Analysis of γ-ray production in NC neutrino-oxygen interactions at energies above 200 MeV

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In collaboration with
O. Benhar, T. Mori, R. Yamaguchi, and **M. Sakuda,**
arXiv:1110.0679, to appear in **Phys. Rev. Lett.**

December 16, 2011, Trento

Detection of NC events

- Knocked out neutrons (~50% of NC events) do not emit Cherenkov light.

- In water Cherenkov detectors, the threshold momentum of proton is 1.07 GeV/c
[at E=600 (900) MeV, 100.0 (93.7)% of events is below the threshold]

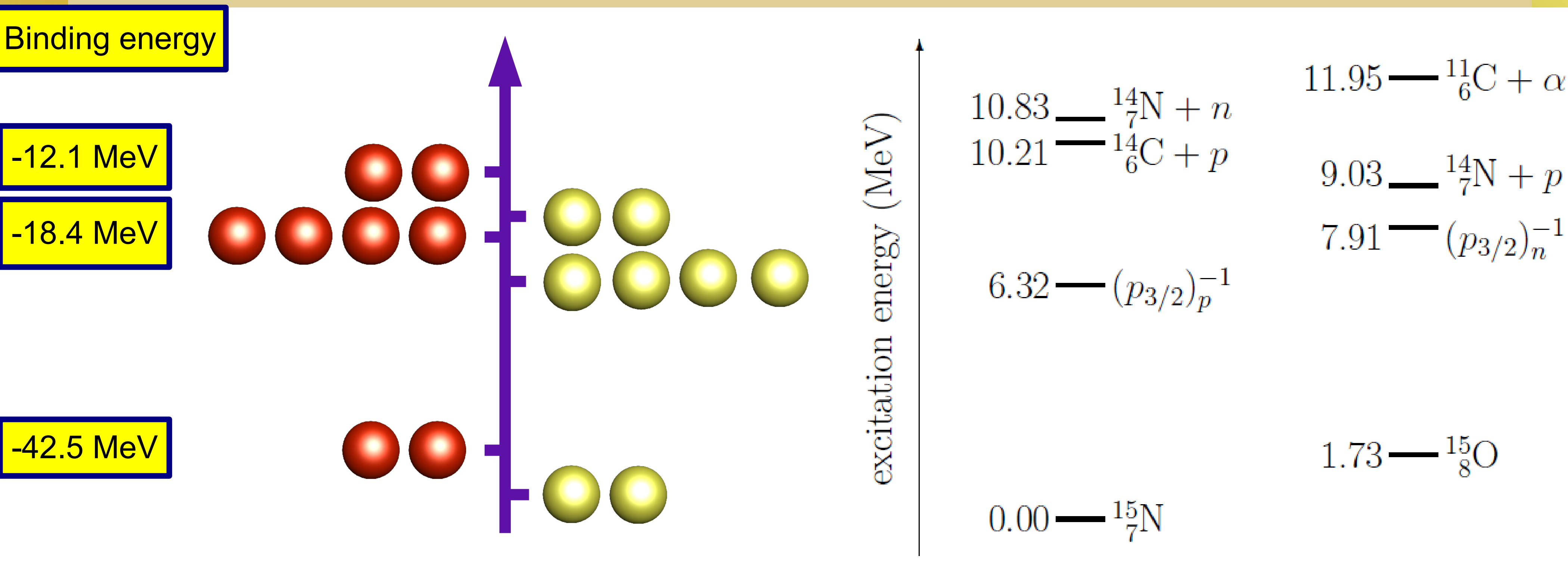
- Hence, an additional signature for NC event might be very useful.

Nuclear deexcitation as a prompt signal of NC event

- Nucleon knockout may leave residual nucleus in an **excited state**.

- Photon produced by **deexcitation** could provide a **useful signal**, especially for water Cherenkov detectors.

Structure of the oxygen nucleus and excitation levels of residual nuclei



Cross section for γ emission following NC event

It is a product of

- NC x-section for the knockout from each shell
- branching ratios for deexcitation by γ emission

$$\sigma_\gamma \equiv \sigma(\nu + {}^{16}_{8}\mathrm{O} \to \nu + \gamma + Y + N)$$
$$= \sum_\alpha \sigma(\nu + {}^{16}_{8}\mathrm{O} \to \nu + X_\alpha + N)\, B(X_\alpha \to \gamma + Y),$$

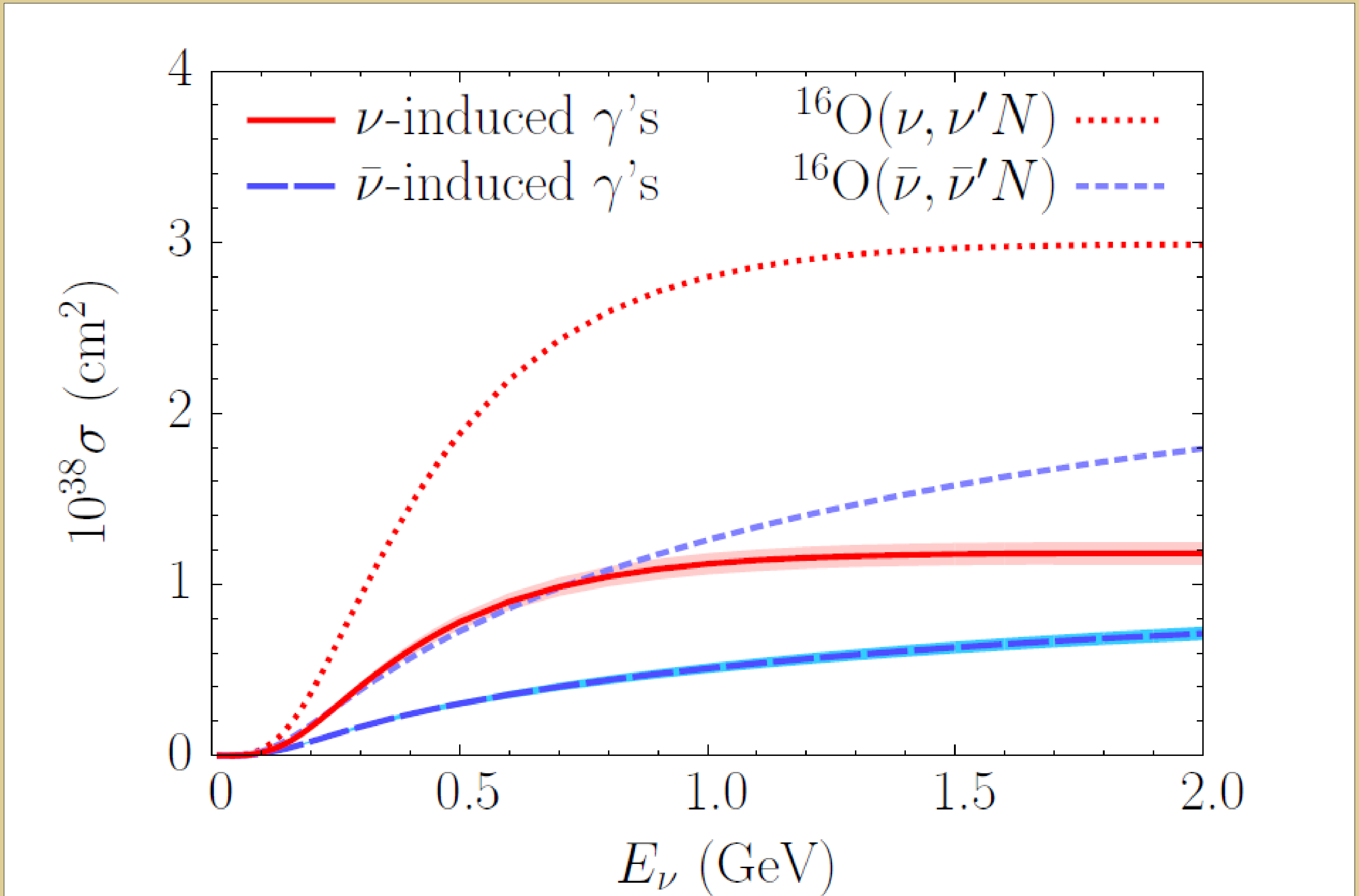
Cross section for γ emission accompanying NC event

Our estimate is that

- photons from the s1/2 knockout (of E > 6 MeV) follow **< 2%** NC events

- 6-MeV photons (from the p3/2 knockout) follow **~40%** NC events

The total γ-ray production x-section



Photons of E > 6 MeV are considered

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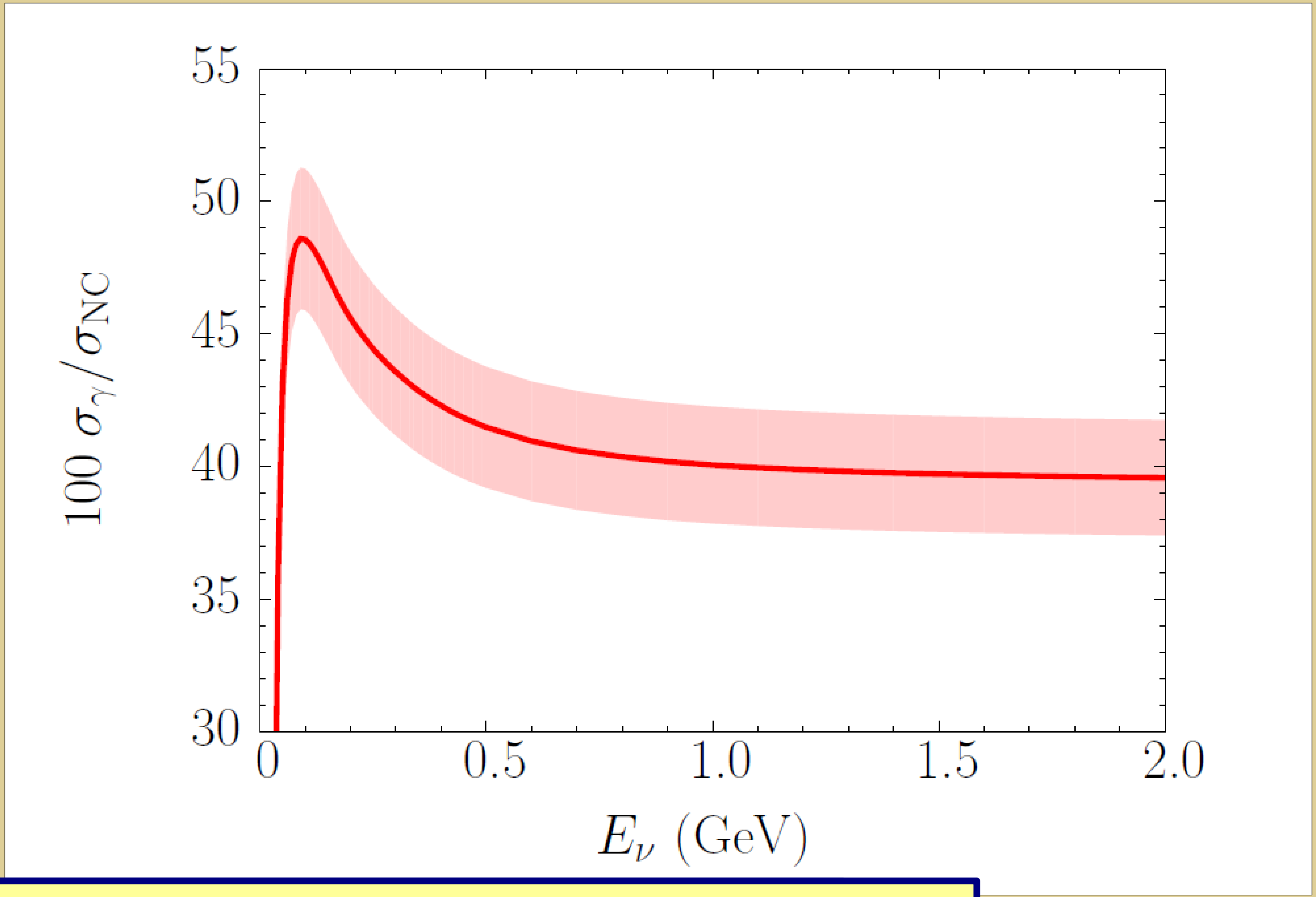

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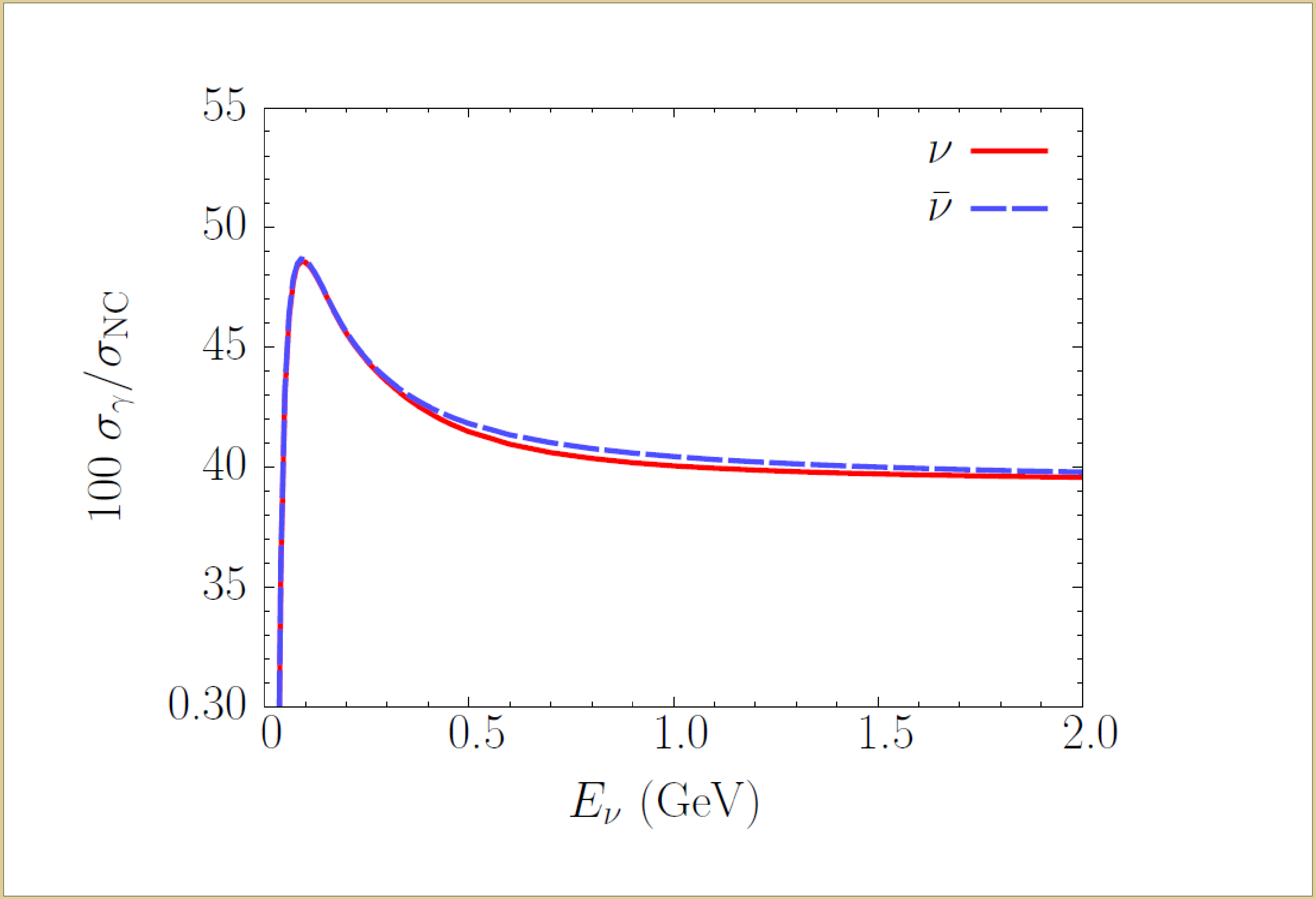

