Results and prospects from the T2K Experiment

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On behalf of the T2K Collaboration

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Neutrino oscillations

- Mixing between distinct flavour eigenstates (interacting states) and mass eigenstates (propagating states), as governed by the **Pontecorvo-Maki-Nakagawa-Sakata matrix**

Bruno Pontecorvo, 1957

B. Pontecorvo, "**Mesonium and antimesonium**," *Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki*, vol. 33, p. 549, 1957

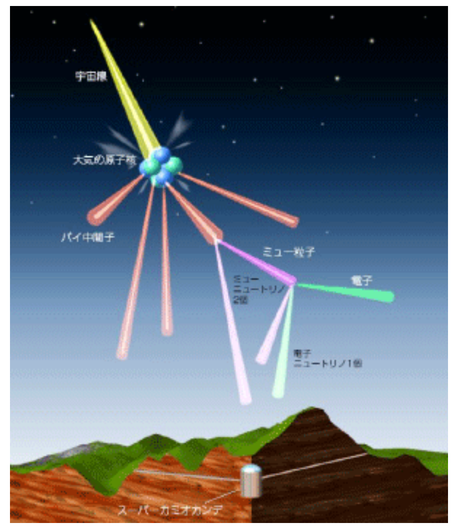
B. Pontecorvo, "**Inverse beta processes and nonconservation of lepton charge**," *Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki*, vol. 34, p. 247, 1957

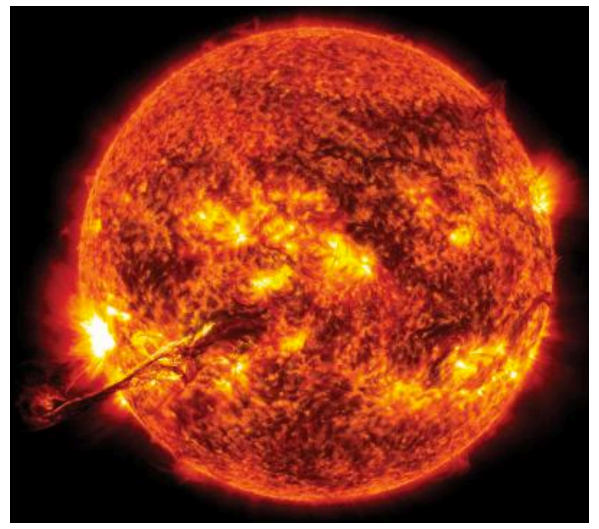
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$s_{ij} = sin\ \theta_{ij}$

$c_{ij} = cos\ \theta_{ij}$

Atmospheric & Accelerator	**Accelerator & Reactor**	**Reactor & Solar**
$\theta_{23} \approx 48^\circ$	$\theta_{13} \approx 8^\circ$	$\theta_{12} \approx 34^\circ$
$\lvert\Delta m^2_{32}\rvert \approx \lvert\Delta m^2_{31}\rvert \approx 2.5 \times 10^{-3}\ eV^2$	$\delta_{CP} = ?$	$\Delta m^2_{21} \approx 7.5 \times 10^{-5}\ eV^2$





Open questions in neutrino oscillation physics

- **Neutrino mass ordering?**
  - Normal $(\Delta m^2_{32} > 0)$ or inverted $(\Delta m^2_{32} < 0)$
- **θ_{23} octant?**
  - Upper $(sin^2\,\theta_{23} > 0.5)$ or lower $(sin^2\,\theta_{23} < 0.5)$
  - $\theta_{23} = 45^{\circ}$ would indicate an underlying $\mu - \tau$ symmetry of the PMNS matrix
- **CP violation in neutrino sector?**
  - Would like to measure with the same precision as CP violation in hadronic weak interactions
  - $\delta_{CP} \neq 0, \pi$ would indicate $P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$ in vacuum
- T2K is well positioned to answer all three questions!

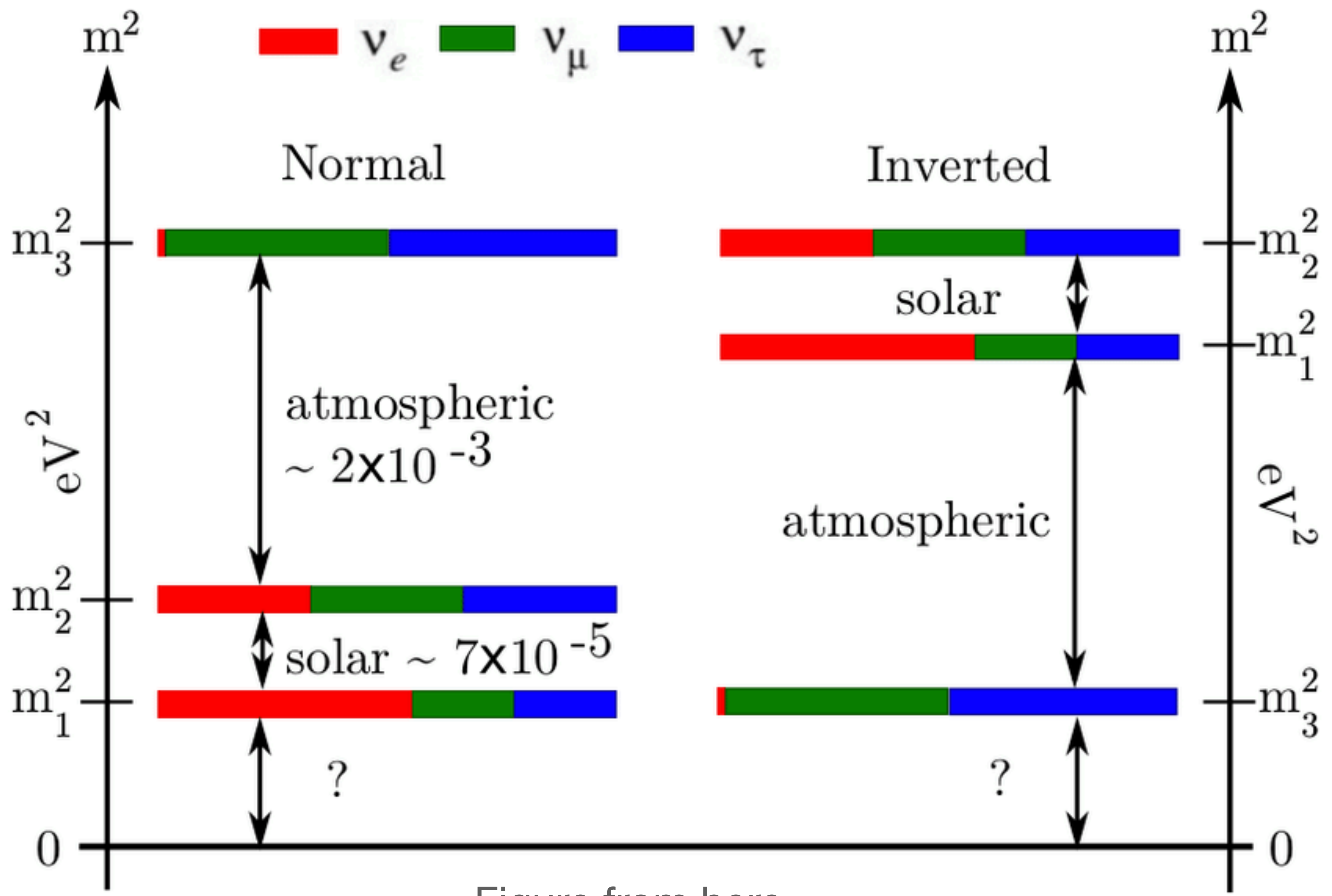


Figure from here

- **PMNS framework validity?**
  - Sterile neutrinos, non standard neutrino interactions etc.

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Tokai-to-Kamioka (T2K) Experiment

Far detector “measures” the oscillated beam composition

Near-detectors “measure” the initial beam composition

Neutrino beam produced at J-PARC

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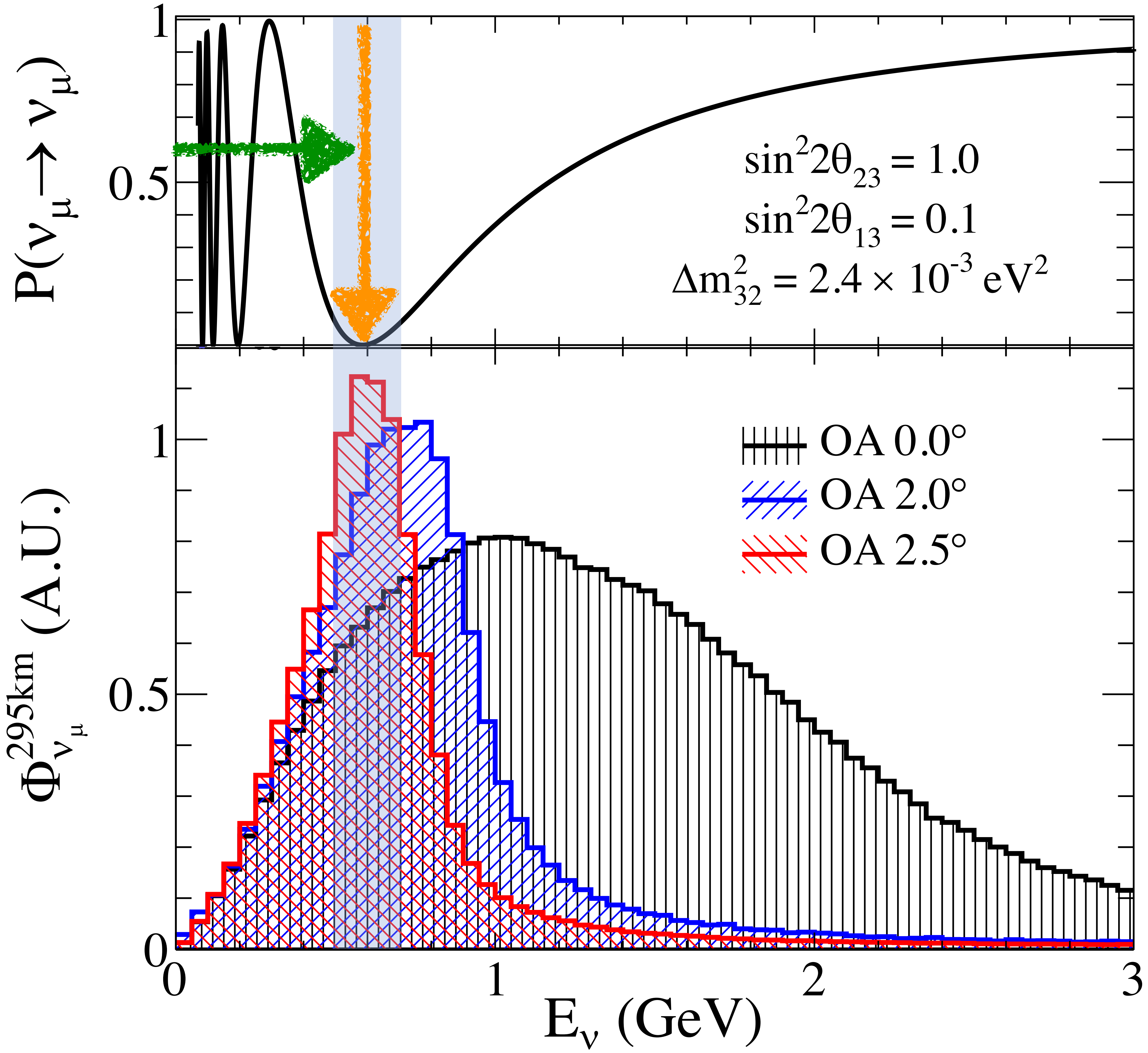
ν_μ ($\bar{\nu}_\mu$) survival probability at T2K

- Muon (anti)neutrino survival probability around oscillation maximum:

$$P_{T2K}(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu) \approx 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}\left(1 - \cos^2\theta_{13}\sin^2\theta_{23}\right)\sin^2\frac{\Delta m^2_{23}L}{4E}$$

CP-conserving terms (survival probability is CP-conserving even at higher orders!)



Position of dip in neutrino survival determines Δm^2_{32}

Size of dip in neutrino survival determines $\sin^2\theta_{23}$

T2K uses a 2.5 degrees off-axis beam for more "monochromatic-like" neutrinos, peaking at the right energy for an oscillation maximum at the position of Super-K

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ν_e $(\bar{\nu}_e)$ appearance probability at T2K

- Electron (anti)neutrino appearance probability in vacuum:

CP-conserving term

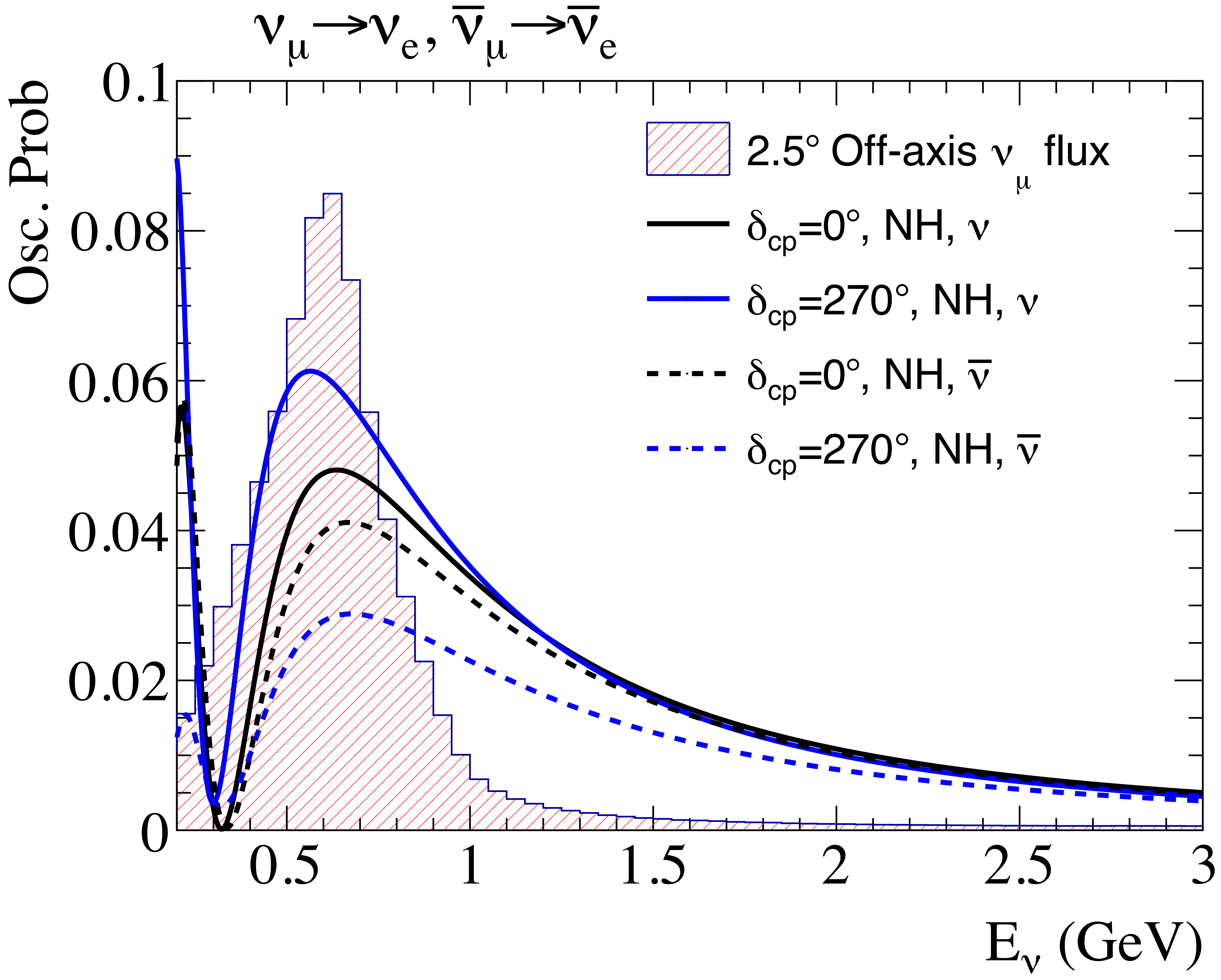
$$P_{T2K}(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx sin^2\, 2\theta_{13}\, sin^2\, \theta_{23}\, sin^2\, \frac{\Delta m^2_{32} L}{4E}$$

$$+ J\, cos\,(\frac{\Delta m^2_{32} L}{4E} \pm \delta_{CP})$$

Minus sign for $\bar{\nu}$

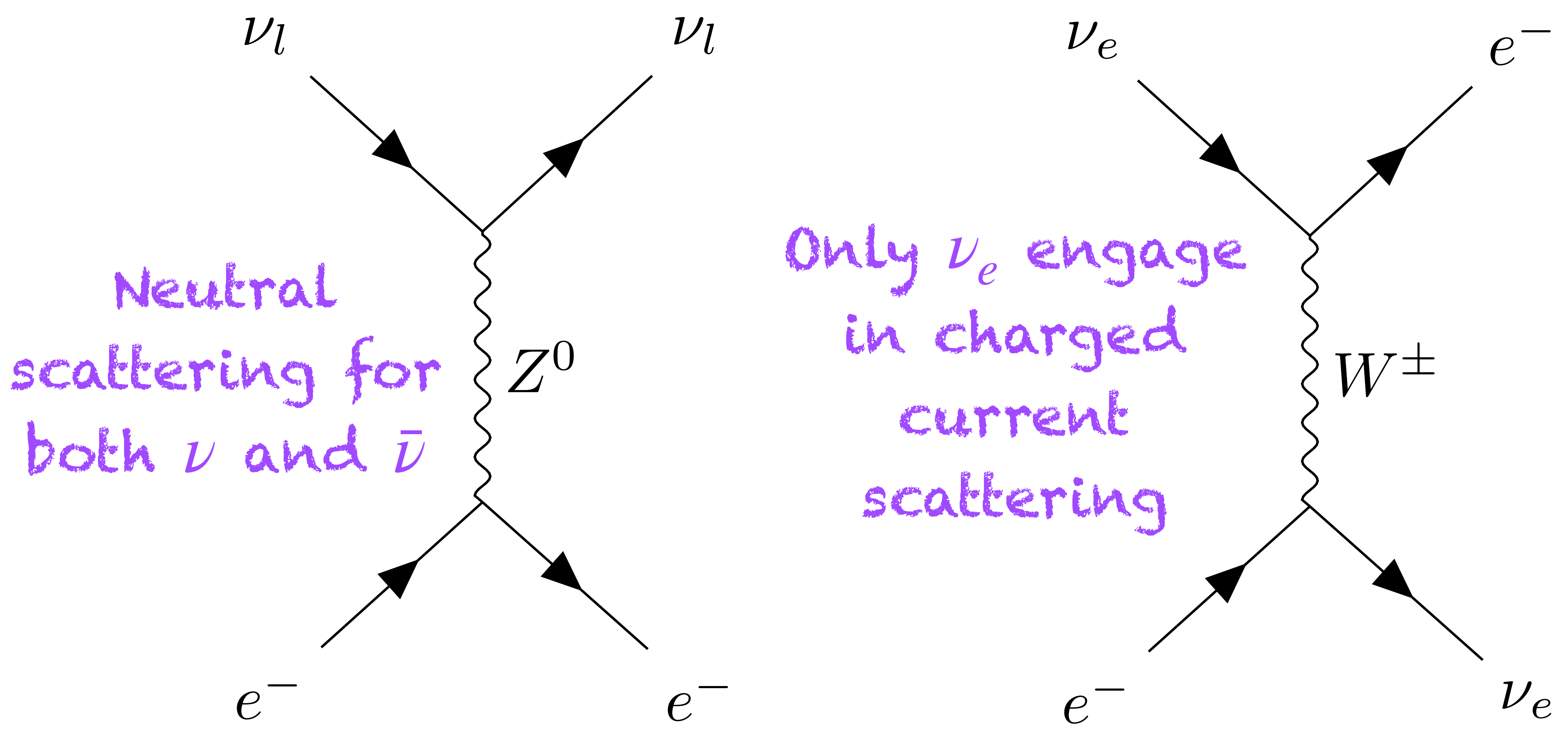
CP-violating term for $\delta_{CP} \neq 0, \pi$

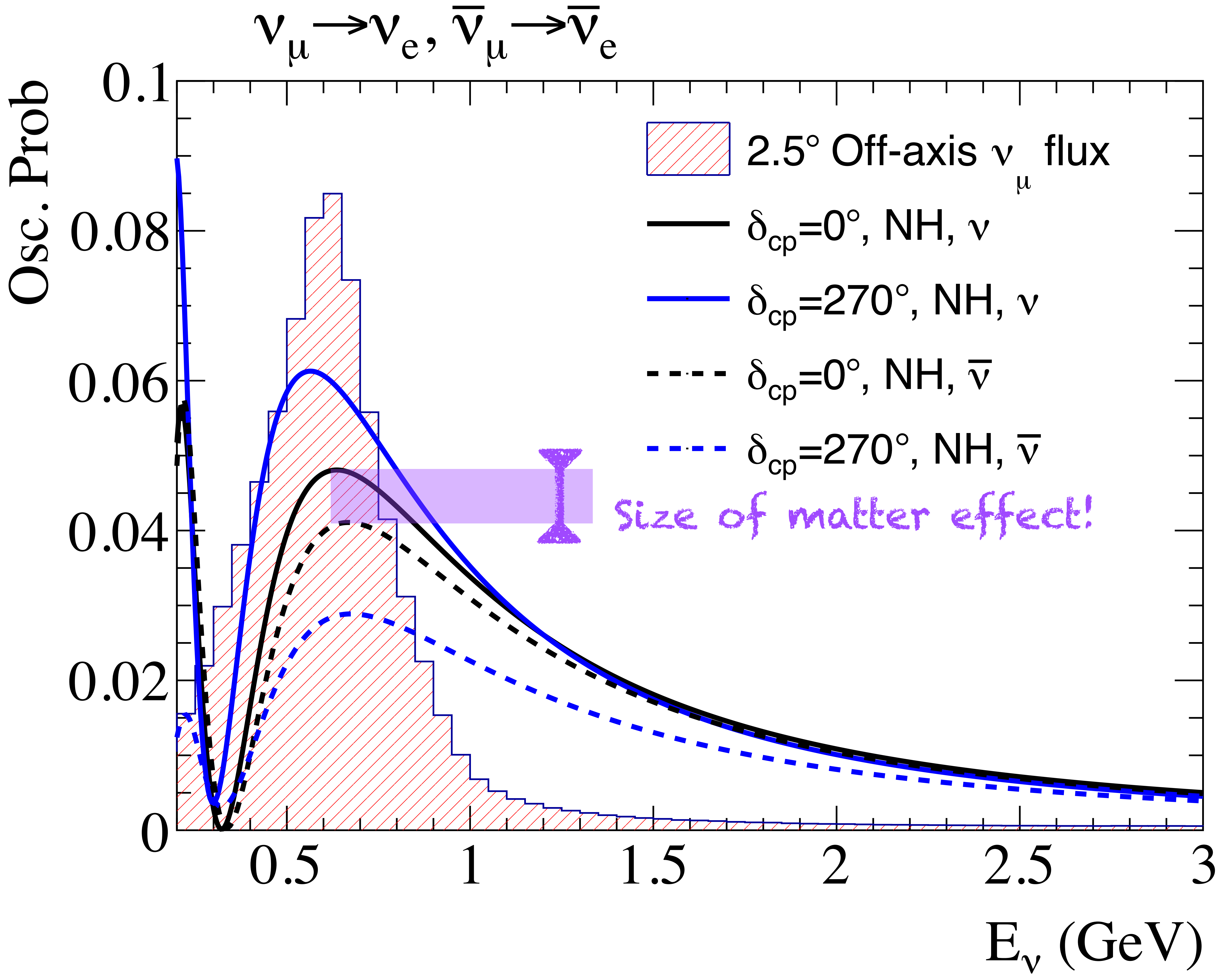
- **The appearance probability gets modified** because of charged current ν_e coherent scattering from electrons in the Earth's crust



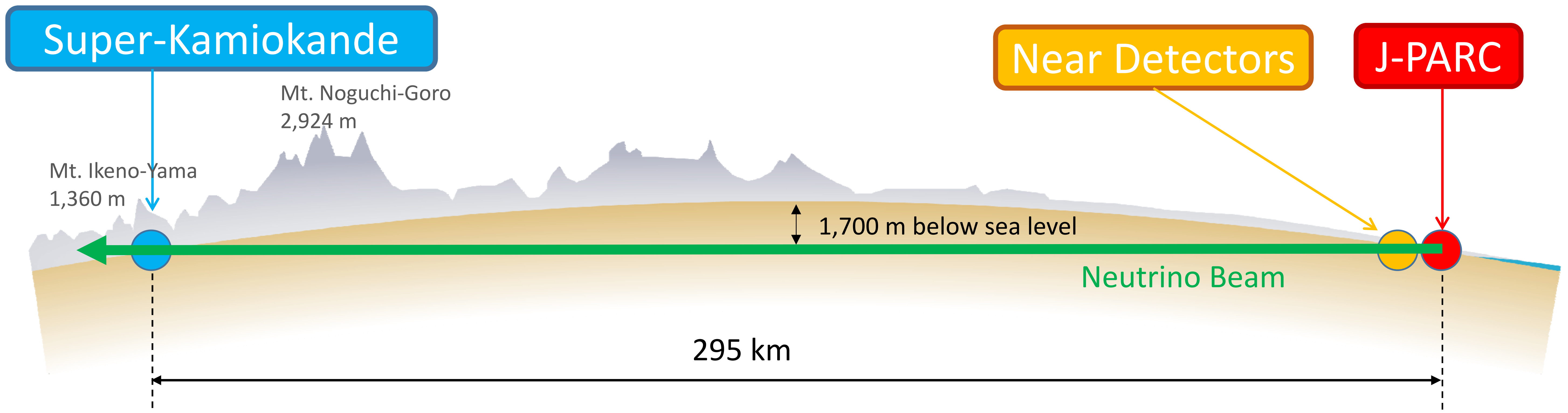
ν_e ($\bar{\nu}_e$) appearance probability at T2K

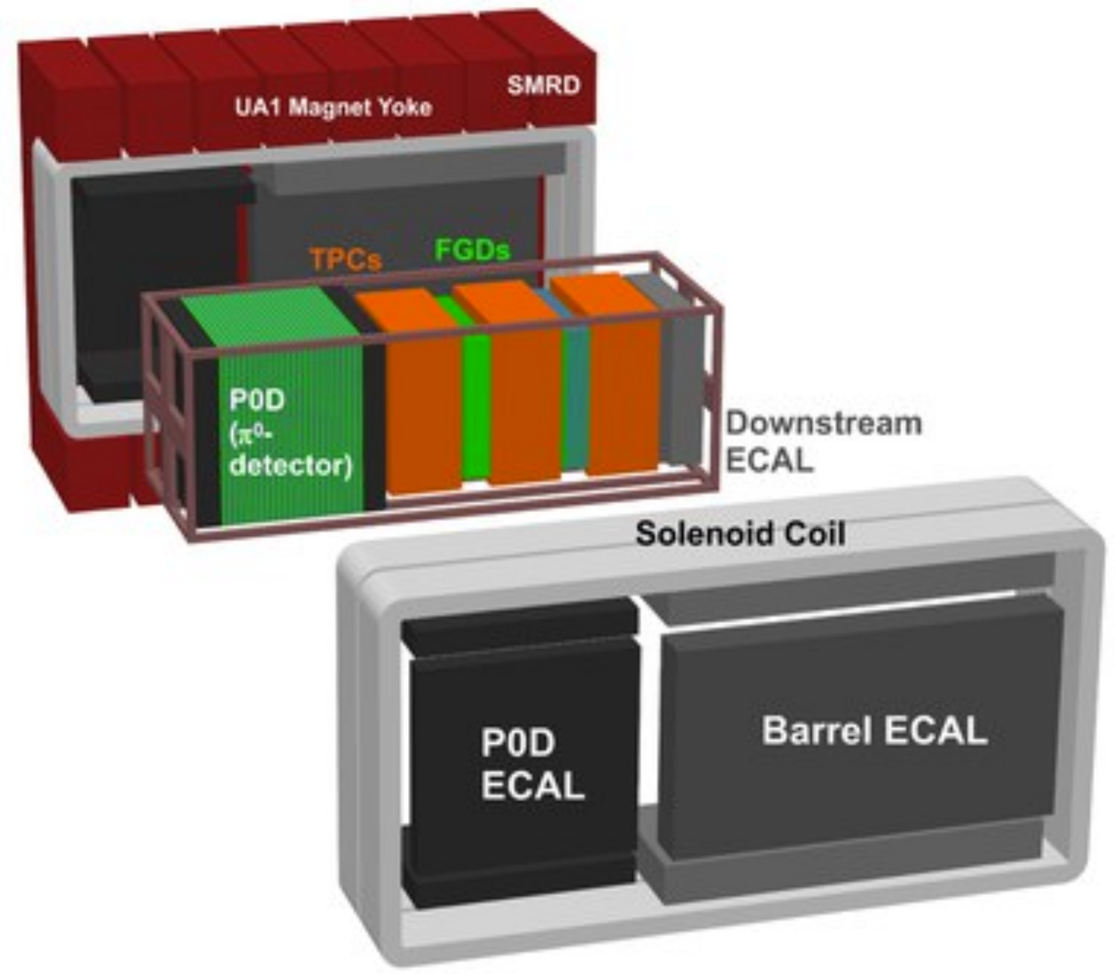
- **The appearance probability gets modified** because of charged current ν_e coherent scattering from electrons in the Earth's crust
- **Mikheyev-Smirnov-Wolfenstein effect**





Neutrino-induced event counting at T2K





ν_μ-induced event count at ND280:

$$N_\mu^{ND}(E_\nu^{rec}) = \sigma^{ND}(E_\nu^{true}) \times \Phi_\nu^{ND}(E_\nu^{true}) \times \epsilon^{ND}(E_\nu^{true}) \times S^{ND}(E_\nu^{true}, E_\nu^{rec})$$

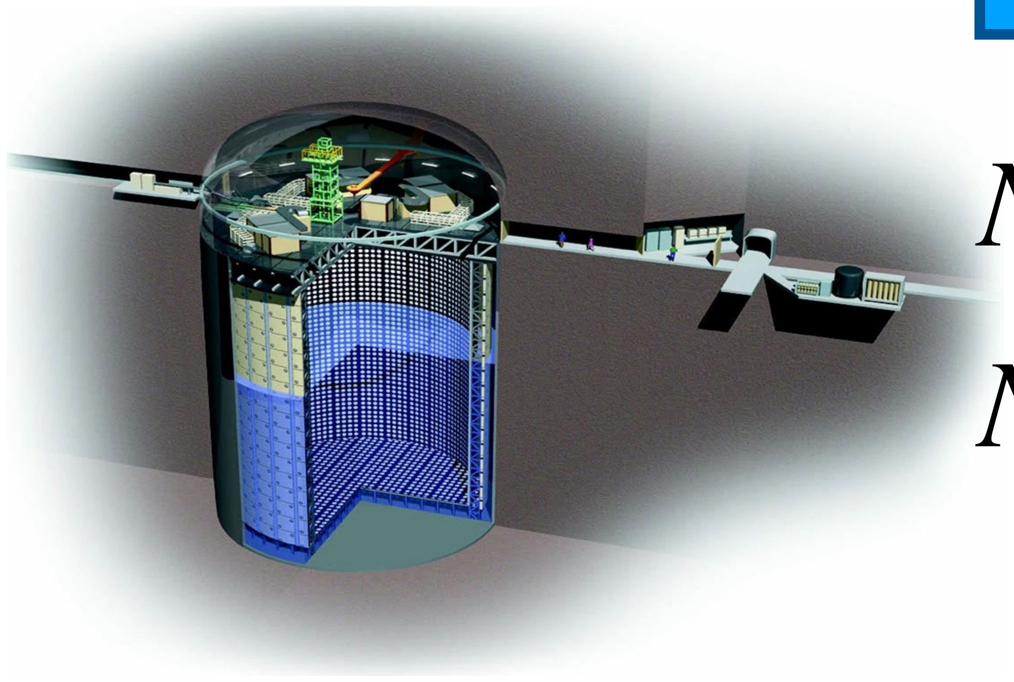
Cross section on CH and H_2O

Unoscillated flux (detector specific)

Efficiency (detector specific)

Smearing matrix (detector specific)

ν_μ (ν_e)-induced event count at Super-K:



$$\begin{matrix} N_\mu^{SK}(E_\nu^{rec}) \\ N_e^{SK}(E_\nu^{rec}) \end{matrix} = \begin{matrix} P(\nu_\mu \rightarrow \nu_\mu) \\ P(\nu_\mu \rightarrow \nu_e) \end{matrix} \times \sigma^{SK}(E_\nu^{true}) \times \Phi_\nu^{SK}(E_\nu^{true}) \times \epsilon^{SK}(E_\nu^{true}) \times S^{SK}(E_\nu^{true}, E_\nu^{rec})$$

Oscillation probability

Cross section on H_2O

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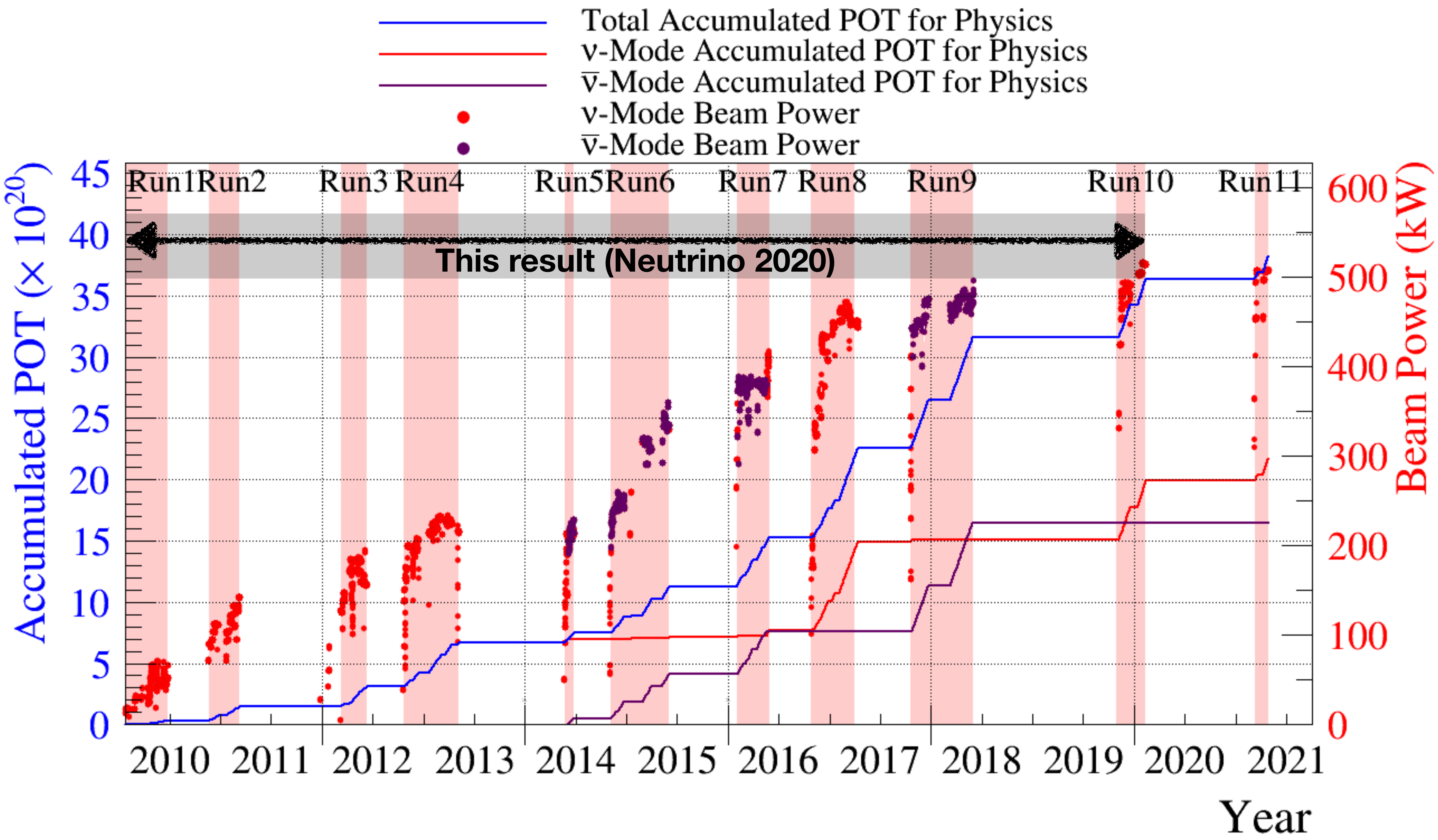
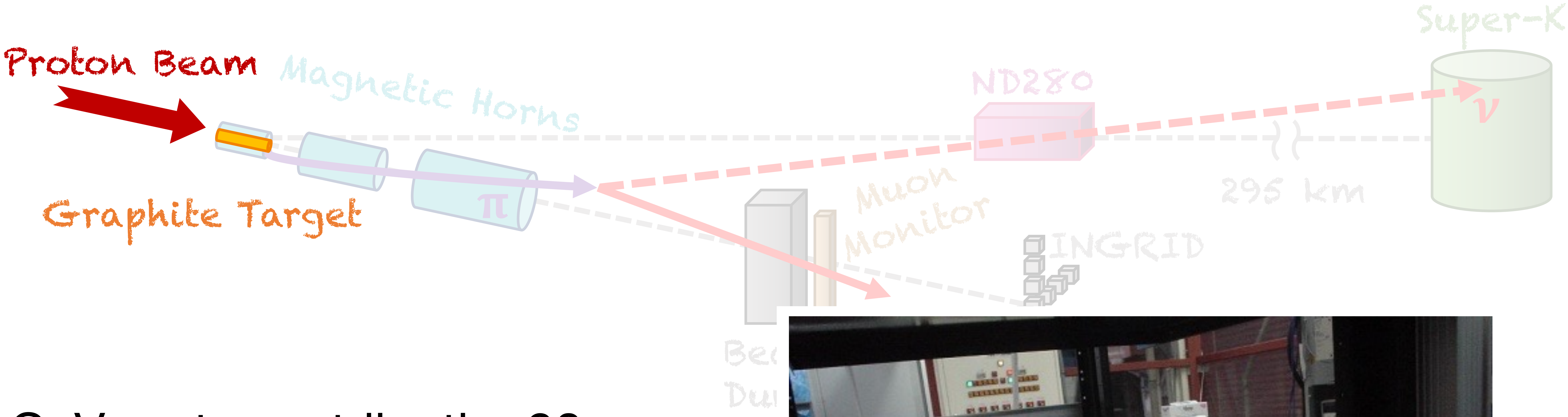
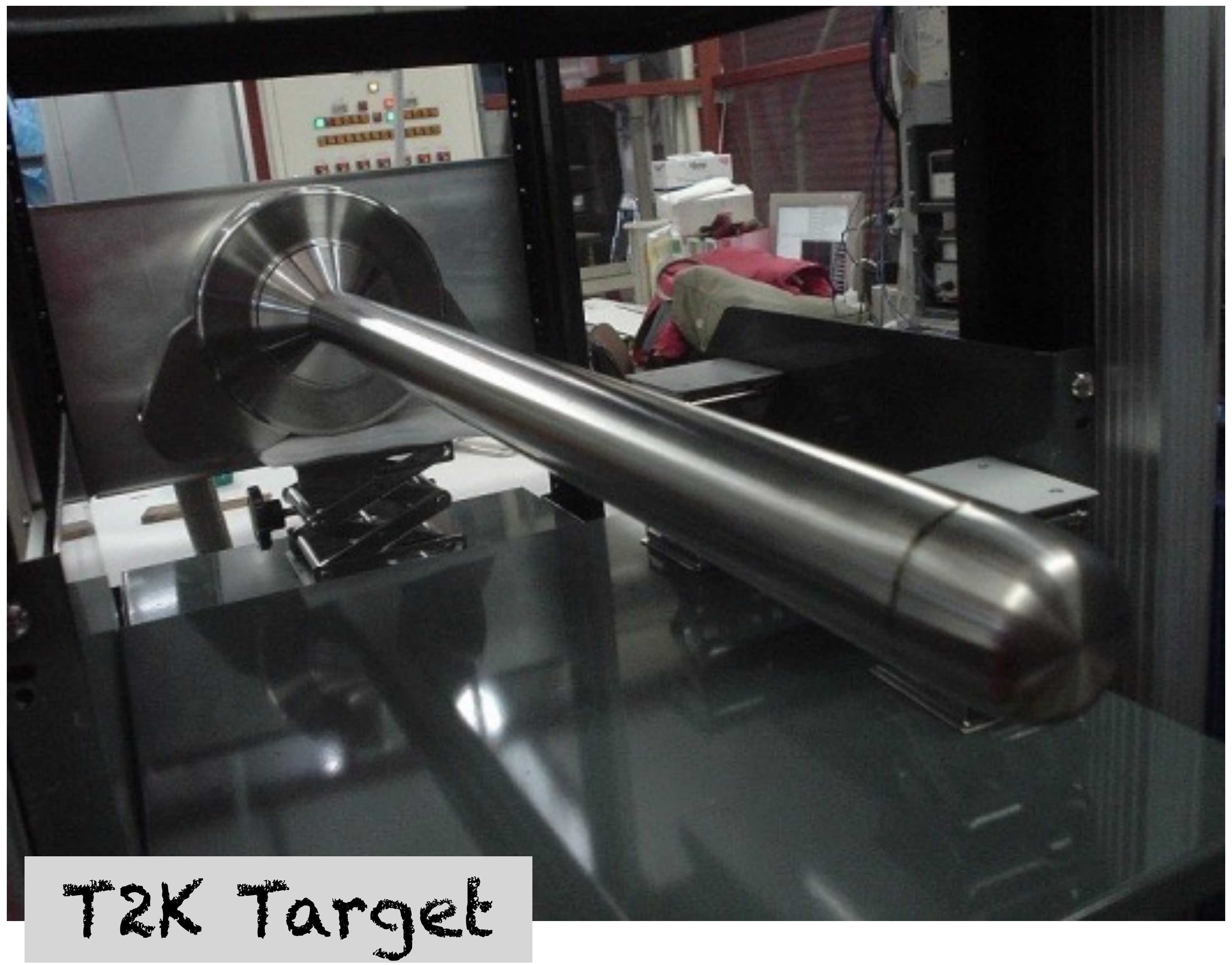
T2K datasets



- Reached maxium beam power of 522.6 kW
- For today's result (Runs 1-10), collected 3.6x10^{21} POT, split into 1.96x10^{21} POT (54.61%) in ν-mode and 1.63x10^{21} POT (45.39%) in $\bar{\nu}$-mode
- **Today's result includes ~33% more POT in ν-mode compared to our previous measurement**
- Stay tuned for new results with the inclusion of Run 11, with 1.78x10^{21} POT in ν-mode, the very first T2K data with a Gd-doped Super-K

