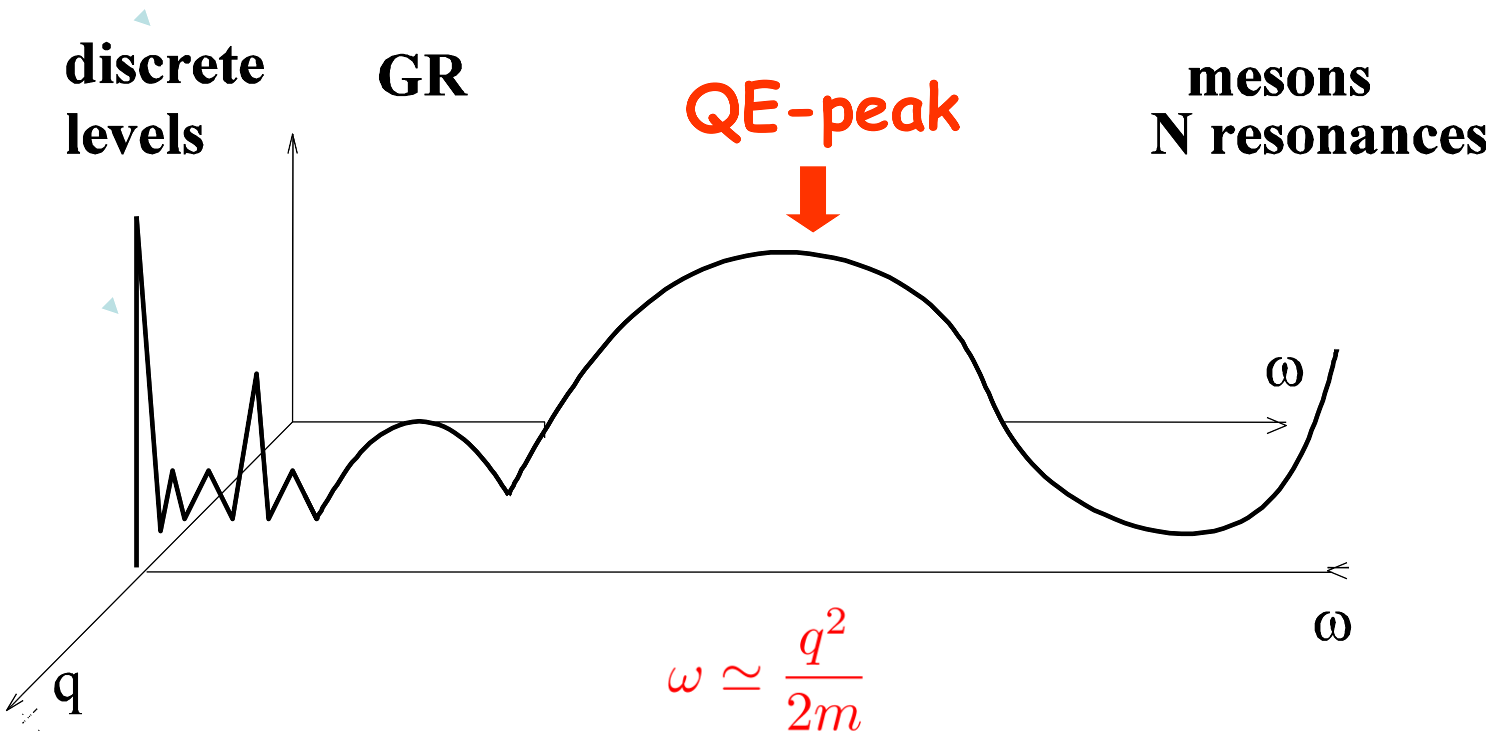
RELATIVISTIC MODELS IN QUASIELASTIC ELECTRON AND NEUTRINO-NUCLEUS SCATTERING

Carlotta Giusti
Università and INFN, Pavia

What Next: sezioni d'urto dei neutrini , Bologna 9-10 novembre 2015

nuclear response to the electroweak probe



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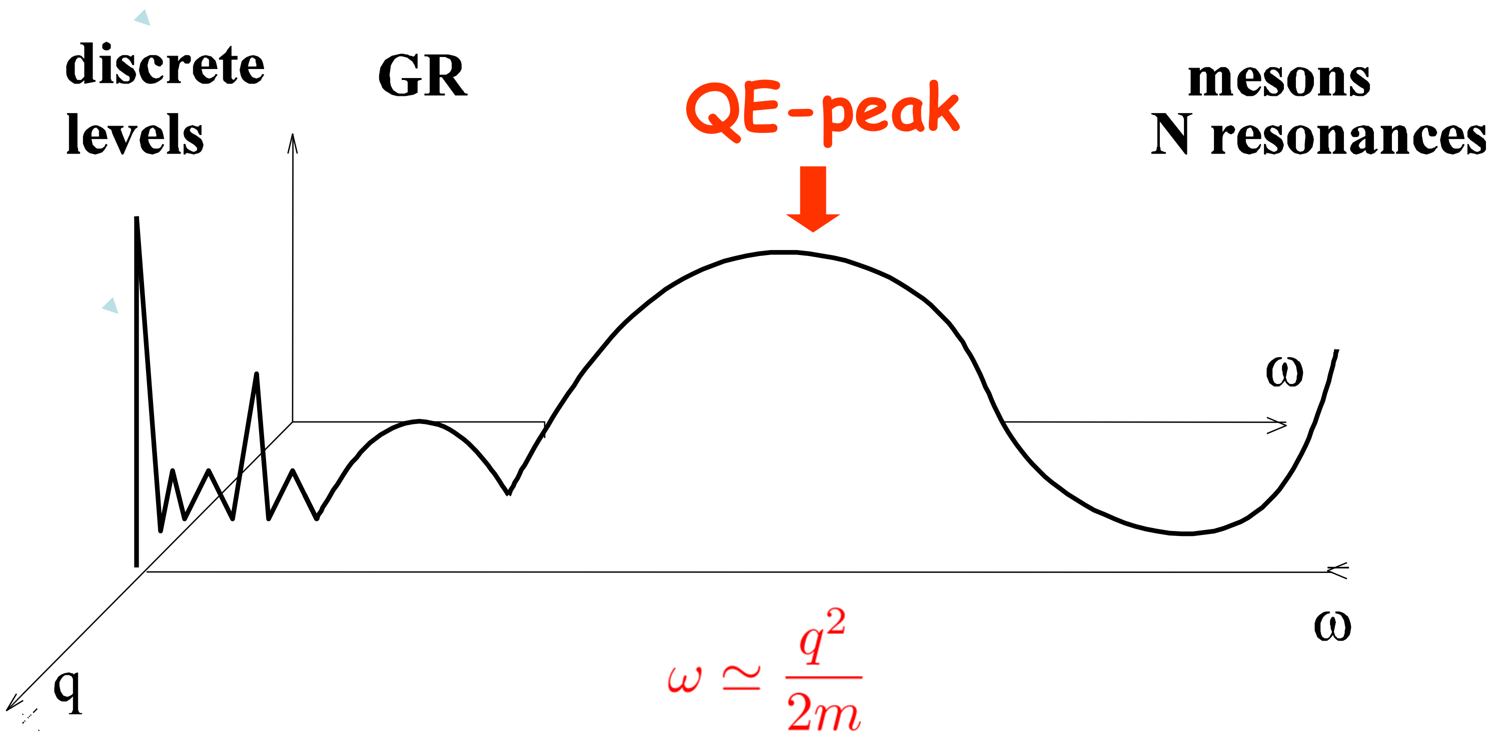

