Hyper-Kamiokande

Constraints on electron neutrino and antineutrino cross-sections for the leptonic CP violation search at Hyper-Kamiokande

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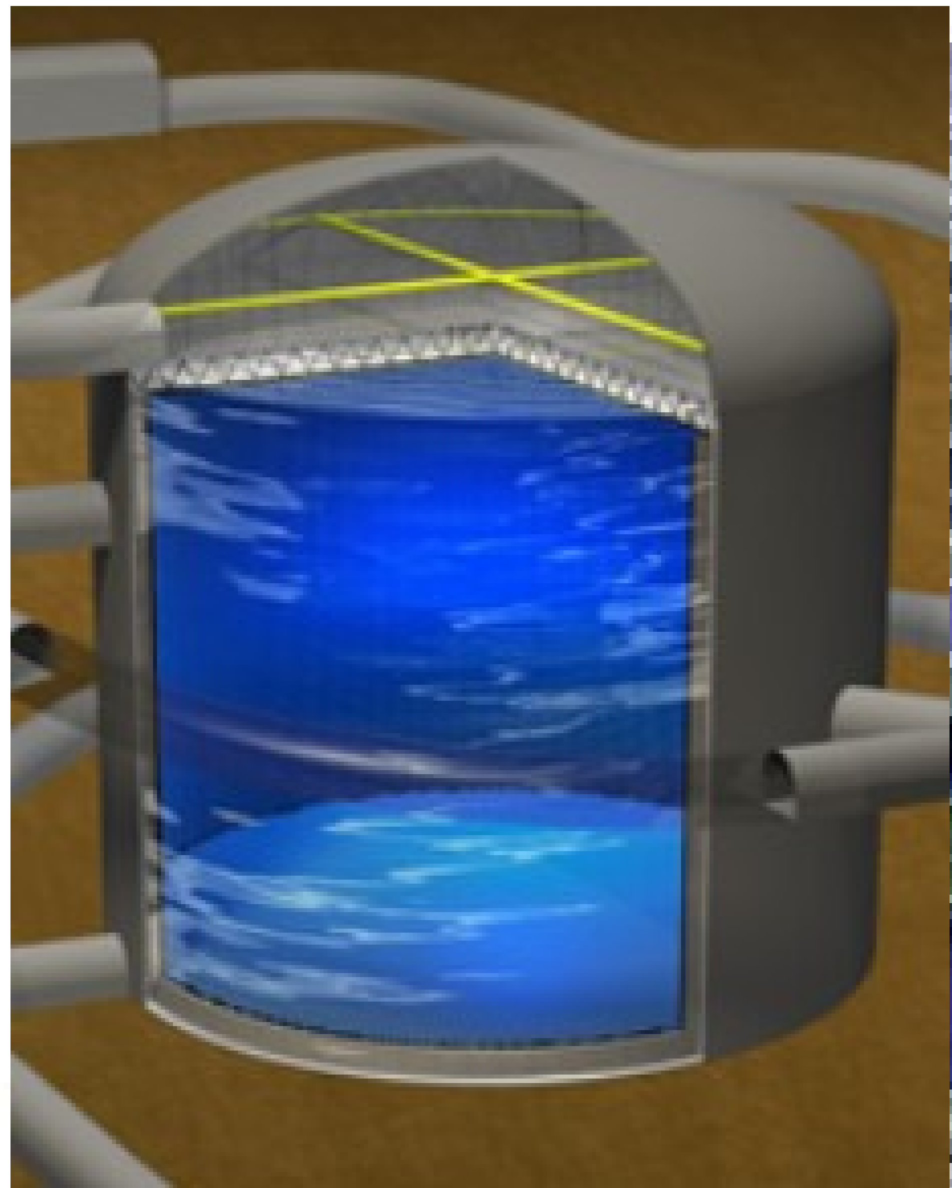
June 8, 2022/W1-1, 2022 CAP Congress

TRIUMF

The Hyper-K long-baseline program



The Hyper-K detector

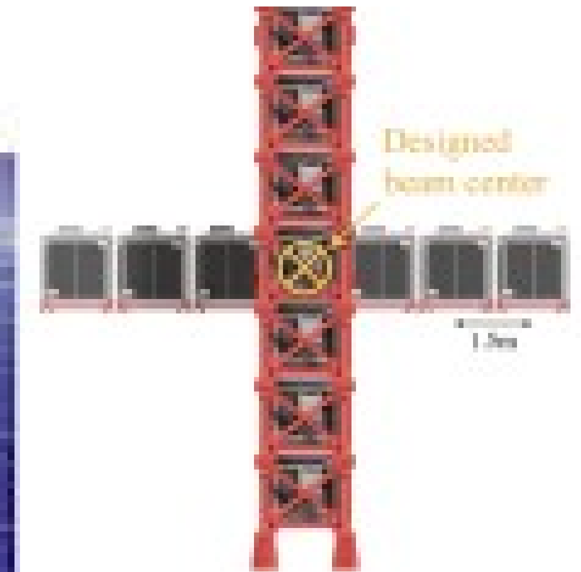
- Will study $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations to search for CP violation, following the successful T2K experiment
- Will have 2.5 x more intense beam and 8 x larger fiducial mass of the far detector
- Interaction rates will be 20 x higher than the T2K's one ⇒ Measurements will be systematically limited

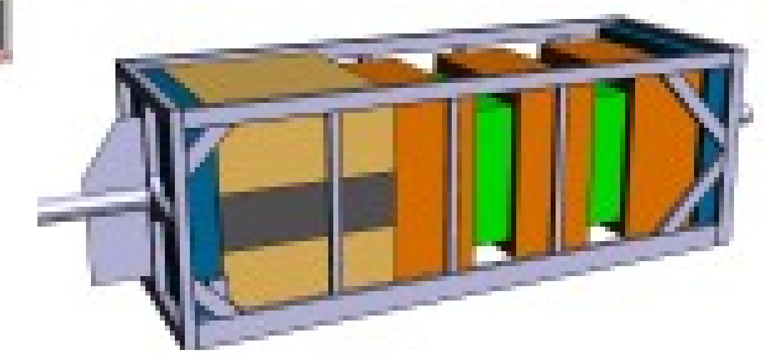
ν_e and $\bar{\nu}_e$ cross-section uncertainties

- The CP violation will be studied by essentially comparing observed ν_e and $\bar{\nu}_e$ event rates
- ν_e and $\bar{\nu}_e$ cross-section uncertainties will be dominant

