3 Flavour Oscillation Group Summary

Karl Warburton, Louise Suter, Ryan Nichol

NOvA Plenary - 18th June 2021

Thanks To Jeremy Wolcott!

- Convened the ν_e and then 3 Flavour group since mid-2018.
- Now Analysis Co-Ordinator.

The Three Flavour Group At This Meeting – Plus Solo Session

External CC1pi and CCnpi data comparison to GENIE	Pierre Lasorak
ND fit status	Maria Martinez-Casales
ND Fit MCMC Report: Data & Fake Data	Michael Dolce
PISCES Covariance Matrix Fit for 3Flavor analysis	Miriama Rajaoalisoa
Non-Data Driven Systematic for fitting ND Samples	Anne Norrick
Discussion on systematics for ND fit and extrap	None

ND Fits and Systs; session covering the implementation of new fitting methods, enhancing the information gained from our Near Detector.

Conclusions

- FD timing peak already probably selects a large fraction of our blinded selection and HD sidebands.
- Maybe it could be optimized further but not clear how much gain there is.
- Adding some automatic metrics on goodness of fit could help with monitoring
- Running some selection over analysis release could be useful, but either going to need to run over a lot of data or use cosmics
- Add new cosmic (numi out of time) monitoring would be useful for detector monitoring.

FD Monitoring; sidebands likely contained in current monitoring but could do detector monitoring using cosmics.

- Making predictions files
  - Job failures, time taken, merging files.
    - Specific function in had_cafana does use more memory, could add options.
    - Human infrastructure is a big project to maintain and expand. May well be worth starting from scratch and overhauling even if feels painful at the time.
- Systematics validation – related but different from above.
  - Being used both in the ND groups and Osc.
- Add/Run new algorithms on the fly.
  - Time taken and repetitive nature of on-fly running.
  - Possibly fighting an inherent limitation of ROOT.
    - Flat CAFs would definitely let you add a dictionary, basically the limitation I was mentioning. Could also run over concats, so less processing.
- Speeding up Feldmann-Cousins.
  - A huge benefit, but as we add complexity even running on HPC's becomes time-consuming.
- Validating analysis? For example validating CAFAna if make a big change to prediction files, adding it to the CI.
  - Has been on to-do list but never got done.
- Enhance our documentation processes. The most obvious of which is "reproducing AnaXXX"

Ana TF; significant overlap with pain points of other groups.

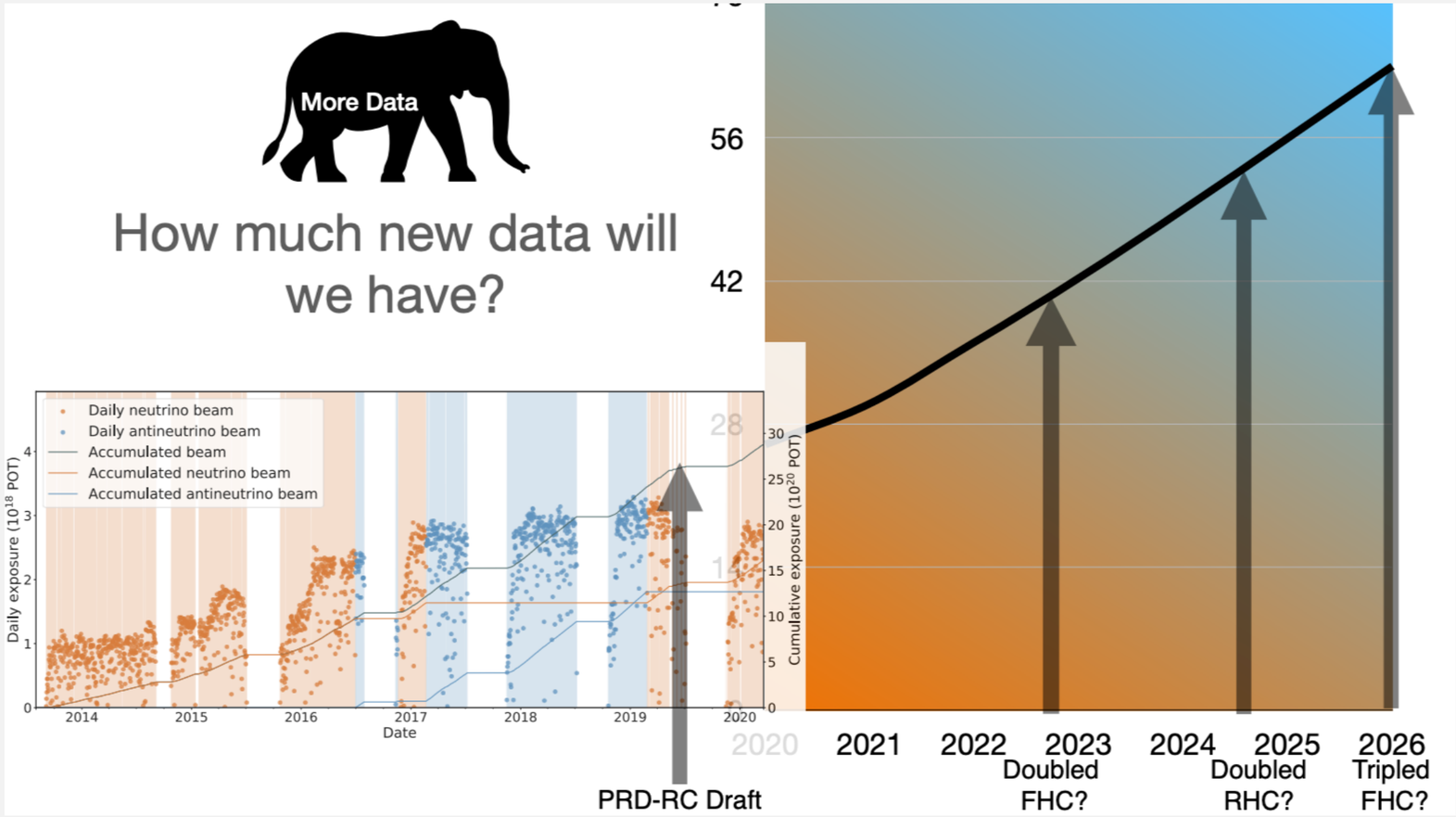
NSI; major result for Nu'22. Will utilise significant 3Flavour infrastructure. Will be providing help and guidance to NuX group as analysis progresses.

Some aspects motivating the study of Nueutrino NSI in NOvA	Mario A Acero *et al.*
NSI Update - CAFAna and Covariance Matrix Frameworks	Prabhjot Singh
NSI Analysis Status	Mario A Acero *et al.*
Discussion	,[Entire Collaboration]

Future Analysis Plans

- Per the AC's proposed strategic plan we will be aim to align major analysis upgrades with notable increases in exposure.
  - Double current FHC in 2023
  - Double current RHC in 2024/5
  - NOvA EOL analysis in 2026/7?

- Anastasiia and Liudmila performed future sensitivity studies to determine optimal beam running mode.
  - With some caveats 50:50 nu/nubar running is optimal.



Future Analysis Plans – What That Looks Like

2022 Analysis – Current dataset

- No new data, will use Prod5 files, but will feature a new Bayesian fit.
- May include additional samples such as high energy numu's.

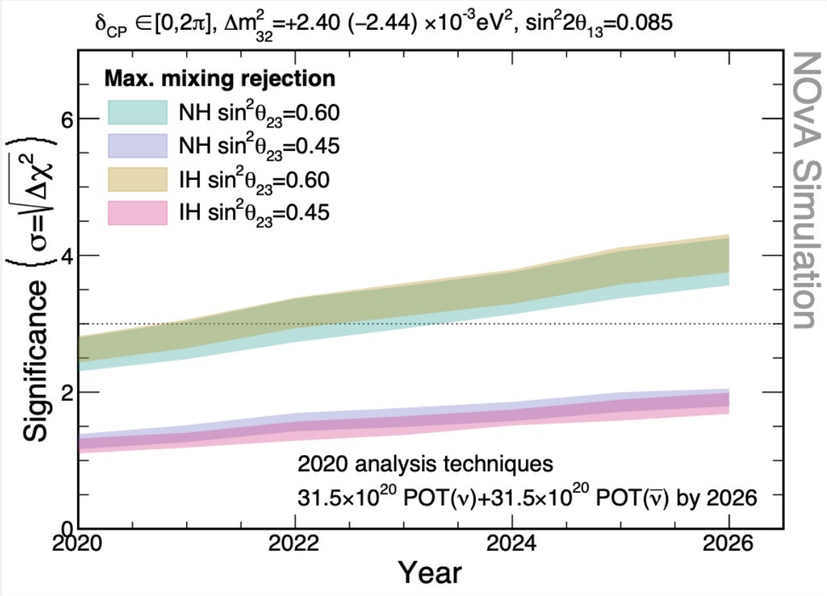
2023 Analysis - Doubled FHC Data

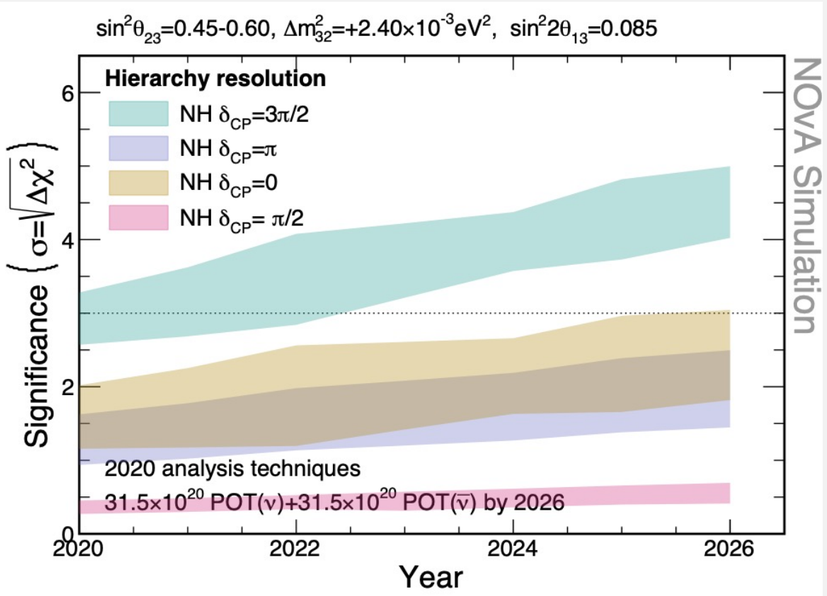
- A full re-analysis, using Prod5.1 files.
- New energy estimators, overhaul of extrapolation and systematic treatment.
  - Could include a ND-fit and/or covariance fitting framework if complete.

2025 Analysis – Doubled RHC Data

- A full re-analysis, likely use Prod6 featuring new Sim/Reco algorithms.
- Full ND-fit and further extrapolation overhauls not present in 2023 analysis.

2027 Analysis – NOvA EOL analysis – Triple FHC?



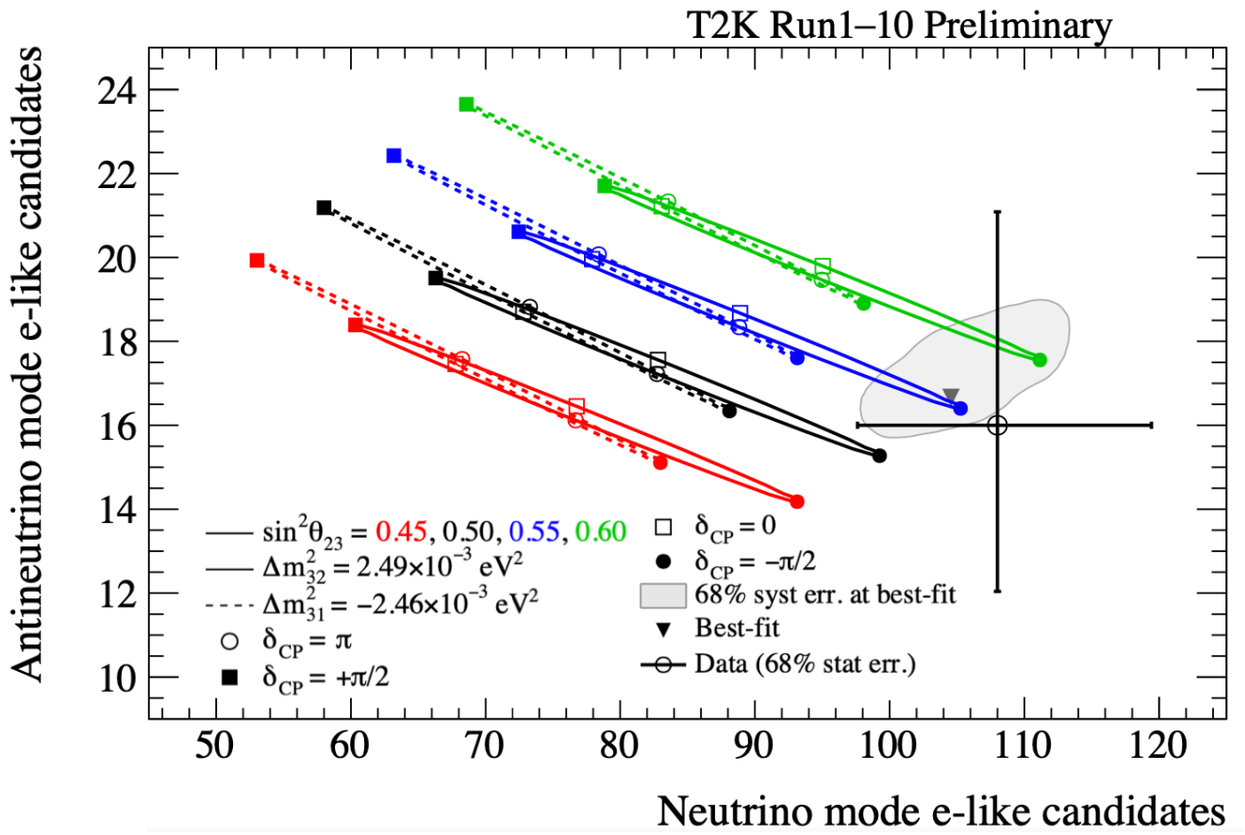


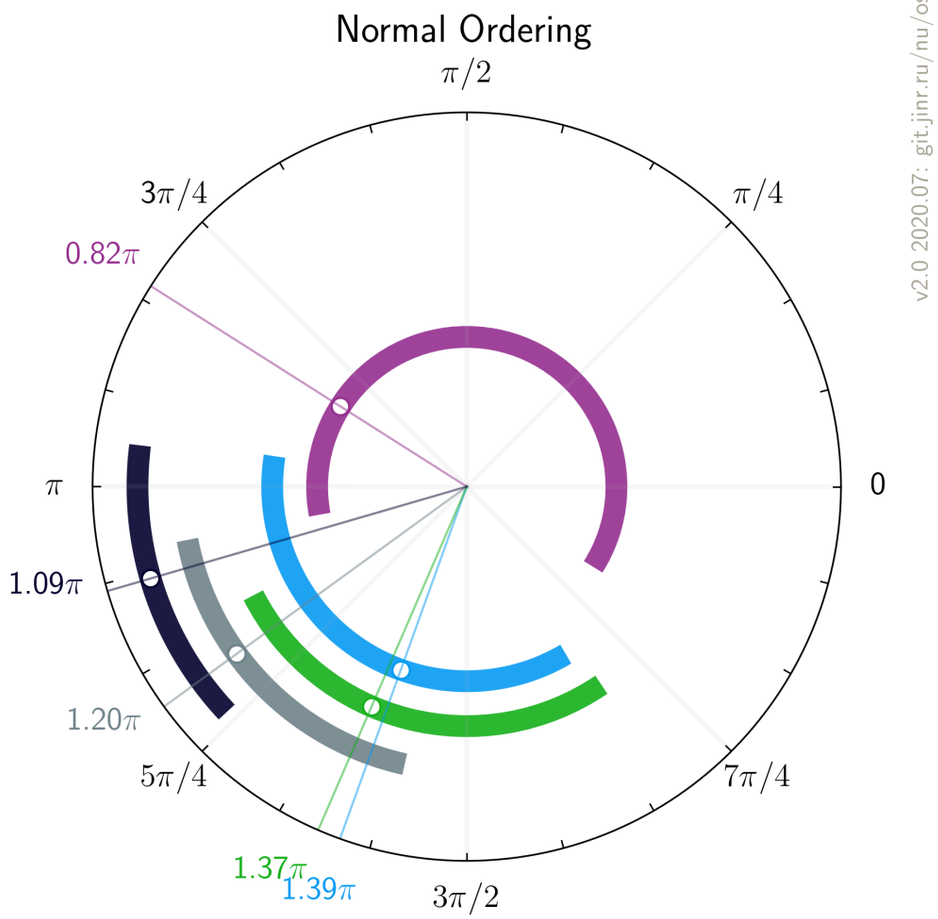
OVER TO LIUDMILA TO TALK ABOUT CP ASYMMETRY MEASUREMENT

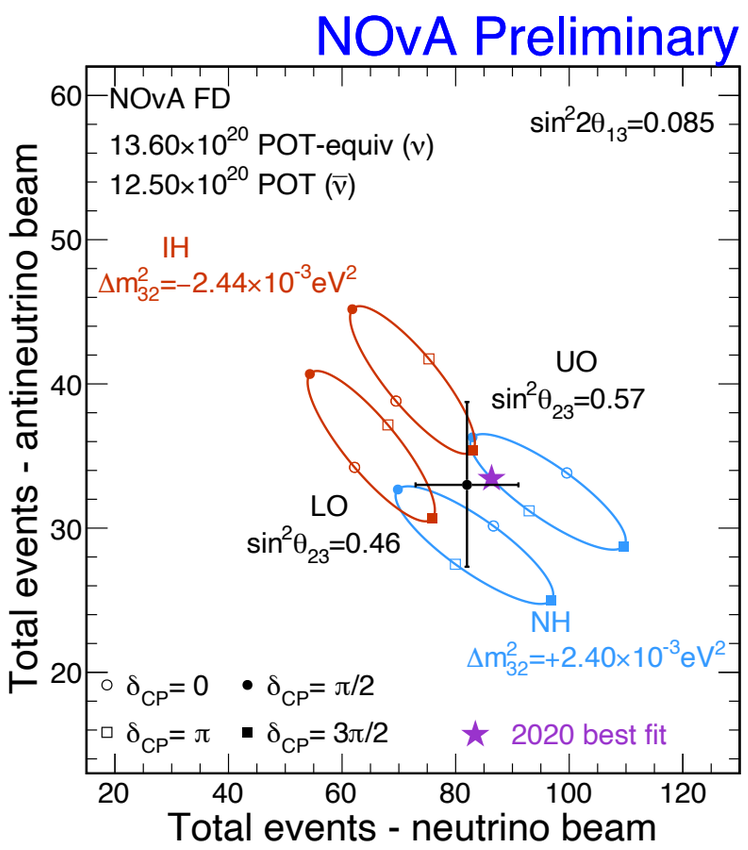
$P(\overset{(-)}{\nu}_{\mu} \rightarrow \overset{(-)}{\nu}_{e})$ and A_{CP} measurement

Liudmila Kolupaeva

Motivation







T2K and NOvA keep a level of excitement in the community.

Various theories appeared: NSI? True IH in Nature?

This work aims at a bit different representation of familiar results.

Intro

What is P here?

CP asymmetry calculation through oscillation probability measurements:

- ✳ oscillation probability = (data - predicted bkg at best fit) / (signal prediction with P = 1);
- ✳ wrong sign component is treated as bkg;
- ✳ ”Signal prediction with P = 1” is collapsed 2D trueE-recoE histogram from PredictionExtrap (FD extrapolated MC prediction) that is used for the actual predictions for the analysis;
- ✳ do this for FHC and RHC data and calculate for each data bin:

obscure explanation...

