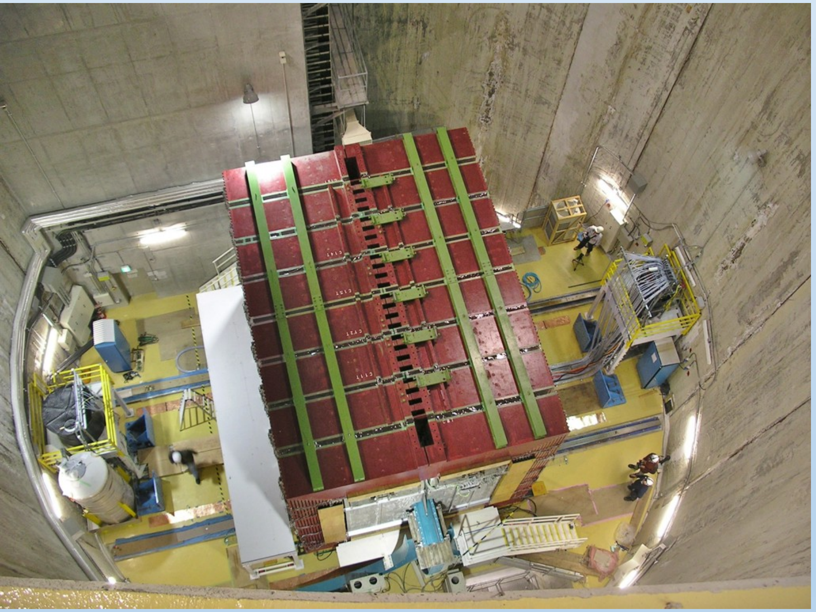
Latest Neutrino Oscillation Results from T2K

Patrick Dunne

Imperial College London



On behalf of the T2K collaboration

NEUTRINO 2020

XXIX INTERNATIONAL CONFERENCE ON NEUTRINO PHYSICS

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Imperial College London

T2K

Overview

- Brief introduction to T2K
- What's new this year
- Preliminary analysis results with all data taken to date
- Future developments
- Conclusions

What questions is T2K answering?

What are the precise values of θ_{23}, θ_{13} and Δm^2_{32}?

Is there significant CP violation in the neutrino sector?

What is the neutrino mass hierarchy?

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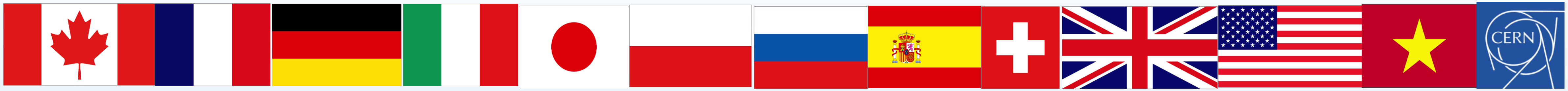
Theory implications

New source of CPV important in satisfying Sakharov conditions



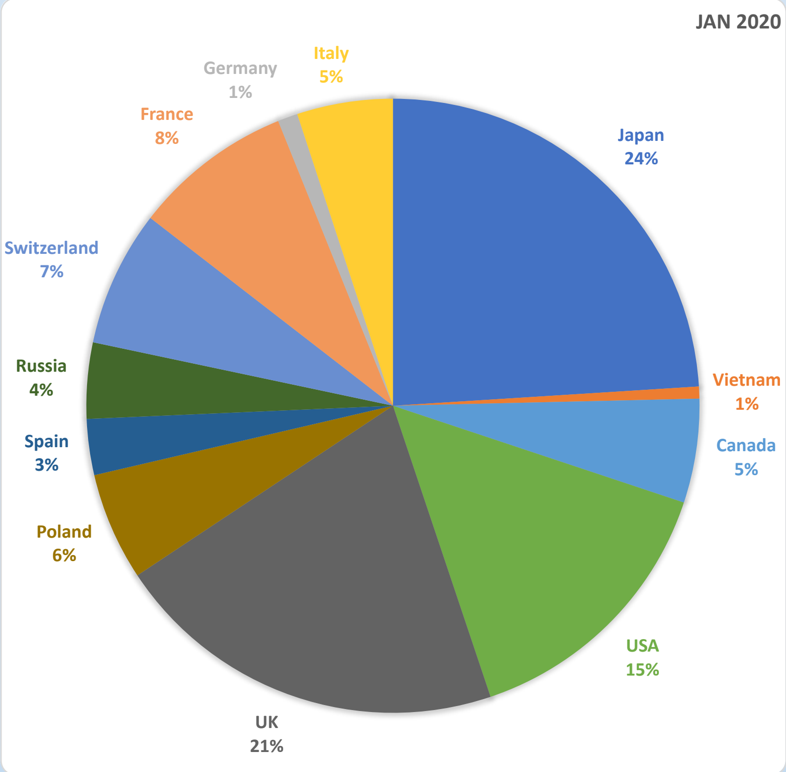
T2K Collaboration

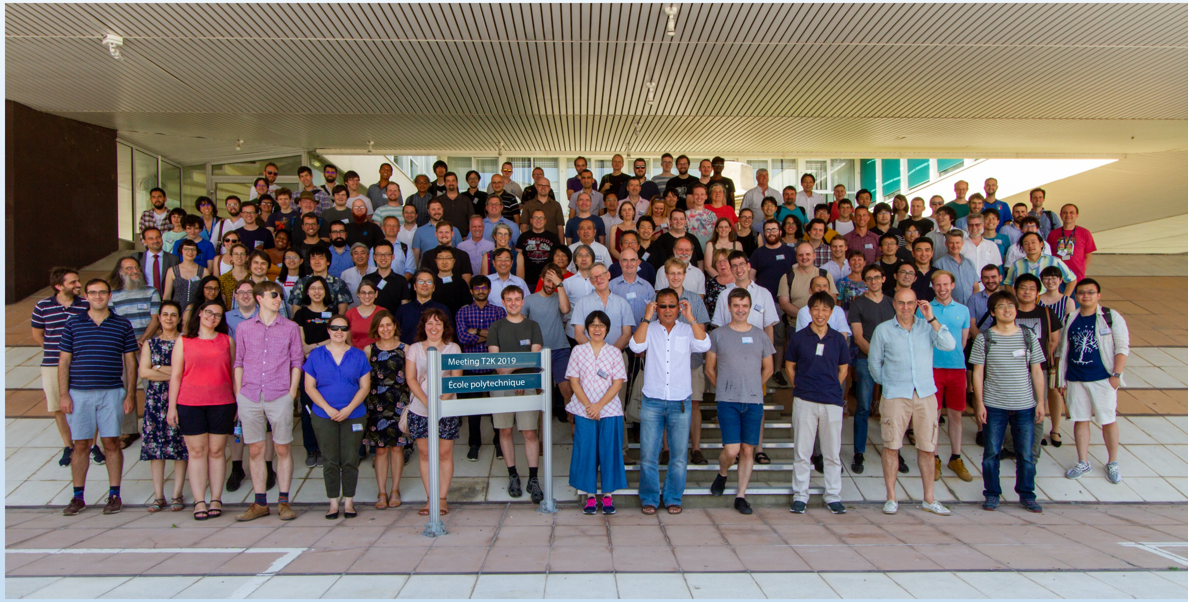
~500 members, 69 institutes, 12 countries

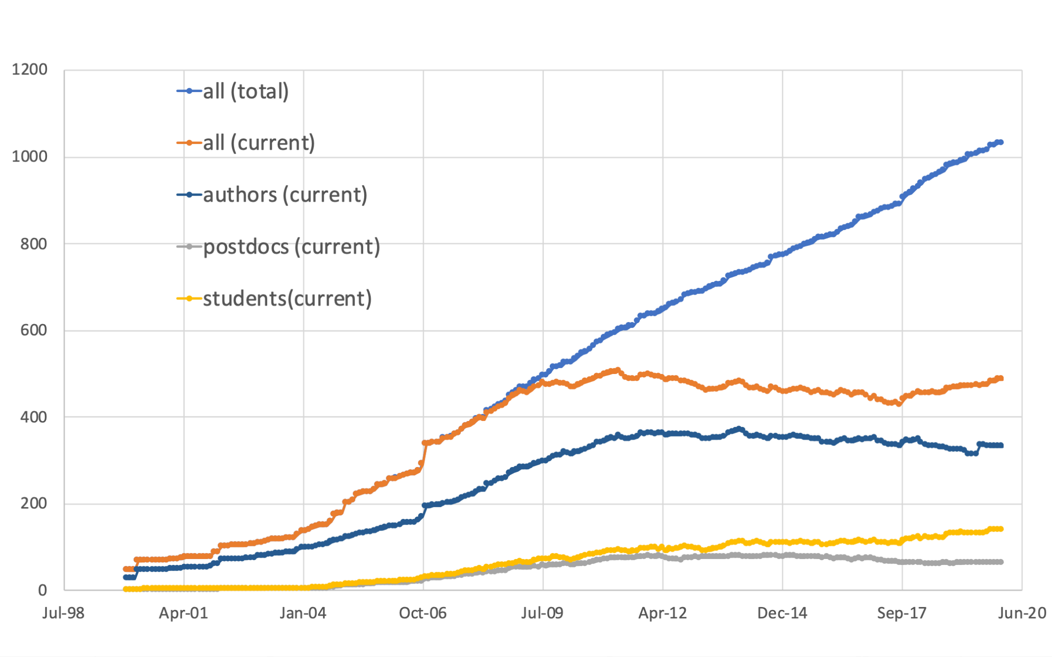
Asia	117
Japan	114
Vietnam	3

Americas	96
Canada	26
USA	70

Europe	262
France	40
Germany	5
Italy	24
Poland	27
Russia	19
Spain	14
Switzerland	34
UK	99

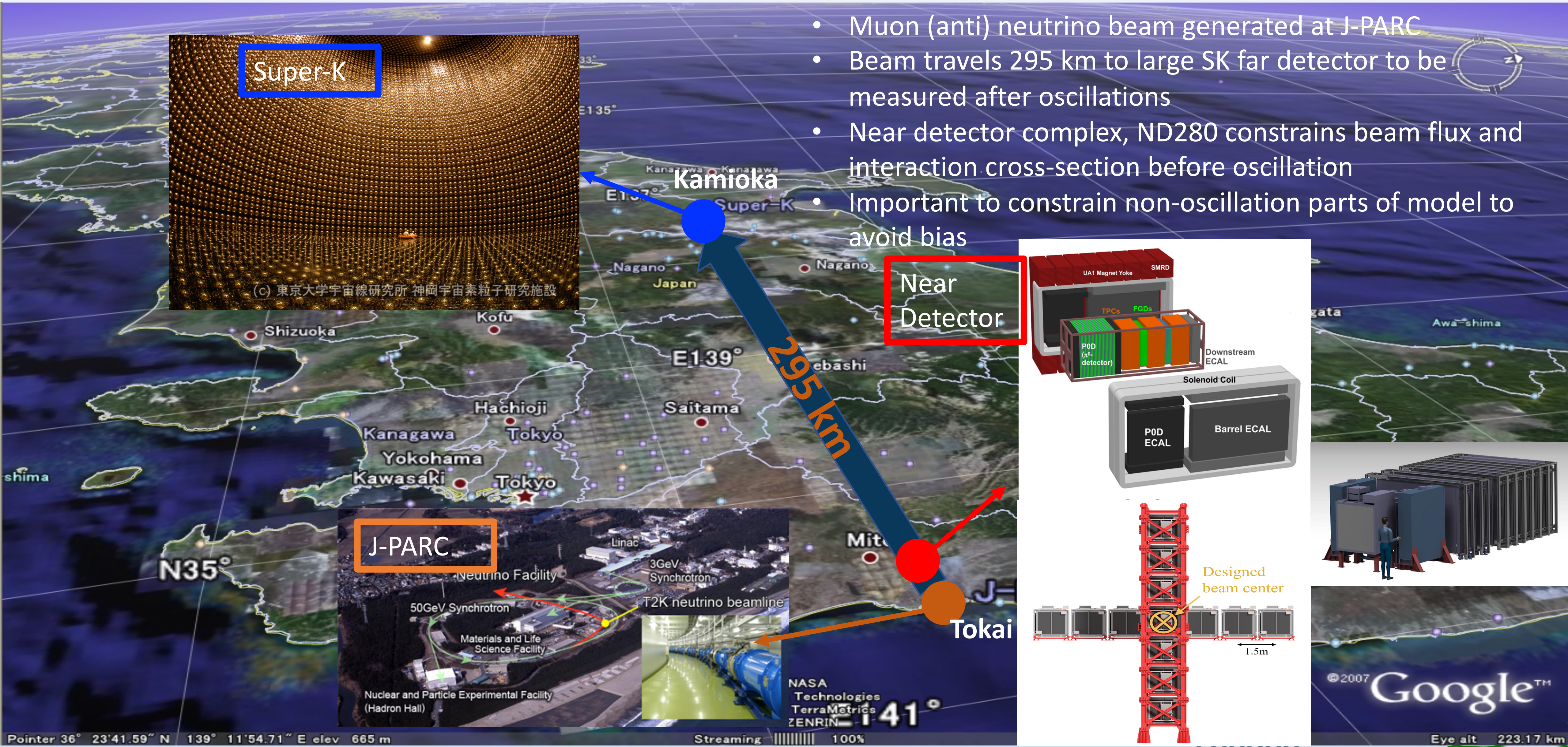




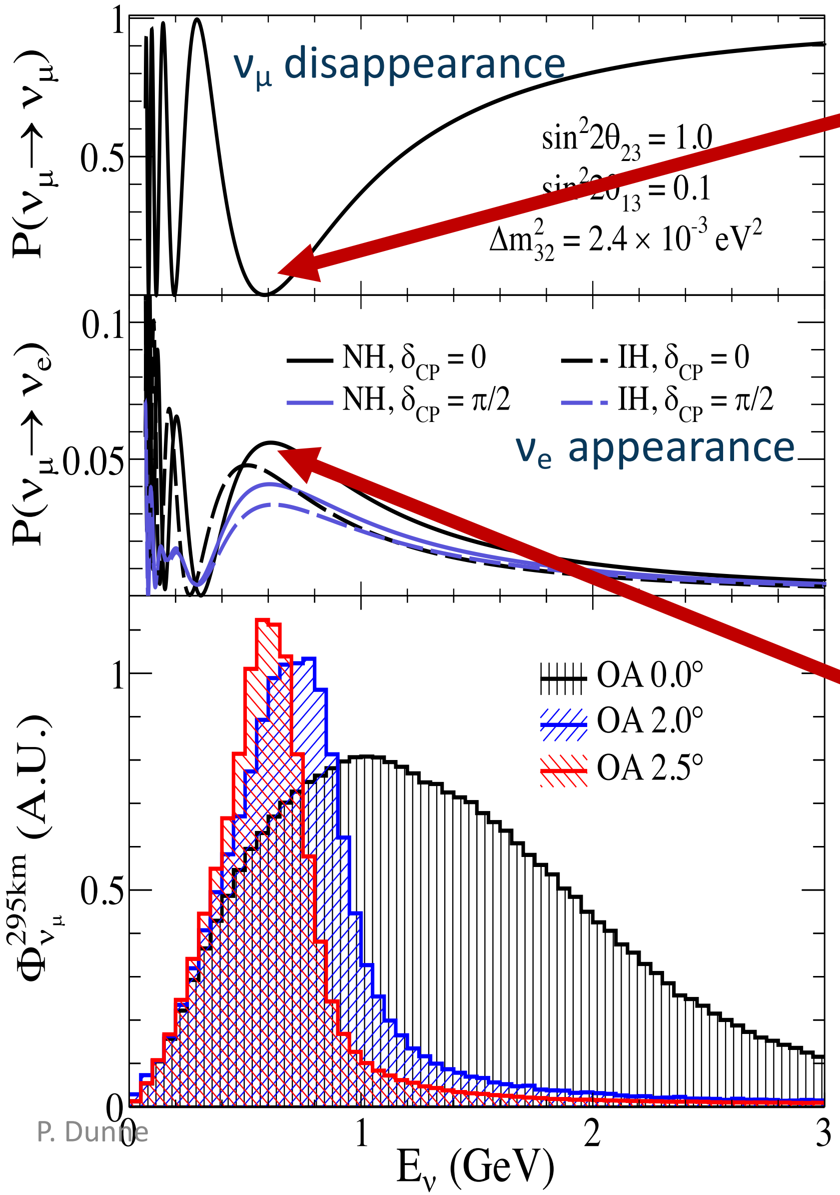


The T2K Experiment

- Muon (anti) neutrino beam generated at J-PARC
- Beam travels 295 km to large SK far detector to be measured after oscillations
- Near detector complex, ND280 constrains beam flux and interaction cross-section before oscillation
- Important to constrain non-oscillation parts of model to avoid bias

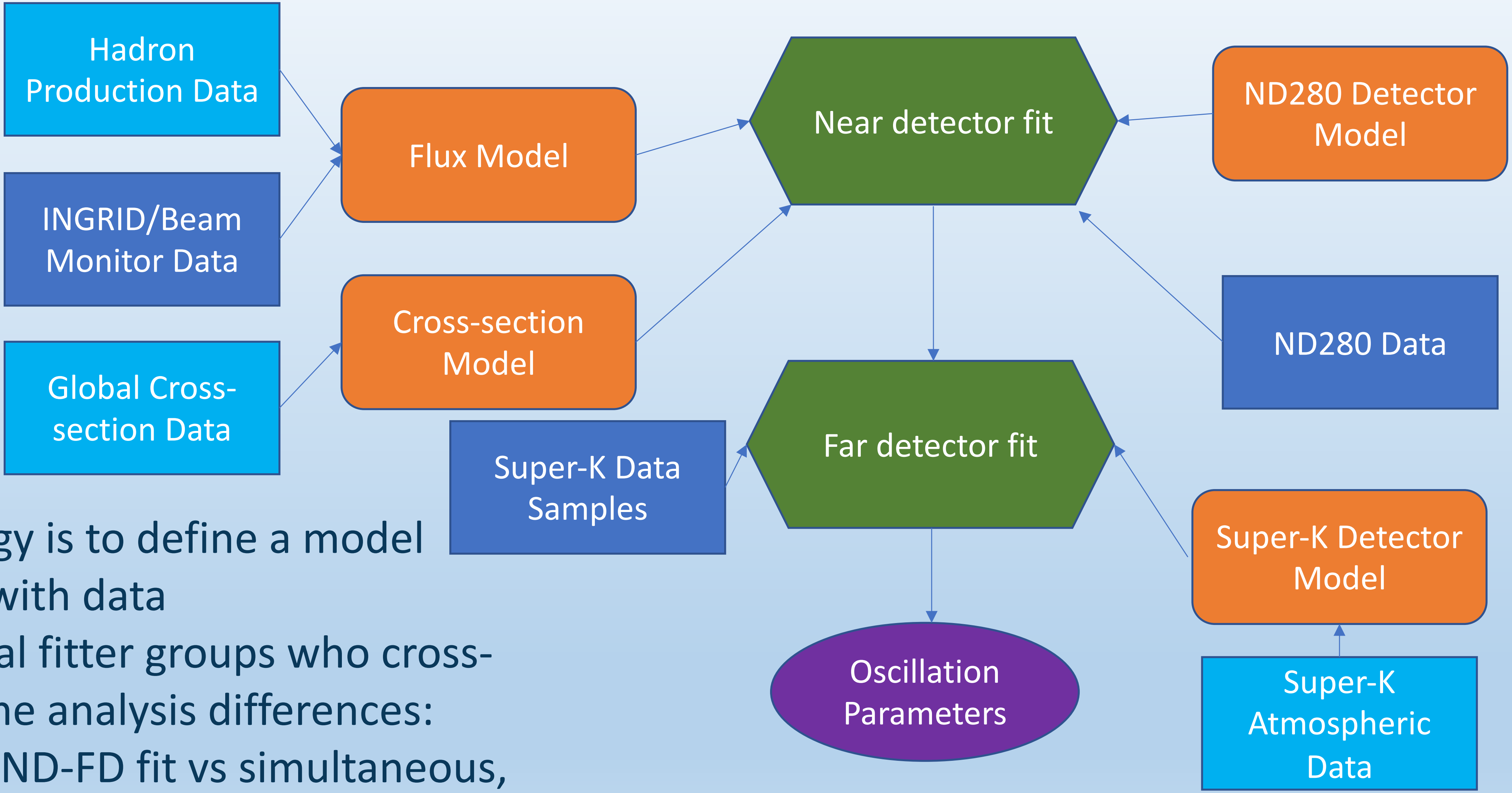


Neutrino oscillations at T2K



- Muon (anti)neutrino disappearance:
  - Location of dip determined by Δm^2_{32}
  - Depth of dip determined by $\sin^2(2\theta_{23})$
- Electron (anti)neutrino appearance:
  - Leading term depends on $\sin^2(\theta_{23})$, $\sin^2(\theta_{13})$ and Δm^2_{32}
  - Sub-leading δ_{CP} dependance (up to 45% on event rate)
    - $\delta_{CP} = \pi/2$: fewer neutrinos, more anti-neutrinos
    - $\delta_{CP} = -\pi/2$: more neutrinos, fewer anti-neutrinos
  - Matter effects give dependence on mass hierarchy (~10%)
- For 295km baseline first oscillation maximum is at 0.6 GeV, we use 2.5° off axis beam to focus flux at this energy

Fitting to data



- Analysis strategy is to define a model and constrain with data
- We have several fitter groups who cross-check with some analysis differences:
  - Sequential ND-FD fit vs simultaneous, Bayesian vs Frequentist, sample binning

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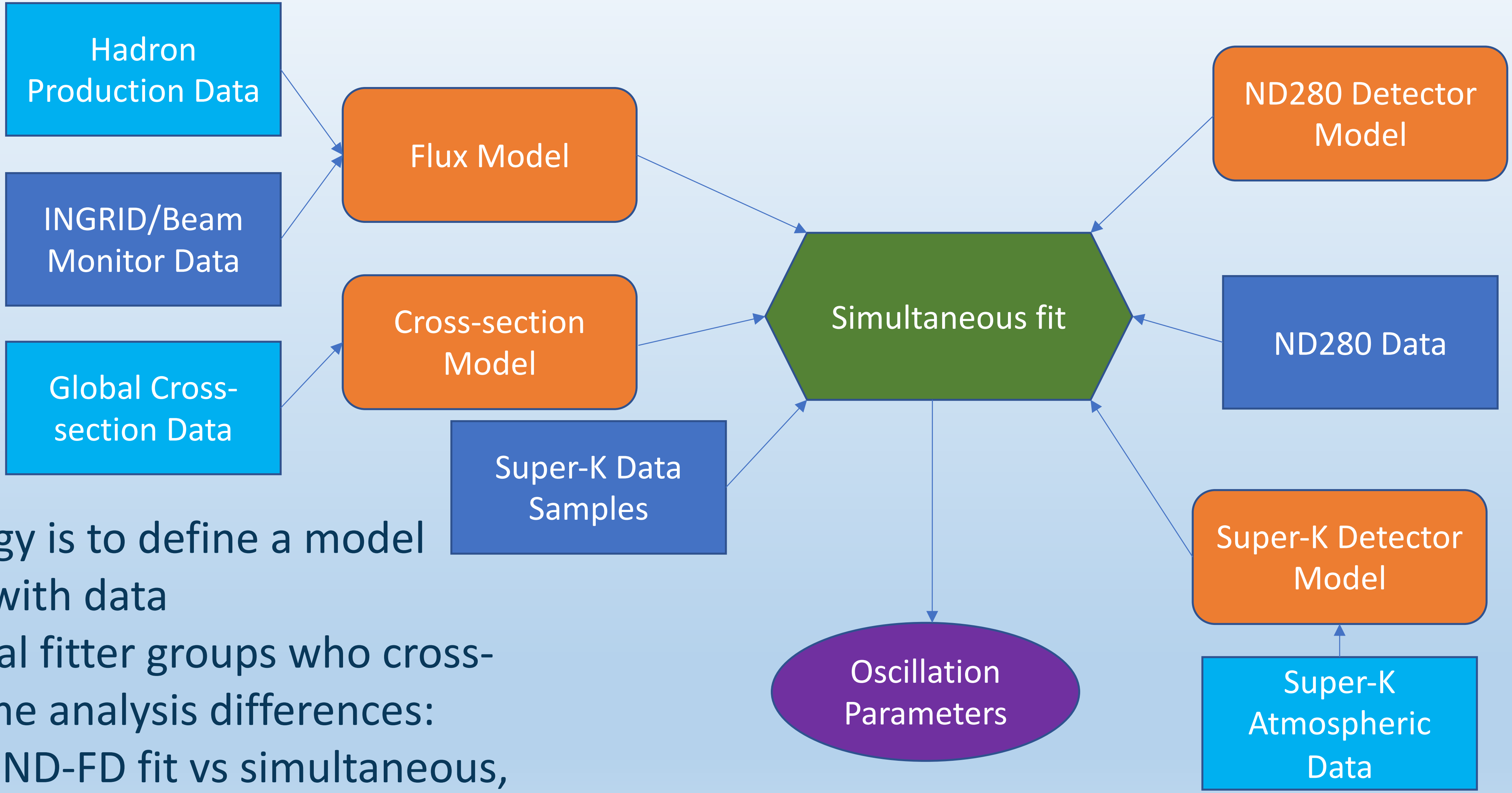
Fitting to data



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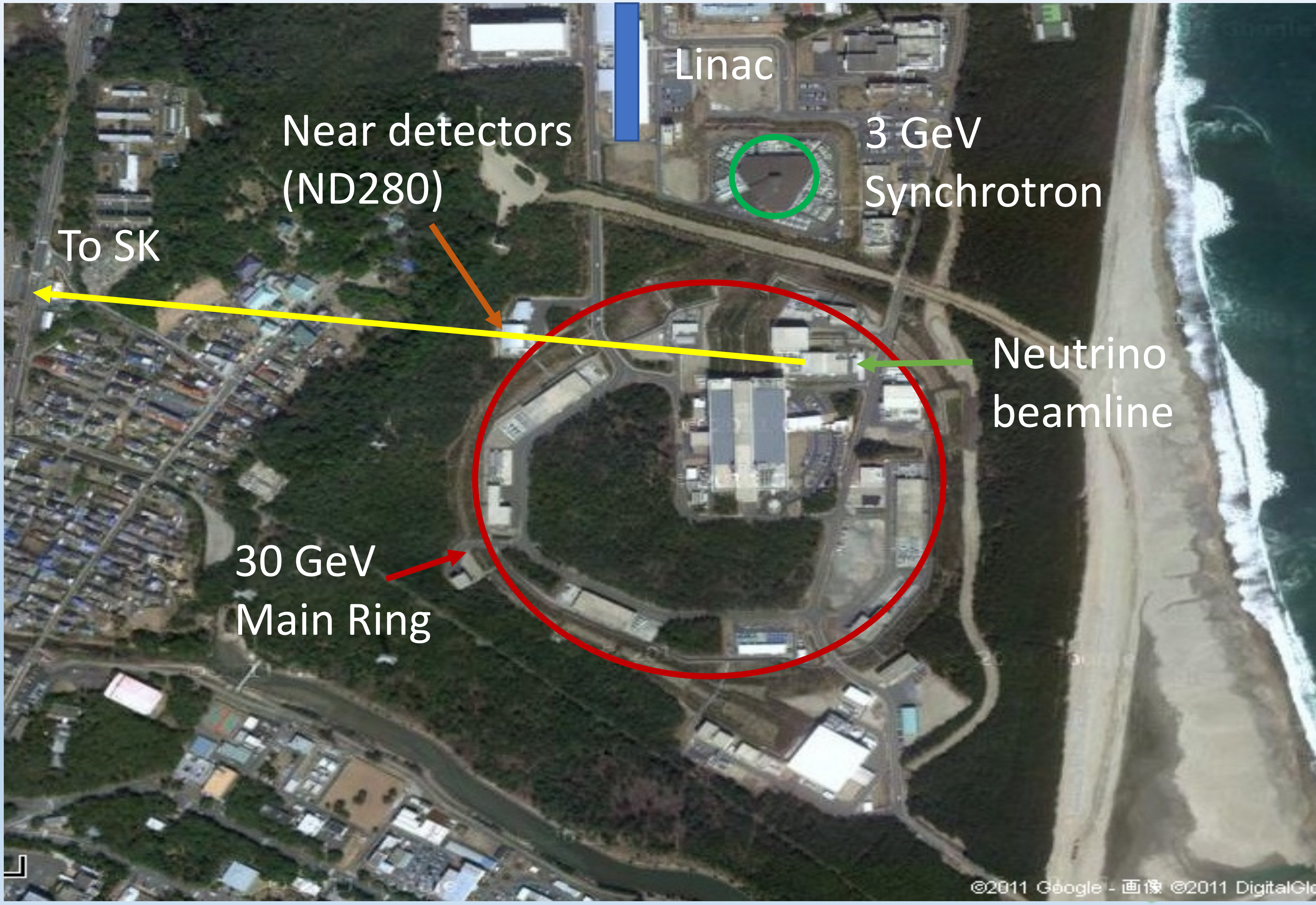
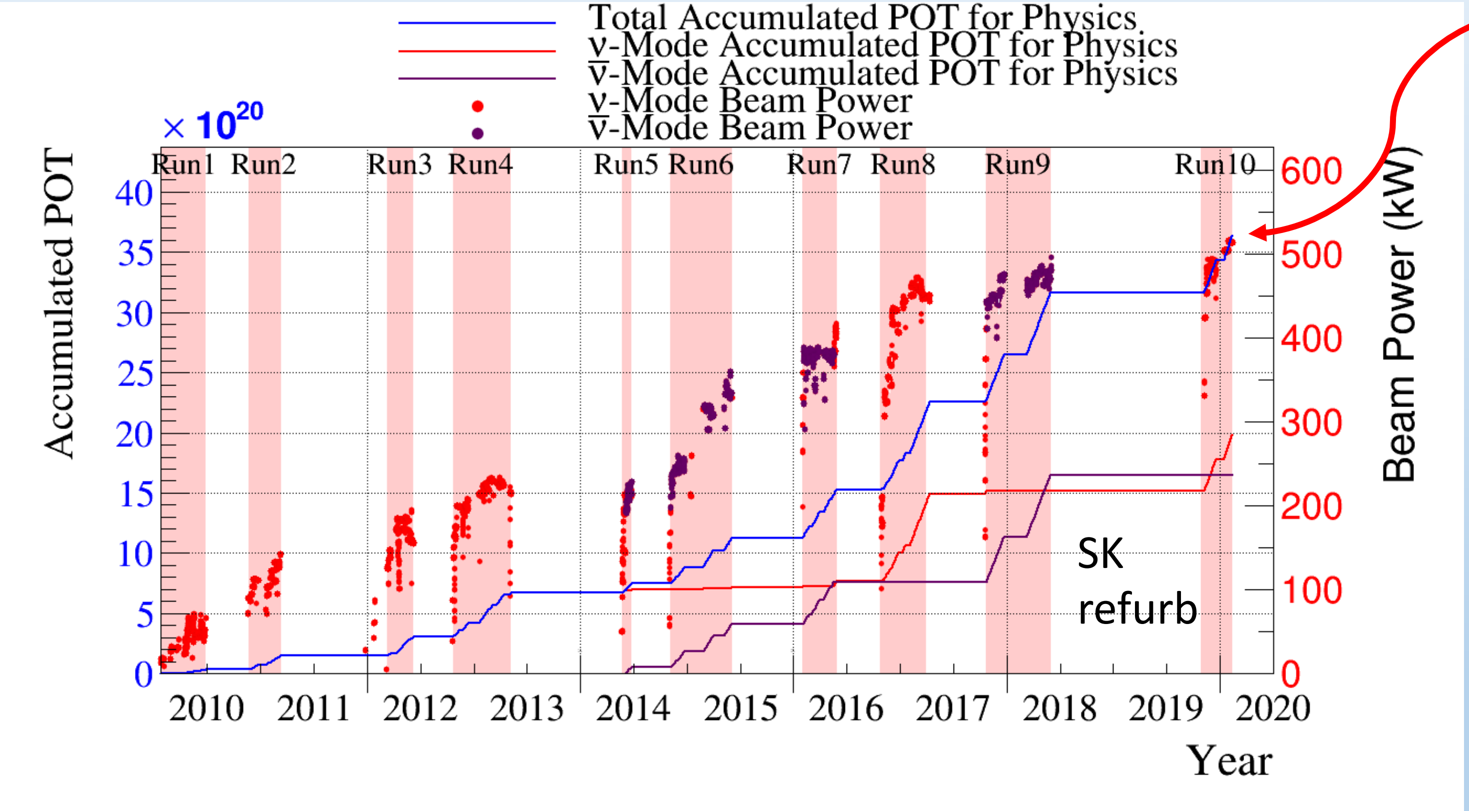
J-PARC and the T2K Beamline

- T2K beamline uses fast extraction from J-PARC main ring with a beam pulse every 2.5 seconds
- Main ring power supply upgrade next year will allow pulse every 1.3 seconds (see Sakashita-san's talk from Monday)



Data taken to date



- 515 kW stable operation achieved this year
- Has allowed an increase of 33% in ν-mode data since 2018
- Total of 1.97×10^{21} protons on target (POT) in ν-mode and 1.63×10^{21} in $\bar{\nu}$-mode

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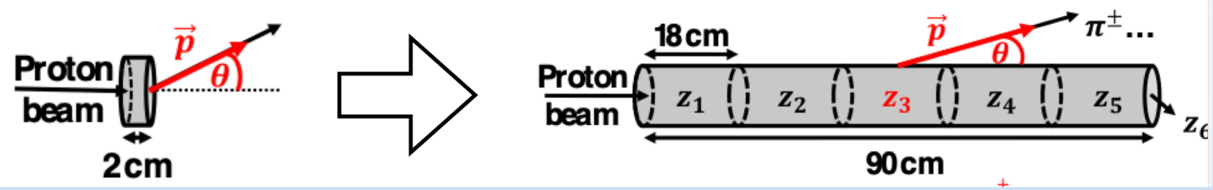
Neutrino flux modelling

- Primary interaction in target simulated with FLUKA
- We reweight this MC to match NA61/SHINE data



- Previous analyses used NA61/SHINE data taken with a thin graphite target
  - Initial pion production reweighted in momentum and angle to match data then subsequent propagation through target was simulated
- New for this year we use NA61/SHINE data with a replica of T2K's target [EPJC 76, 84 (2016)]
  - MC spectrum now reweighted to match data in momentum, angle and target exit point
- Allows significant reduction in input flux uncertainty on SK rate from ~8% to ~5%

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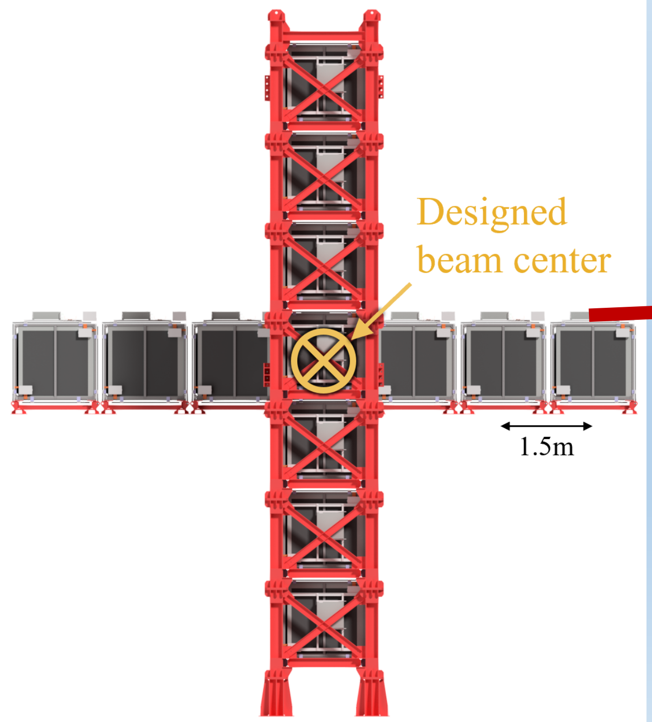
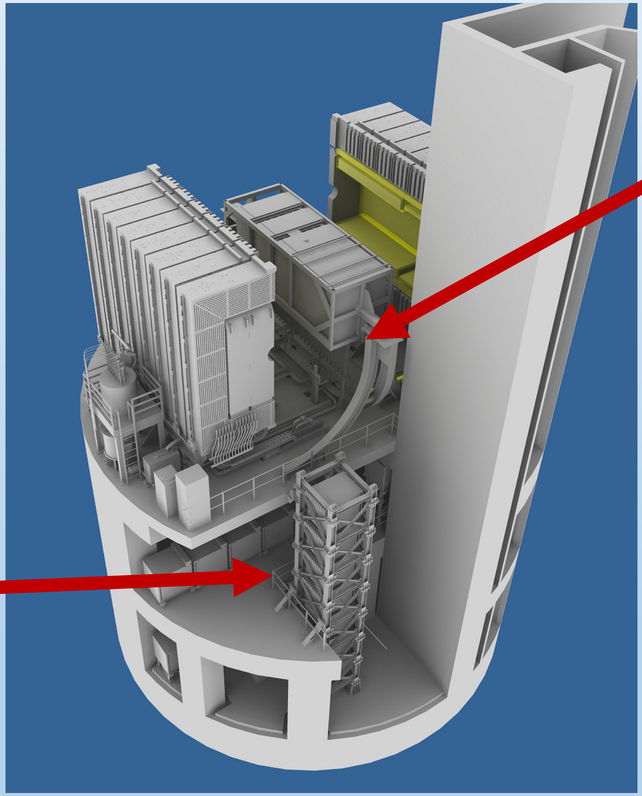
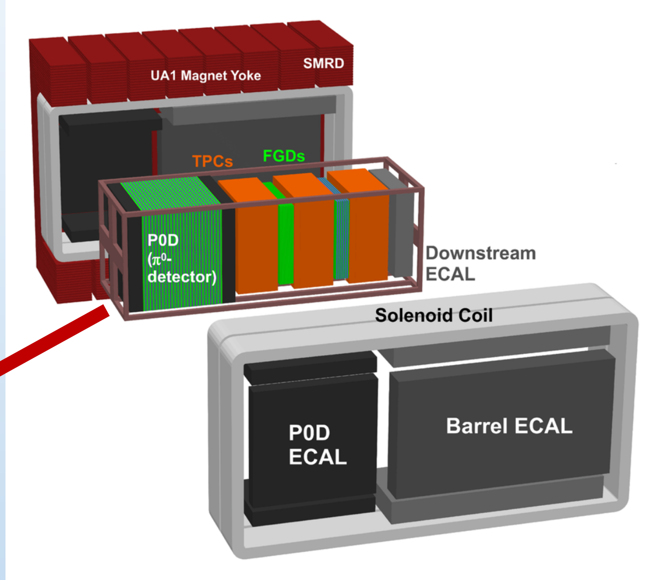
Near detectors used in oscillation analysis

