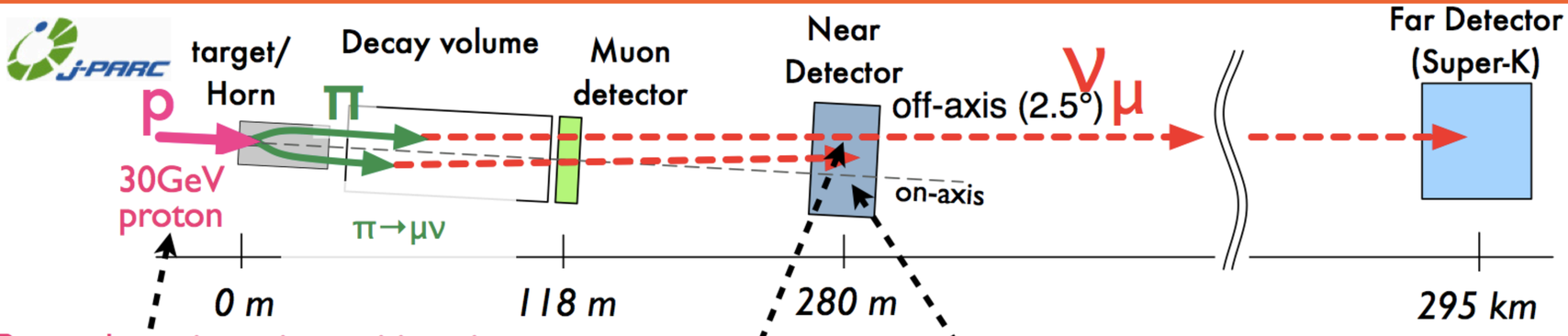
Precise prediction of the neutrino flux in T2K

Reference of the T2K experimental setup : arXiv:1106.1238

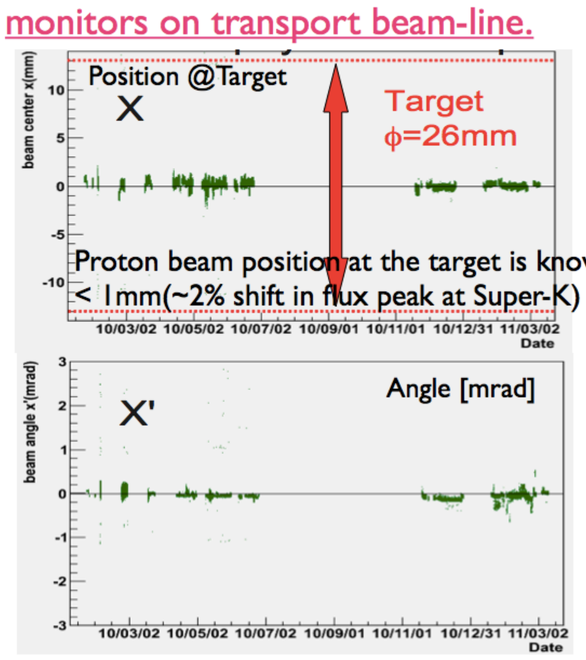
A.Murakami (Kyoto university) for T2K collaboration

Strategy of flux prediction

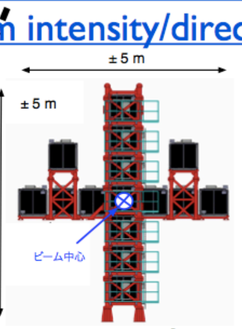
1. FLUKA & GEANT3 (w/ GCALOR)
   1. Hadron production mainly w/ FLUKA
   2. Tracking particles out of the target mainly w/ GEANT3
   3. Input measured parameters of proton beam, beam direction and horn current
2. Tune hadron production to reproduce experimental data (NA61, etc).
3. Modify predicted flux 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)

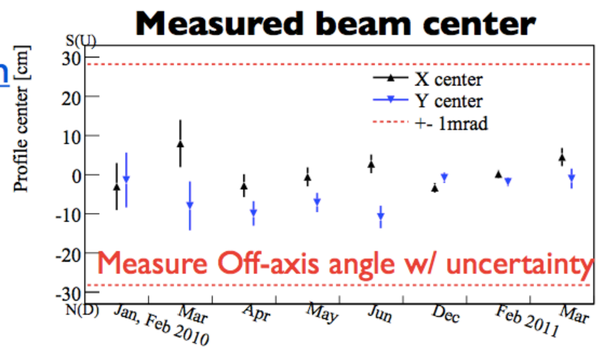


Proton beam intensity, position, size, angle are measured by several monitors on transport beam-line.

