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New modeling of accelerator neutrino flux correlations between multiple detector locations towards model-independent measurements of ν-nucleus X-section

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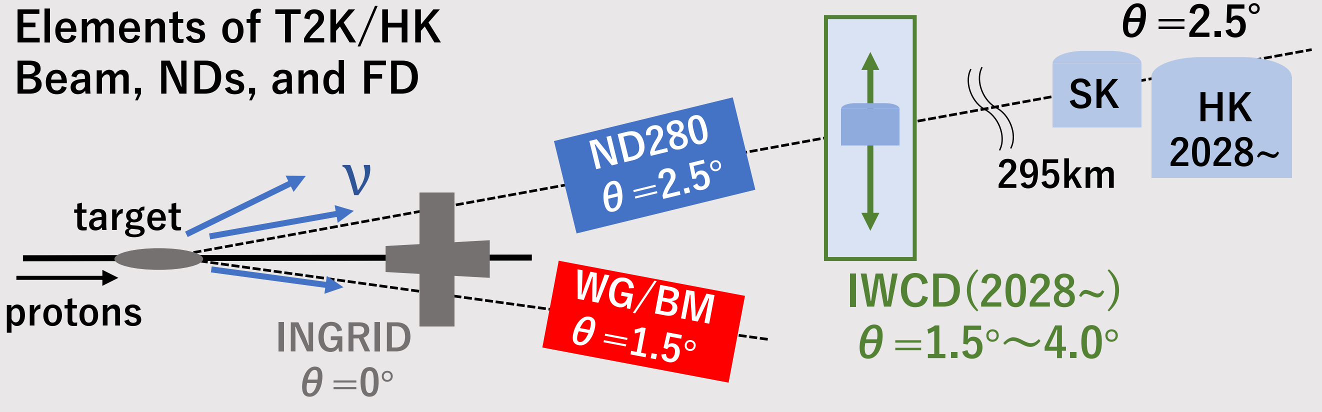
T2K and HK Collaboration

T2K experiment and Hyper-Kamiokande experiment

Elements of T2K/HK
Beam, NDs, and FD



SK→HK (×8 volume) + Beam enhance
→Huge enhance of statistics

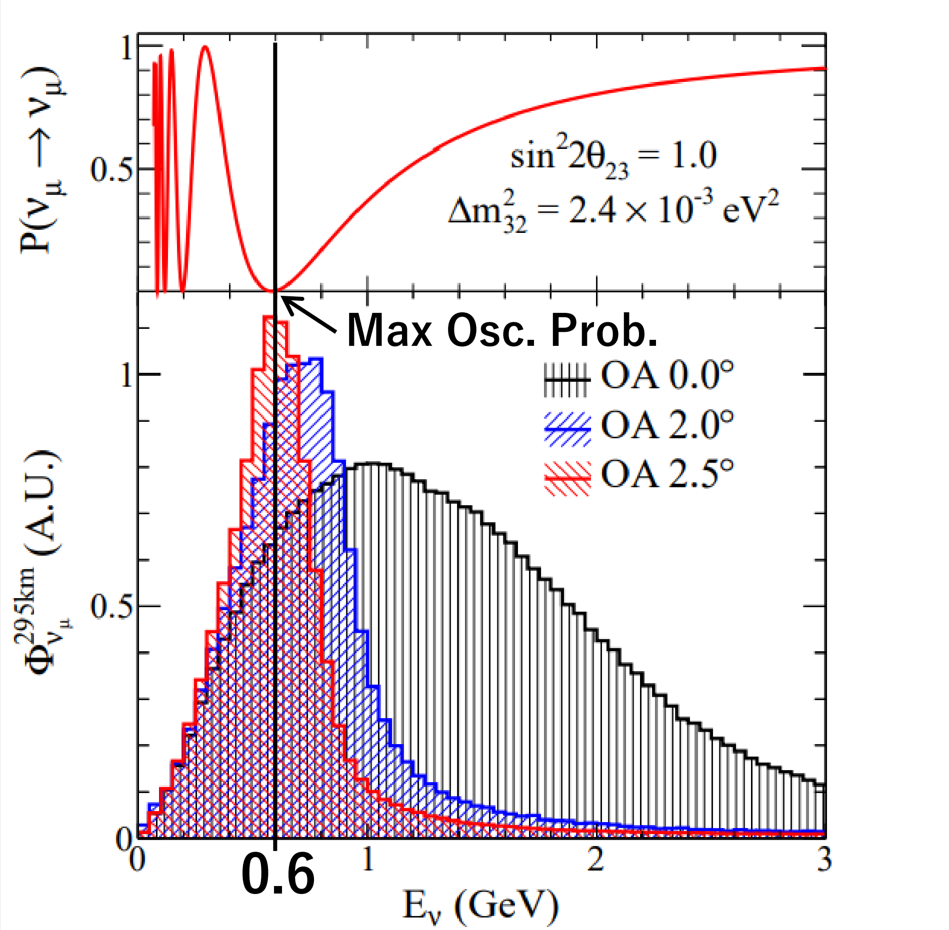
ν-nucleus X-sec will be crucial uncertainty

Need to know energy dependence of X-sec

→use ND280, WAGASCI/BabyMIND (WG/BM)

Construct IWCD for HK experiment

Use **Off-Axis neutrinos** and measure oscillation efficiently



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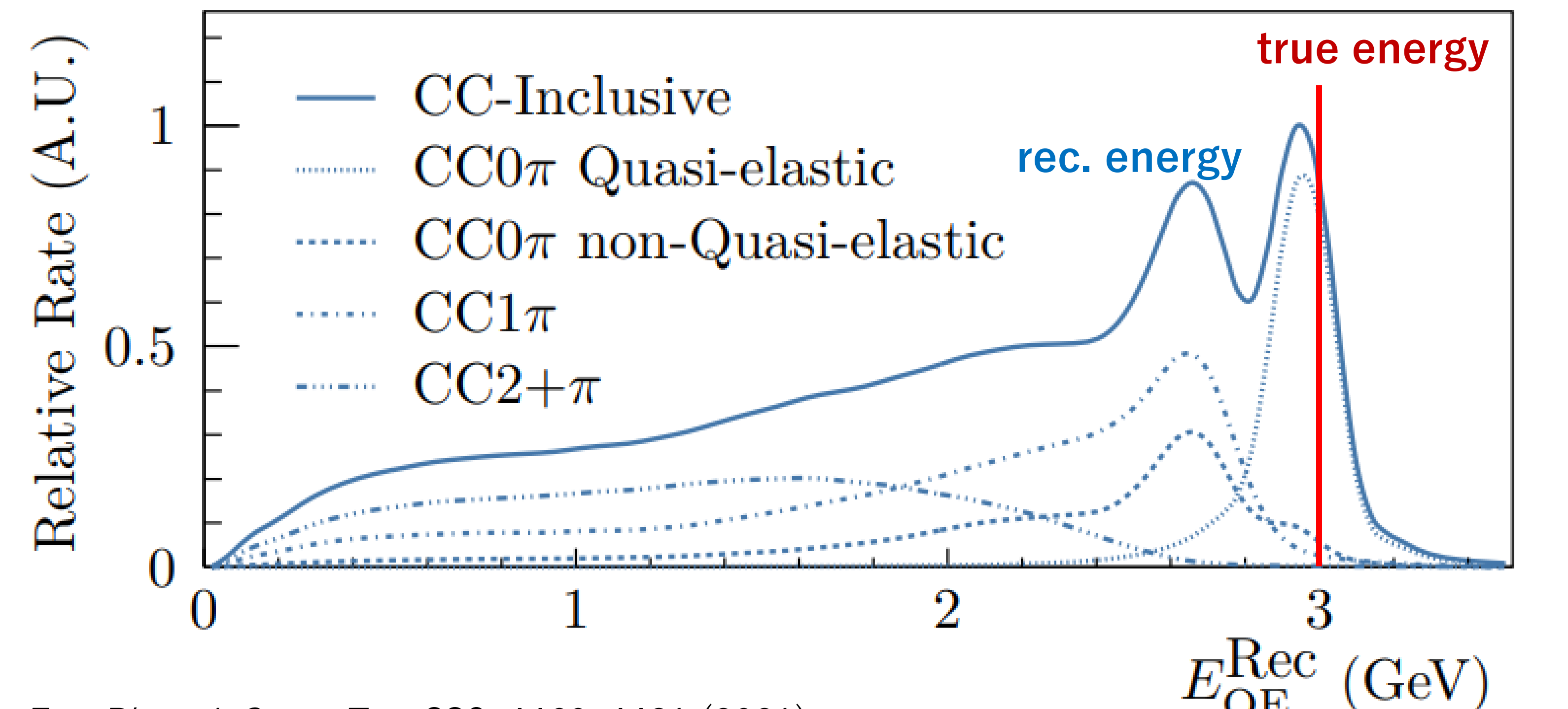
Energy Reconstruction and X-sec of Neutrinos

~~$P(E_\nu) \propto \Phi(E_\nu) \times \sigma(E_\nu)$~~ ← **Not so easy in real measurement…**

$$P\left(E_\nu^{\mathrm{Rec}}\right) \propto \int \Phi\left(E_\nu^{\mathrm{True}}\right) \times \boldsymbol{\sigma}\left(\boldsymbol{E_\nu^{\mathrm{True}}} \rightarrow \boldsymbol{E_\nu^{\mathrm{Rec}}}\right) \mathrm{d}E_\nu^{\mathrm{True}}$$

Need to know X-sec as 2D function of $E_\nu^{\mathrm{True}}, E_\nu^{\mathrm{Rec}}$



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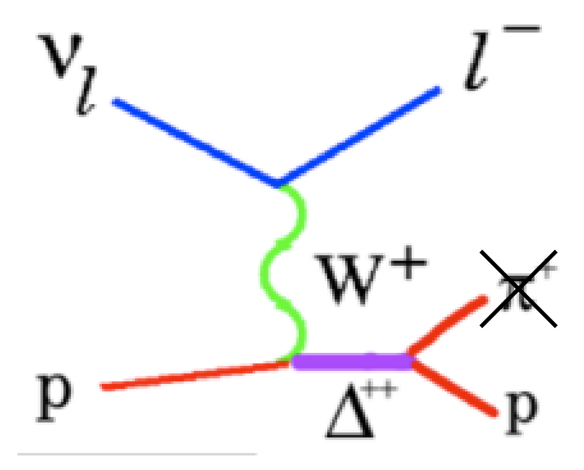


