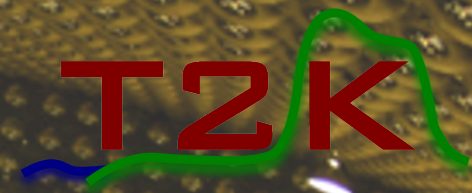




Stony Brook
University



A Bayesian Analysis of T2K's Data for the Measurement of Neutrino Oscillation Parameters

Kevin Wood, kevin.wood@stonybrook.edu

Brookhaven National Lab
Particle Physics Seminar – July 9, 2020

nature

THE MIRROR CRACK'D

An indication of matter–antimatter
symmetry violation in neutrinos

Coronavirus

The models driving
the global response
to the pandemic

Hot source

Remnants of
primordial nitrogen
in Earth's mantle

Origin of a species

Revised age for Broken
Hill skull adds twist to
human evolution

Vol. 580, May 7/8 2020
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- 16 April 2020 cover of Nature
- T2K published first substantial constraint on δ_{CP}

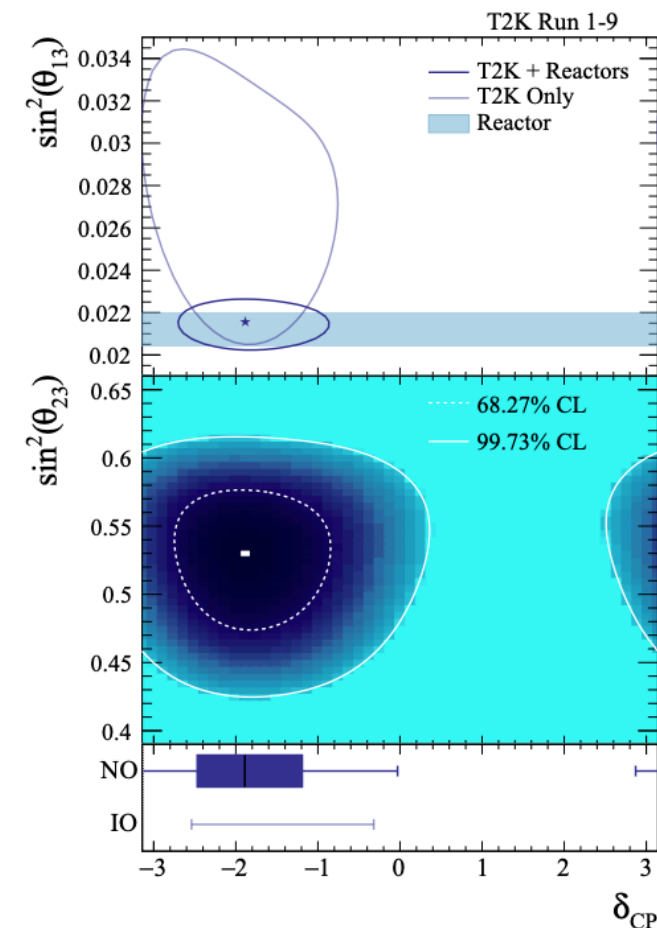
- Excluded 42% of parameter space at 3σ

- Excluded CP conserving values at 2σ

- 1σ intervals:

$$\delta_{CP} = -1.89^{+0.70}_{-0.58} \text{ (N.O.)}$$

$$\delta_{CP} = -1.38^{+0.48}_{-0.54} \text{ (I.O.)}$$



NEUTRINO 2020

Latest Neutrino Oscillation Results from T2K

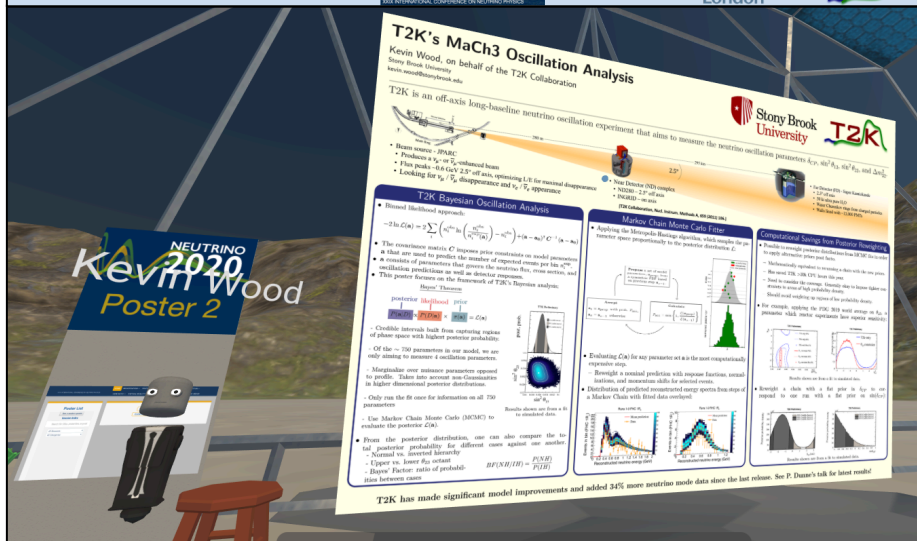
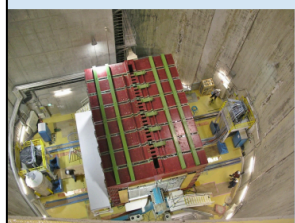
Patrick Dunne
Imperial College London

On behalf of the T2K collaboration

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



Imperial College London T2K



Updated results 1 week ago at 

- 33% more neutrino-mode data
- Significant improvements to the interaction model
- Improved constraints on flux prediction from replica target NA61/SHINE measurements
 - Far detector flux uncertainty $\sim 8\% \rightarrow \sim 5\%$
- Various improvements to the near detector fit
- Updated θ_{13} constraint from reactor experiments
 - PDG 2018: $\sin^2 \theta_{13} = 0.0212 \pm 0.0008$
 - PDG 2019: $\sin^2 \theta_{13} = 0.0218 \pm 0.0007$

Contents

1. Oscillations
2. T2K setup
3. T2K's Bayesian Markov Chain Monte Carlo oscillation analysis
4. Latest results
5. Future prospects

Neutrino Oscillations

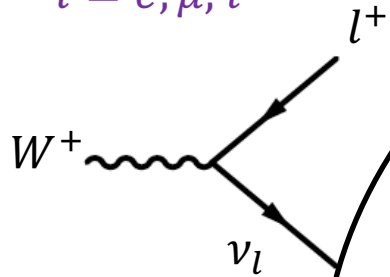
produced in flavor eigenstates

propagate in mass eigenstates

observed in flavor eigenstates

flavor states

$l = e, \mu, \tau$



mass states

$i = 1, 2, 3$

$$|\alpha(0)\rangle = |\nu_l\rangle = \sum_i c_i |\nu_i\rangle$$

$$|\alpha(x)\rangle = \sum_i c_i |\nu_i\rangle e^{-ip_i \cdot x}$$

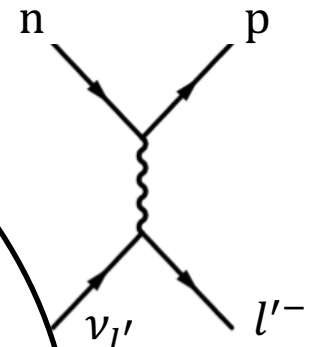
$$\Rightarrow |\langle \nu_l | \alpha(x) \rangle|^2 \neq \delta_{ll'}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}}_{\text{Majorana phases (no effect on oscillations)}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

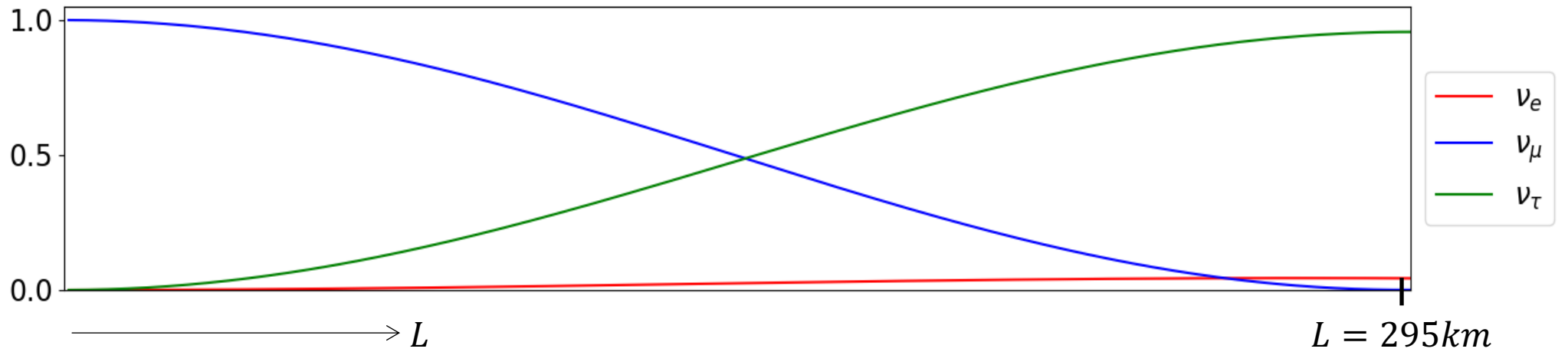
$$c_{ij} \equiv \cos \theta_{ij}$$

U_{PMNS}





0.6 GeV ν_μ



$$P_{osc}(\theta_{ij}, \Delta m_{ij}^2, \delta_{CP}, L/E)$$

mixing angles (3)

CP-violating phase

mass squared splittings (2)

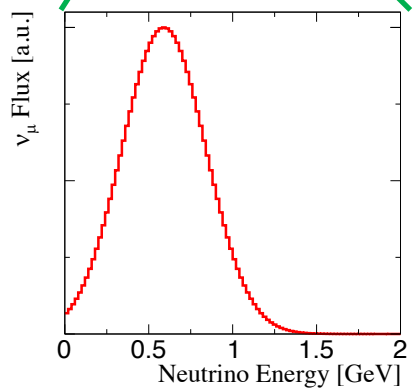
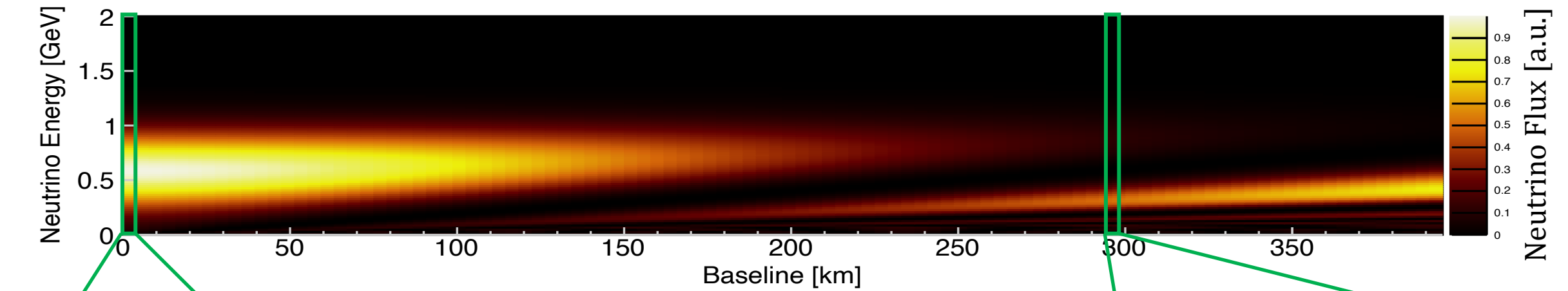
Baseline (distance traveled by ν),
Energy of neutrino

- T2K is sensitive to 4 oscillation parameters:
 - $\theta_{23}, \theta_{13}, \Delta m_{32}^2, \delta_{CP}$
- Questions T2K can shed light on:

What is the neutrino mass hierarchy?

What is the octant of θ_{23} ?

Is there significant CP violation in the neutrino sector?



- Oscillation parameters leave their signatures in the oscillated flux:

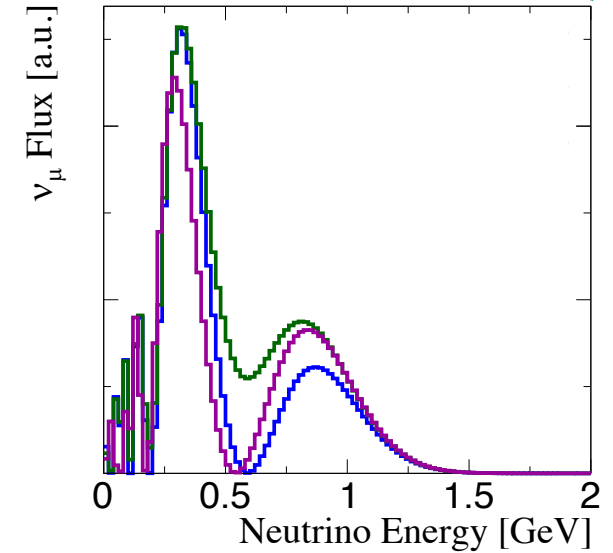
$\nu_\mu / \bar{\nu}_\mu$ disappearance:

- $\sin^2(2\theta_{23}) \leftrightarrow$ depth of the dip
- $\Delta m_{32}^2 \leftrightarrow$ energy at which dip occurs

$\nu_e / \bar{\nu}_e$ disappearance:

- leading term depends on $\sin^2 \theta_{23}, \sin^2 \theta_{13}, \Delta m_{32}^2$
- sub-leading term, δ_{CP}

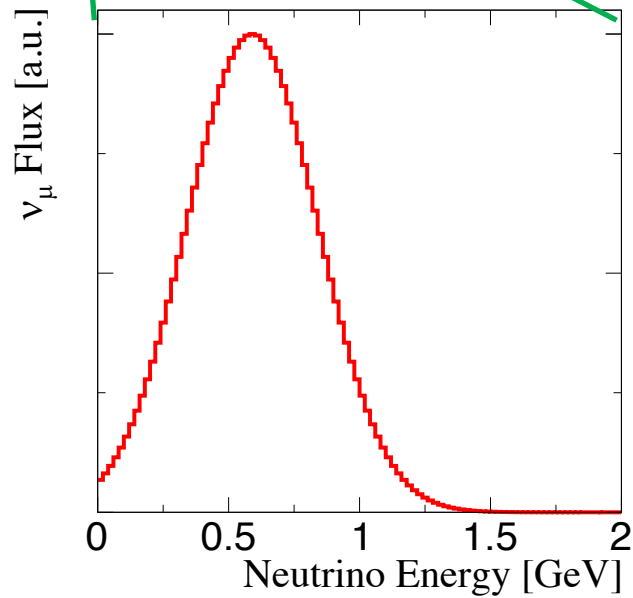
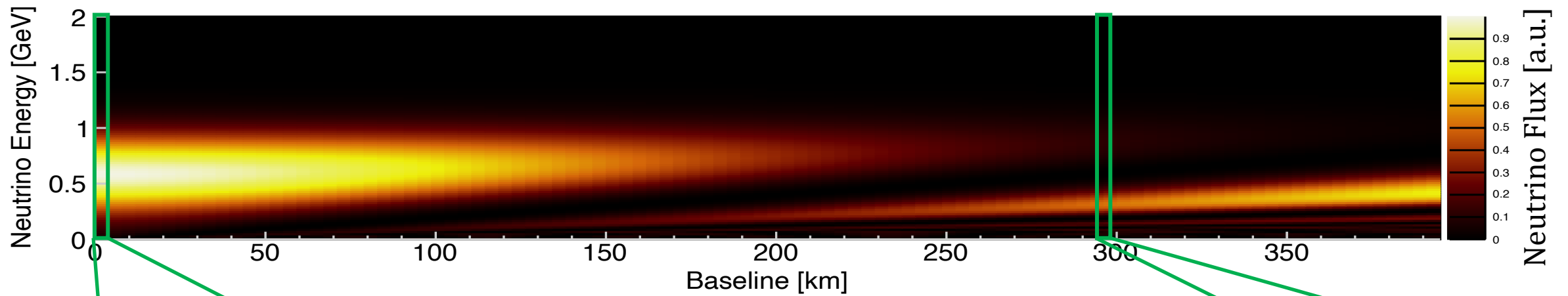
Matter effect provides some sensitivity to mass ordering



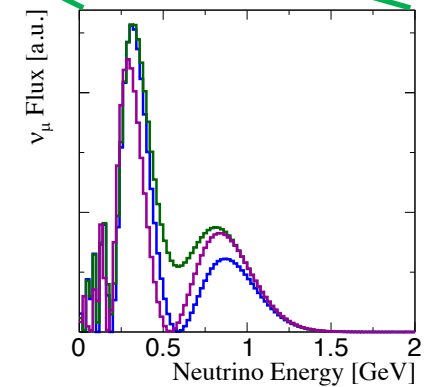
— $\Delta m_{32}^2 = 2.5 \times 10^{-3} \text{ eV}^2, \sin^2(2\theta_{23}) = 1.0$

— $\Delta m_{32}^2 = 2.5 \times 10^{-3} \text{ eV}^2, \sin^2(2\theta_{23}) = 0.9$

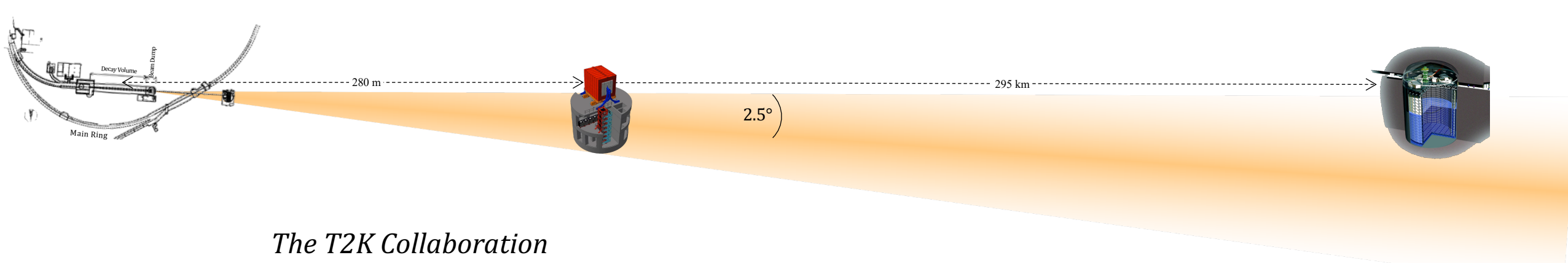
— $\Delta m_{32}^2 = 2.3 \times 10^{-3} \text{ eV}^2, \sin^2(2\theta_{23}) = 1.0$



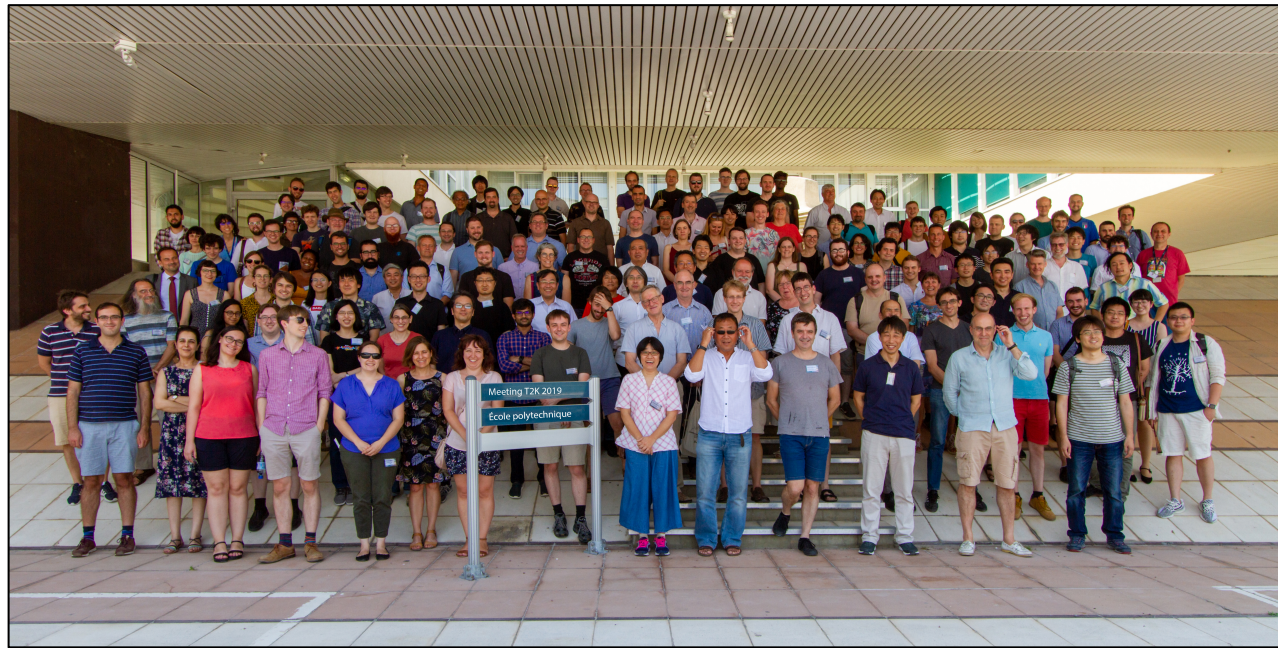
- Use a near detector to measure the unoscillated flux
- $N \propto \phi \times \sigma$ – need to know cross section
- Take advantage of high statistics to constrain interaction model
- Neutrino-nucleus cross section measurements



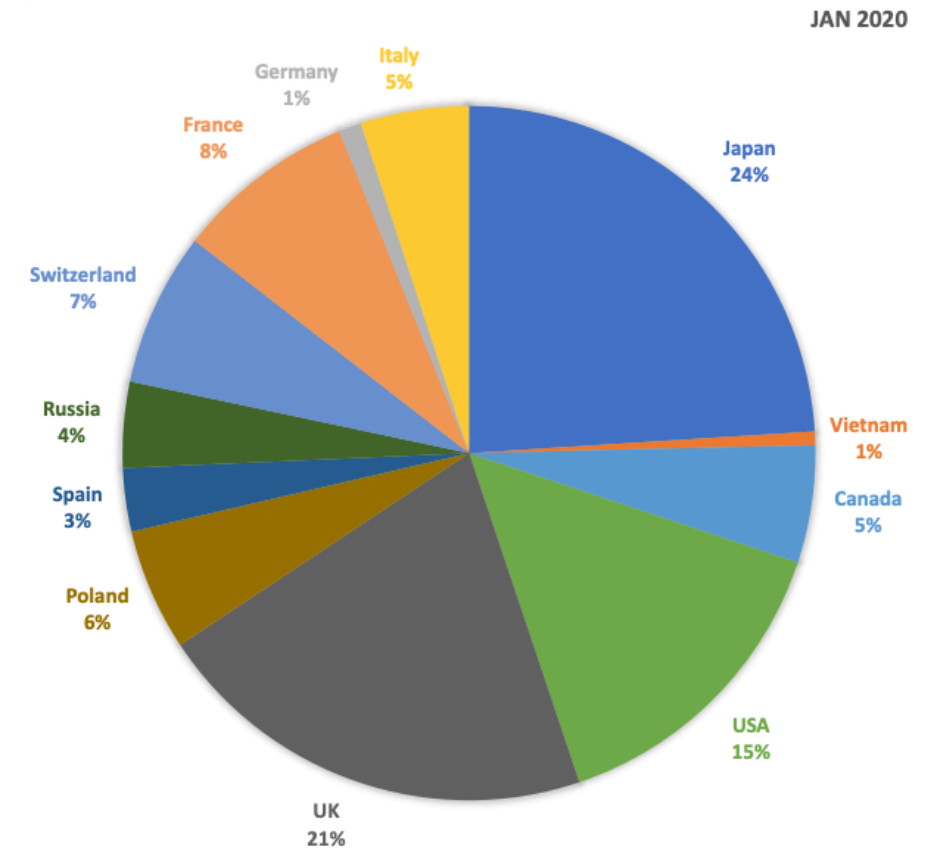
- $\Delta m_{32}^2 = 2.5 \times 10^{-3} \text{ eV}^2, \sin^2(2\theta_{23}) = 1.0$
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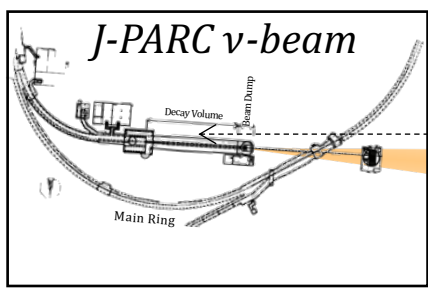


The T2K Collaboration

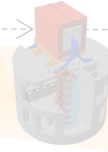


- ~500 collaborators spread across 69 institutions and 12 countries



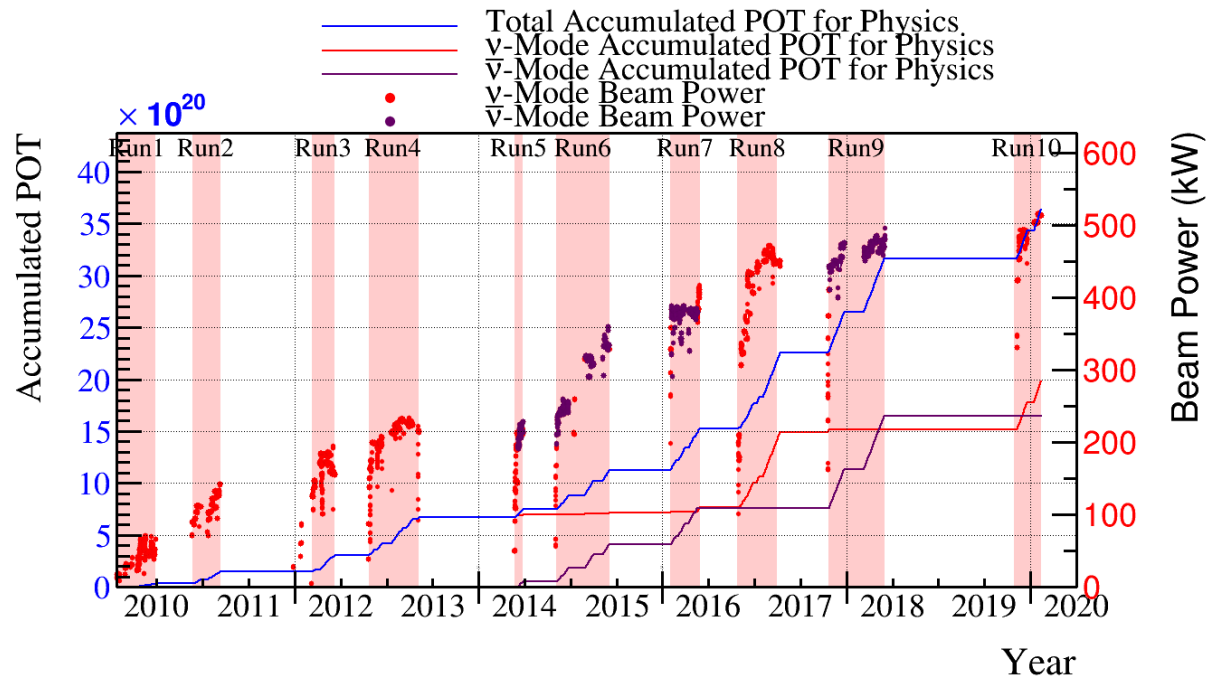
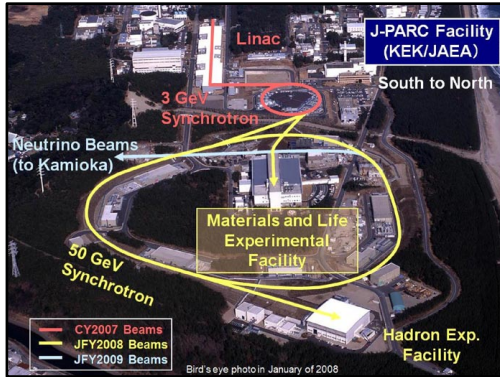
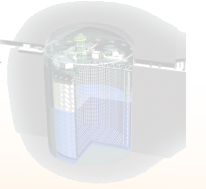


