Electrons for Neutrinos: Old and New Experiments at Jefferson Lab and Beyond

ECR Forum

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University of York
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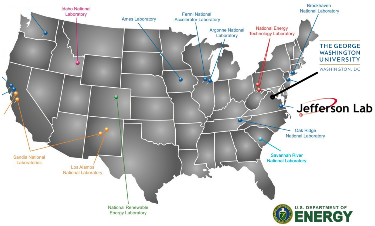
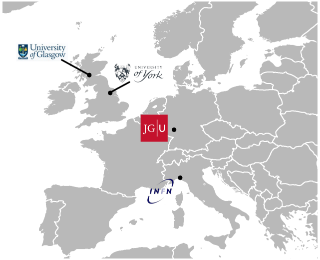
CEBAF Large Acceptance Spectrometer

Who Am I?

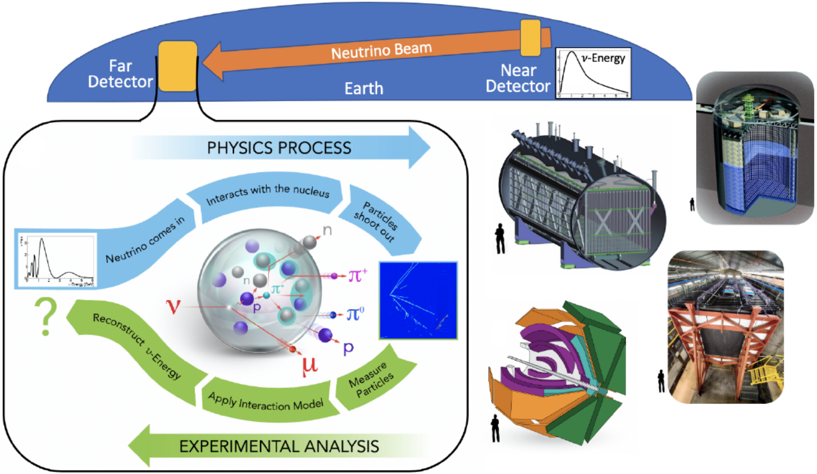




Participated in experimental programs at Jefferson Lab, A2@MAMI and BESIII, with some Jefferson Lab work overlapping with SLAC, FermiLab and Brookhaven

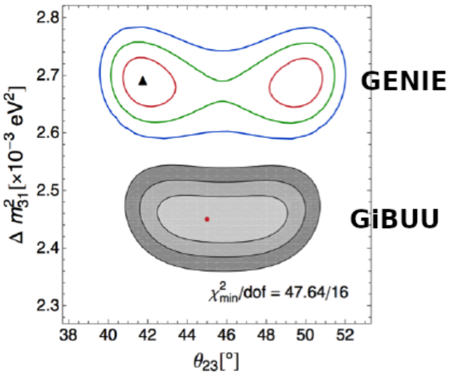
- PhD, University of Glasgow, 2012
- Postdoc, INFN Genova, 2012-14
- Postdoc, JGU Mainz, 2015-17
- Postdoc, GWU, 2017-19
- Postdoc, University of York, 2019-present

Electrons for Neutrinos - e4nu

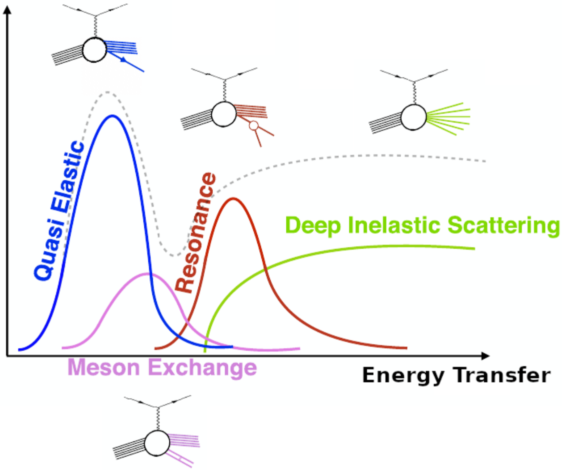


Electrons for Neutrinos - e4nu

- Extracting oscillation parameters from neutrino experiments is sensitive to (currently) poorly constrained physics models
- Key to future success of neutrino experiments is constraining these models of lepton-nucleus interations