T2K beamline

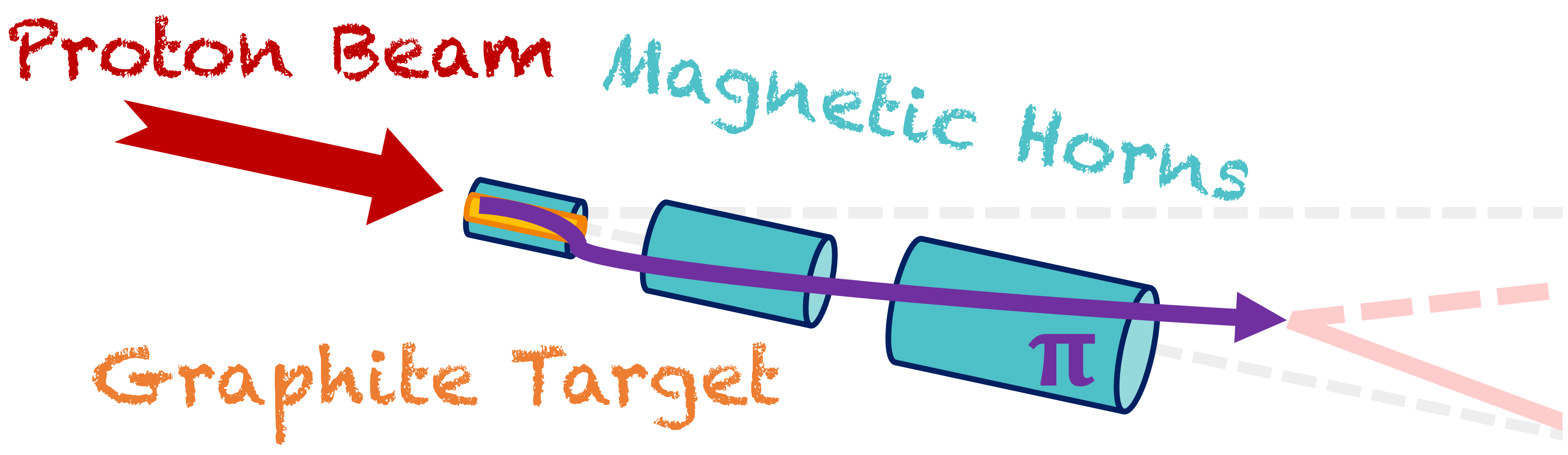


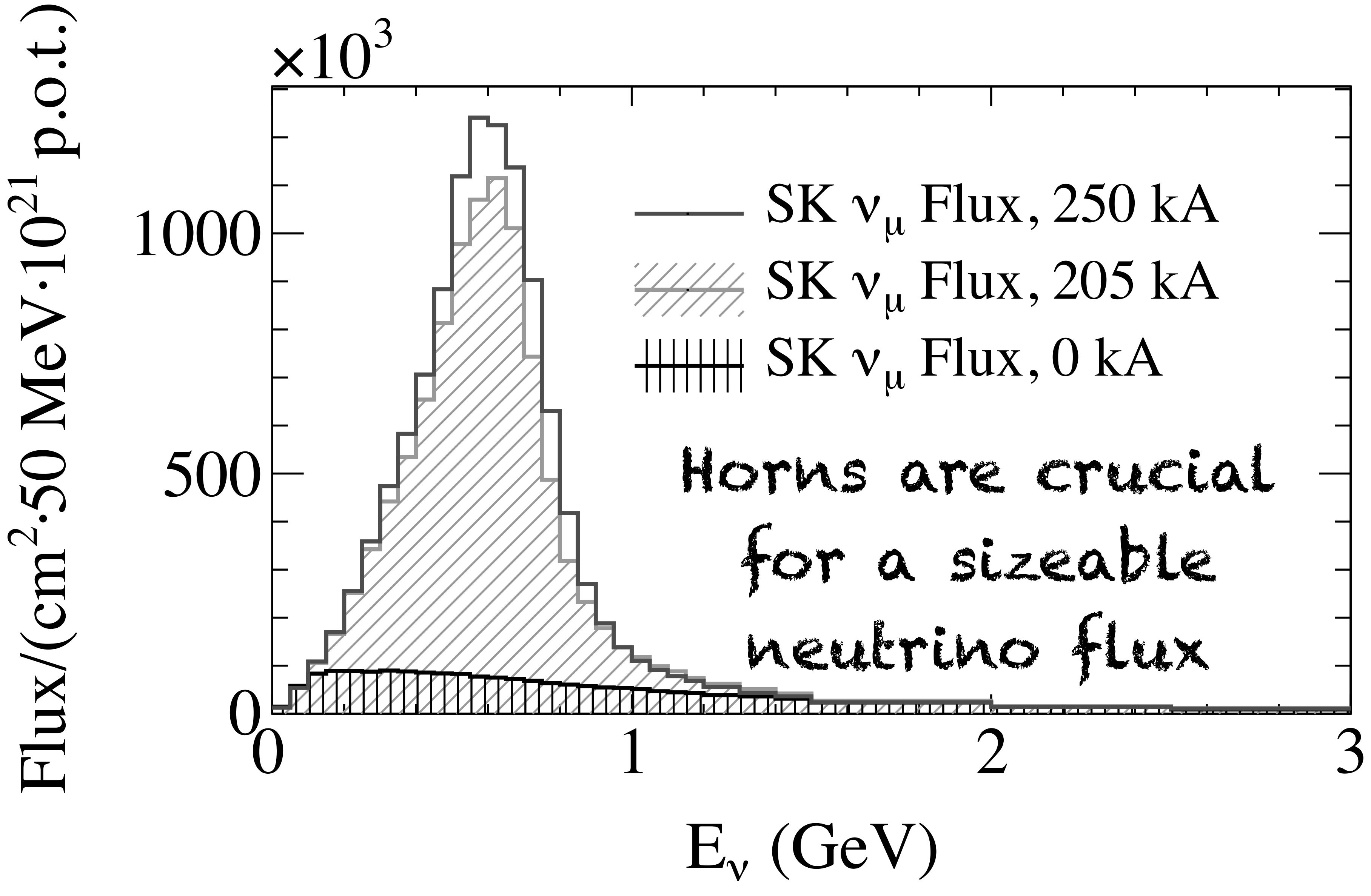


- 30 GeV protons strike the 90 cm long T2K graphite target

- QCD theory is non-perturbative at these energies, thus not easily calculable

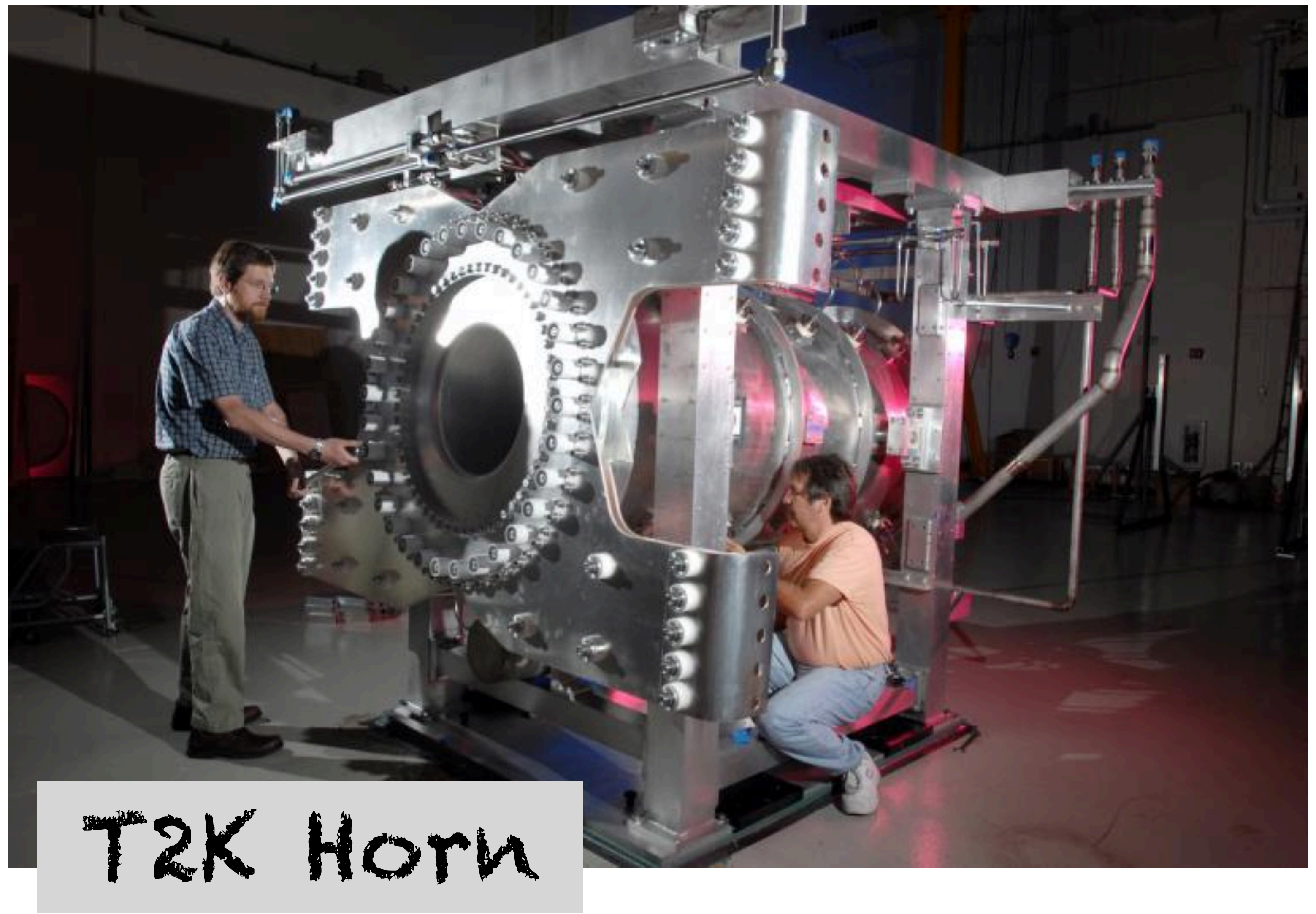
T2K beamline



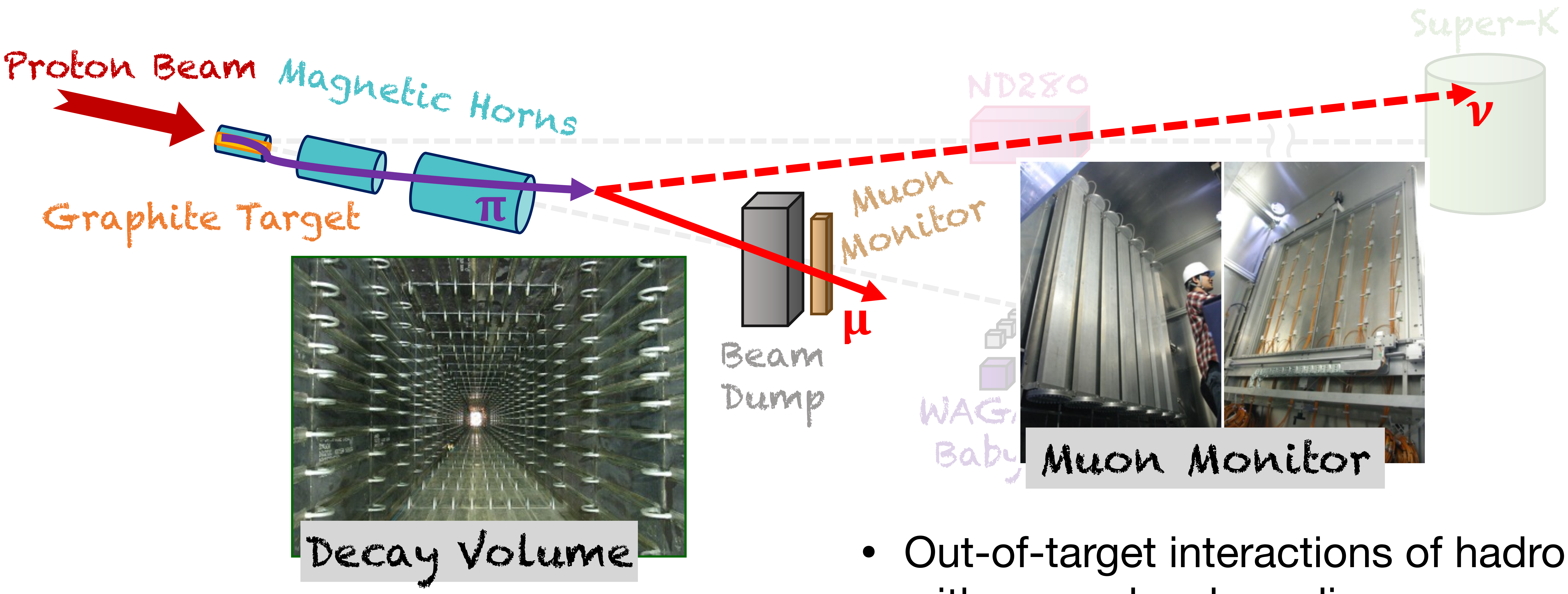


- Hadronic cascade is initiated within the target

- 3 magnetic horns used to bend and (de)focus the pions and kaons leaving the target



T2K beamline



$$\pi^+(K^+) \rightarrow \mu^+ \nu_\mu$$

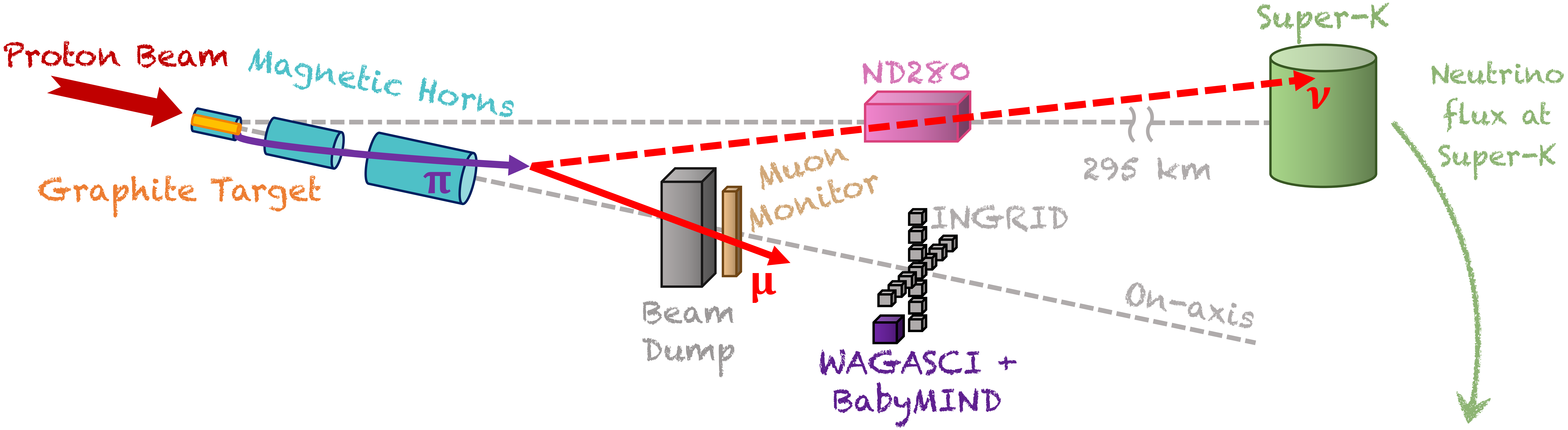
Signal

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

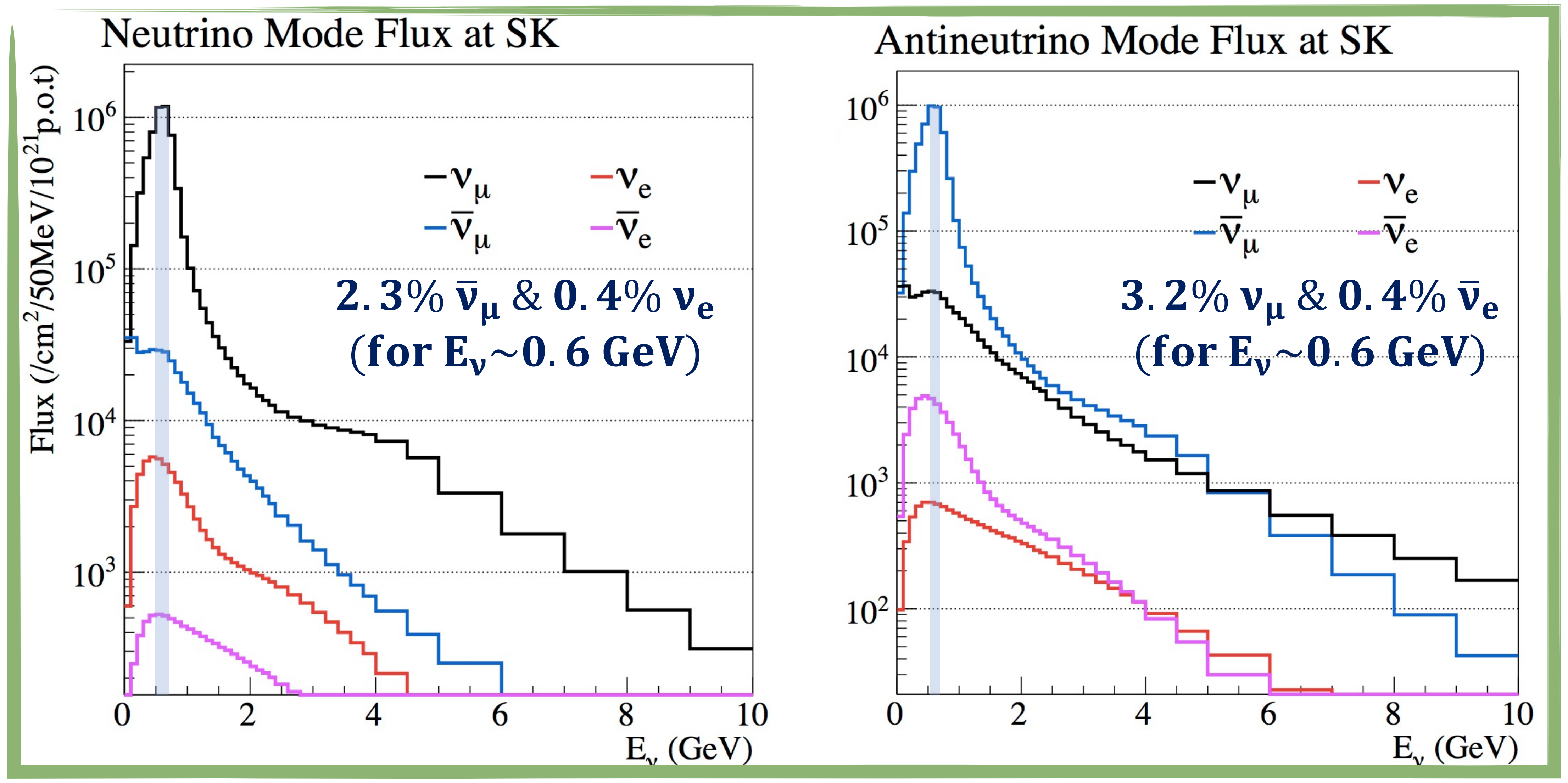
Background

- Out-of-target interactions of hadrons with secondary beamline components affect the neutrino flux
- In-flight pion and kaon decays inside the decay volume (96 m) produce neutrinos

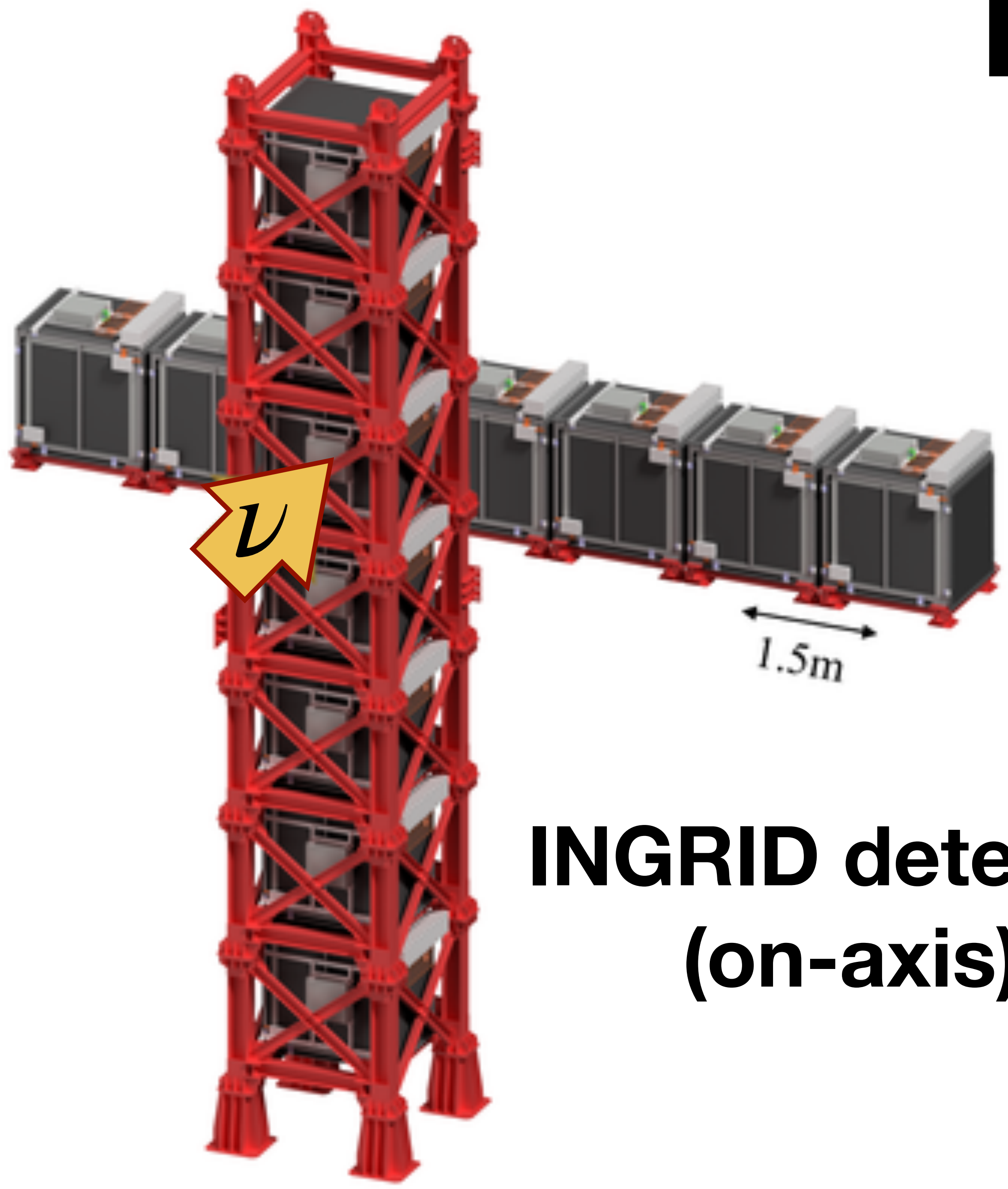
T2K beamline



- By changing the horn current polarity, we can focus either a neutrino or an anti-neutrino enhanced beam towards the T2K detectors

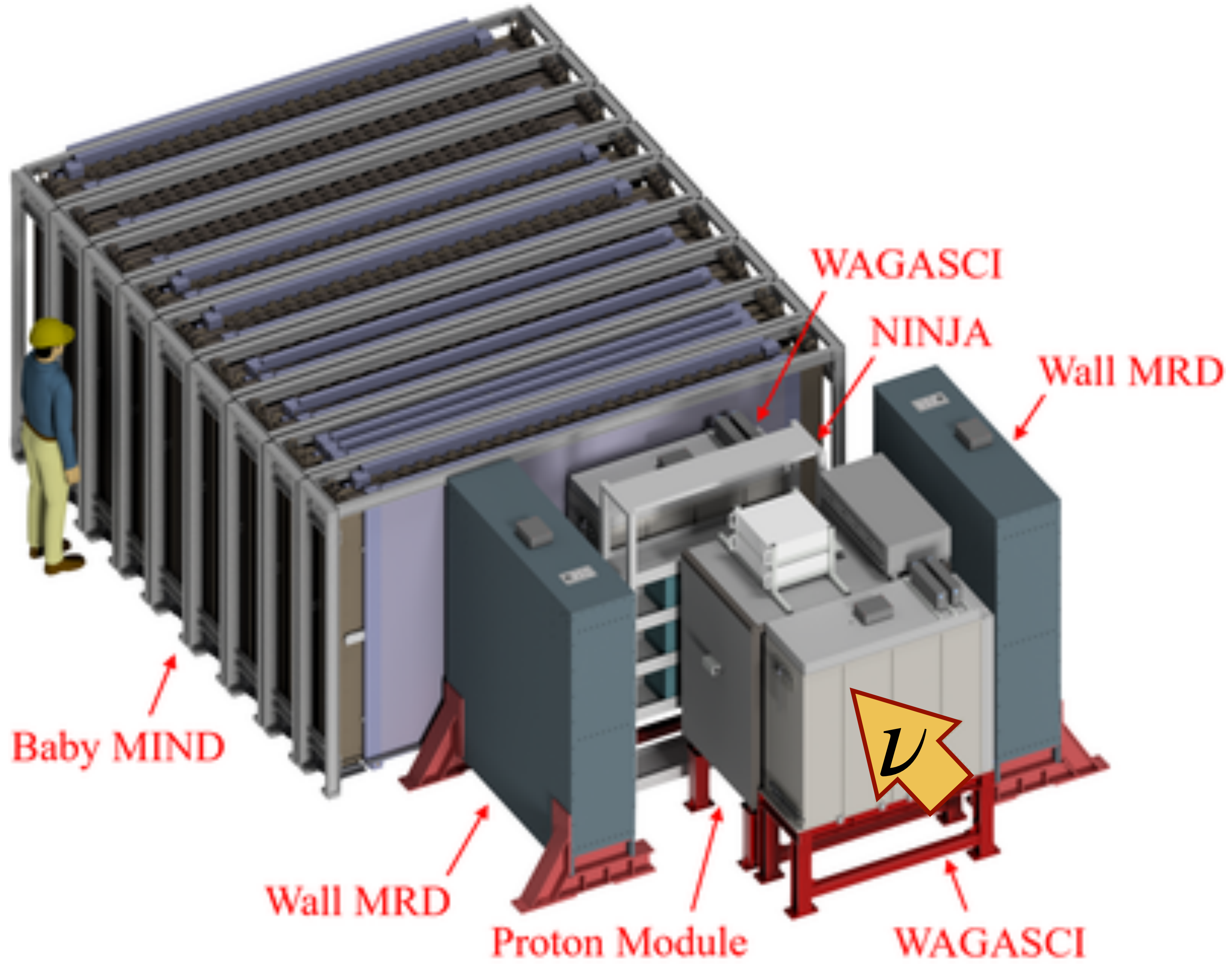


T2K near detectors



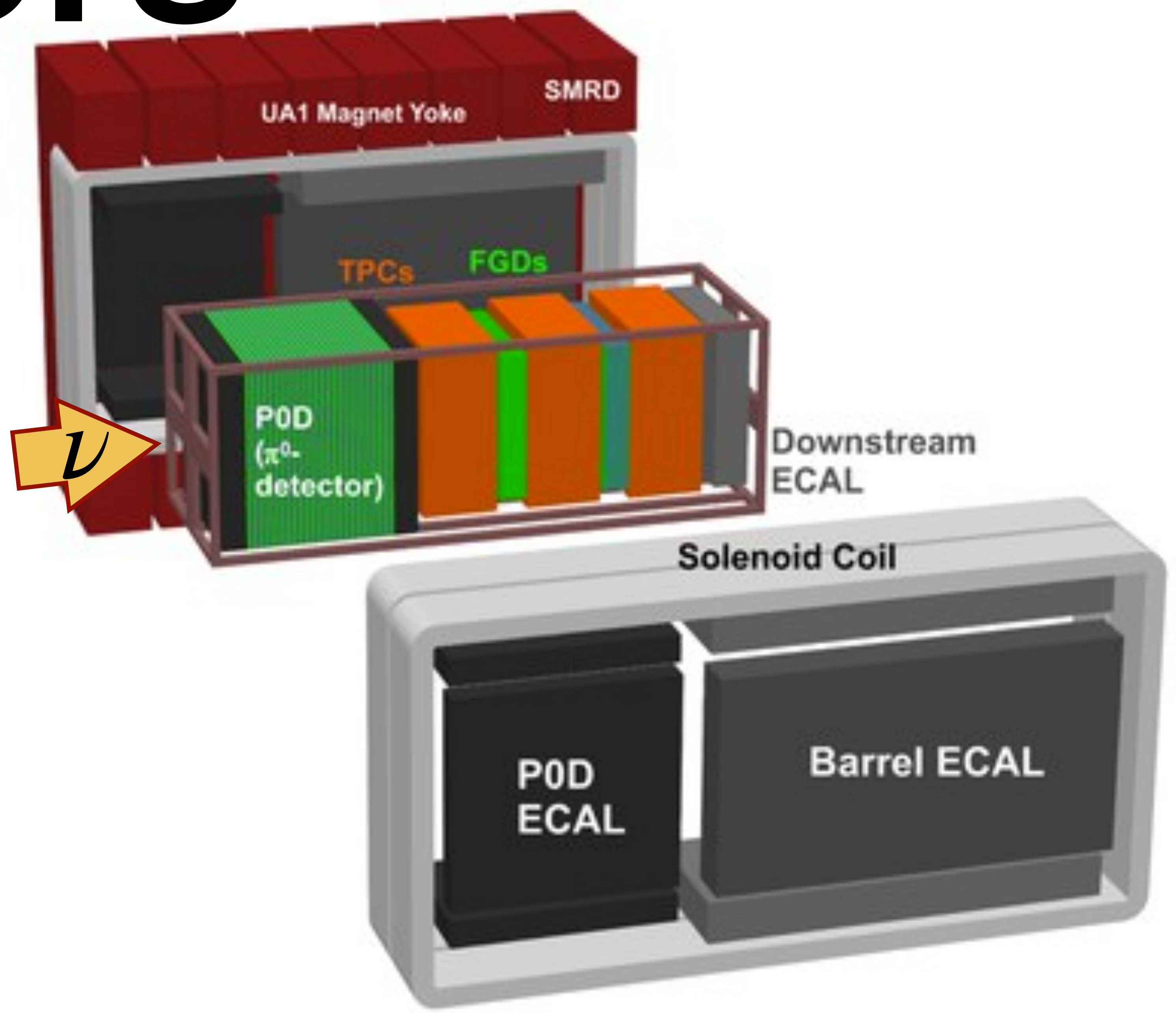
INGRID detector (on-axis)

- Consists of 16 identical modules, each made of alternating iron and plastic scintillator layers
- In the oscillation analysis, **used to constrain neutrino beam systematics** (e.g. off-axis angle)
- Also measures cross sections for neutrino interaction models



WAGASCI and BabyMIND detectors (1.5 degrees off-axis) New!

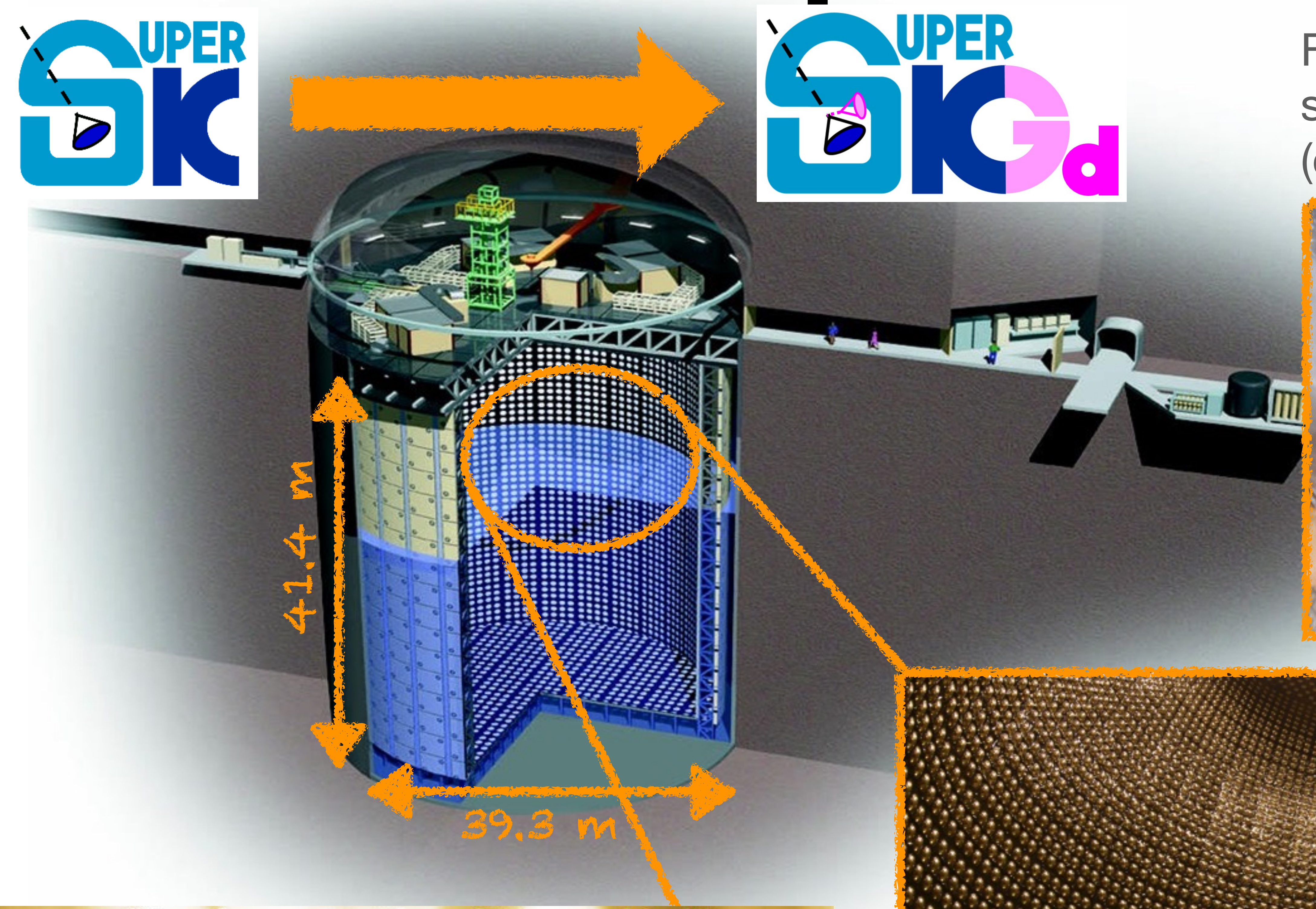
- Water filled plastic scintillator lattice (WAGASCI) and magnetised tracking (BabyMIND) detectors
- Plans to use in the oscillation analysis
- First WAGASCI cross section paper: Phys. Rev. D 97, 012001



ND280 detector (2.5 degrees off-axis)

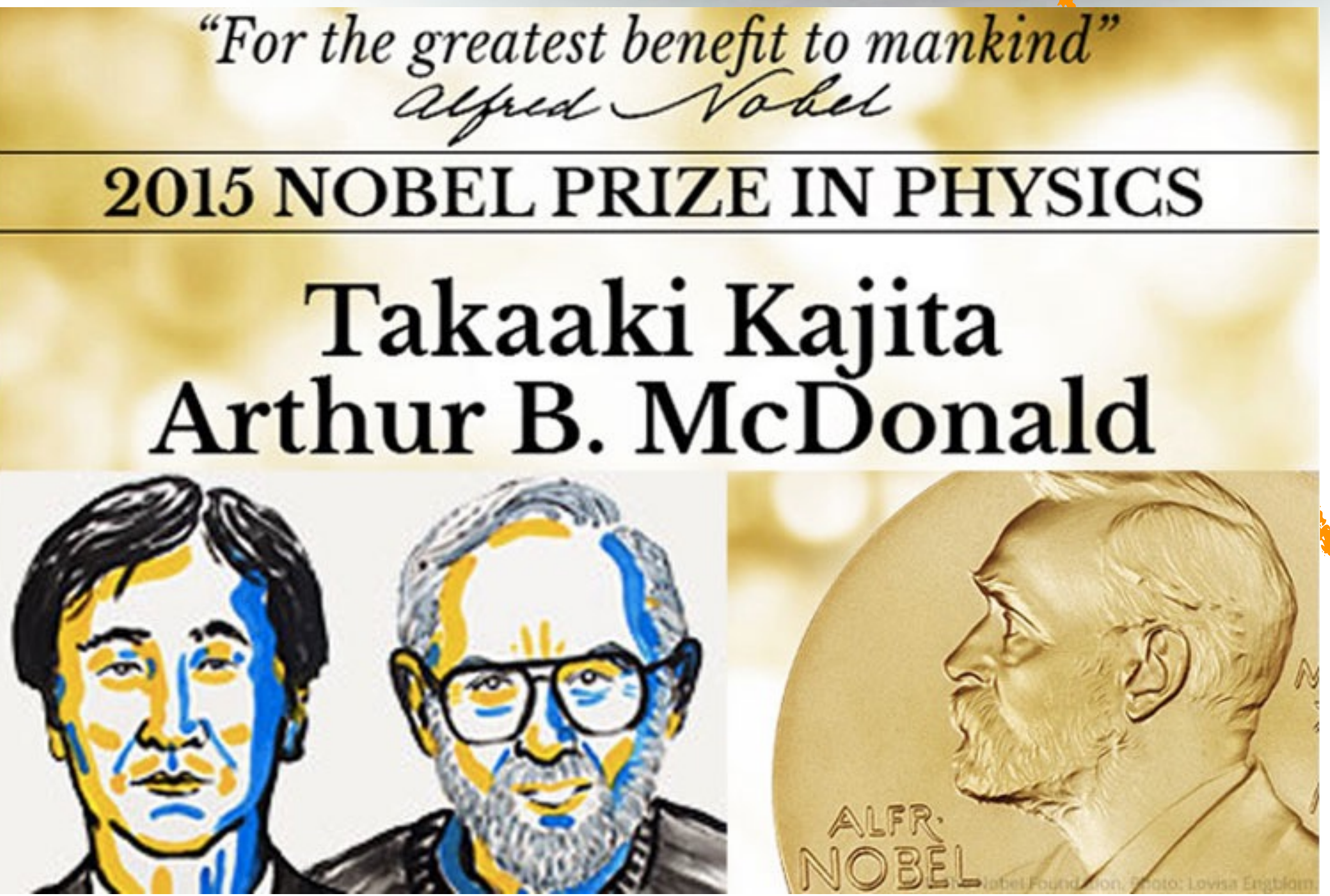
- **Main constraint of flux and cross section model parameters in the oscillation analysis**
- Takes sophisticated cross section measurements for neutrino interaction models (e.g. recently Phys. Rev. D 103, 112009)

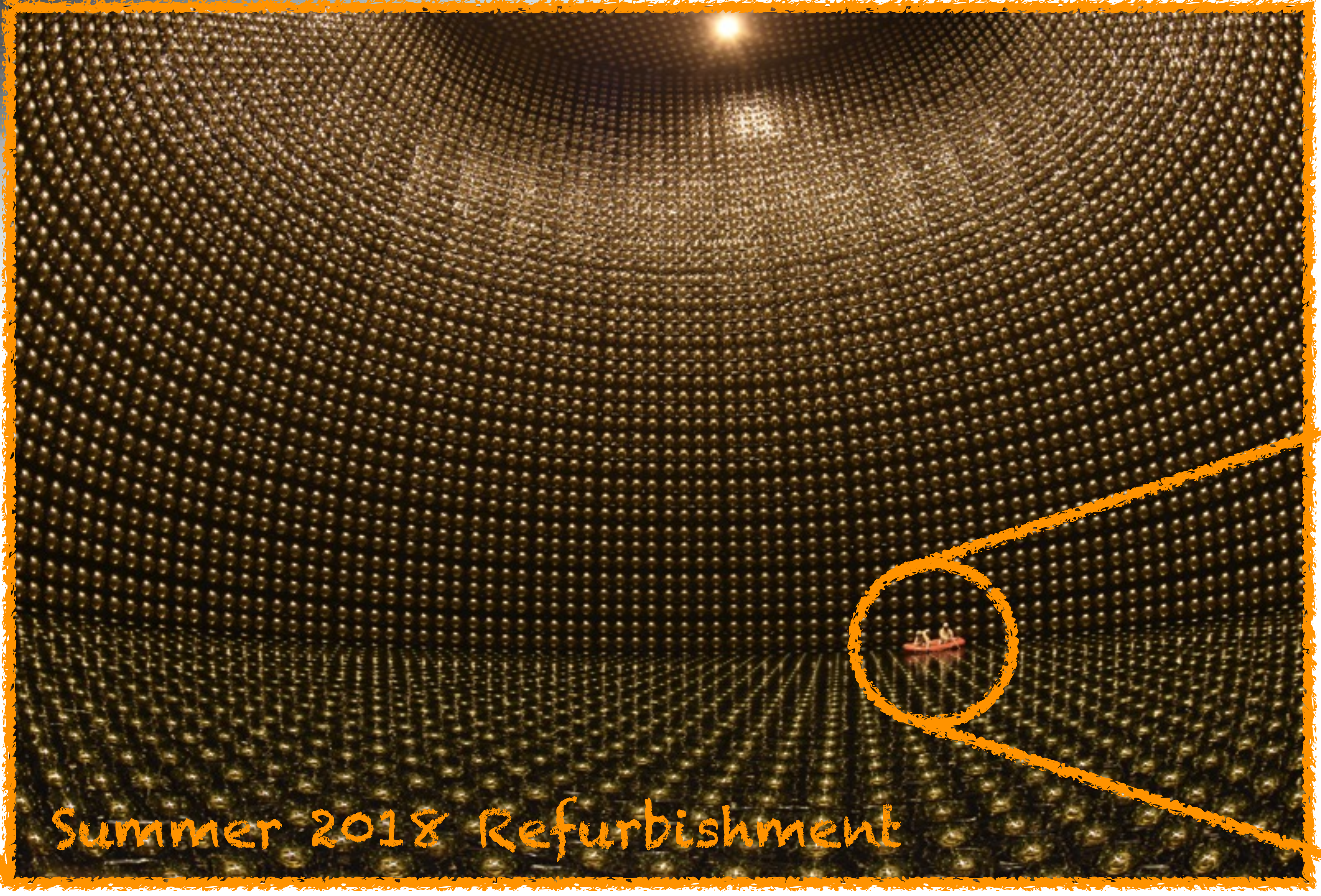
The Super-Kamiokande detector



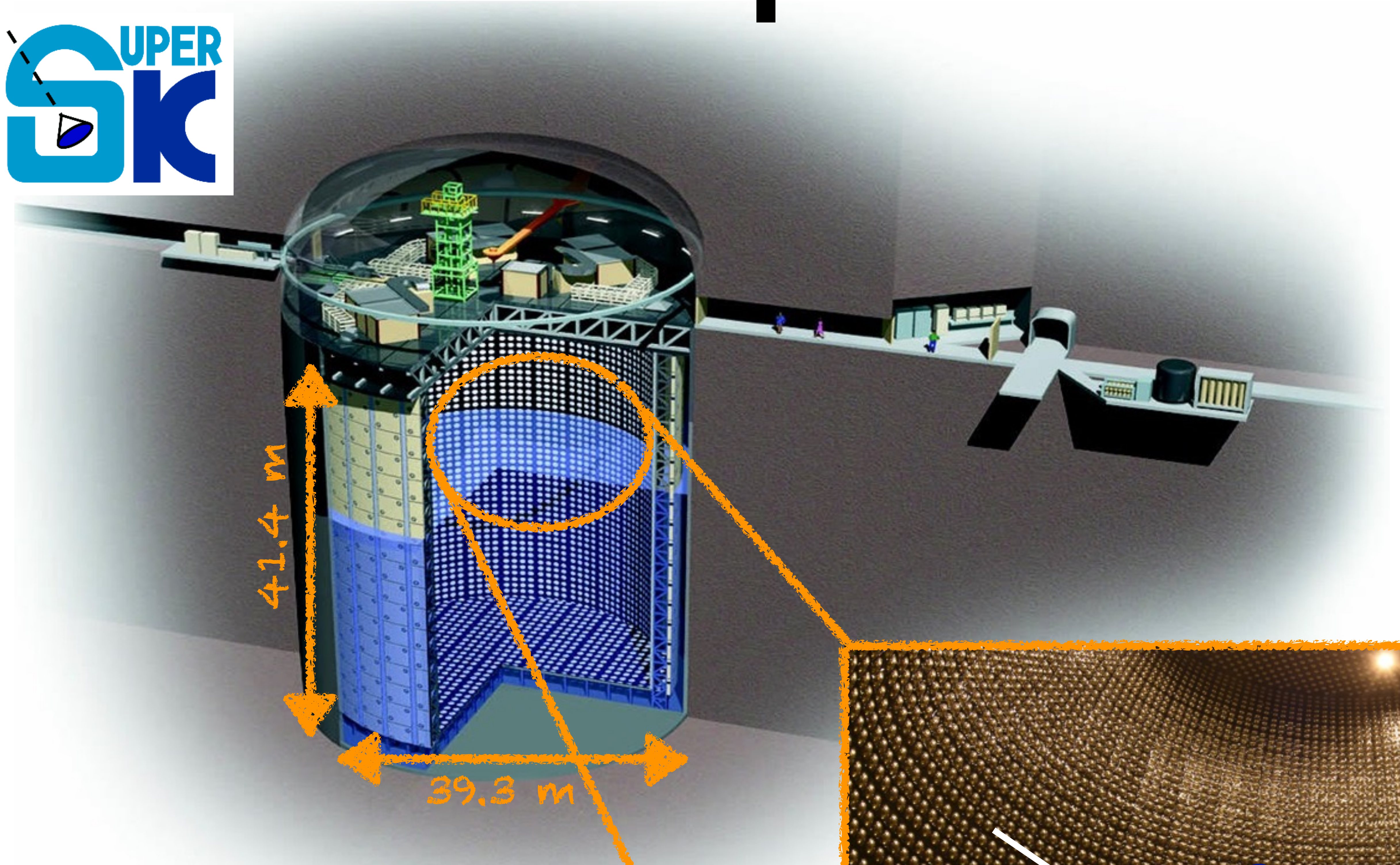
For more details on Gd loading, see the talk from Neutrino 2020 (click here)

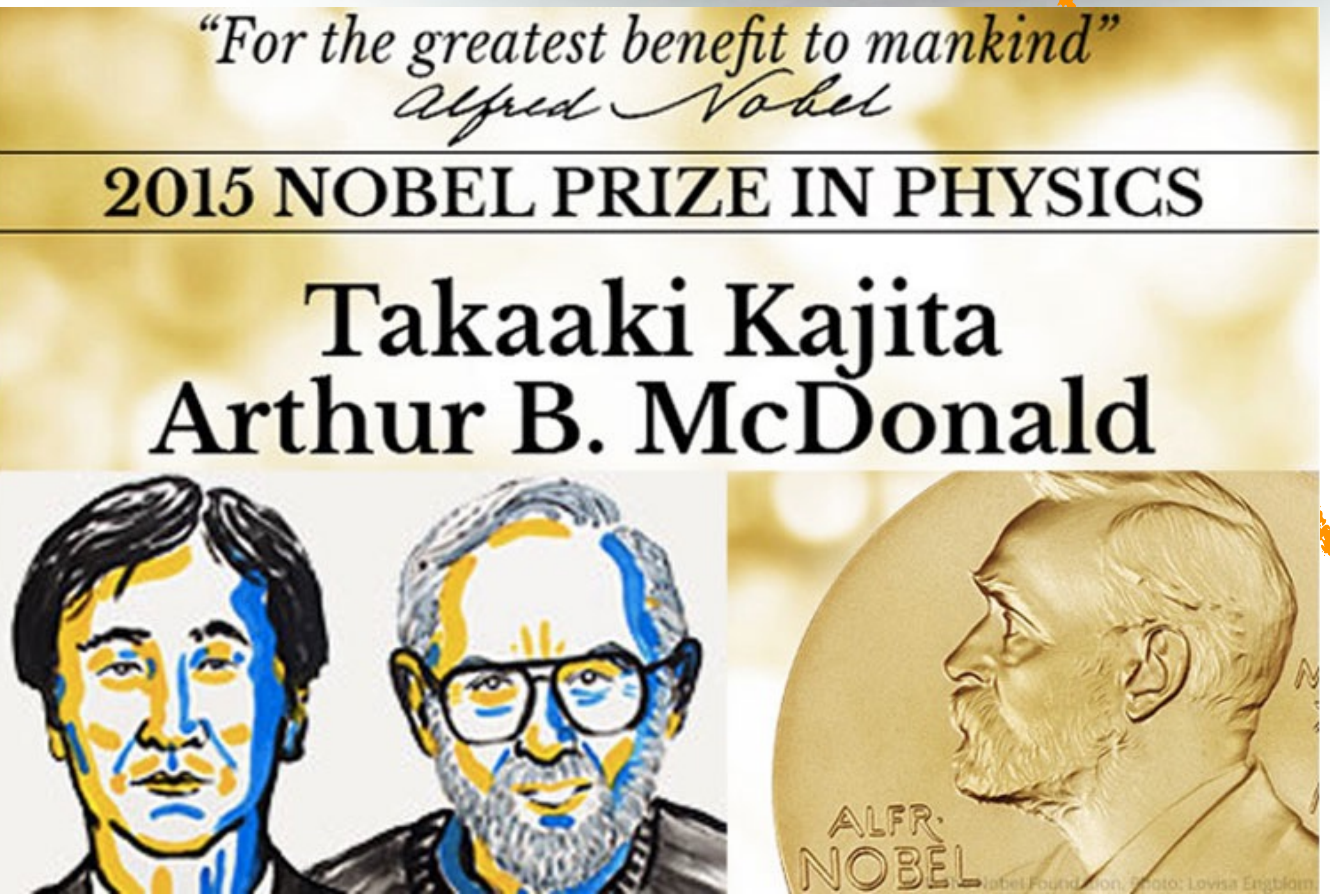
- 50 kt water Cherenkov detector, sensitive to beam, atmospheric, solar, supernova neutrinos
- 11k 20” inner and 1.8k 8” outer (veto) tank PMTs
- Now Gd loaded for enhanced neutron detection, with the potential to separate between ν and $\bar{\nu}$ interactions