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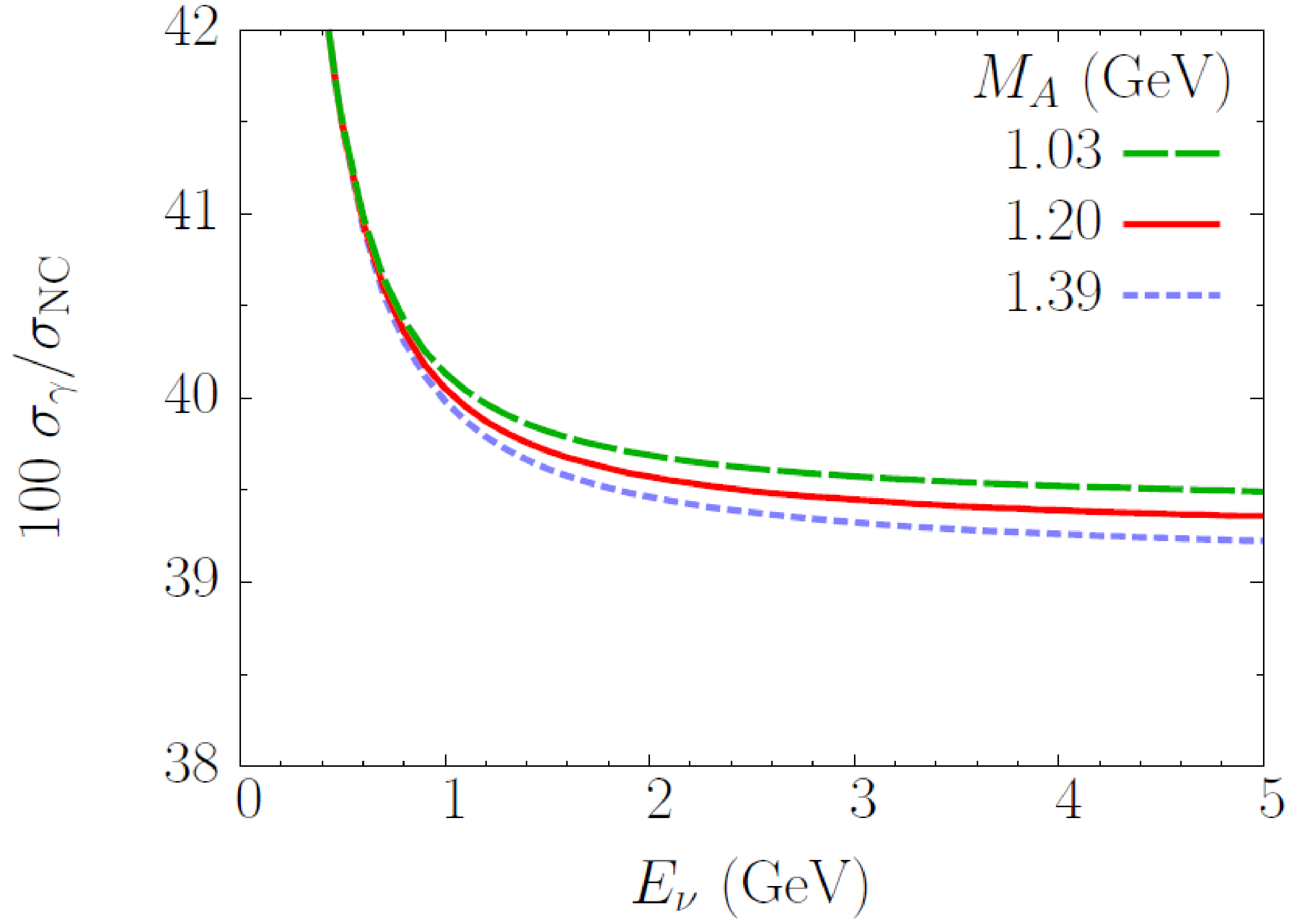


Ratio largely independent of M_A

Summary

❶ **Deexcitation into photons of $E\gamma > 6$ MeV following the NC interaction may provide a useful signature for water Cherenkov detectors**

❷ **The ratio $\sigma(\gamma)/\sigma(NC)$ is largely independent of the axial mass value**

❸ **In the important for T2K region $E \lesssim 1$ GeV, the ratio is ~40% for the 6-MeV γ's from p3/2 knockout. The $E\gamma > 6$ MeV photons from s1/2 hole are just ~2%.**

Analysis of the Q^2-dependence of QE ν_μ-nucleus interactions

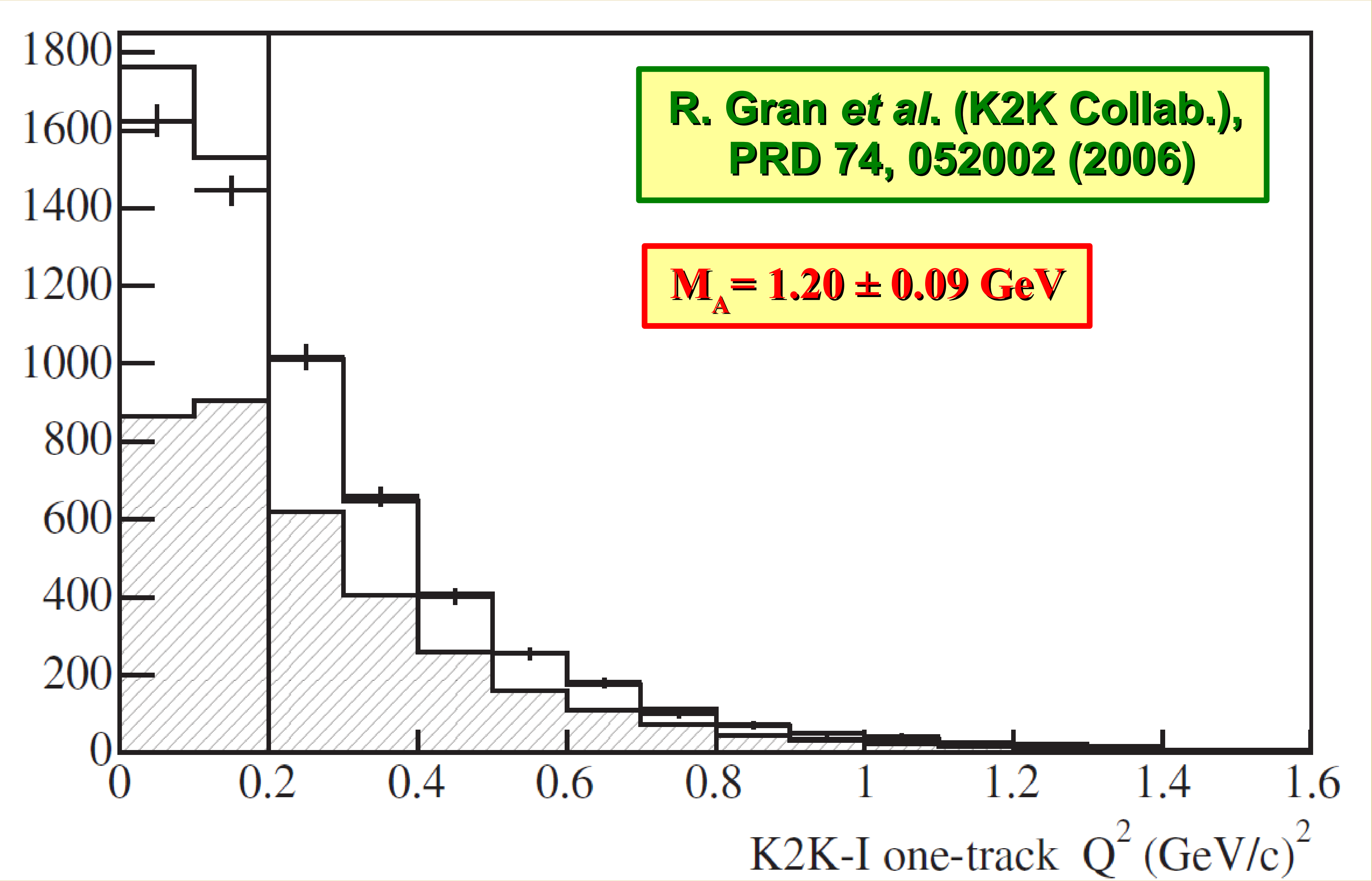
based on the article

A.M.A., O. Benhar, and **N. Farina**

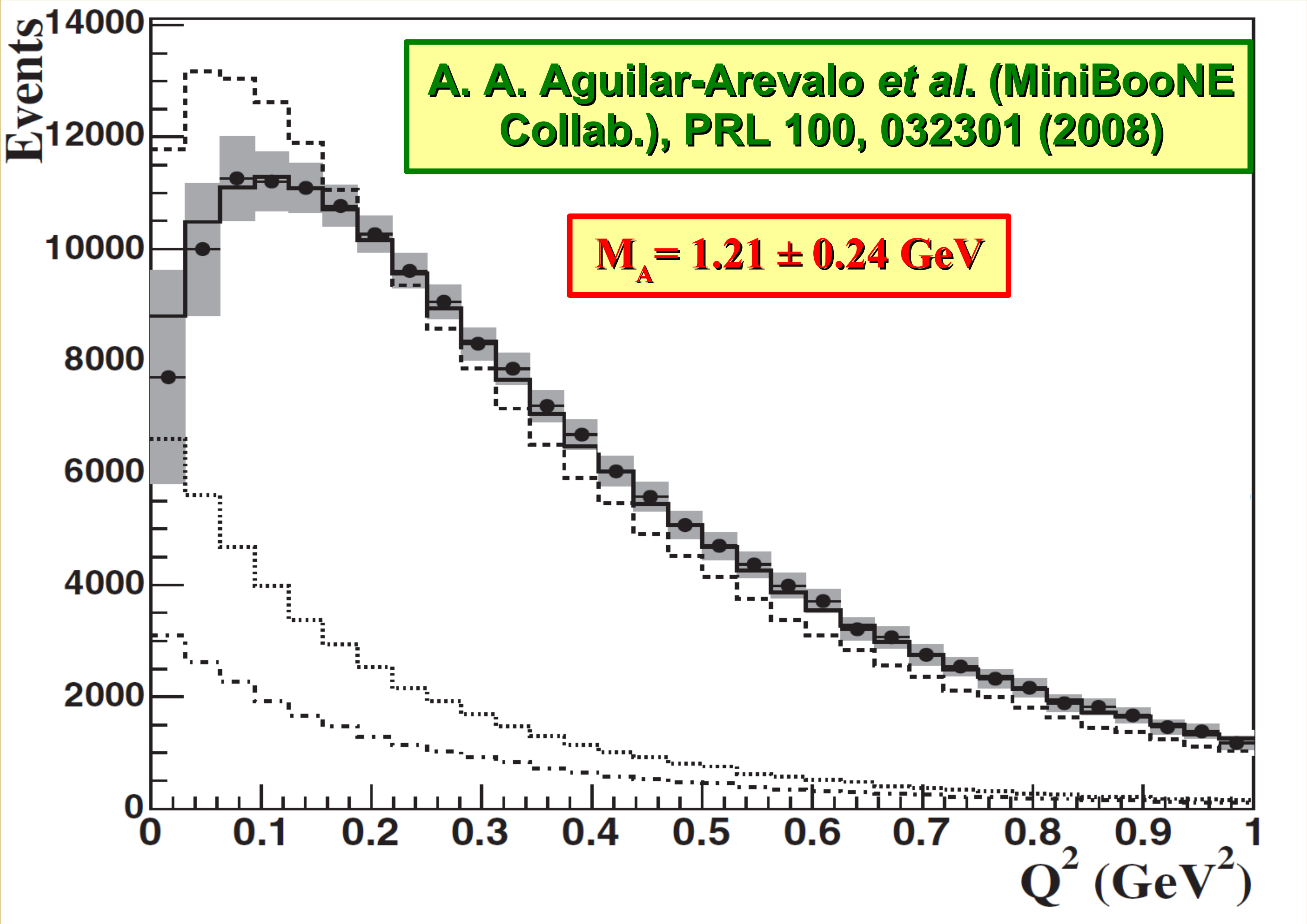
Phys. Rev. D **82**, 013002 (2010)

December 16, 2011, Trento

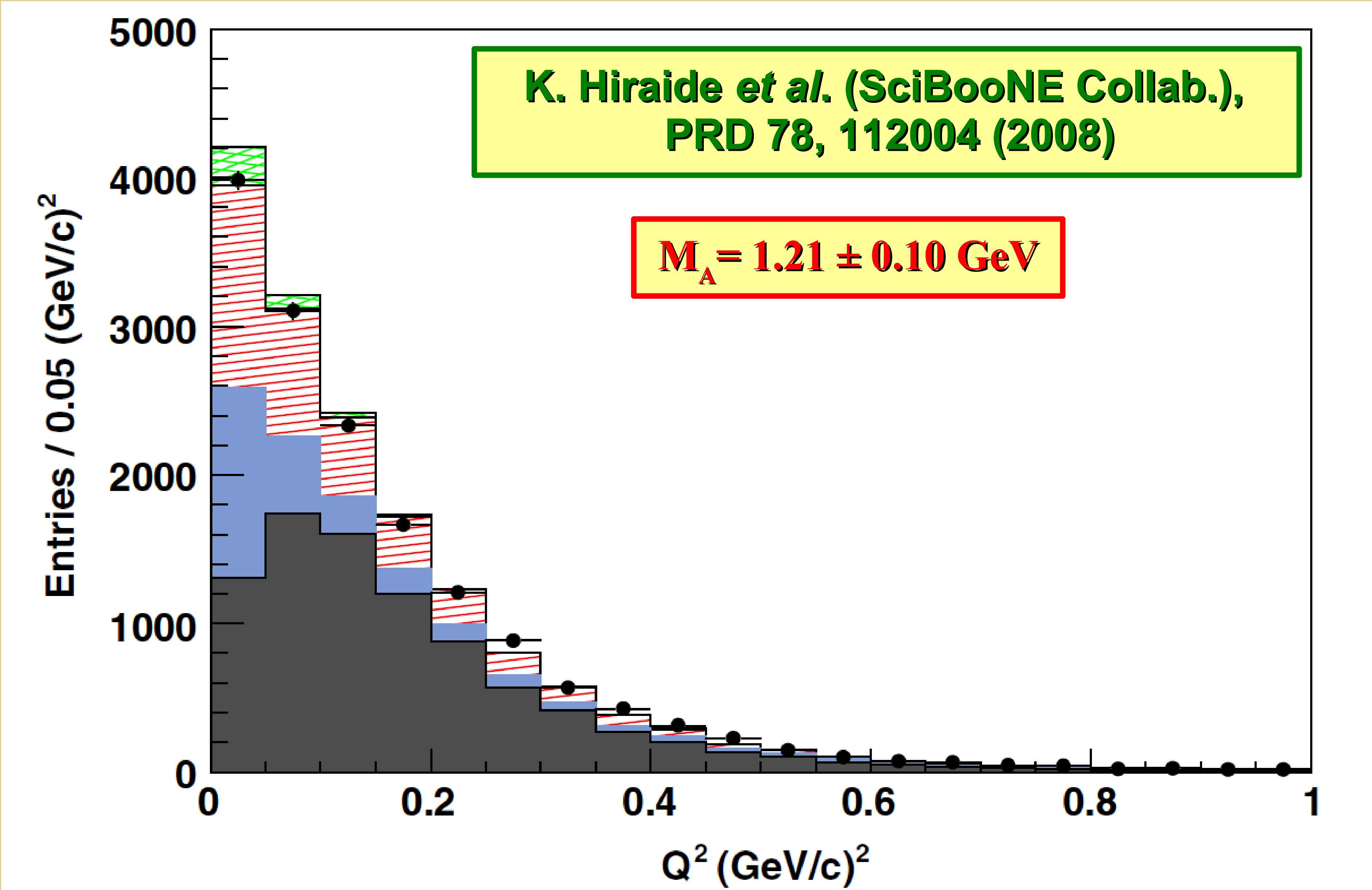
Low-Q^2 problem: K2K



Low-Q^2 problem: MiniBooNE



Low-Q^2 problem: SciBooNE



Are Q^2 vs. Q^2_{rec} *really* equivalent?

