FACULTY OF SCIENCES

DEPARTMENT OF PHYSICS AND ASTRONOMY

THEORETICAL PERSPECTIVES IN ELECTRON(4NU)-NUCLEUS SCATTERING

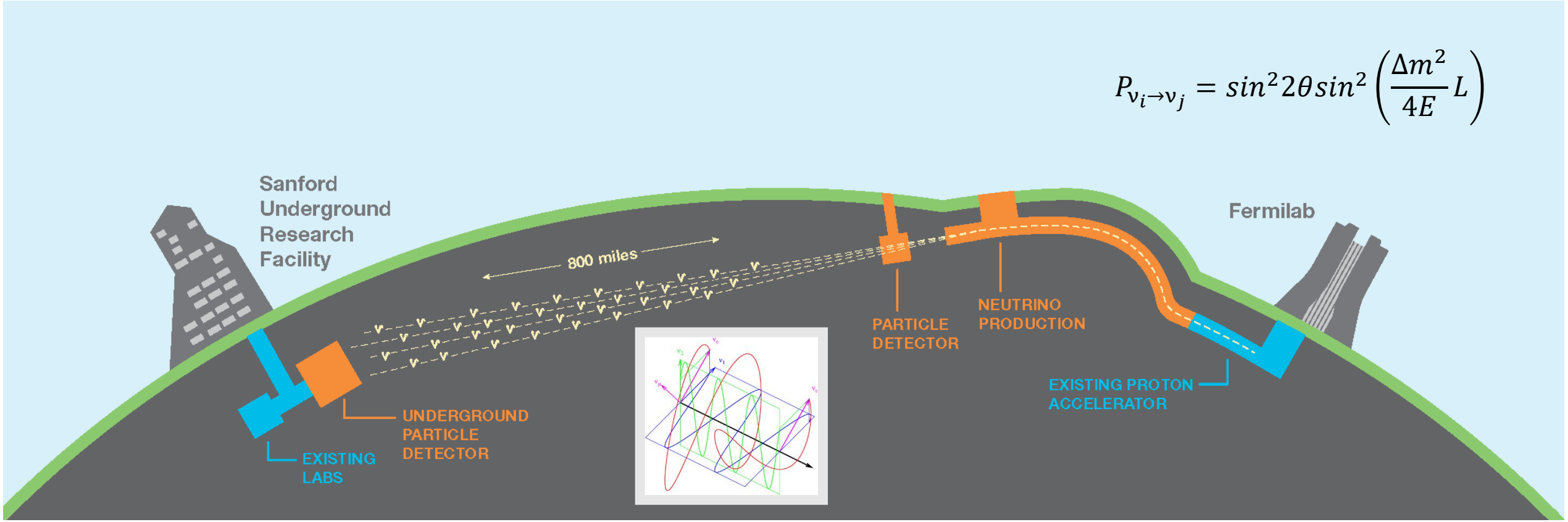
Natalie Jachowicz

GHENT UNIVERSITY

Motivation : Accelerator-based Neutrino-oscillation experiments

- ν_μ are produced, part of them is detected in the near detector
- Neutrinos propagate from near to far detector, neutrino oscillations occur underway
- Neutrinos are detected in the far detector
- Count different neutrino flavors at near and far detector
- Extract information about mass differences and mixing angles, parity violating phase .... from different observations between near and far detector

$$P_{\nu_i \to \nu_j} = sin^2 2\theta sin^2\left(\frac{\Delta m^2}{4E} L\right)$$



Oscillation analysis in a near/far detector experiment :

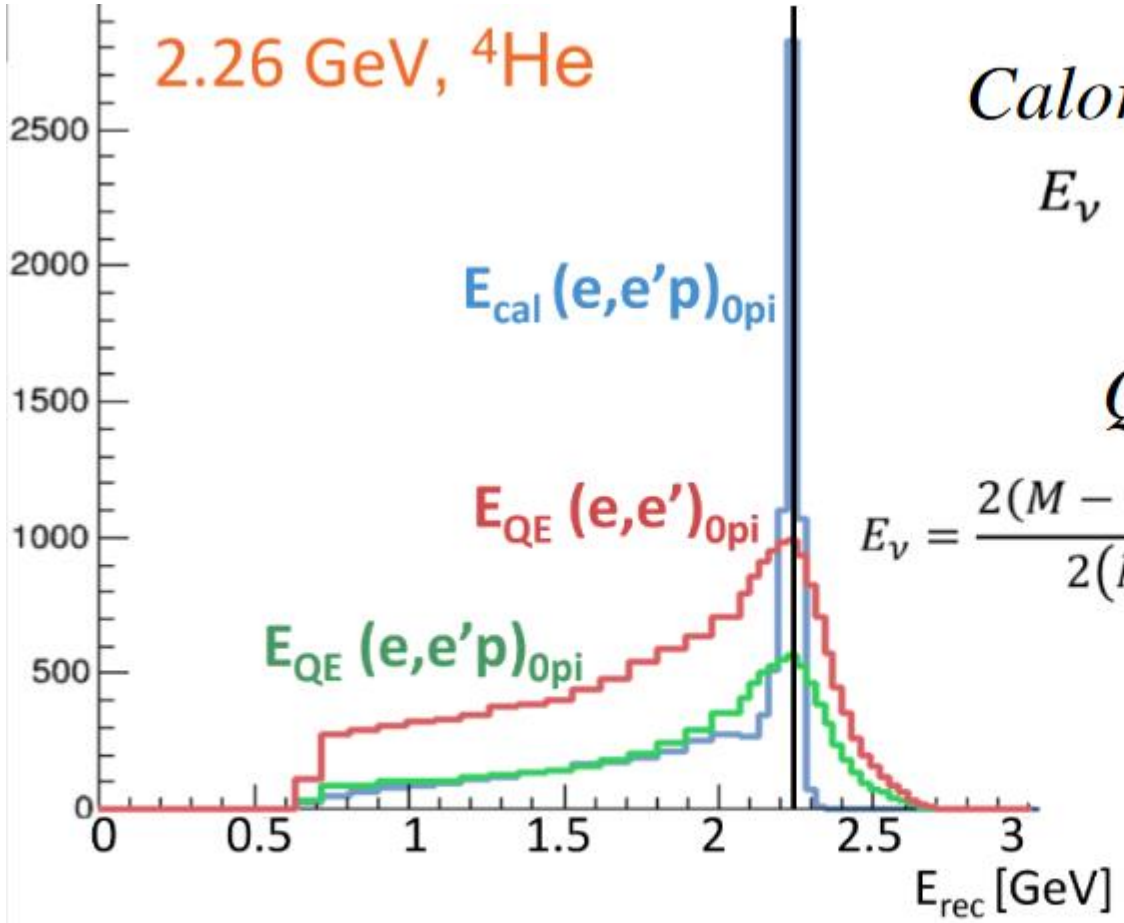
$$P_{\nu_i \to \nu_j} = sin^2 2\theta sin^2 \left(\frac{\Delta m^2}{4E} L \right)$$

$$\frac{N_{far}(\overline{E}_\nu)}{N_{near}(\overline{E}_\nu)} = \frac{\int \Phi(E_\nu)\sigma(E_\nu)P(\overline{E}_\nu|E_\nu)P_{i\to j}(E_\nu)dE_\nu}{\int \Phi(E_\nu)\sigma(E_\nu)P(\overline{E}_\nu|E_\nu)dE_\nu}$$

Reconstructed energy

$$\overline{E}_\nu = \frac{2M'_n E_l - ({M'_n}^2 + m_l^2 - M_p^2)}{2(M'_n - E_l + P_l \cos\theta)}$$

Issues with this reconstruction method ...



Calorimetric Approach

$$E_\nu = E_l + E_p^{kin} + E_b$$

QE Approach

$$E_\nu = \frac{2(M-\varepsilon_n)E_1 + M^2 - (M-\varepsilon)^2 - m_l^2}{2\left(M - \varepsilon - E_1 + |k_1|cos(\theta)\right)}$$

Afroditi papadopoulo talk e4v NuInt 2018

- *E_{QE} has worse peak resolution than E_{cal}*
  - *Long tail for both E_{QE} and E_{cal}*

Theoretical Status

- Driven by the experimental program, the theoretical understanding of neutrino-nucleus interactions has made a lot of progress in recent years
- Detailed microscopic cross sections calculations for (inclusive) neutrino-induced interactions
- Formalism valid over a broad energy range
- The basic interaction mechanisms are well established, still there are important caveats in our knowledge
- *Progress is impeded by the lack of exclusive data (and models) and monochromatic neutrino beams*
- Models that reproduce inclusive scattering data may show widely varying results in semi-inclusive processes
- Full propagation and simulation of FSI is numerically infeasible in a microscopic model. More efforts to implement microscopic models in generators used in analysis are needed

- **Quasi elastic scattering** is used for energy reconstruction analyses
- Identification of QE processes is essential, but hampered by the lack of monochromatic neutrino beams
- Misidentification of e.g. pion production – followed by absorption events as QE, multinucleon mechanism where the outgoing nucleon(s) go unobserved
- A detailed theoretical modeling of various reaction mechanisms over a broad energy range is crucial to guide analyses
- And moreover : **Neutrino-nucleus scattering provides a unique opportunity to study the weak interaction and the axial structure of the nucleus**

The primary weak vertex has to be modeled, as well as initial and final state interactions of the reaction products

Confronting theory and experiment

- Oscillation experiments are reaching the point where the future generation experiments with enormous active masses will quickly accumulate an unprecedented number of neutrino interaction events, and instead of statistics, systematic uncertainties will be limiting the physics reach of the experiments and the CP violation measurement
- Exclusive processes become more important, but models that reproduce inclusive scattering data may show widely varying results in semi-inclusive processes
- Heavier targets are used, but so far most models focus on ^{12}C

Intermediate summary

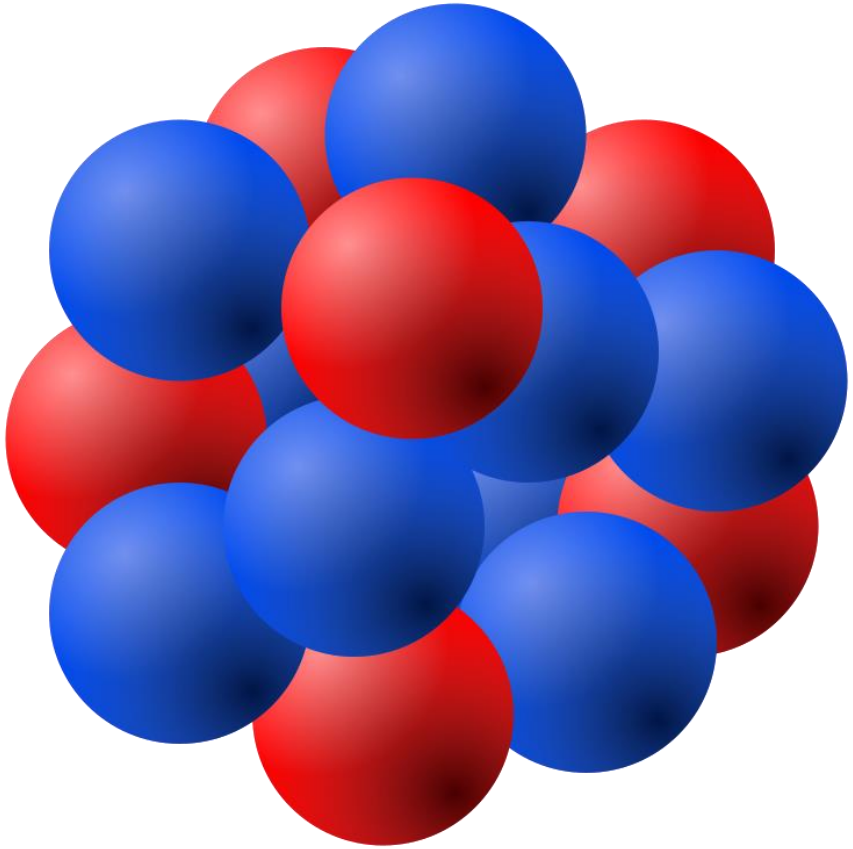
- We want to understand neutrino oscillations ....
- .... Using neutrino-nucleus cross sections
- There is little data on (exclusive) neutrino-nucleon and neutrino-nucleus scattering
- We don’t fully understand neutrino cross sections theoretically

That sounds like a catch 22 ... We could use some help

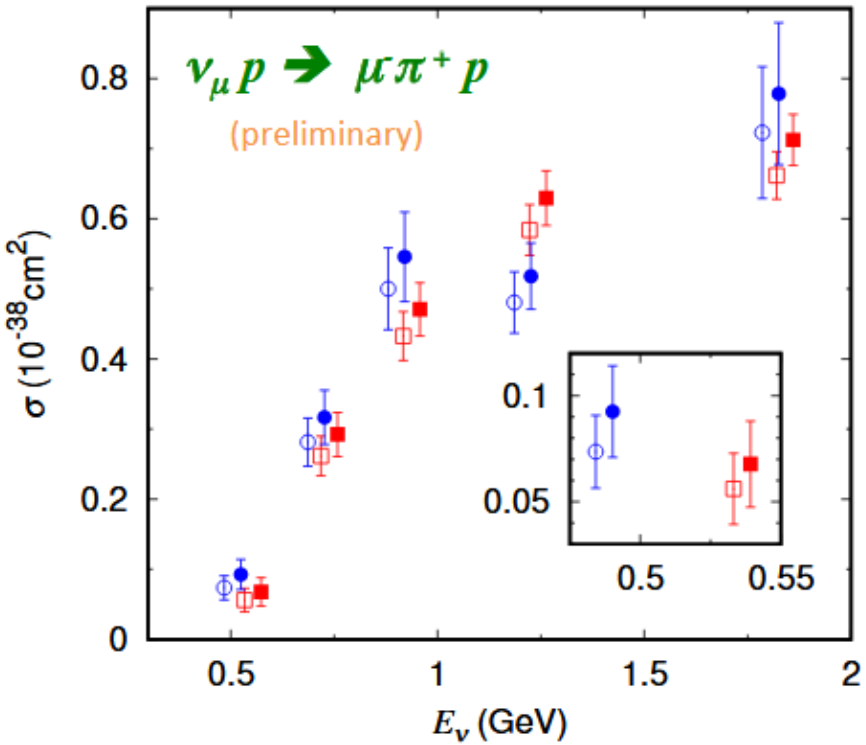
After all, neutrinos and electrons are looking at the same nucleus, through slightly different glasses

For electrons, monochromatic beams are available and exclusive processes experimentally accessible

So electrons can provide important tools to disentangle some of the issues neutrino-nucleus physics is facing



Scattering off the nucleon : data



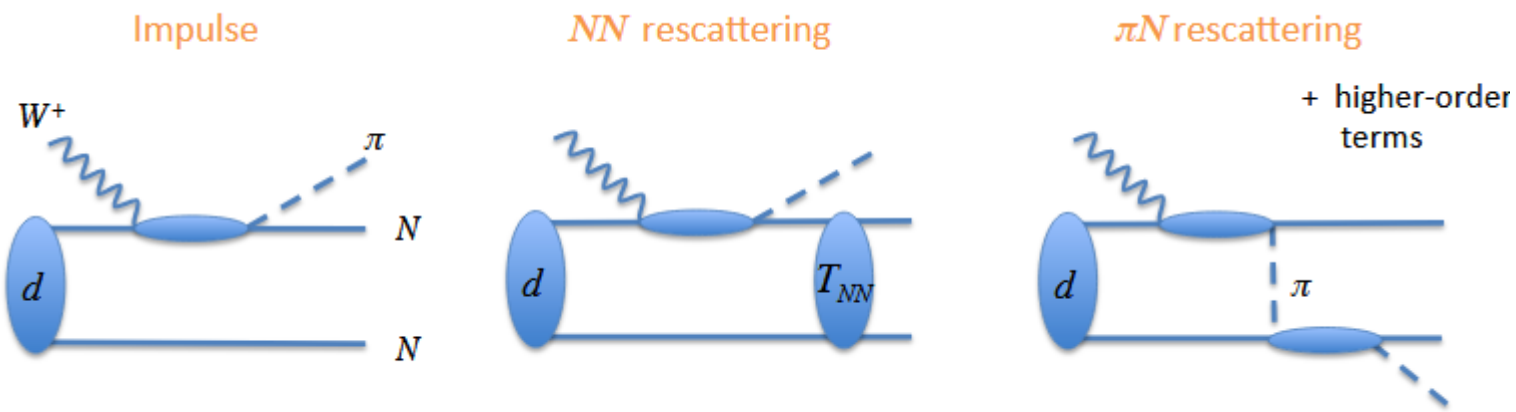
ANL data

- Flux corrected
- FSI, Fermi-motion, Flux corrected

BNL data

- Flux corrected
- FSI, Fermi-motion, Flux corrected

E_ν (GeV)	0.5	1	2
Correction	+24%	+8%	+7%



S. Nakamura, talk NuInt18
Dynamic Coupled Cluster model

Elastic scattering off the nucleon

Information about the structure of the nucleon is encoded in form factors

$$\hat{J}^\mu = F_1(Q^2)\gamma^\mu + \frac{i}{2M_N}F_2(Q^2)\sigma^{\mu\nu}q_\nu + G_A(Q^2)\gamma^\mu\gamma_5 + \frac{1}{2M_N}G_P(Q^2)q^\mu\gamma_5$$

- Vector part of weak nucleon current is relatively well understood through CVC
- Vector form factors are well-studied in electromagnetic process

$$F_i = \begin{cases} (\frac{1}{2} - \sin^2\theta_W)F_i^{EM,V}\tau_3 & \\ -\sin^2\theta_W F_i^{EM,S} - \frac{1}{2}F_i^s & \text{NC} \\ \\ F_i^{EM,V}\tau_\pm & \text{CC}, \end{cases}$$

$$F_i^{EM,S} = F_{i,p}^{EM} + F_{i,n}^{EM}$$

$$F_i^{EM,V} = F_{i,p}^{EM} - F_{i,n}^{EM}$$

Q^2 running : dipole or BBBA (R.Bradford,A.Bodek,H.Budd,J.Arrington,Nucl.Phys.Proc.Suppl.159,127(2006))

Information about the structure of the nucleon is encoded in form factors

- Axial form factors are more subject to uncertainties

$$G_A = \begin{cases} \frac{-g_A\tau_3 + g_A^s}{2} & \text{NC} \\ g_A\tau_\pm & \text{CC} \end{cases}$$

$$G_A(Q^2)$$

Information about the structure of the nucleon is encoded in form factors

Measurement of Muon Neutrino Quasi-Elastic Scattering on Carbon

MiniBooNE collaboration

The observation of neutrino oscillations is clear evidence for physics beyond the standard model. To make precise measurements of this phenomenon, neutrino oscillation experiments, including MiniBooNE, require an accurate description of neutrino charged current quasi-elastic (CCQE) cross sections to predict signal samples. Using a high-statistics sample of muon neutrino CCQE events, MiniBooNE finds that a simple Fermi gas model, with appropriate adjustments, accurately characterizes the CCQE events observed in a carbon-based detector. The extracted parameters include an effective axial mass, M_A^eff = 1.23+/-0.20 GeV, that describes the four-momentum dependence of the axial-vector form factor of the nucleon; and a Pauli-suppression parameter, kappa = 1.019+/-0.011. Such a modified Fermi gas model may also be used by future accelerator-based experiments measuring neutrino oscillations on nuclear targets.

