Systematics in CPV measurement

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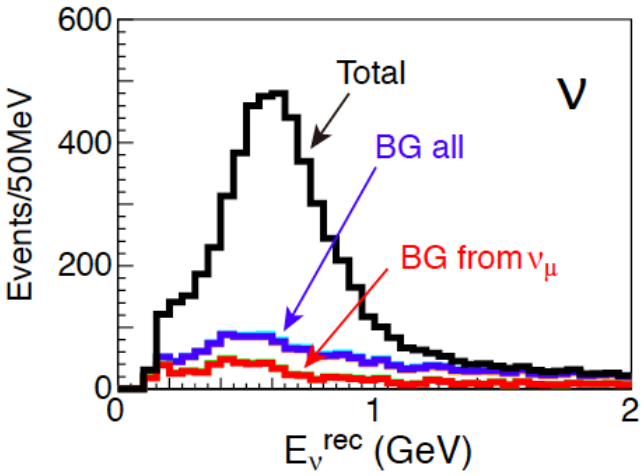
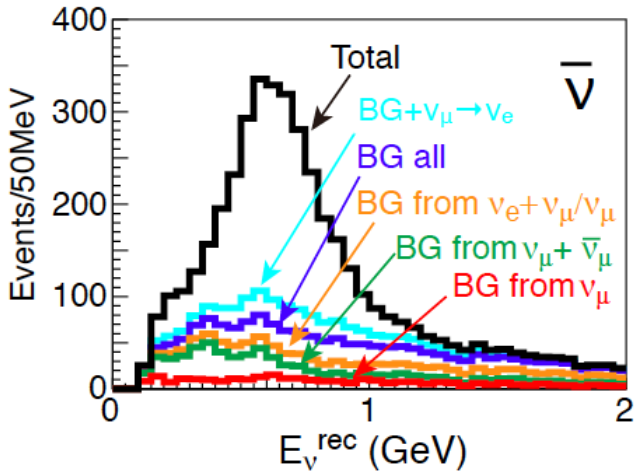
BG in CPV measurement





$\sin^2 2\theta_{13}=0.1$
$\delta=0$

1.66MW	Signal	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	$\nu_e/\bar{\nu}_e$ CC	NC
ν (1.5yrs)	3,940	51	39	974	718
$\bar{\nu}$ (3.5yrs)	2,168	421	25	972 (374/598)	750

- Intrinsic $\nu e(\bar{\nu}e)$CC and NC π^0 are the dominant BG in both runs
- In $\bar{\nu}$ run, ν BG and $\bar{\nu}$ BG are comparable
- In $\bar{\nu}$ run, wrong sign appearance $\nu\mu \rightarrow \nu e$ also has a large fraction

CPV sensitivity study in LOI

ν run & $\overline{\nu}$ run

Erec bin (50MeV/bin, 0-2GeV)

Expected number of events from

νμ→νe + $\overline{\nu}$μ→$\overline{\nu}$e signal

νμ + $\overline{\nu}$μ BG (mostly NC π^0)

νe + $\overline{\nu}$e BG (mostly CC1e)

$$\chi^2 = \sum_{\nu,\overline{\nu}} \sum_{i} \left[N^i - \left\{ 1 \pm \frac{1}{2} f_{\nu/\overline{\nu}} \right\} \cdot \left((1+f_{\rm sig}) \cdot n^i_{\rm sig} + (1+f_{\nu_\mu}) \cdot n^i_{\nu_\mu} + (1+f_{\nu_e}) \cdot n^i_{\nu_e} \right) \right]^2 / N^i$$

$$+ \frac{{f_{\rm sig}}^2}{{\sigma_{\rm sig}}^2} + \frac{{f_{\nu_\mu}}^2}{{\sigma_{\nu_\mu}}^2} + \frac{{f_{\nu_e}}^2}{{\sigma_{\nu_e}}^2} + \frac{{f_{\overline{\nu}/\nu}}^2}{{\sigma_{\nu/\overline{\nu}}}^2},$$

Energy dependent error not considered.