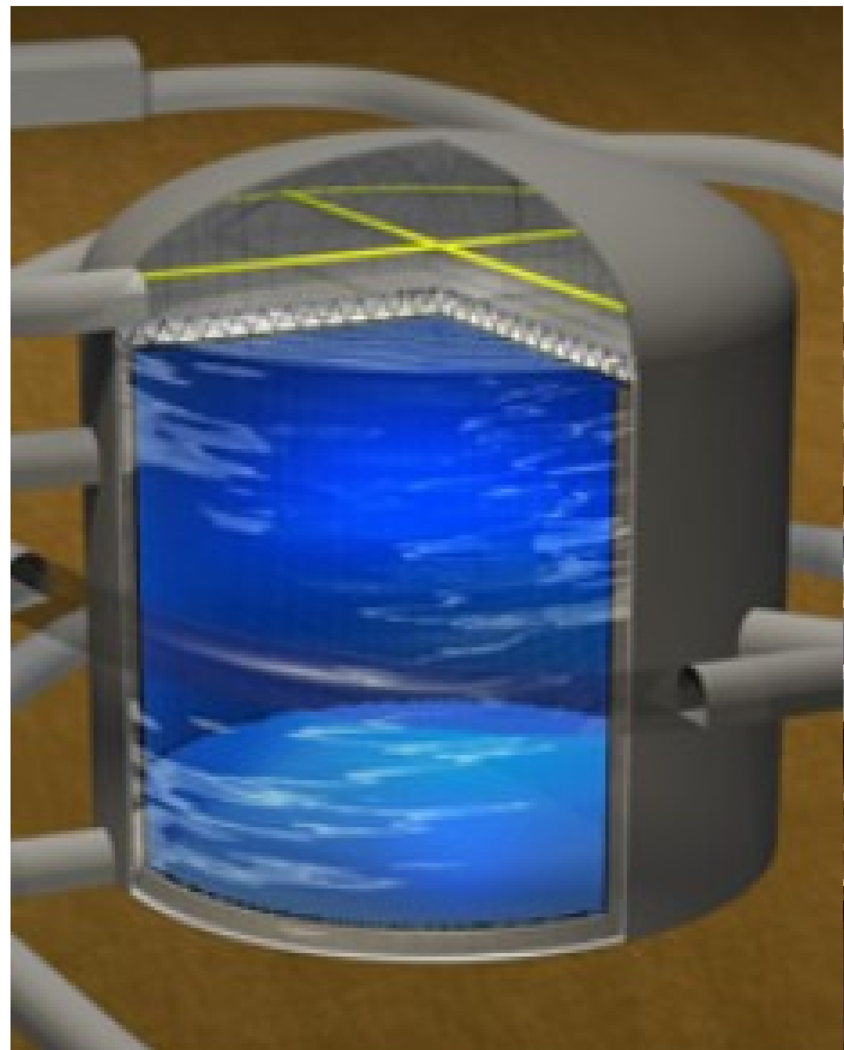
Intermediate Water Cherenkov Detector

Other near detectors @ 280m
- INGRID
- Upgraded ND280

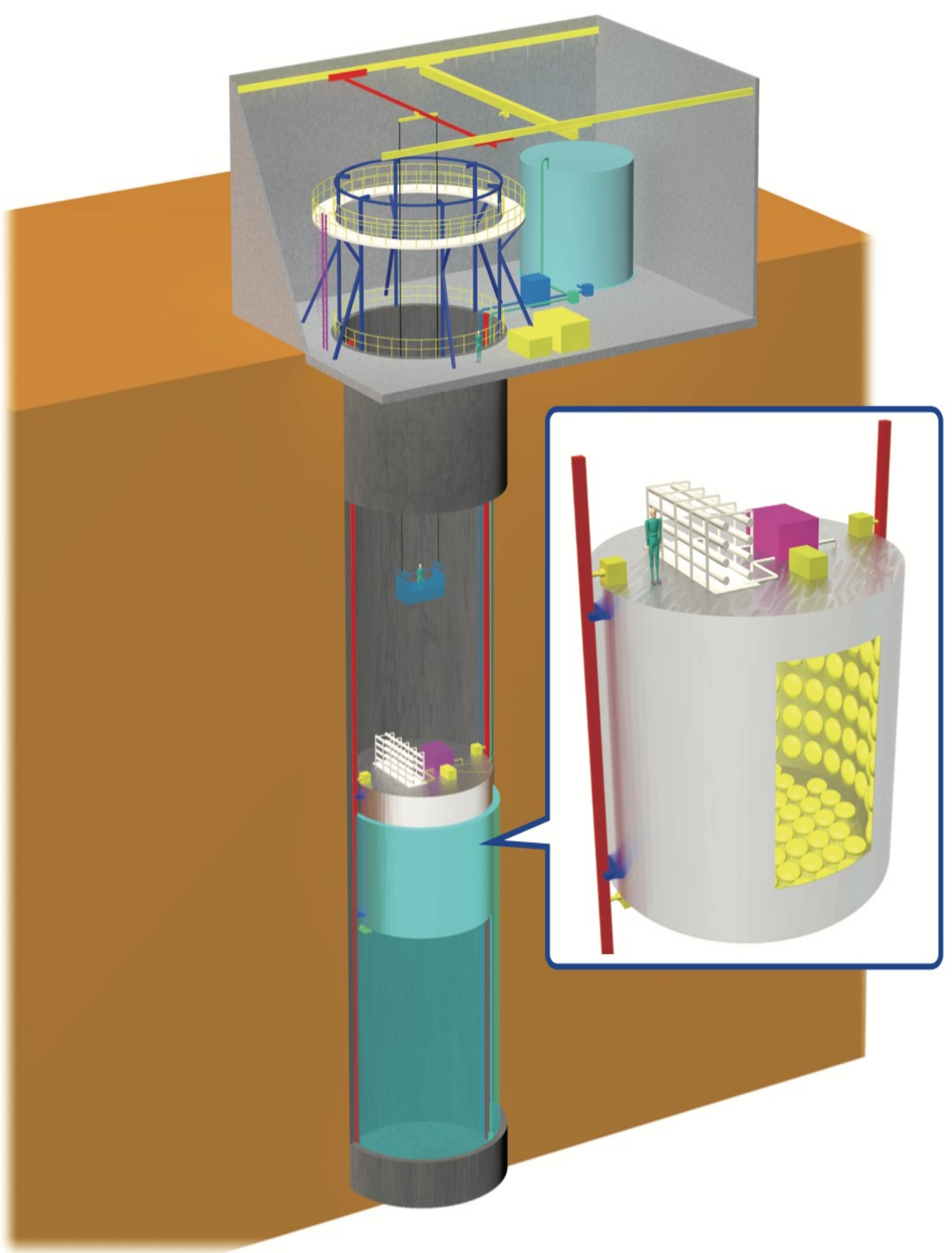




The Hyper-K detector



IWCD



@ ~1km

- Sub-kiloton scale water Cherenkov detector (Φ8m x 6m)
  - ⇒ 480 photosensor modules inside the tank
  - ⇒ 60 ton of fiducial volume
- Gadolinium loading option to add neutron detection capability

The vertically movable detector

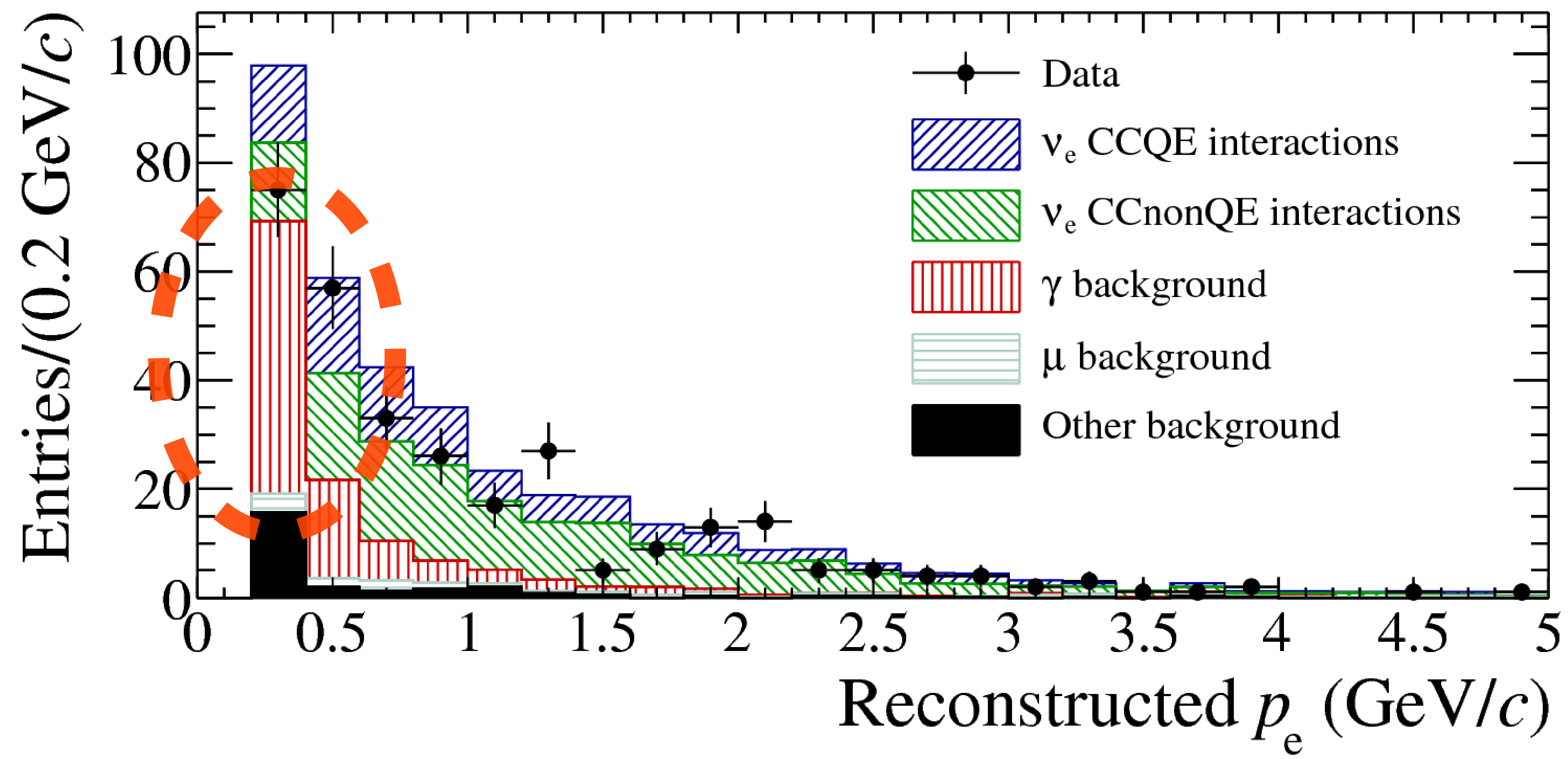
- Neutrino energy spectrum depends on off-axis angle
- Taking data at different vertical positions provides true energy information
  ⇒ Can break the degeneracy between flux and interaction cross-section