280 m

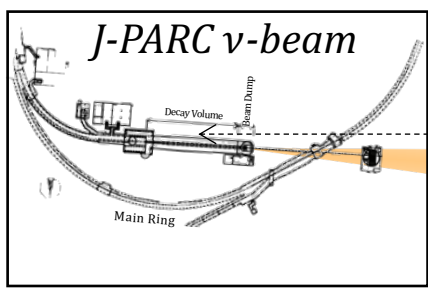


2.5°

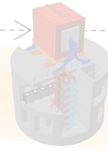
295 km



- 30 GeV protons from J-PARC, demonstrated 515 kW operation
- Incident on graphite target, producing predominantly $\pi^\pm$ and $K^\pm$
- Horns focus and sign select the hadrons before decaying in flight
- Charged decay products are absorbed and a ν_μ - or $\bar{\nu}_\mu$ -enhanced beam emerges
- Flux peaks ~ 0.6 GeV 2.5° off axis, optimizing L/E for maximal disappearance

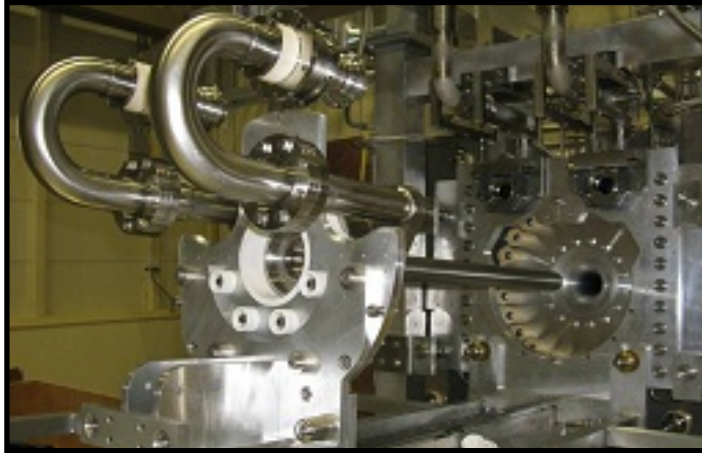
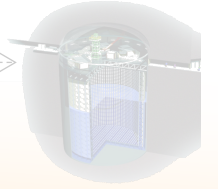


280 m

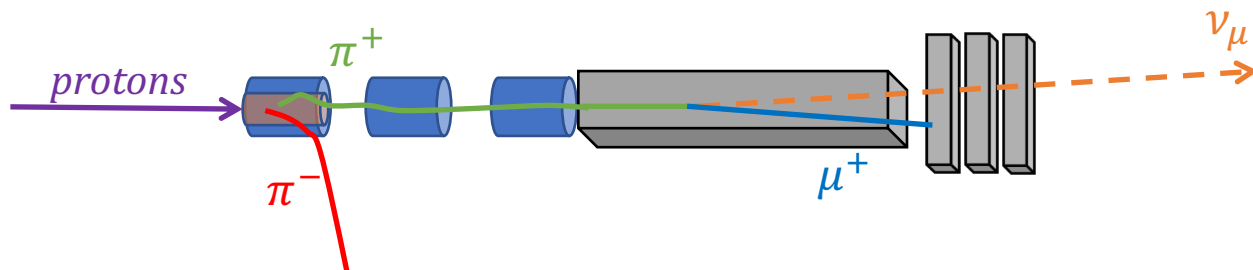


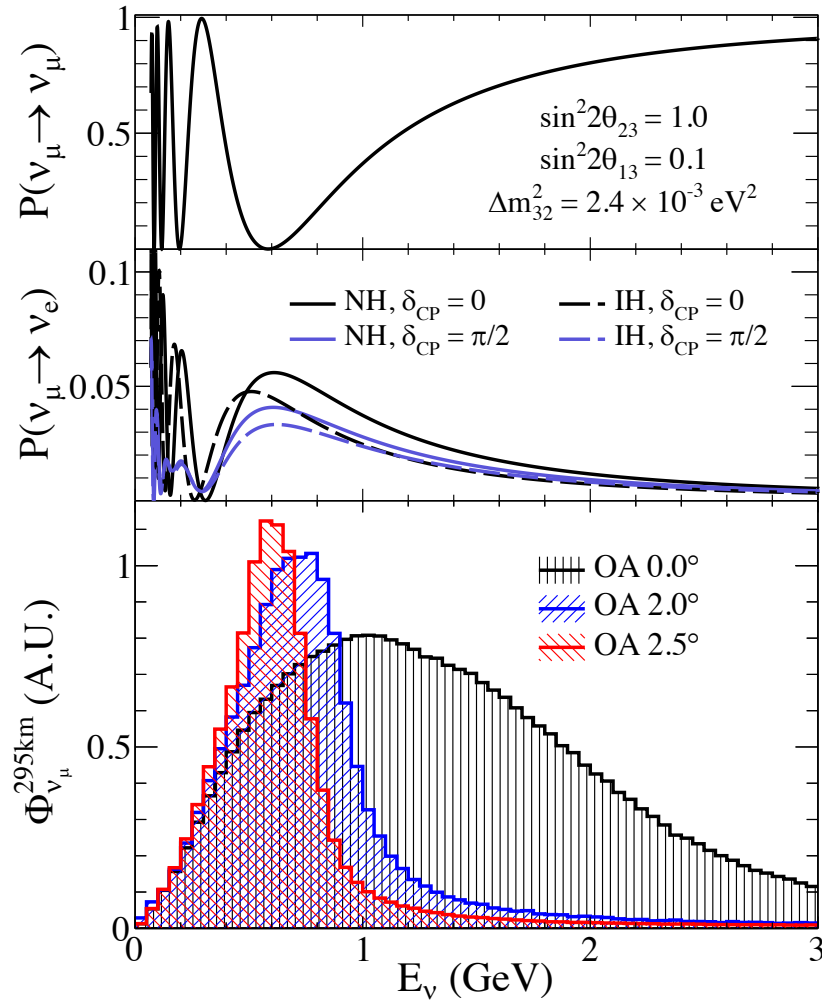
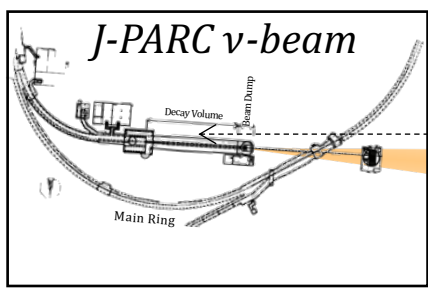
2.5°

295 km

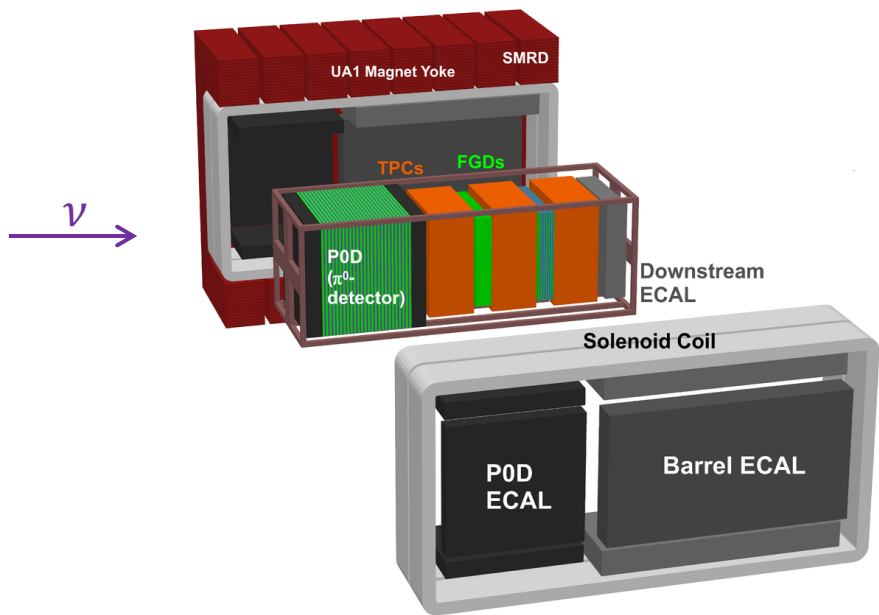
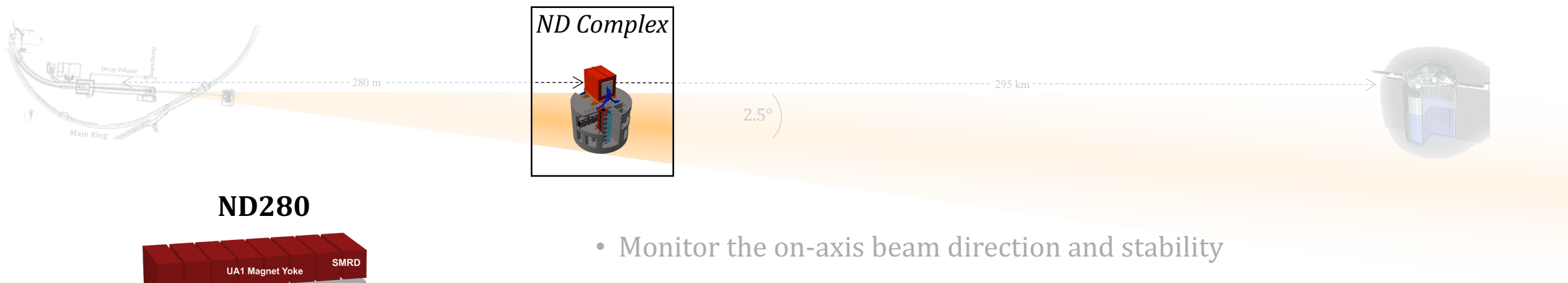


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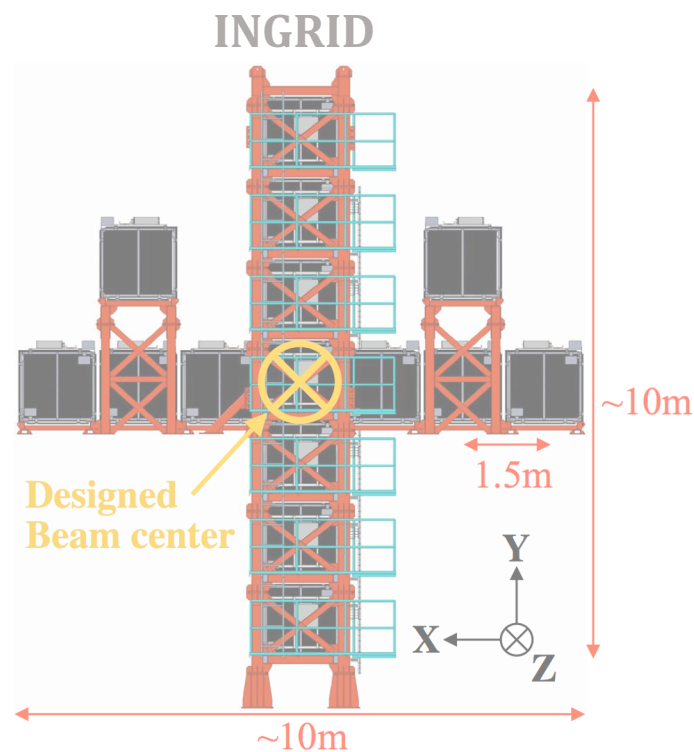




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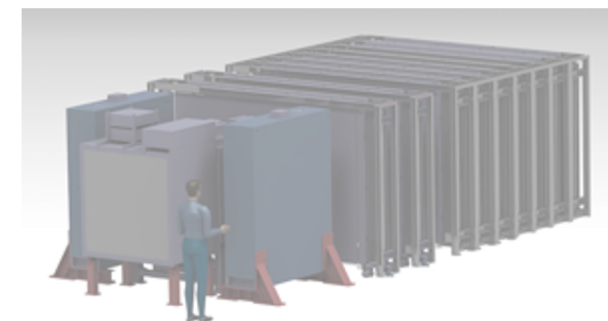


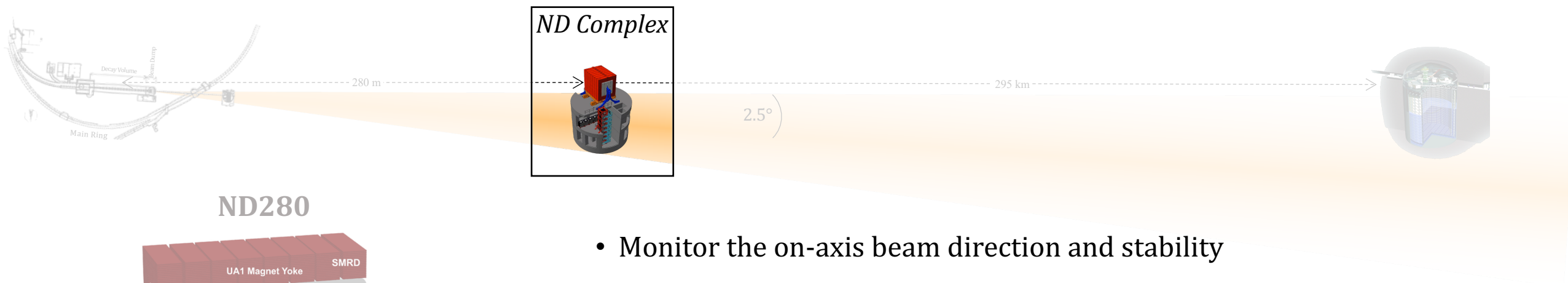
- 2.5° off axis, 280m downstream of the target
- Fine grain detectors (FGD)
 - Active scintillator and passive water targets
- Time projection chambers (TPC)
 - Tracking
- Magnetized for charge separation and momentum measurements



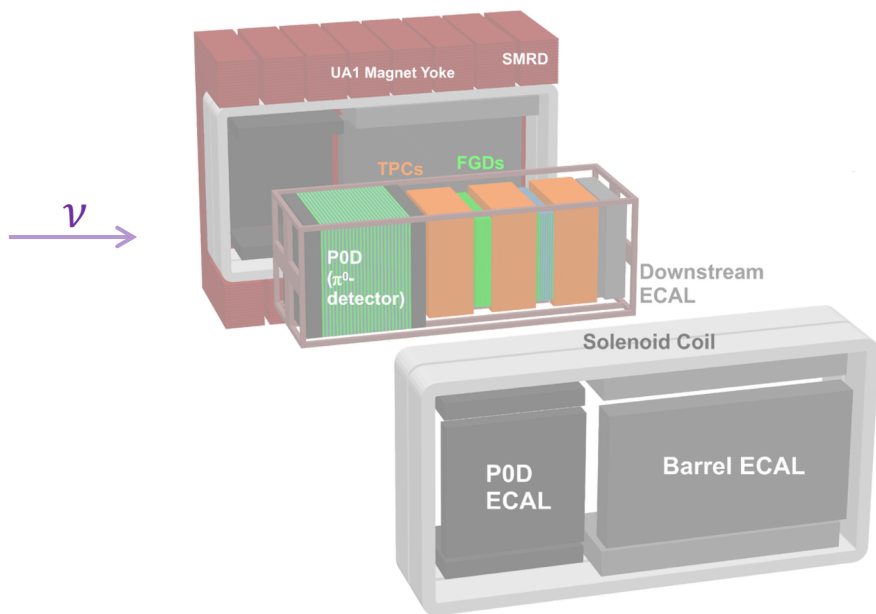
- Intermediate off axis angle of 1.5°
- Will monitor beam and make cross section measurements

WAGASCI/BabyMIND



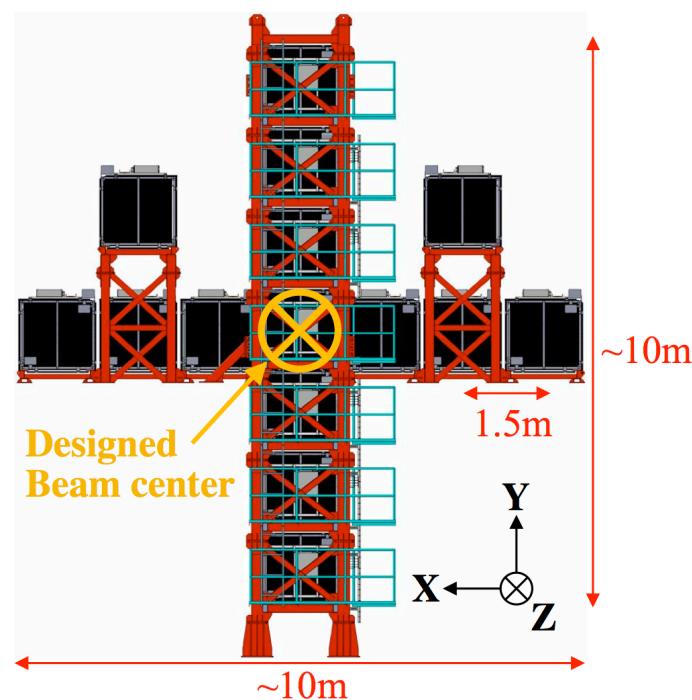


ND280



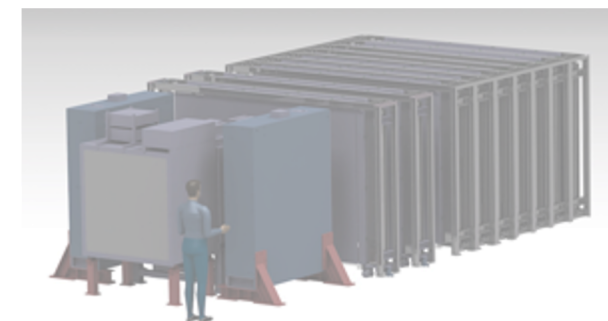
- Monitor the on-axis beam direction and stability

INGRID

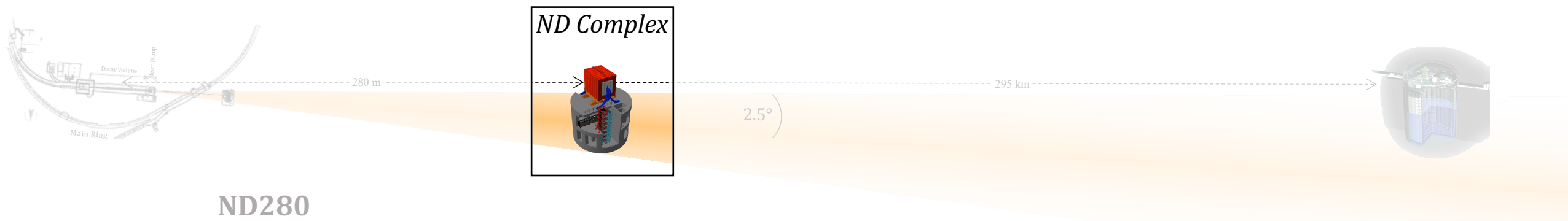


- Intermediate off axis angle of 1.5°
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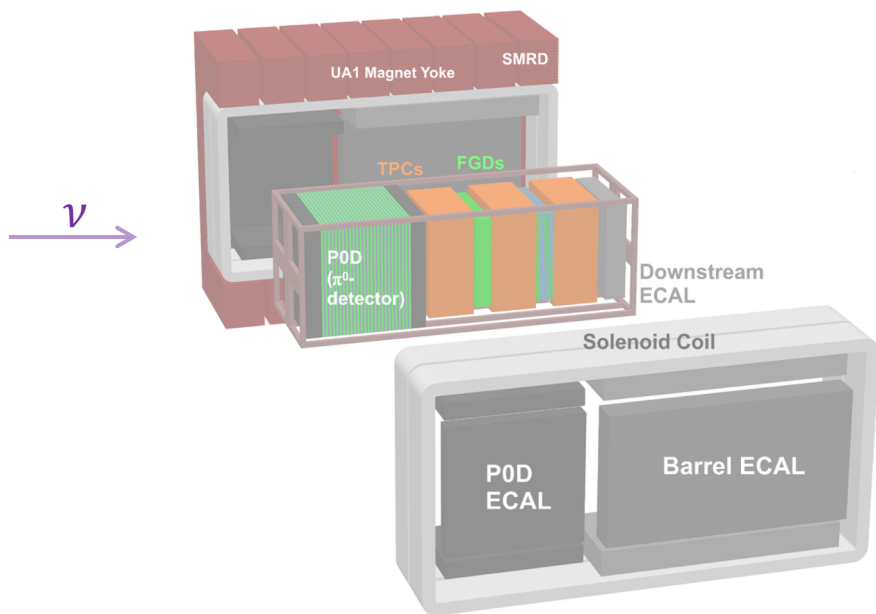
WAGASCI/BabyMIND



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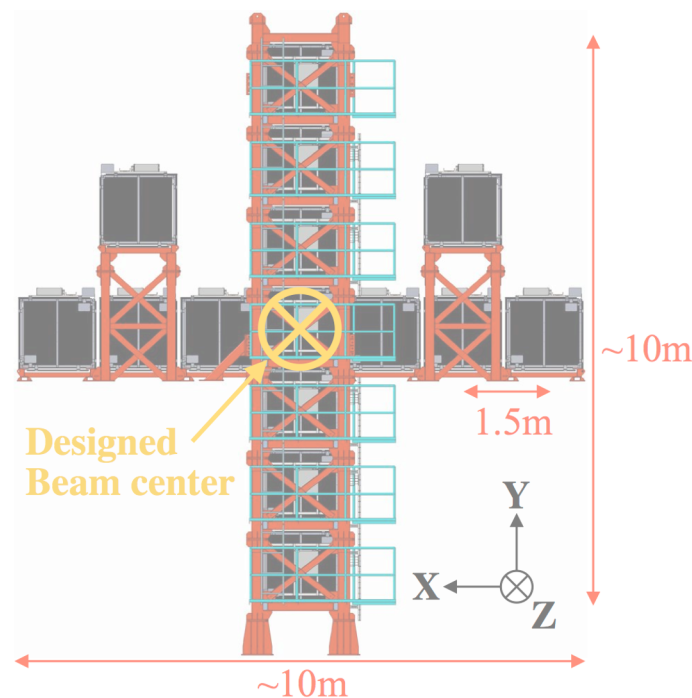


ND280



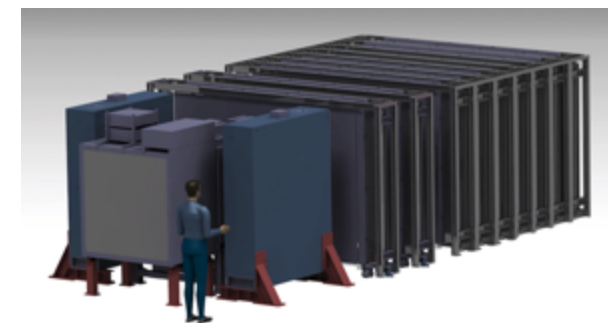
- Monitor the on-axis beam direction and stability

INGRID



- Intermediate off axis angle of 1.5°
- Will monitor beam and make cross section measurements

WAGASCI/BabyMIND

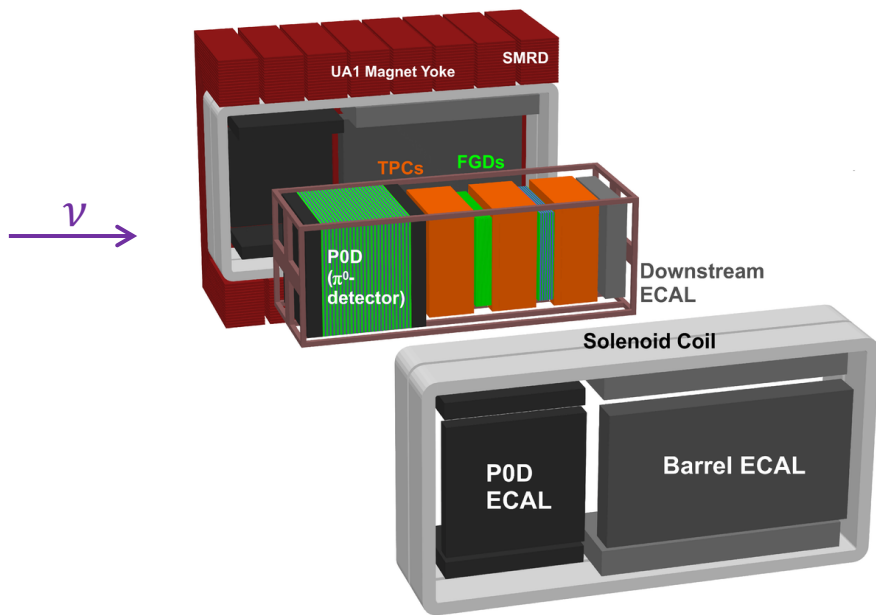


New!