LOI assumption

σ_{sig} : signal normalization (5%)

$\sigma_{\nu\mu}$: νμ BG normalization (5%)

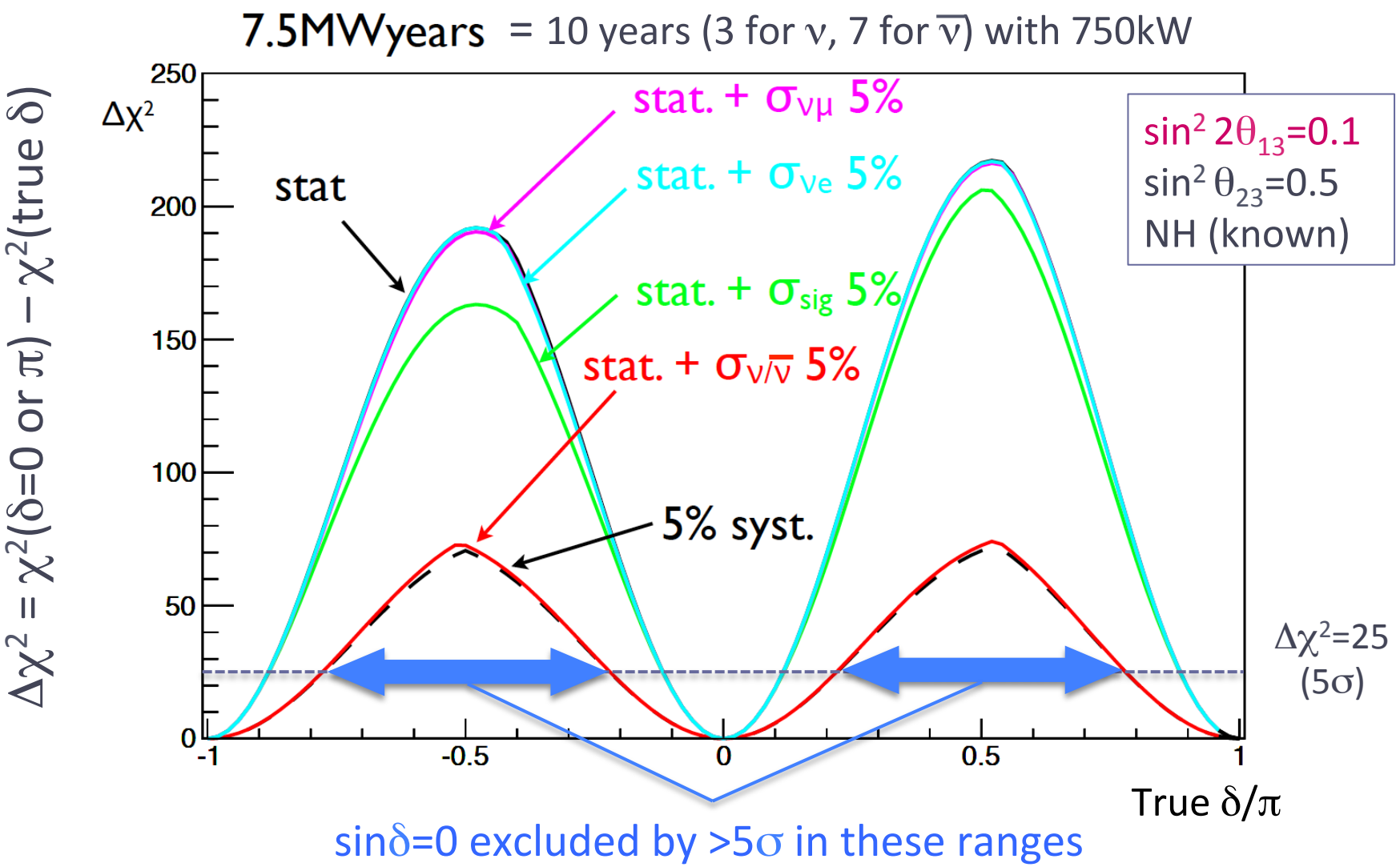
$\sigma_{\nu e}$: νe BG normalization (5%)

$\sigma_{\nu/\overline{\nu}}$: ν run/$\overline{\nu}$ run relative normalization (5%)

Which systematics is important ?

How about our current knowledge ?

Which systematics is important ?