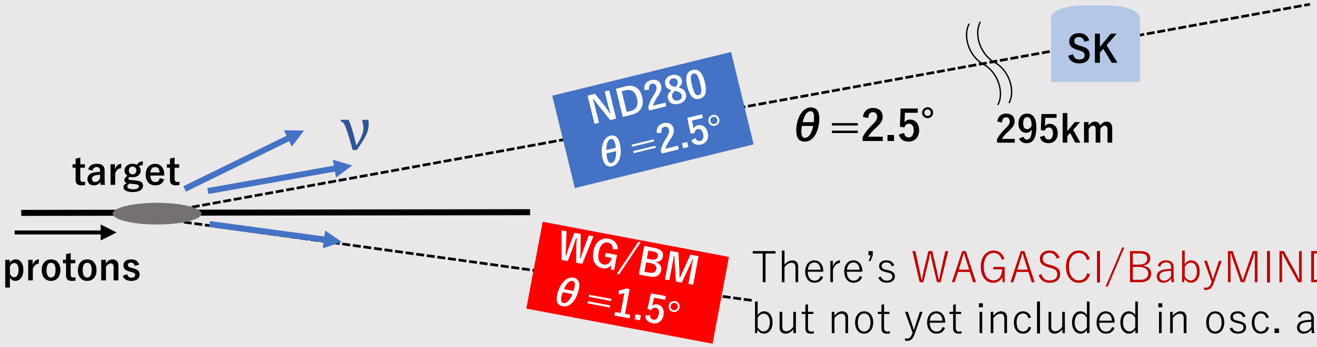
Cannot detect π in CC1π?
→Reconstructed as CCQE

Cross-section measurement in T2K

Measured by ND280

$$\text{Event Rate}\,(p_l,\theta_l) \propto \int \Phi_{\text{ND280}}\left(E_\nu^{\text{True}}\right) \times \sigma\left(E_\nu^{\text{True}} \to (p_l,\theta_l)\right) \mathrm{d}E_\nu^{\text{True}}$$

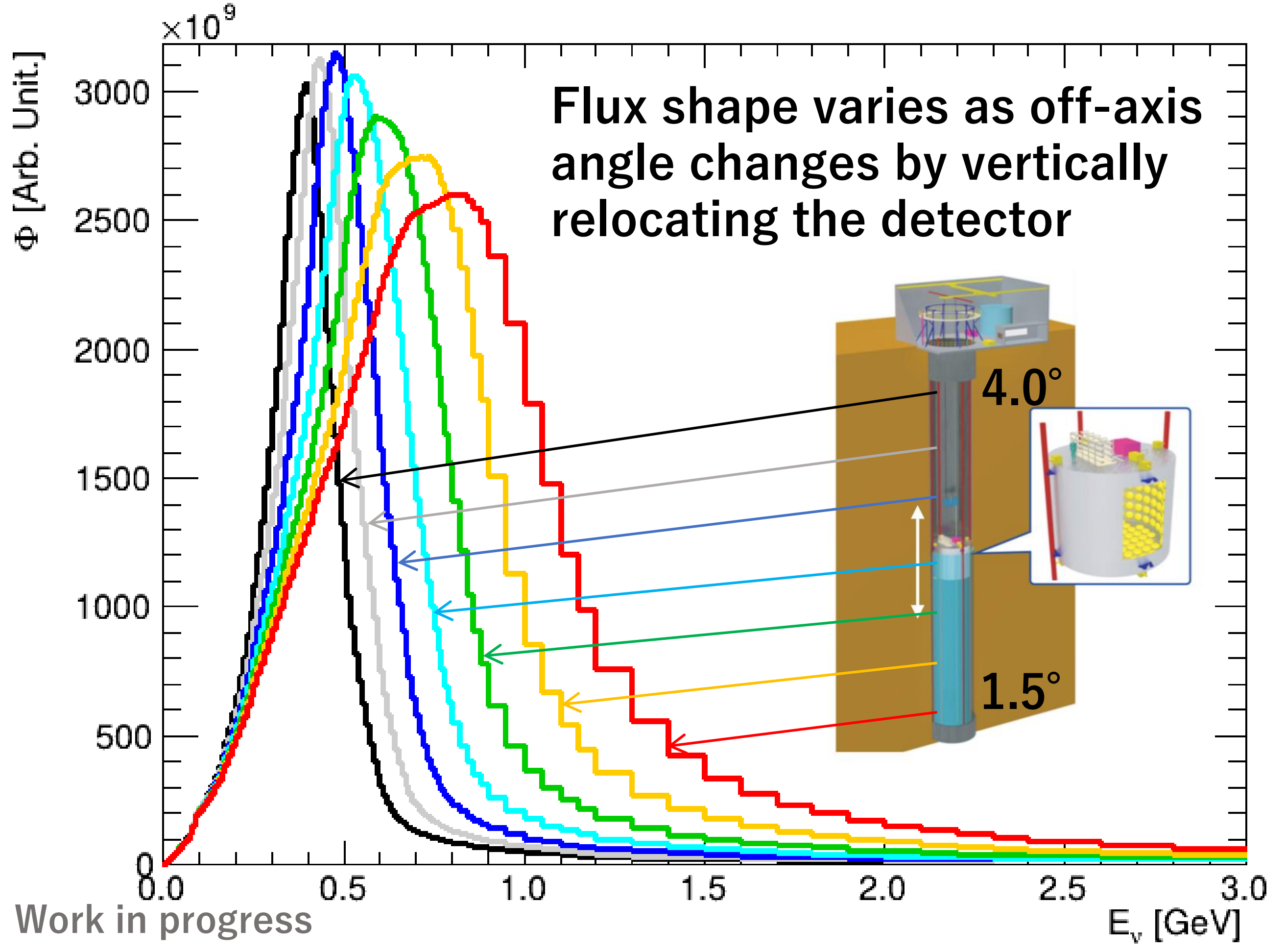
Not enough to solve degeneracy of $\left(E_\nu^{\text{True}},\ E_\nu^{\text{Rec}}\right)$ 2D function
→Rely on model to solve it



There's WAGASCI/BabyMIND at 1.5°
but not yet included in osc. analysis

Cross-section measurement in Hyper-K

Addition of Intermediate Water Cherenkov Detector (IWCD)



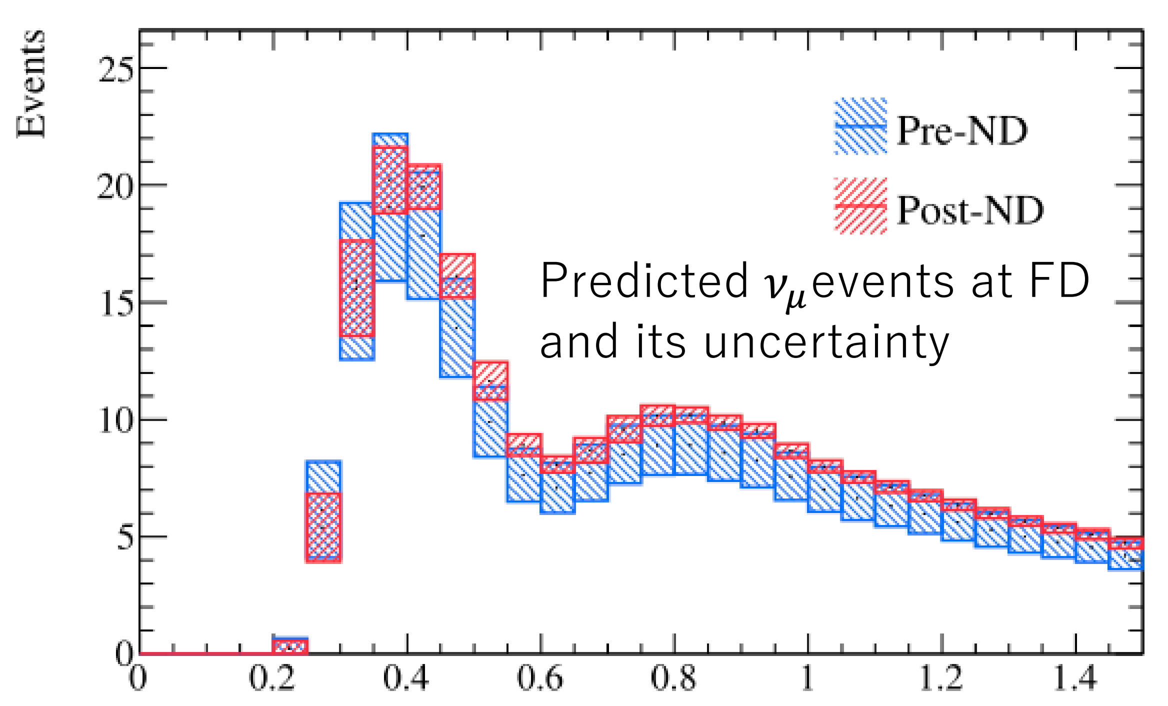
$$\begin{cases} \int \Phi_{1.5^\circ}(E_\nu^{\mathrm{True}}) \times \sigma(E_\nu^{\mathrm{True}} \to E_\nu^{\mathrm{Rec}})\, dE_\nu^{\mathrm{True}} \\ \int \Phi_{2.0^\circ}(E_\nu^{\mathrm{True}}) \times \sigma(E_\nu^{\mathrm{True}} \to E_\nu^{\mathrm{Rec}})\, dE_\nu^{\mathrm{True}} \\ \vdots \end{cases}$$

→ Measurements with various flux conditions enables **model-independent measurements of X-sec**

Covariance Matrix for fit on syst. err. by Near Detectors

NDs constrain main syst. error:
Flux and Neutrino Interaction

- → **Flux and Interaction parameters are fitting parameters**
- → **Their uncertainty before and after the fitting is necessary**



