Mono-chromatic beams for νPRISM

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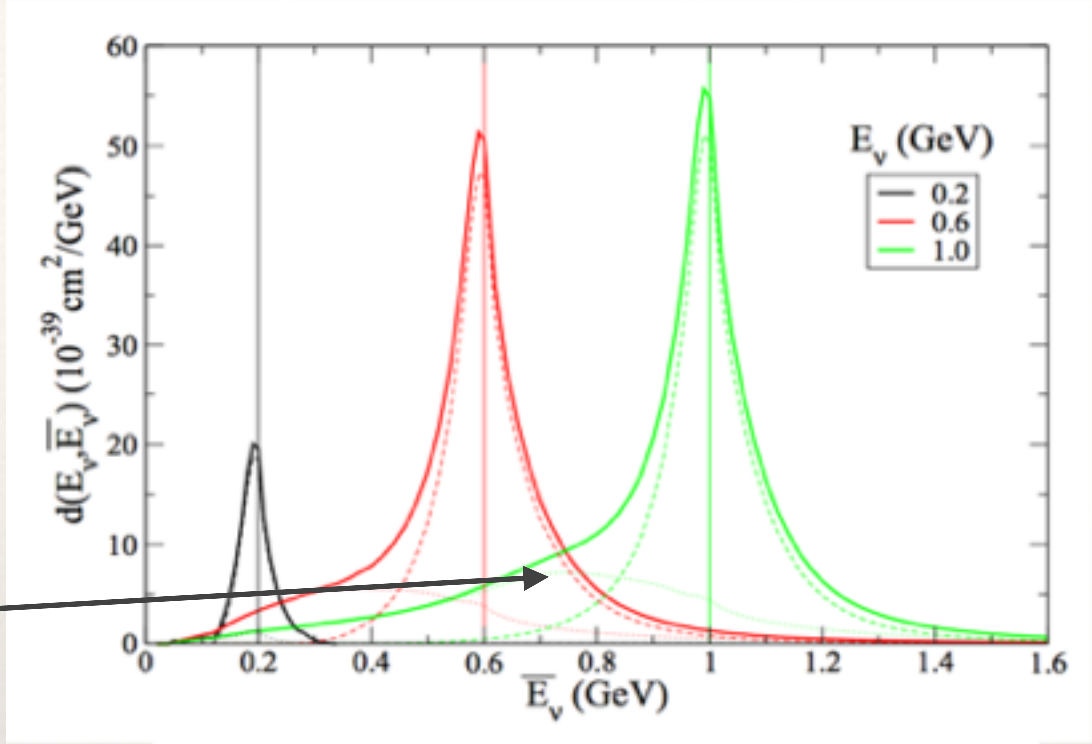
Motivation

- We know that there are large uncertainties in the modeling of nuclear effects, especially in the CC0pi cross section around 1 GeV
- Nuclear effects introduce tails to reconstructed energy distribution away from the quasi-elastic peak - source of systematic uncertainty in oscillation measurements

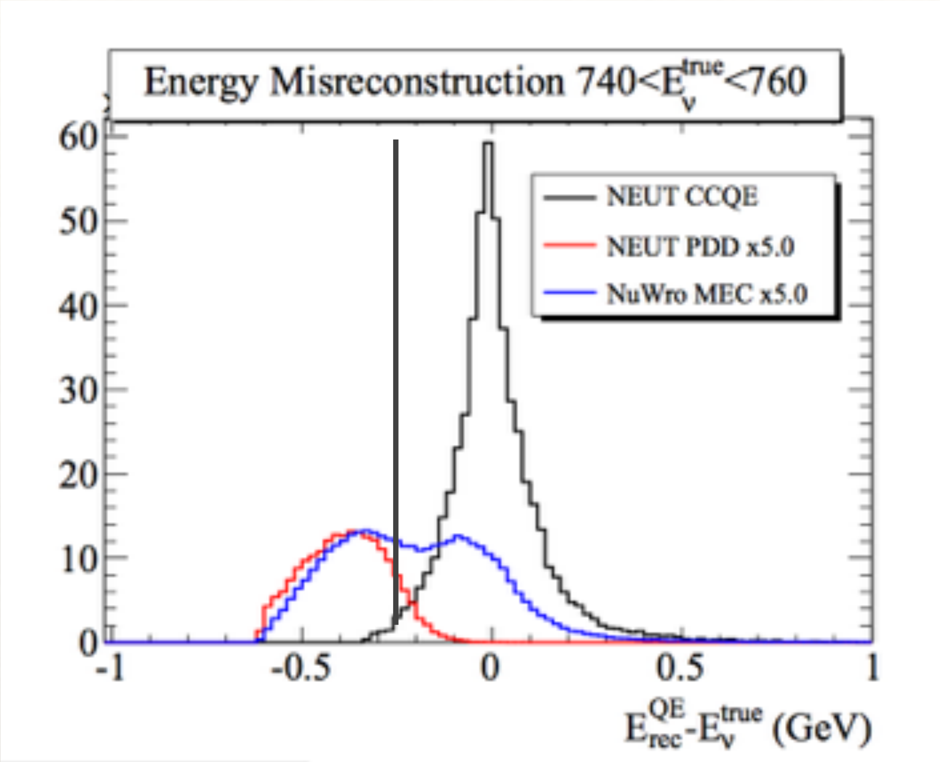


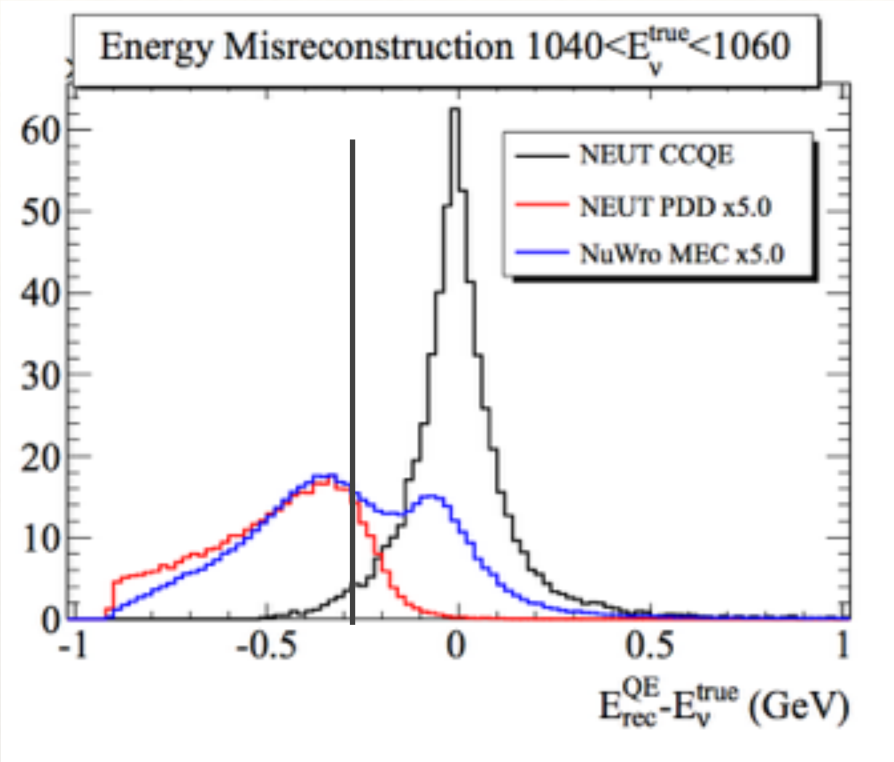
Martini et. al.
Phys.Rev. D87 (2013) 013009

- In electron scattering, these tails can be studied because the four momenta of the initial and final state leptons are measured
- If we know the initial neutrino energy, we can do similar measurements for neutrinos
- We can also directly study the energy dependence of the NC cross-sections

Mono-chromatic widths

- How narrow should the mono-energetic beams be?





- The dominant np-nh effects are at ~300 MeV below the peak energy in the 700-1000 MeV neutrino energy range - We should have a resolution smaller than this
- In principle, it should be possible to have significantly better resolution

Study Procedure

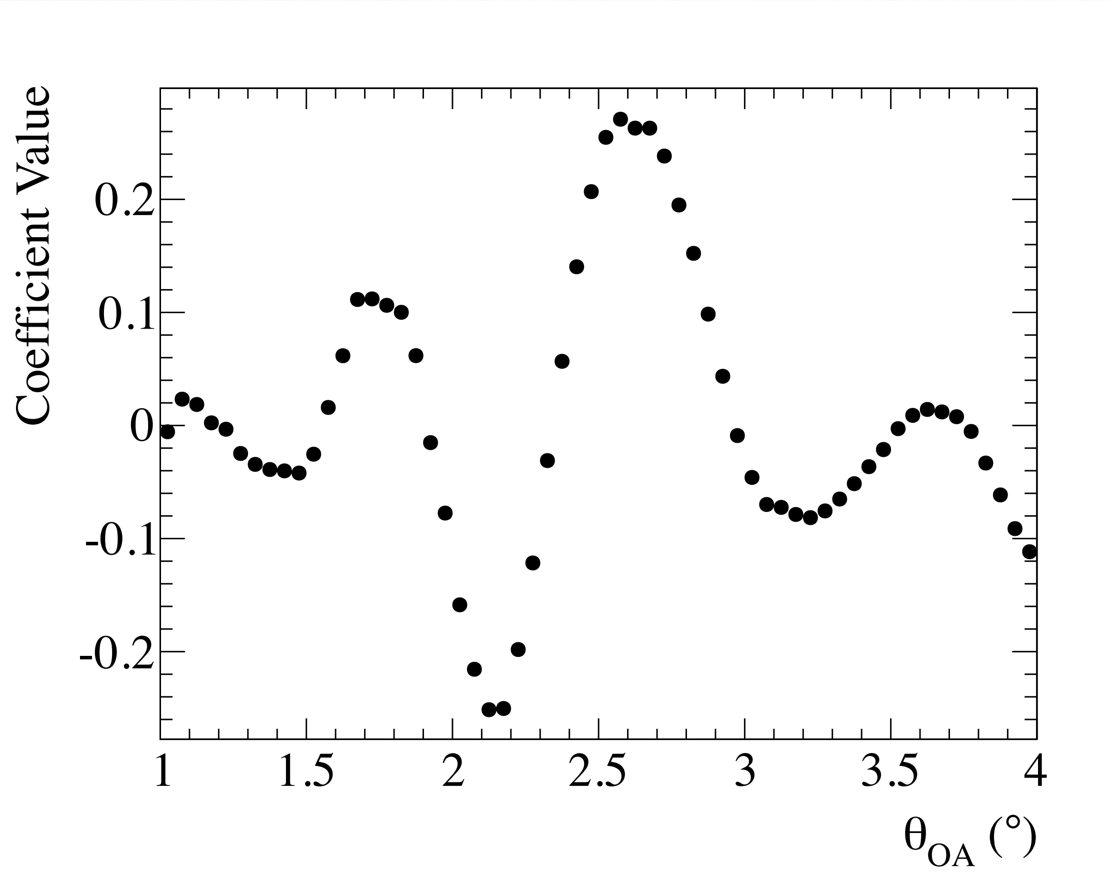
- Use the coefficient fitting code to make mono-energetic beams at 600, 900 and 1200 GeV
  - 60 bins of off-axis flux from 1 to 4 degrees

