Electrons for Neutrinos: How electron scattering data can improve oscillation experiments

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Collaboration

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- MIT
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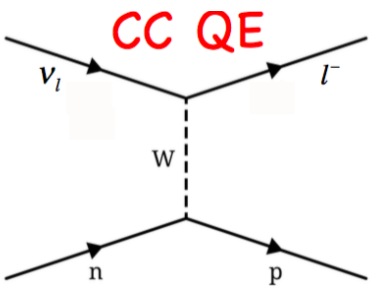
  - Eli Piasetzky
- Michigan State
  - Kendall Mahn
  - Luke Pickering (PD)
- FermiLab
  - Minerba Betancourt (PD)
- Pitt
  - Steve Dytman
- York University, UK
  - Dan Watts

Neutrino Interaction



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

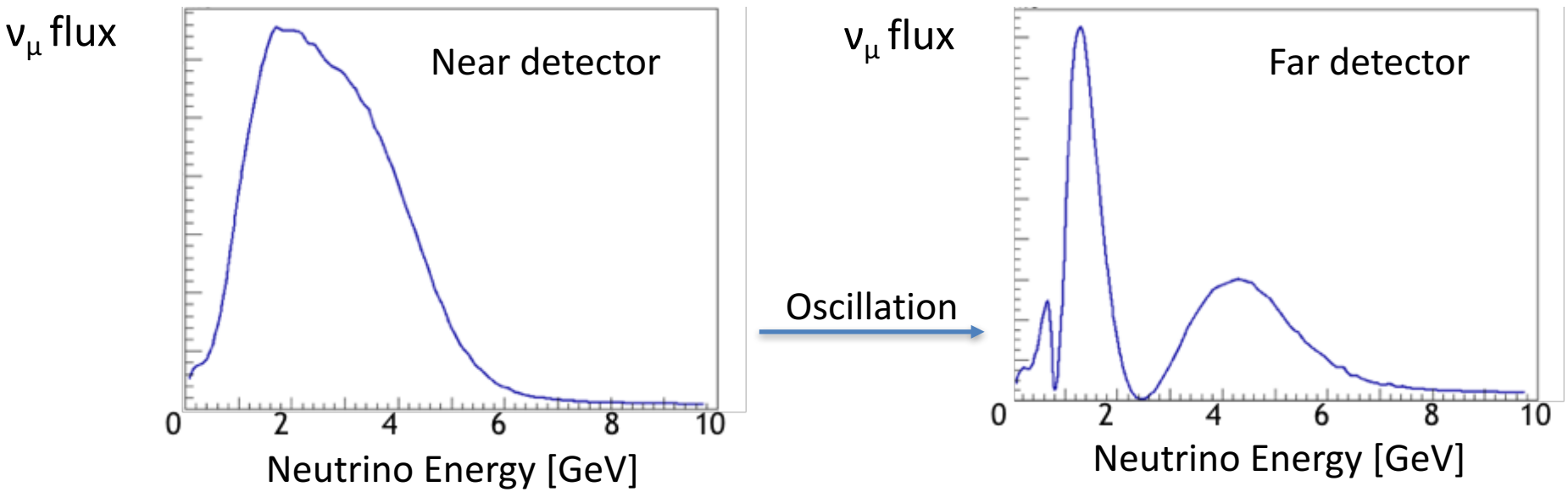
$$\bar{\nu}_l + p \rightarrow l^+ + n$$

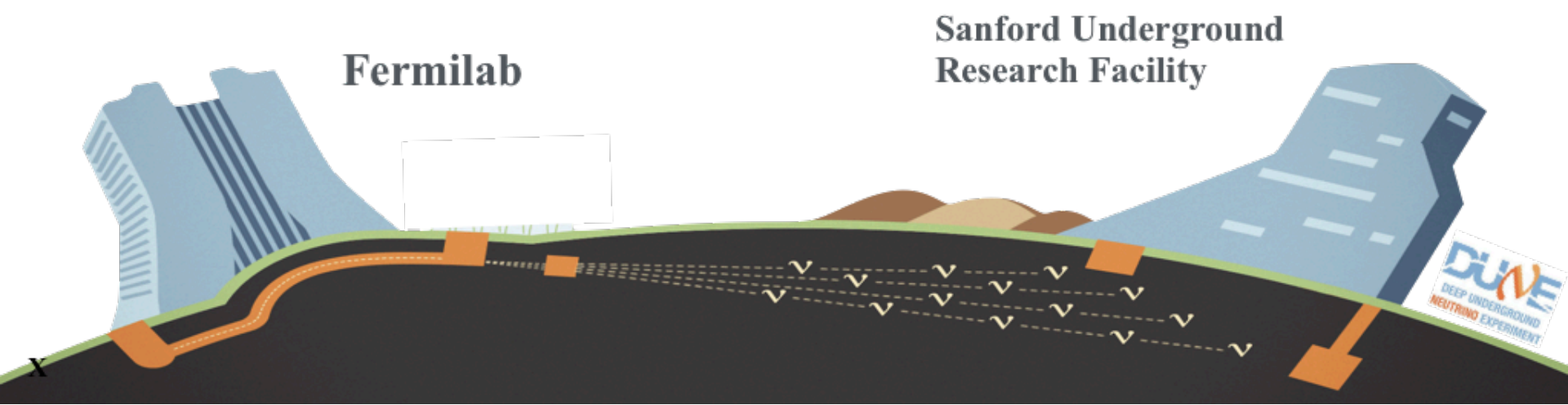
- Weak interaction
- Weak eigenstates ≠ mass eigenstates
- Neutrino mixing PNMS (Pontecorvo-Maki-Nakagawa-Sakata) matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}.$$

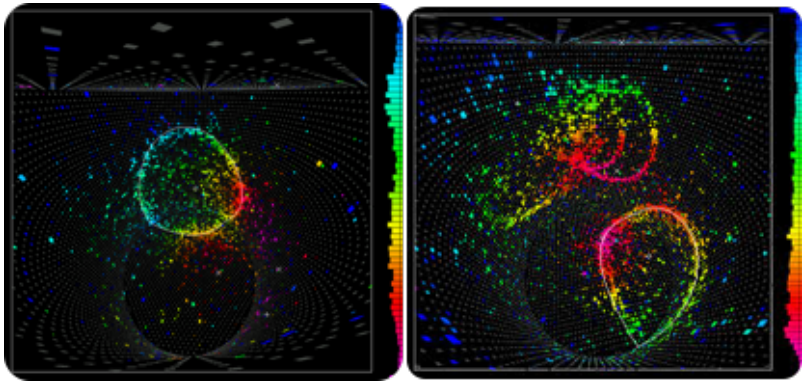
➔ Oscillations

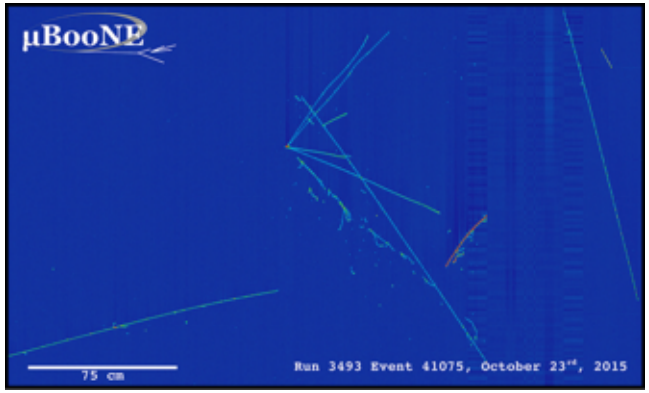
Neutrino Oscillations





Incoming Energy Reconstruction





Cherenkov detectors (T2K,..)

- Assuming Quasielastic (QE) interaction
- Using solely the final state lepton

$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l| cos\theta)}$$

Tracking detectors (DUNE,..)

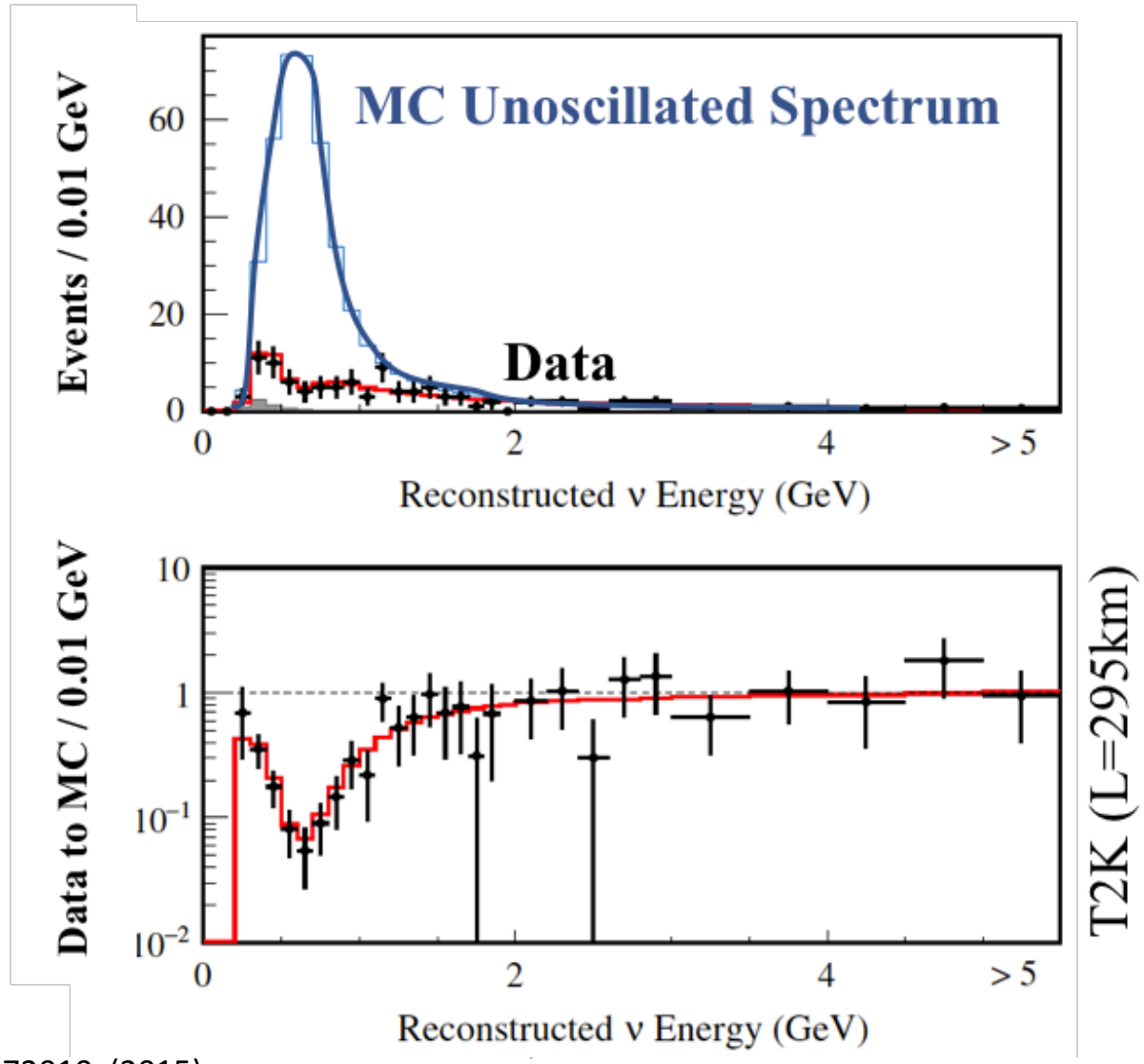
- Detect outgoing hadron and lepton
- Need good hadronic resolution

$$E_{\mathrm{cal}} = E_l + E_p^{\mathrm{kin}} + \epsilon$$

for (e,e‘p)

ε is the nucleon separation energy ~ 20 MeV

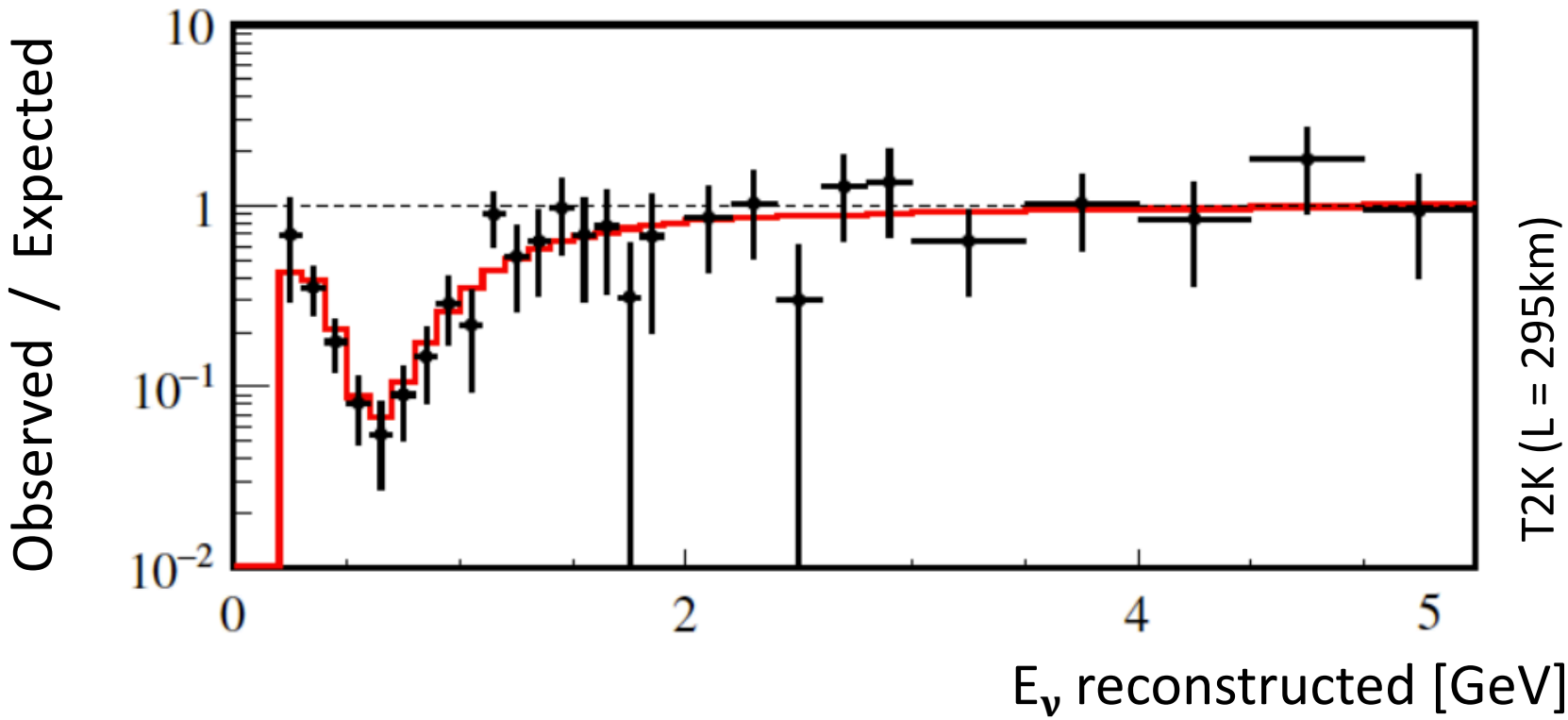
Osciallations need E_ν reconstruction



T2K, Phys. Rev. D 91, 072010 (2015)

