Scaling of Inclusive Electroweak Interactions with Nuclei

Part II: Relativistic Impulse Approximation

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Neutrino Interactions-Nucleus Interaction for Current and Next Generation Neutrino Oscillation Experiments:

INT Workshop INT-13-54W, Seattle, December 3-13, 2013

OUTLINE

- **Quasielastic (e,e') data & Scaling/Superscaling**
- **The Relativistic Impulse Approximation**
  - *The Relativistic Mean Field (RMF)*
  - *Analysis of electron scattering & Scaling behavior*
  - *Application to neutrino (CC and NC) processes*
  - *Comparison with the SuperScaling Approach (SuSA)*
  - *MiniBooNE, MINERνA & NOMAD experiments*
- **SUMMARY AND CONCLUSIONS**

QUASIELASTIC (e, e') DATA & SCALING

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

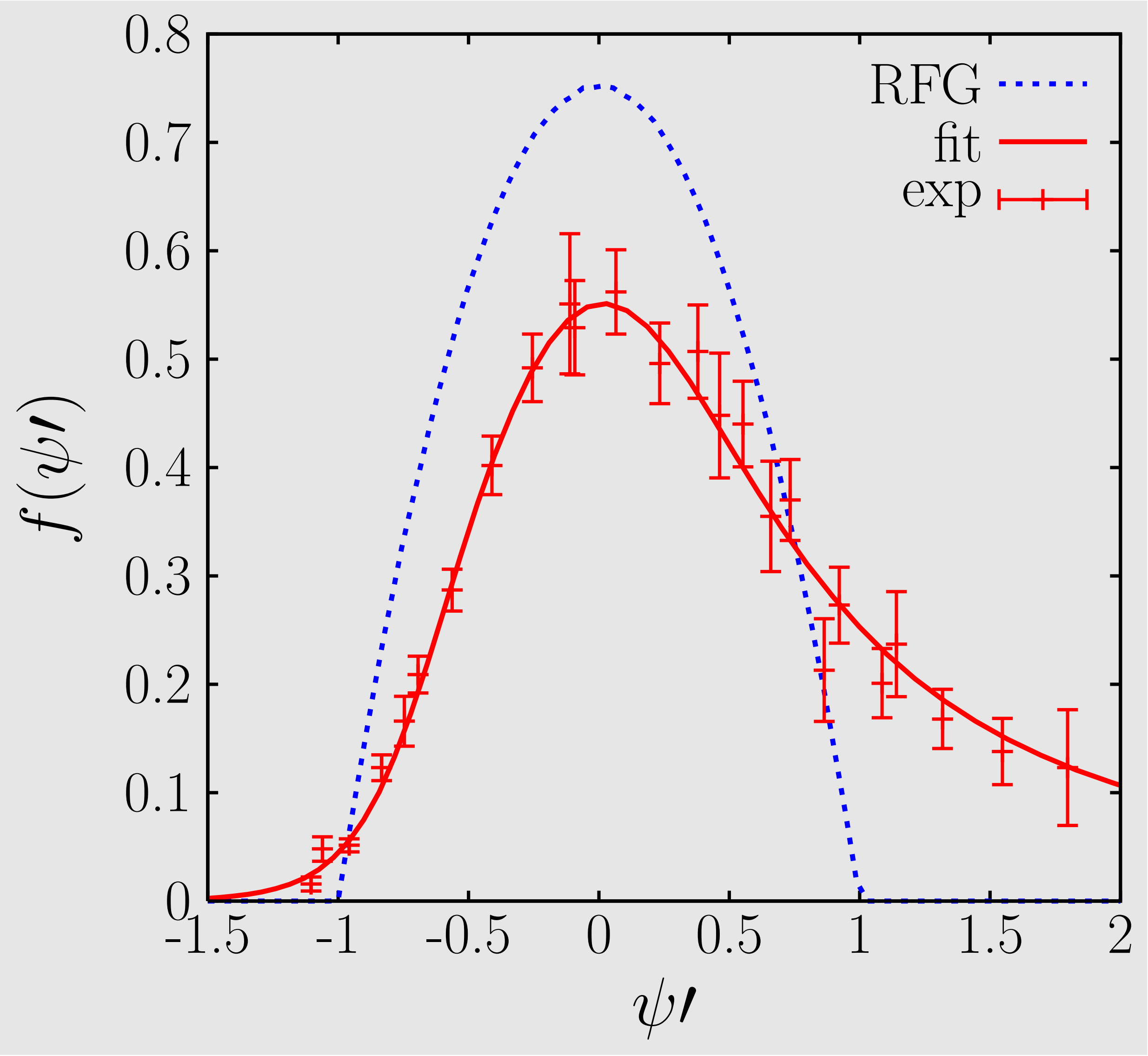
PRC65 (2002) 025502

- **LONGITUDINAL RESPO**

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

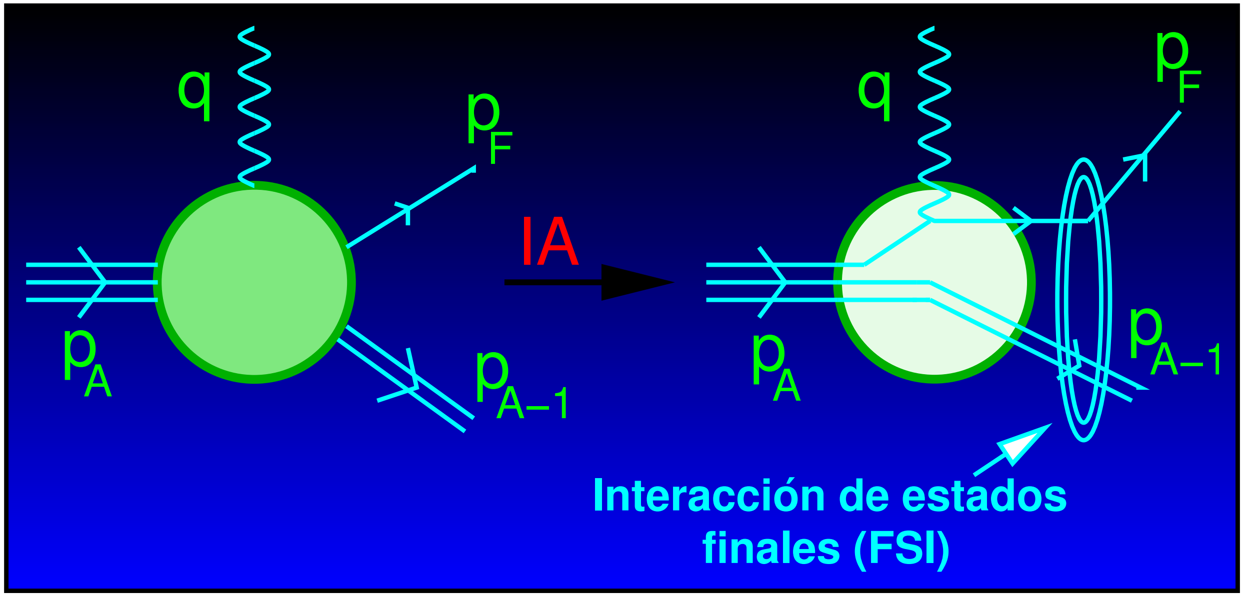
$\Downarrow$

strong constraints to models



THE MODEL: RELATIVISTIC IMPULSE APPROXIMATION

APPLICATION TO (e, e') PROCESSES



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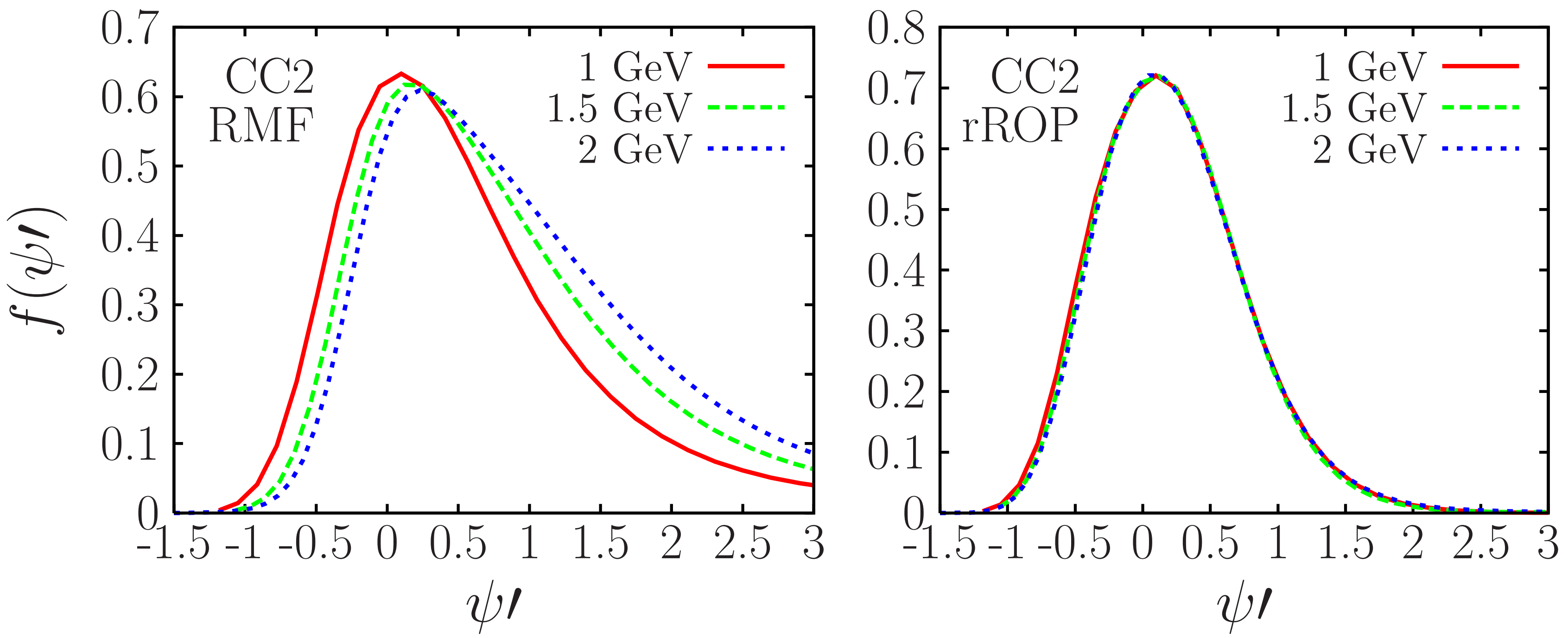
- **Electromagnetic current:** (e, e')

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

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

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

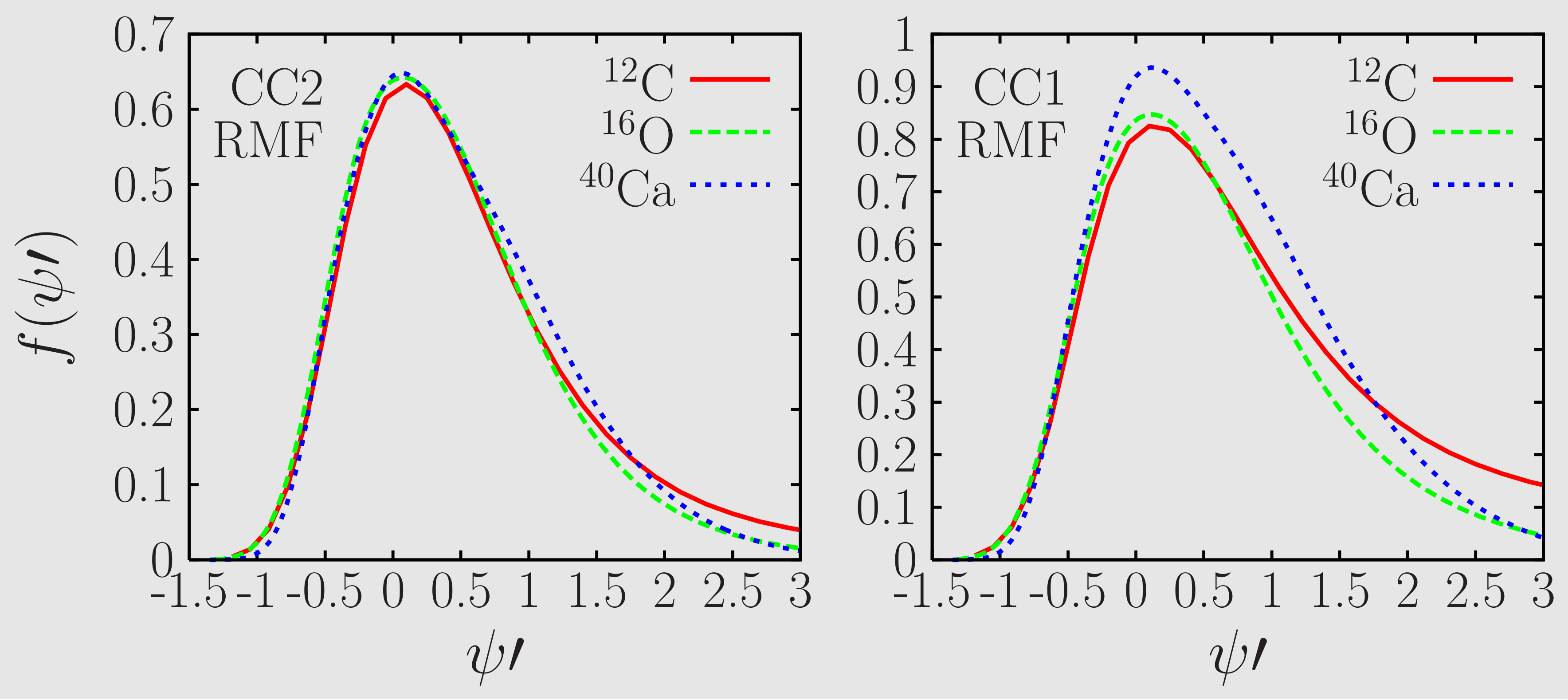
Scaling of the first kind in $^{12}C(e,e')$



RMF: shift in $\psi' < 0$ and breakdown of scaling at roughly $\sim 25 - 30\%$ for $\psi' > 0$ (compatible with data).

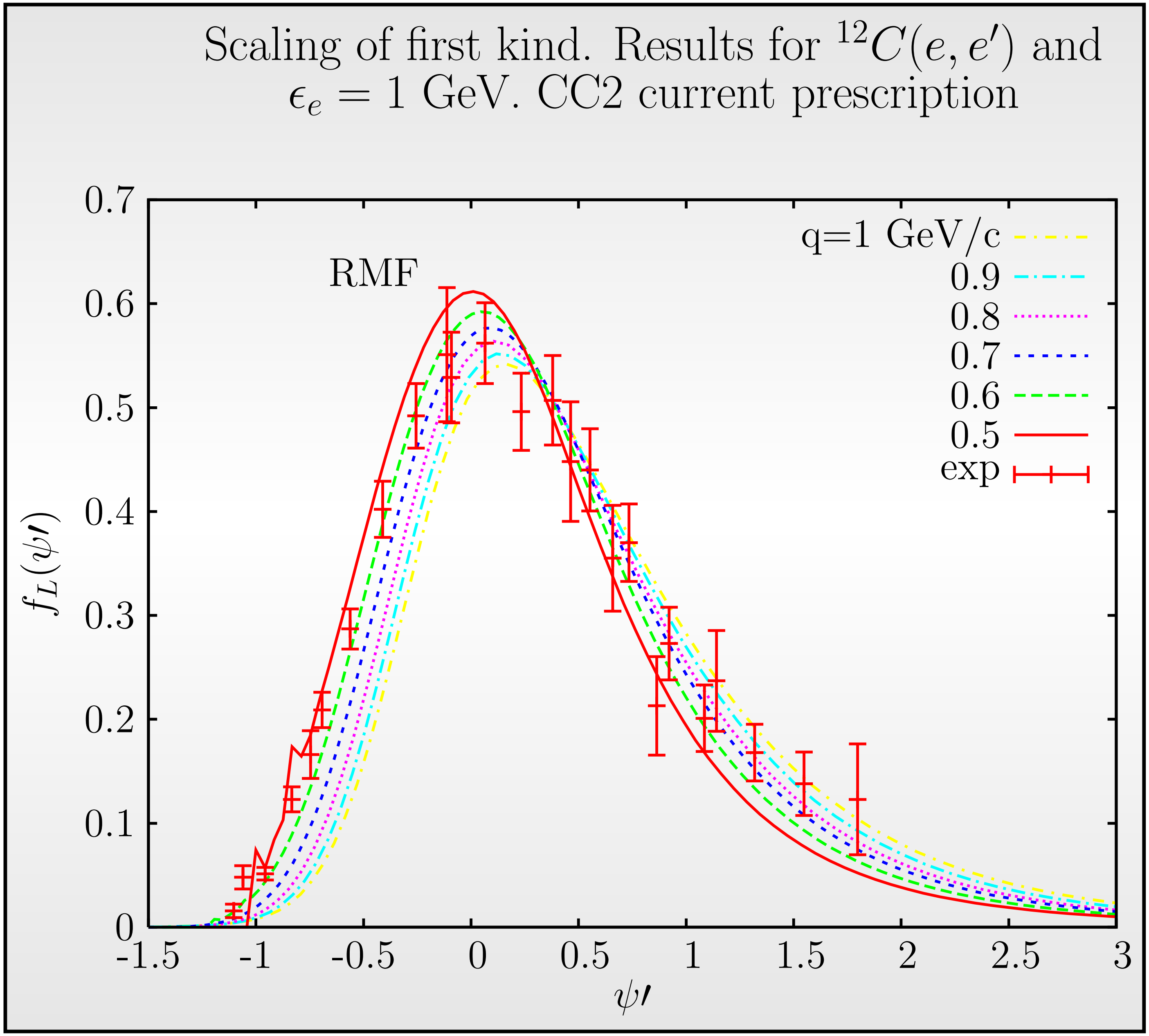
Scaling of the first kind: excelent in rROP approach (and RPWIA)

