FINAL-STATE INTERACTIONS IN QUASIELASTIC ELECTRON AND NEUTRINO-NUCLEUS SCATTERING: THE RELATIVISTIC GREEN'S FUNCTION MODEL

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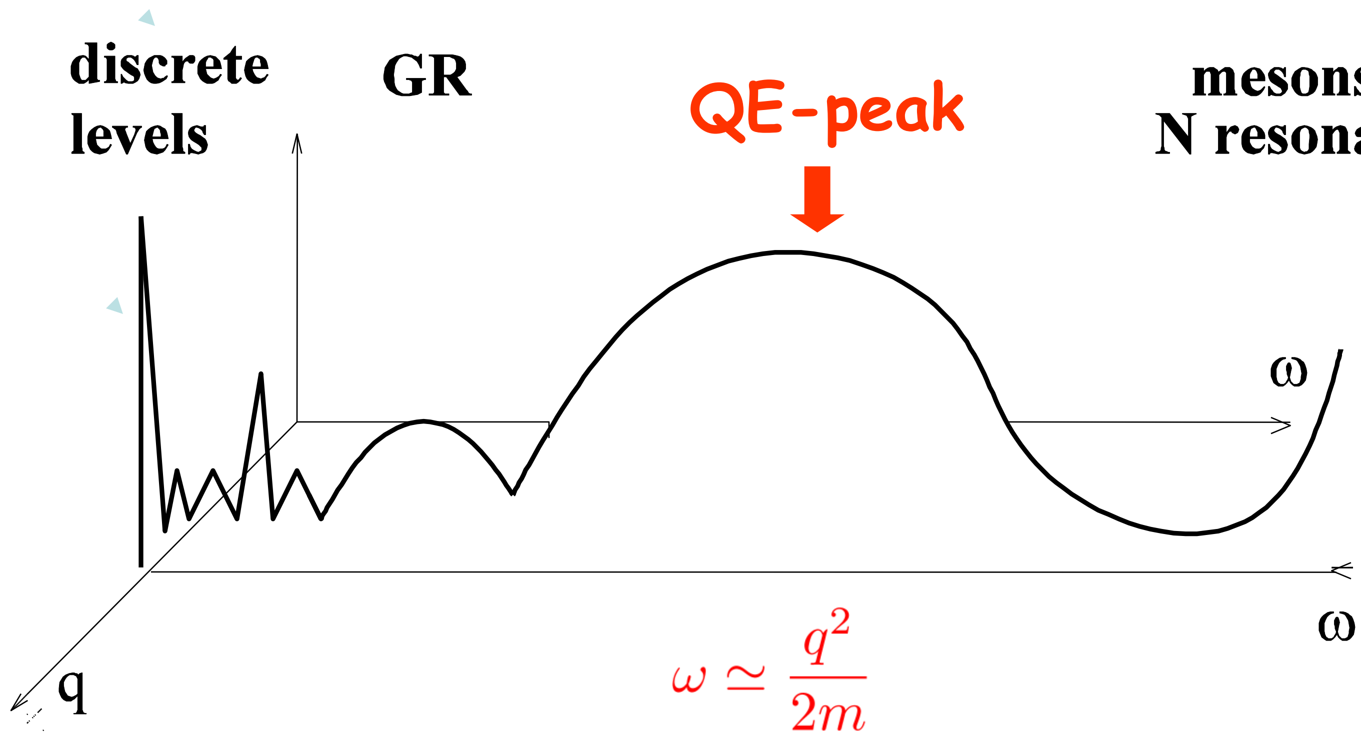
Università and INFN, Pavia

Neutrino-Nucleus Interactions for Current and Next Generation Neutrino Oscillation Experiment

INT-Seattle December 3-13, 2013

nuclear response to the electroweak probe



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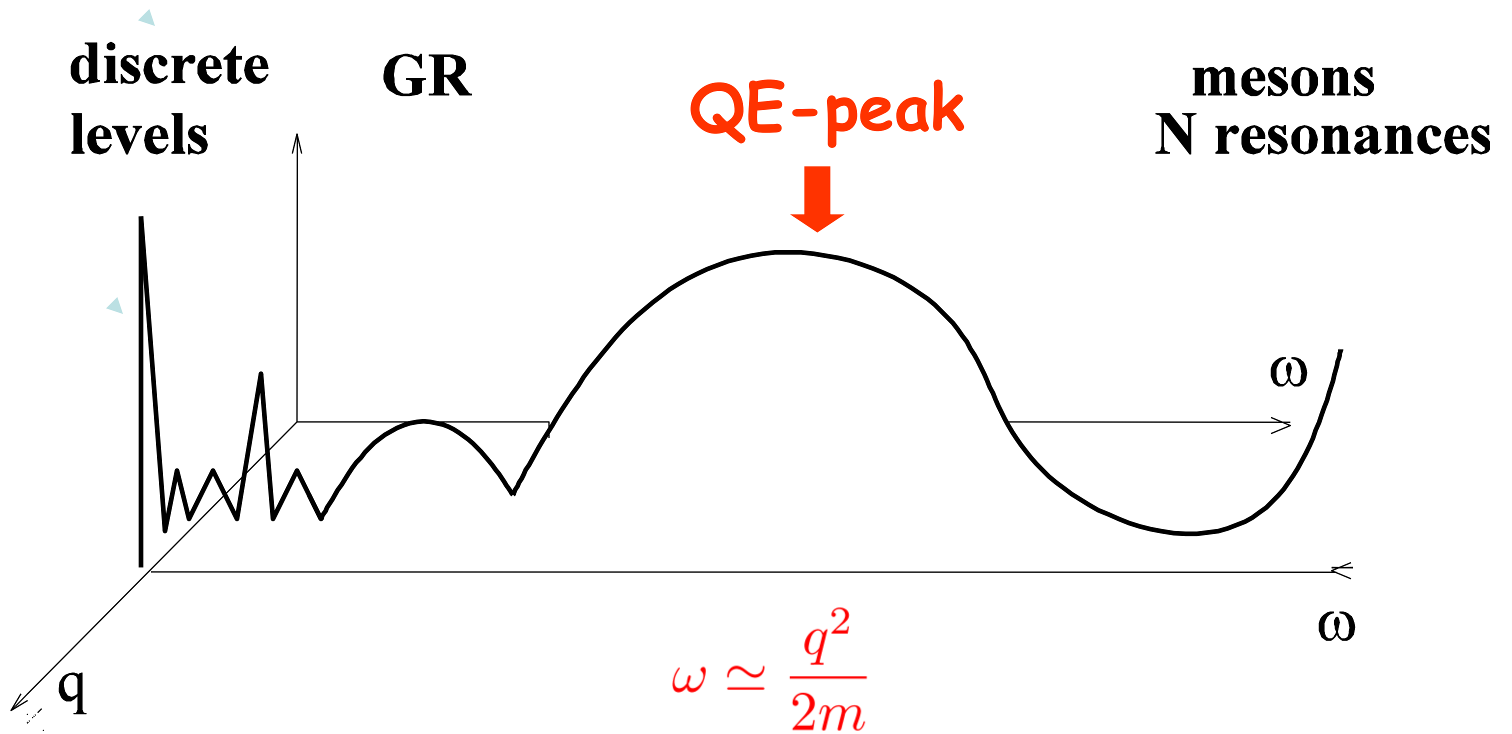

QE-peak dominated by one-nucleon knockout

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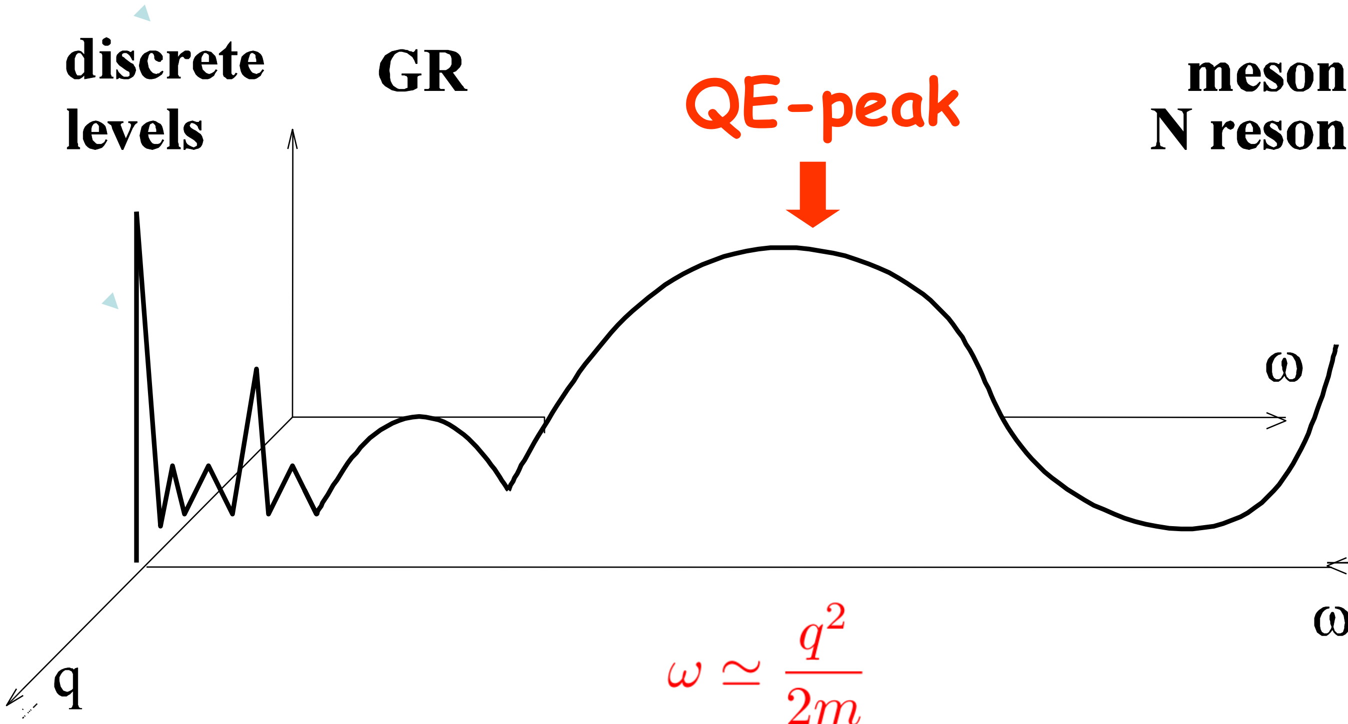