INGRID

- On-axis detector
- Monitors beam direction and monitors stability



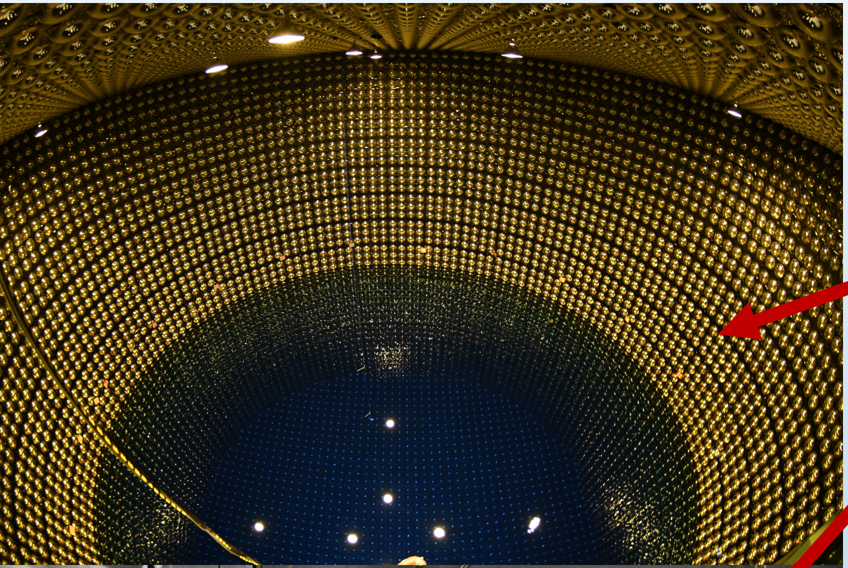




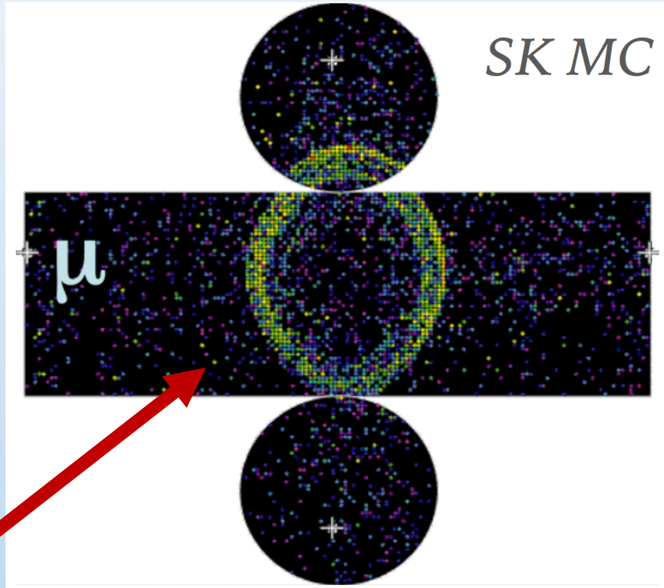
ND280

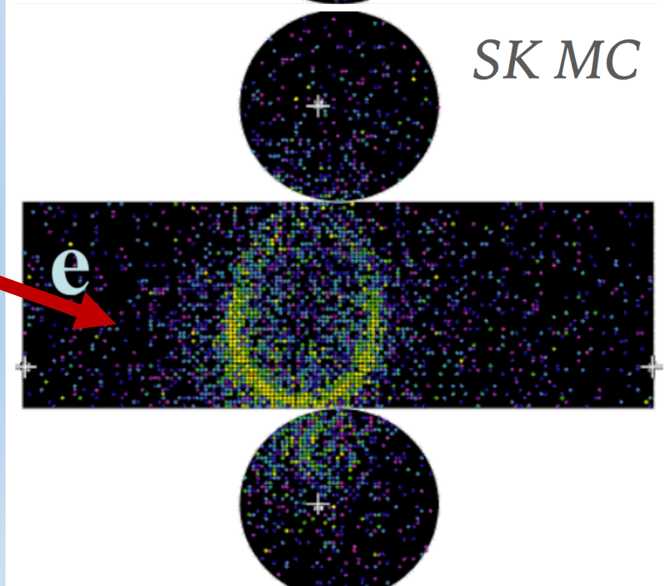
- Water and CH targets (2000 kg mass)
- Magnetized tracker to measure momentum and charge
- 2.5° off-axis (same as Super-K)
- Constrains cross-section and flux uncertainty model

Super-K



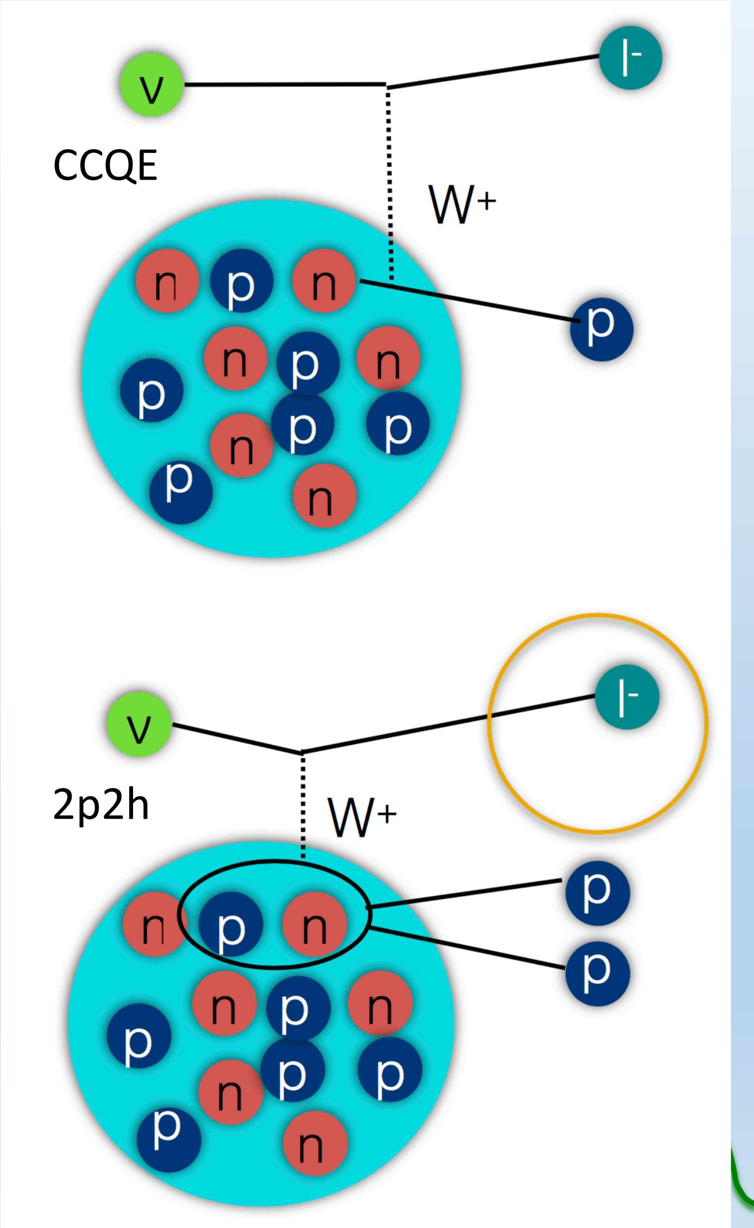
- 50 kt water-Cherenkov detector
- 11,000 20" PMT inner detector
  - 40% photo-coverage
- 2,000 8" PMT outer detector
  - Cosmic veto/exiting particles
- Particle ID via Cherenkov ring pattern:
  - Muons produce sharp rings
  - Electrons scatter more → fuzzier rings
- No charge identification





Neutrino interaction modelling

- At T2K's approximately 0.6 GeV neutrino energy, CCQE dominates plus significant multinucleon '2p2h' and resonant CC1π
- Significant update to interaction model (NEUT 5.4.0):
  - CCQE nuclear initial state model moved from Relativistic Fermi gas [Phys.Rept. **3** 261] plus RPA [Phys. Rev. C **83**, 045501] to tuned spectral function [Nuc. Phys. A **579**, 493]
  - Now treat removal energy as shift in lepton momentum, with smaller uncertainty from better understanding of removal energy in spectral function
  - Generally improved sophistication e.g. new 2p2h energy dependence uncertainty, correlated FSI errors between near and far detector and improved DIS uncertainties



ND280 samples and selection

- ND280 constrains cross-section and flux uncertainties
  - Using twice as much data for this analysis: $1.15\text{x}10^{21}$ ($8.34\text{x}10^{20}$)POT in ν-mode ($\bar{\nu}$-mode)
- Separate samples for CH target FGD1 and CH/Water target FGD2
  - Allows constraint of both Carbon and Oxygen interactions

	FGD1			FGD2		
ν events in neutrino mode	CC0π	CC1π	CCNπ	CC0π	CC1π	CCNπ
$\bar{\nu}$ events in antineutrino mode	CC0π	CC1π	CCNπ	CC0π	CC1π	CCNπ
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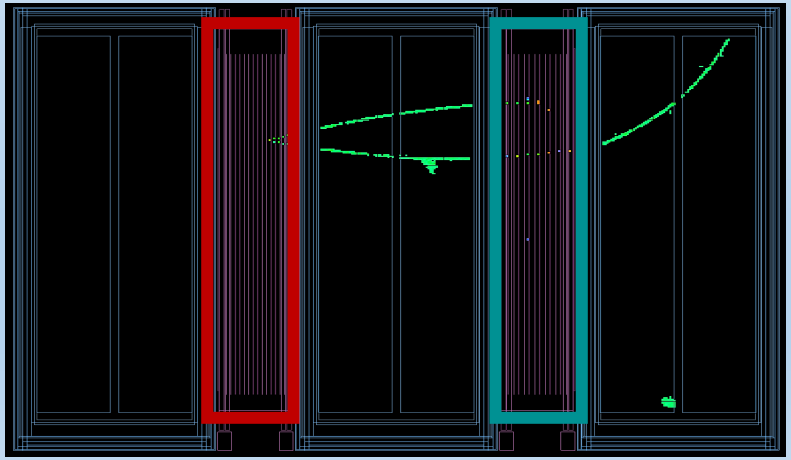

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  - 0π, 1π and $N\pi$ samples enriched in CCQE, resonant and other interactions respectively

	FGD1			FGD2		
ν events in neutrino mode	$CC0\pi$	$CC1\pi$	$CCN\pi$	$CC0\pi$	$CC1\pi$	$CCN\pi$
$\bar{\nu}$ events in antineutrino mode	$CC0\pi$	$CC1\pi$	$CCN\pi$	$CC0\pi$	$CC1\pi$	$CCN\pi$
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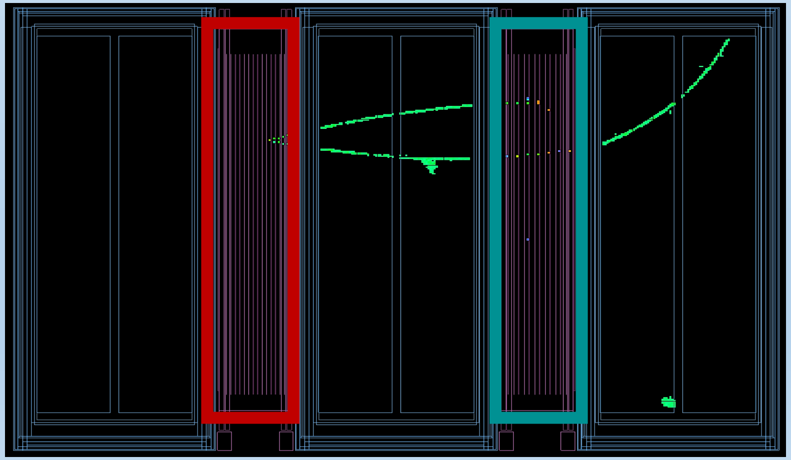

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- Samples to measure wrong-sign background

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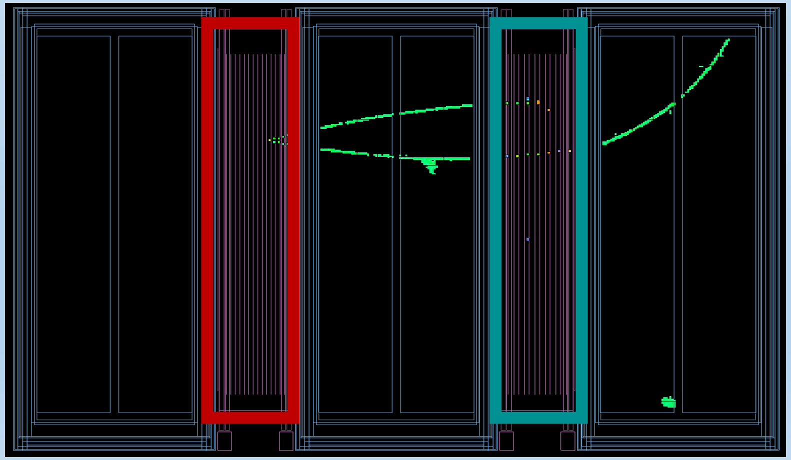

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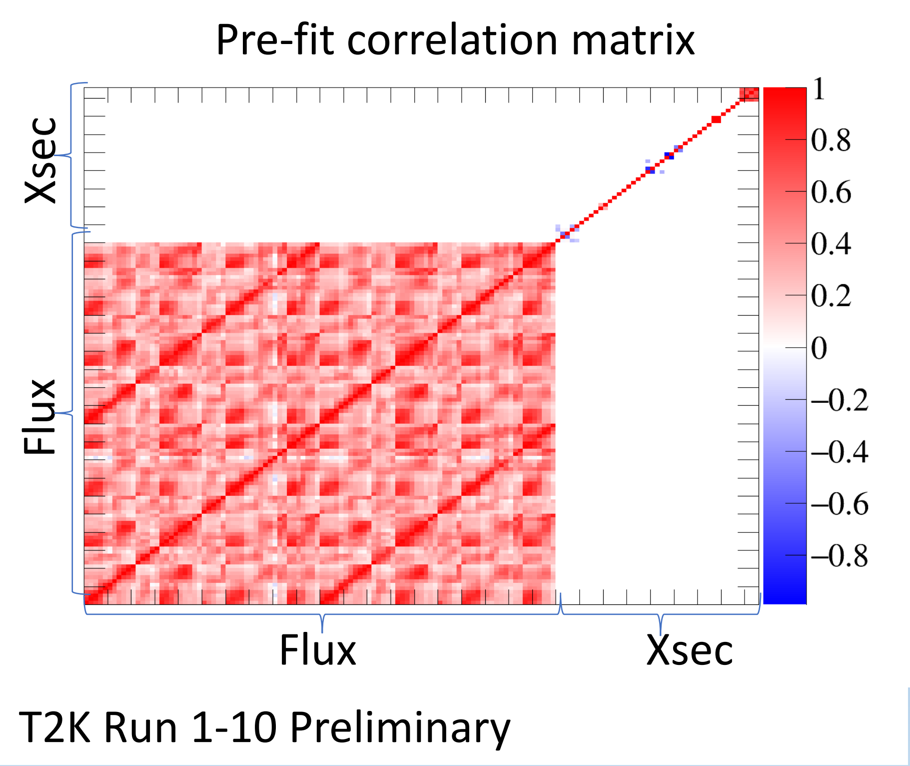
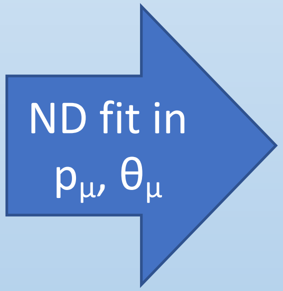
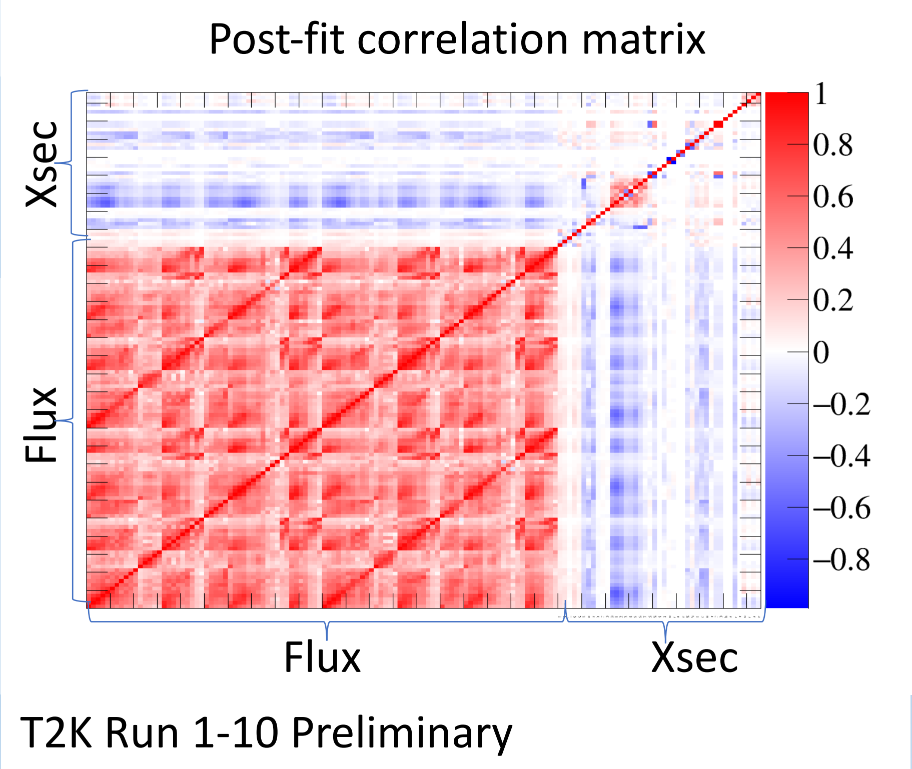
ND fits

- ND fit constrains predicted number of events, which introduces large anticorrelations between flux and cross-section uncertainties
  - Pre-fit uncertainty on SK CC0π electron neutrino event rate goes from 13.0% to 4.7%







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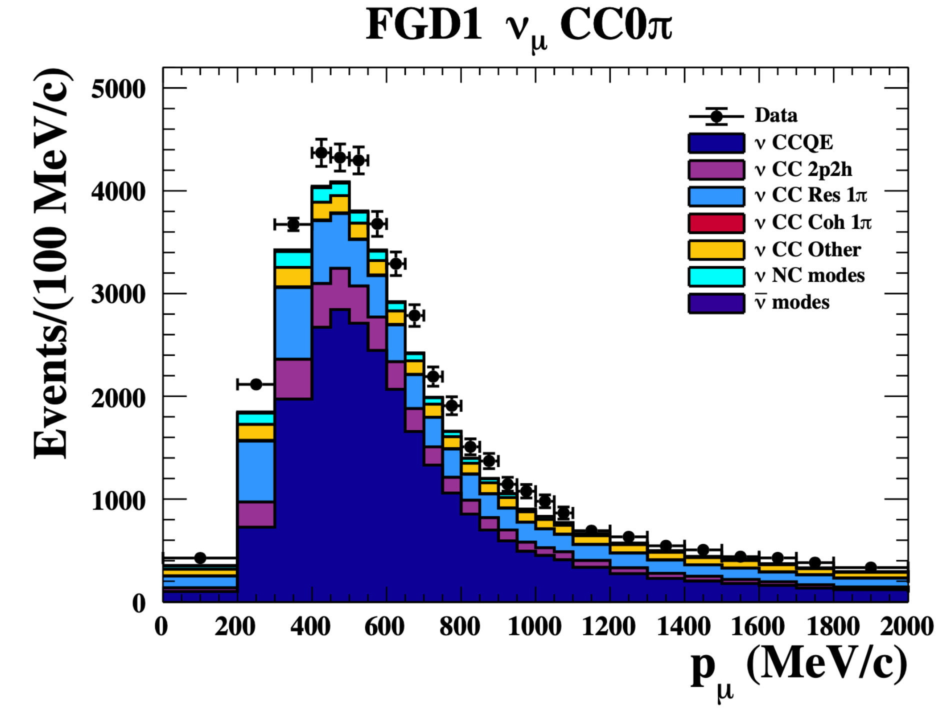
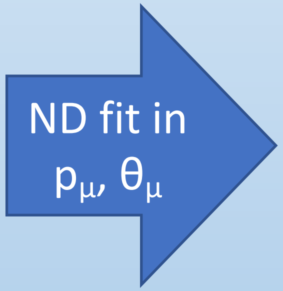
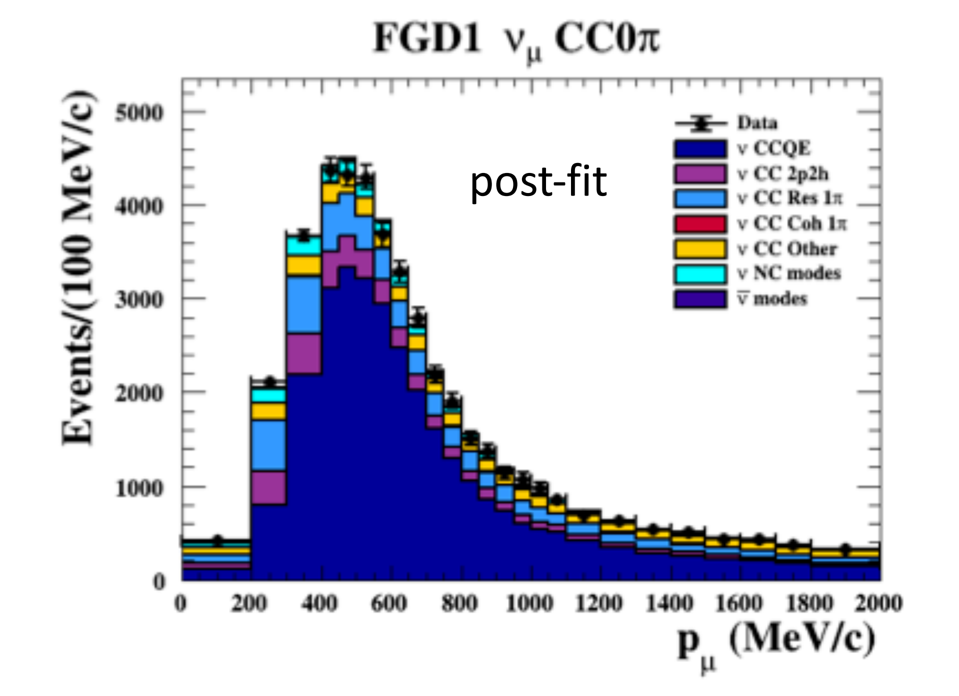
ND fits

- ND fit constrains predicted number of events, which introduces large anticorrelations between flux and cross-section uncertainties
- Our model is a good fit to data (prior model p-value=74%)



T2K Run 1-10 Preliminary

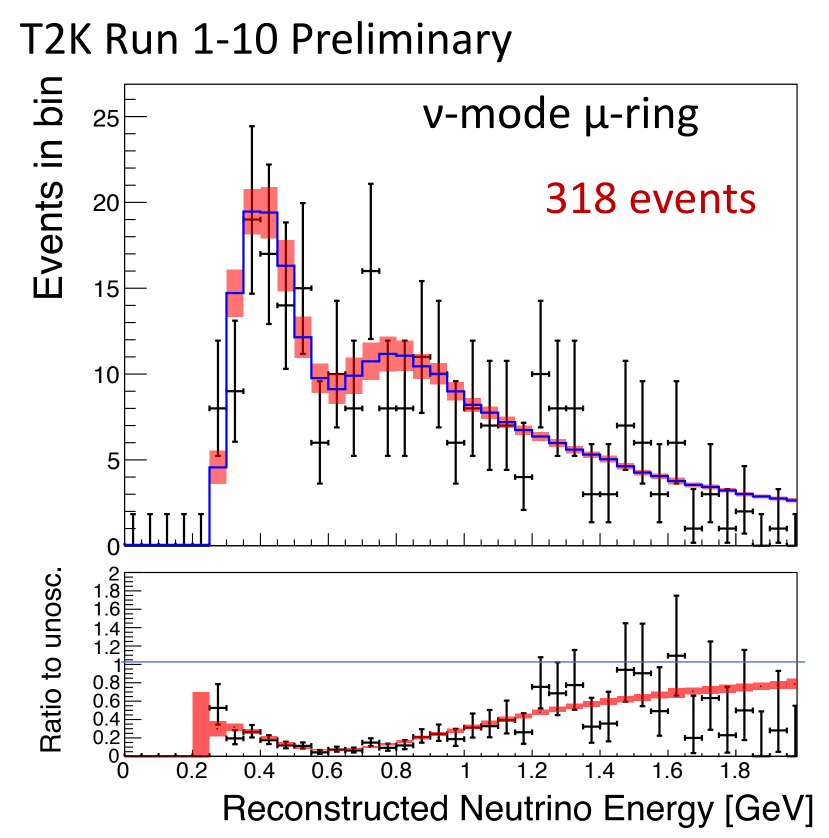


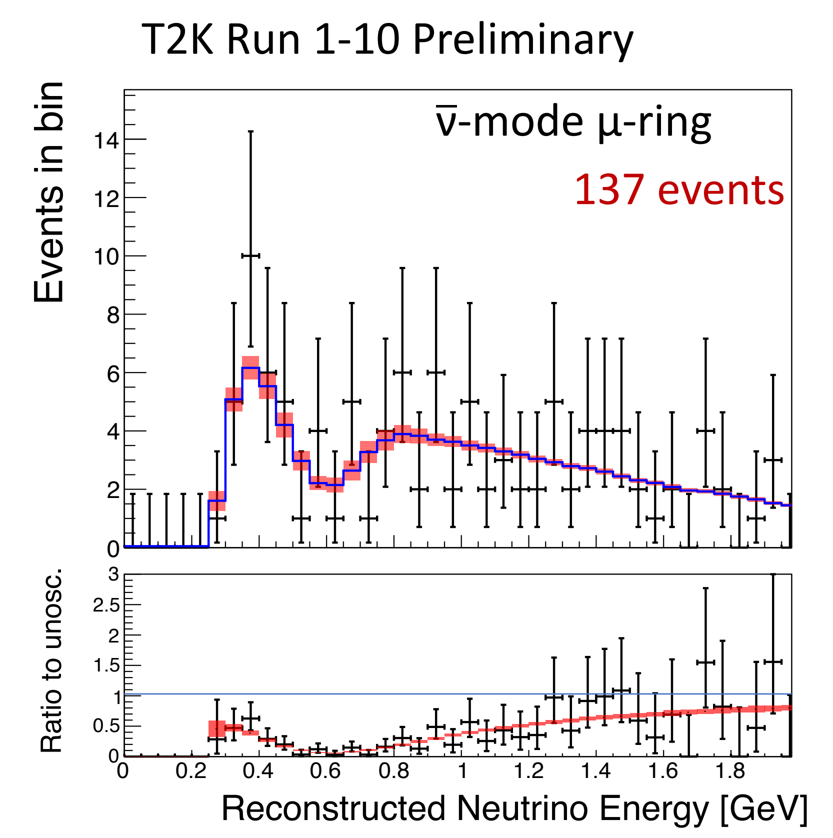


T2K Run 1-10 Preliminary

SK event samples

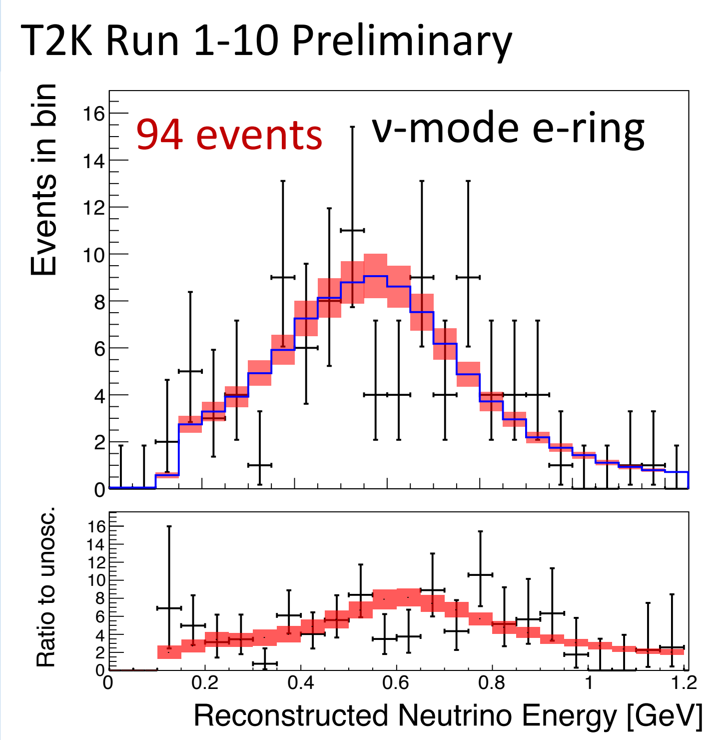
- Two samples with μ-like rings (one in ν-mode, one in ν̄-mode)
- Systematic uncertainty (red band) on rate is 3.0 (4.0)% in ν-mode (ν̄-mode)

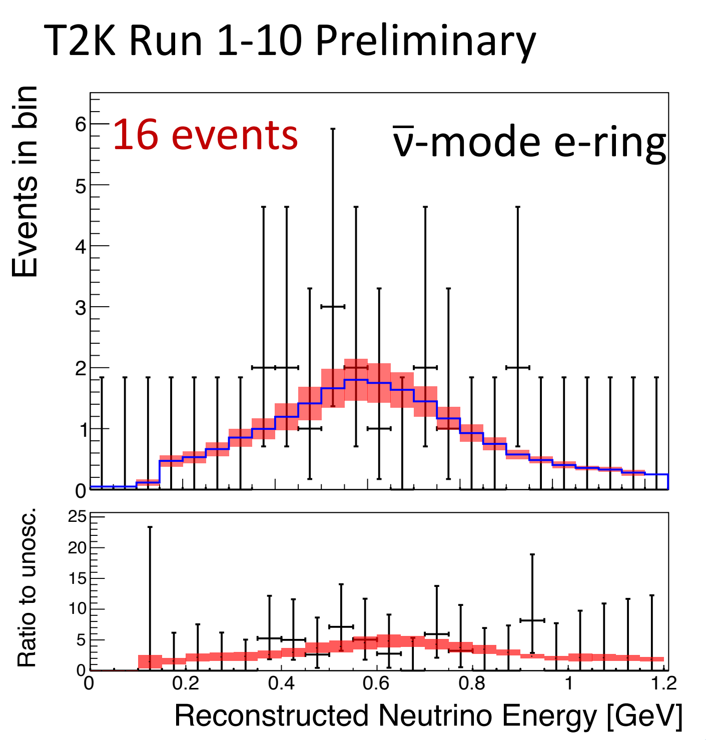


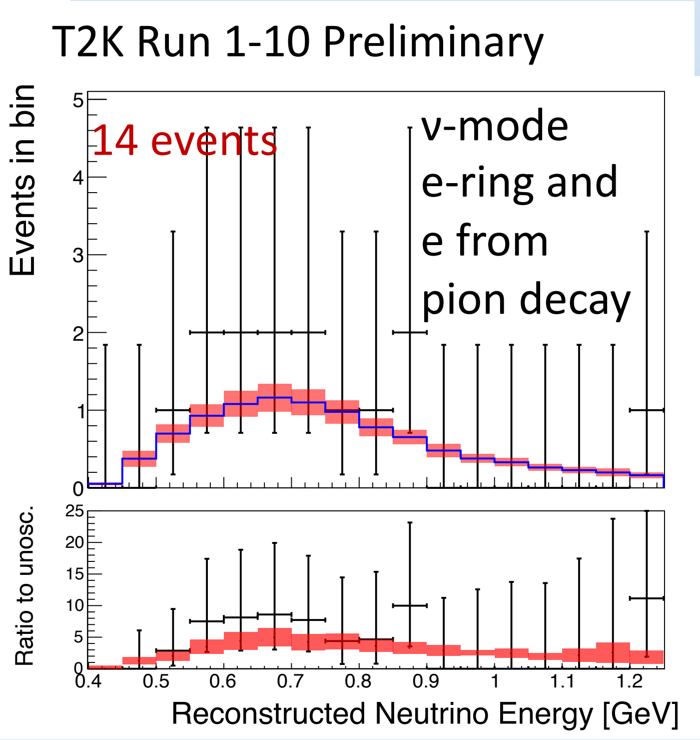


SK event samples

- Three samples with e-like rings
  - Two with e-ring only in ν-mode and ν̄-mode targeting CC0π events
  - One with Michel electron from π decay targeting CC1π events
- Uncertainty on rate is 4.7-5.9% in CC0π samples and 14.3% for CC1π