Oscillations need E_ν reconstruction

$$P(\nu_\mu \rightarrow \nu_x) = \sin^2(2\theta) \times \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$



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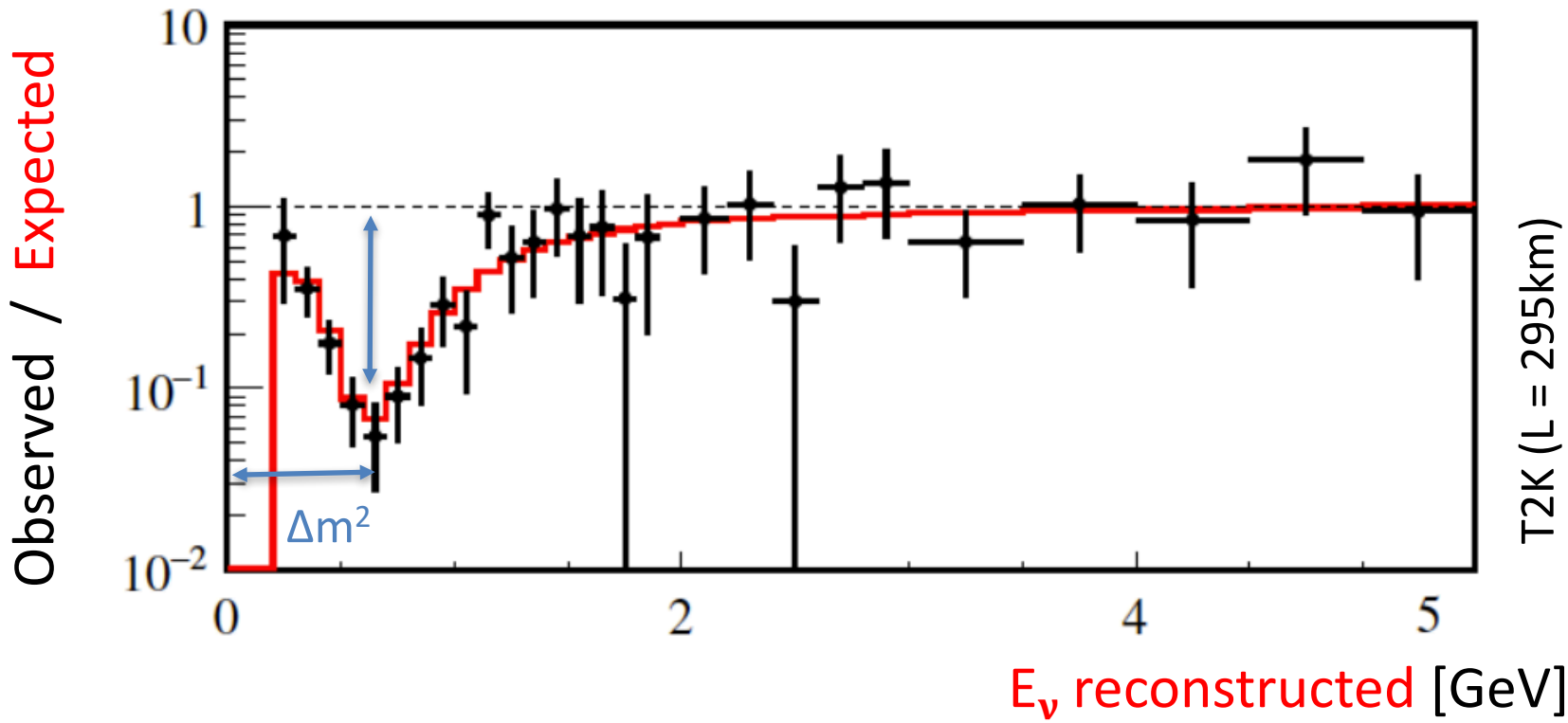
Oscillations need E_ν reconstruction

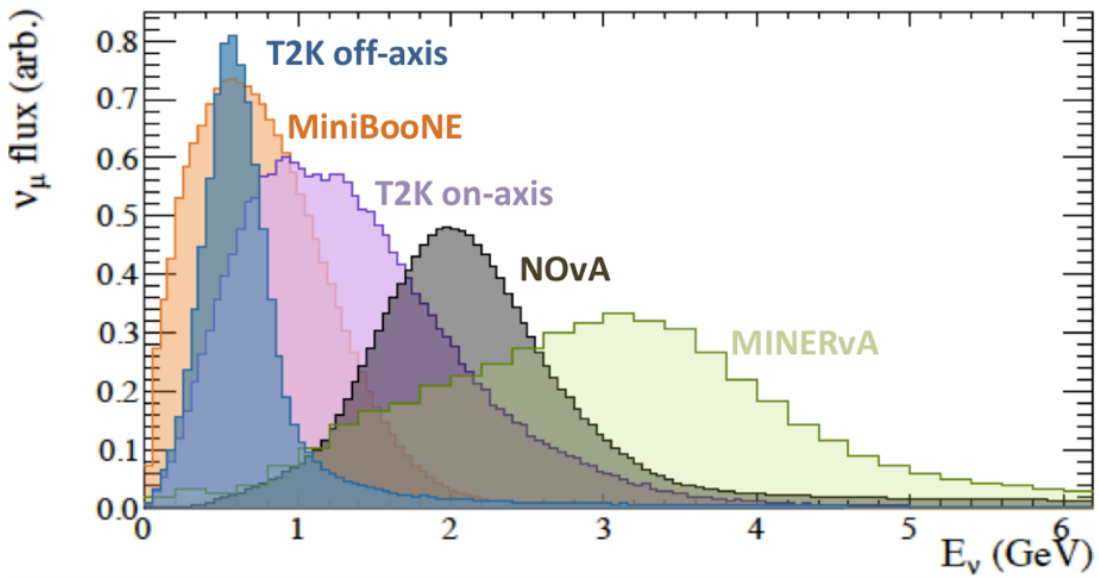
$$P(\nu_\mu \rightarrow \nu_x) = \sin^2(2\theta) \times \sin^2\left(\frac{\Delta m^2 L}{4 E_\nu \text{ real}}\right)$$



T2K, Phys. Rev. D 91, 072010 (2015)

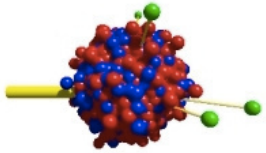
Energy reconstruction

- Wide neutrino beam distribution



- Reconstruction requires knowledge of the nuclear interactions -> event generators

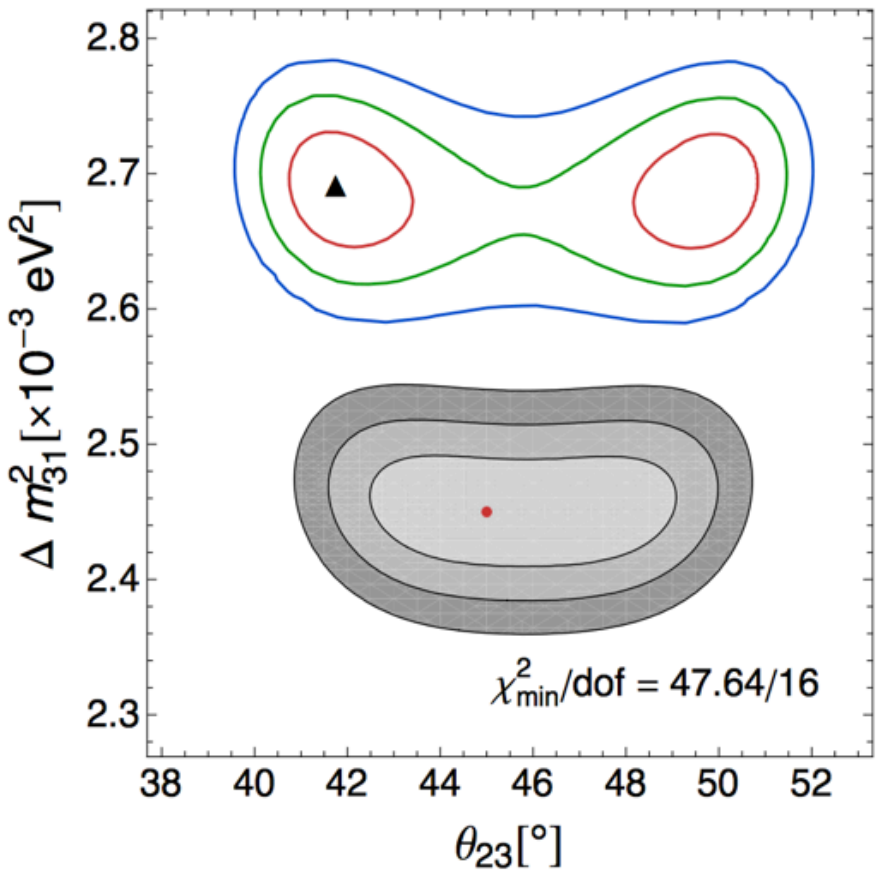
GENIE



GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

and more

Systematic Effects by Nuclear Models



Events generated with GiBUU, reconstruct with Genie

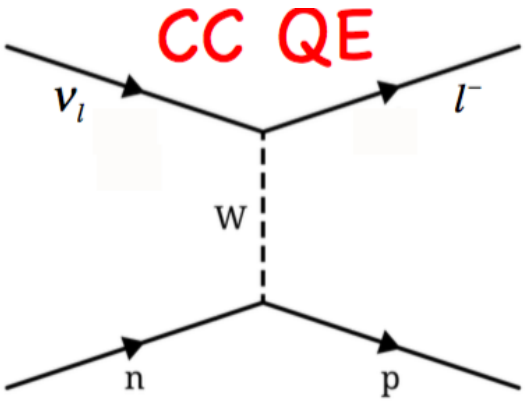
Events generated with GiBUU, reconstruct with GiBUU

→ Imperfect event generators
→ systematic errors!

P. Coloma et. al, Phys. Rev. D 89, 073015 (2014)

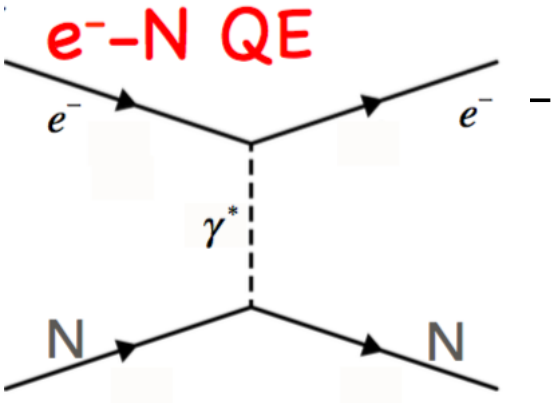
Use electron scattering to improve models

- Known incident energy
- High intensity
- Similar interaction with nuclei
  - Single boson exchange
  - CC Weak current [vector plus axial]
    - $j_\mu^{\pm} = \bar{u}\frac{-ig_W}{2\sqrt{2}}(\gamma^\mu - \gamma^\mu\gamma^5)u$
  - EM current [vector]
    - $j_\mu^{em} = \bar{u}\,\gamma^\mu u$
- Same nuclear physics



