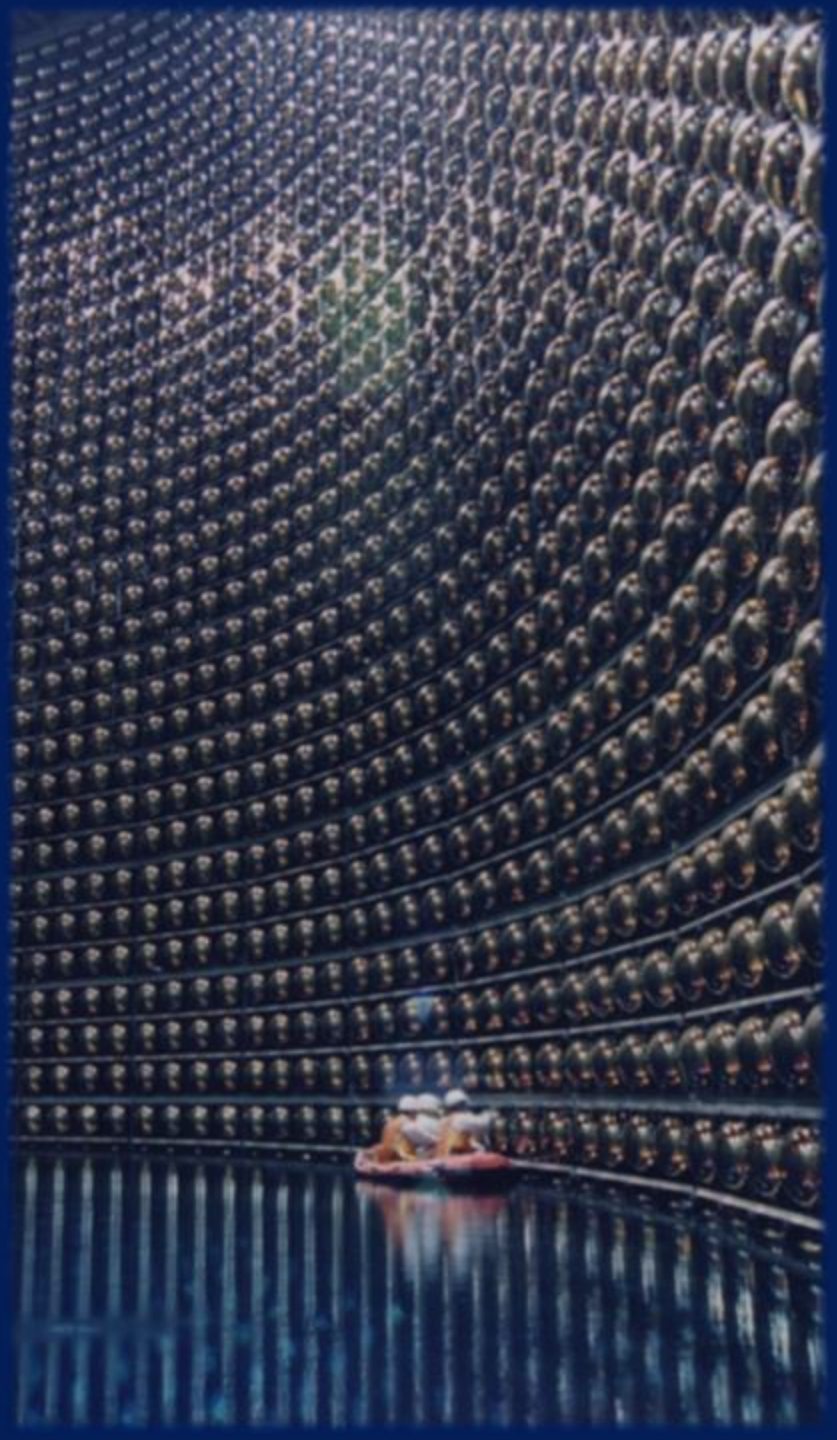


Neutrino Oscillation Analysis with New Event Samples at T2K

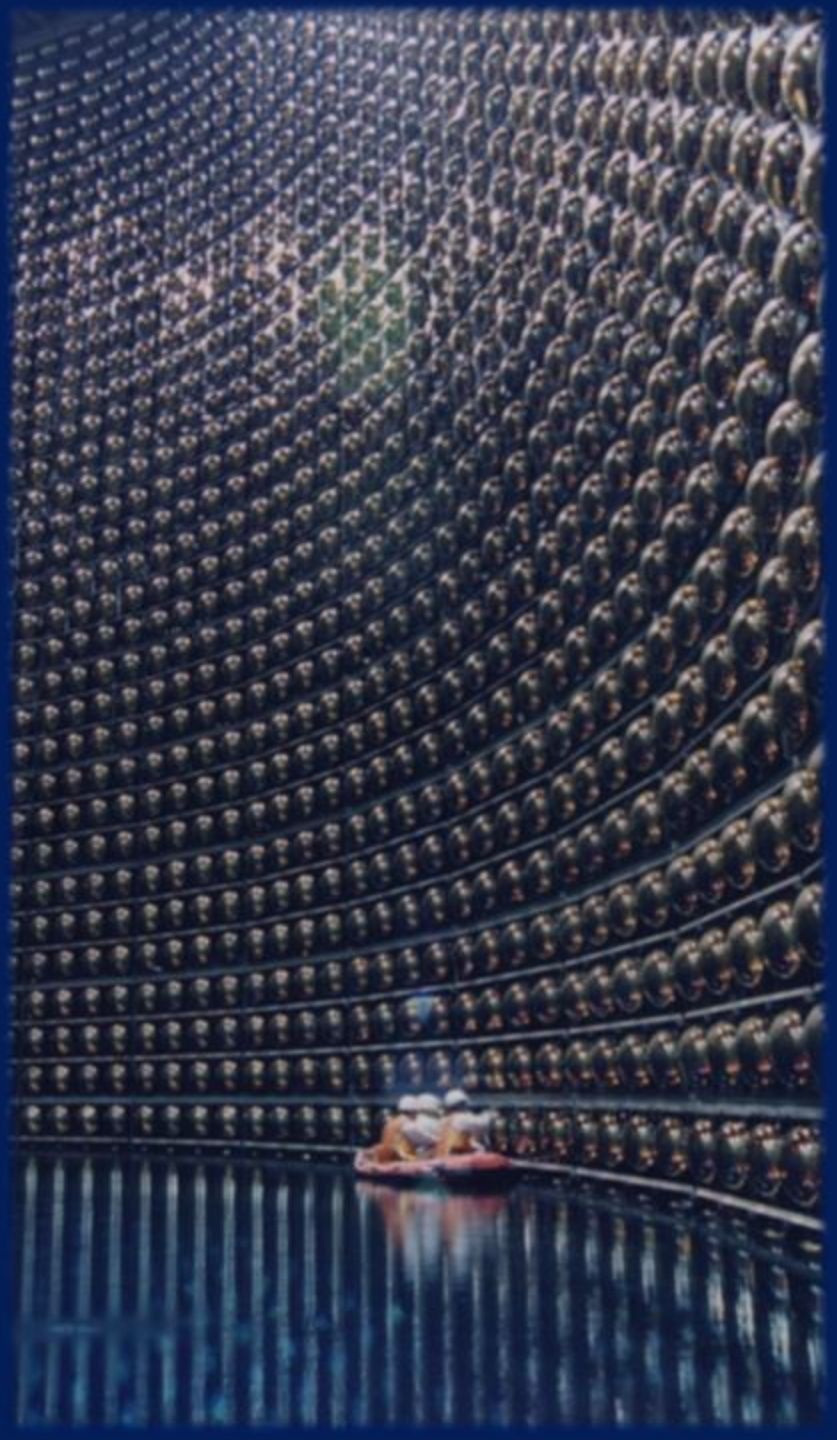
Tailin Zhu

PhD with T2K & Hyper-K → postdoc with Trident

The 8th Shanghai Symposium on Particle Physics and Cosmology

TDLI, Shanghai, Nov 14th

t.zhu20@imperial.ac.uk



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T2K

I. Neutrino oscillation physics recap

II. T2K and parameter model

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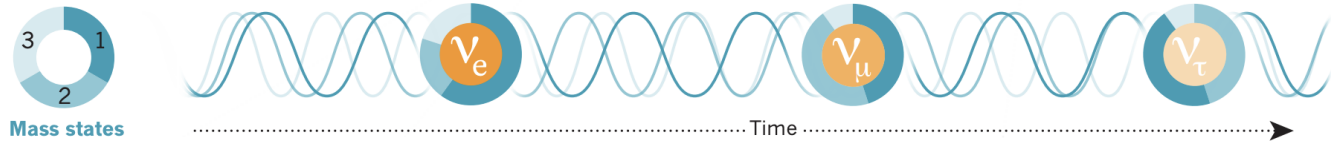
IV. T2K oscillated event samples (in Super-K)

Neutrino Oscillation Physics

- The **3-flavour** mixing



Is $\theta_{23} = 45°$? What's the octant of θ_{23}?

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

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

δ_{CP} – Any CP violation in the lepton sector?

Beam/Atmospheric: $P(\nu_\mu \to \nu_\mu)$, $P(\nu_\mu \to \nu_e)$

Reactor: $P(\bar{\nu}_e \to \bar{\nu}_e)$
Beam: $P(\nu_\mu \to \nu_e)$

Solar: $P(\nu_e \to \nu_e)$
Reactor: $P(\bar{\nu}_e \to \bar{\nu}_e)$

Mass differences

- Δm^2_{21} sensitive from solar neutrinos due to the matter effects in the Sun
- $|\Delta m^2_{32}|$ from ν_μ disappearance; Sign of Δm^2_{32} remain unknown

normal ordering (NO)/ inverted ordering (IO)?

Neutrino Oscillation Physics

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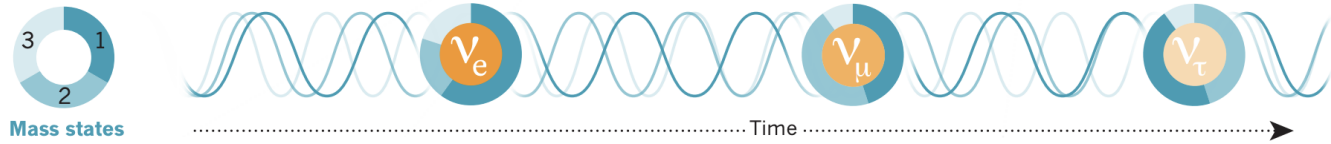

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Beam: $P(\nu_\mu \to \nu_e)$

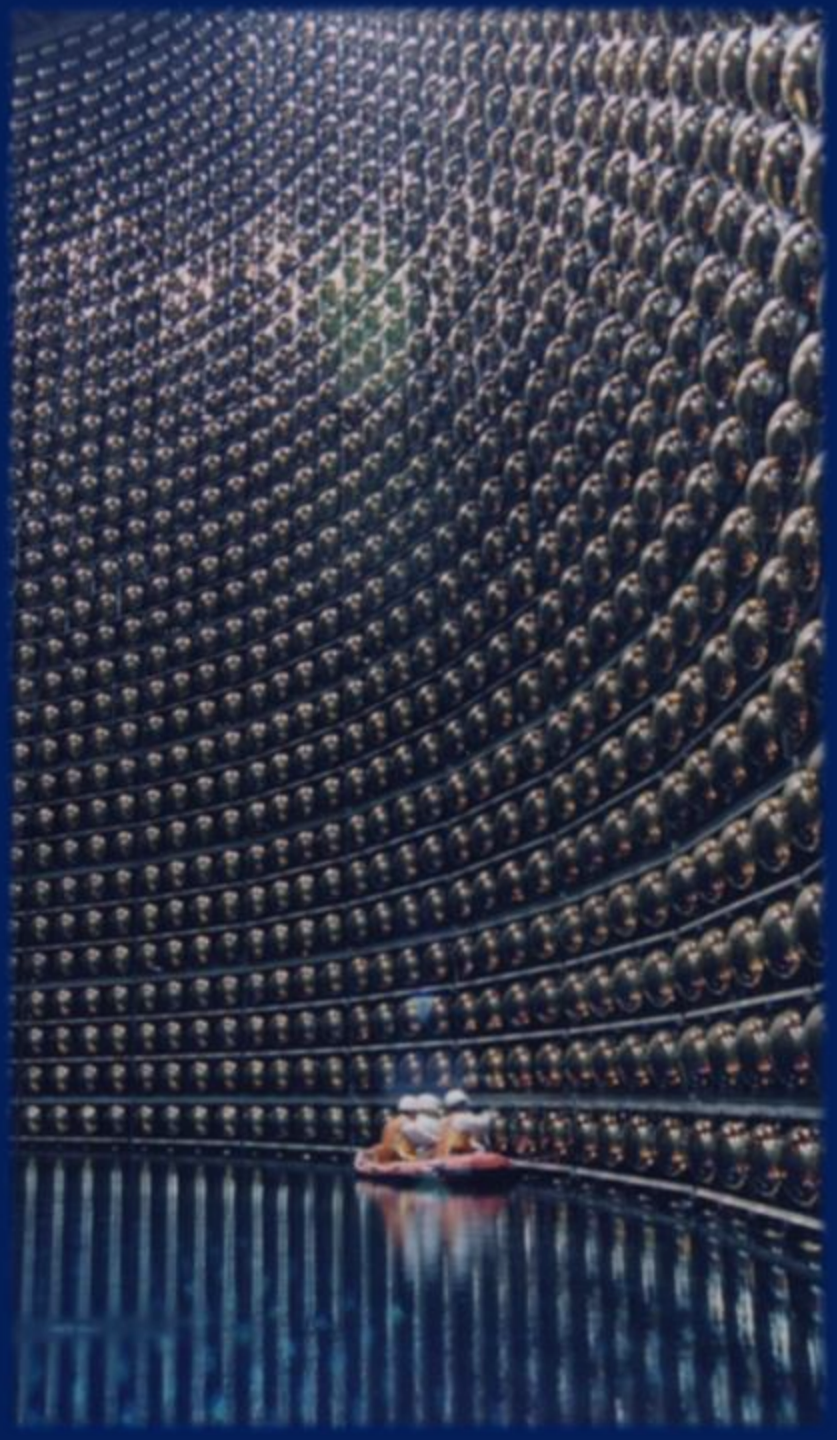
Solar: $P(\nu_e \to \nu_e)$
Reactor: $P(\bar{\nu}_e \to \bar{\nu}_e)$

$\nu_\mu \to \nu_e$ appearance measured by T2K
Next: towards precise measurements of parameters in this channel

normal ordering (NO)/ inverted ordering (IO)?

Mass differences

- Δm^2_{21} sensitive from solar neutrinos due to the matter effects in the Sun
- $|\Delta m^2_{32}|$ from ν_μ disappearance; Sign of Δm^2_{32} remain unknown



