Role of neutrino cross sections and nuclear models on oscillation experiments;

Connecting electron scattering and neutrino scattering

Camillo Mariani
Center for Neutrino Physics, Virginia Tech

Motivation and Contents

- Determination of neutrino oscillation parameters requires knowledge of neutrino energy

- Modern experiments use complicated nuclear targets: from Carbon to Argon

- Nuclear effects affect:
  - event identification
  - final state particles
  - reconstructed neutrino energy
  - event cross section measurements
  - neutrino oscillation parameters

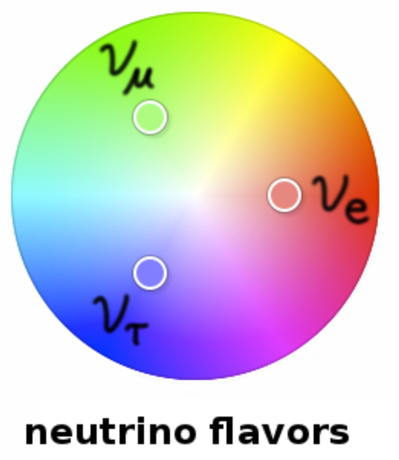
ν_e, ν_μ, and ν_τ *are not the neutrino mass eigenstates* but *superpositions* of the mass eigenstates:

$$\overset{\uparrow}{|\nu_\alpha>} = \sum_i \overset{\uparrow}{U^*_{\alpha i}} \overset{\uparrow}{|\nu_i>} \quad .$$

Neutrino of flavor
α = e, μ, or τ

Neutrino of definite mass m_i

Unitary Leptonic Mixing Matrix



neutrino flavors

The leptonic mixing matrix

$$U = \begin{array}{c} \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \left[\begin{array}{ccc} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{array} \right] \end{array}$$

neutrino masses

The Lepton Mixing Matrix *U*

$$U = \begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}\times\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{bmatrix}\times\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij}$$
$$s_{ij} \equiv \sin\theta_{ij}$$

$$\times\underbrace{\begin{bmatrix}e^{i\alpha_1/2} & 0 & 0\\ 0 & e^{i\alpha_2/2} & 0\\ 0 & 0 & 1\end{bmatrix}}_{\text{Does not affect oscillation}}$$

$$\overbrace{\theta_{12}\approx 33^\circ,\ \theta_{23}\approx 40\text{-}52^\circ,}^{\textit{Note big mixing!}}\ \ \theta_{13}\approx 8\text{-}9^\circ \leftarrow \textit{Not very small!}$$

The phases violate CP. δ would lead to $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \underset{\overset{\uparrow}{\cancel{CP}}}{\neq} P(\nu_\alpha \rightarrow \nu_\beta)$.

But note the crucial role of $s_{13} \equiv \sin\theta_{13}$.

We know essentially nothing about the phases. Only hints.

Neutrinos: they have mass and mix

Neutrino oscillation experiments have revealed that neutrinos change flavor after propagating a finite distance. The rate of change depends on the neutrino energy E_ν and the baseline L.

- $\nu_\mu \to \nu_\tau$ and $\bar{\nu}_\mu \to \bar{\nu}_\tau$ — atmospheric experiments ["indisputable"];
- $\nu_e \to \nu_{\mu,\tau}$ — solar experiments ["indisputable"];
- $\bar{\nu}_e \to \bar{\nu}_{\text{other}}$ — reactor neutrinos ["indisputable"];
- $\nu_\mu \to \nu_{\text{other}}$ — accelerator experiments ["indisputable"].
- $\nu_\mu \to \nu_e$ — accelerator experiments ["very strong"];

Neutrino Oscillations

- 2-Flavor Oscillation:

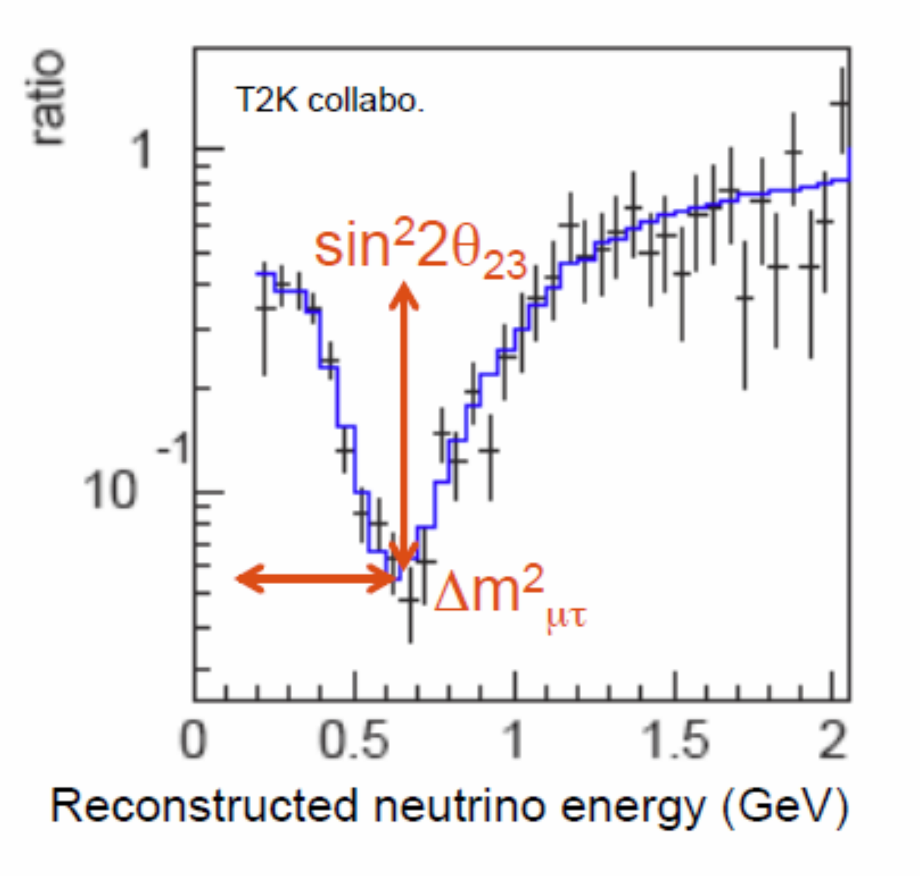
$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4 E_\nu} \right)$$

Know: L, need E_ν to determine Δm^2, θ

- 3-Flavor Oscillation: allows for CP violation

Observable Oscillation Parameters

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



Oscillation probability

Long-Baseline Accelerator Appearance Experiments

- Oscillation probability complicated and dependent not only on θ_{13} but also:
  1. CP violation parameter (δ)
  2. Mass hierarchy (sign of Δm_{31}^2)
  3. Size of $\sin^2\theta_{23}$

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \; (1 - 2S_{13}^2)\right) \\
& + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
& - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
& + 4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2 \frac{\Delta m_{21}^2 L}{4E} \\
& - 8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} \; (1 - 2S_{13}^2)
\end{aligned}
$$

⇒ These extra dependencies are both a "curse" and a "blessing"

Reactor Disappearance Experiments

$$
P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{13}^2 L}{4E} + \; small\ terms
$$

Current Knowledge:

arXiv:1706.03621 [hep-ph]

	θ_{12}	θ_{13}	θ_{23}	$\Delta m^2_{21}/10^{-5}$	$\Delta m^2_{3j}/10^{-3}$	δ_{CP}
Normal Ordering	$33.56^{+0.77}_{-0.75}$	$8.46^{+0.15}_{-0.15}$	$41.6^{+1.5}_{-1.2}$	$7.50^{+0.19}_{-0.17}$	$2.524^{+0.039}_{-0.040}$	261^{+51}_{-59}
Inverted Ordering	$33.56^{+0.77}_{-0.75}$	$8.49^{+0.15}_{-0.15}$	$50.0^{+1.1}_{-1.4}$	$7.50^{+0.19}_{-0.17}$	$-2.514^{+0.038}_{-0.041}$	277^{+40}_{-46}

Current and Future Goals:

- Establish whether there is CP violation in the lepton sector and, if so, measure δ_{CP}
- Improve the accuracy on θ_{23}
- Determine the neutrino mass ordering: $m_1 < m_2 < m_3$ or $m_3 < m_1 < m_2$

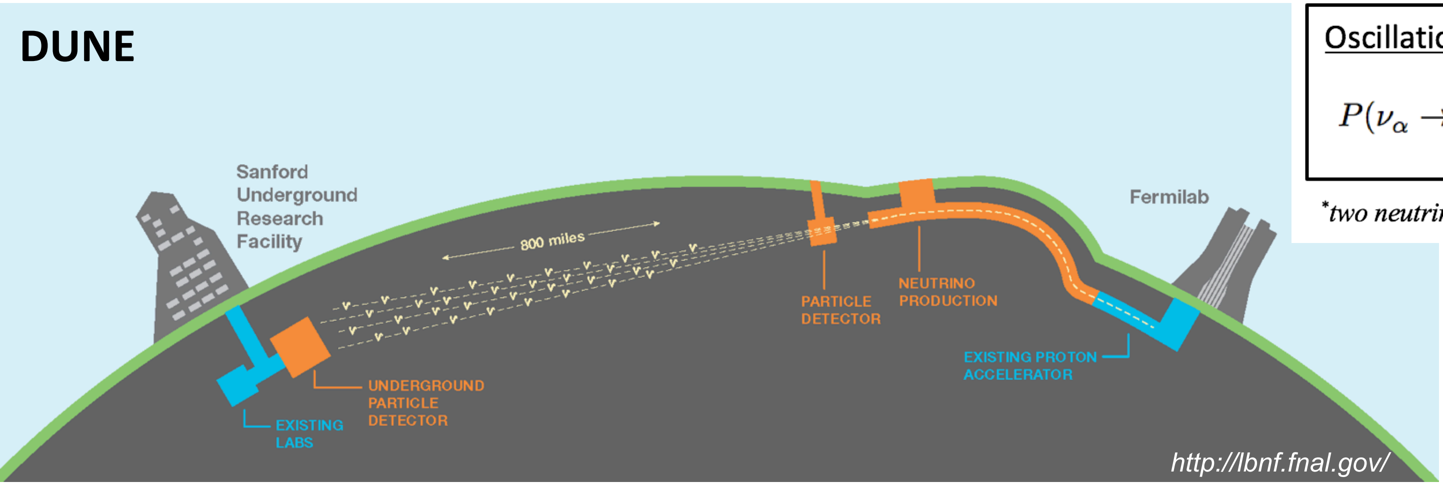
Current and Future Experiments:

- **MiniBooNE** (concluded, re-running), **NOvA** (running), **T2K** (running), **T2HK** (under construction), etc.
- **SBN Program: MicroBooNE** (running), **ICARUS** (under construction), **SBND** (under construction)
- **DUNE** (under construction)

LArTPC

Accelerator-based neutrino-oscillation experiments

DUNE



http://lbnf.fnal.gov/

Oscillation Probability*:

$$P(\nu_\alpha \to \nu_\beta) \simeq \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E}\right)$$

two neutrino flavors, for simplicity

Experiments measure event rates which, for a given observable topology, can be naively computed as:

Event Rate at near detector:

$$N^{\alpha}_{\mathrm{ND}}(\boldsymbol{p}_{\mathrm{reco}}) = \sum_i \phi_\alpha(E_{\mathrm{true}}) \times \sigma^i_\alpha(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\alpha(\boldsymbol{p}_{\mathrm{true}})$$

Event Rate at far detector:

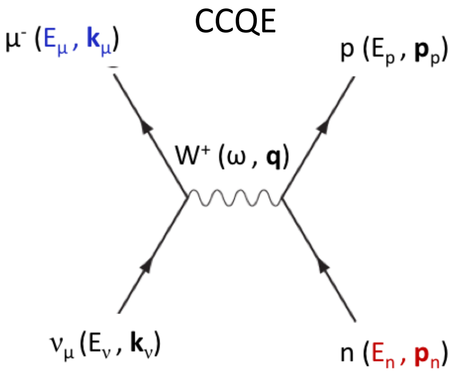
$$N^{\alpha\to\beta}_{\mathrm{FD}}(\boldsymbol{p}_{\mathrm{reco}}) = \sum_i \phi_\alpha(E_{\mathrm{true}}) \times P_{\alpha\beta}(E_{\mathrm{true}}) \times \sigma^i_\beta(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\beta(\boldsymbol{p}_{\mathrm{true}})$$

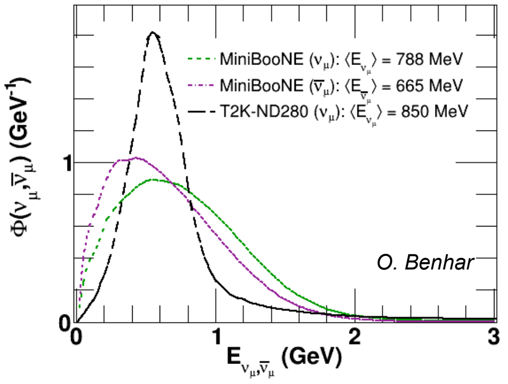
Event Rate at far detector:

$$N_{\rm FD}^{\alpha\to\beta}(\boldsymbol{p}_{\rm reco}) = \sum_i \phi_\alpha(E_{\rm true}) \times P_{\alpha\beta}(E_{\rm true}) \times \sigma_\beta^i(\boldsymbol{p}_{\rm true}) \times \epsilon_\beta(\boldsymbol{p}_{\rm true})$$

$$P(\nu_\alpha \to \nu_\beta) \simeq \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Neutrino Energy: Reconstruction





Neutrino energy distribution

- For CCQE process (assuming single nucleon knock out), The reconstructed neutrino energy is

$$E_\nu = \frac{m_p^2 - m_\mu^2 - E_n{}^2 + 2E_\mu E_n - 2\mathbf{k}_\mu \cdot \mathbf{p}_n + |\mathbf{p}_n{}^2|}{2(E_n - E_\mu + |\mathbf{k}_\mu| \cos\theta_\mu - |\mathbf{p}_n| \cos\theta_n)}$$

where $|k_\mu|$ and θ_μ are measured, while p_n and E_n are the unknown momentum and energy of the interacting neutron.

