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On analysis of the Q^2-dependence of QE ν_μ-nucleus interactions

In collaboration with Omar Benhar and Nicola Farina,
arXiv:1001.0481

Elba XI Workshop
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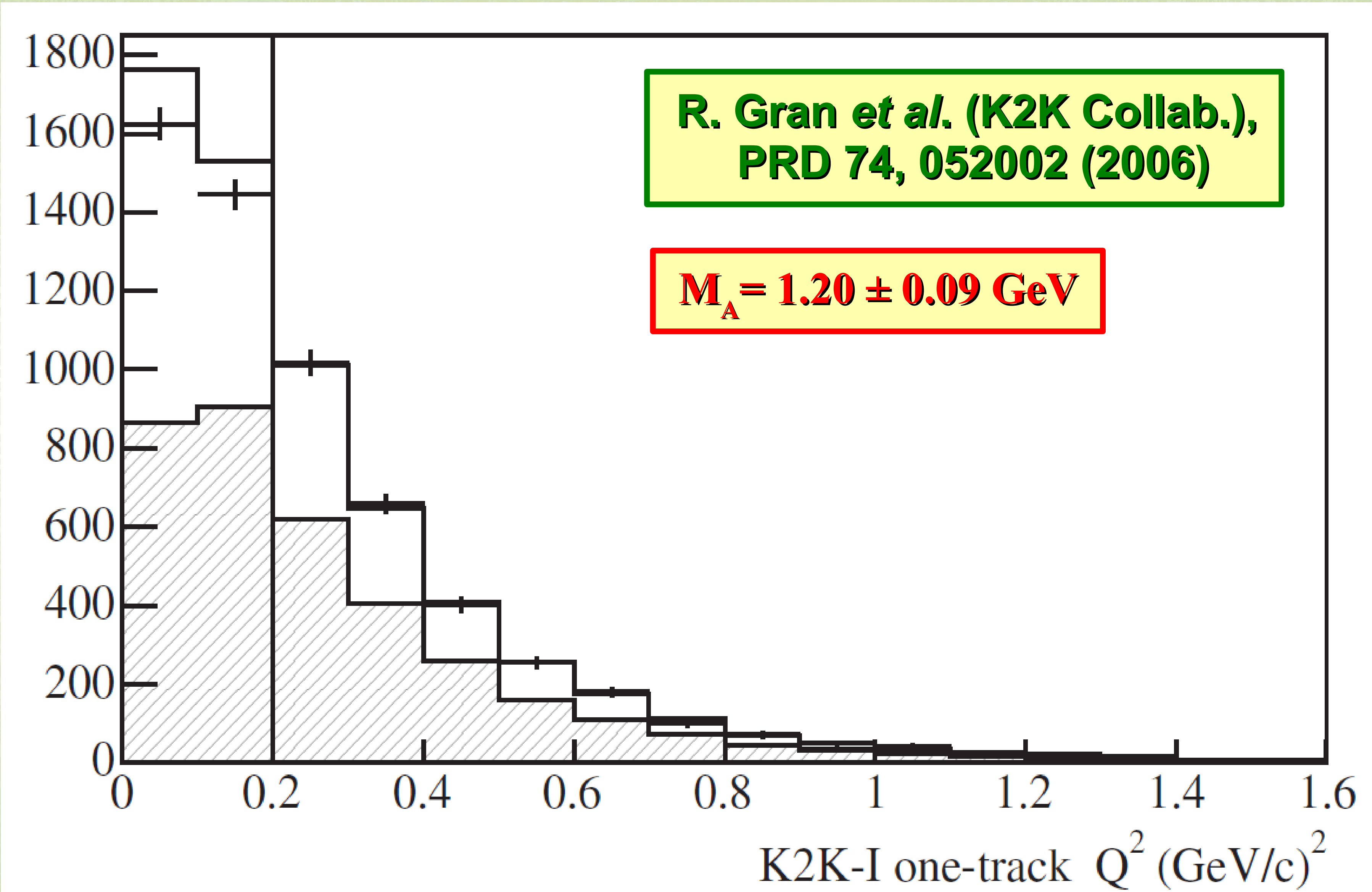
Outline