$$\omega \simeq \frac{q^2}{2m}$$

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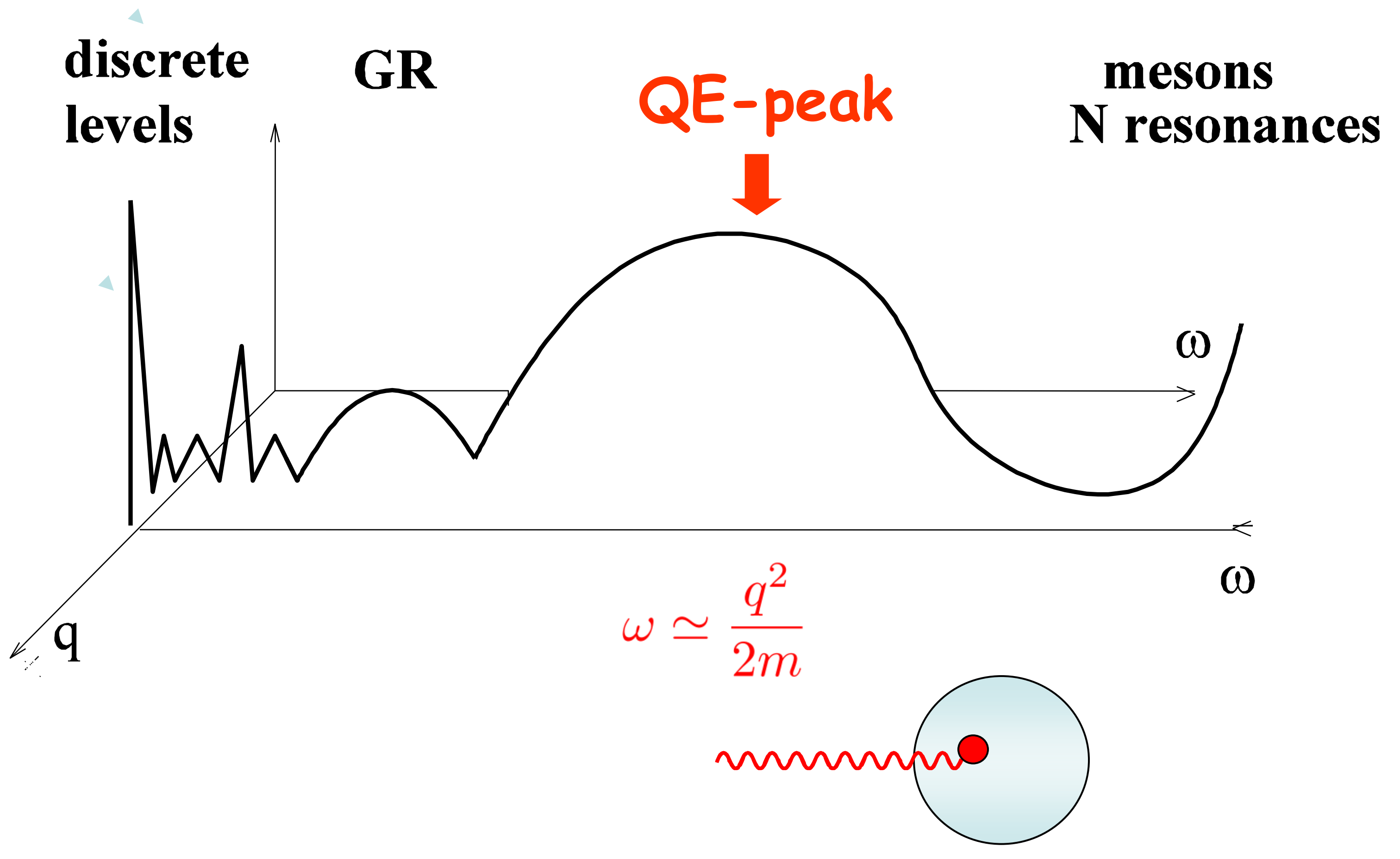

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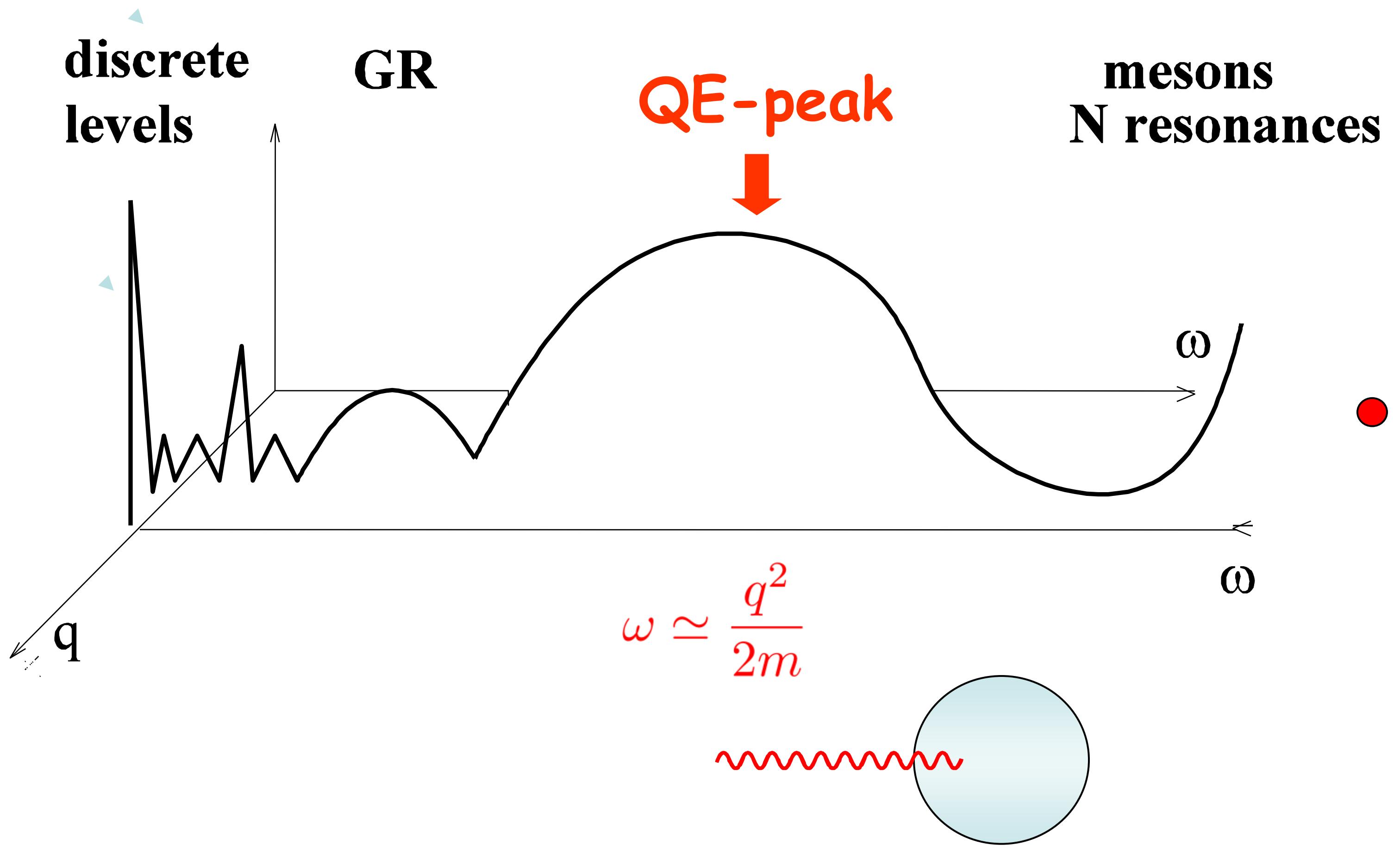

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QE e-nucleus scattering

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

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$$\nu_l(\bar{\nu}_l) + A \Longrightarrow \nu_l(\bar{\nu}_l) + N + (A-1)$$ NC

$$\nu_l(\bar{\nu}_l) + A \Longrightarrow l^-(l^+) + N + (A-1)$$ CC

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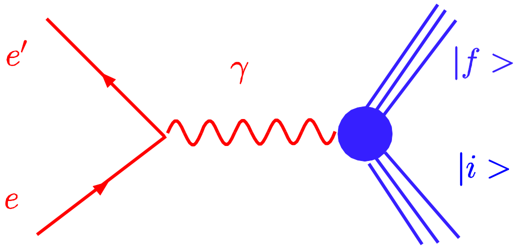
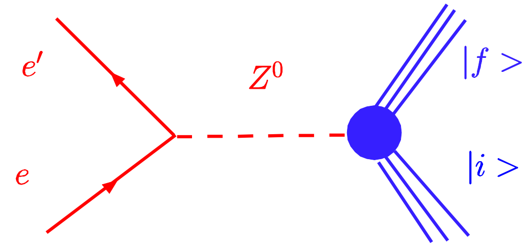
- only N detected semi-inclusive NC and CC
- only final lepton detected inclusive CC

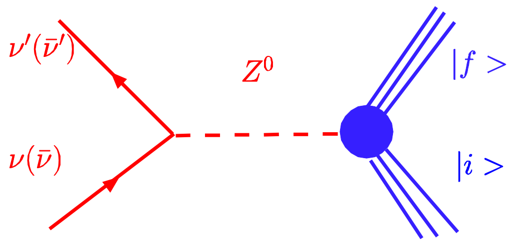
one-boson exchange





PVES

electron scattering



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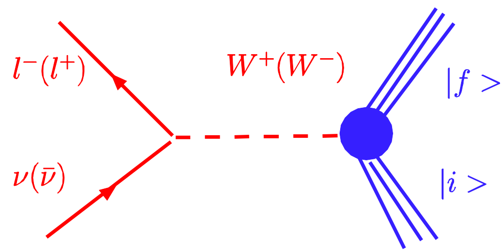

CC

neutrino scattering

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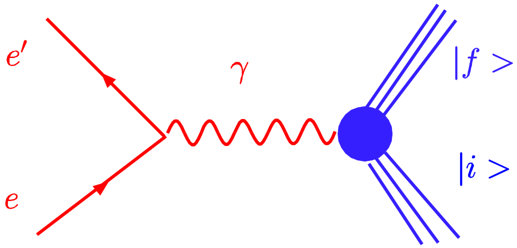

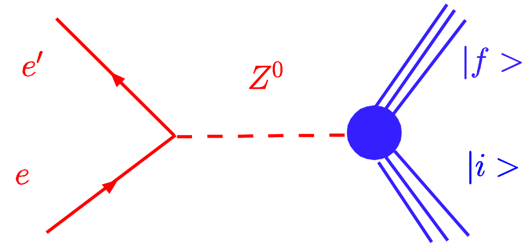

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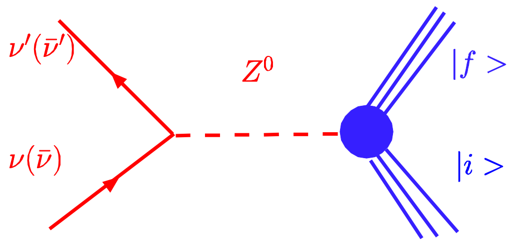

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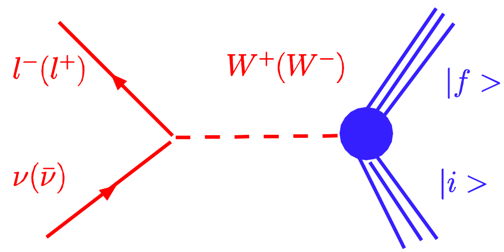
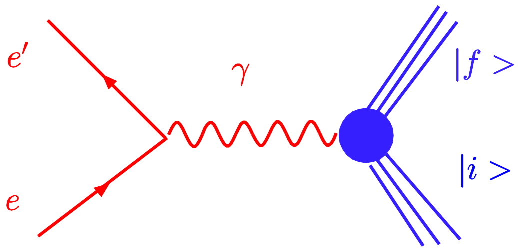
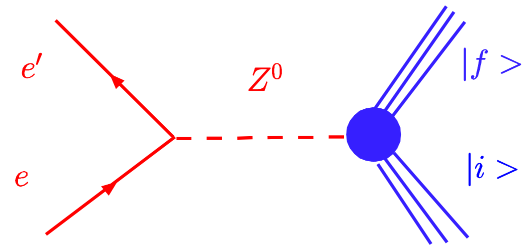


CC

neutrino scattering

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





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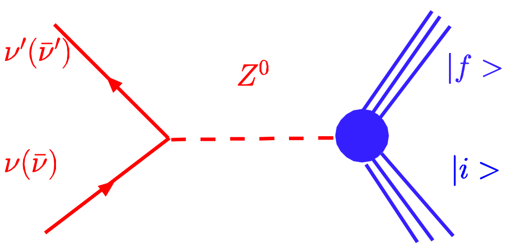

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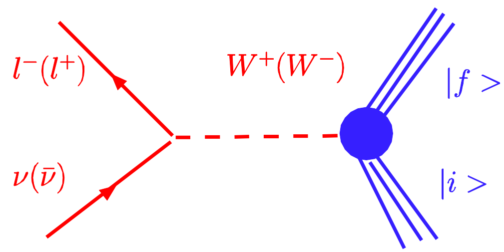


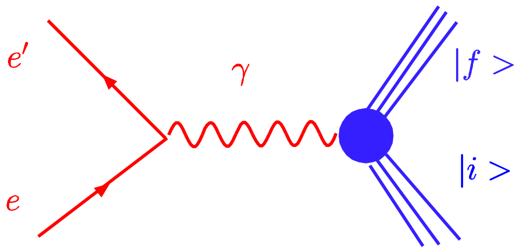
CC

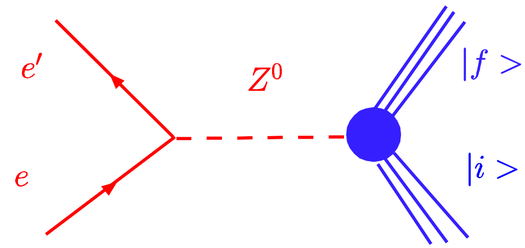
neutrino scattering

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

↓

kin factor





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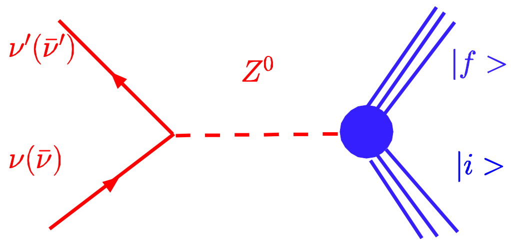