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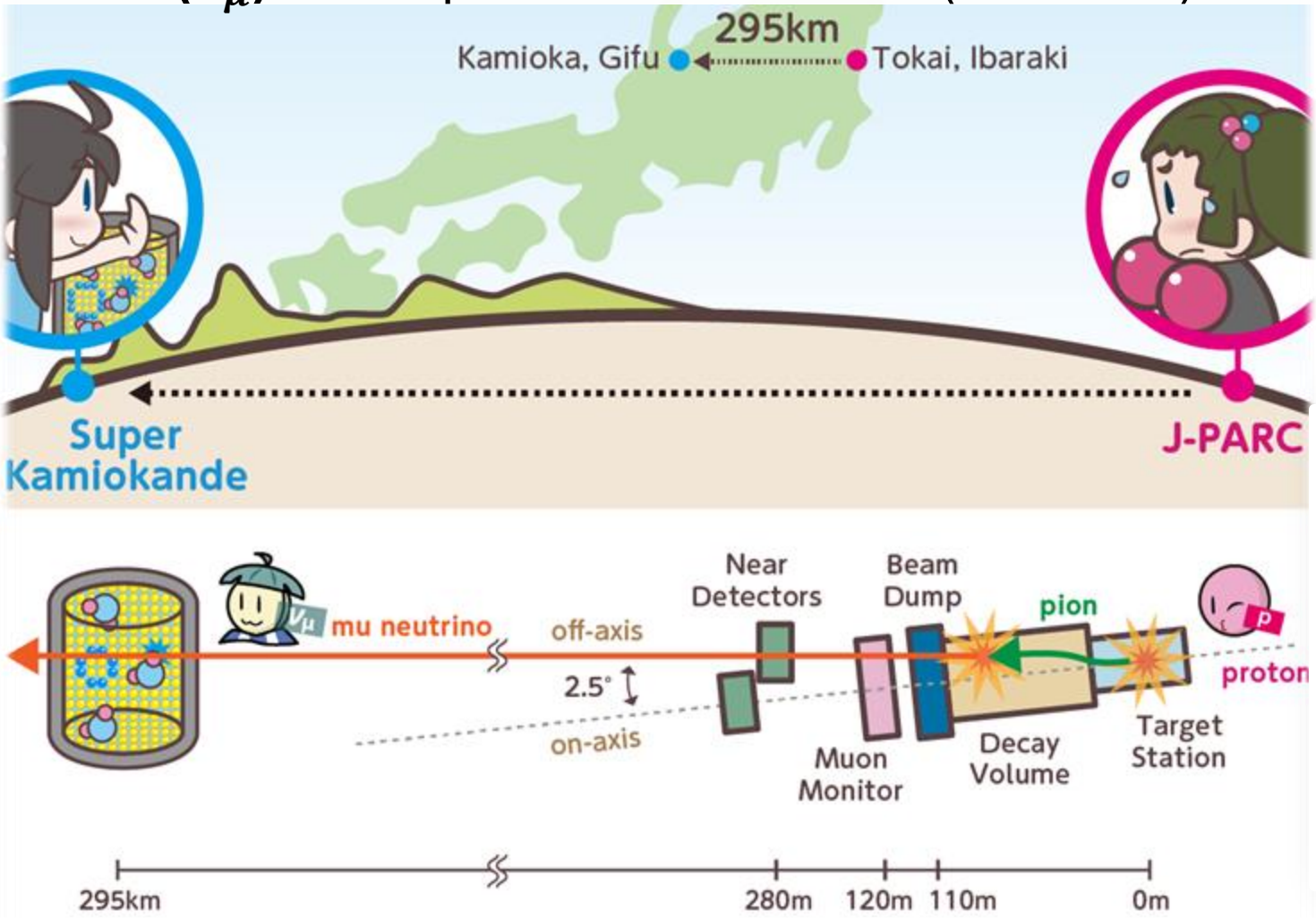
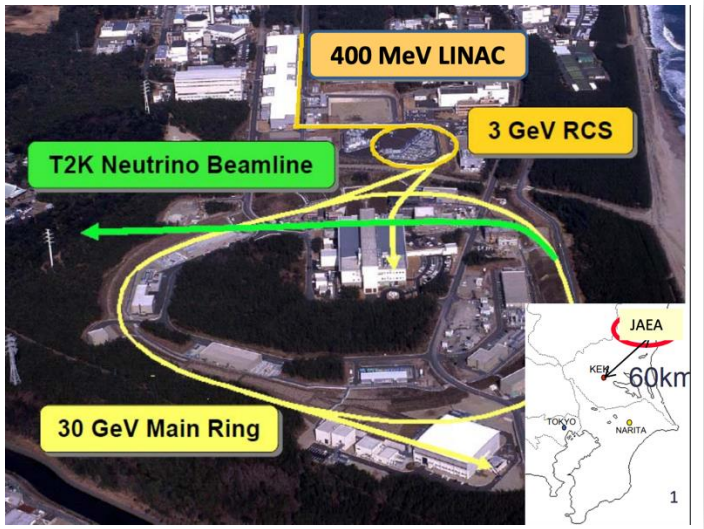
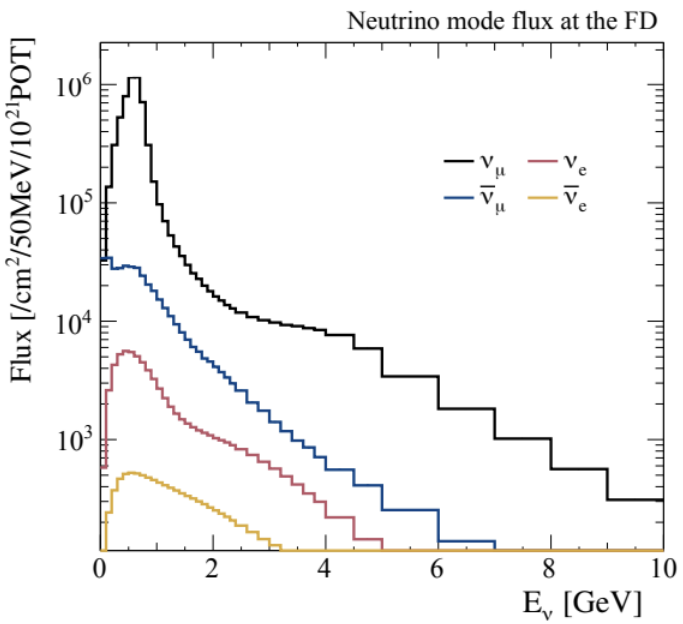
T2K Parameter Model

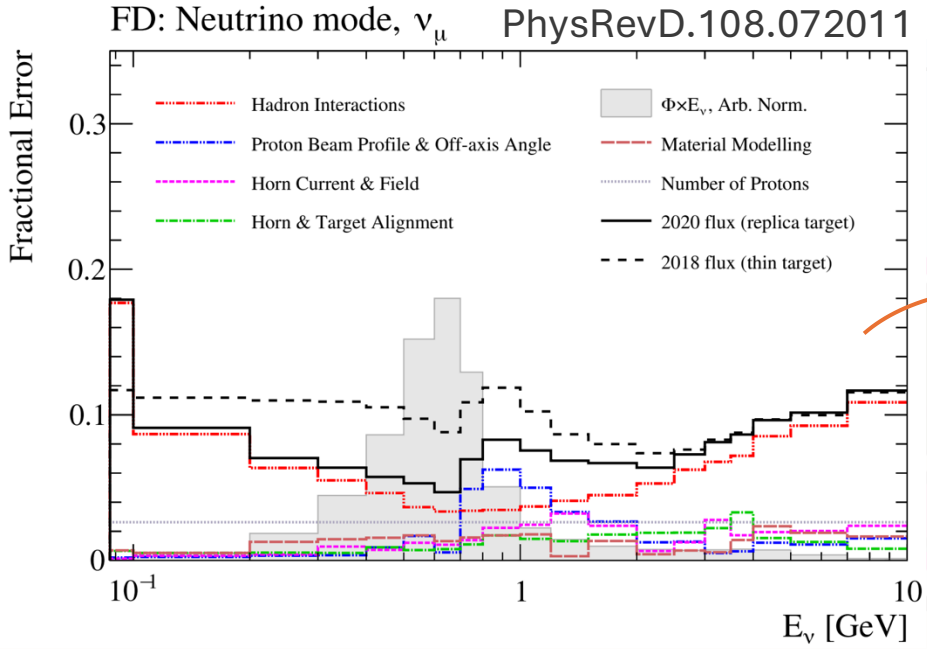
- T2K measures neutrino oscillations with a $\boldsymbol{\nu_\mu}$ **($\boldsymbol{\bar{\nu}_\mu}$) beam** produced at J-PARC (~0.6 GeV)



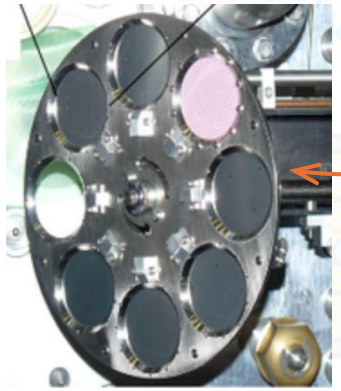


T2K Parameter Model





Neutrino Flux Uncertainty Contributions

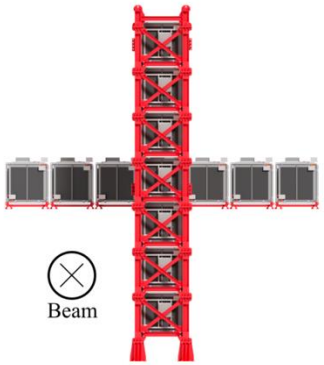


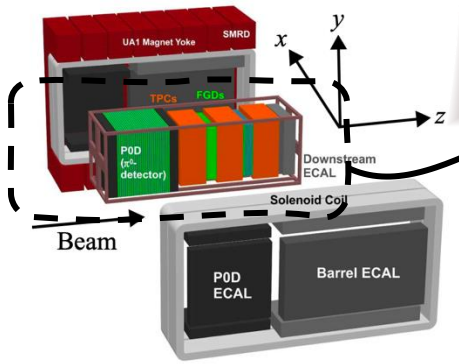
- Beam profiling and off-axis angle direction constrained by **beam monitors**.
- Hadron production uncertainties reduced by external **NA61/SHINE** measurements.

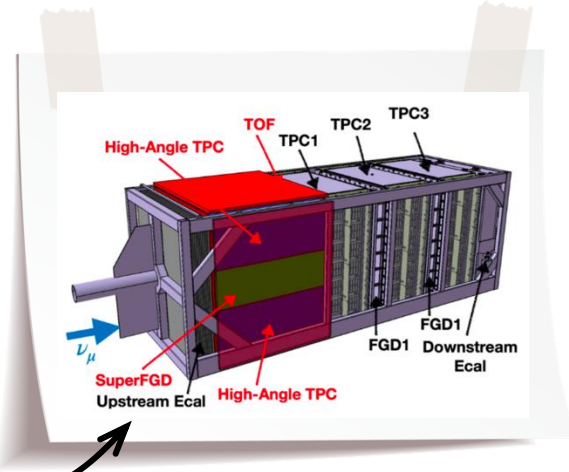
Eur. Phys. J. C (2019) 79:100

T2K Parameter Model

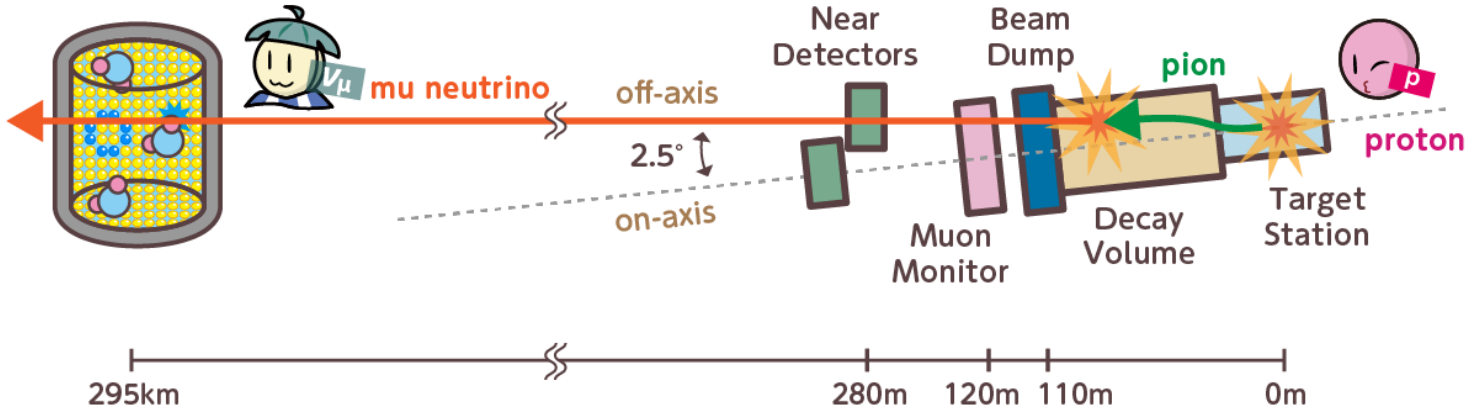
- T2K measures neutrino oscillations with a ν_μ ($\bar{\nu}_\mu$) **beam** produced at J-PARC (~0.6 GeV)
- Near detectors: **INGRID** (on-axis) and **ND280** (off-axis)





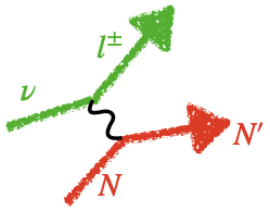


ND280 has fully upgraded!

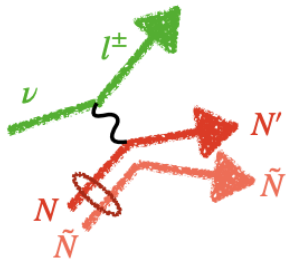


T2K Parameter Model

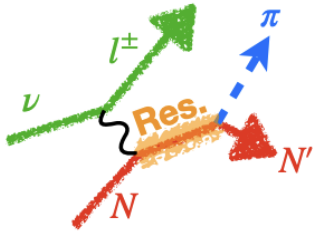
Charged current quasi-elastic (CCQE)



CC multi-nucleon knock-out (2p2h)

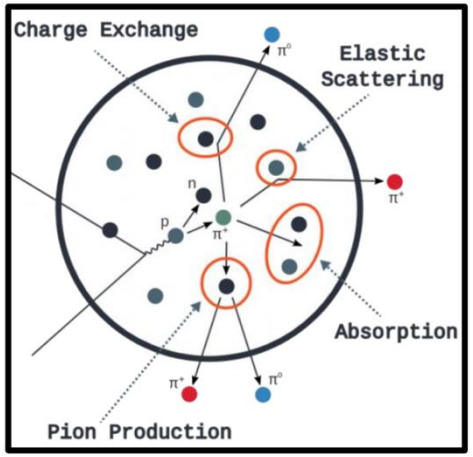


CC Resonant 1π

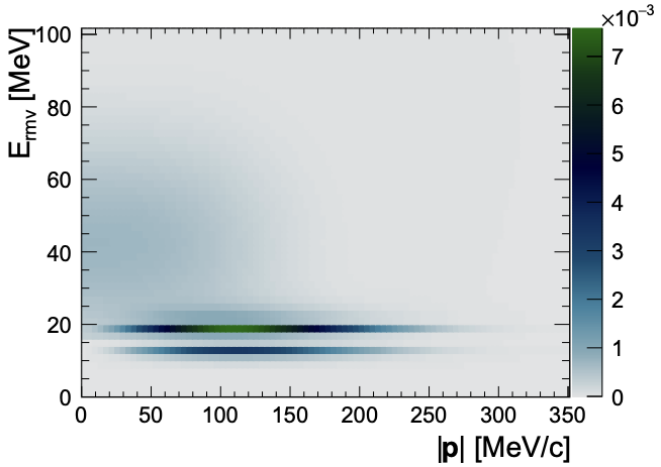


- Neutrino **Interaction cross-section** and **unoscillated flux** constrained by **ND280 data** + theory-driven model + external measurements

Final state interactions



Spectral function model



T2K Parameter Model

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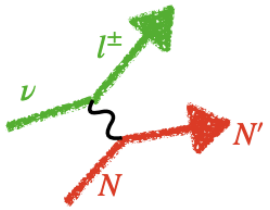

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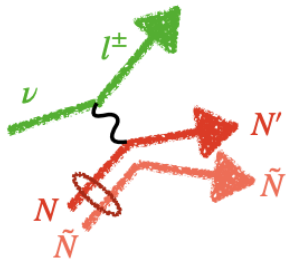

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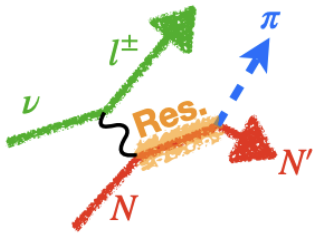

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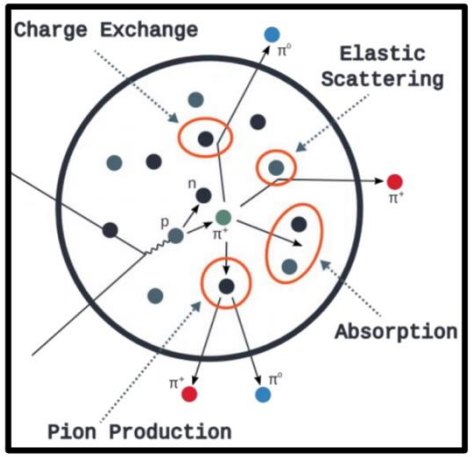

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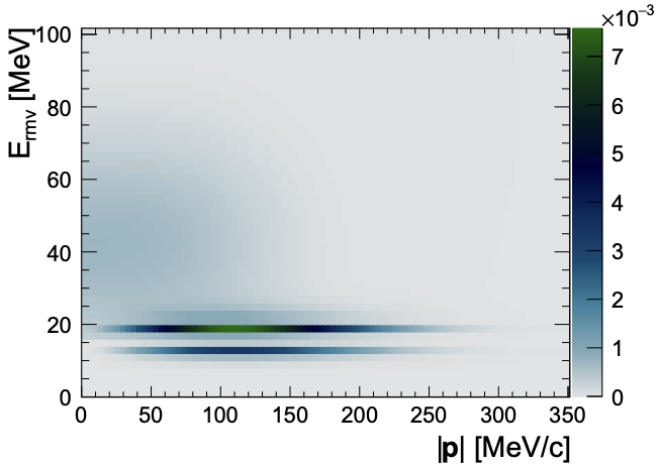
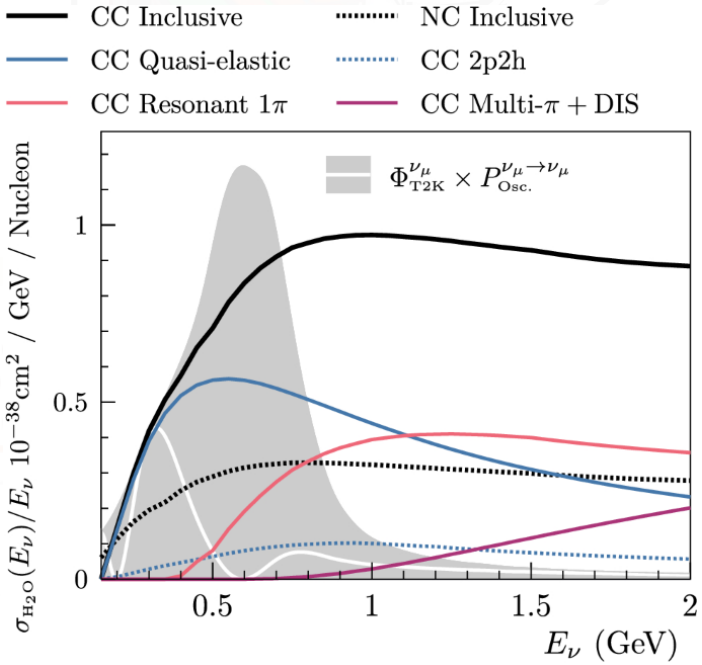




Modelling sub-GeV ν-A interactions using **NEUT**

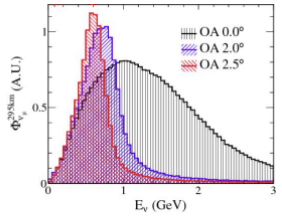
Eur. Phys. J. Spec. Top. 230, 4469–4481 (2021)

T2K Parameter Model

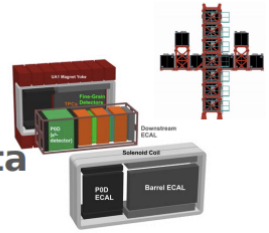
$$\mathbf{N} = \mathbf{\Phi} \times \boldsymbol{\sigma} \times \boldsymbol{\varepsilon} \times \mathbf{P}(\nu_\alpha \rightarrow \nu_\beta)$$