Active water shielding

- T2K results are suffering from large background events induced by external high energy γs

  ⇒ Reduction of this background is important

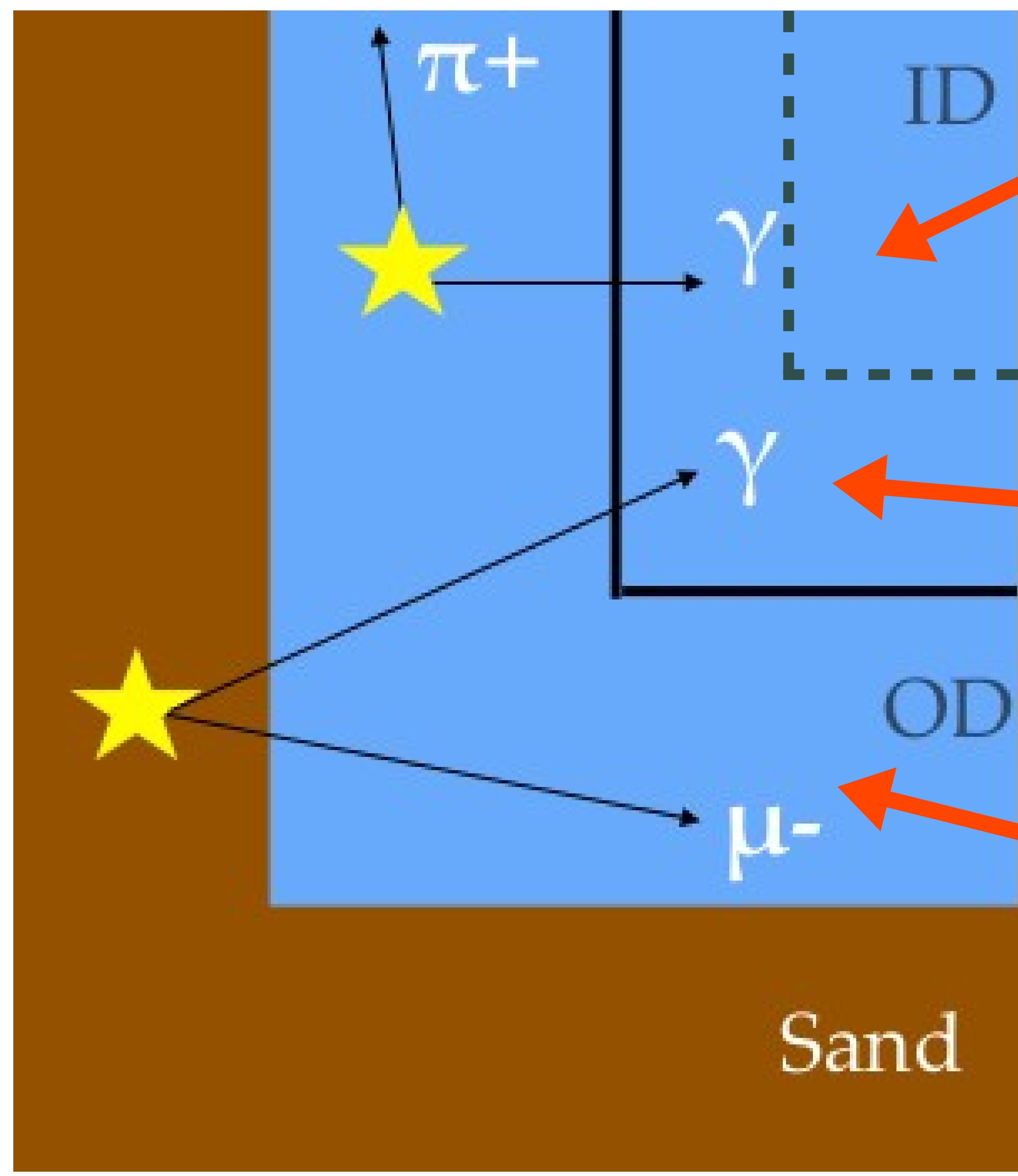
Phys. Rev. Lett. 113, 241803



- IWCD has two regions that can serve as active shield for protecting the γ background