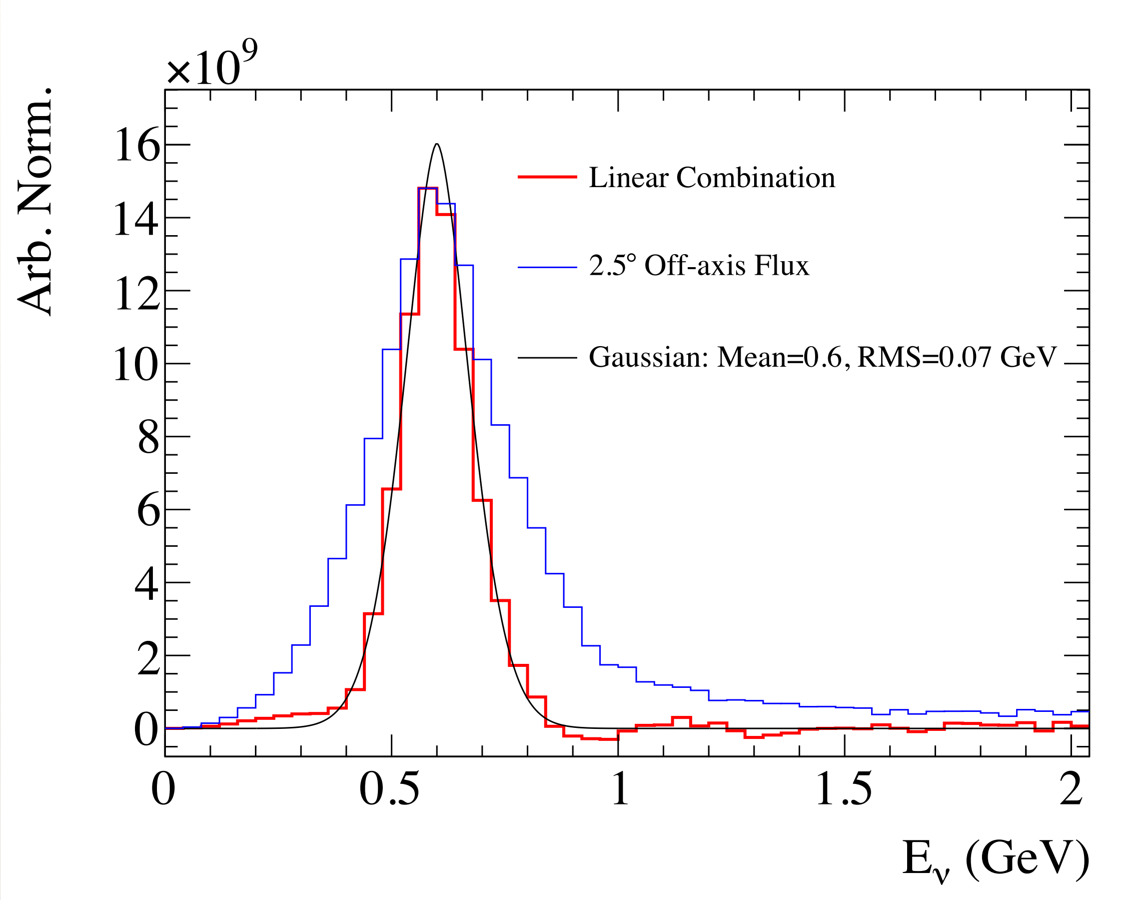
$$G(E_\nu;\mu,\sigma)=\sum_{i=1}^{\#\text{ of Off-axis bins}} c_i \phi_i(E_\nu)$$

- Apply the coefficients to the simulated nuPRISM interactions and evaluate flux systematic and statistical errors
  - For now statistical errors are calculated as the sum in quadrature of the weights (including the coefficients) for each event in the bin. Will check against the poisson throwing method
  - For the flux uncertainty, calculate a normalization and "shape" uncertainty
    - Normalization uncertainty: spread of the integral of the linear combination event rate for each flux throw
    - Shape uncertainty: spread on each bin after each flux throw has been renormalized to the nominal event distribution
- Using full MC stats, but statistical error bars are for 4.5e20 POT

600 MeV Flux Fit

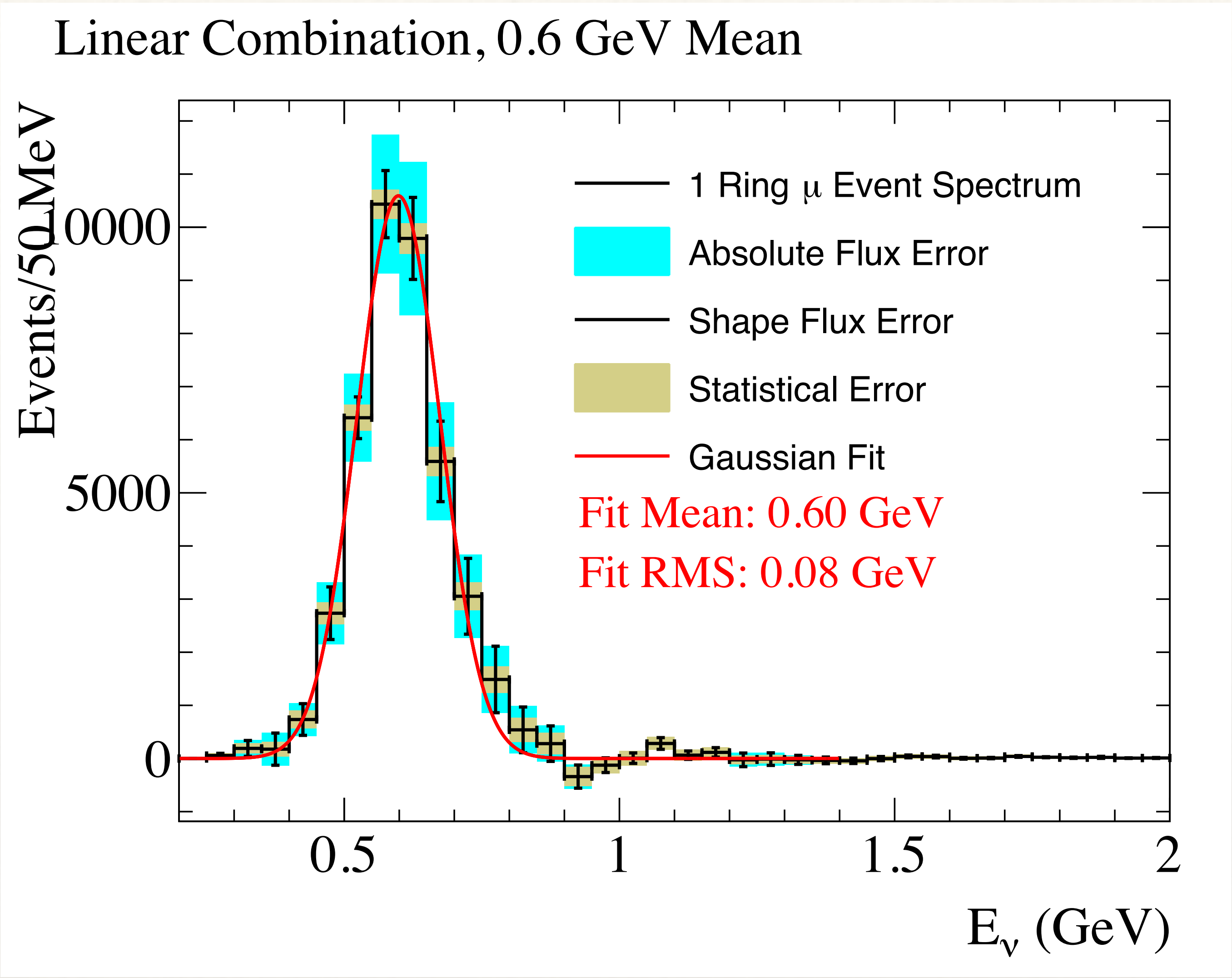
- Can achieve reasonable smoothness of the coefficients with a 70 MeV wide monoenergetic beam





- Here the fluxes are weighted by the energy to approximate the effect of the cross-section
- Haven't completely studied the trade-off between beam width and flux & statistical errors (narrower beam may be possible)