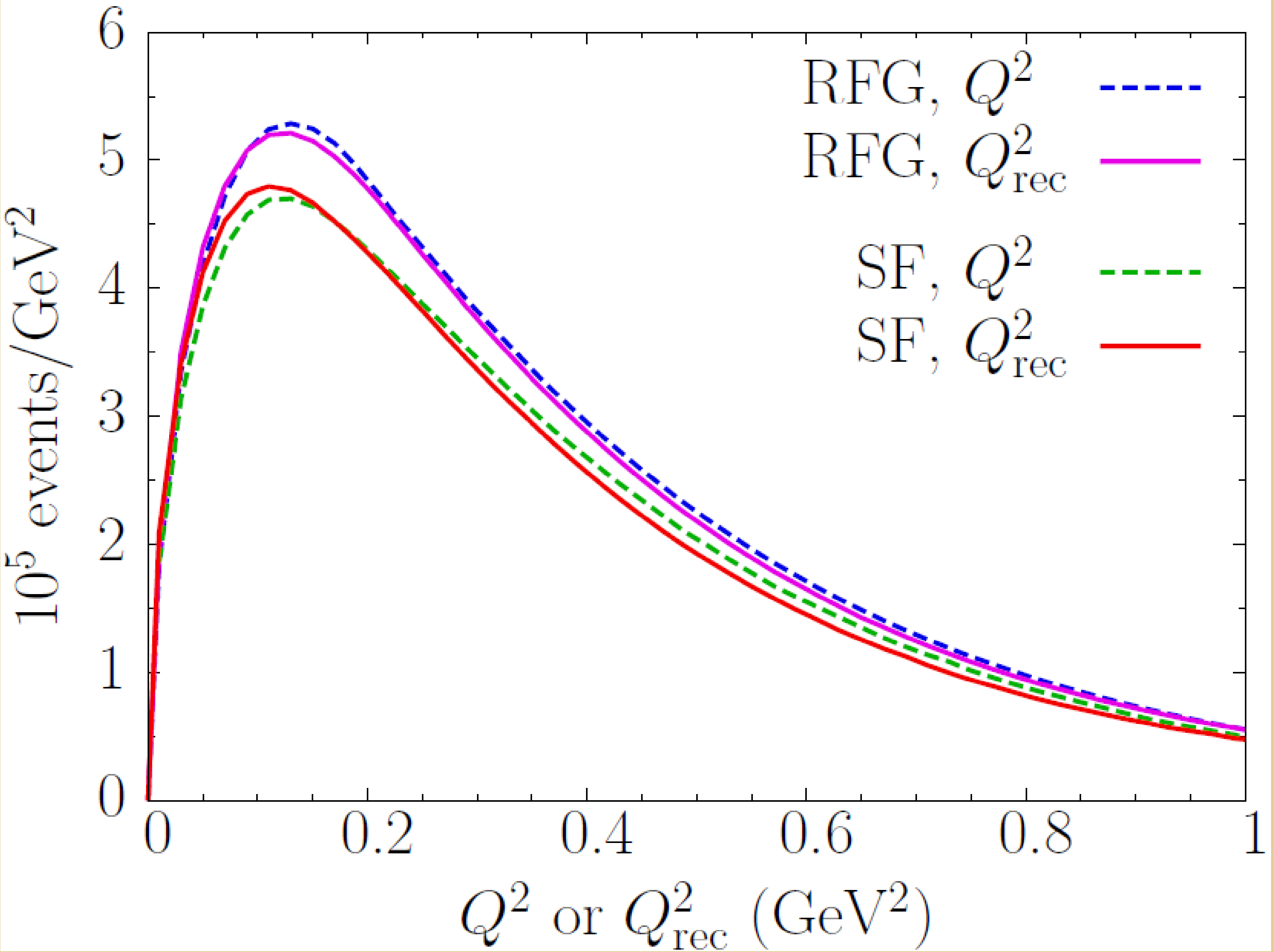
Reconstructed Q^2

- In scattering off nucleus the **true Q^2 cannot be obtained** (only $|\boldsymbol{k}_\mu|$ and θ are measured)

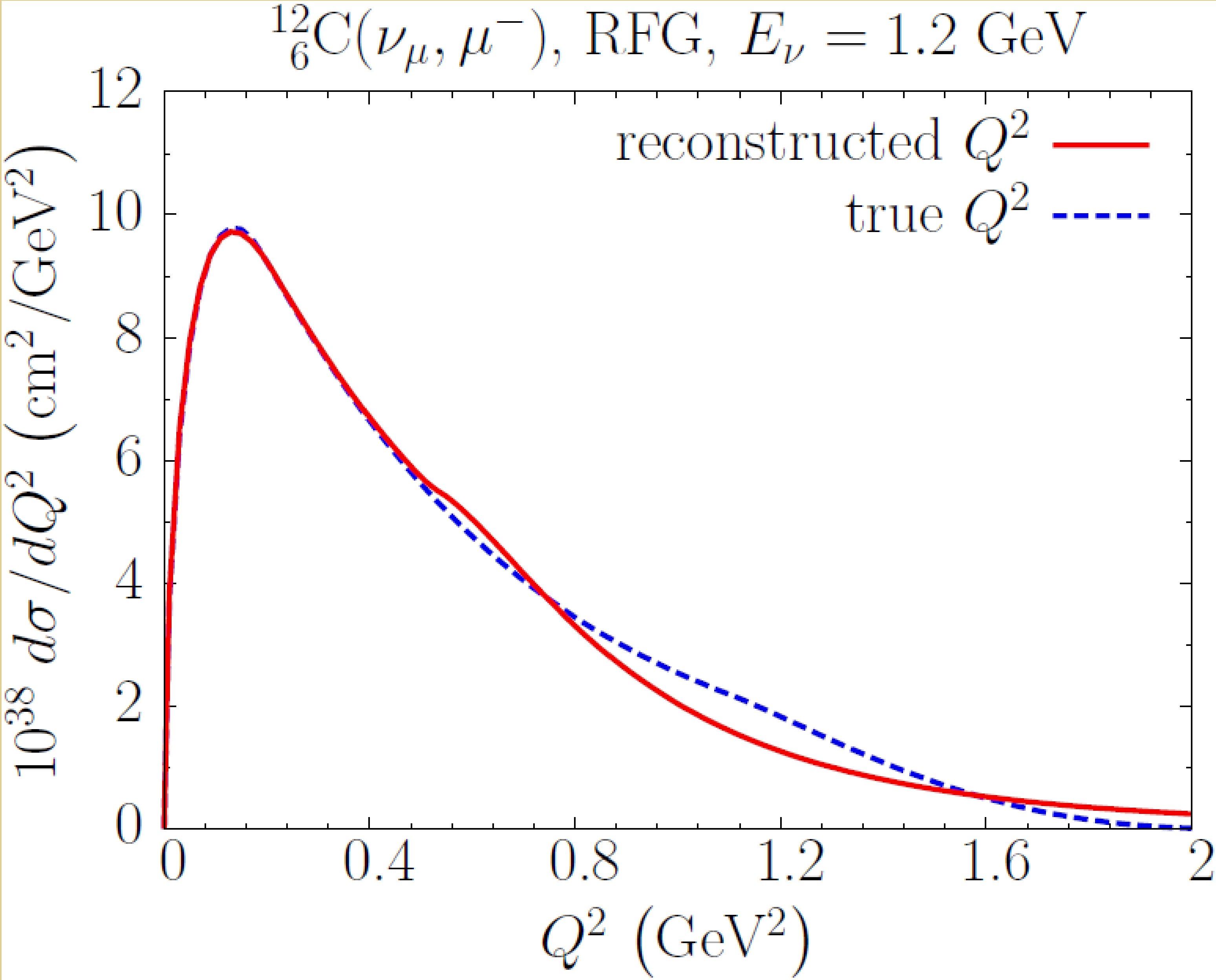
- When $\varepsilon = 0$ the rec. Q^2 is equal to the true Q^2 corresponding to the scattering off a free neutron with the same muon kinematics

- In general case Q^2_{rec} lacks physical meaning but is useful as a quantity for data analysis

Q^2 vs. Q^2_{rec} for the MiniBooNE flux



Q^2 vs. Q^2_{rec} for fixed energy



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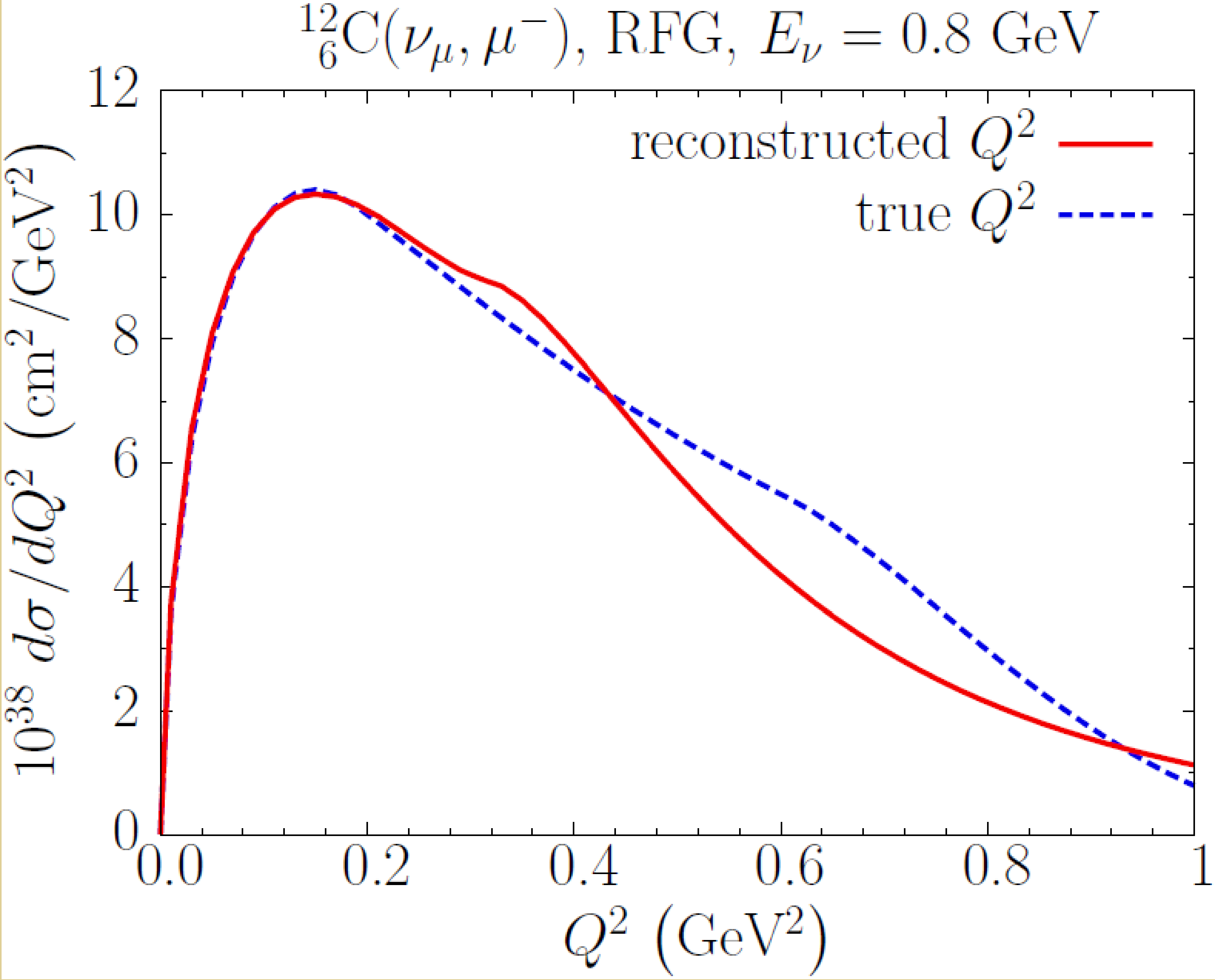
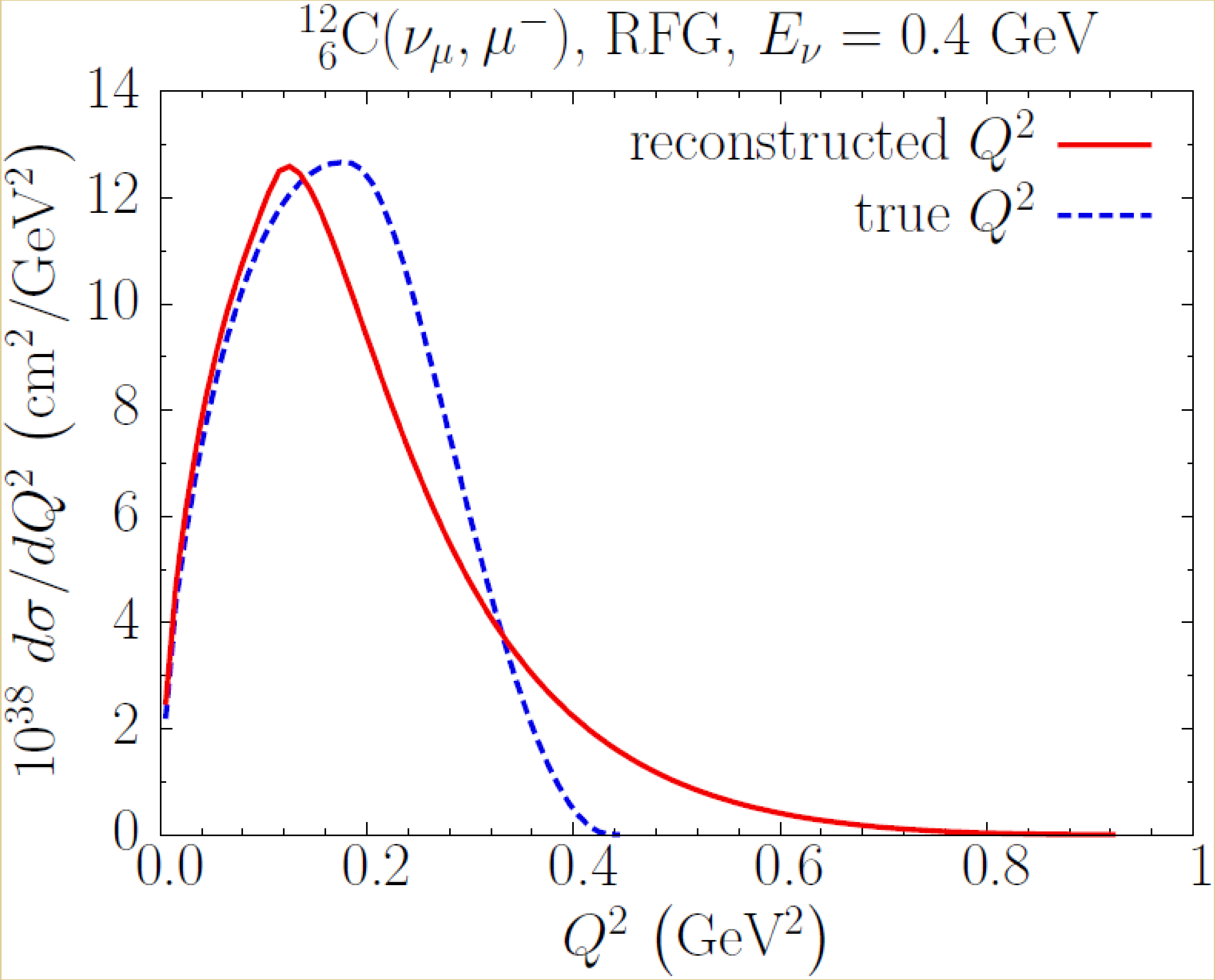
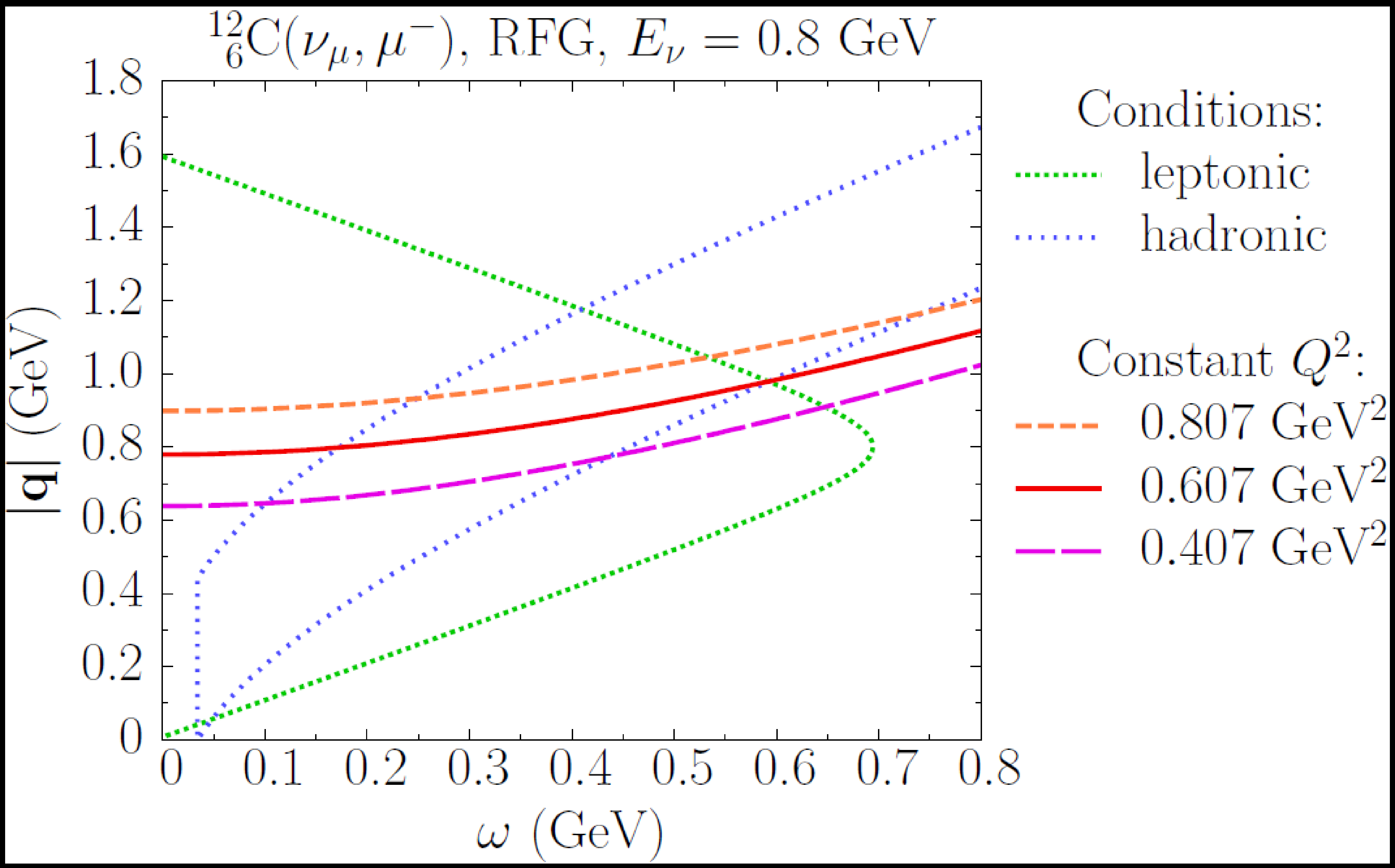