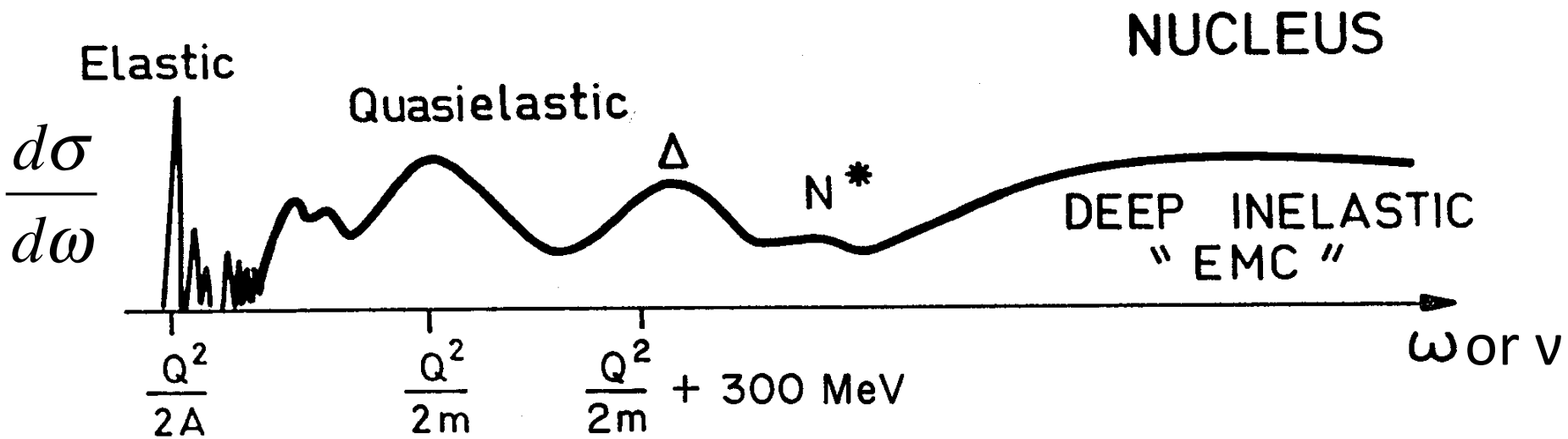
$$\nu_l + n \rightarrow l^- + p$$

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

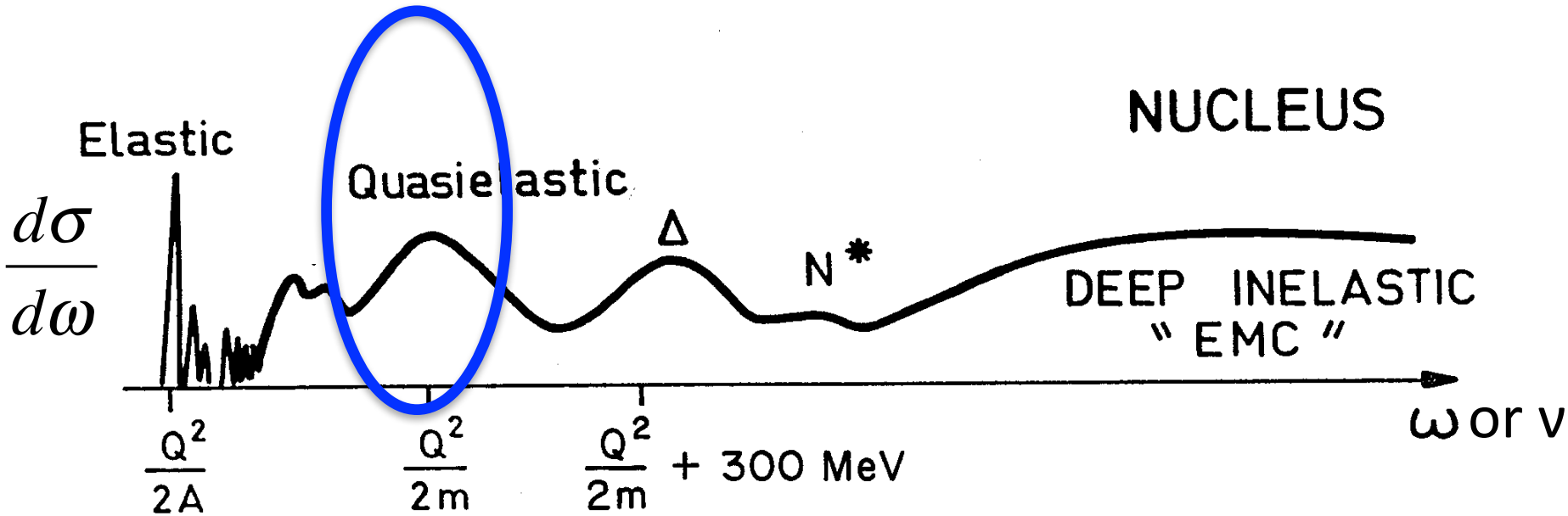


$$e^- + N \rightarrow e^- + N$$

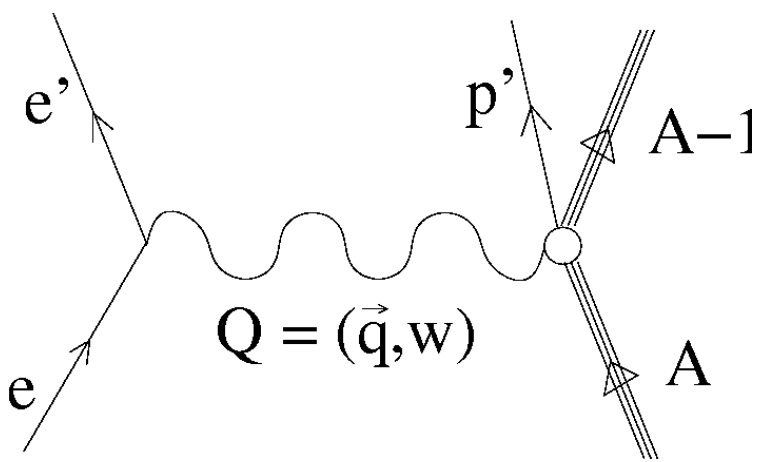
Nuclear Physics



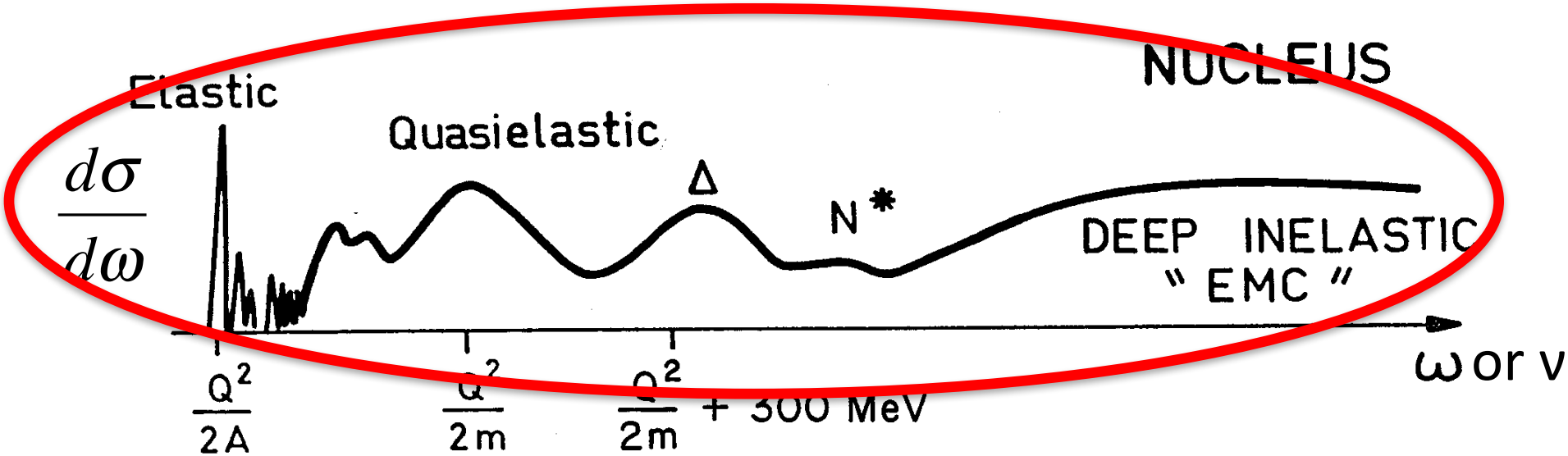
Nuclear Physics



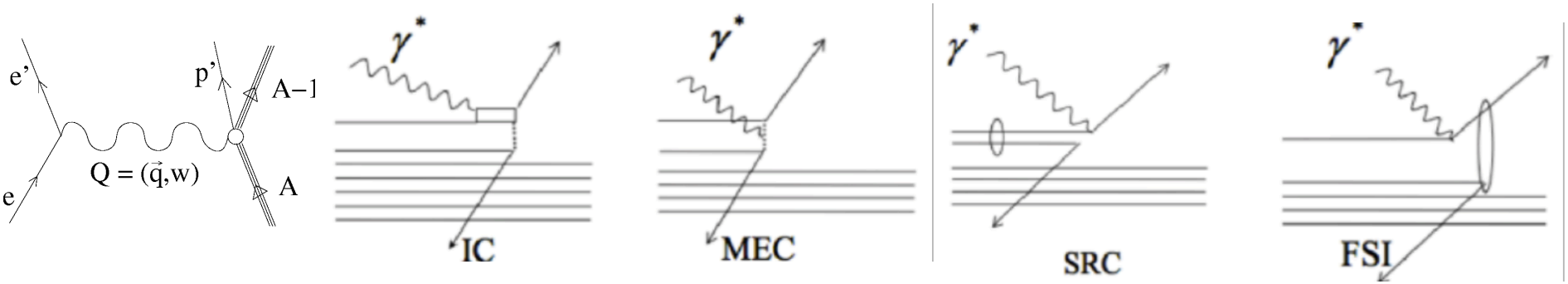
What neutrino experiments want



Nuclear Physics



What one gets



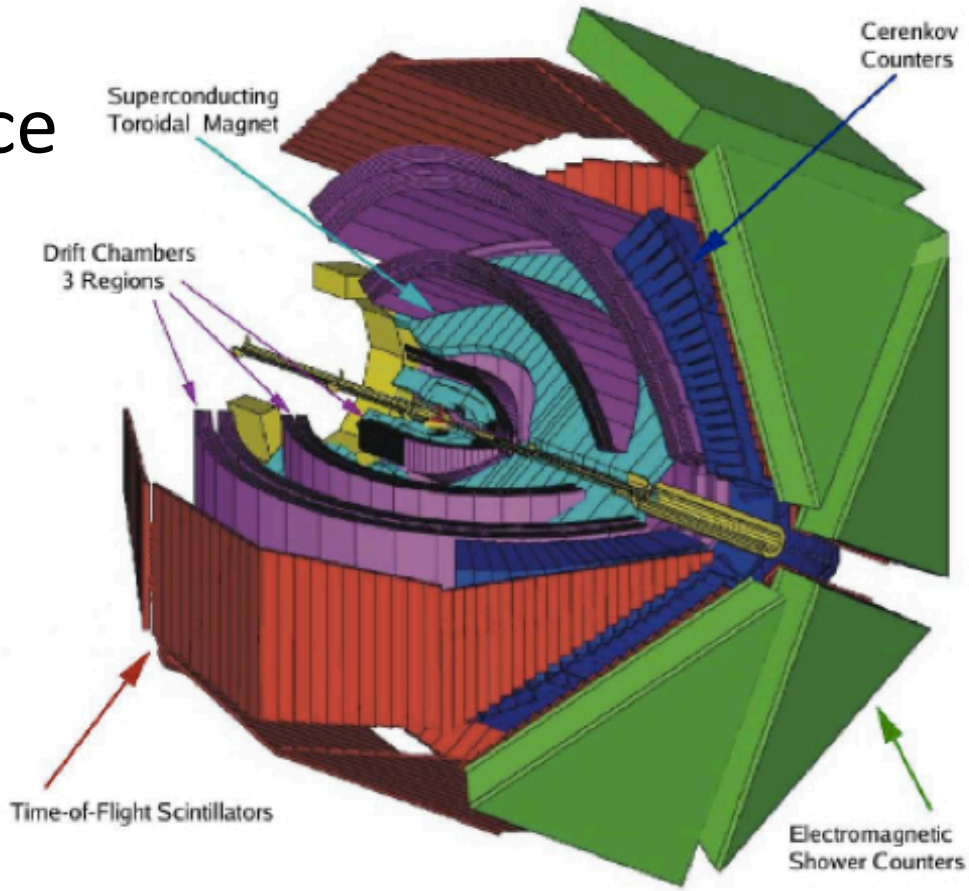
Plus pion production …

Electron Data

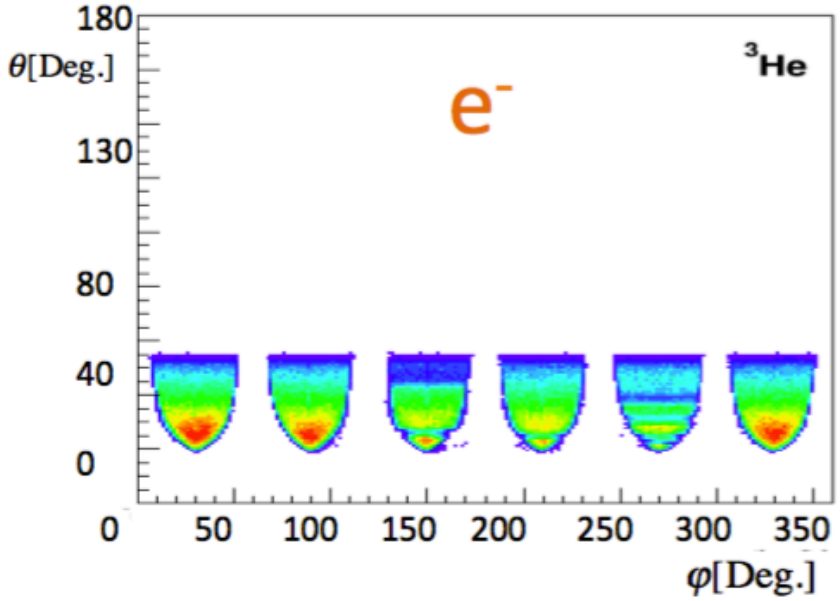
- Large amount of electron scattering data available
- Known beam energy
- Analyze electron data as if it is „Neutrino data“
  - Select specific interaction (e,e‘) or (e,e‘p)
  - Scale electron data using Mott cross section
  - ➢ Test energy reconstruction
  - ➢ Compare with event generators
  - ➢ As a start focus on quasi-elastic (QE) scattering

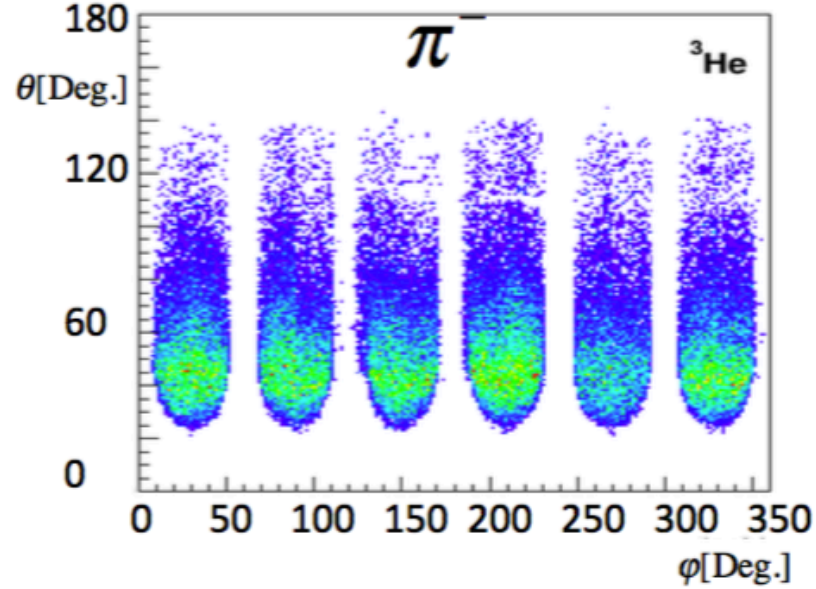
CLAS6 at Jefferson Lab

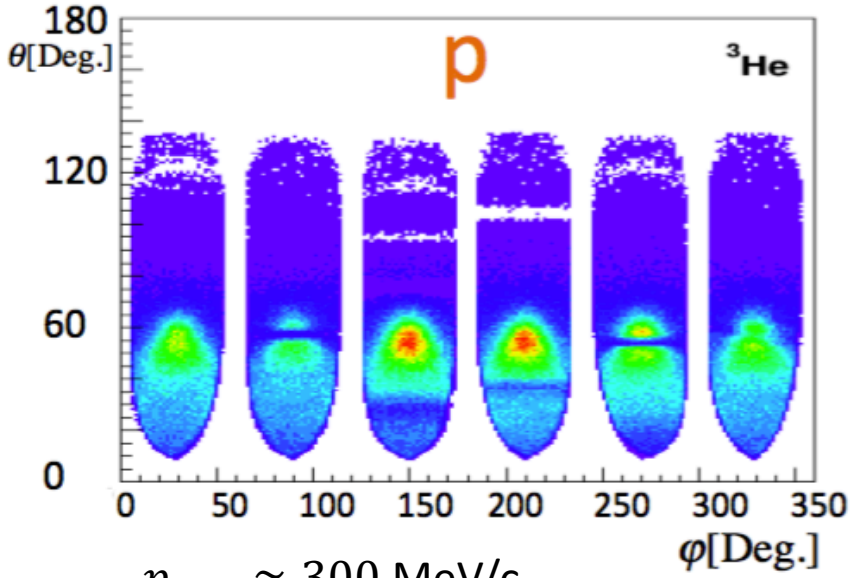
- Large (~2π) acceptance
- Open electron trigger
- Charged hadron threshold
  - P_p > 300 MeV/c
  - $P_{\pi+/-}$ > 150 MeV/c



