Measurement of the Coulomb Sum Rule and Suppression of the Longitudinal Quasielastic Crooss section From an analysis of all available electron scattering data on Carbon and Oxygen

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This talk reports on analysis of all available H, D, Carbon and Oxygen electron scattering data (Analysis will be expanded to all nuclei)

- We update the Bosted-Christy fit to **all of the world's electron scattering data** on H, D and nuclear targets to include the lowest **values of energy transfer ν and q^2** (for **carbon we fit about 8000 cross section measurements and 250 measurements for Oxygen**). We fit the **QE cross section (including Transverse Enhancement/MEC, +longitudinal low q suppression)** **resonance and pion production**, **DIS, nuclear excitations,** elastic scattering data. Note: **Nuclear excitations are significant at low ν and contribute up to 30%** **to the longitudinal Inelastic Coulomb Sum Rule (CSR)**
- Since the cross sections span a large range of energies and scattering angles, we **extract both the longitudinal RL and transverse RT** contributions.

- We parameterize both the **Enhancement of the Transverse QE cross section** and the **Suppression of the Longitudinal QE** **cross** section. **We extract the most precise Coulomb Sum rule as a function of q and compare to theoretical calculations.**
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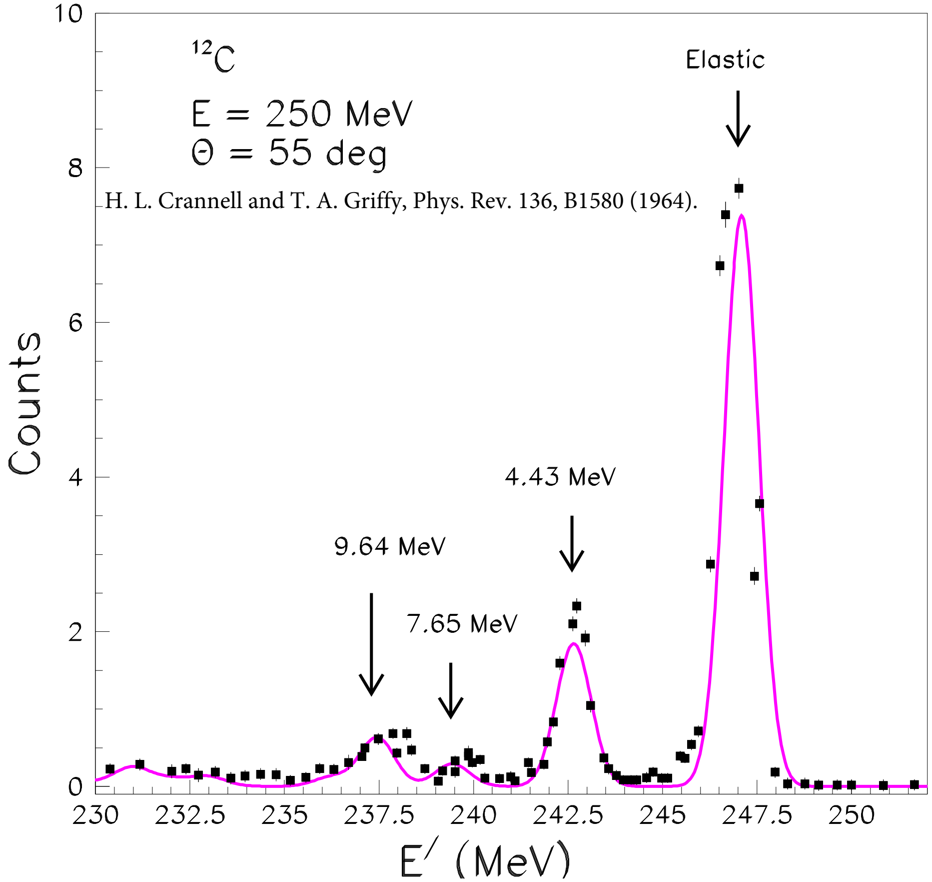
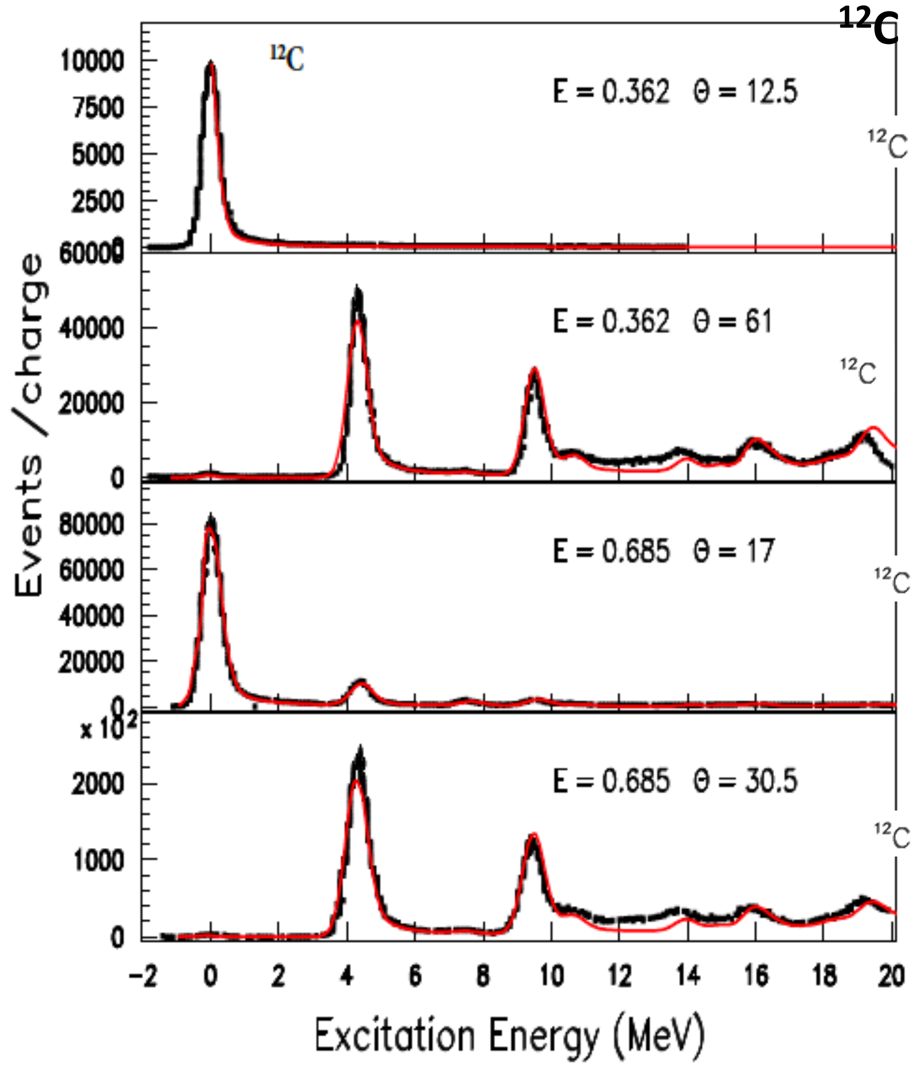
- The fit can be used **in lieu of data to benchmark Monte Carlo predictions** (e.g. for e-H, e-D and e-^{12}C and e-^{1}O cross sections, and to is being used **compute radiative corrections for electron scattering** experiments..