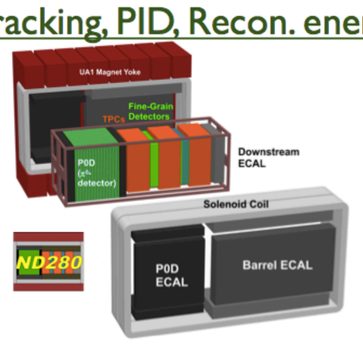


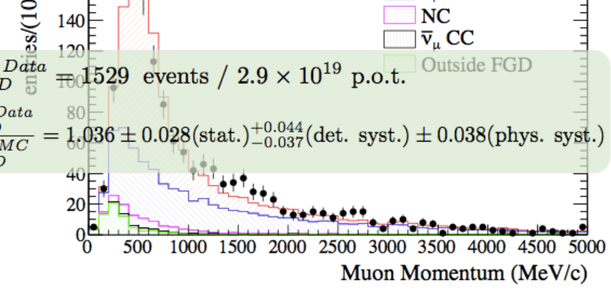
INGRID(On-axis near detector)
Neutrino beam intensity/direction





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



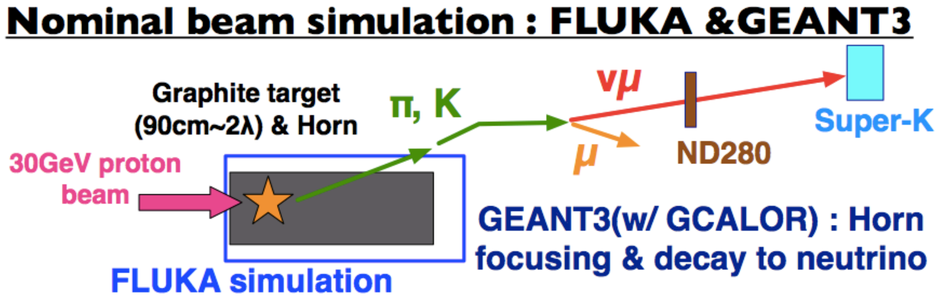


$R_{ND}^{\mu,\,Data} = 1529$ events / 2.9×10^{19} p.o.t.

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

Tuning neutrino beam simulation

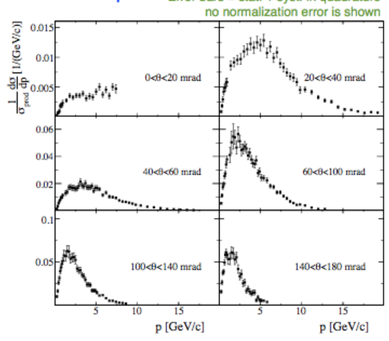
Nominal beam simulation : FLUKA &GEANT3



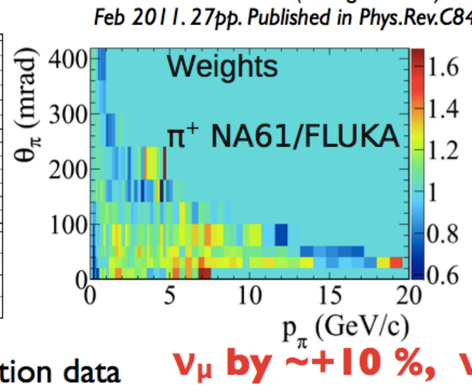
Tuning to reproduce experimental data

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

Differential cross section for π^+ production in 30GeV p+C — Error bars = stat. + syst. in quadrature, no normalization error is shown



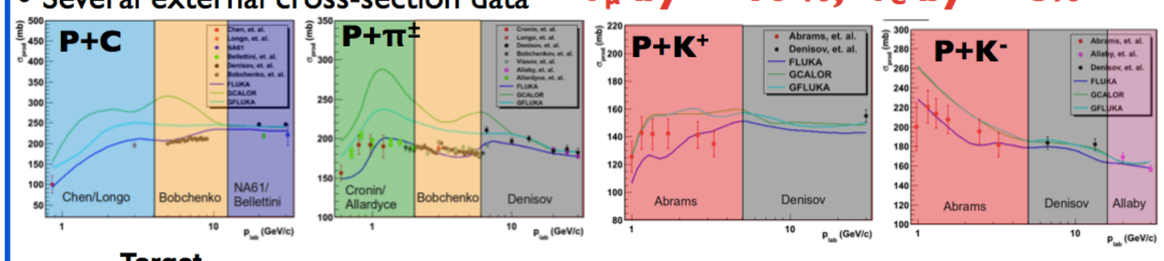
NA61/SHINE Collaboration (N Abgrall et al.) CERN-PH-EP-2011-005, Feb 2011. 27pp. Published in Phys.Rev.C84:034604,2011.