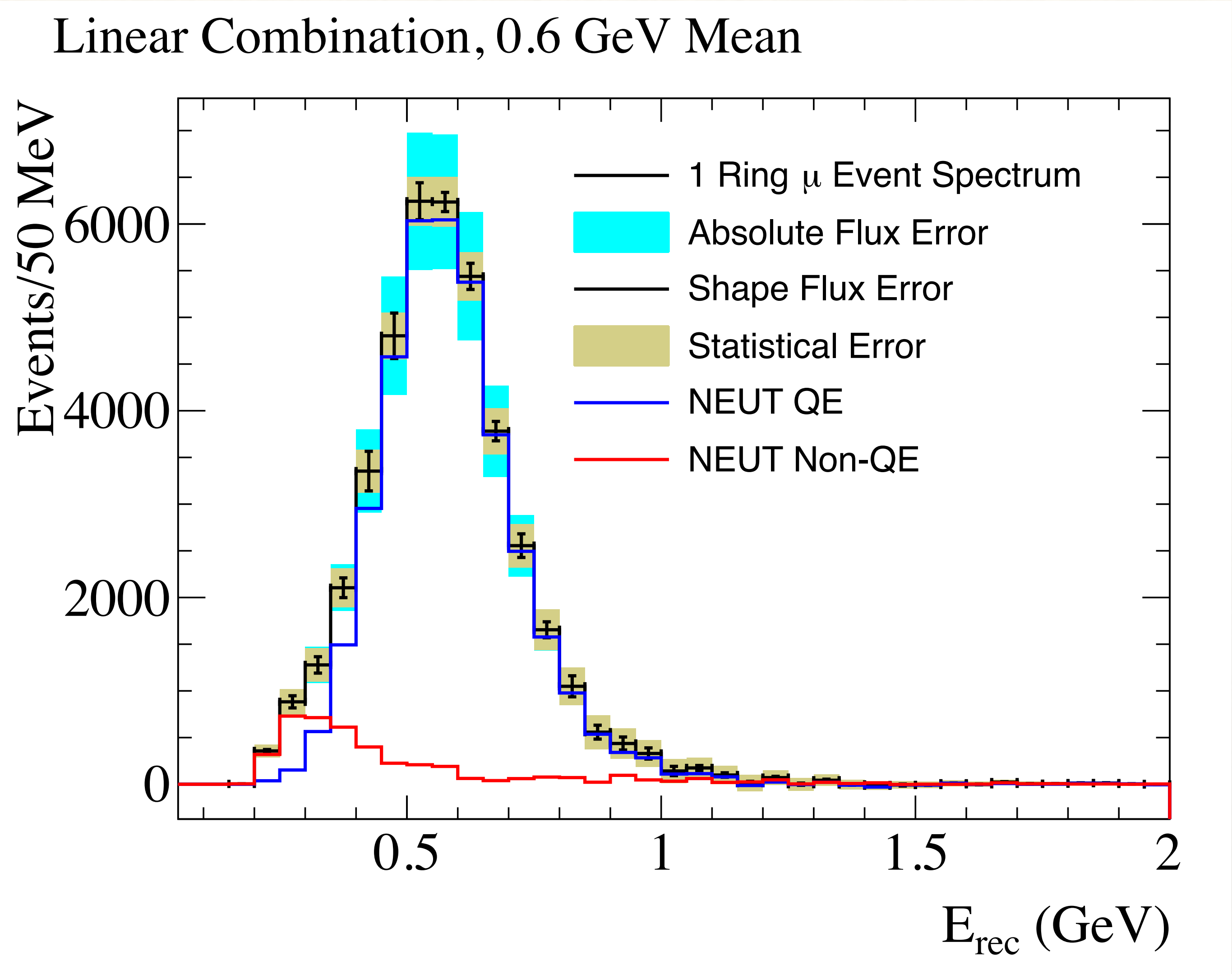
600 MeV Beam Event Rate (E_ν)



- Flux systematic variations:
  - Norm: 11% RMS
  - Mean: 3 MeV RMS
  - Width: 5 MeV RMS

- The flux normalization error is consistent with T2K cross section measurements
- The shape error is reduced near the peak, but not so much in the tails

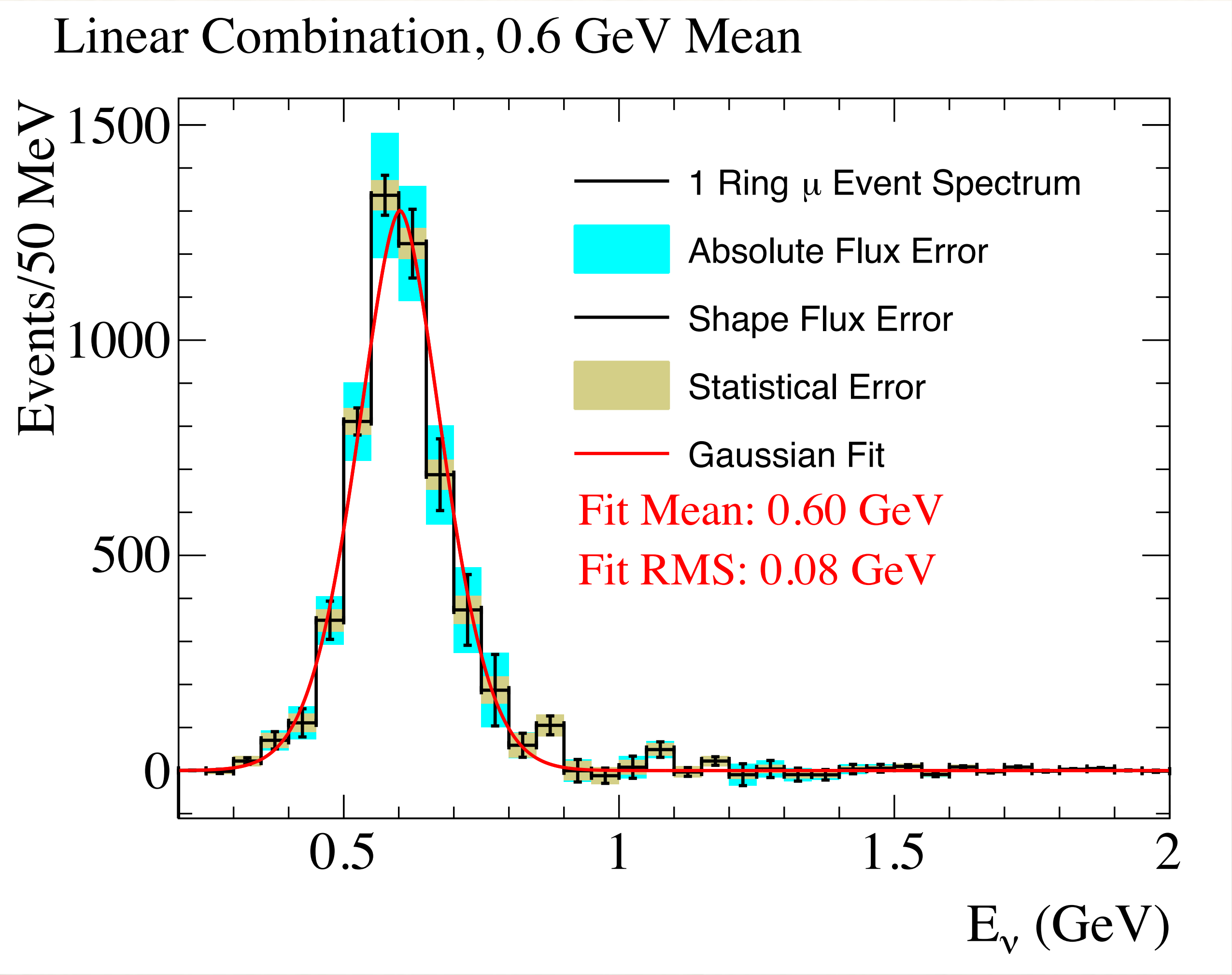
600 MeV Beam Event Rate (E_{rec})



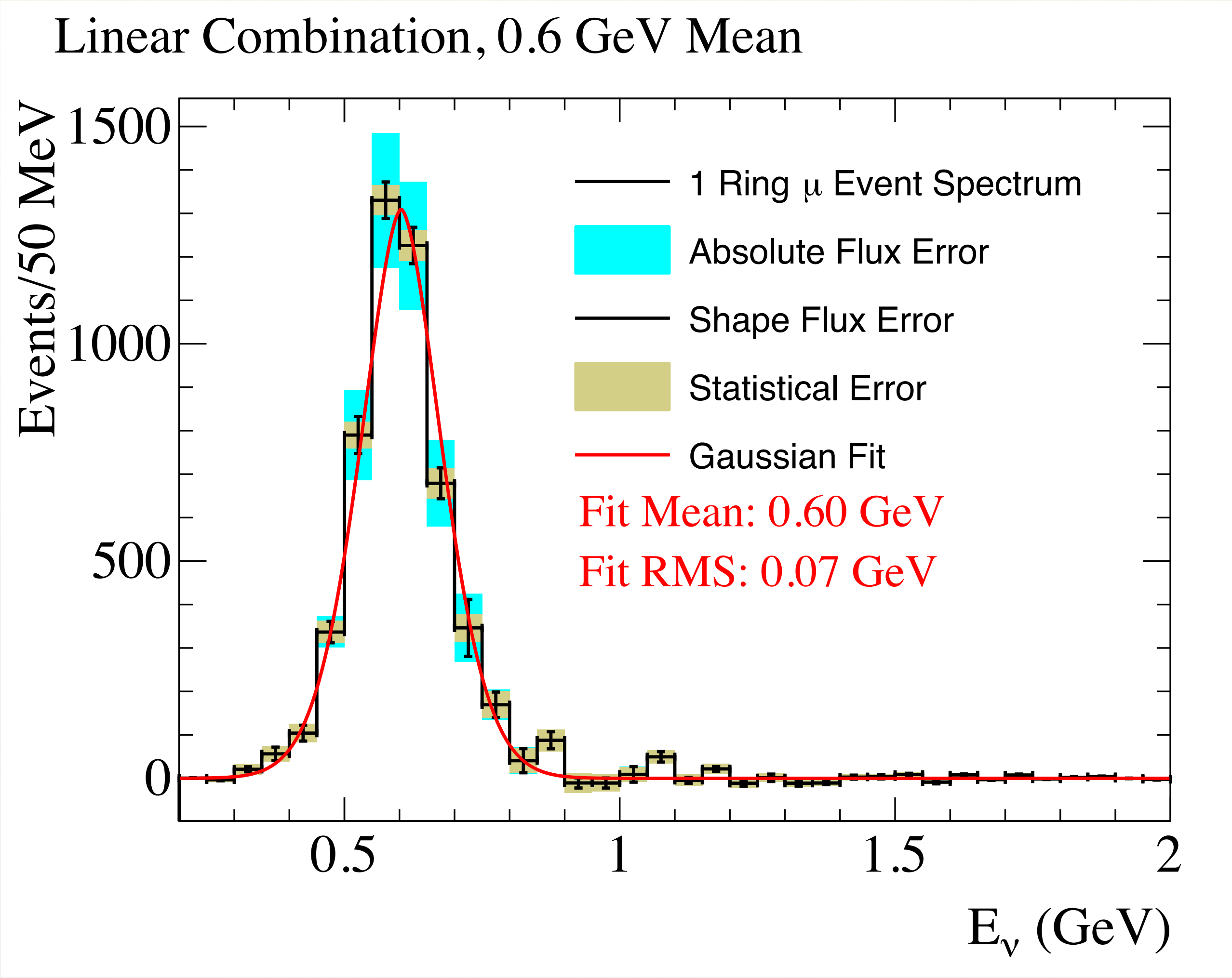
- A significant excess due to non-QE at low reconstructed energy can be observed
- Should update the study using the Nieves model to have more non-QE events