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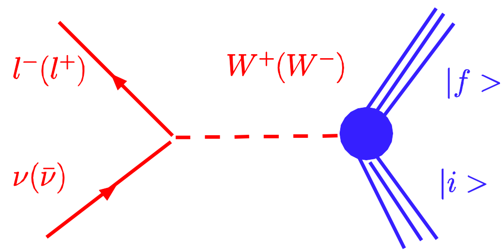

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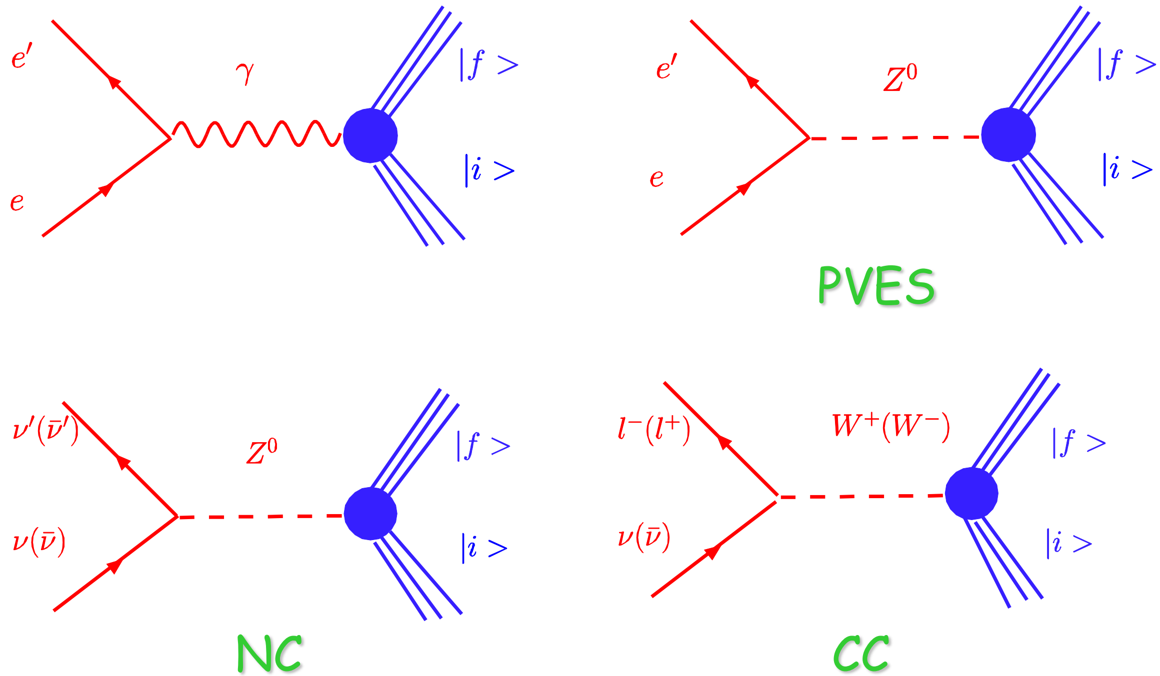
lepton tensor contains lepton kinematics



electron scattering

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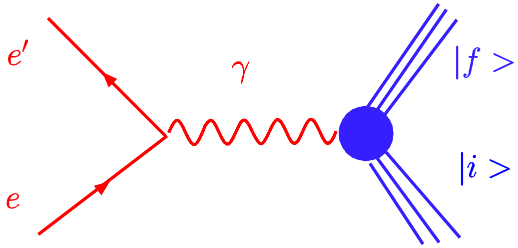
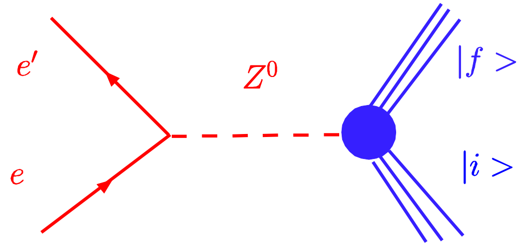
hadron tensor

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

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





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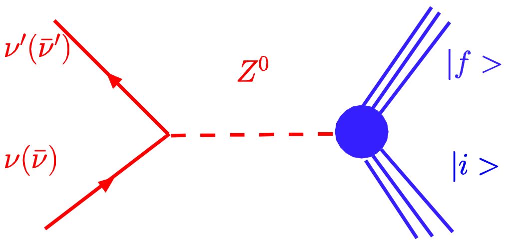

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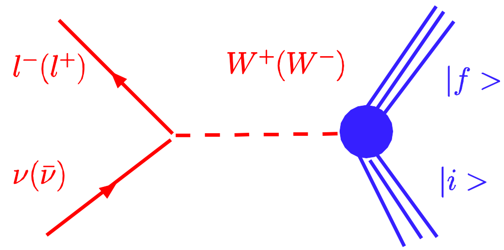

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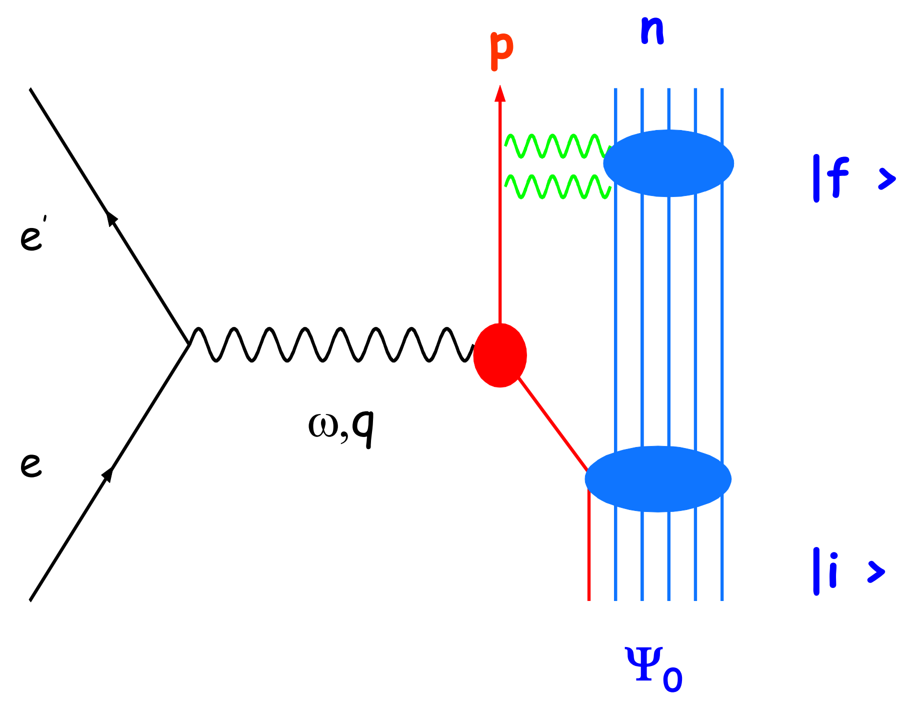
Direct knockout DWIA (e,e′p)

- 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



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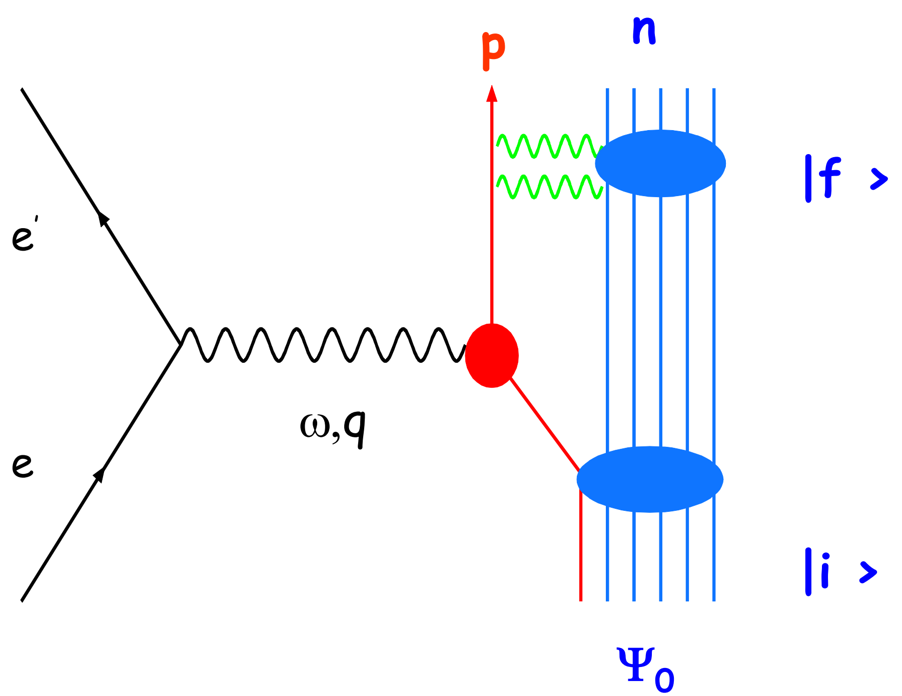

$$\langle f \mid J^\mu(\boldsymbol{q}) \mid i \rangle \Rightarrow \lambda_n^{1/2} \langle \chi_{\boldsymbol{p}}^{(-)} \mid j^\mu(\boldsymbol{q}) \mid \phi_n \rangle$$

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 QUASIELASTIC SCATTERING (e,e')

- only scattered electron detected
- all final nuclear states are included
- in the QE region the main contribution is given by the interaction on single nucleons and direct one-nucleon emission

INCLUSIVE SCATTERING : IMPULSE APPROXIMATION

- IA : c.s given by the sum of integrated direct one-nucleon emission over all the nucleons
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- FSI....?

INCLUSIVE SCATTERING: FSI

RDWIA

sum of 1NKO where FSI are described by a complex OP with an imaginary absorptive part does not conserve the flux

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only the real part of the OP: conserves the flux but it is conceptually wrong

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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

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GREEN'S FUNCTION complex OP conserves the flux
consistent description of FSI in exclusive and inclusive QE electron scattering

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)

A. Meucci, C. Giusti, M. Vorabbi, PRD 88 (2013) 013006

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

R. Gonzalez-Jimenez, J.A. Caballero,, A. Meucci, C. Giusti, M.B. Barbaro, M.V. Ivanov, J.M. Udias PRC 88 (2013) 02502

FSI for the inclusive scattering : Green's Function Model

- the components of the inclusive response are expressed in terms of the Green's function the full A-body propagator
- with 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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$$T_n^{\mu\mu}(\mathcal{E}, E) = \lambda_n \langle \varphi_n \mid j^{\mu\dagger}(\boldsymbol{q}) \sqrt{1 - \mathcal{V}'(E)} \mid \tilde{\chi}_{\mathcal{E}}^{(-)}(E) \rangle \langle \chi_{\mathcal{E}}^{(-)}(E) \mid \sqrt{1 - \mathcal{V}'(E)} j^{\mu}(\boldsymbol{q}) \mid \varphi_n \rangle$$

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interference between different channels

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eigenfunctions of V and V^+

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loss of flux

FSI for the inclusive scattering : Green's Function Model

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

$$T_n^{\mu\mu}(\mathcal{E},E) = \lambda_n \langle \varphi_n \mid j^{\mu\dagger}(\boldsymbol{q}) \sqrt{1-\mathcal{V}'(E)} \mid \tilde{\chi}_{\mathcal{E}}^{(-)}(E)\rangle\langle \chi_{\mathcal{E}}^{(-)}(E) \mid \sqrt{1-\mathcal{V}'(E)} j^{\mu}(\boldsymbol{q}) \mid \varphi_n \rangle$$

gain of flux

loss of flux

FSI for the inclusive scattering : Green's Function Model

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

$$T_n^{\mu\mu}(\mathcal{E},E) = \lambda_n \langle \varphi_n \mid j^{\mu\dagger}(\boldsymbol{q})\sqrt{1-\mathcal{V}'(E)} \mid \tilde{\chi}_{\mathcal{E}}^{(-)}(E)\rangle\langle\chi_{\mathcal{E}}^{(-)}(E) \mid \sqrt{1-\mathcal{V}'(E)}\, j^{\mu}(\boldsymbol{q}) \mid \varphi_n \rangle$$

gain of flux

loss of flux

Flux redistributed and conserved

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

FSI for the inclusive scattering : Green's Function Model

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

$$T_n^{\mu\mu}(\mathcal{E},E) = \lambda_n \langle \varphi_n \mid j^{\mu\dagger}(\boldsymbol{q})\sqrt{1-\mathcal{V}'(E)} \mid \tilde{\chi}_{\mathcal{E}}^{(-)}(E)\rangle\langle\chi_{\mathcal{E}}^{(-)}(E)\mid \sqrt{1-\mathcal{V}'(E)} j^{\mu}(\boldsymbol{q}) \mid \varphi_n\rangle$$