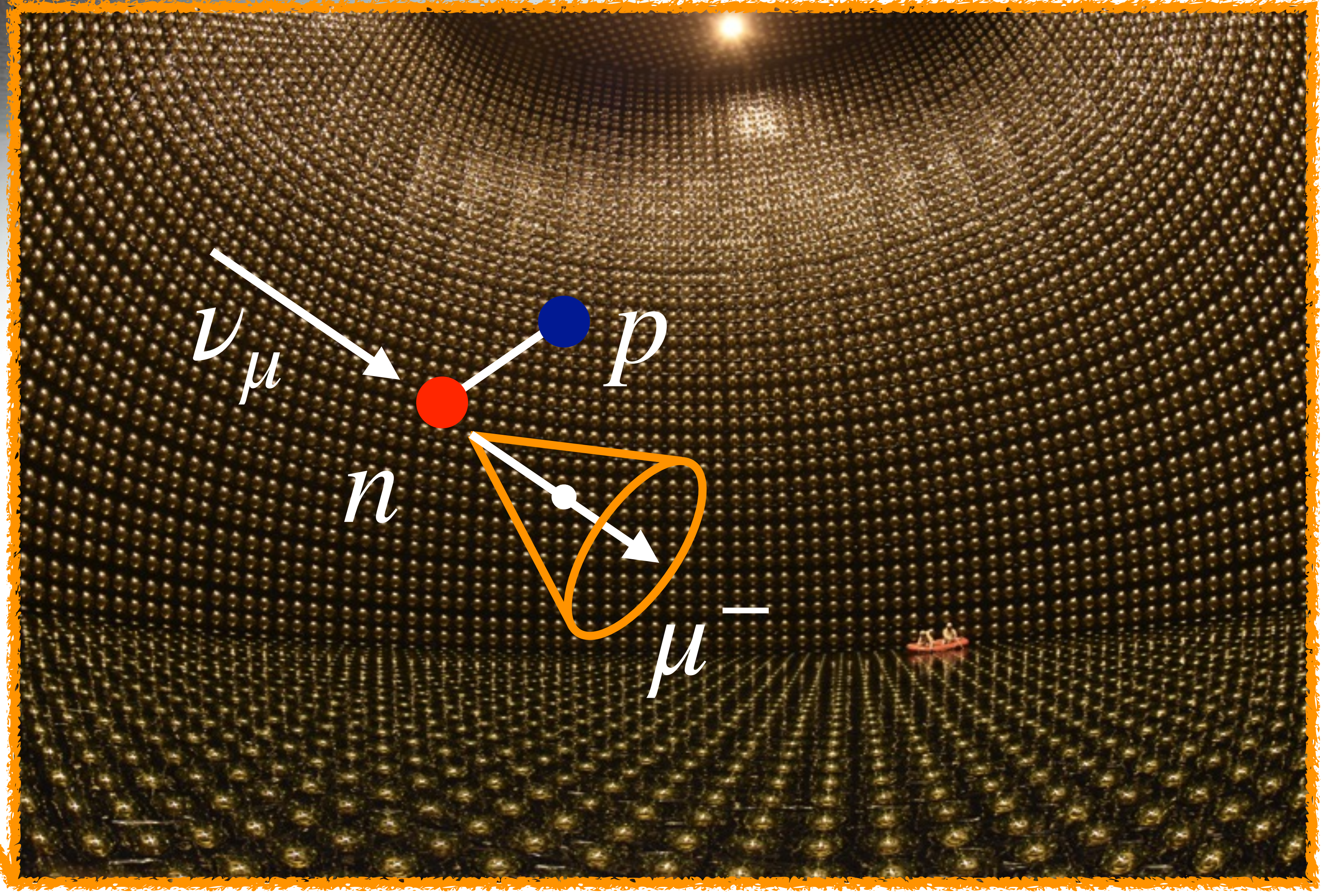


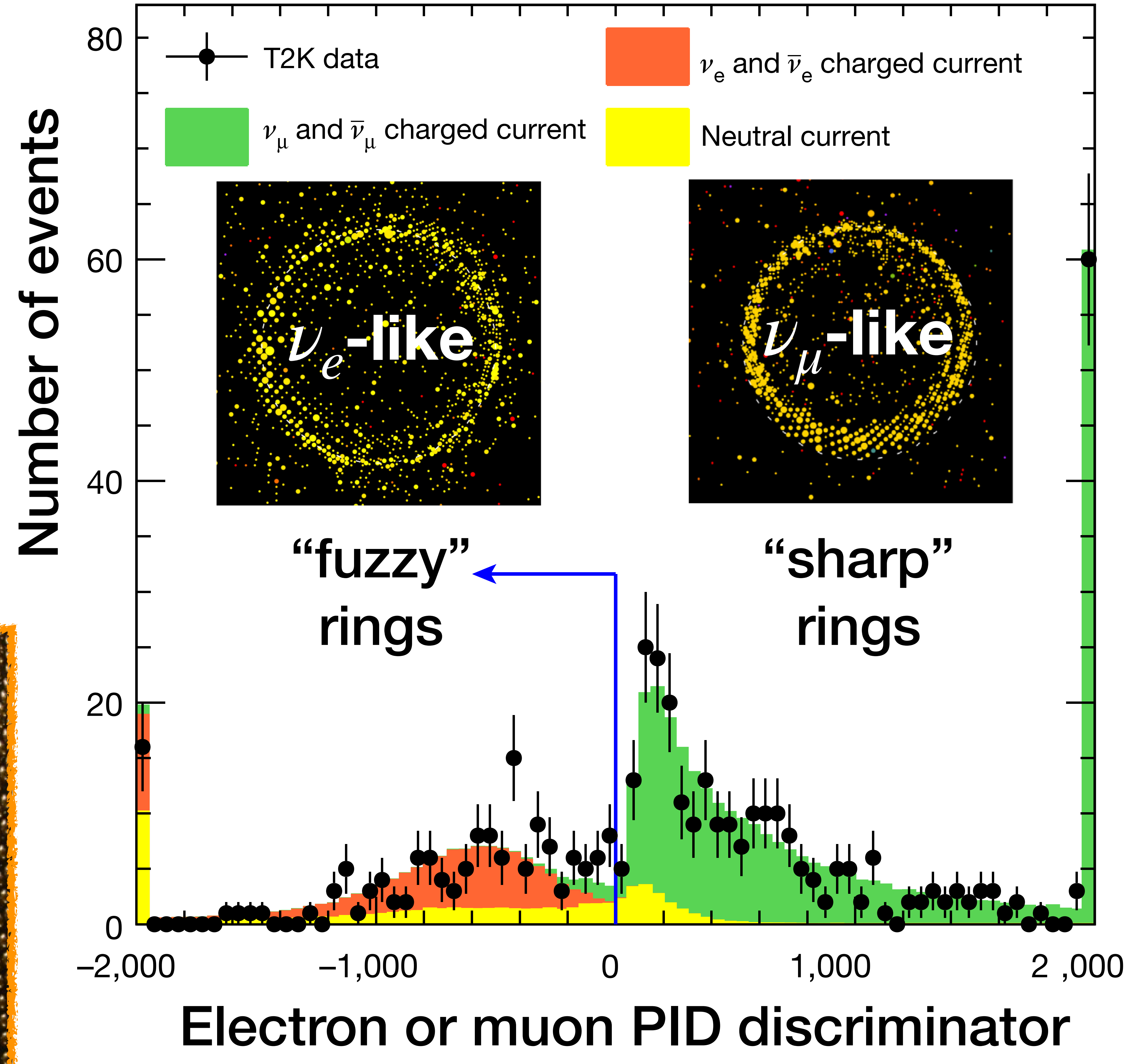


The Super-Kamiokande detector









PID based on "fuzziness" of Cherenkov rings

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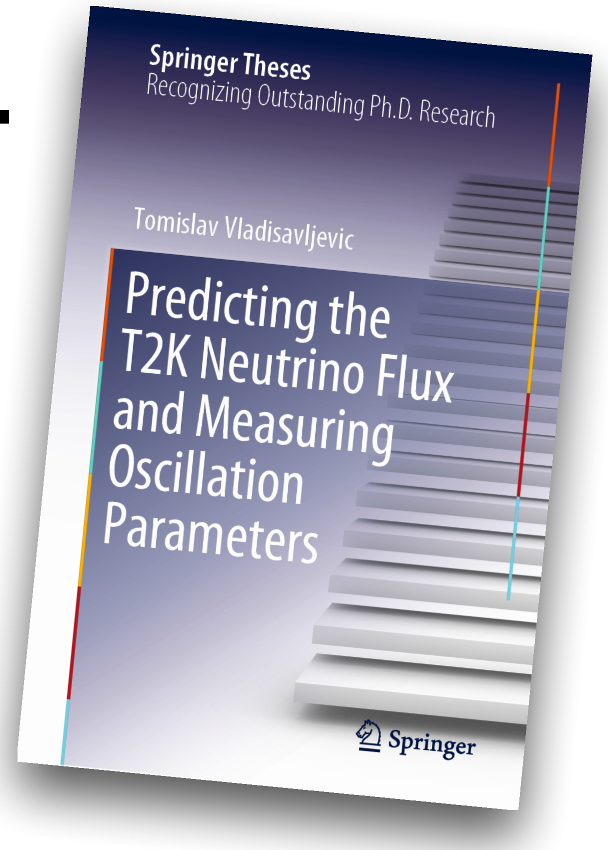
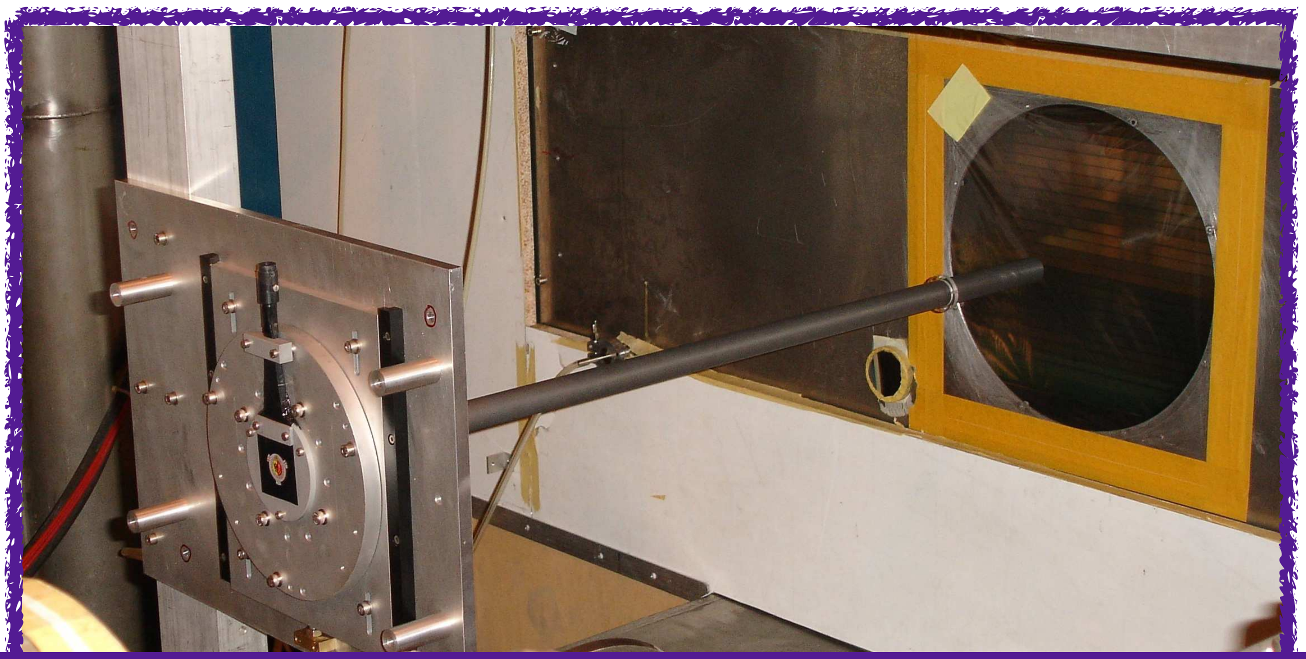
Analysis strategy: flux model

NA61/SHINE data → Neutrino flux model ← T2K beam monitor and INGRID data

- **The addition of NA61 replica-target data reduces the T2K flux prediction uncertainty from ~10% to ~6% in the latest analysis**

(click here for more details)

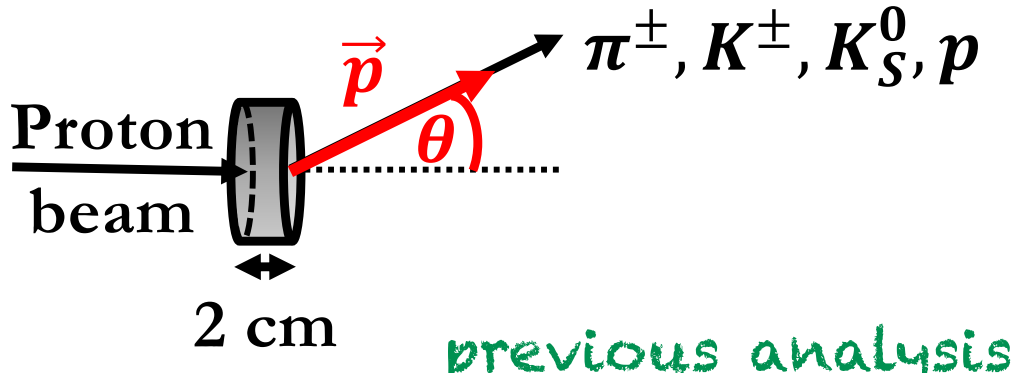




T2K replica-target mounted at NA61

External NA61 hadron production data usage:

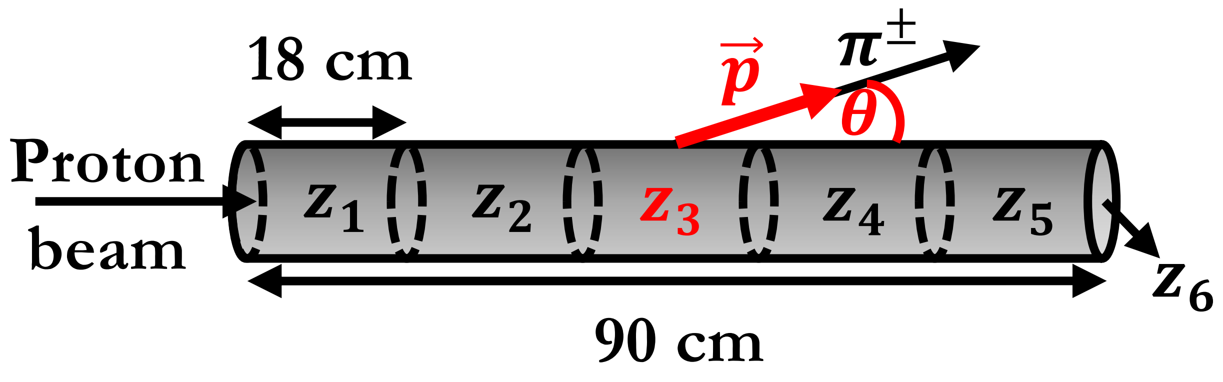
Thin-target data:



previous analysis

+

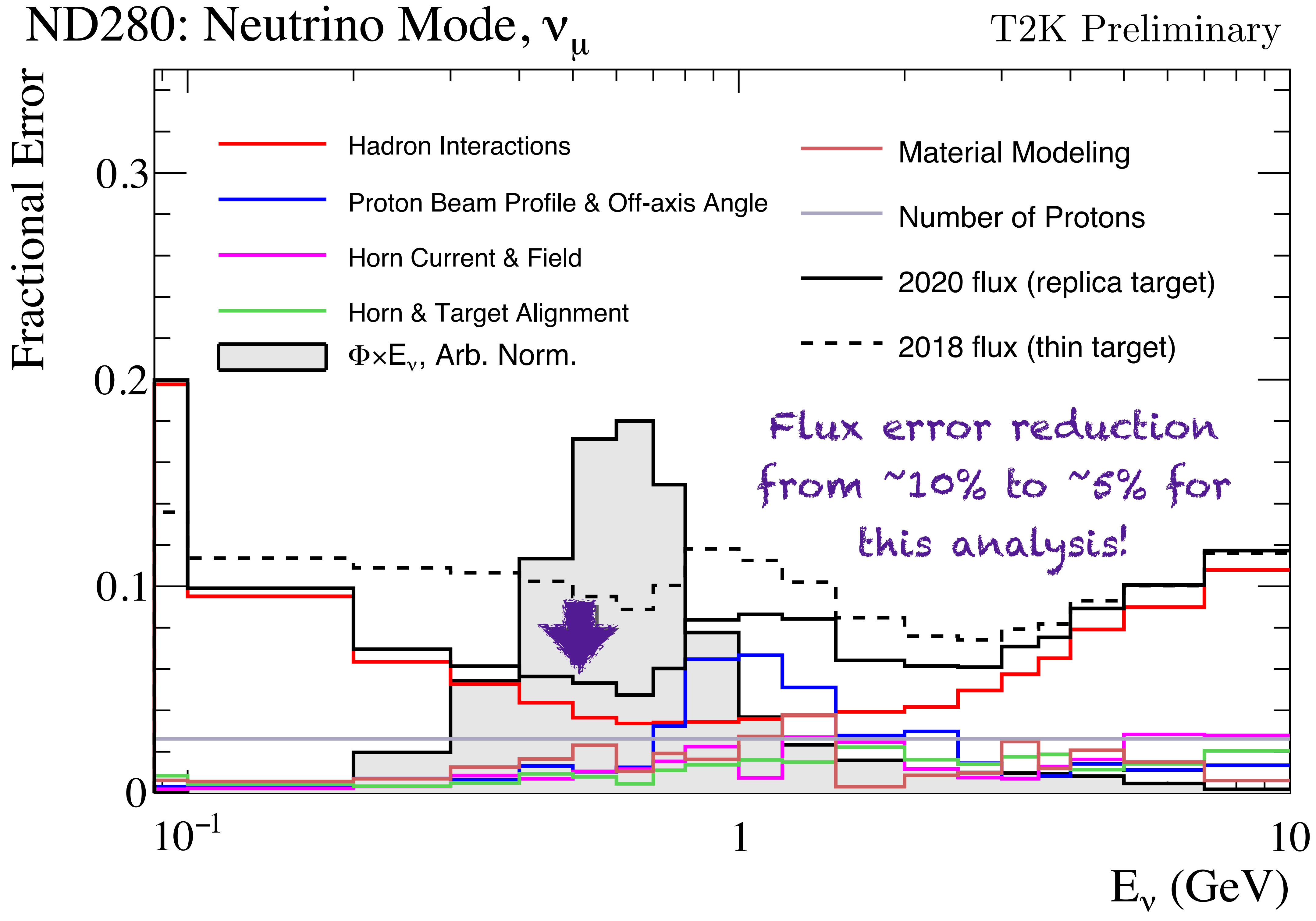
Replica-target data:



current analysis

NA61 2009 thin-target data:
Eur. Phys. J. C 76, 84 (2016)

NA61 2009 replica-target data:
Eur. Phys. J. C 76, 617 (2016)



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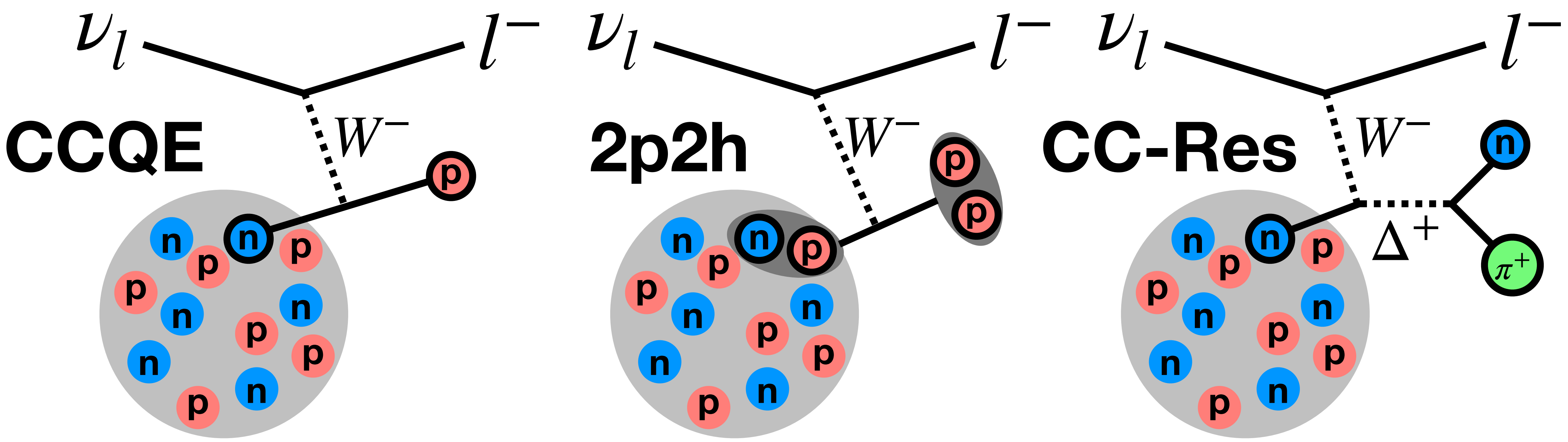
Analysis strategy: cross section model

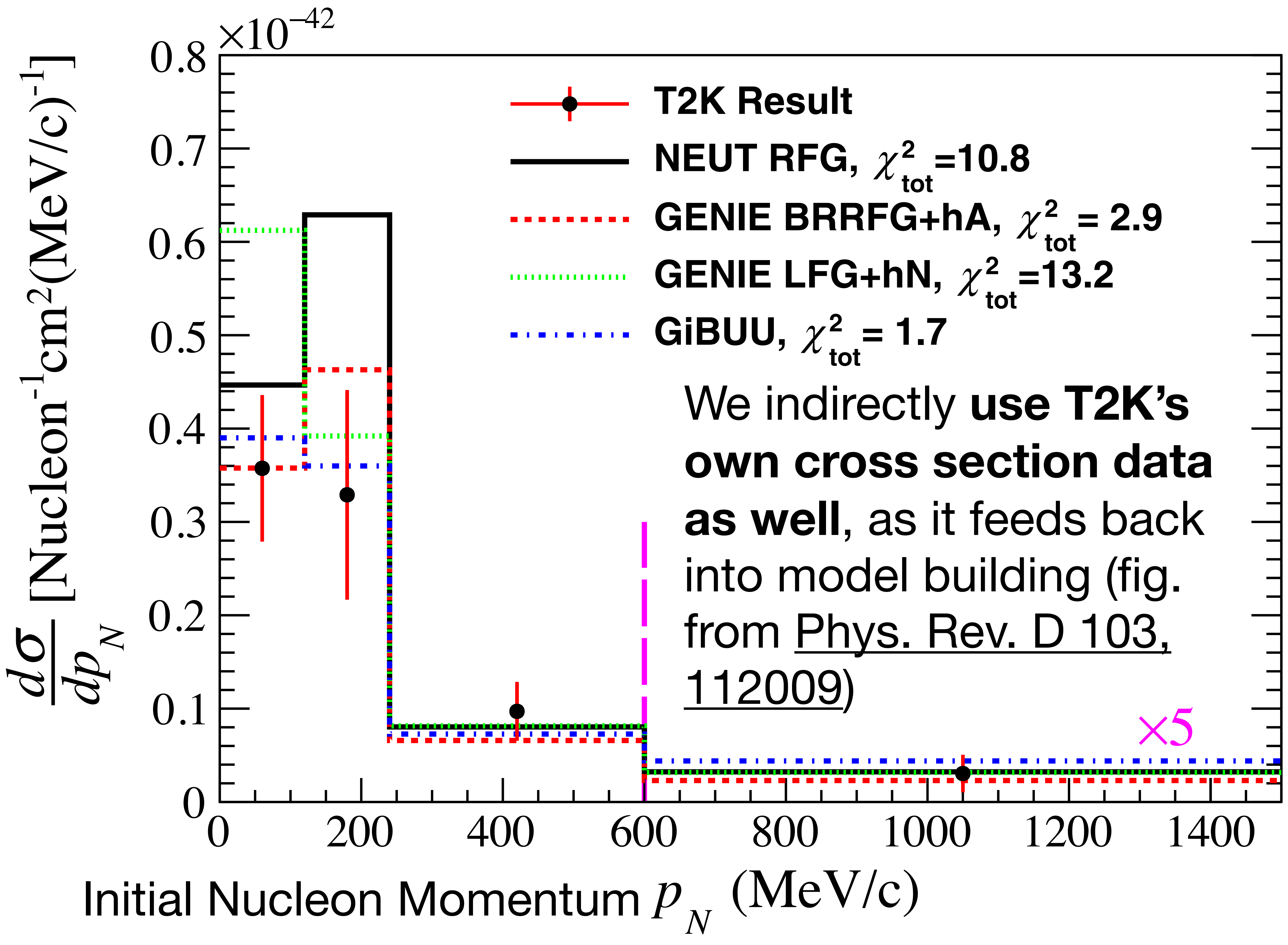
Neutrino cross-section model ← Cross-section data

- At ~0.6 GeV peak beam energy, neutrinos interact via **charged current quasi-elastic (CCQE)** scattering, with subdominant contributions from **multi-nucleon "2p2h"** and **resonant CC1π** scattering



- **Main update for our latest oscillation result: using the Spectral Function CCQE initial state nuclear model** (strongly favoured by electron scattering data)

- Some of the most useful data for our model is still bubble chamber data from the 1980s!



We indirectly **use T2K's own cross section data as well**, as it feeds back into model building (fig. from Phys. Rev. D 103, 112009)

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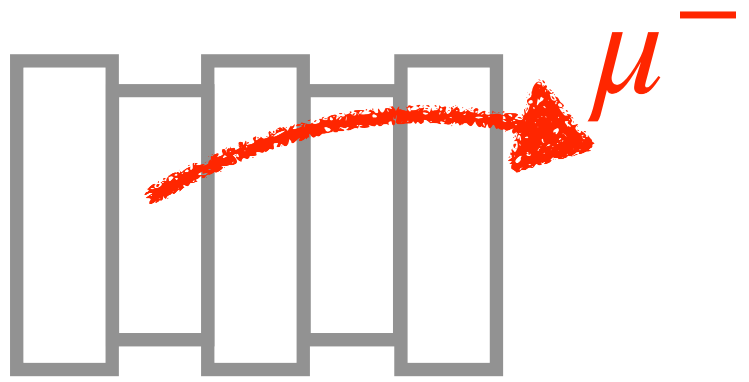
ND280 Analysis Samples

- $18 = 3 \times (1 + 2) \times 2$ classes of neutrino interactions defined at ND280, split by:
  - **3 Interaction Modes, based on pion content:** $CC0\pi$, $CC1\pi$, $CCOther$ $(CCN\pi, N > 1)$

No Pions

FGD1 ν_μ CC0π

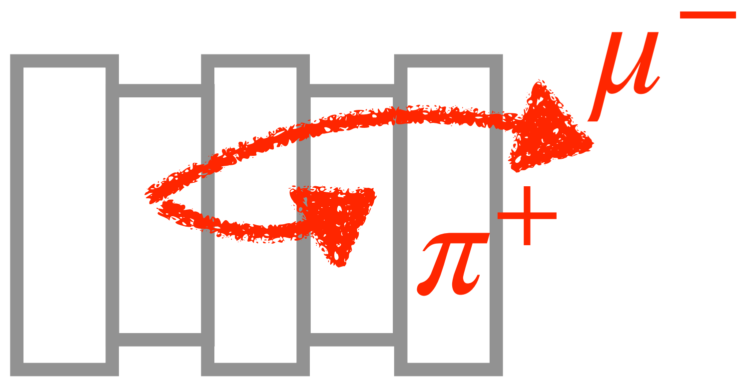
CCQE-enriched sample



One Pion

FGD1 ν_μ CC1π

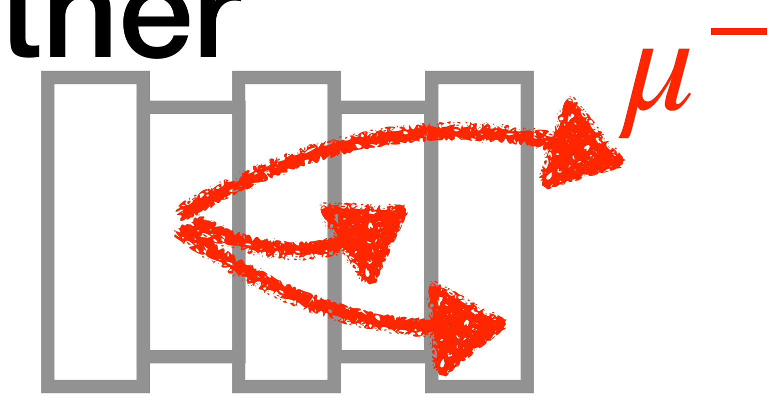
CC resonance production enriched sample

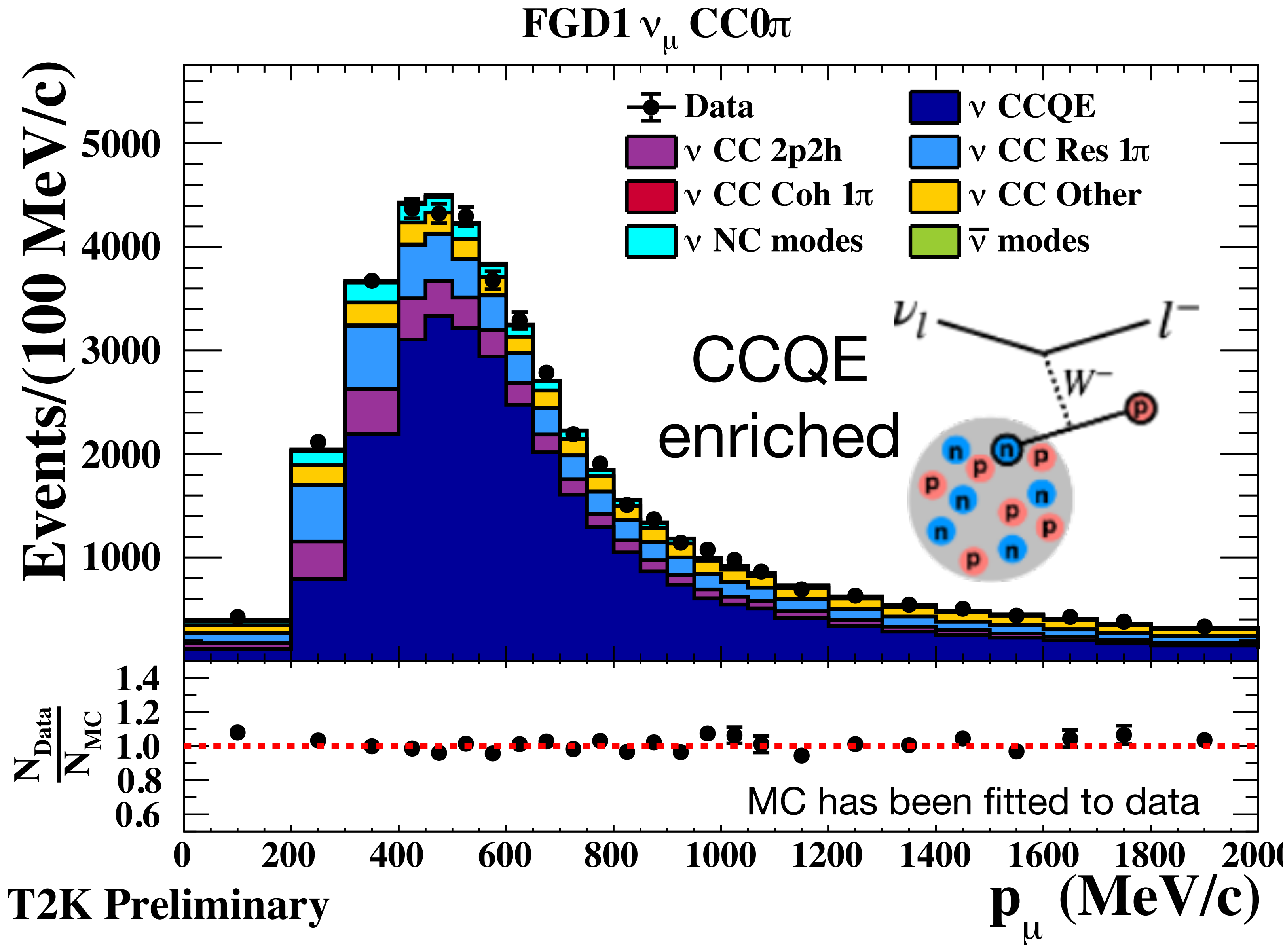


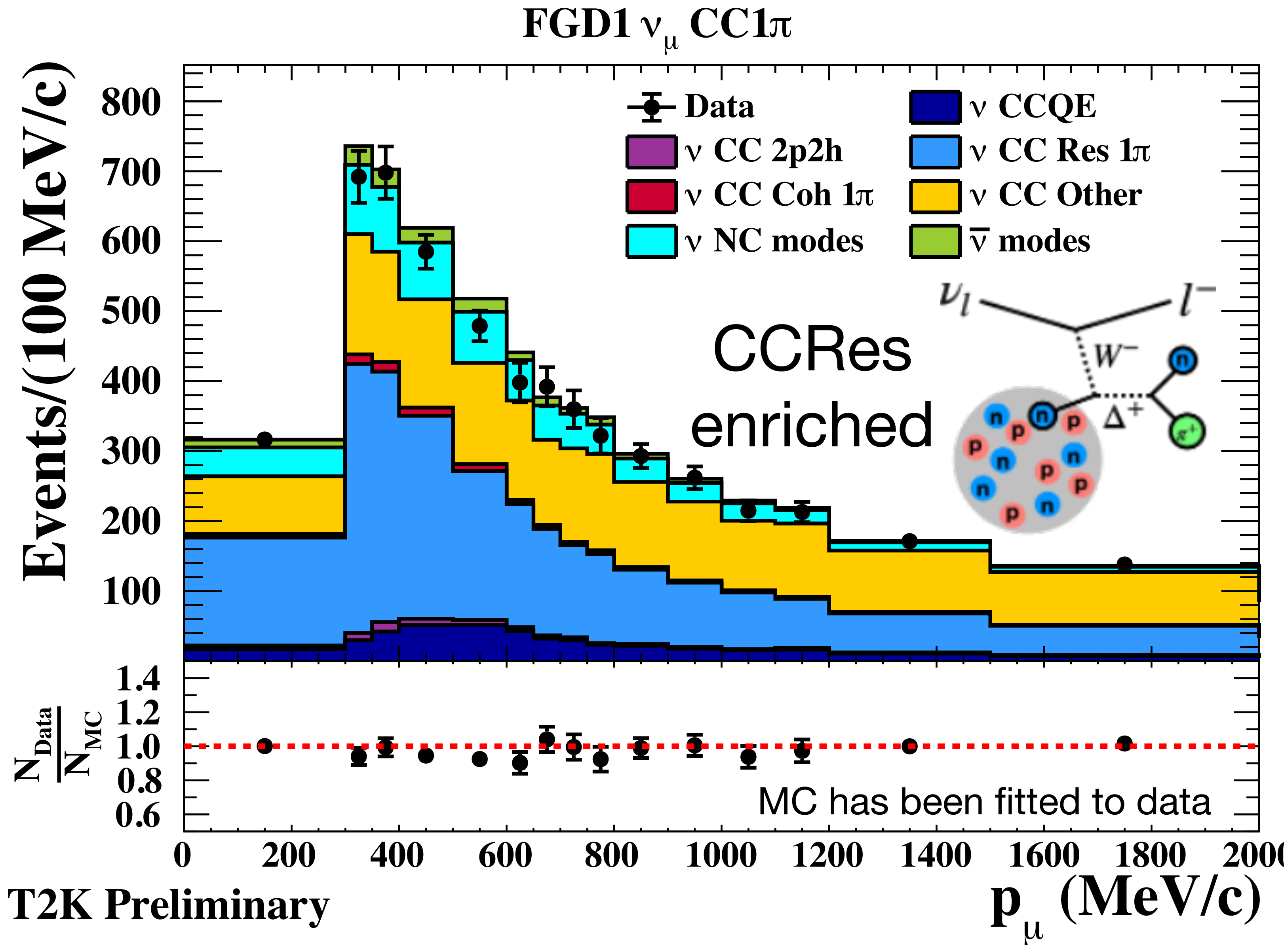
Multiple Pions

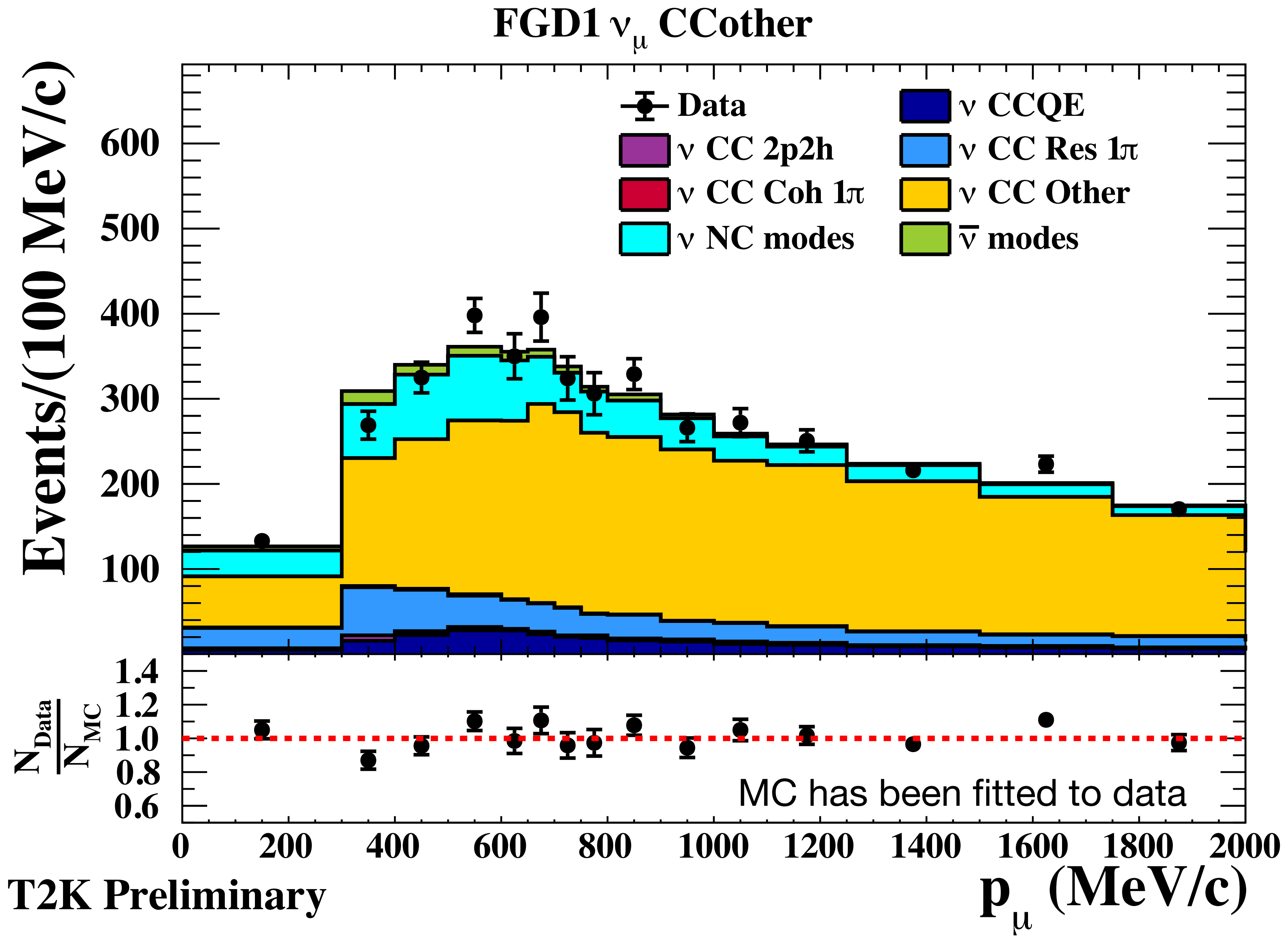
FGD1 ν_μ CCOther

Deep inelastic scattering enriched sample







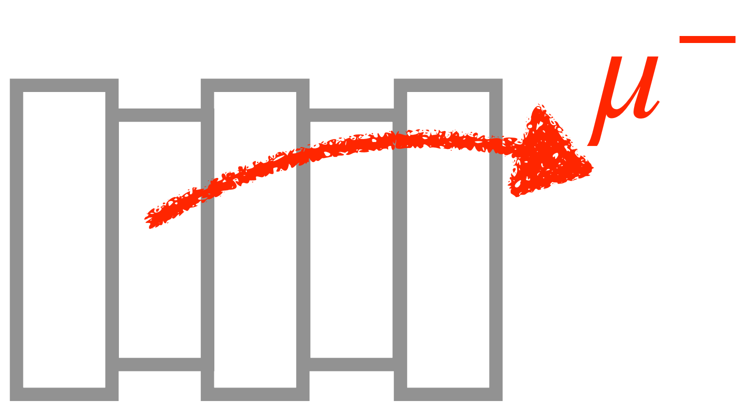


ND280 Analysis Samples

- $18 = 3 \times (1+2) \times 2$ classes of neutrino interactions defined at ND280, split by:
  - **1+2 Modes of Operation:** Neutrino (ν_μ signal) and Anti-neutrino ($\bar{\nu}_\mu$ signal and ν_μ background)
  - **Separation of anti-neutrino mode samples by pion content is a new feature of this analysis!**