Scaling of the second kind in RIA

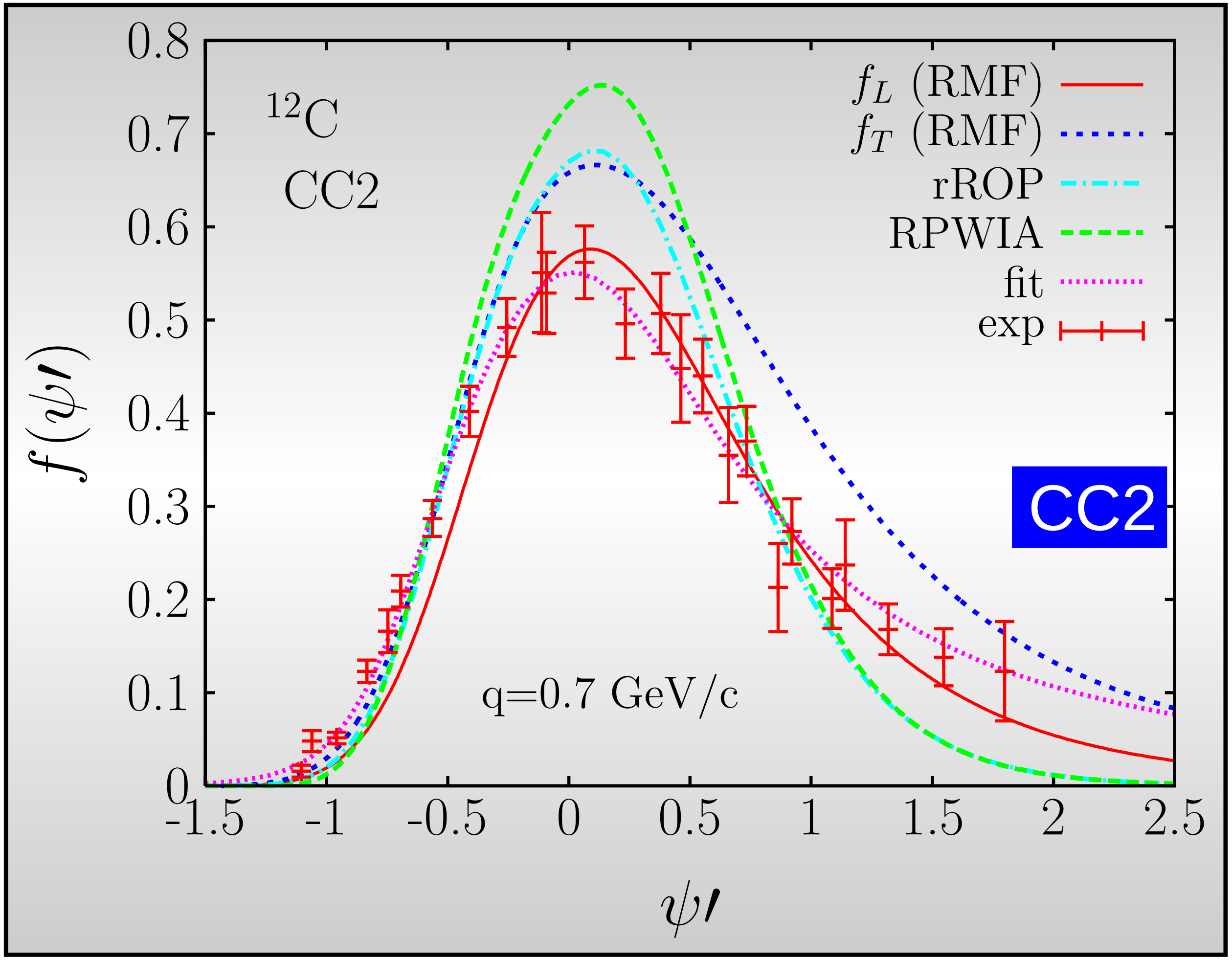


Scaling of 2^a kind: excellent with the CC2 current operator

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



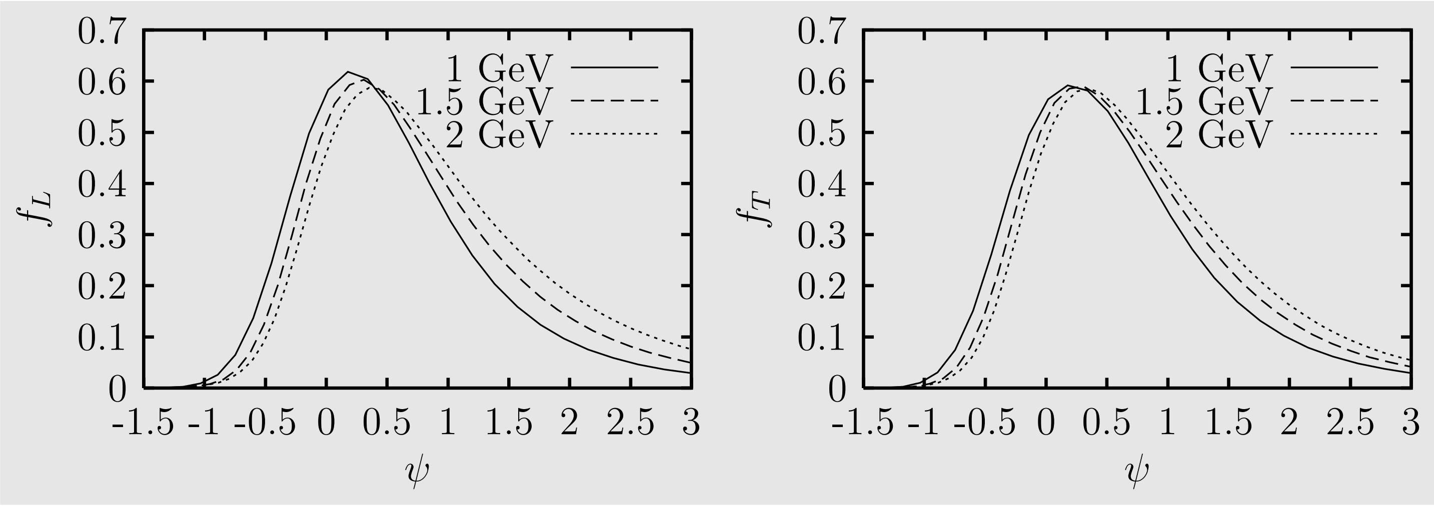
RMF: Comparison with (e, e') data



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

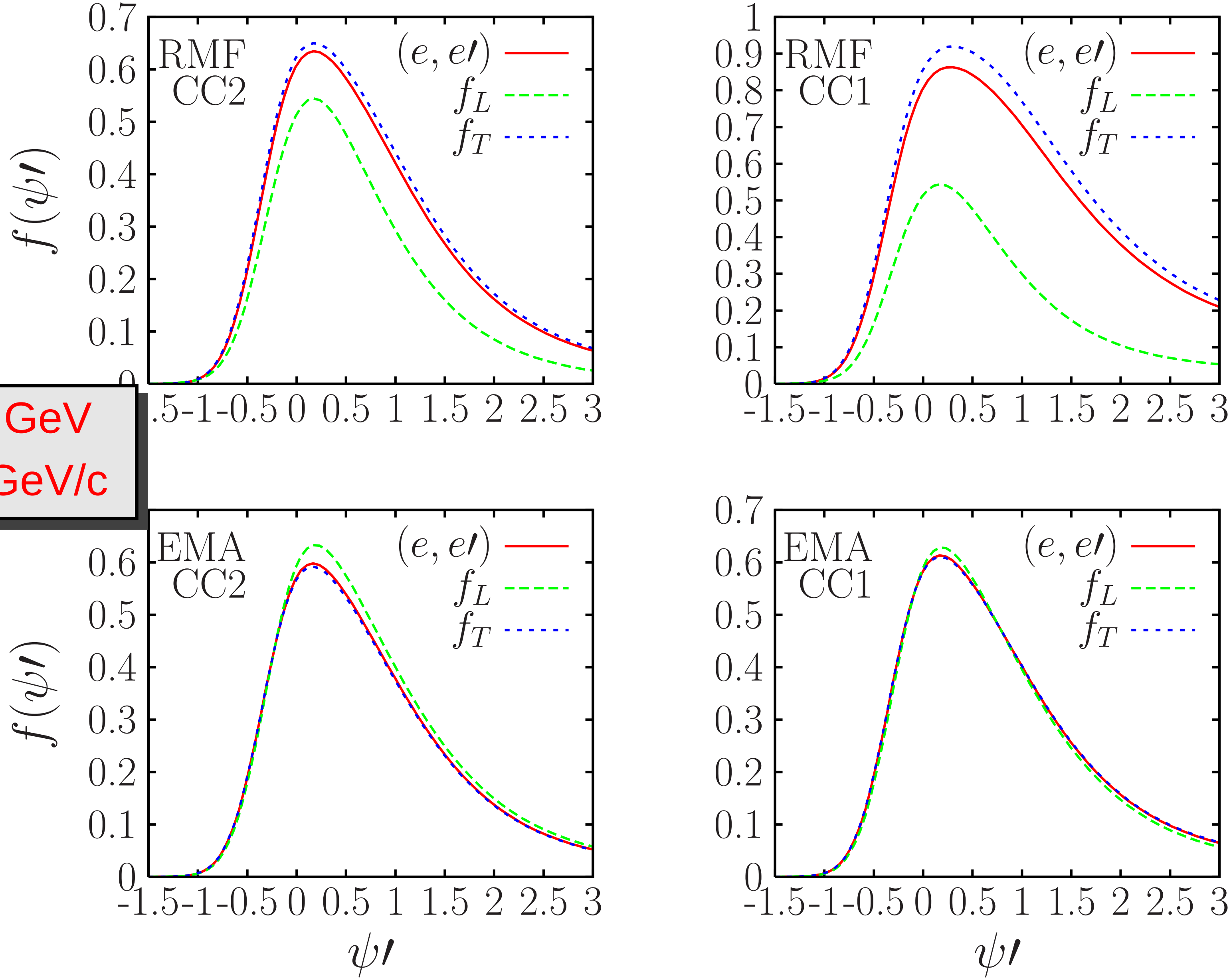
Scaling of the 0^{th} kind

- RFG: by construction $f_L(\psi) = f_T(\psi) = f(\psi)$
- RPWIA: $f_L(\psi) = f_T(\psi) = f(\psi)$–symmetric
- Semi-relativistic (SR) and/or NR approaches with FSI:
  - *Woods-Saxon potential: symmetric scaling functions.*
  - *Dirac Equation-Based (DEB) potential: leads to an asymmetric function $f(\psi)$.*



In all cases: $f_L(\psi) = f_T(\psi) = f(\psi)$

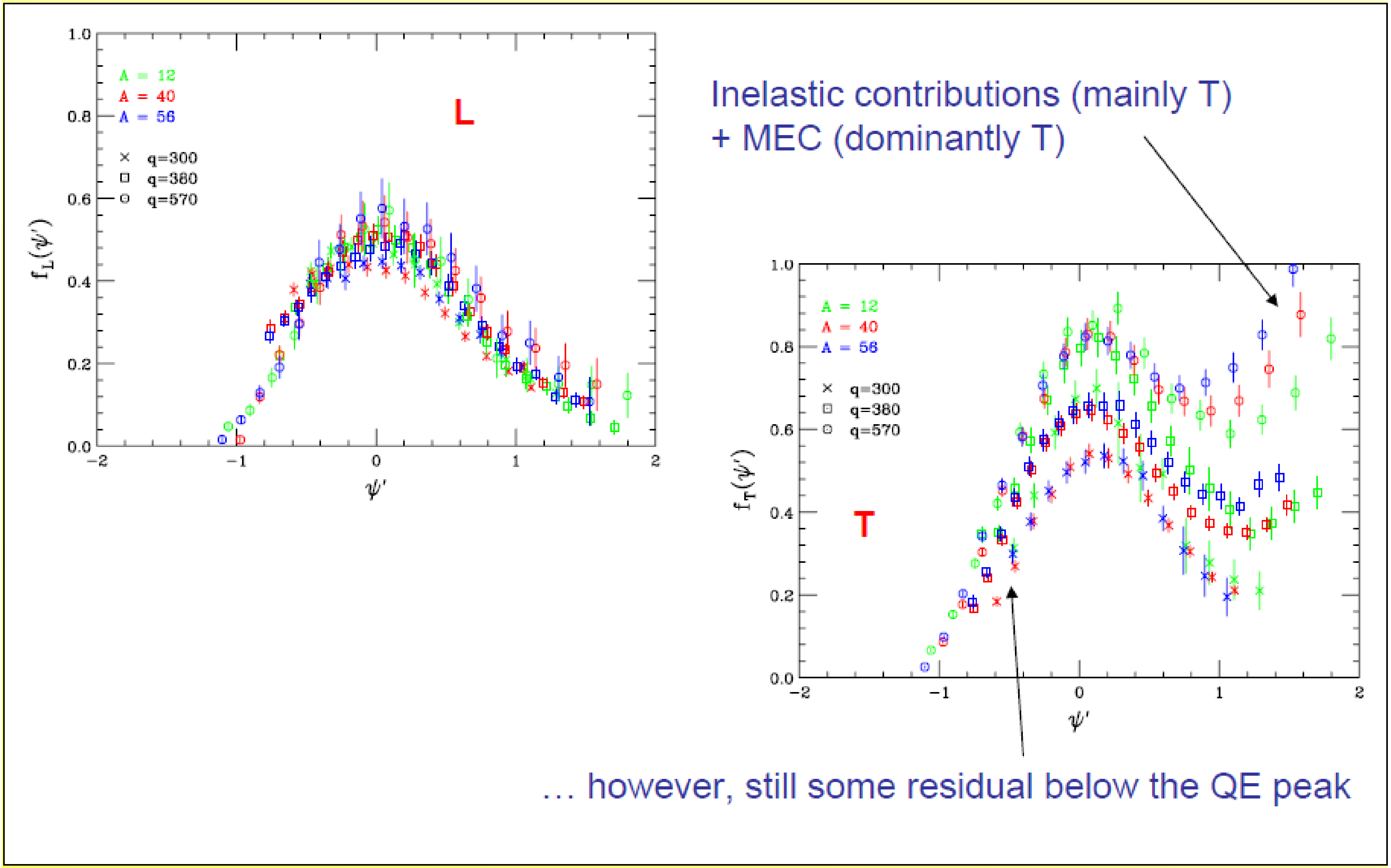
Scaling of the 0^{th} kind in RMF



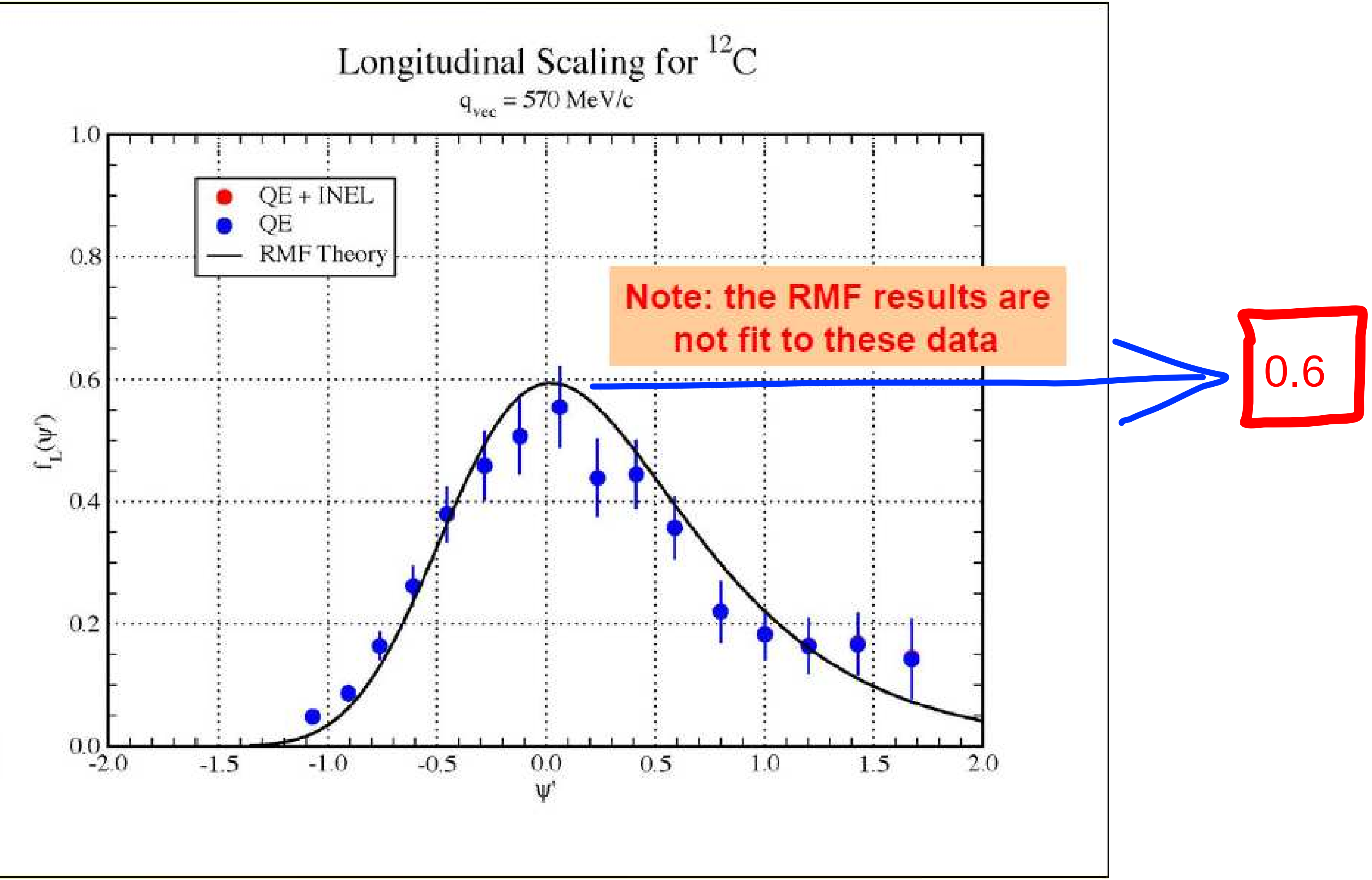
$\varepsilon_e = 1$ GeV

$q = 1$ GeV/c

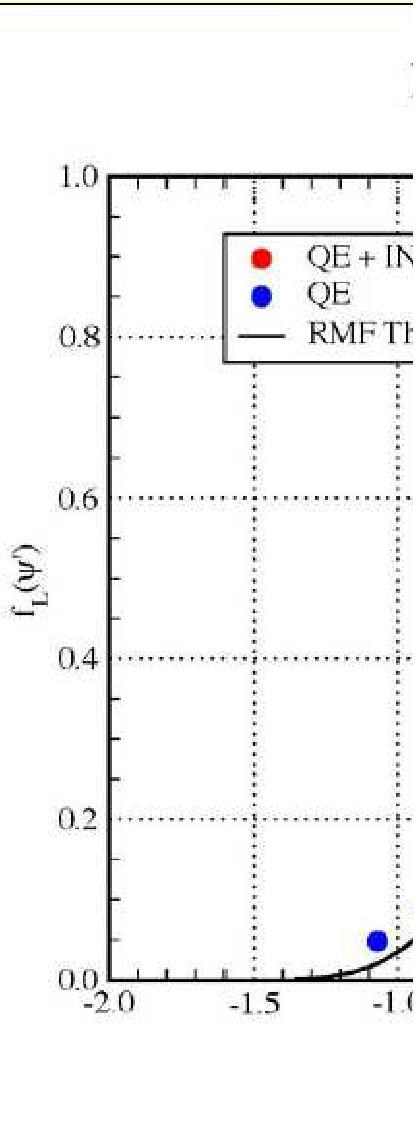
Analysis of data: L/T separation

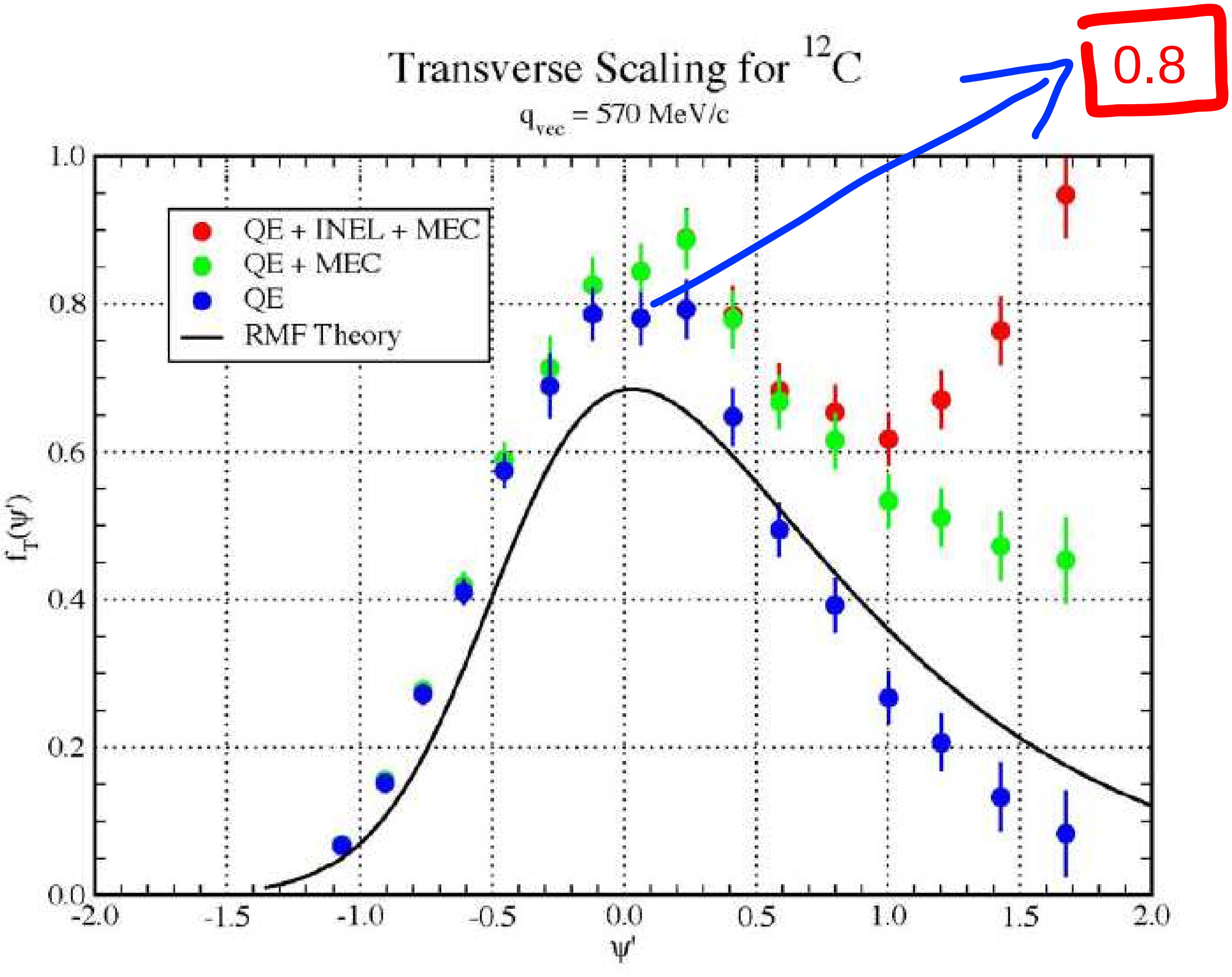


Scaling in QE L/T-channels



Scaling in QE L/T-channels





INTERACTION OF NEUTRINOS with NUCLEI

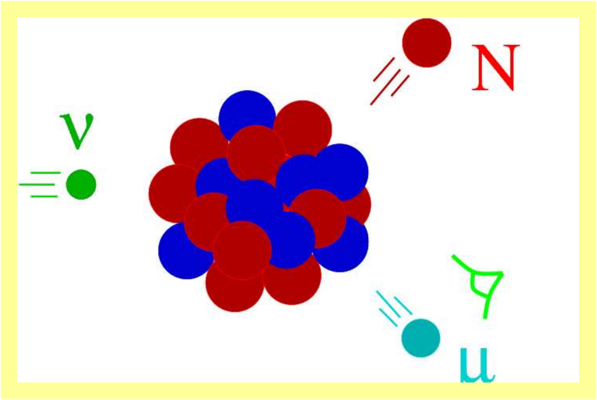
Quasielastic (e, e') versus (ν, μ) reactions