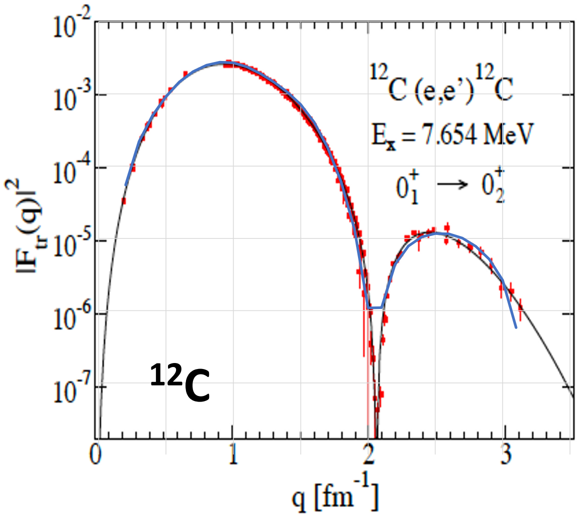
Nuclear excitations in Carbon

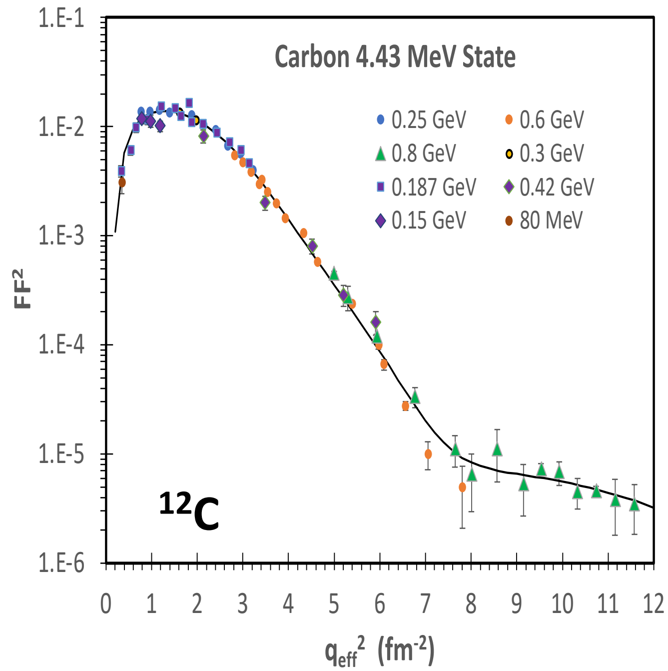


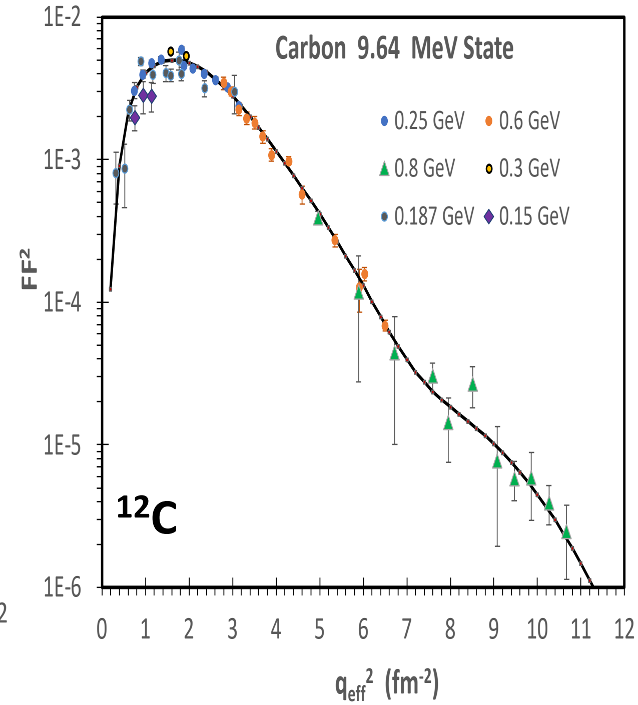


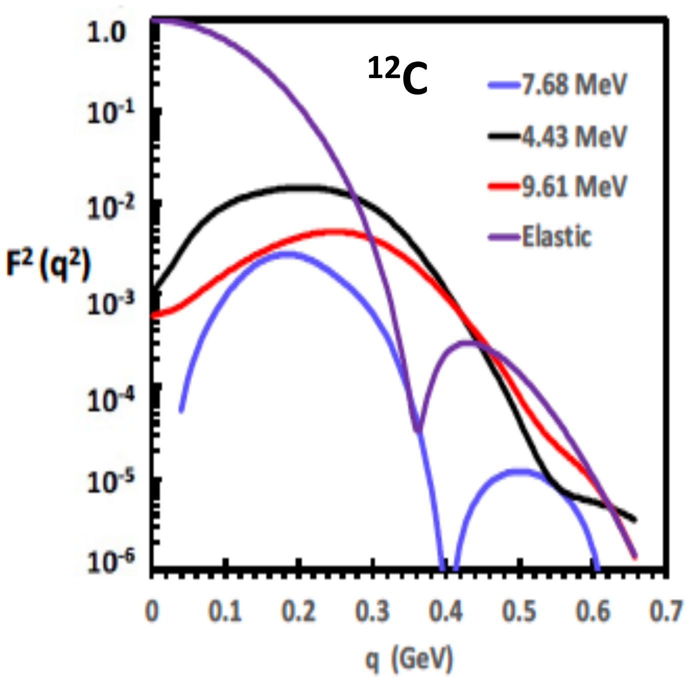
We parameterize form-factors for elastic scattering and for 17 longitudinal and transverse nuclear excitation (2< Excitation Energy<50 MeV) important since they contribution up to 30% to the Coulomb Sum Rule

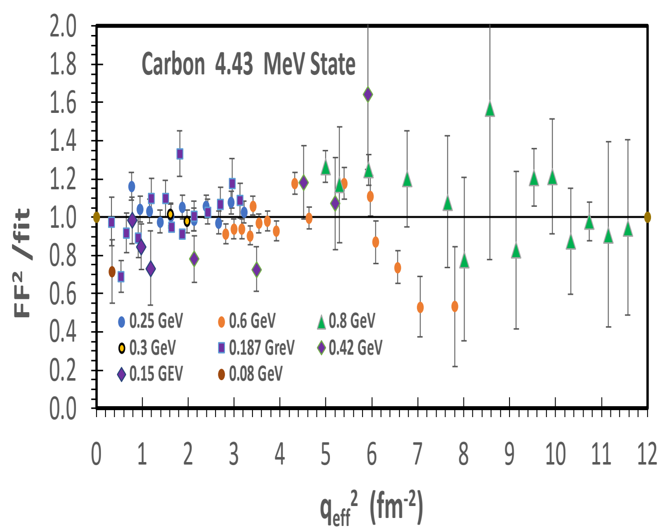
Examples: Squares of Elastic form factor and the form factors for the first 3 nuclear excitation (all are longitudinal)

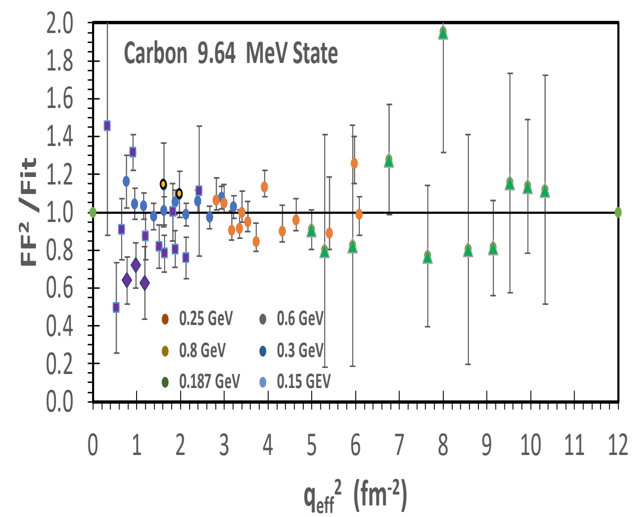












We parameterize form-factors for elastic scattering and for 17 longitudinal and transverse nuclear excitation (2< Excitation Energy<50 MeV)

Cross sections for excitations less than 10 MeV multiplied by (1/6)

