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THE GREEN'S FUNCTION MODEL FOR QUASIELASTIC ELECTRON AND NEUTRINO-NUCLEUS SCATTERING

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collaboration:

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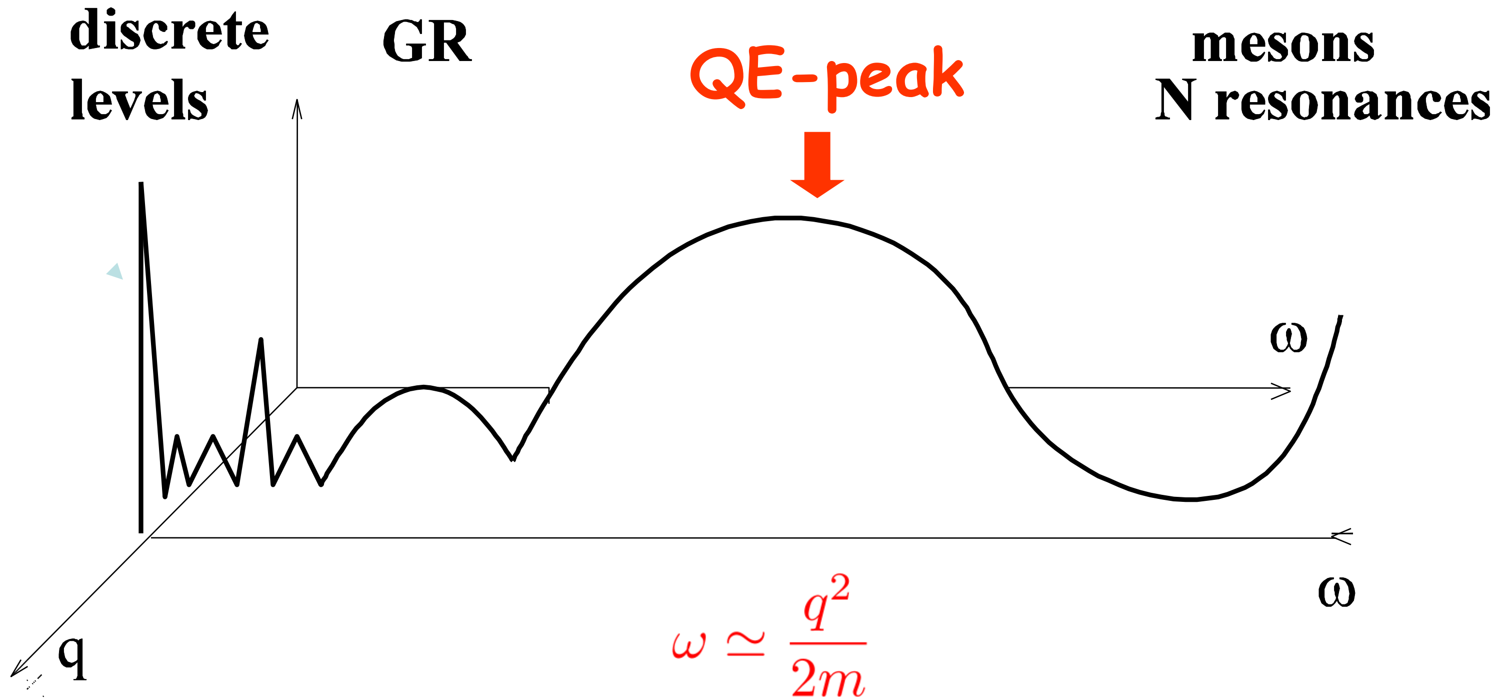
J.A. Caballero (Sevilla)
J.M. Udías (Madrid)

nuclear response to the electroweak probe



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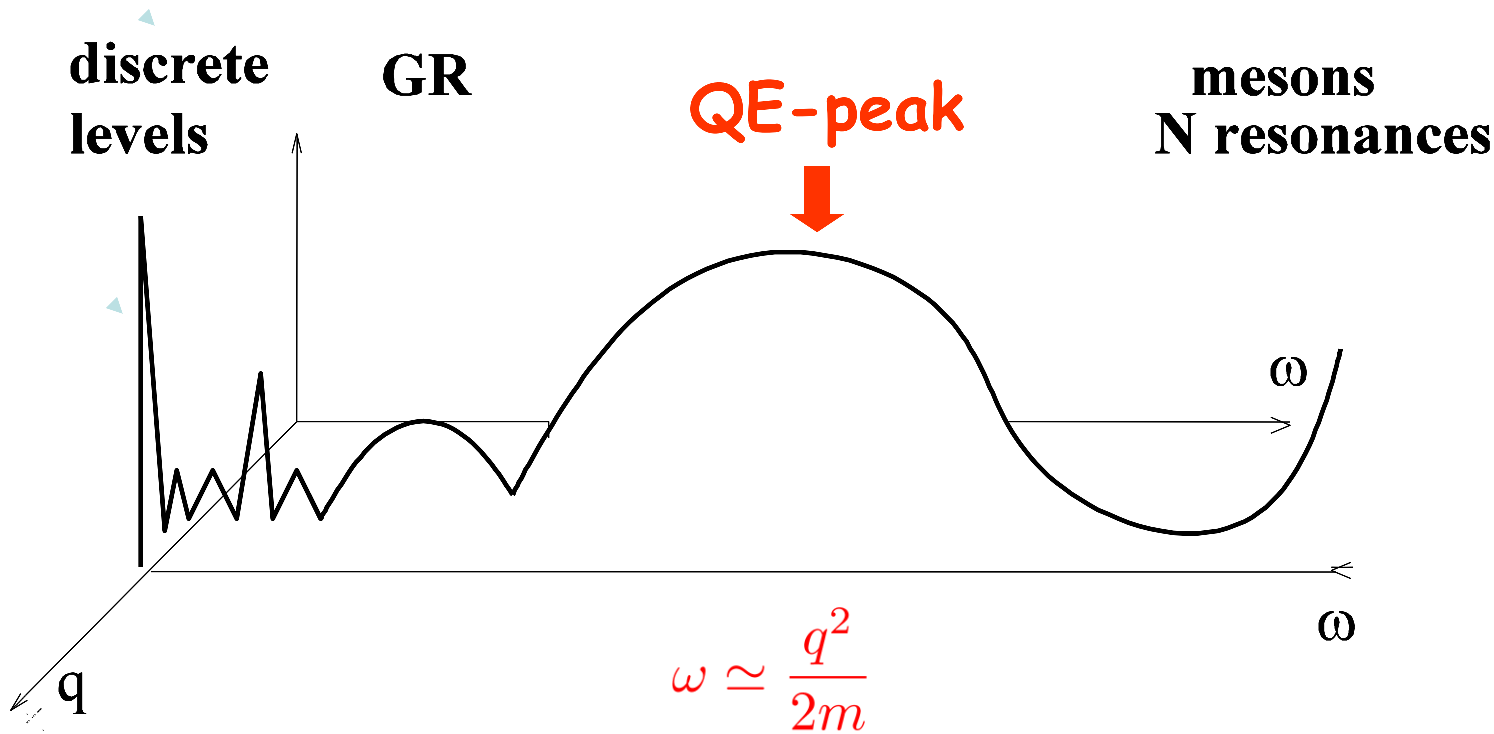

QE-peak dominated by one-nucleon knockout

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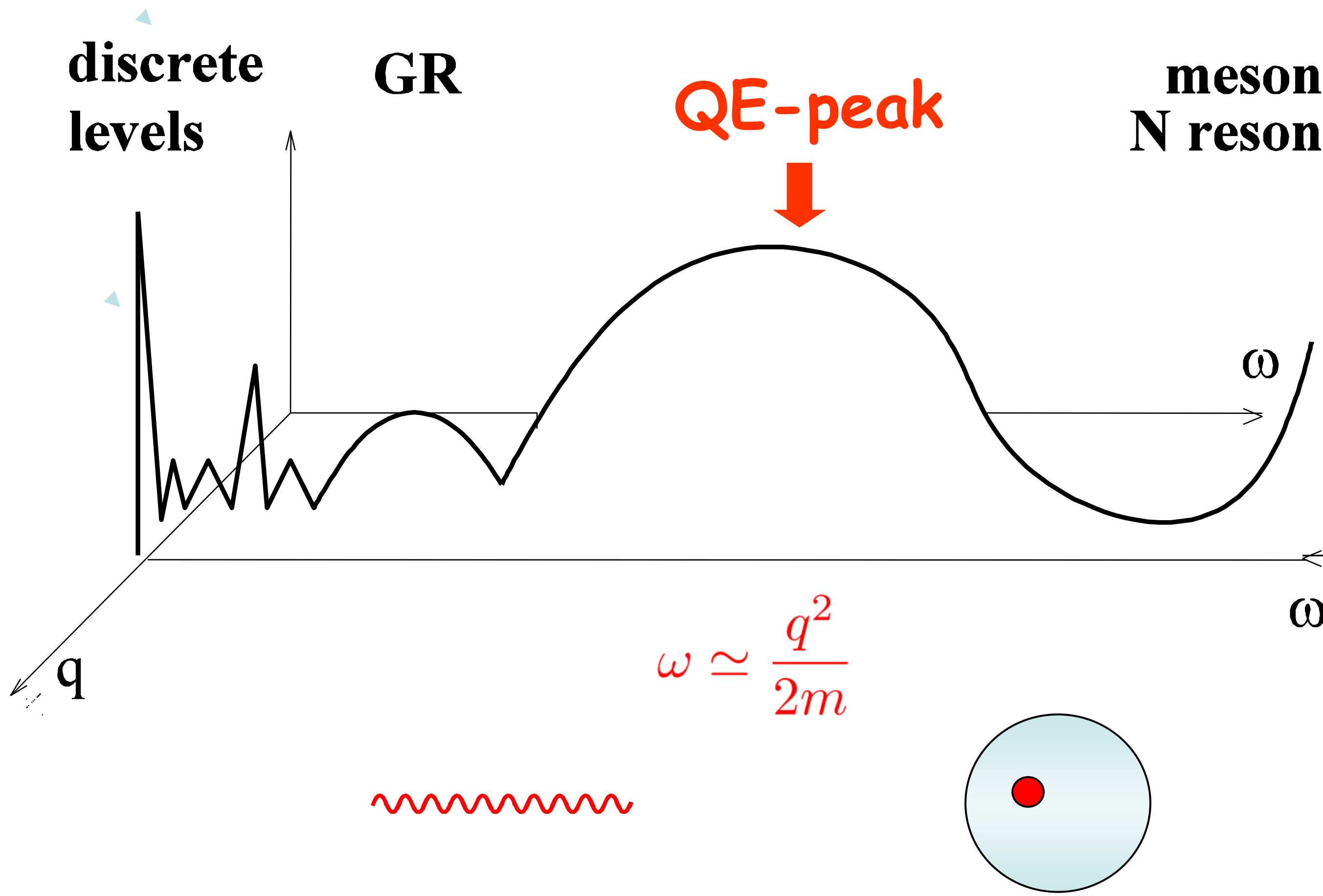

