

Systematic uncertainty for T2K-II : Beam

2017/05/20, 3rd Workshop on Neutrino
Near Detectors based on gas TPCs
Ken Sakashita (KEK/J-PARC) for T2K Beam group

Contents

- Present flux uncertainty
- Prospects for improvement
- Summary

Neutrino flux systematic error in T2K analysis

Oscillation analysis

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



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

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

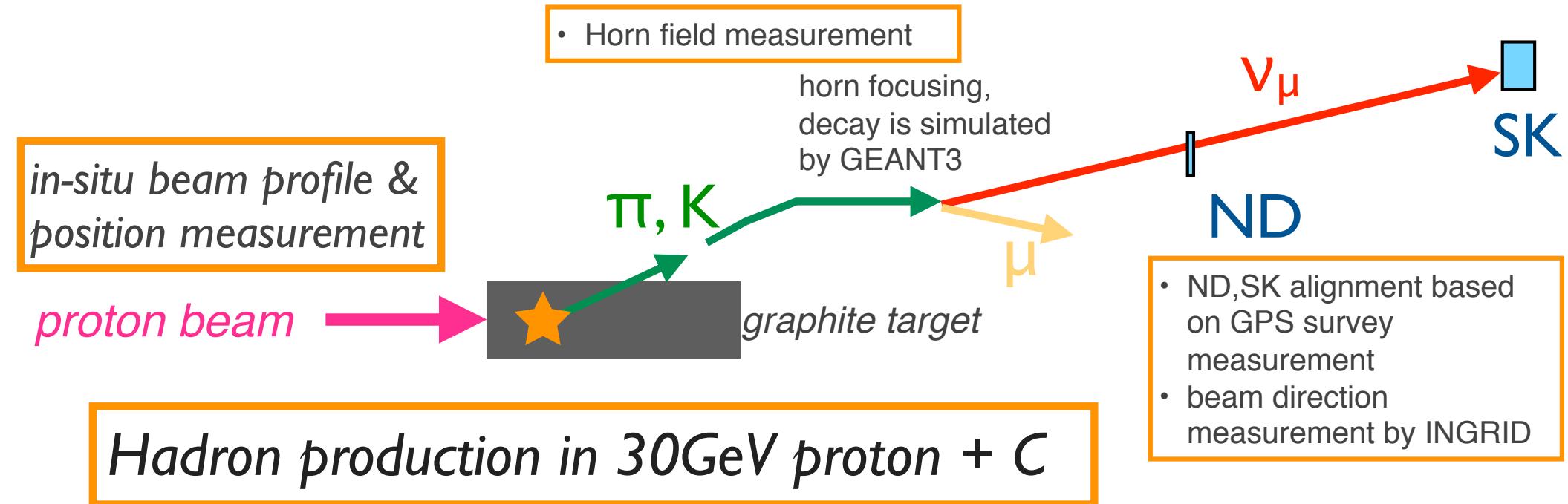
- Φ_{FD} and Φ_{ND} is not identical
- the flux uncertainty is constrained by ND measurement

ν cross section analysis

- absolute flux uncertainty is one of error sources in the cross section measurement

Neutrino flux prediction

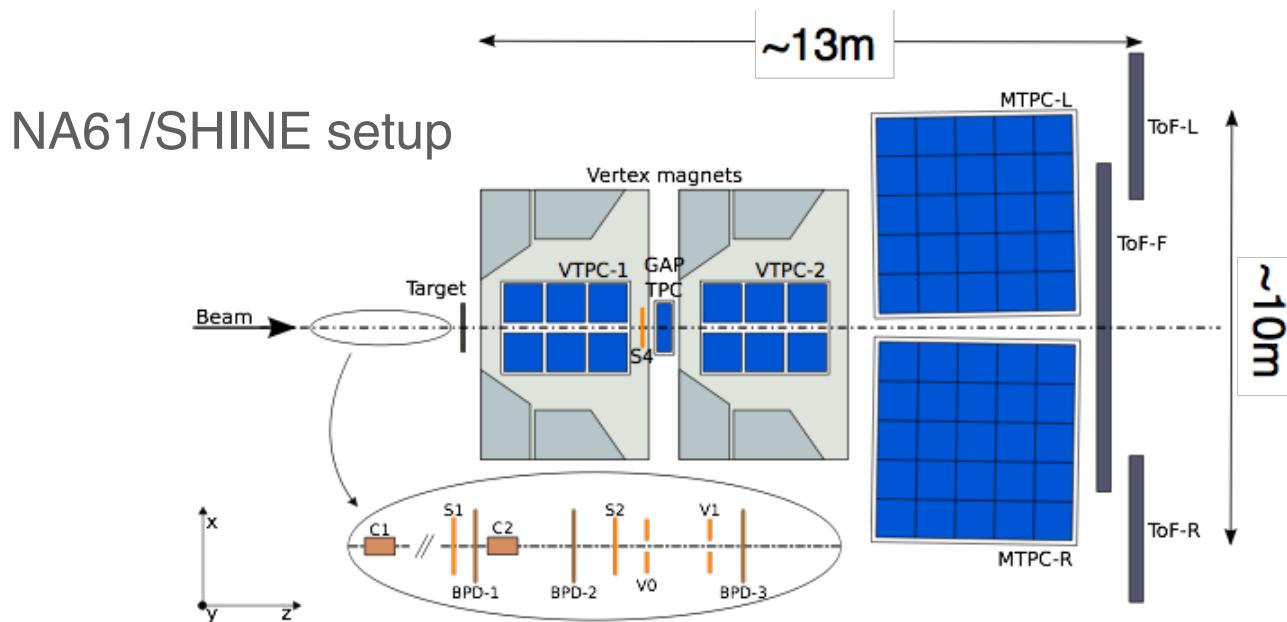
T2K Neutrino beam simulation based on “measurement”



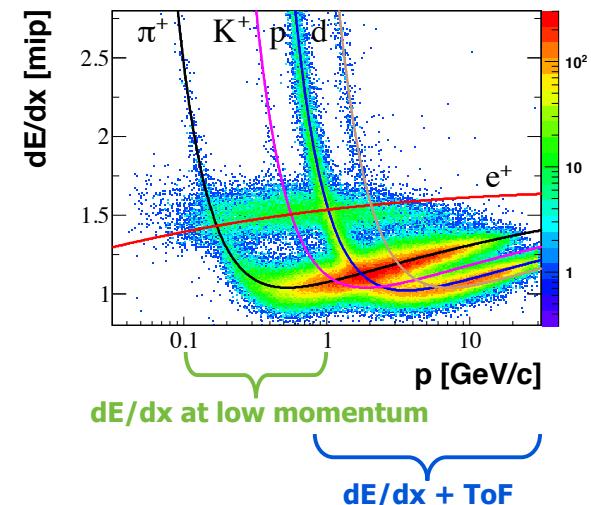
- Use **CERN NA61/SHINE pion & kaon measurement**
(large acceptance: >95% coverage of ν parent pions)
- Kaon, pion outside NA61 acceptance, other interaction in the target were based on FLUKA simulation
- Secondary interaction x-sections outside the target were based on experimental data