Nuclear excitation region

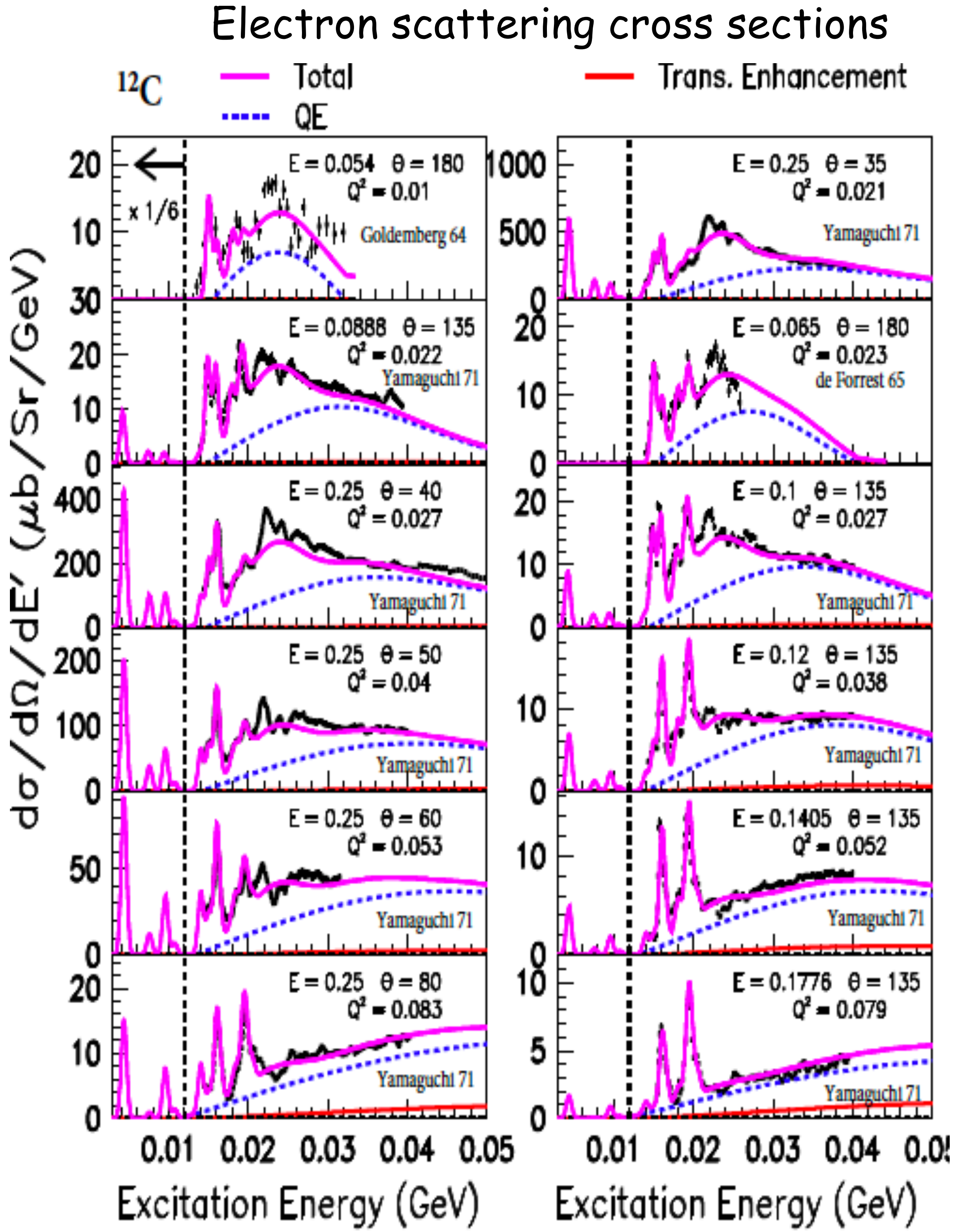
Ex < 50 MeV

Comparison of our fit to representative e-C12 data for **$0.01<q^2< 0.08$ GeV^2** .

Shown: Total including excitations : solid -------

Quasielastic (QE) contribution: dashed------

Transverse Enhancement at large angles accounts for Meson Exchange Currents and Enhancement of TTransverse QE response dashed------



Coulomb Sum rule: Contribution of nuclear excitations

The electron scattering differential cross section can be written in terms of longitudinal ($R_L(\mathbf{q},\nu)$) and transverse ($R_T(\mathbf{q},\nu)$) response functions [7]:

$$\frac{d\sigma}{d\nu d\Omega} = \sigma_M[AR_L(\mathbf{q},\nu) + BR_T(\mathbf{q},\nu)], \quad (1)$$

$$\sigma_M = \frac{\alpha^2\cos^2)(\theta/2)}{4E_0^2\sin^4(\theta/2)}$$

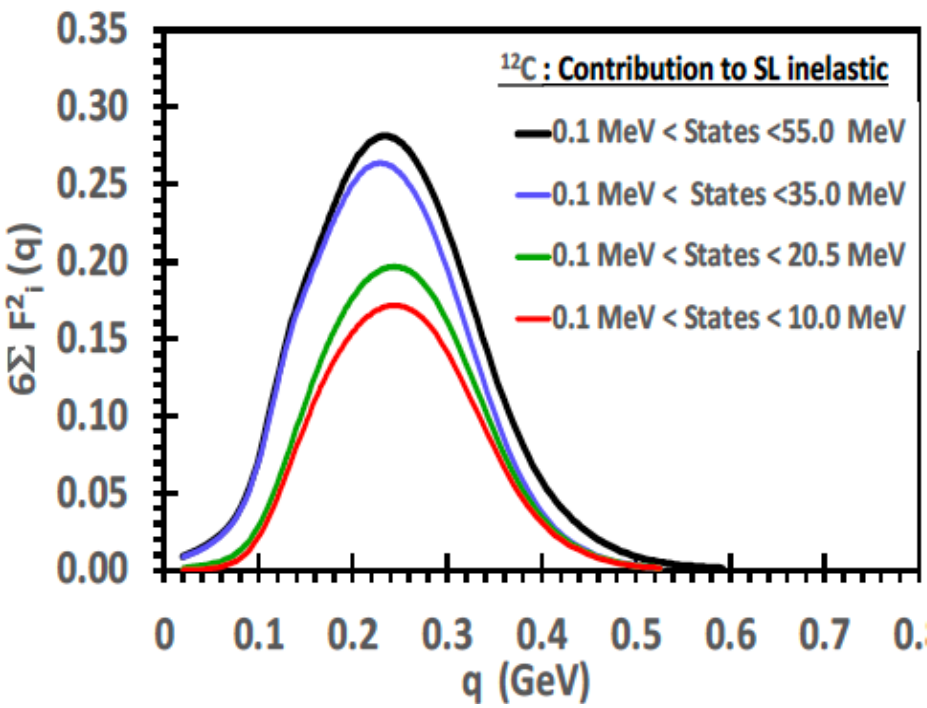
$$\begin{aligned} \mathrm{CSR}(\mathbf{q}) &= \int R_L(\mathbf{q},\nu)d\nu \quad (3) \\ &= \int R_L^{QE}(\mathbf{q},\nu)d\nu + GE'_p(q)\times Z^2\sum_{all}^{L} F_i^2(\mathbf{q}) \\ &= GE'_p(q)\times[Z\int V_L^{QE}d\nu + Z^2\sum_{all}^{L}F_i^2(\mathbf{q})] \end{aligned}$$

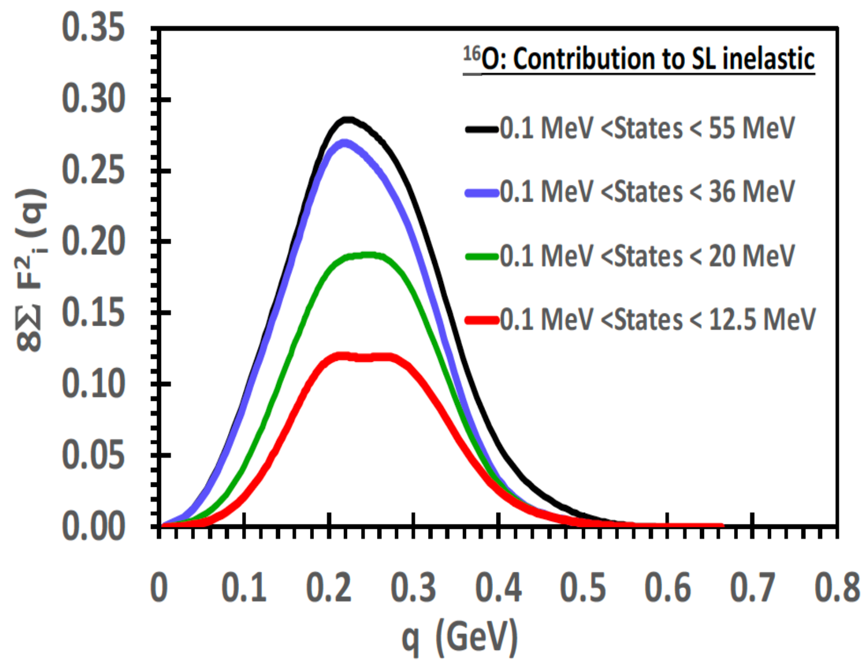
By dividing by $ZGE'_p(\mathbf{q})$ we obtain the normalized inelastic Coulomb Sum Rule is:

$$SL(\mathbf{q}) = \int V_L^{QE}(\mathbf{q},\nu)d\nu + Z\sum_{all}^{L}F_i^2(\mathbf{q}) \quad (5)$$