Event Rate

Neutrino Flux

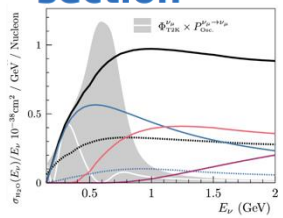


Detector Efficiencies



ND280 Data

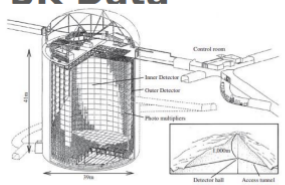
Neutrino-nucleus Interaction Cross section



Oscillation Fit

Oscillation Parameters

SK Data

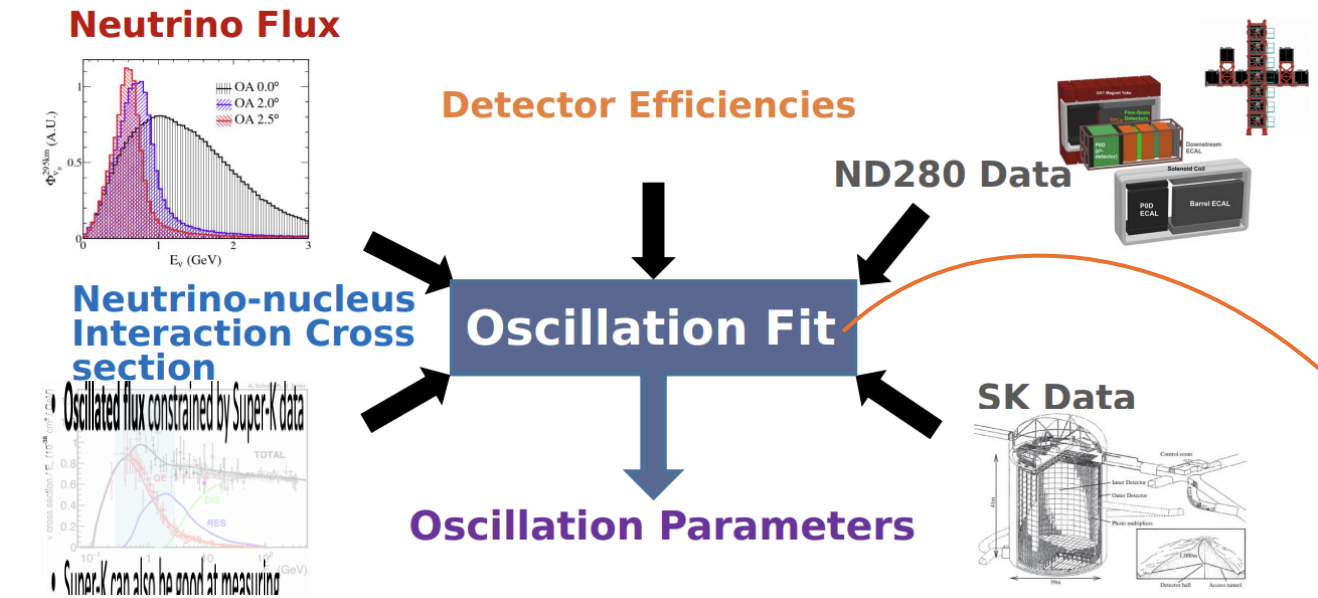


- **Oscillated flux** constrained by Super-K data
- Super-K can also be good at measuring **neutral current** interaction events
  → See later

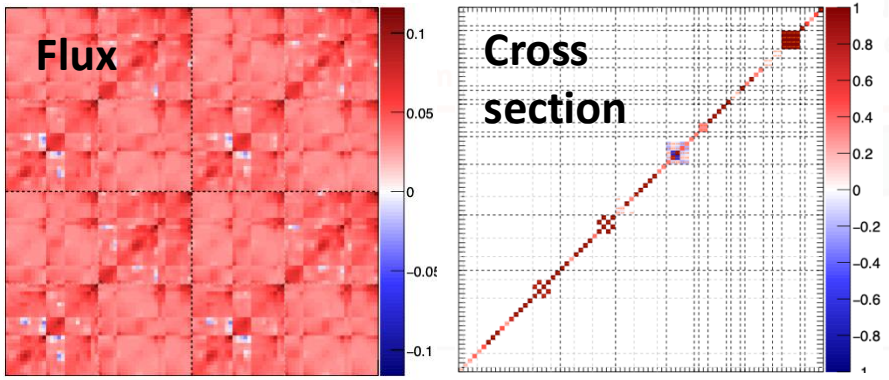
T2K Parameter Model

$$\mathbf{N} = \Phi \times \sigma \times \varepsilon \times \mathbf{P}(\nu_\alpha \to \nu_\beta)$$

Event Rate



- **Oscillated flux** constrained by Super-K data
- Super-K can also be good at measuring **neutral current** interaction events
  → See later
- Simultaneous fit → **Large parameter space + correlations** for uncertainties
  - 50 flux
  - ~70 cross-section
  - ~600 ND+SK detector
- **Degeneracies** between parameters

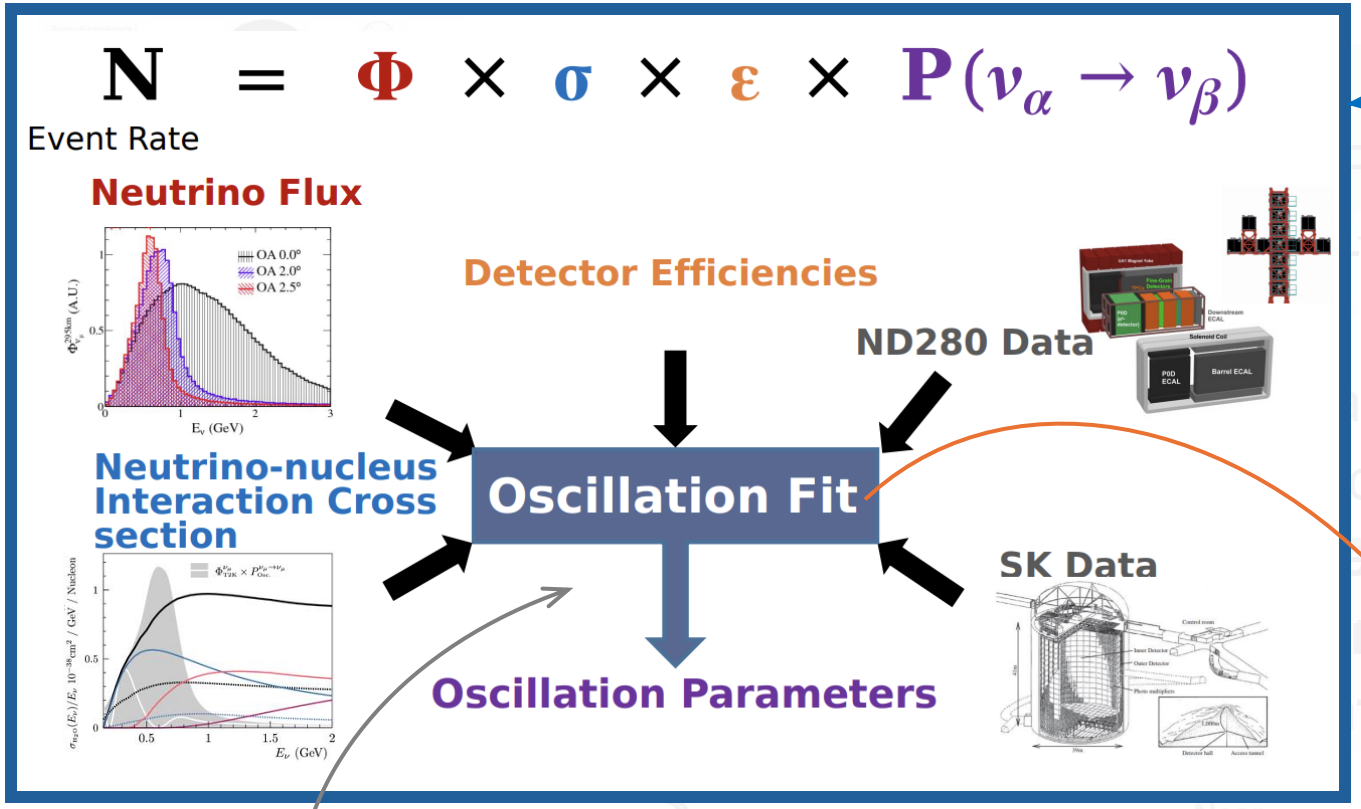


T2K Parameter Model

Junjie Jiang's talk for the pipeline

$$N = \Phi \times \sigma \times \varepsilon \times P(\nu_\alpha \rightarrow \nu_\beta)$$

Event Rate



The **MaCh3** fitter

https://github.com/mach3-software/MaCh3

- Parameter values can be effectively sampled using the **Bayesian Markov Chain Monte Carlo** approach (MCMC)

- Simultaneous fit → **Large parameter space + correlations** for uncertainties
  - 50 flux
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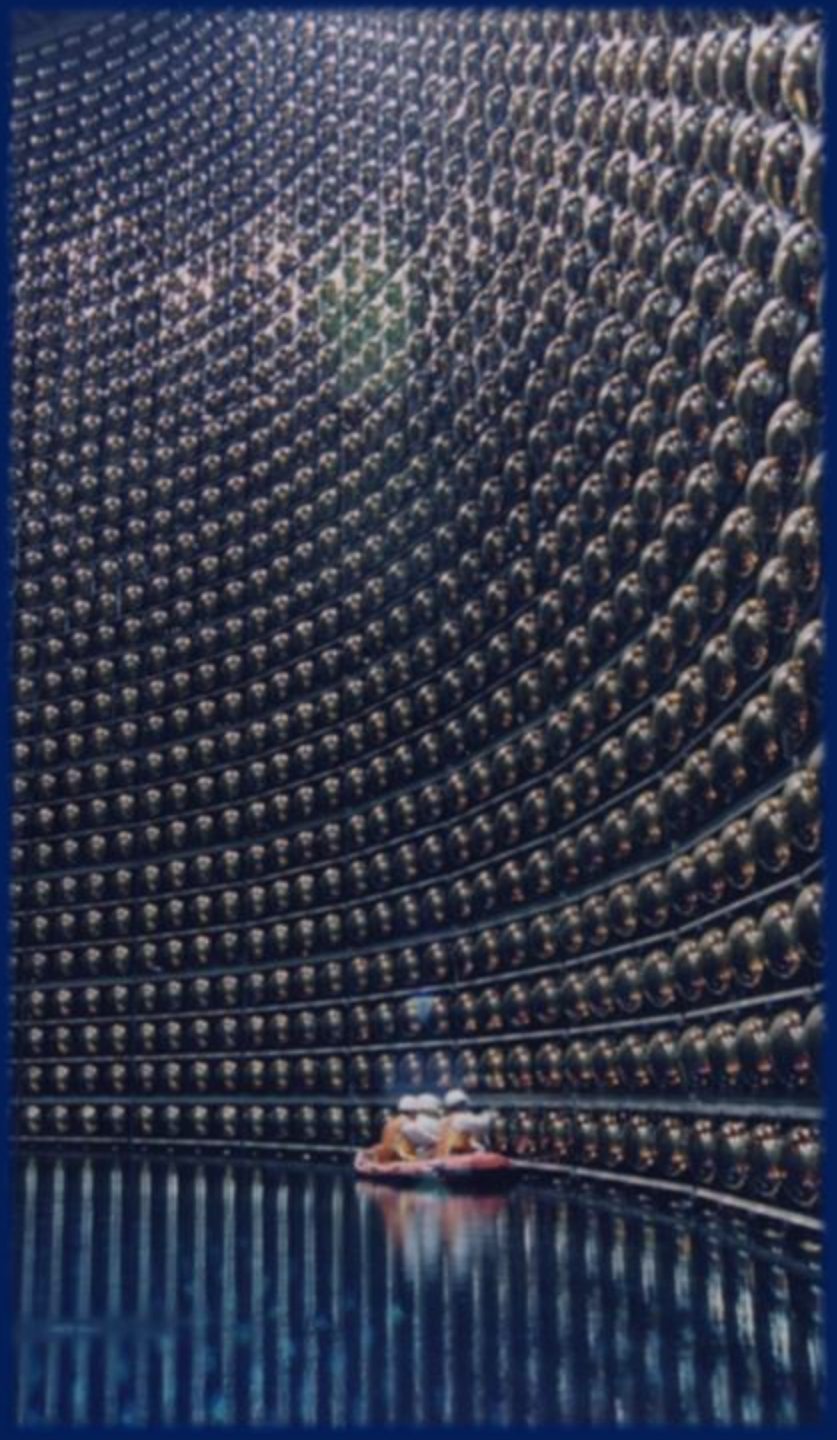

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Bayesian Approach

- **Updating the probability** of a hypothesis according to the observed data

Represents initial beliefs about parameter values （**prior**）

$$-\ln P(\boldsymbol{x}|D) \propto -\ln(P(D|\boldsymbol{x})P(\boldsymbol{x})) \propto -\ln \mathcal{L}_{tot}(\boldsymbol{x}),$$

Likelihood of x to explain the data

Updated beliefs providing the data;
Combining prior and likelihood via
Bayes' theorem

Markov Chain Monte Carlo

- Aims to find the parameter values that maximum the **likelihood** between generated event spectra and the data spectra

- Use Monte Carlo method to approximate the **likelihood function**

$$
\begin{aligned}
-\ln \mathcal{L}_{tot}(\boldsymbol{x},\boldsymbol{\theta}) = & \sum_{i}^{\text{bins}} n_i^{p,ND}(\boldsymbol{x},\boldsymbol{\theta}) - n_i^{o,ND} + n_i^{o,ND} \ln\left(\frac{n_i^{o,ND}}{n_i^{p,ND}(\boldsymbol{x},\boldsymbol{\theta})}\right) \\
& + \sum_{i}^{\text{bins}} n_i^{p,SK}(\boldsymbol{x},\boldsymbol{\theta}) - n_i^{o,SK} + n_i^{o,SK} \ln\left(\frac{n_i^{o,SK}}{n_i^{p,SK}(\boldsymbol{x},\boldsymbol{\theta})}\right) \\
& + \sum_{j}^{\text{syst.}} \frac{1}{2}(\boldsymbol{x}-\boldsymbol{x_0})_j^T \cdot \mathbf{C}_j^{-1} \cdot (\boldsymbol{x}-\boldsymbol{x_0})_j \\
& + \frac{1}{2}(\boldsymbol{\theta}-\boldsymbol{\theta_0})^T \cdot \mathbf{C}_\theta^{-1} \cdot (\boldsymbol{\theta}-\boldsymbol{\theta_0}),
\end{aligned}
$$

All model parameters are treated as random variables: no distinctions between oscillation parameters ($\boldsymbol{\theta}$) and systematic parameters ($\boldsymbol{x}$).

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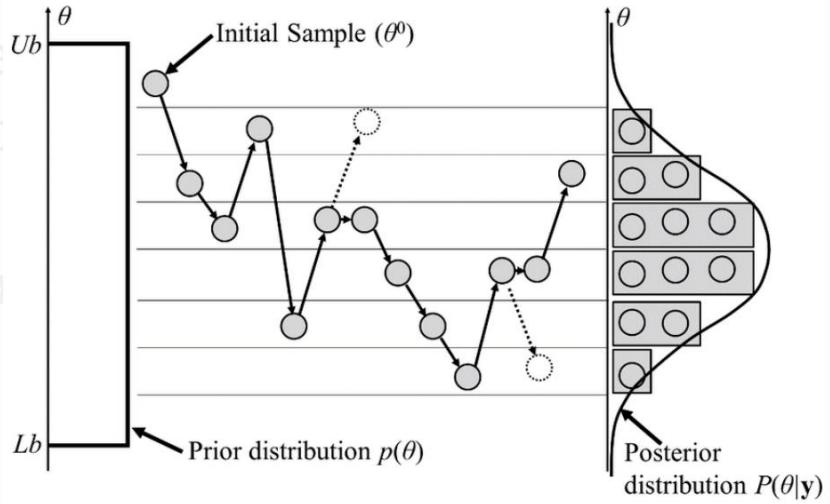
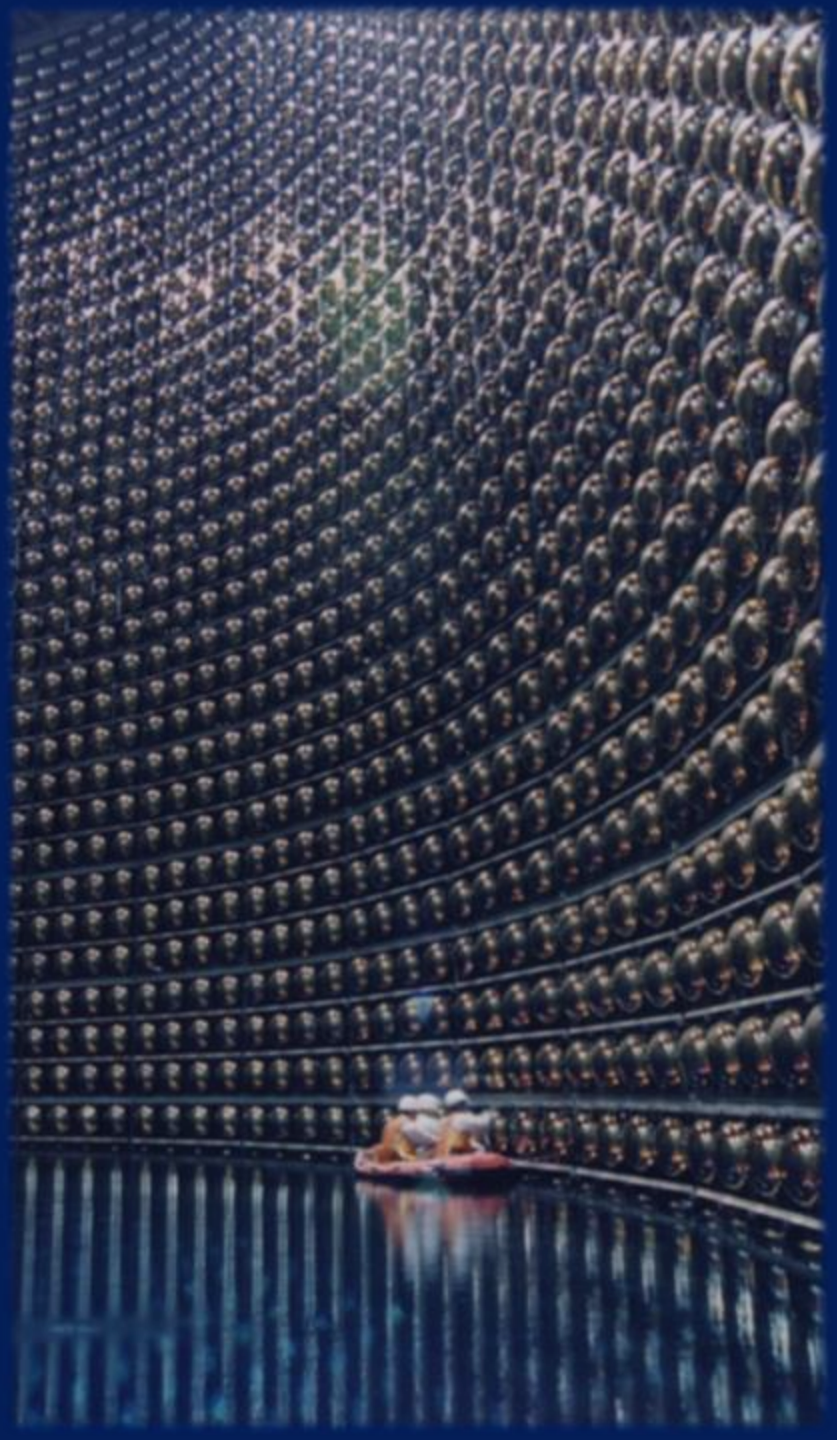
Energies. 2015; 8(6):5538-5554



