How well do we need to know detector parameters for supernova neutrinos?

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DUNE Calibration Task Force Meeting

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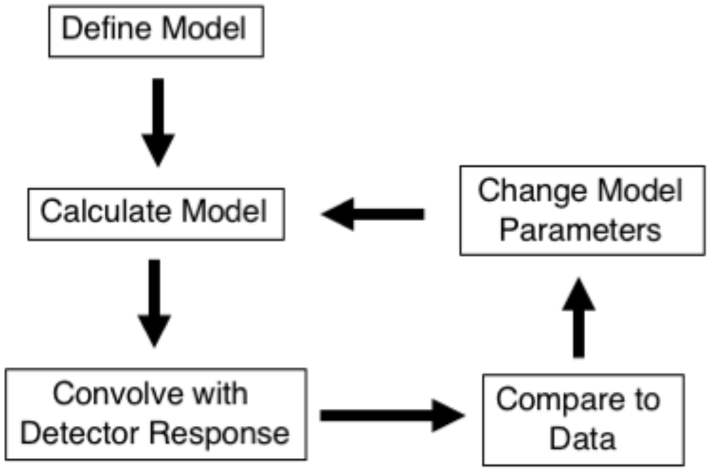
Outline

- Introduction
  - Forward fitting
  - Supernova flux model
- Forward fitting studies
  - Energy resolution
  - Energy scale
  - Energy shift
  - Cross section
- Takeaways + Next Steps

Forward Fitting: Introduction

- Goal: provide information about DUNE's ability to constrain pinched-thermal model parameters
- For the purposes of this study:
  - Model: pinched-thermal flux
  - Detector response: Gaussian smearing
  - Data: SNOwGLoBES smeared event rates



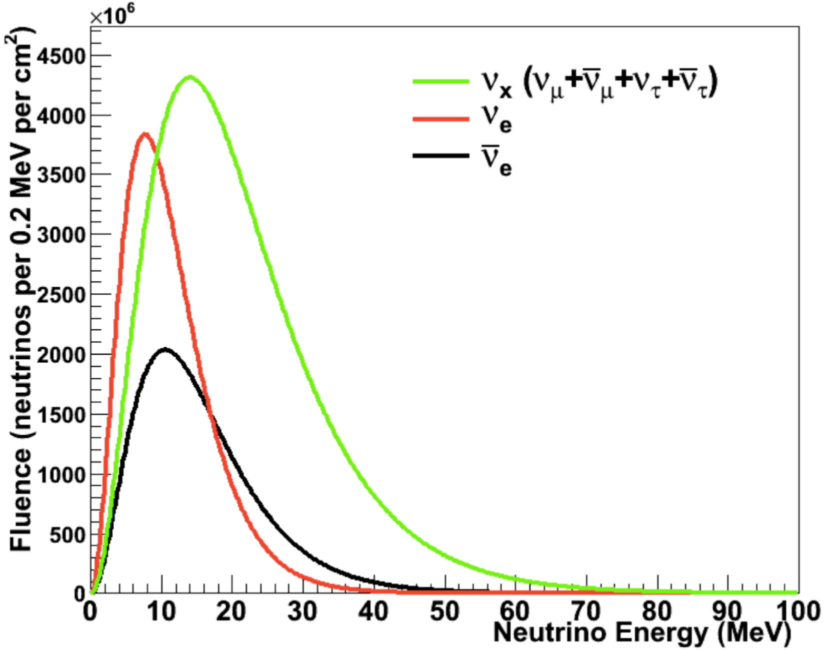
Forward Fitting Schematic

Supernova Flux Model

- Supernova neutrino spectrum AKA "pinched-thermal form":

$$\phi(E_\nu) = \mathcal{N}\left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^\alpha \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu\rangle}\right]$$

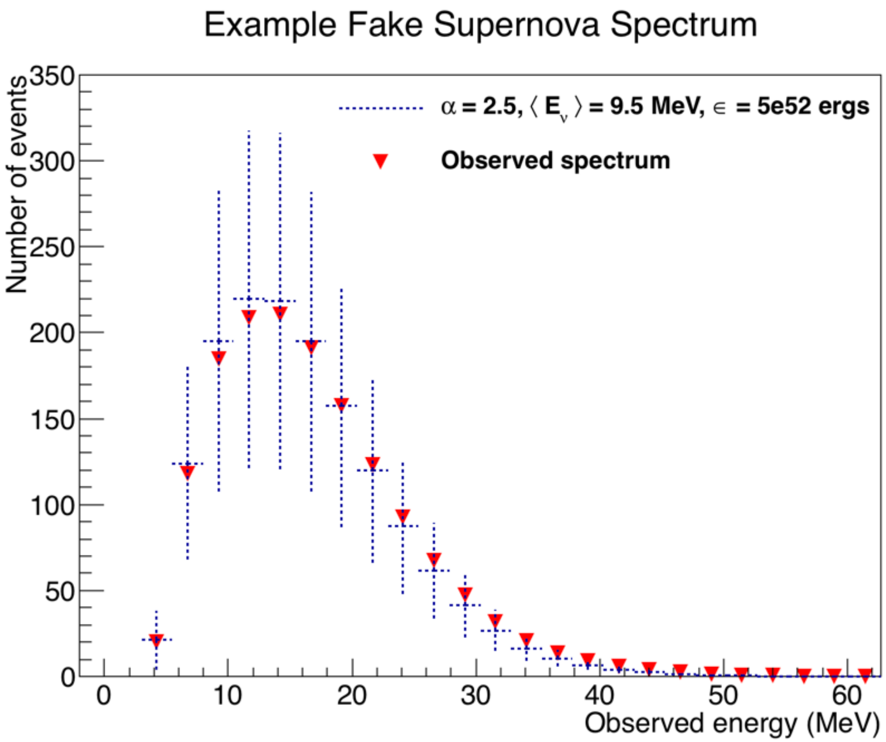
  - E_ν: Neutrino energy
  - $\mathcal{N}$: Normalization constant (related to luminosity, ϵ)
  - $\langle E_\nu\rangle$: Mean neutrino energy
  - α: Pinching parameter; large α corresponds to more pinched spectrum
- Parameters of interest: ϵ, $\langle E_\nu\rangle$, α
- Supernova neutrinos expected to contain information about parameters



Energy spectra for a SN 10kpc from Earth (K. Scholberg)
Note: Fluence refers to a time-integrated flux.

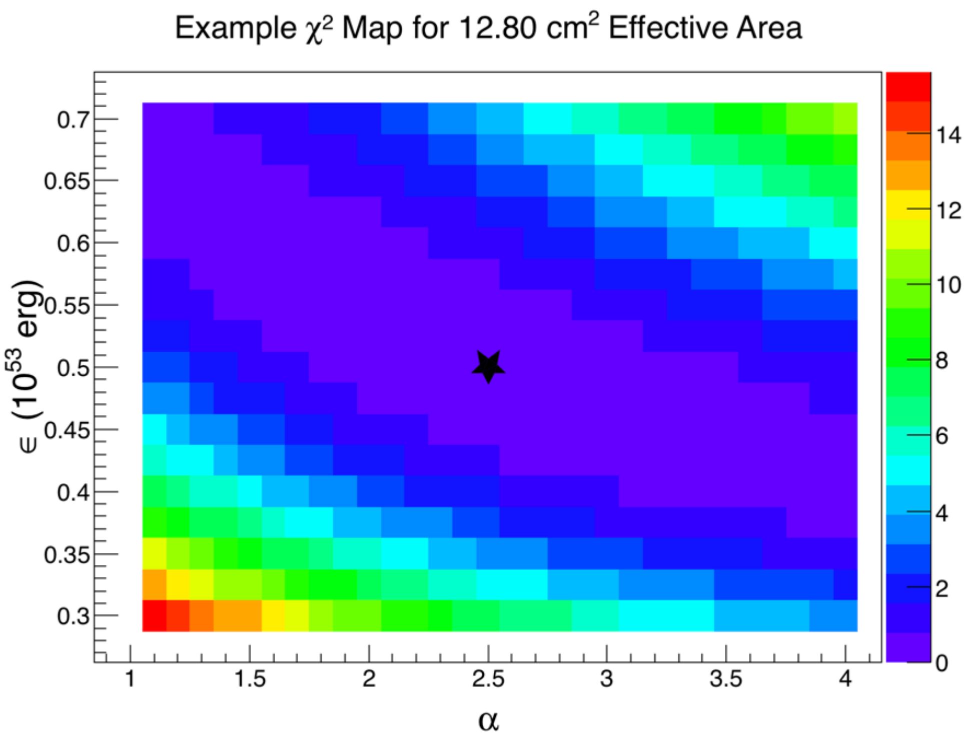
Forwarding Fitting Tools

- χ^2 minimization for supernova energy spectra – how well do we know the parameters?
- Study uses the following tools:
  - "Test spectra" corresponding to supernova event rates in DUNE detector with given set of pinching parameters $(\alpha^0, \langle E_\nu \rangle^0, \varepsilon^0)$
  - Grid of test spectra containing combinations of $(\alpha, \langle E_\nu \rangle, \varepsilon)$



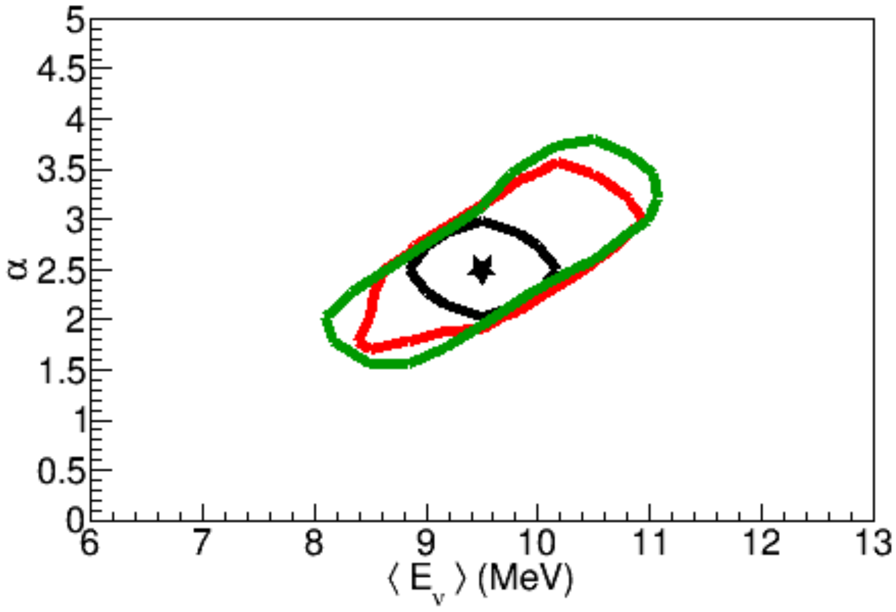
Forward Fitting: "Sensitivity"

- Use SNOwGLoBES to generate binned energy spectra for a given set of pinched-thermal parameters $(\alpha^0, \langle E_\nu \rangle^0, \varepsilon^0) \rightarrow$ "test spectra"
- Determine χ^2 values for all elements in grid containing combinations of $(\alpha,\ \langle E_\nu \rangle,\ \varepsilon)$
- Minimize χ^2 while profiling over 1 or 2 model parameters



Figures of Merit

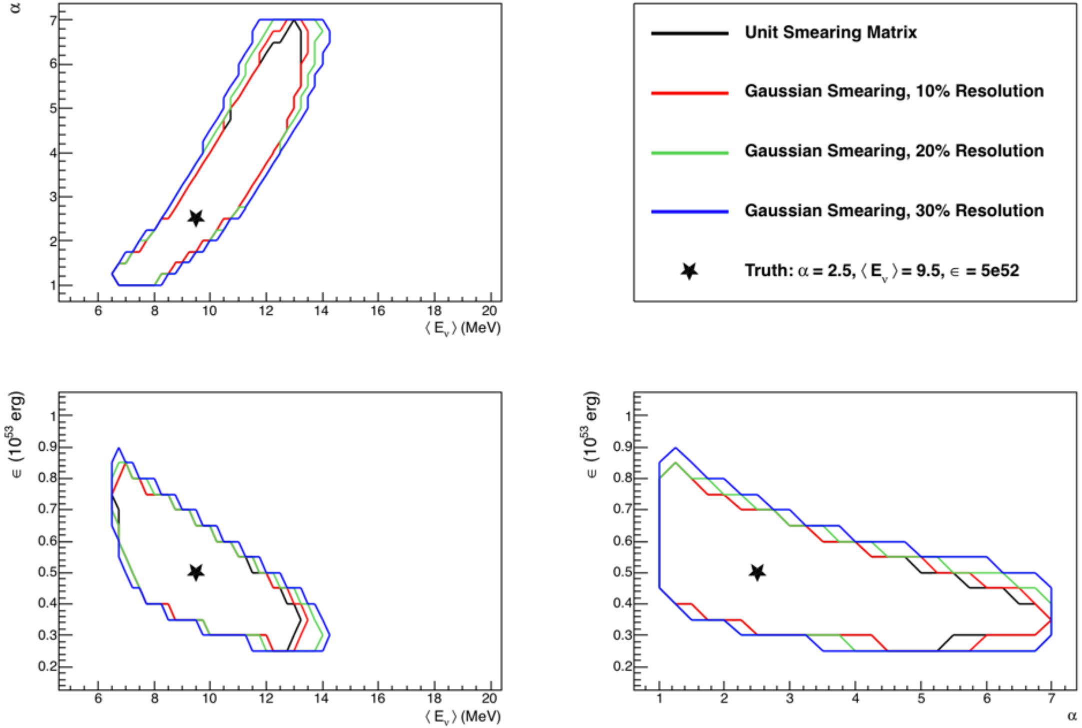
- Overall summary "figure of merit": area of 90% regions
  - Quantification on how well DUNE constrains spectral parameters
- Another figure of merit: best-fit parameter fractional difference from truth
- 2D plots of effective area vs. distance; put different figures of merit on z-axis

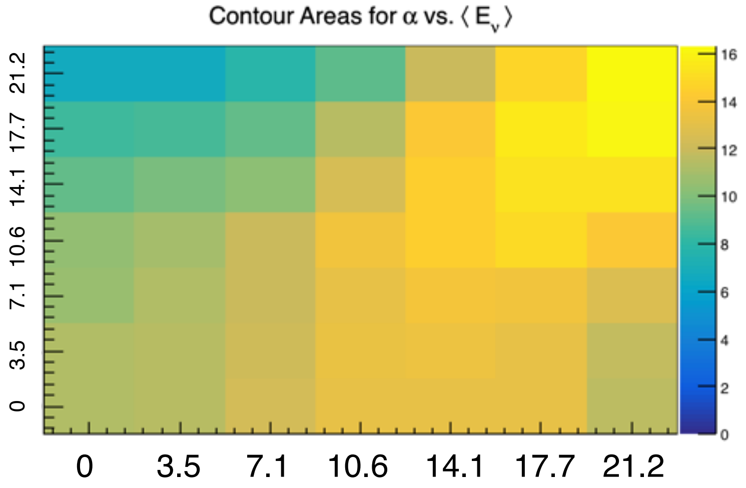


How well do we have to know the energy resolution?

Energy Resolution: Introduction

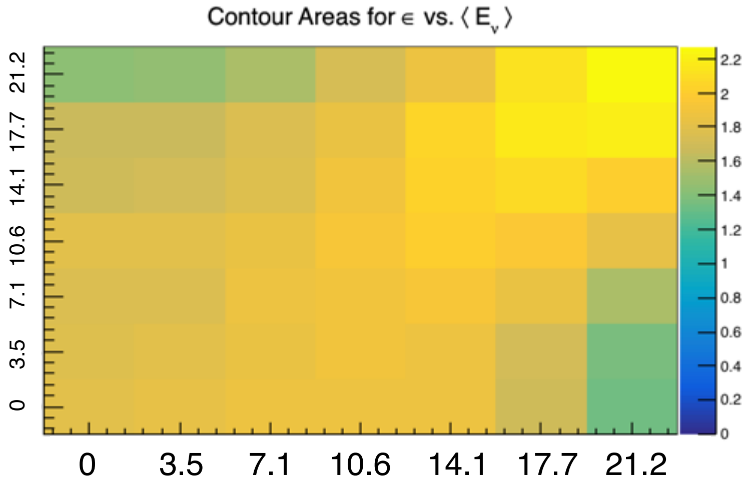
- Initiated study to determine how smearing affects forward fitting – what if our resolution assumptions are incorrect?
- Performed sensitivity study for every combination of Gaussian resolution in grid, test spectra
- Note: due to bug, resolutions off by factor of $\sqrt{2}$ (hence the strange resolution values)