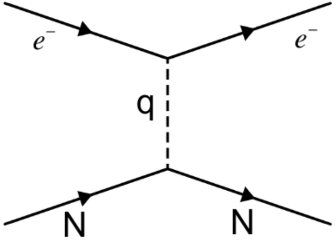
Scattering Processes



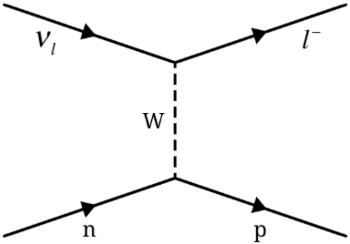
- With increasing energy, scattering is dominated by different interactions
- Start by looking at Quasi-Elastic (QE) process
- Follow up with studies of the role of resonance production

Scattering Processes

- Quasi-Elastic scattering off nuclei similar with both electrons and neutrinos



$$e^- + N \rightarrow e^- + N$$

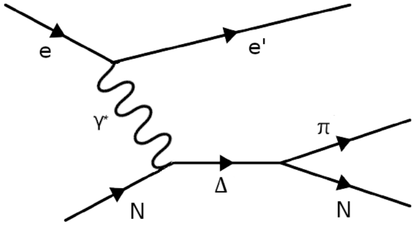


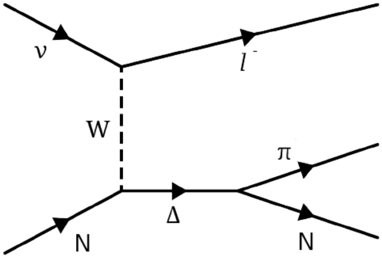
$$\nu_l + n \rightarrow l^- + p$$

$$\bar{\nu}_l + p \rightarrow l^+ + n$$

Scattering Processes - Resonance Production

- Resonance production from electrons also similar to that from neutrinos

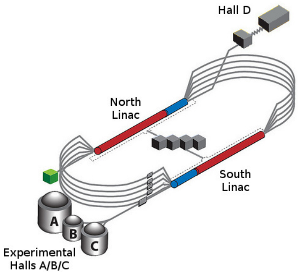




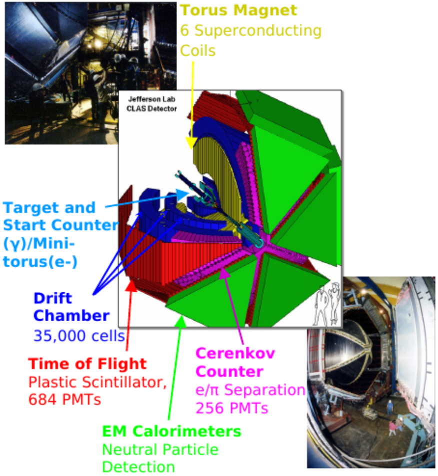
Idea: Use electron scattering data to study electron-nucleon interactions and inform models of neutrino-nucleon interactions!

Jefferson Lab

- US DoE facility, Newport News, VA
- Superconducting RF accelerator electron beams up to 12 GeV
- Four experimental halls

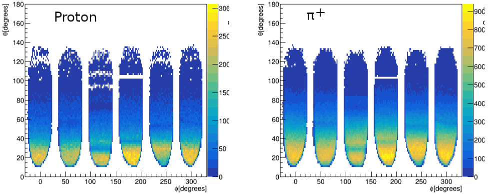


Hall B and CLAS



NIM A, 503(3), 2003

- CEBAF Large Acceptance Spectrometer (1995-2012)
- Multi layered and segmented
- Toroidal magnetic field



Electrons for Neutrinos - e4nu

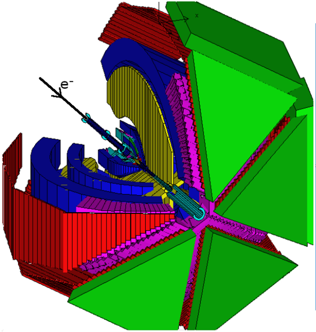
- From a CLAS perspective, e4nu uses electron scattering data on nuclear targets
- Seeking to constrain models of lepton-nucleus interations needed to better describe neutrino interactions
- This started with a PhD student at Old Dominnion University[1]
- I've been working with several collaborators to continue this work
- Particular credit goes to Lucas Tracy, Ali Mand, Afro Papadopoulou and Florian Hausenstein