CERN NA61/SHINE measurement

Measure hadron(π , K, etc.) yield distribution
in 30 GeV p+C inelastic interaction



- thin target $4\% \lambda_1$ (2cm) and replica target (90cm)



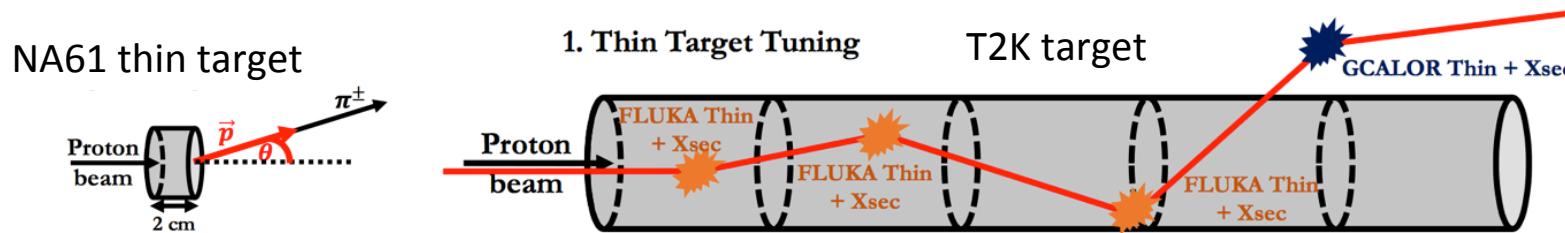
*Large acceptance
spectrometer + TOF*

- List of measurement (year)
 - thin target data (2007,2009)
 - replica target data (2007,2009,2010)

Thin target paper: Eur.Phys.J.C76(2016), 84
Replica target paper : Eur.Phys.J. C76(2016), 617

Hadron production tuning

Flux tuning based on the NA61 thin target data



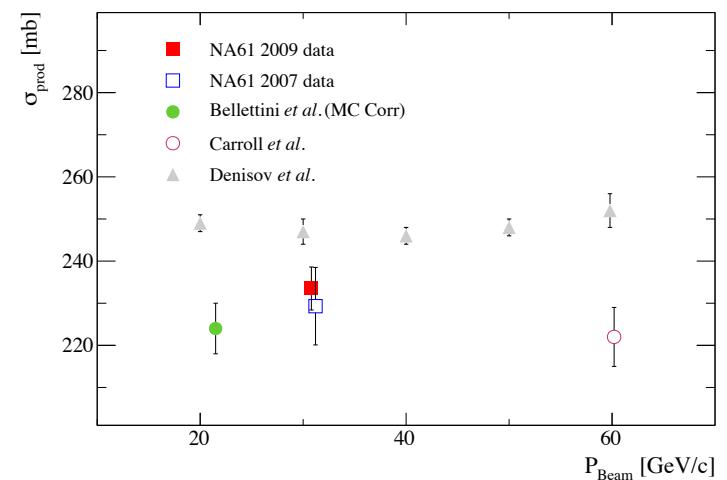
(1) interaction rate tuning

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

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

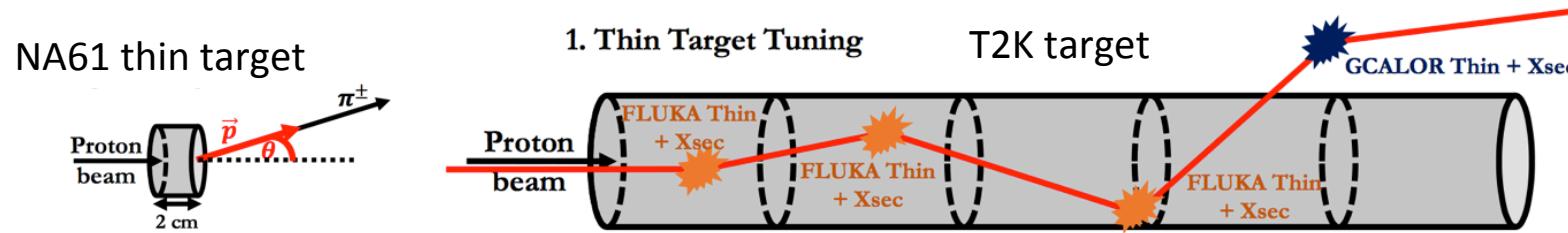
$$\text{FLUKA } \sigma_{\text{prod}} = 240.3 \text{ mb}$$

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



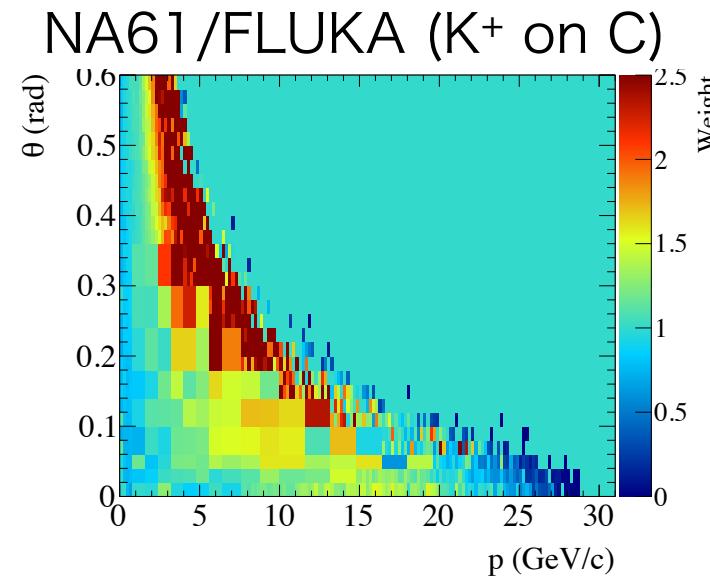
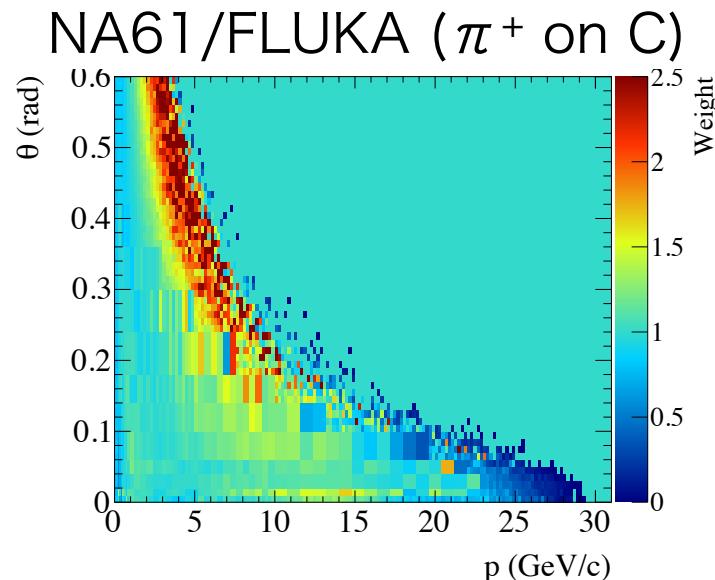
Hadron production tuning (cont.)

