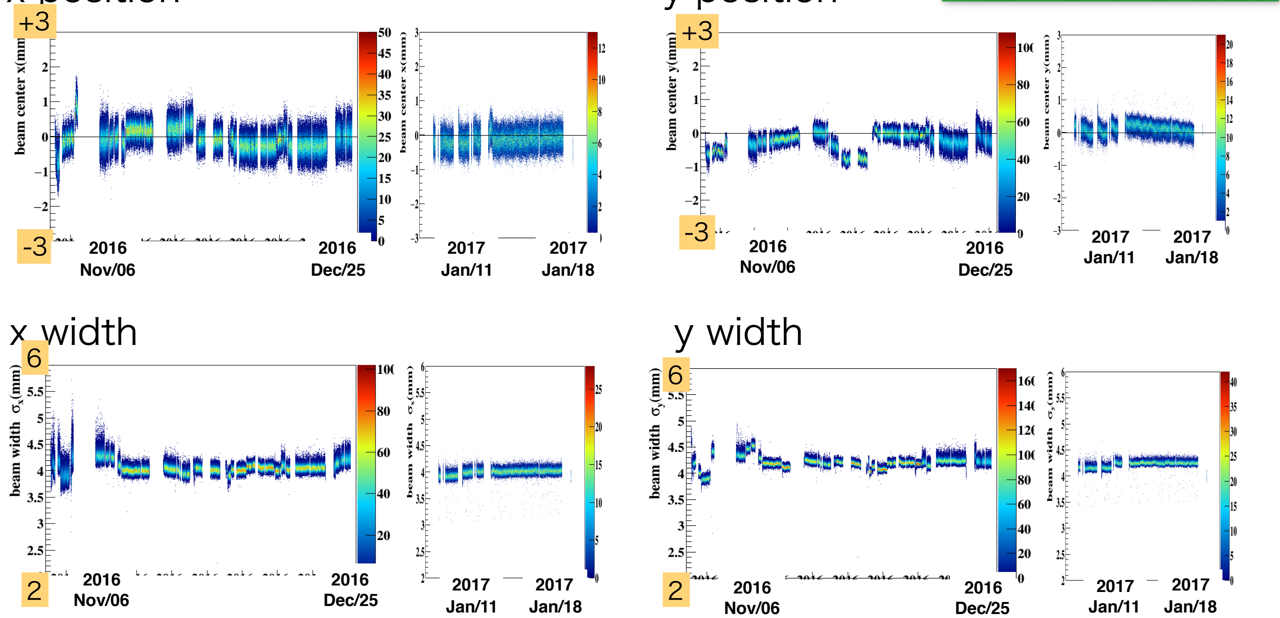
Important to keep the beam direction stable

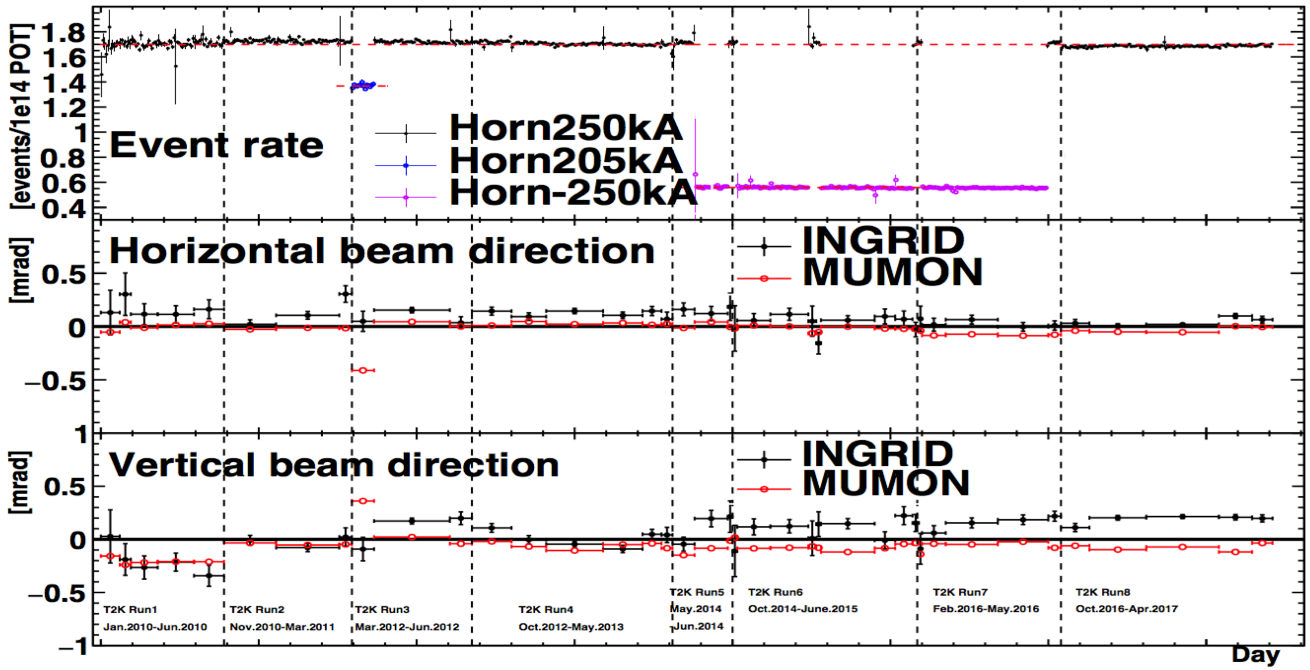
(1mrad corresponds to a 2% shift of peak ν energy at SK)

Beam stability

proton beam

- Proton beam position, angle and width at target is controlled to make the ν beam direction stable within much better than 1mrad
- Event rate is also stable ~1%





Neutrino flux in T2K analysis

- ν oscillation can be studied by comparing FD observation with prediction

$$N_{FD}(E_{rec}) = \sum_{E_t} \sum_{mode} \Phi(E_t) P_{osc}(E_t) \sigma(E_t, mode) \epsilon(E_t, mode) M(E_t, E_{rec})$$

flux, x-sec, efficiency are not identical between FD and ND

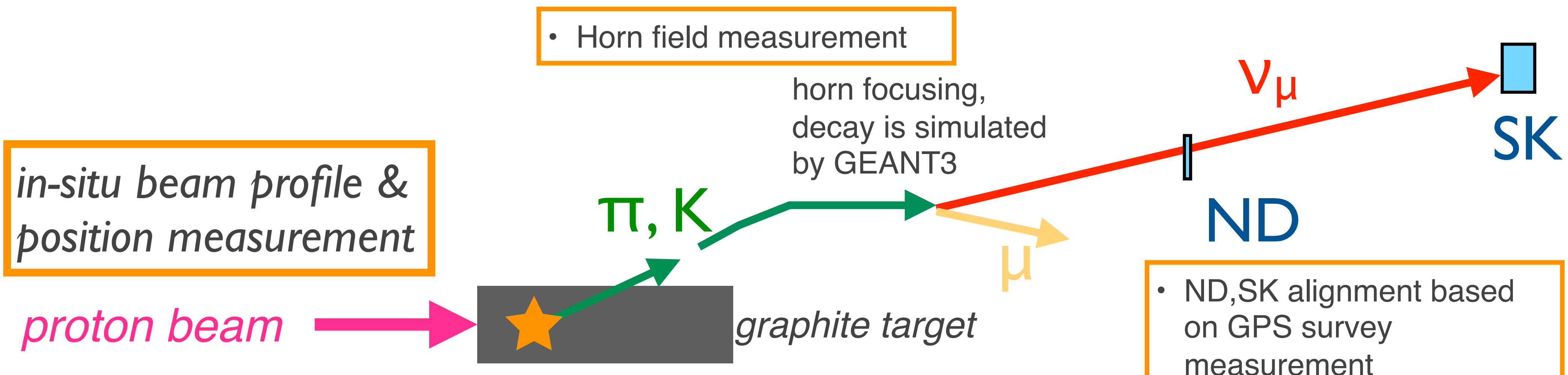
$$N_{ND}(E_{rec}) = \sum_{E_t} \sum_{mode} \Phi(E_t) \sigma(E_t, mode) \epsilon(E_t, mode) M(E_t, E_{rec})$$

