Electron Scattering with the SuperScaling Approach

Application to neutrinos

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OUTLINE

- **ELECTRON SCATTERING:**
  - *Scaling Ideas: the Superscaling Approach (SuSA)*
  - *The Relativistic Impulse Approximation (RIA)*
  - *Meson Exchange Currents & Inelastic Processes*
  - *The SuSAv2-MEC Model: comparison with data*
- **APPLICATION TO NEUTRINO SCATTERING REACTIONS:**
  - *Validity of SuperScaling Approach within the RMF*
  - *Application to CC processes: MiniBooNE, NOMAD, MinerVa, T2K*
- **SUMMARY & CONCLUSIONS**

LET'S LOOK AT QE (e, e') DATA

WHAT ARE THEY SHOWING US?

Analysis of experimental cross sections

Experimental scaling function:

$$F(q,y) = \frac{[d\sigma/d\omega d\Omega']_{exp}}{\overline{\sigma}_{eN}(q,\omega;p=-y,\varepsilon=0)}$$

$$\overline{\sigma}_{eN}(q,\omega;p,\varepsilon) \equiv \frac{1}{2\pi}\int d\phi_N \frac{E_N}{q}\left[Z\sigma_{ep}(q,\omega;p,\varepsilon,\phi_N) + N\sigma_{en}(q,\omega;p,\varepsilon,\phi_N)\right]$$

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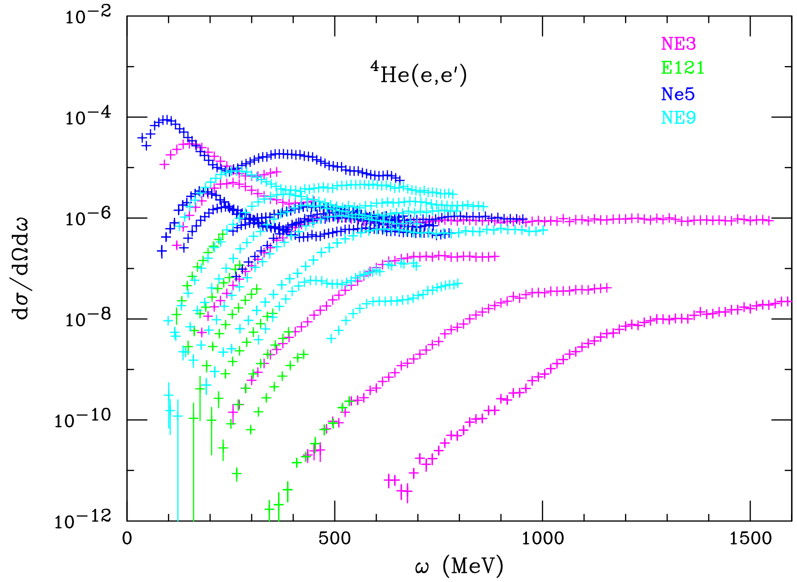

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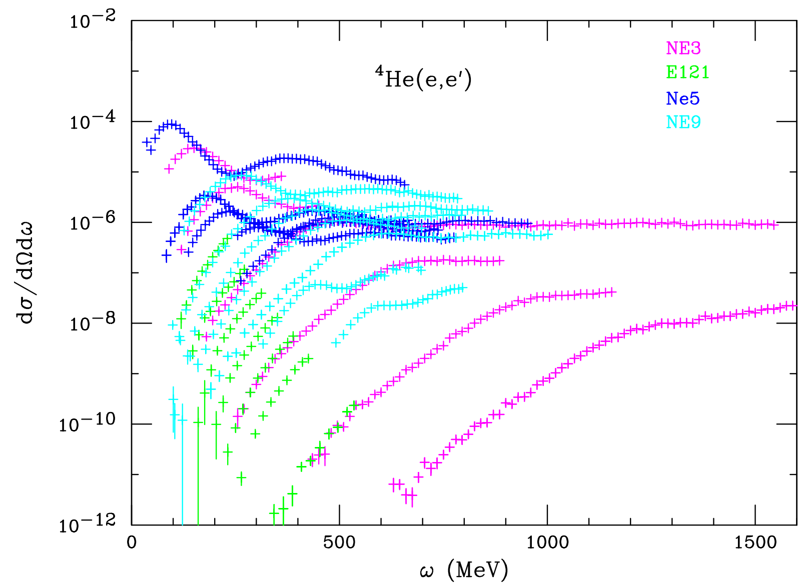
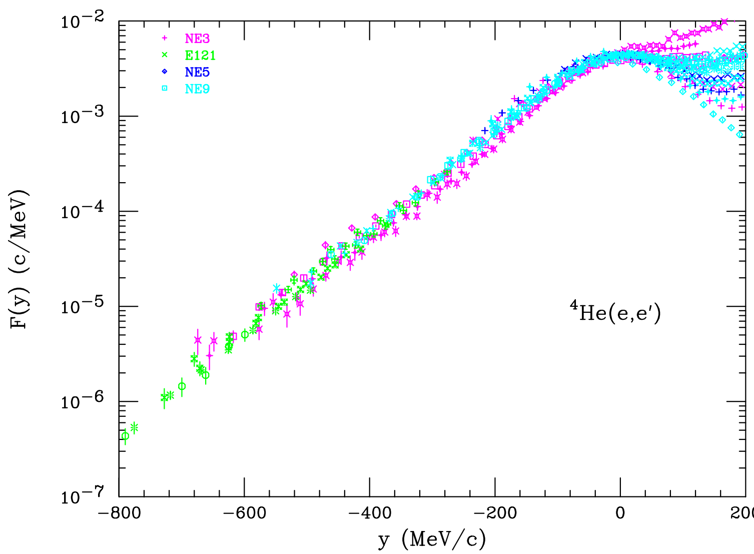
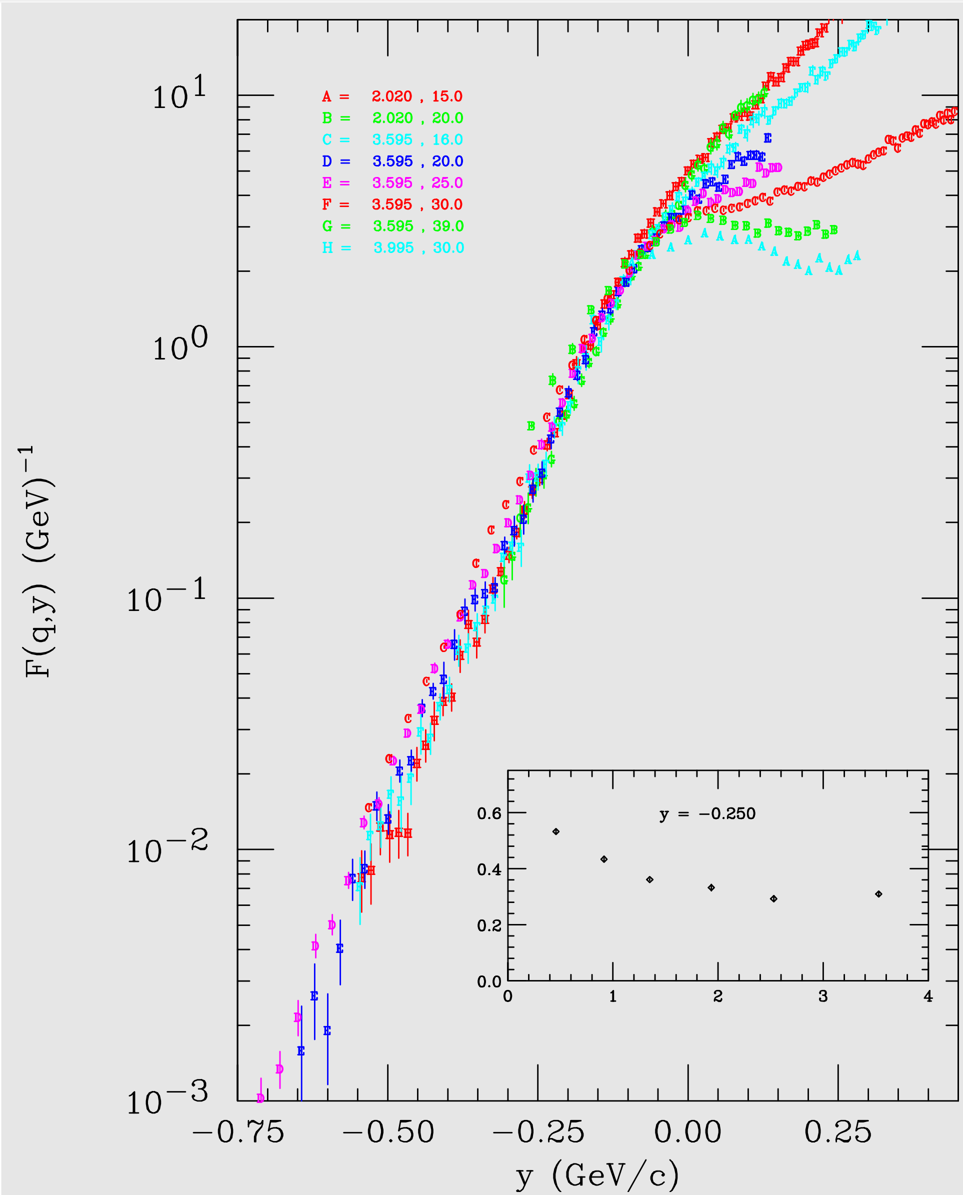




Scaling of the first kind: $q \to \infty \Longrightarrow$ $\boxed{F(q,y) \longrightarrow F(y) \equiv F(\infty,y)}$

Analysis of experimental cross sections



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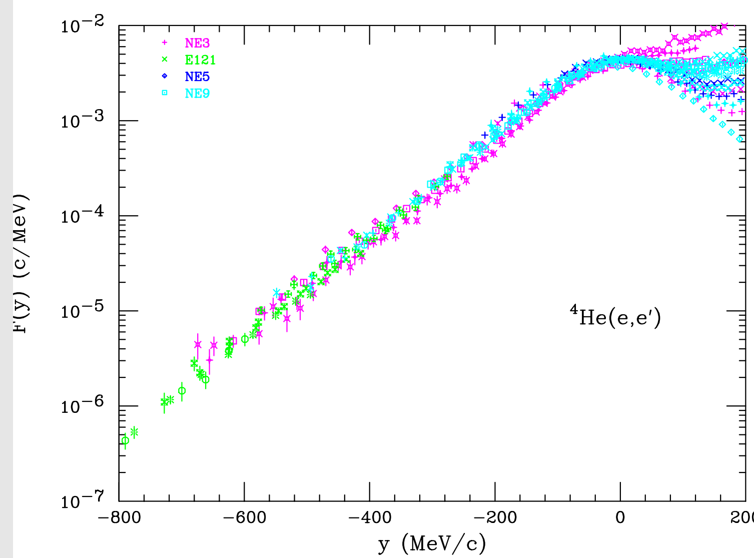
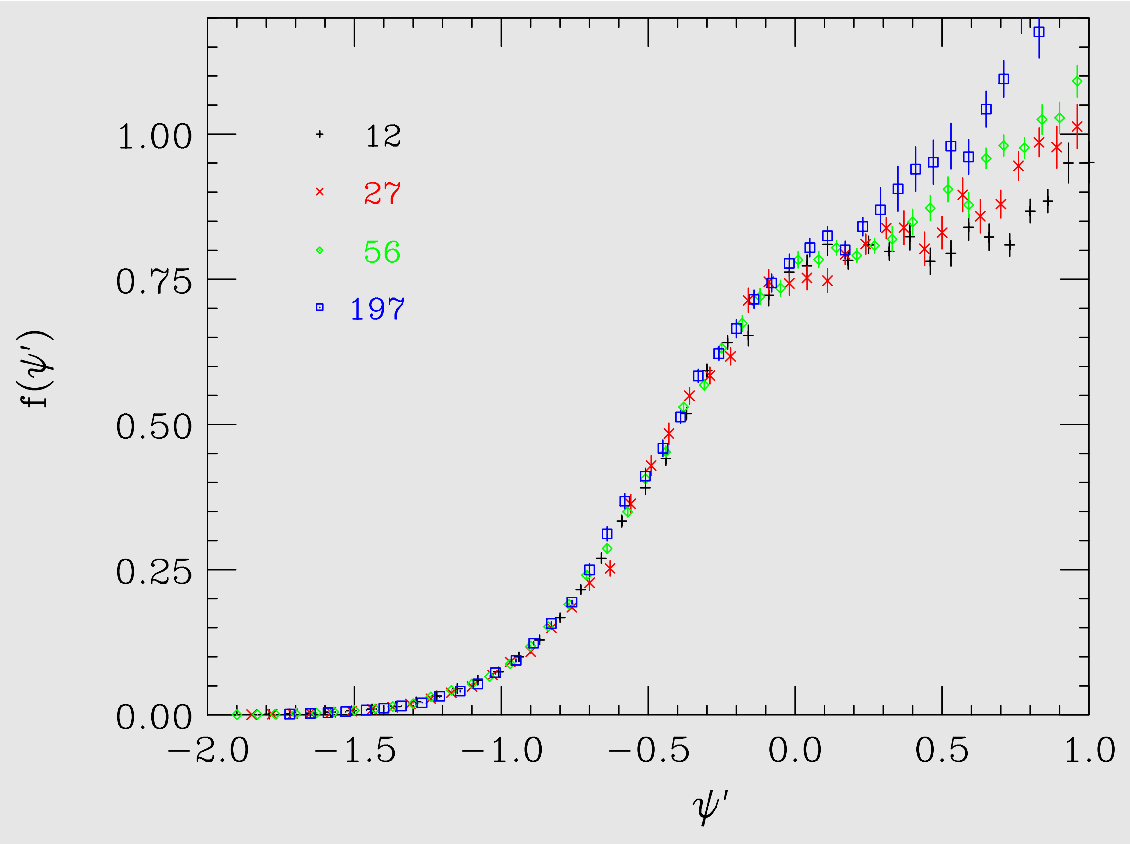
$$q,\omega;p,\varepsilon,\phi_N) + N\sigma_{en}(q,\omega;p,\varepsilon,\phi_N)]$$



$$\Rightarrow \quad F(q,y) \longrightarrow F(y) \equiv F(\infty,y)$$

What are QE (e, e') data showing us? *Cross sections*



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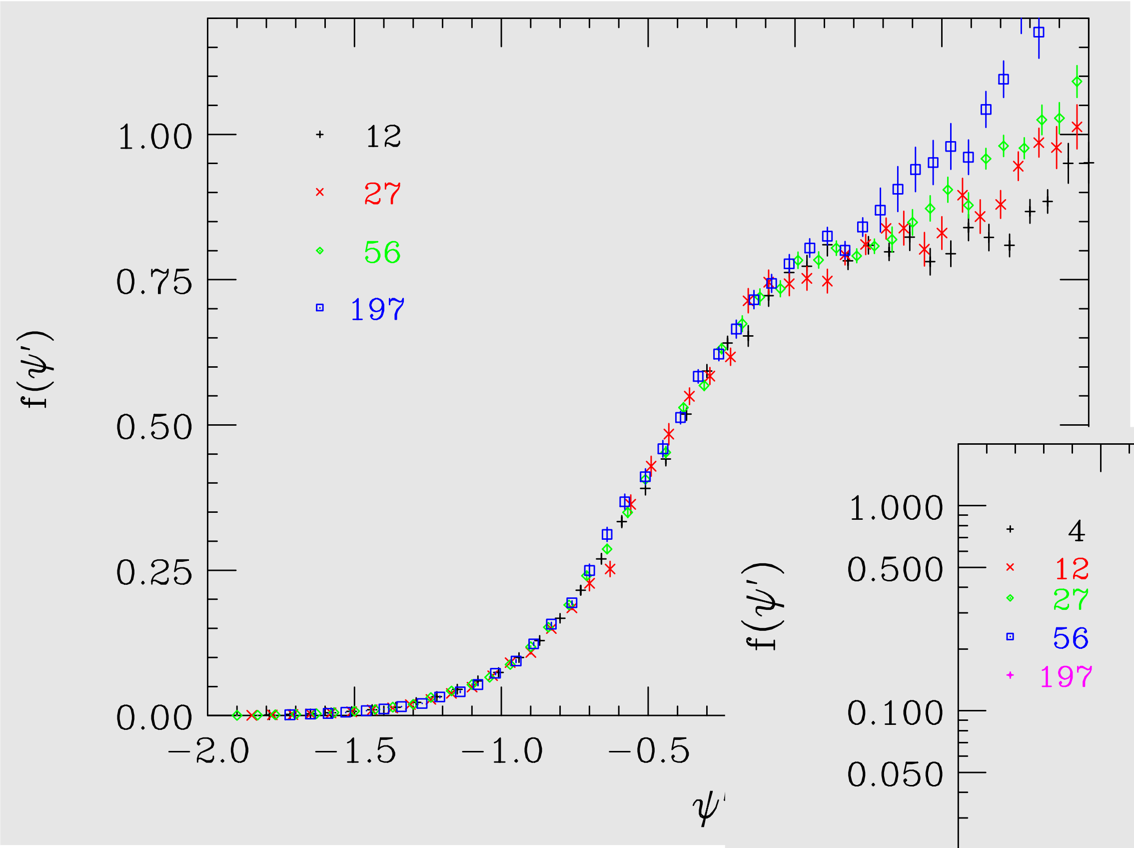