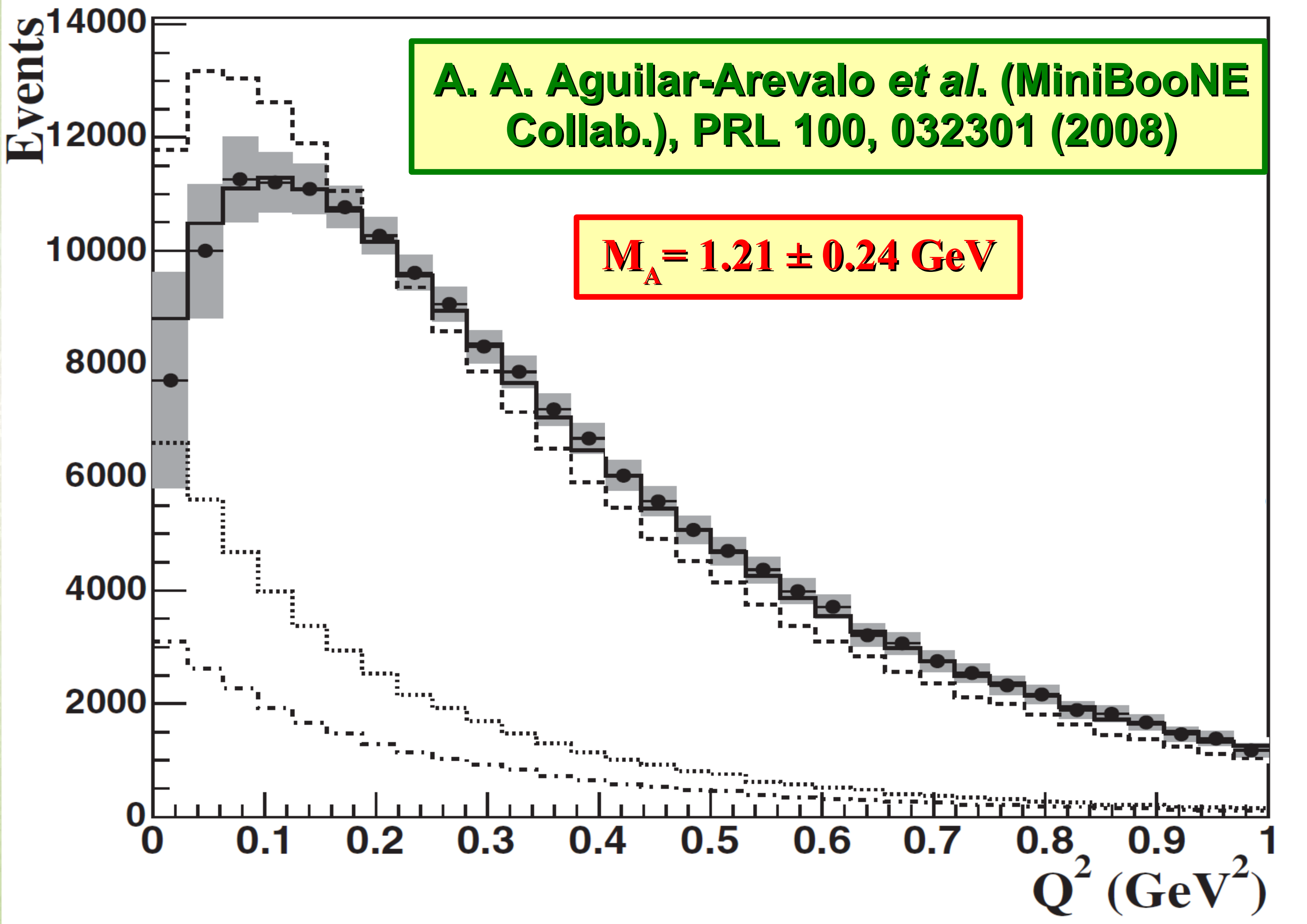
- Introduction
- Are Q^2 vs. Q^2_{rec} really equivalent?
- The impulse approximation
- Proposal of new variables
- Summary

