Neutrino interaction measurements with DUNE-PRISM

Jeremy Atkinson - University of Birmingham
CERN Summer Student
Supervisor - Dr. C. Vilela

Topics

- The DUNE-PRISM programme
- Linear combinations of neutrino fluxes
- Bringing in lepton kinematics
- Simulated data sets
- Summary and next steps

Project goal

To investigate DUNE-PRISM linear combinations using final state lepton variables to access variables analogous to the “electron-scattering” case, such as the energy and momentum transferred from the neutrino to the nucleus.

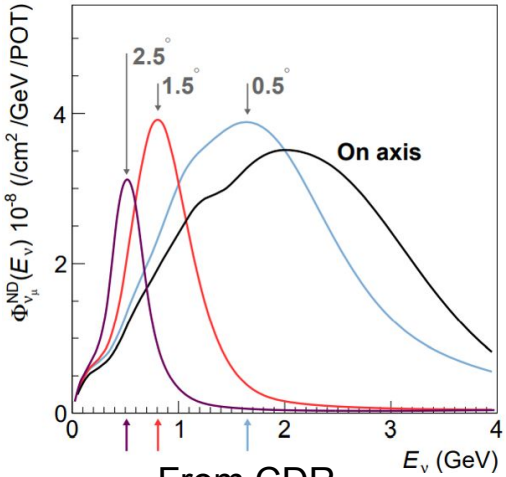
This will allow for neutrino cross-section measurements as a function of previously inaccessible variables.

DUNE Near Detector

DUNE ND - suite of 3 detectors.

SAND (System for on-Axis Neutrino Detection) - stationary on-axis detector.

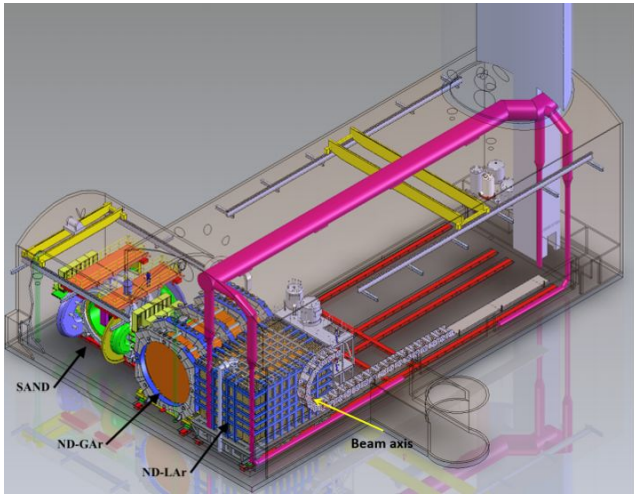
NDGAr and **NDLar** - gaseous and liquid Argon TPC detectors respectively which can move off-axis up to 30.5 meters.

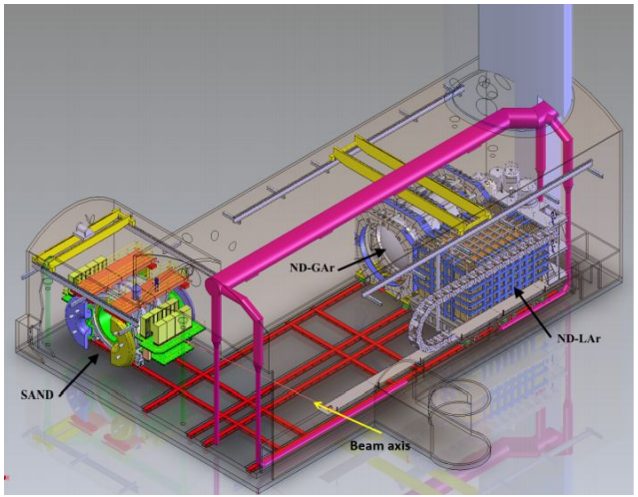


From CDR

This allows for the measurement of varying neutrino energy spectra.

Basis of DUNE-PRISM (DUNE Precision Reaction-Independent Spectrum Measurement)





CDR: arXiv:2103.13910 **[physics.ins-det]**

Electron and Neutrino scattering off nuclei

Well known initial and final states - powerful probes for nuclear models.

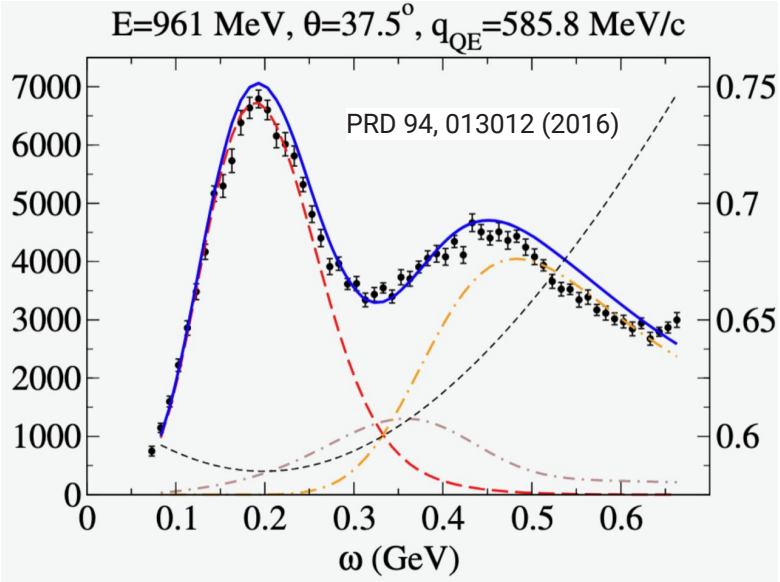
Investigate different interaction modes.

