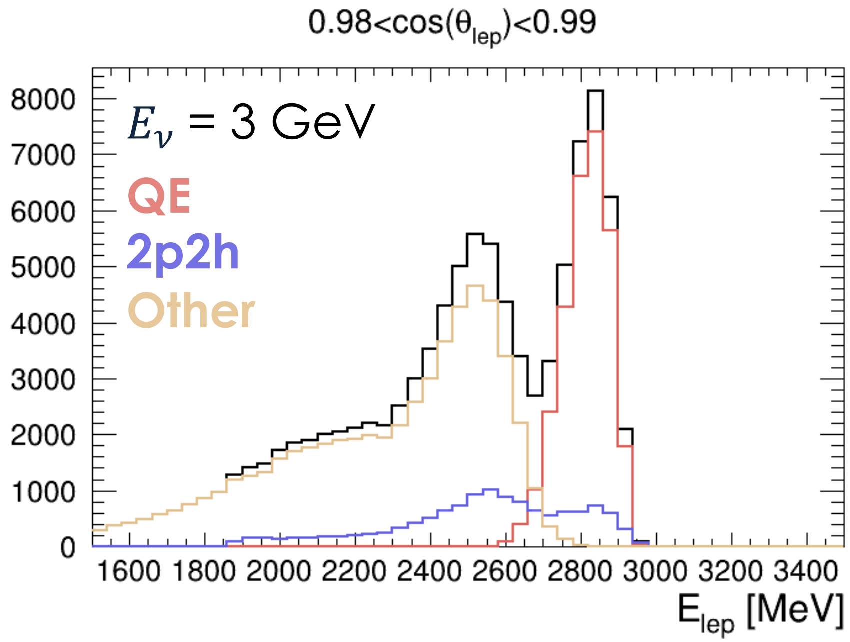
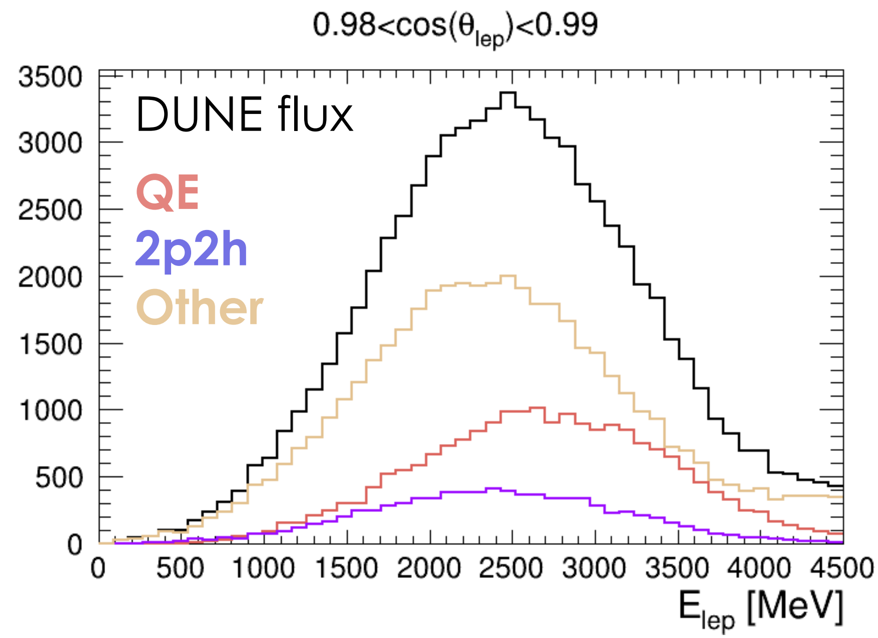
Towards neutrino-nucleus interaction measurements with PRISM

Amir Gruber, Adi Ashkenazi,
***Stephen Dolan** and Cristóvão Vilela*

e scattering vs ν scattering

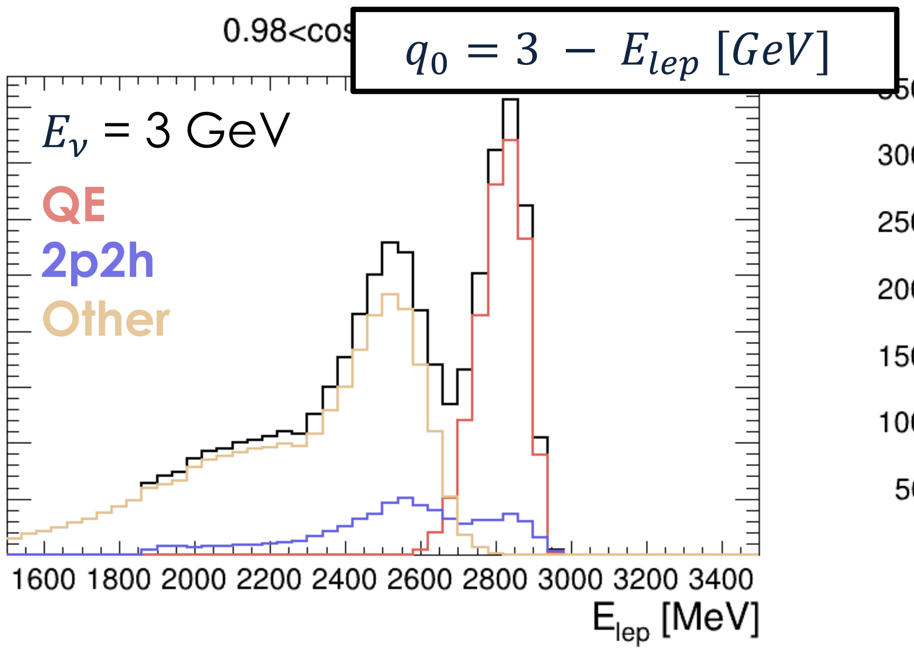
- One of the major advantages of electron scattering measurements over neutrino scattering is the mono energetic beam
- For electron scattering, a measurement of the outgoing lepton momentum corresponds directly to a measurement of energy transfer
  - With the angle, you also get momentum transfer exactly
- Broad band fluxes are responsible for almost all of the degeneracies we have between different nuclear effects.