E_t:true ν energy, ε:efficiency, M: migration matrix

- We want to reduce the uncertainties of FD prediction using ND data
- but, we need to know correlation between FD and ND for ν flux and ν cross section
  - Considering this correlation based on the basis of ν flux and cross section

Neutrino flux prediction

T2K Neutrino beam simulation based on “measurement”



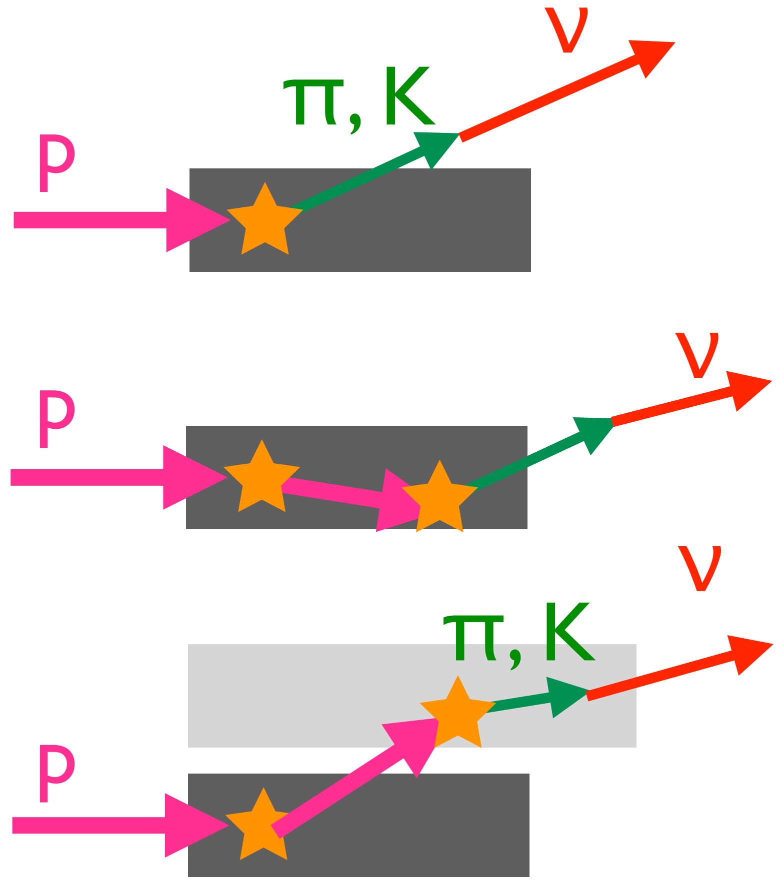
Hadron production in 30GeV proton + C

- ***Use CERN NA61/SHINE pion & kaon measurement (large acceptance: >95% coverage of ν parent pions)***
- *Kaon, pion outside NA61 acceptance, other interaction in the target were based on FLUKA simulation*
- *Secondary interaction x-sections outside the target were based on experimental data*

Breakdown of hadron interaction

- Percentage of T2K FD flux to in-target or out of target interaction

	in-target primary int.	other than the in-target primary int. (out of target int.)
ν_μ	63.2%	36.8% (12.4%)
$\bar{\nu}_\mu$	41.5%	58.5% (45.1%)
ν_e	61.7%	38.3% (12.7%)
$\bar{\nu}_e$	54.0%	46.0% (27.2%)

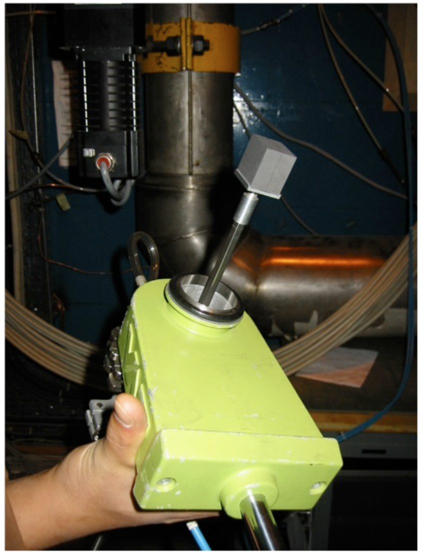


in-target primary interaction is a main contribution while there is a significant contribution from secondary+tertiary and/or out of target interactions for wrong sign flux

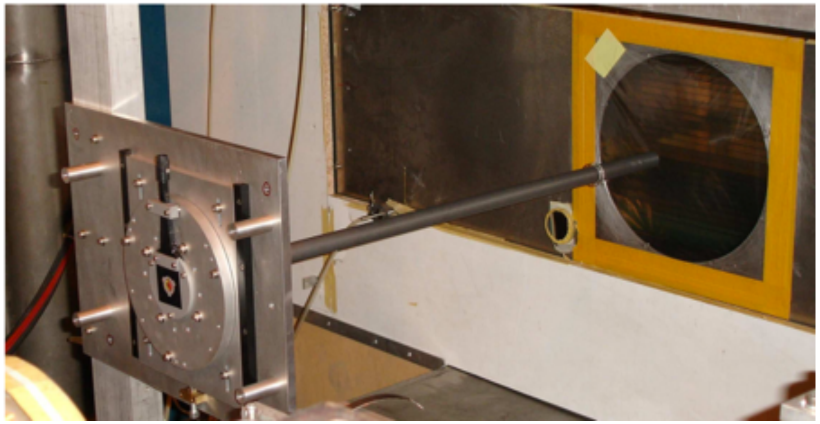
Strategy of the flux prediction with NA61

Use the thin and thick target data (step by step approach)

- Thin target data : 2cm ($0.04\lambda_I$)
  - data taken in 2007 and 2009
  - we can tune the in-target primary interactions
  - for secondary and tertiary interactions, with material(A) and energy scaling
  - current flux prediction uses the 2009 data



- Thick target data : 90cm ($1.9\lambda_I$) = T2K target length
  - data taken in 2007, 2009 and 2010
  - we can tune all the in-target interactions
  - status of T2K flux tuning will be discussed in M.Friend talk



