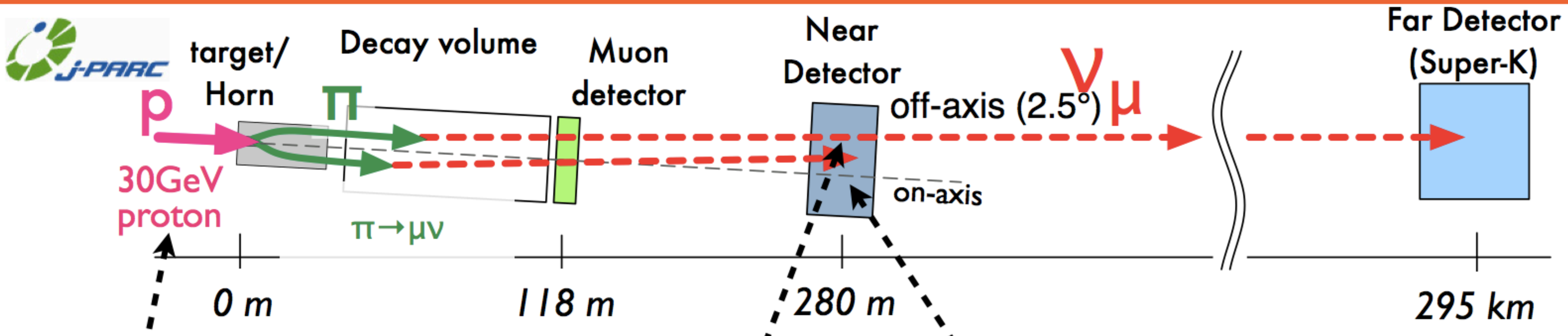
Precise prediction of the neutrino flux in T2K

Reference of the T2K experimental setup : arXiv:1106.1238

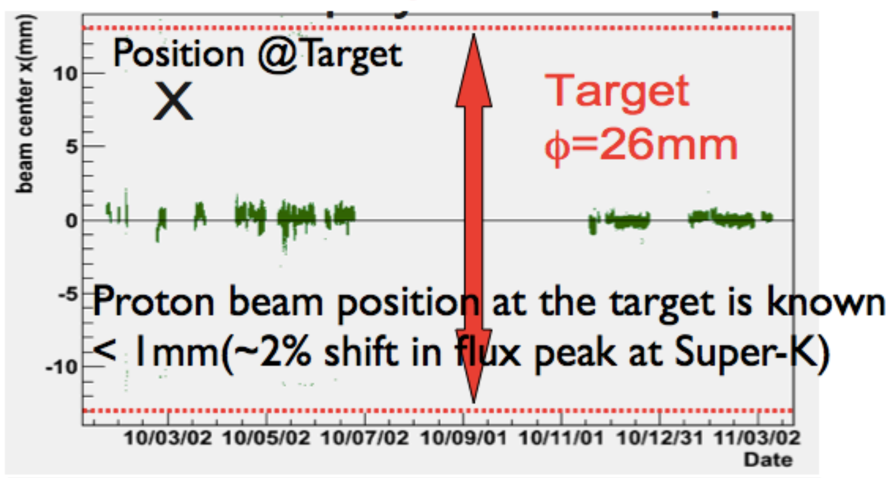
A.Murakami (Kyoto university) for T2K collaboration