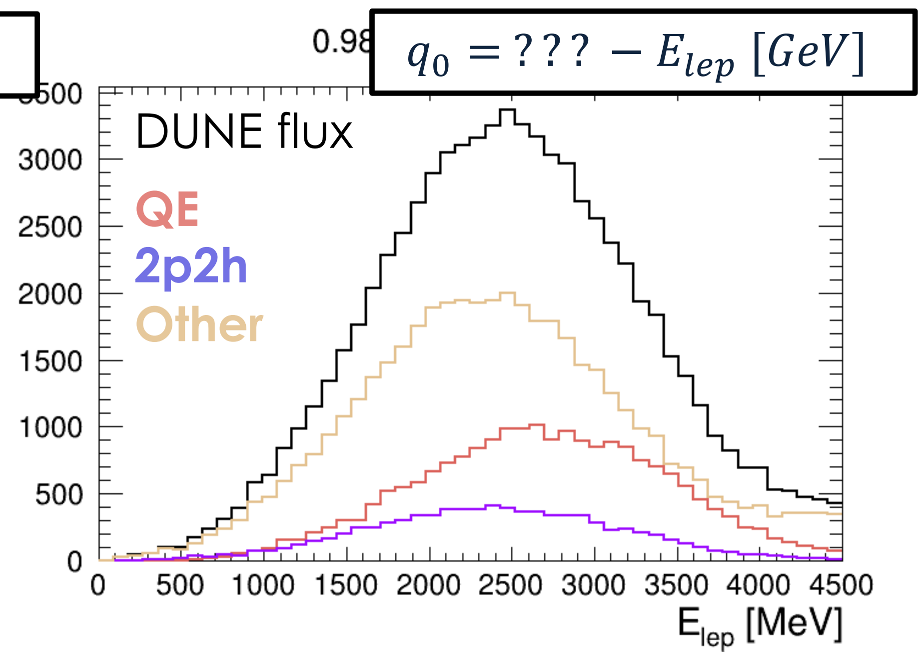




e scattering vs ν scattering

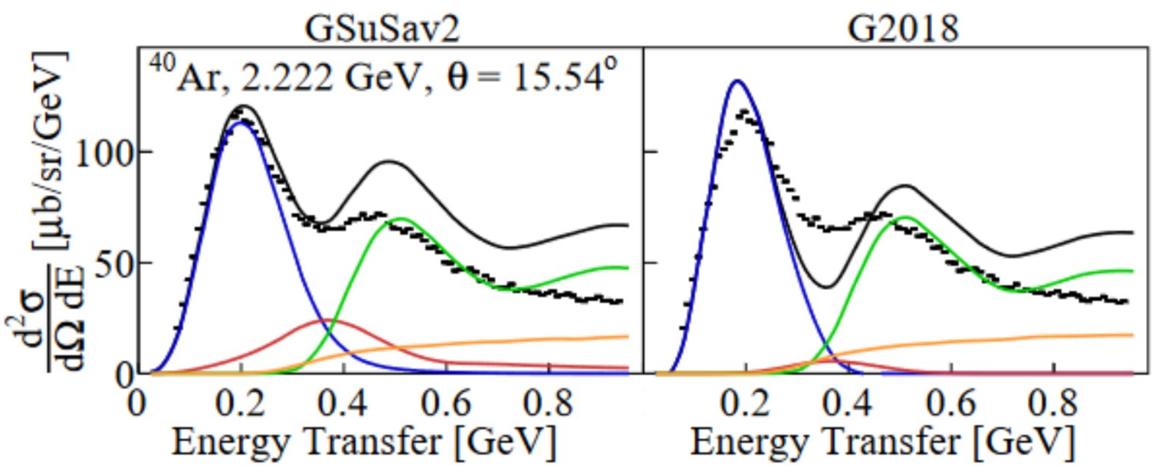
- One of the major advantages of electron scattering measurements over neutrino scattering is the mono energetic beam
- For electron scattering, a measurement of the outgoing lepton momentum corresponds directly to a measurement of energy transfer
  - With the angle, you also get momentum transfer exactly
- Broad band fluxes are responsible for almost all of the degeneracies we have between different nuclear effects.





e scattering vs ν scattering

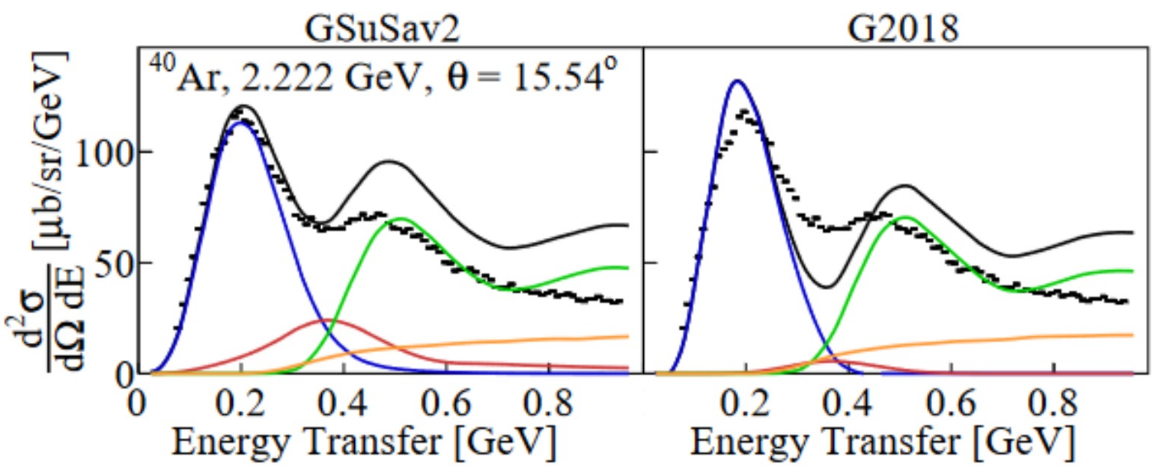
- Electron scattering can teach us a lot about the physics relevant to neutrino interactions:
  - Useful probe of the same nuclear targets we use for neutrinos
  - Almost identical vector part of the interaction
  - No ability to constrain the axial-vector part of the interaction



A. Papadopoulou et al. (e4v Collaboration), Phys. Rev. D 103, 113003 (2021)

e scattering vs ν scattering

- Electron scattering can teach us a lot about the physics relevant to neutrino interactions:
  - Useful probe of the same nuclear targets we use for neutrinos
  - Almost identical vector part of the interaction
  - No ability to constrain the axial-vector part of the interaction



A. Papadopoulou et al. (e4v Collaboration), Phys. Rev. D 103, 113003 (2021)

Wouldn’t it be great if we could measure neutrino interactions from a mono-energetic beam!?

PRISM to the rescue!