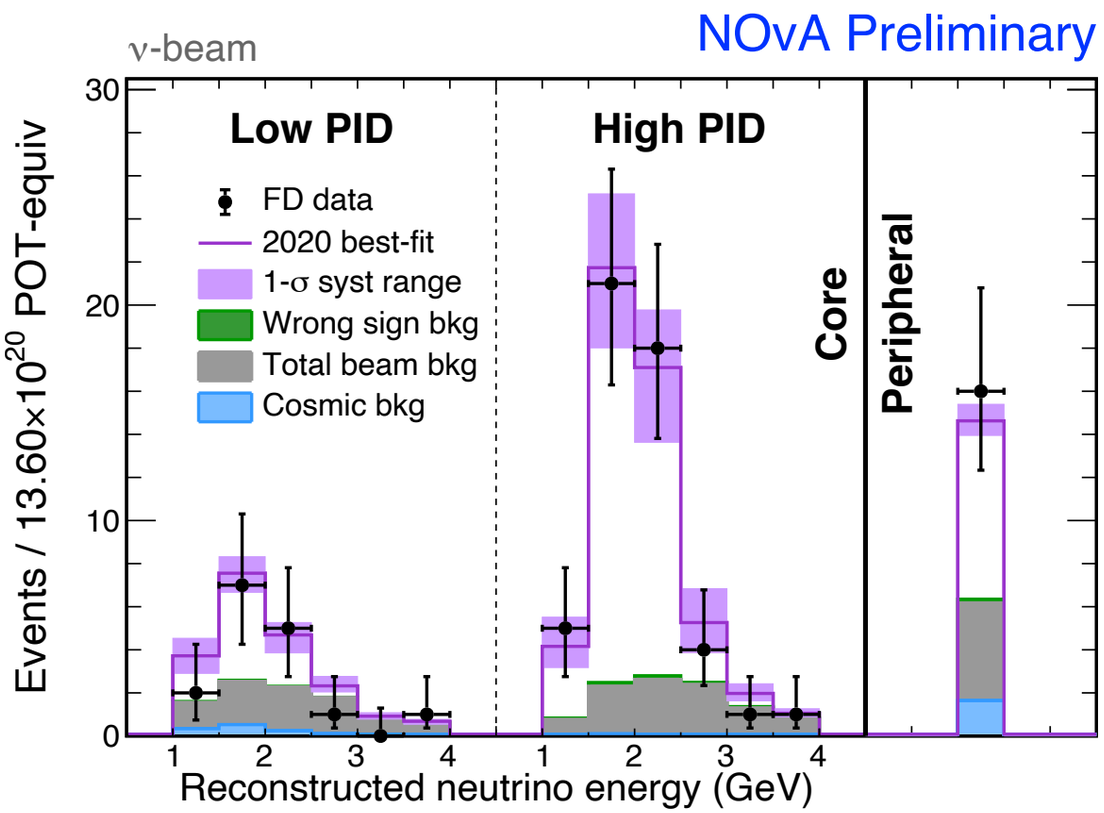
$$\frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

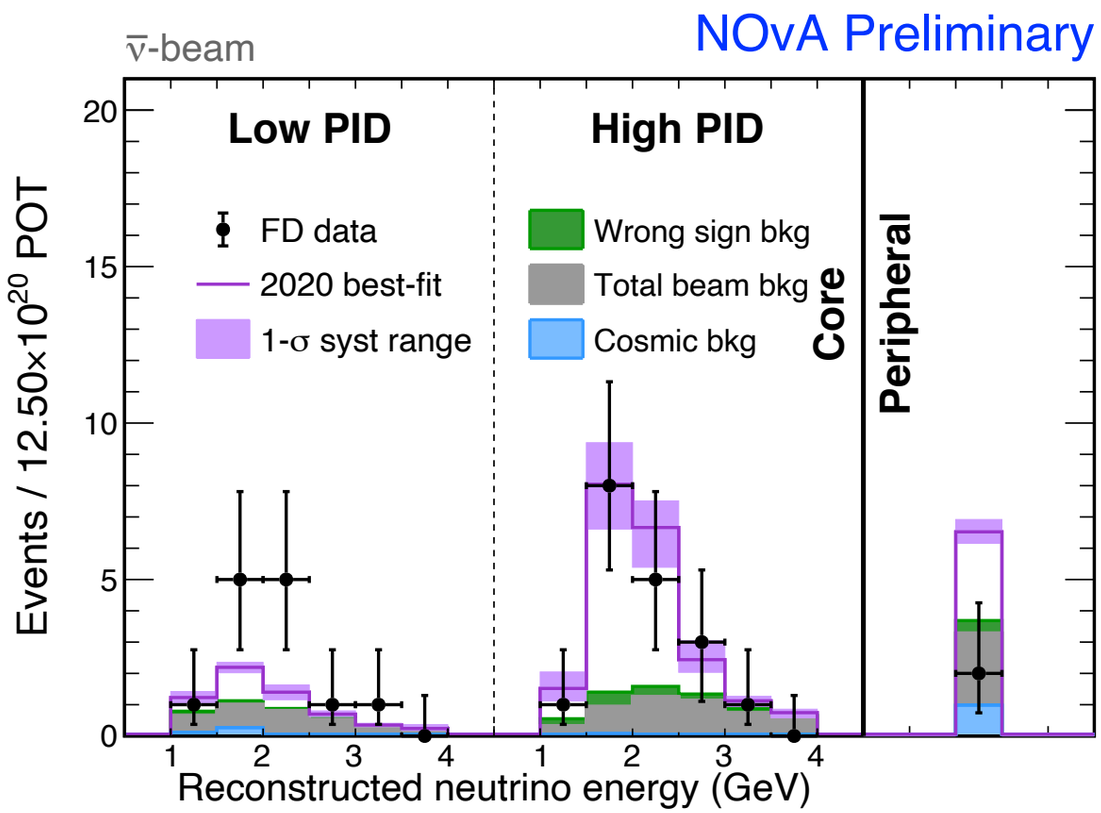
For all inputs and studies, official 2020 predictions were used.

Numerator input

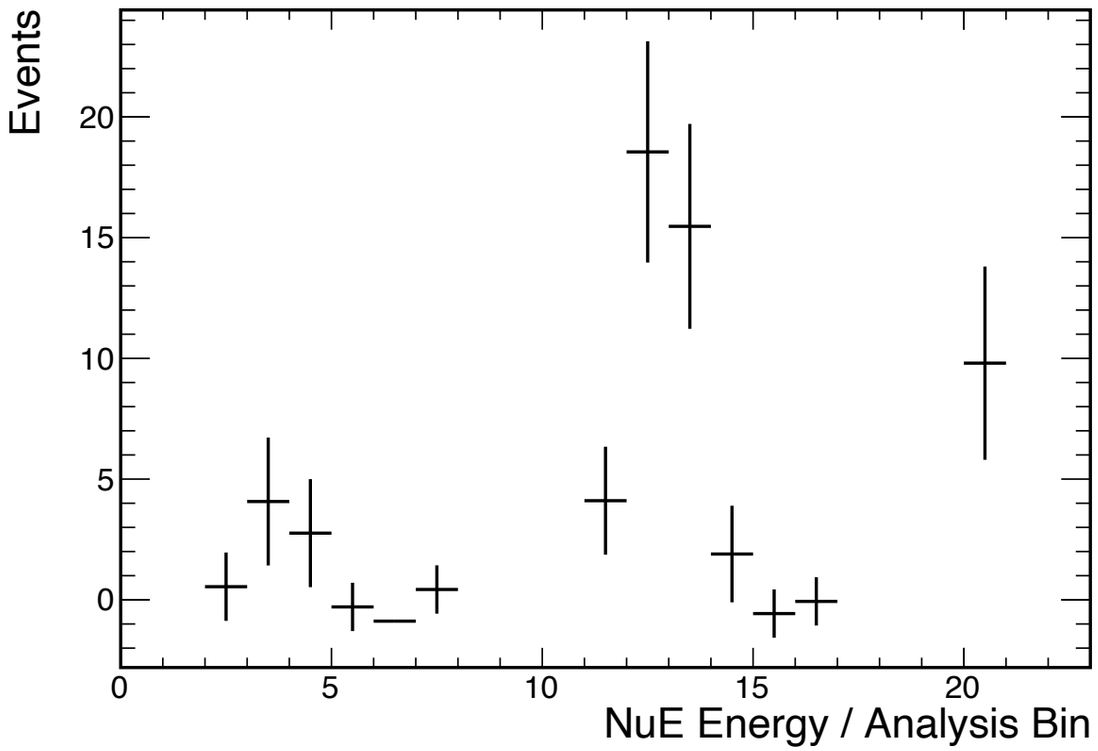
FHC

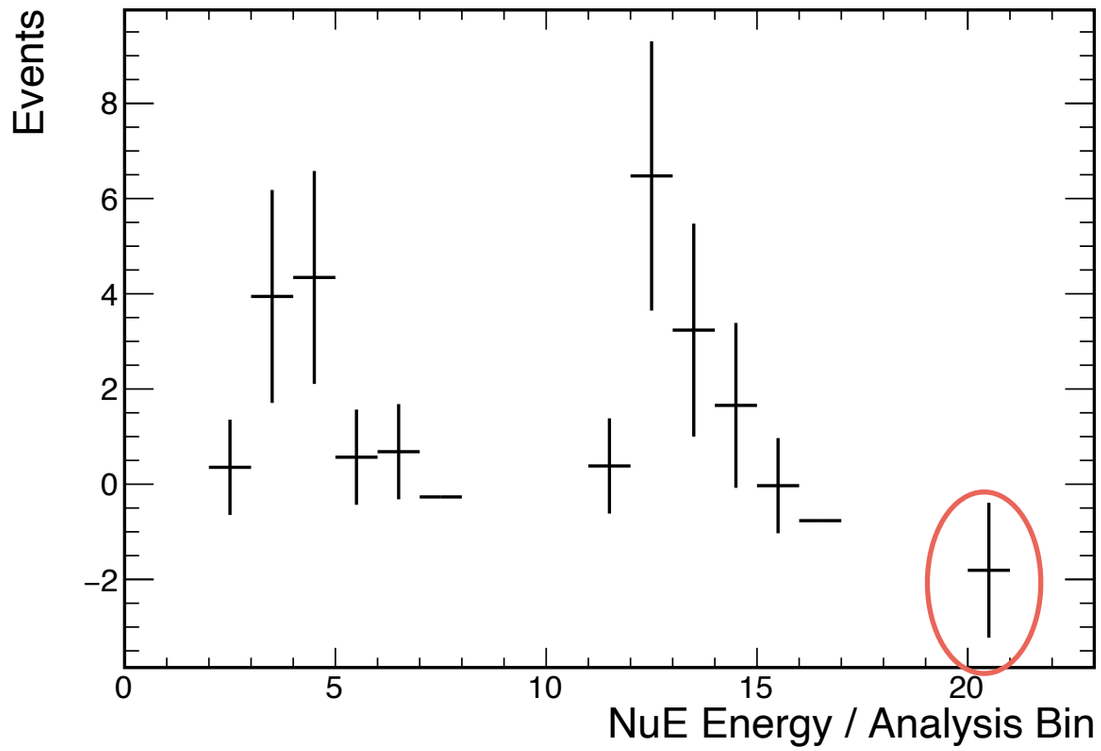
RHC



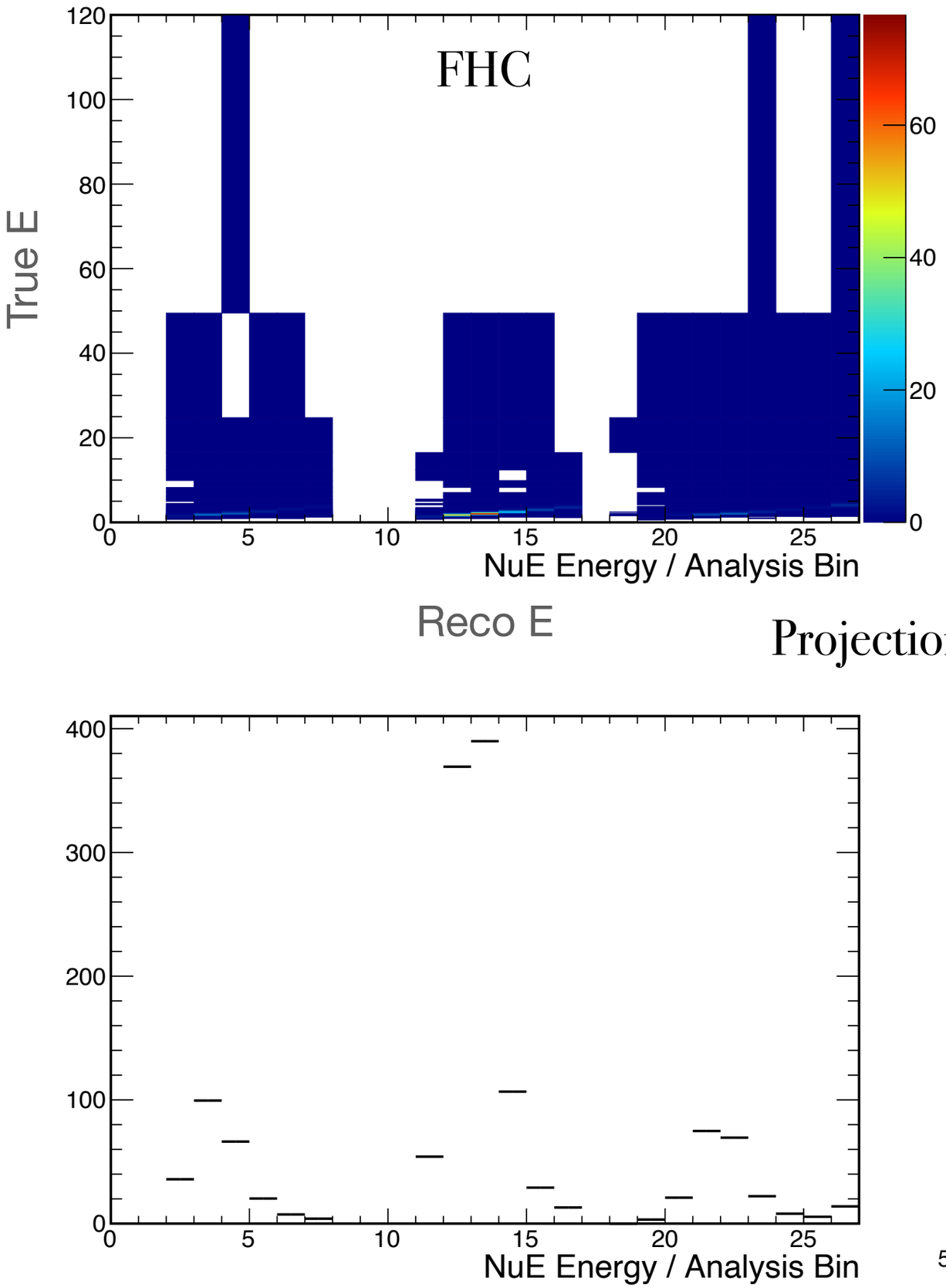


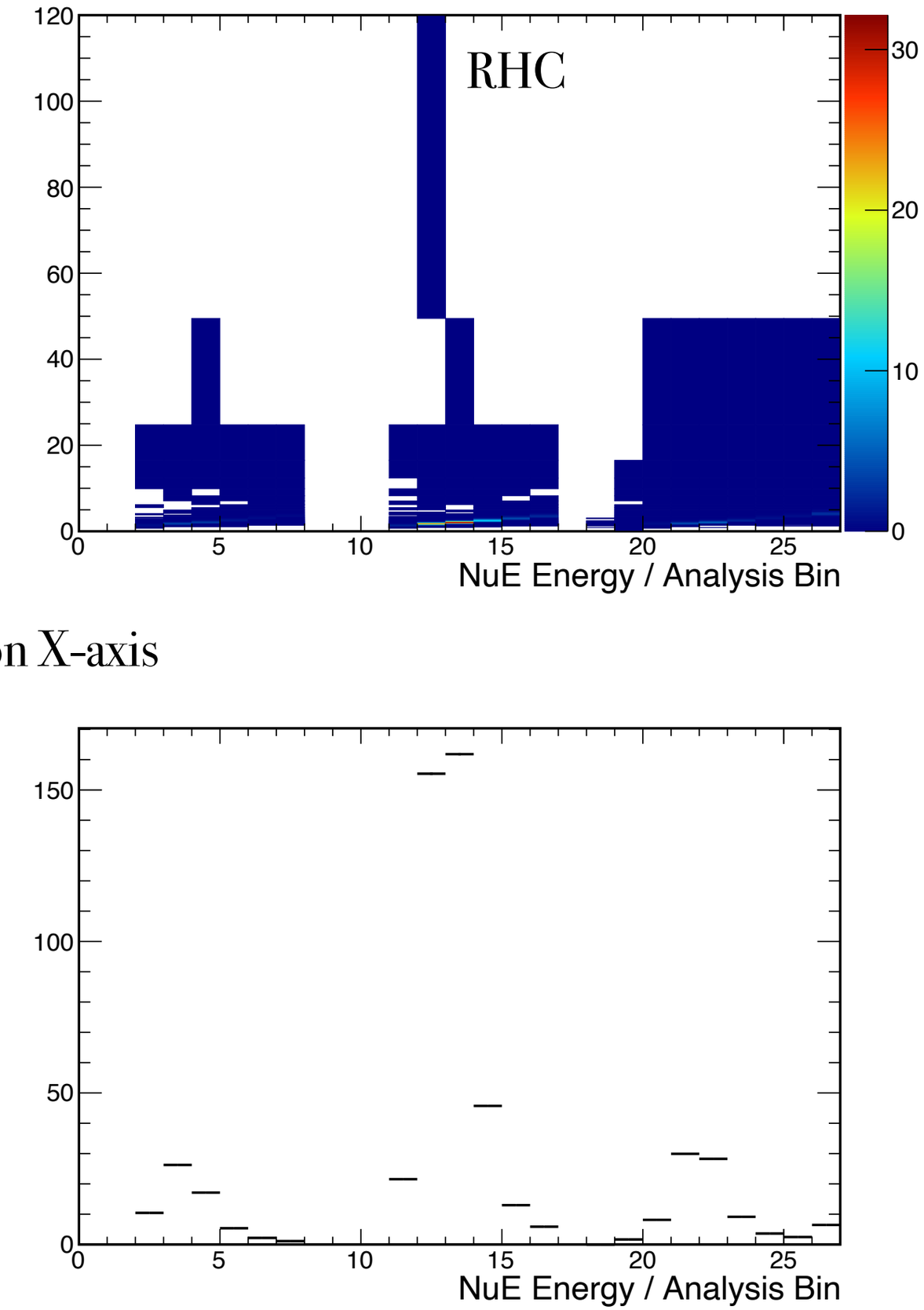
Measured real data ”signal”





Denominator input



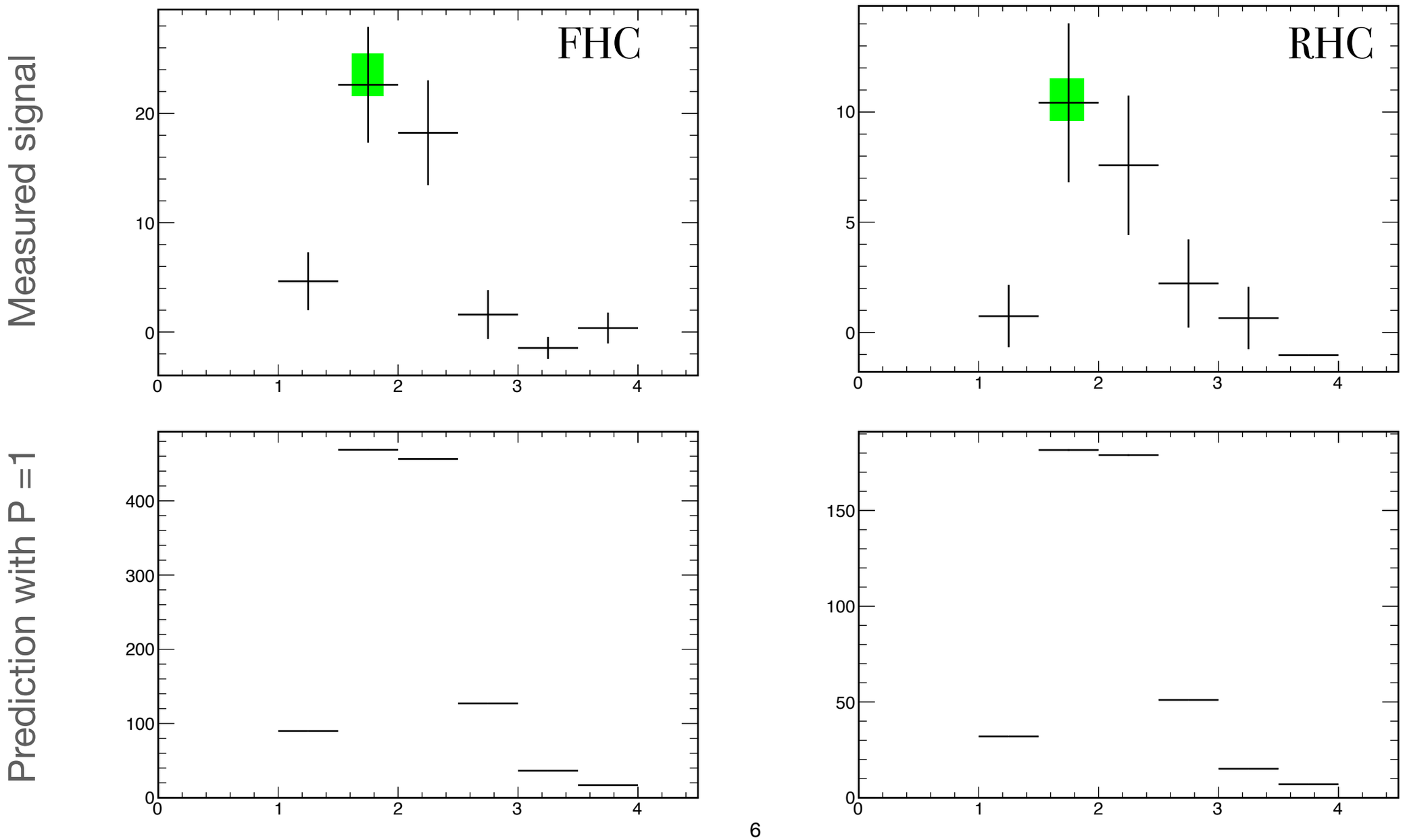


But!

