Mono-chromatic beams for νPRISM

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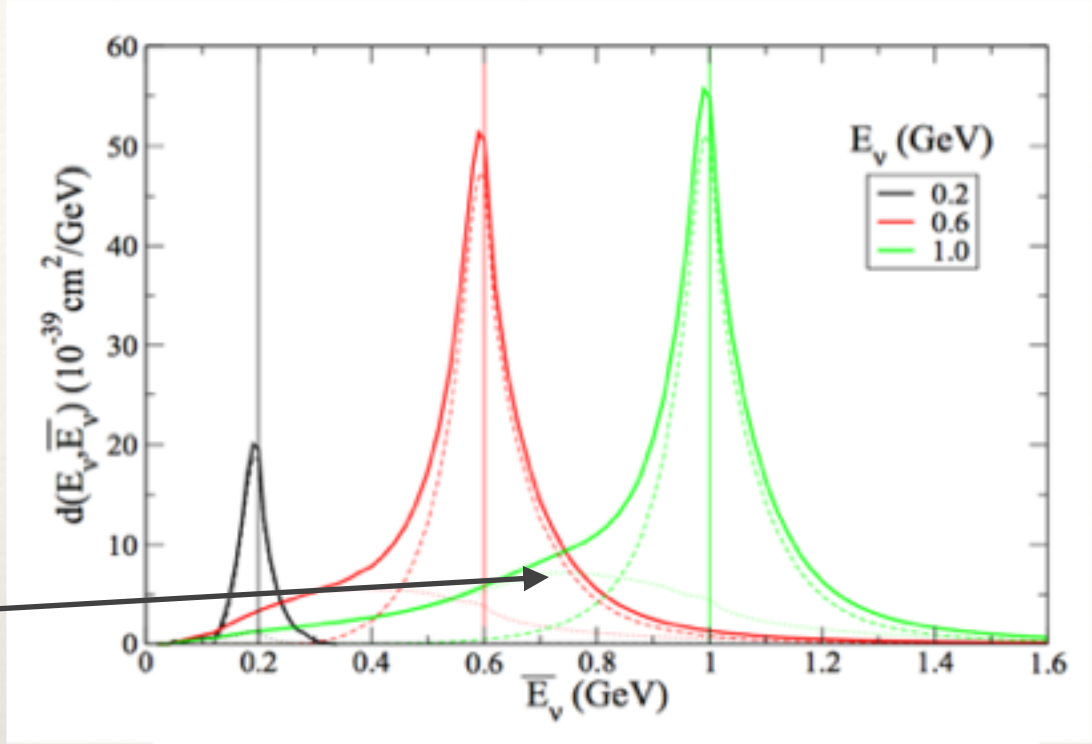
Motivation

- 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

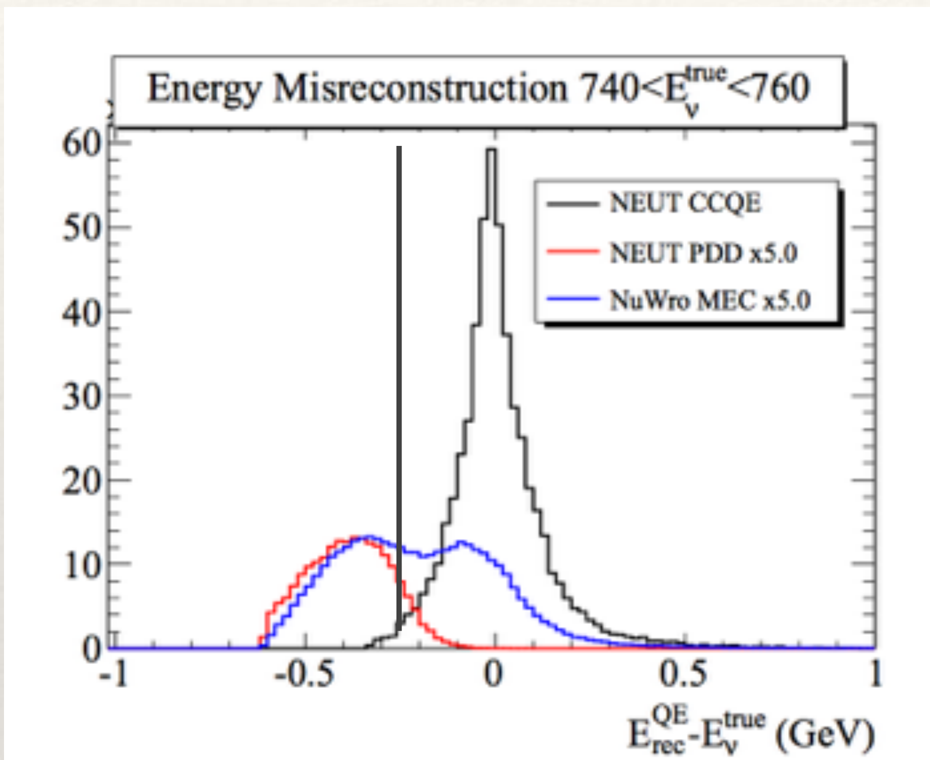


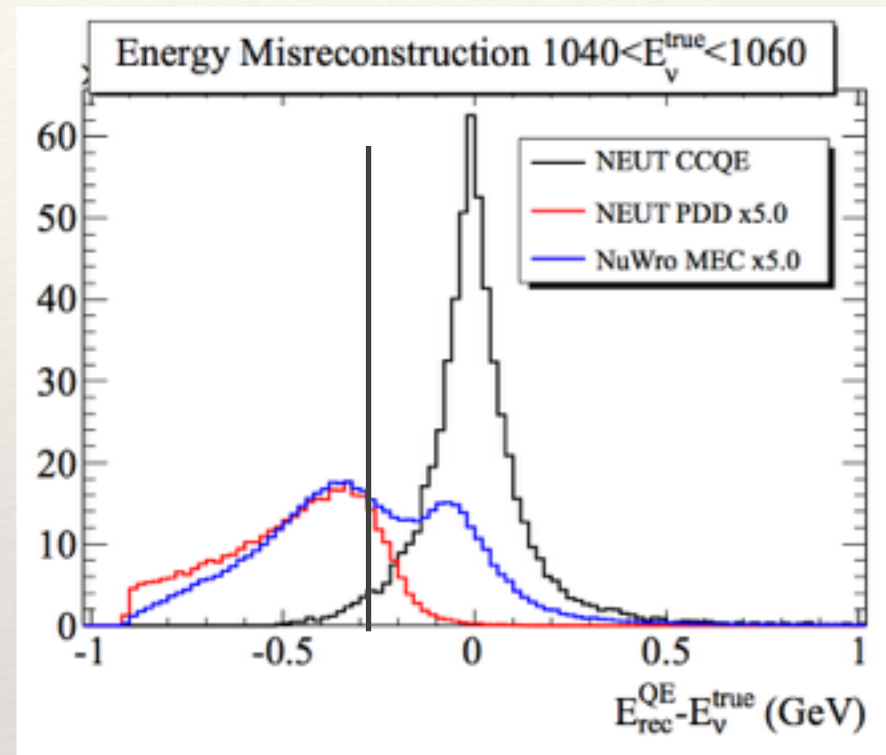
Martini et. al.
Phys.Rev. D87 (2013) 013009

- 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

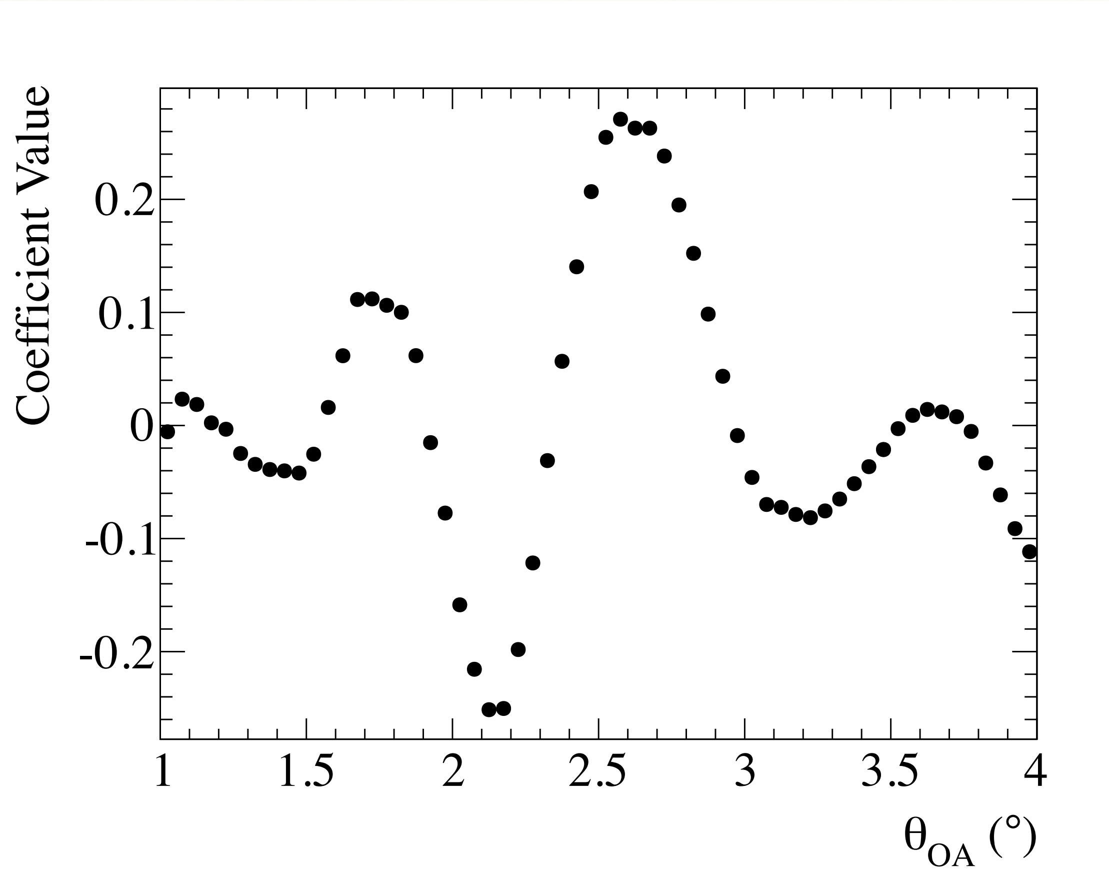
- Use the coefficient fitting code to make mono-energetic beams at 600, 900 and 1200 GeV
  - 60 bins of off-axis flux from 1 to 4 degrees

