The Impact of the Solar Parameters within DUNE (+ ρ)

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DUNE

Part 1 – Solar Parameters

Why Care About Solar Parameters in DUNE?

- Currently we use external experiments for DUNE simulations:
  - $\Delta m^2_{21} = 7.39 * 10^{-5}$ eV² (2.8% uncertainty)
  - $\theta_{12} = 0.5903$ radians (2.3% uncertainty)
    - $(\sin^2 2\theta_{12} = 0.855)$
- Three Big Questions:
  - Does varying the solar parameters affect ν_e (& $\bar{\nu}_e$) detections in DUNE?
  - Can we measure the solar parameters within DUNE?
  - Does varying the solar parameters lead to a higher sensitivity other oscillation parameters in DUNE? (Denton 2023)

Why Care About Solar Parameters in DUNE?

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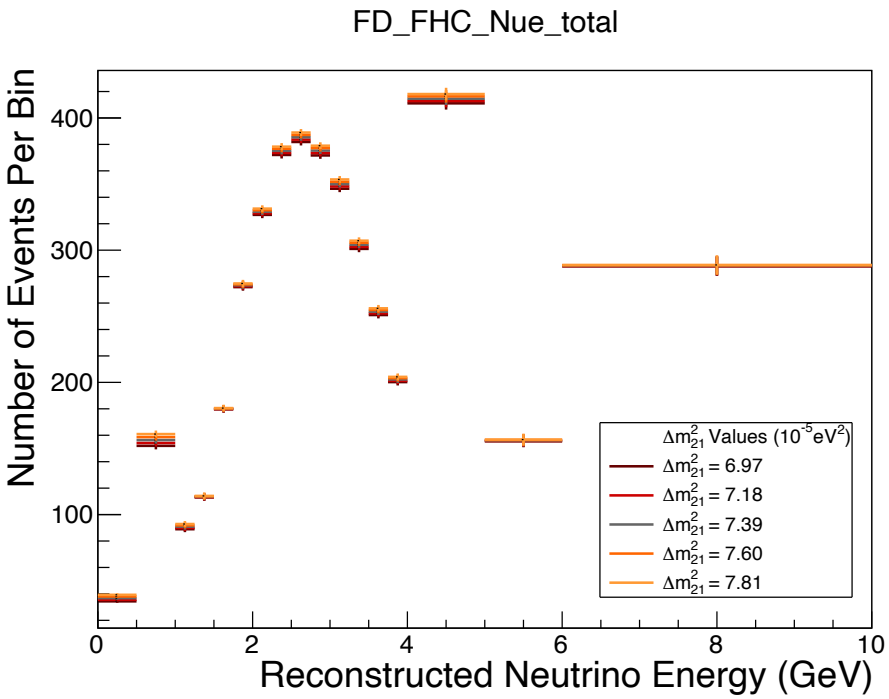
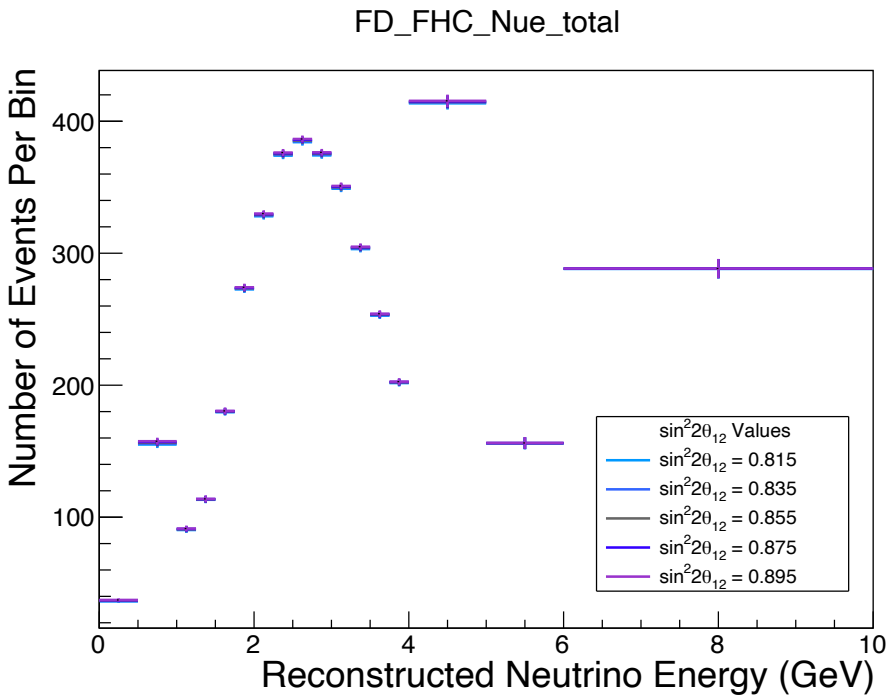
- Three Big Questions:
  - Does varying the solar parameters affect ν_e (& $\bar{\nu}_e$) detections in DUNE?
    → Not substantially
  - Can we measure the solar parameters within DUNE? → No
  - Does varying the solar parameters lead to a higher sensitivity other oscillation parameters in DUNE? (Denton 2023) → Not really

Investigating the Solar Parameters

- Assume less by varying and uncosrtraining the solar parameters
- Two ways to investigate the impact:
- ν_e & $\bar{\nu}_e$ spectra (CAFANA)
  - Solar parameter's impact on neutrino detections
- Oscillation parameter measurements (TDR)
  - DUNE's capability of measuring the solar parameters
  - Solar parameter's impact other oscillation parameters' sensitivity