- 2.5° off axis, 280m downstream of the target
- Fine grain detectors (FGD)
 - Active scintillator and passive water targets
- Time projection chambers (TPC)
 - Tracking
- Magnetized for charge separation and momentum measurements

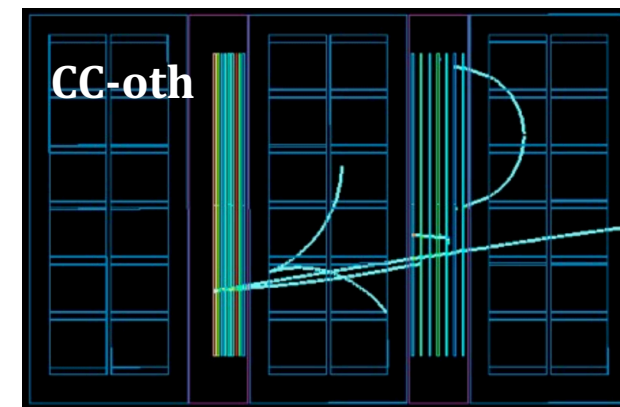
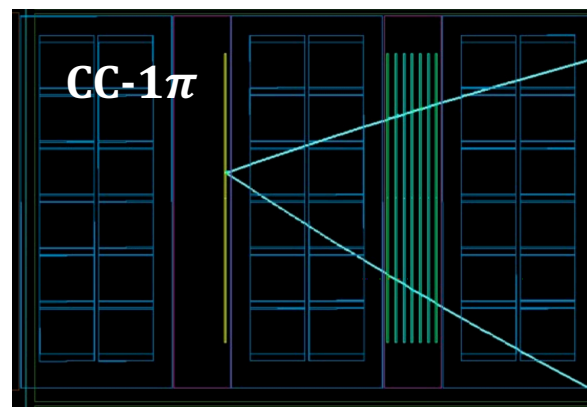
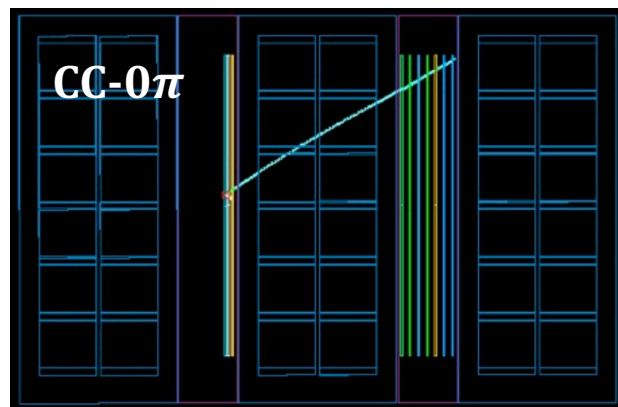


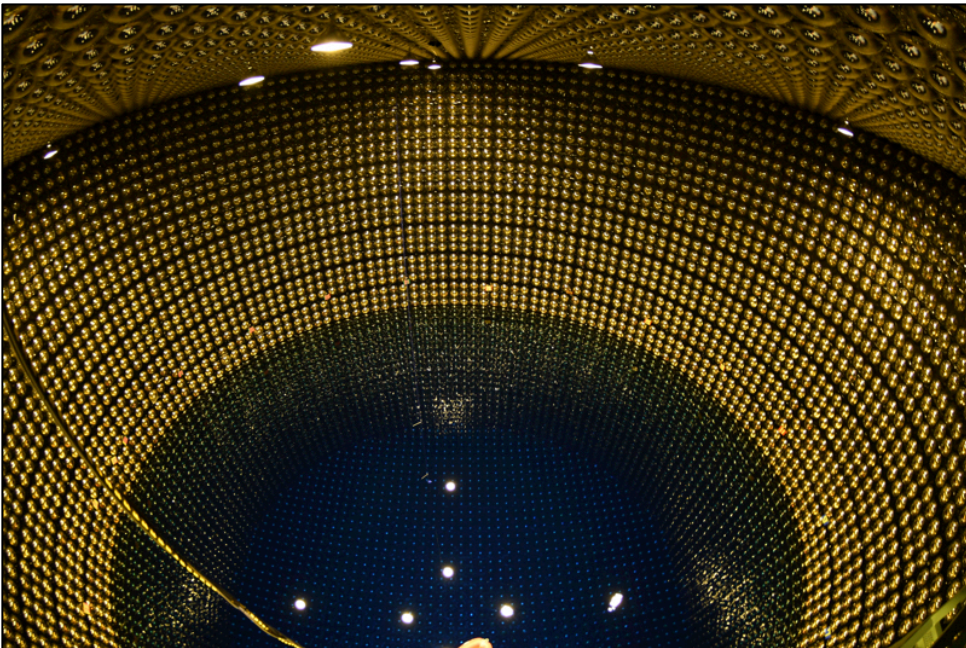
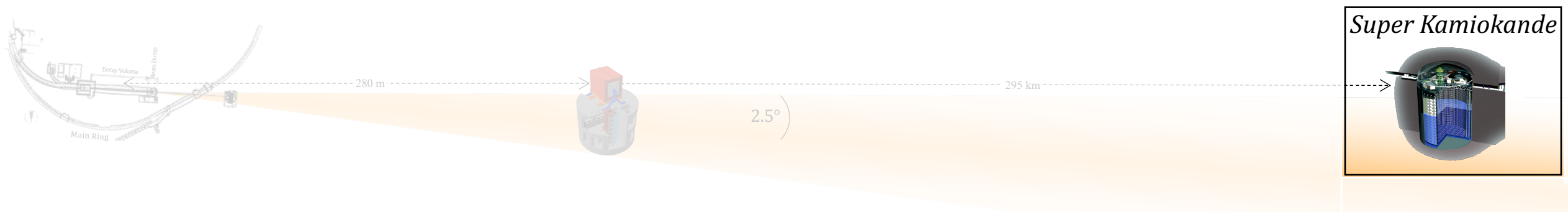
ND280



ND280 samples

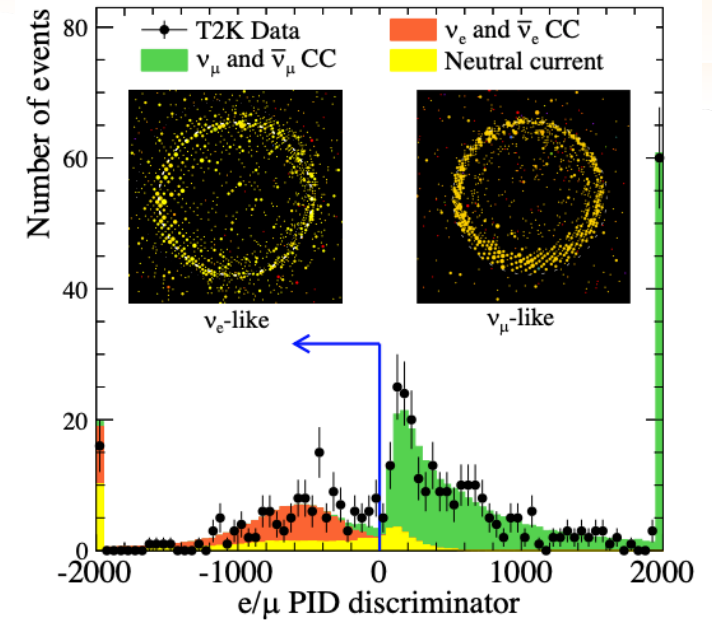
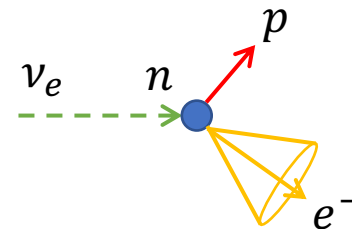
	ν events in ν -mode	$\bar{\nu}$ events in $\bar{\nu}$ -mode	$\bar{\nu}$ events in ν -mode
FGD1 (scintillator)	CC-0 π	CC-0 π	CC-0 π
	CC-1 π	CC-1 π	CC-1 π
	CC-oth	CC-oth	CC-oth
FGD 2 (scintillator + H ₂ O)	CC-0 π	CC-0 π	CC-0 π
	CC-1 π	CC-1 π	CC-1 π
	CC-oth	CC-oth	CC-oth



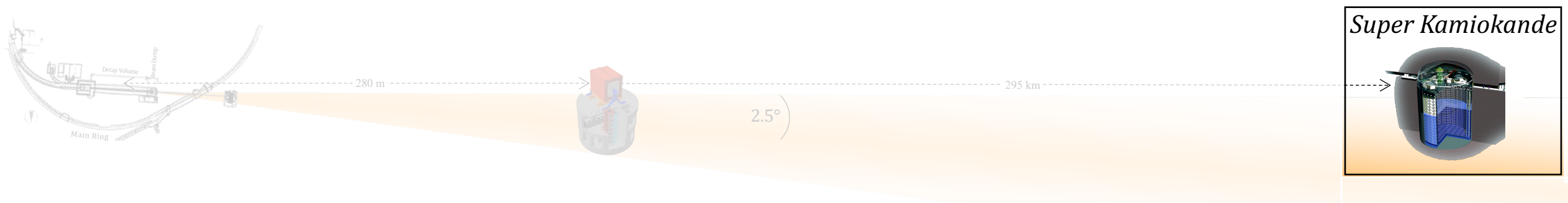


Super Kamiokande

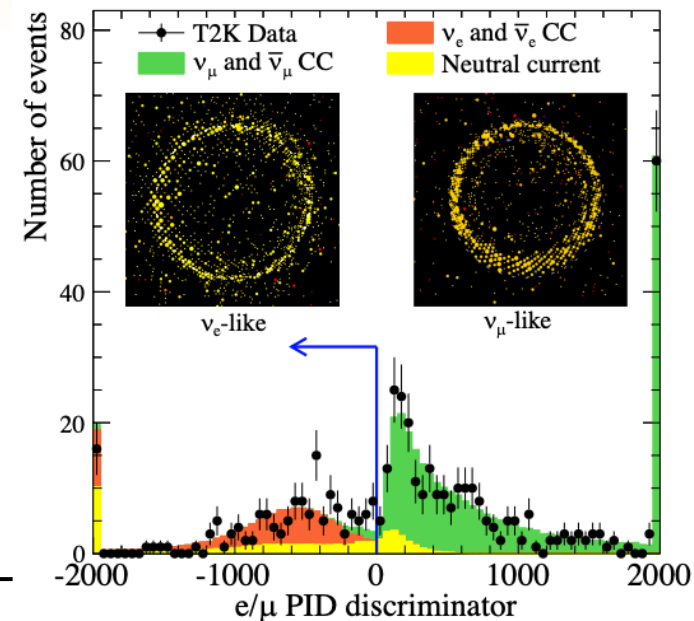
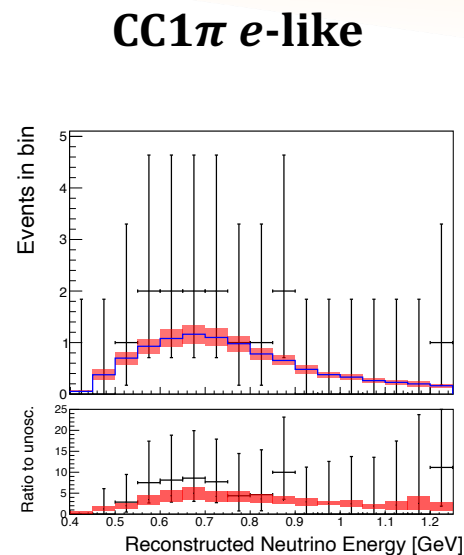
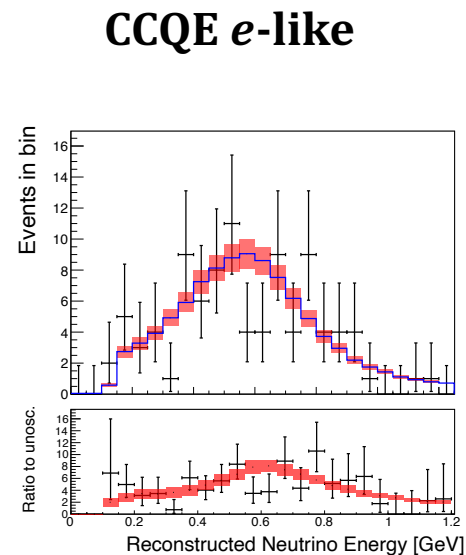
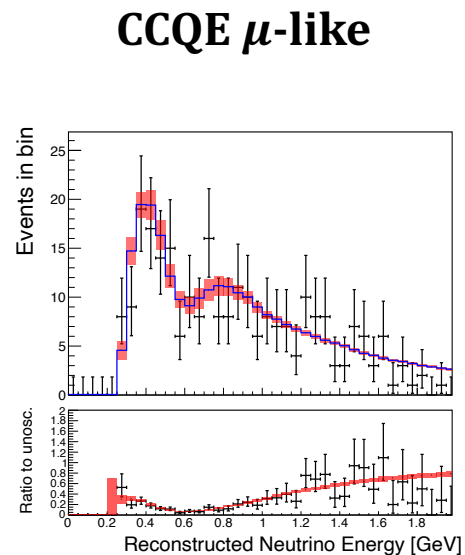
- 39.3m diameter, 41.4m tall cylindrical water tank
- 50 kt ultra pure water
- 11,129 20-inch PMTs watching the inner detector volume
- 1,885 8-inch PMTs line outer detector volume
- Charged particles from neutrino interactions emit Cherenkov radiation



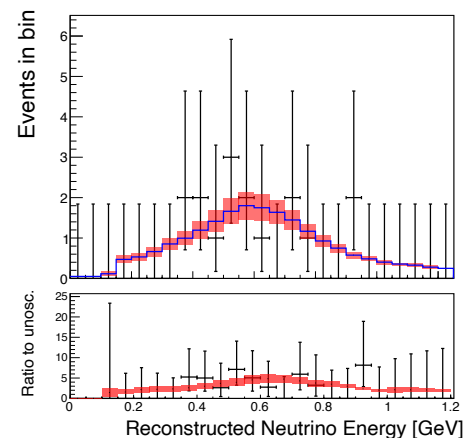
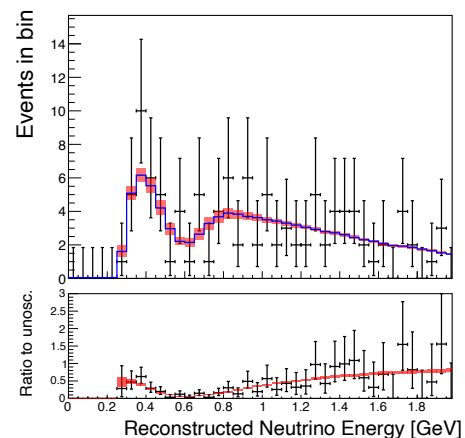
- fiTQun reconstruction algorithm separates muon-like rings from electron-like rings (and more)



FHC
(ν -mode)

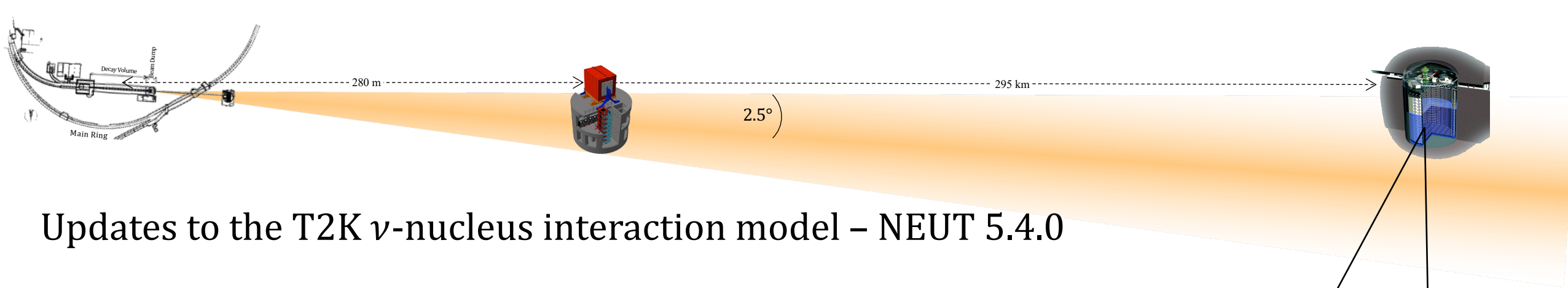


RHC
($\bar{\nu}$ -mode)



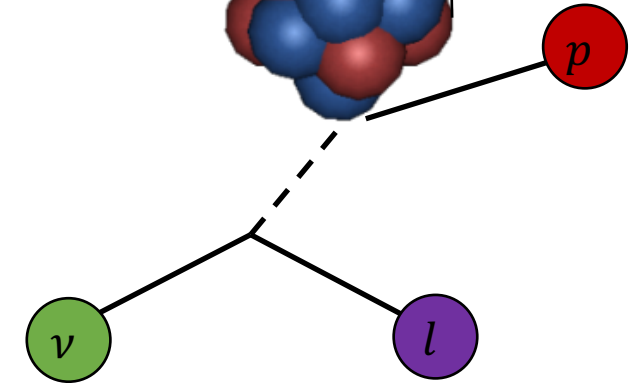
π^- from $\bar{\nu}$ interaction
typically absorbed
before they decay

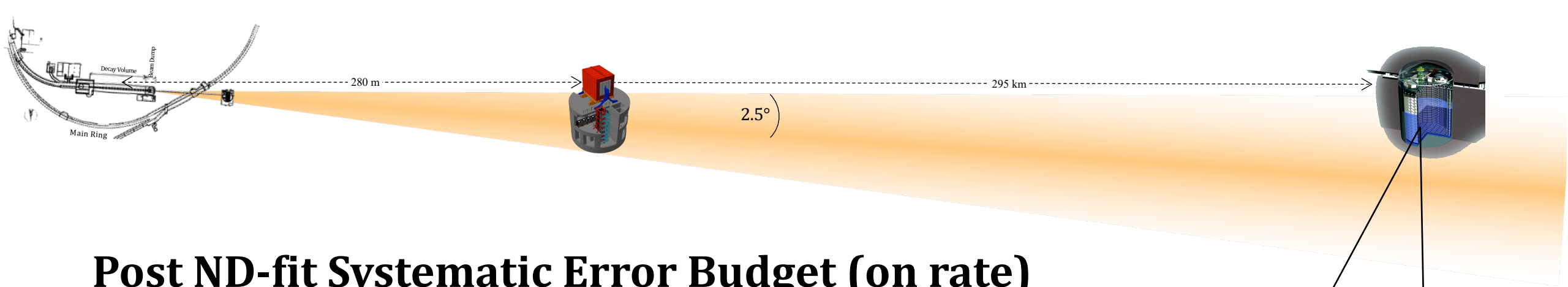
- fiTQun reconstruction algorithm separates muon-like rings from electron-like rings (and more)



Updates to the T2K ν -nucleus interaction model – NEUT 5.4.0

- CCQE nuclear initial state model now using tuned **spectral function**, opposed to **relativistic fermi gas + RPA**
- The nuclear binding potential is now modelled as a systematic that shifts the charged lepton momentum
 - Large impact on reconstructed neutrino energy
- Energy dependent 2p2h uncertainties
- Correlated errors between FSI parameters at near and far detectors
- Improved DIS uncertainties
- etc.





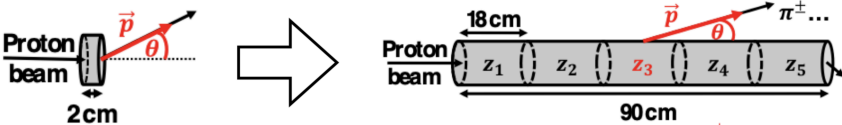
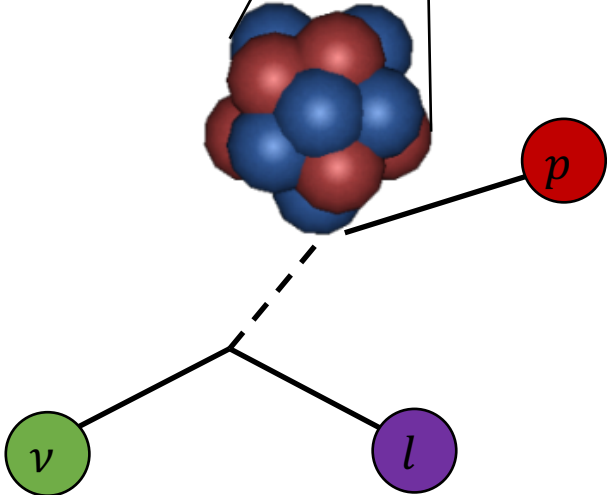
Post ND-fit Systematic Error Budget (on rate)

Run 1-9 Analysis (T2K Nature)

Error source	FHC1R μ	RHC1R μ	FHC1Re	RHC1Re	FHCCC1 π^+
Flux	4.3%	4.1%	4.4%	4.2%	4.4%
Cross-section	5.6%	4.4%	8.4%	6.2%	5.6%
Flux $\times$ cross-section	4.4%	3.9%	7.7%	5.7%	5.6%
SK det (+ FSI)	3.3%	2.9%	4.1%	4.3%	16.6%
Total	5.5%	4.4%	8.8%	7.3%	17.8%

Run 1-10 Analysis (T2K Neutrino 2020)

Error source	FHC1R μ	RHC1R μ	FHC1Re	RHC1Re	FHCCC1 π^+
Flux	2.72%	2.88%	2.77%	2.91%	2.74%
Cross-section	3.21%	4.07%	4.43%	4.79%	5.29%
Flux $\times$ cross-section	2.31%	3.61%	3.82%	4.38%	5.30%
SK det	2.11%	1.88%	3.19%	4.18%	13.17%
Total	3.13%	4.11%	4.93%	6.04%	14.11%

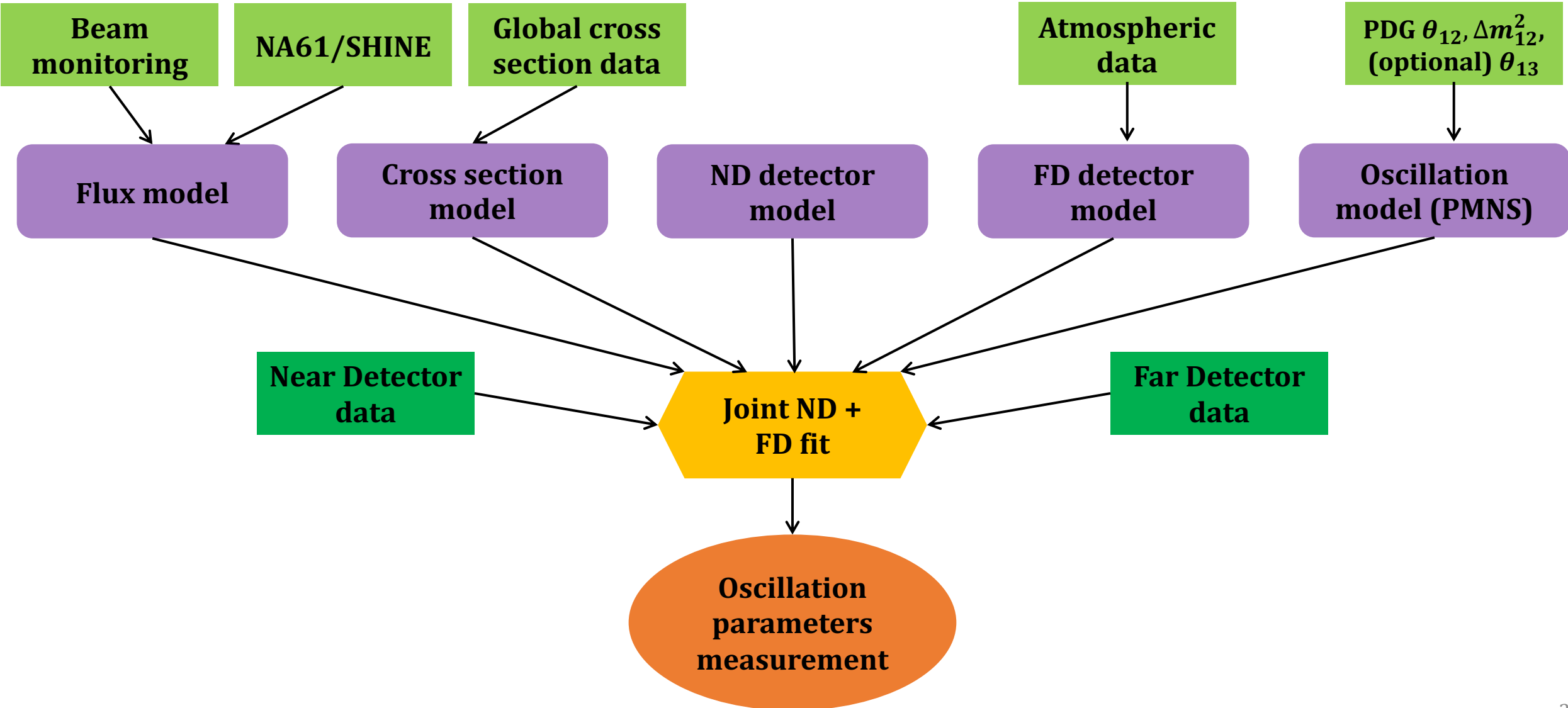


T2K Oscillation Analysis

- 3 different fitters in T2K that make different analysis choices
 - Frequentist vs. Bayesian →
 - Sample binning →
 - Likelihood optimization/evaluation →
 - Incorporation of ND information →
- From here on, focusing on the “MaCh3” Bayesian analysis

MaCh3	P-Theta	VALOR
Bayesian	Frequentist (Bayesian capable)	Frequentist
ν_μ -like: E_{rec} ν_e -like: $E_{rec} - \theta$	ν_μ -like: $E_{rec} - \theta$ ν_e -like: $p - \theta$	ν_μ -like: E_{rec} ν_e -like: $E_{rec} - \theta$
Markov Chain Monte Carlo	Gradient descent algorithm/grid search	Gradient descent algorithm/grid search
Simultaneous fit of ND and FD	Covariance matrix	Covariance matrix

Analysis Strategy



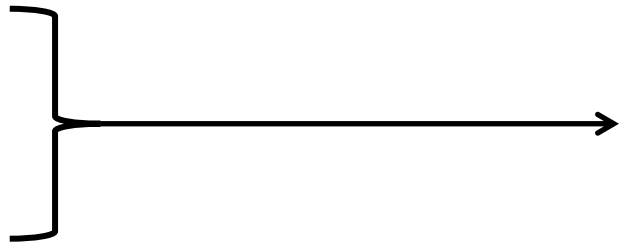
Bayesian Analysis

- Bayes' Theorem:

$$\begin{array}{ccccc} \text{posterior} & & \text{likelihood} & & \text{prior} \\ | & & | & & | \\ \boxed{P(\mathbf{a}|D)} & \propto & \boxed{P(D|\mathbf{a})} & \times & \boxed{\pi(\mathbf{a})} \end{array}$$

- $\mathbf{a}$: model parameters
(nuisance/systematics + oscillation)

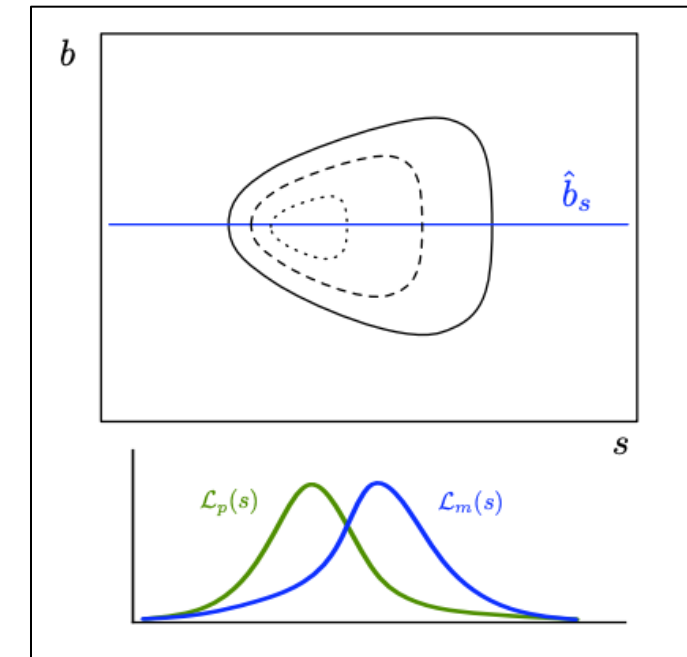
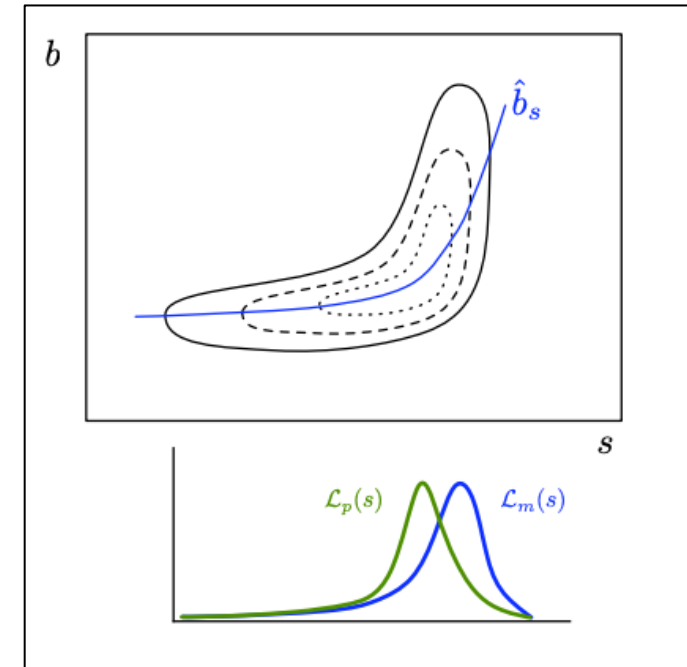
- Flux
- Cross section
- Detector
- Oscillation



- $P(D|\mathbf{a})$: product across bins of Poisson probabilities to observing the number of events/bin
- $\pi(\mathbf{a})$: impose multivariate Gaussian prior constraints on model parameters
- ~750 systematic parameters that are nuisance parameters for the oscillation measurements