Discrepancy between data and the RFG model

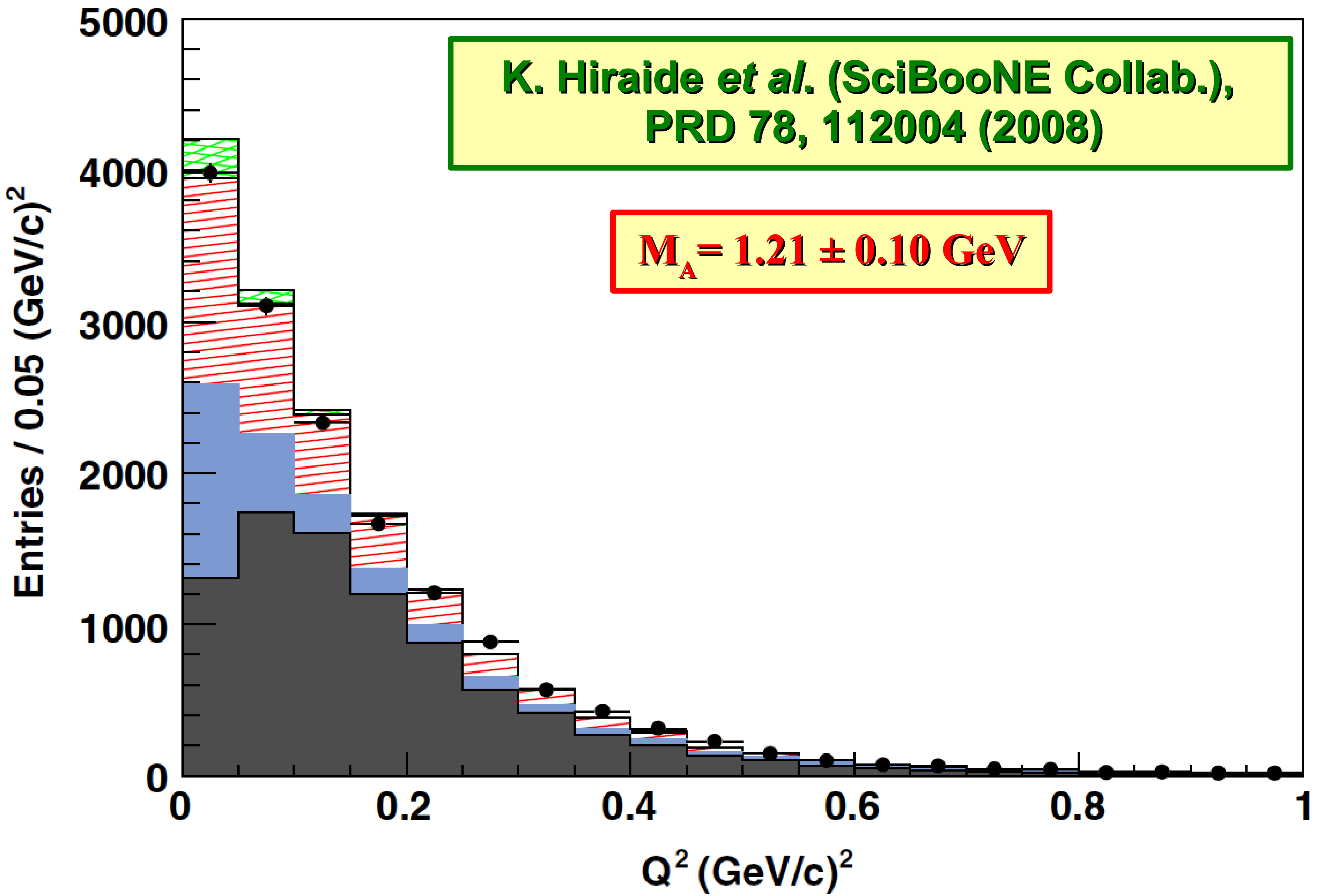
Low-Q^2 problem: K2K



Low-Q^2 problem: MiniBooNE



Low-Q^2 problem:SciBooNE

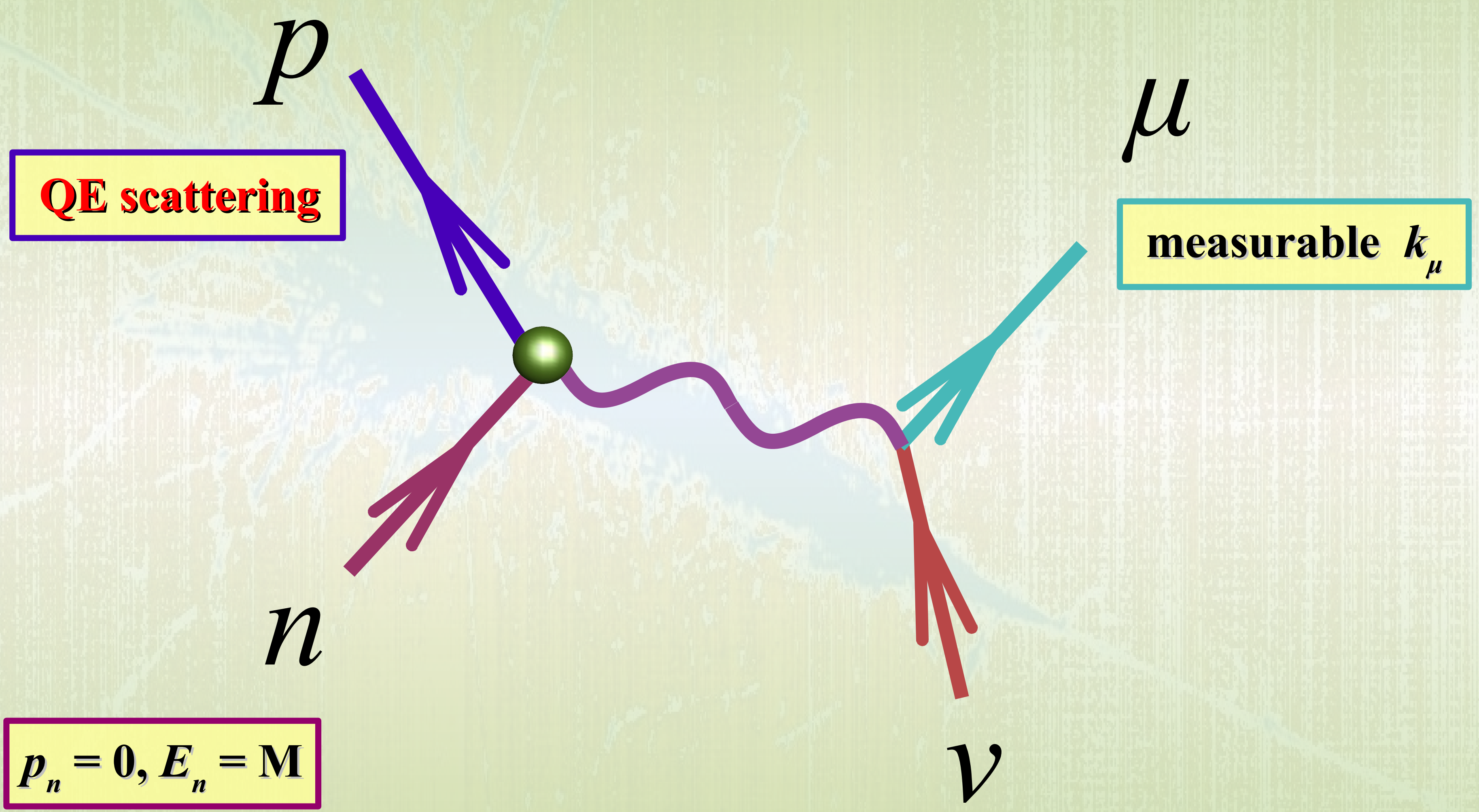