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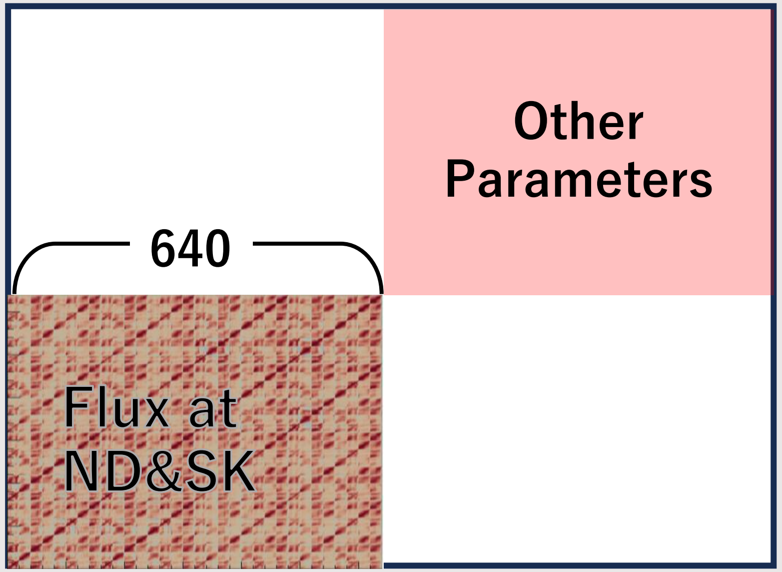
$$\boldsymbol{\sigma}(\boldsymbol{f}(\mathbf{x},\mathbf{y}))^2 \approx \left(\frac{\partial f}{\partial x}\right)^2 \sigma_x^2 + \left(\frac{\partial f}{\partial y}\right)^2 \sigma_y^2 + 2\left(\frac{\partial f}{\partial x} \times \frac{\partial f}{\partial y}\right) \underline{\boldsymbol{\sigma_{xy}}}$$

Expressed as **Covariance Matrix or Correlation Matrix**

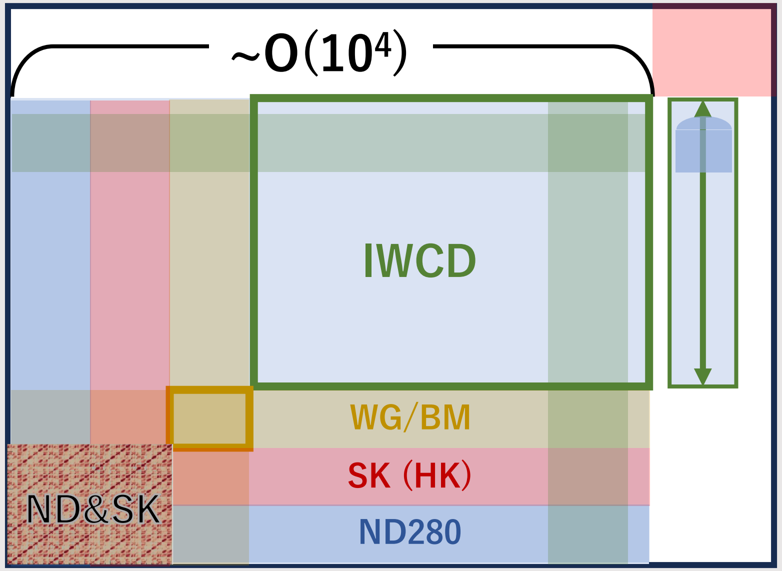
Severe Computational Cost in Hyper-K Experiment

Number of fit parameters will significantly increase due to **IWCD**

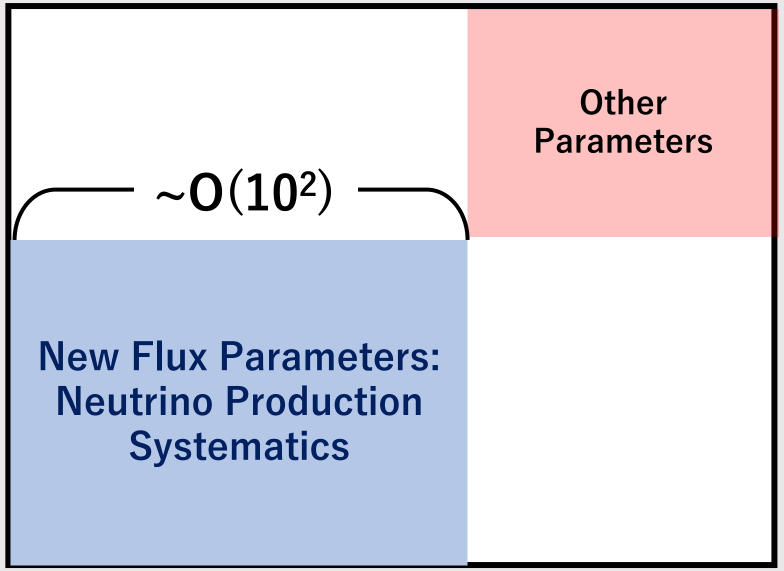
Reduce the number of parameters by **using systematic source parameters of neutrino production system**, instead of using neutrino flux intensity at each detection point



Current Matrix



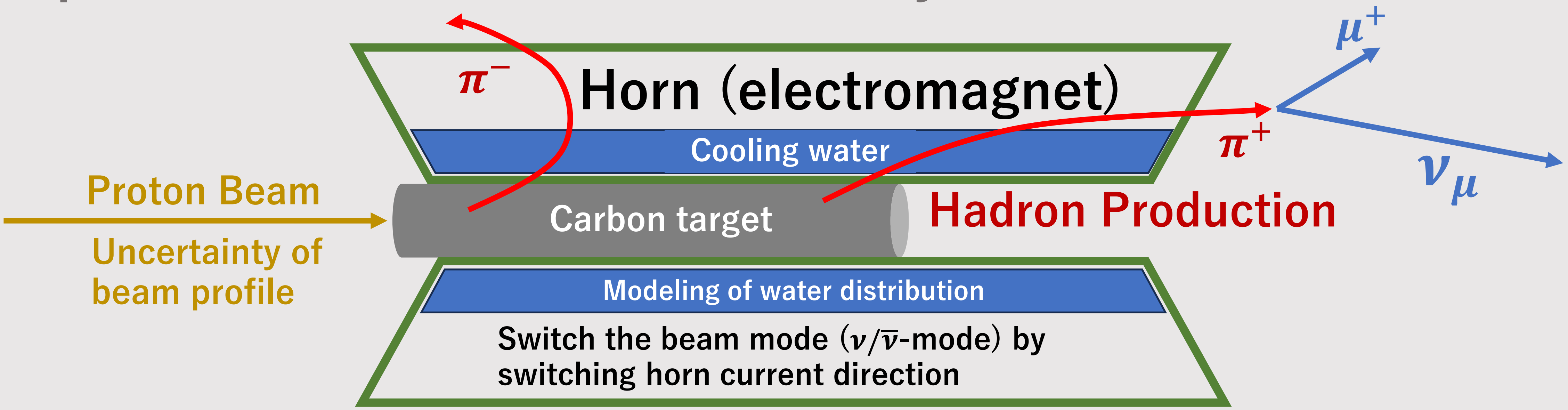
Matrix in HK era but too large…



This work

Systematic Uncertainties of Neutrino Production System

30GeV protons strike a carbon target, which results in production of hadrons which decay into neutrinos

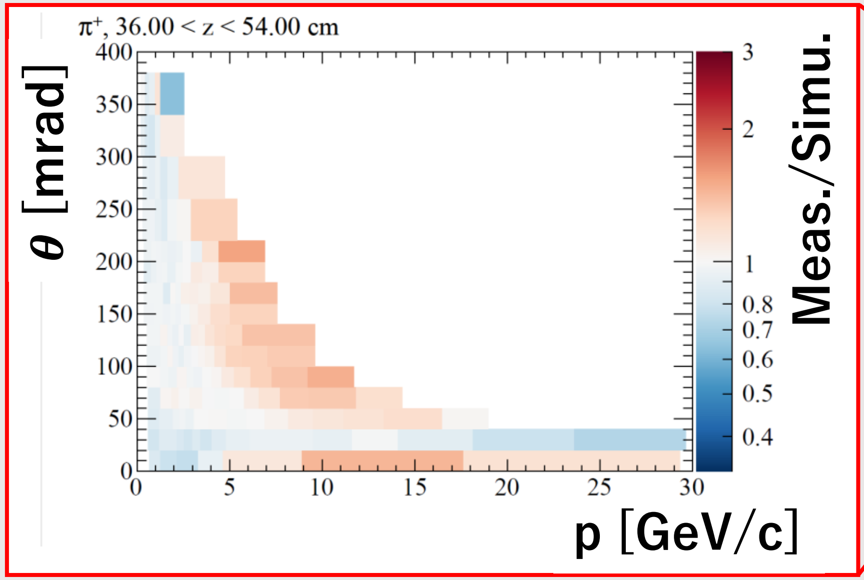


These parameters are independent from detection points

However, **hadron interactions** are described based on experimental data, which requires many parameters