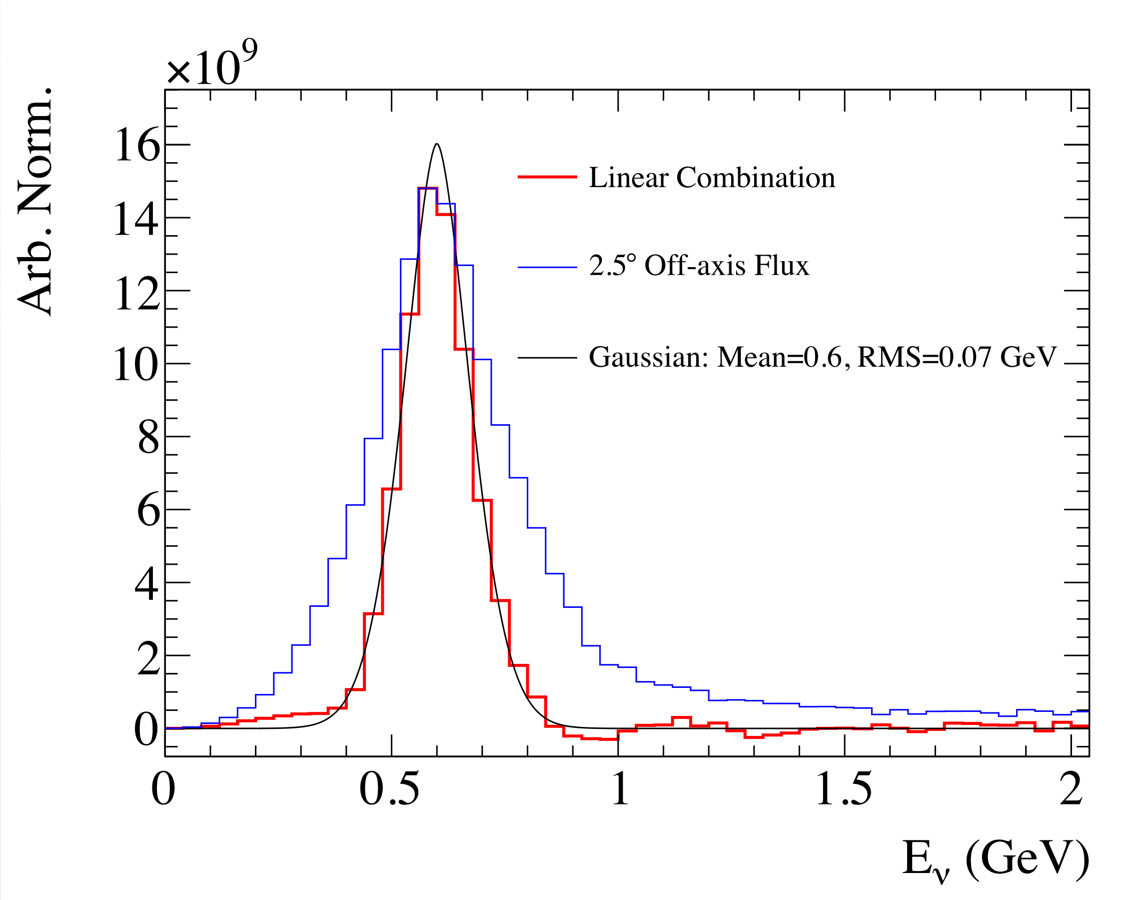
$$G(E_\nu;\mu,\sigma) = \sum_{i=1}^{\#\text{ of Off-axis bins}} c_i \phi_i(E_\nu)$$

- 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

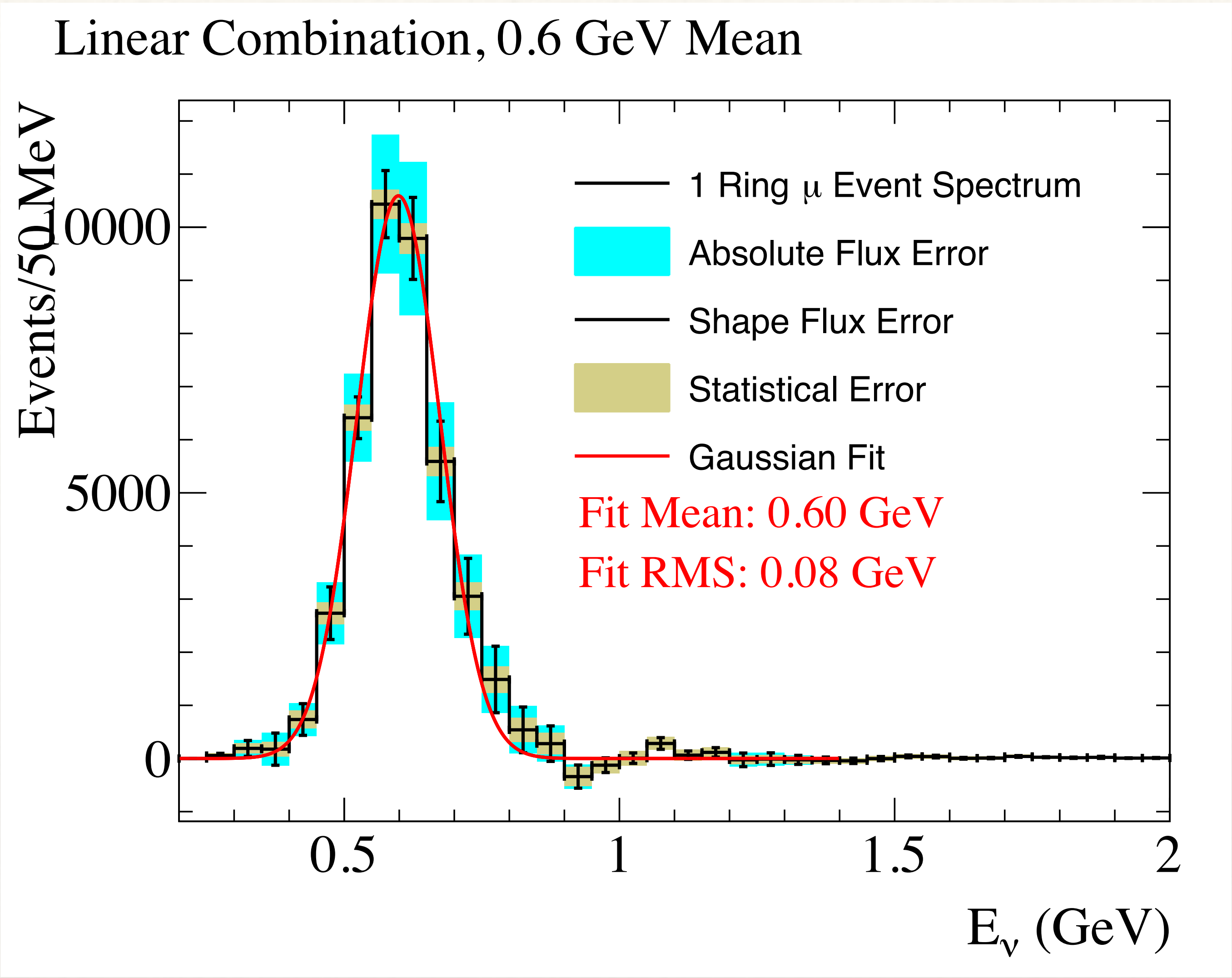
- Can achieve reasonable smoothness of the coefficients with a 70 MeV wide monoenergetic beam





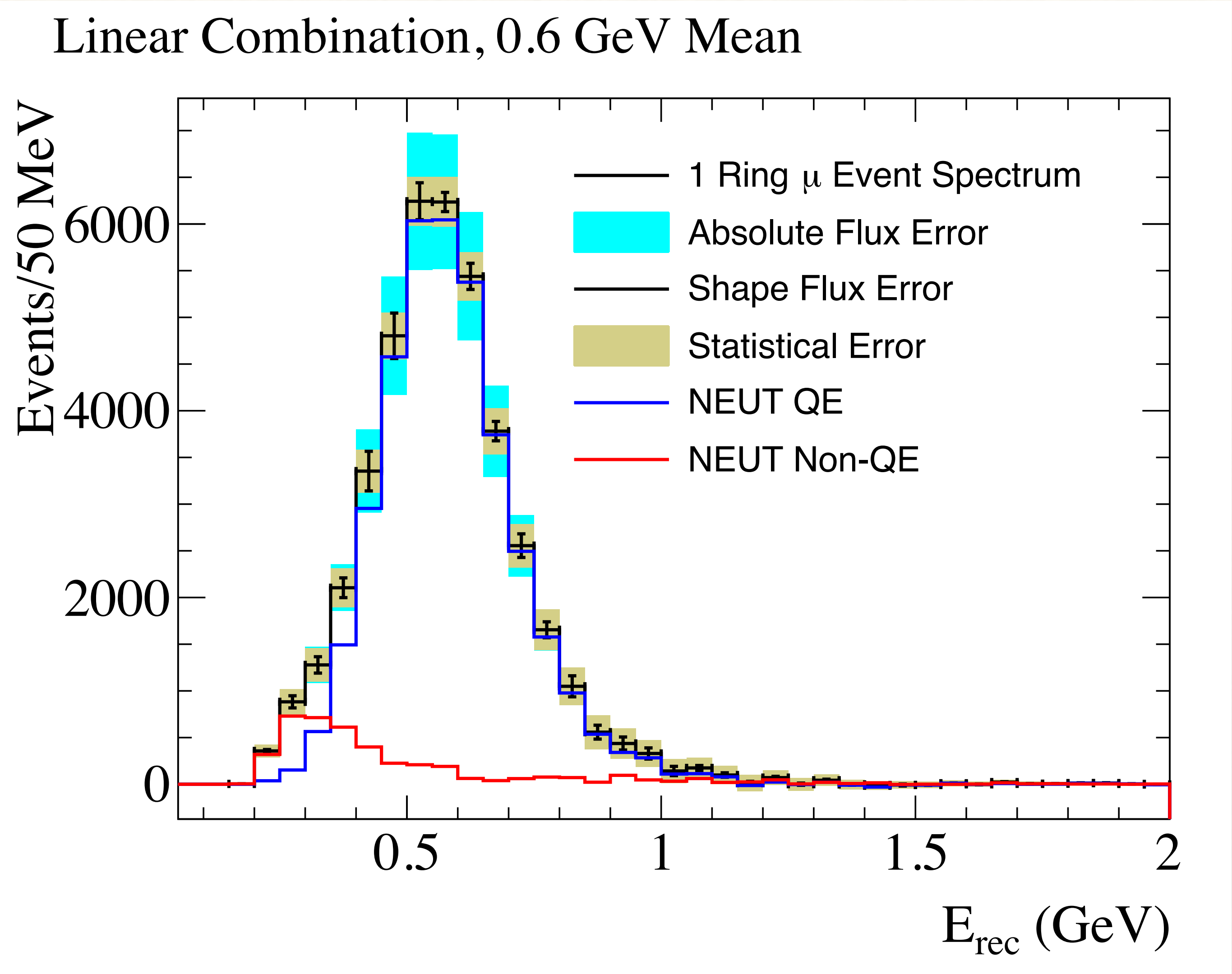
- Here the fluxes are weighted by the energy to approximate the effect of the cross-section
- Haven't completely studied the trade-off between beam width and flux & statistical errors (narrower beam may be possible)