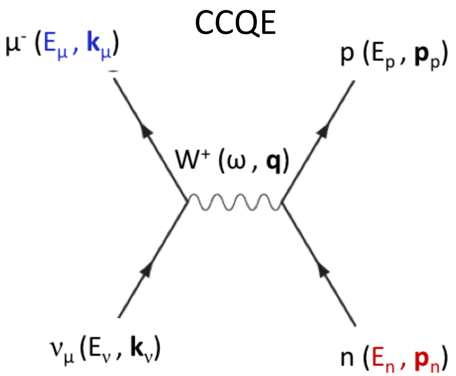
- Existing simulation codes routinely use $|p_n| = 0$, $E_n = m_n - \varepsilon$, with $\varepsilon \sim 20$ MeV for carbon and oxygen, or the Fermi gas (FG) model.

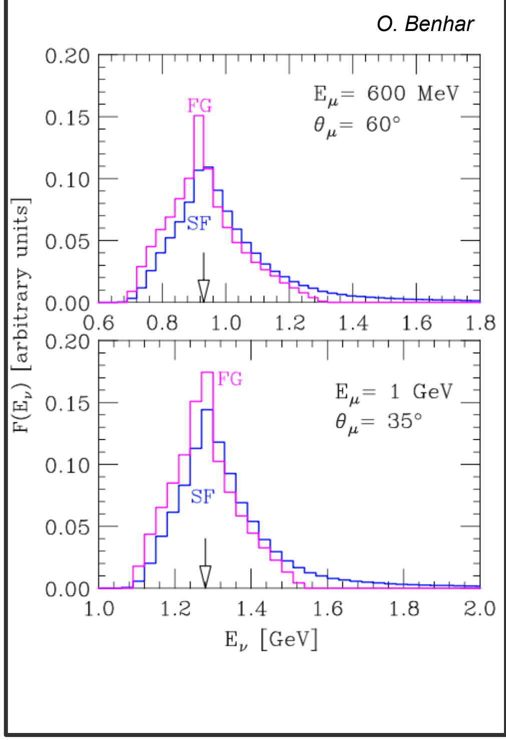
Event Rate at far detector:

$$N_{\mathrm{FD}}^{\alpha\to\beta}(\boldsymbol{p}_{\mathrm{reco}}) = \sum_i \phi_\alpha(E_{\mathrm{true}}) \times P_{\alpha\beta}(E_{\mathrm{true}}) \times \sigma_\beta^i(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\beta(\boldsymbol{p}_{\mathrm{true}})$$

$$P(\nu_\alpha \to \nu_\beta) \simeq \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Neutrino Energy: Reconstruction




O. Benhar

- For CCQE process (assuming single nucleon knock out), The reconstructed neutrino energy is

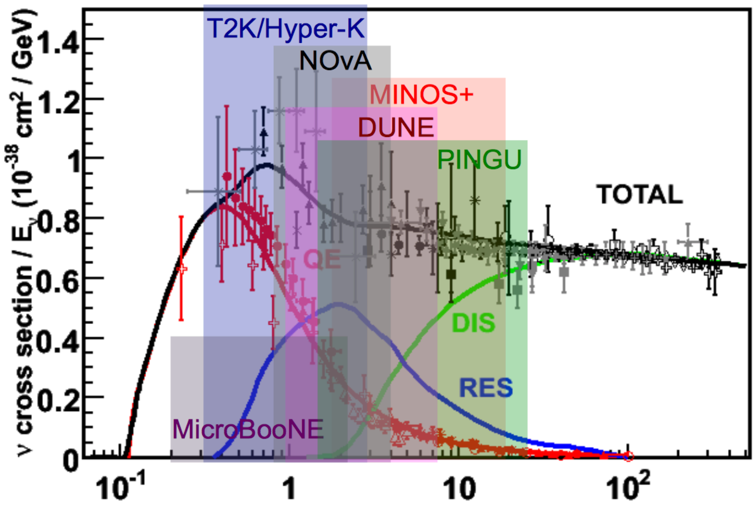
$$E_\nu = \frac{m_p^2 - m_\mu^2 - E_n{}^2 + 2E_\mu E_n - 2\mathbf{k}_\mu \cdot \mathbf{p}_n + |\mathbf{p}_n{}^2|}{2(E_n - E_\mu + |\mathbf{k}_\mu| \cos\theta_\mu - |\mathbf{p}_n| \cos\theta_n)}$$

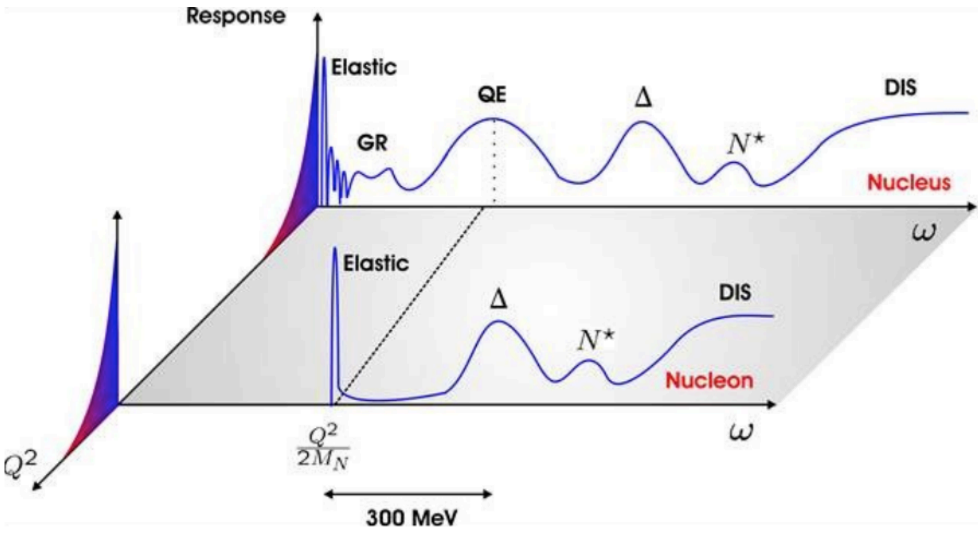
- Neutrino energy reconstructed using 2 ×10^4 pairs of (|p|, E) values sampled from realistic (SF) and FG oxygen spectral functions.
- The average value ⟨E_ν⟩ obtained from the realistic spectral function turns out to be shifted towards larger energy by ~ 70 MeV.

Event Rate at far detector:

$$N_{\mathrm{FD}}^{\alpha\to\beta}(\boldsymbol{p}_{\mathrm{reco}}) = \sum_i \phi_\alpha(E_{\mathrm{true}}) \times P_{\alpha\beta}(E_{\mathrm{true}}) \times \sigma_\beta^i(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\beta(\boldsymbol{p}_{\mathrm{true}})$$

Neutrino-nucleus cross section

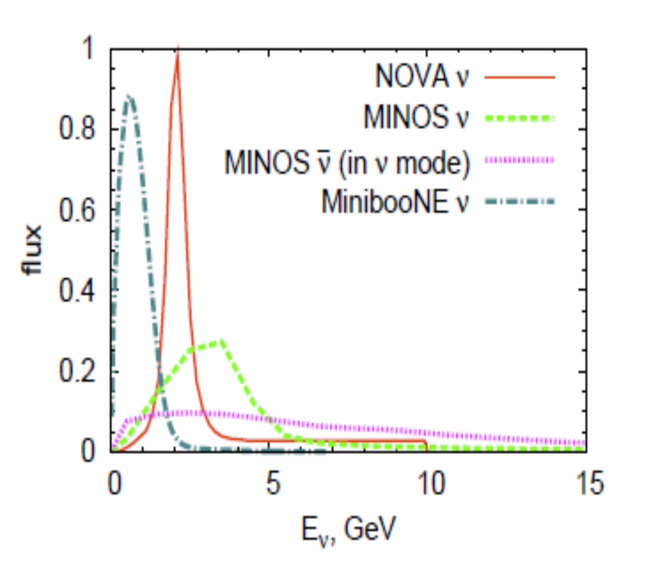


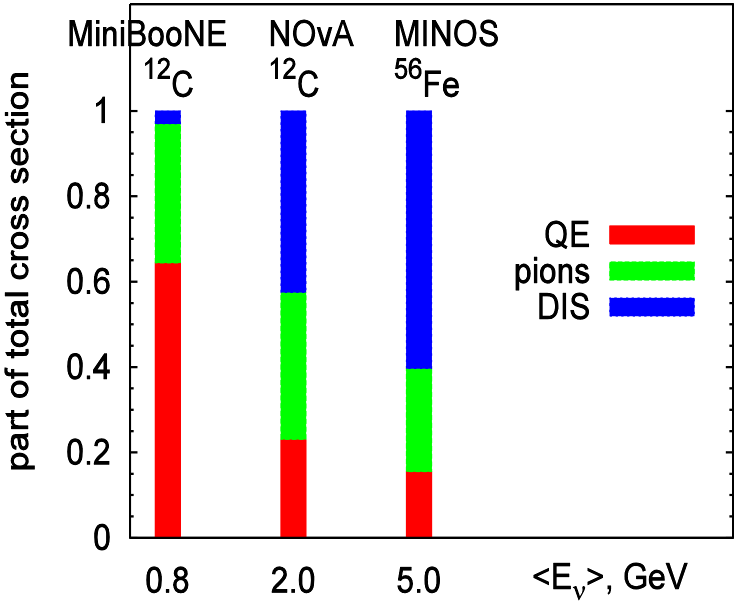


- Need realistic nuclear model (in Monte-Carlo simulations) that can describe neutrino-nucleus cross sections over a wide range of energies.