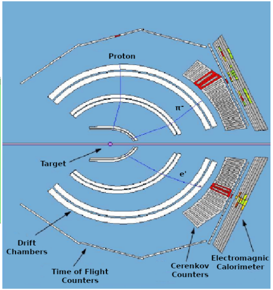
[1] Mariana Khachatryan, "Validation of Neutrino Energy Estimation Using Electron Scattering Data", PhD Thesis, ODU (2019), supervised by Larry Weinstein

e2a Run Period

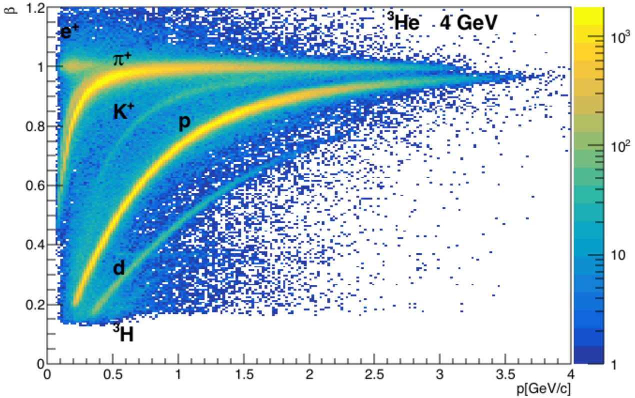
- April/May 1999
- Electron beam experiment
- Various targets

	1.1 GeV	2.2 GeV	4.4 GeV
^{3}He	✓	✓	✓
^{4}He	—	✓	✓
^{12}C	✓	✓	✓
^{56}Fe	—	✓	✓





Particle Identification



- Cuts, corrections and calibrations common to original e2a analyses
- Select events with electron, proton and charged pion in final state
- Minor updates and extensions, e.g. better fiducial cuts, direct π^0 identification

Energy Reconstruction - Zero Pion

- Want to reconstruct beam energy from detected particles
- Beam energy known, can compare to neutrino generators
- Two methods, "Calorimetric", using all final state particles

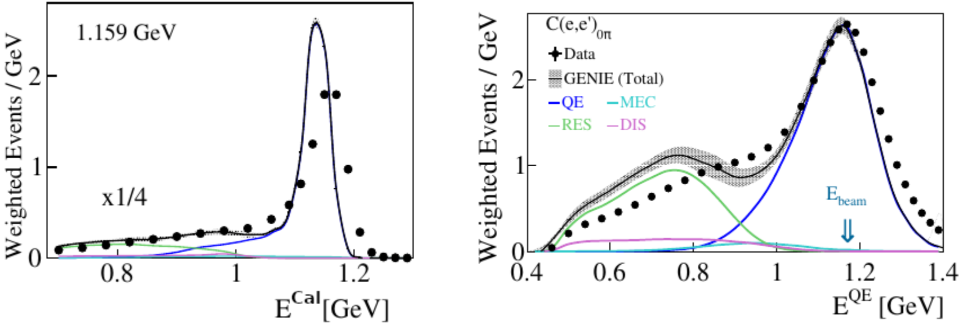
$$E_{cal} = \sum E_i + \epsilon$$

- And "Kinematic", using the scattered electron

$$E_{QE} = \frac{2M_N\epsilon + 2M_N E_l - m_l^2}{2(M_N - E_l + k_l cos\theta_l)}$$

Energy Reconstruction - Zero Pion

Calorimetric reconstruction (left) and QE kinematic reconstruction (right)



[1]Mariana Khachatryan, et. al. "Electron Beam Energy Reconstruction for Neutrino Oscillation Measurements", Accepted for publication by Nature (2021)

Energy Reconstruction - Resonance Production

- We can play the same game of beam energy reconstruction, and neutrino generator comparison, with resonance events
- Same two methods, "Calorimetric", using all final state particles