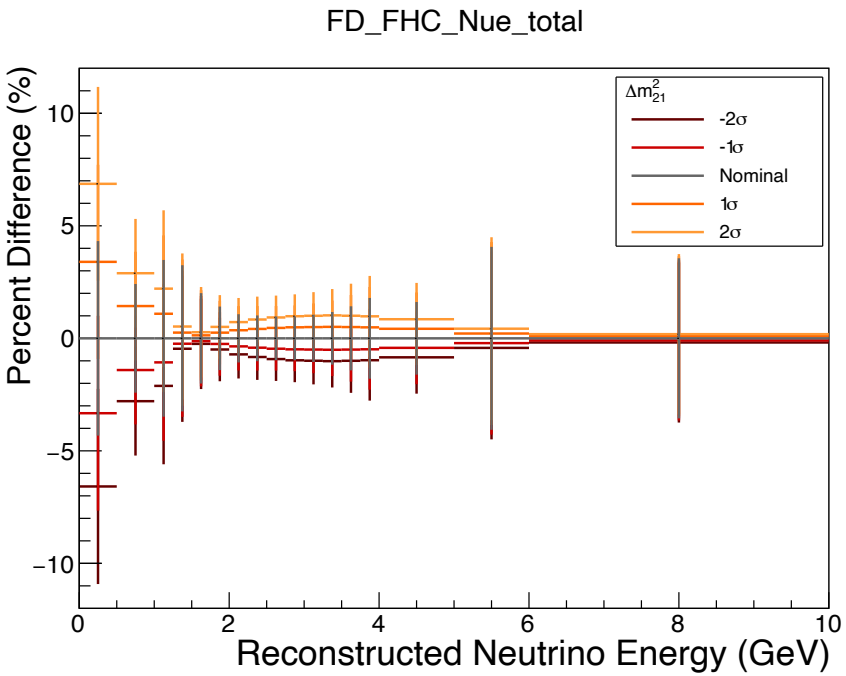
Solar Parameters and ν_e Detections

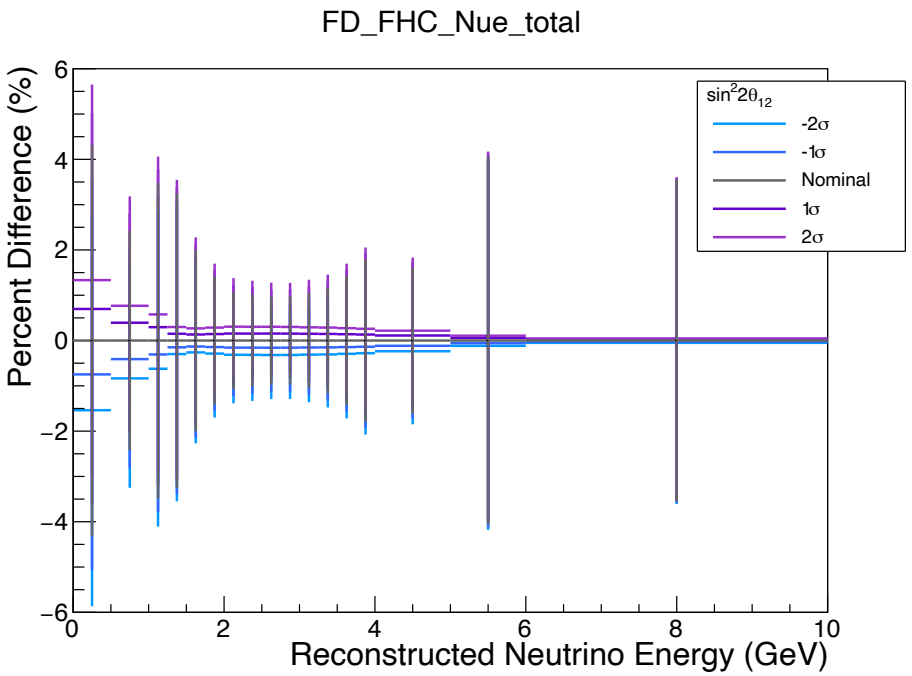




- Fairly unaffected ν_e detections

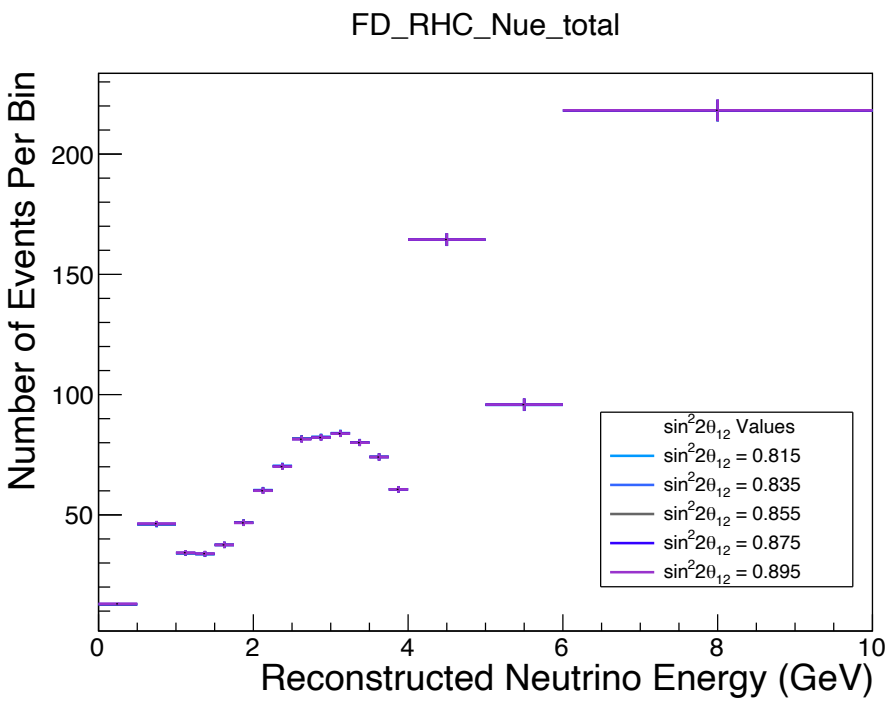
Solar Parameters and ν_e Detections

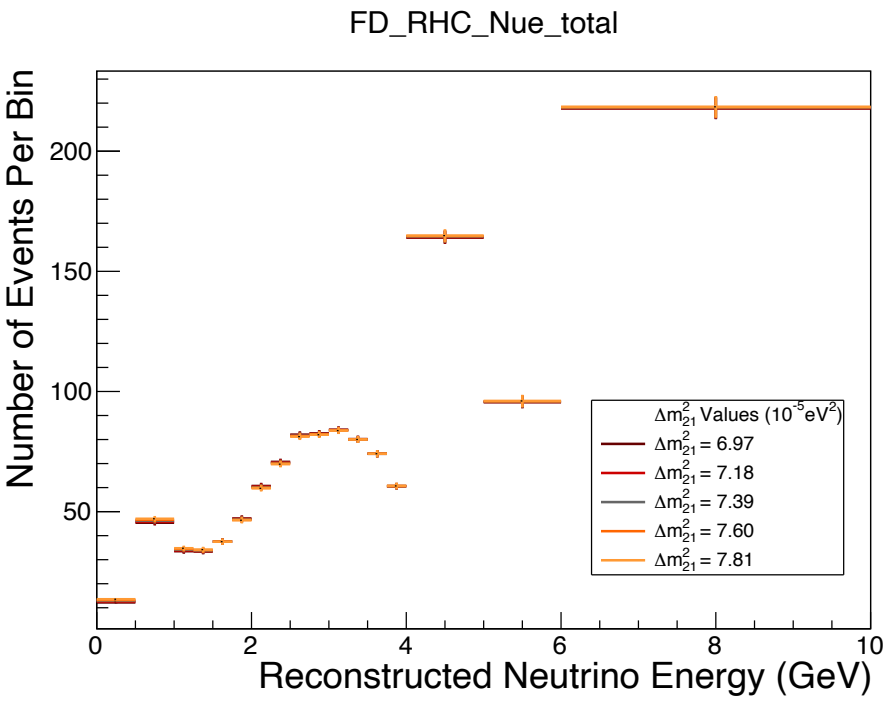




- Biggest effect in lower energy ranges (0-1GeV & 2-4GeV) (σ = 2% of nominal value)

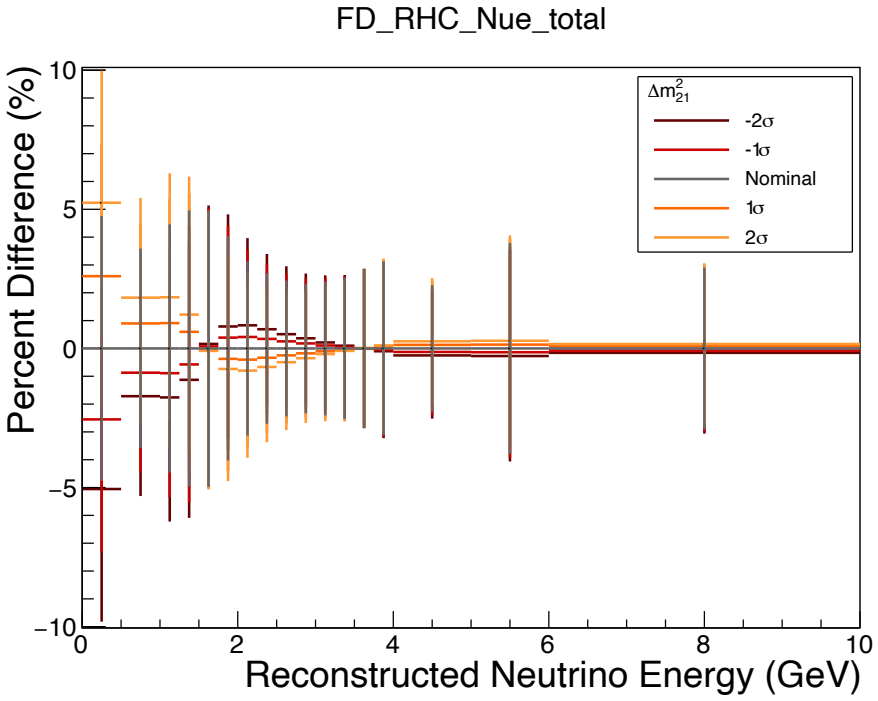
Solar Parameters and $\bar{\nu}_e$ Detections

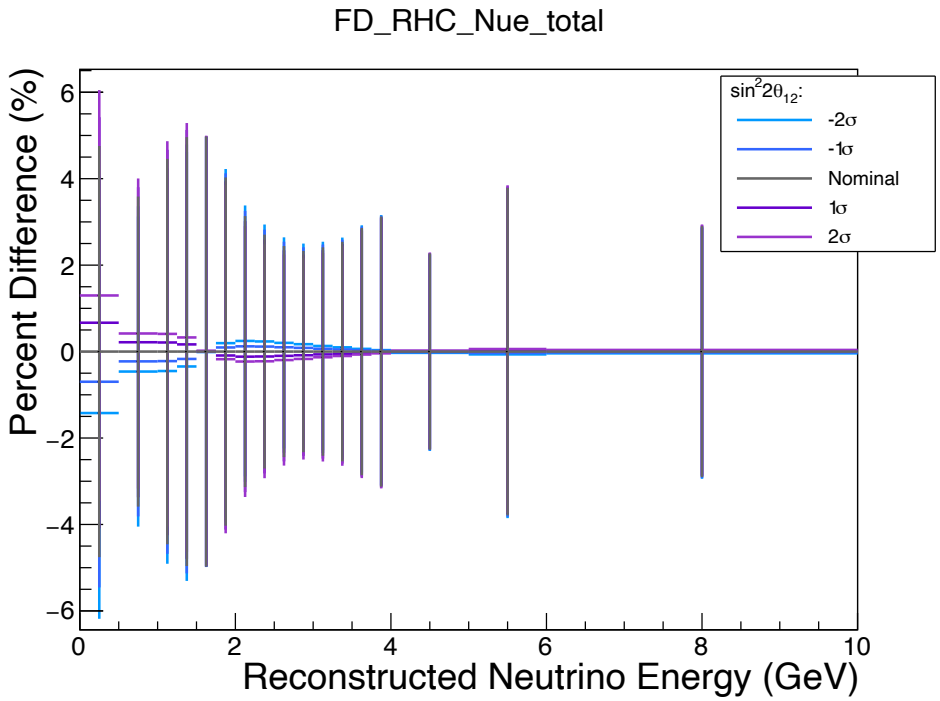




- Fairly unaffected $\bar{\nu}_e$ detections

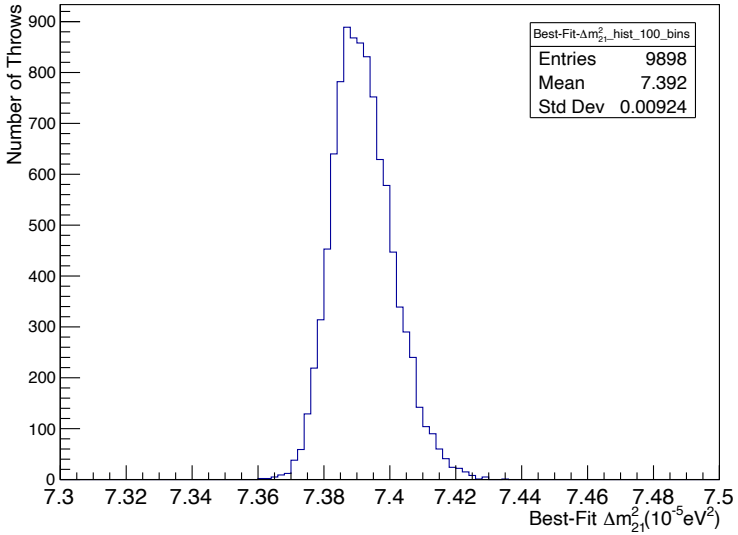
Solar Parameters and $\bar{\nu}_e$ Detections

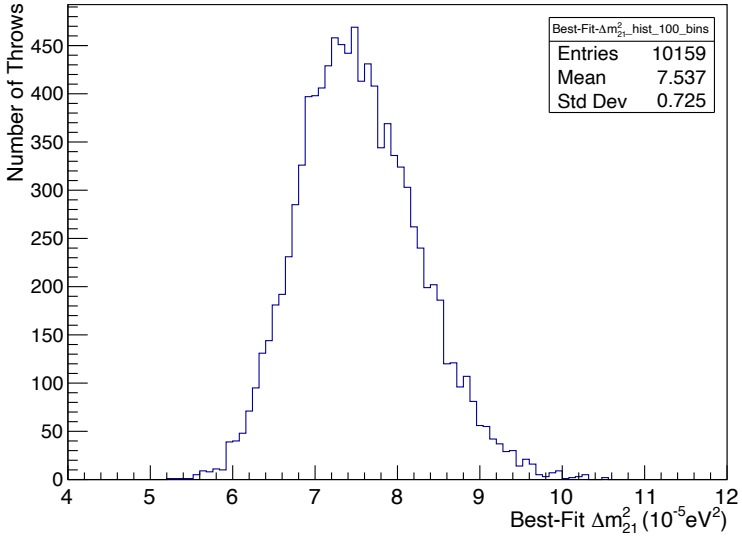




- Biggest effect in lower energy ranges (0-1GeV & 2-4GeV)