Neutrino Beams

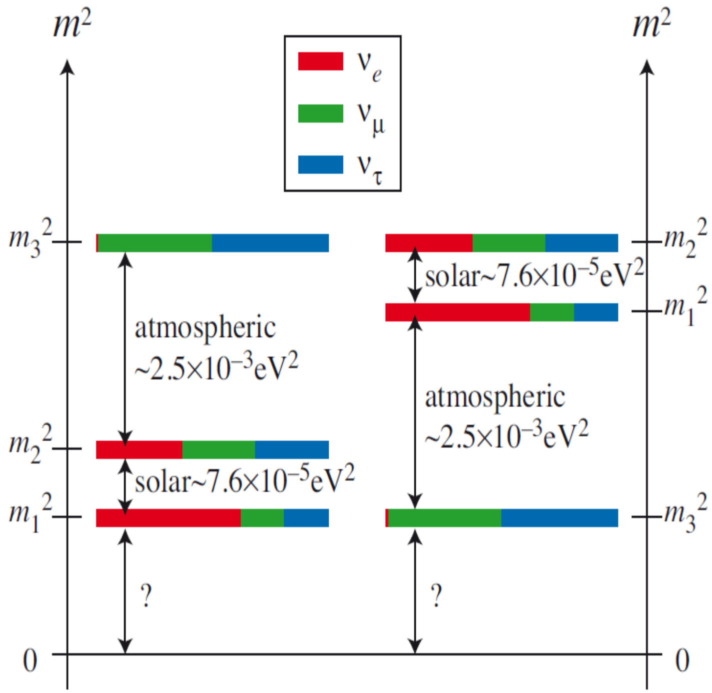
- Neutrinos do not have fixed energy nor just one reaction mechanism





Have to reconstruct energy from final state of reaction
Different processes are entangled

Oscillation Signal: Dependence on Hierarchy and Mixing Angle



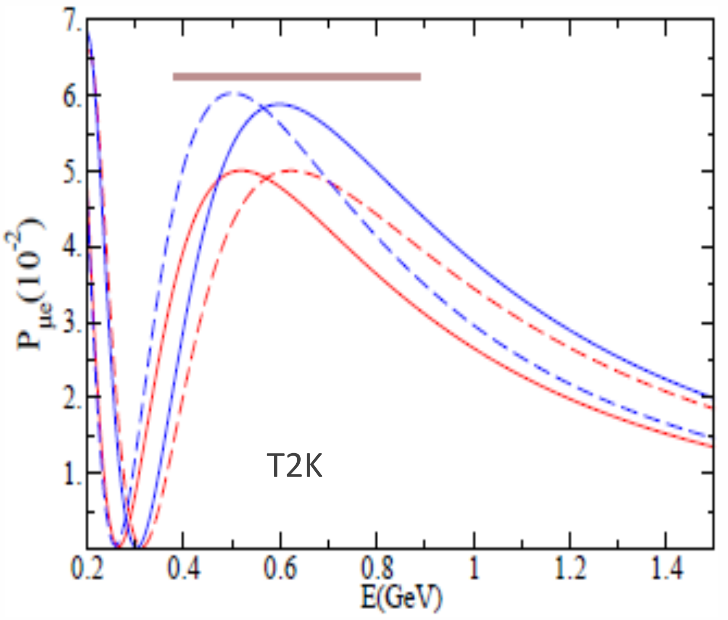


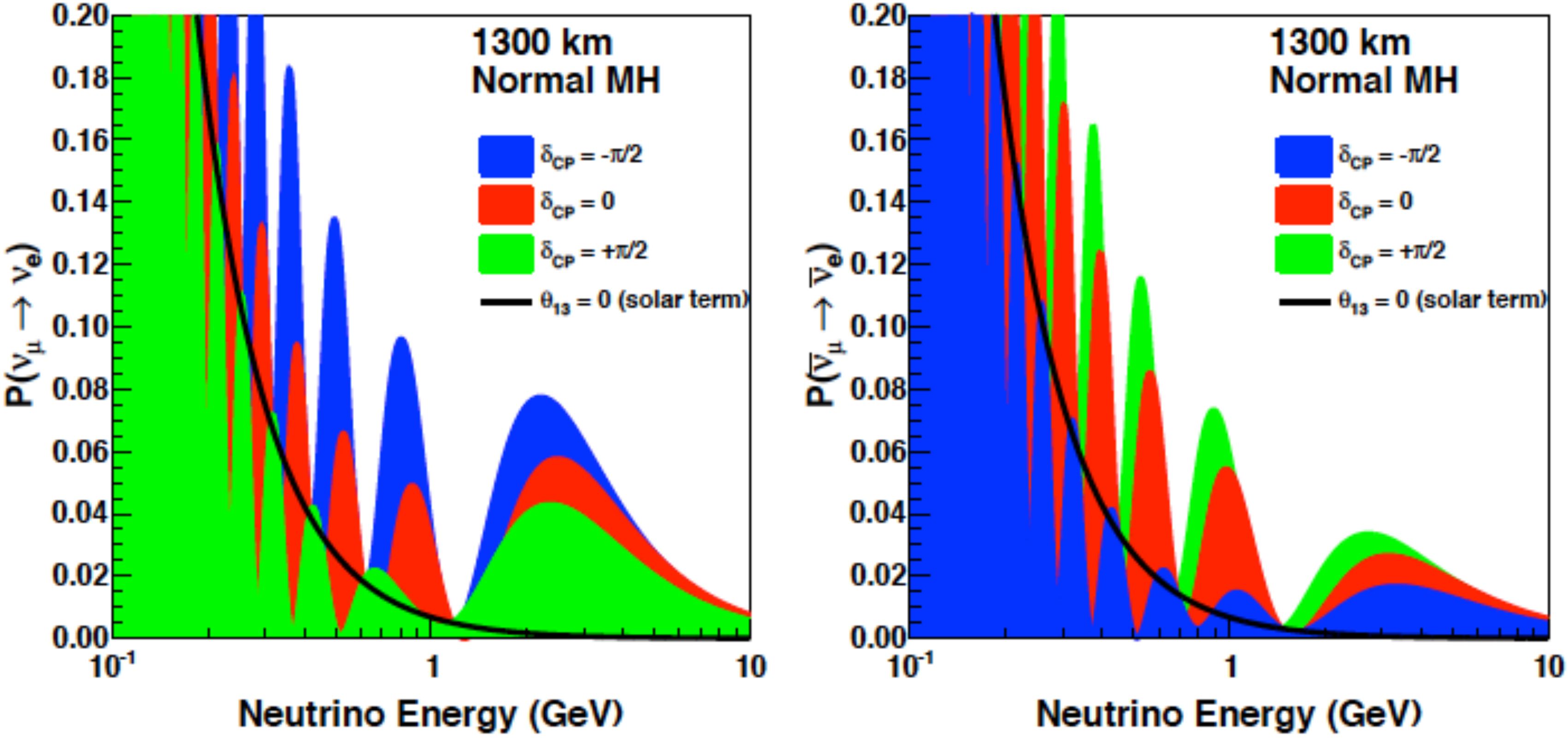
Fig. 2. $\mathcal{P}_{\mu e}$ in matter versus neutrino energy for the T2K experiment. The blue curves depict the normal hierarchy, red the inverse hierarchy. Solid curves depict positive θ_{13}, dashed curves negative θ_{13}

D.J. Ernst et al., arXiv:1303.4790 [nucl-th]

Energy has to be known better than 50 MeV

Shape sensitive to hierarchy and sign of mixing angle

Appearance Probability as function of neutrino energy



Need energy to distinguish between different δ_{CP}

Energy reconstruction

$$\nu_\mu + n \rightarrow \mu^- + p$$

$$E_\nu = E_\nu(E_\mu, \theta_\mu)$$

Kinematic:

  - Rely on underlying interaction to use relate outgoing lepton kinematics to neutrino energy
- Advantage:
  - don’t need hadron reconstruction
- Disadvantages
  - energy is wrong if underlying interaction is wrong (i.e. not CCQE)
  - Nuclear effects smear resolution

$$\nu_\mu + N \rightarrow \mu^- + X$$

$$E_\nu = E_\mu + E_X$$

Calorimetric

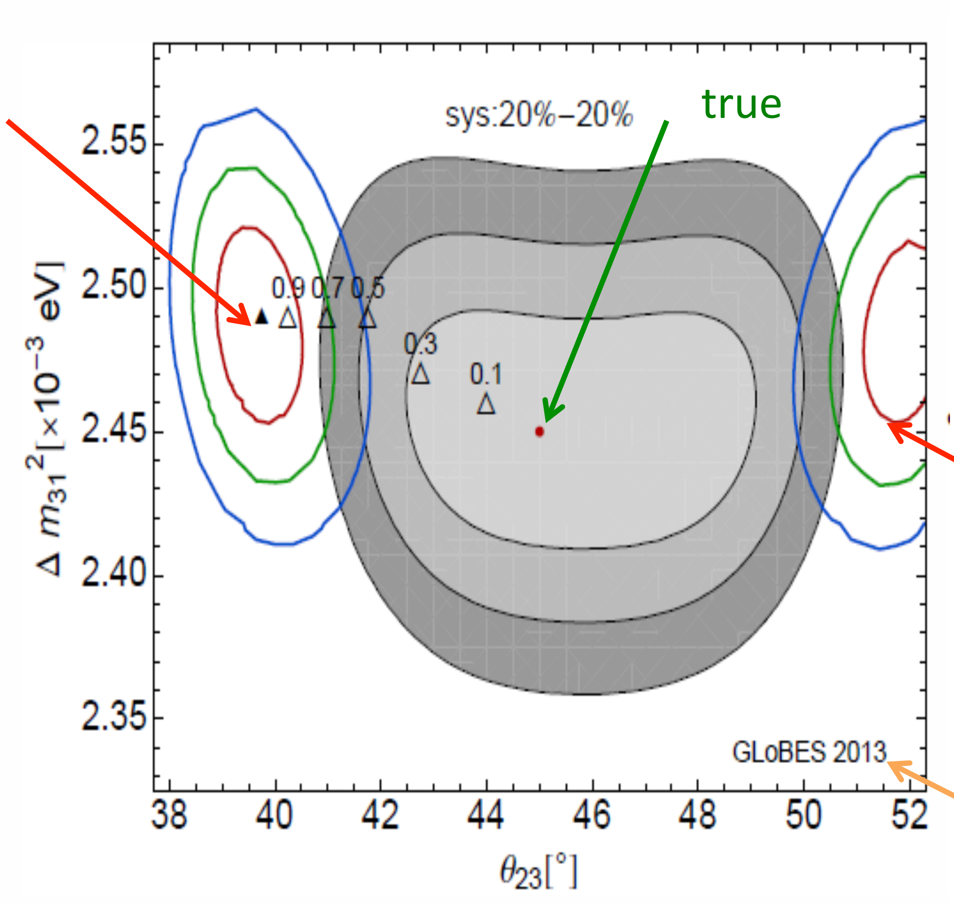
  - Add up the energy from the leptonic and hadronic components
- Advantages
  - No *a priori* assumption about underlying interaction
- Disadvantages
  - Relies on hadron reconstruction

How to quantify effects on oscillation

- Ideal, perfect near detector (^{12}C), 1 km, 1kton
- Far detector at 295 km, 22.5 kton, Carbon (SF)
- Use flux that peak at 0.6 GeV, 750kW, 5 years running
- Use a second flux that peaks at 1.5 GeV, 750kW, 5 years running
- Use Super Kamiokande (water cherenkov detector) reconstruction efficiency as function of energy
- Use migration matrices to take into account how neutrino energy reconstruction is affected by the what kind of interaction the neutrino undergo in the detector and how well we can identify them
- Muon neutrino disappearance only -> fit to atmospheric parameters