- Rather than building the FD flux at the ND, we can try to use PRISM to build quasi-mono-energetic fluxes at the near detector

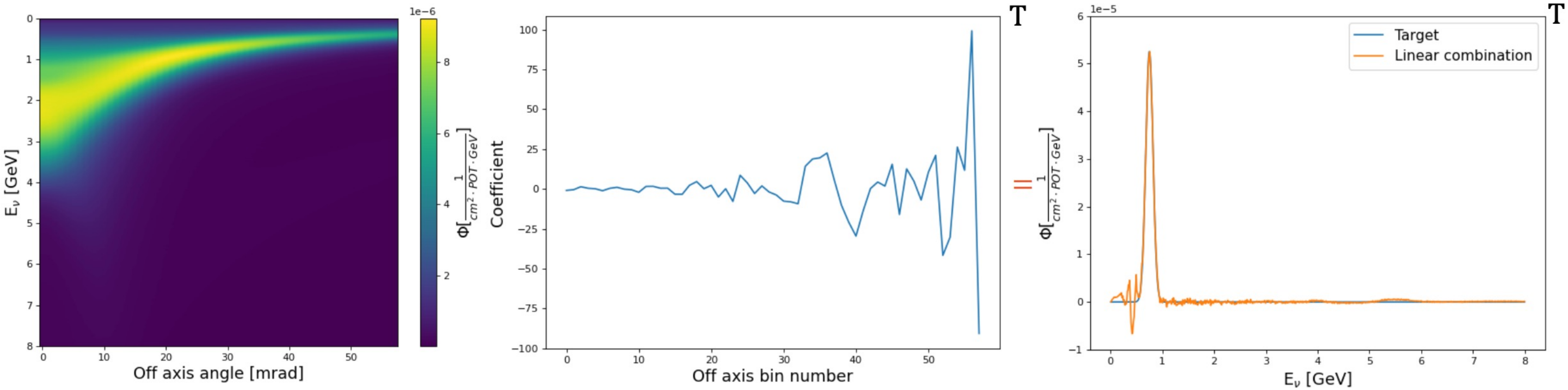
Ingredients:

Flux matrix F - an estimation of what flux distribution we will get for each off-axis angle

Target flux $\vec{T}$ – a flux distribution we would like to approximate

Directions:

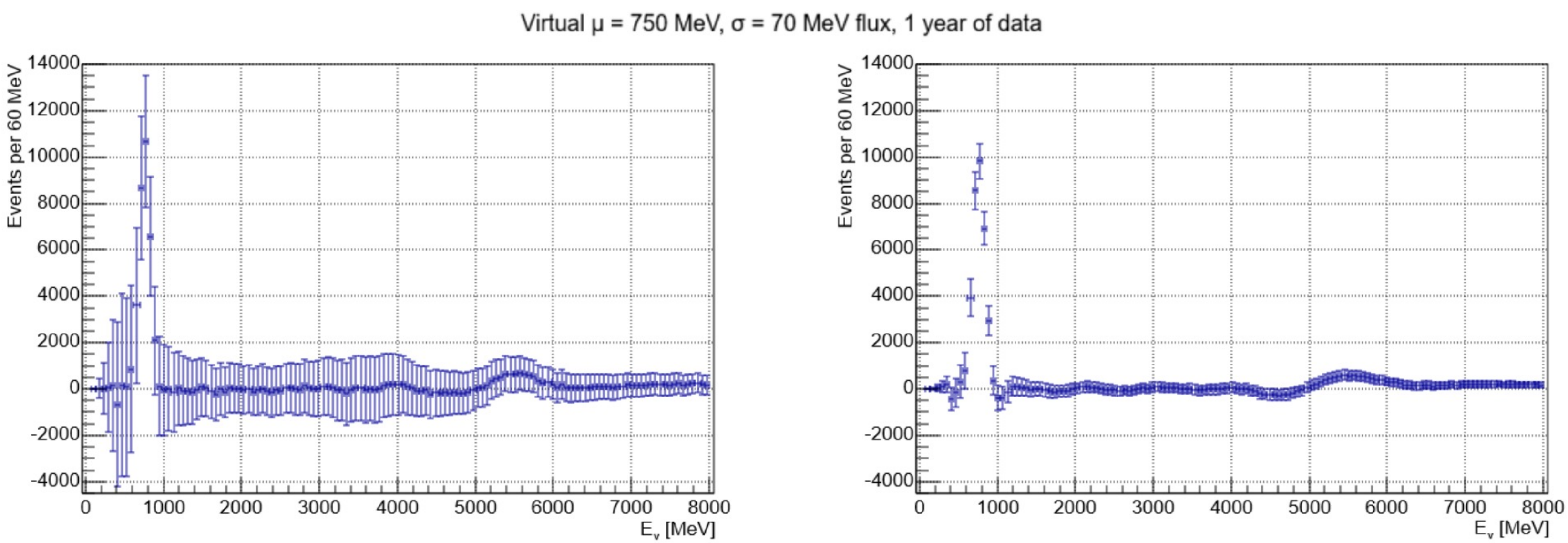
Solve $F\vec{c} = \vec{T}$ - find a solution that will give an approximation of our target as a linear combination of fluxes



Regularisation

- The "best" solution (linear combination flux closest to the target) is not always what we want.
  - Typically involves subtracting large numbers from one another which blows up the statistical error

- But we don't actually care if we match the target perfectly: all we want is a thin flux that we know the shape of
  - Employ Tikhonov regularisation to penalise solutions with large coefficients

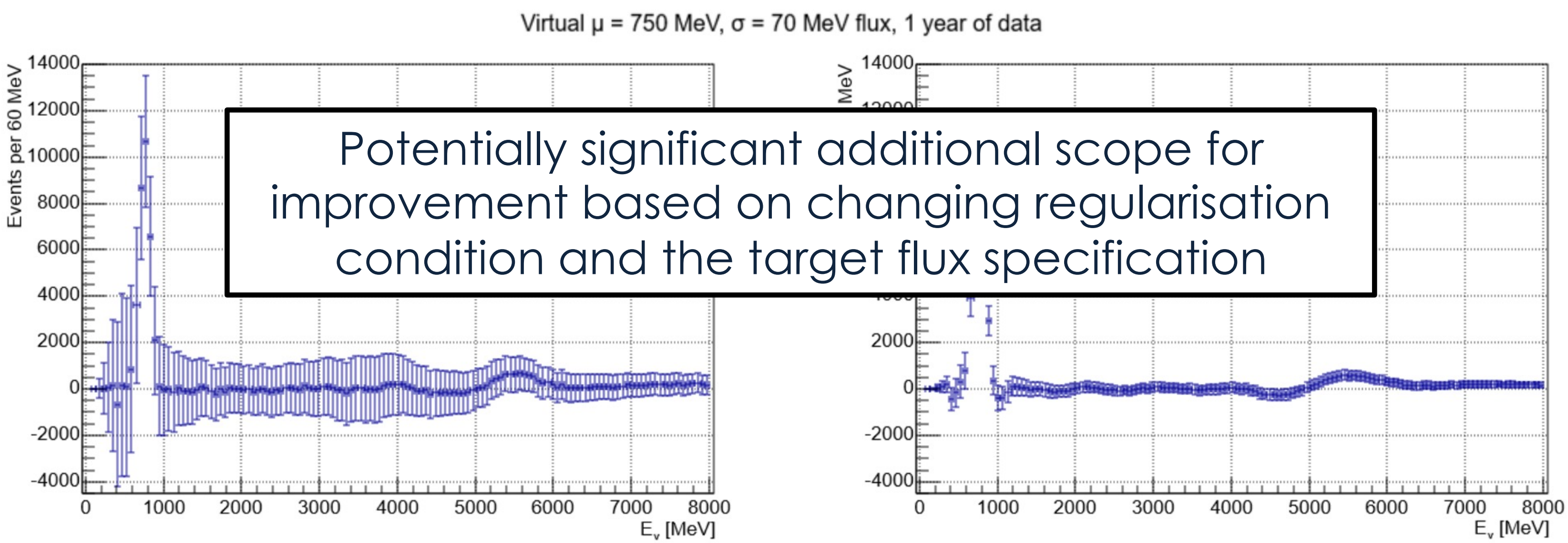


Ordinary least squares
$\mu = 750\ MeV$
$\sigma = 71\ MeV$

Tikhonov regularization (Ridge regression) with $\alpha = 10^{-12}$
$\mu = 750\ MeV$
$\sigma = 78\ MeV$