Comments: 5 pages, 3 figures
Subjects: **High Energy Physics - Experiment (hep-ex)**; Nuclear Experiment (nucl-ex)
Journal reference: Phys.Rev.Lett.100:032301,2008
DOI: 10.1103/PhysRevLett.100.032301
Cite as: arXiv:0706.0926 **[hep-ex]**
(or arXiv:0706.0926v2 **[hep-ex]** for this version)

Information about the structure of the nucleon is encoded in form factors

The nucleon axial mass and the MiniBooNE Quasielastic Neutrino-Nucleus Scattering problem

J. Nieves, I. Ruiz Simo, M.J. Vicente Vacas

The charged-current double differential neutrino cross section, measured by the MiniBooNE Collaboration, has been analyzed using a microscopical model that accounts for, among other nuclear effects, long range nuclear (RPA) correlations and multinucleon scattering. We find that MiniBooNE data are fully compatible with the world average of the nucleon axial mass in contrast with several previous analyses which have suggested an anomalously large value. We also discuss the reliability of the algorithm used to estimate the neutrino energy.

Comments: 6 pages and 3 figures. This version matches accepted version for publication in Physics Letters B
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; Nuclear Theory (nucl-th)
DOI: 10.1016/j.physletb.2011.11.061
Cite as: arXiv:1106.5374 **[hep-ph]**
(or arXiv:1106.5374v2 **[hep-ph]** for this version)

Information about the structure of the nucleon is encoded in form factors

- Axial form factors are more subject to uncertainties

$$G_A = \begin{cases} \frac{-g_A\tau_3 + g_A^s}{2} & \text{NC} \\ g_A\tau_\pm & \text{CC} \end{cases}$$

- ‘Traditional’ dipole ansatz
- Z-expansion (Meyer et al PRD84(2011)) :

$$F_A(q^2) = \sum_{k=0}^{k_{\max}} a_k z(q^2)^k$$

- Lattice QCD efforts

Informatio

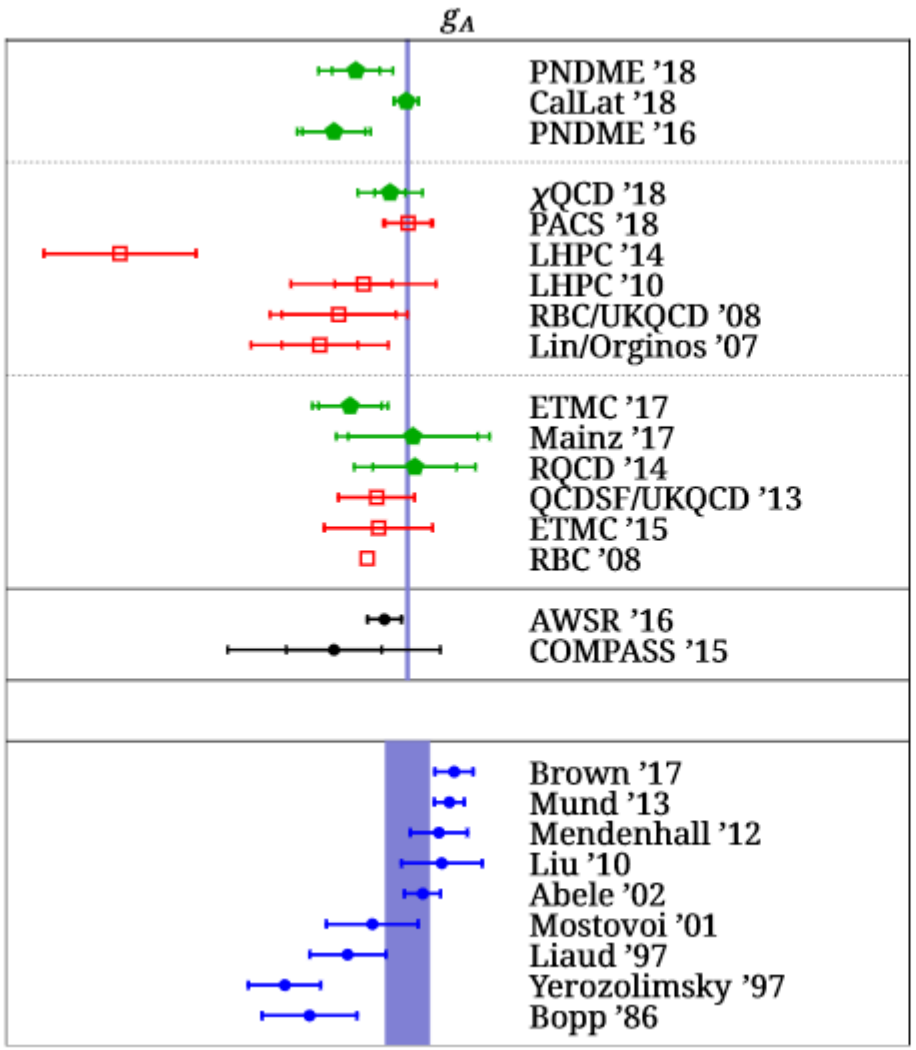
- Axia

$$G_A = \begin{cases} -g_A \\ g_A \tau \end{cases}$$

➢ 'Tradi

➢ z-exp

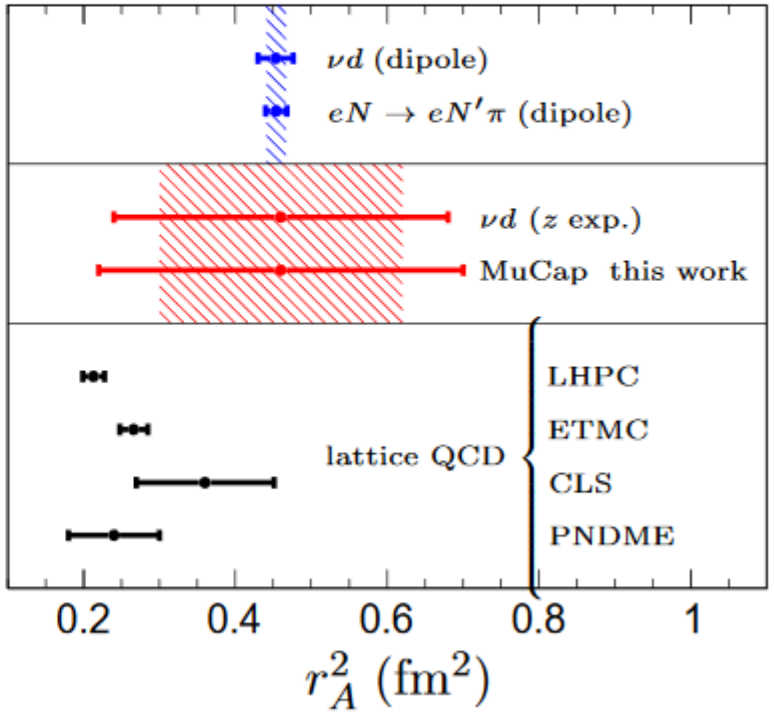
$F_A($



➢

➢ Lattice QCD efforts

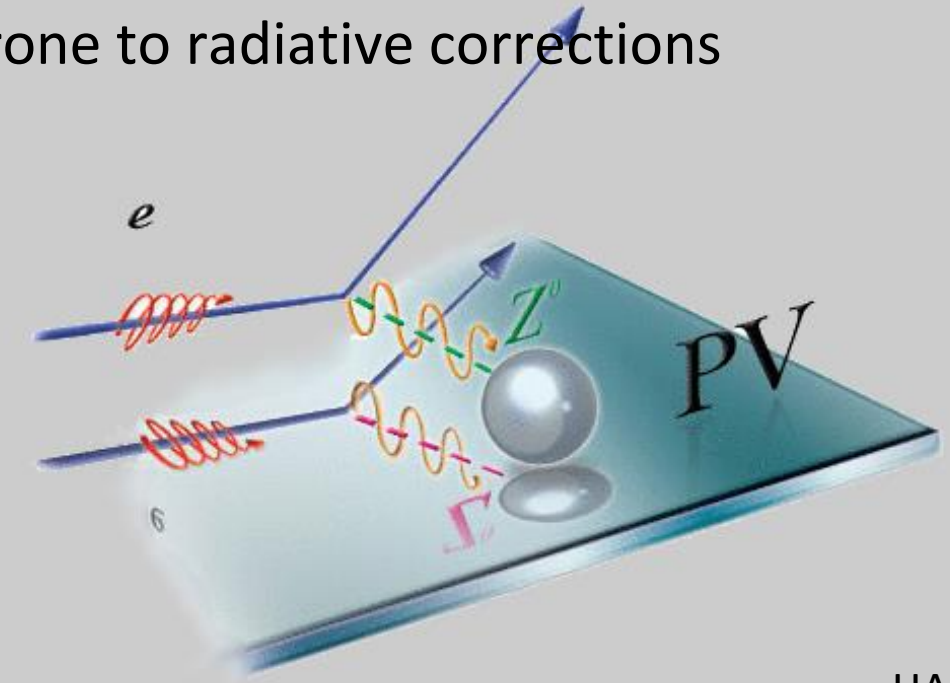
$$r_i^2 \equiv \frac{6}{F_i(0)} \frac{dF_i}{dq^2}\bigg|_{q^2=0}$$



Parity violating electron scattering can provide important information

Using polarized electrons, one gets access to parity violating electron scattering (HAPPEX, G0, SAMPLE, A4)

- Axial-vector interference terms
- Information about axial vector form factor
- Information about strangeness in the nucleon in the vector as well as axial sector
- Larger cross sections
- Prone to radiative corrections

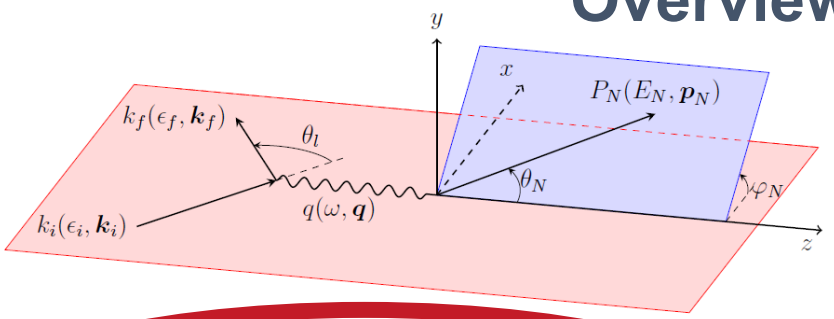


HAPPEX

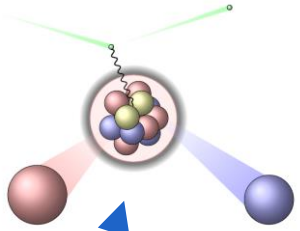
Parity violating asymmetry

$$A^{PV} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L}$$

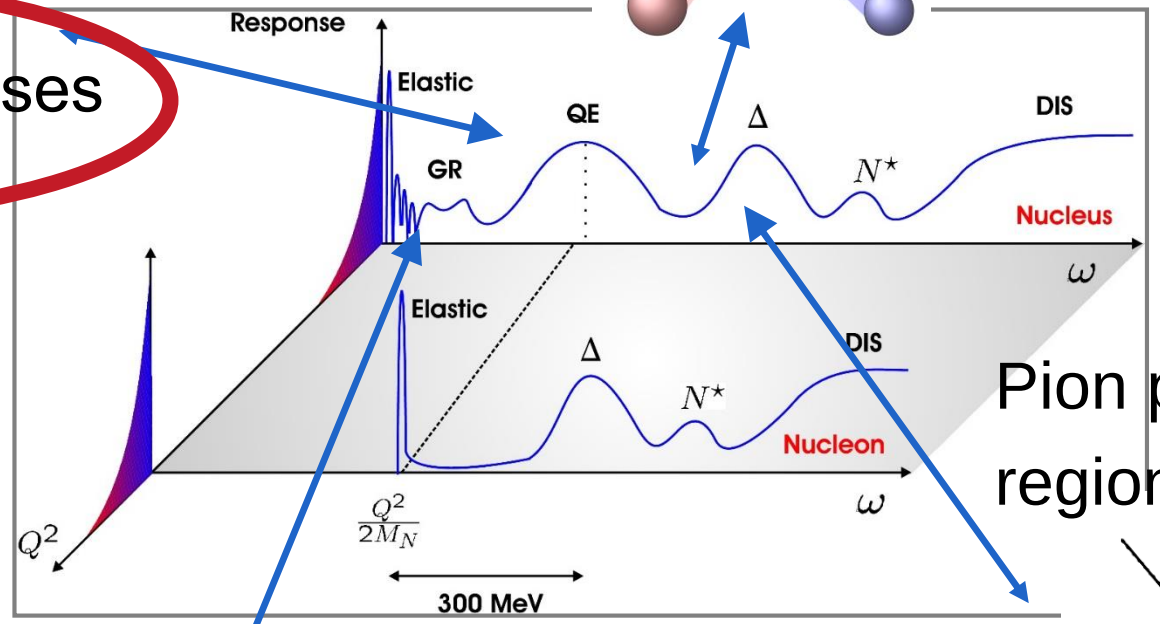
Overview



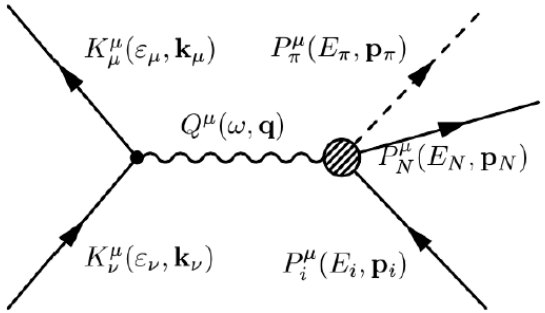
multinucleon mechanisms and 2-nucleon knockout processes in the dip region



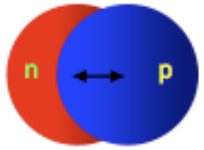
Quasi-elastic processes



Pion production in the delta region and beyond

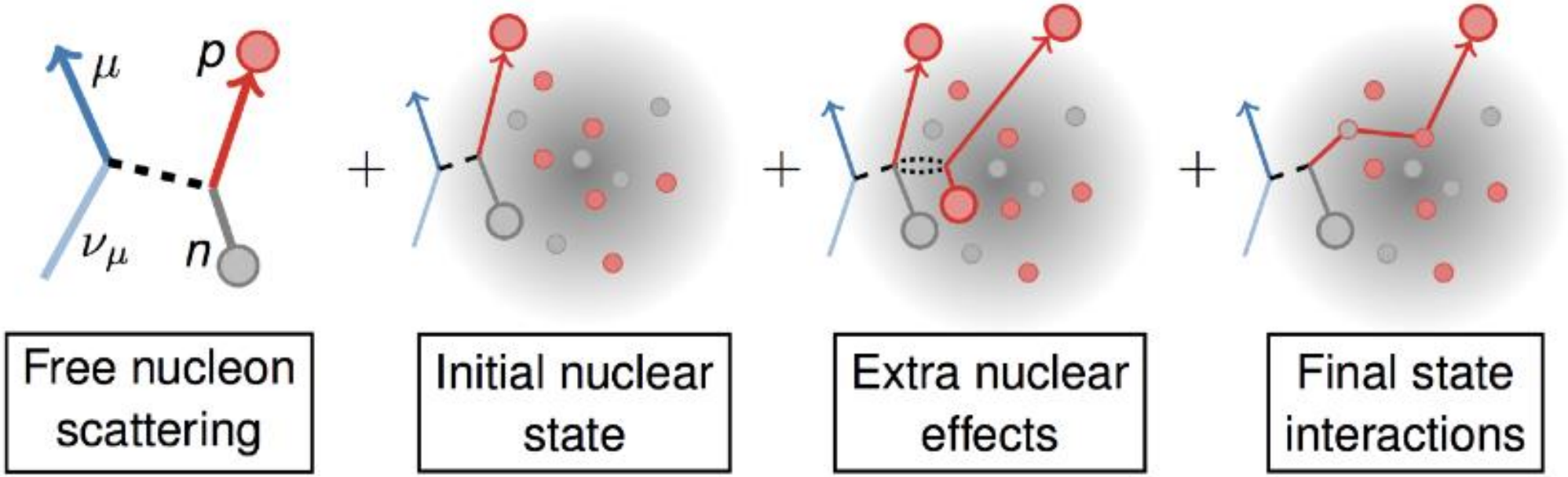


Including the nuclear medium



Low energy collective excitations

What is going on between initial and final state ... ?

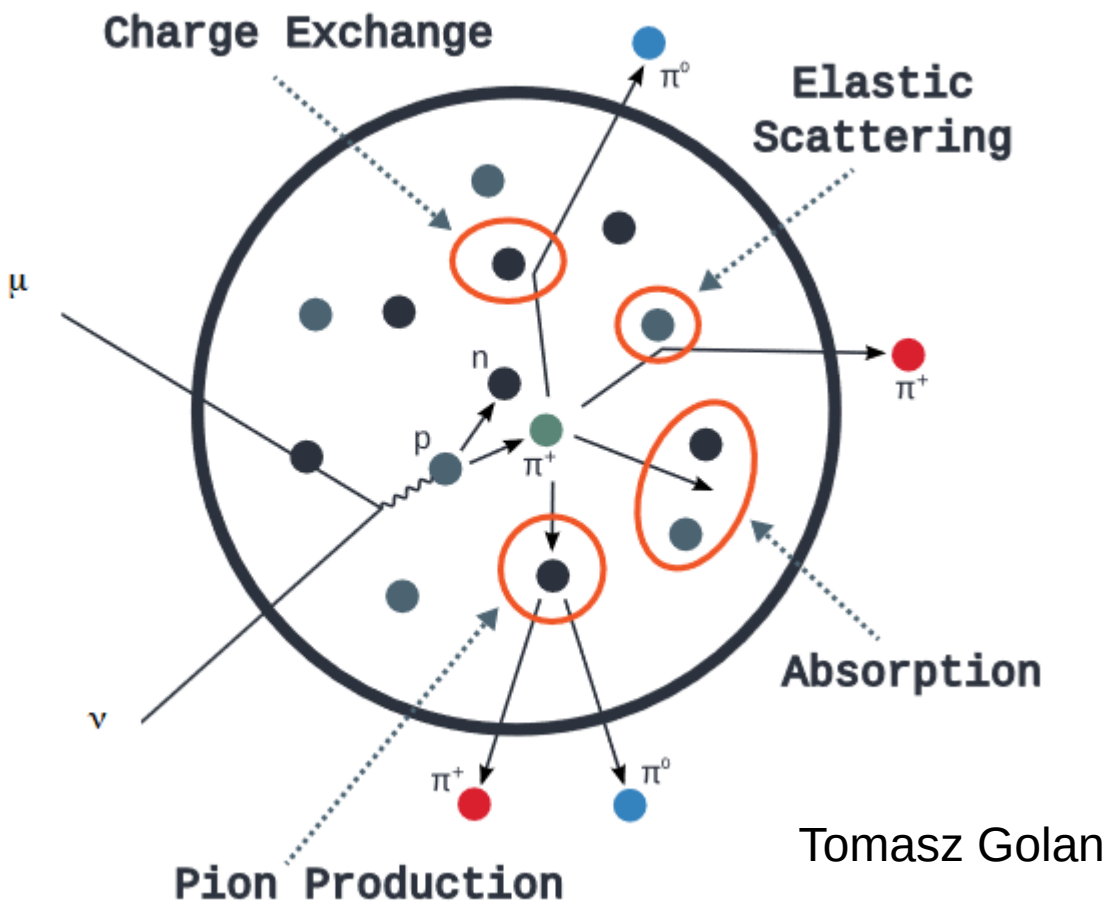


Kajetan Niewczas @ NuFact2018

A couple of problems in a nutshell ...