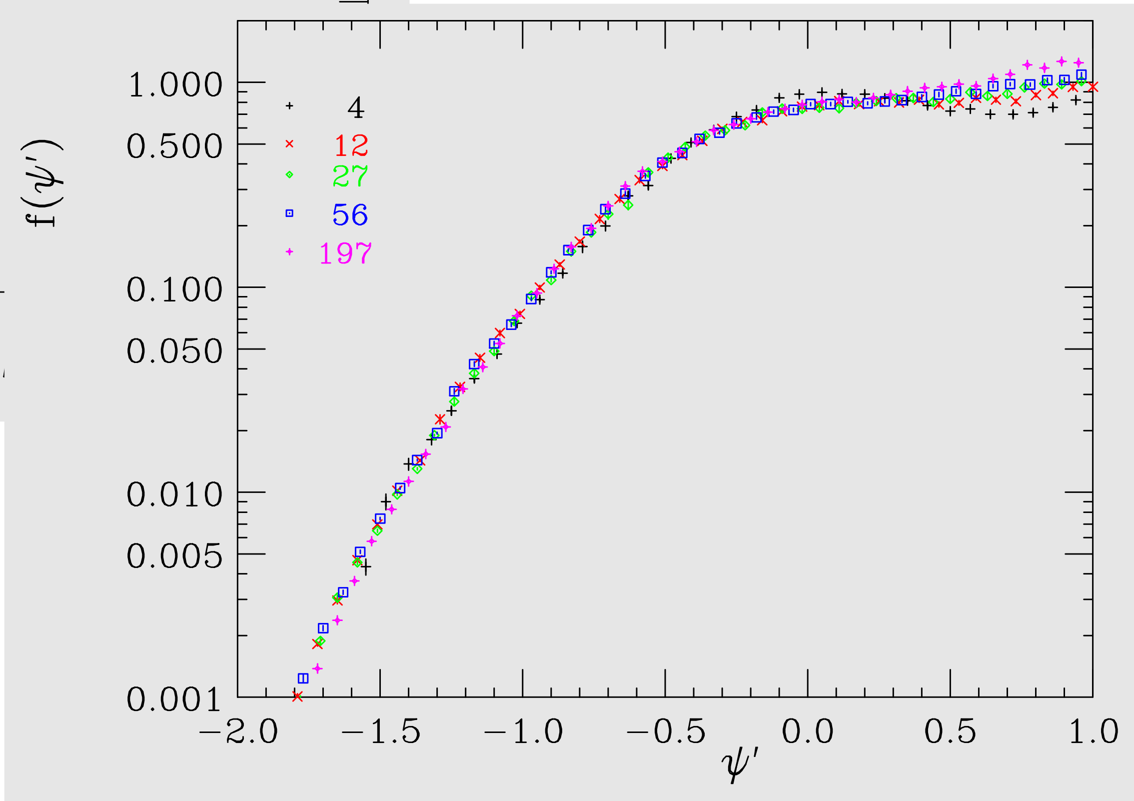

$\psi \longrightarrow \psi'$: $[\omega \longrightarrow \omega' \equiv \omega - E_{shift}]$

SUPERSCALING: analysis of data and L/T separation

$$f(q,\psi) \equiv k_F \frac{[d\sigma/d\omega d\Omega_e]}{\sigma_M\,[v_L G^L + v_T G^T]}, \quad f^L(q,\psi) \equiv k_F \frac{R^L(q,\omega)}{G^L}, \quad f^T(q,\psi) \equiv k_F \frac{R^T(q,\omega)}{G^T}$$

- Scaling of the first kind: $f_{exp}(q,\psi) \stackrel{q\to\infty}{\longrightarrow} f_{exp}(\psi)$; $\psi \approx y/k_F$ – *superscaling variable*
- Scaling of the second kind: $f_{exp}(\psi)$ – *independence on the nuclear system*

SUPERSCALING

- Scaling of the zeroth kind: $f_{exp}(q,\psi) = f^L_{exp}(q,\psi) = f^T_{exp}(q,\psi)$

SUPERSCALING: analysis of data and L/T separation

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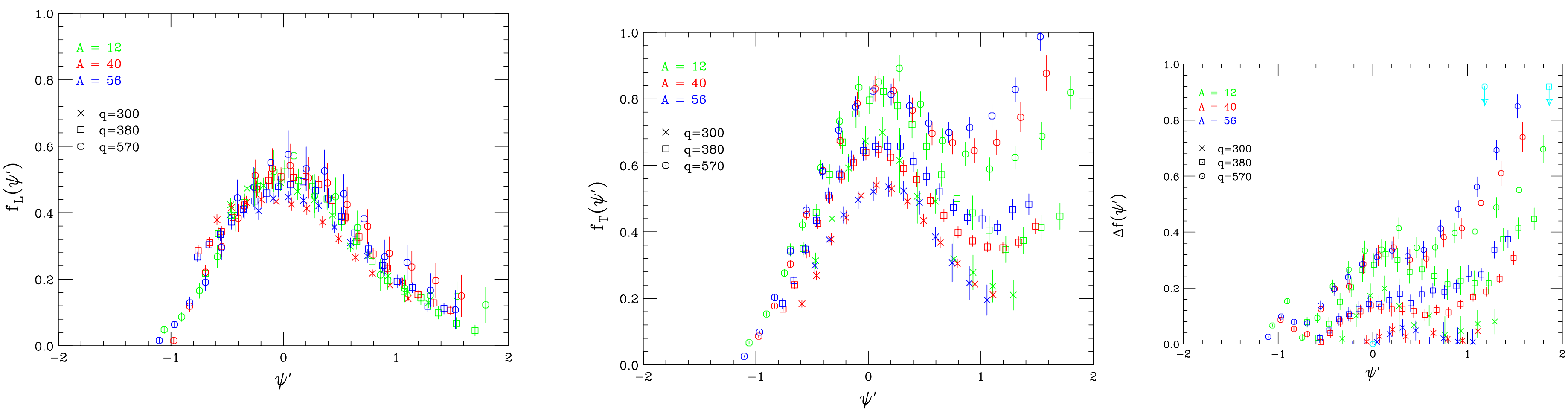


The SuperScaling Approach (SuSA)

- *Scaling of the first kind below the QE peak ($\psi \leq 0$)*
- *Excellent scaling of the second kind in the same region*
- *Breaking of scaling above the QE peak ($\psi > 0$) $\Longrightarrow$ Effects beyond the IA (mainly located in the T channel)*
- **LONGITUDINAL RESPONSE SUPERSCALES**

The SuperScaling Approach (SuSA)

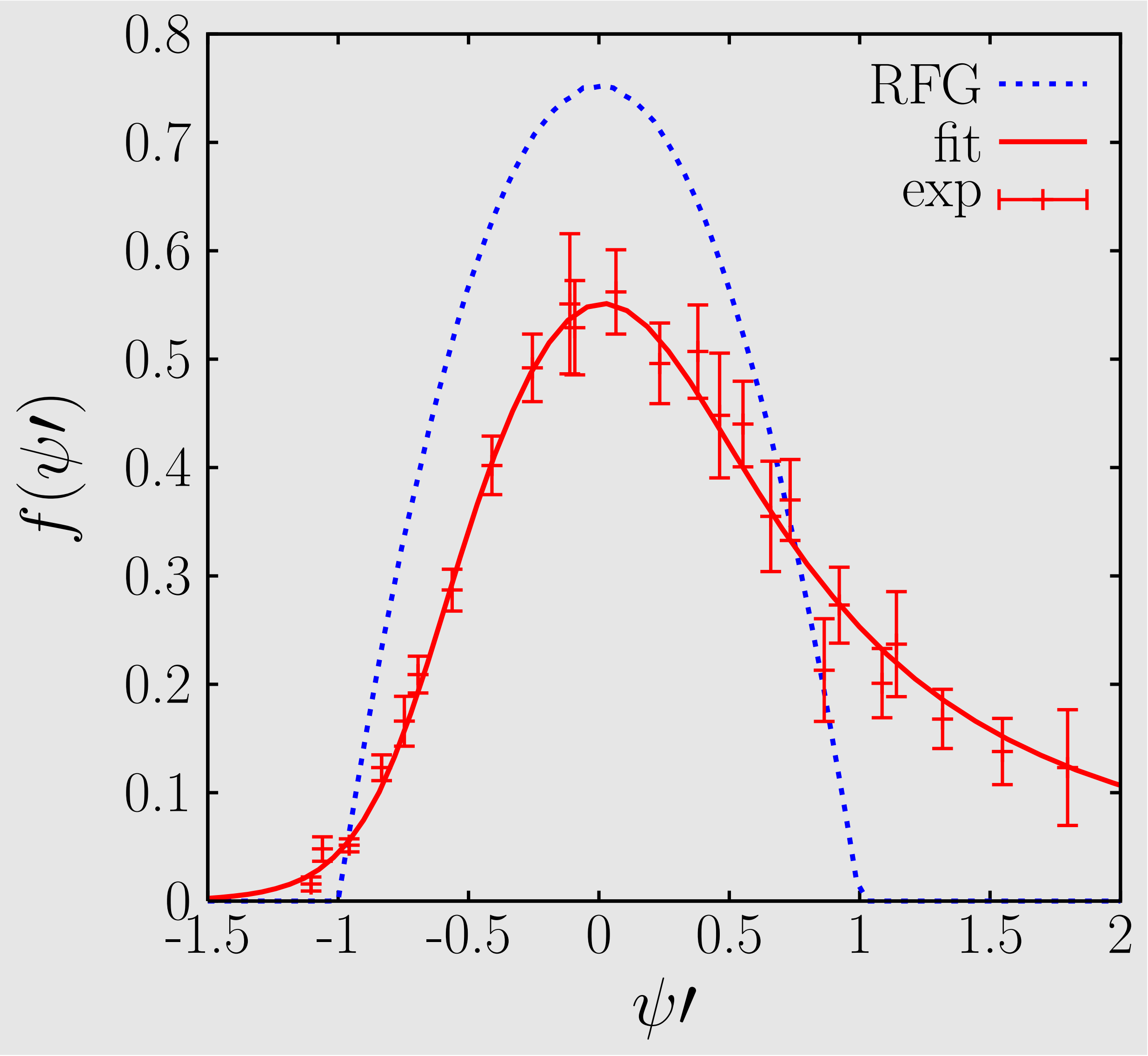
- *Scaling of the first kind be*

PRC60 (1999) 065502

PRL82 (1999) 3212

PRC65 (2002) 025502

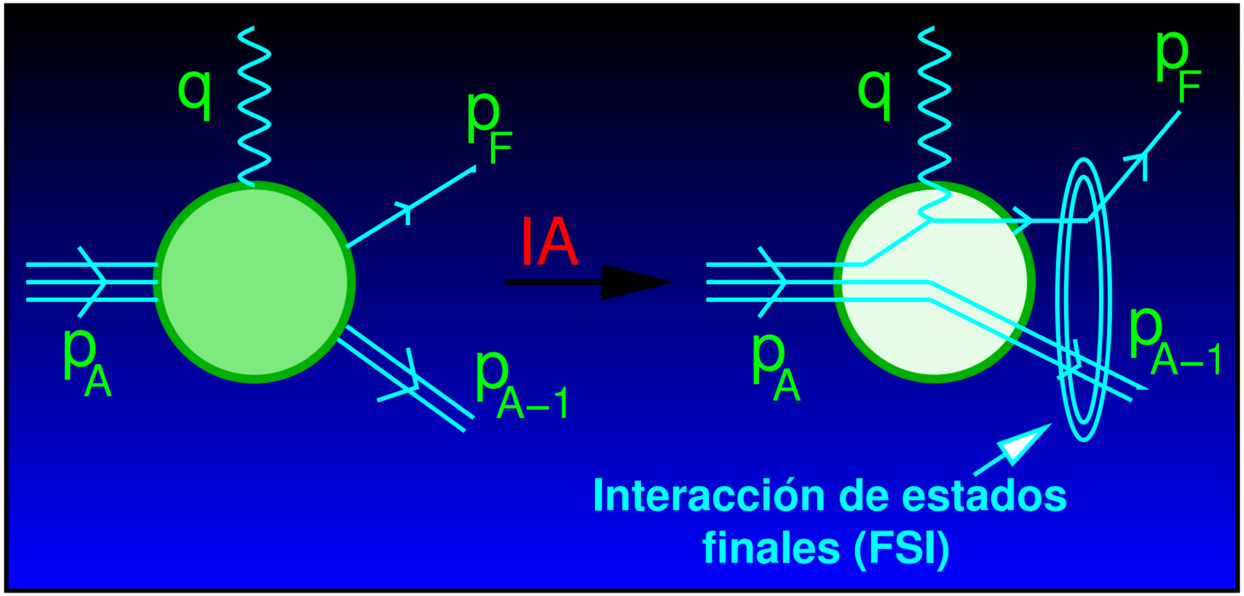
- **LONGITUDINAL RESPO**



Experimental superscaling function: asymmetric shape with a long tail extended to positive ψ-values

$\Downarrow$

strong constraints to models



Nuclear Current $\Longrightarrow$ One-body operator

$$J^\mu_N(\omega,\vec{q}) = \int d\vec{p}\,\overline{\Psi}_F(\vec{p}+\vec{q})\,\hat{J}^\mu_N\,\Psi_B(\vec{p})$$

Scattering off a nucleus $\Longrightarrow$ incoherent sum of single–nucleon scattering processes

Ingredients in RIA: nucleon w.f. & current operator

Solutions of Dirac equation with phenomenological relativistic potentials

- Ψ_B: **Bound nucleon w.f.** $\Longrightarrow$ **Relativistic Mean Field (RMF)**
- Ψ_F: **Ejected nucleon w.f.** $\Longrightarrow$ **Final State Interactions (FSI)**

RMF $\Leftrightarrow$ rROP $\Leftrightarrow$ RPWIA $\Leftrightarrow$ RGFA

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RMF $\Leftrightarrow$ rROP $\Leftrightarrow$ RPWIA $\Leftrightarrow$ RGFA

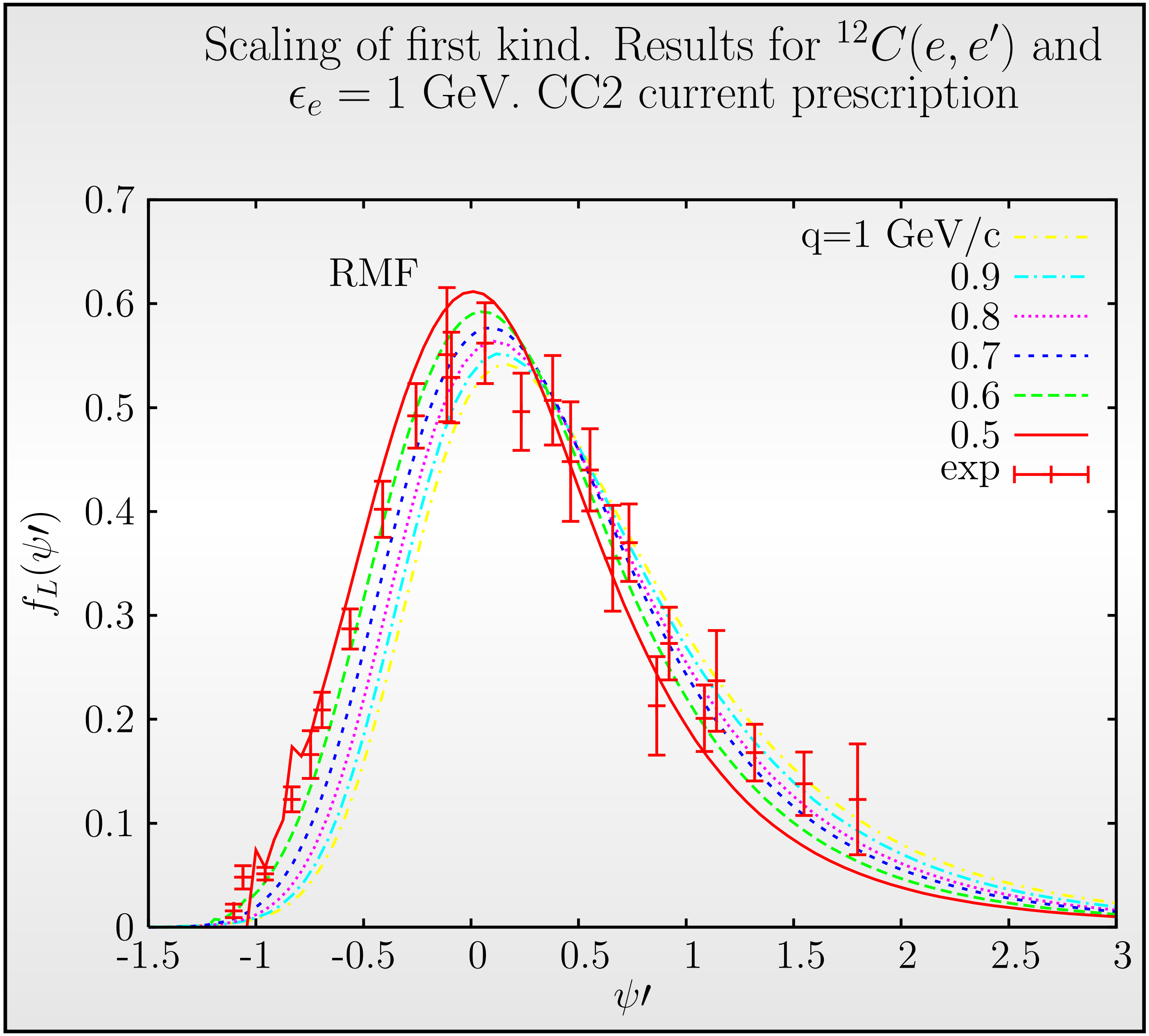
- **Electromagnetic current:** (e, e')

$$\hat{J}^{\mu}_{cc1} = (F_1 + F_2)\gamma^{\mu} - \frac{F_2}{2m_N}(\overline{P} + P_N)^{\mu}$$