Comment on Flux Uncertainties

All flux uncertainties



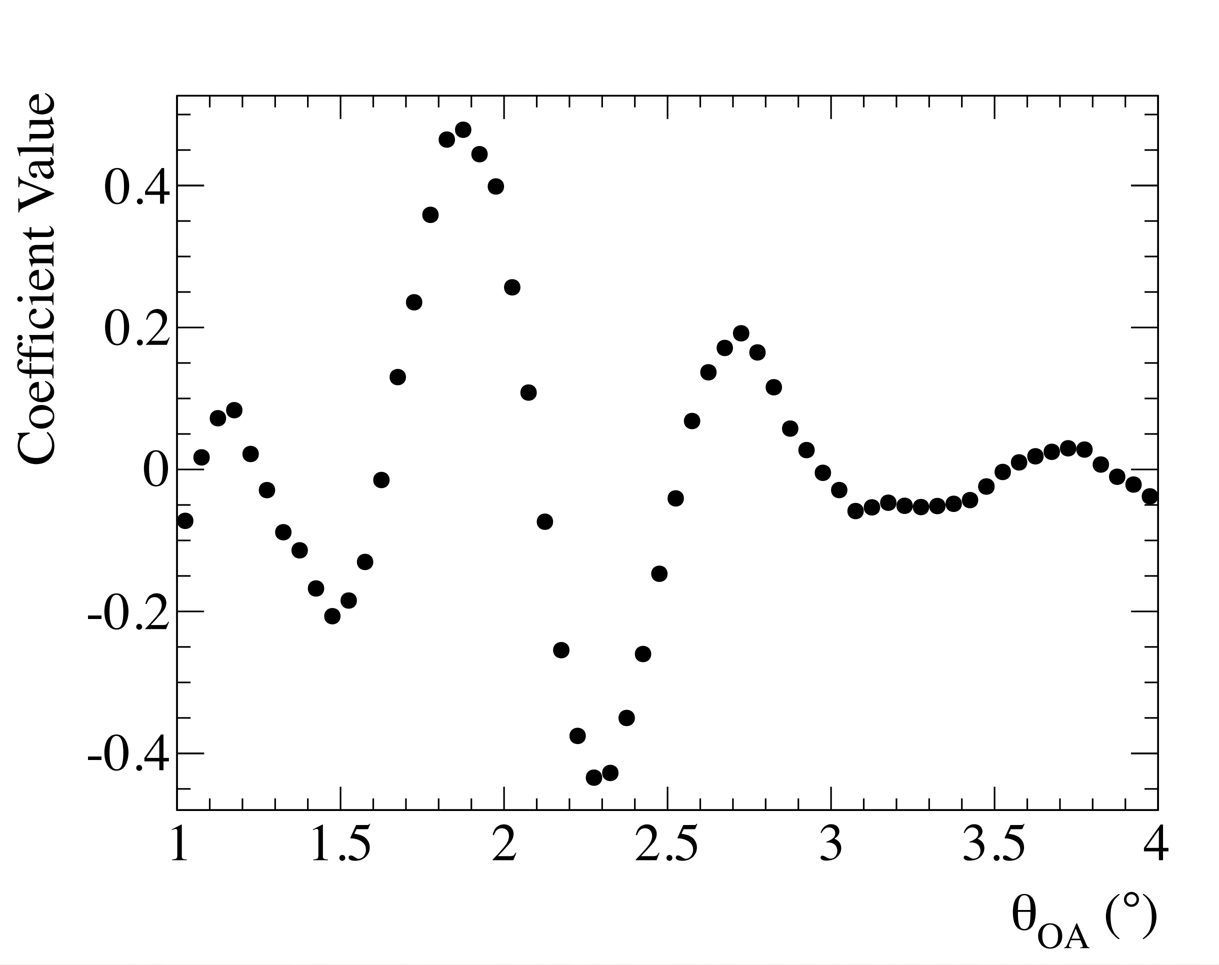
Excluding absolute horn current uncertainty

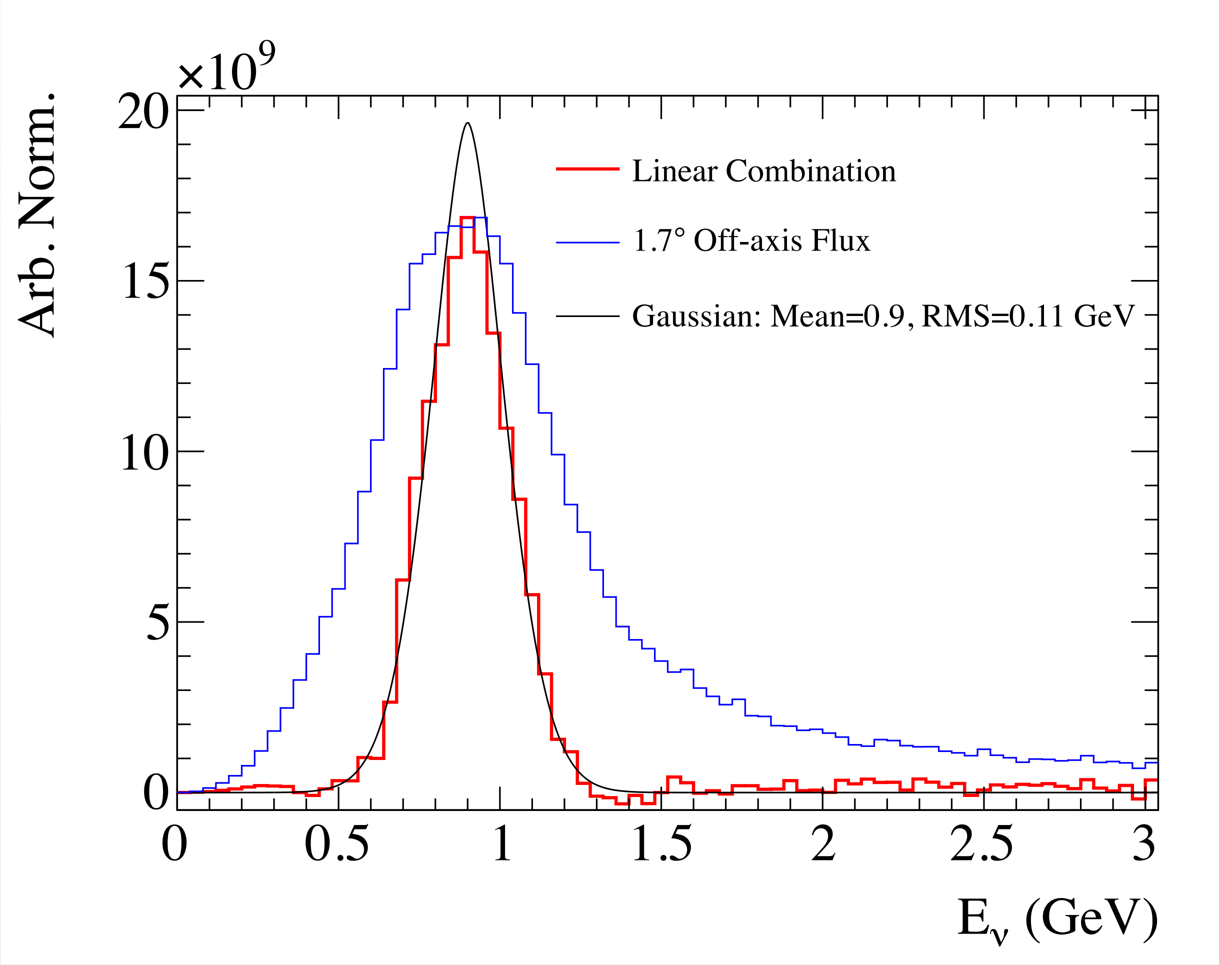


- A significant fraction of the flux uncertainty in the tails is coming from the horn absolute current uncertainty
- This error is made with regenerated nuPRISM fluxes at +5kA horn current
  - Could this be a statistical effect? Need to investigate