Which systematics is important ? (cont'd)

- Systematics on ν run/$\overline{\nu}$ run relative normalization gives a dominant contribution.
  - It's natural since sinδ is sensitive to the asymmetry :

    $\{P(\nu_\mu \rightarrow \nu_e) - P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)\} / \{P(\nu_\mu \rightarrow \nu_e) + P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)\}$

- Systematics on signal normalization also has some effect. BG normalization does not.
  - But this result may be due to rather simplified parameterization. (no energy dependence, common signal & BG normalization between in ν run and in $\overline{\nu}$ run, …)

  → Need studies with more fine systematic parameterization

Total systematic error on N_{SK} in T2K

Note : Erec < 1.25GeV (T2K) vs. Erec < 2GeV (LOI)

(p_μ , θ_μ) distributions of ν_μCCQE and ν_μCCnonQE samples in the near detector are fit to constrain ν flux and cross sections

Error source	w/o ND constraint	w/ ND constraint
Flux + Xsec (M_A^{QE}, M_A^{RES}, CCQEnorm, CC1πnorm, NC1π^0norm)	24 %	6 %
Other Xsec param.	7.5 %	
SK efficiency + FSI	4 %	
Total sys. error	26 %	10 %

12% error on N_{SK}(signal)
15% error on N_{SK}(BG)

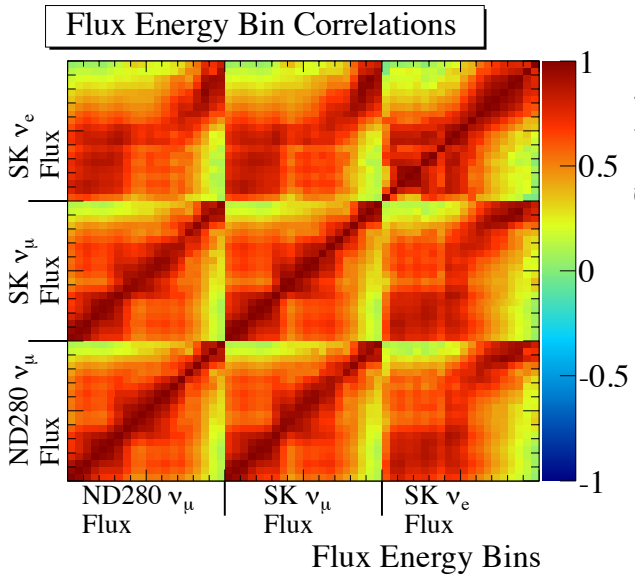
Much reduced by the near detector ν_μCC measurement, but still larger than the LOI assumption

Neutrino flux uncertainties

T2K sys. error on N_{SK} due to flux uncertainties

	% Errors on Sample Predictions		
	N_{ND}	N_{SK}	N_{SK}/N_{ND}
Pion Production	3.41	4.97	1.88
Kaon Production	3.48	1.17	2.99
Secondary Nucleon Production	5.46	6.61	1.34
Hadronic Interaction Length	5.78	6.55	1.89
Proton Beam, Alignment & Off-axis Angle	3.45	2.48	1.90
Horn Current and Magnetic Field	1.40	1.15	1.39
Total	10.04	10.96	4.84

~5%



FD ν_μ,ν_e flux errors constrained by the ND ν_μ measurements

Will be reduced by higher statistics measurements of the kaon production from NA61

Will be reduced by secondary proton and replica target measurements from NA61

$\nu/\bar{\nu}$ relative flux error can be smaller than the absolute flux error.

Neutrino interaction and FSI uncertainties

T2K sys. error on N_{SK} due to interaction uncertainty (%)

	w/o ND	w/ ND
M_A^{QE} (GeV)	18.6	8.0
M_A^{RES} (GeV)	2.3	2.0
CCQE norm ($E_\nu < 1.5$ GeV)	7.8	6.2
CC1π norm ($E_\nu < 2.5$ GeV)	5.4	3.8
NC1π^0 norm	2.4	2.3
CC other shape (GeV)	0.1	0.1
Spectral function	5.4	5.4
p_F (MeV)	0.1	0.1
CC coherent norm	0.2	0.2
NC coherent norm	0.6	0.6
NC1$\pi^\pm$+NC other norm	0.8	0.8
$\sigma_{\nu_e CC}/\sigma_{\nu_\mu CC}$	2.6	2.6
W shape (MeV)	1.0	1.0
Pionless delta decay	3.5	3.5
1π E_ν shape	1.5	1.5
+ Final State Interactions (FSIs)		a few %

correlation between xsec params and flux params

- May be reduced by using high statistics ND data
- To reduce further, higher acceptance(4π) ND with water target may be necessary (WC@2km?)