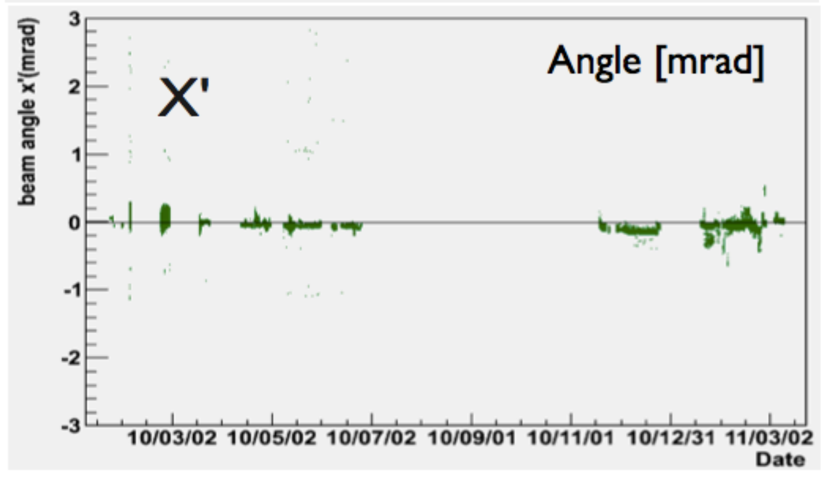
Strategy of flux prediction

1. FLUKA & GEANT3 (w/ GCALOR)
   1. Hadron production mainly w/ FLUKA
   2. Tracking particles out of the target mainly w/ GEANT3
   3. Input measured parameters of proton beam, beam direction and horn current
2. Optimize hadron production w/ external experiment (NA61, etc)
3. Modify predicted flux w/ the near detector measurement
4. The modification is extrapolated to Super-K to reduce various uncertainty ("Near-to-Far extrapolation")
5. Extrapolation uncertainty is evaluated from uncertainties due to measurements (NA61, proton beam, off-axis angle, etc)

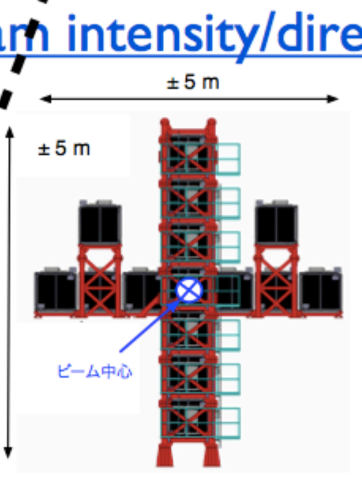


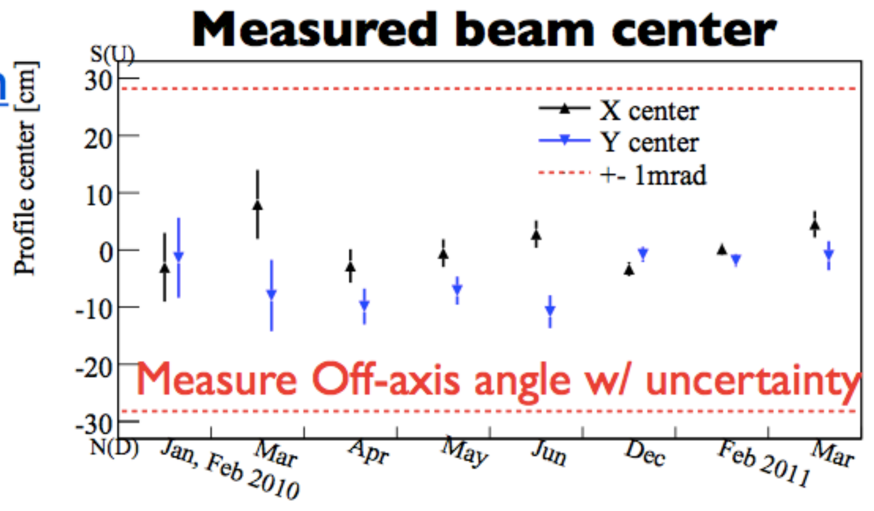
Proton beam intensity, position, size, angle are measured by several monitors on transport beam-line.