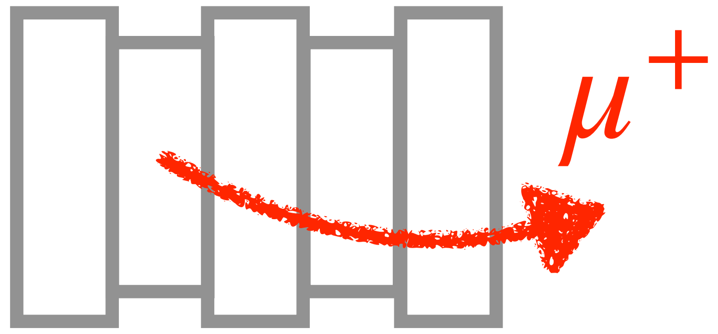
ν-Mode Signal

ν_μ in ν-Mode



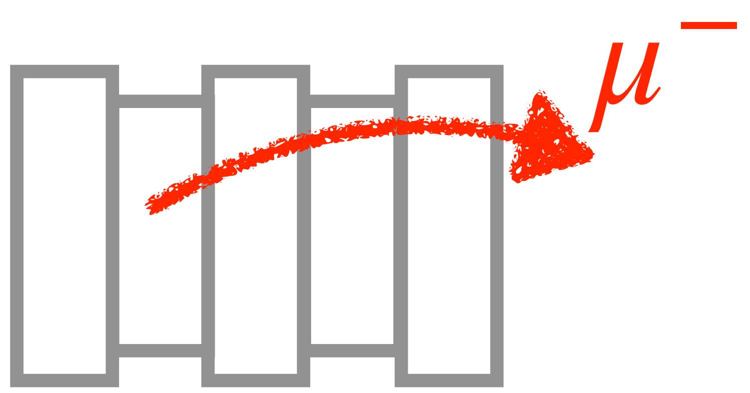
$\bar{\nu}$-Mode Signal

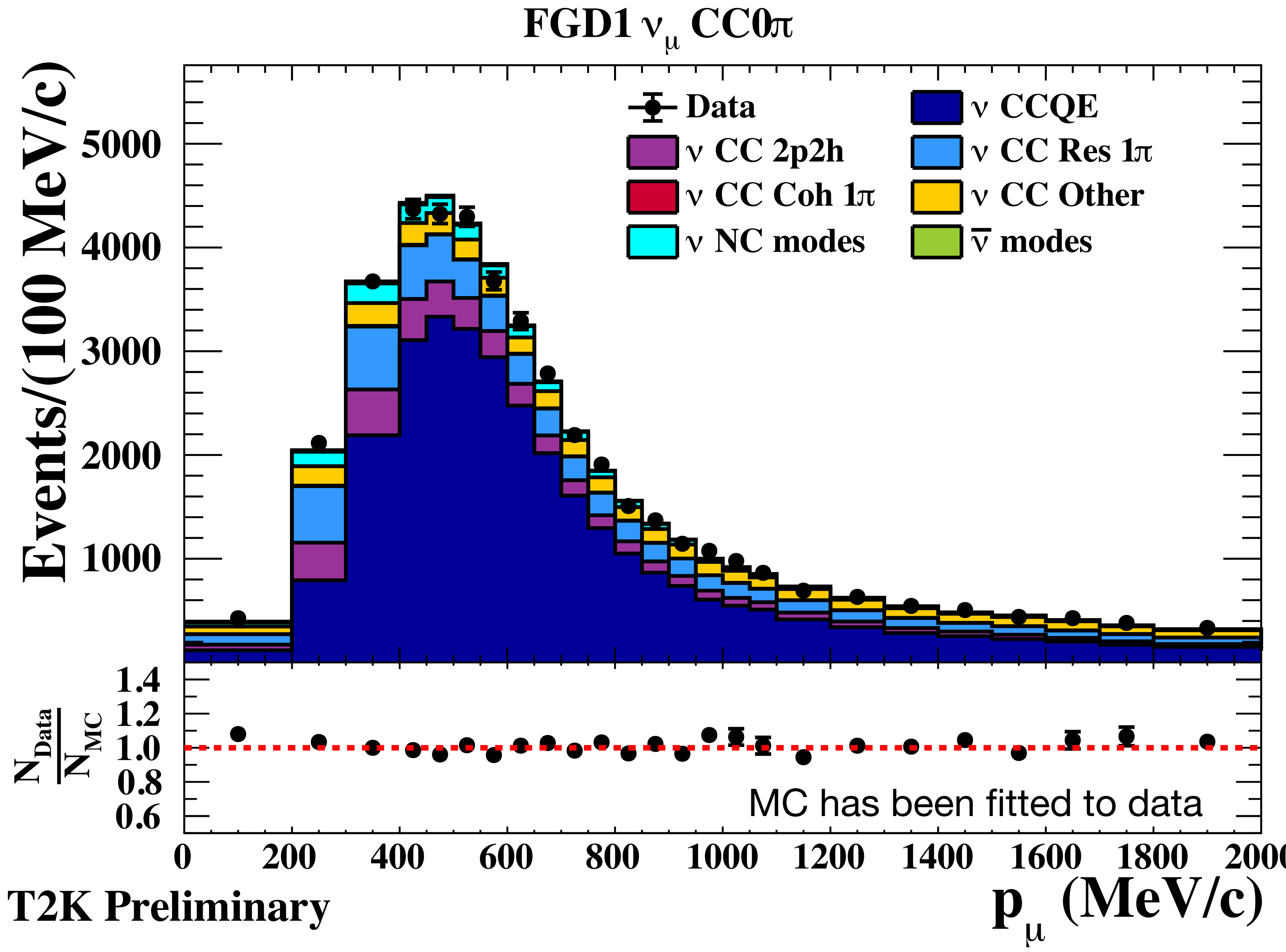
$\bar{\nu}_\mu$ in $\bar{\nu}$-Mode

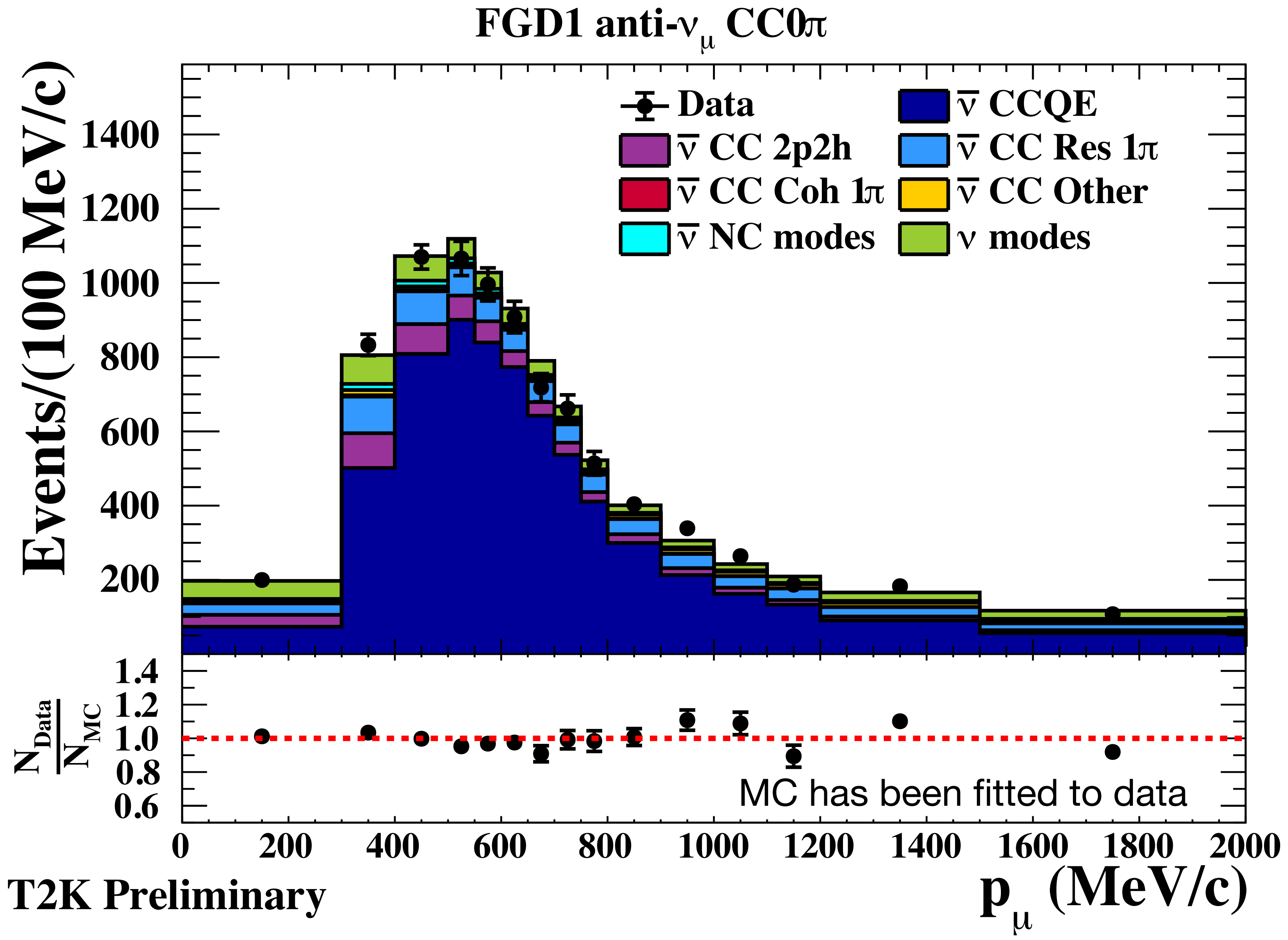


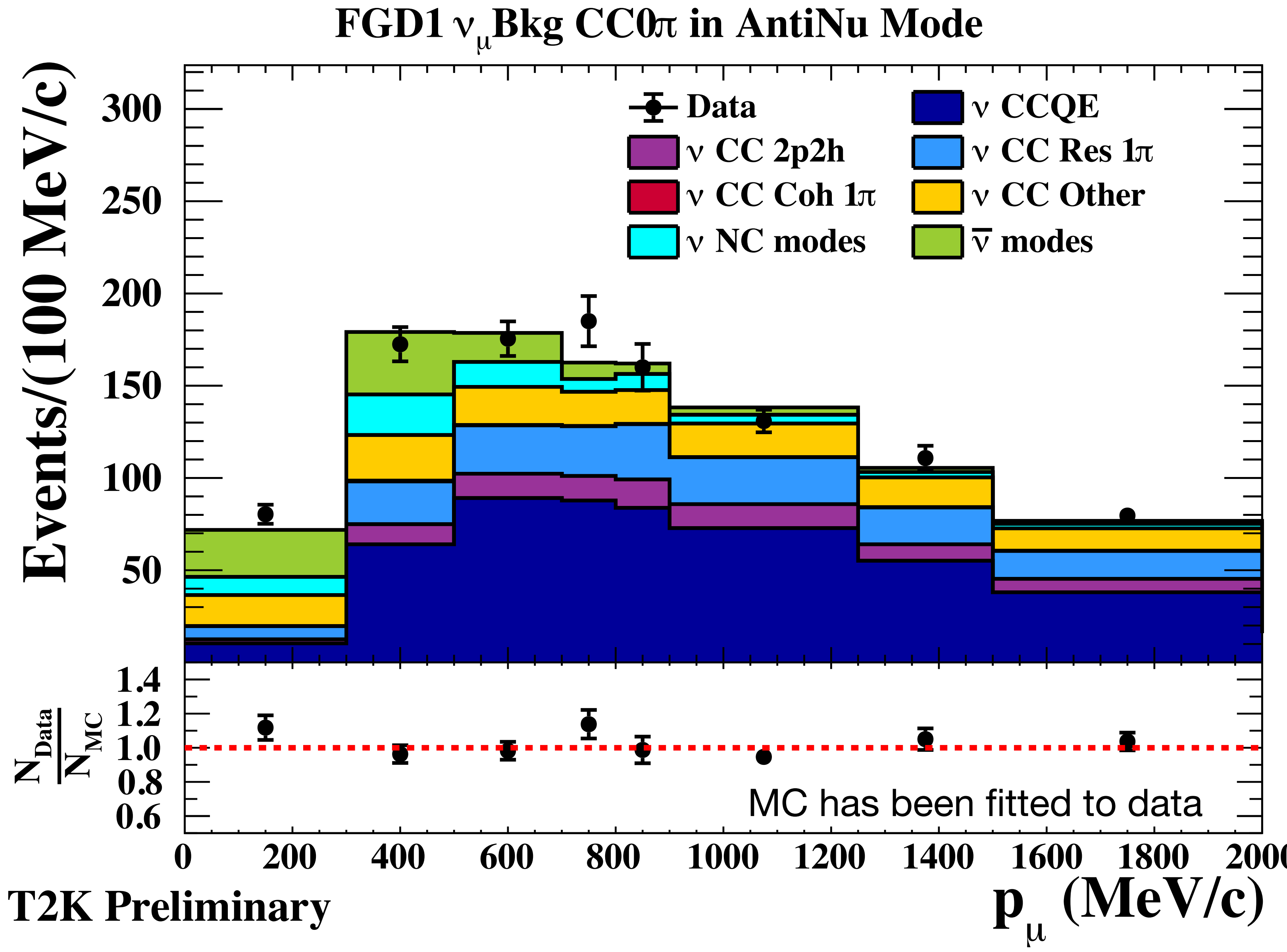
$\bar{\nu}$-Mode Wrong-Sign Background

ν_μ in $\bar{\nu}$-Mode









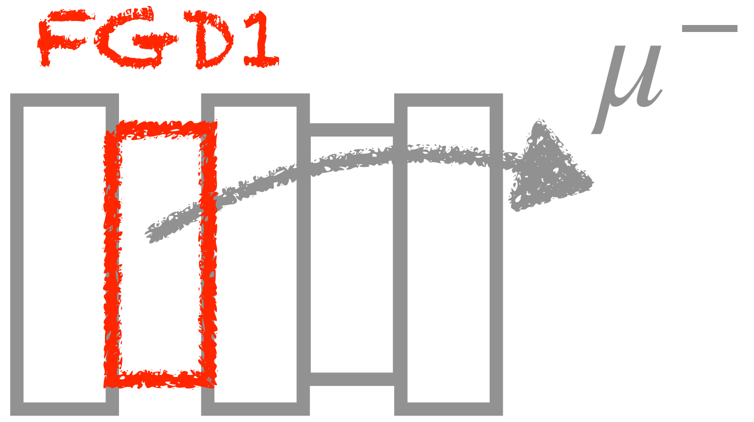
Constrains the wrong sign contamination

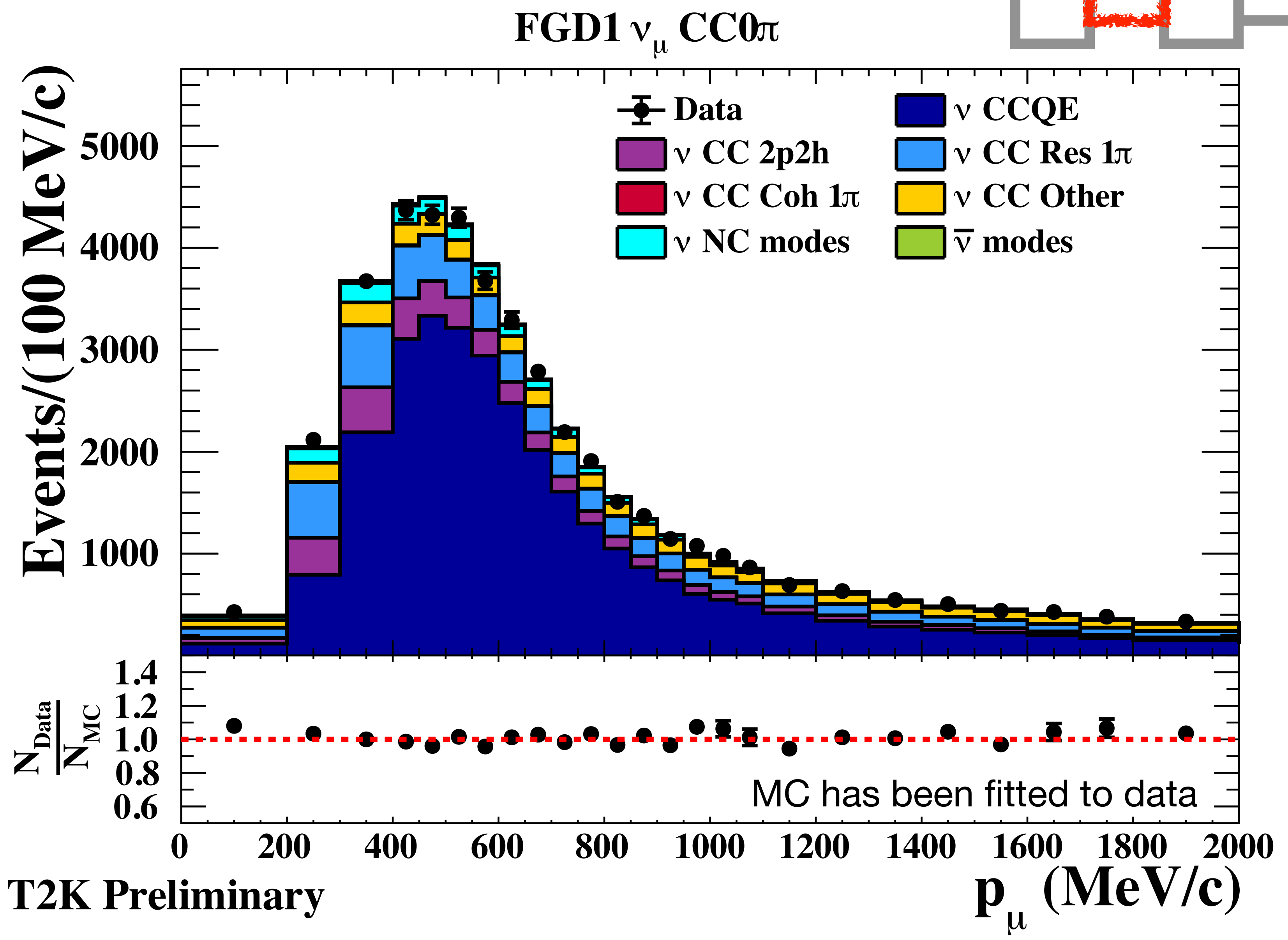
ND280 Analysis Samples

- $18 = 3 \times (1+2) \times 2$ classes of neutrino interactions defined at ND280, split by:
  - **2 Detectors (Target Materials):** FGD1 (C) and FGD2 (C+O)

Polystyrene Scintillator $(C_6H_5CHCH_2)_n$ Target

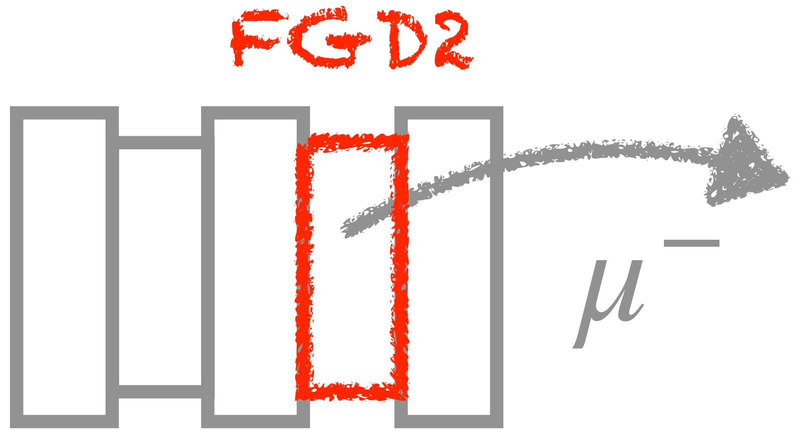
ν_μ CC0π in FGD1

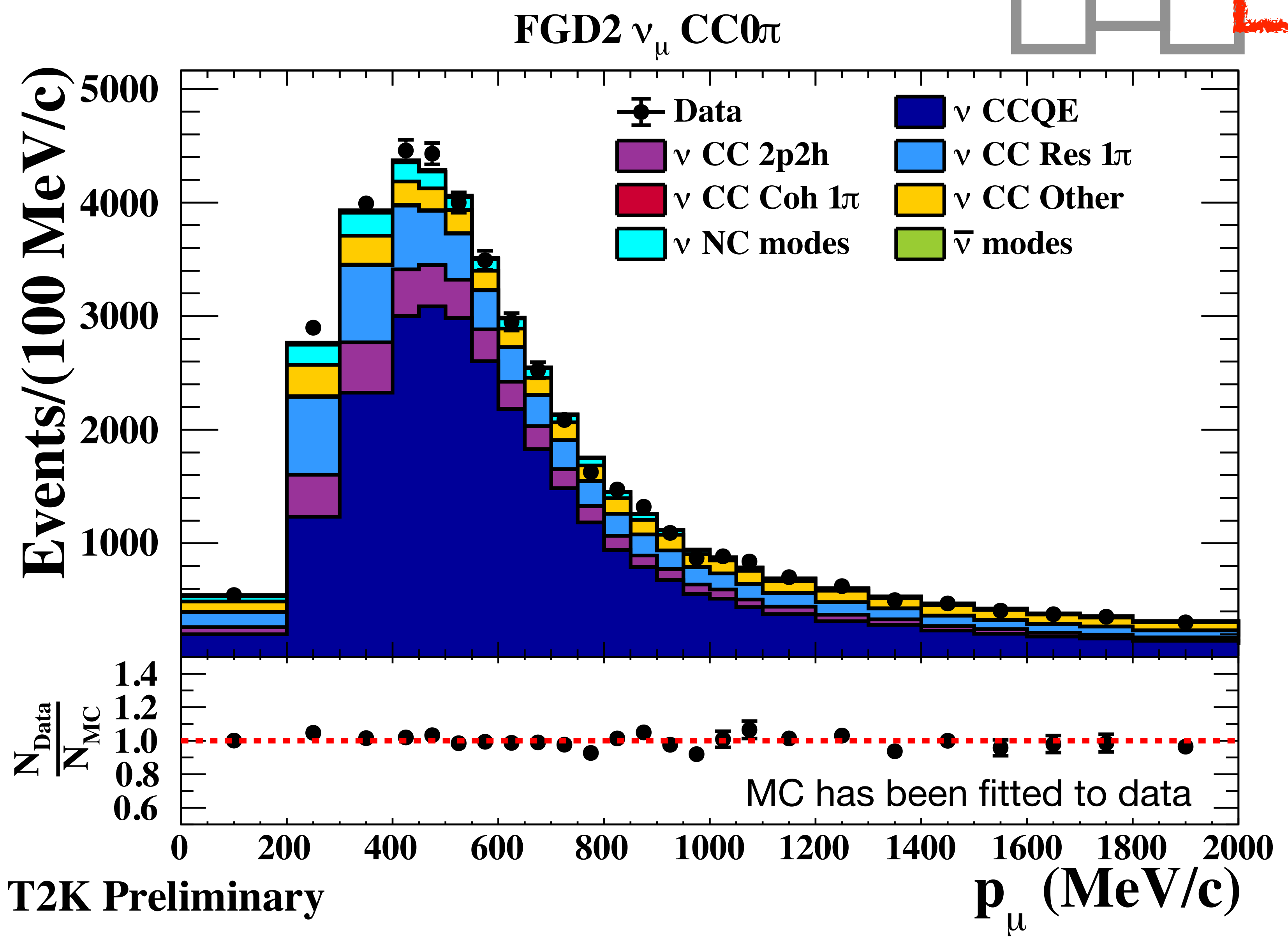




Polystyrene Scintillator $(C_6H_5CHCH_2)_n$ + Water Target

ν_μ CC0π in FGD2



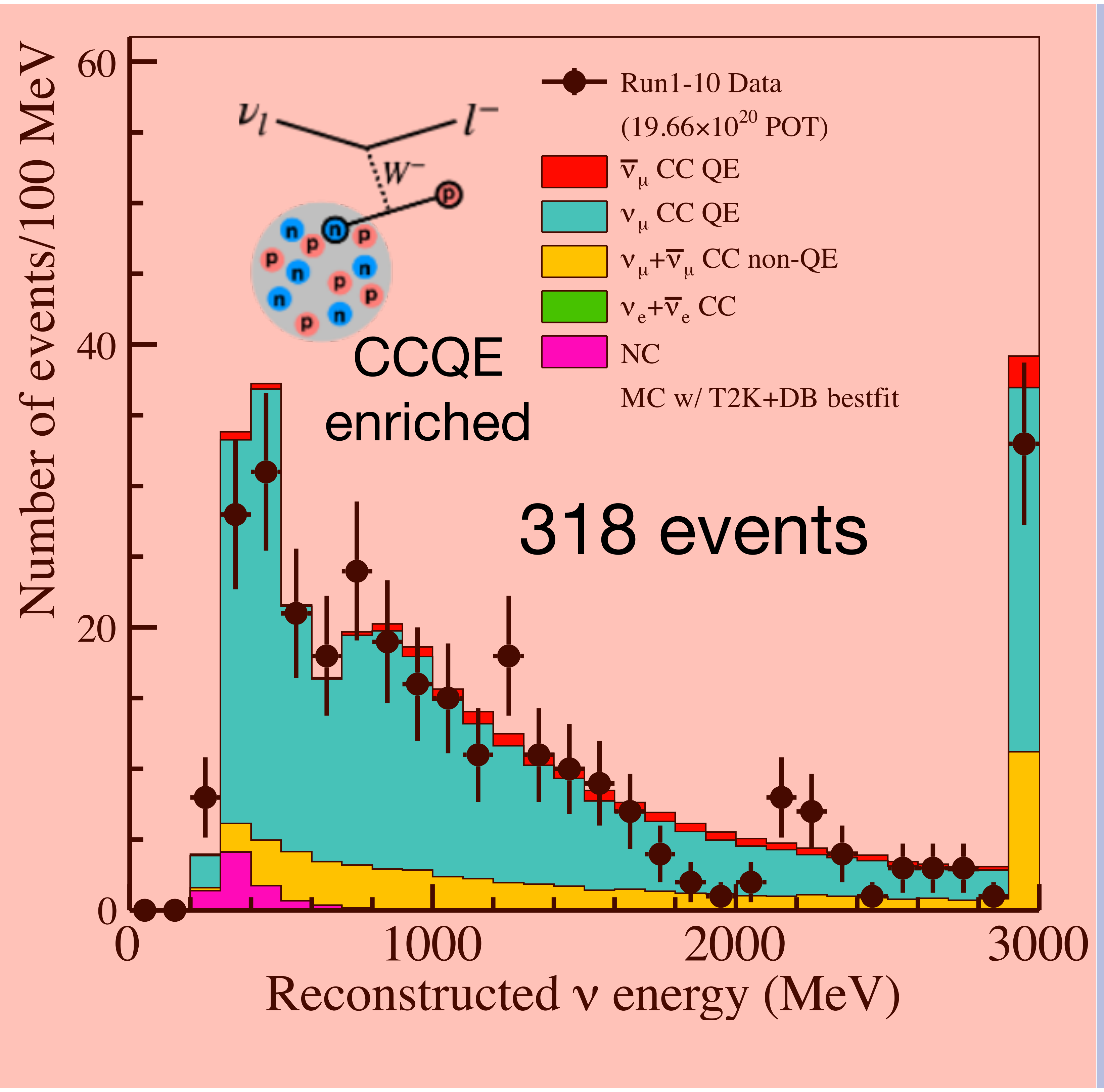


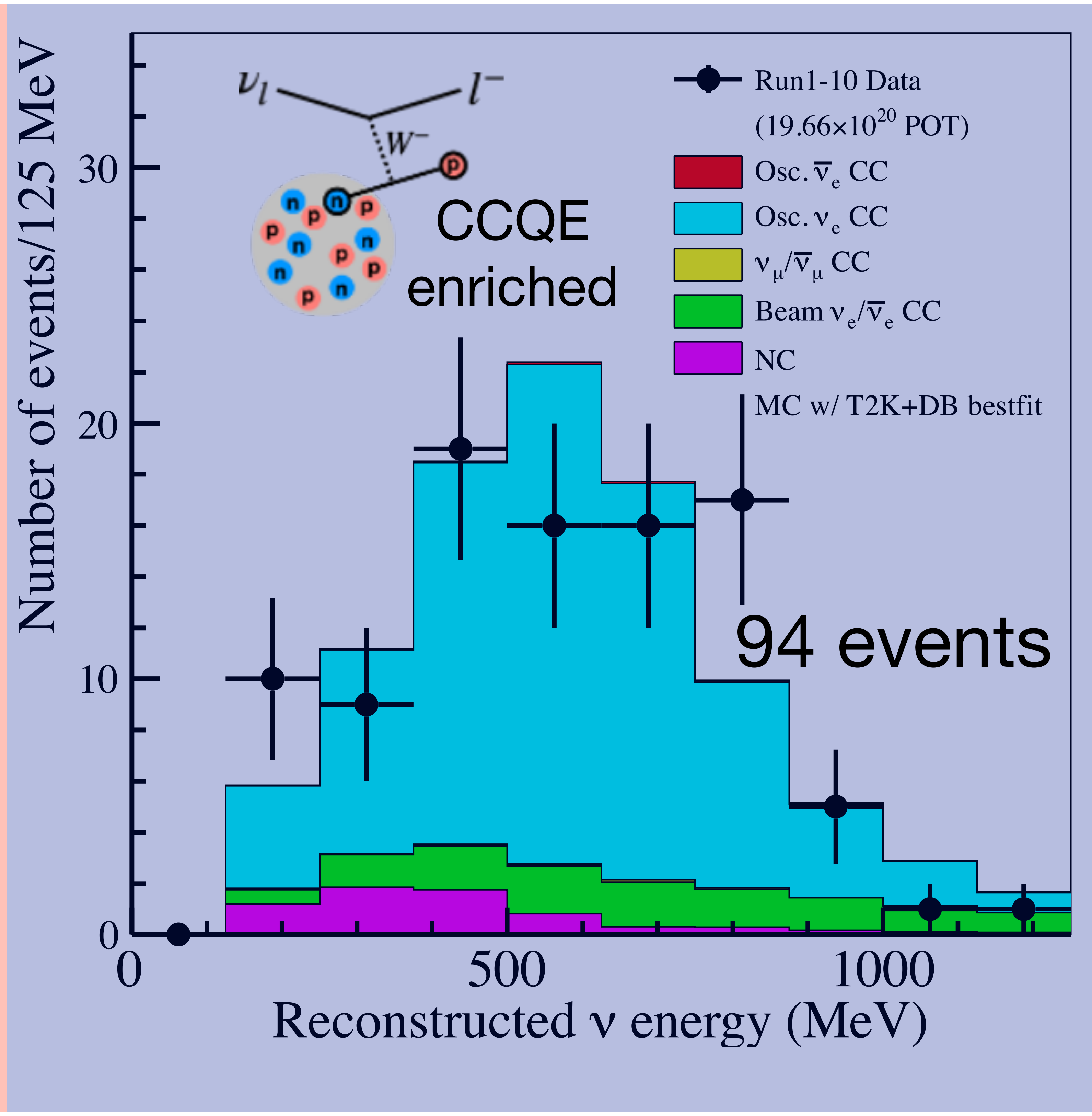
Super-K data samples: neutrino mode

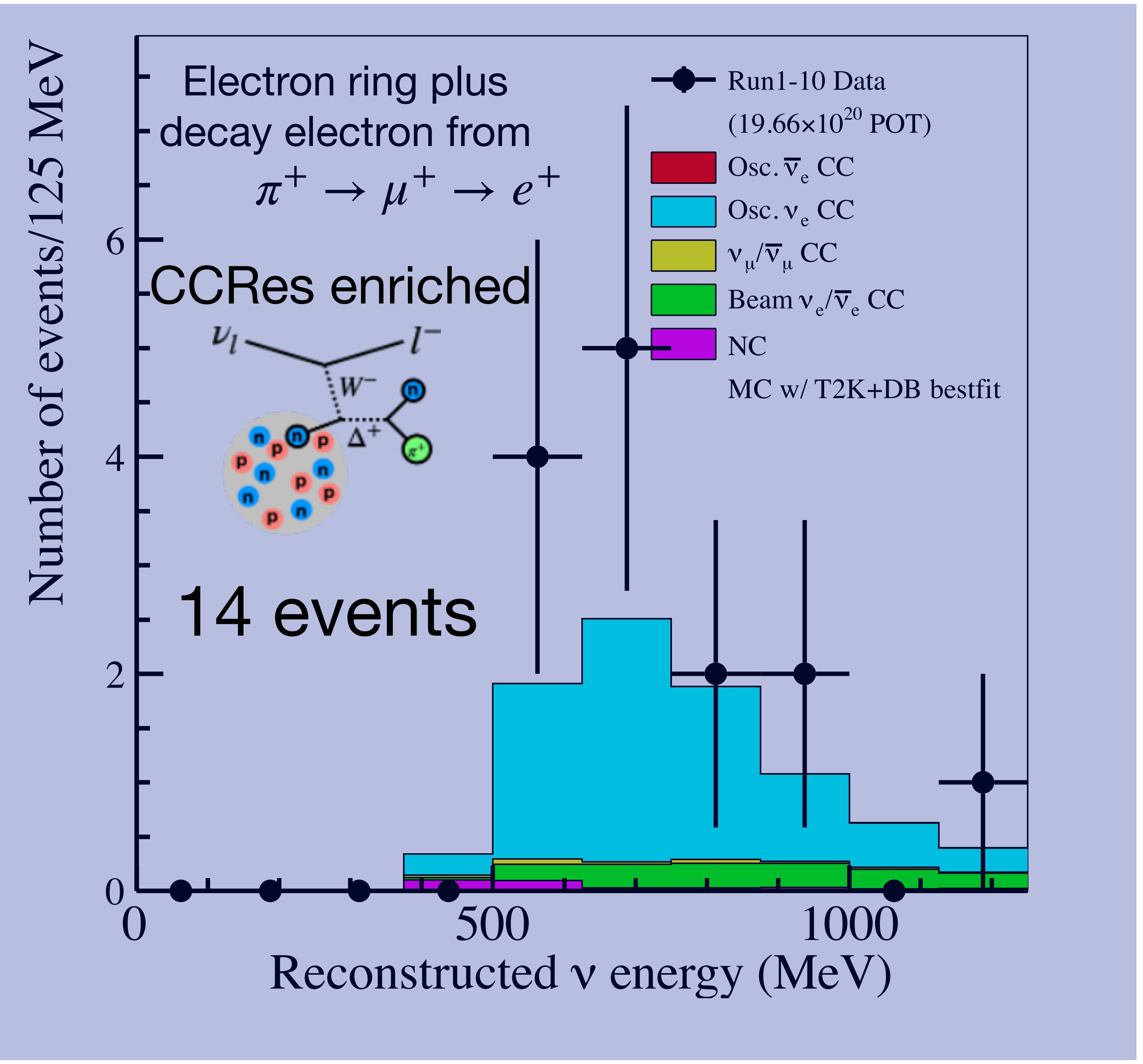
CC0π muon-like:
1 muon-like ring

CC0π electron-like:
1 electron-like ring

CC1π electron-like:
1 electron-like ring + 1 Michel electron







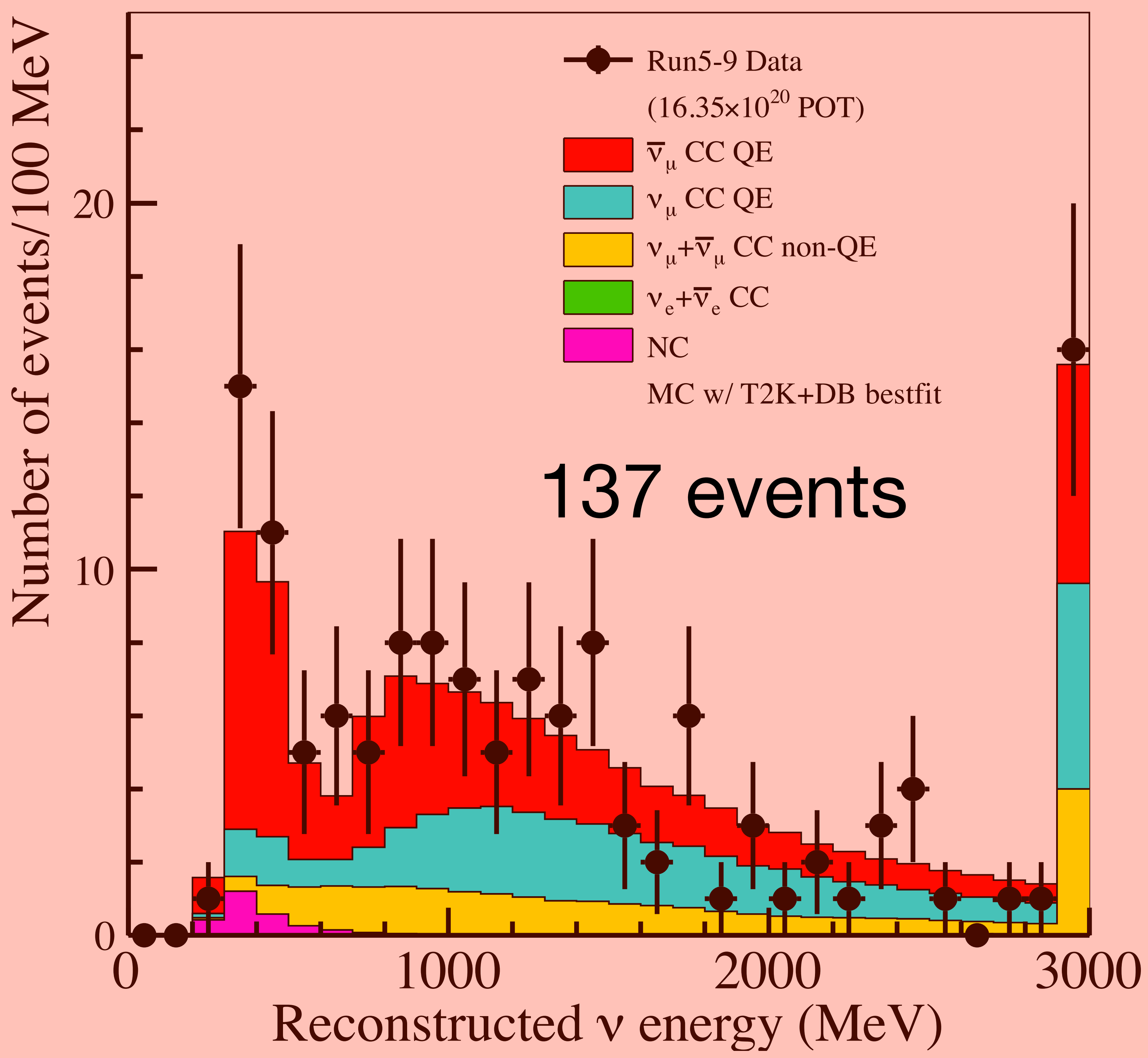
Direct probe of muon neutrino survival

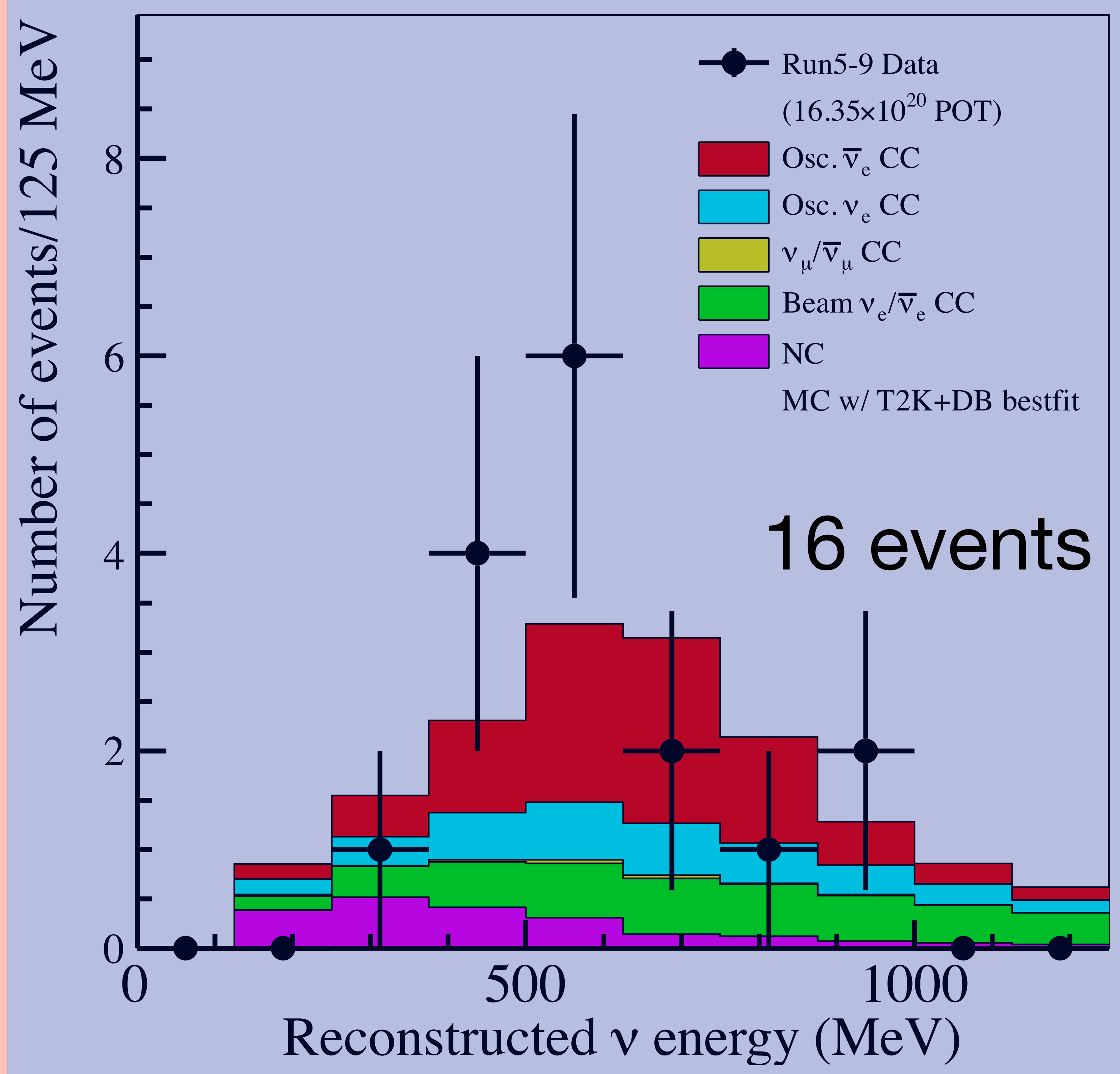
Direct probes of electron neutrino appearance

Super-K data samples: anti-neutrino mode

CC0π muon-like:
1 muon-like ring

CC0π electron-like:
1 electron-like ring



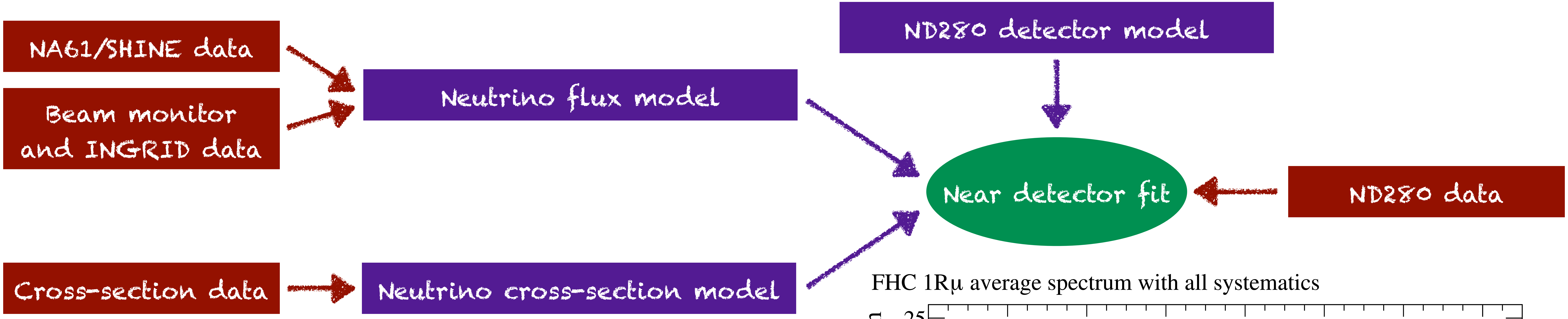


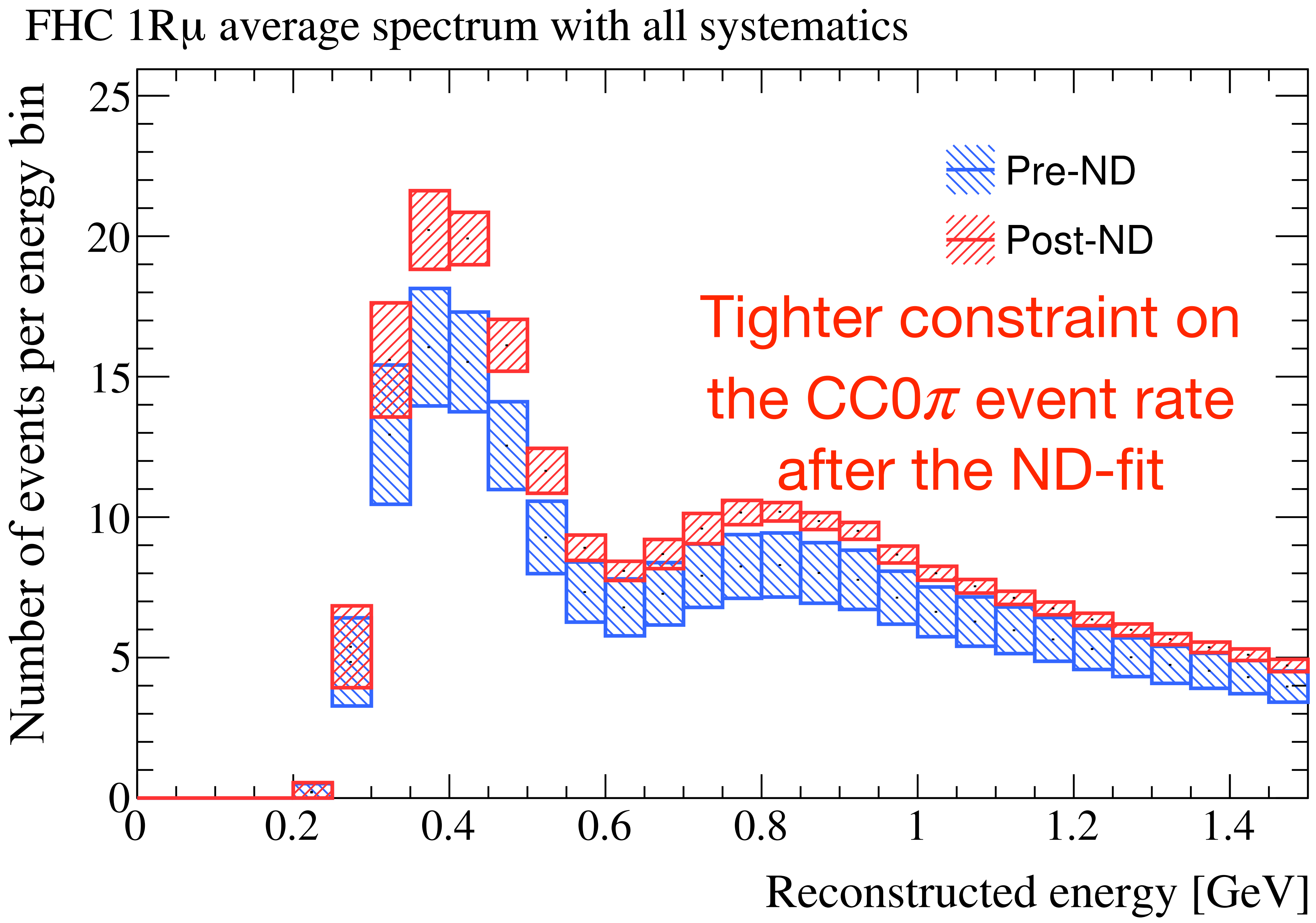
No CC1π electron-like sample in anti-neutrino mode, because of the high absorption of π^- in water

Direct probe of muon neutrino survival

Direct probe of electron neutrino appearance

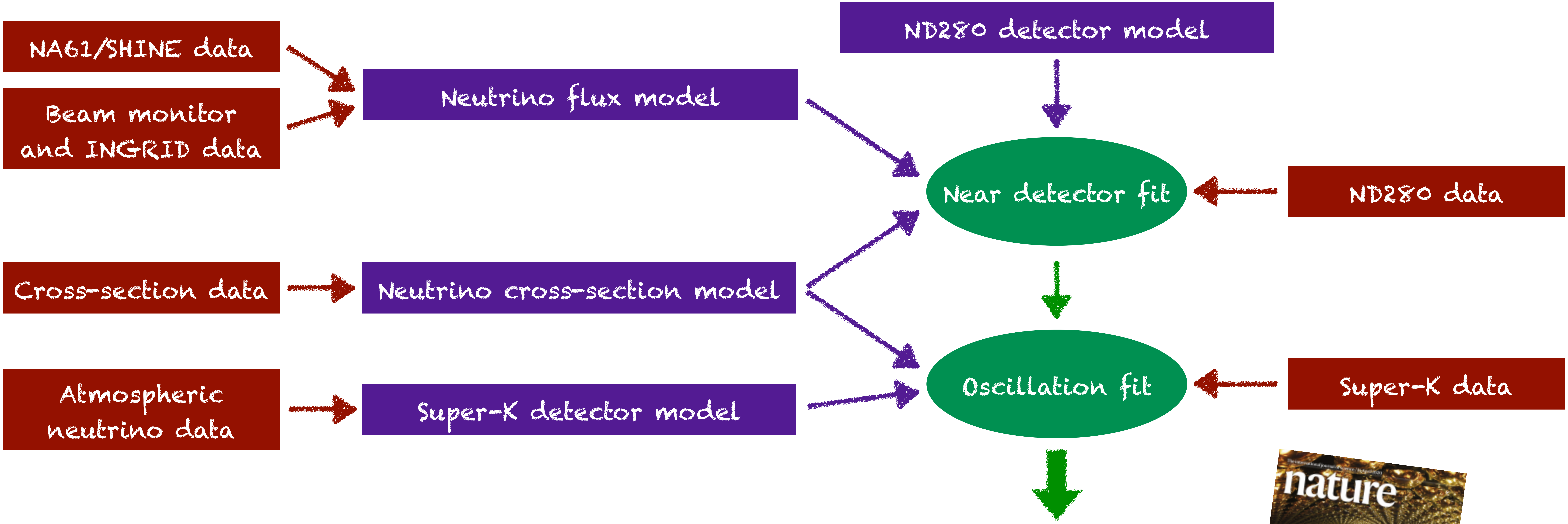
Analysis strategy: near detector fit





- Fits to near detector data dramatically improve our predictive capabilities at Super-K (e.g. from 13.0% to 4.7% systematic uncertainty on the pre-fit CC0π electron neutrino event rate)

Analysis strategy: full overview



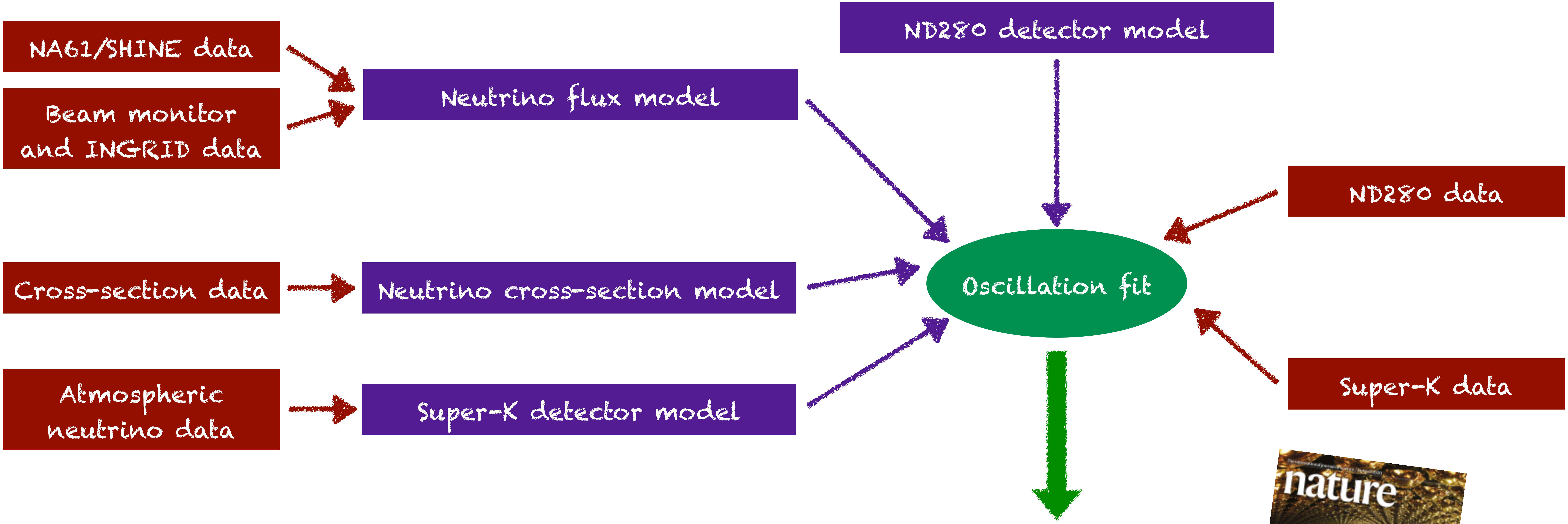
T2K oscillation result!