At very low q, $SL_{inelastic} = 0$

At high q expect $SL_{inelastic} = 1$





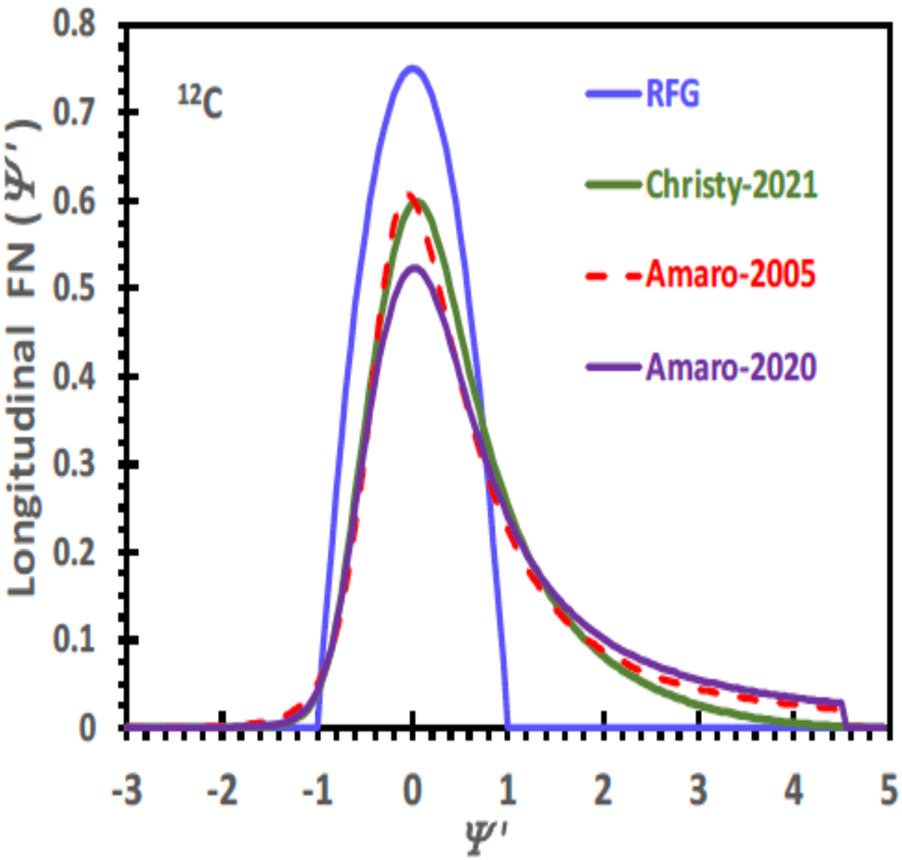
Modeling QE:

Use superscaling- Fit for the longitudinal scaling function parameters in the overall fit

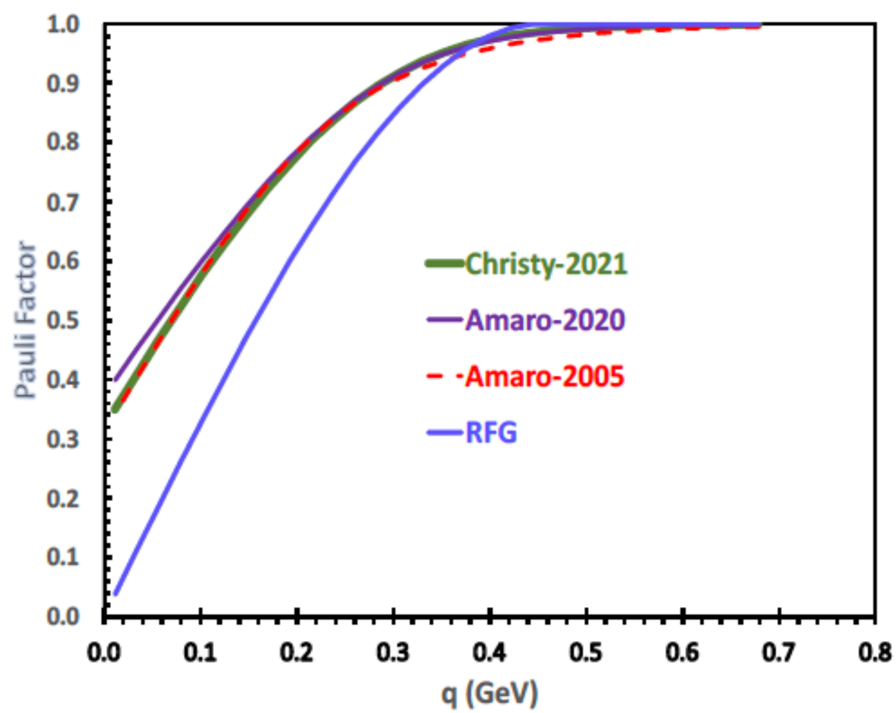
The ψ' superscaling variable is given by the following expression:

$$\psi' \equiv \frac{1}{\sqrt{\xi_F}} \frac{\lambda' - \tau'}{\sqrt{(1+\lambda')\tau' + \kappa\sqrt{\tau'(1+\tau')}}}, \qquad (16)$$

where $\xi_F \equiv [\sqrt{1+\eta_F^2} - 1]$, $\eta_F \equiv K_F/M_n$, $\lambda \equiv \nu/2M_n$, $\kappa \equiv |\mathrm{q}|/2M_n$ and $\tau \equiv |Q^2|/4M_n^2 = \kappa^2 - \lambda^2$.