围绕本页再细看

宜摆正心态，本来就是在实践中学习，然后抽时间来补各种较为系统的知识。
勿忘本分！

- Stat. fluctuations are still significant in data.
- It was decided to make Probability and A_{CP} plots with RecoE axis w/o split into Low and High CVN bins and drop Peripheral bin for a while (see the version of all plots with initial axis in docdb 49782).

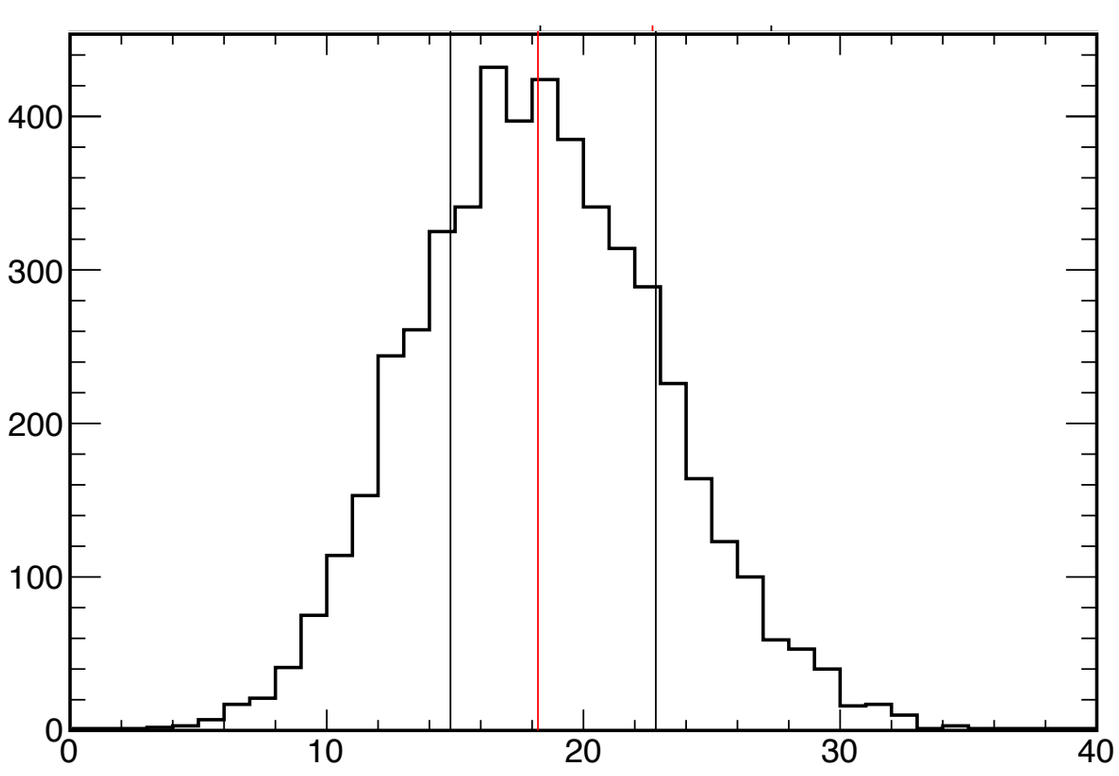


Error bar calculations

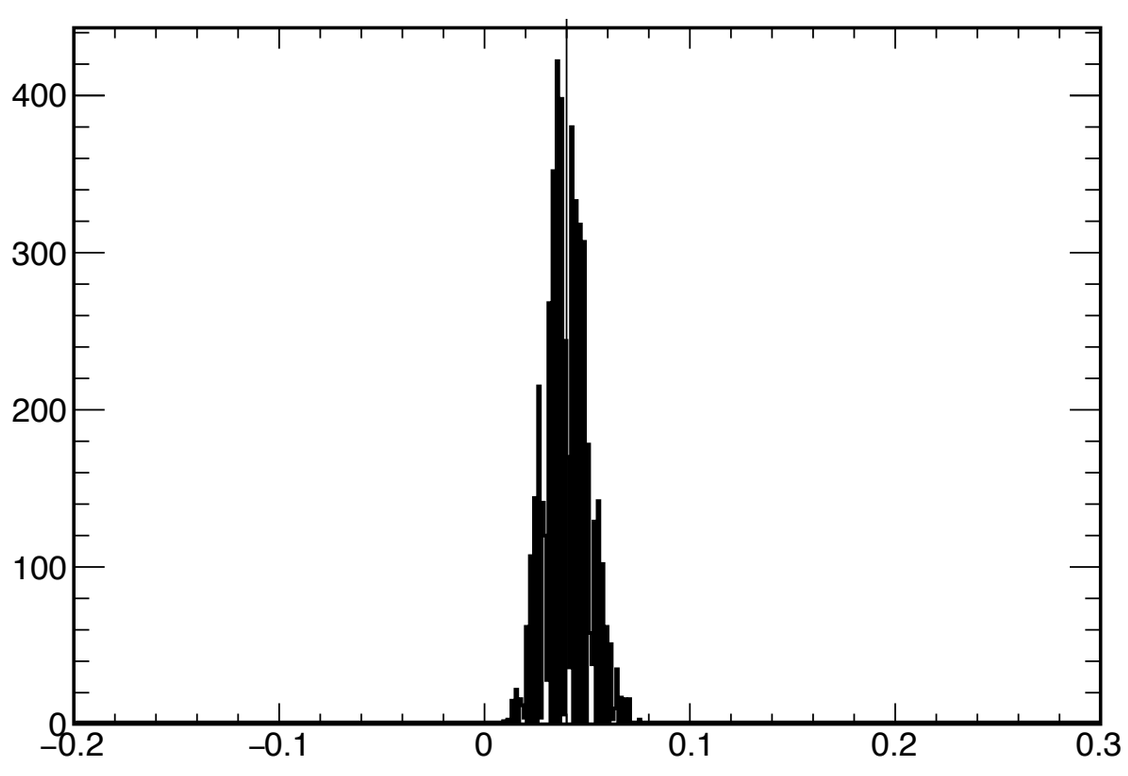
- ✳ It was decided to use Poisson fluctuations applied to real data and assign the region with 68% of experiments to the error bar.
- ✳ Each pseudo-experiment goes through the same chain as it was described in the previous section. For bkg. calculation each experiment is fitted.
- ✳ In total there are 5'000 pseudo-experiments.

Example for the bin 2.0-2.5 GeV

Extracted signal



Oscillation probabilities



Taking into account the systematics

In order to take into account also the systematic effect, the following procedure is proposed.

During the background calculation step for each pseudo-experiment:

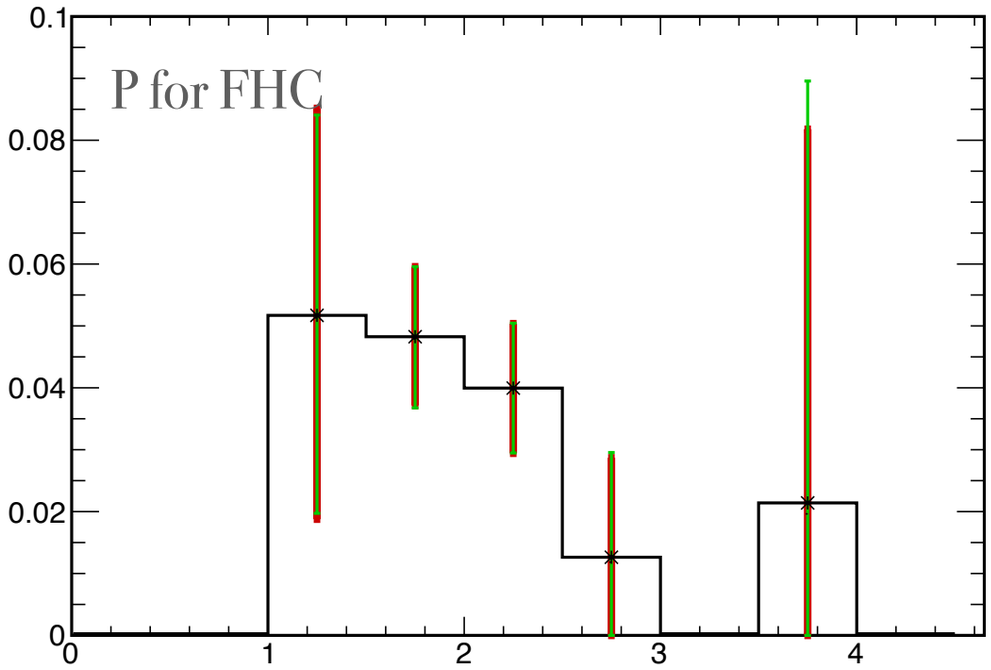
- ✳ oscillation parameters were played with gaussian 1σ taken as error size in 2020 (3% for Δm^2_{32} and 7% for θ_{23}, for δ_{CP} $\pm\pi$ range was used);
- ✳ total systematic error for the background was taken as 6% for FHC and RHC, the scaling factor for histogram was played around 1 with this value as 1σ error;

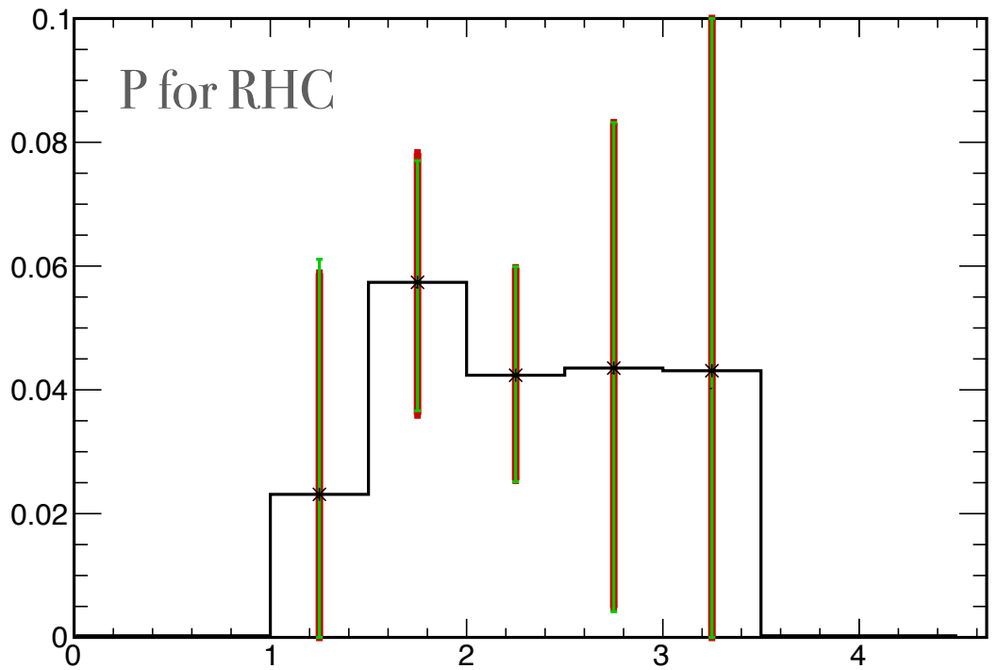
Modified bkg is subtracted from the pseudo-experiment spectra.

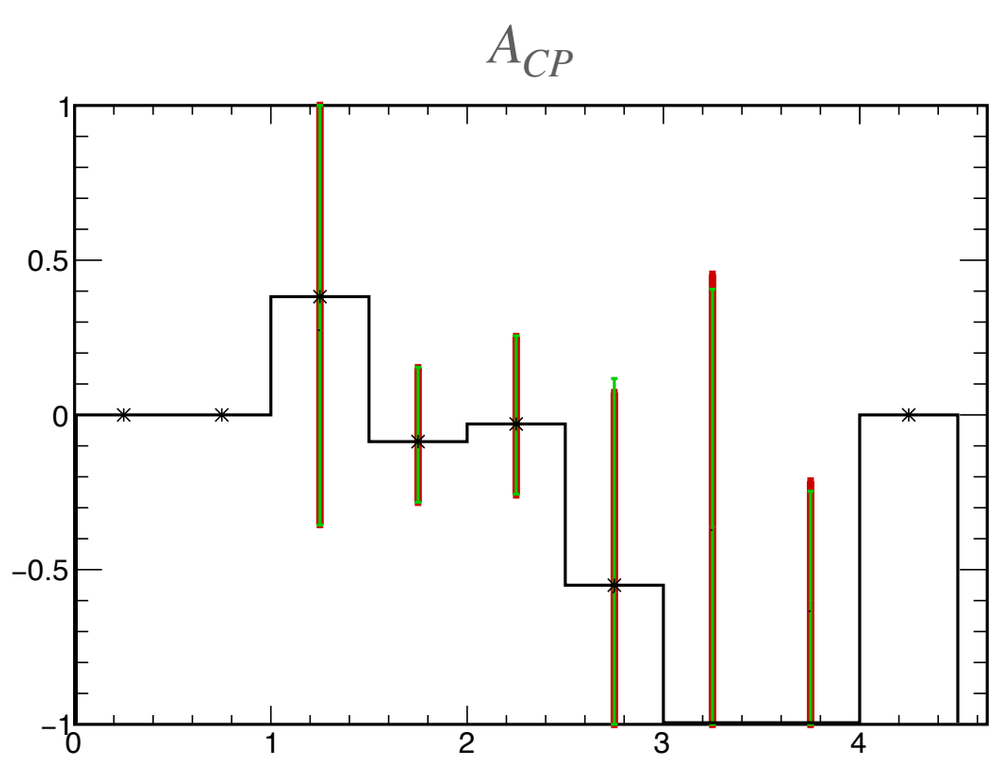
Requested a permission to proceed with real FD data on May 25, deadline for comments was on June 4th.

And thanks very much to Alex H., Chris B., Jon U., Matt S. and Tricia V. for comments, suggestions and discussions on procedure!

Resulted error bars: statistics and systematics.

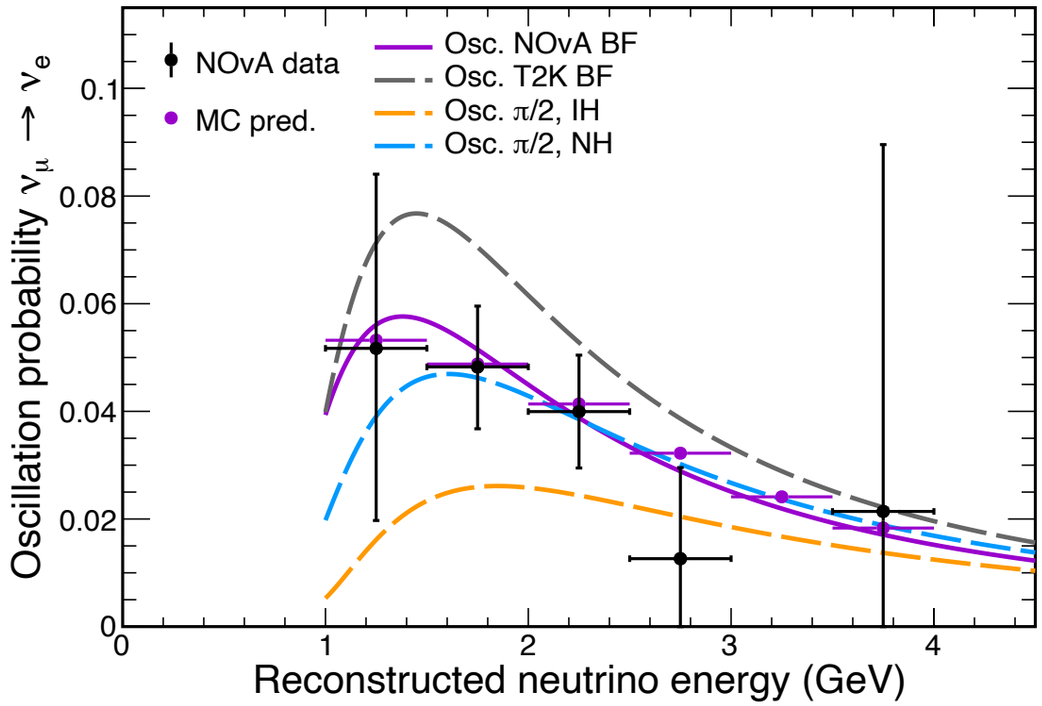


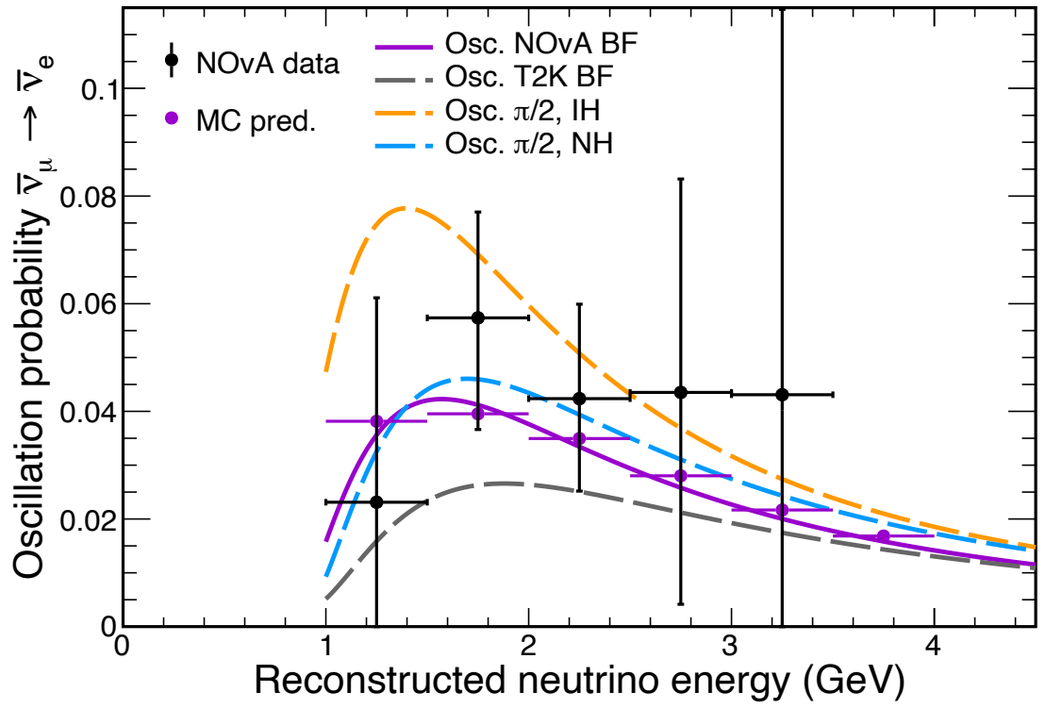


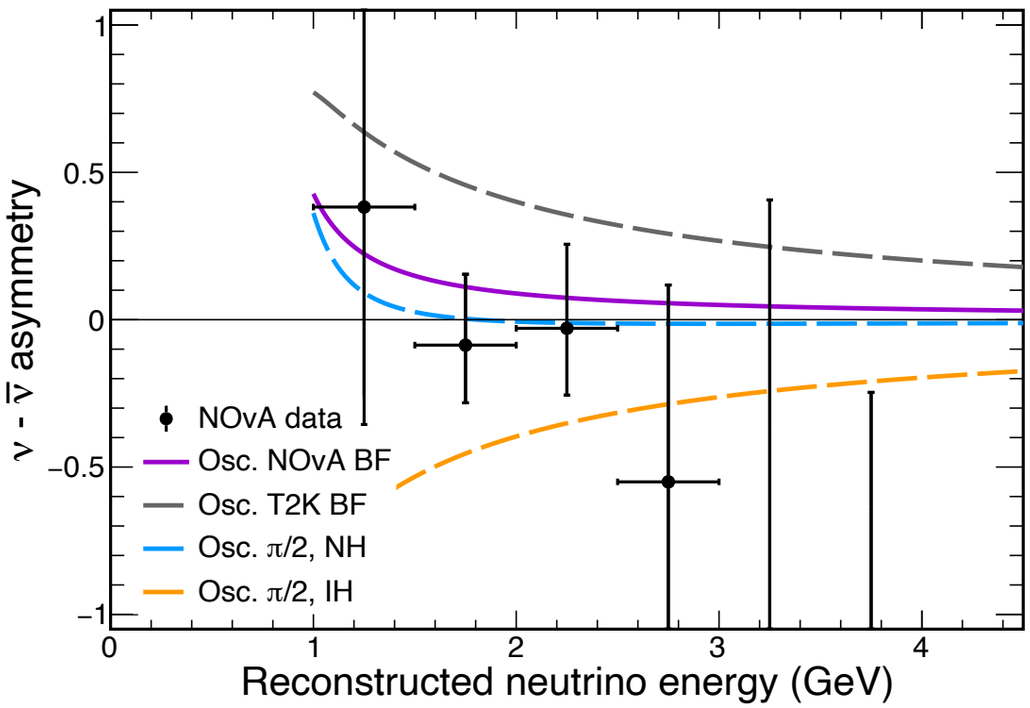


Red: statistics
Green: + systematics

Real data plots!