$\Delta m^2_{32},\ sin^2\ \theta_{23},\ \delta_{CP}$

- **Frequentist** oscillation analyses: **first fit to near detector data, then fit to Super-K data**

For a recent published result check out: Nature 580, 339–344 (2020)

Analysis strategy: full overview



- **MaCh3 (Bayesian)** oscillation analysis: **simultaneous fit to near and far detector data**
- T2K produces consistently converging results from the simultaneous and sequential fitting approaches

T2K oscillation result!

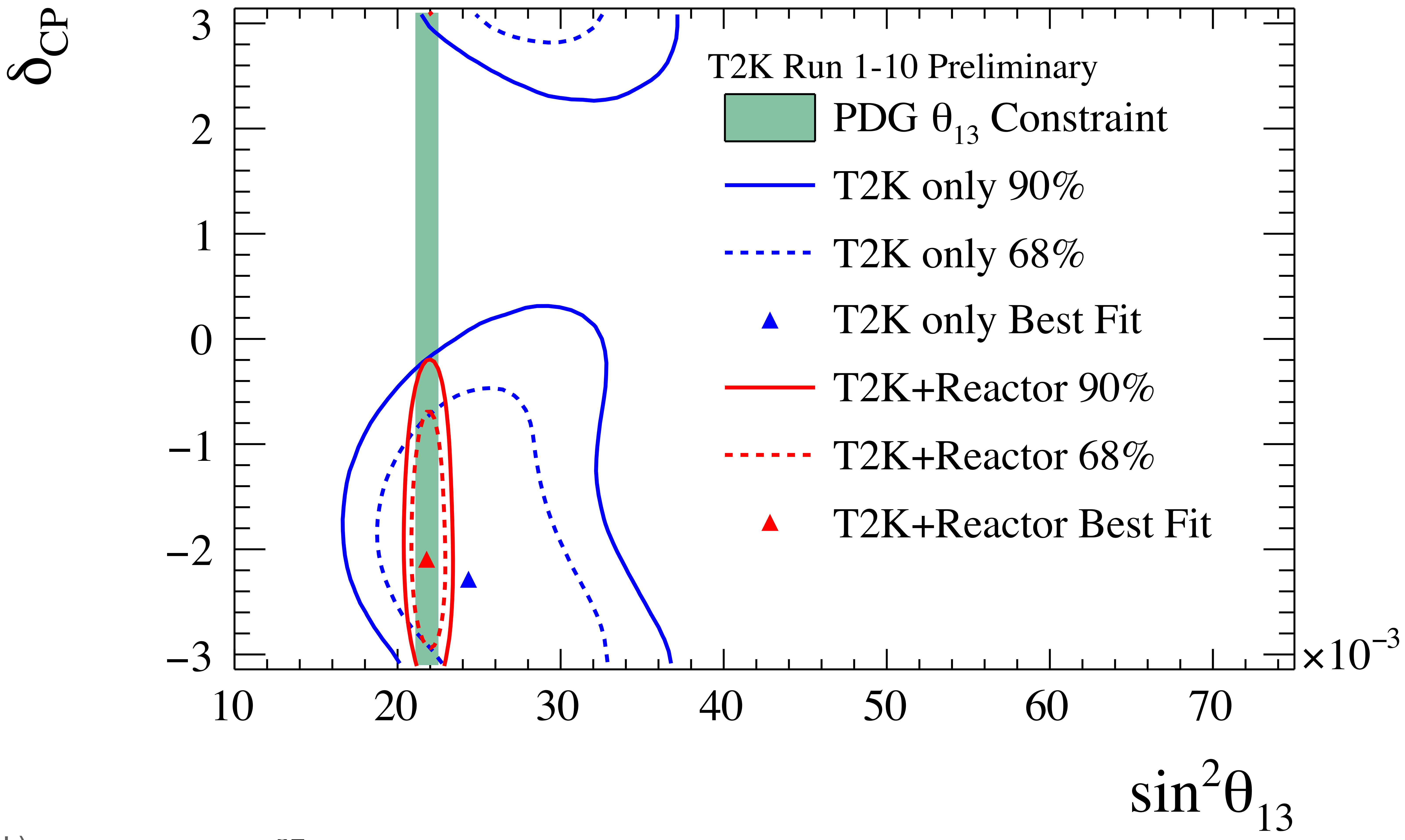
$\Delta m^2_{32}, sin^2\,\theta_{23}, \delta_{CP}$

For a recent published result check out: Nature 580, 339–344 (2020)

δ_{CP} constraint, and external inputs from reactor neutrino experiments

- We measure δ_{CP} both with and without the constraint on θ_{13} from reactor neutrino experiments (2019 PDG Constraint)

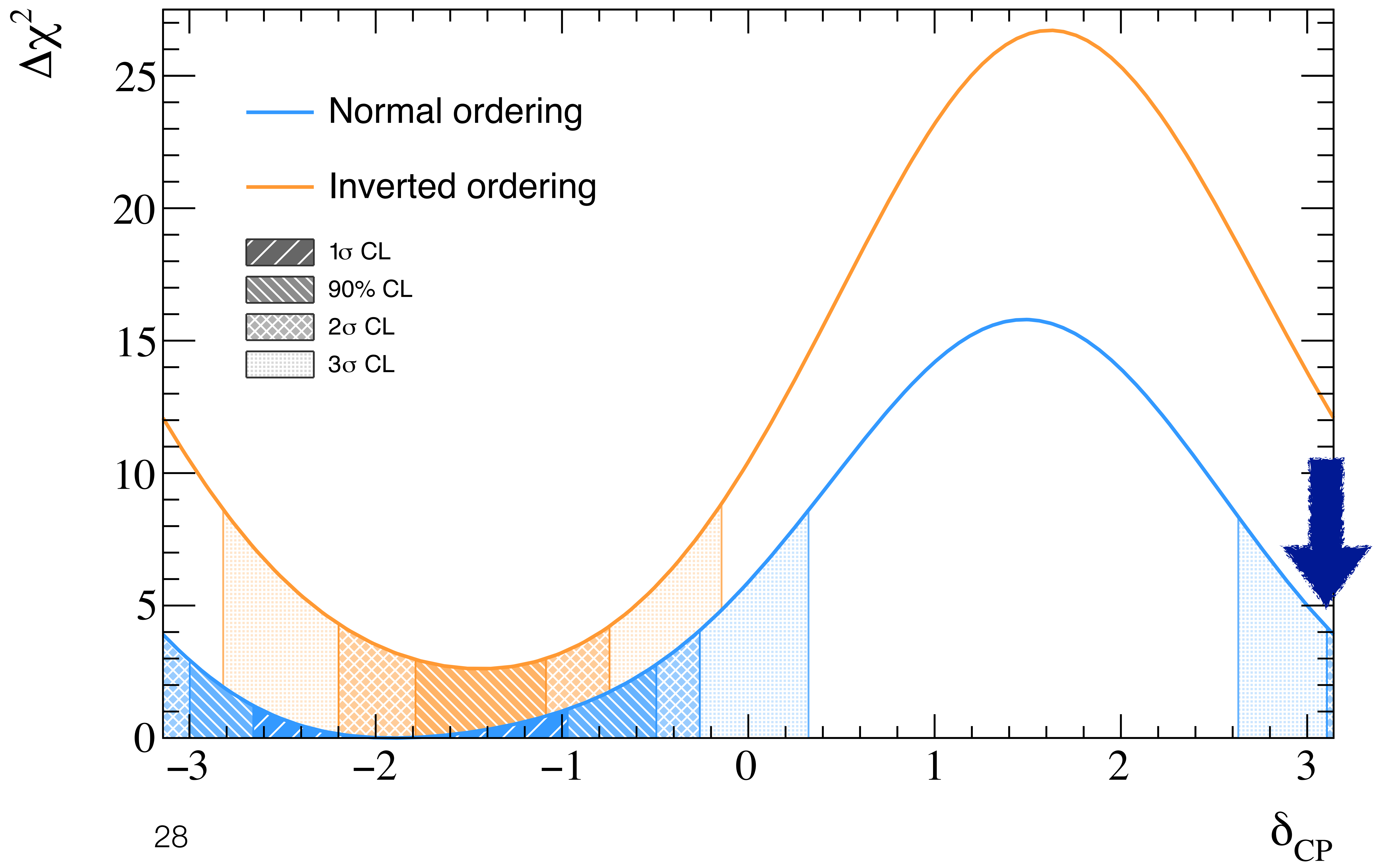
- The **tightest δ_{CP} constraint from T2K incorporates the θ_{13} measurement from combined reactor data**, which will be assumed in all subsequent plots



δ_{CP} constraint

Confidence level	Interval (NH)	Interval (IH)
1σ	$[-2.66, -0.97]$	
90%	$[-3.00, -0.49]$	$[-1.79, -1.09]$
2σ	$[-\pi, -0.26] \cup [3.11, \pi]$	$[-2.20, -0.75]$
3σ	$[-\pi, 0.32] \cup [2.63, \pi]$	$[-2.82, -0.14]$

- **CP conservation excluded at 90% confidence level**, with a **preference for maximal CP violation** $(\delta_{CP} = -\pi/2)$
- $\delta_{CP} = \pi$ **not quite excluded at 2σ**
- Marginalised over both mass hierarchies, 35% of δ_{CP} values excluded at 3σ
- Largest $\Delta\chi^2$ change from a series of robustness studies (cross section modelling bias) would cause the left (right) edge of the 90% CL region to move by 0.073 (0.080)



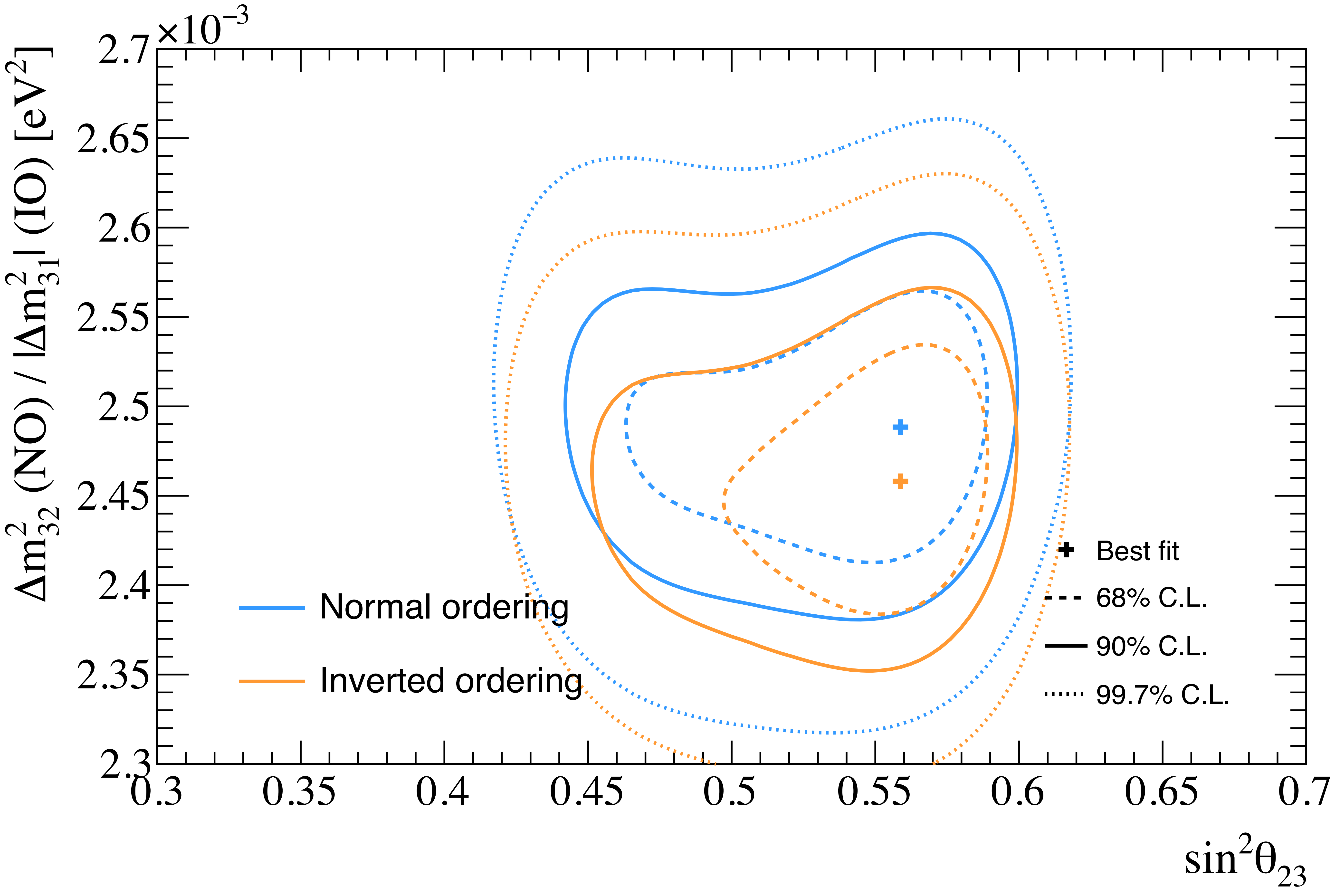
Result in atmospheric (Δm^2_{32}, $sin^2\ \theta_{23}$) sector

- Fitting to all 5 samples at Super-K
- Upper octant (normal ordering) preferred with Bayes factor 3.4 (4.2)

- No definitive conclusions can be drawn yet: Bayes factors within ($10^{\frac{1}{2}}$,10) are classified as either "substantial" (Jeffreys scale) or "positive" (Kass and Raferty scale)

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.195	0.613	0.808
IH ($\Delta m^2_{32} < 0$)	0.035	0.157	0.192
Sum	0.230	0.770	1.000

	$\sin^2\theta_{23}$	$\Delta m^2_{32}(\times 10^{-3})\mathrm{eV}^2$
2D best fit	0.488	2.46
68% C.I. (1σ) range	0.470 – 0.550	2.416 – 2.544 & −2.568 – −2.496
90% C.I. range	0.447 – 0.580	2.376 – 2.584 & −2.616 – −2.436



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Ongoing joint fits

- **T2K-NOvA** and **T2K-SuperK joint fits** are ongoing (agreements have been signed, and working groups formed)
- **Combining different detector/baseline/energy configurations resolves degeneracies**
- Expect an improved measurement sensitivity beyond a simple increase in statistics

T2K-NOvA meeting in J-PARC, Japan

T2K-NOvA meeting in Fermilab, USA

Future of T2K

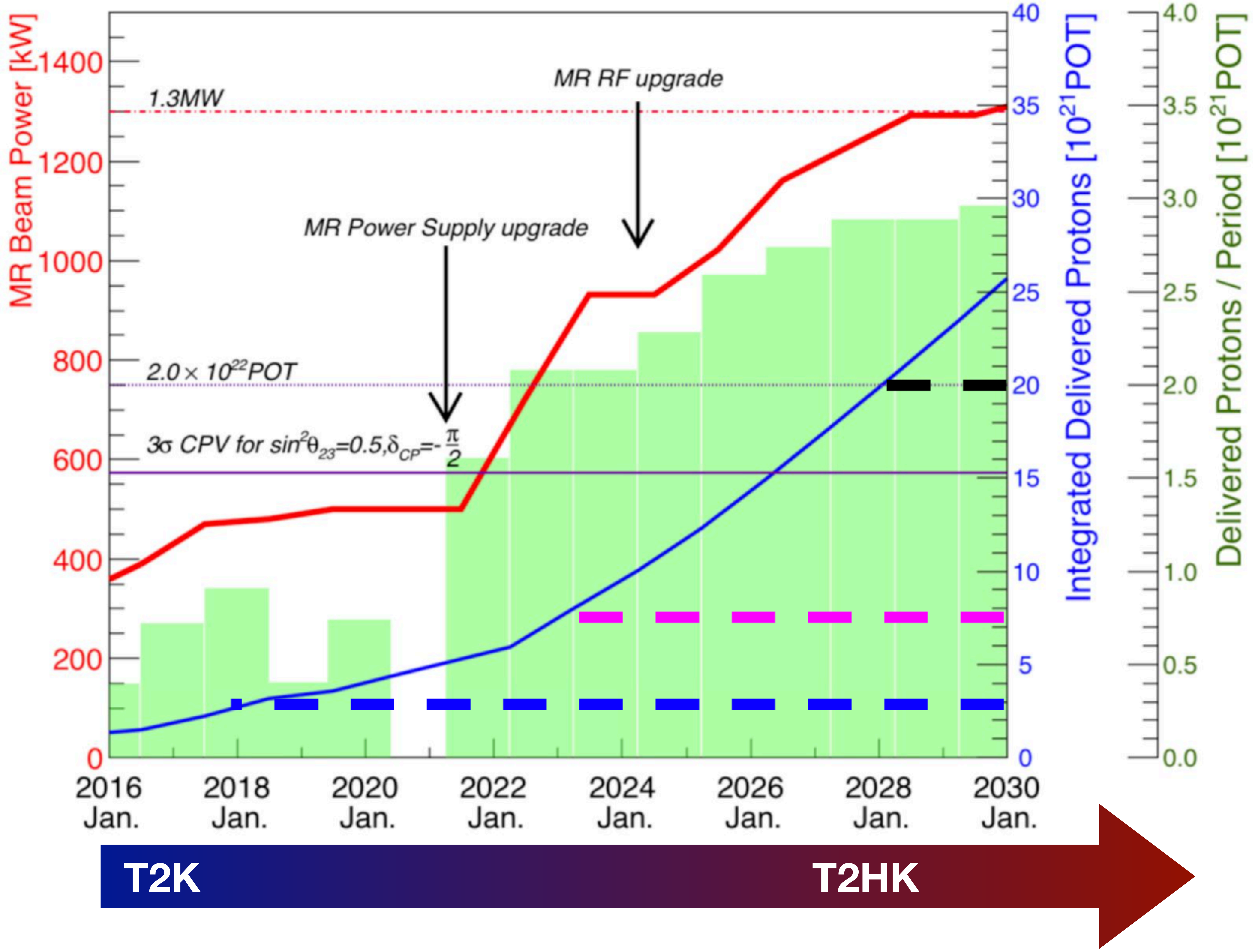
- T2K data taking has been extended until the start of Hyper-K, as per KEK's statement from 6 July 2020:

KEK

> - KEK recognizes the importance of T2K operation with the upgraded near detector (ND280) for further advancement of CPV measurements. This will also strengthen international collaboration on T2K and HK, contribute to the success of the neutrino program in Japan, and enhance the physics program of HK with an upgraded beam intensity from the start of its operation.
>
> - In light of the above, KEK will make its best effort to provide approximately four months of T2K beam operations per year until the start of HK.

- More statistics expected with beam power increase from ~500 kW towards 1.3 MW

- Reduced systematic uncertainties expected with the upgraded ND280 detector



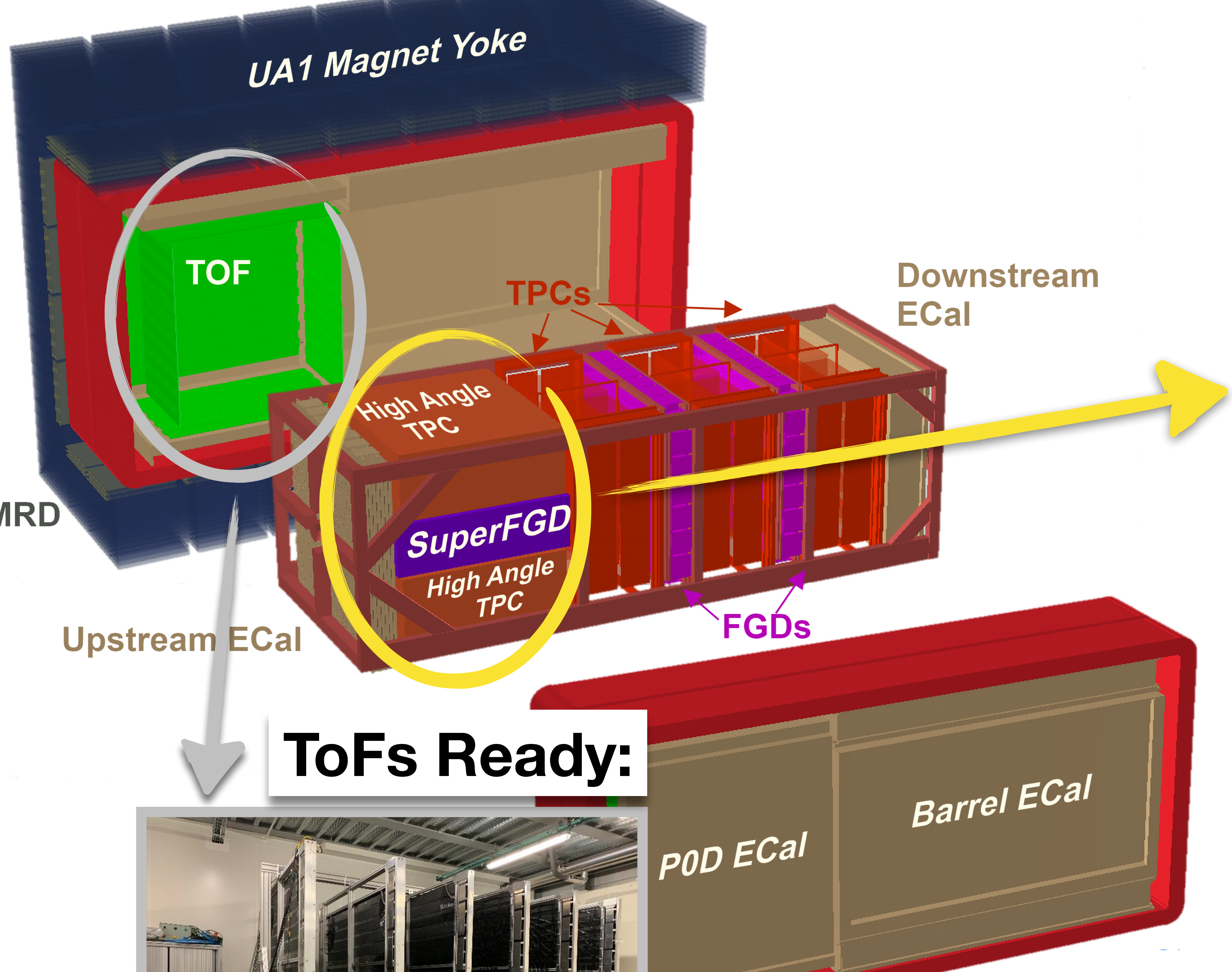
T2K Upgrade

- **SuperFGD:** novel active target detector, surrounded by high angle time projection chambers (HTPCs) and enclosed with time of flight (ToF) detectors

- **Improved detector acceptance,** efficiency, PID, timing resolution etc., feeding into **reduction of cross section systematics**

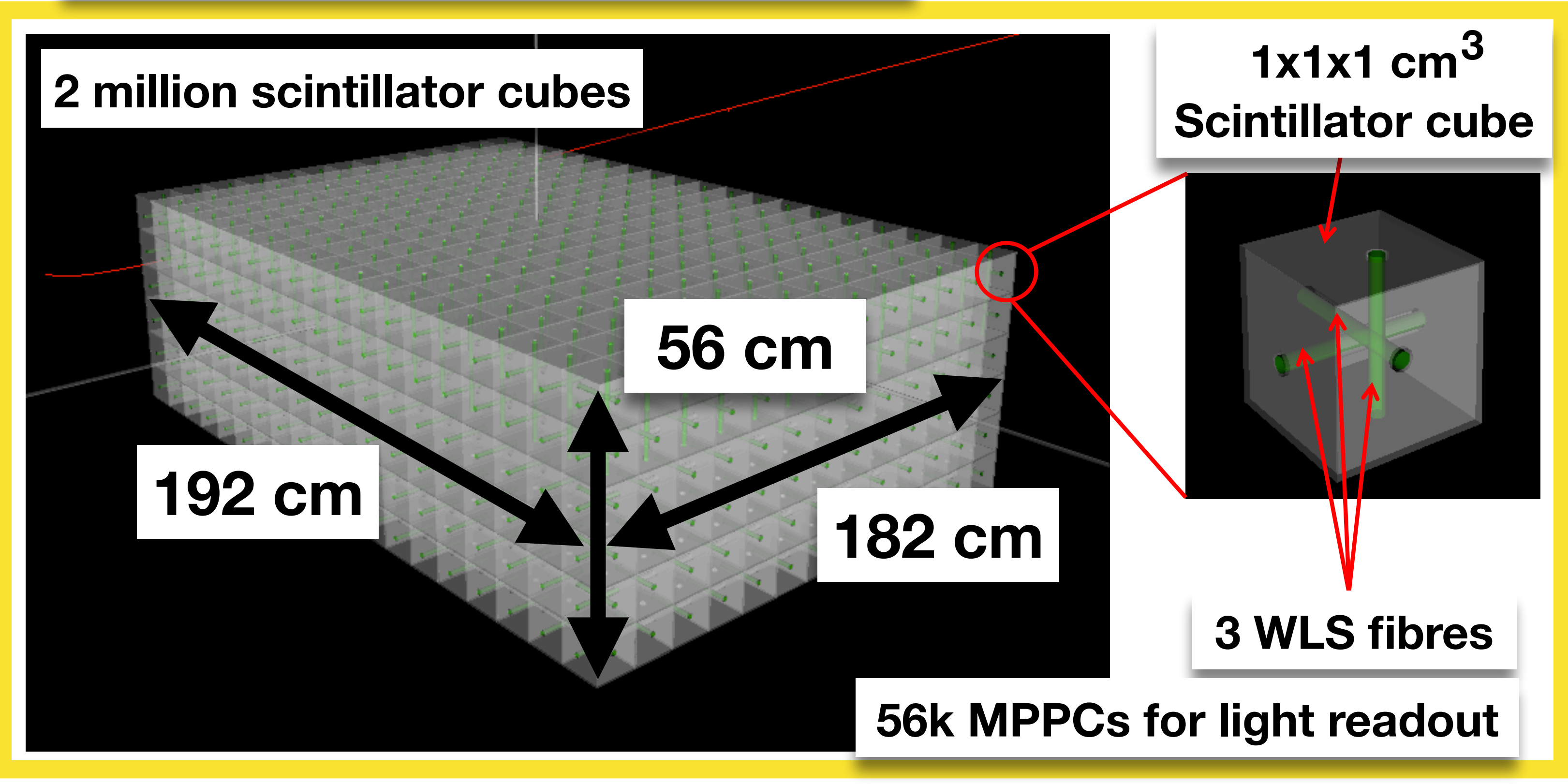
- **Installation at J-PARC planned for the second half of 2022** (this includes a delay estimate due to Covid-19)

P0D sub-detector to be replaced with **SuperFGD**, **HTPCs** and **ToFs**

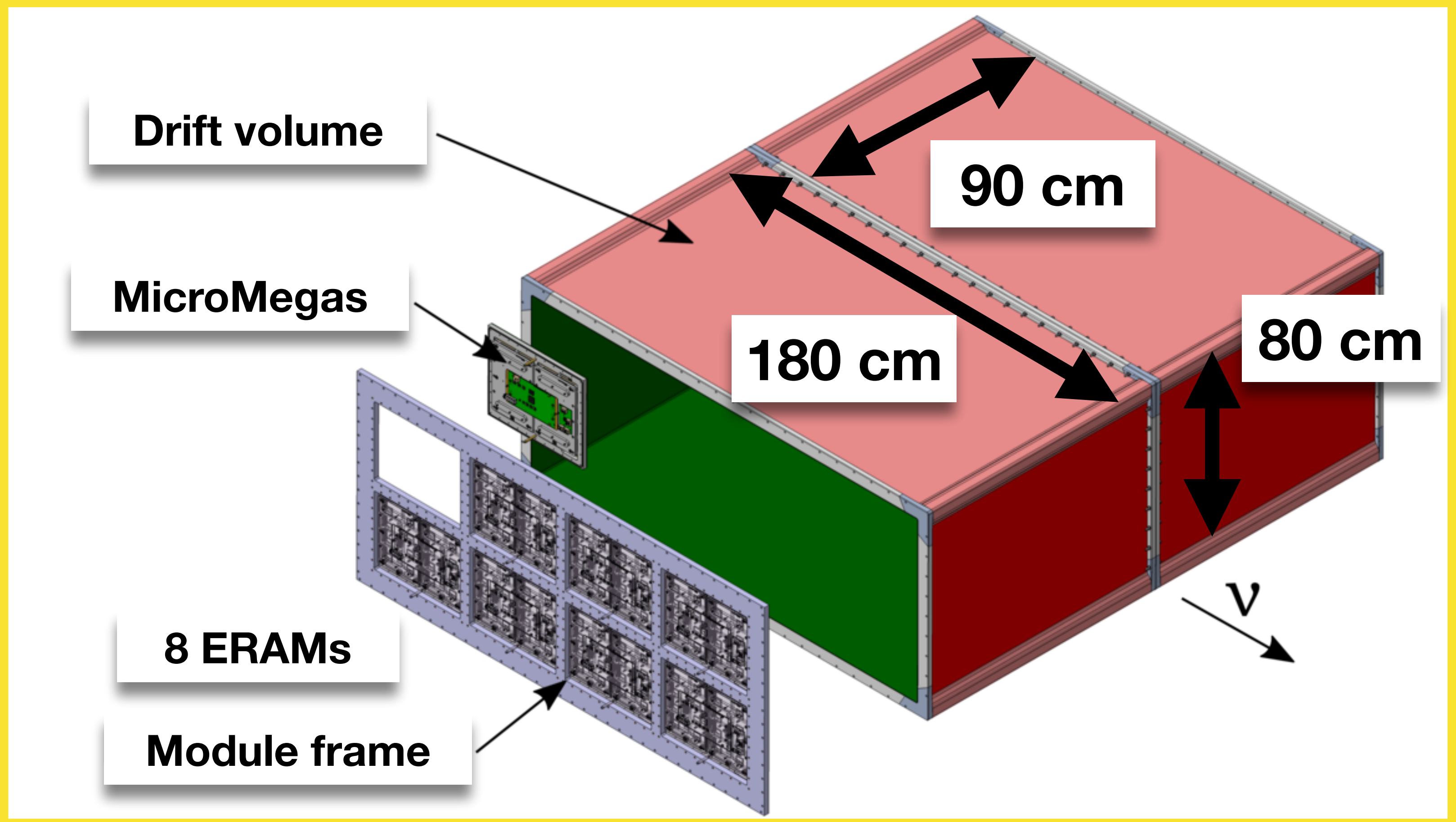


ToFs Ready:

SuperFGD Design:



2 HTPCs Design:

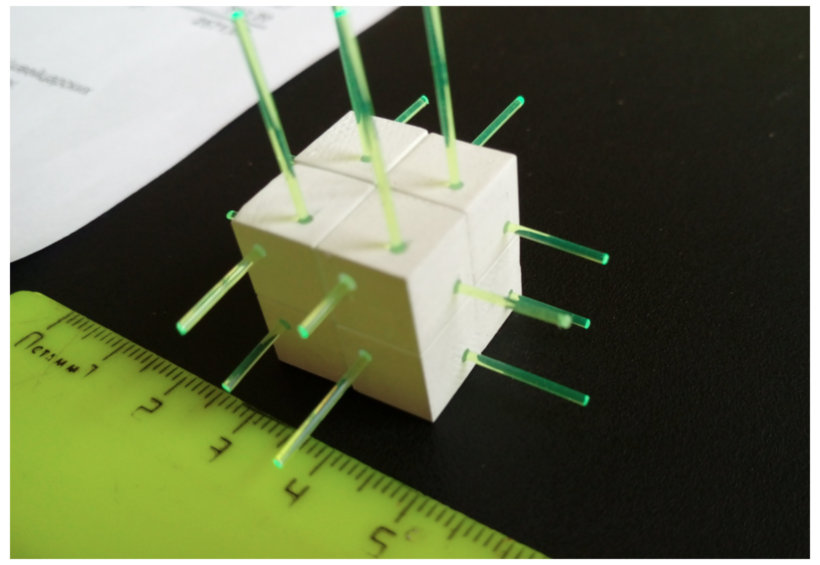


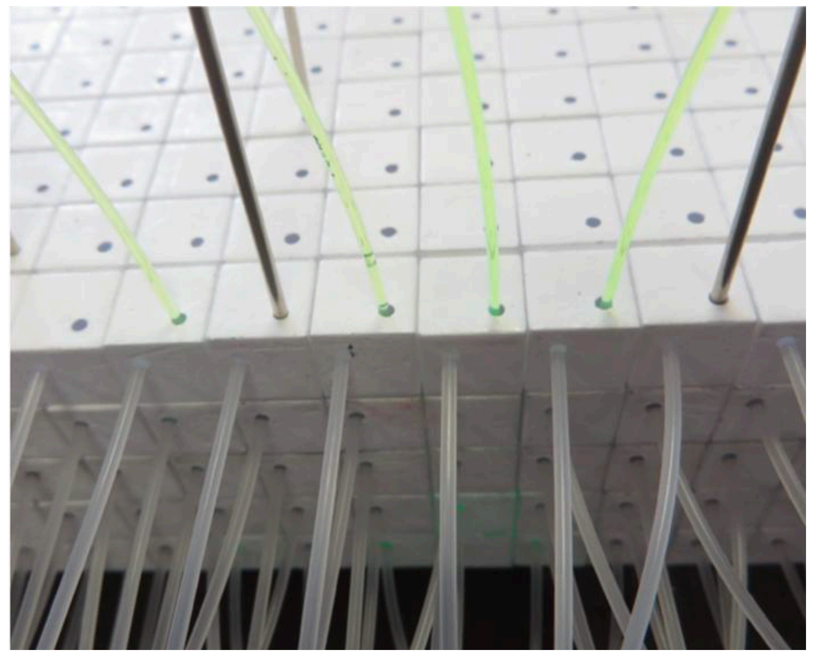
For more details refer to the ND280 Upgrade Technical Design Report, at arXiv:1901.03750

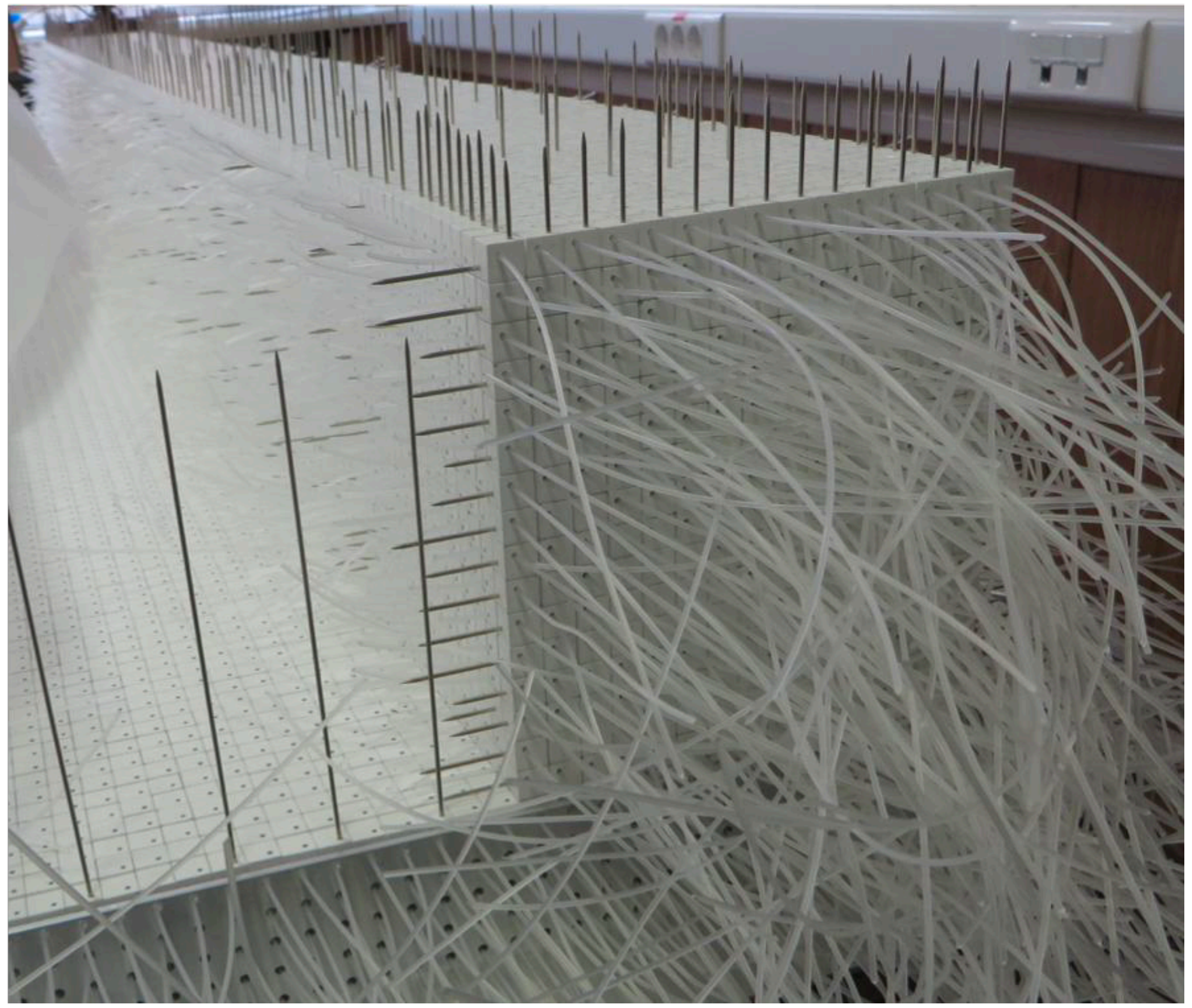
T2K Upgrade: SuperFGD Preparation

- All 2.1 million cubes have been assembled into 56 x-y layers at **the Institute for Nuclear Research, Russia**

INR SuperFGD Assembly Team:







Conclusions

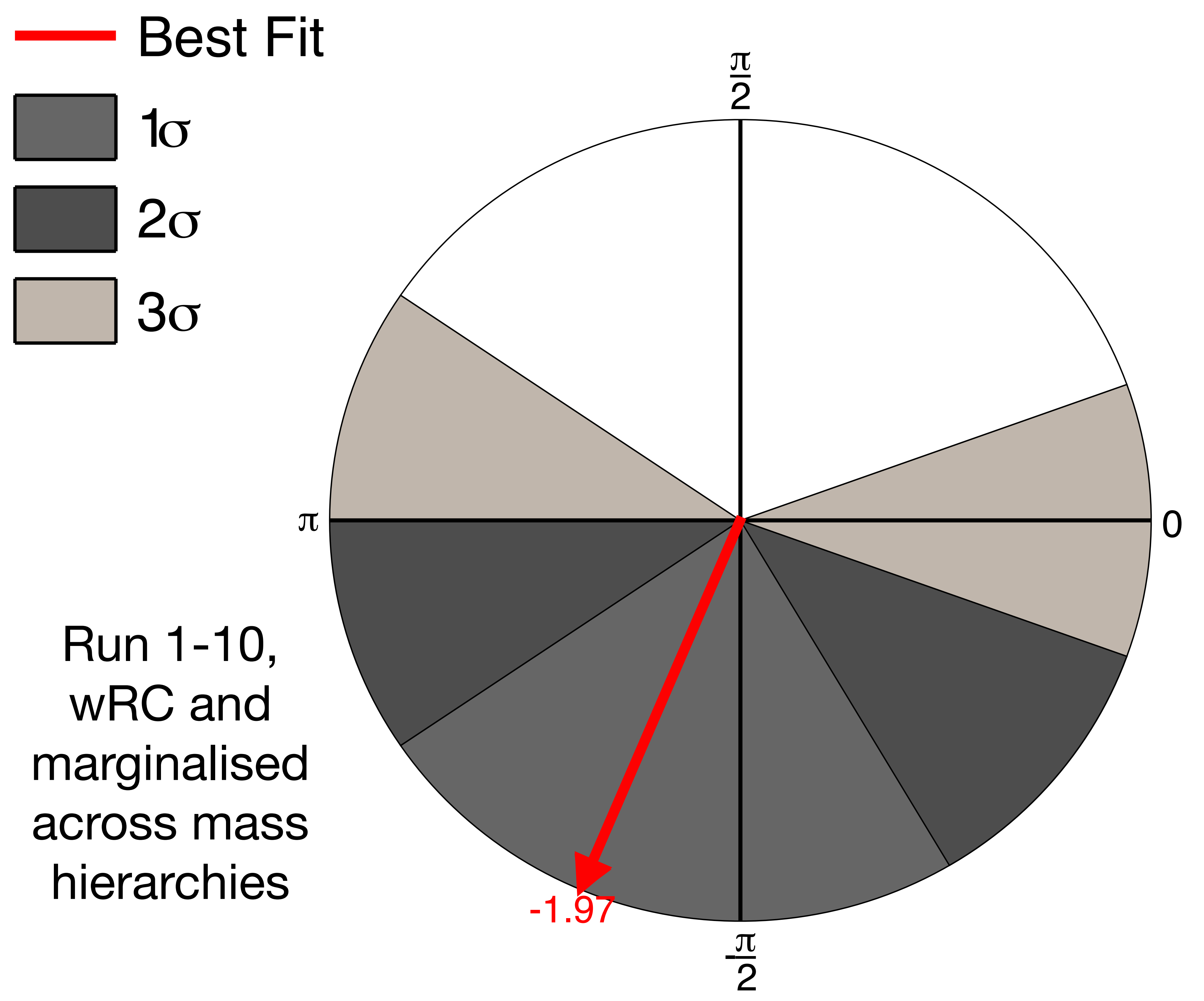
- Presented T2K's oscillation result for Runs 1-10 (data up to Feb 2020, 3.6×10^{21} POT), with 33% more POT in ν-mode compared to earlier

- δ_{CP} conserving values excluded at 90% confidence level, with $\delta_{CP} = \pi$ not quite excluded at 2σ

- Preference for maximum CP violation, normal mass ordering and upper θ_{23} octant

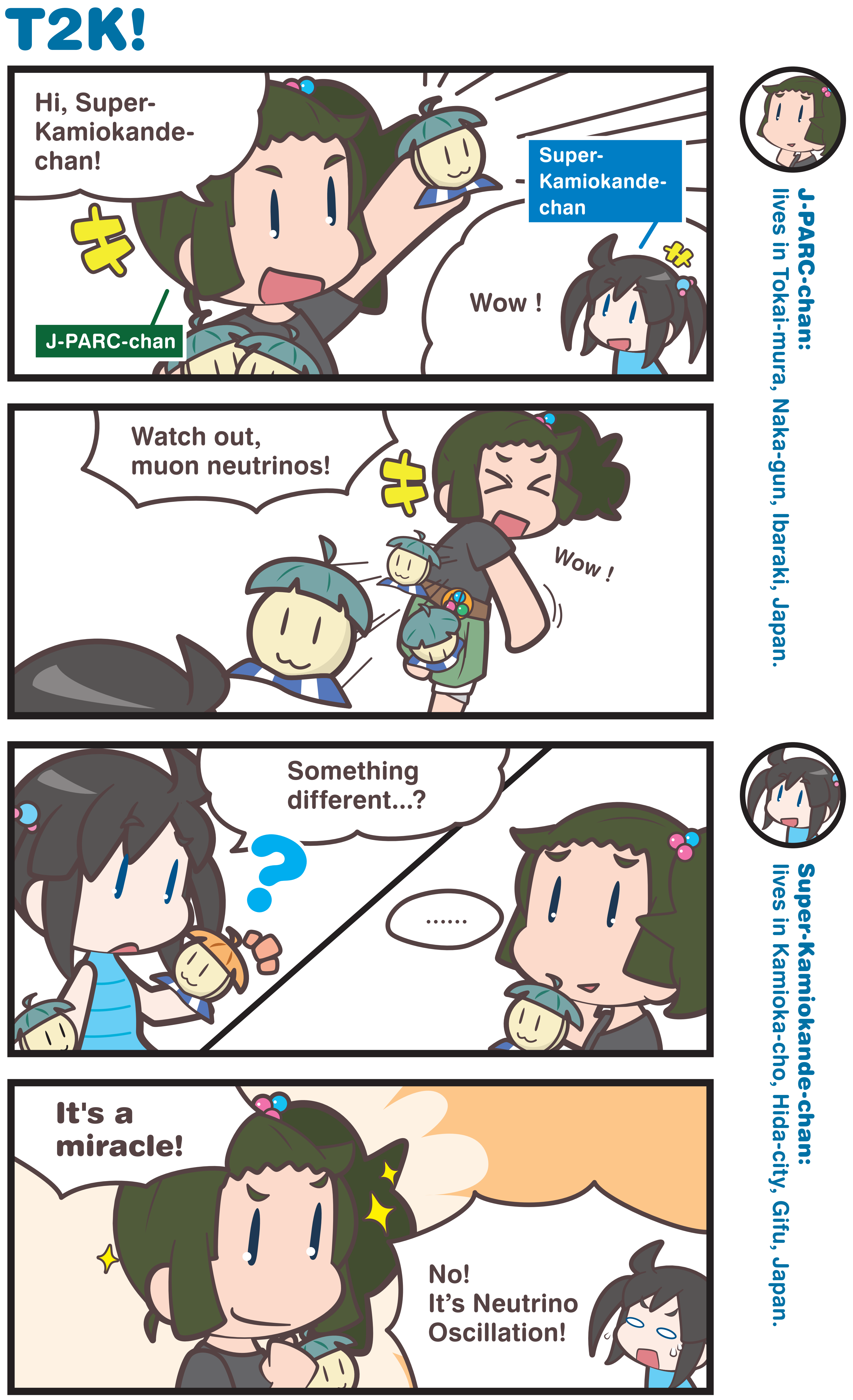
- Ambitious upgrade of near detector planned for second half of 2022

- Future T2K data-taking has been approved until the start of Hyper-K



Thank you!