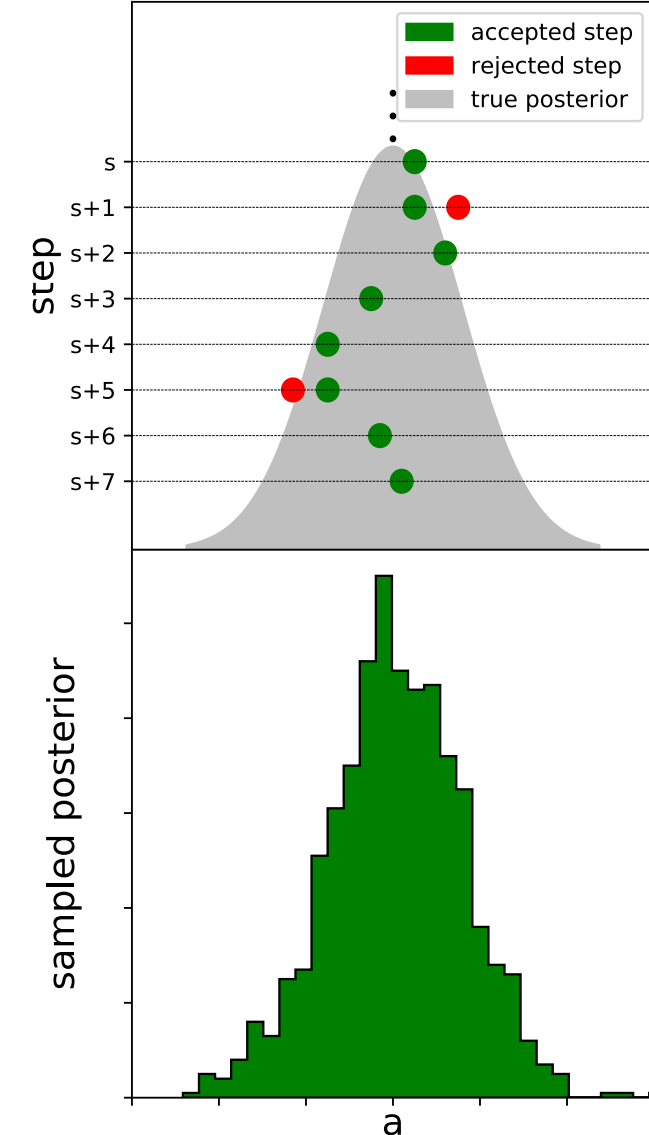
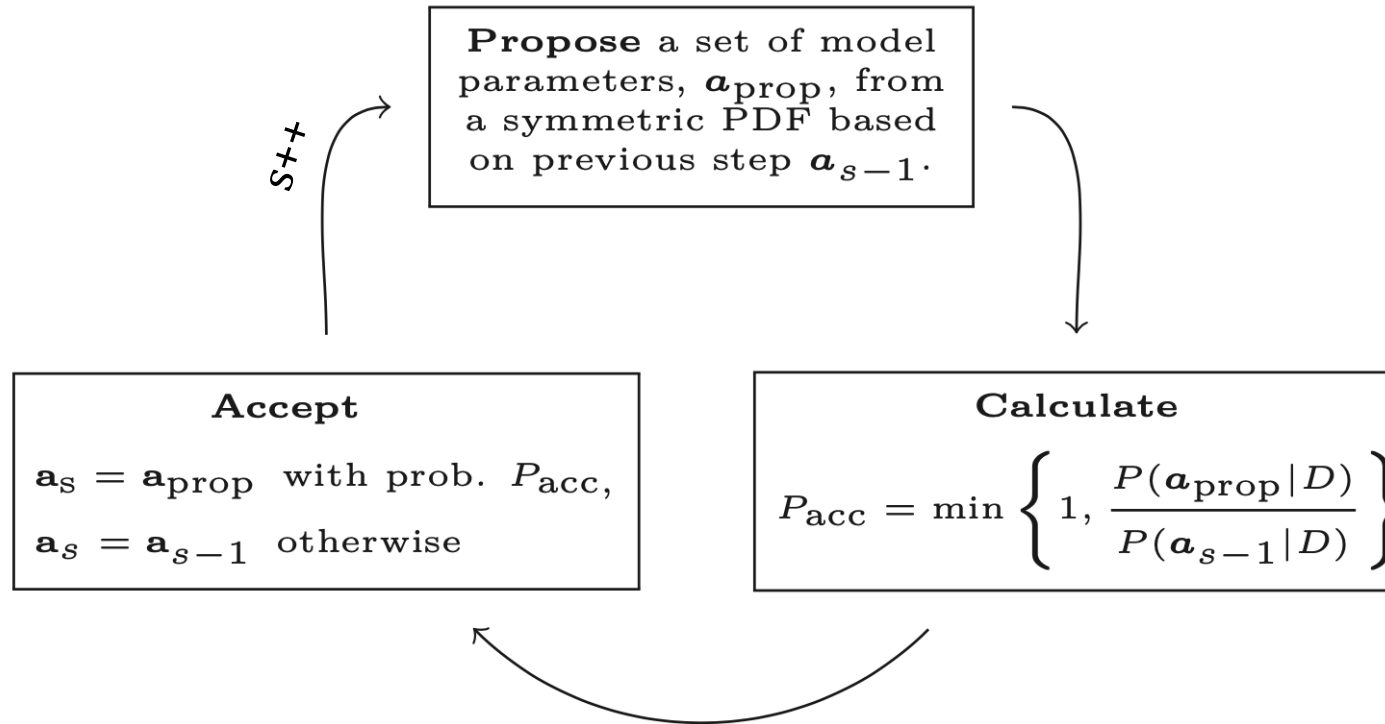
Marginalization

- Choose to marginalize over profile, to account for non-Gaussianities
- Marginalizing and profiling both account for correlations between nuisance parameters (b) and parameters of interest (s)
- Marginalization has the added benefit of accounting for the uncertainty in $\hat{b}$
- Finding the “average” value, not necessarily the “best fit” value

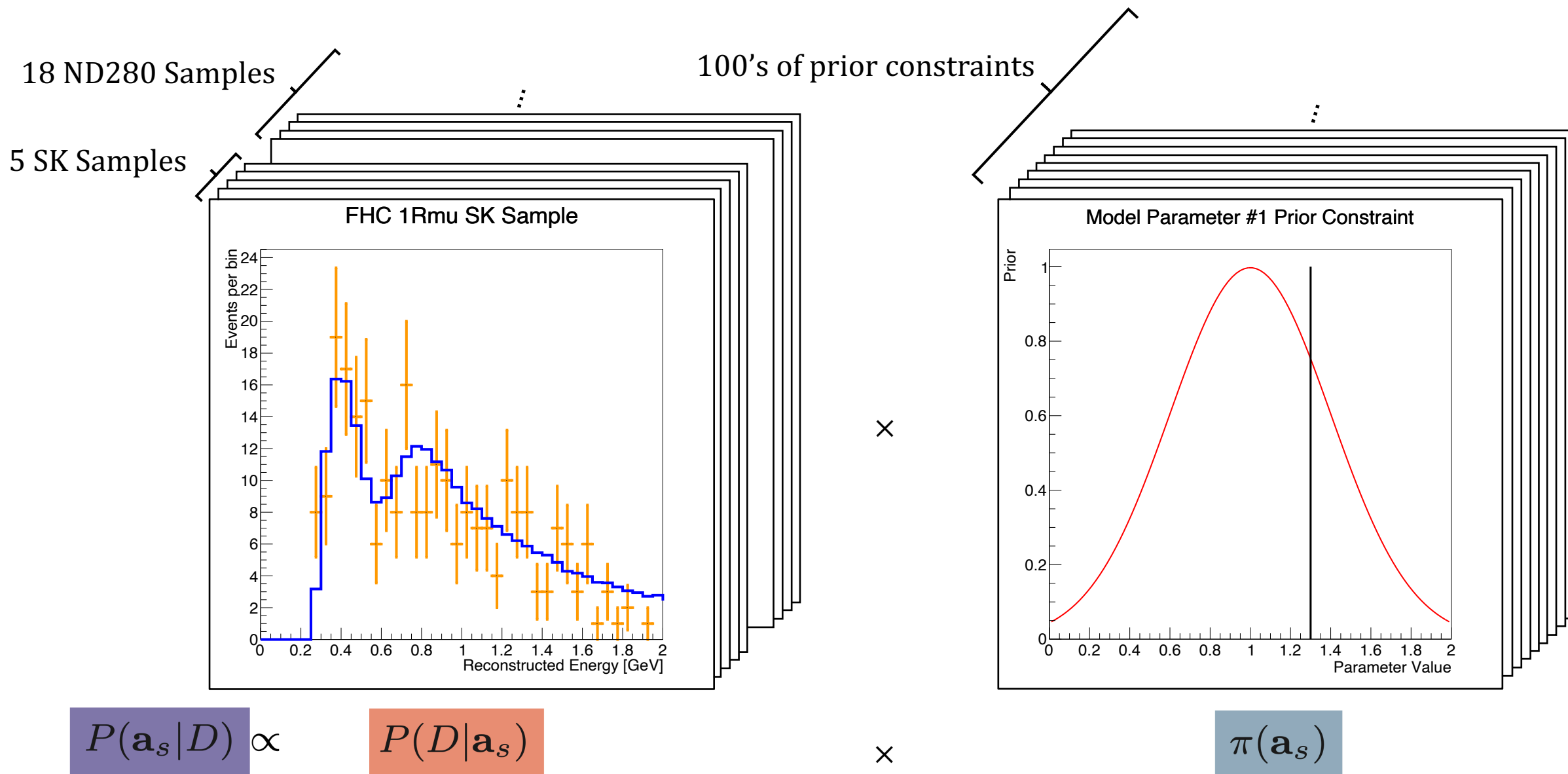


Markov Chain Monte Carlo

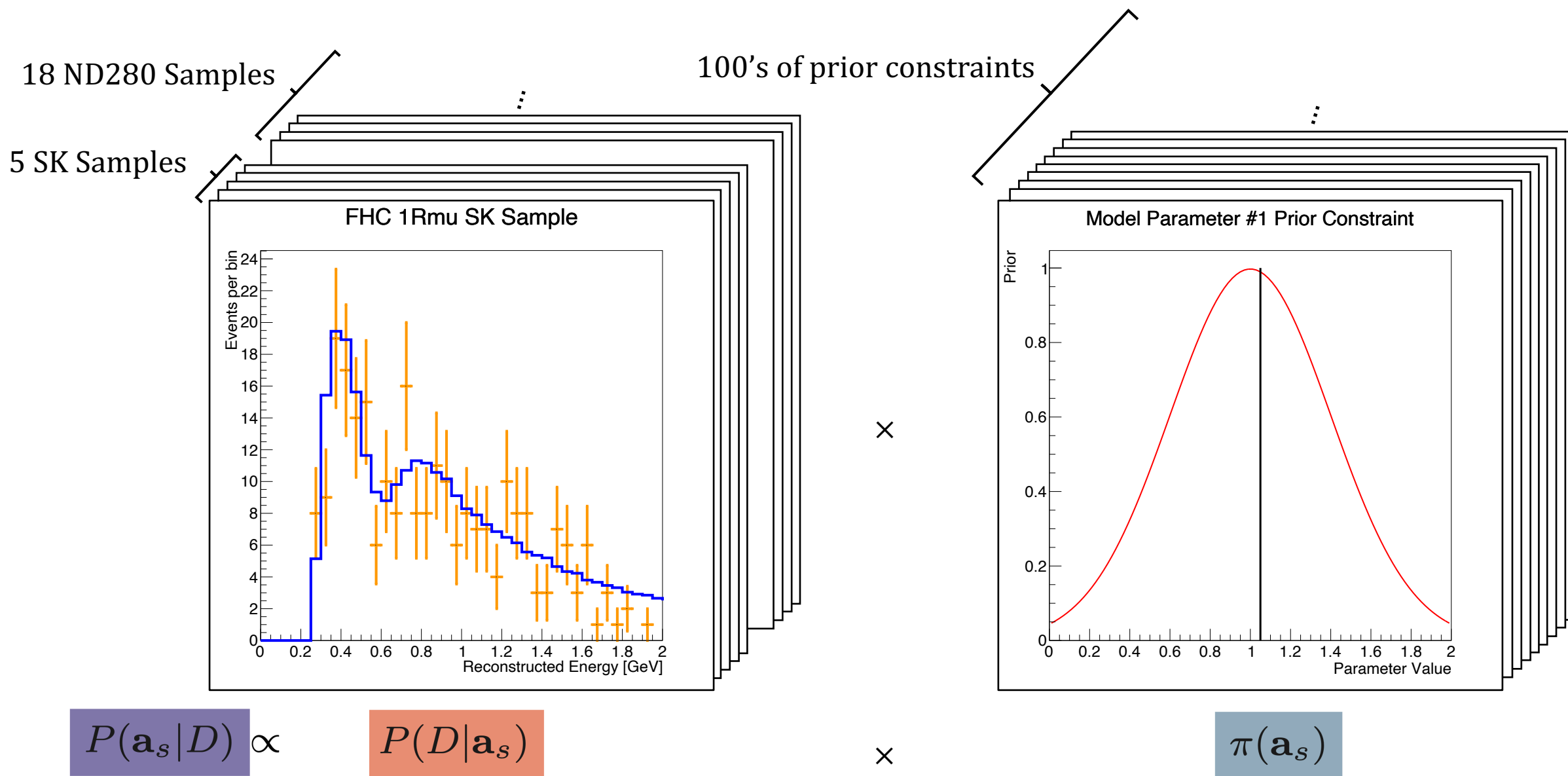
- Sample the parameter space proportionally to the posterior distribution
- Metropolis-Hastings algorithm



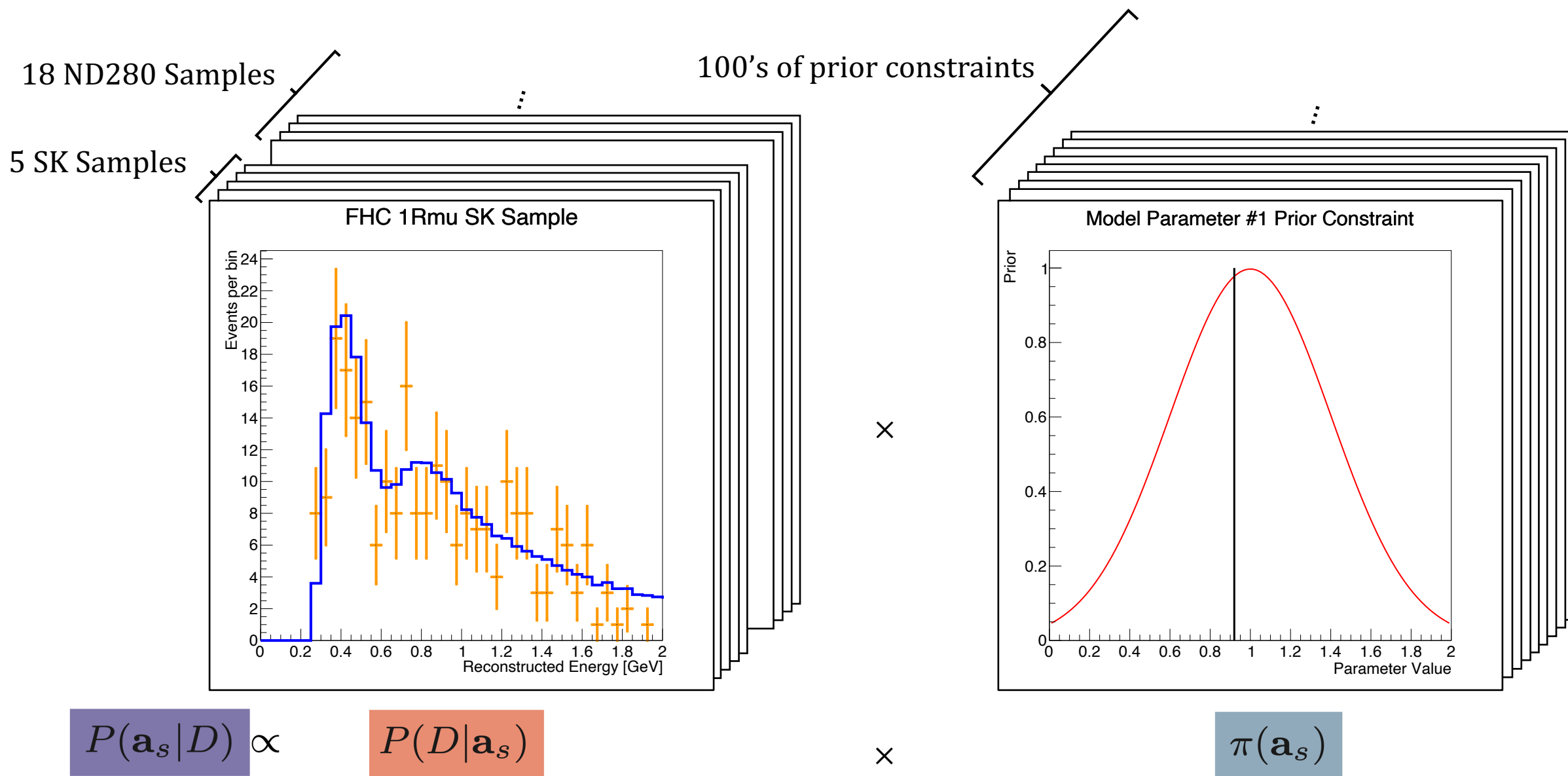
Markov Chain Monte Carlo



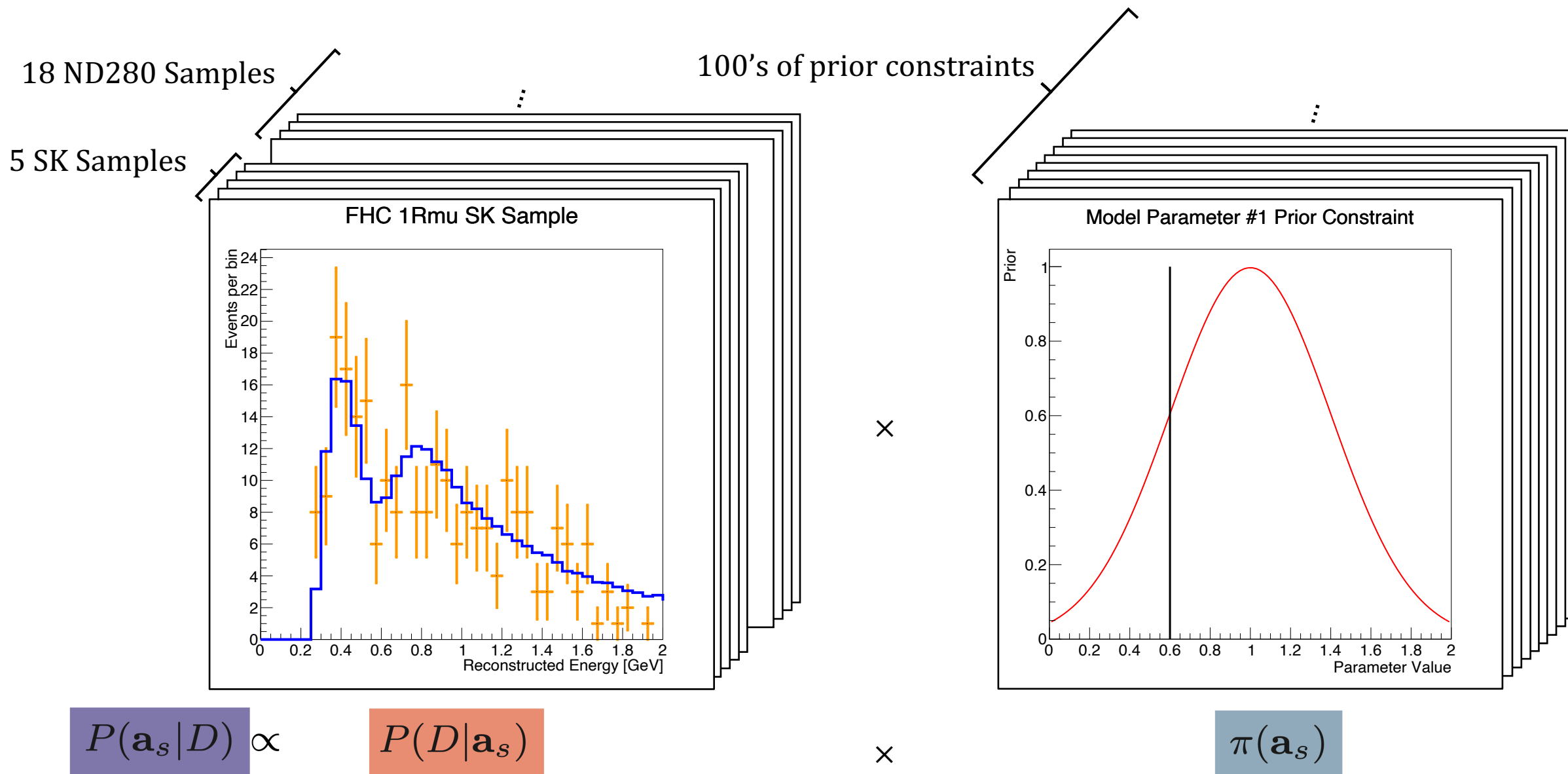
Markov Chain Monte Carlo



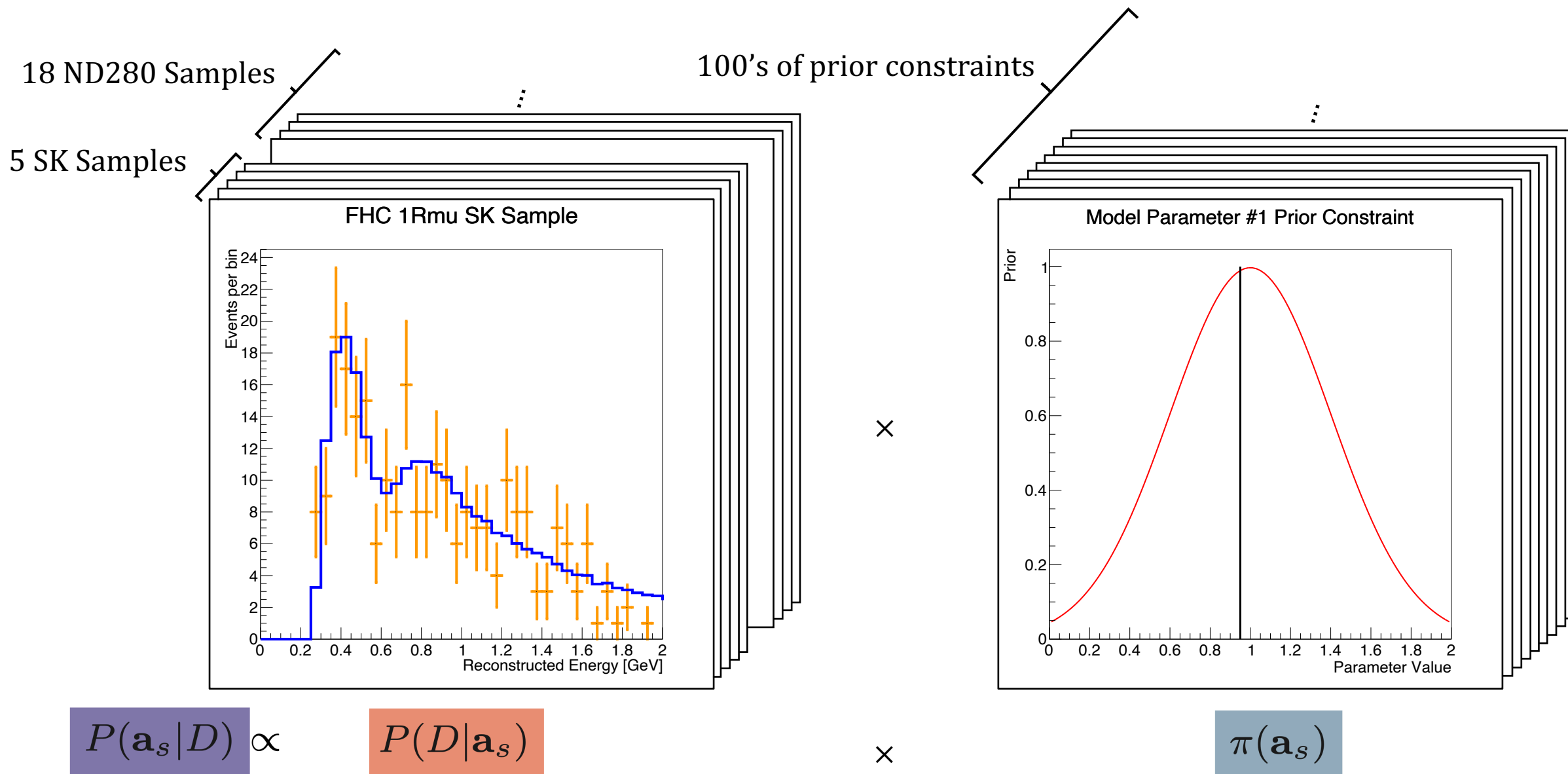
Markov Chain Monte Carlo



Markov Chain Monte Carlo

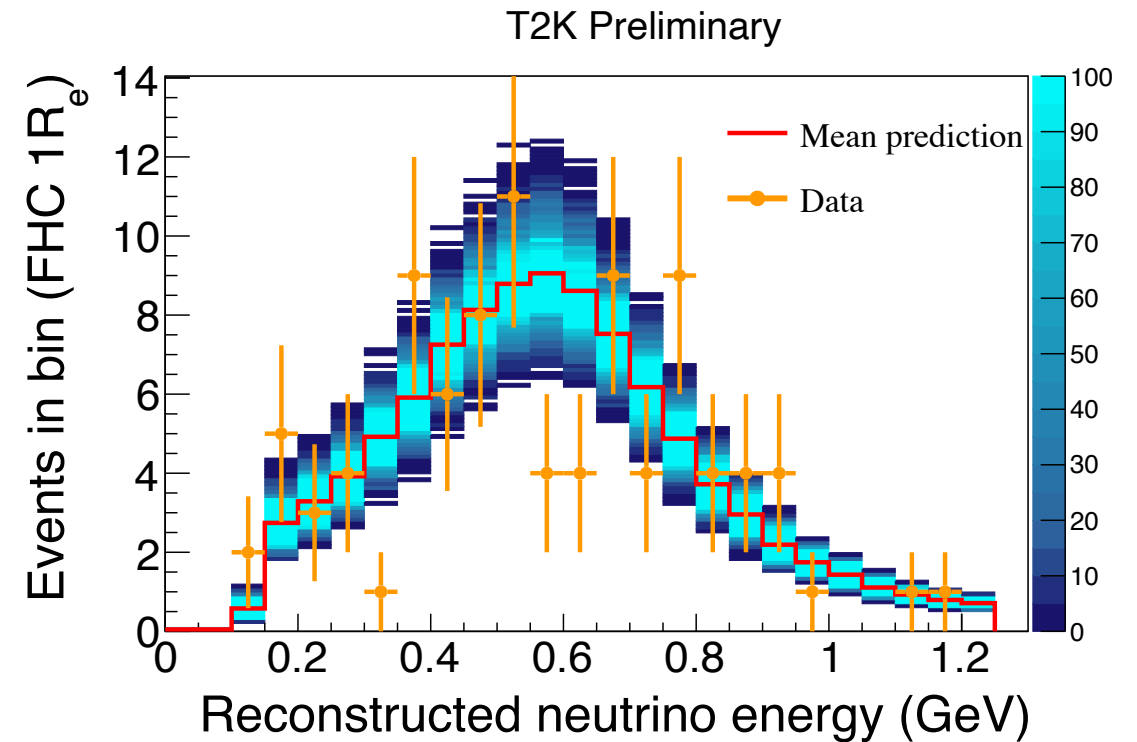
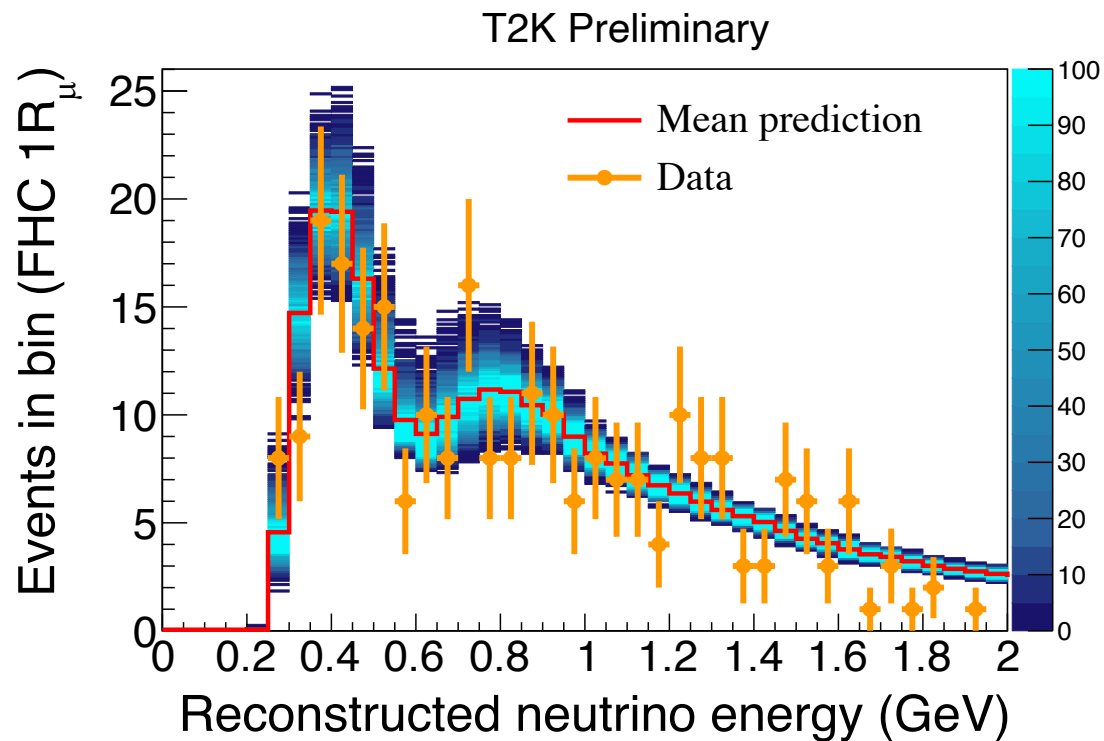