Regularisation

- The "best" solution (linear combination flux closest to the target) is not always what we want.
    - Typically involves subtracting large numbers from one another which blows up the statistical error
- But we don't actually care if we match the target perfectly: all we want is a thin flux that we know the shape of
    - Employ Tikhonov regularisation to penalise solutions with large coefficients



Potentially significant additional scope for improvement based on changing regularisation condition and the target flux specification

Ordinary least squares
$\mu = \mathbf{750\ MeV}$
$\sigma = \mathbf{71\ MeV}$

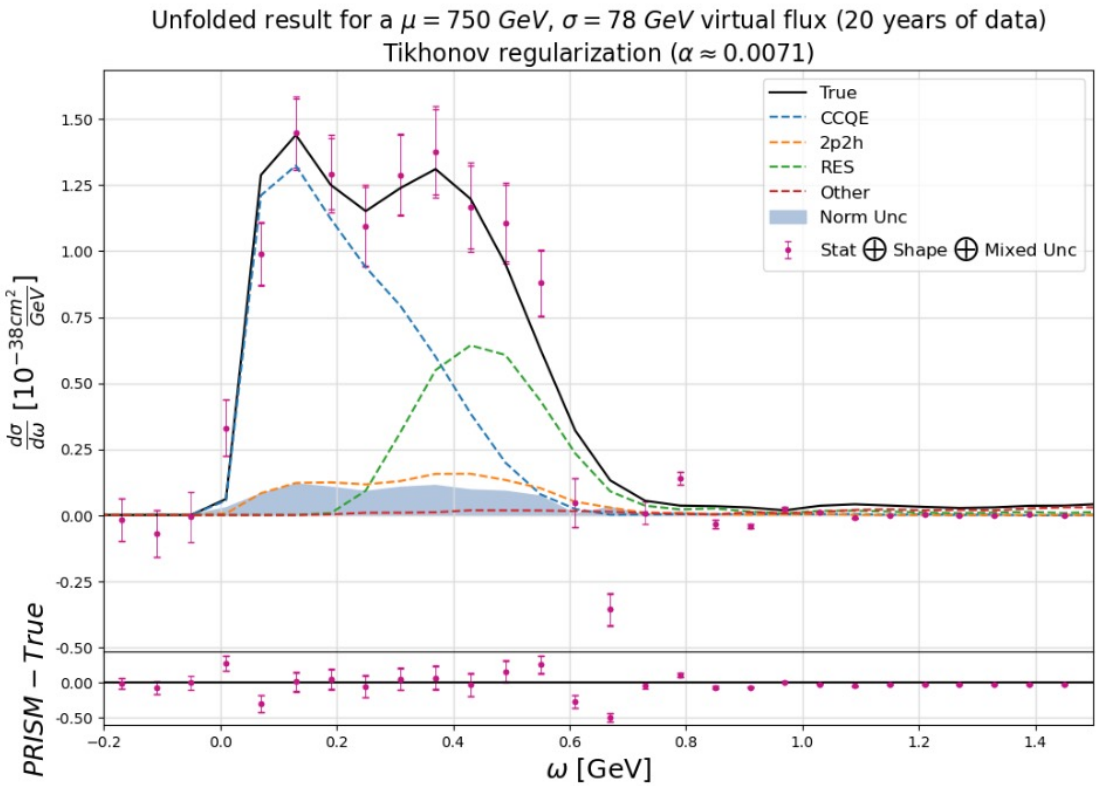
Tikhonov regularization (Ridge regression) with $\alpha = 10^{-12}$
$\mu = \mathbf{750\ MeV}$
$\sigma = \mathbf{78\ MeV}$

What can we measure

- Access to a good proxy for energy transfer: $\omega_{reco} =< E_{\nu} > -E_{lep}$
- Close to energy transfer, but the small width of the flux smears it out
- Suggestion: assume all smearing comes from the flux and unfold
  - I.e. build the unfolding matrix only from the flux spread and not from MC
  - Relies on the cross-section to change negligibly across the flux

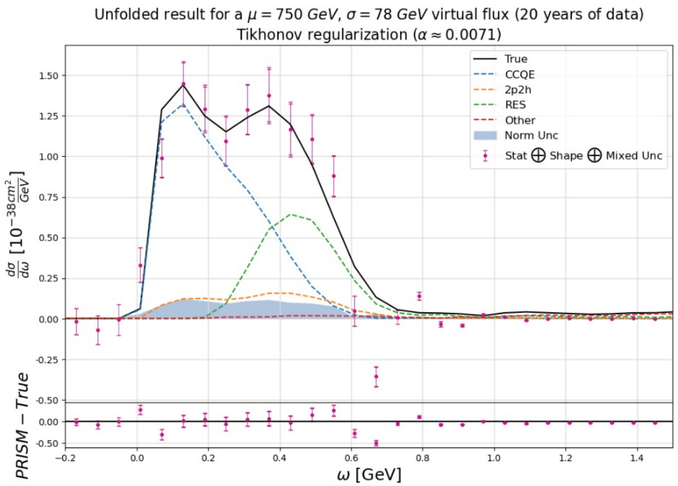
What can we measure

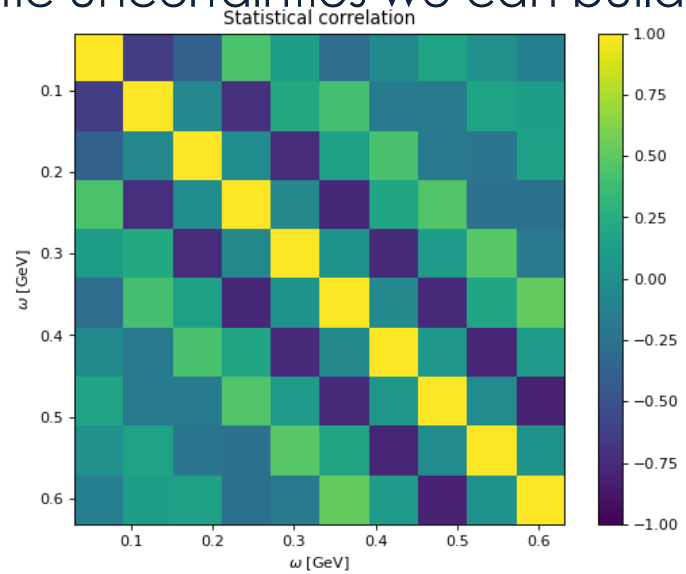
- Access to a good proxy for energy transfer: $\omega_{reco} =< E_\nu > - E_{lep}$
- Close to energy transfer, but the small width of the flux smears it out
- Suggestion: assume all smearing comes from the flux and unfold
  - I.e. build the unfolding matrix only from the flux spread and not from MC
  - Relies on the cross-section to change negligibly across the flux