2009 thin target data

- ~5.4M triggers collected
- production cross section ($\sigma_{prod.} = \sigma_{inel.} - \sigma_{q.e.}$) and multiplicity of $\pi^{\pm}$, $K^{\pm}$, K^0_S, p^+ are used to calculate the T2K ν flux

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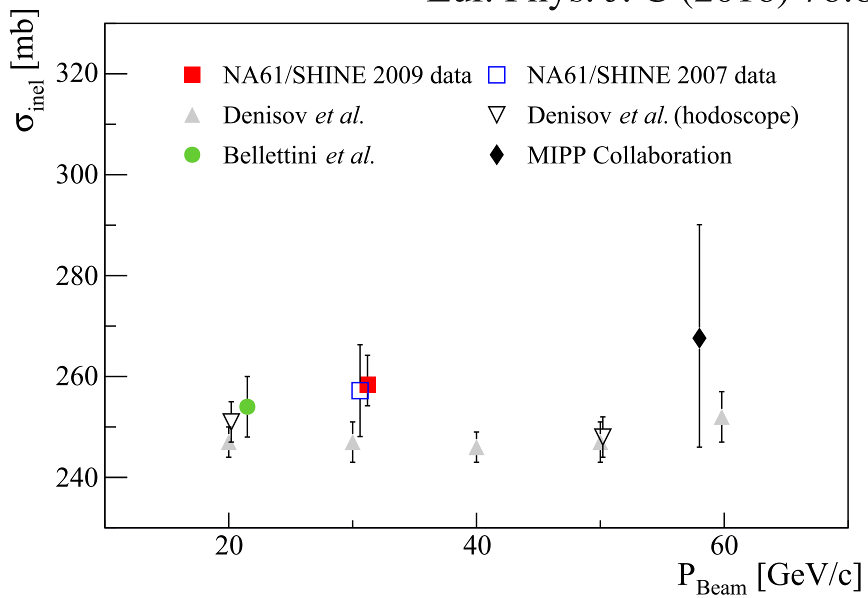
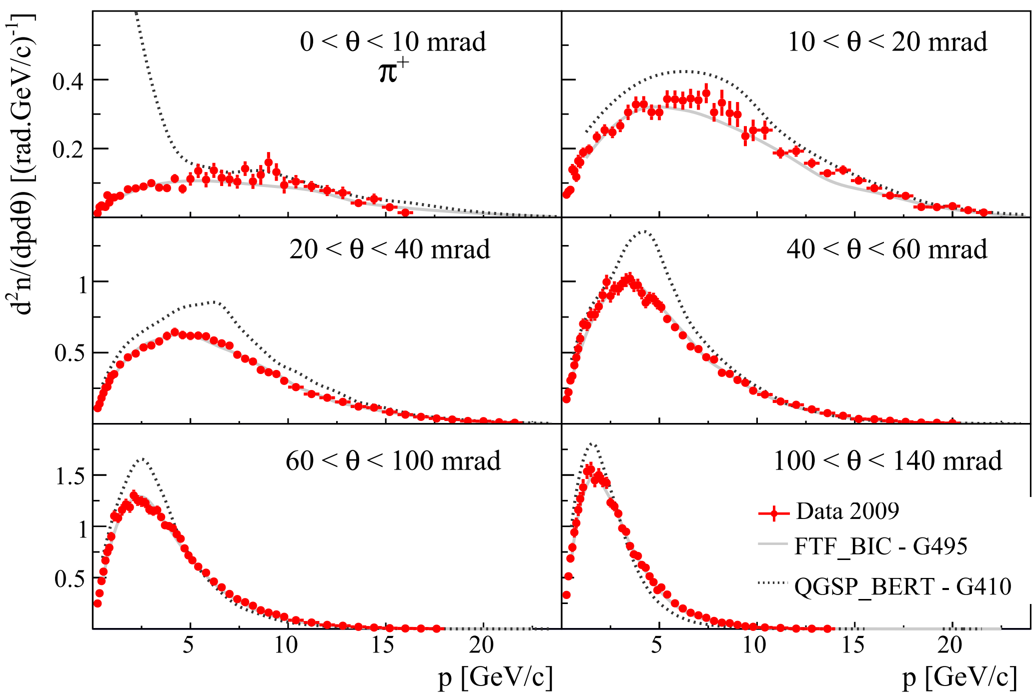
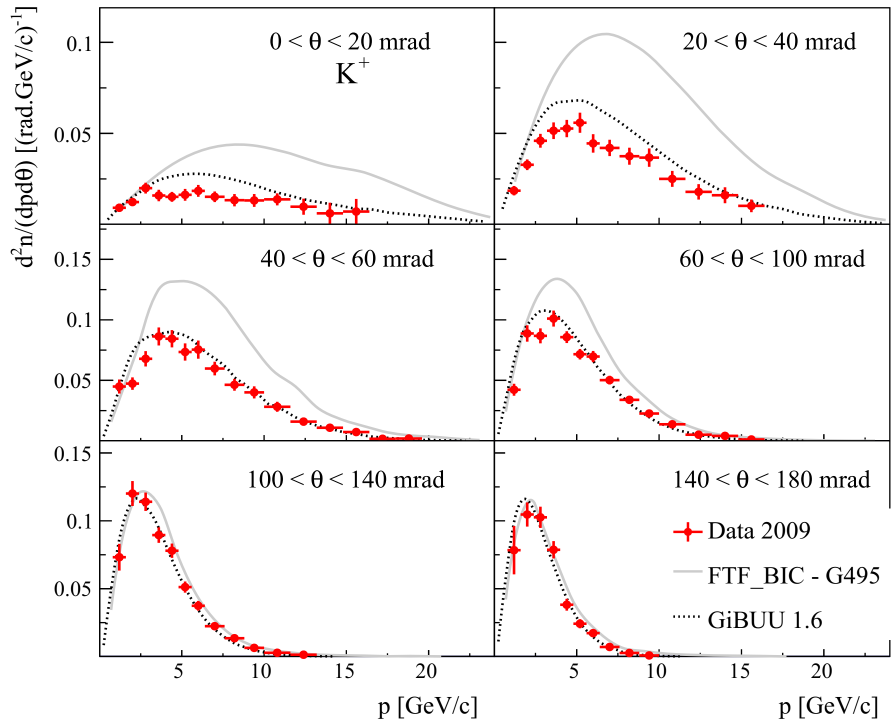
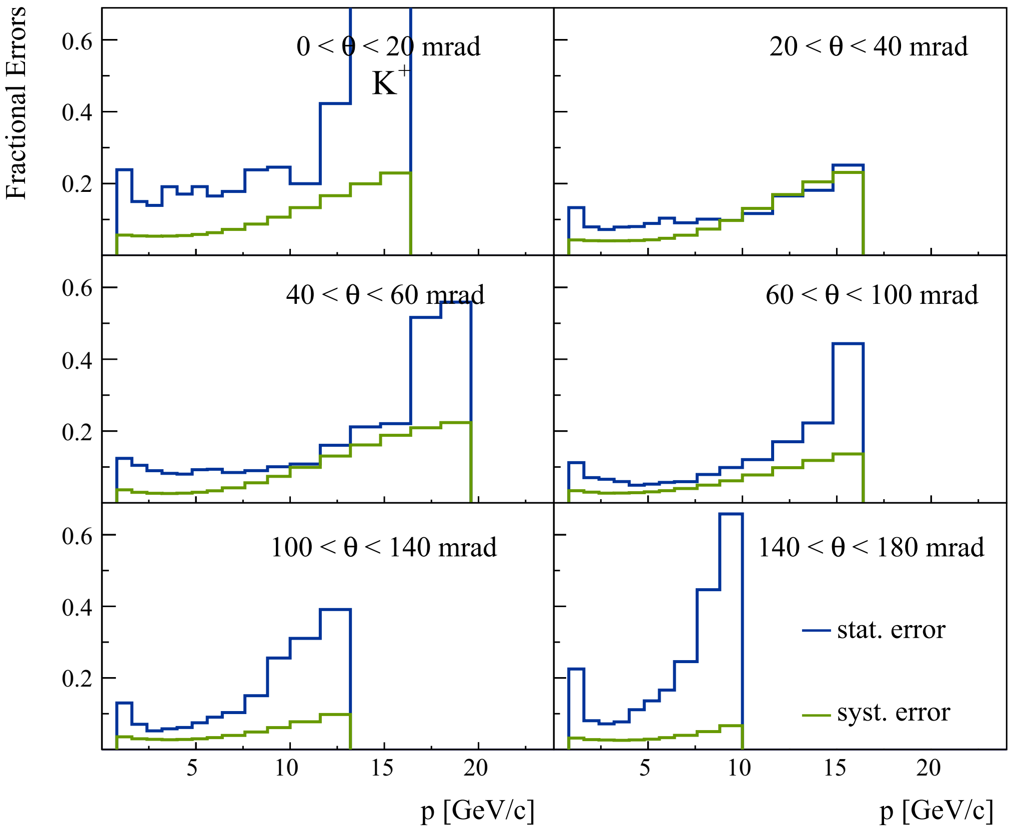