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

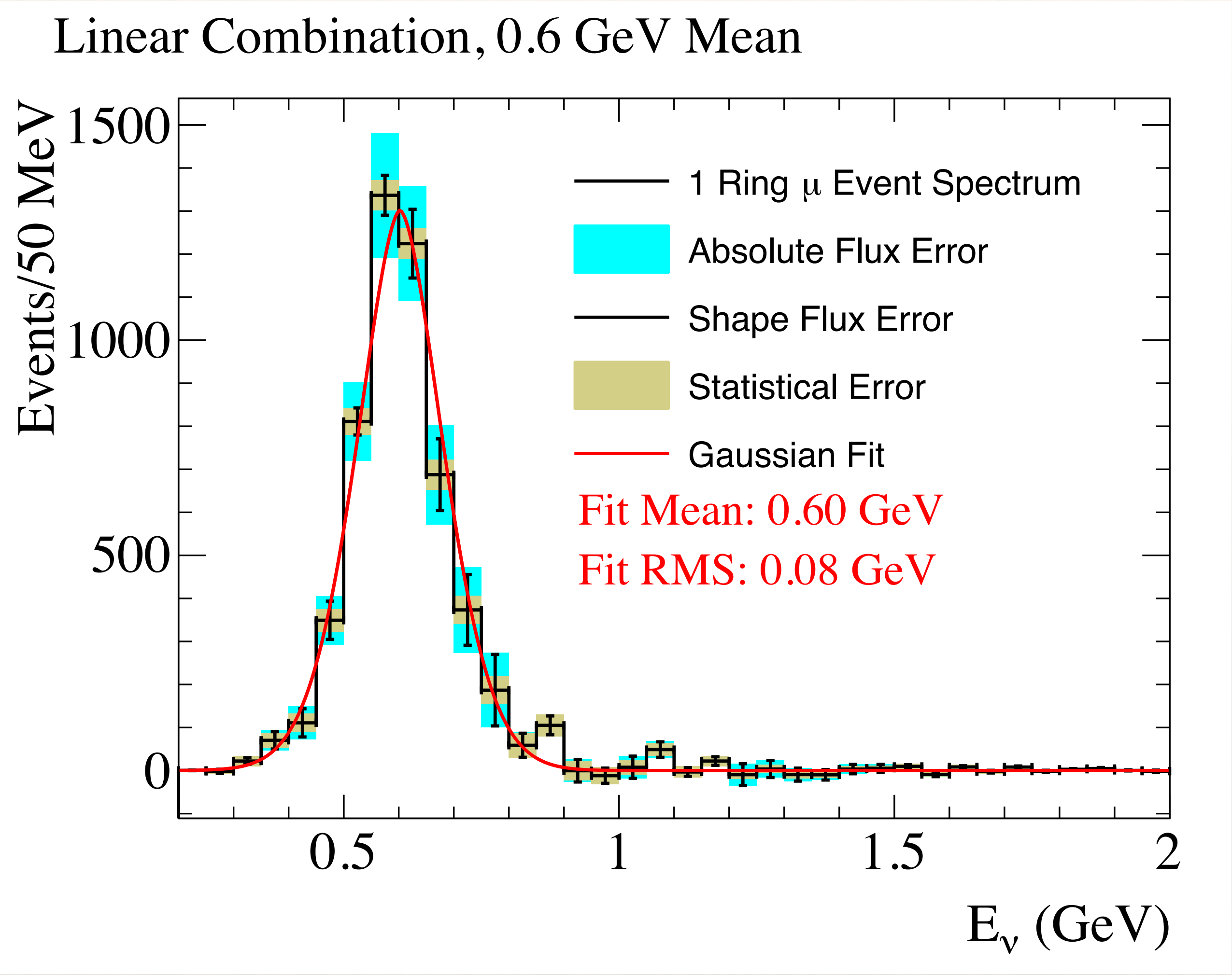
600 MeV Beam Event Rate (E_{rec})



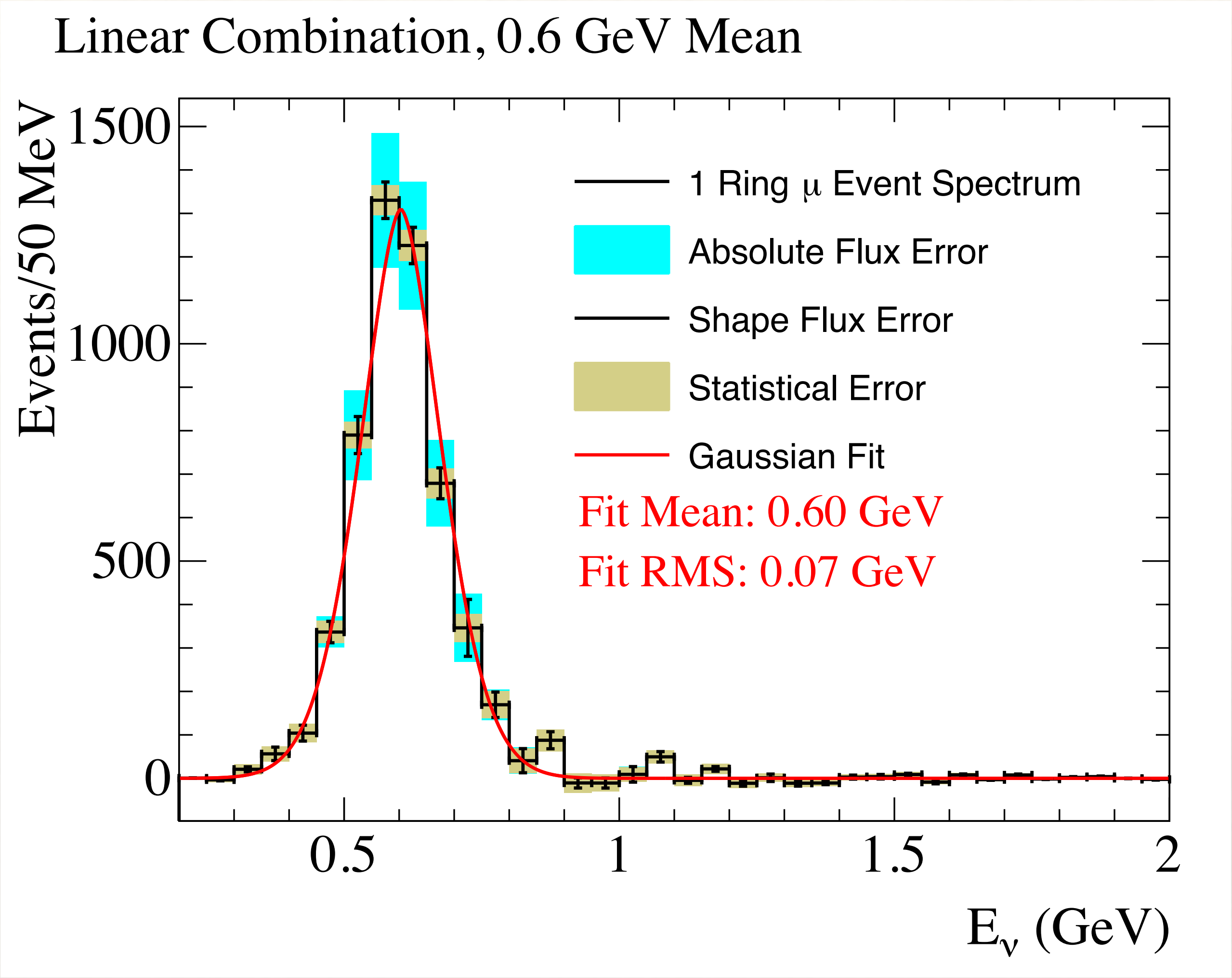
- A significant excess due to non-QE at low reconstructed energy can be observed
- Should update the study using the Nieves model to have more non-QE events

Comment on Flux Uncertainties

All flux uncertainties



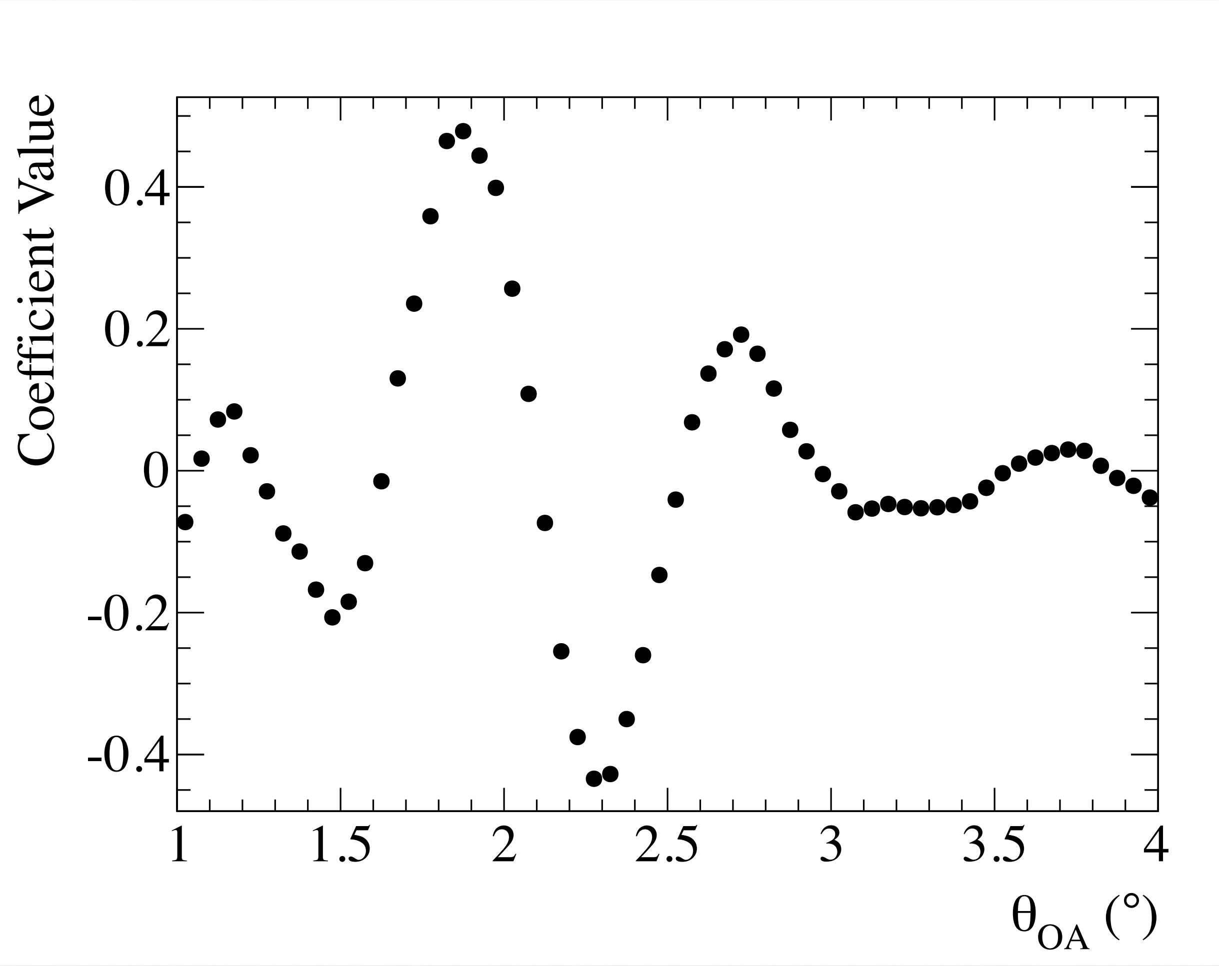
Excluding absolute horn current uncertainty