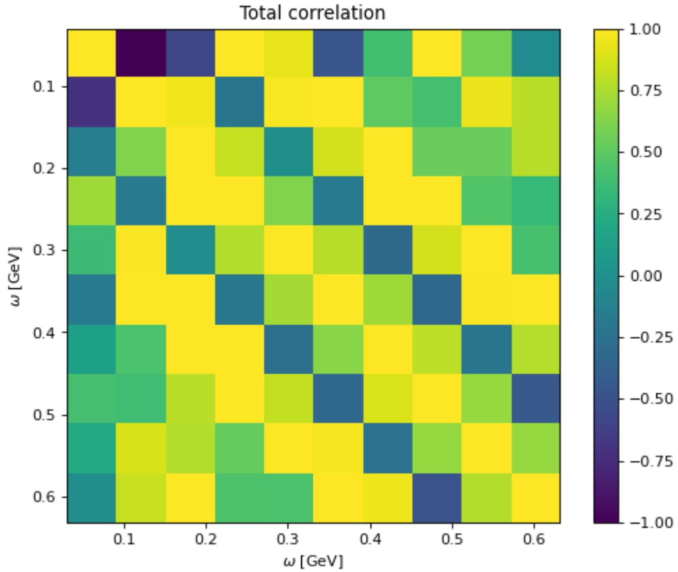


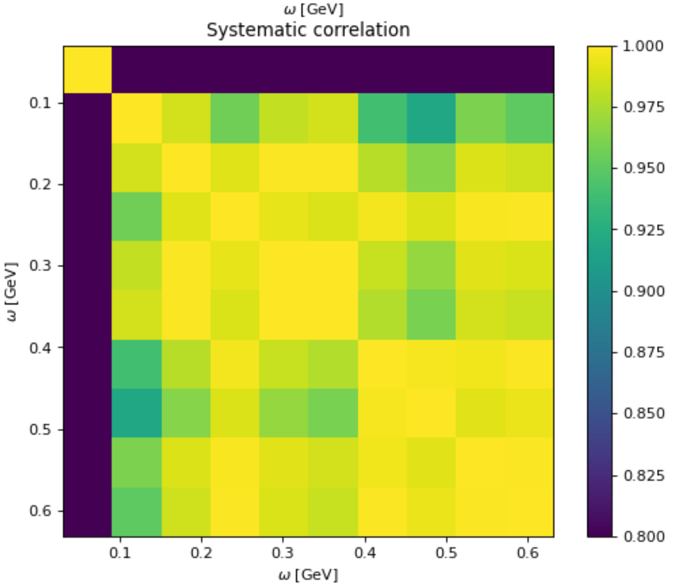
What can we measure

- Considering statistical and all flux systematic uncertainties we can build correlation matrices



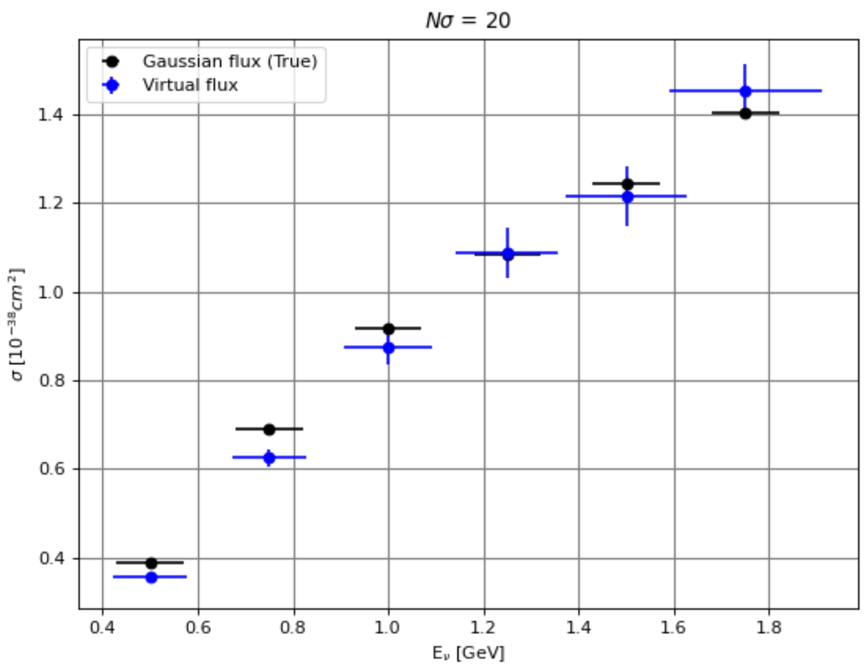






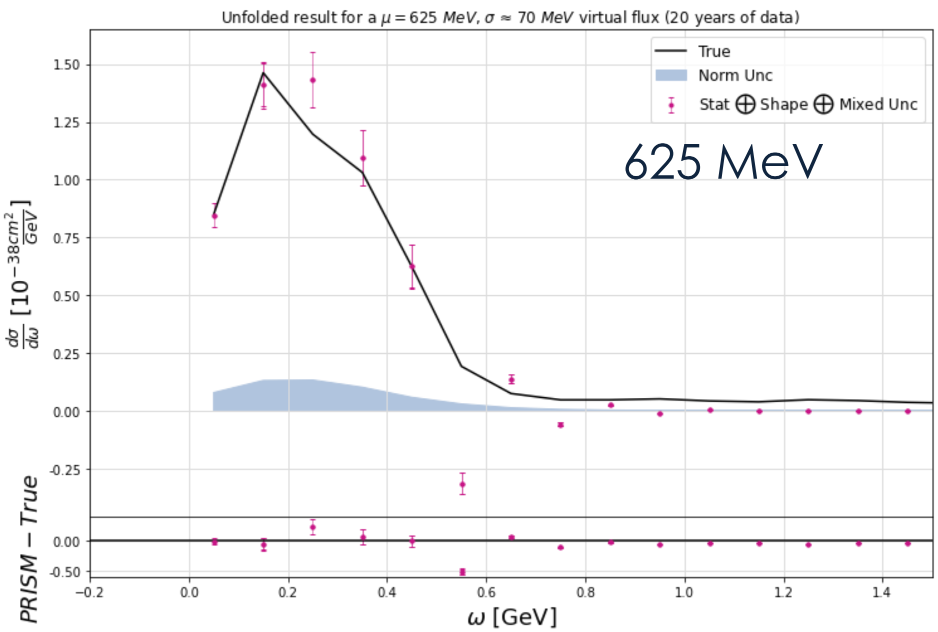
Measuring $\sigma(E_\nu)$

- Understanding the energy dependence of cross-sections is a crucial part of the oscillation analysis
- We can repeat the exercise on the previous slides for different target fluxes to measure $\sigma(E_\nu)$ without model dependence!