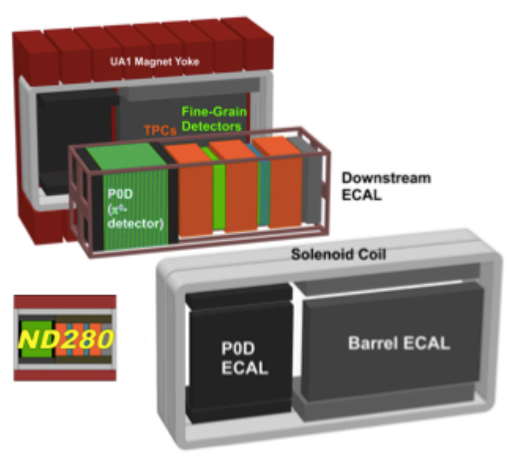


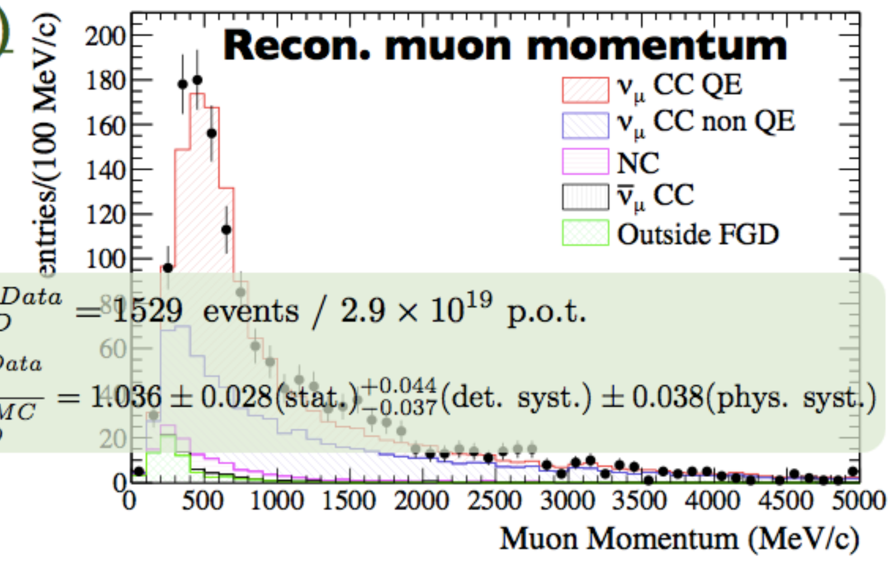
INGRID(On-axis near detector)
Neutrino beam intensity/direction





ND280 (Off-axis near detector)
Tracking, PID, Recon. energy



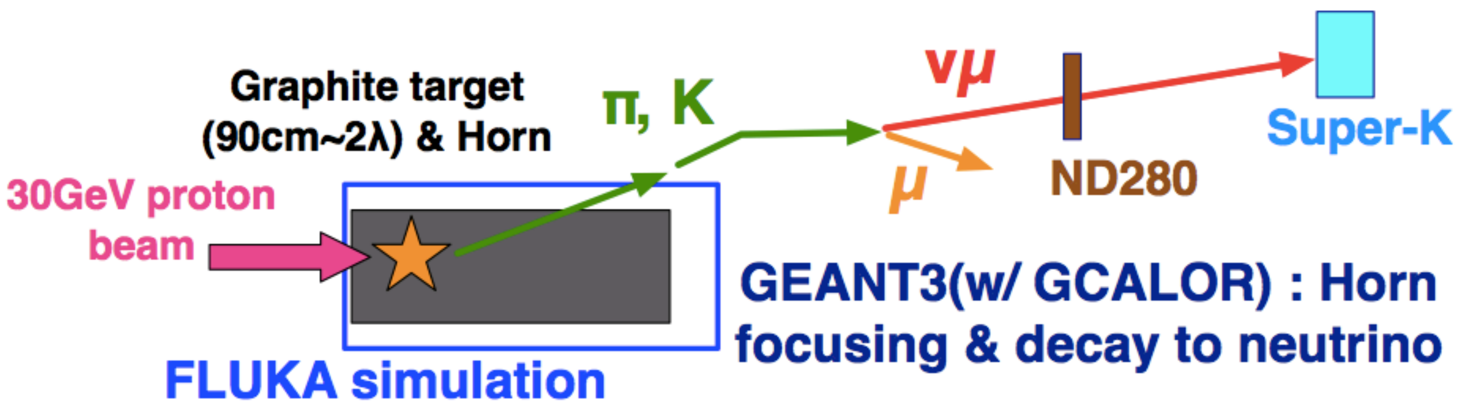


$R^{\mu,\,Data}_{ND}$ = 1529 events / 2.9×10^{19} p.o.t.