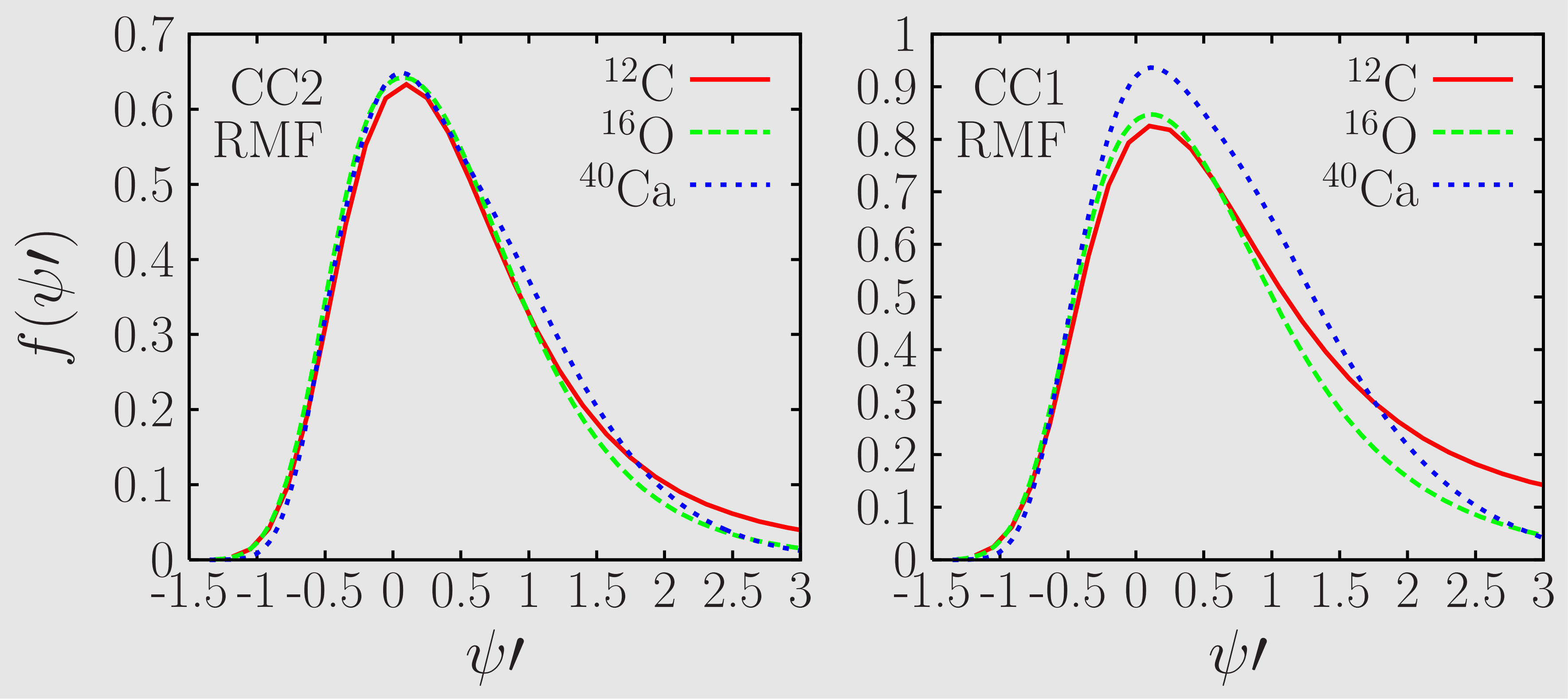
$$\hat{J}^{\mu}_{cc2} = F_1\gamma^{\mu} + \frac{iF_2}{2m_N}\sigma^{\mu\nu}Q_{\nu}$$

Off-shell & Gauge ambiguities ($Q_{\mu}J^{\mu} \neq 0$)

How Scaling of the 1^{er} kind behaves (RMF)

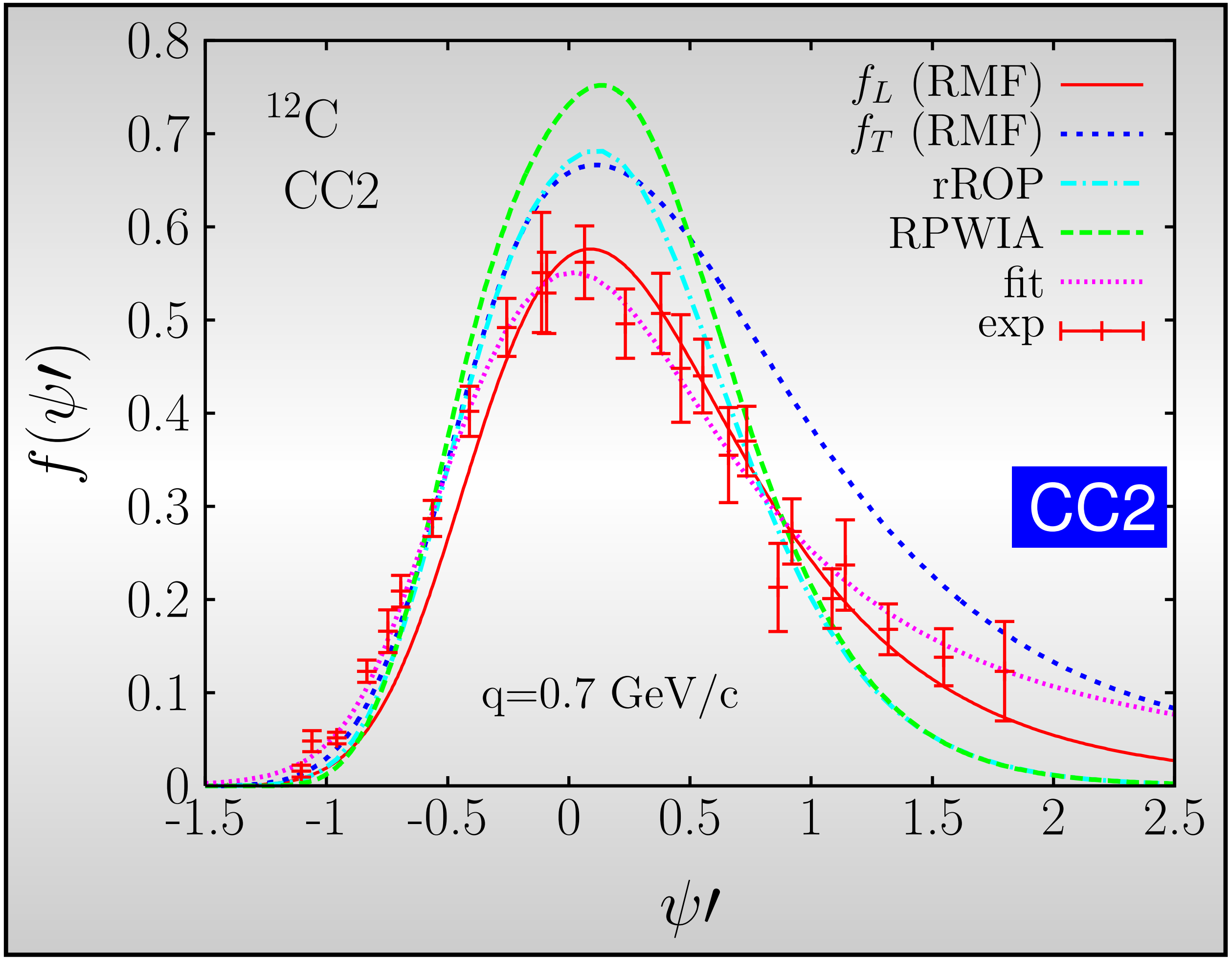


Scaling of the second kind in RIA



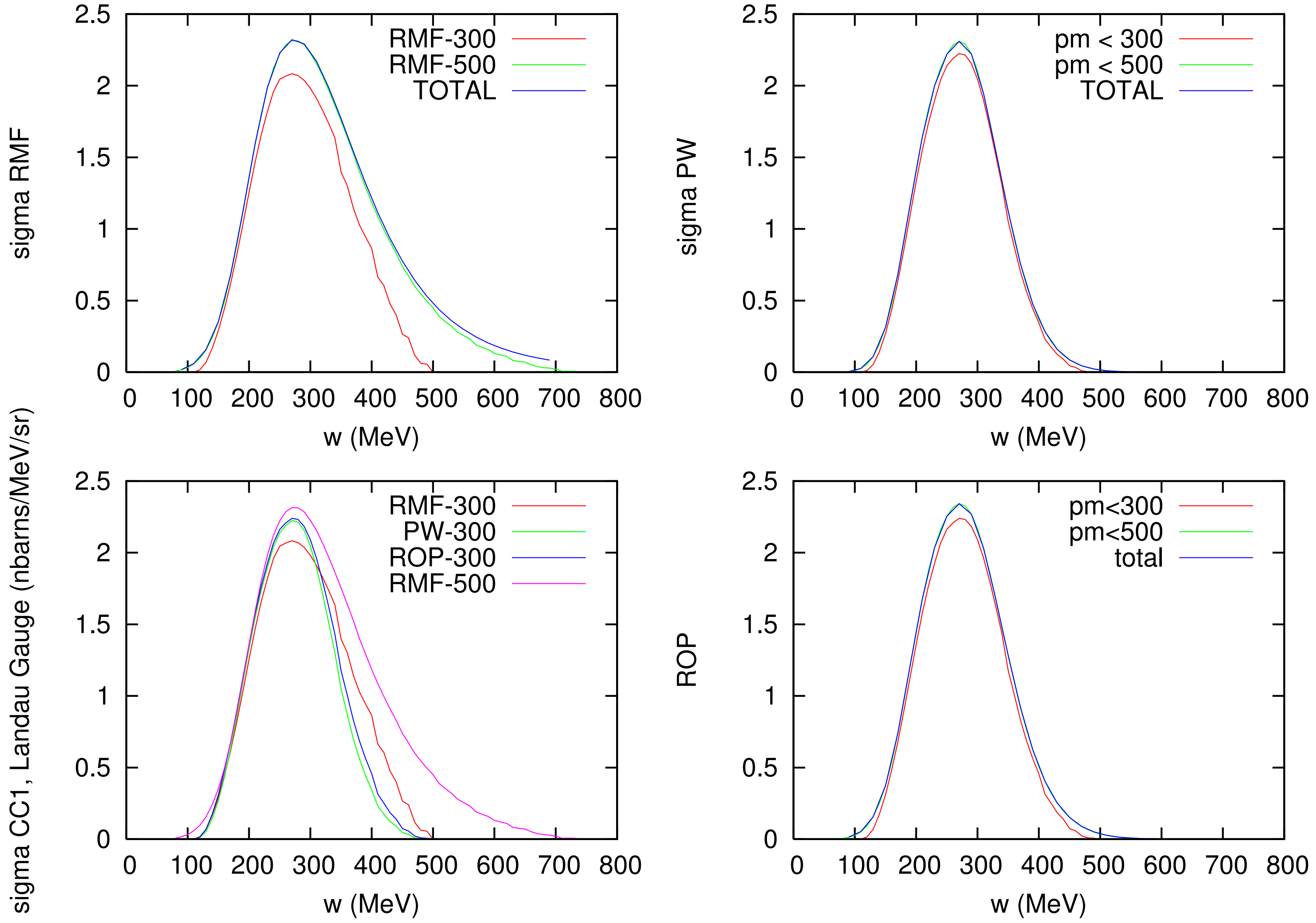
Scaling of 2^a kind: excellent with the CC2 current operator

RMF: Comparison with (e, e') data

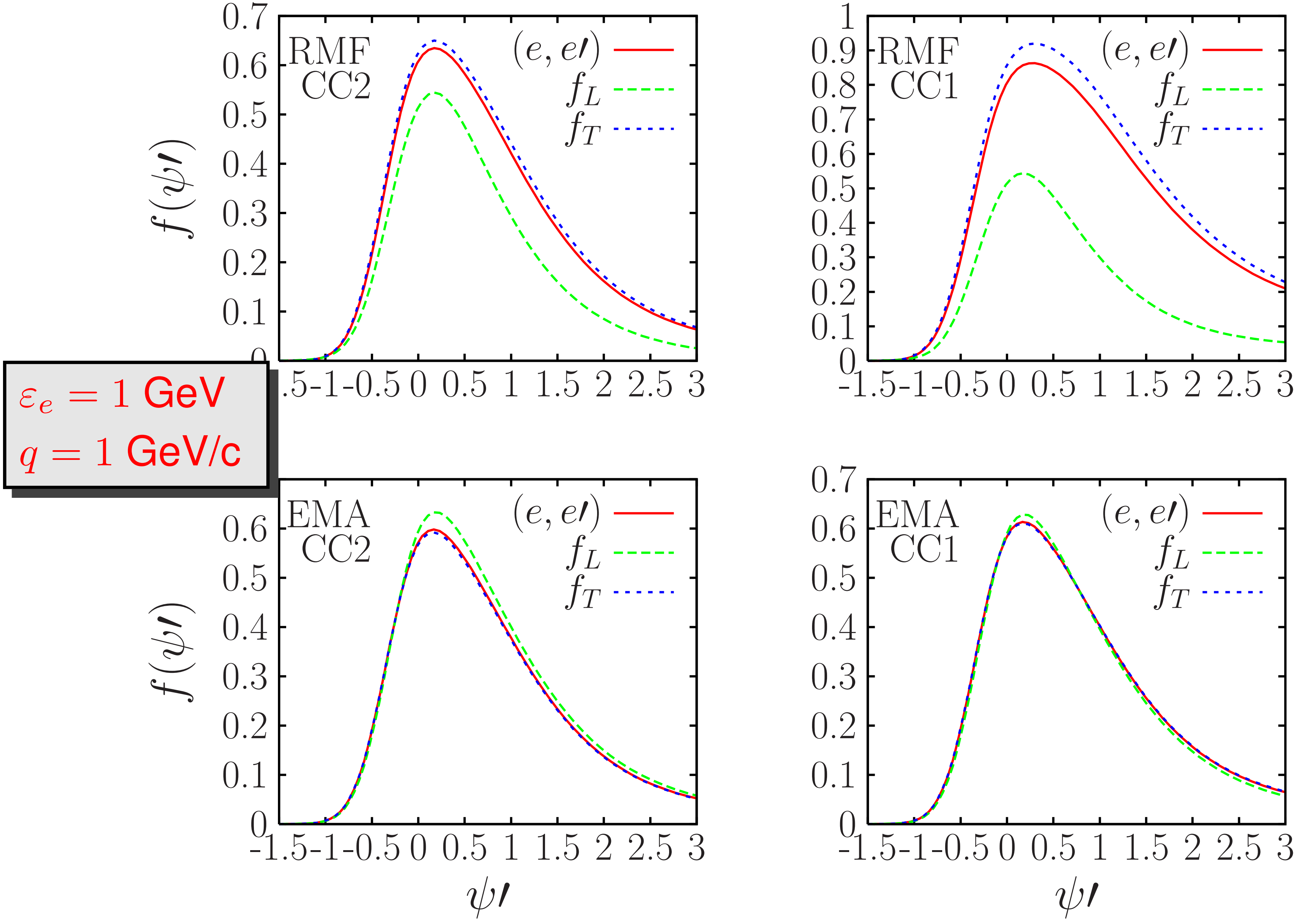


Only the description of FSI provided by RMF leads to an asymmetric function $f(\psi')$ in accordance with the behavior shown by data. Moreover, $f_T > f_L$

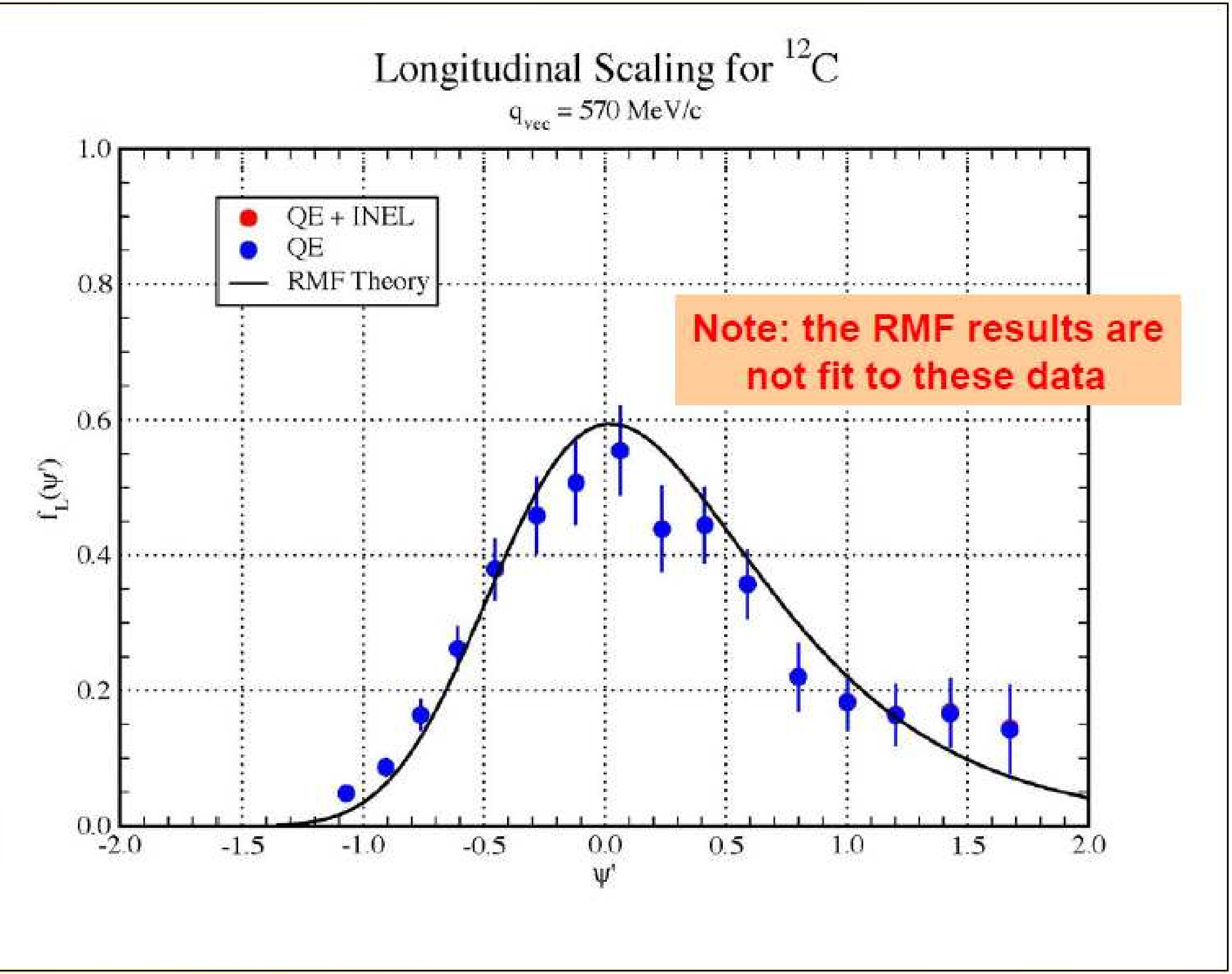
Asymmetry in the RMF approach



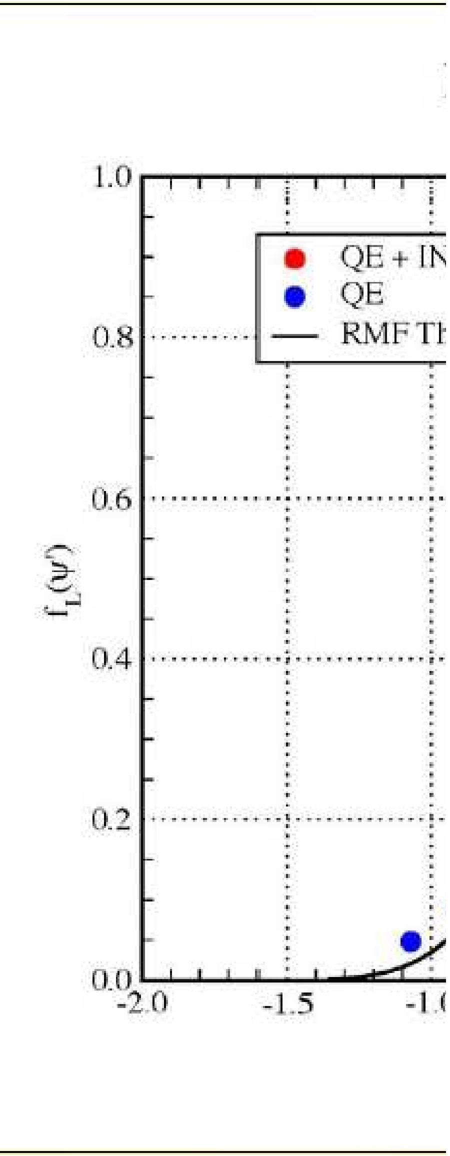
Scaling of the 0^{th} kind in RMF: T enhancement