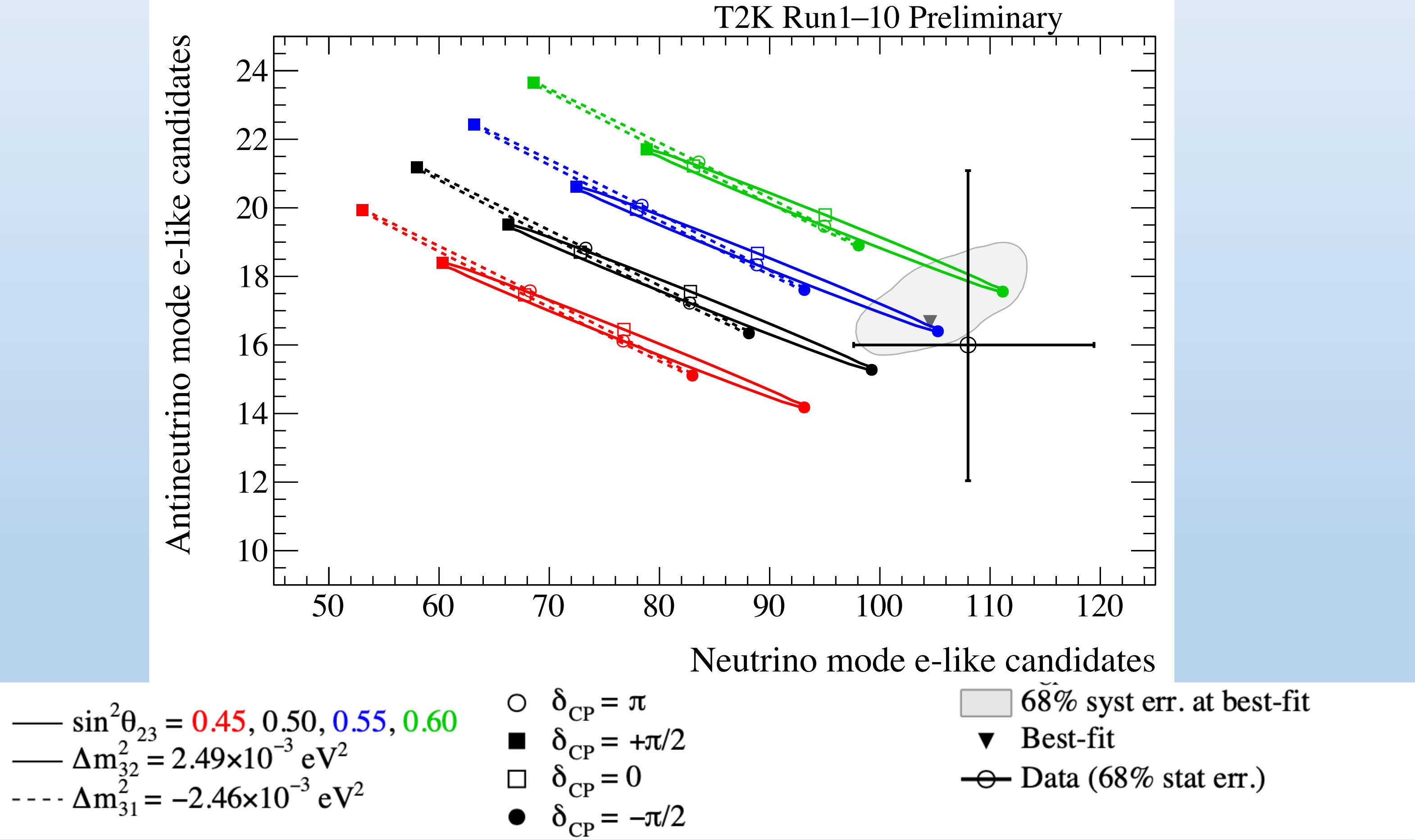


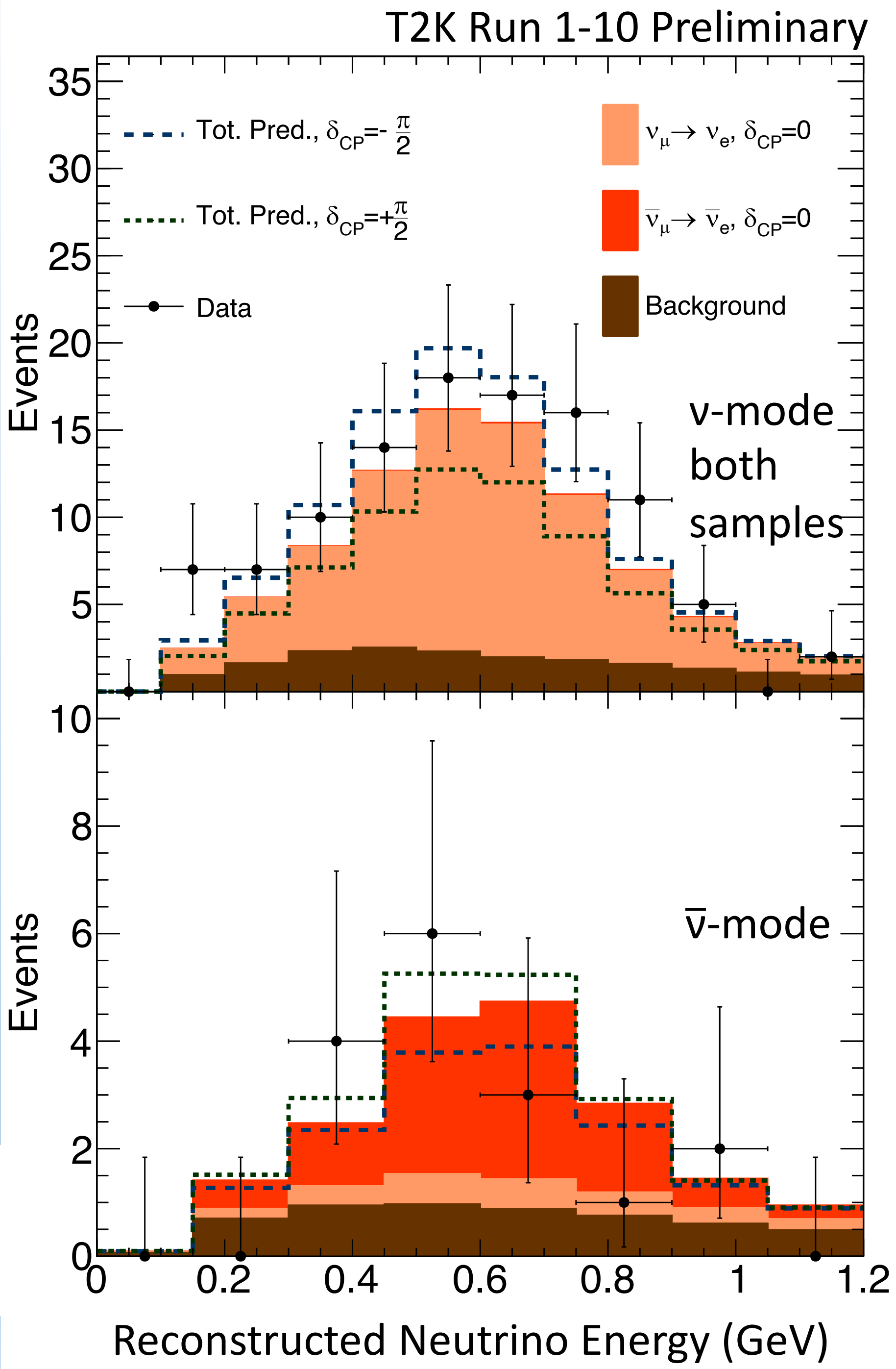




SK event samples

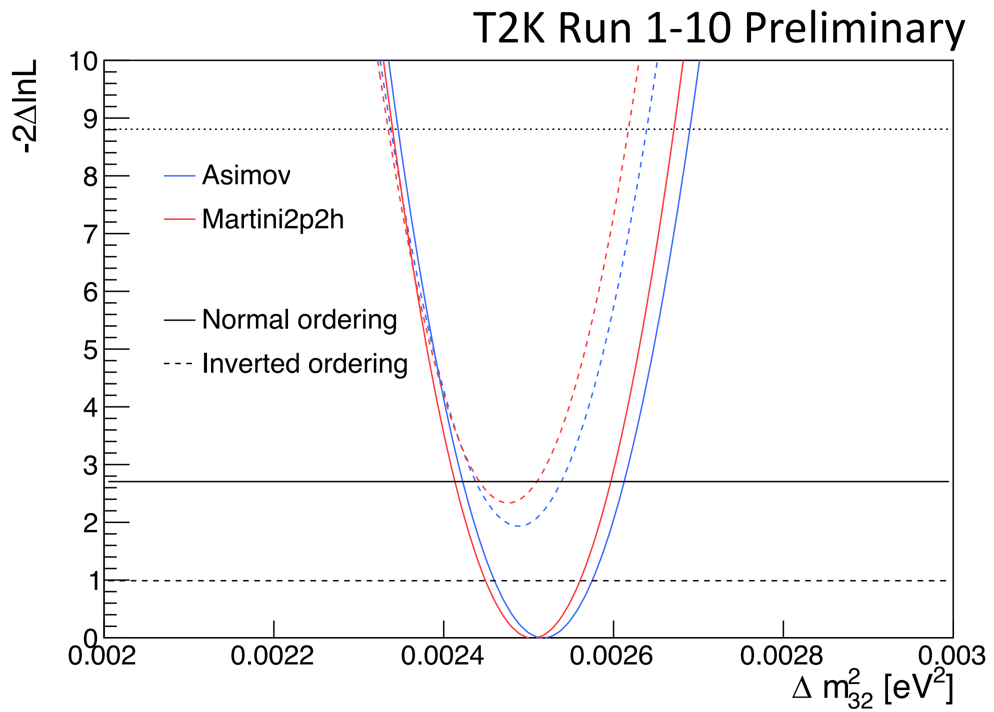
- O(45%) change in electron-like event rate between $\delta_{CP}=+\pi/2$ and $\delta_{CP}=-\pi/2$

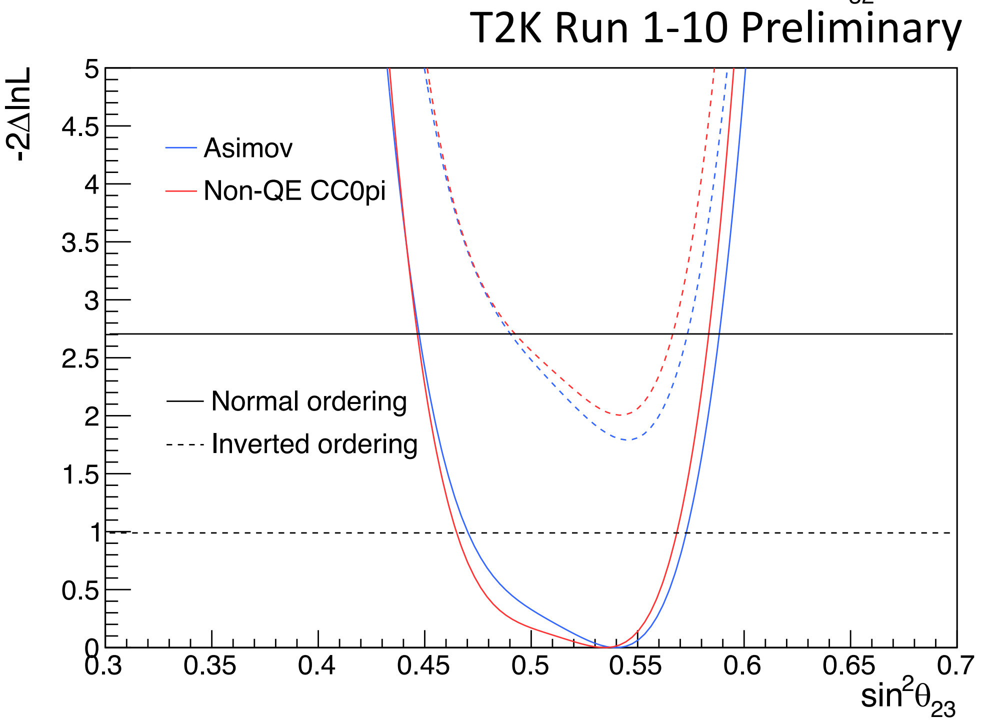




Robustness studies

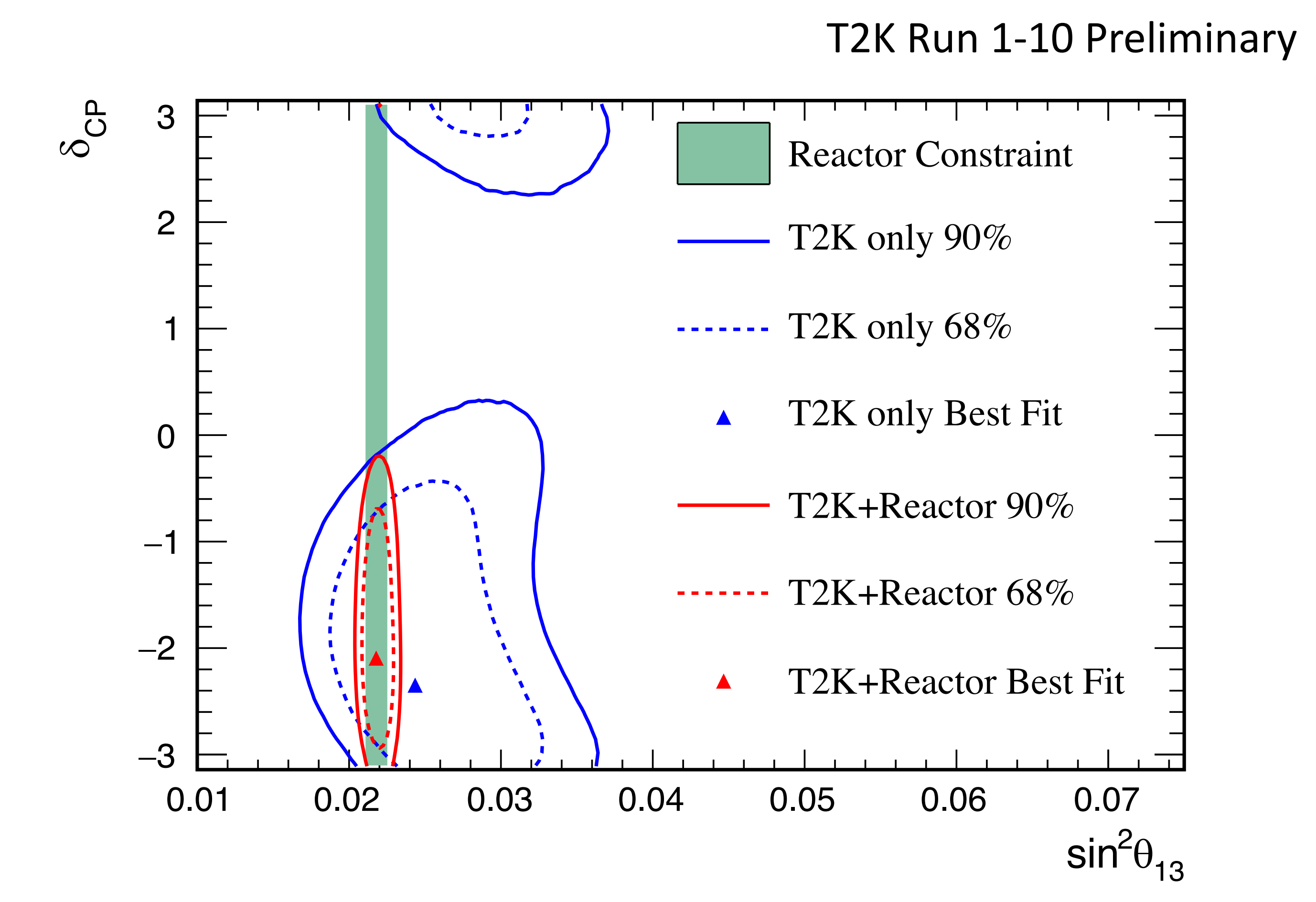
- We test our uncertainty model by fitting data simulated with alternate interaction models and checking for parameter bias
- No significant biases seen on θ_{23}, θ_{13} or δ_{CP} from any of these alternate models
  - Small bias seen on Δm^2_{32} so an additional uncertainty of $1.4\text{x}10^{-5}$ was added to account for this
- New nuclear removal energy systematic uncertainty has reduced previously large bias due to this effect significantly





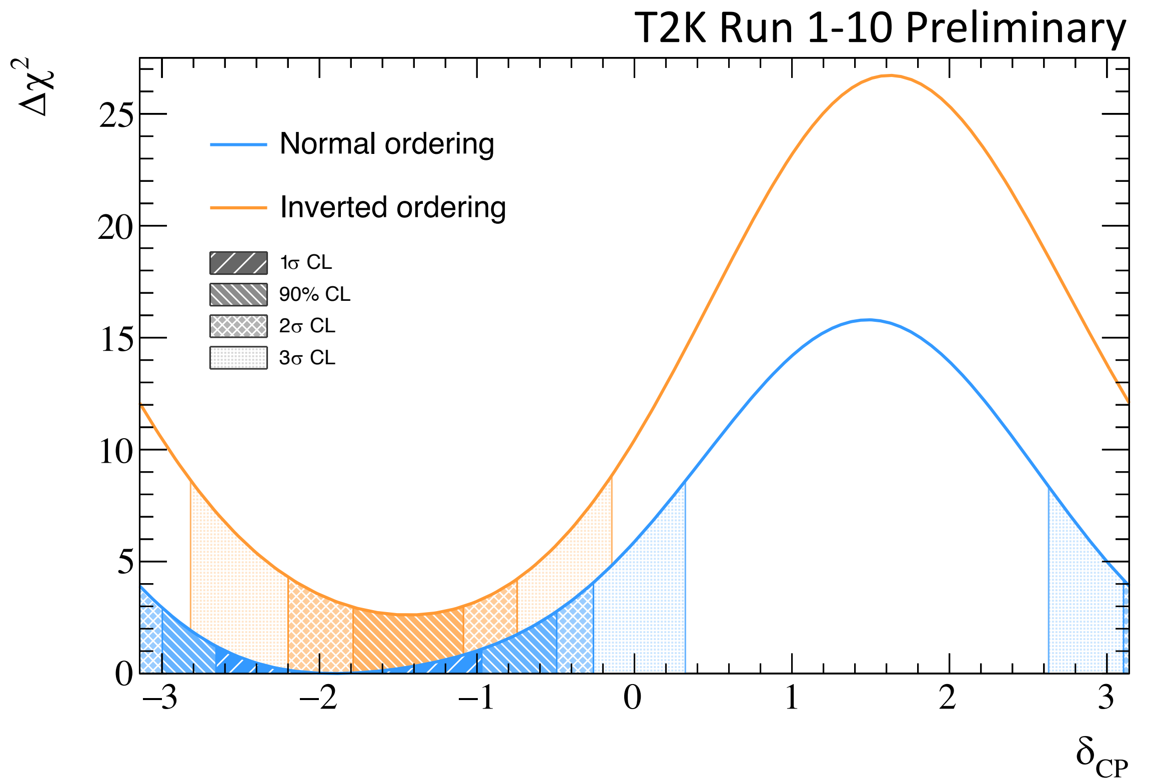
δ_{CP} vs θ_{13}

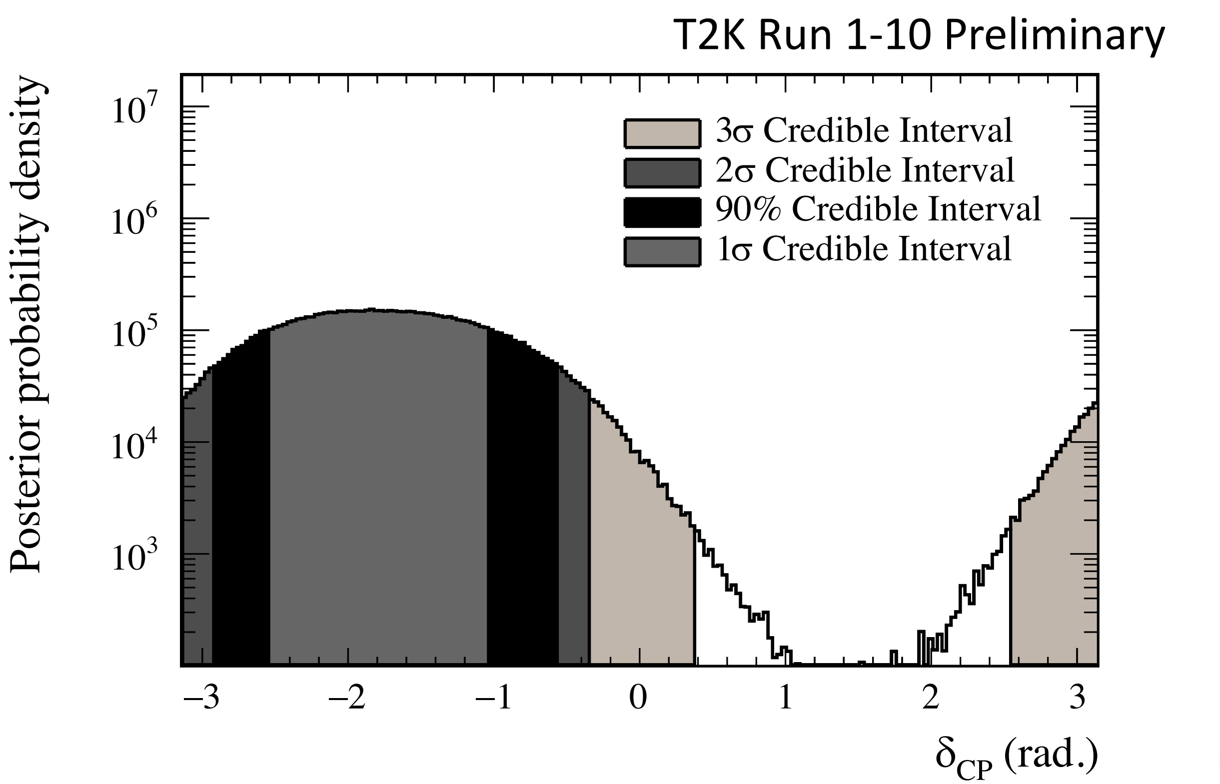
- We produce results with T2K data alone and using PDG2019 constraint on θ_{13} from reactor experiments
- T2K only intervals are compatible with PDG2019 θ_{13} values at better than 1σ
- Results from here on are with reactor constraint



1D δ_{CP}

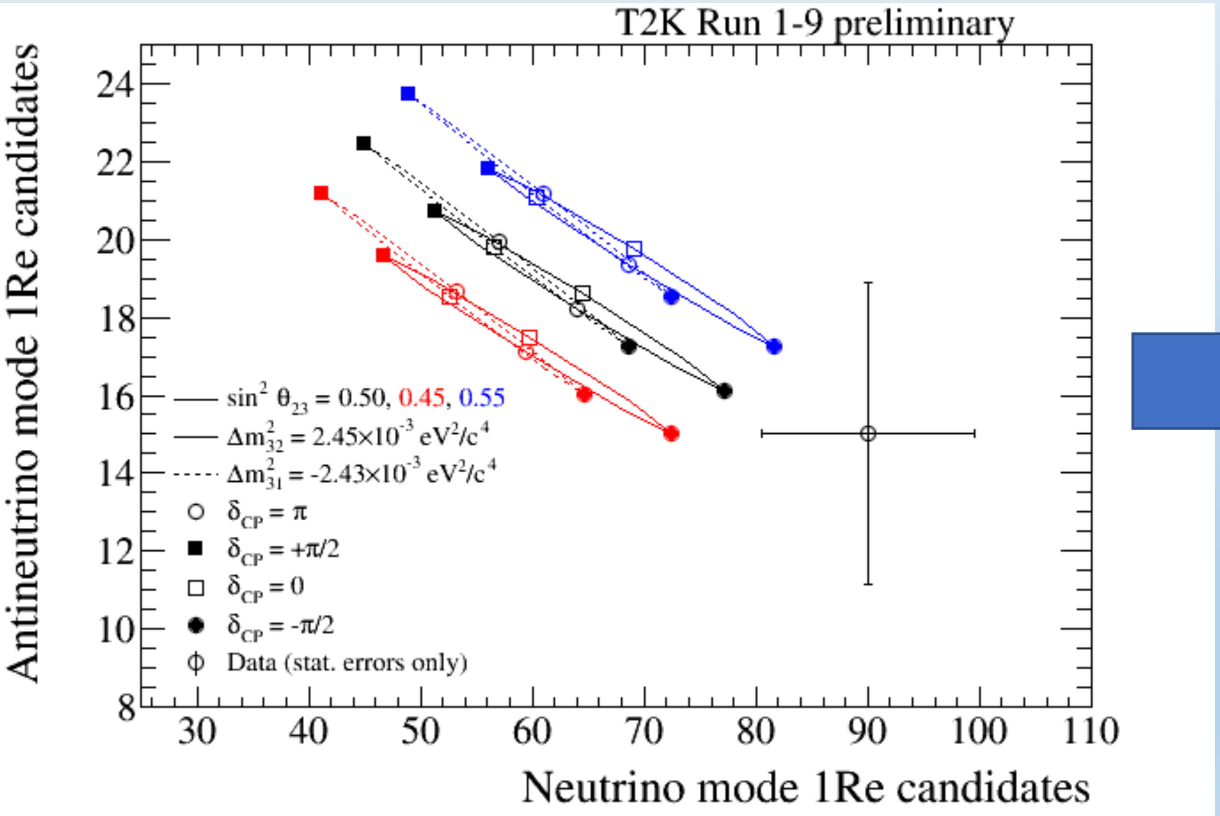
- 35% of values excluded at 3σ marginalized across hierarchies
- CP conserving values $(0,\pi)$ excluded at 90% but π not quite at 2σ
- Largest $\Delta\chi^2$ change seen in any of our robustness studies would cause left (right) edge of 90% interval to move by 0.073 (0.080)

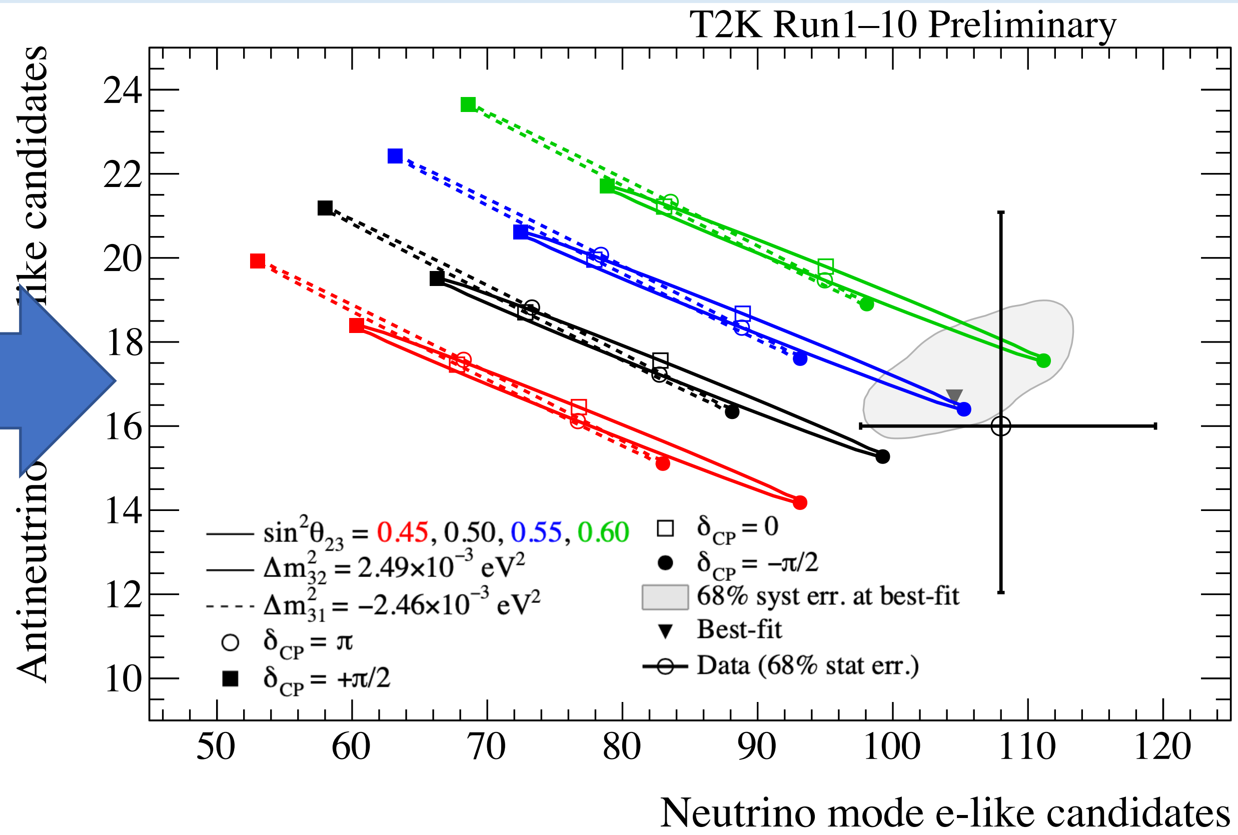




Comparison to previous result

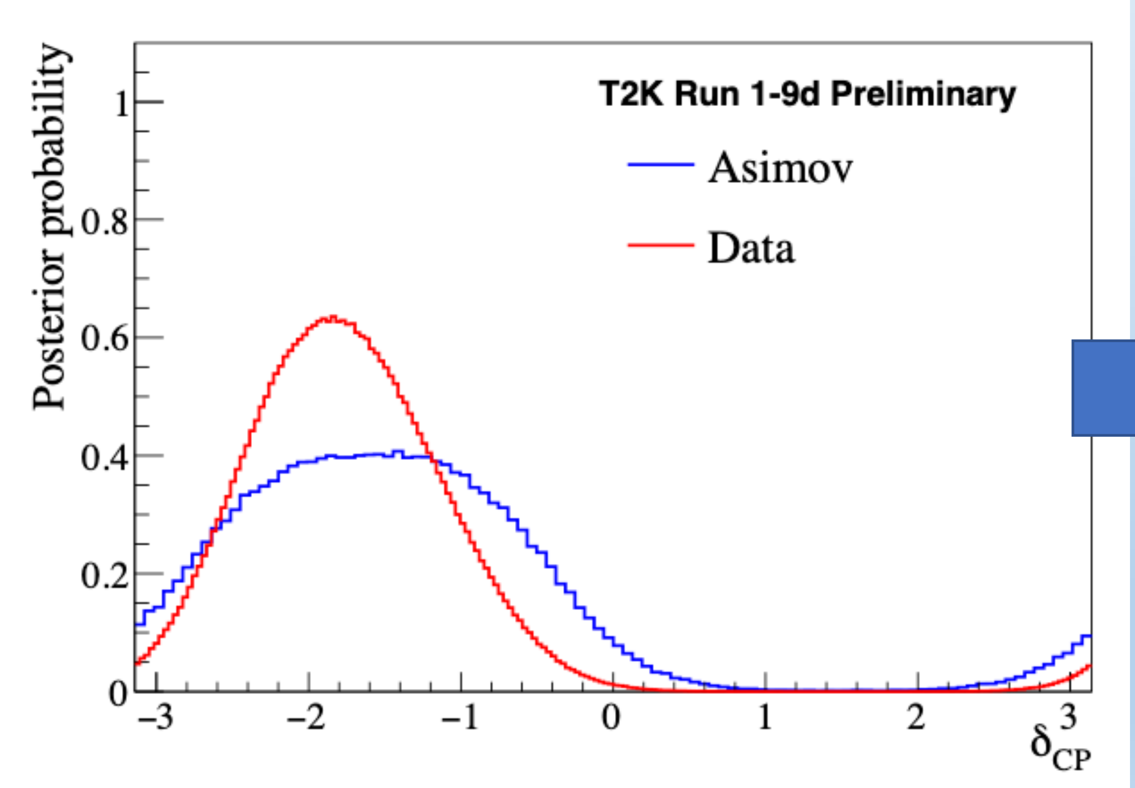
- Data this year closer to PMNS prediction
  - See backup for details of effect of all changes made on results

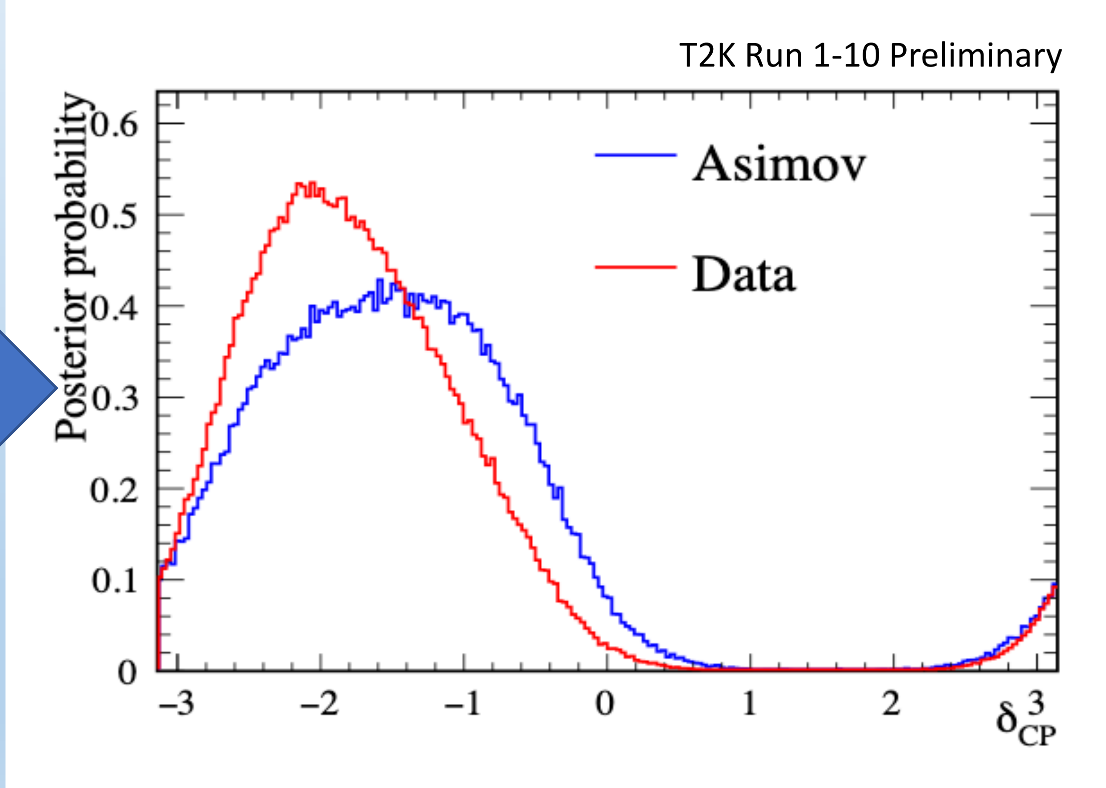




Comparison to previous result

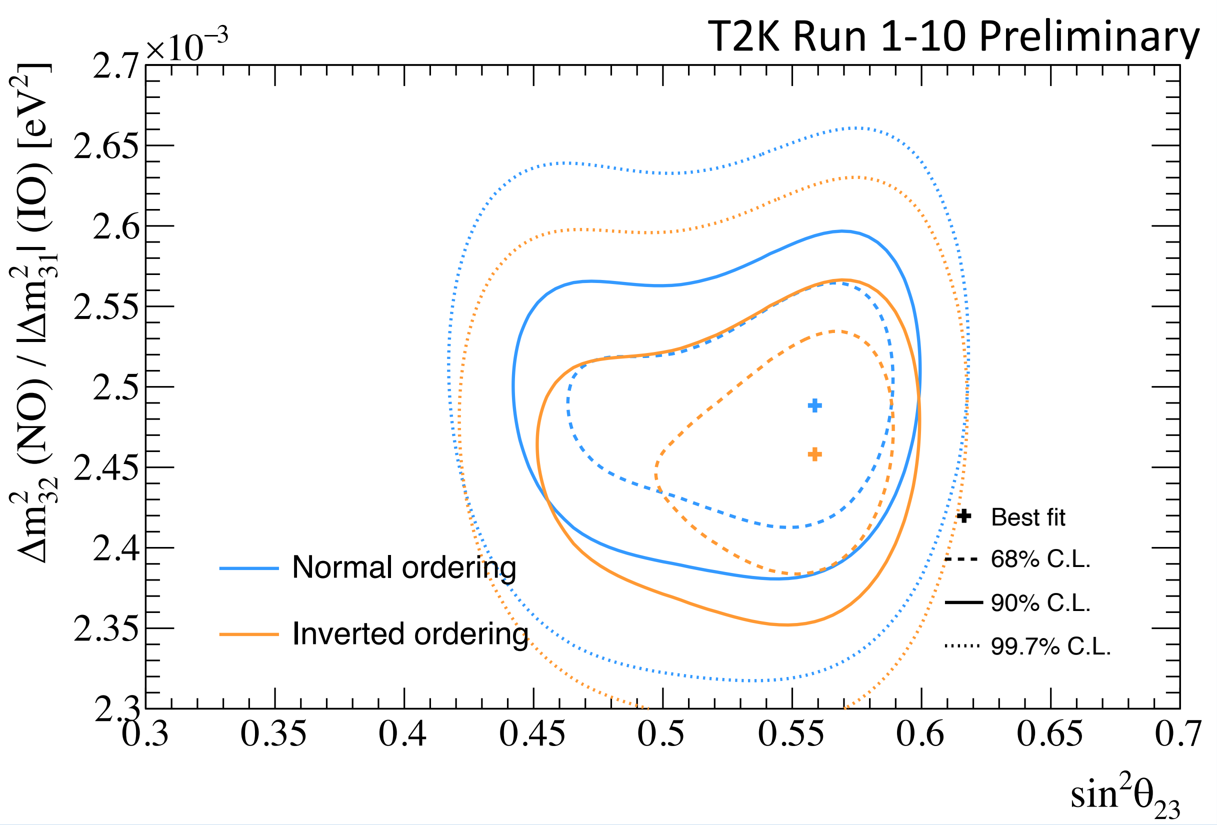
- Data result gives tighter constraint than sensitivity as it did last year
- Consistent with expectation if have slight upwards statistical fluctuation





Atmospheric sector

- Data shows preference for normal hierarchy and upper octant
- Slight preference for non-maximal $\sin^2\theta_{23}$



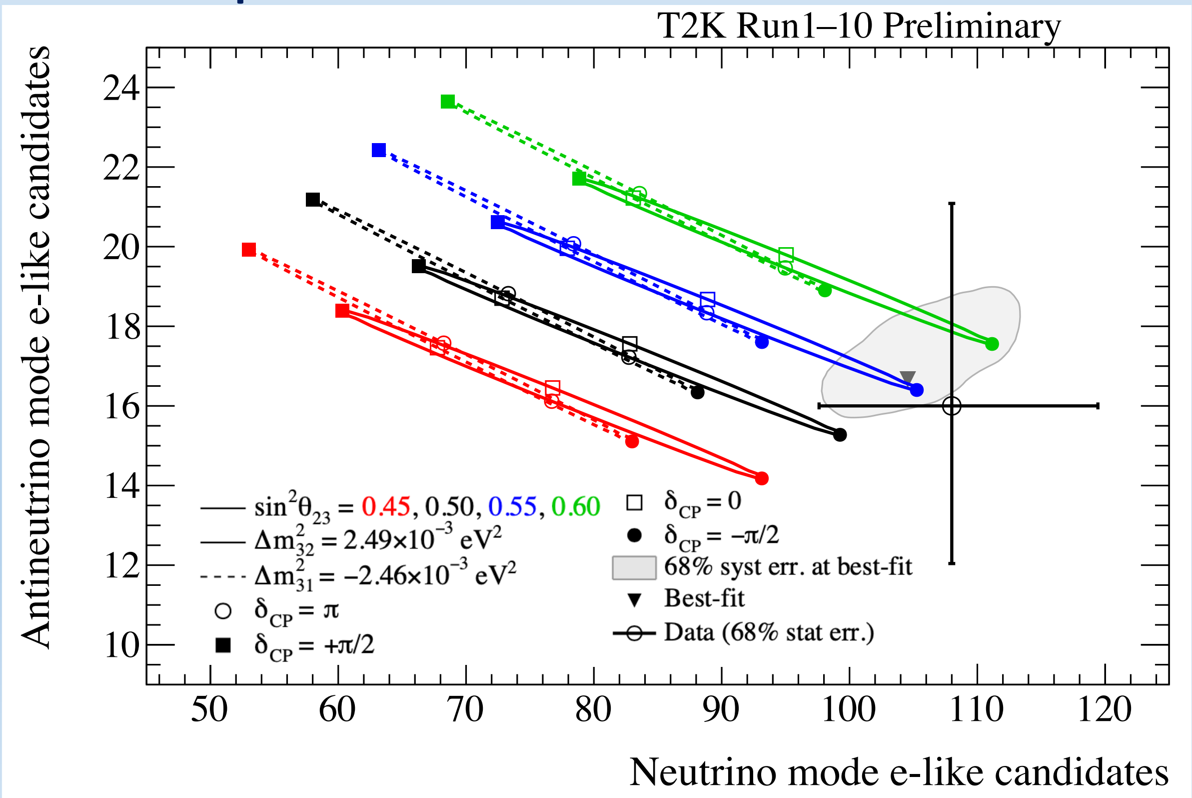
Posterior probability

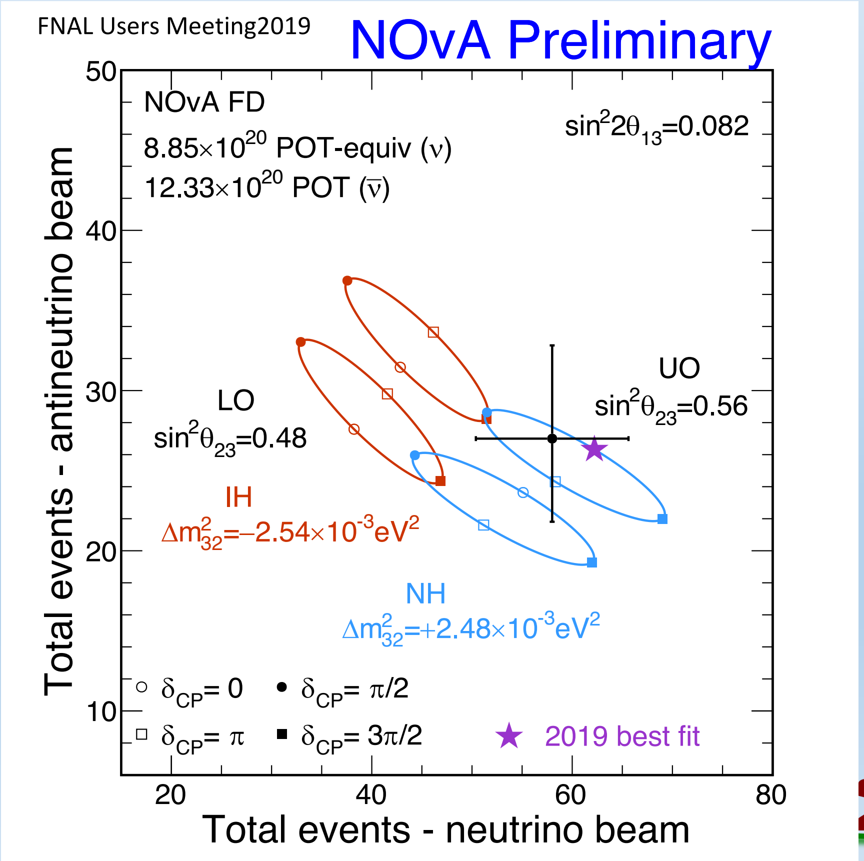
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.195	0.613	0.808
IH ($\Delta m^2_{32} < 0$)	0.034	0.158	0.192
Sum	0.229	0.771	1.000