We include Rosenfelder Pauli suppression



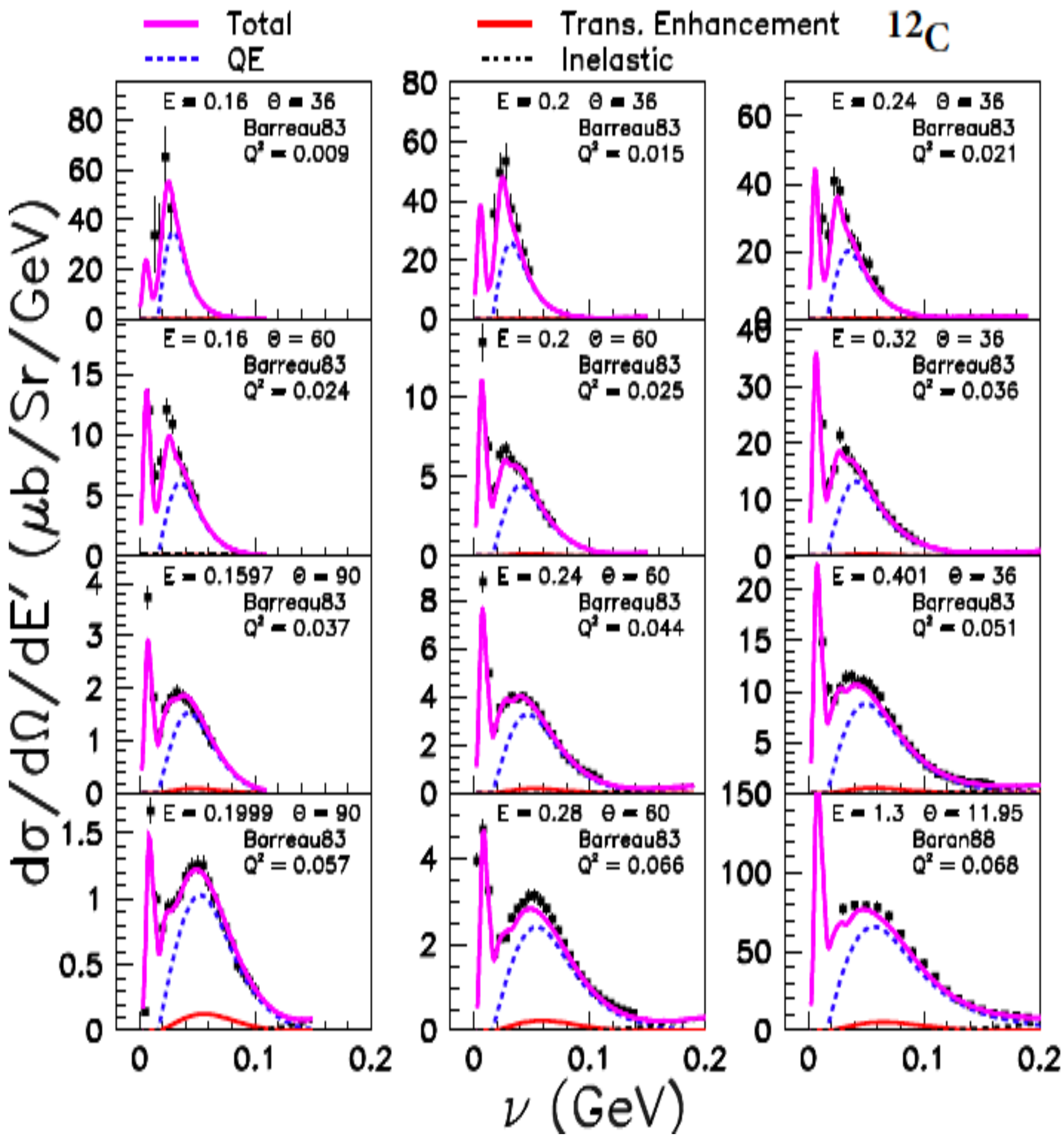
Quasielastic (QE) Region-I

Comparison of our fit to representative e-C12 data **For ν < 0.2 GeV and 0.01 <q^2< 0.068 GeV^2 .**

Shown: Total including excitations solid -------

Quasielastic (QE) contribution dashed ------

Transverse Enhancement at large angles accounts for Meson Exchange Currents and Enhancement of Transverse QE response dashed------