Conventional neutrino experiments don't allow for a known neutrino energy - rely on hadronic reconstruction.

Limited due to undetected hadrons (e.g. neutrons).

To emulate this, linear combinations of the varying neutrino flux spectra can be made to give Gaussian neutrino energy spectra.

Effectively allows for the control of the initial state of the neutrinos.



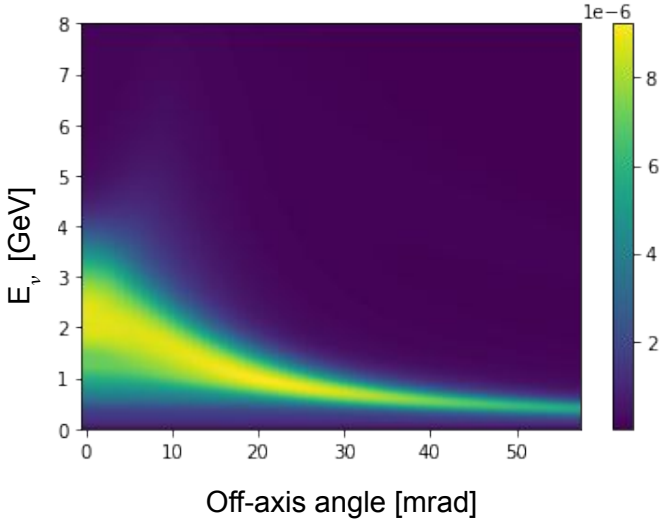
The simple linear algebra problem

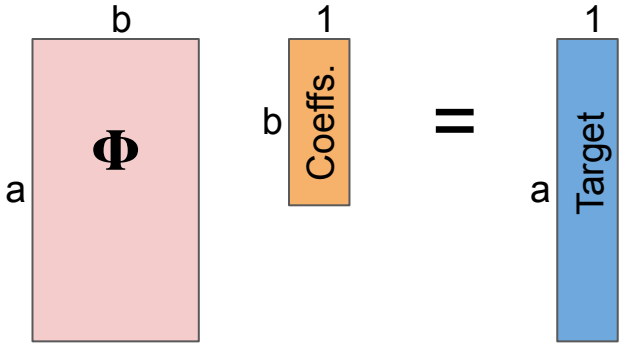
Off-axis neutrino flux matrix gives the neutrino flux for different neutrino energies at different off-axis positions.

Target flux is a gaussian of “dimensions” E_ν.

Need to find a set of coefficients to map the off-axis fluxes to the target.

The neutrino flux model provides the relation between E_ν and off-axis angle.





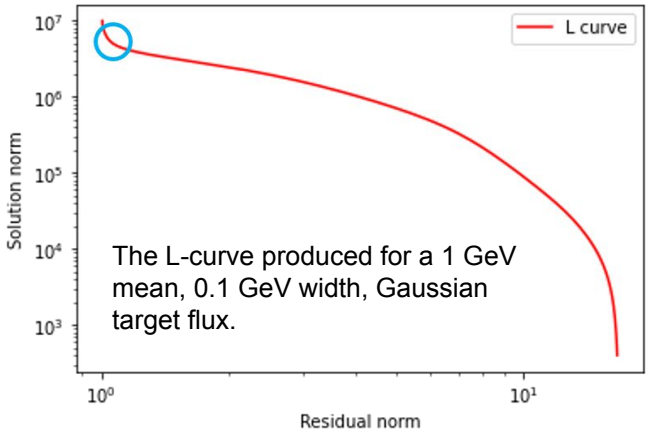
a = E_ν dimension
b = Off-axis angle dimension

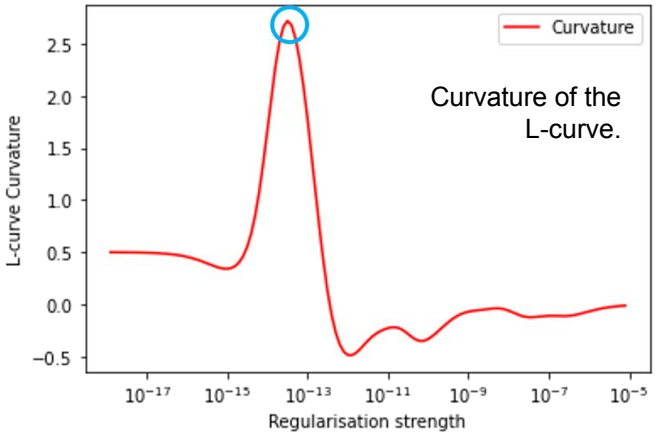
Regularisation

There are various solutions to this problem, so Tikhonov regularisation was implemented.

Regularisation strength λ chosen by producing L-curve and finding point of maximum curvature.