	$\sin^2\theta_{23}$	$\Delta m^2_{32} (\times 10^{-3})\mathrm{eV}^2$
2D best fit	0.546	2.49
68% C.I. (1σ) range	0.50 – 0.57	2.408 – 2.548
90% C.I. range	0.460 – 0.587	−2.596 – −2.452 & 2.368 – 2.592

Future joint fits

- Experiments with different neutrino energies have different oscillation probabilities and systematic uncertainties
- Combined analysis of data allows degeneracies to be broken and maximises impact of data taken



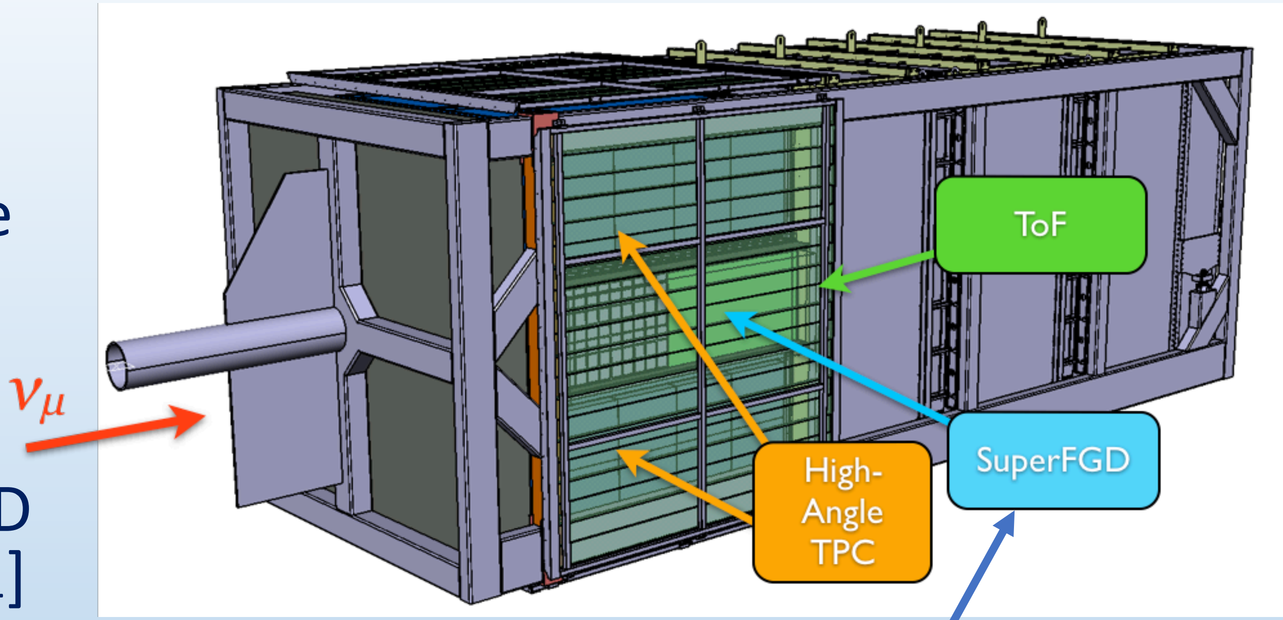


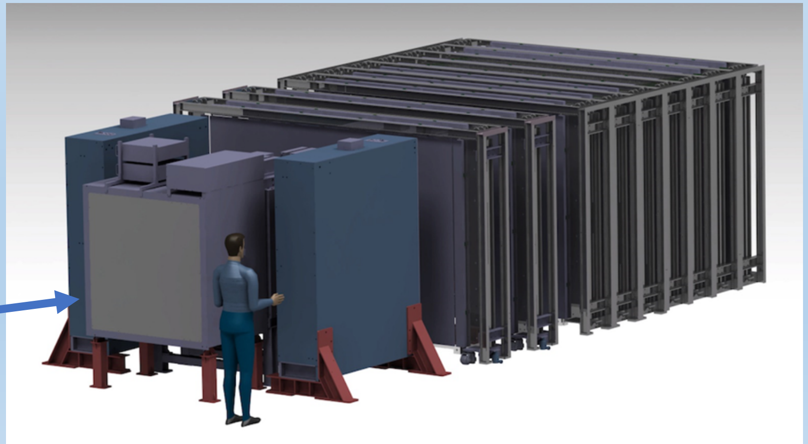
Future joint fits

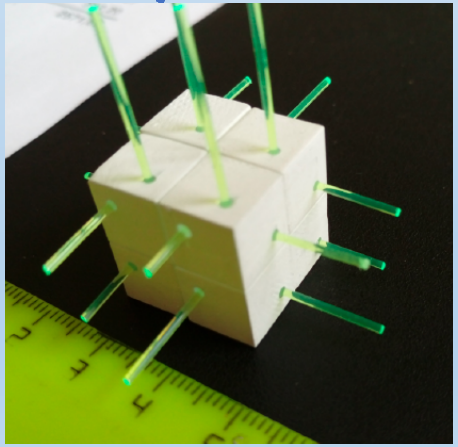
- Experiments with different neutrino energies have different oscillation probabilities and systematic uncertainties
- Combined analysis of data allows degeneracies to be broken and maximises impact of data taken
- Agreements signed with NOvA and SK and work towards T2K+NOvA and T2K+SK atmospheric analyses is underway

Future upgrades

- J-PARC Main Ring power supply upgrade already mentioned
  - 515kW->810kW by FY2022
- ND280 will be upgraded in 2022 with a new higher angular coverage TPC and 3D Super-FGD subdetector [arXiv:1901.03750v1]
  - Better hadron tagging and more similar phase space coverage to SK (S. Dolan's talk)
- SK-Gd loading for neutron tagging imminent (Y. Nakajima's talk)
- Oscillation analyses using our near detectors at other off-axis angles (WAGASCI/BabyMIND)

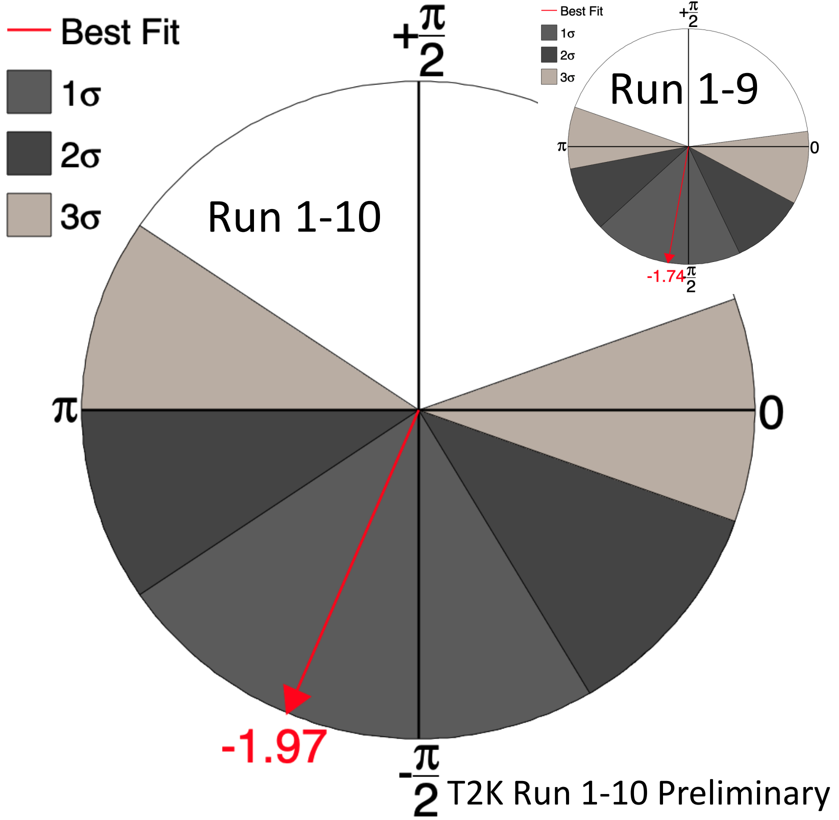


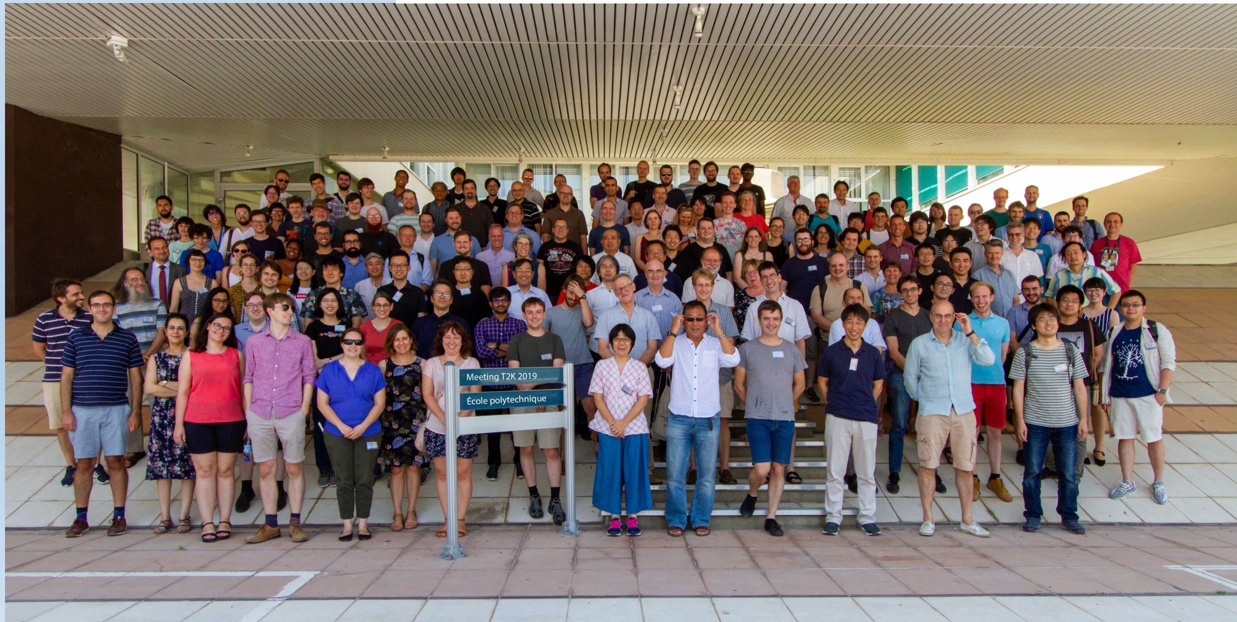




Summary

- Results with 33% more ν-mode data presented
- Significant upgrade has been made to the interaction and flux modeling used for this analysis
- Large range of values of δ_{CP} around $+\pi/2$ are excluded at 99.7%
- T2K has an exciting program of upgrades planned including higher beam power and improved near detectors

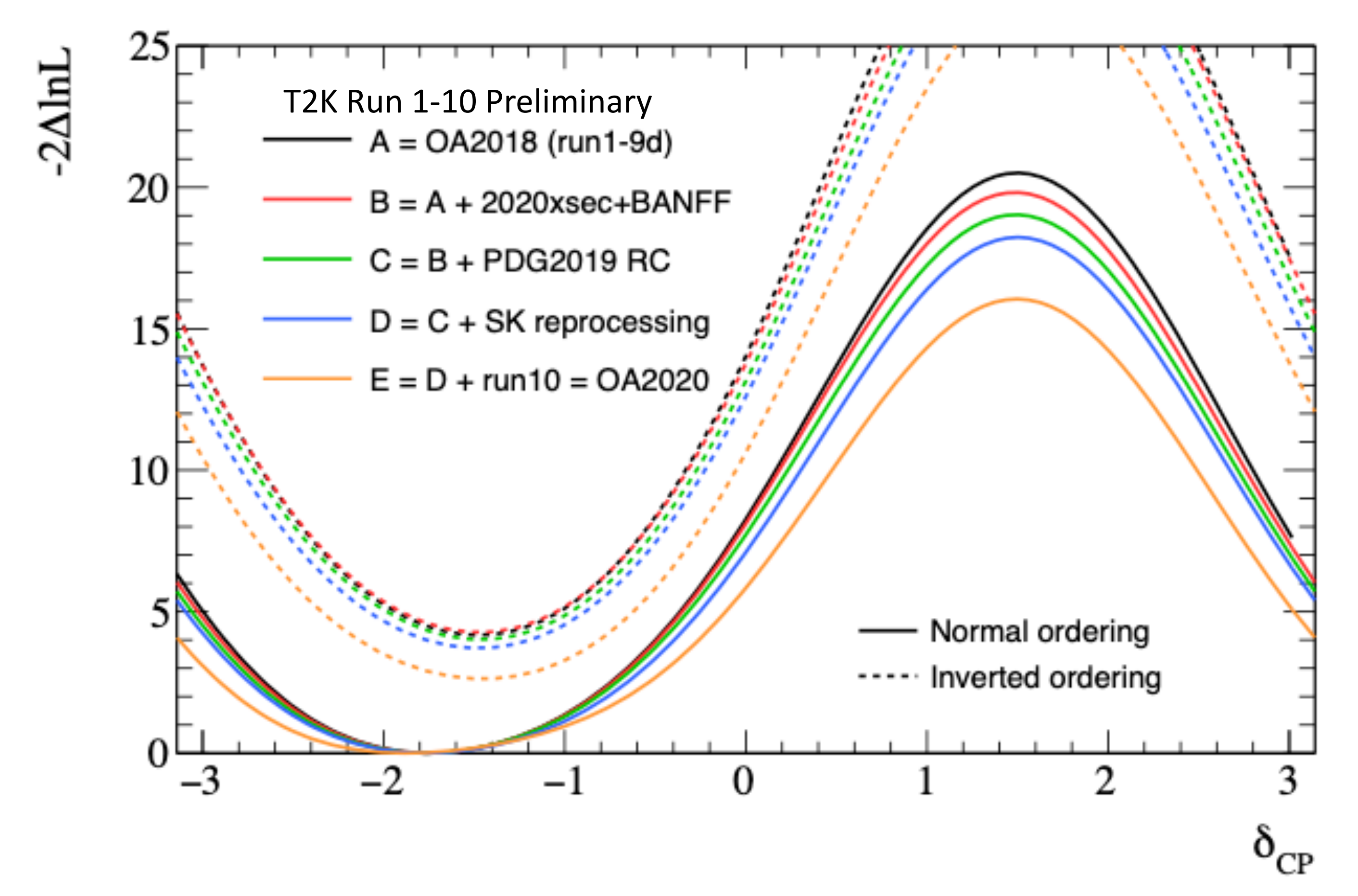




Backup

What changed from Run 1-9? Data

- Sequentially make each of the changes from OA2018 to OA20 one by one
  - B makes analysis changes described above e.g. flux model, xsec model
  - C adds update on θ_{13} constraint from PDG2018 to PDG2019
  - D adds new calibration for SK that caused some events to migrate in and out of samples
  - E adds new run 10 data
- Largest change in δ_{CP} comes from new data



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What changed from Run 1-9? Sensitivity

- Sequentially make each of the changes from OA2018 to OA20 one by one
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  - D new calibration mentioned on previous slide doesn't affect MC
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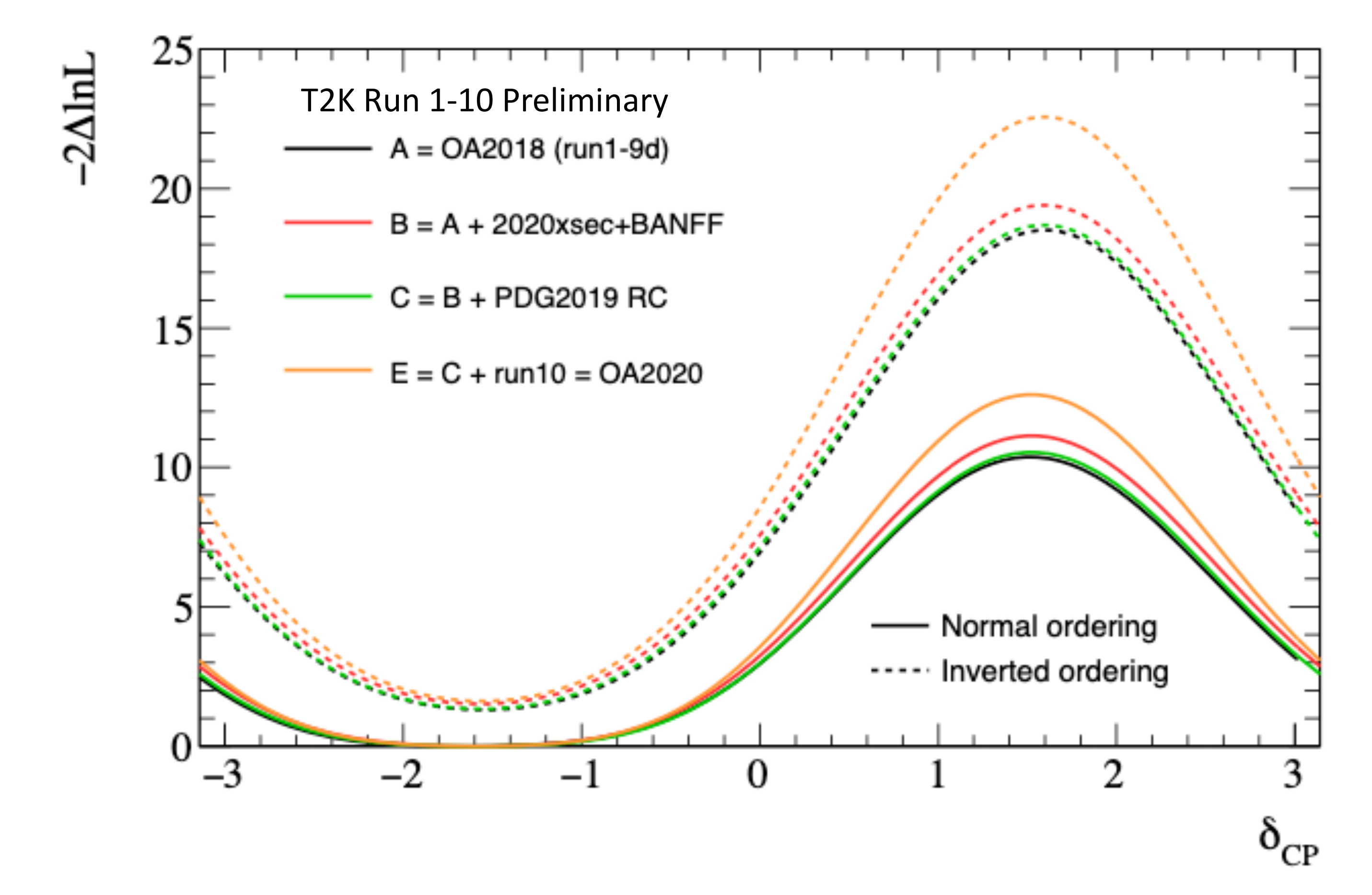

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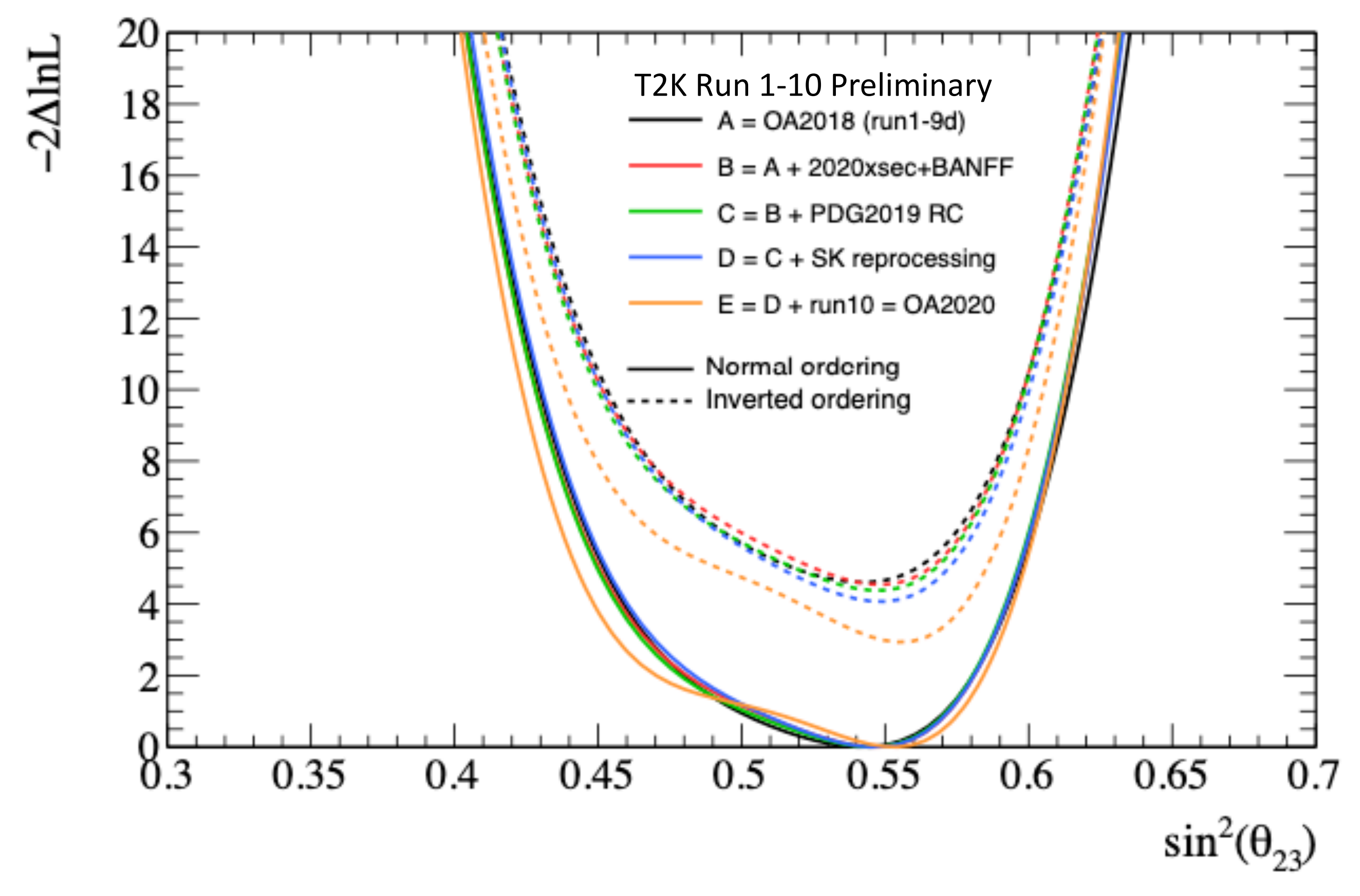
  - D adds new calibration for SK that caused some events to migrate in and out of samples
  - E adds new run 10 data
- Largest change in $\sin^2(\theta_{23})$ comes from new data



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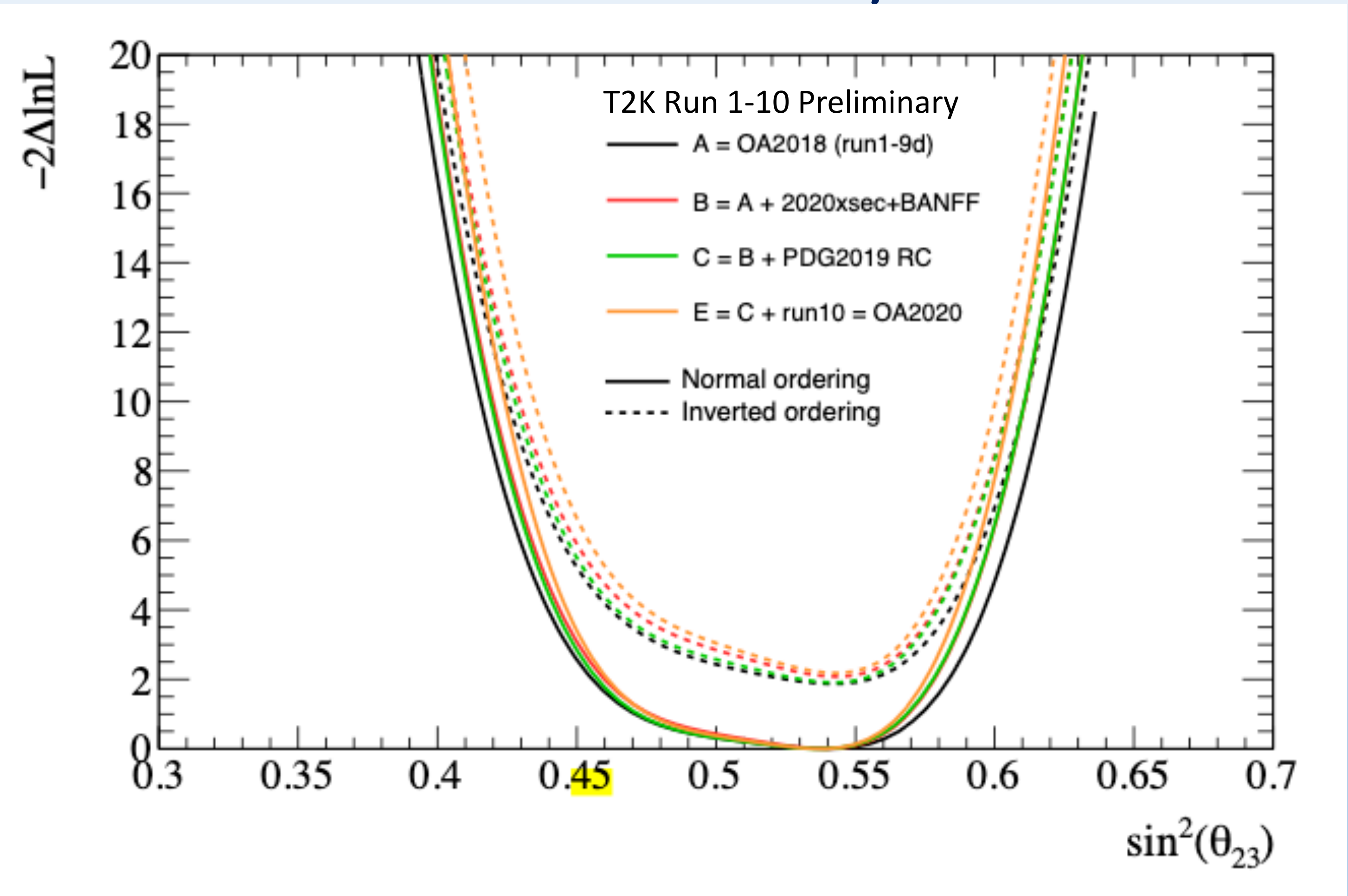

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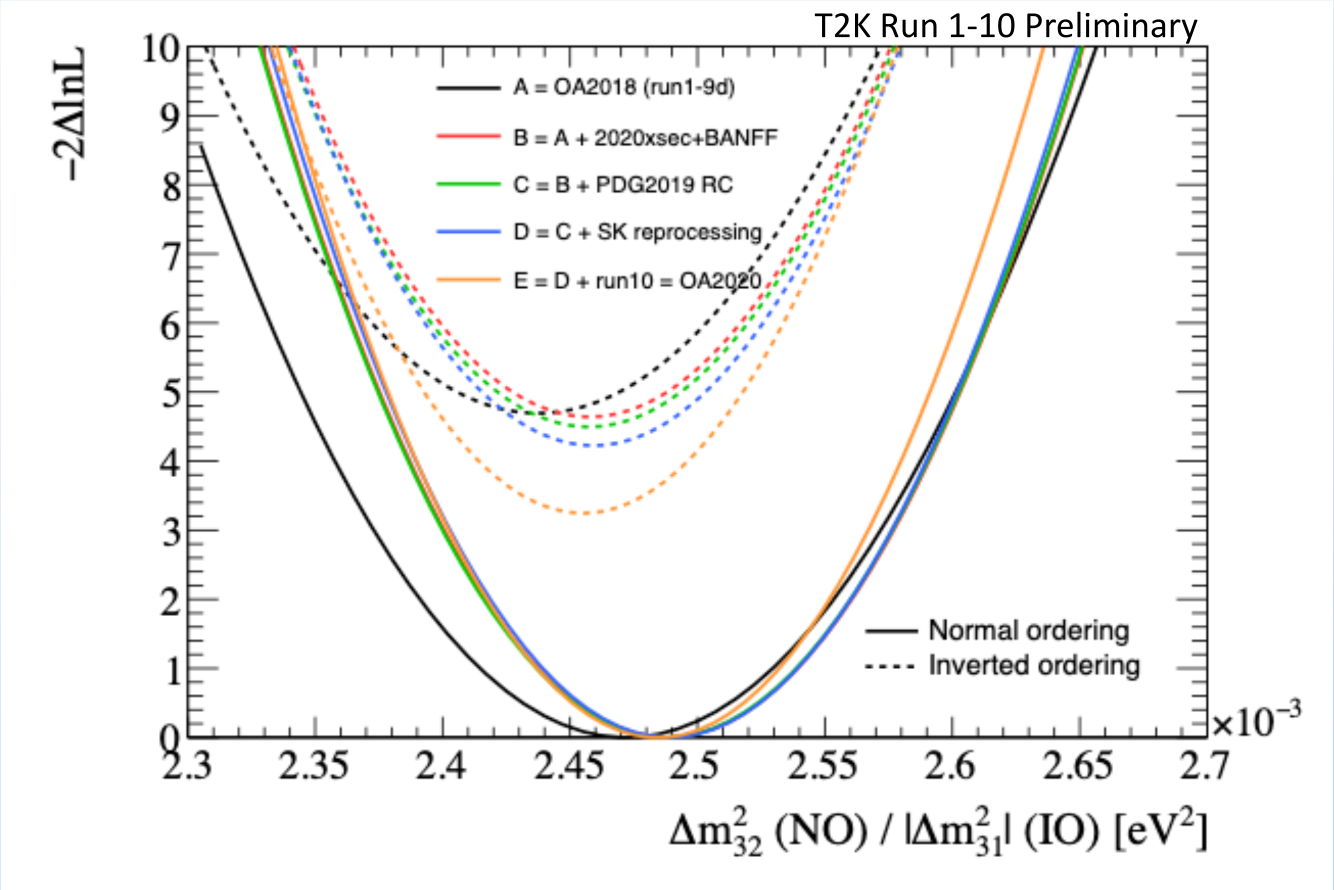
  - E adds new run 10 data
- Largest change in Δm^2_{32} comes from new xsec model (primarily better removal energy treatment)



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What changed from Run 1-9? Data

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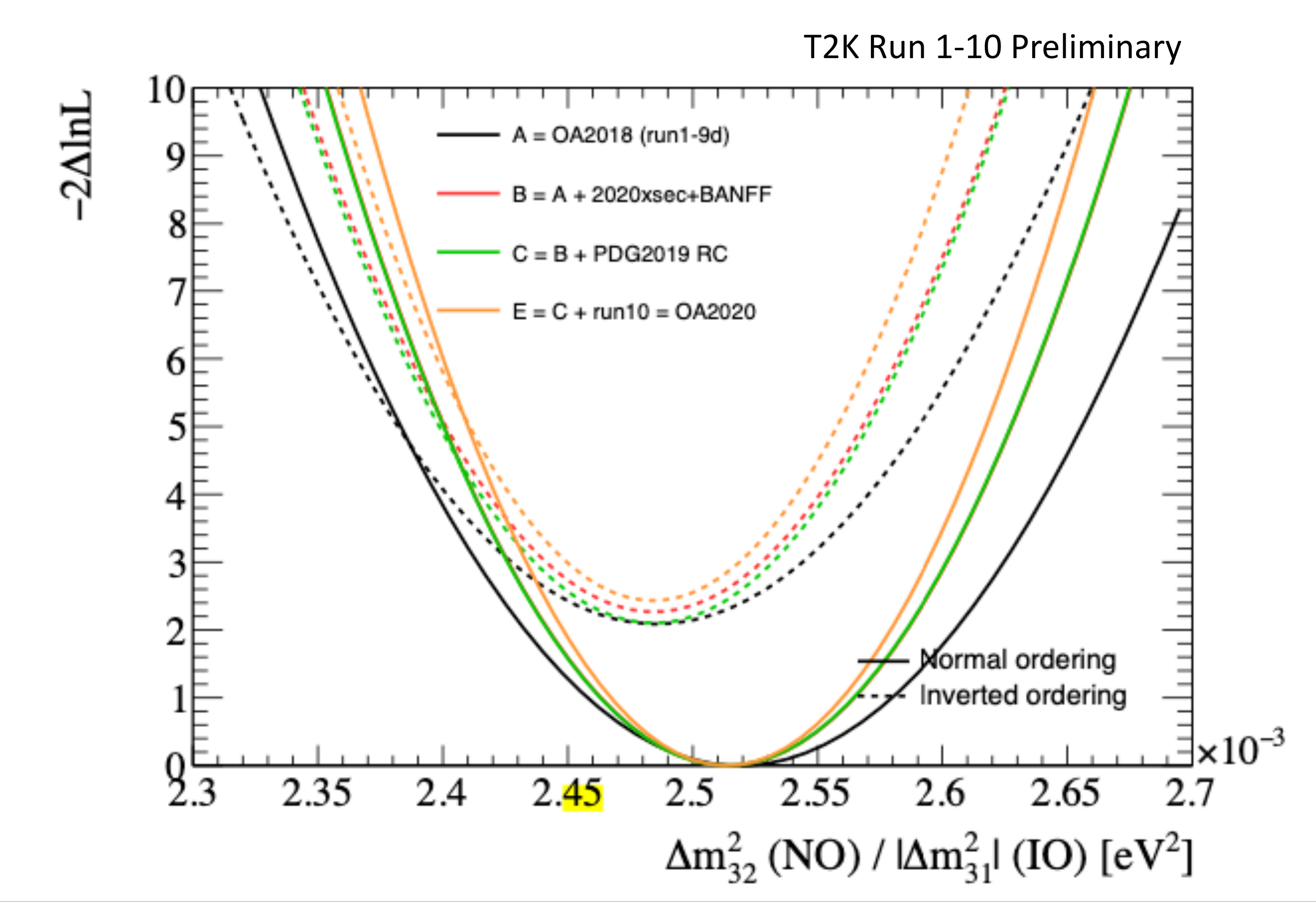
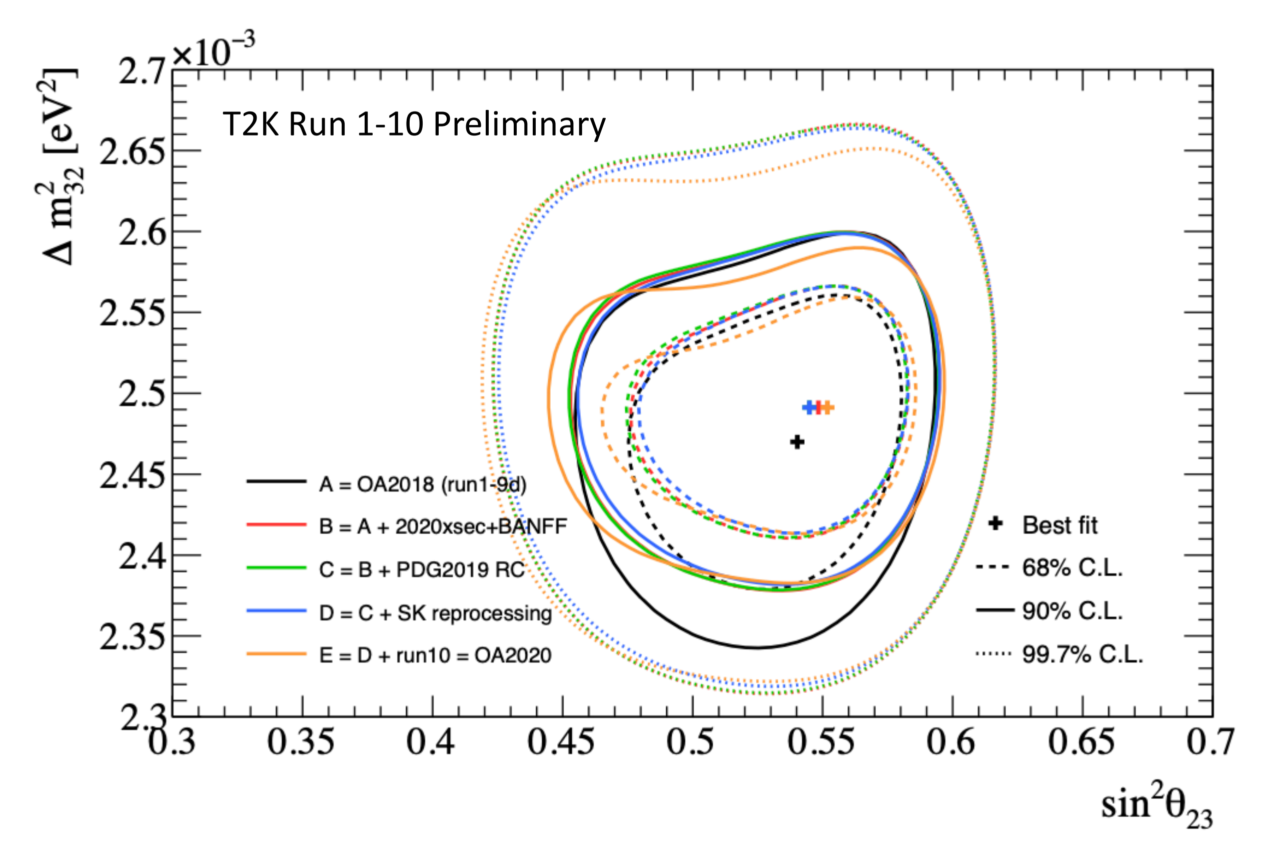