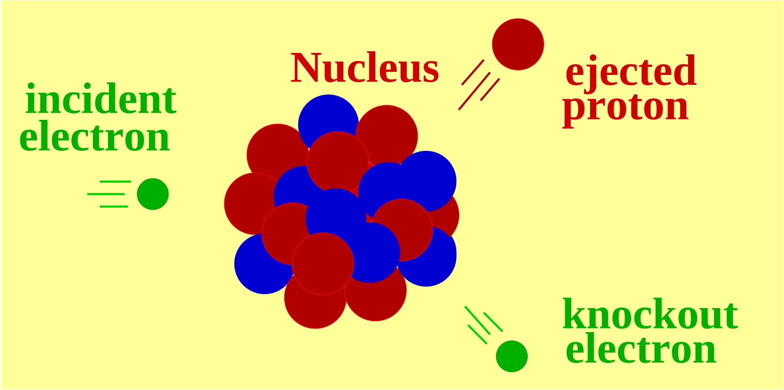
Neutrinos

$$\nu + A \Rightarrow \mu + N + B$$

Electrons

$$e + A \Rightarrow e' + N + B$$





Kinematics in electron and neutrino INCLUSIVE scattering are very similar. One should check models of neutrino scattering against inclusive electron data.

However, caution with models that do not succeed in reproducing the experimental (e, e') scaling function.

General formalism for (ν, μ) processes

Double differential cross section

$$\left[\frac{d\sigma}{dk_\mu d\Omega}\right]_\chi = \sigma_0 \mathcal{F}_\chi^2 \quad ; \quad \sigma_0 = \frac{(G_F^2 \cos\theta_c)}{2\pi^2} \frac{v_0}{2} \left(k_\mu \cos\frac{\tilde{\theta}}{2}\right) \quad ; \quad \chi = +(-) \equiv \nu_\mu(\bar{\nu}_\mu)$$

Nuclear structure information

$$\mathcal{F}_\chi^2 = \hat{V}_L R_L + \hat{V}_T R_T + \chi \left[2\hat{V}_{T'} R_{T'}\right]$$

Rosenbluth-like decomposition

$$R_L = R_L^{VV} + R_L^{AA} \qquad R_{T'} = R_{T'}^{VA}$$
$$R_T = R_T^{VV} + R_T^{AA}$$

Leptonic (j^μ) & hadronic currents (J^μ)

$$j^\mu = j_V^\mu + j_A^\mu \quad ; \quad J^\mu = J_V^\mu + J_A^\mu$$

Weak nuclear current

$$J_V^\mu = \bar{u}(P')\left[F_1^V \gamma^\mu + \frac{i}{2m_N} F_2^V \sigma^{\mu\nu} Q_\nu\right] u(P)$$
$$J_A^\mu = \bar{u}(P')\left[G_A \gamma^\mu + \frac{1}{2m_N} G_P Q^\mu\right] u(P)$$

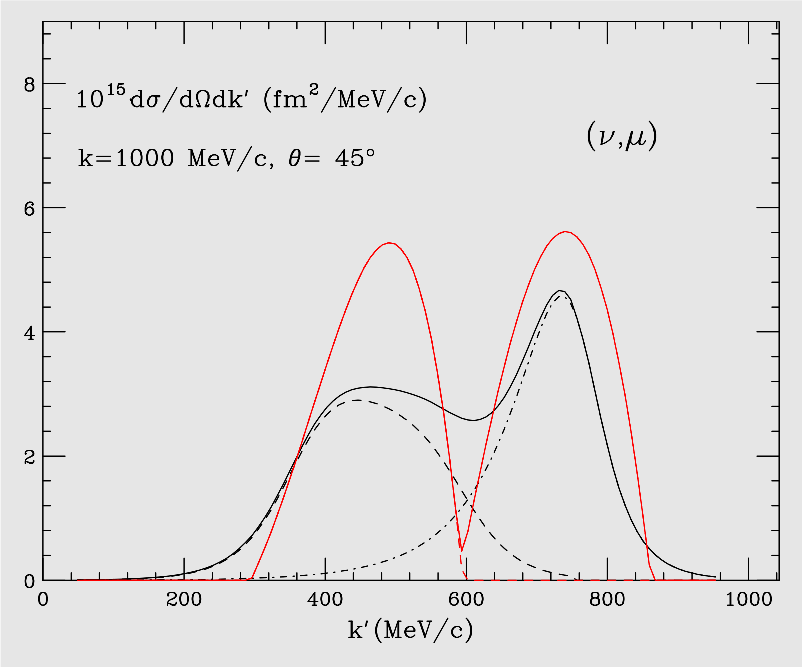
Nuclear responses

Composed of VV (vector-vector), AA (axial-axial) and VA (vector-axial) components arising from the V and A weak nuclear currents.

Scaling applied to (ν, μ) processes

SuSA ("SuperScaling Analysis")

- **Hyphotesis:** *the universal character of the function* $f_{exp}(\psi')$ *extracted from the analysis of* L (e, e') *data* $\Longrightarrow$ *it can be applied to CC* (ν_μ, μ) *processes*.
  Prediction of "realistic" (ν, μ) cross sections
  [MiniBoone, MINERνA, NOMAD]

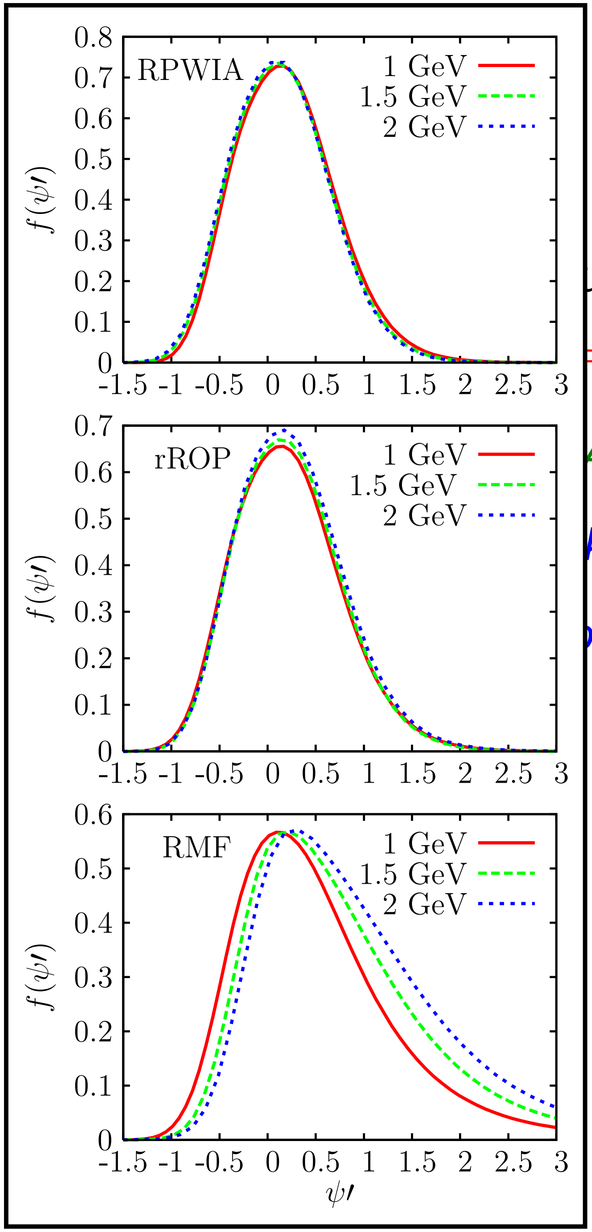


RMF applied to (ν, μ) & Scaling

PROCEDURE

- *Evaluate the inclusive (ν, μ) cross section with a specific RIA model and divide it by the corresponding single-nucleon cross section [weighted by the appropriate proton (Z) and neutron (N) numbers]* $\Longrightarrow$ **THEORETICAL SCALING FUNCTION**
- *Does the theoretical RIA scaling function satisfy scaling properties?*
  - *Scaling of the first kind:* $f(q, \psi) \stackrel{q \to \infty}{\longrightarrow} f(\psi)$
  - *Scaling of the second kind:* $f(\psi)$ – *independent on the nucleus*

RMF applied to (ν, μ) & Scaling



PROCEDURE

$\nu, \mu)$ *cross section with a specific RIA model and divide it by the*

ucleon cross section [weighted by the appropriate proton (Z) and

$\Longrightarrow$ **THEORETICAL SCALING FUNCTION**

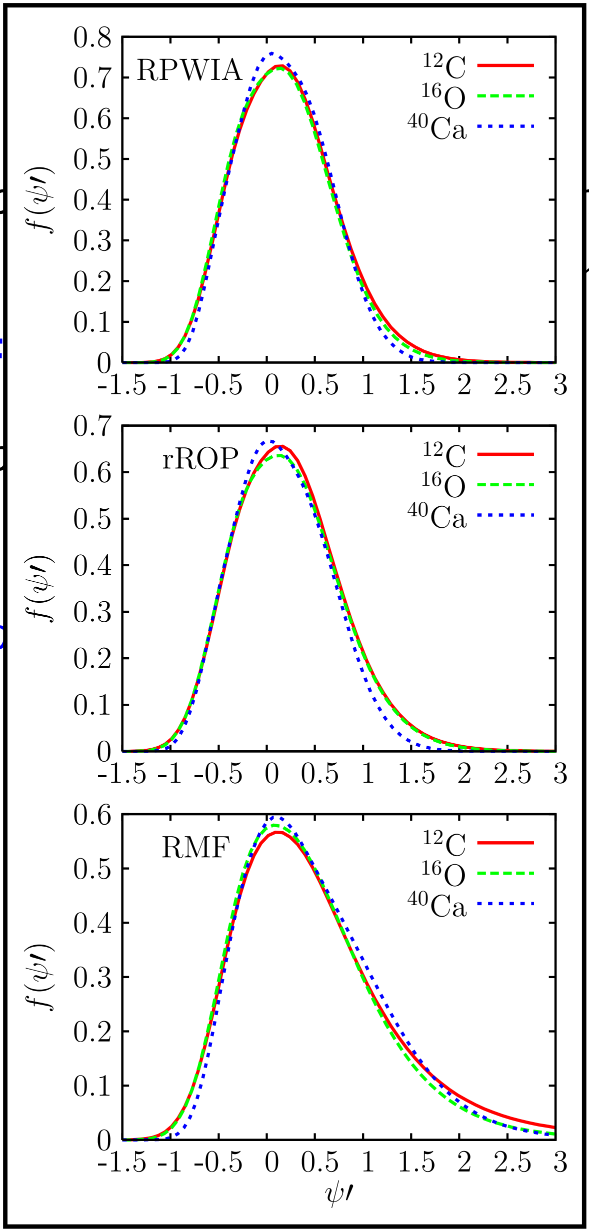
A scaling function satisfy scaling properties?

kind: $f(q, \psi) \xrightarrow{q \to \infty} f(\psi)$

ond kind: $f(\psi)$ – *independent on the nucleus*

RMF applied to (ν, μ) & Scaling

PROCEDURE

- *Evaluate the inclusive* (ν, μ) *cross section with a specific* 

he corresponding single-nucleon cross section [weighted by nd neutron (N) *numbers]* $\Longrightarrow$ **THEORETICAL SCALING F**
- *Does the theoretical RIA scaling function satisfy scaling p*
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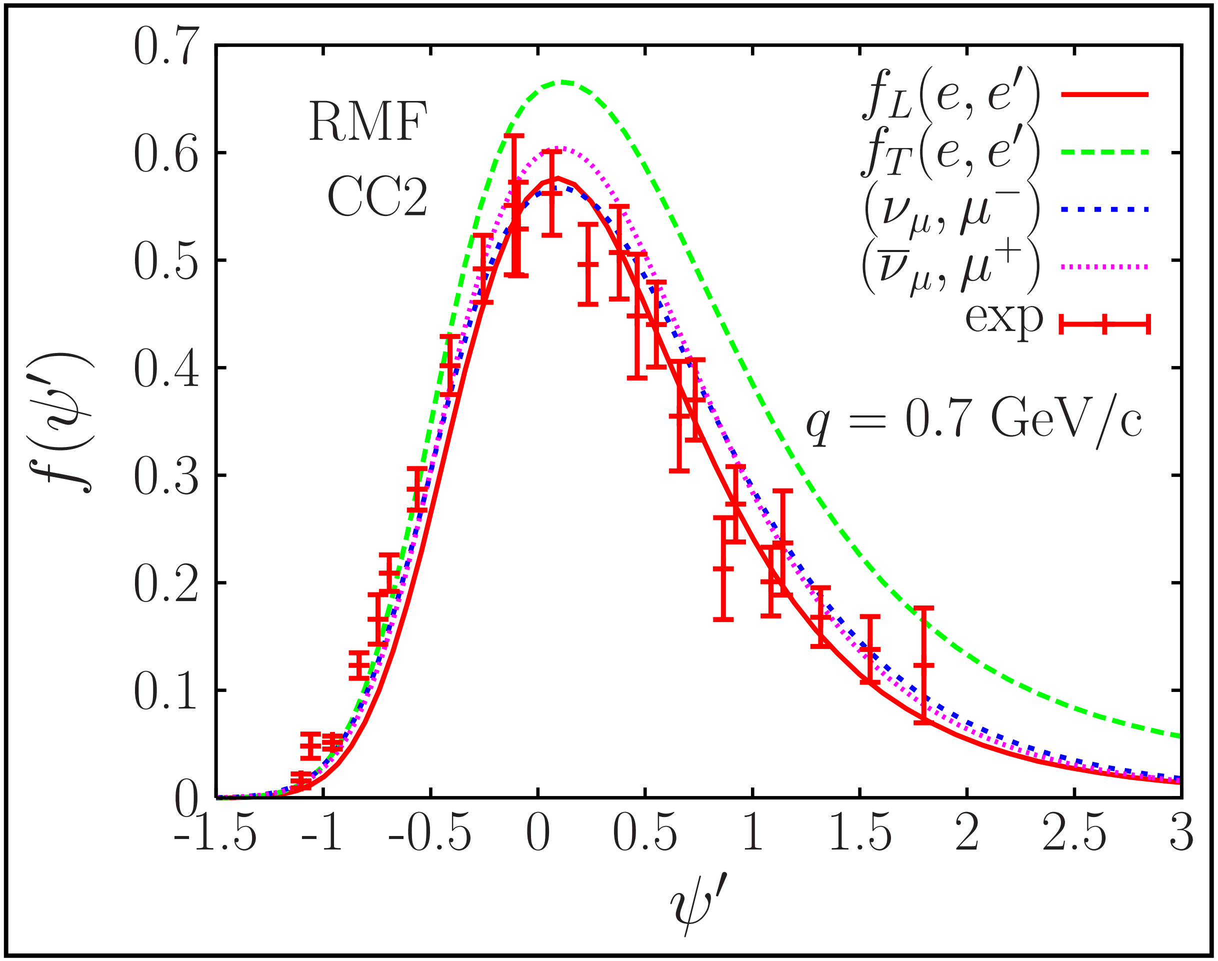
  - *Scaling of the first kind:* $f(q, \psi) \stackrel{q \to \infty}{\longrightarrow} f(\psi)$
  - *Scaling of the second kind:* $f(\psi)$ – *independent on the nucleus*
- *Is the function $f(\psi)$ obtained from (ν, μ) cross sections evaluated within RIA consistent with the function $f(\psi)$ obtained from (e, e') calculations (with the same model)?, and with $f_{exp}(\psi)$?*

Similar scaling function $f(\psi)$ for (e, e') and (ν, μ) processes?

(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 $f_T(\psi)$.*

ISOSPIN: isoscalar vs isovector (3^{er} kind scaling)

Note that (ν, μ) are pure isovector, whereas (e, e') contains both isoscalar and isovector. Thus, SuSA applied to CC neutrino implies **Scaling of the 3rd kind**, i.e., isospin nature in the scaling functions is assumed to be universal.

Analysis of the separate VV, AA and VA contributions in (ν, μ) reactions.