Any questions?



Science and Technology Facilities Council

Backup

Tomislav Vladisavljevic
RAL, UK

On behalf of the T2K Collaboration

XX Lomonosov Conference on Elementary Particle Physics
20 August 2021, Online

Neutrino oscillations, general expression

- Neutrino oscillations occur because of different flavour eigenstates (interacting states) and mass eigenstates (propagating states)

$\theta_{23} \approx 48^\circ$ $\quad |\Delta m^2_{32}| \approx |\Delta m^2_{31}| \approx 2.5 \times 10^{-3}\ eV^2$

$\theta_{13} \approx 8^\circ$ $\quad \delta_{CP} = ?$

$\theta_{12} \approx 34^\circ$ $\quad \Delta m^2_{21} \approx 7.5 \times 10^{-5}\ eV^2$

$s_{ij} = sin\ \theta_{ij}$
$c_{ij} = cos\ \theta_{ij}$

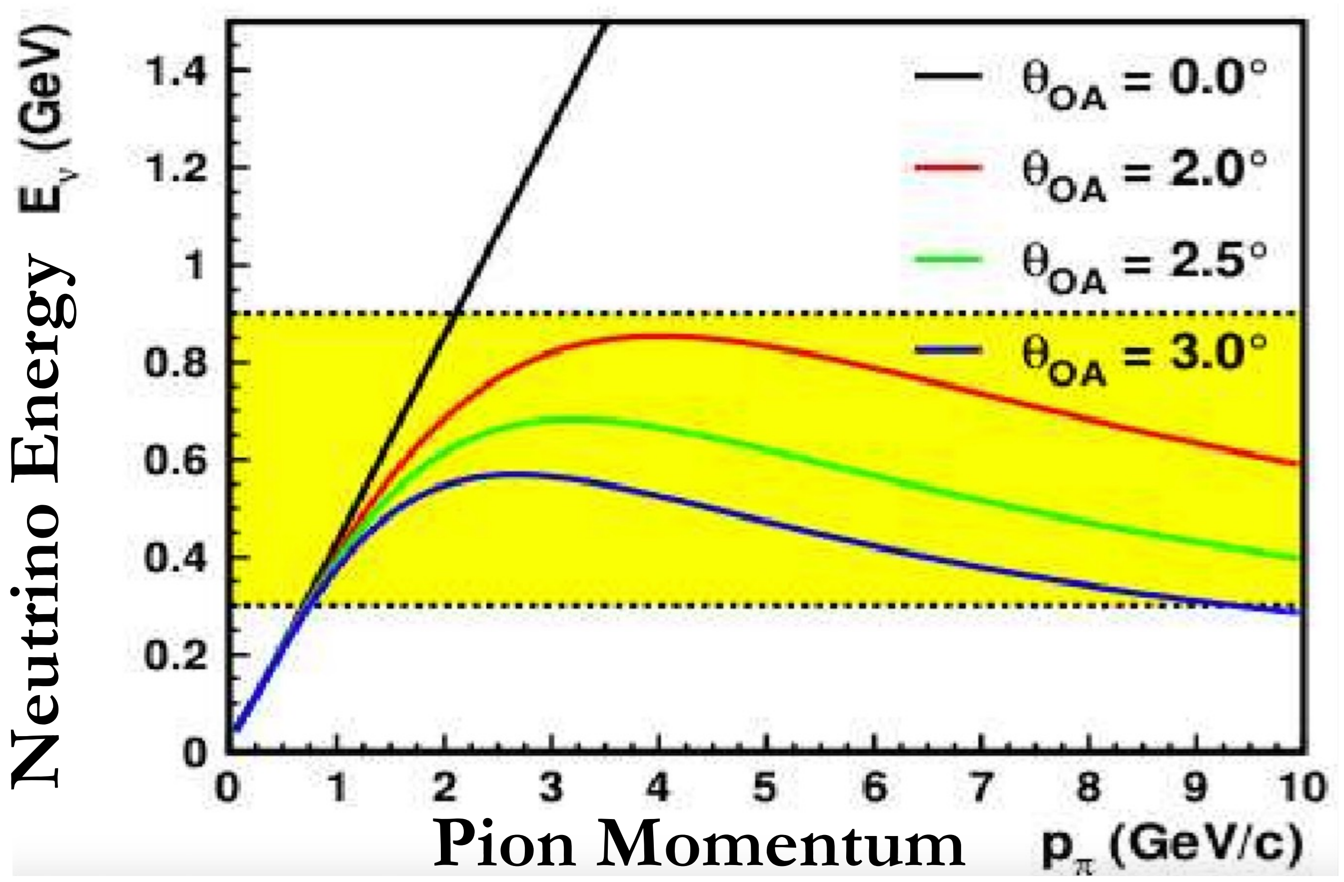
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

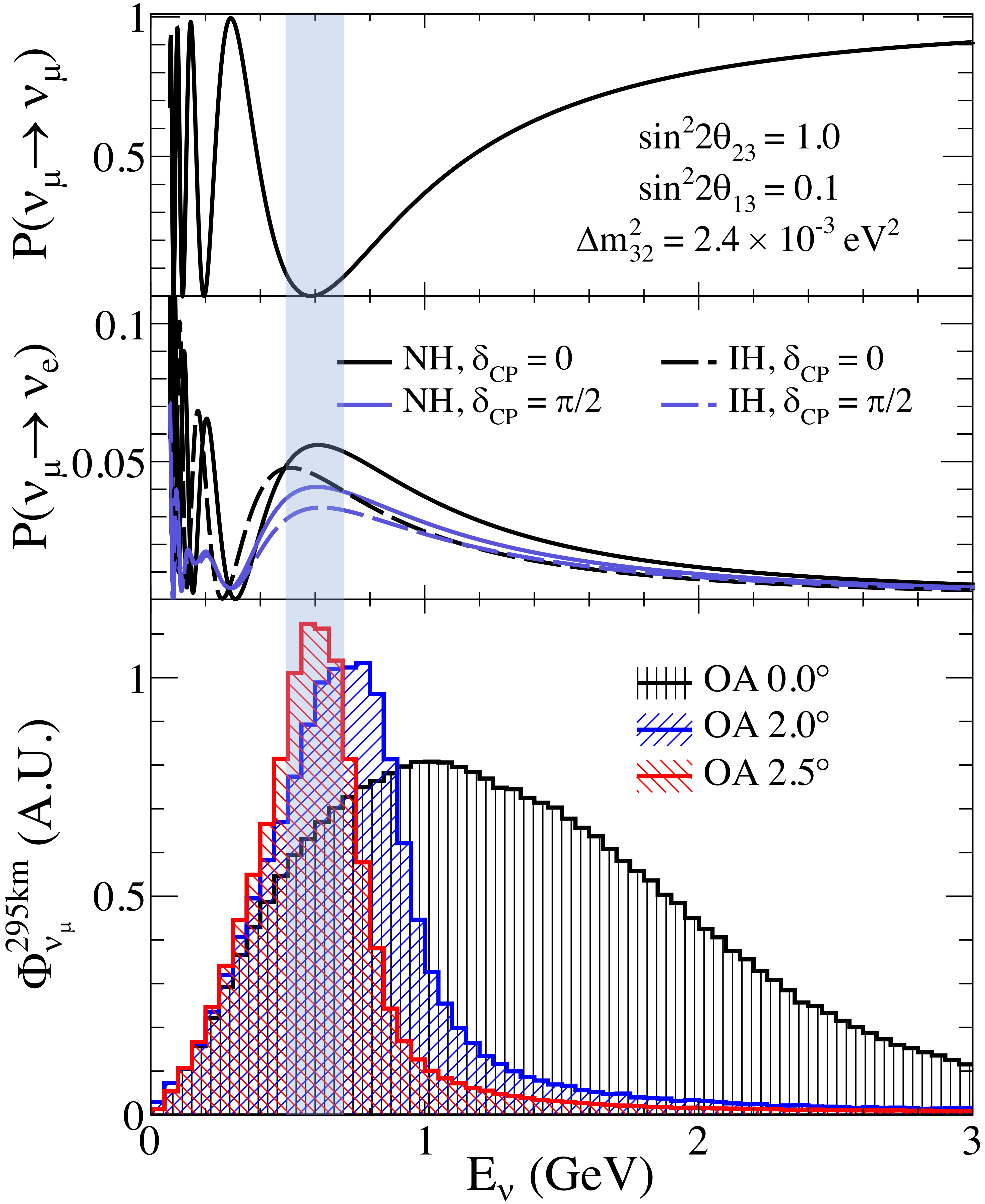
- Three flavour (anti)neutrino oscillation formula in vacuum:

$$P(\overset{(-)}{\nu}_\alpha \rightarrow \overset{(-)}{\nu}_\beta) = \delta_{\alpha\beta} - 4\sum_{k>j} Re\left\{U_{\alpha k}U^\star_{\beta k}U^\star_{\alpha j}U_{\beta j}\right\} sin^2 \frac{\Delta m^2_{kj}L}{4E} \mp 2\sum_{k>j} Im\left\{U_{\alpha k}U^\star_{\beta k}U^\star_{\alpha j}U_{\beta j}\right\} sin\ 2\frac{\Delta m^2_{kj}L}{4E}$$

The T2K Off-Axis Neutrino Flux

- SK and ND280 are placed at 2.5° off-axis angle with respect to the primary proton beam direction
- On-axis near detector (INGRID) used to monitor beam stability and direction
- Off-axis beam makes the ν_μ flux more narrow and peaked around the energies needed for observing the first oscillation maximum at SK (295 km baseline)
- High energy tail gets reduced





$\nu_e\ (\bar{\nu}_e)$ appearance probability at T2K

- Electron (anti)neutrino appearance probability:

$$P_{T2K}(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) = sin^2\, 2\theta_{13}\, sin^2\, \theta_{23}\, sin^2\, \frac{\Delta m^2_{32} L}{4E}$$

$$+ sin^2\, 2\theta_{13}\, sin^2\, \theta_{23}\, sin^2\, \frac{\Delta m^2_{21} L}{4E}$$

$$+ J\, cos\, (\frac{\Delta m^2_{32} L}{4E} \pm \delta_{CP})$$

CP-conserving terms

Can be neglected at L/E of long baseline accelerator experiments

CP-violating term for $\delta_{CP} \neq 0, \pi$

Plus sign for neutrinos

where $J = sin\, 2\theta_{12}\, sin\, 2\theta_{23}\, sin\, 2\theta_{13}\, cos\, \theta_{13}\, sin\, \frac{\Delta m^2_{32} L}{4E}\, sin\, \frac{\Delta m^2_{21} L}{4E}$

Appearance probability at T2K including matter effect

- Electron (anti)neutrino appearance probability around oscillation maximum:

Minus sign for anti-neutrinos

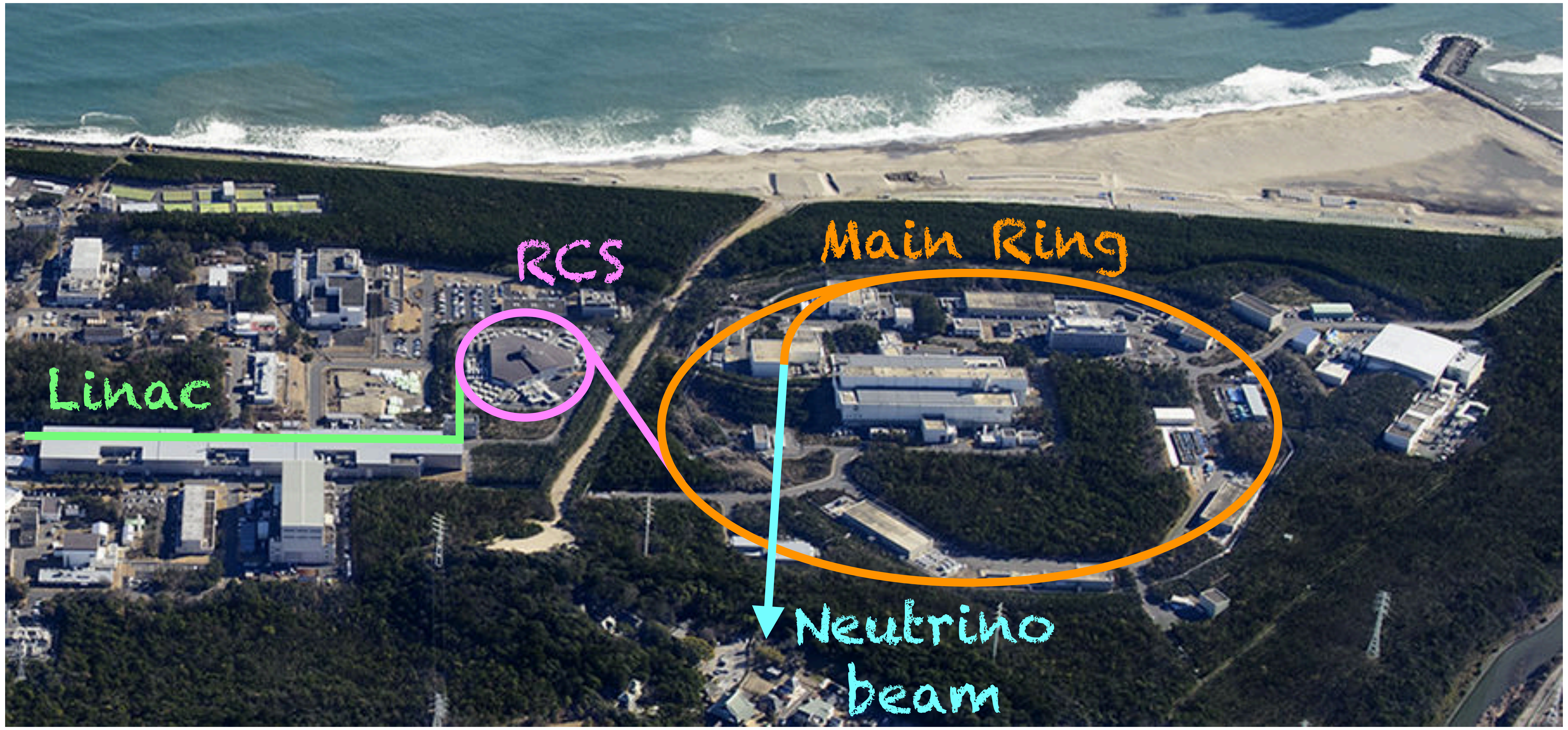
$$P_{T2K}(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx sin^2 2\theta_{13}\, sin^2 \theta_{23}\, sin^2 \frac{\Delta m^2_{32} L}{4E} \left(1 \pm \frac{2a}{\Delta m^2_{31}} (1 - 2\, sin^2 \theta_{13})\right)$$

$$\mp sin\, 2\theta_{12}\, sin\, 2\theta_{23}\, sin\, 2\theta_{13}\, cos\, \theta_{13}\, sin\, \delta_{CP}\, sin^2 \frac{\Delta m^2_{32} L}{4E}\, sin \frac{\Delta m^2_{21} L}{4E}$$

Plus sign for anti-neutrinos

where $a = 2\sqrt{2}\, G_F\, n_e\, E$ depends on the electron density in Earth's crust n_e, and Fermi's constant G_F

J-PARC facility

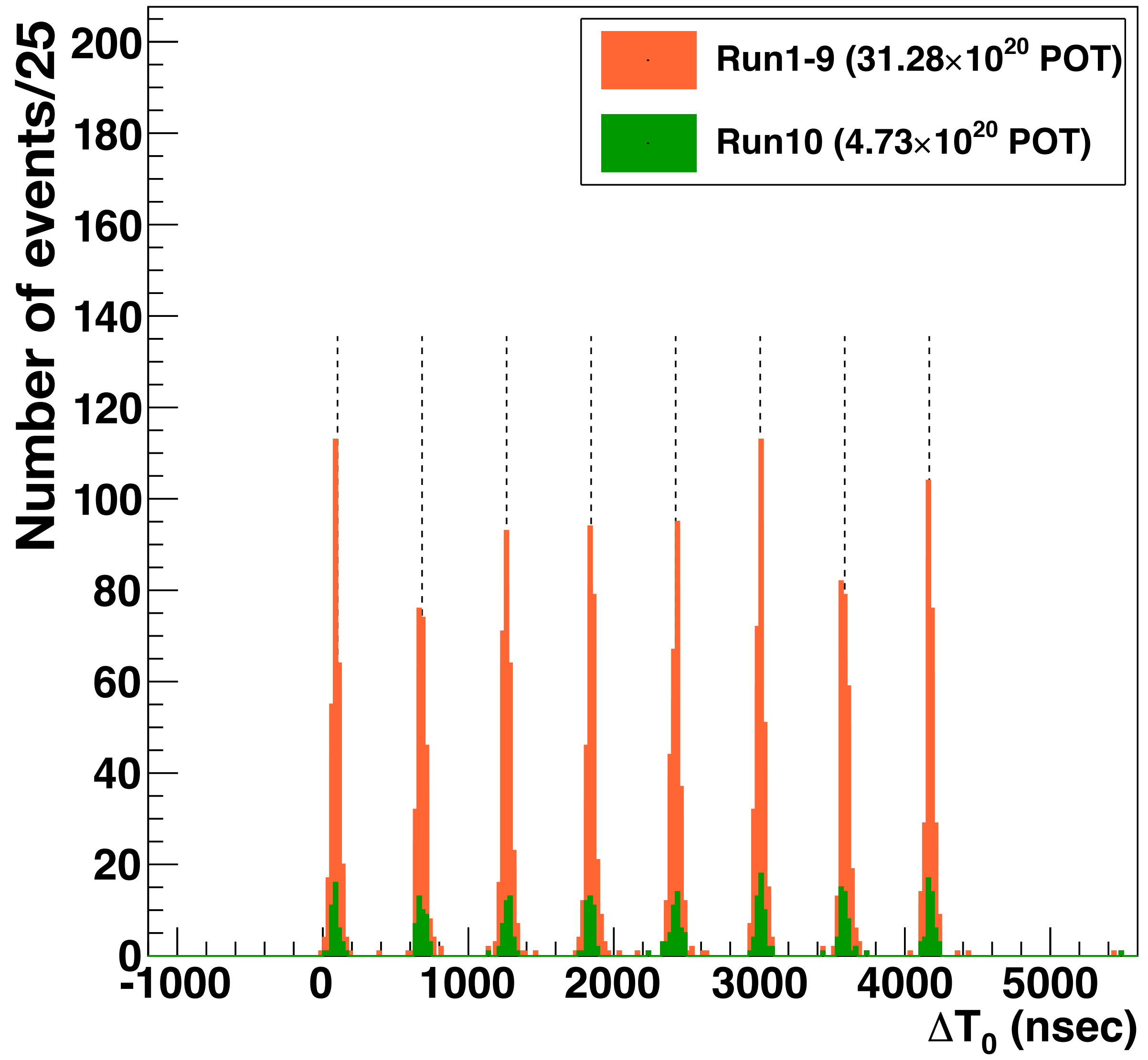


- 400 MeV Linac (H^-) to 3 GeV Rapid Cycling Synchrotron (p) to 30 GeV Main Ring (p) to 600 MeV Neutrino beam (ν)

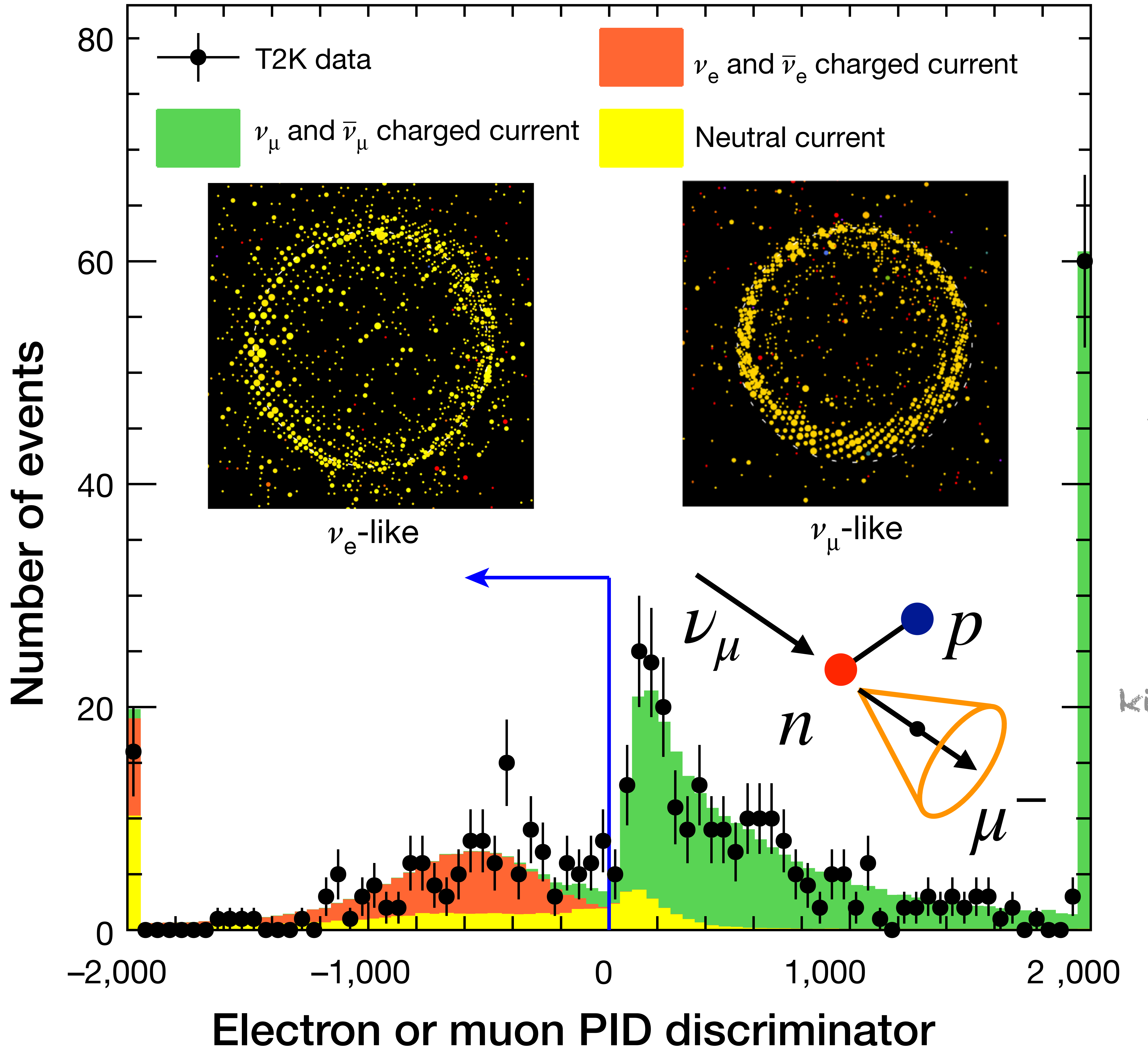
- Low duty cycle for neutrino beam, so beam induced events are selected based on event timing

- 8 bunches per spill, with a spill repetition cycle of 2.48 s

- 80 ns bunch width, and 580 ns bunch separation



Particle identification at Super-K



Electrons undergo more scattering, hence produce “fuzzy” Cherenkov rings

Good PID achieved using times, charge and position of all hit PMTs

Event topology hypothesis (1R muon-like, 1R electron-like etc.)

$$L(\Gamma, \theta) = \prod_{j}^{unhit\ PMTs} P_j(unhit \mid \Gamma, \theta) \prod_{i}^{hit\ PMTs} \{1 - P_i(unhit \mid \Gamma, \theta)\}$$

$$\times f_q(q_i \mid \Gamma, \theta) f_t(t_i \mid \Gamma, \theta)$$

Event kinematics

Charge signal likelihood

Timing likelihood

$$PID = ln\left(\frac{L_\mu^{max}}{L_e^{max}}\right)$$

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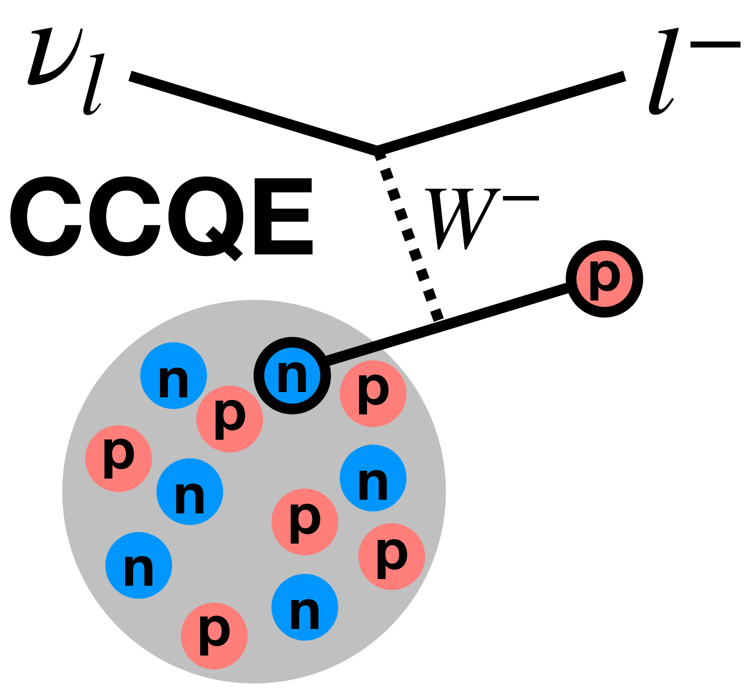
Cross section model updates

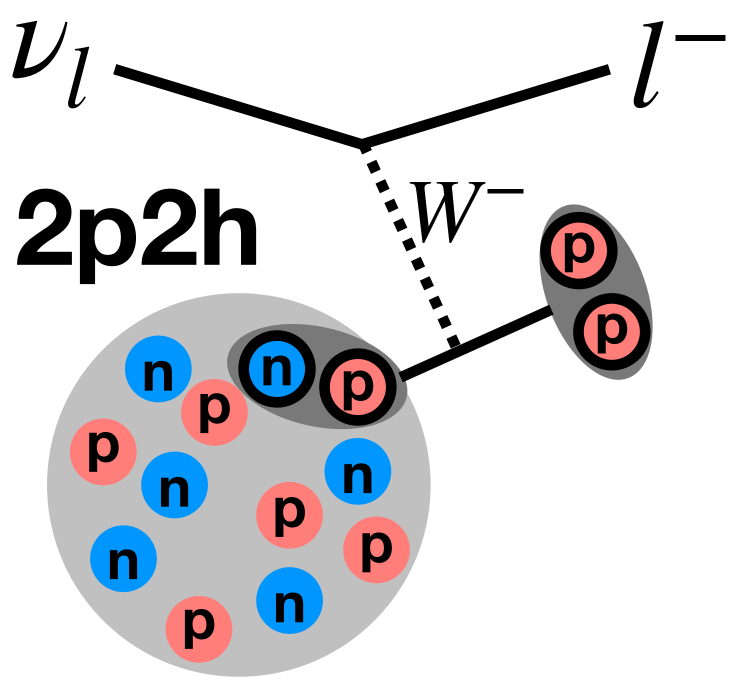
- **Updates for our latest oscillation measurement** (with the new NEUT 5.4.0 interaction model):

  1. **CCQE initial state nuclear model migrated from Relativistic Fermi Gas plus Random Phase Approximation to Spectral Function (strongly favoured by electron scattering data)**

  2. Better (shell-dependent) treatment of removal energy comes with the SF CCQE model

  3. More sophisticated treatments of the energy dependent 2p2h uncertainty, deep inelastic scattering uncertainty and final state interaction correlations between near and far detectors





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Systematic uncertainties before/after ND fit

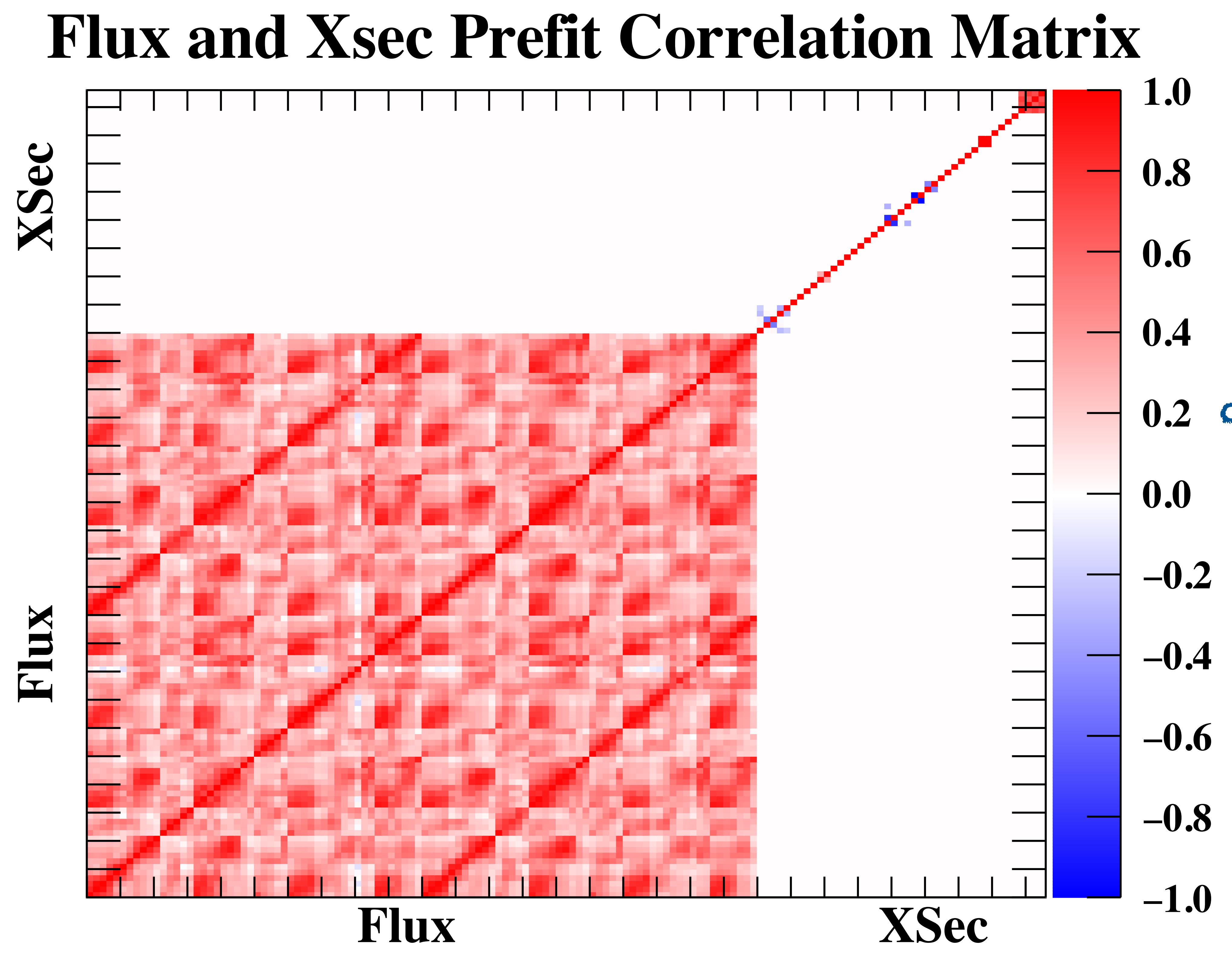
Before Near detector fit:

Error source (units: %)	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	5.1	4.7	4.8	4.7	4.9	2.7
Cross-section (all)	10.1	10.1	11.9	10.3	12.0	10.4
SK+SI+PN	2.9	2.5	3.3	4.4	13.4	1.4
Total	11.1	11.3	13.0	12.1	18.7	10.7

After Near detector fit:

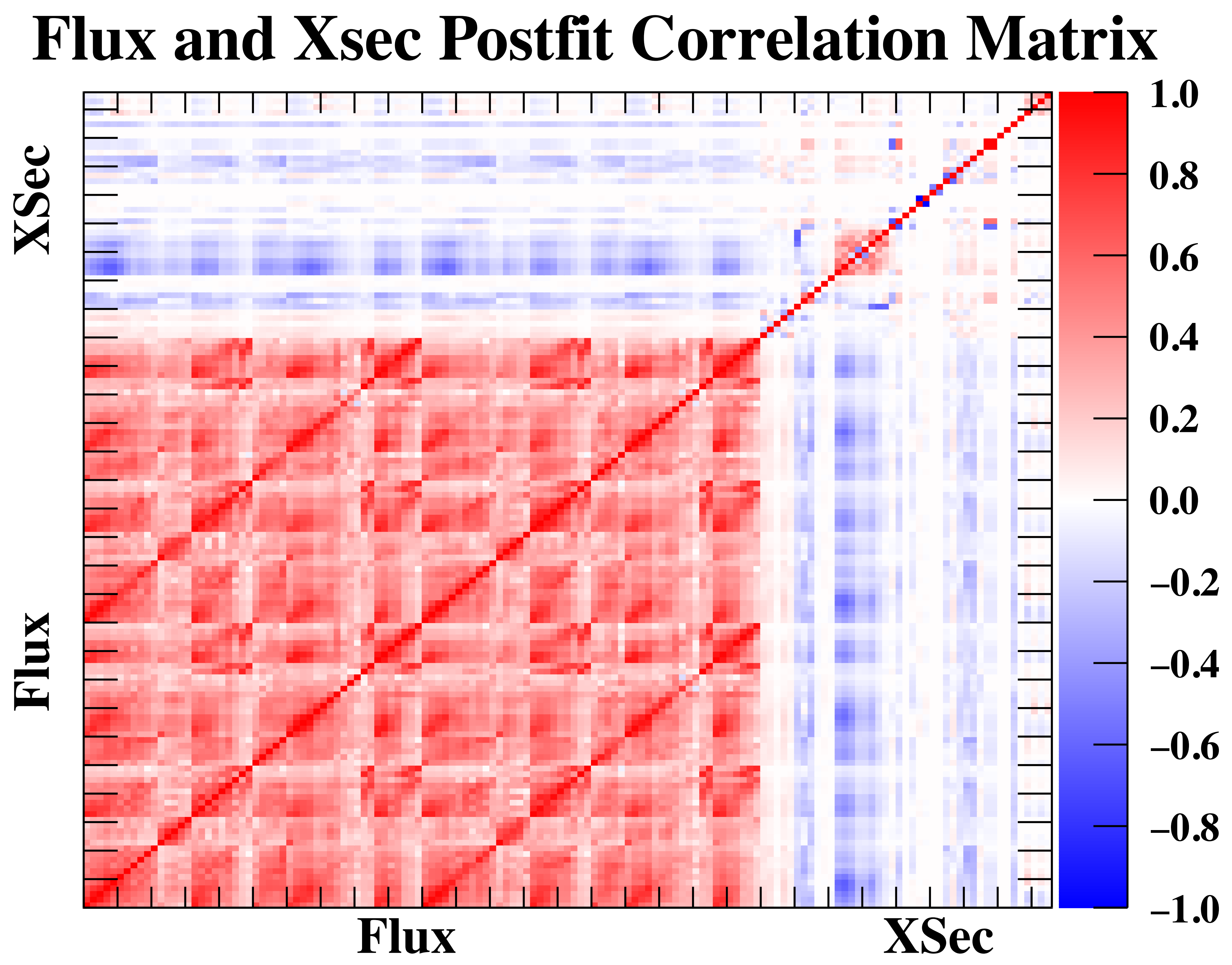
Error source (units: %)	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
Xsec (ND unconstrained)	0.6	2.5	3.0	3.6	2.8	3.8
SK+SI+PN	2.1	1.9	3.1	3.9	13.4	1.2
Total	3.0	4.0	4.7	5.9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

More on the near detector fit



Many more detector systematics enter the fit, which are nore shown here for clarity

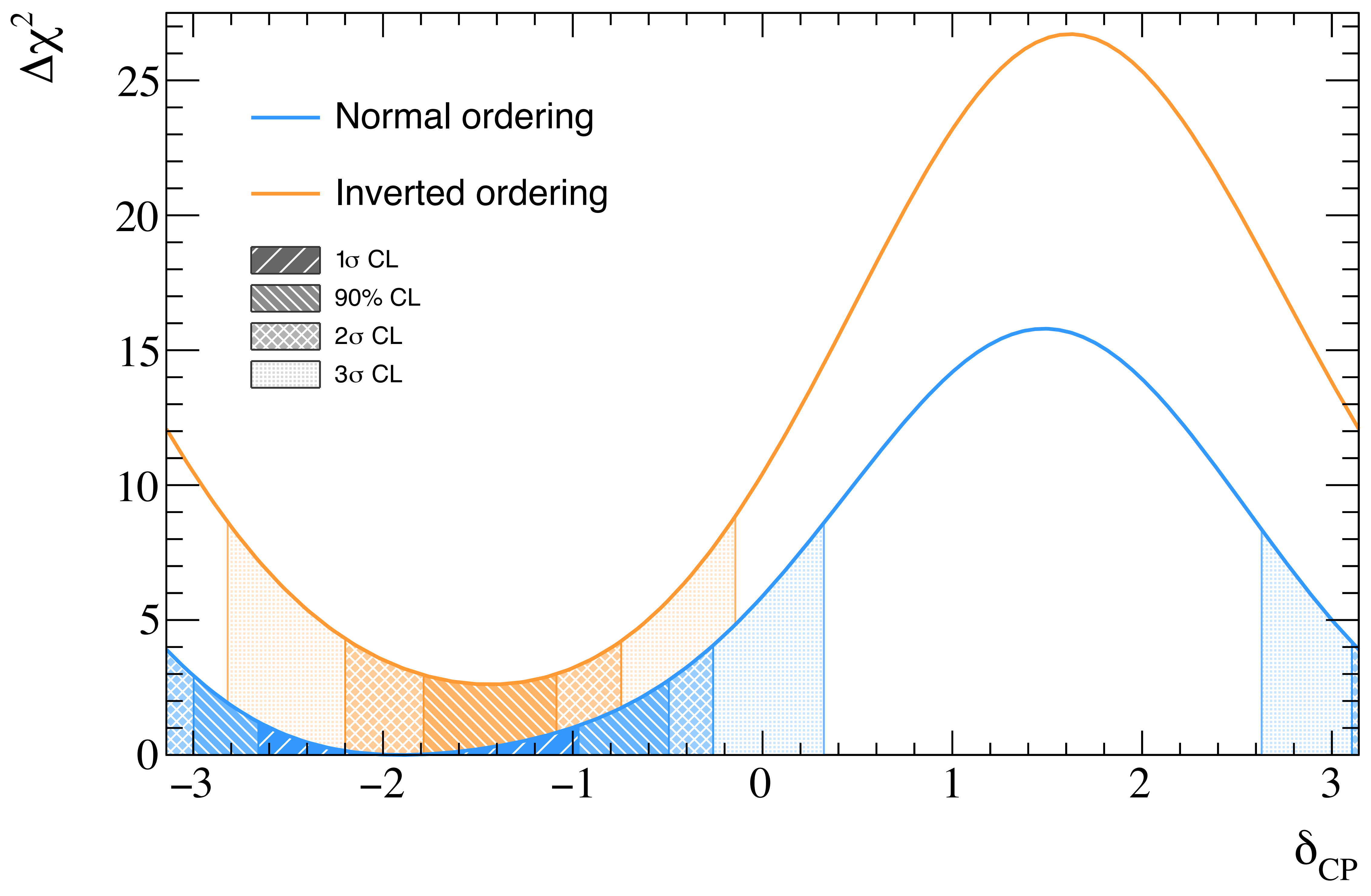
Near detector fit →



Anti-correlations between flux and cross section parameters after ND-fit

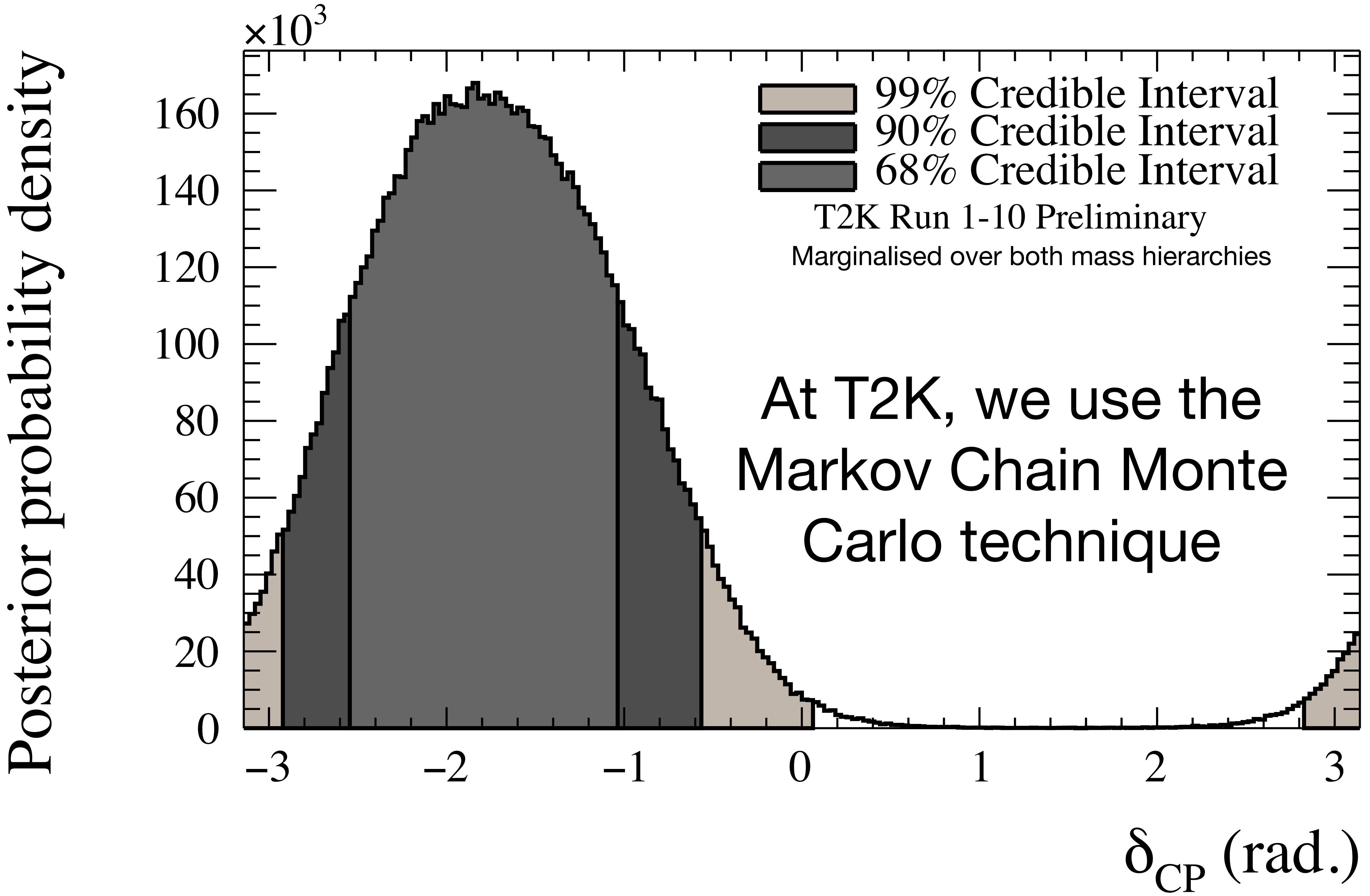
Frequentist vs. Bayesian: Conceptual differences