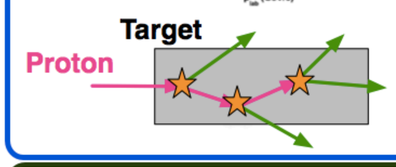


Apply pion production at primary & secondary interaction (by momentum scaling)

νμ by ~+10 %, νe by ~+5%

- Several external cross-section data



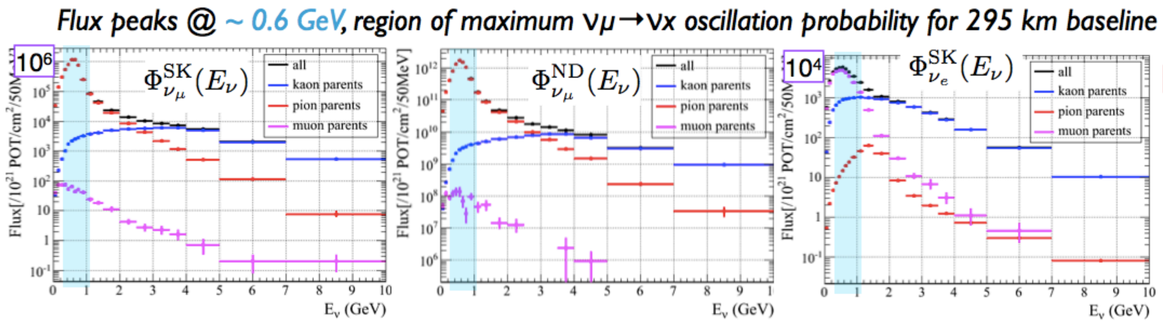


Weighting factor of interaction probability in material based on the interaction length for each particle

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

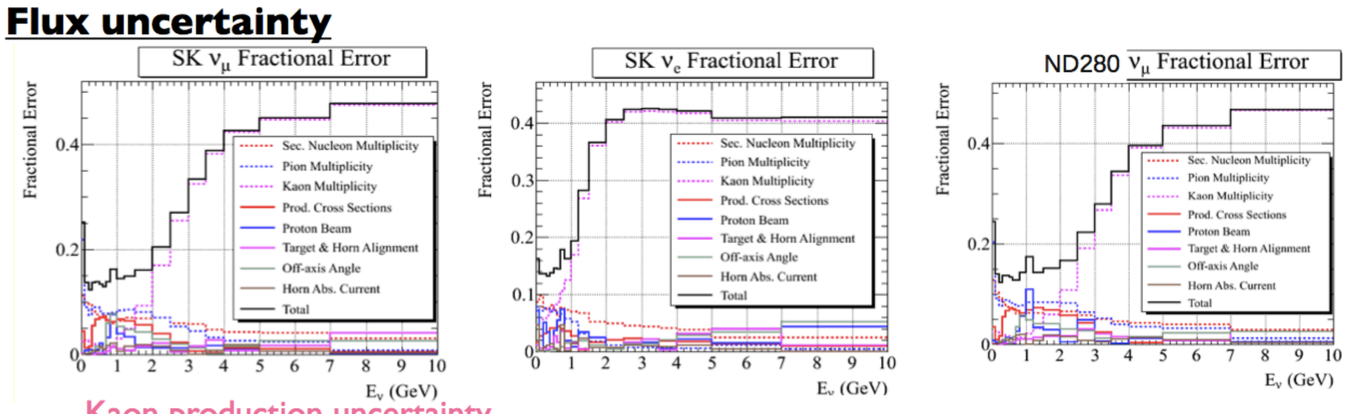


$\pi^+ \rightarrow \mu^+ \nu_\mu$

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

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 T2K flux

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

$$N_{SK}^{exp} = R_{ND}^{\mu,\,Data} \times \frac{N_{SK}^{MC}}{R_{ND}^{\mu,\,MC}}$$

Cancel common uncertainties (hadron production)