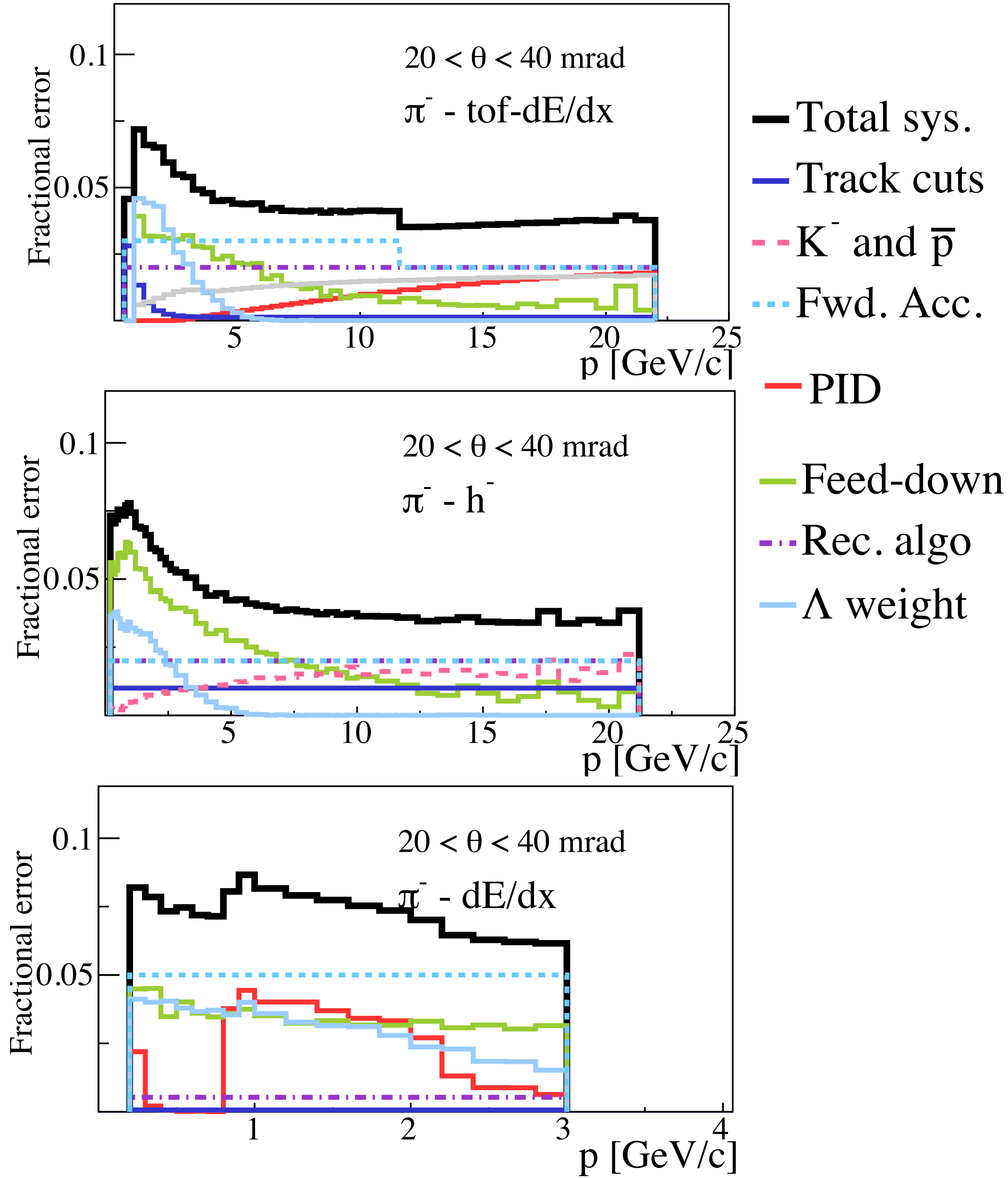




2009 thin target data(cont.)

- We use the systematic uncertainties of NA61 measurement to evaluate the flux uncertainty

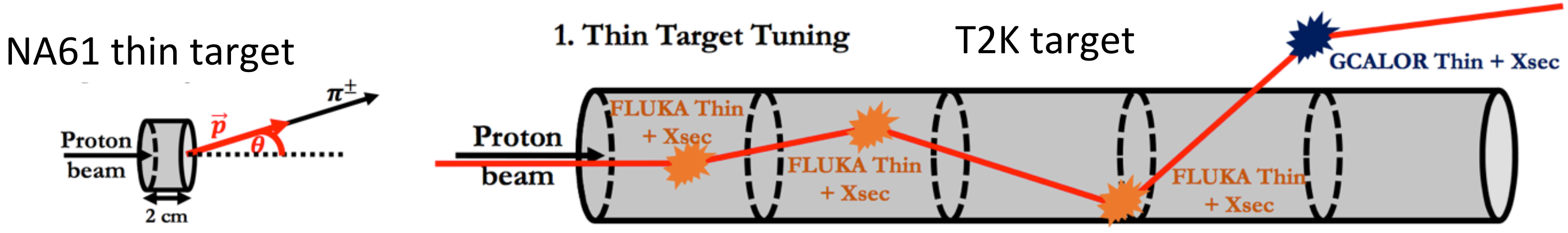




Hadron production tuning

In the flux prediction, hadron production tuning is performed in the two step

(1) interaction rate tuning



- interaction rate is tuned using the experimental $\sigma_{prod.}$ (= $\sigma_{inel.}$ - $\sigma_{qe.}$)
- 30GeV p+C interaction rate tuning is based on the NA61 data