Frequentist results produce $\Delta\chi^2$ distributions



Areas with a lower $\Delta\chi^2$ are more likely to contain the "true" value

Bayesian results produce **posterior probability density** distributions



Areas with a larger probability density are more likely to contain the "true" value

Markov Chain Monte Carlo

- MCMC algorithm presents an efficient solution for sampling from a complex multivariate posterior likelihood distribution
- The algorithm provides a recipe for building the Markov chain
- At each step, an ensemble of model parameters is either accepted or rejected based on a comparison with a metric
- Parameters in the resulting Markov Chain have a distribution density proportional to the posterior likelihood

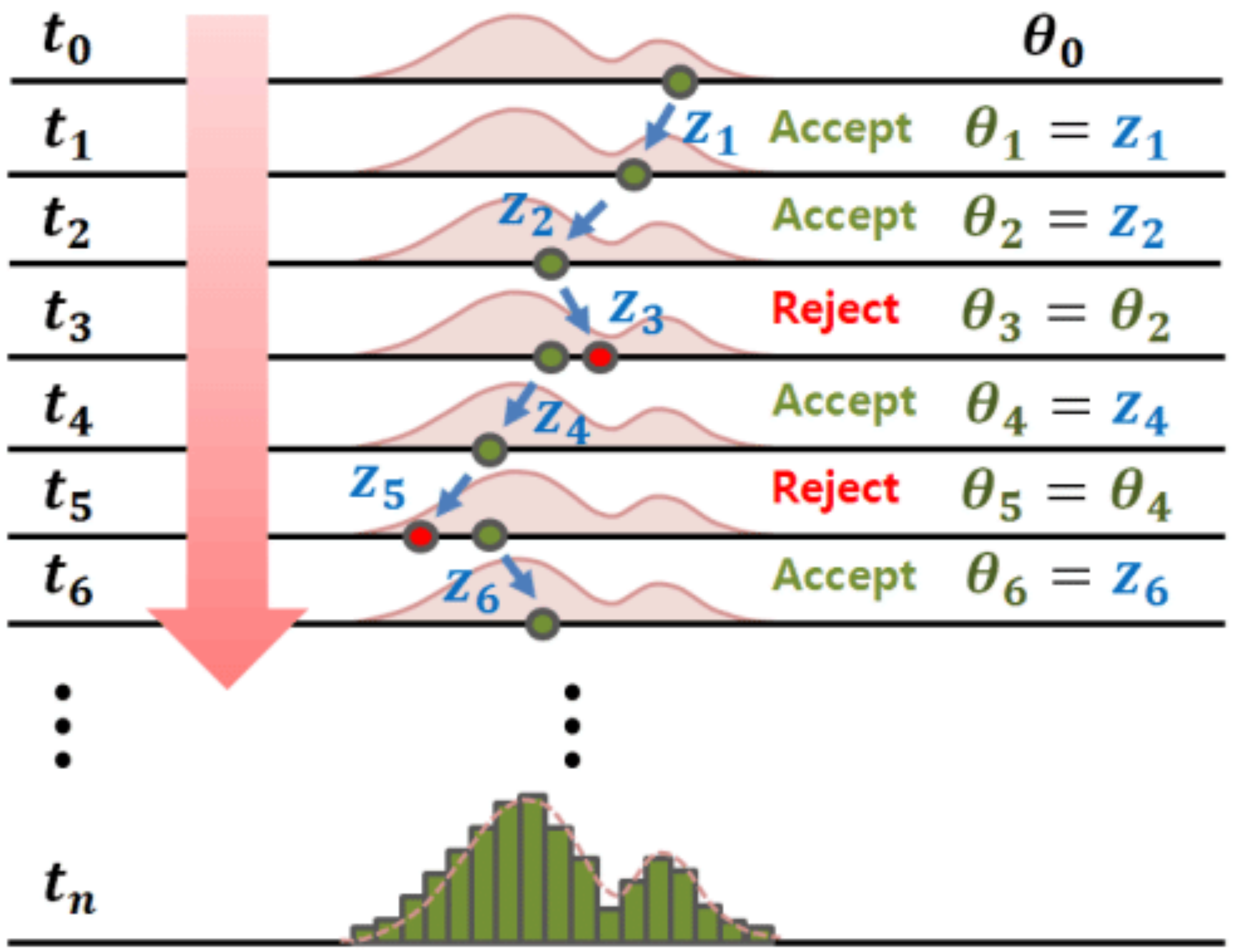
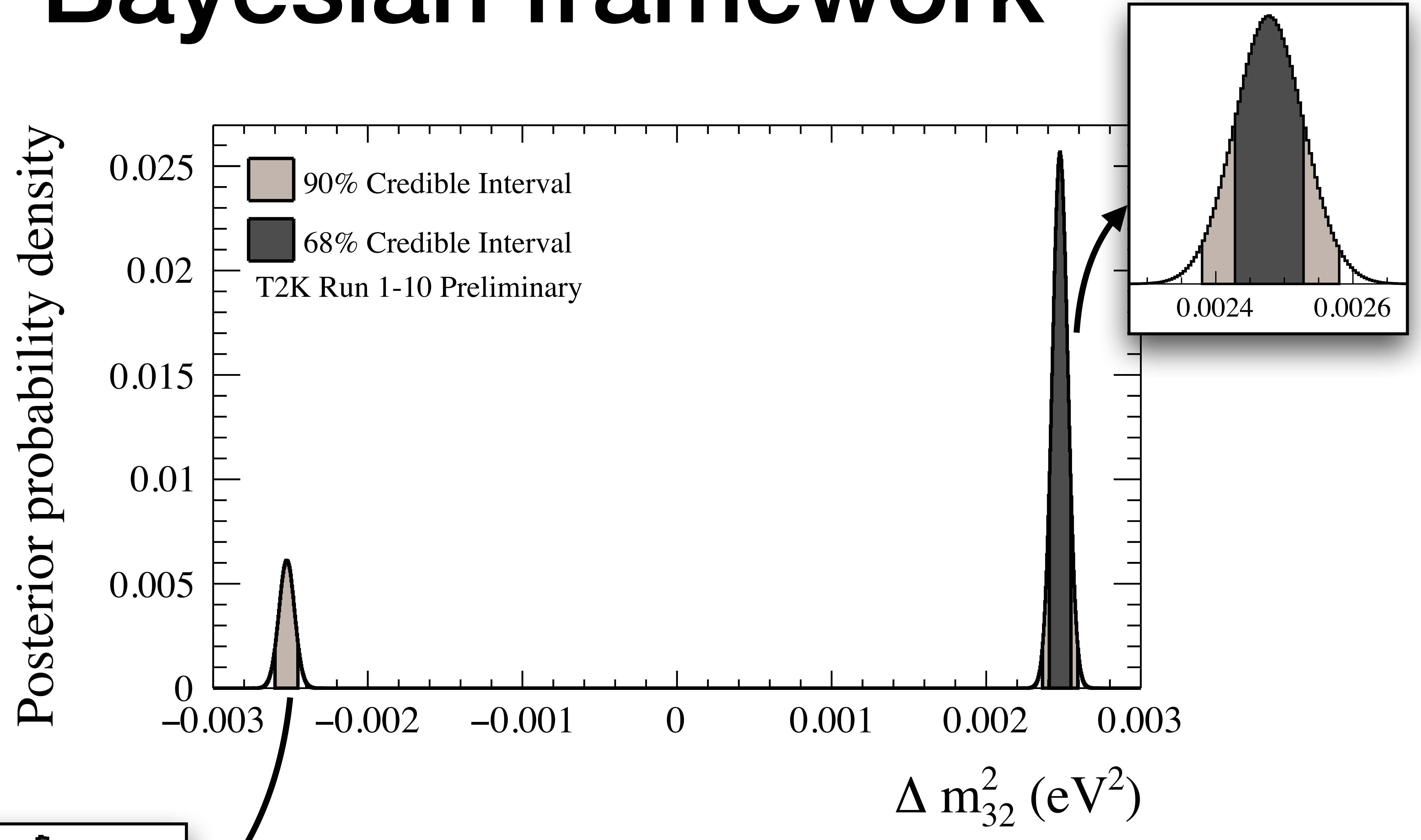
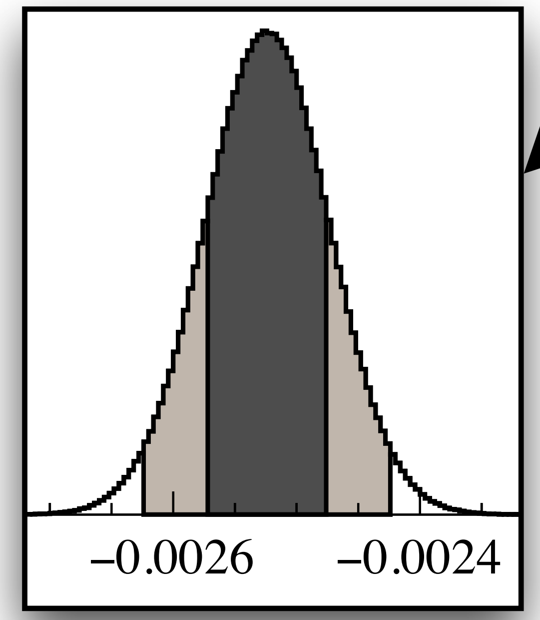


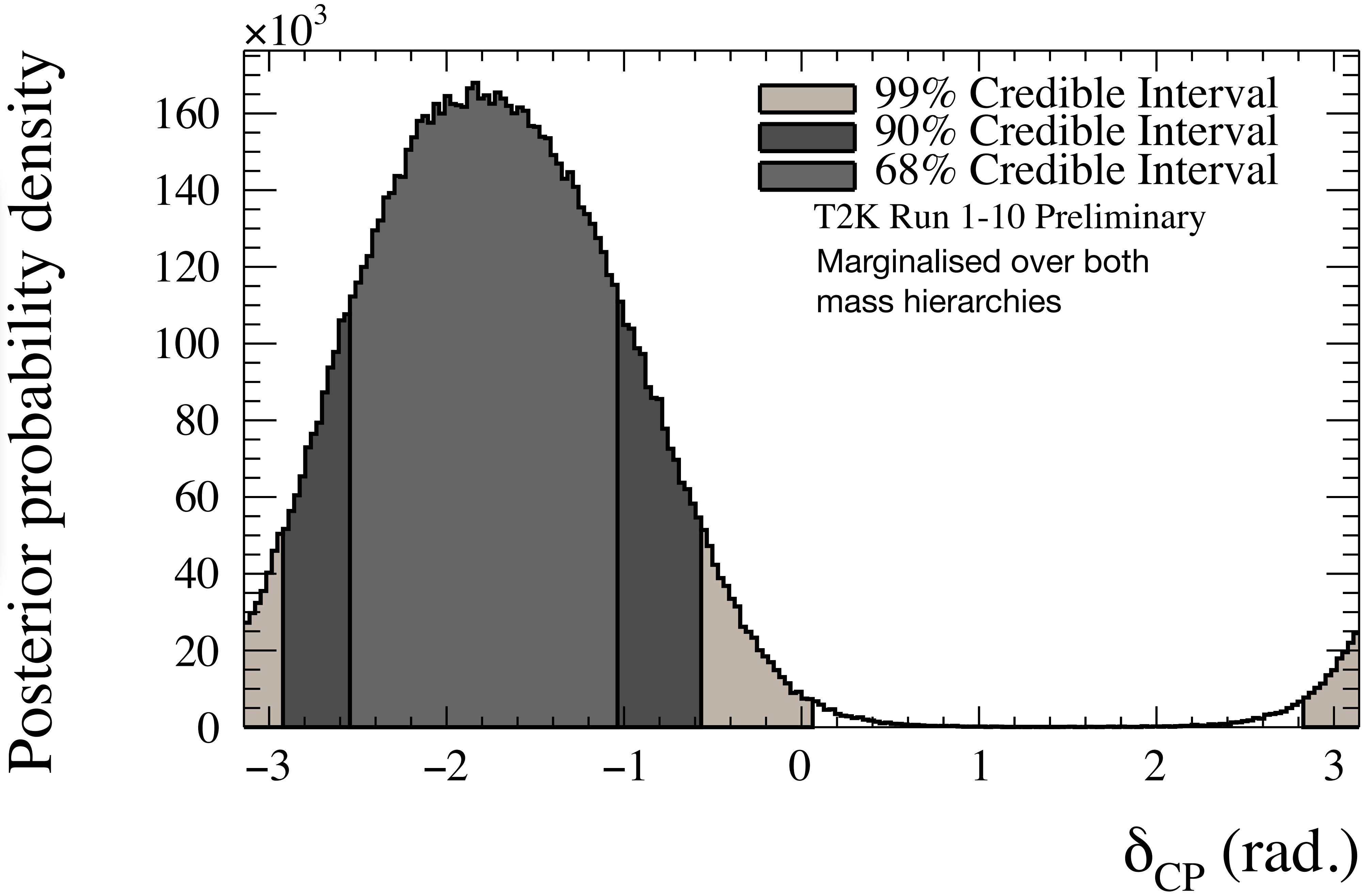
Figure from Adaptive Markov chain Monte Carlo algorithms for Bayesian inference: recent advances and comparative study

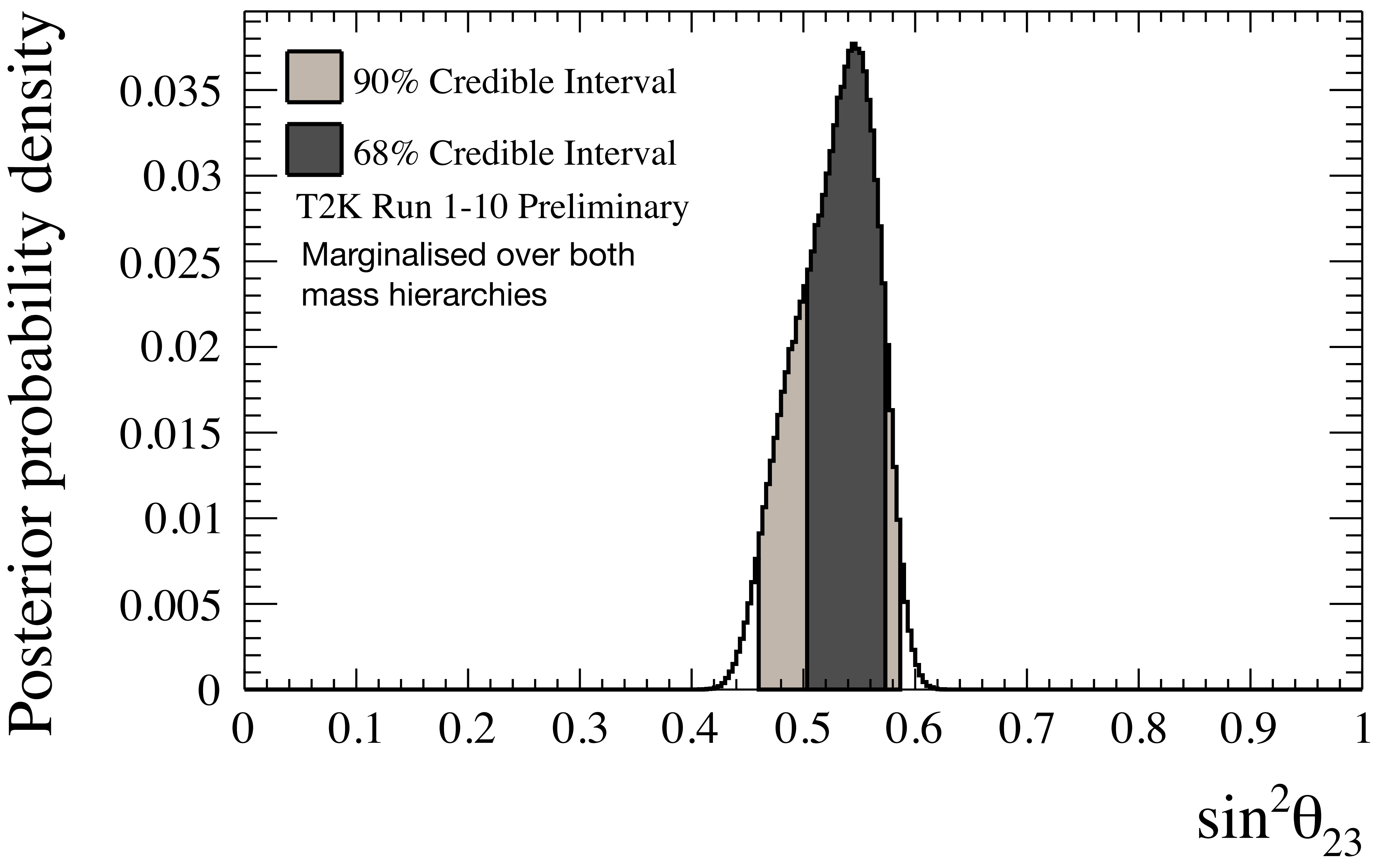
Full inference in Bayesian framework





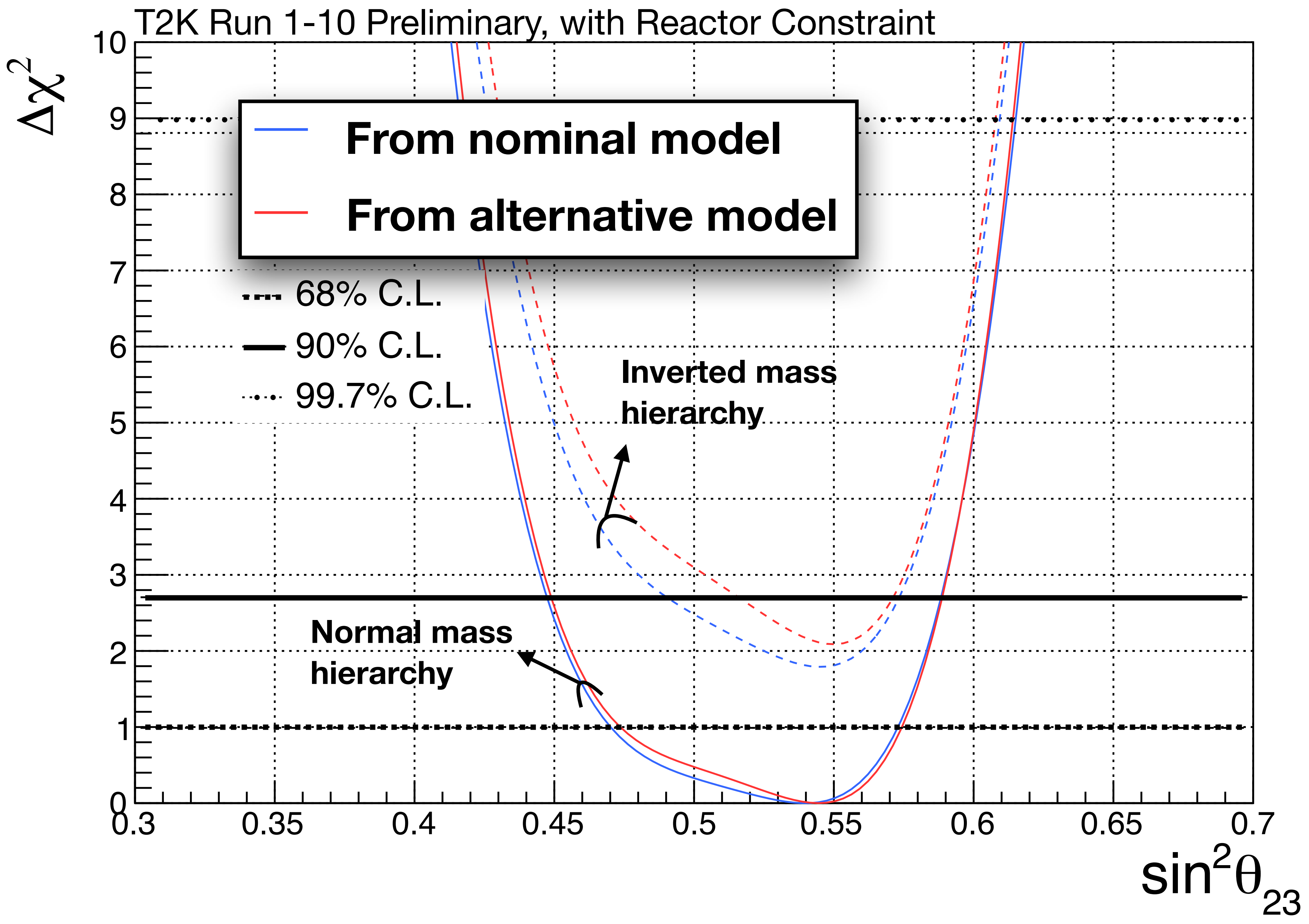
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.195	0.613	0.808
IH ($\Delta m^2_{32} < 0$)	0.035	0.157	0.192
Sum	0.230	0.770	1.000

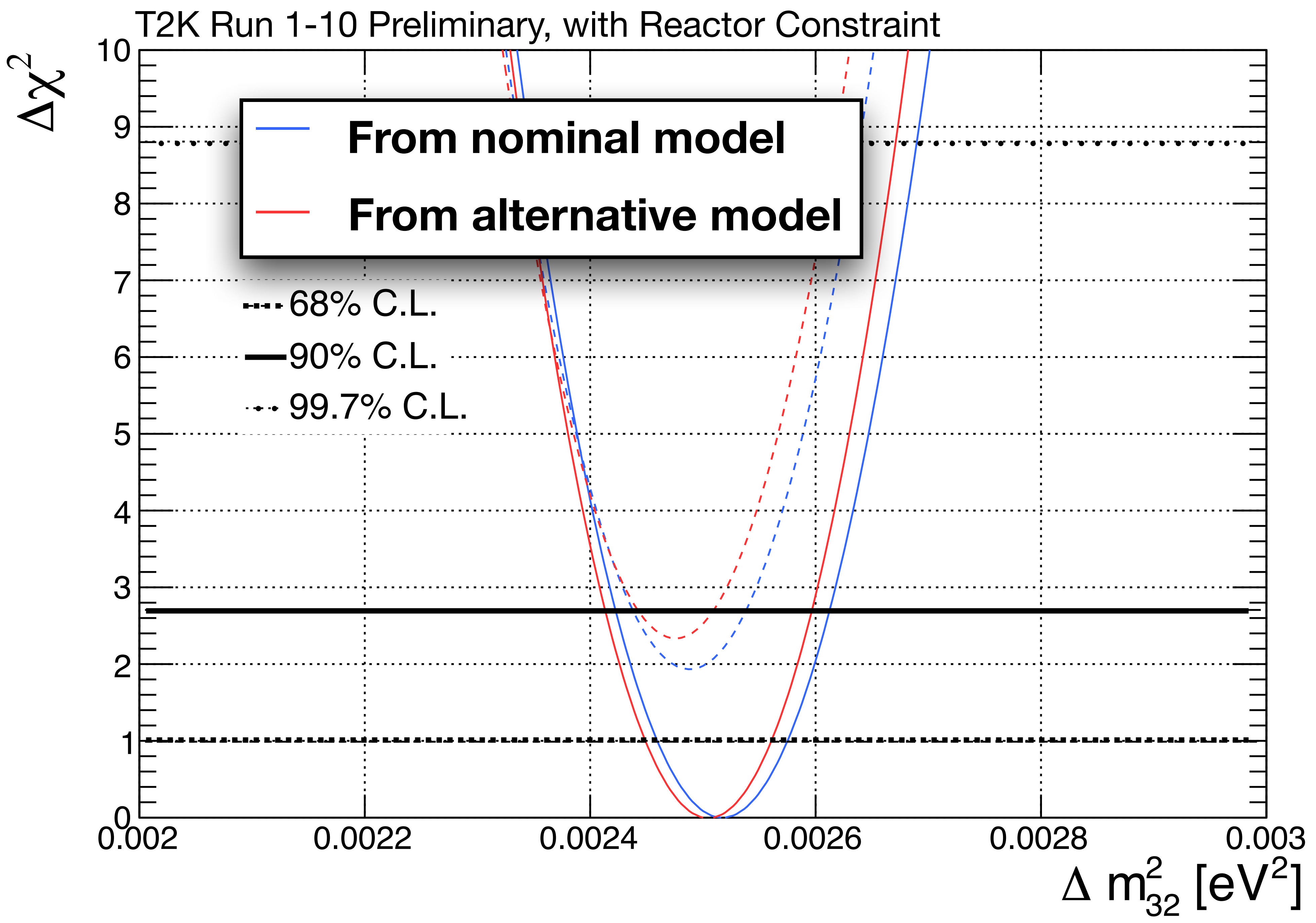




Bias studies for oscillation analyses

- The sturdiness of our analyses is tested by performing **fits on simulated data from alternative theory and data driven models**
- No significant biases have been observed for θ_{13} and θ_{23}
- **Slight bias observed for Δm^2_{32}**, which has been accounted for by adding a **compensating uncertainty of** $1.4 \times 10^{-5}\ eV^2$
- The slight bias on δ_{CP} is accounted for by reporting the maximum observed shift on the δ_{CP} contour boundary (here the contour is completely statistics dominated)





Bayesian vs. Frequentist T2K Analyses Strategies

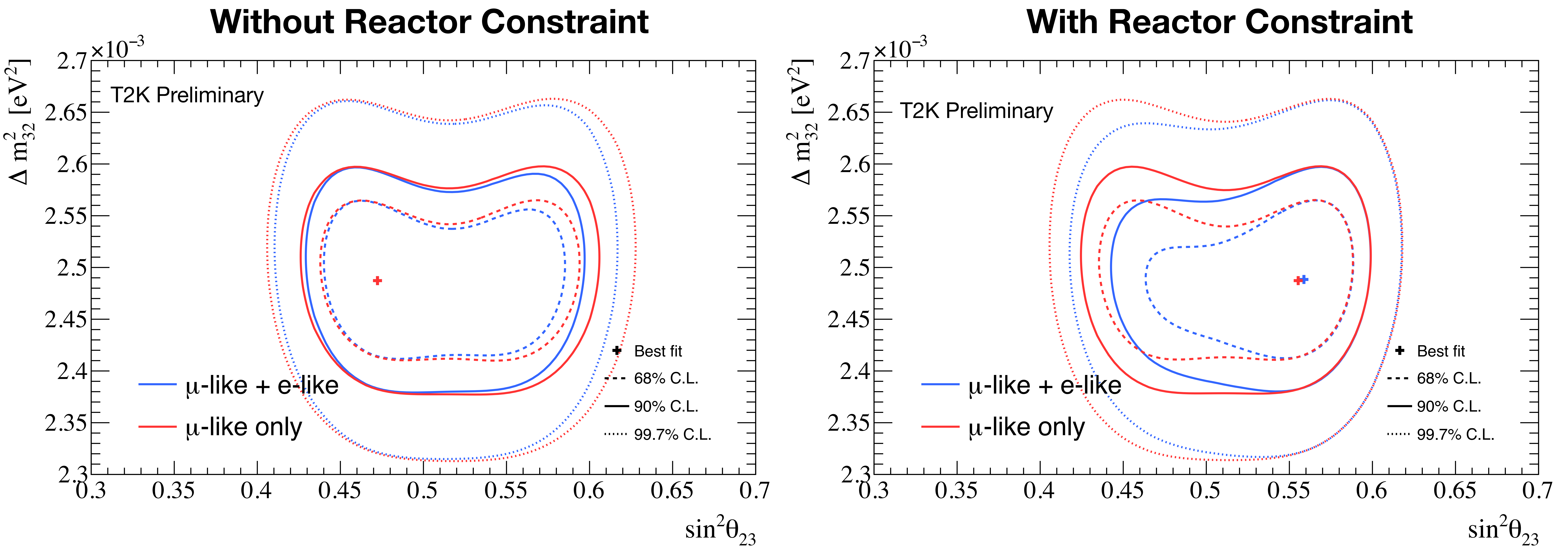
	MaCh3	**P-Theta**	**"MaCh3-like" P-Theta**
Kinematic variables for $CC0\pi\ 1R_e$	$(E_e^{rec}, \theta_e^{rec})$	$(p_e^{rec}, \theta_e^{rec})$	$(E_e^{rec}, \theta_e^{rec})$
Likelihood	Binned Poisson likelihood ratio	Binned Poisson likelihood ratio	Binned Poisson likelihood ratio
Likelihood optimization	Markov chain Monte Carlo	Grid search and gradient descent	Grid search and gradient descent
Resulting contours/ limits	Bayesian credible intervals	Frequentist confidence intervals with Feldman Cousins	Frequentist confidence intervals with Feldman Cousins
Mass hierarchy inference	Bayes factor from fraction of points in each hierarchy	Bayes factor from likelihood integration	Frequentists p-value from generated PDF
Inputs from near detector	Simultaneous near+far detector joint fit	Constrained covariance matrix	Constrained covariance matrix
Systematics handling	Maginalisation after fit	Marginalisation during fit	Marginalisation during fit

Feldman Cousins method gives critical $\Delta\chi^2$ values for the confidence intervals

T2K always employs marginalisation rather than profiling because of inherently better non-Gaussian systematics treatment

Cross-checks between T2K oscillation analyses

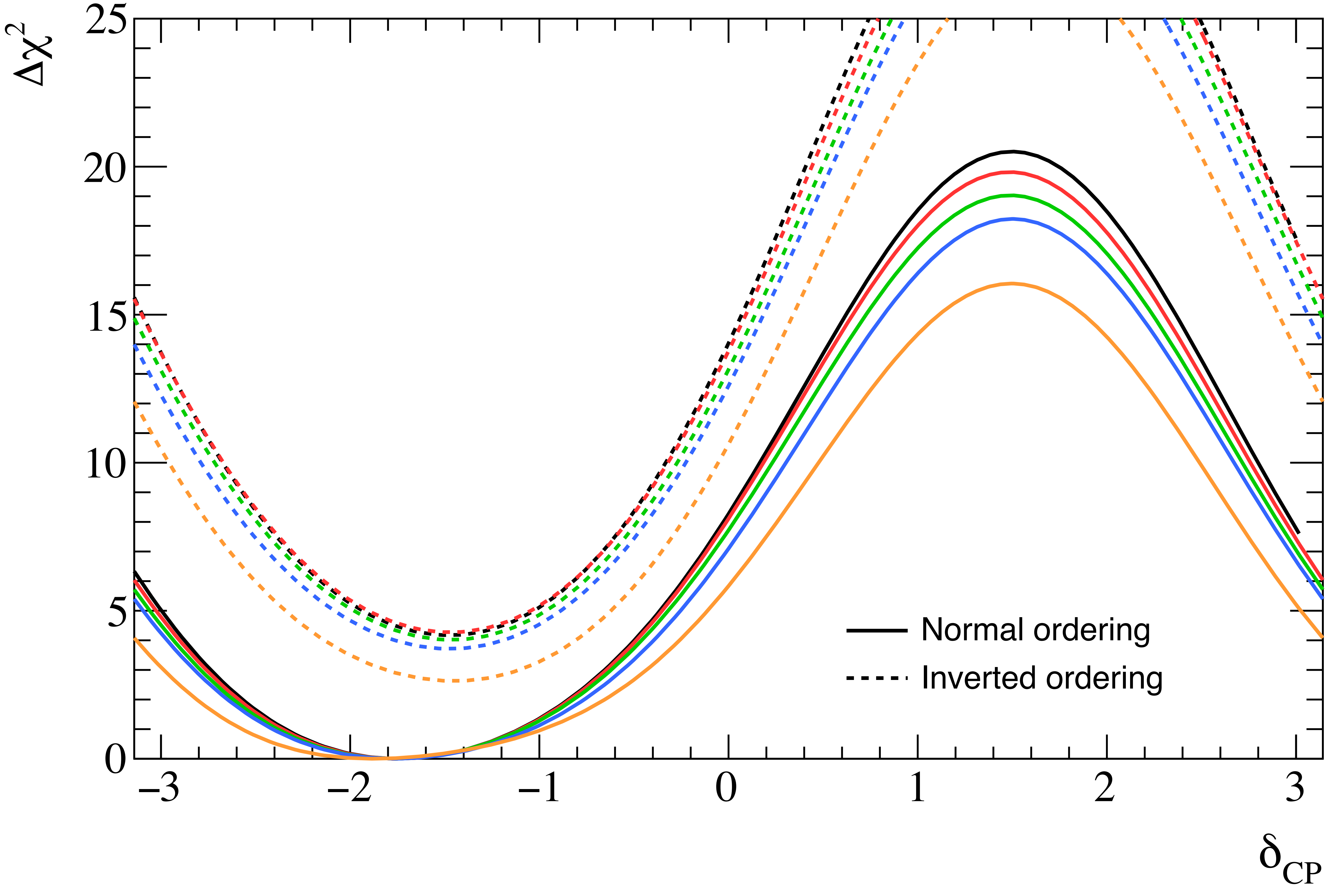
θ_{23} octant preference



Upper θ_{23} octant preference is driven by the electron-like Cherenkov ring sample, in combination with the tighter reactor constraint on θ_{13}

Evolution of T2K's δ_{CP} result

- Can sequentially add improvements to the OA2018 analysis (Nature publication), and examine the measurement sensitivity:
  - A: Nature result
  - B: Improved cross section and flux models mentioned earlier
  - C: Using the updated reactor constraint on θ_{13} (from 2019 Particle Data Group)
  - D: New Super-K calibration, causing some events to drop in and out from samples
  - E: Addition of the new Run 10 T2K data
- **Greatest change in our measurement (slightly weaker constraint) is driven by the addition of new data**



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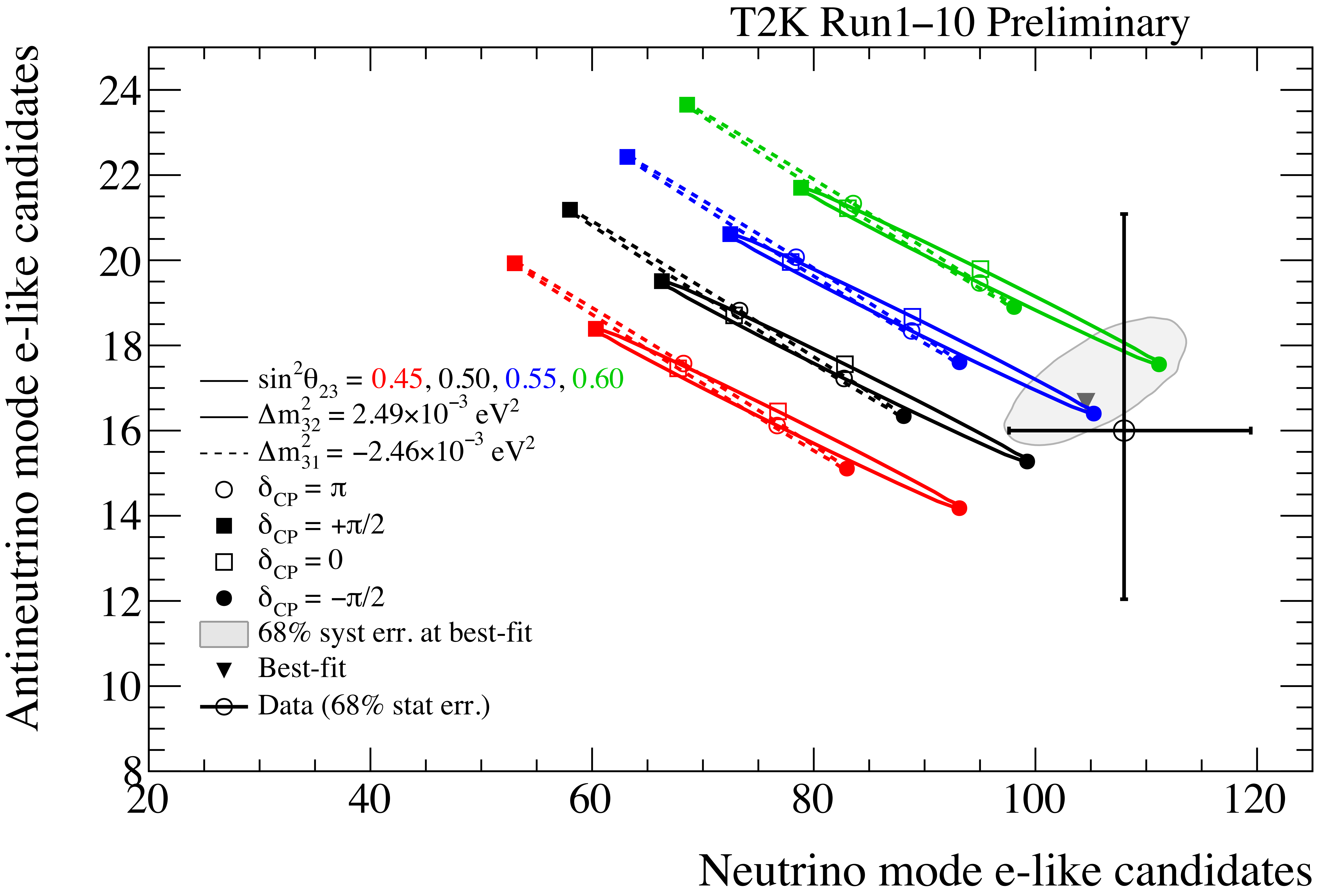
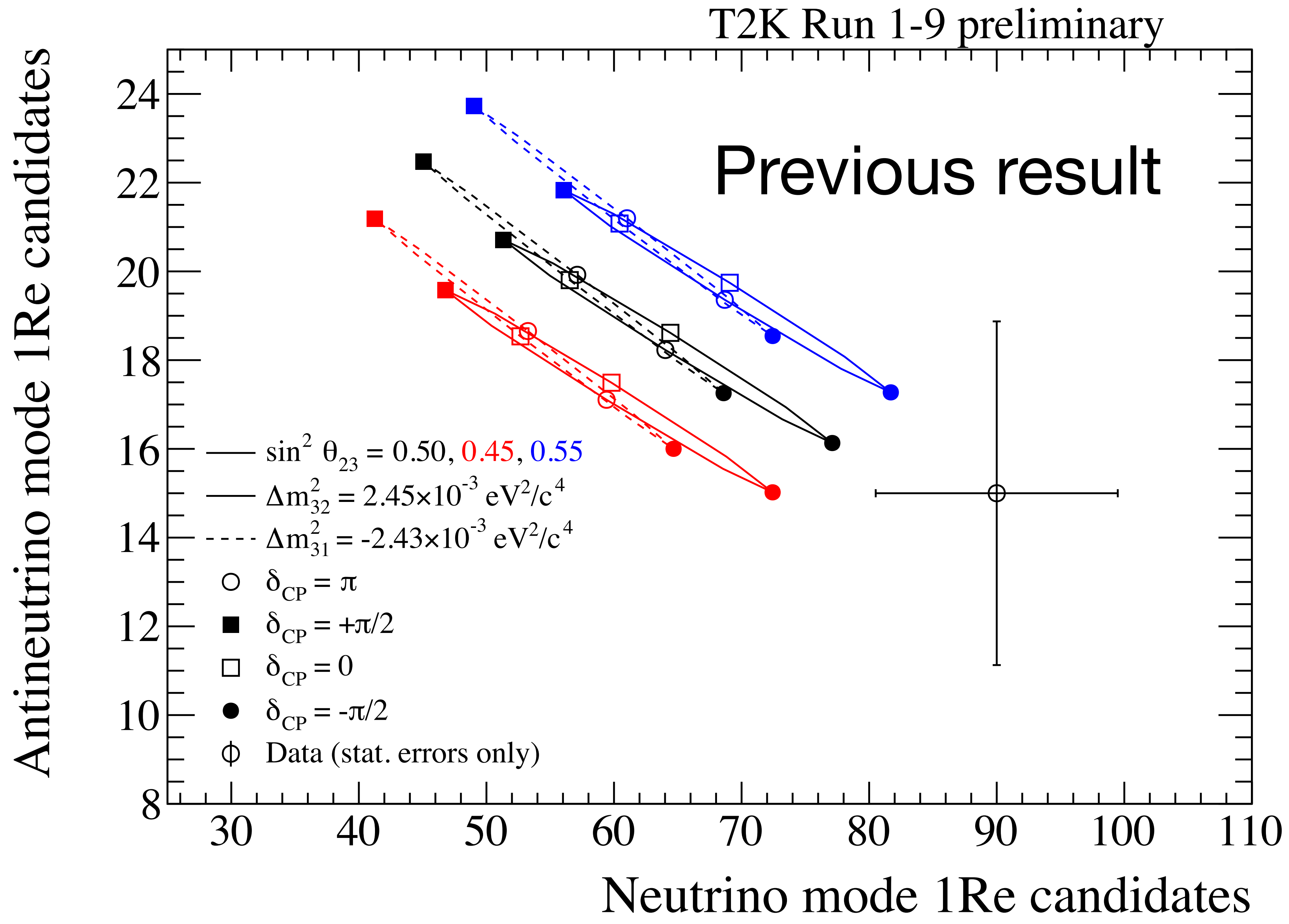
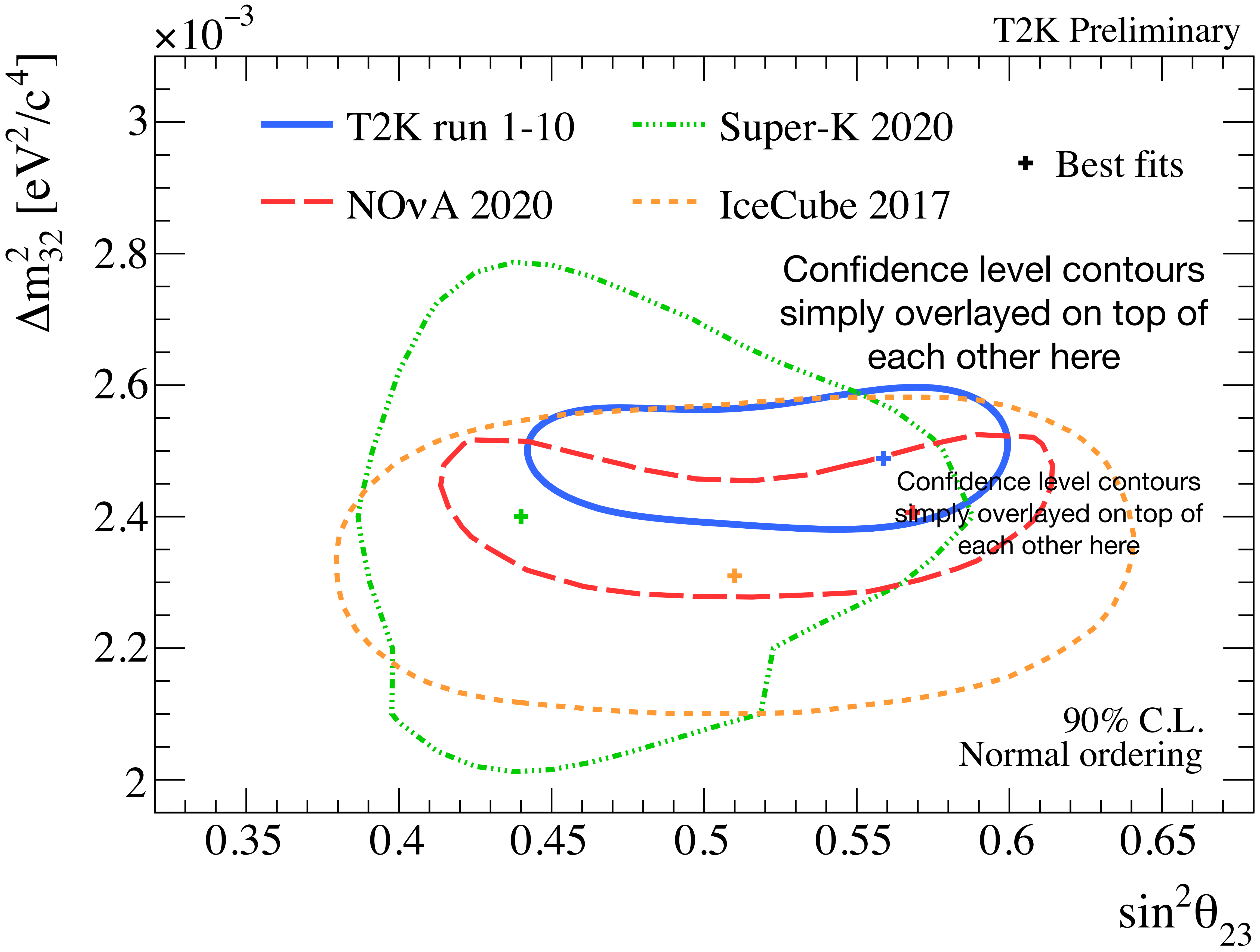
Bi-Probability plots