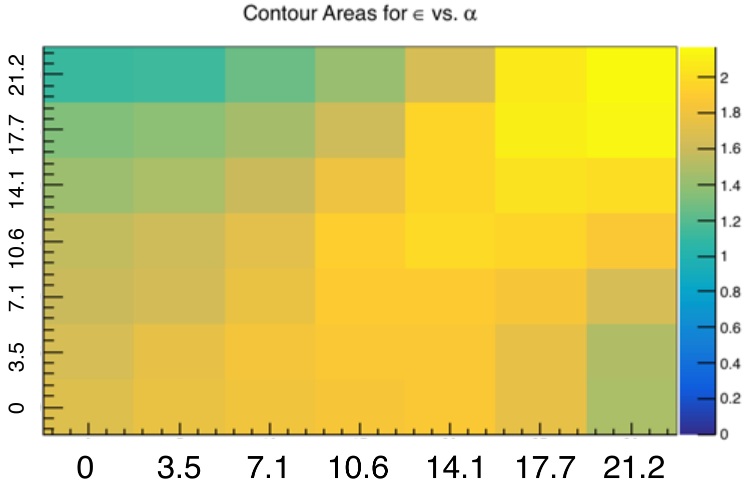




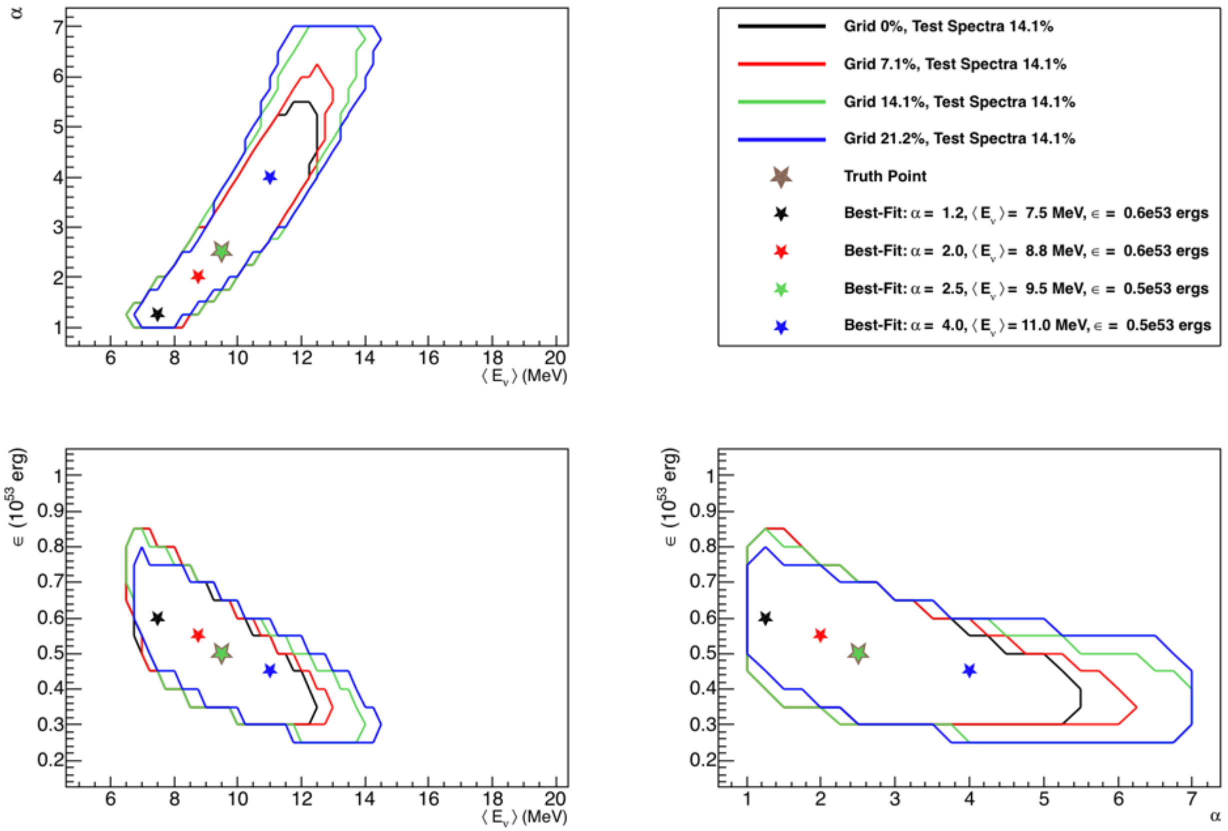
2D Contour Area Plot

- X-axis: Grid resolution
- Y-axis: Test spectra resolution
- Areas get larger as resolution increases (expected)
- Areas get smaller in extreme "corners" where test spectra's resolution is at one extreme and the smearing is at the other extreme



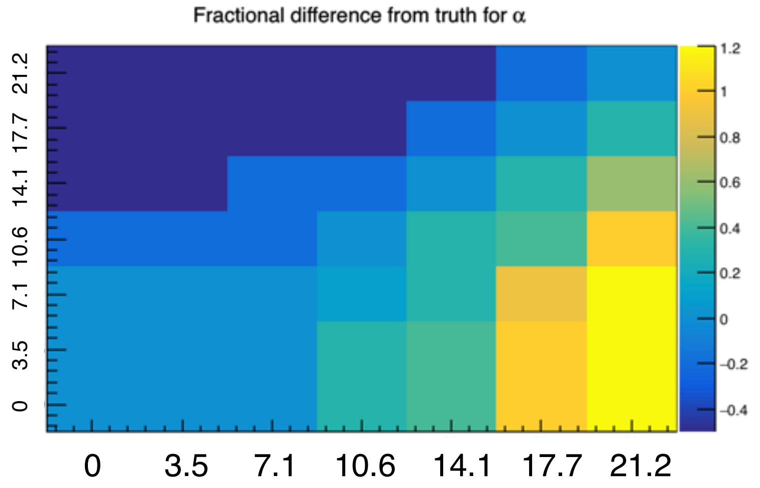


Sensitivity Regions Example



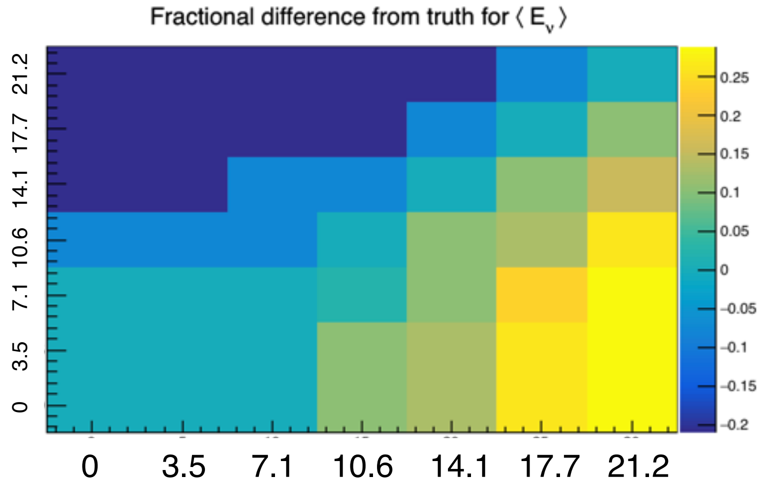
Notes:

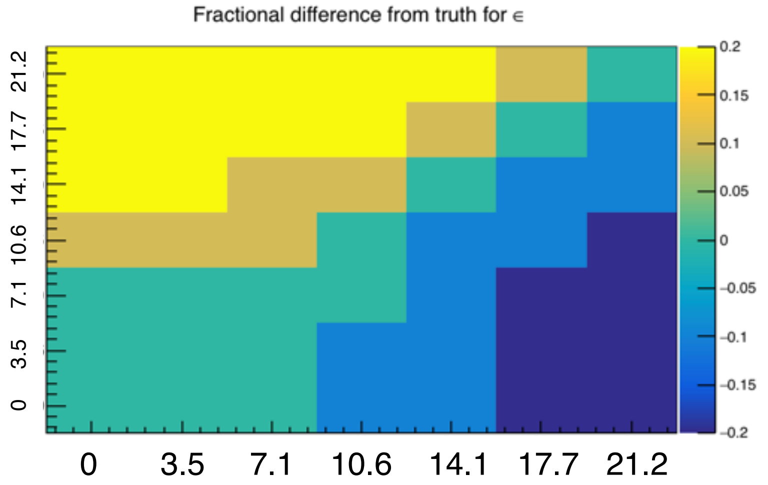
- Here we see superimposed sensitivity regions + best-fit parameters for one test spectra as input into different grids
- We can see both how the areas change, but also how the bias in our predictions change!



2D Fractional Difference Plot

- X-axis: Grid resolution
- Y-axis: Test spectra resolution
- We see how our predictions are biased if we have incorrect assumptions about energy resolution

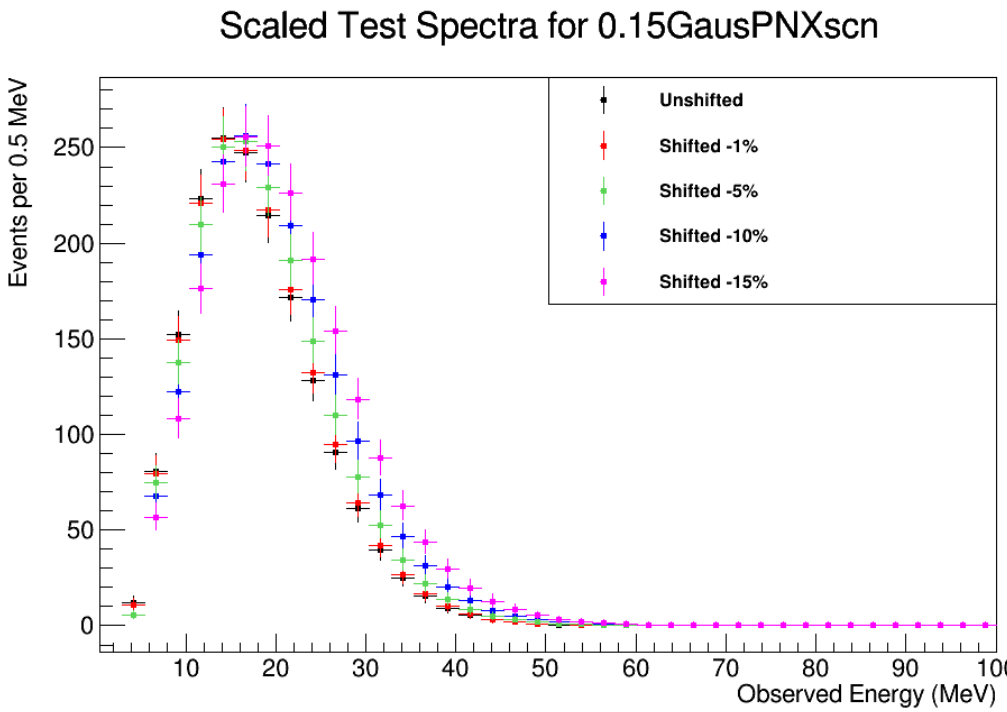


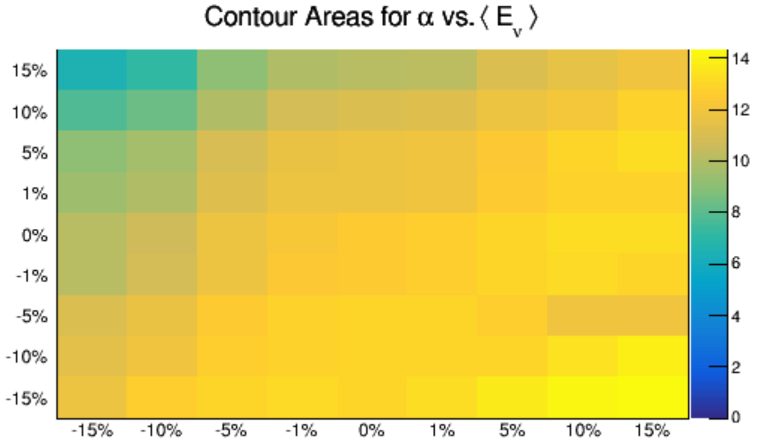


How well do we need to know our energy scale?

Energy Scaling: Introduction

- Goal: quantify how uncertainties in energy spectra affect DUNE's ability to predict SN flux model parameters
- Scale the energy spectra by $\pm\ 1\%, 5\%, 10\%, 15\%$
- Take every combination of scaled spectra for grid, test spectra
  - Determine the sensitivity regions, best-fit parameters → 81 total combinations

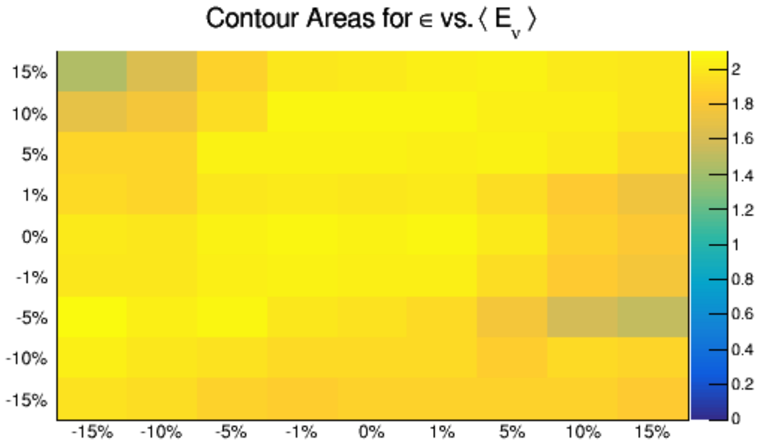


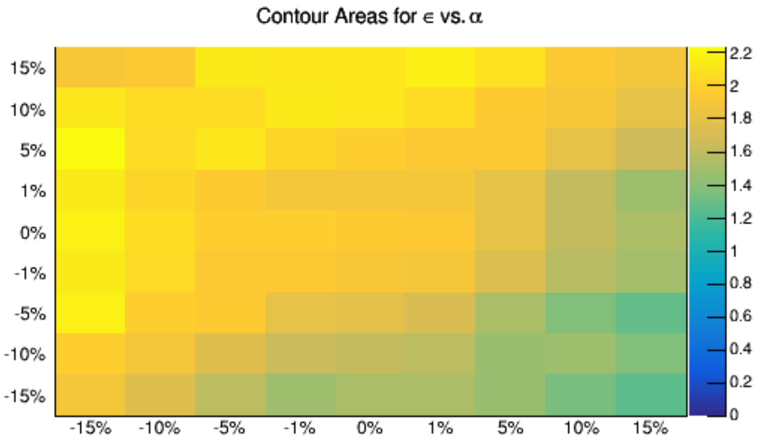


2D Contour Area Plot:

- Color scale indicates the contour area
- Some of the more drastic differences in contour area might be due to grid boundaries – see sensitivity regions in backup

Test Spectrum Scaling

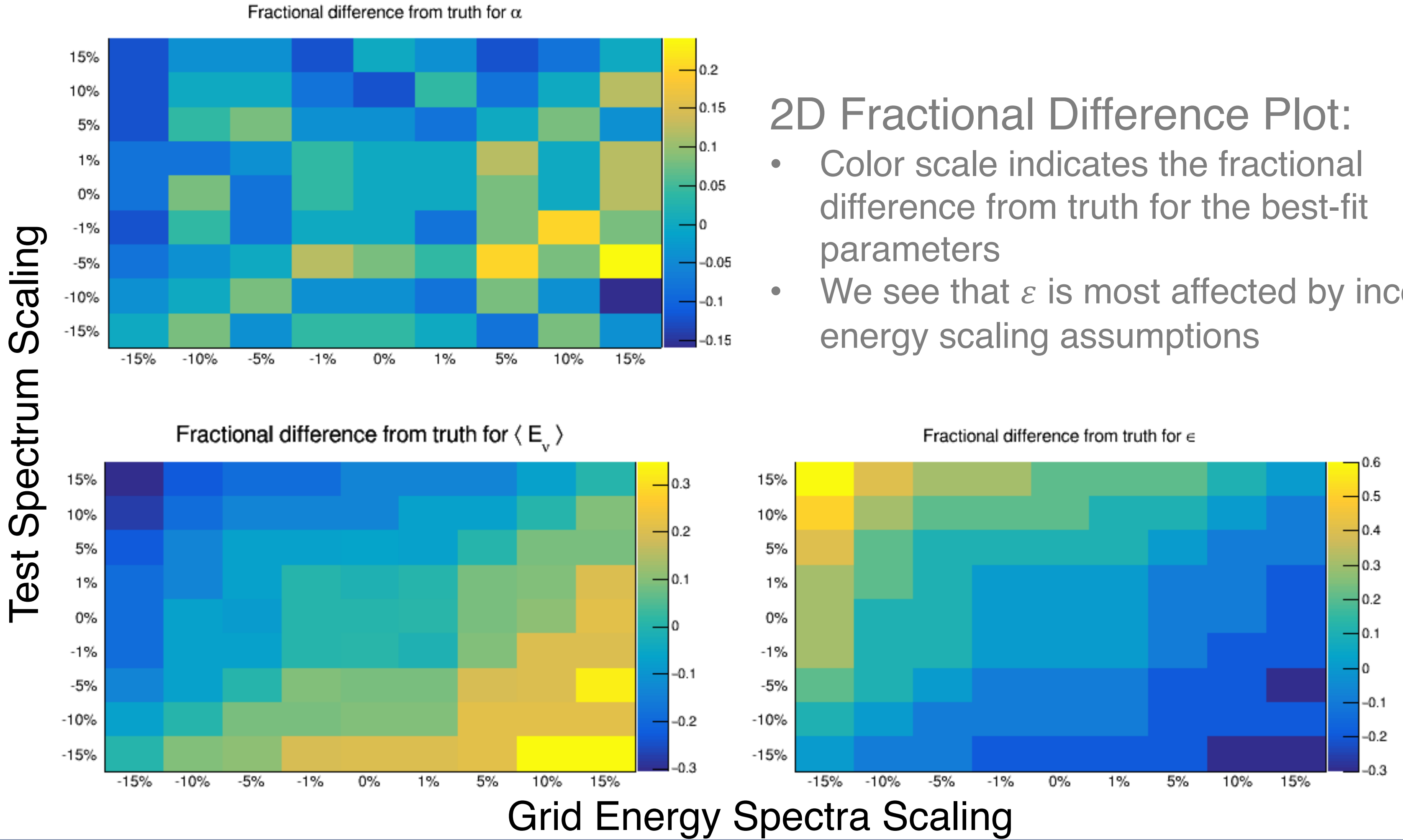




Grid Energy Spectra Scaling

2D Fractional Difference Plot:

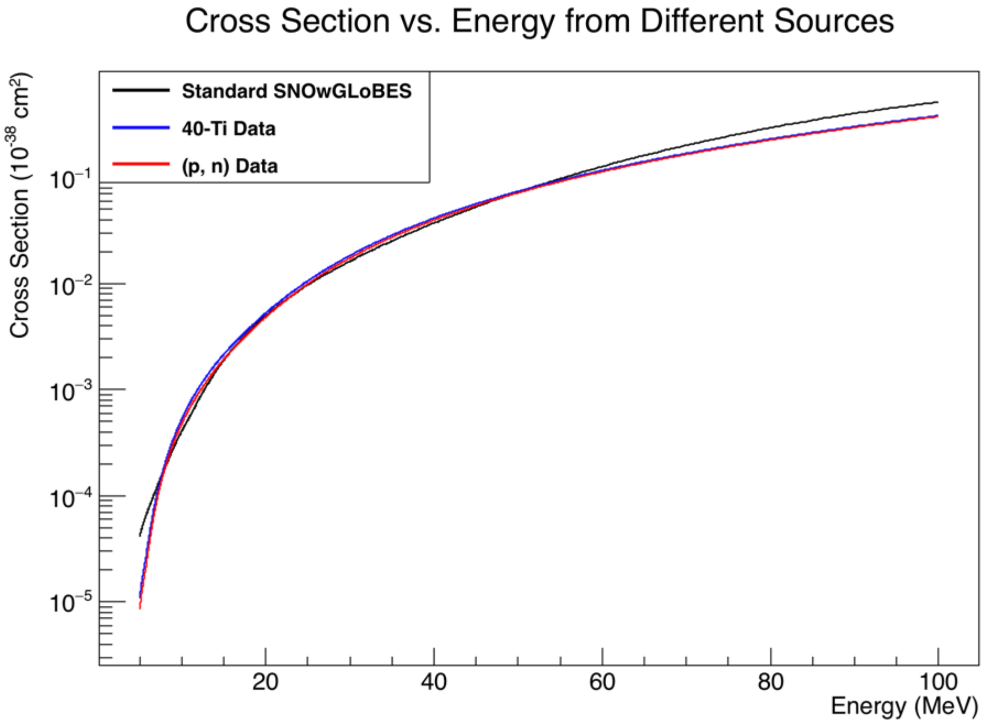
- Color scale indicates the fractional difference from truth for the best-fit parameters
- We see that ε is most affected by incorrect energy scaling assumptions

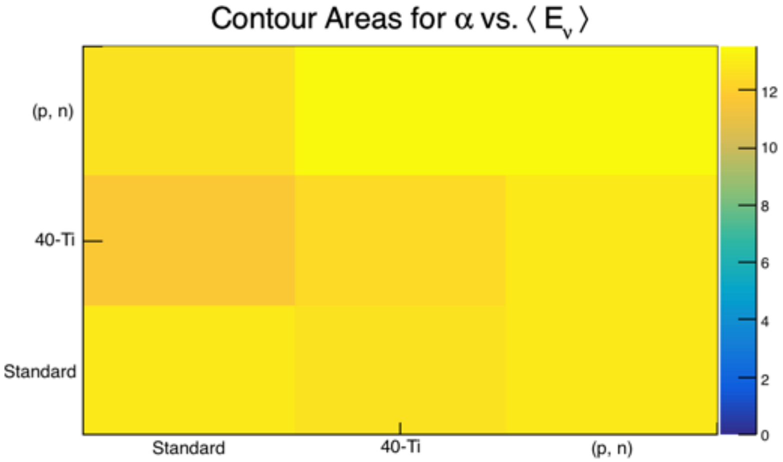


How well do we have to know the cross section?