900 MeV Flux Fit

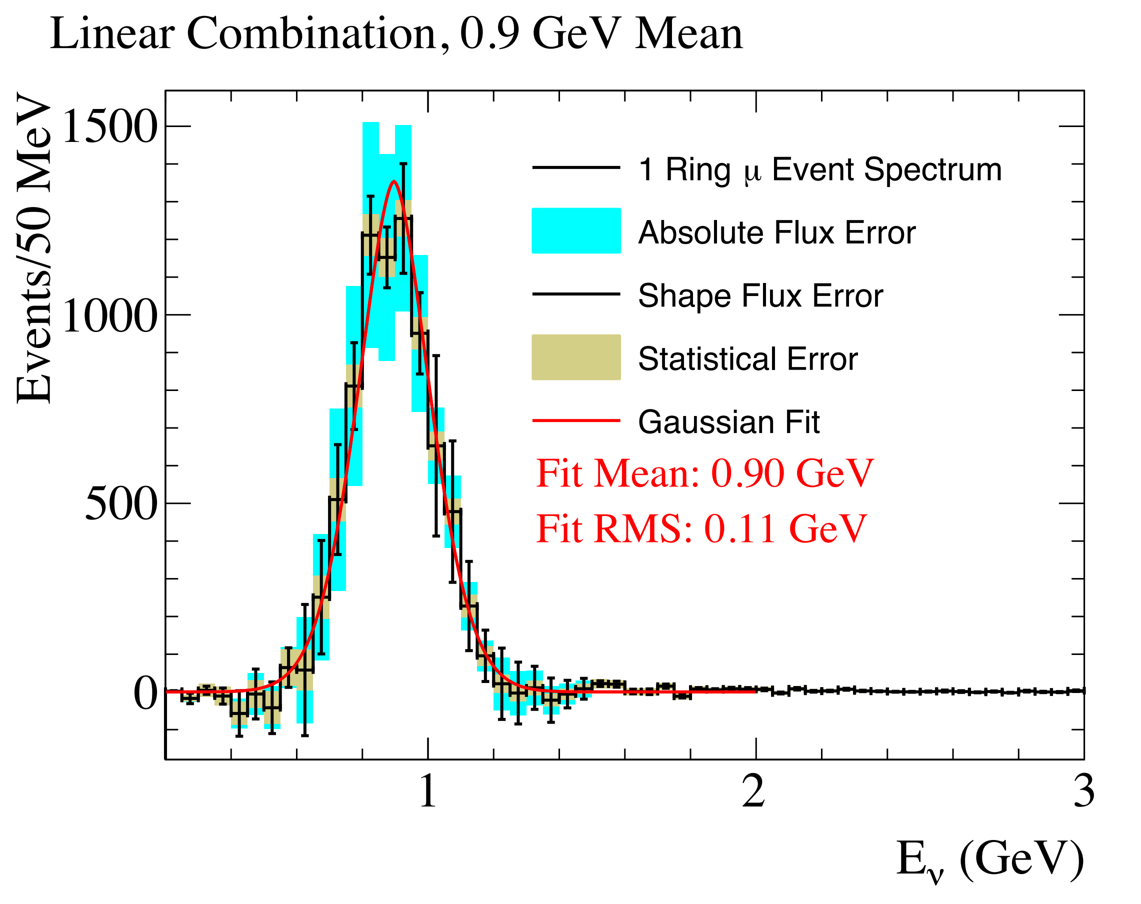
- Can achieve reasonable smoothness of the coefficients with a ~110 MeV wide monoenergetic beam



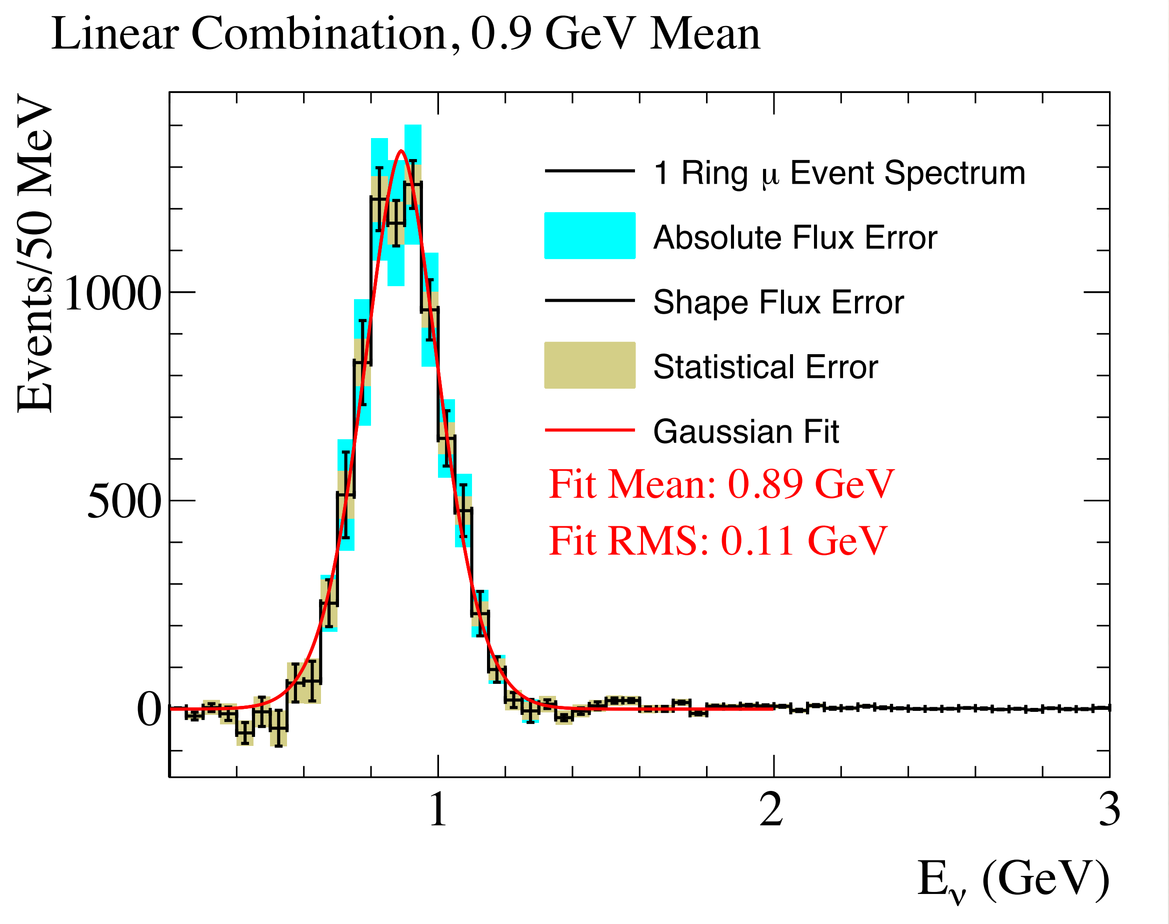


900 MeV Event Rates

All flux uncertainties

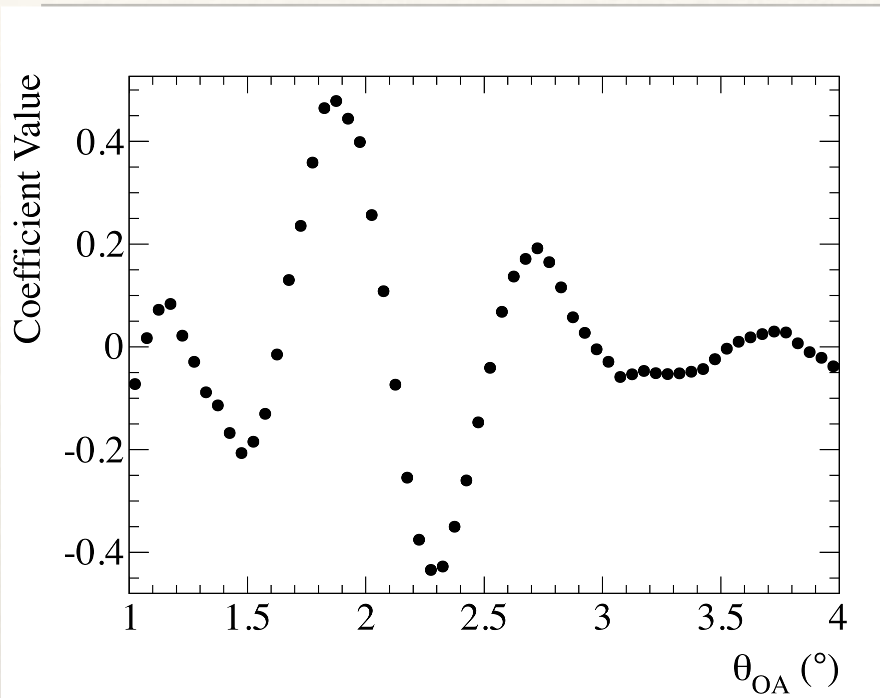


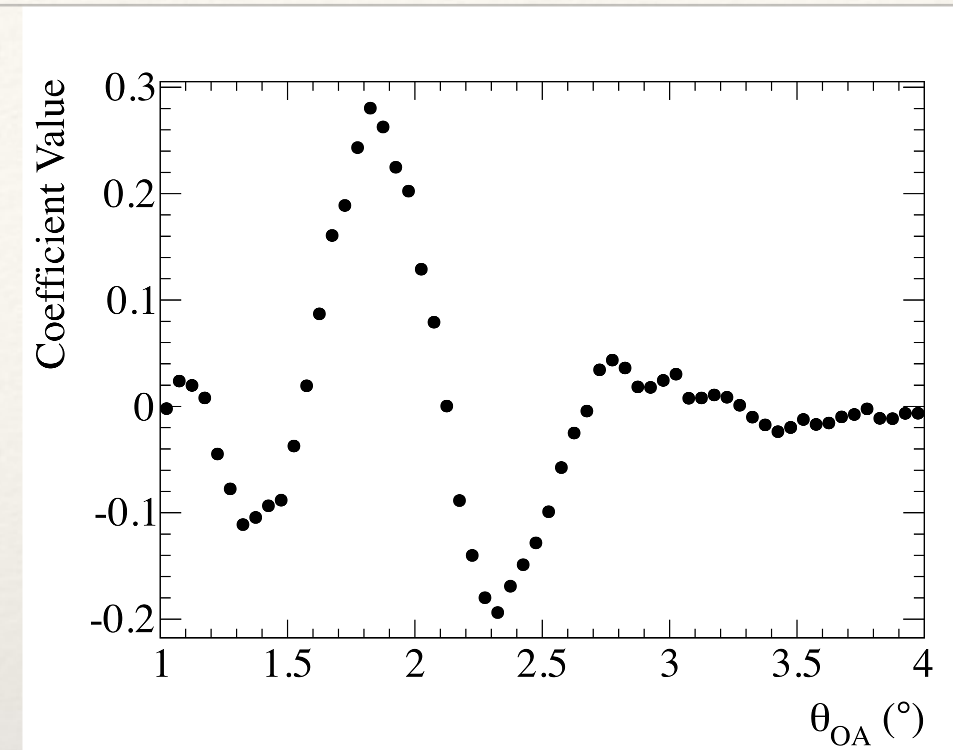
Excluding absolute horn current uncertainty