→ Need studies to determine the ND configuration.

Current knowledge on $\sigma(\overline{\nu})$ must be insufficient.

Far detector (FD) efficiency

- In T2K, SK efficiency error is estimated using
  - control samples from atmospheric neutrino events,
  - NC π^0 topological control sample combining one data electron and one simulated gamma event, etc.

  → Currently, statistics of these control sample is limited.

  → We may be able to reduce FD sys. error with much higher statistics control samples.

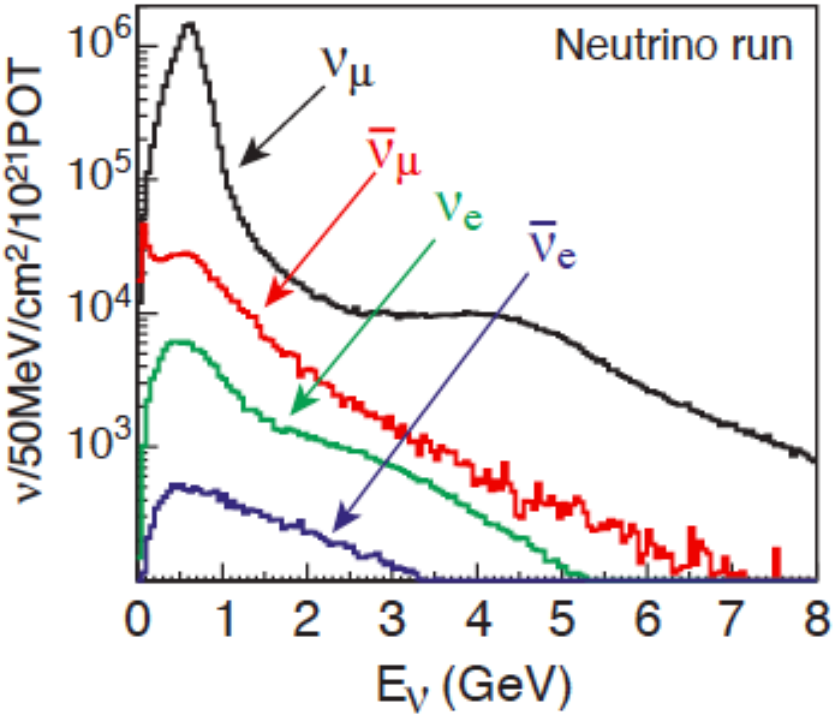
- FD efficiency difference between ν and $\overline{\nu}$ may be small.