QE-peak dominated by one-nucleon knockout

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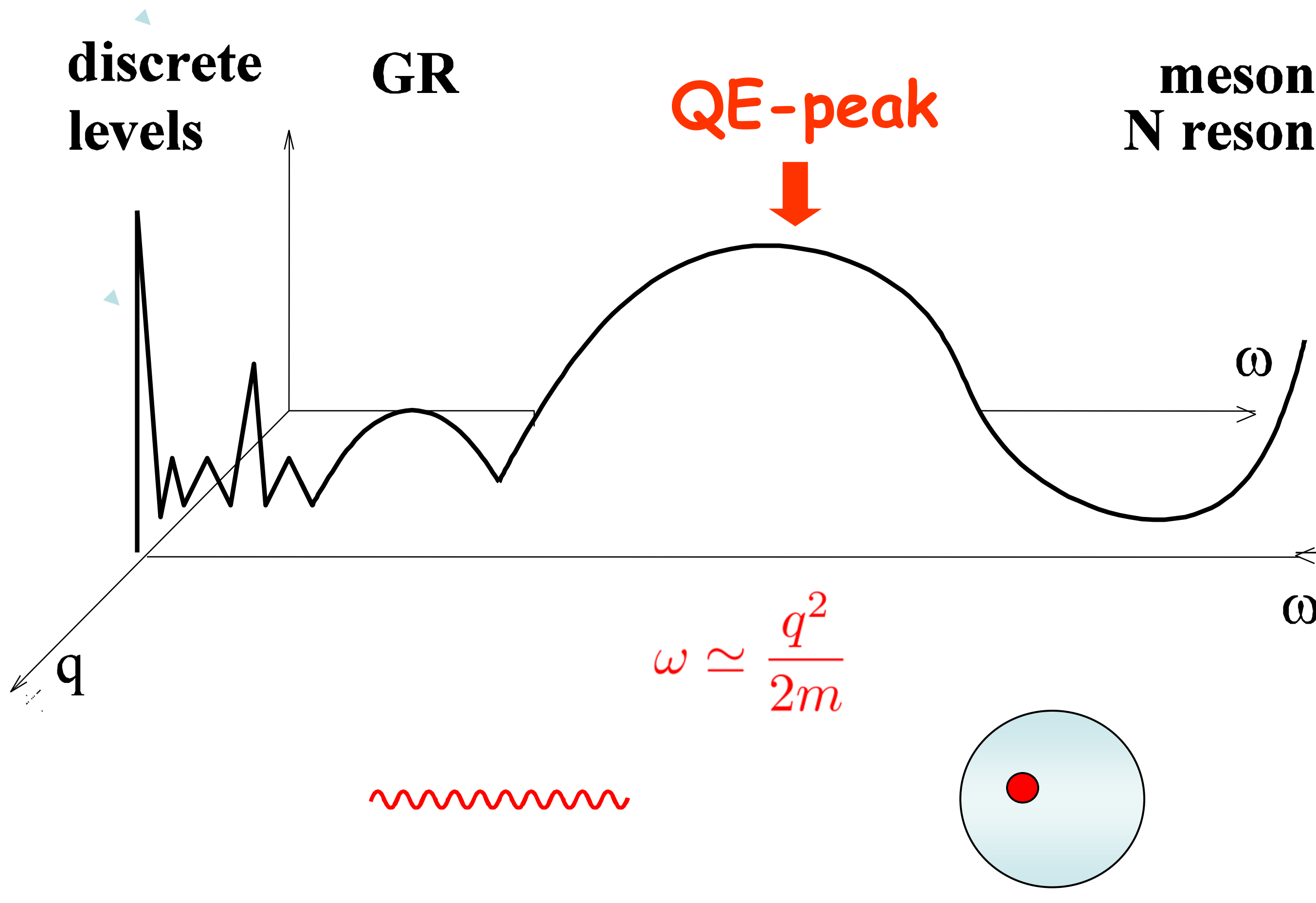

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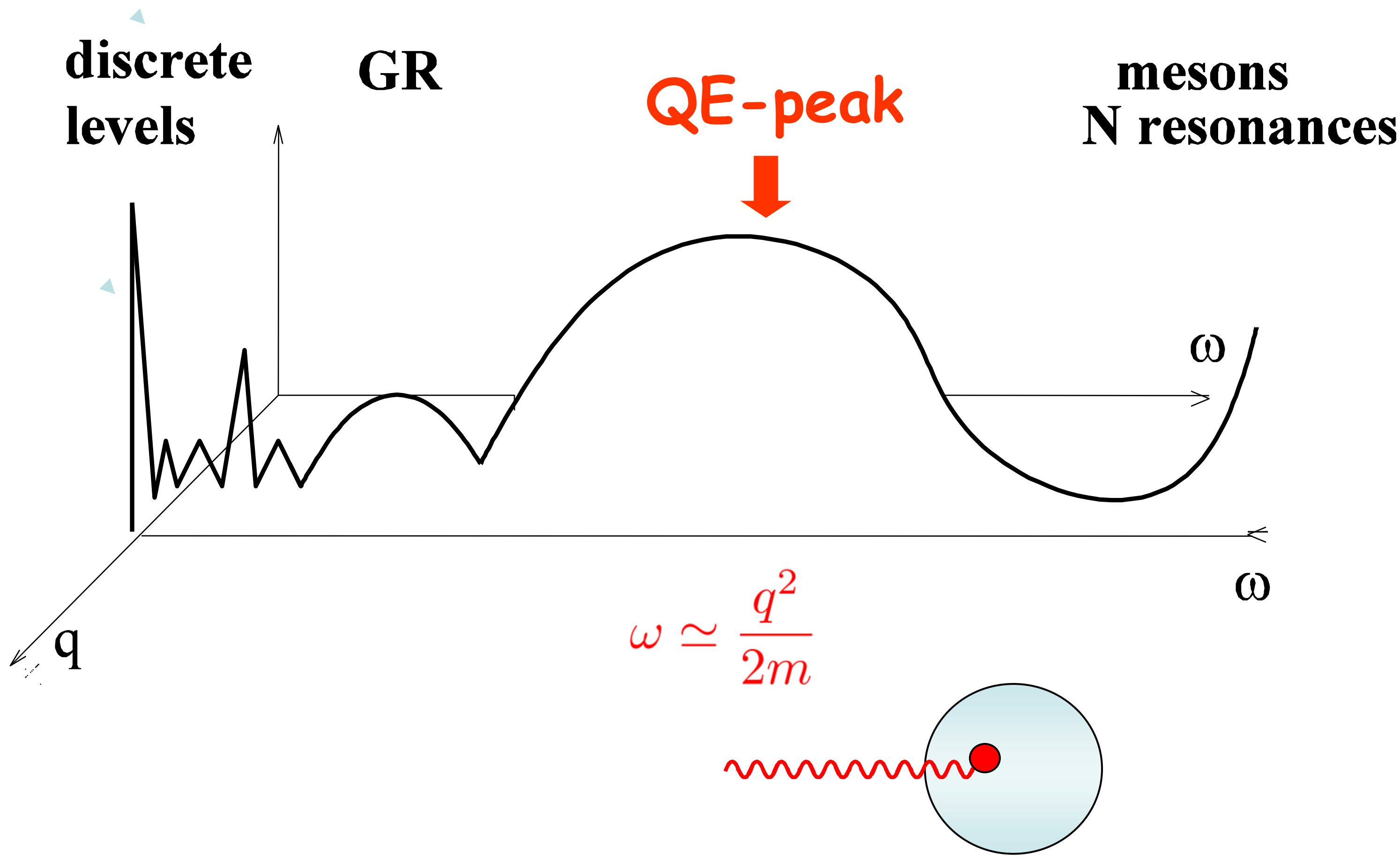

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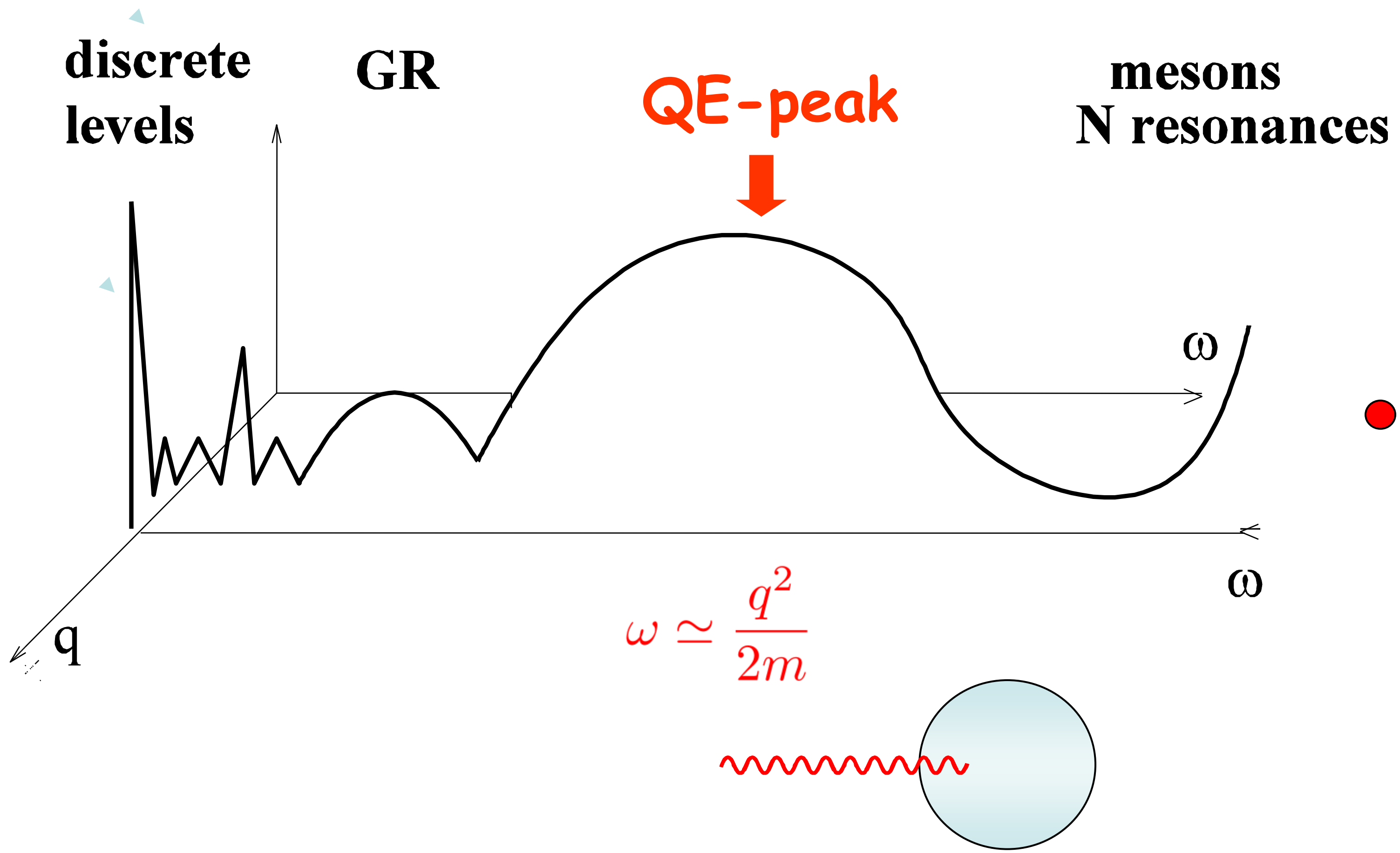