Markov Chain Monte Carlo



Posterior Predictive

- Distributions of sample spectra from posterior agree well with the data being fit



Goodness of Fit

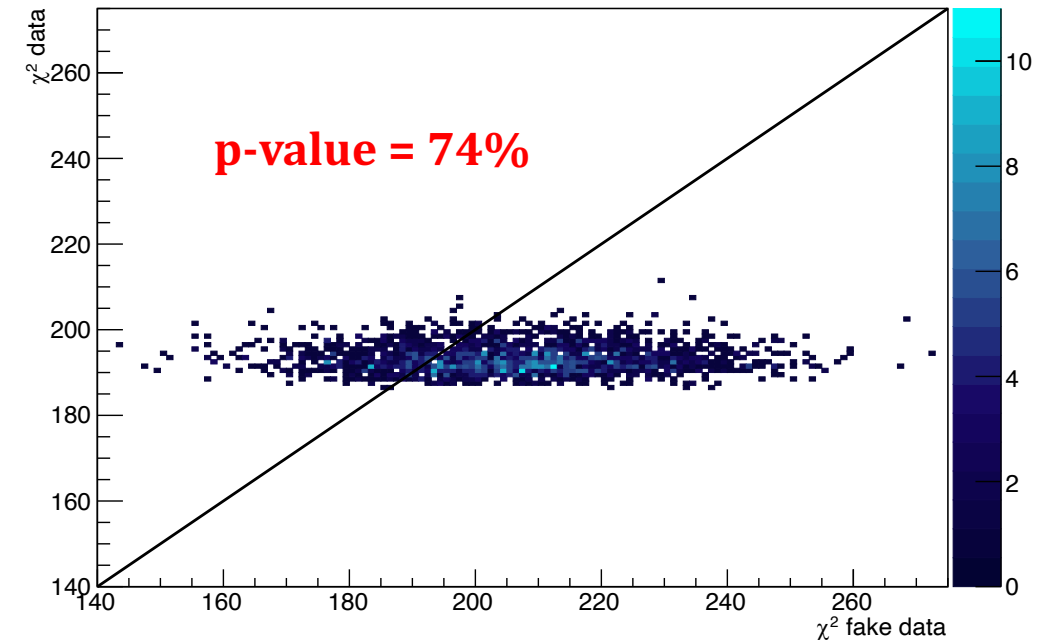
- Throw all model parameters based on posterior distribution of a joint data fit
 - Use this parameter set to make SK sample predictions
 - Compare this prediction to two “data” sets
 1. Fake data: statistical fluctuations of thrown prediction
 2. Real data
 - Calculate χ^2_{fake} and χ^2_{data} for each set

$$\chi^2 = 2 \sum_i^{bins} \left[n_i \ln \frac{n_i}{\nu_i} + \nu_i - n_i \right]$$

- p-value: proportion of throws for which $\chi^2_{data} < \chi^2_{fake}$
 - Proportion of fake data that are at least as “extreme” as the data

A. Gelman, X.L. Meng, and H. Stern. Posterior predictive assessment of model fitness via realized discrepancies. *Statistica Sinica*, 6:733–759, 1996.

Run 1-10, T2K Preliminary



Sample / p-value	Shape-based	Total Rate-based
FHC 1R μ	0.51	0.17
FHC 1Re	0.19	0.51
RHC 1R μ	0.84	0.75
RHC 1Re	0.63	0.40
FHC 1Re1d.e.	0.86	0.22
Total	0.74	0.31

Posterior Reweighting

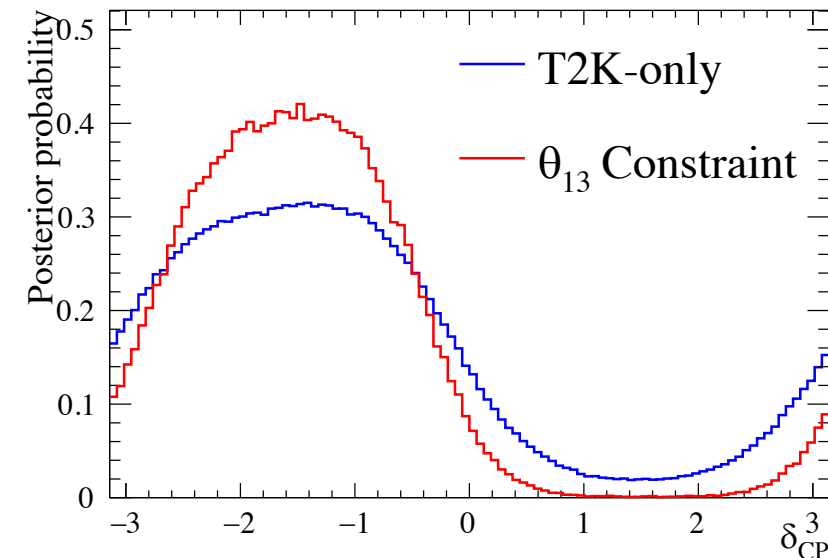
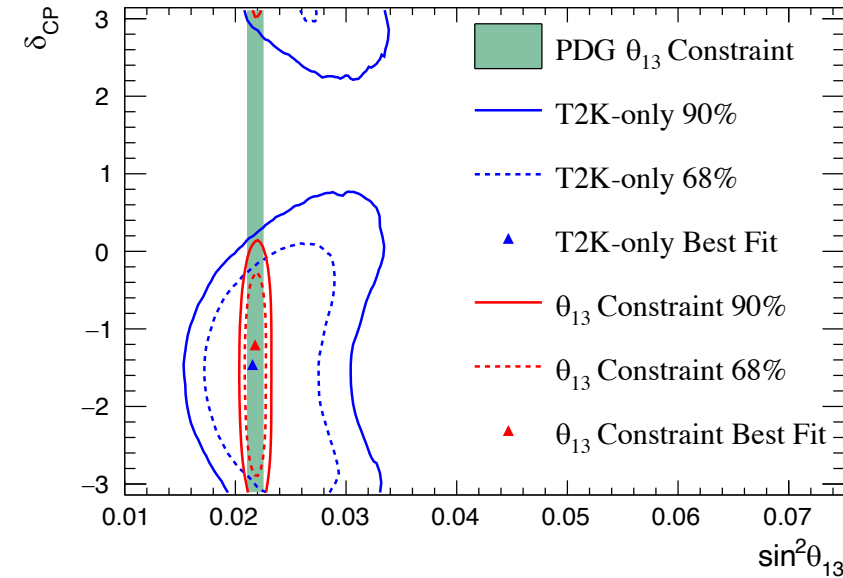
- Possible to reweight posterior distributions from MCMC fits in order to apply alternative priors post facto
 - Has saved T2K >50K CPU hours this year alone
 - Need to consider coverage. Generally okay to impose tighter constraints in areas of high probability density
 - Avoid weighting up regions of low probability density

example 1/3

- E.g. run a fit with flat priors on all oscillation parameters of interest (T2K-only) and apply a gaussian constraint on θ_{13}

Run 1-10, T2K Preliminary

Fit to simulated data, N.O.



Posterior Reweighting

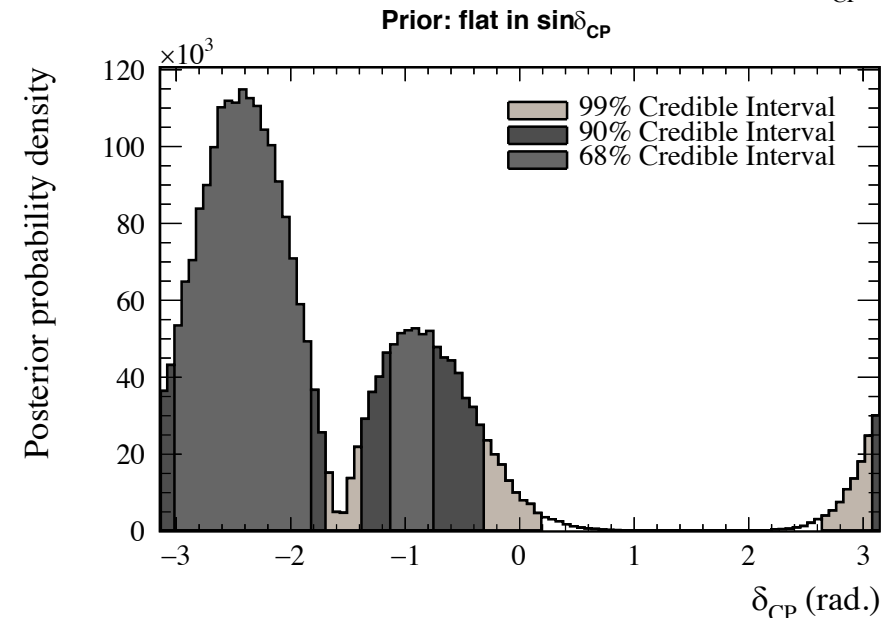
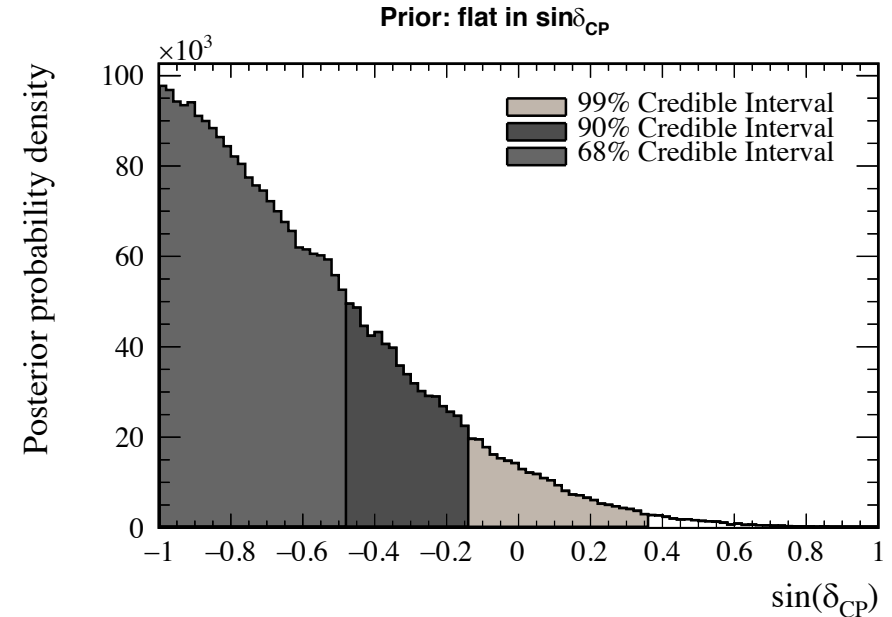
- Possible to reweight posterior distributions from MCMC fits in order to apply alternative priors post facto
 - Has saved T2K >50K CPU hours this year alone
 - Need to consider coverage. Generally okay to impose tighter constraints in areas of high probability density
 - Avoid weighting up regions of low probability density

example 2/3

- E.g. can apply alternative priors on δ_{CP}
 - Nominal is flat in δ_{CP}
 - Reweight to being flat in $\sin \delta_{CP}$

Run 1-10, T2K Preliminary

Fit to simulated data, N.O.



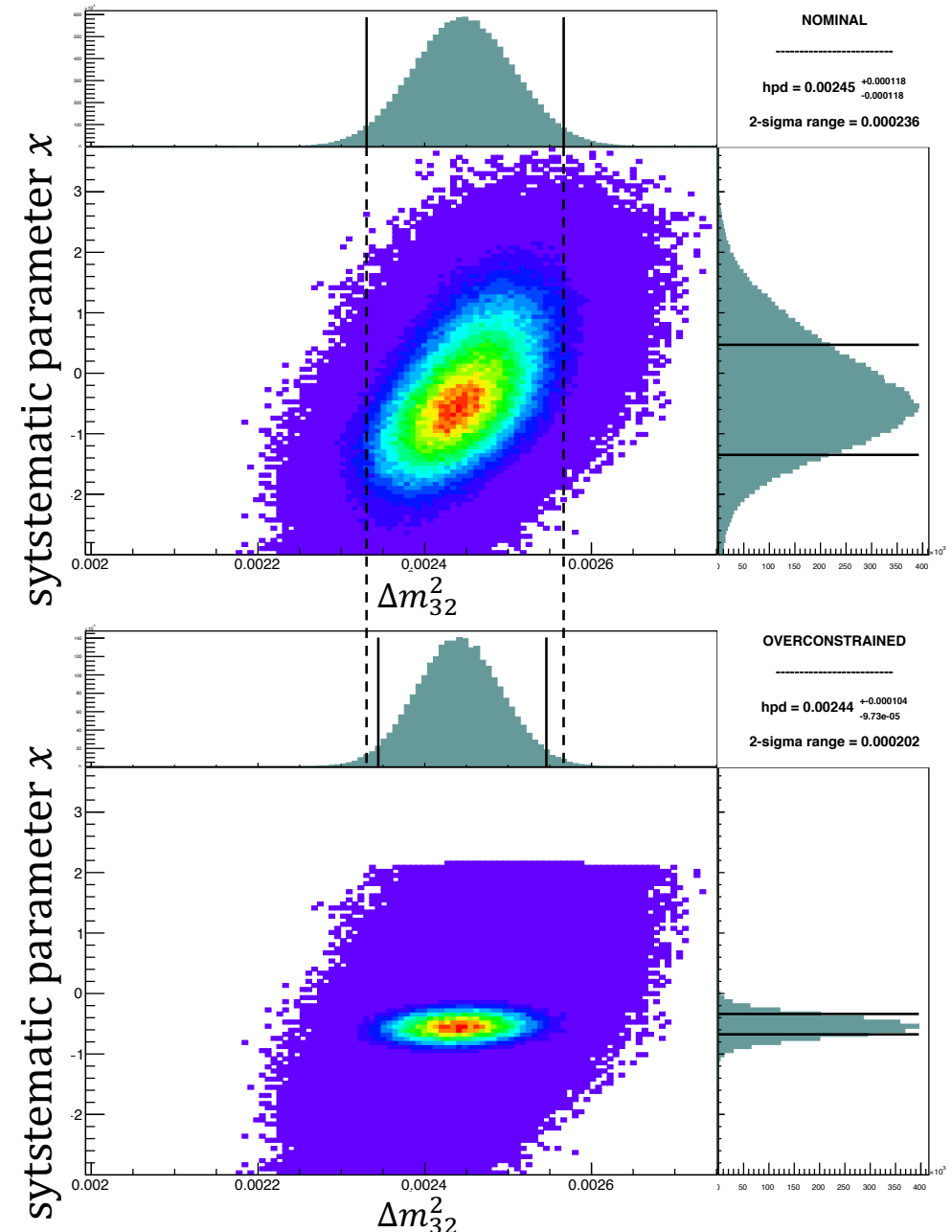
Posterior Reweighting

- Possible to reweight posterior distributions from MCMC fits in order to apply alternative priors post facto
 - Has saved T2K >50K CPU hours this year alone
 - Need to consider coverage. Generally okay to impose tighter constraints in areas of high probability density
 - Avoid weighting up regions of low probability density

example 3/3

- E.g. the effect of constraining your systematics better on the oscillation parameter measurements

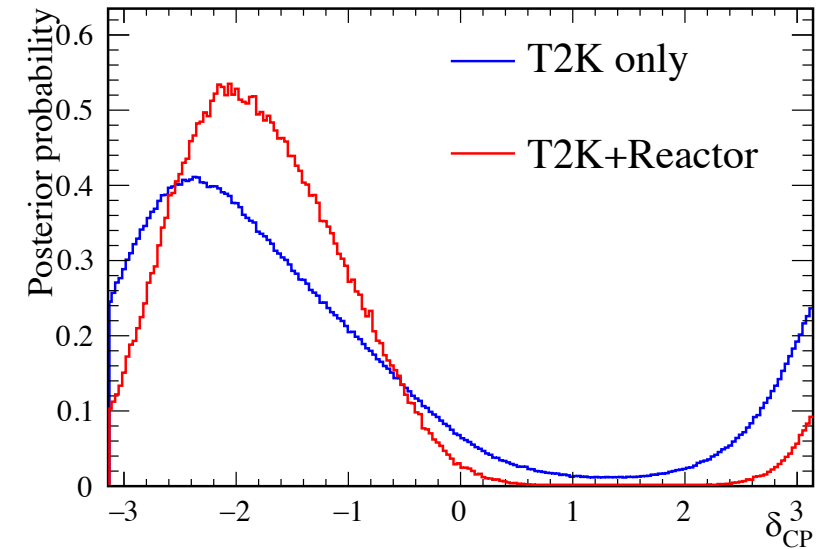
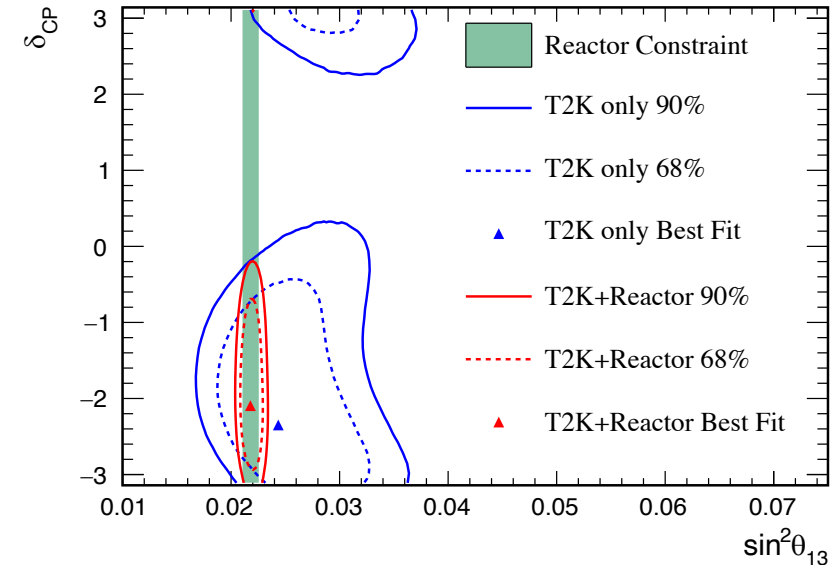
NOTE: This study was not done with the most recent results.



Run 1-10 results

- Showing results from
 - T2K data only fit – flat priors on 4 oscillation parameters of interest
 - T2K + reactor constraint – puts a Gaussian prior on θ_{13} based on PDG world average
- Reactor experiments have superior sensitivity to θ_{13}
- Using this constraint improves T2K's sensitivity to other parameters of interest

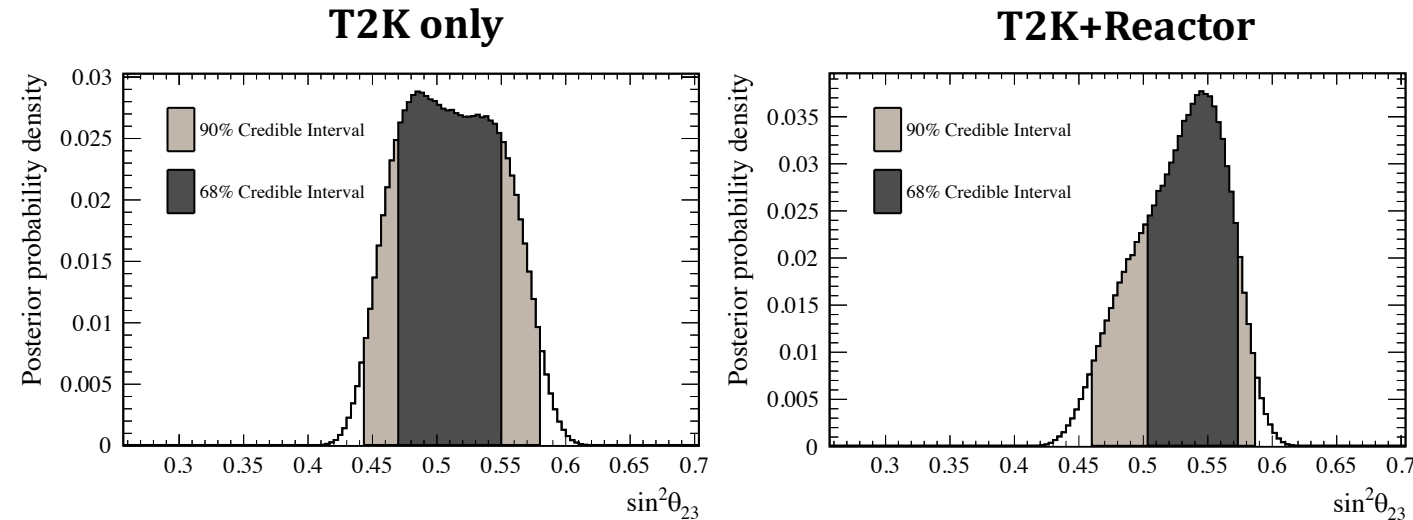
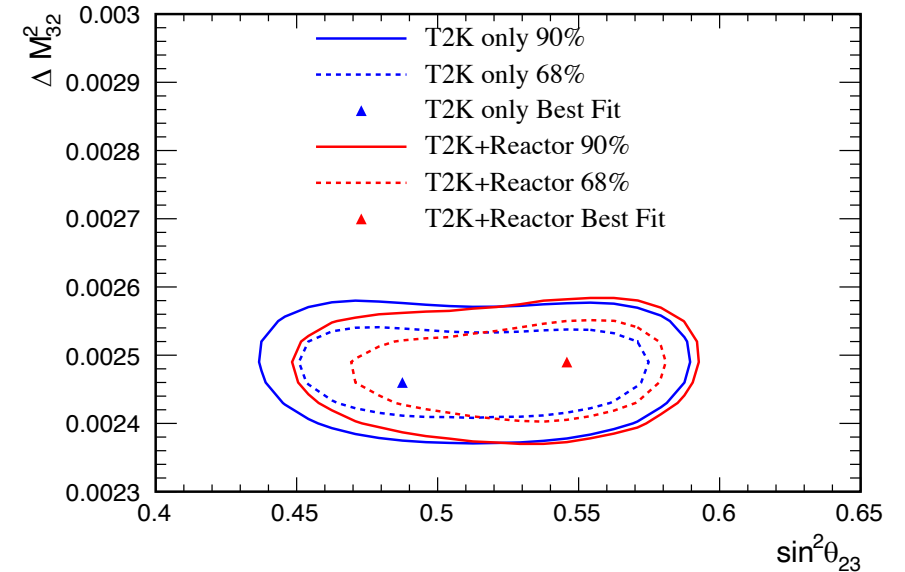
Run 1-10, T2K Preliminary



Run 1-10 results

- Showing results from
 - T2K data only fit – flat priors on 4 oscillation parameters of interest
 - T2K + reactor constraint – puts a Gaussian prior on θ_{13} based on PDG world average
- T2K-only: slight preference for lower octant, quite consistent with maximal mixing
- With reactor constraint: best fit in upper octant, disfavor maximal mixing at 1σ

Run 1-10, T2K Preliminary

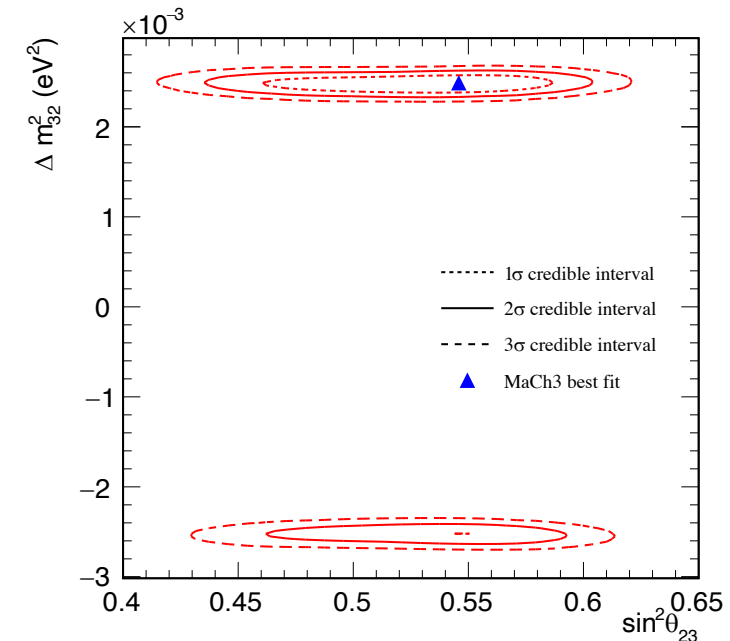
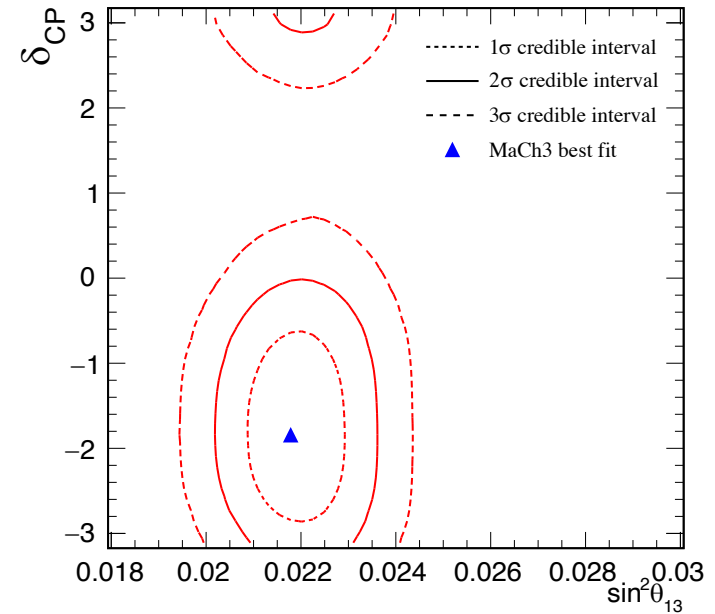