TDR Simulations – Unconstraining the Parameters





Constrained
Penalty: 2%

→

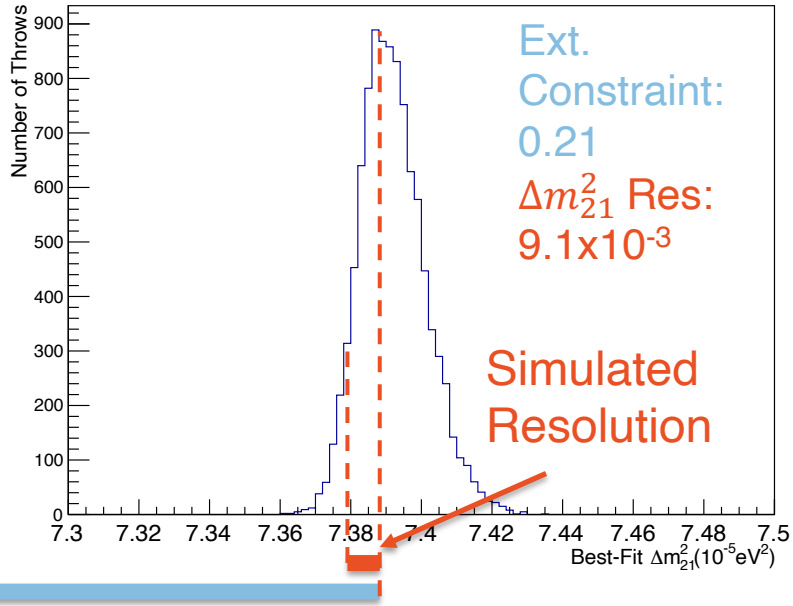
Unconstrained
Penalty: 20%

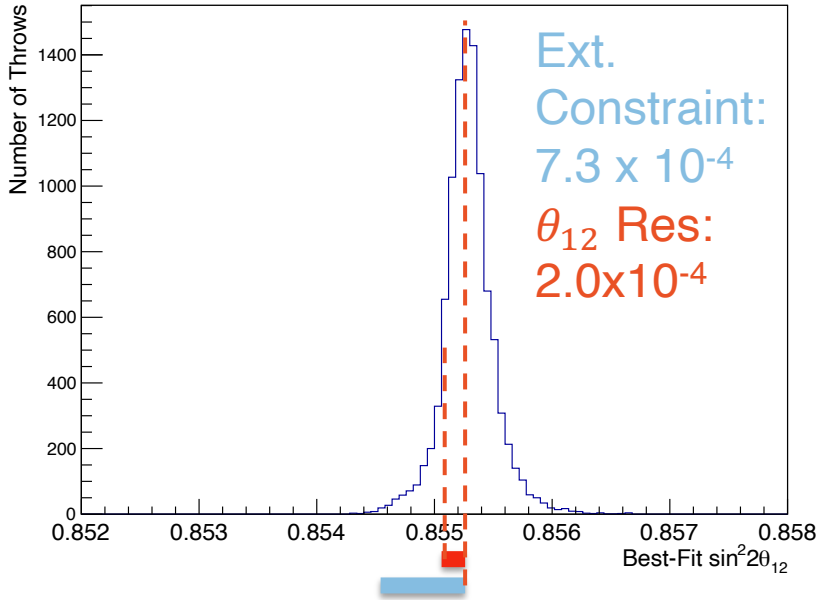
- Fixed true values
- Varied Best-Fit values

Solar Parameter Sensitivity - Constrained

- Simulated Resolutions are higher than External Constraint (nominal∗penalty)
  - 23x more resolute for Δm^2_{21}
  - 4x more resolute for θ_{12}
- Two Possibilities:
  - Measurement Driven
  - Inconsequential

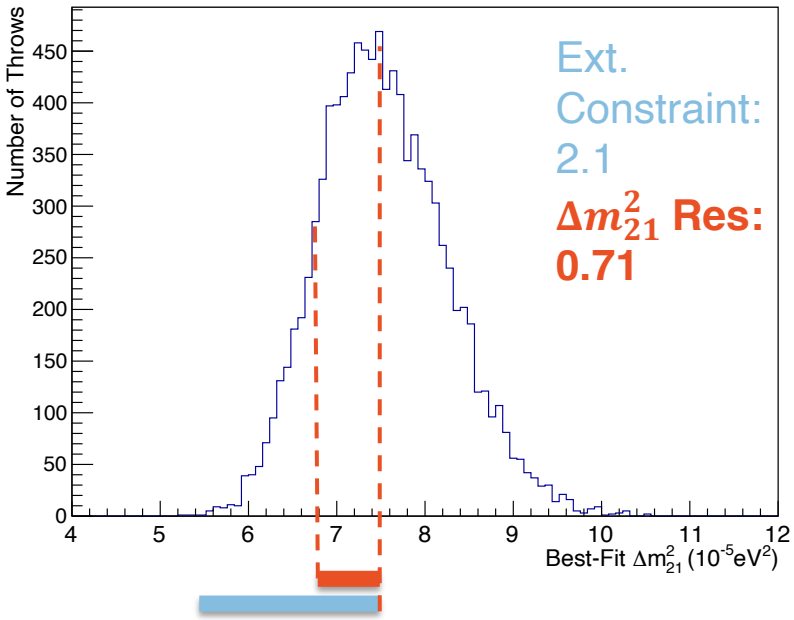
External Constraint

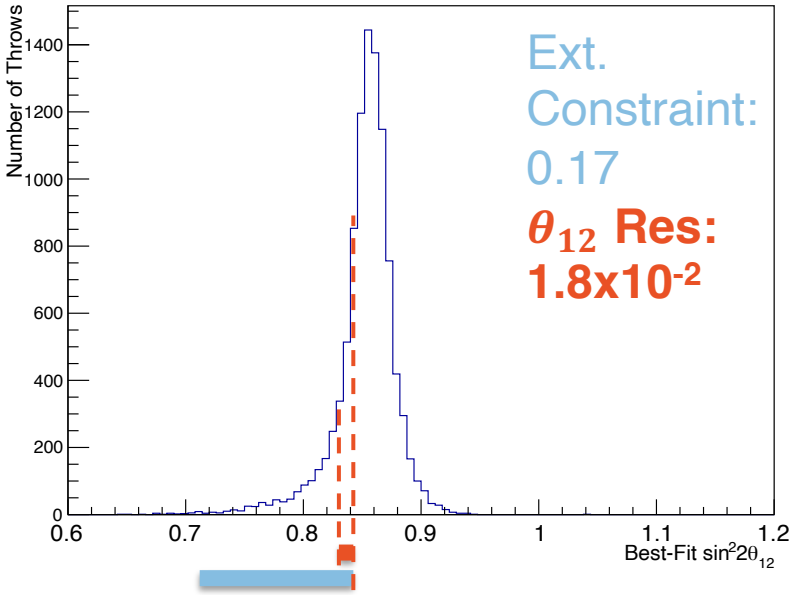




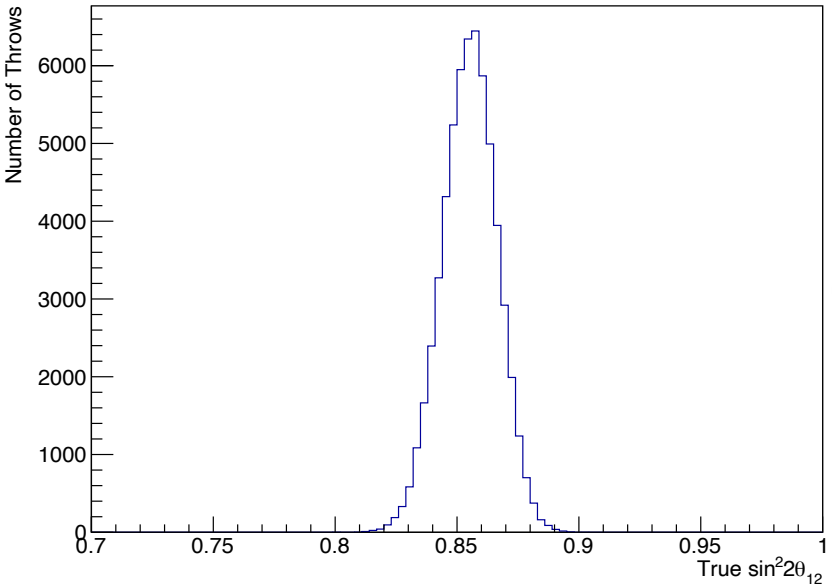
Solar Parameter Sensitivity - Unconstrained

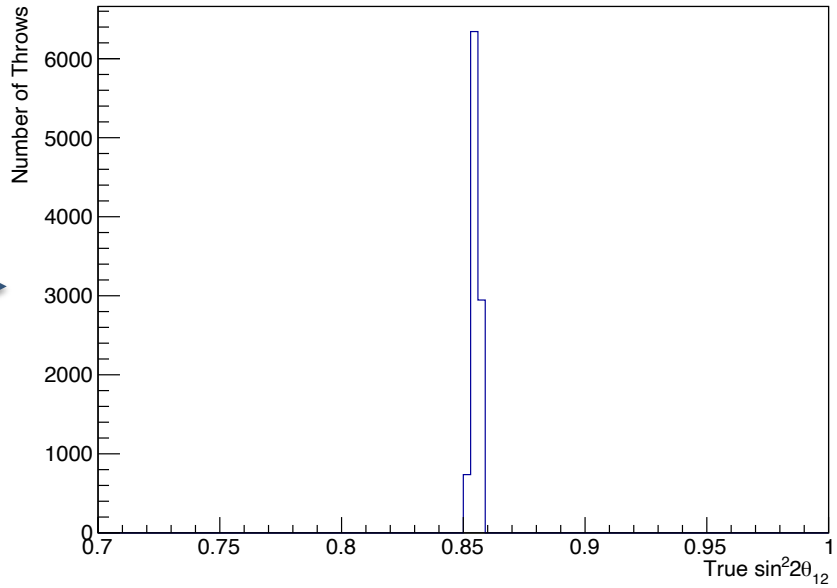
- Simulated Resolutions are still higher than the External Constraint
  - 3x more resolute for Δm^2_{21}
  - 10x more resolute for θ_{12}
- **Inconsequential**
  - Different Resolutions between constrained and unconstrained
    - Solar parameters are ultra sensitive to penalty
- **Solar Parameter's can't be measured in DUNE**





“Fixing” True θ_{12}





~60,000 experiments

~10,000 experiments

- Chopped off widely varying true values until the number of throws was close to the number of throws in the unconstrained simulations
- “Fixing” True θ_{12} worsened δ_{CP} resolution

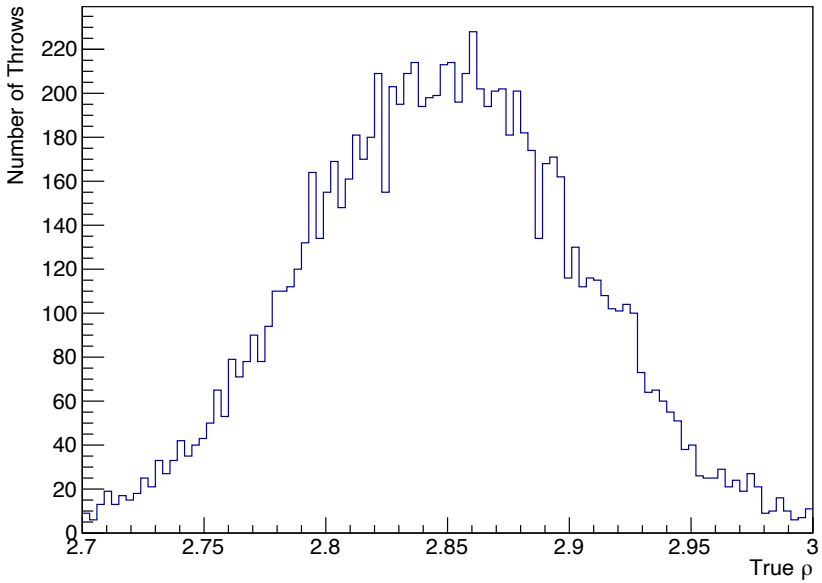
Sensitivity of Other Oscillation Parameters (Fixed True θ_{12})