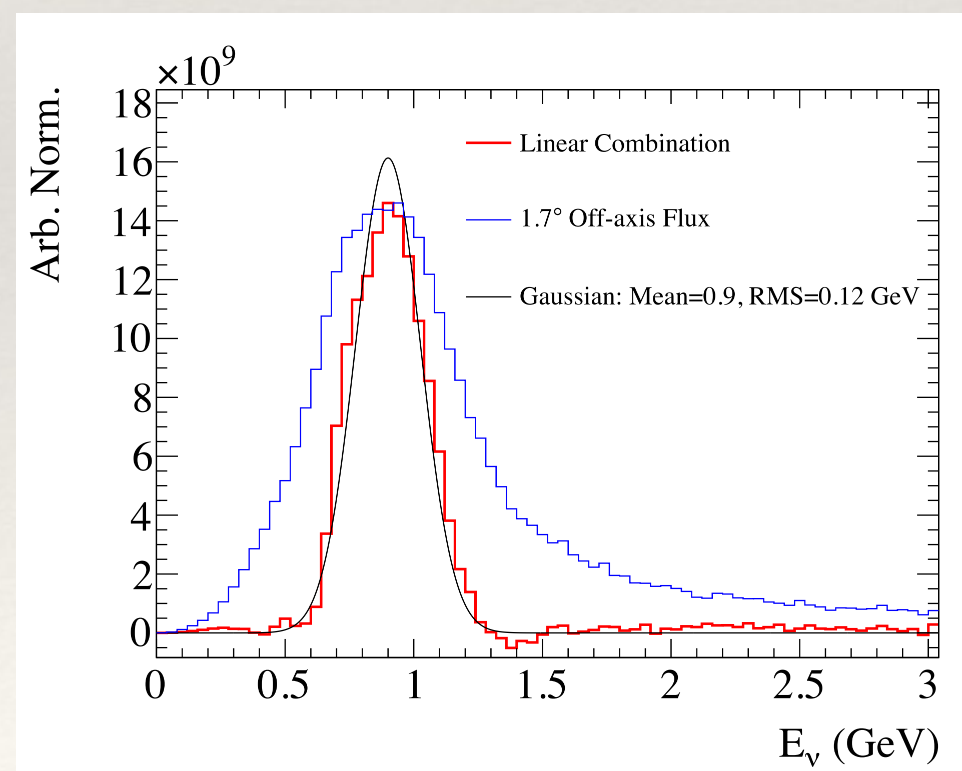
- The flux uncertainties (left) are rather larger around 600-700 MeV (the region of interest for nuclear effects)
- Turning of the horn current uncertainty (right) greatly reduces the error
- Once again, not sure if this is a statistical effect. For now, try choosing coefficients to spread out the contribution to the 600-700 MeV bins from multiple off-axis angles

900 MeV Flux Fit, Take 2

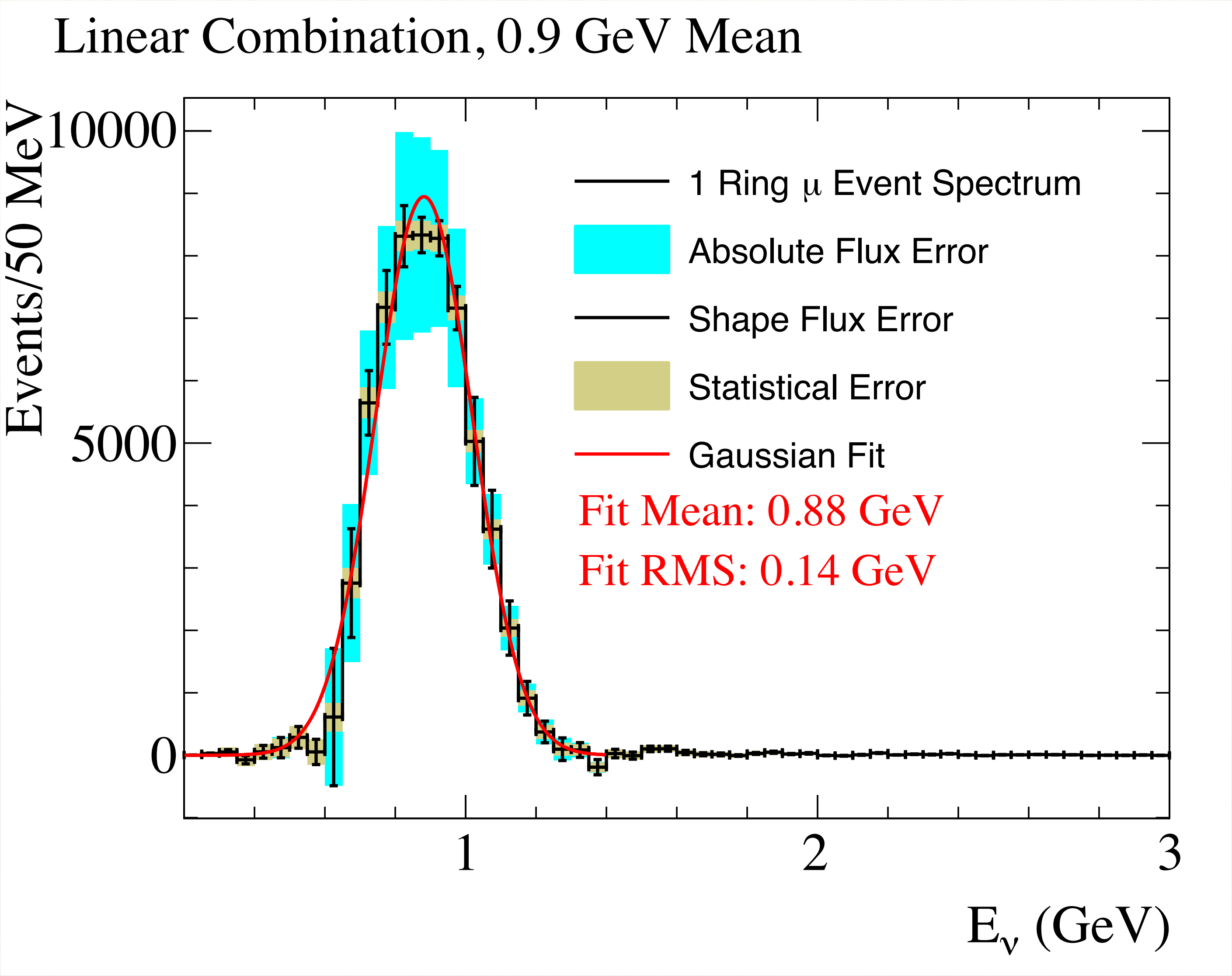




- The coefficient distribution is broader with smaller overall magnitude
- At the cost of a slightly wider mon-energetic beam



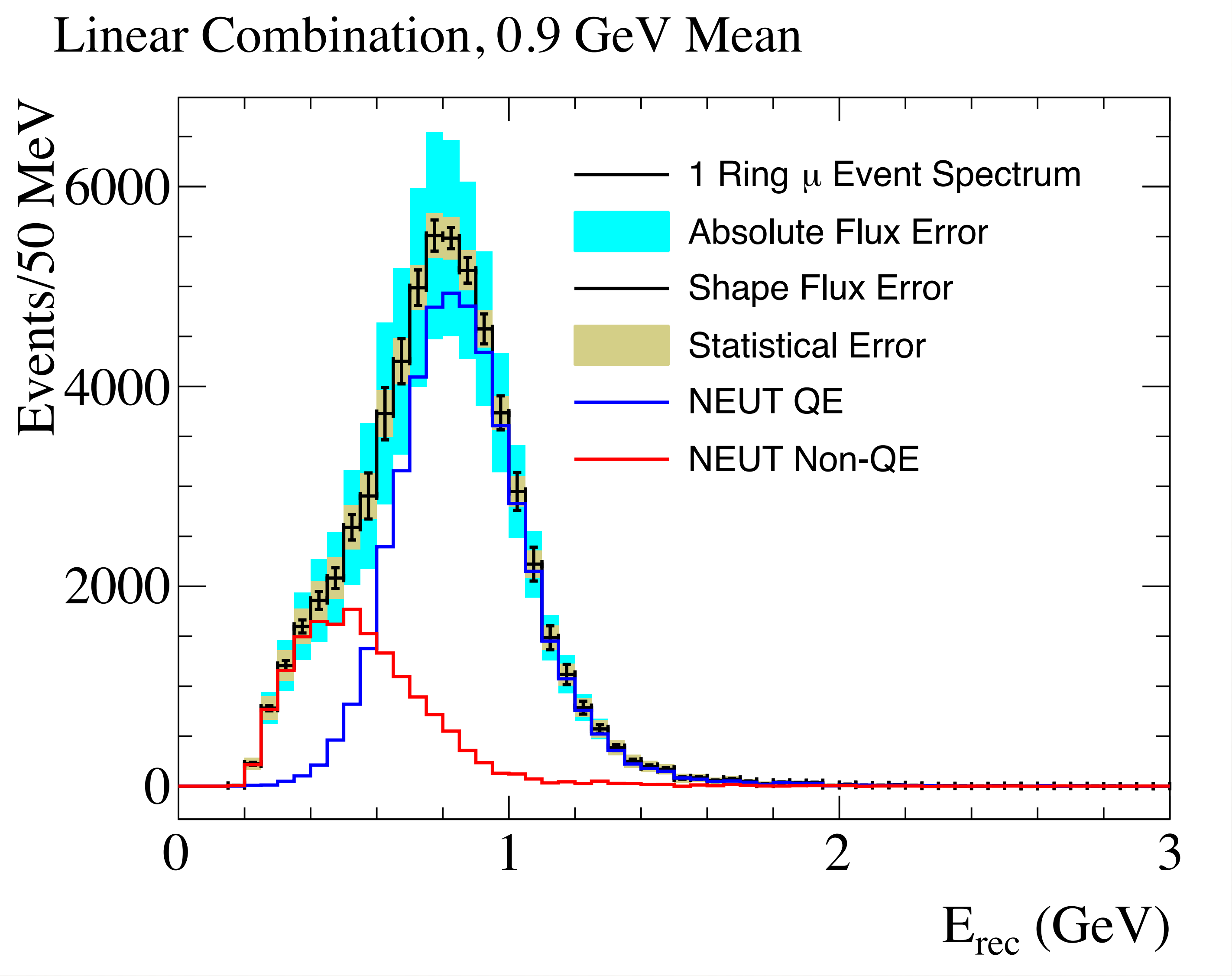
900 MeV Beam Event Rate (E_ν)