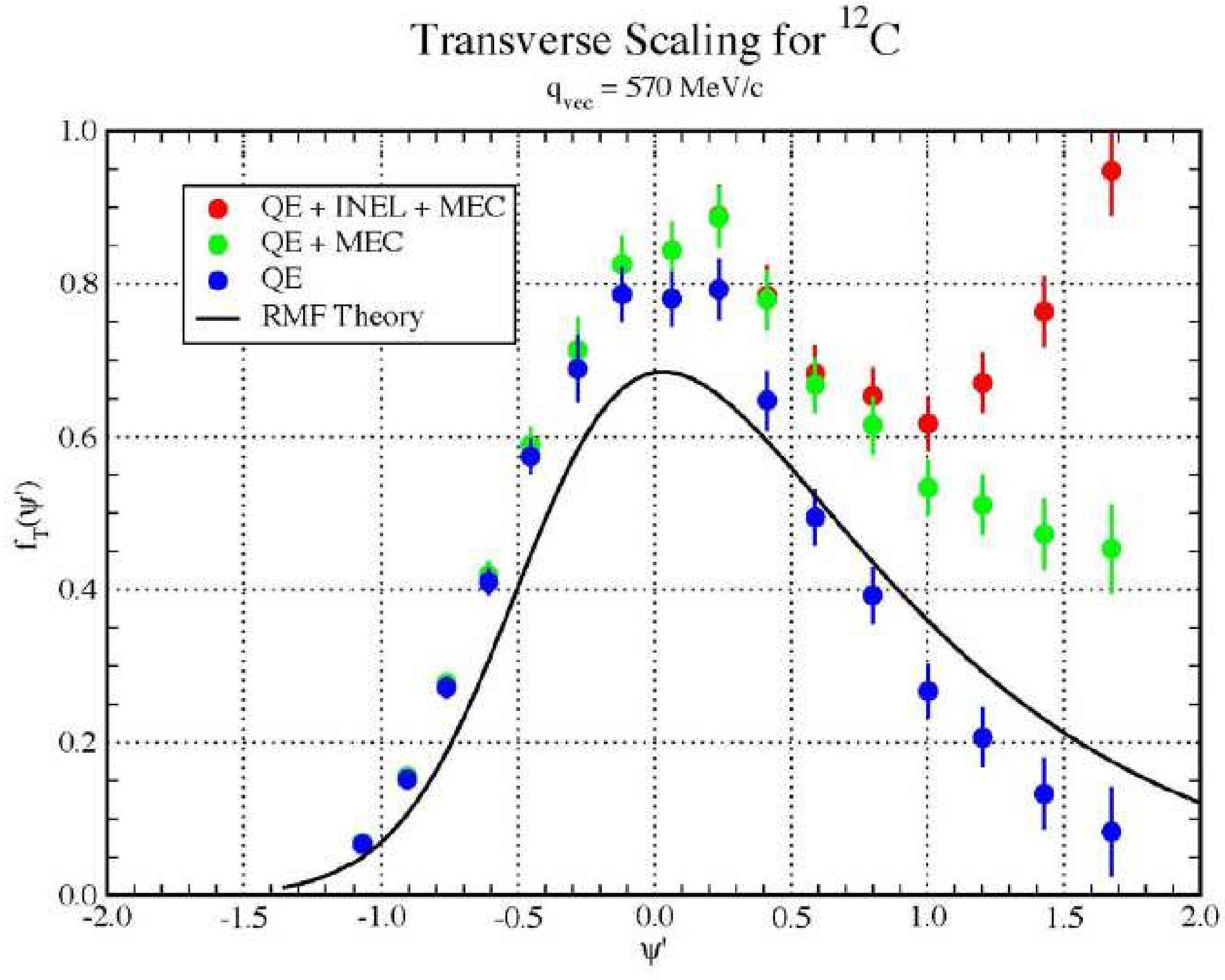


Scaling in QE L/T-channels



Scaling in QE L/T-channels





SuperScaling Approach based on RMF: SuSAv2

Present SuSA

Based on the superscaling function extracted from QE electron-nucleus scattering data.

. . .

SuSAv2

The Relativistic Mean Field model (RMF) is employed to improve the data analysis, where RMF accounts for FSI.

Longitudinal

Description of nuclear responses built only on the longitudinal scaling function. Assumption of $f_L(\psi) \approx f_T(\psi)$, scaling of 0^{th} kind.

. . .

Longitudinal + Transversal

Differences between transverse and longitudinal scaling functions are introduced in order to describe properly the nuclear responses.

Isoscalar + Isovector Structure

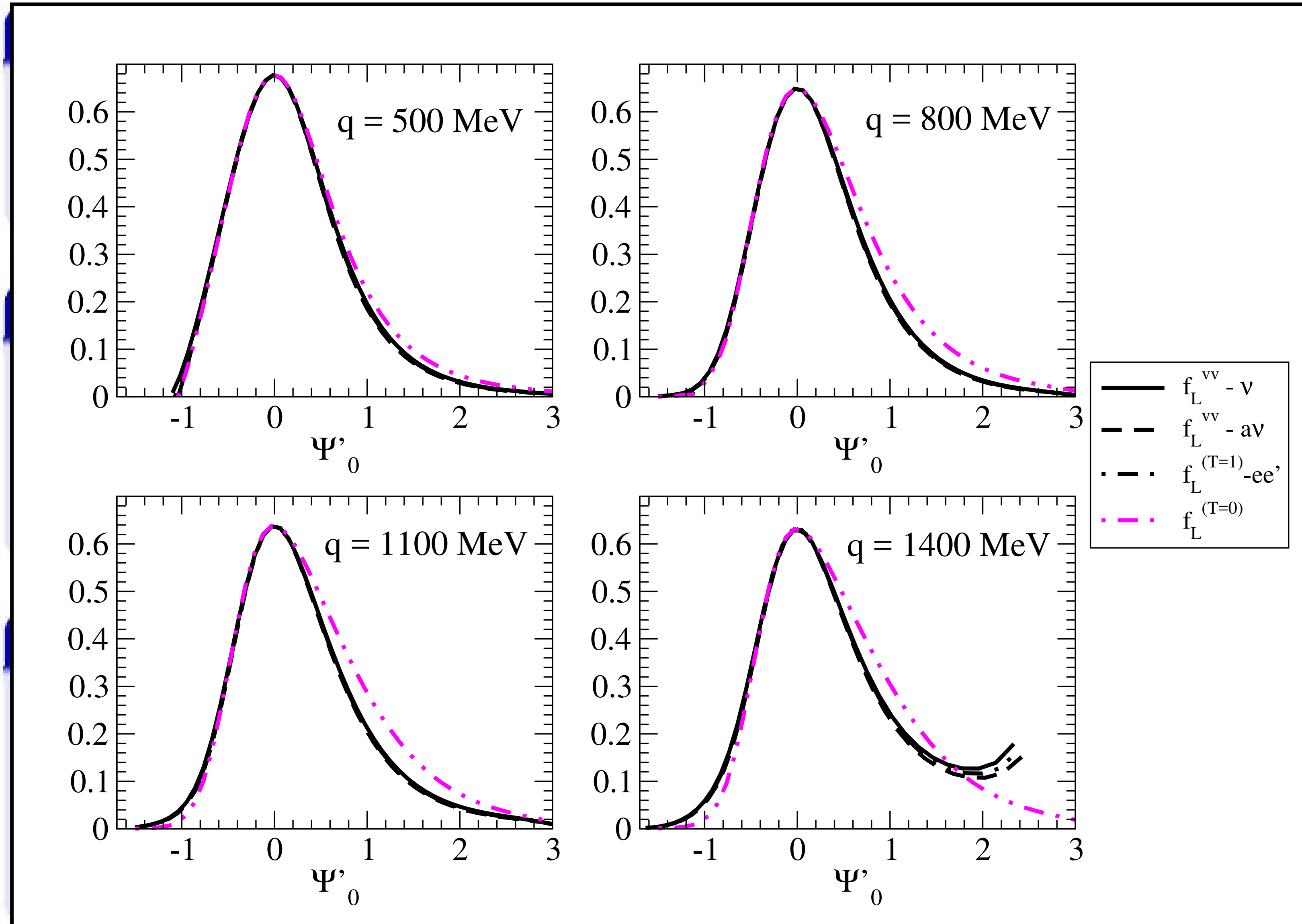
The scaling function based on QE electron scattering data takes into account isovector and isoscalar currents to describe the interaction between the electron and the nucleus.

. . .

Isovector structure

We separate the scaling function into isovector and isoscalar structure so as to employ a purely isovector scaling function for CCQE neutrino-nucleus processes where isospin changes.

SuperScaling Approach based on RMF: SuSAv2



Field model
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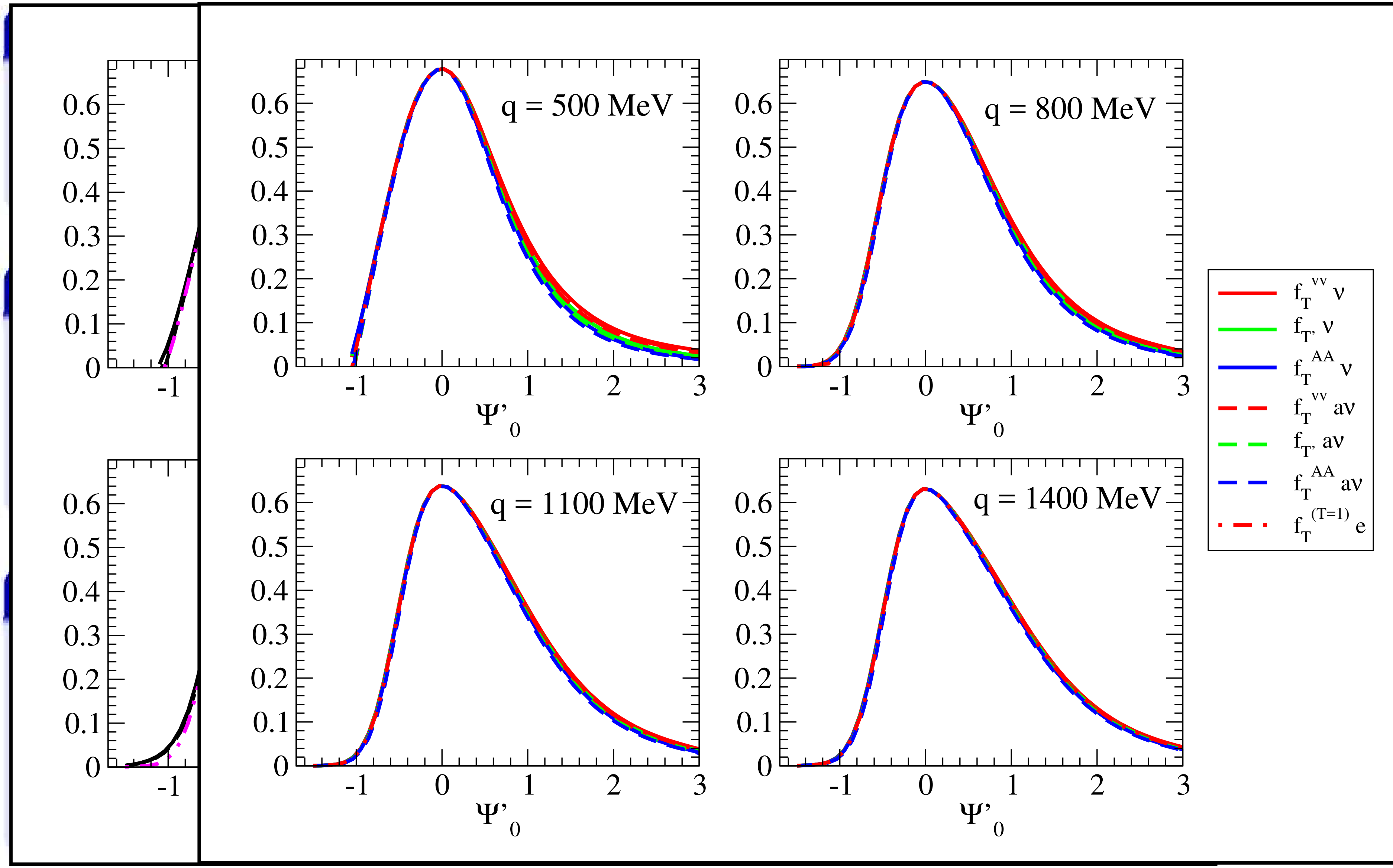
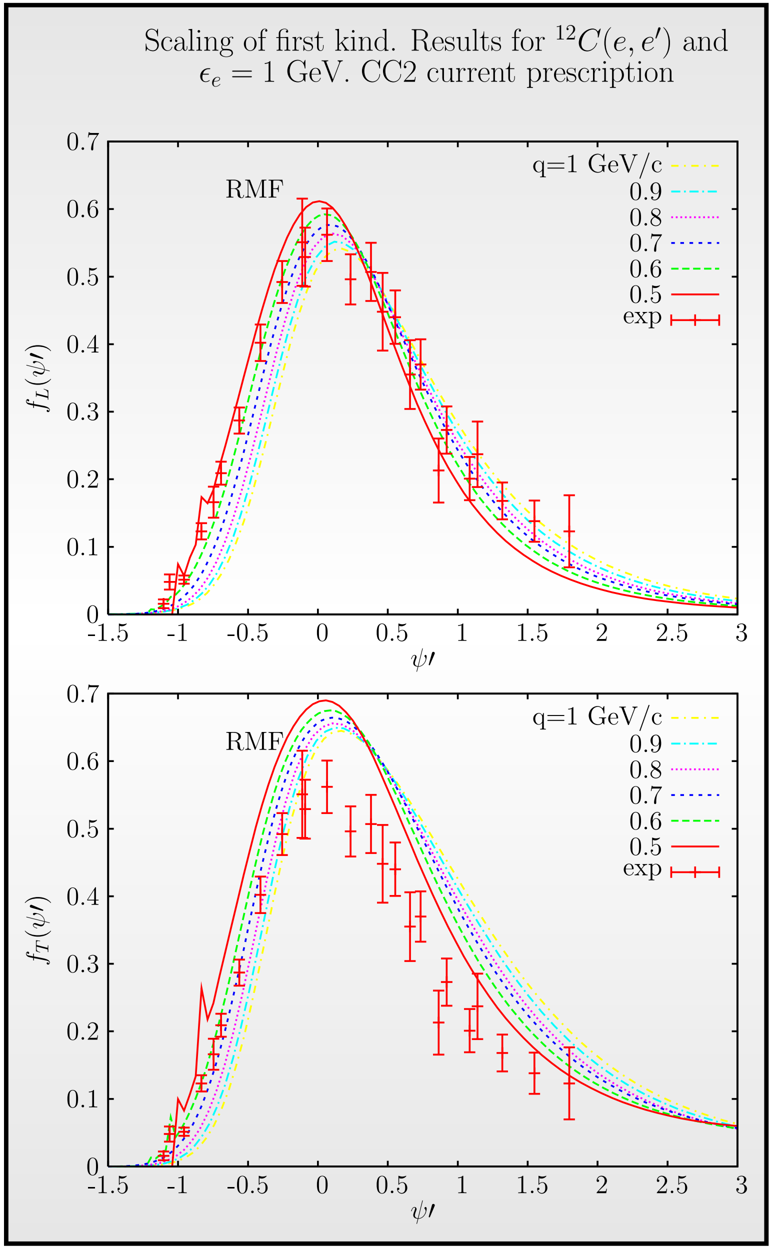


How Scaling of the 1^{er} kind behaves. RMF vs RPWIA



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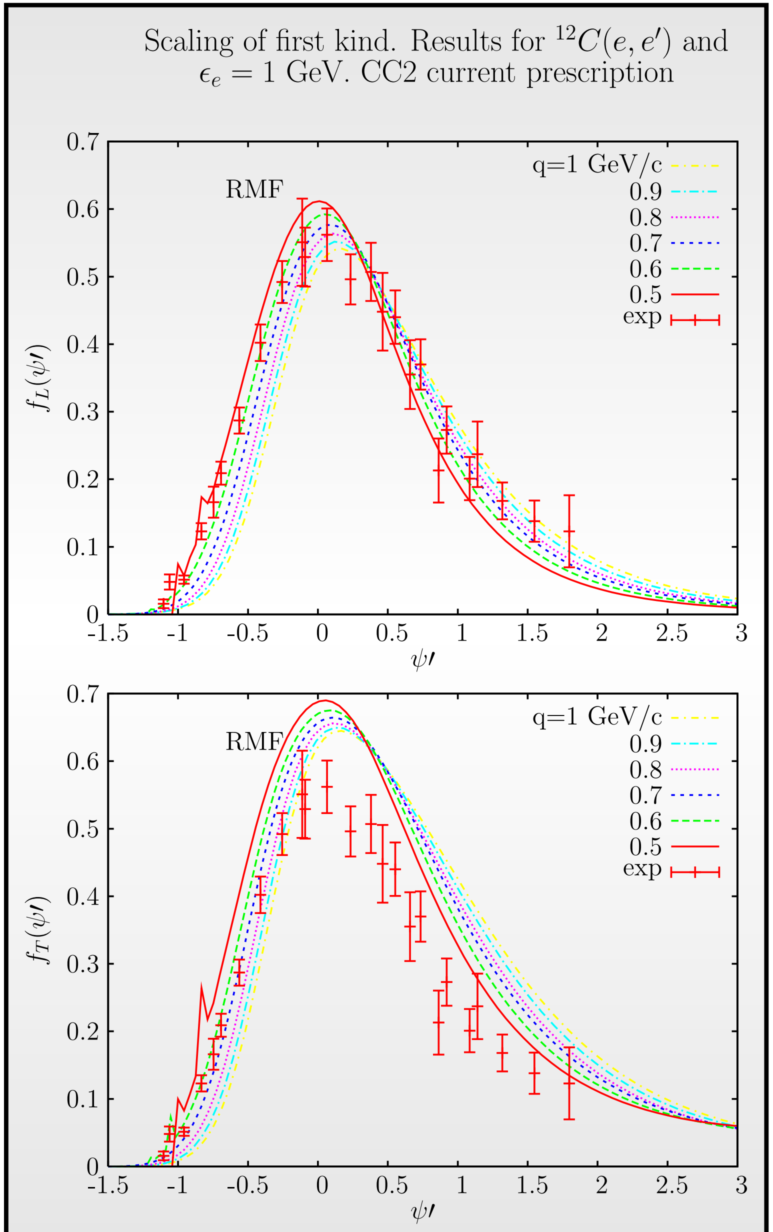