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QE e-nucleus scattering

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

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QE ν-nucleus scattering

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

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

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

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

- only N detected semi-inclusive NC and CC

QE e-nucleus scattering

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

- both e′ and N detected (A-1) discrete eigenstate n exclusive (e,e′p)
- only e′ detected, all final nuclear states included inclusive (e,e′)

QE ν-nucleus scattering

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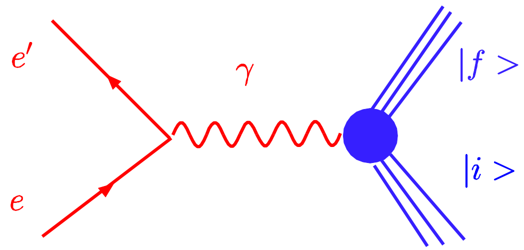
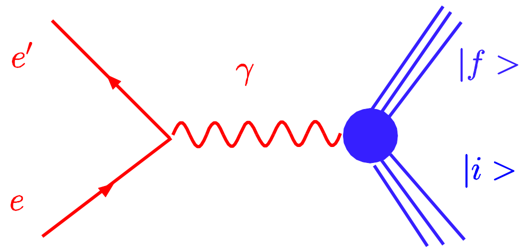
- only N detected semi-inclusive NC and CC
- only final lepton detected inclusive CC

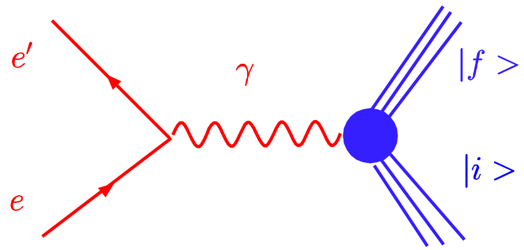


electron
scattering



electron scattering

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



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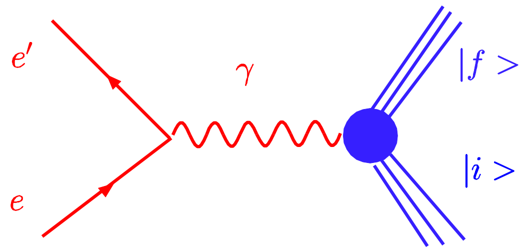
lepton tensor contains lepton kinematics



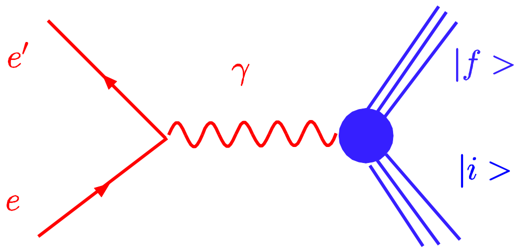
electron scattering

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

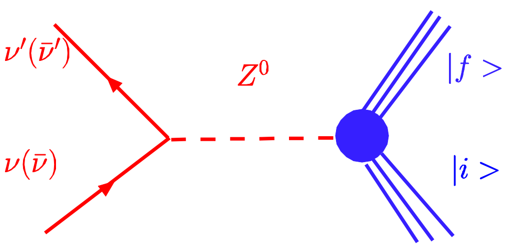
hadron tensor

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

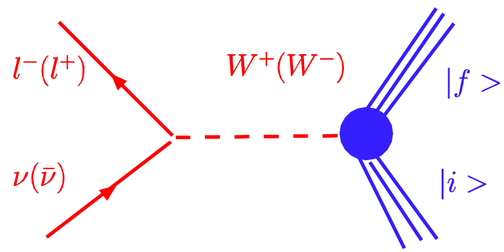
$$J^{\mu}(\boldsymbol{q}) = \int \mathrm{e}^{\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{r}} \langle f \mid \hat{J}^{\mu}(\boldsymbol{r}) \mid i \rangle \mathrm{d}\boldsymbol{r}$$



electron scattering



NC



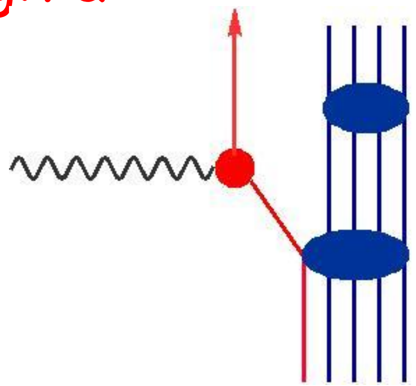
CC

neutrino scattering

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

IMPULSE APPROXIMATION

- EXCLUSIVE SCATTERING: interaction through a 1-body current on a quasi-free nucleon, direct 1NKO



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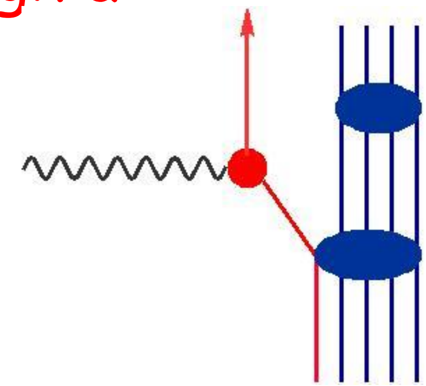
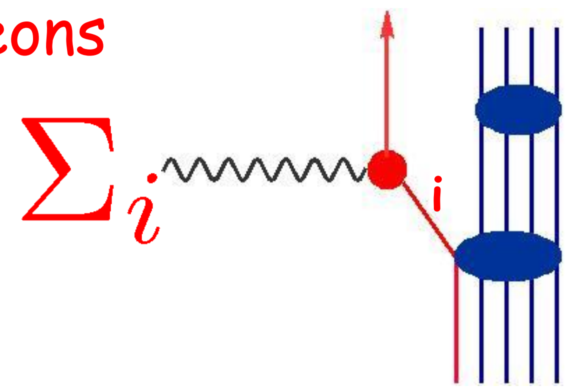


- INCLUSIVE SCATTERING: c.s given by the sum of integrated direct 1NKO over all the nucleons



IMPULSE APPROXIMATION

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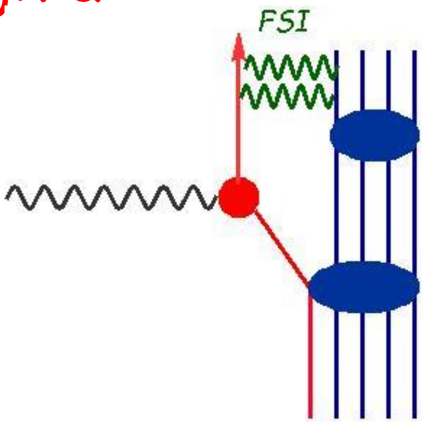

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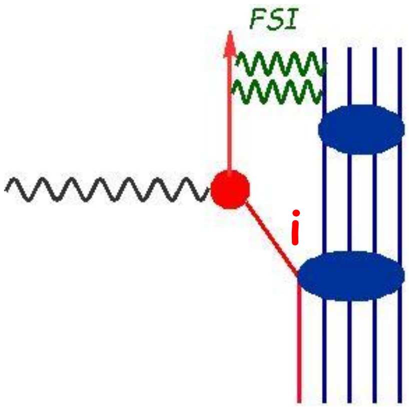
$\sum_i$