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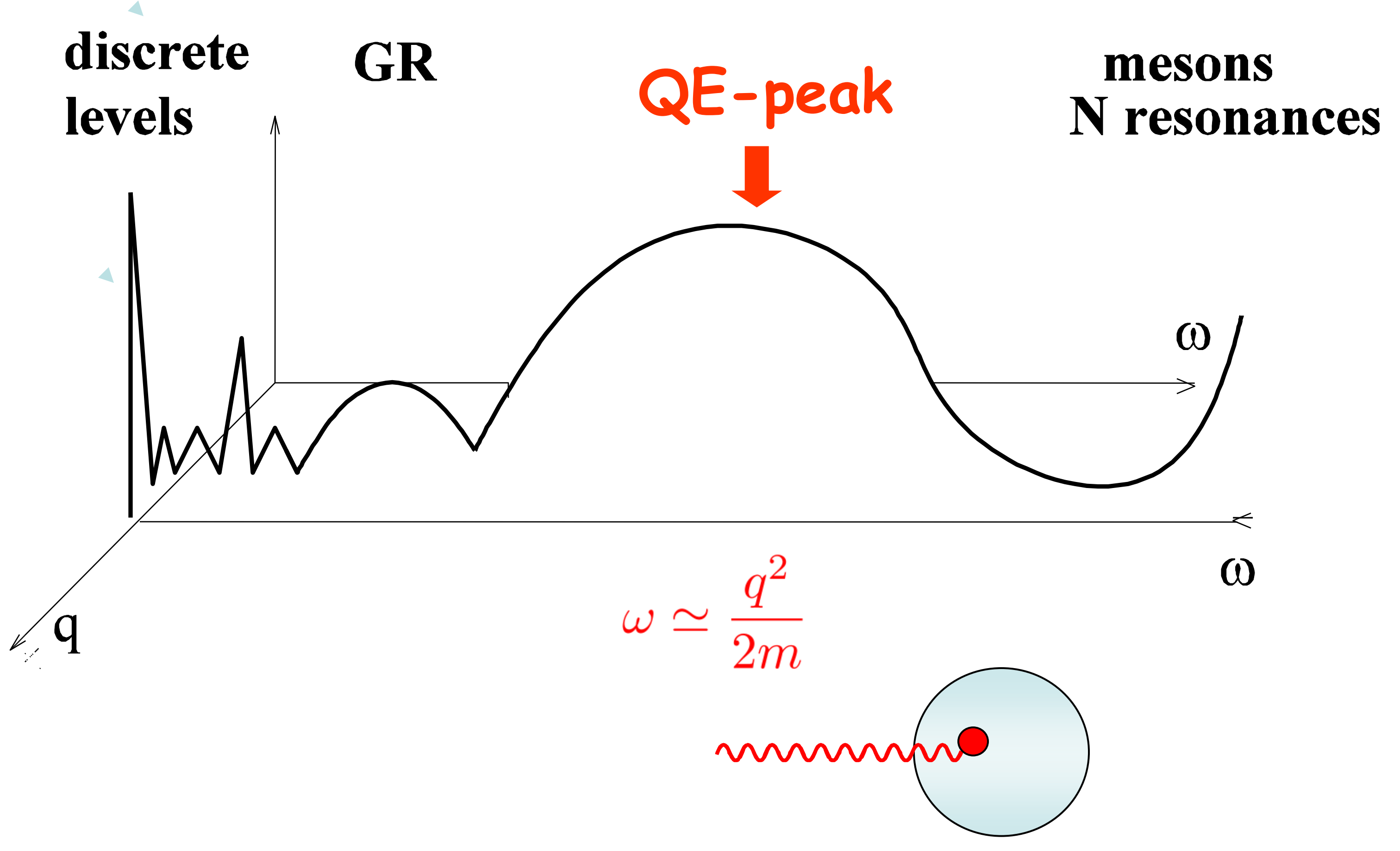

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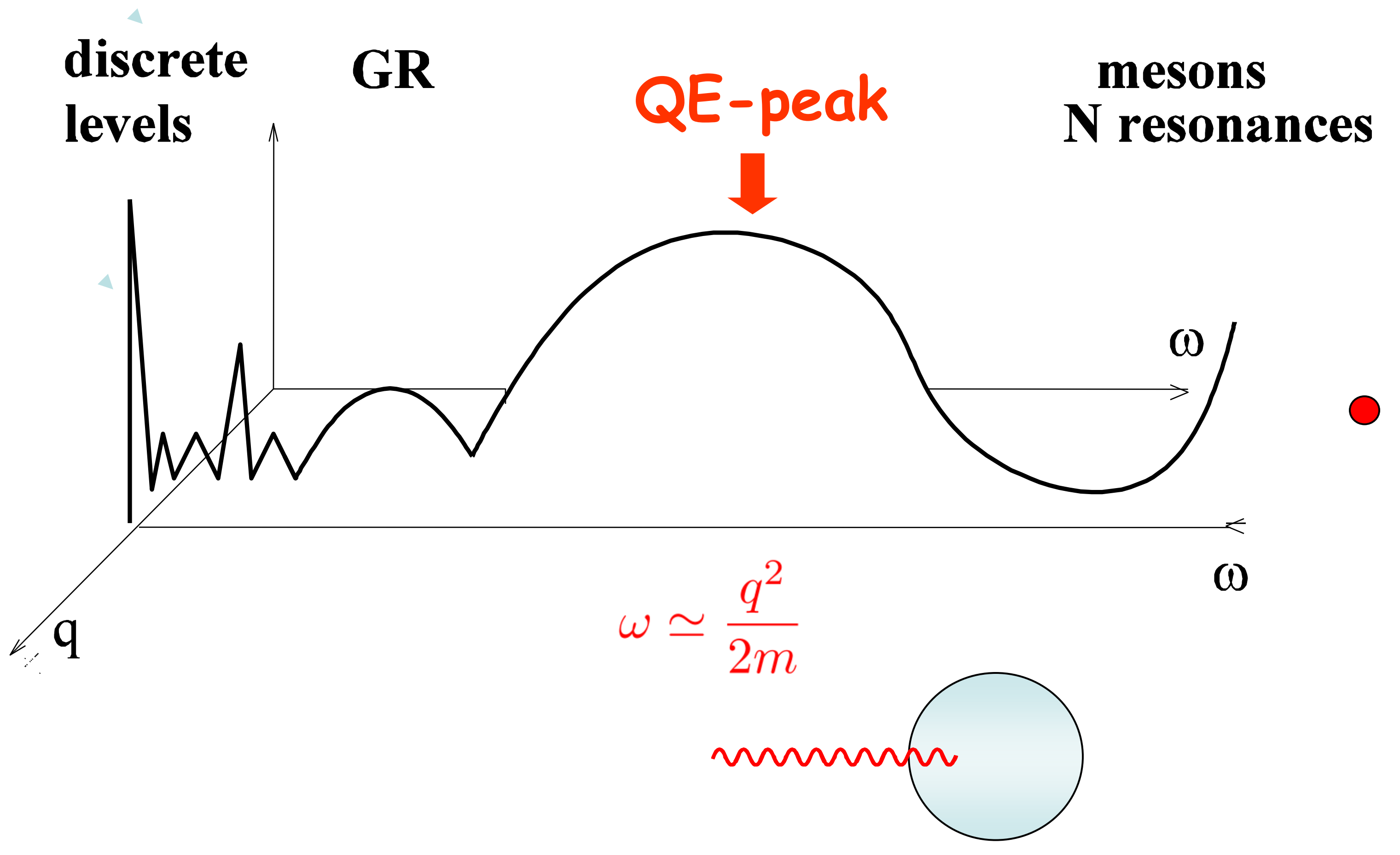

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QE e-nucleus scattering

$$e + A \Longrightarrow e' + N + (A - 1)$$

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- both e′ and N detected one-nucleon-knockout (e,e′p)
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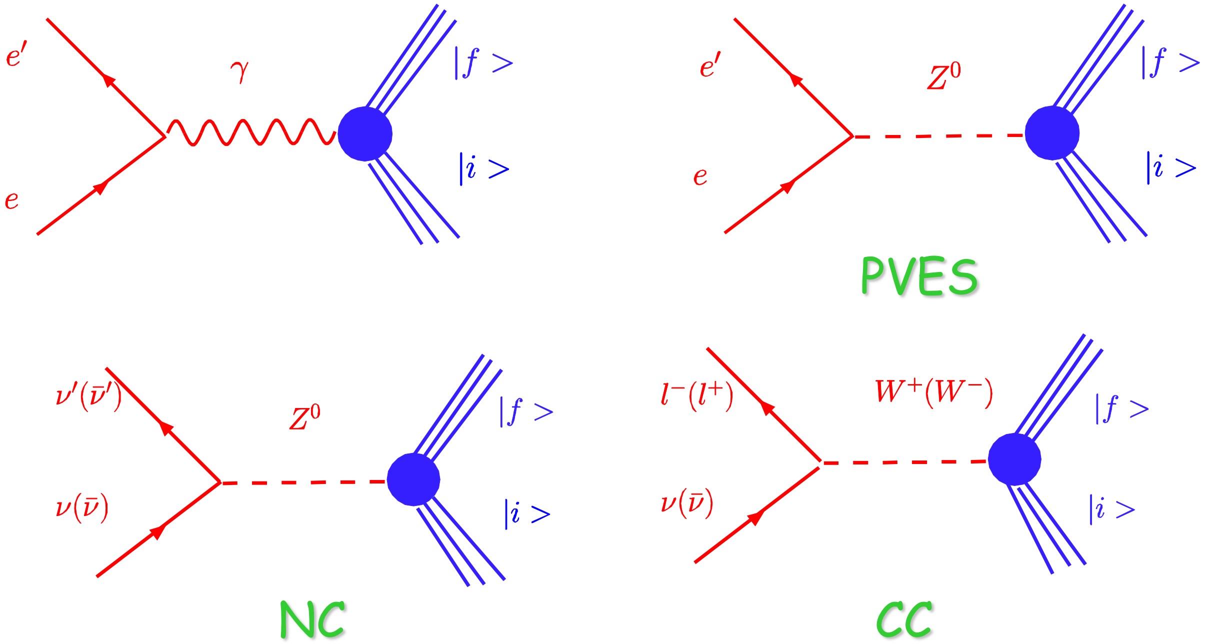
- only final lepton detected inclusive CC

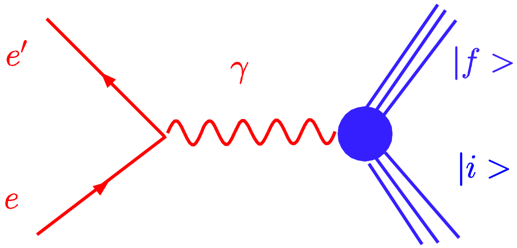
one-boson exchange

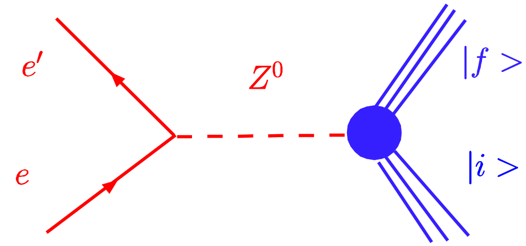


electron scattering

neutrino scattering

one-boson exchange





PVES

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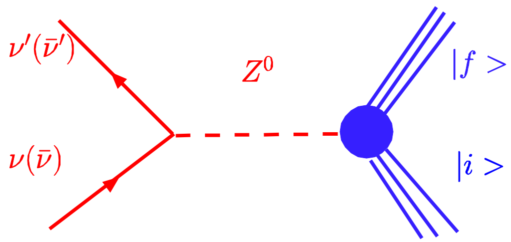