RMF $\Longrightarrow$ low-intermediate q
RPWIA $\Longrightarrow$ higher q values

New SuSAv2 approach: combination of RMF and RPWIA scaling functions

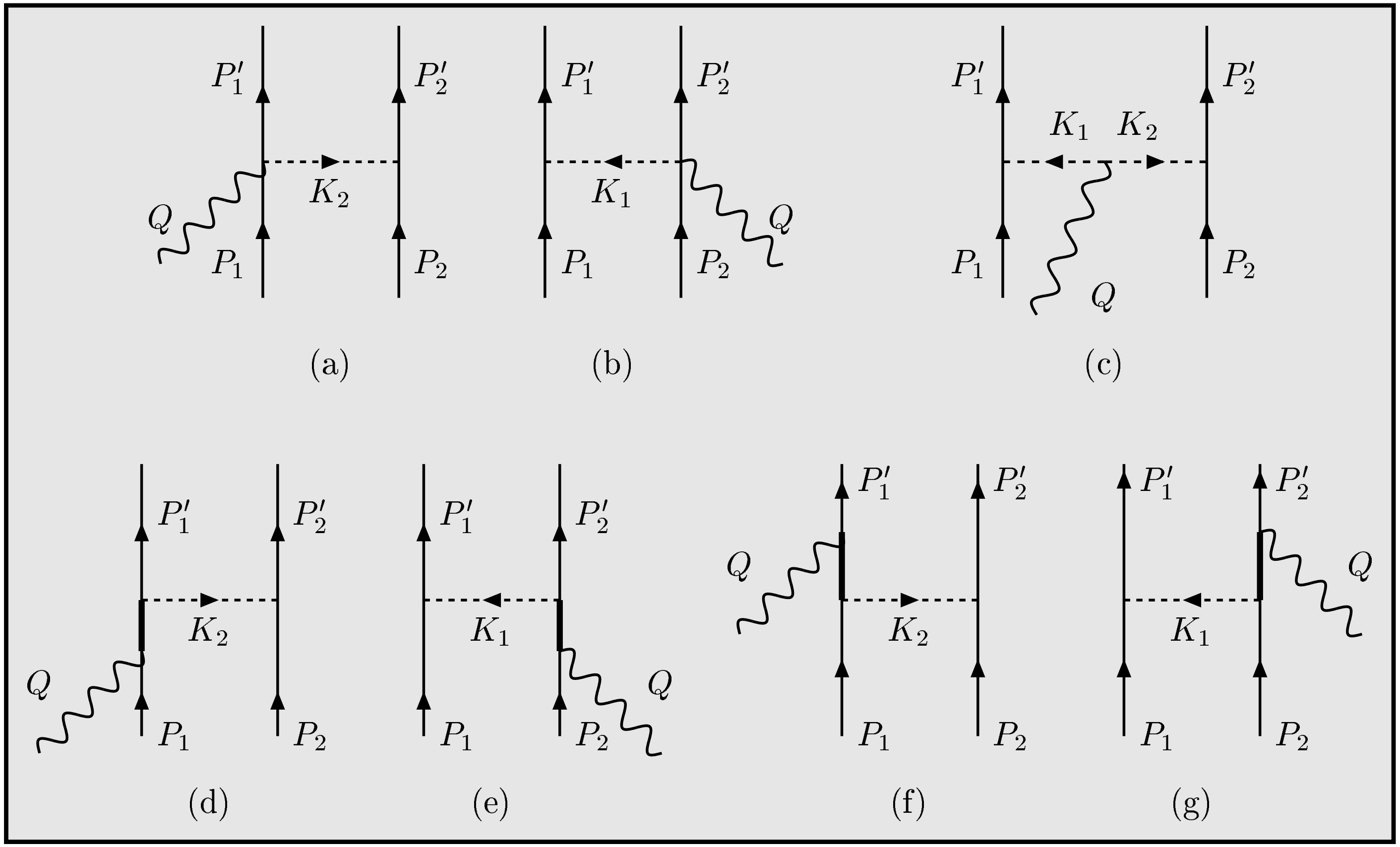
RMF/RPWIA transition:
PRD 94, 013012 (2016)

- RMF ⇒ FSI between the outgoing nucleon and the residual nucleus ⇒ low-intermediate q
- RPWIA ⇒ outgoing nucleon as a relativistic plane wave ⇒ higher q values (negligible FSI)

➥ SuperScaling Approach as a combination of RMF and RPWIA scaling functions by using a transition parameter $q_0(q)$

SuSAv2 extended to the inelastic region

SuSAv2-MEC: QE + 2p-2h MEC + Inelastic



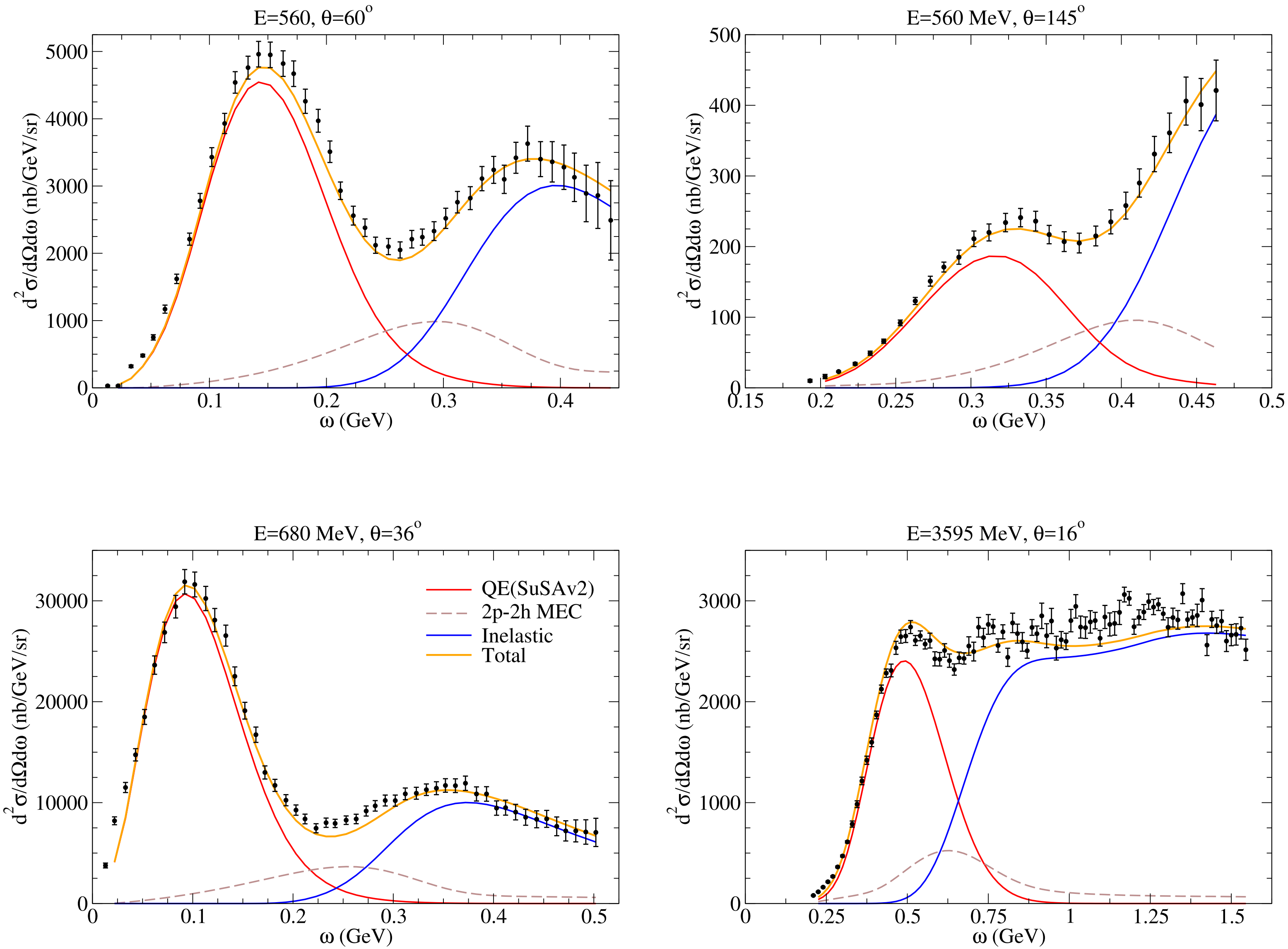
"MEC"

"correlations" and "Δ-MEC"

Application to inclusive electron scattering processes

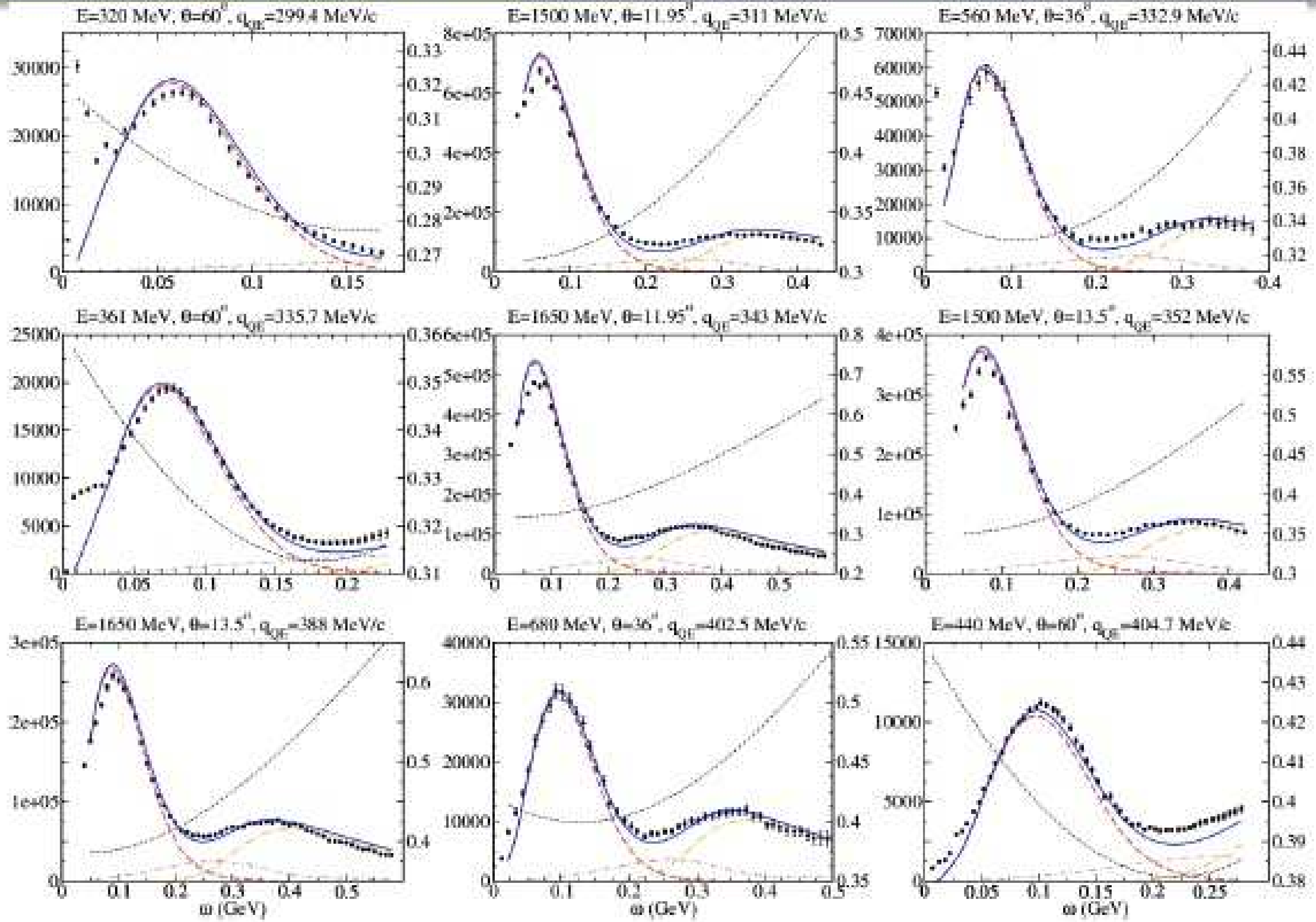
MEC calculation based on the Relativistic Fermi Gas

Inclusive electron scattering: SuSAv2-MEC



SuperScaling Approach based on RMF: SuSAv2

Inclusive $^{12}C(e,e')$ cross sections *PRD 94, 013012 (2016)*



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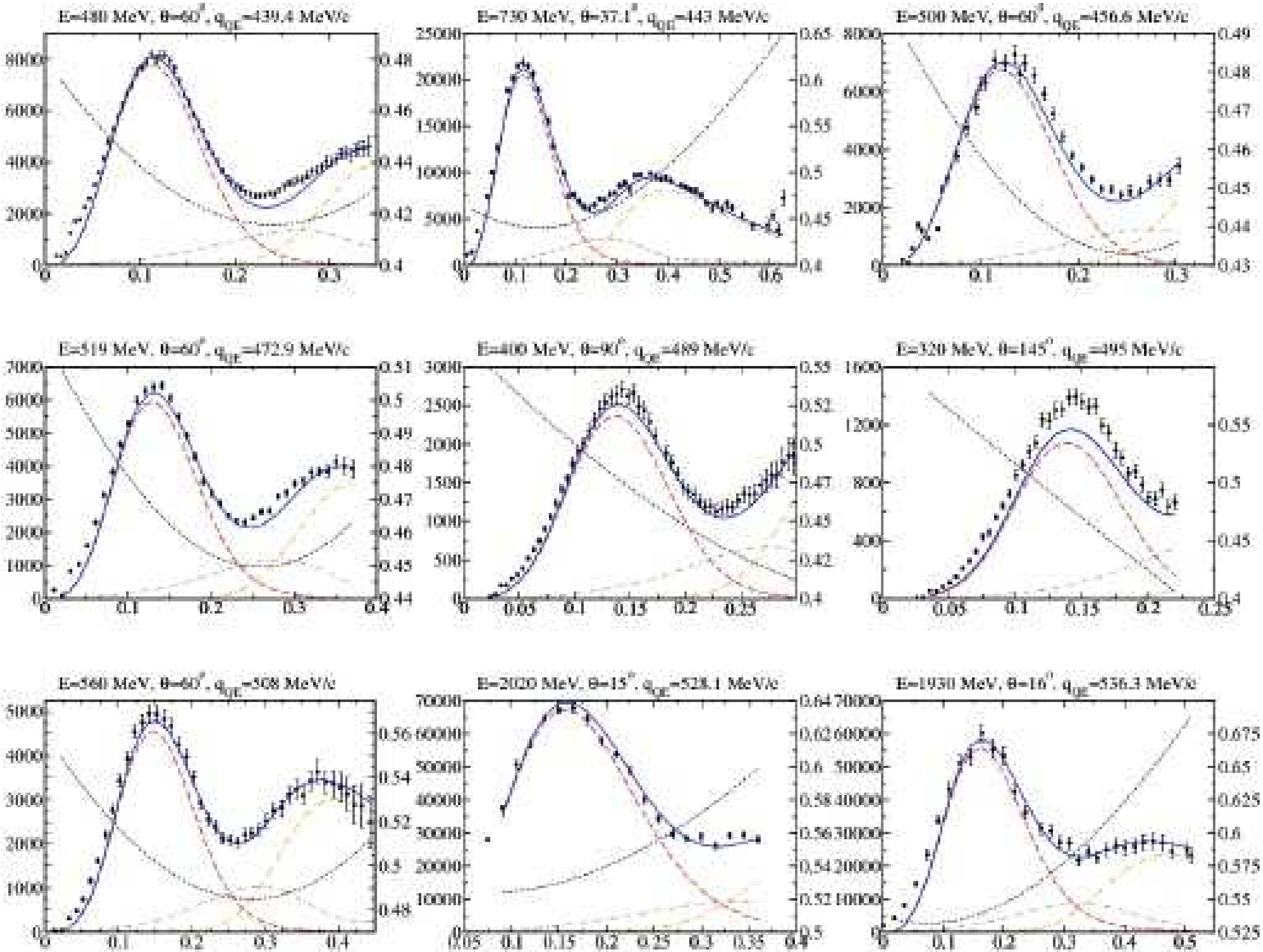