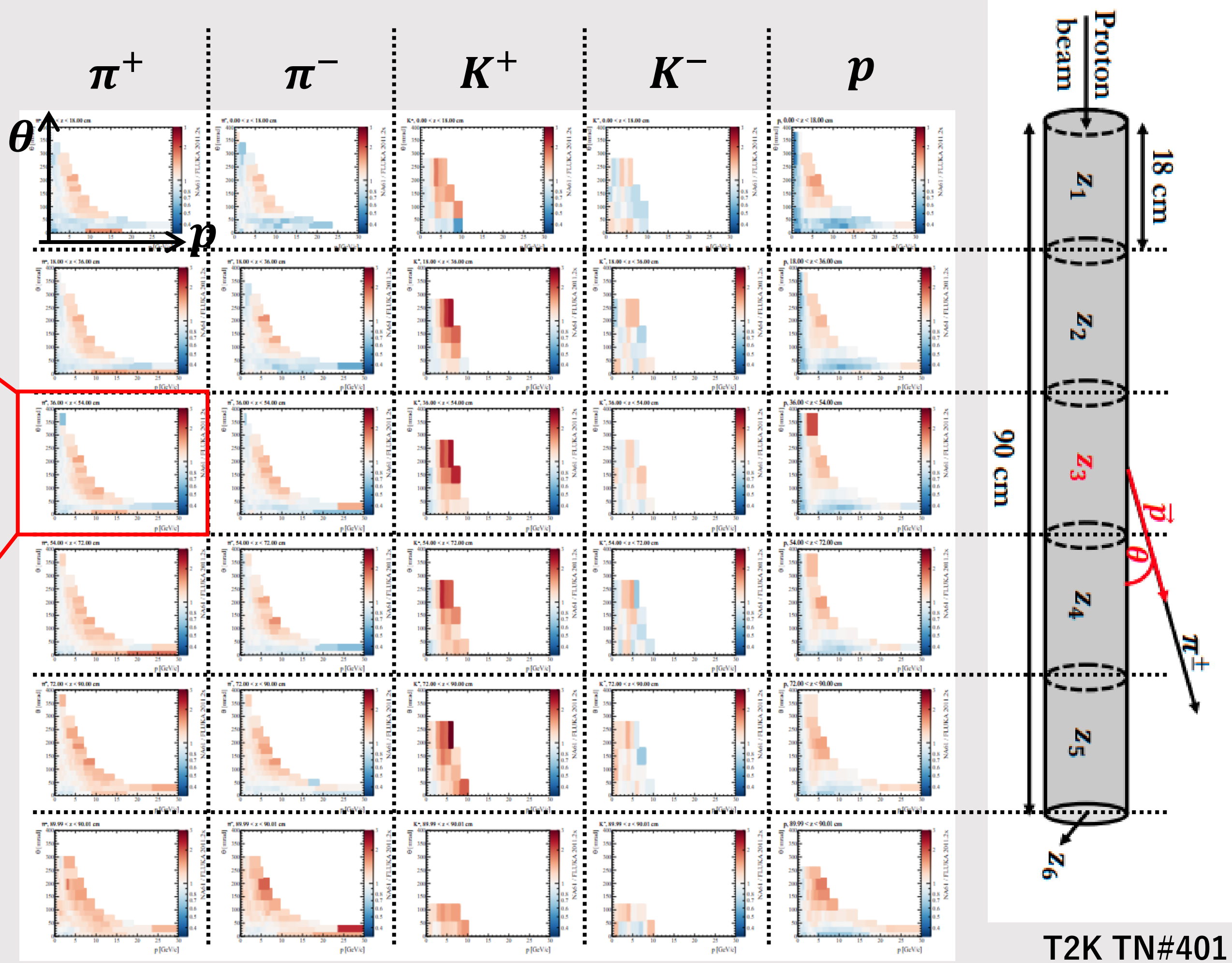
NA61/SHINE experiment

Measurement of hadron production from T2K "Replica" target



Ratio of production rate of model and real

→"Tune" MC samples by this

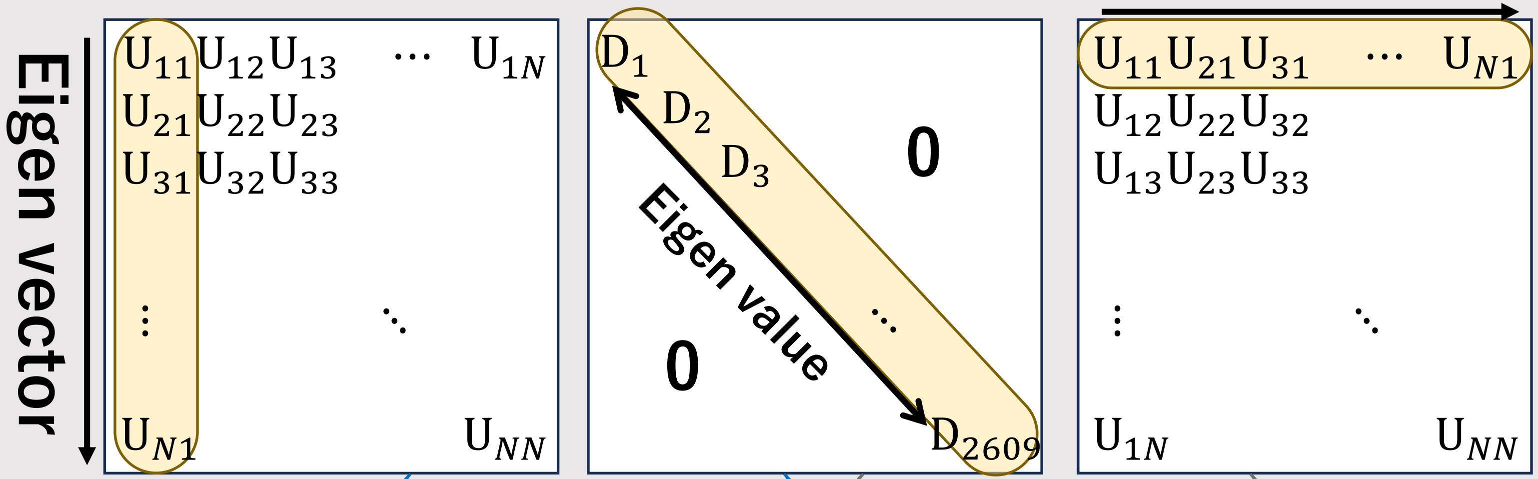


T2K TN#401

↑ All of 2609 data points will be new parameters → **Too many parameters**

How to reduce number of NA61 replica parameters?

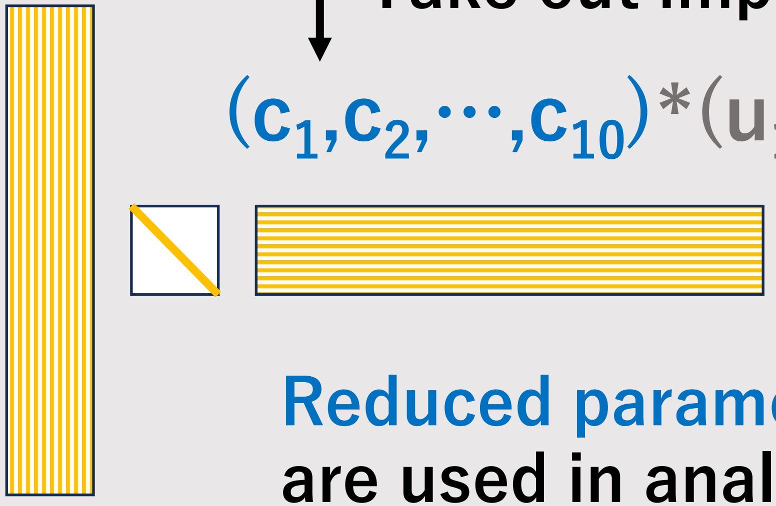
$(x_1, x_2, \cdots, x_{2609})$



$(c_1, c_2, \cdots, c_{2609}) * (u_1, u_2, \cdots, u_{2609})$

Take out important vectors

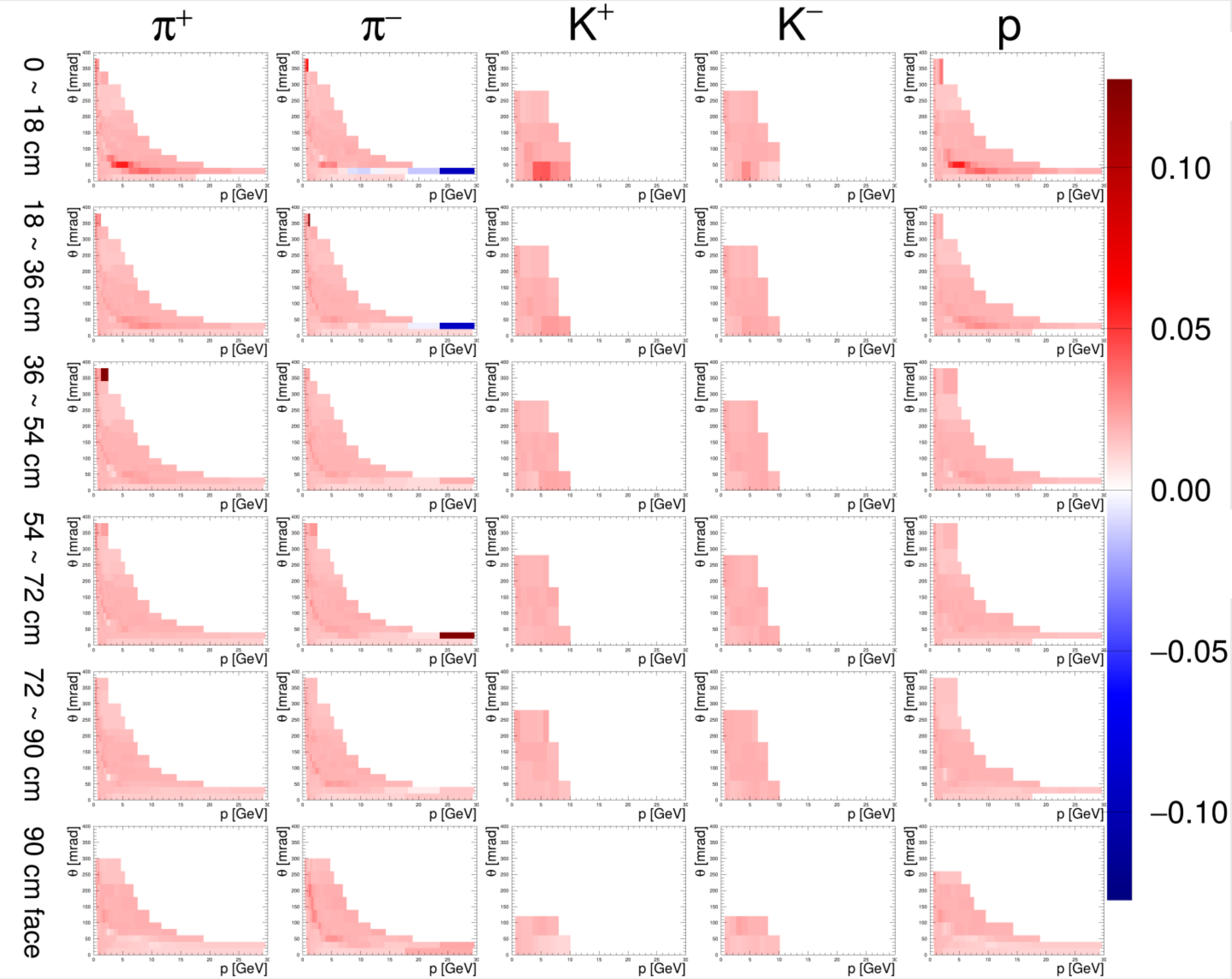
$(c_1, c_2, \cdots, c_{10}) * (u_1, u_2, \cdots, u_{10})$