- Flux systematic variations:
  - Norm: 19% RMS
  - Mean: 15 MeV RMS
  - Width: 4 MeV RMS

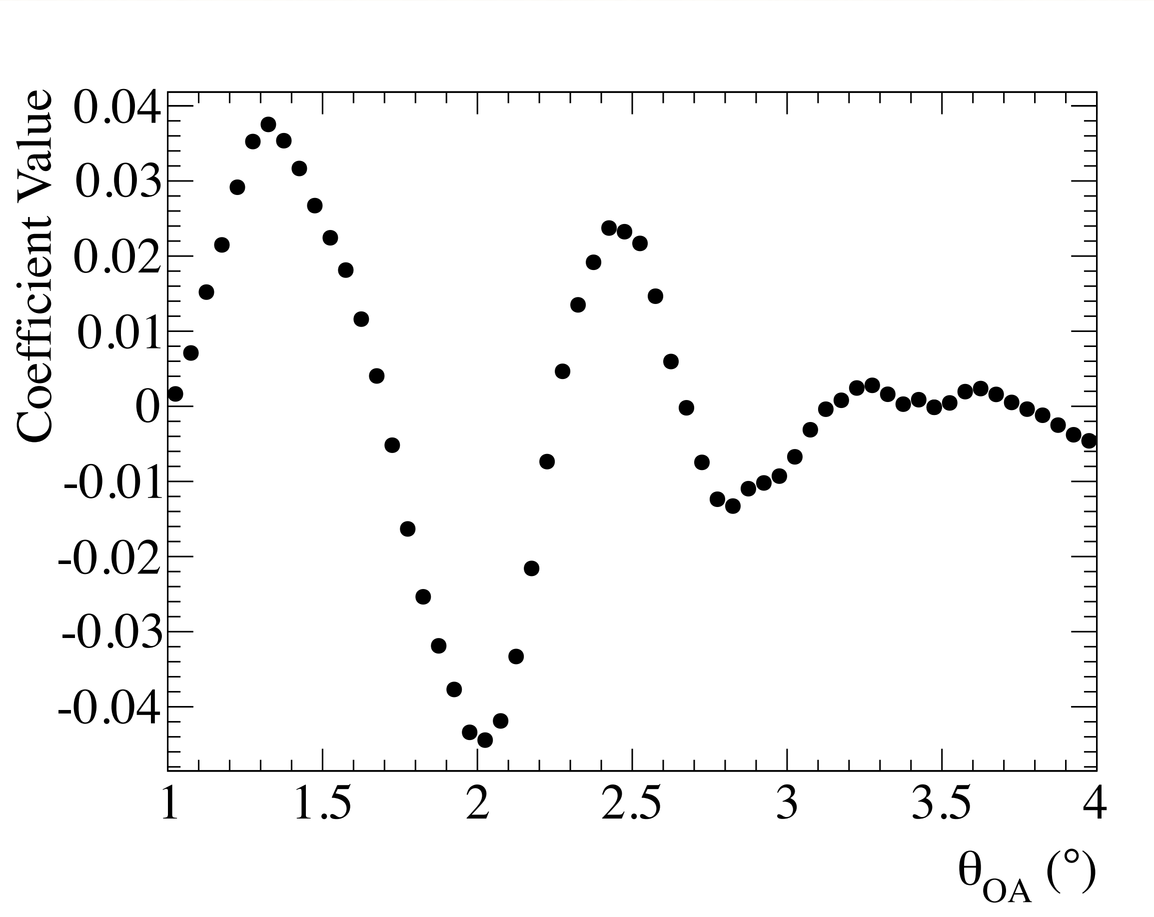
- The flux normalization error is rather larger compared to T2K cross section measurements
- The flux error in 600-700 MeV is improved

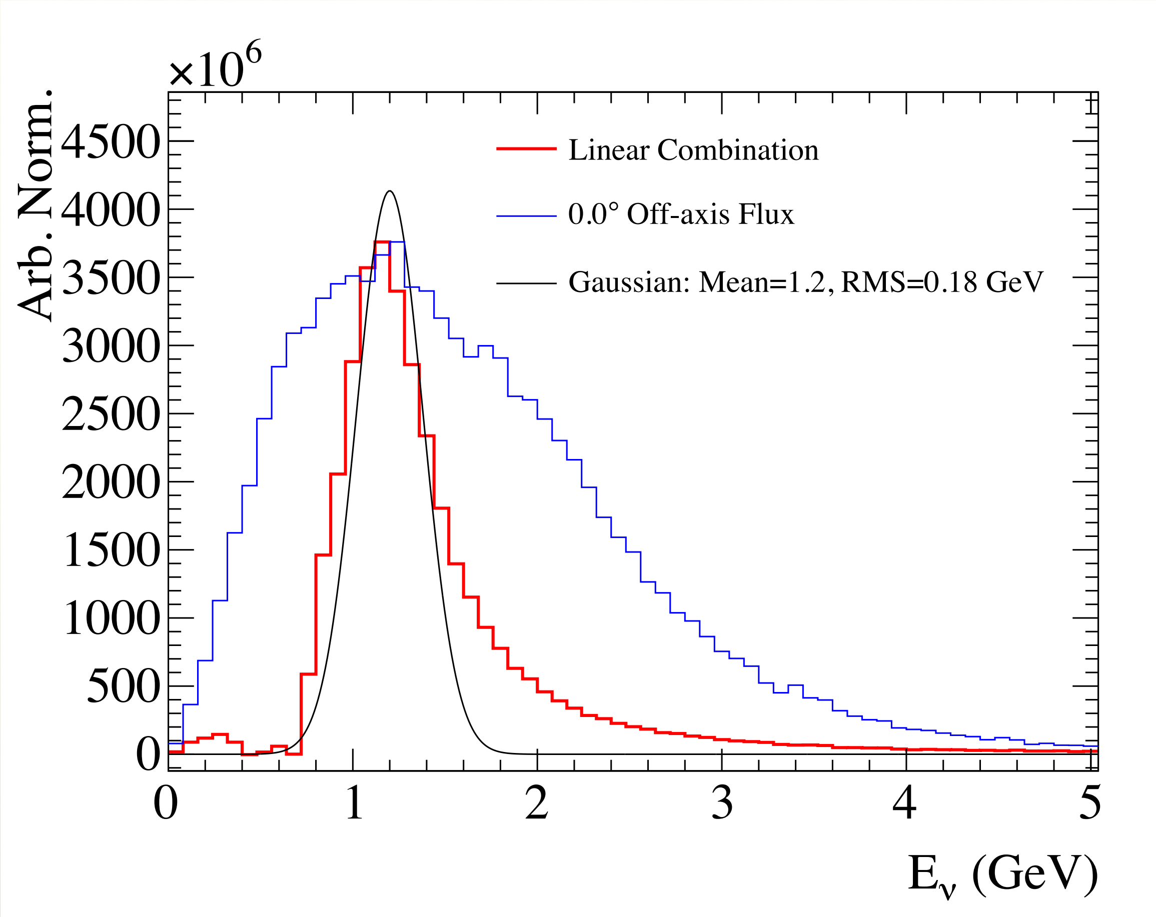
900 MeV Beam Event Rate (E_{rec})



- We can clearly measure the feed-down contribution from non-QE processes
- The flux uncertainty relative to the peak is well controlled