Still issues in implementing regularisation strength optimisation for variables more complex than E_ν.

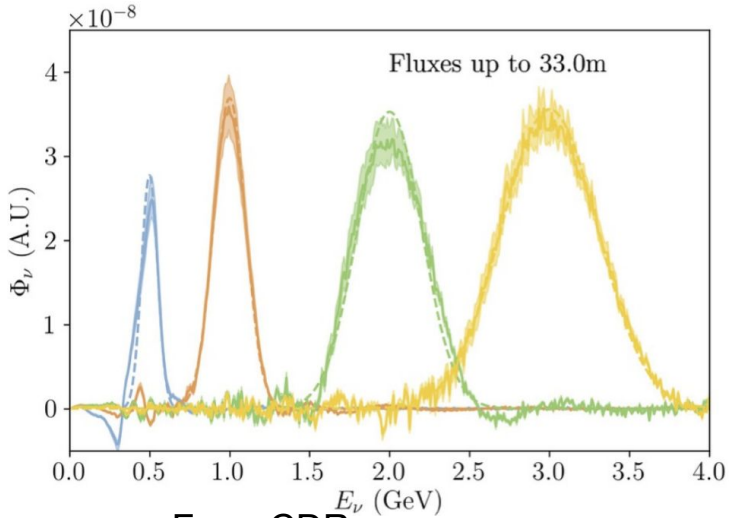




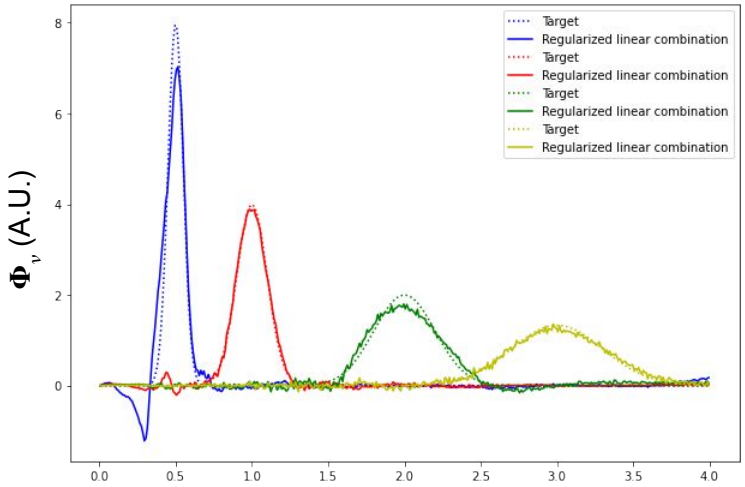
DUNE-PRISM Gaussian neutrino energy spectra

Data from the DUNE-PRISM programme can be linearly combined to give gaussian neutrino energy spectra, as described in the Conceptual Design Report.

First step: reproduce CDR results.



From CDR



E_ν [GeV]

Bringing in lepton kinematics

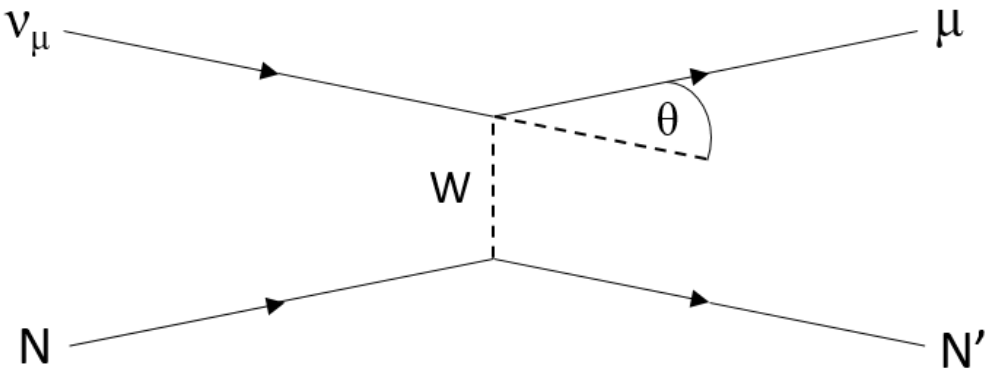
A lepton is produced by the neutrino interaction with the detector material.

Lepton energy and momentum are well reconstructed.

Two key variables defined, lepton energy E_l and lepton angle θ_l.

Allows for further variables of interest to be defined:

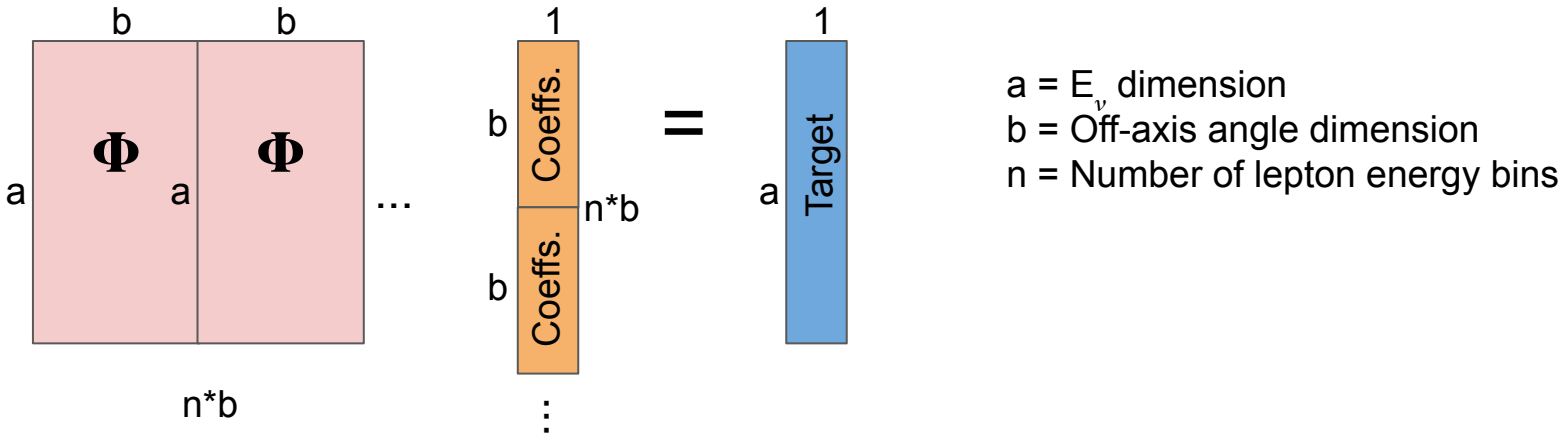
- Energy transferred to the nucleus, $E_\nu - E_l$
- Elasticity of the interaction, E_l / E_ν
- Q^2 value: square of the difference between the four-momenta of the incoming neutrino and the outgoing lepton



Lepton energy

Lepton energy is a variable that is expected to be reconstructed well.

The problem can be adapted by extending the off-axis dimension of the flux matrix, repeating it for every lepton energy bin - coefficient array also extends.



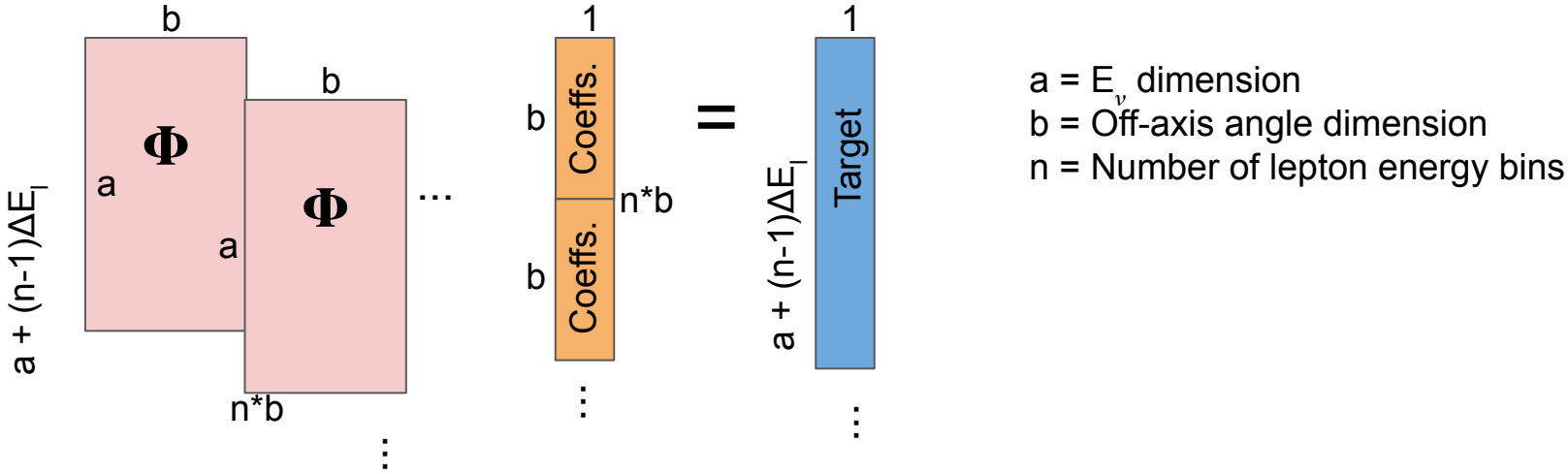
a = E_ν dimension
b = Off-axis angle dimension
n = Number of lepton energy bins

Redefining matrix dimensions

Well defined E_ν, off-axis angle **and** E_l.

Redefine E_ν as E_ν - E_l → energy transferred to the nucleus.

Achieved by shifting each consecutive submatrix down for every value of E_l.