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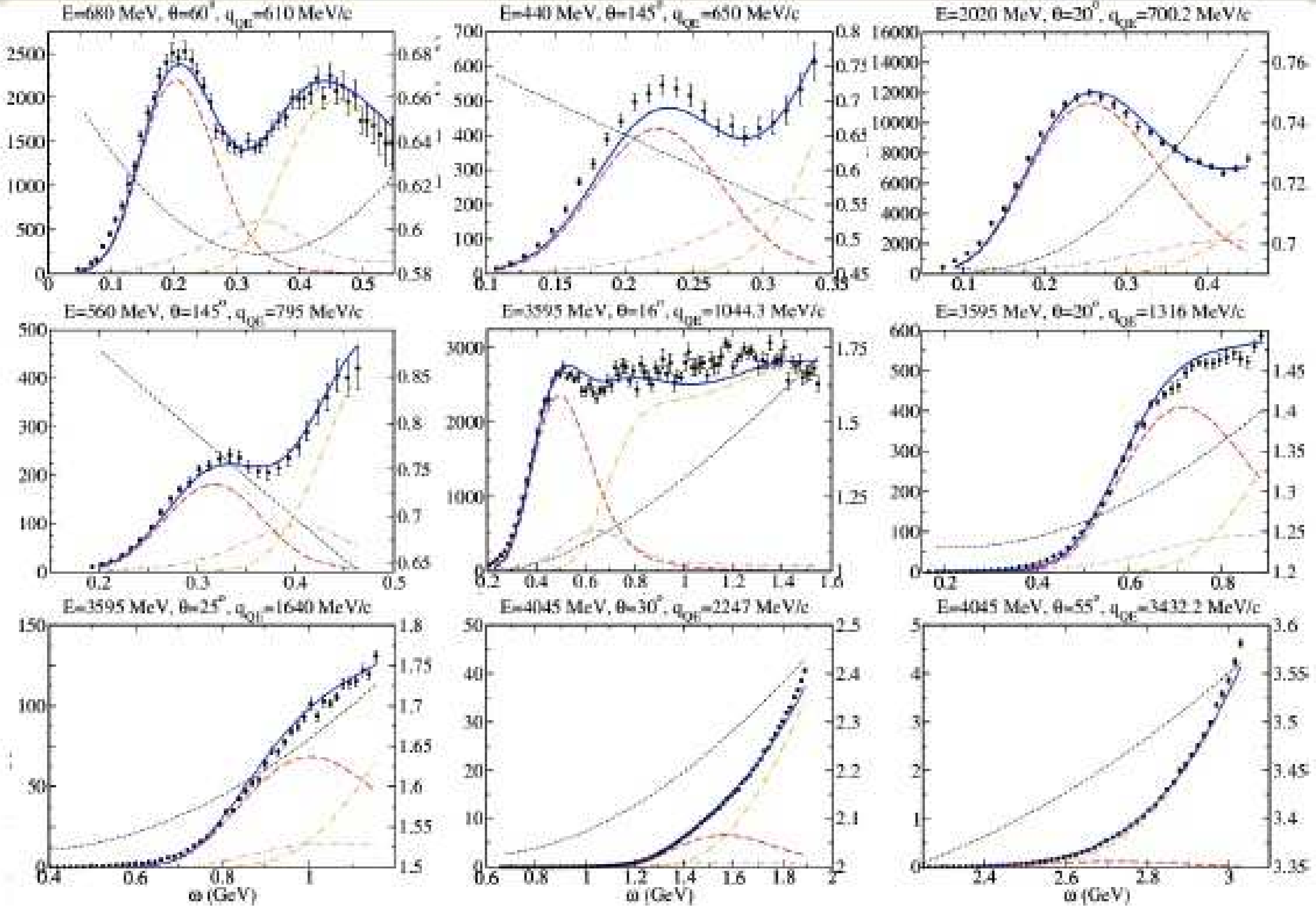
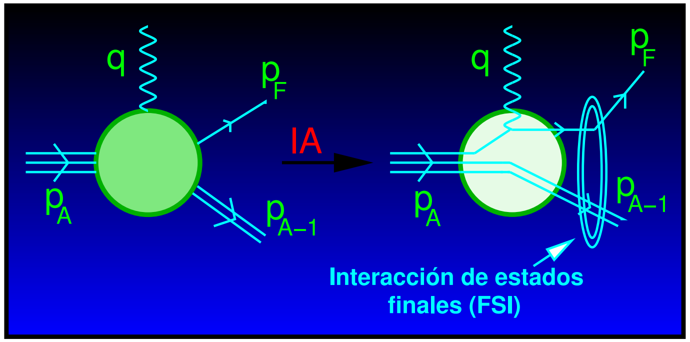


APPLICATION TO NEUTRINO-NUCLEUS REACTIONS

RELATIVISTIC IMPULSE APPROXIMATION



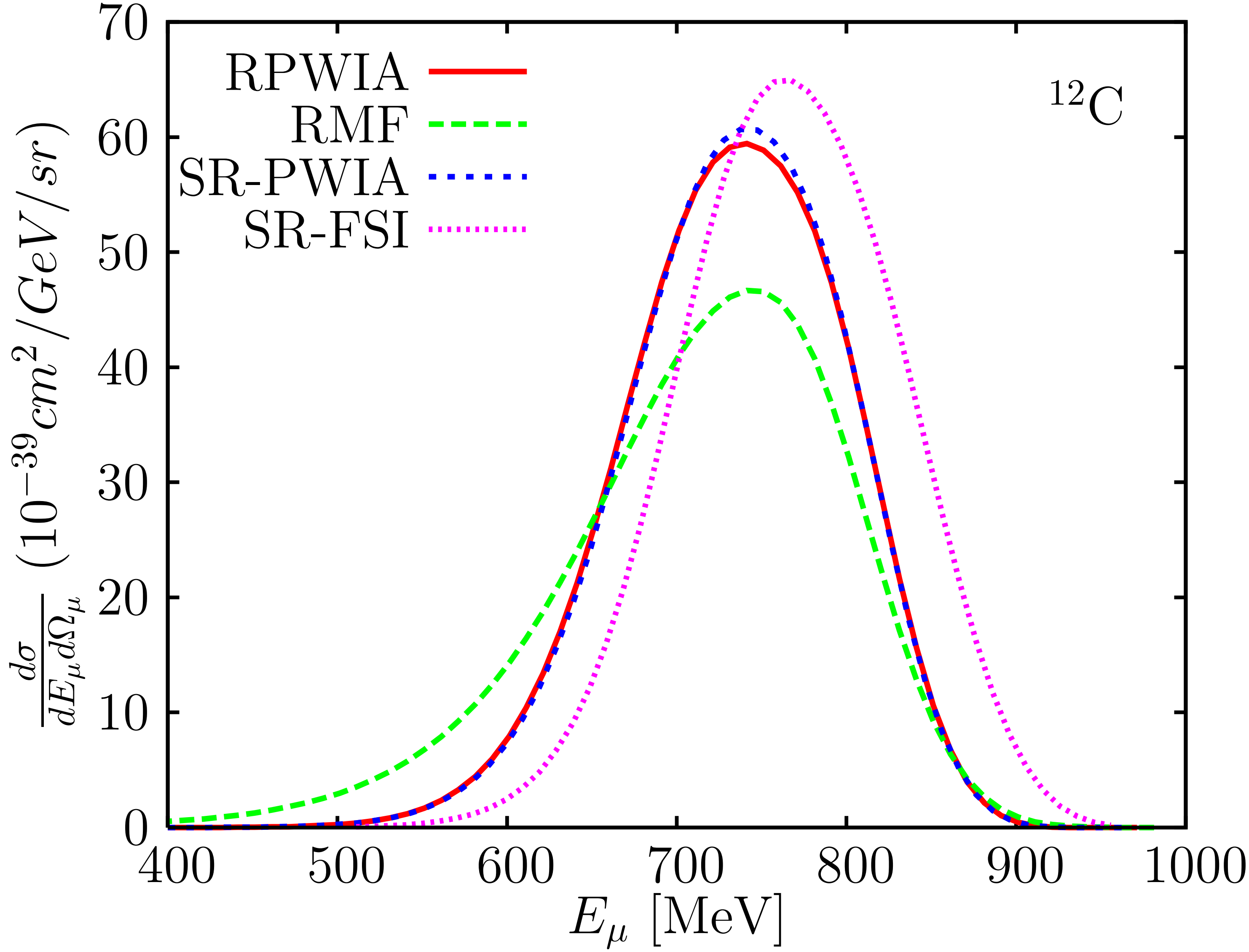
- *Incident neutrino interacts with only one nucleon which is then emitted, while the $(A-1)$ remaining nucleons are simply spectators.*
- *The weak nuclear current is the sum of single nucleon currents.*
- *Target and residual nuclei can be adequately described within an independent particle model.*

Weak single-nucleon current operator

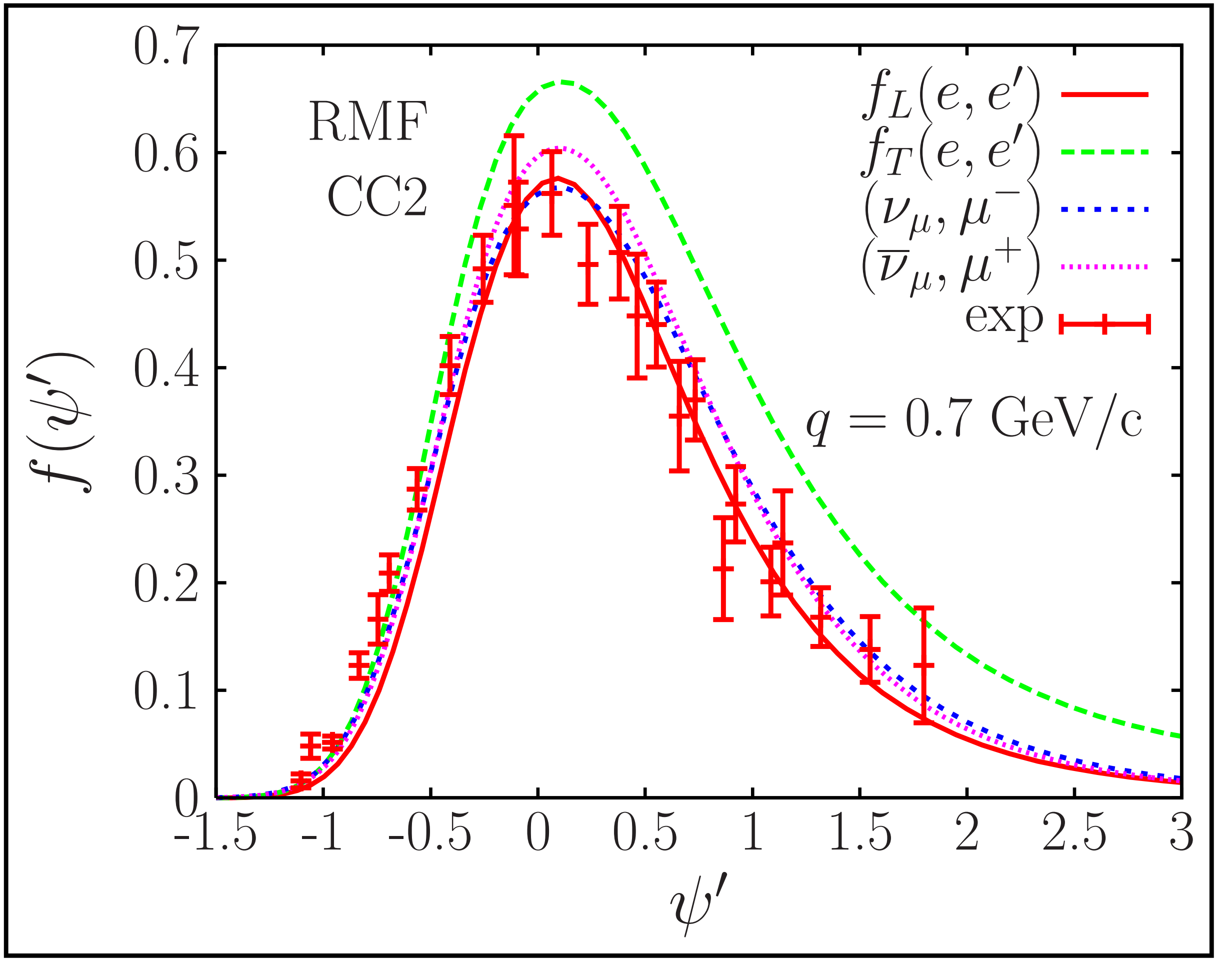
$$\hat{J}^{\mu}_{wsn} = \hat{J}^{\mu}_{V} - \hat{J}^{\mu}_{A} = \tilde{F}_1\gamma^{\mu} + \frac{i\tilde{F}_2}{2m_N}\sigma^{\mu\nu}Q_{\nu} + G_A\gamma^{\mu}\gamma^5 + \frac{G_P}{2m_N}Q^{\mu}\gamma^5$$

- **Neutral Currents**: *Strangeness content in $\tilde{G}_{E,M,A}$ and dependence with Weinberg angle (no G_P)*
- **Charge-changing Currents:** *Pure isovector form factors $\tilde{F}^V_i = (F^p_i - F^n_i)$*

RIA & SR approximations. FSI effects



Scaling: (e, e') vs (ν, μ). SuSA vs RMF

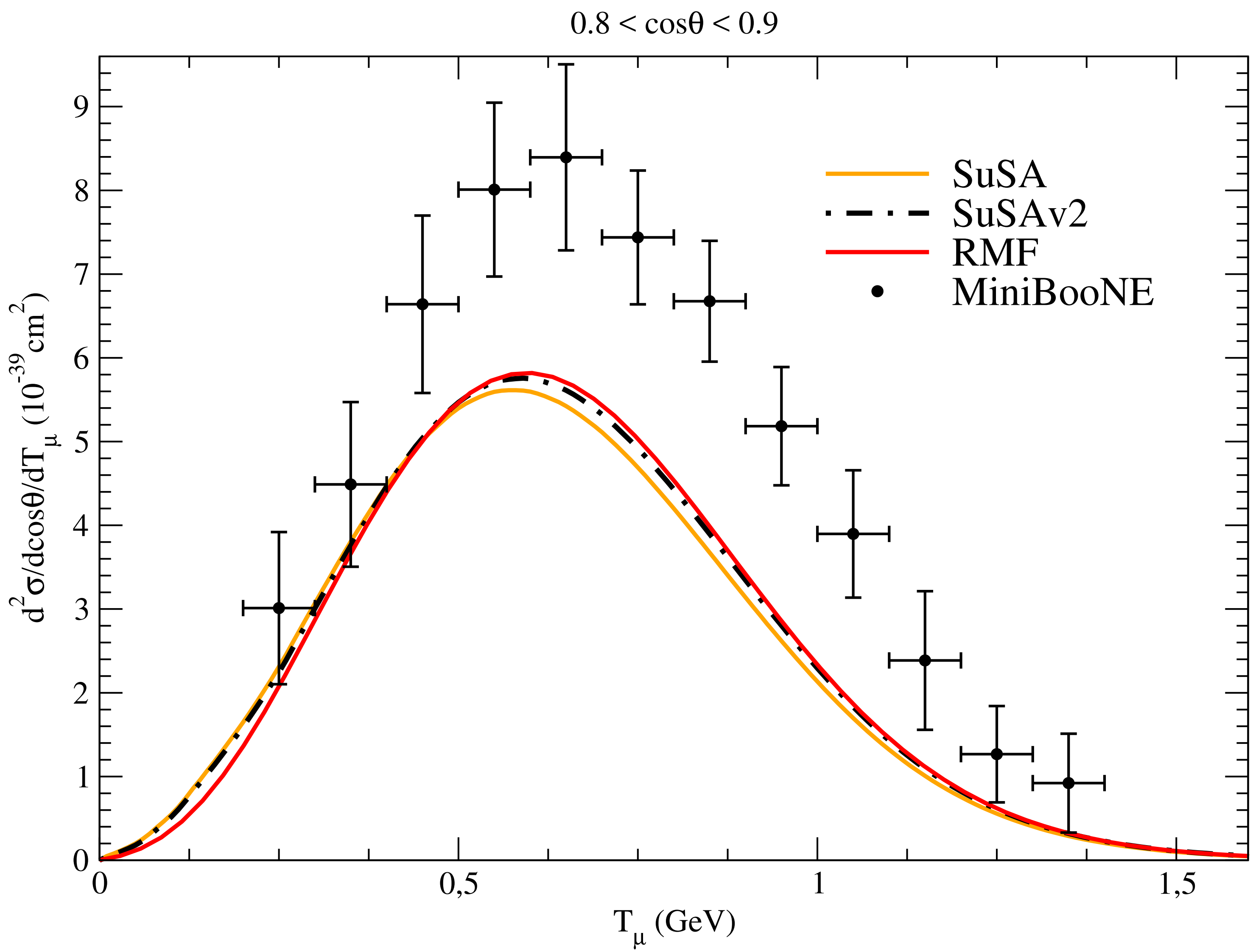


Basic result: *the function $f(\psi)$ evaluated for (ν, μ) processes agrees better with the contribution $f_L(\psi)$ [corresponding to (e, e')] than with $f_T(\psi)$.*

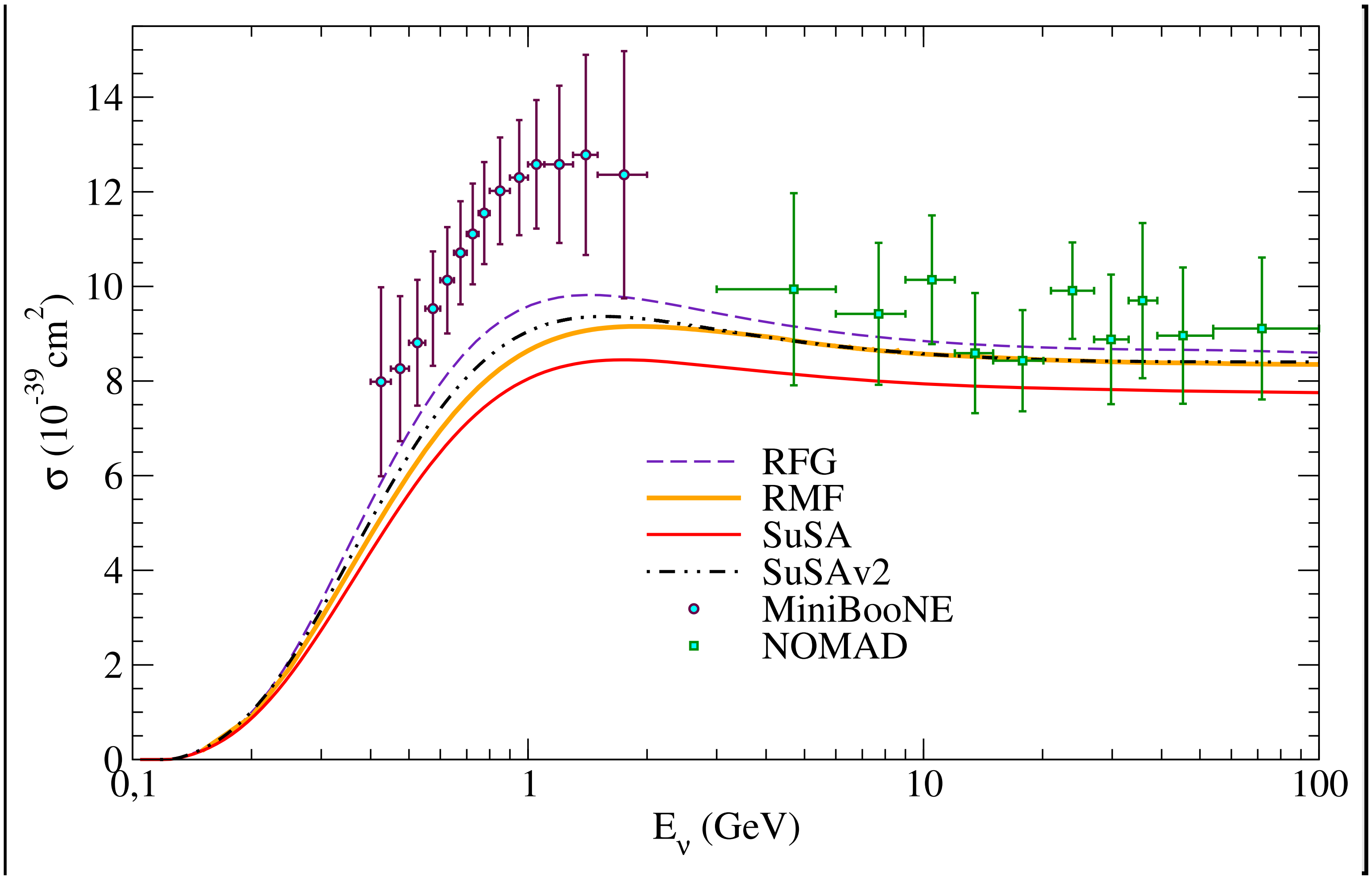
COMPARISON WITH DATA:

MiniBooNE, MinerνA, NOMAD & T2K

Flux-averaged double-differential CCQE: SuSA & RMF



MiniBooNE & NOMAD: SuSA *vs* RMF



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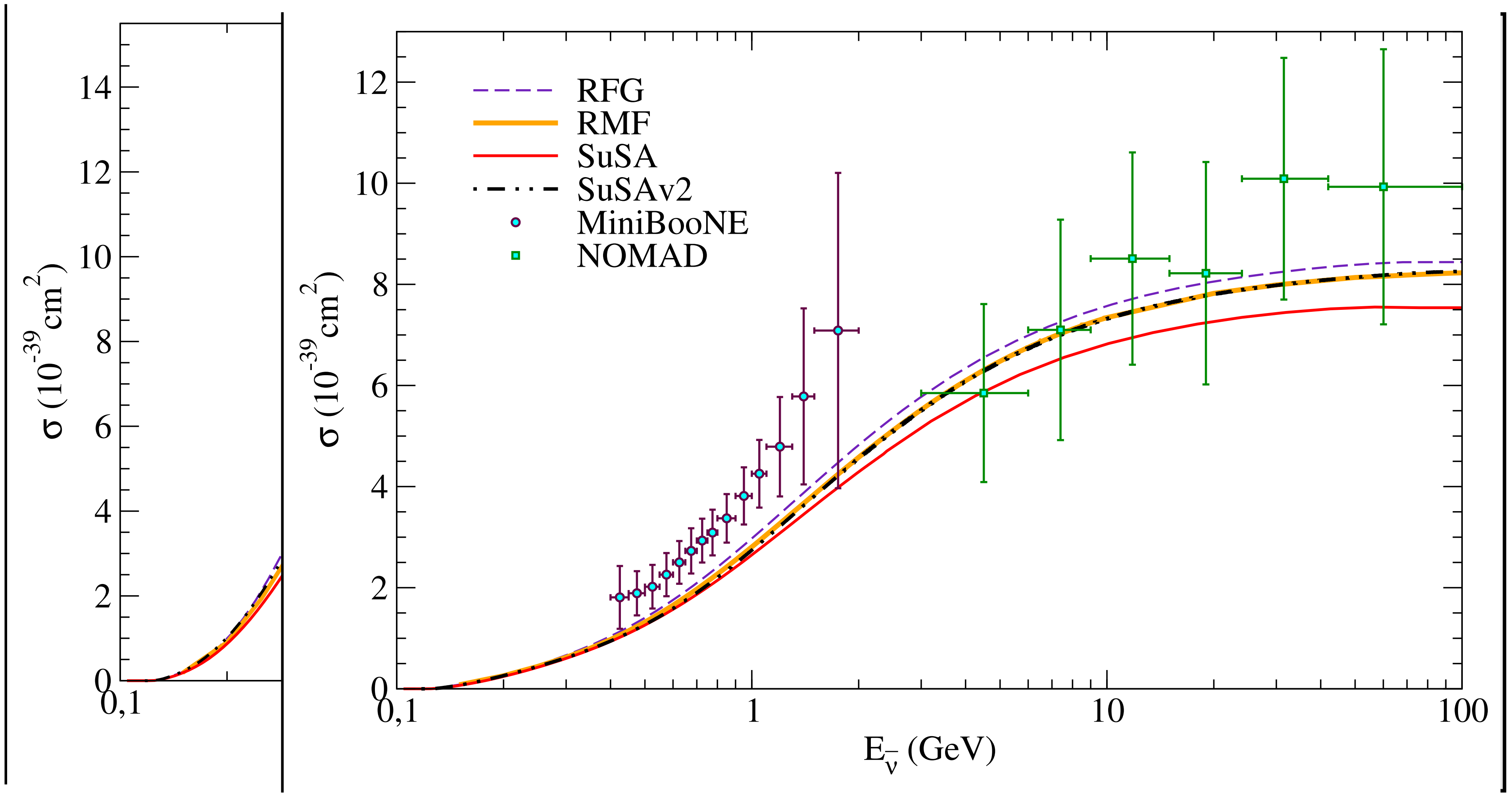
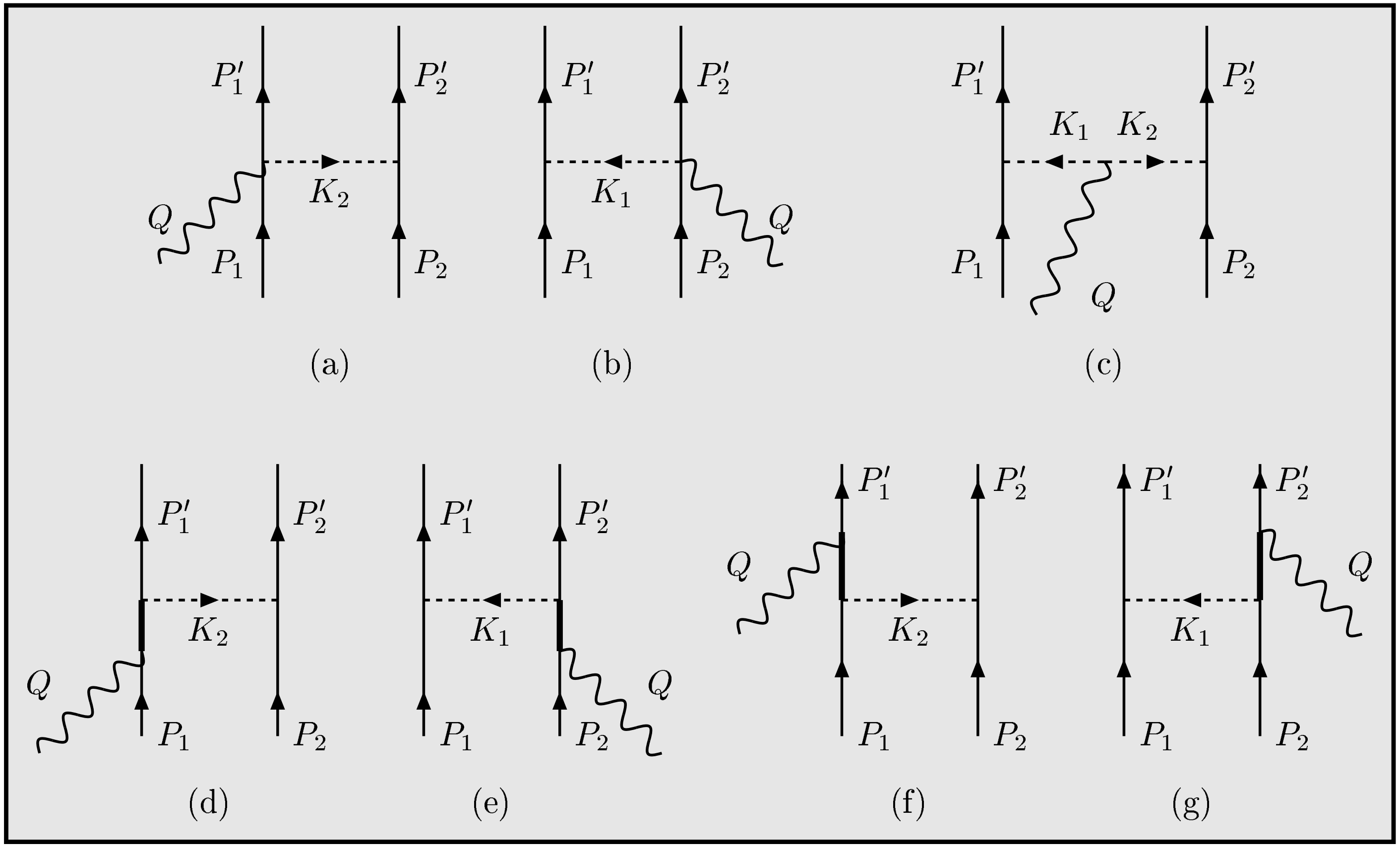


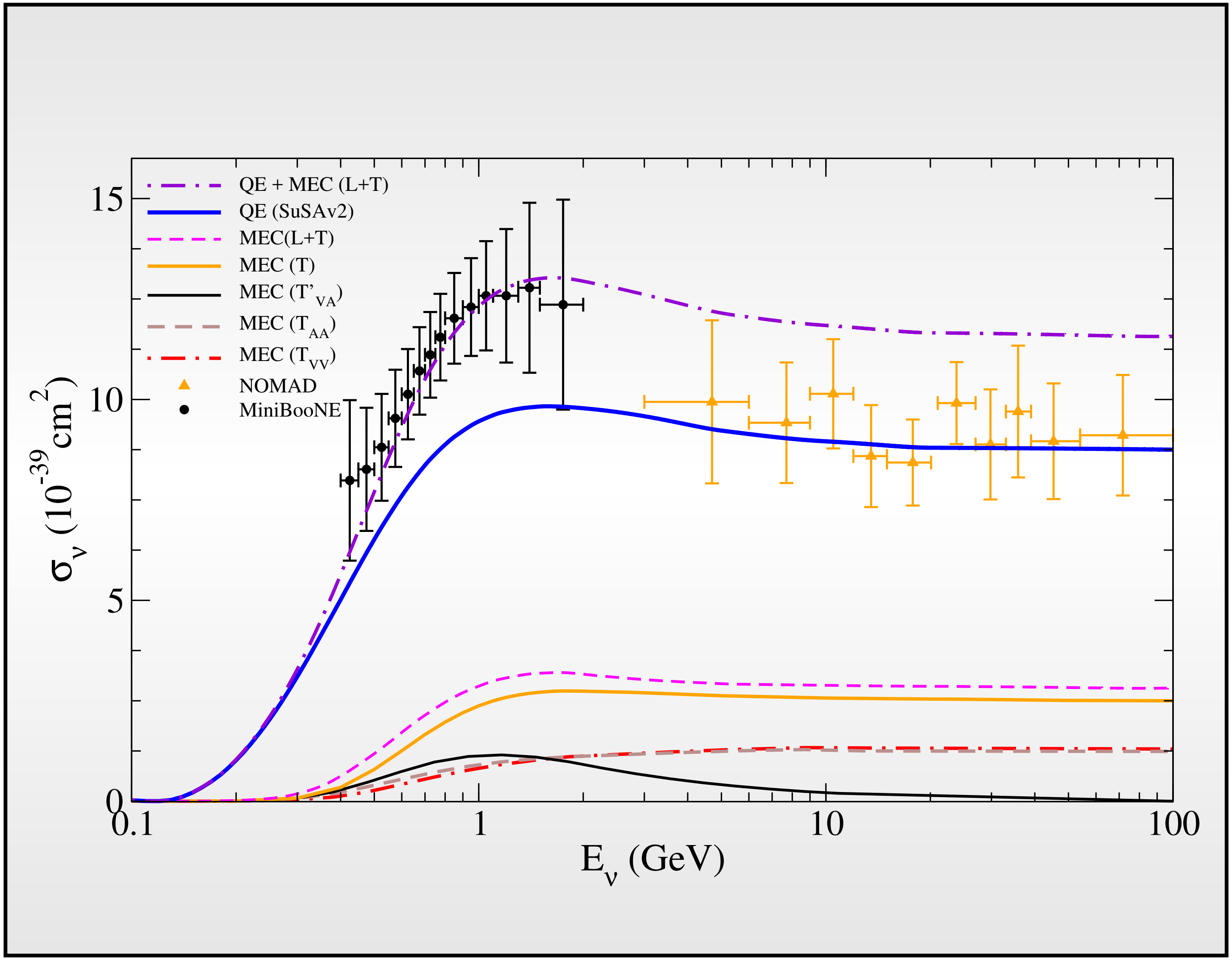


"MEC"

"correlations" and "Δ-MEC"