Measuring $\sigma(E_\nu)$

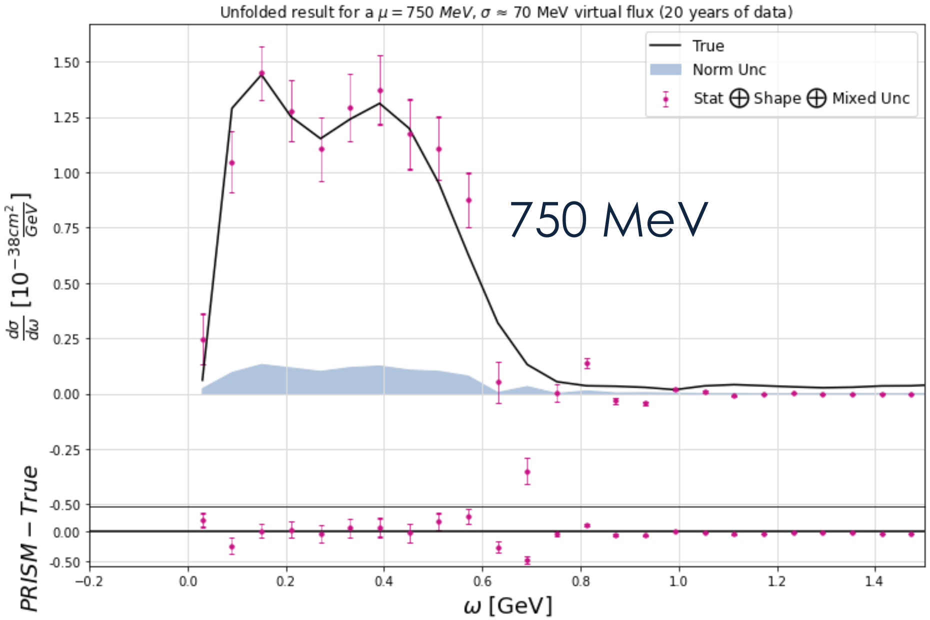
- Understanding the energy dependence of cross-sections is a crucial part of the oscillation analysis
- We can repeat the exercise on the previous slides for different target fluxes to measure $\sigma(E_\nu)$ without model dependence!
- We can also see how the differential cross section changes with E_ν



- The regularisation has scope for optimisation, but it's good to see we see the expected evolution

Measuring $\sigma(E_\nu)$

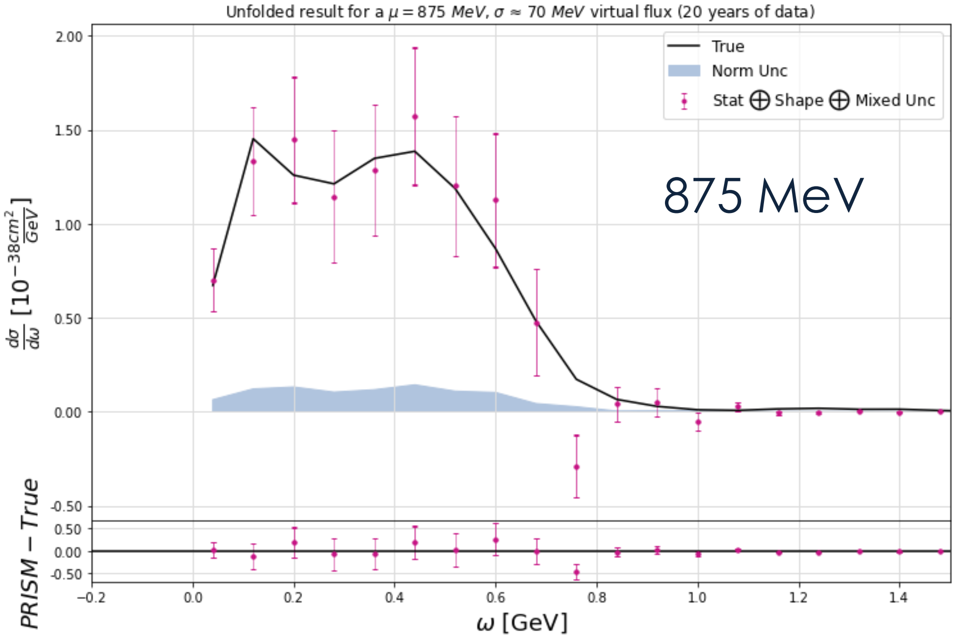
- Understanding the energy dependence of cross-sections is a crucial part of the oscillation analysis
- We can repeat the exercise on the previous slides for different target fluxes to measure $\sigma(E_\nu)$ without model dependence!
- We can also see how the differential cross section changes with E_ν



- The regularisation has scope for optimisation, but it's good to see we see the expected evolution

Measuring $\sigma(E_\nu)$

- Understanding the energy dependence of cross-sections is a crucial part of the oscillation analysis
- We can repeat the exercise on the previous slides for different target fluxes to measure $\sigma(E_\nu)$ without model dependence!
- We can also see how the differential cross section changes with E_ν