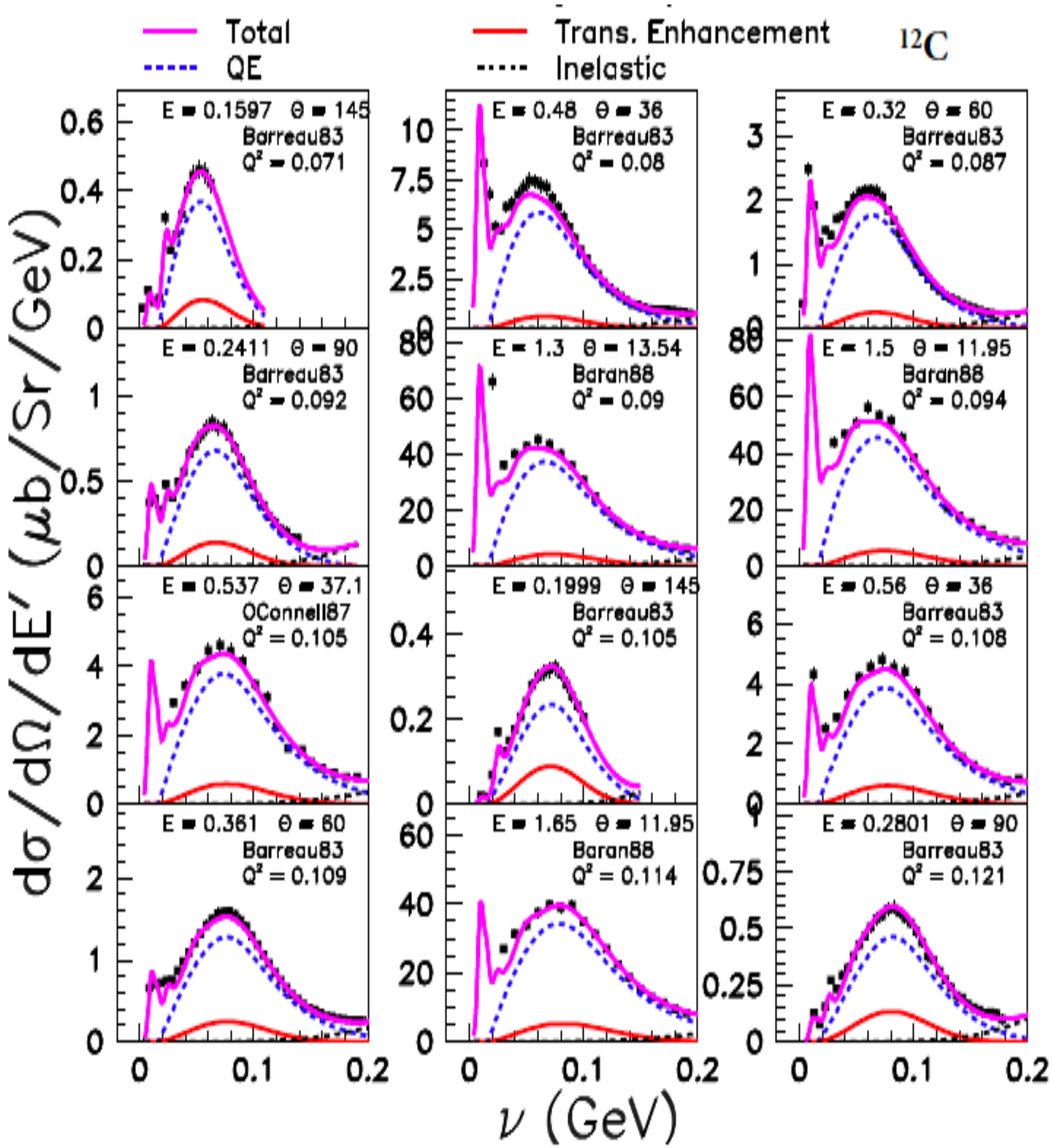
Quasielastic (QE) Region II

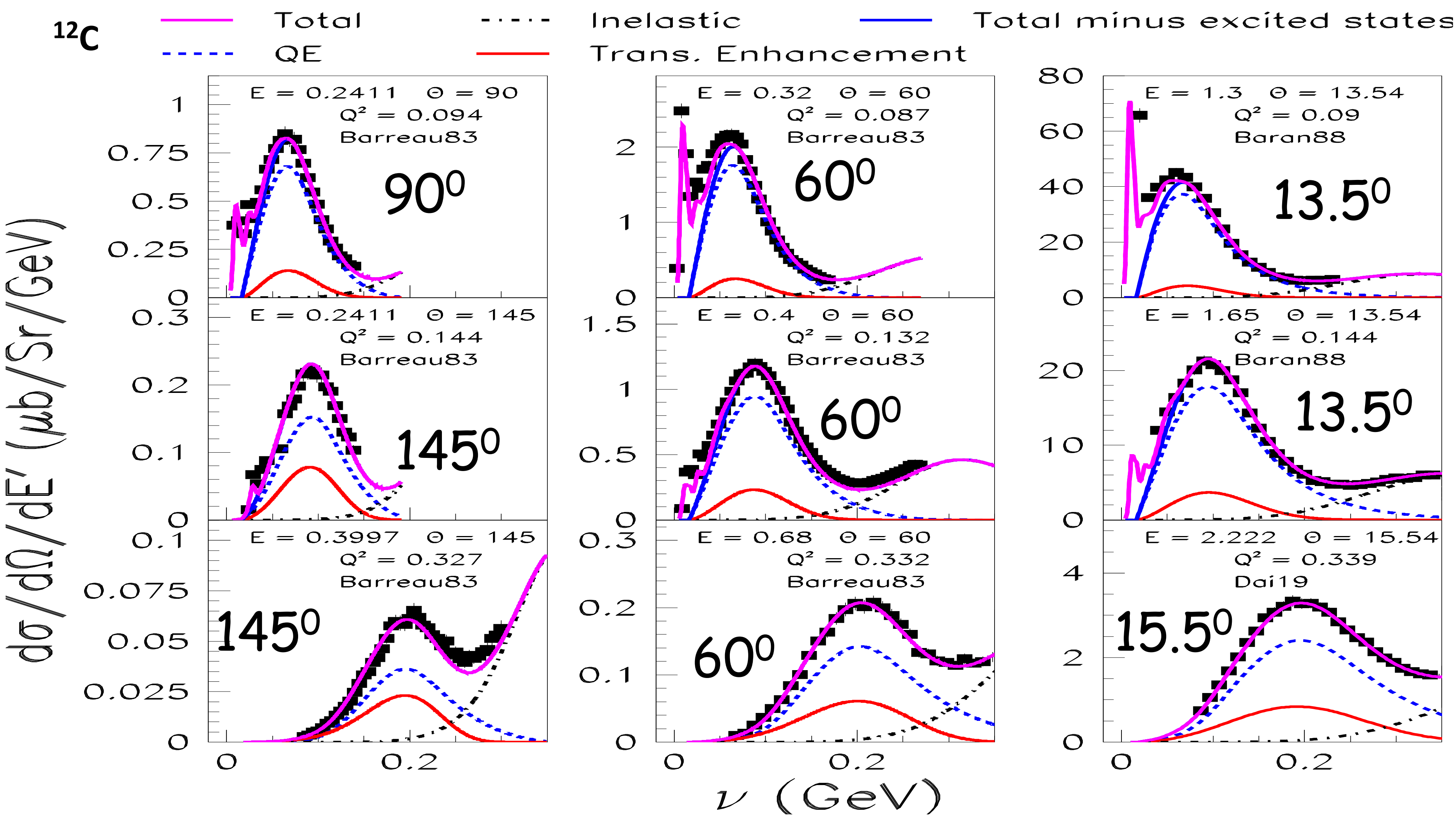
Comparison of our fit to representative e-C12 data for **< 0.2 GeV and**
0.071 <q^2< 0.121 GeV^2 .

Shown: **Total including excitations solid -------**

Quasielastic (QE) contribution dashed ------

Transverse Enhancement at large angles accounts for Meson Exchange Currents and Enhancement of Transverse QE reponse dashed------

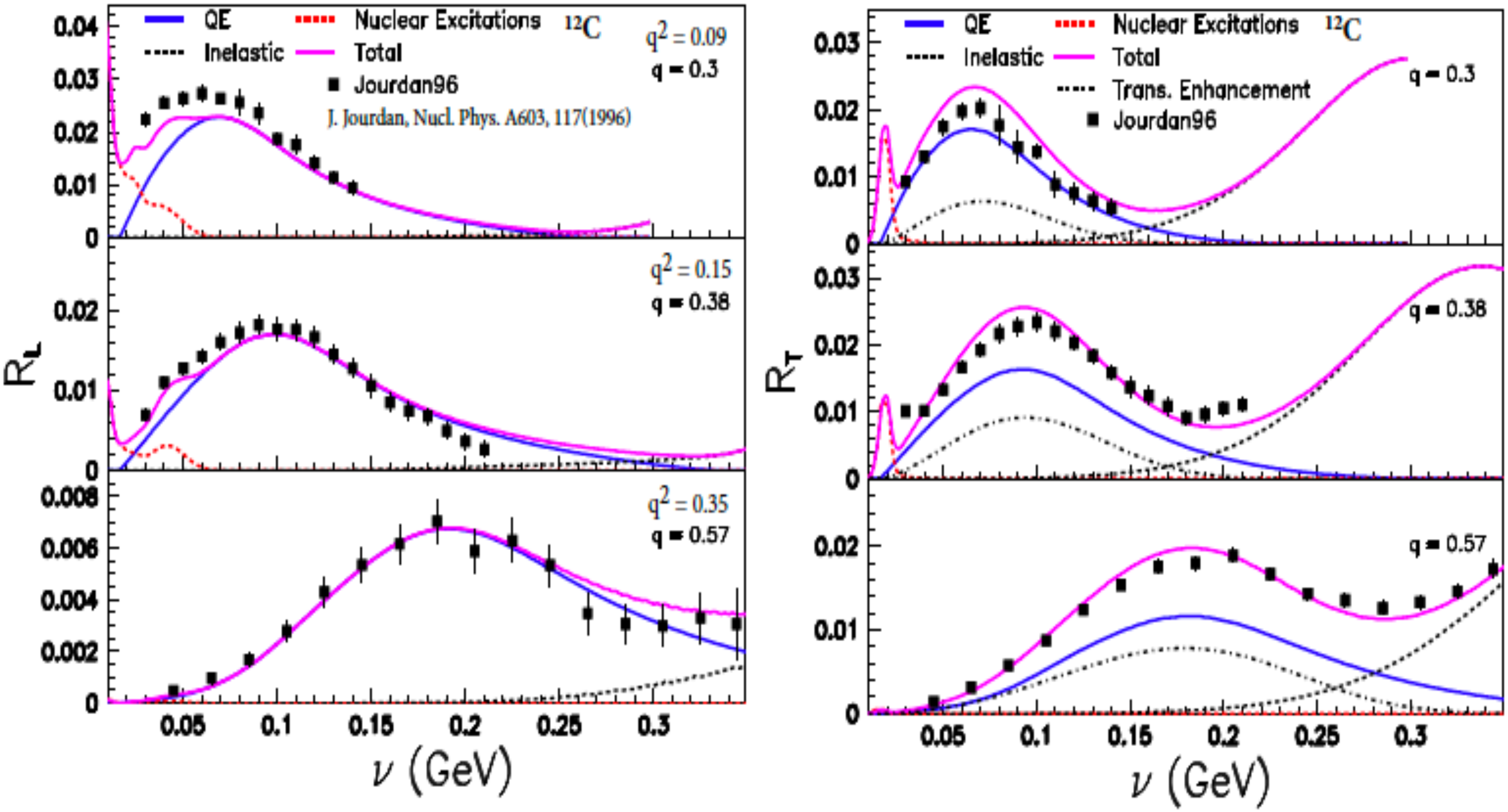




The overall fit provides R_L and R_T at all values of q

Shown are **large and small angle cross sections at the same q** that provide the major contribution to the extraction of R_L and R_T at

q^2=0.09, 0.15 and 0.35 GeV^2 (q=0.3, 0.38 and 0.57 GeV)



Comparison of our R_L and R_T from our universal fit to (~8000 cross sections) to previou extraction by Jourdan at **q^2=0.09, 0.15 and 0.35 GeV^2. (q=0.3, 0.38 and 0.57 GeV)**