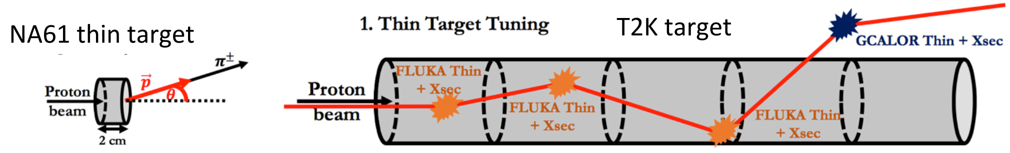
NA61 $\sigma_{\rm prod} = 230.7 \pm 2.8({\rm stat}) \pm 1.2({\rm det})\,^{+6.3}_{-3.5}({\rm mod})\,{\rm mb}$

FLUKA σ_{prod} = 240.3 mb

- uncertainty size is determined by the size of σ_{qe} (=33.3mb@30GeV)

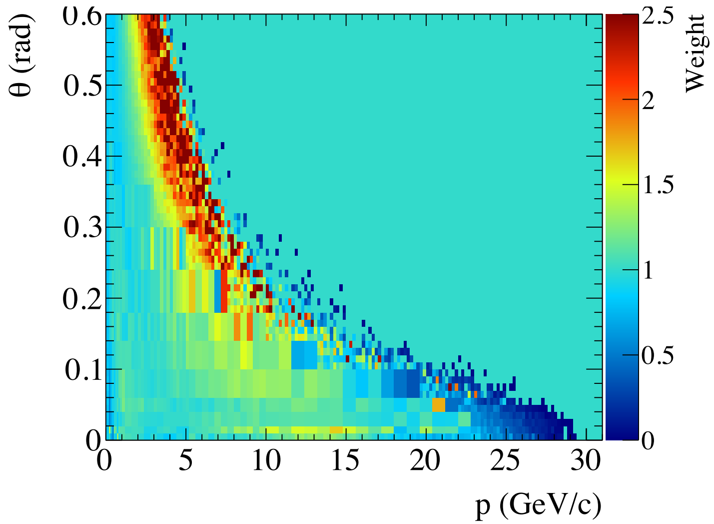
Hadron production tuning (cont.)

(2) multiplicity tuning

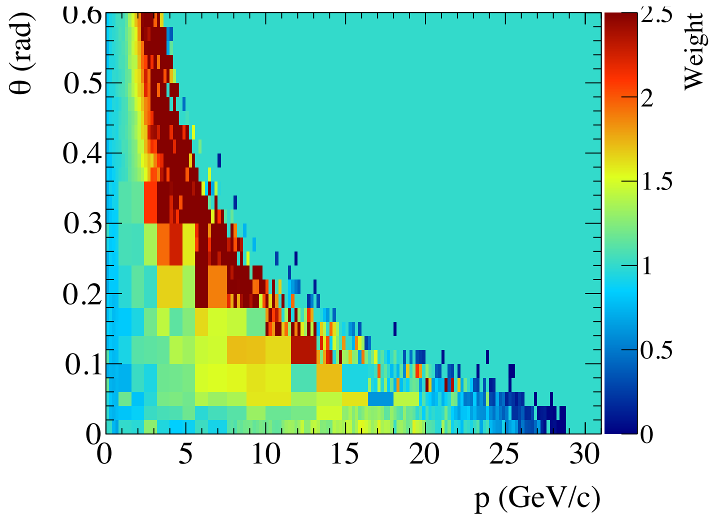


- utilizing the NA61 2009 thin target $\pi^{\pm}$, $K^{\pm}$, K^0_S, p^+ multiplicity data
  - primary p+C interaction
  - secondary & tertiary interaction with A scaling and energy scaling
- flux uncertainties from the NA61 systematic errors, NA61 non-covered phase space and scaling methods are evaluated

NA61/FLUKA (π^+ on C)