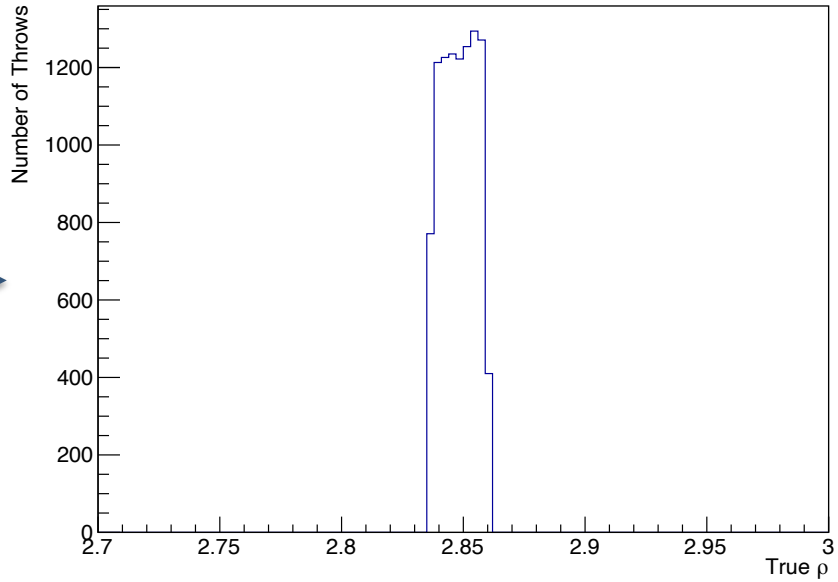
Oscillation Parameter Resolutions	δ_{CP} (π)	$\sin\theta_{23}$	θ_{13}	Δm^2_{32} (10^{-3} eV^2)
Constrained Parameters	0.120	0.0120	0.00561	0.0235
θ_{12} Unconstrained	0.117 (-2.3%)	0.0116 (-2.7%)	0.00548 (-2.3%)	0.0232 (-1.32%)
Δm^2_{21} Unconstrained	0.117 (-2.2%)	0.0117 (-2.4%)	0.00560 (-0.068%)	0.0235 (-0.044%)
Both Unconstrained	0.117 (-2.2%)	0.0116 (-2.5%)	0.00562 (0.213%)	0.0236 (0.33%)

Table 1: Table containing of all the non-solar oscillation parameters in simulations with different constrained and unconstrained solar parameters. Constrained parameters have a penalty value at 2%, and the unconstrained parameters have a penalty at 20%. The percentages in the parentheses are the percent differences from the constrained resolution value of that parameter.

- Virtually no effect on resolutions
  - % Differences ~2%
- **Slight* improvement in δ_{CP}, θ_{23}
  - Added "wiggle room" in the fitter
  - Constrained data had varying true θ_{12} and ρ while unconstrained simulations had all fixed true values

“Fixing” True ρ



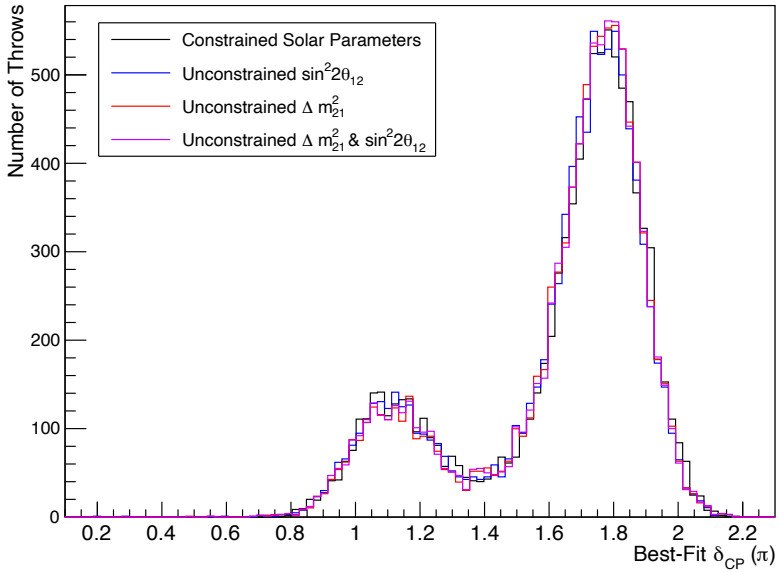


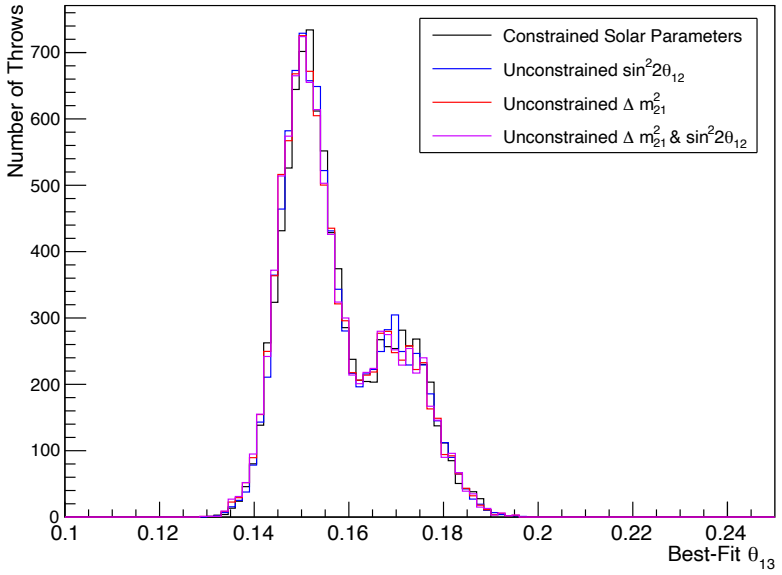
~60,000 experiments

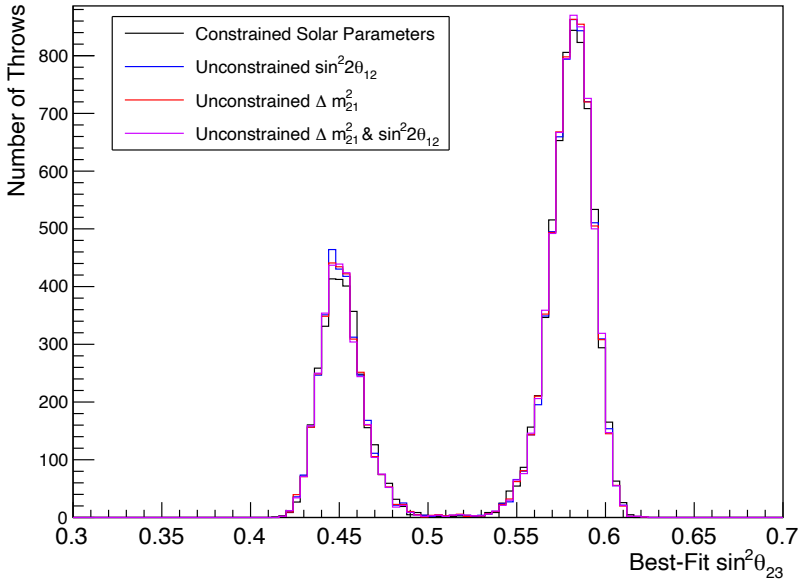
~10,000 experiments

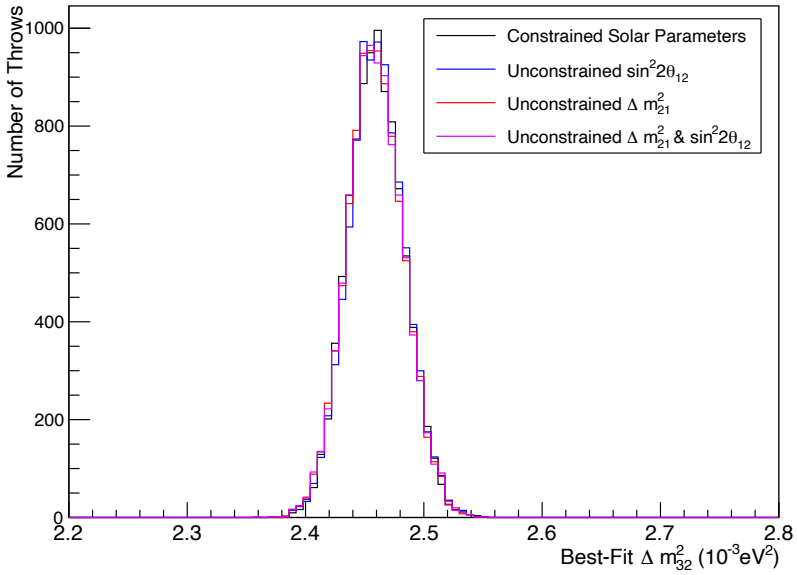
- Fixing true ρ causes resolutions to improve and eliminates the “slight” improvement of δ_{CP} resolution

Other Osc. Parameter Plots









Sunset for Solar Parameters…

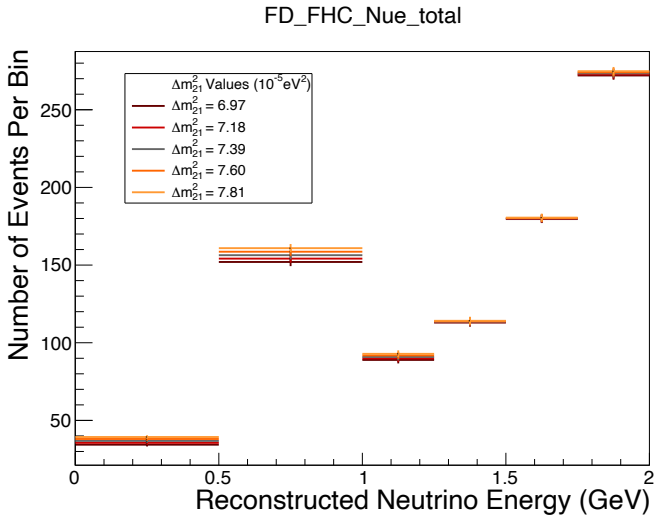
- Varying the solar parameters lead to/are:
  - Largely unaffected ν_e detections
    - Most influential in the lower energy range
  - Largely inconsequential to neutrino oscillation parameters
    - No benefit in measuring solar parameters
    - Unaffected measurements of other oscillation parameters
- What does this mean for DUNE?
  - We can continue to use the world-accepted values of the solar parameters as we continue to prepare for DUNE's operation
  - Sunset the solar parameters