The total uncertainty of Super-K expectation : **23%**

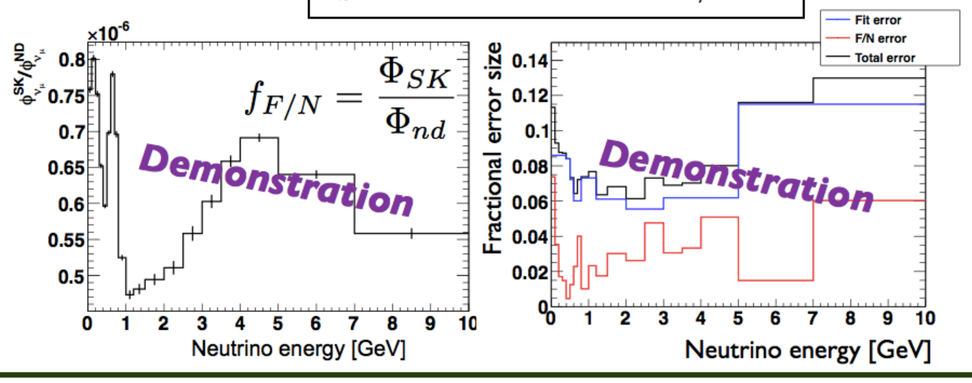
	$N_{SK}^{MC}(\theta_{13}=0)$	N_{SK}^{MC}/R_{ND}^{MC}
Pion Multiplicity	6.2%	2.5%
Kaon Multiplicity	11.1%	7.6%
Other Hadron Int.	9.5%	1.5%
Proton beam, off-axis angle, alignment,horn current	2.2%	2.3%
Total	16.1%	**8.5%**

Investigate more precise prediction by ND280 data according to neutrino energy
→ Fitting pμ-θμ measured at ND280 and extrapolate the results to SK.

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

- More effective cancellation by flux ratio at each energy.
- Simple extrapolation & easy to understand behavior.
- Invalid in view of the correlation b/w ND280 flux this ratio (nonnegligible level) → Complex
  - At K2K, not including flux prior constrain in ND fitting.

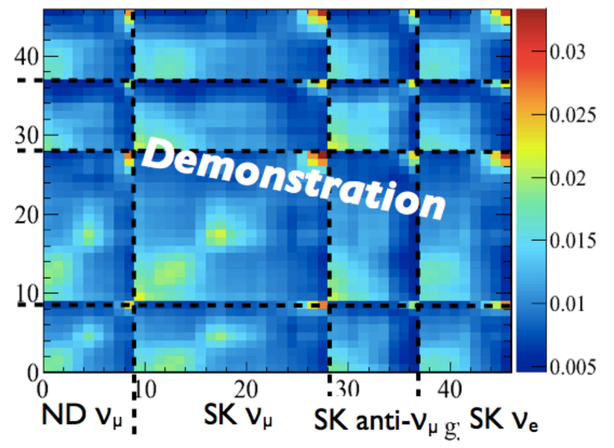
$$\Phi_{SK}^{MC}(E_\nu) = \Phi_{ND}^{Data}(E_\nu) f_{F/N}(E_\nu)$$



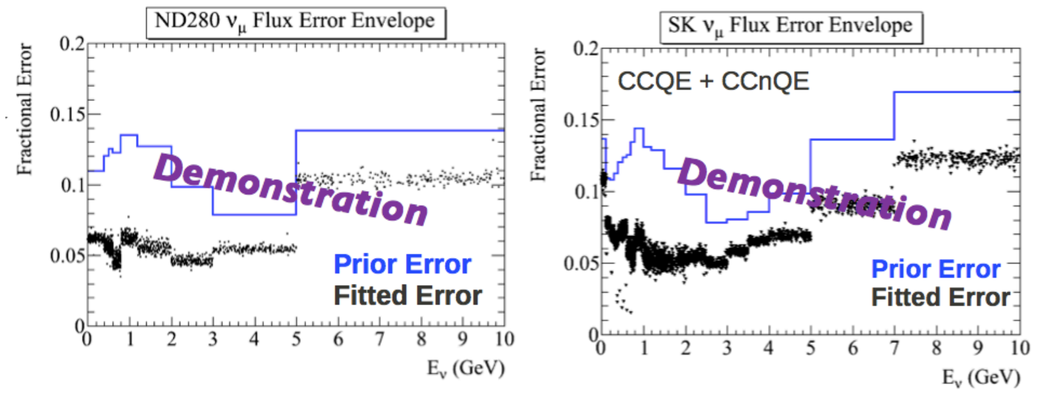
2. Flux covariance method

- 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 only p-theta distribution of ND280, then SK flux uncertainty also reduce according to this matrix correlation.

Fractional covariance matrix (including all flux uncertainty)



There are significant off diagonal terms between ND5 νμ and SK νe



Toward more precise prediction of T2K flux for better sensitivity of the oscillation analysis