$$\frac{R^{\mu,\,Data}_{ND}}{R^{\mu,\,MC}_{ND}} = 1.036 \pm 0.028(\text{stat.})^{+0.044}_{-0.037}(\text{det. syst.}) \pm 0.038(\text{phys. syst.})$$

Optimizing neutrino beam simulation

Nominal beam simulation : FLUKA &GEANT3

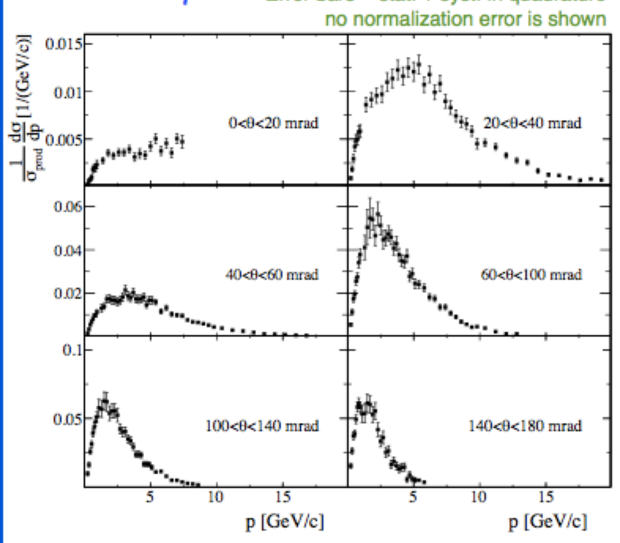


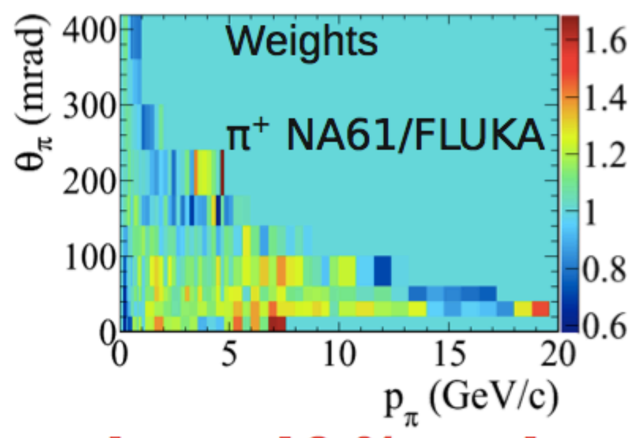
Optimizing

- Pion production : NA61/SHINE data (w/ thin target)

Differential cross section for π^+ production in 30GeV p+C

NA61/SHINE Collaboration (N Abgrall et al.) CERN-PH-EP-2011-005, Feb 2011. 27pp. Published in Phys.Rev.C84:034604,2011.