J.Phys.G, Nucl.Part.Phys. 44 (2017), 054001
Physics Report 700 (2017) 1

How to read the plots in the following slides



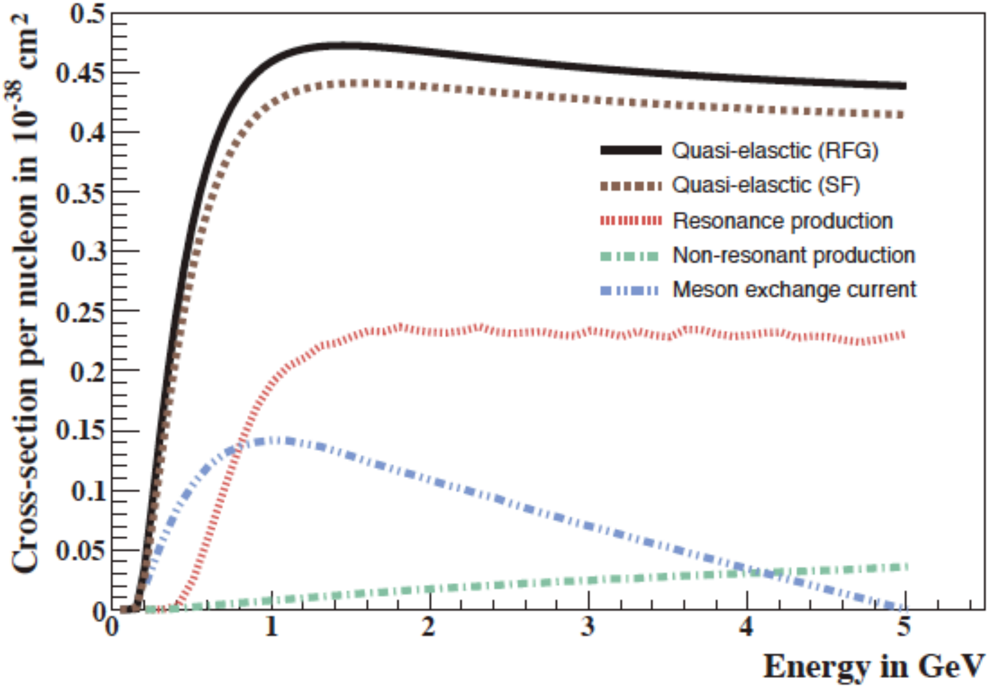
reconstructed from naive QE dynamics

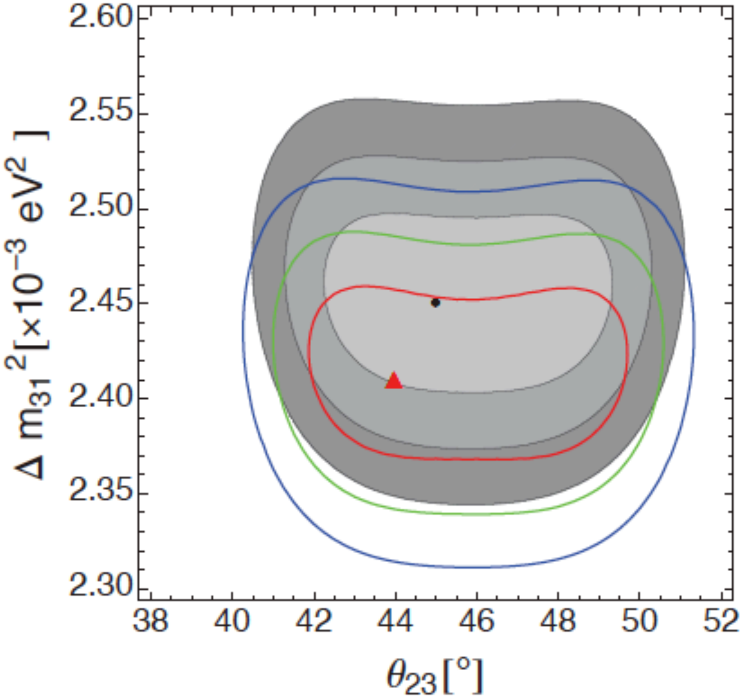
true

1, 2 and 3σ allowed regions

Simulation of long baseline neutrino oscillation

Dependence from nuclear model (1p1h)

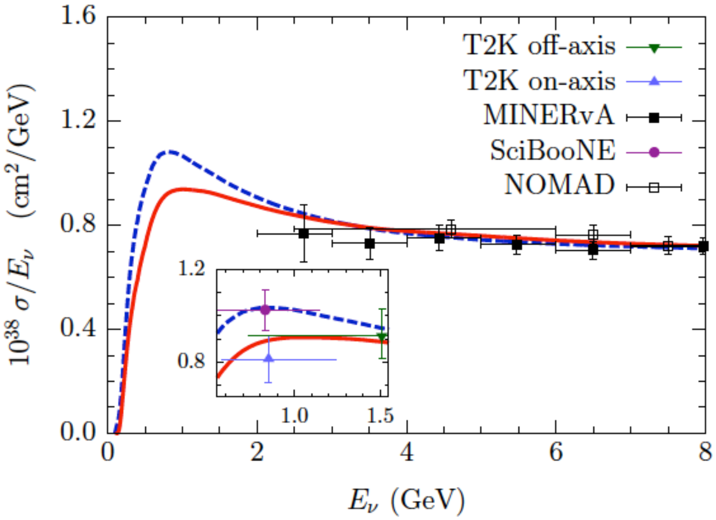


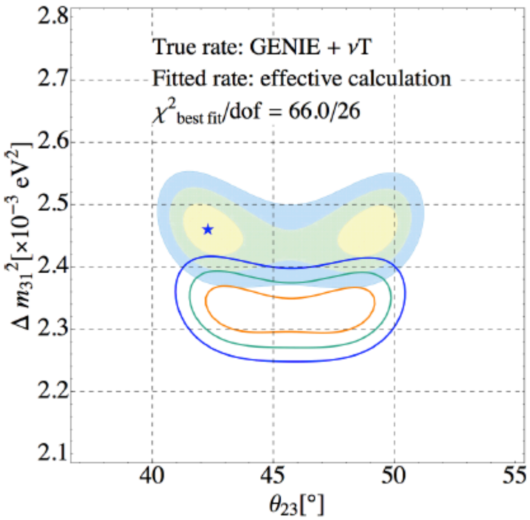


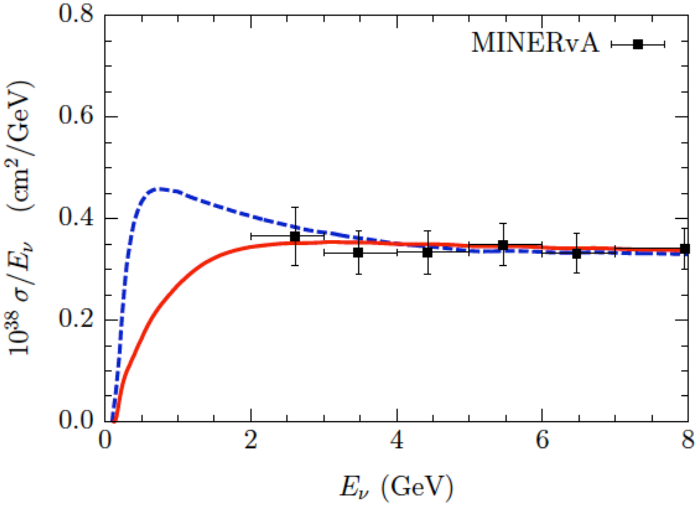
PRD D89, 093004 (2014) - arxiv:1402.6651

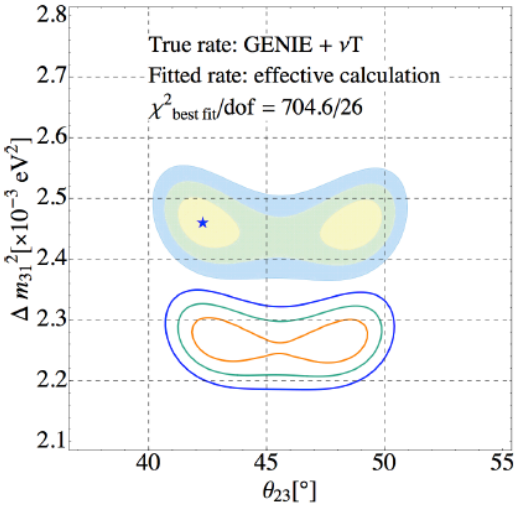
Dependence from nuclear model (2p2h)

PRD D93, 113004 (2016) - arxiv:1603.01072

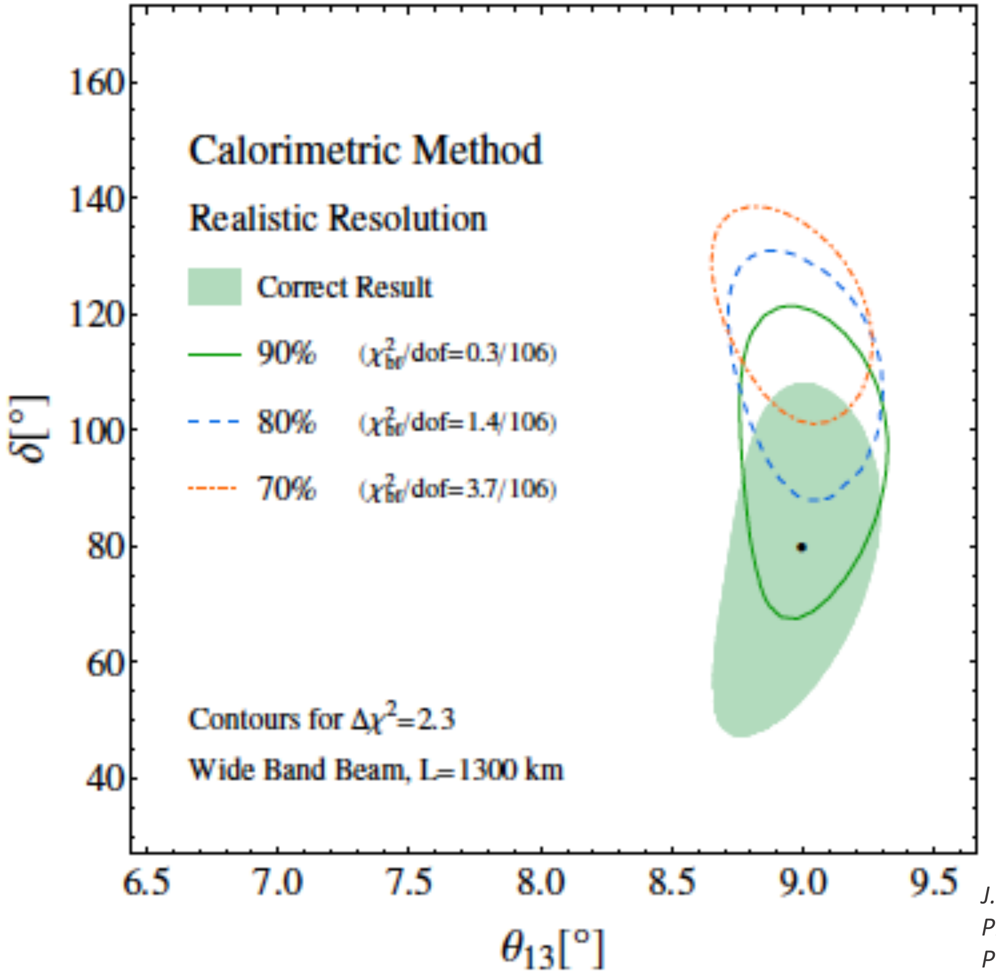








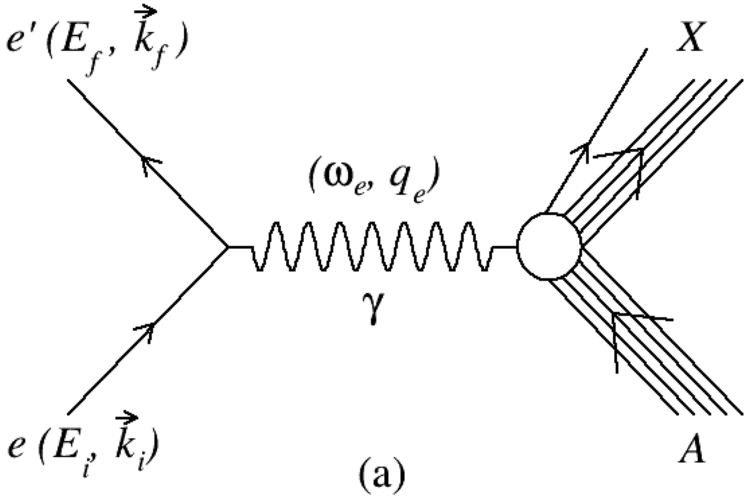
Effect of an underestimation of the missing energy in the calorimetric energy reconstruction on the coincidence regions in the θ_{13},δ plane.