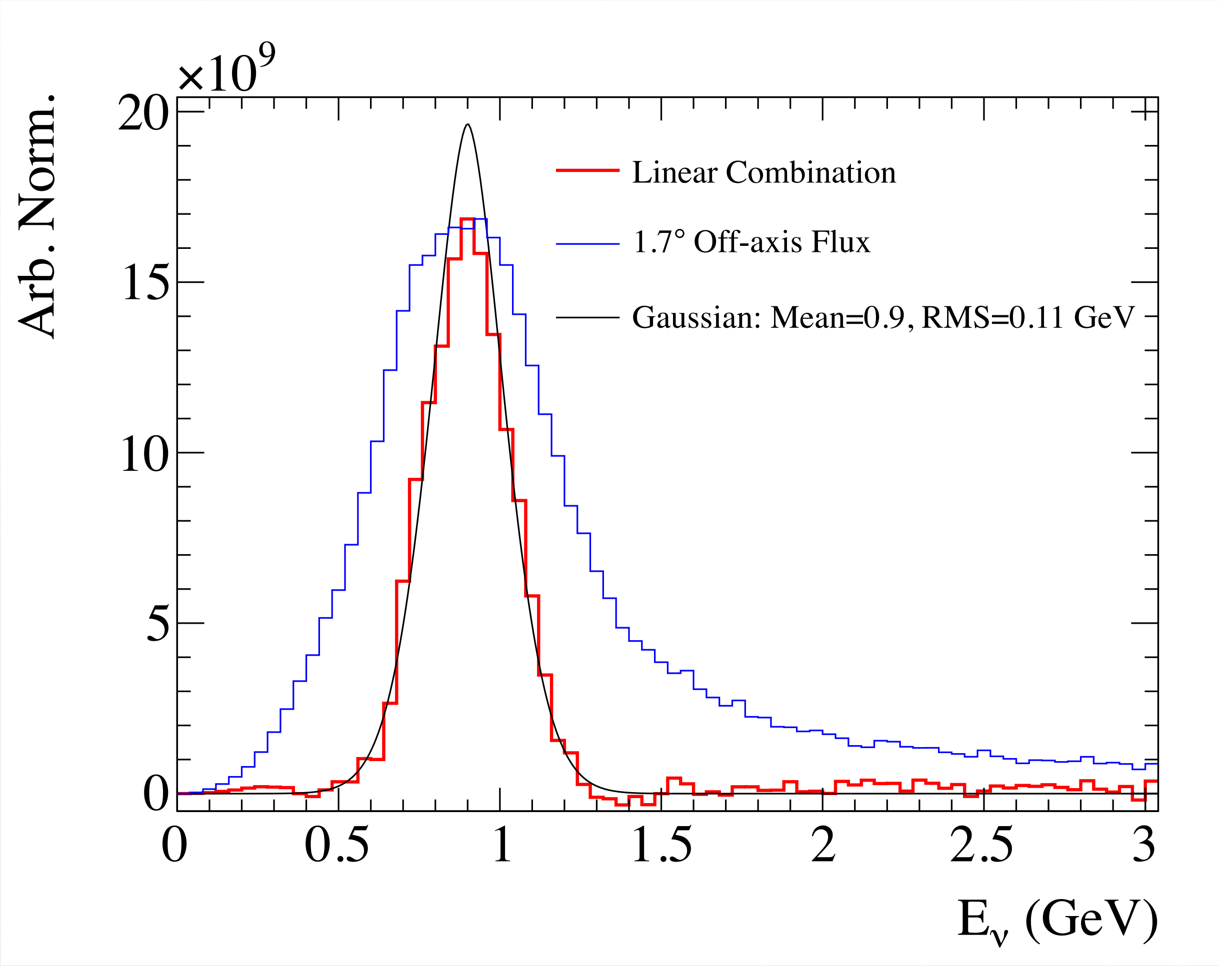


- A significant fraction of the flux uncertainty in the tails is coming from the horn absolute current uncertainty
- This error is made with regenerated nuPRISM fluxes at +5kA horn current
  - Could this be a statistical effect? Need to investigate

900 MeV Flux Fit

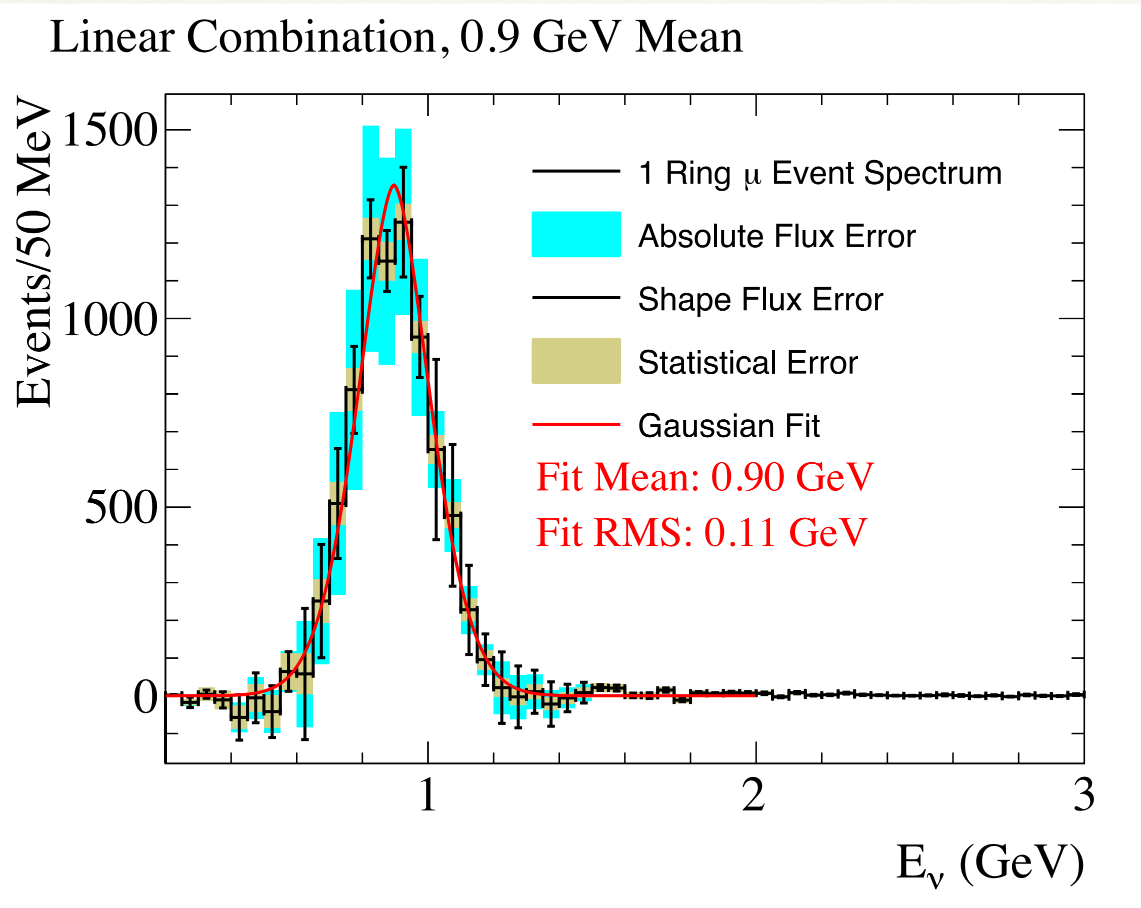
- Can achieve reasonable smoothness of the coefficients with a ~110 MeV wide monoenergetic beam