Create new **uncorrelated variables** by eigen decomposition and **take out important vectors**

Reduced parameters and eig vecs are used in analyses

Response of hadron phase space of eig vec #0



T2K work in progress

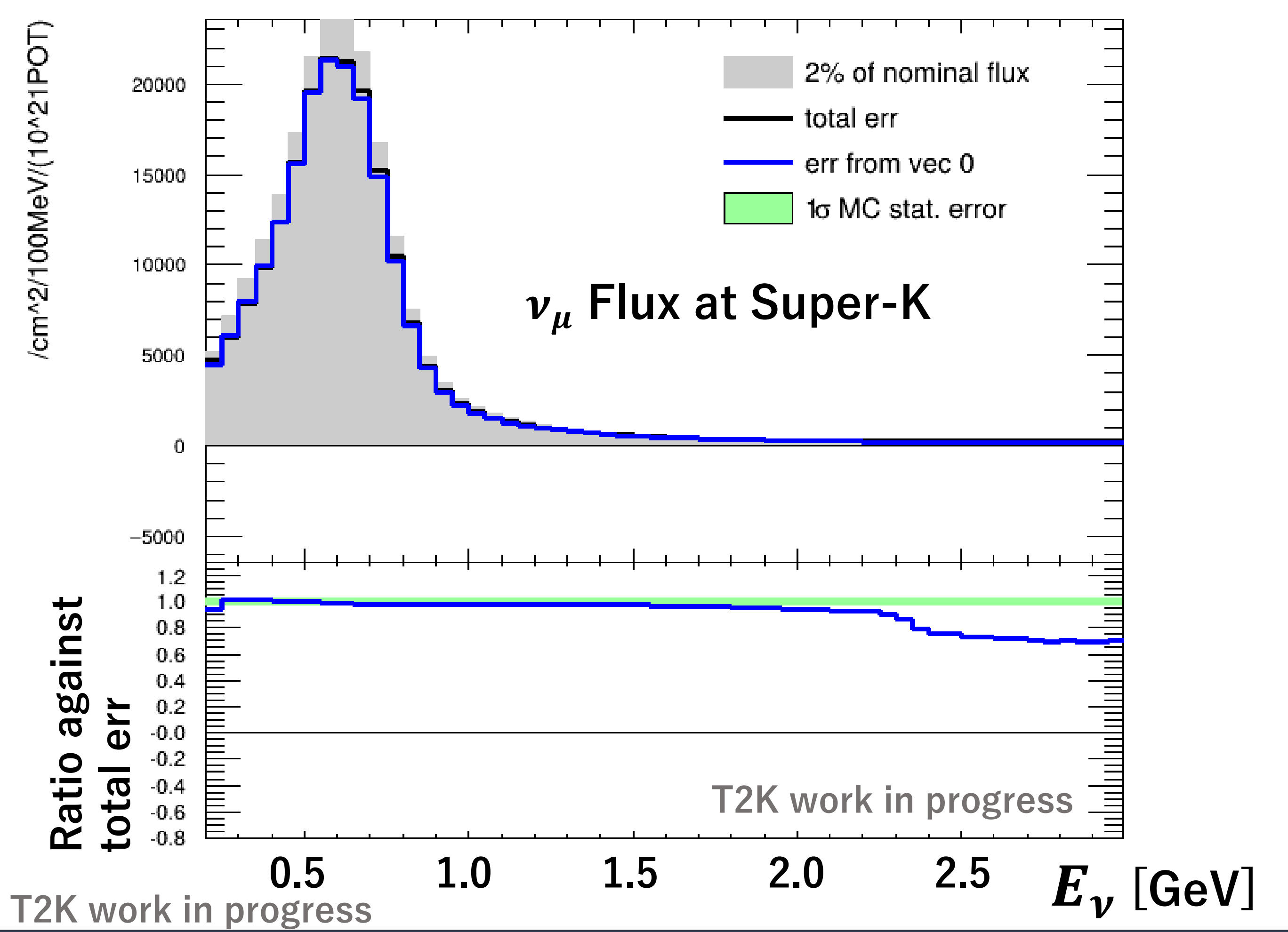
Hadron yields shift almost uniformly (~2% in 1 σ)

Corresponds to reconstruction bias in NA61/SHINE (2% over all the phase space)

Can expect that neutrino flux intensity also shift uniformly

Response of neutrino flux on new parameter: eig vec #0

Change in neutrino flux intensity when eig. vec. shifted 1 σ
Dominant error source for peak region



Gray: Flux intensity (scaled to 2%)
To show the scale of uncertainty

Black: Total Error from NA61 Replica
Evaluated by MC simulation

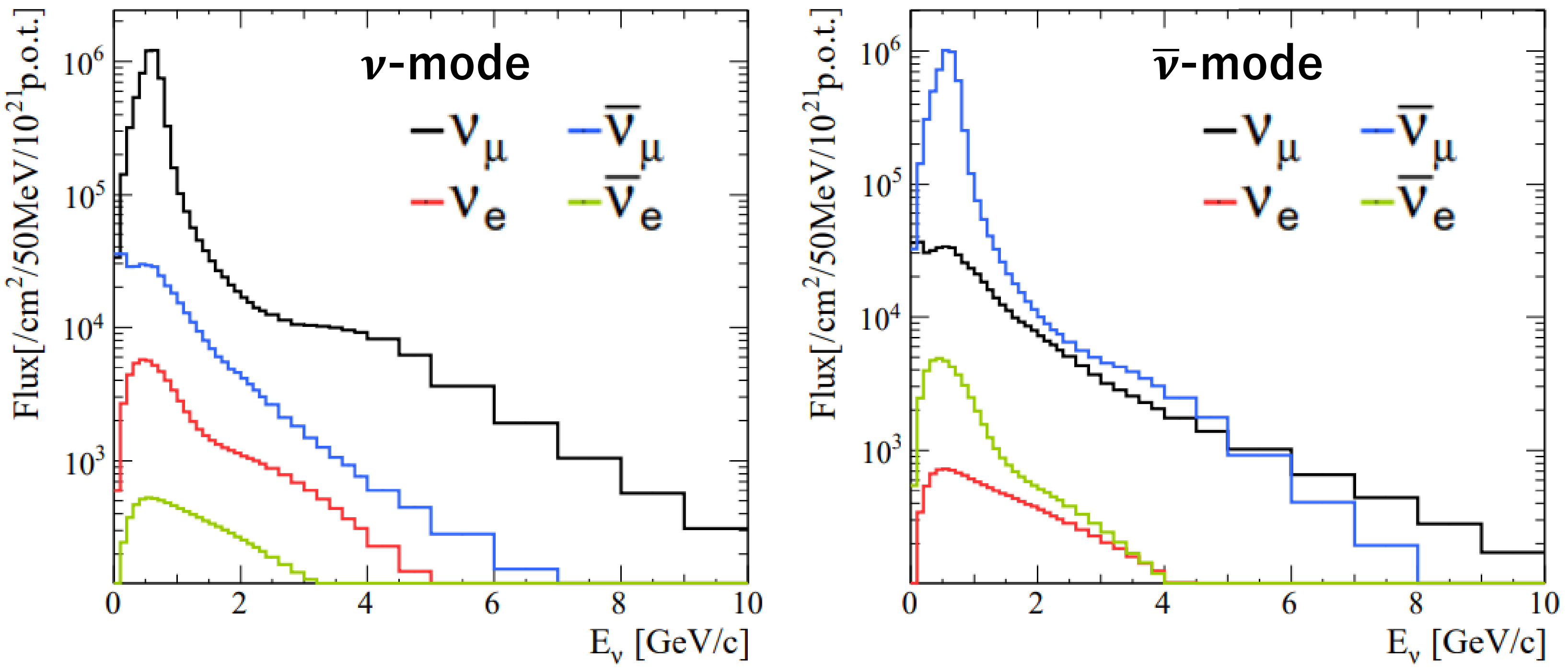
Blue: Response of flux (top)
Ratio against total error (bottom)

Green: Range to reach
1 σ range of total error due to MC statistical error

Flux intensity of each neutrino flavor

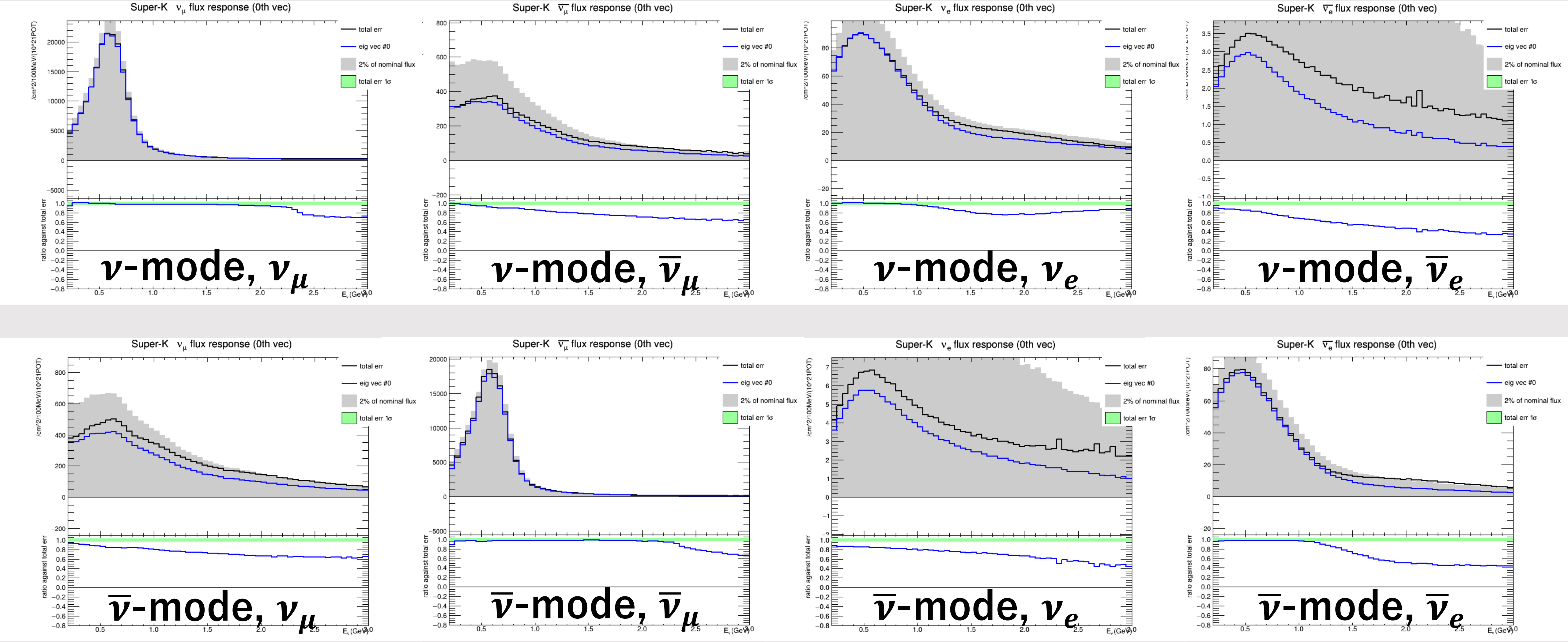
- ν_μ is the largest intensity at ν -mode, but the other flavors are produced from high momentum π^-, etc.
- The orders of intensity are different against each flavor
- Same for $\bar{\nu}$ -mode, thus need to consider 8 patterns of flux