Flux tuning based on the NA61 thin target data

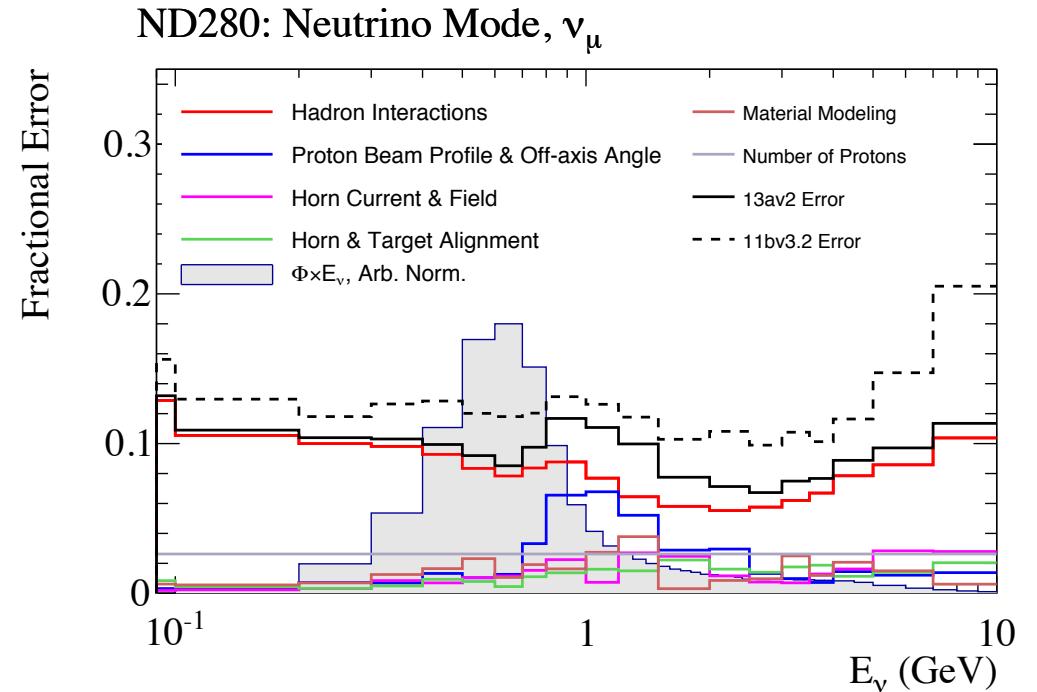
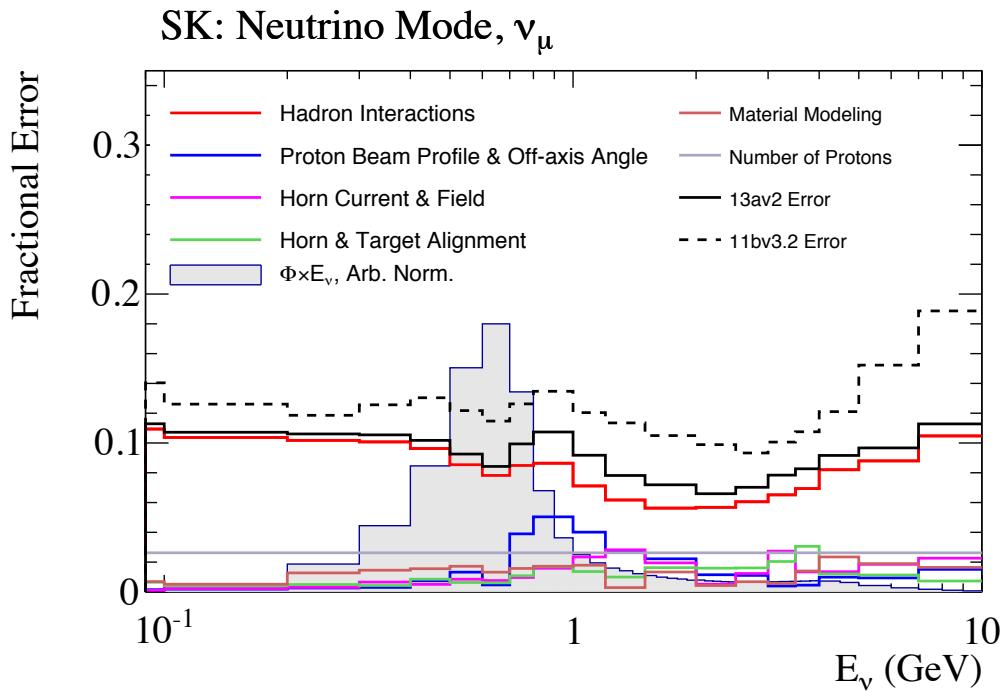


(2) multiplicity tuning

- using the NA61 2009 thin target π^\pm , K^\pm , K^0_s , p^+ multiplicity data
- flux uncertainty is evaluated using NA61 systematic errors