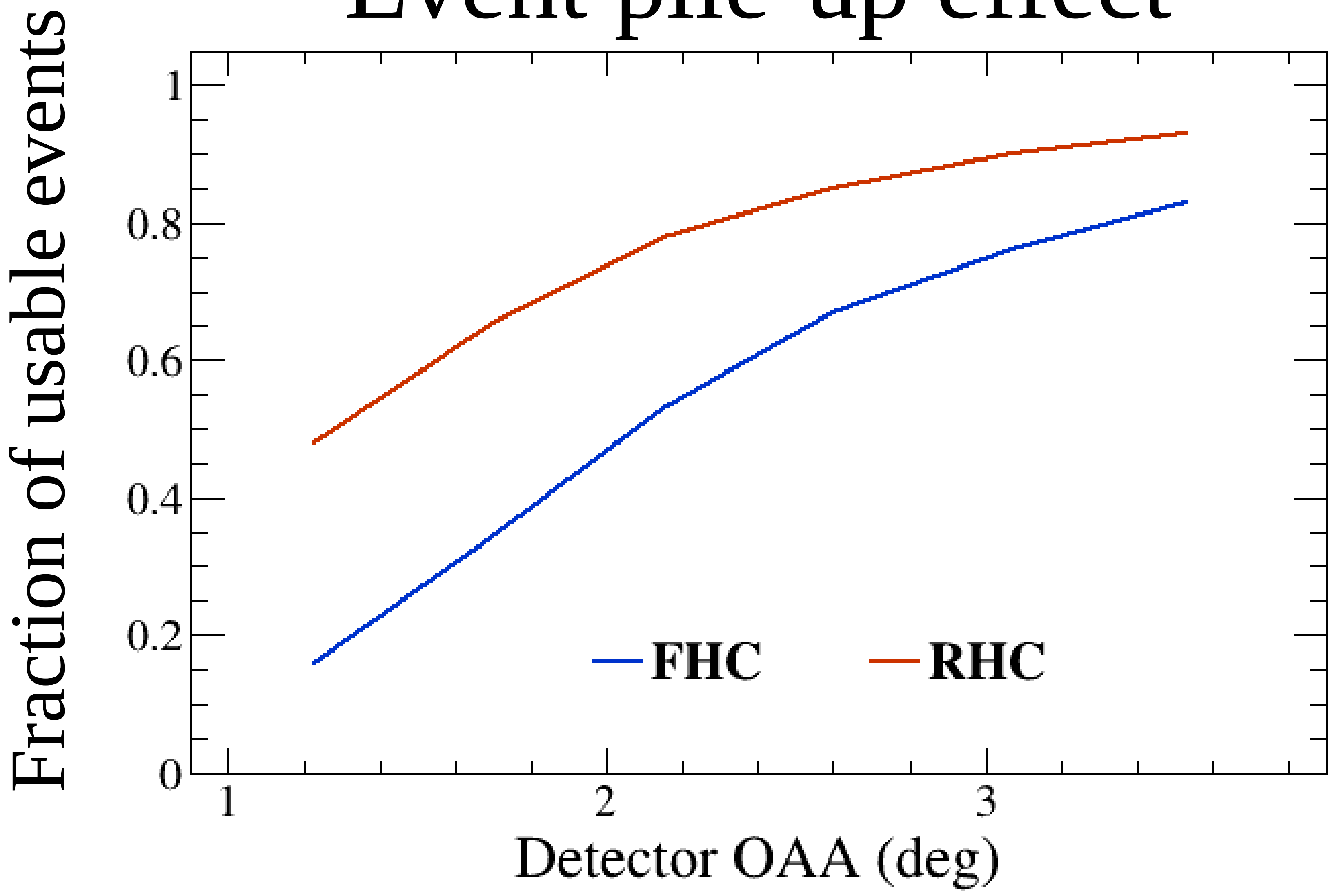
  ⇒ water volume in the pit

  ⇒ non-fiducial volume inside the detector

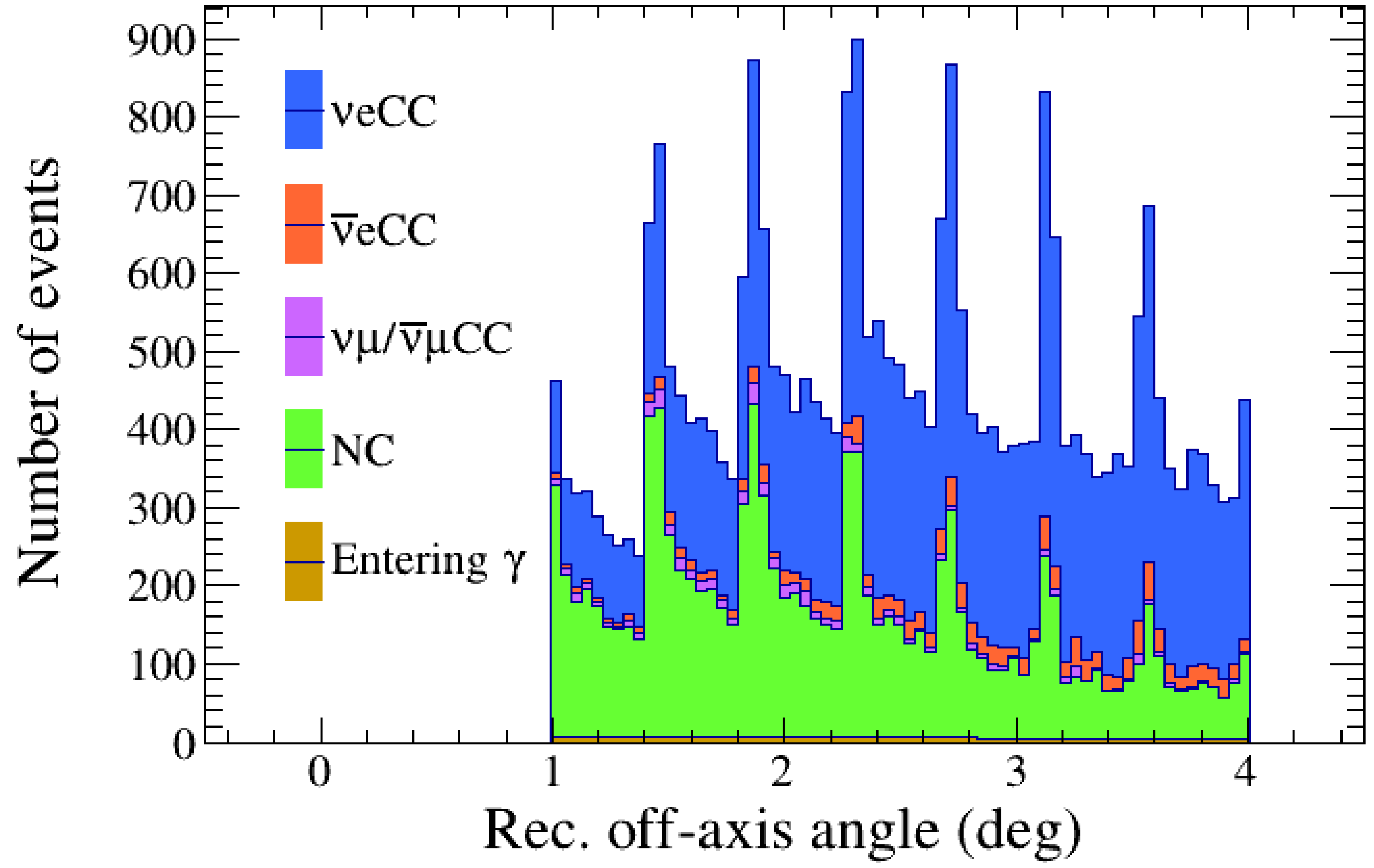


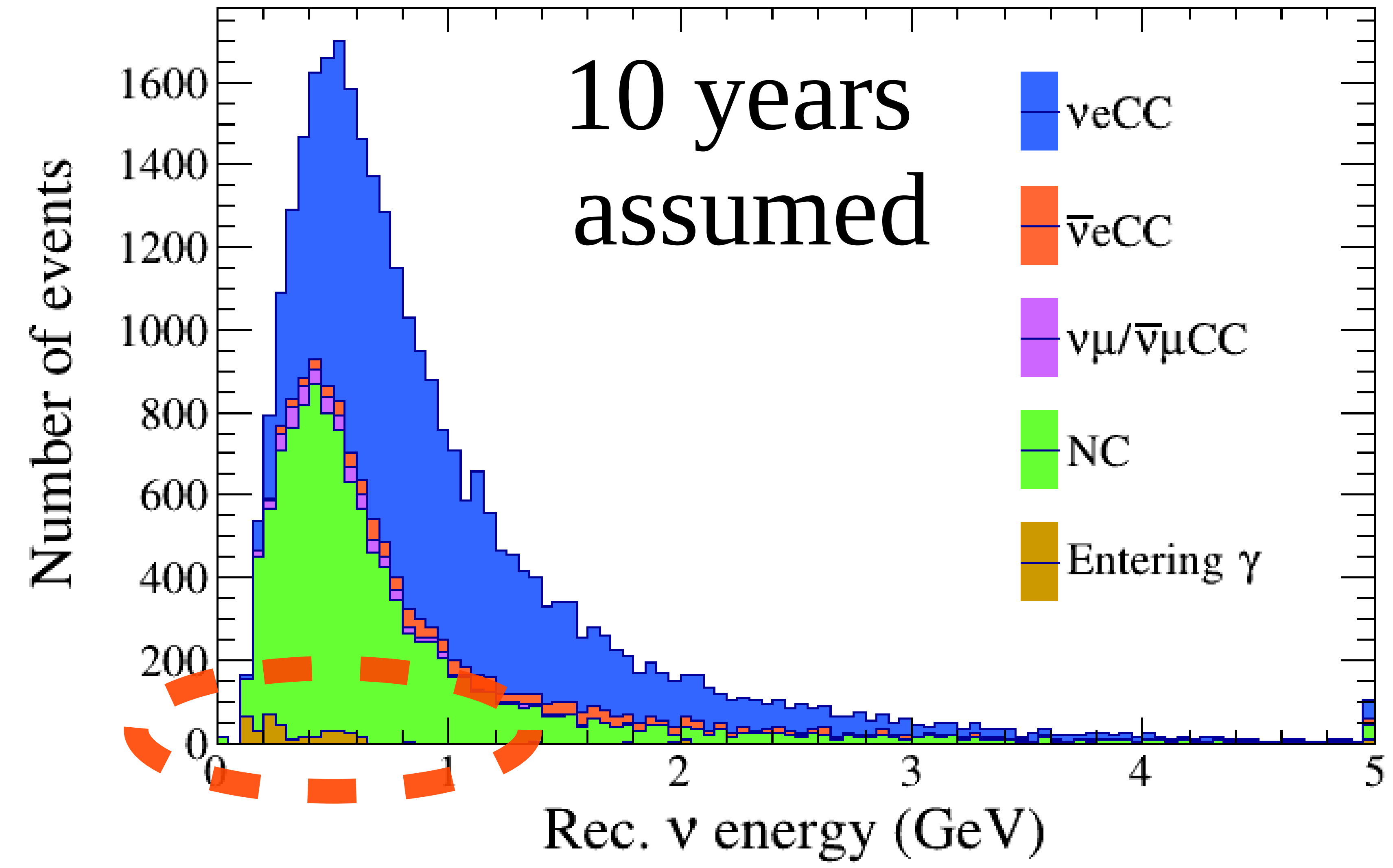
ν_e and $\bar{\nu}_e$ cross-section measurements