Run 1-10 results

- Marginalized over hierarchies, with θ_{13} constraint from PDG 2019 applied
- Close 3σ contours in $\sin^2 \theta_{13} - \delta_{CP}$
- 2D best fit point:
 - $(\sin^2 \theta_{13}, \delta_{CP}) = (0.0220, -1.97)$
- Prefer normal mass ordering ($\Delta m_{32}^2 > 0$) and upper octant ($\sin^2 \theta_{23} > 0.5$)
- 2D best fit point:
 - $(\sin^2 \theta_{23}, \Delta m_{32}^2) = (0.55, 2.49 \times 10^{-3} \text{ eV}^2)$

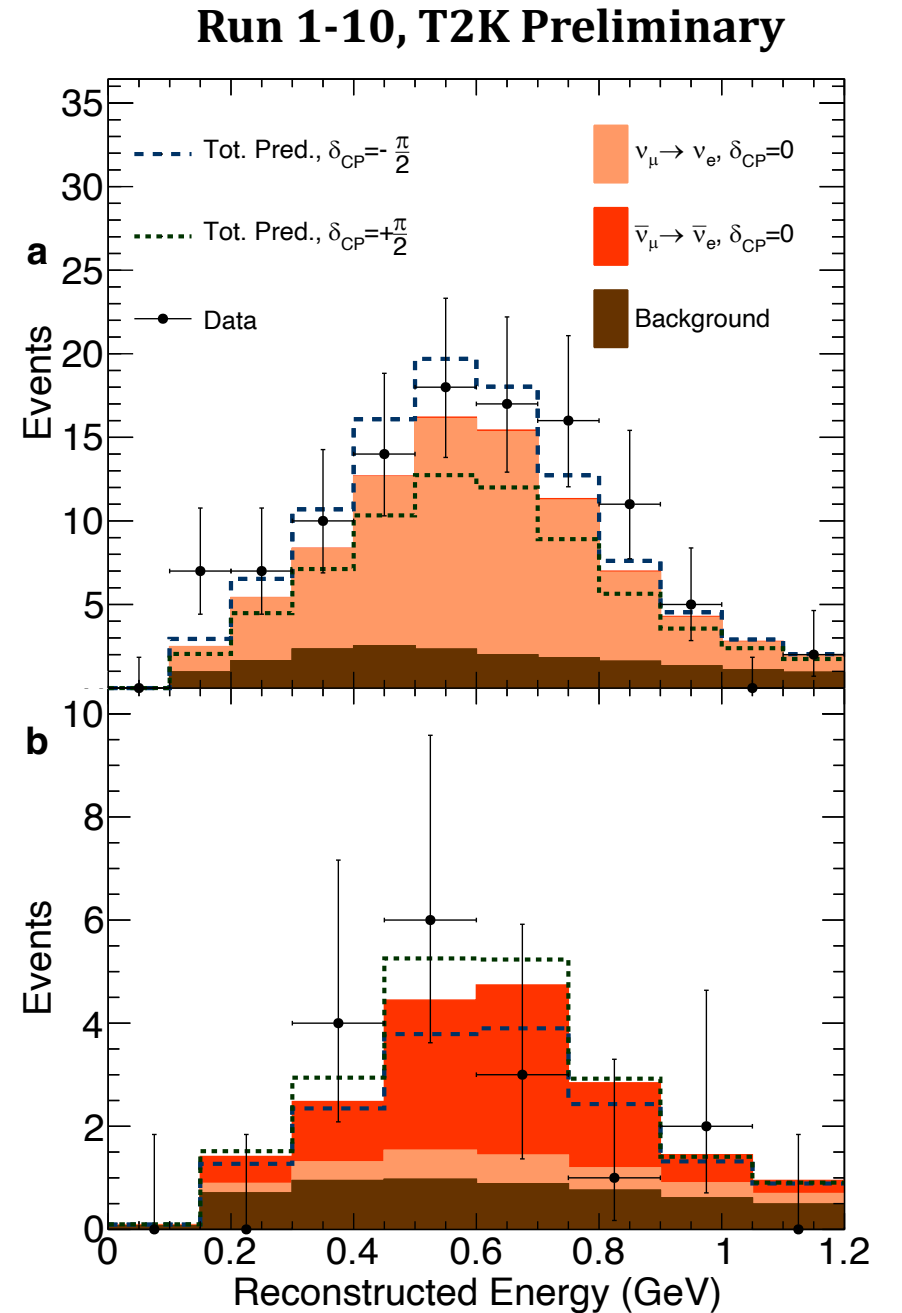
	$\sin^2 \theta_{23} < 0.5$	$\sin^2 \theta_{23} > 0.5$	Sum
NH ($\Delta m_{32}^2 > 0$)	0.195	0.613	0.808
IH ($\Delta m_{32}^2 < 0$)	0.034	0.158	0.192
Sum	0.229	0.771	1.000

Run 1-10, T2K Preliminary



δ_{CP} measurement

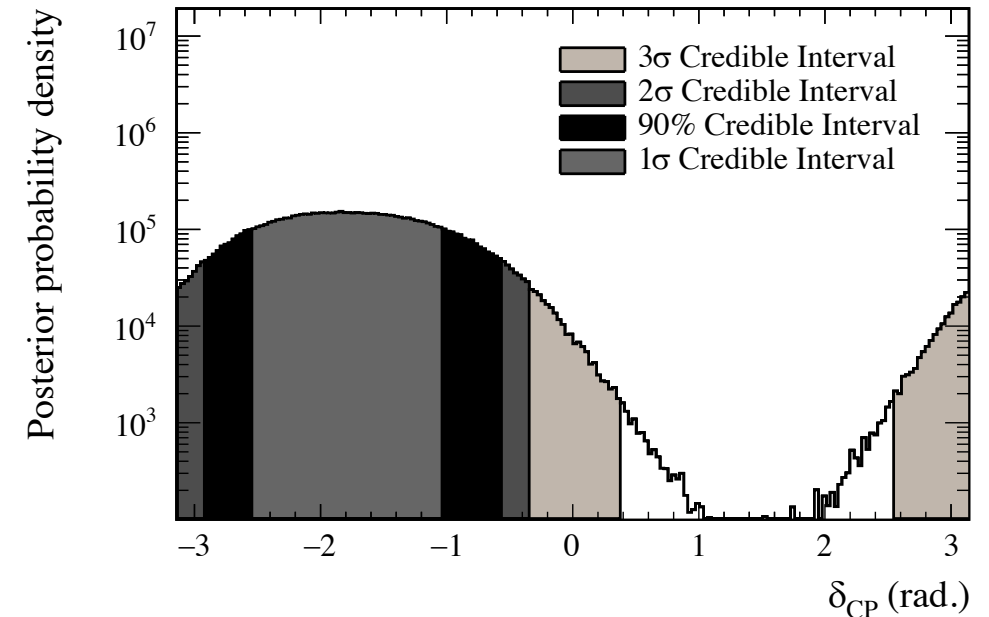
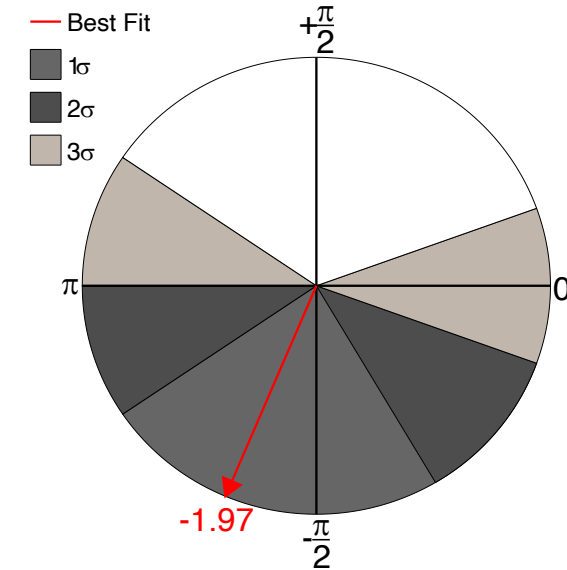
- (Minor) excess of ν_e events with respect to the $\delta_{CP} = 0$ prediction
- Behavior in $\bar{\nu}_e$ sample more mixed
- 35% of values around $\pi/2$ are excluded at 3σ , marginalizing over hierarchies and applying θ_{13} constraint
- CP conserving values excluded at 90%
- Slightly looser constraints, but in better agreement with anticipated sensitivity



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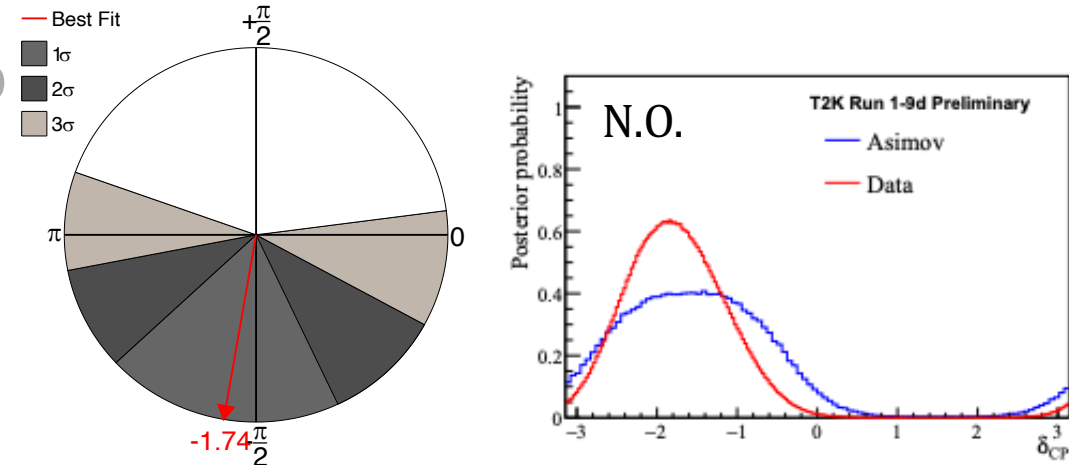
Run 1-10, T2K Preliminary



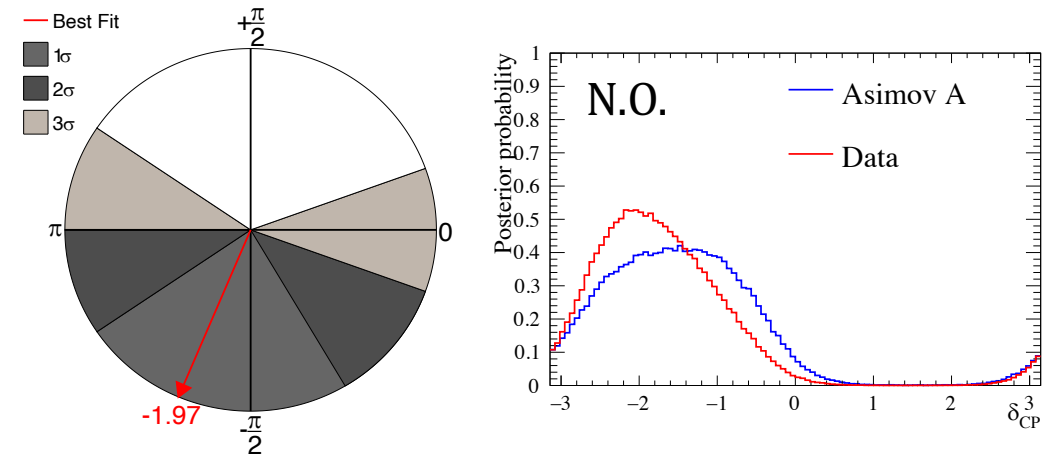
δ_{CP} measurement

- (Minor) excess of ν_e events with respect to the $\delta_{CP} = 0$ prediction
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- Slightly looser constraints, but in better agreement with anticipated sensitivity

Run 1-9, T2K Nature



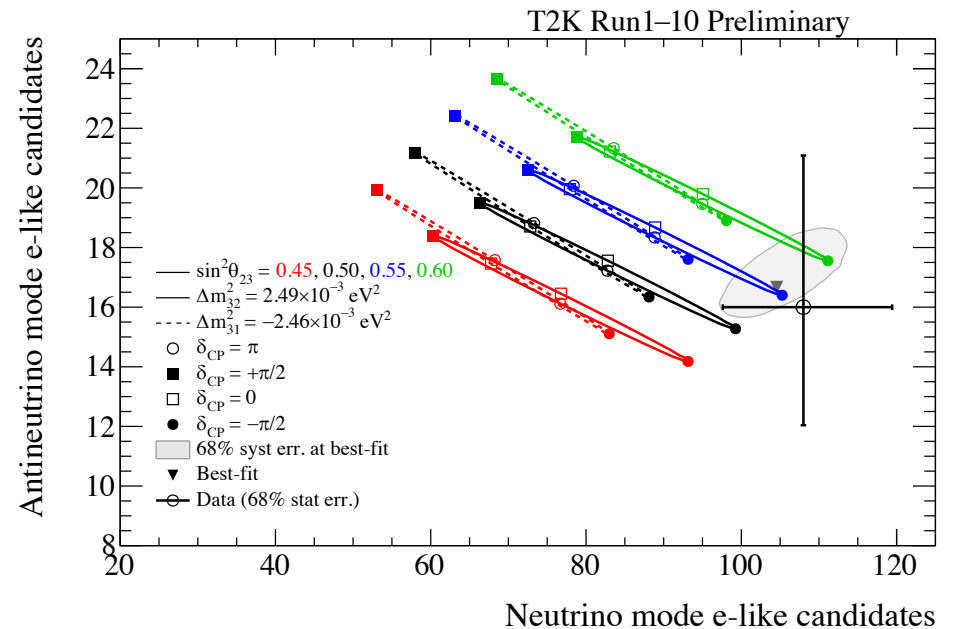
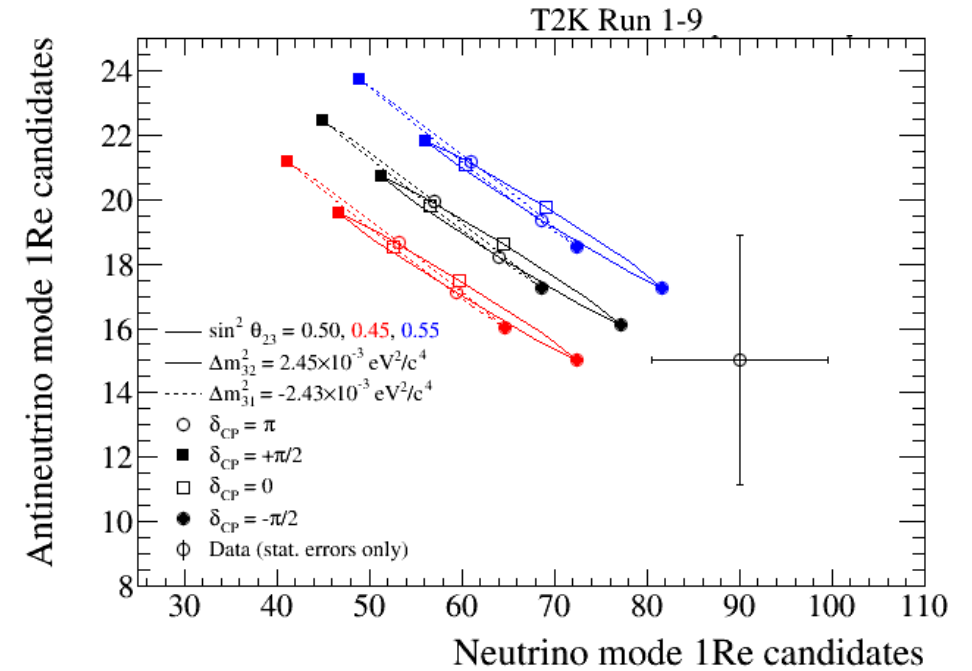
Run 1-10, T2K Preliminary



(with reactor constraint)

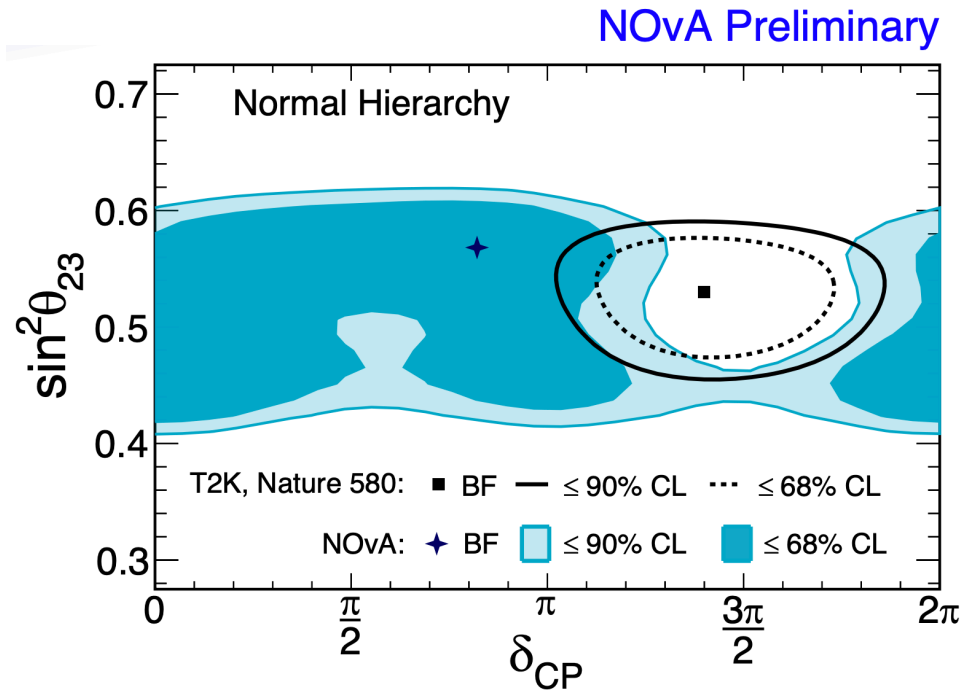
δ_{CP} measurement

- (Minor) excess of ν_e events with respect to the $\delta_{CP} = 0$ prediction
- Behavior in $\bar{\nu}_e$ sample more mixed
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- CP conserving values excluded at 90%
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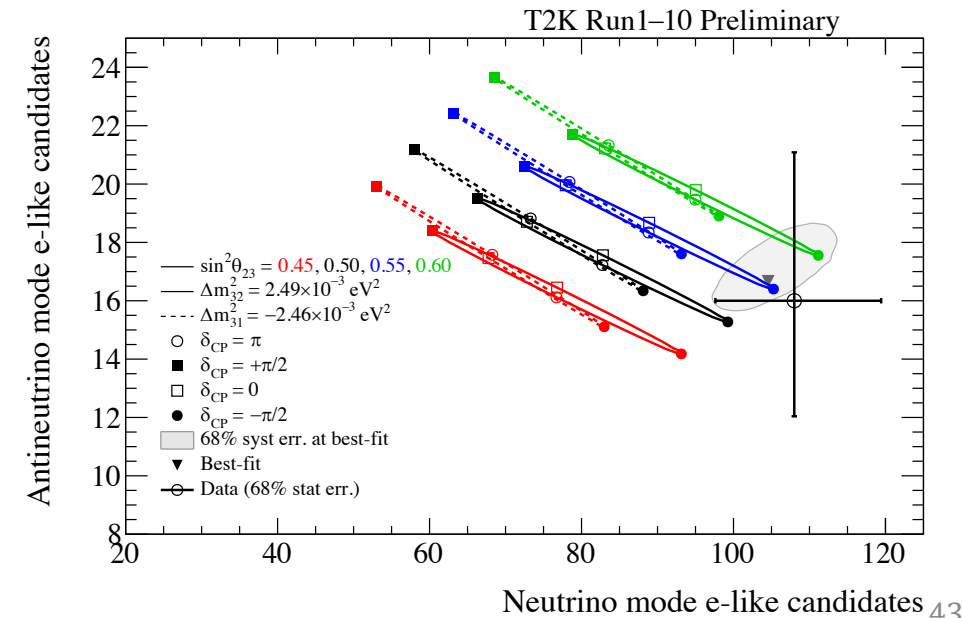
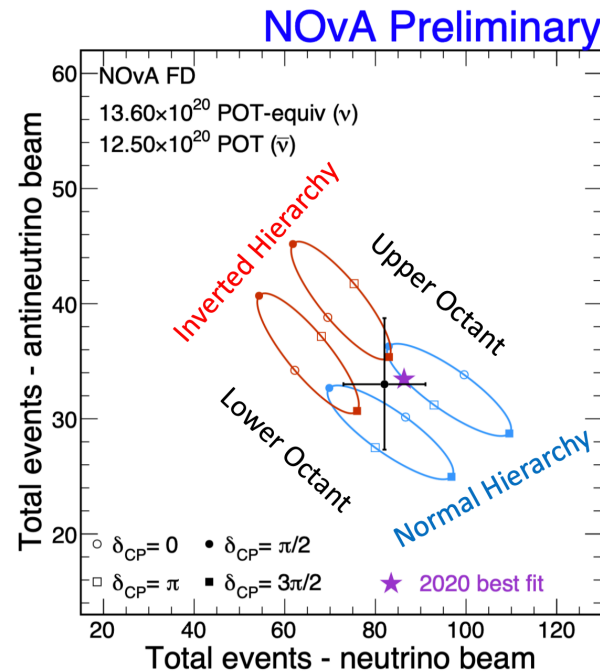


Future of T2K

- **T2K-NOvA joint fit**
- T2K-SK joint fit
- Beam upgrade
- ND280 upgrade
- SK-Gd

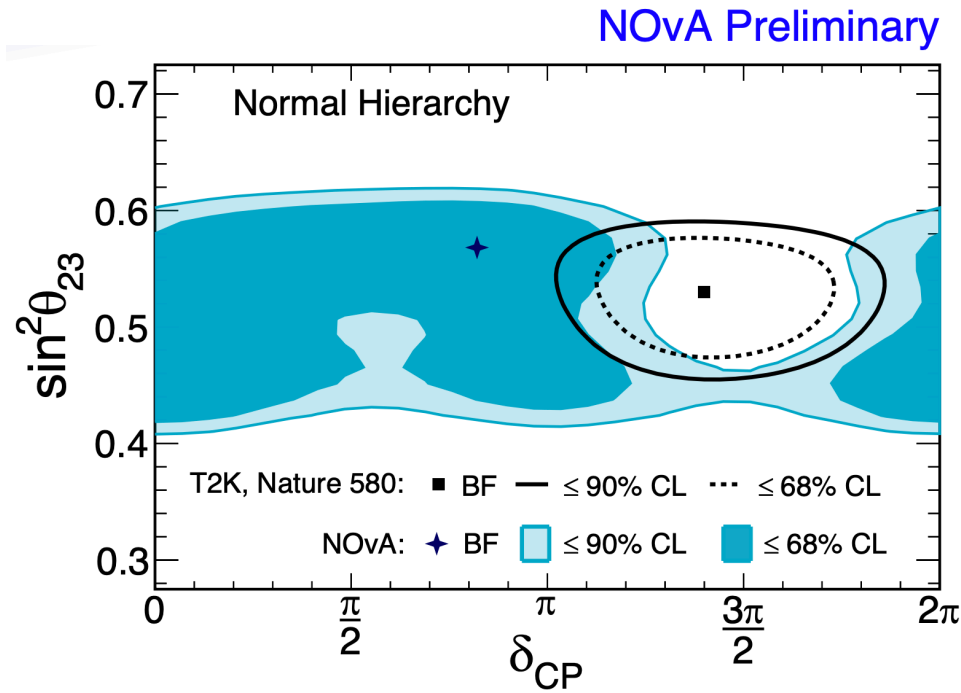


- T2K and NOvA's likelihood surfaces are favoring different regions of δ_{CP} -space
- A proper joint analysis can help break degeneracies and get the most out of the data



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- **T2K-NOvA joint fit**
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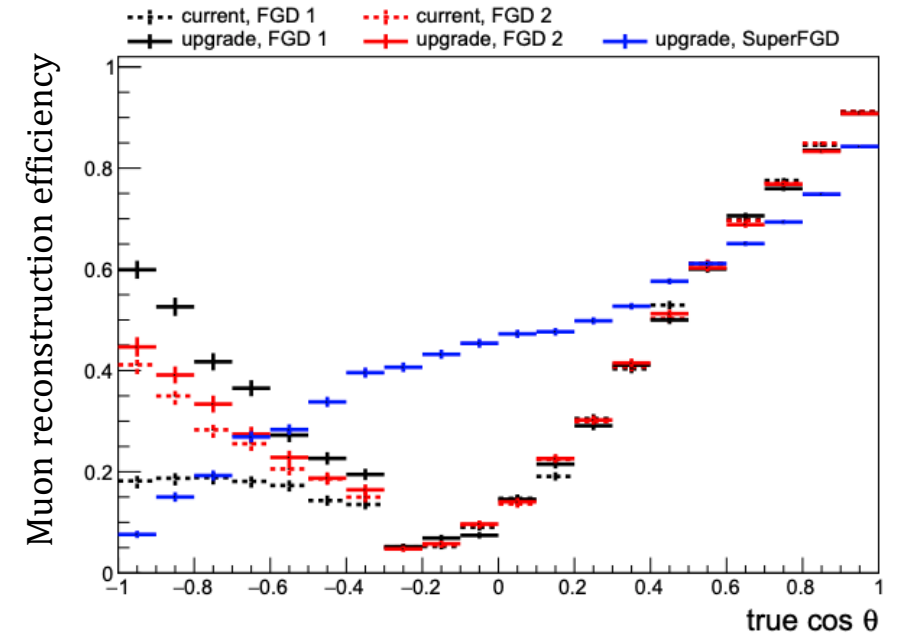
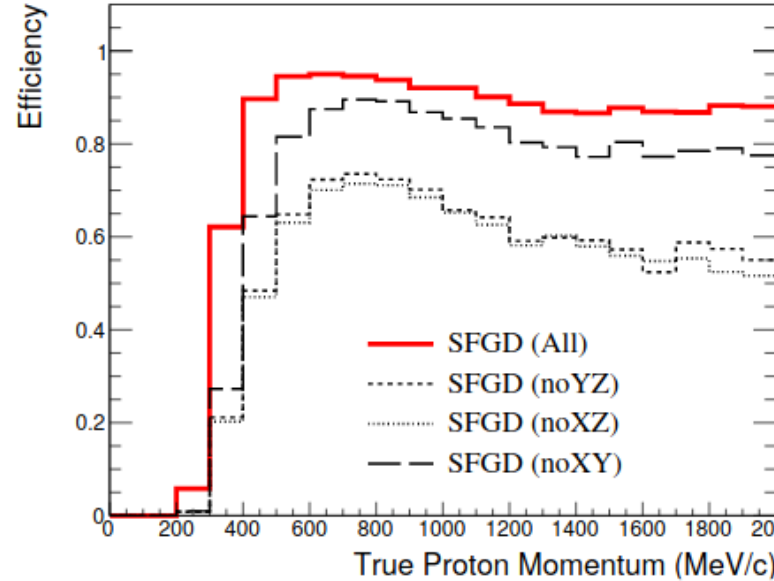


- T2K and NOvA's likelihood surfaces are favoring different regions of δ_{CP} -space
- A proper joint analysis can help break degeneracies and get the most out of the data
- Holding semi-annual workshops
- Several working meetings between workshops