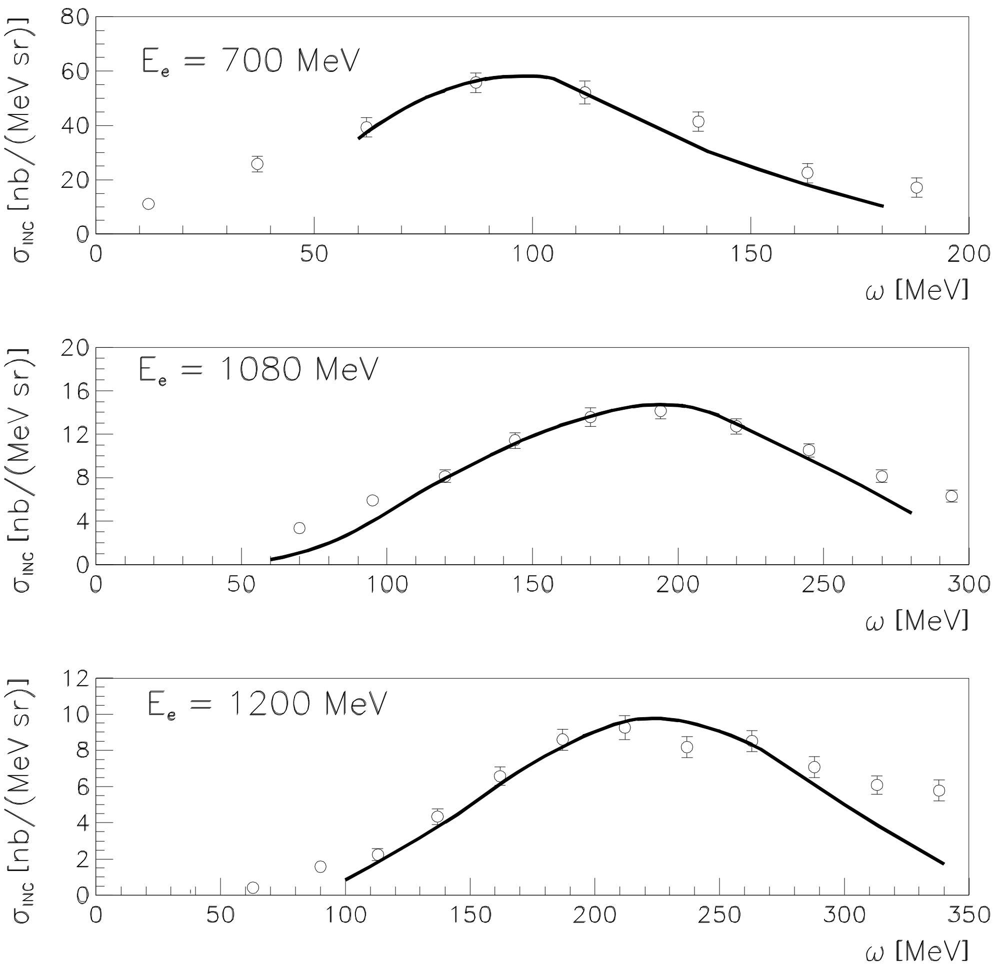
gain of flux

loss of flux

For a real optical potential V=V⁺ the second term vanishes and the nuclear response is given by the sum of all the integrated one-nucleon knockout processes (without absorption)

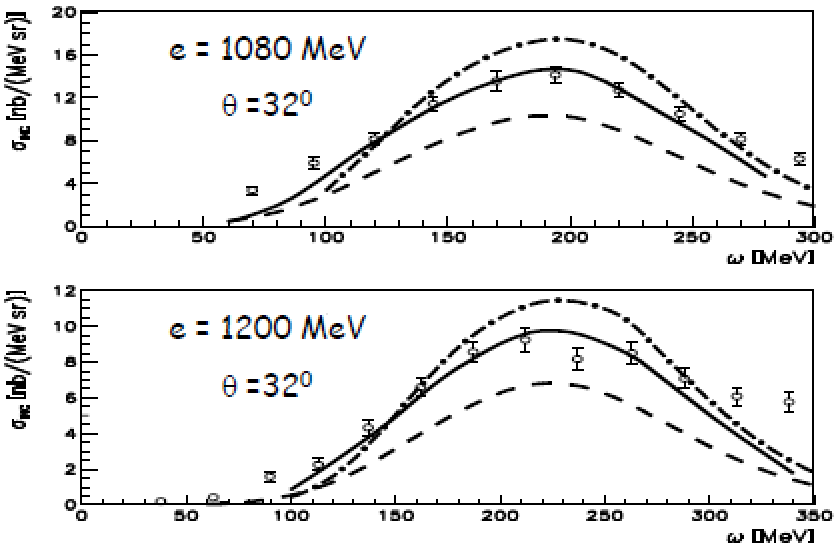
$^{16}O(e,e')$

RGF



data from Frascati NPA 602 405 (1996)

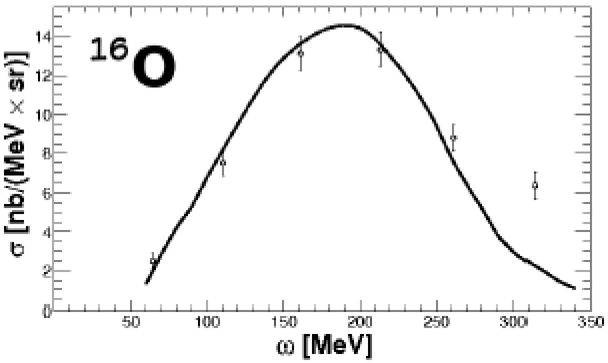
$^{16}O(e,e')$



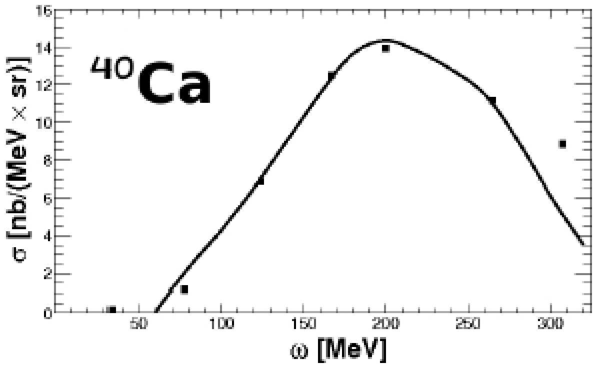
data from Frascati NPA 602 405 (1996)

(e,e')