- High dimensional, local minima, non-Gaussian, degeneracy, computing time, discontinuous, …
- The **Metropolis-Hastings algorithm** allows **random walks** of parameters to accumulate an approximated distribution around the highest likelihood region
- No need to calculate analytical solutions



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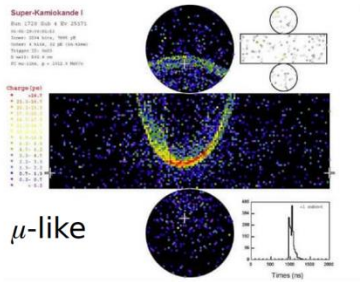
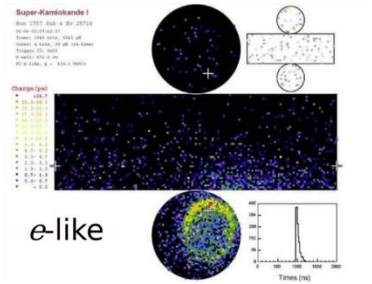
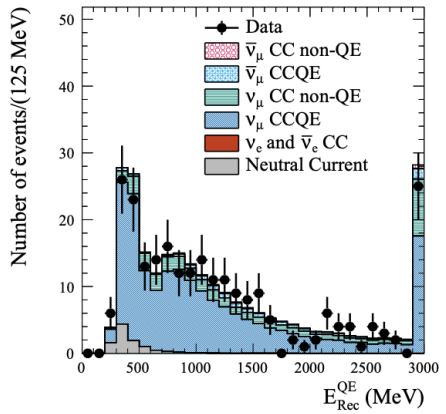
Oscillated Event Samples

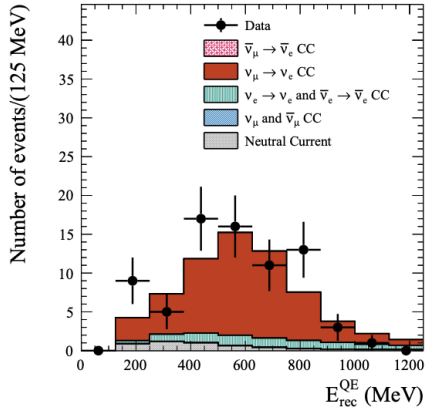
1-ring only



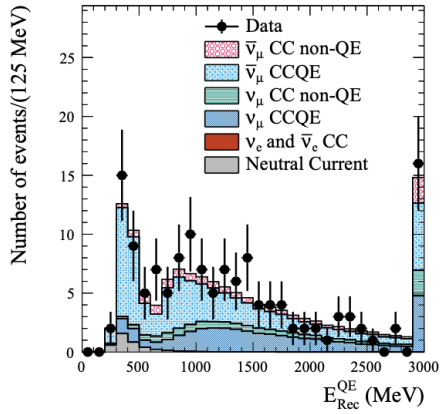


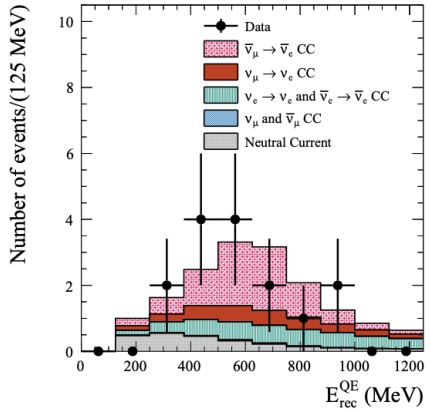
ν-mode





$\bar{\nu}$-mode

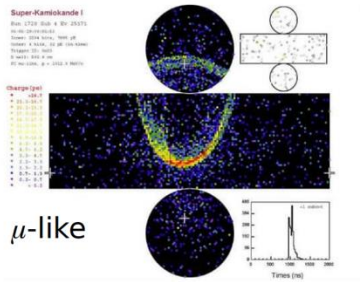


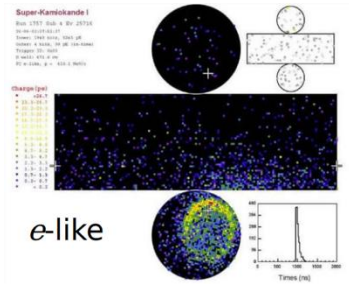


Phys. Rev. D **103**, 112008

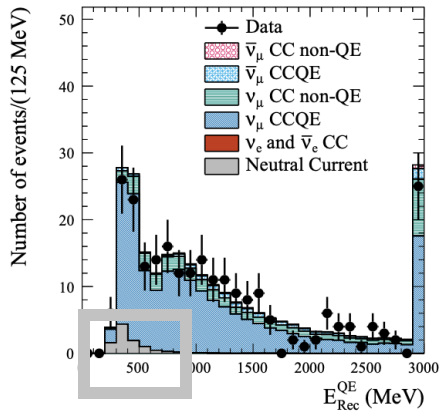
Oscillated Event Samples

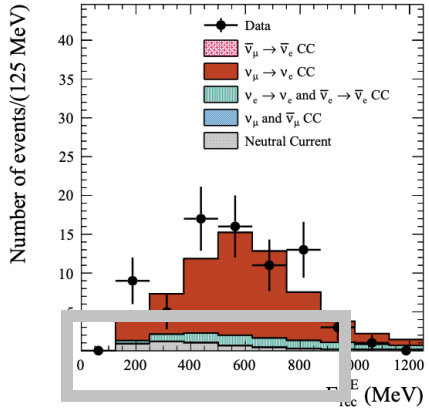
1-ring only



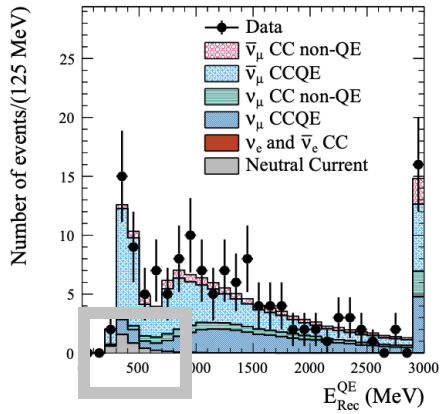


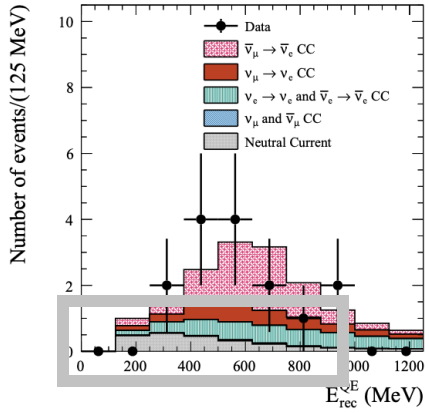
ν-mode





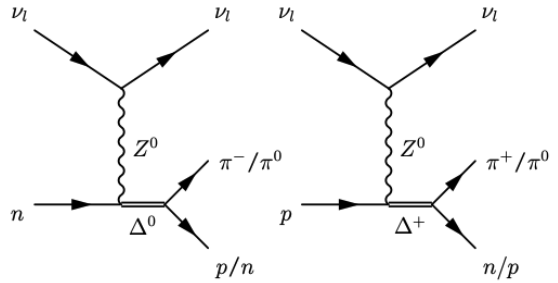
$\bar{\nu}$-mode





Phys. Rev. D **103**, 112008

Neutral Current (NC) background – mainly **NC1π^0** events

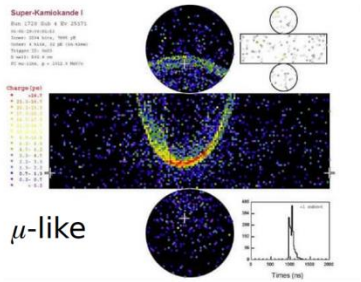


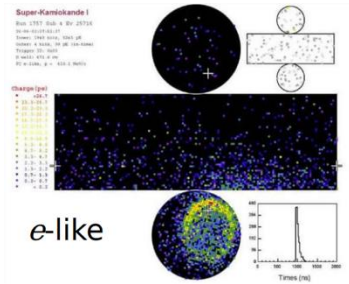
NC **Resonant 1π** (NCπ^0)

NC **Coherent 1π** (NCCoh)

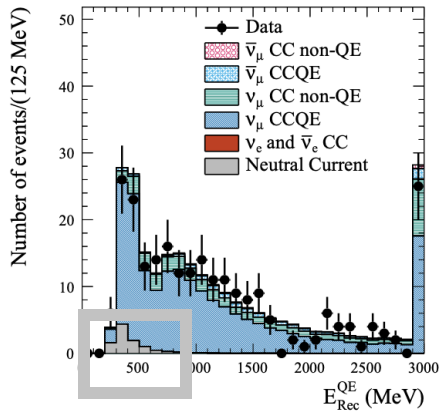
Oscillated Event Samples

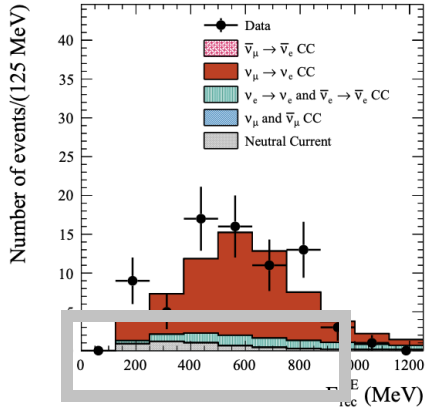
1-ring only



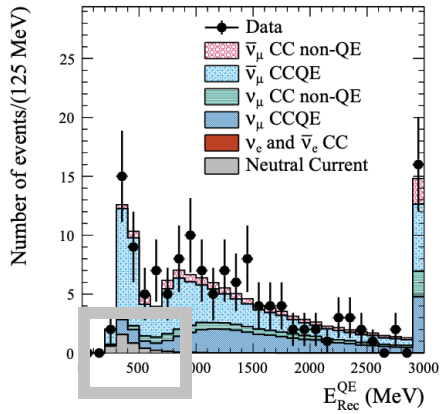


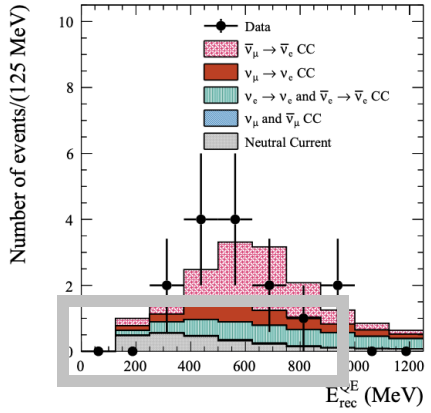
ν-mode





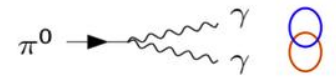
$\bar{\nu}$-mode

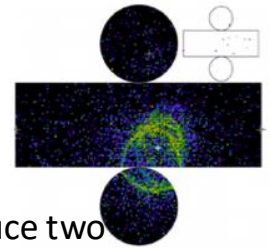




Phys. Rev. D **103**, 112008

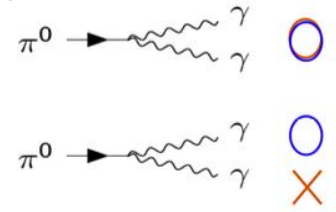
2-ring

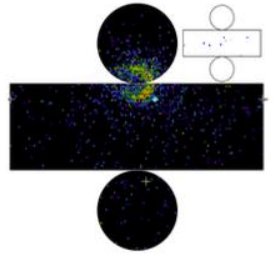




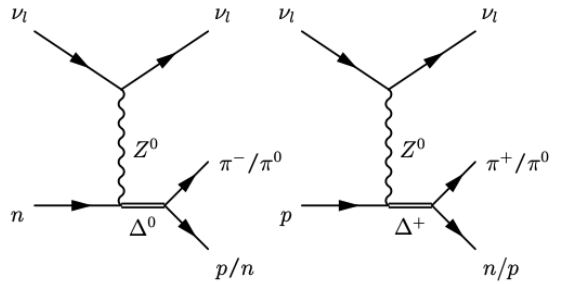
π^0-decayed photons can either produce two separate or highly overlapped rings / 1 visible ring

1-ring

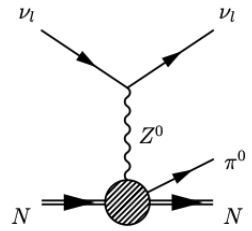




Neutral Current (NC) background – mainly **NC1π^0** events



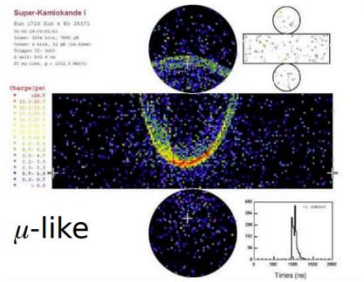
NC **Resonant 1π** (NCπ^0)

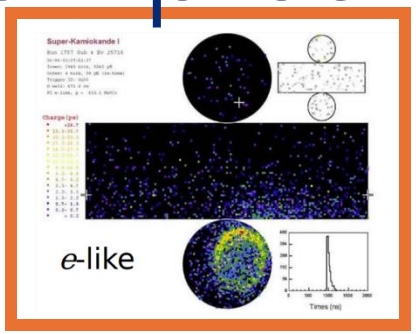


NC **Coherent 1π** (NCCoh)

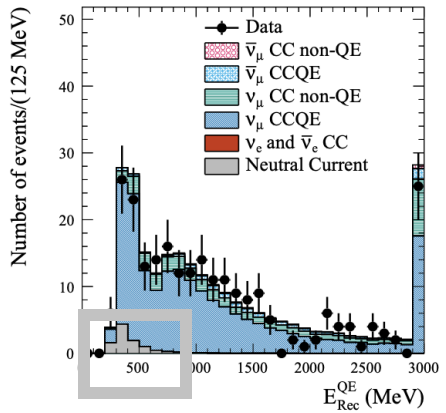
Oscillated Event Samples

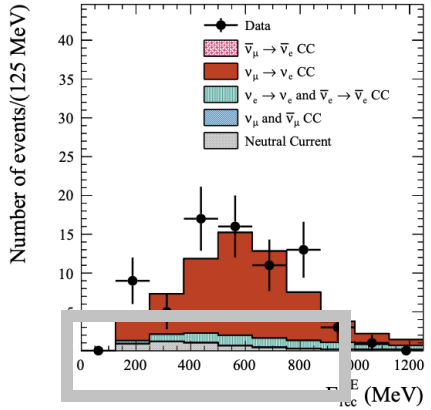
1-ring only



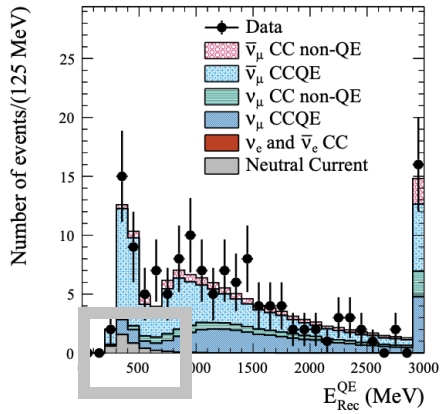


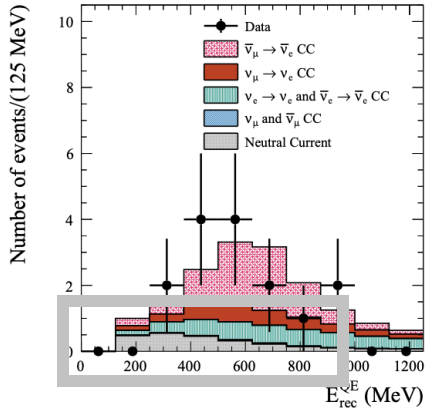
ν-mode





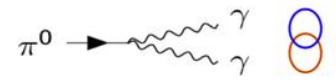
$\bar{\nu}$-mode

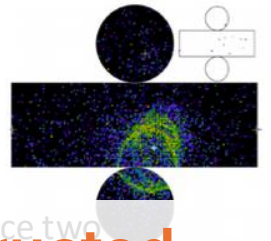




Phys. Rev. D **103**, 112008

2-ring

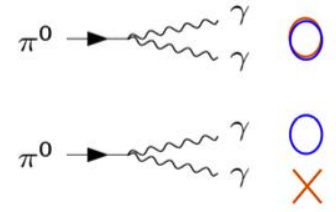


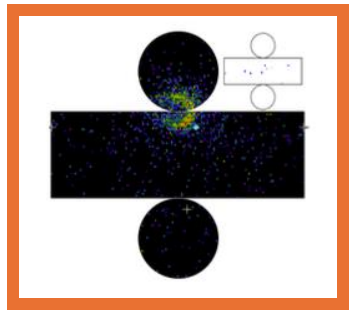


π^0 decayed photons can either produce two separate or highly overlapped rings / 1 visible ring

Could be mis-reconstructed

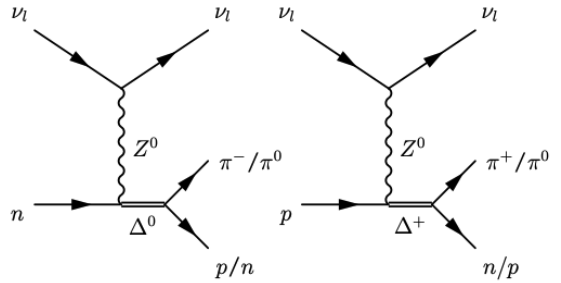
1-ring



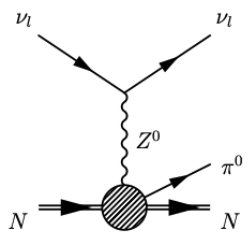


"Overlapping rings? Are you serious?"
—said the reco. algorithm.