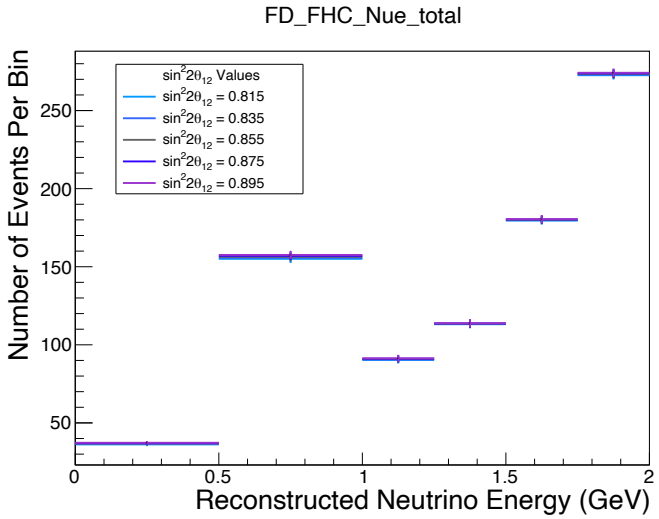
Extra Avenues of the Solar Parameters

- There's a few things left to explore

Explore DUNE's Efficiency @ Lower Energies

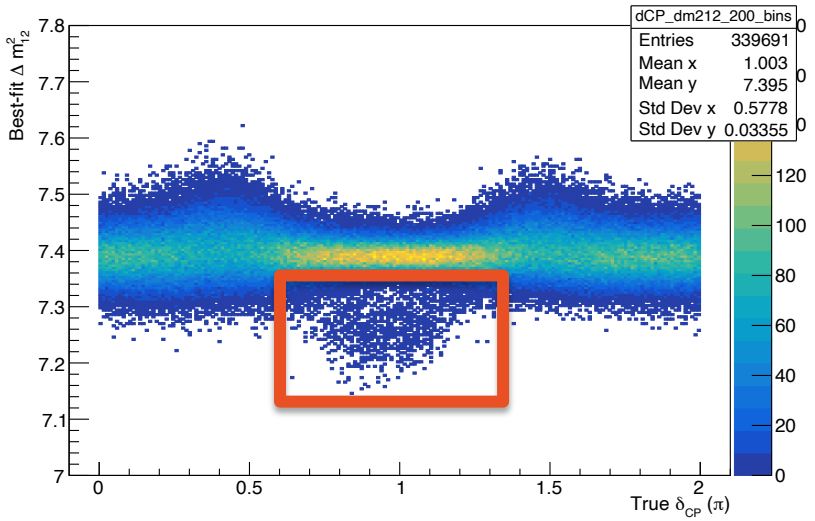
- Create more bins between 0-1GeV
  - How does neutrino variation develop within the 0-1 GeV range?
- Improve DUNE efficiency
  - If we were able to improve DUNE's efficiency in lower energy ranges, how would that affect ν_e detections?
  - **Provide outlook on potential benefits of future upgrades on DUNE**

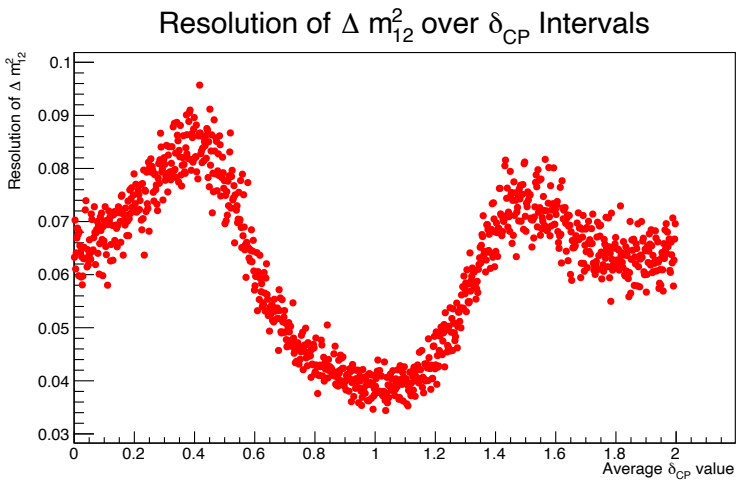




Simulation Anomaly

- Simulation: `final_np_15yr.root`
  - `(Directory: /pnfs/dune/persistent/users/LBL_TDR/throws_v4/ )`
- Explore “flares”
  - Compare these experiments with other parameters





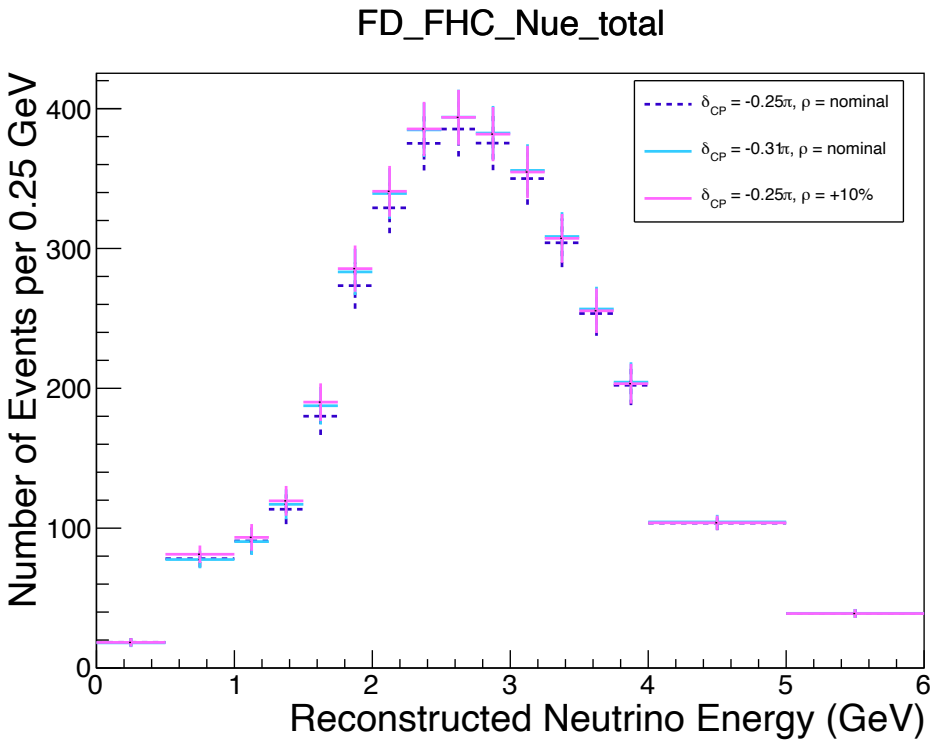
Part 2 – Earth Matter Density ν_e Spectra

Looking into Earth Matter Density, ρ and ν_e Spectra

- Last meeting, Baker showed relationship between δ_{CP} and ρ
  - Seeing the effects on ν_e spectra was brought up
- With already developed CAFANA code, I repurposed the simulation to allow for varying ρ
  - Varied ρ and δ_{CP}
  - Found ratio of ρ & δ_{CP} “pairs”

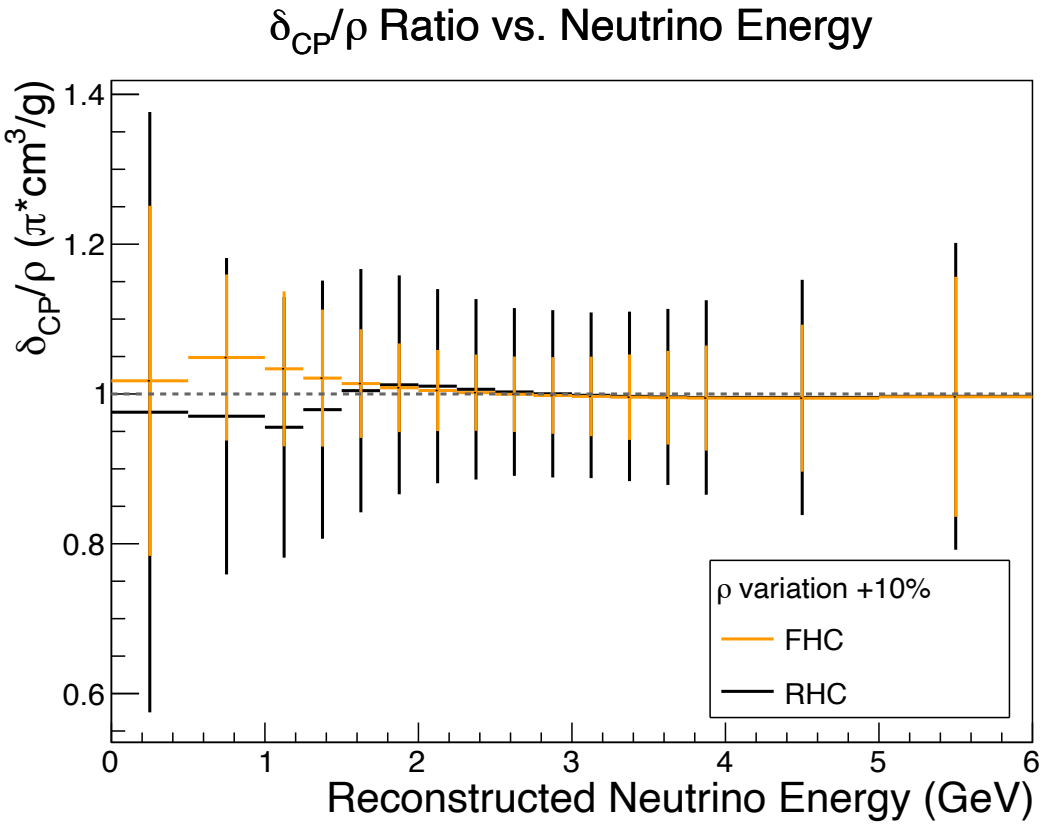
Varying ρ & δ_{CP}

- Baseline parameter values:
  - $\rho = \rho_{nom} = 2.848$ g/cm^3
  - $\delta_{CP} = -0.25\pi$
- Varied ρ by percentage of nominal value
  - $+10\%\ \rho = \rho_{nom} + 0.10(\rho_{nom})$
  - Varied ρ by +10%, +20%, +30%
  - $\delta_{CP} = -0.25\pi$ (fixed)
- Varied δ_{CP} until the first oscillation maximum peak matched with varying ρ spectra
  - $\rho = \rho_{nom}$ (fixed)
  - δ_{CP} & ρ "pairings" (different δ_{CP} for FHC and RHC)