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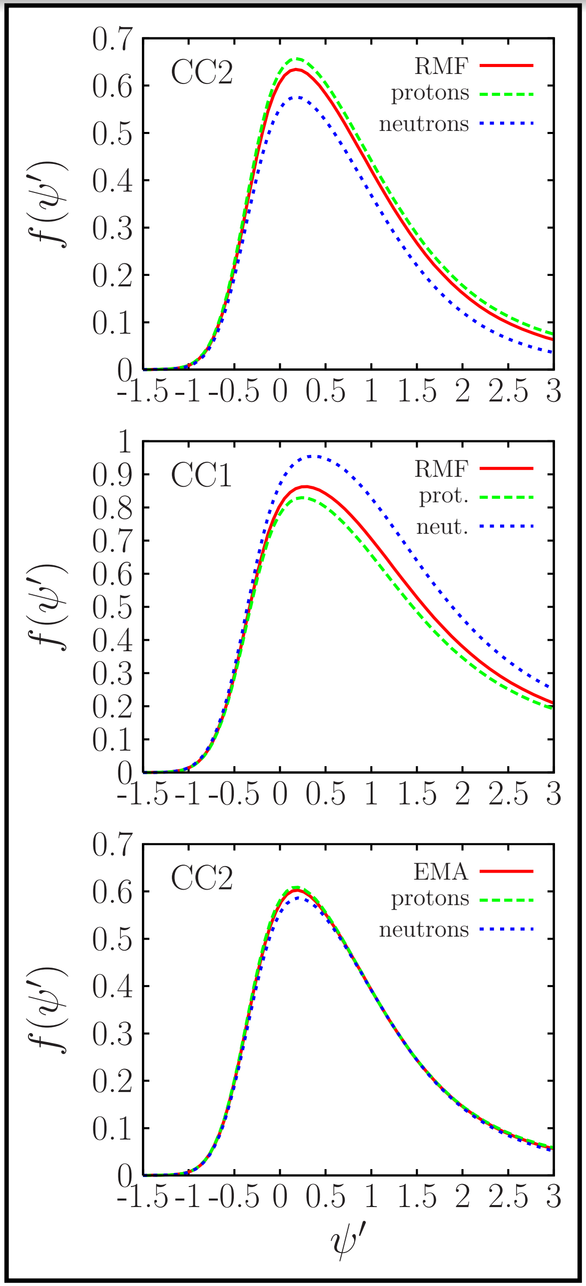


SuperScaling Approach based on RMF: SuSAv2

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

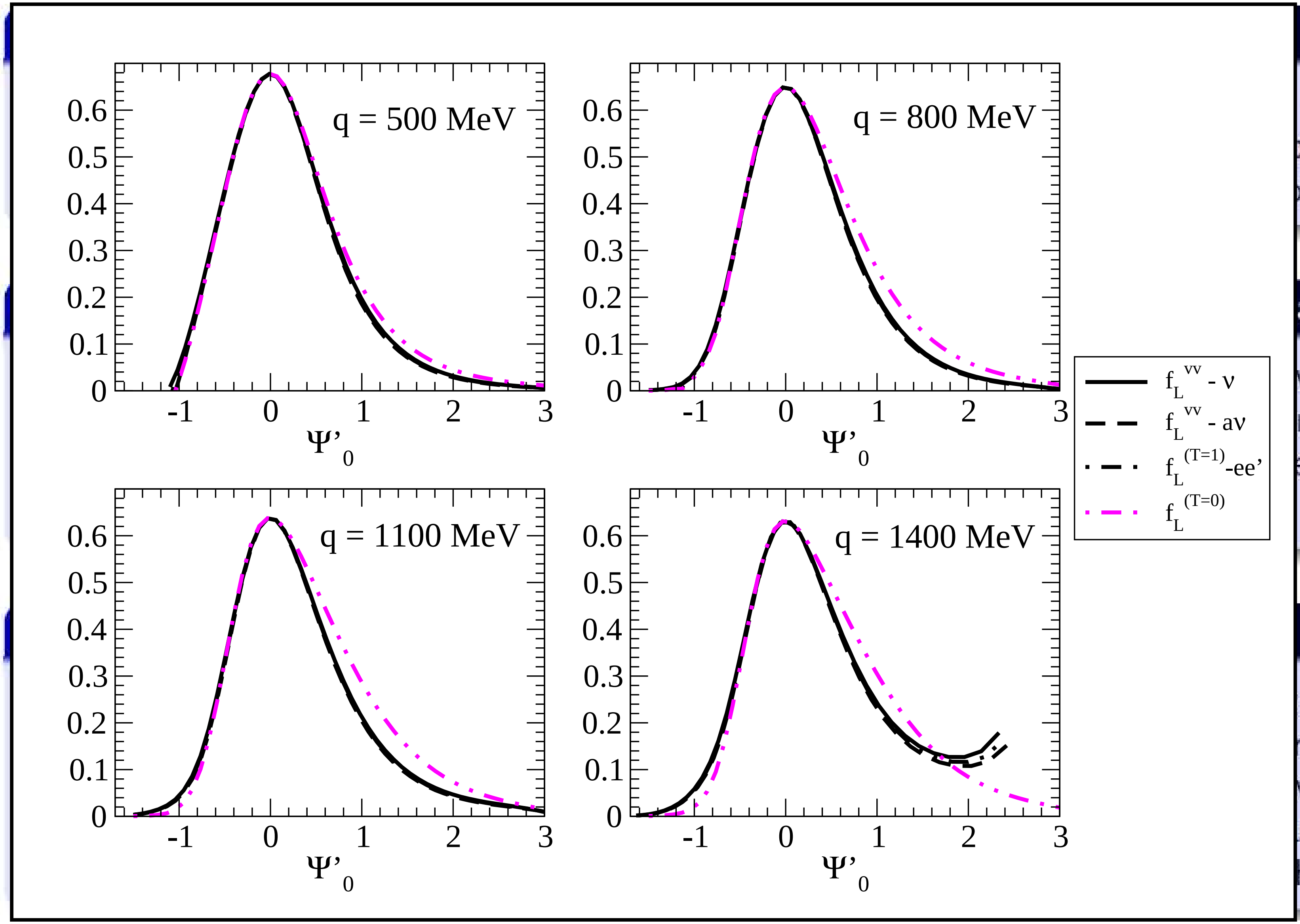
The scaling function based on QE electron scattering data takes into account isovector and isoscalar currents to describe the interaction between the electron and the nucleus.

. . .

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



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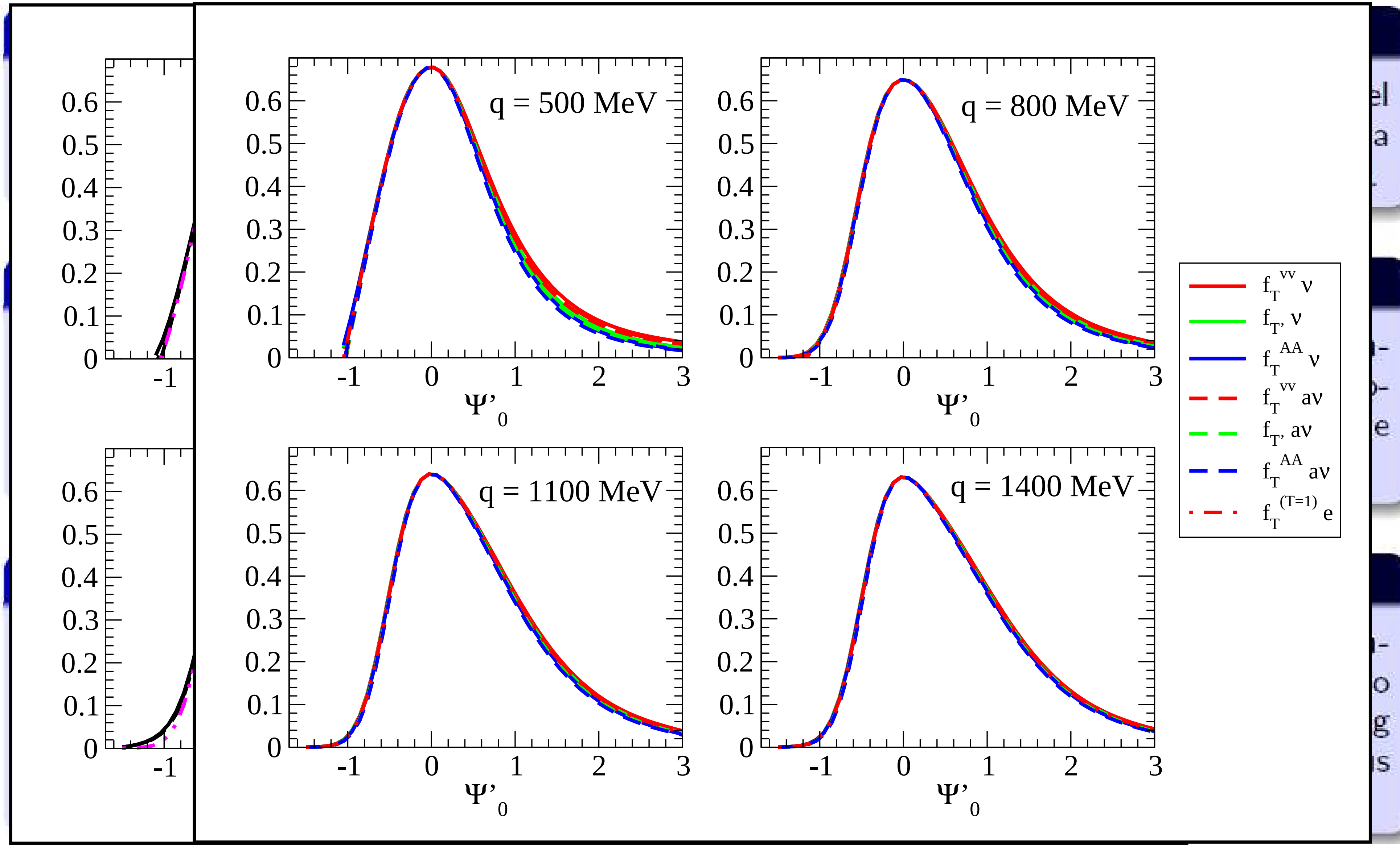
SuperScaling Approach based on RMF: SuSAv2

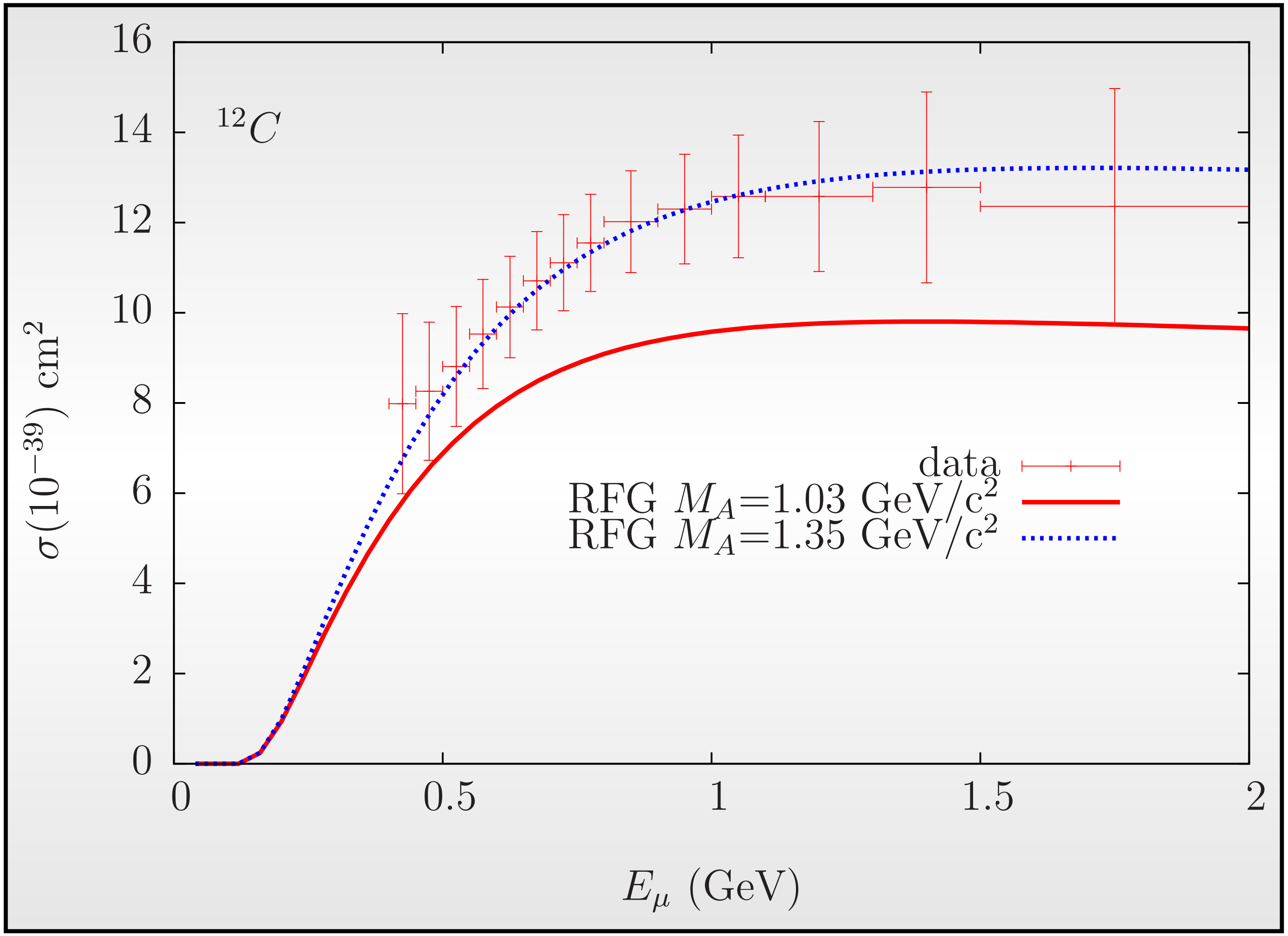


COMPARISON WITH DATA:

MiniBooNE, MinerνA & NOMAD

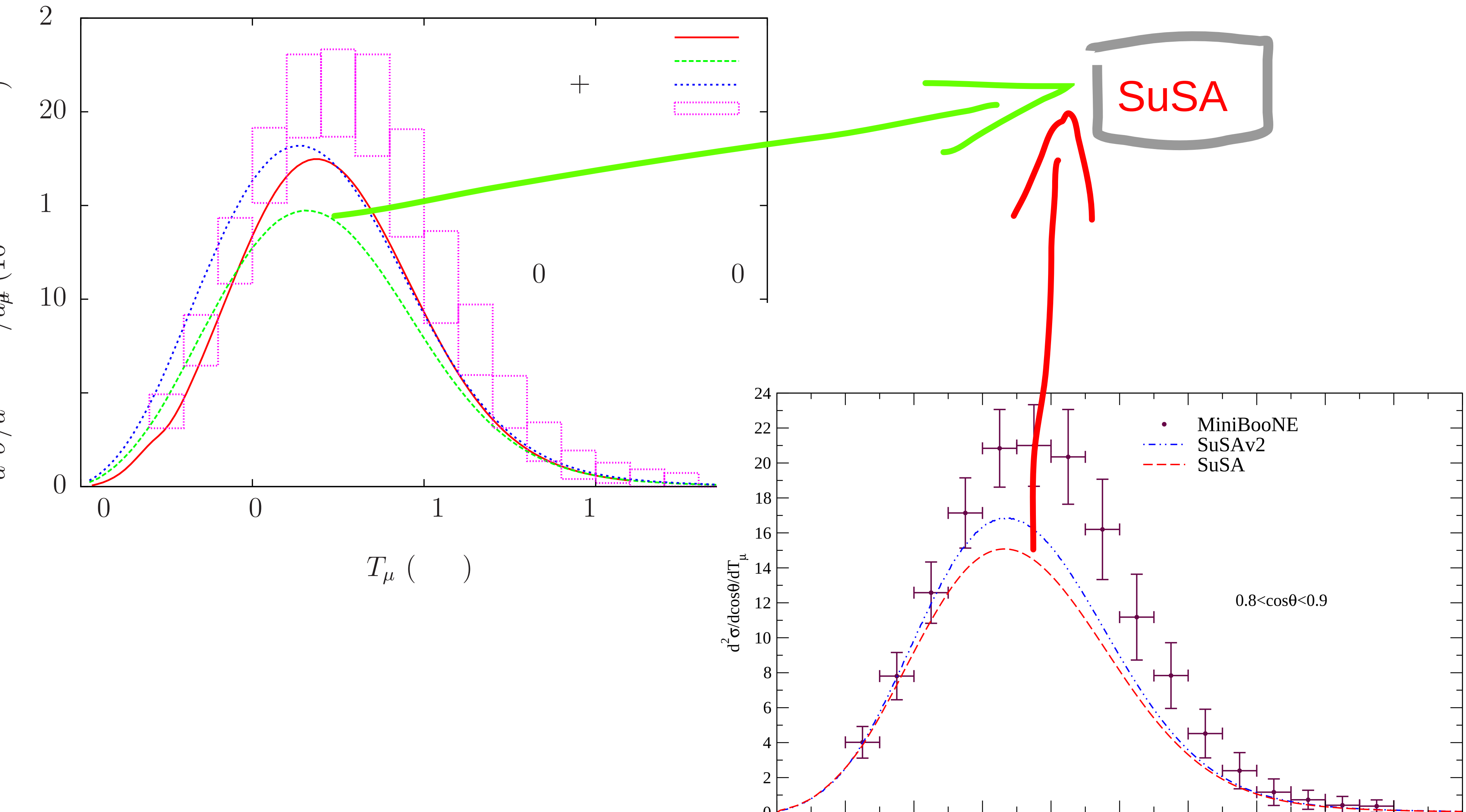
MiniBooNE experiment (PRD 81, 092005 (2010))

Flux-unfolded MiniBooNE ν_μ CCQE cross sections/neutron



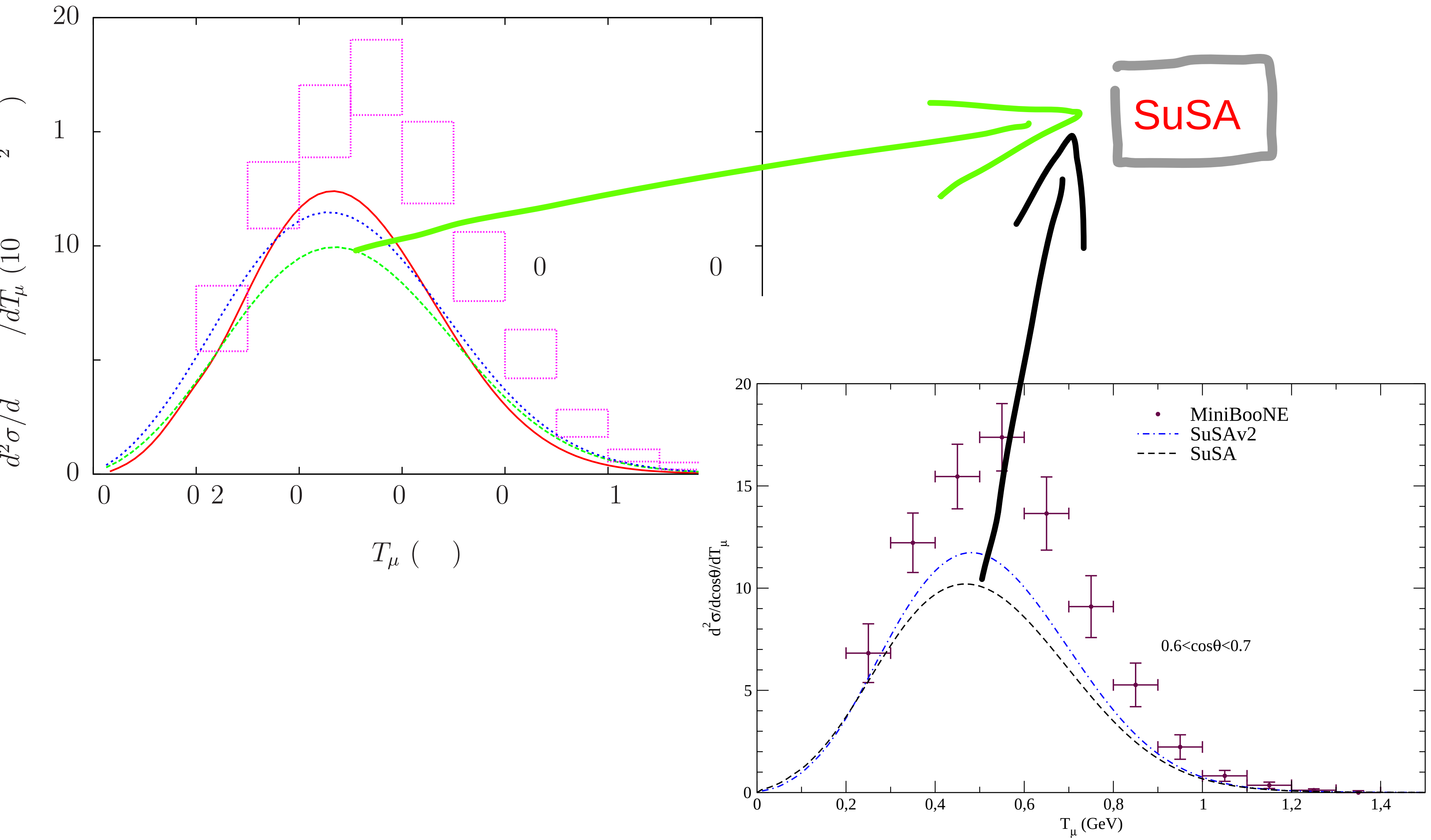
"Unexpected large value extracted for the axial mass M_A?"