We want to establish :

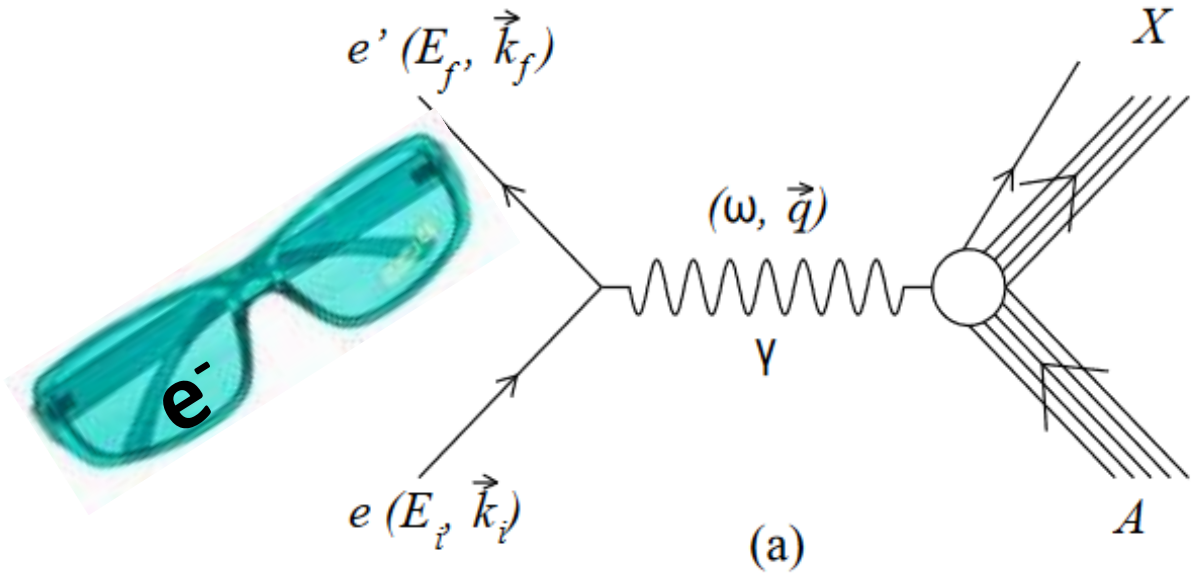
Role of initial state distributions and spectral functions,
short range correlations and meson exchange currents,
final state interactions as rescattering and absorption,
radiative corrections, ...

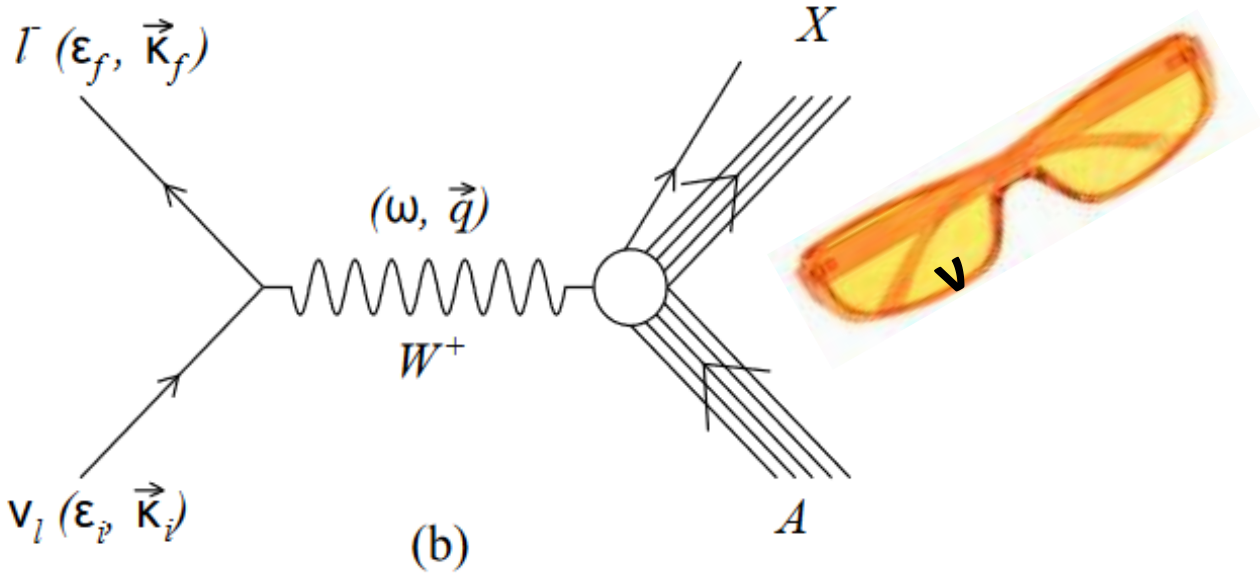


Tomasz Golan

- For a weak interaction
- With no monochromatic beams available

Electron versus neutrino scattering

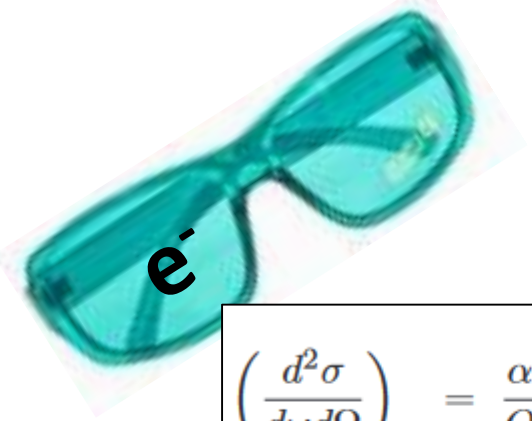




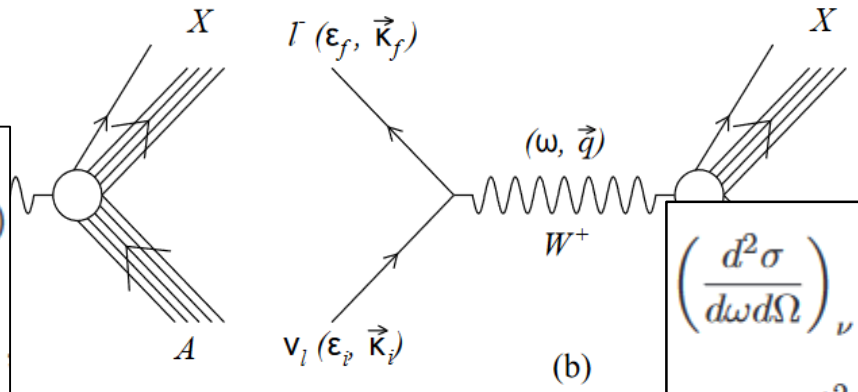
$$\left(\frac{d^2\sigma}{d\omega d\Omega}\right)_e = \frac{\alpha^2}{Q^4}\left(\frac{2}{2J_i+1}\right) E_f k_f \cos^2(\theta/2) \times \zeta^2\left(Z', E_f, |q|\right)\left[\sum_{J=0}^{\infty}\sigma^J_{L,e} + \sum_{J=1}^{\infty}\sigma^J_{T,e}\right]$$

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

Electron versus neutrino scattering



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



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

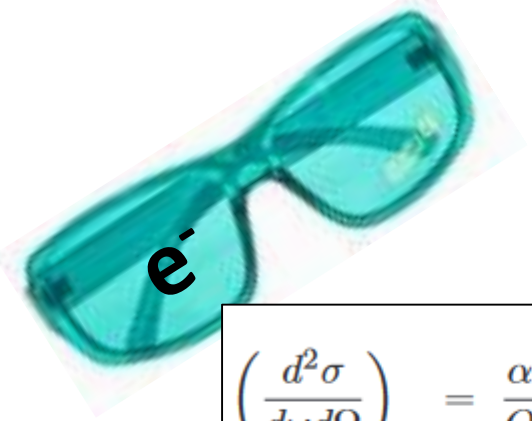
$$\sigma^J_{L,e} = v^L_e R^L_e,$$

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

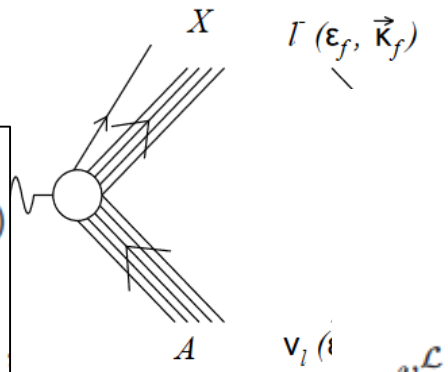
$$\sigma^J_{T,e} = v^T_e R^T_e,$$

$$\sigma^J_{T,\nu} = \left[v^T_\nu R^T_\nu \pm 2\, v^{TT}_\nu R^{TT}_\nu\right],$$

Electron versus neutrino scattering



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



$$v_e^L = \frac{Q^4}{|\vec{q}|^4},$$

$$v_e^T = \left[\frac{Q^2}{2|\vec{q}|^2} + \tan^2(\theta/2)\right]$$

$$v_\nu^{\mathcal{M}} = \left[1 + \frac{\kappa_f}{\varepsilon_f}\cos\theta\right],$$

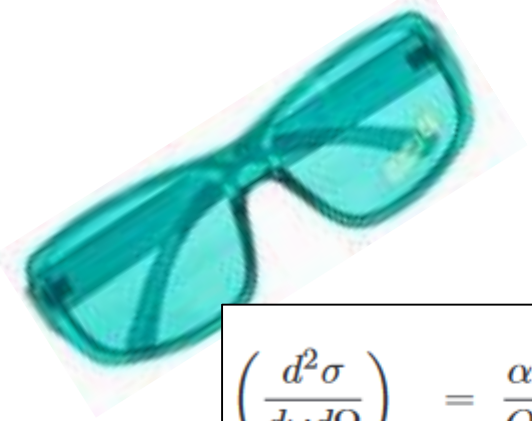
$$v_\nu^{\mathcal{L}} = \left[1 + \frac{\kappa_f}{\varepsilon_f}\cos\theta - \frac{2\varepsilon_i\varepsilon_f}{|\vec{q}|^2}\left(\frac{\kappa_f}{\varepsilon_f}\right)^2\sin^2\theta\right],$$

$$v_\nu^{\mathcal{ML}} = \left[\frac{\omega}{|\vec{q}|}\left(1 + \frac{\kappa_f}{\varepsilon_f}\cos\theta\right) + \frac{m_l^2}{\varepsilon_f|\vec{q}|}\right],$$

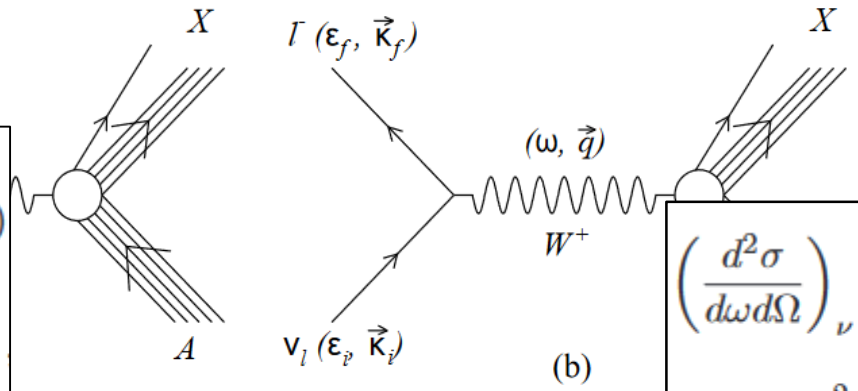
$$v_\nu^{T} = \left[1 - \frac{\kappa_f}{\varepsilon_f}\cos\theta + \frac{\varepsilon_i\varepsilon_f}{|\vec{q}|^2}\left(\frac{\kappa_f}{\varepsilon_f}\right)^2\sin^2\theta\right],$$

$$v_\nu^{TT} = \left[\frac{\varepsilon_i + \varepsilon_f}{|\vec{q}|}\left(1 - \frac{\kappa_f}{\varepsilon_f}\cos\theta\right) - \frac{m_l^2}{\varepsilon_f|\vec{q}|}\right],$$

Electron versus neutrino scattering



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



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

$$R_e^L = |\langle J_f||\widehat{\mathcal{M}}^e_J(|\vec{q}|)||J_i\rangle|^2,$$

$$R_e^T = \left[|\langle J_f||\widehat{\mathcal{J}}^{mag,e}_J(|\vec{q}|)||J_i\rangle|^2 + |\langle J_f||\widehat{\mathcal{J}}^{el,e}_J(|\vec{q}|)||J_i\rangle|^2\right]$$

$$R_\nu^{\mathcal{M}} = |\langle J_f||\widehat{\mathcal{M}}^\nu_J(|\vec{q}|)||J_i\rangle|^2,$$

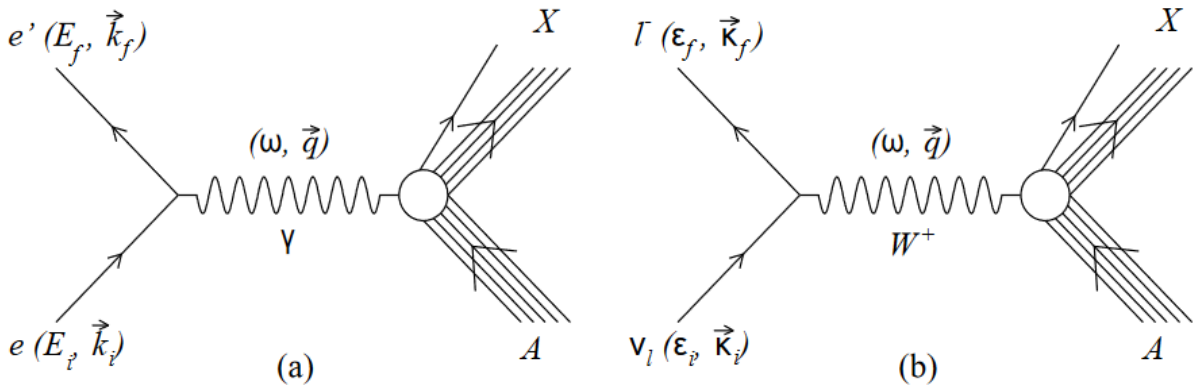
$$R_\nu^{\mathcal{L}} = |\langle J_f||\widehat{\mathcal{L}}^\nu_J(|\vec{q}|)||J_i\rangle|^2,$$

$$R_\nu^{\mathcal{ML}} = \mathcal{R}\left[\langle J_f||\widehat{\mathcal{L}}^\nu_J(|\vec{q}|)||J_i\rangle\langle J_f||\widehat{\mathcal{M}}^\nu_J(|\vec{q}|)||J_i\rangle^*\right],$$

$$R_\nu^T = \left[|\langle J_f||\widehat{\mathcal{J}}^{mag,\nu}_J(|\vec{q}|)||J_i\rangle|^2 + |\langle J_f||\widehat{\mathcal{J}}^{el,\nu}_J(|\vec{q}|)||J_i\rangle|^2\right],$$

$$R_\nu^{TT} = \mathcal{R}\left[\langle J_f||\widehat{\mathcal{J}}^{mag,\nu}_J(|\vec{q}|)||J_i\rangle\langle J_f||\widehat{\mathcal{J}}^{el,\nu}_J(|\vec{q}|)||J_i\rangle^*\right].$$

Electron versus neutrino scattering



$$\widehat{\mathcal{M}}_{JM}(\kappa) = \int d\vec{x} \; \left[j_J \; (\kappa r) \; Y_J^M \; (\Omega_x) \right] \; \hat{J}_0(\vec{x}) \quad ,$$

$$\widehat{\mathcal{L}}_{JM}(\kappa) = \frac{i}{\kappa} \int d\vec{x} \; \left[\vec{\nabla} \left(j_J \; (\kappa r) \; Y_J^M \; (\Omega_x) \right) \right] \; \cdot \; \widehat{\vec{J}}(\vec{x}) \quad ,$$

$$\widehat{\mathcal{T}}^{el}_{JM}(\kappa) = \frac{1}{\kappa} \int d\vec{x} \; \left[\vec{\nabla} \; \times \; \left(j_J \; (\kappa r) \; \vec{\mathcal{Y}}^M_{J,J} \; (\Omega_x) \right) \right] \; \cdot \; \widehat{\vec{J}}(\vec{x}) \quad ,$$

$$\widehat{\mathcal{T}}^{mag}_{JM}(\kappa) = \int d\vec{x} \; \left[j_J \; (\kappa r) \; \vec{\mathcal{Y}}^M_{J,J} \; (\Omega_x) \right] \; \cdot \; \widehat{\vec{J}}(\vec{x}) \quad .$$

$$\langle a || \widehat{\mathcal{M}}^{Coul}_J [\widehat{\rho}_V] || b \rangle = G_E(Q^2) \int \mathrm{d}r \; \langle a || \tau_{\pm} j_J(qr) Y_J(\Omega_1) || b \rangle_r$$

$$\langle a || \widehat{\mathcal{M}}^{Coul}_J [\widehat{\rho}_A] || b \rangle = \frac{G_A(Q^2)}{2m_N i} \int \mathrm{d}r \; \langle a || \tau_{\pm} j_J(qr) Y_J(\Omega_1) \, \boldsymbol{\sigma}_1 \cdot \left(\overrightarrow{\boldsymbol{\nabla}}_1 - \overleftarrow{\boldsymbol{\nabla}}_1 \right) || b \rangle_r$$

$$\langle a || \widehat{\mathcal{O}}^{\lambda}_J \left[\widehat{J}_{conv} \right] || b \rangle = \frac{G_E(Q^2)}{2m_N i} \int \mathrm{d}r \; \langle a || \tau_{\pm} j_{J+\lambda}(qr) \times \left[Y_{J+\lambda}(\Omega_1) \otimes \left(\overrightarrow{\boldsymbol{\nabla}}_1 - \overleftarrow{\boldsymbol{\nabla}}_1 \right) \right]_J || b \rangle_r$$