Introduction

Introduction

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

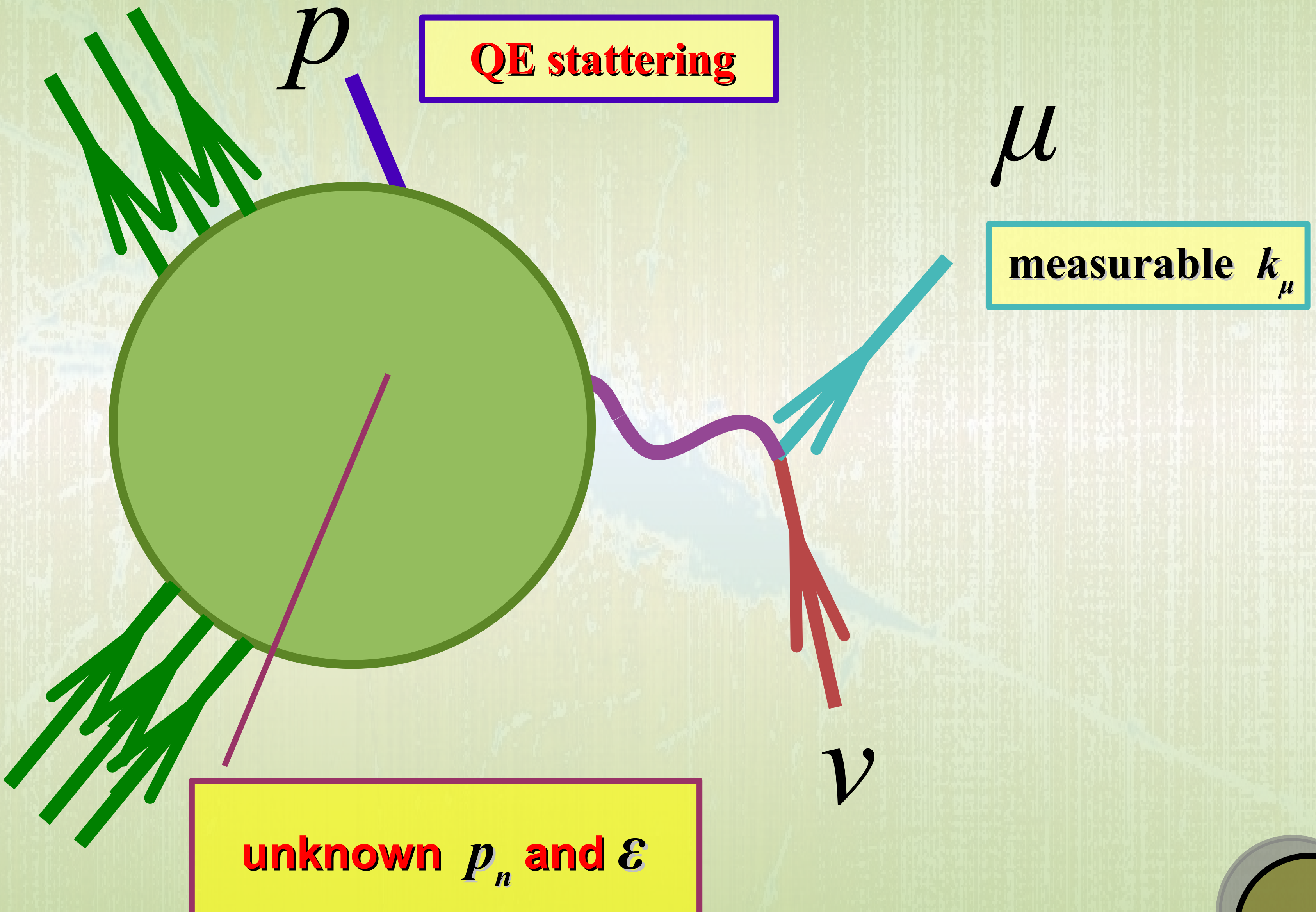
$$(E_n + E_\nu - E_\mu)^2 - (\mathbf{p}_n + \mathbf{k}_\nu - \mathbf{k}_\mu)^2 = M^2$$