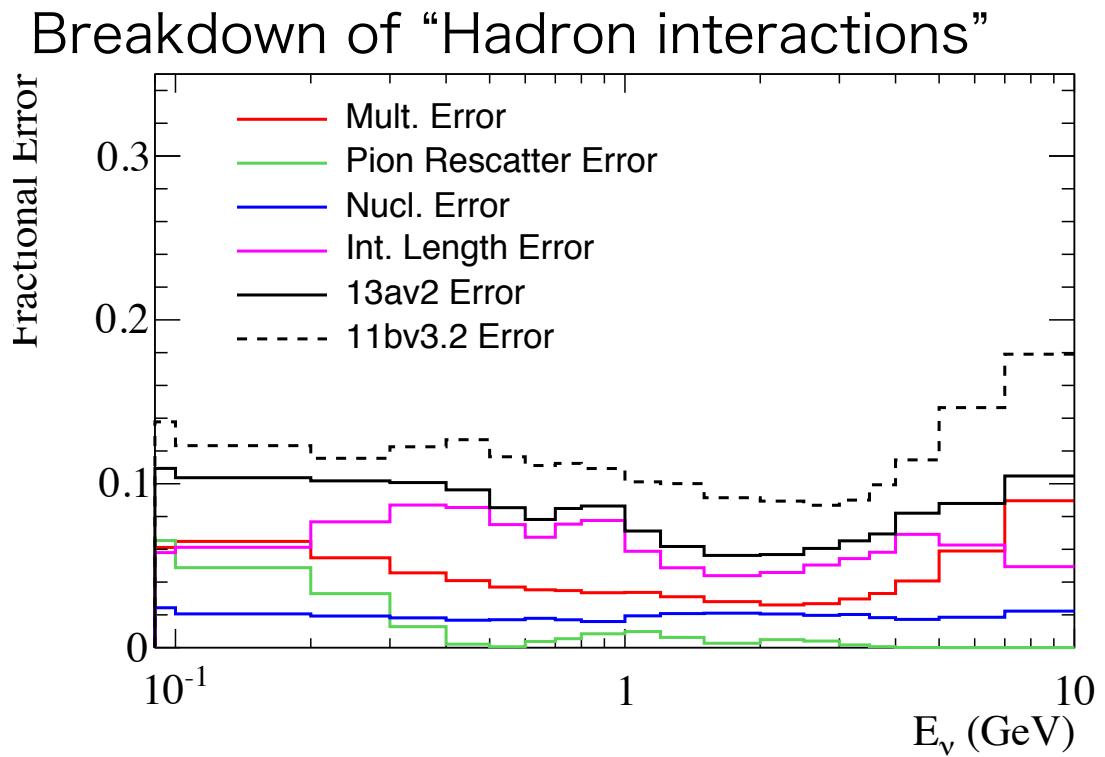
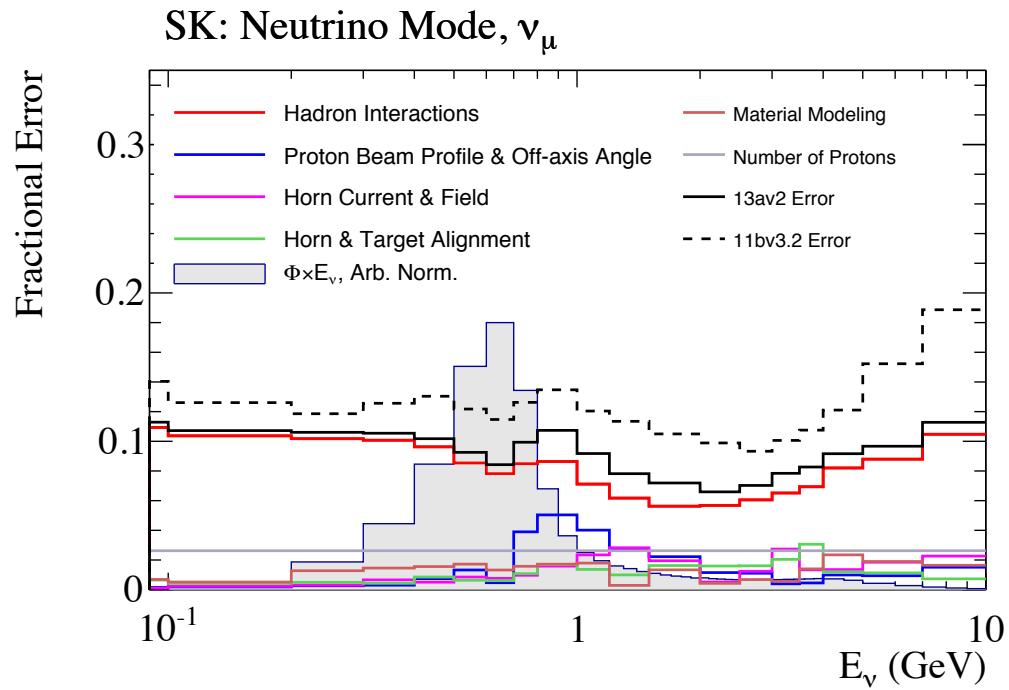


Present flux error



- total uncertainty is ~10% at peak (it is comparable between ν and anti- ν mode)
- correlation between FD and ND is also calculated

Present flux error (cont.)



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

T2K systematic error table

Fractional error on N_{sk} (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%

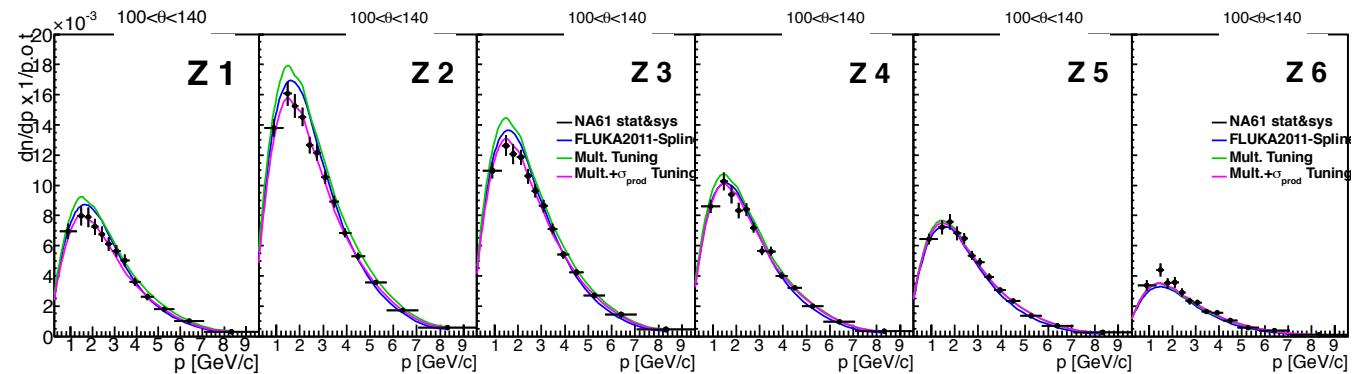
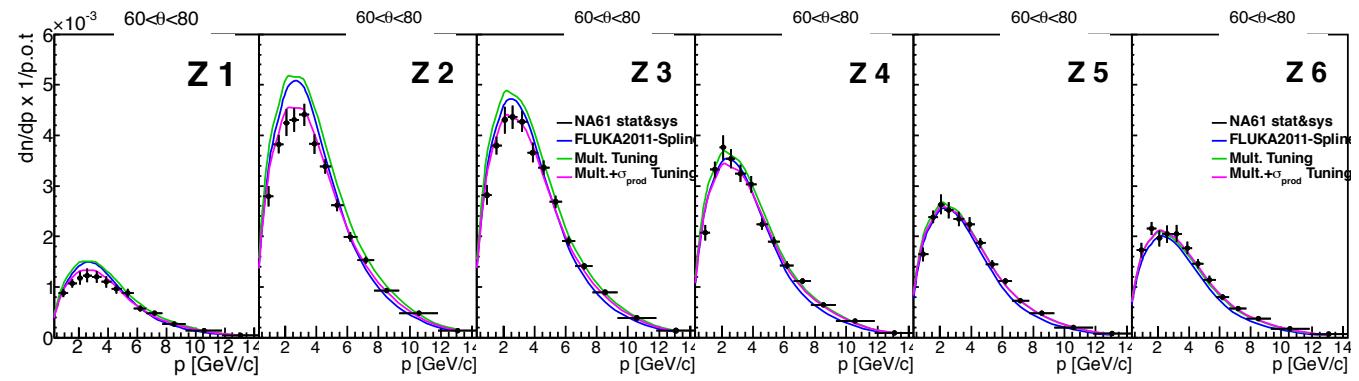
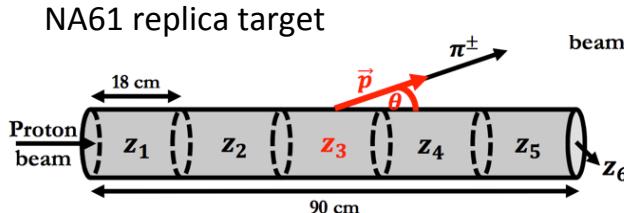
- the flux uncertainties is reduced using ND data thanks to the correlation between FD and ND
 - e.g. F/N ratio error is already <2%
- for the cross section measurement at ND280, the flux uncertainty (~10% at peak) is the largest error
- flux error improvement contributes ND280 cross section error → oscillation analysis

