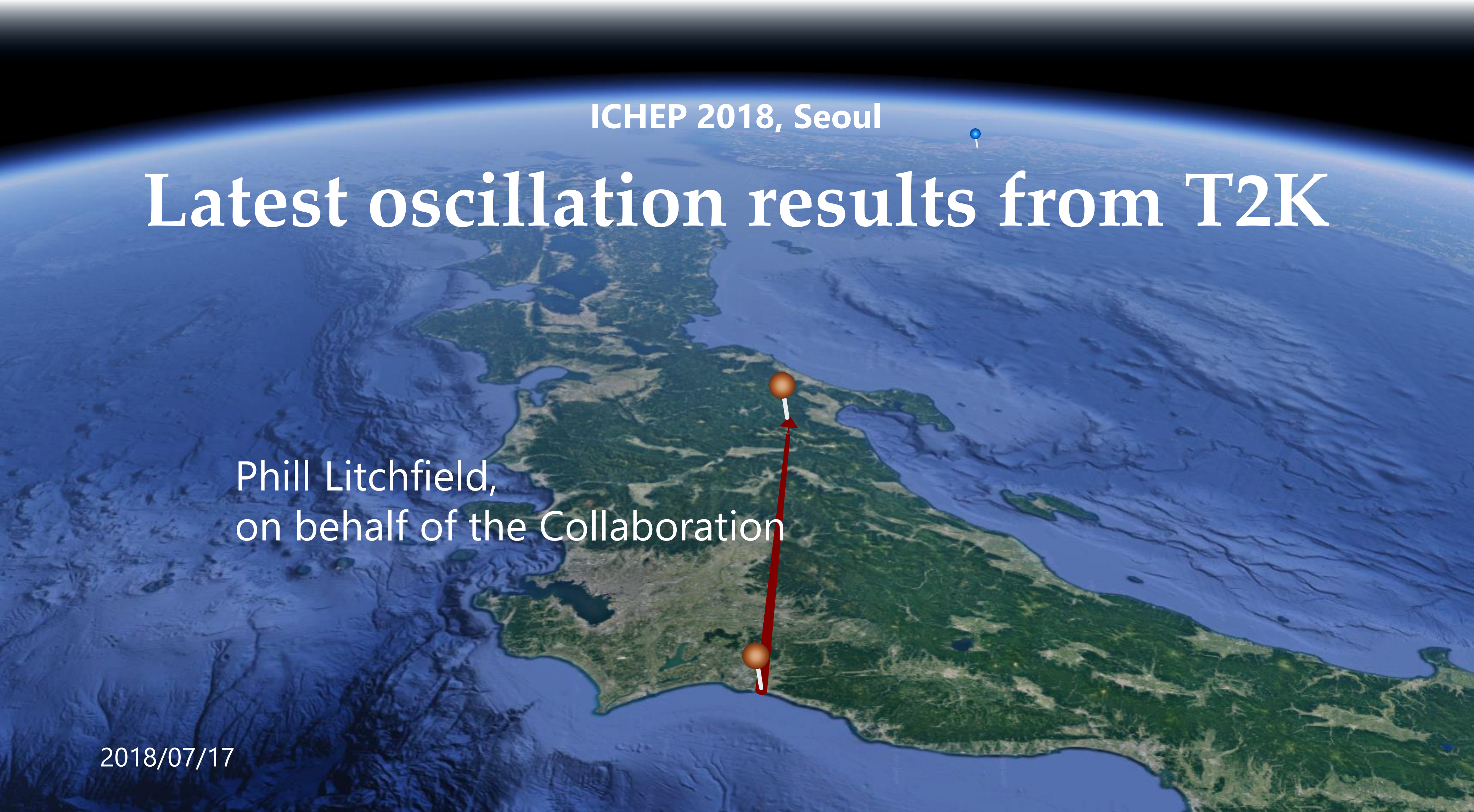
Imperial College London

T2K

ICHEP 2018, Seoul

Latest oscillation results from T2K



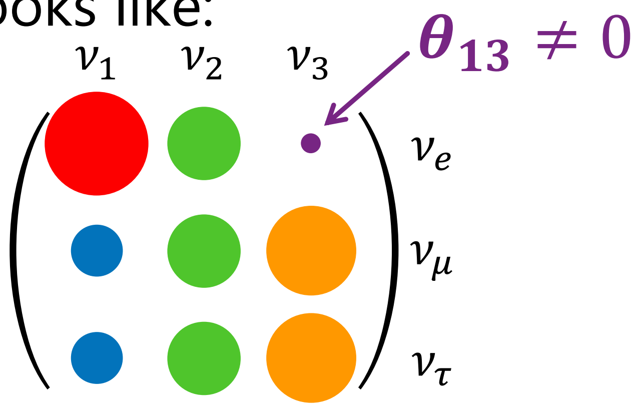
Phill Litchfield,
on behalf of the Collaboration

2018/07/17

Standard neutrino picture

- Neutrino flavours are a mix of mass eigenstates: $|\nu_\alpha\rangle = U_{\text{PMNS}}|\nu_i\rangle$
- We know fairly well what the mixing matrix looks like:

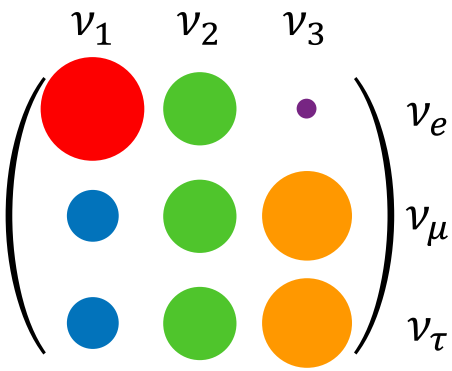
$|U_{\text{PMNS}}|^2 \simeq$



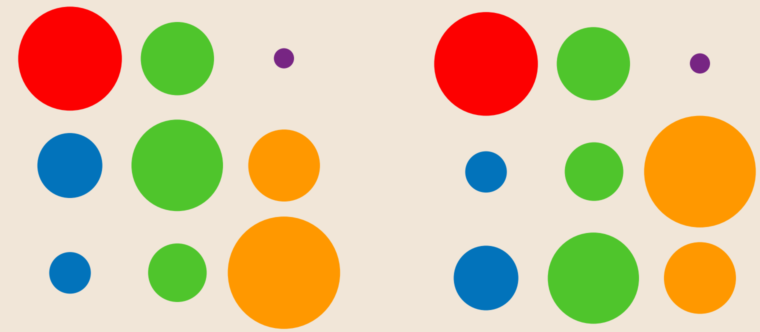
Open questions

- Neutrino flavours are a mix of mass eigenstates: $|\nu_\alpha\rangle = U_{\mathrm{PMNS}}|\nu_i\rangle$
- We know *fairly* well what the mixing matrix looks like:

$$|U_{\mathrm{PMNS}}|^2 \simeq$$

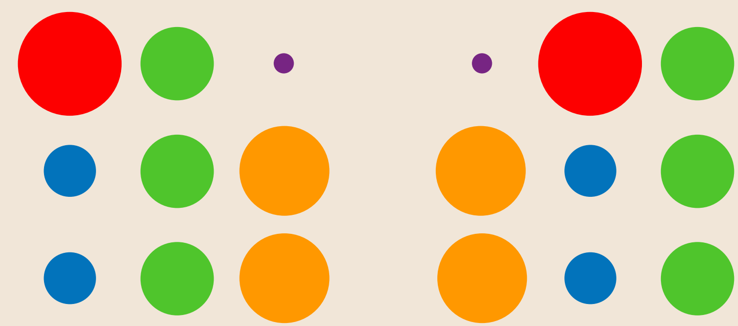


Octant deceneracy



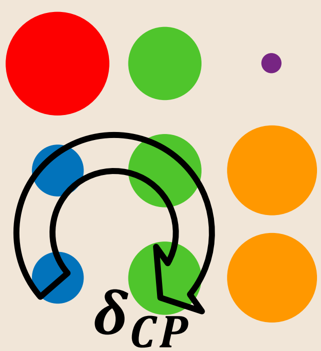
Lower ($\theta_{23} < 45°$) Upper ($\theta_{23} > 45°$)