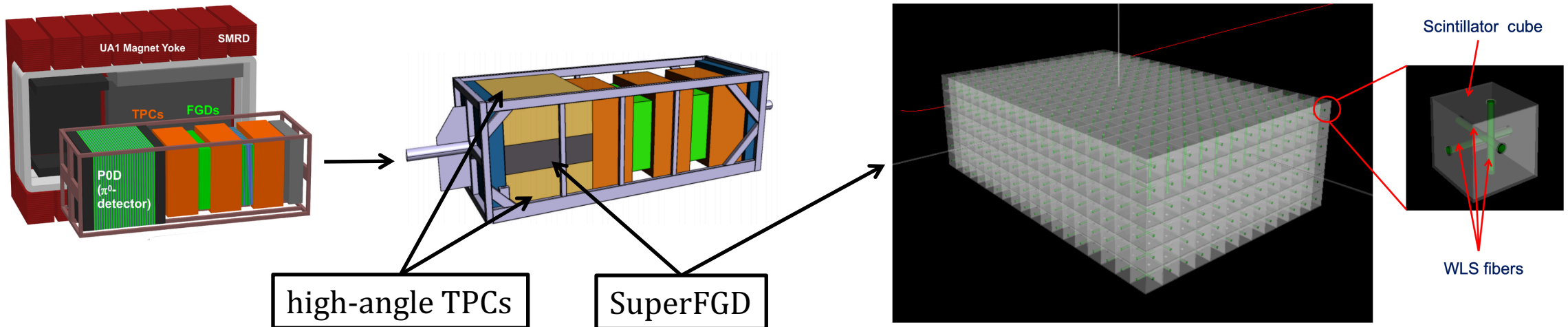


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- **ND280 upgrade**
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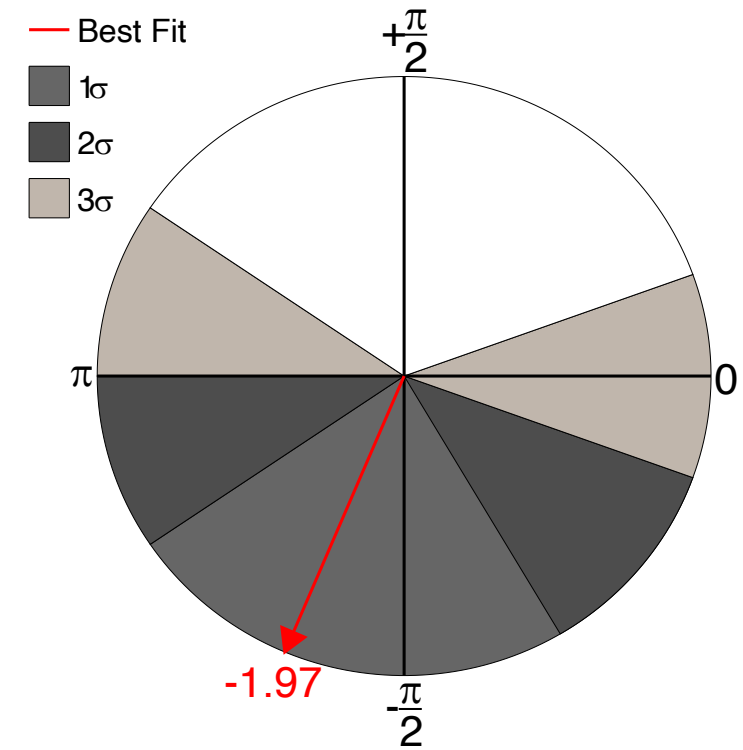


- Replace POD detector with SuperFGD and high-angle TPCs encased in TOF system



Summary

- Presented an overview of T2K and its Bayesian Markov Chain Monte Carlo Oscillation Analysis
- Showed the latest results using the full run 1-10 data set corresponding to
 - 1.97×10^{21} POT in neutrino-mode
 - 1.63×10^{21} POT in antineutrino-mode



- 1-sigma credible intervals:
 - $\sin^2 \theta_{23} = 0.546_{-0.046}^{+0.024}$
 - $\Delta m_{32}^2 = 2.49_{-0.08}^{+0.06} \times 10^{-3} \text{eV}^2$
 - $\sin^2 \theta_{13} = 0.0220_{-0.0008}^{+0.0006}$
 - $\delta_{CP} = -1.97_{-0.58}^{+0.93}$



Stony Brook
University

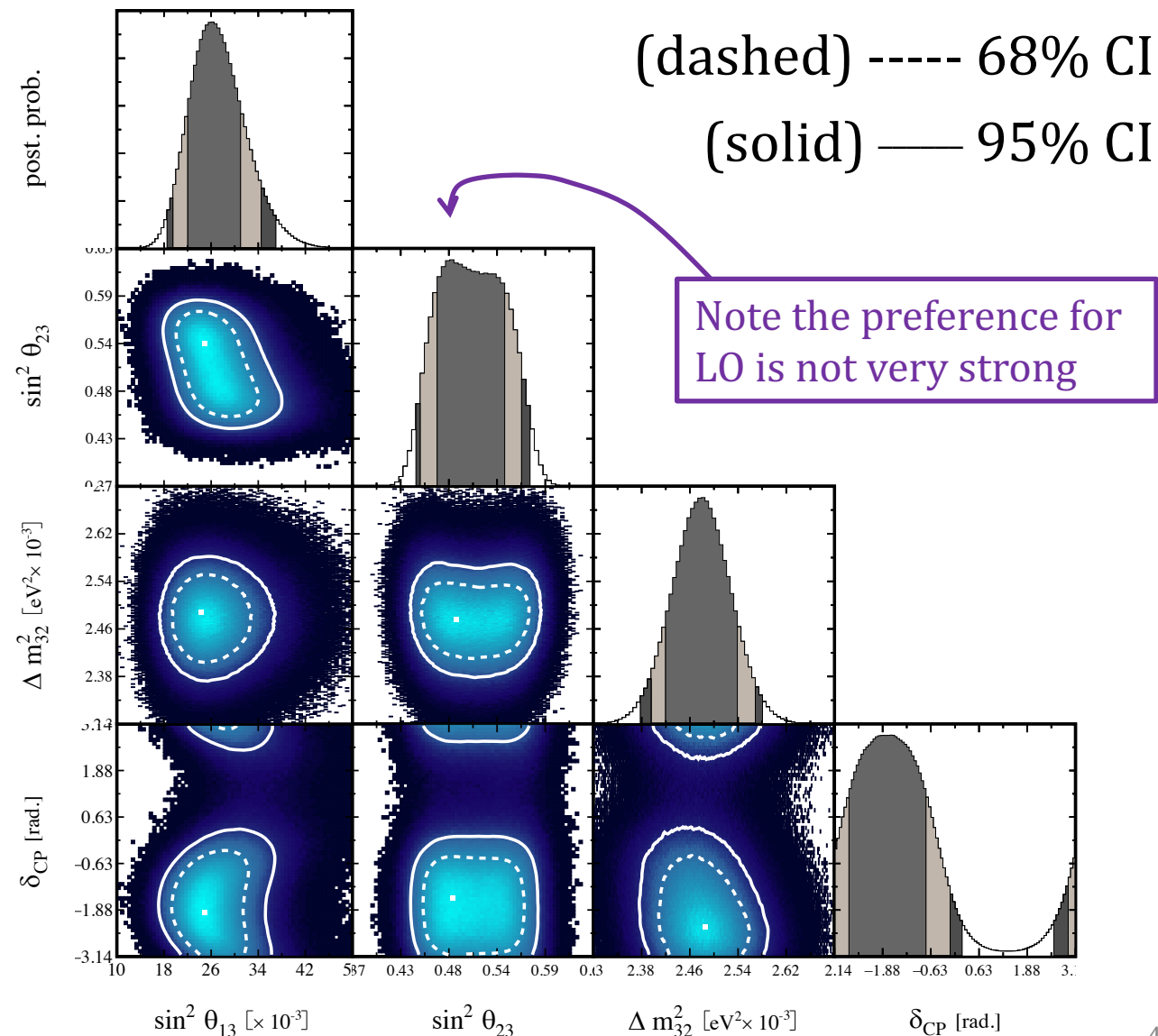
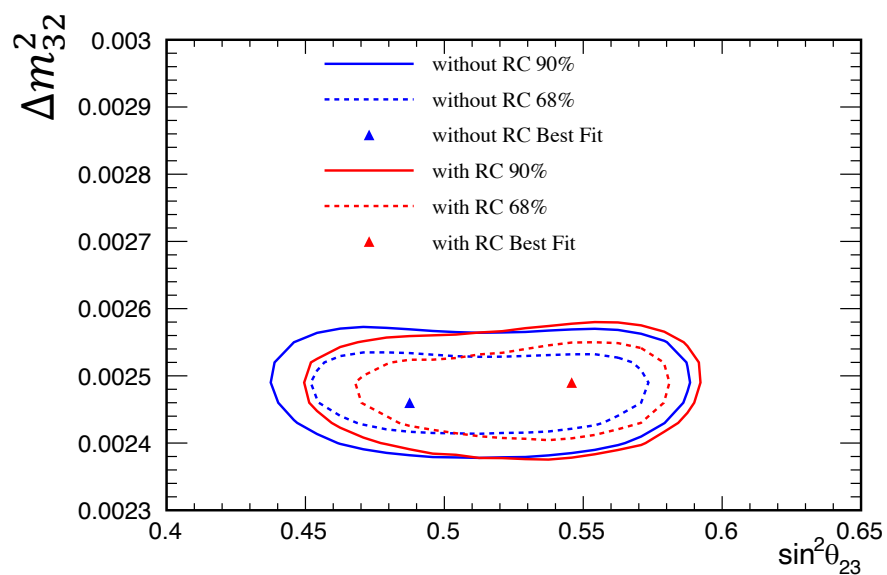
Thanks!



Backups

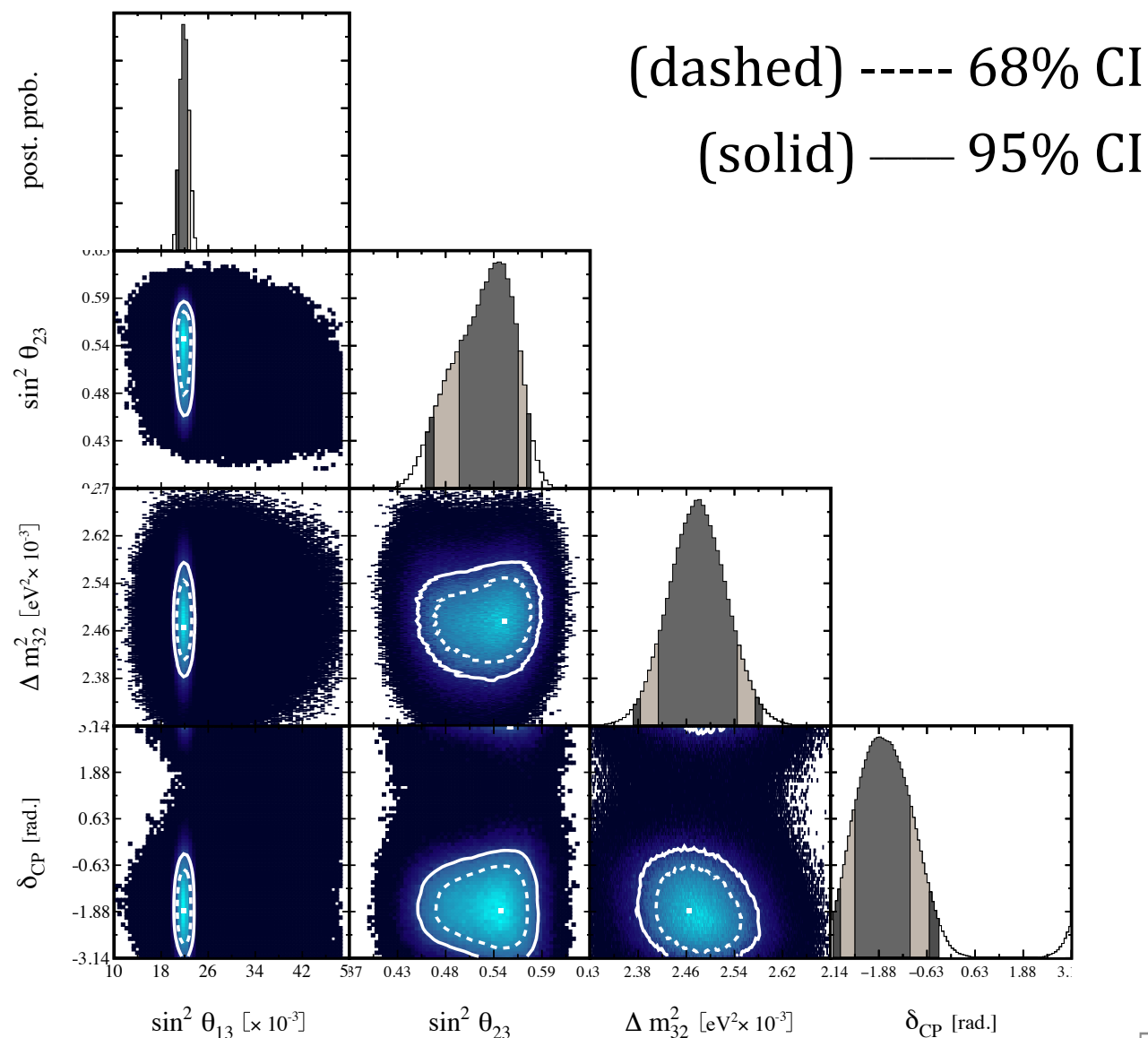
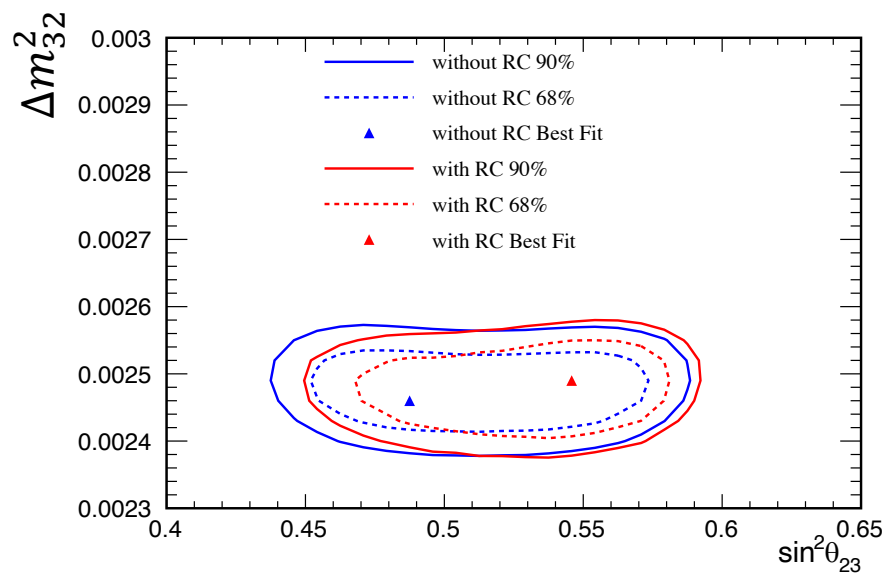
Triangle Plot – without reactor constraint

- Note the $\sin^2 \theta_{13} - \sin^2 \theta_{23}$ contour
 - 2D best fit point in upper octant (unlike δ_{CP} - and $\Delta m_{32}^2 - \sin^2 \theta_{23}$ 2D BF)
 - Relatively strong correlation
 - RC of $\sin^2 \theta_{13} = 0.0218 \pm 0.0007$ will move all 2D BFs into the upper octant



Triangle Plot – with reactor constraint

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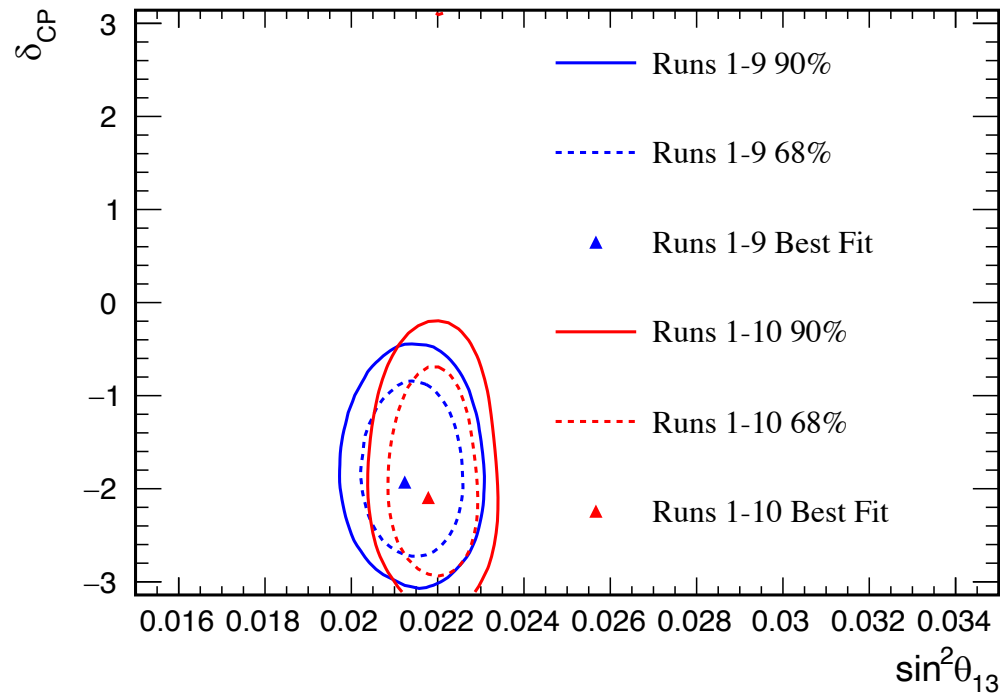


Run 1-10 Comparison to Run1-9

- With reactor constraint

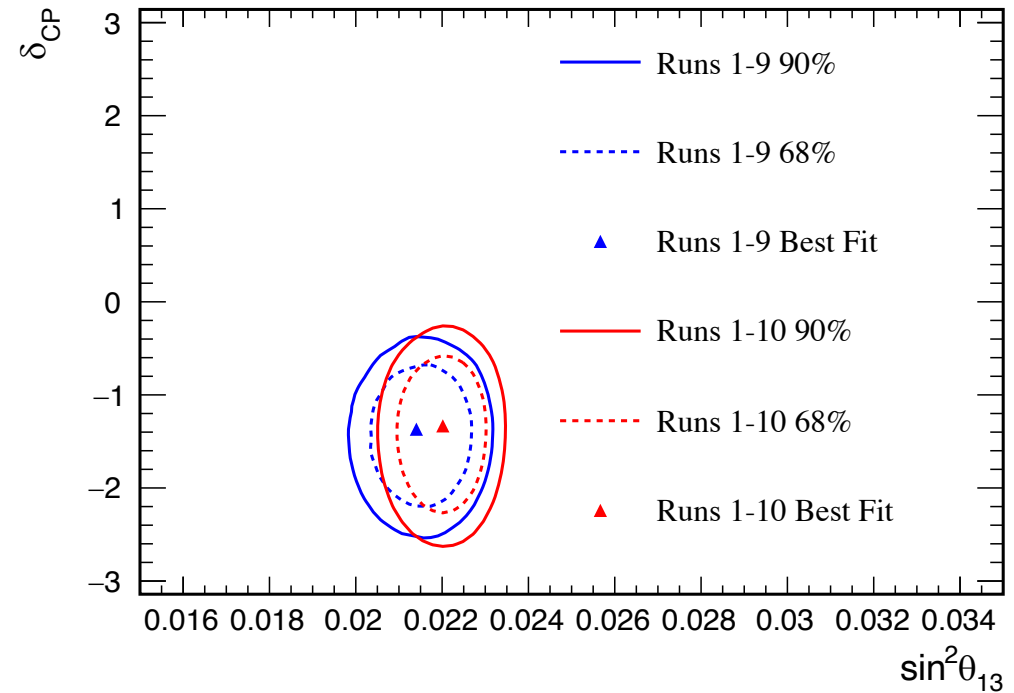
Normal Ordering

MaCh3 Joint Fit, wRC



Inverted Ordering

MaCh3 Joint Fit, wRC

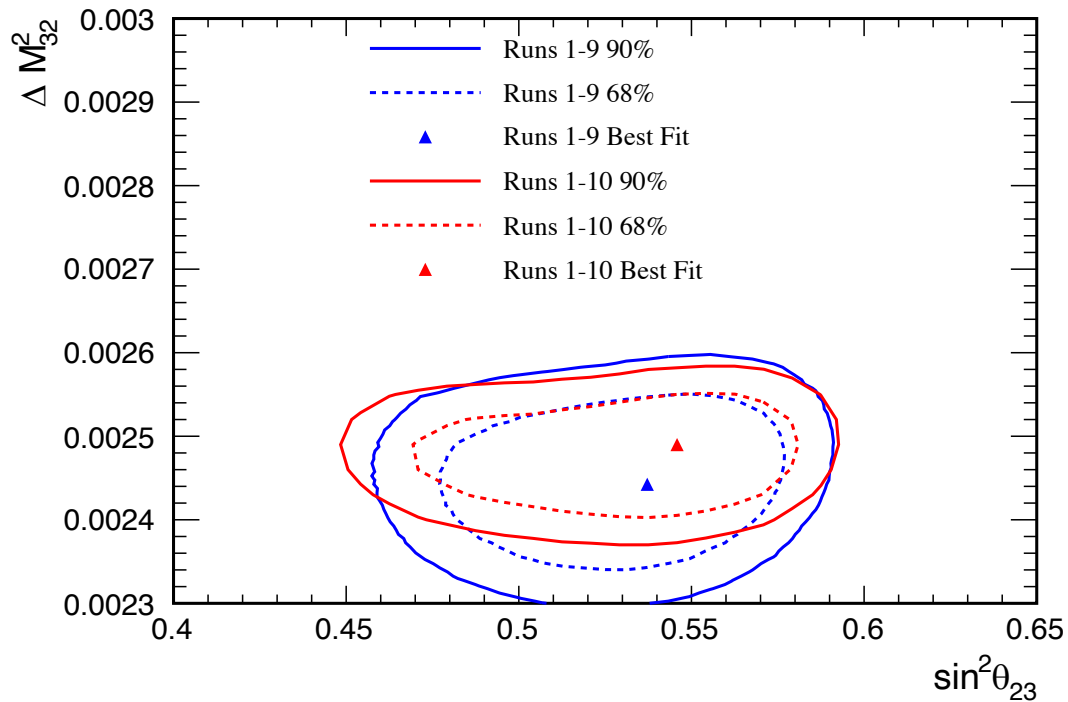


Run 1-10 Comparison to Run1-9

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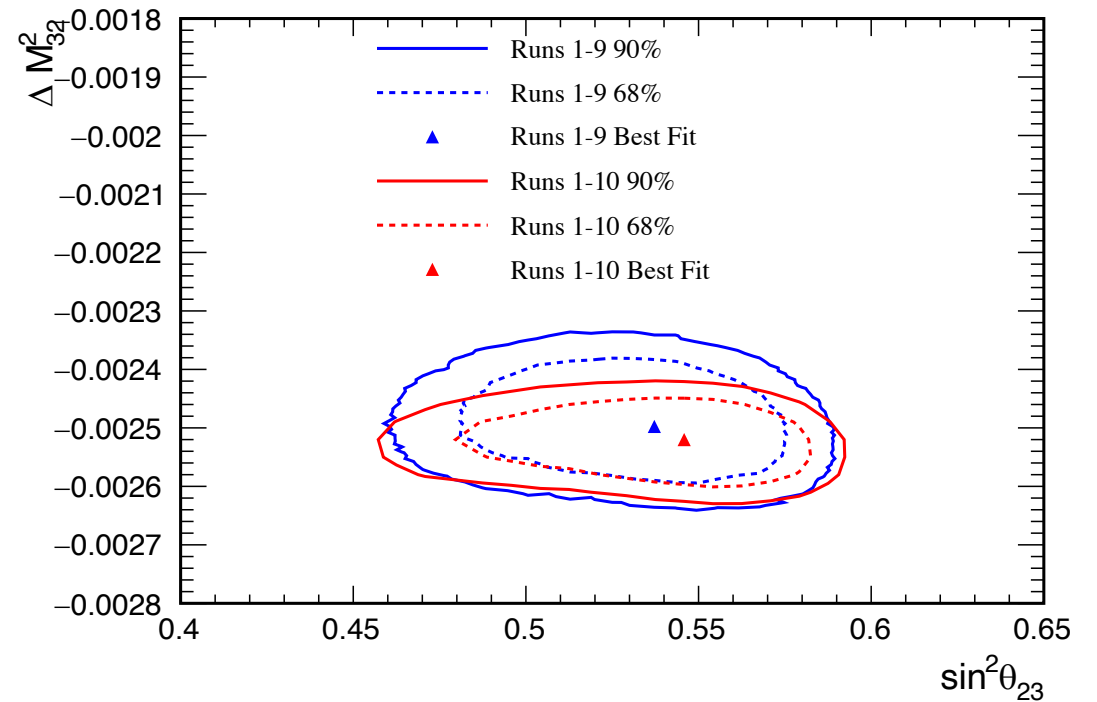
Normal Ordering