Prospects for further improvement

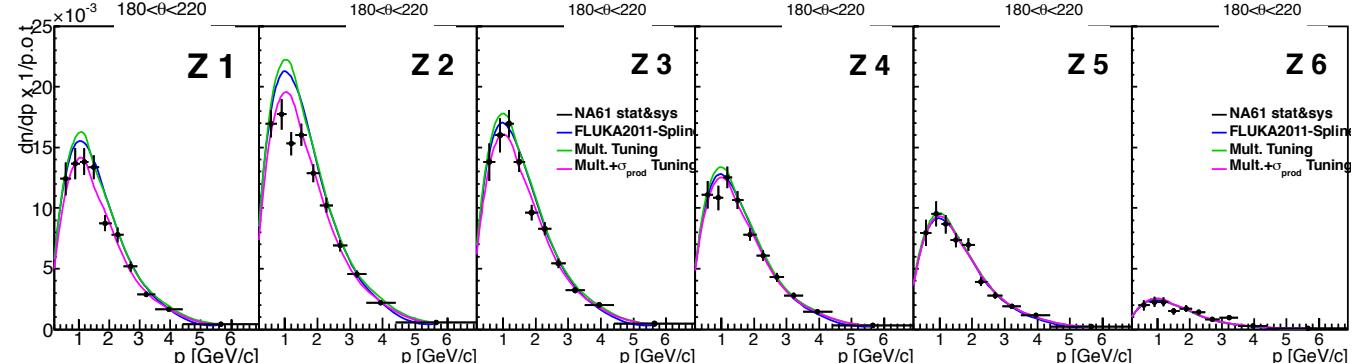
- Hadron production tuning using NA61 replica target data
- Proton beam profile error + off-axis error improvement
- Normalization error (CT) improvement

NA61 replica target data (2009)

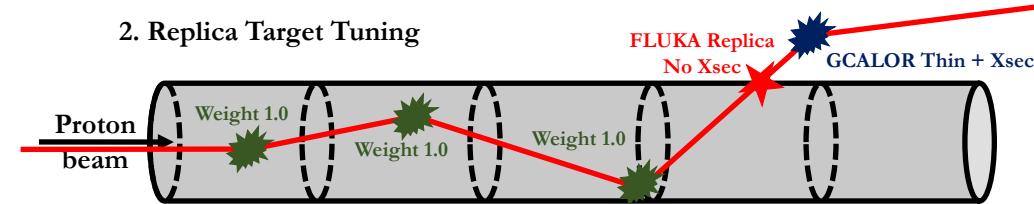
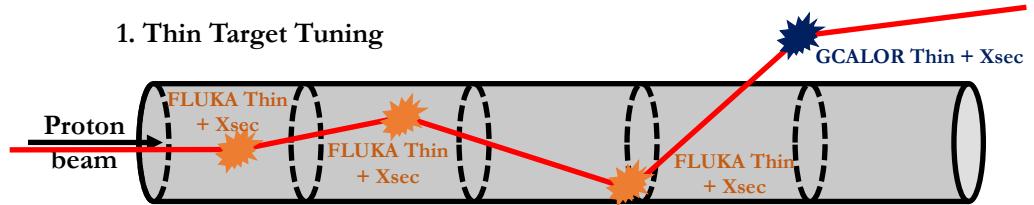
π^\pm multiplicities
on the surface of
target measured
in (p, θ, z) bin



Studying two
approaches to use
the data in the flux
prediction



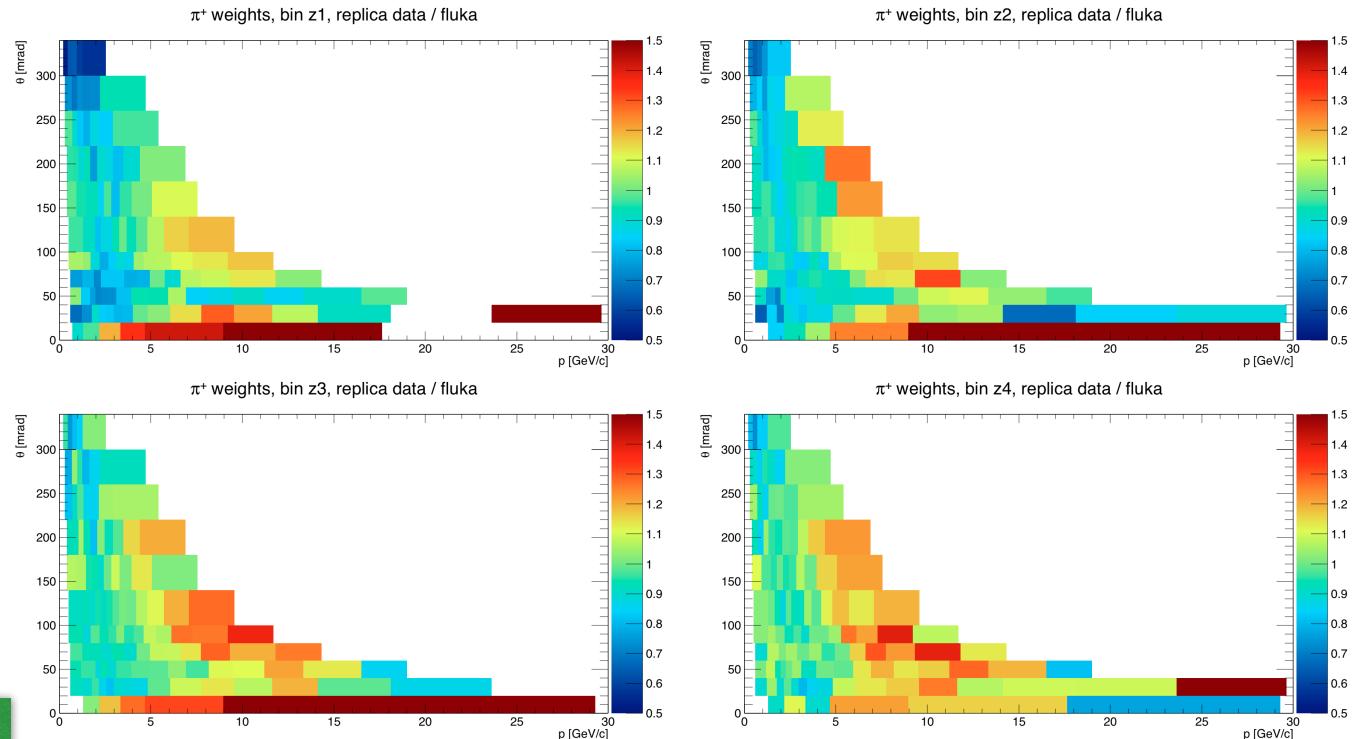
Re-weighting method



π^+ replica weights
(NA61 replica data / fluka)