Mass Ordering (Hierarchy)



Normal (NO) Inverted (IO)

CP Violation



Complex mixing of these 4 elements causes

$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

Key parameter: $\boldsymbol{\delta_{CP}}$

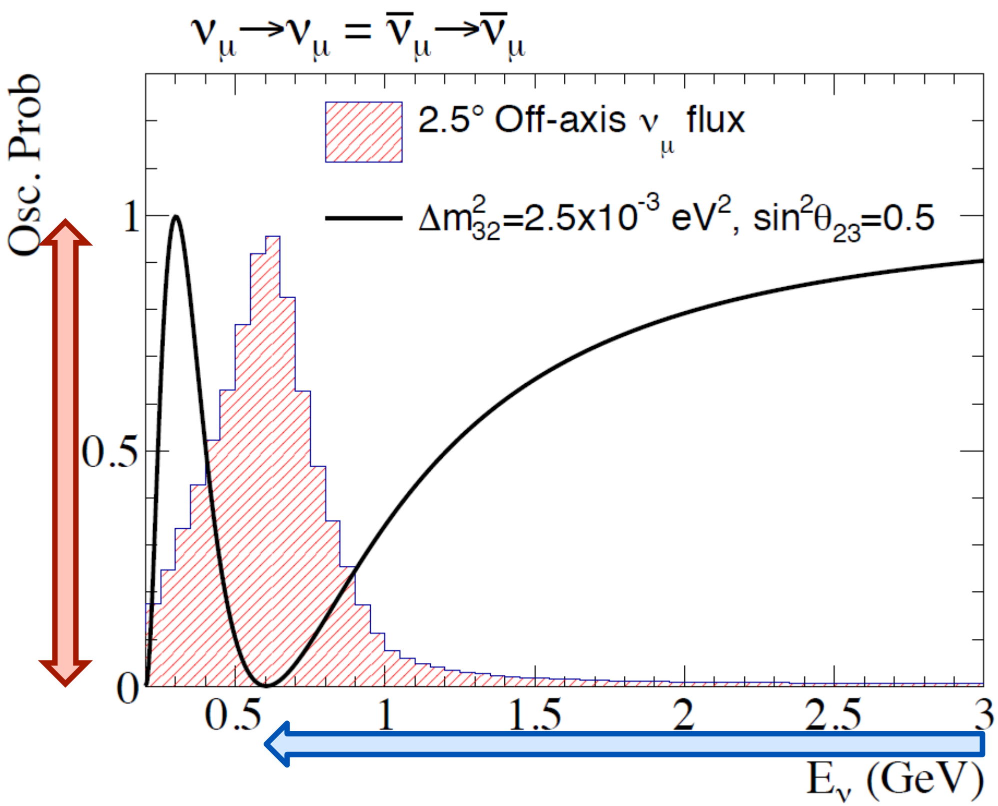
T2K measurements

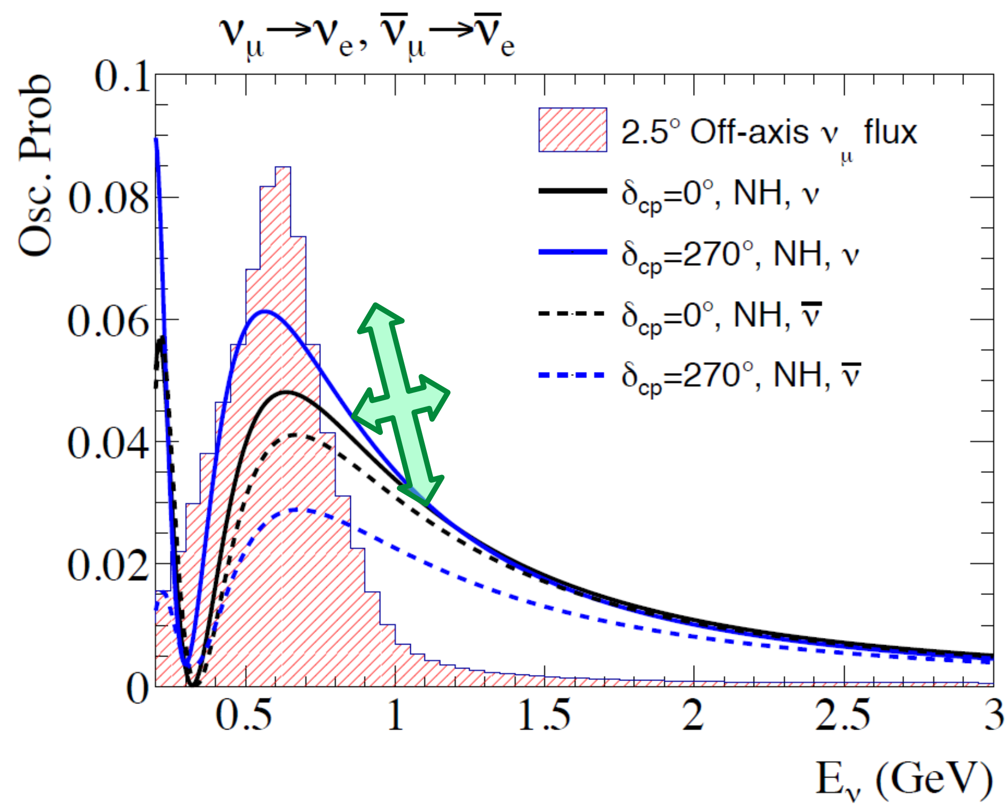
ν_μ Disappearance:

- Precision measurement of $\sin^2 2\theta_{23}$ and Δm^2_{32}

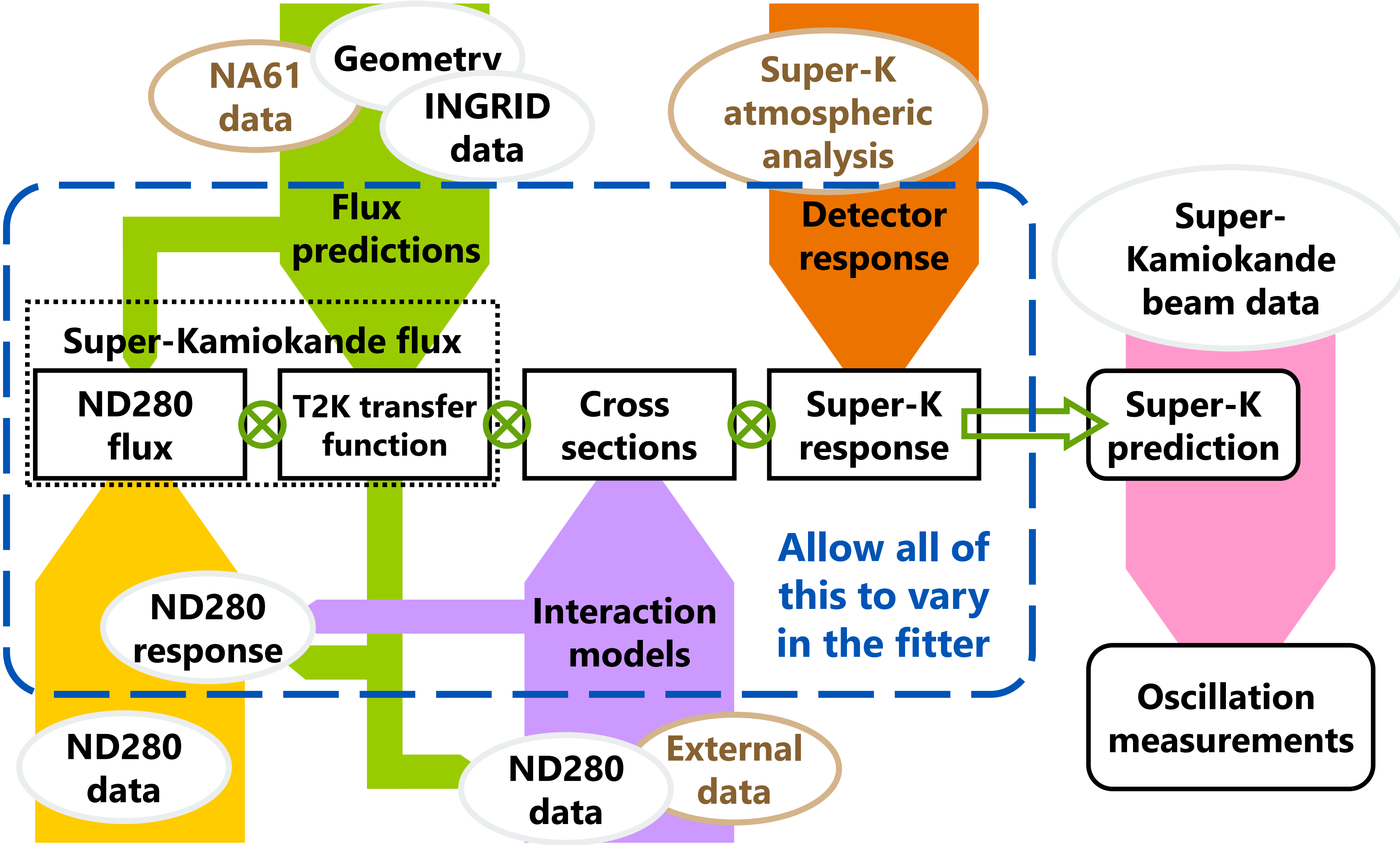
ν_e Appearance:

- Enhanced for ν if $-\pi < \delta_{CP} < 0$
- NO/NH also enhances ν



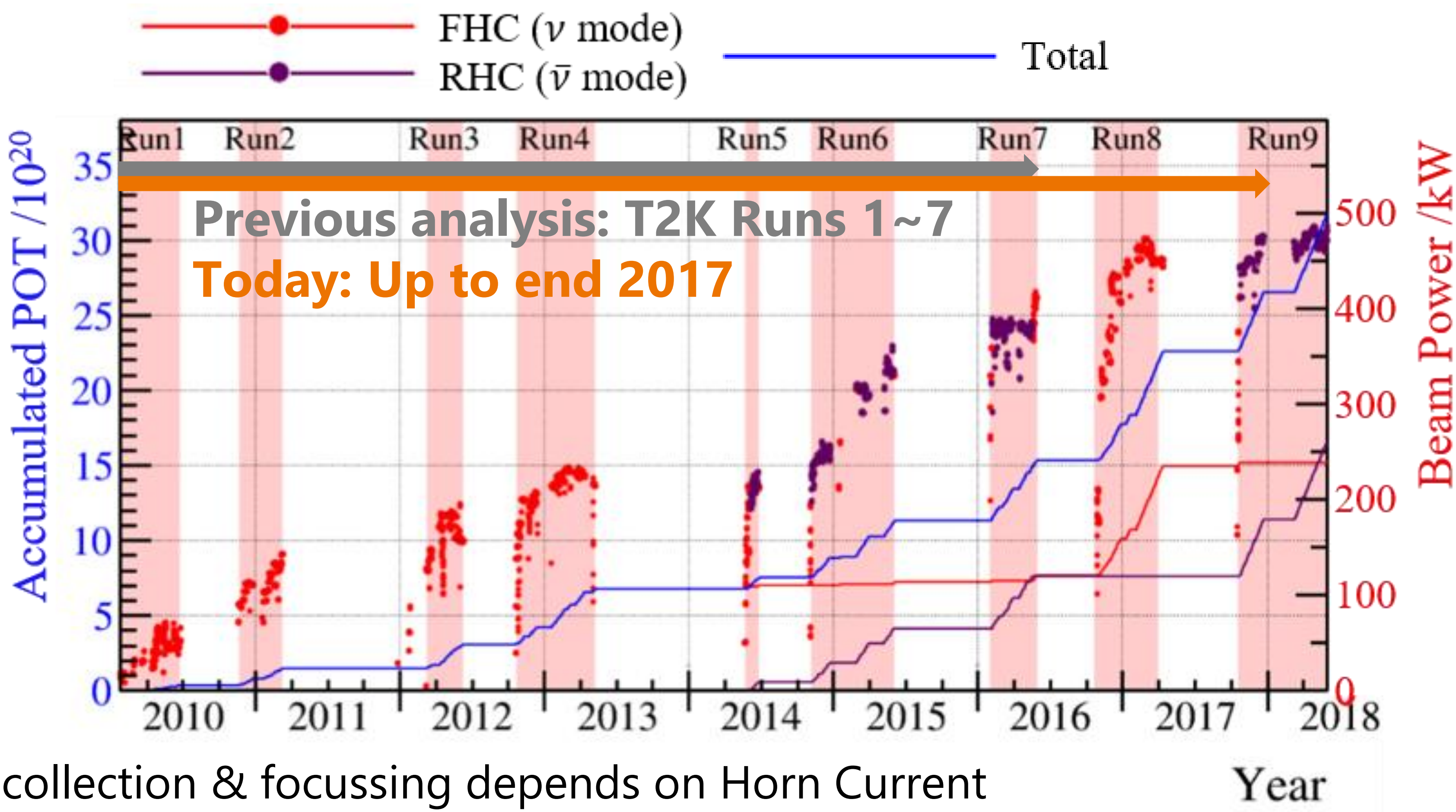


Analysis strategy



Beam exposure

T2K Imperial College London

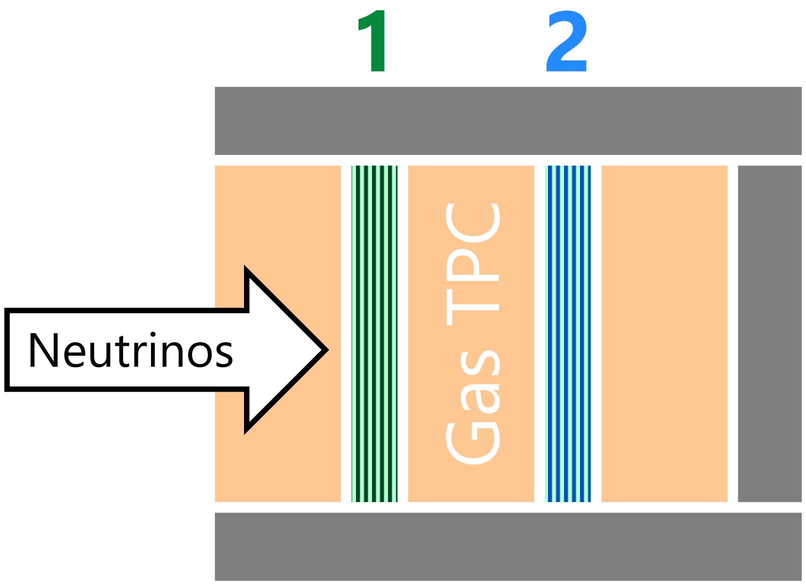


Pion collection & focussing depends on Horn Current

Forward Horn Current: $\pi^+ \rightarrow \mu^+ + \nu_\mu$ 1.49×10^{21} POT

Reverse Horn Current: $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$ 1.12×10^{21} POT

Constraint using ND280 data



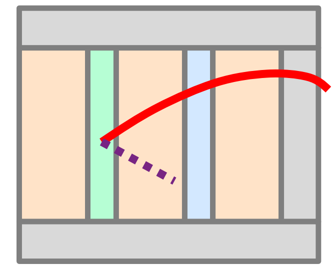
Analysis uses pairs of samples from 2 active target volumes

1. **Pure scintillator**: **Carbon** (+H)
2. **Water+ scint.**: **Oxygen** (+C, H)

Allows separate constraints for C vs O nuclear effects

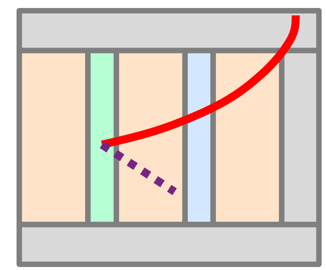
Forward Horn Current mode:

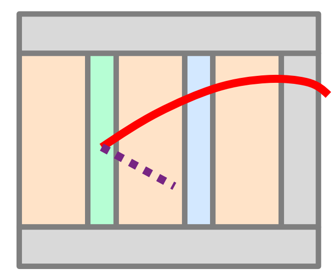
- Require 1 –ive muon-like track
- Sub-samples with {0,1,*n*} pion-like tracks



Reverse Horn Current mode:

- Require 1 muon-like track
- Sub-samples based on muon charge and {0, *n*} extra tracks

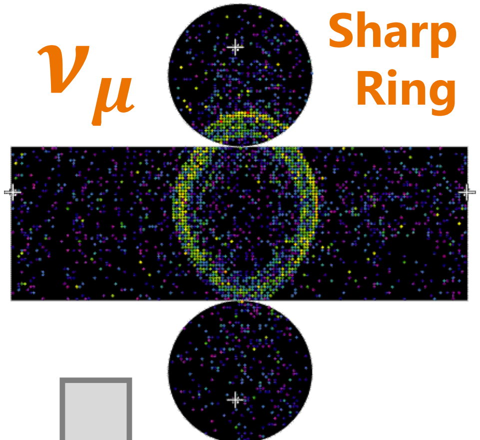




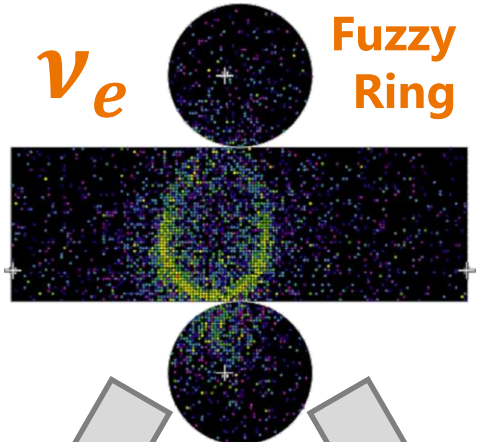
(Larger 'wrong-sign' B/G in RHC mode)

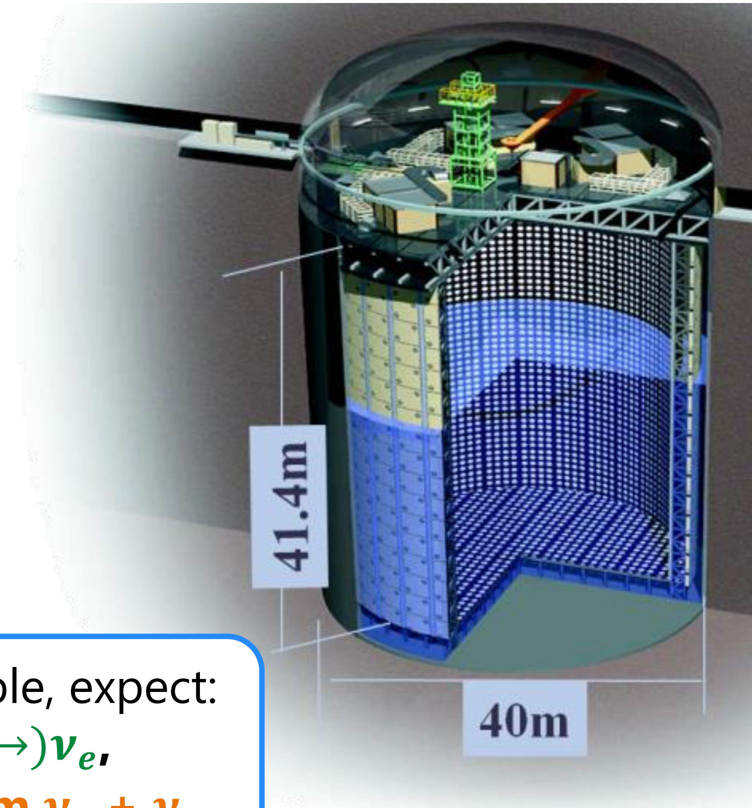
Super-Kamiokande samples

ν_μ **Sharp Ring**



ν_e **Fuzzy Ring**





1R-μ

FHC sample, expect:
94%+6% $\nu_\mu + \bar{\nu}_\mu$

RHC sample, expect:
60%+40% $\bar{\nu}_\mu + \nu_\mu$

1R-e

FHC sample, expect:
81% $(\nu_\mu \to)\nu_e$,
18% beam $\nu_e + \nu_\mu$

RHC sample, expect:
45% $(\bar{\nu}_\mu \to)\ \bar{\nu}_e$,
10% $(\nu_\mu \to)\ \nu_e$

1R-e + d.e.

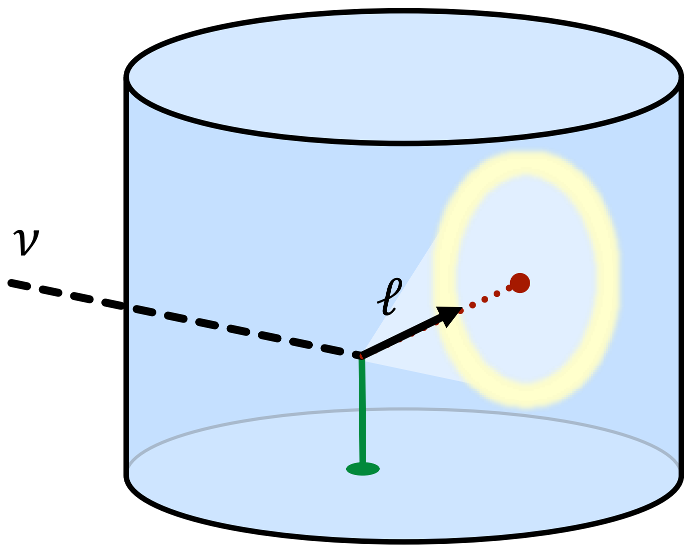
FHC sample, expect:
79% $(\nu_\mu \to)\nu_e$,
21% beam $\nu_e + \nu_\mu$

New! Sample added with delayed-coincidence Michel electron (tags low momentum pion in FHC)

Changes since 2016

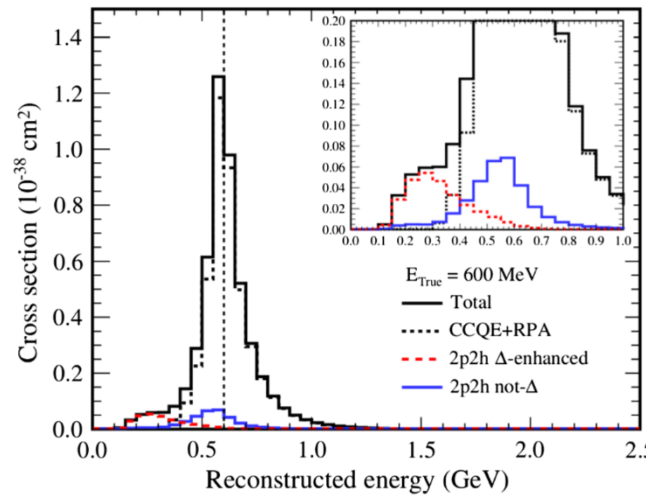
Improvements to the selection

- More powerful reconstruction and classifier employed at SK
- Expanded Fiducial Volume utilising both closest d_{wall} and along-path d_{towall}
  - Recover **~20%** more events



Changes in the model

- Better accounting for in-nucleus effects on nucleon weak current (RPA)
- Scattering from correlated pairs of nucleons (2p2h)