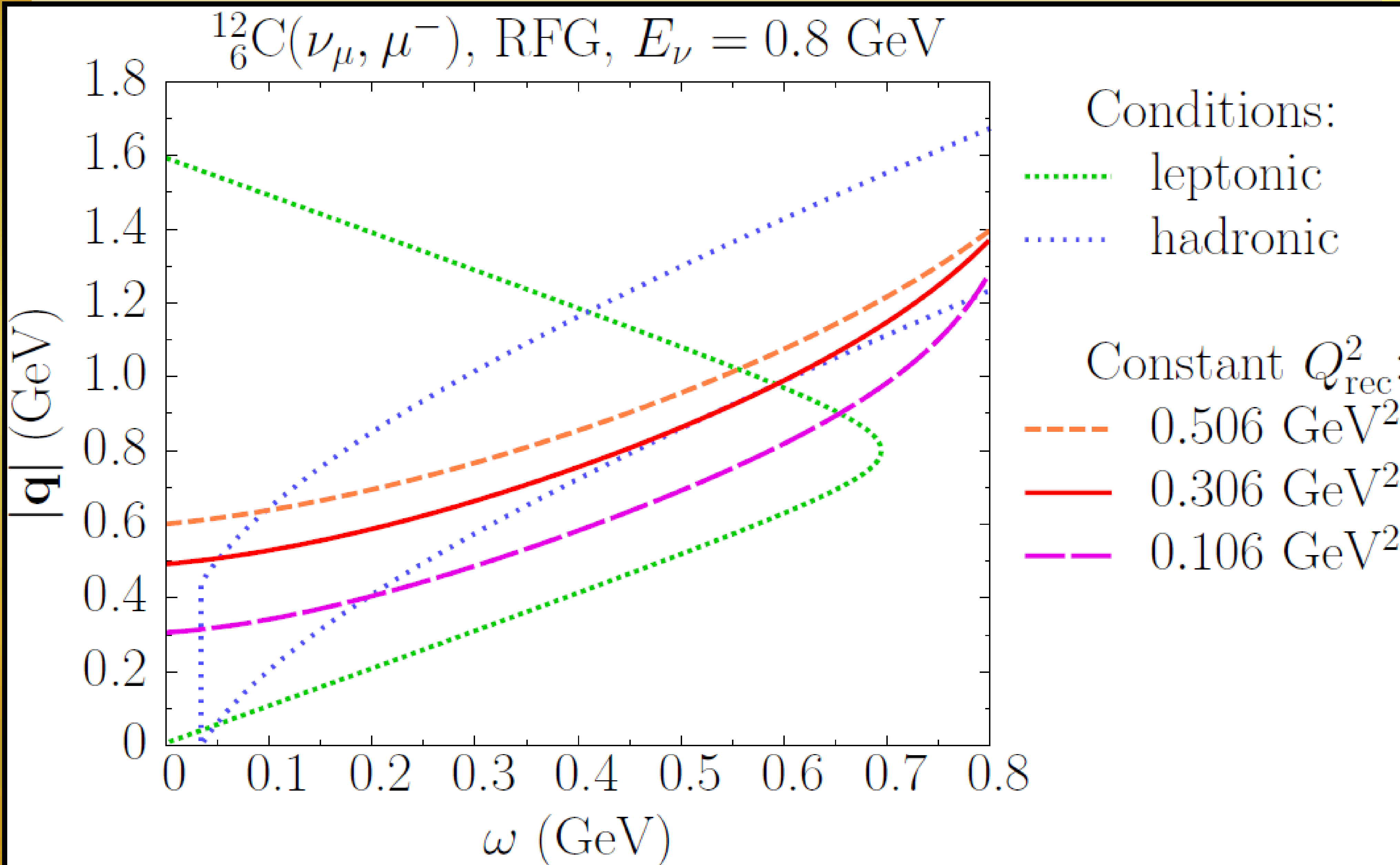
Q^2 vs. Q^2_{rec} for fixed energy



Q^2 at the (ω, |q|) plane



Q^2_{rec} at the (ω, |q|) plane



Why these conclusions are model-independent?

The presented effects are related to the Jacobian only, not to the specific (model-dependent) cross section

$$\int dE_\nu \underline{J(Q^2, Q^2_{\rm rec}, E_\nu)} \frac{d\sigma}{dQ^2_{\rm rec}} \Phi(E_\nu) = \int dE_\nu \frac{d\sigma}{dQ^2} \Phi(E_\nu)$$

Relation between Q^2 and Q^2_{rec} is **complicated** and involves **neutrino energy**.

The physics is **relatively simple** in terms of **$|q|$**.

Using Q^2 makes the situation more difficult,

and Q^2_{rec} produces further complications.

New variables

Proposal of new variables

Instead of Q^2_{rec} one may analyze data using

$$\beta = E_\mu - |\mathbf{k}'| \cos\theta$$

or

$$\phi = \frac{1}{m_\mu + \beta}$$

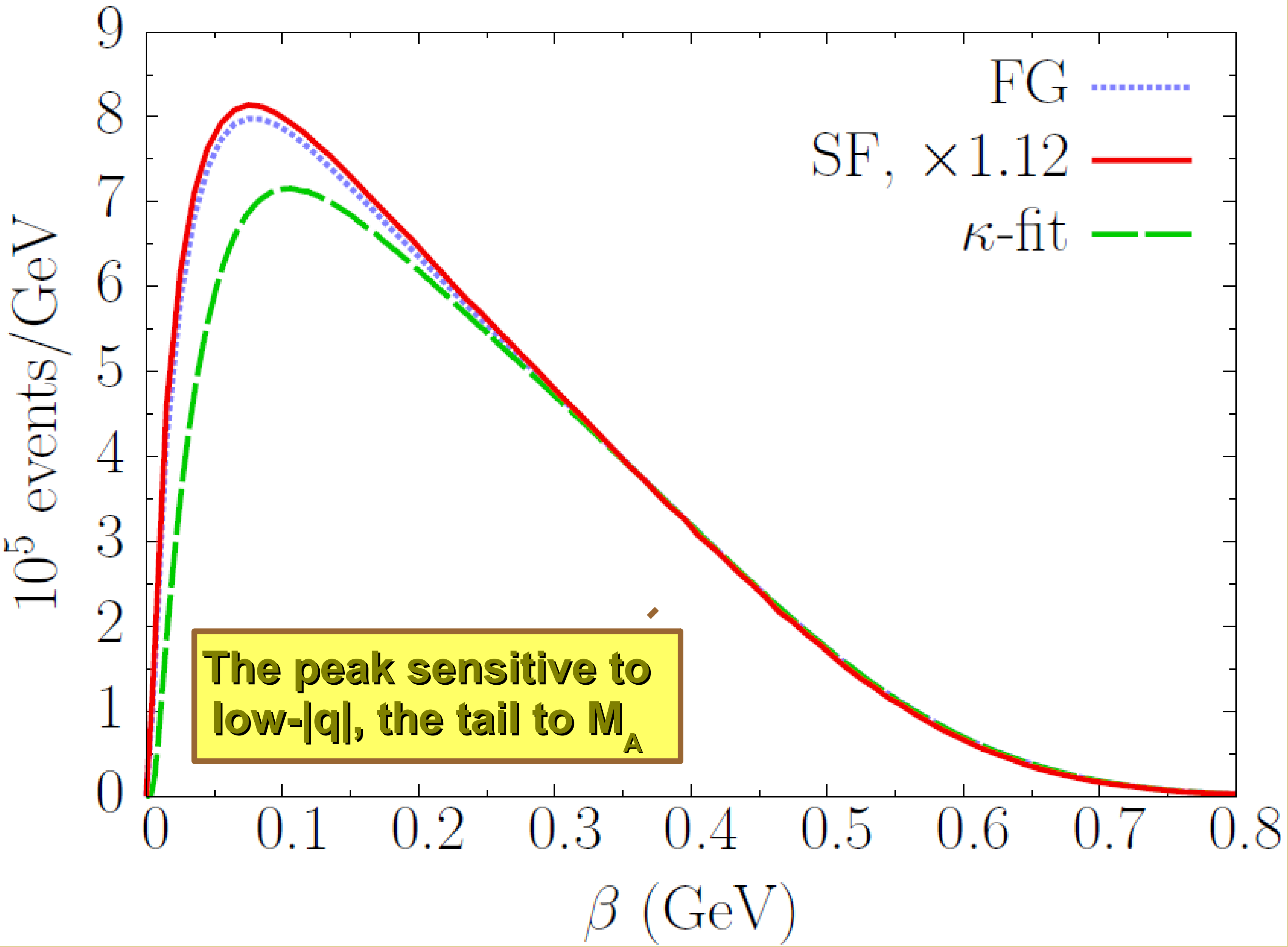
Proposal of new variables

Advantages:

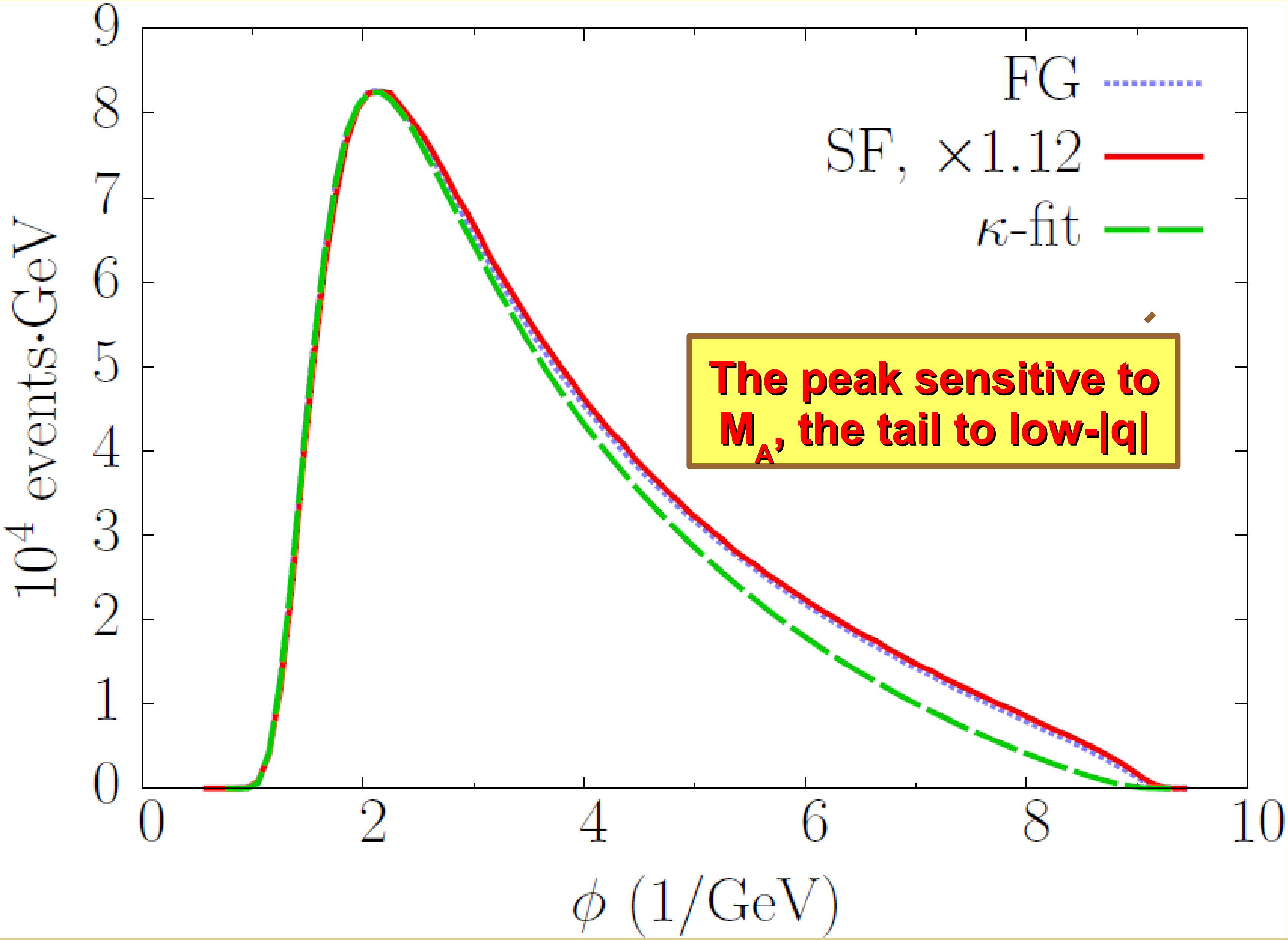
- model independent
- contain only measurable quantities
- independent of the interaction's dynamics, work well even for low energy
- sensitive to the axial mass due to

$$\beta = \frac{k \cdot k'}{E_\nu} = \frac{Q^2 + m_\mu^2}{2E_\nu}$$

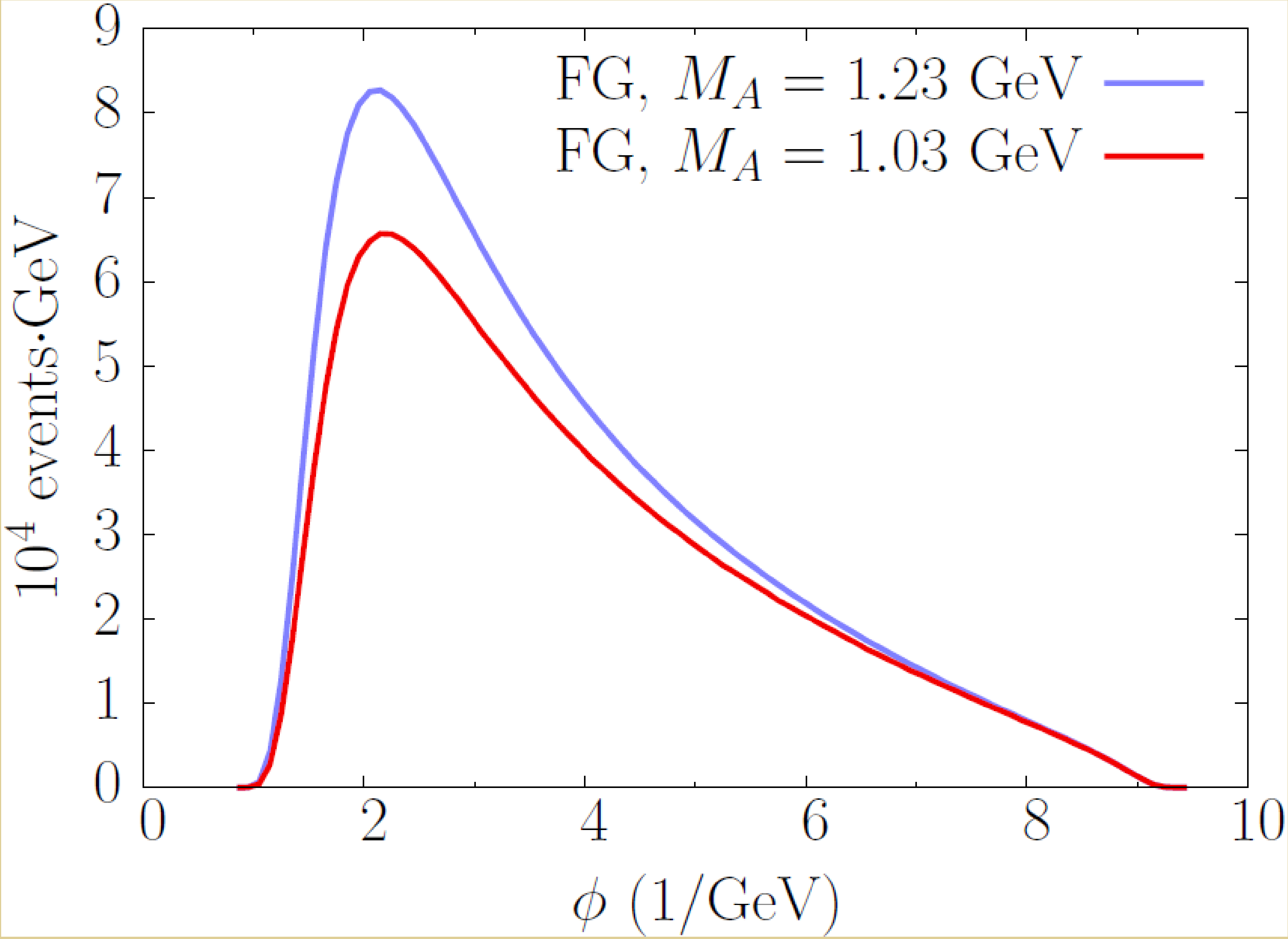
Results for the MiniBoone flux: beta



Results for the MiniBoone flux: phi



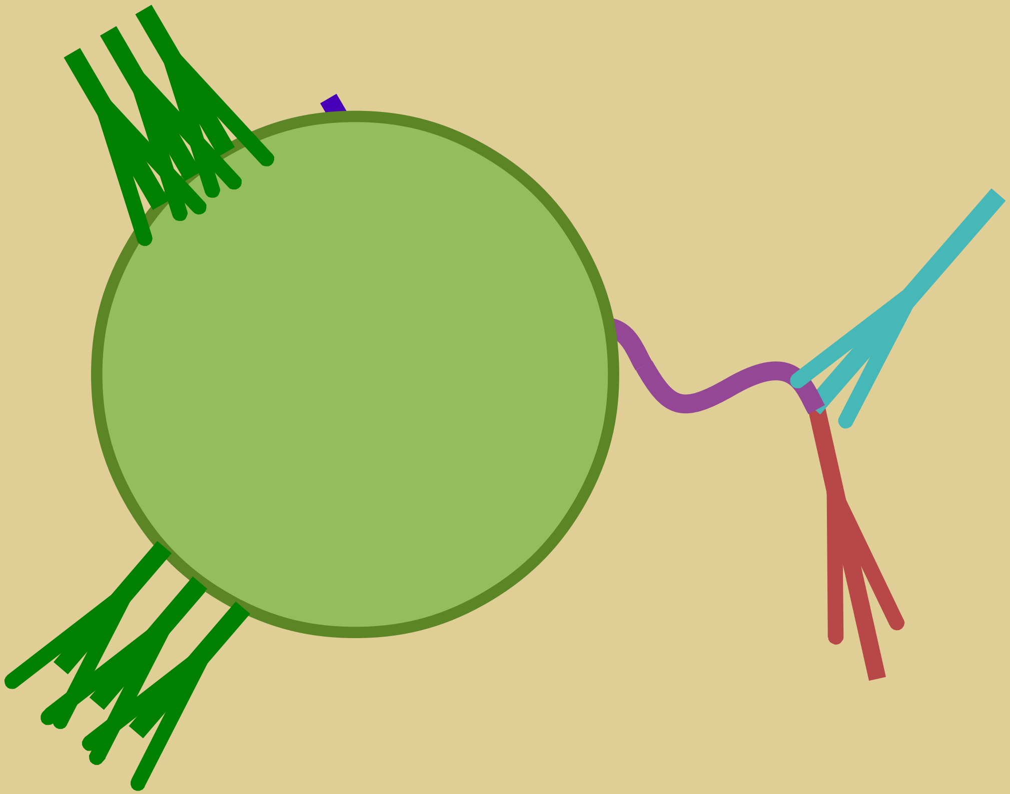
Results for the MiniBoone flux: phi



The impulse approximation

The impulse approximation

The probe **transferring momentum |q|** sees the structures of the size ~ 1/|**q**|



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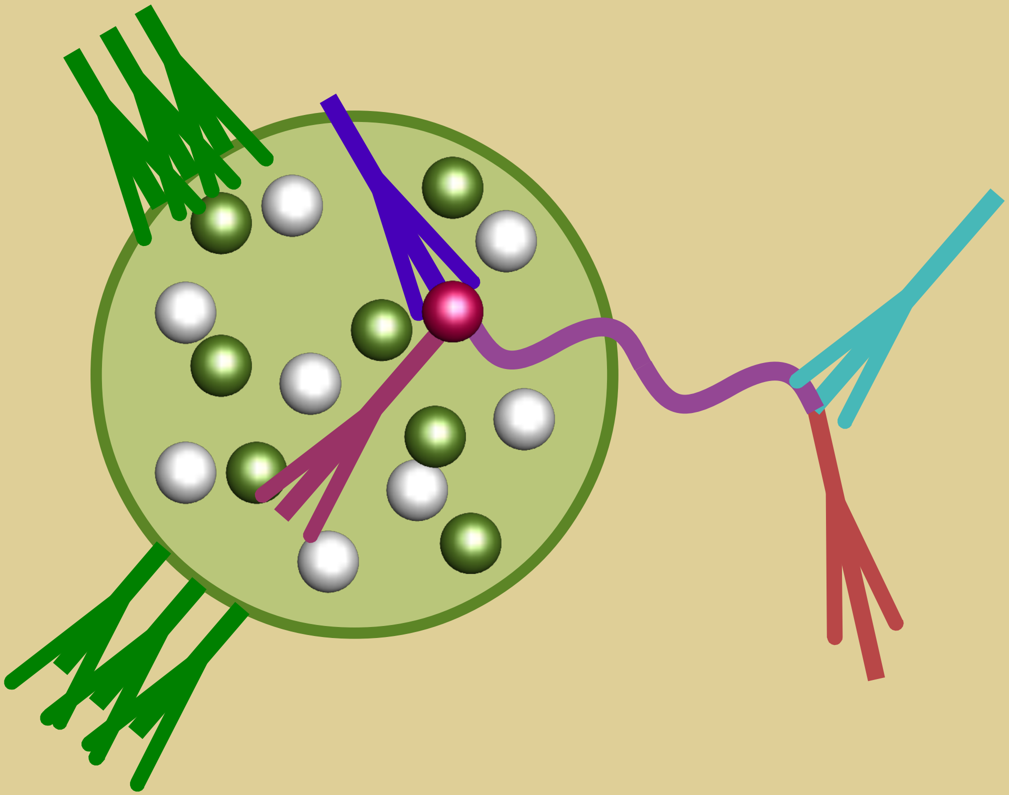
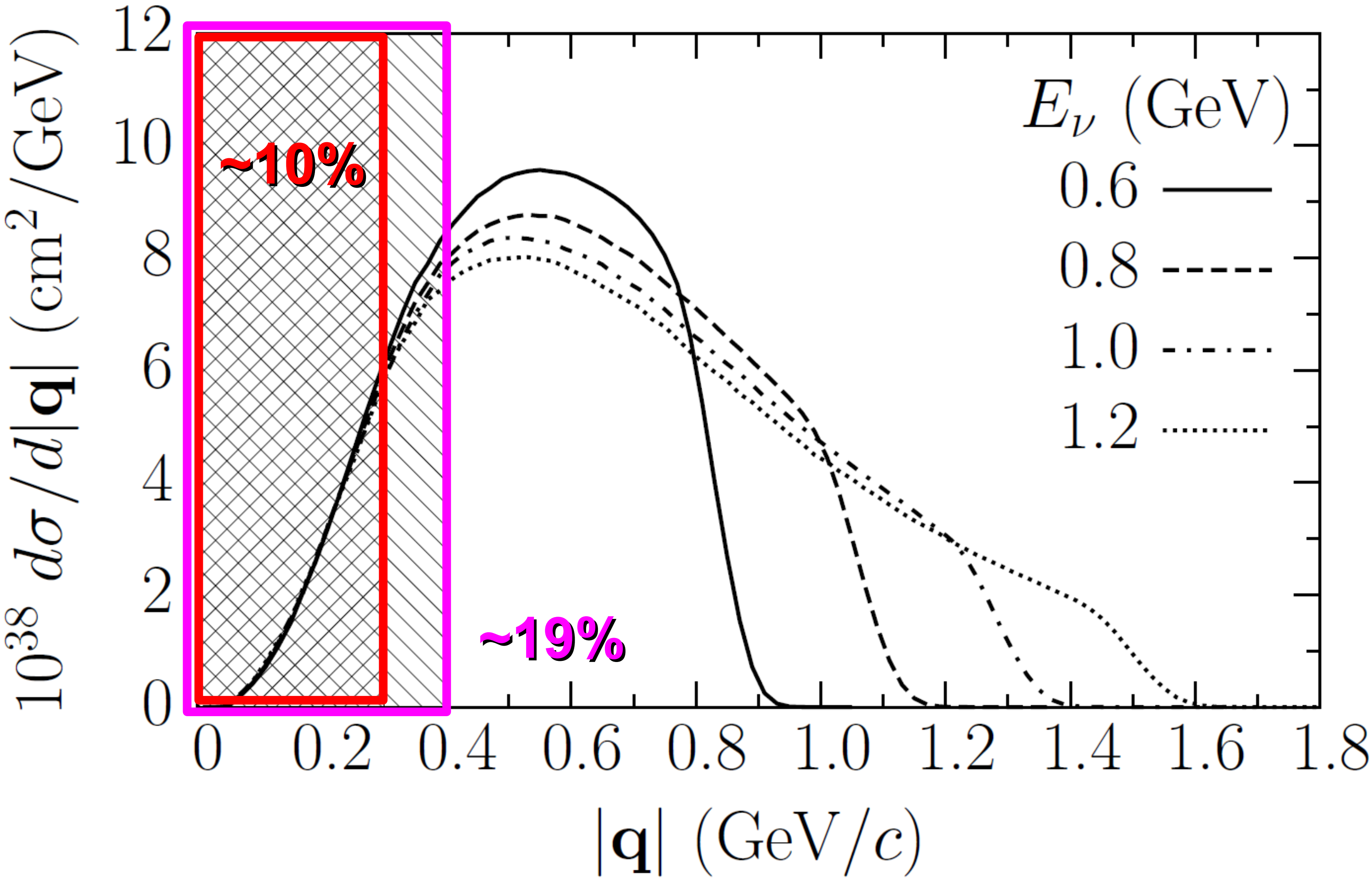