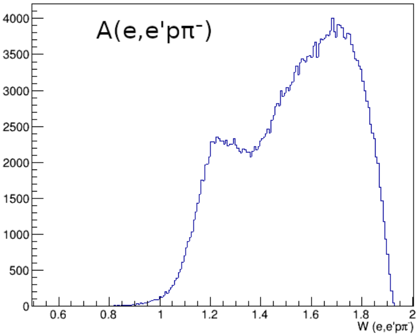
$$E_{cal} = \sum E_i + \epsilon = E'_{e^-} + E_p + \epsilon + E_\pi$$

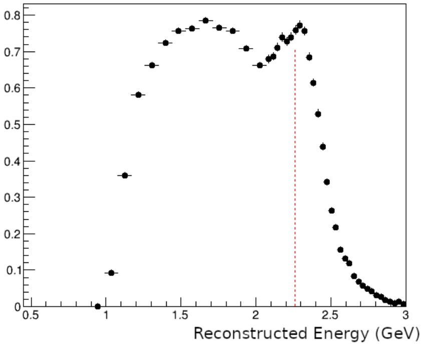
- And "Kinematic", using the scattered electron, assuming Δ production

$$E_{Del} = \frac{m_\Delta^2 - (m_p - \epsilon)^2 - 2(m_p - \epsilon)E'_{e^-}}{2(m_p - \epsilon - E'_{e^-} + E'_{e^-} cos\theta_{e^-})}$$

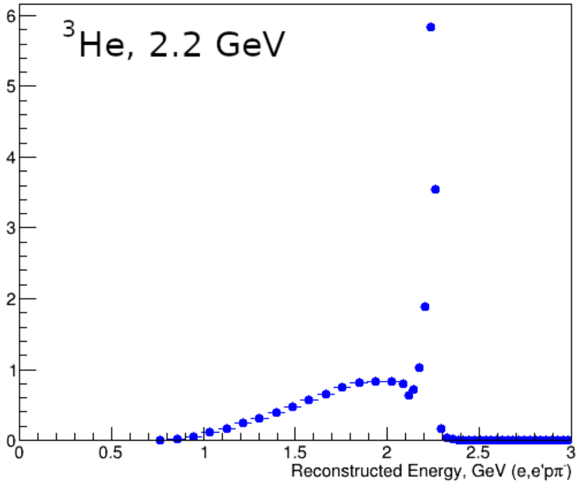
Energy Reconstruction, Kinematic Method

- ^{3}He at 2.2 GeV
- A(e,e'pπ) not Δ dominated, "Kinematic" reconstruction of limited use



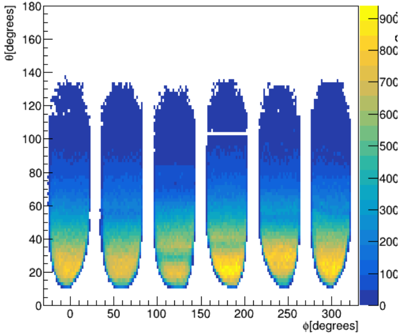


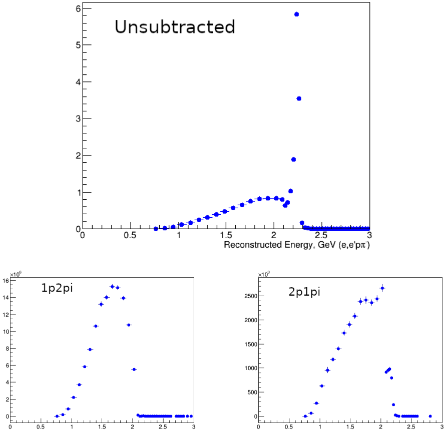
Energy Reconstruction, Calorimetric Method



Undetected Particles

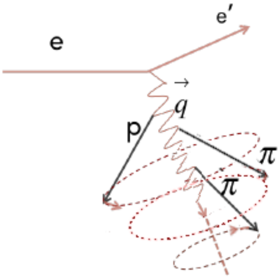
- Some particles undetected, fall through CLAS acceptance gaps
- Effect on energy reconstruction