Run 1-9 vs Run 1-10 2D Atmospheric Parameters - Data

- Sequentially make each of the changes from OA2018 to OA20 one by one
  - B makes analysis changes described above e.g. flux model, xsec model
  - C adds update on θ_{13} constraint from PDG2018 to PDG2019
  - D adds new calibration for SK that caused some events to migrate in and out of samples
  - E adds new run 10 data
- Same conclusions as 1D

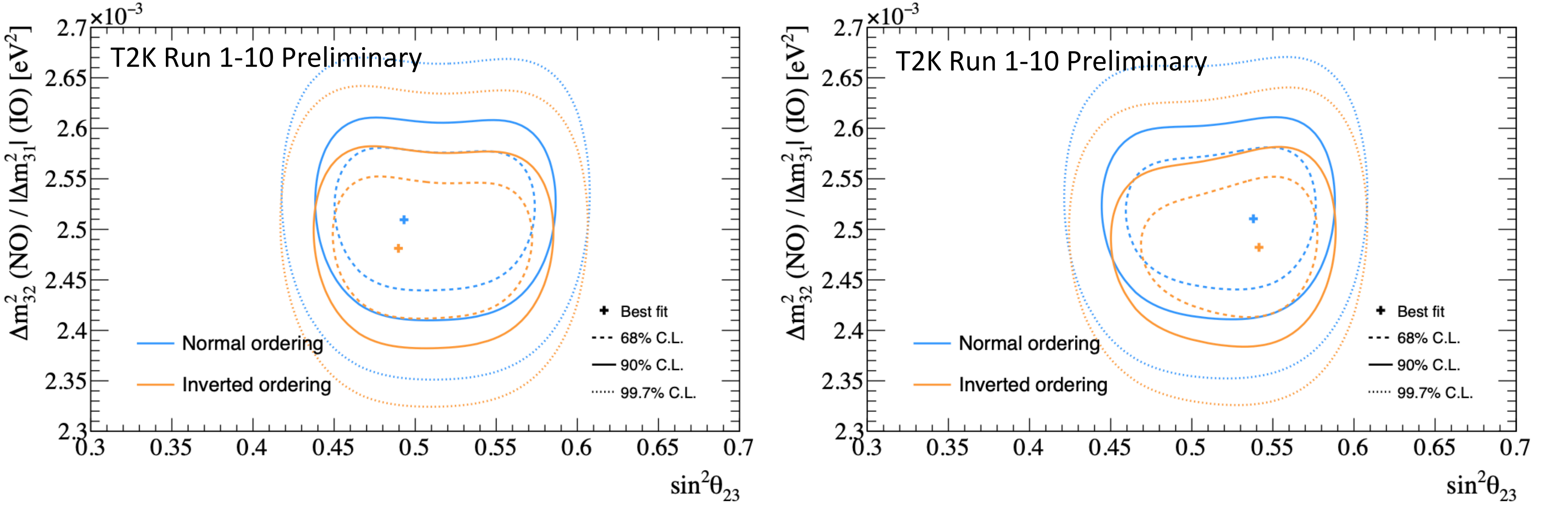


Definition of Oscilltion parameter set A used for sensitivity studies

Oscillation parameter set (Asimov A):

1. $\sin^2\theta_{12} = 0.307$
2. $\sin^2\theta_{23} = 0.528$
3. $\sin^2\theta_{13} = 0.0218$
4. $\Delta m^2_{12} = 7.53 \times 10^{-5}$
5. $\Delta m^2_{23} = 2.509 \times 10^{-3}$
6. $\delta_{CP} = -1.601$

Sensitivity plots without comparison overlays

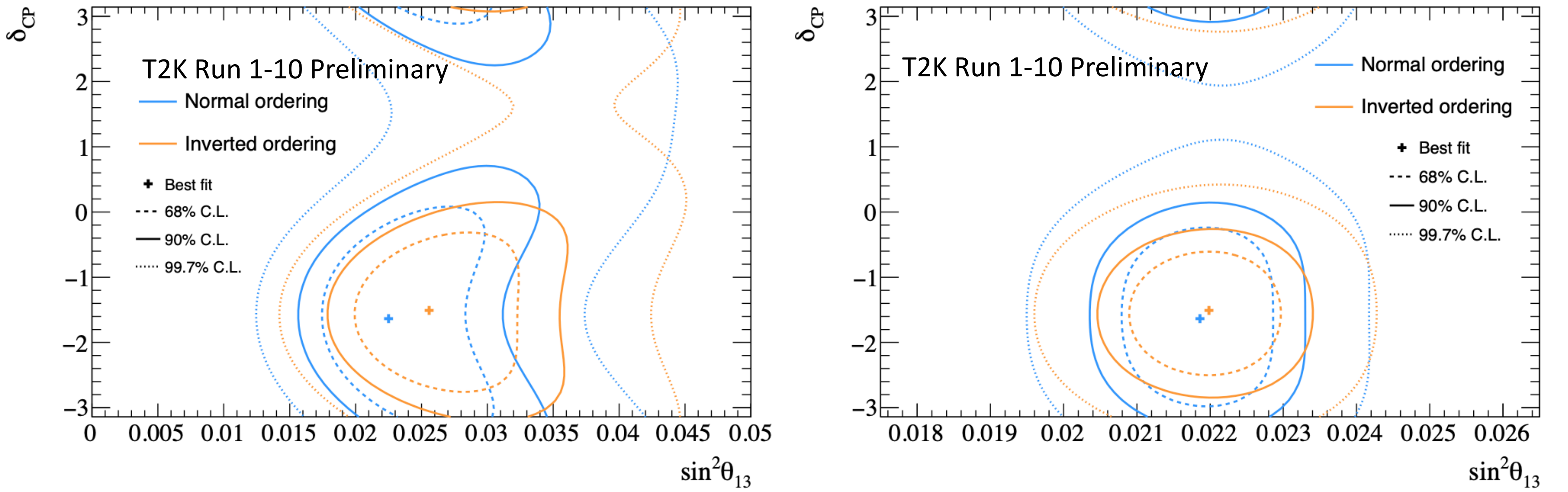


(a) T2K only

(b) T2K + reactor

Figure 7: Asimov sensitivity 2D confidence level contours in Δm^2_{32} vs. $\sin^2\theta_{23}$ for normal and inverted hierarchy for true values of the parameters corresponding to the Set A

Sensitivity plots without comparison overlays



(a) T2K only

(b) T2K + reactor

Figure 10: Asimov sensitivity 2D confidence level contours in δ_{CP} vs. $\sin^2\theta_{13}$ for normal and inverted hierarchy for true values of the parameters corresponding to the Set A

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Sensitivity plots without comparison overlays

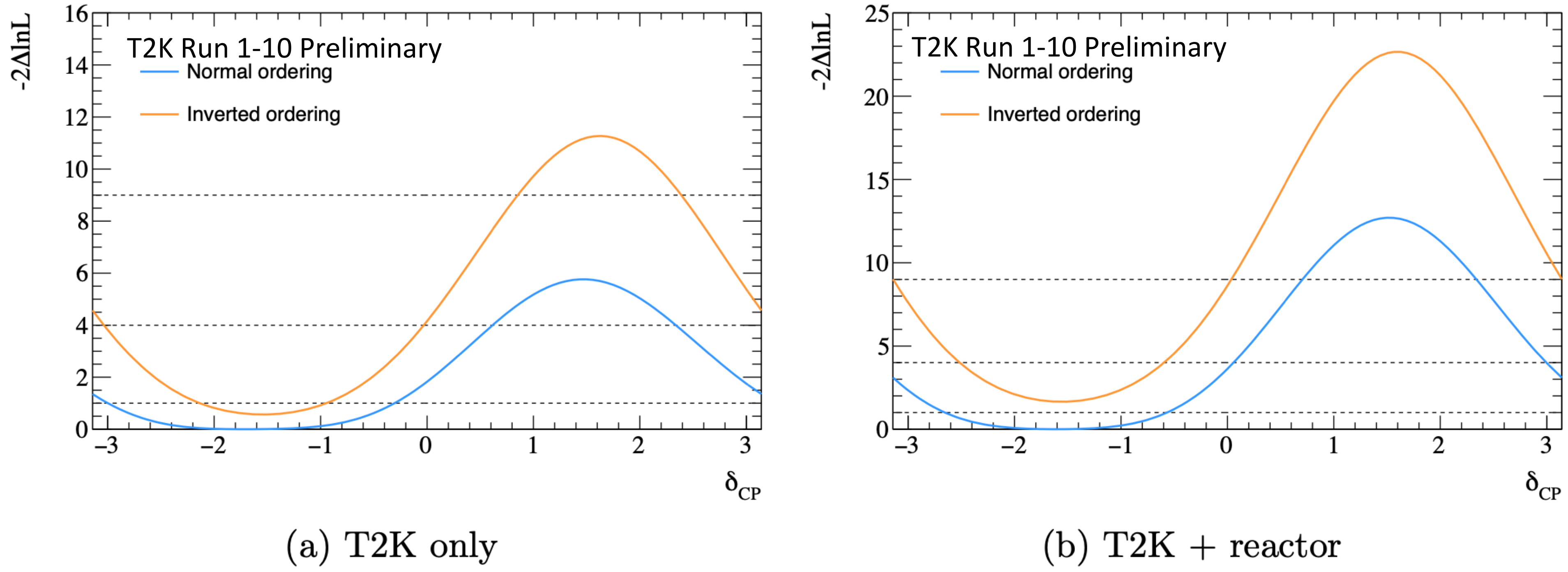

Figure 12: Asimov sensitivity 1D $\Delta\chi^2$ in δ_{CP} for normal and inverted hierarchy for true values of the parameters corresponding to the Set A

Systematic error breakdown

After ND fit

Table 20: Uncertainty on the number of event in each SK sample broken by error source after the BANFF fit. To obtain error rates comparable with the "Flux+Xsec (ND constrained)" presented by MaCh3 [22], square sum the "Flux+Xsec (ND constr)", "$\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$", "NC γ".

Error source	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
2p2h Edep	0.4	0.4	0.2	0.2	0.0	0.2
BG_A^{RES} low-p_π	0.4	2.5	0.1	2.2	0.1	2.1
$\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$	0.0	0.0	2.6	1.5	2.7	3.0
NC γ	0.0	0.0	1.4	2.4	0.0	1.0
NC Other	0.2	0.2	0.2	0.4	0.8	0.2
SK	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

Before ND fit

Table 21: Uncertainty on the number of event in each SK sample broken by error source before the BANFF fit.

Error source	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%

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Parameter best fit and credible intervals T2K only

	$\sin^2\theta_{23}$	$\Delta m^2_{32}(\times 10^{-3})\mathrm{eV}^2$
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

Table 8: Best-fit values and 68% and 90% 1D credible interval ranges for disappearance parameters from the T2K data only fit. The 2D best-fit values are taken from the mode of the 2D marginal posterior distributions in $\sin^2\theta_{23} - \Delta m^2_{32}$, and the 1D 68% and 90% credible intervals correspond to the 1 σ and 90% central area of the marginalised posterior distributions, correspondingly.

	$\sin^2\theta_{13}$	δ_{CP}
2D best fit	0.0244	-2.094
68% C.I. (1σ) range	0.0223 – 0.0308	-2.796 – -0.723
90% C.I. range	0.0203 – 0.0335	$-\pi$ – -0.126 & 2.890 – π
95.4% (2σ) C.I. range	0.0195 – 0.0348	$-\pi$ – 0.220 & 2.545 – π
99% C.I. range	0.0178 – 0.0350	$-\pi$ – 0.880 & 1.885 – π
99.7% (σ) C.I. range	0.0165 – 0.0350	$-\pi$ – 1.131 & 1.571 – π

Table 9: Best-fit values and 68% and 90% 1D credible interval ranges for appearance parameters from the T2K data only fit. The 2D best-fit values are taken from the mode of the 2D marginal posterior distributions in $\sin^2\theta_{13} - \delta_{CP}$, and the 1D 68% and 90% credible intervals correspond to the 1 σ and 90% central area of the marginalised posterior distributions, correspondingly.

Parameter best fit and credible intervals T2K+reactor

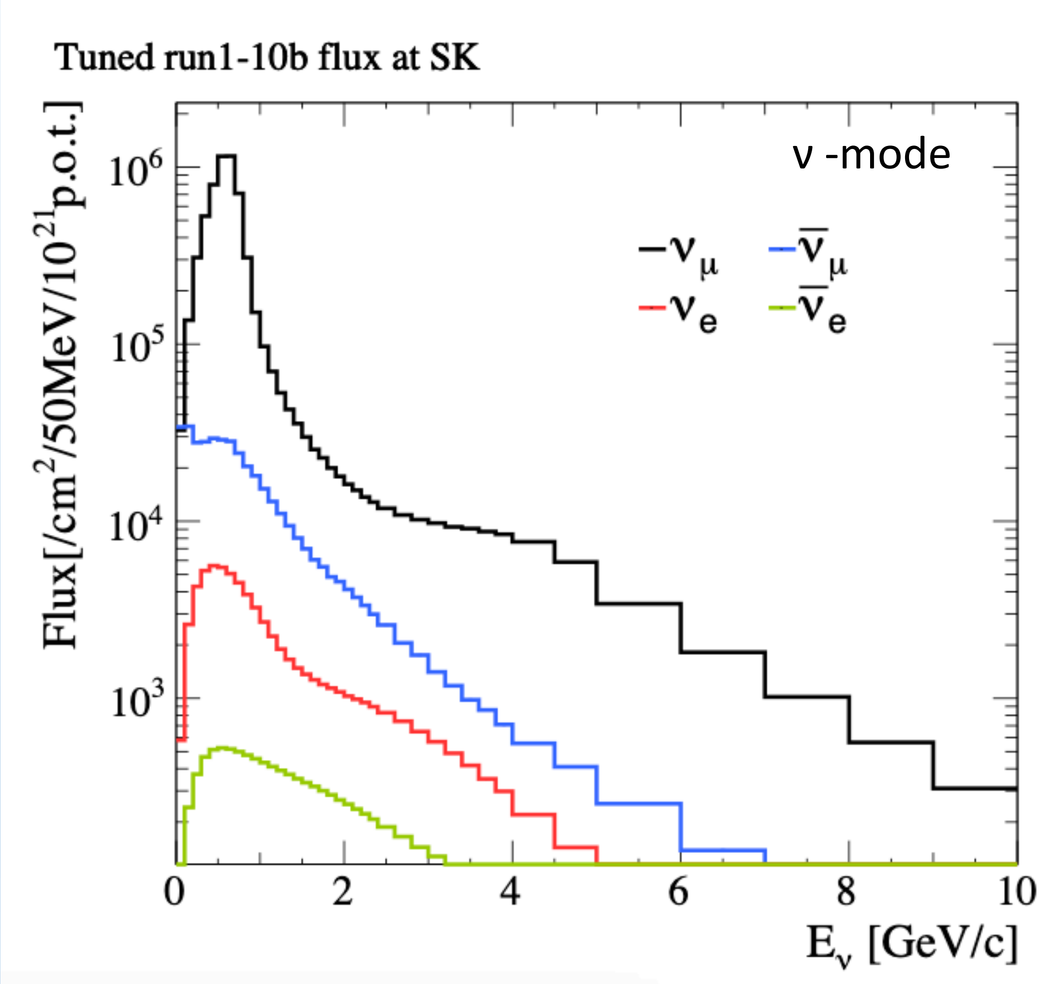
	$\sin^2\theta_{23}$	$\Delta m^2_{32}(\times 10^{-3})\mathrm{eV}^2$
2D best fit	0.546	2.49
68% C.I. (1σ) range	0.50 – 0.57	-3.004 – -3.000 & 2.408 – 2.548
90% C.I. range	0.460 – 0.587	-2.596 – -2.452 & 2.368 – 2.592

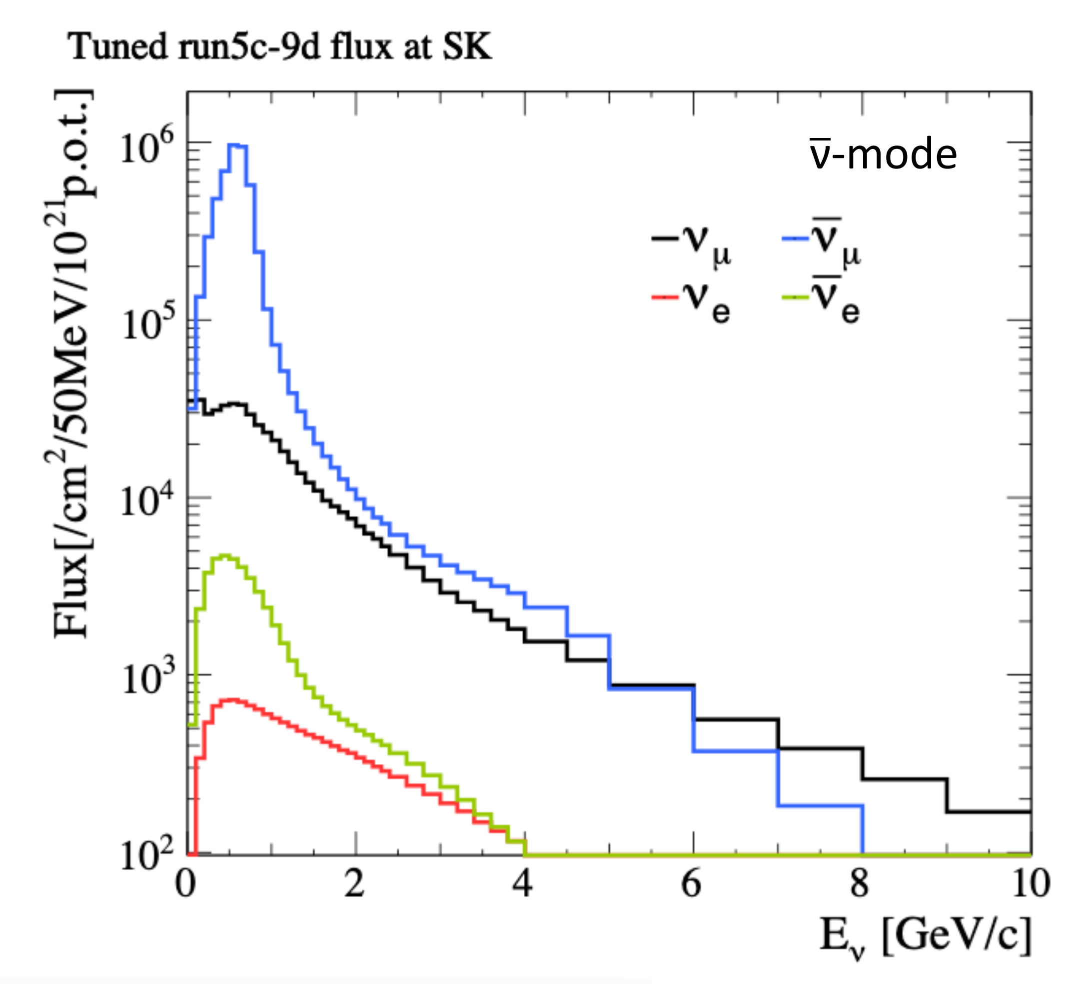
Table 11: Best-fit values and 68% and 90% 1D credible interval ranges for disappearance parameters from the data fit with reactor constraint. The 2D best-fit values are taken from the mode of the 2D marginal posterior distributions in $\sin^2\theta_{23} - \Delta m^2_{32}$, and the 1D 68% and 90% credible intervals correspond to the 1 σ and 90% central area of the marginalised posterior distributions, correspondingly.

	$\sin^2\theta_{13}$	δ_{CP}
2D best fit	0.0220	-1.967
68% C.I. (1σ) range	0.0212 – 0.0226	-2.545 – -1.037
90% C.I. range	0.0208 – 0.0231	-2.922 – -0.565
95.4% C.I. range	0.0206 – 0.0234	$-\pi$ – -0.346
99% C.I. range	0.0201 – 0.0237	$-\pi$ – 0.063 & 2.827 – π
99.7% C.I. range	0.0198 – 0.0240	$-\pi$ – 0.346 & 2.545 – π

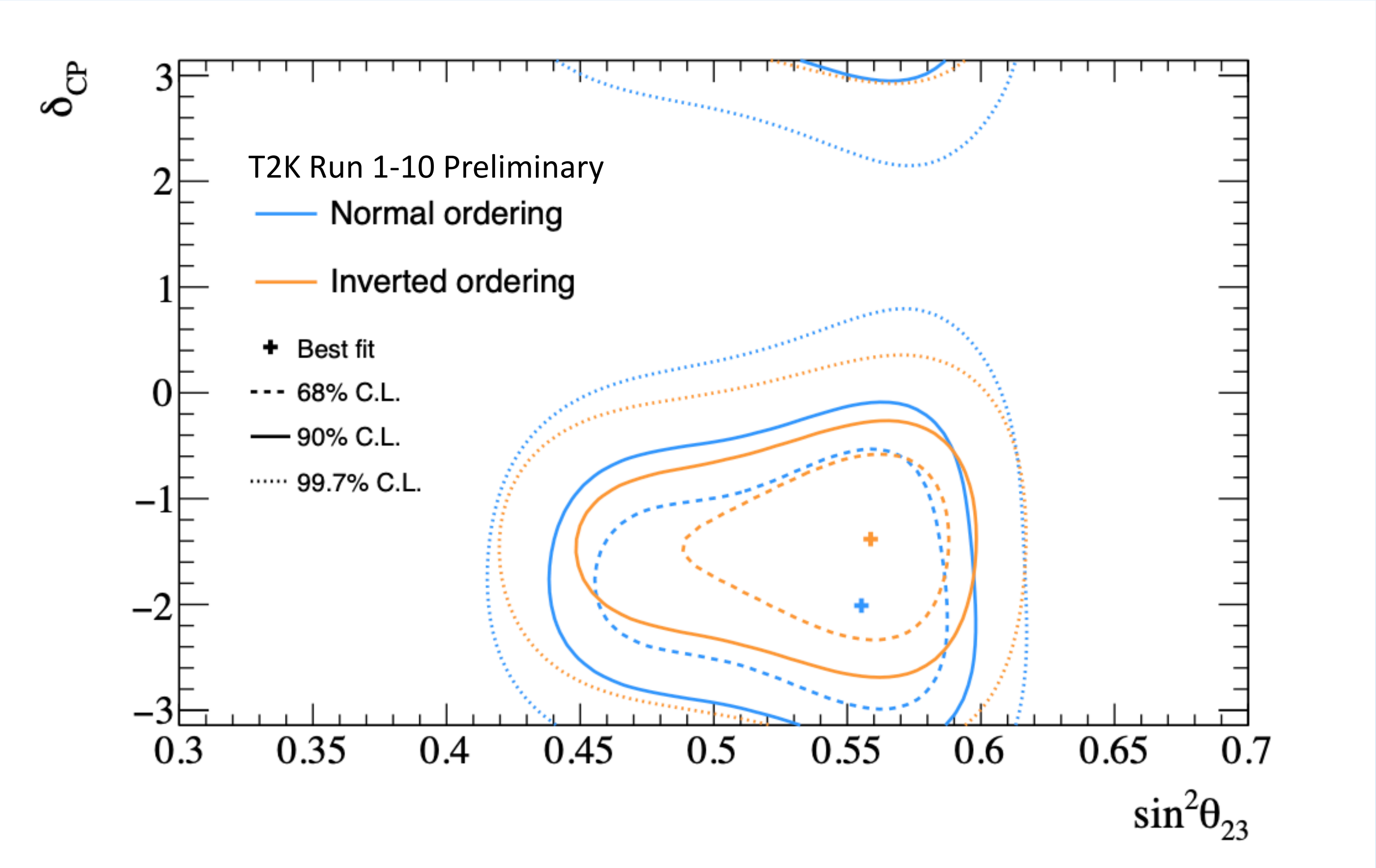
Table 12: Best-fit values and 68% and 90% 1D credible interval ranges for appearance parameters from the data fit with reactor constraint. The 2D best-fit values are taken from the mode of the 2D marginal posterior distributions in $\sin^2\theta_{13} - \delta_{CP}$, and the 1D 68% and 90% credible intervals correspond to the 1 σ and 90% central area of the marginalised posterior distributions, correspondingly.

Flux composition of beam nu vs nubar





θ_{23}-δ_{CP} plots – data with reactor constraint



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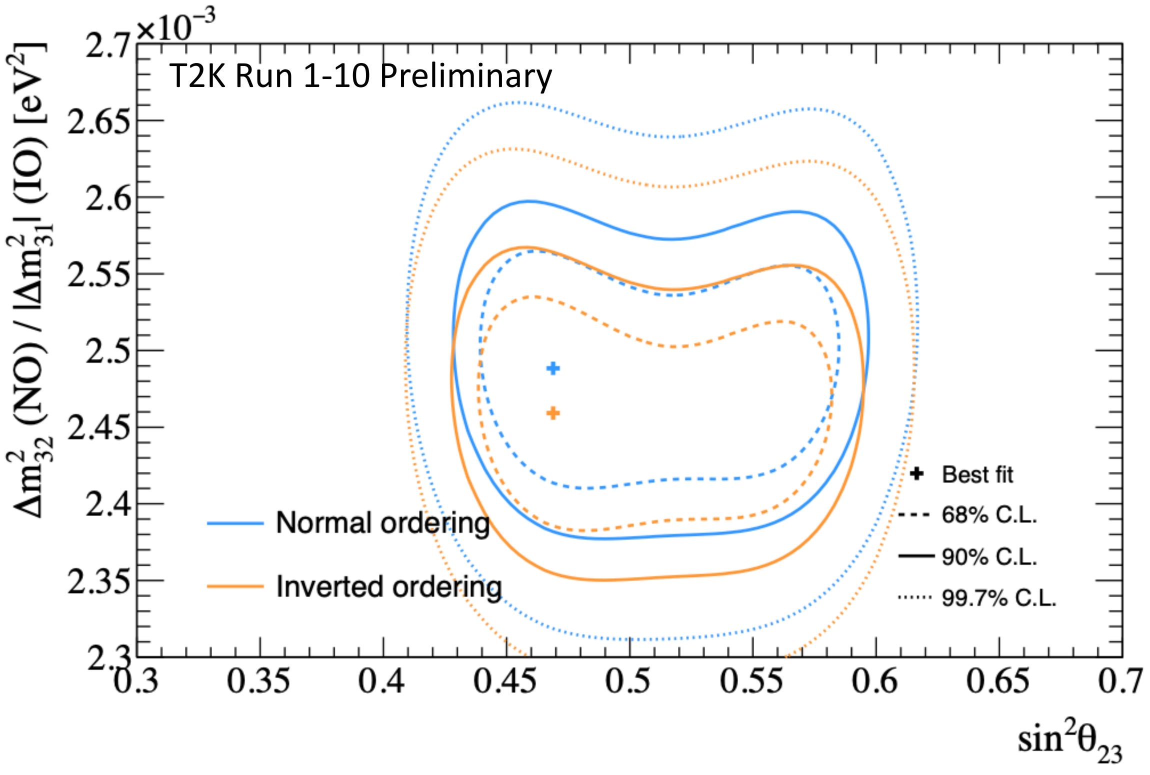
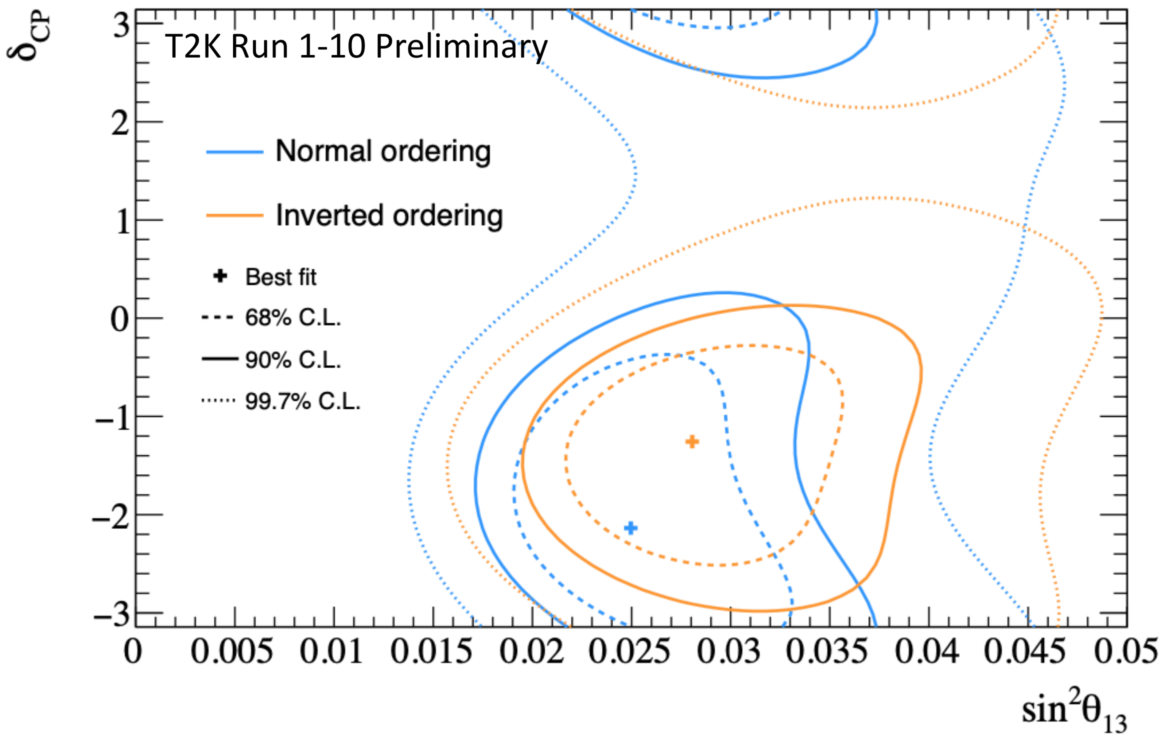
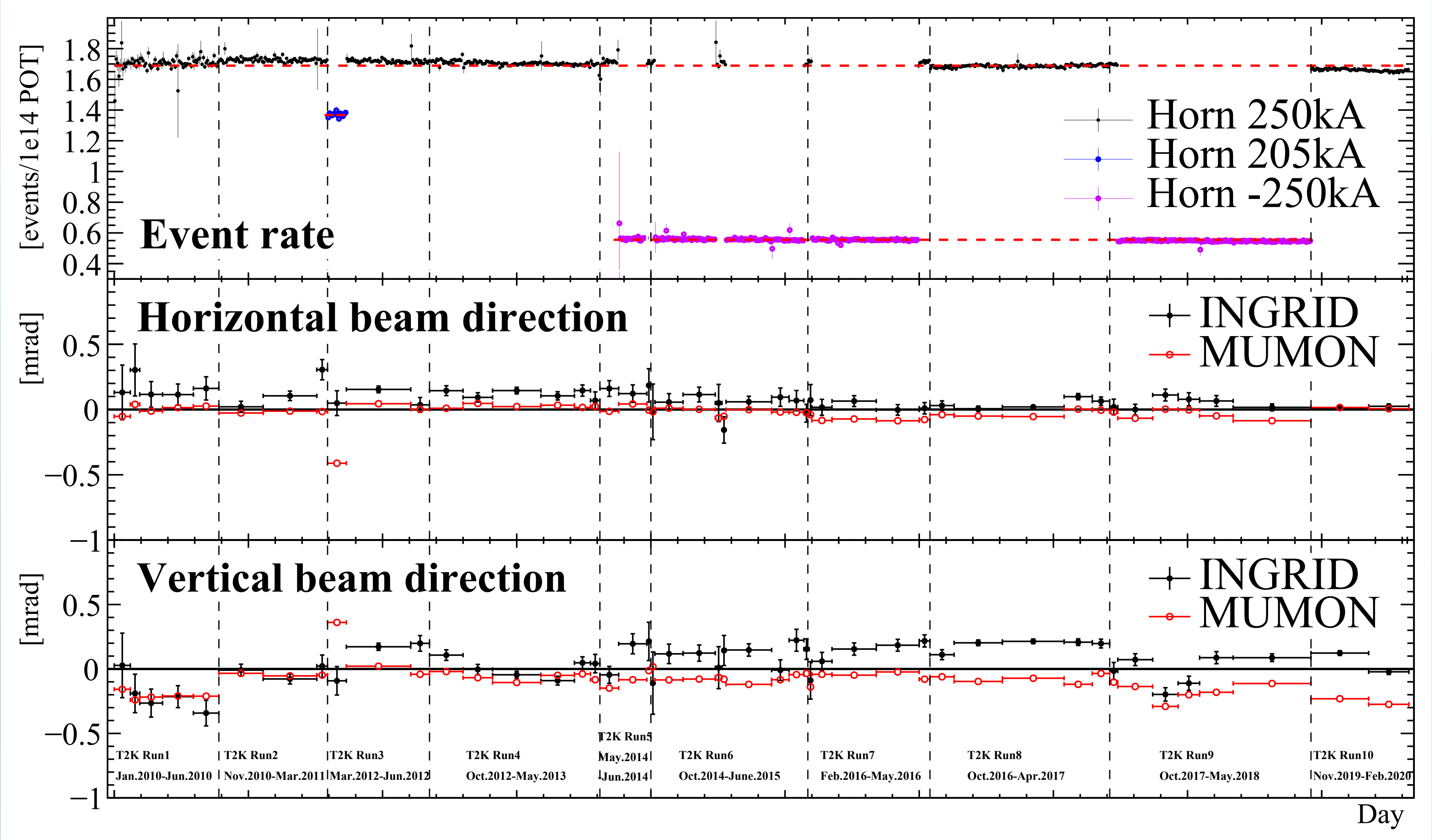
T2K

T2K only results without reactor constraint





Beam stability plot



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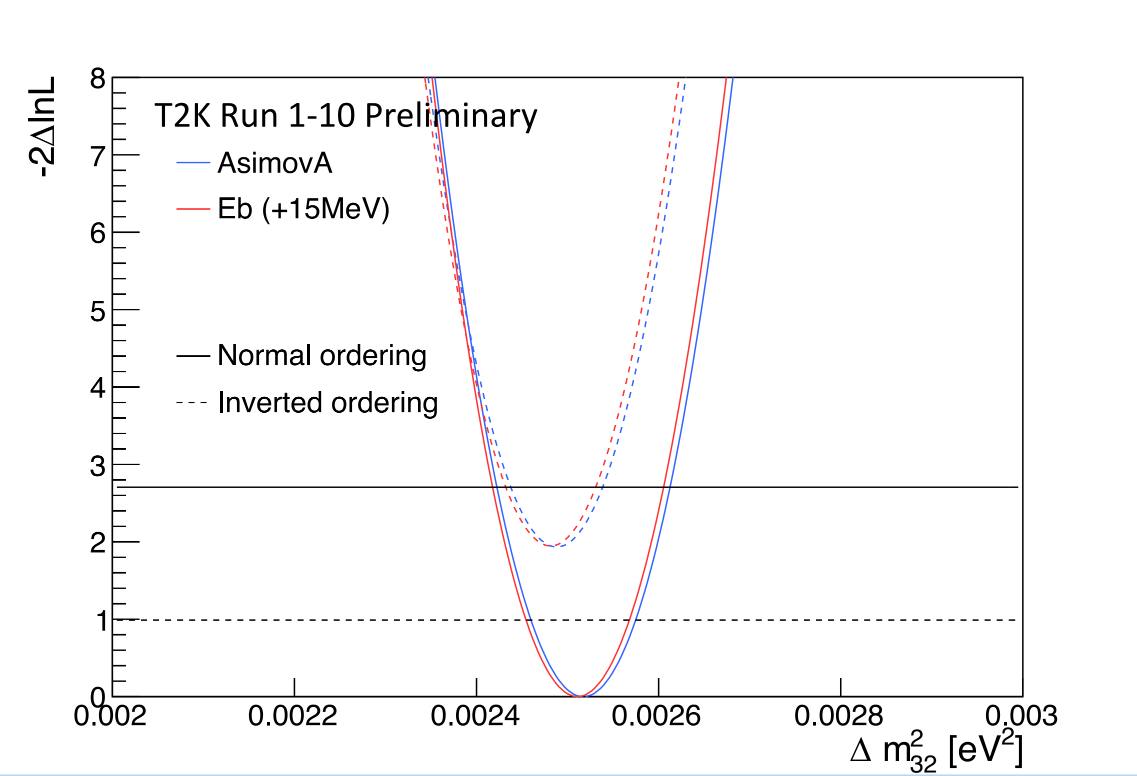
P-values for SK samples from MaCh3

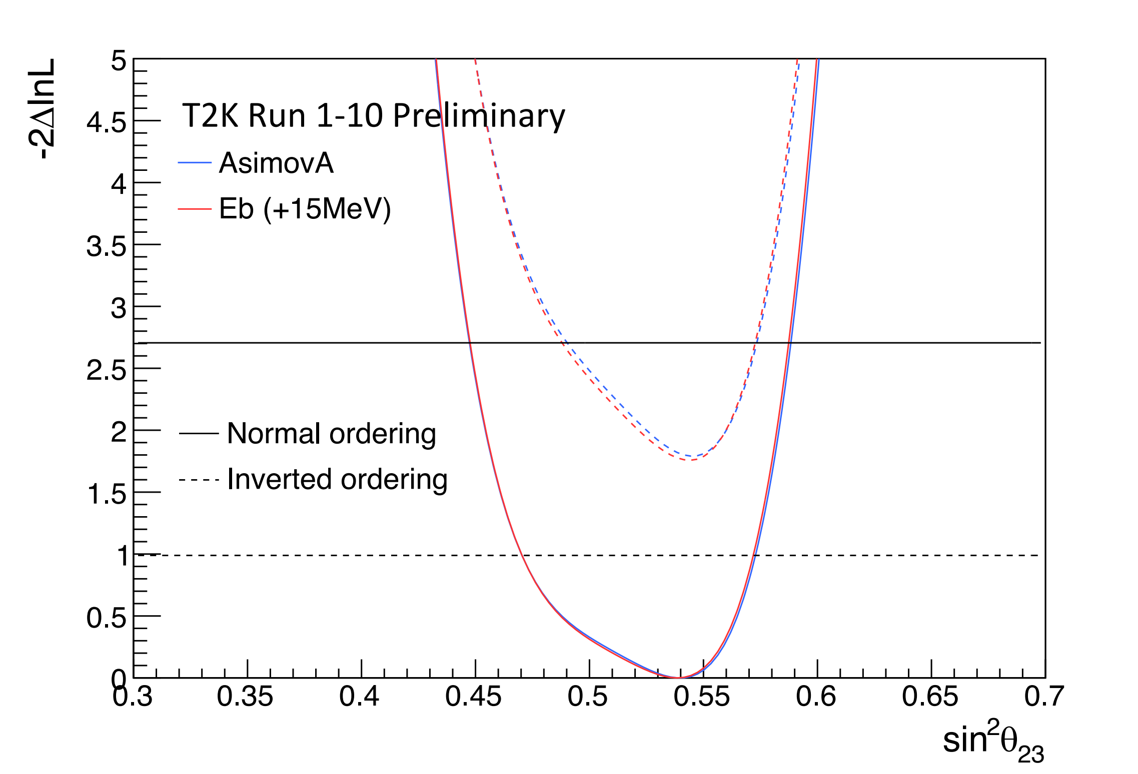
Sample / p-value	**Shape-based**	**Total Rate-based**
FHC 1Rμ	0.48	0.18
FHC 1Re	0.19	0.49
RHC 1Rμ	0.85	0.74
RHC 1Re	0.61	0.39
FHC 1Re1d.e.	0.86	0.22
Total	0.73	0.30

Table 7: Breakdown of goodness-of-fit p-values values, quoted separately for bin-by-bin (Shape-based) and total rate (Total Rate-based) based χ^2 calculation, used as a test for the compatibility between the best-fit model and the data, using T2K data fit with reactor constraint.