The impulse approximation

Comparison of the of the nuclear response at saturation density calculated using the IA and without it [O. Benhar and N. Farina, Phys. Lett. B680, 305 (2009)] suggests **validity of the IA for $|q| \gtrsim 2k_F$**

Low-|q|'s in the QE x-section



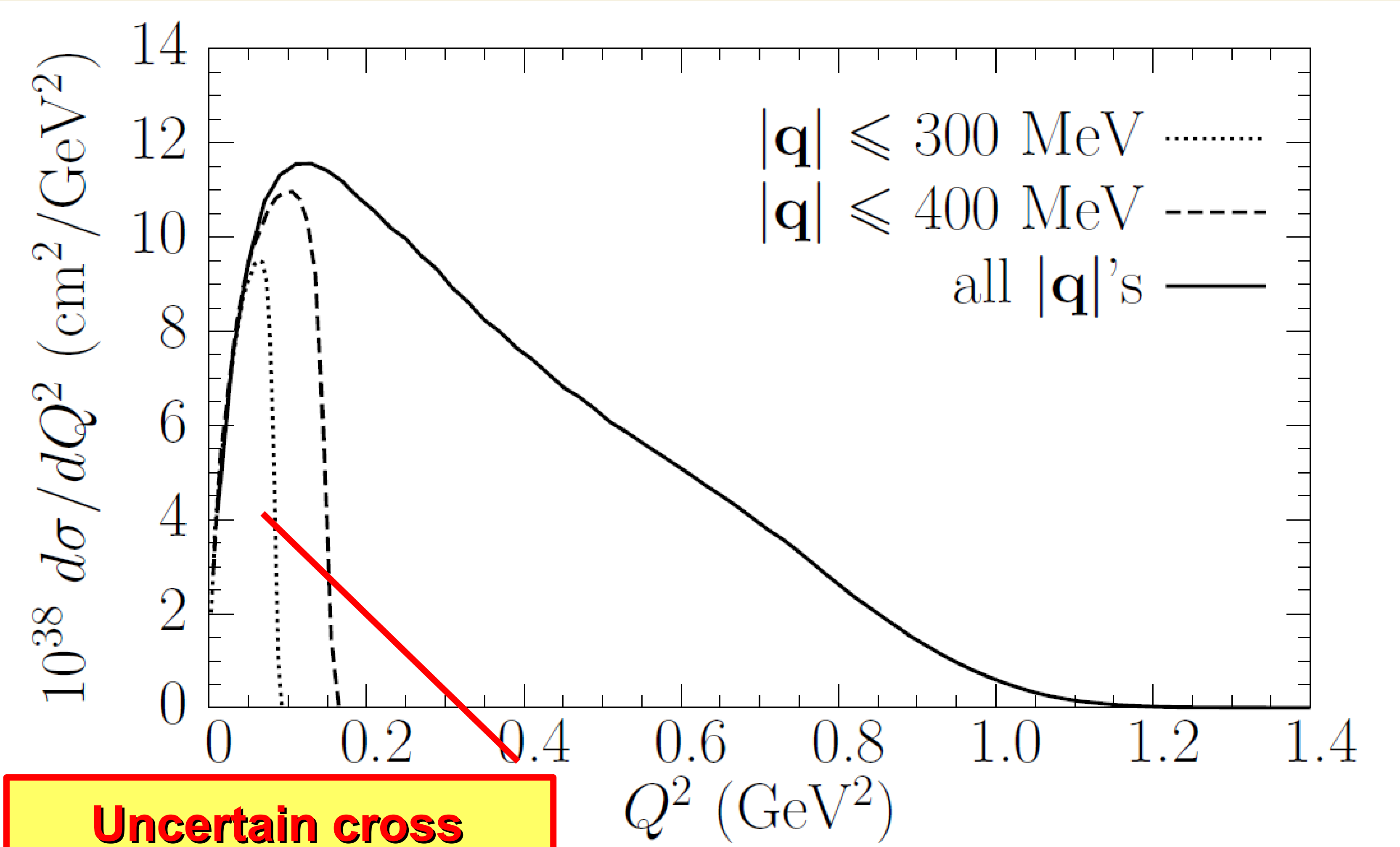
Low-|q|'s in the QE x-section

	Neutrino energy (GeV)						
	0.2	0.4	0.6	0.8	1.0	1.2	1.4
$\lvert\mathbf{q}\rvert \le 300$ MeV/c	97.2%	18.9%	11.9%	10.1%	9.4%	9.1%	9.0%
$\lvert\mathbf{q}\rvert \le 400$ MeV/c	100.0%	43.3%	26.2%	21.6%	19.8%	19.1%	18.8%

	Neutrino energy (GeV)						
	2.0	2.5	3.0	3.5	4.0	4.5	5.0
$\lvert\mathbf{q}\rvert \le 300$ MeV/c	9.1%	9.2%	9.3%	9.3%	9.4%	9.4%	9.5%
$\lvert\mathbf{q}\rvert \le 400$ MeV/c	18.8%	18.9%	19.1%	19.1%	19.3%	19.3%	19.4%

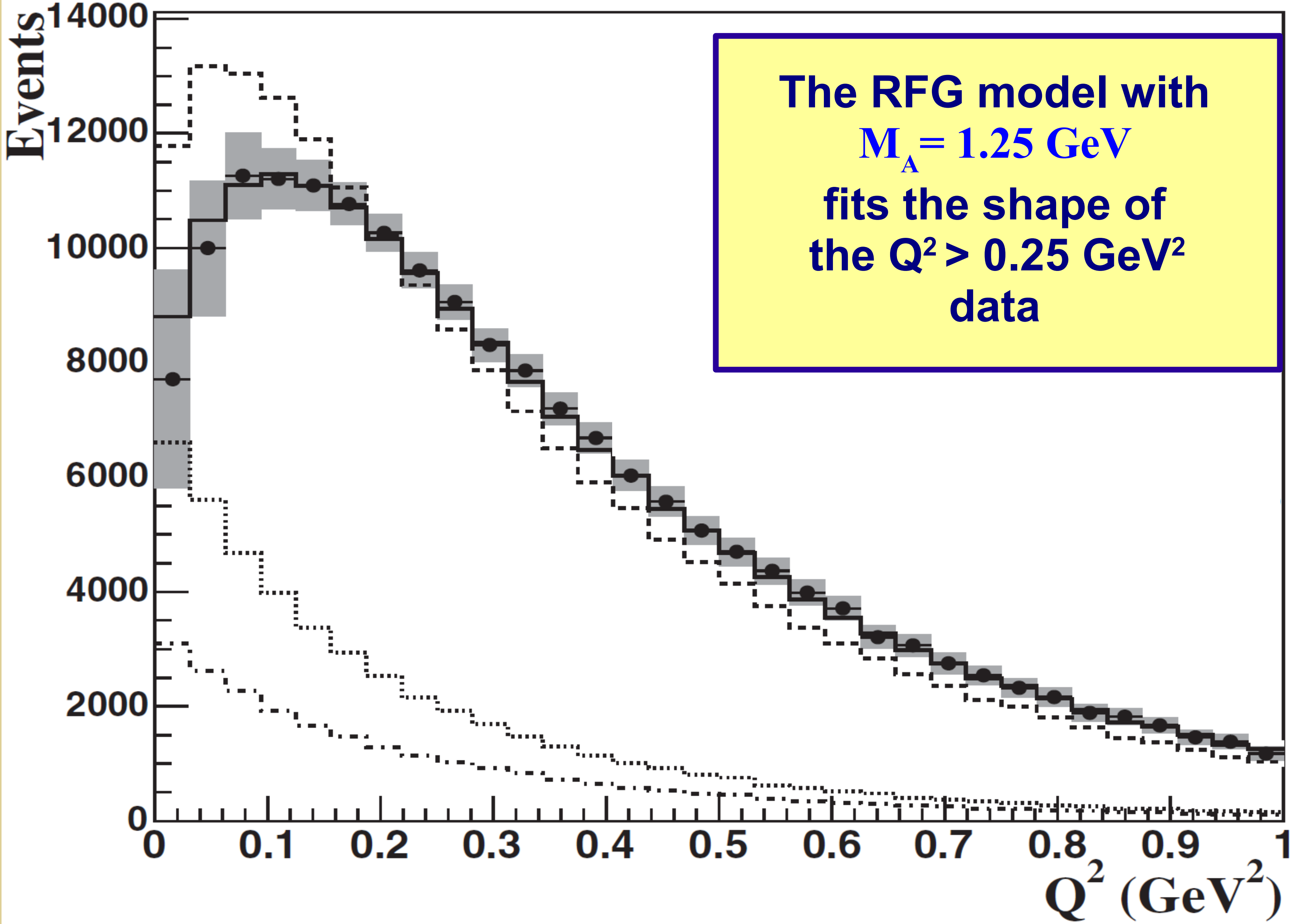
Low-|q|'s in the QE x-section

A.M.A., PoS (NUFACT08) 118 (2008)



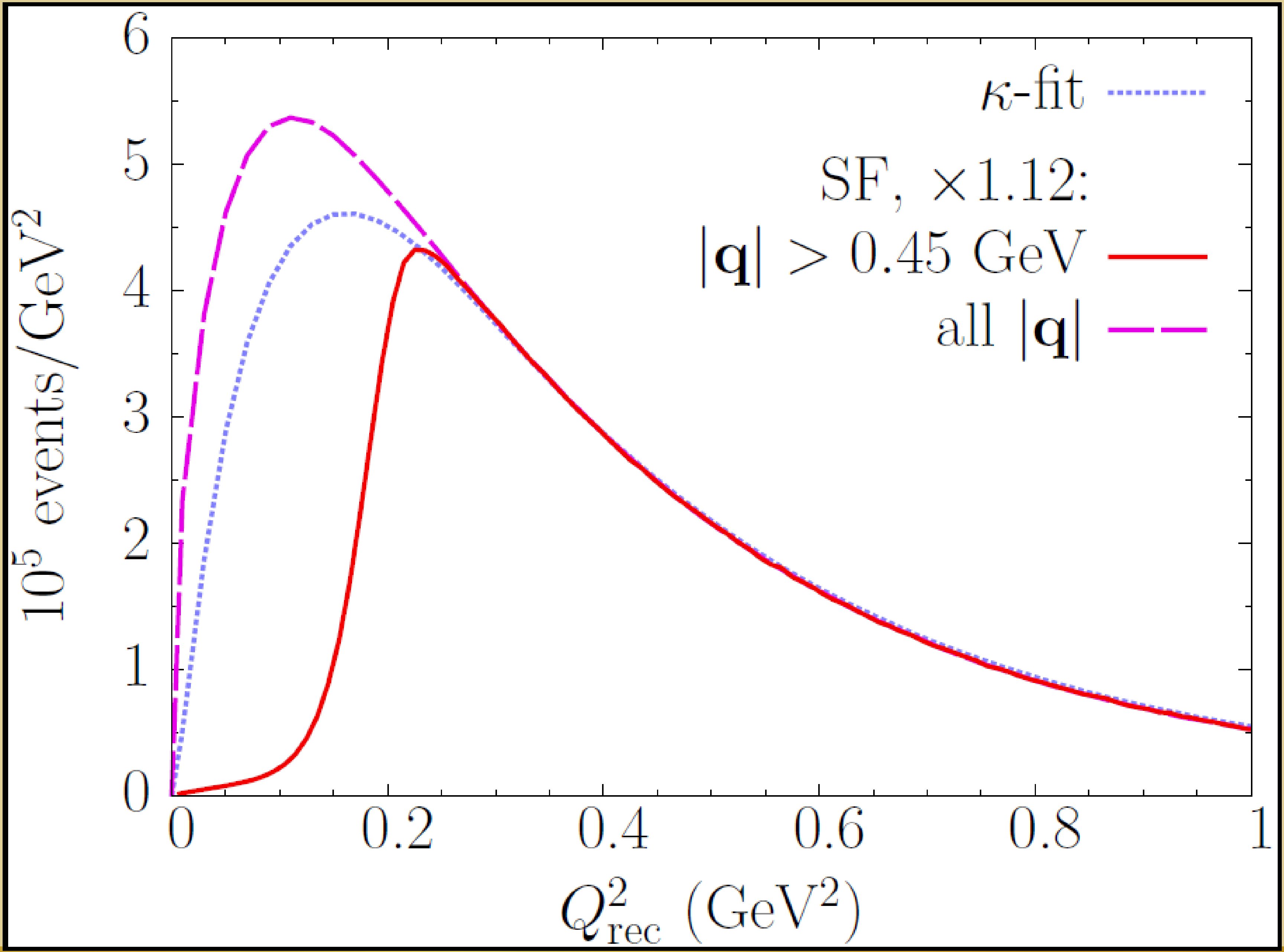
Uncertain cross section

Low-Q^2 problem: MiniBooNE



The RFG model with
$M_A = 1.25$ GeV
fits the shape of
the $Q^2 > 0.25$ GeV^2
data

Comparison to the MiniBooNE's fit



For low |q| one should not rely on the IA, as

NN correlations are important.

Neutrino QE cross section at low-Q^2 is affected by these effects **nearly independently of energy.**

Summary

- The true and reconstructed Q^2 are not equivalent even when flux-averaged event distributions are considered
- At low |q| the IA is not reliable as NN correlations become significant, what affects the QE cross section at any neutrino energy.
- The proposed variables may be useful in data analysis.