- Significant retuning of the pion production models

Event rates

Sample	Expectation, $\sin^2\theta_{23} = 0.528$, $\delta =$ $-\pi/2$	0	π	$+\pi/2$	Observed
FHC 1R-μ	268.5	268.2	268.9	268.9	**243**
RHC 1R-μ	95.5	95.3	95.8	95.5	**102**
Sum of 1R-μ	*364.0*	*363.5*	*364.7*	*364.5*	***345***
FHC 1R-e	73.8	61.6	62.2	50.0	**75**
FHC 1R$-e$ +d.e.	6.9	6.0	5.8	4.9	**15**
RHC 1R-e	11.8	13.4	13.2	14.9	**9**

See fewer ν_μ like events than expected,
⇒ fit will prefer maximal disappearance

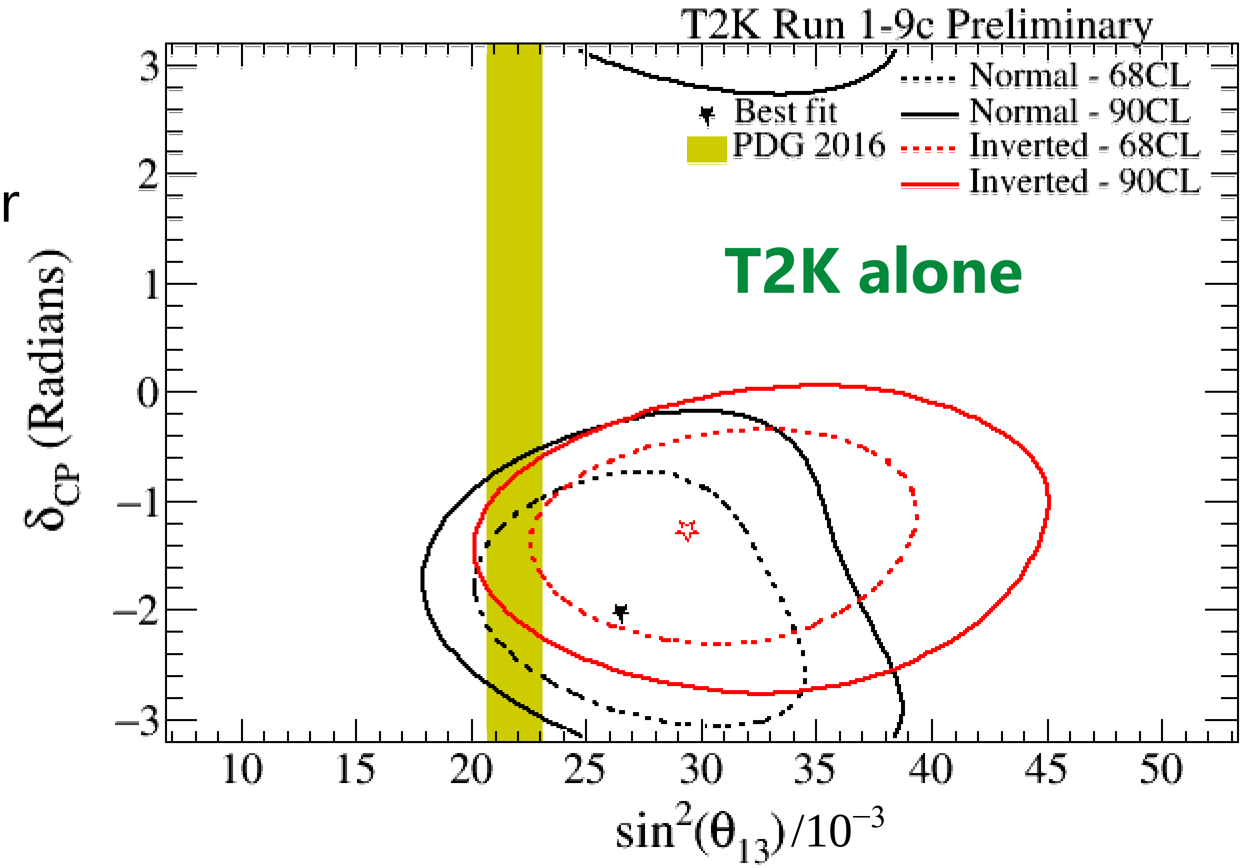
See more ν_e and fewer $\bar{\nu}_e$ than expected, even for $\delta = -\pi/2$
⇒ fit will have a strong preference for CP-violation that enhances neutrino rates

- Excess in d.e. sample has p~1%, but does not have disproportionate impact on fit

Appearance* Results

T2K results in $\sin^2\theta_{13} - \delta_{CP}$ plane are S-curves

- One curve for FHC, another for RHC
- New RHC data improves T2K-only constraints
- Inverted Ordering needs slightly larger $\sin^2\theta_{13}$

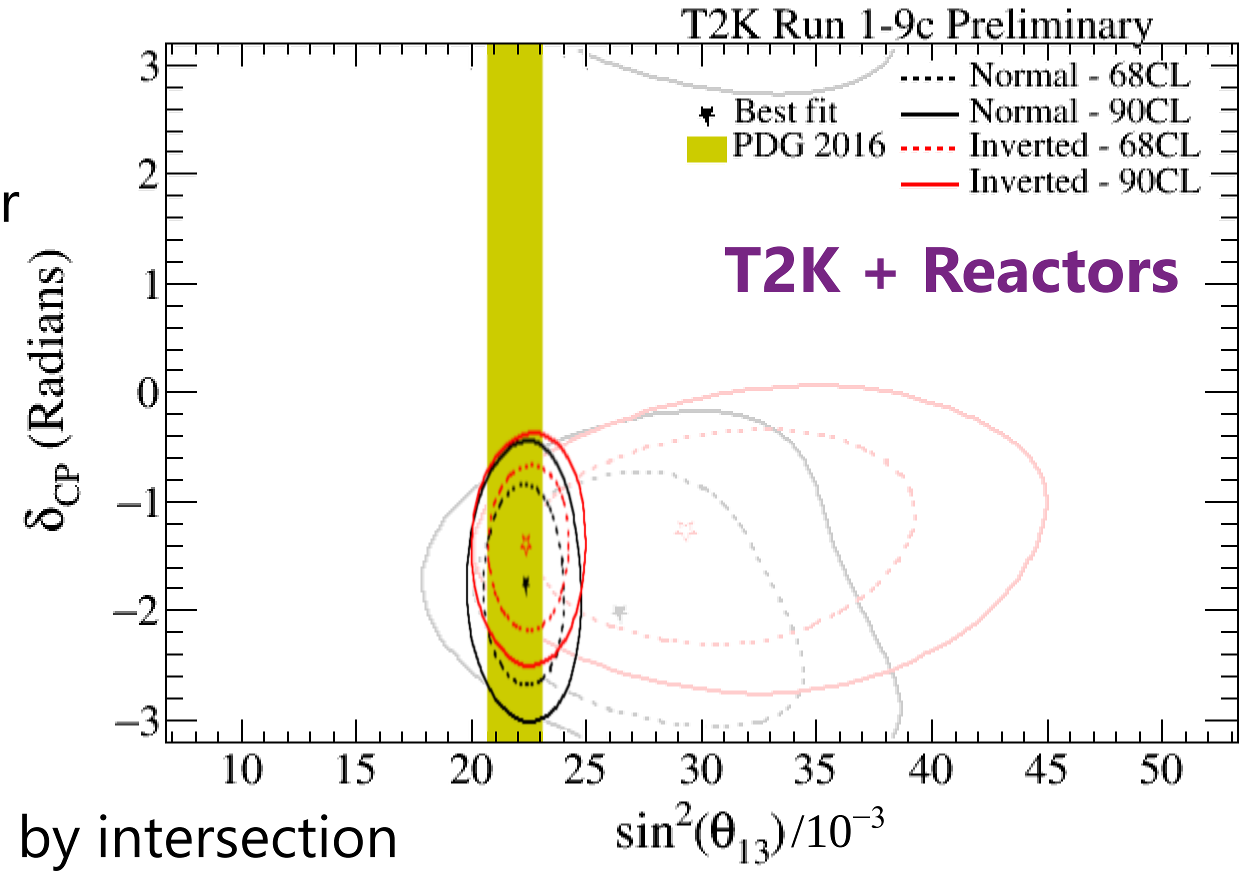


*Uses ν_μ data; marginalises over relevant parameters

Appearance* Results

T2K results in $\sin^2\theta_{13} - \delta_{CP}$ plane are S-curves

- One curve for FHC, another for RHC
- New RHC data improves T2K-only constraints
- Inverted Ordering needs slightly larger $\sin^2\theta_{13}$



δ_{CP} constraint then improved by intersection with reactor value.