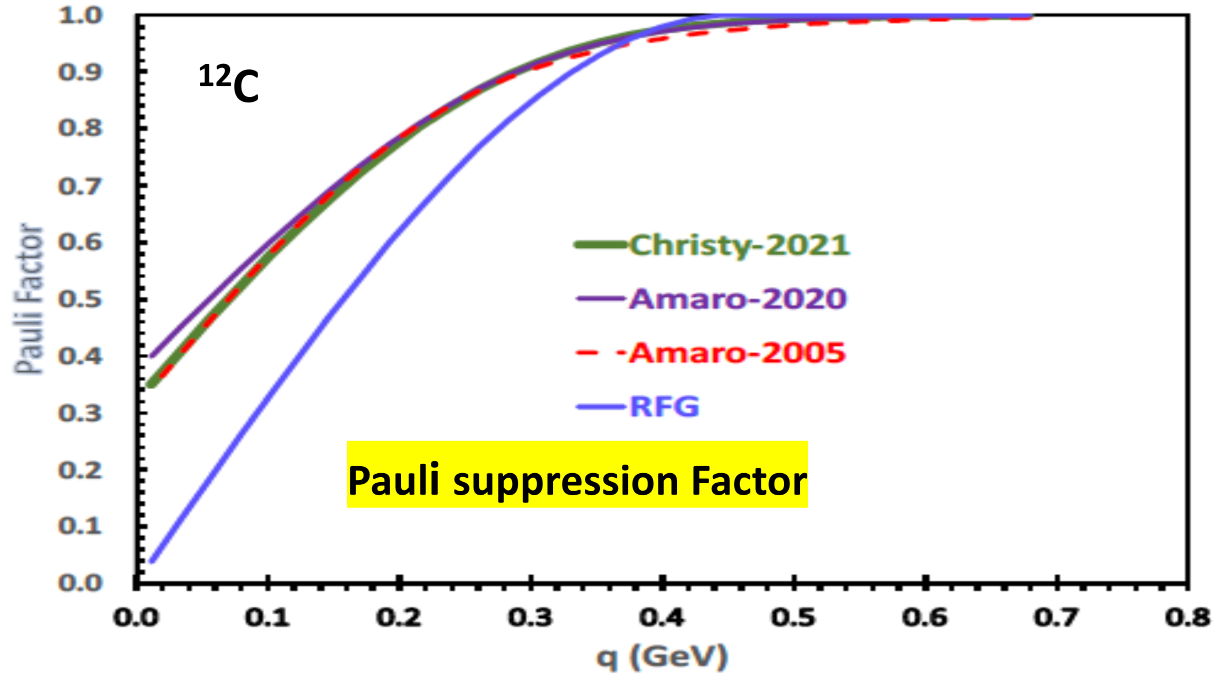
Our extraction is more reliable since we include all of the world's data in the fit

- **At low q** the contribution of the **nuclear excitations** important.
- The **superscaling fit function** describes the QE distribution at higher ν.
- **Resonance region** is modeled with **Fermi Smeared H and D data**.

Pauli Suppression Factor. We use the Rosenfelder method.

P_1= Pauli factor for the Christy 2021 QE superscaling model.

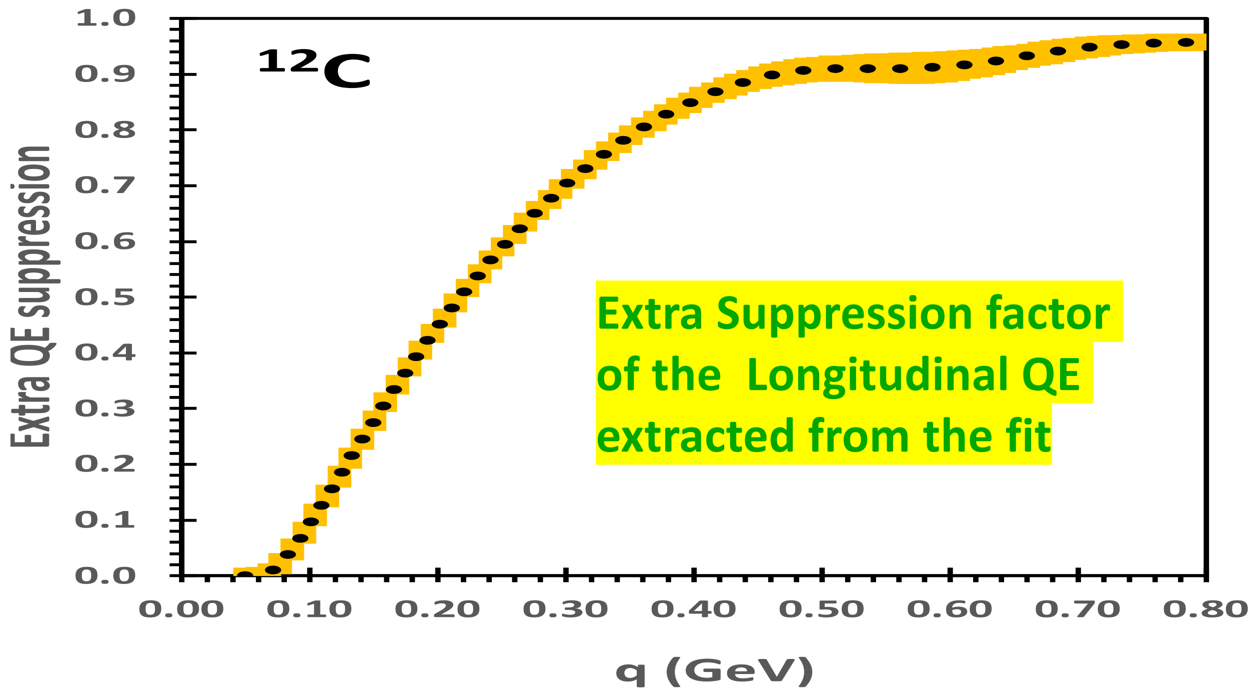
P_2 = Pauli factor for another QE model (e.g. Amaro-2020)



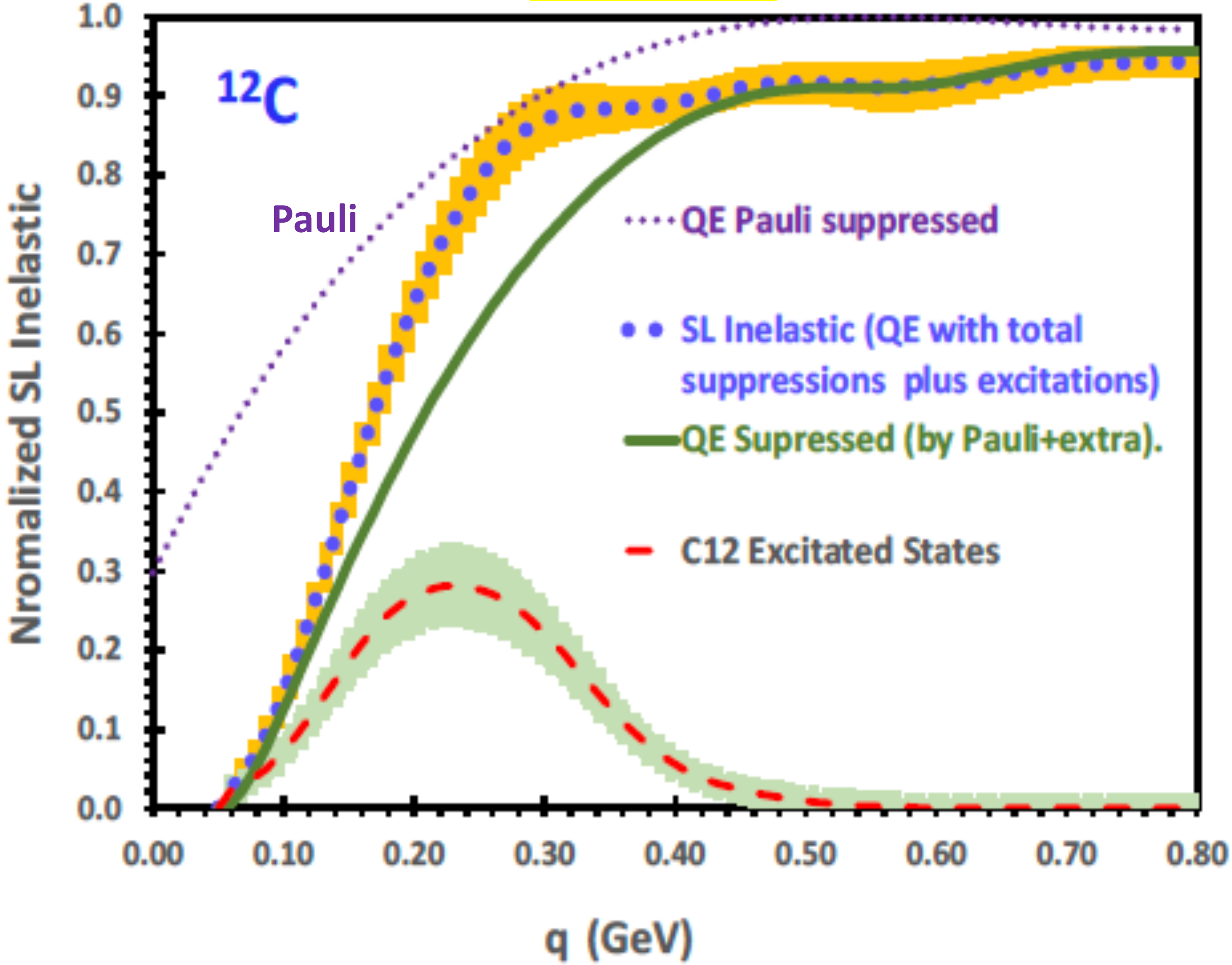
ES_1 =The Extra Suppression of the longitudinal QE cross section (in addition to Pauli) extracted from the fit