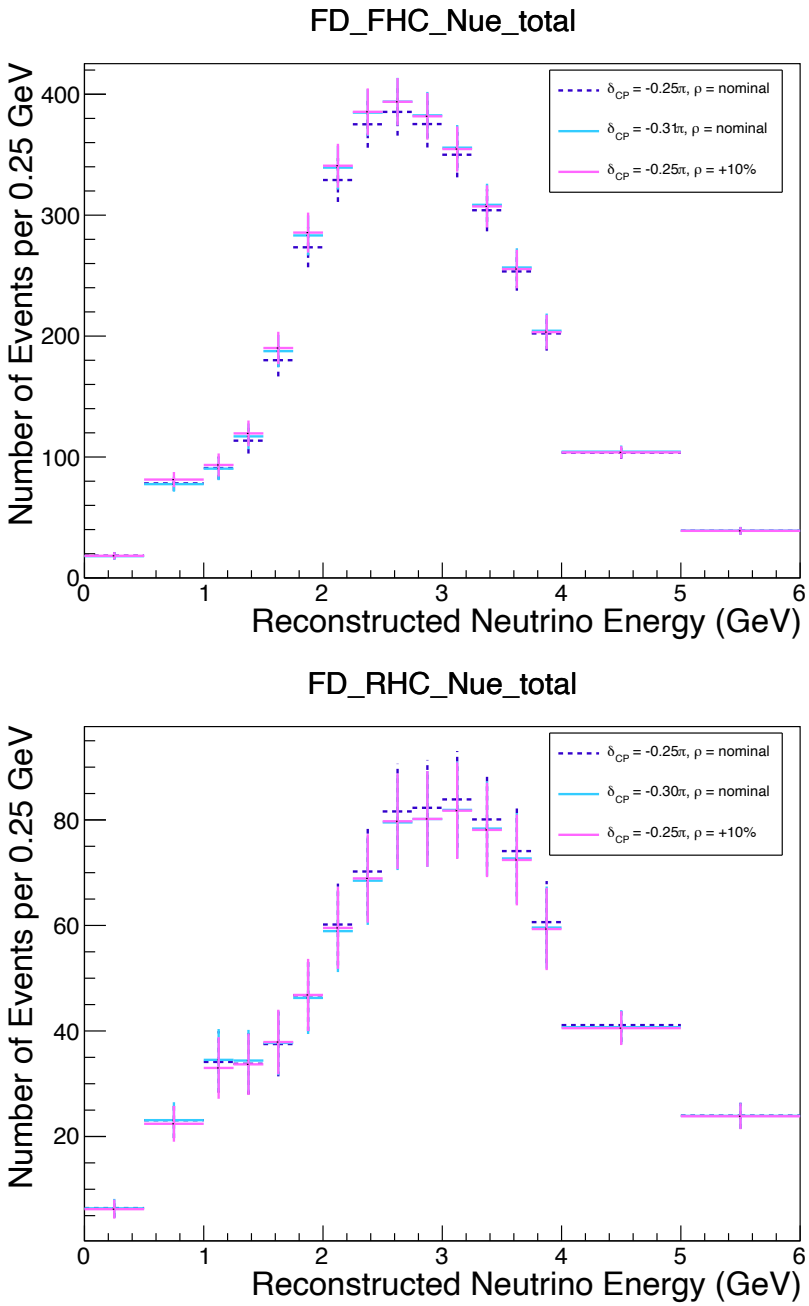


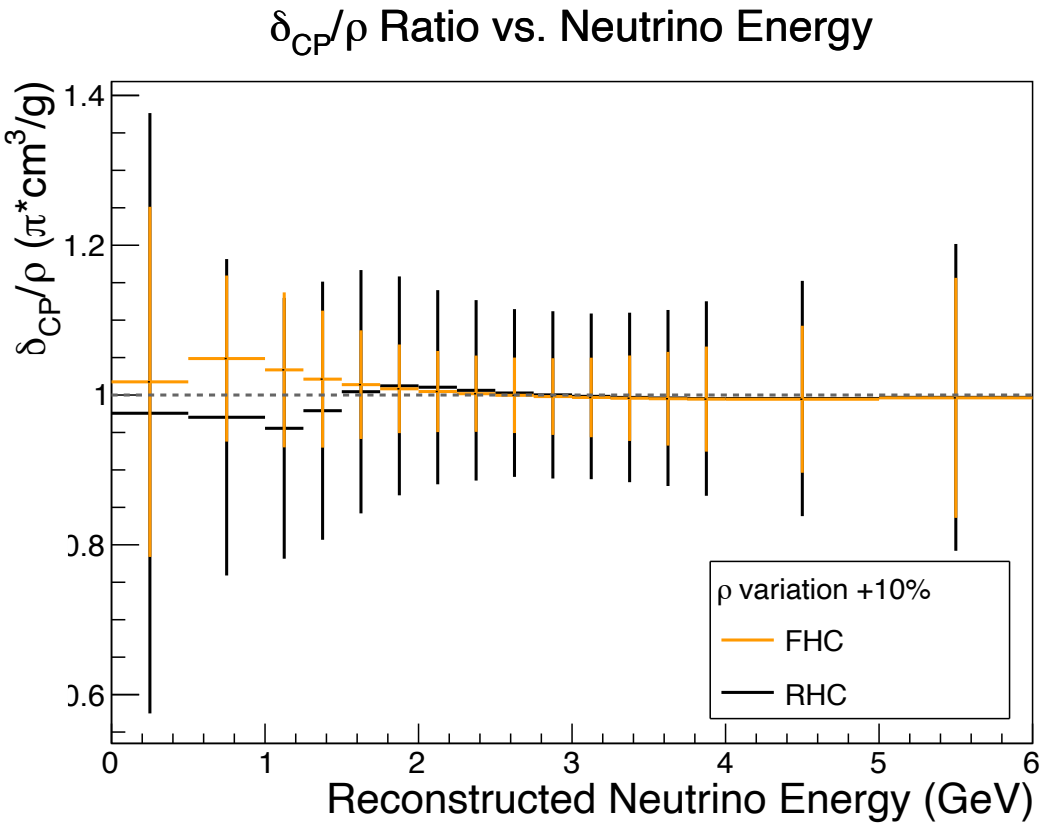
δ_{CP}/ρ Ratio Plots

- For each varied rho spectra, we plotted the δ_{CP}/ρ ratio for each bin
  - Plotted both FHC & RHC

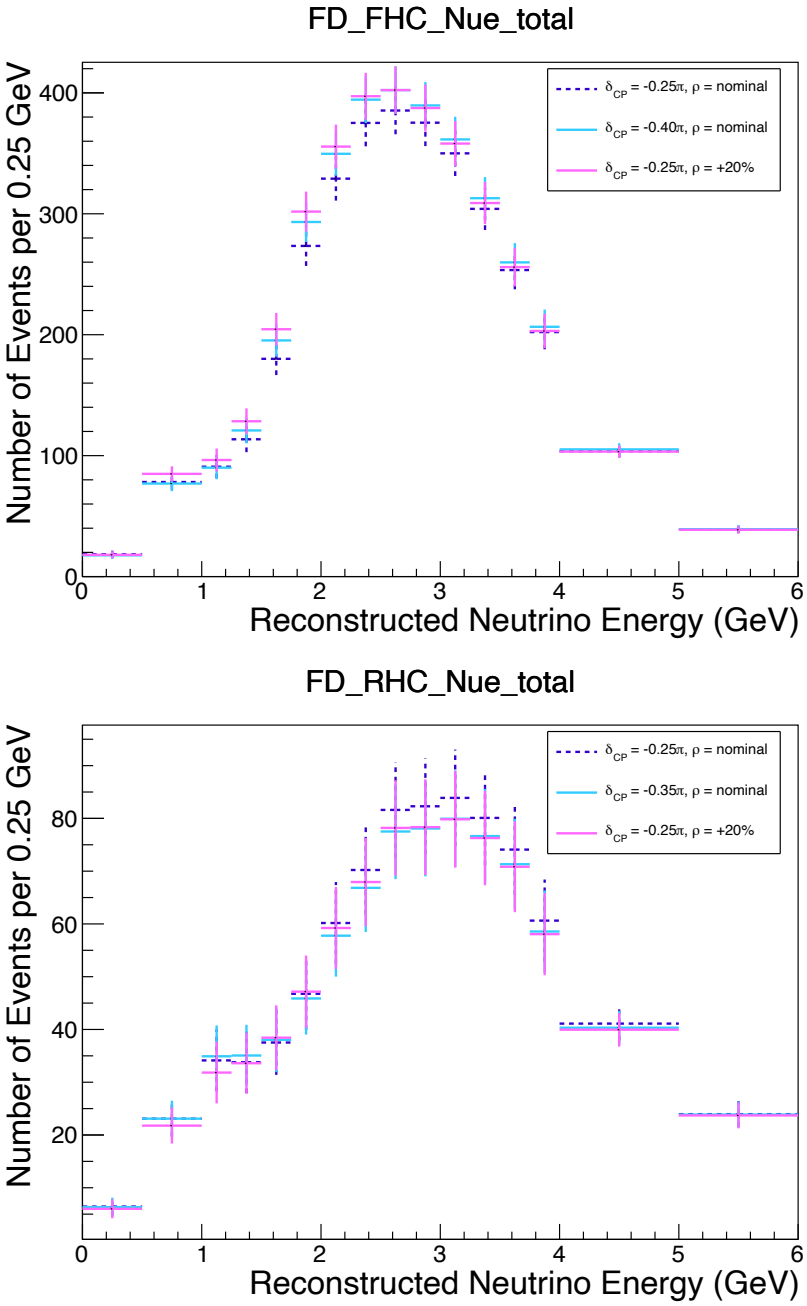


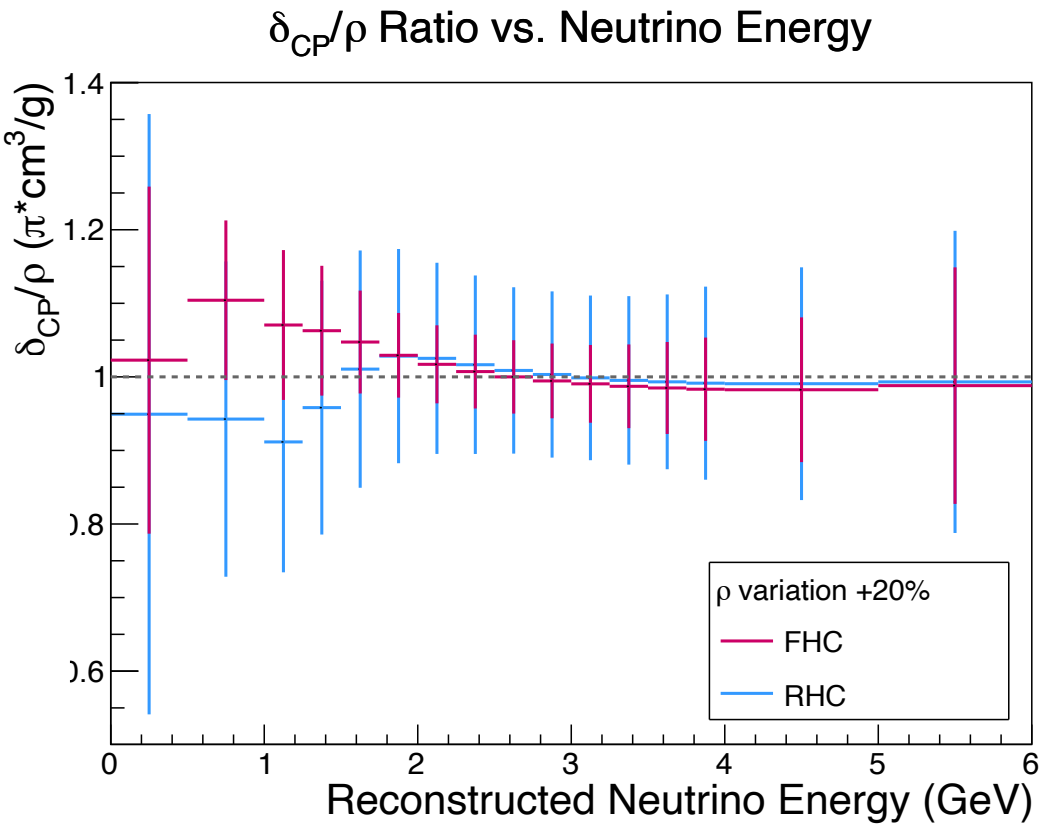
+10% ρ Plots


FD_FHC_Nue_total
Number of Events per 0.25 GeV
Reconstructed Neutrino Energy (GeV)
δCP = -0.25π, ρ = nominal
δCP = -0.31π, ρ = nominal
δCP = -0.25π, ρ = +10%
FD_RHC_Nue_total
Number of Events per 0.25 GeV
Reconstructed Neutrino Energy (GeV)
δCP = -0.25π, ρ = nominal
δCP = -0.30π, ρ = nominal
δCP = -0.25π, ρ = +10%