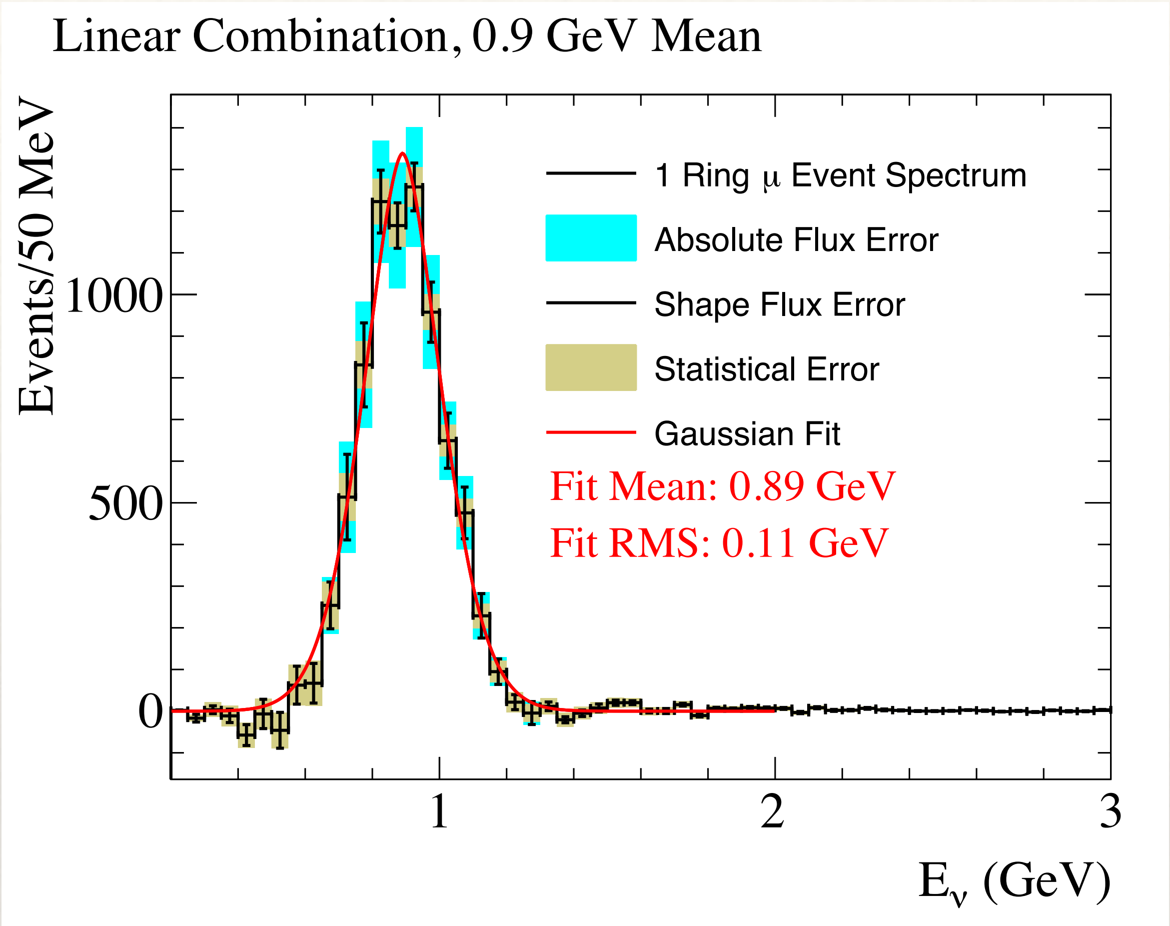


900 MeV Event Rates

All flux uncertainties

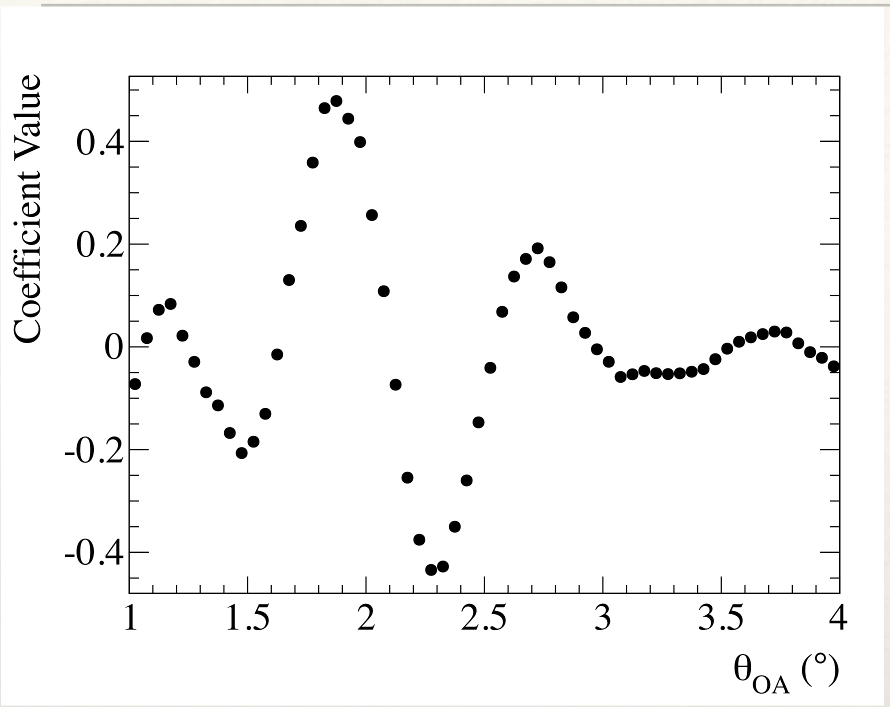


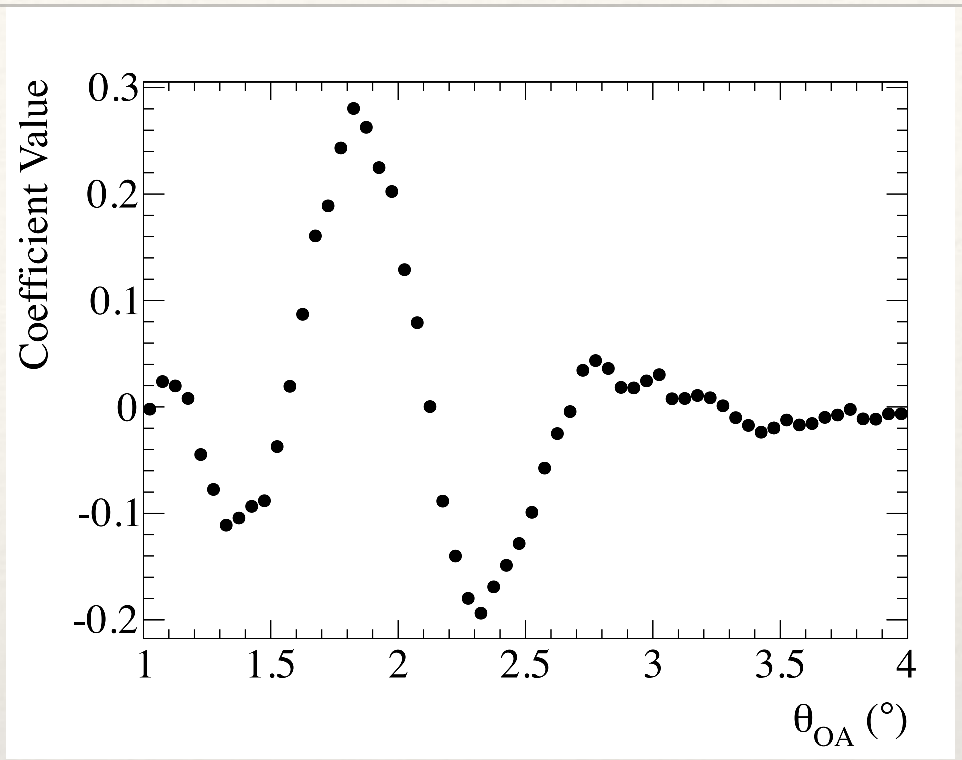
Excluding absolute horn current uncertainty



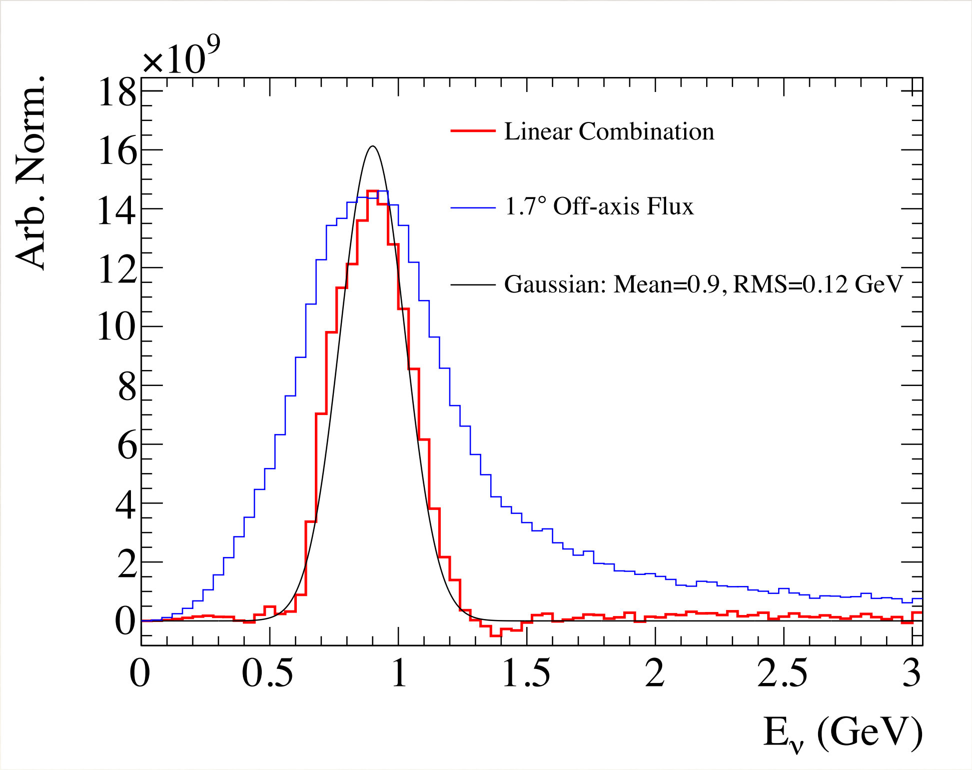
- The flux uncertainties (left) are rather larger around 600-700 MeV (the region of interest for nuclear effects)
- Turning of the horn current uncertainty (right) greatly reduces the error
- Once again, not sure if this is a statistical effect. For now, try choosing coefficients to spread out the contribution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

900 MeV Flux Fit, Take 2

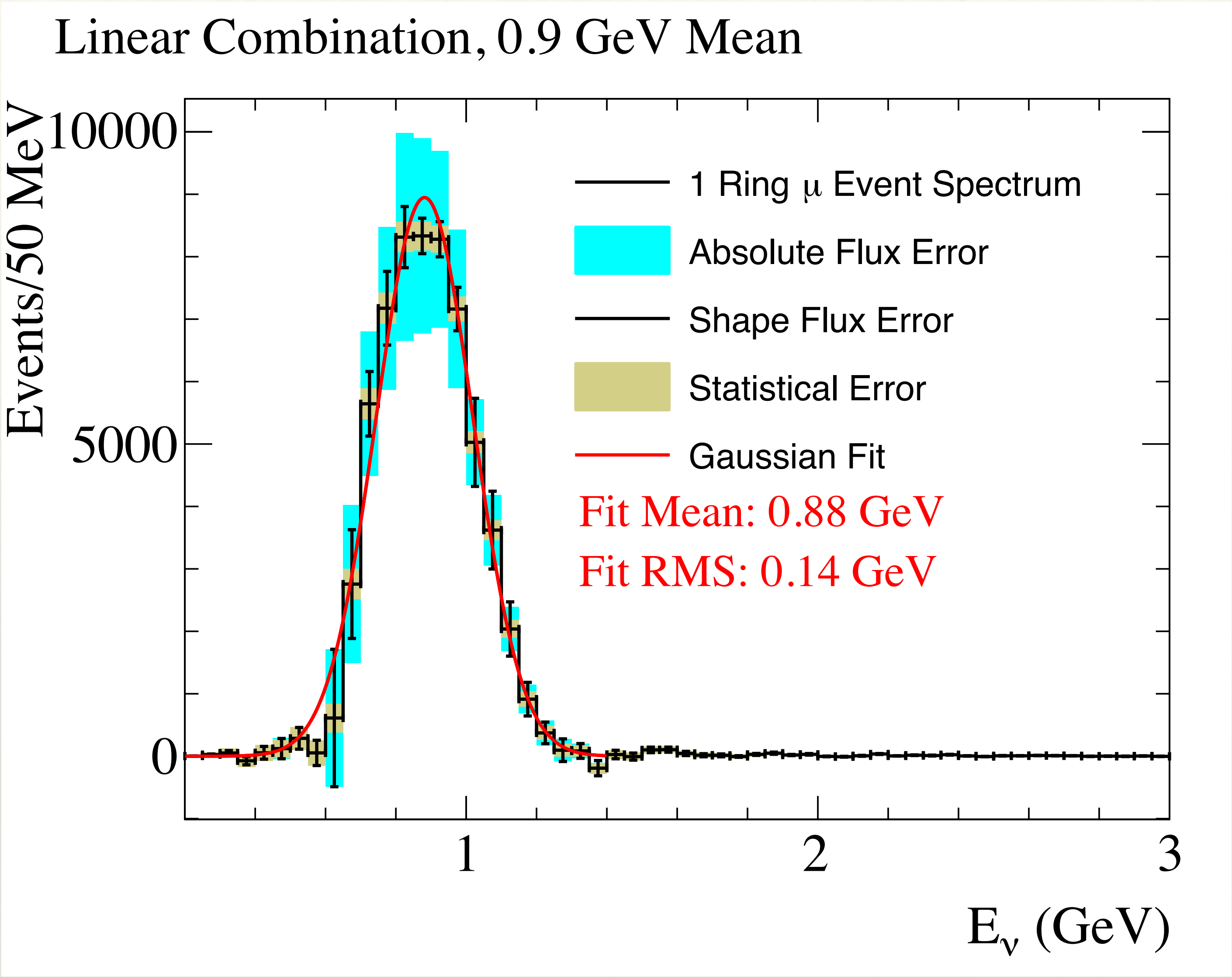




- The coefficient distribution is broader with smaller overall magnitude
- At the cost of a slightly wider mon-energetic beam