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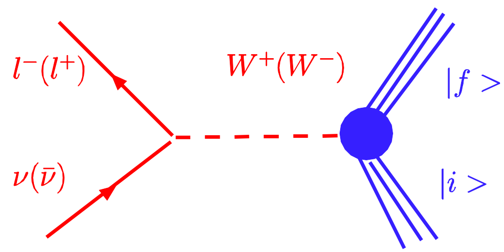
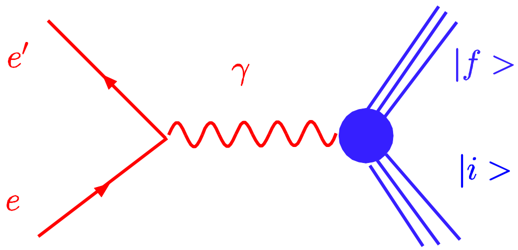
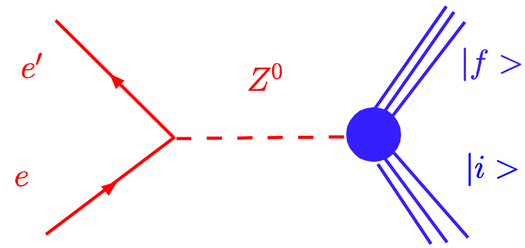


CC

neutrino scattering

$$\sigma = K L^{\mu\nu} W_{\mu\nu}$$





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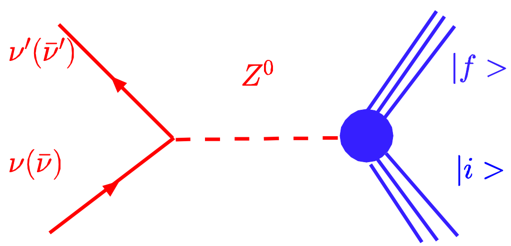

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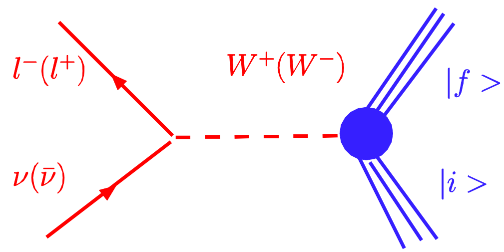

CC

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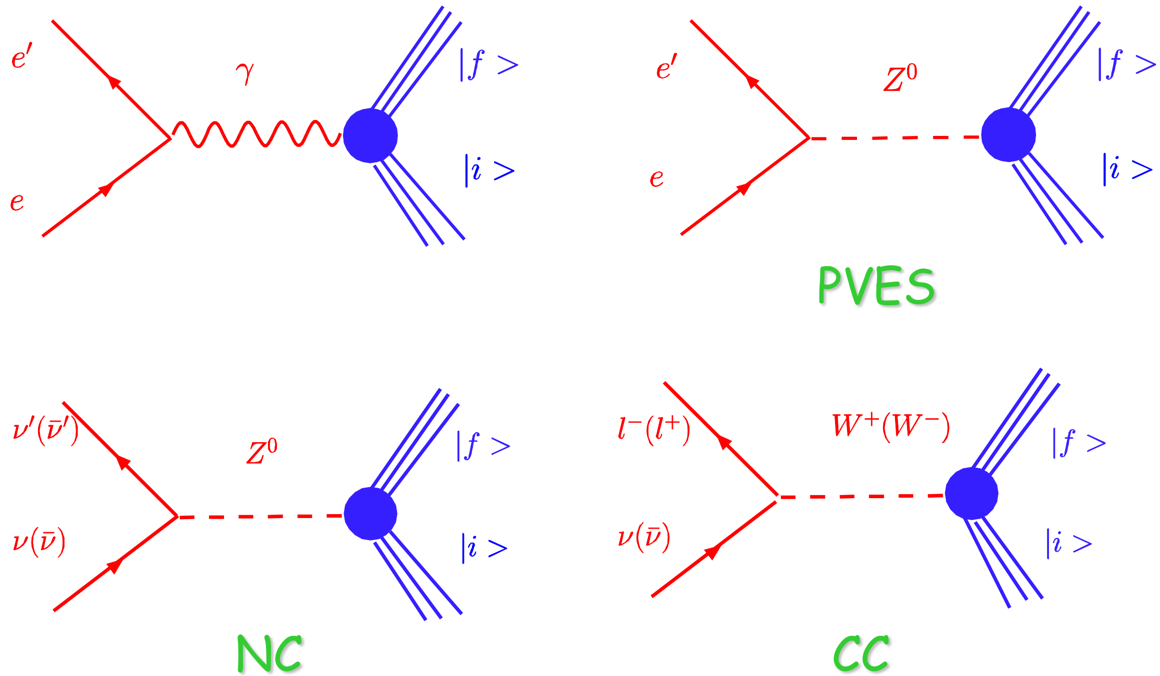
$$\sigma = K L^{\mu\nu} \; W_{\mu\nu}$$

$$\big\downarrow$$

kin factor

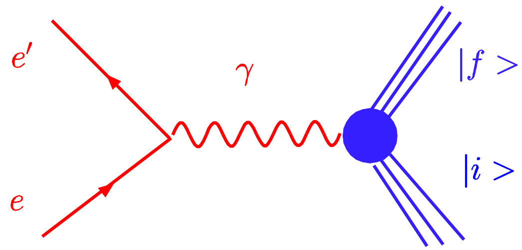


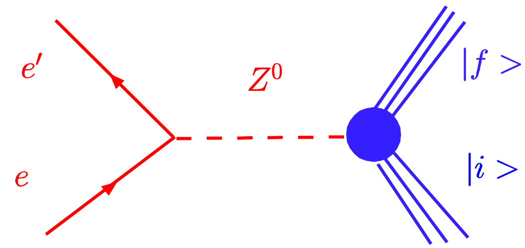
electron scattering

neutrino scattering

$$\sigma = K L^{\mu\nu} \; W_{\mu\nu}$$

lepton tensor contains lepton kinematics





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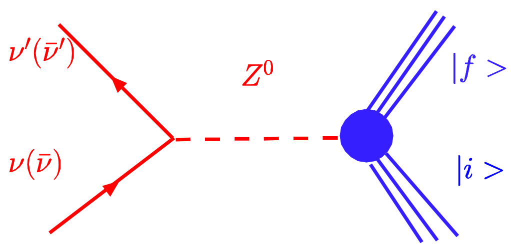

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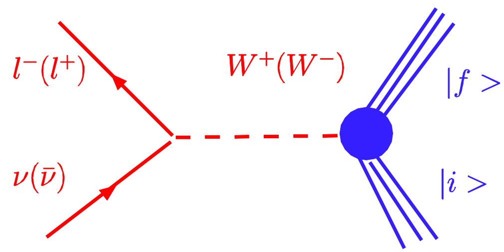

CC

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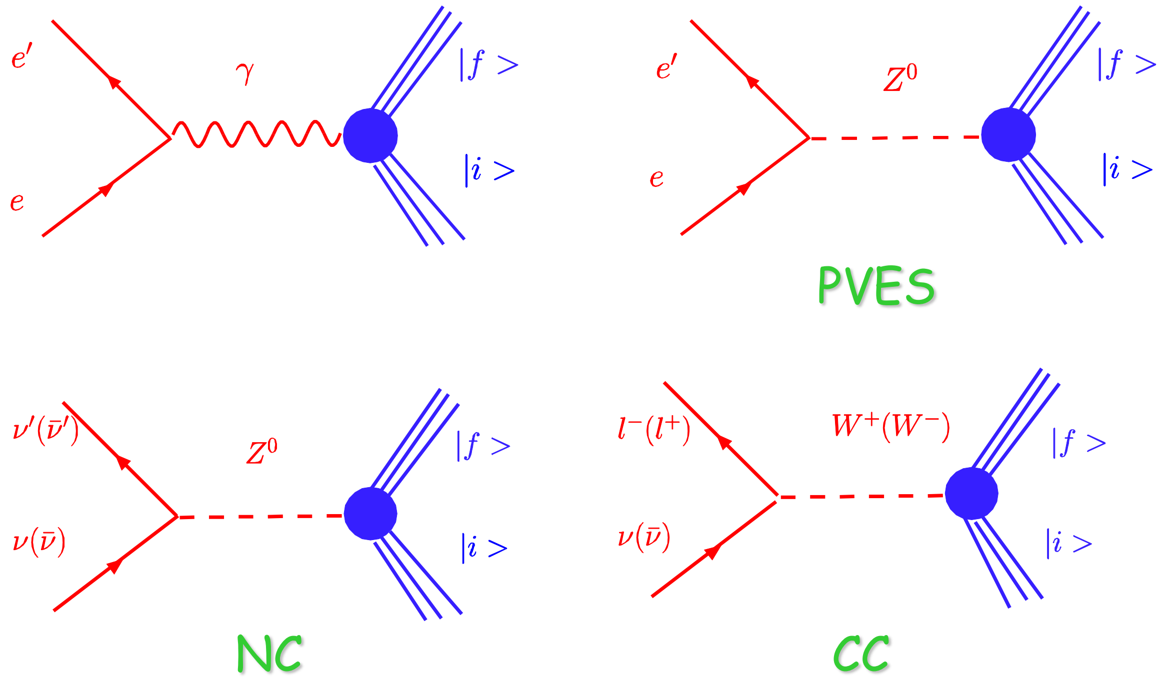
$$\sigma = K L^{\mu\nu} \ W_{\mu\nu}$$

hadron tensor

$$W^{\mu\nu} = \overline{\sum_{\mathrm{i,f}}} J^{\mu}(\boldsymbol{q}) \, J^{\nu *}(\boldsymbol{q}) \, \delta(E_{\mathrm{i}} + \omega - E_{\mathrm{f}})$$

$$J^{\mu}(\boldsymbol{q}) = \langle f \mid \hat{J}^{\mu}(\boldsymbol{q}) \mid i \rangle$$



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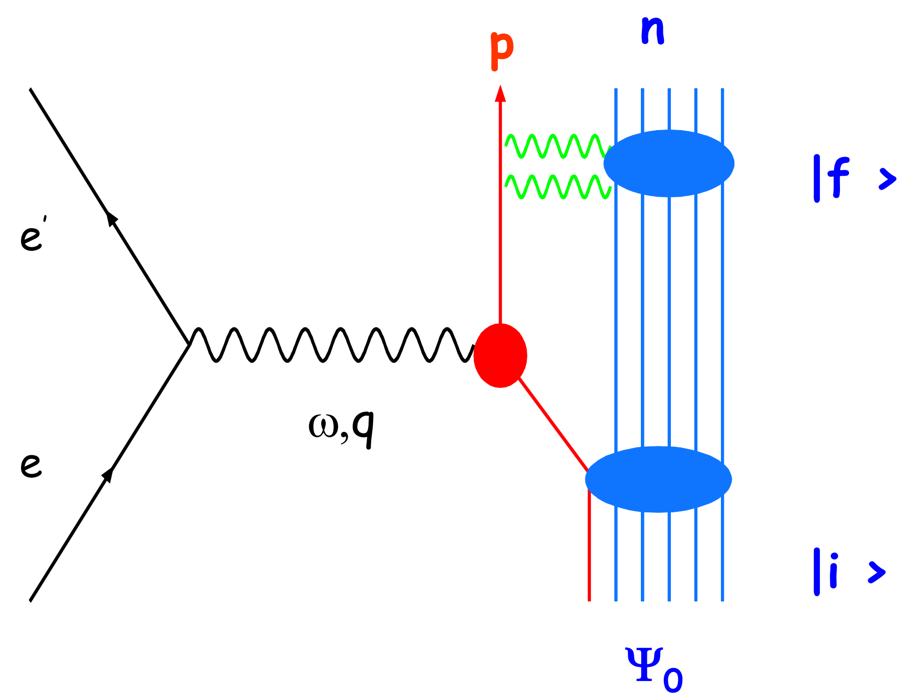
Direct knockout DWIA (e,e′p)

- exclusive reaction: n
- DKO mechanism: the probe interacts through a one-body current with one nucleon which is then emitted the remaining nucleons are spectators



$$\langle f \mid J^\mu(\boldsymbol{q}) \mid i\rangle \Rightarrow \lambda_n^{1/2} \langle \chi_{\boldsymbol{p}}^{(-)} \mid j^\mu(\boldsymbol{q}) \mid \phi_n\rangle$$

Direct knockout DWIA (e,e'p)

$$\lambda_n^{1/2} \langle \chi^{(-)} \mid j^\mu \mid \phi_n \rangle$$

- j^μ one-body nuclear current
- $\chi^{(-)}$ s.p. scattering w.f. $H^+(\omega+E_m)$
- ϕ_n s.p. bound state overlap function $H(-E_m)$
- λ_n spectroscopic factor
- $\chi^{(-)}$ and ϕ consistently derived as eigenfunctions of a Feshbach optical model Hamiltonian

$$\mathcal{H}(E) = PHP + PHQ\frac{1}{E - QHQ + \mathrm{i}\eta}QHP$$

Direct knockout DWIA (e,e'p)

in the calculations

- phenomenological ingredients usually adopted
- $\chi^{(-)}$ phenomenological optical potential
- ϕ_n phenomenological s.p. wave functions
- λ_n extracted in comparison with data: reduction factor applied to the calculated c.s. to reproduce the magnitude of the experimental c.s.