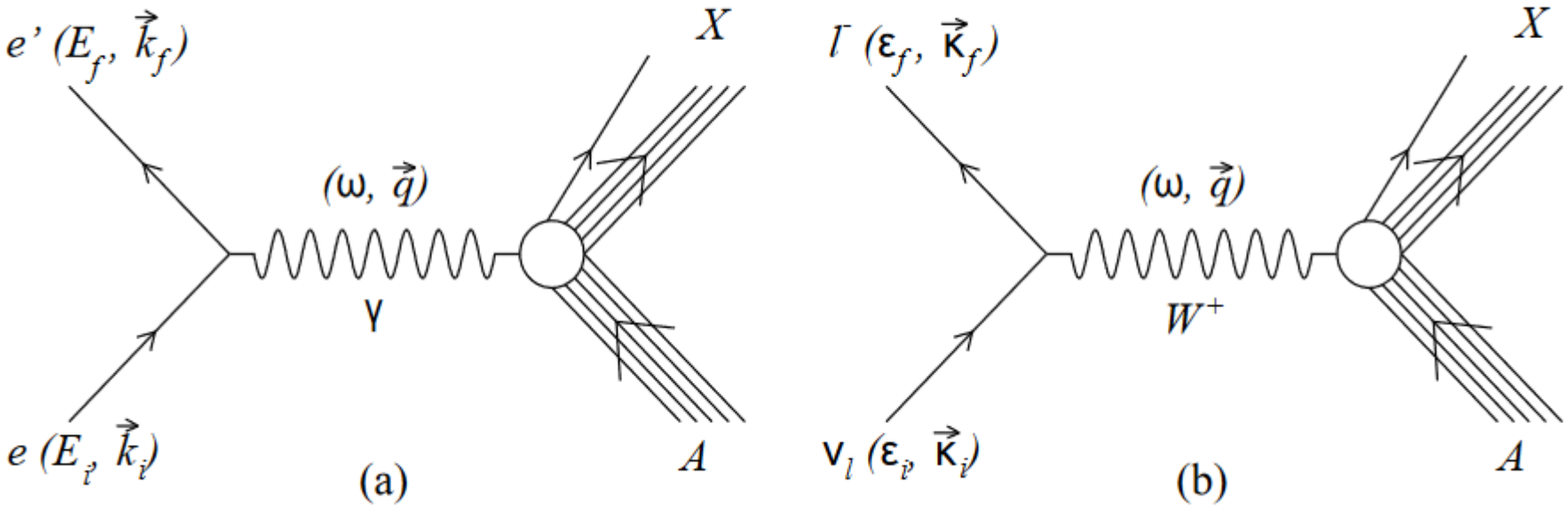
$$\langle a || \widehat{\mathcal{O}}^{\lambda}_J \left[\widehat{J}_{magn} \right] || b \rangle = i\sqrt{6} q \frac{G_M(Q^2)}{2m_N} \int \mathrm{d}r \sum_{\eta=\pm 1} \sqrt{J + \lambda + \delta_{\eta,+1}} \times \begin{Bmatrix} J & J+\lambda & 1 \\ 1 & 1 & J+\lambda+\eta \end{Bmatrix} \times \langle a || \tau_{\pm} j_{J+\lambda+\eta}(qr) \left[Y_{J+\lambda+\eta}(\Omega_1) \otimes \boldsymbol{\sigma}_1 \right]_J || b \rangle_r$$

$$\langle a || \widehat{\mathcal{O}}^{\lambda}_J \left[\widehat{J}_A \right] || b \rangle = G_A(Q^2) \int \mathrm{d}r \; \langle a || \tau_{\pm} j_{J+\lambda}(qr) \left[Y_{J+\lambda}(\Omega_1) \otimes \boldsymbol{\sigma}_1 \right]_J || b \rangle_r$$

Tools for making use of e-scattering to understand neutrino-nucleus interactions
Universality and scaling

Electron scattering data is obtained with well defined incoming electron energies, such that

- energy and momentum transfer, kinematics at the vertex are well established and
- different reaction mechanisms can be separated



Neutrinos probe both vector and axial responses unlike upolarized electrons

Scaling : a strong argument in favor of porting information from one process/regime to another

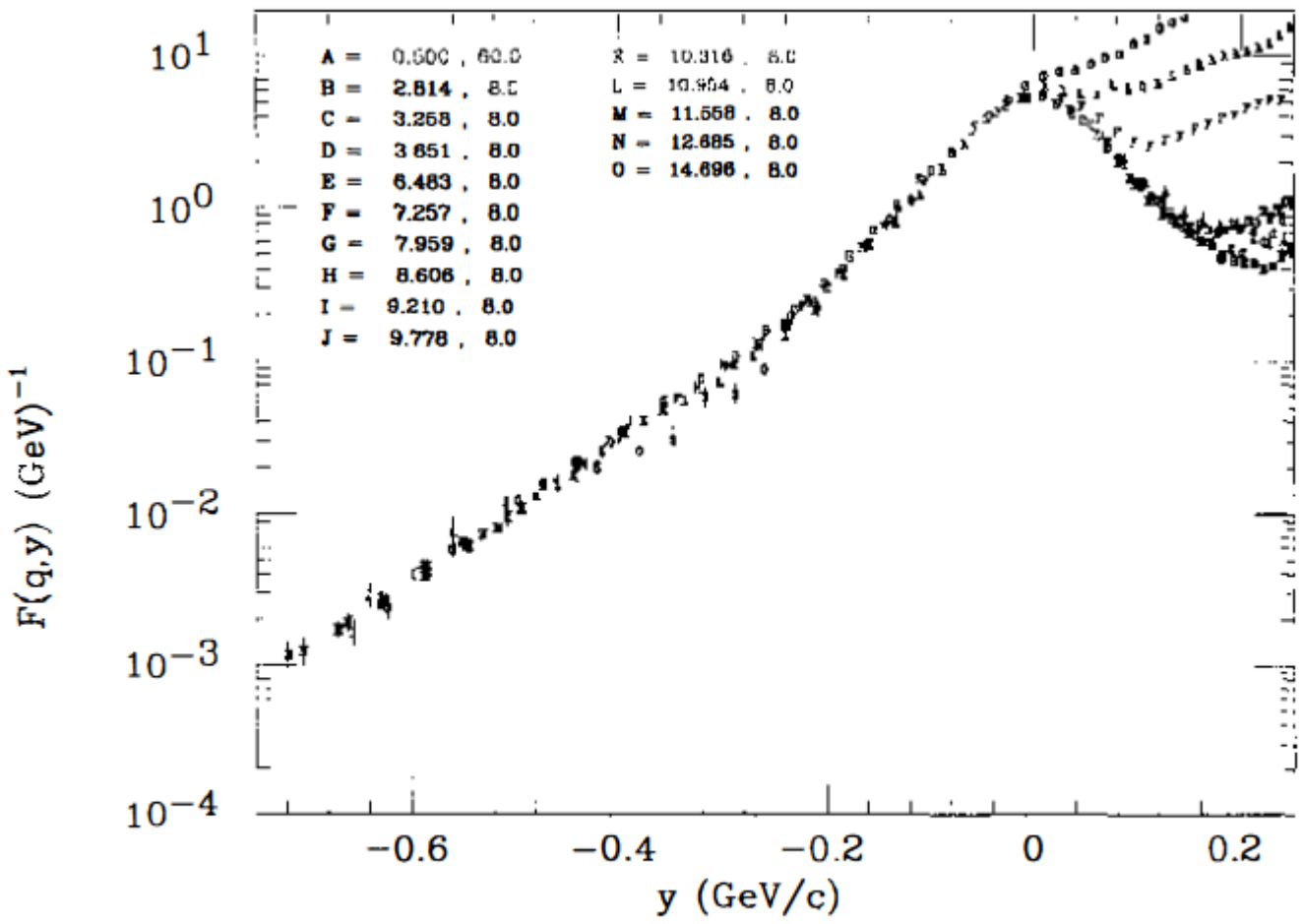


Figure 5 Experimental scaling function for ^{3}He determined from data in Figure 4. The letters label different incident electron energy and scattering angle pairs (ε, θ) in (GeV, degrees).

Separates QE cross section in a averaged single-nucleon factor and a scaling function encoding the influence of nuclear dynamics

$$F(q,\omega) = \frac{d^2\sigma/d\omega d\Omega}{\sigma_{Mott}(v_L G_L + V_T G_T)}$$

→Scaling of first kind

Day et al., Annu. Rev. Nucl. Part. Sci. (1990)

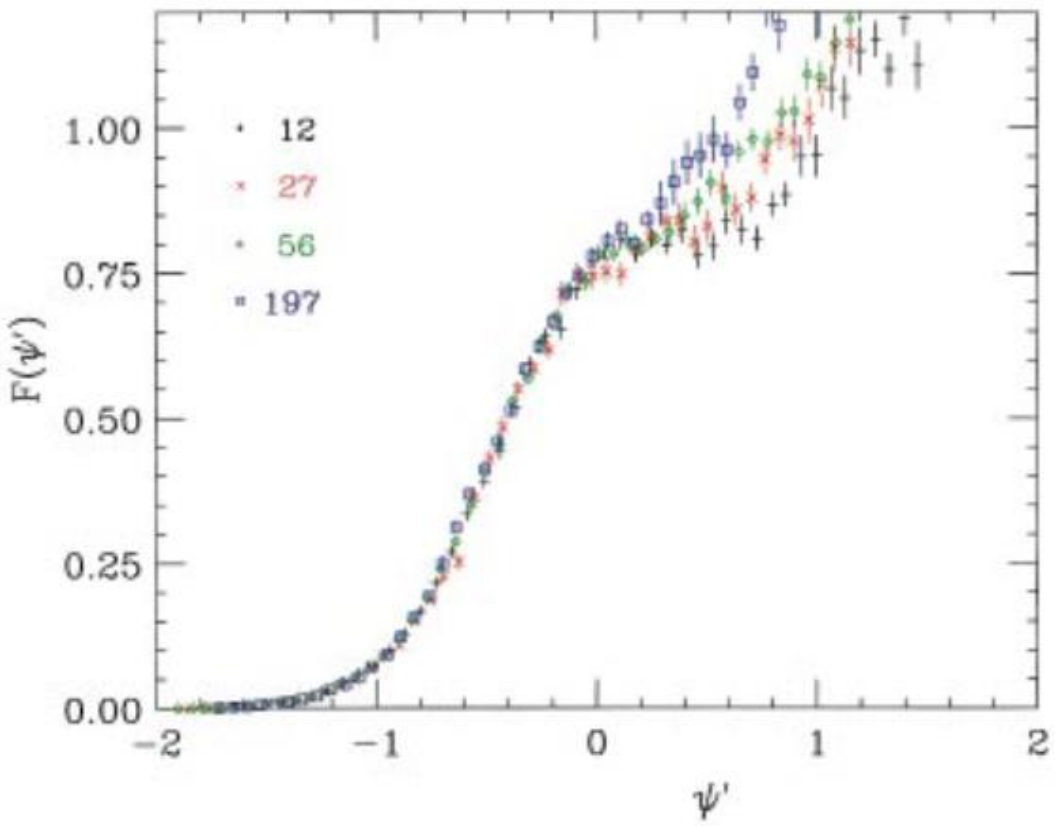


FIG. 2(color). Scaling function for C, Al, Fe, and Au and fixed kinematics [25]. The correspondence of symbol and mass number of the nucleus is also shown.

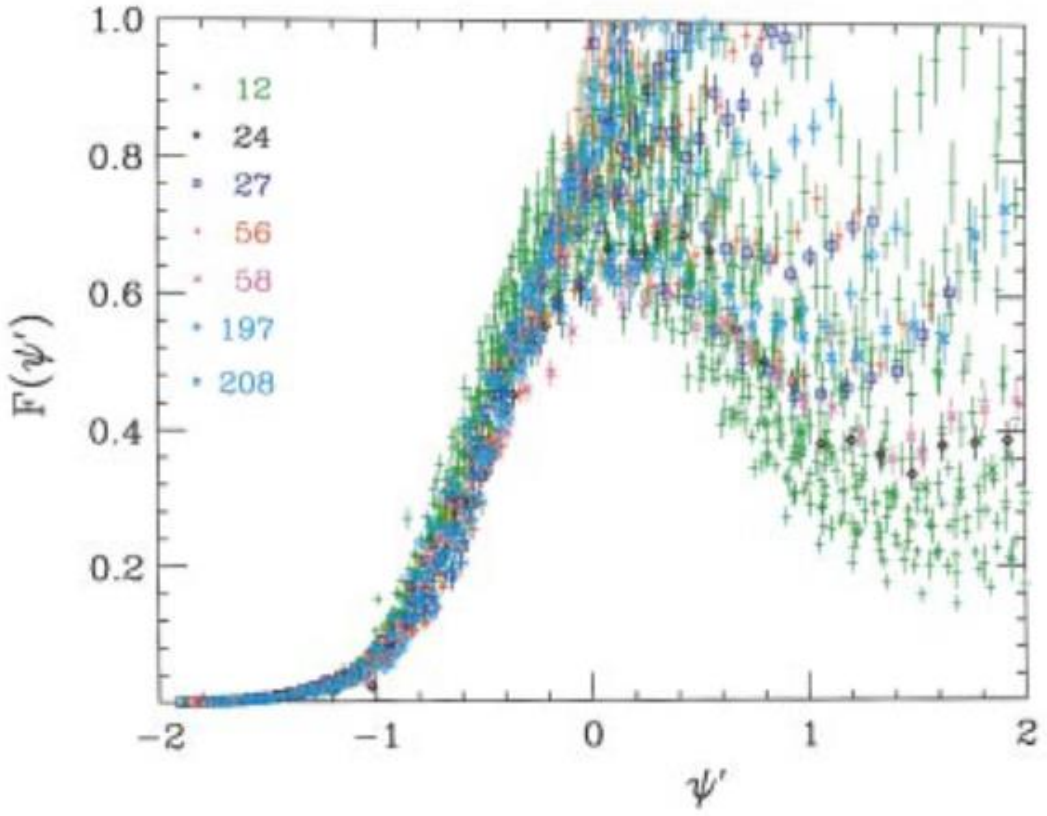


FIG. 1(color). Scaling function $f(\psi')$ as function of ψ' for all nuclei $A \geq 12$ and all kinematics. The values of A corresponding to different symbols is also shown.

→Scaling function independent of A (k_F): → Scaling of second kind

Day et al., Annu. Rev. Nucl. Part. Sci. (1990)

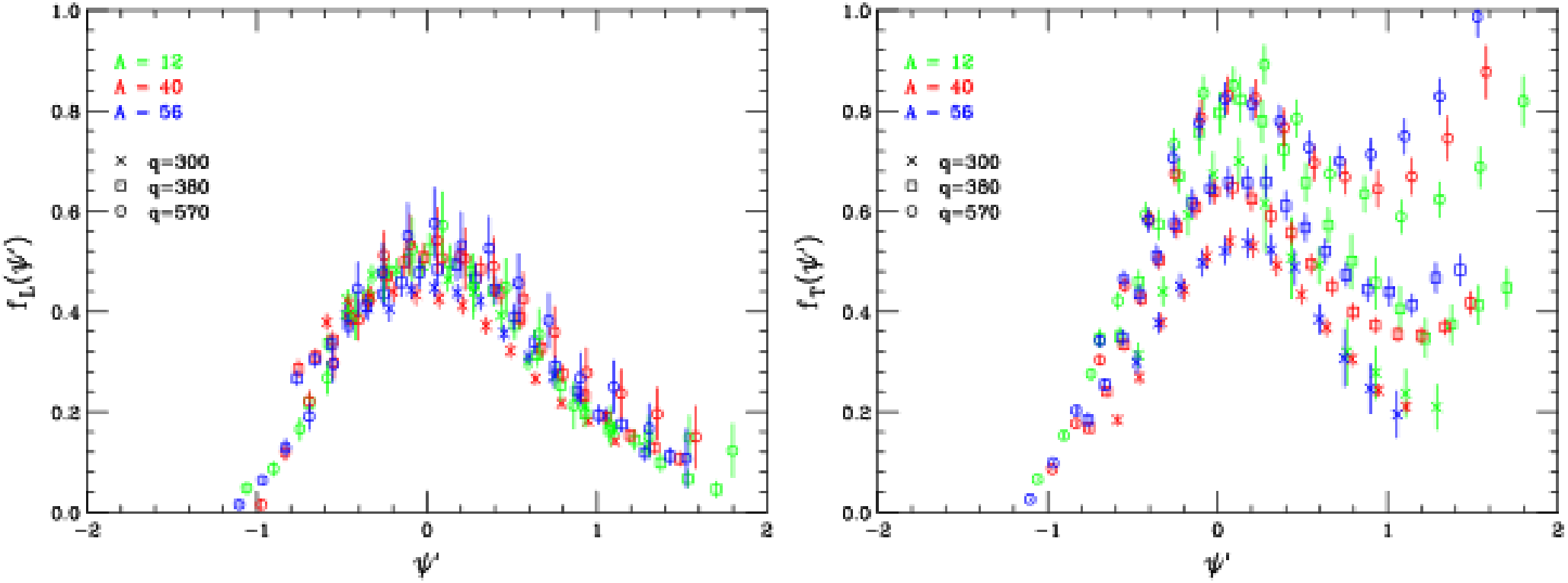
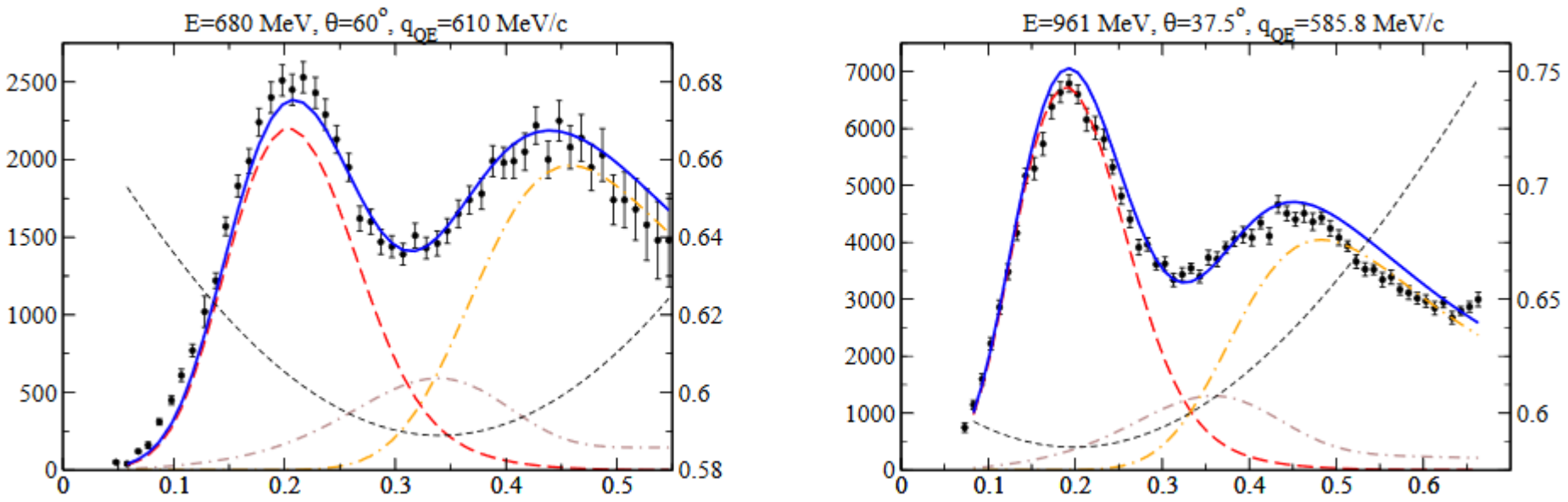


FIG. 15. Scaling function, $f_L(\psi')$ and $f_T(\psi')$, from the longitudinal and transverse response, respectively, as a function of ψ' for different nuclei ($A \geq 12$) and for different values of q (in MeV/c). Data taken from [23].