Cross Section: Introduction

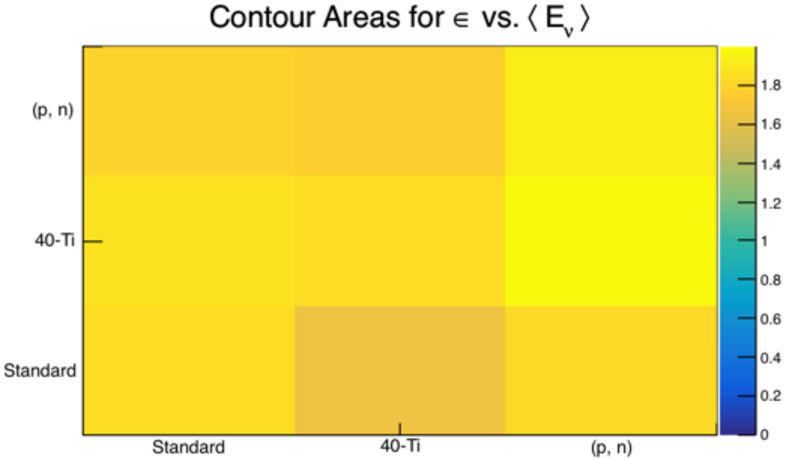
- Initiated study to determine how cross section affects forward fitting – what if our cross section model assumptions are incorrect?
- Change cross section among three models:
  – Standard SNOwGLoBES
  – Two MARLEY cross sections:
    - 40Ti
    - (p, n)

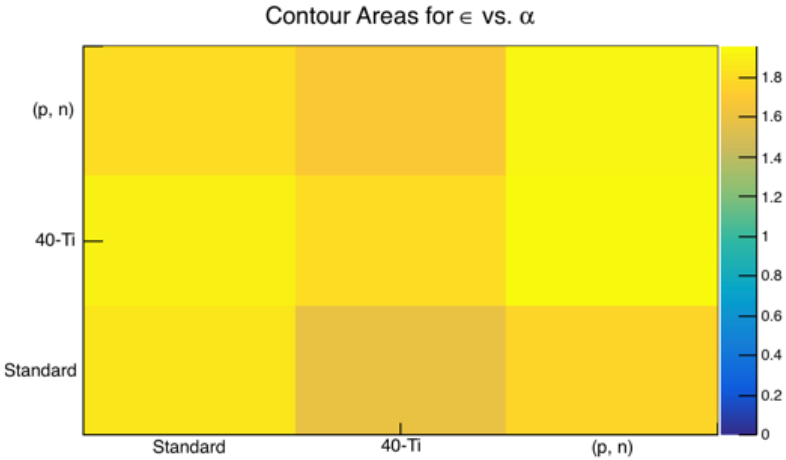


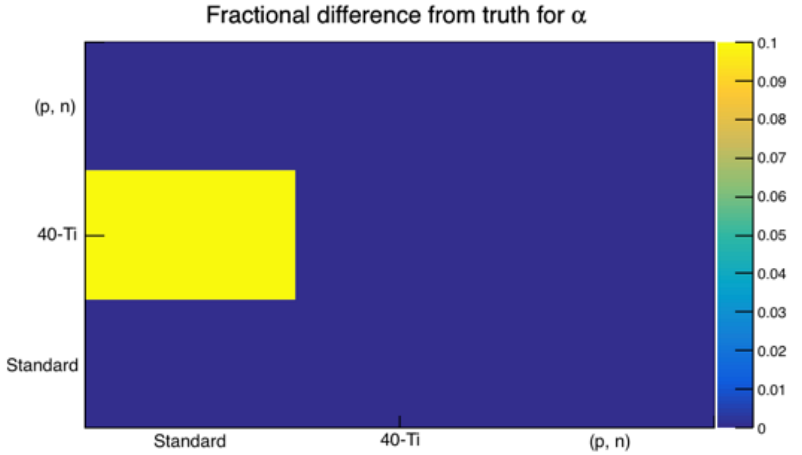


2D Contour Area Plot:

- X-axis: cross section used to generate grid
- Y-axis: cross section used to generate test spectra
- No big differences in contour areas – indicates that uncertainties in cross sections has small effect on sensitivity regions

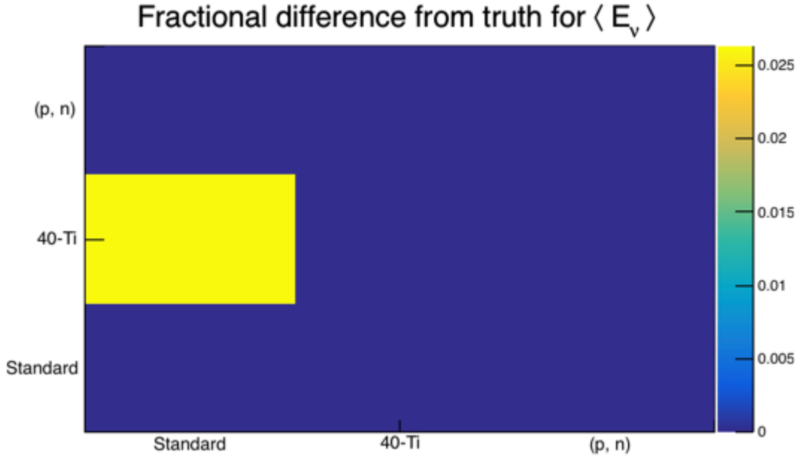


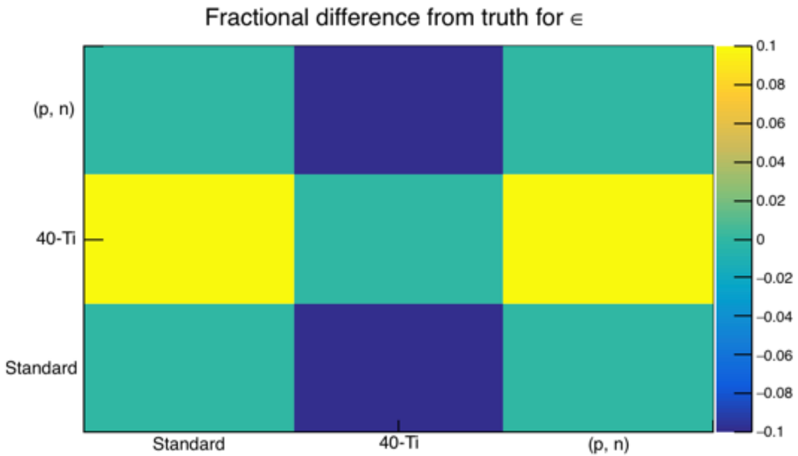




2D Fractional Difference Plot:

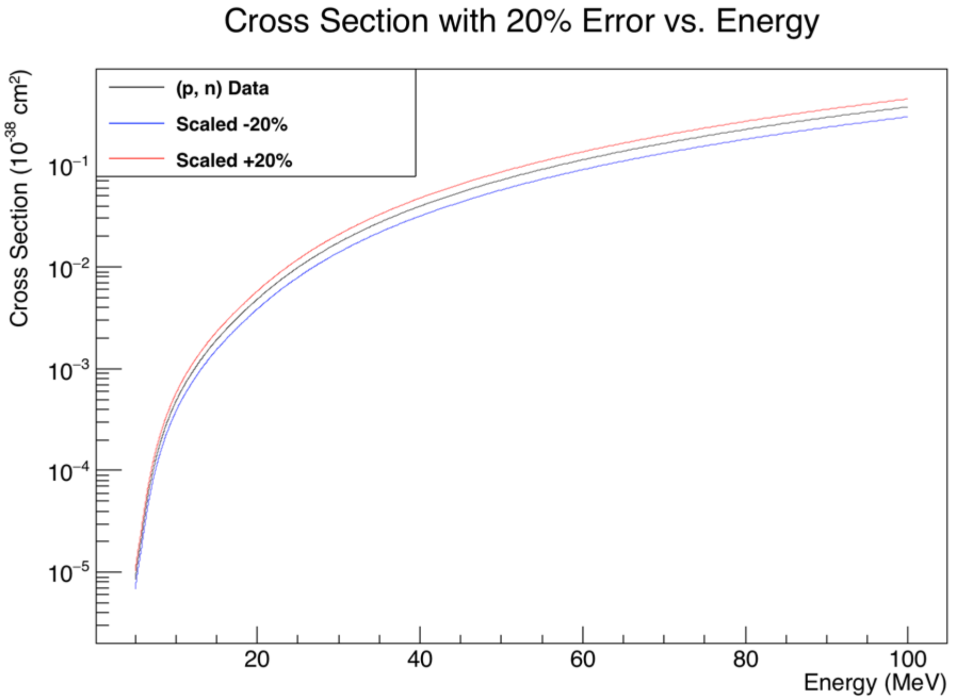
- X-axis: cross section used to generate grid
- Y-axis: cross section used to generate test spectra

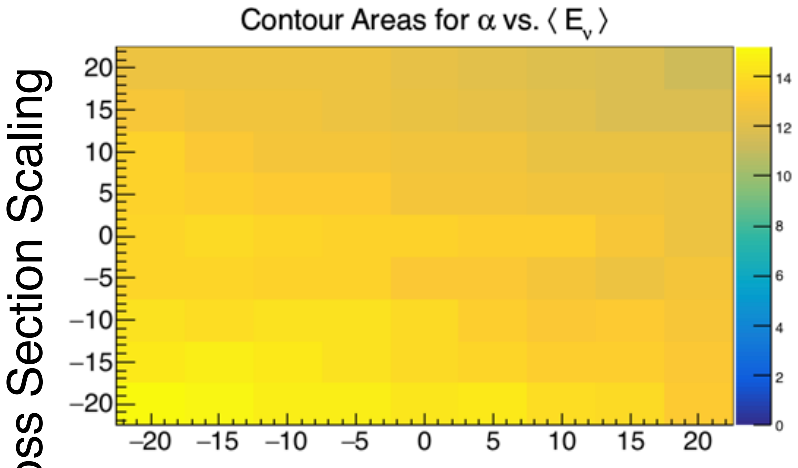




Cross Section Uncertainty: Introduction

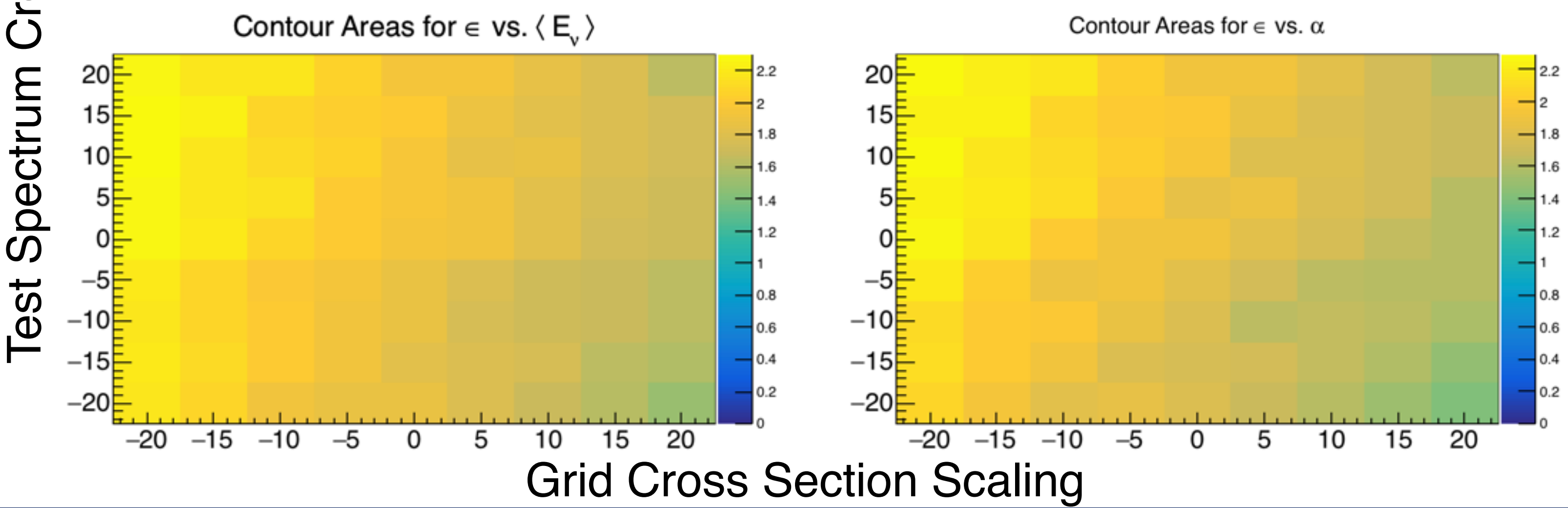
- Goal: quantify how uncertainties in the $\nu_e\text{−}\mathrm{Ar40}$ cross section affect DUNE's ability to predict SN flux model parameters
- Scale the cross section by $\pm\ 5\%, 10\%, 15\%, 20\%$ → 9 different cross section "models"
  - Take every combination of test spectra + grid and determine the sensitivity regions, best-fit parameters → 81 total combinations

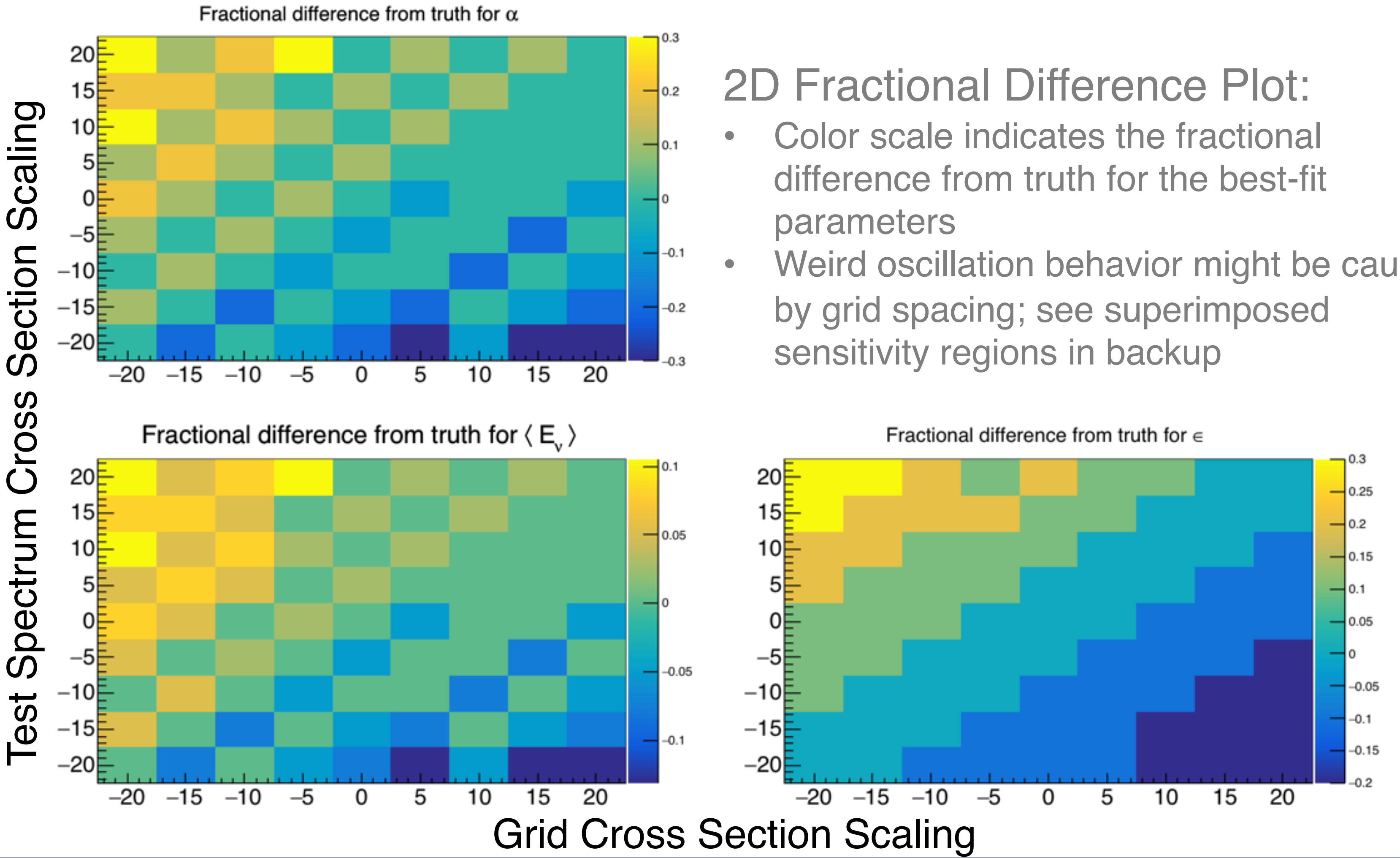




2D Contour Area Plot:

- Color scale indicates the contour area
- We see relatively small differences in the contour area → sensitivity regions remain about the same size for all combinations





2D Fractional Difference Plot:

- Color scale indicates the fractional difference from truth for the best-fit parameters
- Weird oscillation behavior might be caused by grid spacing; see superimposed sensitivity regions in backup