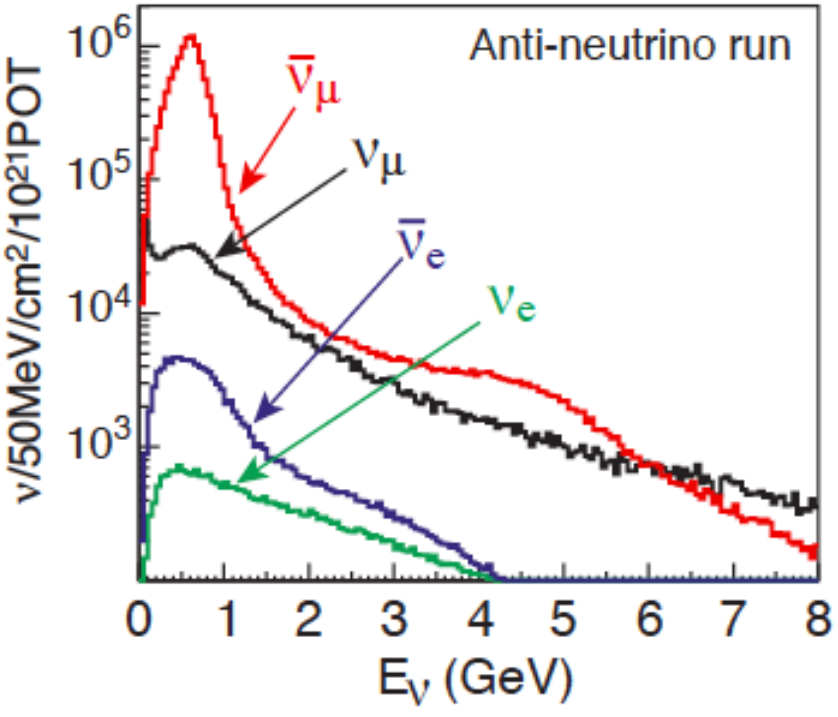
Summary

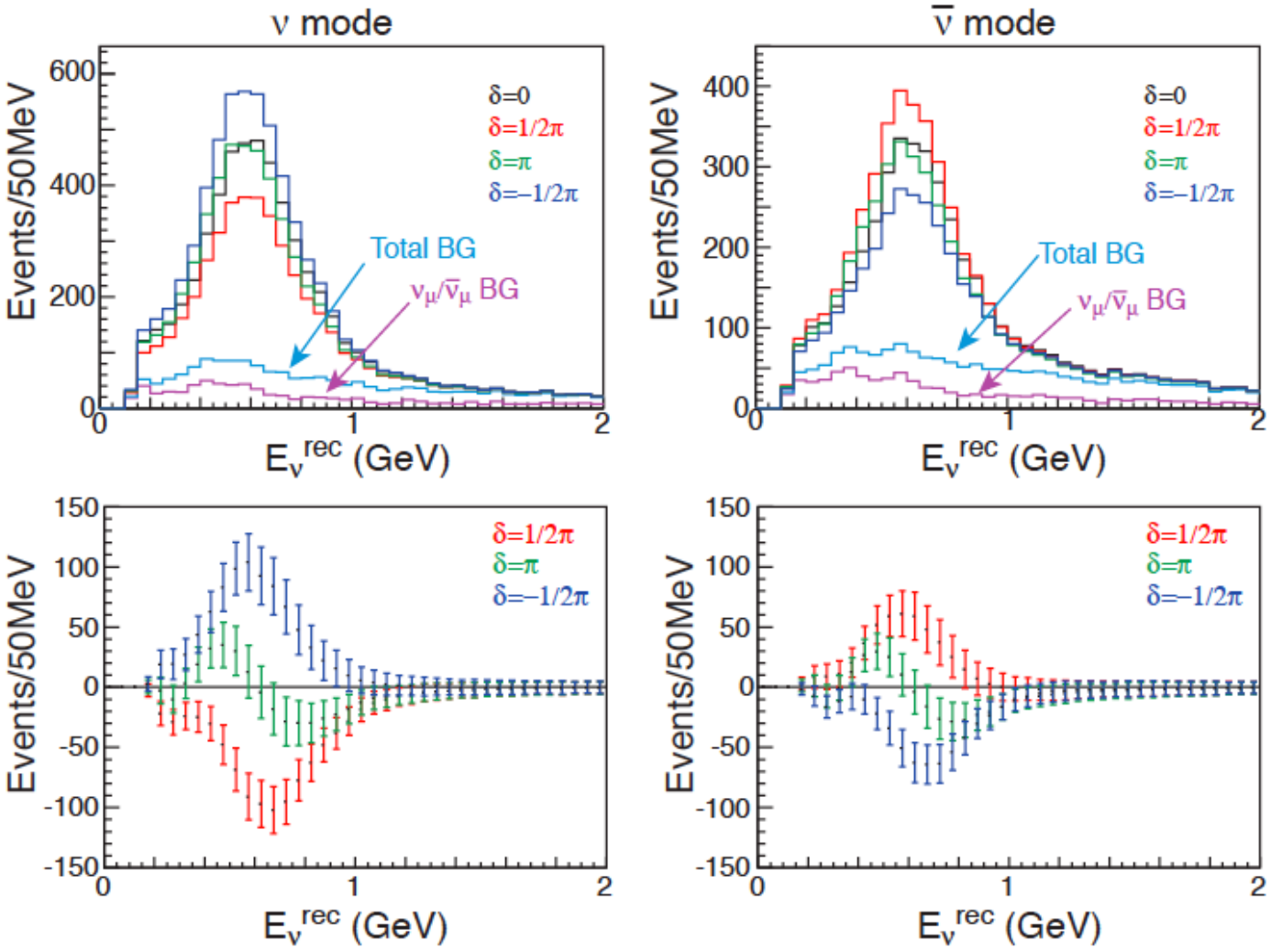
- Systematics on the $\nu/\overline{\nu}$ relative normalization gives dominant contribution in the CPV measurement
- As for the systematic errors in ν run, we have experiences in T2K etc. and have some visions to reduce them further
  - cross section (and FSI) uncertainties have the largest contribution
- For the $\overline{\nu}$ run errors and $\nu/\overline{\nu}$ errors, need to make a clear strategy to reduce them
  - necessary ND configuration, extrapolation method, …
  - T2K $\overline{\nu}$ run (if possible) must help much