Separating longitudinal and transverse contributions :

- Allows for a more sophisticated and accurate description
- Shows that transverse channels violate scaling beyond the quasi-elastic peak : multinucleon effects

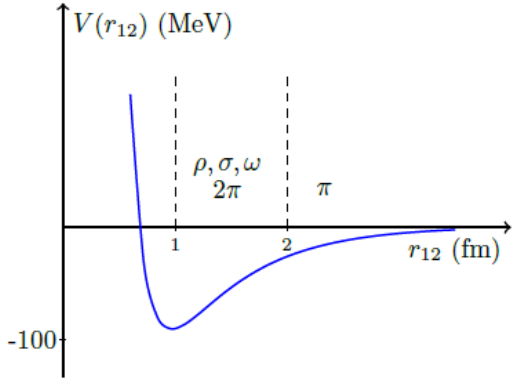


Megias et al., PRD 94, 013012 (2016)

SuSa Collaboration :
scaling functions extracted from e-scattering data->
→Scaling functions extracted from RMF calculations
→ predictions for neutrino processes

Electron- versus neutrino-nucleus scattering
J. E. Amaro, M. B. Barbaro, J. A. Caballero, R. González-Jiménez, G. D. Megias, I. Ruiz Simo
arXiv:1912.10612

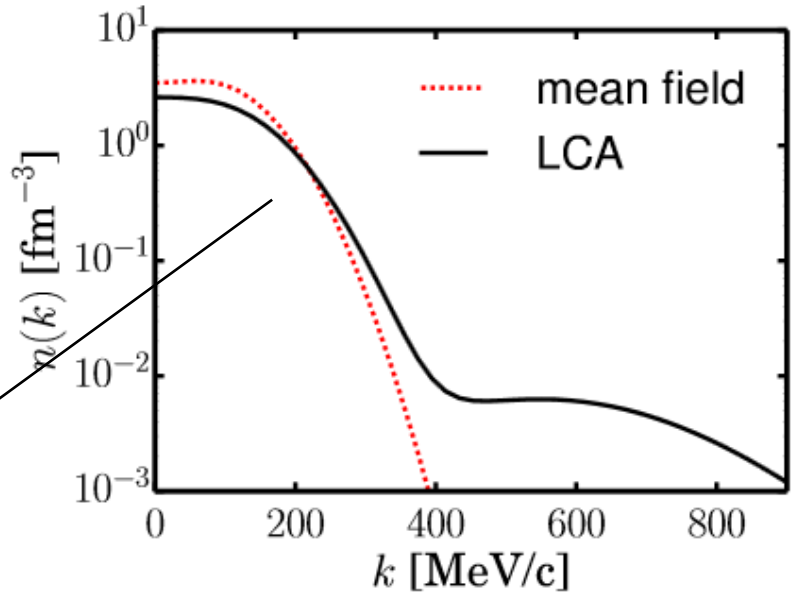
Multinucleon mechanisms : short range correlations

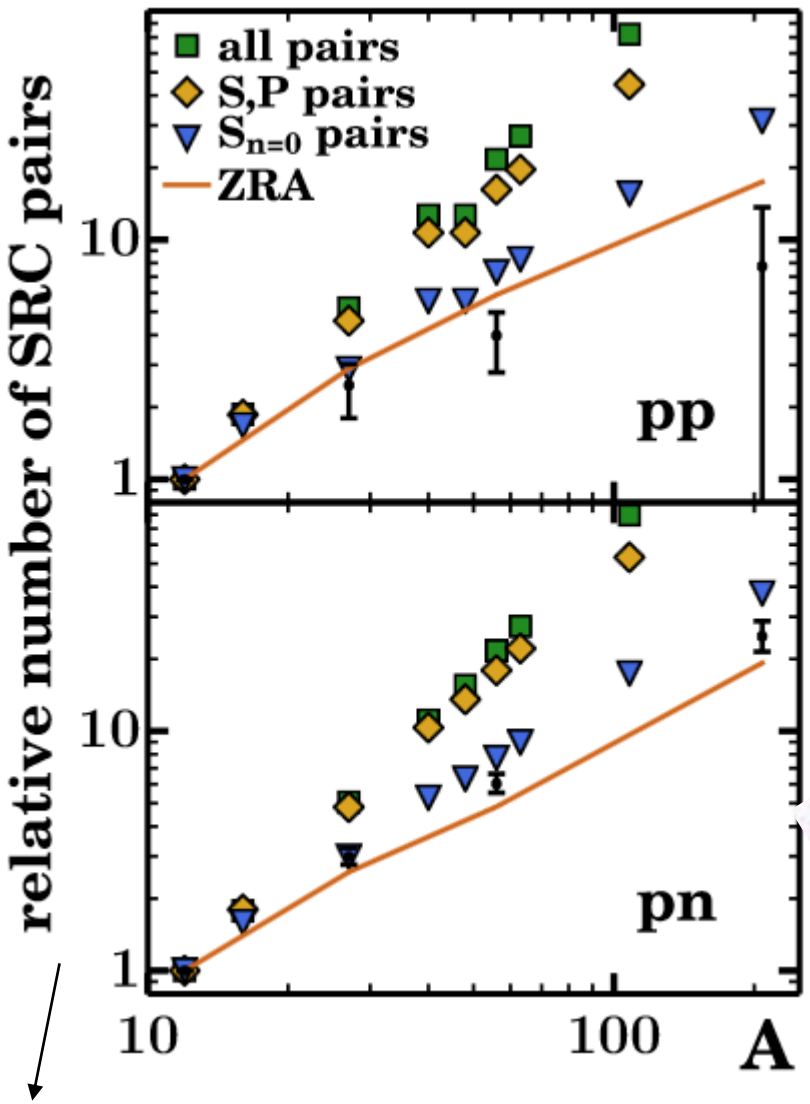


- The short-range repulsive character of the nuclear force, which correlates with the Pauli exclusion principle, results in a large mean free path of the nucleons with respect to the size of the nucleus
- In an independent particle model nucleons move independently from each other in a mean field
- This approach fails to capture short-range features of nucleon-nucleon correlations

- SRC : short-range repulsive, tensor component of the nuclear force
- Individual nucleons receive large momenta compared to the Fermi momentum

IPM single-particle orbitals are depleted by SRC and higher energy levels are populated



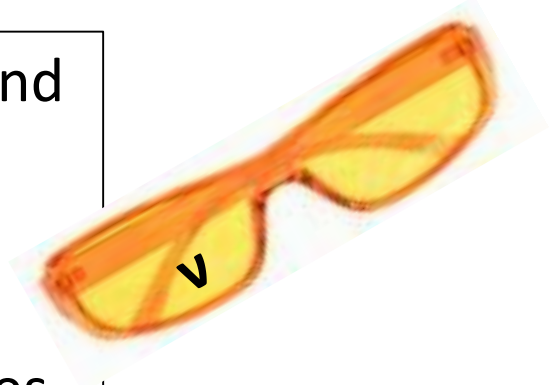


To ^{12}C

Data : CLAS A(e,e',pN) data

- mass dependence ~ $A^{1.12}$:soft !
- Predominantly pn, s-pairs
- Universal over mass table
- Tensor force dominates at short distances

Different couplings and isospin structure for electrons and neutrinos,
but still these particles are probing the same nuclear dynamics



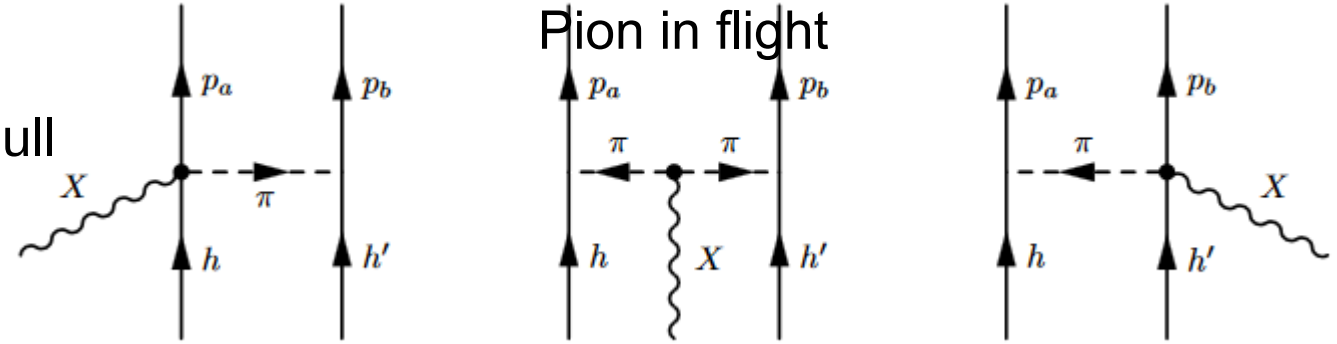
C. Colle, W. Cosyn, and J. Ryckebusch, Phys. Rev. C **93**, 034608 (2016)
C. Colle, W. Cosyn, J. Ryckebusch, and M. Vanhalst, Phys. Rev. C **89**, 024603 (2014)
C. Colle, O. Hen, W. Cosyn, I. Korover, E. Piasetzky, J. Ryckebusch, and L. B. Weinstein, Phys. Rev. C **92**, 024604 (2015).

Multinucleon mechanisms: meson exchange currents

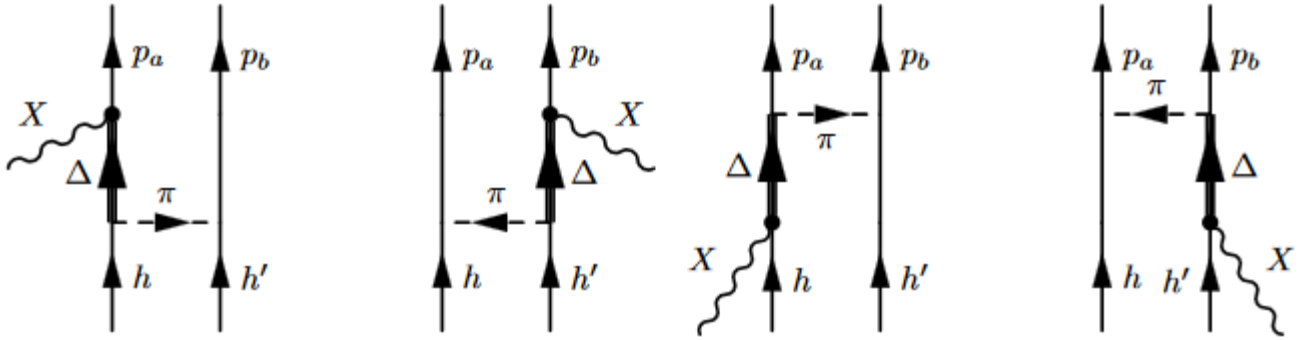
When an electroweak boson interacts with a pair of nucleons which are correlated through the exchange of a meson, this will cause the knockout of one or both of the particles from the nucleus. The boson was interacting with a current consisting of two nucleons, a two-body current, called a MEC

Seagull

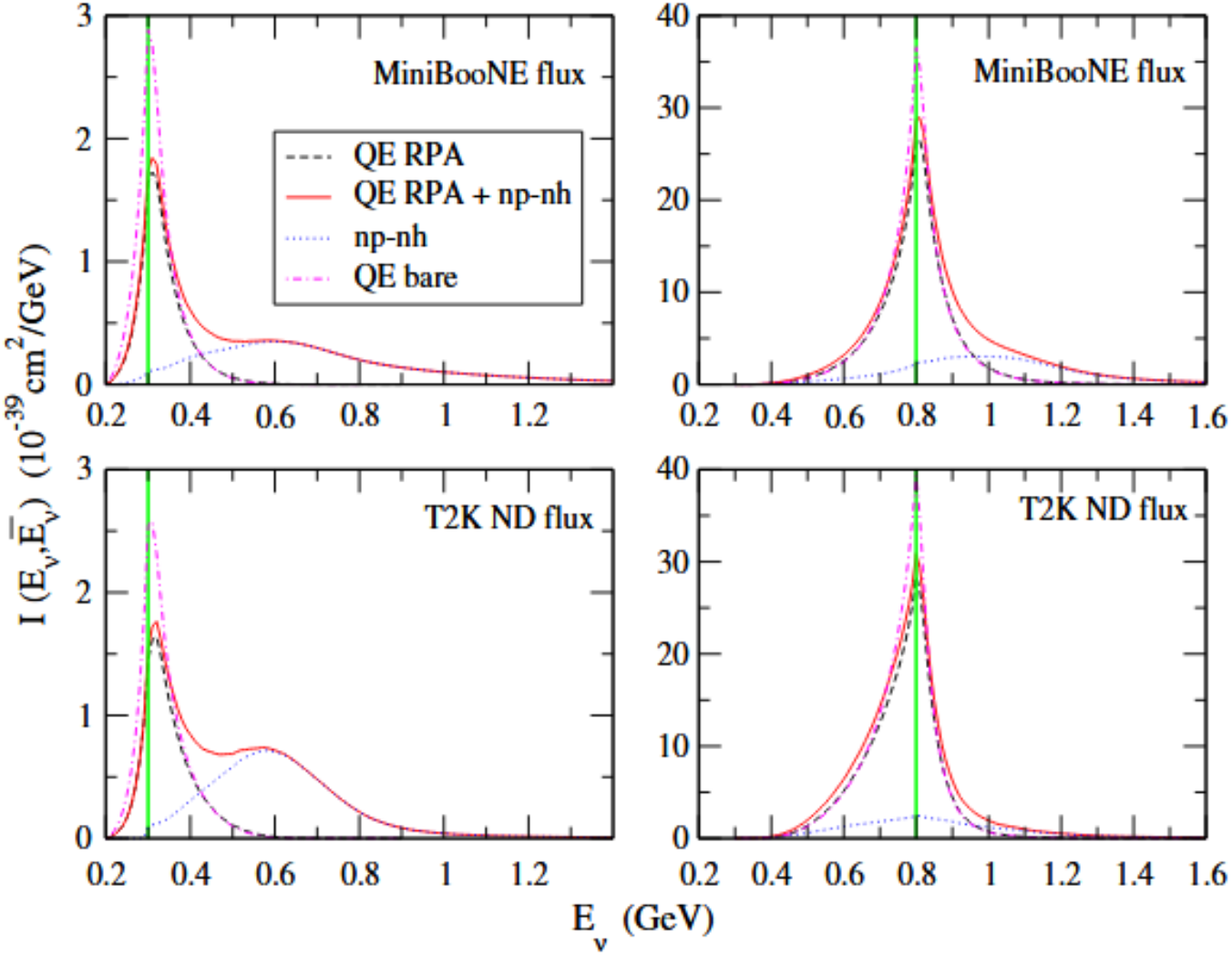
Pion in flight



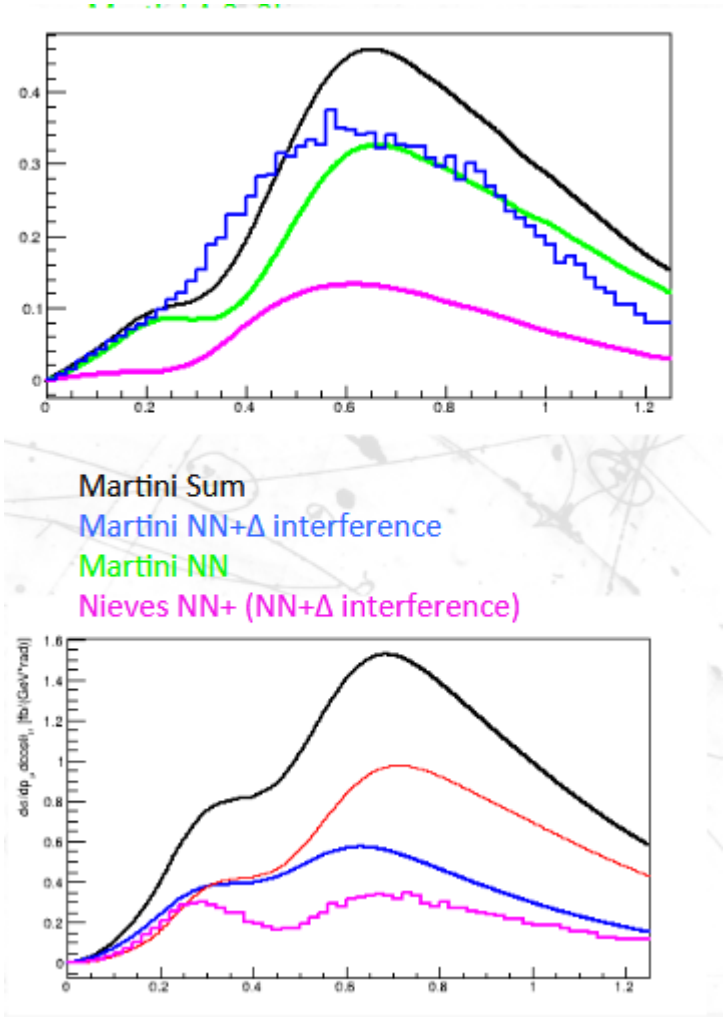
Delta currents



Multinucleon effects affect energy reconstruction !