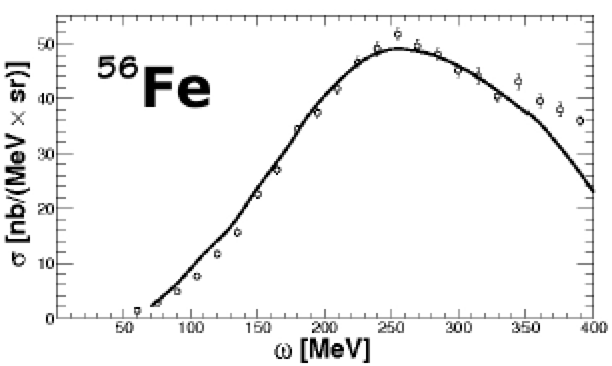
RGF



E_0 = 1080 MeV ϑ = 32°



E_0 = 841 MeV ϑ = 45.5°



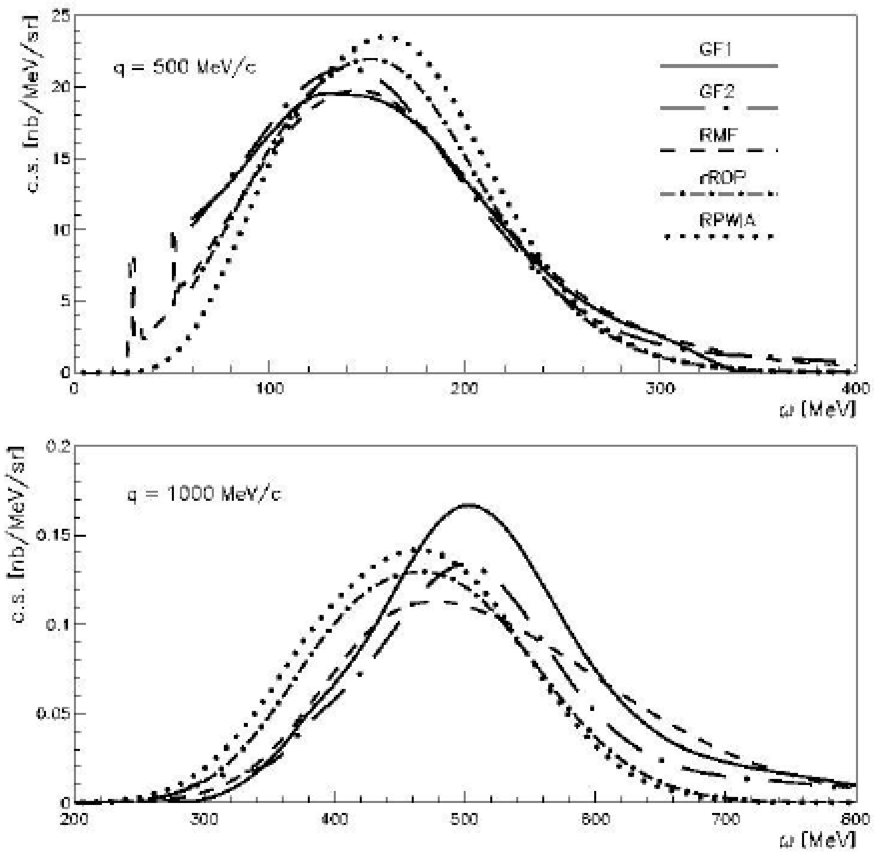
E_0 = 2020 MeV ϑ = 20°

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

comparison of relativistic models

E_0 = 1 GeV

FSI



q=500 MeV/c

q=1000 MeV/c

RPWIA

rROP

RGF1

RGF2

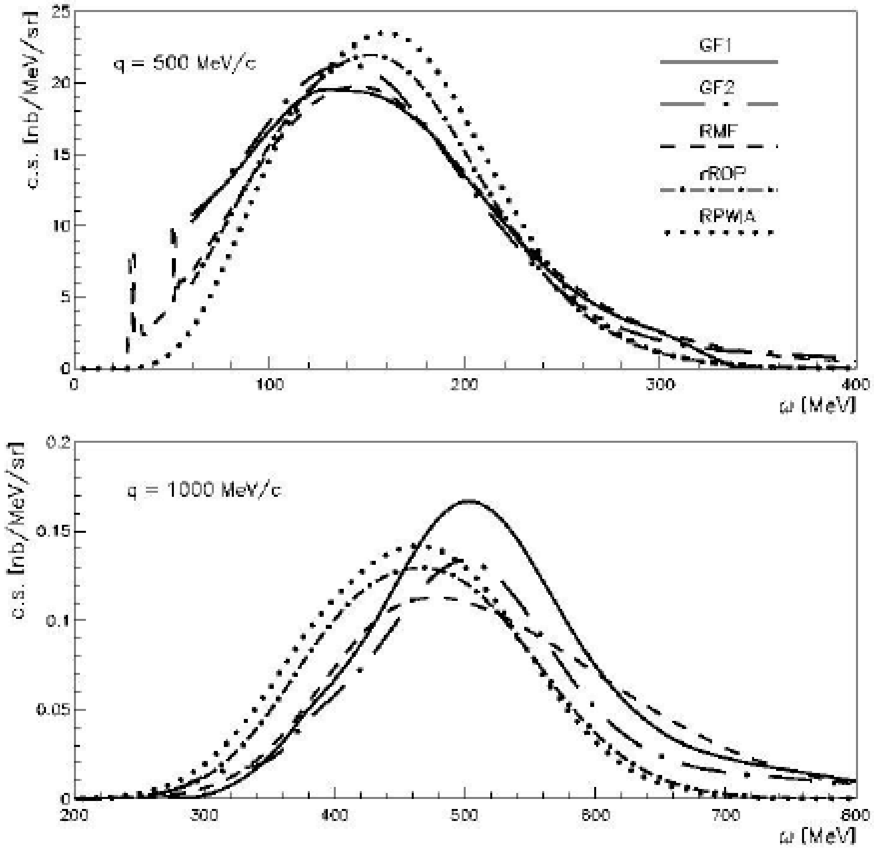
RMF

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

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

comparison of relativistic models

E_0 = 1 GeV



q=500 MeV/c

q=1000 MeV/c

FSI

RPWIA

rROP

RGF1 ←

RGF2 ←

RMF

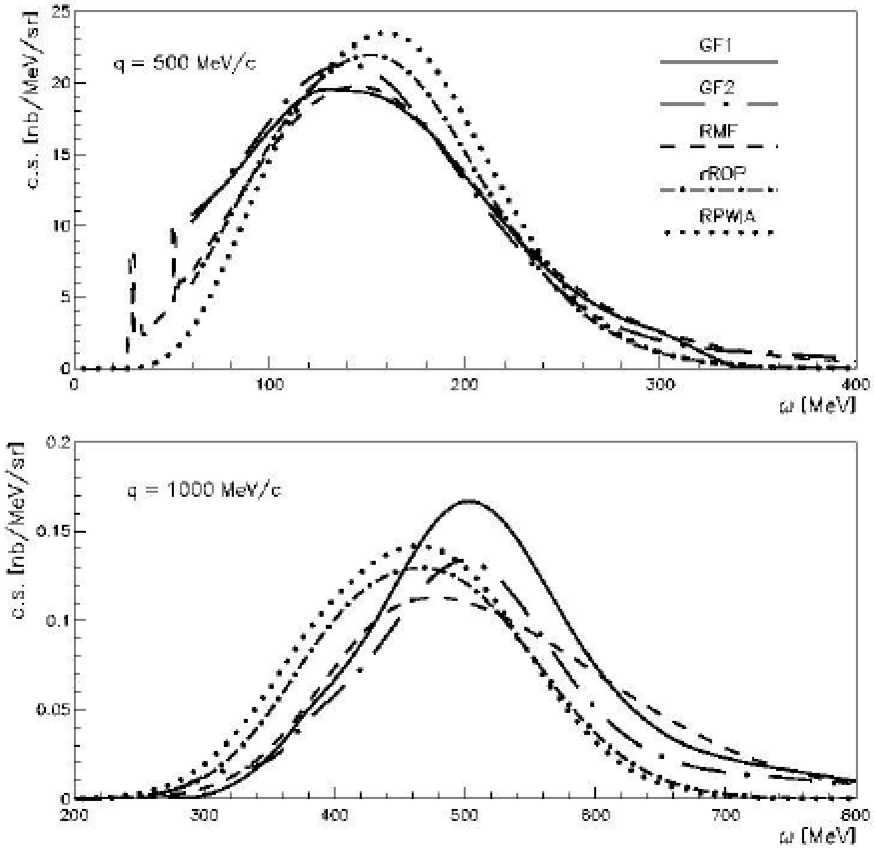
different parameterization of the optical potential: EDAD1 EDAD2