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both DWIA and RDWIA give an excellent description of (e,e′p) data in a wide range of nuclei and in different kinematics

INCLUSIVE SCATTERING

- only final lepton detected: different treatment of FSI

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- RMF — RELATIVISTIC MEAN FIELD: same real energy-independent potential of bound states

  Orthogonalization, fulfills dispersion relations and maintains the continuity equation
- RGF — GREEN'S FUNCTION: same COMPLEX OP of the exclusive scattering, but here the imaginary part redistributes the strength in all the channels and the flux is conserved

FSI for the inclusive scattering : Green's Function Model

(e,e') nonrelativistic

F. Capuzzi, C. Giusti, F.D. Pacati, Nucl. Phys. A 524 (1991) 281

F. Capuzzi, C. Giusti, F.D. Pacati, D.N. Kadrev Ann. Phys. 317 (2005) 492 (AS CORR)

(e,e') relativistic

A. Meucci, F. Capuzzi, C. Giusti, F.D. Pacati, PRC (2003) 67 054601

A. Meucci, C. Giusti, F.D. Pacati Nucl. Phys. A 756 (2005) 359 (PVES)

A. Meucci, J.A. Caballero, C. Giusti, F.D. Pacati, J.M. Udias PRC (2009) 80 024605 (RGF-RMF)

CC relativistic

A. Meucci, C. Giusti, F.D. Pacati Nucl. Phys. A739 (2004) 277

A. Meucci, J.A Caballero, C. Giusti, J.M. Udias PRC (2011) 83 064614 (RGF-RMF)

comparison with MiniBooNE data

A. Meucci, M.B. Barbaro, J.A. Caballero, C. Giusti, J.M. Udias PRL (2011) 107 172501

A. Meucci, C. Giusti, F.D. Pacati PRD (2011) 84 113003

A. Meucci, C. Giusti, PRD (2012) 85 093002

FSI for the inclusive scattering : Green's Function Model

- the components of the inclusive response are expressed in terms of the Green's operators
- under suitable approximations can be written in terms of the s.p. optical model Green's function
- the explicit calculation of the s.p. Green's function can be avoided by its spectral representation which is based on a biorthogonal expansion in terms of the eigenfunctions of the non Herm optical potential V and V^+
- matrix elements similar to RDWIA
- scattering states eigenfunctions of V and V^+ (absorption and gain of flux): the imaginary part redistributes the flux and the total flux is conserved
- consistent treatment of FSI in the exclusive and in the inclusive scattering

FSI for the inclusive scattering : Green's Function Model

$$W^{\mu\mu}(\omega, q) = \sum_n \left[\mathbf{Re} T_n^{\mu\mu}(E_\mathbf{f} - \varepsilon_n, E_\mathbf{f} - \varepsilon_n) - \frac{1}{\pi}\mathcal{P}\int_M^\infty \mathbf{d}\mathcal{E} \frac{1}{E_\mathbf{f} - \varepsilon_n - \mathcal{E}} \mathbf{Im} T_n^{\mu\mu}(\mathcal{E}, E_\mathbf{f} - \varepsilon_n) \right]$$

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interference between different channels

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eigenfunctions of V and V⁺

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Flux redistributed and conserved

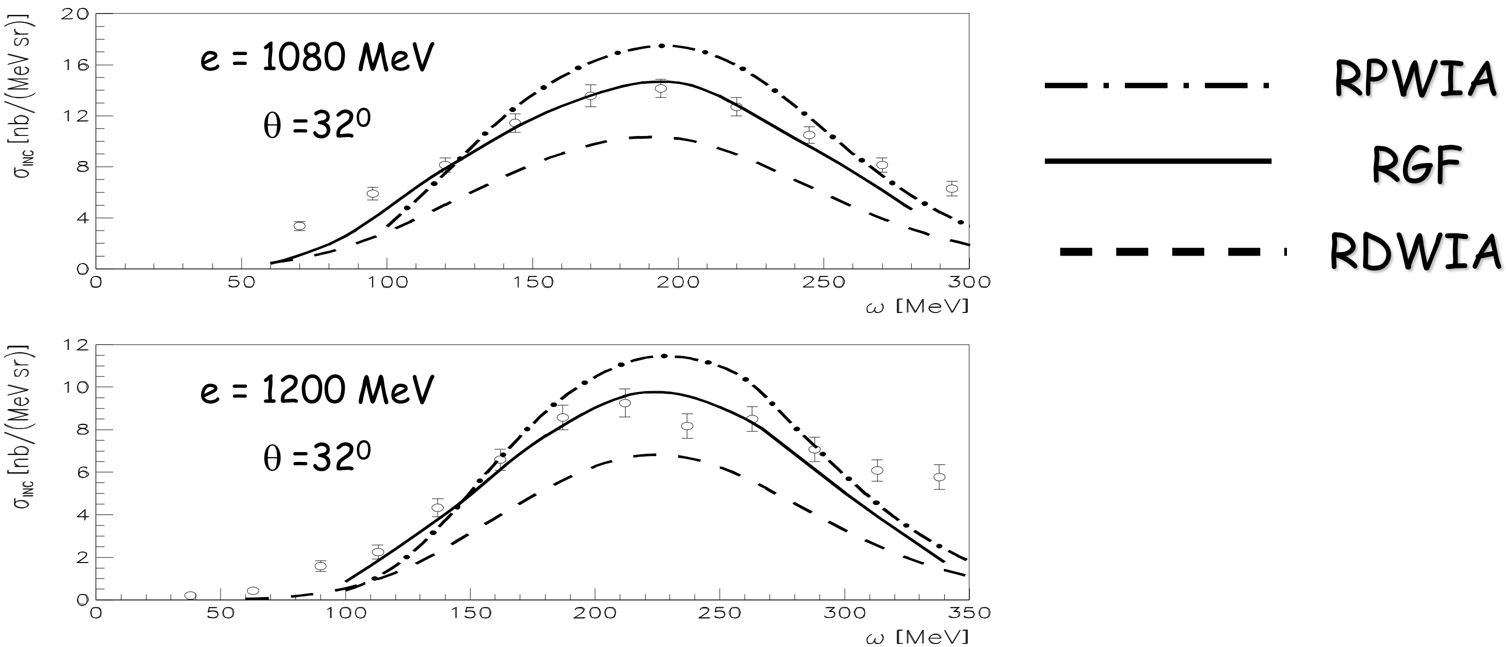
The imaginary part of the optical potential is responsible for the redistribution of the flux among the different channels

CALCULATIONS

- phenomenological bound and scattering states: same ingredients in the inclusive and exclusive scattering
- FSI: phenomenological optical potential
- bound states: mean-field approach
- pure Shell Model description: ϕ_n one-hole states in the target with a unitary spectral strength
- $\sum_n$ over all occupied states in the SM: all the nucleons are included but correlations are neglected

$^{16}O(e,e')$

relativistic Green's function model RGF



FSI

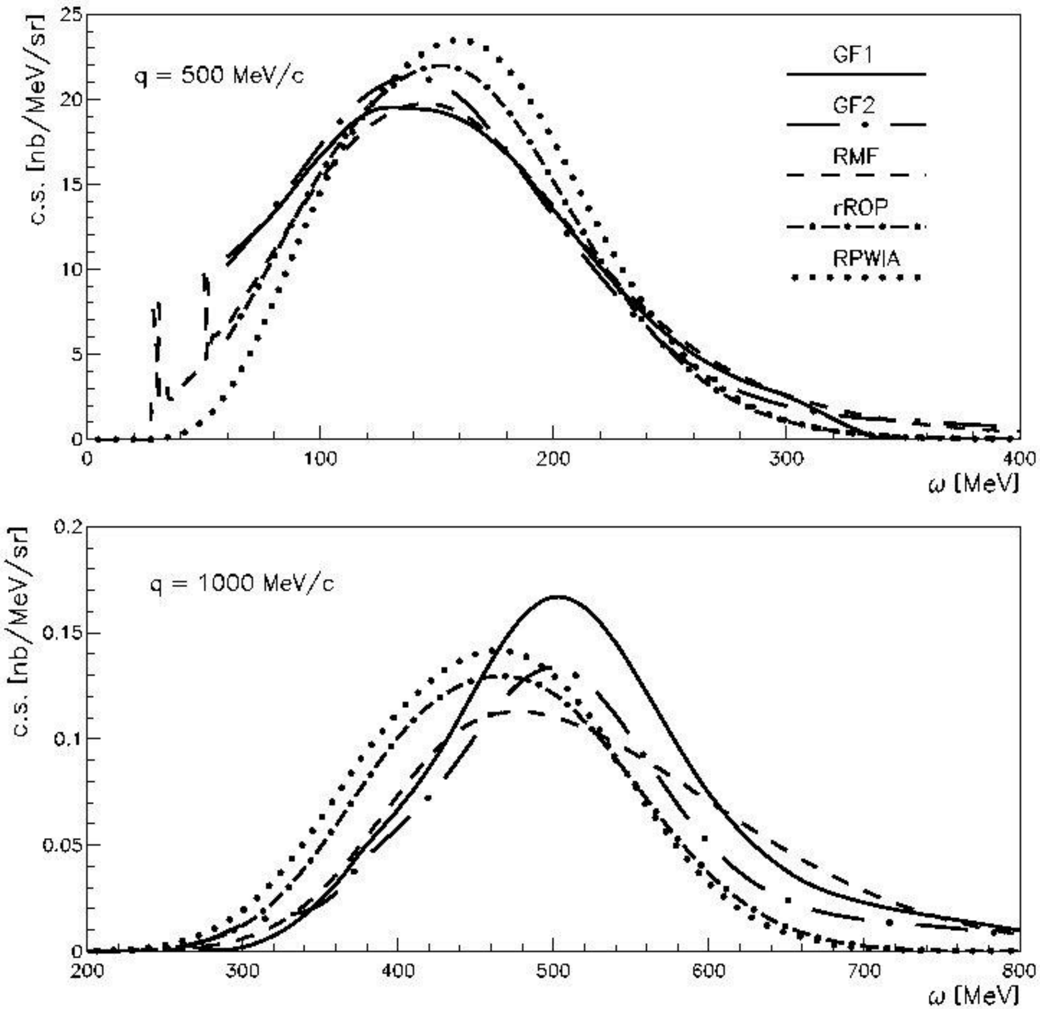
data from Frascati NPA 602 405 (1996)