J.Phys.G, Nucl.Part.Phys. 44 (2017), 054001
Physics Report 700 (2017) 1
PRD D92, 091301 (2015) - arxiv: 1507.08560

Electron vs neutrino scattering

QE e-A scattering



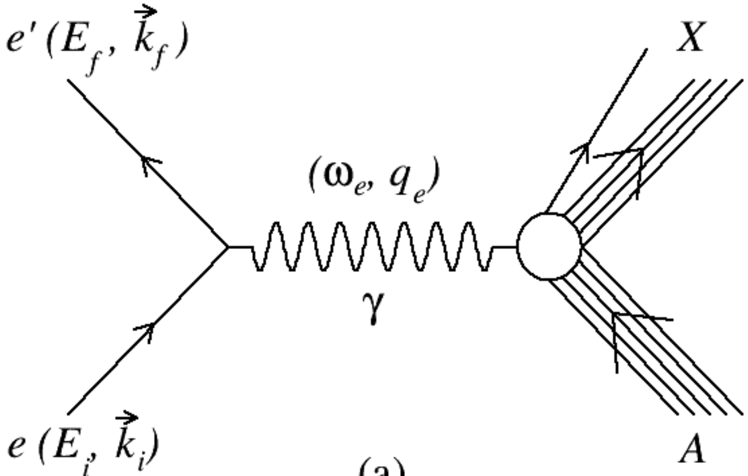
$$\left(\frac{d^2\sigma}{d\omega_e d\Omega}\right)_e = \frac{\alpha^2}{Q^4}\left(\frac{2}{2J_i+1}\right)\frac{1}{k_f E_i}$$
$$\times\ \zeta^2(Z', E_f, q_e)\left[\sum_{J=0}^{\infty}\sigma_{L,e}^J + \sum_{J=1}^{\infty}\sigma_{T,e}^J\right]$$

$$\sigma_{L,e} = v_e^L R_e^L$$

$$\sigma_{T,e} = v_e^T R_e^T$$

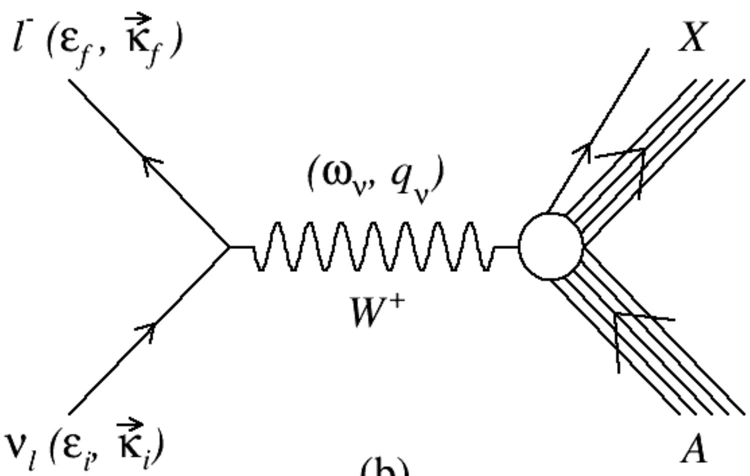
v's → Leptonic coefficients → Purely kinematical → Easy to calculate

QE e-A scattering



(a)

QE ν-A scattering



(b)

$$\left(\frac{d^2\sigma}{d\omega_e d\Omega}\right)_e = \frac{\alpha^2}{Q^4}\left(\frac{2}{2J_i+1}\right)\frac{1}{k_f E_i} \times \zeta^2(Z', E_f, q_e)\left[\sum_{J=0}^{\infty}\sigma^J_{L,e} + \sum_{J=1}^{\infty}\sigma^J_{T,e}\right]$$

$$\left(\frac{d^2\sigma}{d\omega_\nu d\Omega}\right)_\nu = \frac{G_F^2\cos^2\theta_c}{(4\pi)^2}\left(\frac{2}{2J_i+1}\right)\varepsilon_f\kappa_f \times \zeta^2(Z', \varepsilon_f, q_\nu)\left[\sum_{J=0}^{\infty}\sigma^J_{CL,\nu} + \sum_{J=1}^{\infty}\sigma^J_{T,\nu}\right]$$

$$\sigma_{L,e} = v_e^L R_e^L$$

$$\sigma_{T,e} = v_e^T R_e^T$$

$$\sigma^J_{CL,\nu} = \left[v_\nu^{\mathcal{M}} R_\nu^{\mathcal{M}} + v_\nu^{\mathcal{L}} R_\nu^{\mathcal{L}} + 2\, v_\nu^{\mathcal{ML}} R_\nu^{\mathcal{ML}}\right]$$

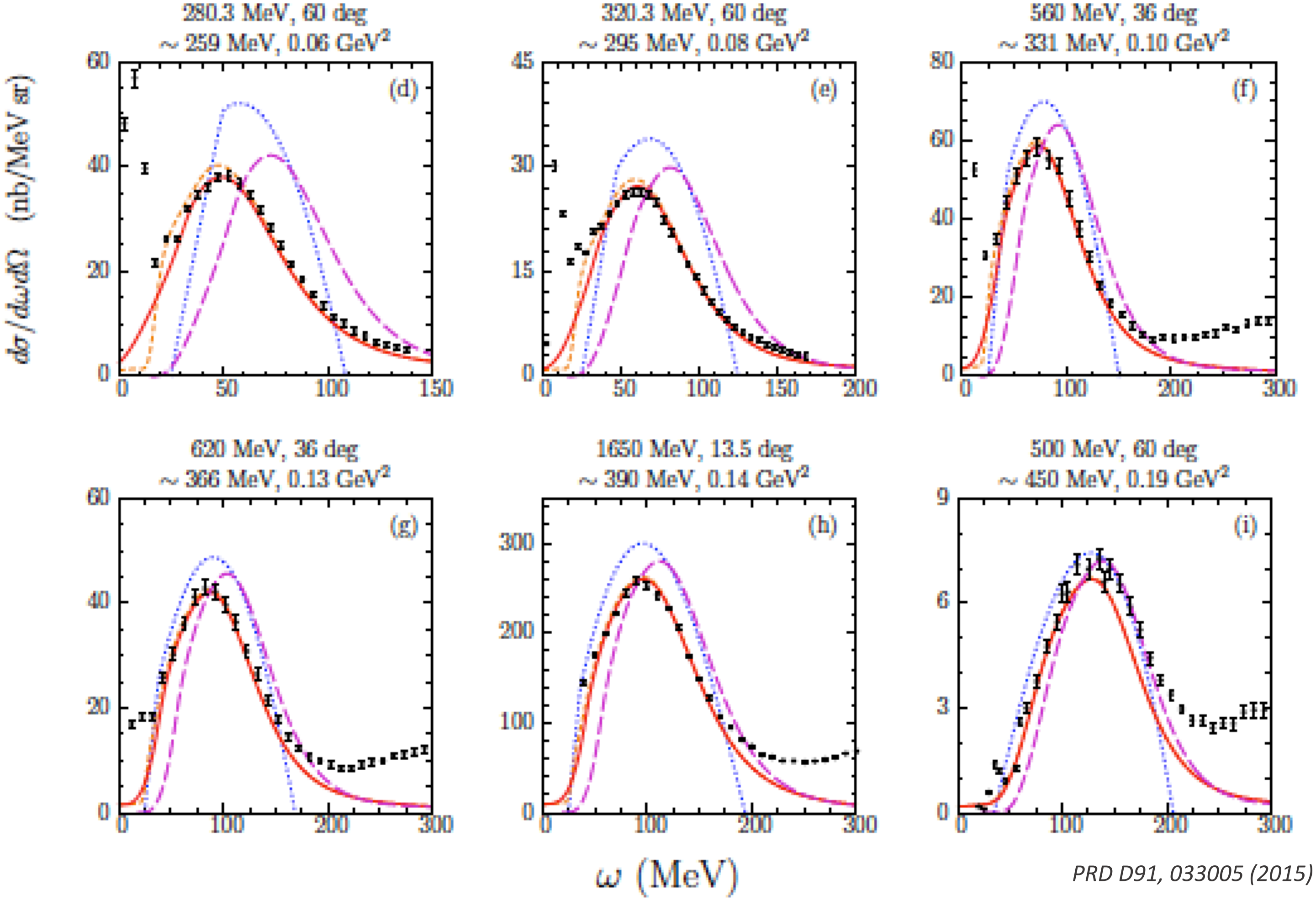
$$\sigma^J_{T,\nu} = \left[v_\nu^T R_\nu^T \pm 2\, v_\nu^{TT} R_\nu^{TT}\right]$$

v's → Leptonic coefficients → Purely kinematical → Easy to calculate

R's → Response functions → Nuclear dynamics → **Need nuclear models to calculate!**

Electron scattering data as a validation

$e + {}^{12}\mathrm{C} \rightarrow e' + X$ quasi elastic cross section computed within the IA including FSI. The predictions of the Relativistic Fermi Gas Model (RFGM) are also shown for comparison.



PRD D91, 033005 (2015) - arxiv:1404.5687

Jefferson Lab E12-14-012

- Primary Goal
- Extracting Spectral Function from data
- Experimental Setup:
  - Hall A
  - target system
- Inclusive Data analysis
  - C
  - Ti

E12-14-012 Experiment

- **Primary Goal:** Measurement of the **spectral functions** of **argon nucleus** through (e,e′p) reaction

- Nevertheless, a new high precision e-Ar data will provide vital information about argon nucleus and it's electroweak interaction to the community that can be used as a testbed for the development of theoretical models/frameworks. And will be a significant step ahead in improving the accuracy of the measurement of the neutrino-oscillation parameters, more importantly the CP violation phase in leptonic sector.

Extracting Spectral Function from Data

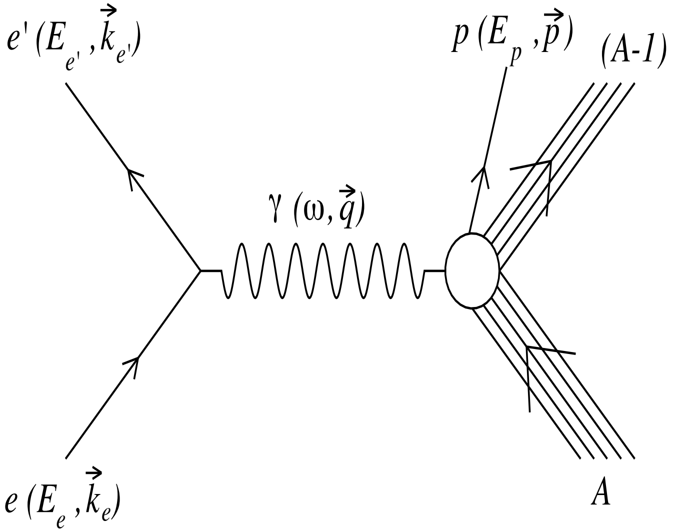
- We plan to study the **coincidence (e,e'p) processes** in the **kinematical region** in which single nucleon knock out of a nucleon occupying a shell model orbit is the dominant reaction mechanism.

Coincidence *(e,e'p)* process:

- Both the outgoing electron and the proton are detected in coincidence, and the recoiling nucleus can be left in any bound state.
- Within the Plane Wave Impulse Approximation (PWIA) scheme:

$$\frac{d\sigma_A}{dE_{e'}d\Omega_{e'}dE_p d\Omega_p} \propto \sigma_{ep} P(p_m, E_m)$$

- The initial energy and momentum of the knocked out nucleon can be identified with the measured missing momentum and energy, respectively as



$$\mathbf{p}_m = \mathbf{p} - \mathbf{q}$$

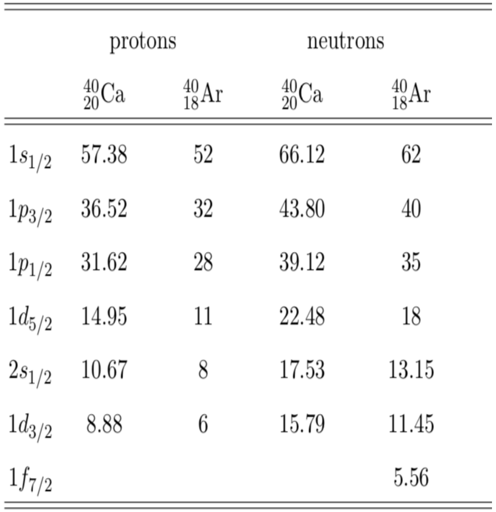
$$E_m = \omega - T_p - T_{A-1} \sim \omega - T_p$$

Where $T_p = E_p - m$, is the kinetic energy of the outgoing proton.