El. and Quasi-el. interactions included

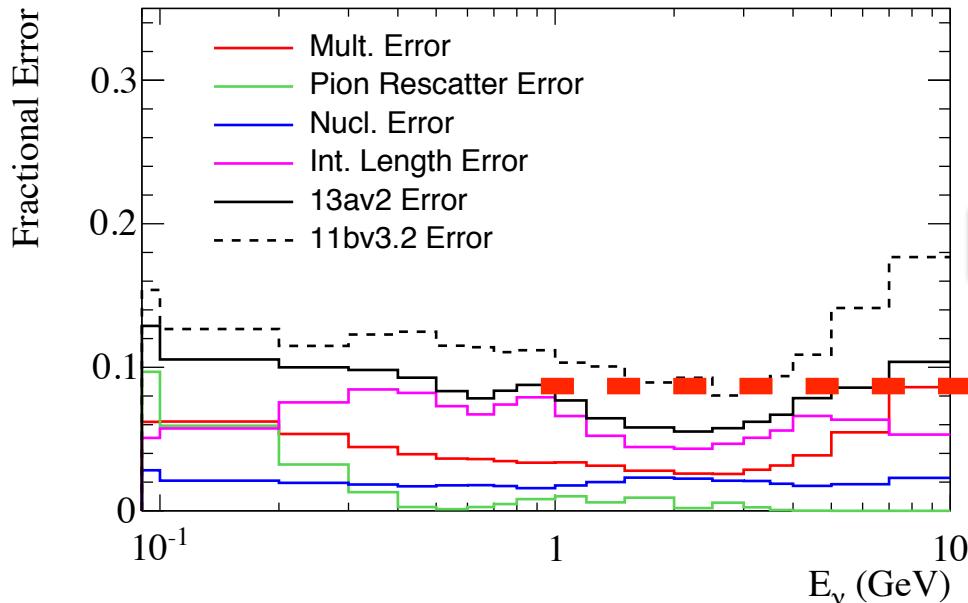
instead of tuning the interaction rate and multiplicity in the target, tuning the multiplicity at the surface of target



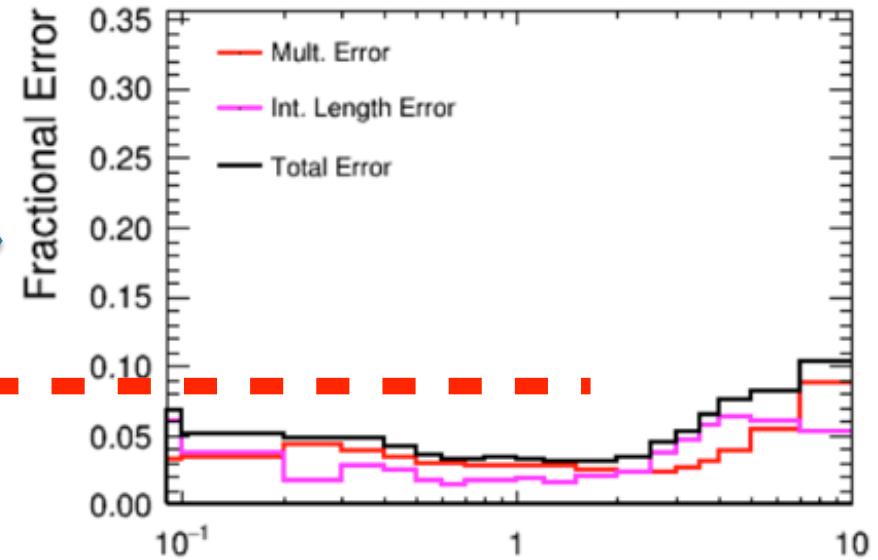
Improved flux uncertainties (preliminary)

Breakdown of “Hadron interactions”