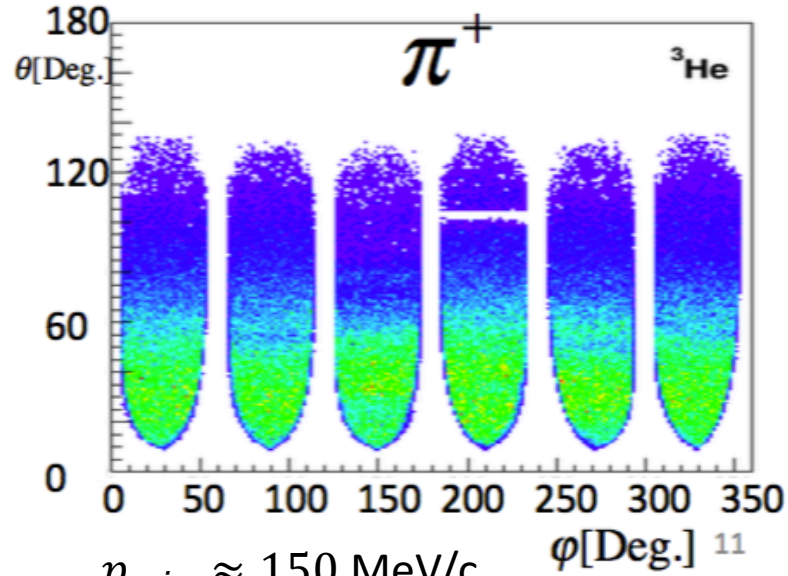
CLAS6 coverage







$p_{min} \approx 300$ MeV/c



$p_{min} \approx 150$ MeV/c

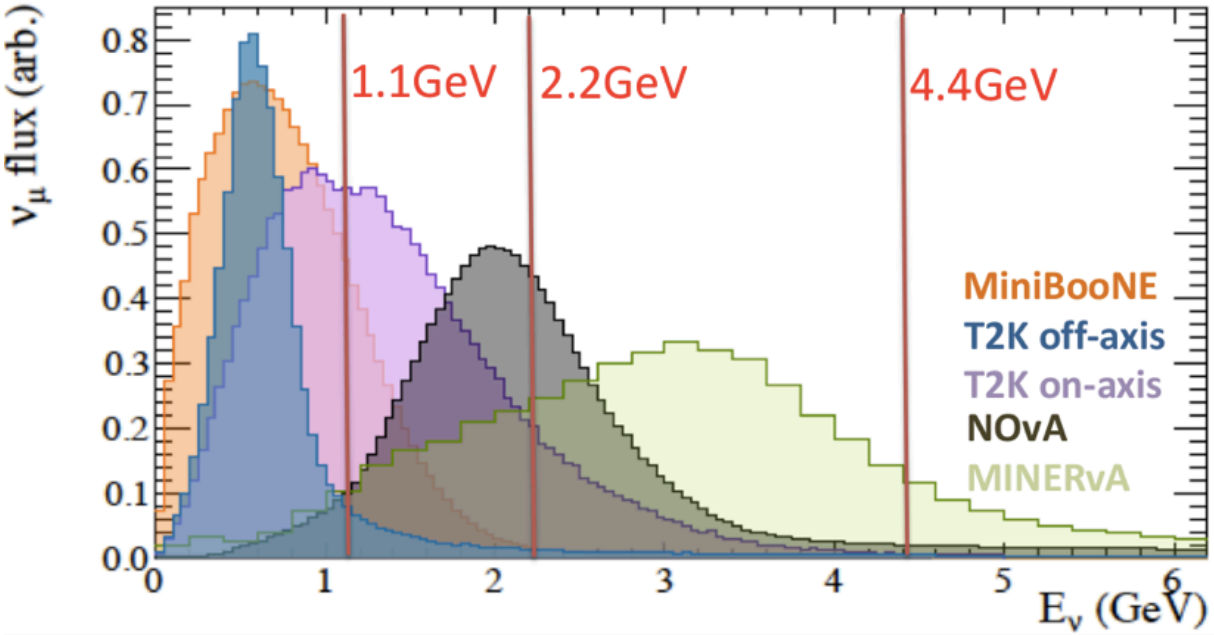
CLAS6 E2a Data

Targets:

- ^{3}He
- ^{4}He
- ^{12}C
- ^{56}Fe

Energies:

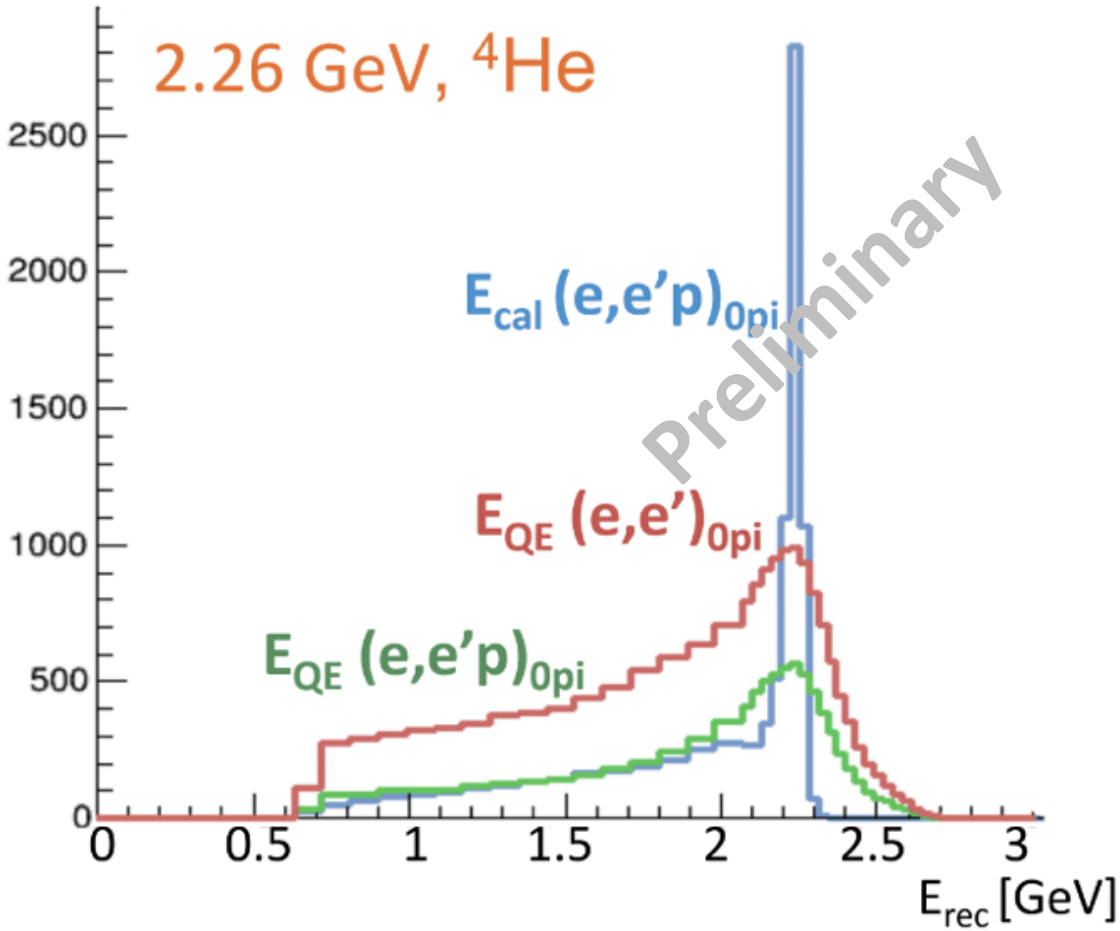
- 1.1 GeV
- 2.2 GeV
- 4.4 GeV



Reconstructing the initial energy

- Choose 0π events to enhance the Quasi-elastic (QE) sample
  - Subtract "undetected pions"
- Reconstruct the incident lepton energy:
  - $E_{QE} = \frac{2M_N\epsilon + 2M_N E_l - m_l^2}{2(M_N - E_l + k_l cos\theta_l)}$
    - ϵ: nucleon separation energy, M_N nucleon mass
    - $\{m_l, E_l, k_l, \theta_l\}$ scattered lepton mass, energy, momentum and angle
    - broadened by nucleon fermi motion
  - $E_{cal} = E_e + T_p + \epsilon$ [for (e,e'p)]

Reconstructing the Incident Energy

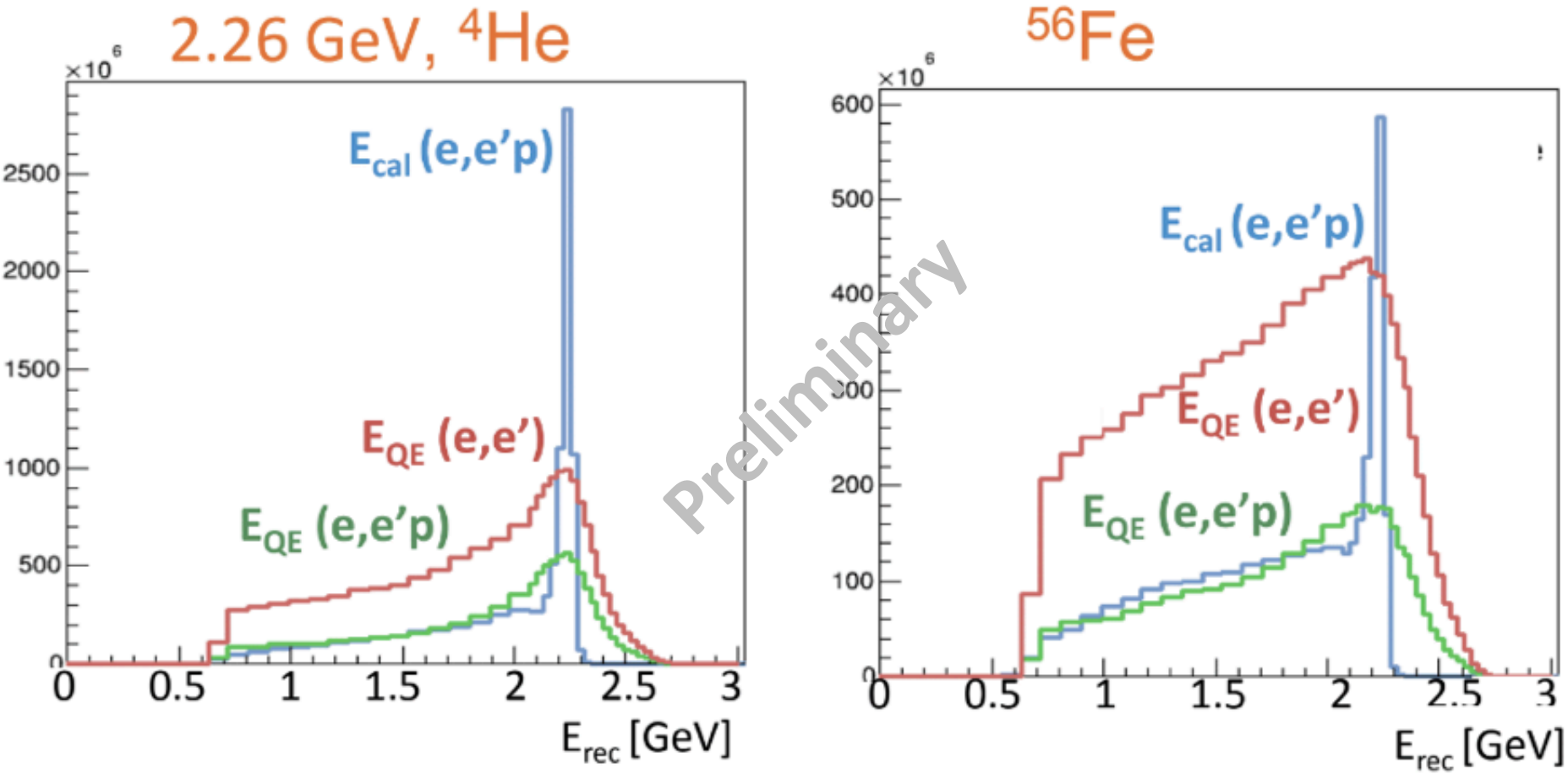


$$E_{QE} = \frac{2M_N\epsilon + 2M_N E_l - m_l^2}{2(M_N - E_l + k_l cos\theta_l)}$$

$$E_{cal} = E_e + T_p + \epsilon$$

Reconstruction Incoming Energy

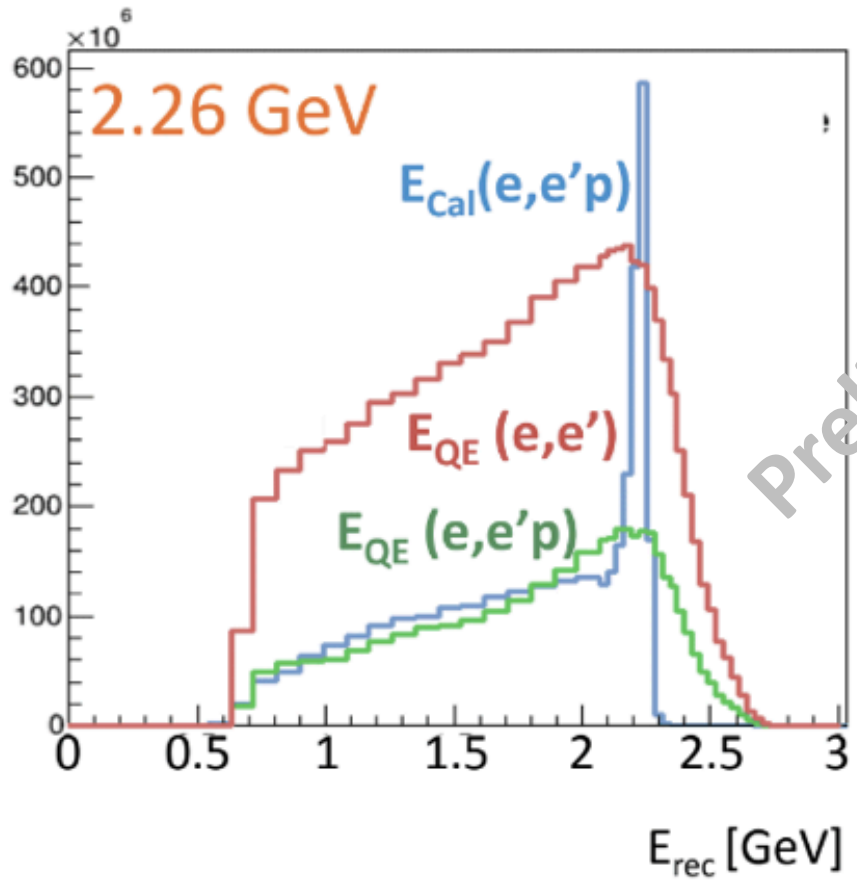
worse for higher masses

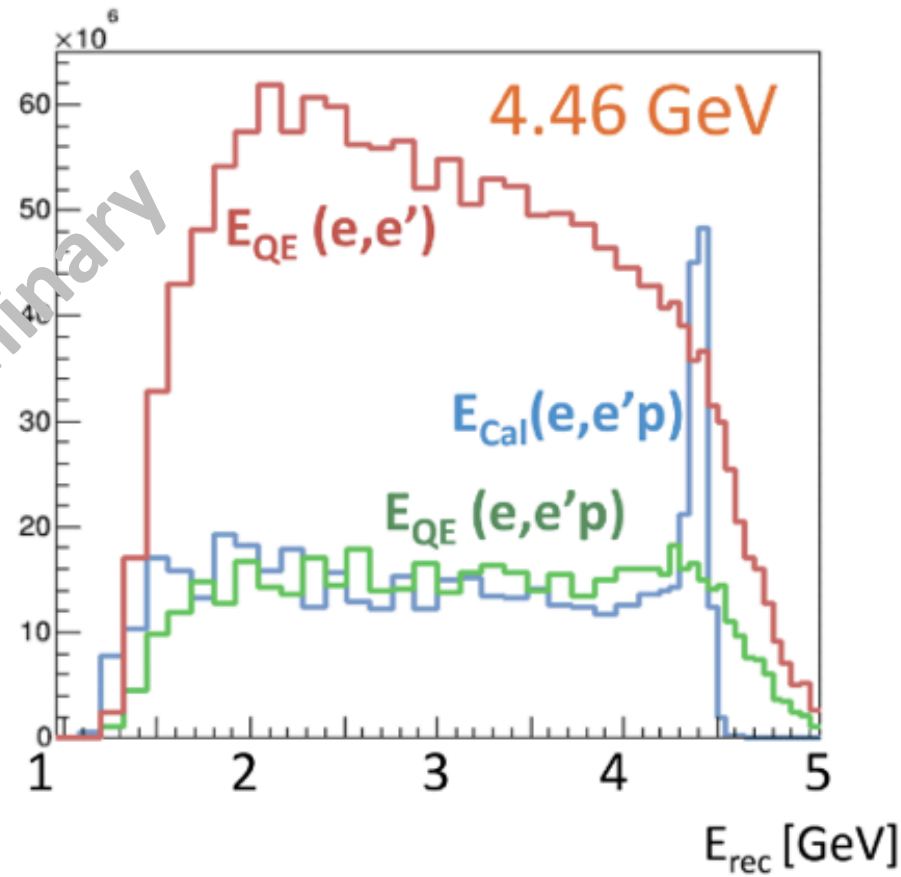


Reconstruction Incoming Energy

worse for higher beam energies

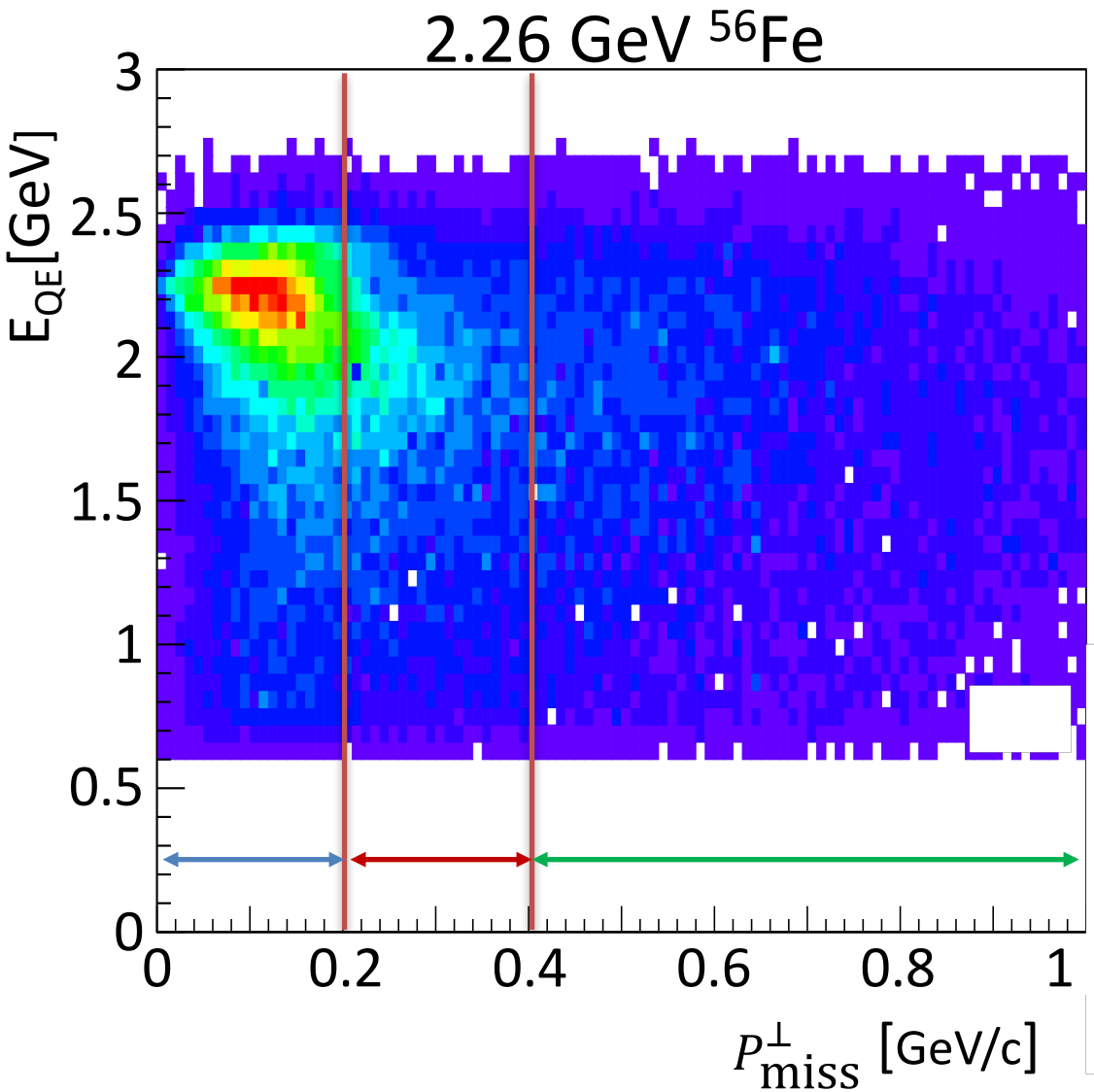
^{56}Fe



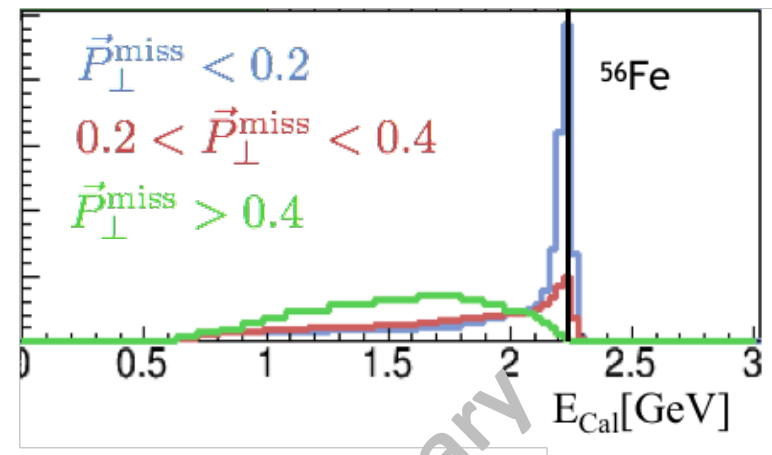


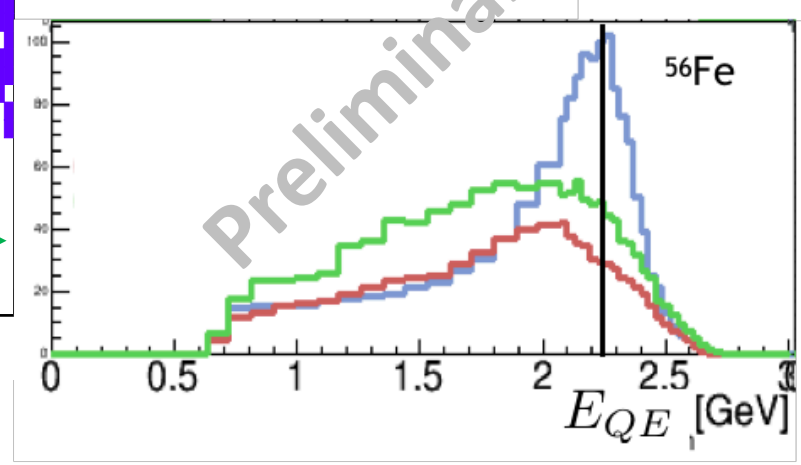
Preliminary

Energy reconstruction dependence on $P^{\perp}$



$$P^{\perp}_{\text{miss}} = P^{\perp}_{e^-} + P^{\perp}_{p} = P^{\perp}_{\text{init}}$$





Event Generators

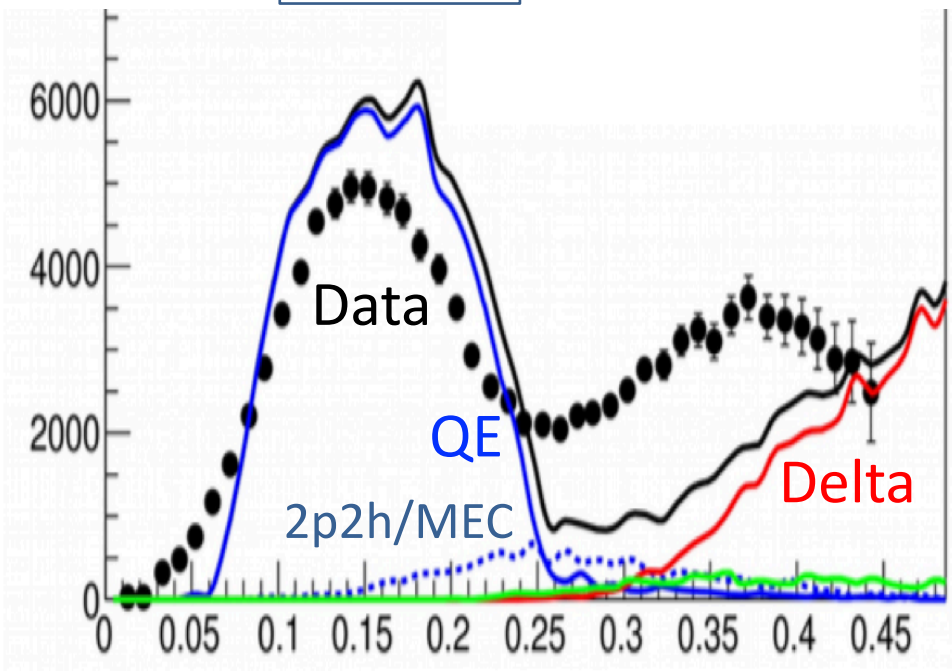
- Bad reconstruction is OK if the generator describes reality

  → Can be checked by comparing with data
- Several generators used in neutrino experiments
  - Neut (T2K)
  - NuWro (MicroBoone, Minerva)
  - GiBUU (KM3Net, ...)
  - GENIE (MicroBoone, Minerva, DUNE,...)

We are improving Genie

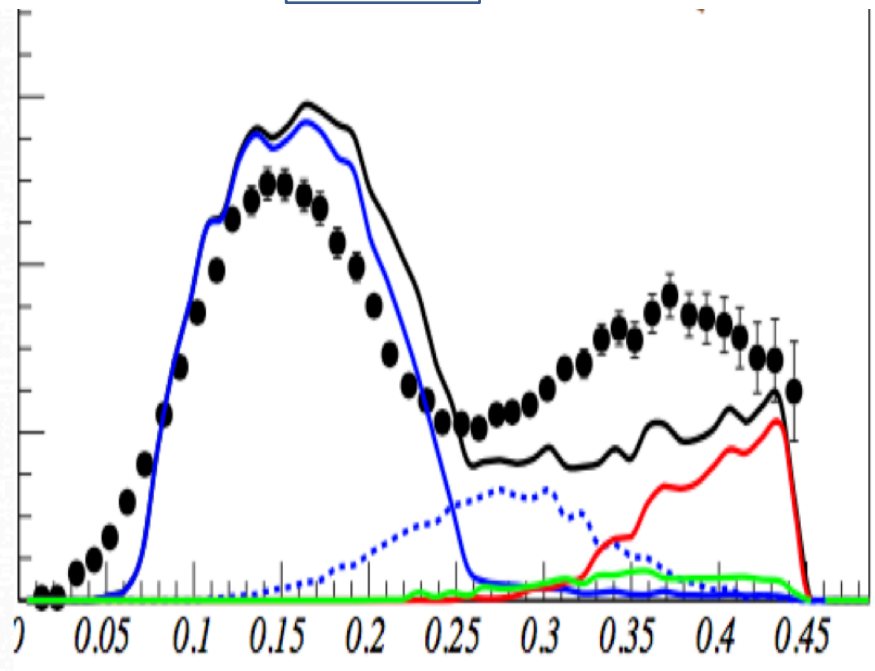
$$\mathrm{C(e,e')}\ 560\ \mathrm{MeV}\ \theta = 60^o$$

Before



Energy Transfer [GeV]

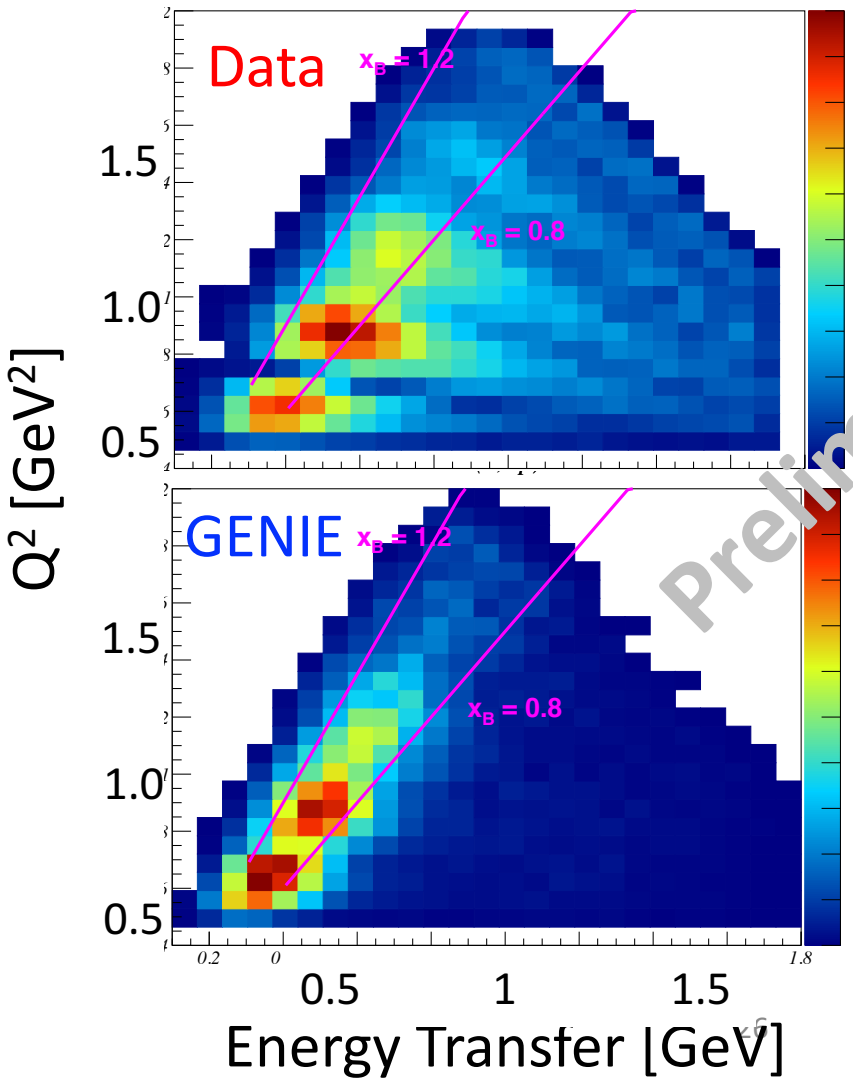
After



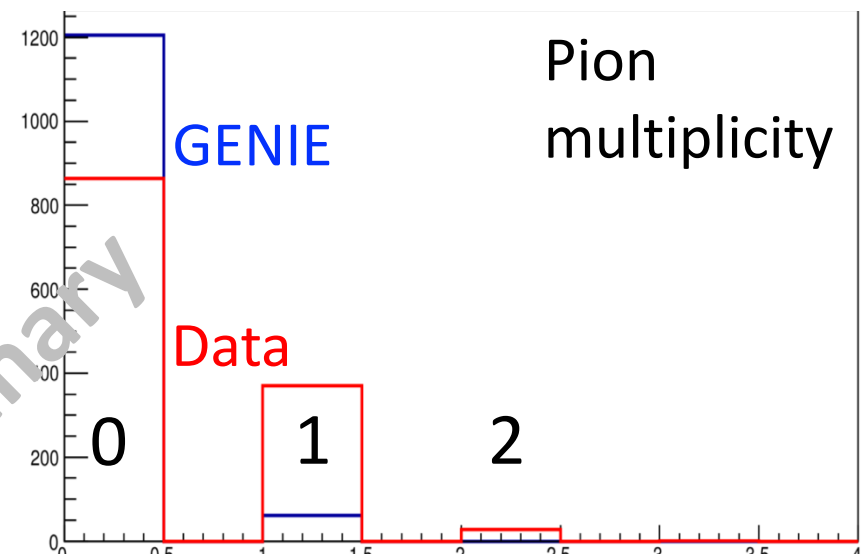
Energy Transfer [GeV]

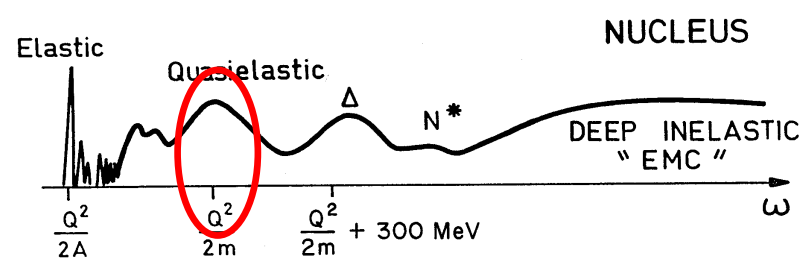
Data-Genie Comparisons

C(e,e'p) 2.26 GeV
No x or W cuts



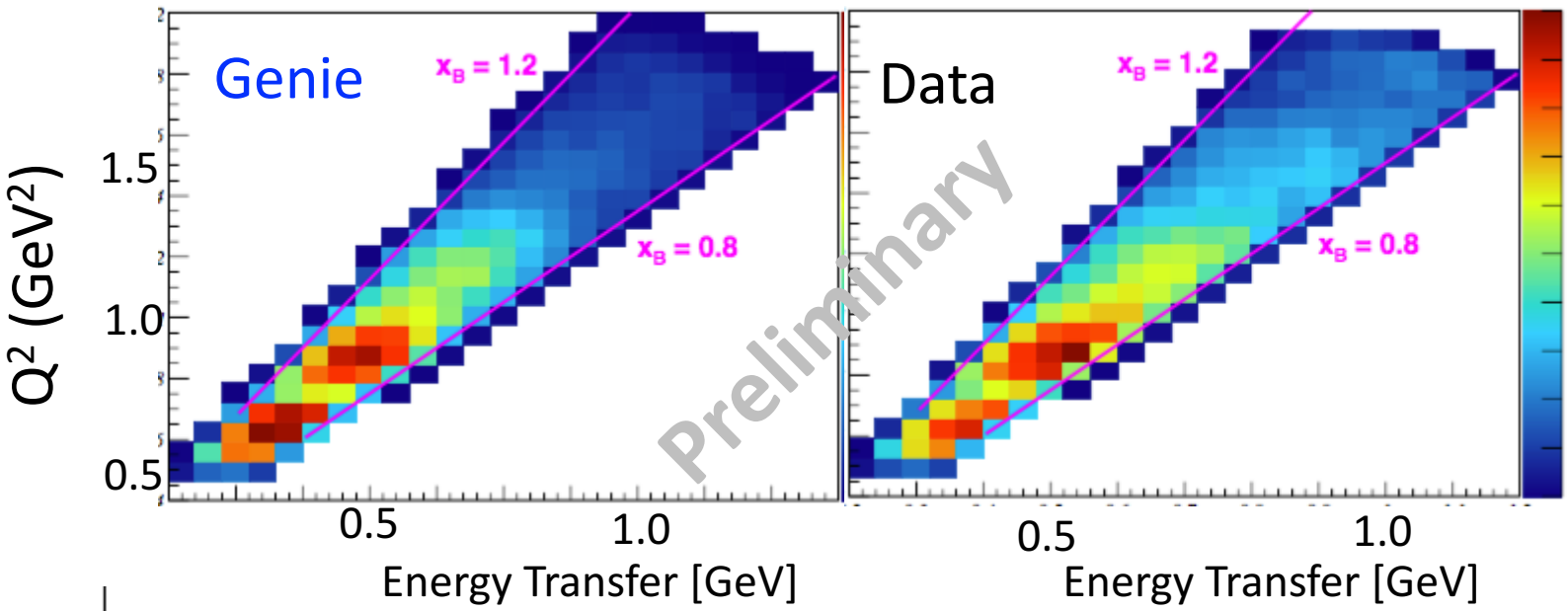
C(e,e'p) 4.46 GeV
0.8 < x < 1.2, W < 2 GeV

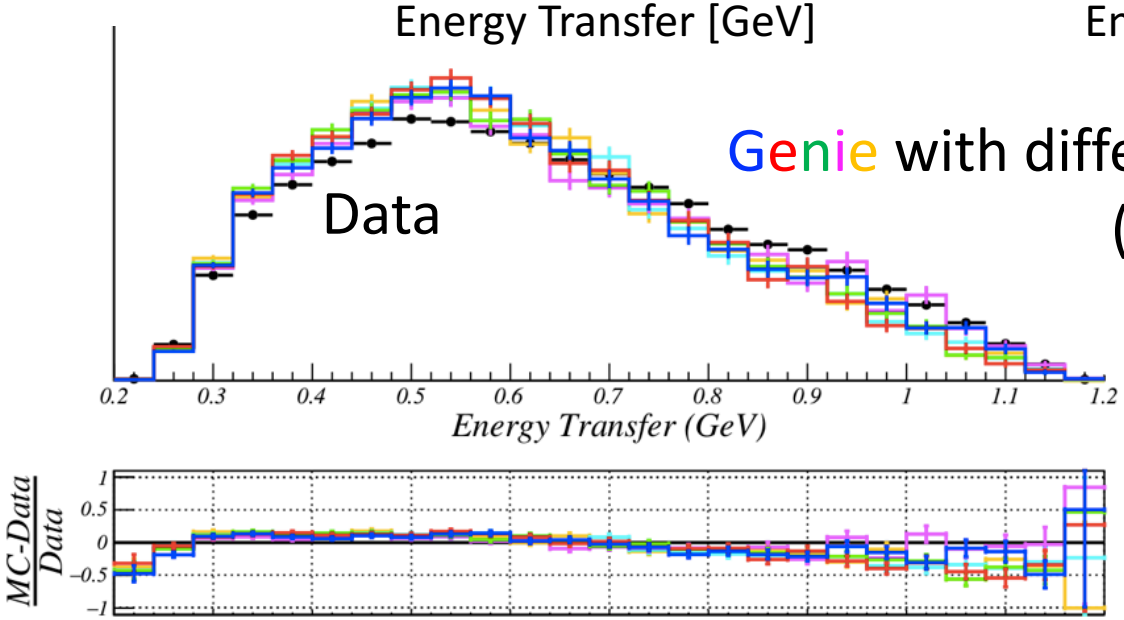




Data-Genie Comparisons - QE peak

C(e,e'p) 2.26 GeV, 0.8 < x < 1.2



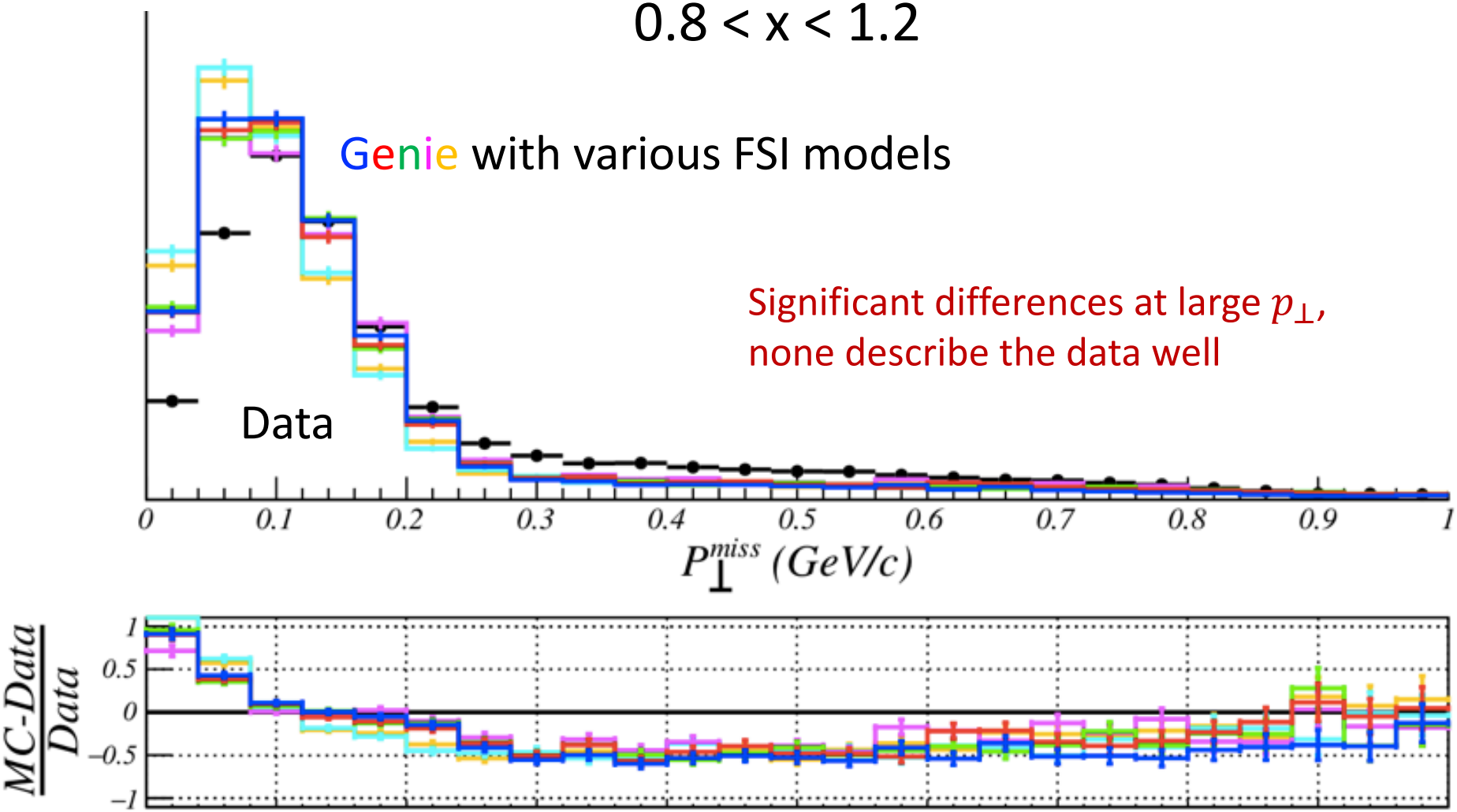


Genie with different Final-State-Interaction (FSI) models

Data-Genie Comparisons - QE peak

C(e,e'p) 2.26 GeV

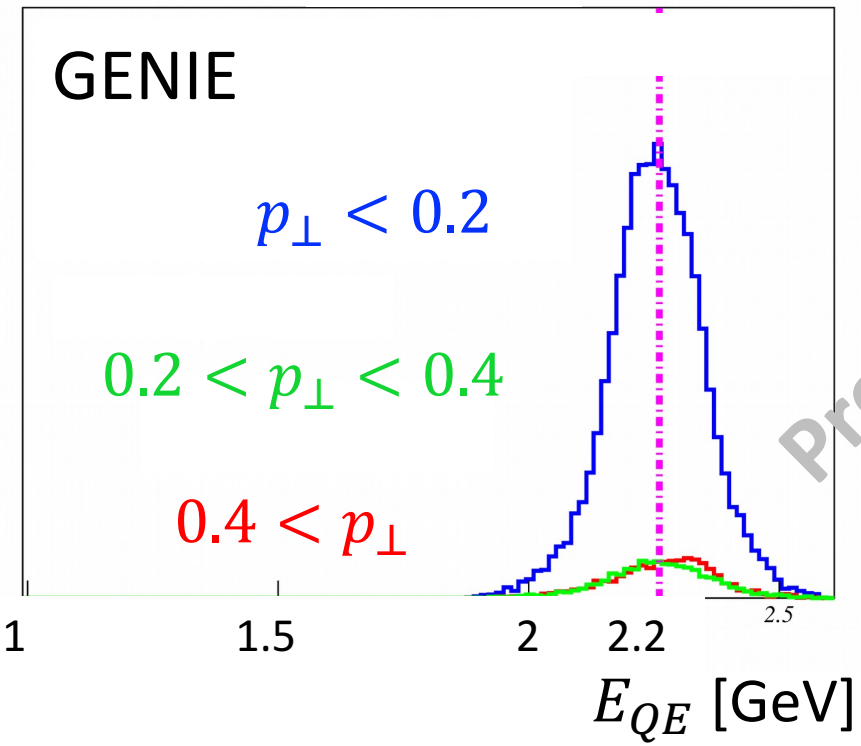
0.8 < x < 1.2



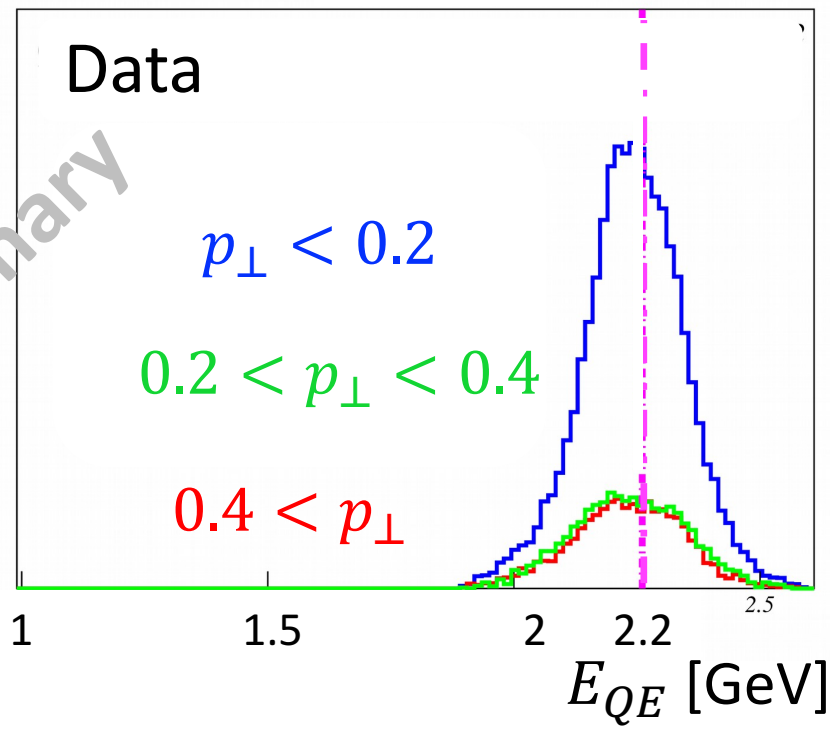
Data-Genie Comparisons - E_{beam} Reconstruction

$$E_{QE} = \frac{2ME_l + 2M\varepsilon - m_l^2}{2(M - E_l + |k_l|\cos\theta)}$$

C(e,e'p)



C(e,e'p)



Preliminary

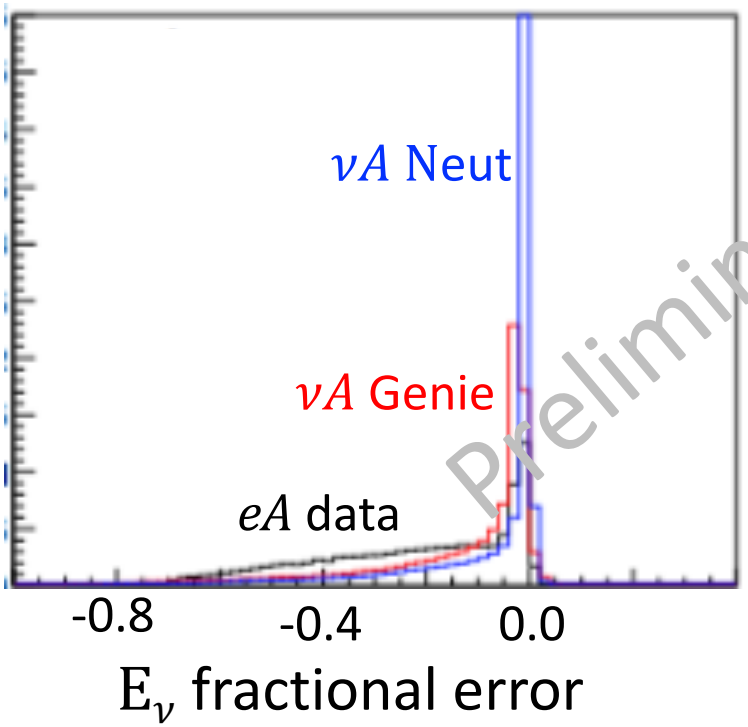
Peaks in same location

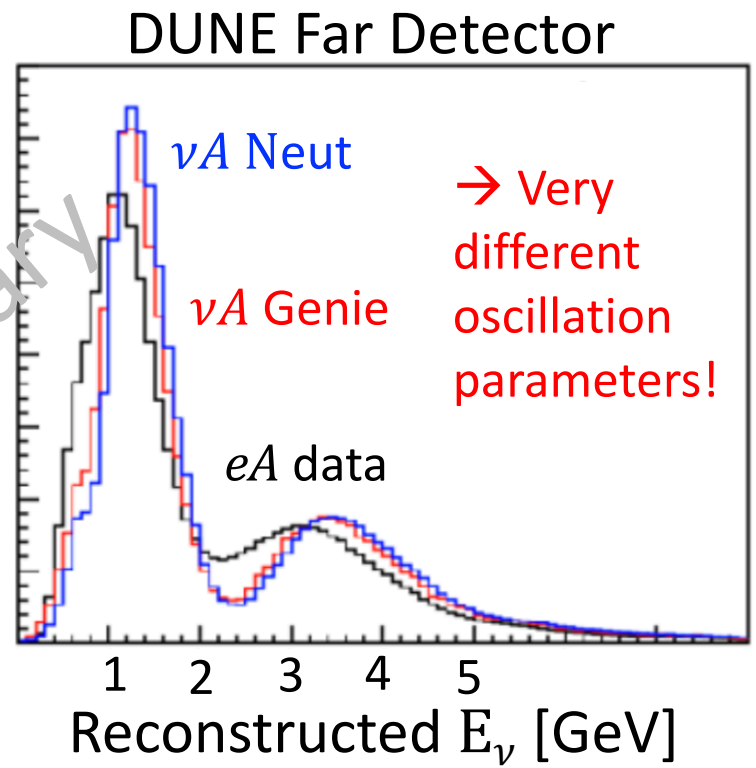
Summary Data-Genie: E_{beam} Reconstruction

Fe	e^- Data	ν GENIE
2.26 GeV	26%	62%
4.46 GeV	14%	62%

Fraction of Fe$(e, e'p)$ events with E_{Cal} within 5% of E_{beam}

Possible effect on DUNE Oscillation





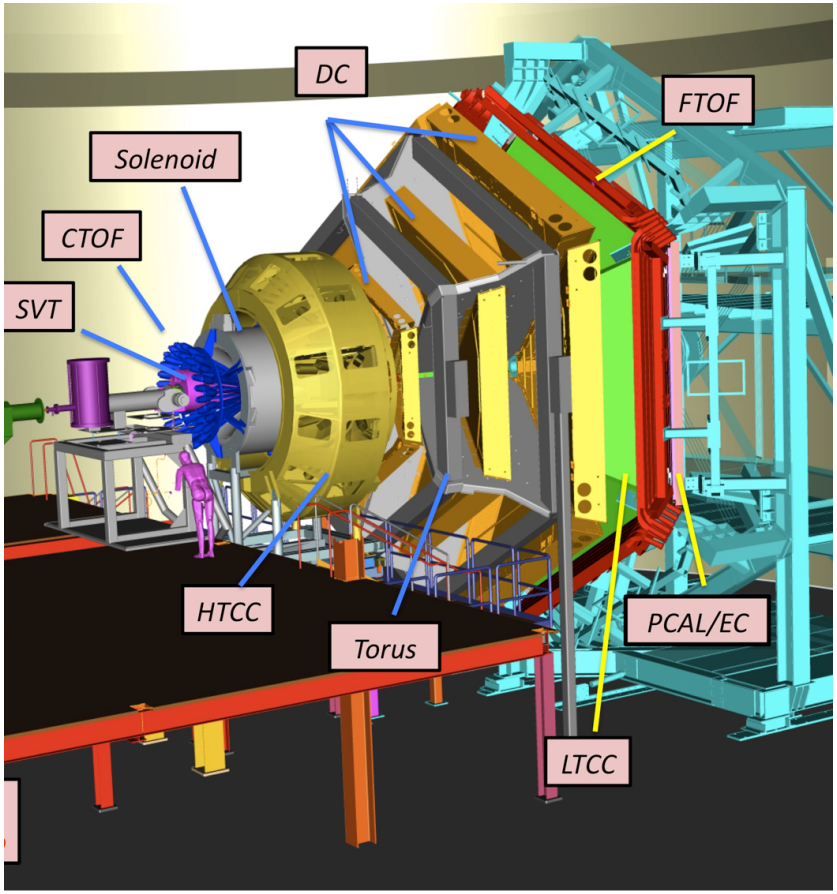
(Chris Marshall, LBNL)

- Proof of principle to show potential impact
- Threw events with νA Genie
  - Reconstructed with νA Neut or eA data
- Compared E_{rec} for eA to E_{rec} for νA
- Used 2.26 GeV eA E_{rec} for all incident energies

e4ν at CLAS12

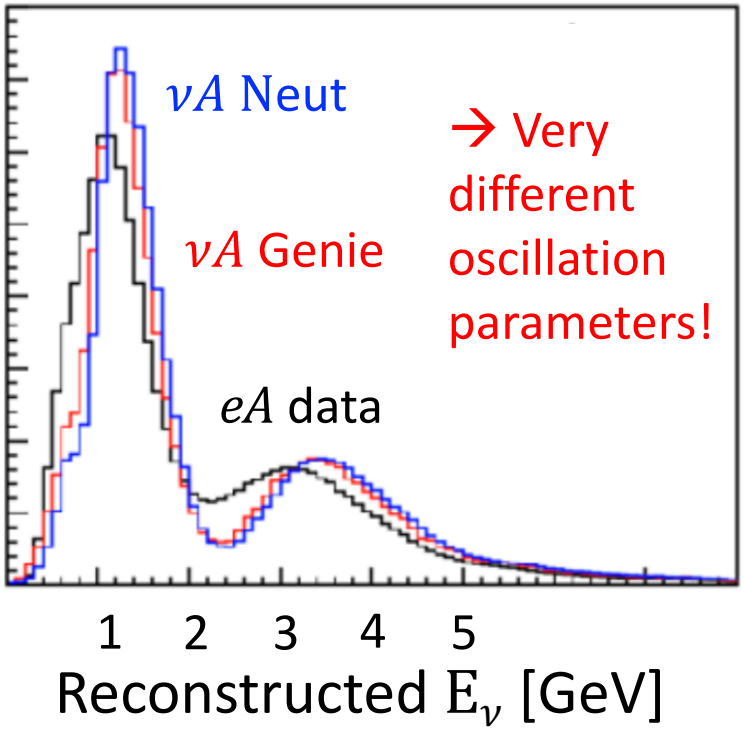
CLAS12

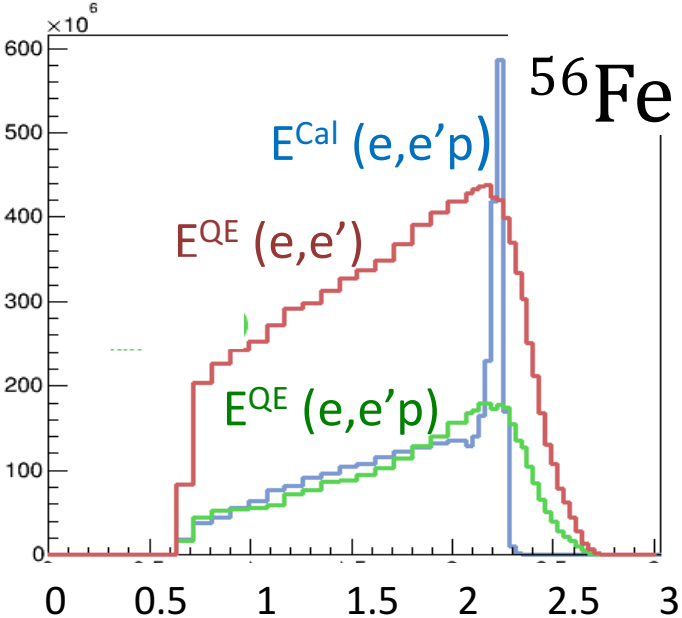
- ~ 4π acceptance
- forward detector (8 – 40°)
  - Toroidal magnetic field
- Hermetic central detector (40 – 135°)
  - 5 T solenoidal field
- Backward Angle Neutron Detector
- x10 larger luminosity than CLAS 6



- 45 beam days approved with an A rating for
  - 1.1, 2.2, 4.4, and 6.6 GeV beam energies
  - d, He, C, O, Ar, and Sn targets