Extracting Spectral Function from Data

Kinematic region:

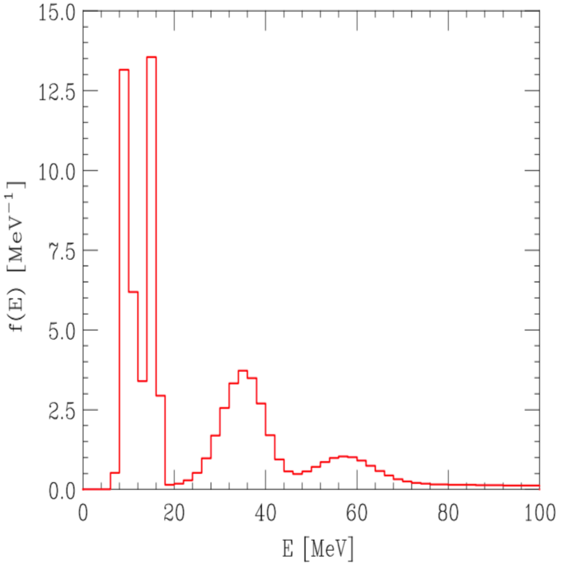
- Separation energies of the proton and neutron shell model states for Ca (measured) and Ar ground states (predicted)



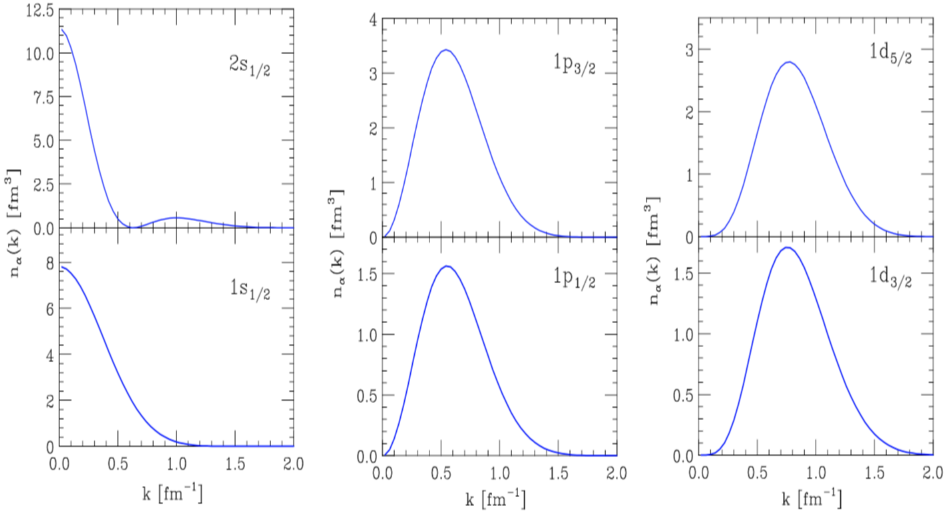
	protons		neutrons	
	$^{40}_{20}$Ca	$^{40}_{18}$Ar	$^{40}_{20}$Ca	$^{40}_{18}$Ar
$1s_{1/2}$	57.38	52	66.12	62
$1p_{3/2}$	36.52	32	43.80	40
$1p_{1/2}$	31.62	28	39.12	35
$1d_{5/2}$	14.95	11	22.48	18
$2s_{1/2}$	10.67	8	17.53	13.15
$1d_{3/2}$	8.88	6	15.79	11.45
$1f_{7/2}$				5.56

- The energy distribution

$$f(E) = 4\pi \int dk\, k^2 P(k, E)$$

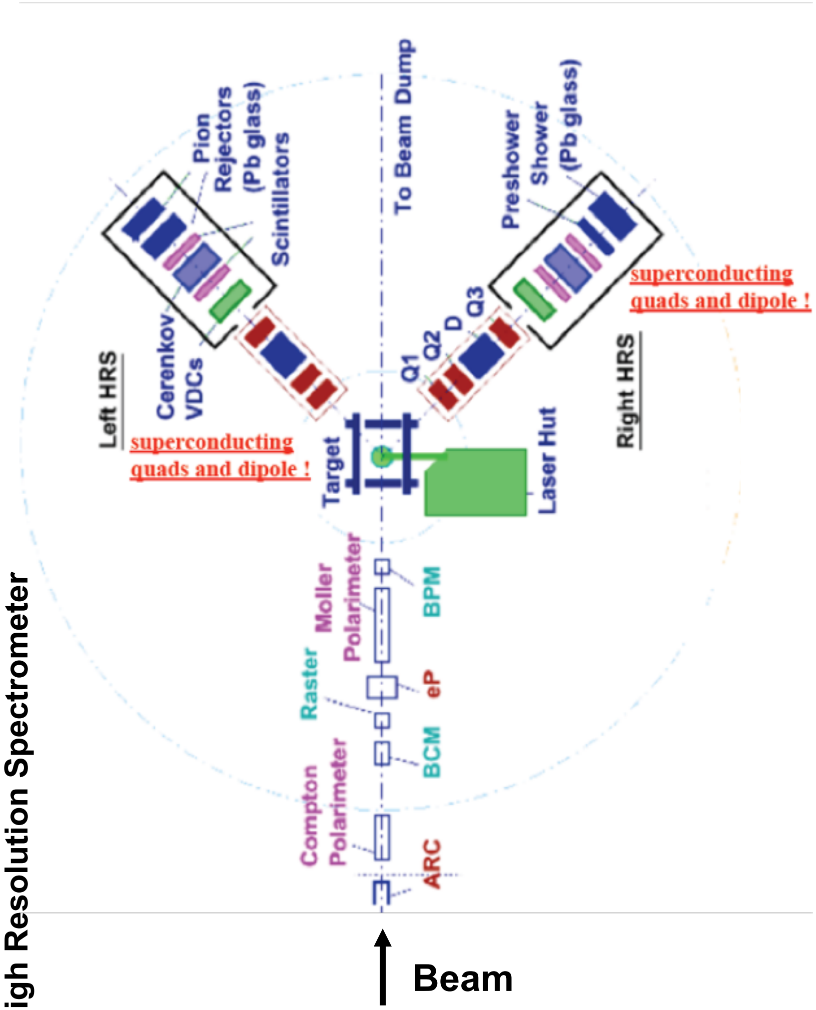


- The momentum distribution (need to have good energy resolution)



➢ Kinematic region for argon
6 MeV $\lesssim E_m \lesssim 60$ MeV
$\mathbf{p}_m \lesssim 350$ MeV

HALL A Schematics



HRS: High Resolution Spectrometer

High Resolution Spectrometer

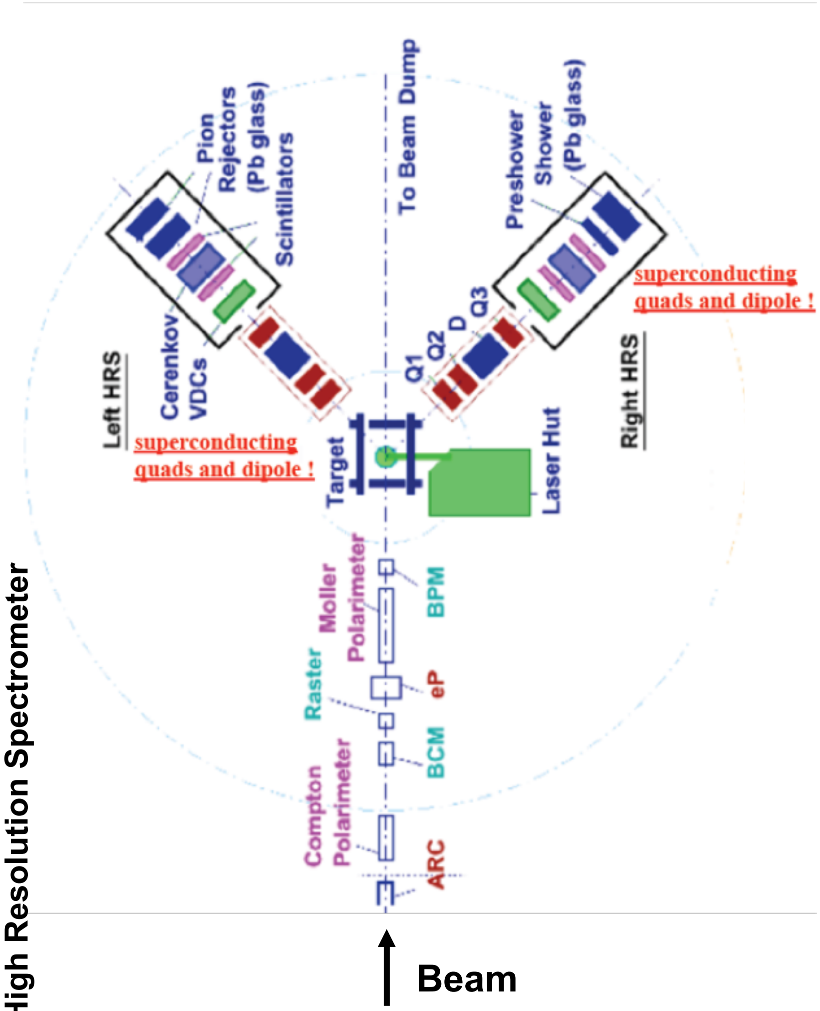
Superconducting magnets:

- large acceptance in both angle and momentum
- excellent resolution in position and angle

Detector Package:

- Vertical Drift Chambers:
  - high resolution tracks reconstruction (position and direction)
- Scintillators:
  - trigger to activate the data-acquisition electronics
  - precise timing information for time-of-flight measurements and coincidence determination
- Cherenkov:
  - The particle identification, obtained from a variety of Cherenkov type detectors (aerogel and gas) and lead-glass shower counters

HALL A Schematics



HRS: High Resolution Spectrometer

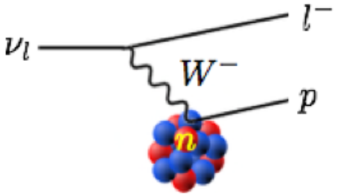
High Resolution Spectrometer

Beam Energy Resolution	5 x 10^{-4}
Momentum Range	0.3 – 4.0 GeV/c
Momentum Acceptance	$-4.5\% < \delta p/p < 4.5\%$
Momentum Resolution	2 x 10^{-4}
Angular Range	
Left Arm (electron)	12.5°-130°
Right Arm (proton)	12.5°-120°
Angular Acceptance	
Left Arm (electron)	± 30 mrad
Right Arm (proton)	±60 mrad
Angular Resolution	
Left Arm (electron)	0.5 mrad
Right Arm (proton)	1.0 mrad

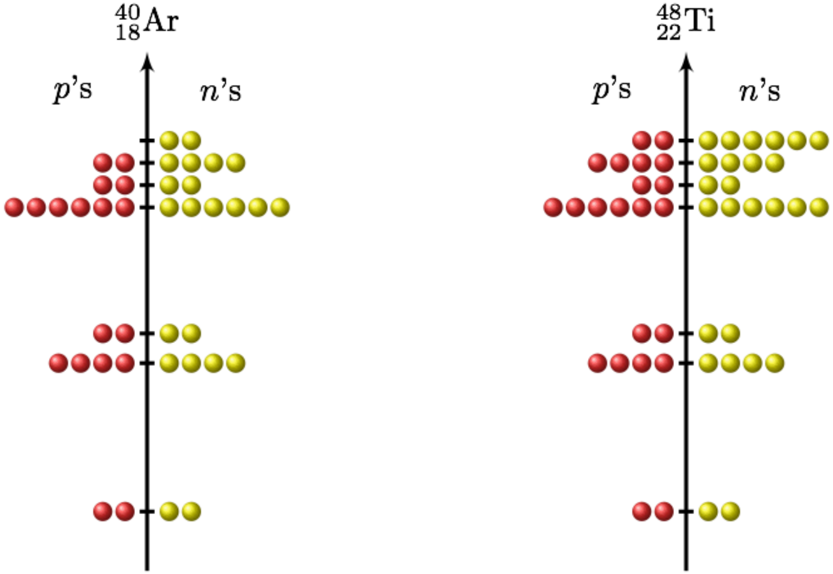
Why Ti ?

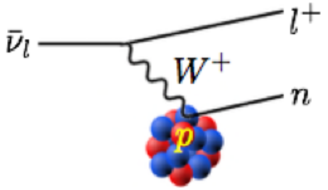
- The reconstruction of neutrino and antineutrino energy in liquid argon detectors will require the understanding of the spectral functions describing both neutrons and protons.

- Exploiting the correspondence of the level structures, the neutron spectral function of argon can be obtained from the proton spectral function of titanium.