Flux-averaged double-differential CCQE: SuSA, SuSAv2 & RMF



SuSA (particularly, SuSAv2) and RMF agree, but understimate data. 2p2h increase results but are still below data *[Phys. Rev. D84 (2011) 033004]*

Flux-averaged double-differential CCQE: SuSA, SuSAv2 & RMF



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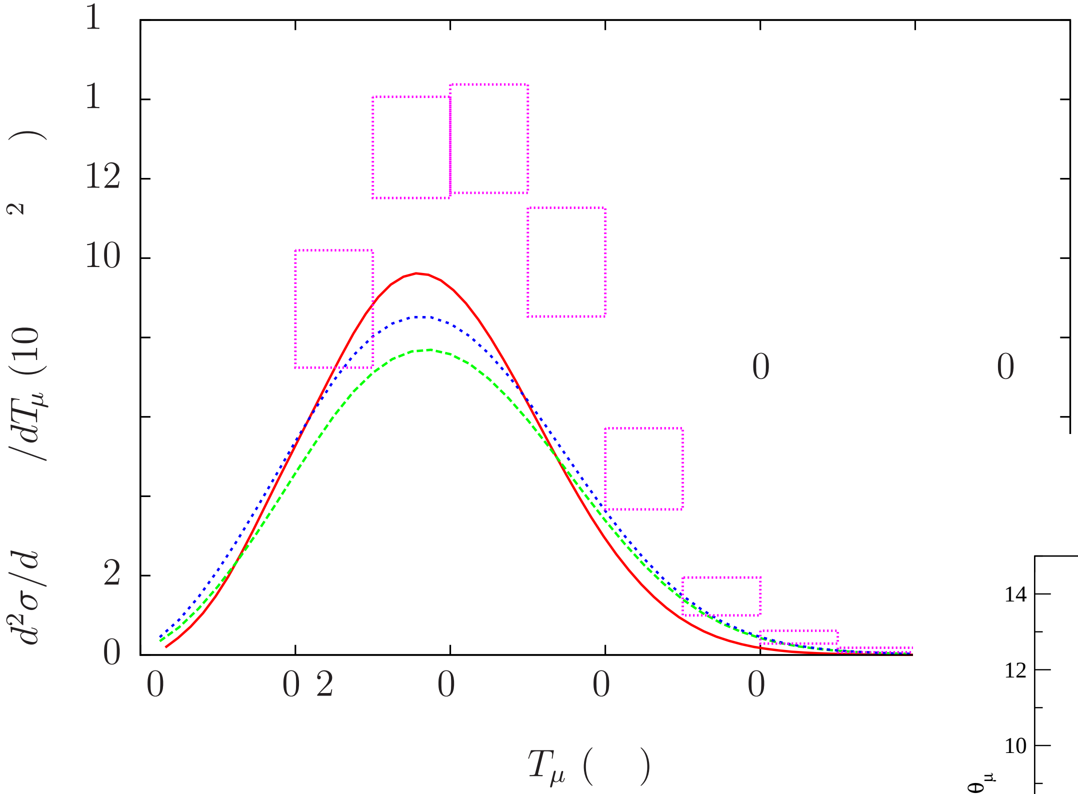
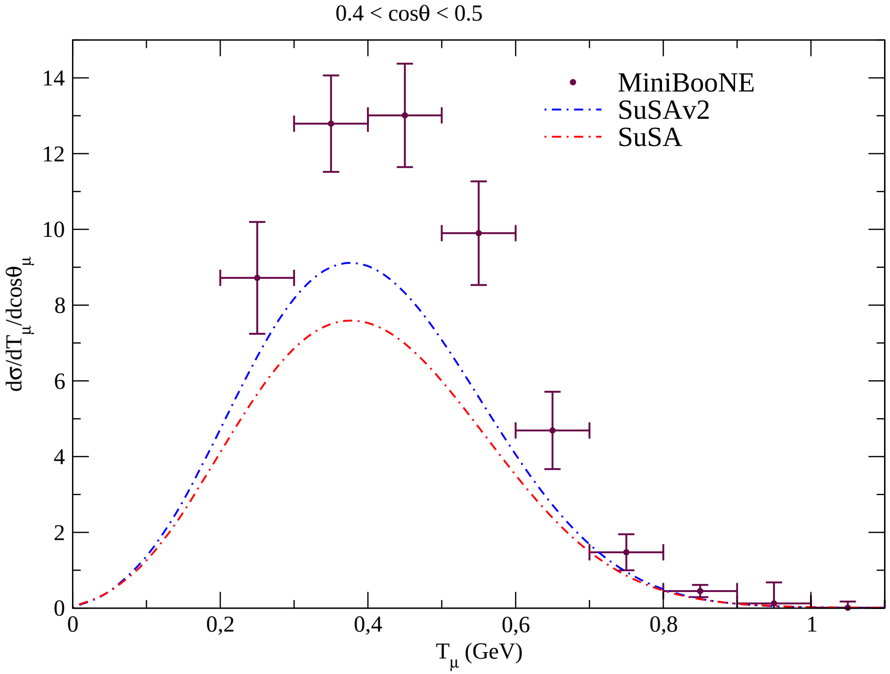
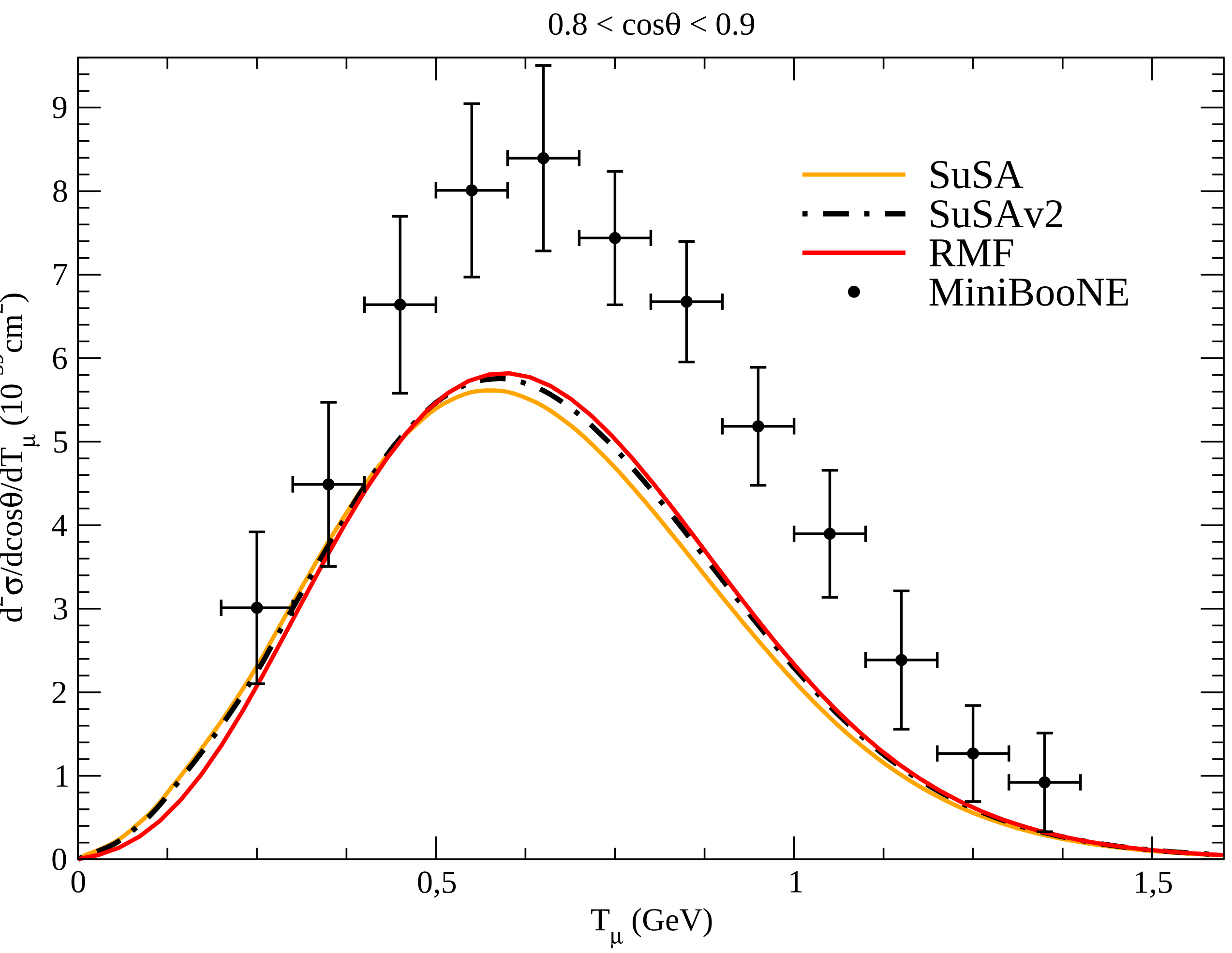




Antineutrinos: strong enhancement of 2p2h effects?



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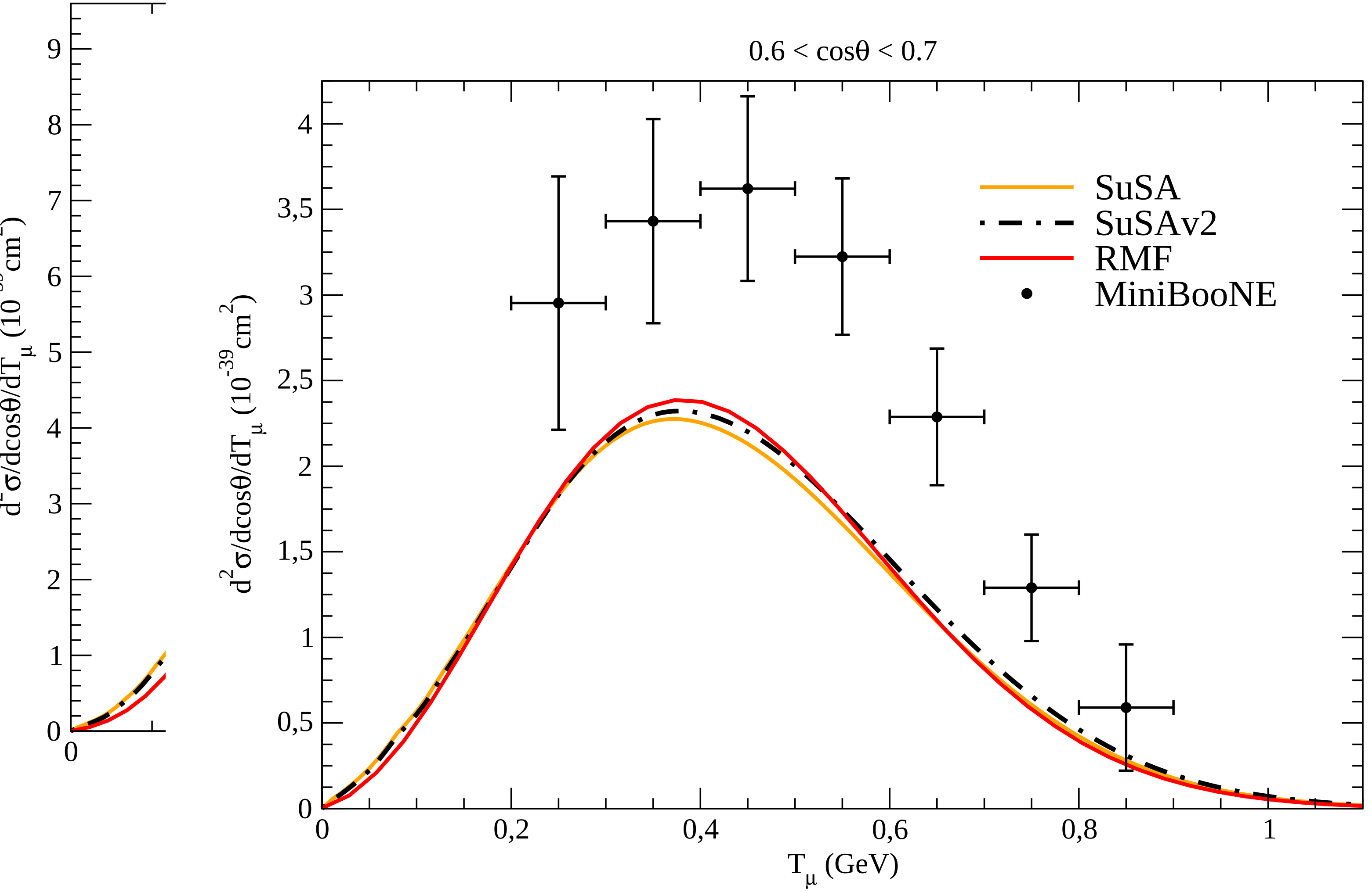

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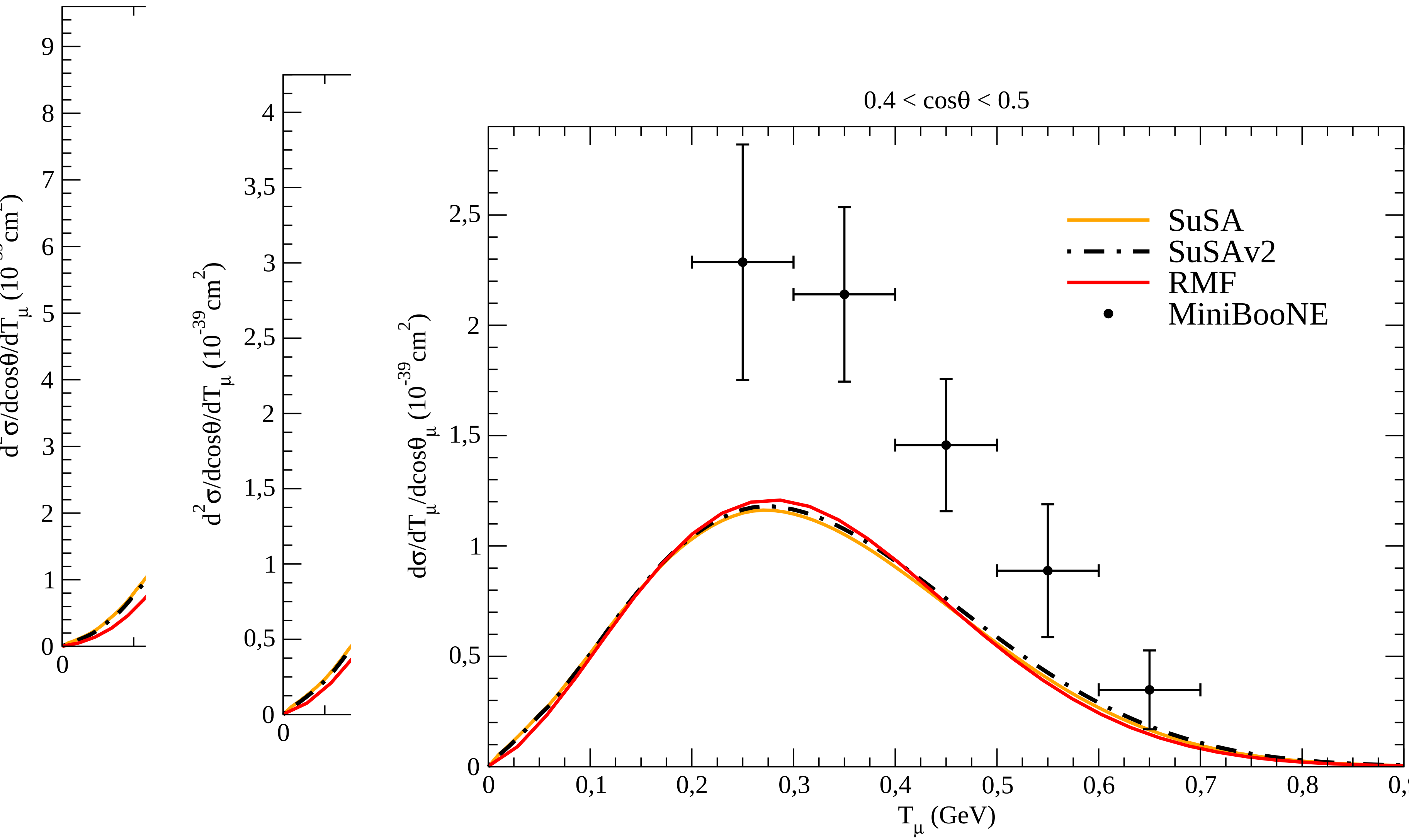

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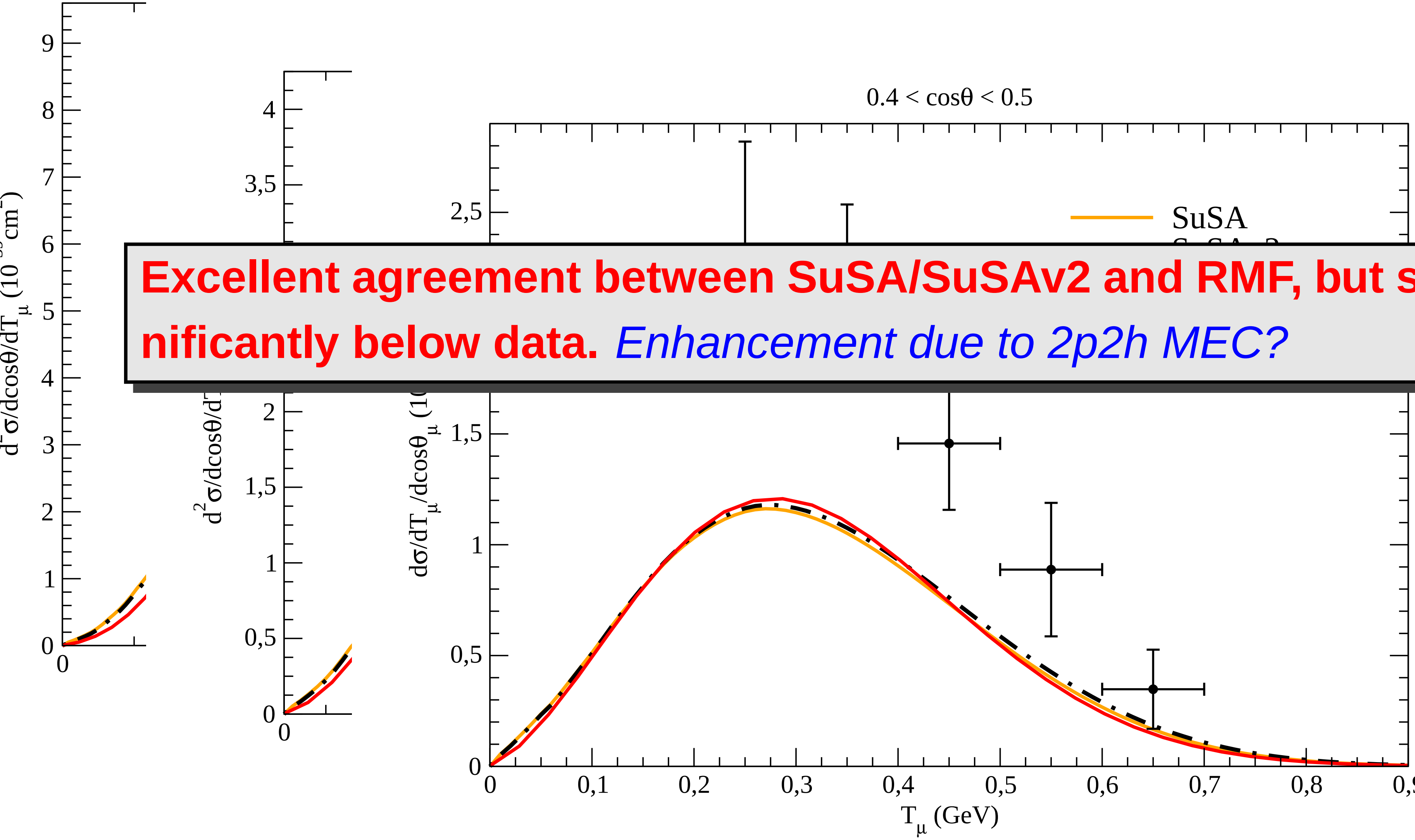
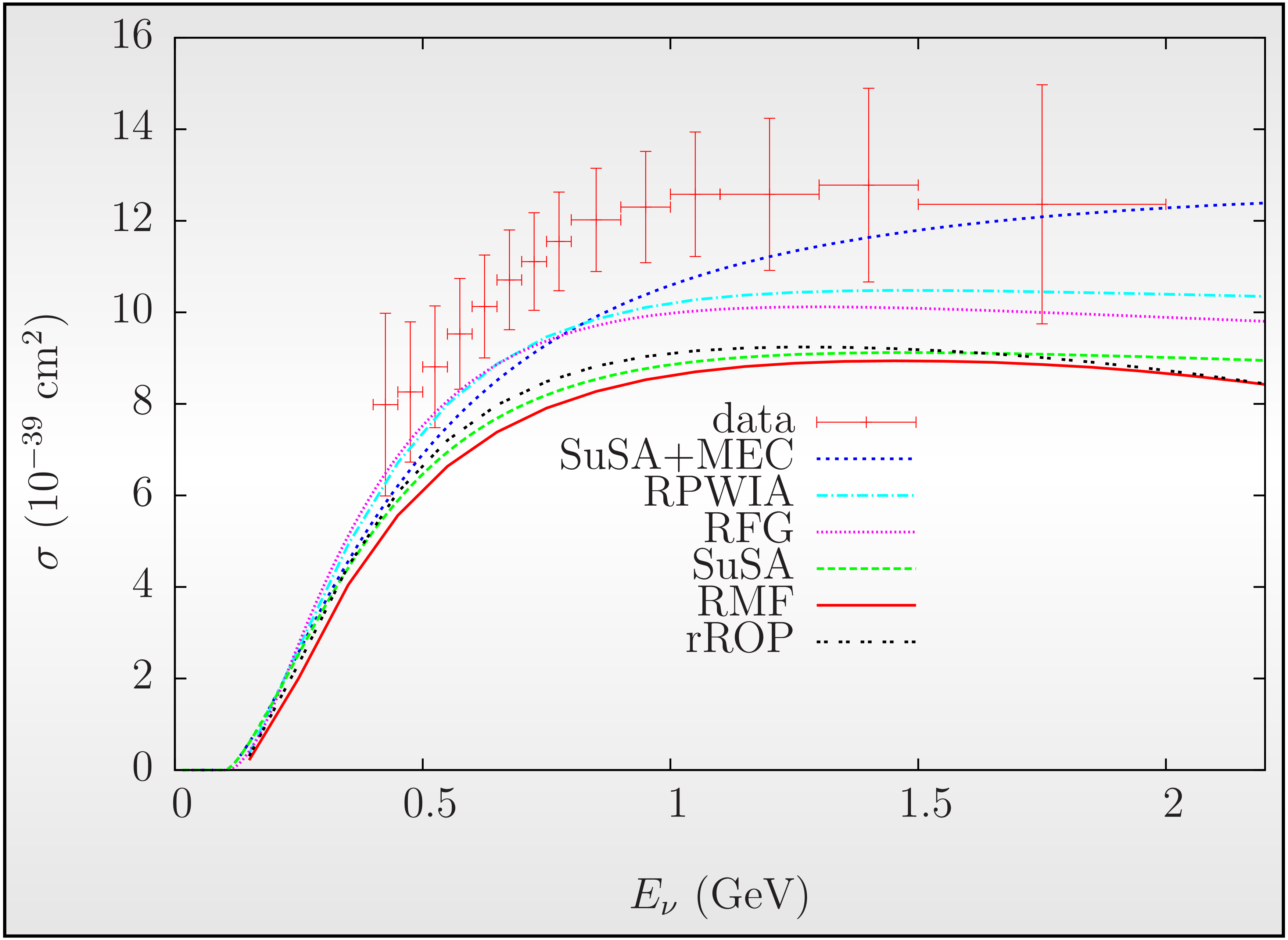