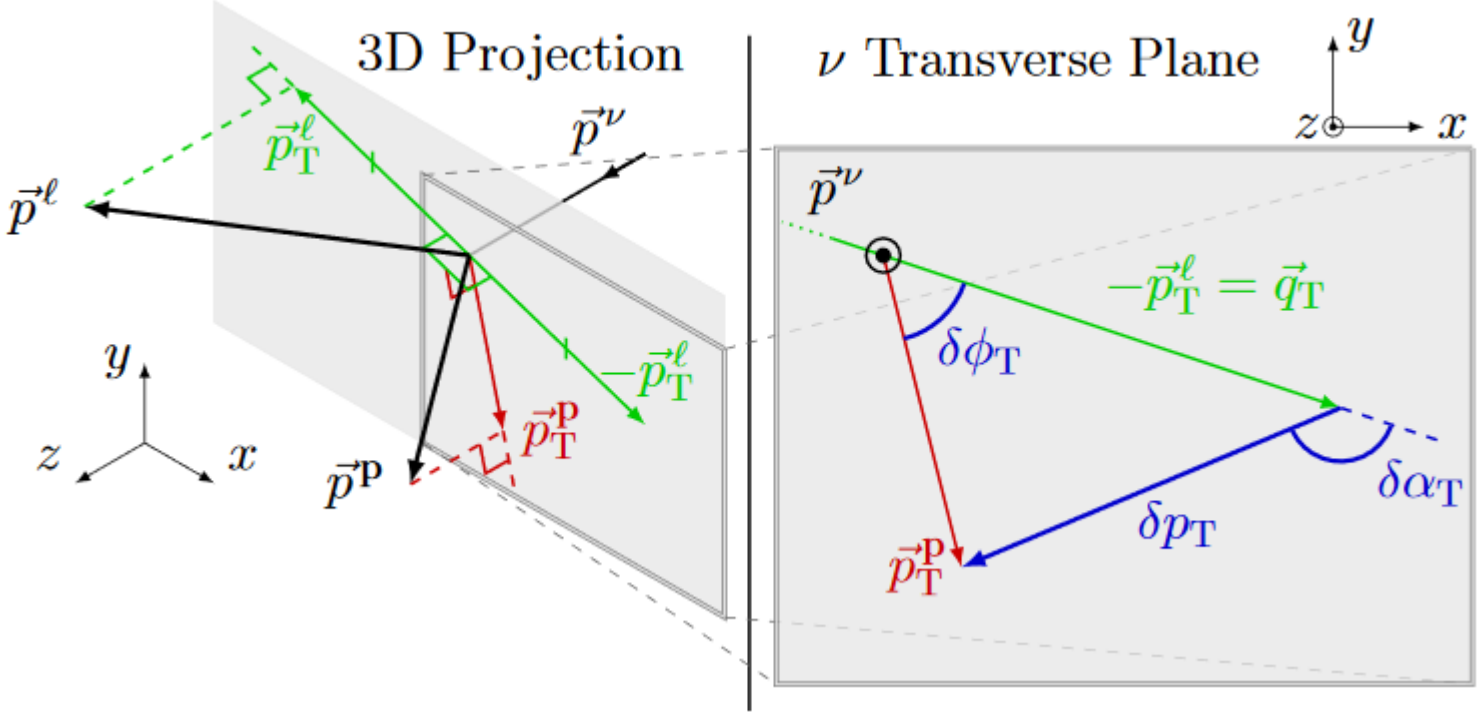


M. Martini et al. PRD85, 093012 (2012)



F. Sanchez, NuInt2017 'Outlook to 2020'

Strong tool in determining the nature of the nuclear effects : transverse imbalance

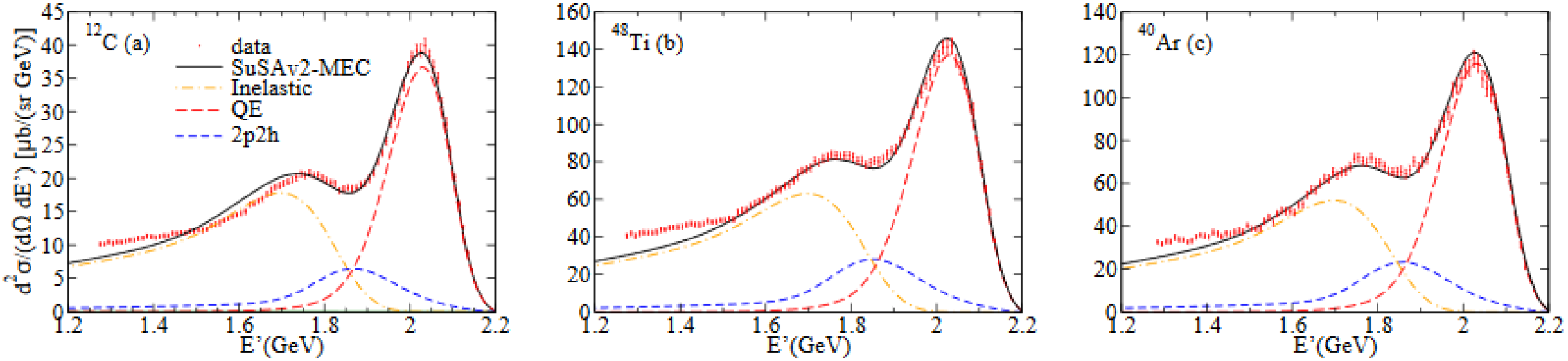


$\delta P_T \neq 0 \rightarrow$ Nuclear effects
$\delta\alpha_T \neq 0 \rightarrow$ FSI
$\delta\phi_T \neq 0 \rightarrow$ 2p2h, FSI

- **Need to benchmark, test and constrain theoretical models and generator implementations using electron scattering data**
- **Need electron scattering data that facilitate these comparisons and in a format that optimizes comparisons**

Theory : SuSA

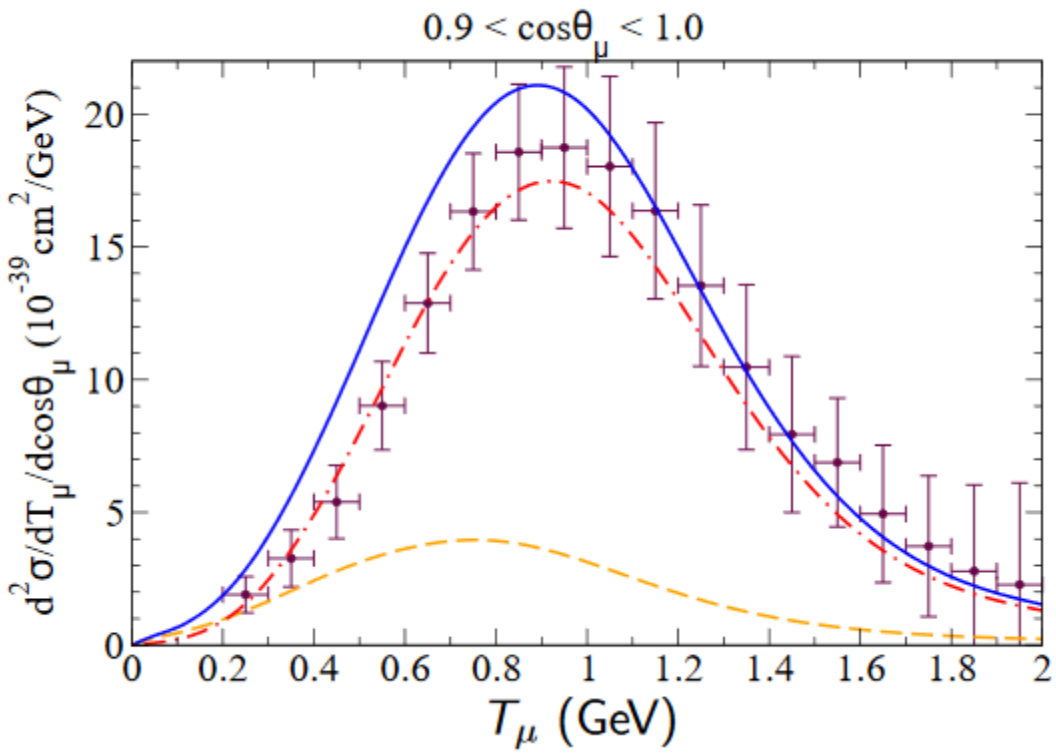
(e,e') inclusive



Theory : SuSA

ν inclusive

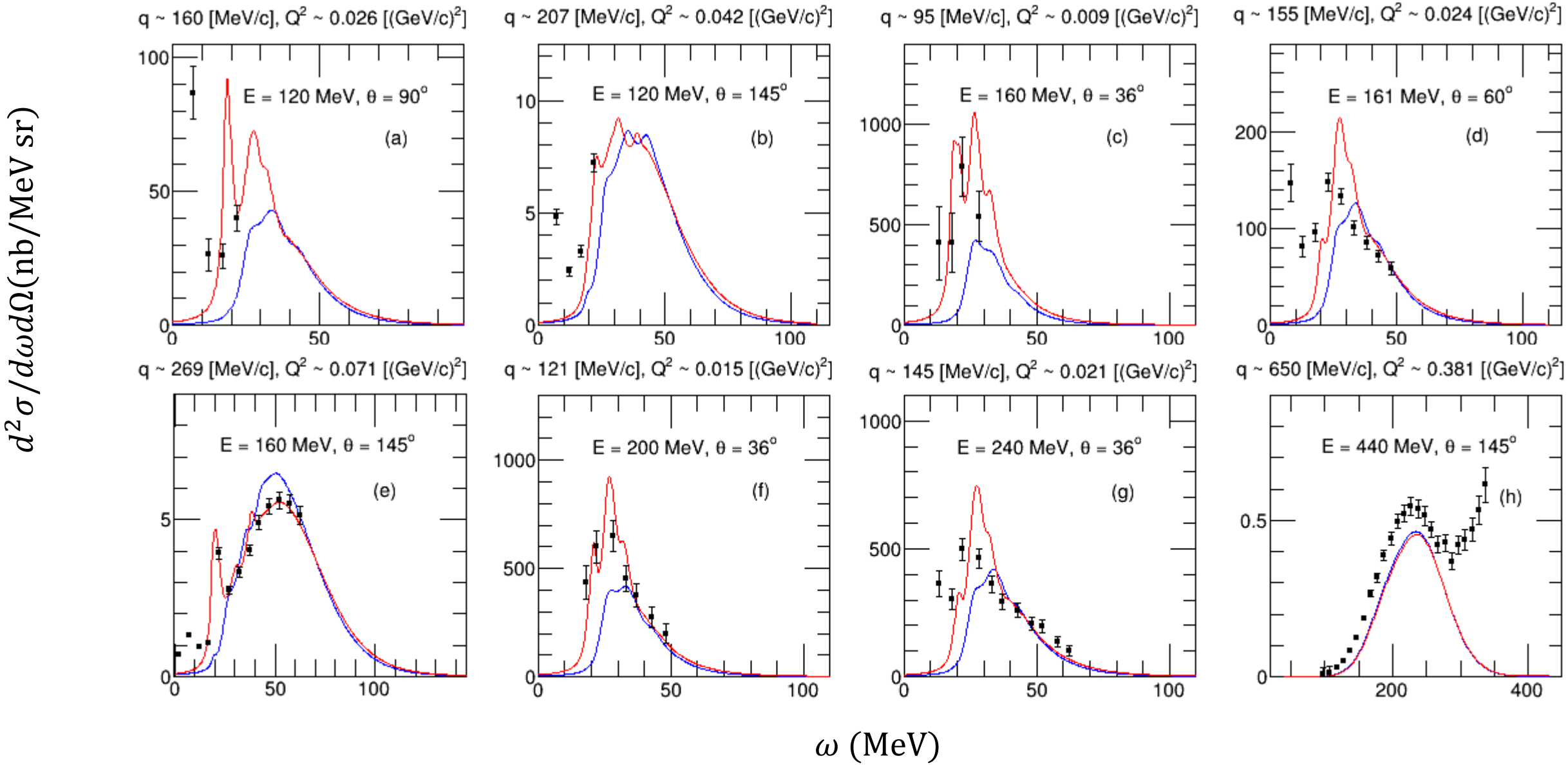
MiniBooNe neutrino on carbon

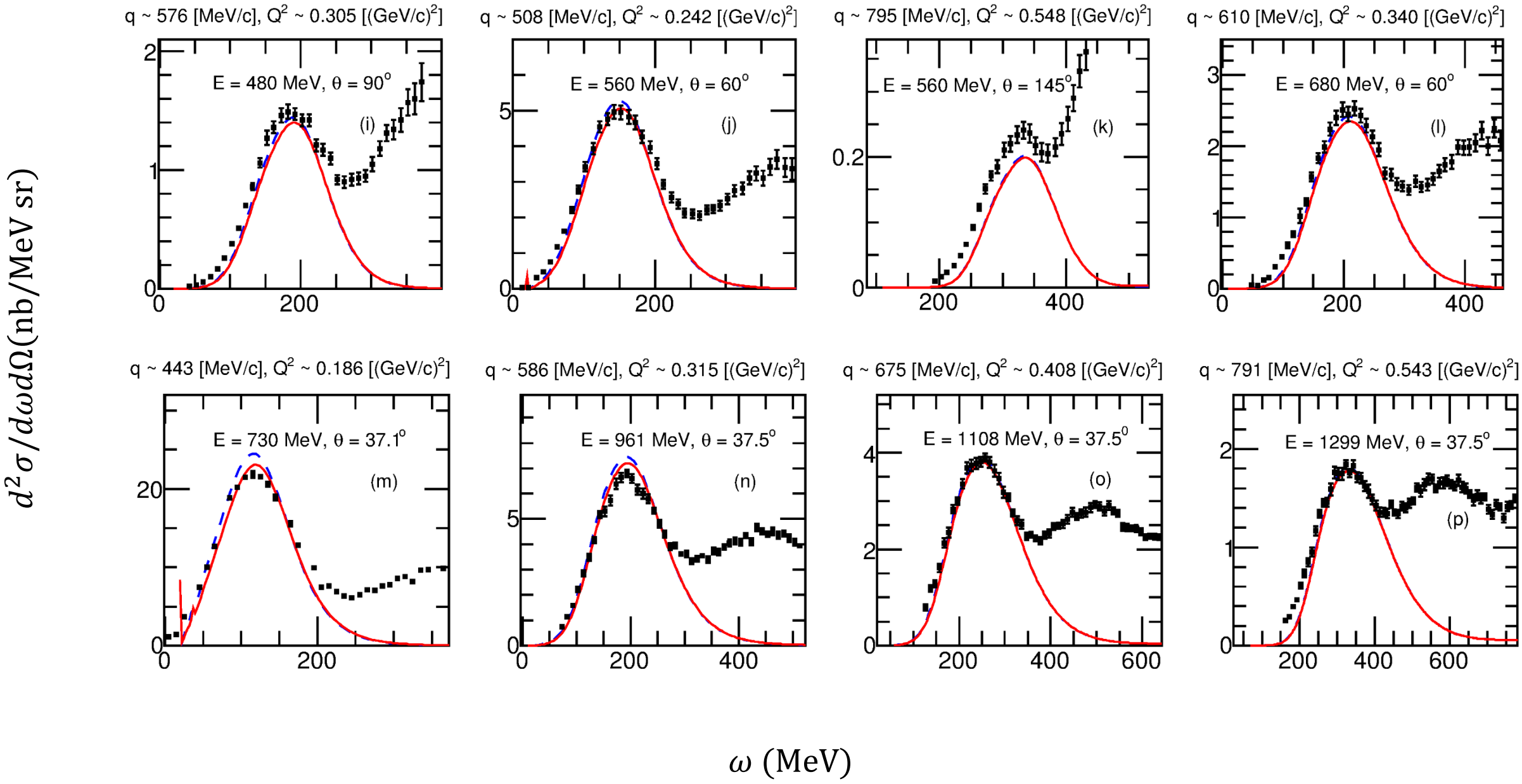


Megias et al., PRD 94, 093004 (2016)

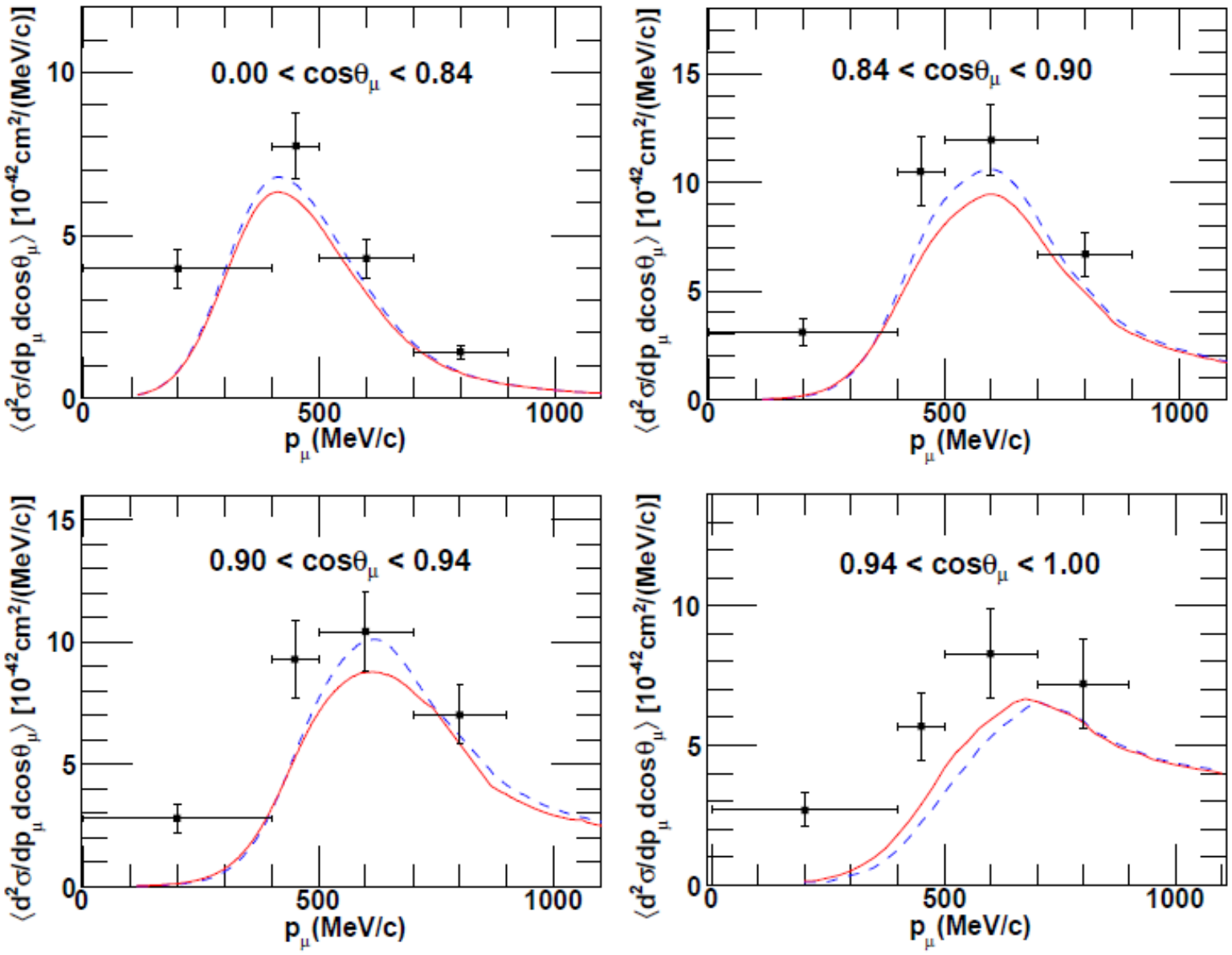
HF-CRPA : comparison with electron scattering data