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





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

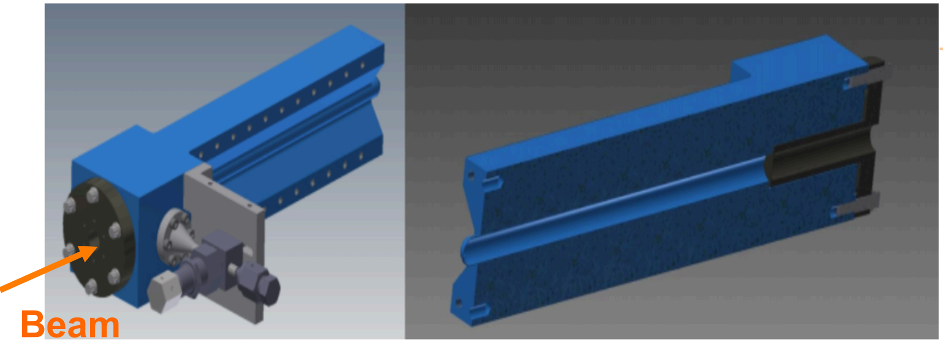
Target Setup

Dummy target: same as the entry and exit window as the gas target

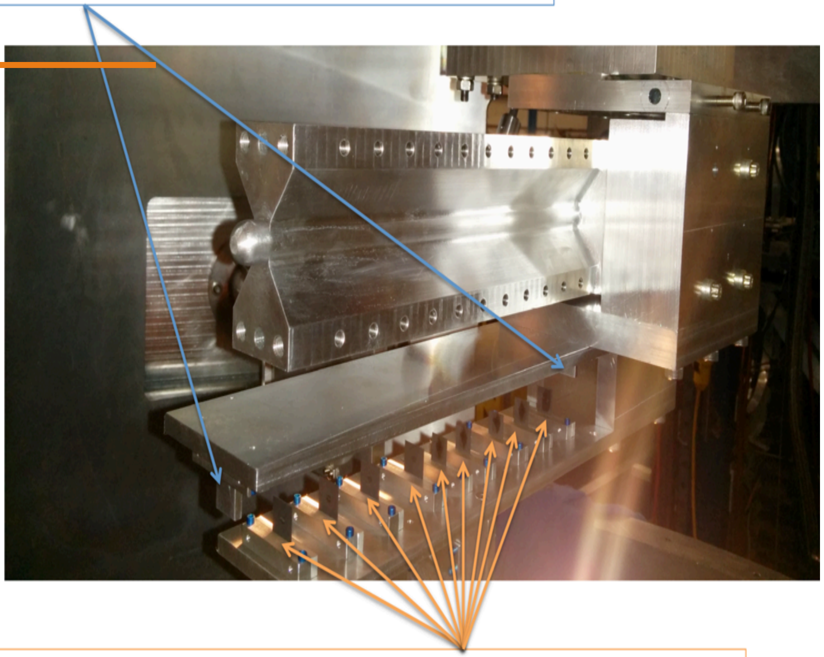
Optical target: a series of foils of carbon (9) to check the alignment of target and spectrometers (optics)

Argon Target

- Gas Cell
- Length = 25 cm
- Pressure = 500 PSI
- Temperature = 300 K
- Target thickness = 1.381 g cm^{-2}
- Luminosity = 4.33×10^{37} atoms cm^{-2} sec^{-1}
- Density @10μA beam current = 87%

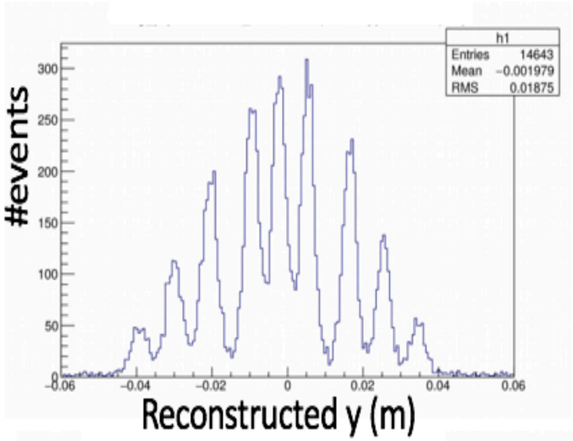


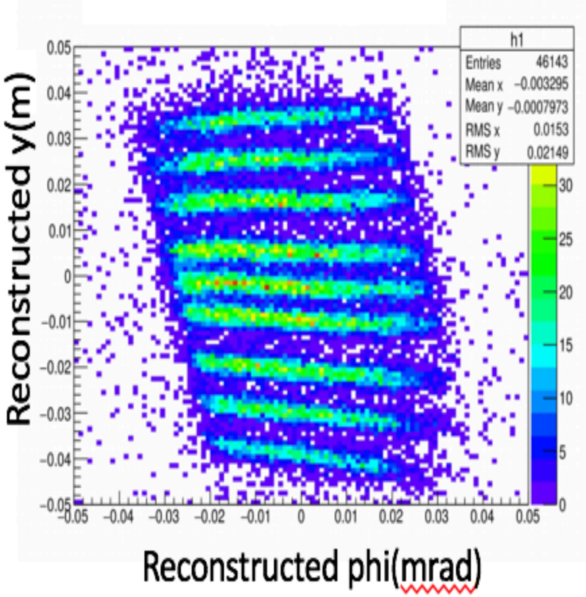
Dummy target: same as the entry and exit window as the gas target



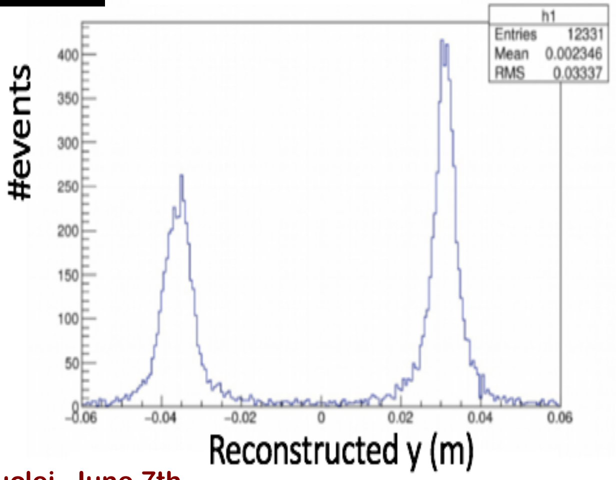
Optical target: a series of foils of carbon (9) to check the alignment of target and spectrometers (optics)

LEFT

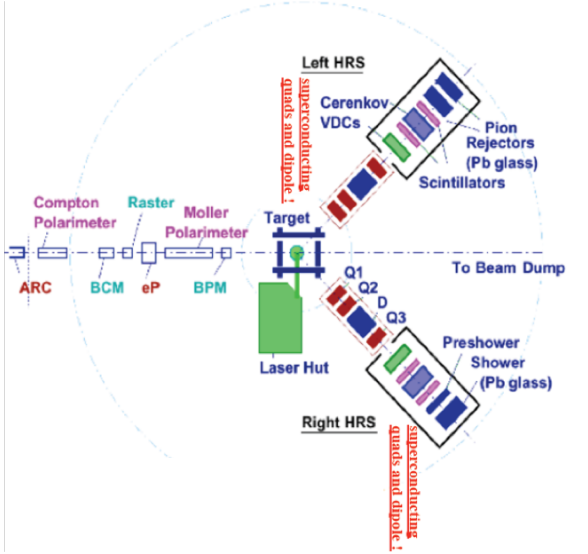




Dummy:



	E_e	$E_{e'}$	θ_e	P_p	θ_p	$\|\mathbf{q}\|$	p_m
	MeV	MeV	deg	MeV/c	deg	MeV/c	MeV/c
kin1	2222	1799	21.5	915	−50.0	857.5	57.7
kin3	2222	1799	17.5	915	−47.0	740.9	174.1
kin4	2222	1799	15.5	915	−44.5	658.5	229.7
kin5	2222	1716	15.5	1030	−39.0	730.3	299.7
kin2	2222	1716	20.0	1030	−44.0	846.1	183.9
kin5	2222		15.5				



kin1

Collected Data	Hours	Events(k)
Ar	29.6	43955
Ti	12.5	12755
Dummy	0.75	955

kin3

Collected Data	Hours	Events(k)
Ar	13.5	73176
Ti	8.6	28423
Dummy	0.6	2948

kin2

Collected Data	Hours	Events(k)
Ar	32.1	62981
Ti	18.7	21486
Dummy	4.3	5075
Optics	1.15	1245
C	2.0	2318

kin4

Collected Data	Hours	Events(k)
Ar	30.9	158682
Ti	23.8	113130
Dummy	7.1	38591
Optics	0.9	4883
C	3.6	21922

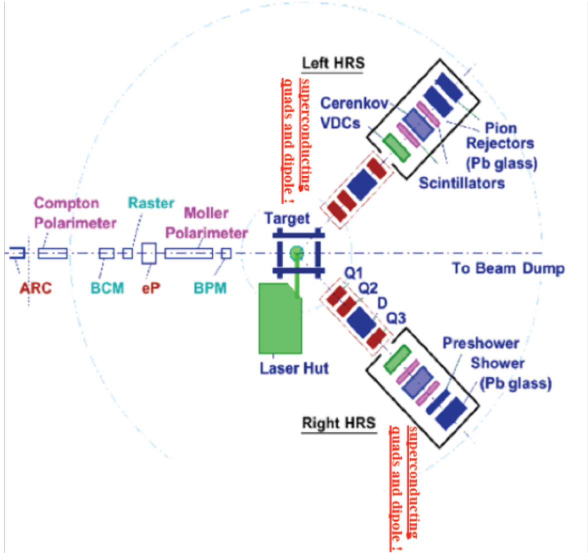
kin5

Collected Data	Hours	Events(k)
Ar	12.6	45338
Ti	1.5	61
Dummy	5.9	16286
Optics	2.9	160

kin5 - Inclusive

Collected Data	Minutes	Events(k)
Ar	57	2928
Ti	50	2993
Dummy	56	3235
C	115	3957

	E_e	$E_{e'}$	θ_e	P_p	θ_p	$\lvert\mathbf{q}\rvert$	p_m
	MeV	MeV	deg	MeV/c	deg	MeV/c	MeV/c
kin1	2222	1799	21.5	915	-50.0	857.5	57.7
kin3	2222	1799	17.5	915	-47.0	740.9	174.1
kin4	2222	1799	15.5	915	-44.5	658.5	229.7
kin5	2222	1716	15.5	1030	-39.0	730.3	299.7
kin2	2222	1716	20.0	1030	-44.0	846.1	183.9
kin5	2222		15.5				



kin1

Collected Data	Hours	Events(k)
Ar	29.6	43955
Ti	12.5	12755
Dummy	0.75	955

kin3

Collected Data	Hours	Events(k)
Ar	13.5	73176
Ti	8.6	28423
Dummy	0.6	2948

kin2

Collected Data	Hours	Events(k)
Ar	32.1	62981
Ti	18.7	21486
Dummy	4.3	5075
Optics	1.15	1245
C	2.0	2318

kin4

Collected Data	Hours	Events(k)
Ar	30.9	158682
Ti	23.8	113130
Dummy	7.1	38591
Optics	0.9	4883
C	3.6	21922

kin5

Collected Data	Hours	Events(k)
Ar	12.6	45338
Ti	1.5	61
Dummy	5.9	16286
Optics	2.9	160

kin5 - Inclusive

Collected Data	Minutes	Events(k)
Ar	57	2928
Ti	50	2993
Dummy	56	3235
C	115	3957

Carbon Analysis

Analysis is mainly performed by graduate students - Hongxia Dai (VTech), Matt Murphy (VTech), and Daniel Abrams (UVA).

VDC efficiency

- Non-zero track ratio: R1
  - Cut1: Trigger, PID cut
  - $R1 = \frac{N_{track>0}}{N_{sample1}}$
- One track ratio: R2
  - Cut2: Trigger, PID cut, acceptance cut
  - $R2 = \frac{N_{track==1 \&\& \text{ y within } 5\sigma}}{N_{sample2}}$
- Efficiency=R1*R2 ~ 95 %

Calorimeter cut efficiency

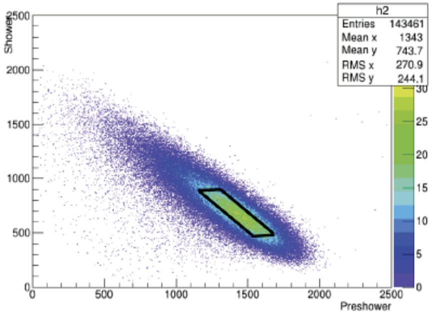
- Set cut as E/p0 > 0.3
- Select Sample events
  - T3 (S0&&S2)&&(GC||PR)
  - Single track
  - Acceptance cuts
  - Cerenkov cut
- $\epsilon = \frac{\#events\ with\ E/p0>0.3}{\#sample\ events}$
- Efficiency ~ 99.9 %

Trigger Efficiency

- Production trigger: T3: (S0&&S2) && (GC||PR) [LEFT]
- Efficiency trigger: T5: (S0||S2) && (GC||PR) [LEFT]
- Selected Sample
  - T5
  - Single track cut
  - Acceptance Cuts
  - PID Cuts
- $Eff = \frac{\#events\ with\ signal\ on\ both\ S0\ and\ S2}{\#sample\ events}$ ~ 99.9 %

Cerenkov cut efficiency

- Negligible pion contamination, cer cut at 400
- Select Sample events
  - T3 (S0&&S2)&&(GC||PR)
  - Single track
  - Acceptance cuts
  - Calorimeter cut
- $\epsilon = \frac{\#events\ with\ cer>400}{\#sample\ events}$ ~ 99.9%



Carbon Analysis

Analysis is mainly performed by graduate students - Hongxia Dai (VTech),
Matt Murphy (VTech),
Linjie Gu (Vtech),
and Daniel Abrams (UVA).