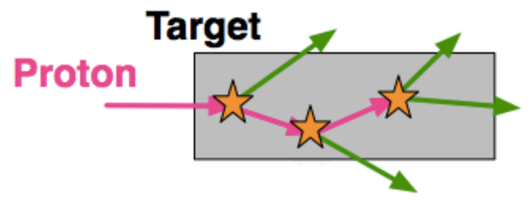




ν_μ by ~+10 %, ν_e by ~+5%

- External cross-section data

Data	Hadrons	Nuclei	p_{lab} (GeV/c)
Denisov, et. al. [17]	$\pi^\pm, K^\pm, p$	C, Al (others)	6-60
Allaby, et. al. [18]	π^-, K^-	C, Al (others)	20-65
Longo, et. al. [19]	π^+, p	C, Al	3
Bobchenko, et. al. [15]	π^-, p	C, Al (others)	1.75-9
Cronin, et. al. [20]	π^-	C, Al	0.73-1.33
NA61 [7]	p	C	31
Belletini, et. al. [14]	p	C, Al (others)	~20
Chen, et. al. [21]	p	C, Al (others)	1.53
Abrams, et. al. [22]	$K^\pm$	C, Cu	1.0-3.3
Allardyce, et. al. [23]	$\pi^\pm$	C, Al (others)	0.71-2
Vlasov, et. al. [24]	π^-	C, Al	2-6.7
Carrol, et. al. [25]	$\pi^\pm, K^\pm, p$	C, Al (others)	60-280

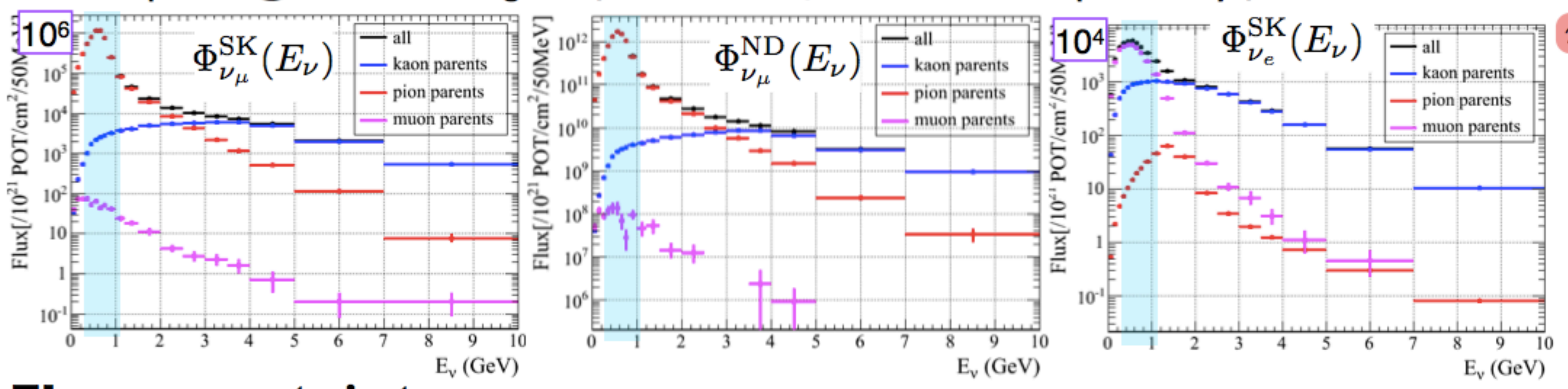


Weighting factor of interaction probability in material based on the interaction length for each particle

νμ, νe by ~+2%

Neutrino flux (no osc.) of ND280, Super-K

Flux peaks @ ~ 0.6 GeV, region of maximum νμ→νx oscillation probability for 295 km baseline