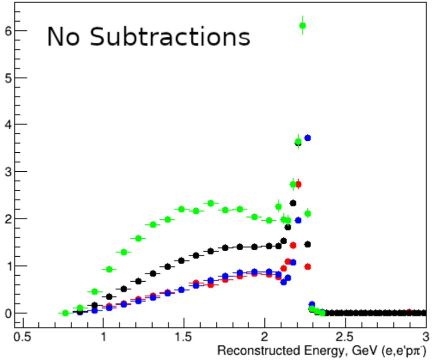
Rotations

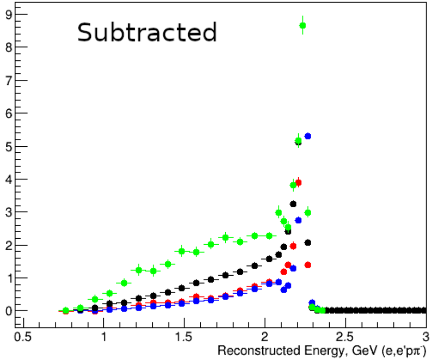
- Select events with multiple hadrons
- Randomly rotate around direction of three momentum transfer
- Some events fall into acceptance gaps
- Proportion of events lost used to estimate undetected ones
- Subtract from energy reconstruction spectra
- Produce "true" 1p1π event samples



Energy Reconstruction, Calorimetric Method, 2.2 GeV

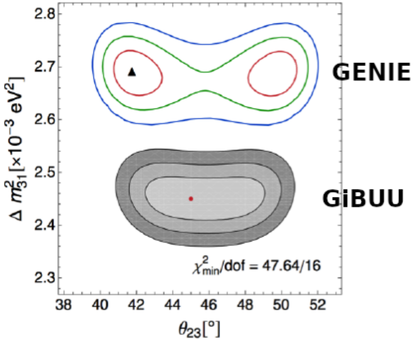
Targets: ^{3}He, ^{4}He, ^{12}C, ^{56}Fe





Event Generators

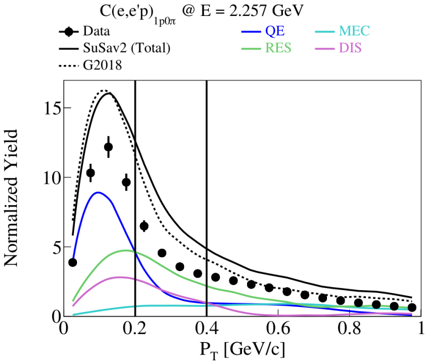
- GENIE (Generates Events for Neutrino Interaction Experiments)
- GiBUU (The Giessen Boltzmann-Uehling-Uhlenbeck Project)



- Each model has different approaches to describing lepton-nucleus interactions
- Different values of neutrino oscillation parameters extracted

Event Generators

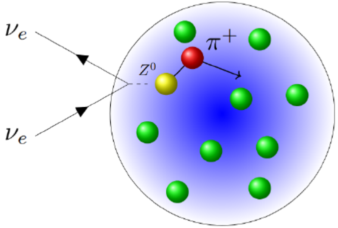
- GENIE is the basis for event generator studies
- Used in predecessor analysis
- Expertise (and code) readily available in e4nu



- GiBUU a possible cross-check
- Used already for other projects in York, can also apply to e4nu

Other Measurements

Pion Transparency



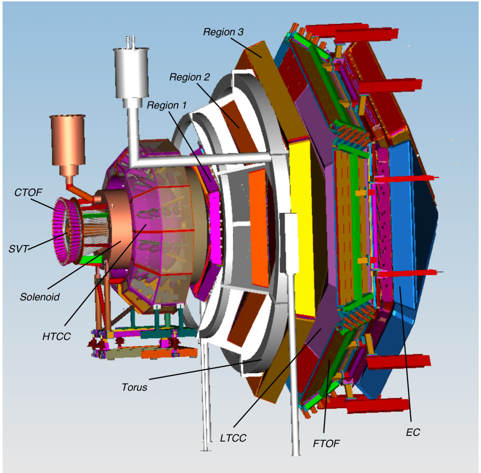
- All neutrino generators use hadron beam data to tune final state interactions
- Reliant on total cross section, with numerous contributions
- Possible alternative is to use *transparency*, the probability a hadron produced in nuclear medium escapes
- Like beam energy reconstruction, this is easier and more accurate to achieve with electron scattering data than with neutrino data