Neutral Current (NC) background – mainly **NC1π^0** events



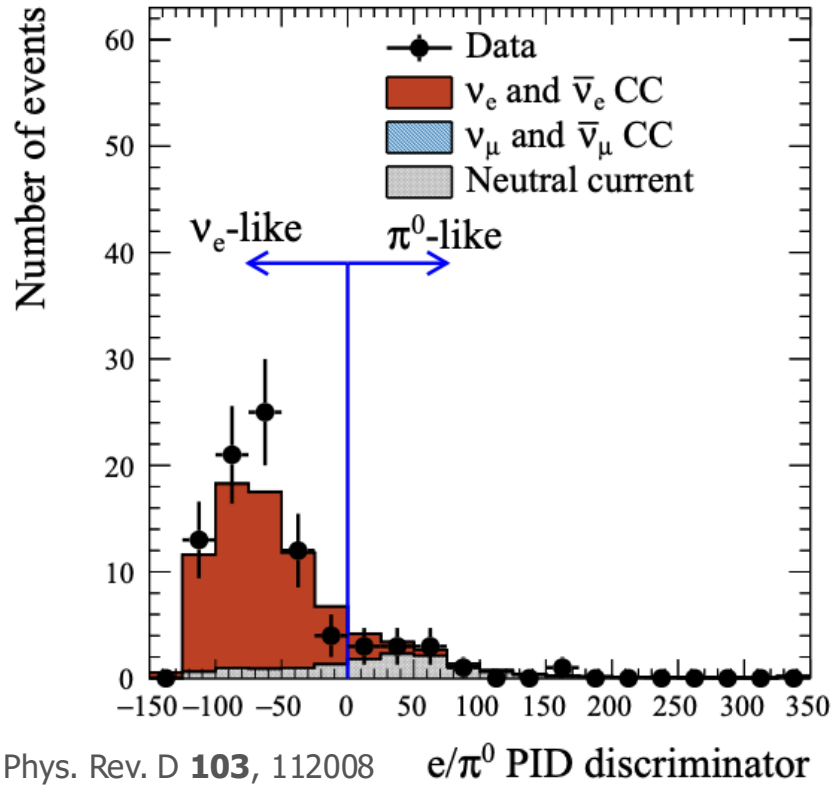
NC **Resonant 1π** (NCπ^0)



NC **Coherent 1π** (NCCoh)

Oscillated Event Samples

- The **1-ring e-like** sample was selected from an e/π^0 **particle ID cut**, with a dependence on π^0 **invariant mass**



Phys. Rev. D **103**, 112008

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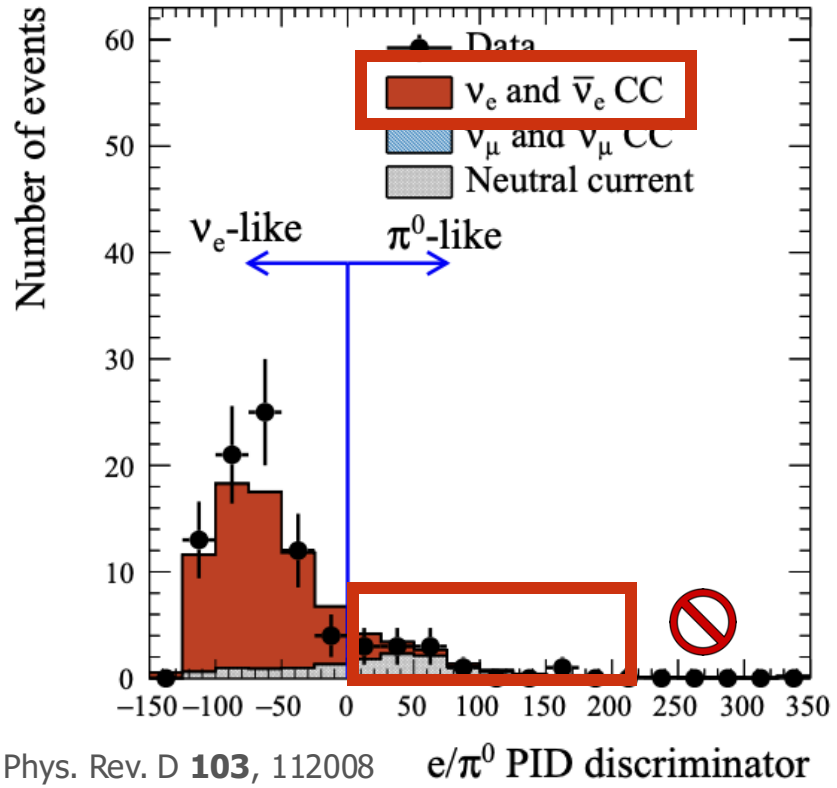
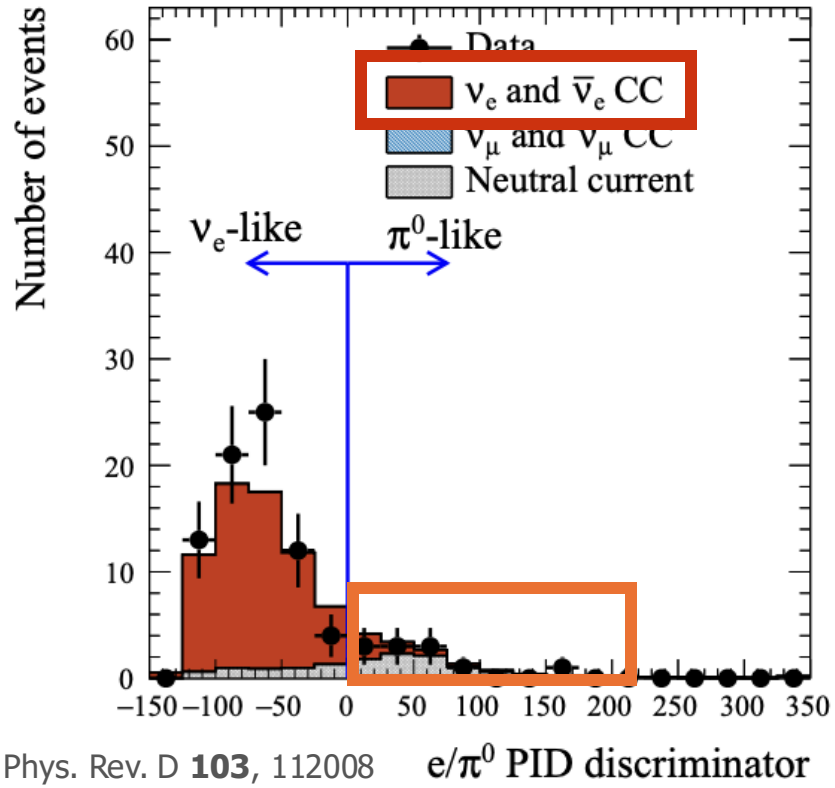


Phys. Rev. D **103**, 112008

Meanwhile, a number of oscillated ν_e ($\bar{\nu}_e$) signals are also **removed**.

Oscillated Event Samples

- The **1-ring e-like** sample was selected from an e/π^0 **particle ID cut**, with a dependence on π^0 **invariant mass**

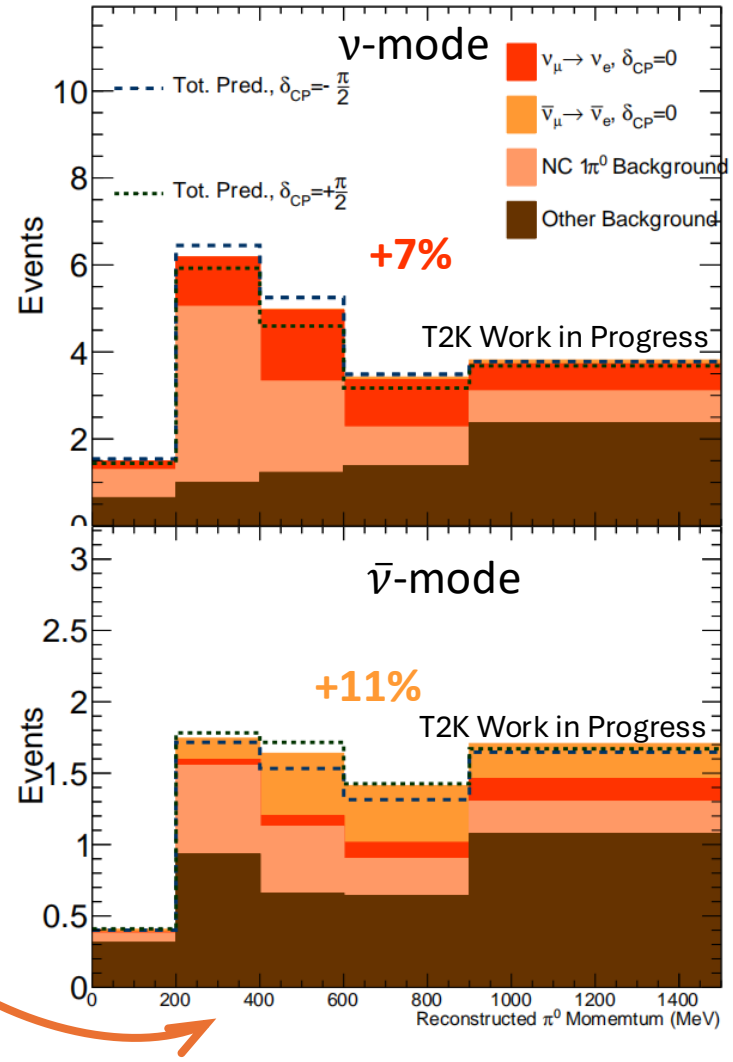


Phys. Rev. D **103**, 112008

Meanwhile, a number of oscillated ν_e ($\bar{\nu}_e$) signals are also **removed**.

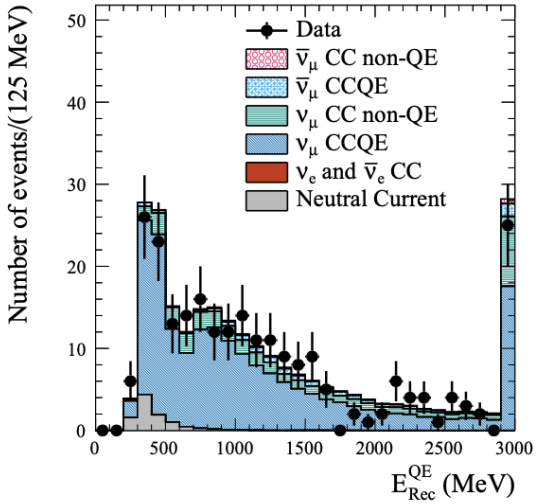
Re-selecting the 1-ring π^0-like events will include these additional signal events.

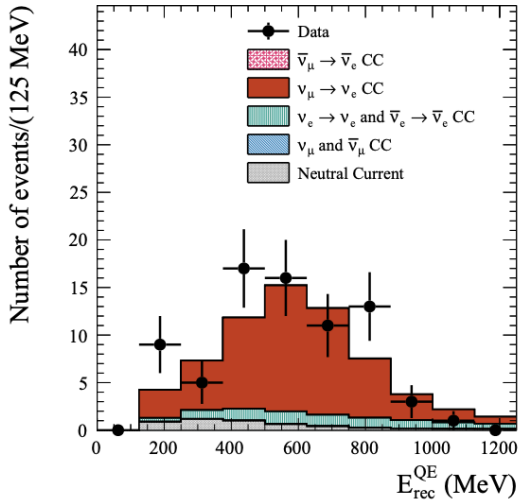
The new 1-ring π^0-like samples

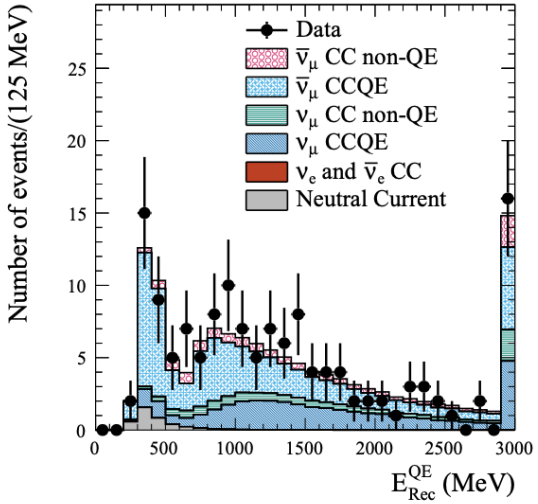


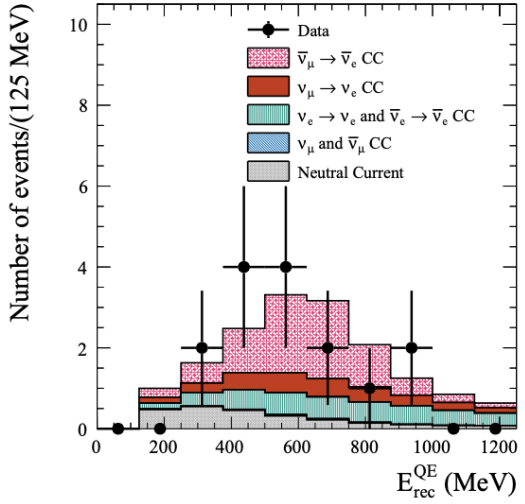
NC1π^0 Control Samples

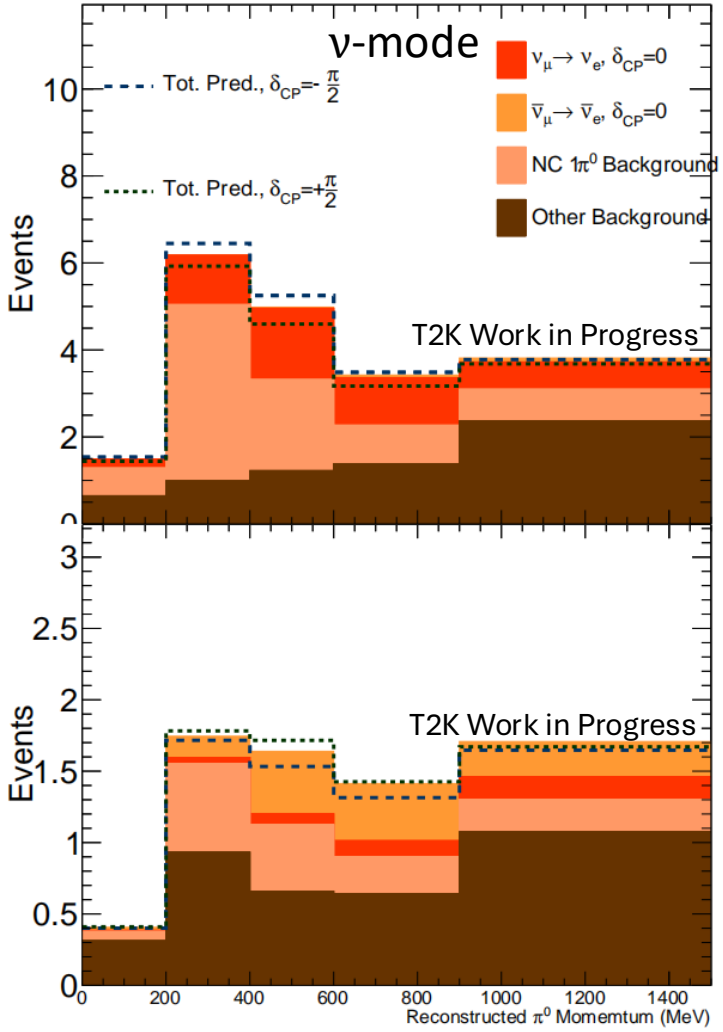
- What's the treatment for the **NC1π^0 background** in all these samples?