Excellent agreement between SuSA/SuSAv2 and RMF, but significantly below data. *Enhancement due to 2p2h MEC?*

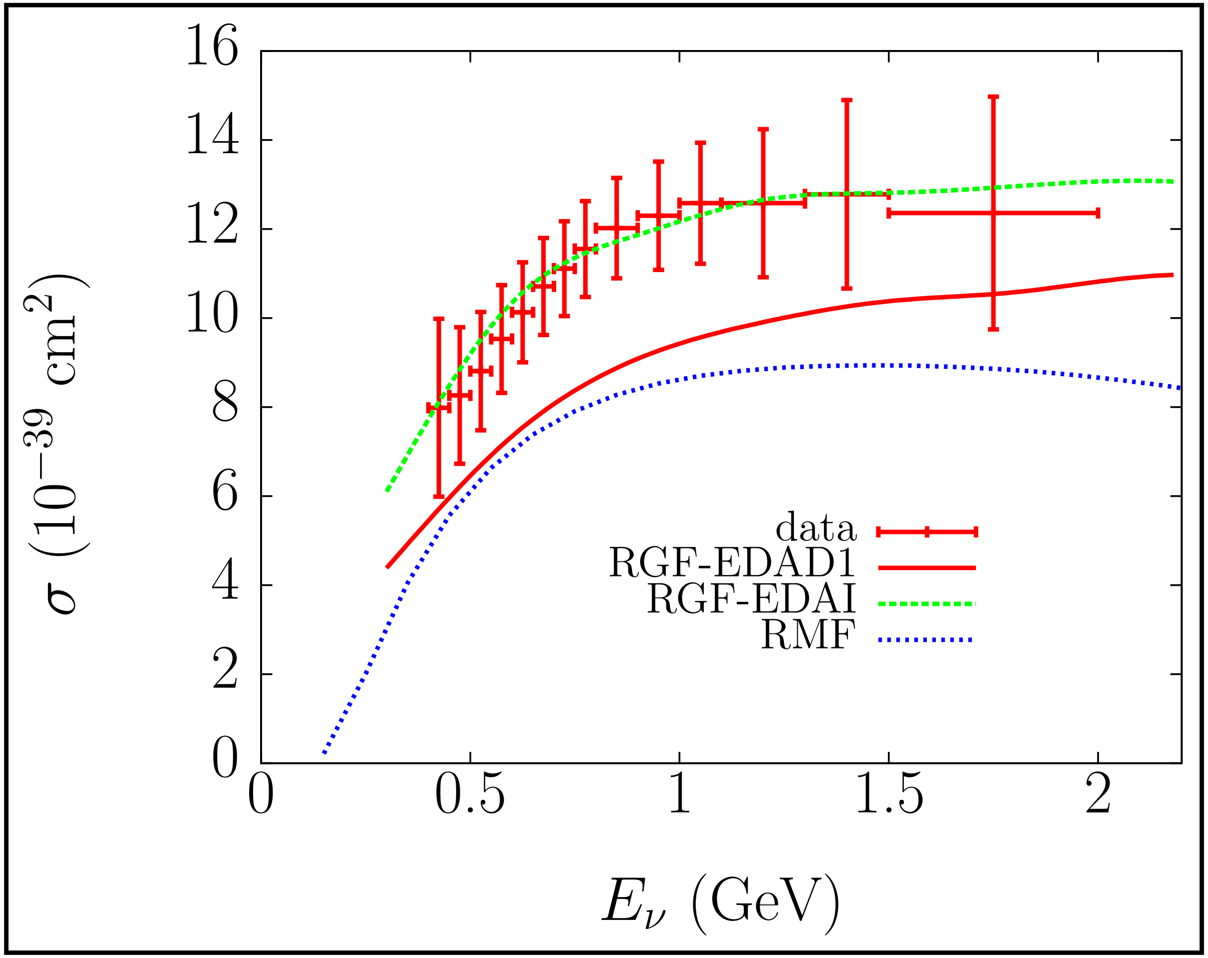
Total integrated ν-CCQE cross section



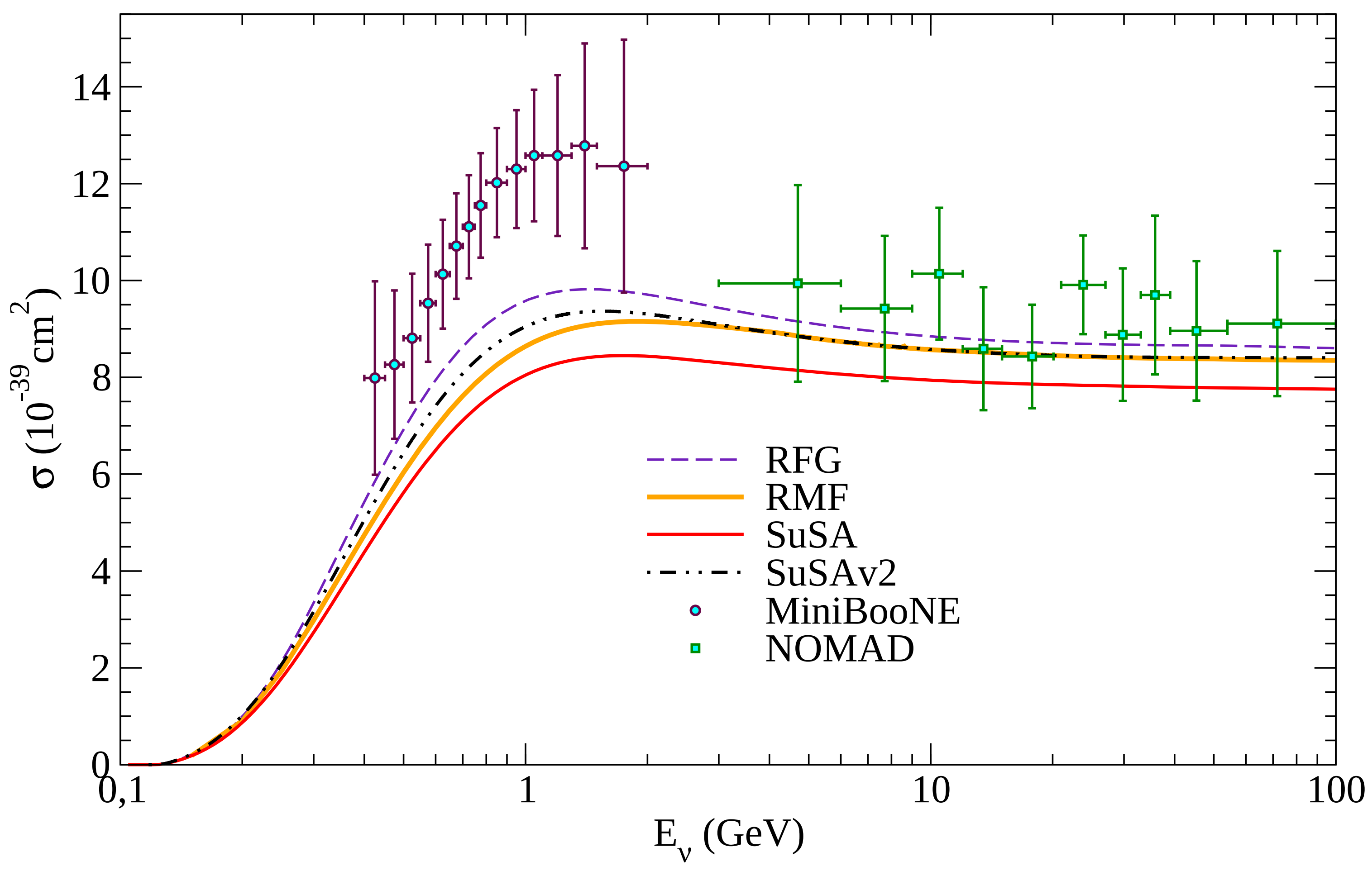
Other Relativistic Approaches (Pavia Group)

Relativistic Green Function Approach (RGF): *FSI treated consistently in the exclusive & inclusive channels (same relativistic complex optical potential used in both cases, but flux conserved in the latter)*

Phys. Rev. Lett. 107, 172501 (2011)



NOMAD: high-energy. SuSA *vs* RMF



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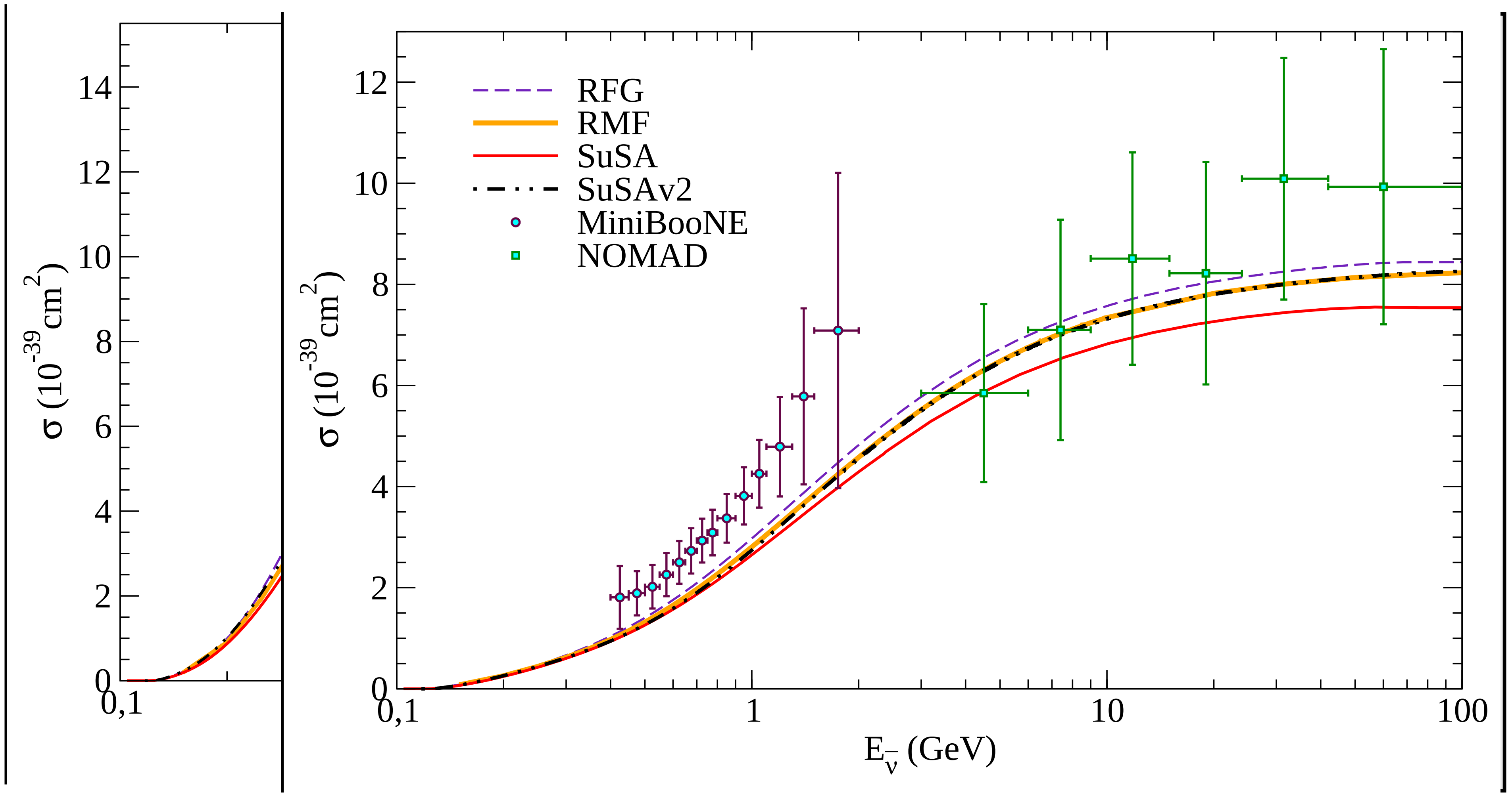
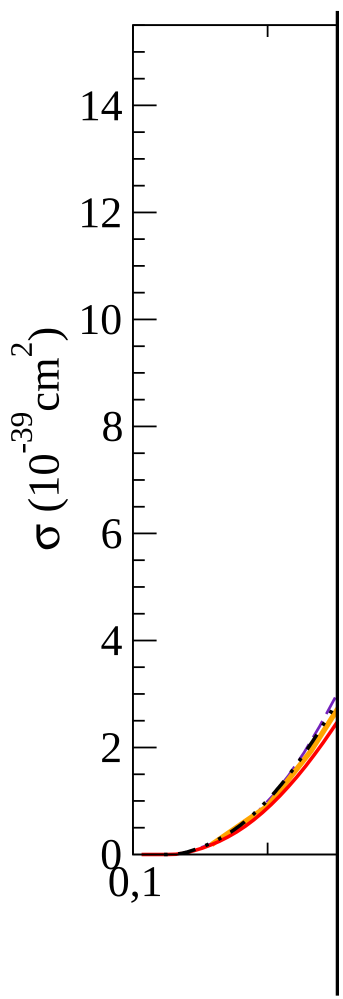
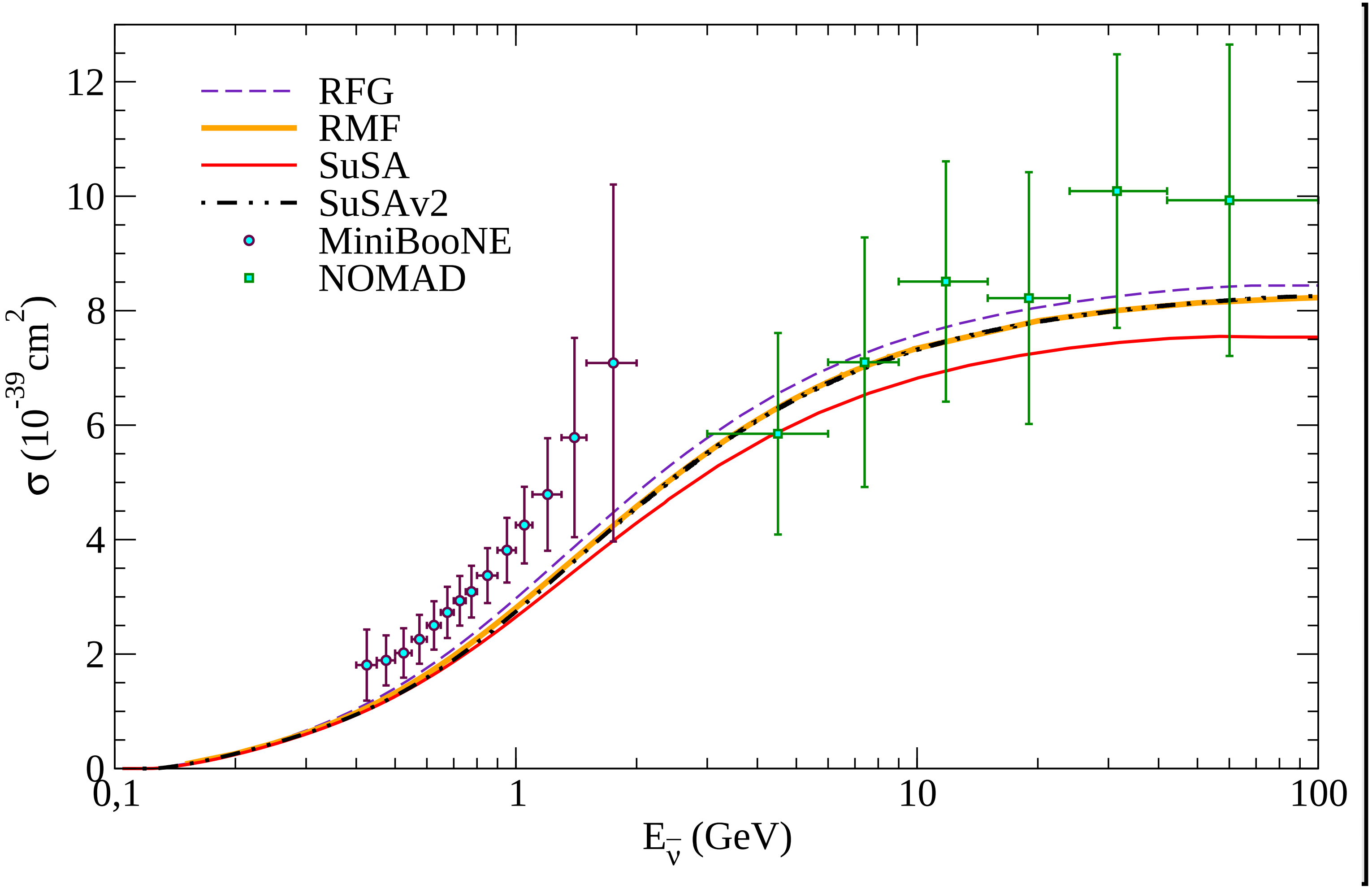