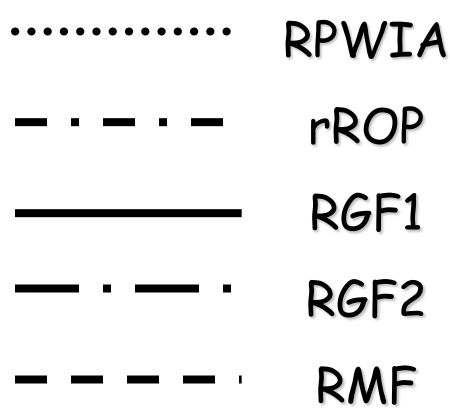
$^{12}C(e,e')$

comparison of relativistic models

e = 1 GeV

FSI





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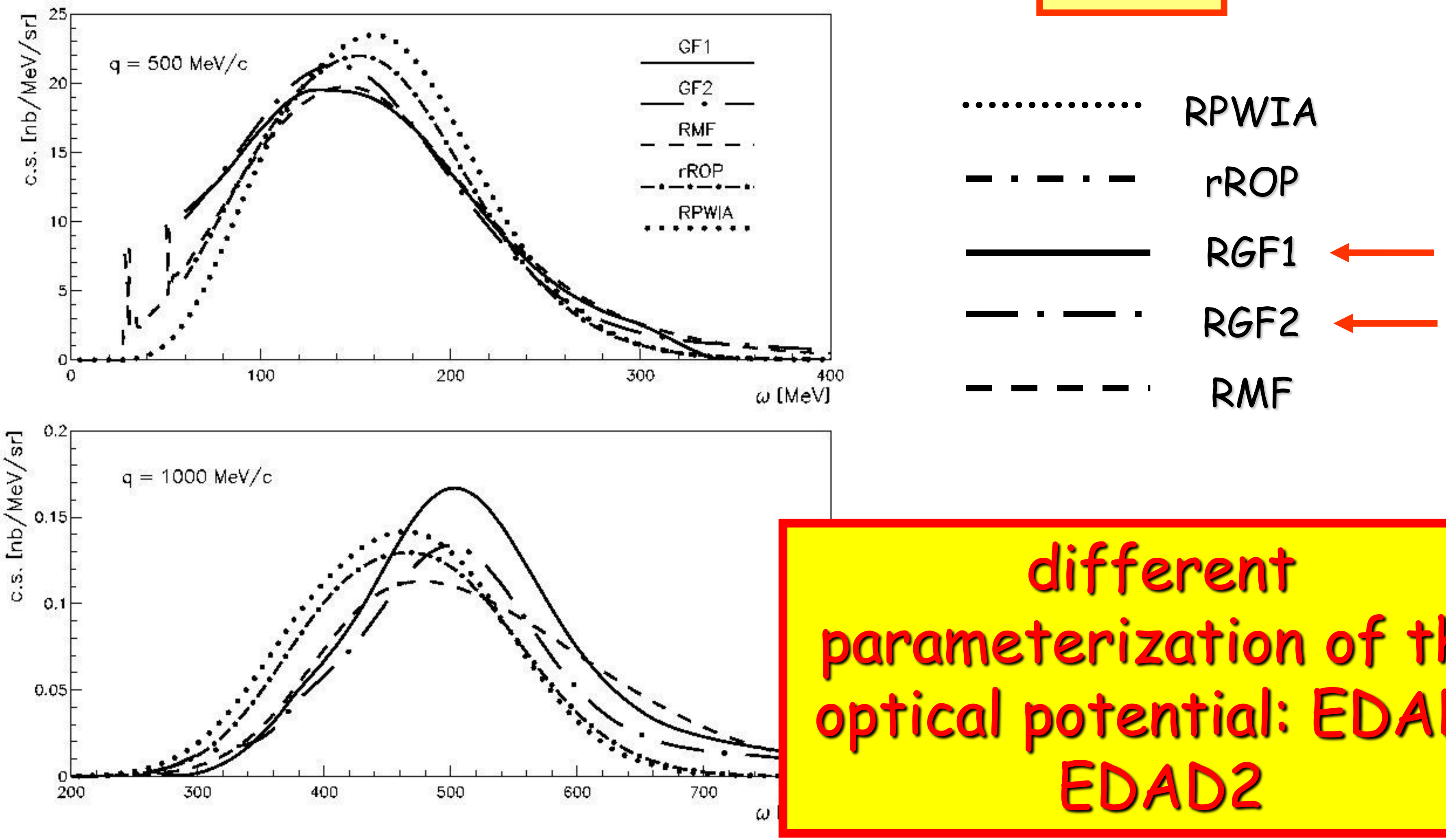

different parameterization of the optical potential: EDAD1 EDAD2

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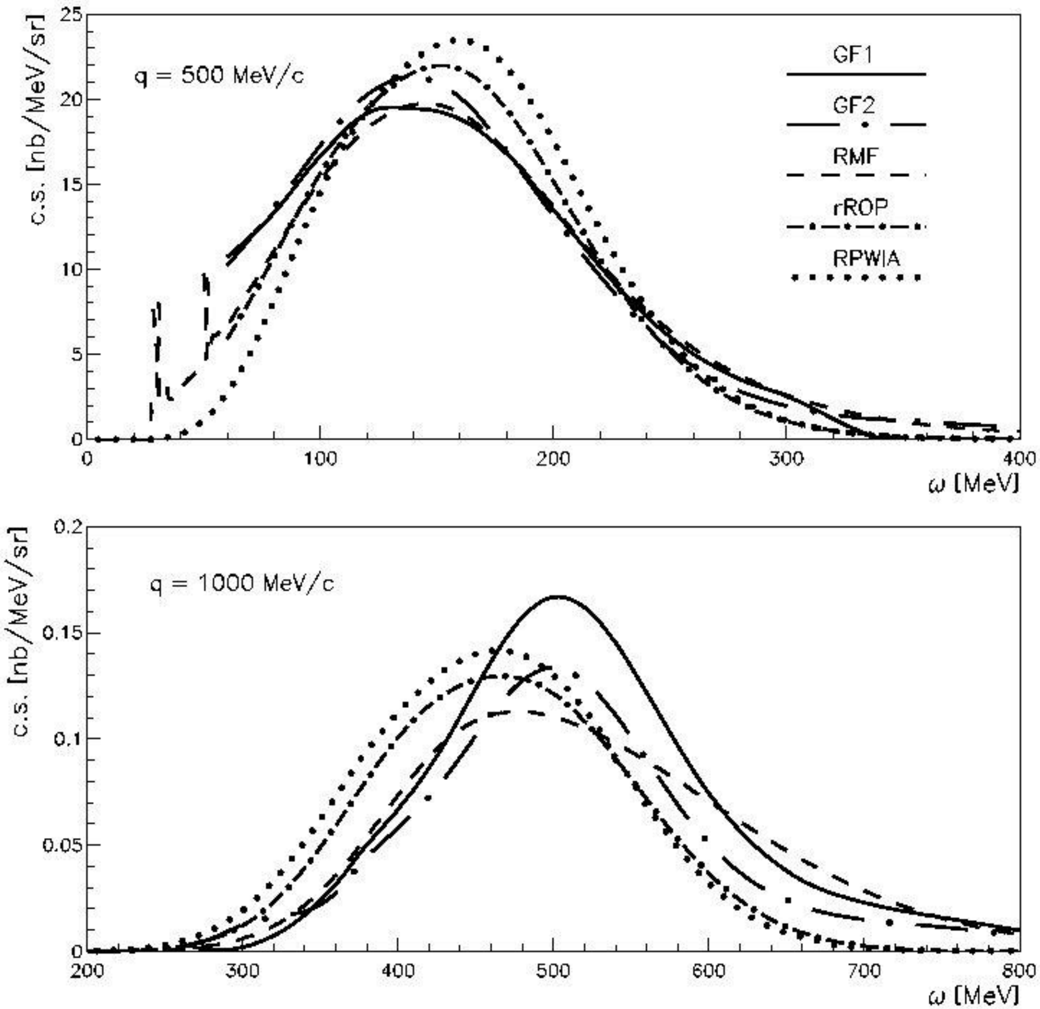
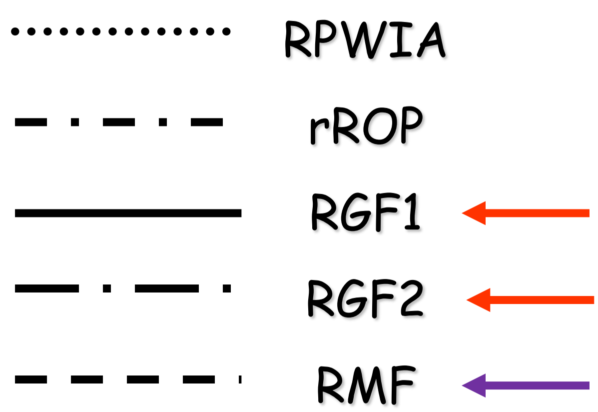
e = 1 GeV