$^{12}C(e, e')$



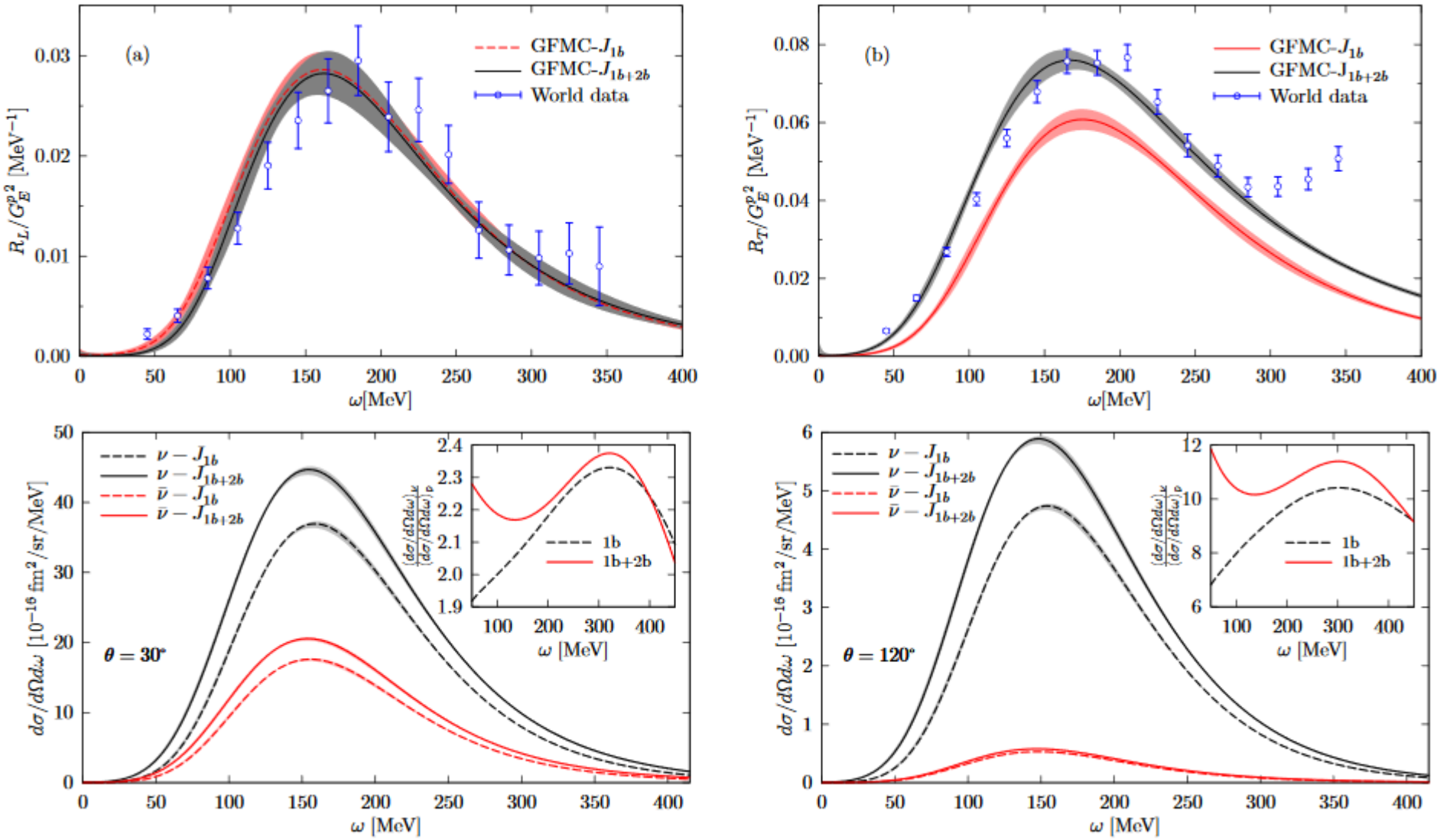

q ~ 576 [MeV/c], Q² ~ 0.305 [(GeV/c)²]
E = 480 MeV, θ = 90°
(i)
q ~ 508 [MeV/c], Q² ~ 0.242 [(GeV/c)²]
E = 560 MeV, θ = 60°
(j)
q ~ 795 [MeV/c], Q² ~ 0.548 [(GeV/c)²]
E = 560 MeV, θ = 145°
(k)
q ~ 610 [MeV/c], Q² ~ 0.340 [(GeV/c)²]
E = 680 MeV, θ = 60°
(l)
q ~ 443 [MeV/c], Q² ~ 0.186 [(GeV/c)²]
E = 730 MeV, θ = 37.1°
(m)
q ~ 586 [MeV/c], Q² ~ 0.315 [(GeV/c)²]
E = 961 MeV, θ = 37.5°
(n)
q ~ 675 [MeV/c], Q² ~ 0.408 [(GeV/c)²]
E = 1108 MeV, θ = 37.5°
(o)
q ~ 791 [MeV/c], Q² ~ 0.543 [(GeV/c)²]
E = 1299 MeV, θ = 37.5°
(p)
$d^2\sigma/d\omega d\Omega$(nb/MeV sr)
ω (MeV)

HF-CRPA : comparison with neutrino data

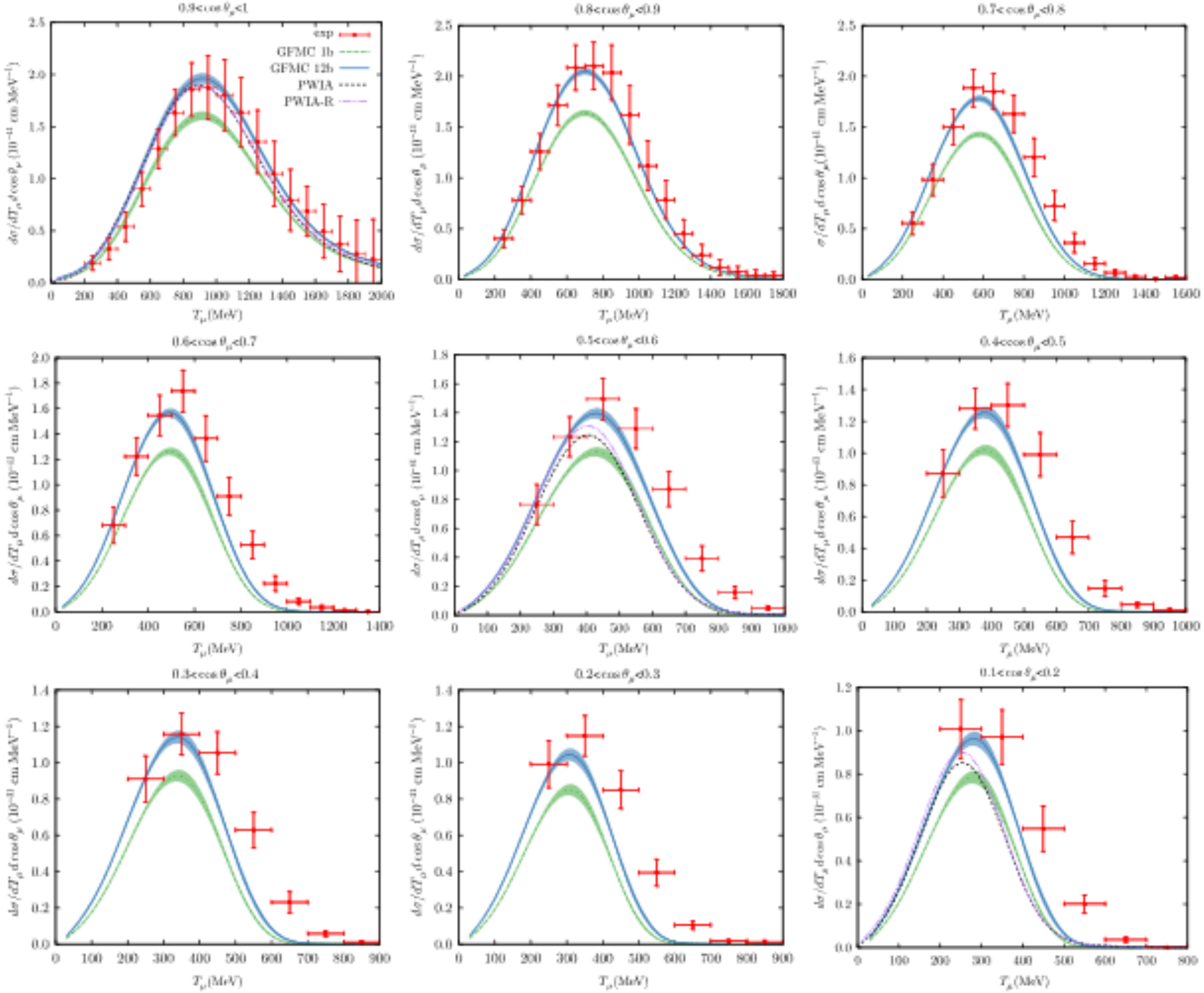


T2K ν_μ

Theory : GFMC

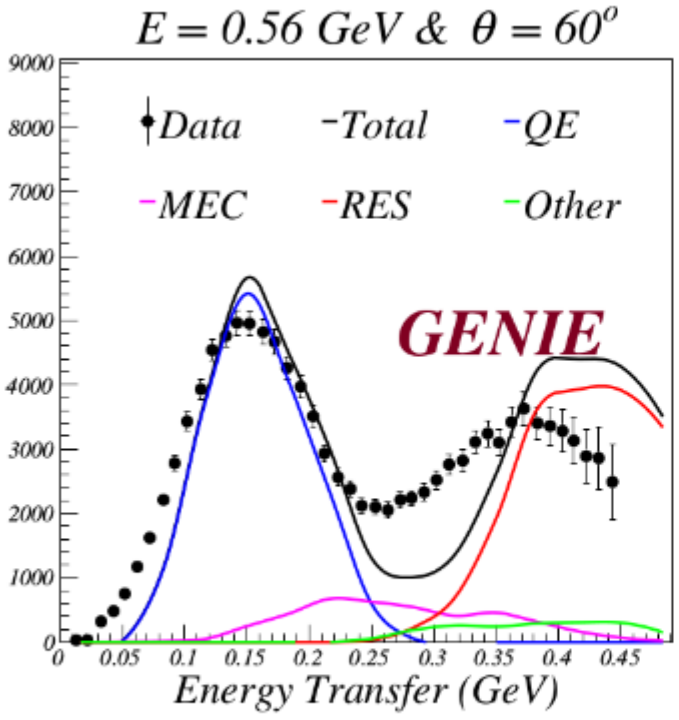


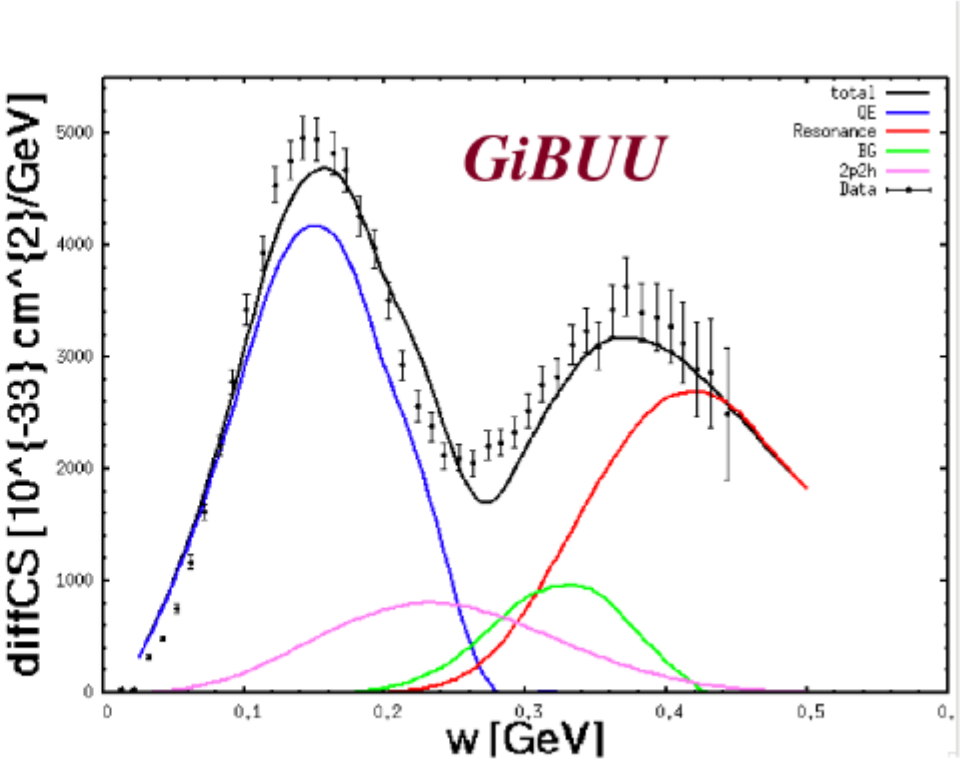
J. E. Lynn, I. Tews,S. Gandolfi,and A. Lovato Annu. Rev. Nucl. Part. Sci. 2019.AA:1–27



Ab initio, MiniBooNe
A. Lovato et all PRX10, 031068 (2020)