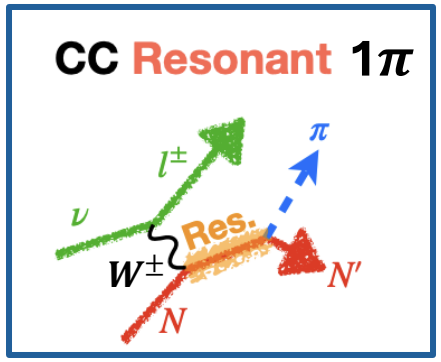


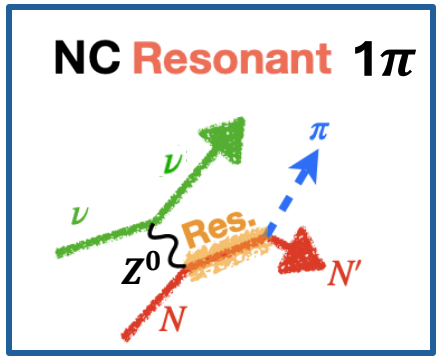




NC1π^0 Control Samples

- What's the treatment for the **NC1π^0 background** in all these samples?
- T2K uses **Rein-Sehgal model** for the **resonant single pion production** cross sections
  - Constrained by the **charged current (CC) 1π** events measured **at ND280 –** also used to constrain the **NC** interactions





NC1π^0 Control Samples

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- T2K uses **Rein-Sehgal model** for the **resonant single pion production** cross sections
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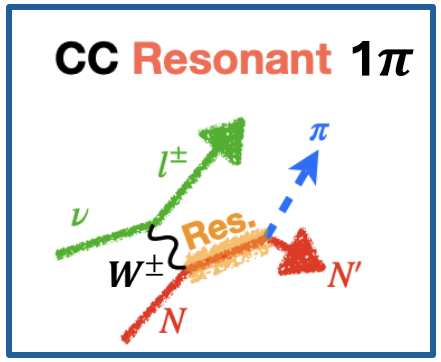
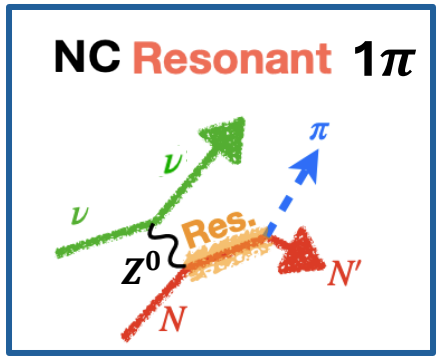
  - **Super-K** is good at detecting NC1π^0 events, providing a pure sample with **consistent detector acceptance**, whereas ND280 is less efficient in detecting these events.





NC1π^0 Control Samples

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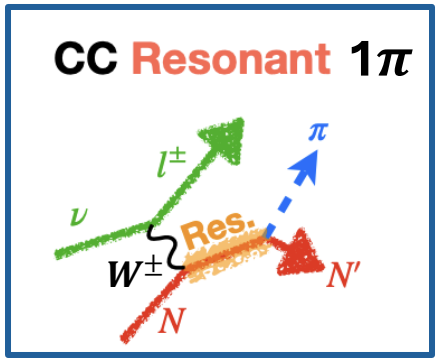
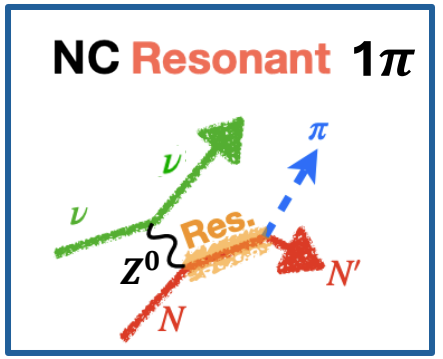




➢ Super-K **control samples** for NC1π^0 events

➢ Adding **extra uncertainties** to NC1π^0 events **(updating cross-section model with new normalisation parameters)** and selecting the **2-ring π^0-like samples** to constrain them

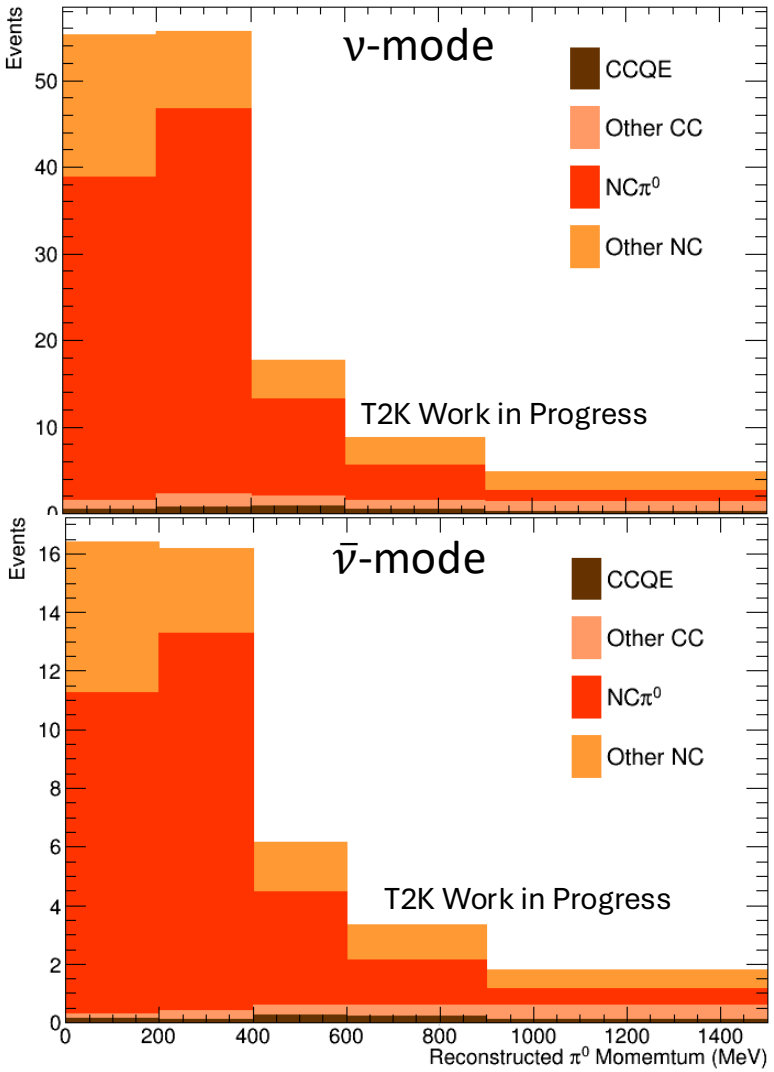
NC1π^0 Control Samples

- Selected 2-ring π^0-like samples to constrain NC1π^0 interaction cross-sections
- **They are Flavour independent ☺**
  - ➢ Plenty of events at Super-K

High purity (NCπ^0 + NCCoh events > 70%)

High event topology selection efficiency (>70%)

The new 2-ring π^0-like samples



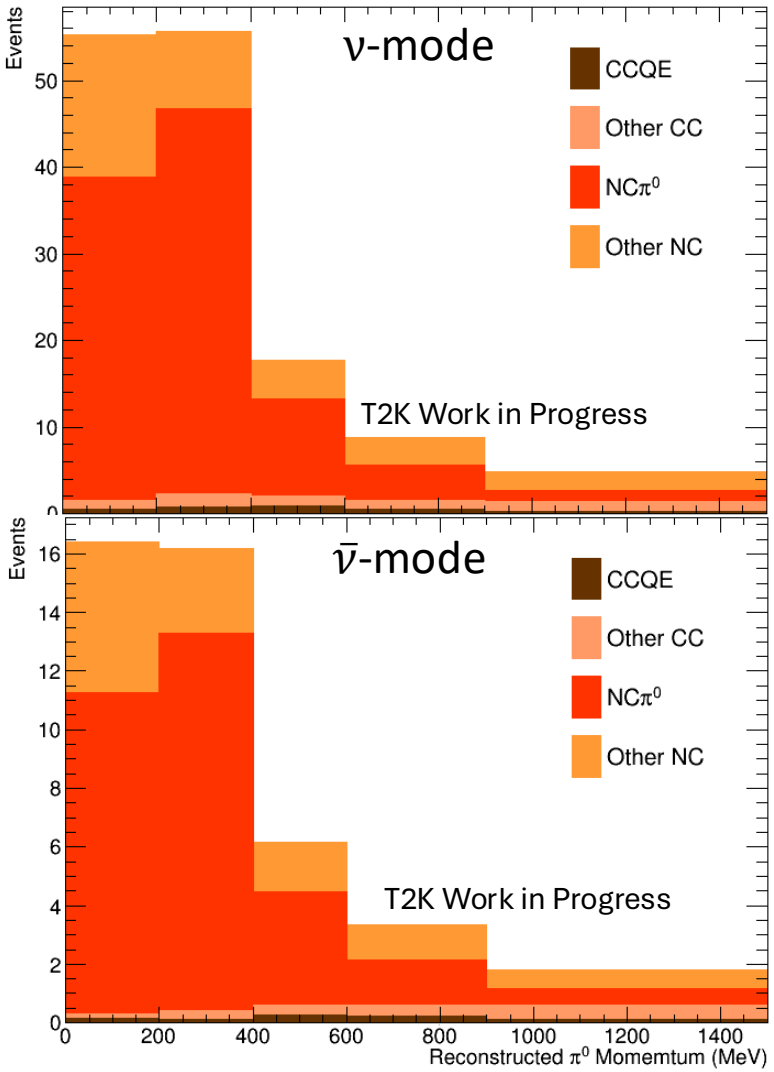
NC1π^0 Control Samples

- Selected 2-ring π^0-like samples to constrain NC1π^0 interaction cross-sections
- **They are Flavour independent ☺**
  - ➢ Plenty of events at Super-K
  - ➢ Probe to **sterile neutrino oscillations** arXiv:1902.06529
  - ➢ **Additional constraints** on the **unoscillated neutrino flux**

High purity (NCπ^0 + NCCoh events > 70%)

High event topology selection efficiency (>70%)

The new 2-ring π^0-like samples

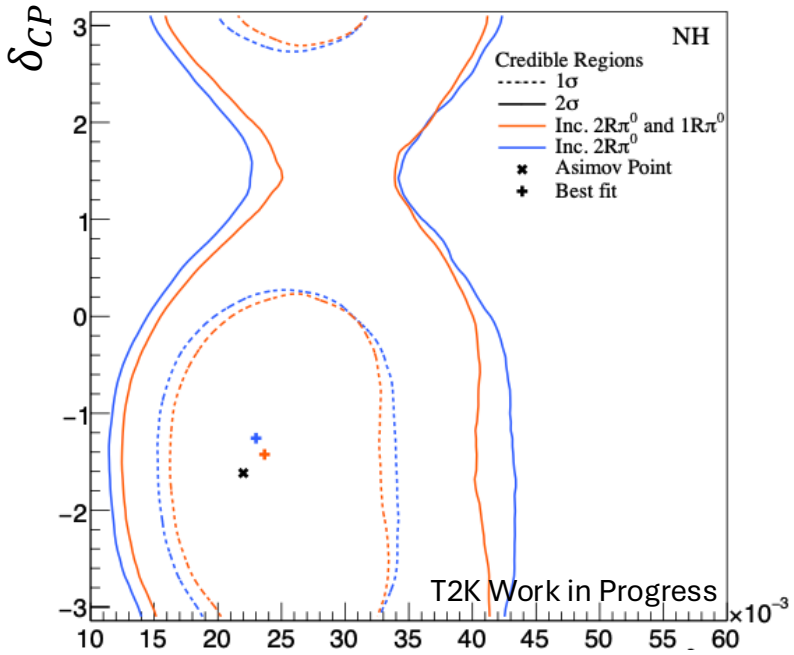


NC1π^0 Control Samples

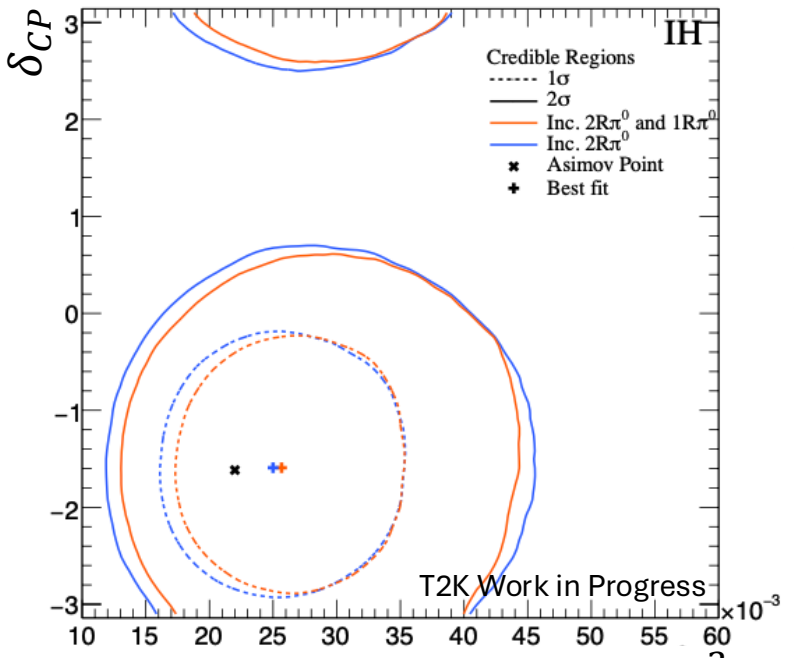
- Selected 2-ring π^0-like samples to constrain NC1π^0 interaction cross-sections

  → **Improved sensitivities on oscillation parameters**

Without reactor constraints on θ_{13} applied

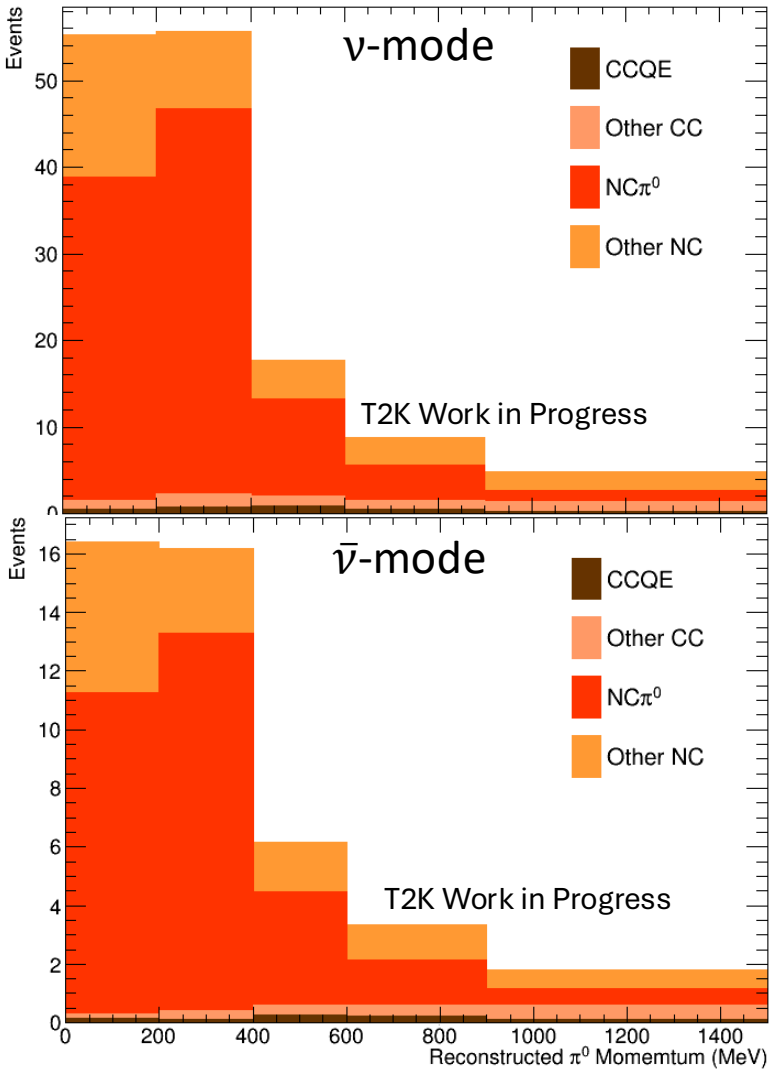


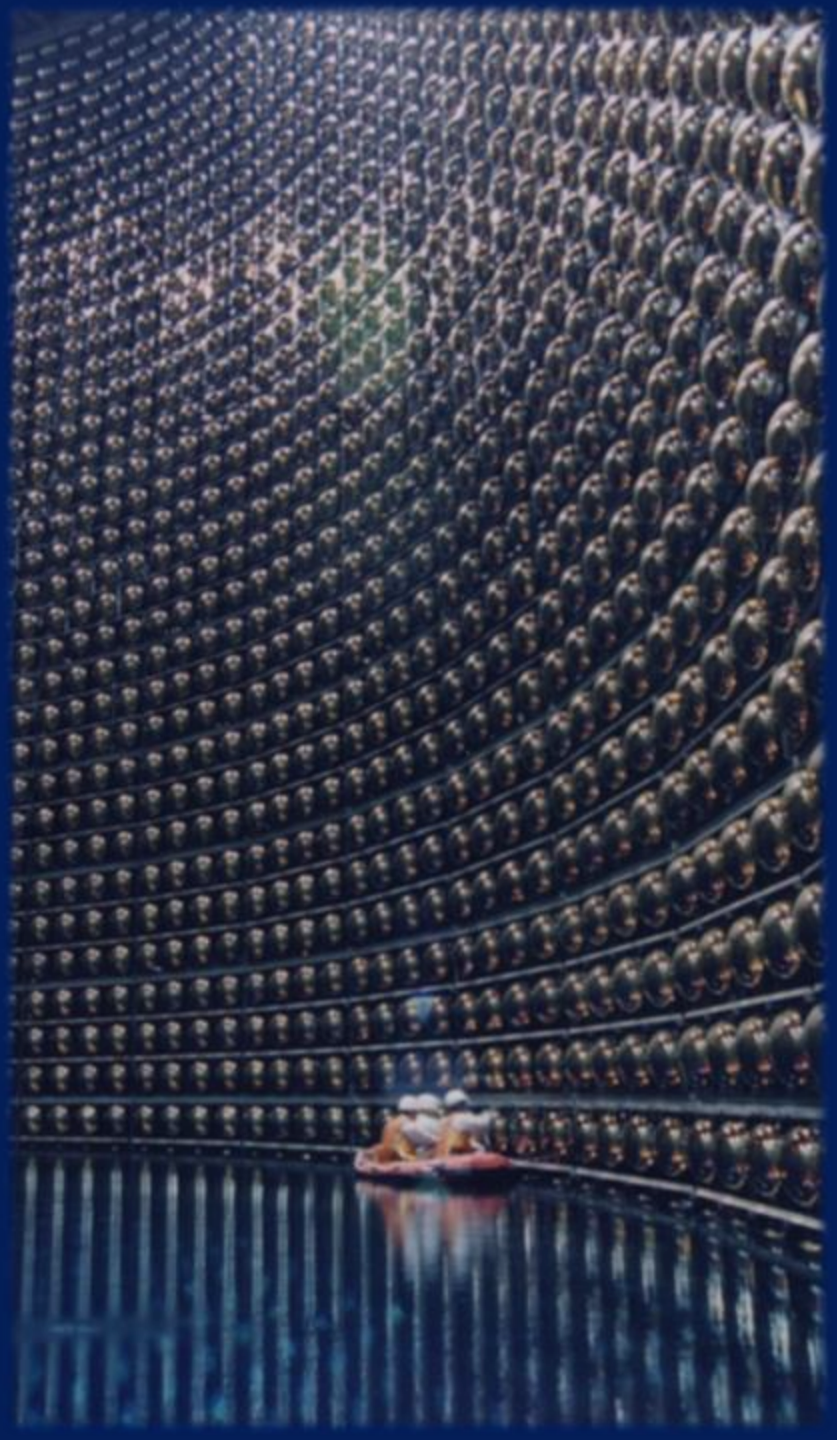
Normal Ordering



Inverted Ordering

The new 2-ring π^0-like samples





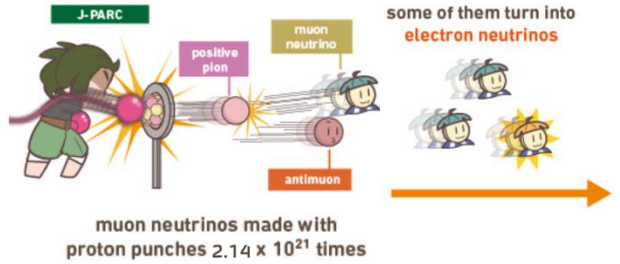
Outlook & Summary

Outlook

- **Bayesian MCMC methods**
  - ➢ More demanded as parameter space and datasets expanding
  - ➢ MaCh3 has been the official fitter for various neutrino oscillation experiments + joint analysis between a few of them