What else can be done and further steps

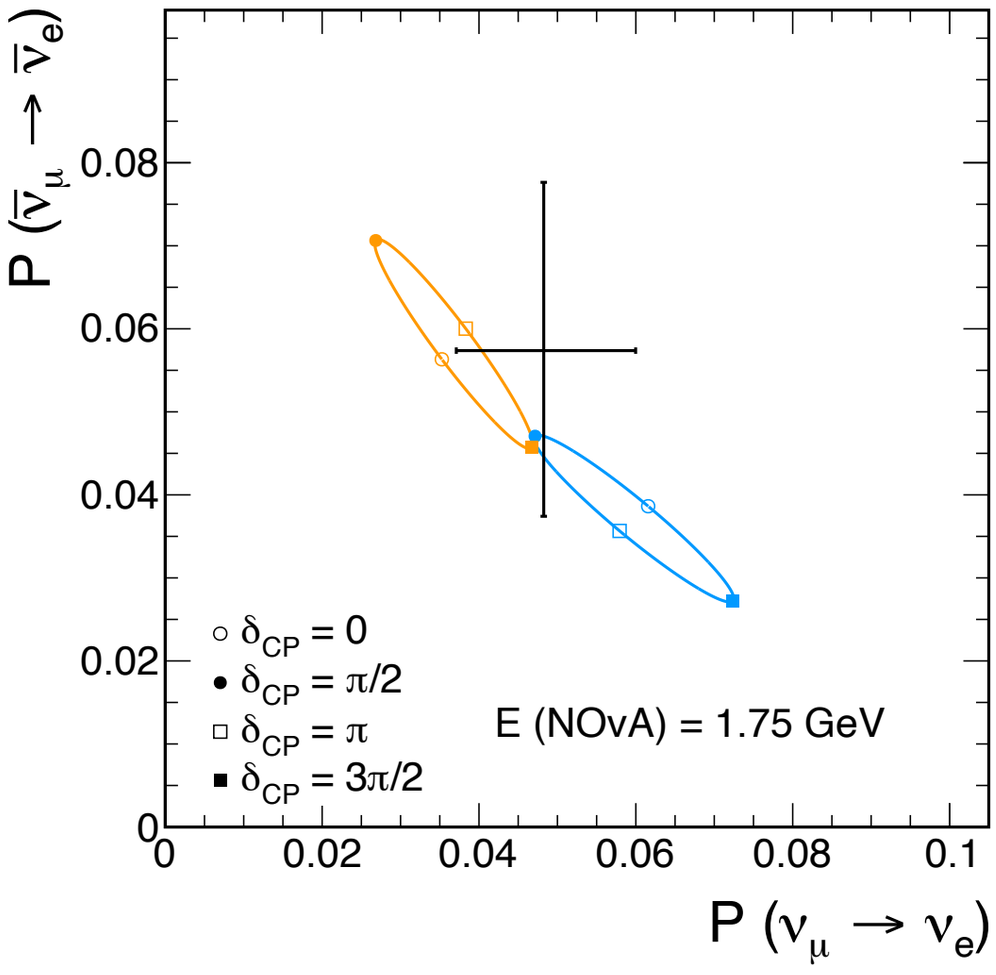
As Jon U. fairly noted, the described procedure is actually a Bayesian way since it is the conditional probability defined based on observed data.
True frequentist way would be in generating pseudo experiments for all Asymmetry values in [-1, 1] and then find confidence interval.

Pros: would be cool to compare!
Cons: there are a lot of degenerates in osc. parameters that will represent the same Asymmetry

Doable in general but will take some time.

Curious and very preliminary plots

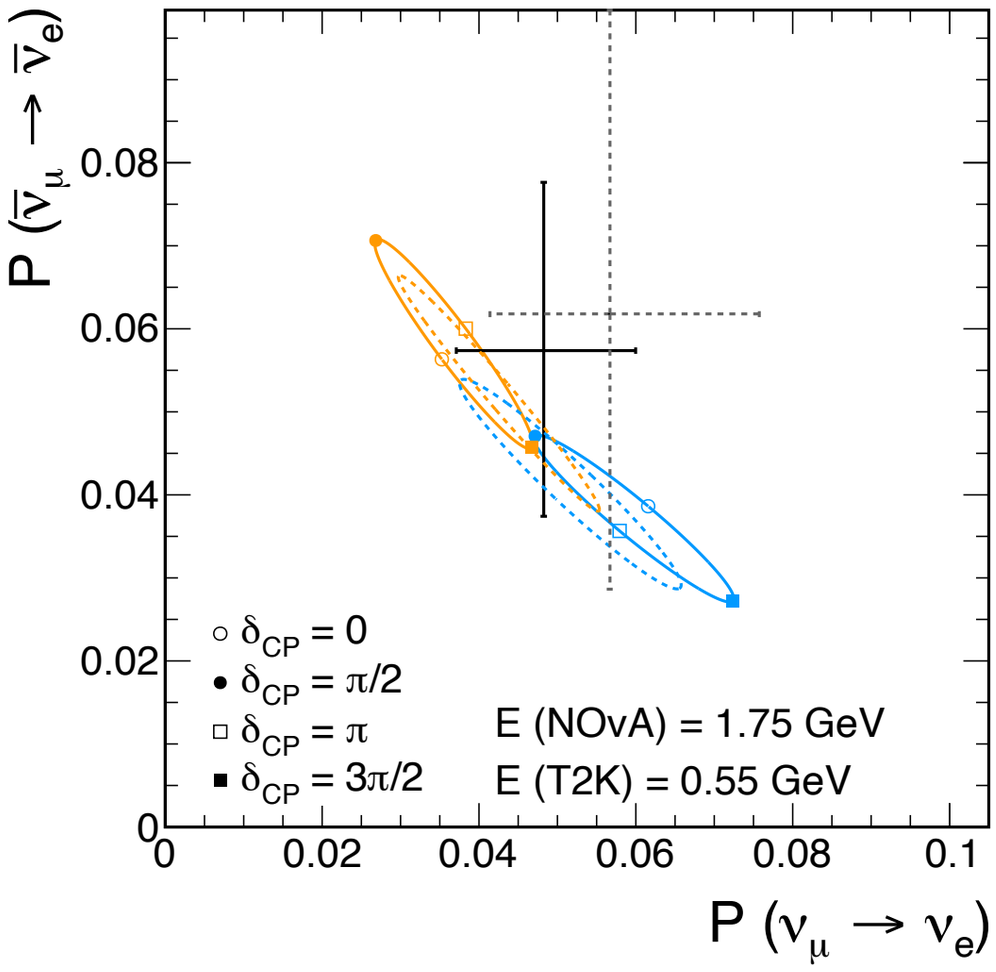
How measured osc. probabilities and asymmetry can be used by the community and us

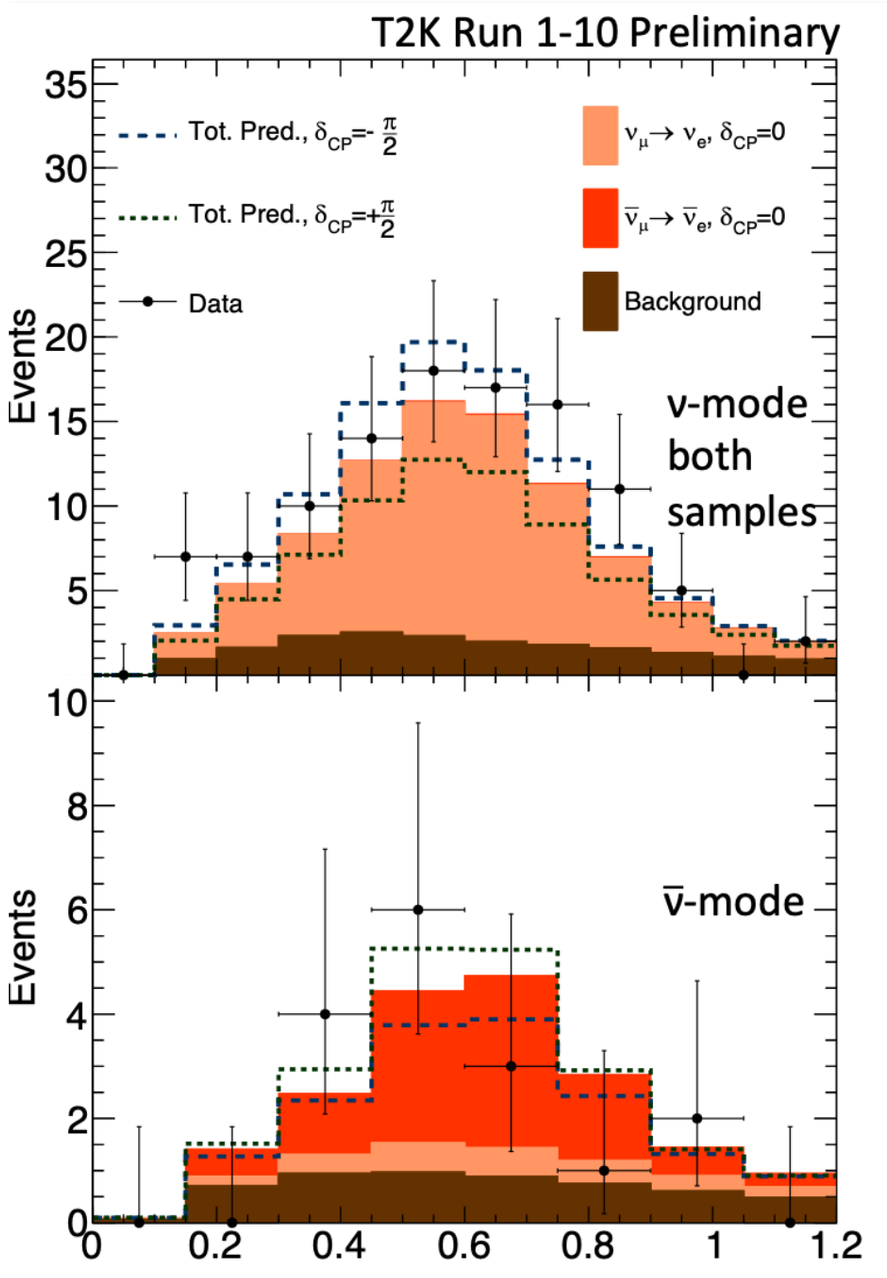


Curious and very preliminary plots

How measured osc. probabilities and asymmetry can be used by the community and us

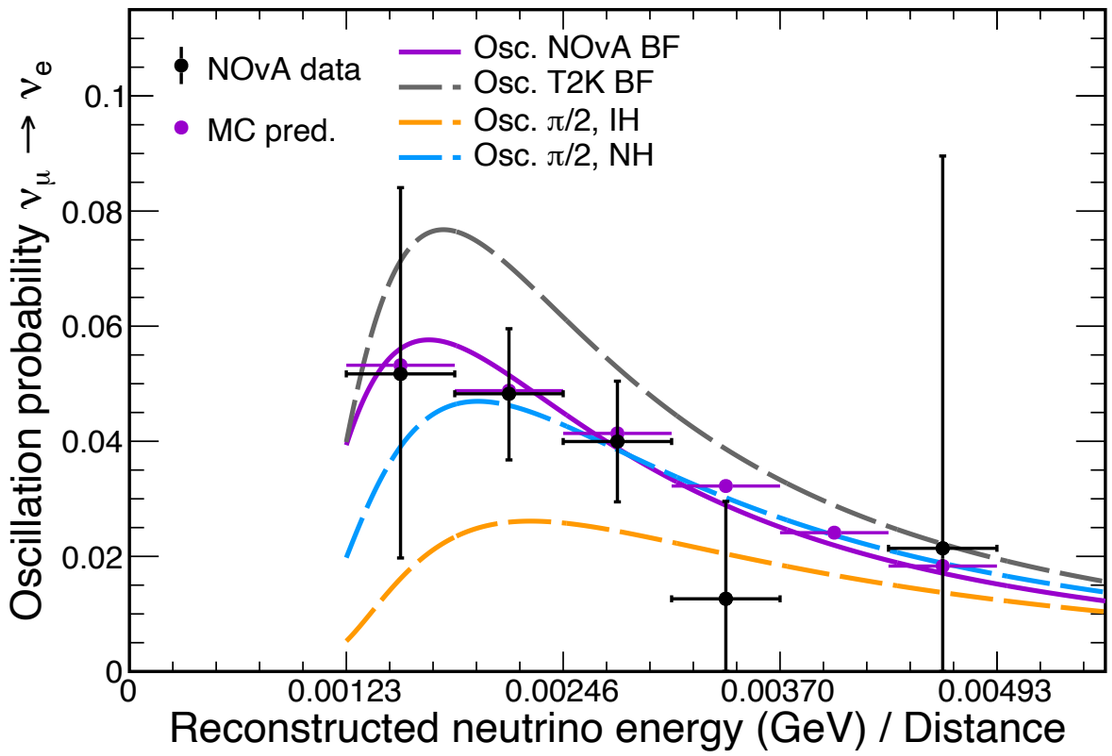
T2K's cross was digitized and approximately calculated from the Neutrino talk plot.