Electroweak nuclear-matter response at moderate momentum transfer

based on the article
A.M.A. and O. Benhar
Phys. Rev. C **83**, 054616 (2011)

December 16, 2011, Trento

Current reduction

The upper and lower Pauli spinor describing on-shell Dirac particle are related through

$$\phi_\sigma = \hat{\mathrm{p}} \cdot \sigma \chi_\sigma ,$$

what allows to reduce the current as

$$\left(\chi^\dagger_{\sigma'},\ \phi^\dagger_{\sigma'}\right)(\Gamma^\mu_V + \Gamma^\mu_A)\begin{pmatrix}\chi_\sigma \\ \phi_\sigma\end{pmatrix} \to \chi^\dagger_{\sigma'}(V^\mu + A^\mu)\chi_\sigma ,$$

LO result

$$V^0 = F^1,$$

$$V^k = \left(F^1 + F^2\right) \frac{i\left[\sigma \times (\mathbf{p}' - \mathbf{p})\right]^k}{2M} + F^1 \frac{(\mathbf{p} + \mathbf{p}')^k}{2M},$$

$$A^0 = F_A \frac{\sigma \cdot (\mathbf{p}' + \mathbf{p})}{2M} - F_P \frac{\mathbf{p}'^2 - \mathbf{p}^2}{2M^2} \frac{\sigma \cdot (\mathbf{p}' - \mathbf{p})}{2M},$$

$$A^k = F_A \sigma^k - F_P \frac{(\mathbf{p}' - \mathbf{p})^k}{M} \frac{\sigma \cdot (\mathbf{p}' - \mathbf{p})}{2M}.$$

Exact result

$$\frac{V^0}{\lambda_p\lambda_{p'}} = \left(F^1+F^2\right)\left[1+\hat{\mathrm{p}}'\cdot\hat{\mathrm{p}}+i\sigma\cdot(\hat{\mathrm{p}}'\times\hat{\mathrm{p}})\right]$$
$$-F^2\frac{E_{p'}+E_p}{2M}\left[1-\hat{\mathrm{p}}'\cdot\hat{\mathrm{p}}-i\sigma\cdot(\hat{\mathrm{p}}'\times\hat{\mathrm{p}})\right],$$

$$\frac{V^k}{\lambda_p\lambda_{p'}} = \left(F^1+F^2\right)\left[(\hat{\mathrm{p}}'+i\sigma\times\hat{\mathrm{p}}')^k+(\hat{\mathrm{p}}-i\sigma\times\hat{\mathrm{p}})^k\right]$$
$$-F^2\frac{(\mathrm{p}+\mathrm{p}')^k}{2M}\left[1-\hat{\mathrm{p}}'\cdot\hat{\mathrm{p}}-i\sigma\cdot(\hat{\mathrm{p}}'\times\hat{\mathrm{p}})\right],$$

$$\frac{A^0}{\lambda_p\lambda_{p'}} = F_A\,\sigma\cdot(\hat{\mathrm{p}}'+\hat{\mathrm{p}})-F_P\frac{E_{p'}-E_p}{M}\,\sigma\cdot(\hat{\mathrm{p}}'-\hat{\mathrm{p}}),$$

$$\frac{A^k}{\lambda_p\lambda_{p'}} = F_A\left[\sigma^k+\hat{p}'^k(\sigma\cdot\hat{\mathrm{p}})+\hat{p}^k(\sigma\cdot\hat{\mathrm{p}}')-(\hat{\mathrm{p}}'\cdot\hat{\mathrm{p}})\,\sigma^k\right]$$
$$-iF_A(\hat{\mathrm{p}}'\times\hat{\mathrm{p}})^k-F_P\frac{(\mathrm{p}'-\mathrm{p})^k}{M}\,\sigma\cdot(\hat{\mathrm{p}}'-\hat{\mathrm{p}}),$$

Electron scattering

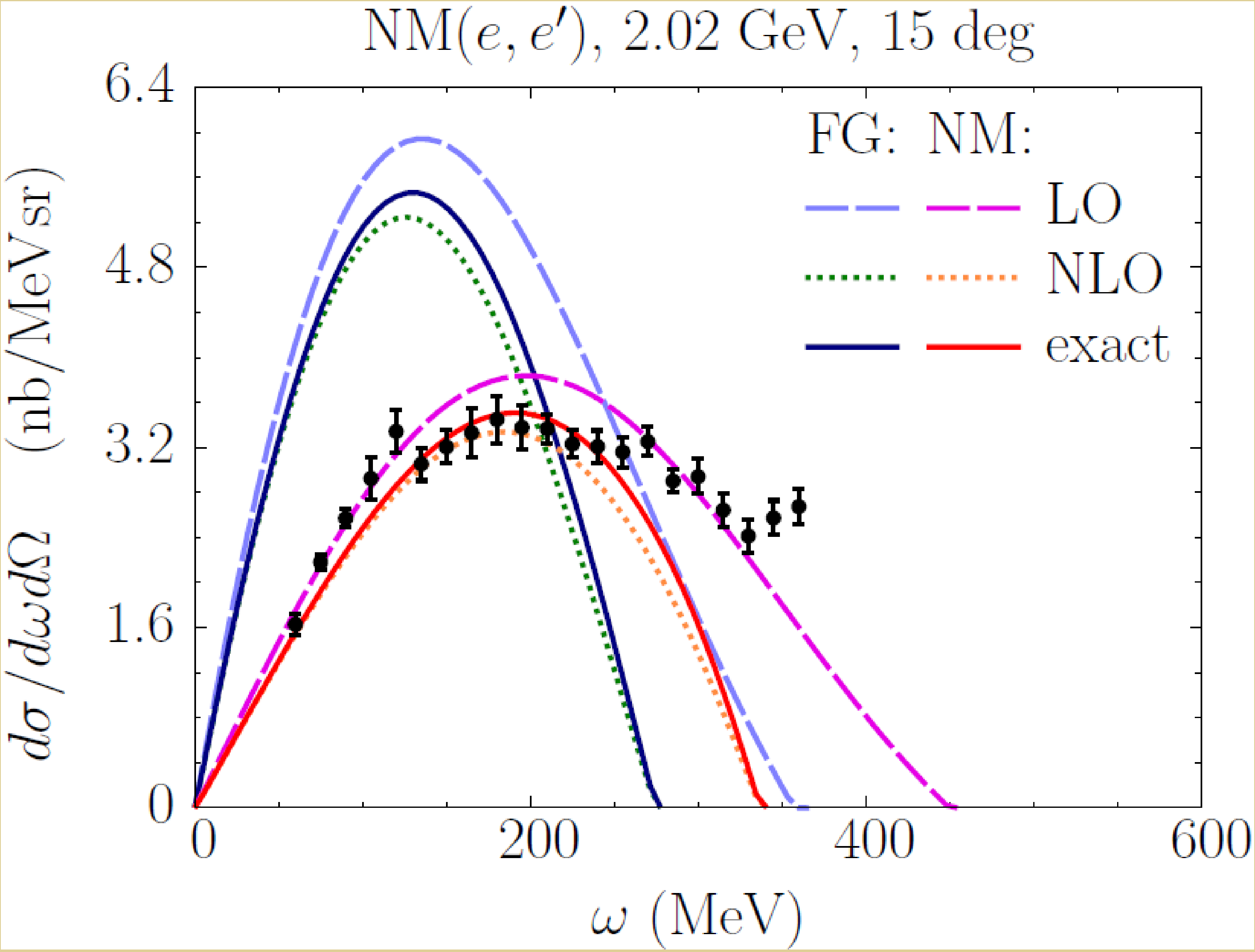
$$V^0 = F^1,$$

$$V^k = \left(F^1 + F^2\right) \frac{i\left[\sigma \times (\mathbf{p}' - \mathbf{p})\right]^k}{2M} + F^1 \frac{(\mathbf{p} + \mathbf{p}')^k}{2M},$$

$$A^0 = F_A \frac{\sigma \cdot (\mathbf{p}' + \mathbf{p})}{2M} - F_P \frac{\mathbf{p}'^2 - \mathbf{p}^2}{2M^2} \frac{\sigma \cdot (\mathbf{p}' - \mathbf{p})}{2M},$$

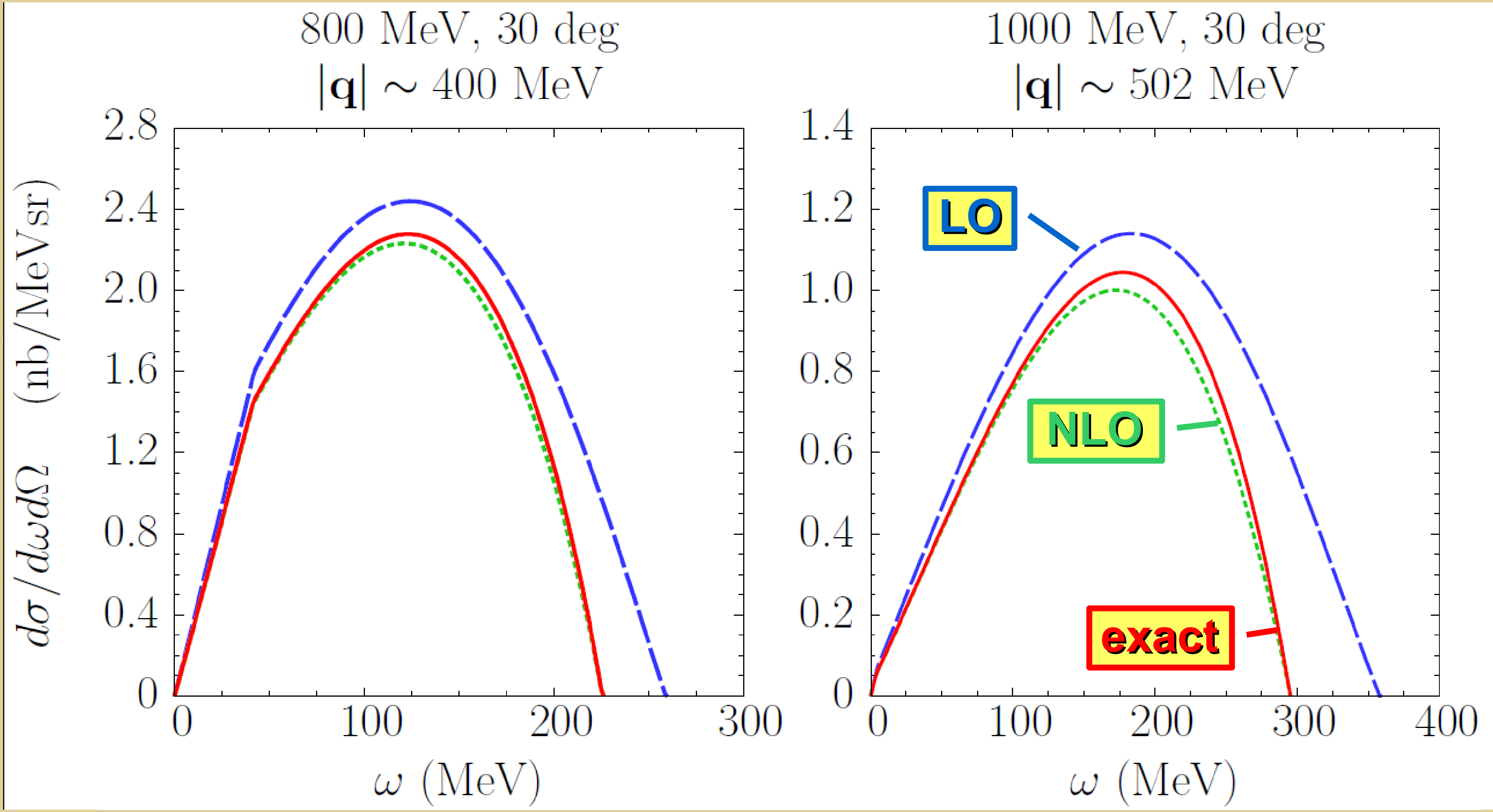
$$A^k = F_A \sigma^k - F_P \frac{(\mathbf{p}' - \mathbf{p})^k}{M} \frac{\sigma \cdot (\mathbf{p}' - \mathbf{p})}{2M}.$$

Electron scattering

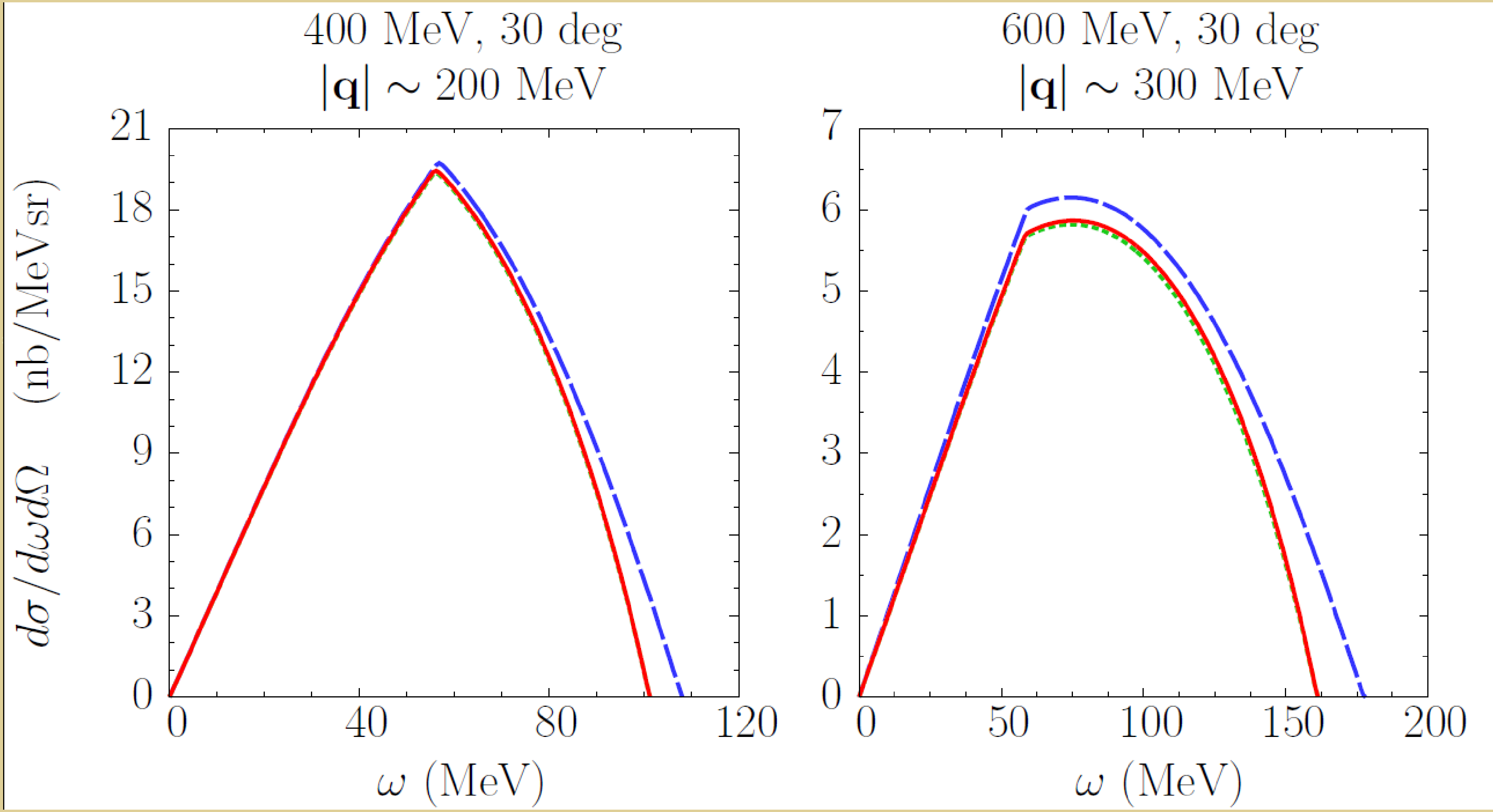


Data from D.B. Day et al., PRC 40, 1011 (1989)