Removal energy robustness study

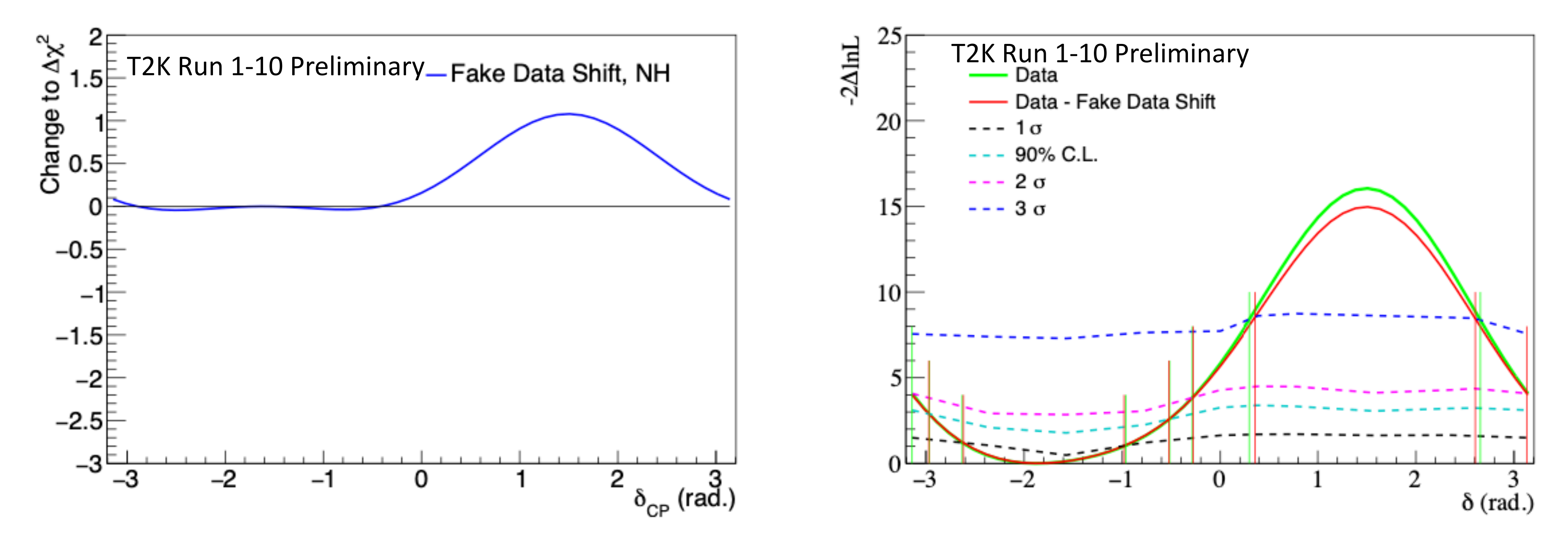
- Very small bias seen with new removal energy uncertainty parametrisation





δ_{CP} robustness study details

- Test impact of alternate model on δ_{CP} result by subtracting change in $\Delta\chi^2$ seen in alternate model study from data $\Delta\chi^2$ distribution
- We report the largest shift in either direction on both left and right edges of 90% interval



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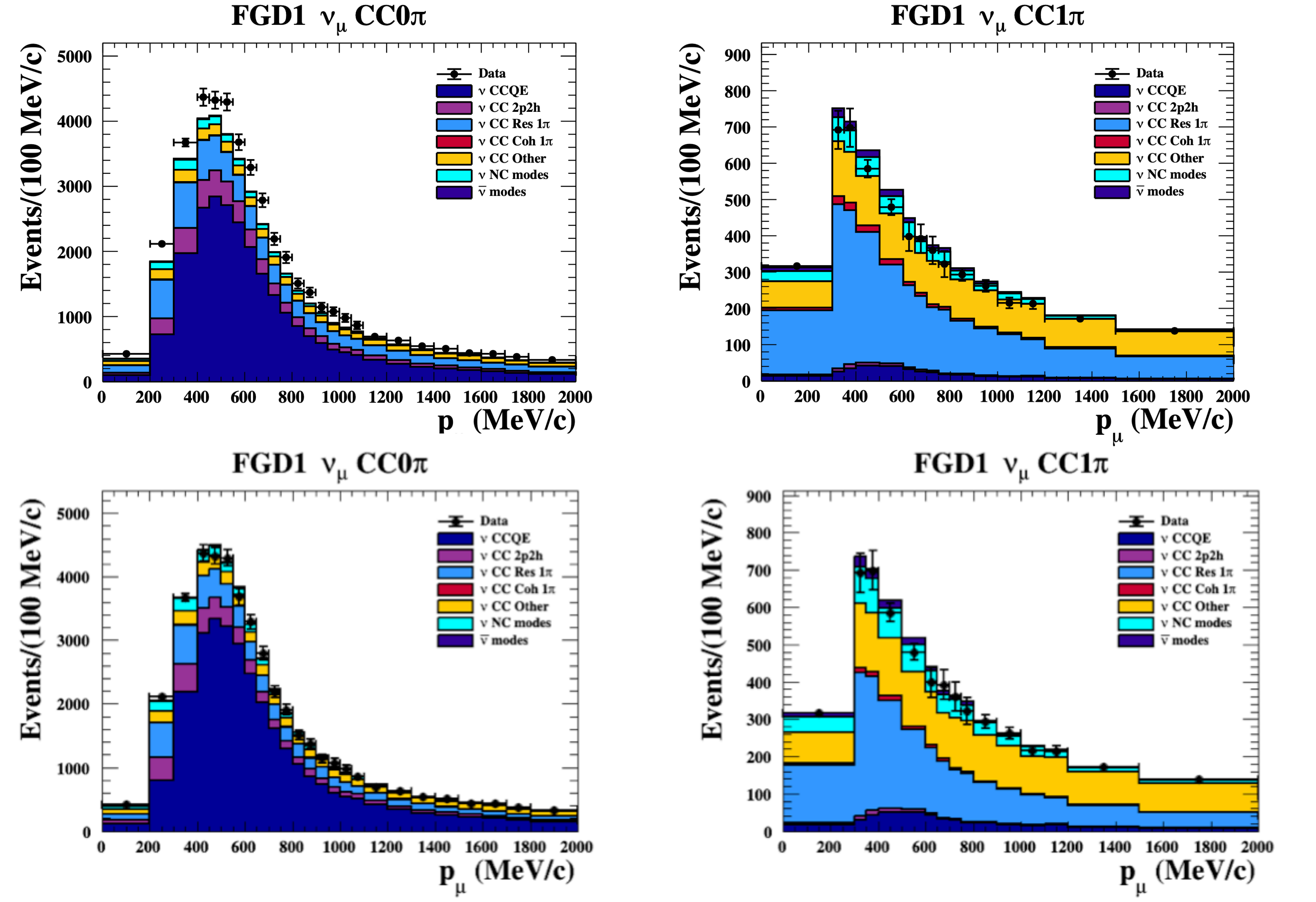
All ND data samples pre- and post-fit

nb:
FHC is ν-mode
RHC is $\bar{\nu}$-mode

Pre-fit

Post-fit



(a) FGD1 FHC ν_μ 0π

(b) FGD1 FHC ν_μ 1π

All ND data samples pre- and post-fit

nb:
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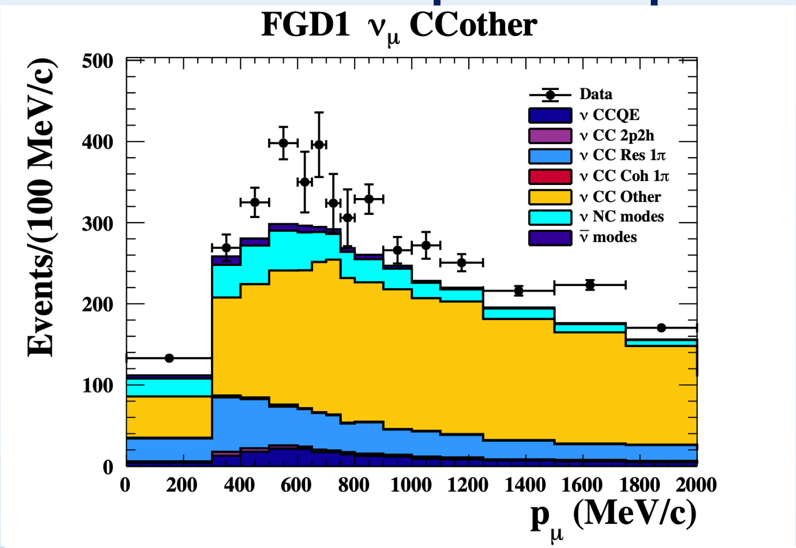
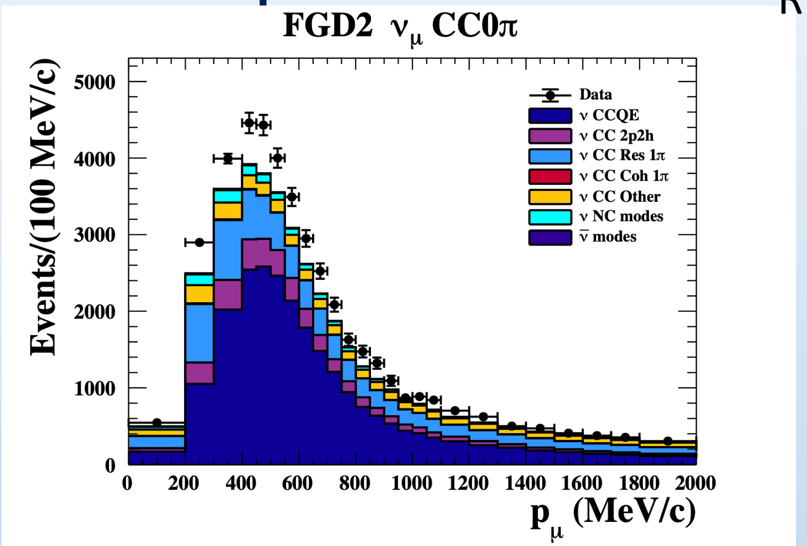
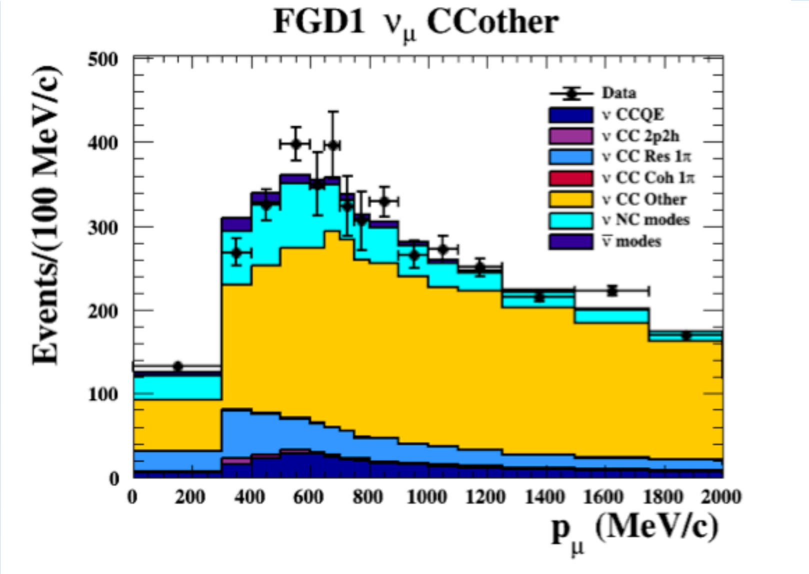
RHC is $\bar{\nu}$-mode

Pre-fit

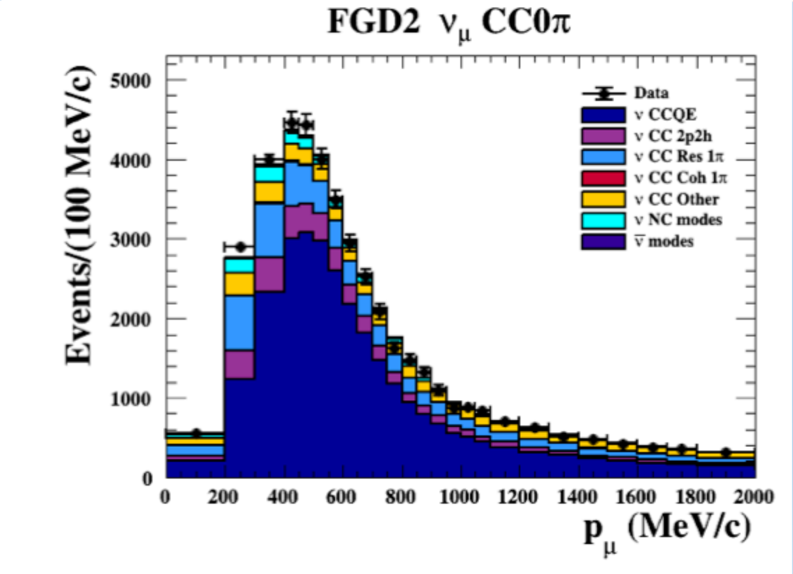




Post-fit



(c) FGD1 FHC ν_μ Other



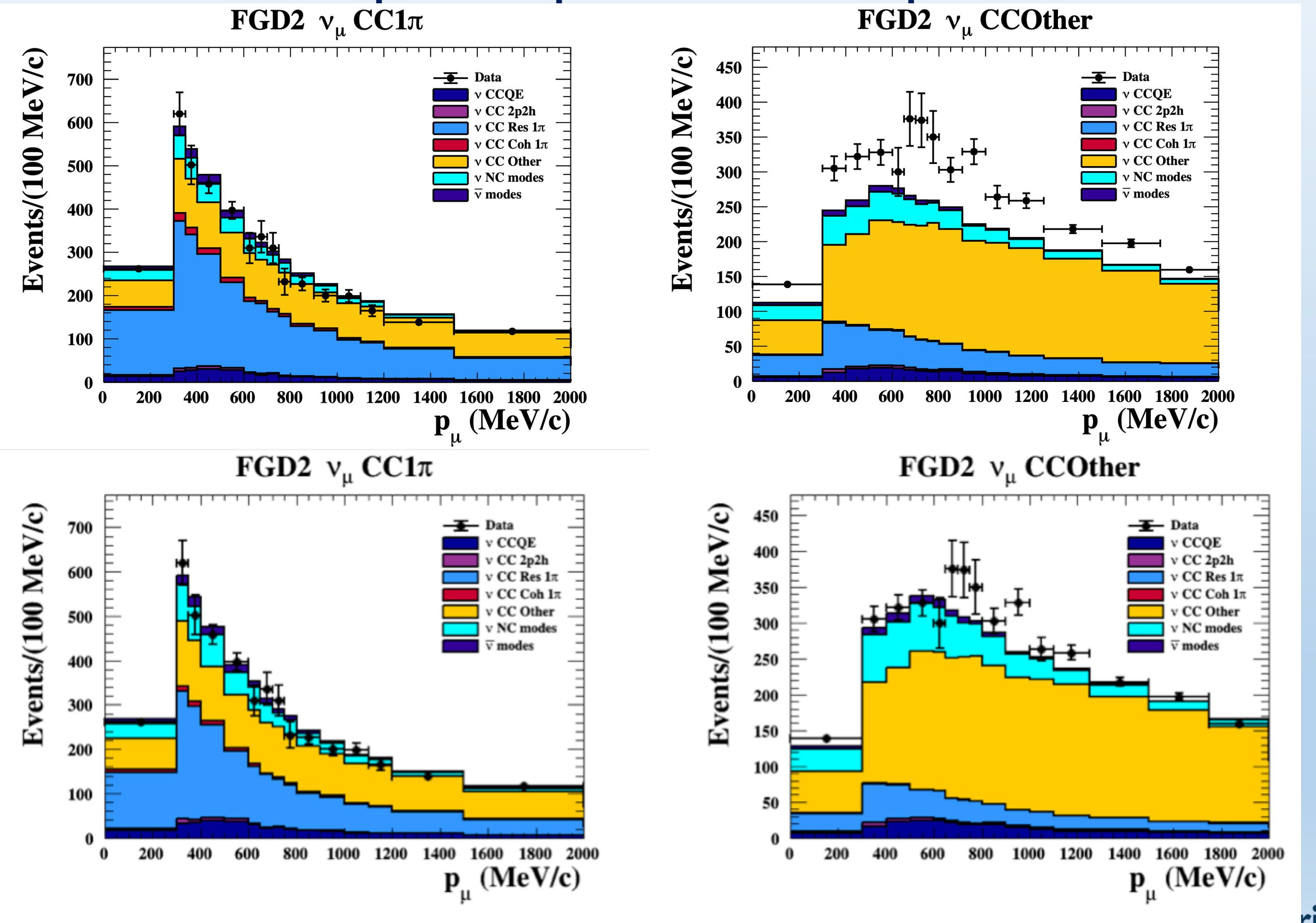
(d) FGD2 FHC ν_μ 0π

All ND data samples pre- and post-fit

nb:
FHC is ν-mode
RHC is $\bar{\nu}$-mode

Pre-fit

Post-fit



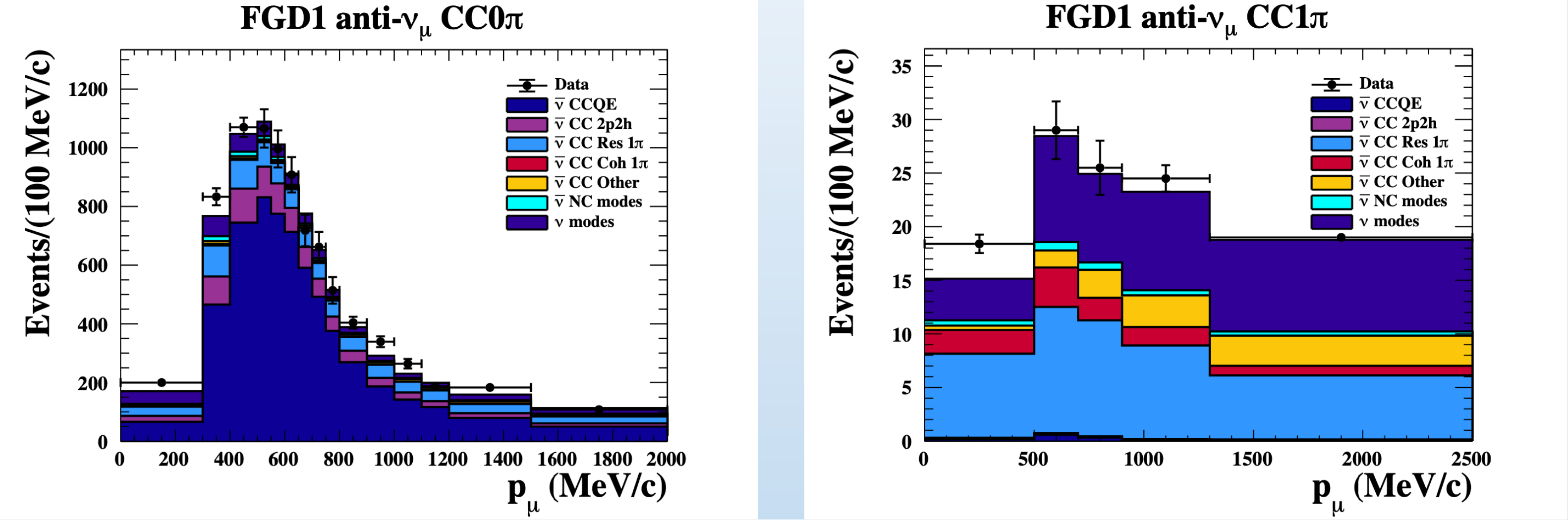
(e) FGD2 FHC ν_μ 1π

(f) FGD2 FHC ν_μ Other

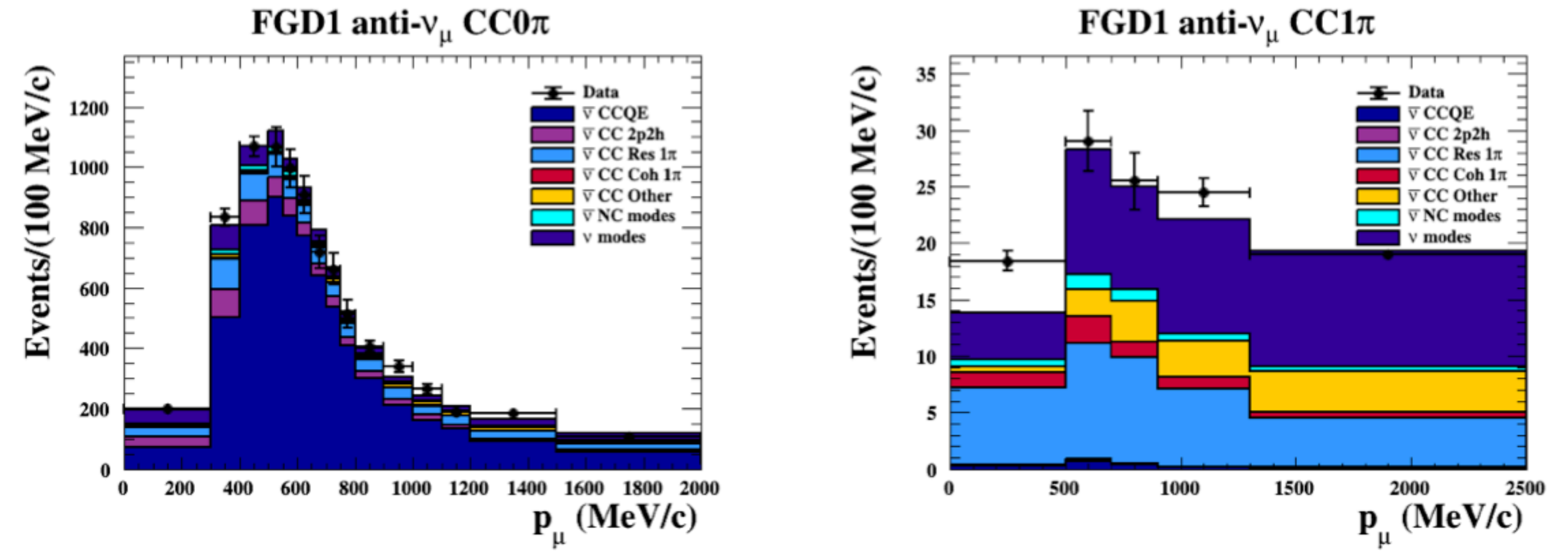
All ND data samples pre- and post-fit

nb:
FHC is ν-mode
RHC is $\bar{\nu}$-mode

Pre-fit



Post-fit



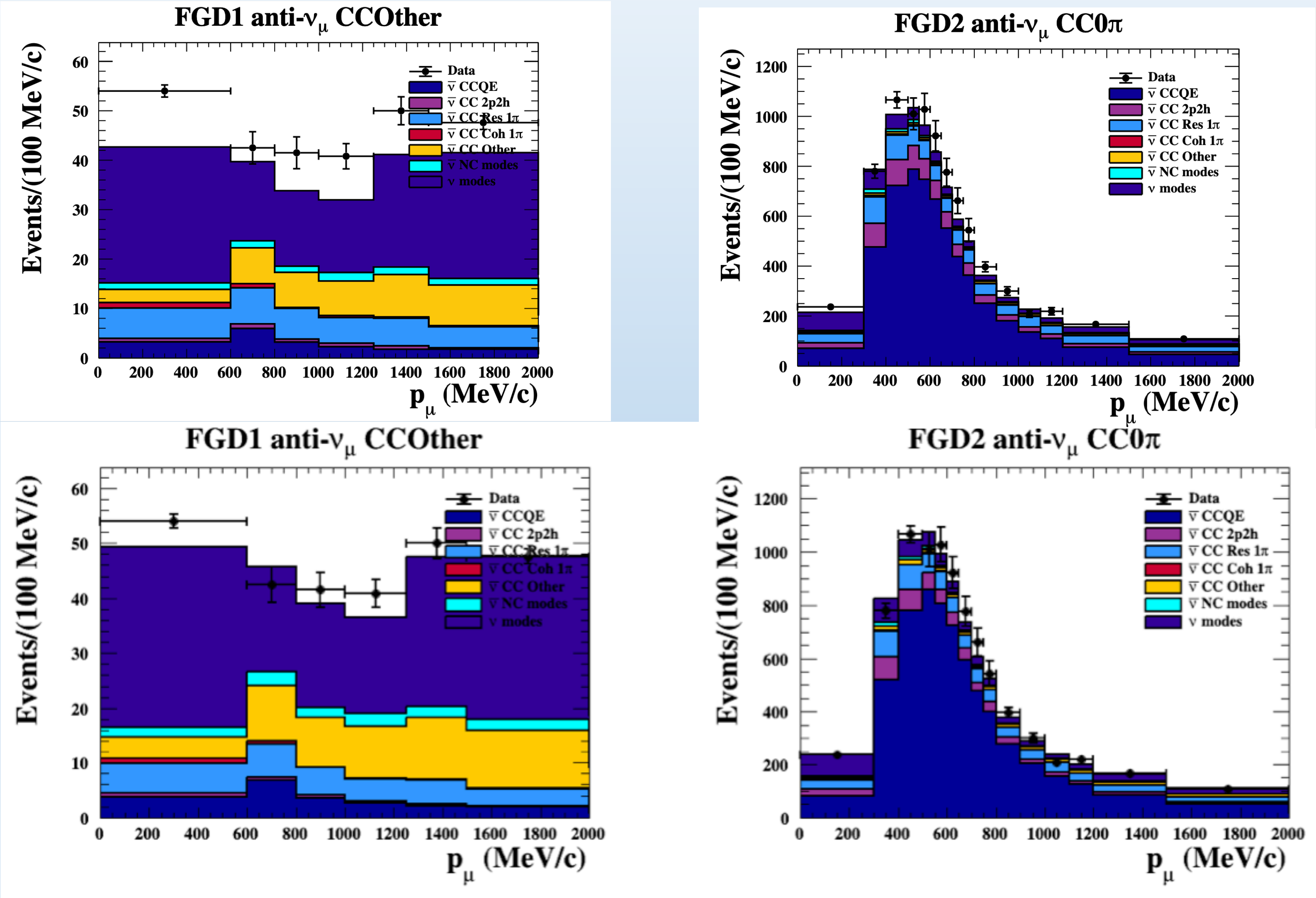
(a) FGD1 RHC $\bar{\nu}_\mu$ 0π (b) FGD1 RHC $\bar{\nu}_\mu$ 1π

All ND data samples pre- and post-fit

nb:
FHC is ν-mode
RHC is $\bar{\nu}$-mode

Pre-fit

Post-fit



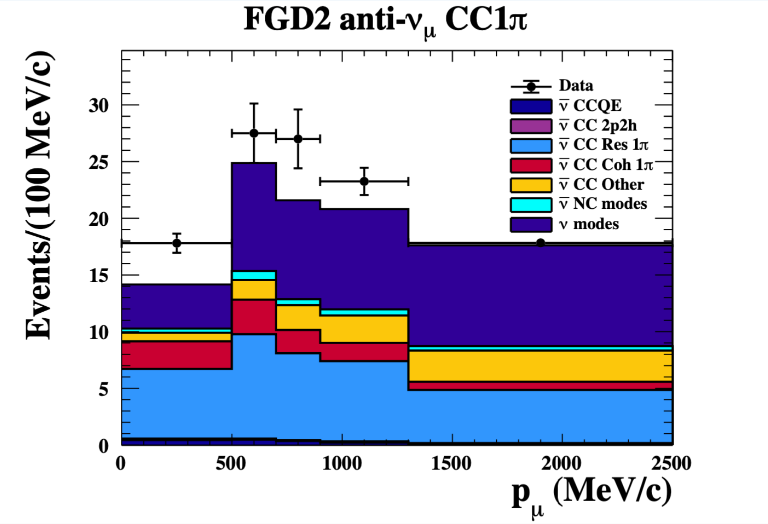
(c) FGD1 RHC $\bar{\nu}_\mu$ Other

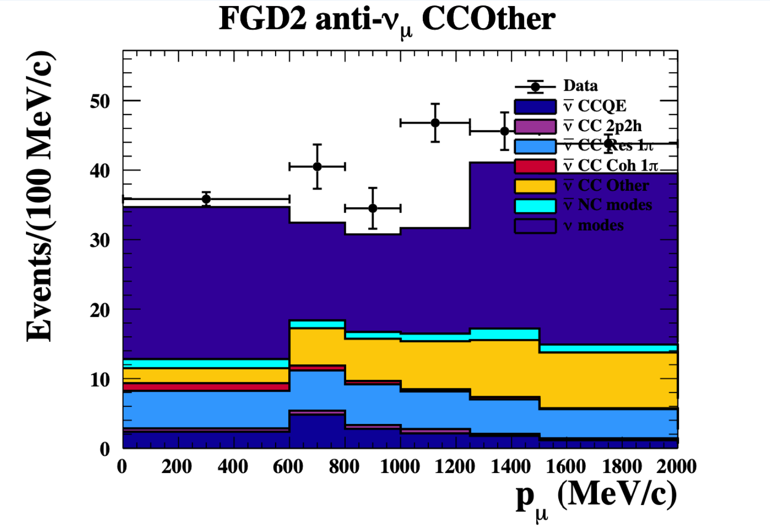
(d) FGD2 RHC $\bar{\nu}_\mu$ 0π

All ND data samples pre- and post-fit

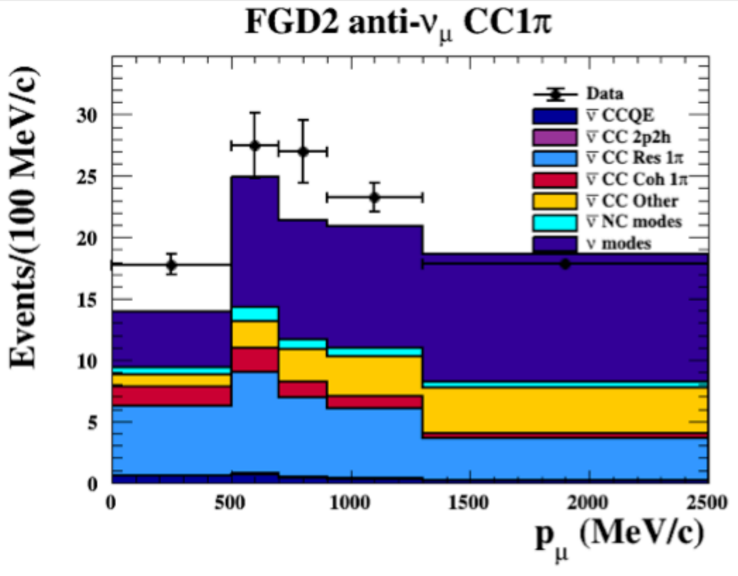
nb:
FHC is ν-mode
RHC is $\bar{\nu}$-mode

Pre-fit

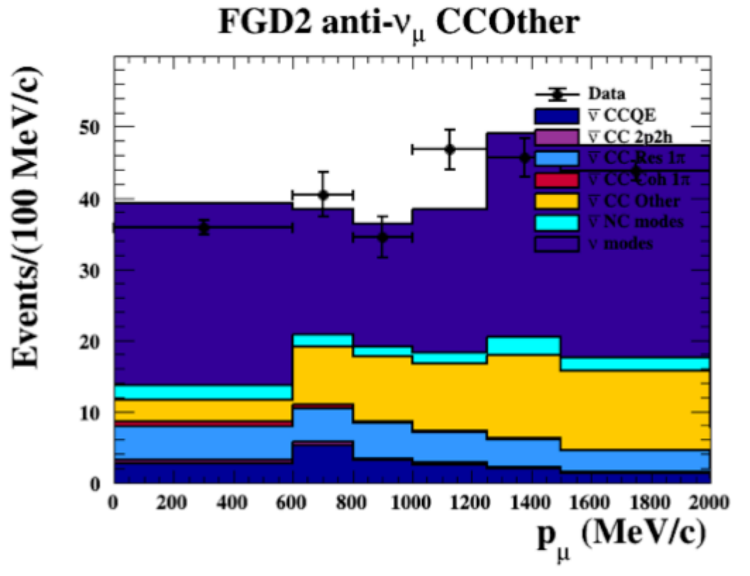




Post-fit



(e) FGD2 RHC $\bar{\nu_\mu}$ 1π

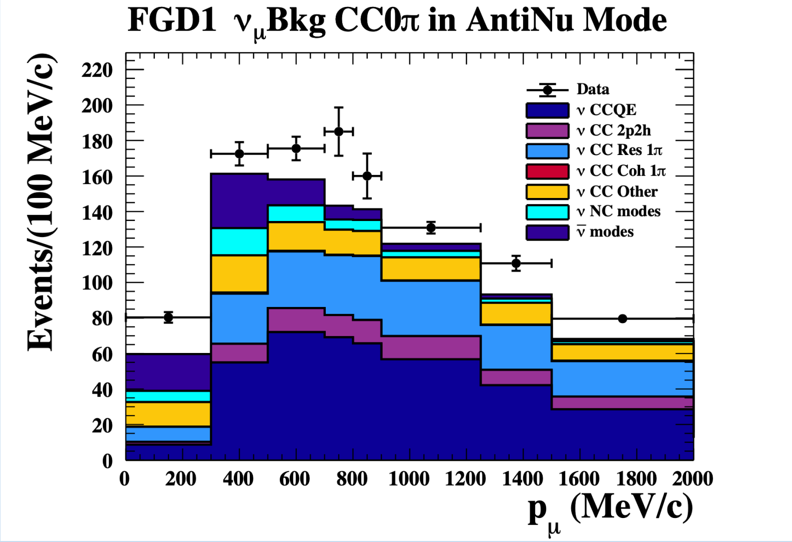


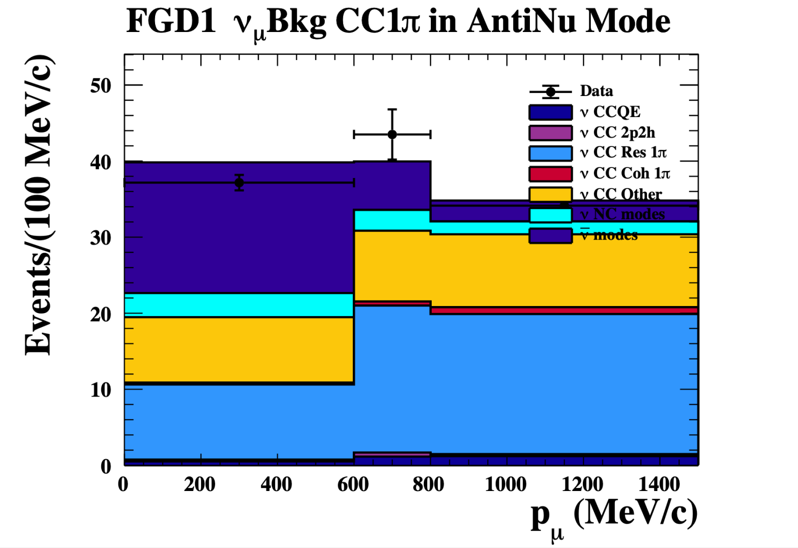
(f) FGD2 RHC $\bar{\nu_\mu}$ Other

All ND data samples pre- and post-fit

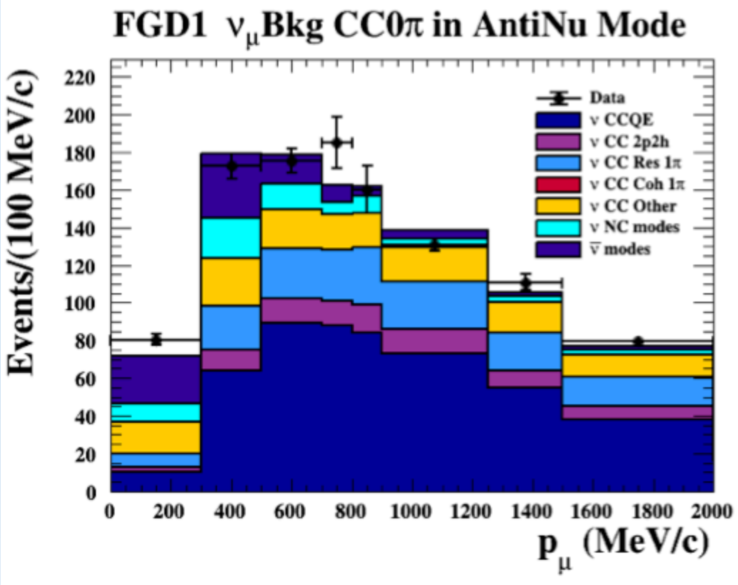
nb:
FHC is ν-mode
RHC is $\bar{\nu}$-mode