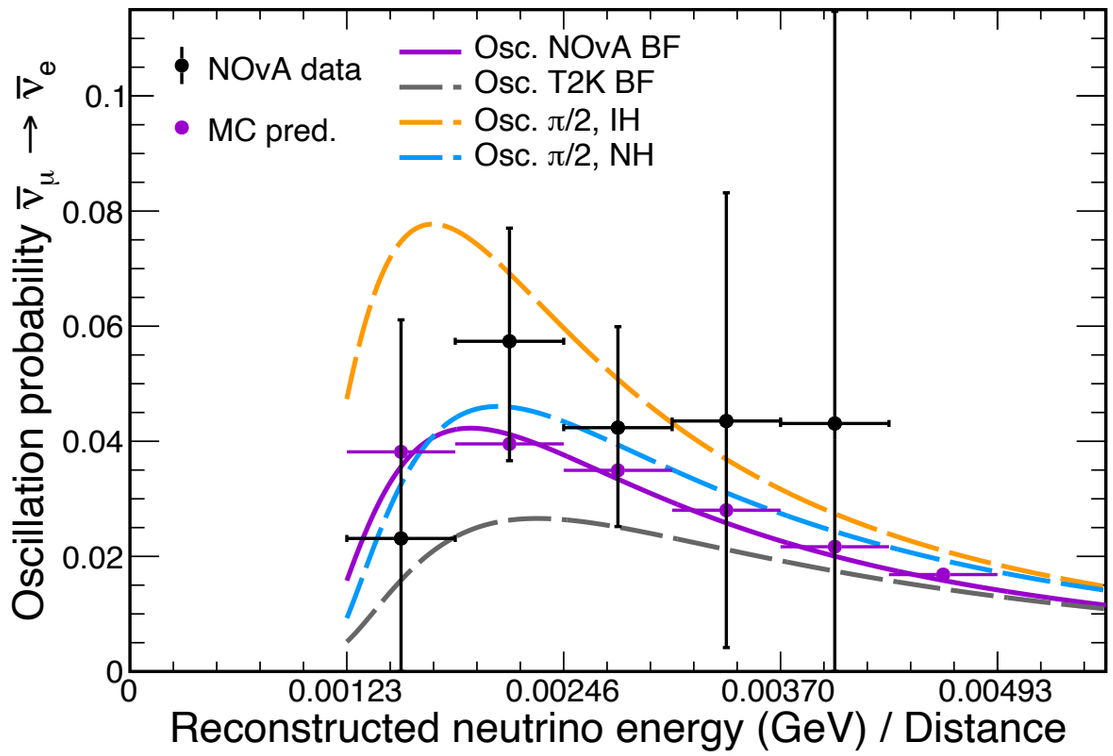




Curious and very preliminary plots

Or transforming to E / L will make osc. probability plots quite universal





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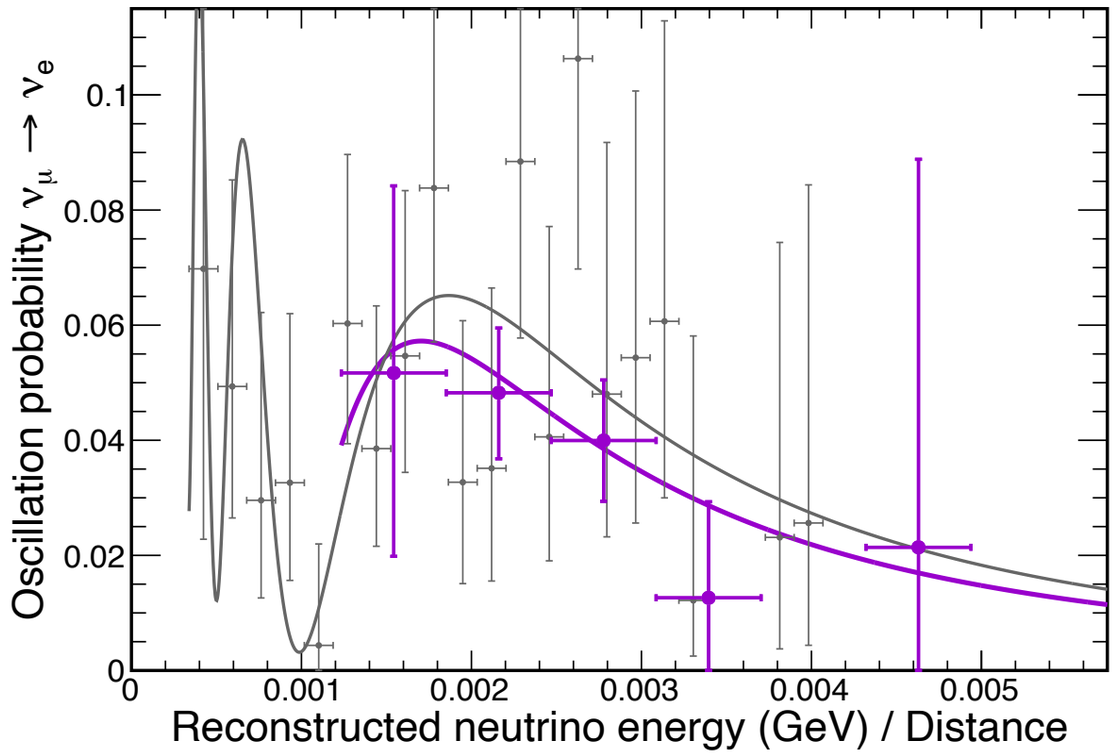
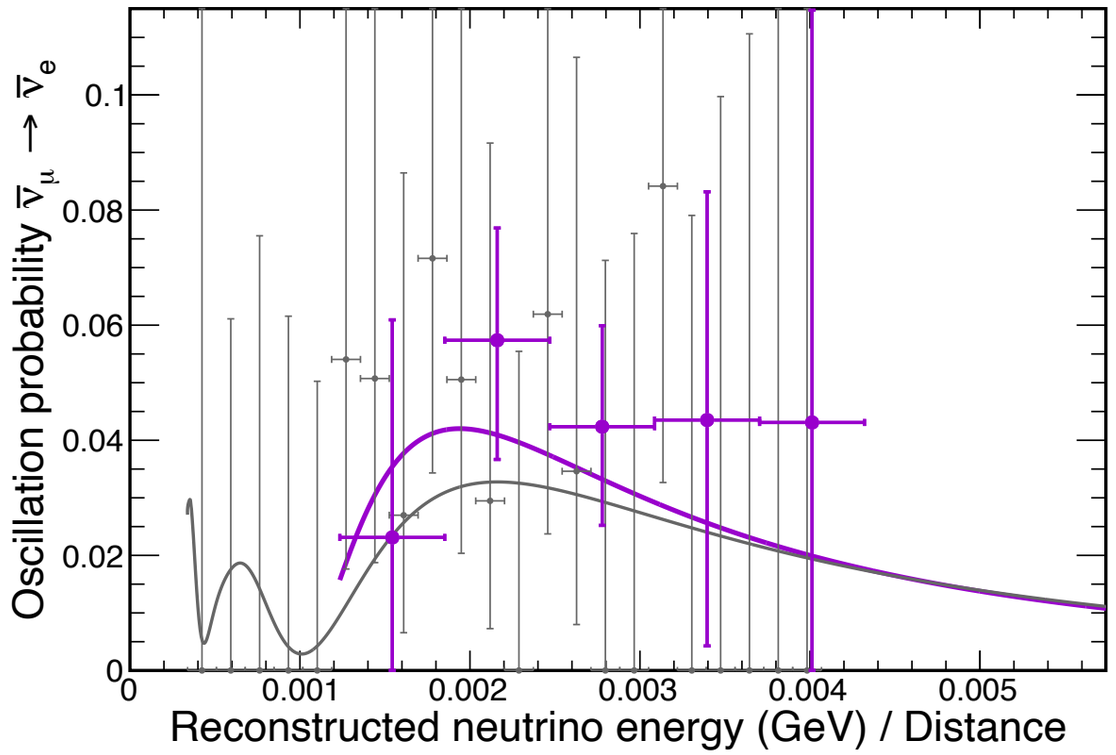
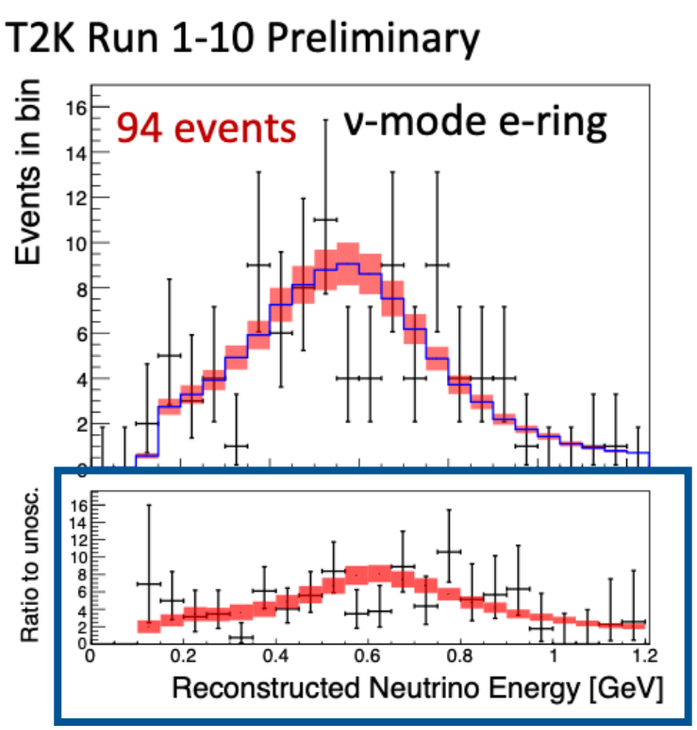
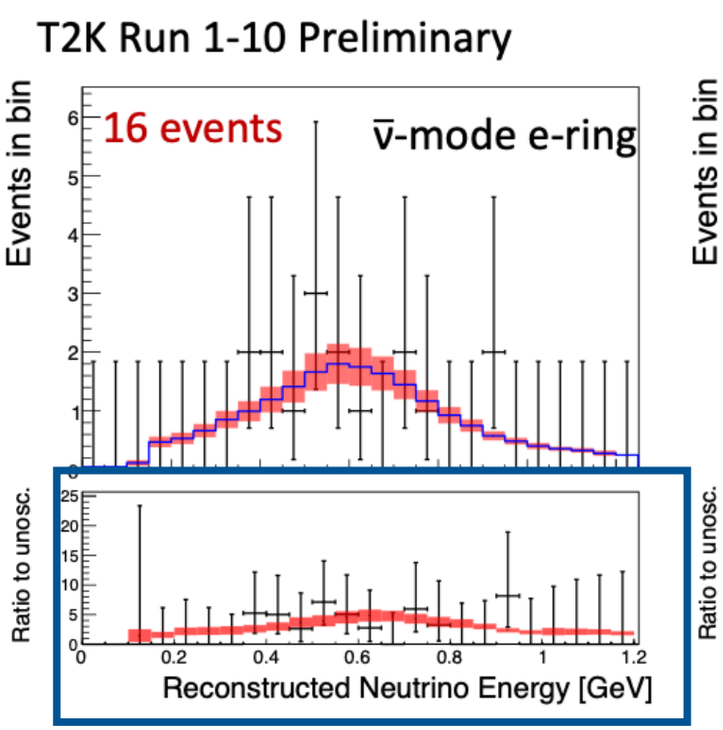
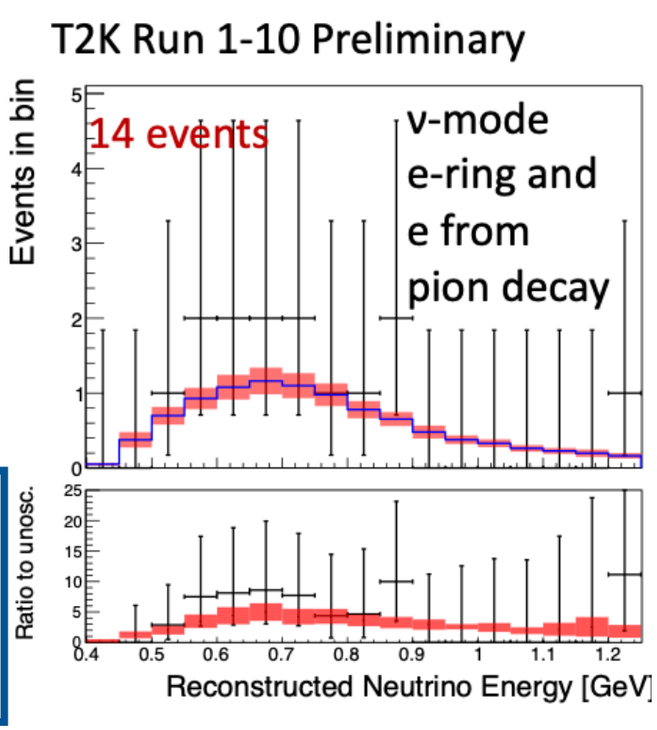




Digitized these dots



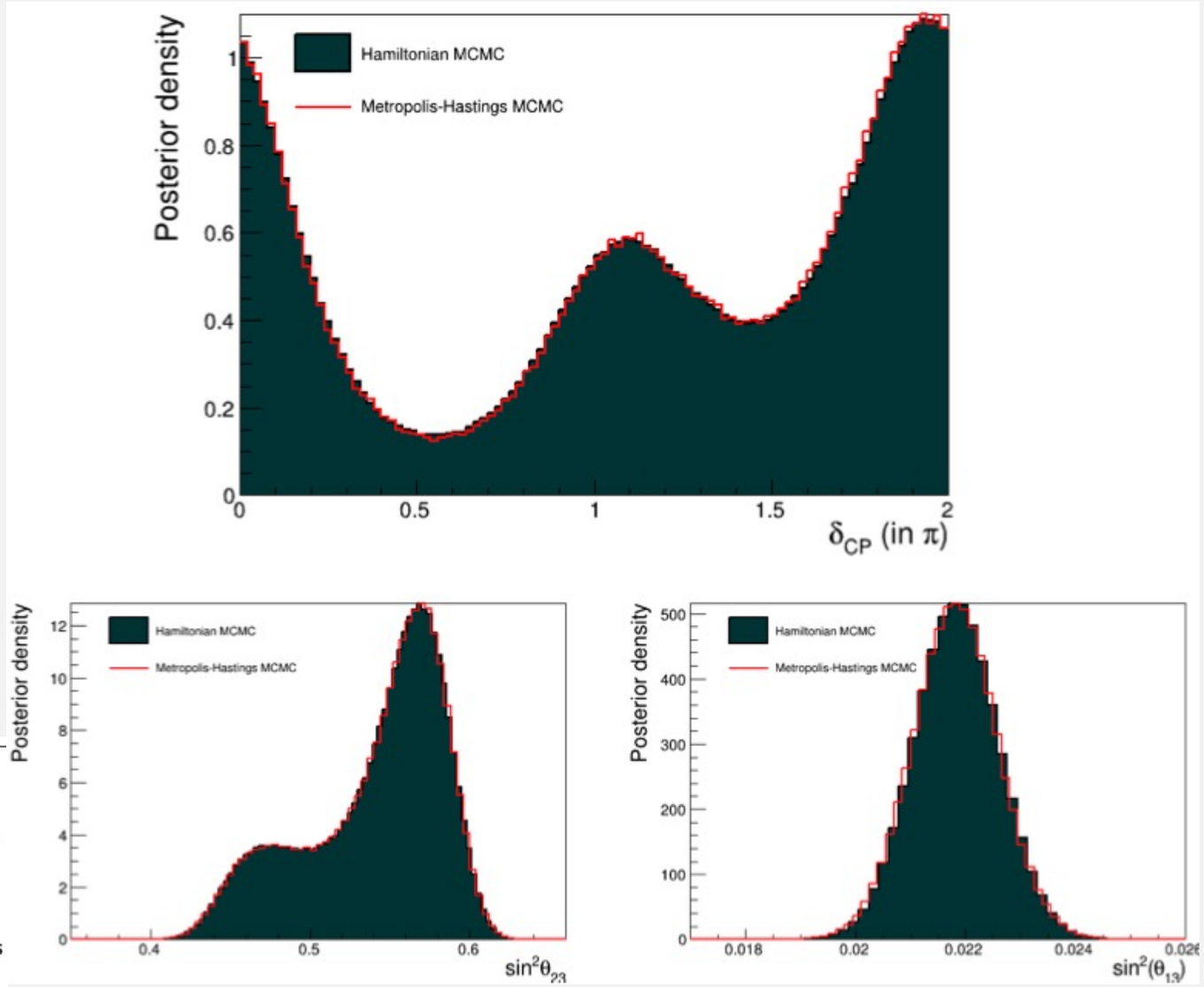




BACK TO KARL ☹

The 2022 Analysis – Bayesian Fit (Artur/Pierre)

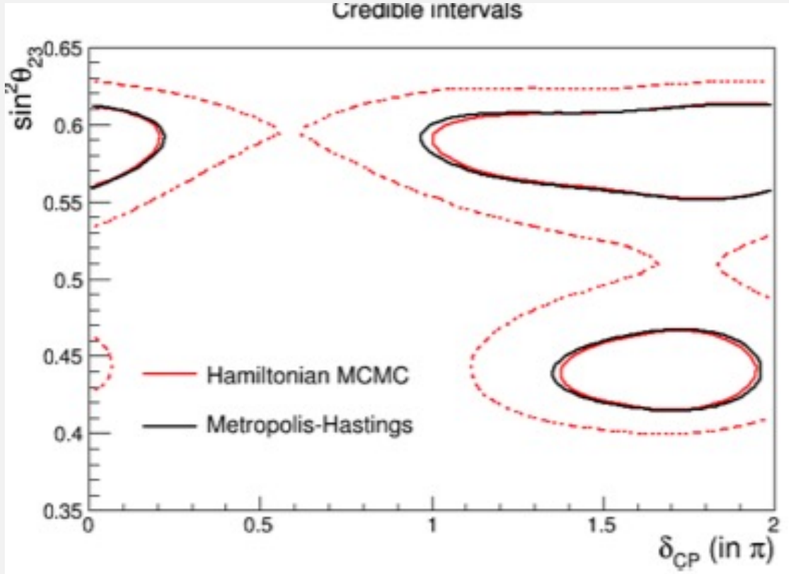
- Currently exploring two efforts to implement a Bayesian analysis.
  - Hamiltonian MCMC cannot be used for the NOvA-T2K fit, due to experiment infrastructure differences.
- Number of bugs have been fixed, and the two methods now provide very similar profiles.
- All comparisons are currently stats-only.

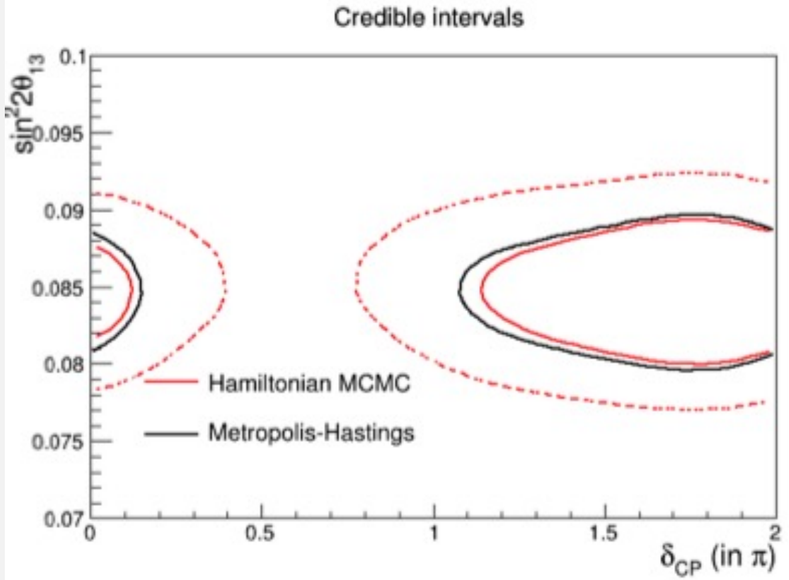


Hamiltonian MCMC with STAN	Metropolis-Hastings MCMC for NOvA-T2K
Advantages: • Higher efficiency with more parameters • Analyser doesn't have to tune step-sizes	Advantages: • Higher efficiency with less parameters • Easy to implement
Disadvantages: • Difficult to implement • Lower efficiency with less parameters	Disadvantages: • Lower efficiency with more parameters • Analyser has to tune step-sizes

The 2022 Analysis – Bayesian Fit (Artur/Pierre)

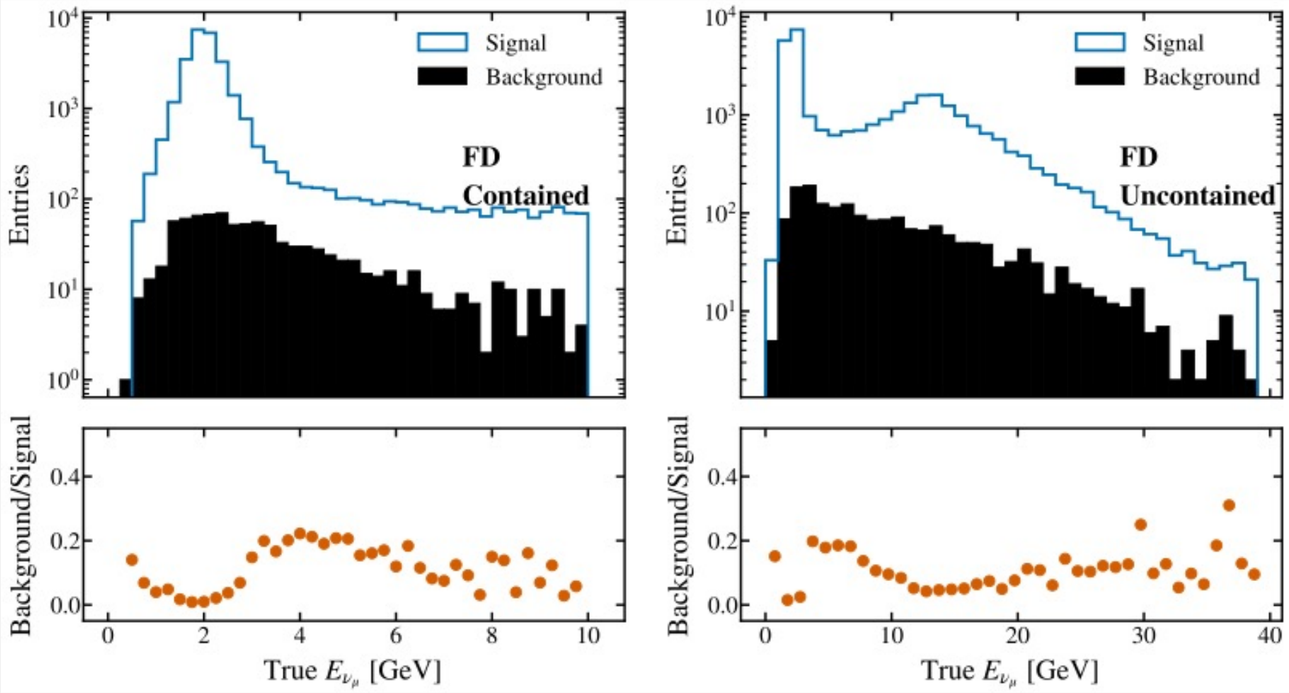
- Small differences remain in the slices and contours of two methods.
  - Residual differences for low values of δ_{CP}, possibly due to boundary conditions.
  - Small differences in θ_{13}, possibly due to differences in the reactor constraint.
  - Still need to make comparisons for Δm^2_{32}.
- This will be available well before neutrino, with an accompanying technote.
  - Tentative plan for release by the end of the year, so keep your eyes out for that.