Electron scattering

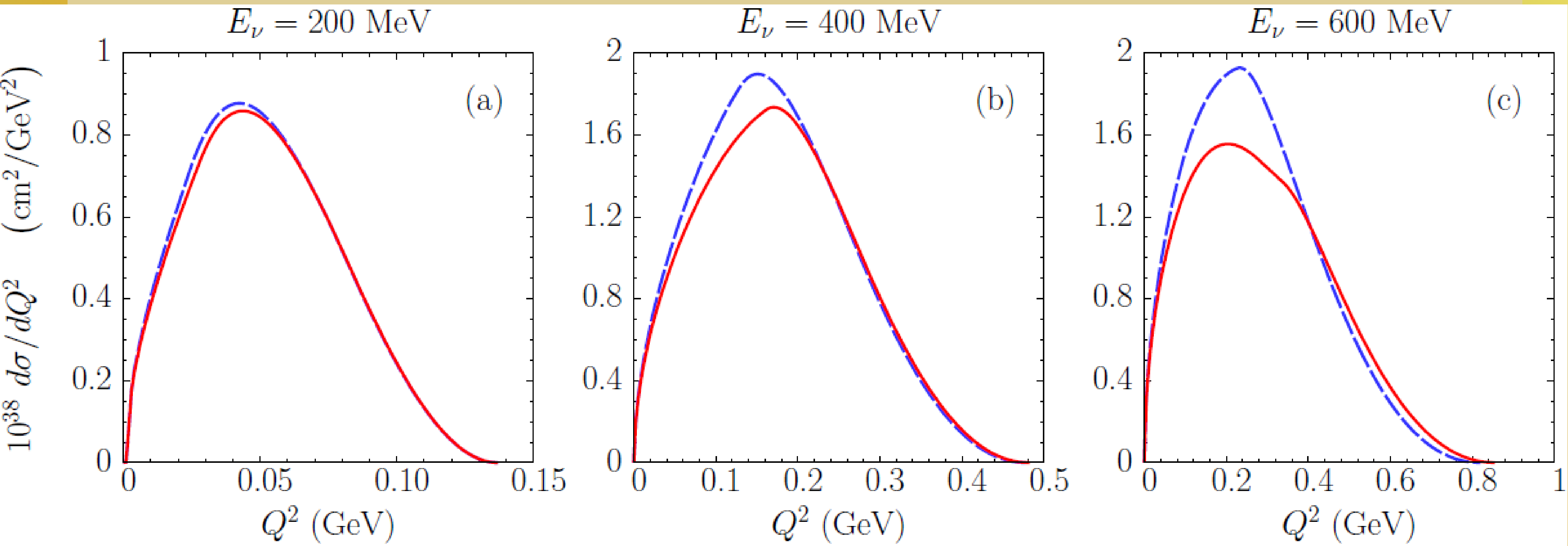


Electron scattering



Data from D.B. Day et al., PRC 40, 1011 (1989)

Neutrino scattering



Summary

- Exact calculations doable for the nuclear matter

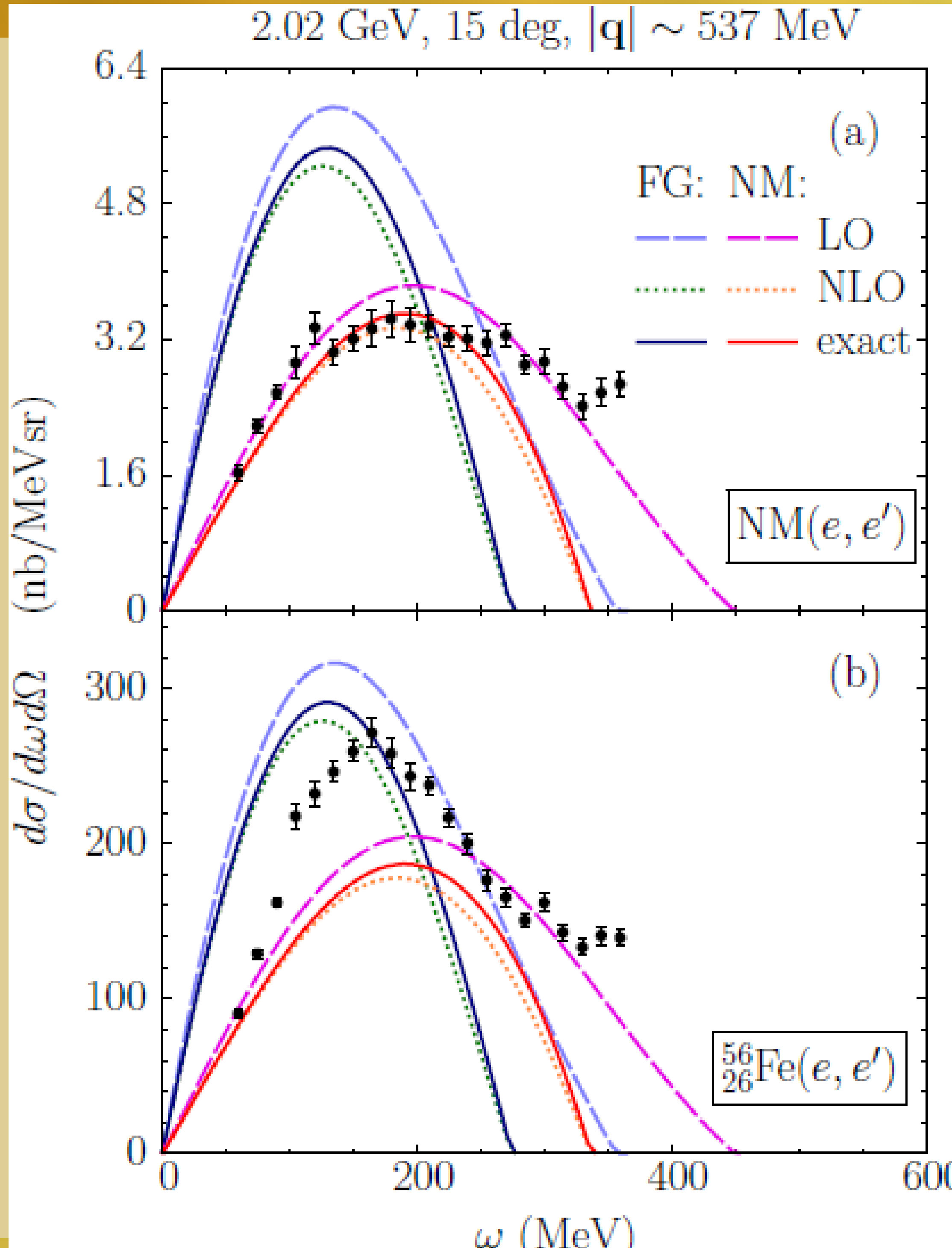
- LO approximation fails for |q| > 300 MeV,

  relativistic kinematic is important

Similar conclusions for the MF approach in

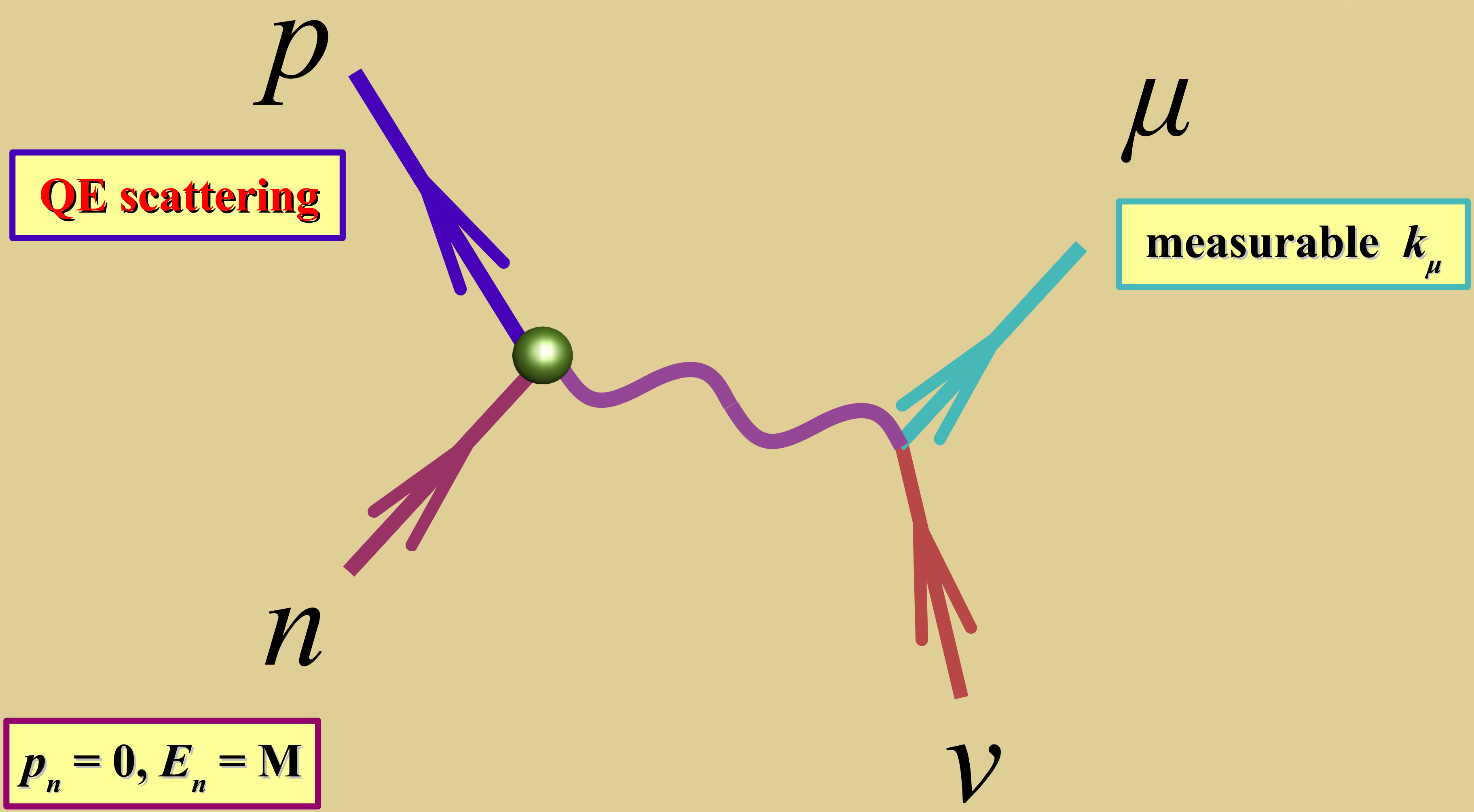
J.E. Amaro et al., Nucl. Phys. A 602, 263 (1996);
J.E. Amaro et al., Phys. Rep. 368, 317 (2002).

Back-up slides


2.02 GeV, 15 deg, |q| ~ 537 MeV
(a)
FG: NM:
LO
NLO
exact
NM(e, e′)
(b)
56 26 Fe(e, e′)
dσ/dωdΩ (nb/MeV sr)
ω (MeV)
6.4
4.8
3.2
1.6
0
300
200
100
0
0
200
400
600

In neutrino physics many complications result from **non-monoenergetic** beams and the necessity for reconstruction of the probe's energy.

Neutrino scattering off a free neutron



Neutrino scattering off a free neutron

What we know:

- the final state is only p and μ

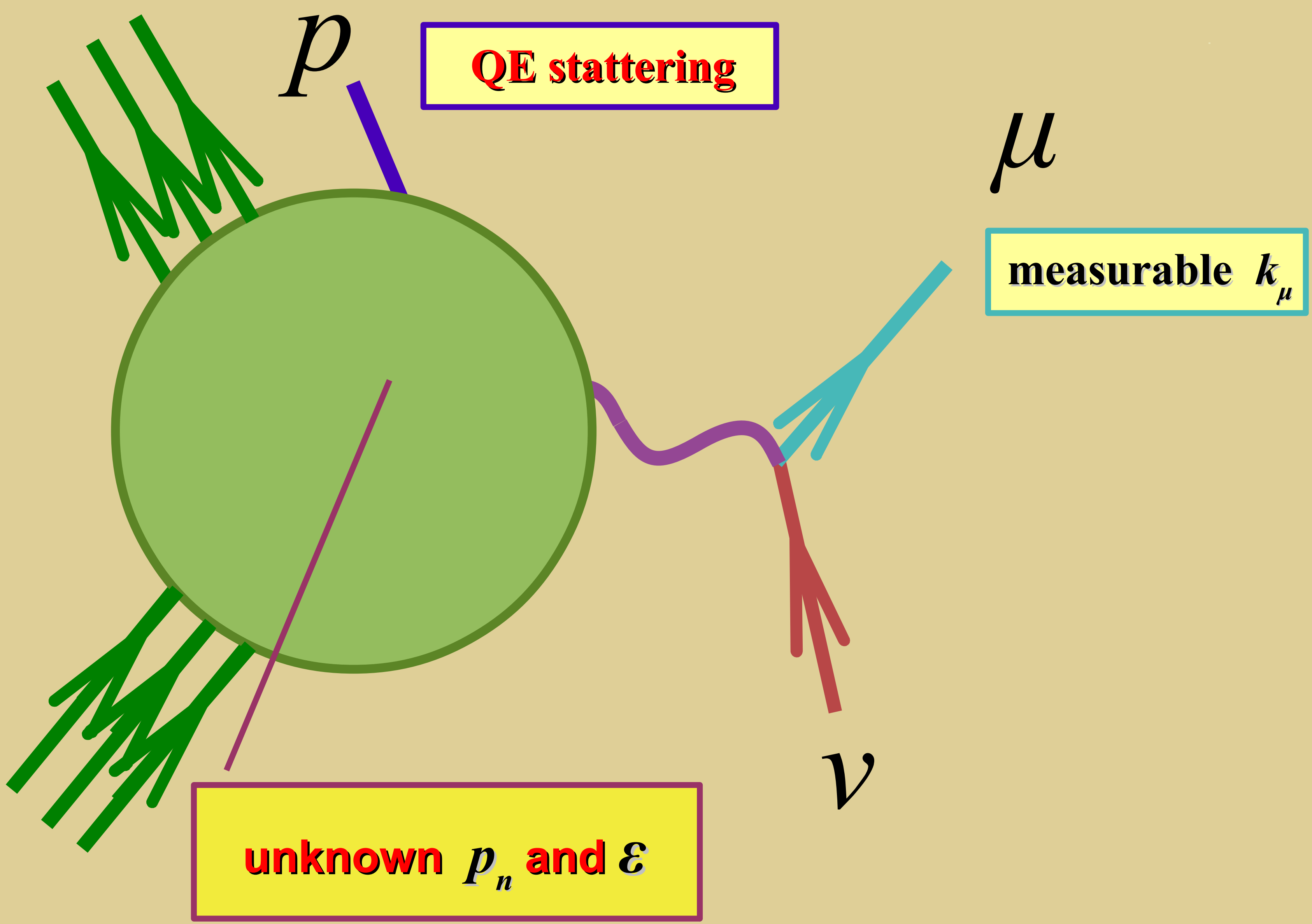
$$(E_n + E_\nu - E_\mu)^2 - (\mathbf{p}_n + \mathbf{k}_\nu - \mathbf{k}_\mu)^2 = M^2$$

- n is at rest

$$(M + E_\nu - E_\mu)^2 - (\mathbf{k}_\nu - \mathbf{k}_\mu)^2 = M^2$$

- Hence $\boldsymbol{E}_\nu = |\boldsymbol{k}_\nu|$ **may be calculated** from the measured vector $\boldsymbol{k}_\mu$ i.e. from $|\boldsymbol{k}_\mu|$ and muon production angle θ

Neutrino scattering off a free neutron



Neutrino scattering off a free neutron

What we know:

- the initial neutron (?) is bound and moves

$$(\underline{E_n} - \underline{\epsilon} + E_\nu - E_\mu)^2 - (\underline{\mathbf{p}_n} + \mathbf{k}_\nu - \mathbf{k}_\mu)^2 = M^2$$

Approximations:

$p_n = \mathbf{0}$ and constant ε

$$E_\nu^{\text{rec}} \neq E_\nu$$

Q^2 and Q^2_{rec}

- **True Q^2**

$$Q^2 = (\mathbf{k}_\nu - \mathbf{k}_\mu)^2 - (E_\nu - E_\mu)^2$$

$$Q^2 = -m_\mu^2 + 2E_\nu(E_\mu - |\mathbf{k}_\mu| \cos\theta)$$

- **Reconstructed Q^2**

$$Q^2_{\rm rec} = -m_\mu^2 + 2E_\nu^{\rm rec}(E_\mu - |\mathbf{k}_\mu| \cos\theta)$$