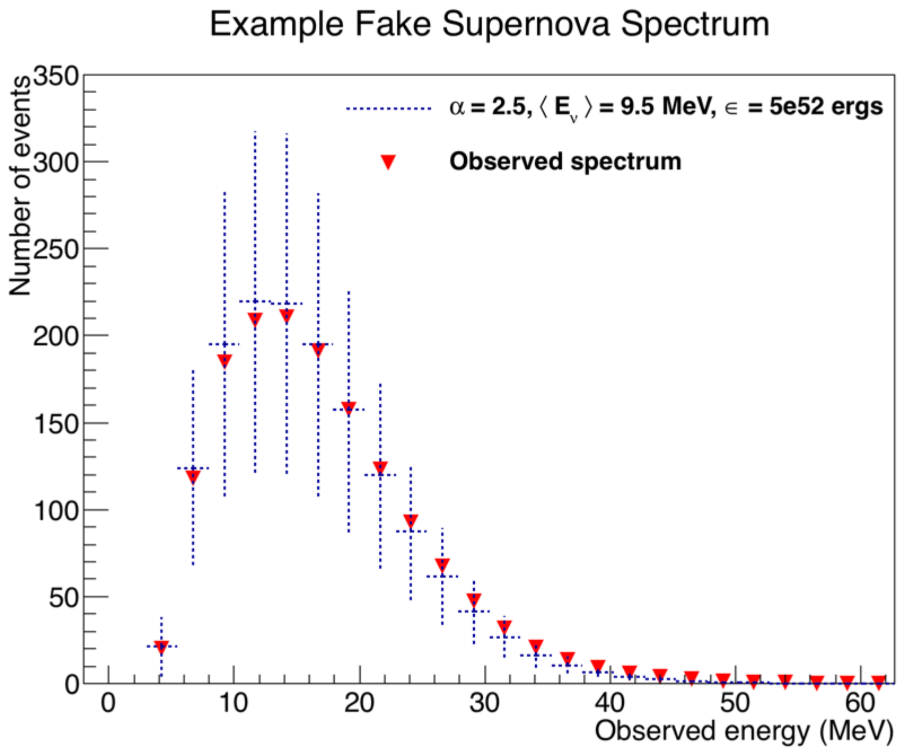
Takeaways + Next Steps

- Forward fitting studies help show DUNE's ability to constrain SN flux parameters for various detector parameter assumptions
  - The 2D contour area and fractional difference plots show how DUNE's predictions change for incorrect assumptions
- These studies also quantifies bias in spectral parameter predictions under incorrect assumptions; for example, consider ε:
  - Energy resolution: 21.2% resolution yields -20% to +20% bias on ε
  - Energy scaling: +15% scaling yields -30% to +60% bias on on ε
  - Cross section: 20% uncertainty yields -20% to +30% bias on ε
- Some next steps:
  - Update grids for some studies
  - Cross section shape systematics study
  - Fake supernovae method for all studies

Backup Slides

Forward Fitting: Fake Supernova Sample

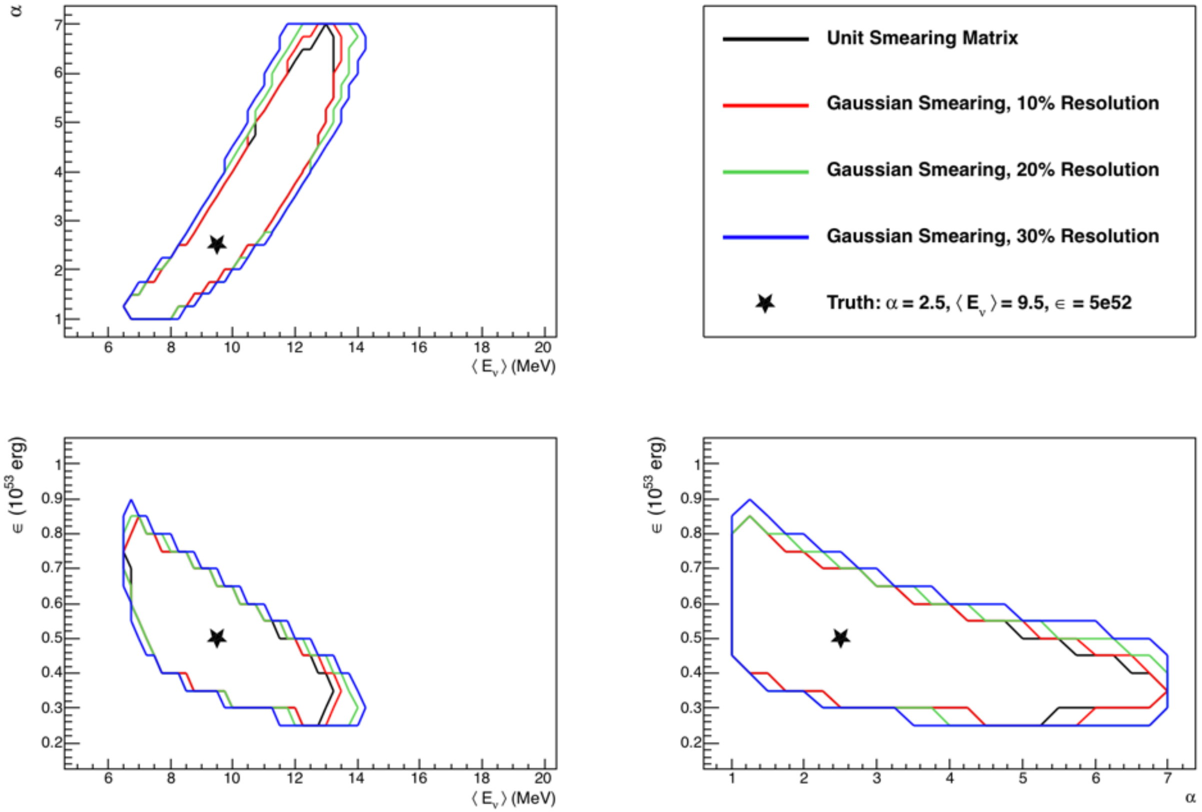
- Take ν_e flux parameters from Rosso et al.: $(\alpha,\ \langle E_\nu \rangle,\ \varepsilon) = (2.5,\ 9.5,\ 0.5 \times 10^{53})$
- Use SNOwGLoBES to make smeared energy spectra using this flux + smearing matrix
- Sample randomly from this spectra to generate "fake supernovae" test spectra
- Many fake supernovae → distribution of best-fit parameters based on χ^2 minimization



Backup Slides

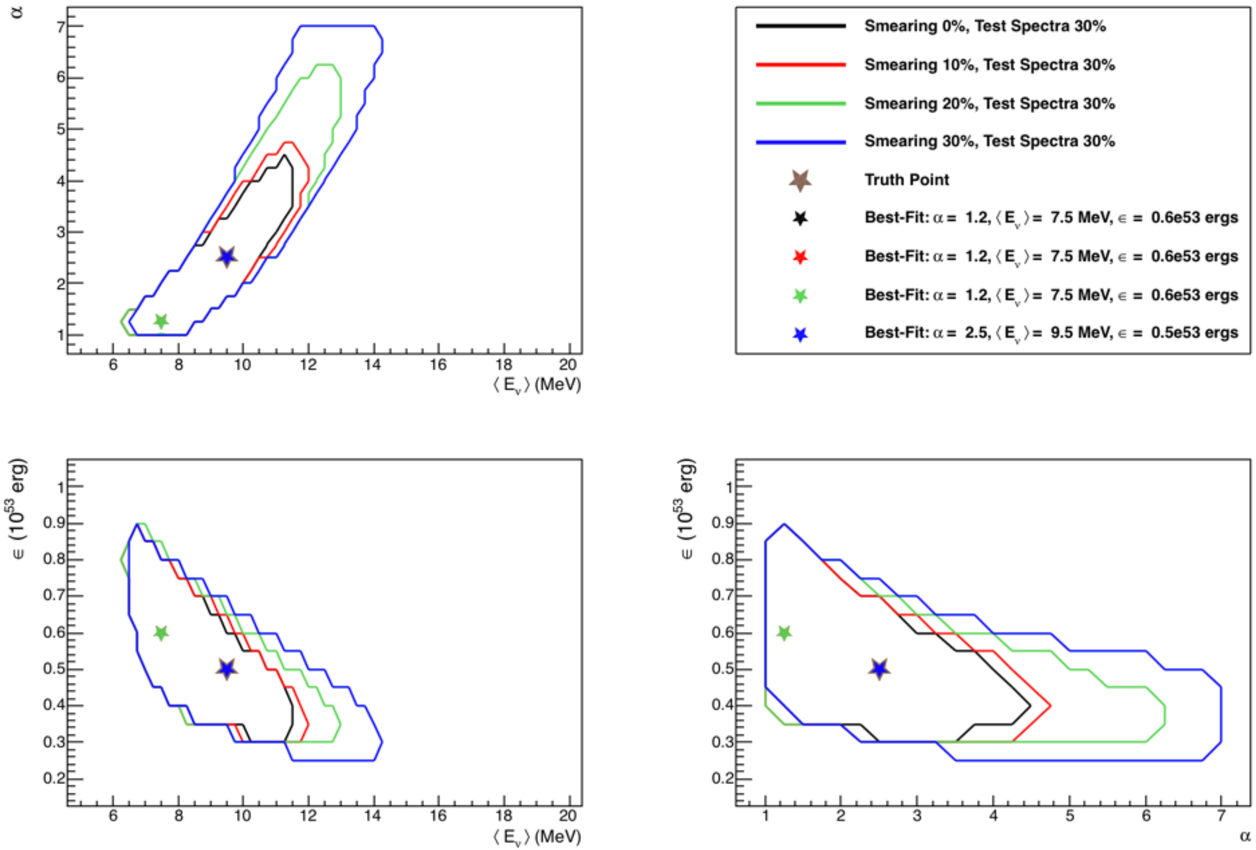
ENERGY RESOLUTION STUDY

Contours from the Diagonal



Note: these set of contours were produced before I included finer bins

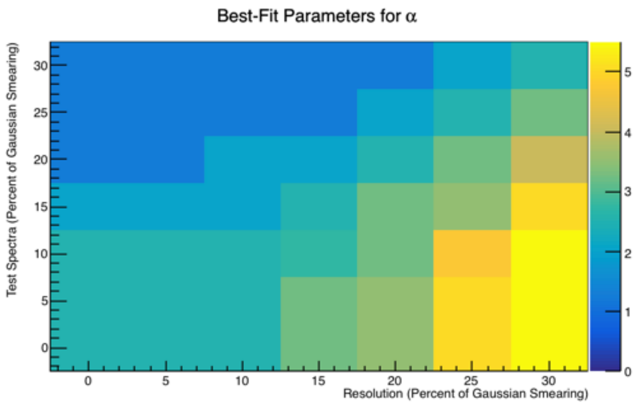
Contours with Best-Fit Points: “Top Row”



Notes:

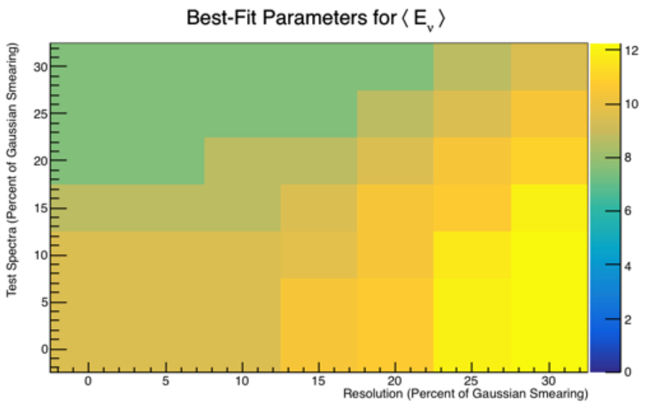
- These set of contours were produced before I included finer bins
- “Top row” refers to the combinations of grid/test spectra resolutions in the top row of the 2D contour area plot

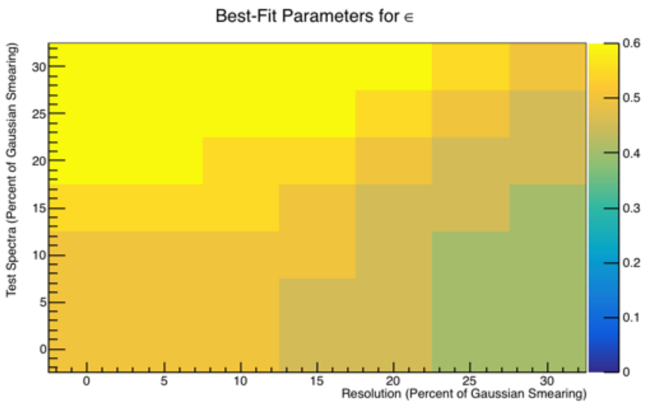
Best-Fit Values



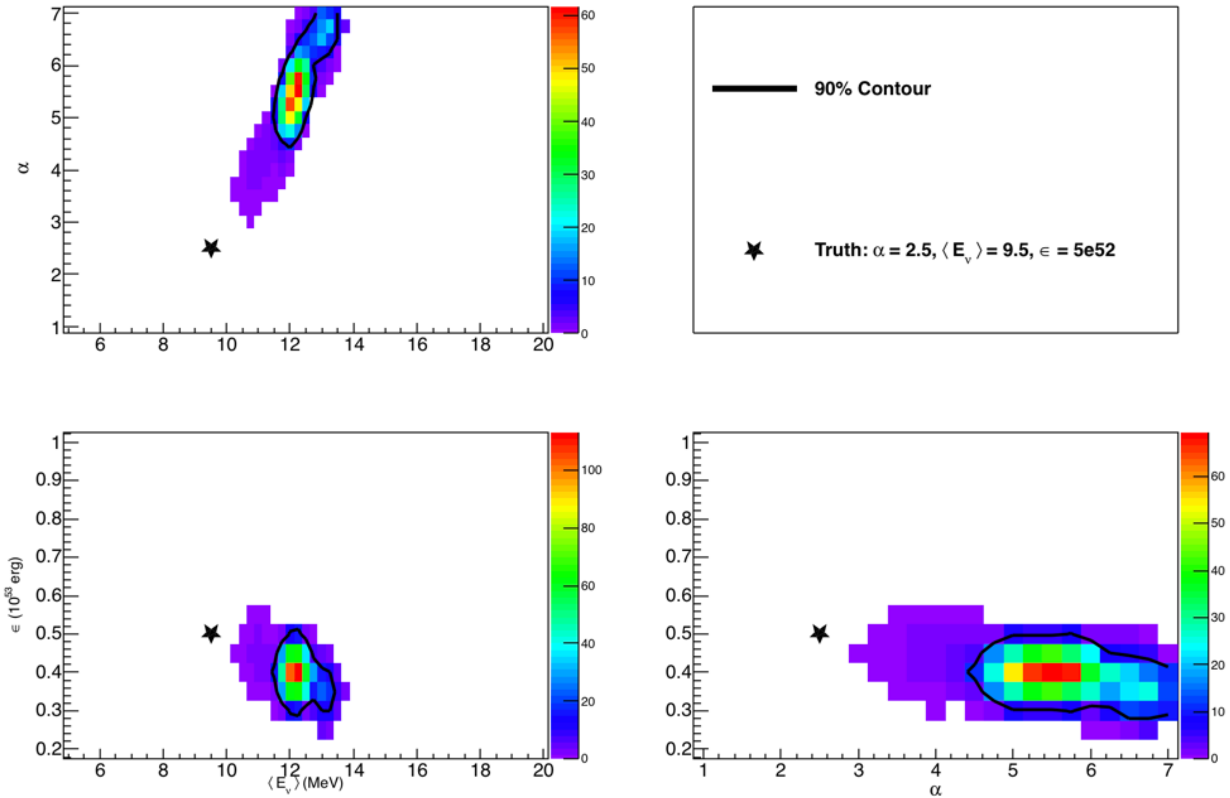
Notes:

- The diagonal, lower quadrant of [0, 10] (resolution) best-fit back to truth
- If our smearing assumptions are lower than reality: Test spectra with true 20-30% smearing predict lower values of alpha, E0; higher values of luminosity
- If our smearing assumptions are higher than reality: Test spectra with true 0-10% smearing predict higher values of alpha, E0; lower values of luminosity





Fake Supernova Spectra Example



Notes:

- This example uses a grid with 30% resolution + test spectra with 10% resolution
- 1000 randomly generated supernovae spectra at 10kpc from Earth
- Here we see the bias in DUNE's predictions from an incorrect resolution assumption
- The bias is more significant than I expected…need to look into it more

Backup Slides

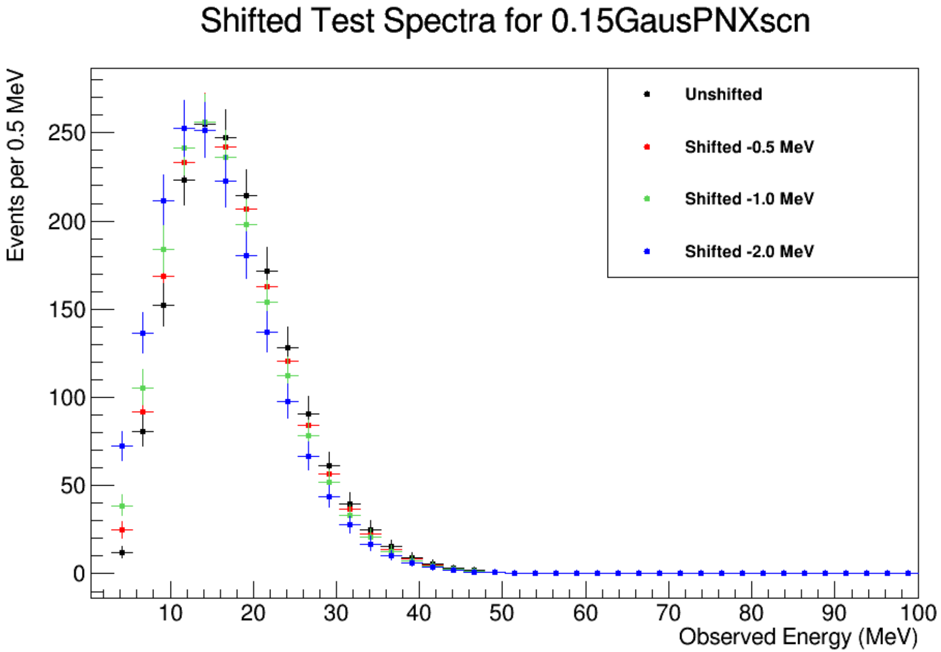
ENERGY SHIFT STUDY

Introduction

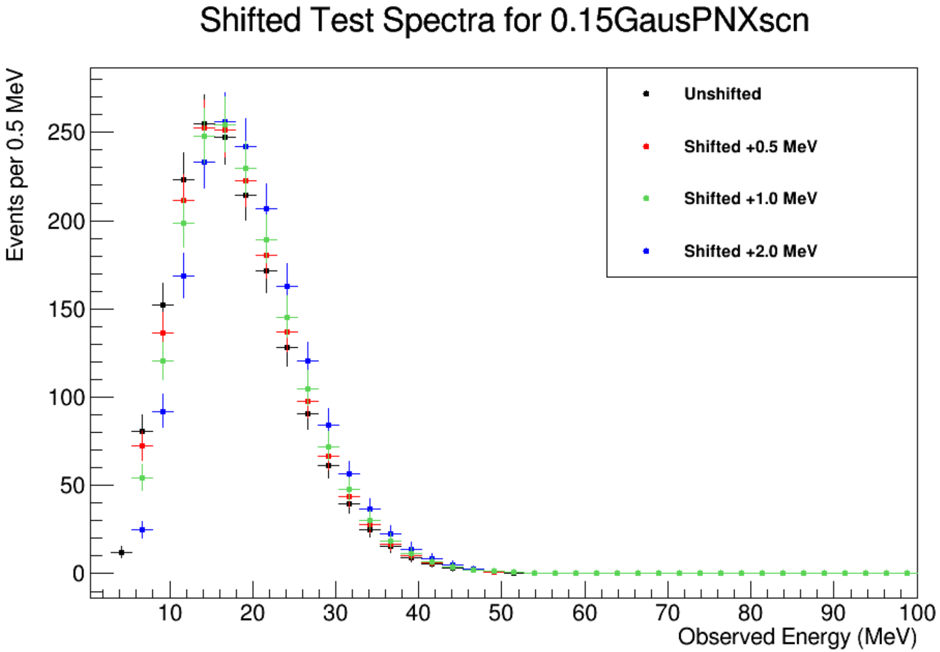
- Goal: determine how shifting the “test” energy spectra changes the forward fitting results
  - Context: direct unfolding dramatically affected by shifting the energy scale
- Initial studies: Gaussian smearing with 15% resolution
  - MARLEY (p, n) cross section; 100% above threshold efficiency; no oscillations
  - Shifted that test spectrum by $\pm$ 0.5, 1, 2 MeV
- Then did forward fit using sensitivity/Asimov method for 10kpc SN:
  - Grid: unshifted 15% resolution
  - Changed the test spectra’s shift