Event pile-up effect



ν-mode single-ring e-like events





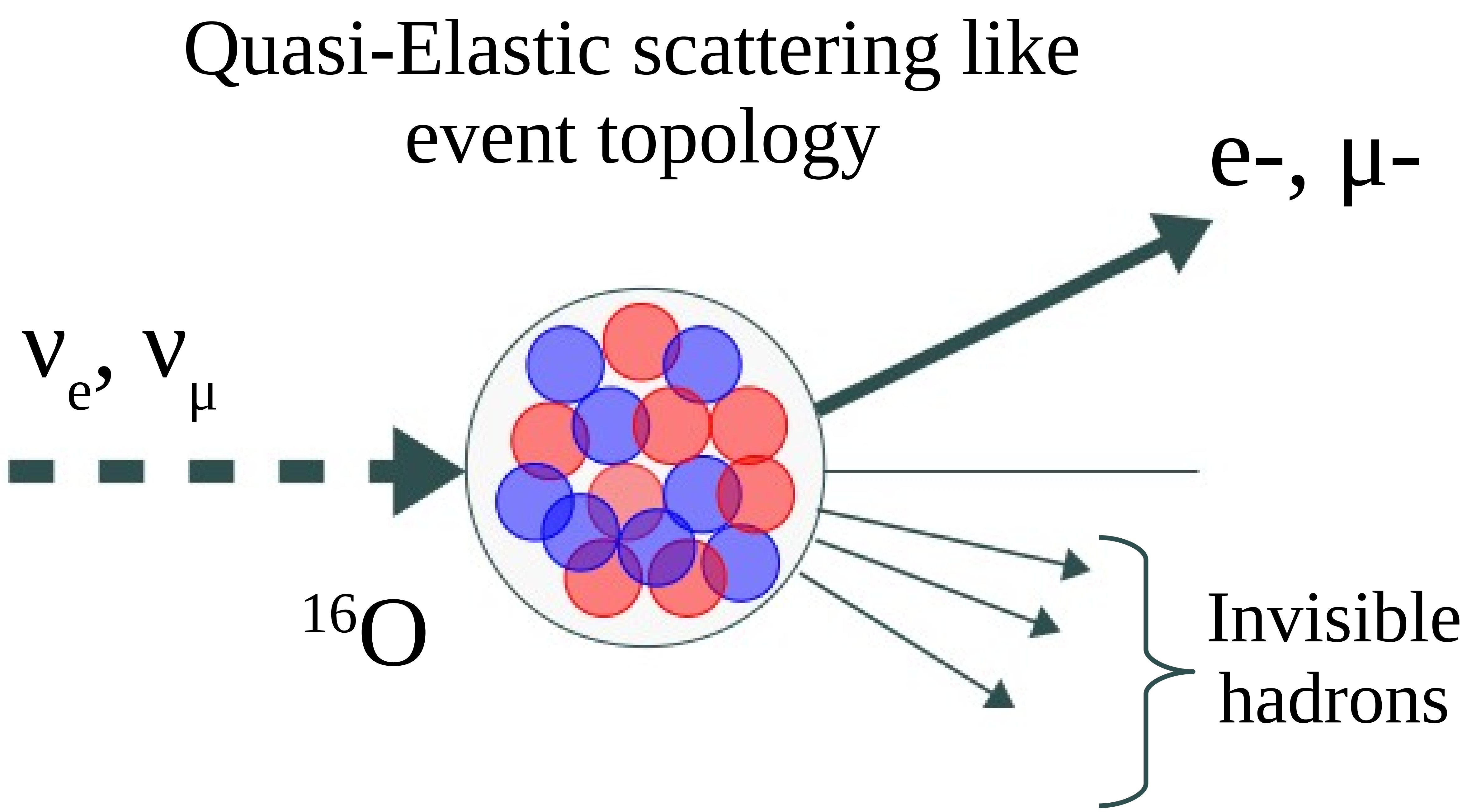
- Although the ν_e and $\bar{\nu}_e$ components make up only ~1% of the total beam flux, IWCD can identify these small components with very low misidentification rate of ν_μ interactions

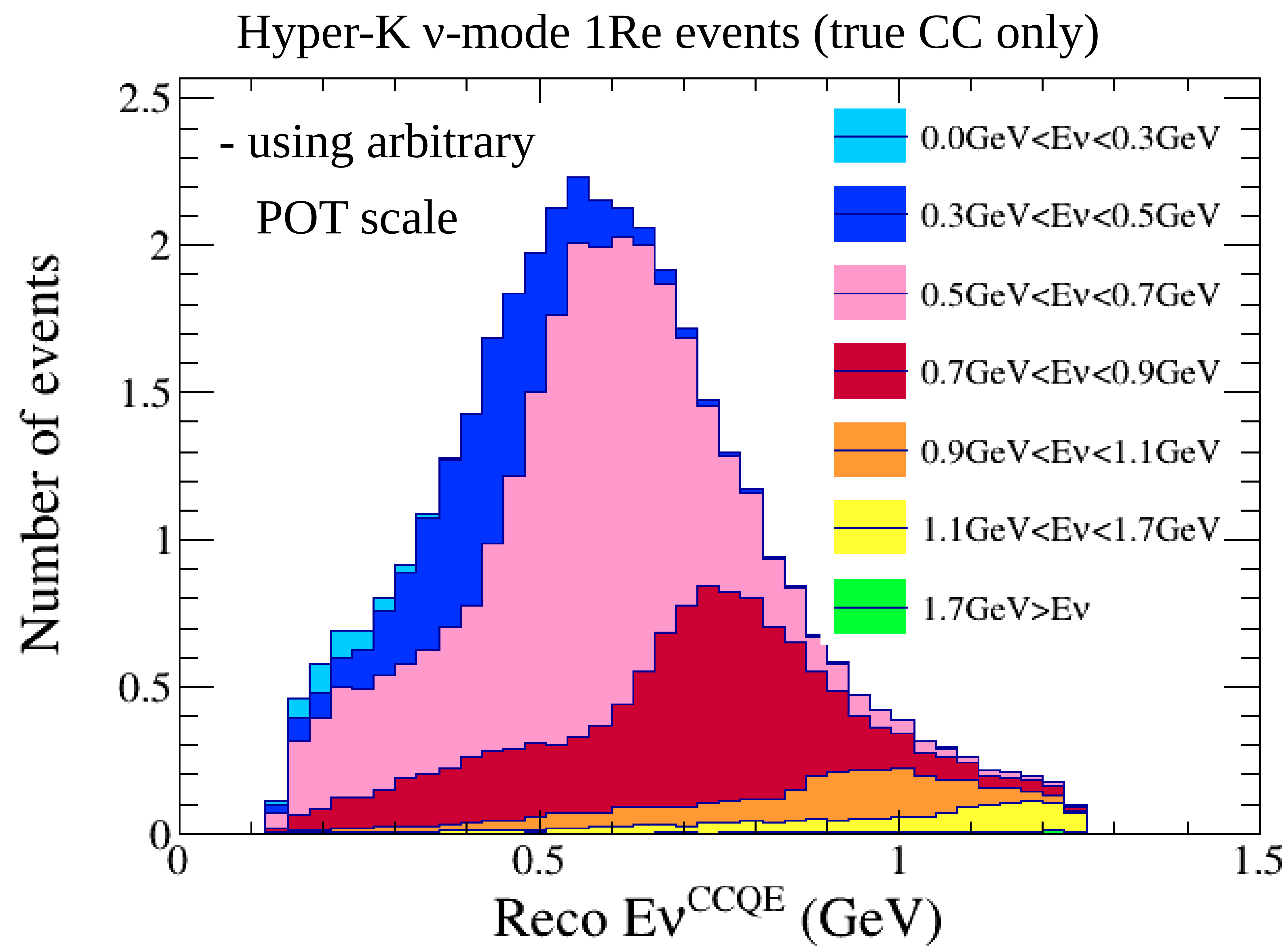
- Event rates have been predicted with the effect of even pile-up

  ⇒ Over 18,000 ν_e CC events expected (after event selection)

- In addition to ν_e events, over million ν_μ events and neutral current π^0 events are also used to measure $\nu_e/\bar{\nu}_e$ cross-sections