FINAL-STATE INTERACTION between the emitted nucleon and the residual nucleus

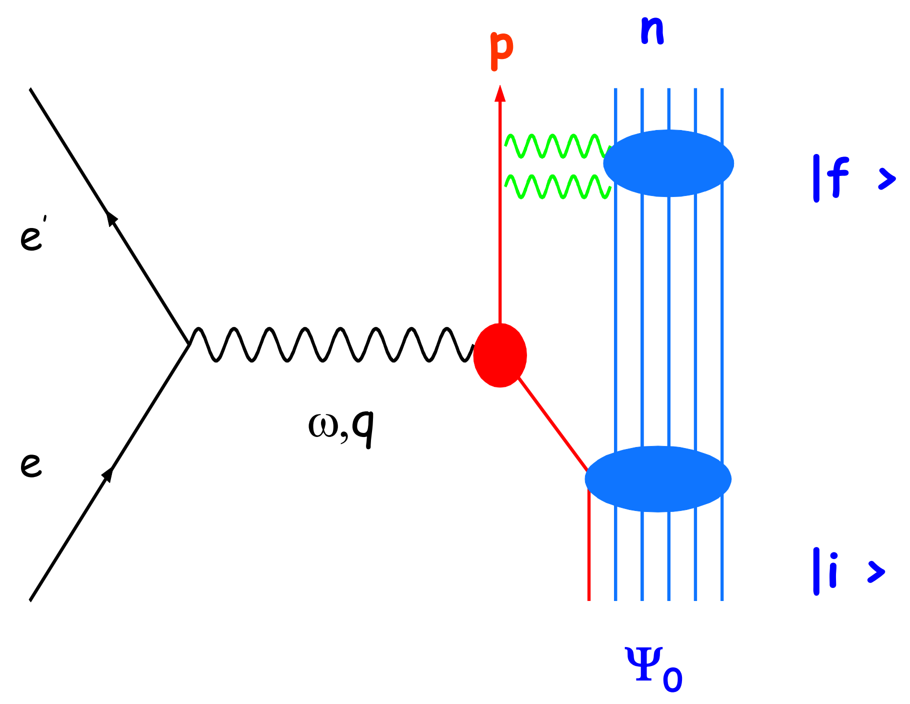
EXCLUSIVE SCATTERING: FSI

DWIA

FSI described by a complex OP with an imaginary absorptive part. The imaginary part gives a reduction of the calculated c.s. which is essential to reproduce data

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
- ϕ_n s.p. bound state overlap function
- λ_n spectroscopic factor
- $\chi^{(-)}$ s.p. scattering w.f. eigenfunction of an OP

Direct knockout DWIA (e,e′p)

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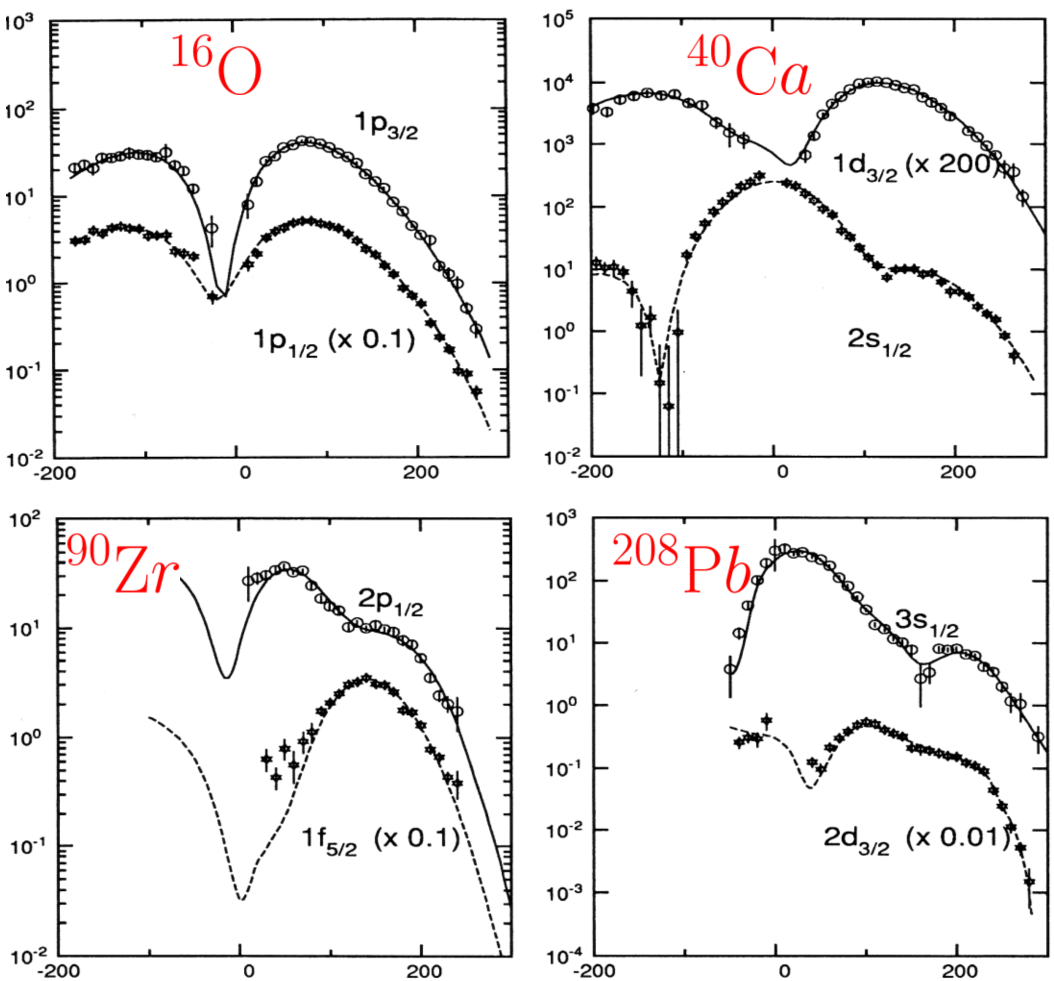
- j^{μ} one-body nuclear current
- ϕ_n s.p. bound state overlap function
- λ_n spectroscopic factor
- $\chi^{(-)}$ s.p. scattering w.f. eigenfunction of an OP

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

NIKHEF data & CDWIA calculations



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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RPWIA

FSI neglected

REAL POTENTIAL

rROP

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

RMF

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

INCLUSIVE SCATTERING: FSI

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RGF

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

- with suitable approximations (basically related to the IA) the components of the inclusive response can be written in terms of the s.p. optical model Green's function
- the explicit calculation of the s.p. GF 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

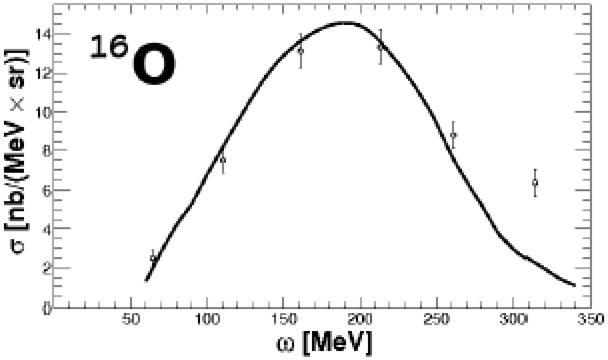
Relativistic Green's Function Model

- consistent treatment of FSI in the exclusive and in the inclusive scattering
- the imaginary part of the OP includes inelastic channels
- with a complex OP the model can include contributions not included in other models based on the IA, beyond IA
- contributions included by a phenomenological OP, in a relatively simple and less model dependent way than with an explicit microscopic calculation
- energy dependence of the OP reflects the different contribution of the different inelastic channels open at different energies, results sensitive to the kinematic conditions

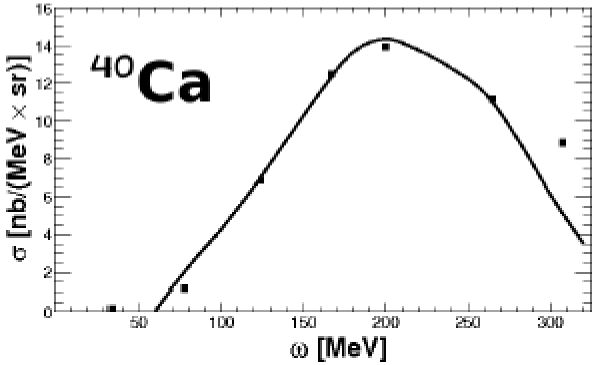
RGF: successful description of QE data

(e,e')

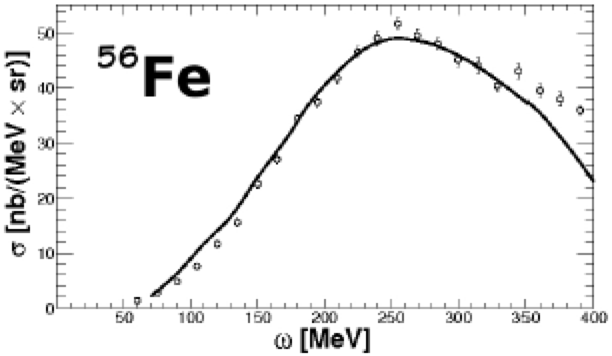
RGF



E_0 = 1080 MeV ϑ = 32^o



E_0 = 841 MeV ϑ = 45.5^o



E_0 = 2020 MeV ϑ = 20^o

C.G. and A. Meucci

Differences between Electron and Neutrino Scattering

- electron scattering :

  beam energy known, cross section as a function of ω

- neutrino scattering:

  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 direct 1-nucleon emission

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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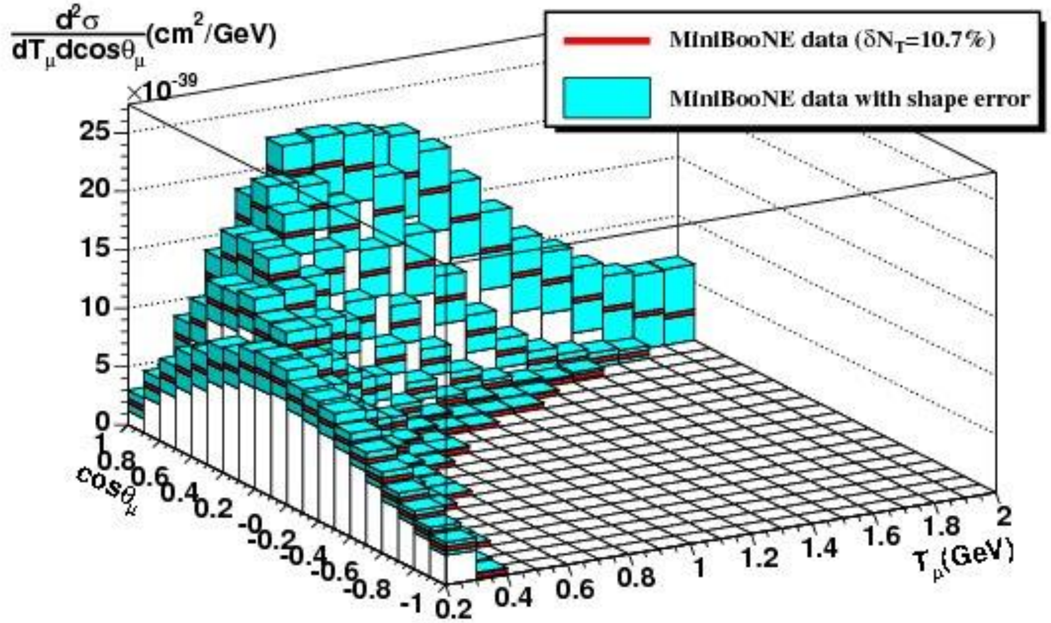
⬇

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

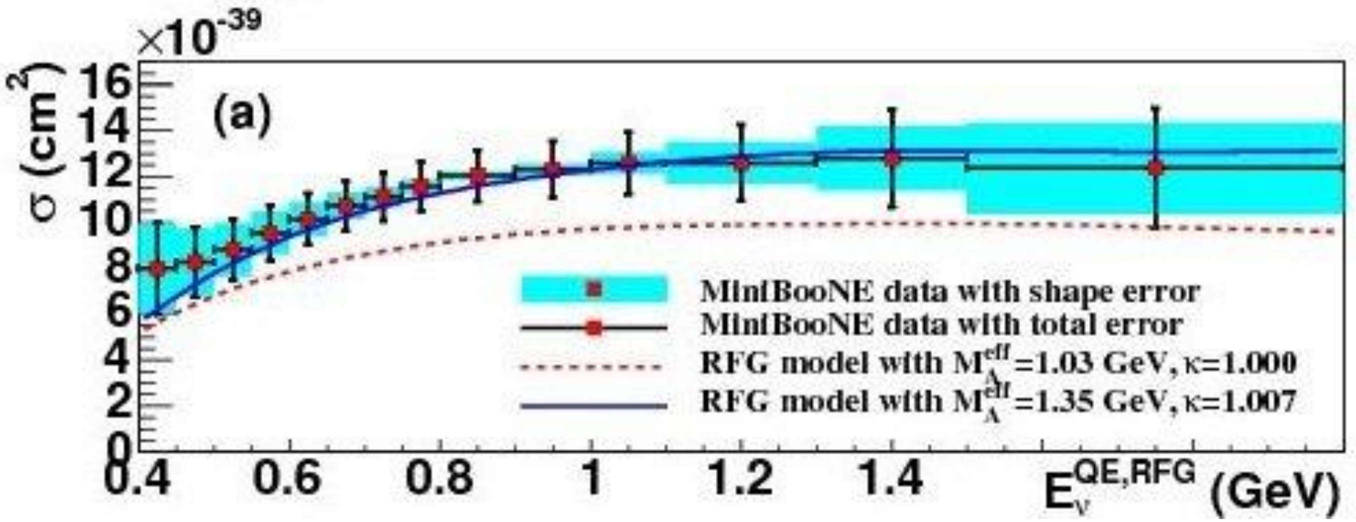
Unusually large values of the nucleon axial mass must be used to reproduce the data (about 30% larger)