Test Spectra + Shifts

Left-ward/Negative Shifts

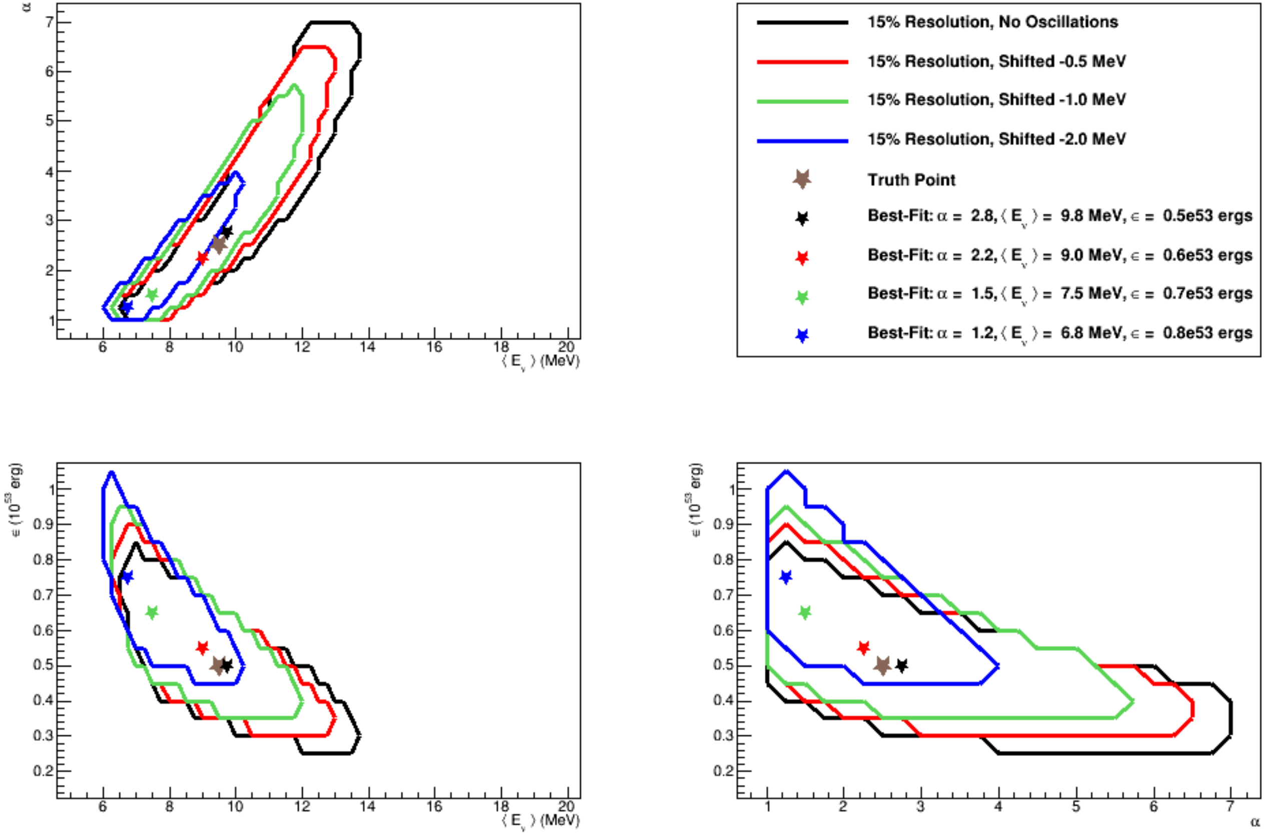


Right-ward/Positive Shifts



Sanity check that the shifts are working as expected!

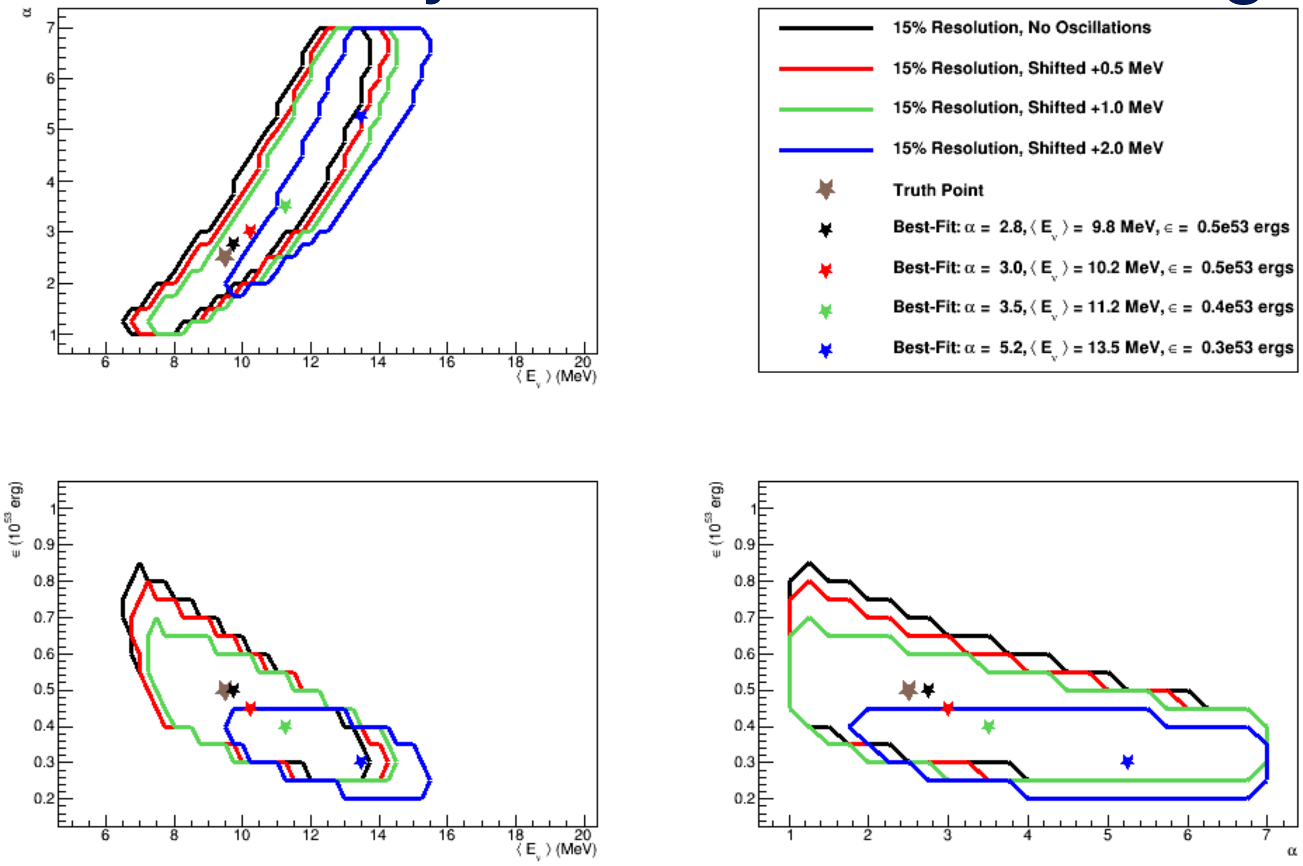
Sensitivity Method: Negative/Left Shift



Notes:

- The contours + best-fit points show how the predictions are biased if we incorrectly assume the energy scale
- The contours probably extend beyond the grid boundaries

Sensitivity Method: Positive/Right Shift



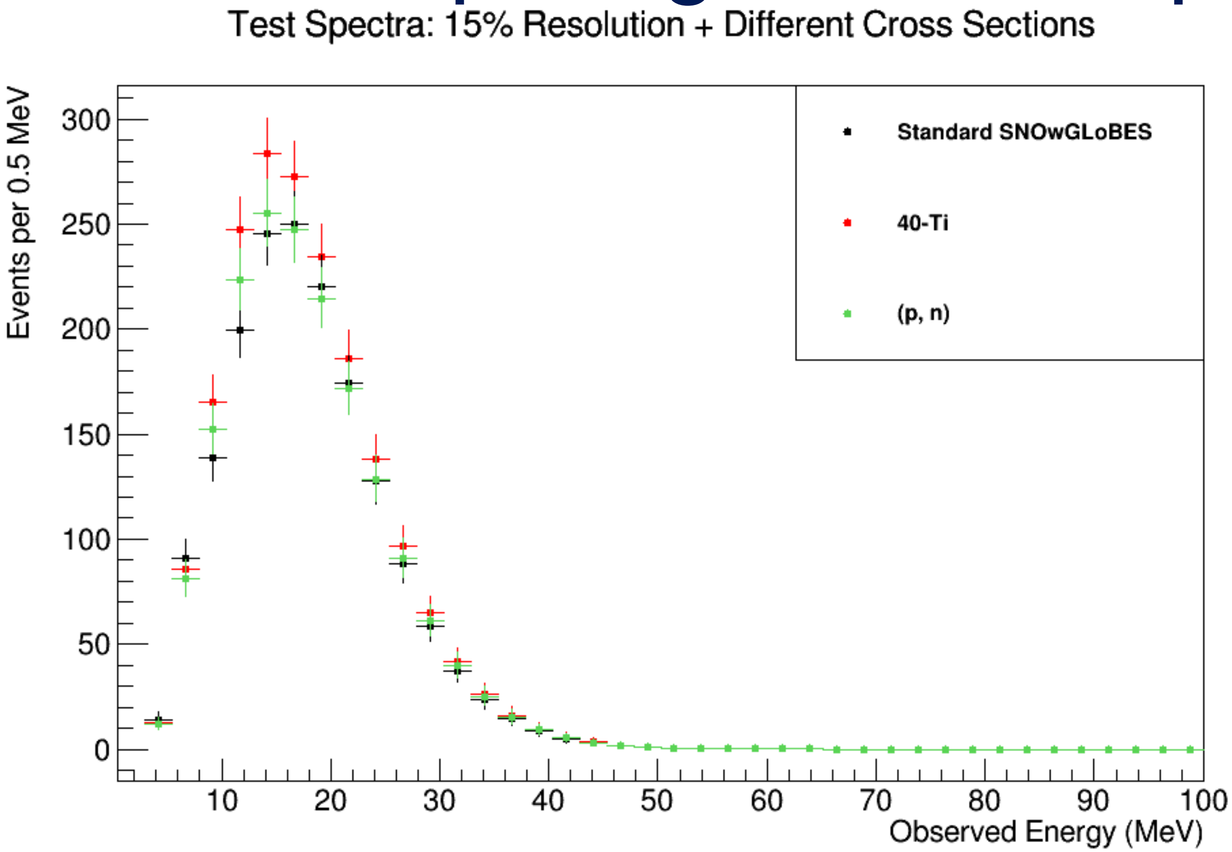
Notes:

- The contours + best-fit points show how the predictions are biased if we incorrectly assume the energy scale
- We also see that the bias is different compared to the other shift!

Backup Slides

CROSS SECTION STUDY

Comparing the Test Spectra



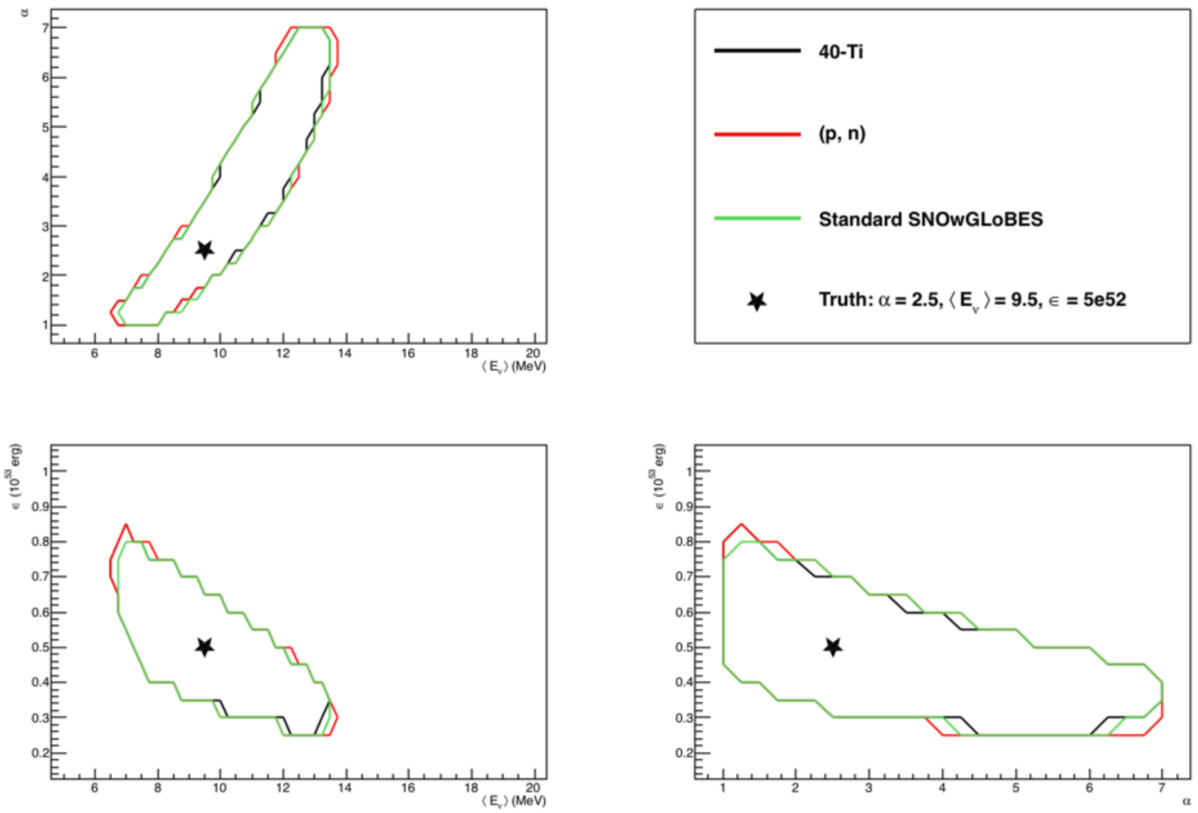
Total number of events:

- Standard SNOwGLoBES: 1702.94
- 40-Ti: 1894
- (p,n): 1740.35

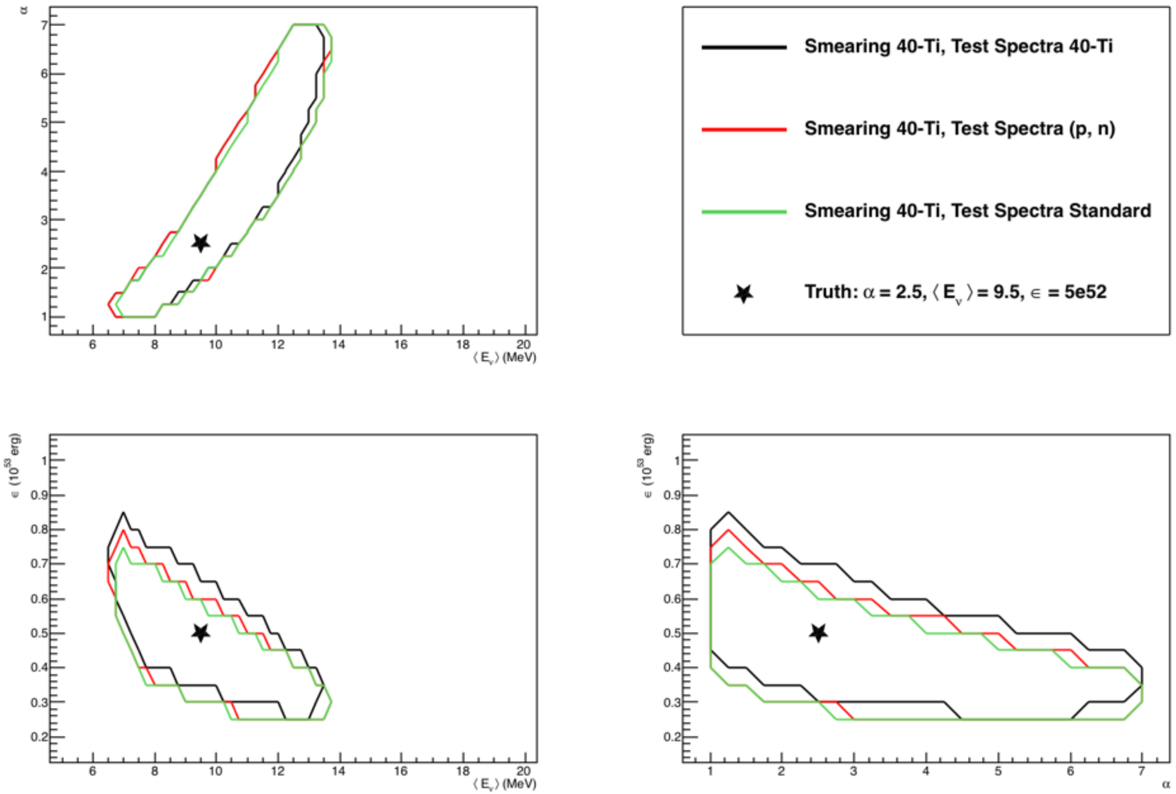
Notes:

- Error bars are statistical
- Since ε related to statistics, naively expect biggest tension(s) in ε best-fit between standard, 40-Ti

Contours from the Diagonal



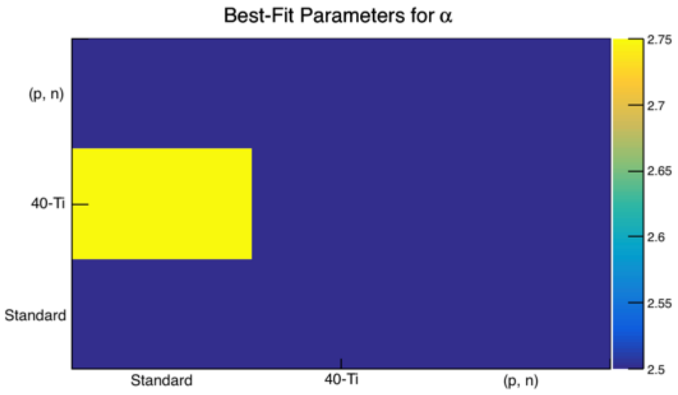
Contours from Middle Column



2D Best-Fit Parameter Plot: Cross Section Study

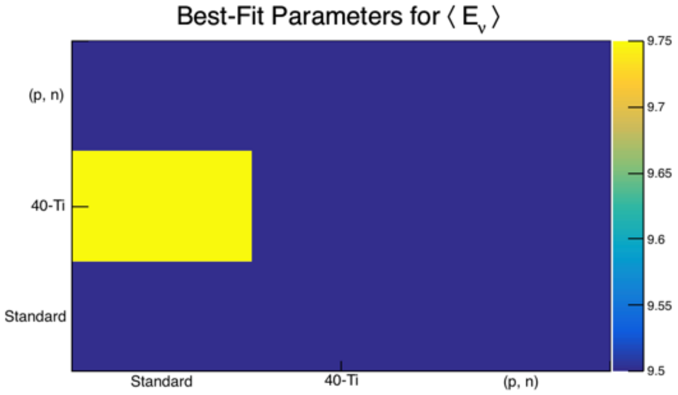
X-axis: cross section used to generate grid

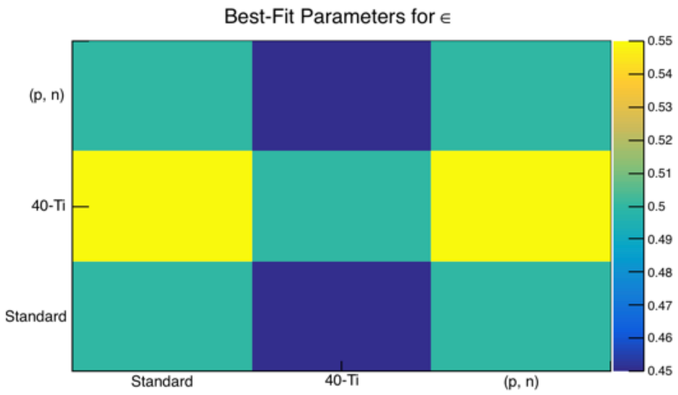
Y-axis: cross section used to generate test spectra



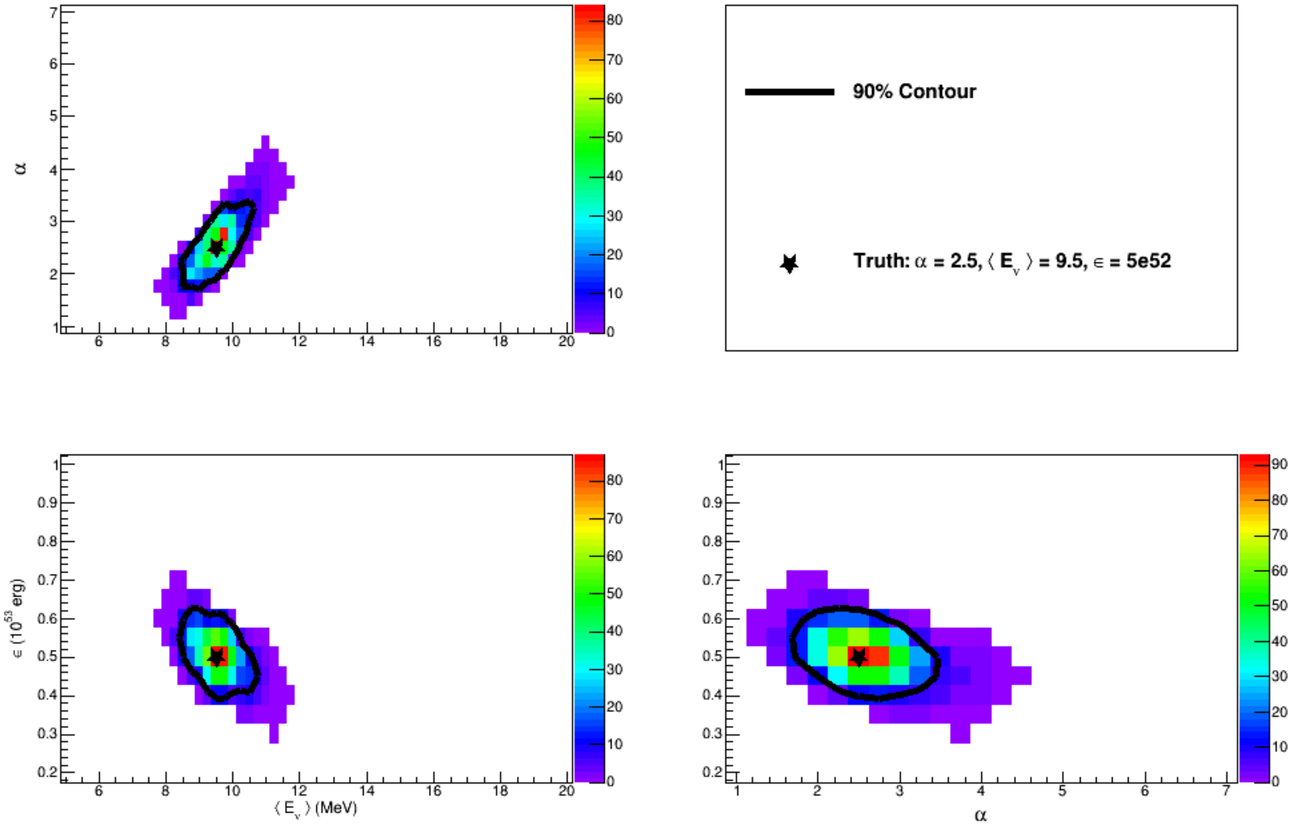
Notes:

- The z-scale is not zero suppressed! This was done on purpose to better differentiate the elements
- We see relatively light tension for α, $\langle E_\nu \rangle$; more tension for ε
- We see biggest tensions in ε between standard SNOwGLoBES cross section, 40-Ti cross section (expected from looking at test spectra)





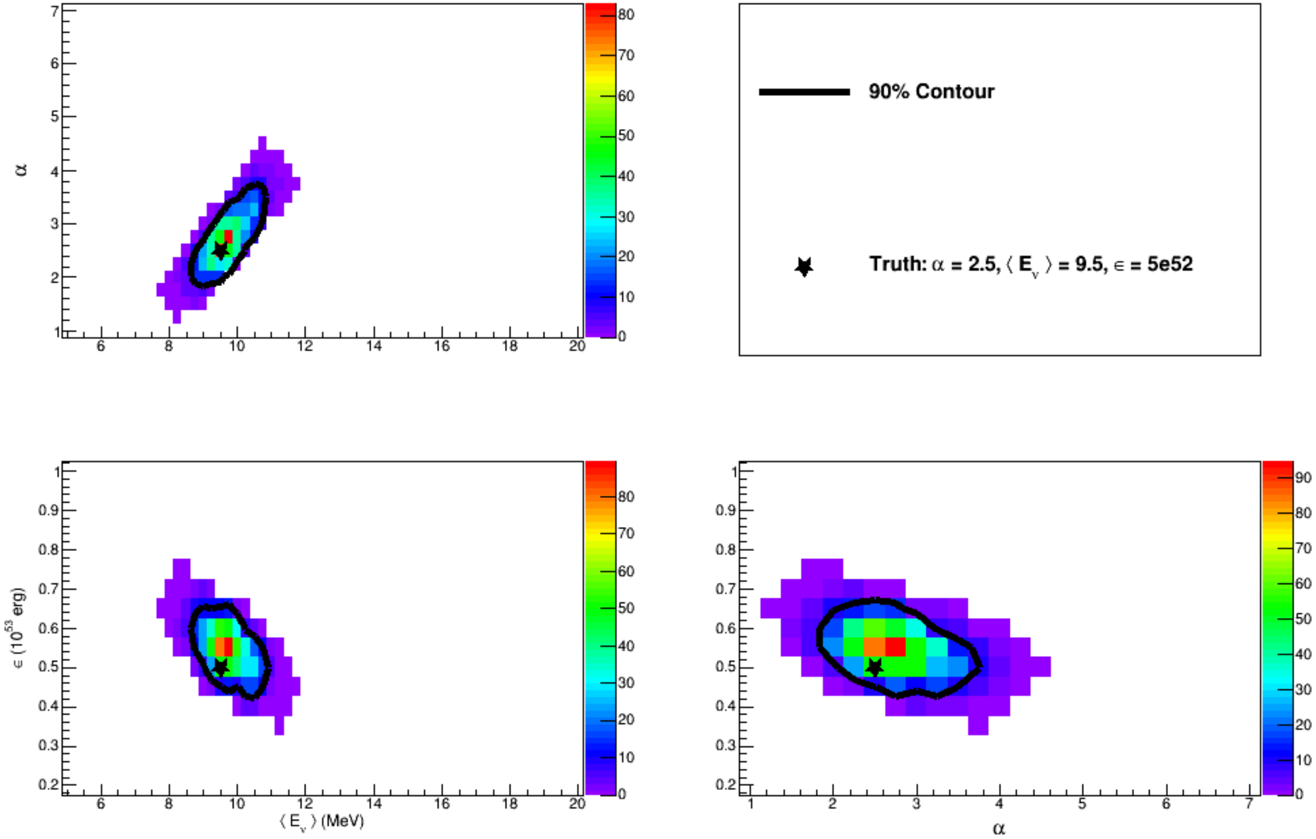
Fake Supernovae Spectra: Standard vs. (p,n)



Notes:

- Used grid with standard SNOwGLoBES cross section + test spectra with (p, n) cross section
- We see good agreement between the truth + randomly generated supernovae spectra!
- Indicates that cross section uncertainties have less impact on DUNE's best-fit ability versus resolution

Fake Supernovae Spectra: Standard vs. 40-Ti



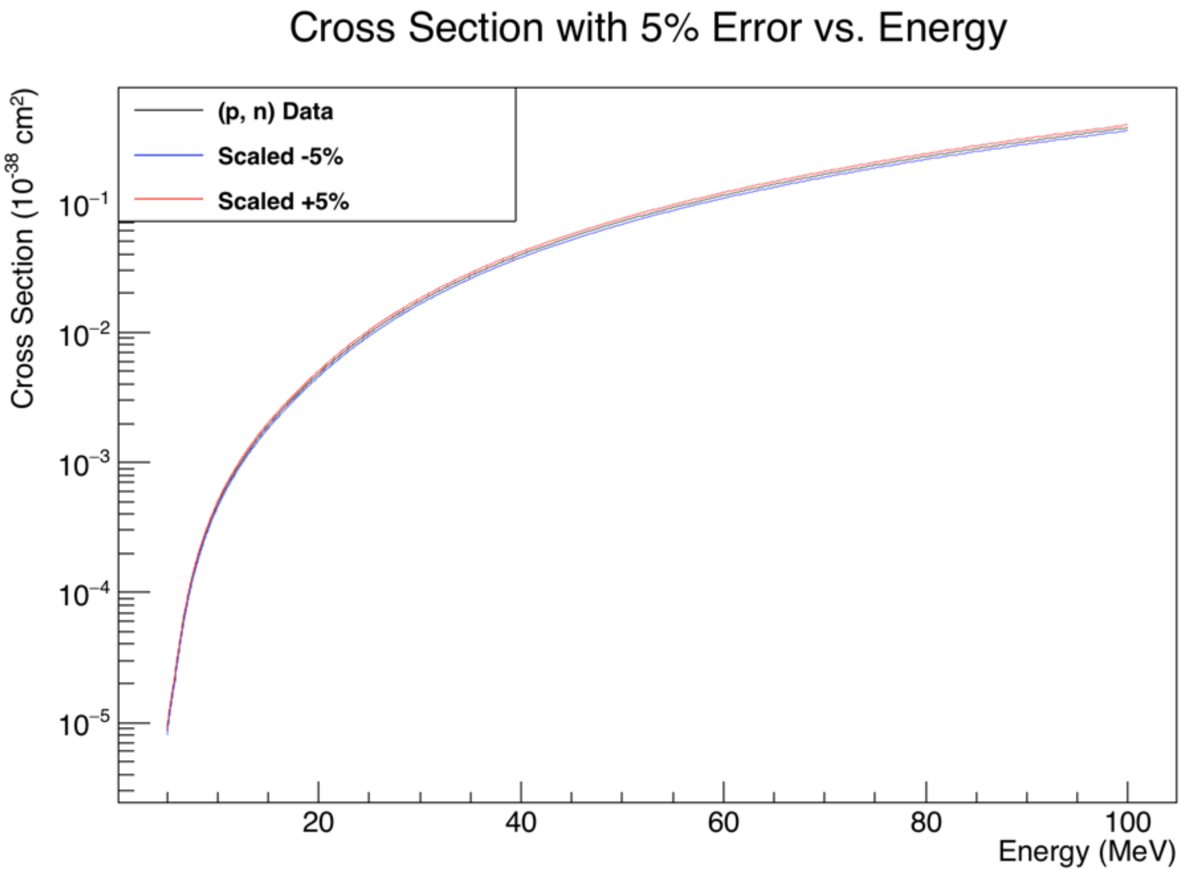
Notes:

- Used grid with standard SNOwGLoBES cross section + test spectra with 40-Ti cross section
- We see a bias in the results; not as bad as the smearing studies
- Indicates that cross section uncertainties have less impact on DUNE's best-fit ability versus resolution, but there's still an impact.