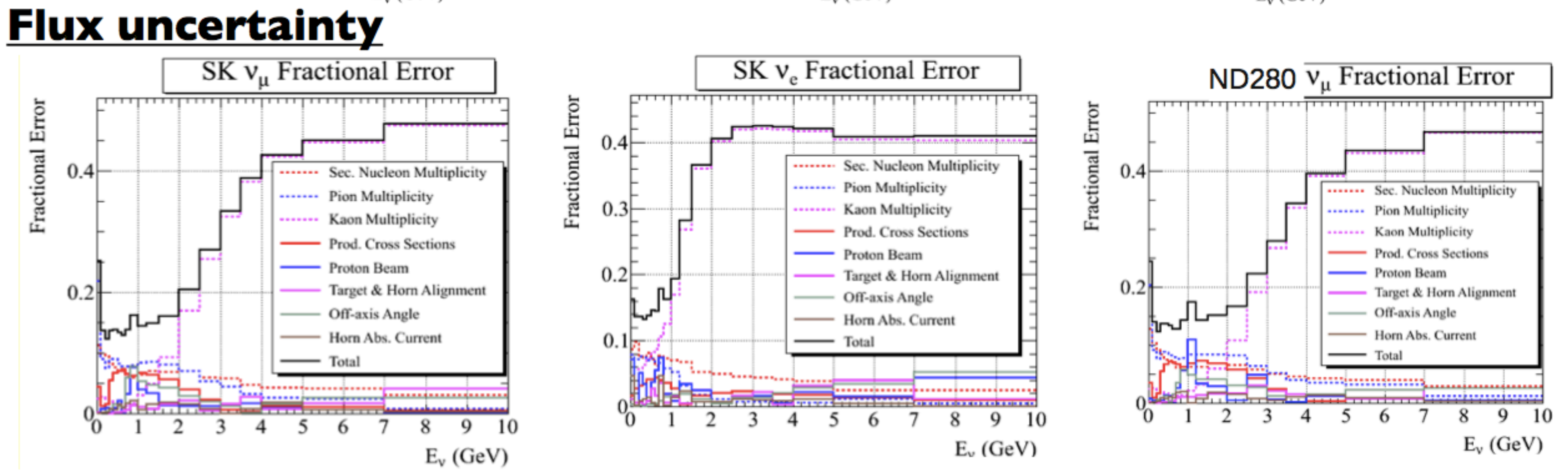


$\pi^+ \rightarrow \mu^+\nu_\mu$

$\mu^+ \rightarrow e^+\bar{\nu}_\mu\nu_e$

NA61 pion data helps the beam νe prediction

Flux uncertainty



Kaon production uncertainty
Estimated by comparing FLUKA/Eichten et. al.(*Nucl. Phys. B 44 333(1972)*)→ Reduce by using NA61 kaon data (now investigate)

Other hadron production uncertainties
Expected to reduce by using NA61 data w/ T2K replica target

Other uncertainties
Estimate based on measurement in T2K
- proton beam : proton beam monitor,
- Off-axis : INGRID

	N_{ND}^{MC}	$N_{SK}^{MC}(\theta_{13}=0)$
Pion Multiplicity	5.7%	6.2%
Kaon Multiplicity	10.0%	11.1%
Other Hadron Int.	9.7%	9.5%
Proton beam, off-axis angle, alignment,horn current	3.6%	2.2%
Total	15.4%	16.1%

Precise prediction of Super-K flux

Predict # of expectation at Super-K based on # of observation at ND280 (*Phys. Rev. Lett. 107, 041801 (2011)*)

$$N^{exp}_{SK} = R^{\mu,\,Data}_{ND} \times \frac{N^{MC}_{SK}}{R^{\mu,\,MC}_{ND}}$$

	$N_{SK}^{MC}(\theta_{13}=0)$	N_{SK}^{MC}/R_{ND}^{MC}
Pion Multiplicity	6.2%	2.5%
Kaon Multiplicity	11.1%	7.6%
Other Hadron Int.	9.5%	1.5%
Proton beam, off-axis angle, alignment,horn current	2.2%	2.3%
Total	16.1%	8.5%