Observable

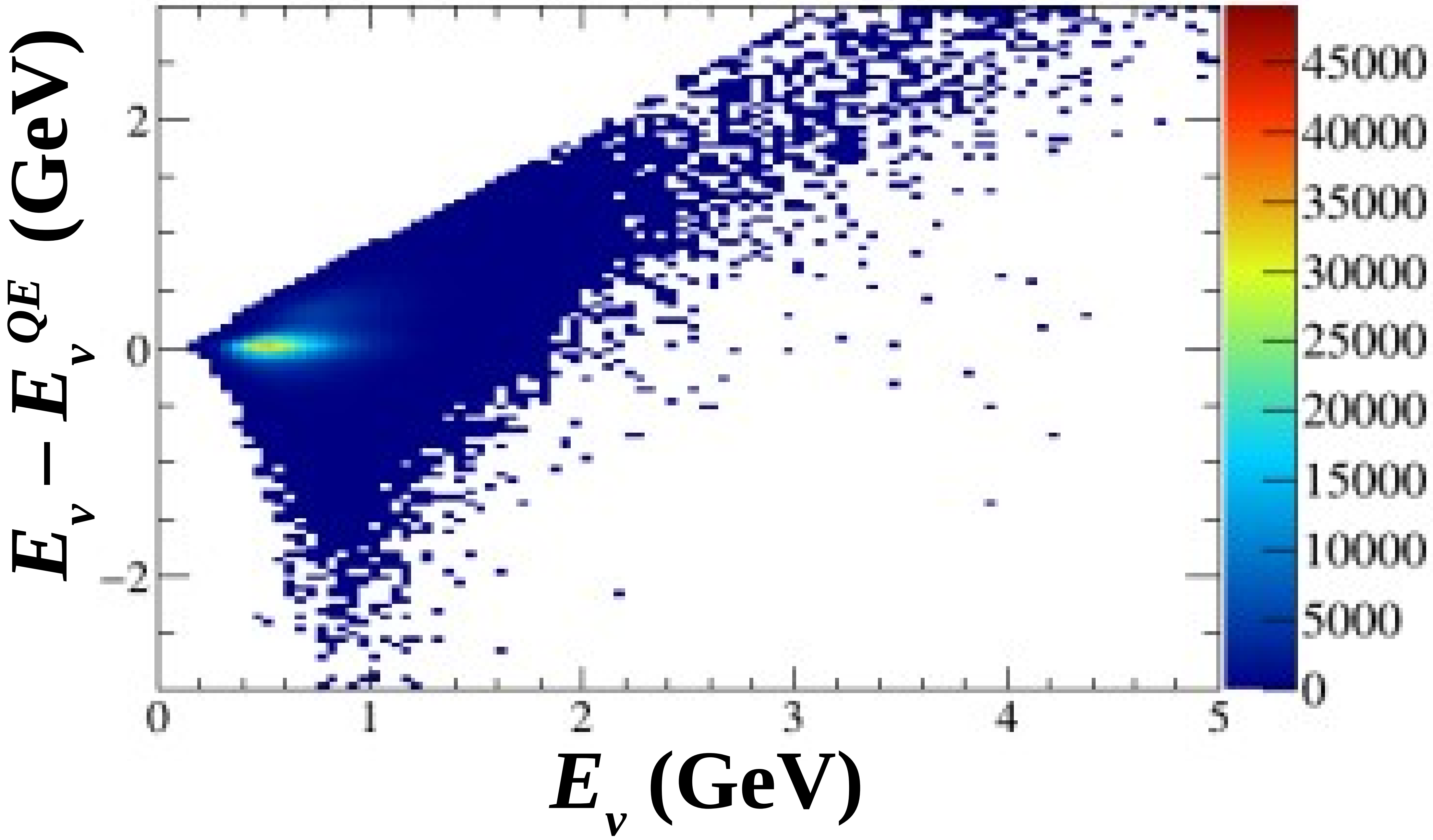




- In long-baseline experiments, ν oscillations depend only on true neutrino energy ($\boldsymbol{E_\nu}$)
- Charge-Current Quasi-Elastic interaction is the dominat channel in the Hyper-K beam energies
- Water Cherenkov detector infers neutrino energy from lepton momentum and scattering angle, assuming QE interaction ($\boldsymbol{E_\nu^{QE}}$)

Cross-section parameterization

Selected true νμ CC events



New cross-section parameters

Parameter name	Interaction type applied	Parameter binning	# parameters
2D ν	ν_μCC, ν_eCC	E_ν vs E_ν - E_ν^{QE}	29
1D ν_e	ν_eCC	E_ν	5
2D $\bar{\nu}$	$\bar{\nu}_\mu$CC, $\bar{\nu}_e$CC	E_ν vs E_ν - E_ν^{QE}	29
1D $\bar{\nu}_e$	$\bar{\nu}_e$CC	E_ν	5

68 free parameters

- It is difficult to model the relationship between $\boldsymbol{E_\nu}$ and $\boldsymbol{E_\nu^{QE}}$ due to the complicated nuclear effects

  ⇒ 2 sets of new cross-section parameters (1D & 2D) are introduced to constrain the relationship at IWCD

- 2D parameters: constraining the relationship by ν_μ interactions

  ⇒ In theory, ν_μ has the same cross-section as ν_e except for the effects of charged lepton mass

- 1D parameters: constraining the ν_μ/ν_e cross-section difference by ν_e interactions

Sensitivity study

- A median sensitivity to the new cross-section parameters was evaluated as a covariance matrix

- Simulated events were re-weighted for given parameter variation, and the re-weighted event rates are compared with the nominal ones by using the binned Poisson likelihood function

Nominal event rates

$$-2\ln\mathcal{L} = \sum^{\text{samples}} \sum^{\text{bins}} 2\left(\mathcal{E} - \mathcal{O} + \mathcal{O}\ \ln\left(\frac{\mathcal{O}}{\mathcal{E}}\right)\right)$$

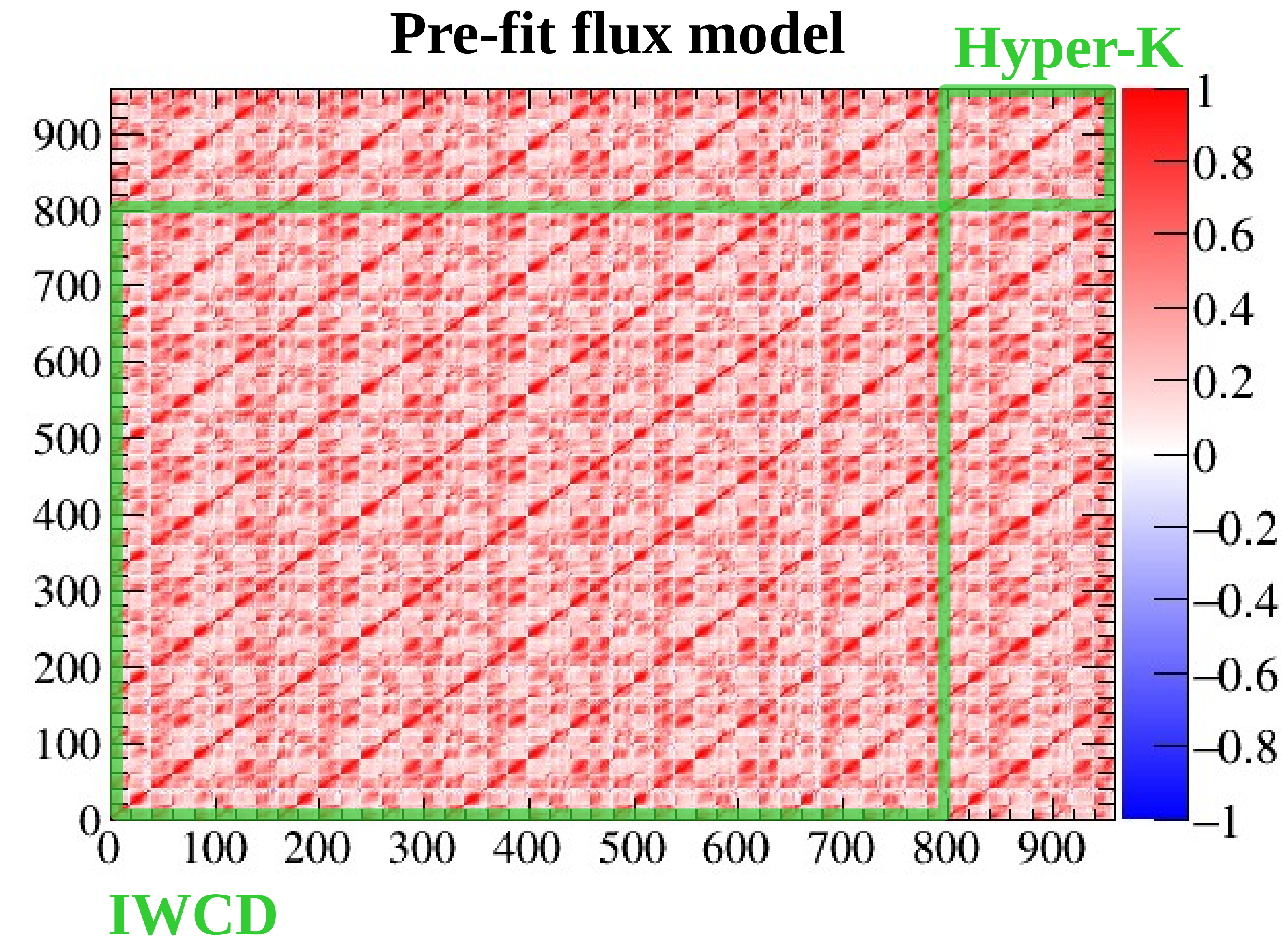
Re-weighted event rates

$$+ \sum_i^{\text{pars}} \sum_j^{\text{pars}} (p_i - p_i^{\text{prior}})(V_{cov}^{-1})_{ij}(p_j - p_j^{\text{prior}})$$