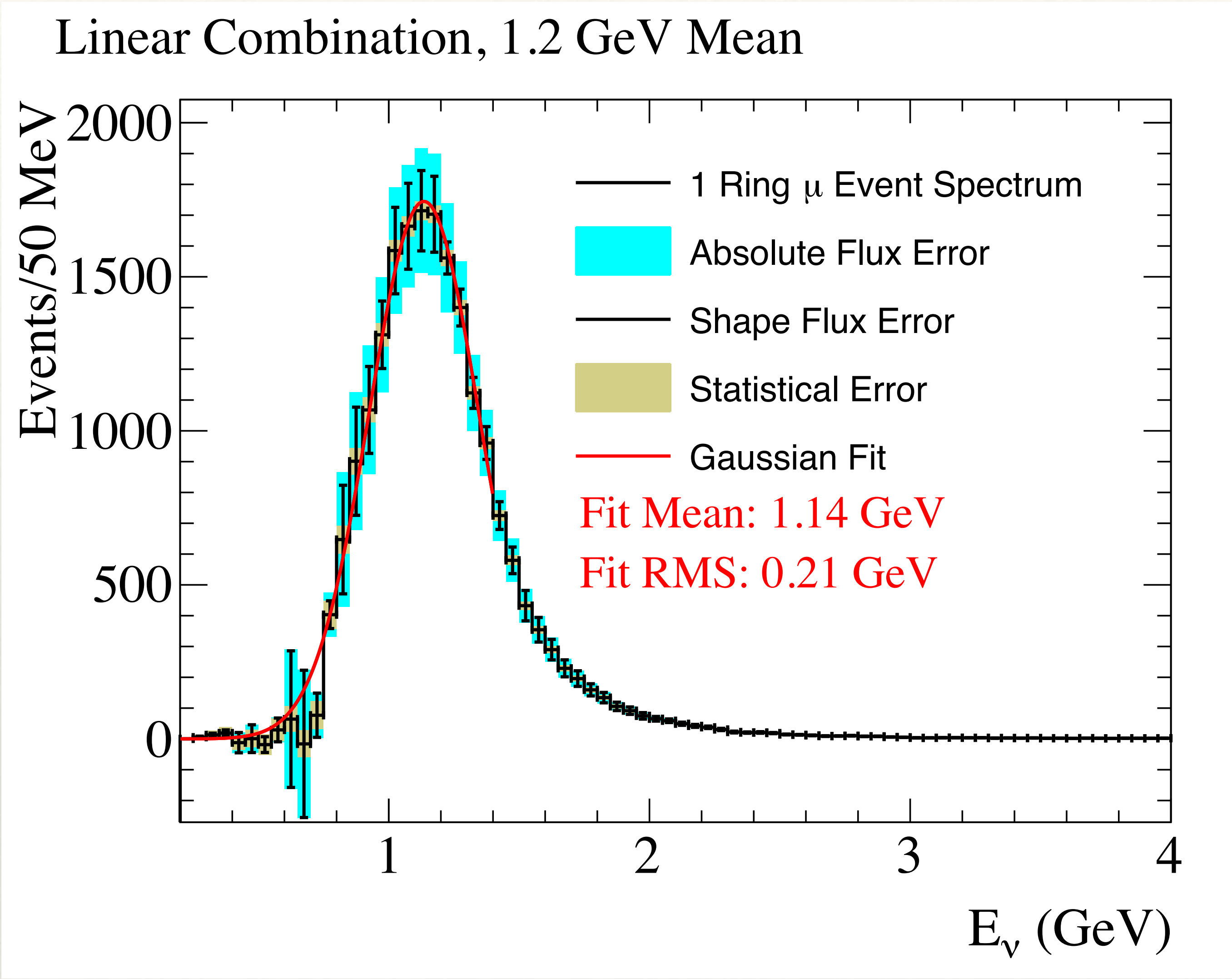
1200 MeV Flux Fit





- 1200 MeV is about the limit of what we can achieve with a narrow band beam fit
- Even so, it is hard to completely reduce the high energy tail

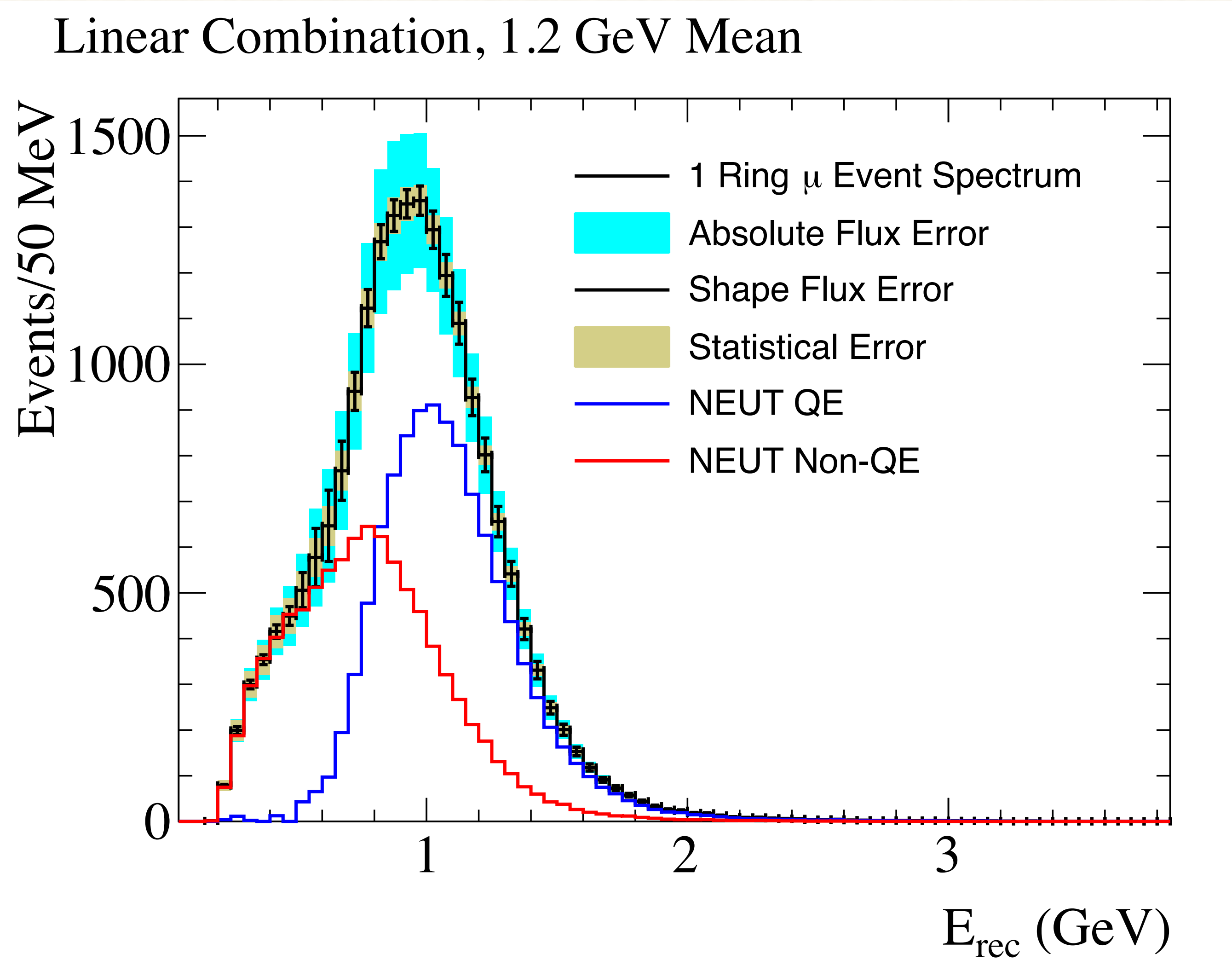
1200 MeV Beam Event Rate (E_ν)



- Flux systematic variations:
  - Norm: 11% RMS
  - Mean: 14 MeV RMS
  - Width: 23 MeV RMS

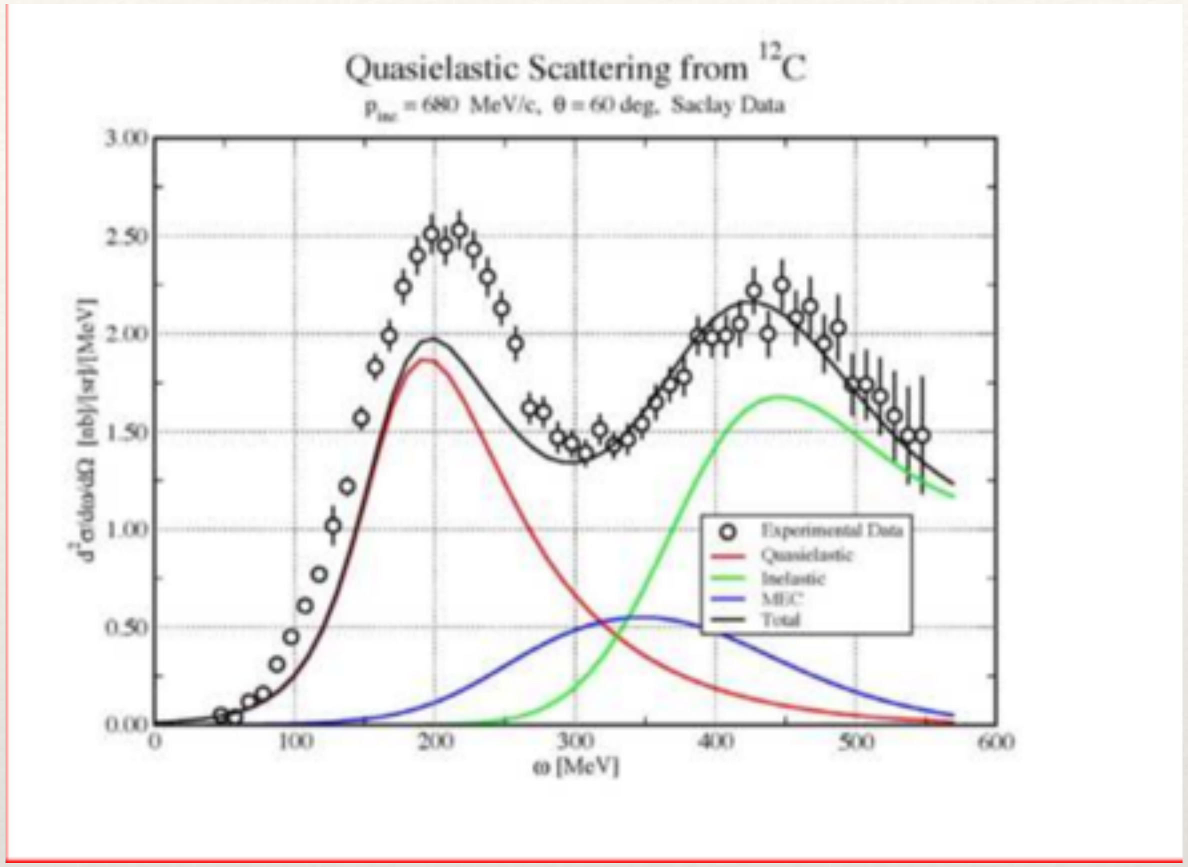
- Once again the error bars on the 500-600 MeV region are large.

1200 MeV Beam Event Rate (E_{rec})



- The reconstructed distributions nicely shows the ability to observe the tail from nuclear effects
- The flux shape errors are smaller here (indicating it is statistical effect that is cancelled out in the smearing due to the reconstruction).

Electron Scattering Variables



- In electron scattering, they are often measuring the energy transfer from the initial state lepton to the target
- If we know the initial state neutrino and final state muon four momentum, we can produce energy transfer plots for CC neutrino scattering as well

Conclusion

- Mono-chromatic beams up to 1.2 GeV appear to work well
- Flux systematic errors are well controlled
  - Need further investigation into the horn current systematic error around 500 MeV
- Statistical errors are not too large
- Preparing plots form the nuPRISM concept paper