MiniBooNe CCQE data



flux integrated double differential cross section

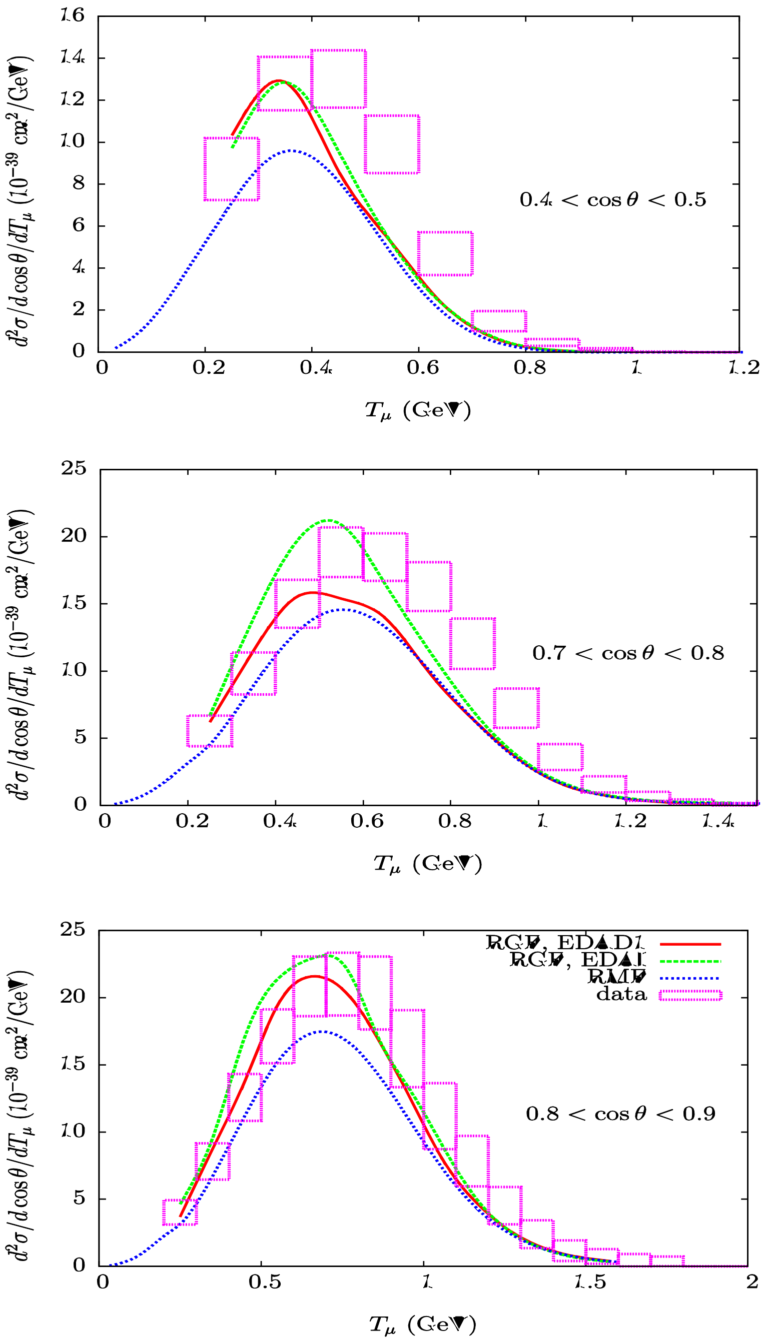
M_A = 1.35 GeV



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



$0.4 < cos\theta_\mu < 0.5$

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

$0.7 < cos\theta_\mu < 0.8$

RGF-EDAI

RGF-EDAD1

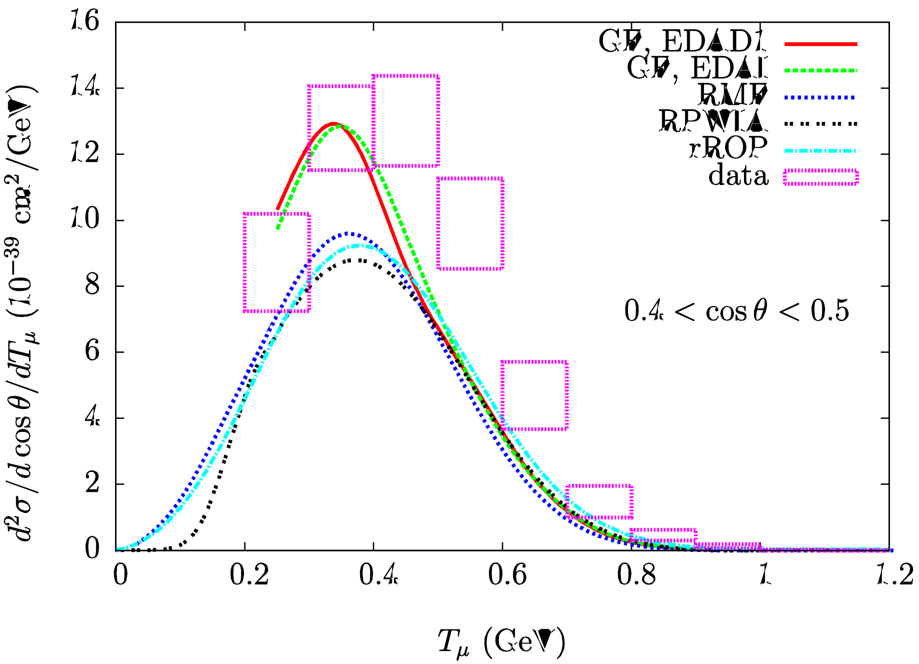
RMF

$0.8 < cos\theta_\mu < 0.9$

A. Meucci et al. PRL 107 (2011) 172501

Comparison with MiniBooNe CCQE data

$0.4 < cos\theta_\mu < 0.5$



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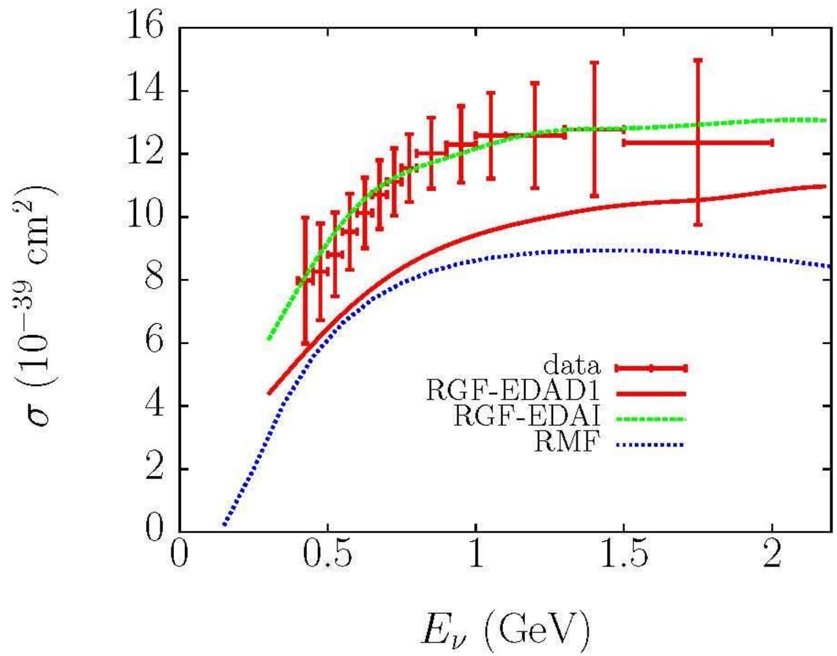

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A. Meucci et al. PRL 107 (2011) 172501

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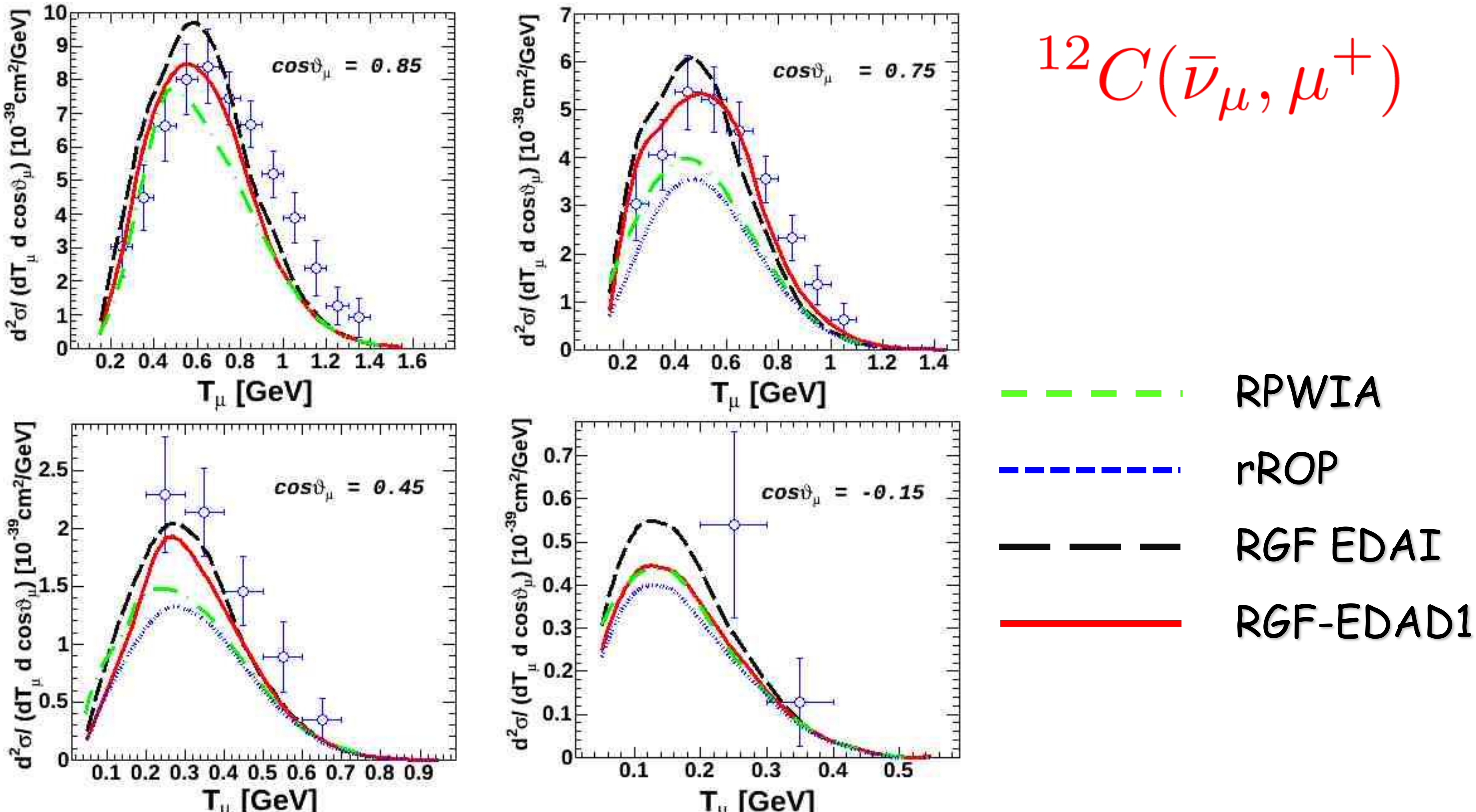
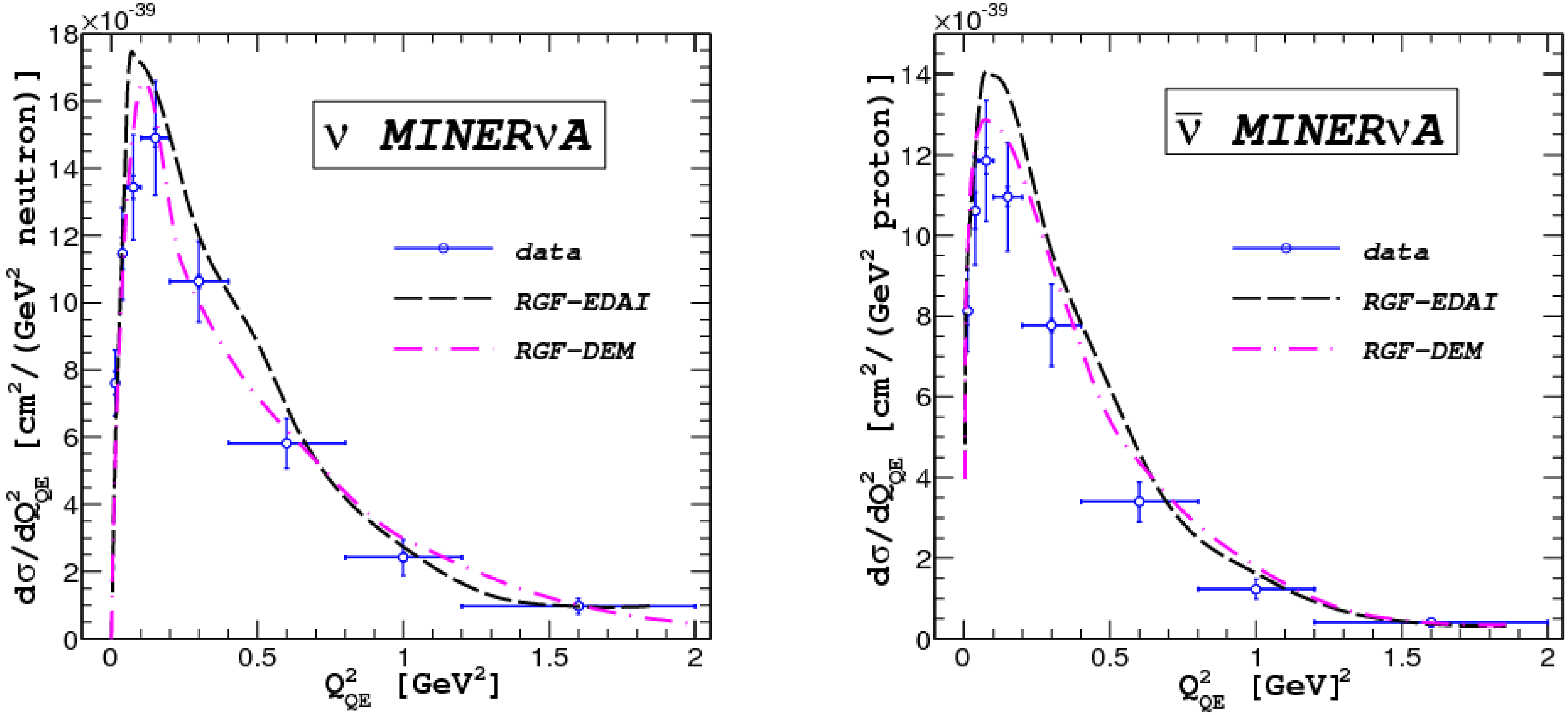
$^{12}C(\bar{\nu}_\mu, \mu^+)$