Comparison of flux intensity of each flavor at Super-K



Response of neutrino flux on new parameter: eig vec #0

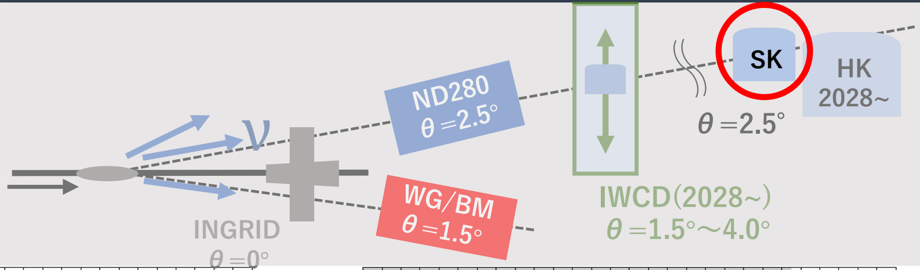
Response on large part of flux

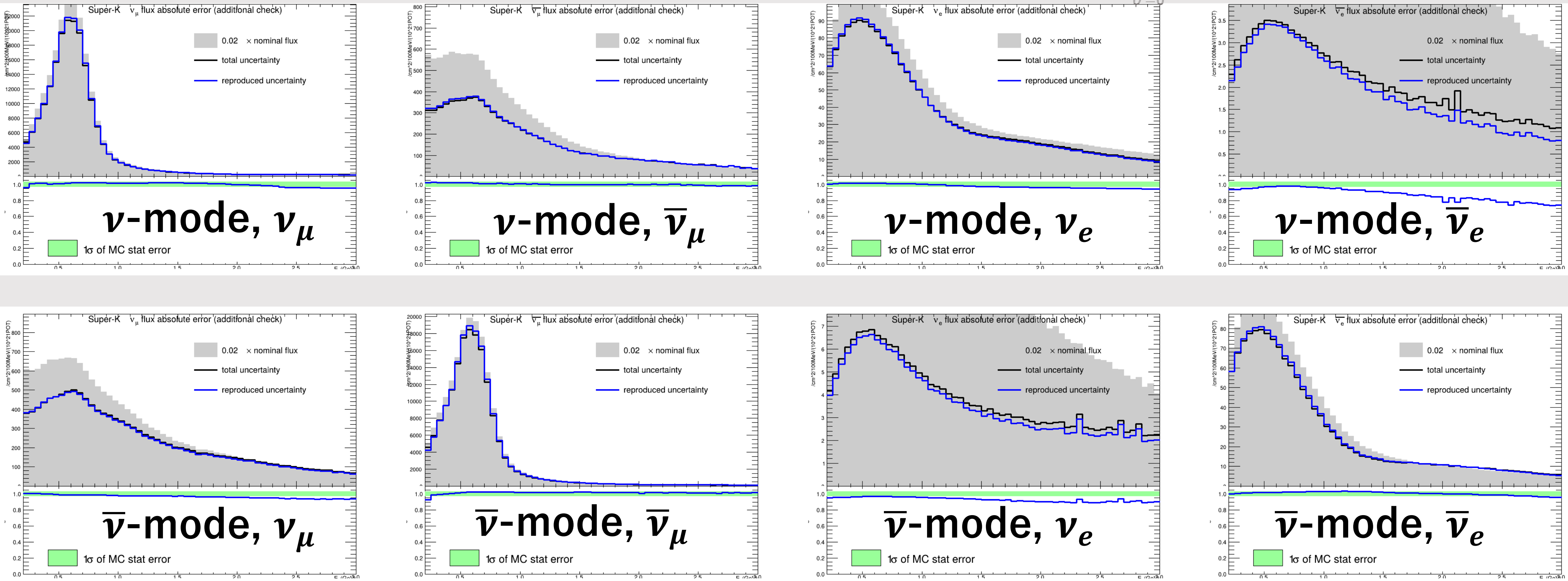


T2K work in progress

Reproduction of flux uncertainty at Super-Kamiokande

By using 11 parameters instead of 2609, uncertainties are reproduced

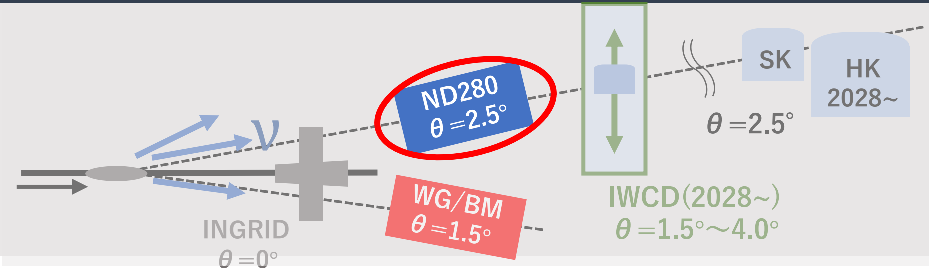


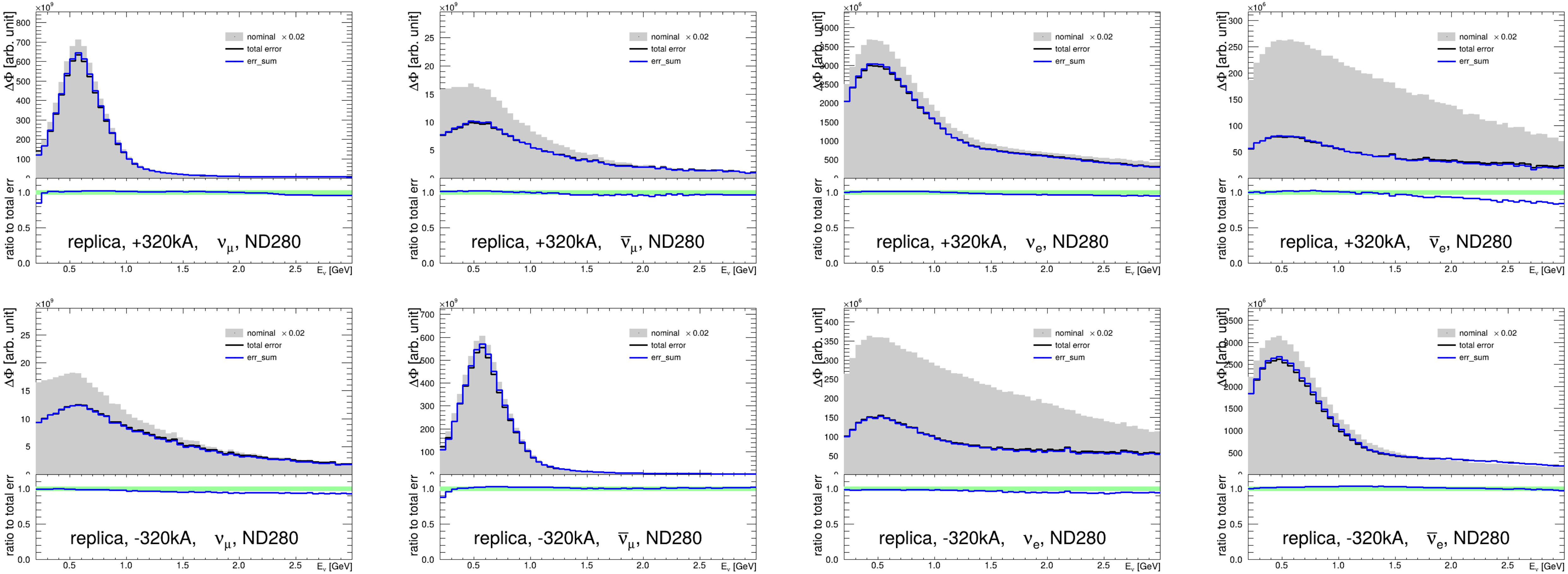


T2K work in progress

Reproduction of flux uncertainty at ND280