- More tension in Inverted Ordering, leading to stronger than expected preference for Normal Ordering

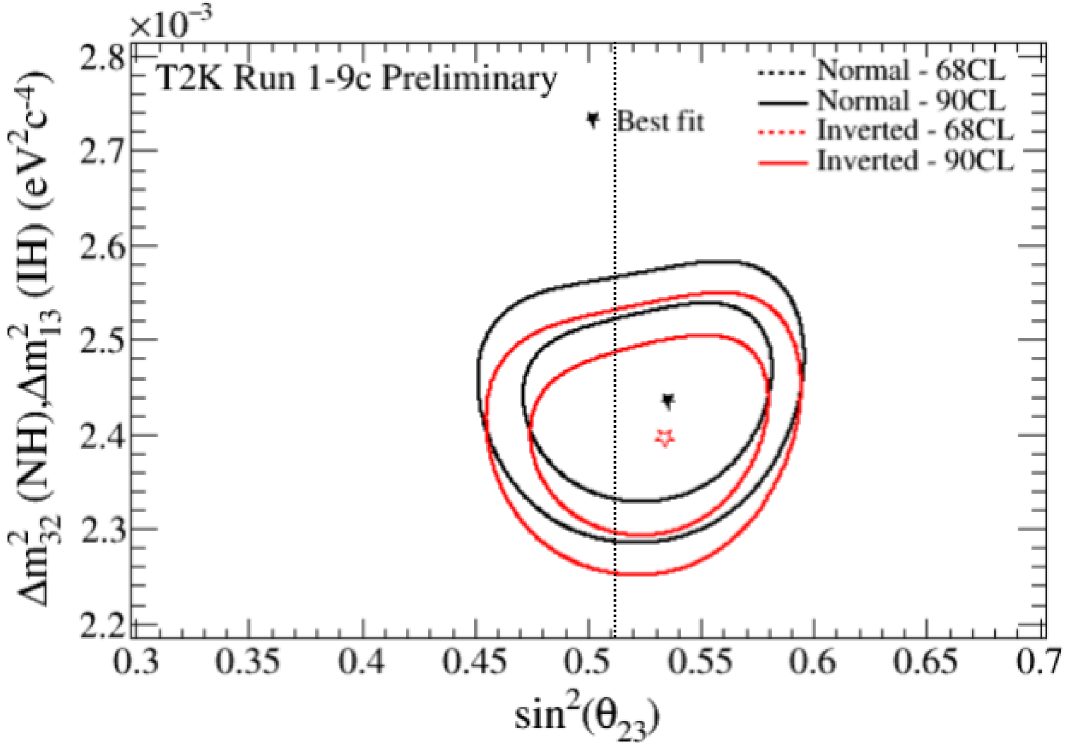
Disappearance* Results

Δm_{32}^2, $\sin^2\theta_{23}$ results mostly dependent on the ν_μ data.

Low **observed/expected** ratio so expect maximal disappearance…

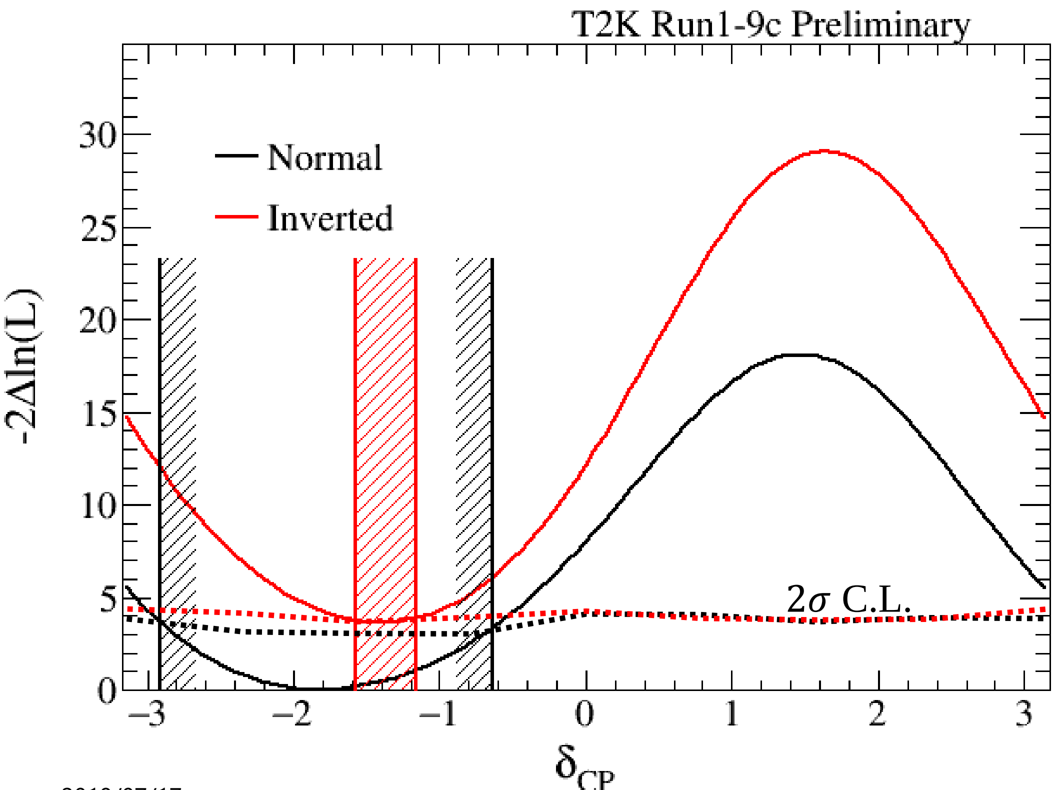
This happens for $\sin^2\theta_{23} \simeq 0.51$

- Small preference for *Upper octant* from disappearance alone
- But large values of $\sin^2\theta_{23}$ also enhance *appearance* rates and improve fit to ν_e appearance.

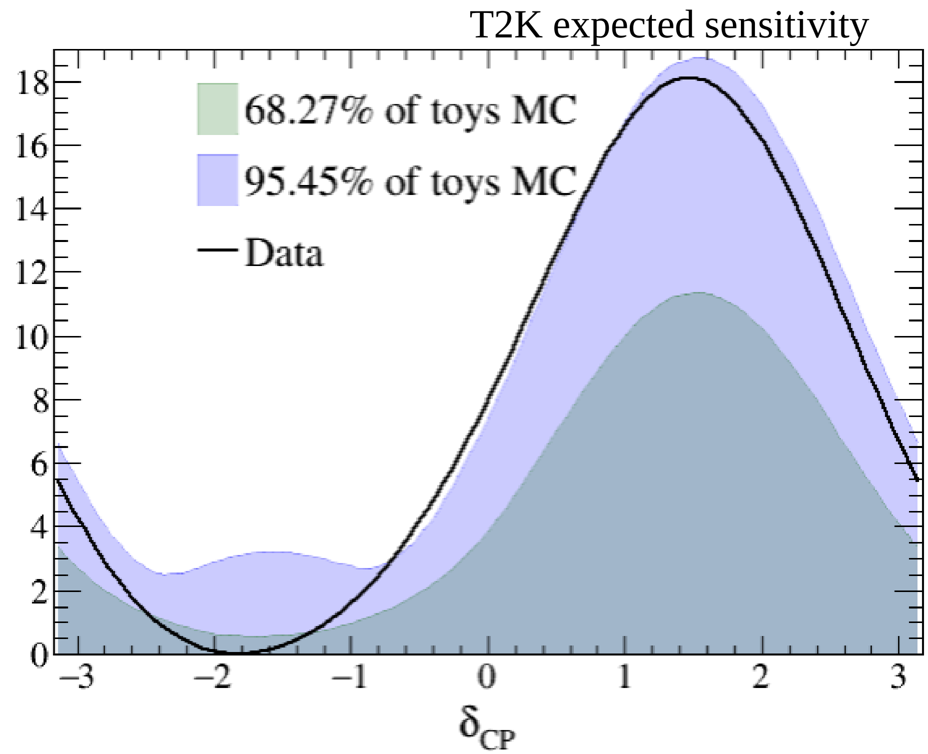


Constraint on δ_{CP}

- Marginalise over everything except δ_{CP}
- Compare to frequentist critical values
- Exclude CP conservation at $> 2\sigma$ C.L.
- Inverted ordering only just $< 2\sigma$ C.L.