FSI

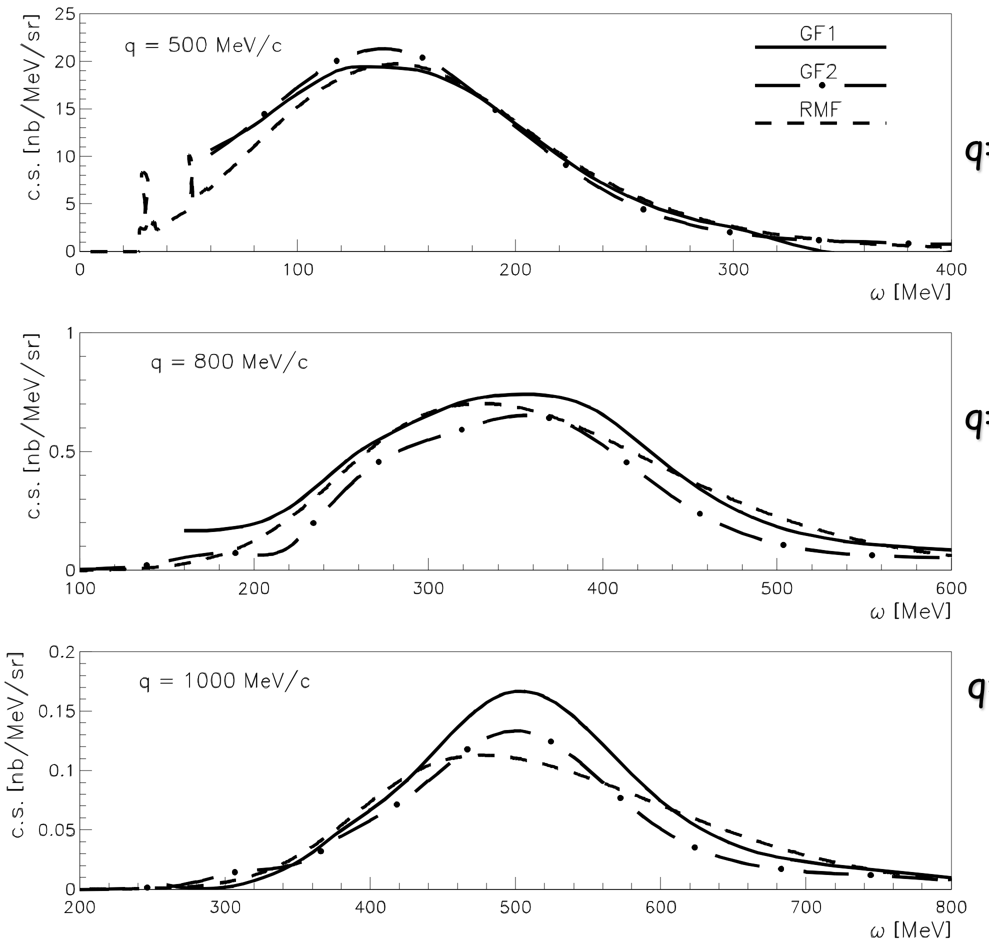




$^{12}C(e,e')$

comparison of relativistic models

e = 1 GeV



q=500 MeV/c

q=800 MeV/c

q=1000 MeV/c

FSI

RGF1

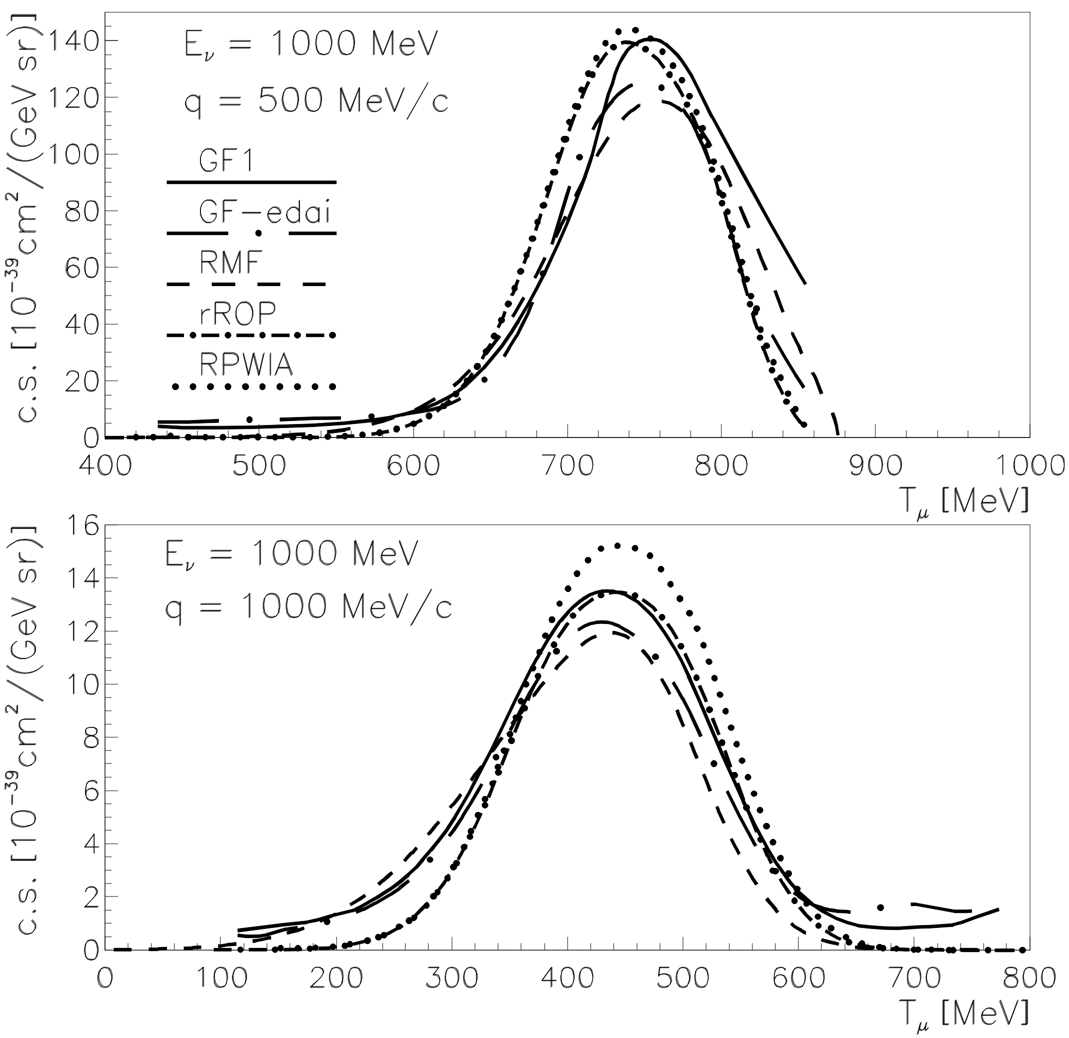
RGF2

RMF

Differences increase with q

$^{12}C(\nu_\mu, \mu^-)$

comparison of relativistic models



FSI

RPWIA

rROP

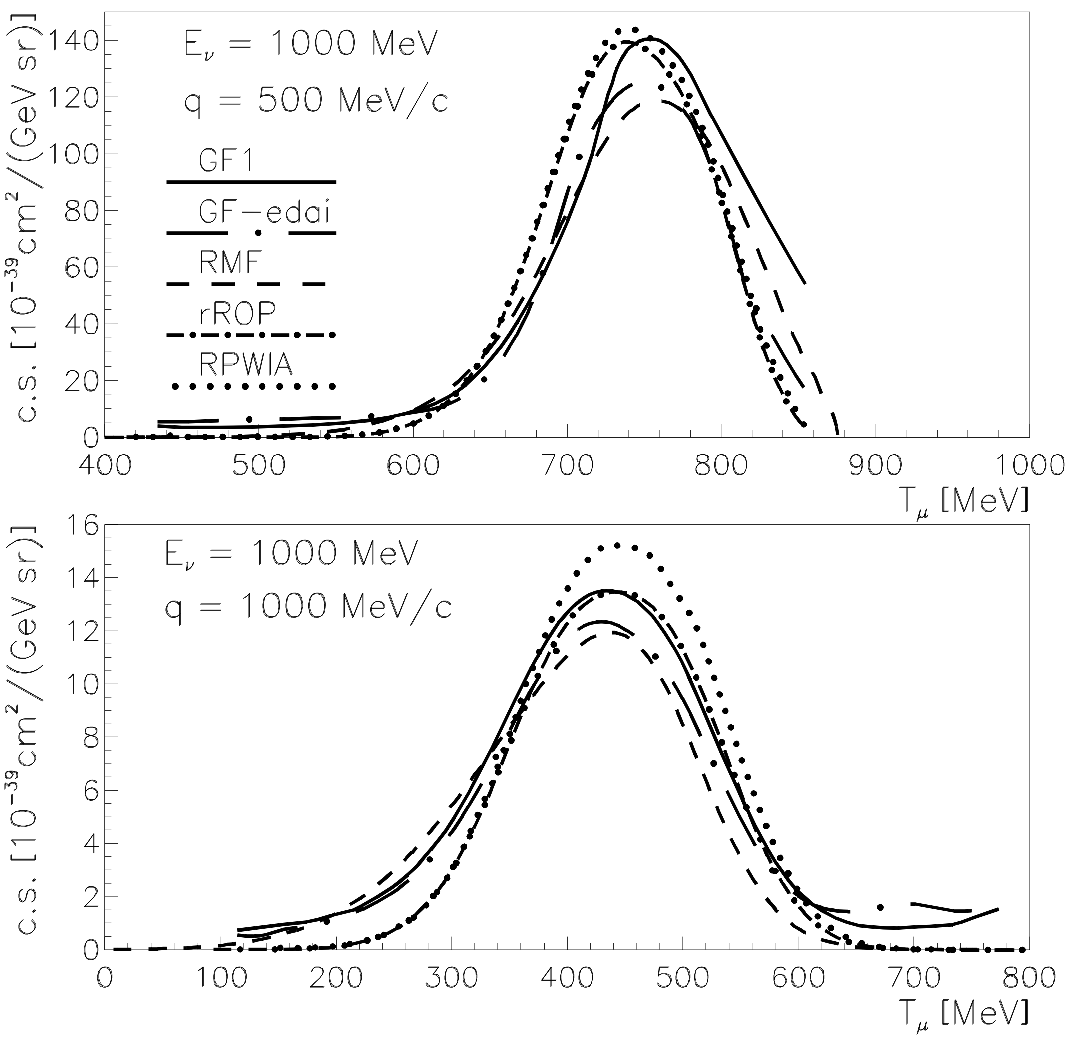
RGF1

RGF-EDAI

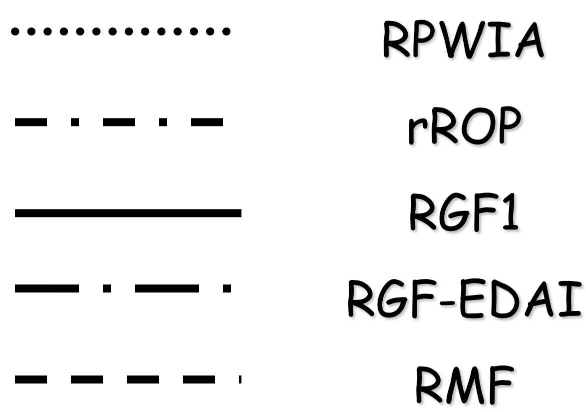
RMF

$^{12}C(\nu_\mu, \mu^-)$

comparison of relativistic models



FSI



EDAI A-independent for ^{12}C

DIFFERENT DESCRIPTIONS OF FSI

RMF

real energy-independent RMF reproduces nuclear saturation properties, purely nucleonic contribution, no information from scattering reactions explicitly incorporated

RGF

complex energy-dependent phenomenological OP fitted to elastic p-A scattering information from scattering reactions

the imaginary part includes the overall effect of inelastic channels, different contributions at each energy, not only 1-N emission (multi-nucleon, non-nucleonic, rescattering…)

DIFFERENT DESCRIPTIONS OF FSI

RMF ⟷ RGF

Comparison RMF-RGF deeper understanding of nuclear effects (FSI) which may play a crucial role in the analysis of MiniBooNE data, which may receive important contributions from non-nucleonic excitations and multi-nucleon processes

Comparison with MiniBooNe CCQE data

First Measurement of the Muon Neutrino Charged Current Quasielastic Double Differential Cross Section, PRD 81 (2010) 092005

$$\nu_\mu + {}^{12}\mathrm{C} \longrightarrow \mu^- + \mathrm{X}$$

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First Measurement of the Muon Neutrino Charged Current Quasielastic Double Differential Cross Section, PRD 81 (2010) 092005

$$\nu_\mu + {}^{12}\mathrm{C} \longrightarrow \mu^- + \mathrm{X}$$

Measured cross sections larger than the predictions of the RFG model and of other more sophisticated models.

Unusually large values of the nucleon axial mass must be used to reproduce the data (about 30% larger)

One-body CC nuclear weak current

$$j^\mu = \left[F_1^{\mathrm{V}}(Q^2)\gamma^\mu + i\frac{\kappa}{2M} F_2^{\mathrm{V}}(Q^2)\sigma^{\mu\nu}q_\nu - G_{\mathrm{A}}(Q^2)\gamma^\mu\gamma^5 + F_{\mathrm{P}}(Q^2)q^\mu\gamma^5 \right]\tau^\pm$$

$$F_{\mathrm{P}} = \frac{2MG_{\mathrm{A}}}{m_\pi^2 + Q^2}$$ induced pseudoscalar form factor

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axial current

$$F_{\rm P} = \frac{2MG_{\rm A}}{m_\pi^2 + Q^2}$$

induced pseudoscalar form factor

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axial current

$$F_{\rm P} = \frac{2MG_{\rm A}}{m_\pi^2 + Q^2}$$ induced pseudoscalar form factor

$$G_{\rm A} = 1.26\left(1 + \frac{Q^2}{M_{\rm A}^2}\right)^{-2}$$ axial form factor

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$$M_{\rm A} = (1.03 \pm 0.02){\rm GeV}$$

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$$M_{\mathrm{A}} = (1.03 \pm 0.02)\mathrm{GeV}$$

World average of measured values, mostly obtained from deuteron data

Comparison with MiniBooNe CCQE data

A larger axial mass may be interpreted as an effective way to include medium effects not taken into account by the RFG model and by other models.