    → How much data is needed? What should be measured?
- Need studies with more realistic χ^2 definition (systematic error parameterization)

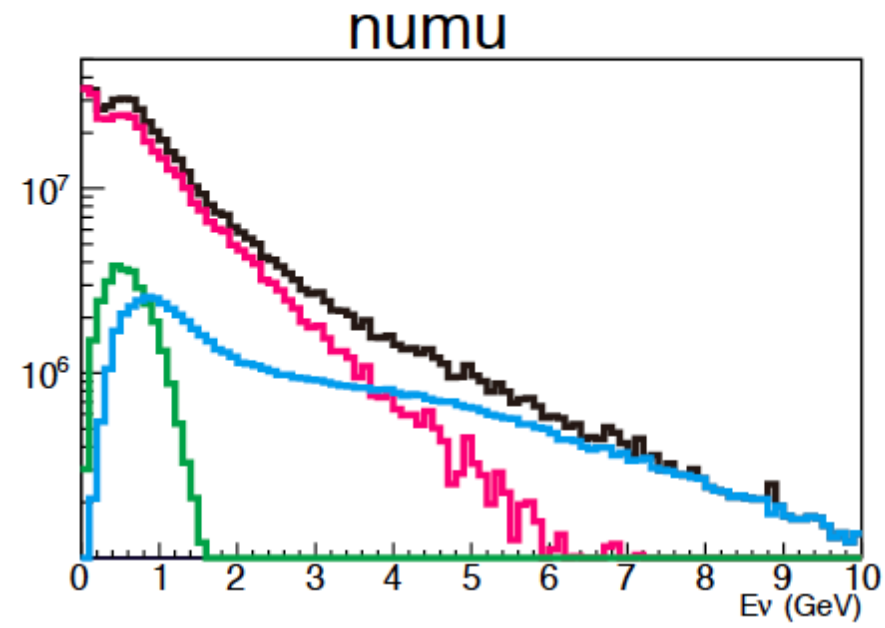
Supplement

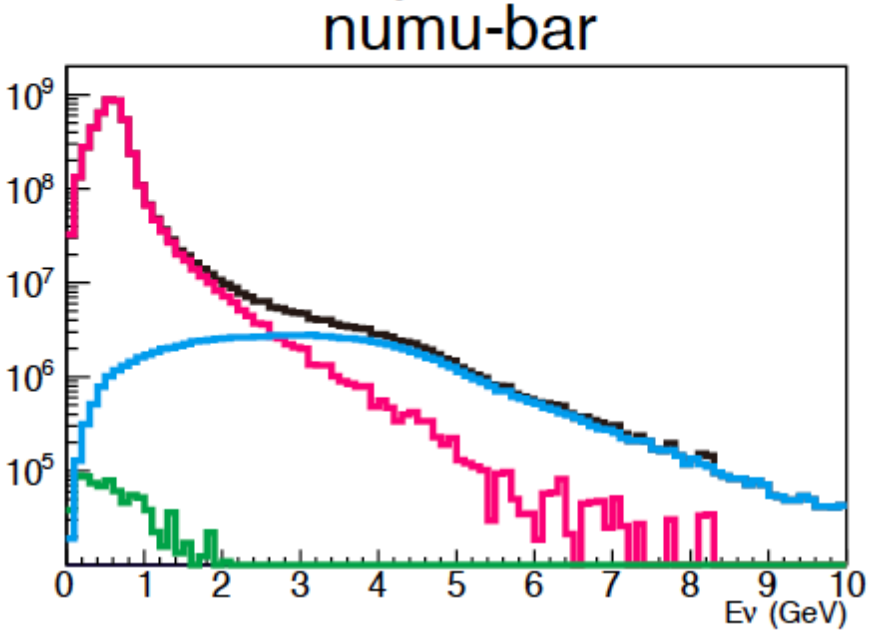

Neutrino run
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$
10^6
10^5
10^4
10^3
ν/50MeV/cm²/10²¹POT
0 1 2 3 4 5 6 7 8
E_ν (GeV)