- *n* is at rest

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

- Hence $E_\nu = |k_\nu|$ **may be calculated** from the measured vector k_μ i.e. from $|k_\mu|$ and muon production angle θ

Neutrino scattering off a nucleus



Neutrino scattering off a nucleus

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:

$p_n = 0$ and constant ε

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

Q^2 and Q^2_{rec}

- **True Q^2**

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

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

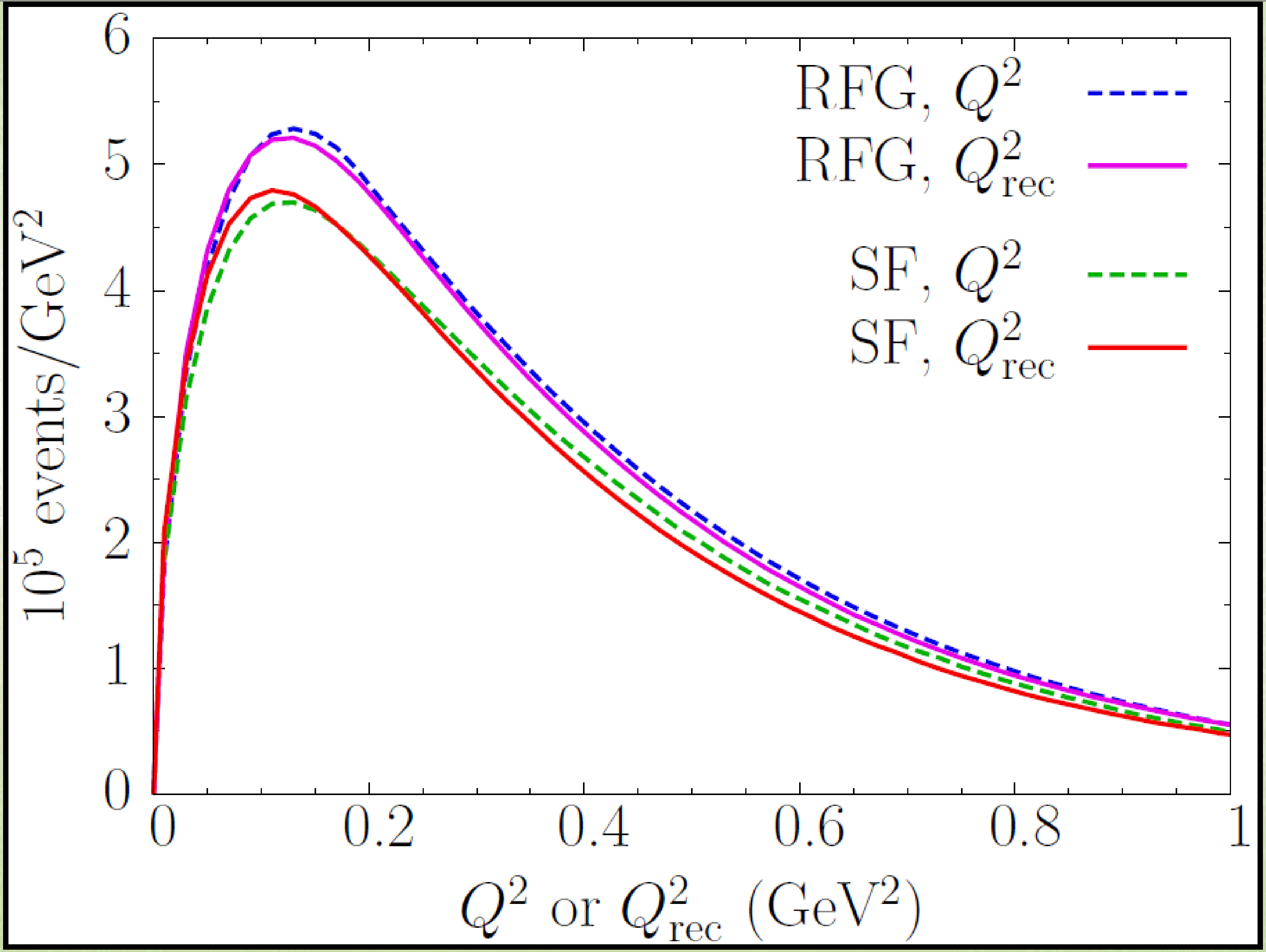
- **Reconstructed Q^2**

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

Reconstructed Q^2

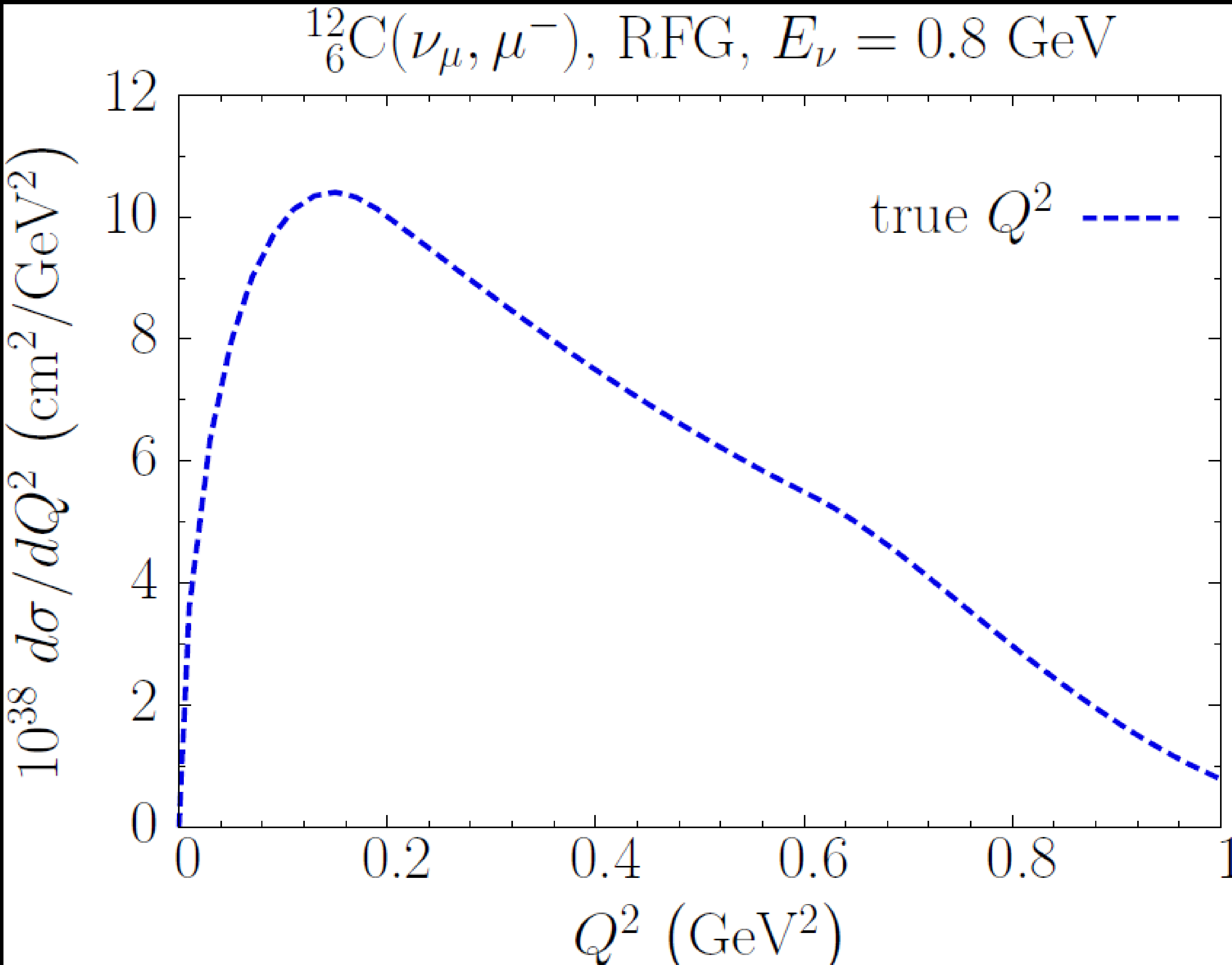
- In scattering off nucleus the true Q^2 cannot be obtained (only $|\boldsymbol{k}_\mu|$ and θ are measured)
- When $\varepsilon = 0$ the rec. Q^2 is equal to the true Q^2 corresponding to the scattering off a free neutron with the same muon kinematics
- In general case Q^2_{rec} lacks physical meaning but is useful as a quantity for data analysis