Before drawing conclusions all nuclear effects must be investigated

Comparison with MiniBooNe CCQE data

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Before drawing conclusions all nuclear effects must be investigated

FSI

Differences between Electron and Neutrino Scattering

- electron scattering :

  beam energy known, cross section as a function of ω

- neutrino scattering:

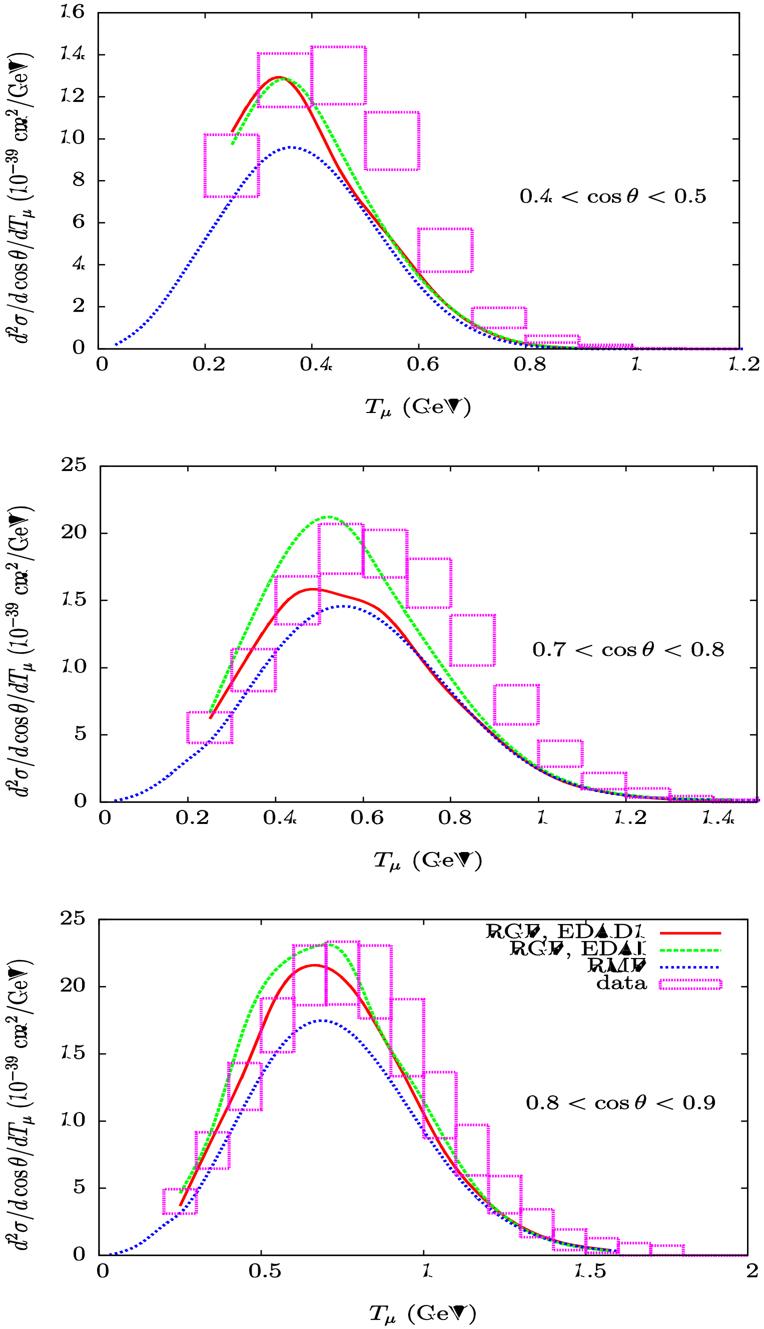
  axial current

  beam energy and ω not known

  calculations over the energy range relevant for the neutrino flux

the flux-average procedure can include contributions from different kinematic regions where the neutrino flux has significant strength, contributions other than 1-nucleon emission