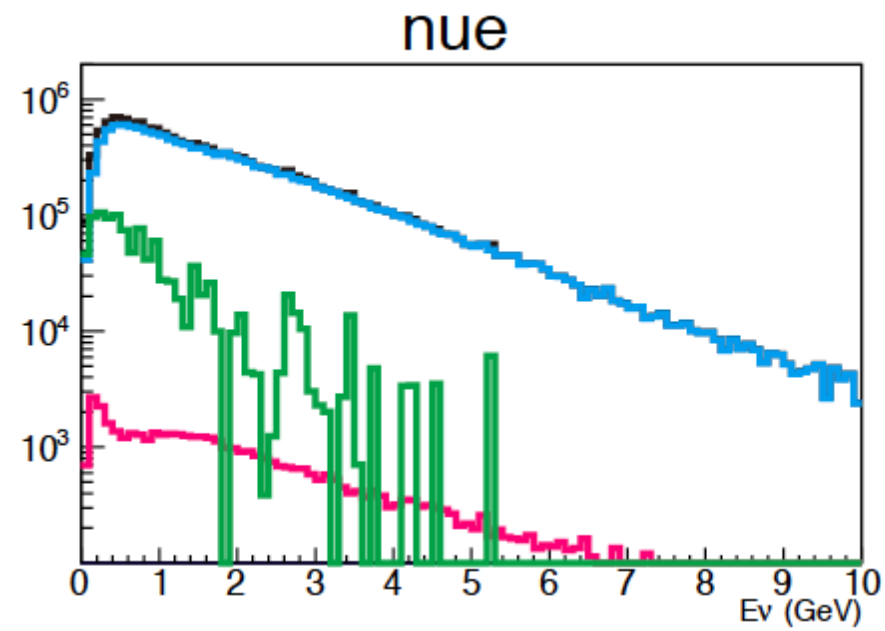

Anti-neutrino run
$\bar{\nu}_\mu$
ν_μ
$\bar{\nu}_e$
ν_e
10^6
10^5
10^4
10^3
ν/50MeV/cm²/10²¹POT
0 1 2 3 4 5 6 7 8
E_ν (GeV)

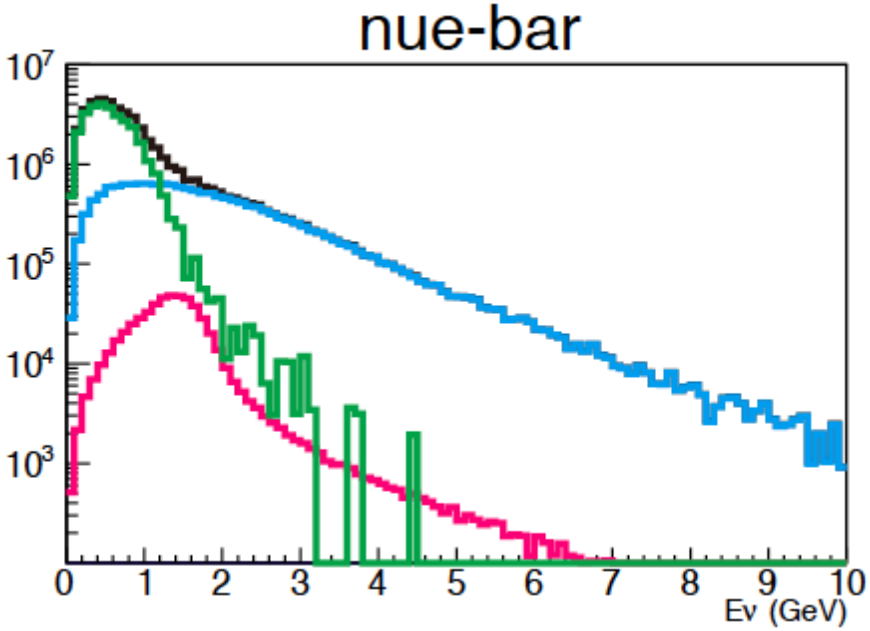

ν mode
ν̄ mode
Events/50MeV
δ=0
δ=1/2π
δ=π
δ=−1/2π
Total BG
νμ/ν̄μ BG
Eν rec (GeV)

Flux by parents (anti-ν run) π,K,μ









Flux error in T2K