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

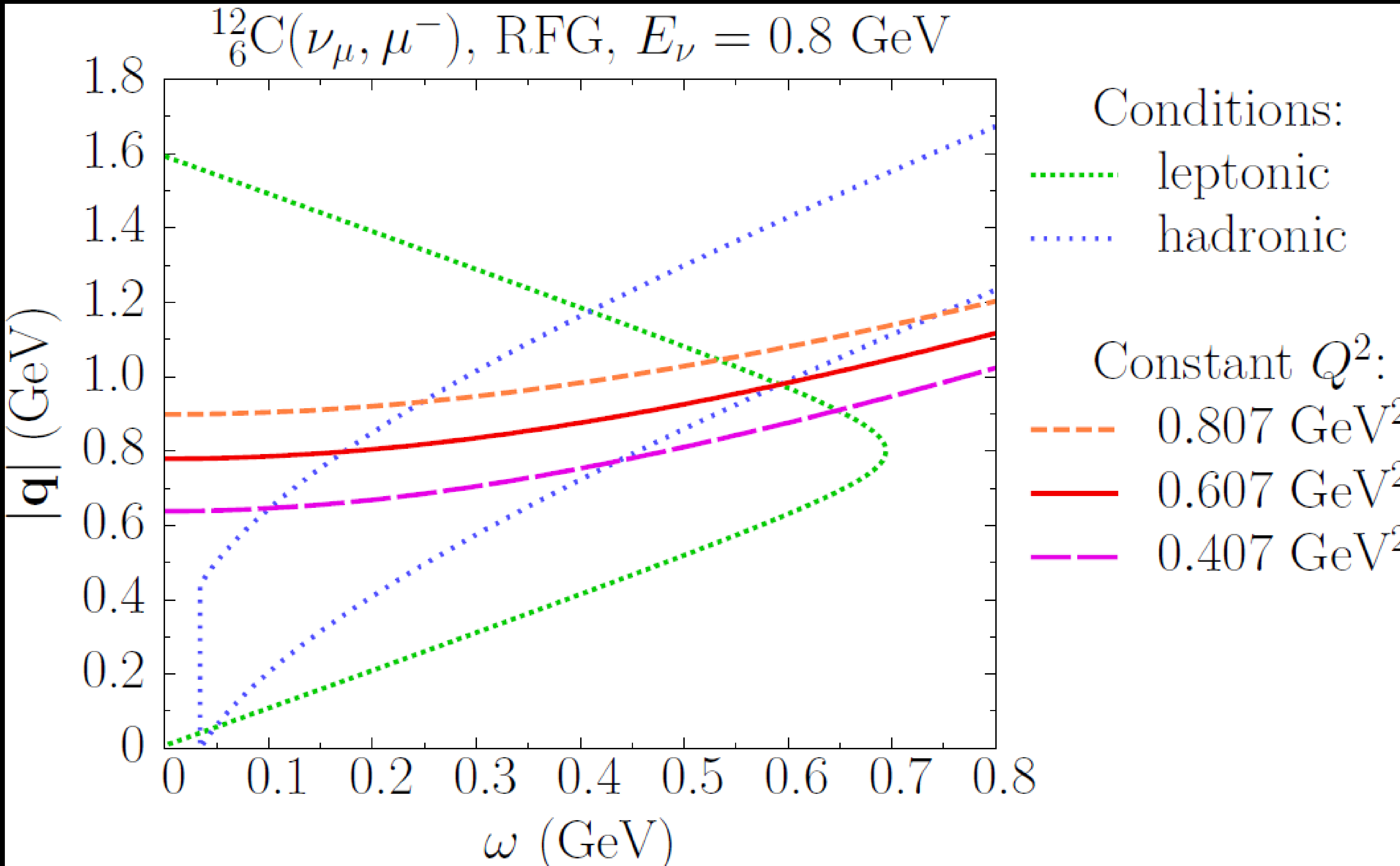


Are Q^2 vs. Q^2_{rec} really equivalent?