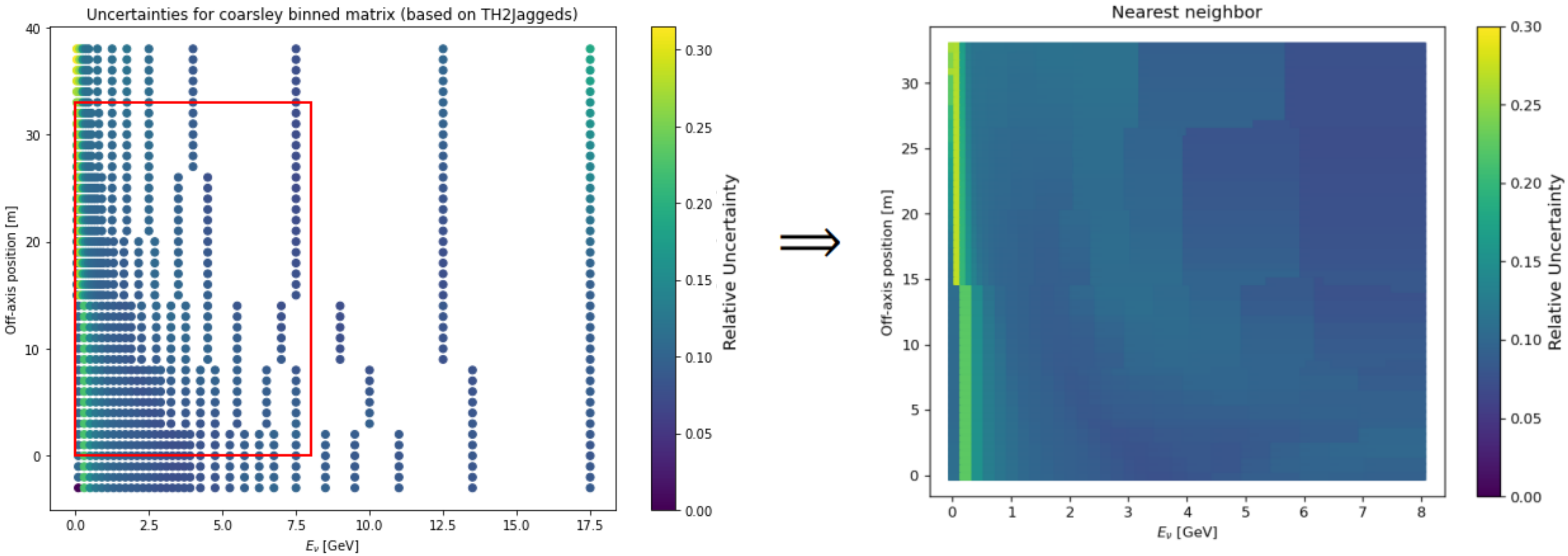
- The regularisation has scope for optimisation, but it's good to see we see the expected evolution

Summary

- Investigating the possibility of using PRISM measurements of neutrino interactions in effective quasi-mono-energetic fluxes
- Allows e-scattering like measurements and a much more model-independent access to $\sigma(E_\nu)$
- But, even with DUNE's huge statistics, uncertainties remain large
- Scope for further optimisation by altering regularisation and target flux
- Flux systematic uncertainties are large, but strongly correlated across PRISM measurements (so do not strongly impact shape analyses)
- Amir will continue this analysis as part of his masters thesis studies. Hope to contribute as a proof-of-concept to the ND TDR
- Lukas Koch has suggested an alternative statistical approach to achieving the measurements shown here
    - Doesn't involve the specification of a target flux
    - Treats everything as an unfolding problem: can use regularisation methods we're well acquainted with

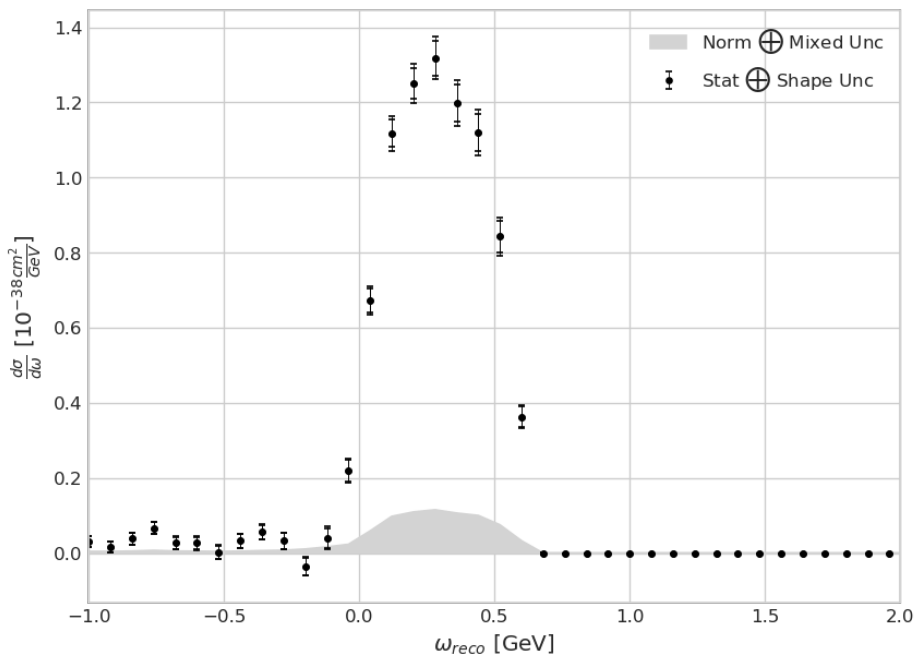
Flux systematics

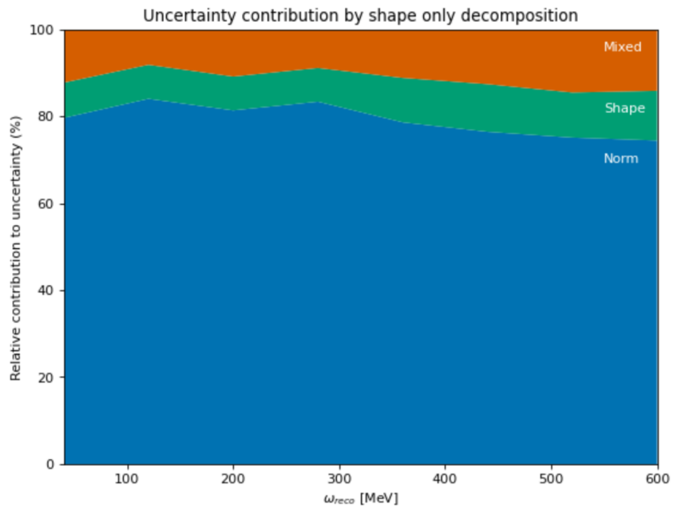
- Flux systematics are included using the inputs prepared for PRISM oscillation analyses.
- But we need to produce toy fluxes in finer binning than the systematics are available: rely on some interpolation

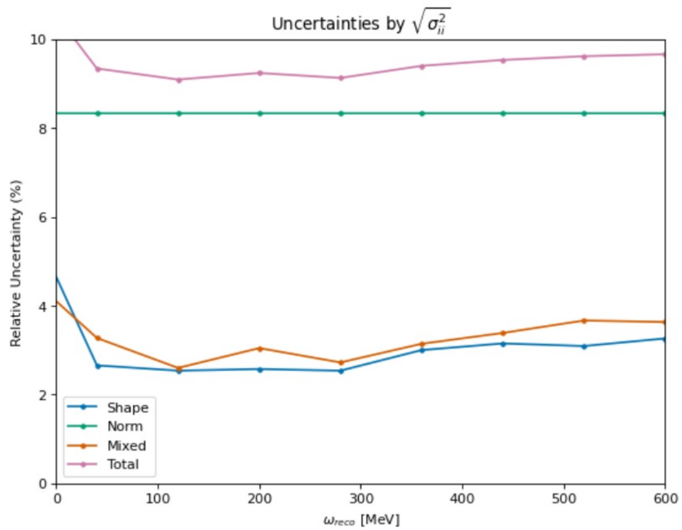


Flux systematics

- Repeating the analysis at the start of this presentation (before the unfolding)