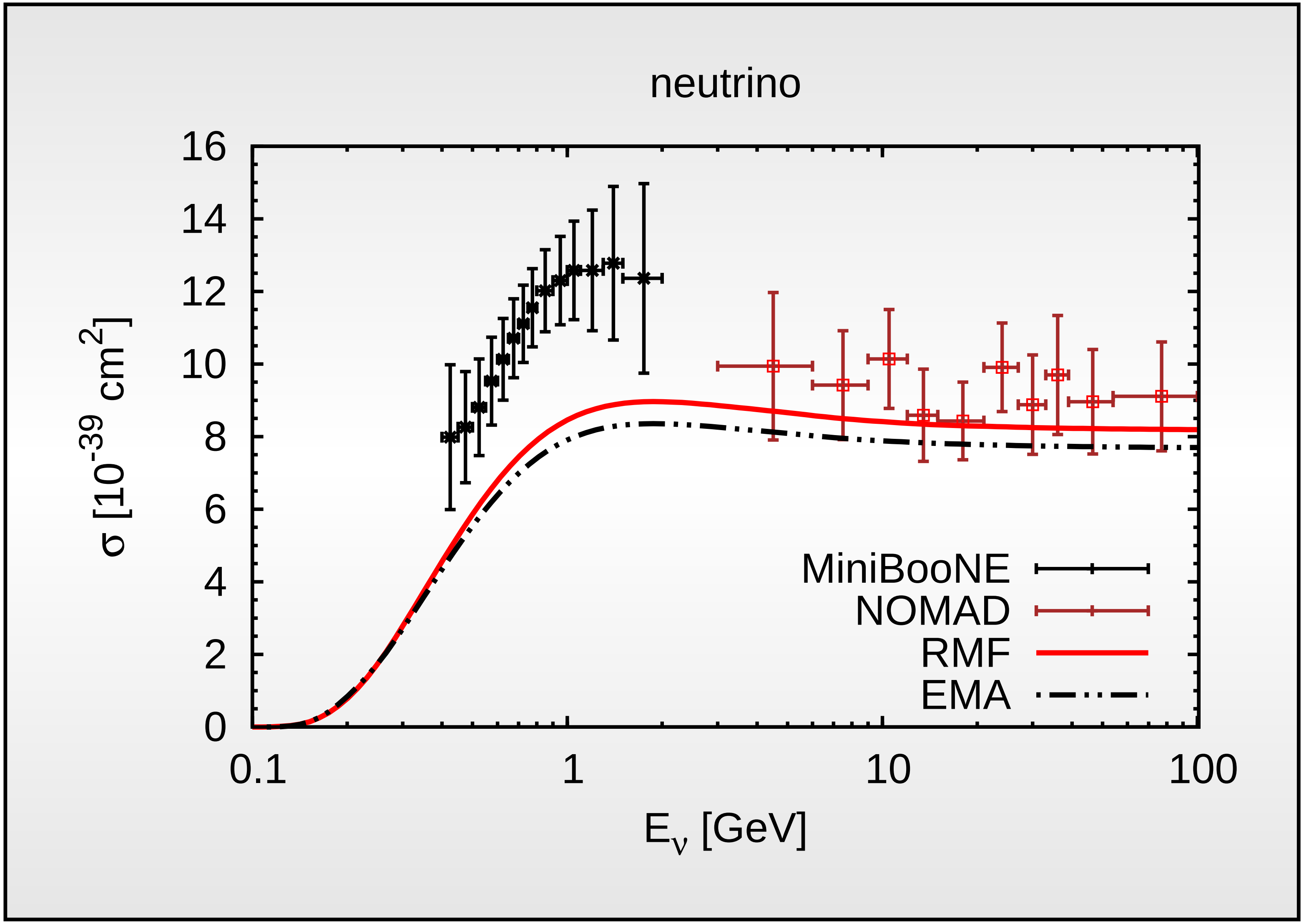
NOMAD: high-energy. SuSA *vs* RMF

Excellent agreement between SuSA/SuSAv2 and RMF for all energies. Both models reproduce NOMAD but underpredict MiniBooNE (standard value of the axial mass). [PLB 725 (2013) 170]





NOMAD: spinor distortion in RMF



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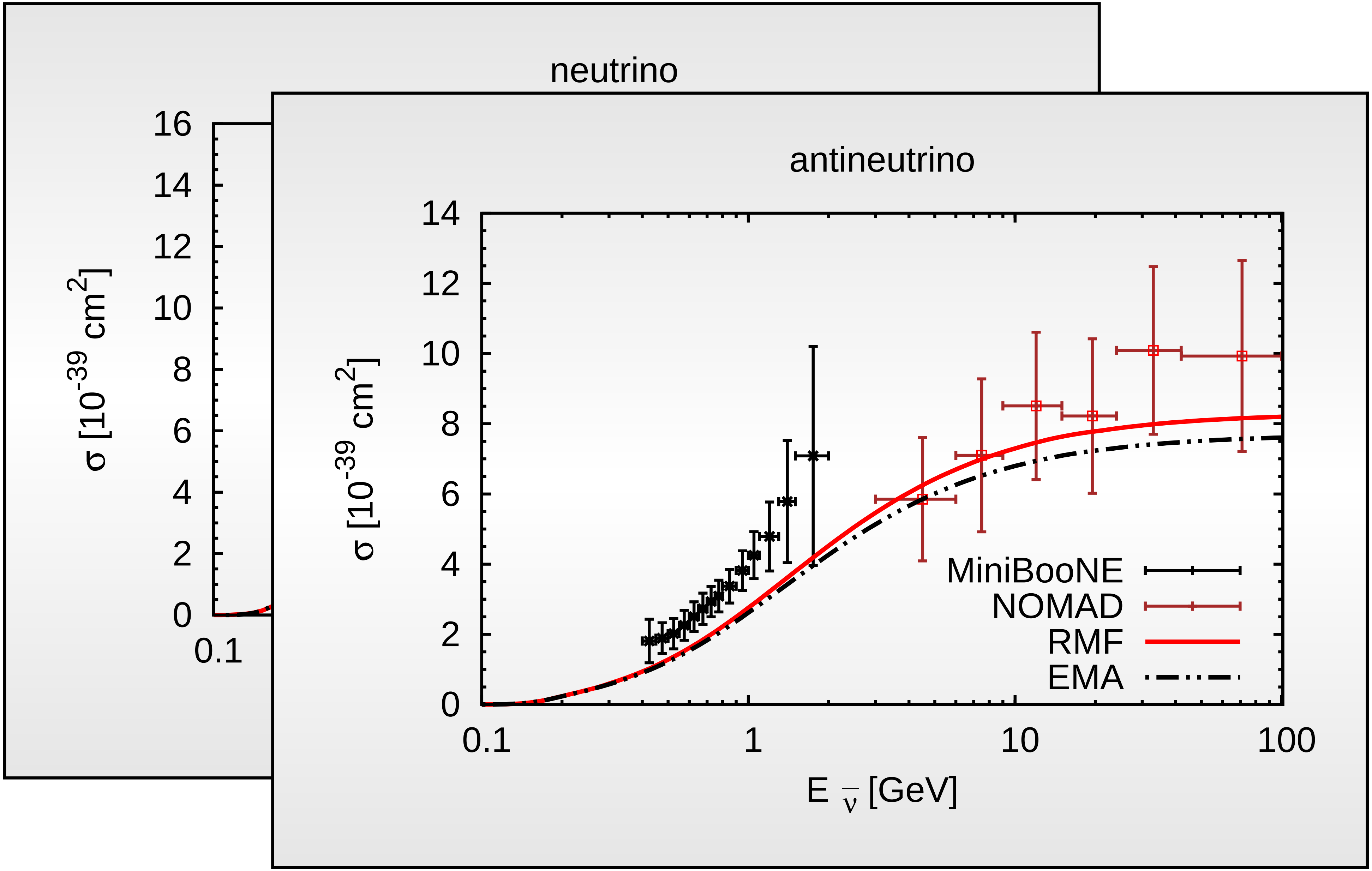
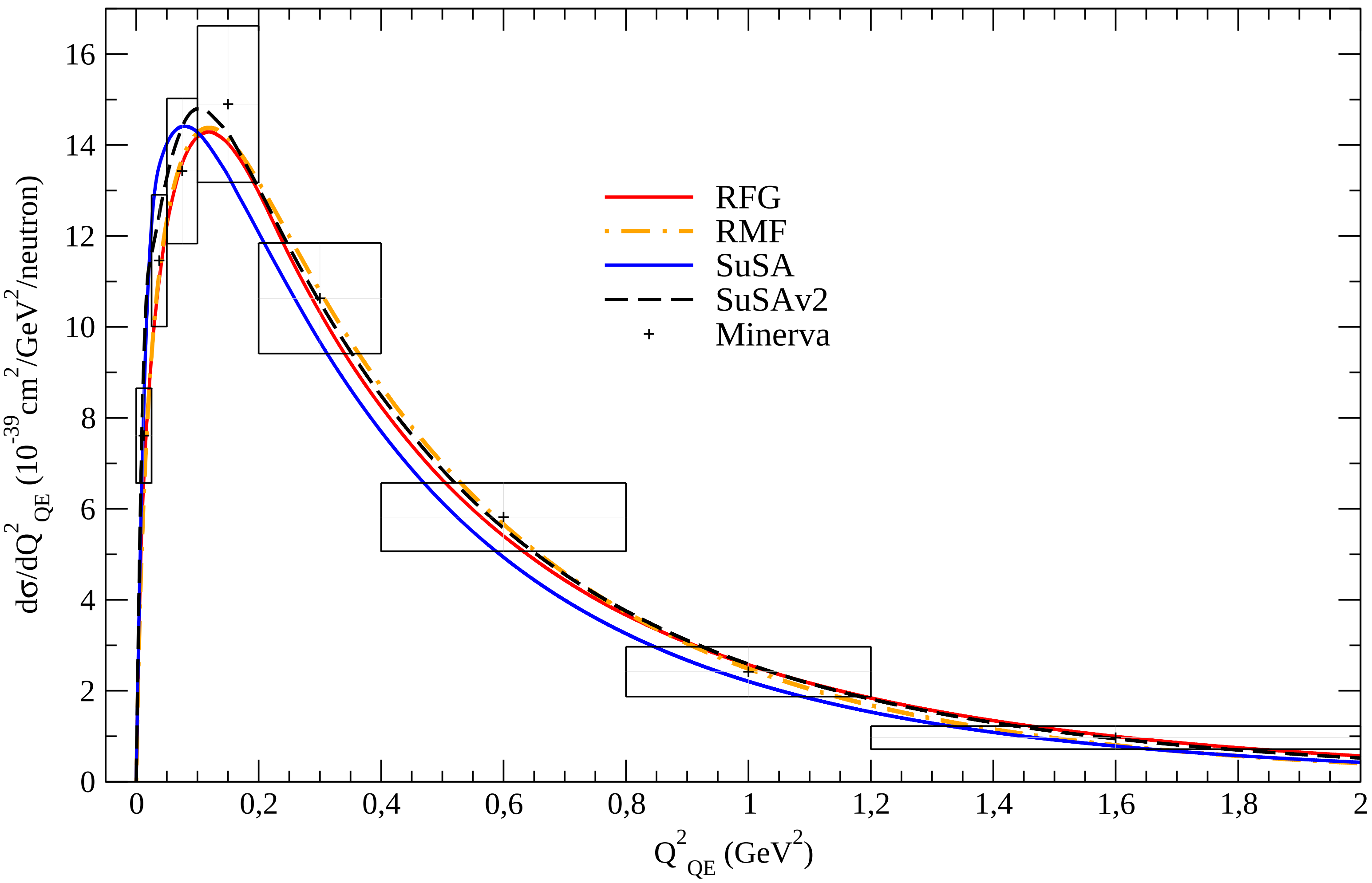
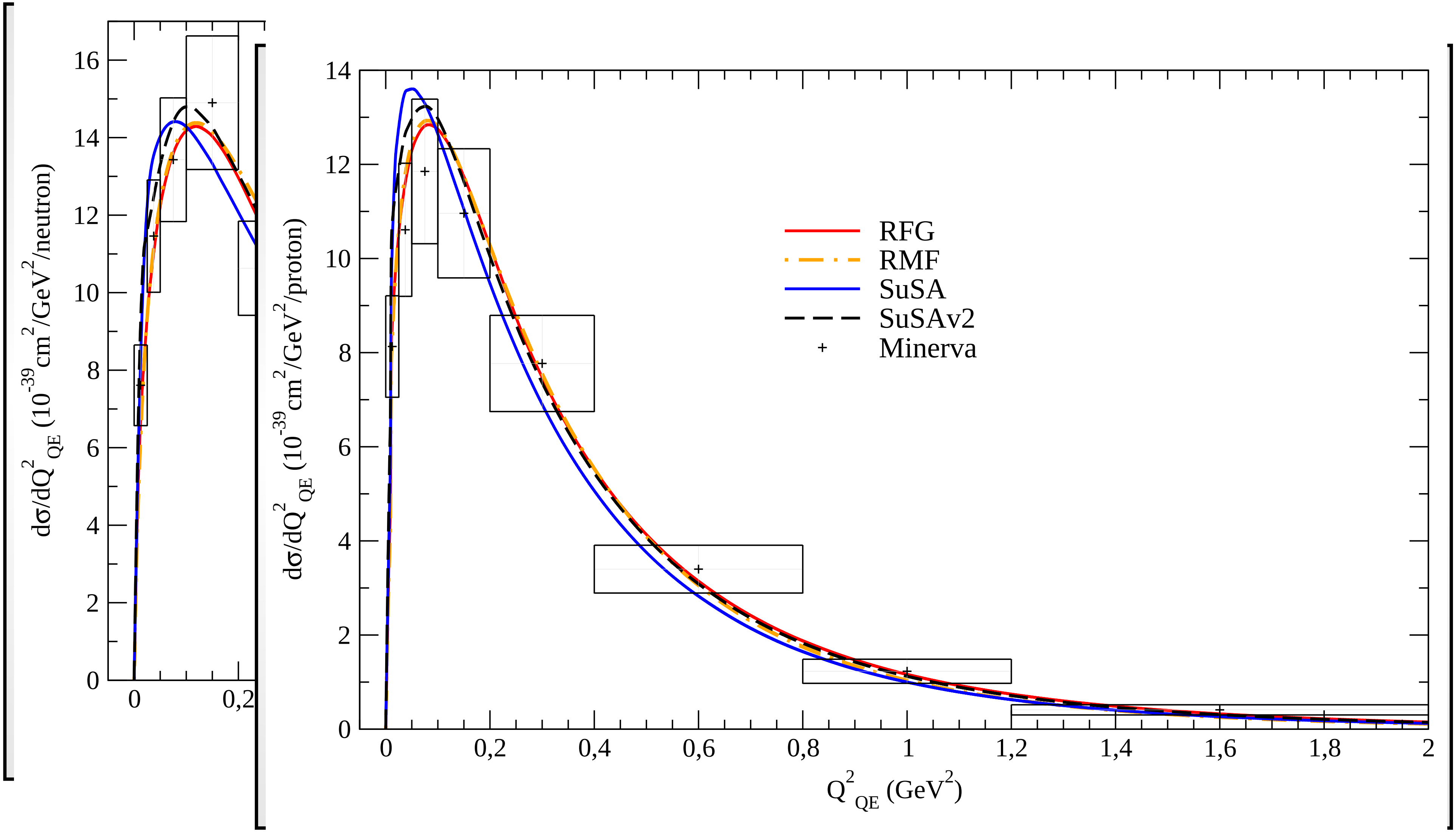


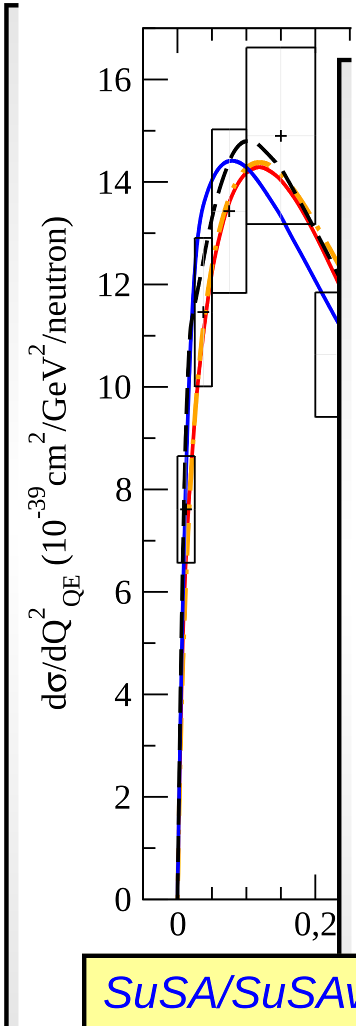
MINERνA: SuSA *vs* RMF

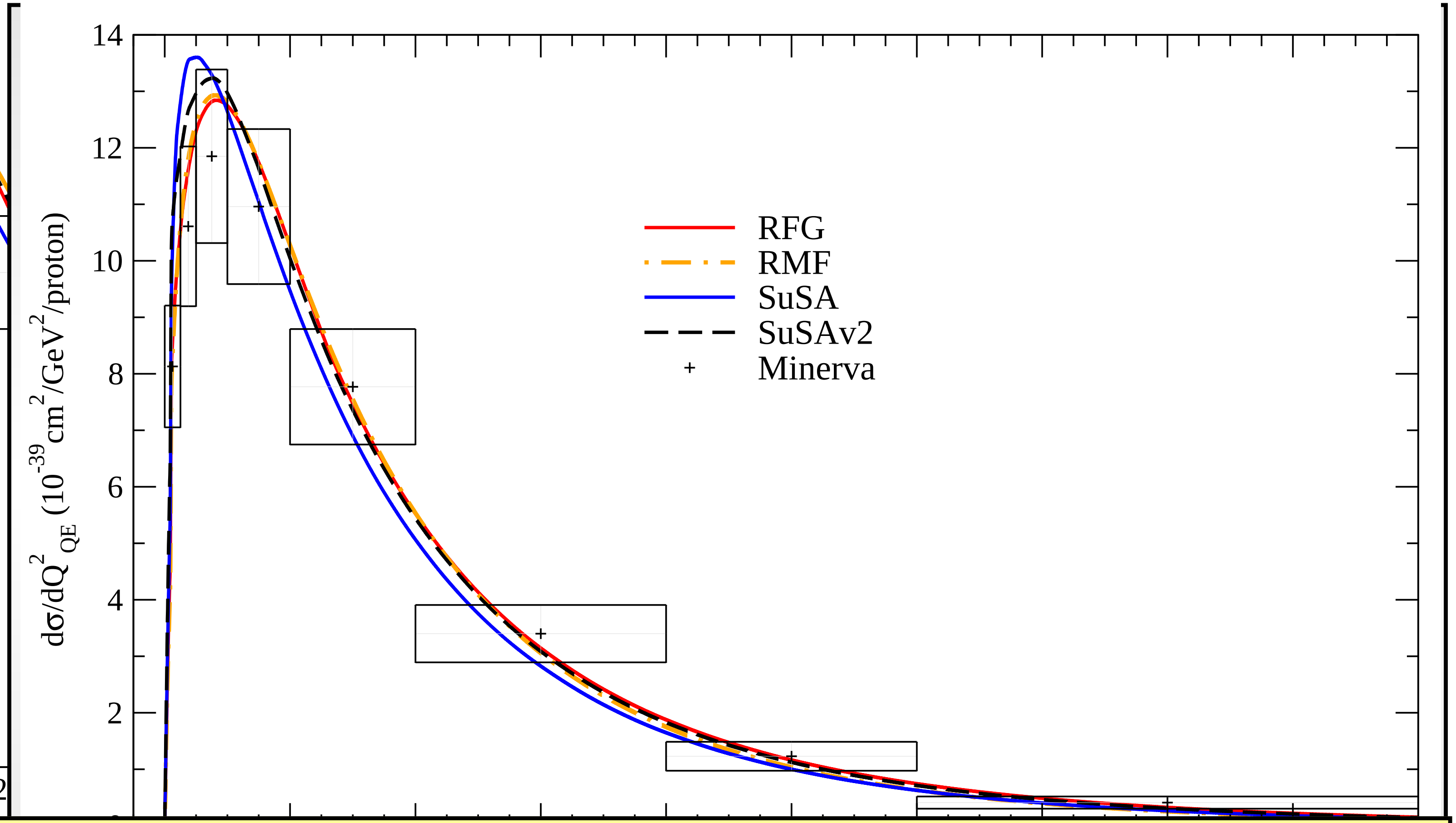


MINERνA: SuSA *vs* RMF



MINERνA: SuSA *vs* RMF





SuSA/SuSAv2 and RMF are able to reproduce in an excellent way the data without need to increase the value of the axial mass. Consistency with NOMAD but not with MiniBooNE.