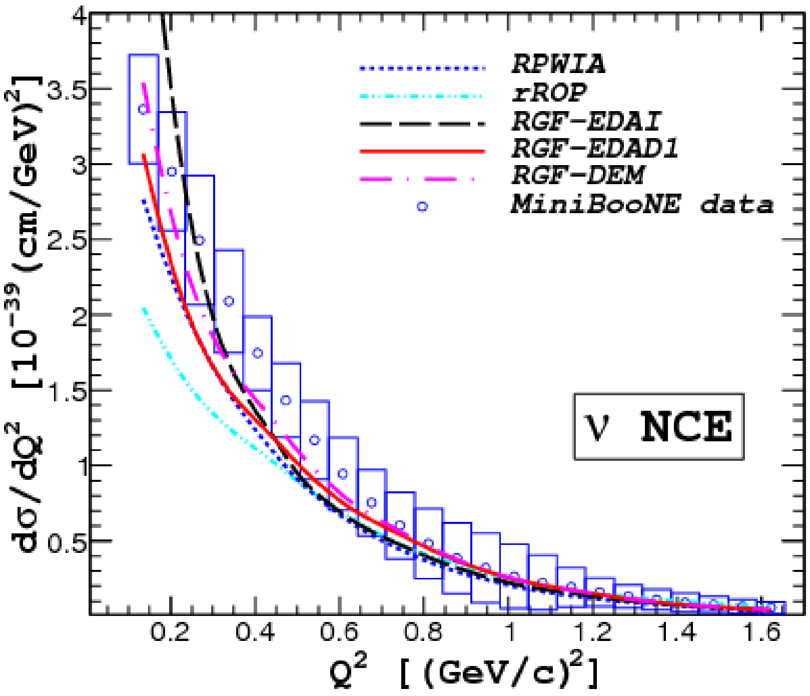
A. Meucci and C. Giusti PRD 85 (2012) 093002

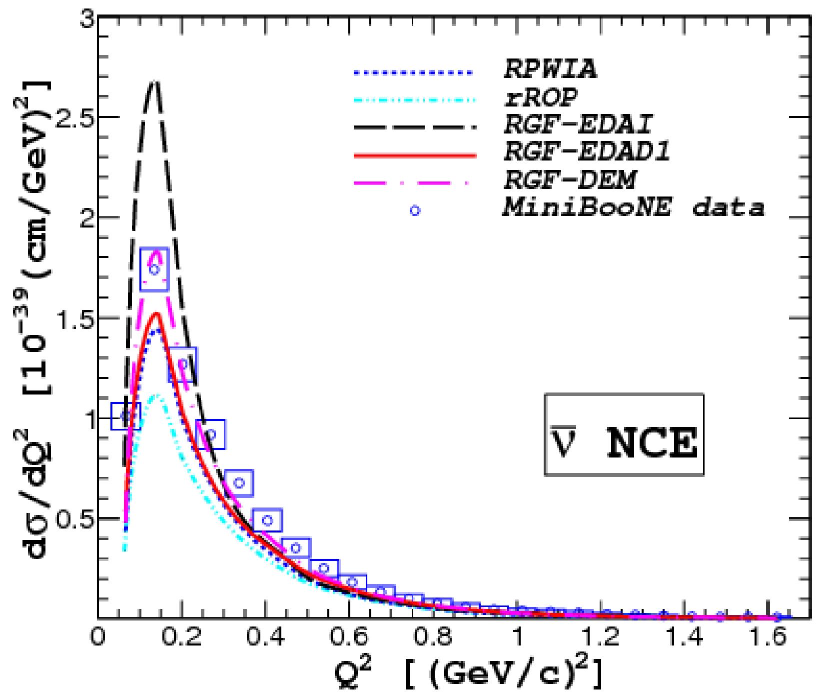
Comparison MINERνA CCQE neutrino-antineutrino scattering



A. Meucci and C.Giusti PRD 89 (2014) 117301

Comparison with MiniBooNE NCE data





A. Meucci and C.Giusti PRD 89 (2014) 057302

RGF: successful description of QE electron and neutrino-scattering data

BUT there are some caveats

- The OP is an important tool to include important contributions non included in other models but the use of a phenomenological OP does not allow us to disentangle and evaluate the role of a specific contribution
- Available proton-nucleus scattering data do not completely constrain the shape and size of the OP
- Different OP's available, with different imaginary parts, give different inelastic contributions in RGF calculations and produce theoretical uncertainties on the predictions of the RGF model

RGF

To reduce theoretical uncertainties due to different OPs a less phenomenological optical potential has been obtained for ^{12}C within RIA:

GLOBAL spanning a wide range of nucleon energies (20-1040 MeV)

RELATIVISTIC

FOLDING the relativistic Horowitz-Love-Franey t-matrix for the NN scattering amplitudes with relativistic mean-field nuclear densities via the $t\rho$ approximation

OPTICAL

POTENTIAL

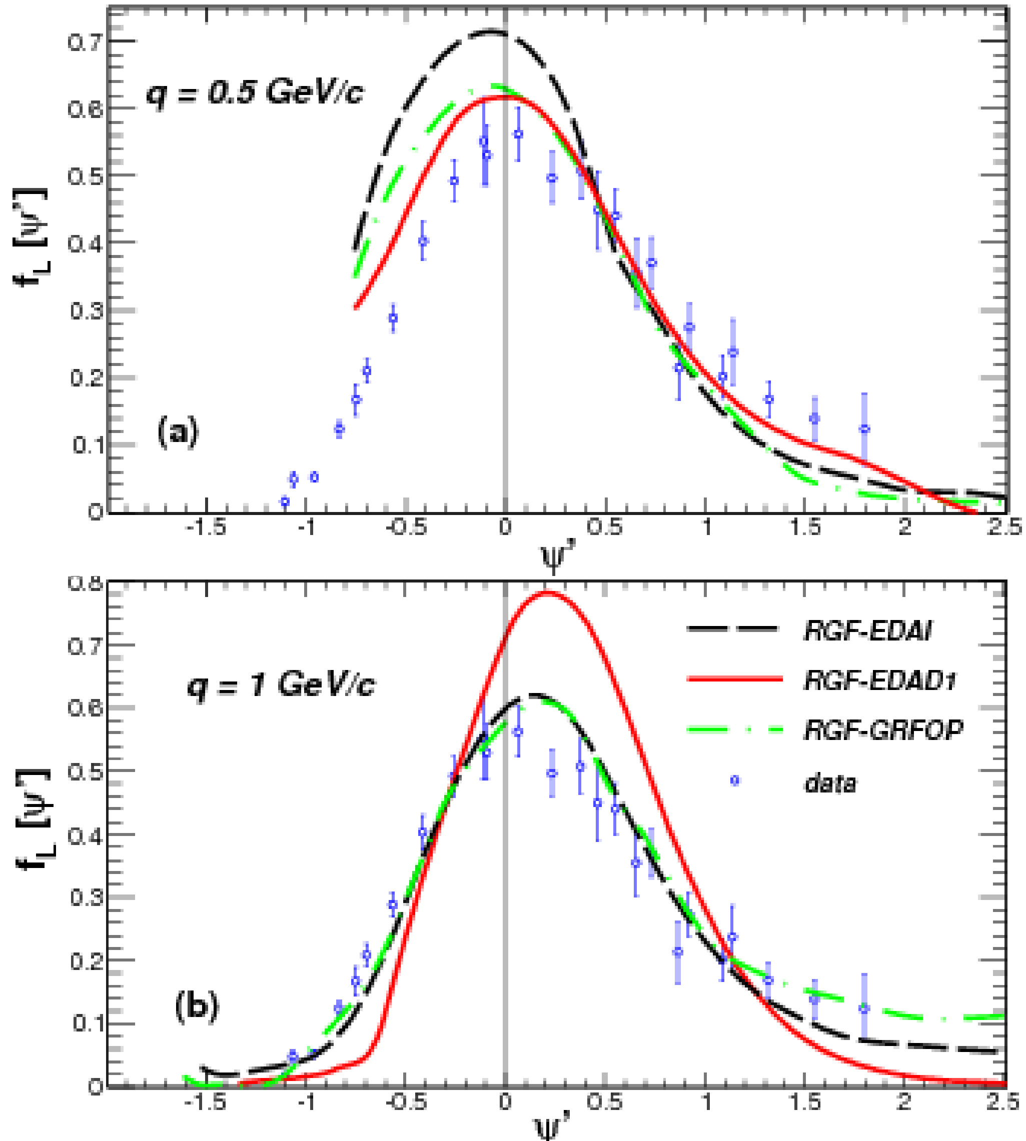
GRFOP

GRFOP

- derived from all available elastic proton-^{12}C scattering data
- folding approach with proton density taken from electron scattering data and neutron density fitted to data
- imaginary part built from the effective NN interaction