A. Meucci, J.A. Caballero, C. Giusti, F.D. Pa

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

comparison of relativistic models

E_0 = 1 GeV



q=500 MeV/c

q=1000 MeV/c

FSI

RPWIA

rROP

RGF1

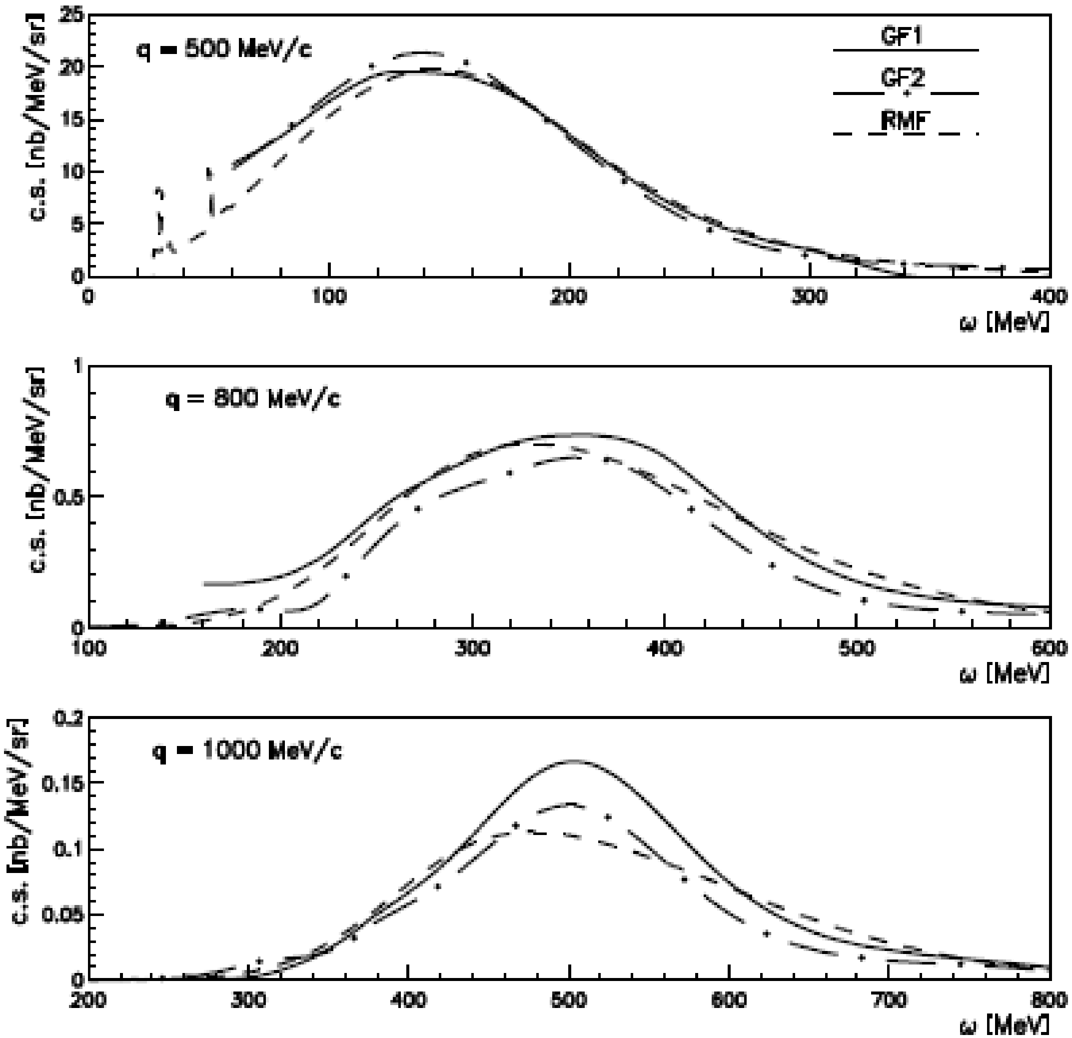
RGF2

RMF

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

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

comparison of relativistic models



FSI

q=500 MeV/c

q=800 MeV/c

q=1000 MeV/c

RGF1

RGF2

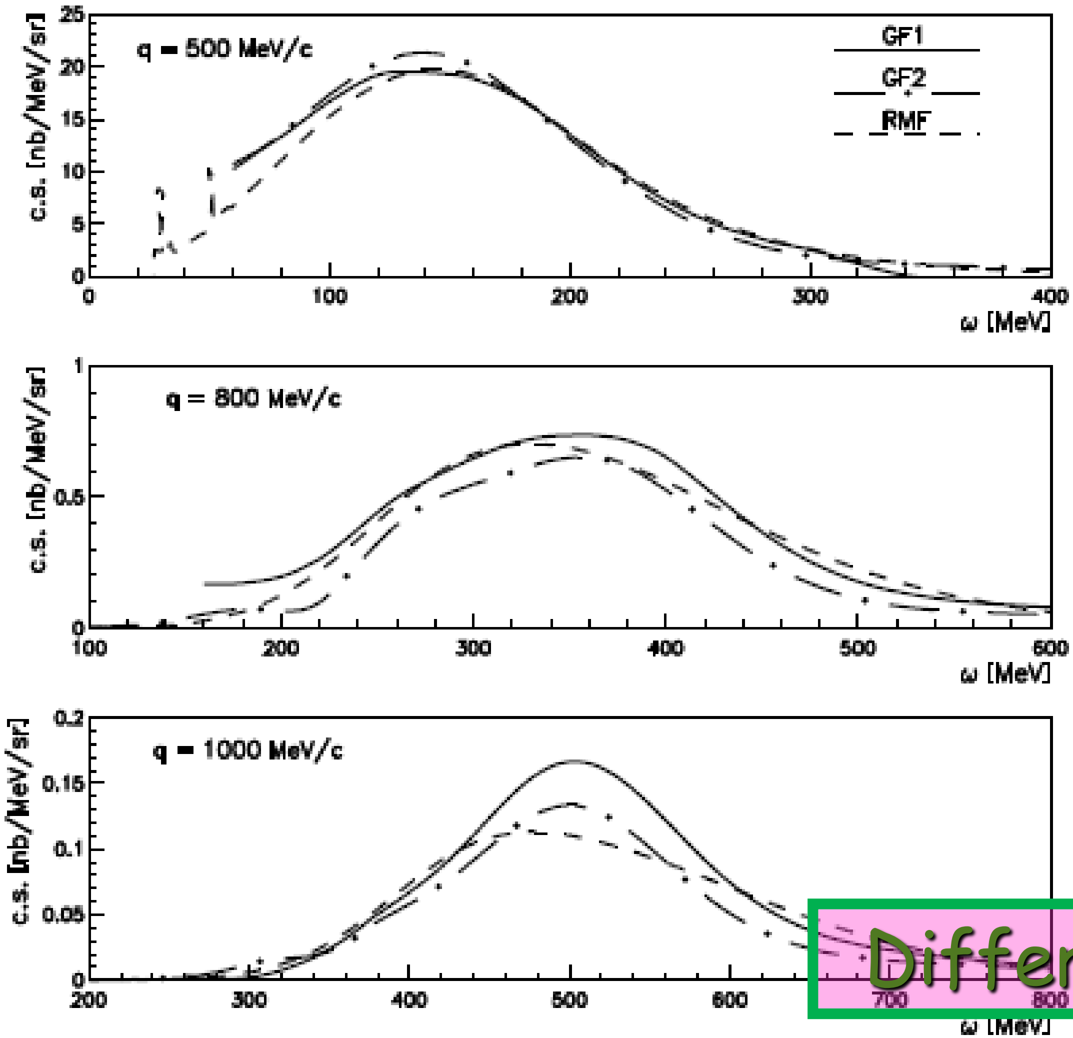
RMF

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

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

comparison of relativistic models

FSI



q=500 MeV/c

q=800 MeV/c

q=1000 MeV/c

RGF1

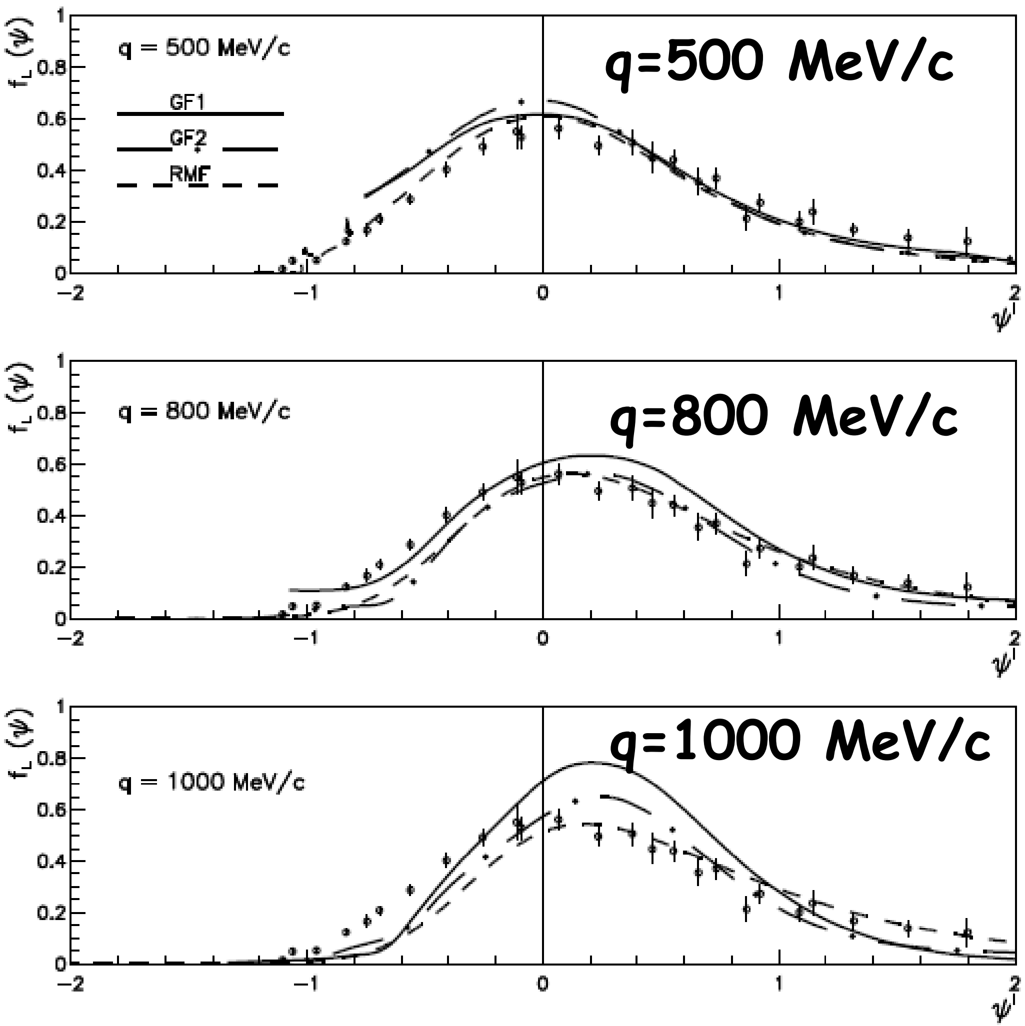
RGF2

RMF

Differences increase with q

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

QE SCALING FUNCTION: RGF, RMF



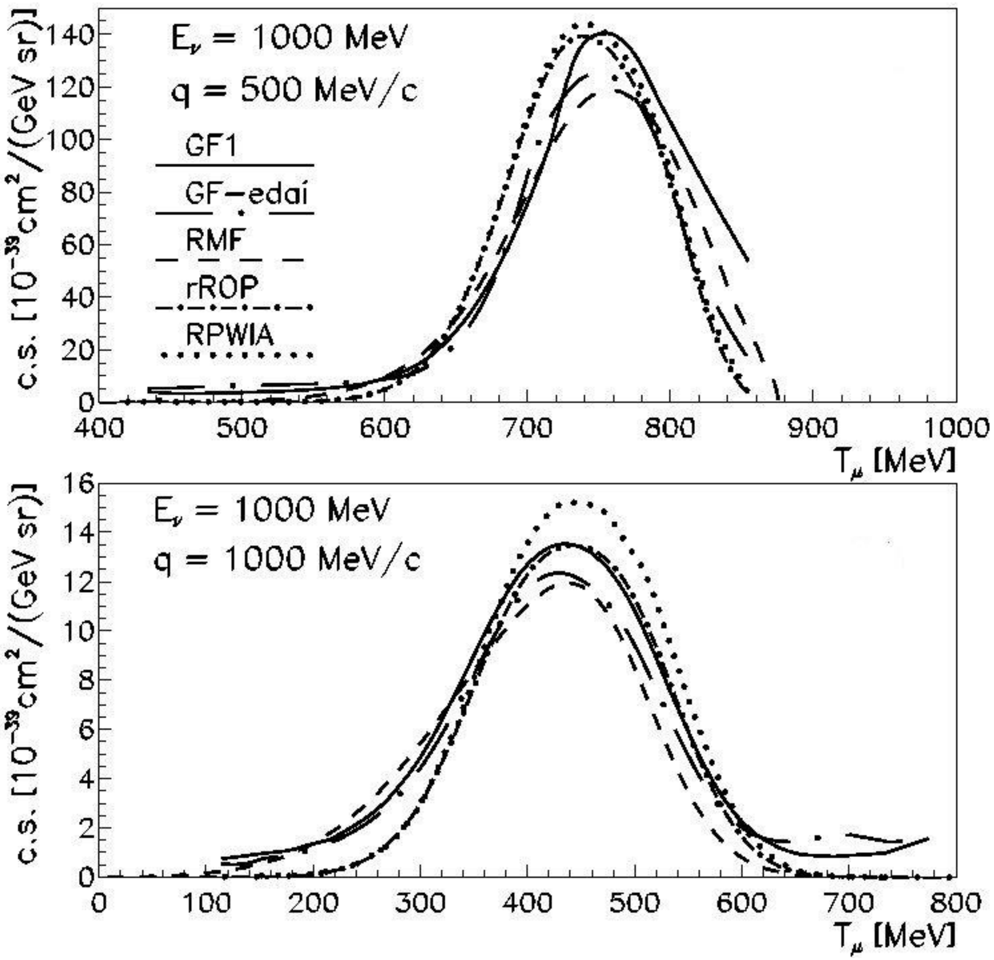
asymmetric shape

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

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

comparison of relativistic models

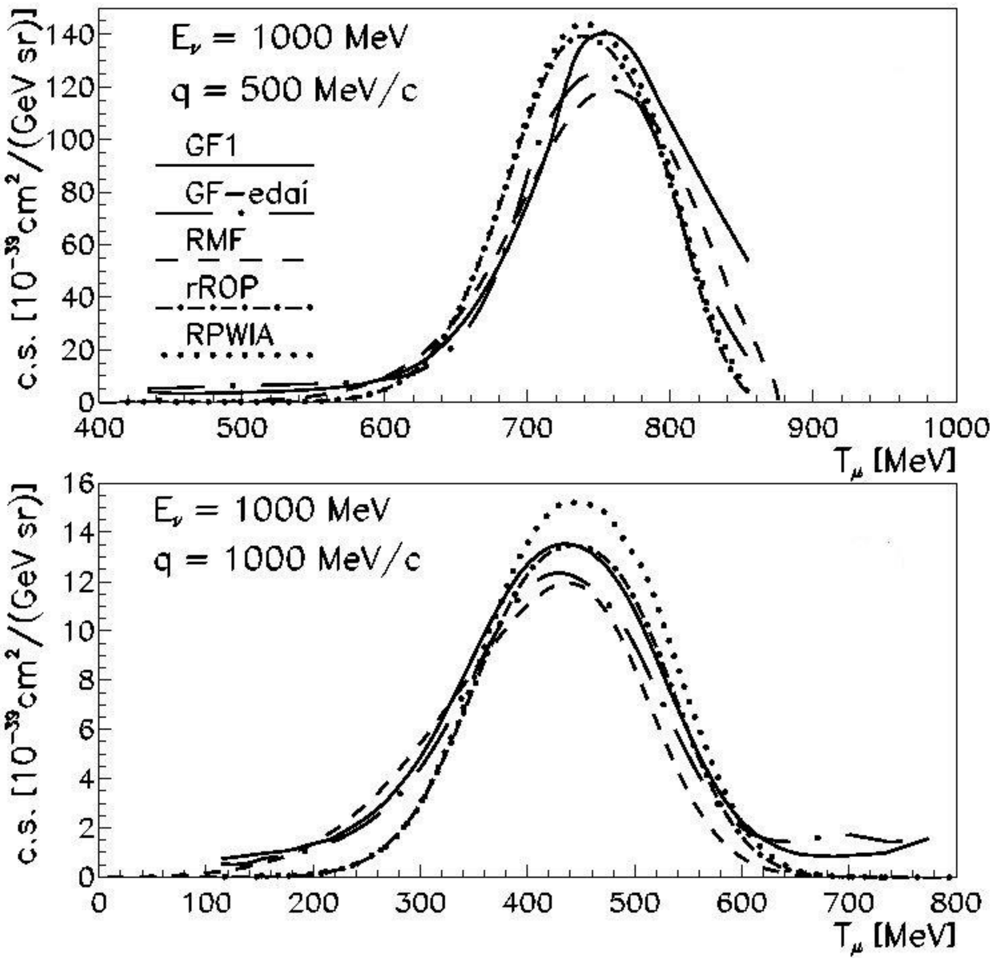
FSI



A. Meucci, J.A. Caballero, C. Giusti, F.D. Pacati, J.M. Udias PRC 83 (2011) 064614

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

comparison of relativistic models



FSI

RPWIA

rROP

RGF1

RGF-EDAI

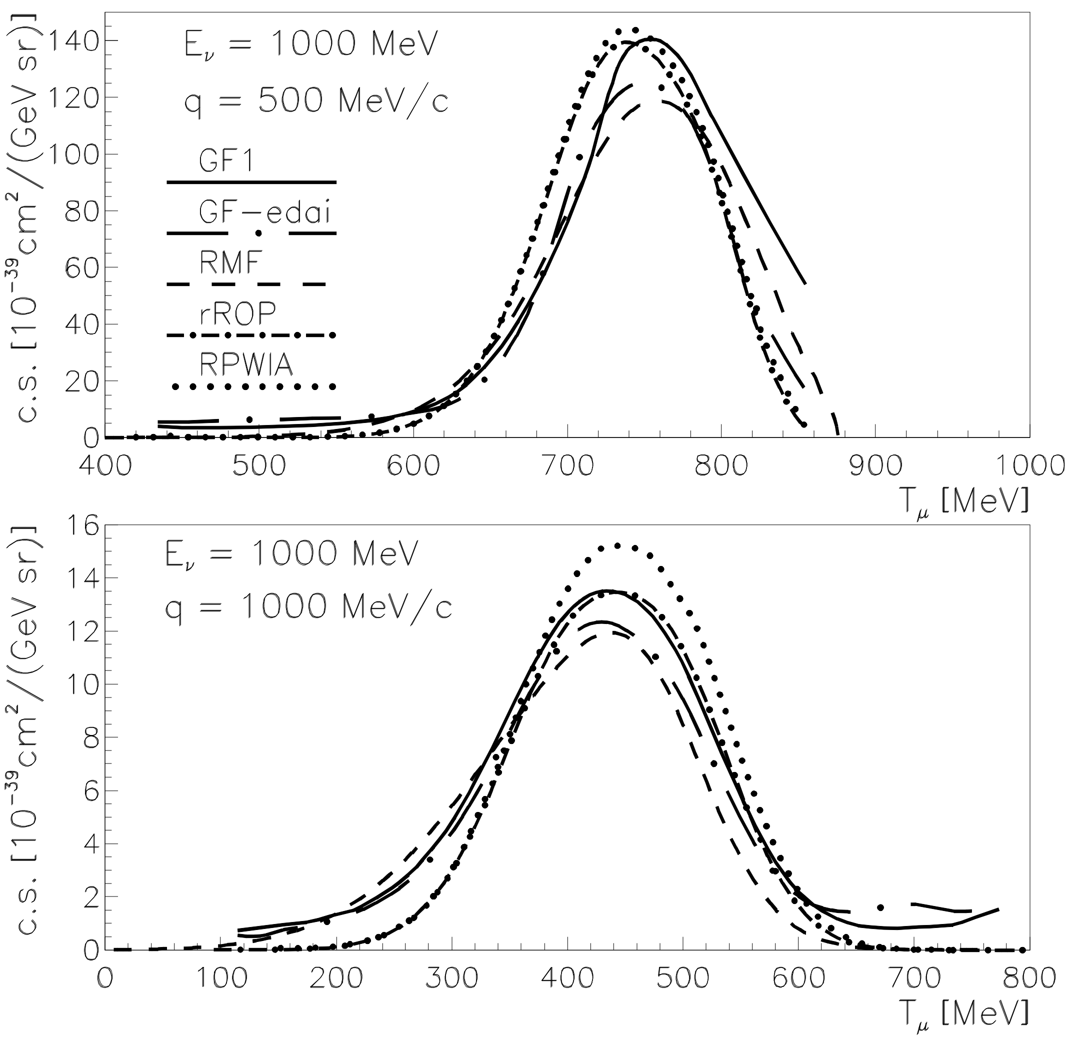
RMF

electron and neutrino scattering: different results

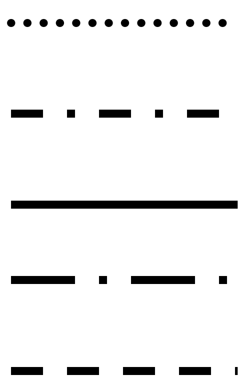
A. Meucci, J.A. Caballero, C. Giusti, F.D. Pacati, J.M. Udias PRC 83 (2011) 064614

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

comparison of relativistic models



FSI



EDAI A-independent for ^{12}C

DIFFERENT DESCRIPTIONS OF FSI

RMF

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

RGF

complex energy-dependent phen. ROP fitted to elastic p-A scattering, incorporates information from scattering reactions

the imaginary part includes the overall effect of inelastic channels not included in other models based on the IA, (multinucleon, rescattering, non nucleonic).