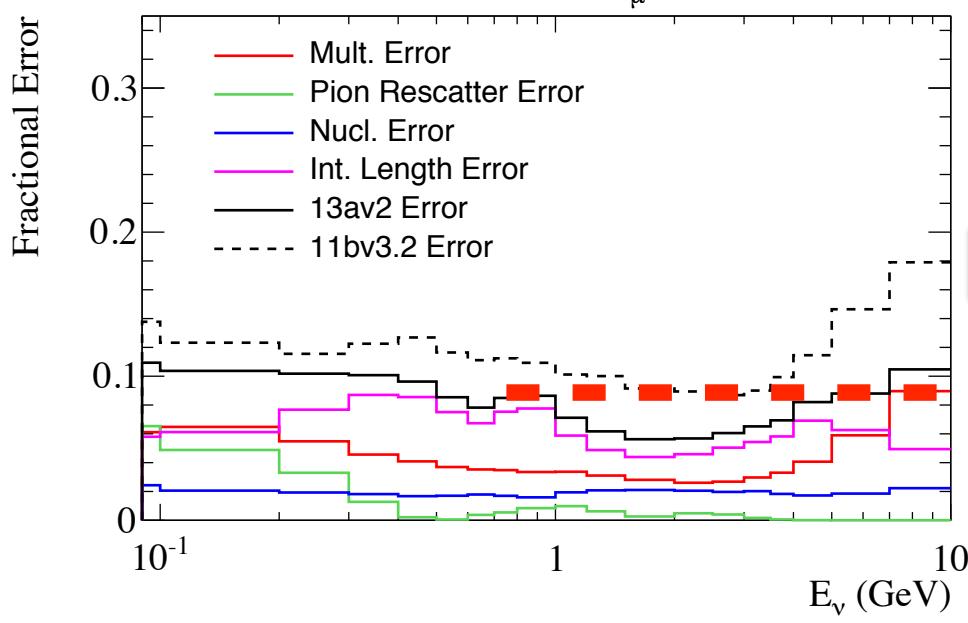
ND280: Positive Focussing (ν) Mode, ν_μ



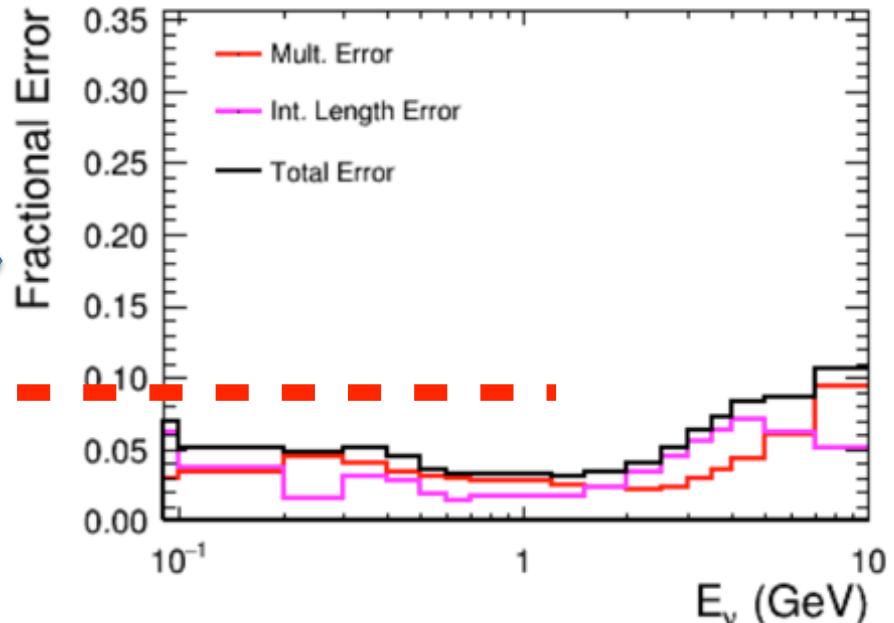
ND280: Positive Focusing Mode, ν_μ



SK: Positive Focussing (ν) Mode, ν_μ



SK: Positive Focusing Mode, ν_μ



Modeling method

- considering two parameters, proton and pion σ_{prod} , as a first step of modeling
 - $\sigma_{\text{prod}} = \sigma_{\text{inel}} - \sigma_{\text{qe}}$ (allow to vary σ_{qe})

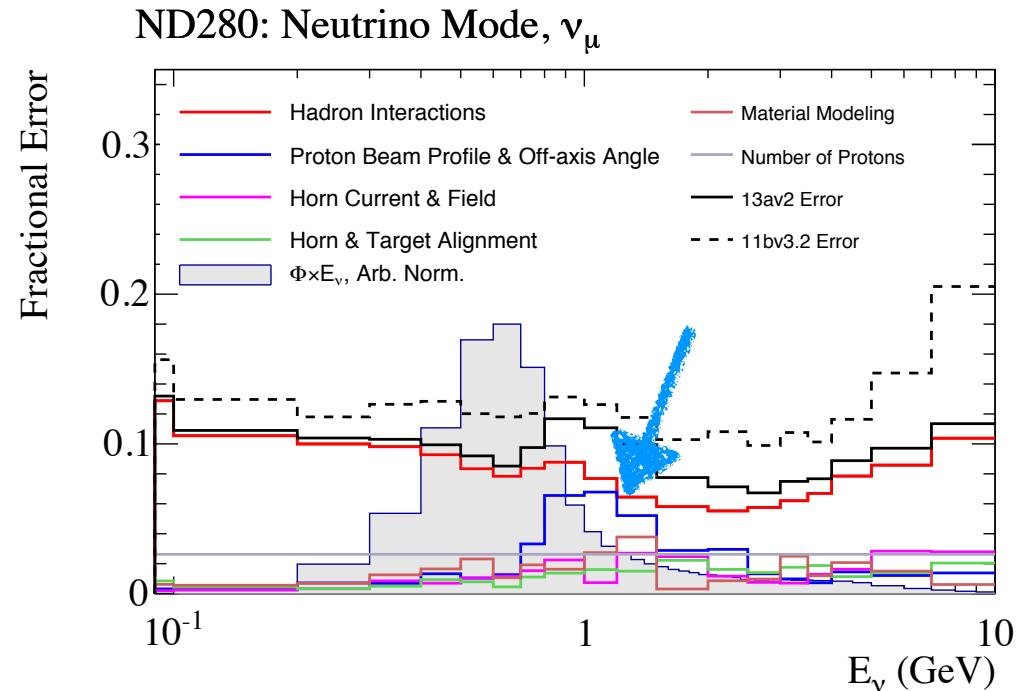
$$\chi^2 = \sum_{i,j} \left(\left[\frac{1}{\text{pot}} \frac{dn}{dp} \right]_{i,NA61} - \left[\frac{1}{\text{pot}} \frac{dn}{dp} \right]_{i,MC} \right) V^{-1}_{i,j} \left(\left[\frac{1}{\text{pot}} \frac{dn}{dp} \right]_{j,NA61} - \left[\frac{1}{\text{pot}} \frac{dn}{dp} \right]_{j,MC} \right) + \sum_k T_{wkDials}^2_k$$

	proton dial (σ_{prod} @30GeV/c)	pion dial	$\chi^2/\text{d.o.f}$
FLUKA2011 thin target tuned	0.0 (230.7 mb)	0.0	4492/1383 = 3.25
Fit to replica target data	-0.97 ± 0.03 (198 mb)	-0.17 ± 0.09	$3519/(1383-2) = 2.55$
Fit to replica target data (w/ model dependence uncertainties)	-0.95 ± 0.03 (199 mb)	-0.25 ± 0.09	$3201/(1383-2) = 2.32$

- σ_{prod} @30GeV is 7σ below the NA61 measurement
- it is still within present assigned error in the flux uncertainty but need to look other parameters to vary
 - under checking z-bin dependence, target density error