The 2022 Analysis – Additional Samples

Juan Miguel

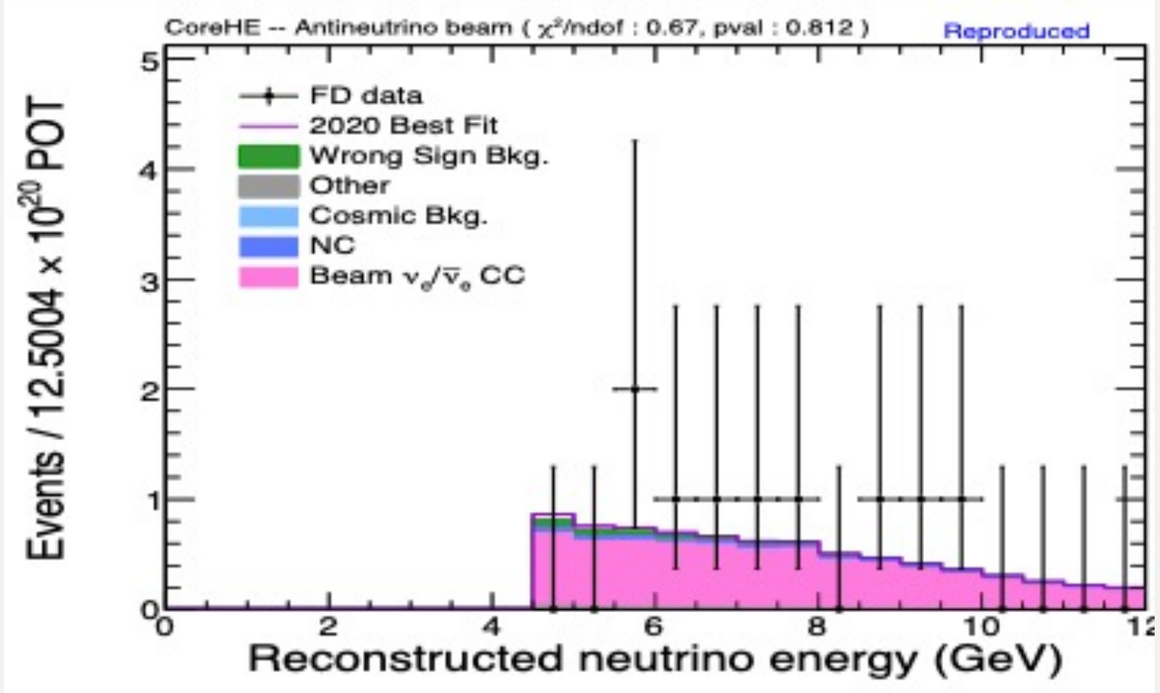


Exploring uncontained ν_μ events, by relaxing the containment cut and true energy cut.

Trained a BDT to estimate the energy of these events, which had an RMS of 30% (compared to contained RMS of 11%)

Future plans include using Multiple Coulomb Scattering to better estimate energy, and to produce sensitivities including this sample.

Ishwar Singh



Has reproduced the 2020 Analysis sideband plots.

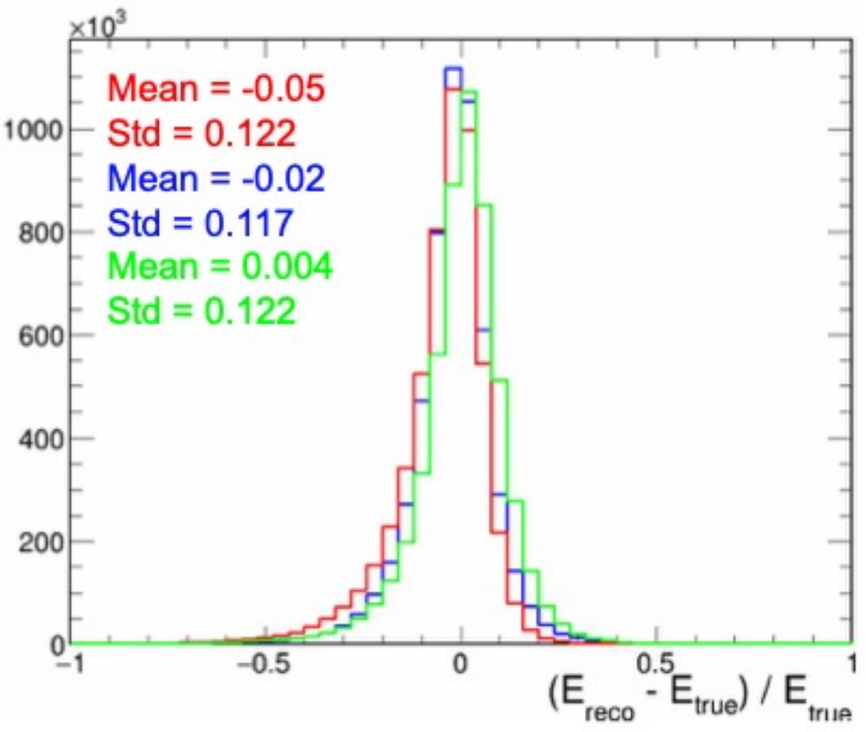
Could provide an important constraint on the ν_e beam background, as those events dominate this sample.

Plan to produce sensitivities including this sample.

Future studies will not include FD NUMI data.

The 2023 Analysis – Energy Estimators

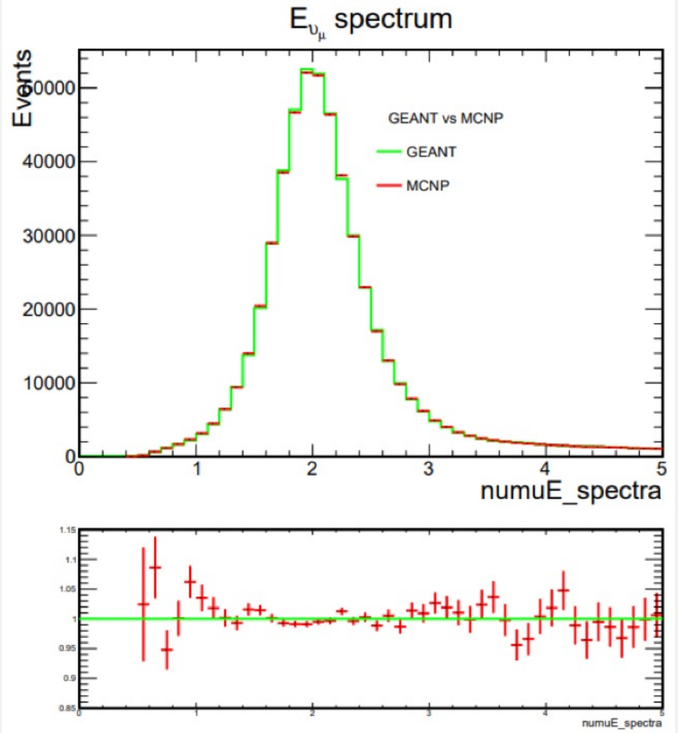
Reg CVN – Ben



Can Compare the performance of traditional, LSTM and Reg CVN energy estimators in Prod5.1 ND files.

Can notice similar performance between all three energy estimators, with the CNN performing particularly well on DIS and Res events.

LSTM – Shaowei



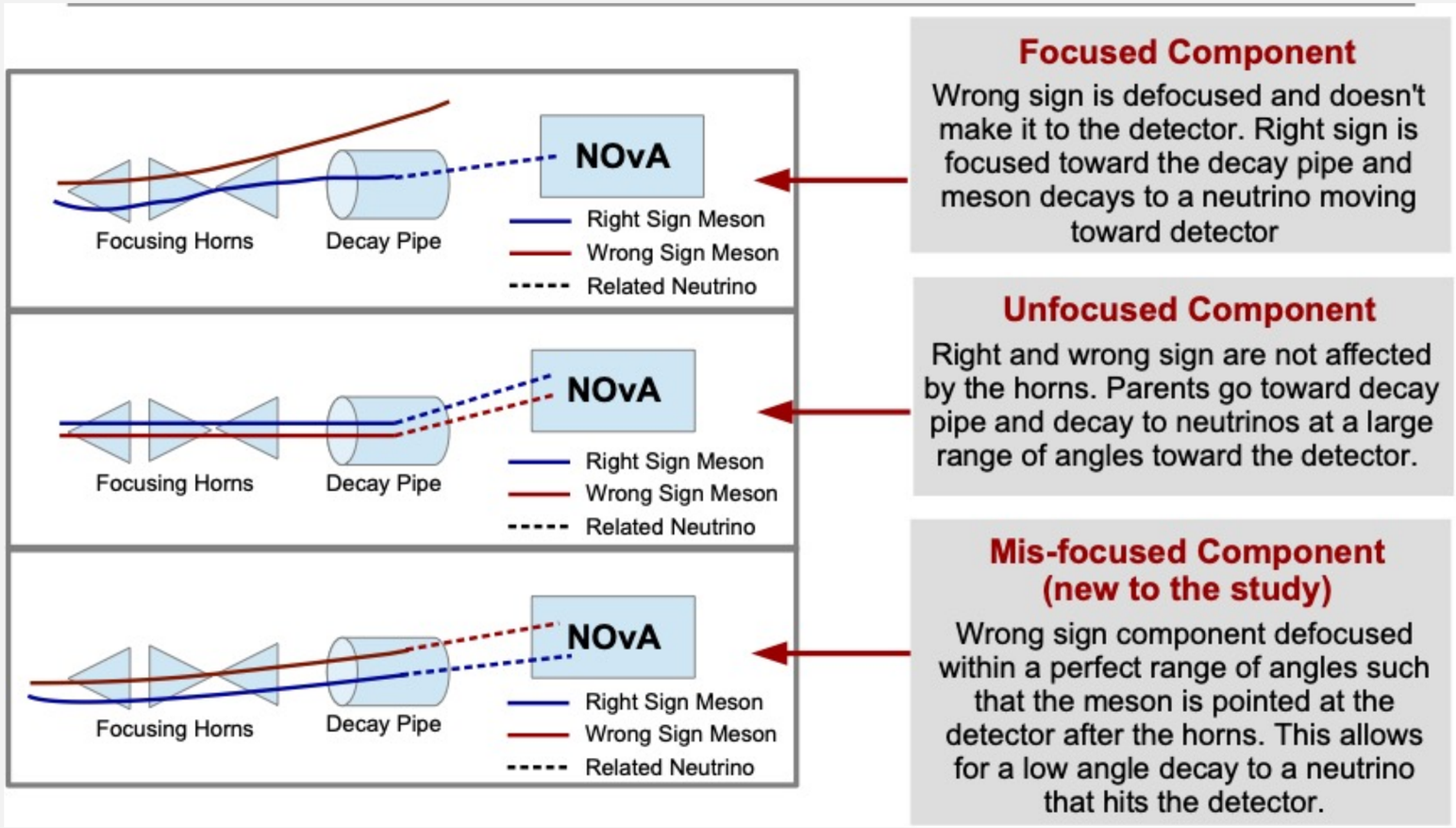
Has considered how the LSTM performance is affected by different systematic shifts.

Have considered prong length shifts (scaled shifts), final state interactions (NOvA Rwgt) and neutron propagation (MCNP – shown above).

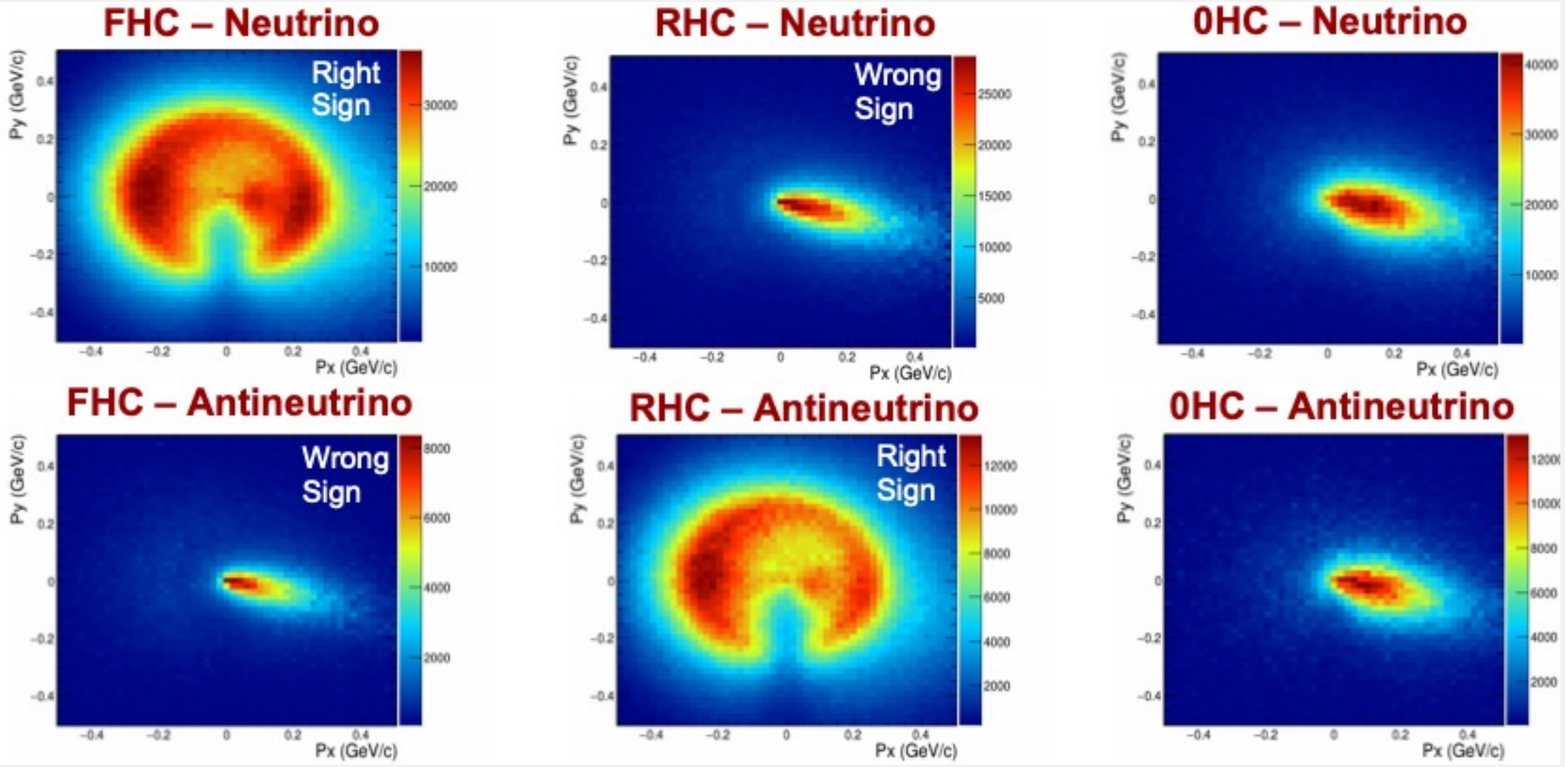
The 2023 Analysis – Decomposition Improvements (Miranda)

- Want to expand BEN to consider wrong sign components such that it could be applied to both FHC and RHC.
  - Currently only applied to FHC due to the large neutrino component (WS) in RHC beam.
- Expected the wrong sign component to come from unfocused particles.
  - This is only true for on-axis experiments.
- Studies have shown that we have an additional mis-focused component that we weren't previously aware of.

In FHC: neutrinos = right sign / anti-neutrinos = wrong sign
In RHC; neutrinos = wrong sign / anti-neutrinos = right sign



The 2023 Analysis – Decomposition Improvements (Miranda)



0HC is mostly neutrinos and has momentum distributions like the wrong sign of FHC/RHC, but with a slightly larger spread of P_y vs P_z.

- The right sign events come from most angles, and are focused towards the detector.
- The wrong sign events are a combination of unfocused and mis-focused.
  - Unfocused meson move on-axis to the beam and appear near (0,0).
  - Mis-focused come in at low angles from a specific direction since NOvA is off-axis, explaining the tail in wrong sign dists.
- Distributions from pions and kaons both show focused and mis-focused components, so kaons aren't predominantly unfocused.

The 2023 Analysis – Decomposition Improvements (Miranda)

In considering how to apply this to BEN a number of questions emerged.

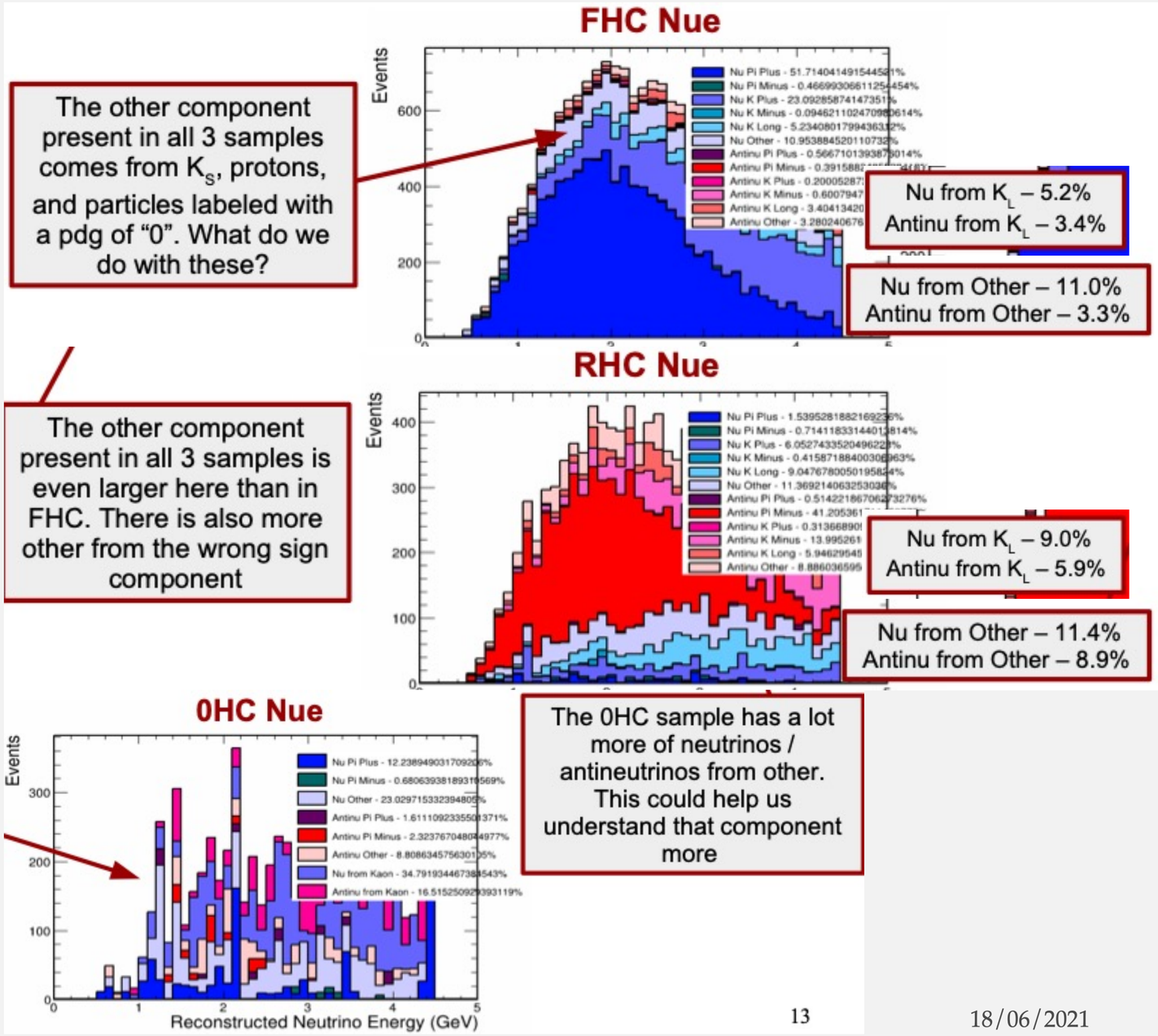
1. There is an ”Other" beam component made from K_s, protons, and ***PDG=0***.

   Ryan did a quick study showing that the PDG info may be being lost at g4numi and appears to happen more for wrong-sign events in both FHC and RHC.

2. K_L are numerous in both the FHC and RHC ν_e samples, can’t fit using ν_μ.

3. There is a large neutrino (WS) tail in RHC, particularly in the uncontained events which complicates separating K^+/K^-.