Contributions of inelastic channels not included microscopically but recovered in the model by the Im part of the ROP, not univocally determined only from elastic phenomenology

different ROP reproduce elastic p-A scatt. can give different predictions for non elastic observables

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

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

Comparison with MiniBooNe CCQE data

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

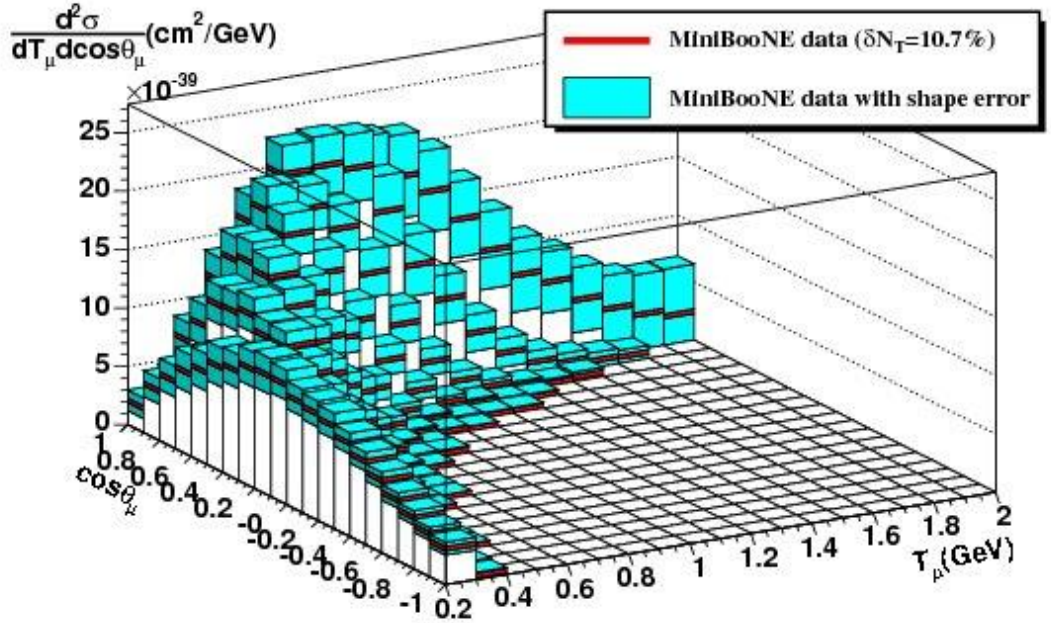
$$\nu_\mu + {}^{12}\mathrm{C} \longrightarrow \mu^- + \mathrm{X}$$

⇓

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

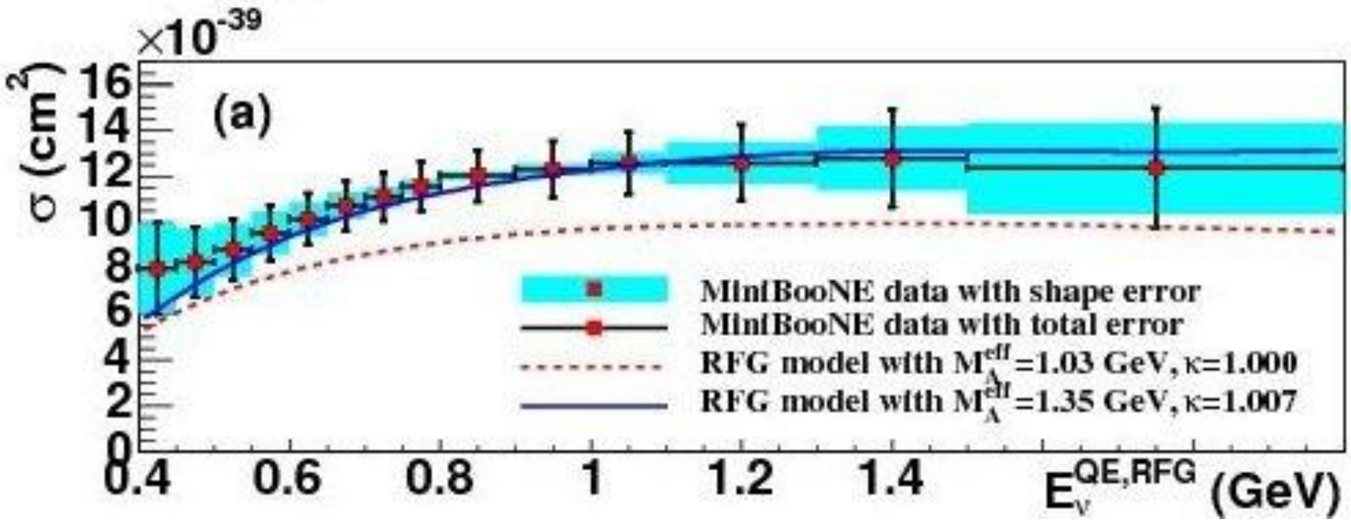
Unusually large values of the nucleon axial mass must be used to reproduce the data (about 30% larger)

MiniBooNe CCQE data



flux integrated double differential cross section

M_A = 1.35 GeV



flux unfolded ν_μ CCQE cross section per neutron as a function of E_ν compared with predictions of a RFG model

A.A Aguilar-Arevalo et al. PRD PRC 81 (2010) 092005

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

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

FSI

Differences between Electron and Neutrino Scattering

- electron scattering :

  beam energy known, ω and q known. cross section as a function of ω

- neutrino scattering:

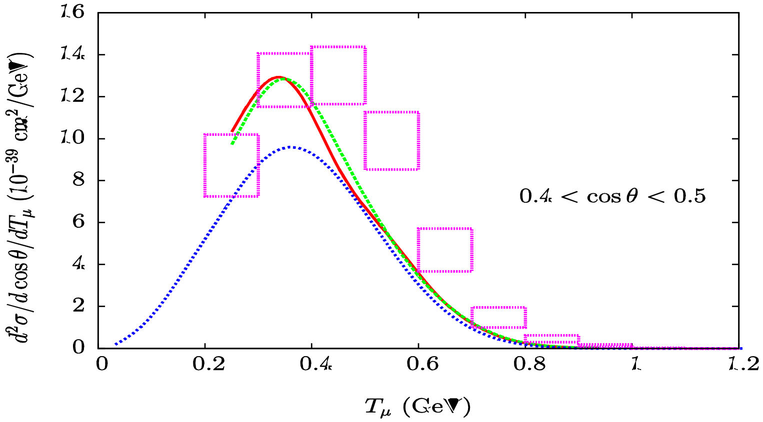
  axial current

  beam energy and ω not known

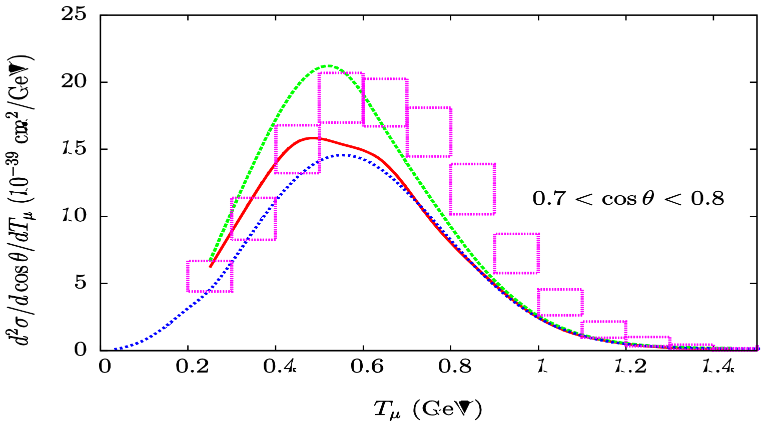
  calculations over the energy range relevant for the neutrino flux