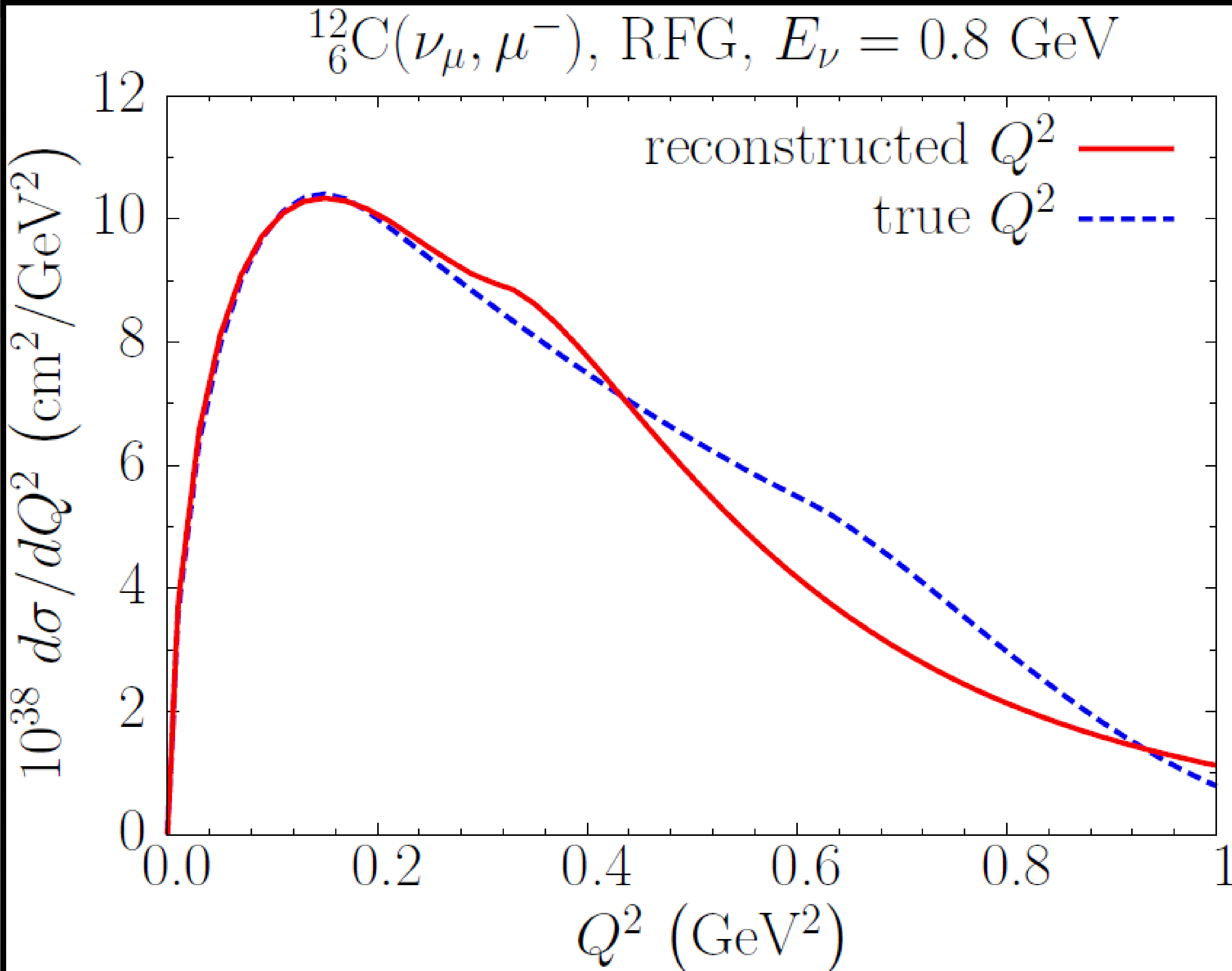
Q^2 vs. Q^2_{rec} for fixed energy



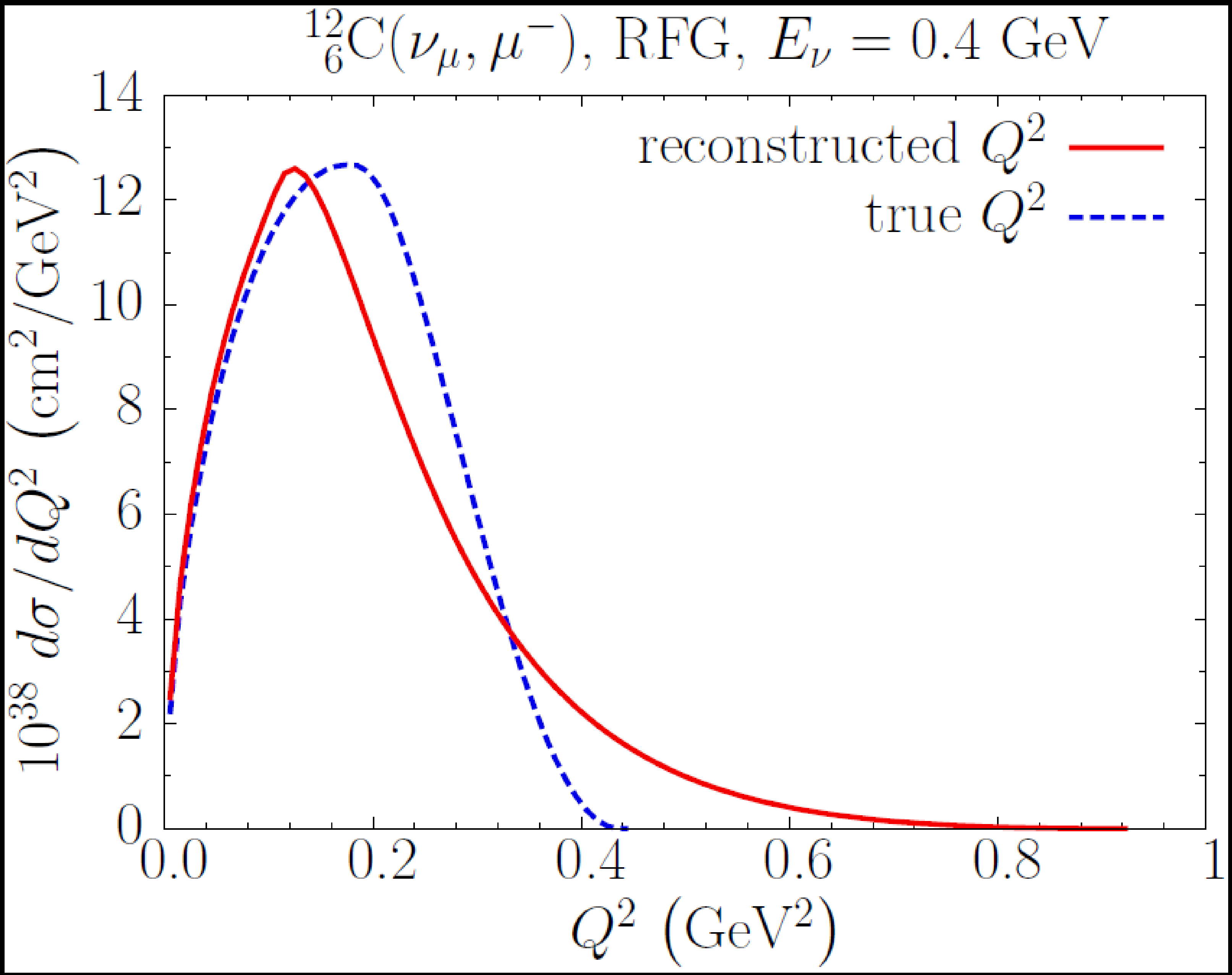
Q^2 at the (ω, |q|) plane