M.V. Ivanov, J.R. Vignote, R. Alvarez-Rodirguez, A. Meucci. C.Giusti, J.M. Udias PRC to be published

QE SCALING FUNCTION



q=500 MeV/c

RGF-EDAI

RGF-EDAD1

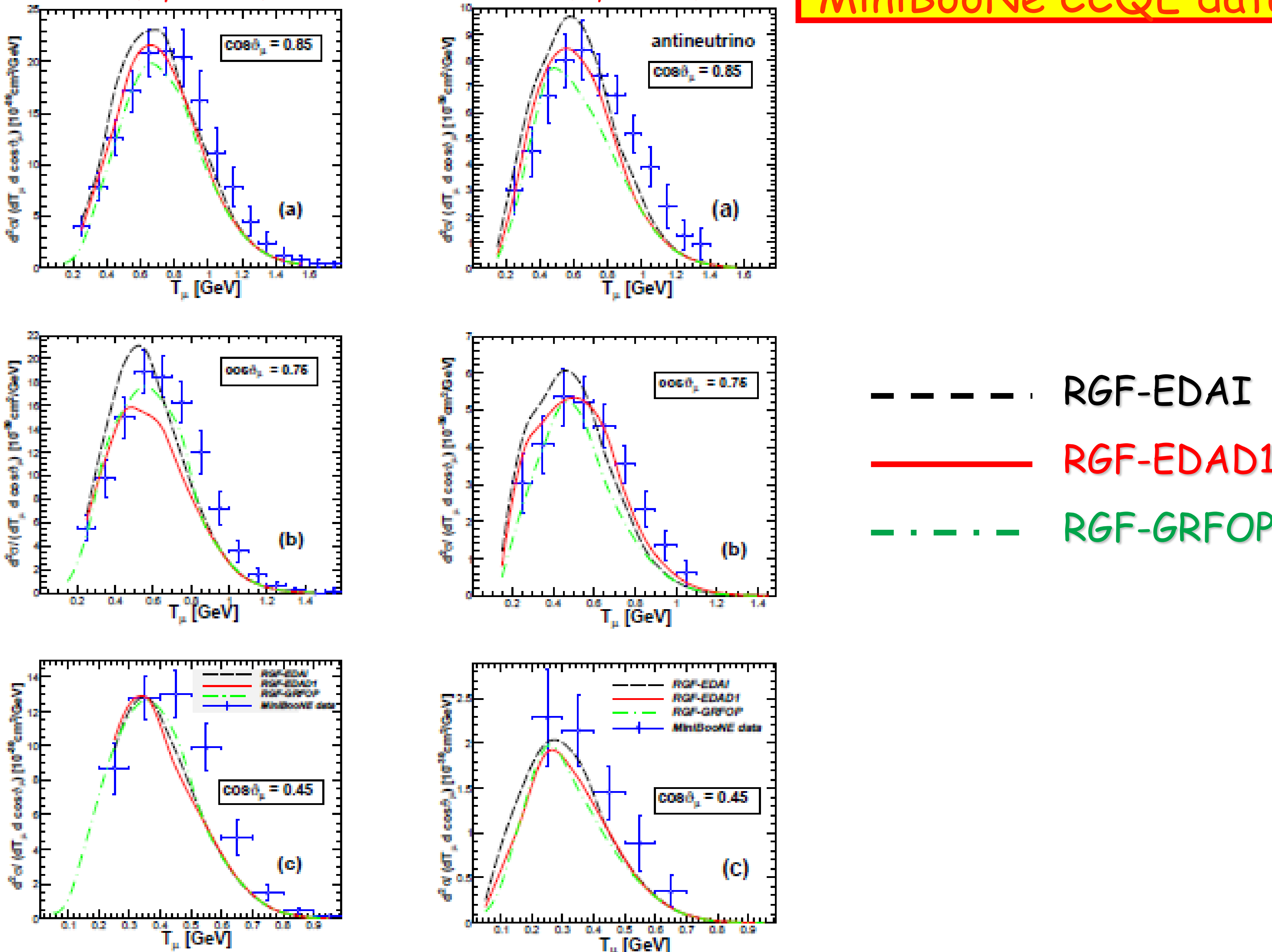
RGF-GRFOP

q=1 GeV/c

M.V. Ivanov, J.R. Vignote, R. Alvarez-Rodriguez, A. Meucci. C.Giusti, J.M. Udias PRC to be published

MiniBooNe CCQE data

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



MiniBooNe CCQE data

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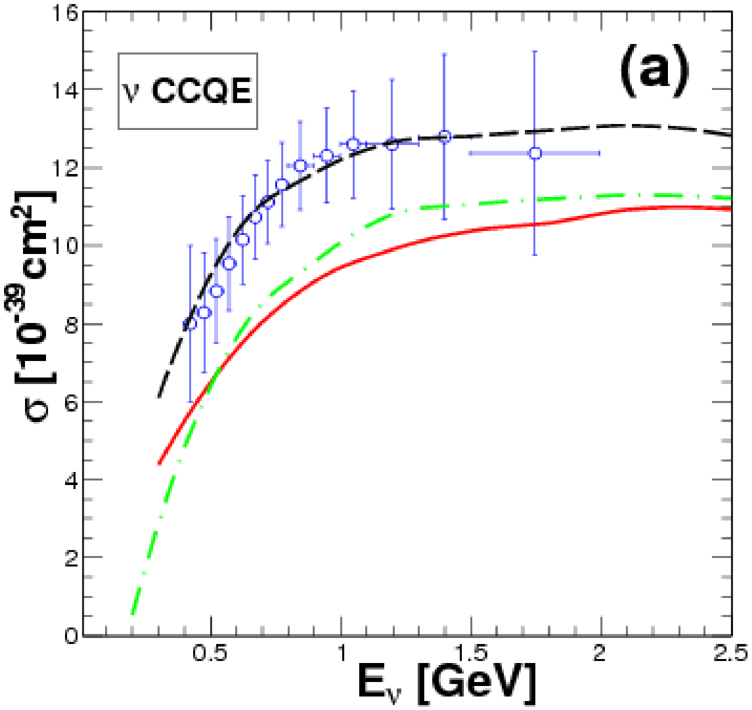

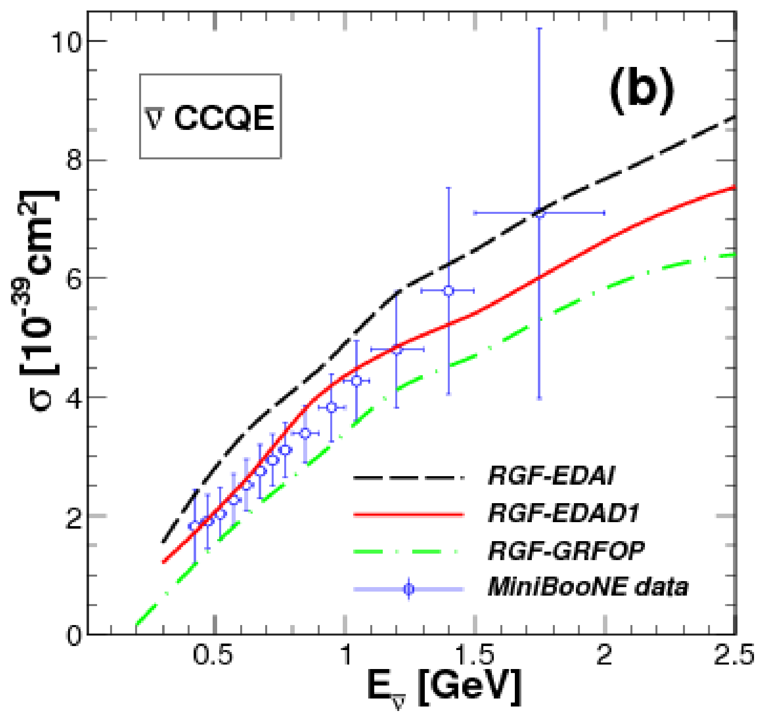

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Perspectives

- reduce theoretical uncertainties
- RGF microscopic optical potential
- comparison of different models
- 2p-2h MEC….?