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

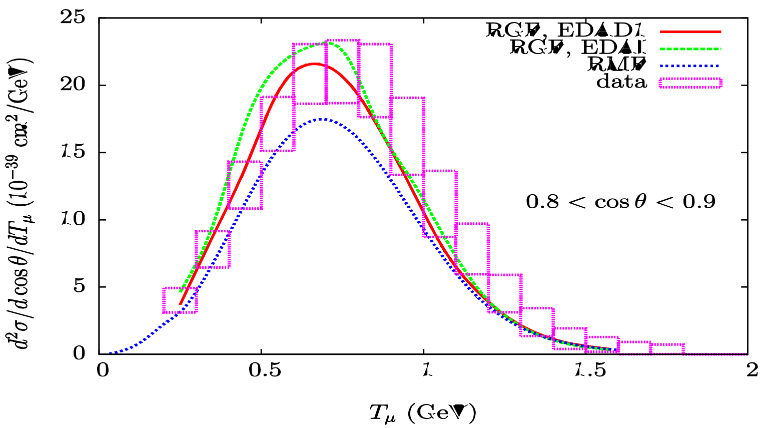
Comparison with MiniBooNe CCQE data



$0.4 < cos\theta_\mu < 0.5$



$0.7 < cos\theta_\mu < 0.8$



$0.8 < cos\theta_\mu < 0.9$

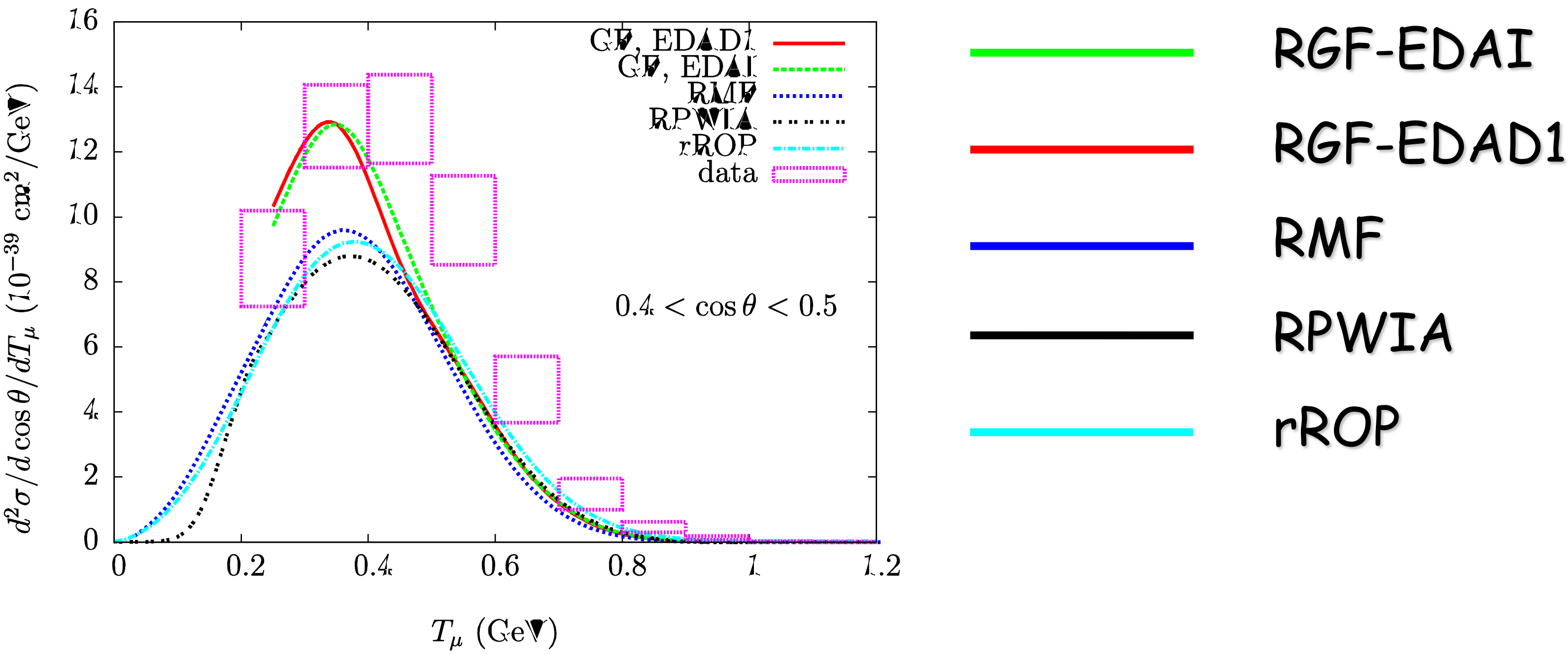
RGF-EDAI

RGF-EDAD1

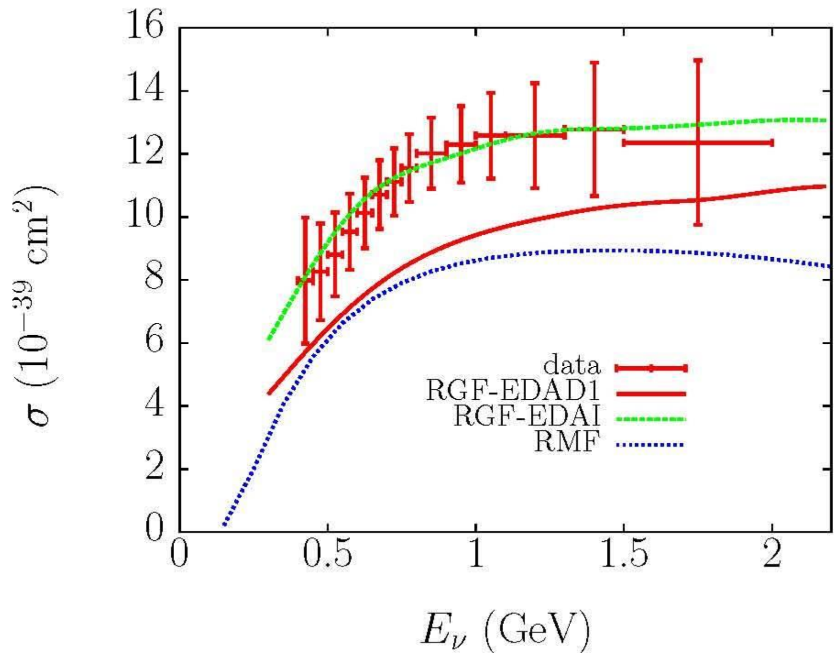
RMF

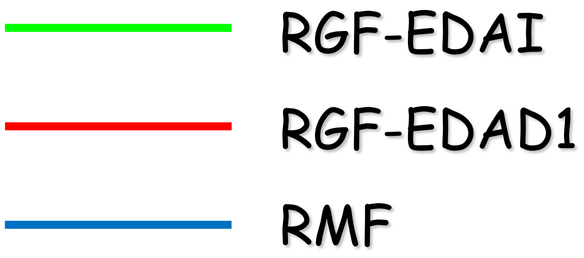
Comparison with MiniBooNe CCQE data

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



Comparison with MiniBooNe CCQE data



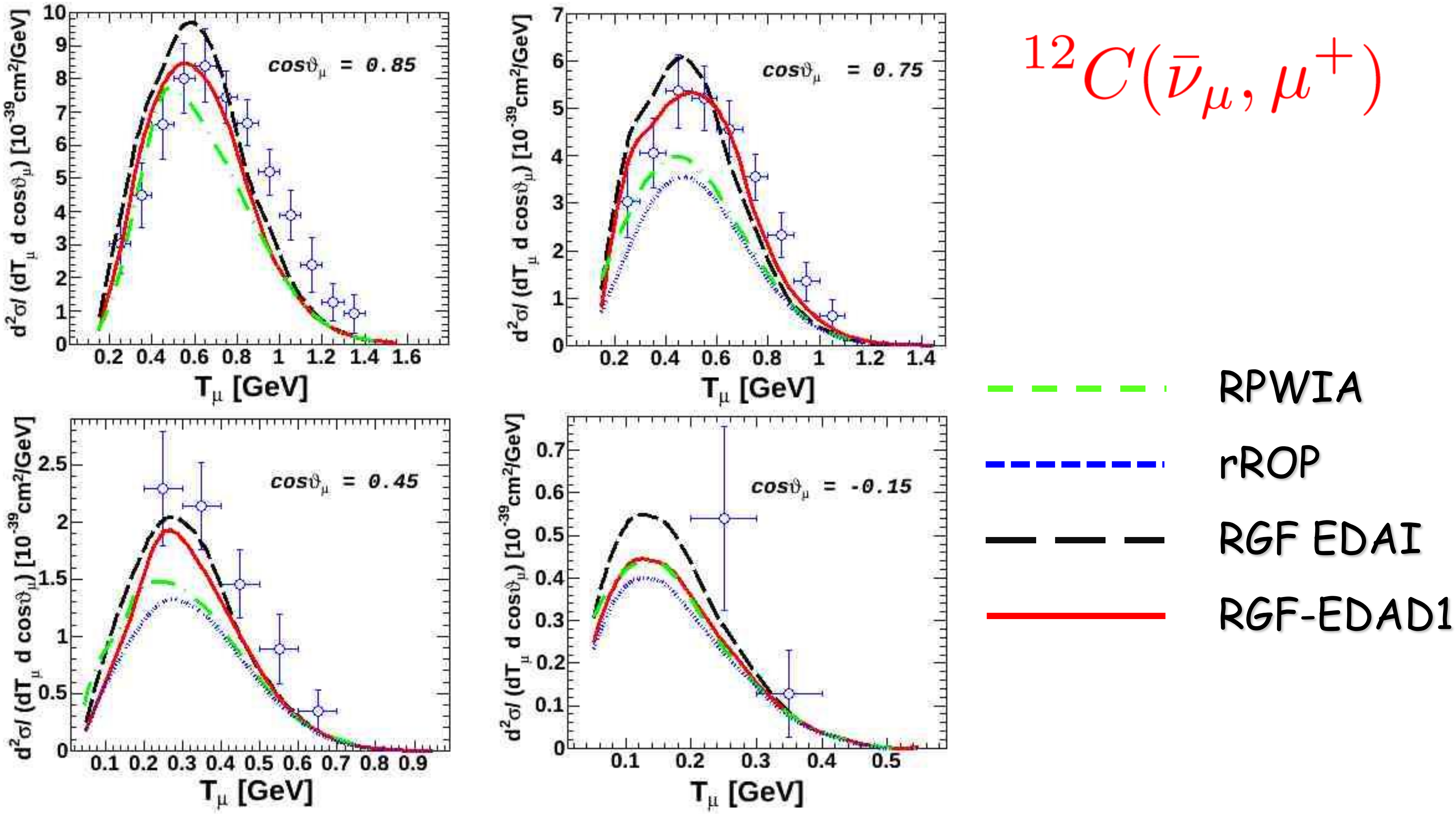


CCQE antineutrino-nucleus scattering

- The MiniBooNE collaboration has measured CCQE $\bar{\nu}$ events
A.A. Aguilar-Arevalo et al. arXiv:1301.7067 [hep-ex]
- 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

CCQE antineutrino scattering

$^{12}C(\bar{\nu}_{\mu}, \mu^{+})$



Comparison with MiniBooNE NCE data

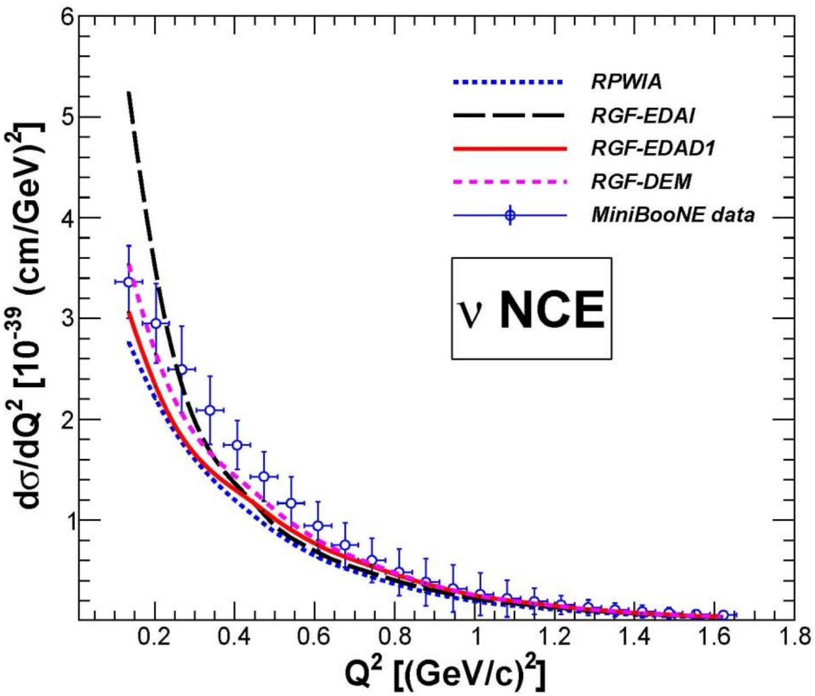
Measurement of the flux averaged neutral-current elastic (NCE) differential cross section on CH_2 as a function of Q^2
PRD 82 092005 (2010)

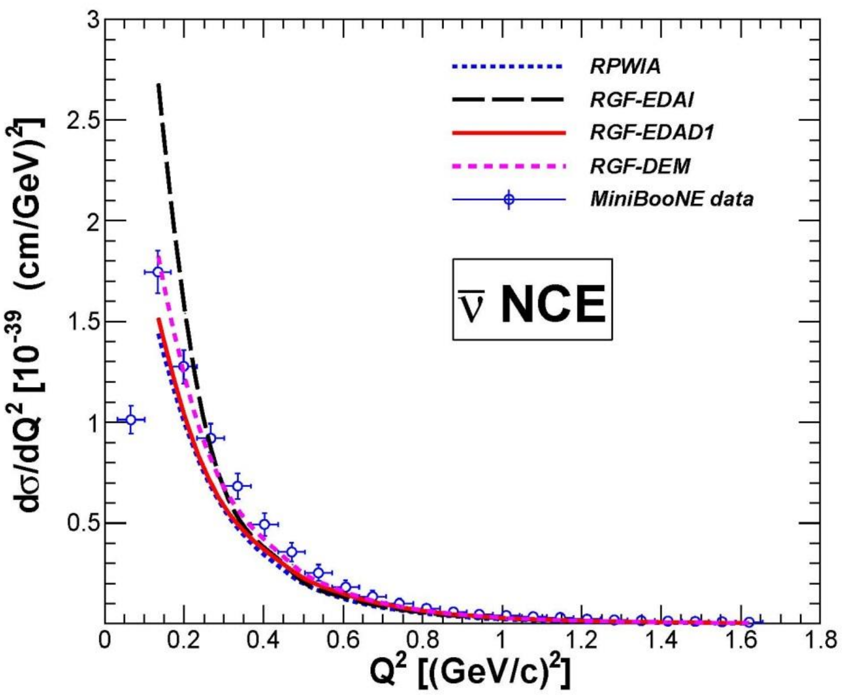
The NCE cross section presented as scattering from individual nucleons and consists of 3 different processes: scattering of free protons in H, bound protons and neutrons in C

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





QE ν-nucleus scattering

- models developed for QE electron-nucleus scattering 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…. effects beyond IA

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
- reduce theoretical uncertainties
- RGF 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-particle GF)
- everything should be done consistently in the model