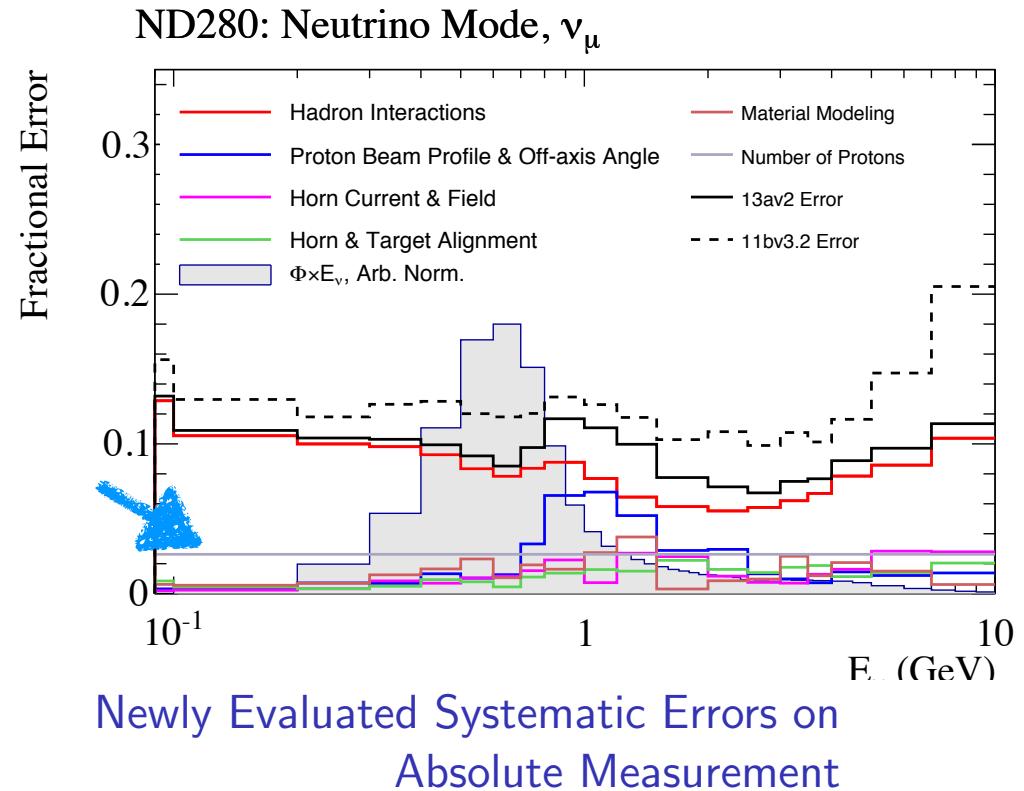
Proton beam profile error

- dominant source of proton beam profile error is uncertainty of y , θ_y measurement
 - primary-secondary beam-line alignment
- size is $\Delta y \sim 0.6\text{mm}$, $\Delta \theta_y \sim 0.3\text{mrad} \rightarrow$ it causes 6% flux error at 1 GeV
- it can be improved by constraining w/ INGRID measurement
 - currently, the error is double counting (INGRID off-axis angle measurement is treated as another flux error source)



Normalization error (CT)

- Update analysis method and new calibration reduce the POT uncertainty from 2.7% to 2.0%
- No effect on oscillation analysis because of F/N effect but small improvement on cross section measurement

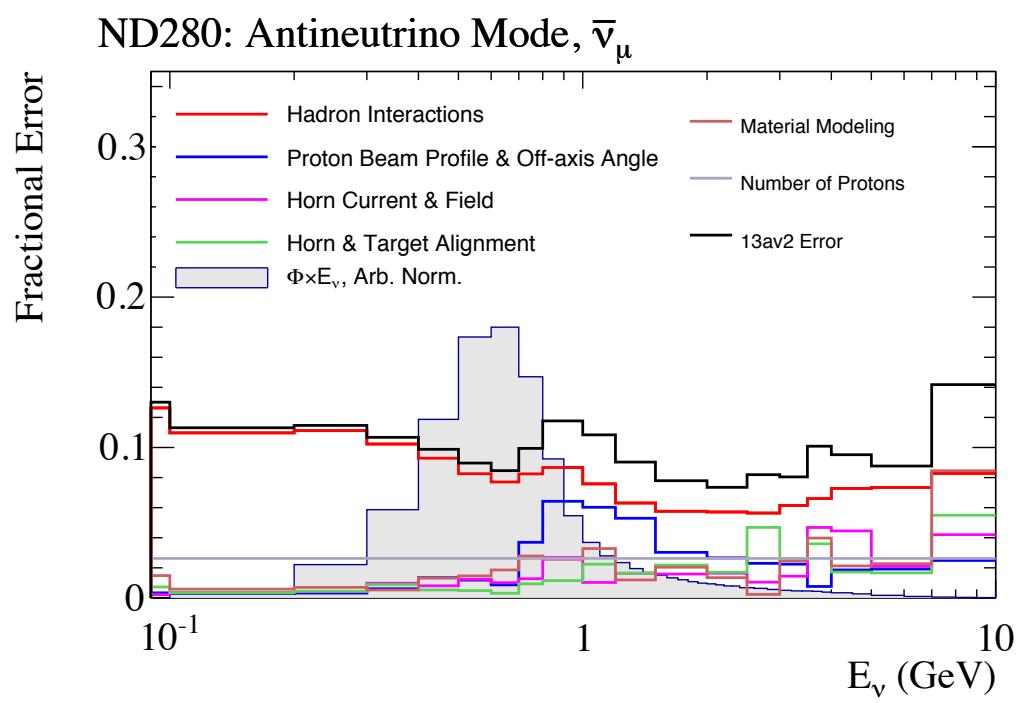
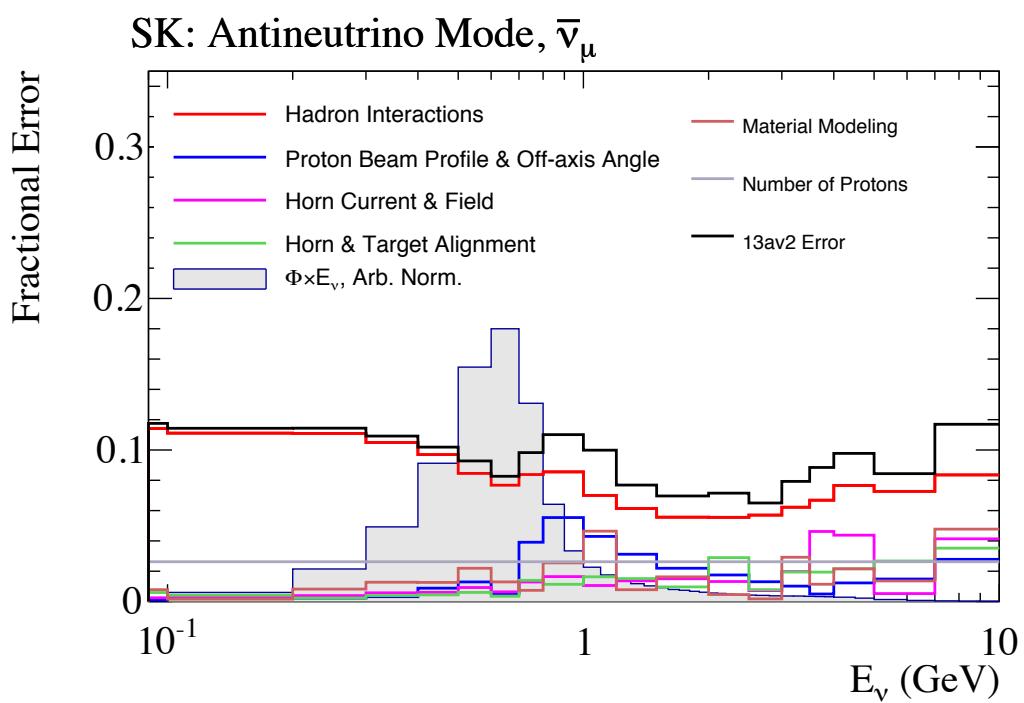


Error Source	% Error
Scope Input Impedance	1%
Scope DC Gain Accuracy	1.5%
Frequency Dependence	0.6% ??
Electronics Noise ?	0% ??
CT Attenuator Calibration	??
Reproducibility/Calib. Measurement Statistical Error	0.3%
Propagation from CT02 to CT05, etc.	0.5%
Analysis (Integration Window)	1.7% → 0.1% ??
New Total	2.0(+?)%
Previous Total	2.7%

Summary

- Present flux uncertainty is ~10% at peak energy
 - SK flux uncertainty is reduced using ND280 data (F/N effect)
 - Currently, this is a largest uncertainty in most of ND280 cross section measurements
- The absolute flux uncertainty can be reduced down to 5~6% in total (at peak energy)
 - Use of NA61 replica target data in tuning, INGRID beam direction measurement and new normalization error

backup



two parameters in replica target modeling