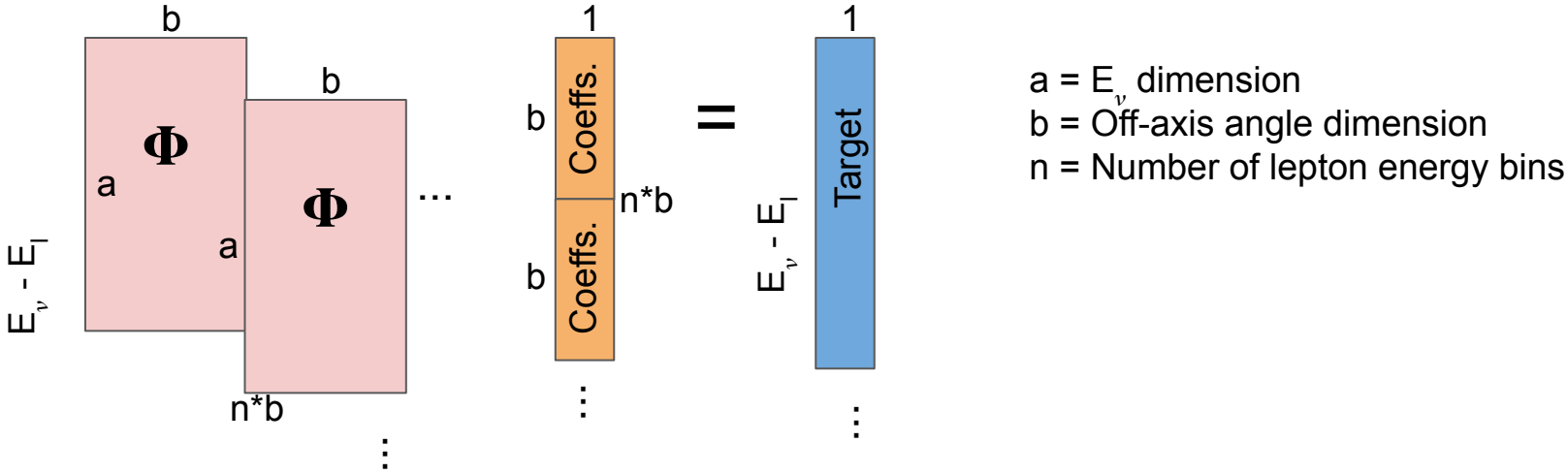
a = E_ν dimension
b = Off-axis angle dimension
n = Number of lepton energy bins

Redefining matrix dimensions

Well defined E_ν, off-axis angle **and** E_l.

Redefine E_ν as E_ν - E_l → energy transferred to the nucleus.

Achieved by shifting each consecutive submatrix down for every value of E_l.



a = E_ν dimension
b = Off-axis angle dimension
n = Number of lepton energy bins

Forming the megamatrix

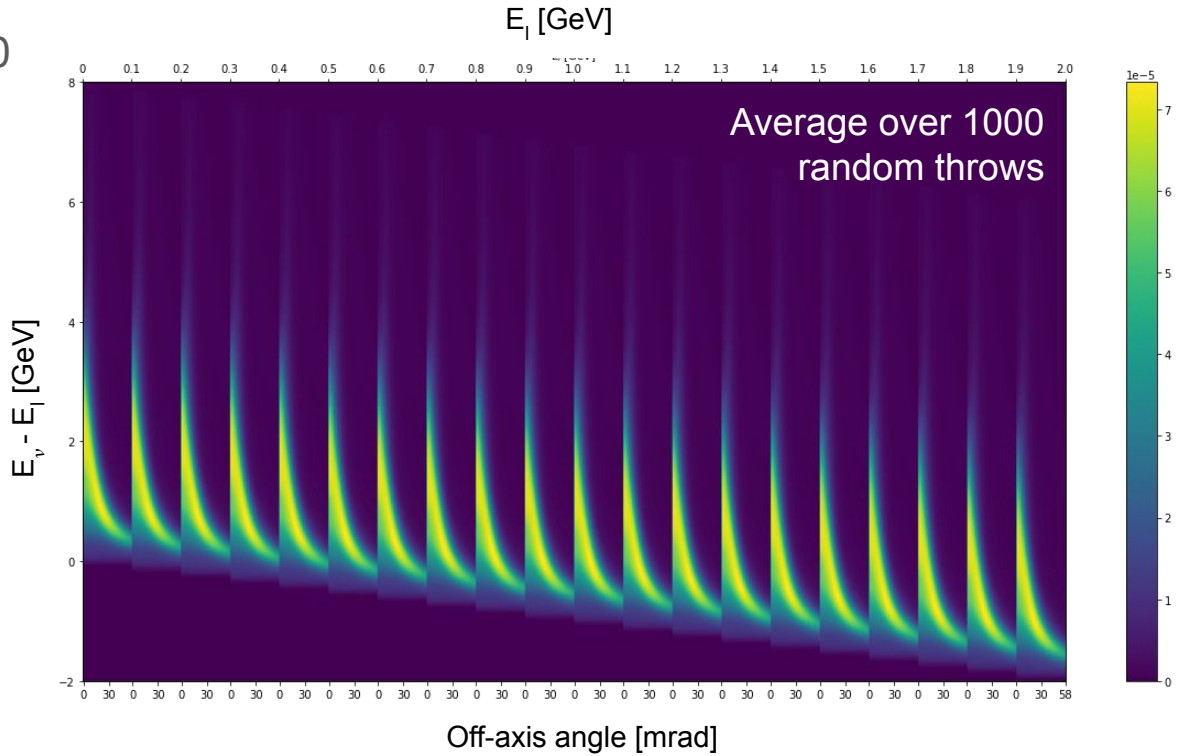
Resulting megamatrix produced from the original flux matrix.