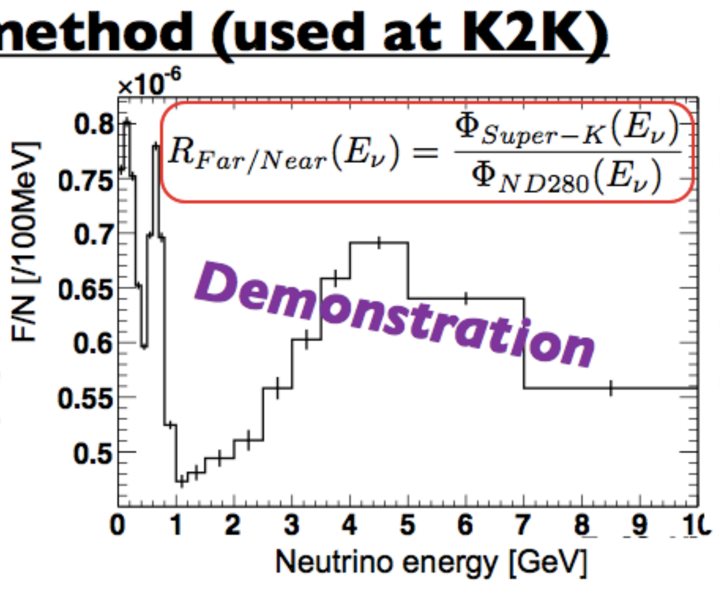
Common uncertainties (mainly hadron production) cancelled.

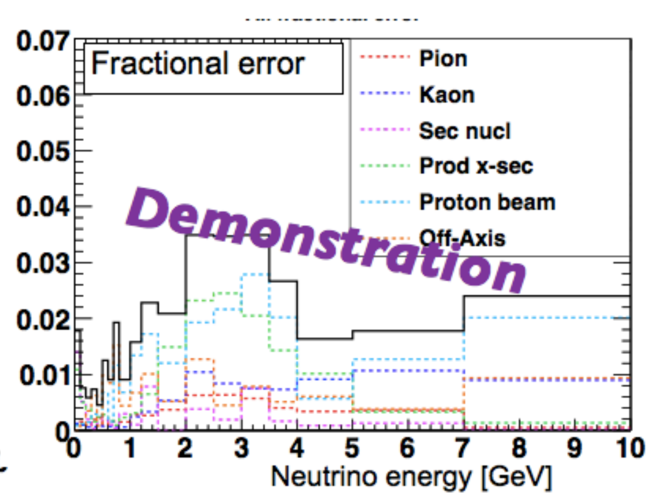
The total (flux, cross-section, detector systematics) uncertainty **23%**

→ Investigate Super-K flux prediction with neutrino energy dependency.

1. Far/Near ratio method (used at K2K)

Simple prediction when assume no correlation w/ the ND280 flux. To be precise, it is not correct
→ Possible to use as quick & simple benchmarks.