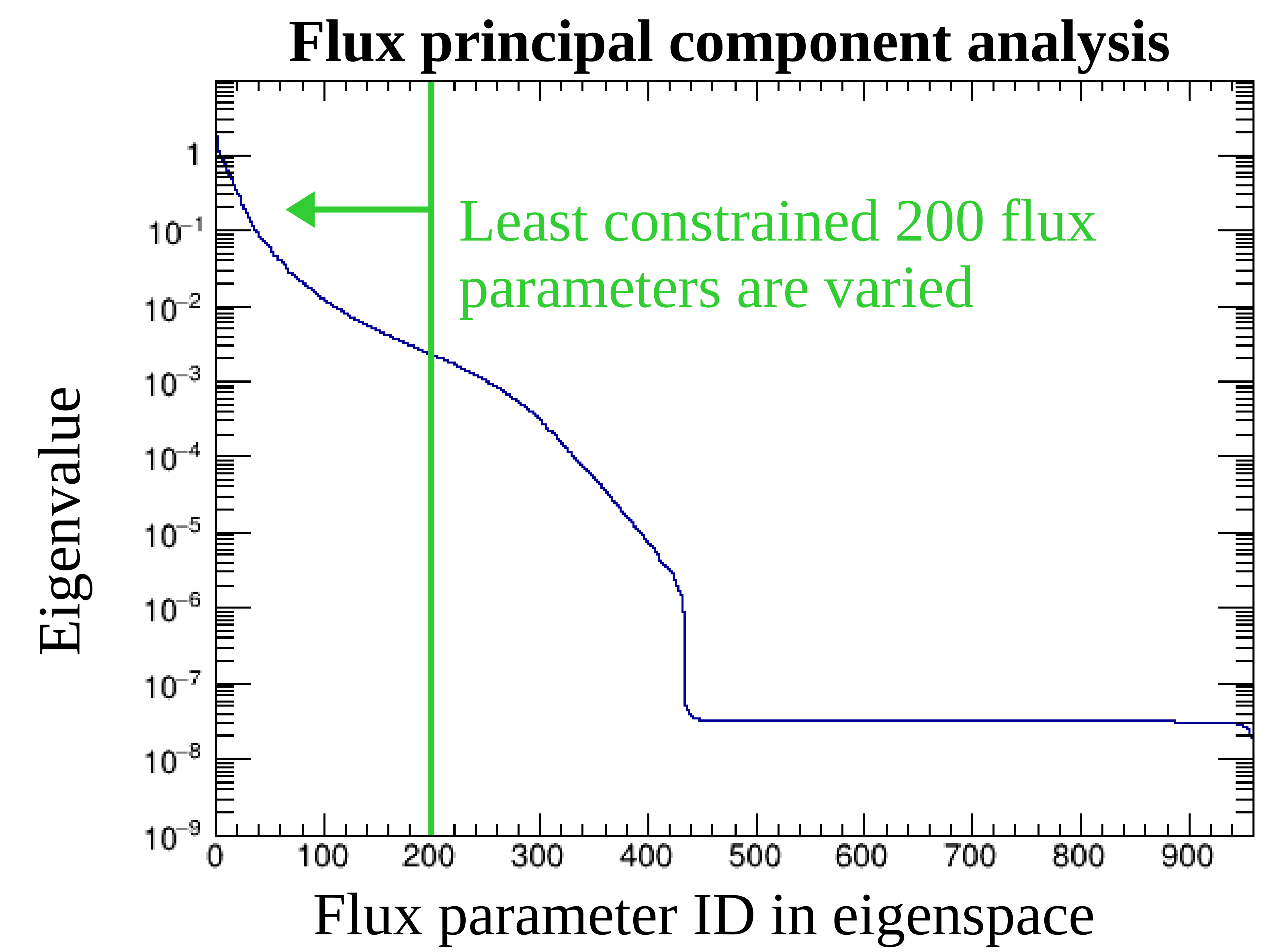
Prior errors on parameters describing systematic uncertainties

Systematic uncertainties

- Flux uncertainties
  - Estimated by the same method developed by the T2K experiment
  - Hyper-K flux can be constrained via the prior correlations
  - Principal component analysis adopted to reduce # flux parameters



- Conventional interaction cross-section uncertainties
  - A model developed by the T2K experiment (**K.Abe, etl, PRL 121, 171802**)
  - The overall normalization parameters for $\nu_e/\bar{\nu}_e$ were removed to properly accommodate the new 1D parameters

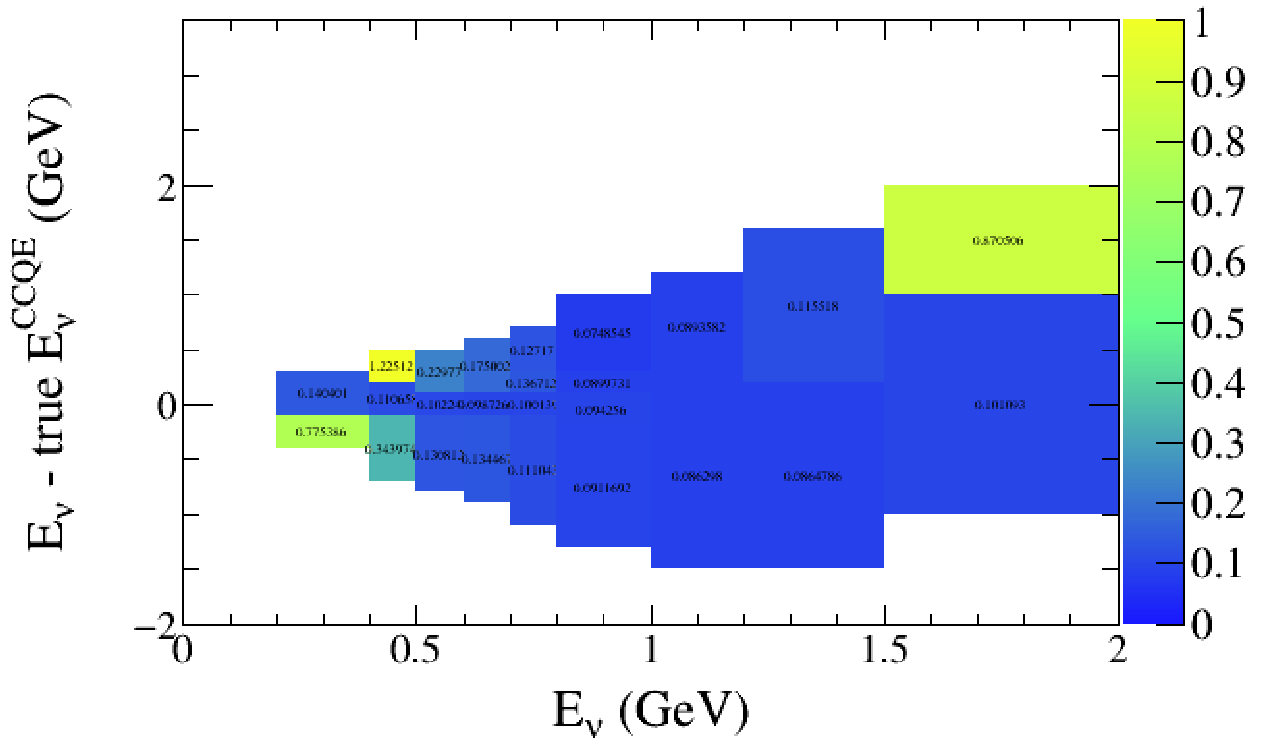


- IWCD detector uncertainties
  - 10% errors assumed for the selection efficiency due to event-pileup
  - 10% errors for a normalization parameter that scales entering gamma background events

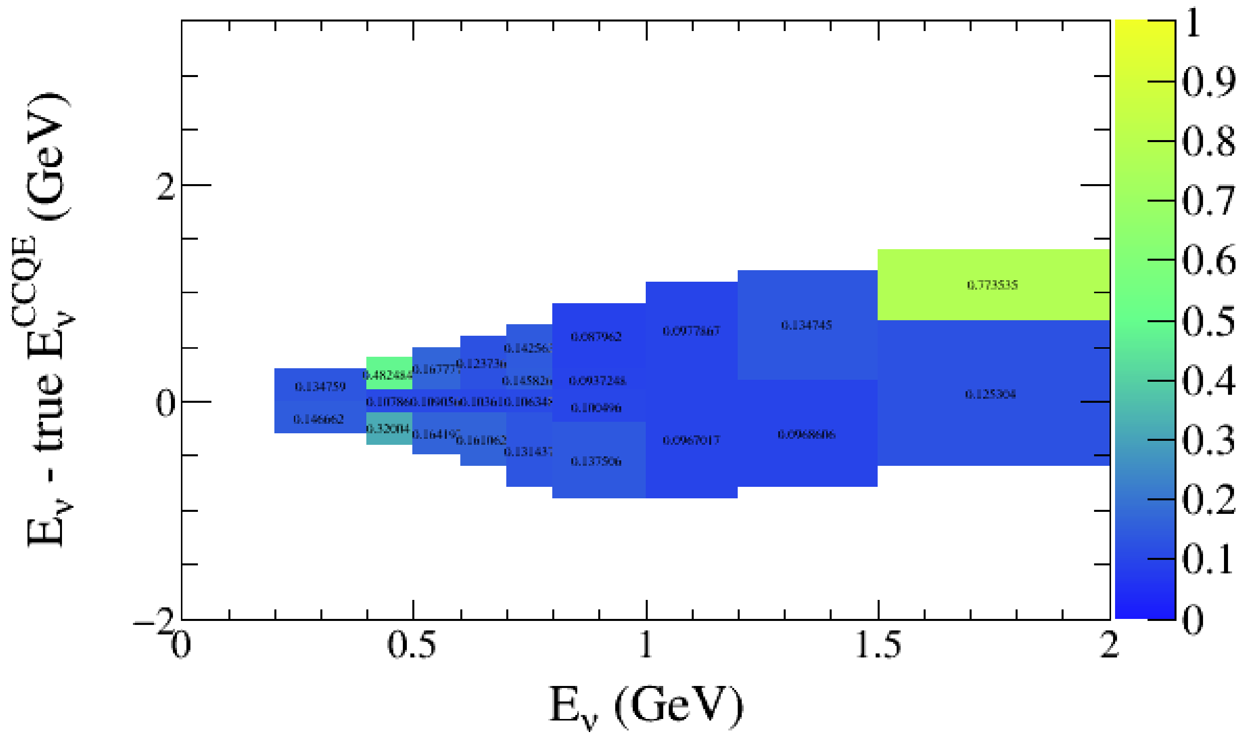
Error propagation to Hyper-K far detector