Results see Junjie Jiang's talk

- **The new NC π^0 samples**
  - ➢ Ready for the forthcoming T2K oscillation analysis
  - ➢ Probe to the overall neutrino flux
  - ➢ Bright potential to the next generation, Hyper-K, upon new water Cherenkov detector facilities and significantly larger datasets

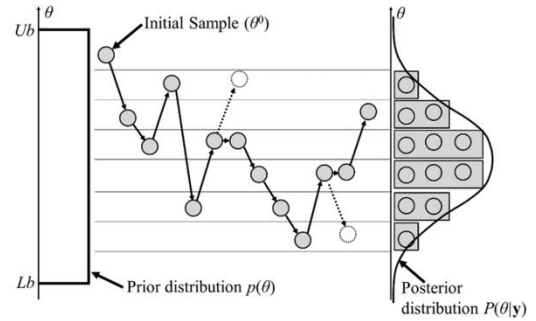


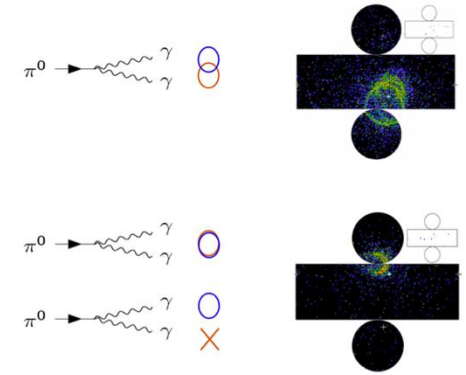
Summary

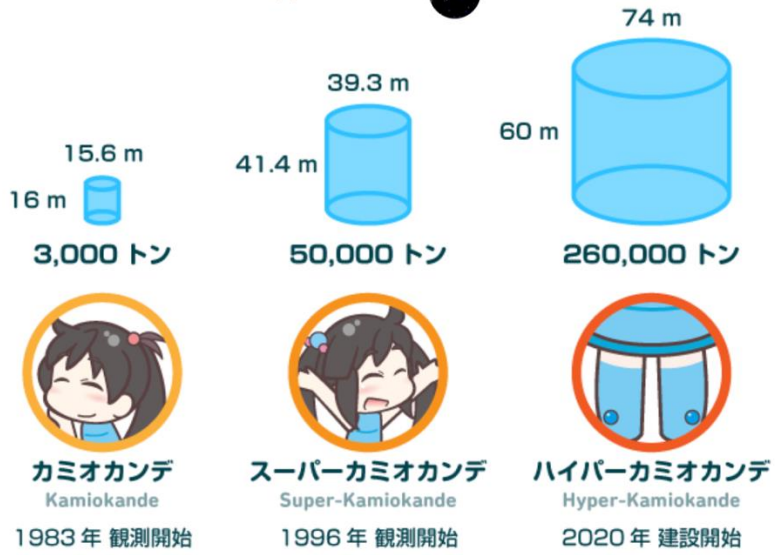
- Bayesian MCMC approach is a powerful tool for handling large parameter spaces and predicting non-analytical likelihood distributions

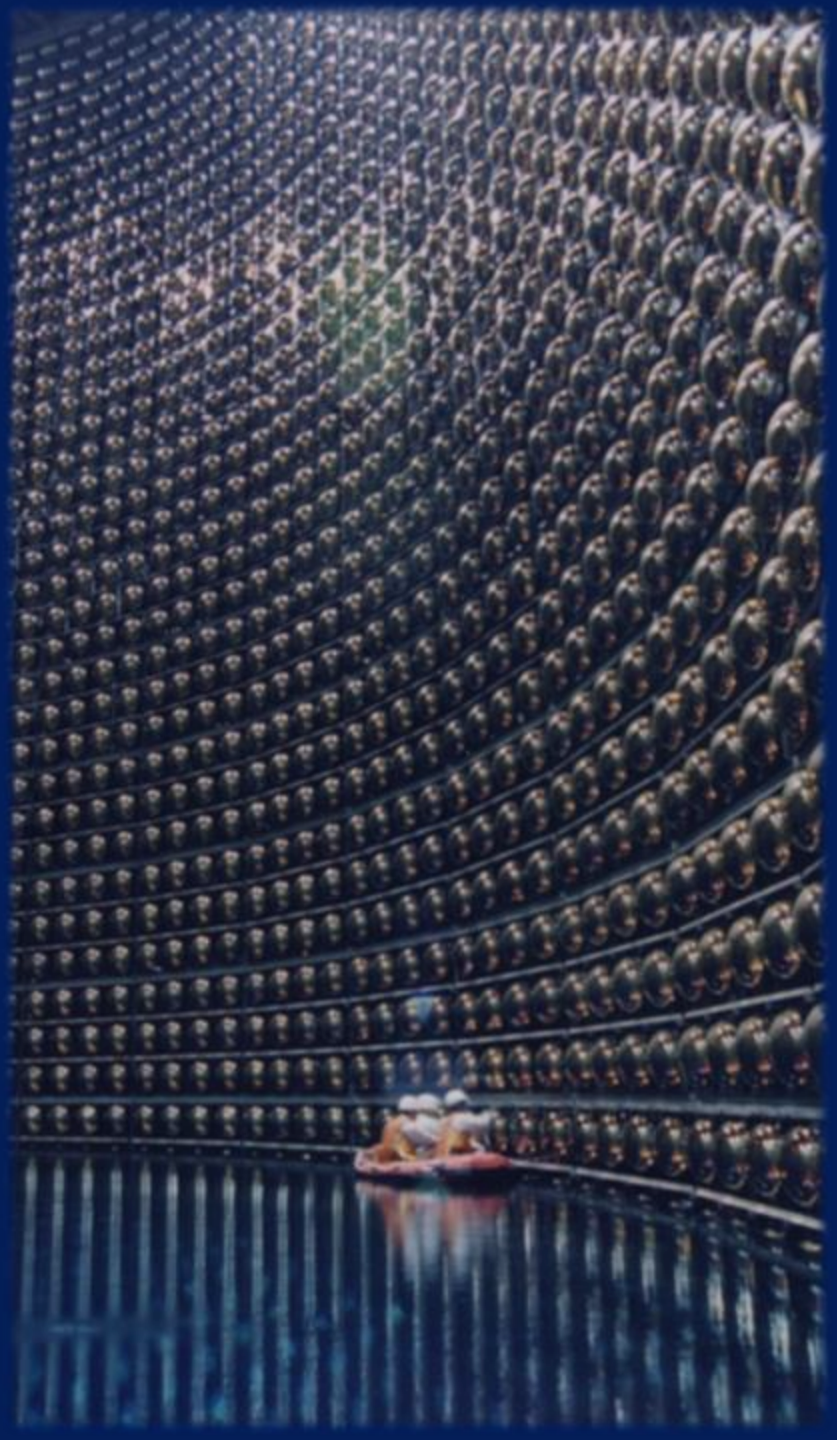
- First neutral current and first SK control samples established for T2K oscillation analysis, showing improved sensitivities to $\nu_\mu \rightarrow \nu_e$ appearance

- These advancements will be crucial for future T2K/SK/HK analyses and the next generation neutrino experiments









Backup

Neutrino Oscillation Physics

- The **3-flav**

Parameter	NO	IO
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.41^{+0.21}_{-0.20}$	
$\sin^2(\theta_{12})$	$0.307^{+0.012}_{-0.011}$	
$\sin^2(\theta_{13})$ $[10^{-2}]$	$2.224^{+0.056}_{-0.057}$	$2.222^{+0.069}_{-0.057}$
Δm^2_{32} $[10^{-3}\text{eV}^2]$	$2.505^{+0.024}_{-0.026}$	$-2.487^{+0.027}_{-0.024}$
$\sin^2(\theta_{23})$	$0.454^{+0.019}_{-0.016}$	$0.568^{+0.016}_{-0.021}$
δ_{CP} [rad]	$-2.23^{+0.68}_{-0.44}$	$-1.51^{+0.41}_{-0.45}$

arXiv:2007.1479 **Global Fit Results**

δ_{CP} unmeasured – Any CP violation in the lepton sector?

- **Beam**
- $P(\nu_\mu \rightarrow \nu_e)$ vs $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

Is $\theta_{23} = 45°$? If not, what is the octant of θ_{23}?

- **Beam**/Atmospheric
- $P(\nu_\mu \rightarrow \nu_e)$

Mass differences:

- Δm^2_{21} sensitive from **solar neutrinos** due to the **matter effects** in the Sun
- **Sign of Δm^2_{32}** remain unknown: normal ordering (NO) vs inverted ordering (IO)

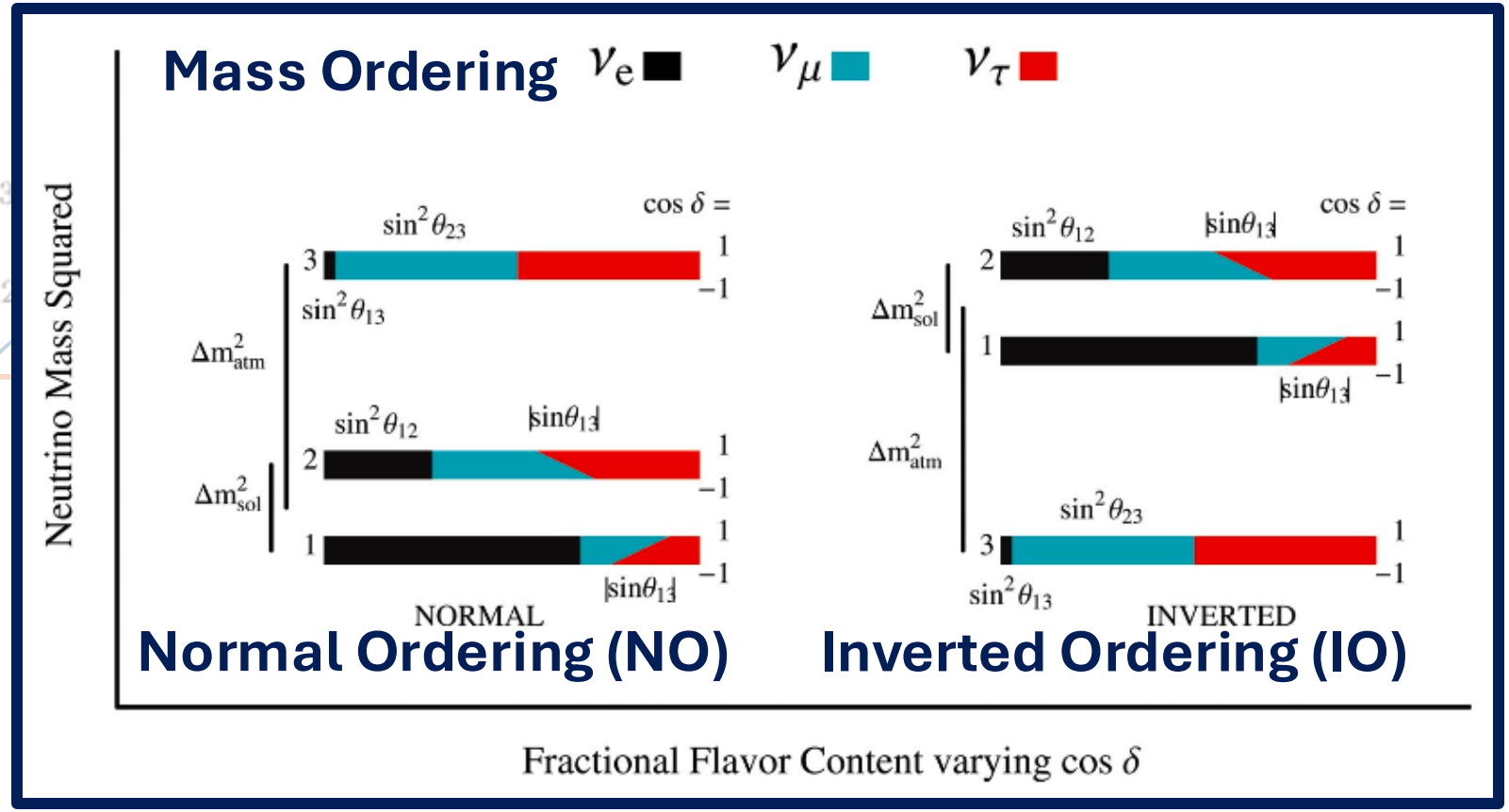
Neutrino Oscillation Physics

- The **3-flavour** framework

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & c_{23} \\ 0 & -s_{2} \end{pmatrix}$$

Flavour states

- Beam/Atmospheric
- $P(\nu_\mu \rightarrow \nu_\mu)$
- $P(\nu_\mu \rightarrow \nu_e)$



Mass differences:

- Δm^2_{21} sensitive from **solar neutrinos** due to the **matter effect** in the Sun
- **Sign of Δm^2_{32}** remain unknown: normal ordering (NO) vs inverted ordering (IO)

Neutrino Oscillation Physics

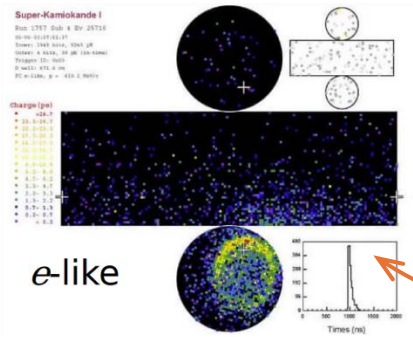
- The "**3+1" Sterile Neutrino Mixing**

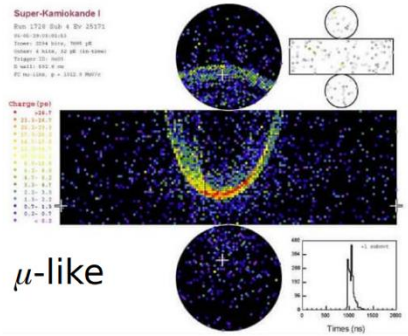
$$\begin{pmatrix} \nu_e(x) \\ \nu_\mu(x) \\ \nu_\tau(x) \\ \nu_s(x) \end{pmatrix}_L = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1(x) \\ \nu_2(x) \\ \nu_3(x) \\ \nu_4(x) \end{pmatrix}_L$$

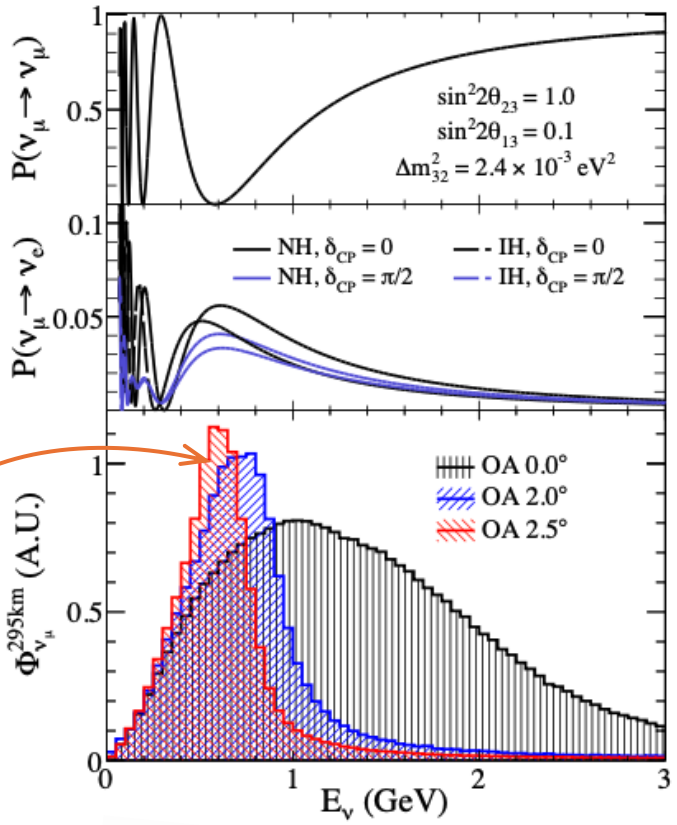
- 3 new mixing angles and 2 new CP-violating phases
- Modifies the rates oscillating to the SM flavours