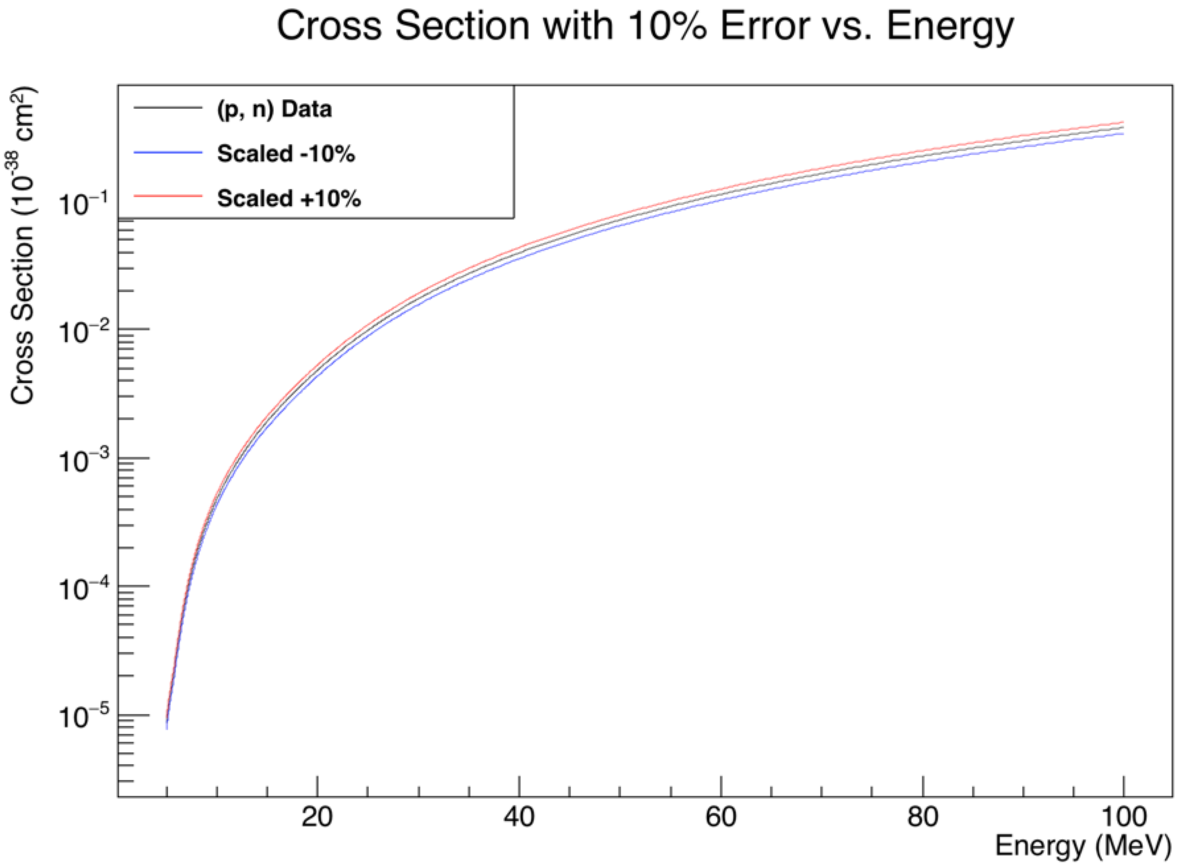
Backup Slides

CROSS SECTION UNCERTAINTY STUDY

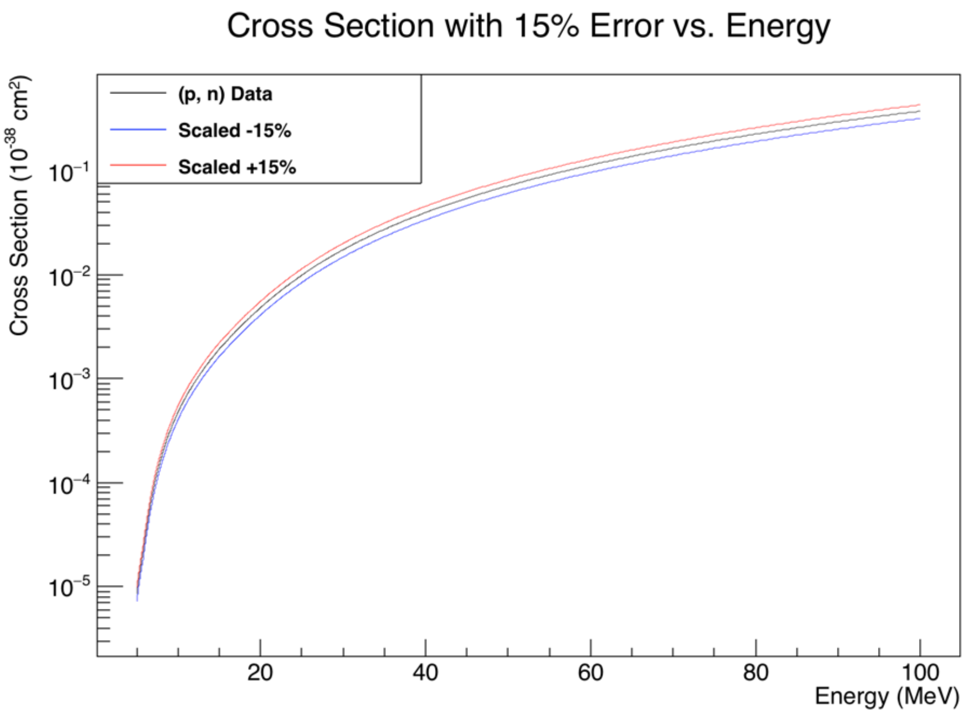
Cross Section Vs. Energy: 5% Scaling



Cross Section Vs. Energy: 10% Scaling

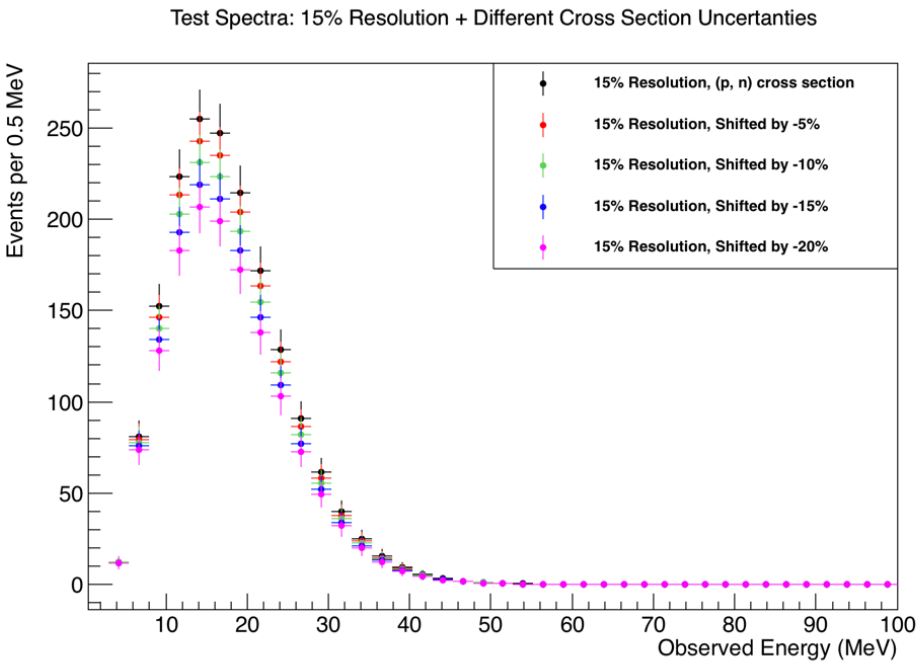


Cross Section Vs. Energy: 15% Scaling

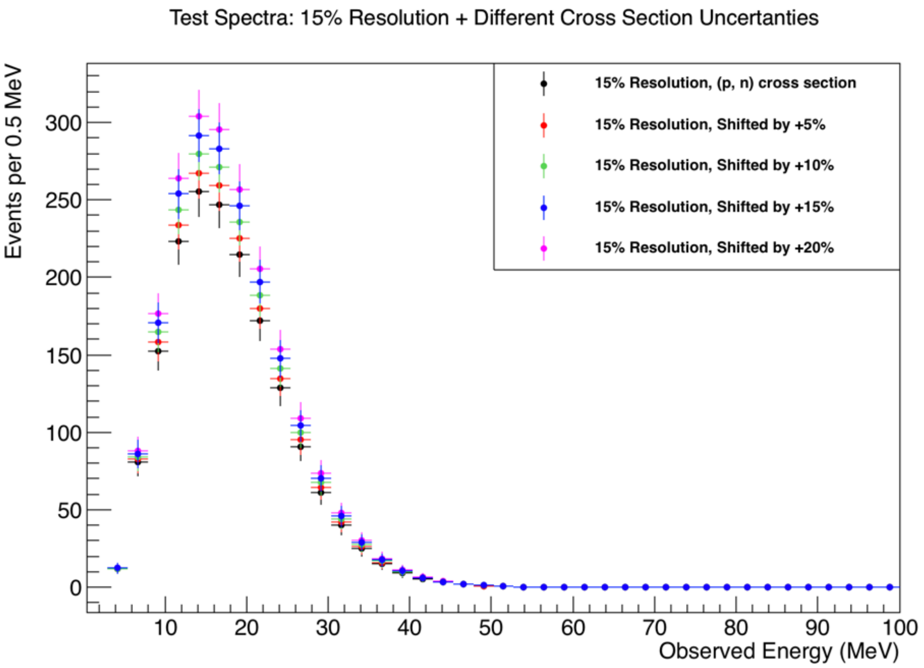


Comparing the Test Spectra

Negative Scaling

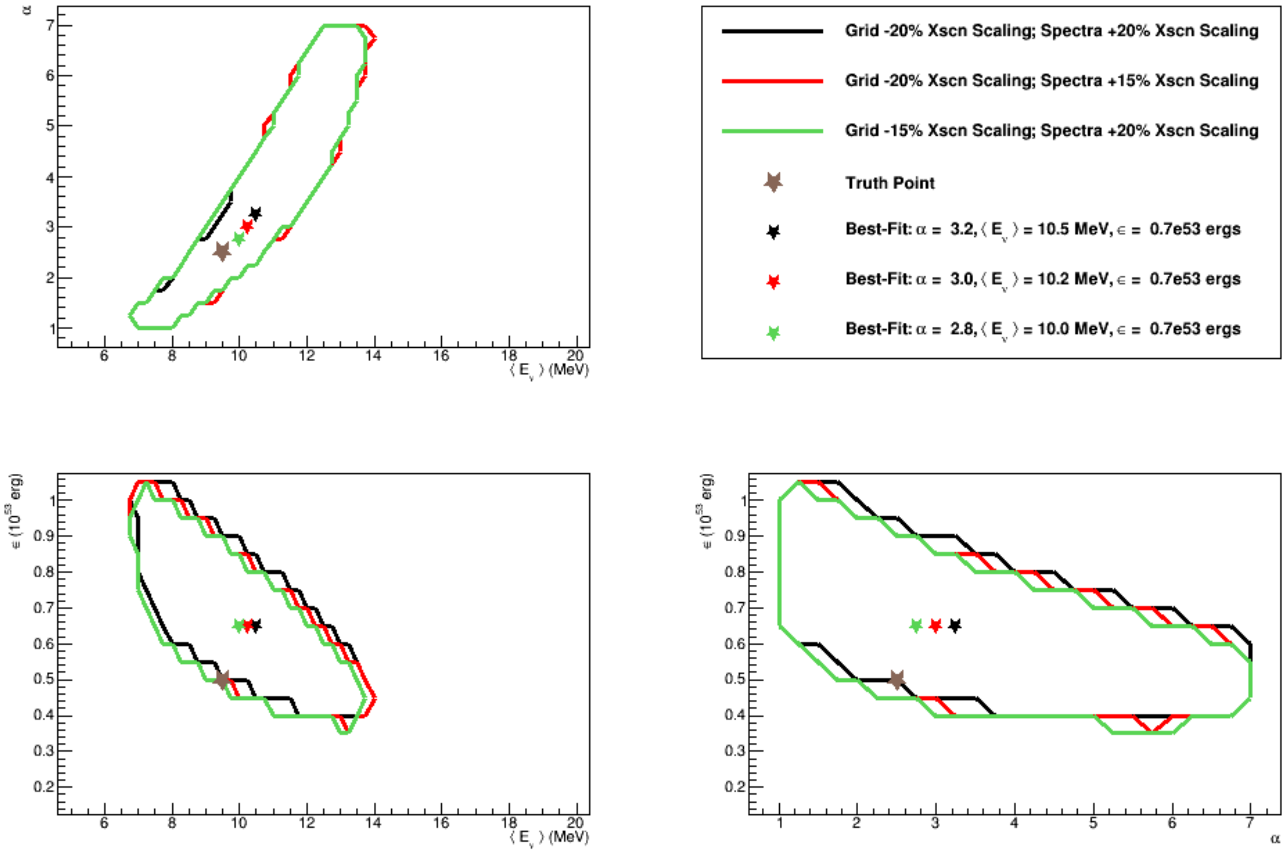


Positive Scaling

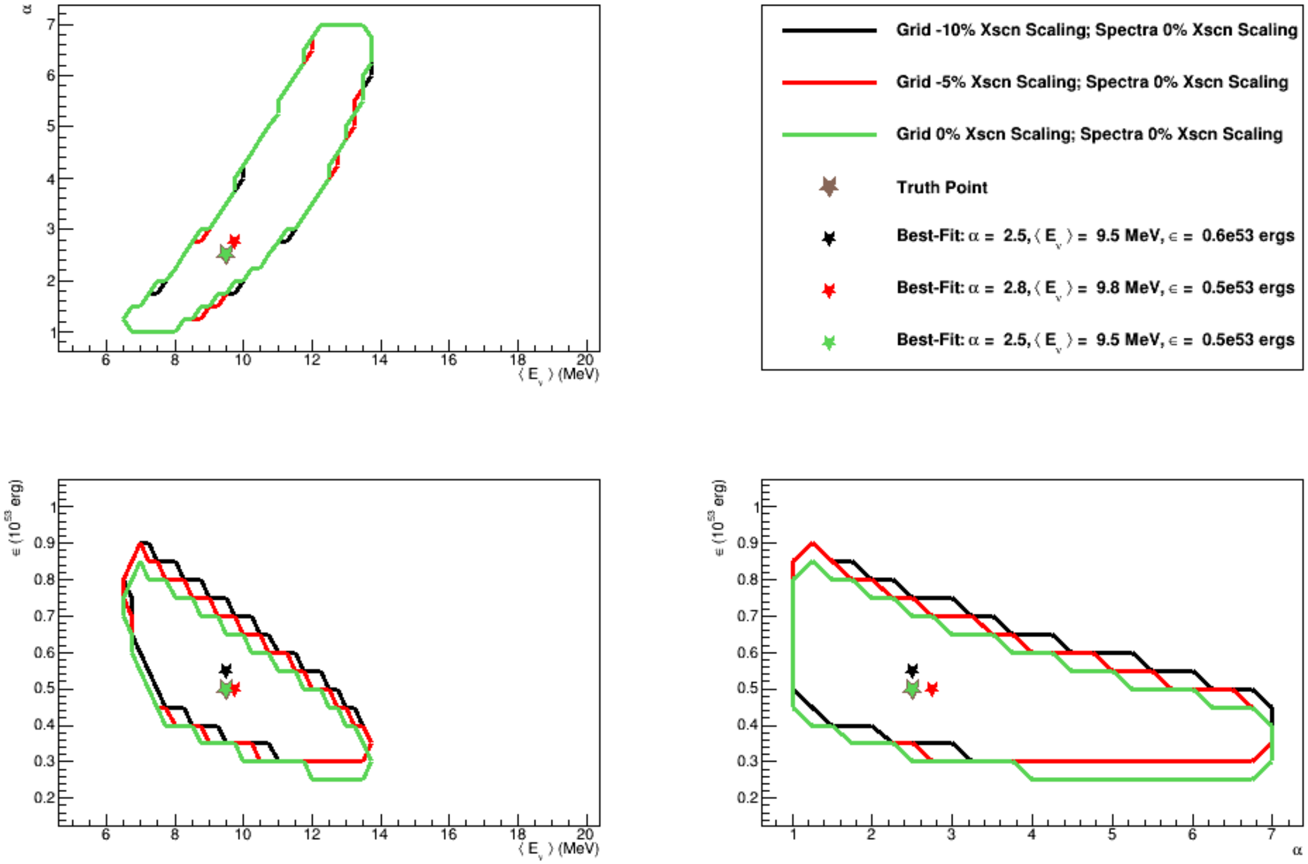


Expect ε to experience the most significant bias

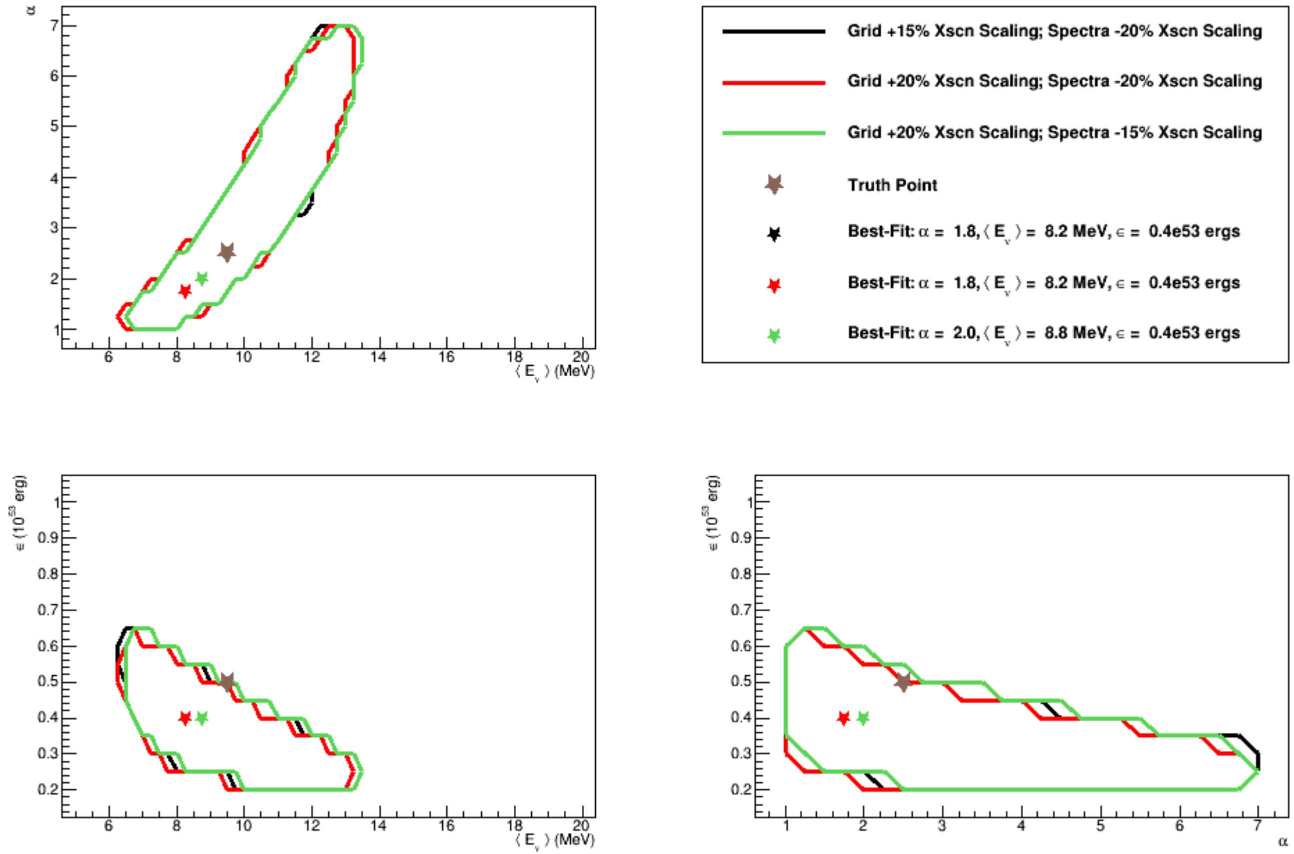
Contours: Upper Left Corner