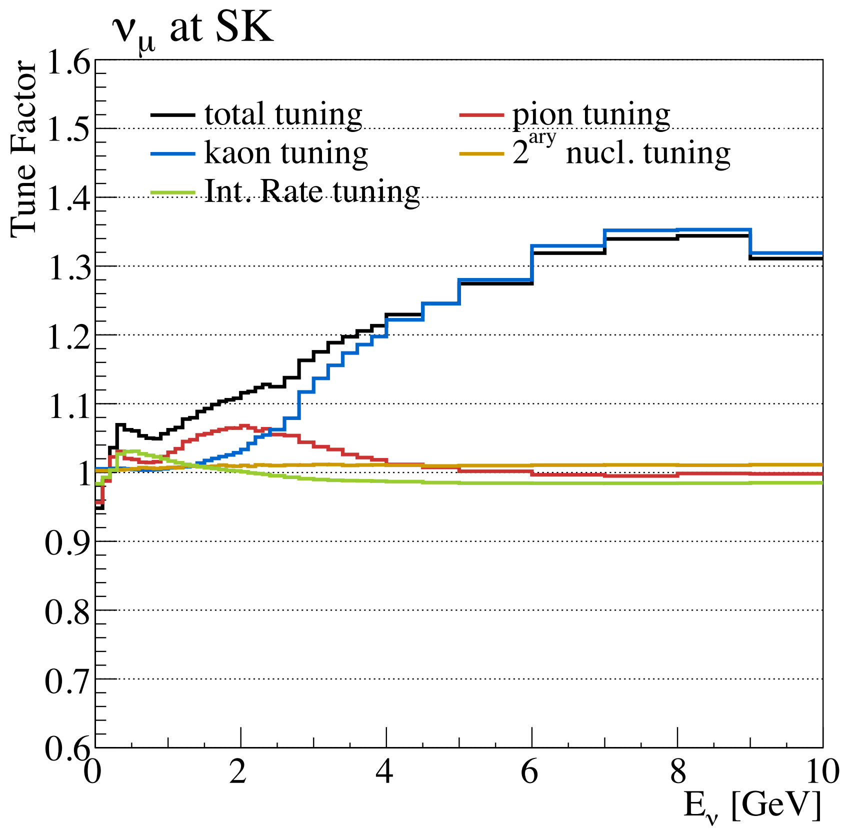


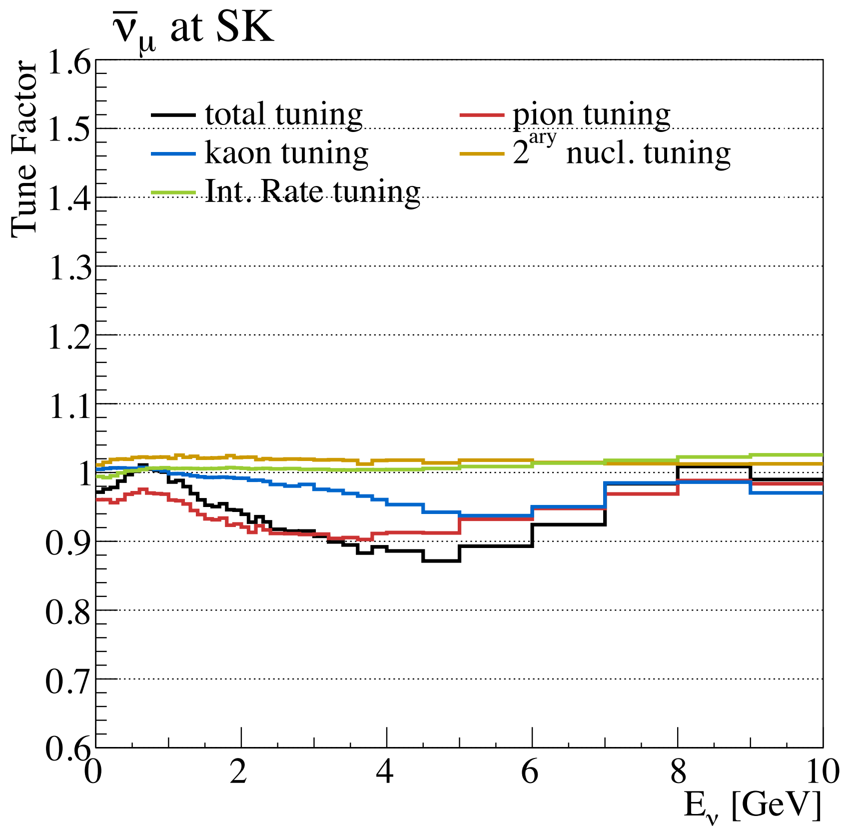
NA61/FLUKA (K^+ on C)



Results of hadron production tuning

- contribution of each hadron production tuning for FD flux (forward horn current) is shown



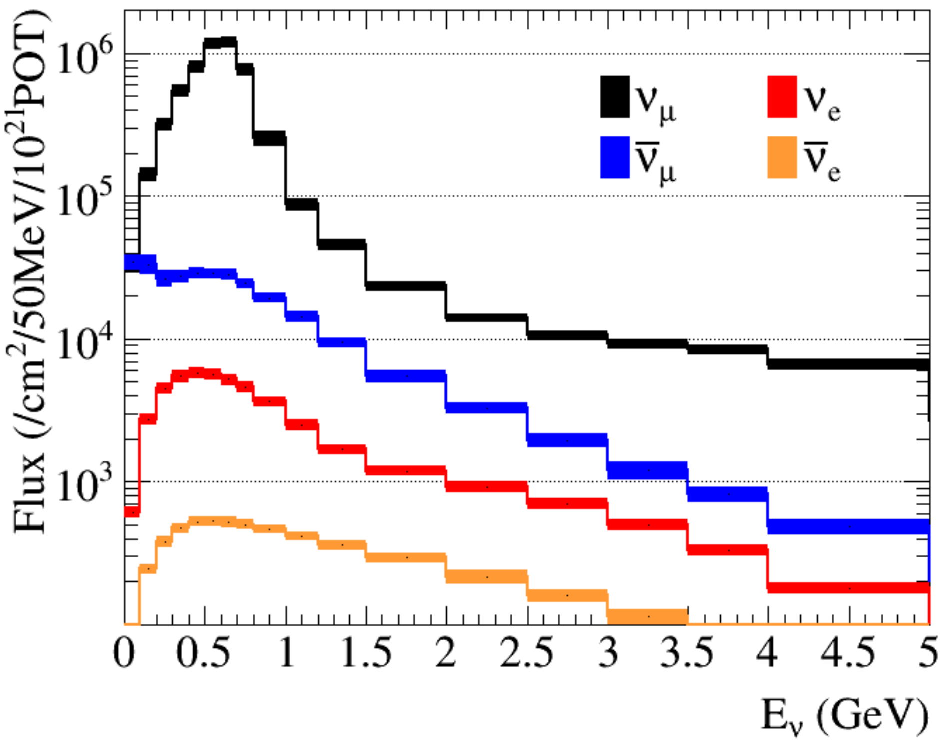


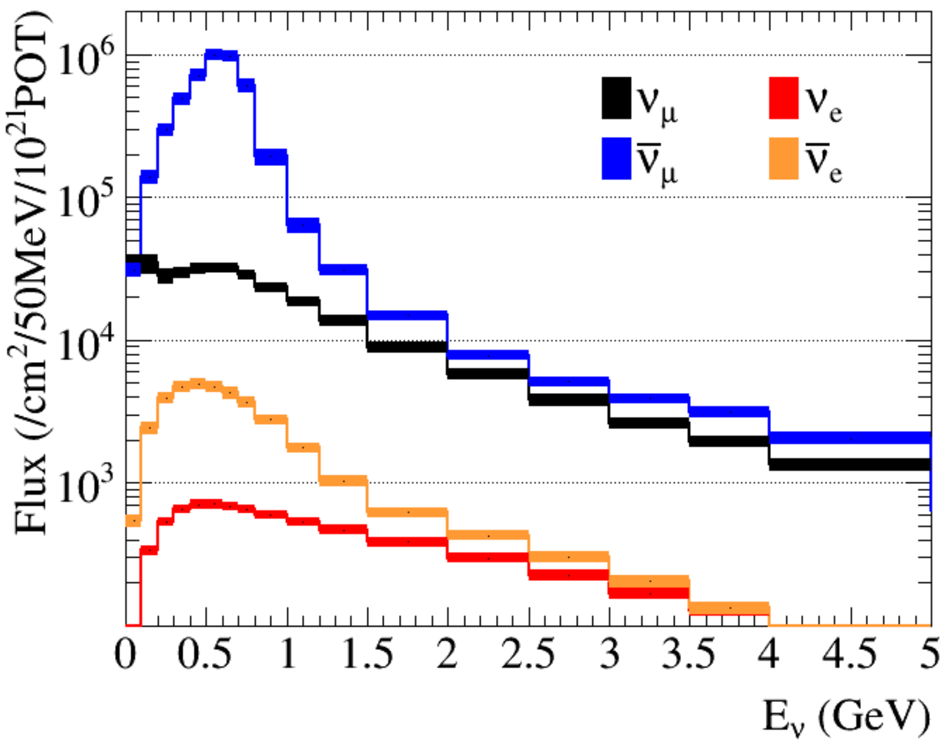
- major contribution at T2K peak energy (0.6GeV) is the pion multiplicity and interaction rate tuning