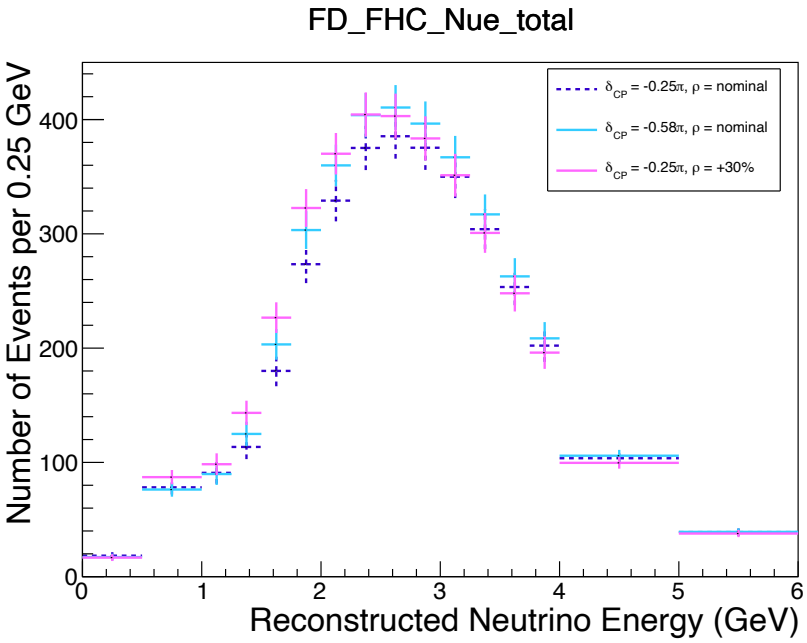

δCP/ρ Ratio vs. Neutrino Energy
δCP/ρ (π*cm3/g)
Reconstructed Neutrino Energy (GeV)
ρ variation +10%
FHC
RHC

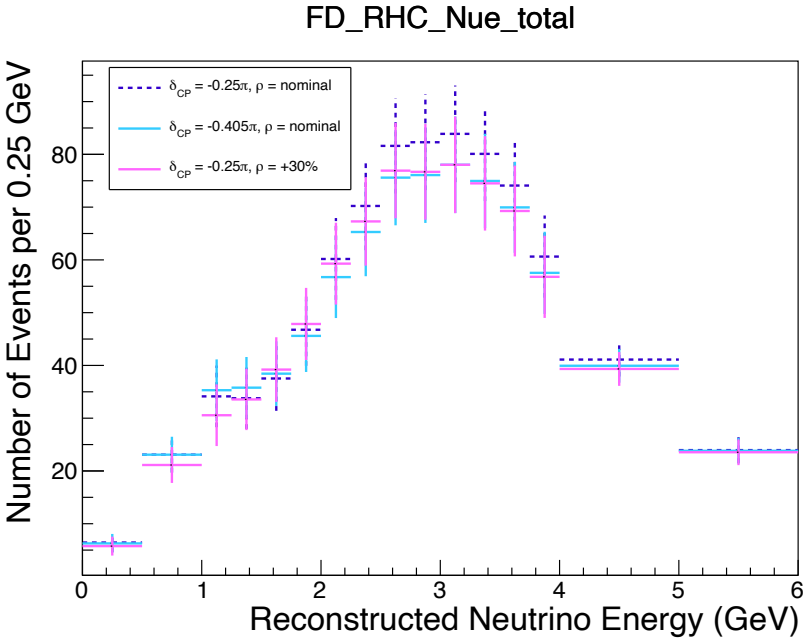
+20% ρ Plots

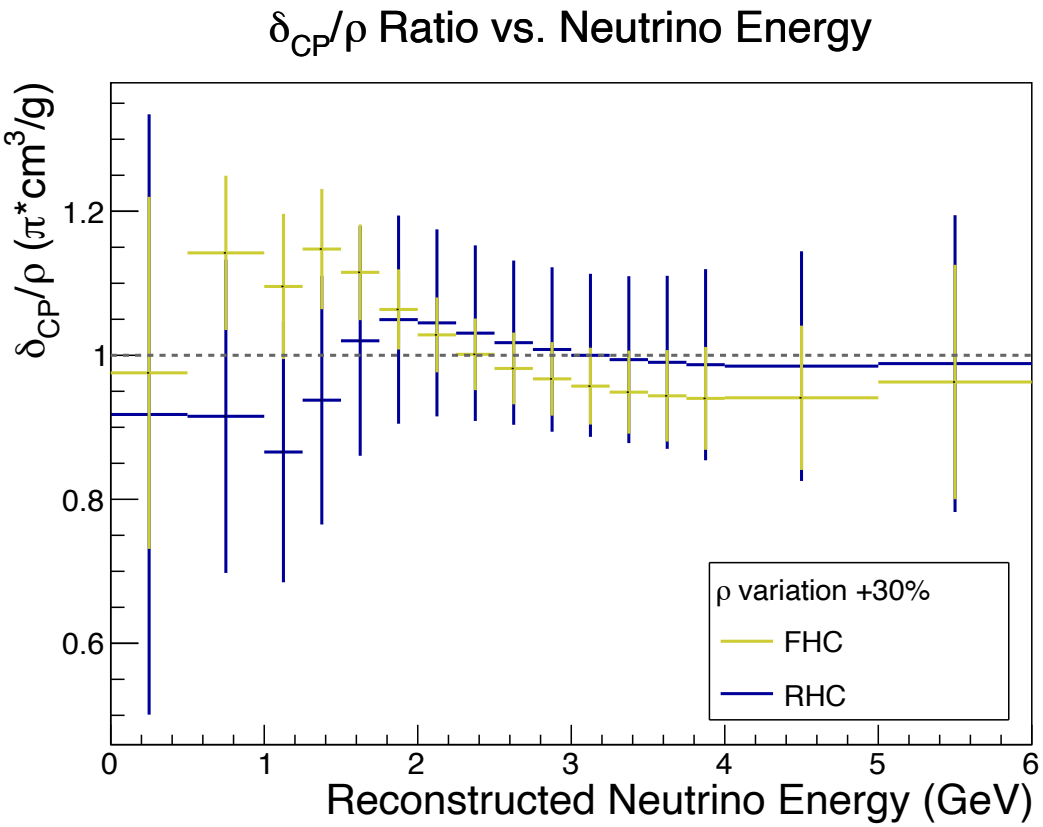

FD_FHC_Nue_total
Number of Events per 0.25 GeV
Reconstructed Neutrino Energy (GeV)
δCP = -0.25π, ρ = nominal
δCP = -0.40π, ρ = nominal
δCP = -0.25π, ρ = +20%
FD_RHC_Nue_total
Number of Events per 0.25 GeV
Reconstructed Neutrino Energy (GeV)
δCP = -0.25π, ρ = nominal
δCP = -0.35π, ρ = nominal
δCP = -0.25π, ρ = +20%


δCP/ρ Ratio vs. Neutrino Energy
δCP/ρ (π*cm3/g)
Reconstructed Neutrino Energy (GeV)
ρ variation +20%
FHC
RHC

+30% ρ Plots


FD_FHC_Nue_total
δ_{CP} = -0.25π, ρ = nominal
δ_{CP} = -0.58π, ρ = nominal
δ_{CP} = -0.25π, ρ = +30%
Number of Events per 0.25 GeV
Reconstructed Neutrino Energy (GeV)


FD_RHC_Nue_total
δ_{CP} = -0.25π, ρ = nominal
δ_{CP} = -0.405π, ρ = nominal
δ_{CP} = -0.25π, ρ = +30%
Number of Events per 0.25 GeV
Reconstructed Neutrino Energy (GeV)

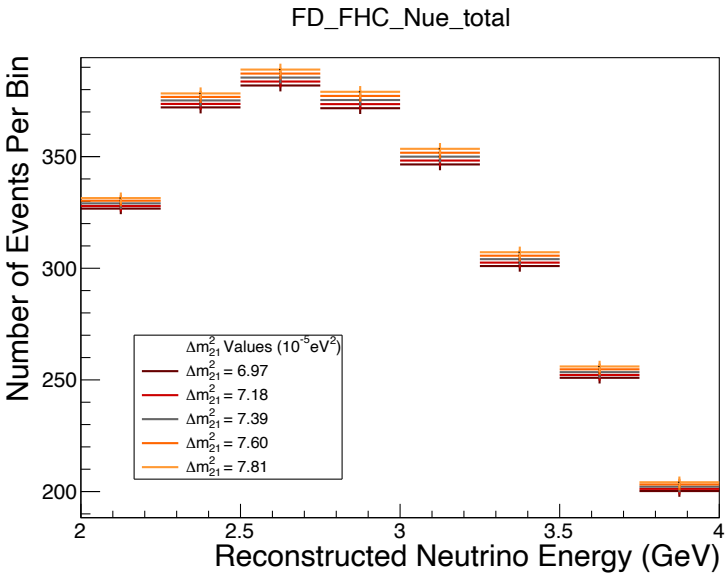

δ_{CP}/ρ Ratio vs. Neutrino Energy
δ_{CP}/ρ (π*cm^3/g)
ρ variation +30%
FHC
RHC
Reconstructed Neutrino Energy (GeV)