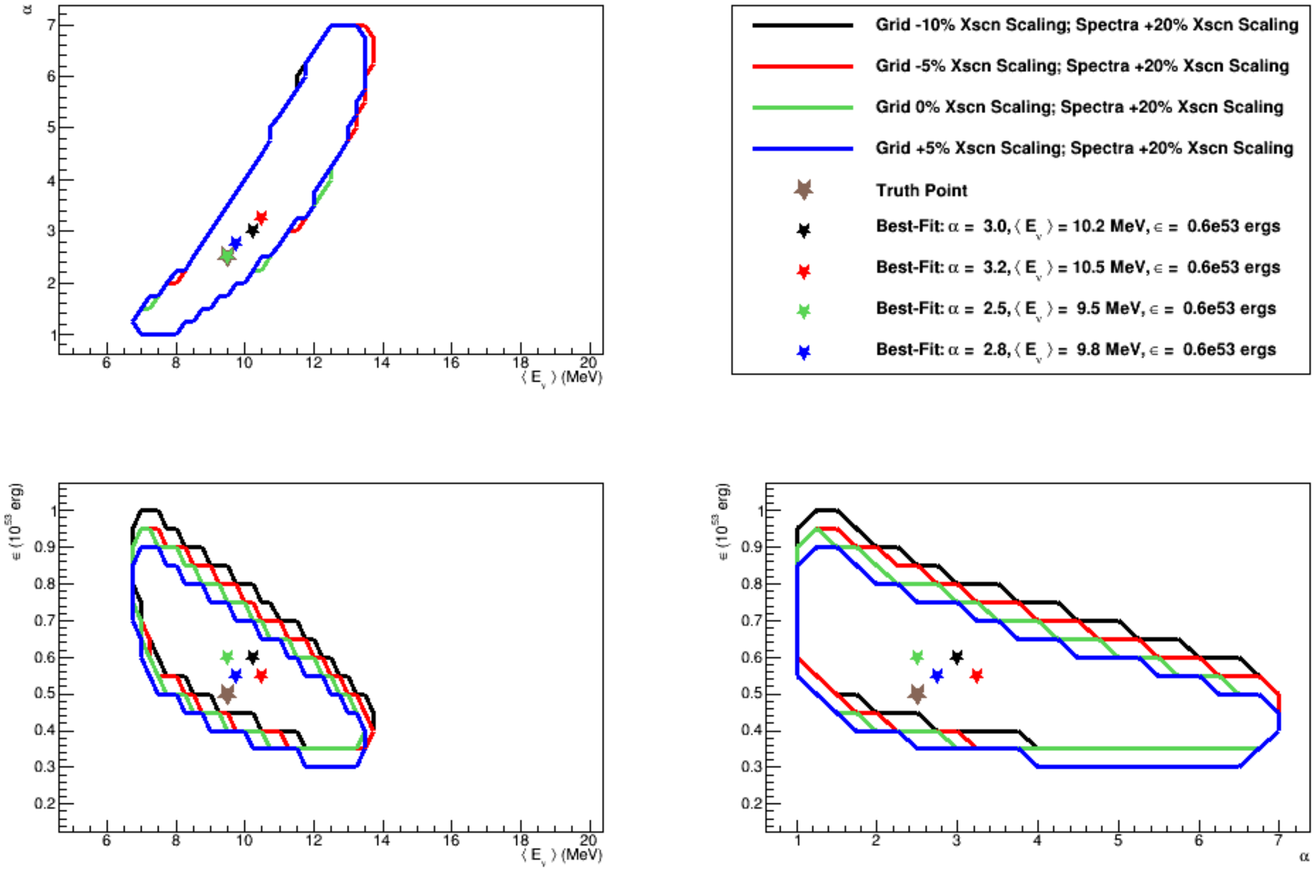
Contours: Center



Contours: Bottom Right Corner



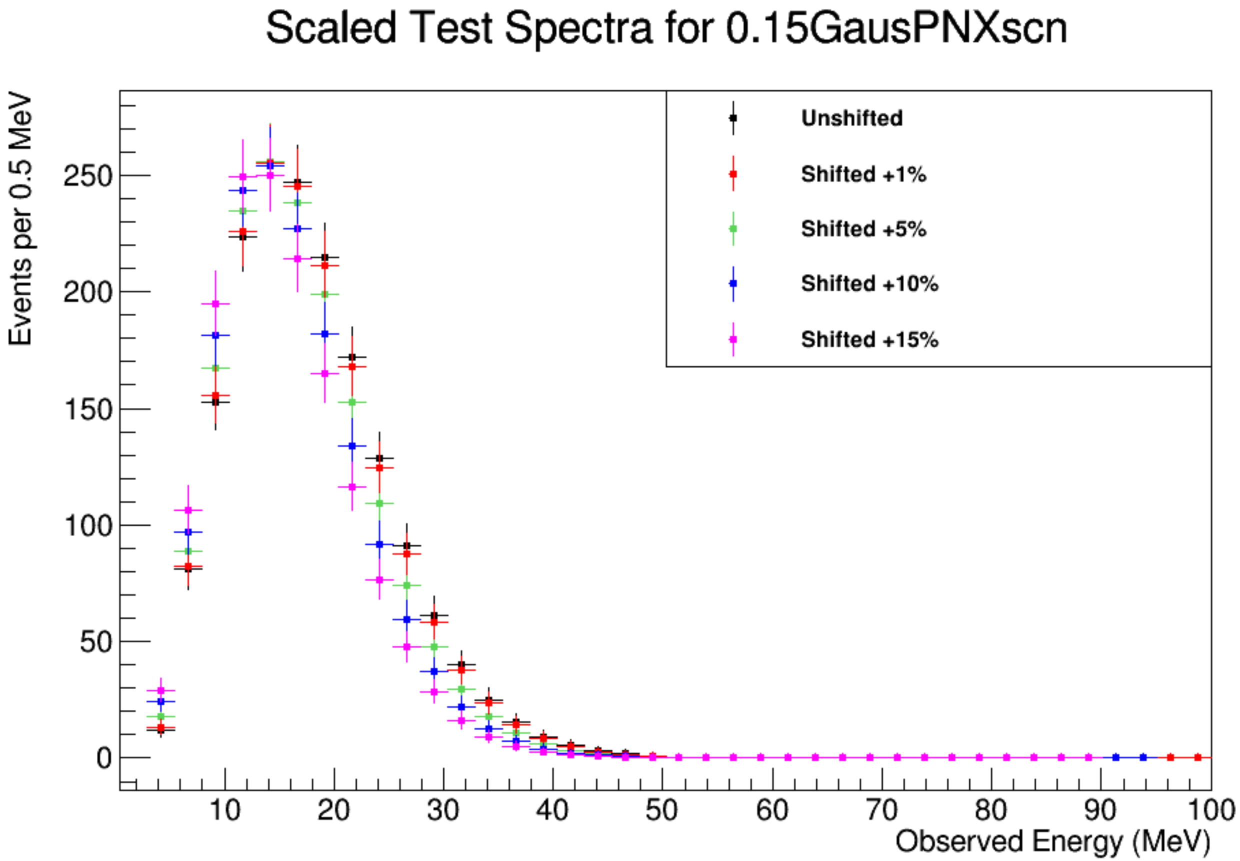
Contours: Top Row Elements



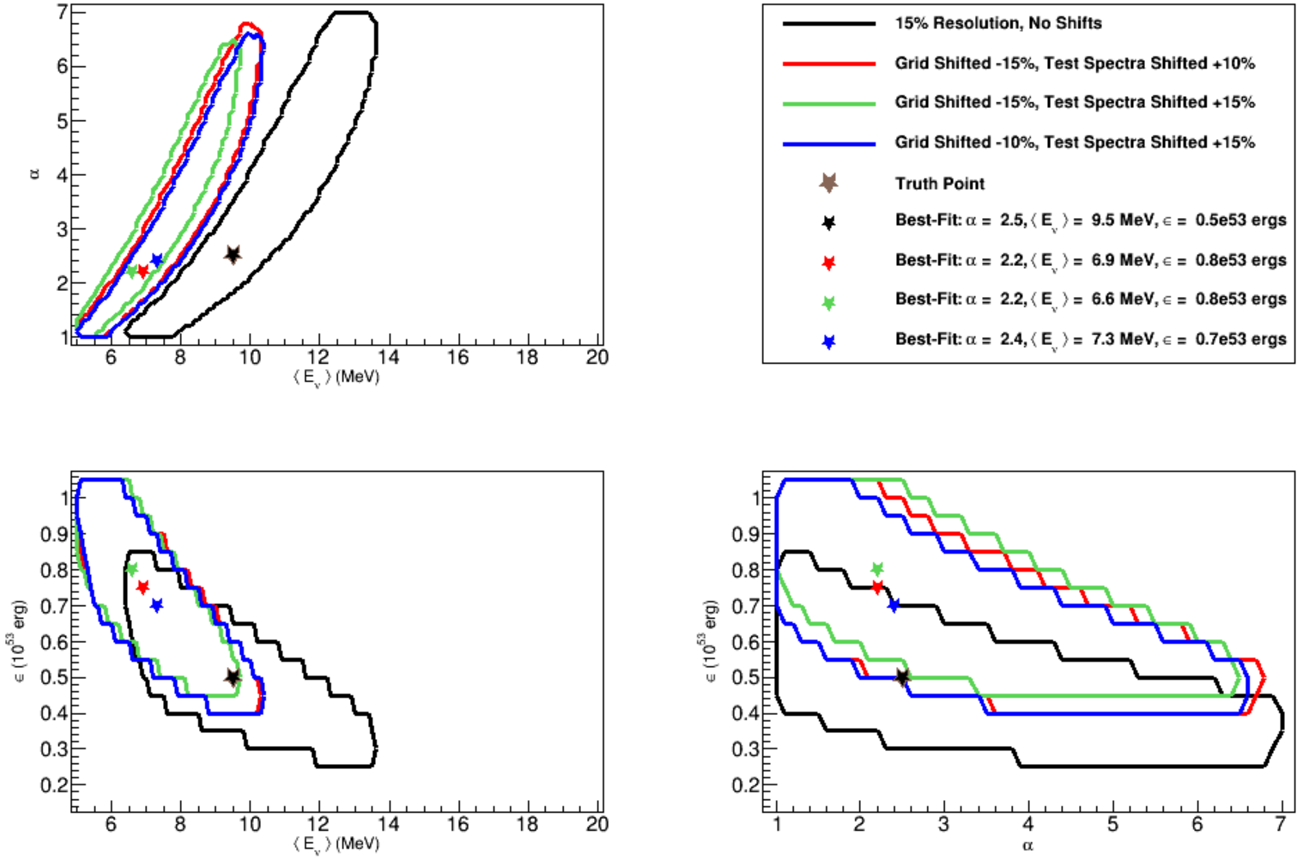
Backup Slides

ENERGY SCALING STUDY

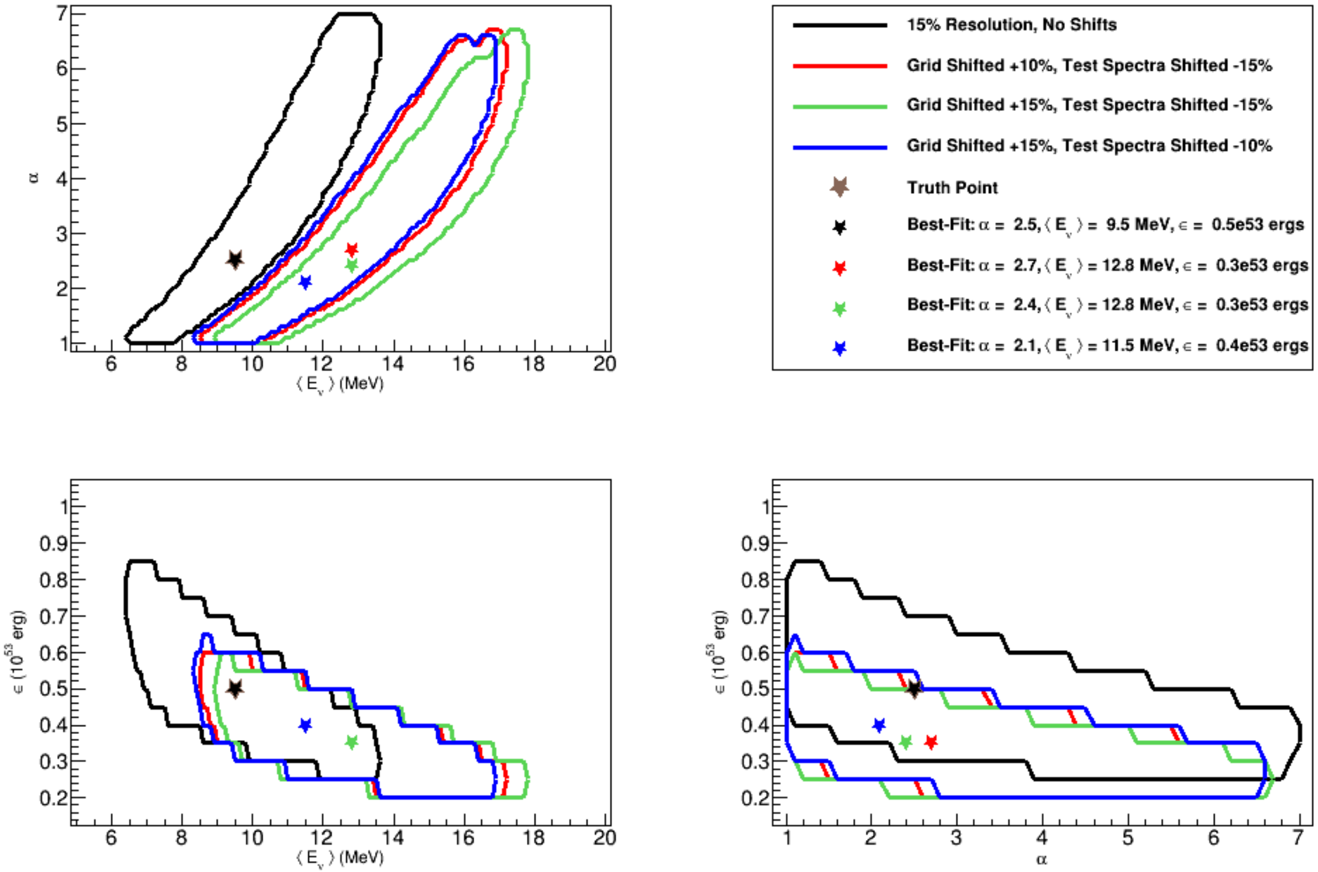
Scaled by Energy Fraction: Test Spectra



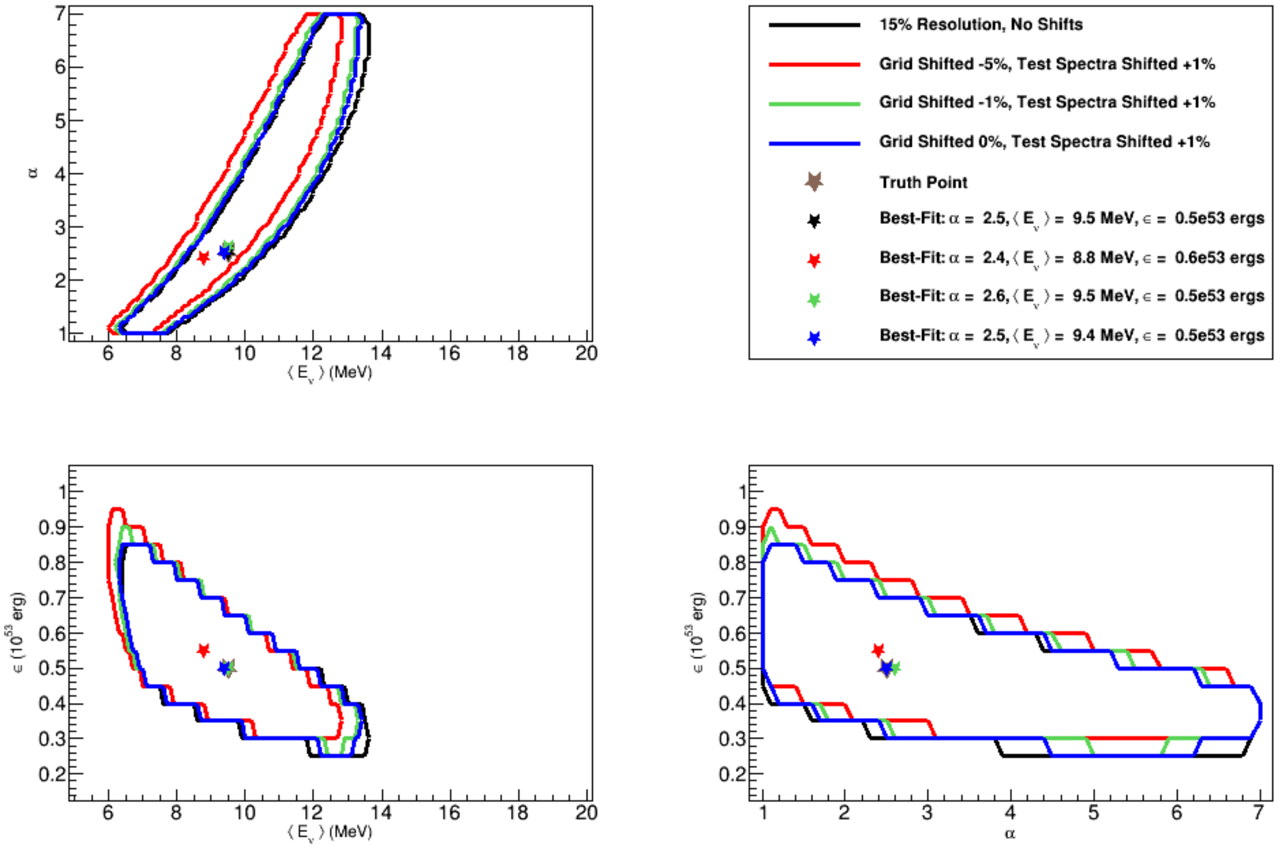
Contours: Upper Left Corner



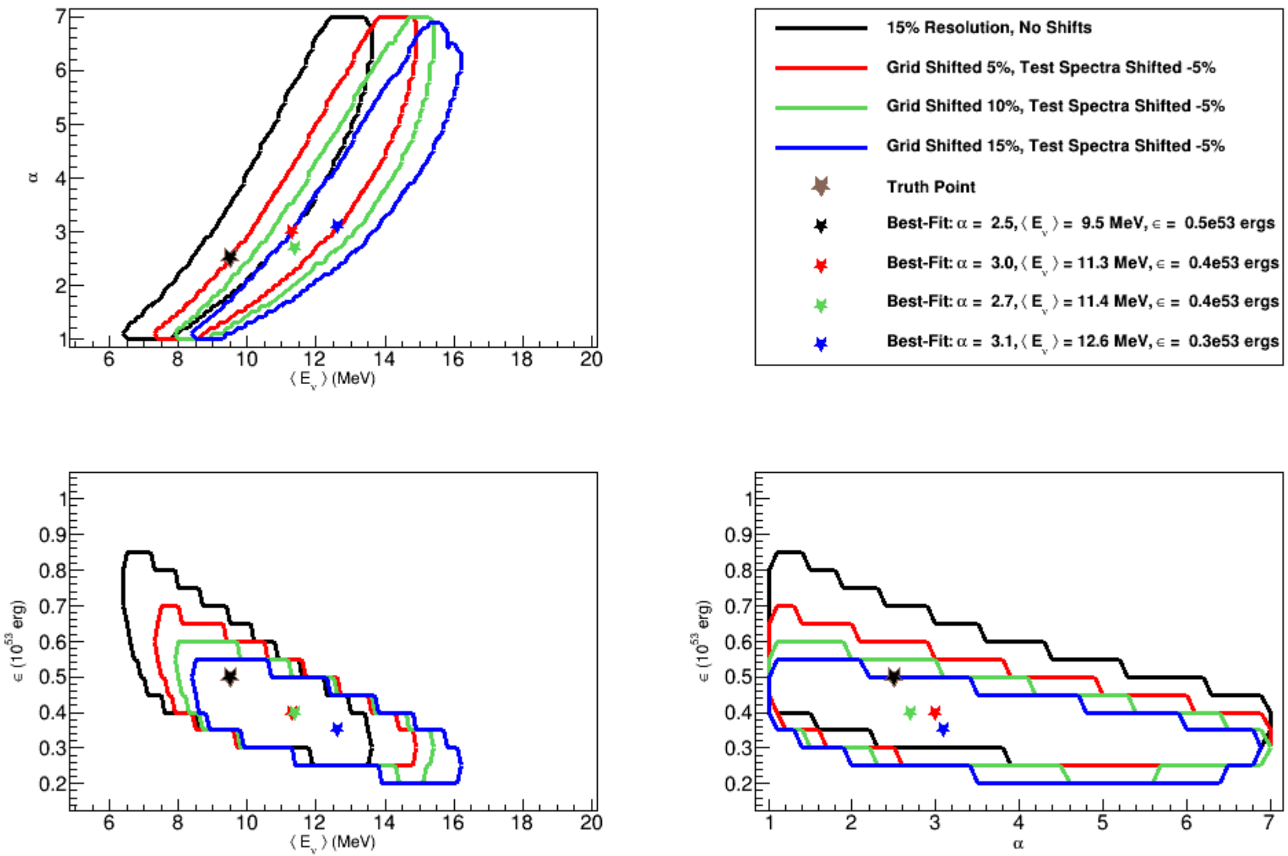
Contours: Lower Right Corner



Contours: Test Spectrum Shifted +1%



Contours: Test Spectrum Shifted -5%



Contours: Grid Spectra Shifted +15%