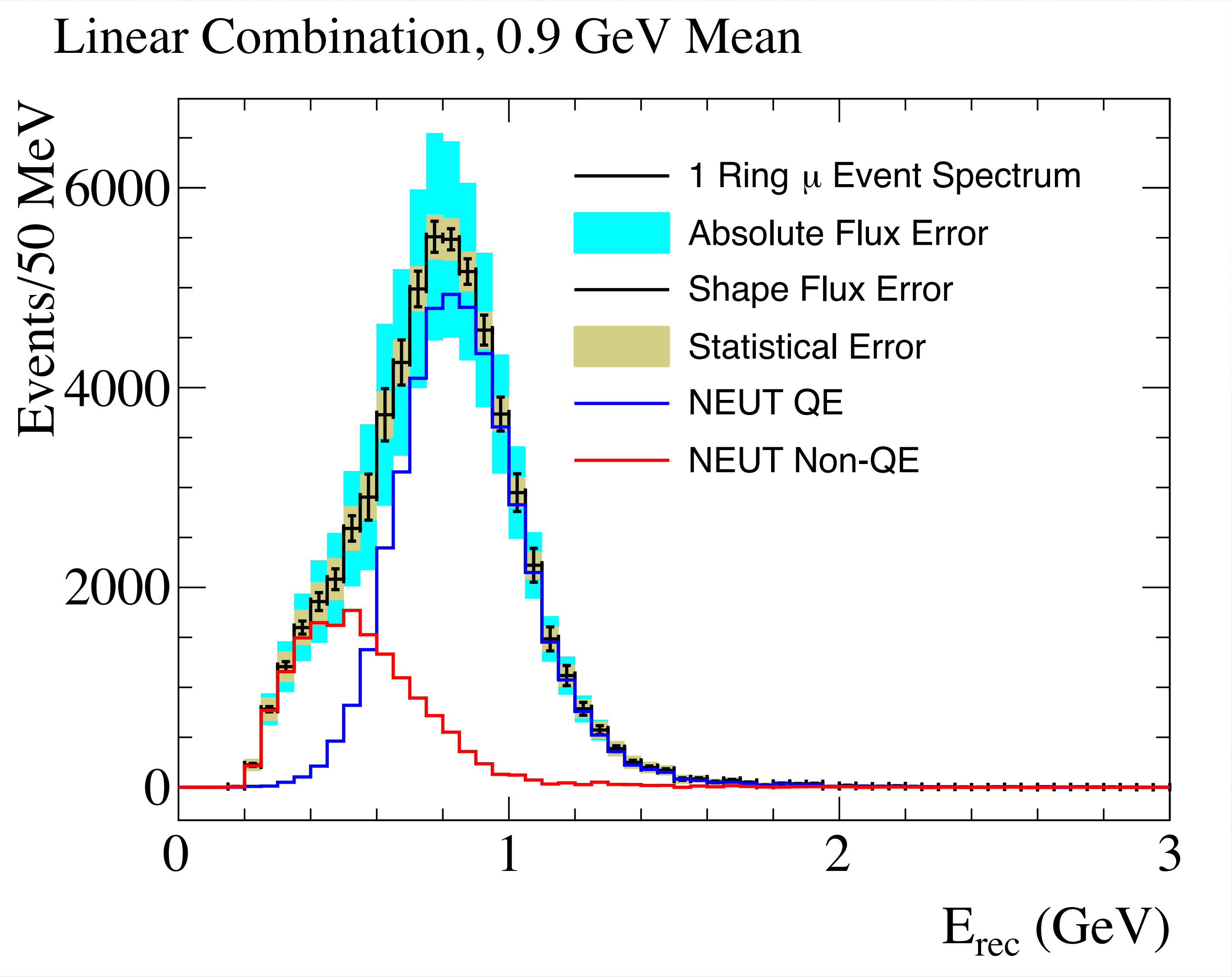
900 MeV Beam Event Rate (E_ν)



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

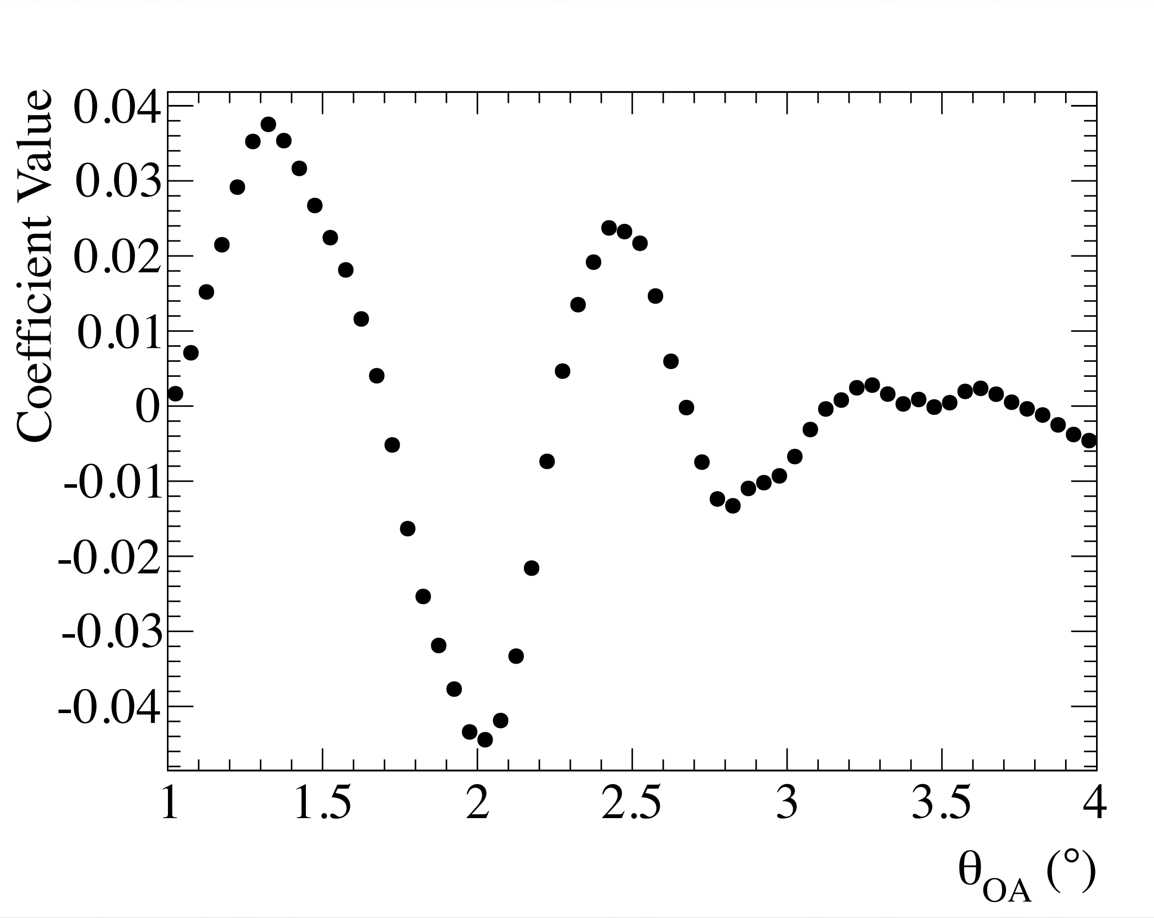
- The flux normalization error is rather larger compared to T2K cross section measurements
- The flux error in 600-700 MeV is improved

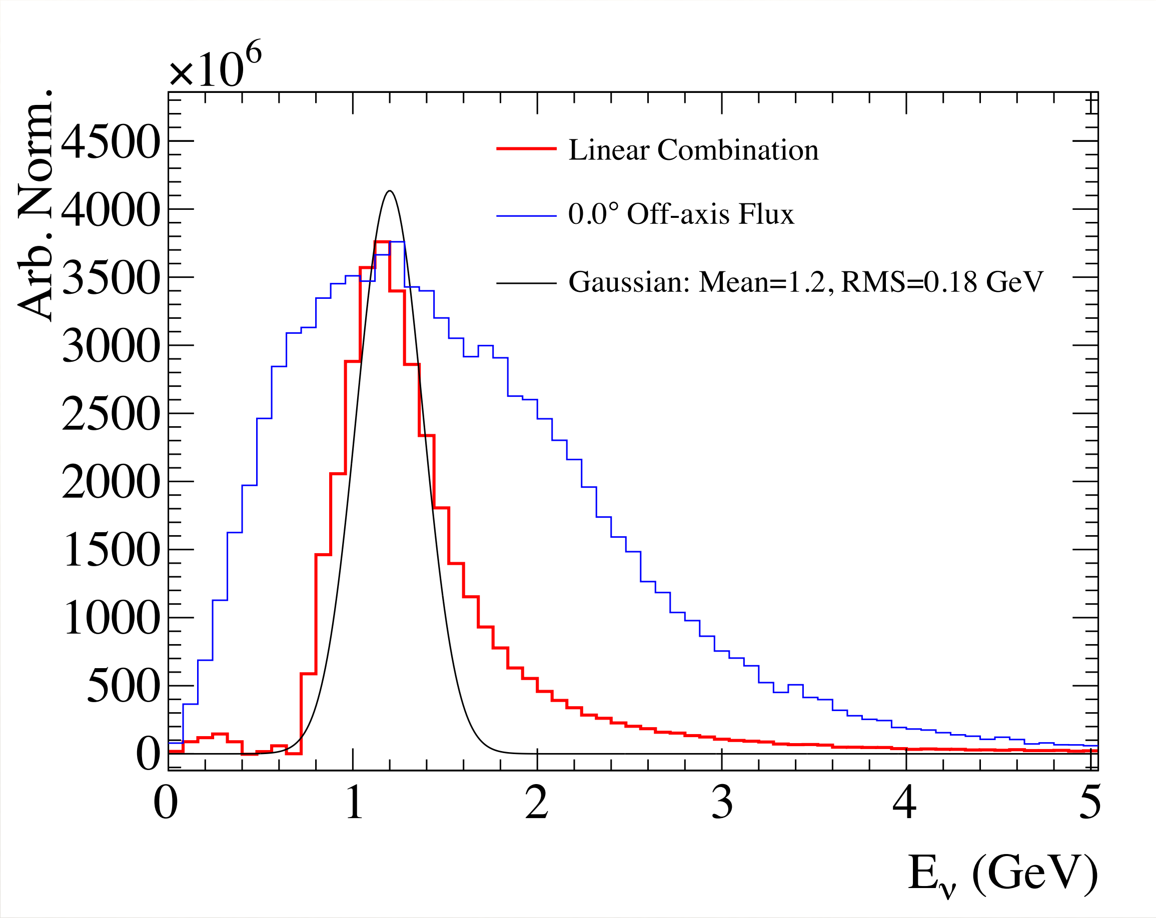
900 MeV Beam Event Rate (E_{rec})