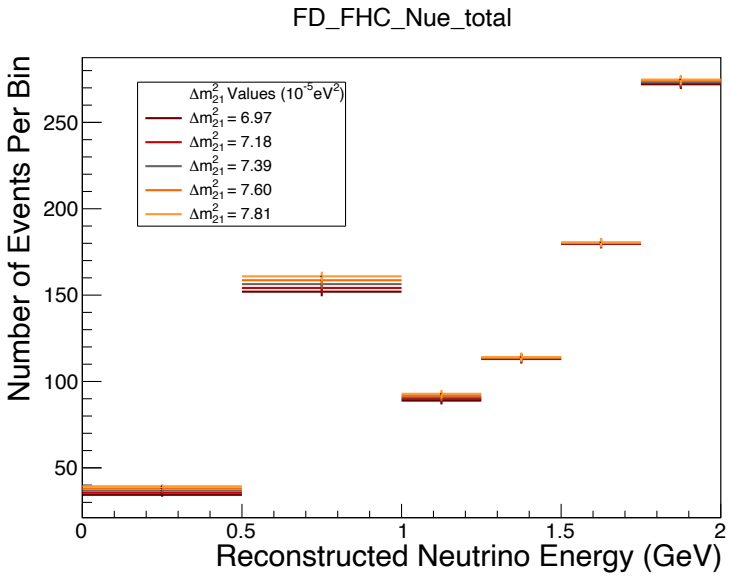
Summary

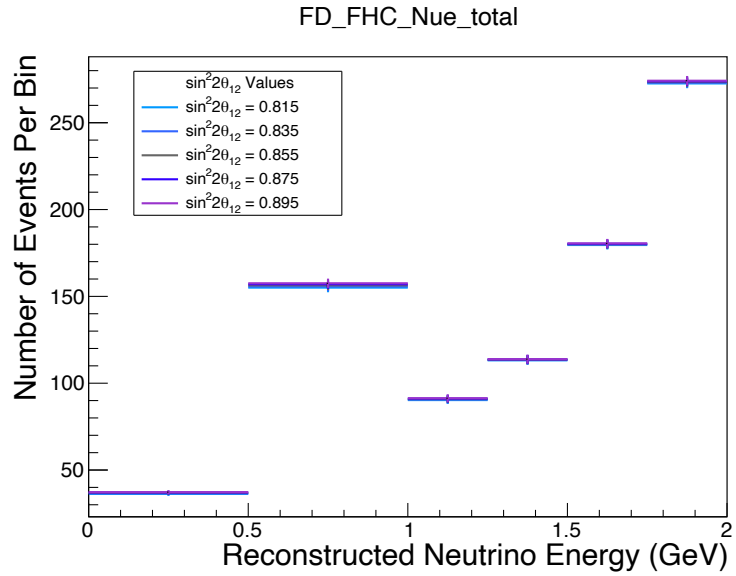
- Solar parameters have little to no impact within DUNE
  - Potential Avenues:
    - Exploring the Lower energy Range of ν_e detections with varying solar parameters
      - Potentially provide outlook on potential benefits of future upgrades on DUNE
    - Exploring the weird behavior with δ_{CP}
      - Compare these experiments with other parameters
- Spectra reaffirms the similarity of ρ's and δ_{CP}'s effects on the first oscillation maximum for ν_e & $\bar{\nu}_e$ detections

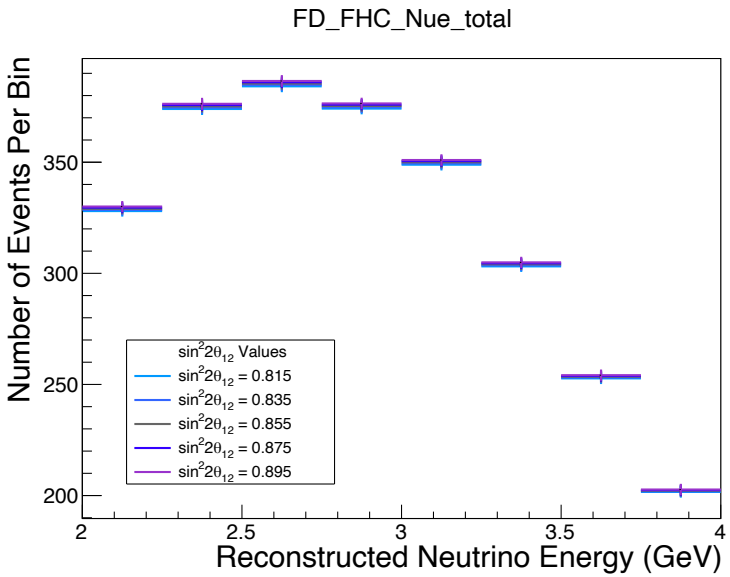
Backup Slides

ν_e Detections Continued…

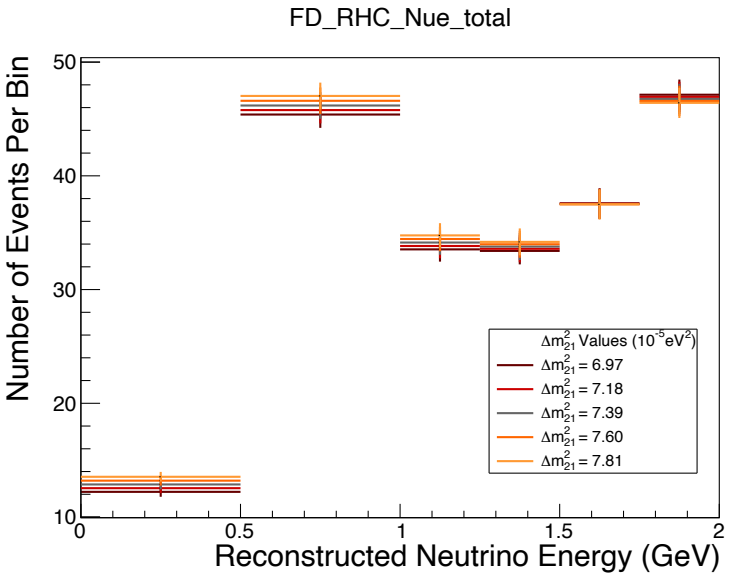


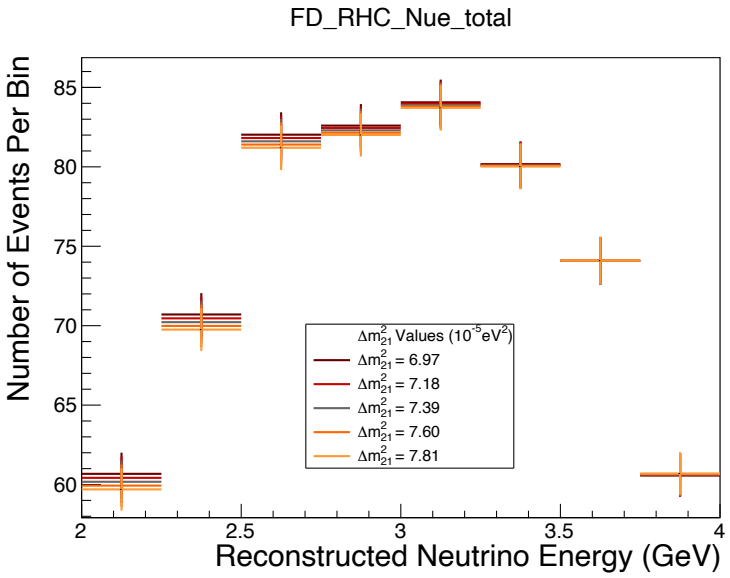


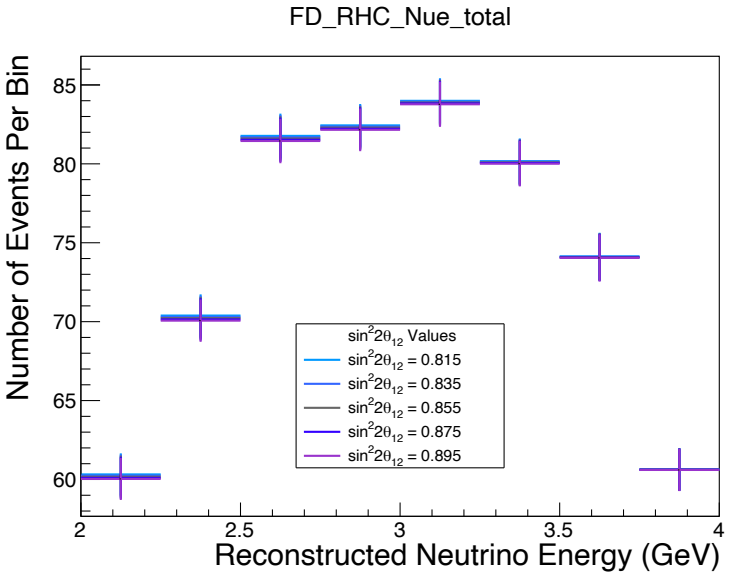


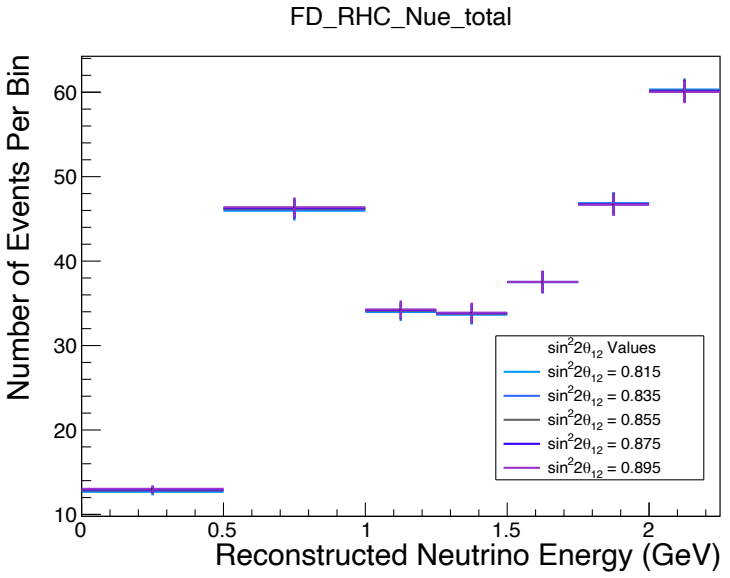


$\bar{\nu}_e$ Detections Continued…









ρ Variation values:

	per	Rho Values
-4.00%	-0.04	2.734
-2.00%	-0.02	2.791
-1.00%	-0.01	2.820
0.00%	0	2.848
1.00%	0.01	2.876
2.00%	0.02	2.905
4.00%	0.04	2.962
rho value		
2.848		
	per (by10%)	Rho Values
-50.00%	-0.5	1.424
-40.00%	-0.4	1.709
-30.00%	-0.3	1.994
-20.00%	-0.2	2.278
-10.00%	-0.1	2.563
0.00%	0	2.848
10.00%	0.1	3.133
20.00%	0.2	3.418
30.00%	0.3	3.702
40.00%	0.4	3.987
50.00%	0.5	4.272