- Stronger than expected



- In toy experiments at best fit, 2σ exclusion of $\delta = \{0, \pi\}$ occurs in 19% of cases

Summary numbers

Almost double exposure since last paper [Phys.Rev.D96, 092006 (2017)]

- FHC (mainly ν): 7.482×10^{20} → $\mathbf{1.49\times10^{21}}$ POT
- RHC (mainly $\bar{\nu}$): 7.471×10^{20} → $\mathbf{1.12\times10^{21}}$ POT

CP conserving values of δ_{CP} lie outside the 2σ interval

- For IO even the best value of δ_{CP} is disfavoured at around 2σ

Mass ordering	Best fit δ_{CP}	2σ interval
Normal	−1.82 (−0.58π)	[−2.91, −0.64]
Inverted	−1.38 (−0.44π)	[−1.57, −1.16]

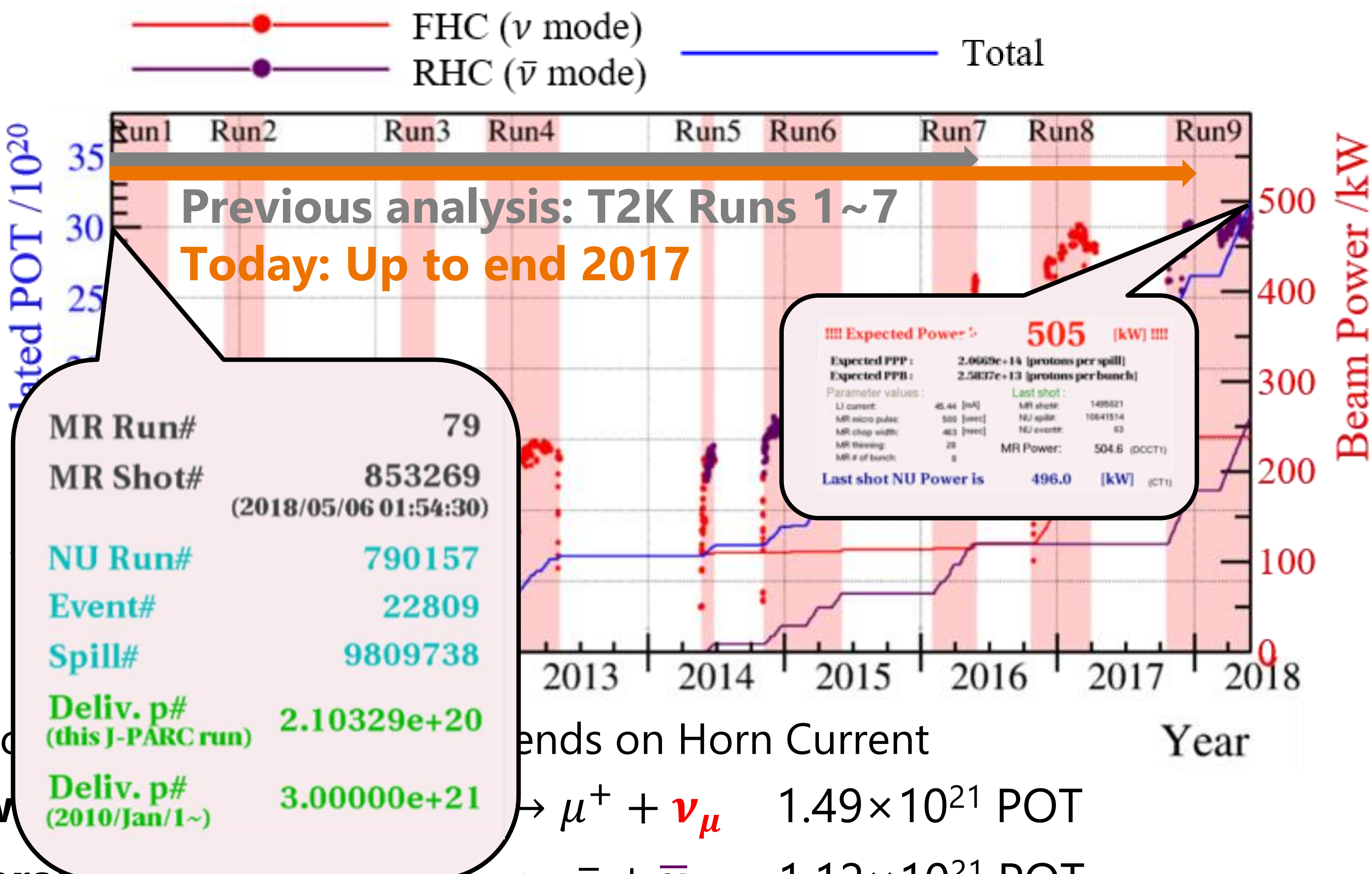
Updated constraints on other parameters:

Parameter	Best fit [NO]	1σ interval	Best fit [IO]	1σ interval
$\sin^2\theta_{23}$	0.536	[0.490, 0.567]	0.536	[0.495, 0.567]
Δm^2_{32} /10^{-3} eV^2	+2.43	[+2.37, +2.50]	−2.49	[−2.55, −2.42]
$\sin^2\theta_{13}$ /10^{-3} (T2K only)	2.68	[2.22, 3.19]	3.05	[2.53, 3.69]

Extras

Beam exposure

T2K
Imperial College London



Pion c… ends on Horn Current

Forw… → $\mu^+ + \nu_\mu$ 1.49×10^{21} POT

Reverse Horn Current: π^- → $\mu^- + \bar{\nu}_\mu$ 1.12×10^{21} POT

Other representations

Calculated **Bayes factors** for octant and mass ordering preference:

$$\mathcal{B}_{\theta_{23}} = \frac{\mathrm{P}\left(\sin^2\theta_{23} > 0.5 \middle| Data\right)}{\mathrm{P}\left(\sin^2\theta_{23} < 0.5 \middle| Data\right)} = \frac{0.77}{0.23}$$

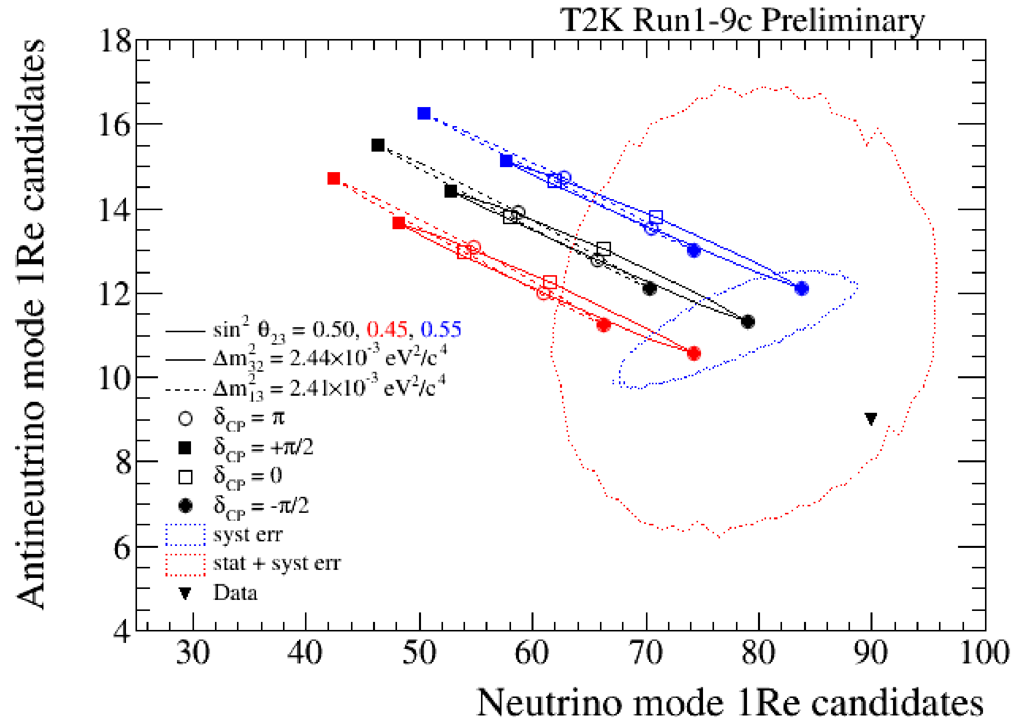
$$\mathcal{B}_{\mathrm{MO}} = \frac{\mathrm{P}(\mathrm{NO}|Data)}{\mathrm{P}(\mathrm{IO}|Data)} = \frac{0.89}{0.11}$$