Pre-fit

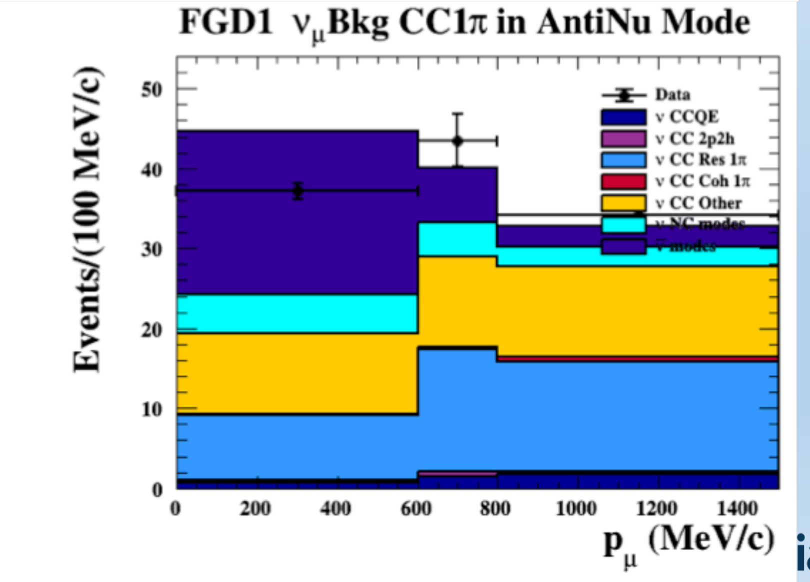




Post-fit



(a) FGD1 RHC ν_μ 0π



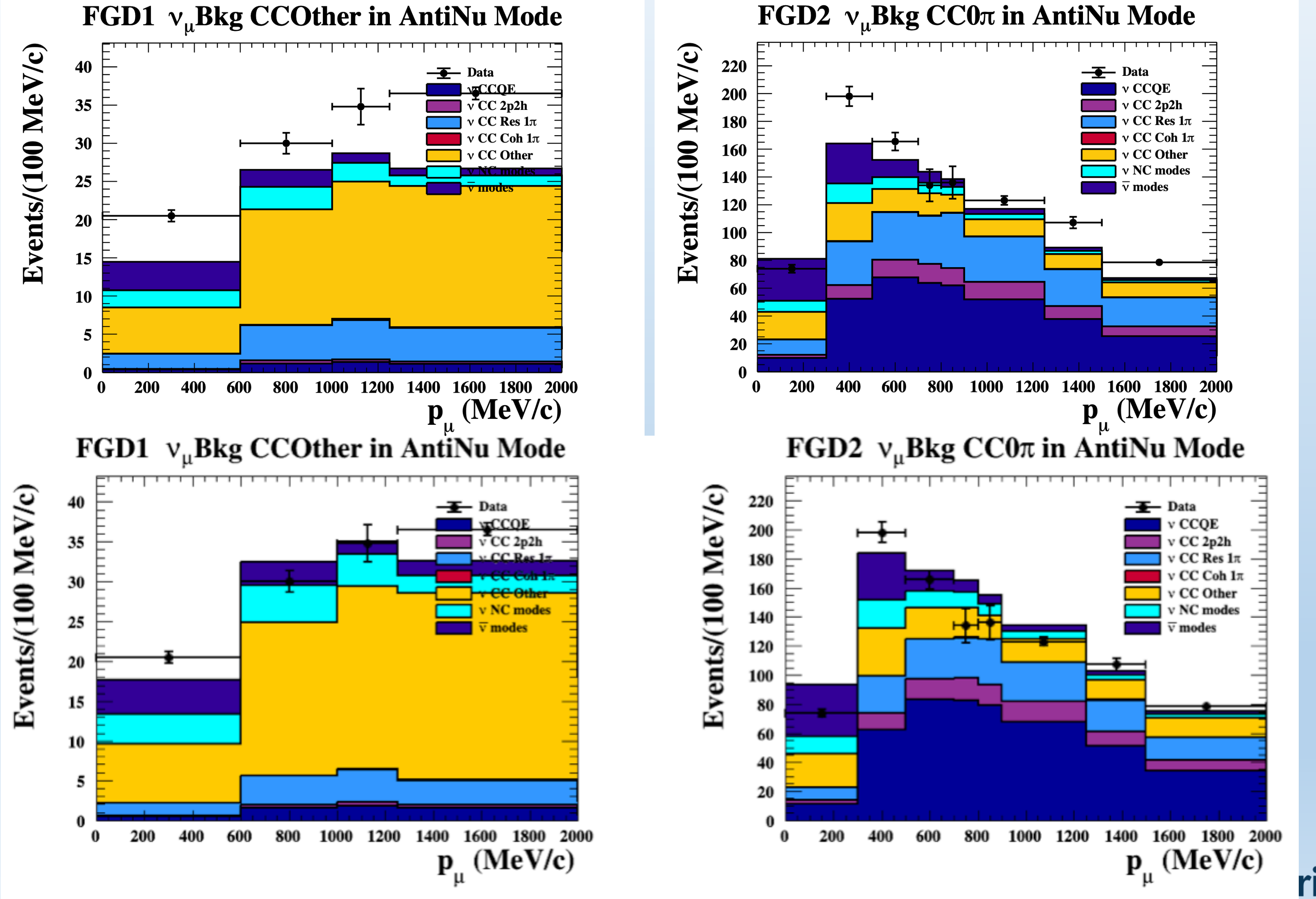
(b) FGD1 RHC ν_μ 1π

All ND data samples pre- and post-fit

nb:
FHC is ν-mode
RHC is $\bar{\nu}$-mode

Pre-fit

Post-fit



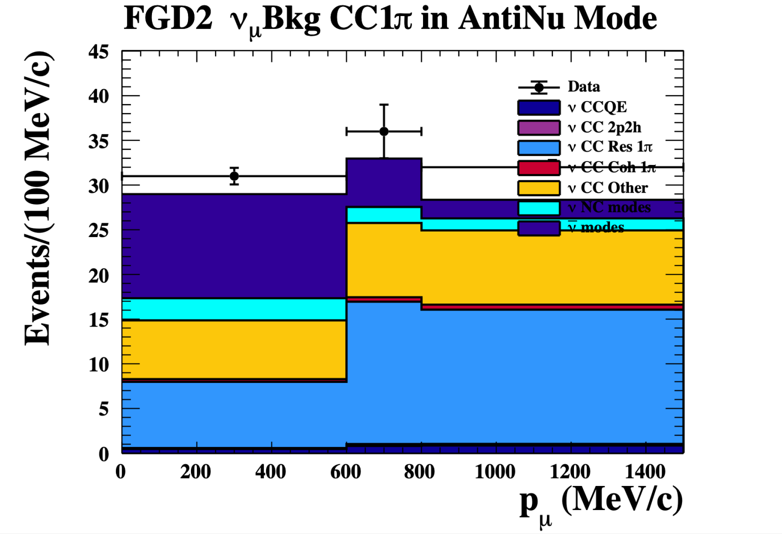
(c) FGD1 RHC ν_μ Other

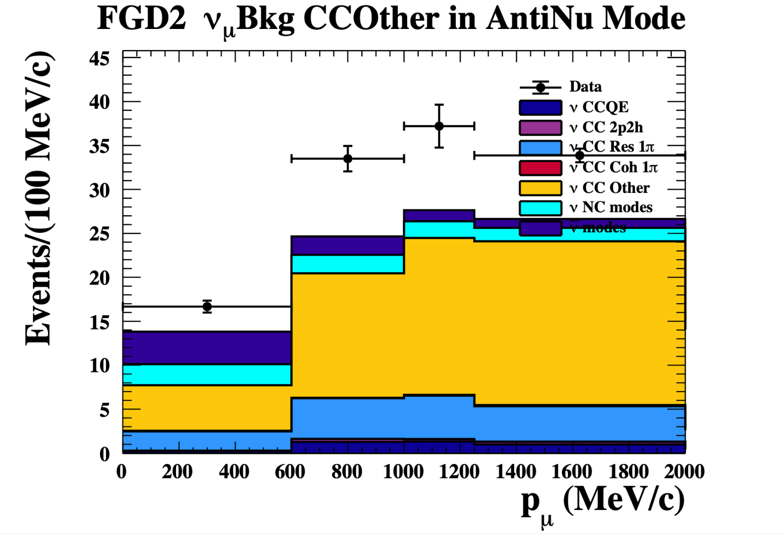
(d) FGD2 RHC ν_μ 0π

All ND data samples pre- and post-fit

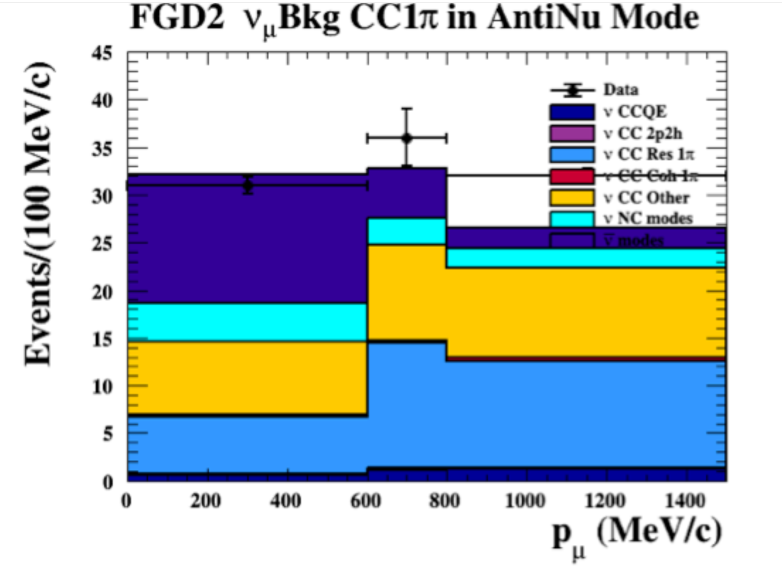
nb:
FHC is ν-mode
RHC is $\bar{\nu}$-mode

Pre-fit

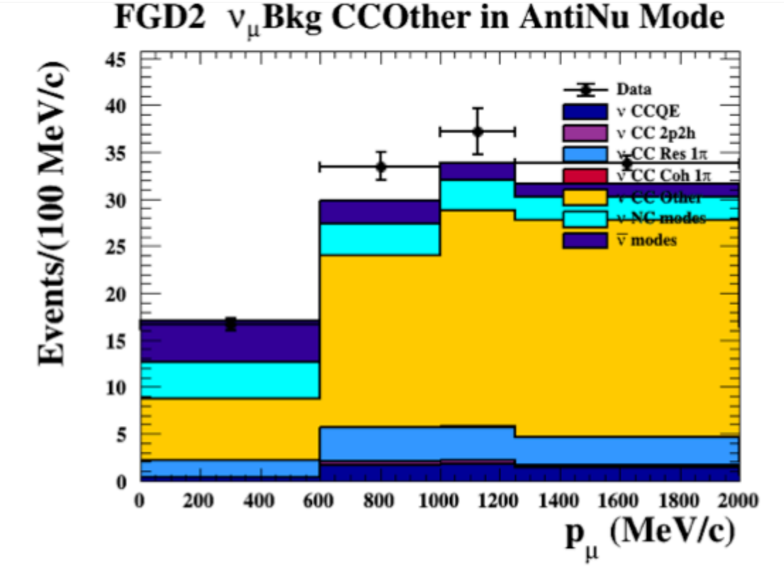




Post-fit

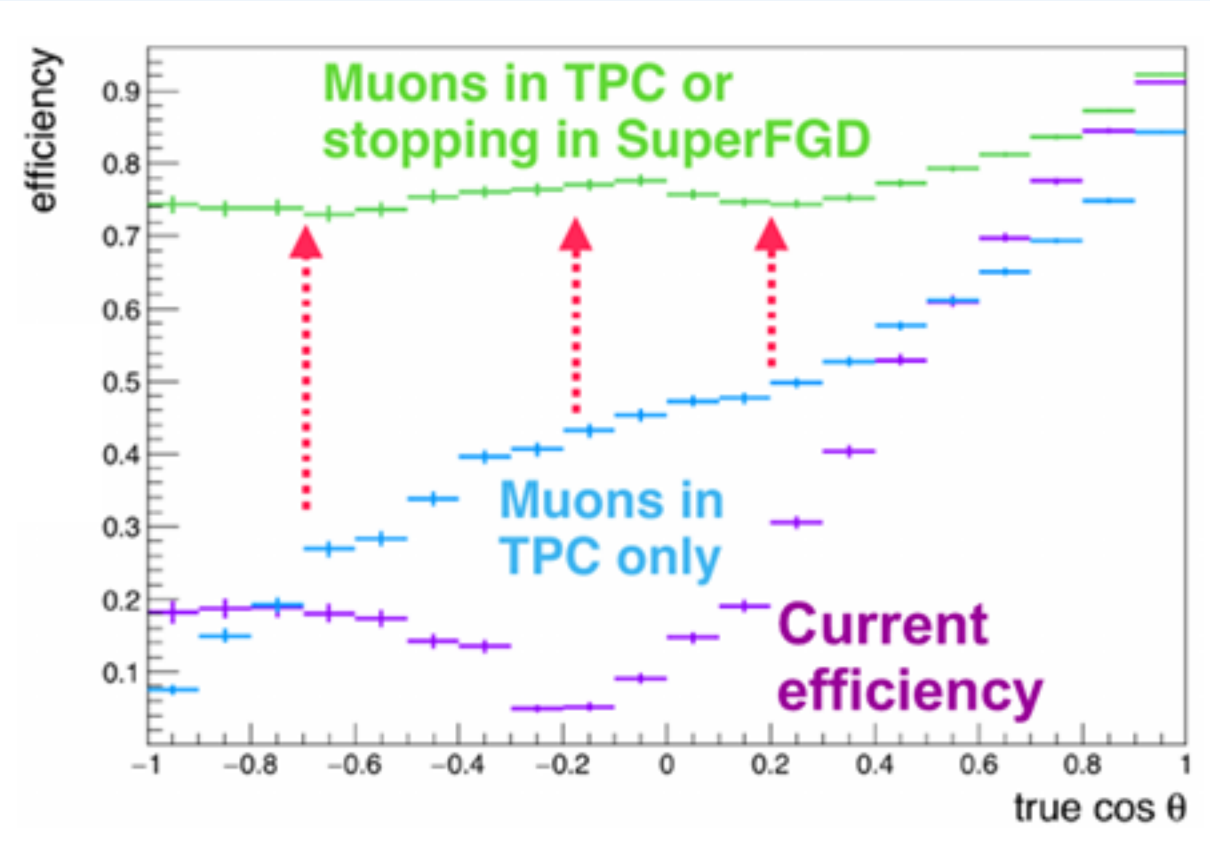


(e) FGD2 RHC ν_μ 1π



(f) FGD2 RHC ν_μ Other

ND280 angular efficiency before and after upgrade



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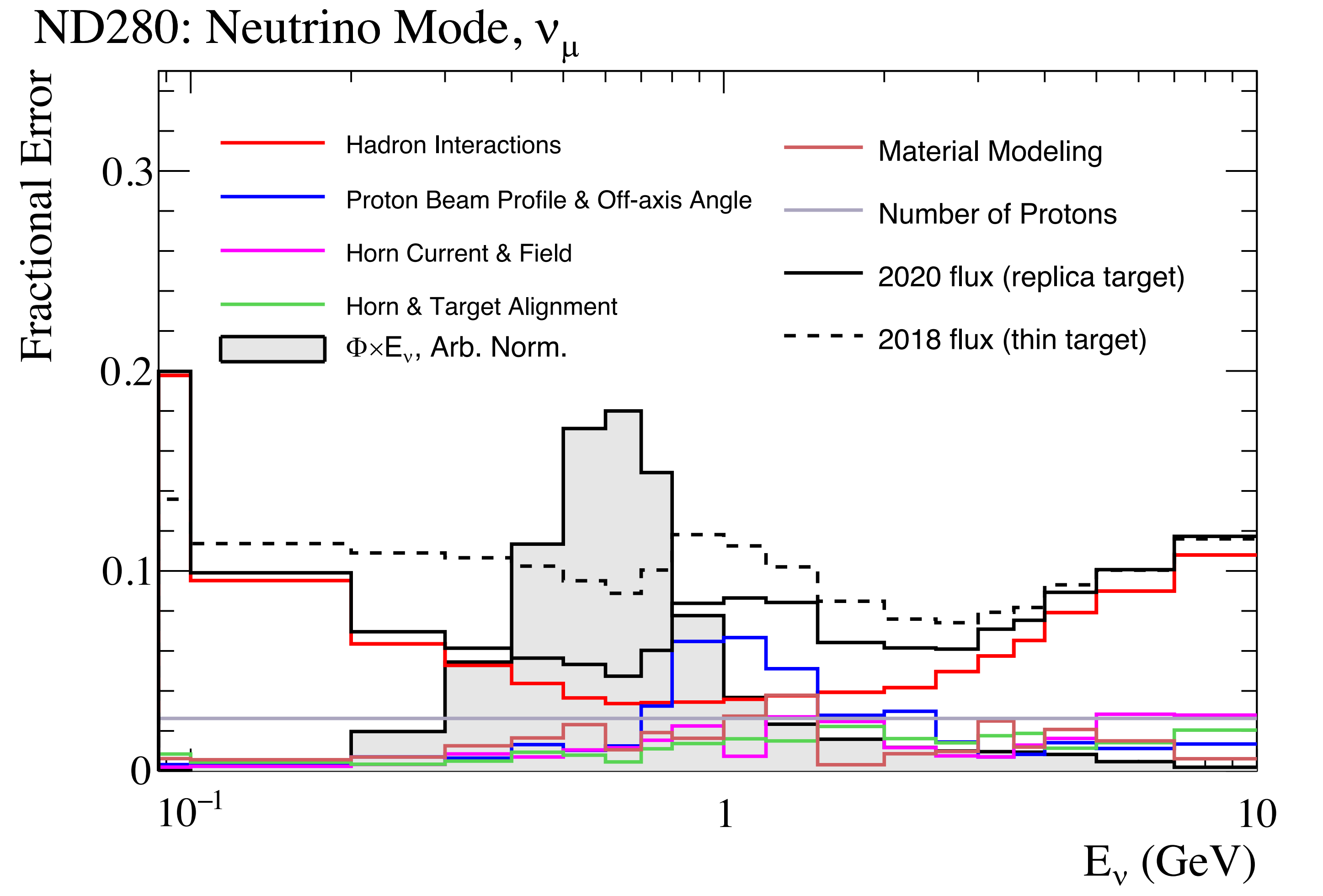
Flux old vs new component contributions and values



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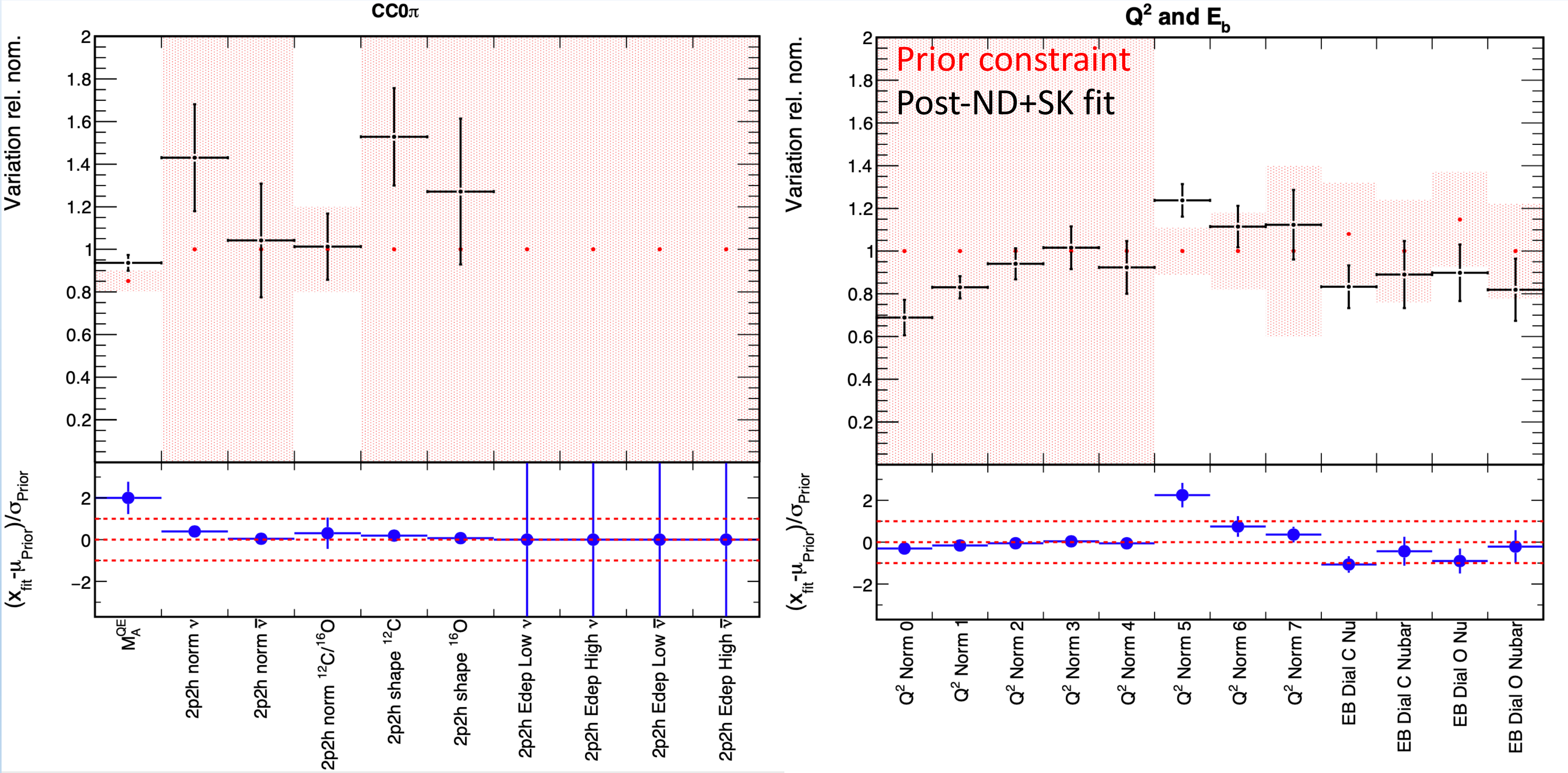
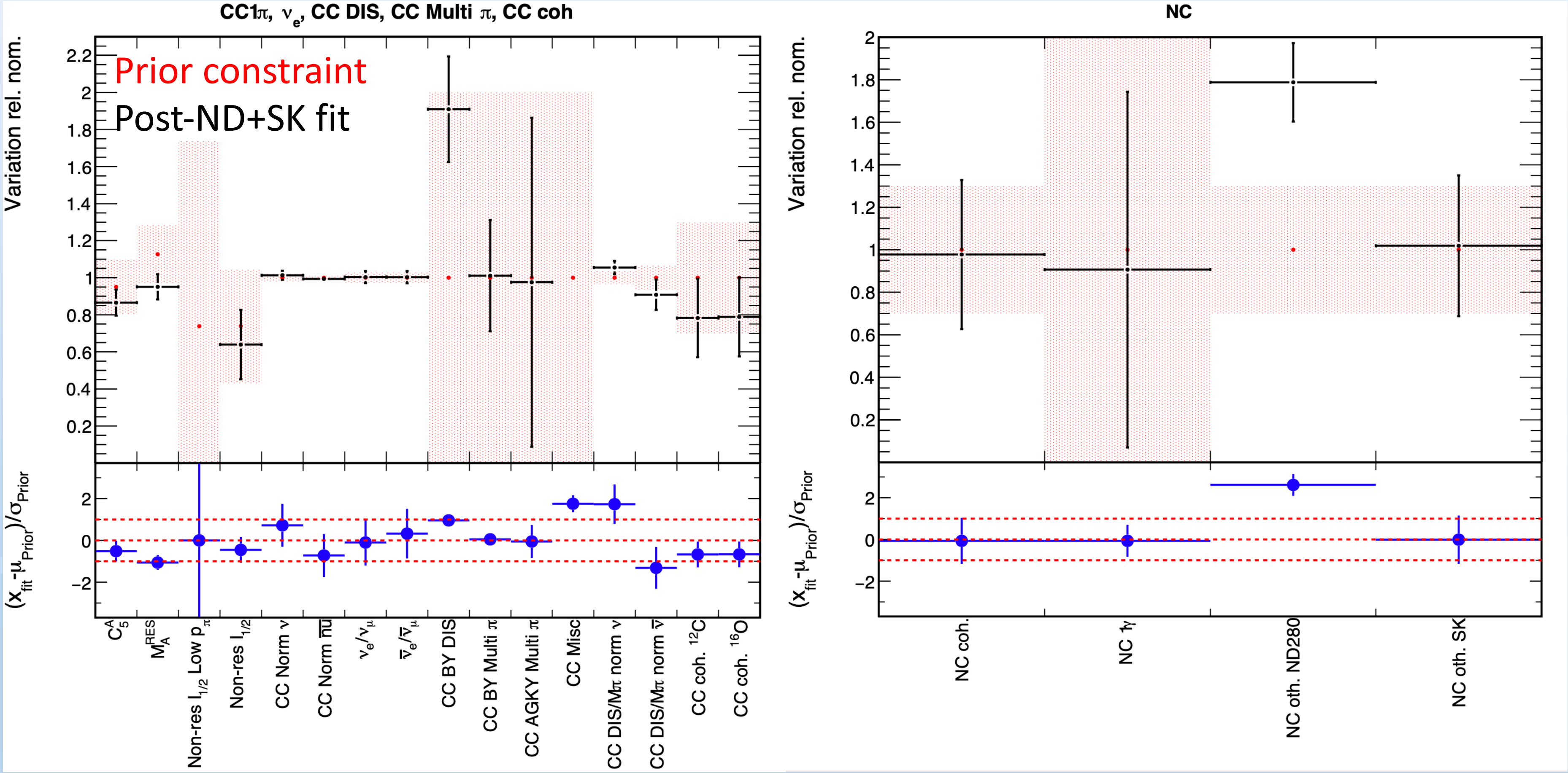
Pre- vs post-fit xsec parameter values



Pre- vs post-fit xsec parameter values



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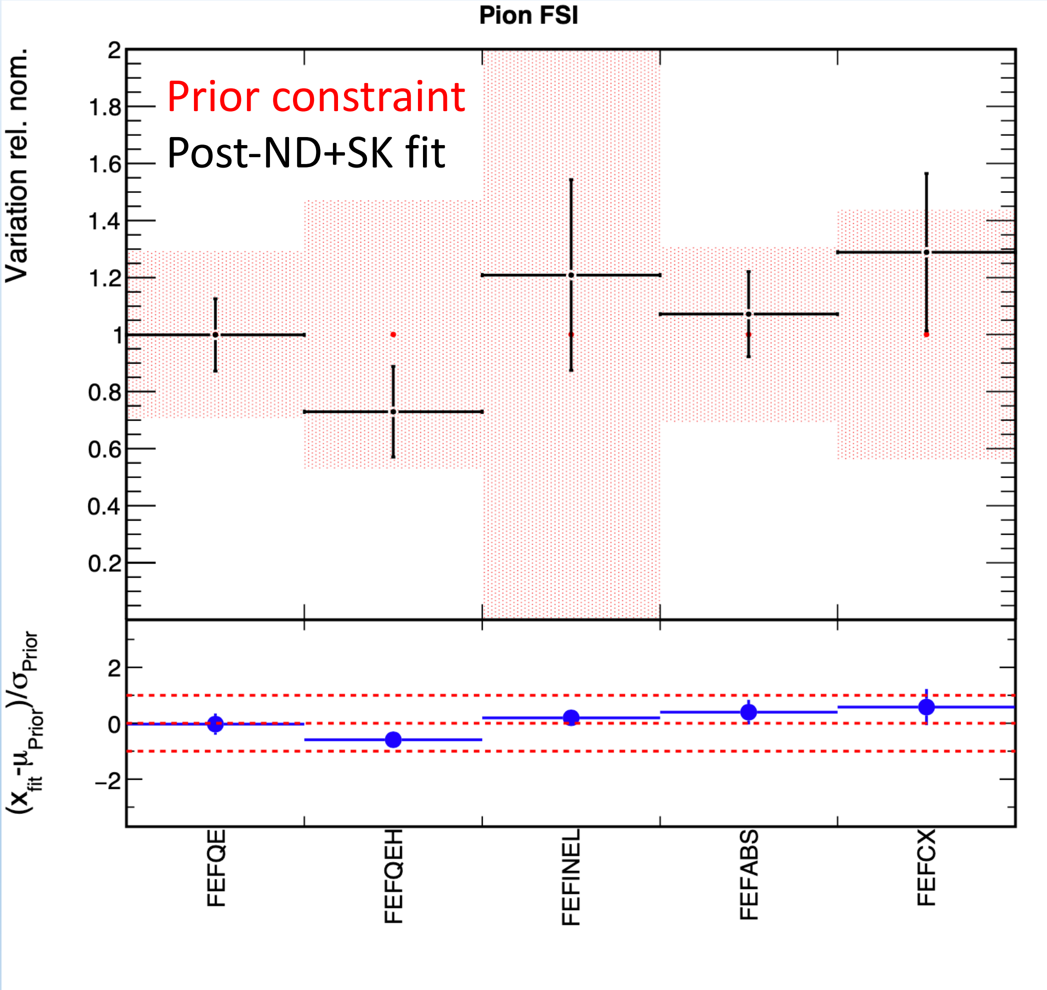
Pre- vs post-fit xsec parameter values

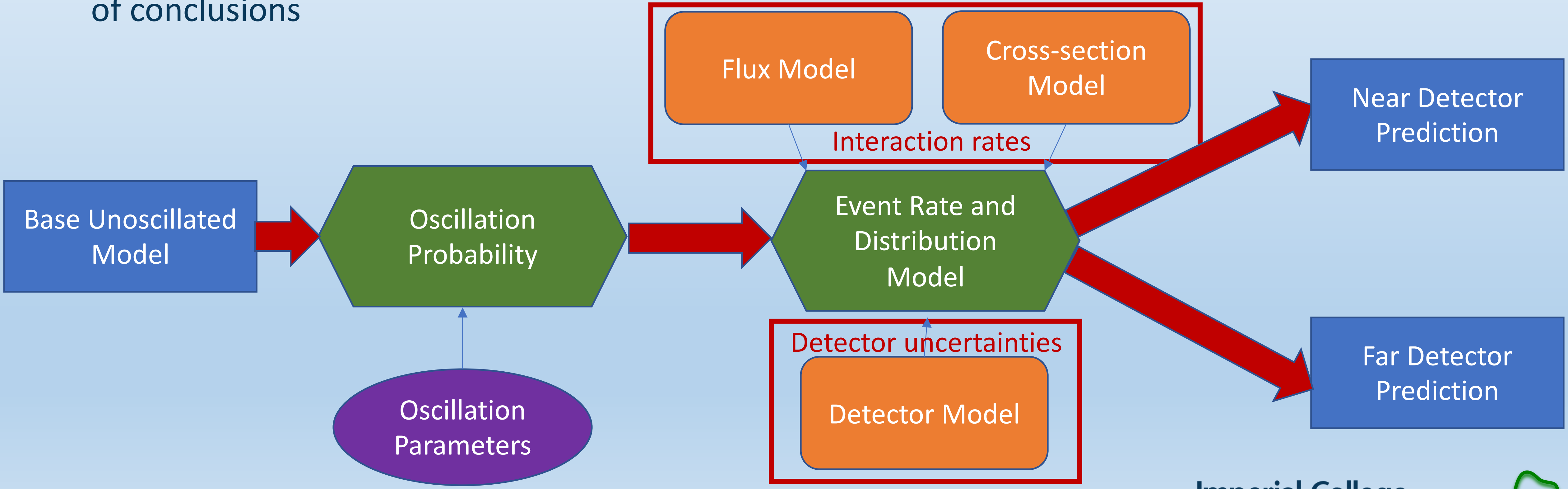


Tuned Spectral Function Model

- The starting point for our CCQE interaction model is the Benhar Spectral Function (SF) for Carbon and Oxygen (Nucl. Phys. A, **579,** 493-517)
- Numerous CC0π cross section measurements have shown a need for a suppression at low Q^2 (e.g. Phys. Rev. D **101**, 112004; Phys. Rev. D, **99**, 012004)
  - We introduce parameters allowing *ad-hoc* low Q^2 suppression on the SF predictions with no prior constraint
  - The impact of giving this suppression to the CCQE rather than other processes is tested within our robustness studies
  - The central values for the parameters for supplementary studies is chosen based on a tune to global cross-section data
- A large part of the SF is built from exclusive electron scattering (e,e'p) data where the target nucleon is a *proton*
  - To account for instead having a target *neutron* in neutrino interactions we shift the position of shells in the SF in accordance with theoretical mean-field shell model predictions
  - Parameters to separately shift the shells are included (separate parameters for protons and neutrons on Carbon and Oxygen) with prior uncertainties derived mostly from e,e'p data

How to do a neutrino oscillation analysis

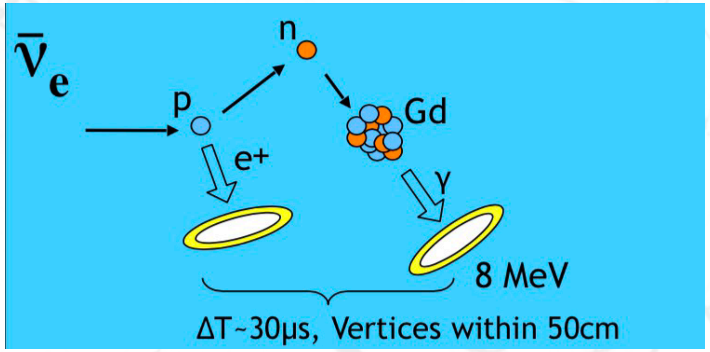
- Like any particle physics experiment make prediction and compare to data
- Need to ensure experiment can constrain non-oscillation elements of model
  - Accurate modelling of flux, cross-section and detector model uncertainties key to preventing bias
- T2K has several fitter groups who implement same model and cross-check
  - Analysis differences between groups (e.g. simultaneous ND-FD fit vs sequential) test robustness of conclusions

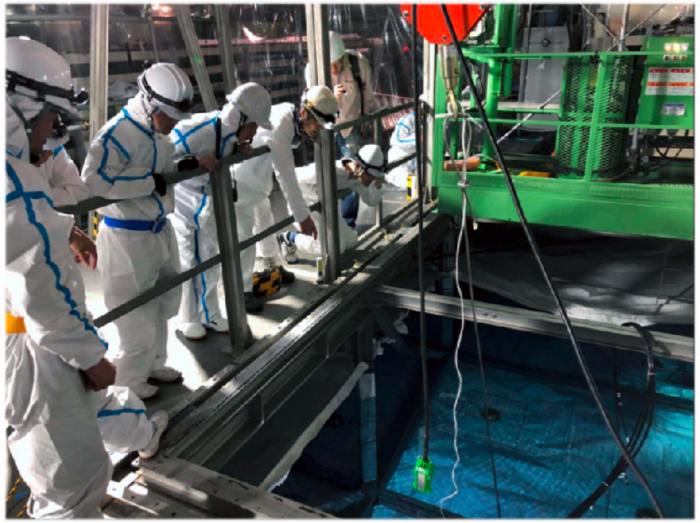


SK-Gd

SK Gadolinium

- SK Gadolinium project
  - enhance neutron detection improve low-energy ν_e detection (non-T2K goal).
  - may provide wrong-sign background constraint in $\bar{\nu}_e$
    - more data samples.
- Leak repairs to SK tank finished in 2019.
- Load $Gd_2(SO_4)_3$ in stages up to 0.2%.
- Loading to start in 2020.