Same parameter set are used
ND280 is same Off-Axis angle with SK

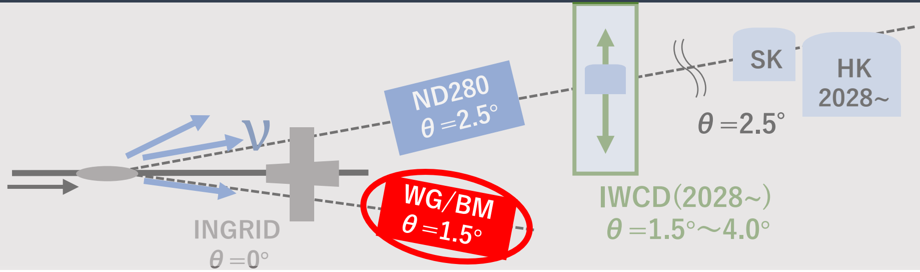


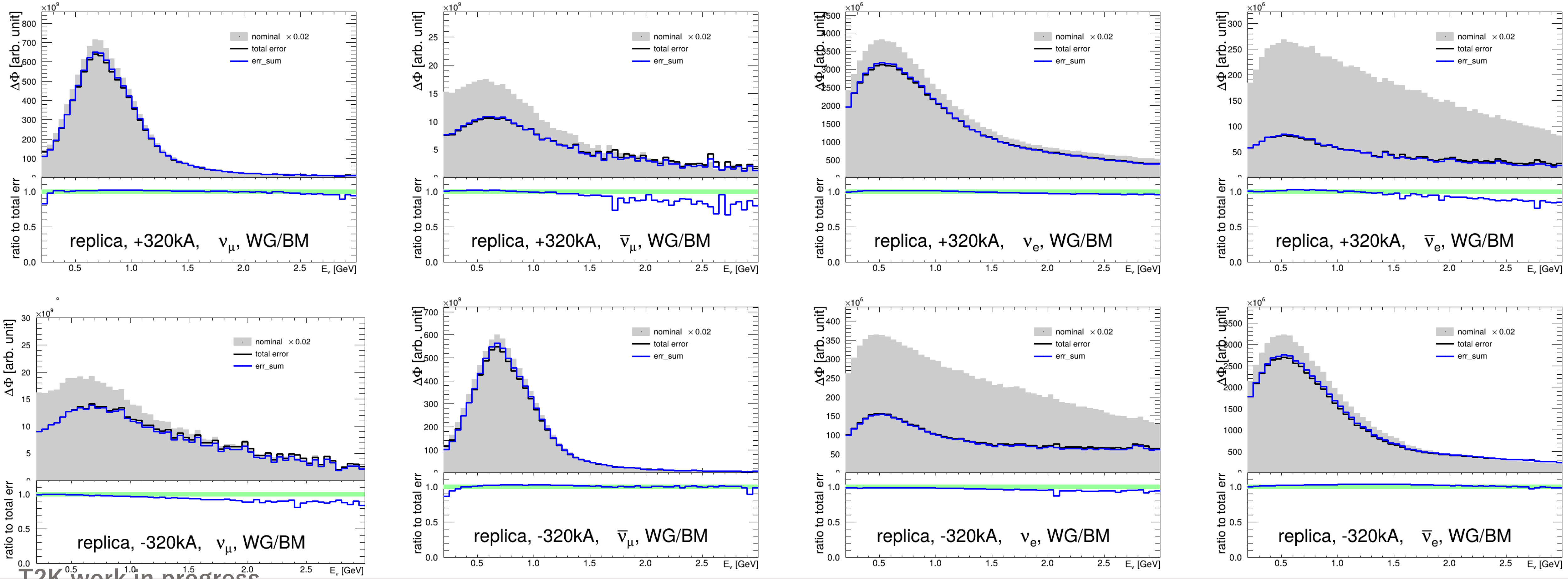


T2K work in progress

Reproduction of flux uncertainty at WAGASCI/BabyMIND

WG/BM is located at different angle, But reproduced with same parameters



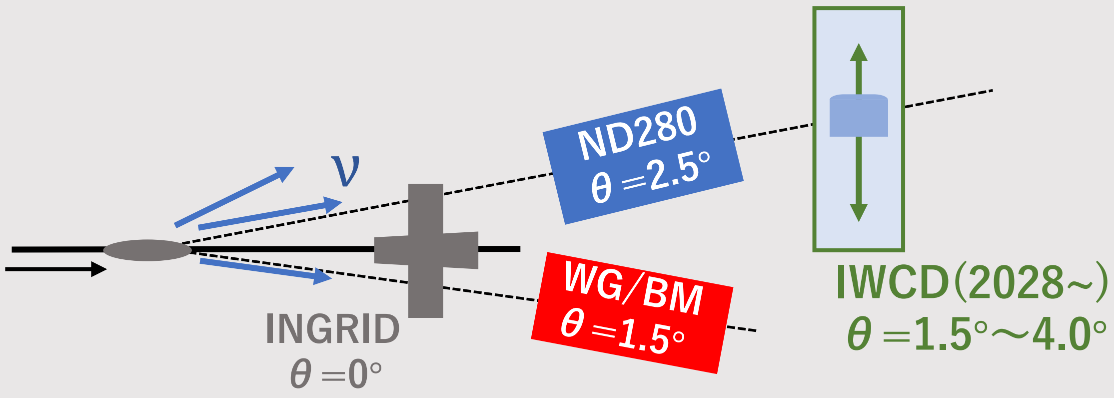


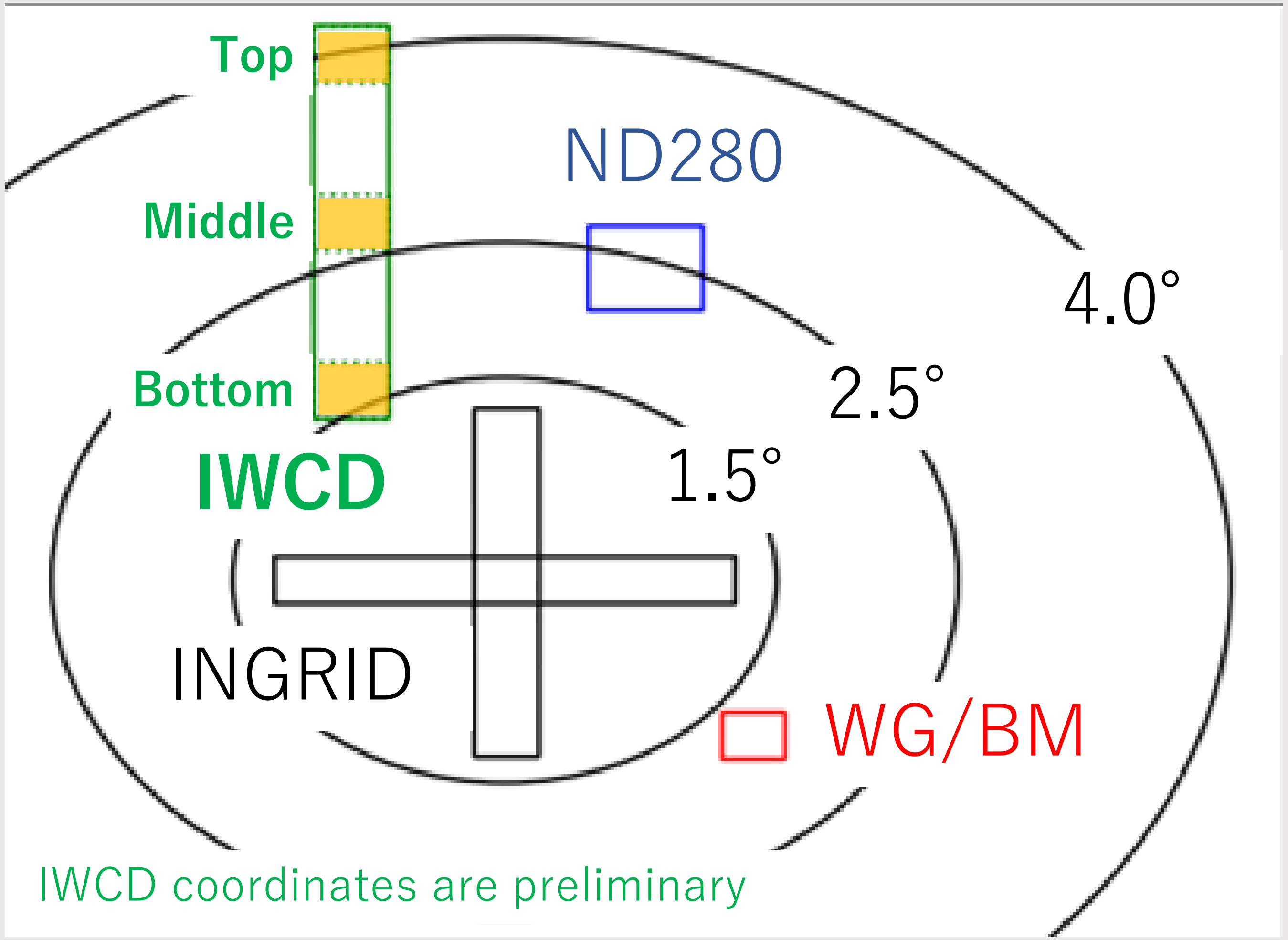
T2K work in progress

Tests for IWCD

Detector locations as Off-Axis Angle

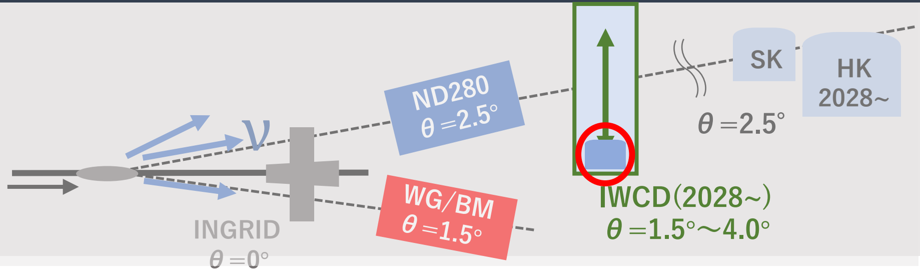
Will show results on 3 sample positions of IWCD