The original flux matrix is compressed to keep the megamatrix within a reasonable size:

- Neutrino energy bins: 800 → 200
- Off-axis angle bins: 58 → 29

Lepton energy won't be evenly spread in set bins → E_l randomised within each bin.

Repeated and averaged → results in approximately even steps but with smeared flux matrices.



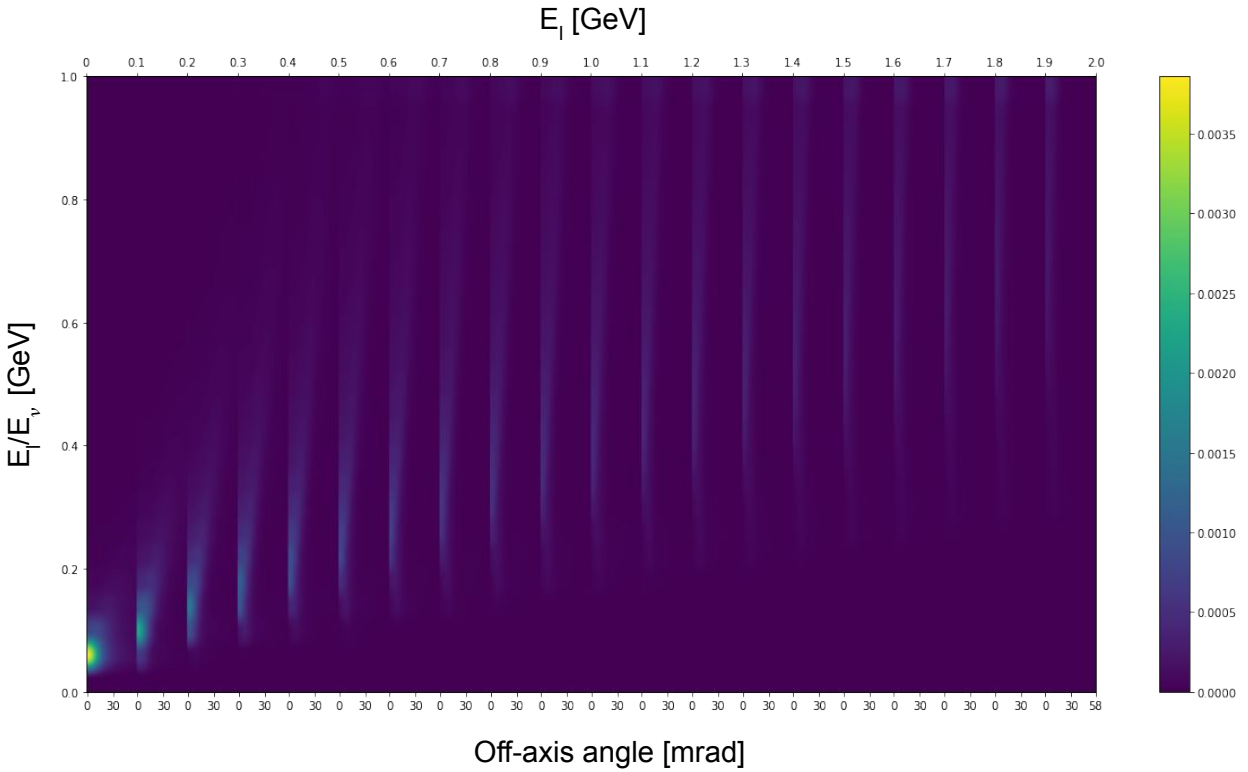
Generalising the megamatrix

Megamatrix can be adapted to investigate other variables:

- Elasticity E_l / E_ν
- Q^2 value

Elasticity also only dependent on neutrino and lepton energy.

Dimensions limited between 0 and 1.