Comparison with MiniBooNe CCQE data



$0.4 < cos\theta_\mu < 0.5$

$0.7 < cos\theta_\mu < 0.8$

$0.8 < cos\theta_\mu < 0.9$

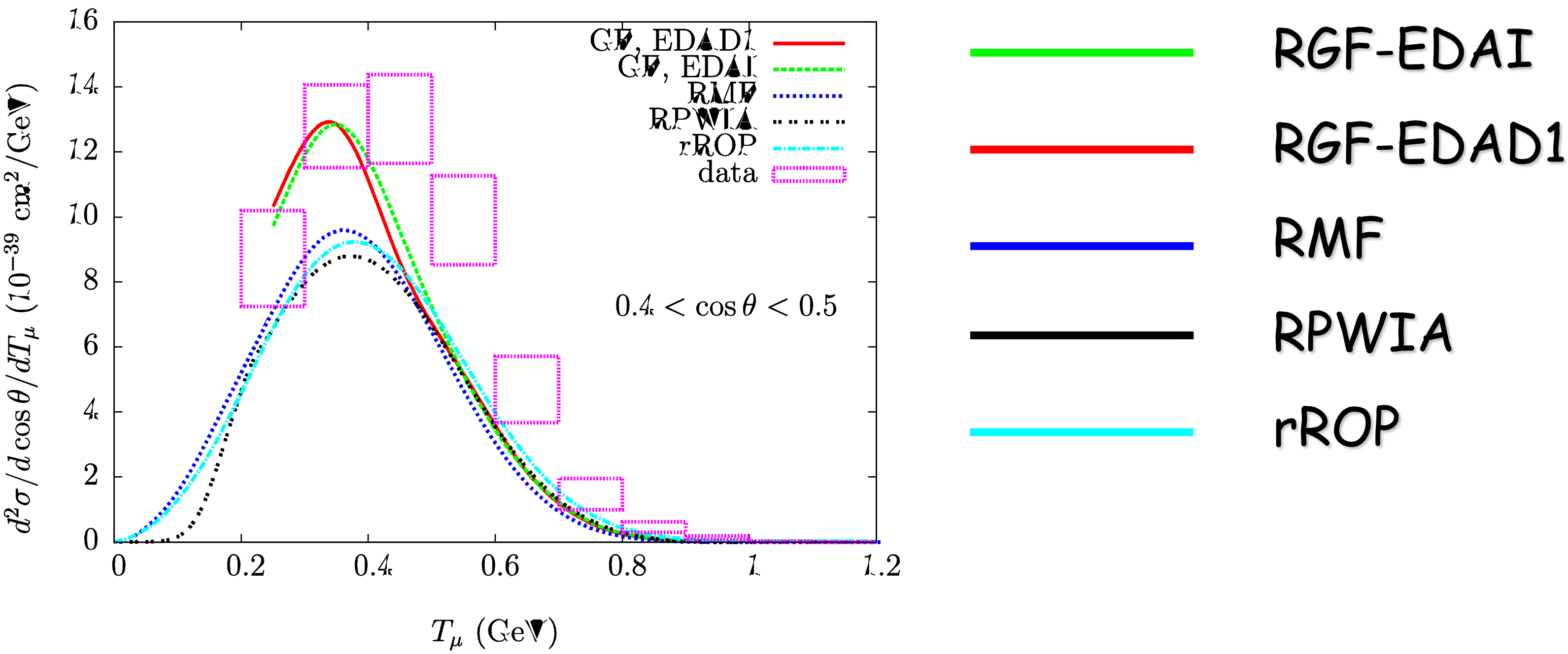
RGF-EDAI

RGF-EDAD1

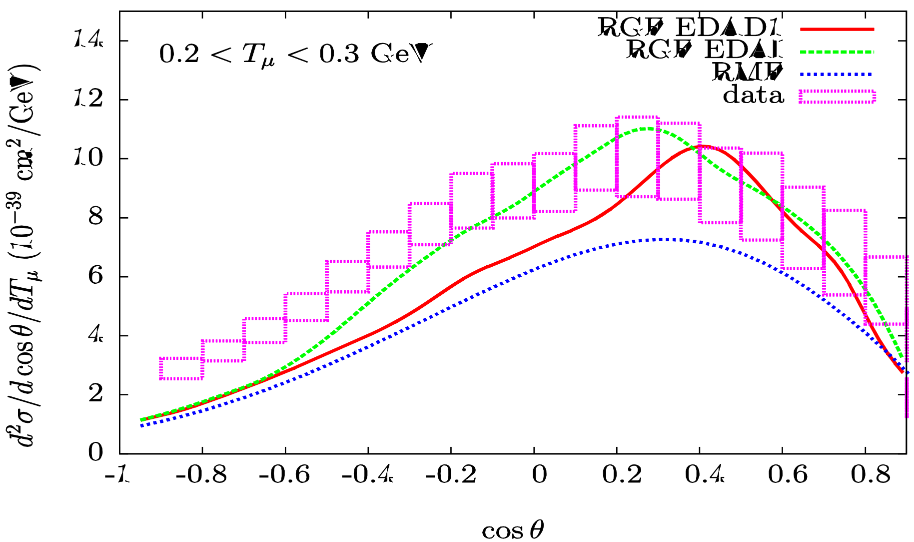
RMF

Comparison with MiniBooNe CCQE data

$$0.4 < cos\theta_{\mu} < 0.5$$



Comparison with MiniBooNe CCQE data

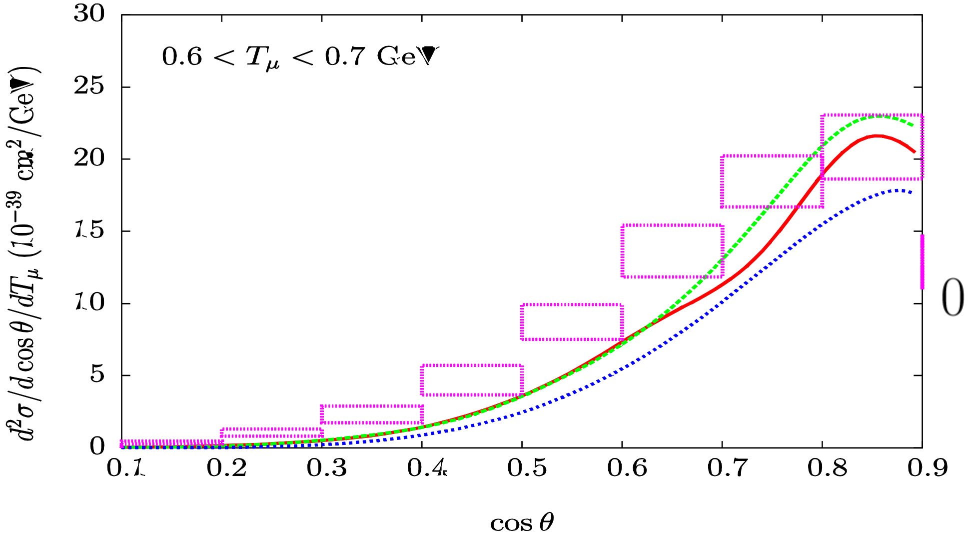


$0.2 < T_\mu < 0.3$ GeV

RGF-EDAI

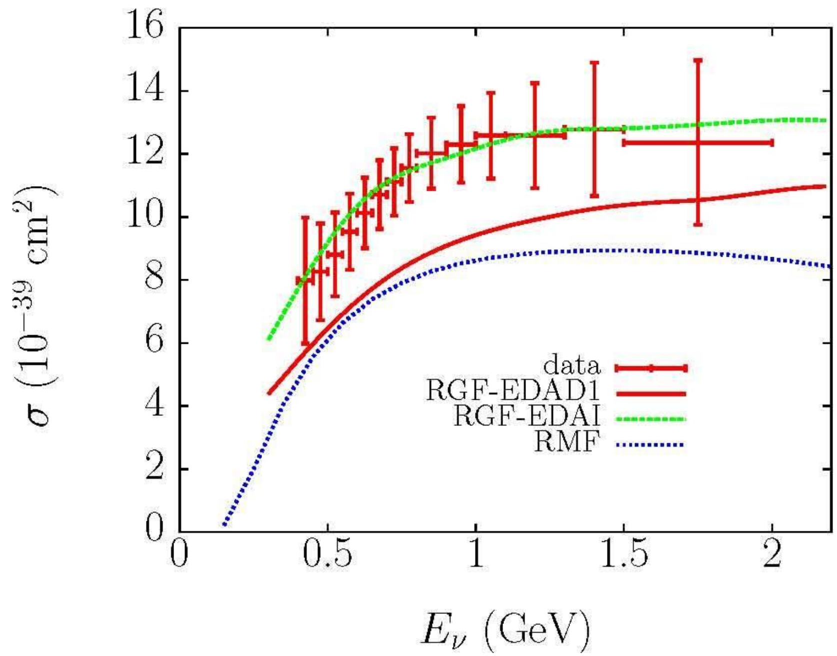
RGF-EDAD1

RMF



$0.6 < T_\mu < 0.7$ GeV

Comparison with MiniBooNe CCQE data



RGF-EDAI

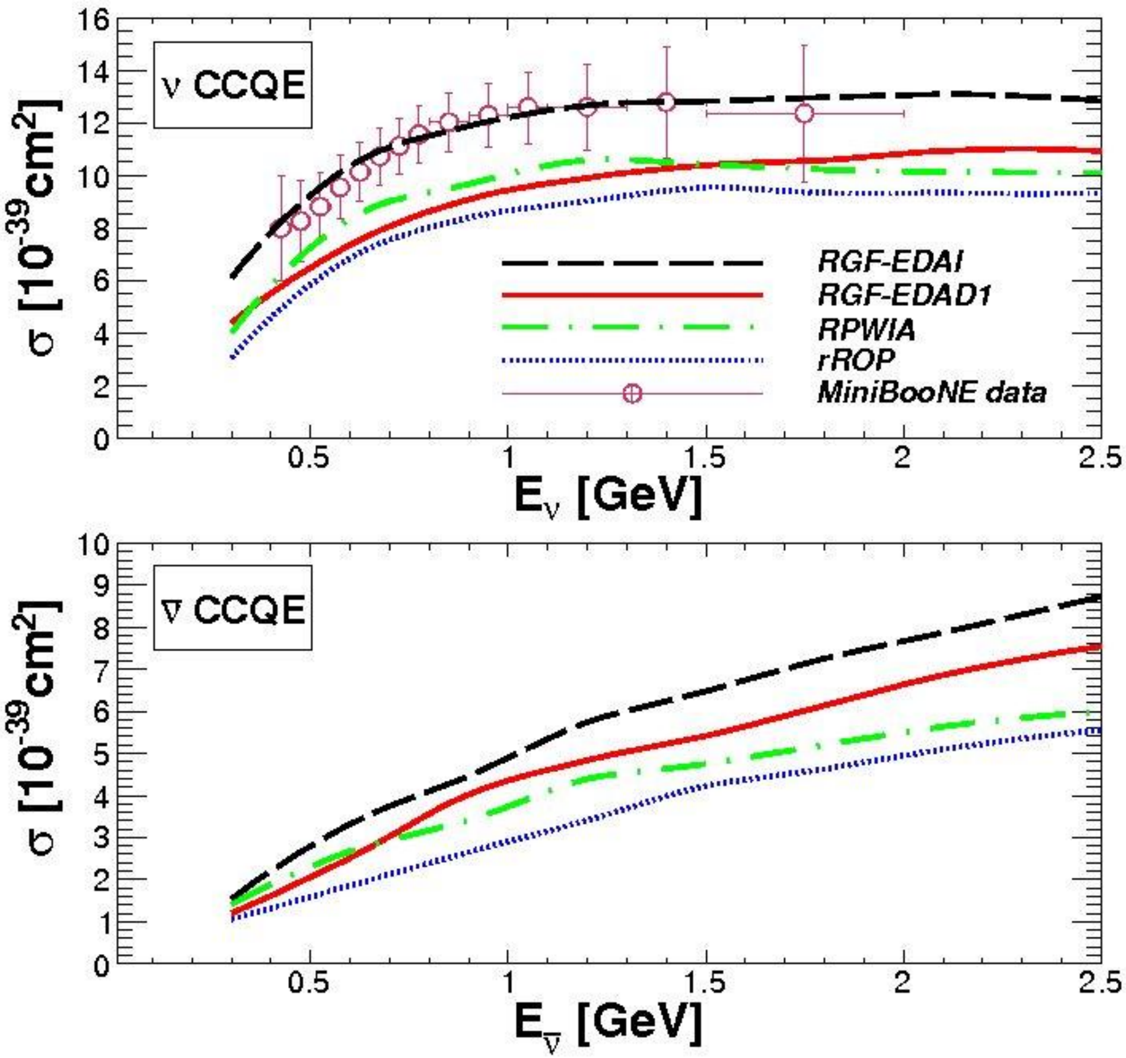
RGF-EDAD1

RMF

CCQE antineutrino-nucleus scattering

- The MiniBooNE collaboration has measured CCQE $\bar{\nu}$ events
- Additional information, data analysis ongoing
- In the calculations vector-axial response constructive in neutrino scattering destructive in antineutrino scattering with respect to L and T responses
- $\bar{\nu}_\mu$ flux smaller and with lower average energy than ν_μ flux

Comparison CCQE neutrino-antineutrino scattering



Comparison with MiniBooNE NCE data

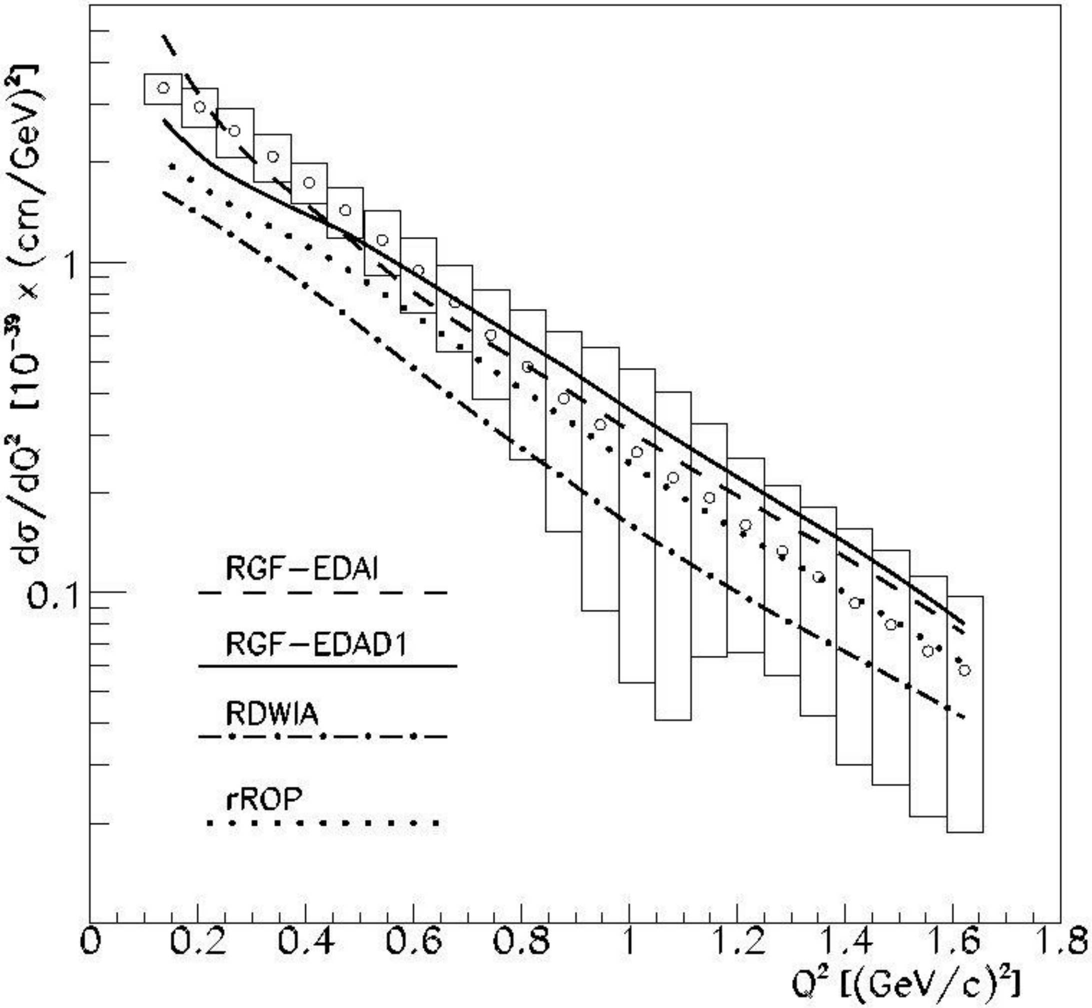
Measurement of the flux averaged neutral-current elastic (NCE) differential cross section on CH_2 as a function of Q^2
PRD 82 092005 (2010)

The NCE cross section presented as scattering from individual nucleons and consists of 3 different processes: scattering of free protons in H, bound protons and neutrons in C

NC ν-nucleus scattering

- only the outgoing nucleon is detected: semi-inclusive scattering
- FSI ?
- RDWIA : sum of all integrated exclusive 1NKO channels with absorptive imaginary part of the ROP. The imaginary part accounts for the flux lost in each channel towards other inelastic channels. Some of these reaction channels are not included in the experimental cross section when one nucleon is detected. For these channels RDWIA is correct, but there are channels excluded by the RDWIA and included in the experimental c.s.
- RGF recovers the flux lost to these channels but can include also contributions of channels not included in the semi-inclusive cross section
- we can expect RDWIA smaller and RGF larger than the experimental cross sections
- relevance of contributions neglected in RDWIA and added in RGF depends on kinematics

Comparison with MiniBooNE NCE data



- models developed for QE electron-nucleus scattering, successfully tested in comparison with electron-scattering data applied to QE neutrino-nucleus scattering
- RGF description of FSI in the inclusive scattering
- RGF enhances the c.s. and gives results able to reproduce the MiniBooNE data with the standard value of M_A
- enhancement due to the translation to the inclusive strength of the overall effect of inelastic channels (multi-nucleon, non-nucleonic rescattering....)
- inelastic contributions recovered in the RGF by the imaginary part of the ROP, not included explicitly in the model with a microscopic calculation, the role of different inelastic processes cannot be disentangled and we cannot attribute the enhancement to a particular effect
- other models including multi-nucleonic excitations reproduce the MiniBooNE data
- different models..... indicate that contributions other than direct 1-N emission are important

conclusions....?

before drawing conclusions....

- more data needed, comparison of the results of different models helpful for a deeper understanding, careful evaluation of all nuclear effects is required
- better determination of the phenomenological ROP which closely fulfills dispersion relations
- 2-body MEC not included in the model would require a new model (two-body GF)
- everything should be done consistently in the model