Predicted flux at FD

ν mode $\bar{\nu}$ mode

box indicates size of the systematic uncertainty

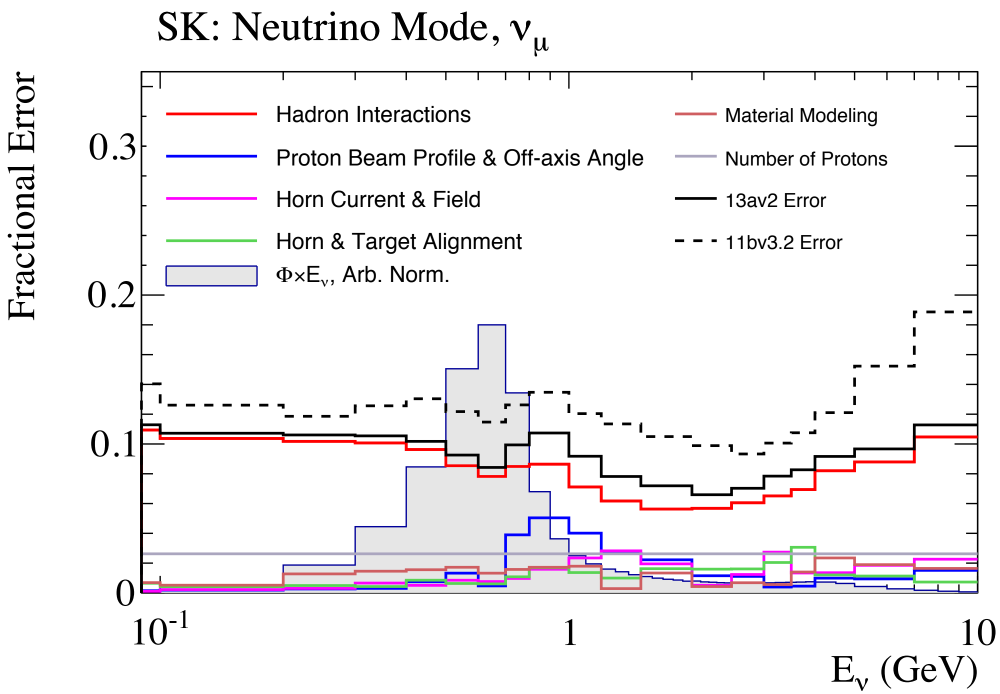


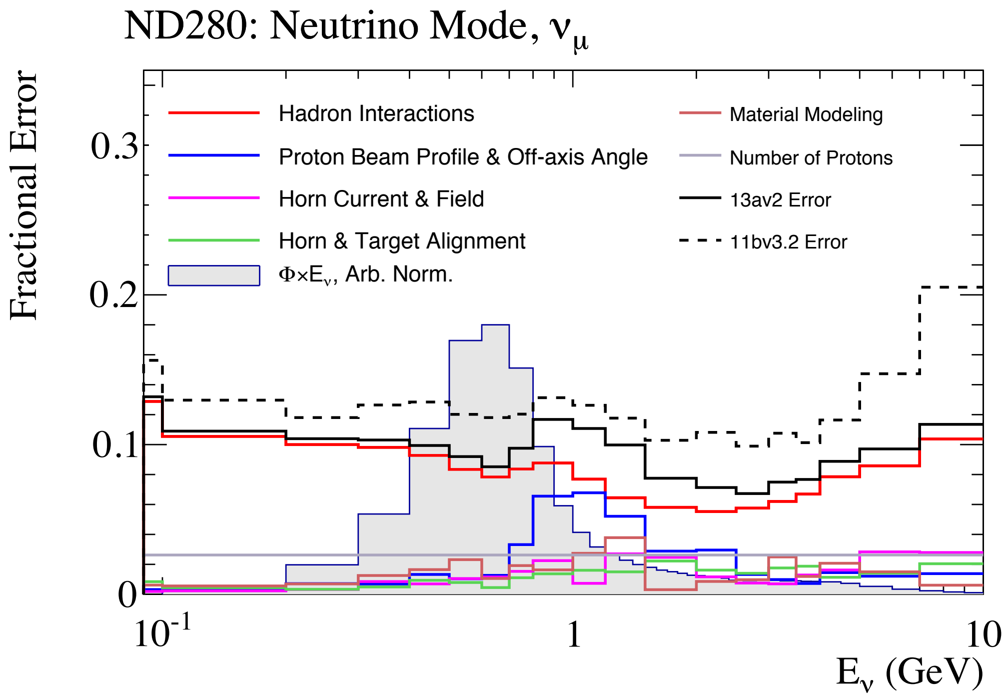


- ν_μ mainly comes from π decay
- ν_e comes from μ and K decays
  (μ decay is dominant below 1GeV)
  - less than 1% intrinsic beam ν_e