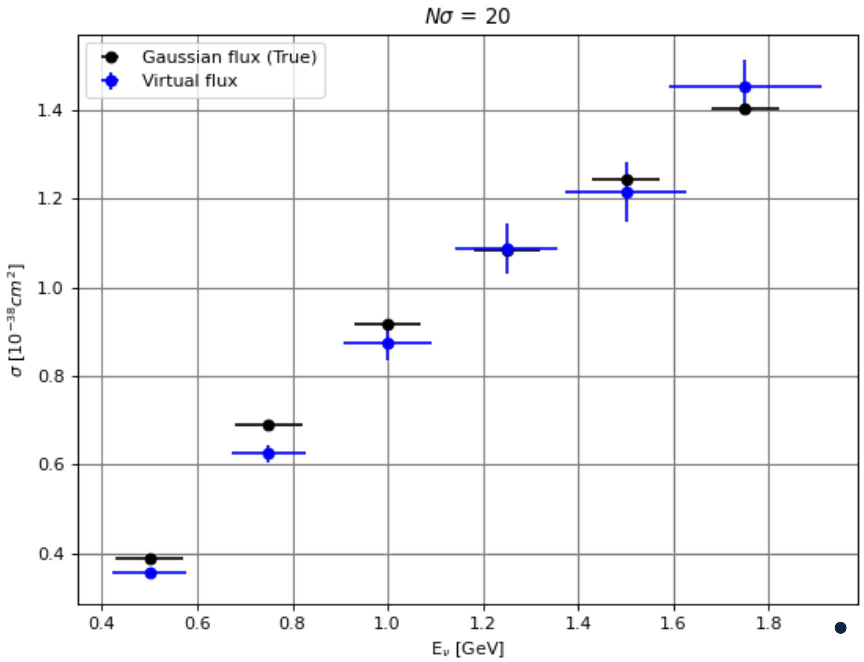




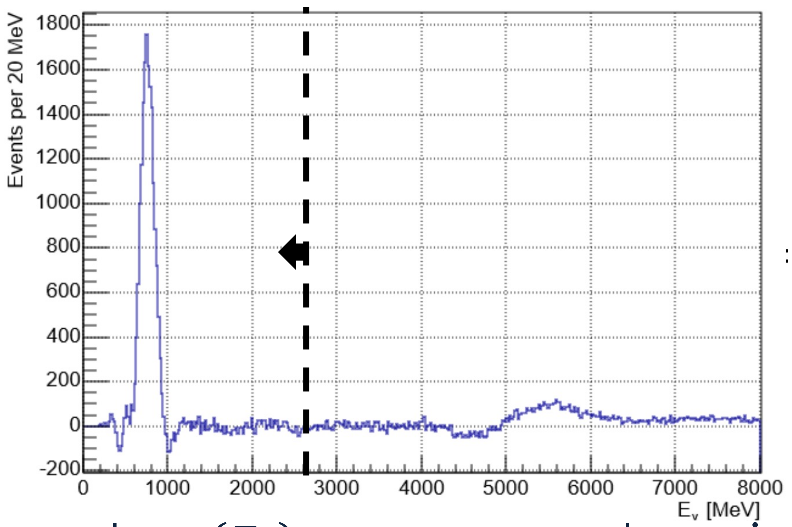
- The flux uncertainties are large, but are generally strongly correlated across bins
- Fairly precise shape measurements are not prevented and in-situ flux constraints may mitigate the issue

Measuring $\sigma(E_\nu)$

- Understanding the energy dependence of cross-sections is a crucial part of the oscillation analysis
- We can repeat the exercise on the previous slides for different target fluxes to measure $\sigma(E_\nu)$ without model dependence!



- To note: the fluxes we produce are not symmetric and can often have small contributions at E_ν very far from the mean

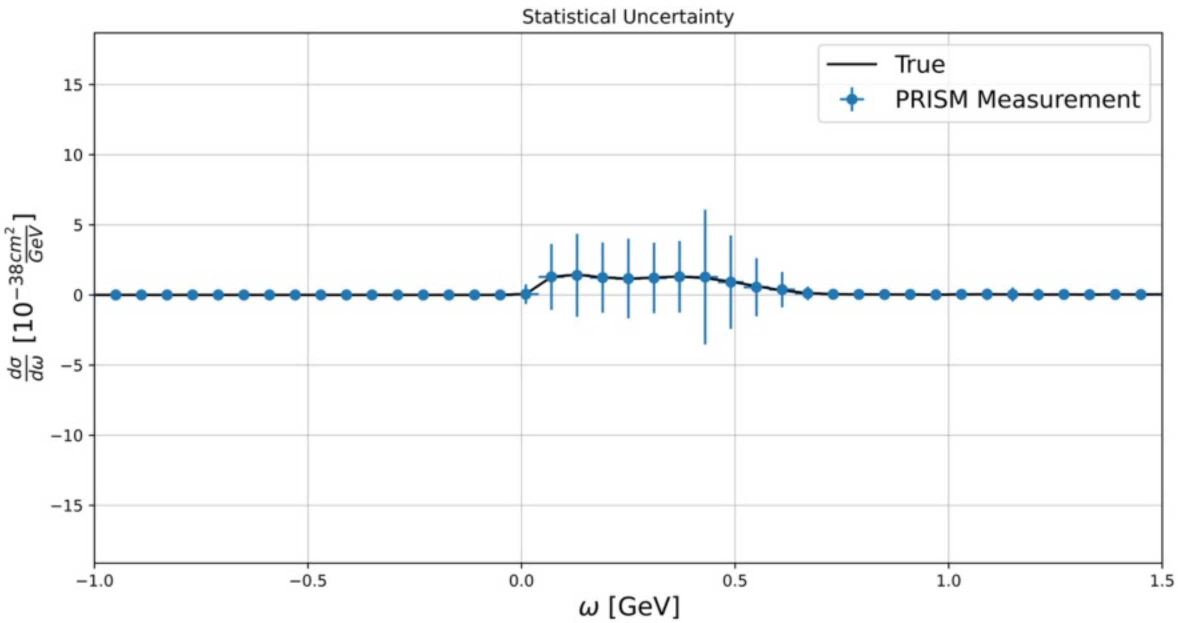


- Can make $\sigma(E_\nu)$ measurements easier to interpret a **very** loose cut in E_ν^{rec} to remove contributions far from the peak

Unbiased analysis

- Biases in the unfolded cross section come from two sources:
  - Regularisation in the unfolding (the usual suspect!)
  - Using a smearing matrix built from the flux rather than from the simulated smearing in ω

- We can use no regularisation and the real smearing in ω to produce and unbiased result, but with huge uncertainties.



Unbiased analysis

- Biases in the unfolded cross section come from two sources:
  - Regularisation in the unfolding (the usual suspect!)
  - Using a smearing matrix built from the flux rather than from the simulated smearing in ω

- Applying only the regularisation in the unfolding: