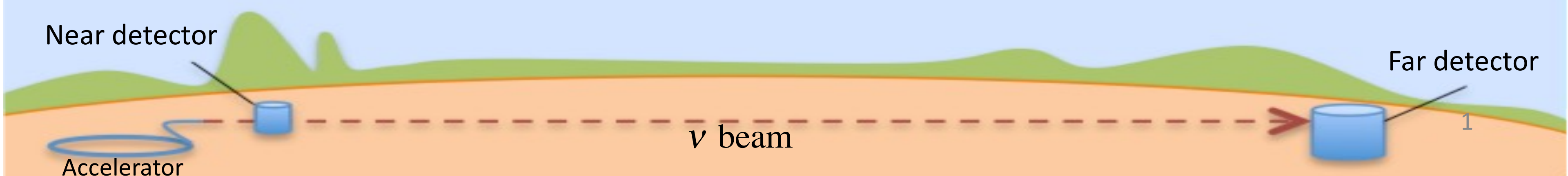
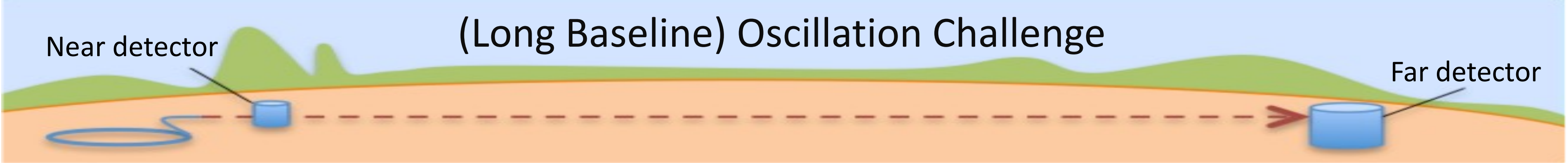
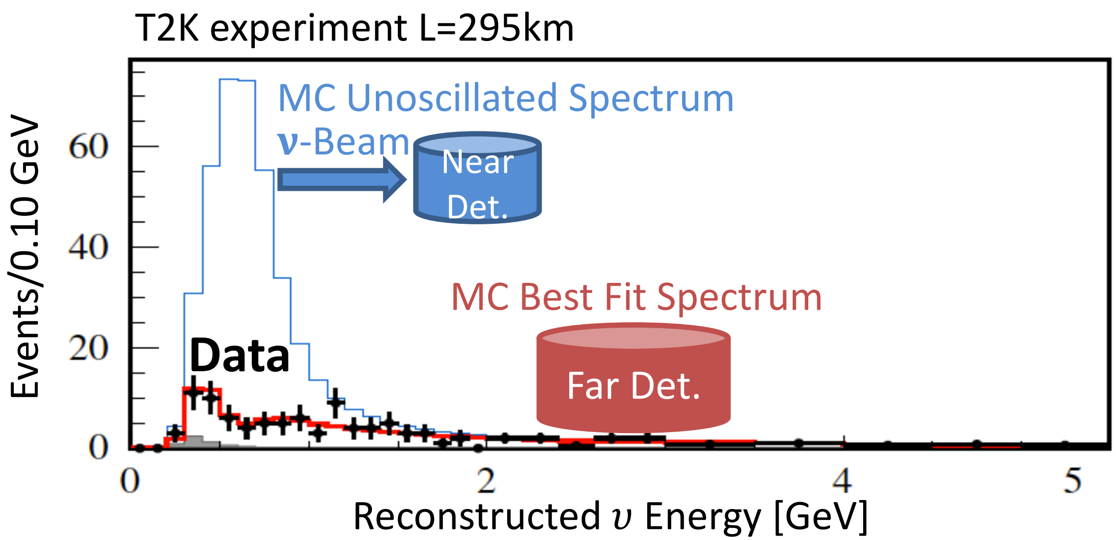
# Validation of neutrino energy estimation using electron scattering data

Mariana Khachatryan

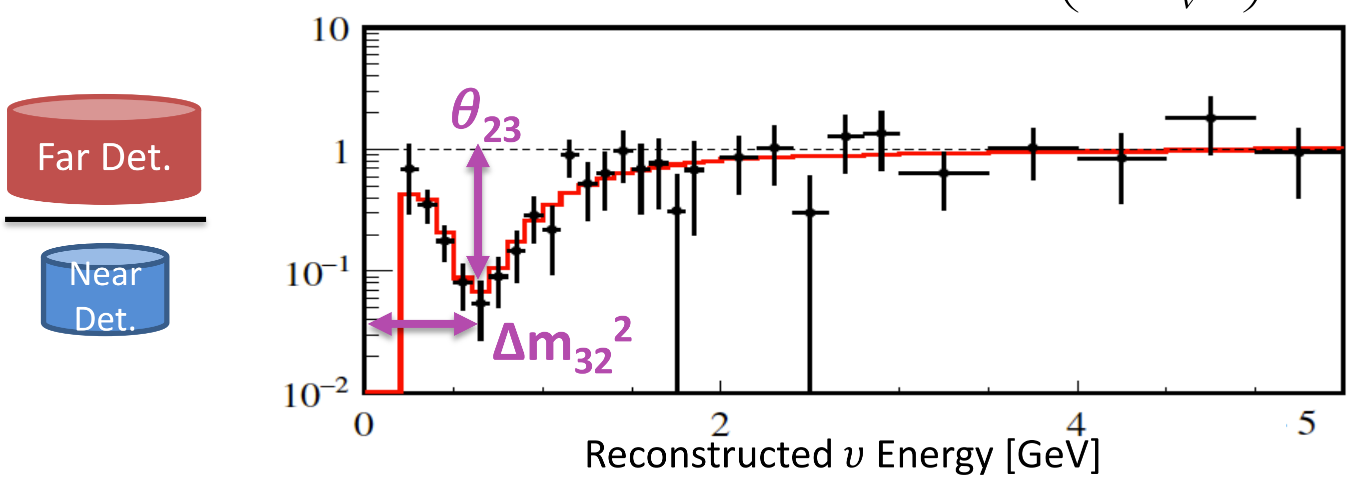


# (Long Baseline) Oscillation Challenge



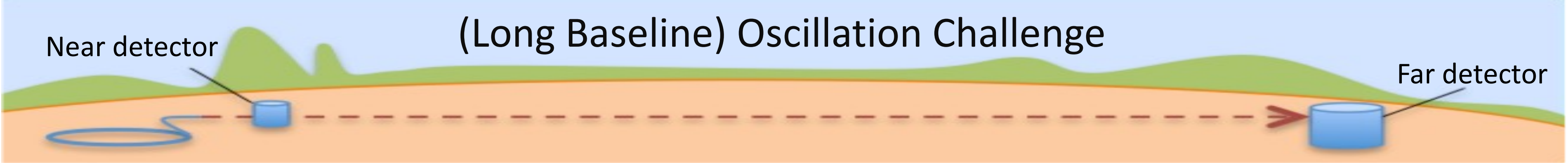




$$P(\nu_\mu \to \nu_\mu) = \sin^2(2\theta_{23}) \times \sin^2\left(\frac{\Delta m_{32}{}^2 L}{4E_\nu}\right)$$

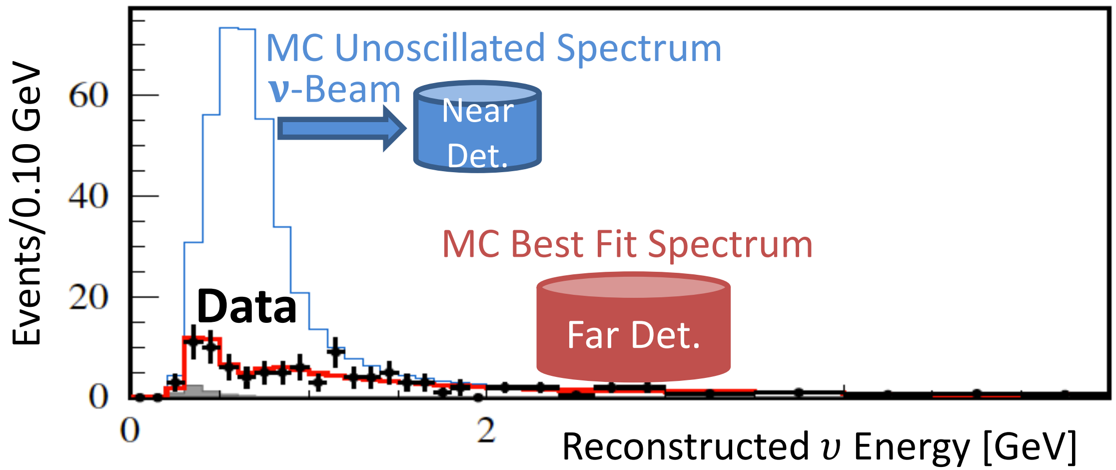



T2K, Phys. Rev. D 91, 072010 (2015)

# (Long Baseline) Oscillation Challenge




T2K experiment L=295km




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

Measured $\upsilon$ interaction rate

True flux Modeling input

$$N(E_{rec},L) \propto \int \Phi(E,L)\sigma(E) f_{\sigma}(E,Erec)\,dE$$

True flux from measured flux and modeling input.
Models are phenomenological, semi-classical (no interference) implemented in **Neutrino Event Generators.**

# Electron for neutrinos

Measured $\upsilon$ interaction rate

Incoming true flux

Modeling input

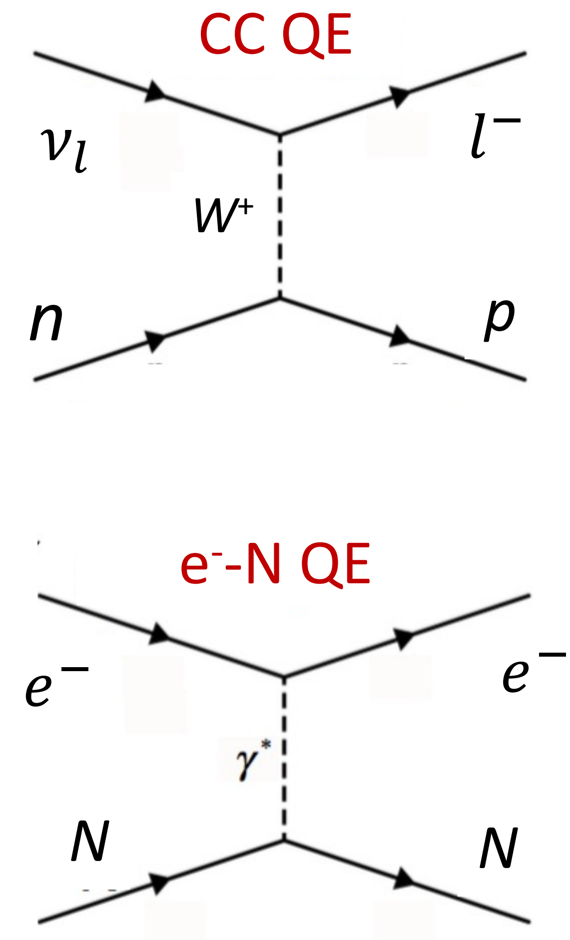
$$N_\alpha(E_{rec}, L) \propto \sum_i \int \Phi_\alpha(E, L)\sigma_i(E) f_{\sigma_i}(E, E_{rec}) dE$$

Use electron scattering data to constrain neutrino event generators

- GENIE v3! Papadopoulou et al, Phys. Rev. D 103, 113003 (2021)
  - Unified $eA$ and $\nu A$ code
  - Implement better models and theories
    - Two GENIE tunes: SuSAv2 vs G2018
  - Electron radiative corrections

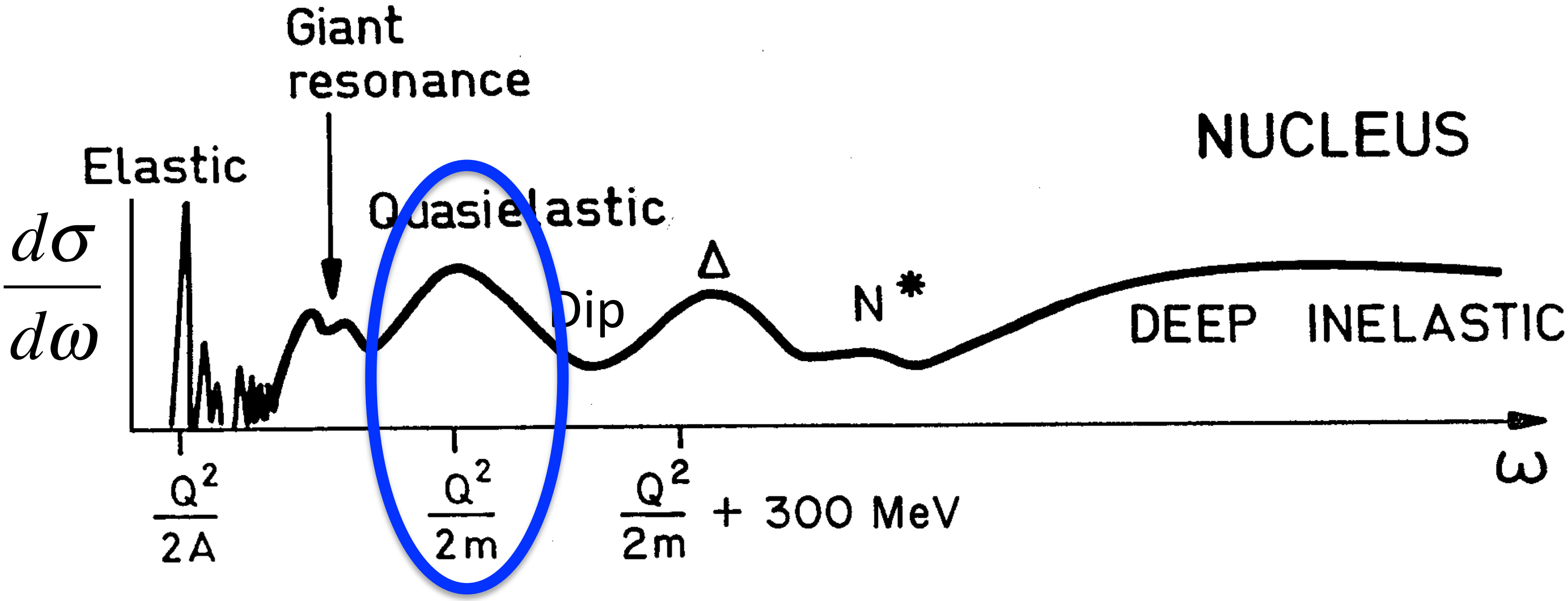
# Why electrons?

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

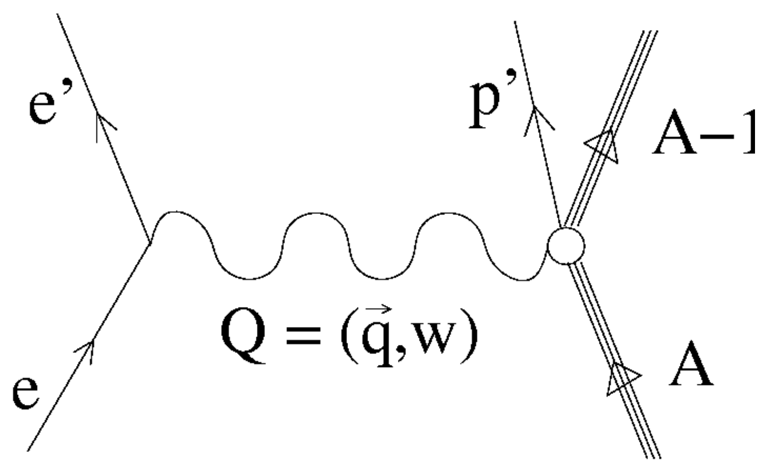


Quasielastic (QE) scattering from a single nucleon

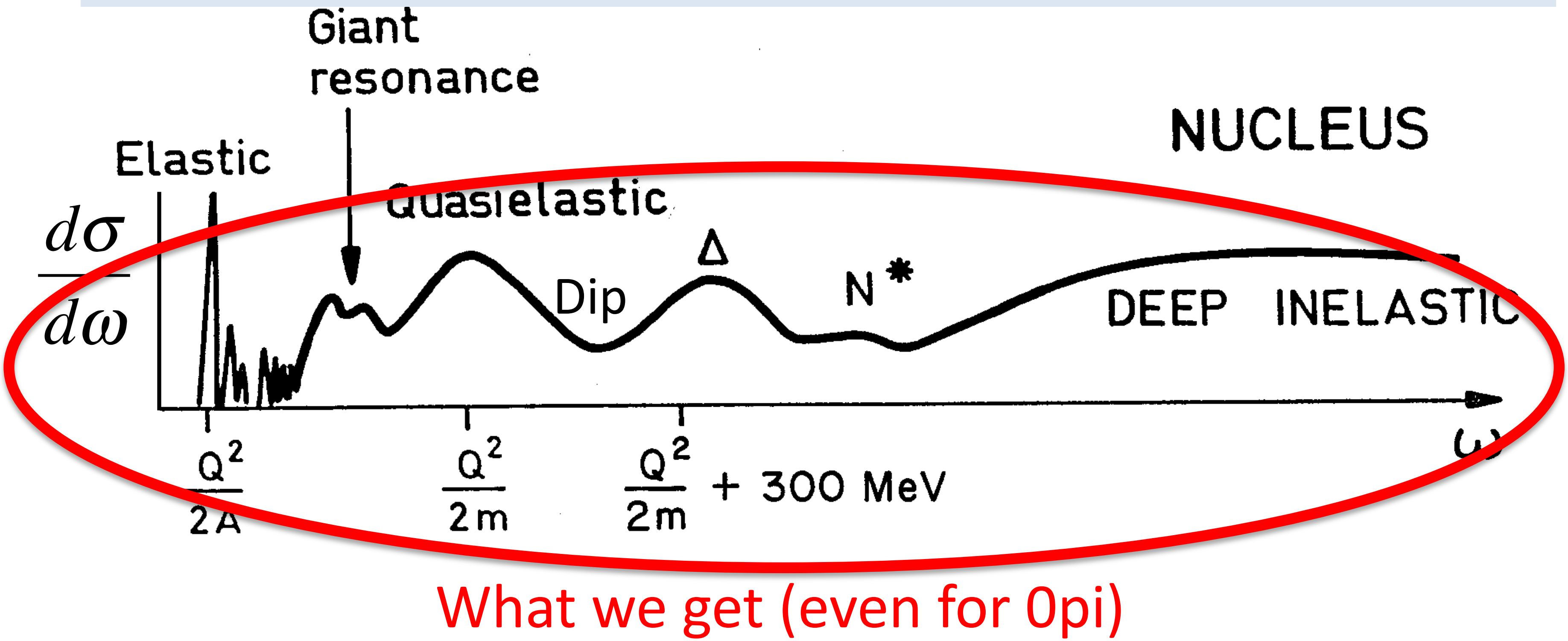
# Nuclear Physics

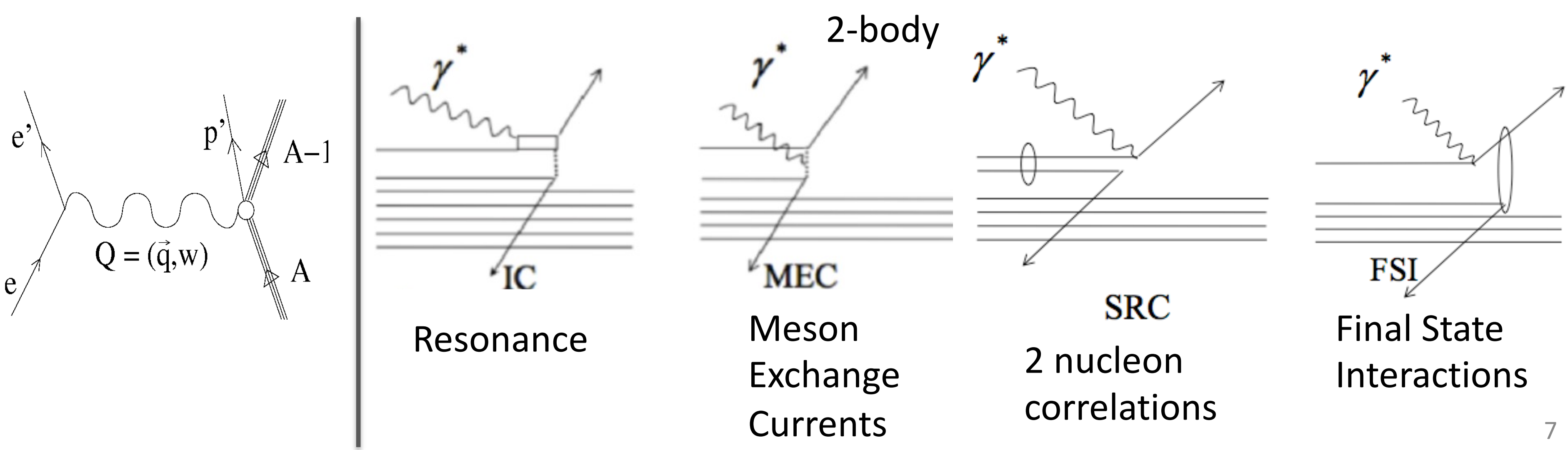



What neutrino expts want



# Nuclear Physics



# Targets and beam energies

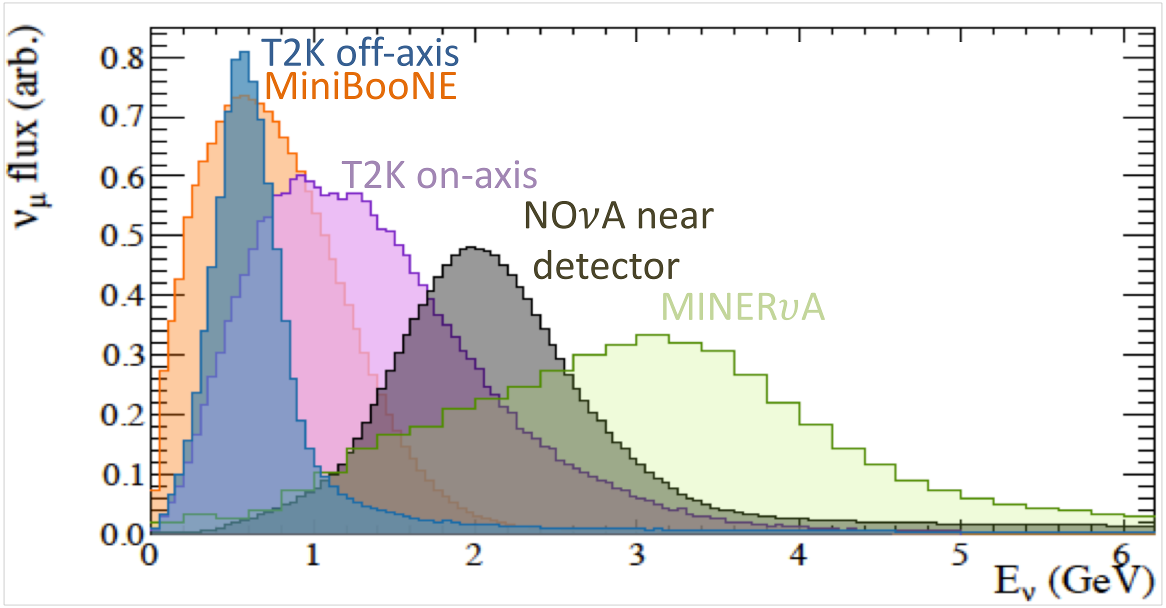
**CLAS E2a (April/May 1999)**,

- standard inclusive e- trigger
- **Energies**: 1.16, 2.26 and 4.45 GeV
- **Targets**: $^{3}He$, $^{4}He$, $^{12}C$, $^{56}Fe$

**Neutrino targets:**

Water, argon, scintillant (H, C, O, Ar)

**Neutrino beam energies**

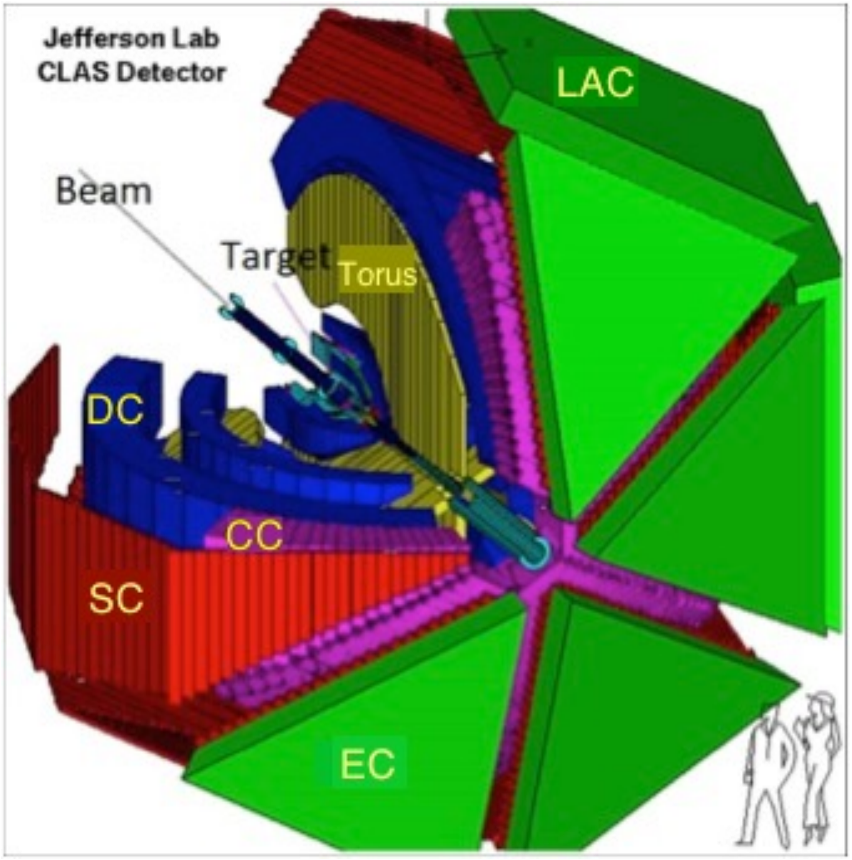


# CLAS

- Large ($\sim 2\pi$) acceptance
- Charged particle thresholds similar to neutrino tracking detectors:
  - $P_p > 300$ MeV/c
  - $P_{\pi+/-} > 150$ MeV/c

- $\gamma$ threshold $E_\gamma > 300$ MeV

3D view

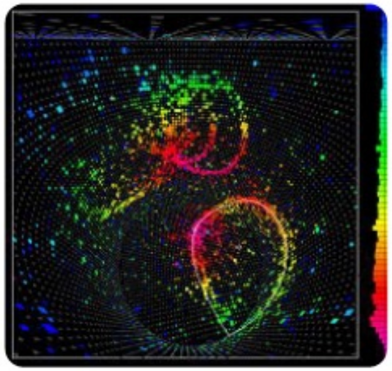


# Data analysis

- Reconstruct $E_{lepton}$
  - Cherenkov detectors: $e^-$ parameters only

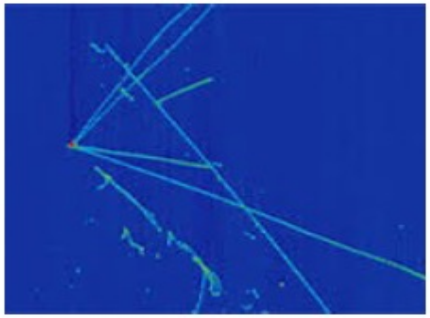
$$E_{QE} = \frac{2M\varepsilon + 2ME_l - m_l^2}{2\left(M - E_l + |k_l|cos(\theta_l)\right)}$$

$\varepsilon$ =average nucleon separation energy



  - Tracking detectors: $e^-$ and p

$$E_{Cal} = E_l + T_p + \varepsilon$$



- Select zero $\pi/\gamma$ events to enhance the QE sample
  - two event sets (e,e’) and (e,e’p)
  - subtract for undetected $\pi/\gamma$ and $p$

- Weight by $Q^4$ to account for photon propagator
- Correct for electron radiation and CLAS acceptance
- Extract Cross Section
- Compare to e-GENIE simulation predictions

# Background Subtraction

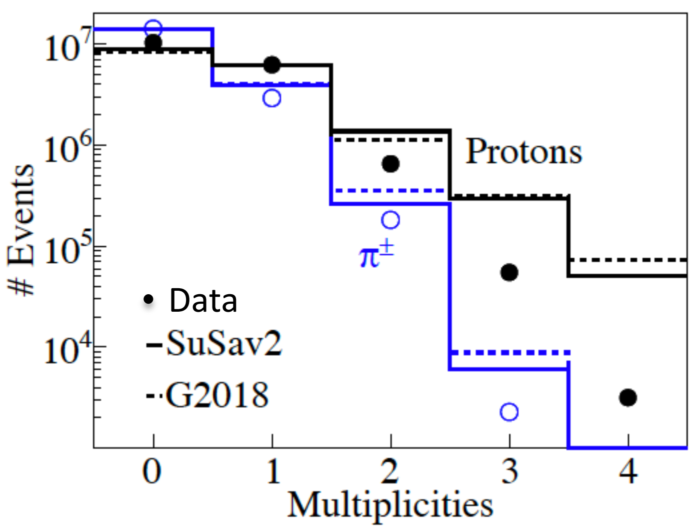
Want $0\pi$ event sample

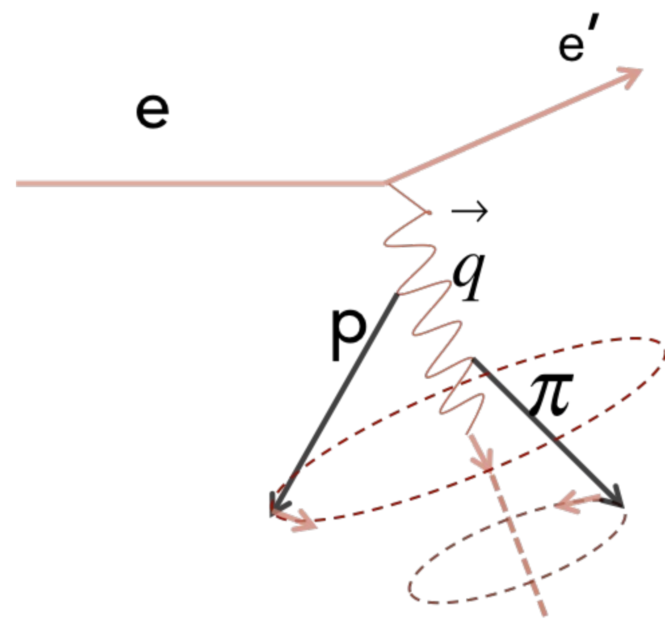
(e,e') background: undetected pions and photons

(e,e'p) background: undetected pions, photons and extra protons

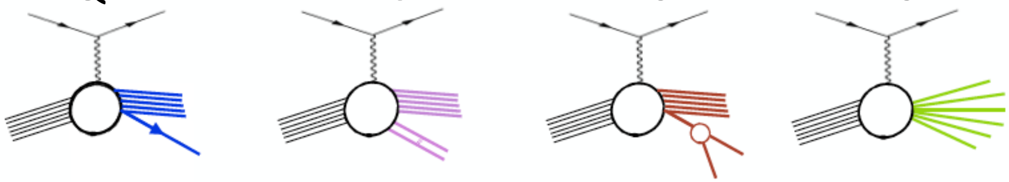
Data Driven Correction:

1. Use measured (e,e'p$\pi/\gamma$) events,
2. Rotate $\pi$ or $\gamma$ around **q** to determine its acceptance,
3. Subtract (e,e'p$\pi/\gamma$) contributions
4. Do the same for 2p, 3p, 2p+ $\pi$ etc.



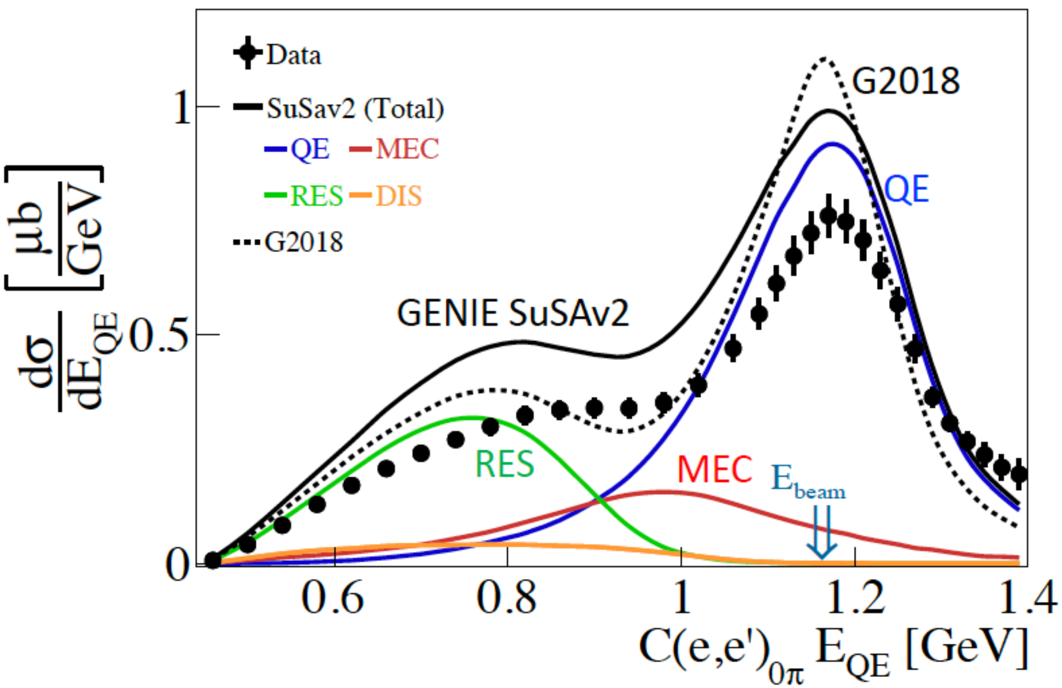



# (e,e') energy reconstruction




Consider **two "tunes"** of GENIE models for QE and MEC:

- **G2018** (Rosenbluth cross section and Local Fermi Gas + empirical Dytman model of MEC)
- **SuSAv2**(theoretically-inspired, follows the universal SuSAv2 super-scaling approach to lepton scattering and Relativistic Mean Field theory for nuclear ground state)
- Common RES and DIS: Berger-Sehgal + Bodek and Yang
- Similar FSI




SuSAv2

- Correct peak width
- Incorrect cross section

G2018

- peak too narrow
- Incorrect cross section

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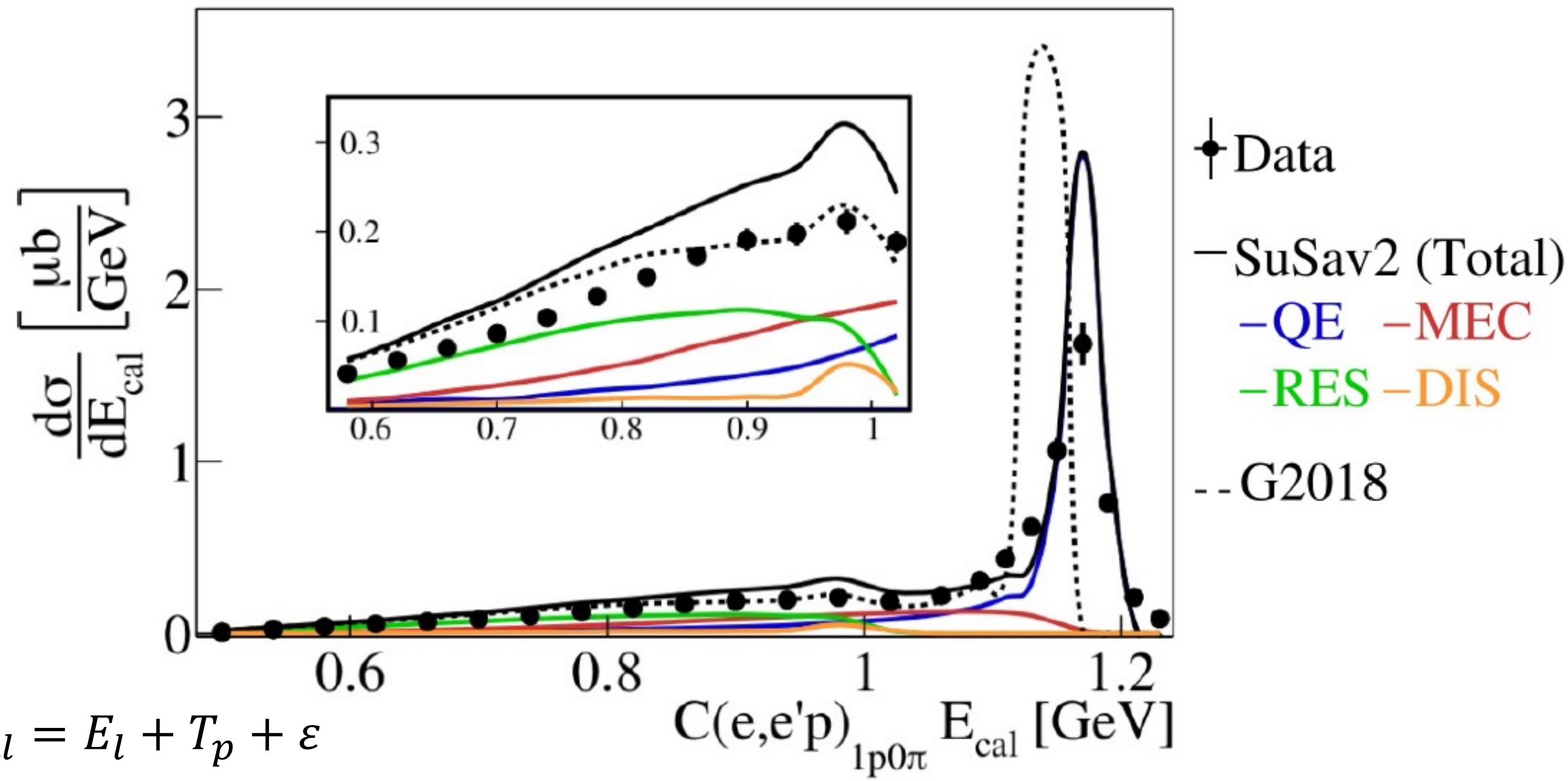
# (e,e'p) calorimetric energy




$$E_{Cal} = E_l + T_p + \varepsilon$$

e-GENIE overpredicts the % of events in the peak

G2018:

- reconstructs the peak position to be 25 MeV too low
- describes tail relatively well

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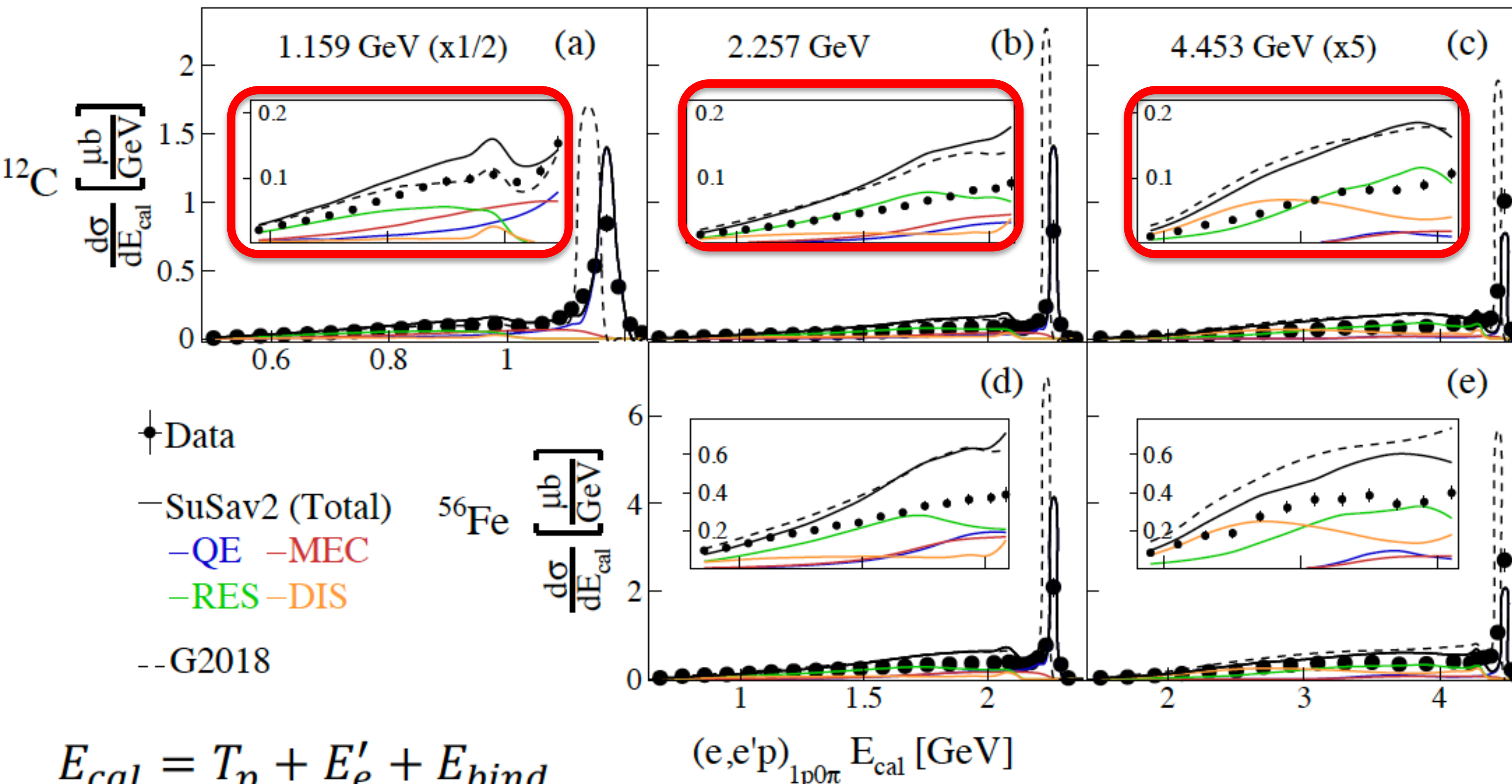
# A and E dependence




$$E_{cal} = T_p + E'_e + E_{bind}$$

- Data/MC disagreement
- Worse at higher E
- Due to RES and DIS

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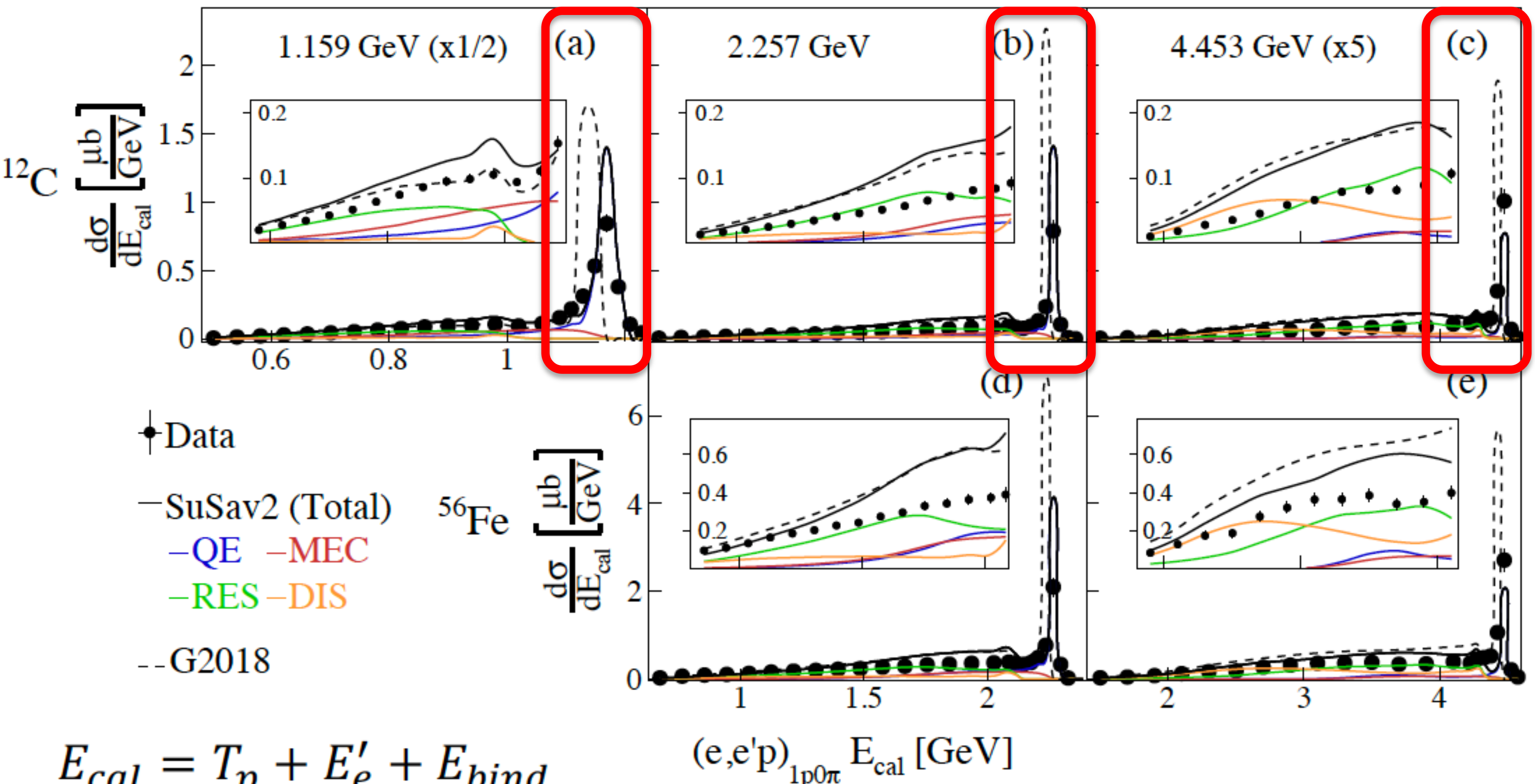
# A and E dependence




$$E_{cal} = T_p + E'_e + E_{bind}$$

SuSAv2
- Correct peak energy
- Incorrect cross section

% of events within 5% of $E_{beam}$

$^{12}$C 30-40%

$^{56}$Fe 20-25%

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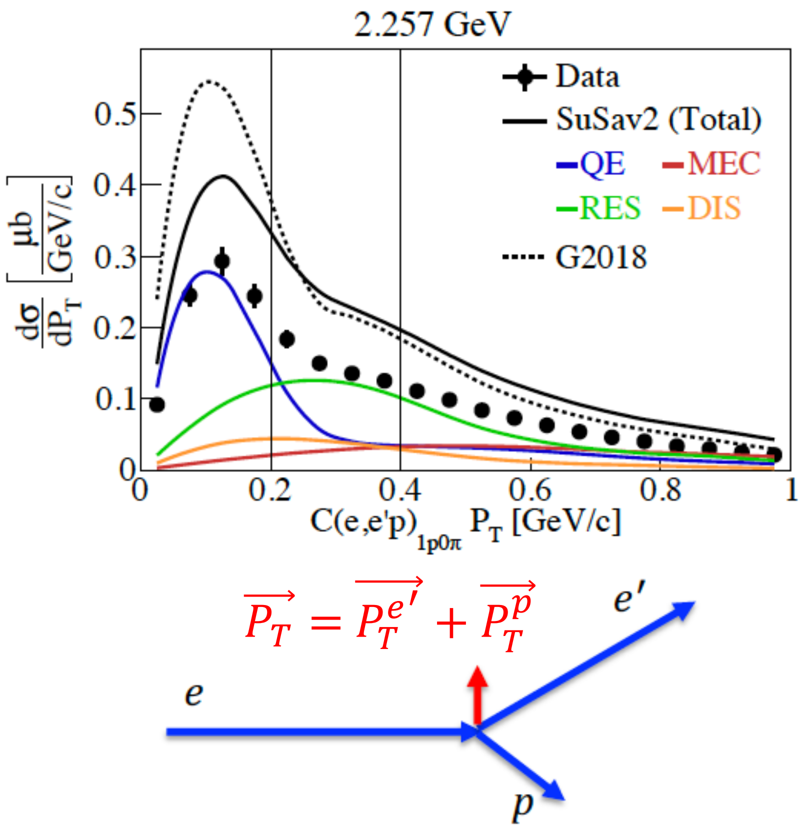
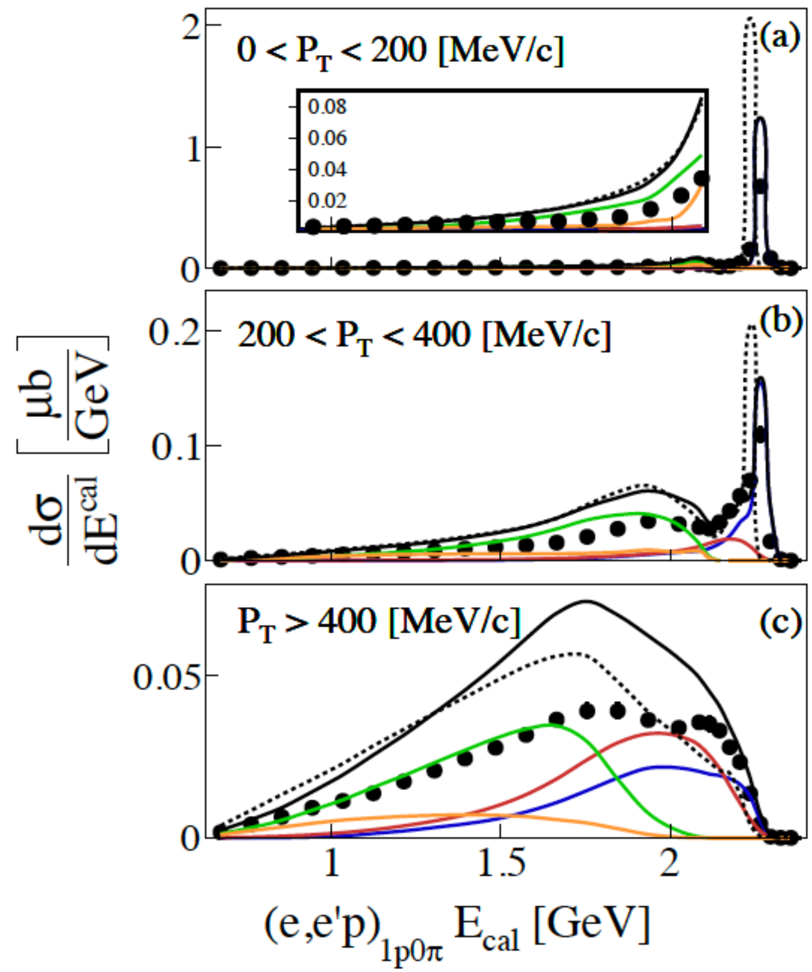
# Missing perpendicular momentum ($P_T$)




$$E_{cal} = T_p + E'_e + E_{bind}$$

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# Summary

1. Neutrino oscillation measurements are important
2. Extracting oscillation parameters depends on knowledge of $\nu A$ interactions
3. First test of beam energy reconstruction showed serious problems:
   - most 1p0pi events reconstructed to the wrong energy
   - models failed to predict data
4. More results coming:
   - more channels
   - dedicated CLAS12 data
5. Large e4$\nu$ collaboration using this data to improve $\nu A$ modeling

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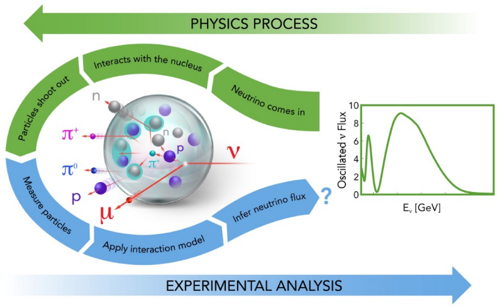
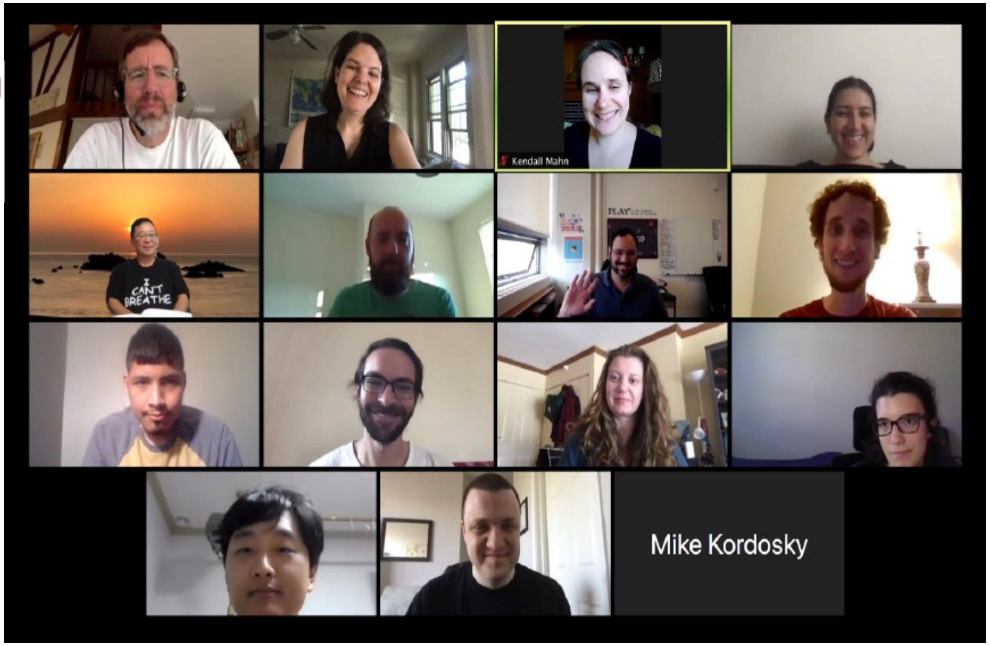



e4$\nu$



# Thank you for your attention!

## The current knowledge on neutrinos oscillation parameters in the three neutrino framework

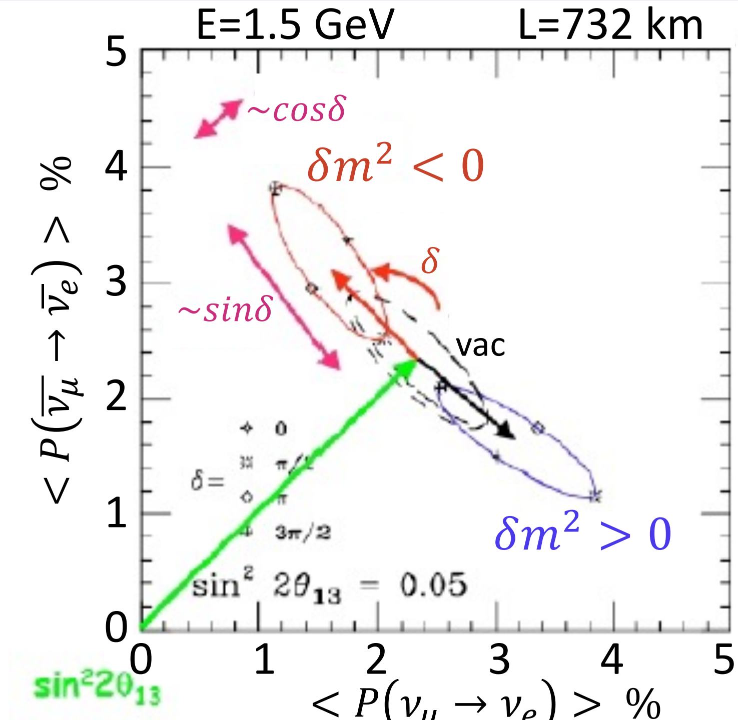
What is known:

- The mixing angles $\theta_{ij}$ and mass splittings $\Delta m_{ij}^2$.

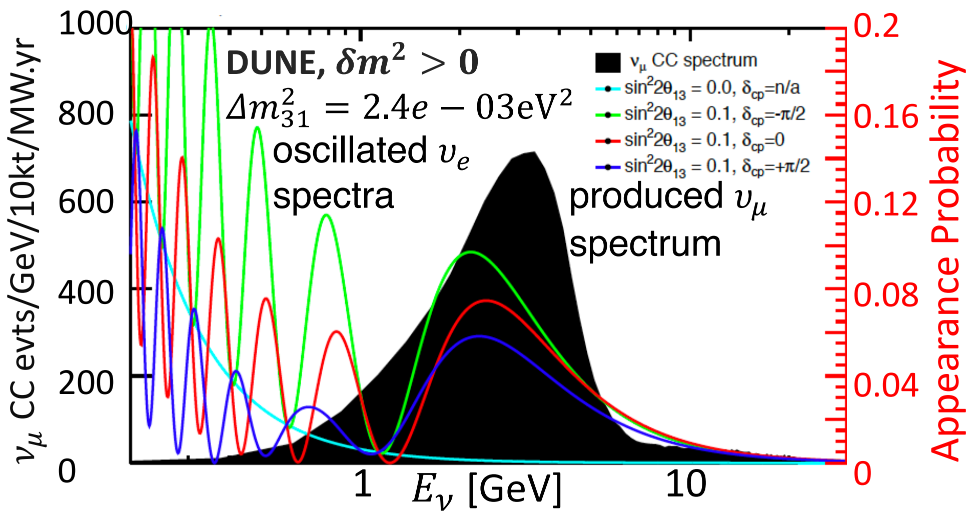
Fundamental open questions:

- The mass hierarchy

$(m_1 < m_2 < m_3$(NH) or $m_3 < m_1 < m_2$(IH) ?)



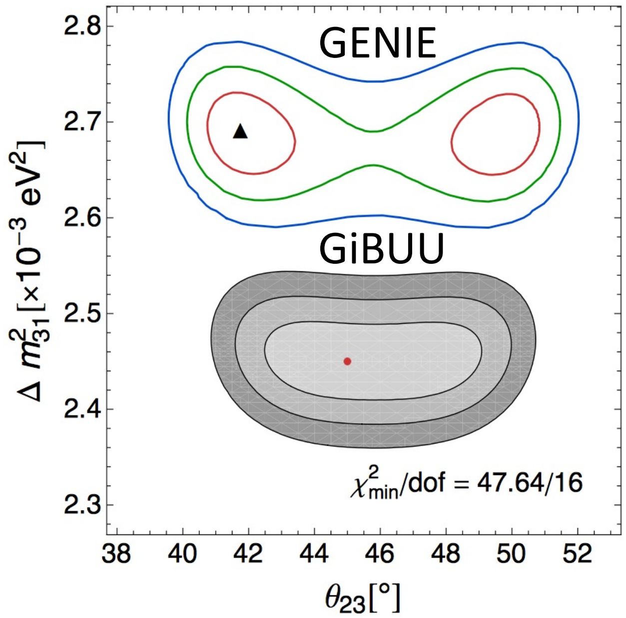

- The value of CP violation phase $\delta_{CP}$.




$\Rightarrow$need improved measurements of the mass splittings and mixing angles.

# (Long Baseline) Oscillation Challenge

=> Incorrect neutrino-nucleus interaction modeling can bias the extracted oscillation parameters




Events created with GiBUU and reconstructed with GiBUU and GENIE.

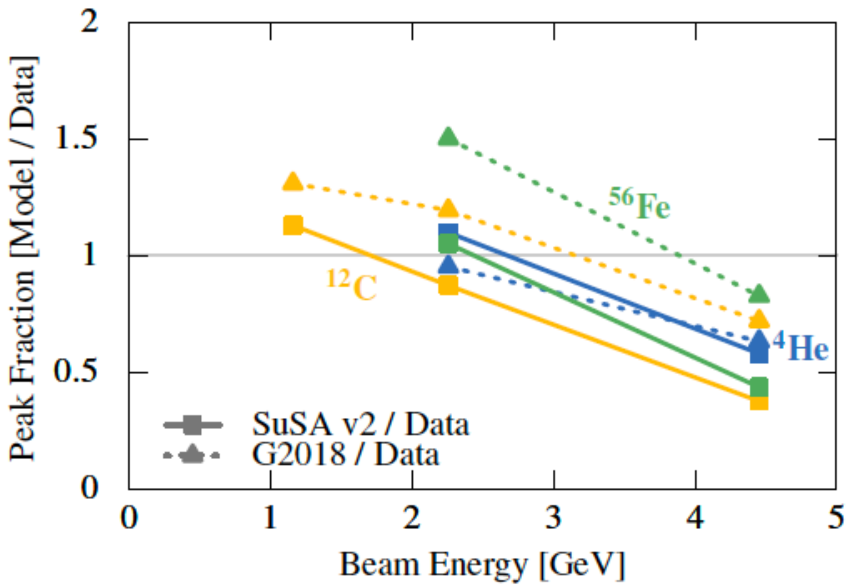
Biggest systematic uncertainties due to neutrino interactions.

Cross section systematics

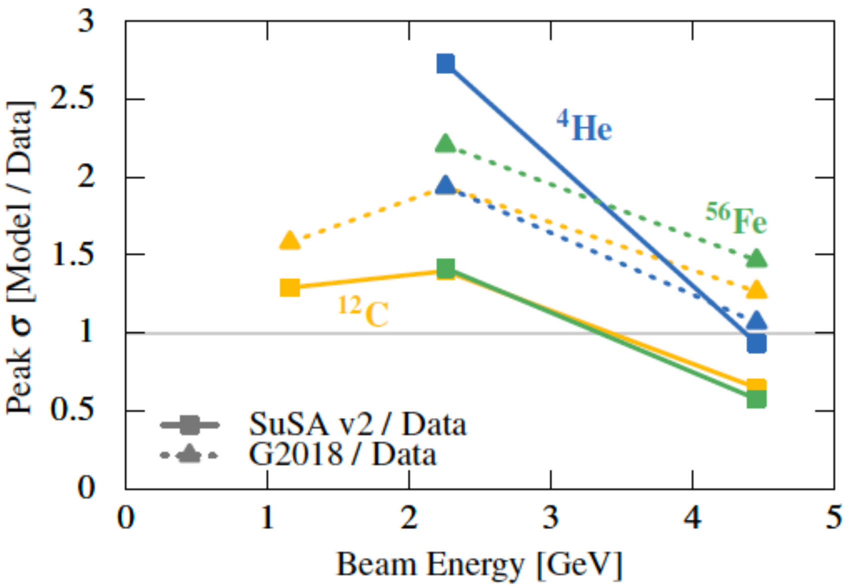
| **Xsec uncertainties** | $\nu_\mu$ disap. | $\nu_e$ app. | |
|---|---|---|---|
| T2K | $\pm 5.0\%$ | $\pm 4.7\%$ | Phys. Rev. D **91**, 072010 |
| NO$\upsilon$A | | $\pm 7\%$ | Matthew Muether. 2015. NuInt |

# A and E dependence

Peak fraction (model/data)




Peak cross section (model/data)

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# Sources of uncertainty

- Statistical uncertainty is shown by error bars.
- Uncertainties of the weights for subtraction of undetected $\pi$ and protons.
  - ✧ Systematic uncertainty due to the $\phi$-dependence of the pion cross section modeled and found to be negligible (less than 1%).
  - ✧ Rotate (e,e'$\pi$) events enough times to reduce statistical uncertainty below 1%.
  - ✧ Systematic uncertainty due to imperfect description of the geometrical acceptance.
  - ✧ Systematic uncertainty due to $\gamma$ ID (missing $\gamma s$ and n contamination).

| E [GeV] | Uncertainty due to | | | | | |
|---|---|---|---|---|---|---|
| | $\varphi$ dep. | Imperf. accept. In subtraction | $\gamma$ ID cut | Cross section overall normalization from H(e,e') | CLAS sector-to-sector variation of cross section | CLAS acceptance correction |
| 1.1 | 1% | 0.8% | 0.1% | 3% | 6% | Up to 4% |
| 2.2 | 1% | 1.2% | 0.5% | 3% | 6% | Up to 13% |
| 4.4 | 1% | 4% | 2% | 3% | 6% | Up to 12% |

Point to point systematic uncertainties ranged from 7 to 25%

# Radiative Corrections to Single Photon Exchange

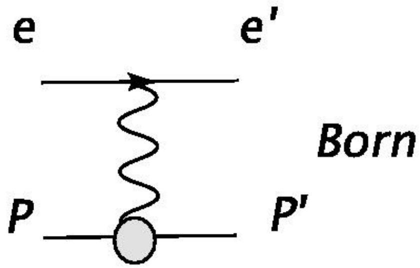
Radiation and reabsorption of a virtual photon (vertex correction)

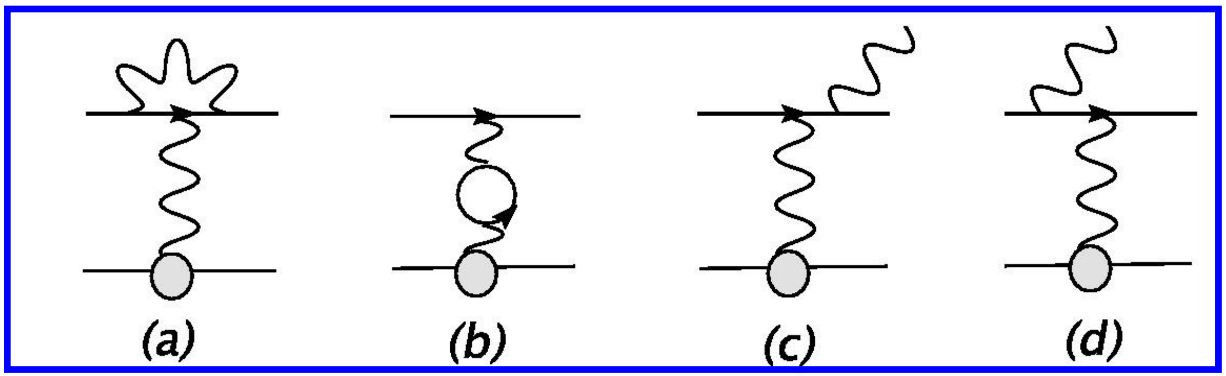
Virtual pair production by the exchanged photon (vacuum polarization)

Up to 6% of $E_{e-}$

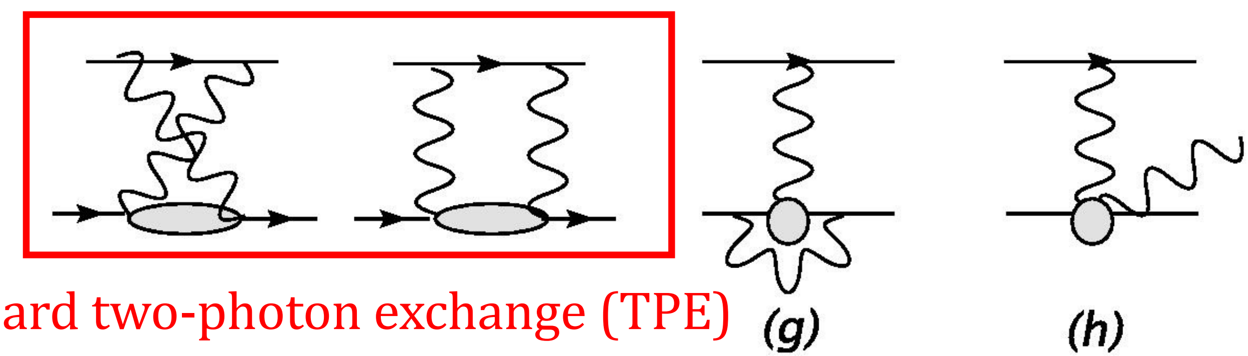
Radiation of real photon either before or after

Up to 15% of $E_{e-}$



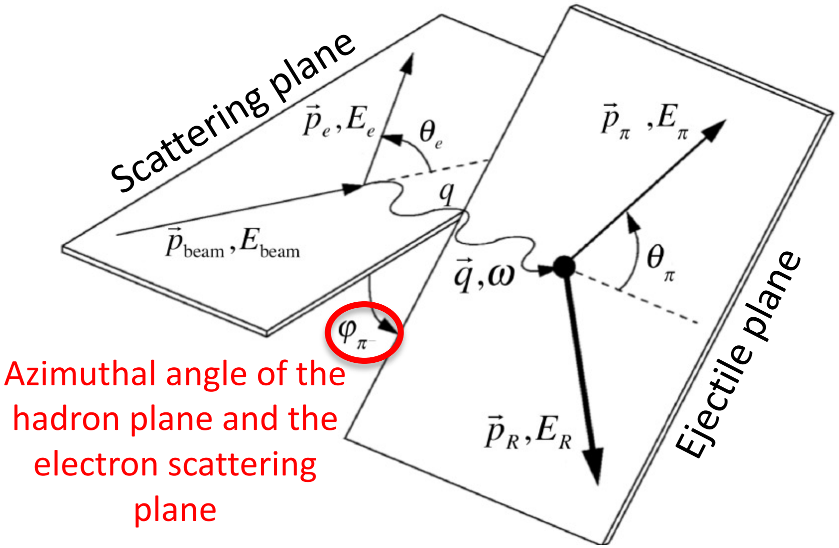

Standard radiative corrections




Hard two-photon exchange (TPE)
Smaller by a factor of α

# Phi dependence

Cross section for unpolarized pion electroproduction on a single nucleon:




$$\frac{d^4\sigma}{dW\,dQ^2 d\Omega_\pi^*} = J\Gamma_\nu\left(A + B\cos\phi_\pi + C\cos 2\phi_\pi\right)$$

$$A = (\sigma_{\rm T} + \epsilon\sigma_{\rm L})\frac{p_\pi^*}{k_\gamma^*}$$

$$B = \sigma_{\rm LT}\frac{p_\pi^*}{k_\gamma^*}\sin\theta_\pi\sqrt{2\epsilon(\epsilon+1)}$$

$$C = \sigma_{\rm TT}\frac{p_\pi^*}{k_\gamma^*}\sin^2\theta_\pi\epsilon$$

$$W = \sqrt{M^2 + 2M\nu - Q^2} \quad k_\gamma = \frac{W^2 - M^2}{2M} \quad k_\gamma^* = k_\gamma M/W \quad \epsilon = \frac{1}{1 + 2(1 + \frac{\nu^2}{Q^2}\tan^2\frac{\theta_e}{2})} \quad \Gamma_\nu = \frac{\alpha}{2\pi^2}\frac{E_f}{E_i}\frac{k_\gamma}{Q^2}\frac{1}{1-\epsilon}$$

Where $p_\pi^*, \theta_\pi$ and $\varphi_\pi$ are the momentum, scattering and azimuthal angles of the $\pi^0$ in the CM frame.
Jacobian $J$=$\partial(Q^2, W)/\partial(E', cos\theta_e, \theta_e)$, $\Gamma_\upsilon$ is virtual photon flux.

N. Markov et al. arXiv:1907.11974

Weight without $\varphi_\pi$ dependence

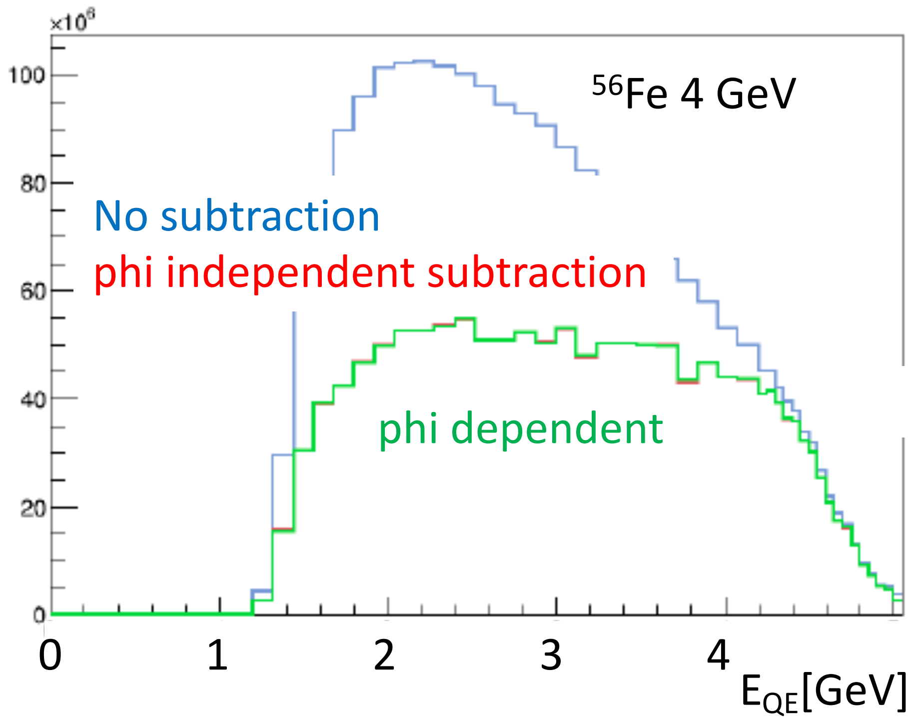
$$W = \frac{\sum_{i=1}^{N_{\rm Undet}} 1}{\sum_{i=1}^{N_{\rm Det}} 1}$$

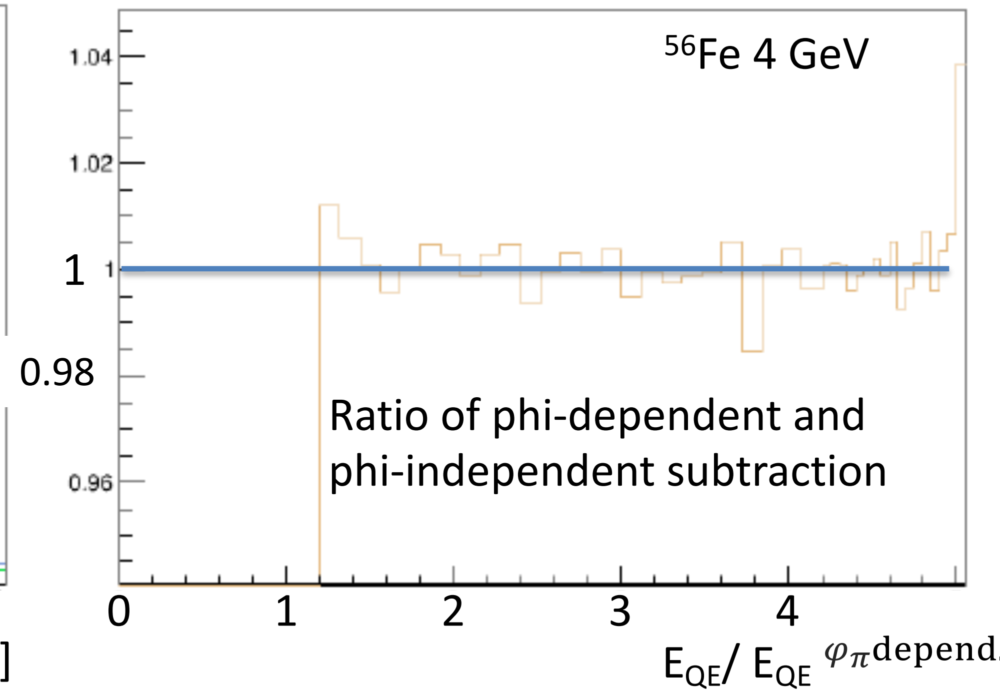
Weight with $\varphi_\pi$ dependence

$$W = \frac{\sum_{i=1}^{N_{\rm Undet}} 1 + B/A\cos\phi_\pi + C/A\cos 2\phi_\pi}{\sum_{i=1}^{N_{\rm Det}} 1 + B/A\cos\phi_\pi + C/A\cos 2\phi_\pi}$$

# Phi dependence

Subtracting for undetected one $\pi$ events in $^{56}$Fe(e,e') 4 GeV analysis




Negligible phi dependence!

# Phi dependence

Use maximum of structure functions from Markov et al. paper for $0.4 \leq Q^2 \leq 1\ GeV^2$.

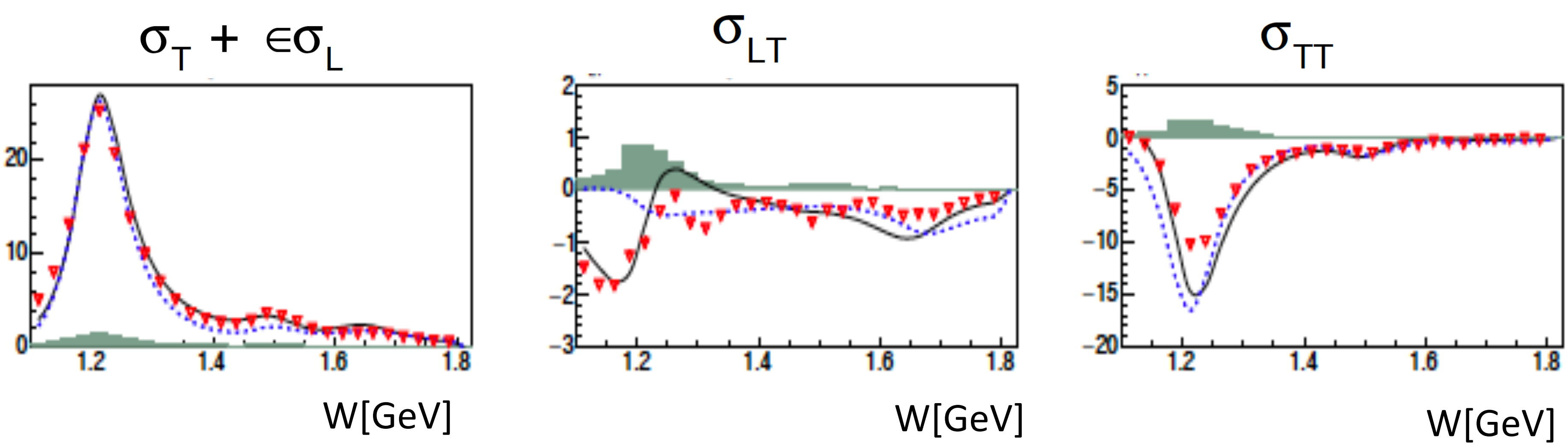
The absolute values are the biggest for $cos\theta_\pi = 0.1$, $W = 1232\text{ GeV}$, $Q^2$=0.45 GeV$^2$.
$\sigma_T + \epsilon\sigma_L = 30\text{ µb}$, $\sigma_{TT} = -10\text{ µb}$ and $\sigma_{LT} = -2\text{ µb}$.

$$A = (\sigma_\mathrm{T} + \epsilon\sigma_\mathrm{L})\frac{p_\pi^*}{k_\gamma^*}$$

$$B = \sigma_\mathrm{LT}\frac{p_\pi^*}{k_\gamma^*}\sin\theta_\pi\sqrt{2\epsilon(\epsilon+1)}$$

$$C = \sigma_\mathrm{TT}\frac{p_\pi^*}{k_\gamma^*}\sin^2\theta_\pi\epsilon$$

$\cos\theta^*_{\pi_0}$=0.1 $Q^2$=0.45 GeV$^2$




N. Markov et al. arXiv:1907.11974

Acceptance correction factors, acceptance correction factor uncertainties, and) electron radiation correction factors plotted vs $E_{cal}$