Application to CC neutrino scattering processes

Integrated cross section: 2p-2h effects



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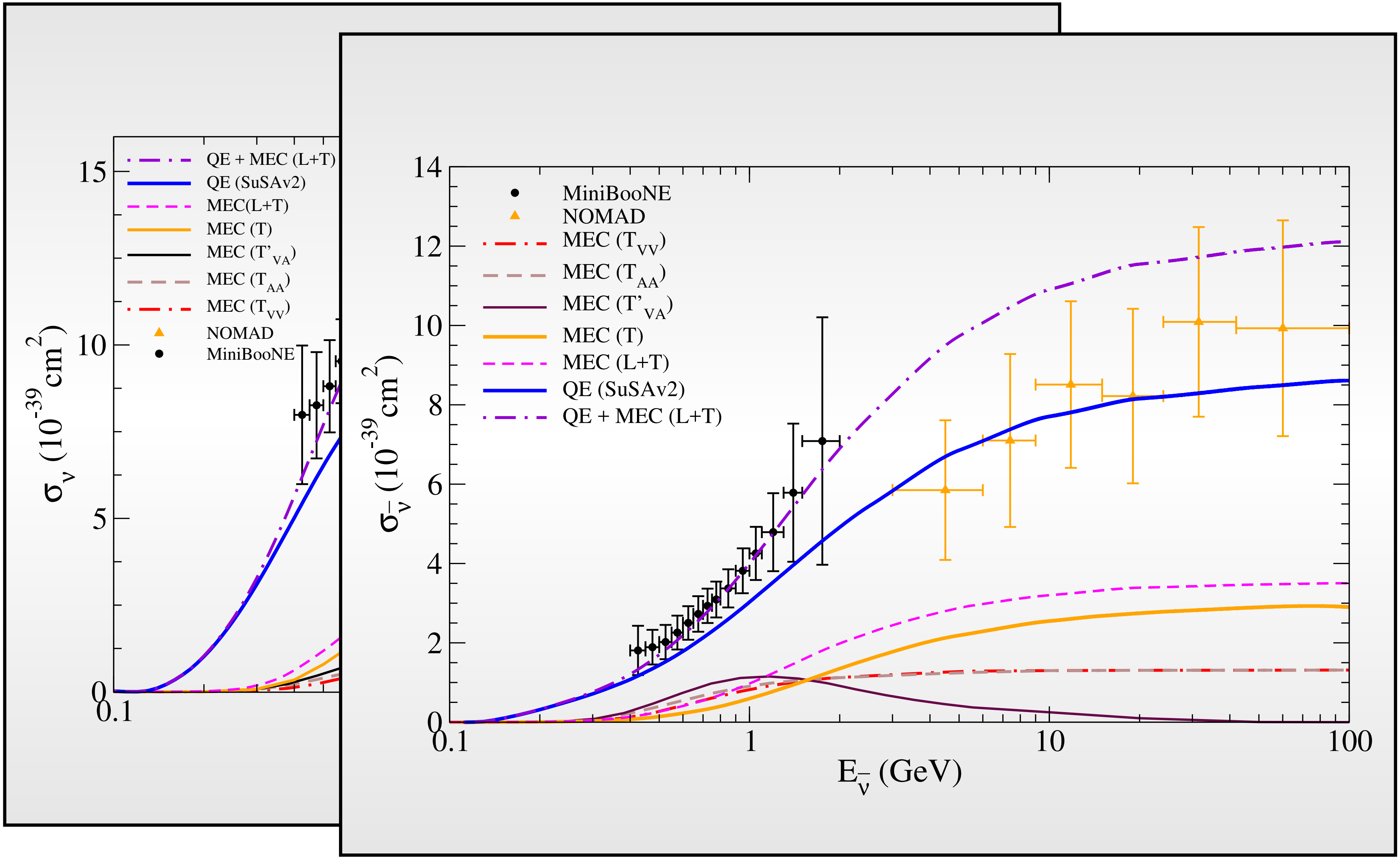
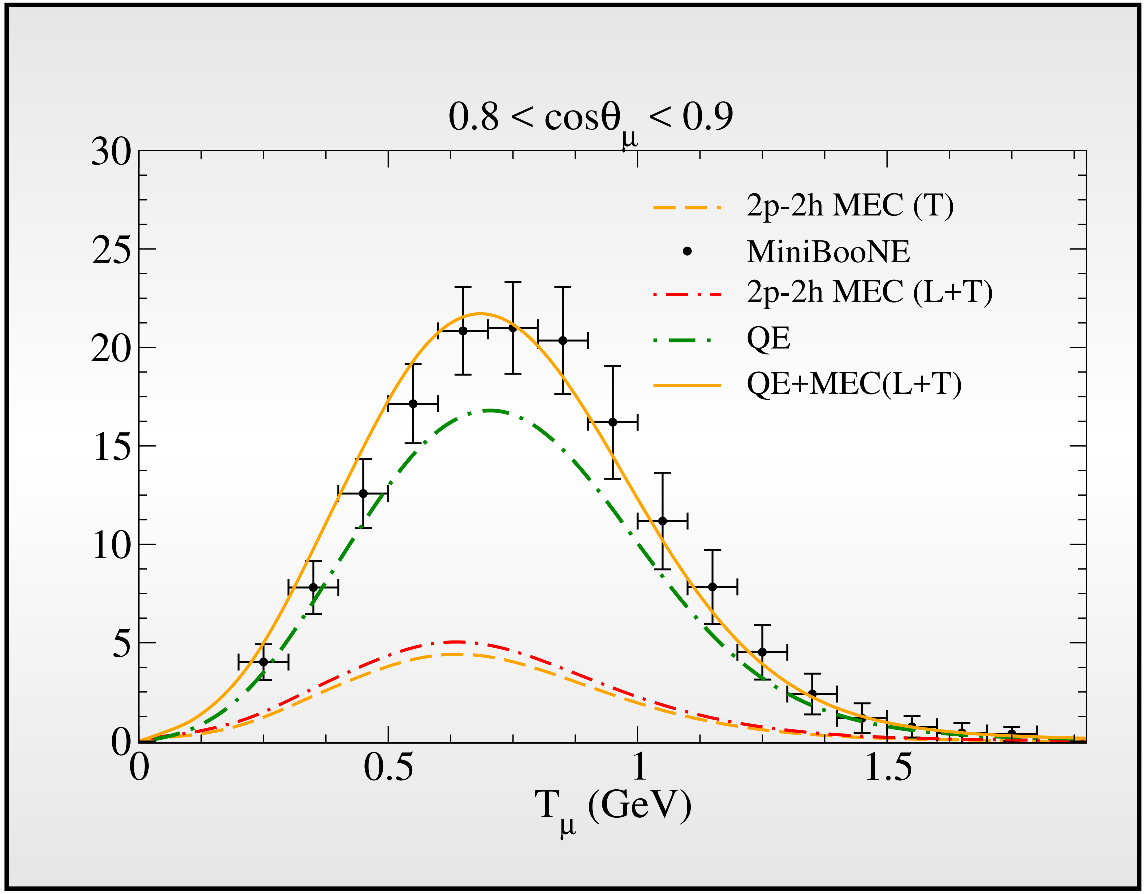
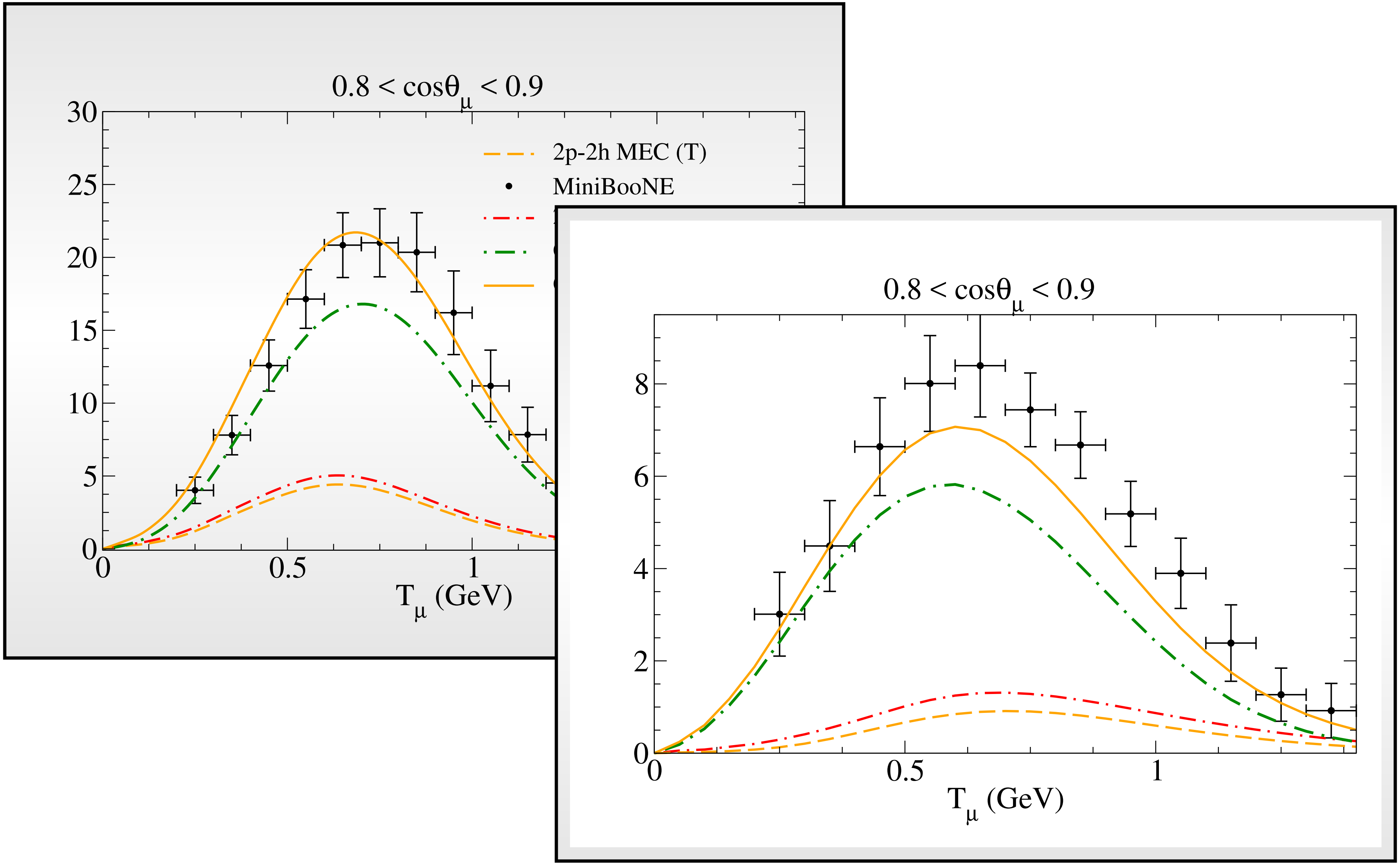
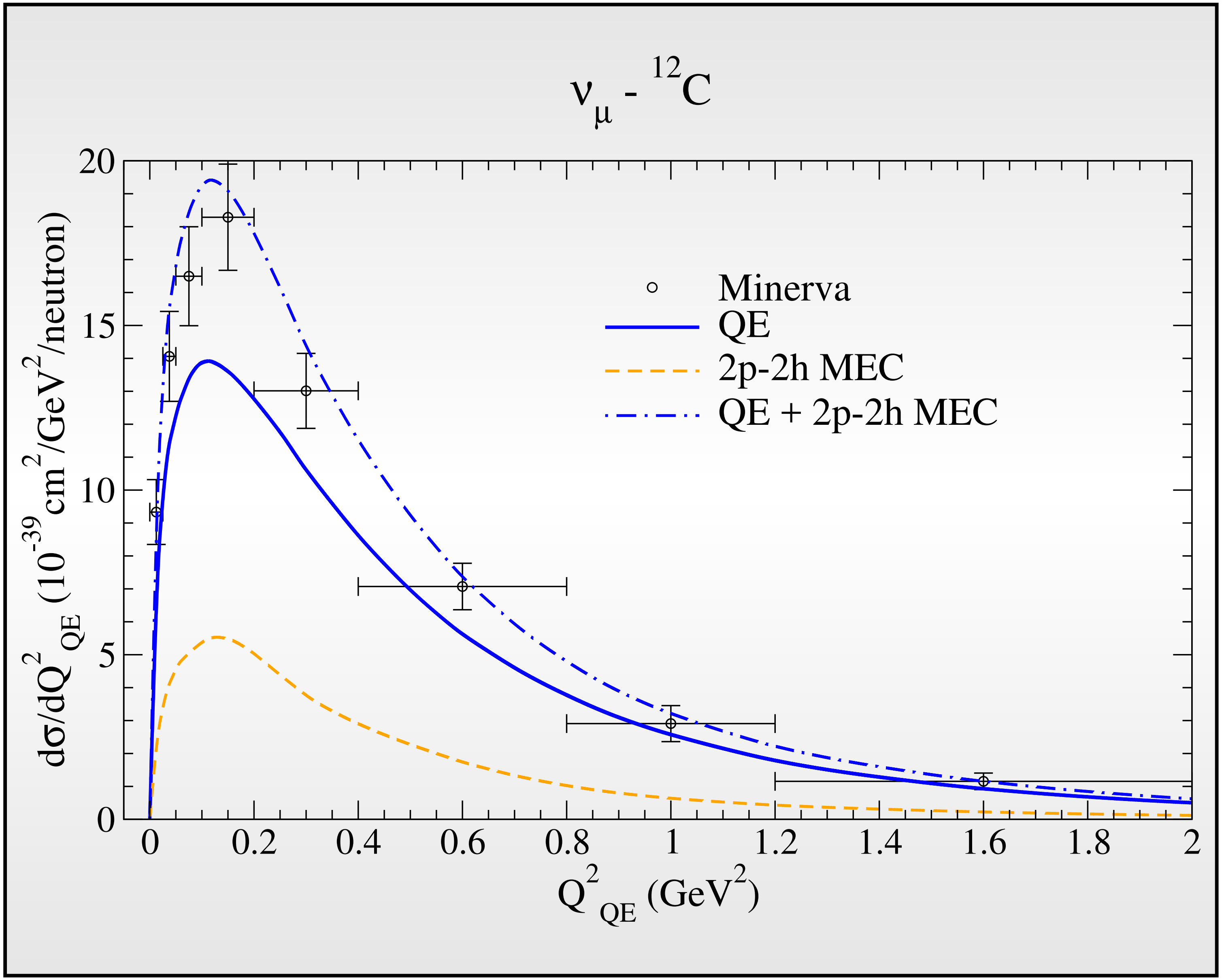


Flux-averaged double-differential CCQE-ν_μ & $\overline{\nu}_\mu$

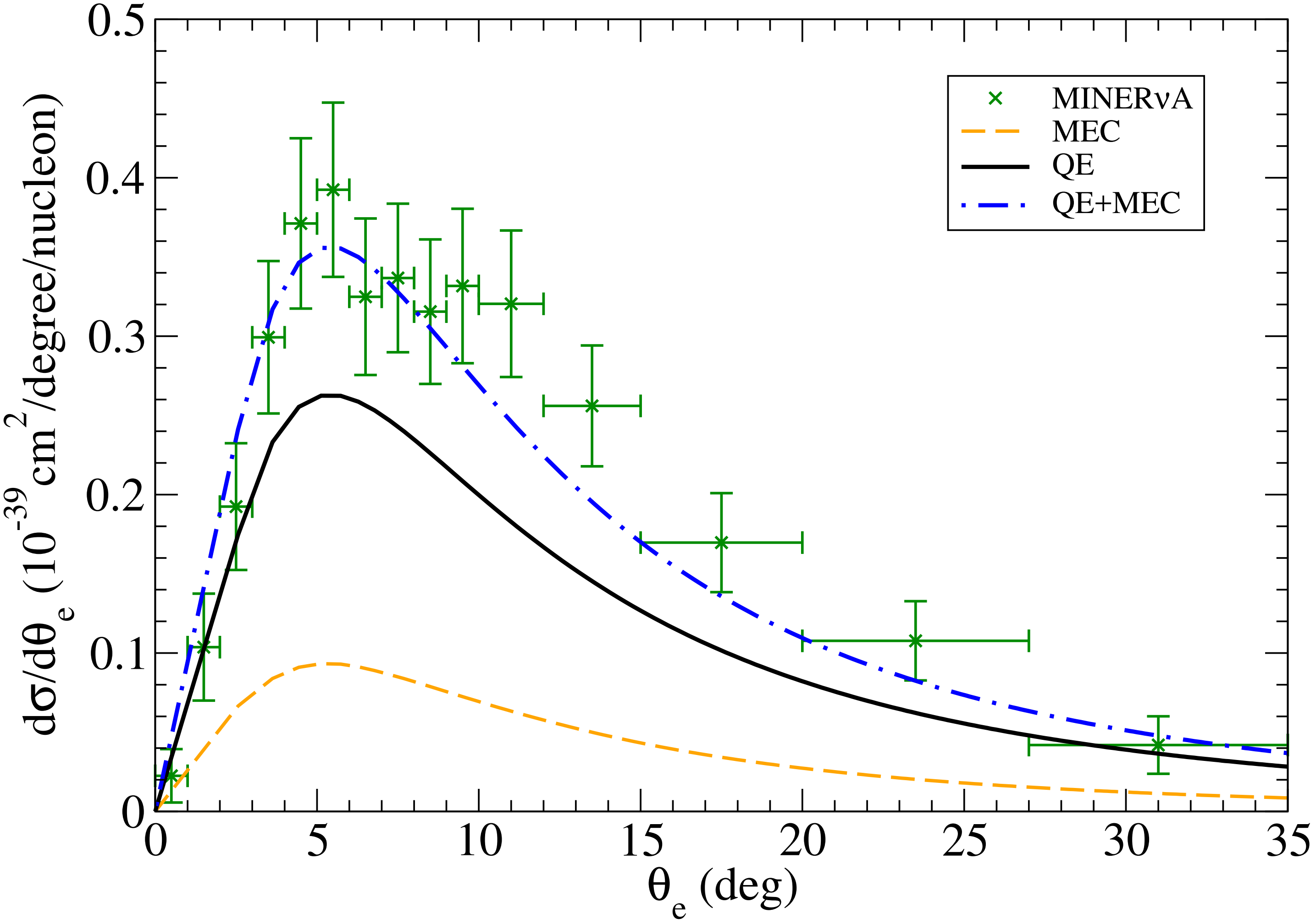



0.8 < cosθ$_\mu$ < 0.9
30
25
20
15
10
5
0
0
0.5
1
T$_\mu$ (GeV)
2p-2h MEC (T)
MiniBooNE
0.8 < cosθ$_\mu$ < 0.9
8
6
4
2
0
0
0.5
1
T$_\mu$ (GeV)

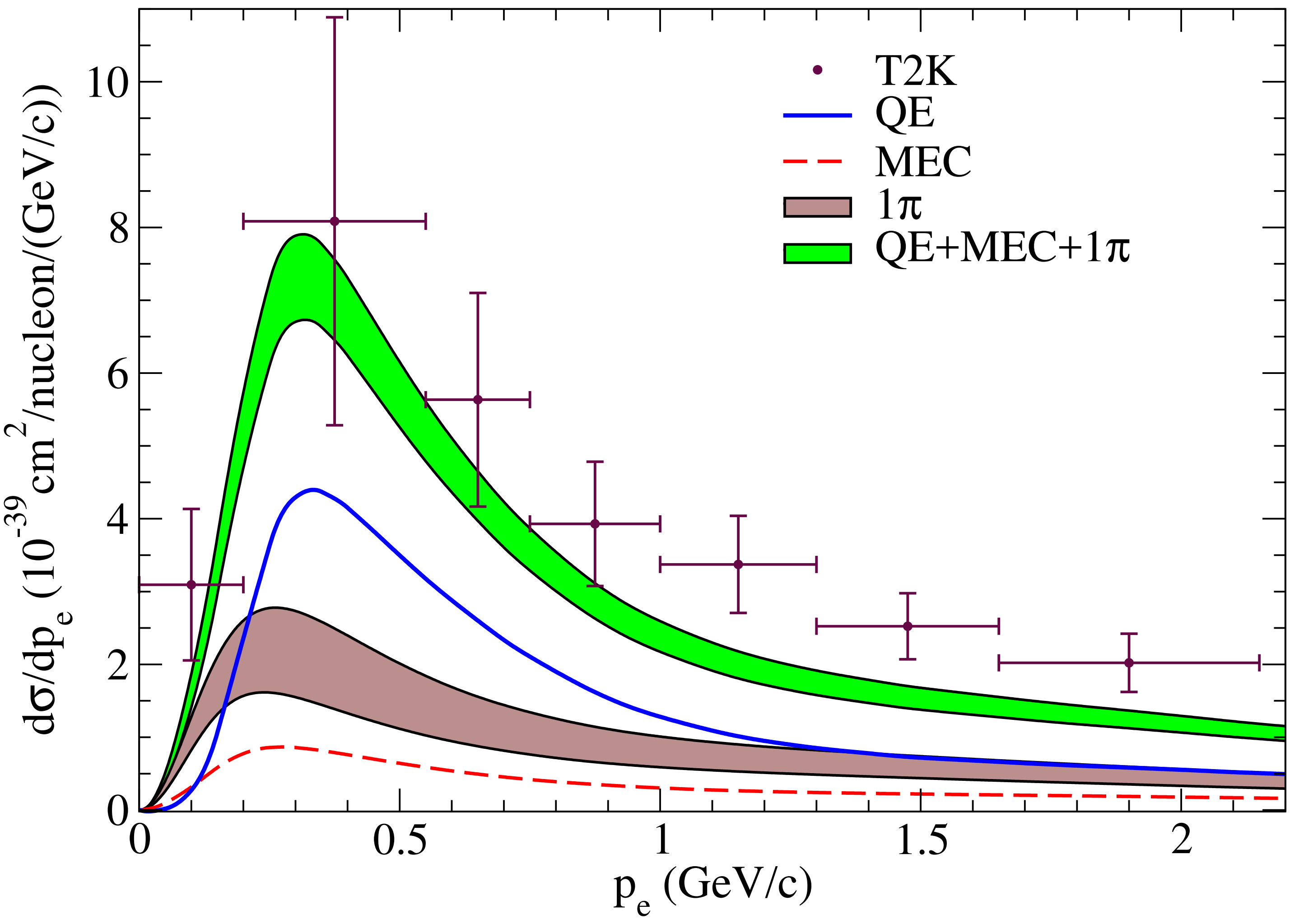
MINERνA: case of ν_μ



MINERνA: case of ν_e



T2K experiment: Δ-contribution



SUMMARY

- *The RIA/RMF describes in a reasonable way QE (e, e') data, satisfying scaling behavior and providing an asymmetric superscaling L function in accordance with data.*
- *Contrary to most NR/SR models (likewise RFG), RMF violates scaling of zeroth order, i.e., $f_T > f_L$. This seems to be consistent with (e, e') data analysis.*
- *RMF applied to neutrino scattering also satisfies scaling/superscaling properties.*
- *RMF in agreement with SuSA and provides the basis for the new SuSAv2 approach.*
- *SuSAv2 extended to the inelastic region + 2p2h MEC $\Longrightarrow$ excellent description of (e, e') data.*
- *SuSAv2-MEC applied to neutrino reactions describes properly MiniBooNE, MinerVa and T2K data. Significant enhancement due to 2p2h-MEC.*

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