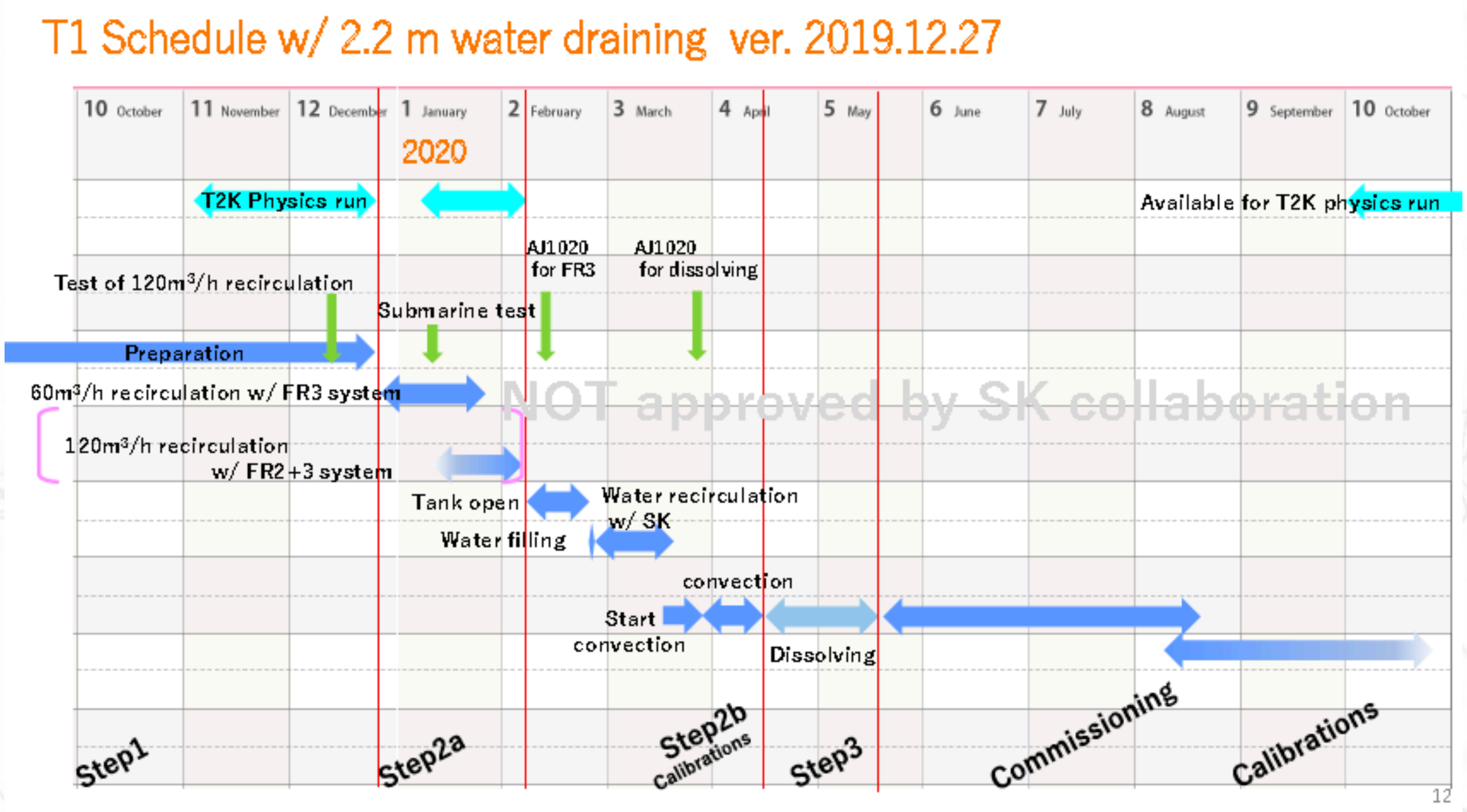




Patrick Dunne (p.dunne12@imperial.ac.uk)

SK-Gd

SK-Gd



First attempt to dissolve Gd salt stopped because of COVID-19

Patrick Dunne (p.dunne12@imperial.ac.uk)

X

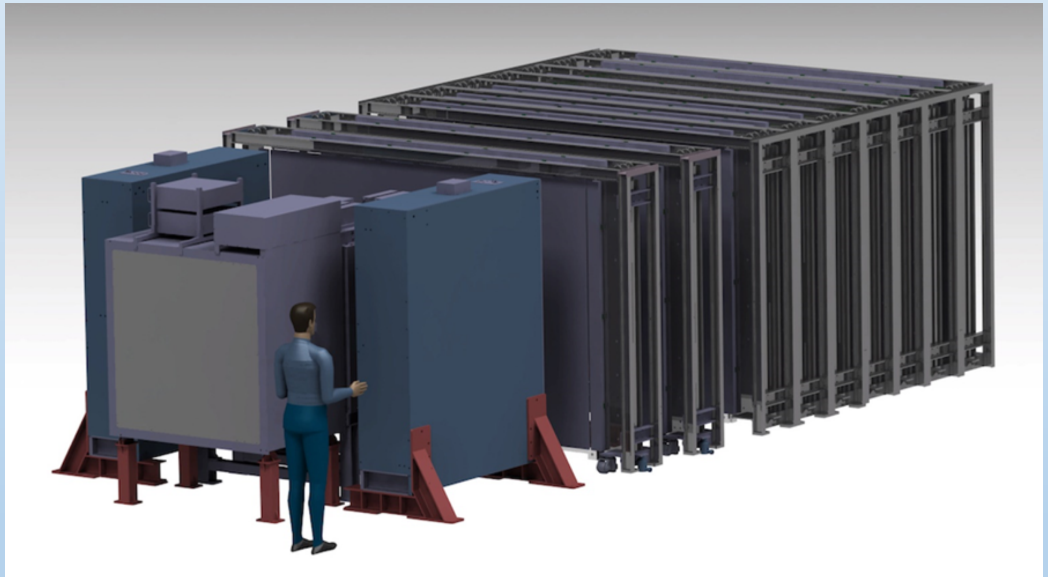
Statistics

- Three analyses all cross-checked against each other

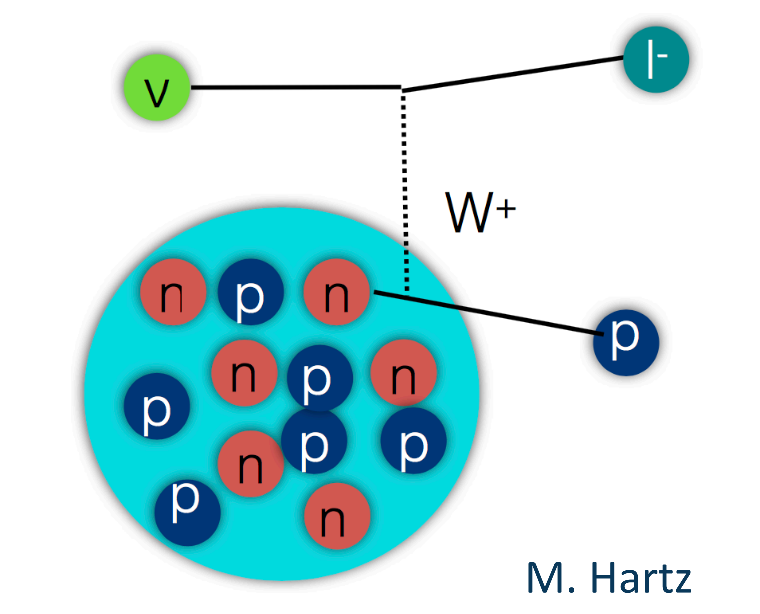
	Analysis 1	Analysis 2	Analysis 3
Kinematic variables for 1Re sample at SK	Erec-θ	p_e-θ	Erec-θ
Likelihood	Binned Poisson Likelihood Ratio	Binned Poisson Likelihood Ratio	Binned Poisson Likelihood Ratio
Likelihood Optimization	Markov Chain Monte Carlo	Gradient descent and grid scan	Gradient descent and grid scan
Contours/limits produced	Bayesian Credible Intervals	Frequentist Confidence Intervals with Feldman-Cousins (credible intervals supplemental)	Frequentist Confidence Intervals with Feldman-Cousins
Mass Hierarchy Analysis	Bayes factor from fraction of MCMC points in each hierarchy	Bayes factor from likelihood integration	Frequentist p-value from generated PDF
Near Detector Information	Simultaneous joint fit	Constraint Matrix	Constraint Matrix
Systematics Handling	Simultaneous fit then marginalization	Marginalization during fit	Marginalization during fit

WAGASCI/Baby MIND/NINJA

- WAGASCI uses water filled plastic scintillator lattice to measure H_2O cross-section
- BabyMIND downstream is a magnetized tracking detector for muons giving charge identification and momentum measurement
- NINJA is a moveable emulsion detector with very low momentum threshold to study neutrino-water interactions
- Located on B2 level of ND280 giving access to a more ‘on-axis’ slightly higher energy flux than SK



Detecting neutrinos



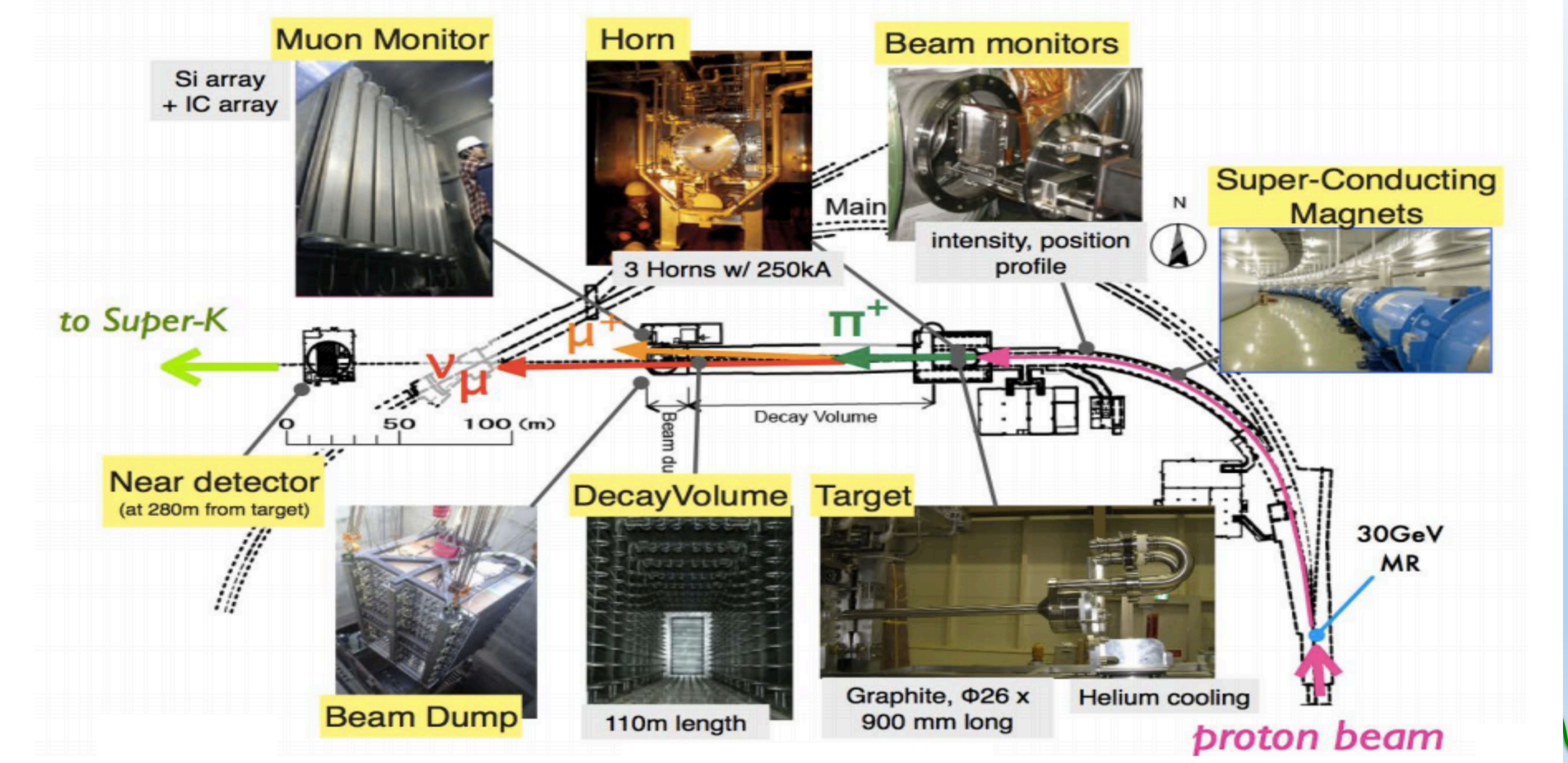
- Use charged-current neutrino-nucleus interactions
- Detect energetic final state lepton
  - Gives kinematic information and flavour ID
- Oscillation effects vary with E_ν
  - Recoil hadrons often below detection threshold and nuclear effects important so hard to reconstruct
- Construct variable as close to true energy as possible

- Assume quasi-elastic scattering from single bound nucleon (CCQE):

$$E_\upsilon^{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_l}{2(m_n - E_b - E_l + p_l \cos\theta_l)}$$

- Only uses particle masses, lepton kinematics and nuclear model

Making a Neutrino Beam

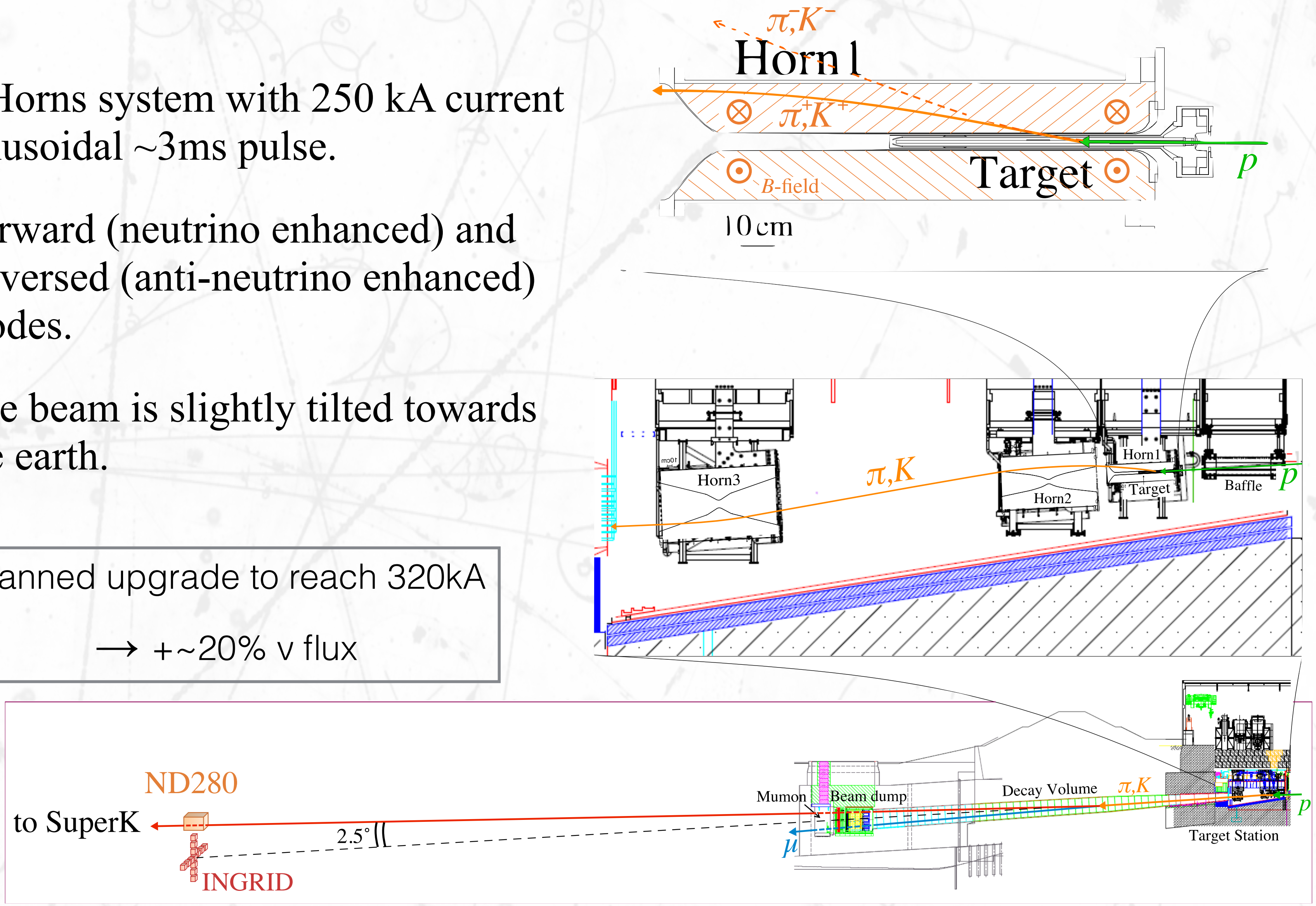


Neutrino beam

- 3 Horns system with 250 kA current sinusoidal ~3ms pulse.
- Forward (neutrino enhanced) and Reversed (anti-neutrino enhanced) modes.
- The beam is slightly tilted towards the earth.

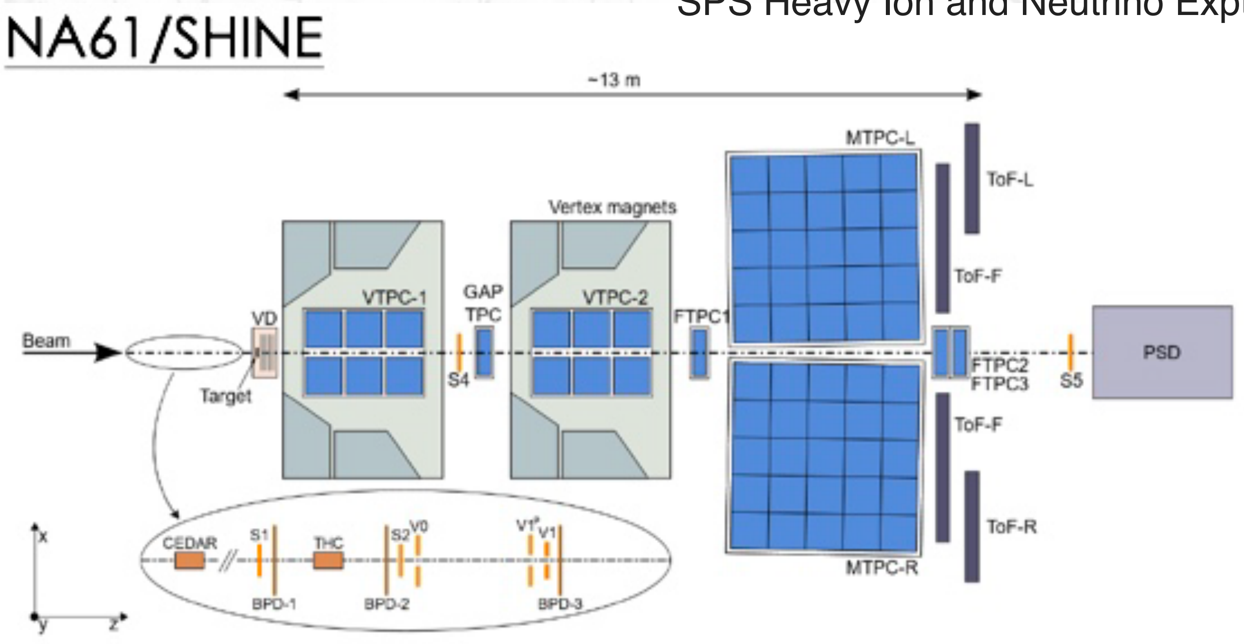
planned upgrade to reach 320kA

⟶ +~20% ν flux



NA61-SHINE

SPS Heavy Ion and Neutrino Expt (SHINE)



NA61/Shine measures the production of pions and kaons as function of the momentum and angle for protons interacting with carbon.

Hadro production experiments carried in equal conditions to ν beam experiments are critical!

Latest measurements made with exact T2K replica target

Beam monitors

Proton beam monitors are essential for protecting beam-line equipment, as well as for understanding and predicting the **neutrino flux**

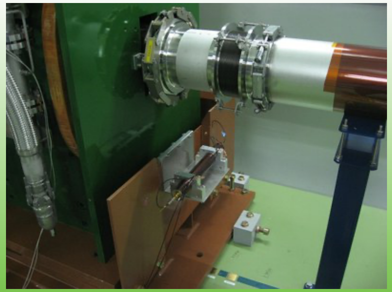
Beam intensity

Current transformers

<2.7% precision

Beam Loss

Sensitive down to 16mW loss



Beam position

Electro Static monitors

450μm precision

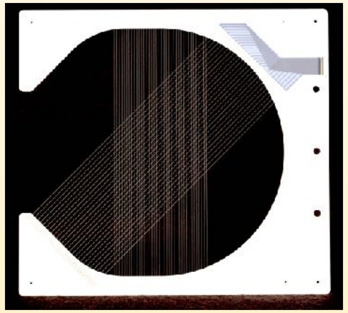
Beam position and profile

Segmented Secondary Emission Monitors

100μm position
200μm width

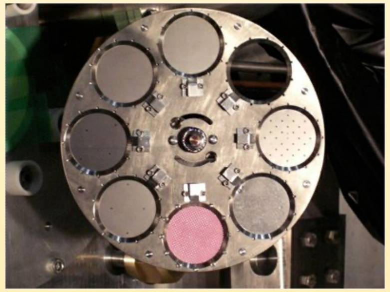
Wire Secondary Emission Monitors

100μm position
200μm width

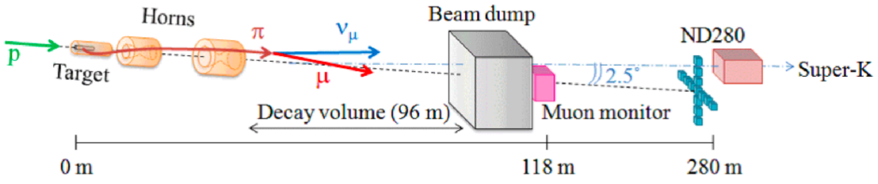


Optical transition radiation

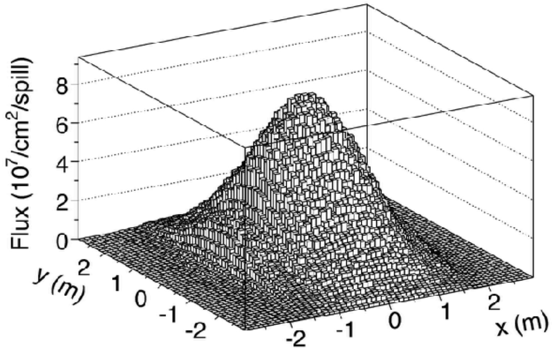
<500μm precision



Muon monitors



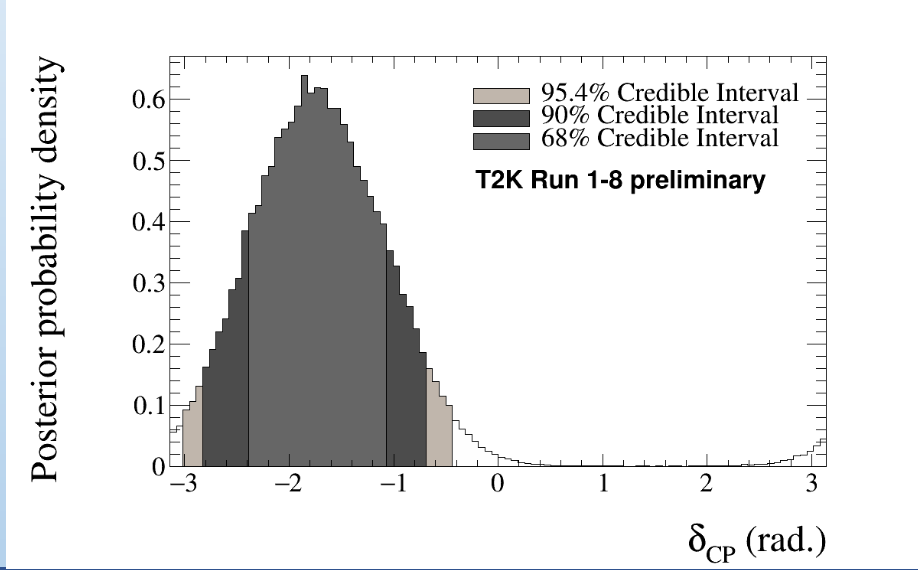
- Monitors the beam direction from the μ produced in π decays.
- Embedded in the beam dump samples the high energy muons.
- ionisation chambers and silicon PIN diodes.
- High irradiation area: $\sim10^{14}$ electrons/cm/month at 750 KW.

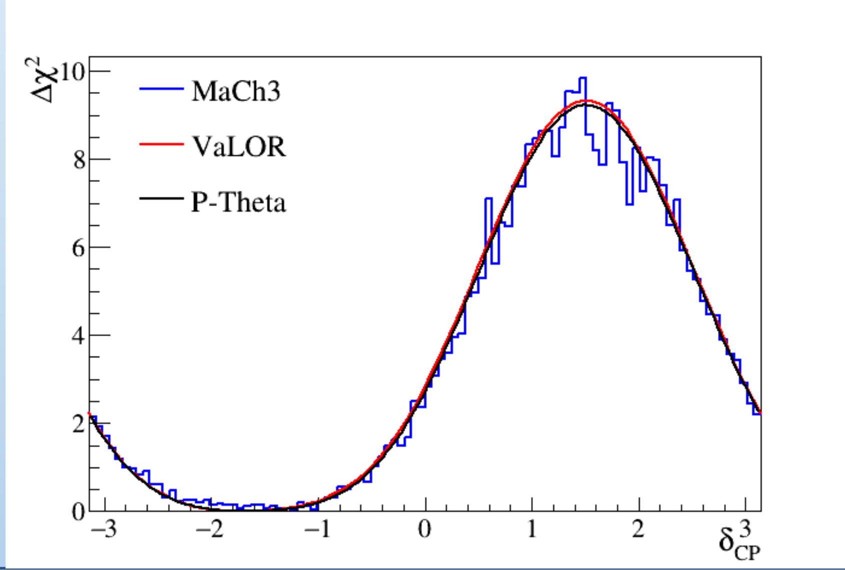


Simulation of fluence

T2K analyses

- T2K has several separate analysis frameworks: some fit near detector first and propagate, others do joint fit
- Joint fit analysis is Bayesian, one of separate fitters is frequentist and the other is a mix
- All three able to construct frequentist confidence intervals for comparisons
  - Very good agreement is seen (this is from previous result for illustration)





Bayesian analysis shows posterior probability density (high values mean more likely this is the "correct" parameter value)	Frequentist analyses show $\Delta\chi^2$ (low values mean better agreement with the data for this parameter value)

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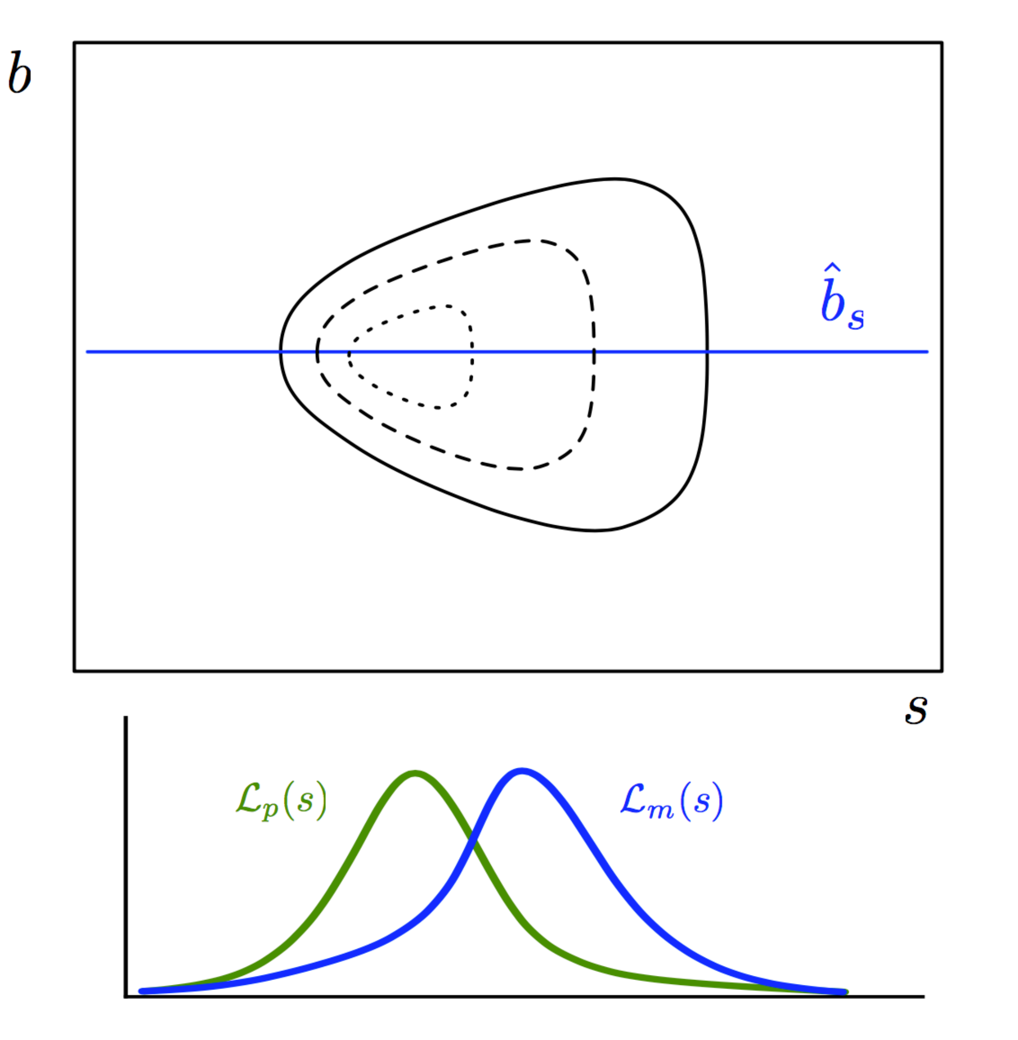
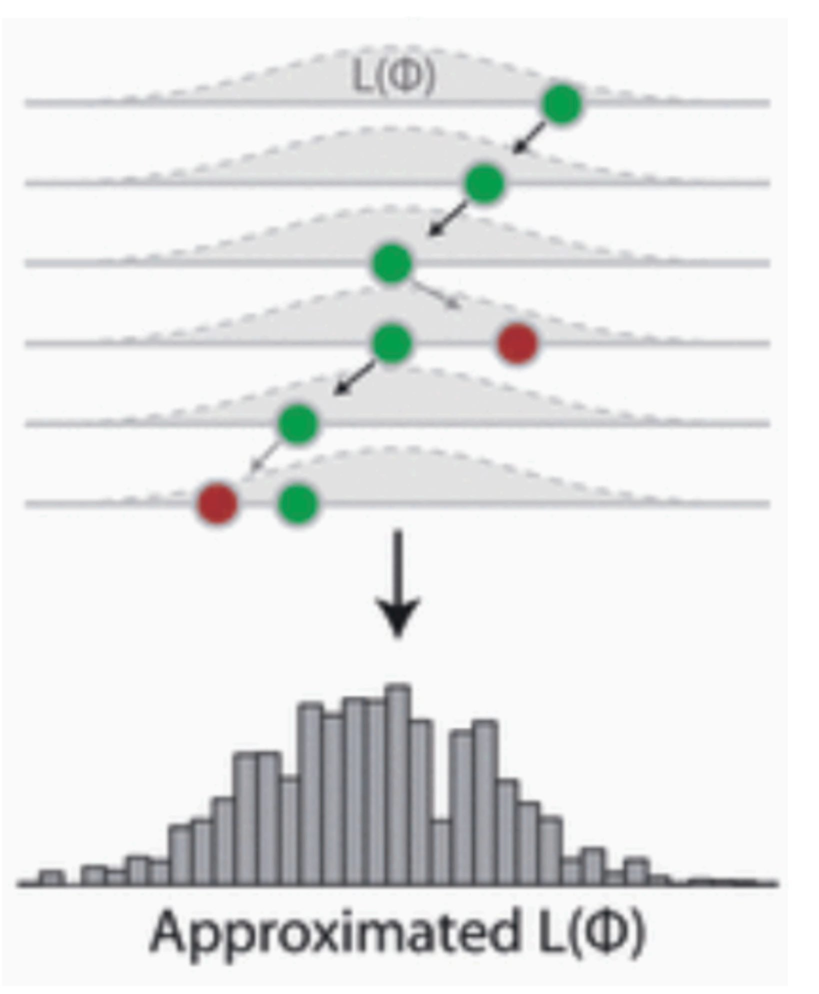
Dealing with nuisance parameters

- Likelihood has >750 parameters but want plots in ≤2 of them at once
- Two main options:
  - Profiling: Pick values of nuisance params that maximise likelihood for each set of values of parameters of interest
  - Marginalisation: Integrate over nuisance parameters
- T2K choose marginalisation to take into account non-Gaussian shape of distributions
- Also finding maximum likelihood point for given osc par values is hard in 750 dimensions



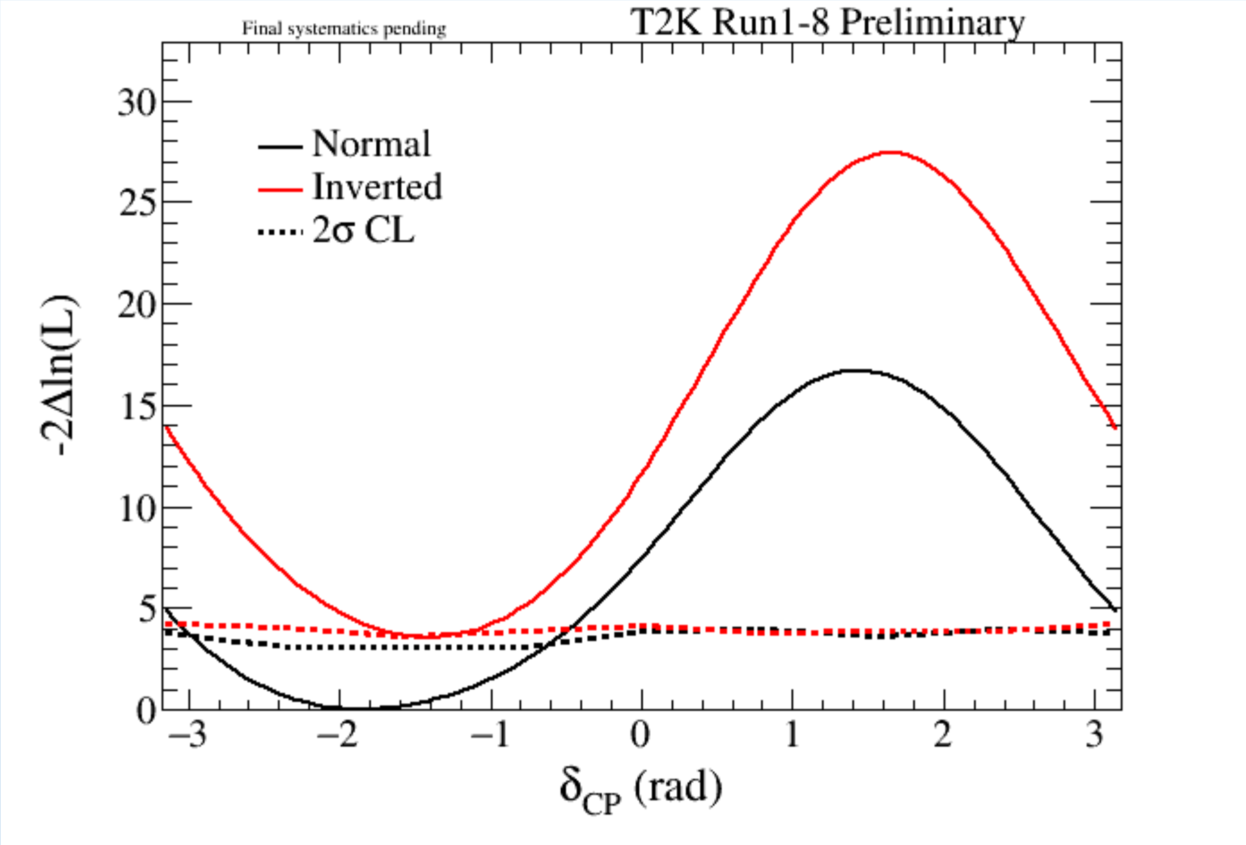
MCMC vs grid search

- Bayesian analysis samples likelihood space with Markov Chain MC
- Rule for stepping in parameter space ensures distribution of parameter values proportional to marginalised posterior probability
- Generate large number of ‘steps’ with a vector of values of each parameter for each step
- Create contours using highest posterior density



MCMC vs grid search

- Other analyses use random throws of nuisance parameters from covariance matrices to marginalise
- Then do a grid search in 1D/2D calculating average $\Delta\chi^2$ across ensemble of marginalisation throws
- Use Feldman-Cousins to find critical $\Delta\chi^2$ values for δ_{CP}



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Robustness check details

- Check robustness of results to neutrino interaction model by using our model to fit ``fake data" generated with other model assumptions
- Compare fit to fake data to nominal model fit
- If getting the interaction model wrong leads to significantly different constraints: further investigation
- Some examples here from previous analyses where we initially saw biases on $\sin^2\theta_{23}$ and Δm^2_{23}
  - Caused because ND fit to fake data propagated to SK (purple) doesn't reproduce SK fake data (blue)
  - Previously had a heuristic dial to account for this misfitting but inflated error by a large amount
  - This year we have Eb dial which removed this bias without overestimating uncertainty
- No significant biases seen on δ_{CP}