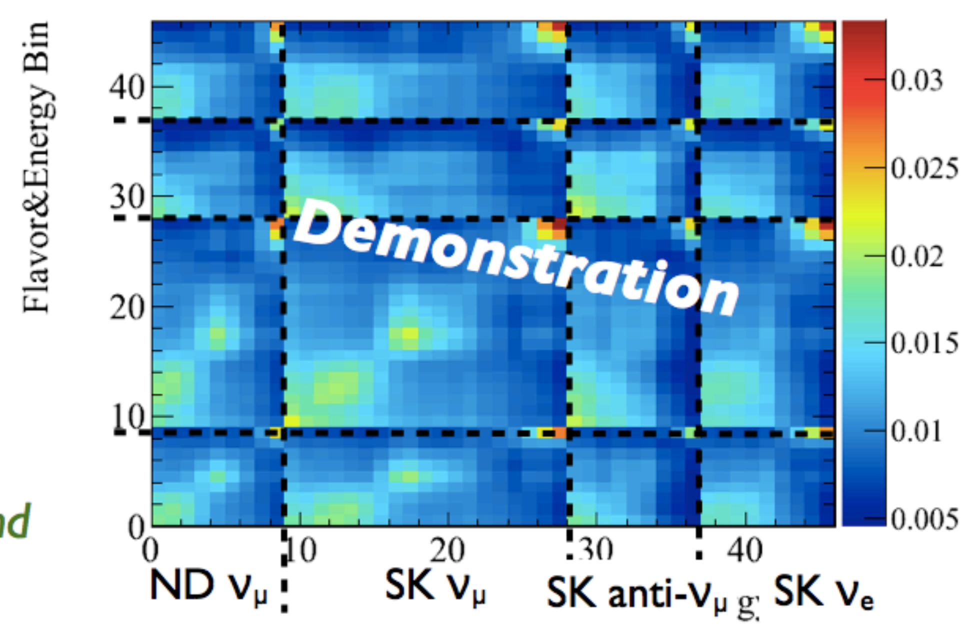


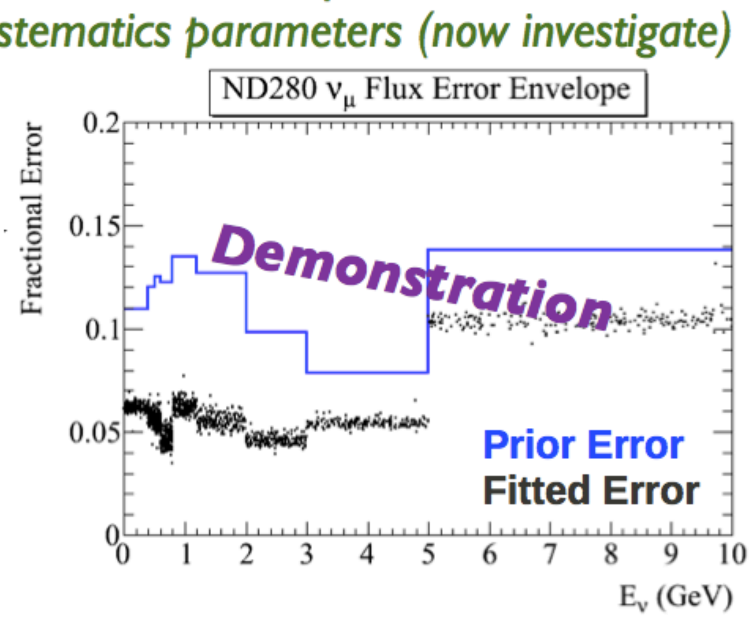
2. Flux covariance method

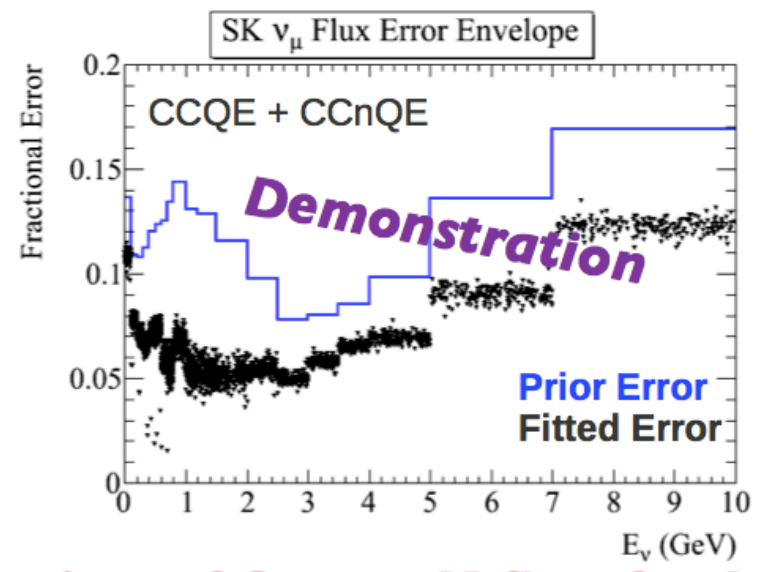
- Calculate the flux covariance matrix including the flux bins of ND280 and Super-K according to each systematic uncertainty.
- ND280 flux uncertainty reduce by fitting p-theta distribution of ND280 and SK flux uncertainty also reduce according to this matrix.

→ Need to consider the correlation b/w flux and neutrino x-section parameters, detector systematics parameters (now investigate)

Fractional covariance matrix (including all flux uncertainty)







Toward more precise prediction of Super-K flux for better sensitivity of the oscillation analysis