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

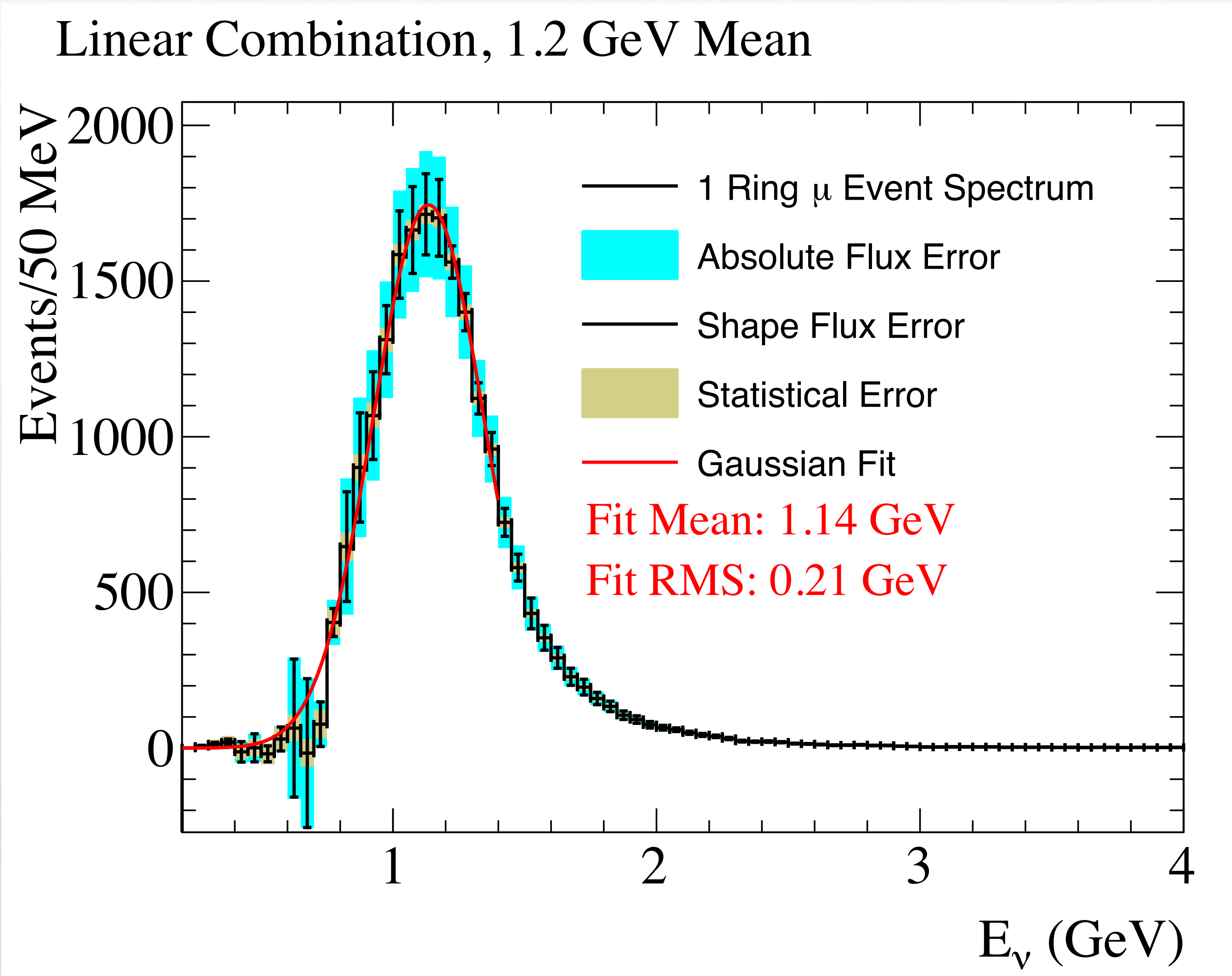
1200 MeV Flux Fit





- 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

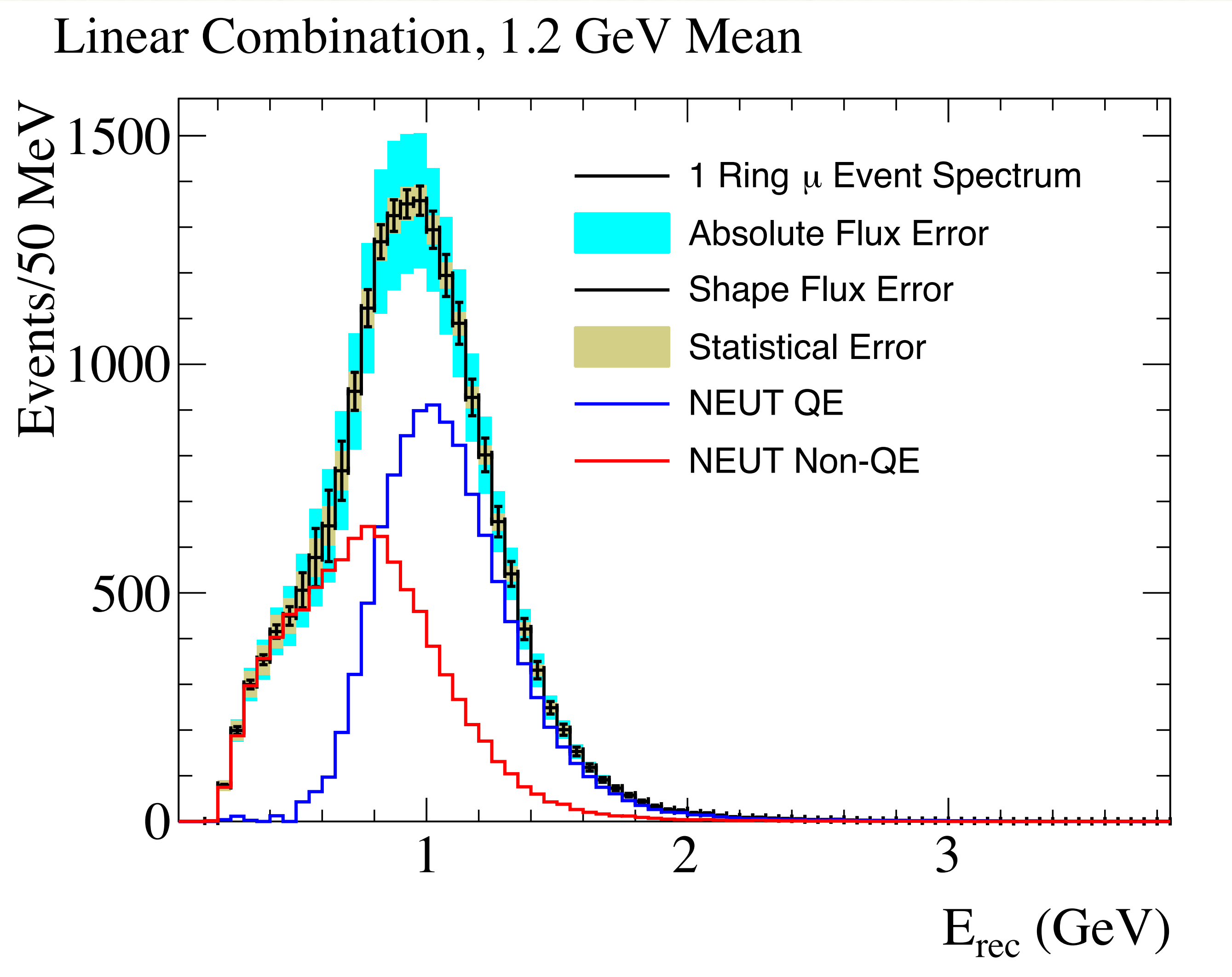
1200 MeV Beam Event Rate (E_ν)



- 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.

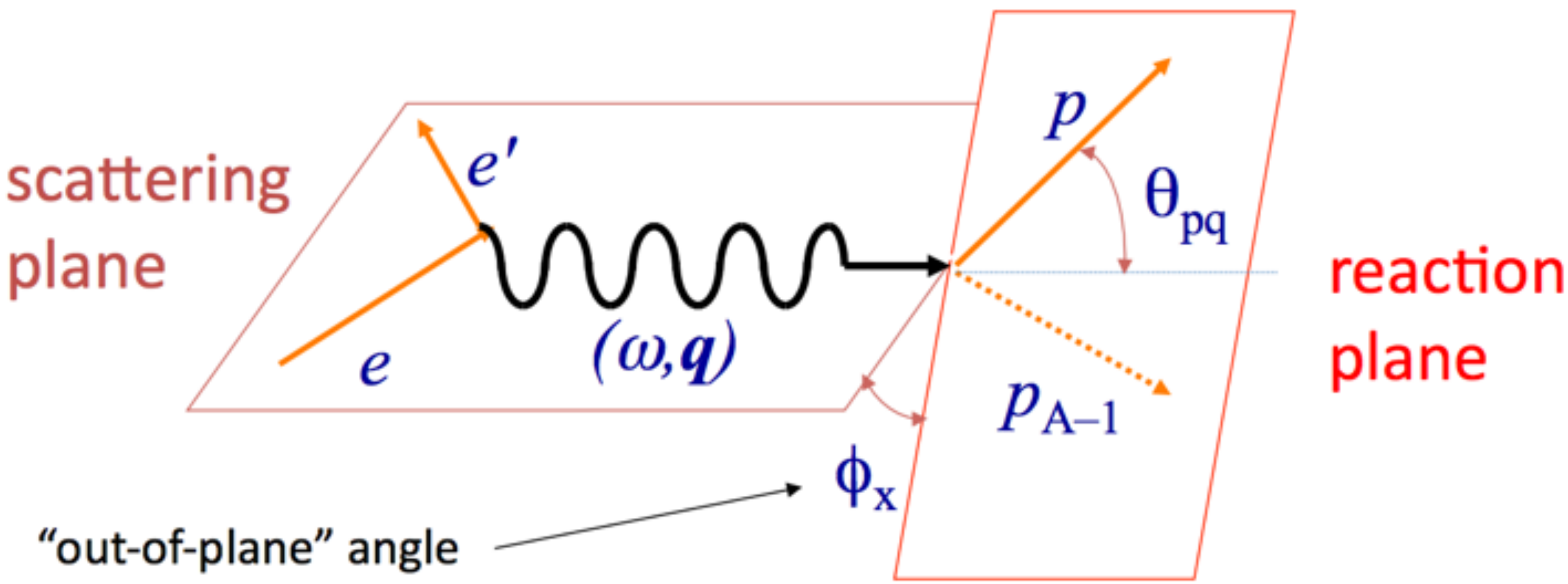
1200 MeV Beam Event Rate (E_{rec})



- 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

Electron Scattering Kinematics



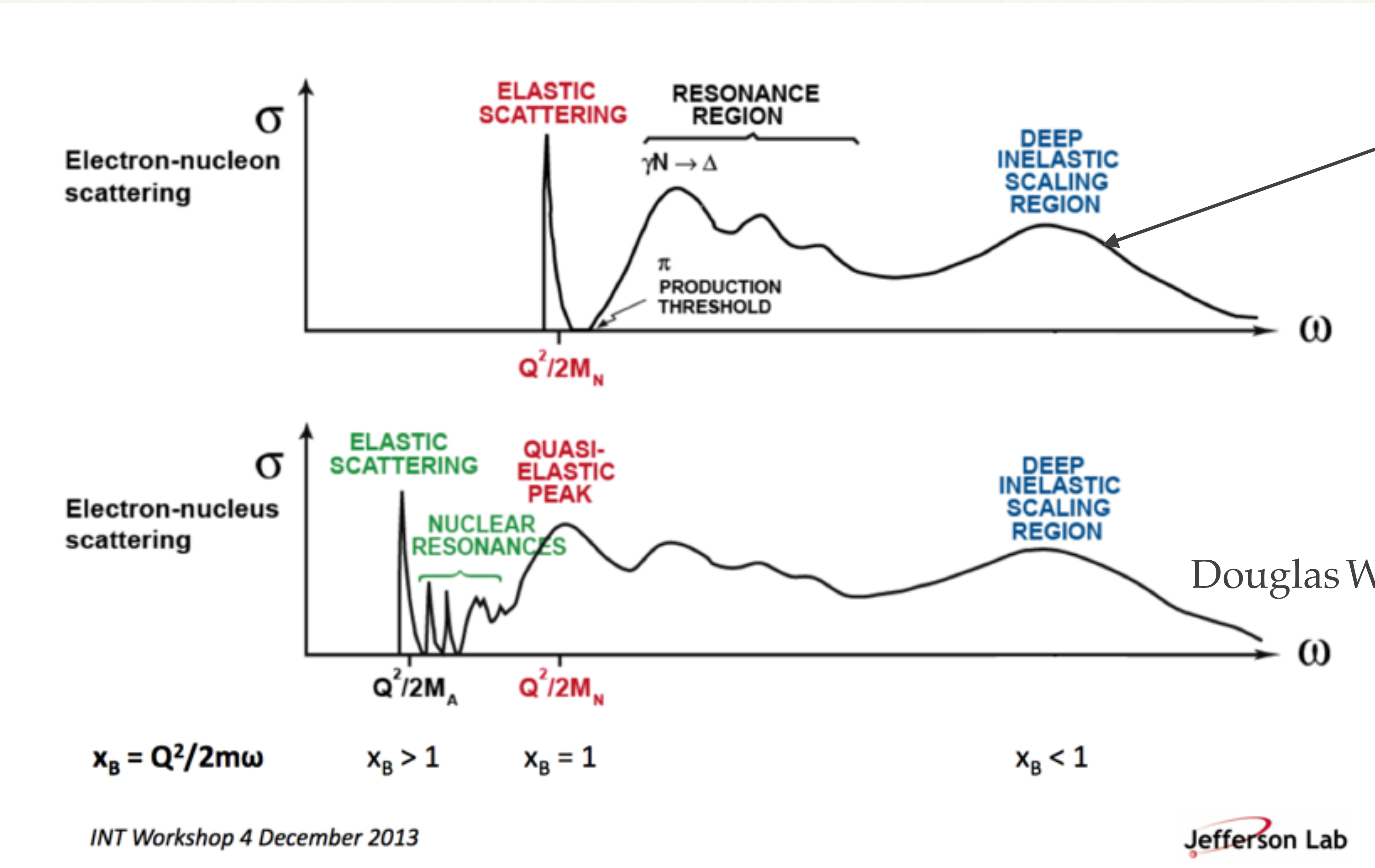
Douglas W. Higinbotham

Energy transfer:	$\omega = e - e'$
Four-momentum transfer:	$Q^2 \equiv -q_\mu q^\mu = \boldsymbol{q}^2 - \omega^2$
Missing momentum:	$\boldsymbol{p}_m = \boldsymbol{q} - \boldsymbol{p} = \boldsymbol{p}_{A-1}$
Bjorken x:	$x_B = Q^2/2m\omega$ ***(just kinematics!)***

INT Workshop 4 December 2013

Jefferson Lab

Energy Transfer Distribution



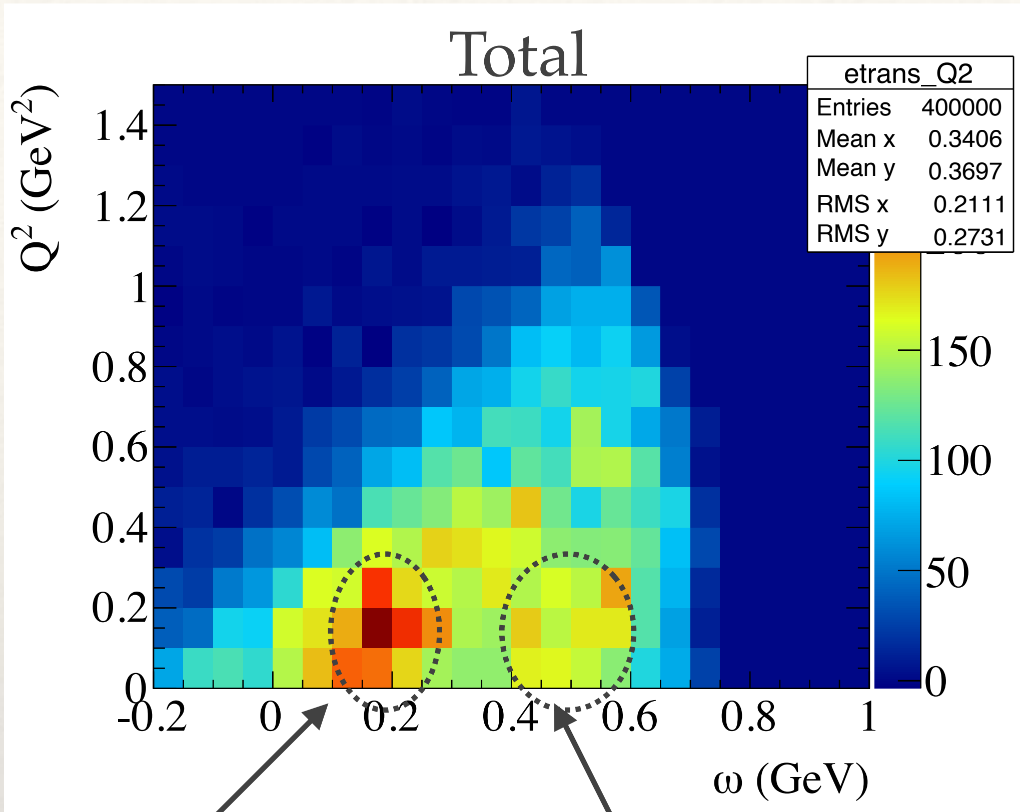
At fixed Q^2

Douglas W. Higinbotham

Application to nuPRISM

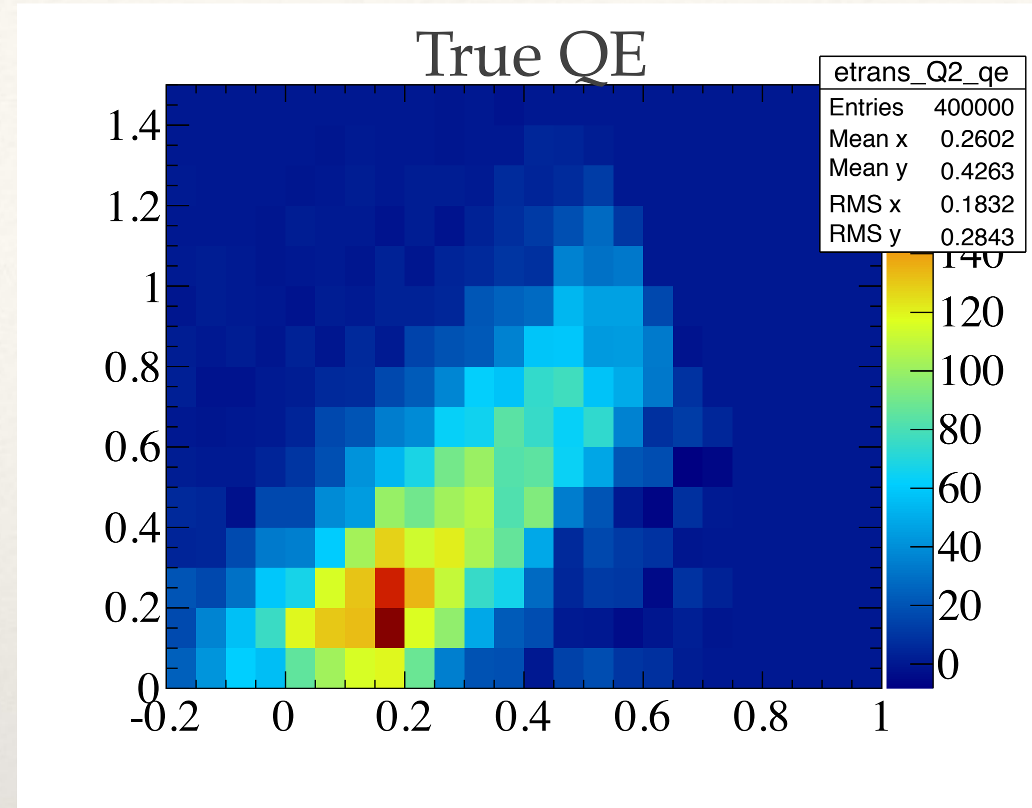
- In nuPRISM, we measure the charged lepton kinematics and know the neutrino kinematics (with some resolution) from the mono-chromatic beam method
- We should be able to construct ω and Q^2 for a given event
  - Only limited by the resolution of the charged lepton measurement and the mono-energetic beam
- Can we see the structure of the QE peak, dip region and resonant peak with nuPRISM?
  - Ideally, we should do the study with CC-inclusive but only 1 ring candidates at the moment

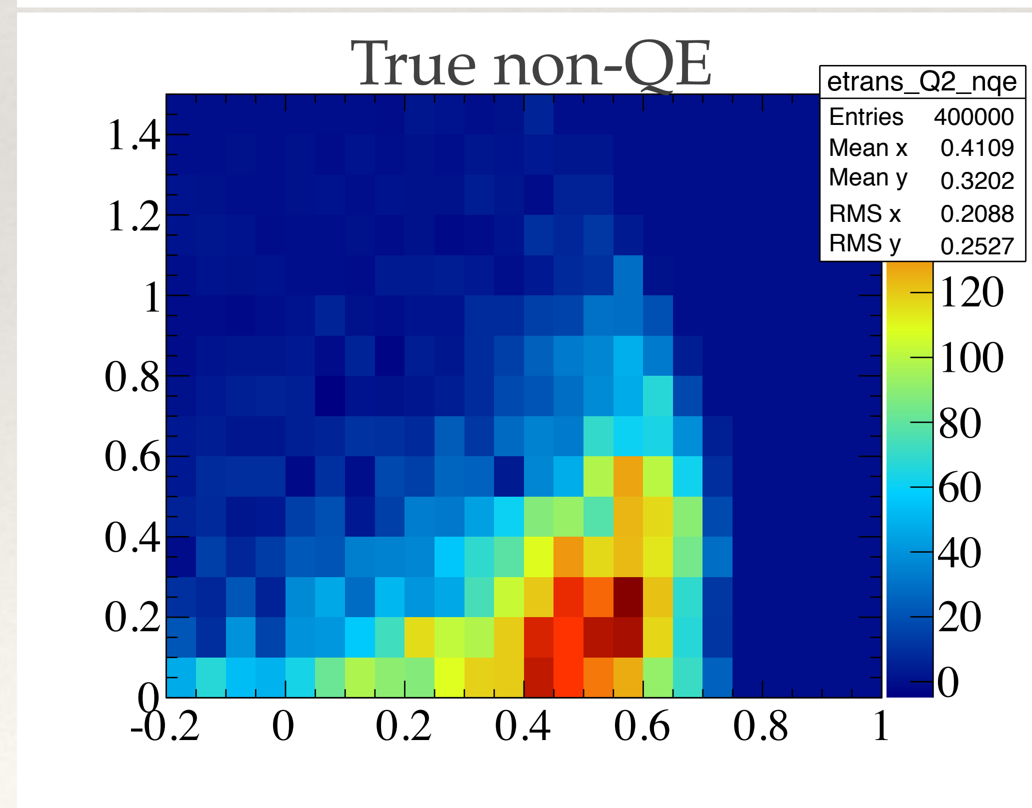
900 MeV Beam



Quasi-elastic peak

Resonant peak?





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
- Investigating electron scattering variables