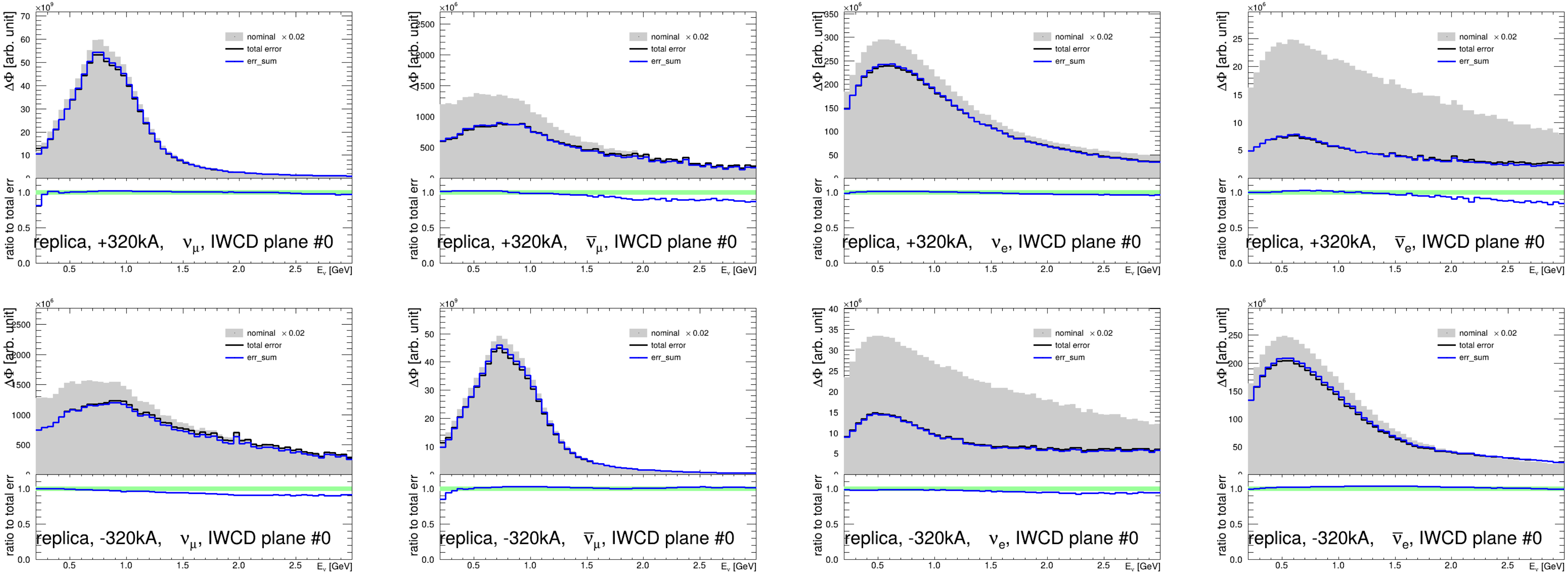




IWCD at bottom (1.5° Off-Axis)

Reproduced with same parameter set

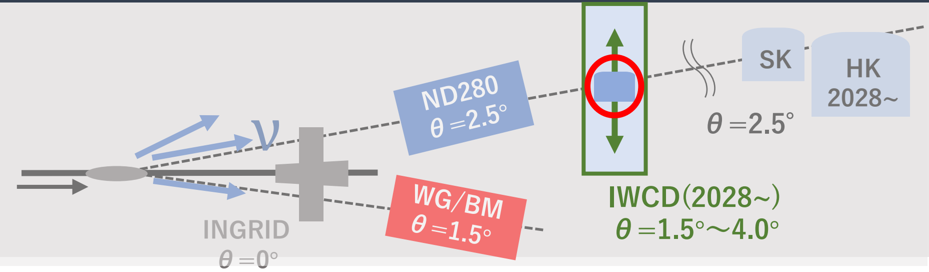


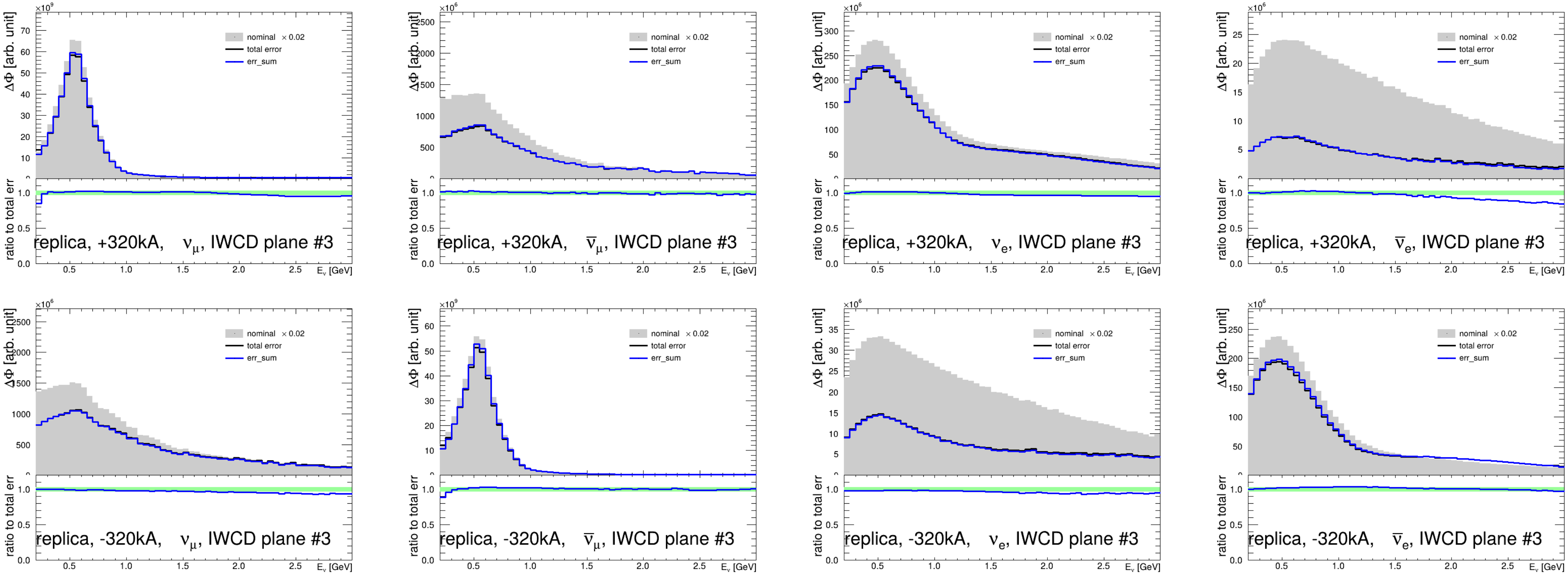


work in progress

IWCD at middle (2.7° Off-Axis)

Reproduced with same parameter set

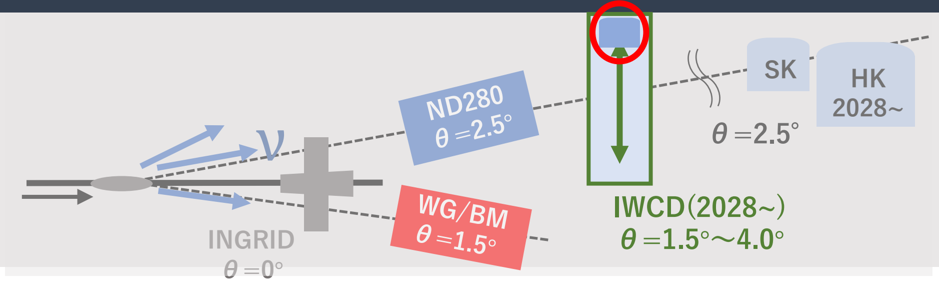


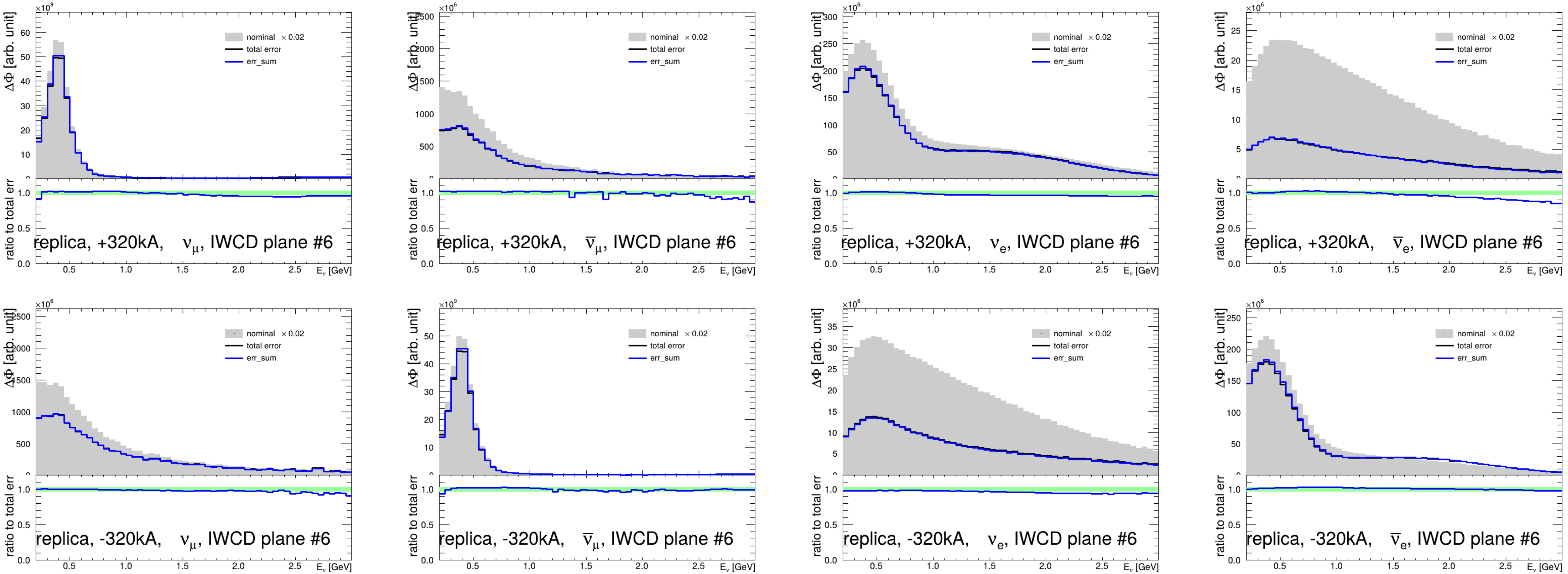


work in progress

IWCD at top (4.0° Off-Axis)

Reproduced with same parameter set





work in progress

Summary and plans

- We need a new method to handle flux correlations between multiple detection points with reduced number of parameters
- Energy bin-based flux parameters → Original systematic parameters
  But the number of parameters for hadron interaction is large
- Reduced parameters of NA61 Replica parameters (2609→11)
- Flux error of all detectors are reproduced with same parameter set
  → Important elements don't change with small difference of OA angle

Plans:

- Off-Axis Angle interpolation for IWCD