Are effects due to MEC, multinucleon... particularly significant at MiniBooNE kinematics?

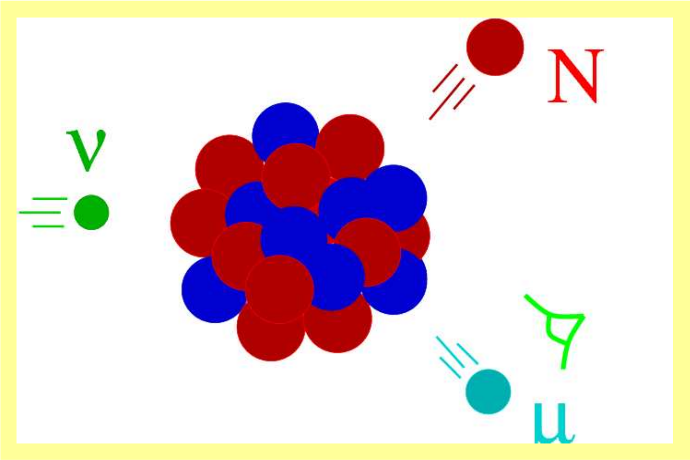
APPLICATION TO NEUTRAL CURRENT NEUTRINO PROCESSES: $(\nu, N)\nu'$

NC vs CC neutrino-nucleus QE scattering

The dominant processes in the QE region are assumed to be:

Charged-Current

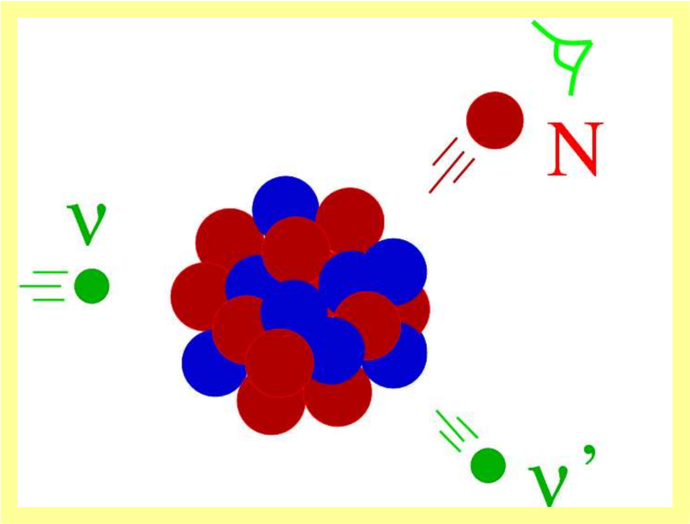
$$\nu + A \Rightarrow \mu + N + B$$



Outgoing lepton detected, fixed Q^2 *as in* (e, e')*:* **t-channel kinematics**

Neutral-Current

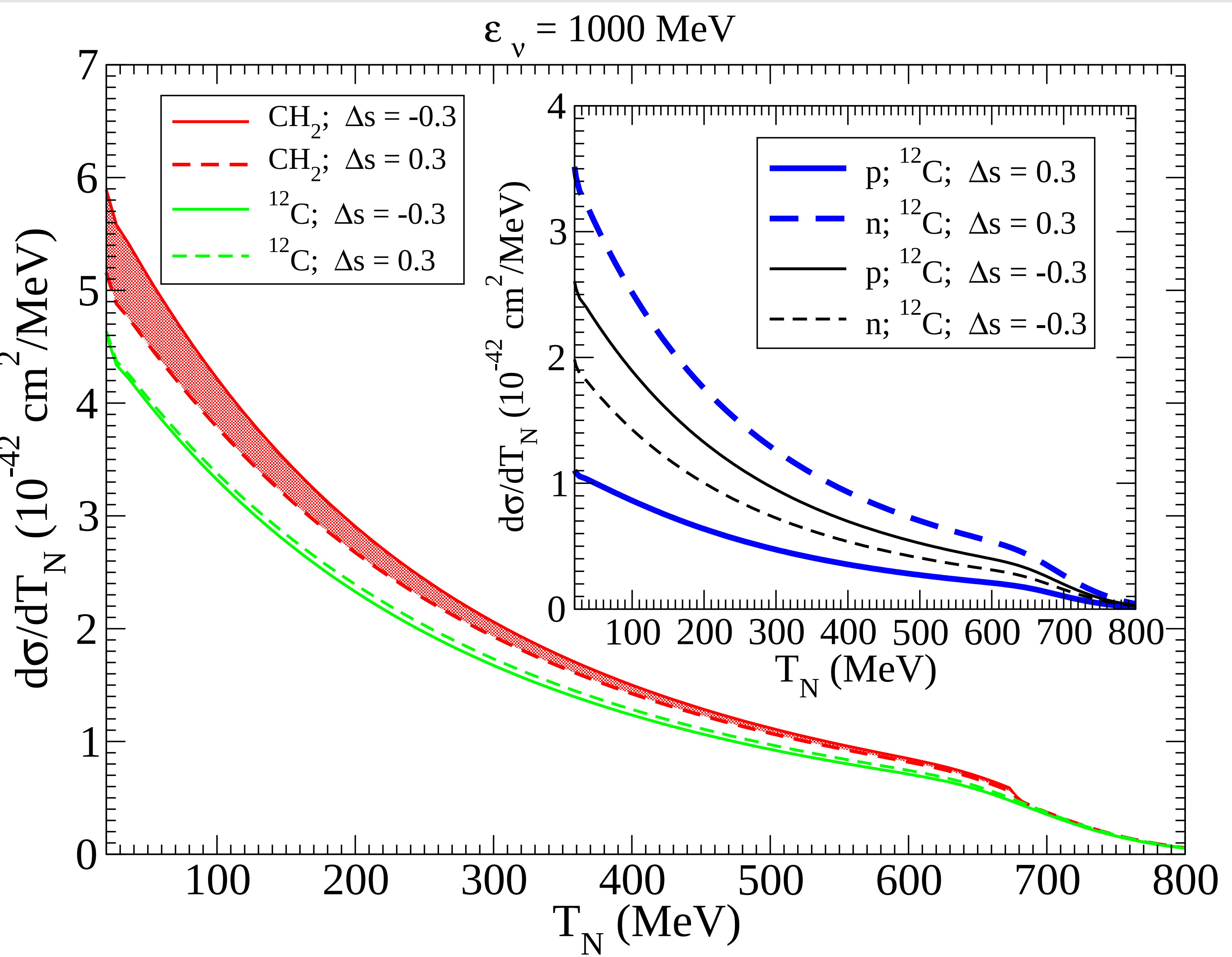
$$\nu + A \Rightarrow \nu' + N + B$$



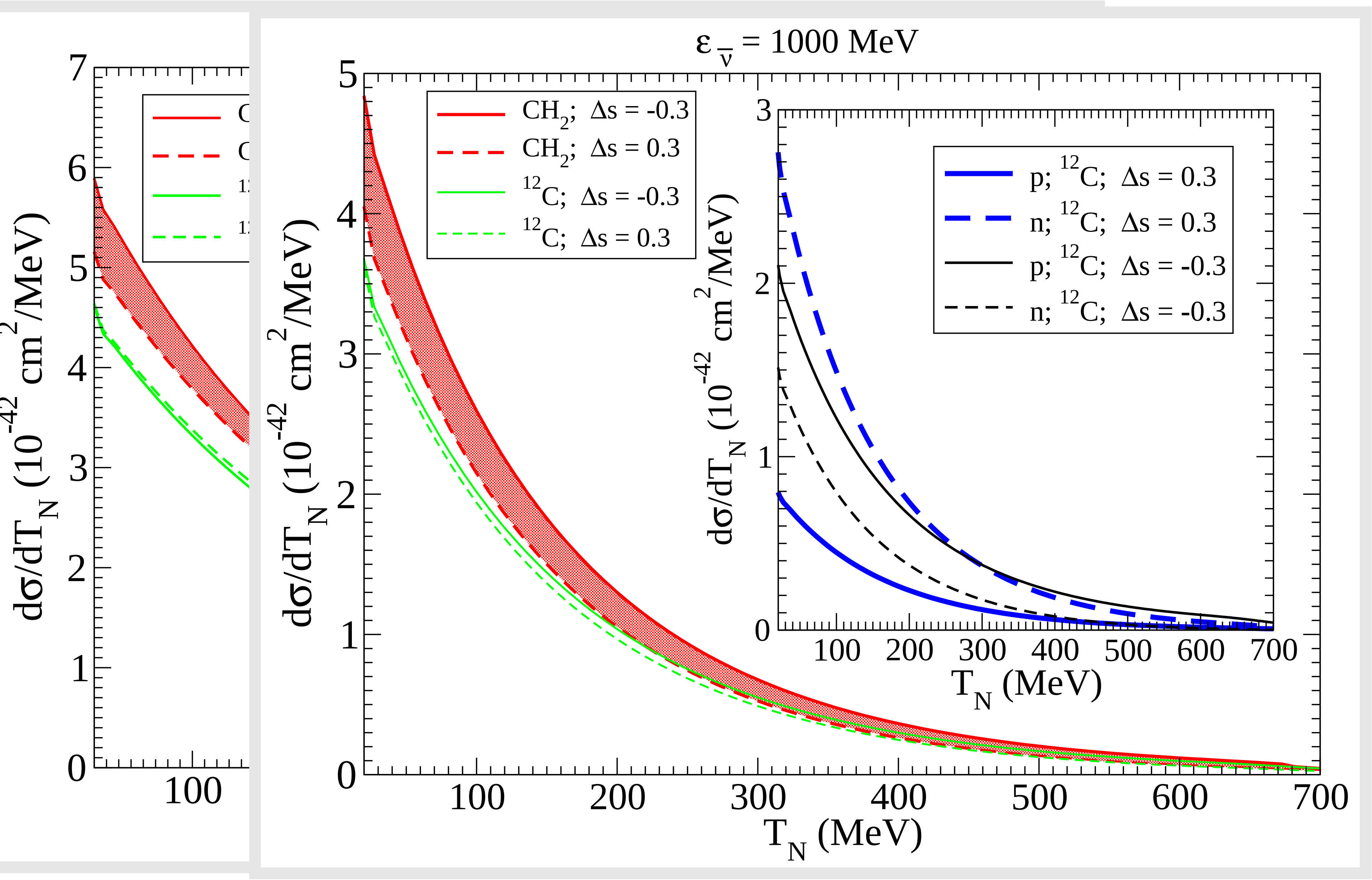
Only the nucleon is detected, Q^2 *is not fixed:* **u-channel kinematics**

Very different kinematics in both processes. Do they reveal different sensitivity to the nuclear dynamics underlying scaling?

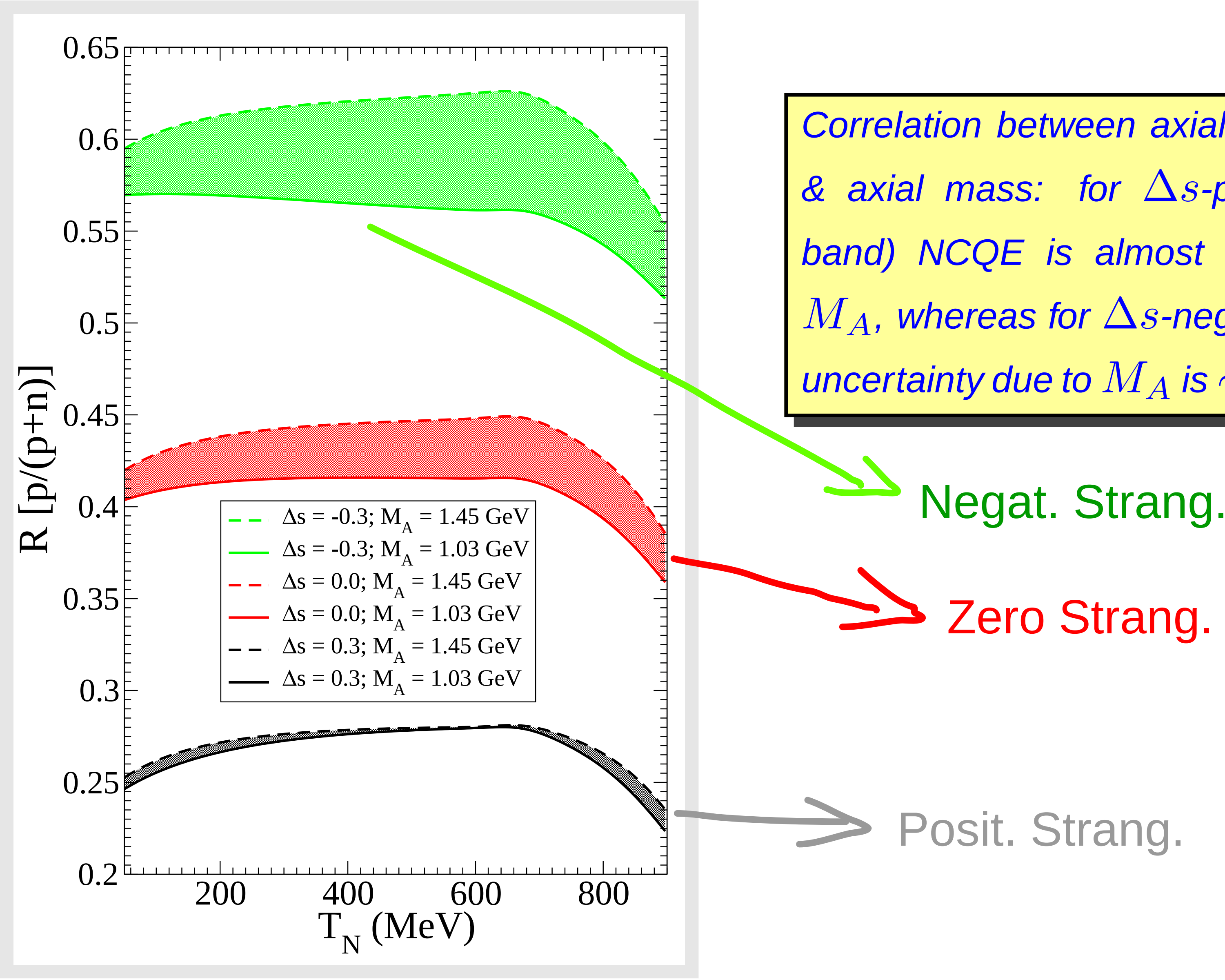
NCQE & axial strangeness



NCQE & axial strangeness

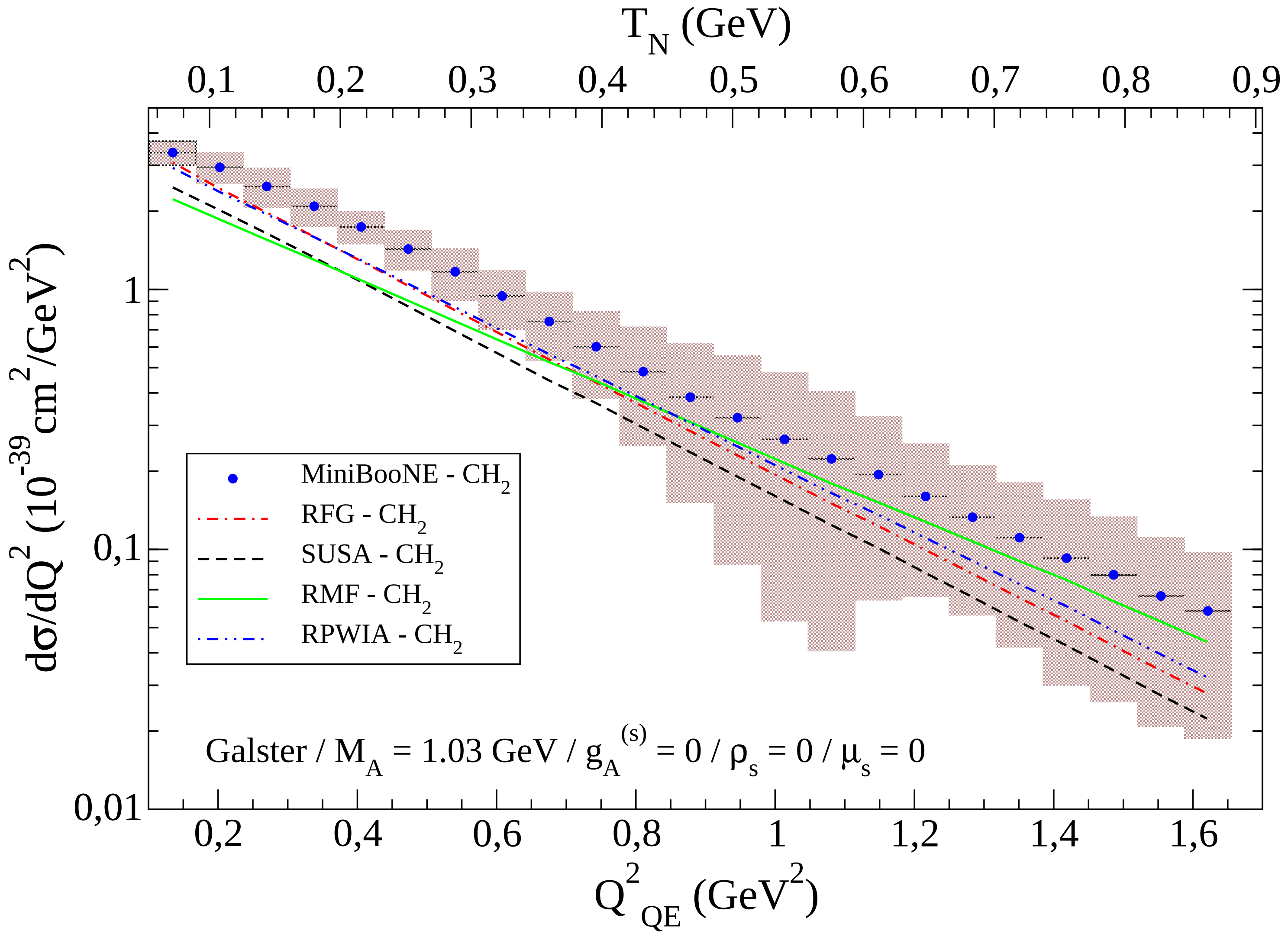


P/N RATIO: axial strangeness *vs* axial mass



Correlation between axial strangeness & axial mass: for Δs-positive (grey band) NCQE is almost insenstive to M_A, whereas for Δs-negative (green) uncertainty due to M_A is $\sim 10-12\%$.

Comparison with MiniBooNE data



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 provides results in excellent agreement with SuSA/SuSAv2 approaches.*
- *Significant discrepancy with MiniBooNE data: Important enhancement of 2p-2h effects?*
- *RMF results (likewise SuSA/SuSAv2) in accordance with NOMAD and MinerVA data (without need to increase the axial mass).*
- *Correlation between axial strangeness and axial mass in NC processes. Some discrepancy with MiniBooNE data: role of 2p-2h?, strangeness? ...*

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