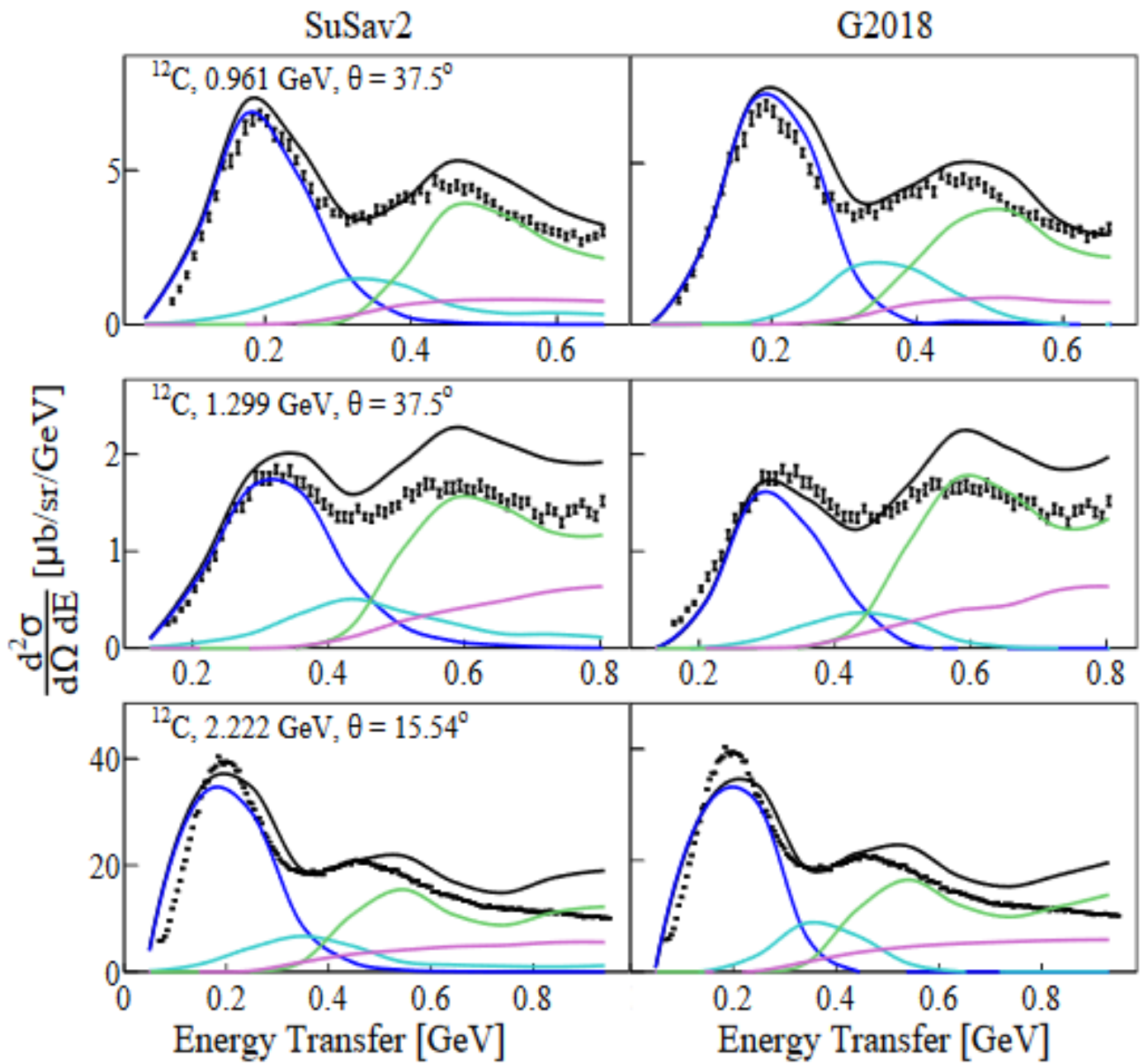
Generators

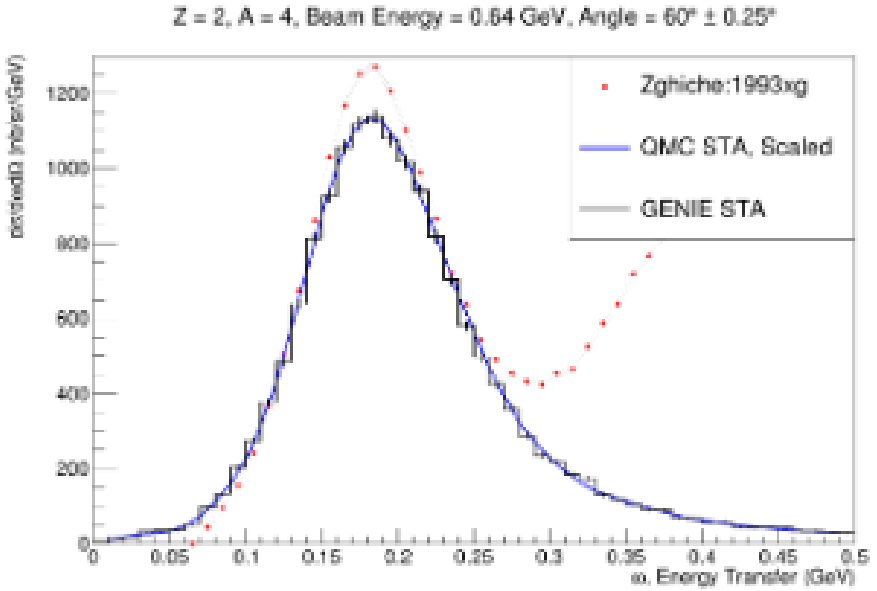


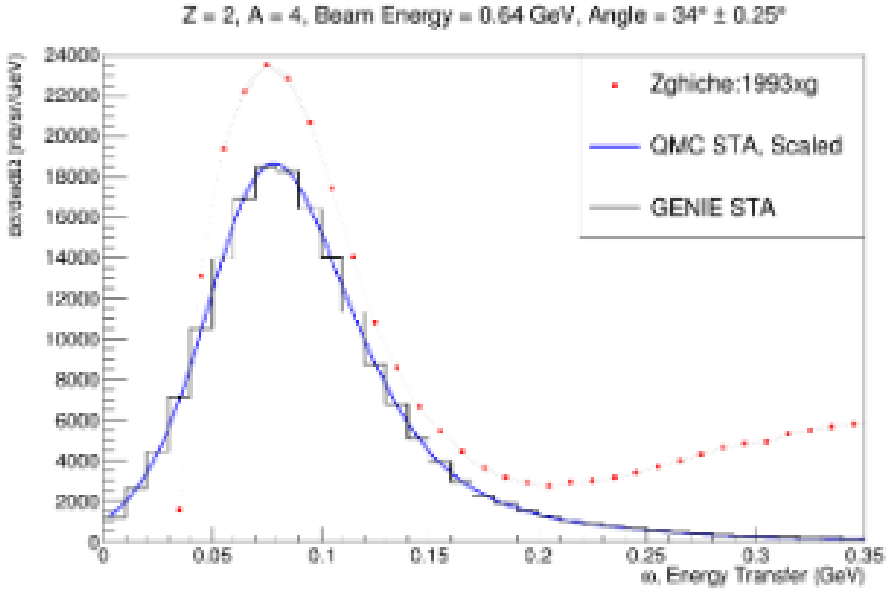


Afroditi Papadopoulo NuInt 2018

e4v
arXiv:2009.07228v1







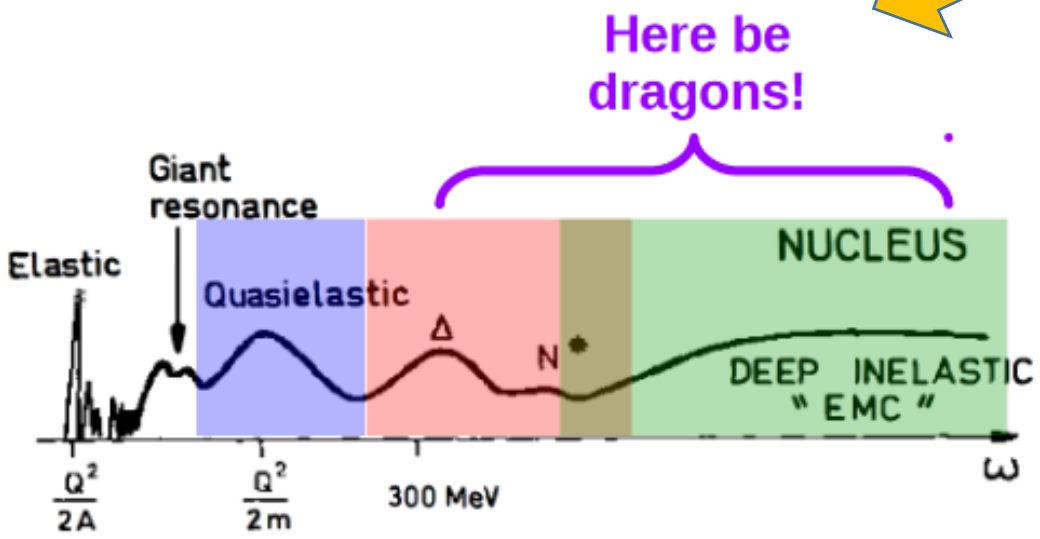
Recent developments !

Short time approximation

Quasielastic Electromagnetic Scattering Cross Sections and World Data Comparisonsin the GENIE Monte Carlo Event Generator

J. L. Barrow, S. Gardiner, S. Pastore, M. Betancourt,and J. Carlson arXiv:2010.04154v1

Pion production



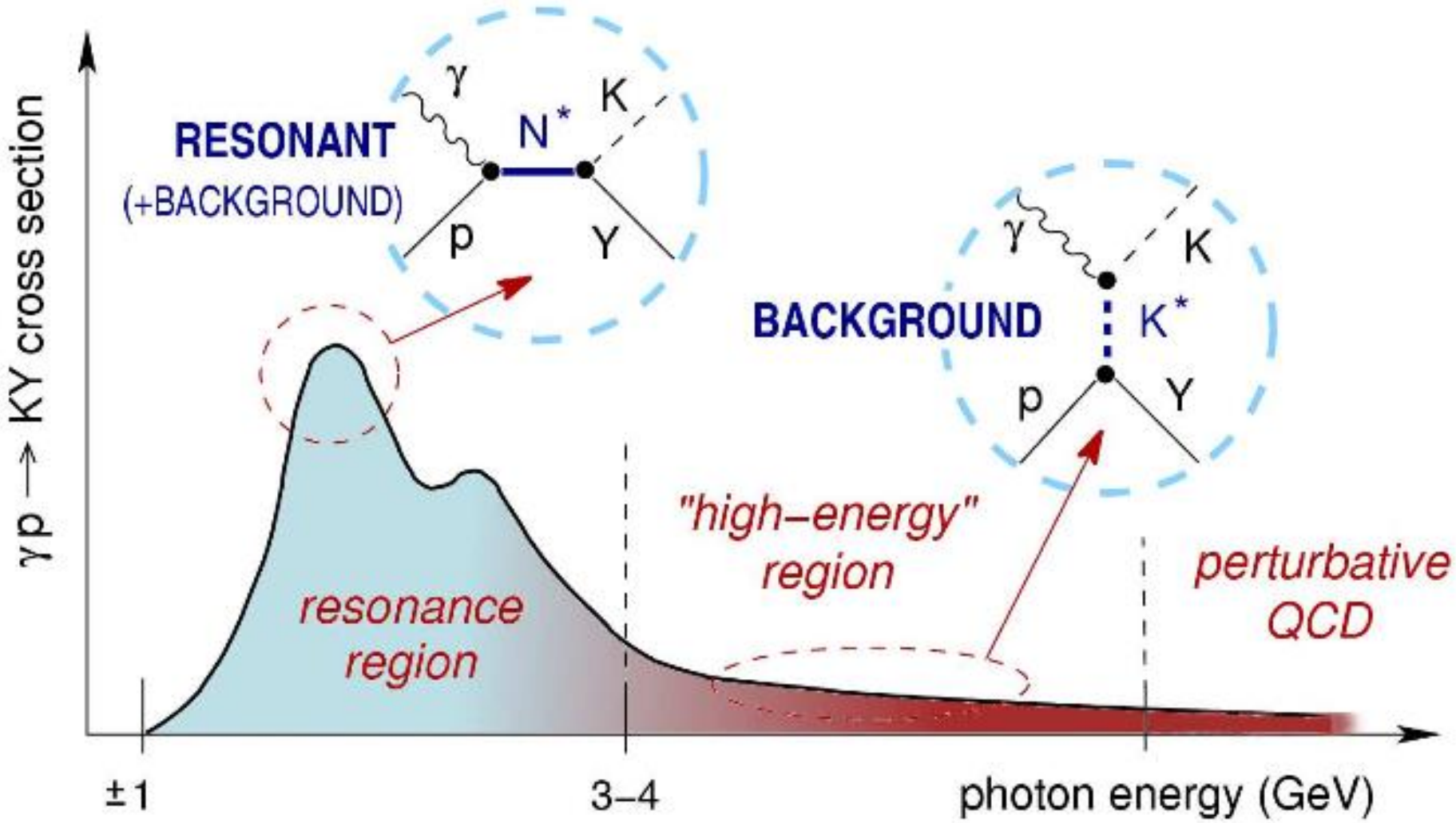
Callum Wilkinson, NuPhys 2019

Pion production from broader ω space than CC0π, spans very different theory models:

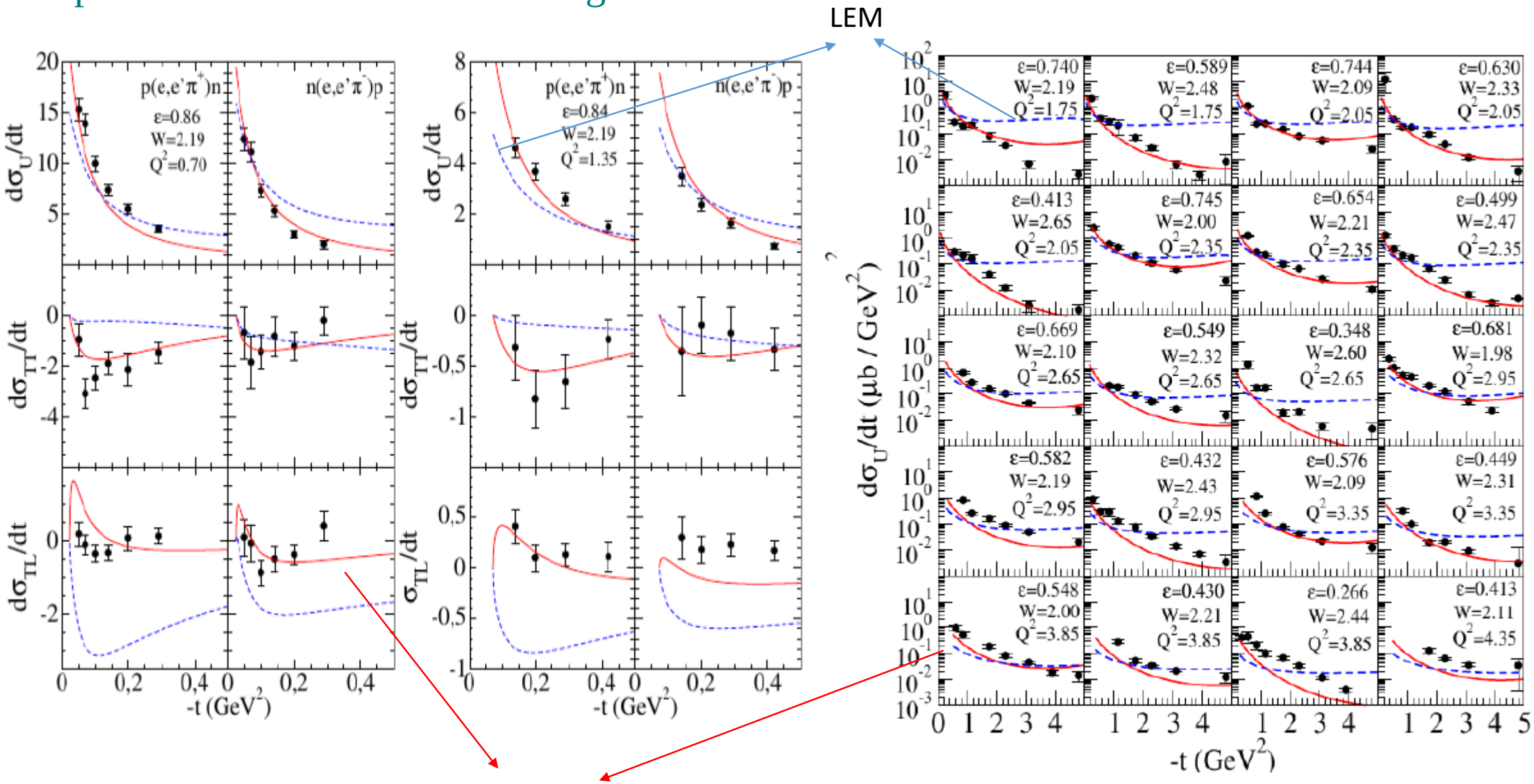
- Coherent
- Resonant
- DIS

ω

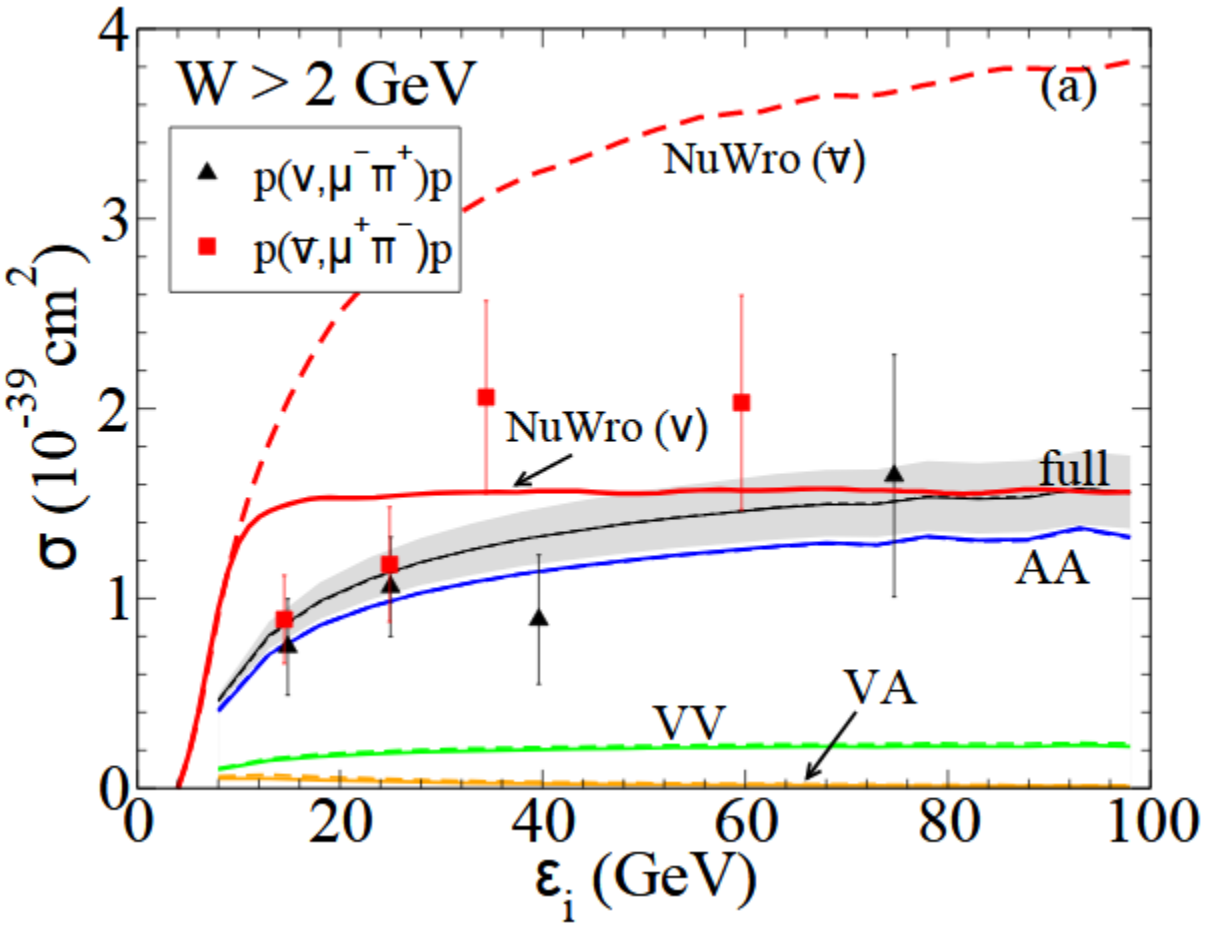
Much harder to measure experimentally (higher multiplicities)

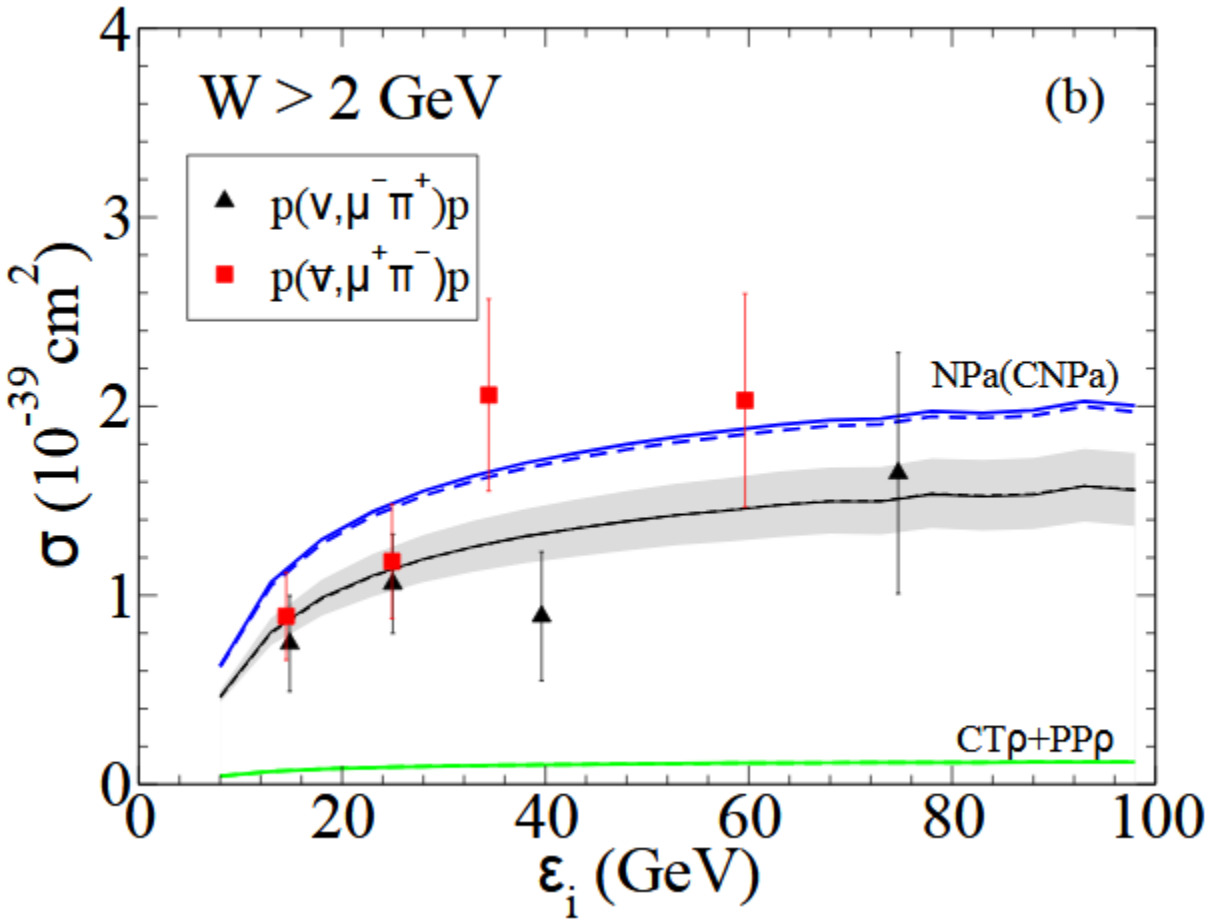

γp → KY cross section
RESONANT
(+BACKGROUND)
γ
N*
K
p
Y
BACKGROUND
γ
K
K*
p
Y
resonance region
"high–energy" region
perturbative QCD
±1
3–4
photon energy (GeV)

Pion production in electron scattering



Neutrino-induced pion production





Data :P. Allen et al. Nucl. Phys. B264, 221 (1986).

Summary ....or ... a wish list

- Electron scattering has been paving the way for a better understanding of neutrino-nucleus physics
- Vector contributions to the cross section are well constrained by electron data through CVC
- Various aspects of nuclear structure and dynamics influencing the cross section can be studied in electron scattering
- *Oscillation developments need more exclusive data and modeling*
- We need more data in kinematic regions that are less strongly covered in 'traditional' electron scattering experiments
- What about 236 electrons vs kaon-decay-at-rest neutrinos ?
- Typical 'neutrino' targets could do with more e-scattering constraints
- SIS - DIS region need much more study
- ….