ES_2 = Extra Suppression for another QE model

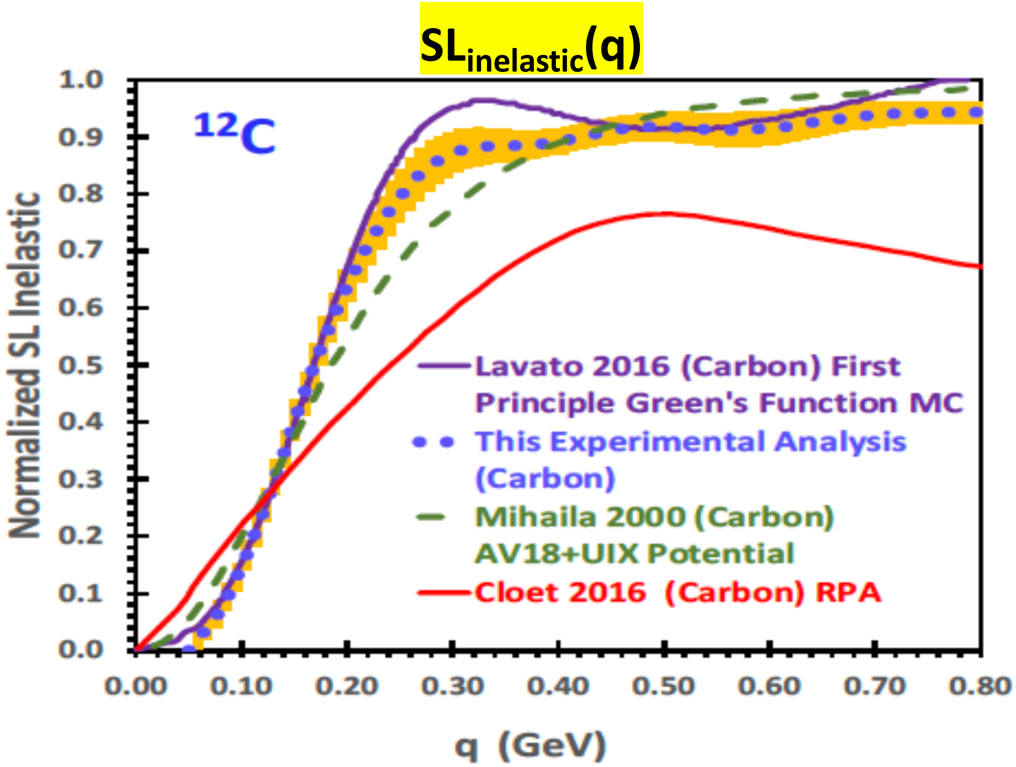
ES_2= ES_1 (P_1/P_2)



$SL_{inelastic}(q)$



The different contribution from our fit to the extracted Inelastic Coulomb sum Rule: **$SL_{inelastic}(q)$**



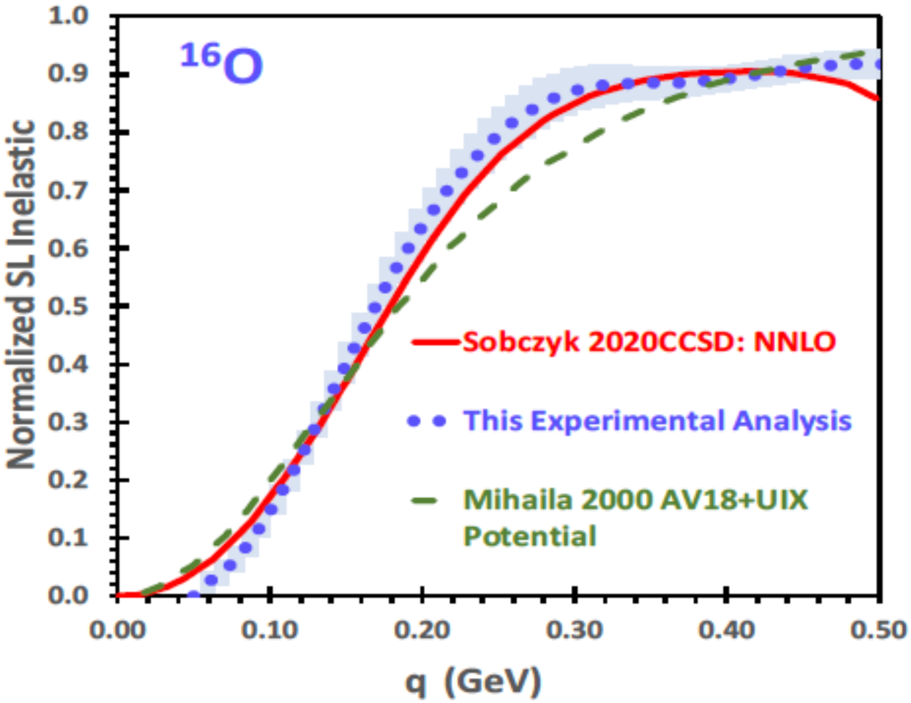
Comparison to theory for <u>Coulomb sum Rule</u>: SL$_{inelastic}$(q) ^{12}C

1. Reasonable agreement with Lavato 2016 First Principle Green's function MC.
2. Poor agreement with Mihaila 2010 Coupled Cluster AVI8-UIX potential
3. Poor agreement with Cloet 2016 (RPA)

A. Lovato et. al, Phys. Rev. Lett. 117, 082501 (2016)

Ian C. Cloet, Wolfgang Bentz, Anthony W. Thomas, Phys. Rev. Lett. 116, 032701 (2016) (arxiv.org/abs/1506.05875).

. Bogdan Mihaila and Jochen H. Heisenberg, Phys, Rev. Lett. 84 (2000) 1403. 2009.01761 [nucl-th]



Comparison to theory for <u>Coulomb sum Rule</u>: SL$_{inelastic}$(q) ^{16}O

1. Reasonable agreement with Sobczyk 2000 CCSD:NNLO

2, Poor agreement with Mihaila 2010 Coupled Cluster AVI8-UIX potential

J. E. Sobczyk, B. Acharya, S. Bacca, and G. Hagen Phys.Rev.C 102 (2020) 064312 (arXiv: 2009.01761 [nucl-th])

Conclusions

- **We fit all existing e-H, e-D, e- ^{12}C and e-^{16}O data including** elastic, nuclear excitations, Quasielastic, Resonance and Inelastic region.
- **Fit provides a benchmark** to test electron and neutrino MC generators. (all parameters will be published).
- **The contributions of nuclear excitations** is important at low q and should be added to electron and neutrino MC generators.
- For the QE Longitudinal structure function, we find that the QE cross section is suppressed by **an Extra Suppression in addition to Pauli blocking.** We provide a parameterization of the Extra Suppression.
- We extract the inelastic Coulomb sum rule and compare to theoretical calculations. Since all available e- ^{12}C data is included in the fit, **this is the best extraction of the Inelastic Coulomb Sum Rule from all the world's data on** ^{12}C **.**