- Electron scattering can contribute dramatically to neutrino experiments
  - Similar physics
  - Lots of data available
  - Lots more to come
- Worse energy reconstruction for higher beam momenta and larger p_T
- Disagreement between data and GENIE
- Impact on neutrino oscillation parameters

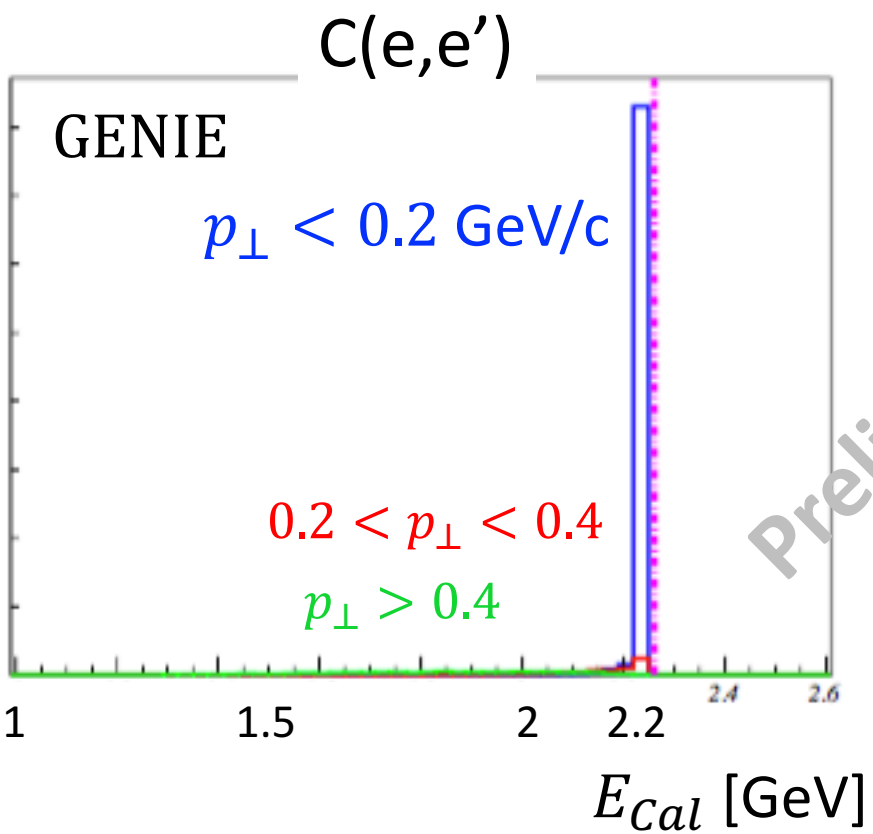


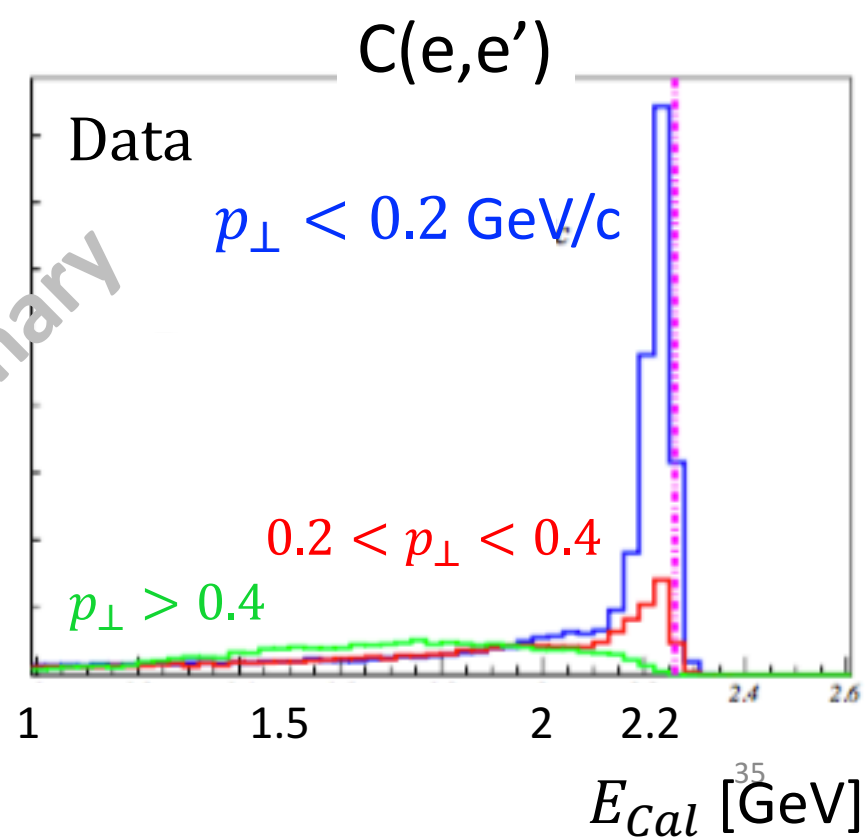


Backup

Data-Genie Comparisons - E_{beam} Reconstruction

$$E_{cal} = E_e + T_p + \epsilon$$





Preliminary

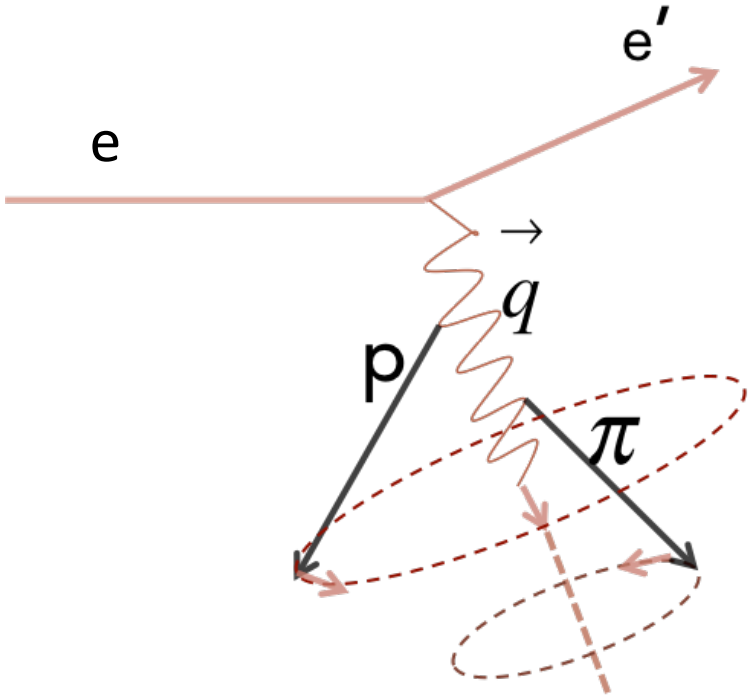
Background Subtraction

Non-QE interactions lead to multi hadron final states.

Gaps in CLAS acceptance will make them look like (e,e'p) events.

Data Driven Correction:

1. Use measured (e,e'pπ) events,
2. Rotate π around q to determine its acceptance,
3. Subtract (e,e'pπ) contributions



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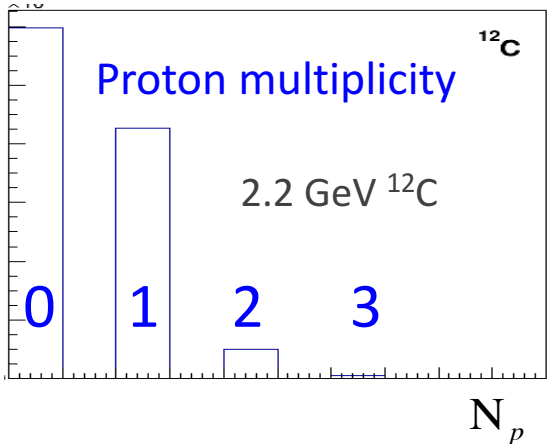

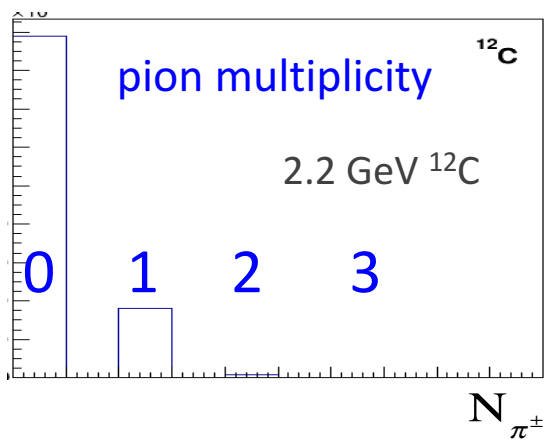

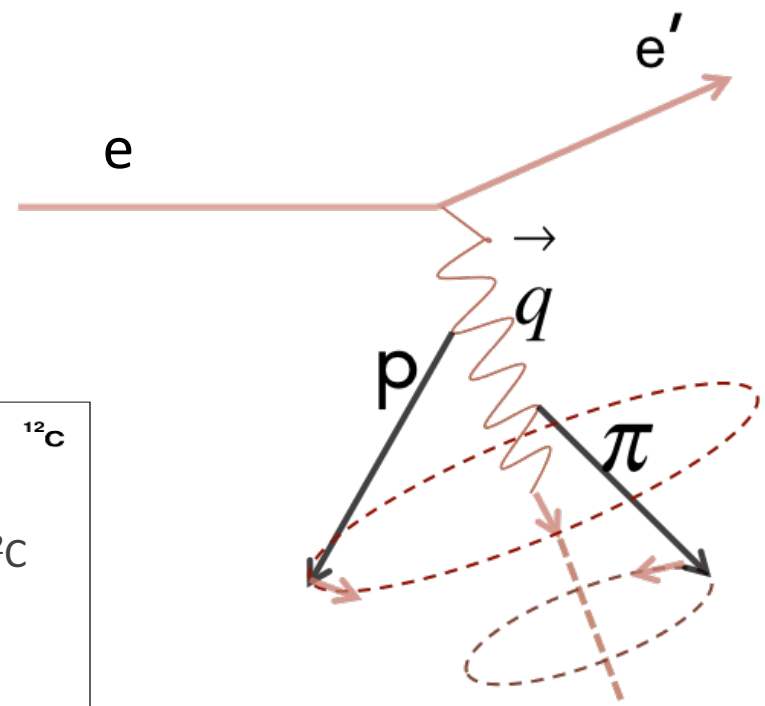

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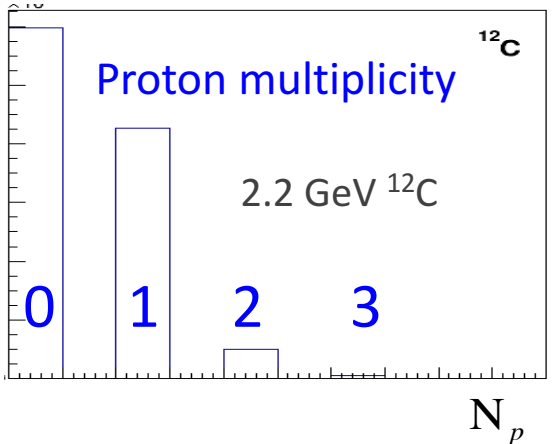

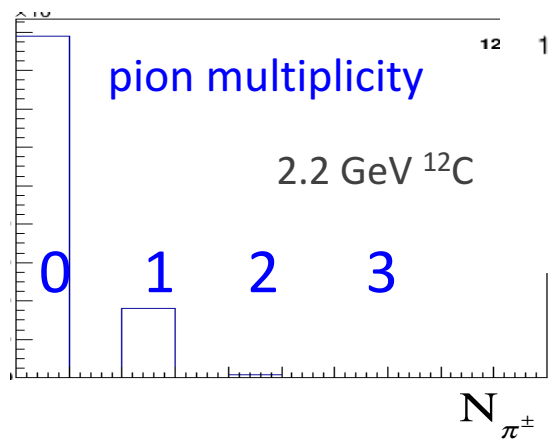

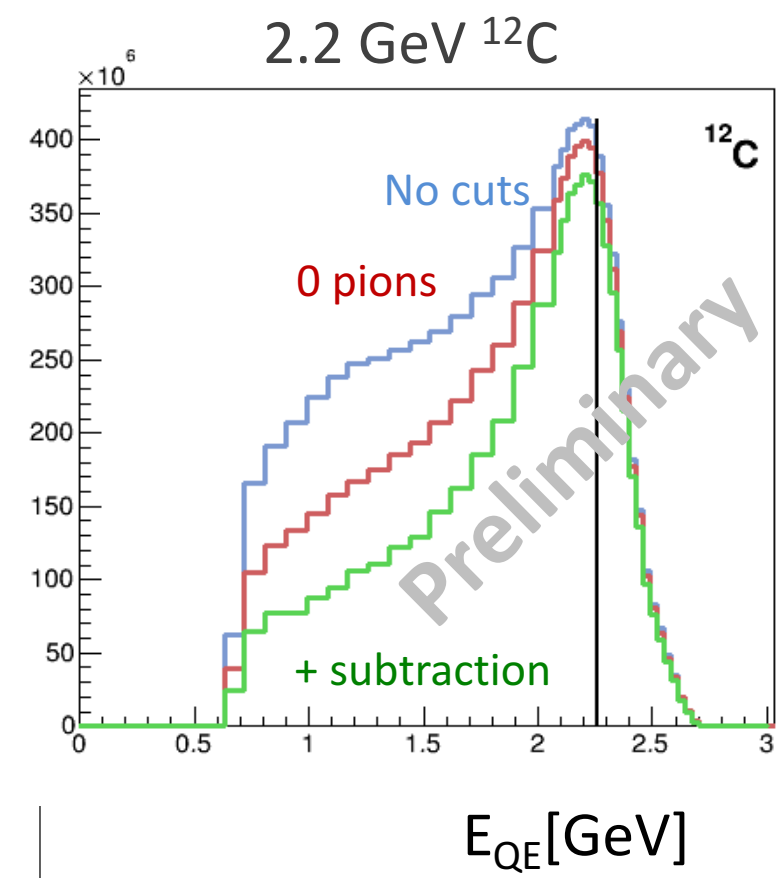

We're Also Improving Genie

1. Corrected expression for Mott cross section in QE
2. MEC/2p2h
    1. Added boost back to lab frame
    2. Corrected mass for cluster of particles
    3. Corrected Form Factors
3. Resonance
    1. Replaced old calculation with GSL Minimizer (now gives correct peak location)
    2. Switched to Berger-Seghal model
    3. Used corrected coupling constant for EM interactions
4. Nucleon momentum distributions
    1. Switched to Local Fermi Gas Model

Beginning work on NuWro and GiBUU.
Consulting with the relevant experts on each code.