MaCh3 Joint Fit, wRC



Inverted Ordering

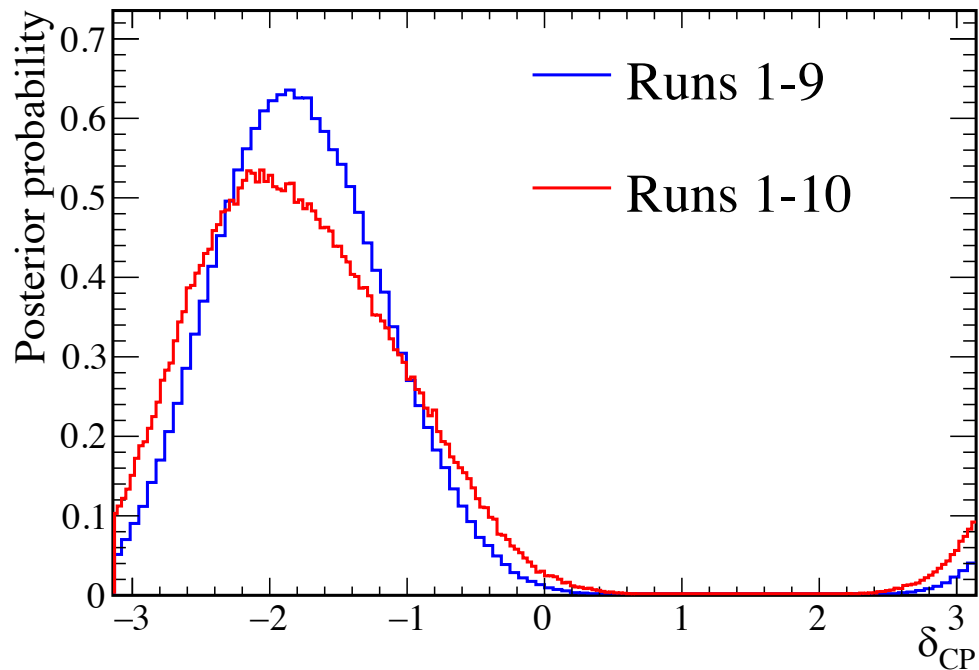
MaCh3 Joint Fit, wRC



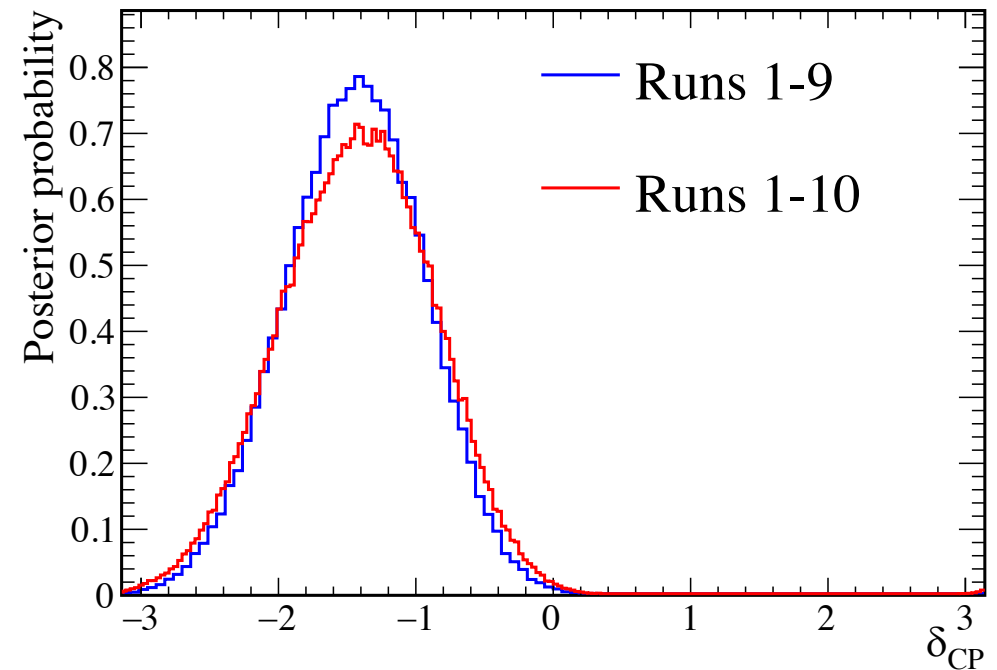
Run 1-10 Comparison to Run1-9

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Normal Ordering

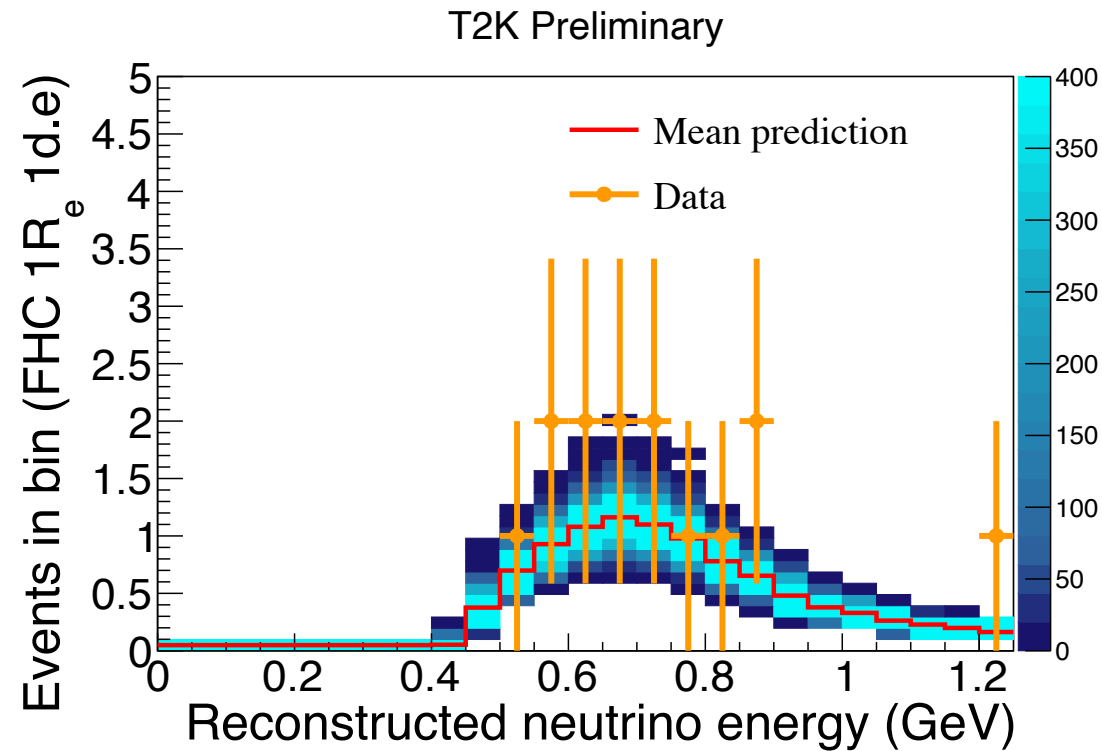


Inverted Ordering



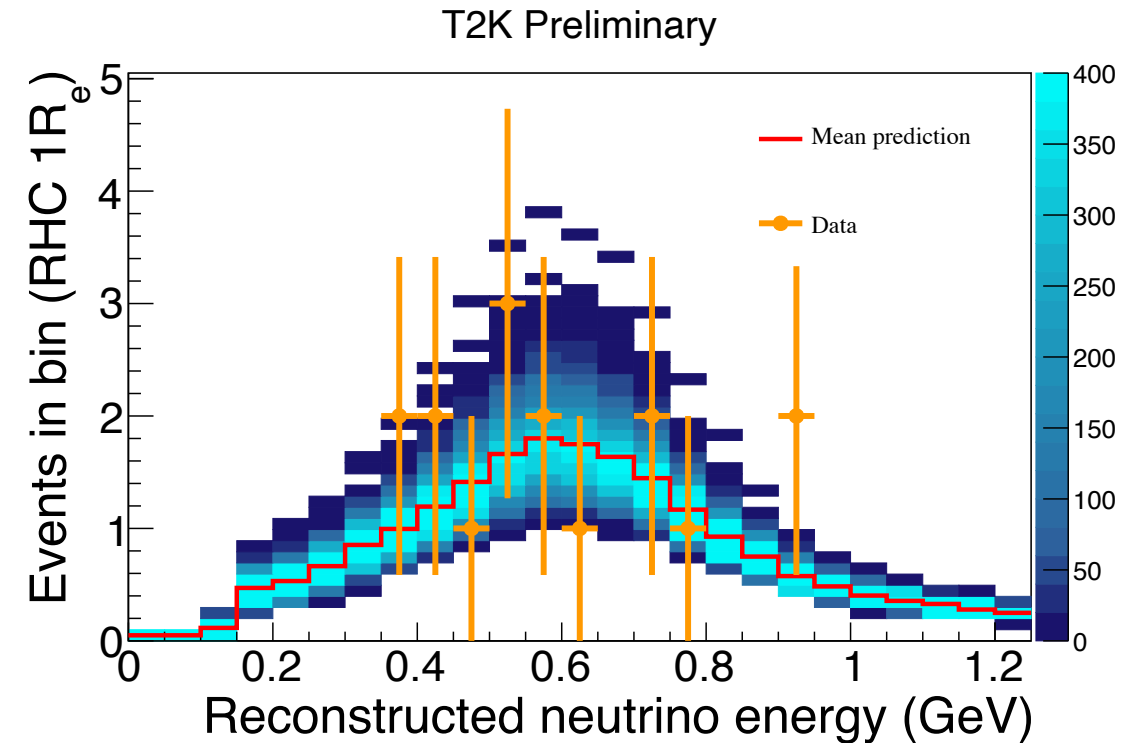
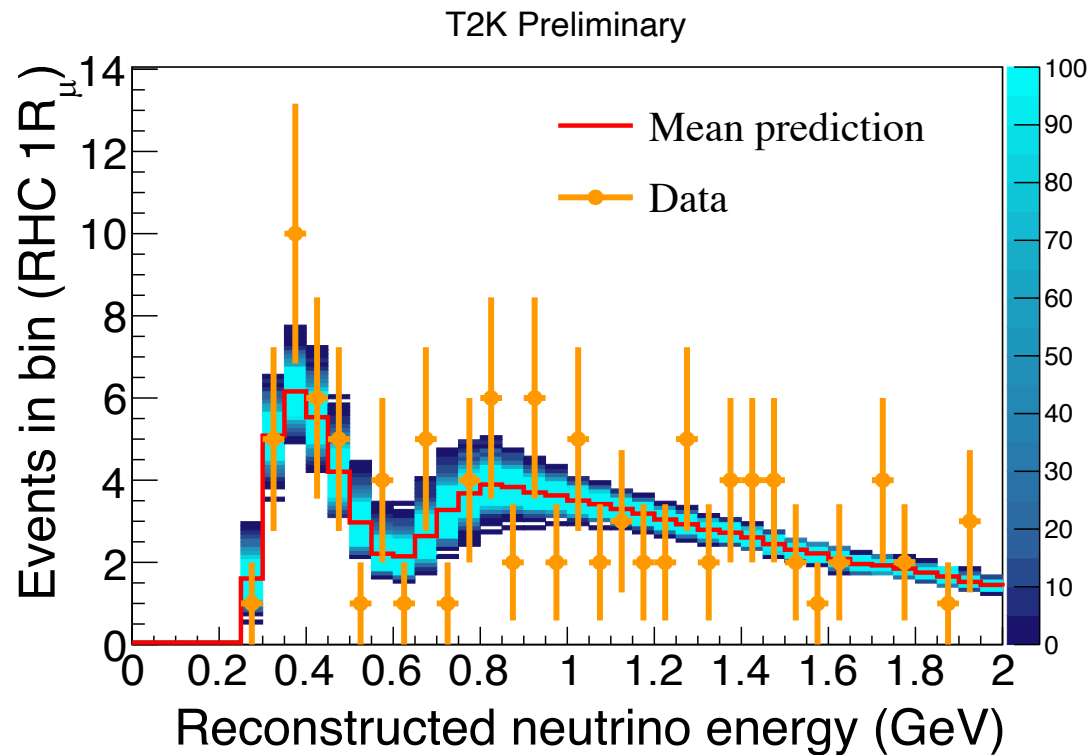
Posterior Predictive

- Distributions of sample spectra from posterior agree well with the data being fit
 - Neutrino-mode, cc1pi sample



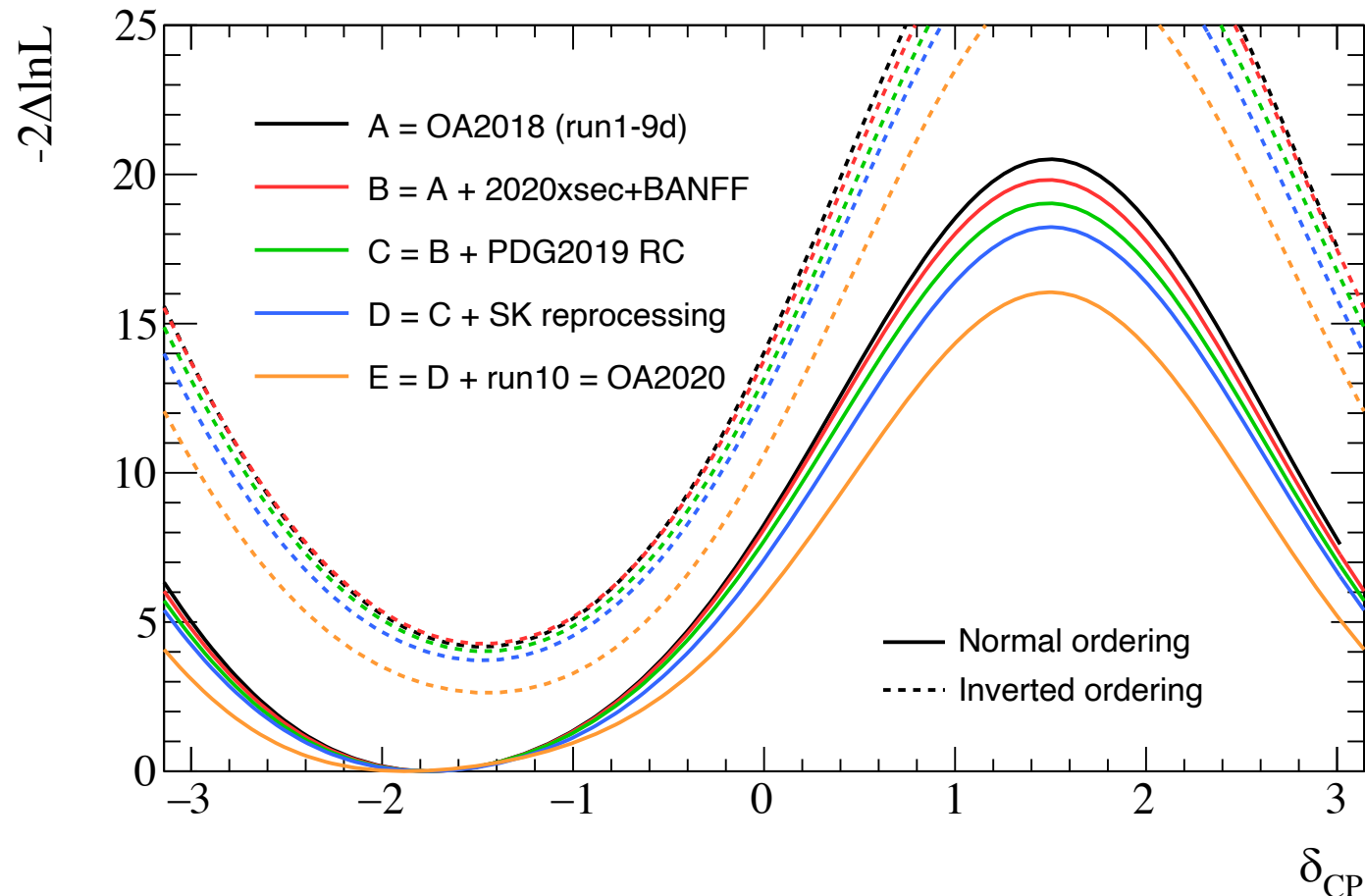
Posterior Predictive

- Distributions of sample spectra from posterior agree well with the data being fit
 - Anti-neutrino mode samples



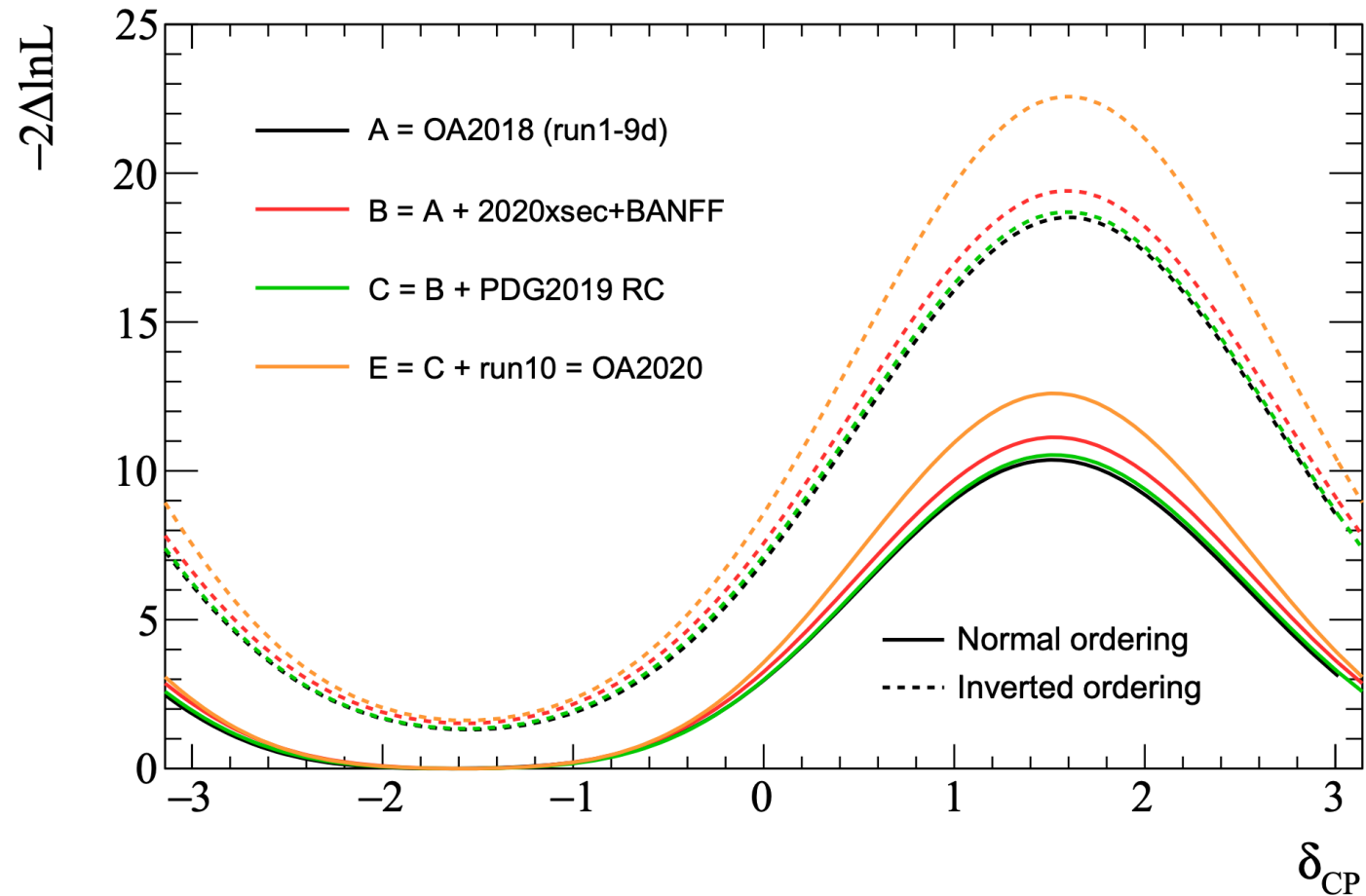
Incremental Changes to δ_{CP} - data fit

- NOTE: These are showing $\Delta\chi^2$ distributions from a frequentist analysis
- Biggest change due to run10 data



Incremental Changes to δ_{CP} - sensitivity

- NOTE: These are showing $\Delta\chi^2$ distributions from a frequentist analysis
- Biggest change due to run10 data



ν_e event rates

Period	Rate [evts/ 10^{20} POT]
Run 1-9	6.02
Run 1-10	5.49
Run 10	3.81
Best fit prediction	5.34

Kolmogorov–Smirnov test - ν_e accumulation

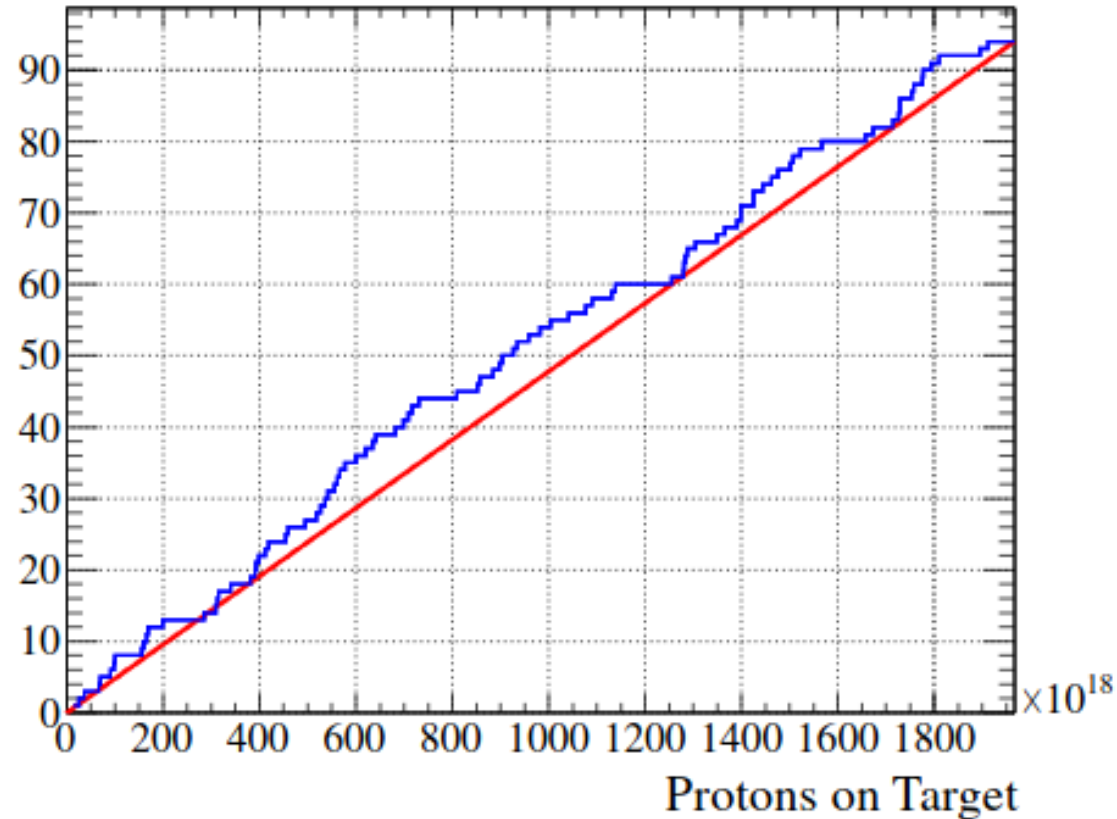


Figure 20: Cumulative number of observed ν_e candidate events as a function of POT in neutrino mode. For data taken during Runs 1-10, the largest vertical distance D between observation (blue) and a constant event rate hypothesis (shown in red) was found to be 0.097 (D normalized such that its maximum possible value is 1). The KS probability to obtain values larger than 0.097 from statistical fluctuations was calculated to be 32.6%.

Kolmogorov–Smirnov test - ν_e CC1 π accumulation

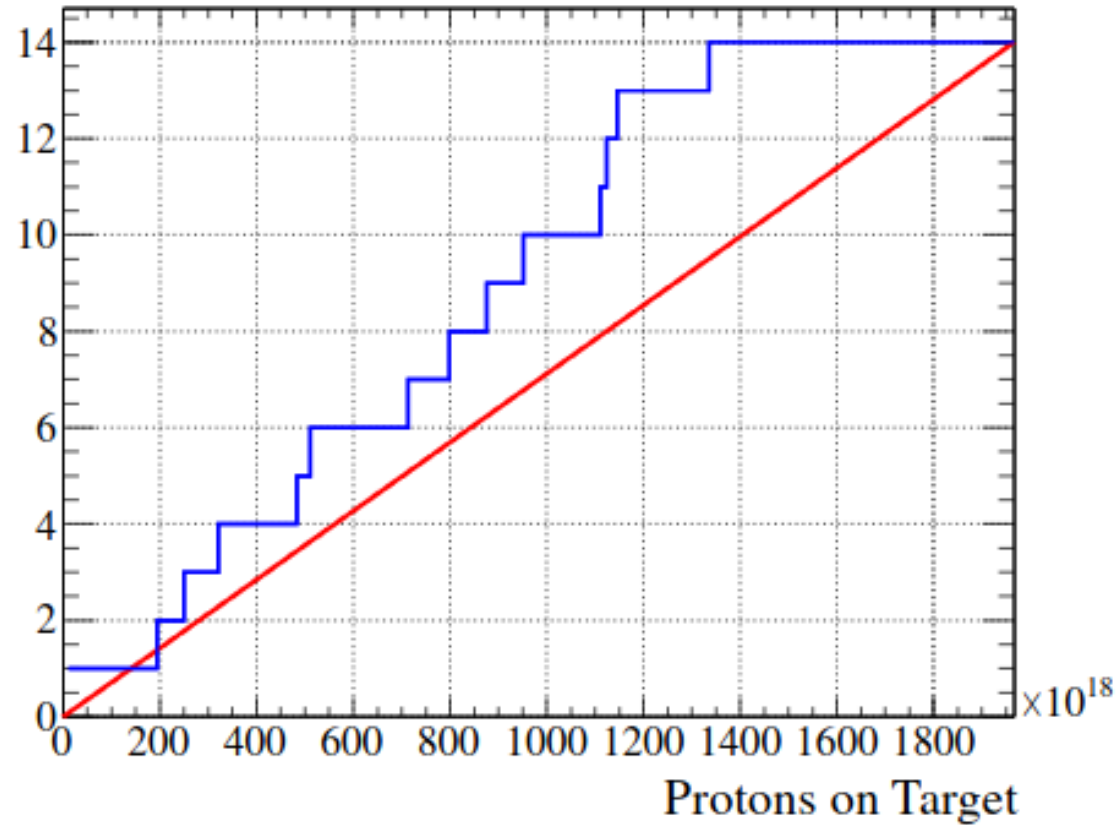


Figure 37: Cumulative number of observed ν_e CC1 π^+ candidate events as a function of POT in neutrino mode. For data taken during Runs 1-10, the largest vertical distance D between observation (blue) and a constant event rate hypothesis (shown in red) was found to be 0.346 (D normalized such that its maximum possible value is 1). The KS probability to obtain values larger than 0.346 from statistical fluctuations was calculated to be 5.7%.

Kolmogorov–Smirnov test - ν_μ accumulation

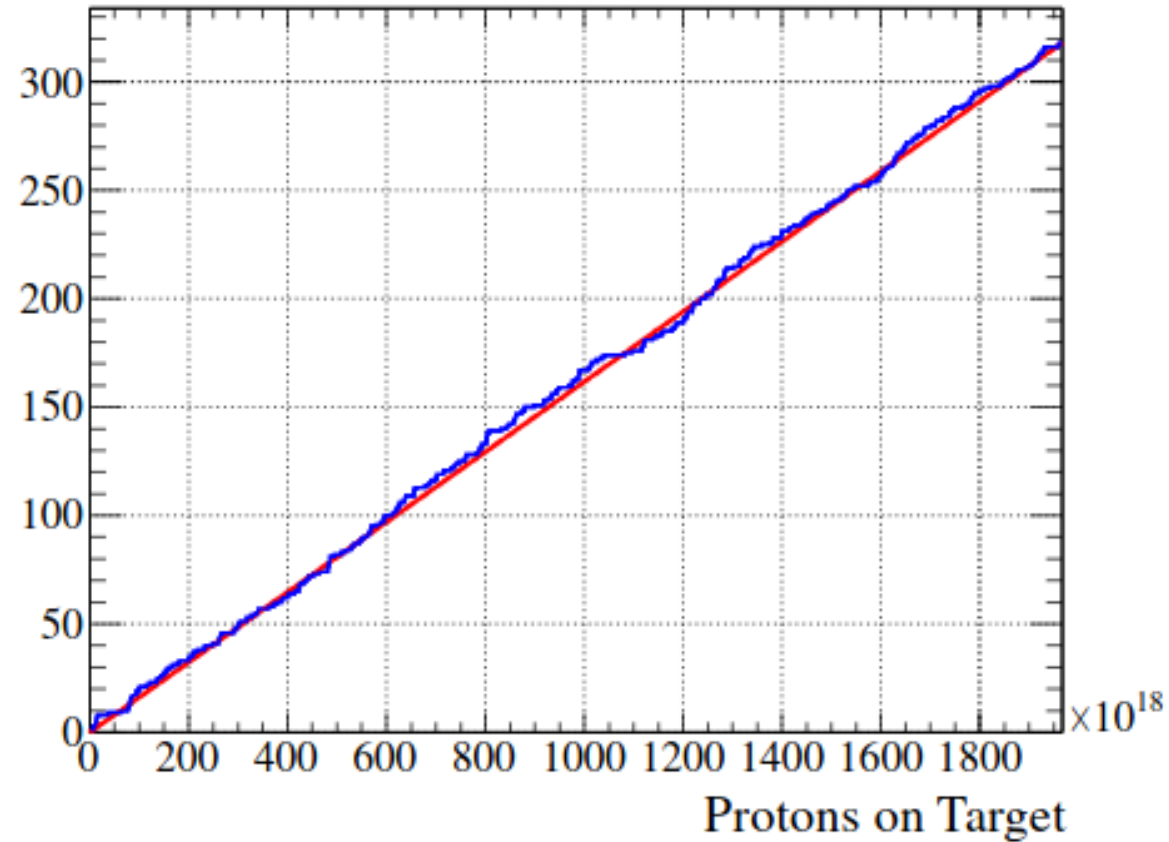


Figure 54: Cumulative number of observed ν_μ events as a function of POT in neutrino mode. For data taken during Runs 1-10, the largest vertical distance D between observation (blue) and a constant event rate hypothesis (shown in red) was found to be 0.027 (D normalized such that its maximum possible value is 1). The KS probability to obtain values larger than 0.027 from statistical fluctuations was calculated to be 97.41%.