Post-fit 1σ errors

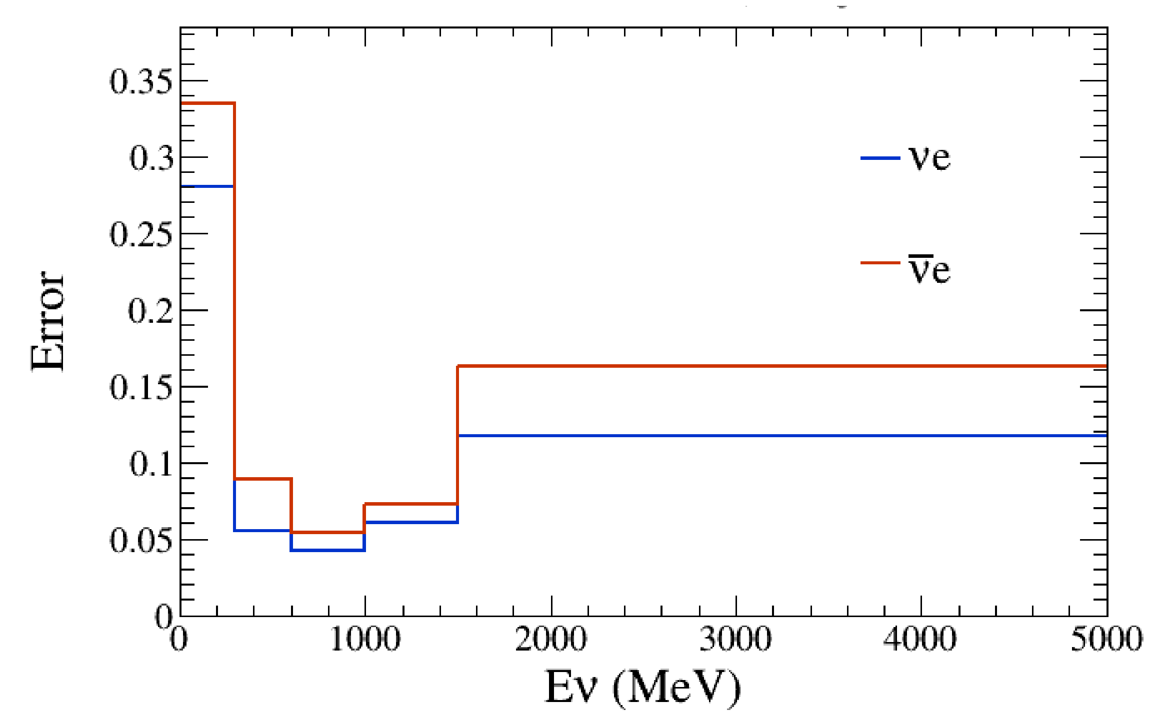
2D



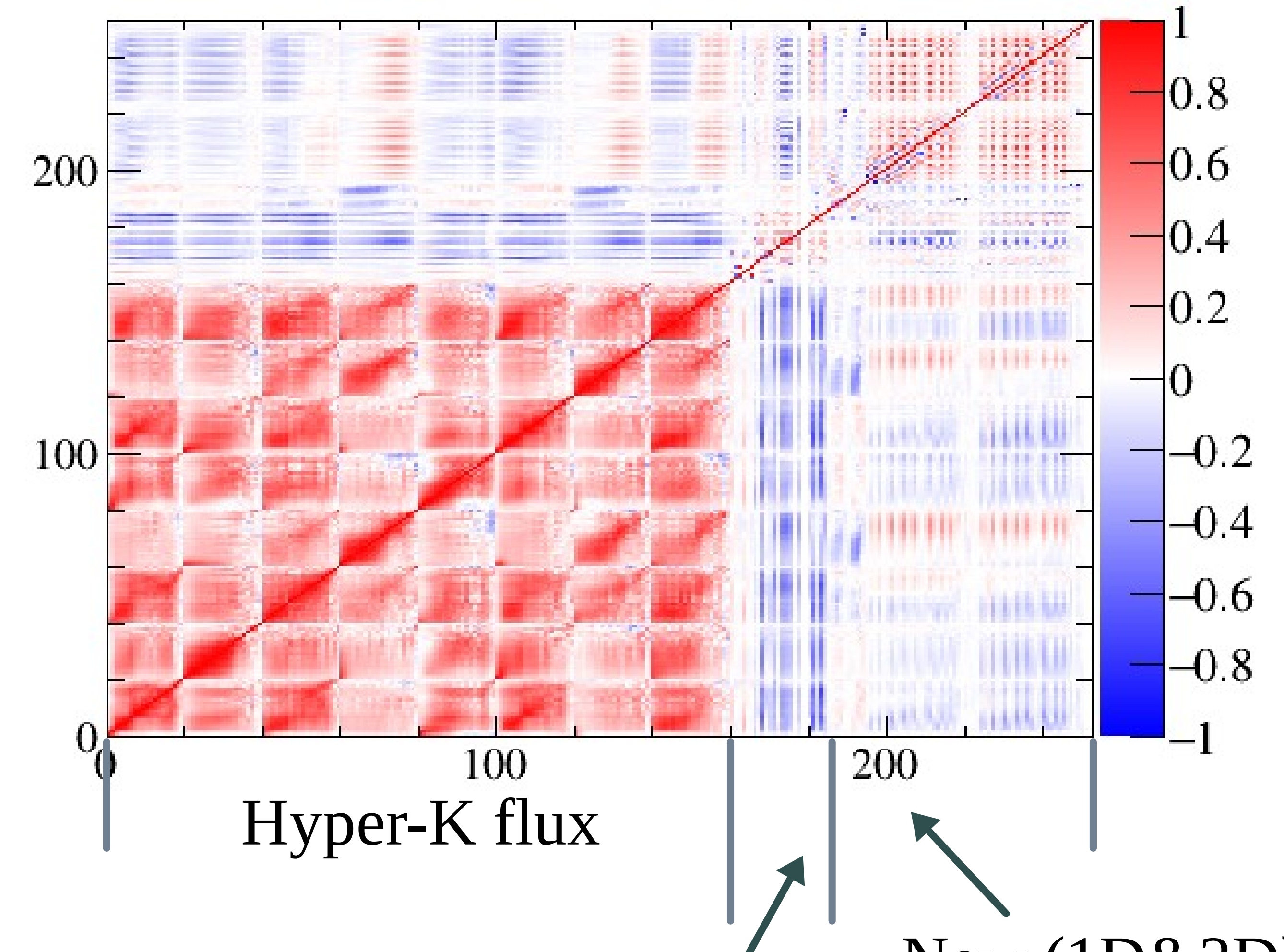
2D $\bar{\nu}$



1D $\nu_e/\bar{\nu}_e$



Correlations



- For the CPV study, the right-sign ratio is a good proxy for the effect of CPV

- Errors on the new parameters were propagated to the Hyper-K far detector by considering full correlations between the flux, conventional cross-section, and new parameters

$$\text{Ratio} = \frac{[\ \#\ \text{true}\ \nu_e\ \text{interactions in}\ \nu\text{-mode's e-like sample}\ ]}{[\ \#\ \text{true}\ \bar{\nu}_e\ \text{interactions in}\ \bar{\nu}\text{-mode's e-like sample}\ ]}$$

- The resultant error on the ratio: **4%** ⇔ the theory based constraint: **5%**

Summary

- Controlling $\nu_e/\bar{\nu}_e$ cross-section uncertainties are essential to make full use of the high beam data statistics at the Hyper-K far detector
- The Intermediate Water Cherenkov Detector is planned to control the critical systematic uncertainties for the CP violation study
- We have developed a method that constrains $\nu_e/\bar{\nu}_e$ cross-section, specifically for the CP violation study
- We found that the uncertainties can be reduced directly by using IWCD data
- We will further develop the measurement method