Determining the inclusive cross section

For ith bin:

$$\boxed{{\sigma^i}_{data} = {\sigma^i}_{model} \frac{{Y^i}_{data}(E',\theta)}{{Y^i}_{MC}(E',\theta)}}$$

Where,

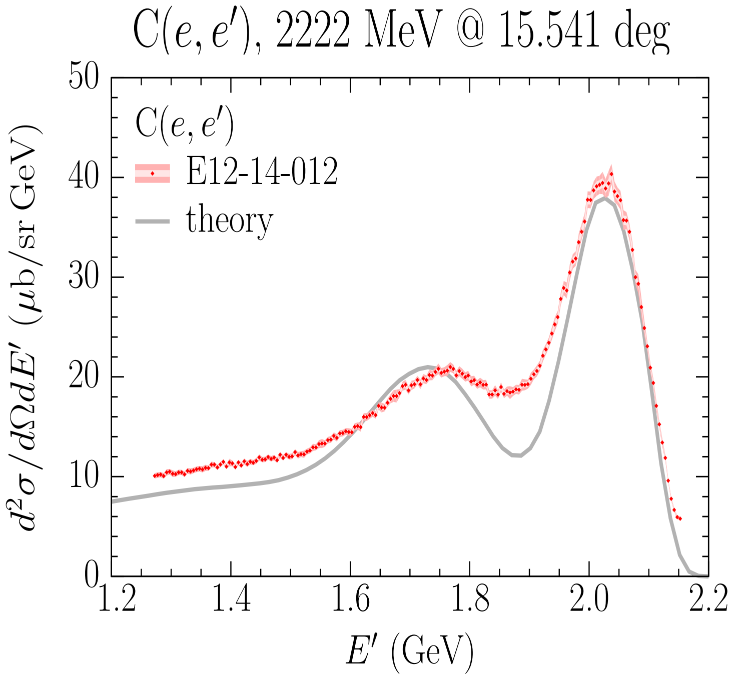
$${Y^i}_{data} = \frac{N_s^i * prescale}{N_e * (live\ time) * \epsilon_{eff}}$$

N_s^i : Number of scattered electrons
N_e : Total number of electrons in the beam
ϵ_{eff} : Total efficiency

Carbon (e,e’) inclusive cross-section

- The carbon data allowed us to study systematics and to compare our measurements with the previous experiments.

  - Error bars up to ~ 2.5%, corresponding to the statistical (1.2%) and systematic (2.2%) uncertainties summed in quadrature.
  - **Theoretical** calculations *[Benhar et al.] are* based on the factorization ansatz dictated by the impulse approximation (IA) and the spectral function formalism. The approach does not involve any adjustable parameters, and allows for a consistent inclusion of single-nucleon interactions—both elastic and inelastic—and meson-exchange current (MEC) contributions.

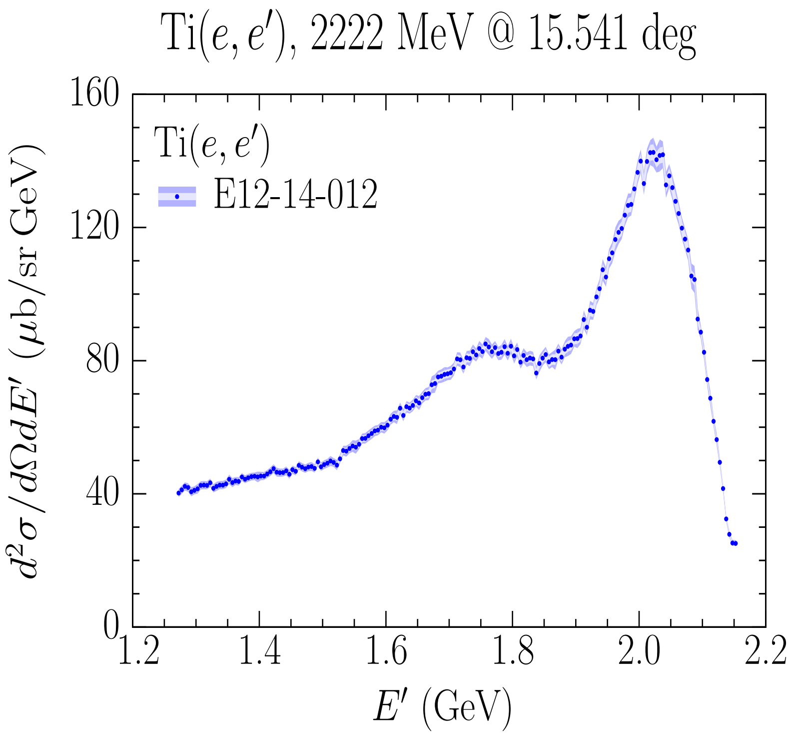


Dai, H. et al., arxiv 1803.01910.

Titanium (e,e’) inclusive cross-section

- The first electron-scattering data ever collected on titanium target.

- Error bars up to ~ 2.75%, corresponding to the statistical (1.65%) and systematic (2.2%) uncertainties summed in quadrature.



Dai, H. et al., arxiv 1803.01910.

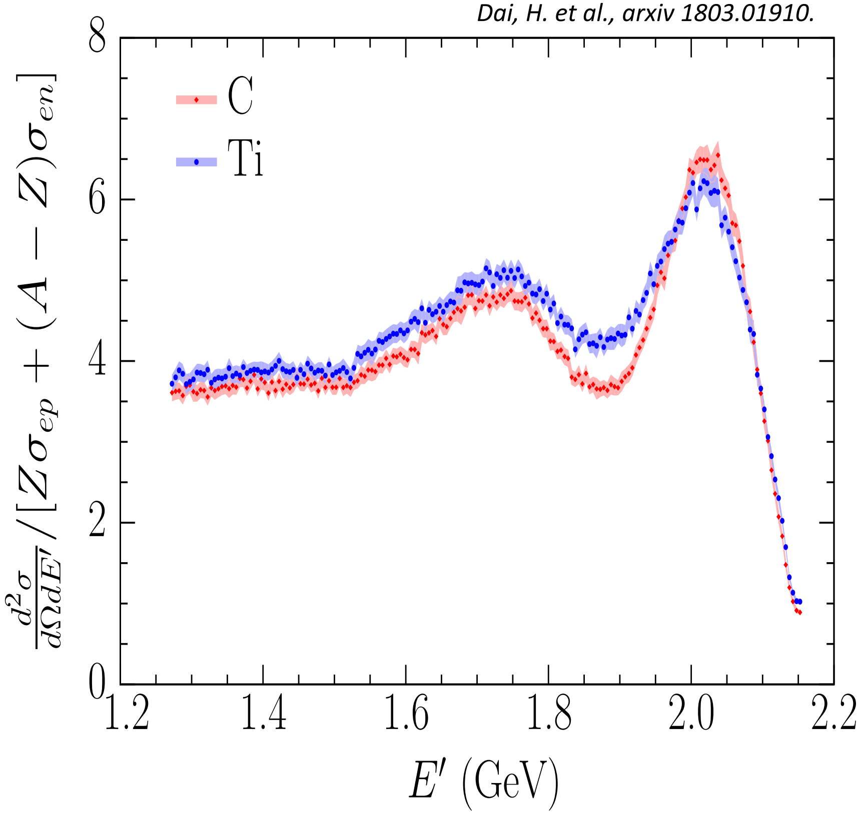
Comparing Ti (e,e’) and C(e,e’) cross-section

$$\frac{d^2\sigma}{d\Omega dE'}/[Z\sigma_{ep} + (A - Z)\sigma_{en}]$$

- The quantities σ_{ep} and σ_{en} are the elementary electron-proton and electron-neutron cross sections in the QE channel stripped of the energy-conserving delta function.

- The difference between the results obtained using the measured carbon and titanium cross sections reflect different nuclear effects.

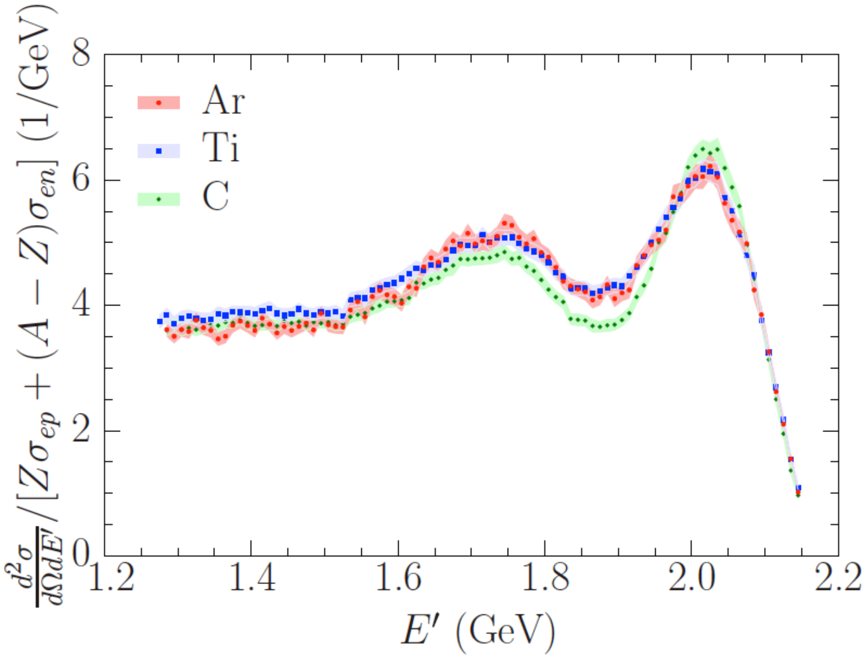
Dai, H. et al., arxiv 1803.01910.



Argon (e,e’) inclusive cross-section

- The second electron-scattering data ever collected on argon target but previous data set affected by normalization problem.

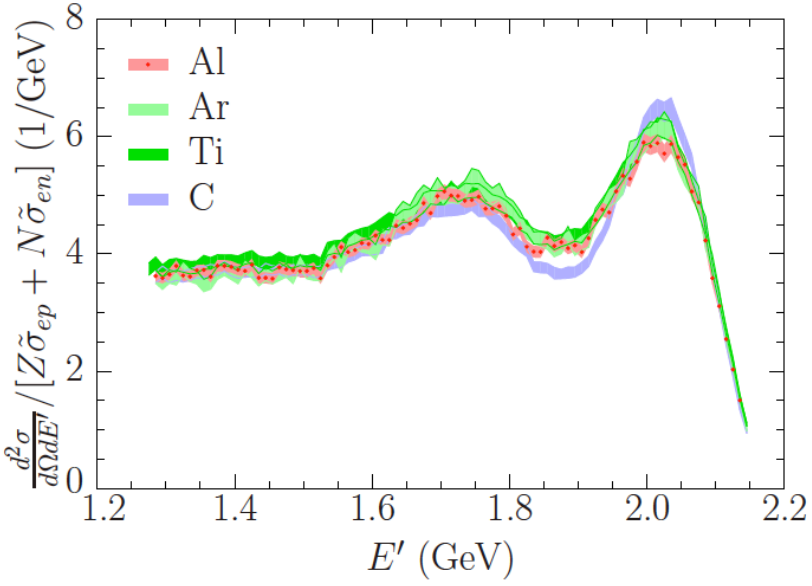
- Error bars up for Ar to ~ 4%, corresponding to the statistical (1.7%) and systematic (2.9%) uncertainties summed in quadrature.



Dai, H. et al., PRC99,054608, 2019.

Al (e,e’) inclusive cross-section

- Error bars for the Al measurement up to ~ 3%, corresponding to the statistical (1.3%) and systematic (2.7%) uncertainties summed in quadrature.



Murphy, M. et al., in preparation.

Conclusions

- Energy reconstruction essential for precision determination of neutrino oscillation parameters and neutrino-hadron cross sections

- Impact on neutrino oscillation experiments due to nuclear models, what they are and how they are implemented is not negligible (order 10%)

- JLab Ar-Ti (e,e'p) experiment (E12-14-012) took data successfully in 2017.

- The first results, consisting of the Ar(e,e'), Ti(e,e'), Al(e,e') and C(e,e') cross sections at beam energy E = 2.222 GeV and scattering angle θ =15.541 deg with uncertainties < 2.75%, are presented and has been submitted to PRL.

- Our measurement, providing the first experimental information ever on electron-titanium scattering, will be of great value for the development of realistic models of the electroweak response of neutron-rich nuclei.

- Exclusive analysis is ongoing and results are expected by end of 2019