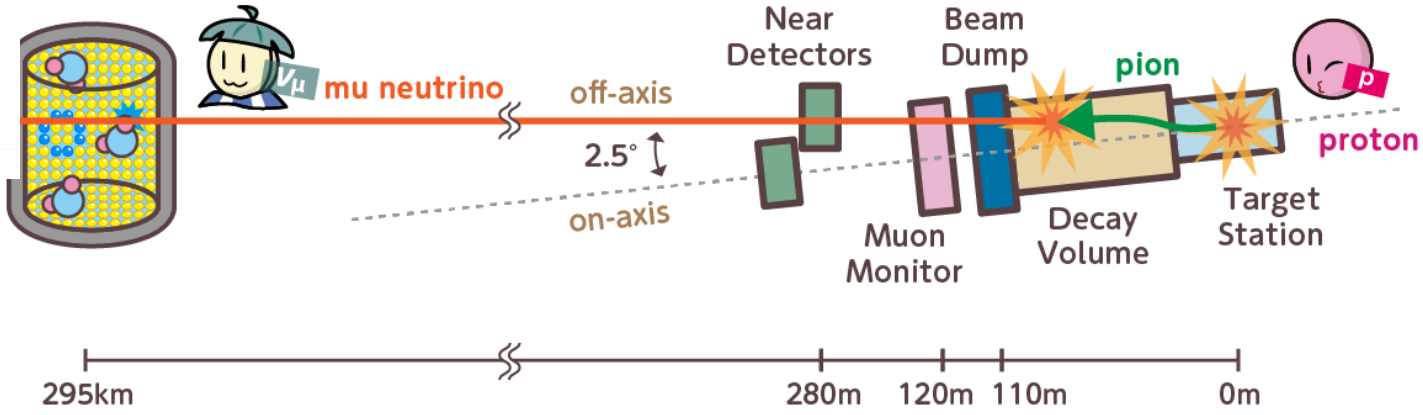
T2K Experiment

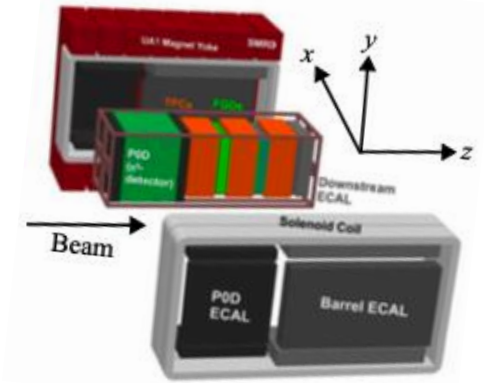
- T2K measures neutrino oscillations with a $\boldsymbol{\nu_\mu}$ **($\boldsymbol{\bar{\nu}_\mu}$) beam** produced at J-PARC
- Near detectors: **INGRID** (on-axis) and **ND280** (off-axis)
- **Off-axis neutrino beam** peaked at **0.6 GeV** goes to Super-K to measure oscillated flux
- At Super-K, **charged particles** produced from **neutrino-nucleus interactions** can emit water **Cherenkov radiations**









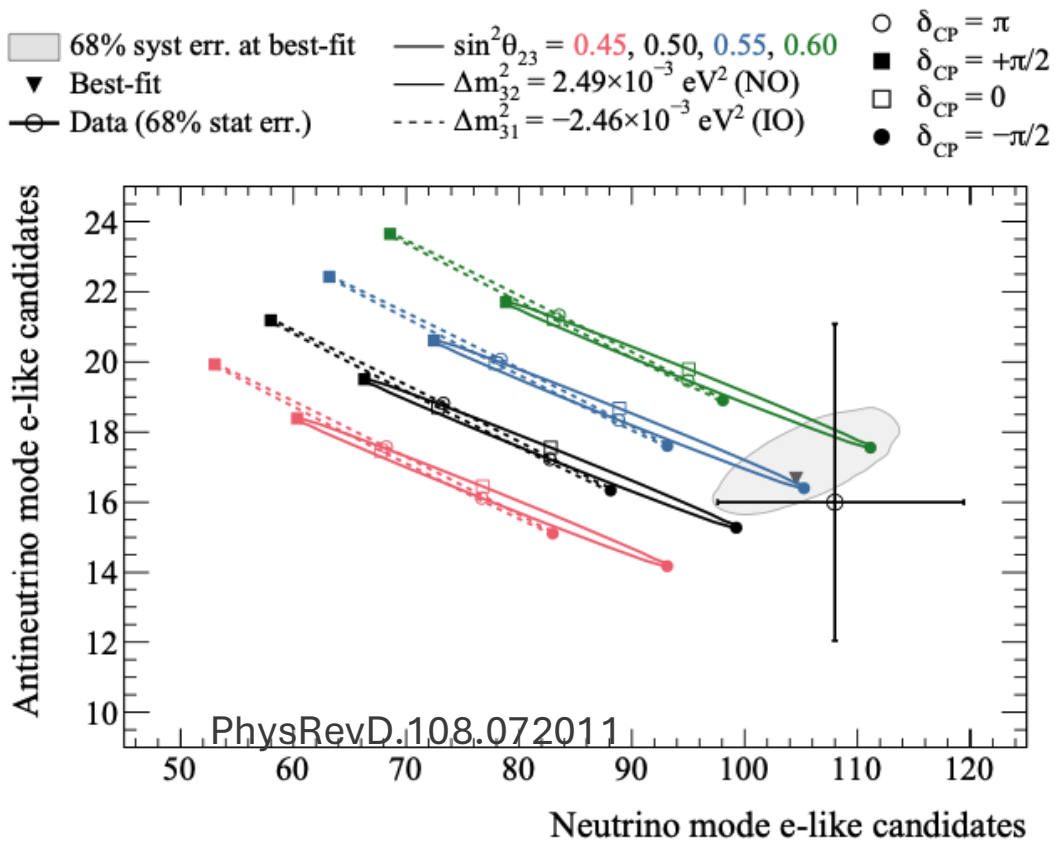


T2K Parameter Model

$$\mathbf{N} = \Phi \times \sigma \times \varepsilon \times \mathbf{P}(\nu_\alpha \to \nu_\beta)$$

Event Rate

- **Oscillated flux** constrained by Super-K data



Oscillation parameter degeneracy

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu) \simeq 1 - 4c_{13}^2 s_{23}^2 \left(1 - c_{13}^2 s_{23}^2\right) \sin^2\left(1.27\frac{\Delta m_{32}^2 L}{E}\right)$$

$$\simeq 1 - \sin^2 2\theta_{23} \sin^2\left(1.27\frac{\Delta m_{32}^2 L}{E}\right)$$

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \cdot \sin^2\Delta_{31}$$

$$+ 8c_{13}^2 s_{12} s_{13} s_{23}\left(c_{12}c_{23}\cos\delta_{CP} - s_{12}s_{13}s_{23}\right) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

$$- (+)8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta_{CP} \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

$$+ 4c_{13}^2 s_{12}^2\left(c_{12}^2 c_{23}^2 + s_{12}^2 s_{13}^2 s_{23}^2 - 2c_{12}c_{23}s_{12}s_{13}s_{23}\cos\delta_{CP}\right) \cdot \sin^2\Delta_{21}.$$

$c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$ $\quad \Delta_{ij} \equiv \Delta m^2_{ij}\frac{L}{4E}$.

Metropolis-Hastings Algorithm

- During the random walks, the chain will

$$\boldsymbol{x}_p = \boldsymbol{x}_i + \mathbf{random}(f(\boldsymbol{x}_p|\boldsymbol{x}_i)),$$

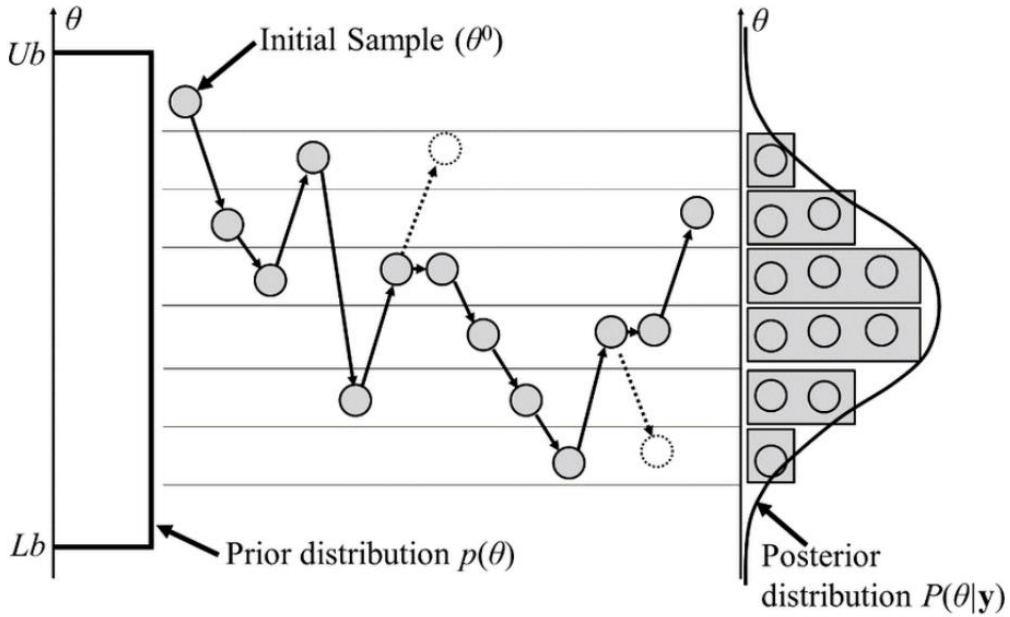
  - **Propagate to the next step** when the **proposal is accepted**

$$\alpha = \min\left[1,\ \frac{P(\boldsymbol{x}_p|D)}{P(\boldsymbol{x}_i|D)}\right] = \min\left[1,\ \frac{\mathcal{L}_{tot}(\boldsymbol{x}_p)}{\mathcal{L}_{tot}(\boldsymbol{x}_i)}\right]$$

$$\boldsymbol{x}_{i+1} = \begin{cases} \boldsymbol{x}_p & \text{for } \alpha \geq u, \\ \boldsymbol{x}_i & \text{for } \alpha < u. \end{cases}$$

For random unform number *u* in [0, 1]

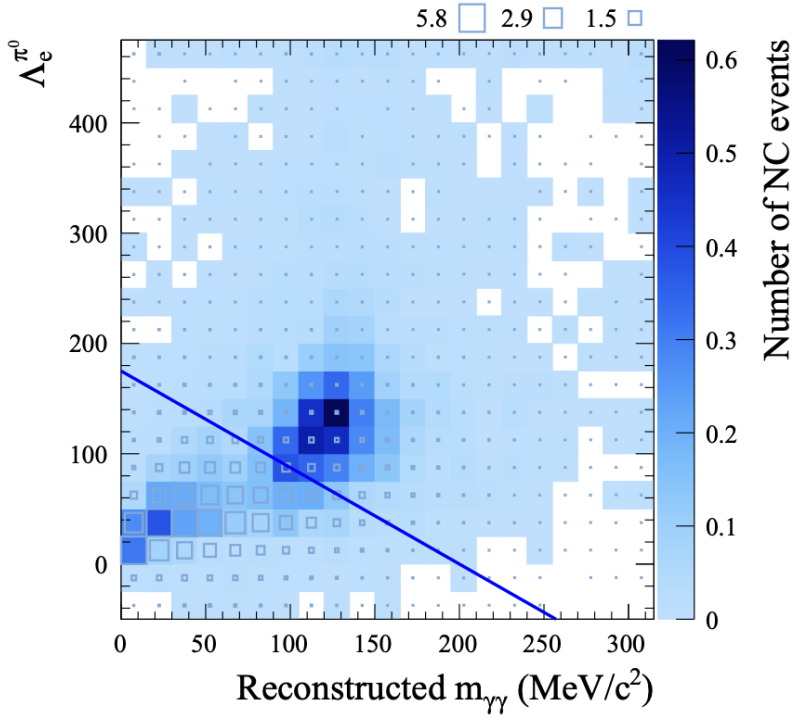
  - Or **stay at the same step** for the next proposal if the current **proposal is rejected**



Energies. 2015; 8(6):5538-5554

Oscillated Event Samples

- The **1-ring e-like** sample was selected from an e/π^0 **particle ID cut**, with a dependence on π^0 **invariant mass**

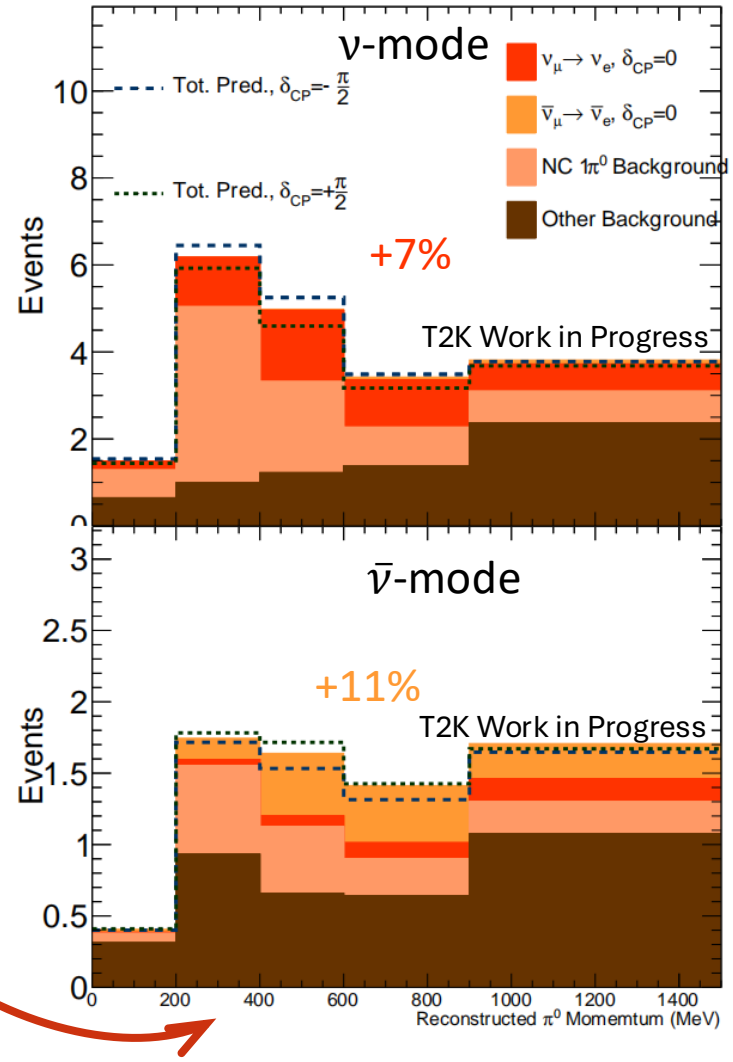


Phys. Rev. D **103**, 112008

Meanwhile, a number of oscillated ν_e ($\bar{\nu}_e$) signals are also removed.

Re-selecting the 1-ring π^0 events can include these additional signal events.

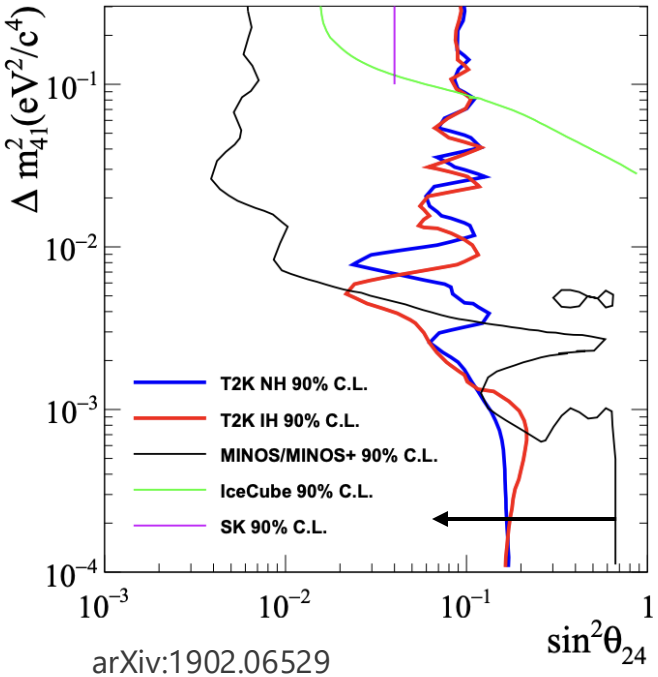
The new 1-ring π^0-like samples



NC1π^0 Control Samples

- Selected **large** dataset for 2-ring π^0-like samples
- **Flavour independent** due to neutral current
  - Can act as a probe to **sterile neutrino oscillations**

$$
\begin{aligned}
P_{NC} &= 1 - P(\nu_\mu \to \nu_s) \\
&\approx 1 - \sin^2 2\theta_{23}(A^2 - \frac{1}{4}B^2)\sin^2\frac{\Delta m^2_{31}L}{4E} \\
&\quad - B(B\cos^2\theta_{23} - A\sin 2\theta_{23})\sin^2\frac{\Delta m^2_{41}L}{4E} \\
&\quad - B(B\sin^2\theta_{23} + A\sin 2\theta_{23})\sin^2\frac{\Delta m^2_{43}L}{4E}
\end{aligned}
$$



arXiv:1902.06529

The new 2-ring π^0-like samples