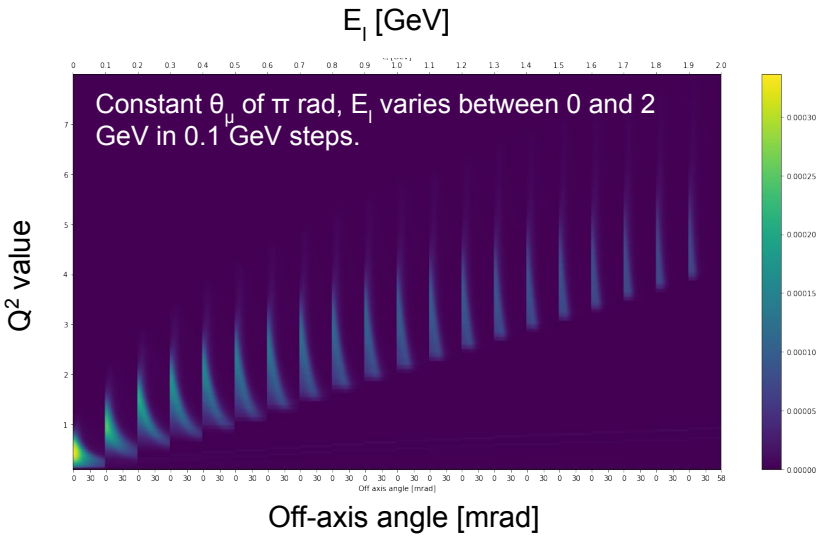
Q^2 values

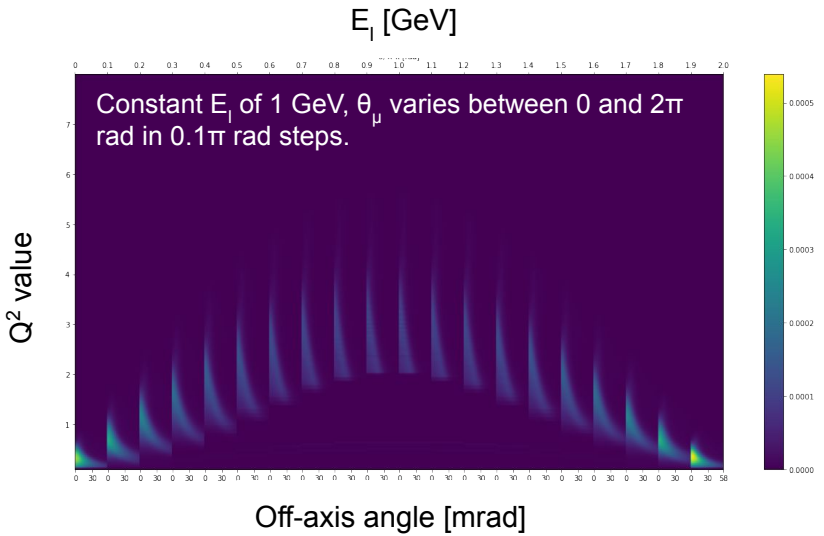
Defined as the square of the difference between the four-momenta of the incoming neutrino and the outgoing lepton.

Assumptions:

- $|p_\nu| = E_\nu$
- leptons are muons, μ

$$Q^2 = m_\mu^2 + 2E_\nu \left(\sqrt{E_\mu^2 - m_\mu^2} \cos\theta_\mu - E_\mu \right)$$

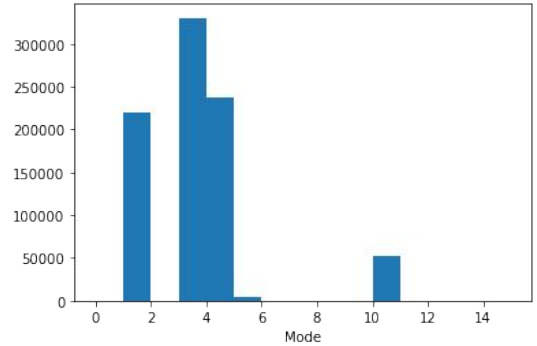




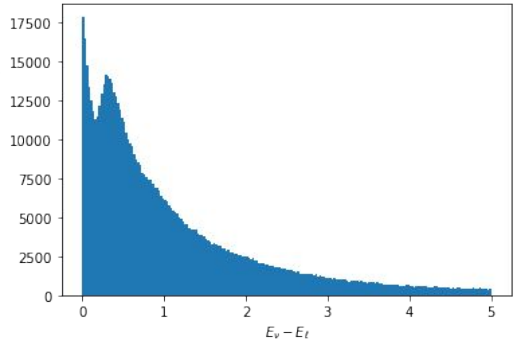
Simulated data sets

Comparisons were made to simulated data to support validity of the method.

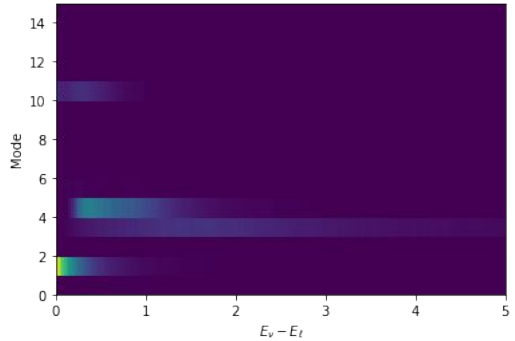
Simulated data has a certain distribution of interaction modes.



E_ν - E_l investigated - unweighted distribution.



2D histogram showing the relative number of events for each mode for each E_ν - E_l energy.



Most visible modes:

- Mode 1 - Quasi-elastic scattering
- Mode 3 - Deep inelastic scattering
- Mode 4 - Resonant scattering
- Mode 10 - two-particle-two-hole (2p2h) scattering.

Gaussian combinations in energy transfer

Gaussian target flux: mean 0.1 GeV, width 0.1 GeV.

Coefficients calculated from linear algebra problem.

For each simulated event, lepton energy and off-axis angle determined and matched to corresponding coefficient value.

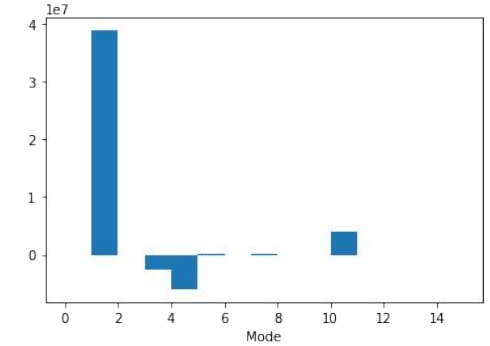
Coefficient used as weight for event.