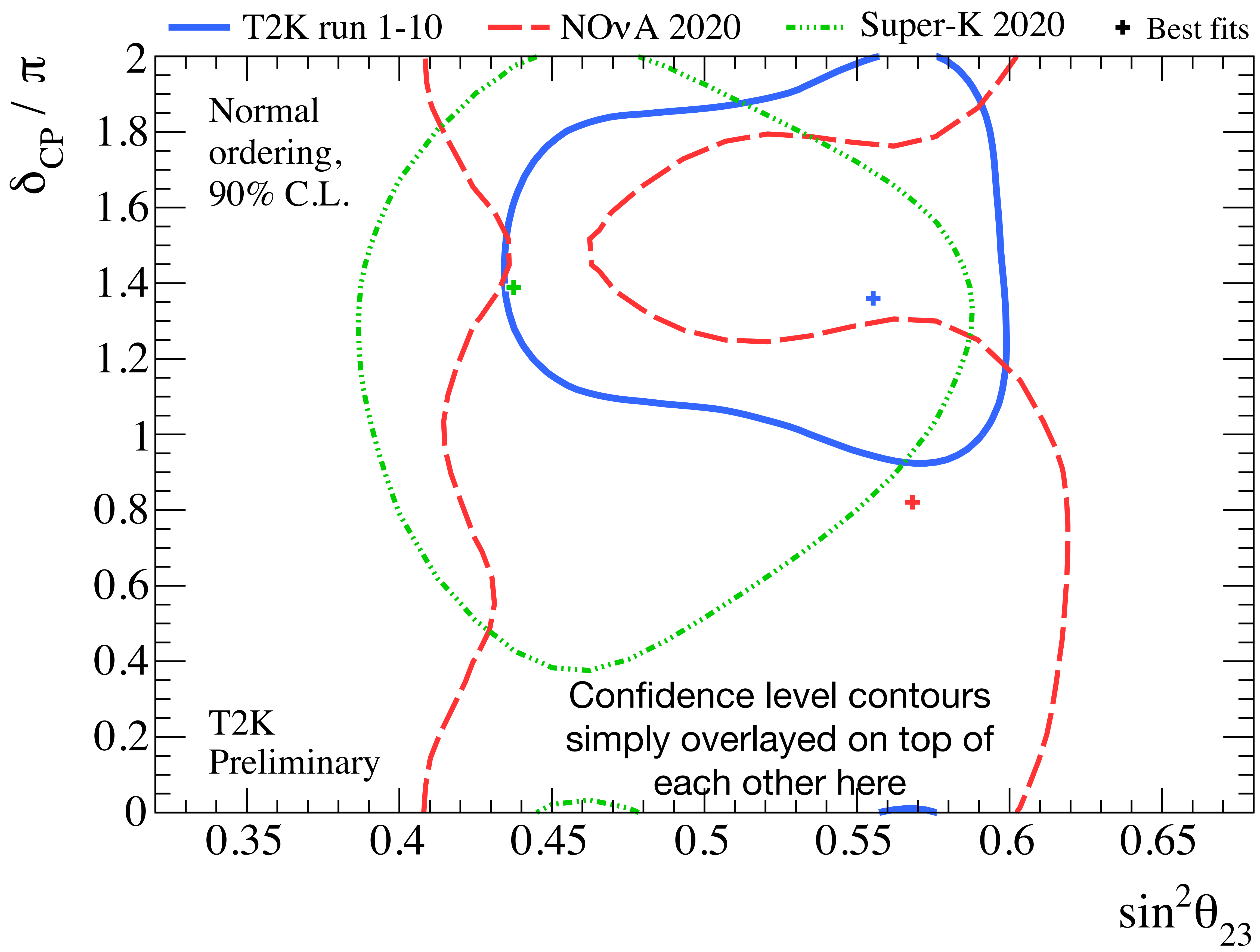


- Change in electron neutrino event rate ~o(45%) between $\delta_{CP} = \pi/2$ and $\delta_{CP} = -\pi/2$
- Latest result is slightly closer to the PMNS prediction than last year



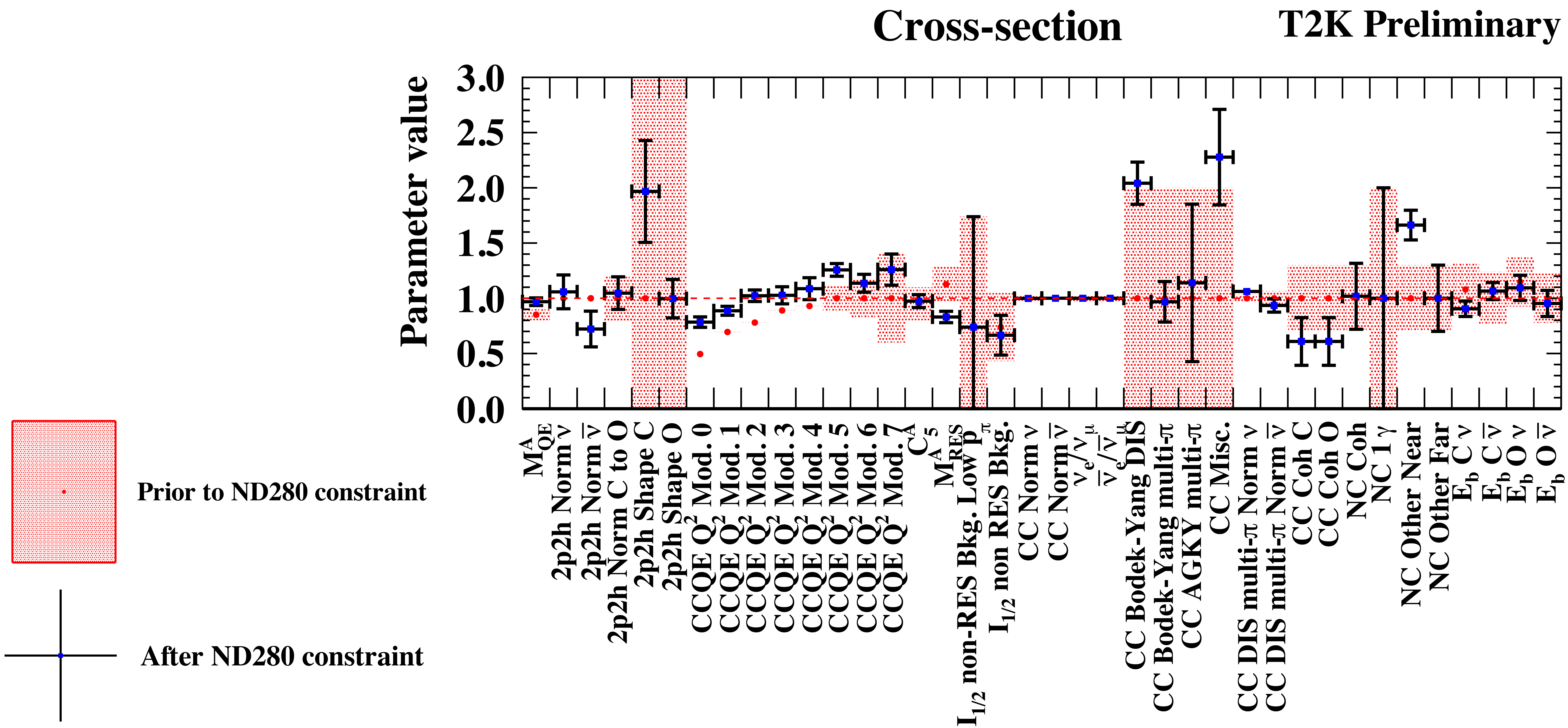
Combined oscillation parameter knowledge: current landscape



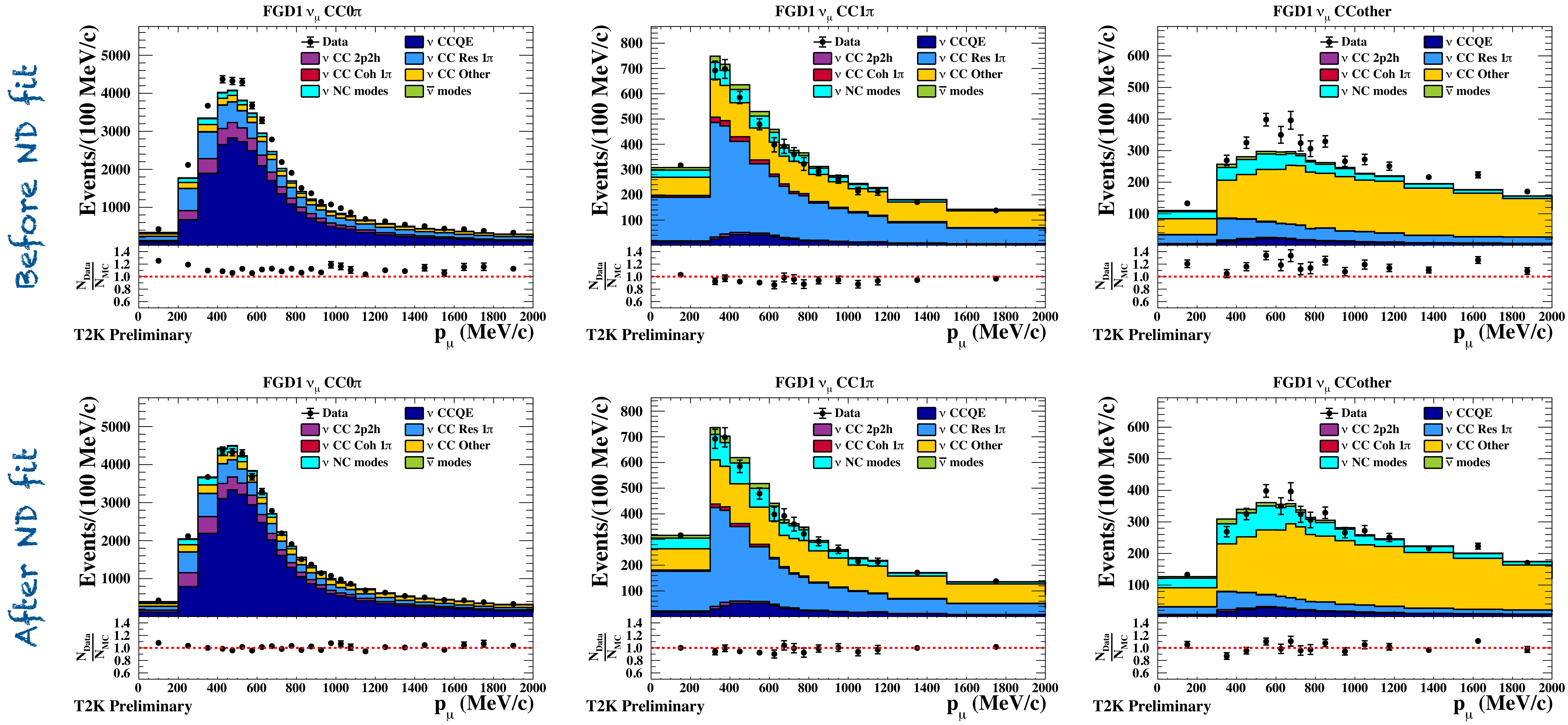


NOvA 2020: results from here
Super-K 2020: preliminary results from here
IceCube 2017: results from here

Fits to near detector data: cross section model parameters

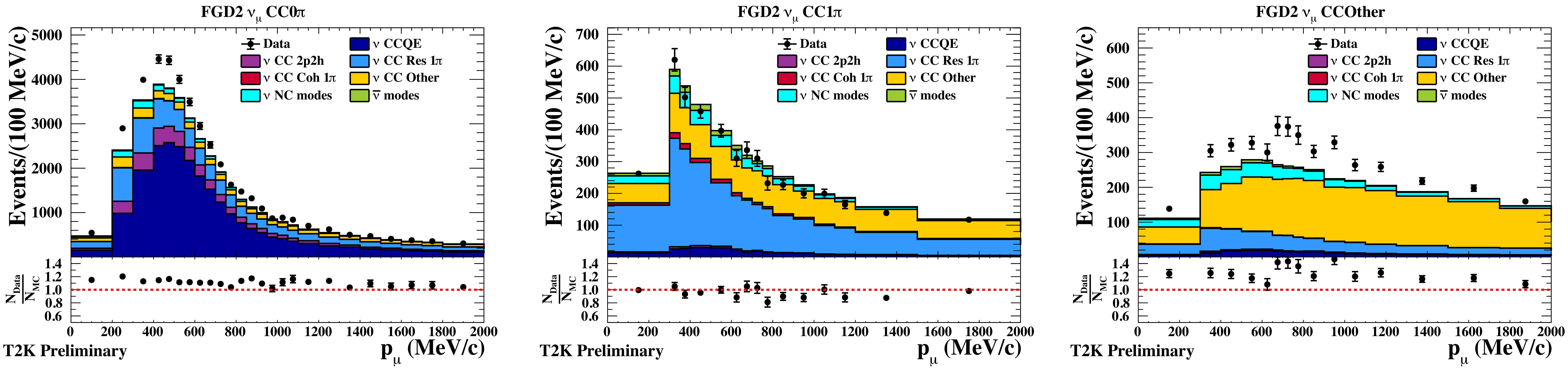


Fits to near detector FGD1 ν_μ signal data in ν-mode

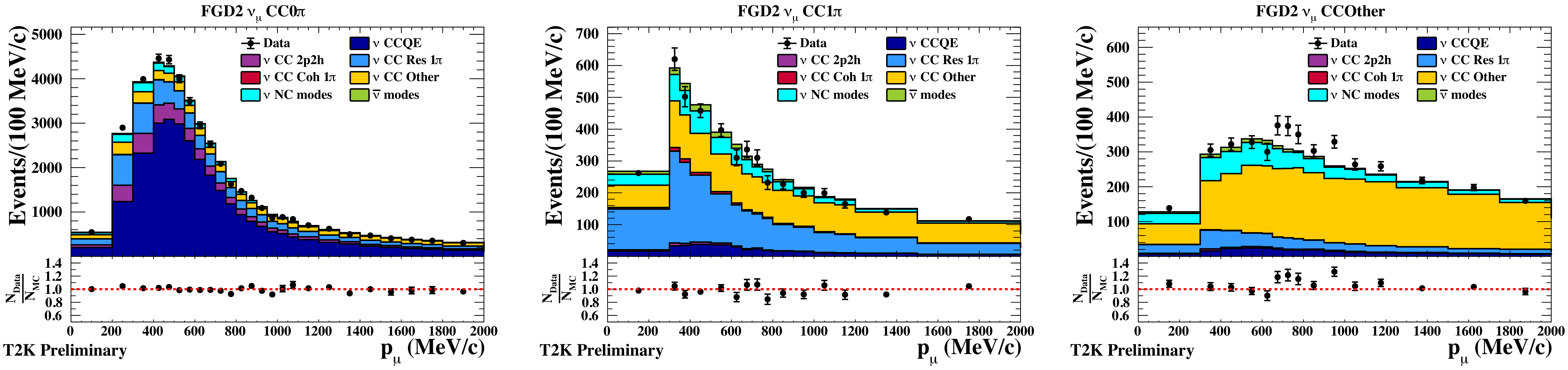


Fits to near detector FGD2 ν_μ signal data in ν-mode

Before ND fit



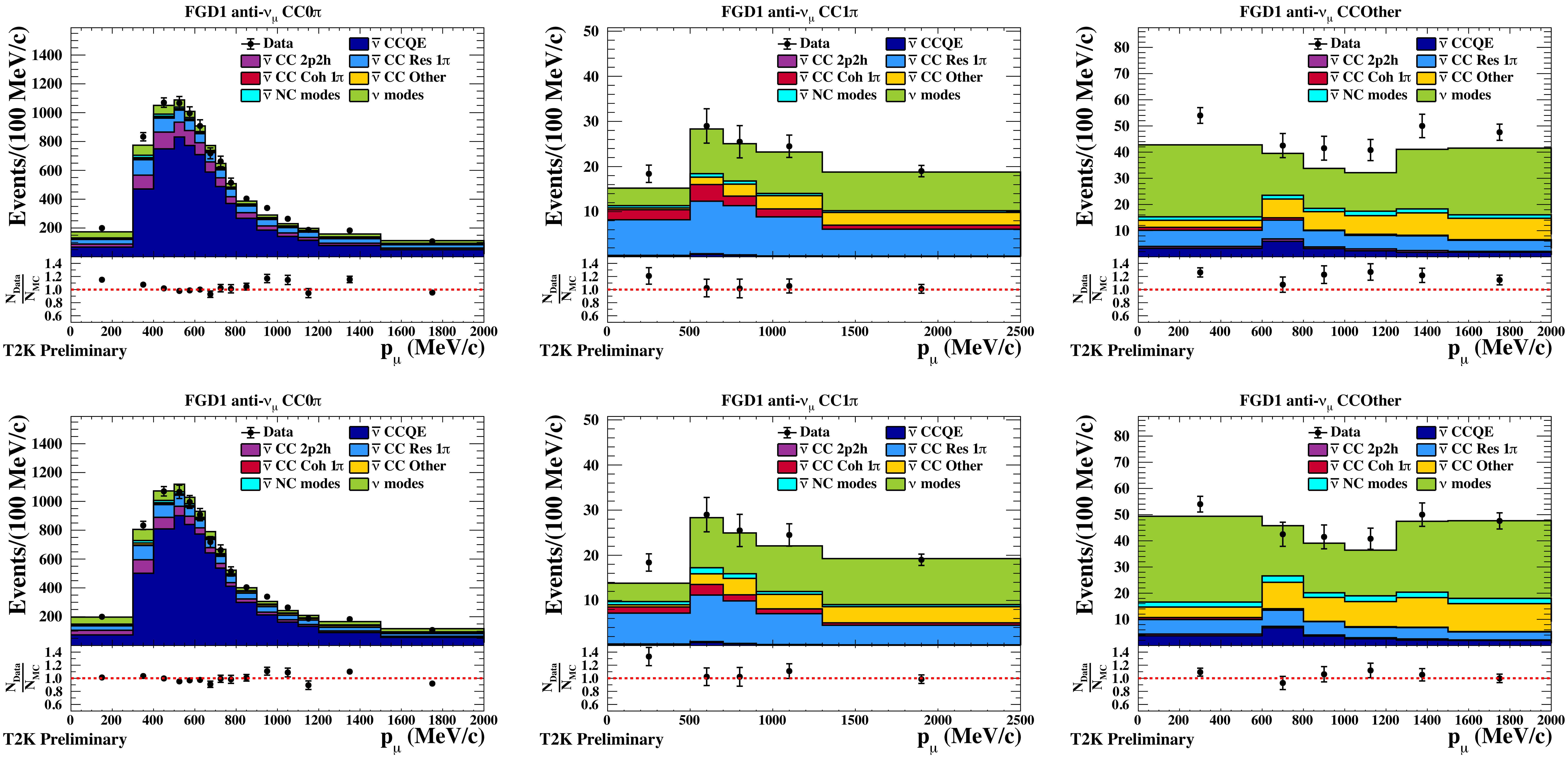
After ND fit



Fits to near detector FGD1 $\bar{\nu}_\mu$ signal data in $\bar{\nu}$-mode

Before ND fit

After ND fit



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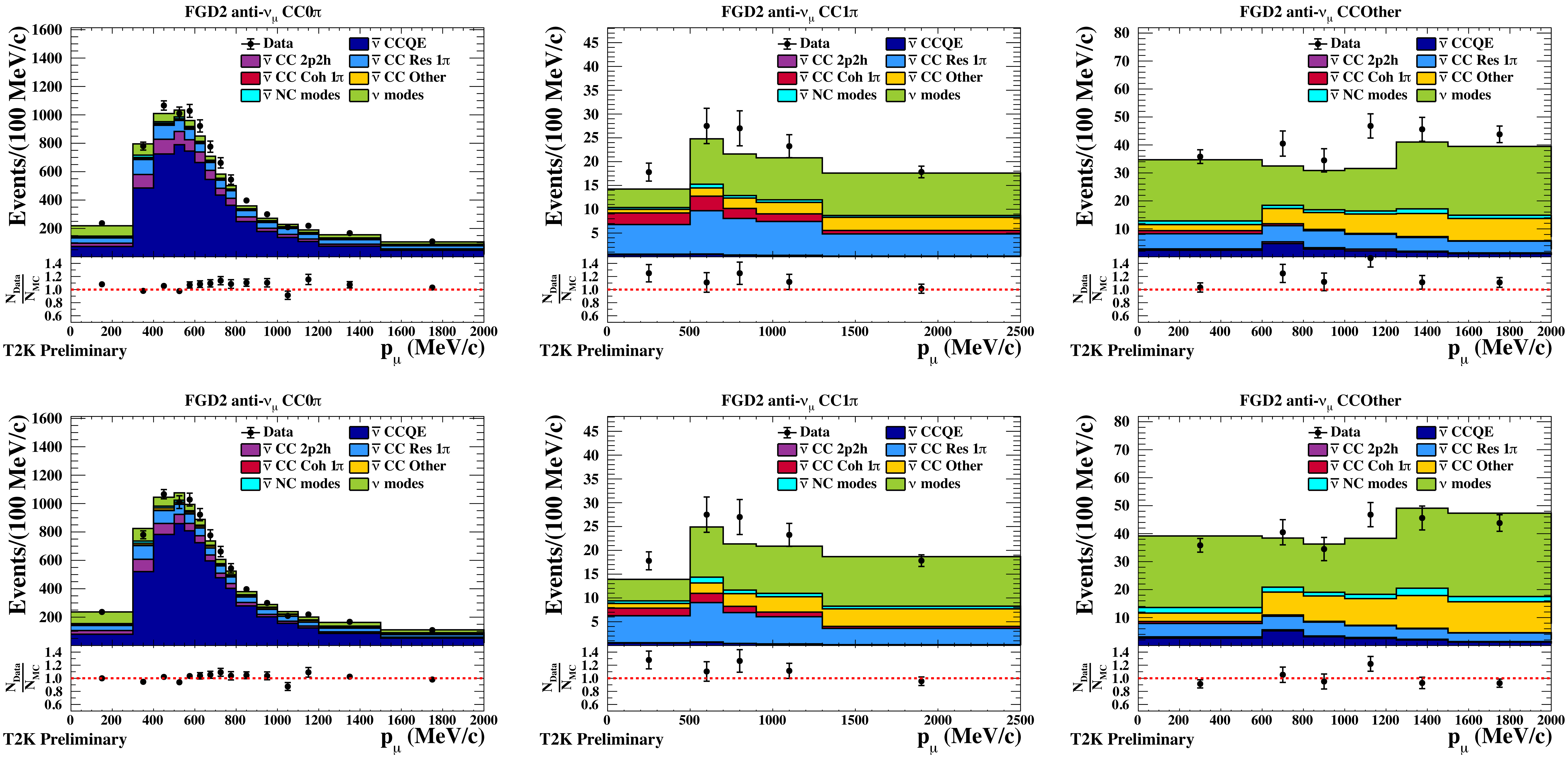
Fits to near detector FGD2 $\bar{\nu}_\mu$ signal data in $\bar{\nu}$-mode

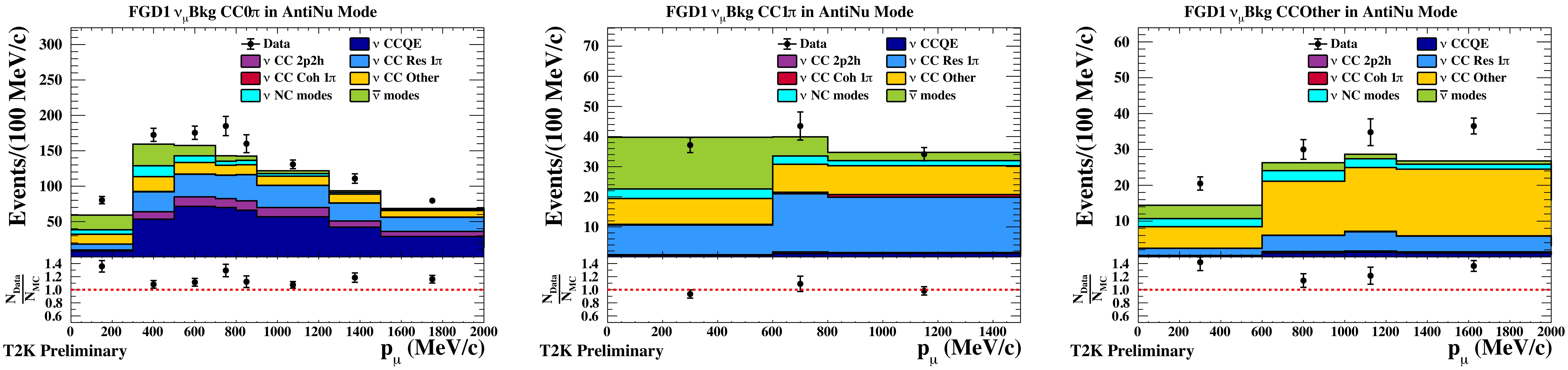
Before ND fit

After ND fit

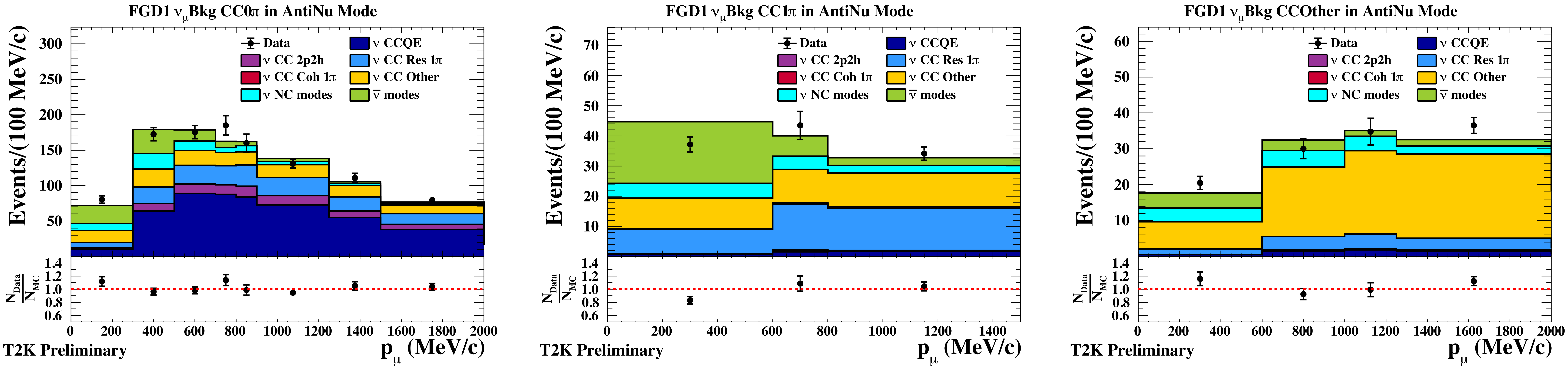


Fits to near detector FGD1 ν_μ wrong-sign bkg. in $\bar{\nu}$-mode

Before ND fit



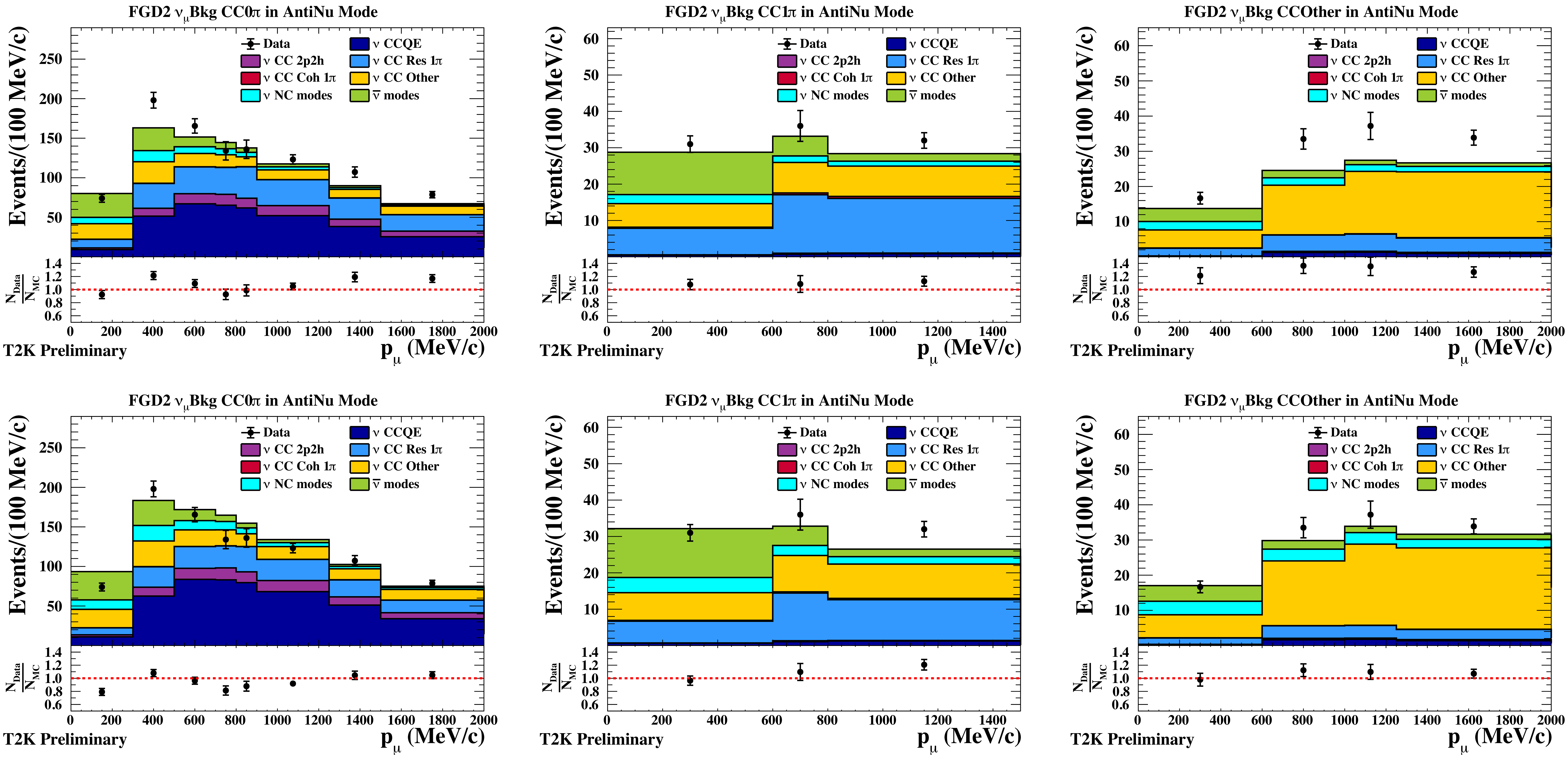
After ND fit



Fits to near detector FGD2 ν_μ wrong-sign bkg. in $\bar{\nu}$-mode

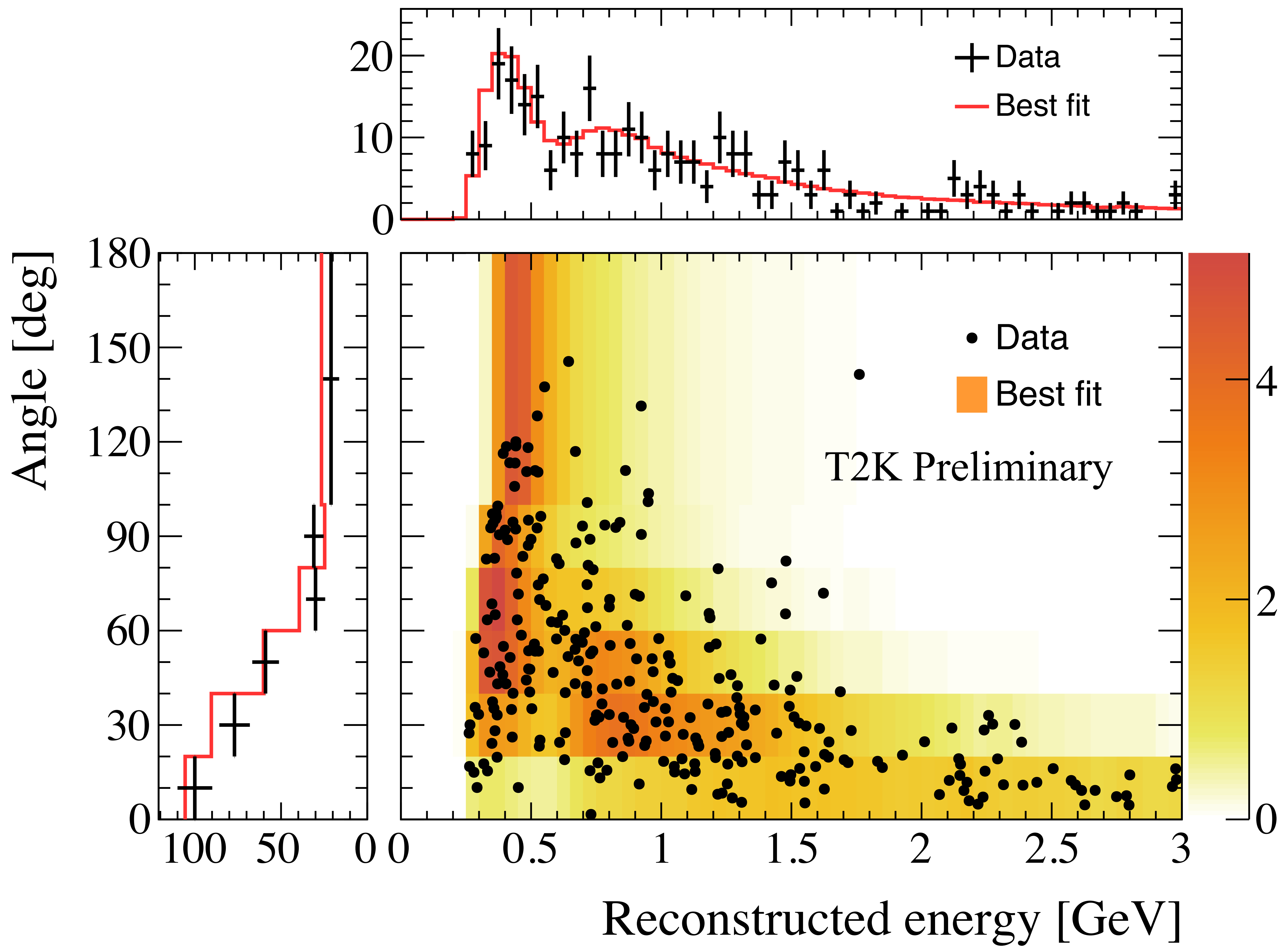
Before ND fit

After ND fit

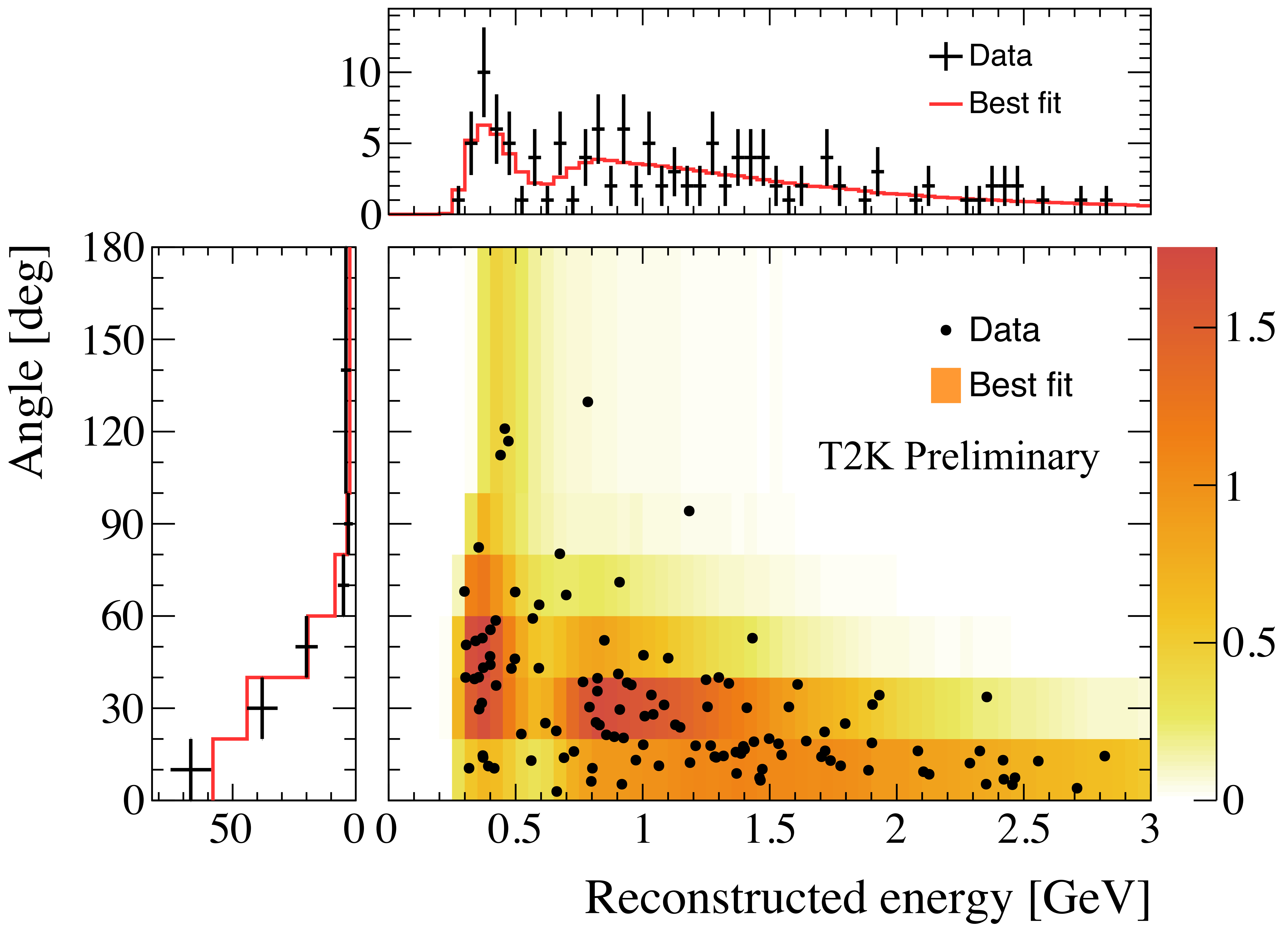


Joint fit to near and far detector data: muon-like samples at Super-K

Neutrino mode
1 muon-like ring



Anti-neutrino mode
1 muon-like ring



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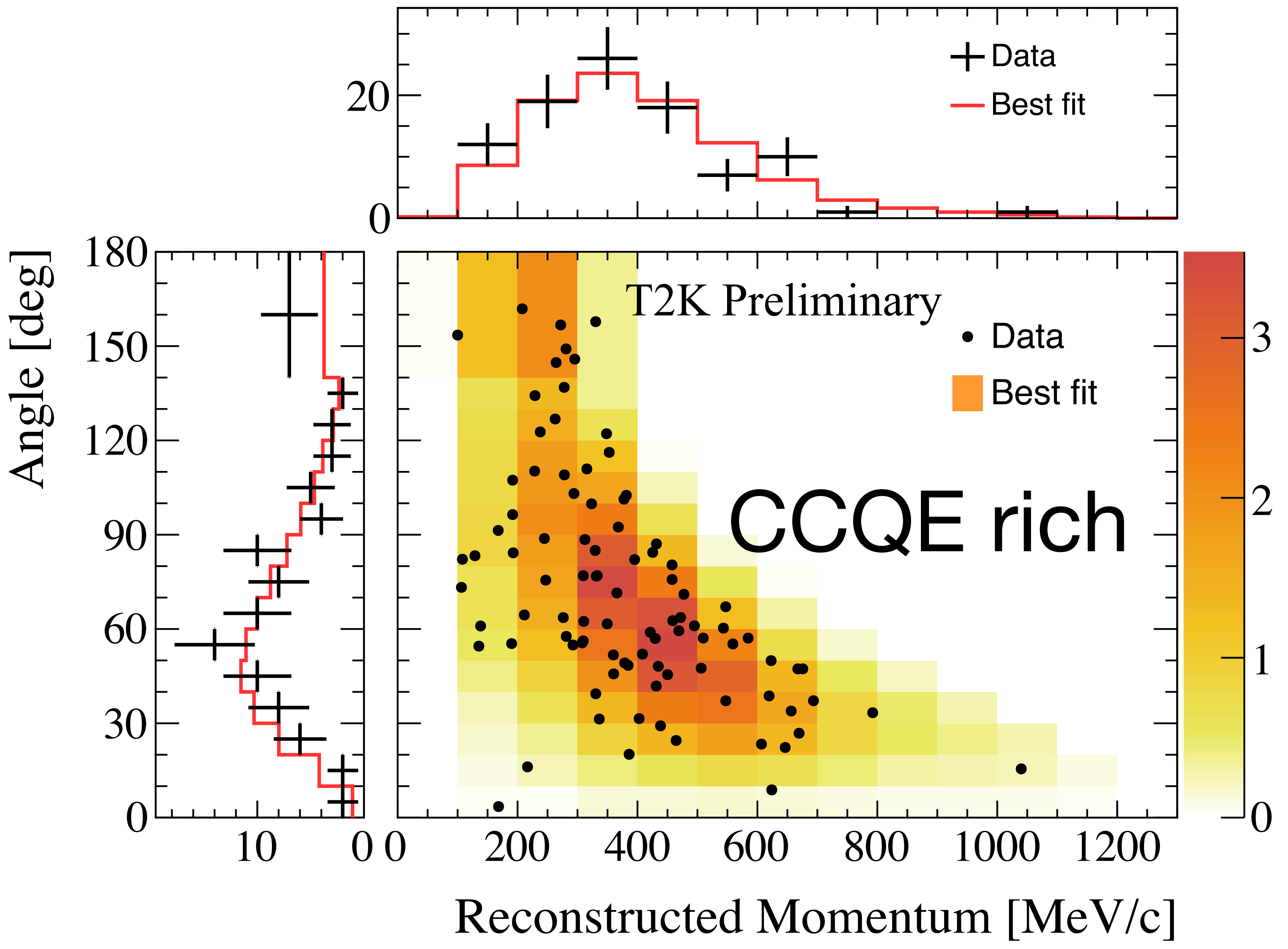
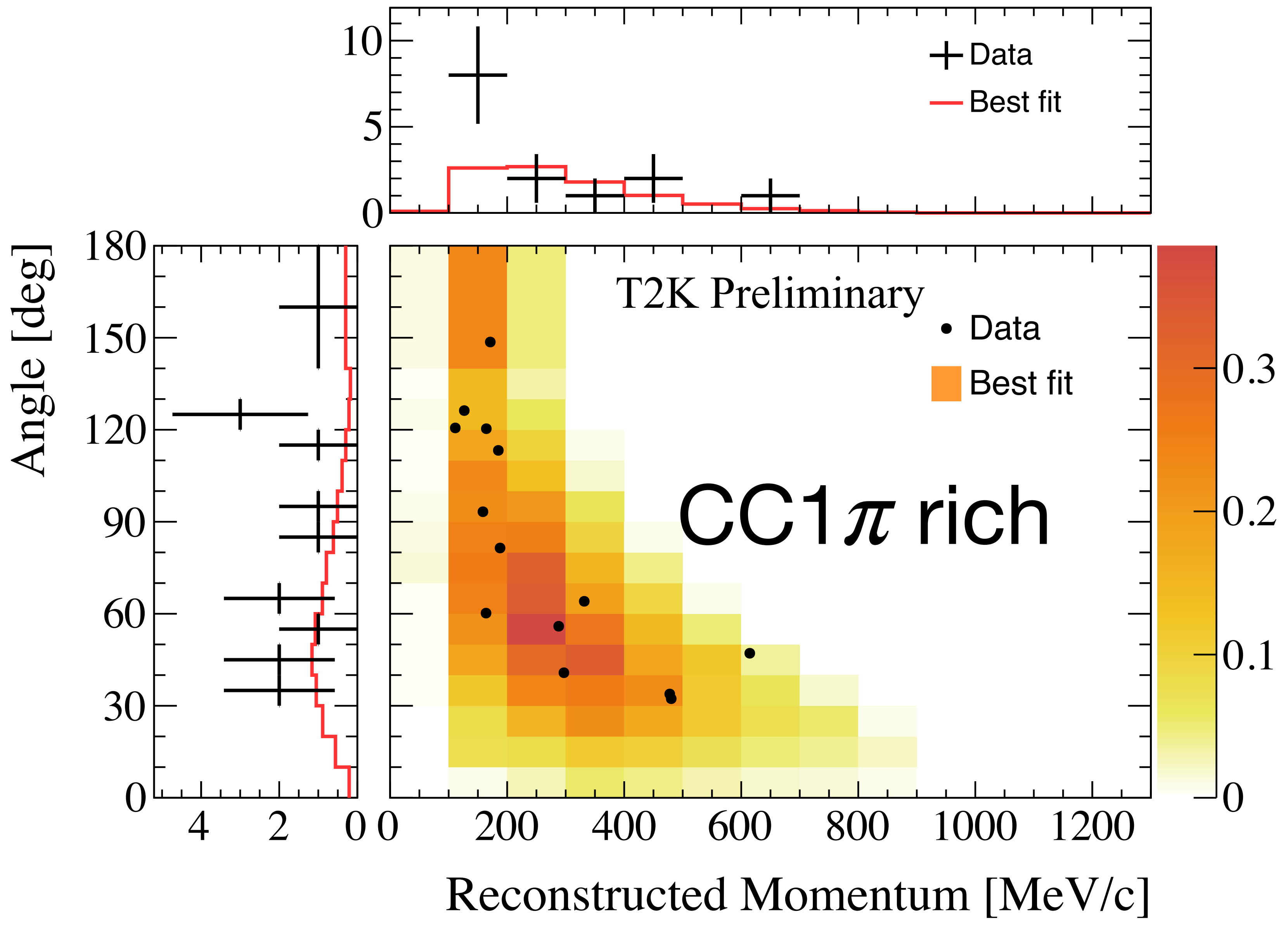
Joint fit to near and far detector data: electron-like samples at Super-K

Neutrino mode
1 electron-like ring



Neutrino mode
1 electron-like ring + 1 decay electron



Anti-neutrino mode
1 electron-like ring