- a large wrong-sign components in anti-ν mode
  - ~3% at peak energy

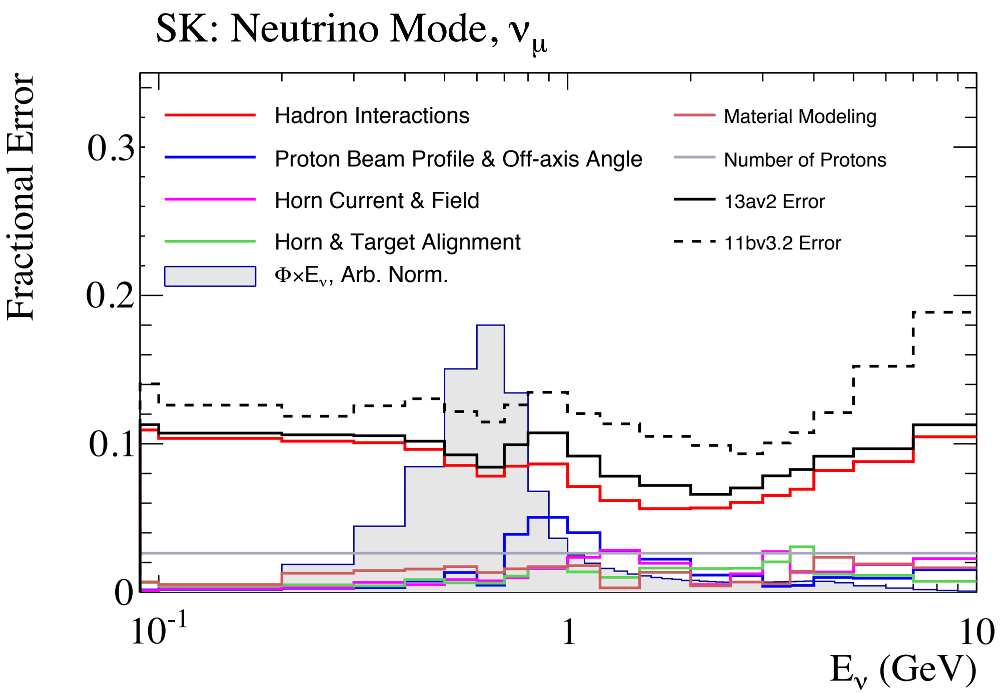
T2K flux uncertainty



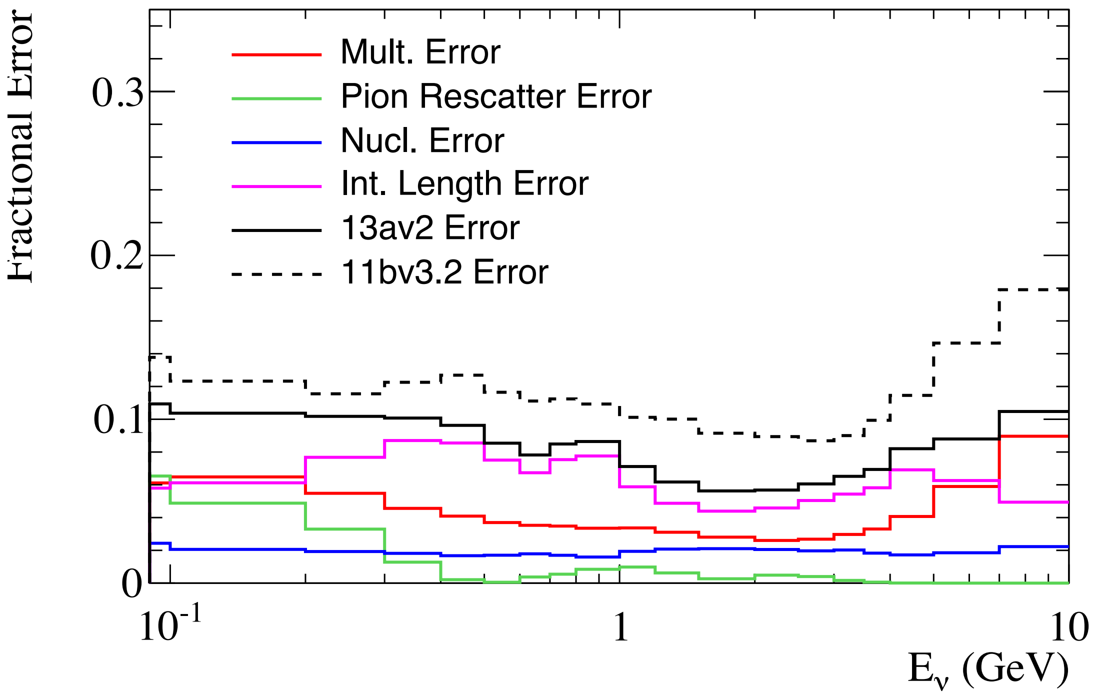


- total uncertainty is ~10% at peak (it is comparable between ν and anti-ν mode)

T2K flux uncertainty (cont.)



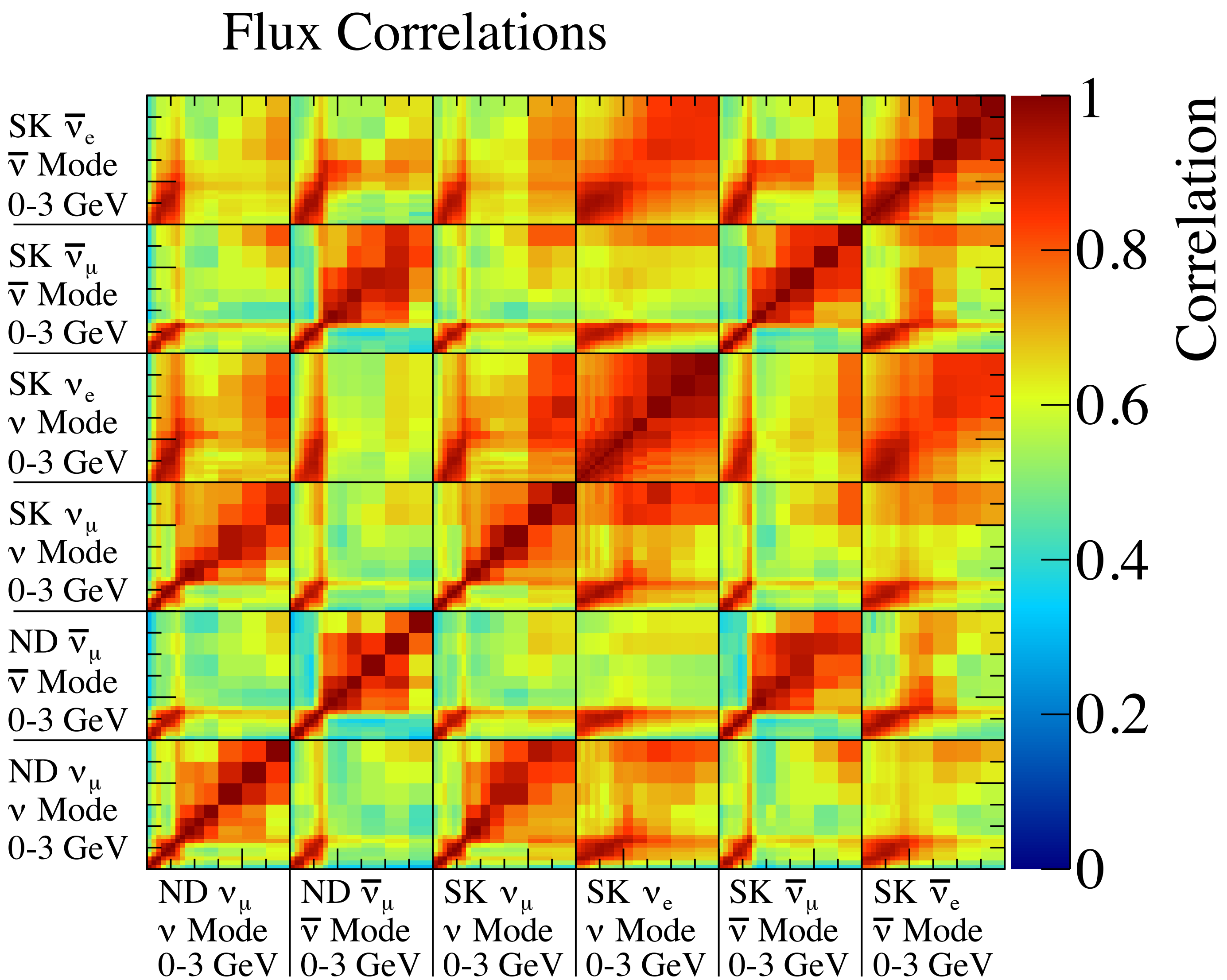
Breakdown of "Hadron interactions"



- Interaction length error is the largest source of the hadron interaction error

Flux correlation

- correlation between FD and ND (as well as the covariance matrix) is also calculated thanks to the knowledge of hadron production data



energy bin definition:
0.0-0.1, 0.1-0.2, 0.2-0.3, 0.3-0.4, 0.4-0.5, 0.5-0.6, 0.6-0.7, 0.7-0.8, 0.8-1.0, 1.0-1.2, 1.2-1.5, 1.5-2.0, 2.0-2.5, 2.5-3.0

Toward further improvement

Fractional error on N_{FD} (T2K 2016 OA paper)

Source (%)	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
ND280-unconstrained cross section	0.7	3.0	0.8	3.3
Flux and ND280-constrained cross section	2.8	2.9	3.3	3.2
Super-Kamiokande detector systematics	3.9	2.4	3.3	3.1
Final or secondary hadron interactions	1.5	2.5	2.1	2.5
Total	5.0	5.4	5.2	6.2

w/o ND280 fit
flux error is 7~9%
xsec error is 7~10%

- The flux uncertainties is reduced using ND data thanks to the correlation between FD and ND
  - e.g. F/N ratio error is already less than 2% (sufficient precision)
- Next step is to reduce the ND280 flux uncertainty (~10% at peak) which is the present largest error in the cross section measurement
- We can reduce the N_{FD} error with the improved cross section measurement

Summary

- T2K flux prediction with ~10% uncertainty is achieved thanks to NA61/SHINE measurement
  - we were able to tune the flux with the 2007 thin target data before the T2K ν_e appearance indication in 2011
- Hadron production tuning is still a largest uncertainty of T2K flux
  - we plan to reduce this using the replica target data
  - M.Friend will give a talk of future improvement