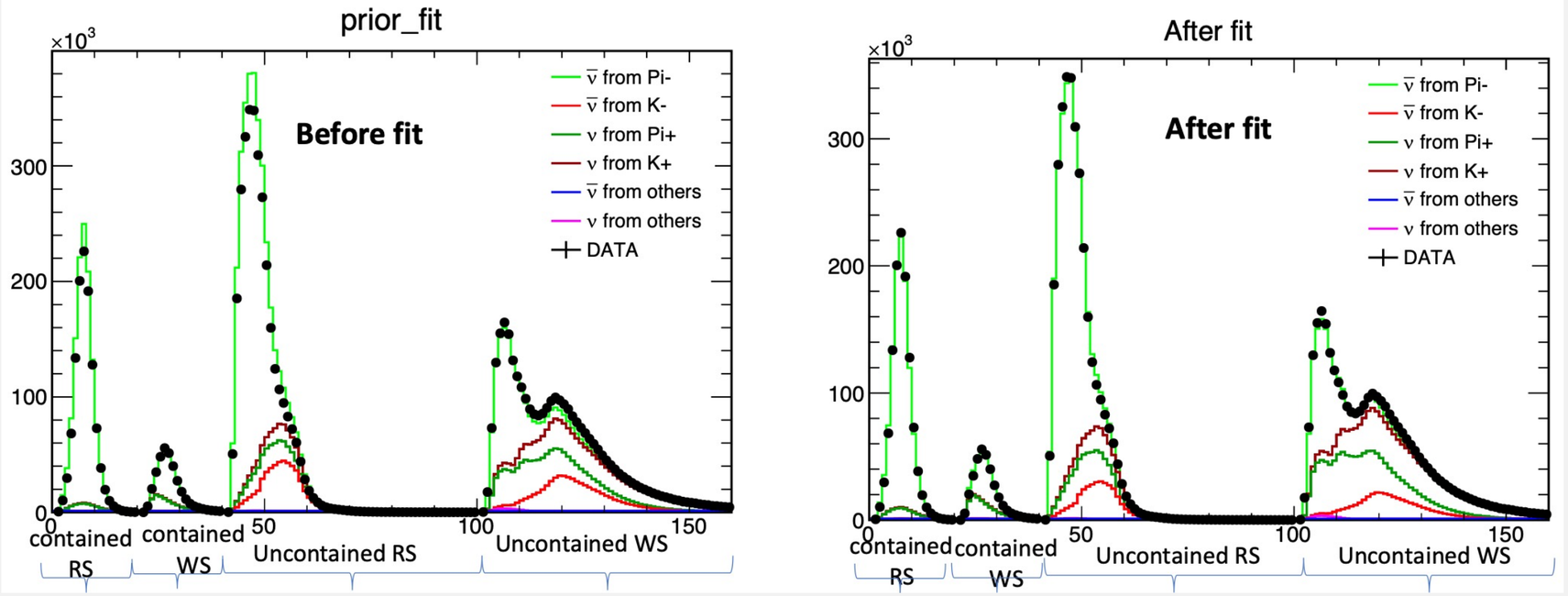
Will require further study and will follow up with beam experts concerning these questions.



The 2023 Analysis – Wrong Sign Decomposition (Abhilash)

- Wants to use the wrong sign fraction to better control decomp.
  - Using the Wrong Sign CVN to select a neutrino / anti-neutrino enriched sample.
- Has performed modified the decomp procedure to include this enhanced sample.
- The Wrong Sign fractions are within systematic uncertainties.

Template fit using WS-RS split sample



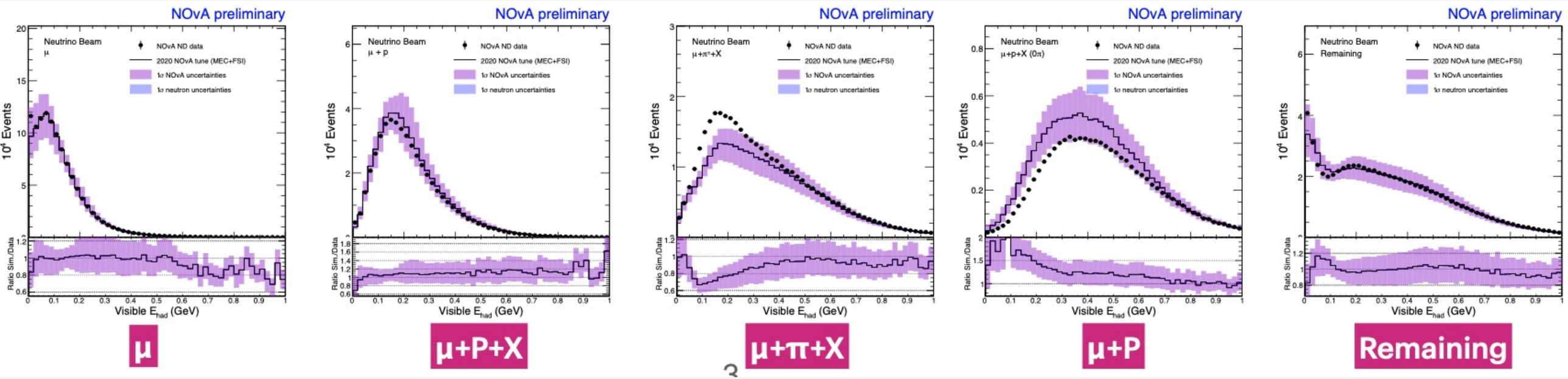
Performs a template fit using the neutrino / anti-neutrino split in RHC.
Observes that components from K- and Pi+ change significantly post-fit.

The 2023 Analysis – ND Fit Status (Maria/Michael)

Developing two methods of performing more sophisticated ND fits to better account for systematic uncertainties.

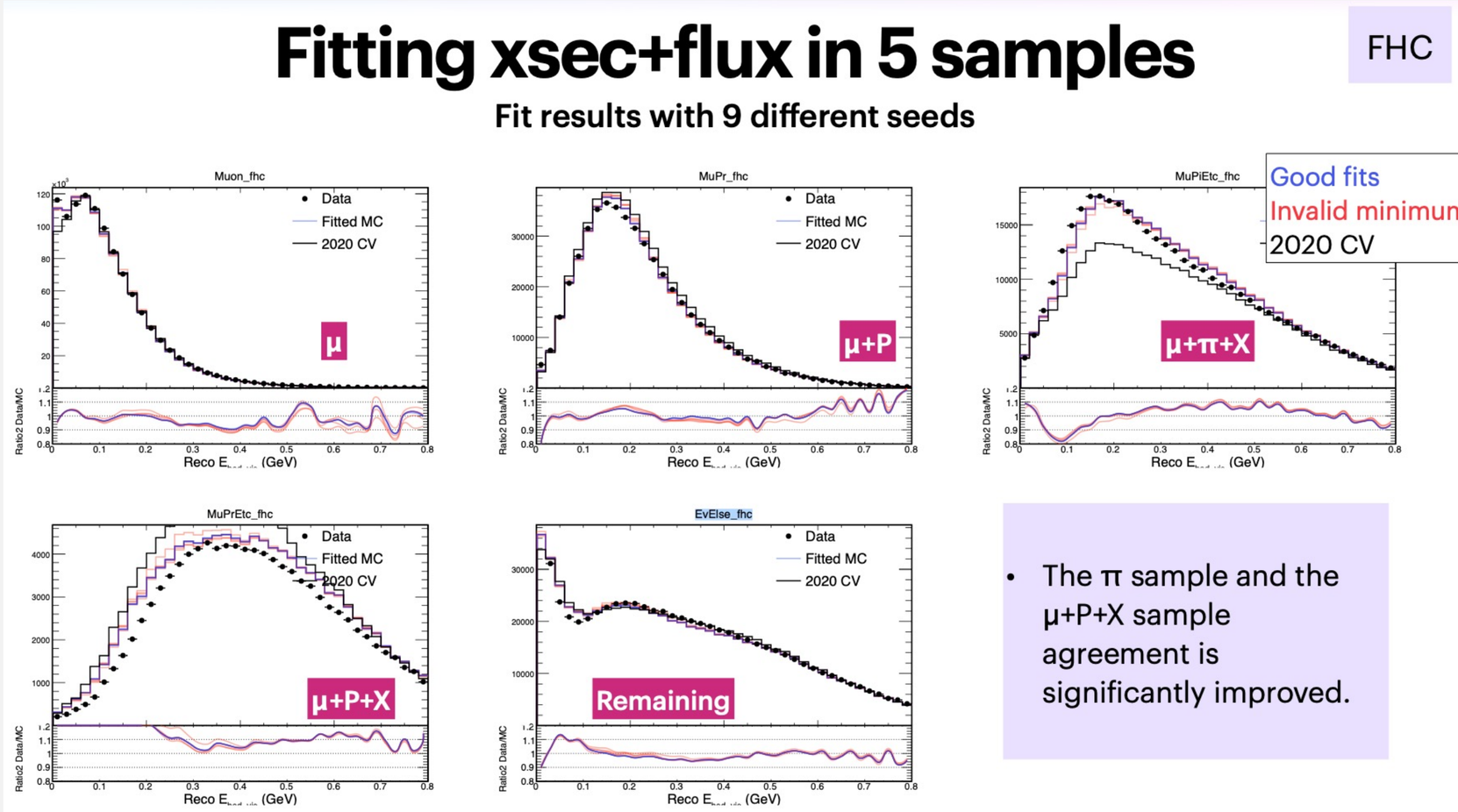
Up to this point there has been significant overlap with the Cross-Section Tuning Working Group.

- ***Maria*** is developing a Frequentist approach using 10 samples, based on topology and using MINUIT.
- Would serve to replace extrapolation, and could develop into a 2-detector fit.
- ***Michael*** is using MCMC to develop a Bayesian approach.
- Fits Maria's predictions in E_{had} and Reco $|q_3|$.
- Now using real ND Data, and working to remove insensitive systematics from fit.



The 2023 Analysis – ND Fit Stability (Maria)

- Fitting 10 samples using MINUIT doesn't always give valid results, but studying subsets of the fits has shown;
  - Require many seeds to profile all parameter space.
  - Some systematics have large pulls.
  - MEC/QE Systs have overlap/degeneracies which can be addressed by modifying some of the MEC Systs.
- May be necessary to implement a hybrid extrap/nd-fit if unable to constrain pion sample.



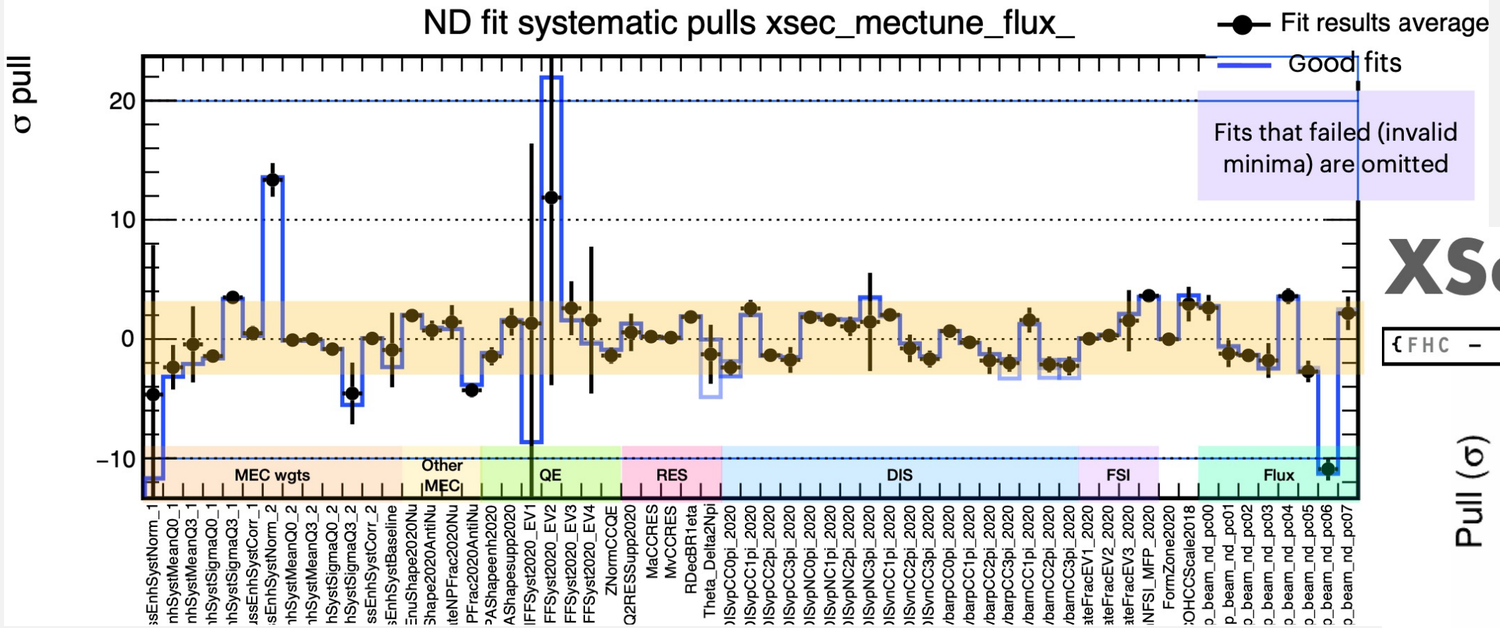
Maria has produced similar plots for RHC.

Agreement post-fit is much better than the 2020 CV tune.

The 2023 Analysis – ND Fit Systematic Pulls (Maria/Michael)

Fitting flux & cross section systematics

Fit results with 9 different seeds (showing avg of 4 fits that converged)

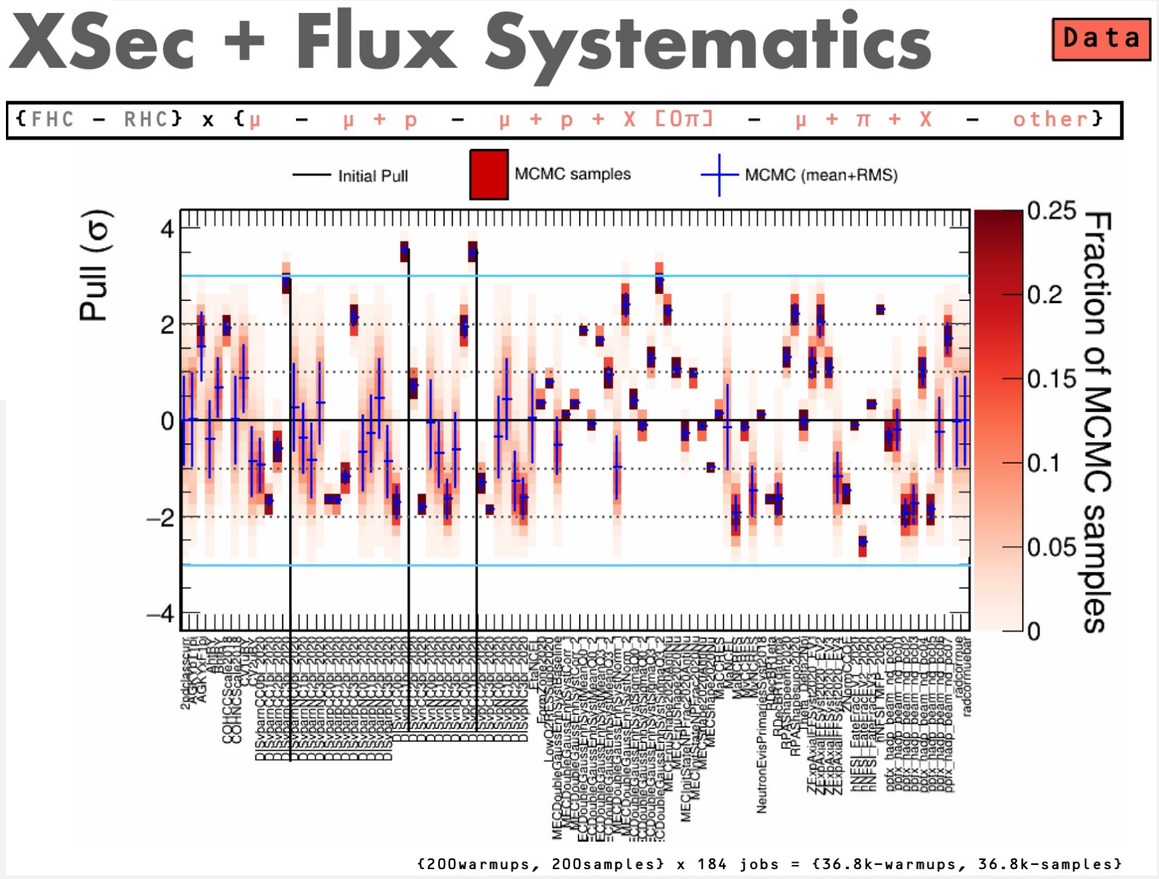


Both Maria and Michael are able to profile over different systematics and measure their pulls.

Each technique identifies specific systematics which have very large pulls.

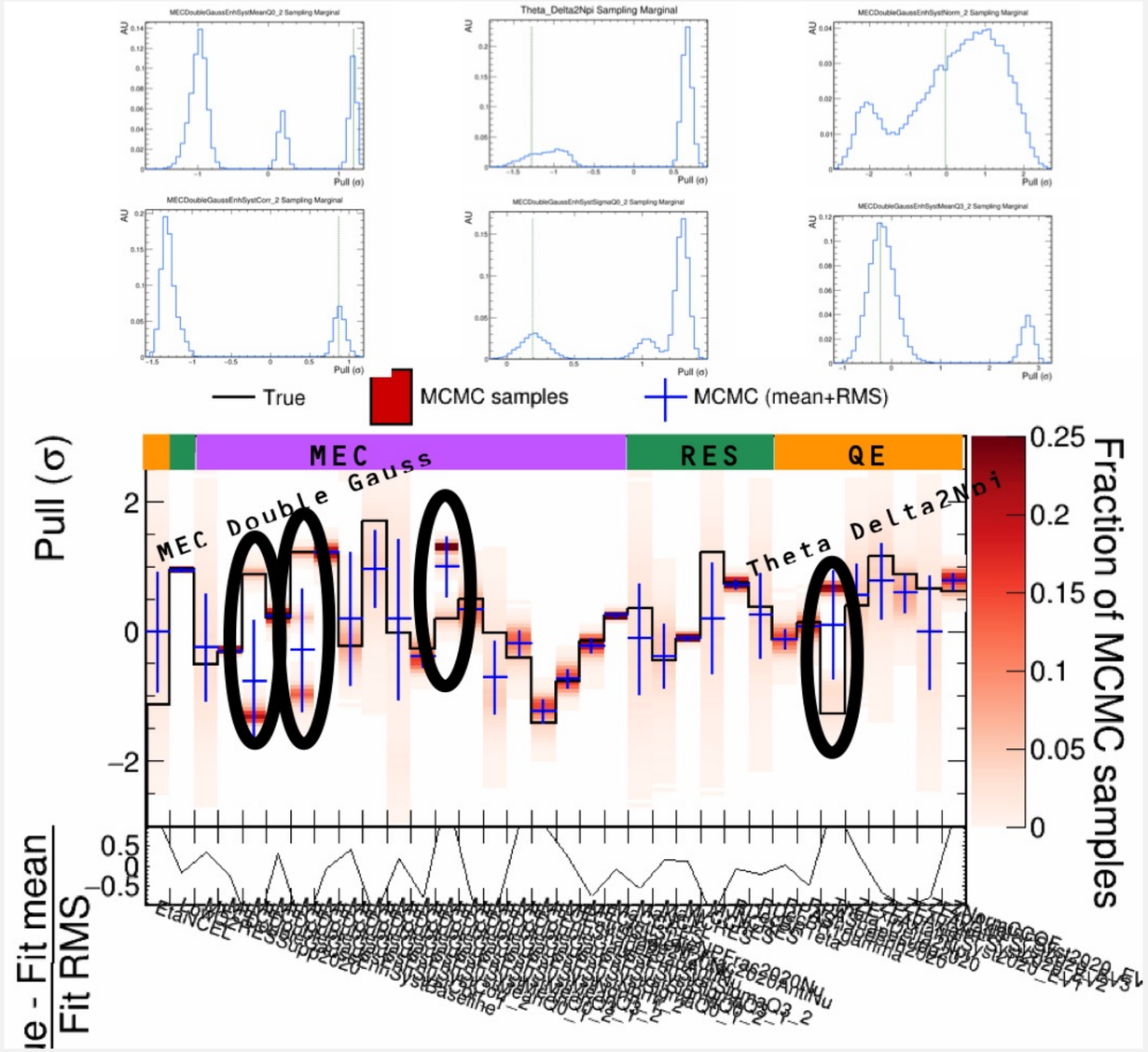
Michael identifies specific systematics which are bi-modal or insensitive to MCMC fitting.

XSec + Flux Systematics



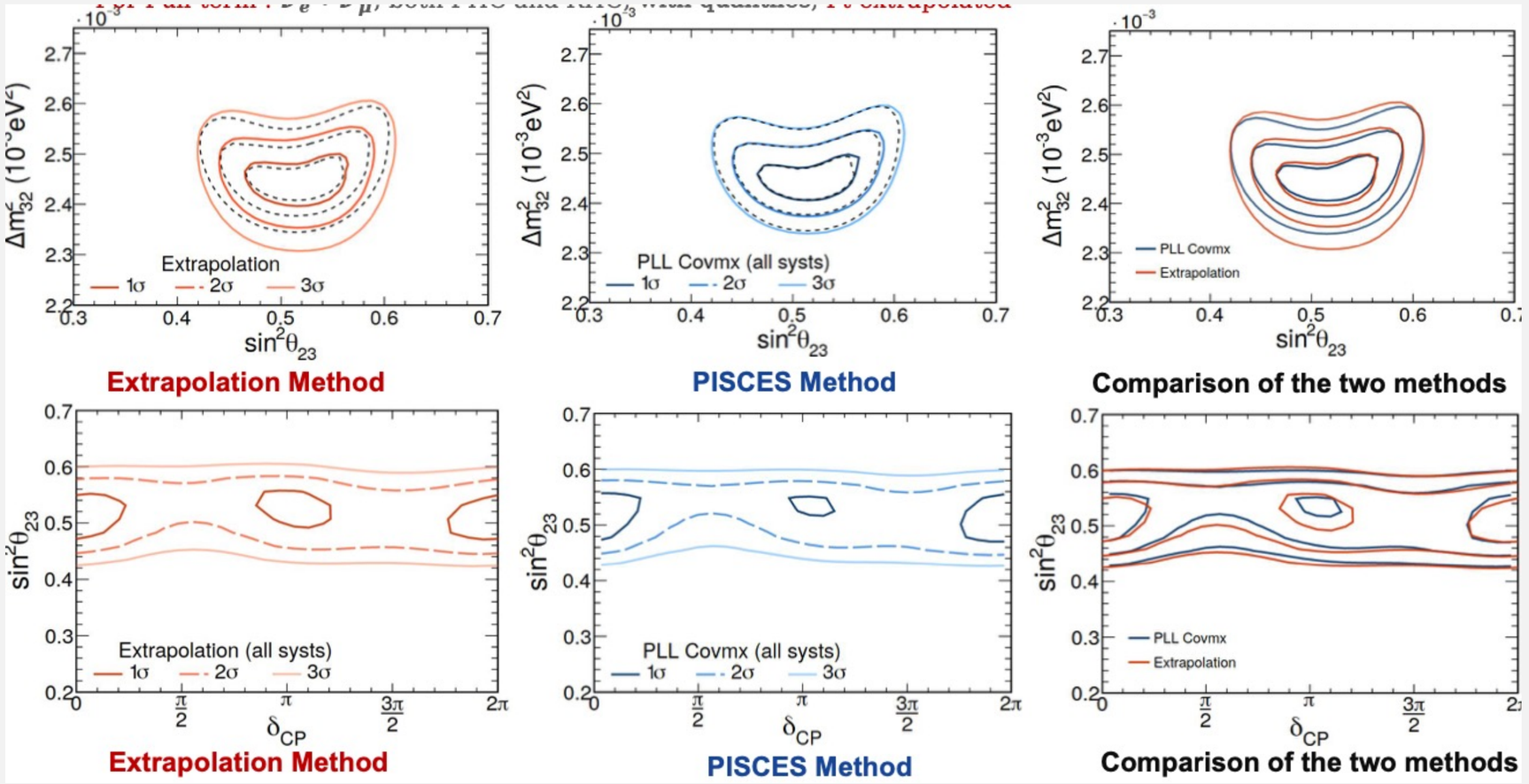
The 2023 Analysis – Removing Systs From ND Fit (Michael)

- A number of systematics are degenerate when fitting against Fake/Real Data.
  - Removing them from the fit reduces resource requirements.
  - Right; can see the 6 systs which do not converge (eg EtaNCEL).
- Other systematics (circled) have multiple probable values.
  - More work is required to understand exactly what is happening.
  - 5/6 systs for which this occurs are MECDoubleGauss.
- Will also likely need to consider a NOvARwgtSyst for pion production.



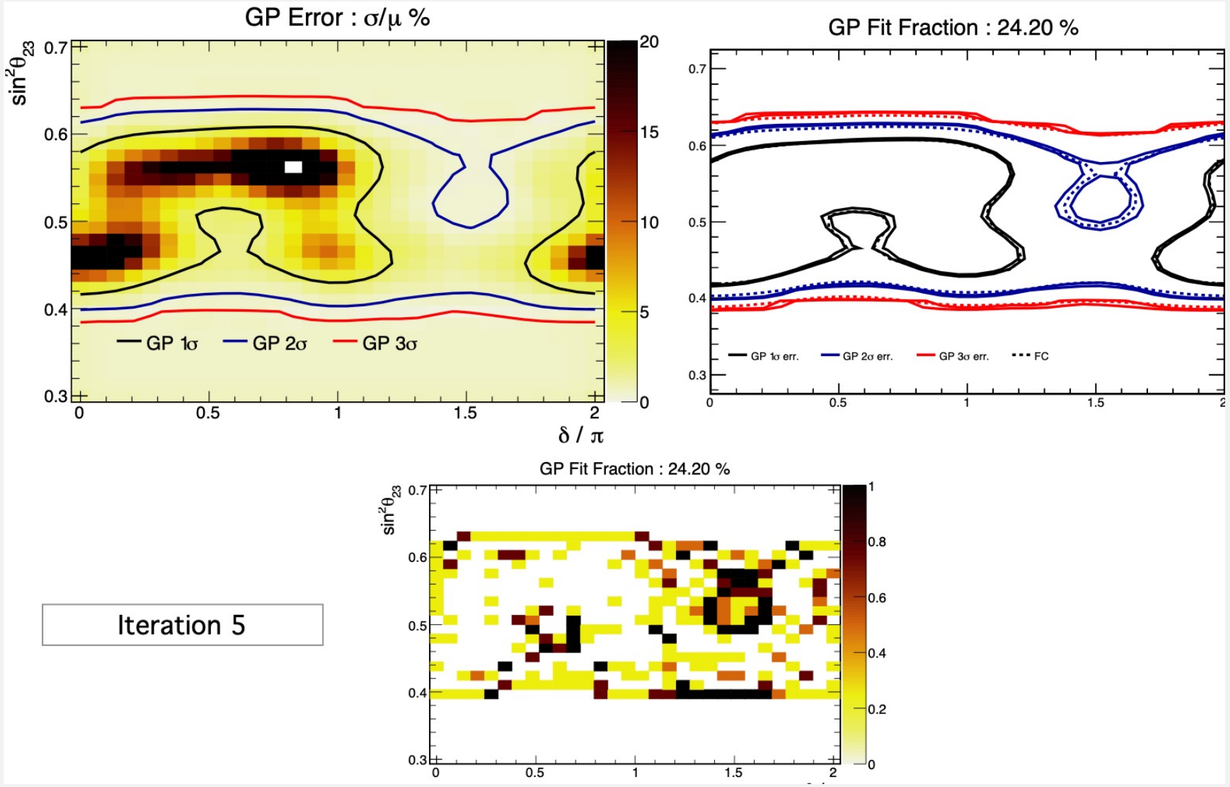
The 2023 Analysis – PISCES (Covariance Matrix) Fit (Miriama)

- Encodes systematic uncertainties in a covariance matrix, creating a two-detector fit.
- Produces slightly tighter contours than the Extrapolation method.
- Performing fit robustness tests;
  - Stability of using predictions with(out) XSec CV tune.
  - Check that 90% Asimov contour accurately covers pseudo expts.
- Developed a Conditional fit to improve fitting speed.



Comparison between Full Analysis for the Extrap and PISCES methods.
Top: Solid lines are wSysts / Dashed lines are Stats-only.

The 2023 Analysis – Feldman-Cousins (Multiple)



- As the analysis becomes more complicated, even running FC on NERSC becomes time-consuming.
- Many avenues being pursued to improve speedups.
- Nitish recently gave a presentation on using Gaussian Processes which may result in a 5X speed-up for contour-making, and 2+X speed-up overall.
  - Can replicate our FC contours with around 20-25% of the pseudo experiments.

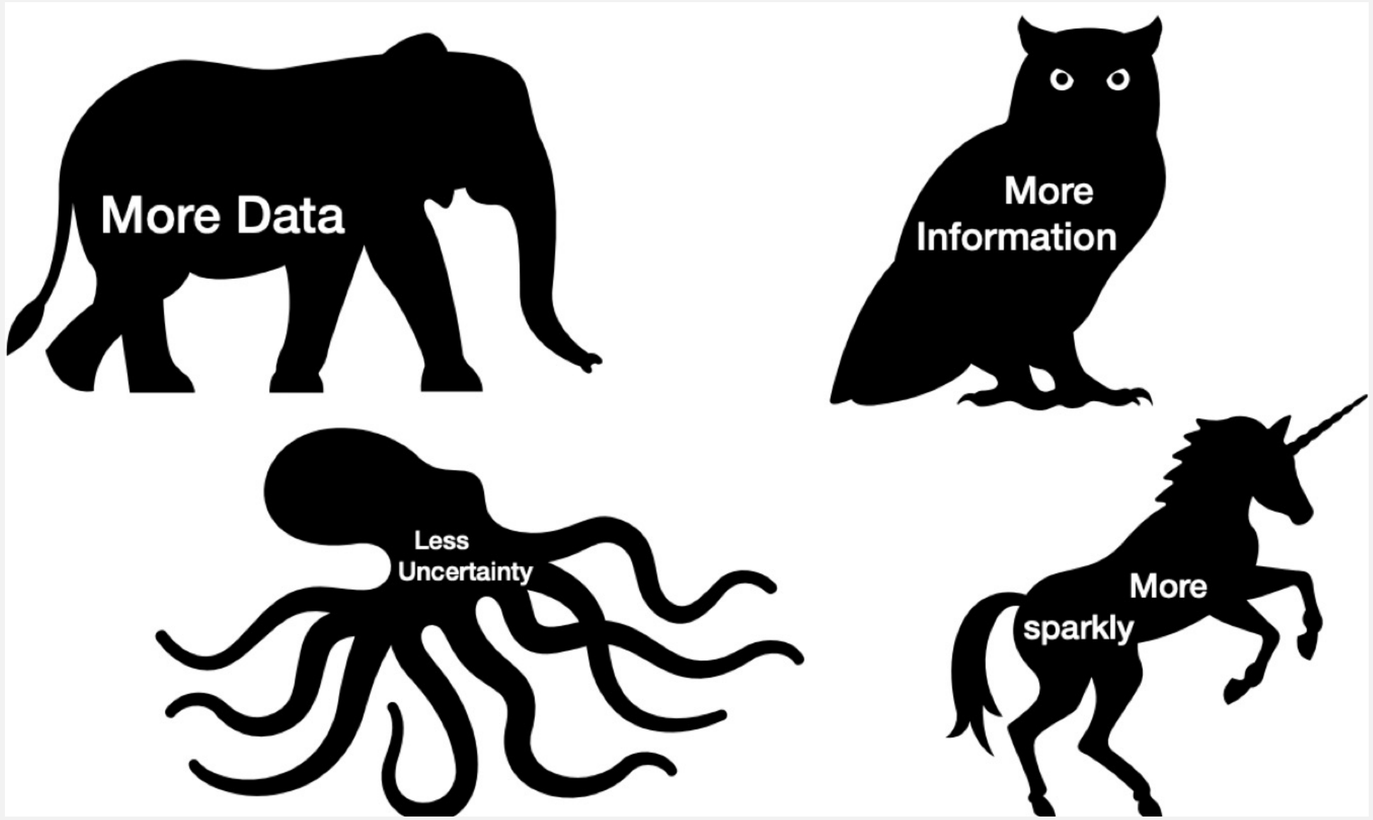
Summary

- Tons of really exciting studies in progress.

- Don’t be fooled into thinking that just because we won’t be releasing a major analysis update until 2023 there isn’t lots of activity!

- Some of the updates planned for 2023 and beyond will be fundamental changes to how we perform our three flavour oscillation measurements.

- If you want to get involved please reach out to Louise, Ryan or myself.

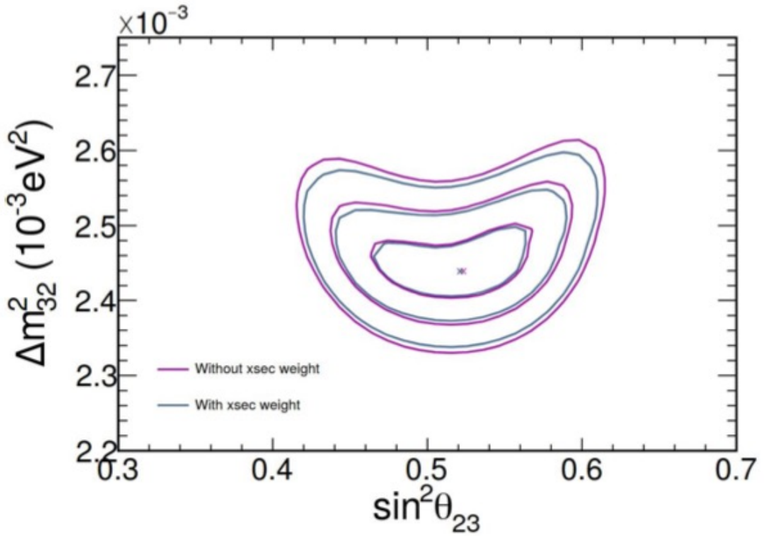


ADDITIONAL SLIDES

The 2023 Analysis – PISCES (Covariance Matrix) Fit (Miriama)

PISCES method

- Keep the predictions with the xsec CV tune weight but fit with fake data without the xsec CV tune weight.



With xsec CV weight

- Best fit $(sin^2\theta_{23}, \Delta m^2_{32})$: **(0.521229, 0.00243921)**

Without xsec CV weight

- Best fit $(sin^2\theta_{23}, \Delta m^2_{32})$: **(0.523233, 0.00243934)**

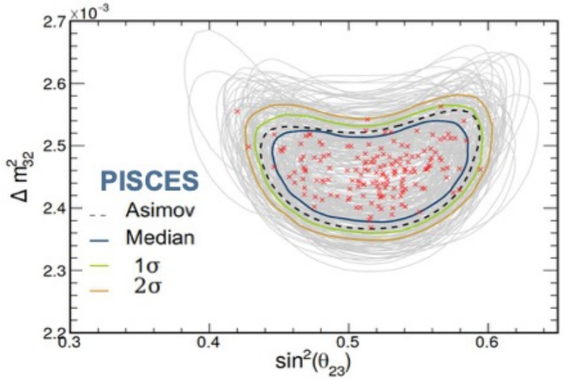
- Comparison with the extrapolation method will be done in the future.

Need to modify the Extrapolation code in order to perform comparative studies.

Currently exploring method of how to do this. Slightly involved.

Coverage for pseudoexperiments (2Detector fit)

- Generate pseudo experiments with random statistic and systematic fluctuations around the nominal values.
- Used 170 pseudo experiments to generate 90% C.L. median contour.



- Tendency to overcover with the current POT values and livetime.
- Some of the preconditions of Wilk's theorem may be violated:
  - Low statistics.
  - Parameters at the boundary of their allowed region.
- We are currently testing with increased values of POT for a higher statistic fit to see if coverage improves.

- Note: we currently do not know the extent of under/overcoverage at 90% CL with the extrapolation method. Future studies will help determine this.

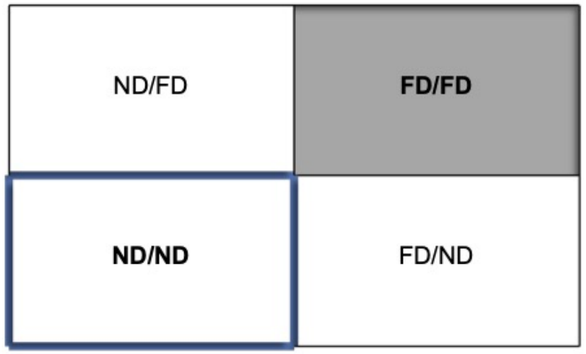
The 2023 Analysis – PISCES (Covariance Matrix) Fit (Miriama)

Conditional Method

- Using ND+FD, $\nu_e + \nu_\mu$ with quantiles samples lead to a 3500x3500 covmx → considerable fitting time.
- Conditional fit method: a new method that also allows the use of auxiliary samples such as the Decomp samples.
- Create a conditional matrix using ND data and fit using FD samples:

$$\bar{\mu} = 1 + \Sigma_{FD/ND}\Sigma^{-1}_{ND/ND}\left(\frac{a}{\mu_2} - 1\right) \qquad \bar{\Sigma} = \Sigma_{FD/FD} - \Sigma_{FD/ND}\Sigma^{-1}_{ND/ND}\Sigma_{FD/ND}$$

ND data — ND prediction



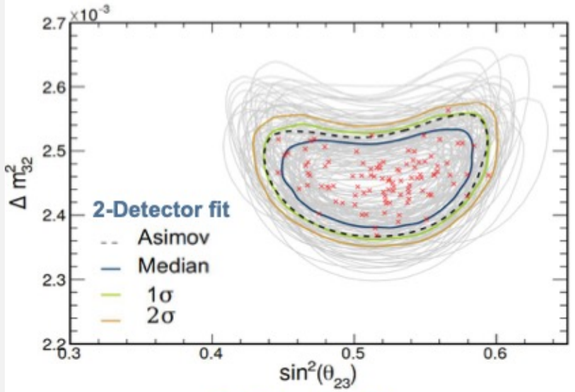
Significantly reduced the parameter space which one is fitting over.

Conditional fit fitting time is comparable to that of the Extrapolation method (2 min/bin), vs the 2-Det-fit which takes 17 min/bin

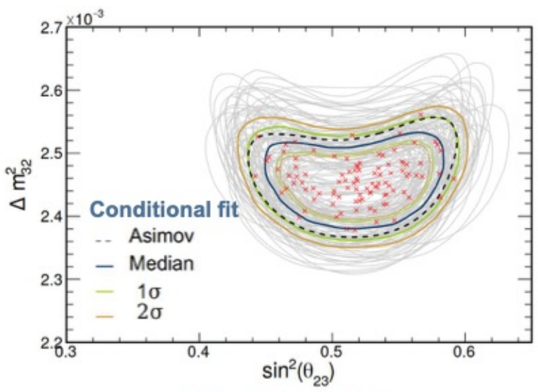
Throwing pseudo experiments is also 20 times faster (3 min/bin vs 60 min/bin)

Median contours comparison

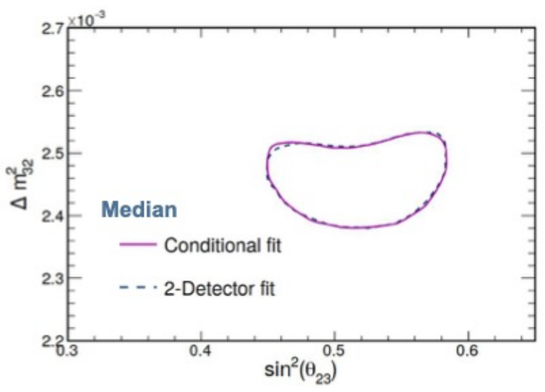
- Test both metods using 100 statistically and systematically fluctuated pseudoexperiments and compare 90% CL median contours.



2-Detector fit



Conditional fit



Comparison of the two methods

- Reasonable agreement between the PISCES 2-Detector fit and PISCES conditional method for systematically fluctuated pseudoexperiments.