Using [0,1] and equal priors

Calculate ***p*-values for** non-unitary model in which $\bar{\nu}_\mu \nrightarrow \bar{\nu}_e$:

Hypothesis	*p*-value
$\bar{\nu}_\mu \nrightarrow \bar{\nu}_e$	0.233
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (FHC-BF)	0.0867

- Only 9 events observed so low PMNS *p*-value expected



Bi-rate plot summed over spectra of selected events.

- Systematic error uses parameter covariance from ND280 data.

Systematic errors

	FHC 1R-μ	RHC 1R-μ	FHC 1R-e	FHC 1R−e +d.e.	RHC 1R-e	FHC / RHC
ND prediction	2.9%	2.7%	3.0%	2.9%	3.8%	2.3%
Unconstrained	0.3%	0.3%	2.8%	3.0%	2.9%	3.4%
Binding Energy	3.4%	1.7%	7.3%	3.7%	3.0%	2.3%
SK Detector	3.3%	2.8%	4.1%	4.4%	17.4%	2.1%
Total	**4.9%**	**4.3%**	**8.8%**	**7.0%**	**18.3%**	**5.9%**
Stat $\sqrt{N}$ $\delta = \pi/2$ $\delta = -\pi/2$	6.1%	10.2%	11.6 ~ 14.1%	38.0 ~ 45.1%	29.1 ~ 25.9%	—

Indicative errors on the total rate — actual analysis doe not use these!

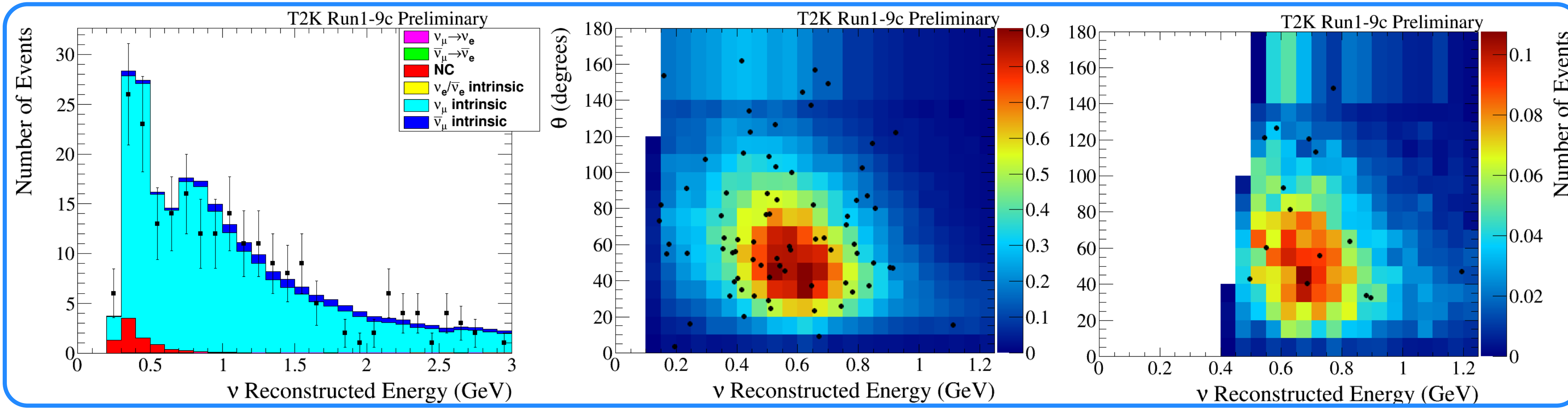
ND prediction: Extrapolated flux and constrained interaction effects

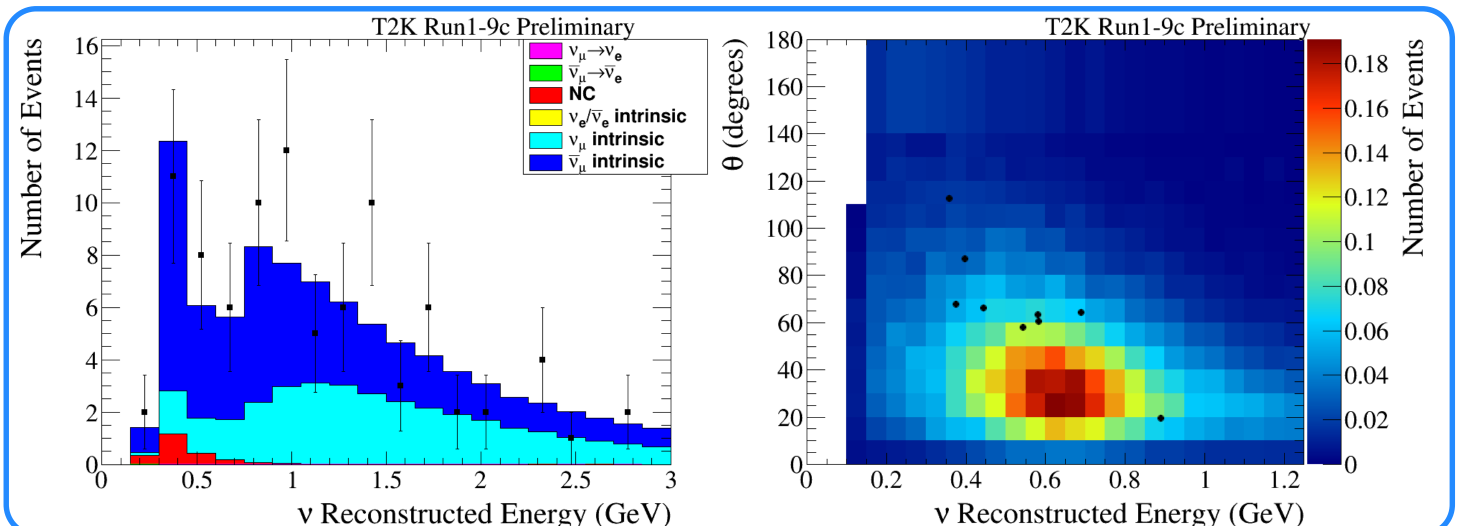
Unconstrained: Cross-sections not constrained by ND280 [Naïve sum]

Binding Energy: Parameterised residual of effect after ND280 prediction

SK Detector: Reconstruction and re-interactions

SK event distributions





Upper: FHC
1R(ing)-μ; 1R-e;
1Re + decay e^+

Lower: RHC
1R-μ; 1R-e;

Disappearance* Results

Δm^2_{32}, $\sin^2\theta_{23}$ results mostly dependent on the ν_μ data.

- *Upper octant* solutions for $\sin^2\theta_{23}$ enhances *appearance* rates
  - Leading term $\propto \sin^2\theta_{23} \sin^2 2\theta_{13}$

Reactor constraint