e2a Summary

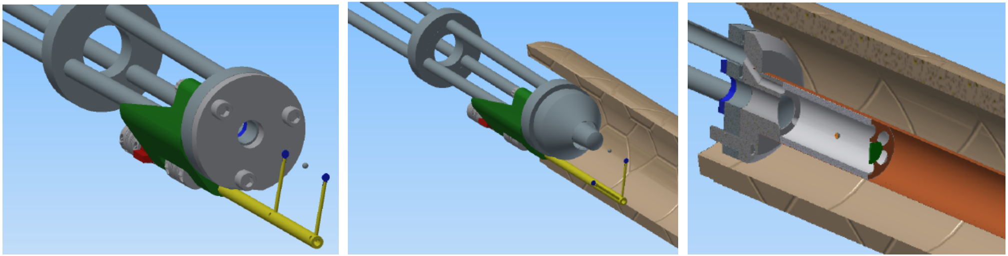
- Energy reconstruction analysis has beeen highly successful on zero pion analysis
- Extension to $p\pi$ events
- Beam energy peaks clear for $p\pi^-$, less so for $p\pi^+$ and $p\pi^0$
- Next steps in energy reconstruction analysis are to bin in kinematic variables, make measurements and fully compare to neutrino event generators
- Expansion beyond the game of energy reconstruction already underway

Future Experiments - Run Group M

- Starting this month, a dedicated beamtime for e4nu takes place at JLab
- Once again in Hall B, with CLAS12, the 12 GeV upgraded version of CLAS
- Much of the analysis software uses the format of GENIE trees in ROOT, i.e. good to go almost as soon as we have data

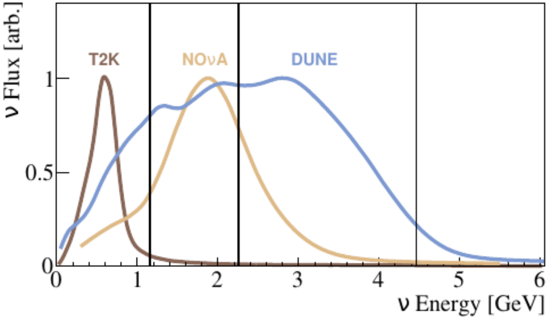


Run Group M



- Nuclear targets, including Deuterium, Calcium, Argon and Tin
- 1, 2, 4 and 6 GeV beams

Run Group M



- RGM will greatly expand our available data for e4nu
- Kinematic overlap with the latest generation of neutrino experiments

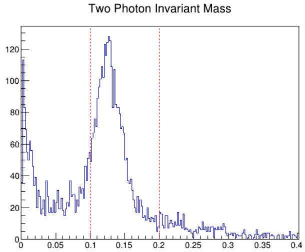
Summary

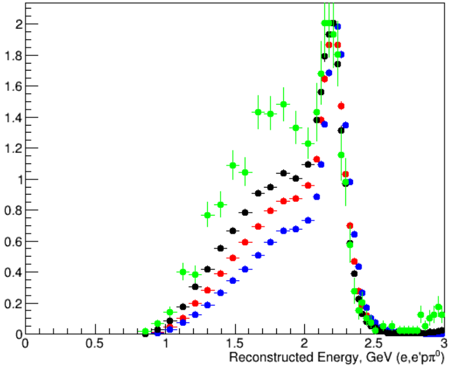
E4nu is a successful demonstration of:

- Interdisciplinary research - Fresh perspectives from other fields
- Data mining - Breathing new life into older data
- Diversifying the JLab program - Motivating new experimental work

(Backup) Energy Reconstruction, Calorimetric Method, $p\pi^0$, 2.2 GeV

Targets: ^{3}He, ^{4}He, ^{12}C, ^{56}Fe, A(e,e'pπ^0)





- Very loose π^0 selection from two photon invariant mass
- Beam energy peak visible

(Backup) Energy Reconstruction, $p\pi^+$, 2.2 GeV

Targets: ^{3}He, ^{4}He, ^{12}C, ^{56}Fe