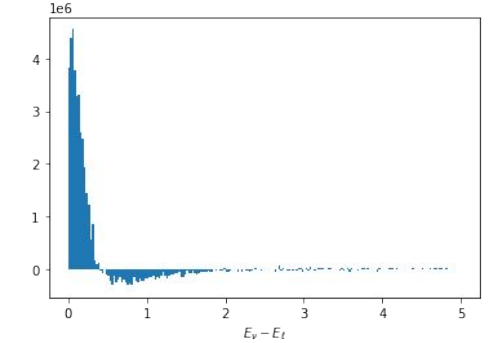
Weight is applied to histogram of modes:

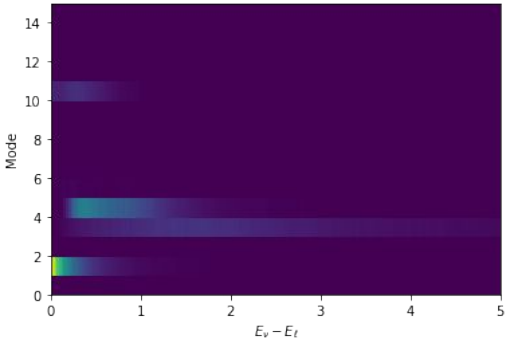
- Large boost to mode 1, small boost to mode 10
- Modes 3 and 4 suppressed

Matches prediction.

Weights applied to histogram for $E_\nu - E_l$ → Gaussian distribution centred on 0.1 GeV recovered.





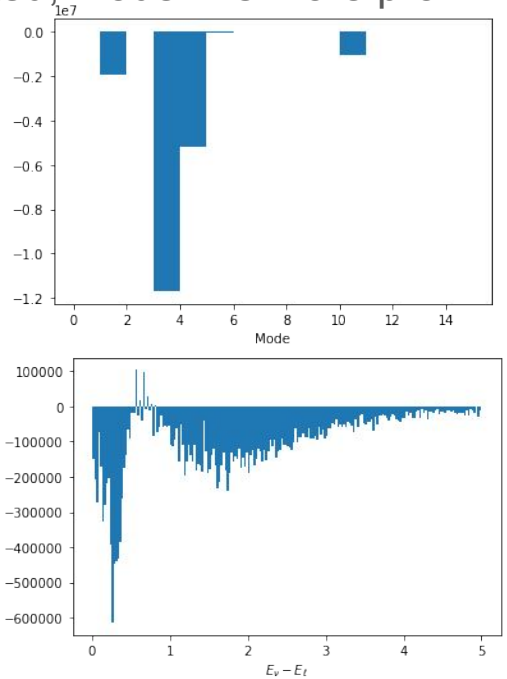


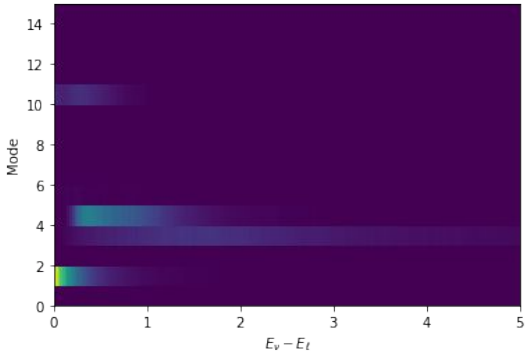
Gaussian combinations in energy transfer

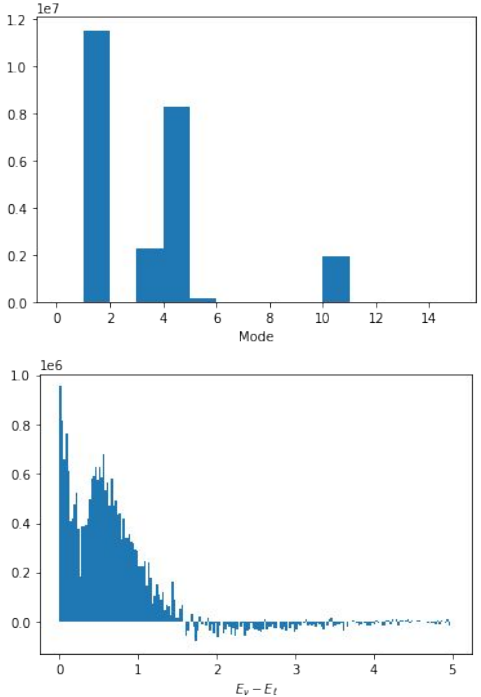
Repeated for Gaussian target flux: mean 0.5 GeV, width 0.1 GeV.

Applying the weights gives a negative histogram, by applying an arbitrary offset of 100 to each weight can recover a positive distribution - requires further investigation.

As expected, mode 4 is more prominent than mode 3.







Summary

Megamatrix constructions for energy transfer E_ν - E_l, elasticity E_l / E_ν and Q^2 value are successful.

By applying the method to simulated data for the E_ν - E_l variable, it has been shown to be a promising technique.

Next steps:

- Regularisation strength optimisation need to be improved to select the best set of coefficients.
- Further testing with different target gaussian fluxes and different variables.
- Resolving issues with negative weights.
- Error calculations.
- Incorporating lepton efficiency.