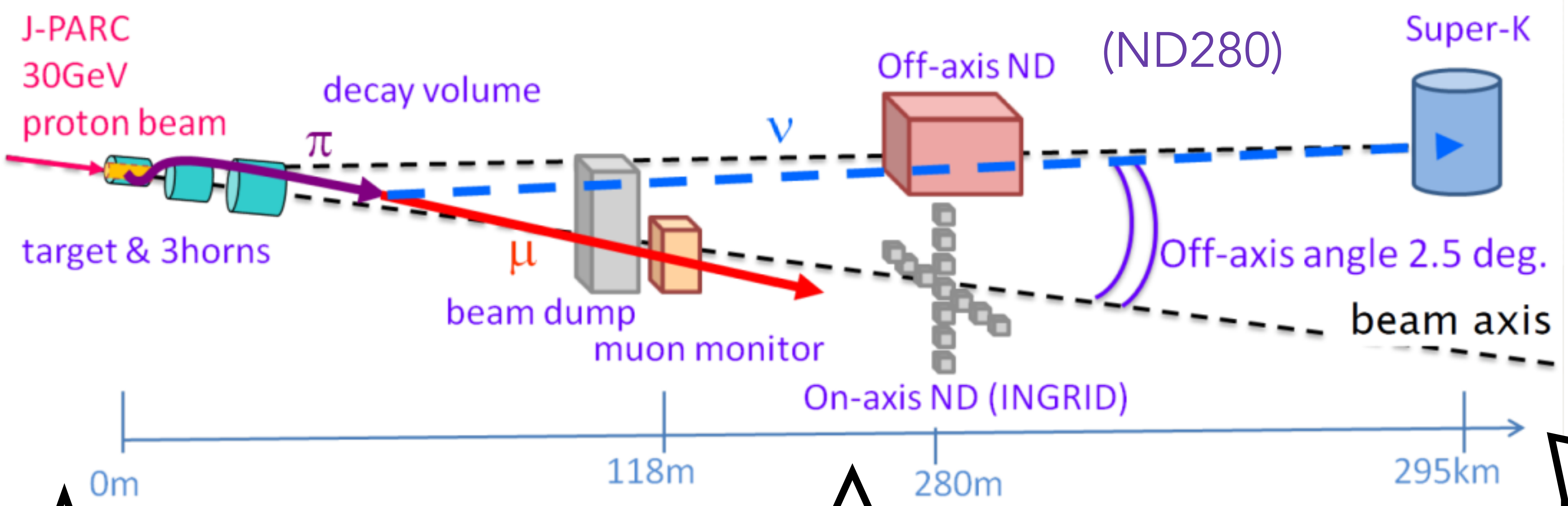
T2K oscillation analysis results
— latest improvements at the far detector —

Kenji Yasutome for the T2K collaboration
NuFACT 2022 parallel, 5th August

The T2K experiment



T2K Plenary talk
Laura Kormos

Produce neutrino beam

Measure neutrino interaction/flux before oscillations

Measure neutrino oscillations
1. $\nu_\mu \rightarrow \nu_e$ appearance
2. $\nu_\mu \rightarrow \nu_\mu$ disappearance

T2K parallel talk
Beam upgrade: T. Yasui, M.Friend, Takeshi Nakadaira
Beam monitor: T. Honjo

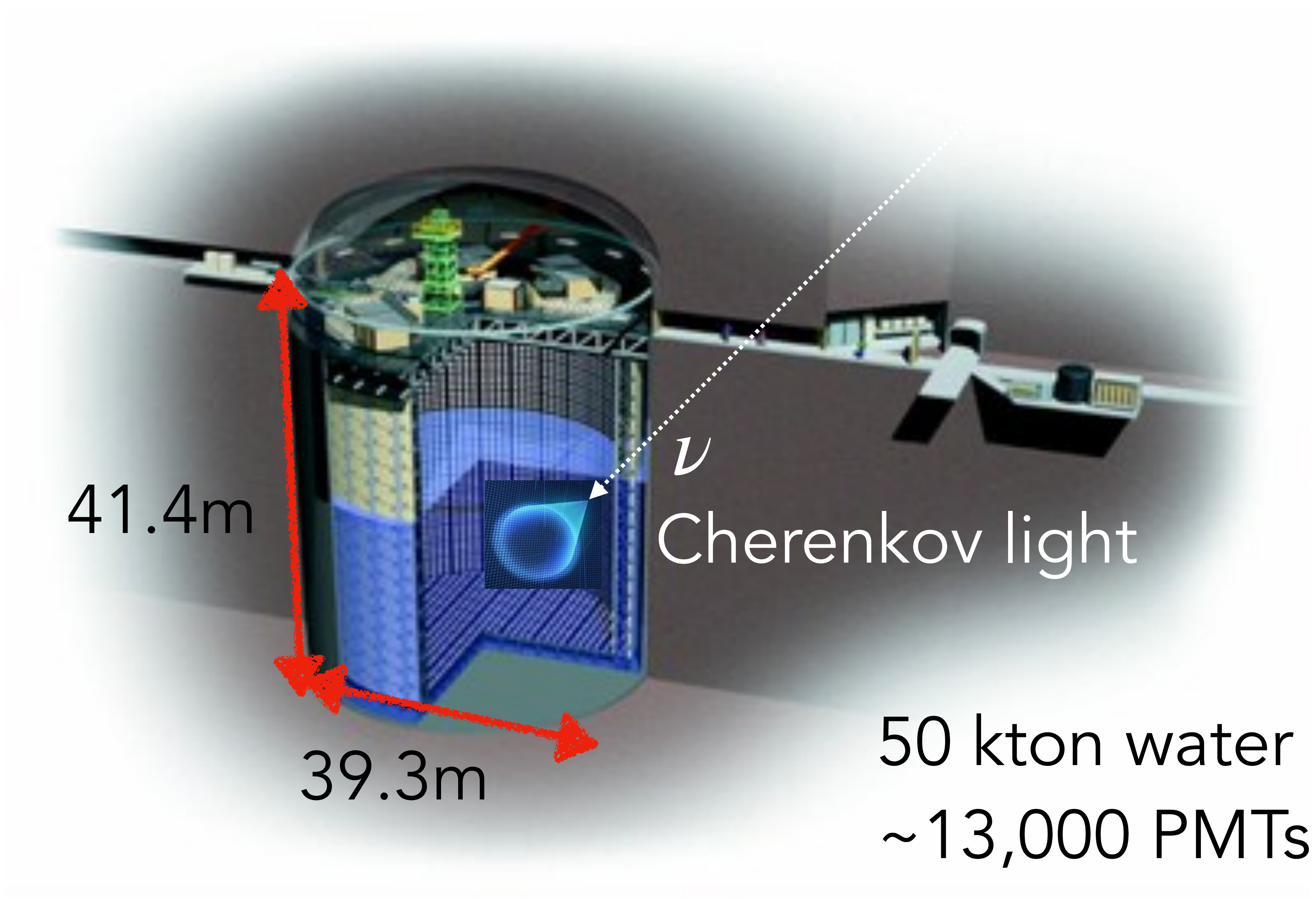
T2K parallel talk
Neutrino interaction: S. Dolan, A. Cudd
Near detector: C. Wilkinson
Upgraded detectors: A. Eguchi, M. Kawaue, C. Mauger, M. Feltre

This talk

- Measure neutrino oscillations at far detector with high-intensity neutrino beam and precise understanding of ν interactions and flux based on measurements by near detectors.
  - Test CP symmetry breaking (δ_{CP}).
  - World leading θ_{23}, Δm^2_{32}, and determine θ_{23} octant & the mass ordering.
  - Precise measurements of neutrino cross sections

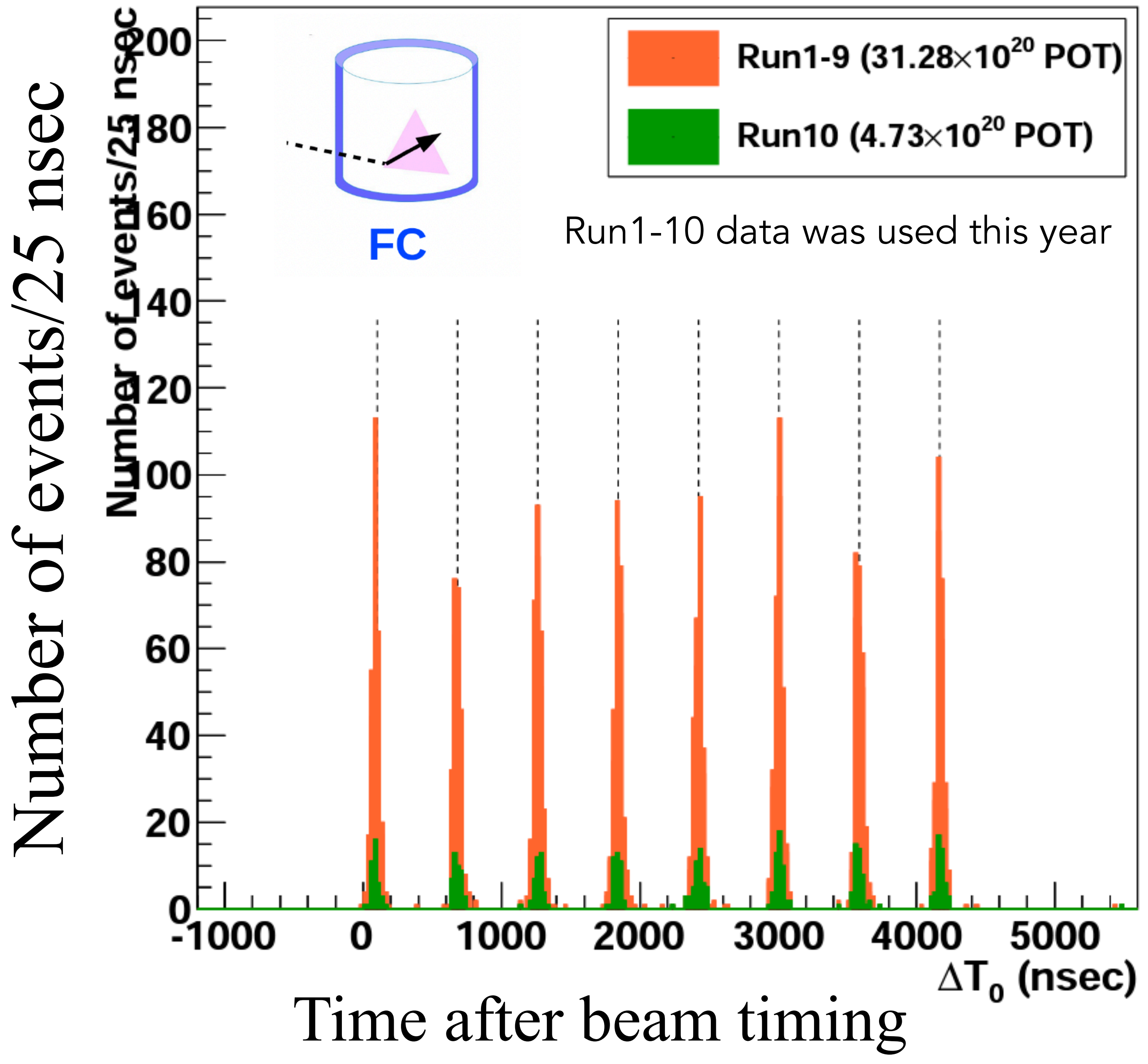
T2K far detector (Super Kamiokande)

Detector



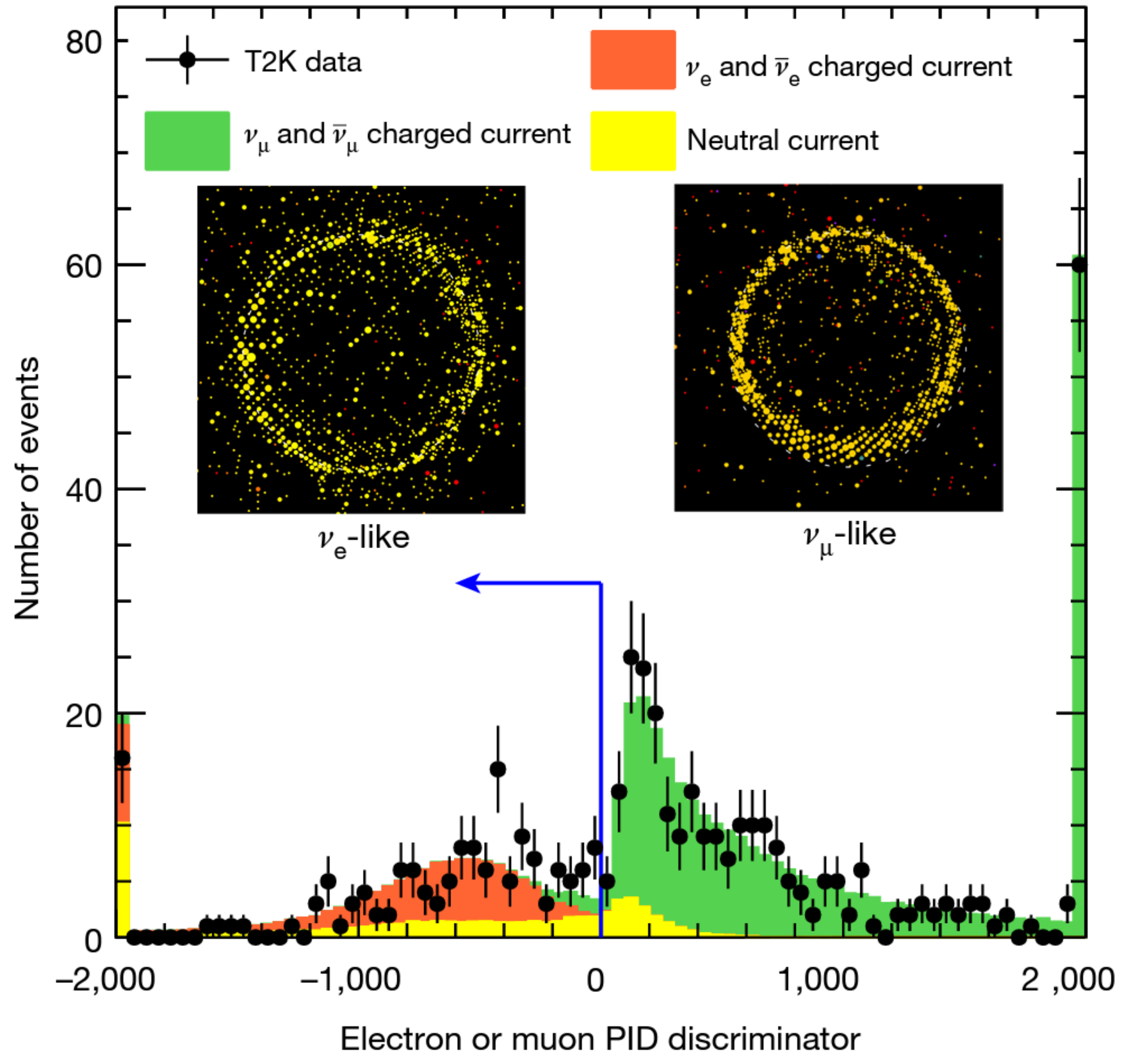
Detect Cherenkov light by PMTs

Event timing



Clearly see the T2K beam structure with observed fully contained (FC) events

PID performance



T2K collaboration, Nature 580, 339-344 (2020)

Less than 1% mis-PID at 1GeV for single ring event

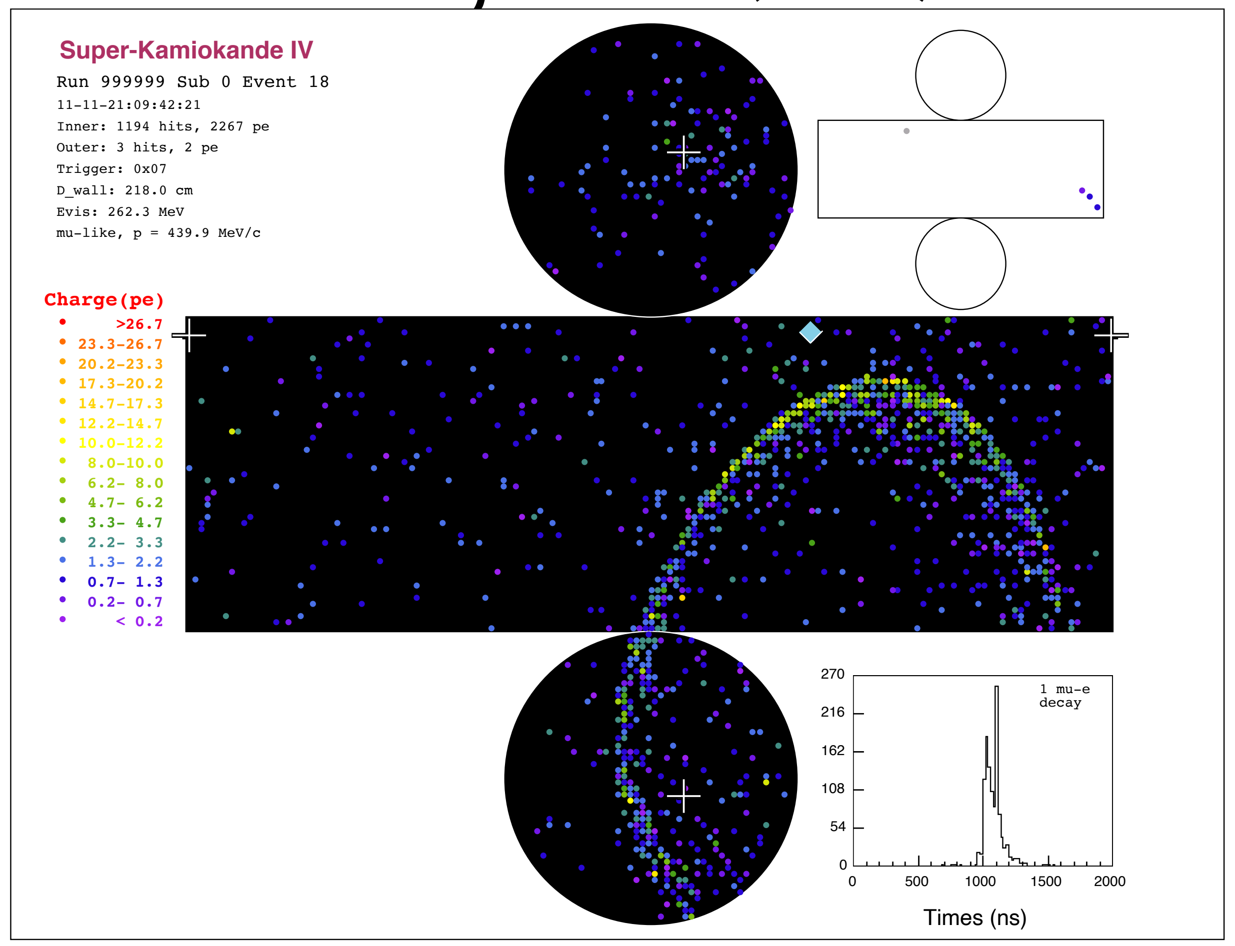
- Great separation between μ and e, but limited separation between ν and $\bar{\nu}$.

T2K Analysis samples at far detector

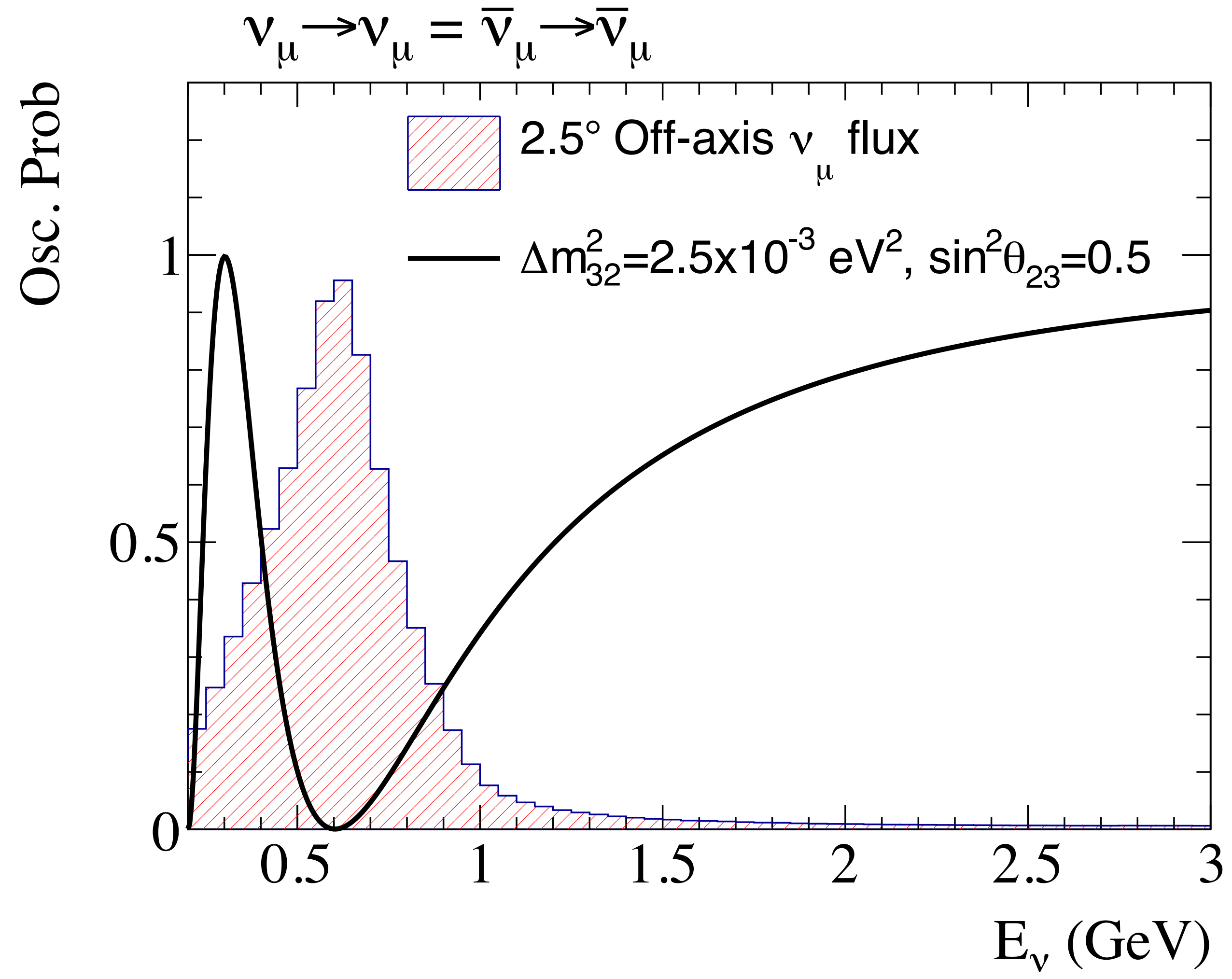
μ-like samples

- 1Ring ν_μ sample
- 1Ring $\bar{\nu}_\mu$ sample
- ν_μCC1π^+
  (New in this analysis)

1R μ-like (MC)



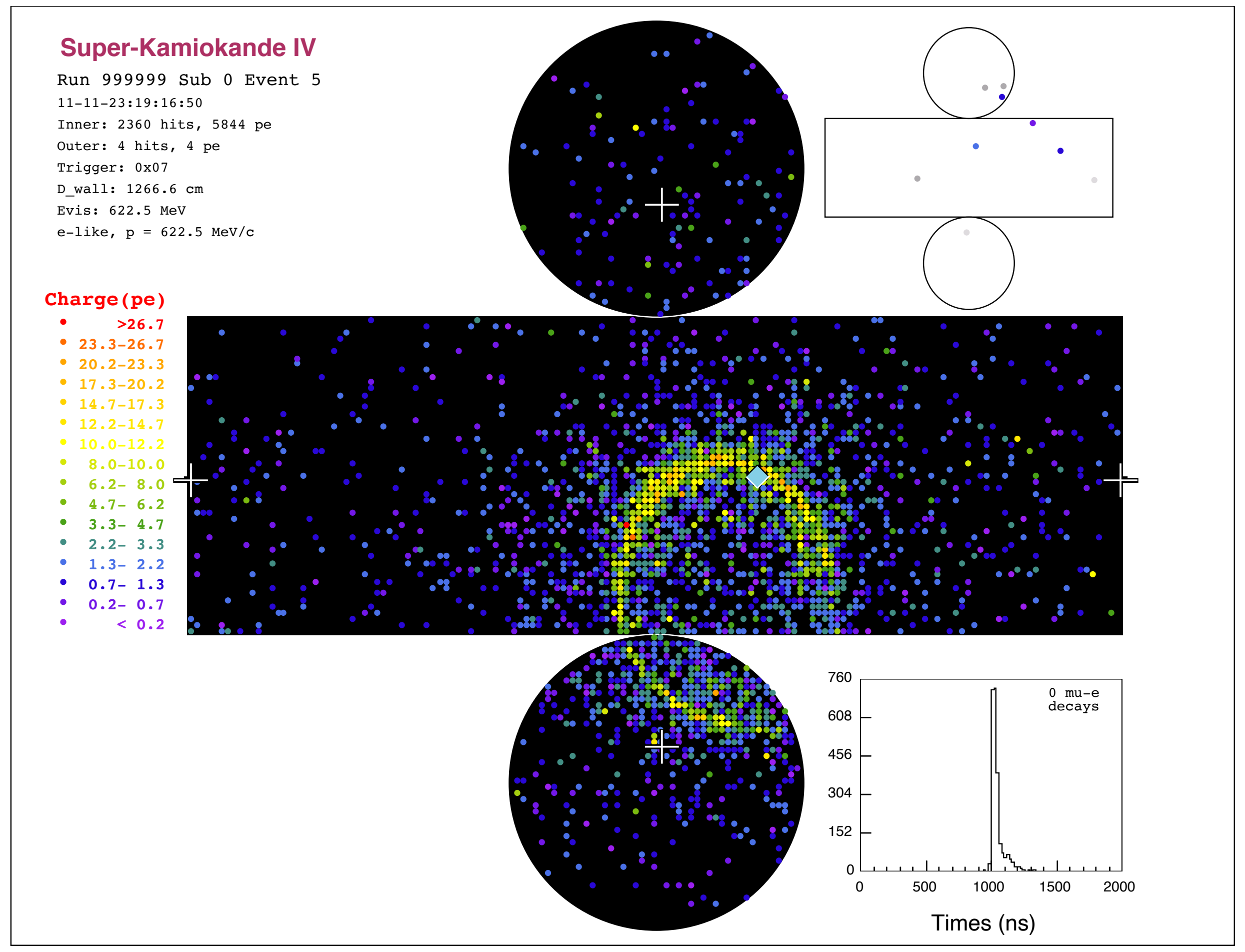
Sensitivity



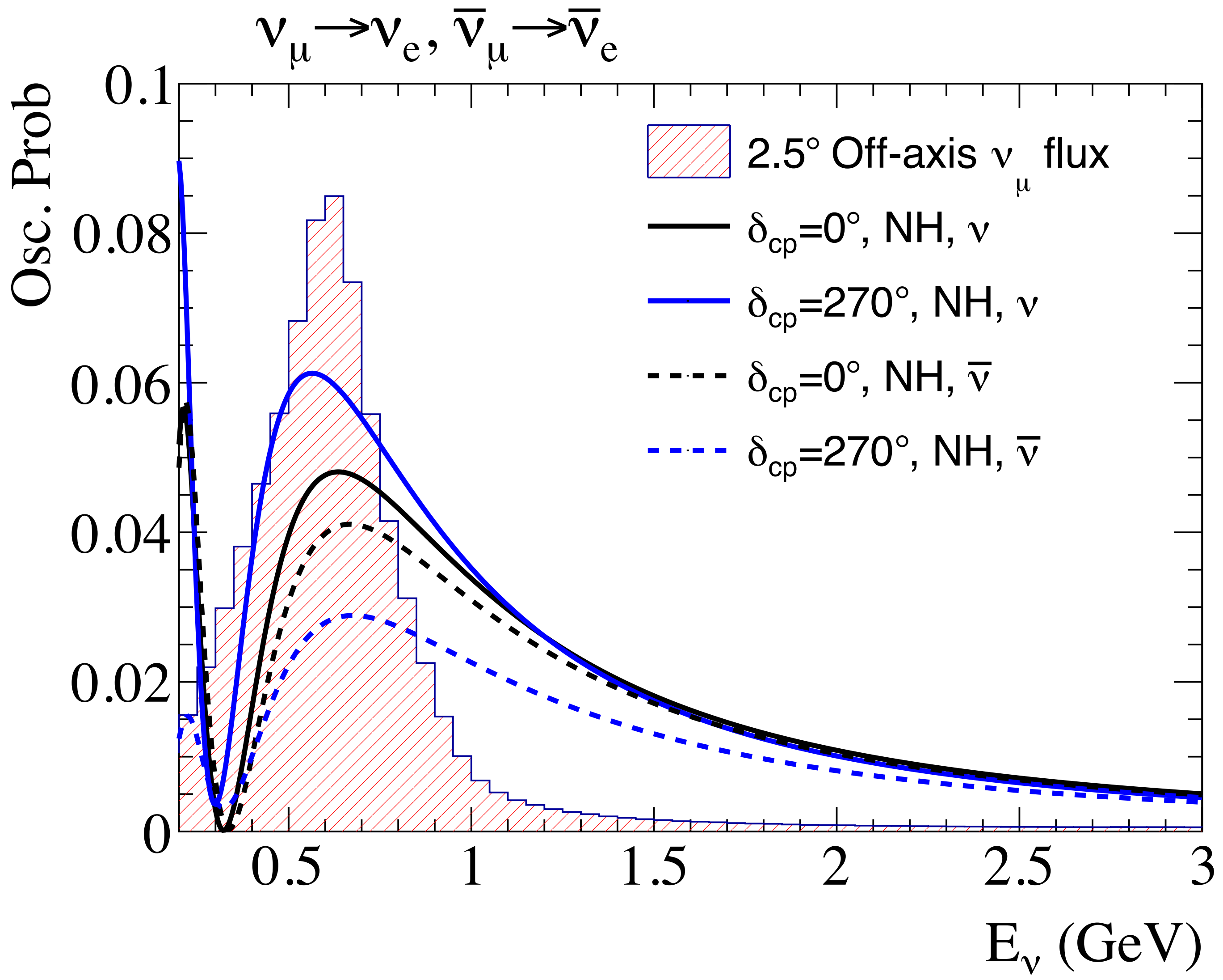
e-like samples

- 1Ring ν_e sample
- 1Ring $\bar{\nu}_e$ sample
- 1Ring $\bar{\nu}_e$ + 1 d.e. sample
  *d.e. = decay electron

1R e-like (MC)

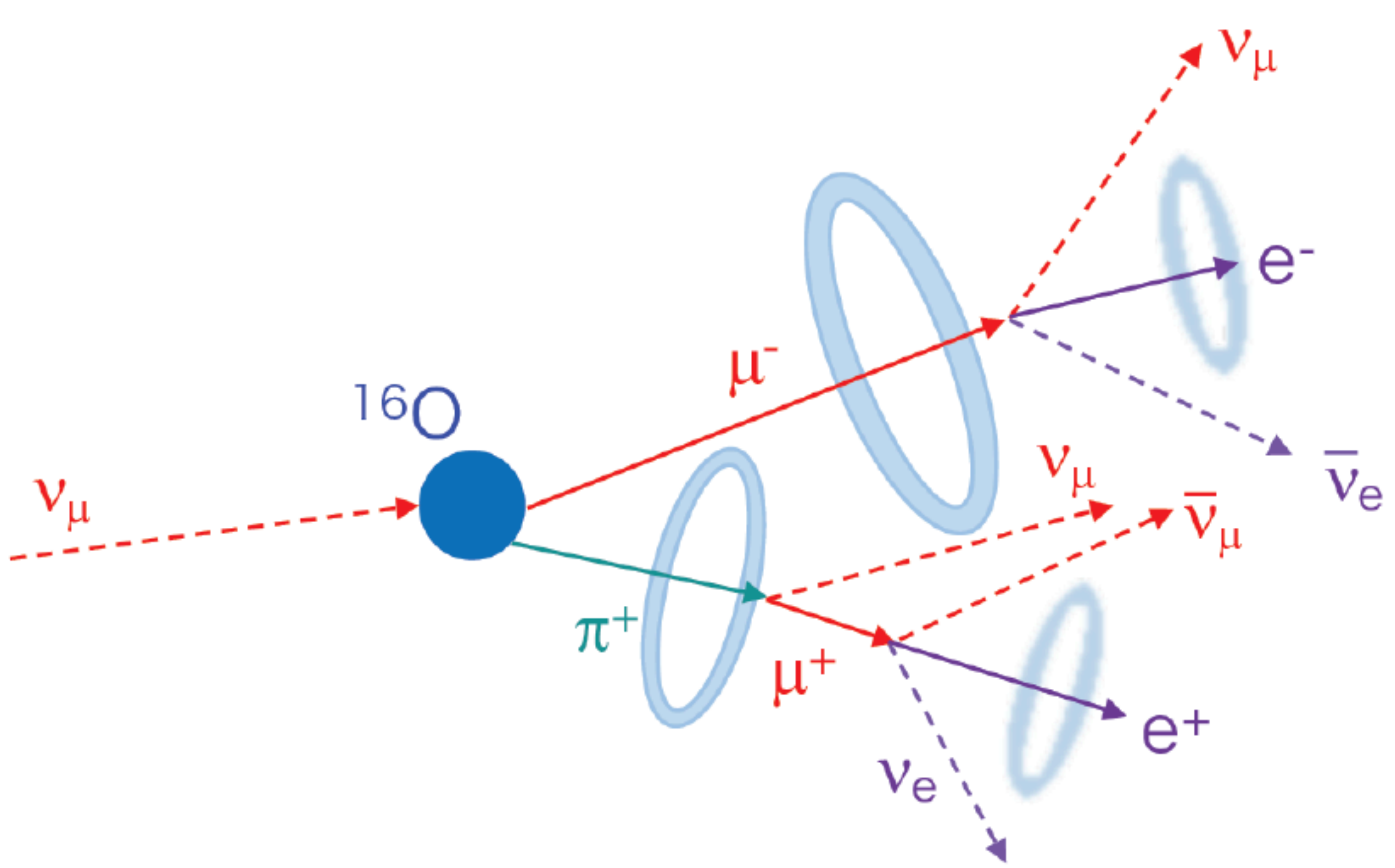


Sensitivity

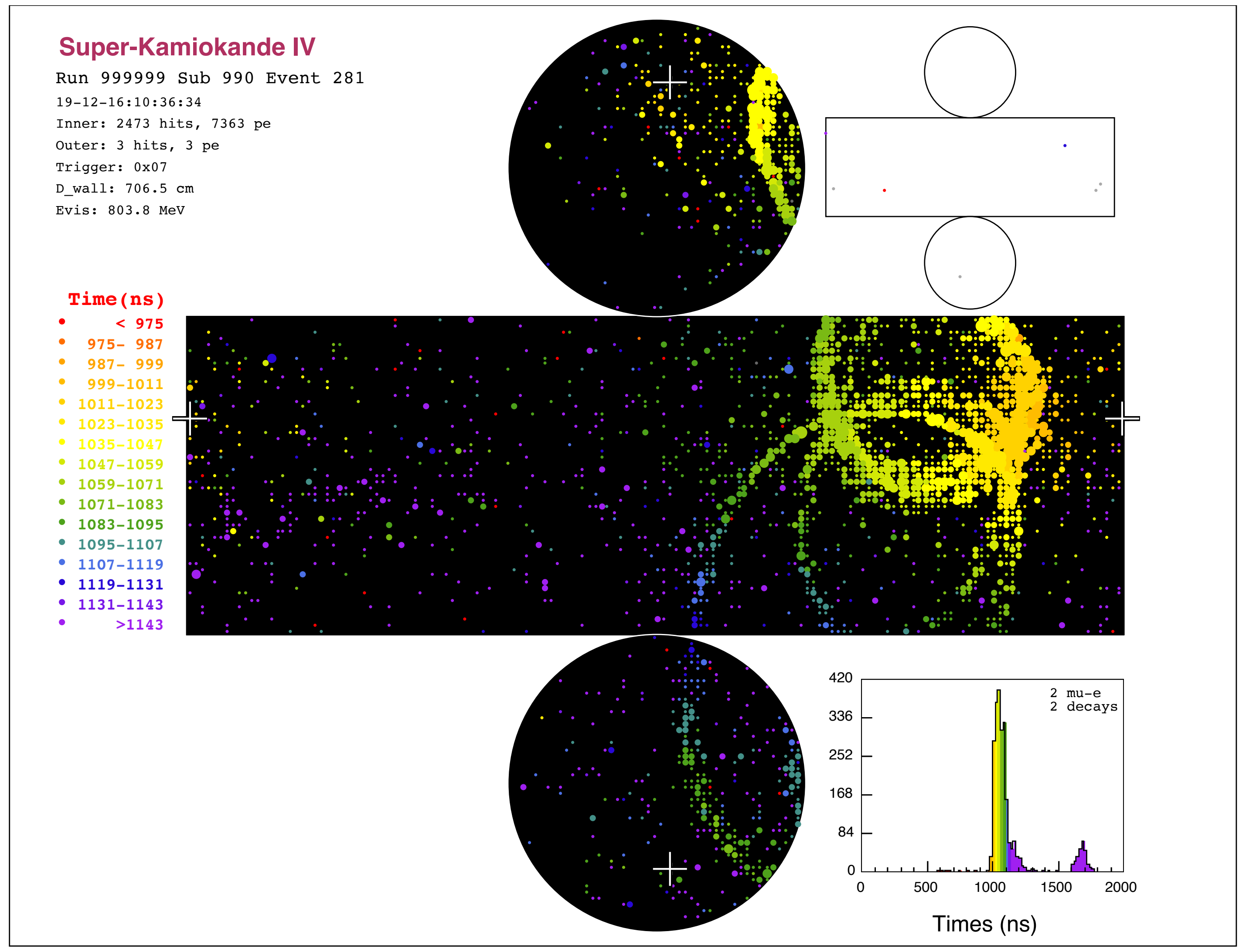


$\nu_\mu CC1\pi^+$ sample

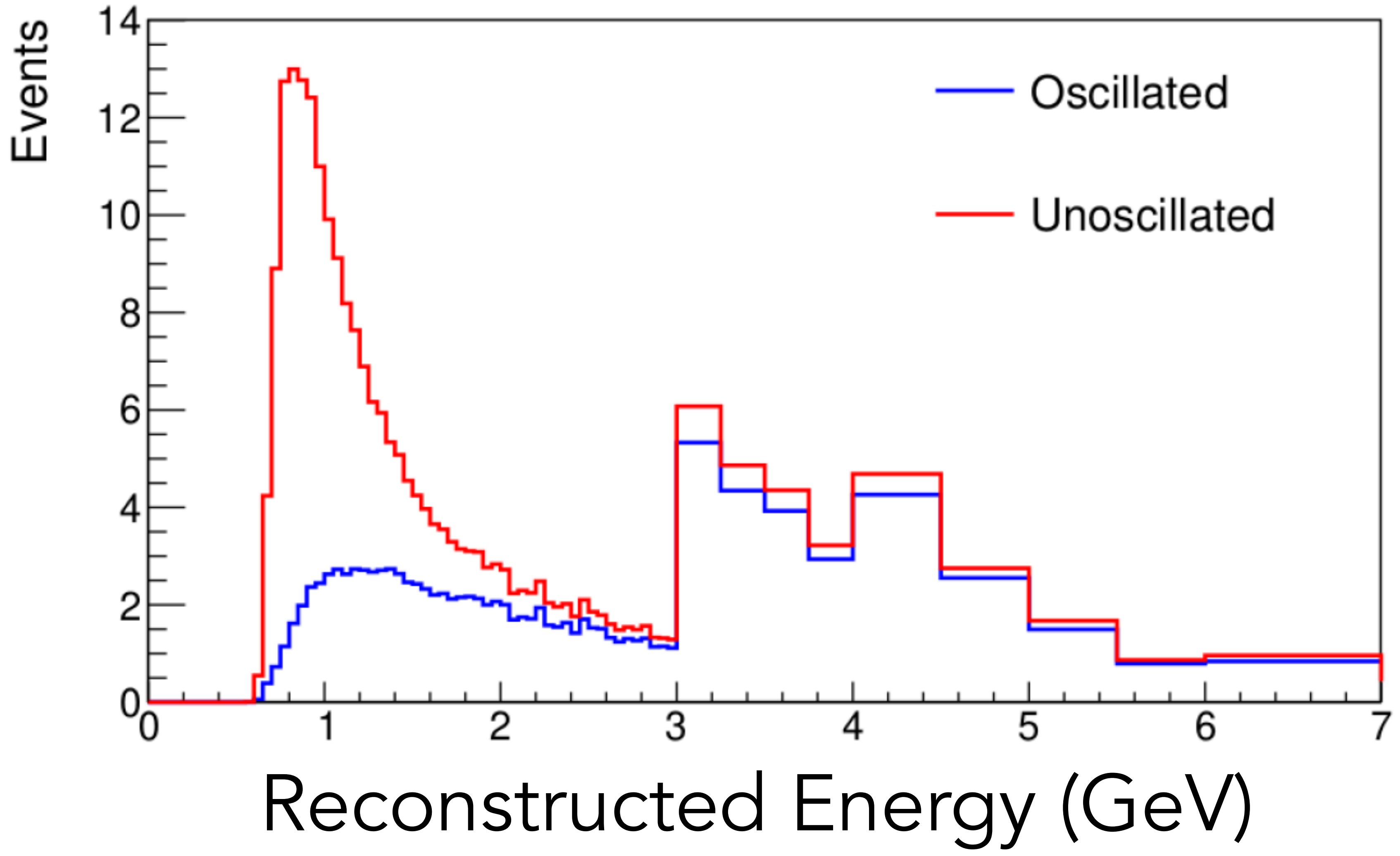
Schematic view



Event display (MC)
Multi-Ring + 2 decay electrons



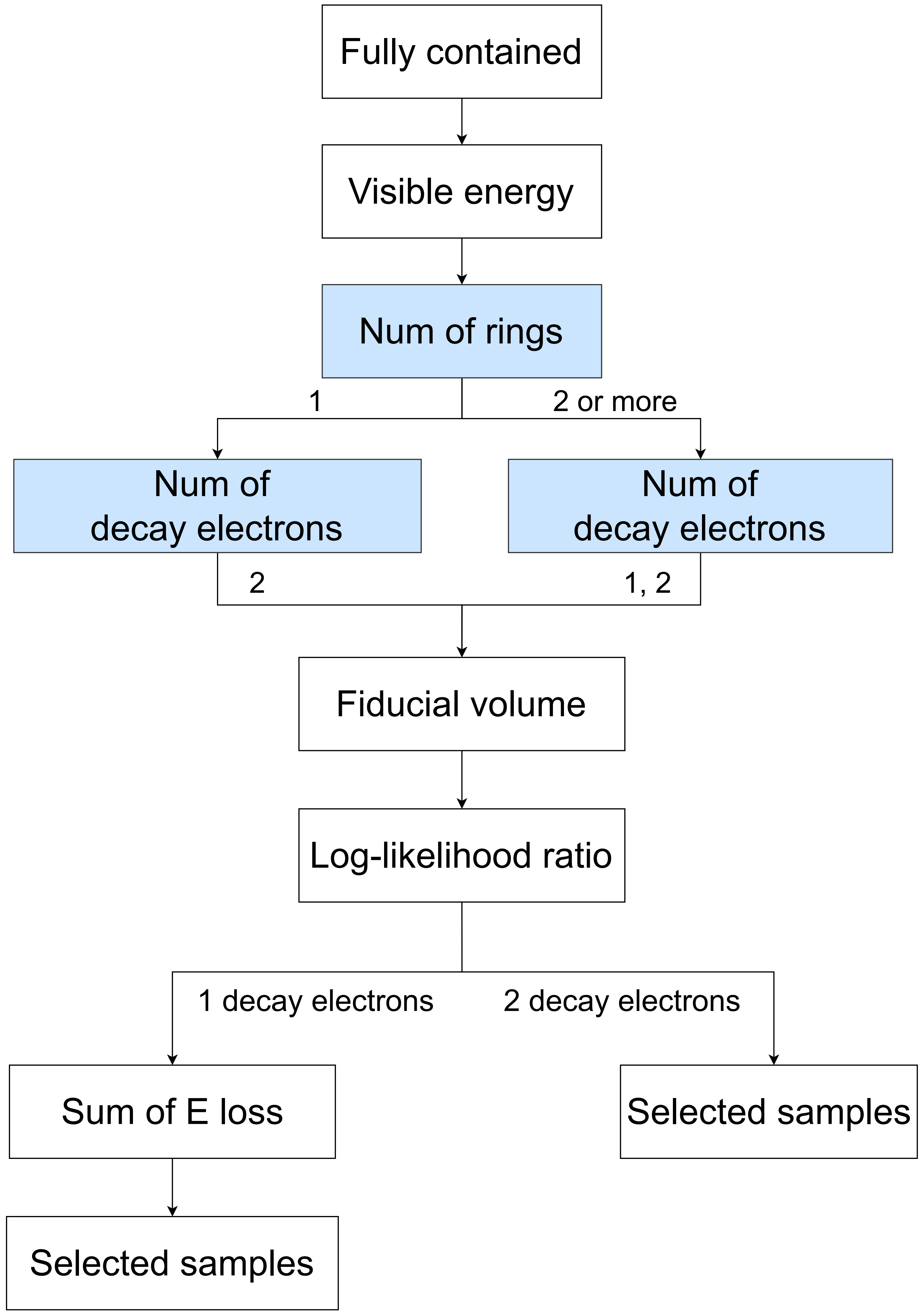
(Un)oscillated spectrum



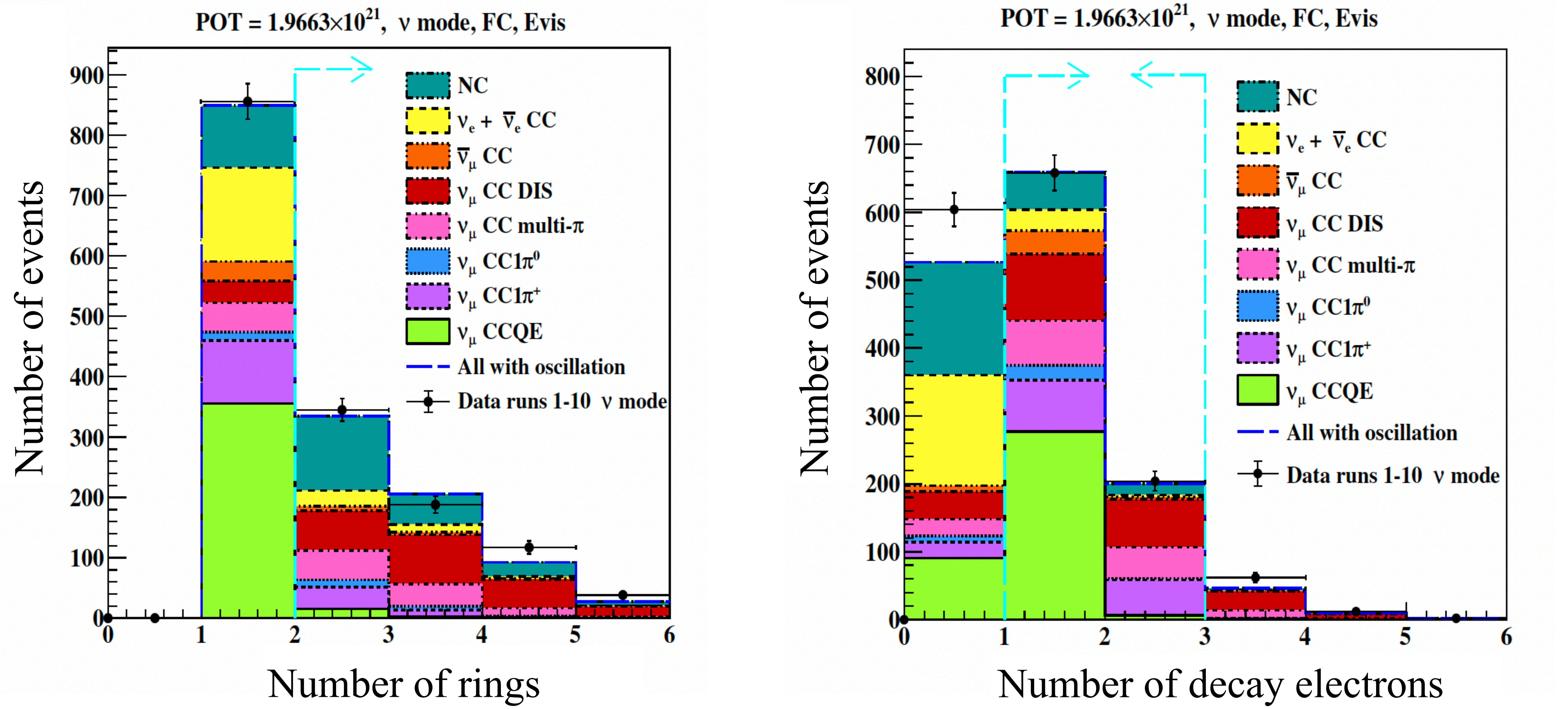
- $\nu_\mu CC1\pi^+$ has been introduced as an oscillation analysis sample for the first time.
  - Two rings from $1\mu^- + 1\pi^+$, and 1 decay electron
  - One or two rings from $1\mu^- + 1\pi^+$, and 2 decay electrons
- Parent neutrino energy is ~1.2 GeV, but oscillation effect is still present
- Increase muon neutrino sample by ~30%

Event selection for $\nu_\mu CC1\pi^+$

Event selection of ν_μ CC1π^+

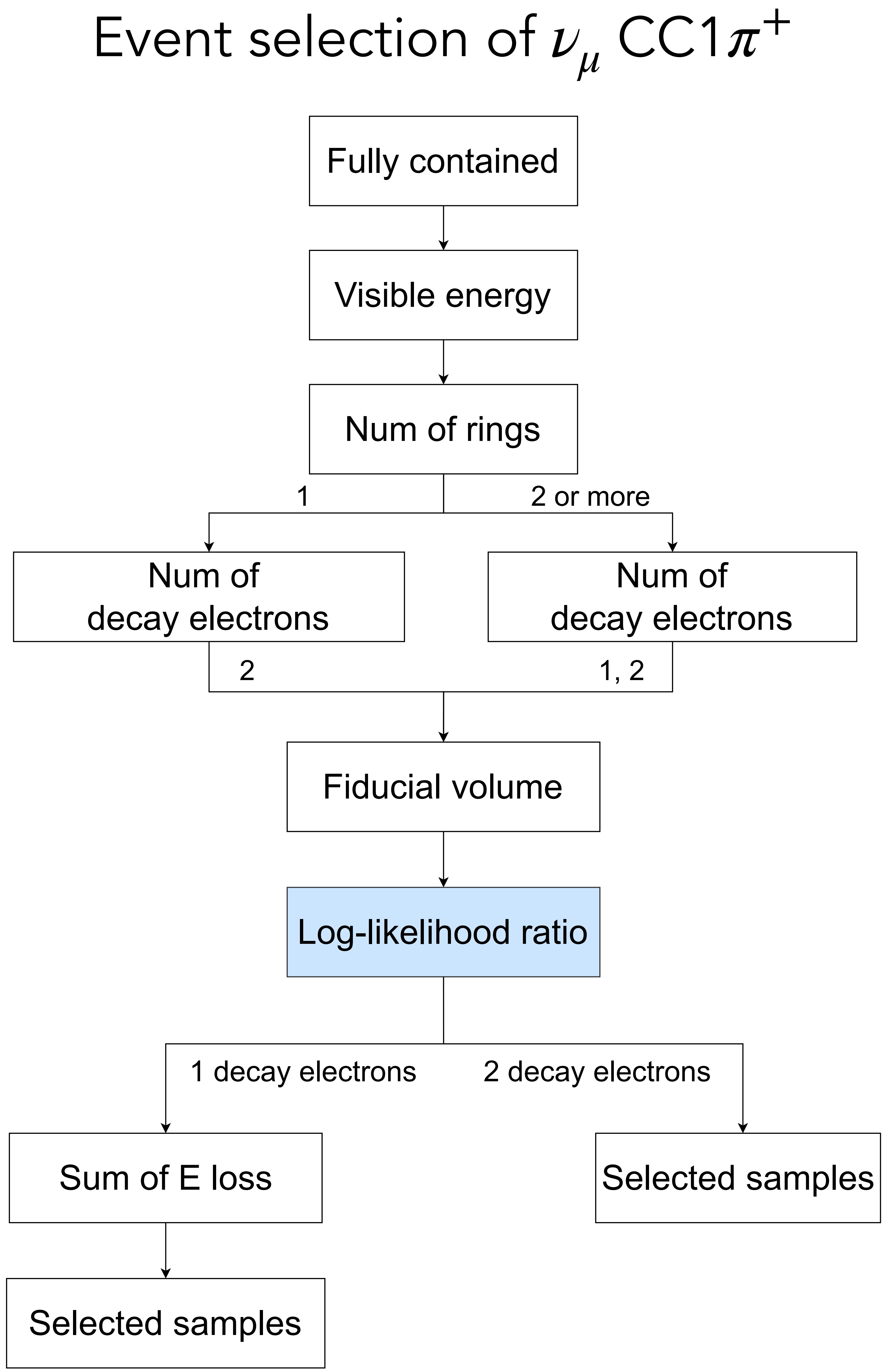


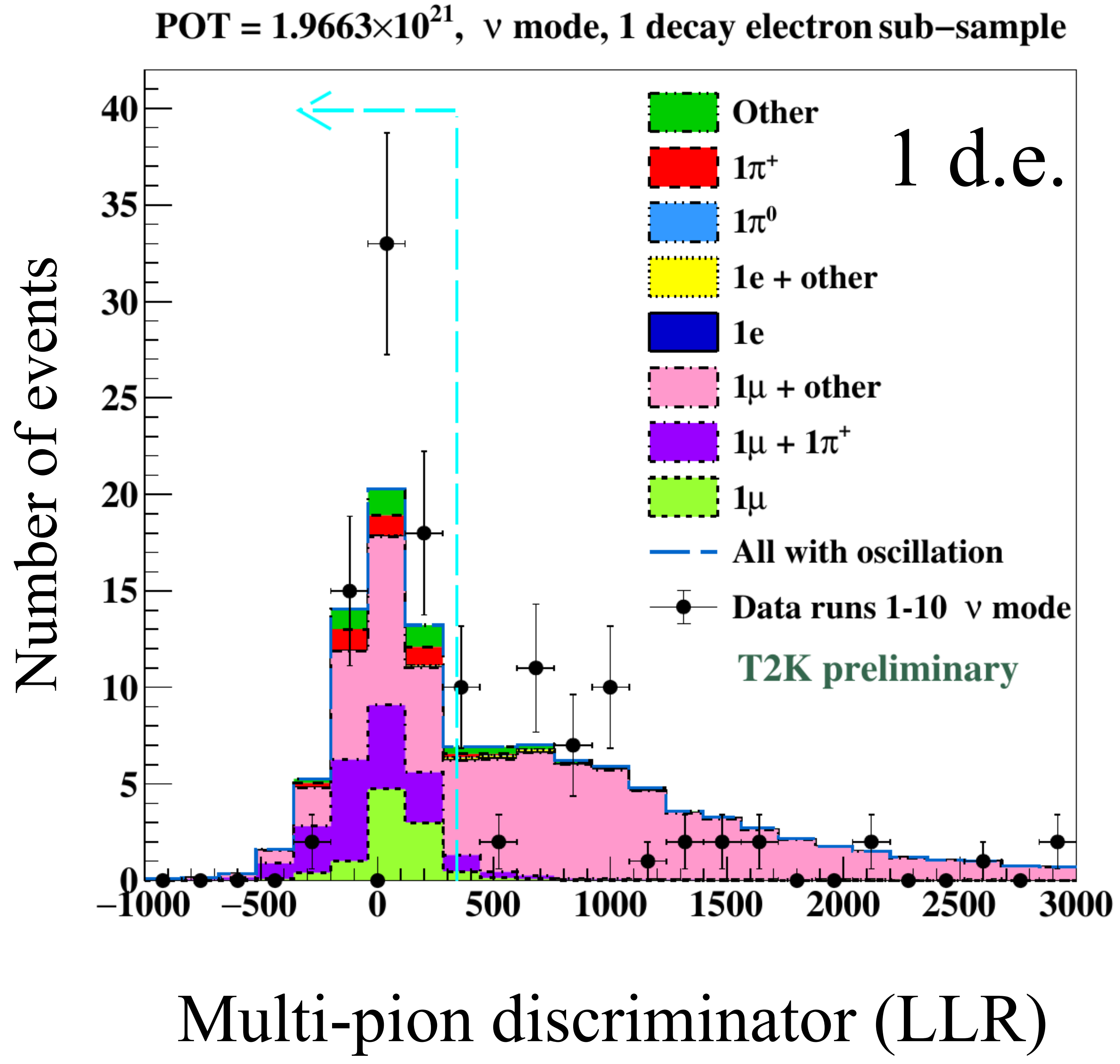
Multi-ring case

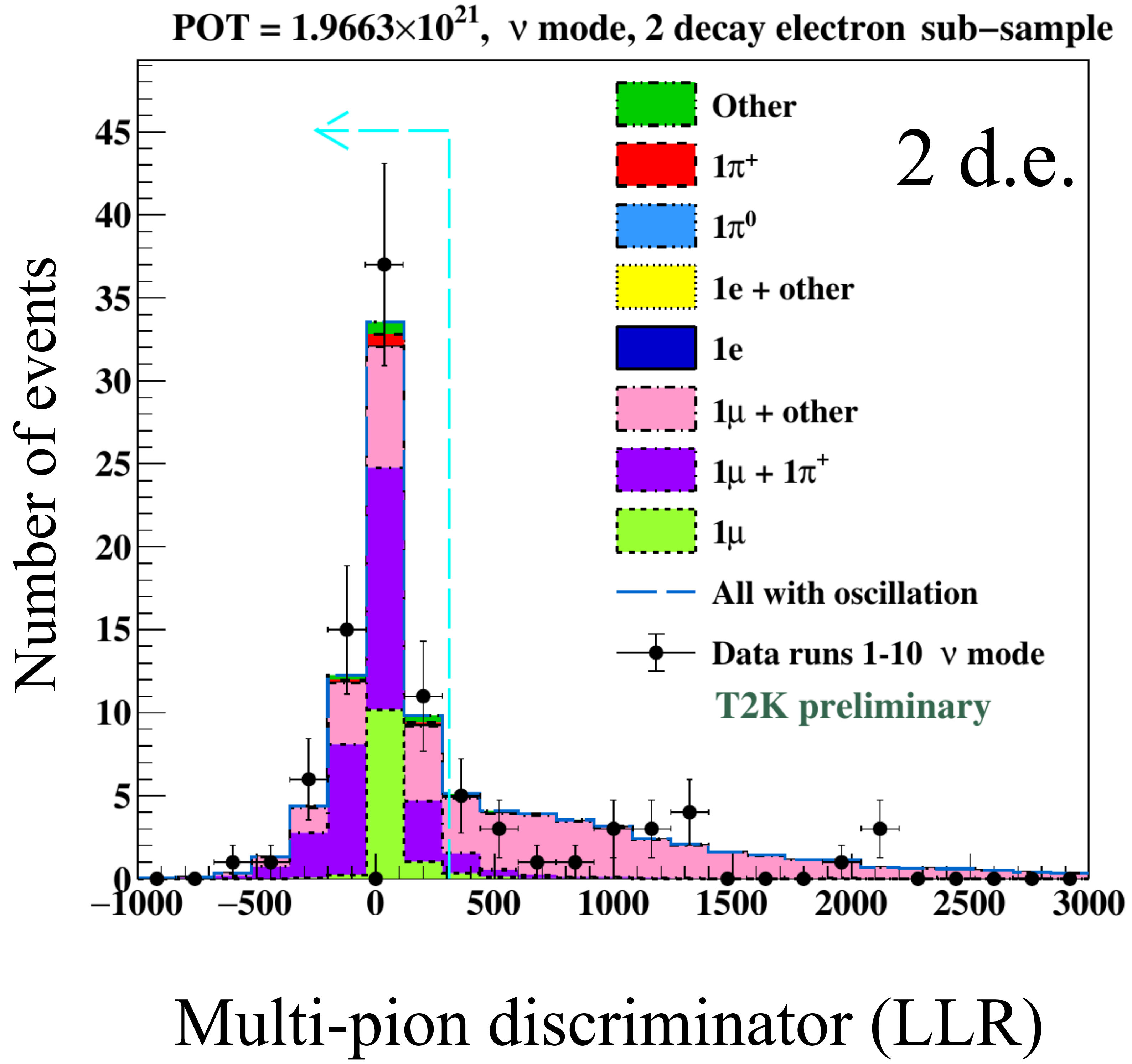


- Both 1 and 2 decay electrons are accepted.
  → Pion interactions can cause the loss of a decay electron.
- This sample is statistically independent of 1Ring events.

Event selection for MR $\nu_\mu CC1\pi^+$







- Good separation of (1μ or 1μ + other) and ($1\mu + 1\pi$) final state topologies.
- Reduce multi-pion production and DIS backgrounds.

Selection summary

Interaction mode	1-decay electron	Selection Efficiency (%)	Purity (%)	2-decay electrons	Selection Efficiency (%)	Purity (%)
ν_μ CCQE	12.1	68.9	—	4.6	86.9	—
ν_μ CC1π^+	**15.8**	**56.1**	**32.3**	**35.6**	**89.1**	**55.9**
ν_μ CC1π^0	1.2	10.8	—	0.7	52.2	—
ν_μ CC multiπ	8.5	19.7	—	13.0	35.0	—
ν_μ CC DIS	5.1	7.0	—	6.1	11.0	—
$\bar{\nu}_\mu$ CC	3.6	36.2	—	1.1	38.8	—
$\nu_e + \bar{\nu}_e$ CC	0.1	0.7	—	0.0	0.4	—
NC all	2.5	6.1	—	2.0	16.1	—
Total MC	49.0	—	—	63.1	—	—
Data	62	—	—	73	—	—

- Both one-ring and multi-ring samples are merged into 2-decay electrons here.
- Main interaction mode for both samples is ν_μCC1π^+.
- 2 decay electron sample is purer than 1 decay electron sample.

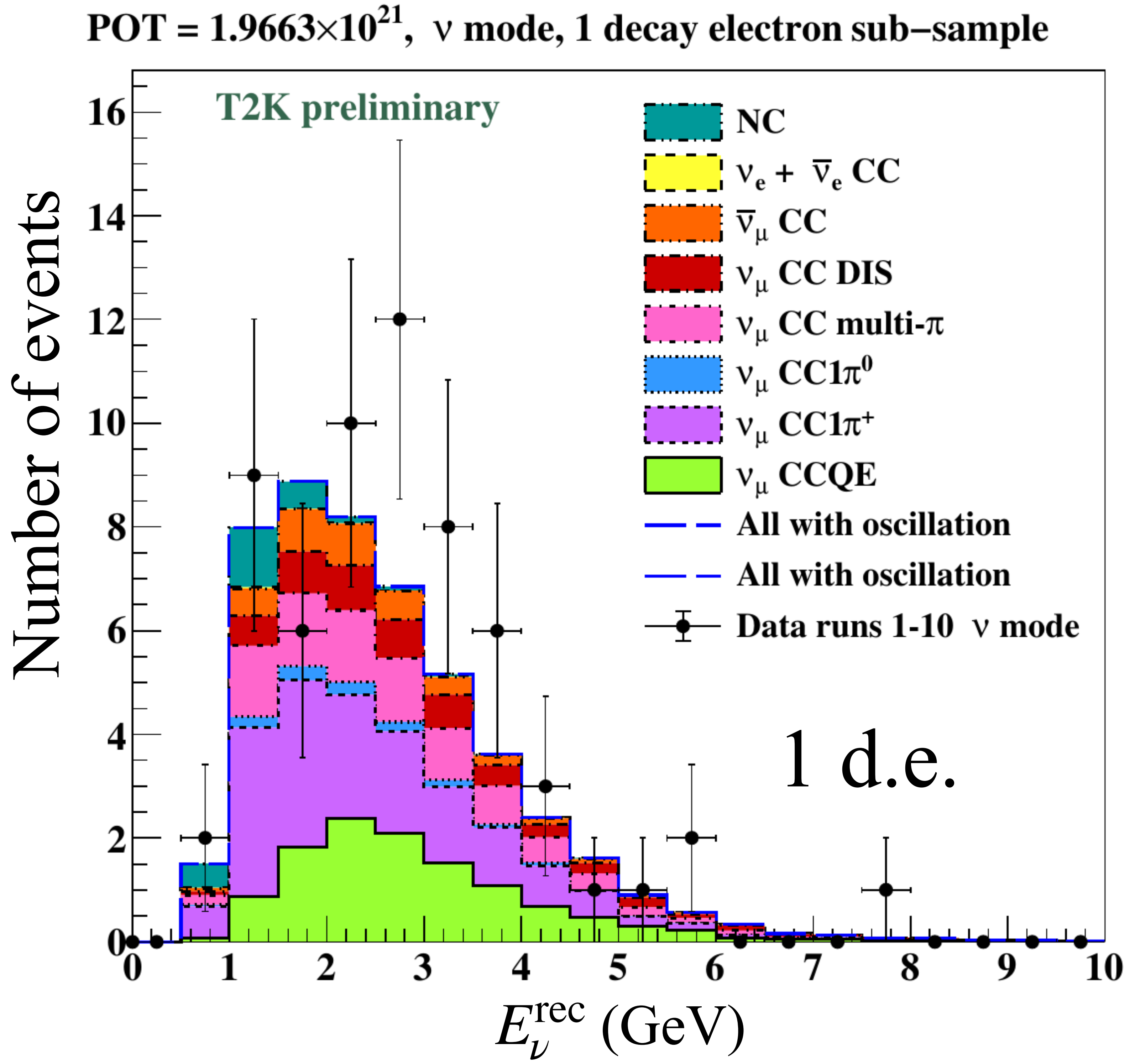
ν_μCC1π^+ (Reconstructed energy)

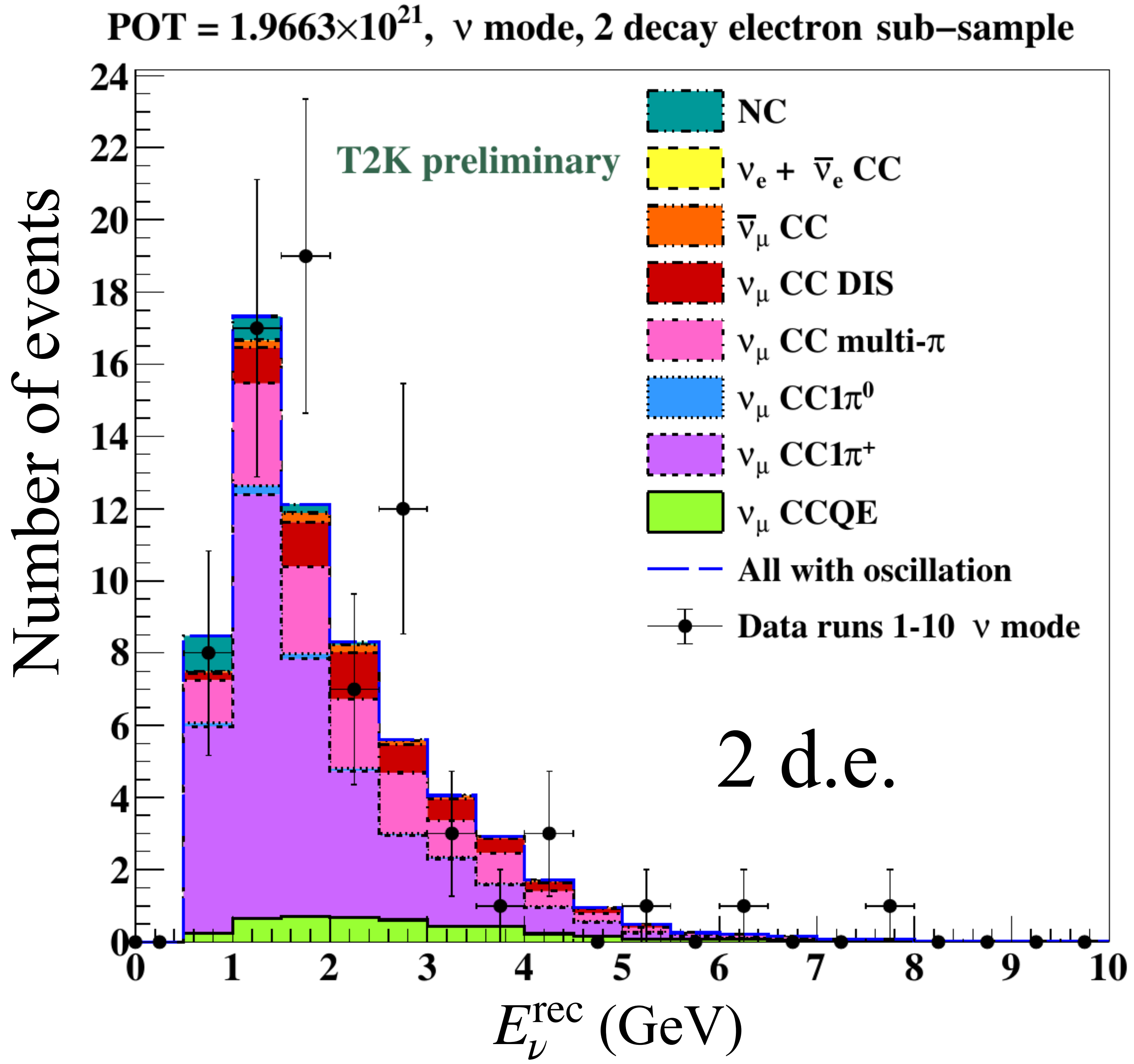
Energy of outgoing muon — Δ^{++} mass — Proton mass — Muon mass

$$E_{\rm rec}^{\nu_\mu {\rm CC}\Delta^{++}} = \frac{2M_p E_\mu + M^2_{\Delta^{++}} - M_p^2 - M_\mu^2}{2\left(M_p - E_\mu + |p_\mu| \cos\theta_\mu\right)}$$

Momentum and angle of outgoing muon

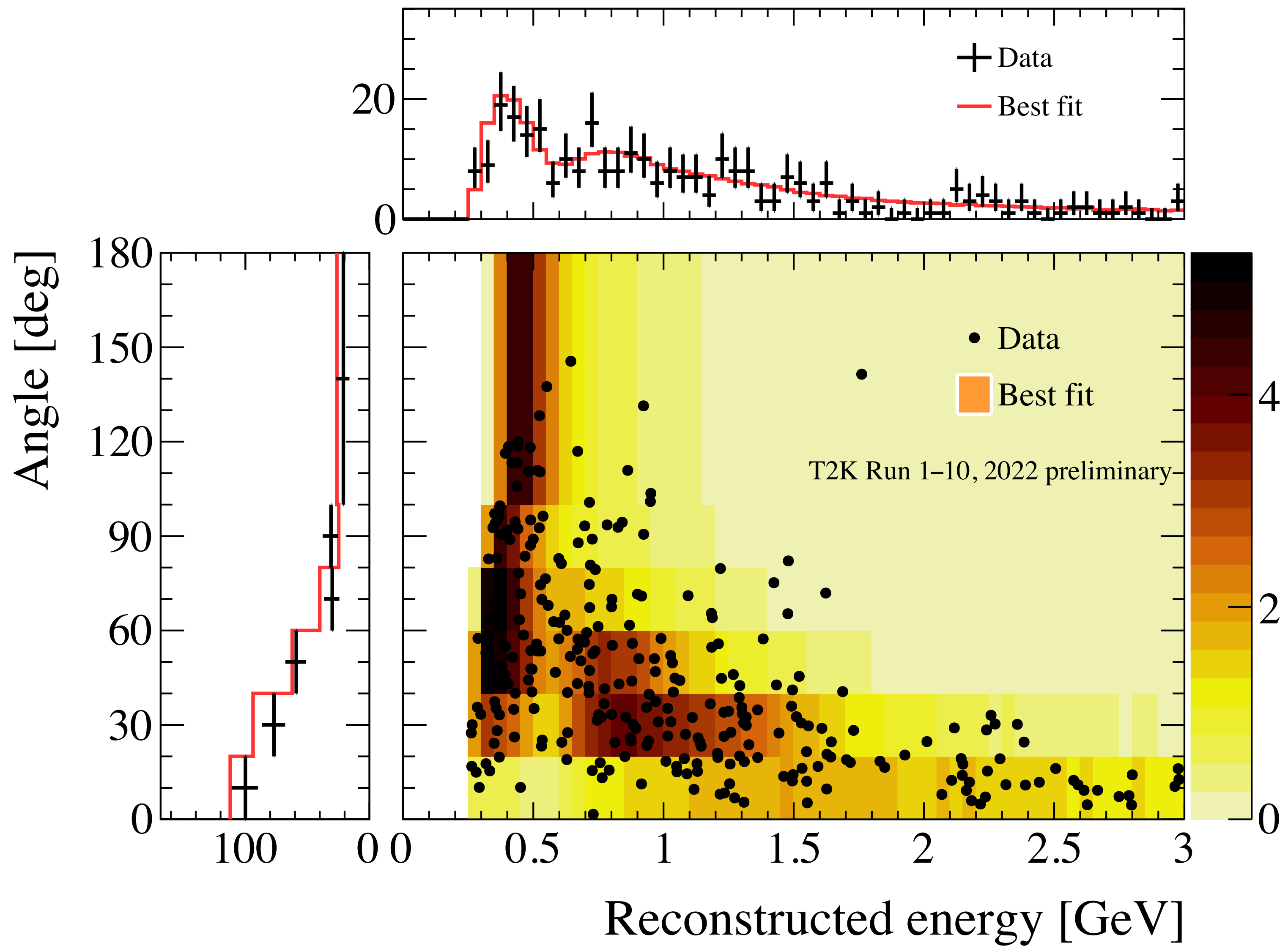
- Muon kinematics ($p_\mu, \cos\theta_\mu$) are taken as the reconstructed ($p, \cos\theta$) of the ring with the highest energy.



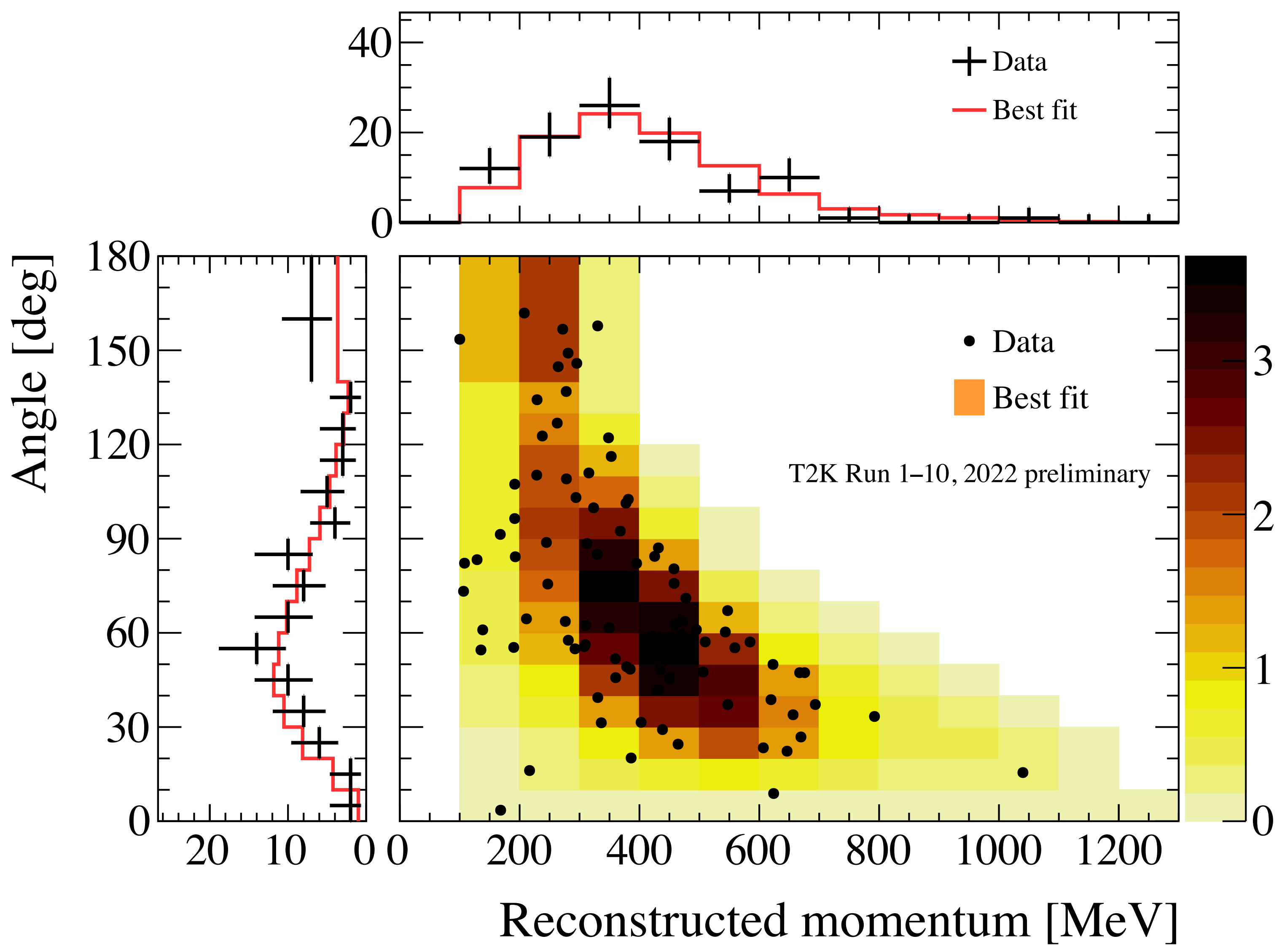


Far detector fit

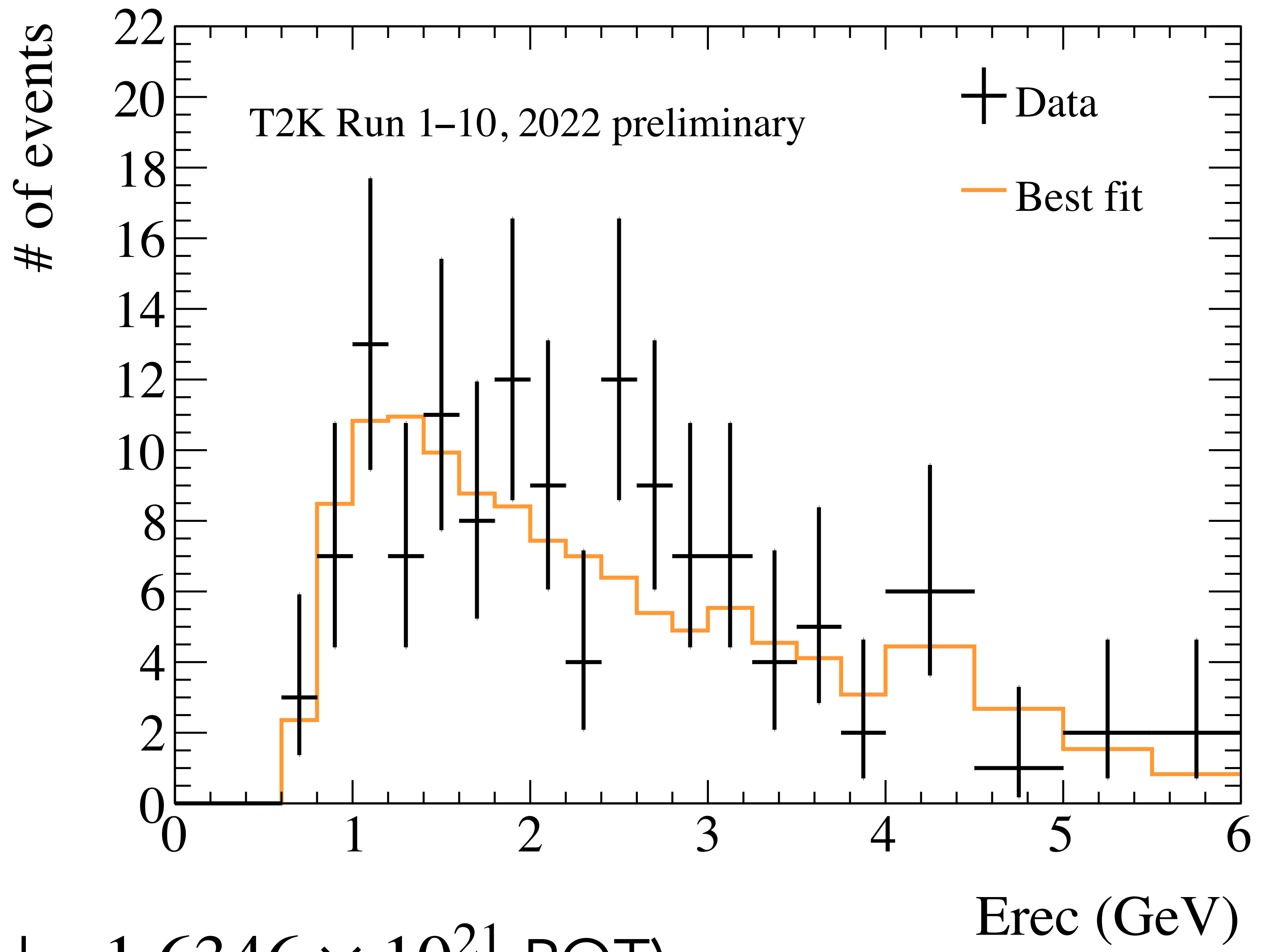
μ-like 1Ring ν_μ



e-like 1Ring ν_e



$\nu_\mu CC1\pi^+$



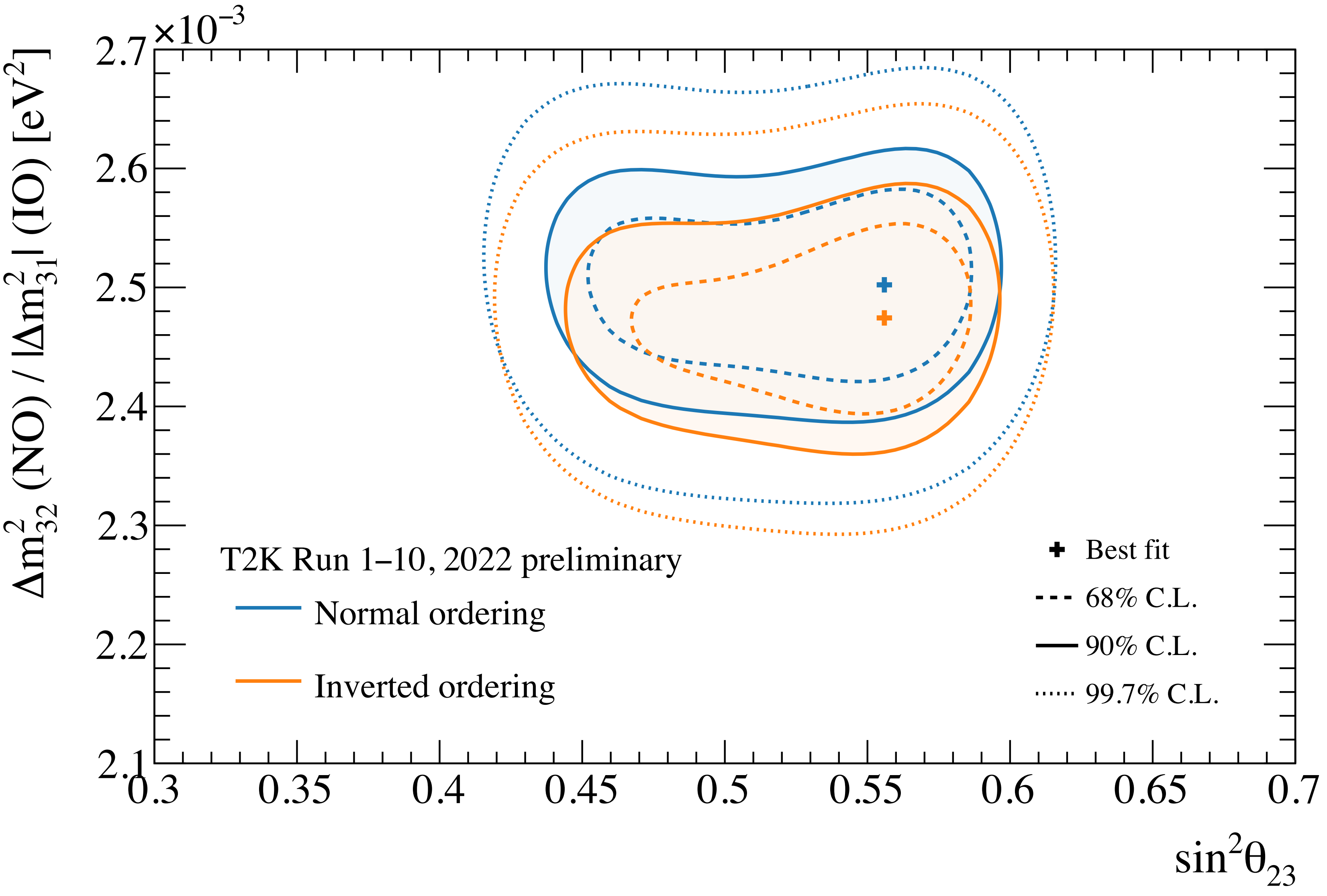
Run1-10 statistics used (ν mode: 1.9664×10^{21} protons on target (POT) $\bar{\nu}$ mode: 1.6346×10^{21} POT)

- Define binning scheme for six samples, $E_{\rm rec}^{\rm lepton}$-$\theta_{\rm wrt\ \nu}^{\rm lepton}$ for 1R ν_μ, $P^{\rm lepton}$-$\theta_{\rm wrt\ \nu}^{\rm lepton}$ for 1R ν_e, $E_{\rm rec}^{\rm lepton}$ for $\nu_\mu CC1\pi^+$
- Calculate likelihood with marginalisation over nuisance parameters ($\sin^2\theta_{12}$: fixed to 0.307, $\sin^2\theta_{13} = 0.0220 \pm 0.0007$ (gaussian))
- Create contours for certain oscillation parameters with either fixed $\Delta\chi^2$ method or Feldman-Cousins method

Fits were done by Bayesian MCMC as well. In this talk, $\Delta\chi^2$ confidence intervals will be discussed.

Highlight of the T2K latest results

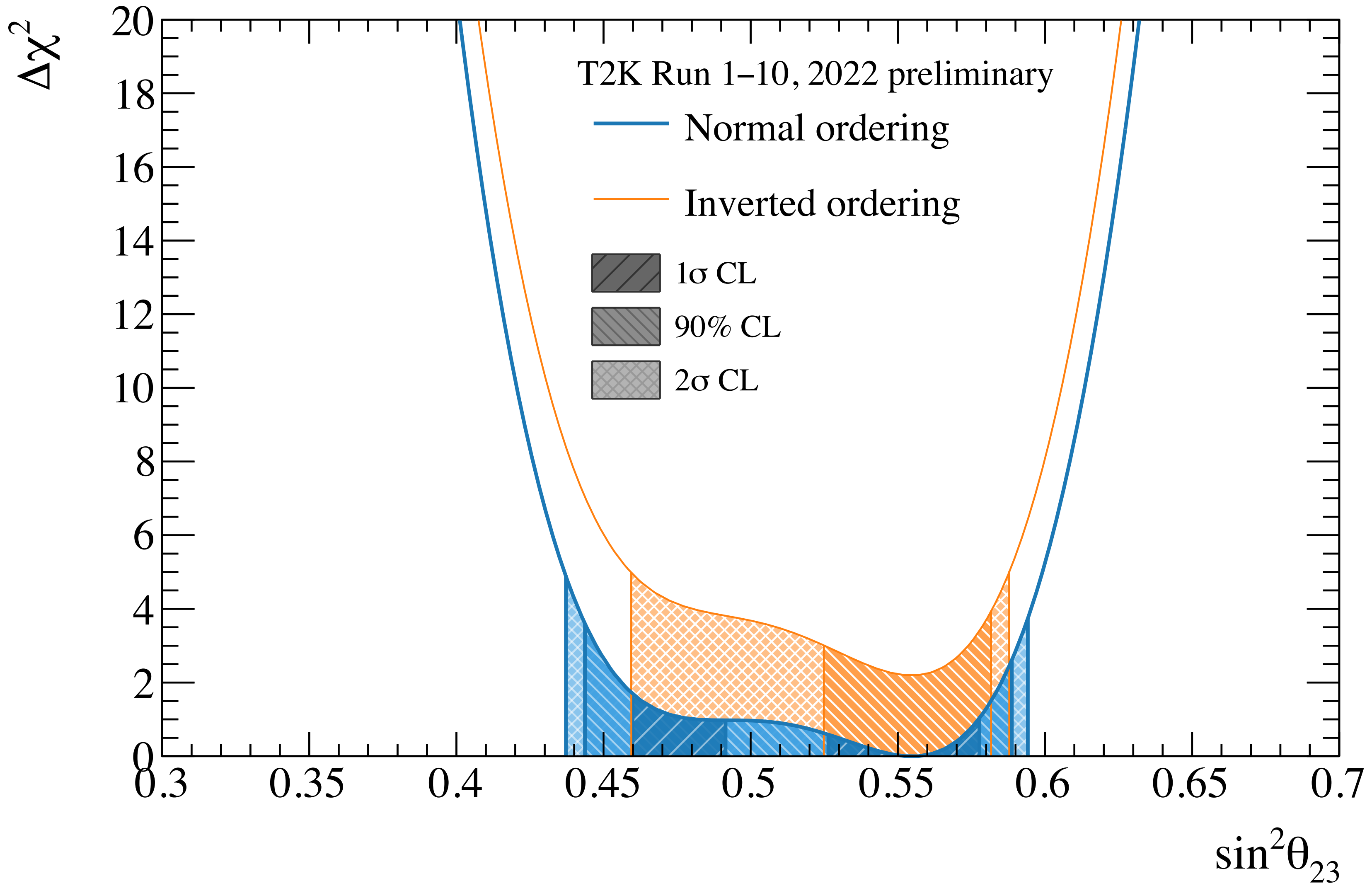
Contours by Fixed $\Delta\chi^2$



Details in **T2K plenary talk: Laura Kormos**

Contours by Feldman-Cousins (FC)

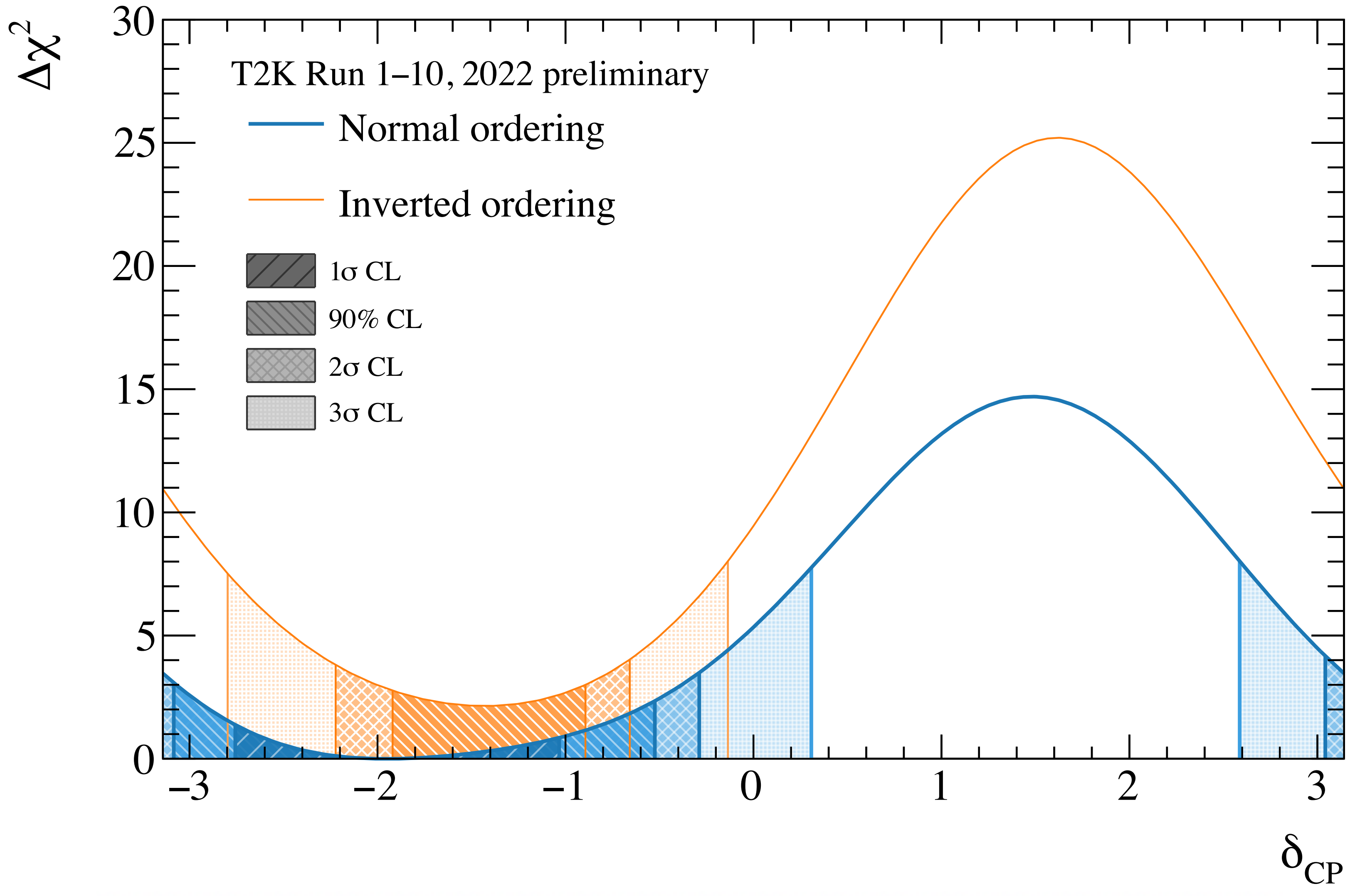
$\sin^2\theta_{23}$



Confidence level	Interval (NH)	Interval (IH)
1σ	$[0.460, 0.491] \cup [0.526, 0.578]$	
90%	$[0.444, 0.589]$	$[0.525, 0.582]$
2σ	$[0.437, 0.594]$	$[0.459, 0.588]$

T2K Run 1-10, preliminary

δ_{CP}



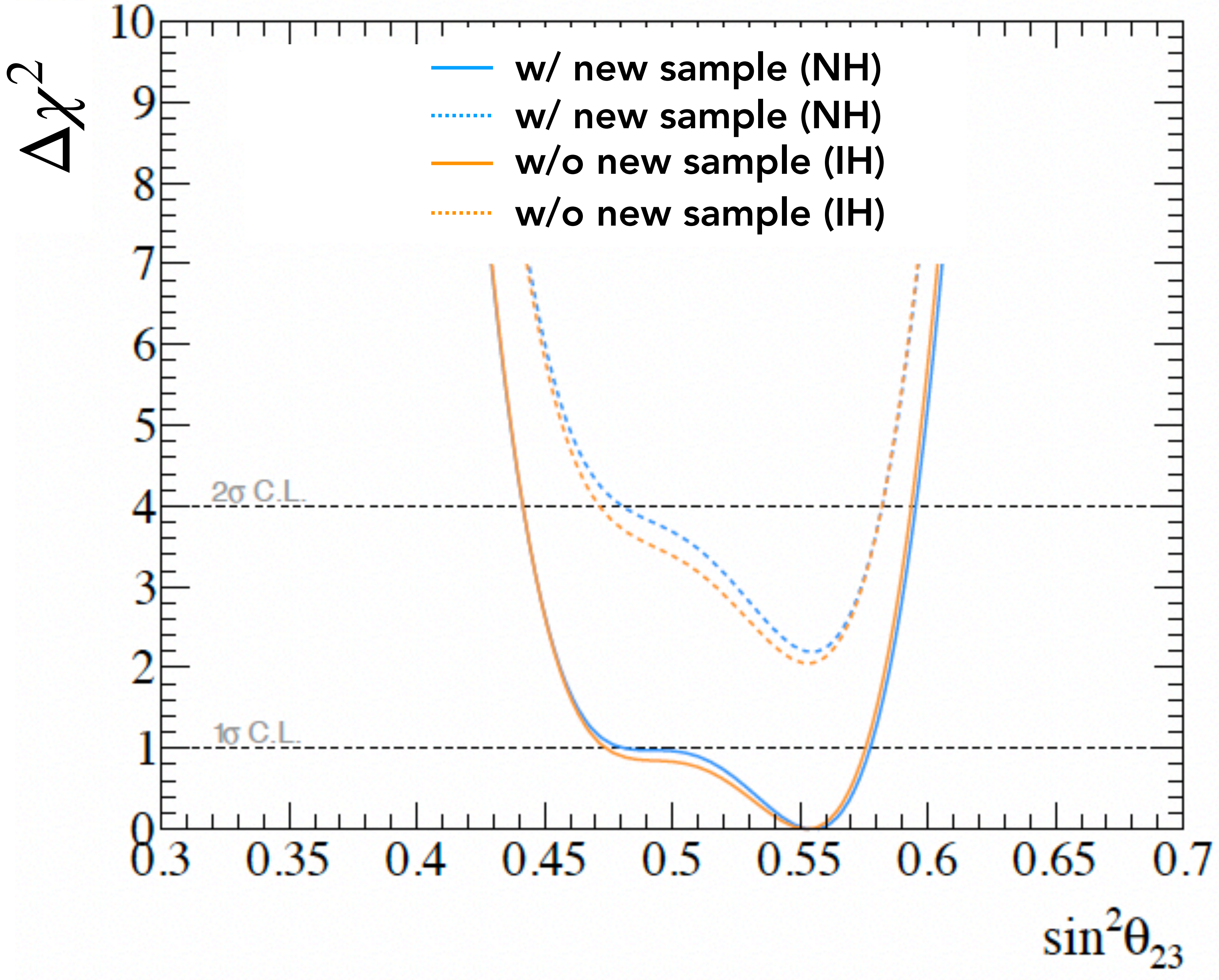
Confidence level	Interval (NH)	Interval (IH)
1σ	$[-2.76, -1.03]$	
90%	$[-3.08, -0.52]$	$[-1.92, -0.89]$
2σ	$[-\pi, -0.29] \cup [3.04, \pi]$	$[-2.22, -0.66]$
3σ	$[-\pi, 0.31] \cup [2.59, \pi]$	$[-2.80, -0.14]$

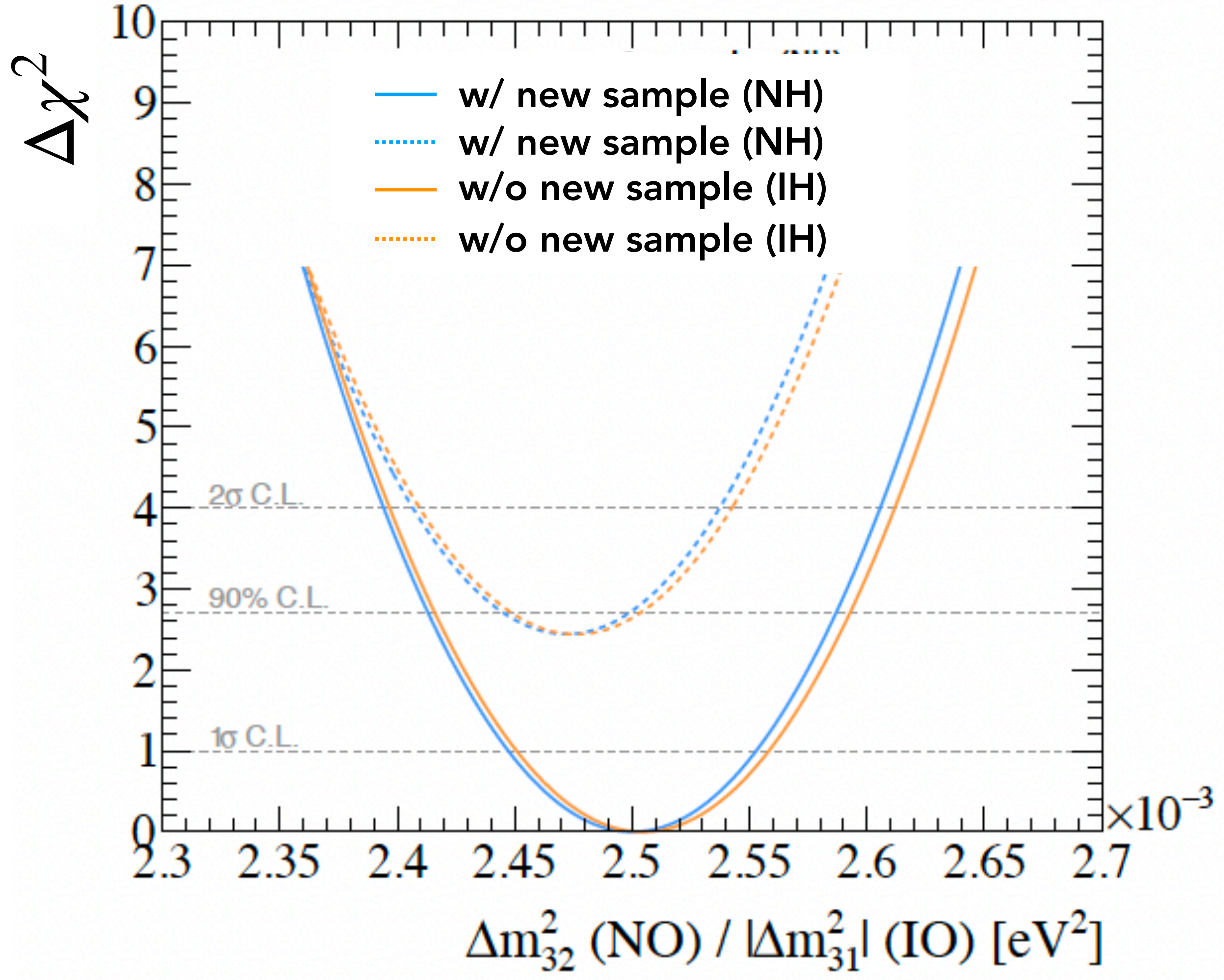
T2K Run 1-10, preliminary

- Additional Gaussian smearing ($\sigma = 0.027 \times 10^{-3}\mathrm{eV}^2/c^4$) in Δm^2_{32} from results of potential bias studies using alternative neutrino interaction models.
- Both θ_{23} octants are still allowed at 1σ confidence level.
- CP conserving values are excluded at 90% CL.

Impact of ν_μCC1π^+ on $\sin^2\theta_{23}$, Δm^2_{32}

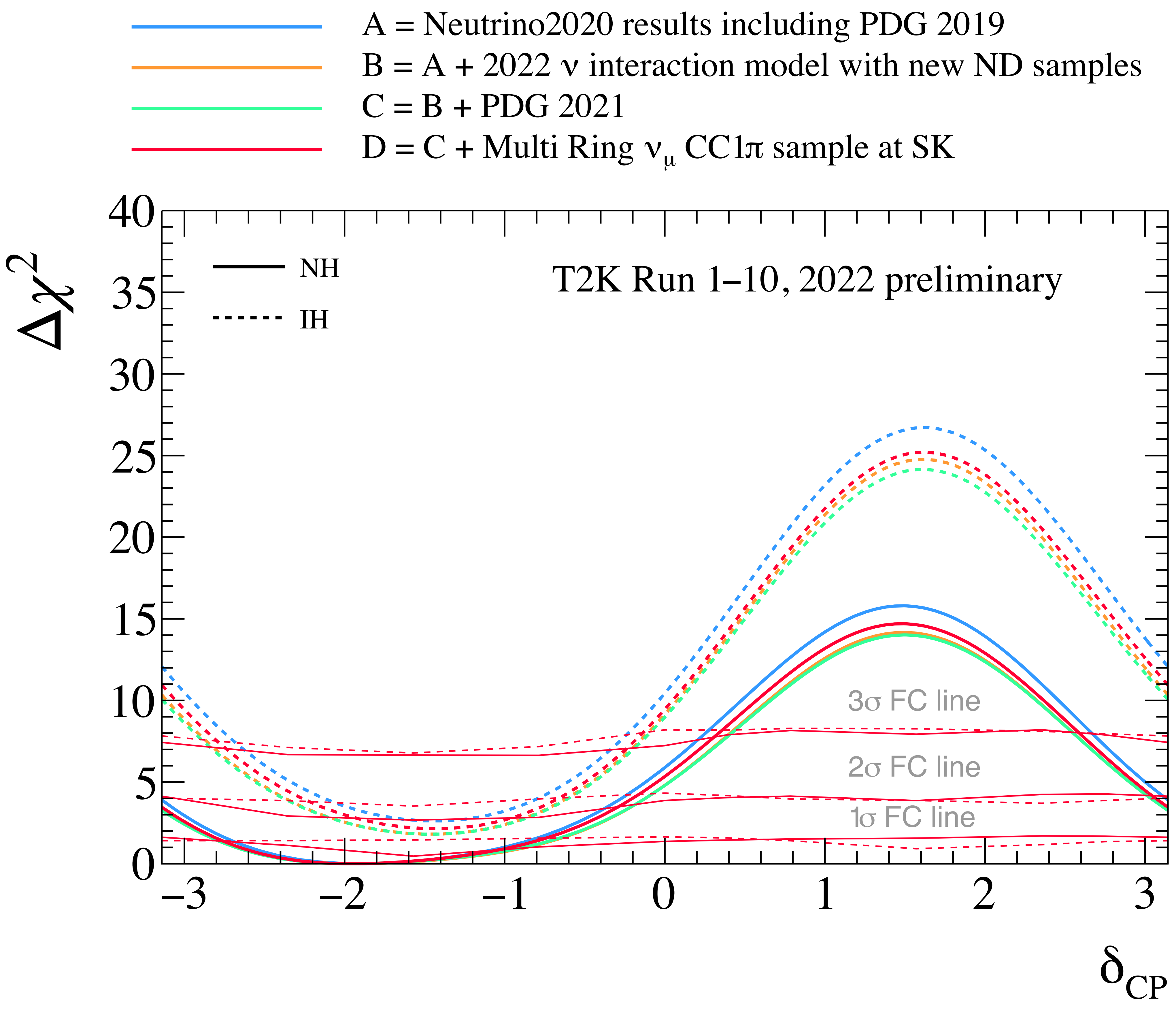
All contours are produced with constraint on $\sin^2\theta_{13}$ by reactor experiments. $\sin^2\theta_{13} = 0.0220 \pm 0.0007$ from PDG2021

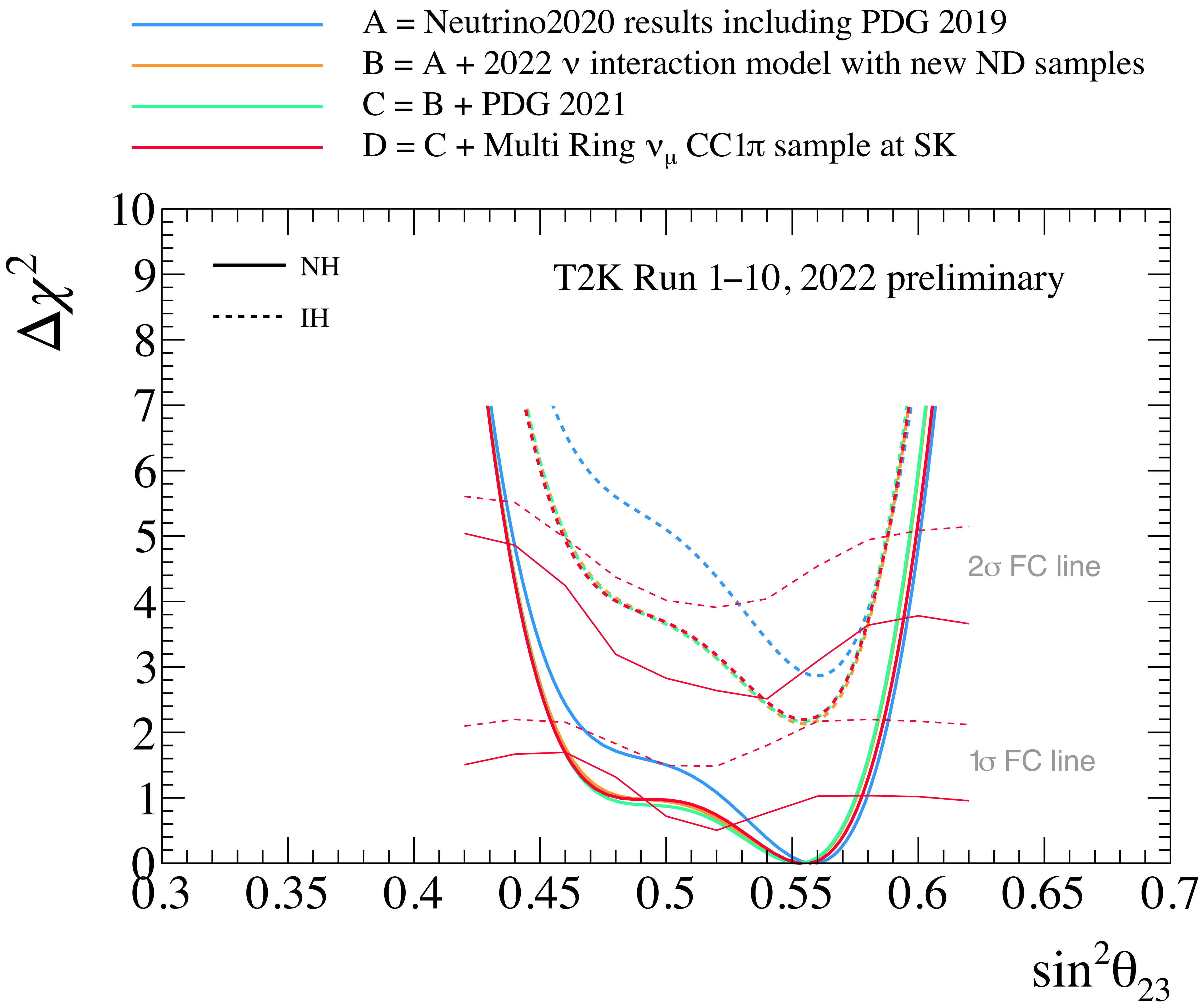




- Other improvements from neutrino interaction and near detector fit have been applied.
  Interaction model talk: Stephen Dolan (2/8, WG1), Near detector talk: Callum Wilkinson (4/8, WG1)
- Improvements from this sample on constraints for parameters ($\sin^2\theta_{23}$, Δm^2_{32}) are small but visible.
  - ~5% improvement wrt 1σ error of Δm^2_{32}
  - Peak energy in ν_μCC1π^+ sample (~1.2 GeV) is away from the maximum oscillation prob. region (0.6 GeV).

Effect of each analysis improvement

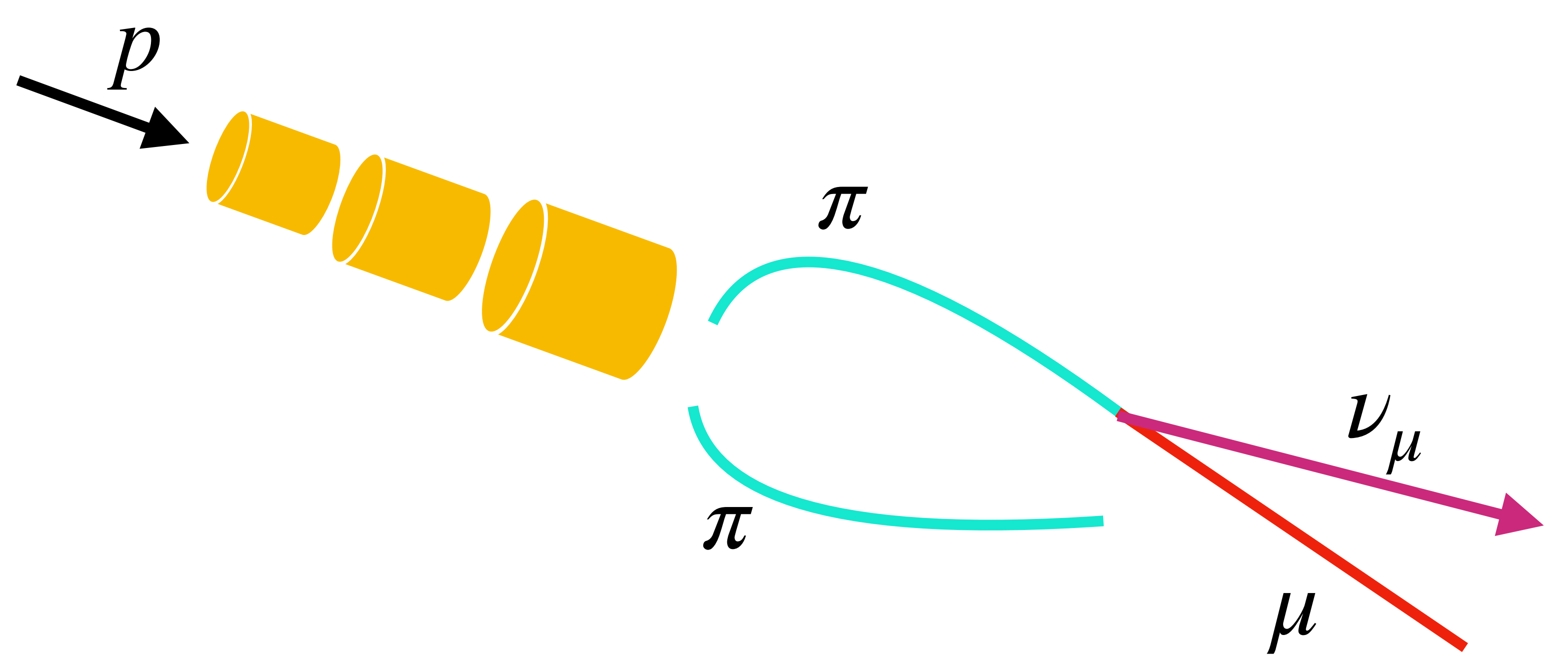




- The largest impact comes from updates to the neutrino interaction model and the near detector analysis.

Joint fit analysis of atmospheric and beam neutrino

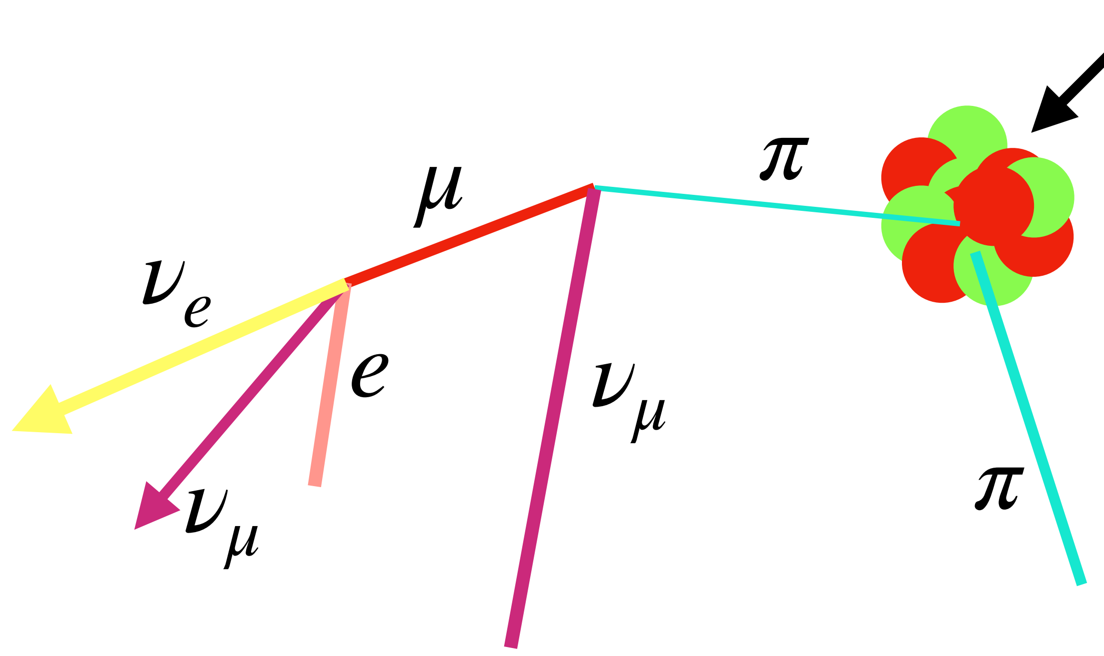
T2K beam neutrino samples (5 samples)



- Optimised ν_μ flux for oscillations

+

SK atmospheric neutrino samples (18 samples)

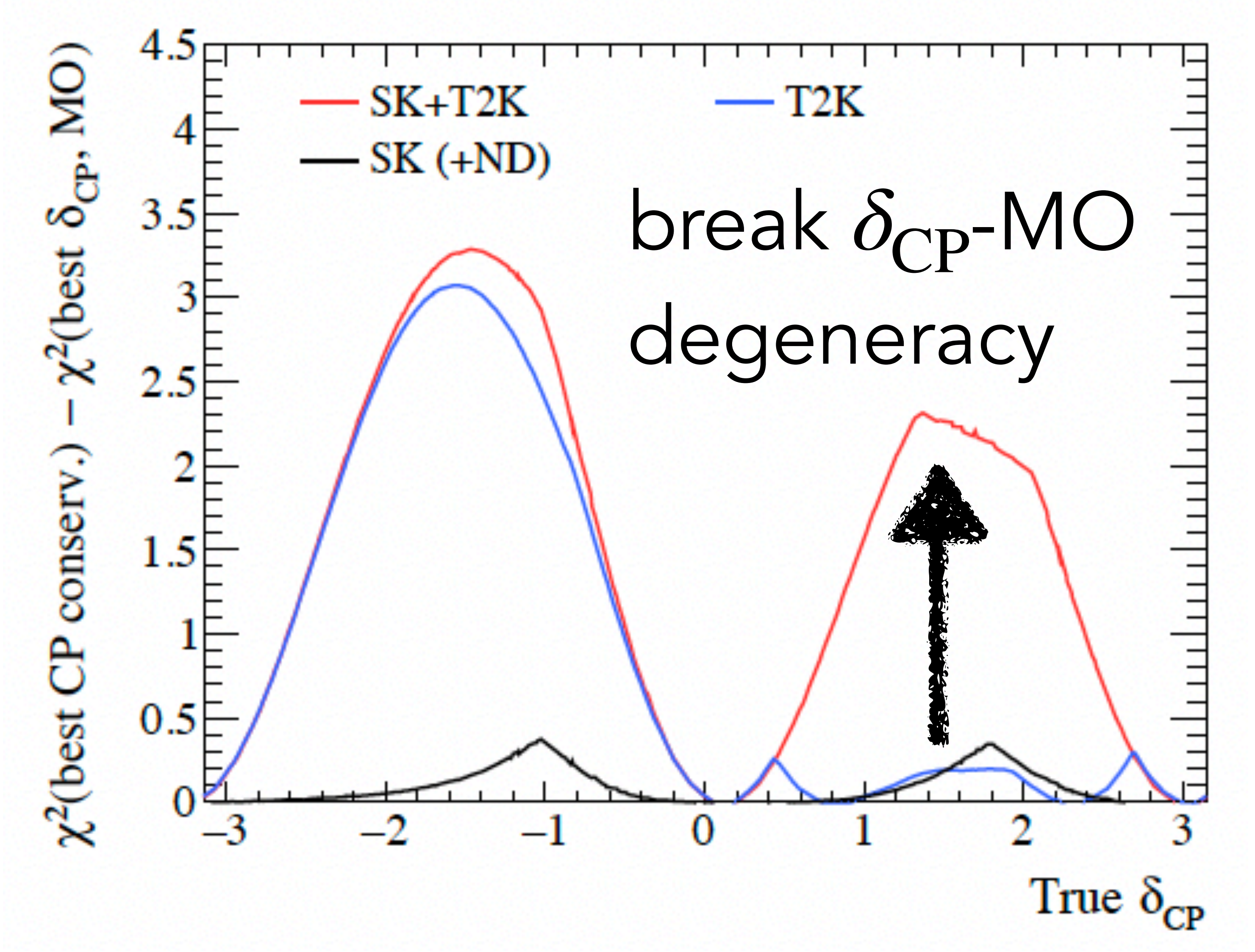


- Broader energy range and baselines
- More matter effect due to mantle/core resonance

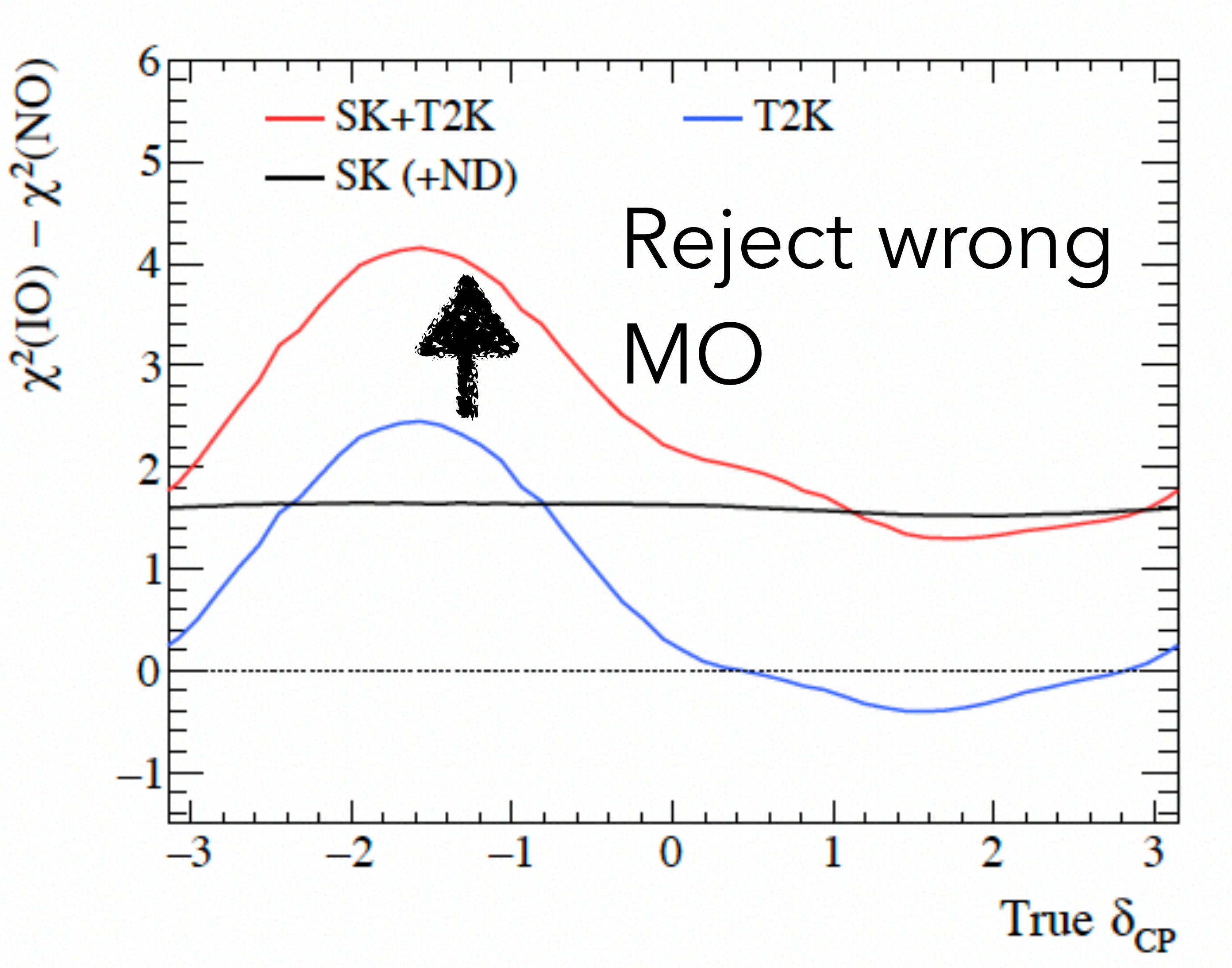
- Not only adds the sensitivities from both measurements but has a synergy giving additional constraints.
  → The sensitivity of SK to the mass ordering is limited by the uncertainty on $\sin^2\theta_{23}, \delta_{CP}$ but T2K can constrain both
- Break degeneracies, in particular δ_{CP}-MO and the θ_{23} octant.
- Correlations of systematic uncertainties among two experiments.
  - T2K and SK flux are uncorrelated, and most detector systematics are almost uncorrelated.
  - Interaction model: For T2K samples and low-energy atm. samples use a unified model, for high-energy atm. samples use mainly SK model.

Sensitivity results

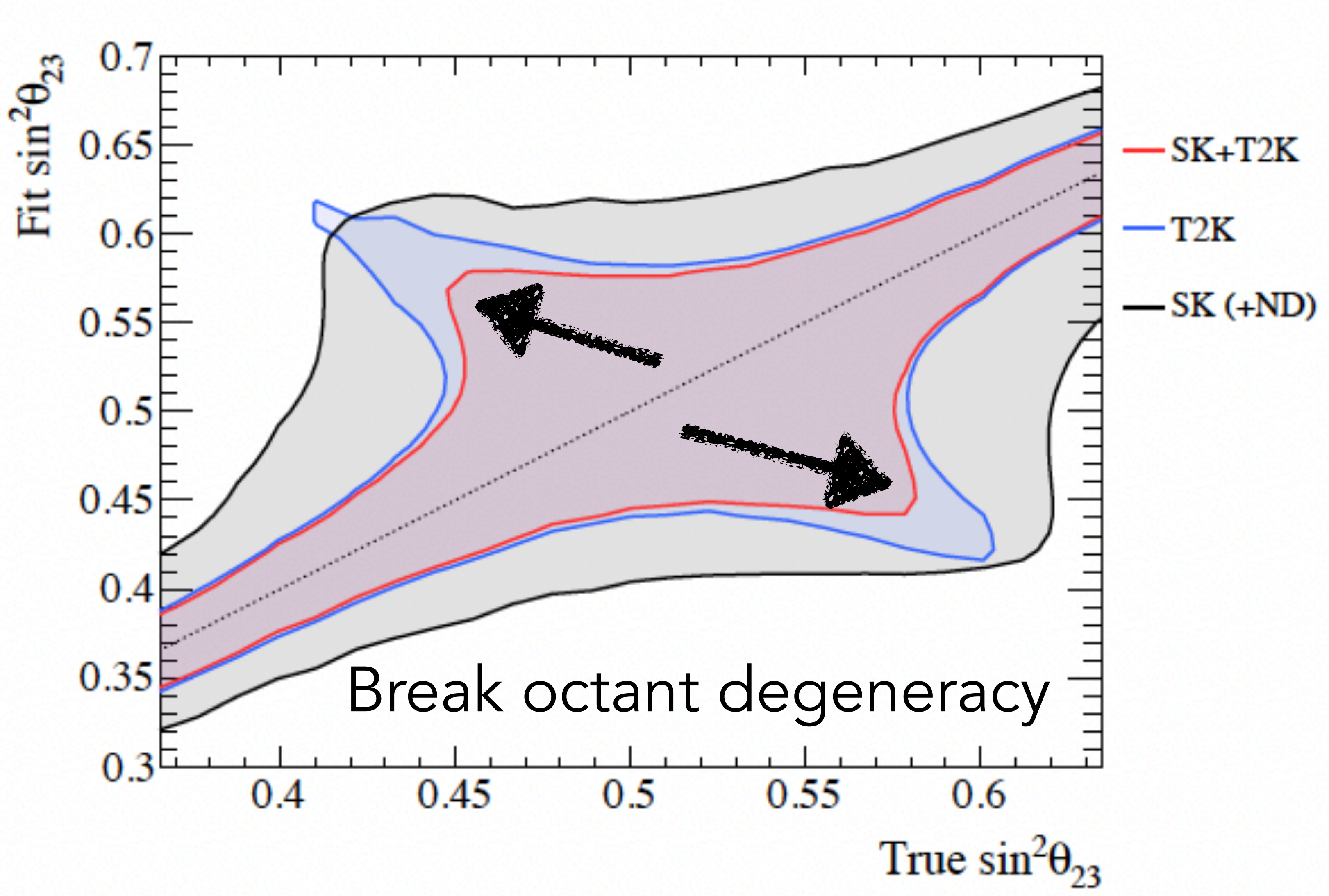
δ_{CP} conservation



Mass ordering



θ_{23} octant preference



Run1-10 POT assumed (ν mode: 1.9664×10^{21} POT $\bar{\nu}$ mode: 1.6346×10^{21})

True values assumed in fits: $\sin^2\theta_{23} = 0.528$, $\Delta m^2_{32} = 2.509 \times 10^{-3} \mathrm{eV}^2/\mathrm{c}^4$, $\sin^2\theta_{13} = 0.0218$, NO

- δ_{CP} conservation

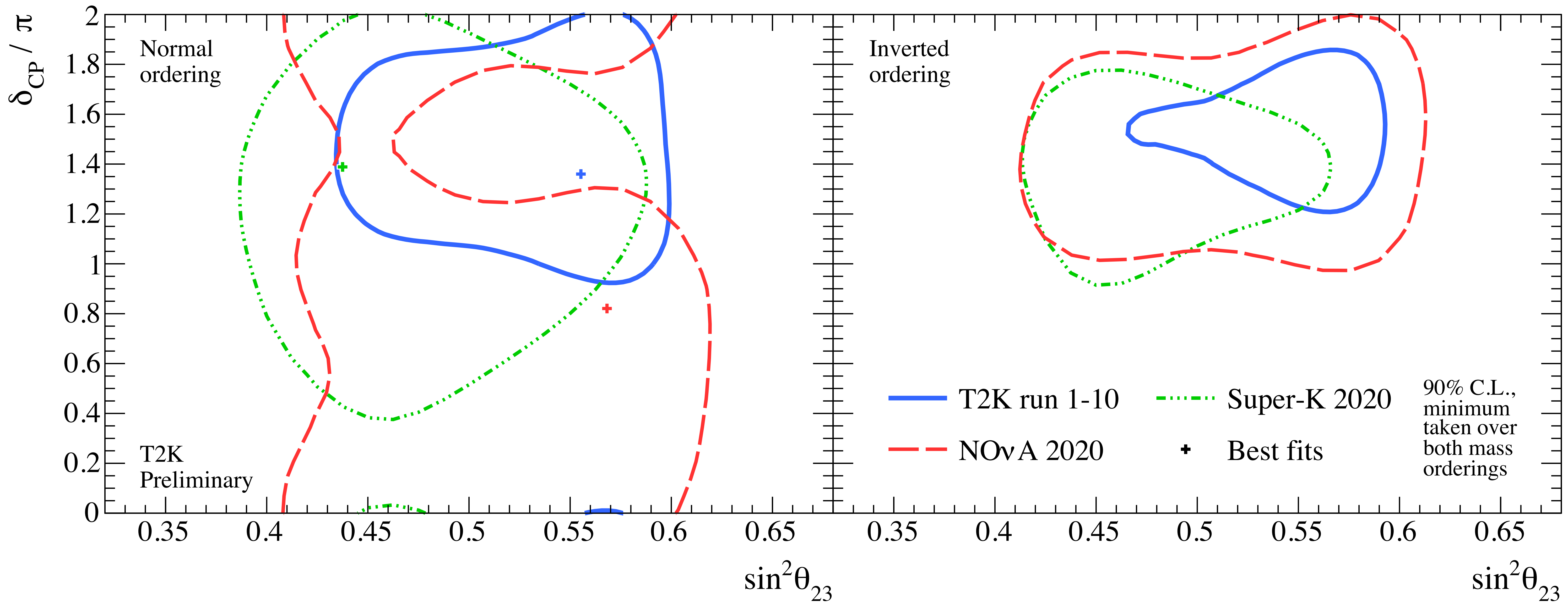
  δ_{CP}-independent MO sensitivity from atmospheric samples breaks δ_{CP}-MO degeneracy.
  Increase δ_{CP} sensitivity in the case $\delta_{CP} < 0$ in NO.

- MO & octant preference

  Atmospheric samples being sensible to MO via mantle/core resonance significantly increase the power to reject wrong MO and to break the θ_{23} octant degeneracy.

Joint fit analysis of T2K and NOvA experiments

Comparison with other experiments (90% CL)



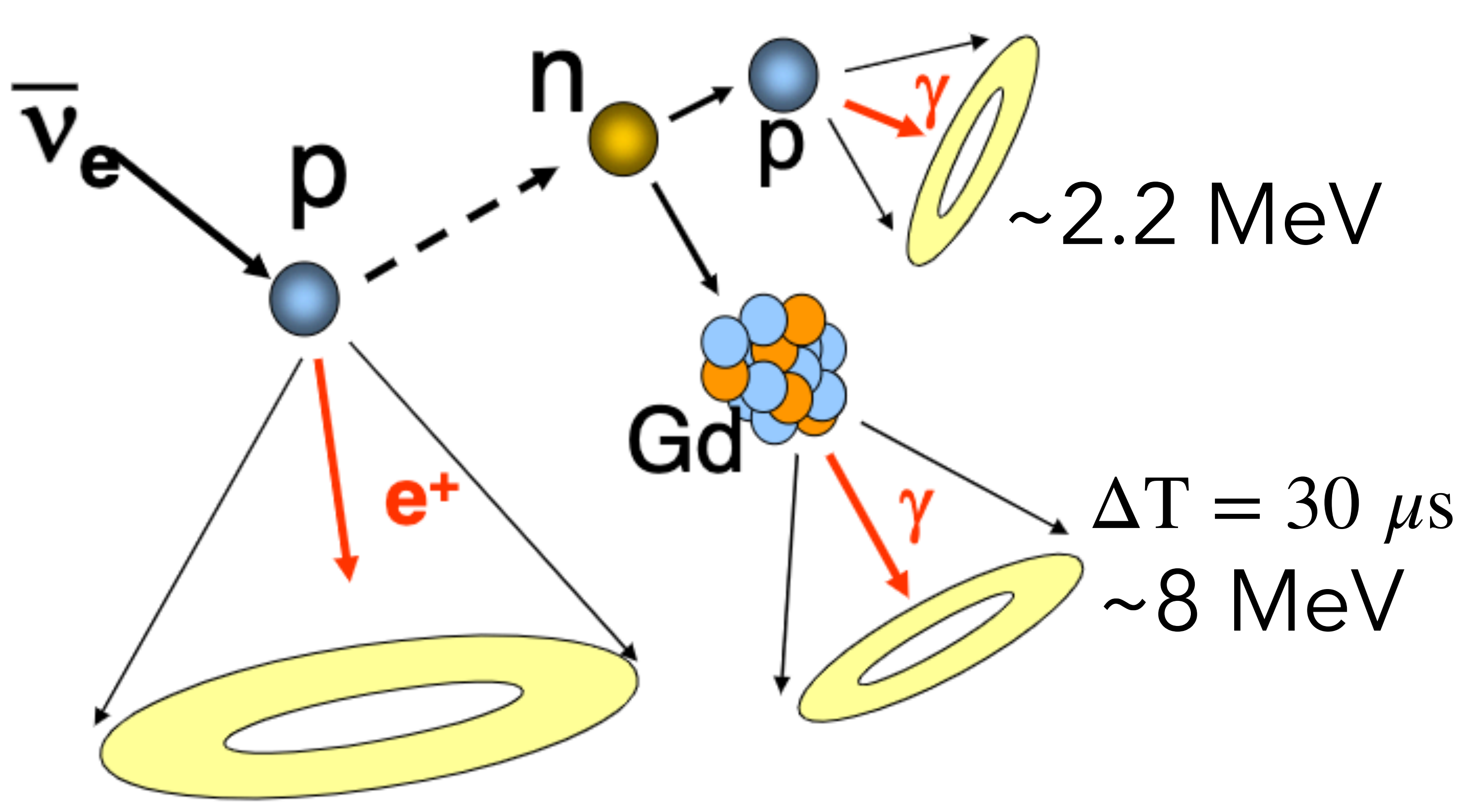
Comparison between T2K and NOvA

Experimental property	T2K	NOvA
Proton Beam Energy	30 GeV	120 GeV
Baseline	295 km	810 km
Peak neutrino energy	0.6 GeV	2 GeV
Detection technology	Water Cherenkov	Segmented liquid Scintillator bars
CP Effect	32%	22%
Matter Effect	9%	29%

- A unified statistical treatment for combined regions.
  → Increase sensitivity
- A notable synergy to break the degeneracy between MO and δ_{CP}.
- Work in progress and we're well on our way to having a combined analysis. Stay tuned!

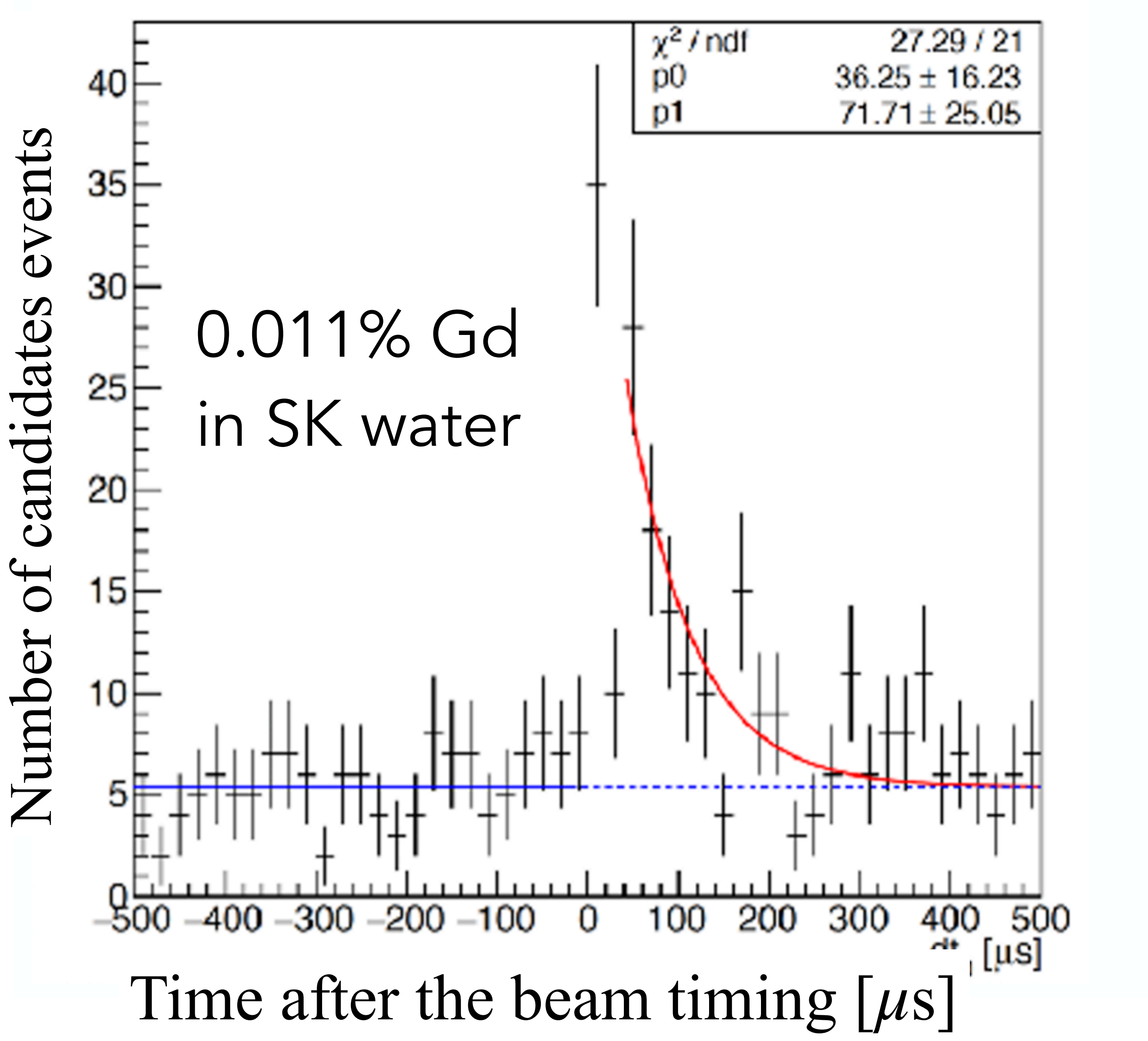
Prospects with SK+Gd analysis

Neutron tagging by Gd



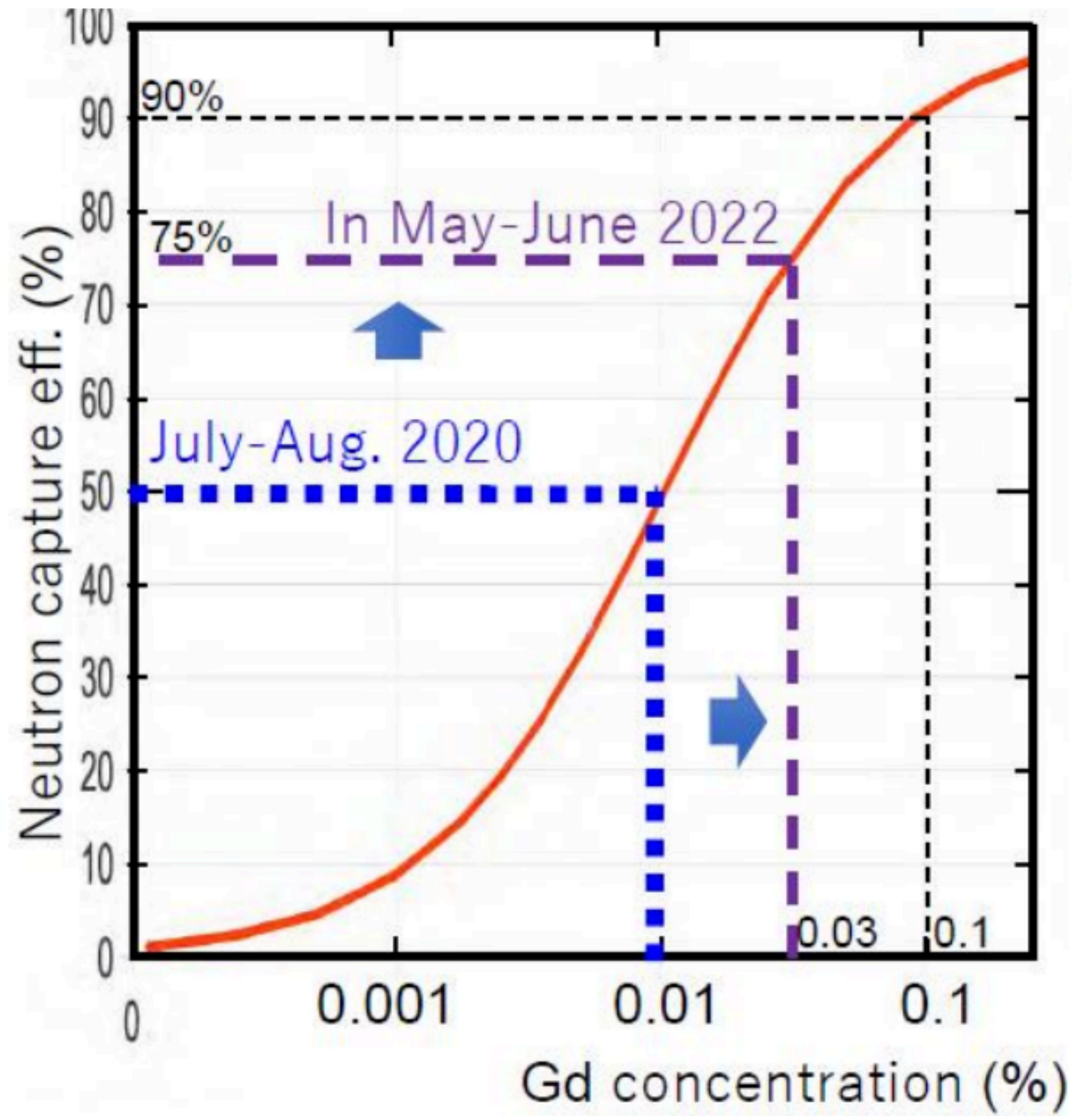
$\bar{\nu}_e$ can be identified by delayed coincidence

Presence of neutrons in T2K data



Exponential curve indicates presense of neutrons

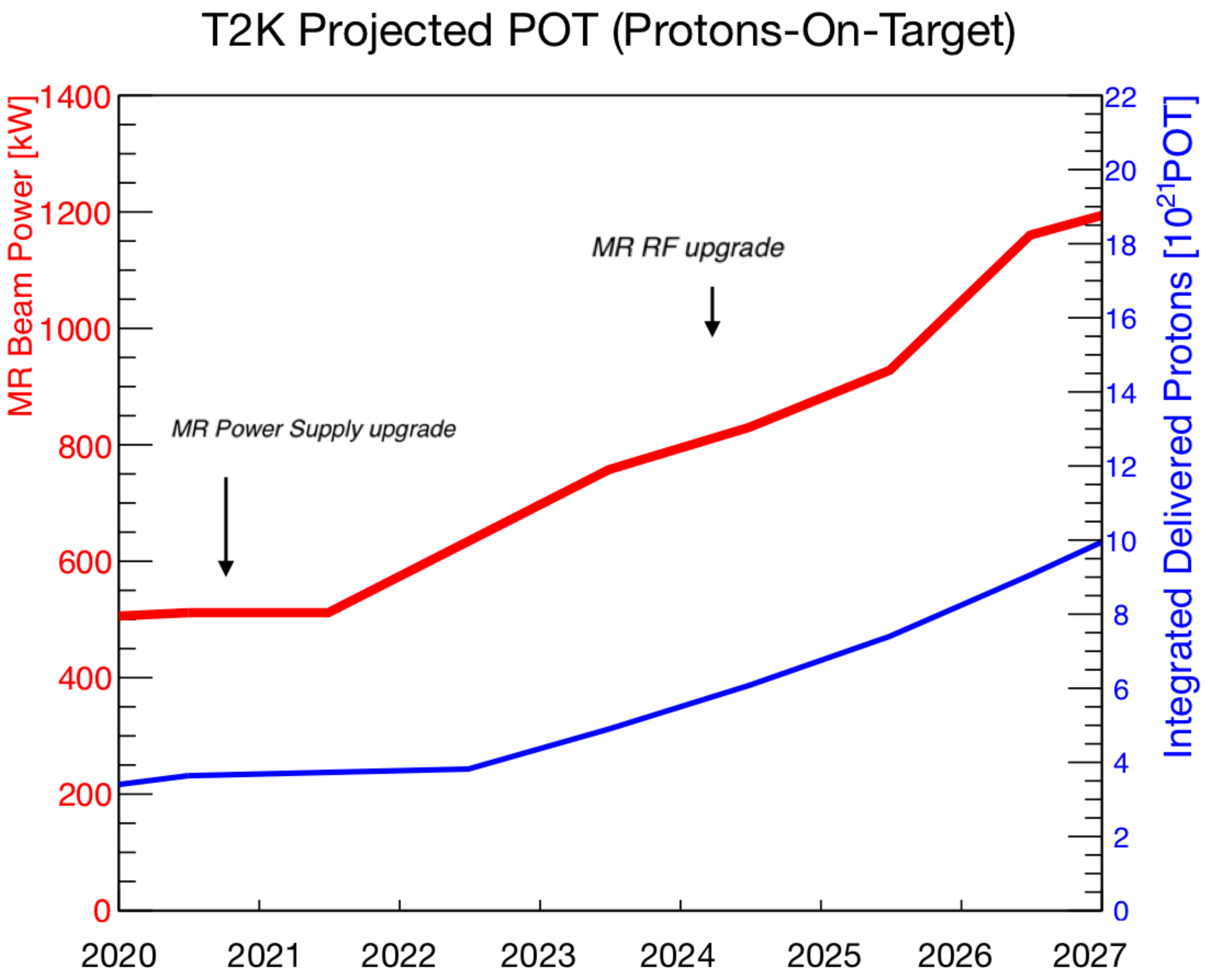
Plan of Gd loading



0.03% Gd concentration in this July (Fraction of n-capture: 50%→75%)

- Neutron tagging with Gd is expected to reduce background to Diffuse Supernova Neutrino Background (DSNB) search and proton decay.
- Also, it will open a road for $\nu/\bar{\nu}$ separation for T2K beam.

Prospects of neutrino beam upgrade



- Current status
  - 511 kW stable operation with 250 kA horns
- Aim for higher intensity
  - Reduced repetition cycle (2.48 sec → 1.3 sec → 1.16 sec)
  - Increase the number of protons per spill ($2.6 \times 10^{14} \rightarrow 3.2 \times 10^{14}$)
  - Higher horn current (250 kA → 320 kA)

$\sim$10% gain in ν flux @SK

Details in M.Friend + T. Nakadaira talk

Summary

- The latest results from T2K oscillation analysis have a variety of improvements this year. Adding a ν_μCC1π^+ far detector sample is a major analysis update.
  - This new sample has sensitivity to parameters, $\sin^2\theta_{23}, \Delta m^2_{32}$. The effect on oscillation contours is visible.
- T2K joint fit program of atmospheric neutrino and beam neutrino is underway.
  - Sensitivity plots clearly show it will have a significant impact on breaking the δ_{CP}-MO degeneracy, rejecting a wrong MO and breaking the θ_{23} octant degeneracy.
- T2K-NOvA joint fit analysis is also underway.
  - It will have the power to break the degeneracy between δ_{CP} and MO.
- SK-Gd analyses are ongoing.
  - Neutron tagging with Gd will pave the way to reducing the backgrounds to DSNB search and proton decay.
- T2K beam upgrade
  - Many upgrades to the J-PARC neutrino extraction beamline are underway to aim for higher intensity.

Backup

- Abstract
- Leading parameters
- T2K neutrino flux
- The other method for reconstructed energy of ν_μCC1π^+ sample
- Systematic uncertainties for SK detector
- Systematic uncertainties for all
- Data distribution for far detector samples
- Data distributions for ν_μCC1π^++1Rμ combined samples
- Other plots for joint fit analysis
- Jarlskog invariant
- Event selections (details)

Abstract

T2K is a long baseline neutrino experiment which exploits a neutrino and antineutrino beam produced at the Japan Particle Accelerator Research Centre (JPARC) to provide world-leading measurements of the parameters governing neutrino oscillation. Neutrino oscillations are measured by tuning the neutrino rates and spectra at a near detector complex, located at JPARC, and extrapolate them to the water-Cherenkov far detector, Super-Kamiokande, located 295 Km away, where oscillations are observed as modifications of such rates and spectra.

The latest T2K results include multiple analysis improvements, in particular a new sample is added at the far detector, requiring the presence of a pion in muon-neutrino interactions. It is the first time that a pion sample is included in the study of neutrino disappearance at T2K and, for the first time, a sample with more than one Cherenkov ring is exploited in the T2K oscillation analysis, opening the road for further samples with charged- and neutral-pion tagging. The inclusion of such sample enables proper control of the oscillated spectrum on a larger neutrino-energy range and on subleading neutrino-interaction processes. Finally, T2K is engaged with the Super-Kamiokande collaboration to combine T2K neutrino beam data and Super-Kamiokande atmospheric data to perform a joint fit to the oscillation parameters. Such combination allows the degeneracies between the measurement of the CP-violating phase δCP and the measurement of the ordering of the neutrino mass eigenstates to be lifted. Precise evaluation of the enhanced sensitivity of this joint fit will be presented.

Leading parameters

- $\nu_\mu \to \nu_e$ appearance

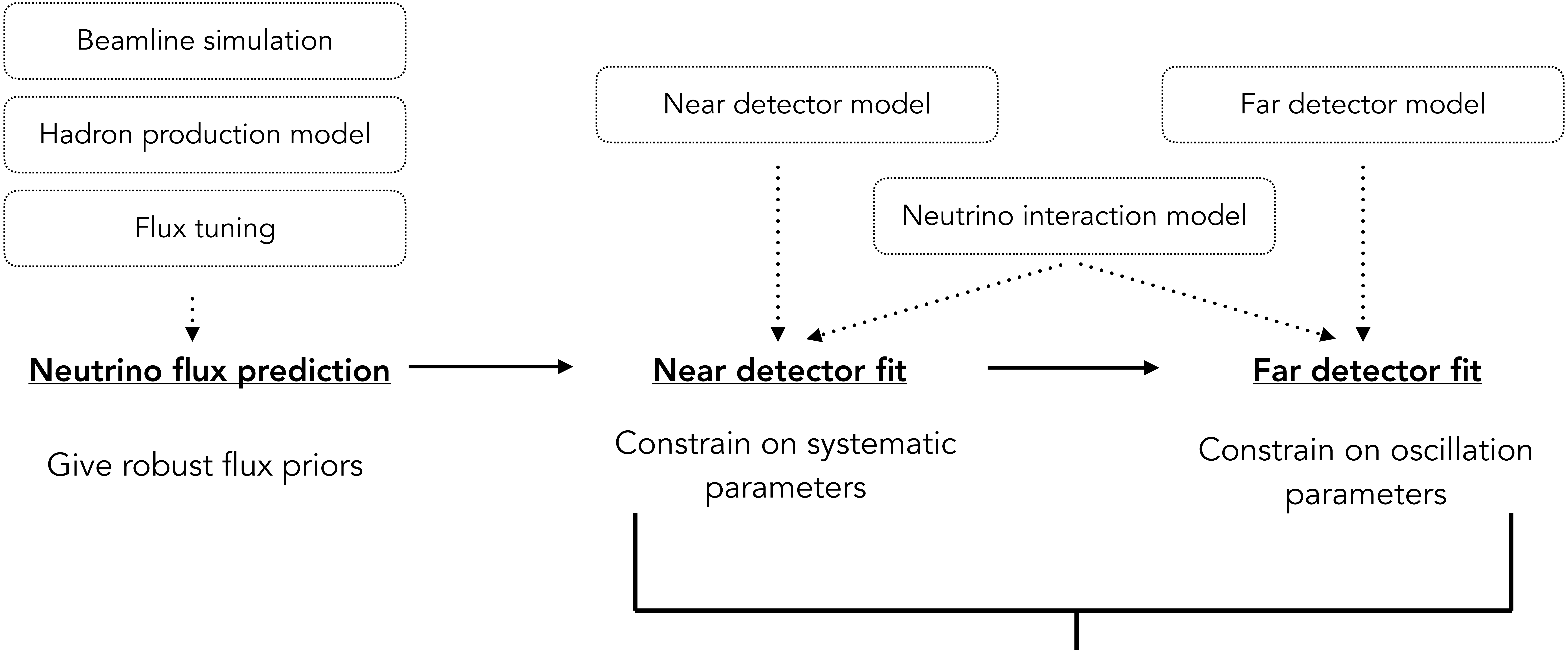
$$P(\nu_\mu \to \nu_e) \sim \sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \propto \sin\delta_{CP}$$

- $\nu_\mu \to \nu_\mu$ disappearance

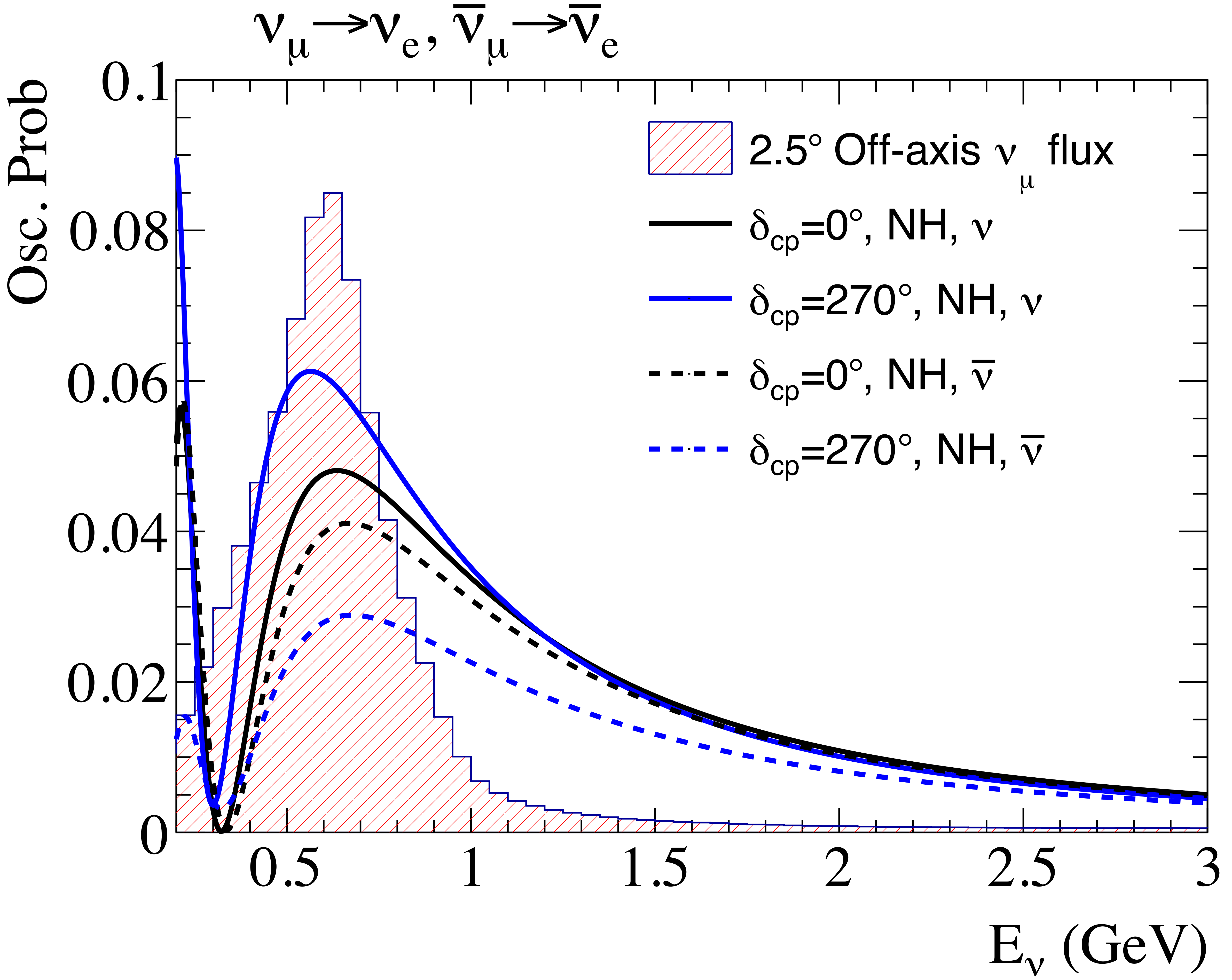
$$P(\nu_\mu \to \nu_\mu) \sim 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

Analysis strategy



- Bayesian approach: Spontaneous fits of near and far detector fit with MCMC
- Frequentist approach: Sequential fits of near and far detector fit with Minuit minimiser

T2K neutrino flux



- The off-axis angle has been tuned so that oscillation probability comes to be maximum under this condition.

Formulae for reconstructed energy of ν_μCC1π^+ sample

Modified form of the one in p12

1232 MeV

$$E_{\text{rec}}^{\nu_\mu \text{CC}\Delta^{++}} = \frac{2M_p\sqrt{|p_\mu^{\pi^+\text{hypothesis}}|^2 + M_{\pi^+}^2} + M_{\Delta^{++}}^2 - M_p^2 - M_\pi^2}{2\left(M_p - \sqrt{|p_\mu^{\pi^+\text{hypothesis}}|^2 + M_{\pi^+}^2} + |p_\mu^{\pi^+\text{hypothesis}}|\cos\theta_\mu^{\pi^+\text{hypothesis}}\right)}$$

Reconstructed momentum and direction of the ring with larger energy loss by 2-ring $\pi^\pm\pi^\pm$ hypothesis

$$E_{rec}^{\nu\text{CCQE-like}} = \frac{2E_l(M_n - E_b) - M_l^2 + 2M_nE_b - E_b^2 + M_p^2 - M_n^2}{2(M_n - E_b - E_l + P_l\cos\theta_l)}$$

Reconstructed neutrino energy for CCQE-like interactions

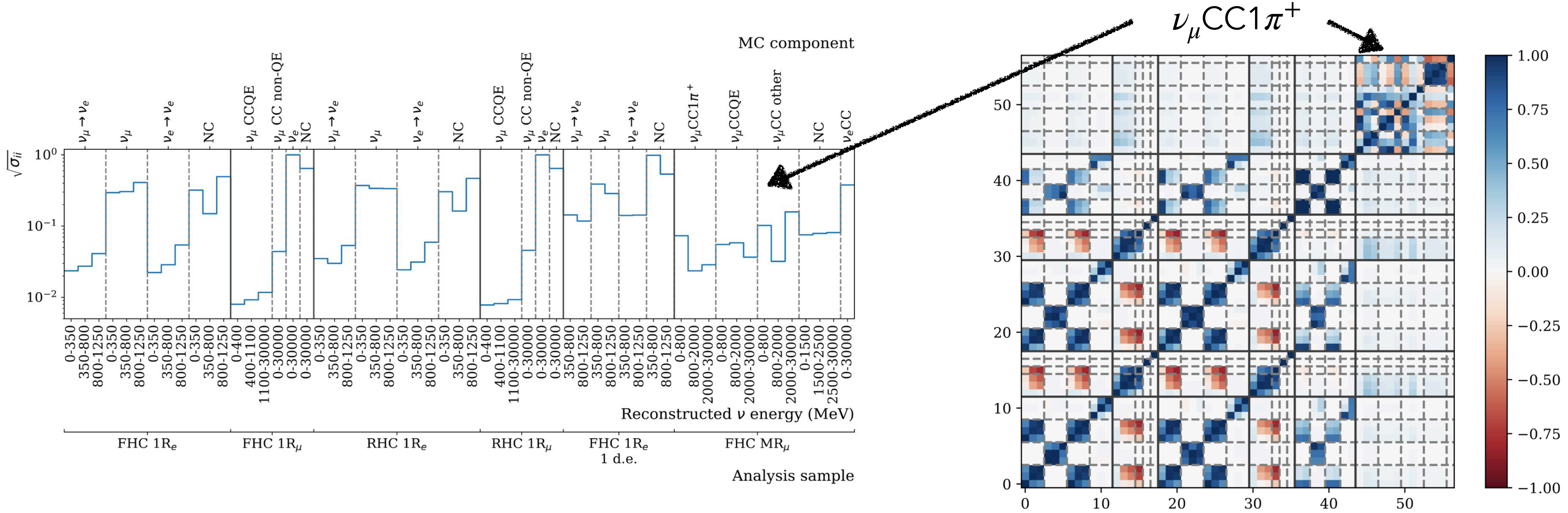
E_b: Binding energy (27 MeV)

The other method

$$E_{\text{rec}}^{\nu_\mu \text{CC}\Delta^{++}} = \frac{2M_p(E_\mu + E_{\pi^+}) - 2p_\mu \cdot p_{\pi^+} - M_{\pi^+}^2 - M_\mu^2}{2\left(M_p - E_\mu - E_{\pi^+} + |p_\mu|\cos\theta_\mu + |p_{\pi^+}|\cos\theta_{\pi^+}\right)}$$

This formula is subject to relatively large pion FSI + SI uncertainties.

SK detector systematic uncertainties



- Almost no correlation between conventional samples and ν_μCC1π sample. Small correlation arises from fiducial volume and decay electron tagging.
- Fully correlated uncertainty will be produced for the next iteration of oscillation analysis.

Systematic uncertainties for all

2020

Error source (units: %)	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
Xsec (ND unconstrained)	0.6	2.5	3.0	3.6	2.8	3.8
SK+SI+PN	2.1	1.9	3.1	3.9	13.4	1.2
Total	3.0	4.0	4.7	5.9	14.3	4.3

2022

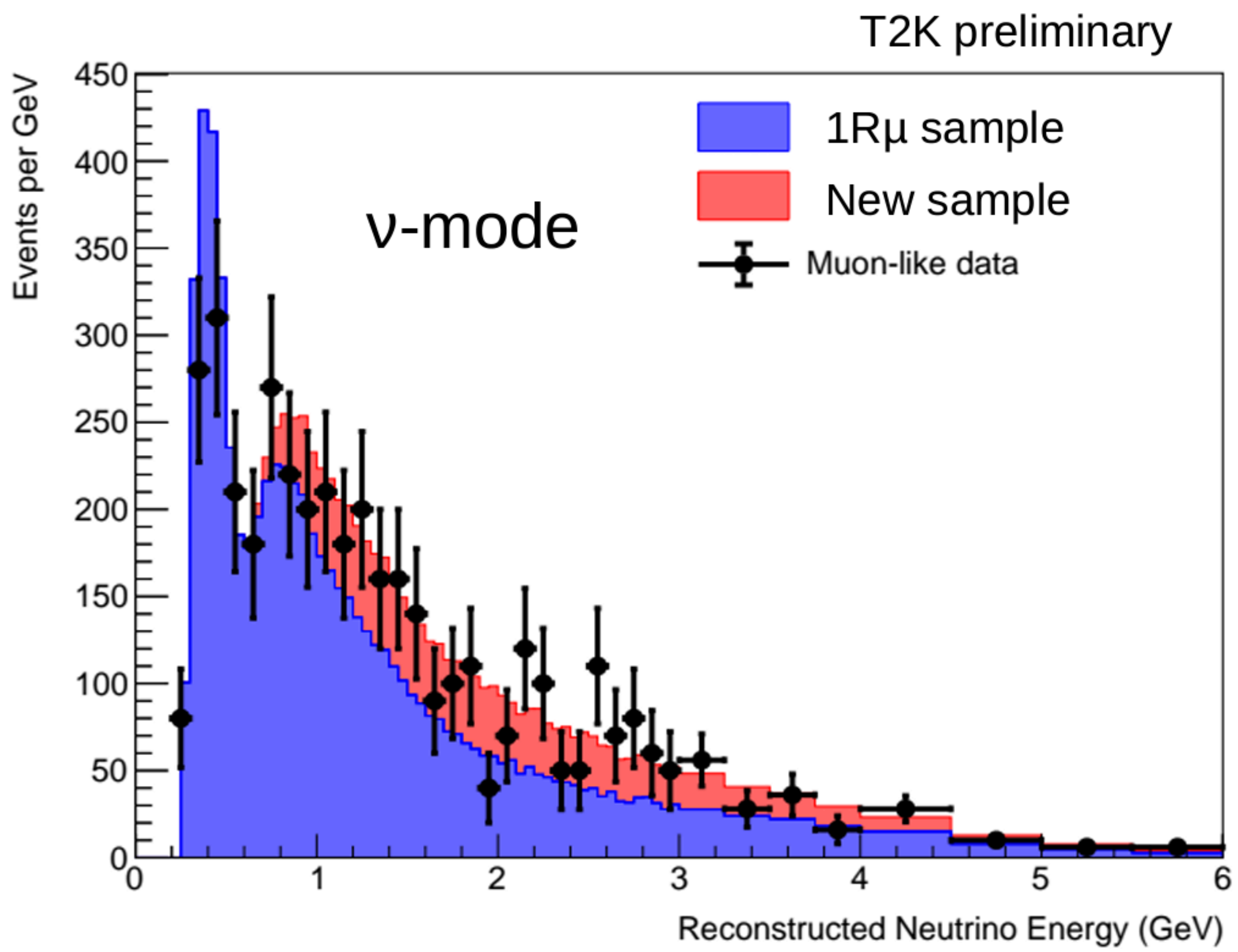
Error source (units: %)	1R FHC	1R RHC	MR FHC CC1π^+	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	2.8	2.9	2.8	2.8	3.0	2.8	2.2
Xsec (ND constr)	3.7	3.5	3.0	3.8	3.5	4.1	2.4
Flux+Xsec (ND constr)	2.7	2.6	2.2	2.8	2.7	3.4	2.3
Xsec (ND unconstr)	0.7	2.4	1.4	2.9	3.3	2.8	3.7
SK+SI+PN	2.0	1.7	4.1	3.1	3.8	13.6	1.2
Total All	3.4	3.9	4.9	5.2	5.8	14.3	4.5

T2K Run 1-10, preliminary

SI: Secondary Interaction, PN: Photonuclear effect

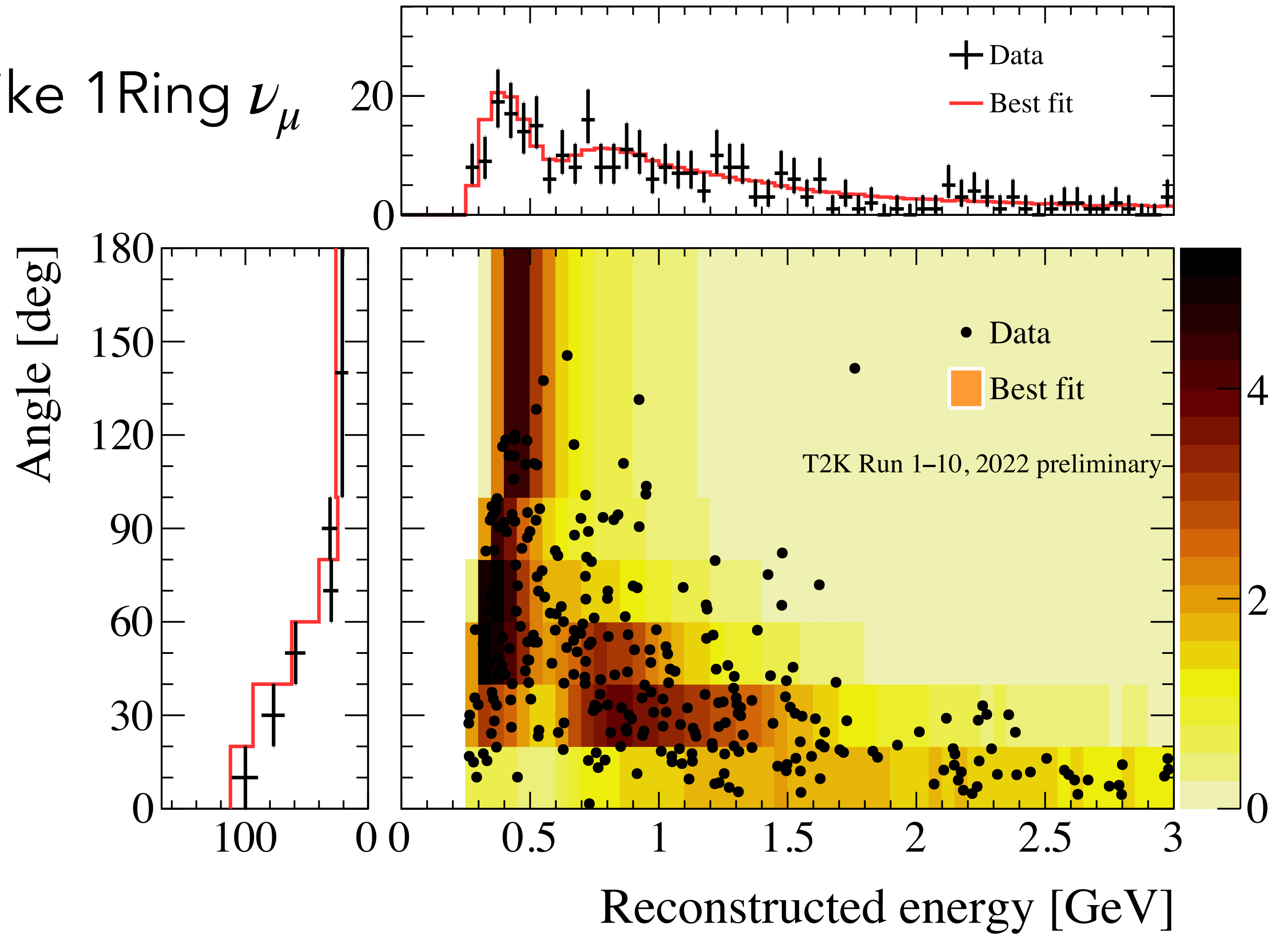
- For 1R μ-like samples, the errors are bit increased.
  - This is partly because we used more xsec parameters which have more conservative priors.

Data distributions for $\nu_\mu CC1\pi^+$+1R combined samples

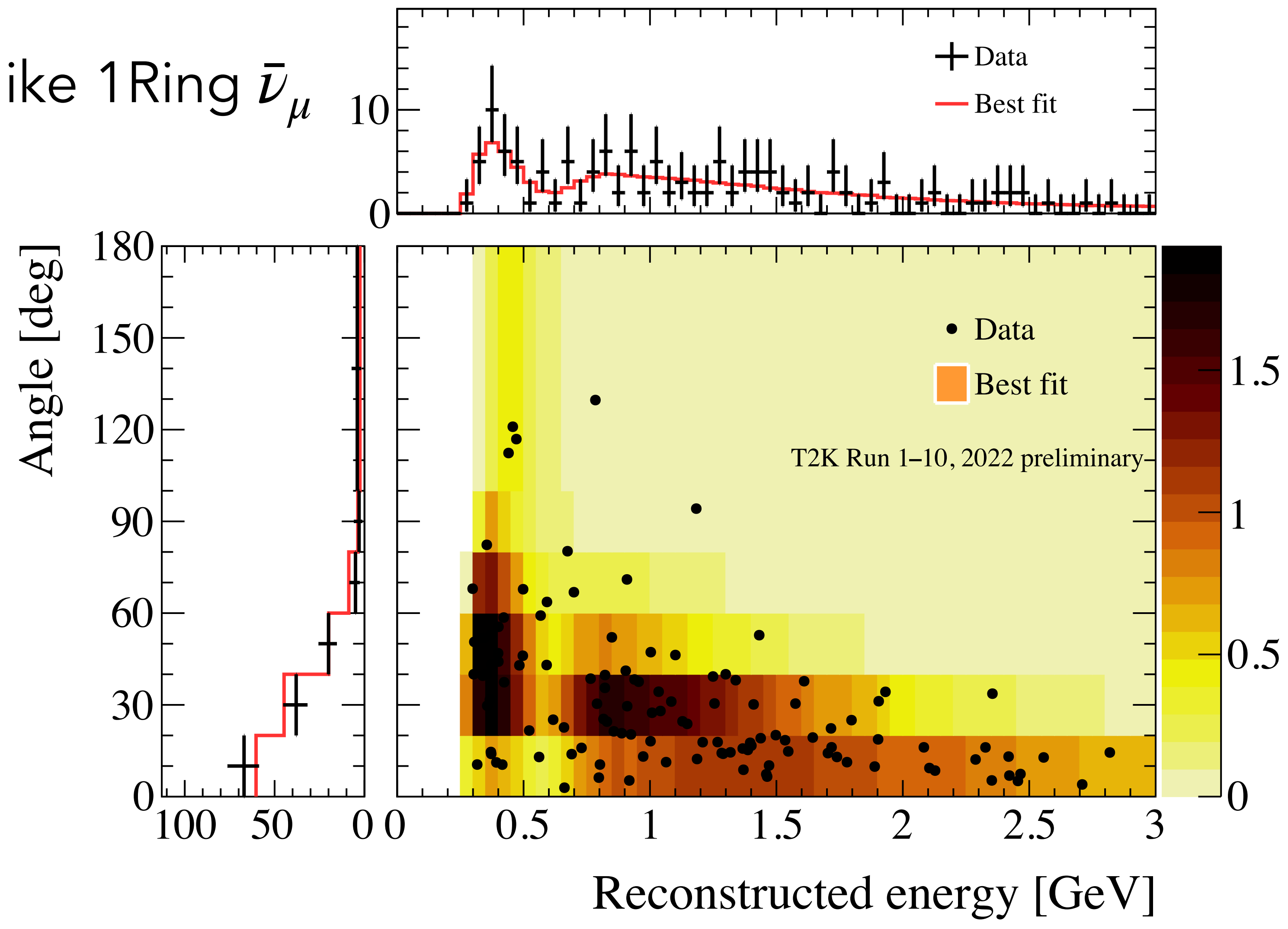


Data distributions for far detector samples

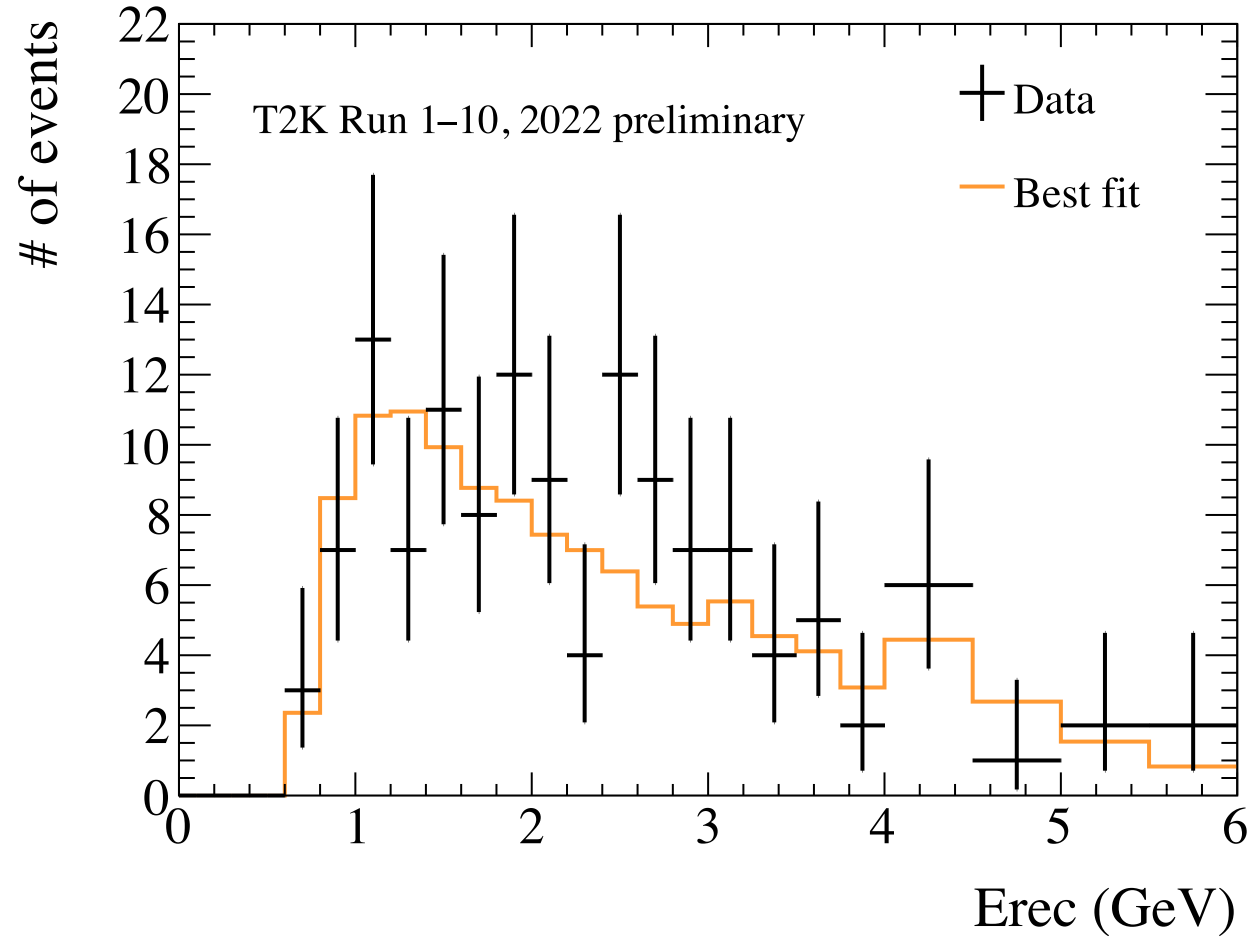
μ-like 1Ring ν_μ



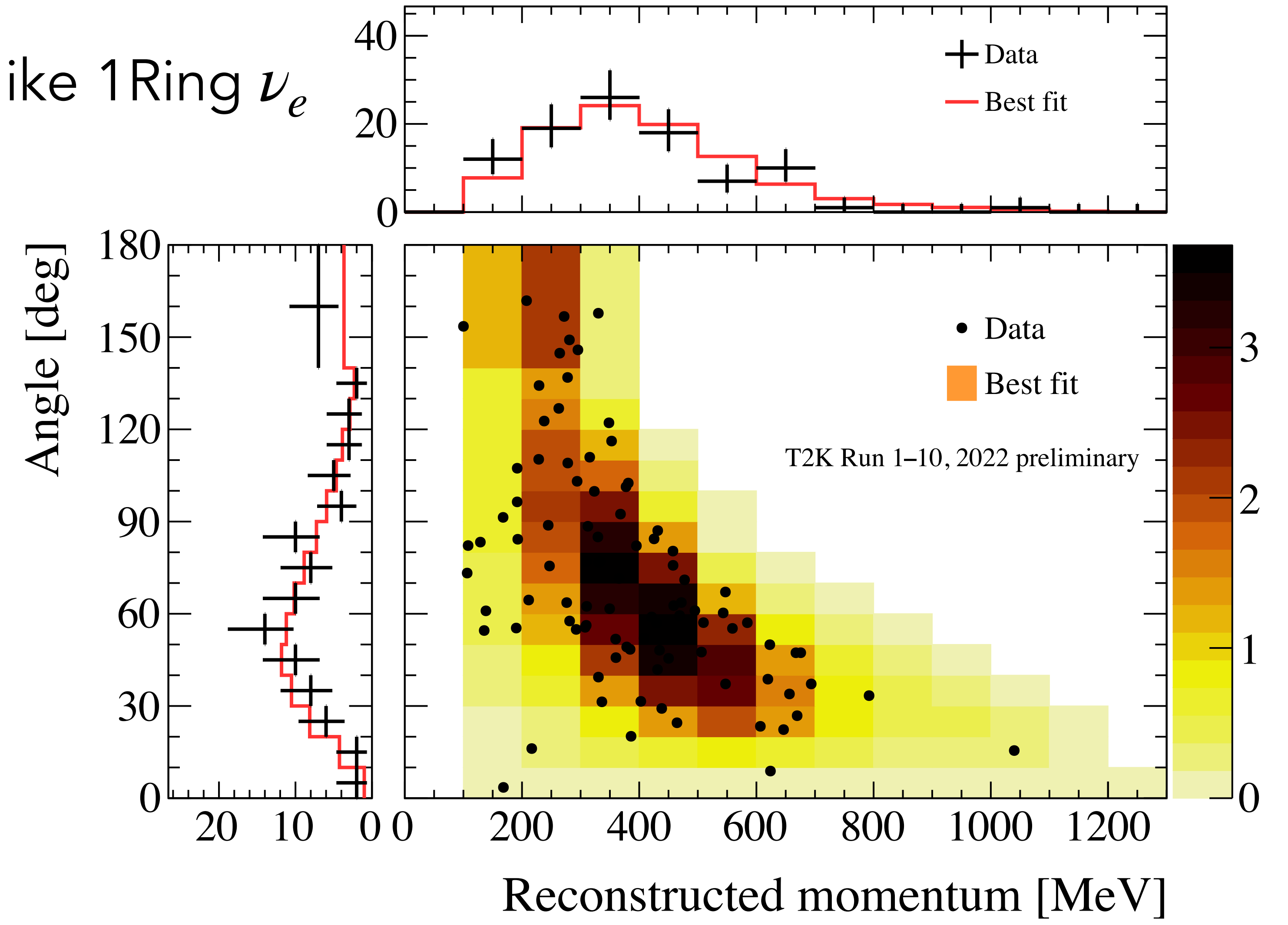
μ-like 1Ring $\bar{\nu}_\mu$



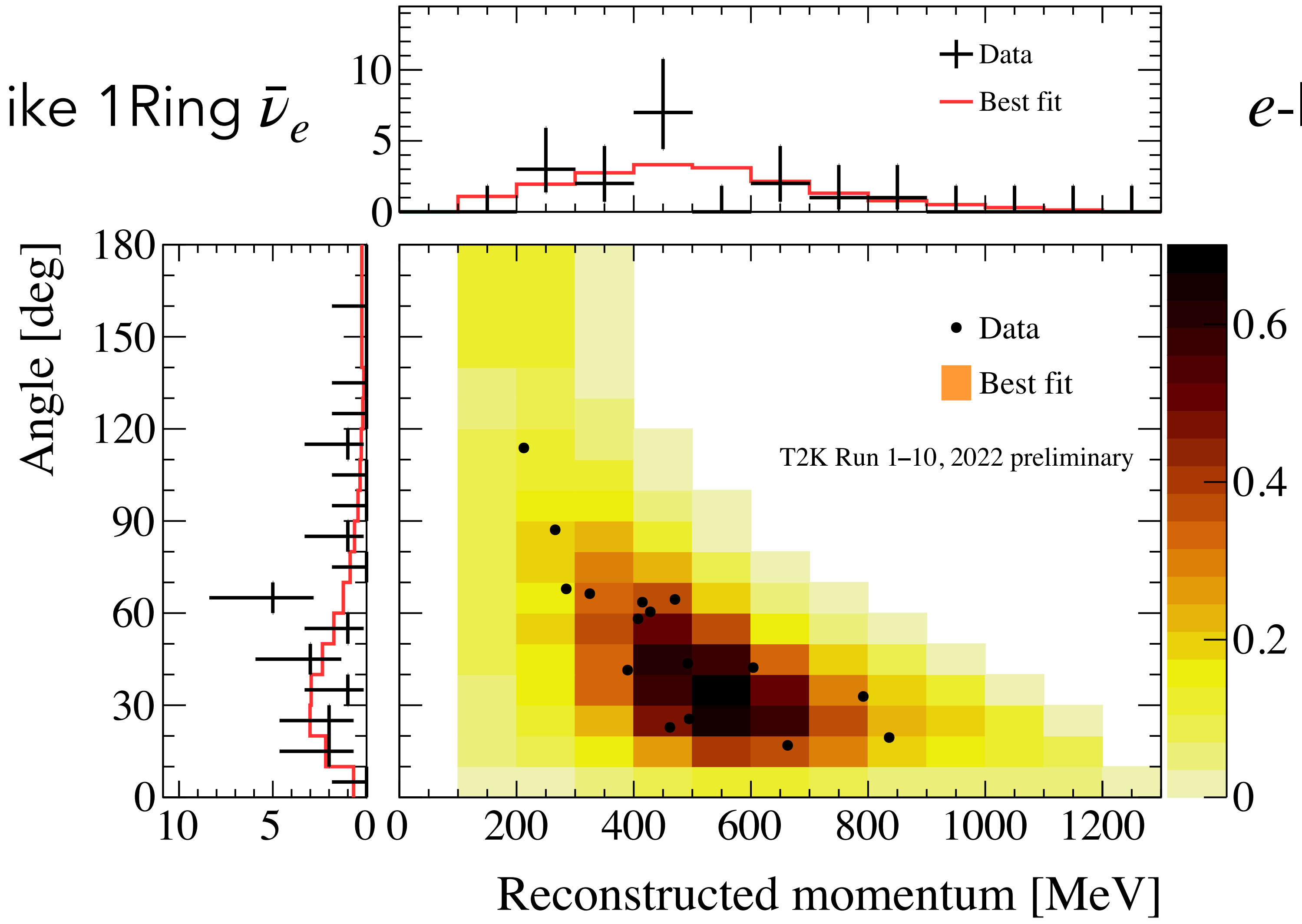
μ-like MR



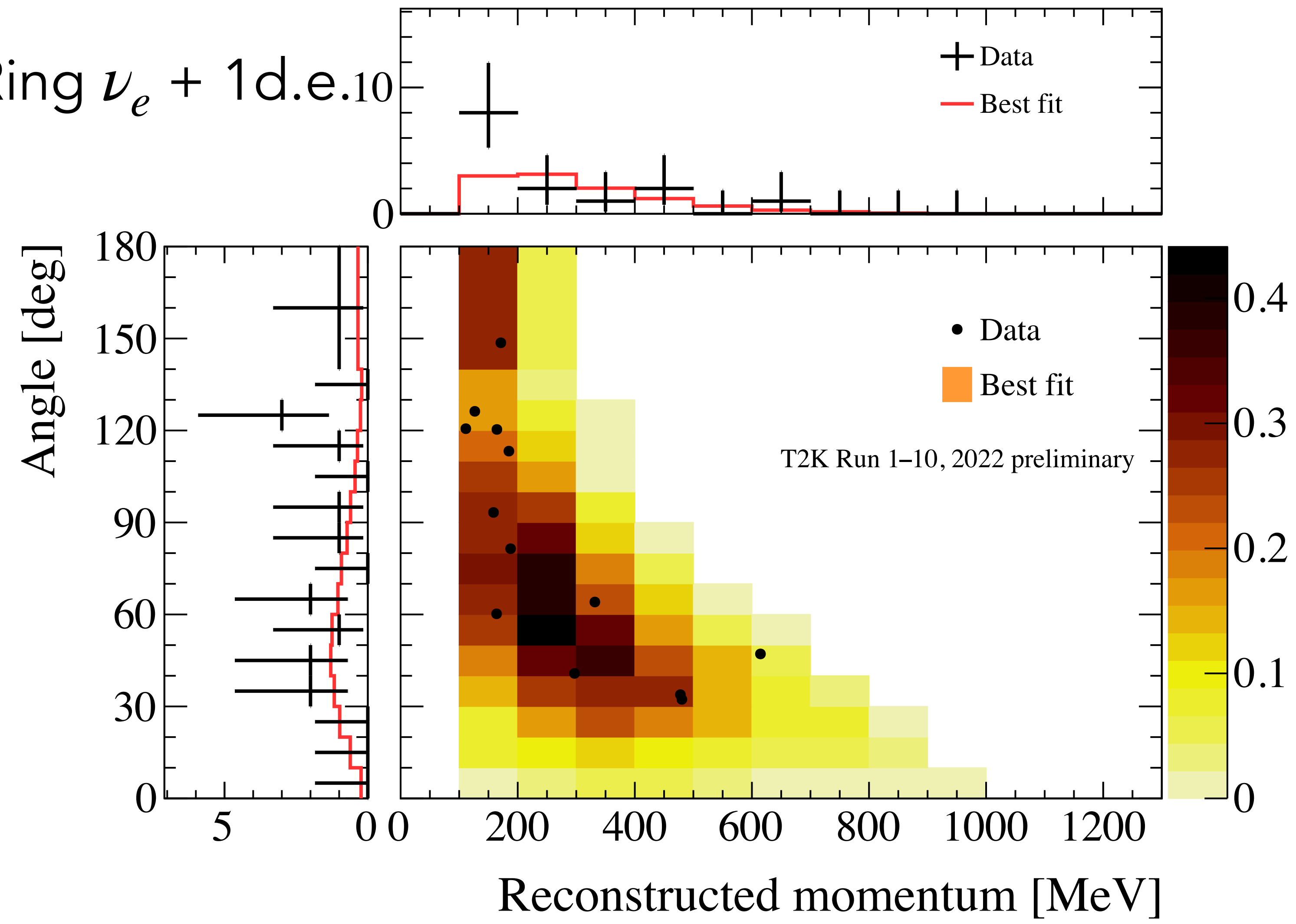
e-like 1Ring ν_e



e-like 1Ring $\bar{\nu}_e$



e-like 1Ring ν_e + 1d.e.



Far detector fit

Overview

Define samples and binnings

μ-like 1R samples (2 samples)	e-like 1R samples (3 samples)	μ-like MR sample (1 sample)
Binning: $E_{\mathrm{rec}}^{\mathrm{lepton}}$-$\theta_{\mathrm{wrt}\ \nu}^{\mathrm{lepton}}$	Binning: P^{lepton}-$\theta_{\mathrm{wrt}\ \nu}^{\mathrm{lepton}}$	Binning: $E_{\mathrm{rec}}^{\mathrm{lepton}}$

↓

Calculate maximum likelihood

$$L(N^{\mathrm{obs}}, \mathbf{x}^{\mathrm{obs}}, \mathbf{o}, \mathbf{f}) = \prod_{s \in \mathrm{samples}} \left[L_s(N_s^{\mathrm{obs}}, \mathbf{x}_s^{\mathrm{obs}}, \mathbf{o}, \mathbf{f}) \right] \times L_{\mathrm{syst}}(\mathbf{f})$$

↓

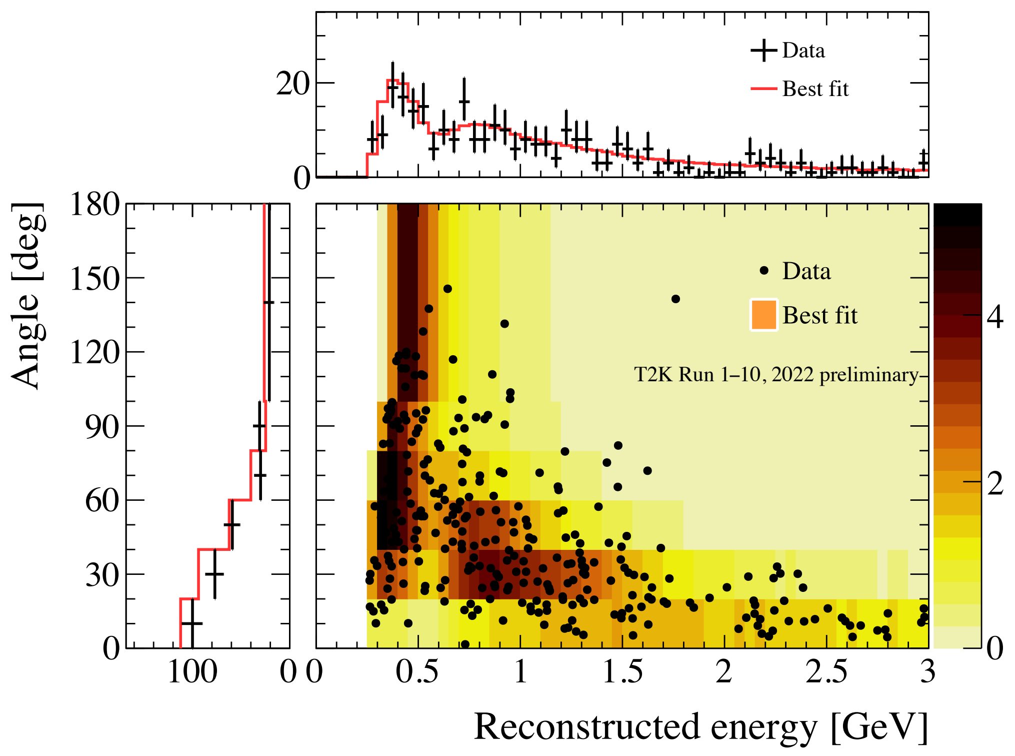
Marginalization of likelihood over systematic parameters

$$L_{\mathrm{marg}}(N^{\mathrm{obs}}, \mathbf{x}^{\mathrm{obs}}, \mathbf{o}) = \frac{1}{N} \sum_{i=1}^{N} \left[\prod_{s \in \mathrm{samples}} L_s(N_s^{\mathrm{obs}}, \mathbf{x}^{\mathrm{obs}}, \mathbf{o}, \mathbf{f}_i) \right], \left(\int d\mathbf{f} L_{\mathrm{syst}}(\mathbf{f}) \rightarrow \frac{1}{N} \sum_{i=1}^{N} \right)$$

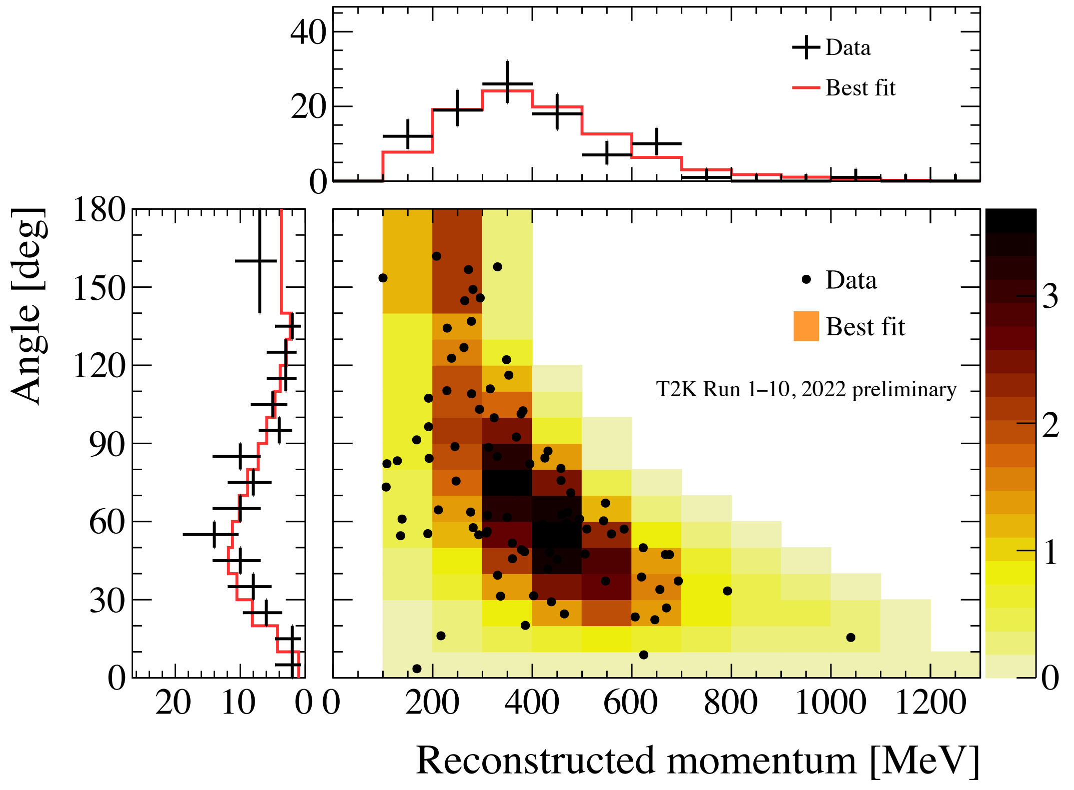
Typically N=100k

Fixed χ^2 | Feldman-Cousins χ^2

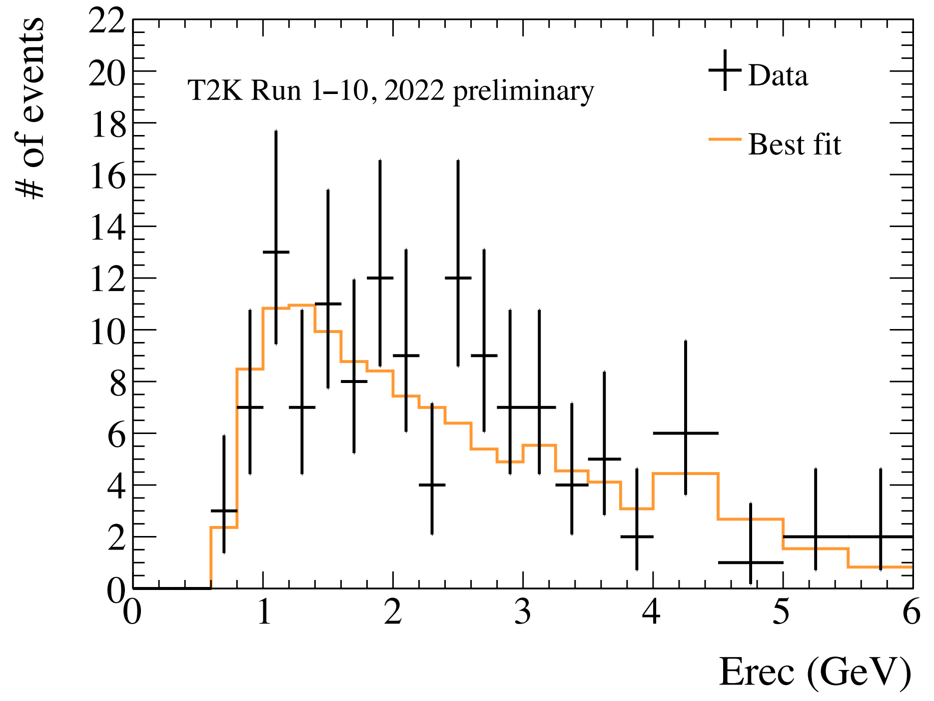
μ-like 1Ring ν_μ



e-like 1Ring ν_e



μ-like MR



6 samples are used in this fit.

other three samples: μ-like 1Ring $\bar{\nu}_\mu$, e-like 1Ring $\bar{\nu}_e$, e-like 1Ring $\bar{\nu}_e$+1 decay electron

Likelihood function

N^{obs}: the number of candidate events

$\mathbf{x}^{\mathrm{obs}}$: measurement variables (1D or 2D vector)

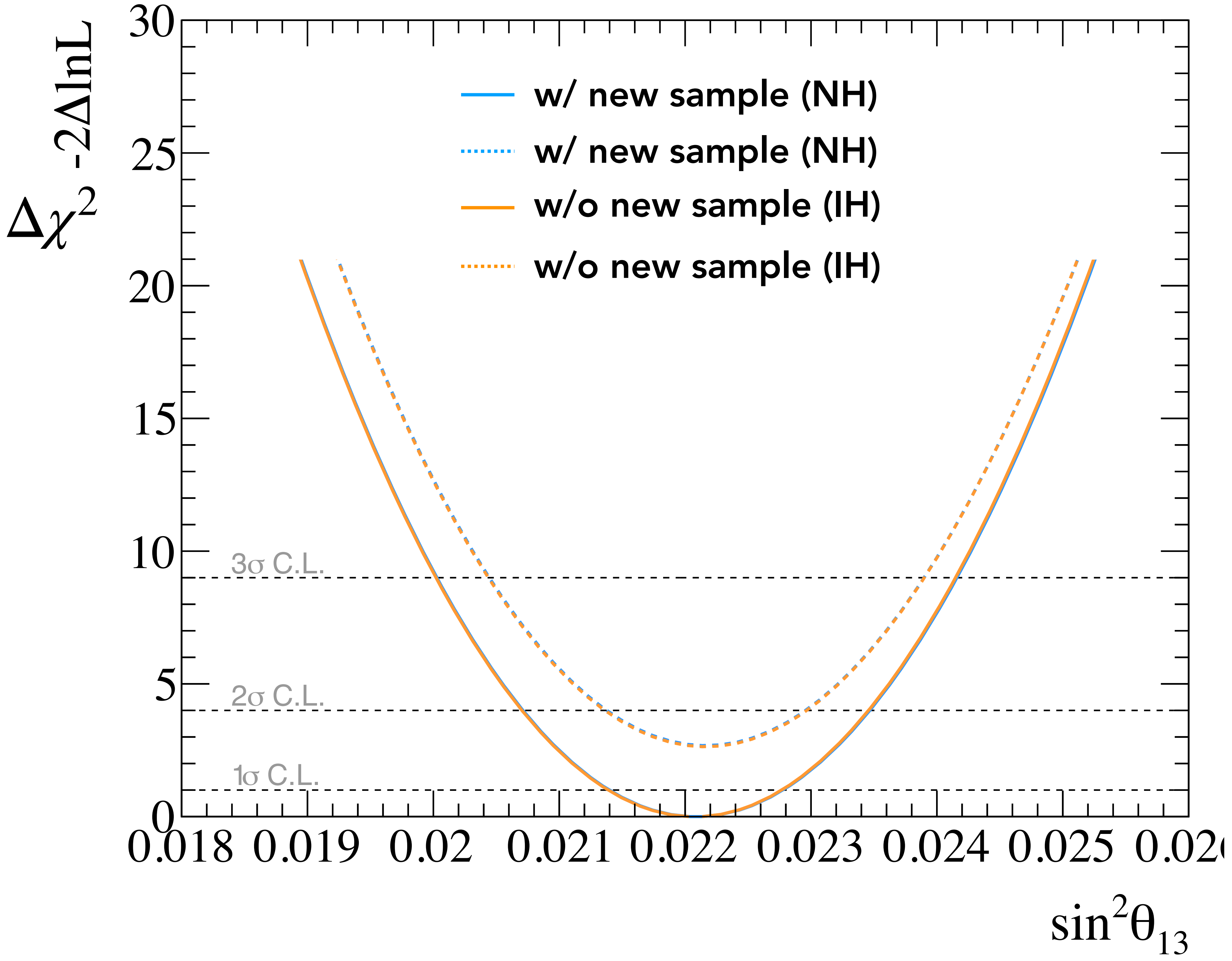
$\mathbf{o}$: oscillation parameters (flat priors except for $\sin^2\theta_{12}, \sin^2\theta_{13}$)

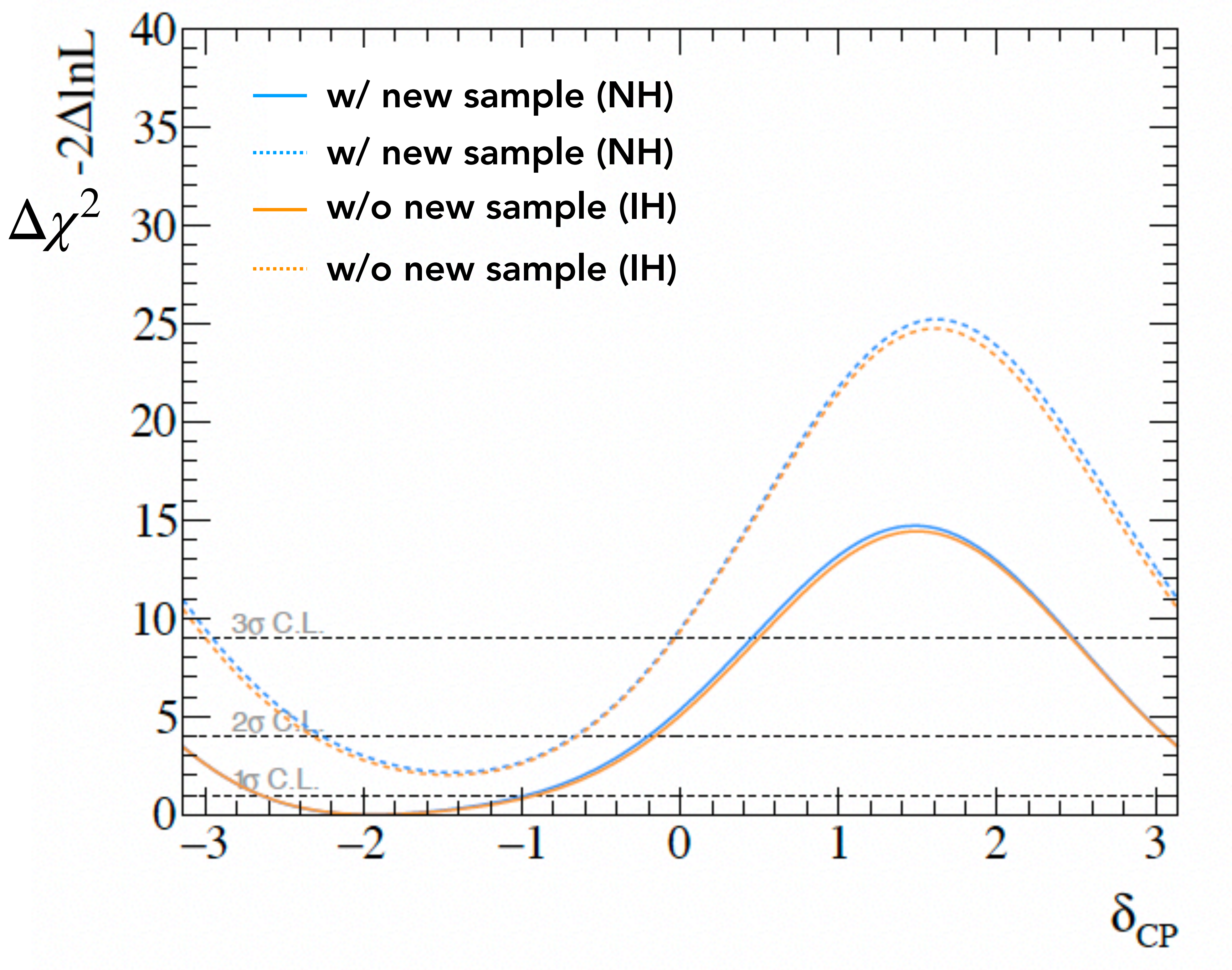
$\sin^2\theta_{12}$: fixed to 0.307, $\sin^2\theta_{13} = 0.0220 \pm 0.0007$ (gaussian)

$\mathbf{f}$: systematic parameters (from near detector fit)

$$\text{Fixed } \chi^2 = -2 \times \ln \left(\frac{L_{\mathrm{marg}}(\mathbf{o})}{L_{\mathrm{marg}}^{\mathrm{max}}} \right)$$

Impact of $\nu_\mu CC1\pi^+$ on $\sin^2\theta_{13}, \delta_{CP}$



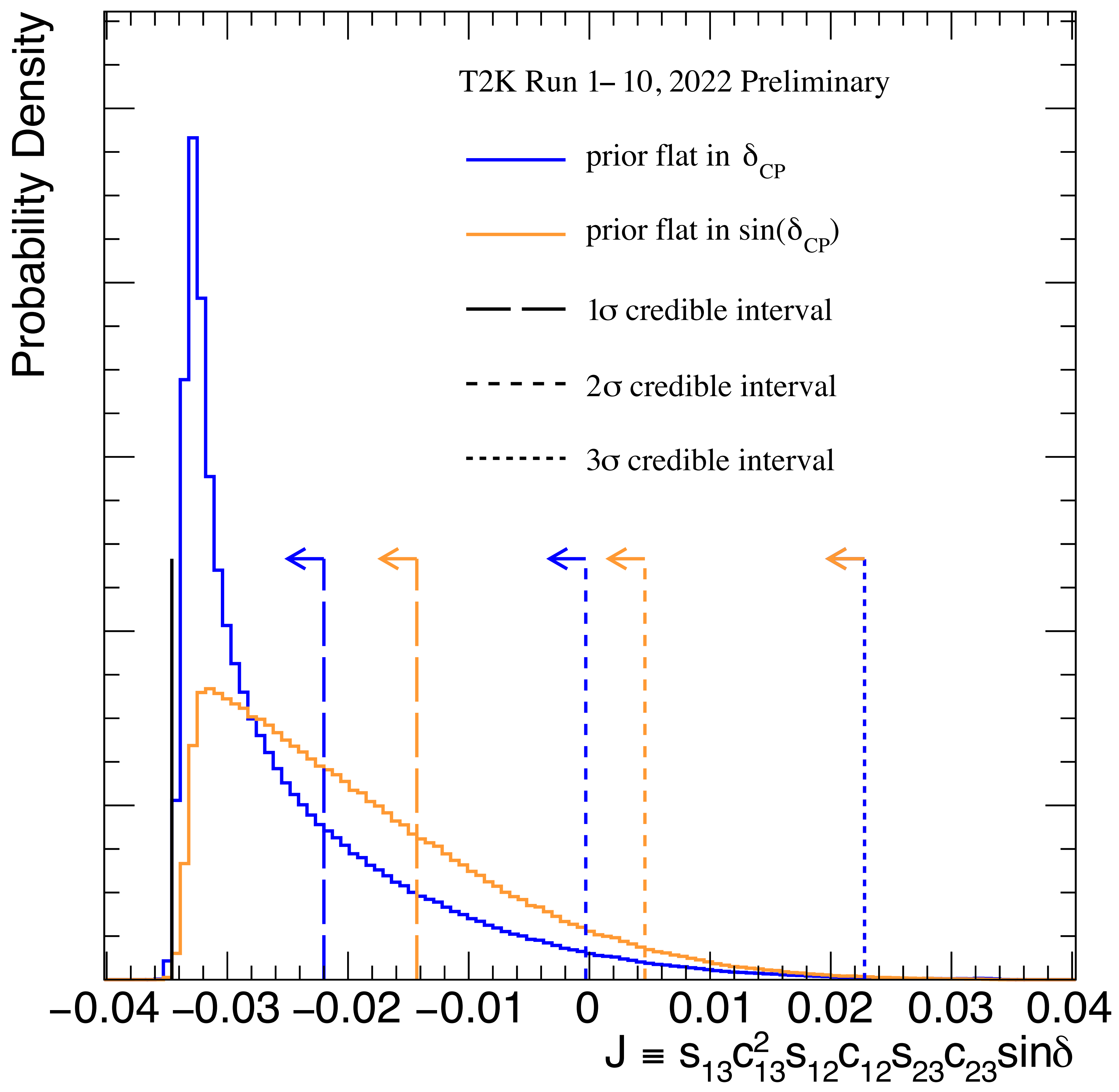


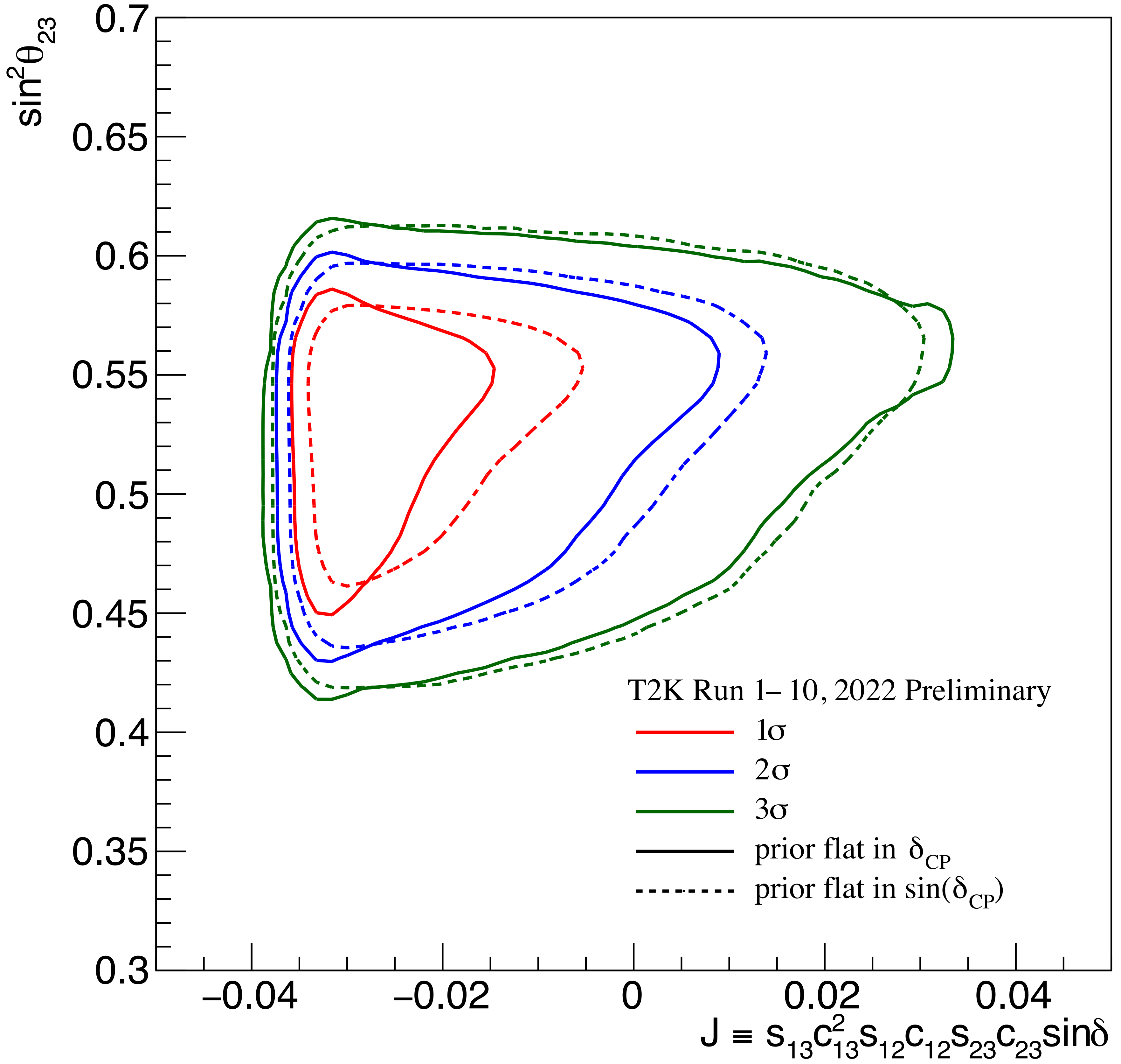
- This sample has little impact on these parameters which are driven by e-like samples.

All contours are produced with constraint on $\sin^2\theta_{13}$ by reactor experiments. $\sin^2\theta_{13} = 0.0220 \pm 0.0007$ from PDG2021

Jarlskov invariant (J_{CP})

J_{CP} **distributions marginalising over both MO (MCMC analysis)**





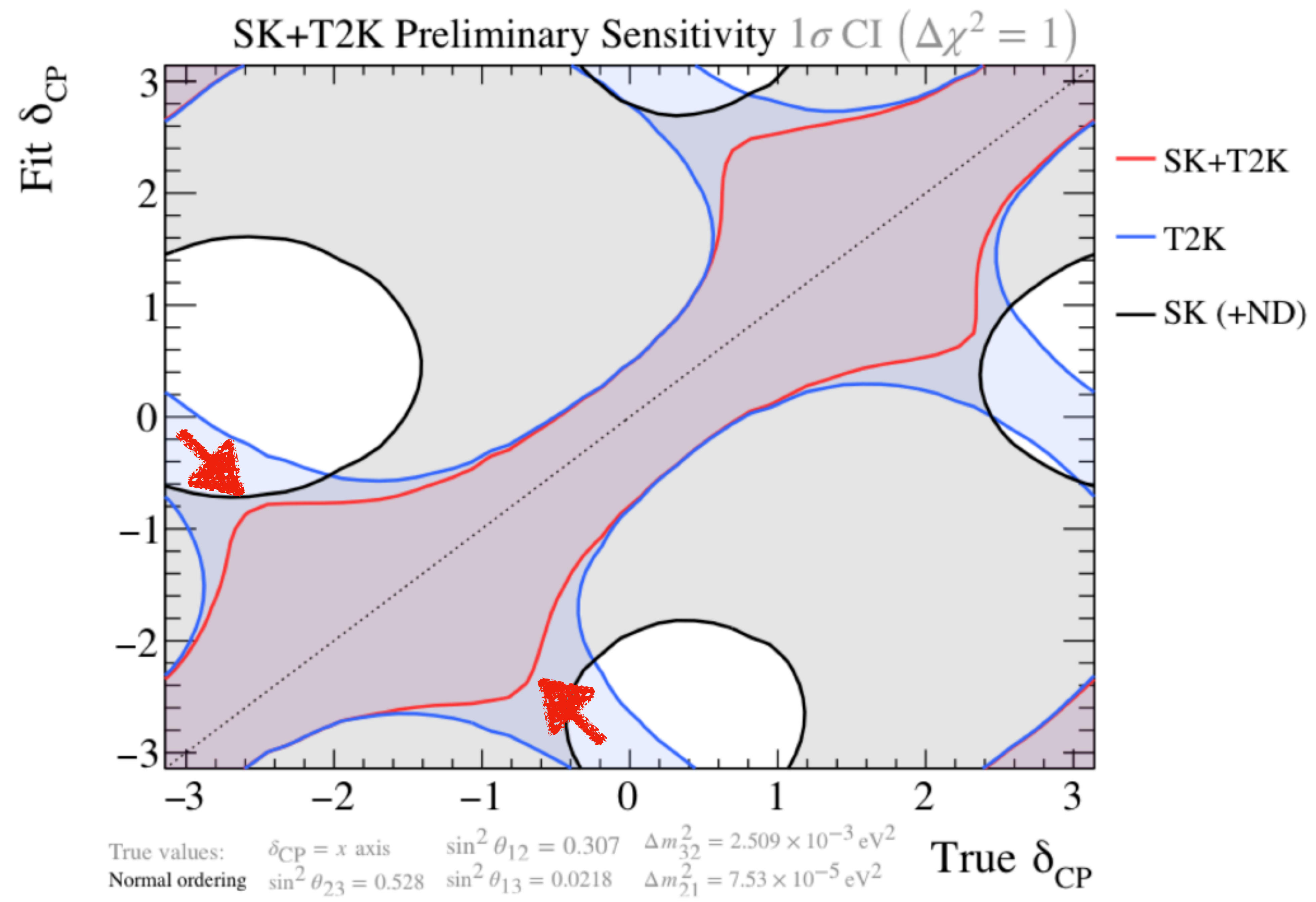
θ_{13} is constrained by reactor experiment
($\sin^2 2\theta_{13} = 0.0861 \pm 0.0027$)

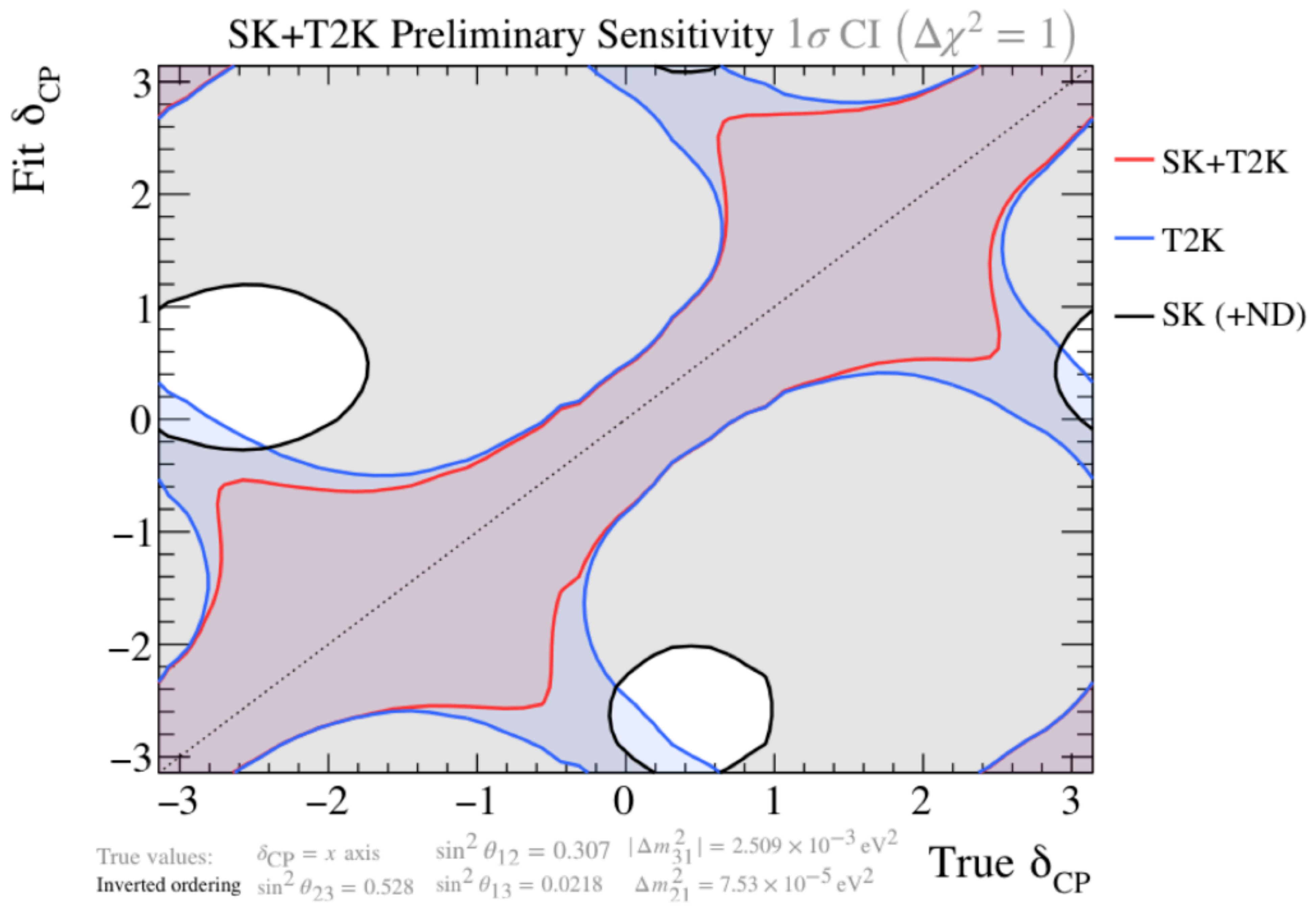
Different priors for δ are used (prior flat in δ_{CP} or $\sin(\delta_{CP})$)

- Can explore the potential CP violation in the lepton sector by looking at the posterior probability and credible intervals for J_{CP}

Other plots for joint fit analysis

1σ sensitivity to δ_{CP}





- T2K (sensitive to $\sin\delta_{CP}$) contours have $\cos\delta_{CP}$ degeneracy in particular around regions of (true $\delta = 0$, fitted $\delta = \pm\pi$) but SK measurements (sensitive to both $\sin\delta_{CP}$ and $\cos\delta_{CP}$) in combination with the T2K measurement seem to break this degeneracy.

Event selections (detail)

Selection summary

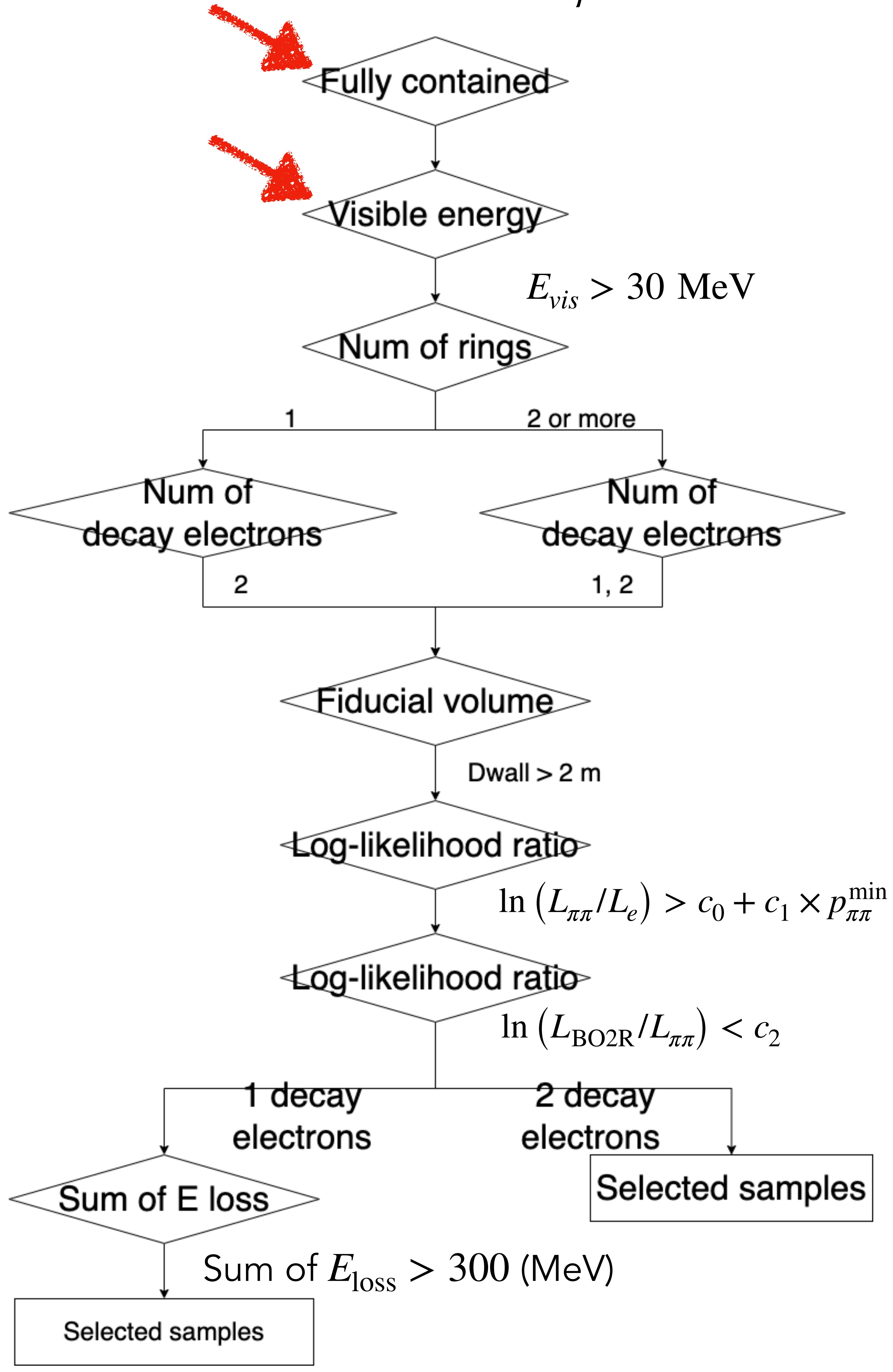
Interaction mode	1-decay electron	Selection Efficiency (%)	Purity (%)	2-decay electrons	Selection Efficiency (%)	Purity (%)
ν_μ CCQE	12.1	68.9	—	4.6	86.9	—
ν_μ CC1π^+	**15.8**	**56.1**	**32.3**	**35.6**	**89.1**	**55.9**
ν_μ CC1π^0	1.2	10.8	—	0.7	52.2	—
ν_μ CC multiπ	8.5	19.7	—	13.0	35.0	—
ν_μ CC DIS	5.1	7.0	—	6.1	11.0	—
$\bar{\nu}_\mu$ CC	3.6	36.2	—	1.1	38.8	—
$\nu_e + \bar{\nu}_e$ CC	0.1	0.7	—	0.0	0.4	—
NC all	2.5	6.1	—	2.0	16.1	—
Total MC	49.0	—	—	63.1	—	—
Data	62	—	—	73	—	—

**Selection efficiency = (number of selected events) / (events passing the cuts up to fiducial volume)*
**Purity = (number of selected signal events) / (number of total selected events)*
Assumed parameters: $\sin^2\theta_{12} = 0.307, \sin^2\theta_{13} = 0.022, \sin^2\theta_{23} = 0.561, \Delta m^2_{32} = 7.53\times10^{-5}\text{eV}^2, \Delta m^2_{21} = 2.49\times10^{-3}\text{eV}^2, \delta_{CP} = 1.601$

- Main interaction mode for both samples is ν_μCC1π^+.
- 2 decay electron sample is purer than 1 decay electron sample.

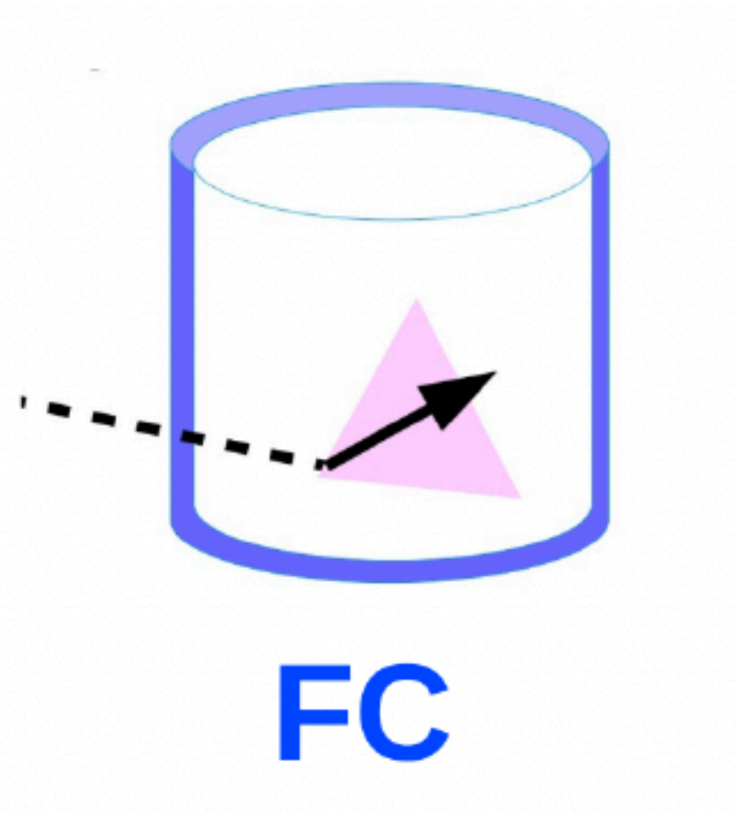
$\nu_\mu CC1\pi^+$ (Event selection)

Event selection of ν_μ CC1π^+



Fully contained

- The number of hits in the outer detector should be less than 16.
- Reduce backgrounds of charged particles entering SK water tank.

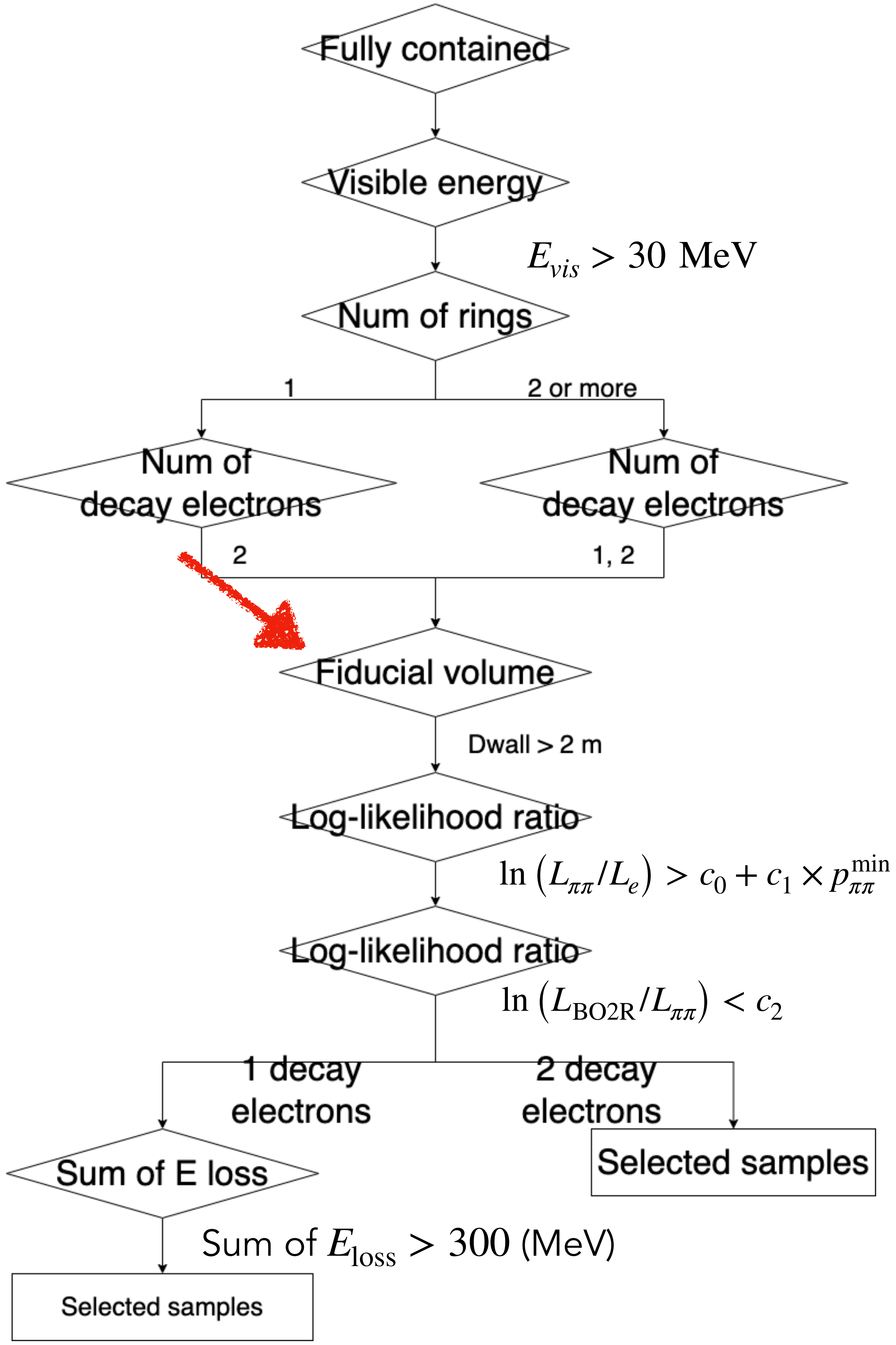


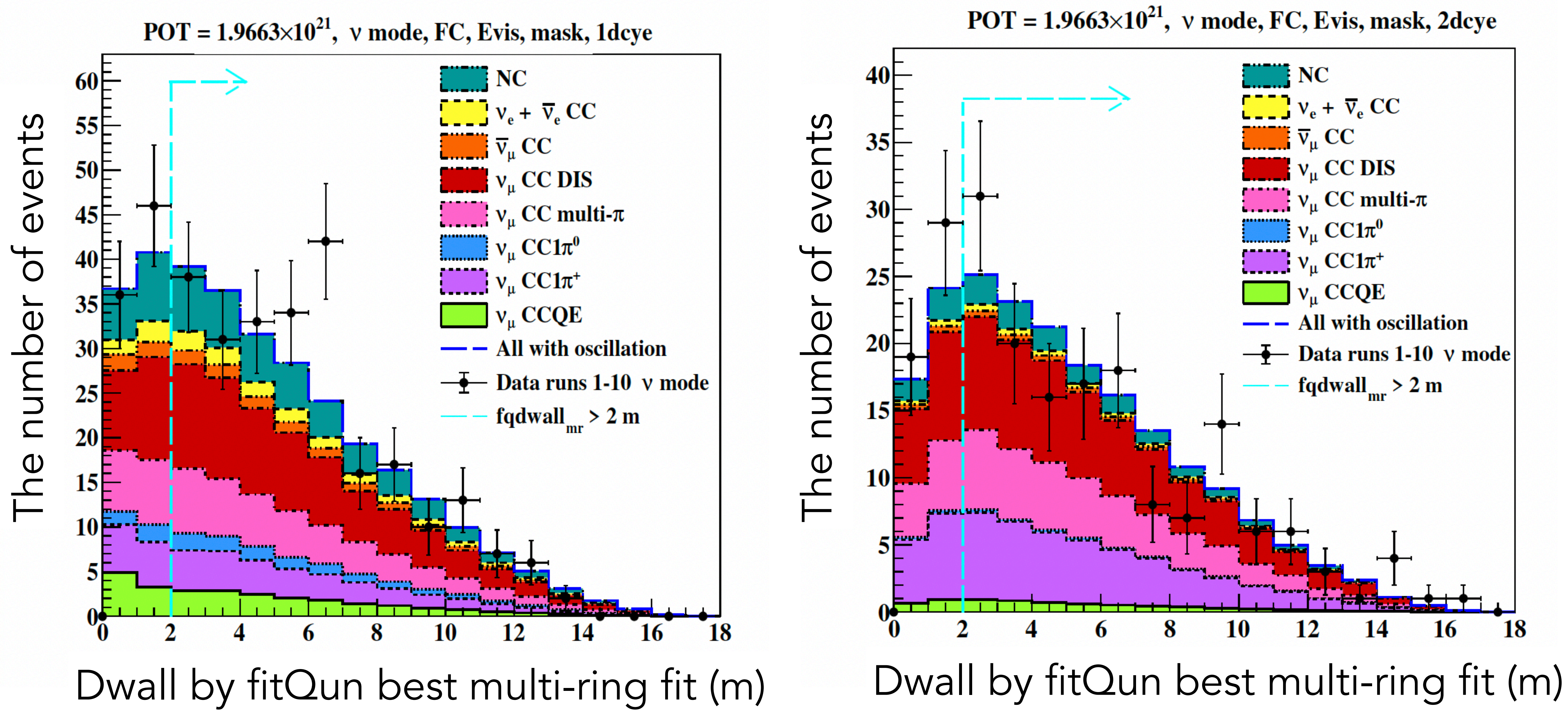
Visible Energy

- The sum of $P_{\mathrm{rec}}^{e-\mathrm{like}}/E_{\mathrm{rec}}^{\mu-\mathrm{like}}/E_{\mathrm{loss}}^{\pi,p-\mathrm{like}}$ of rings depending on each type of ring.
- Reduce contamination from neutral current interaction.

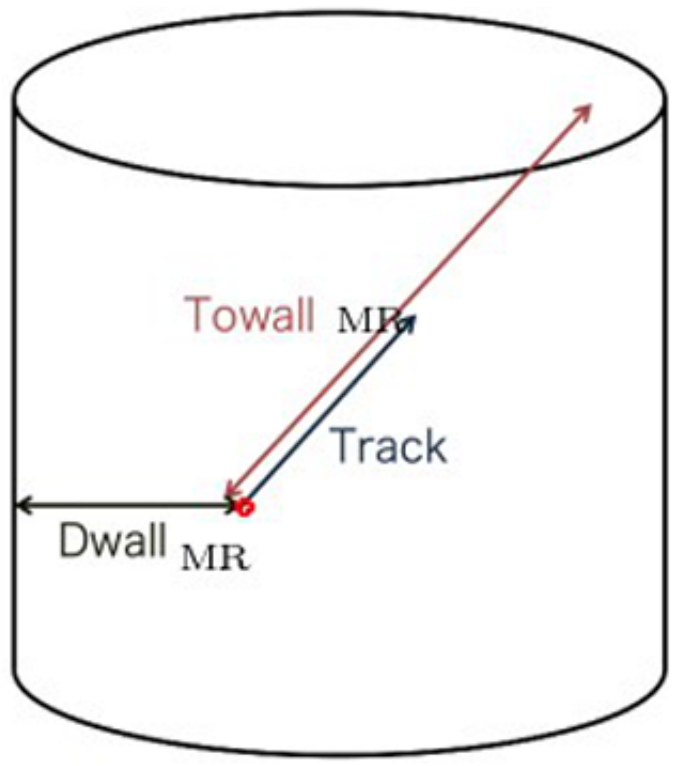
$\nu_\mu CC1\pi^+$ (Event selection)

Event selection of ν_μ $CC1\pi^+$



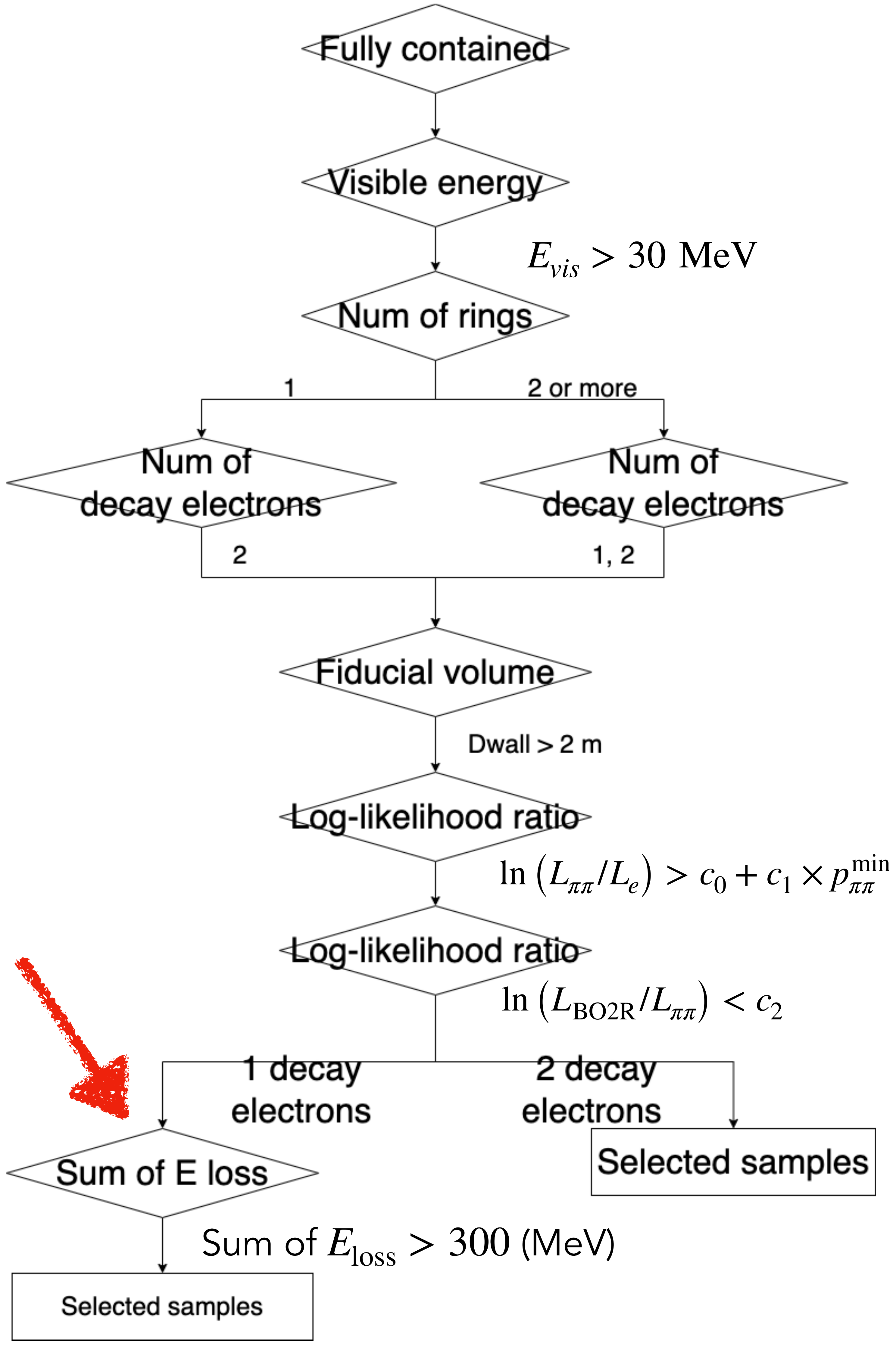


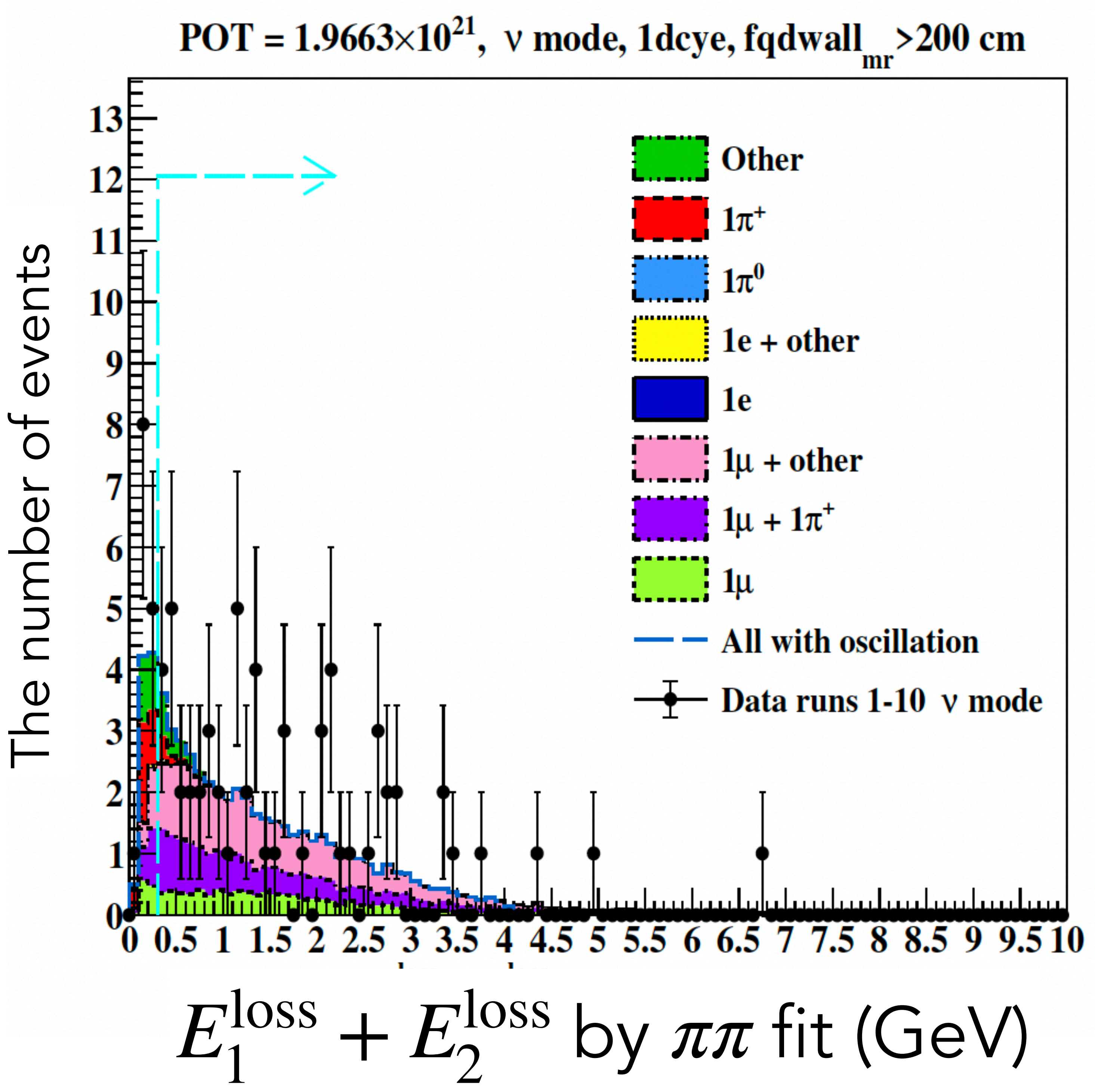
- Play a complementary role of the fully contained cut to reduce entering background.



ν_μCC1π^+ (Event selection)

Event selection of ν_μ CC1π^+





- Reduce NC1π^+ background

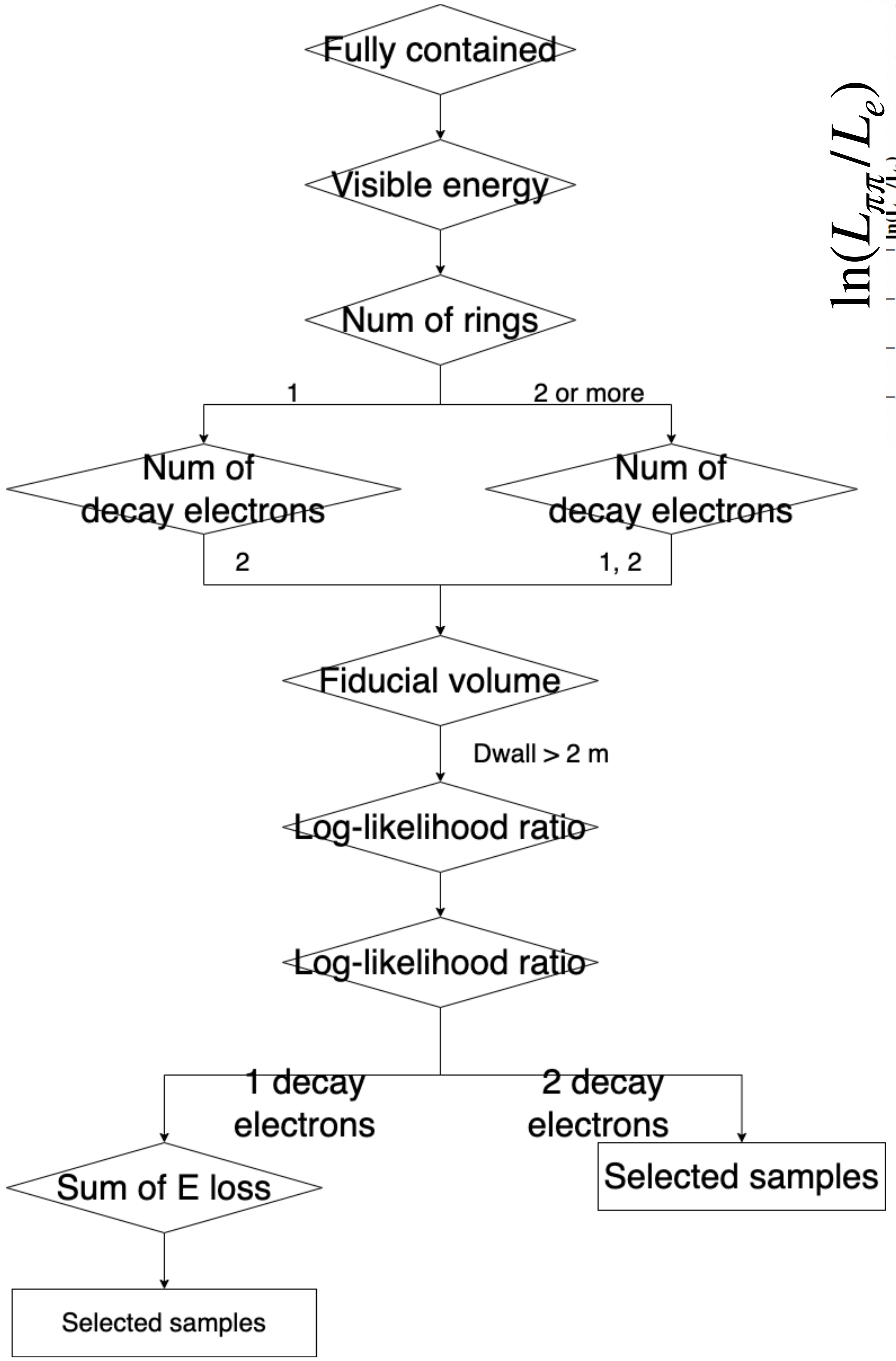
  (NC1π^+: $\nu_{\mathrm{lepton}} + p \rightarrow \nu_{\mathrm{lepton}} + \pi^+ + n$

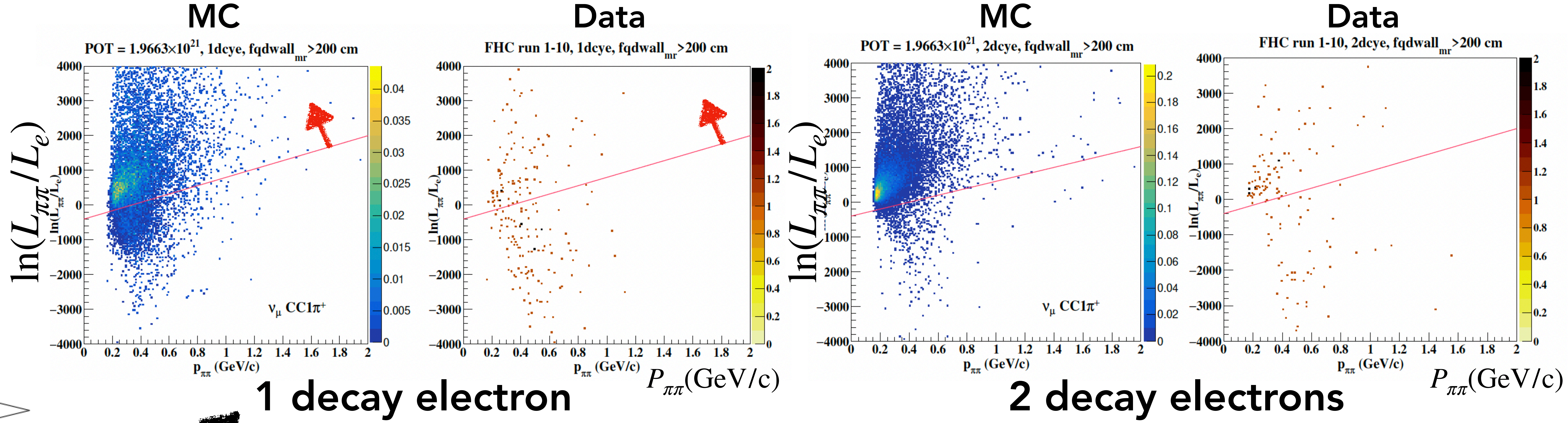
  π^+ can mimic μ if it does not create a secondary ring.

  $\pi^\pm$ tends to produce less light than μ from CC interactions.)

ν_μCC1π^+ (Event selection)

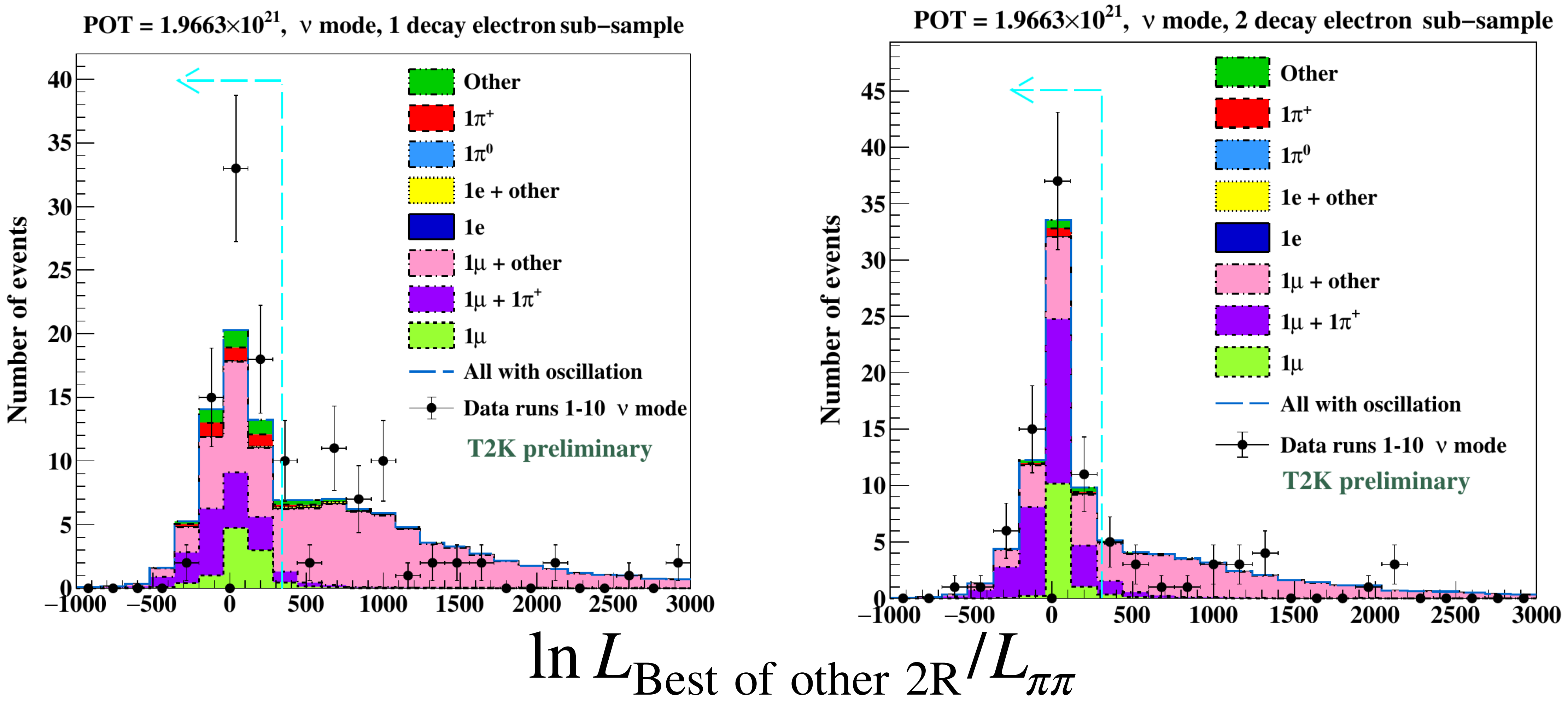
Event selection of ν_μ CC1π^+





$L_{\pi\pi}$: Likelihood (LLh) of the two ring hypothesis, where both rings are assumed to be $\pi^{\pm}$-like.

L_{BO2R}: the largest LLh of $L_{ee}, L_{e\pi^\pm}, L_{\pi^\pm e}$ (best of the other 2ring-hypothesis)



- Good separation of (1μ or 1μ + other) and (1μ + 1π) final state topologies.