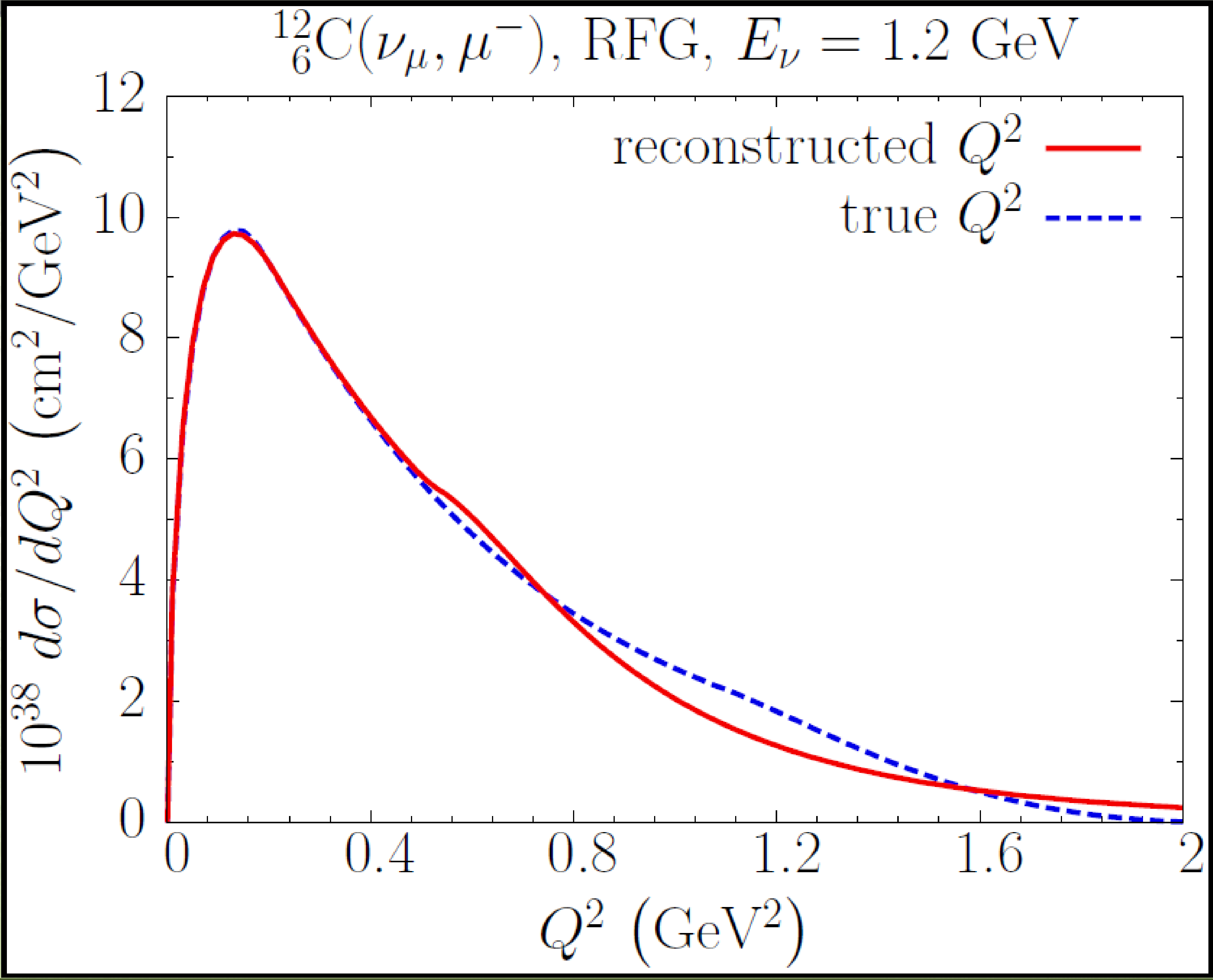
Q^2 vs. Q^2_{rec} for fixed energy



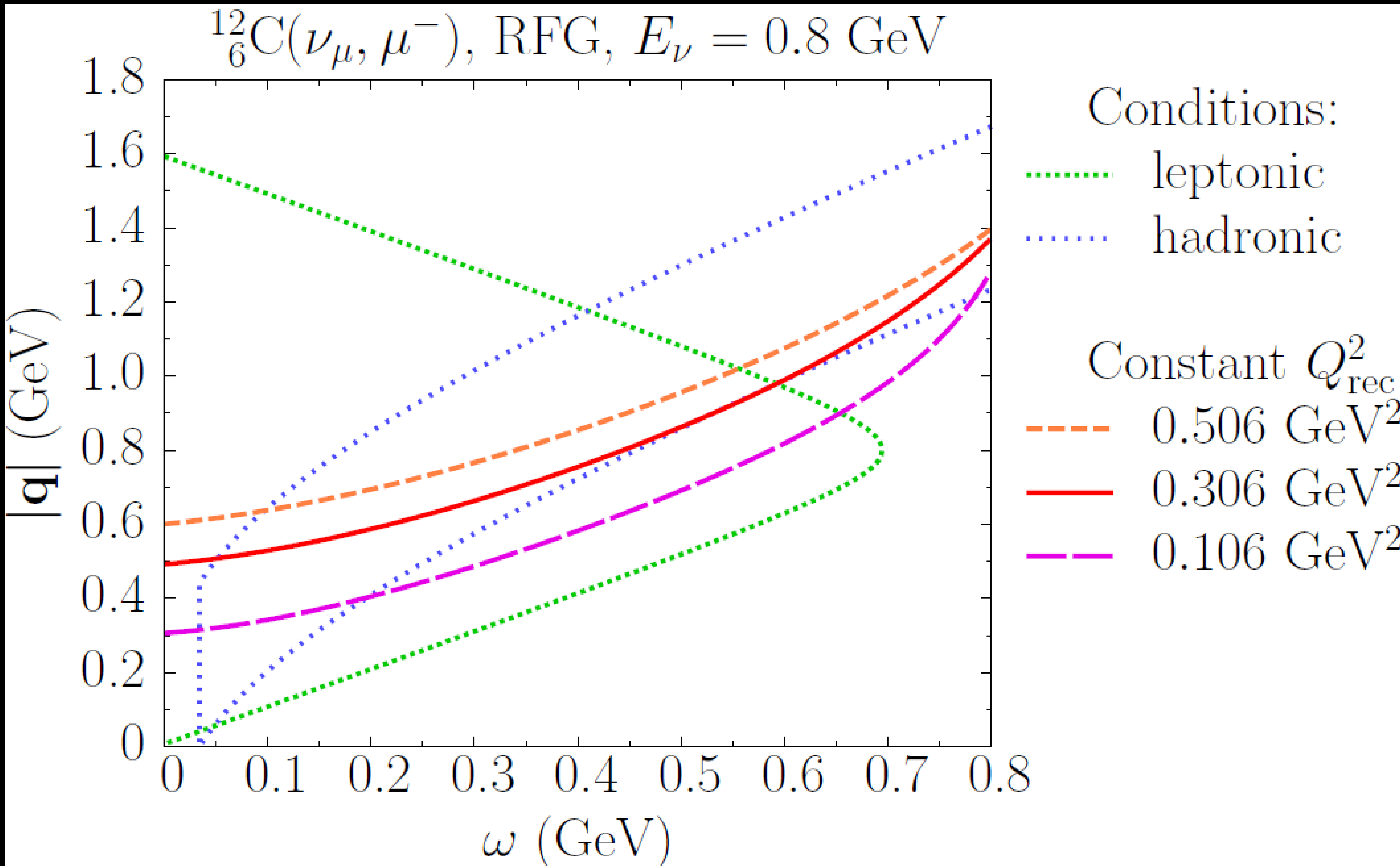
Q^2 vs. Q^2_{rec} for fixed energy



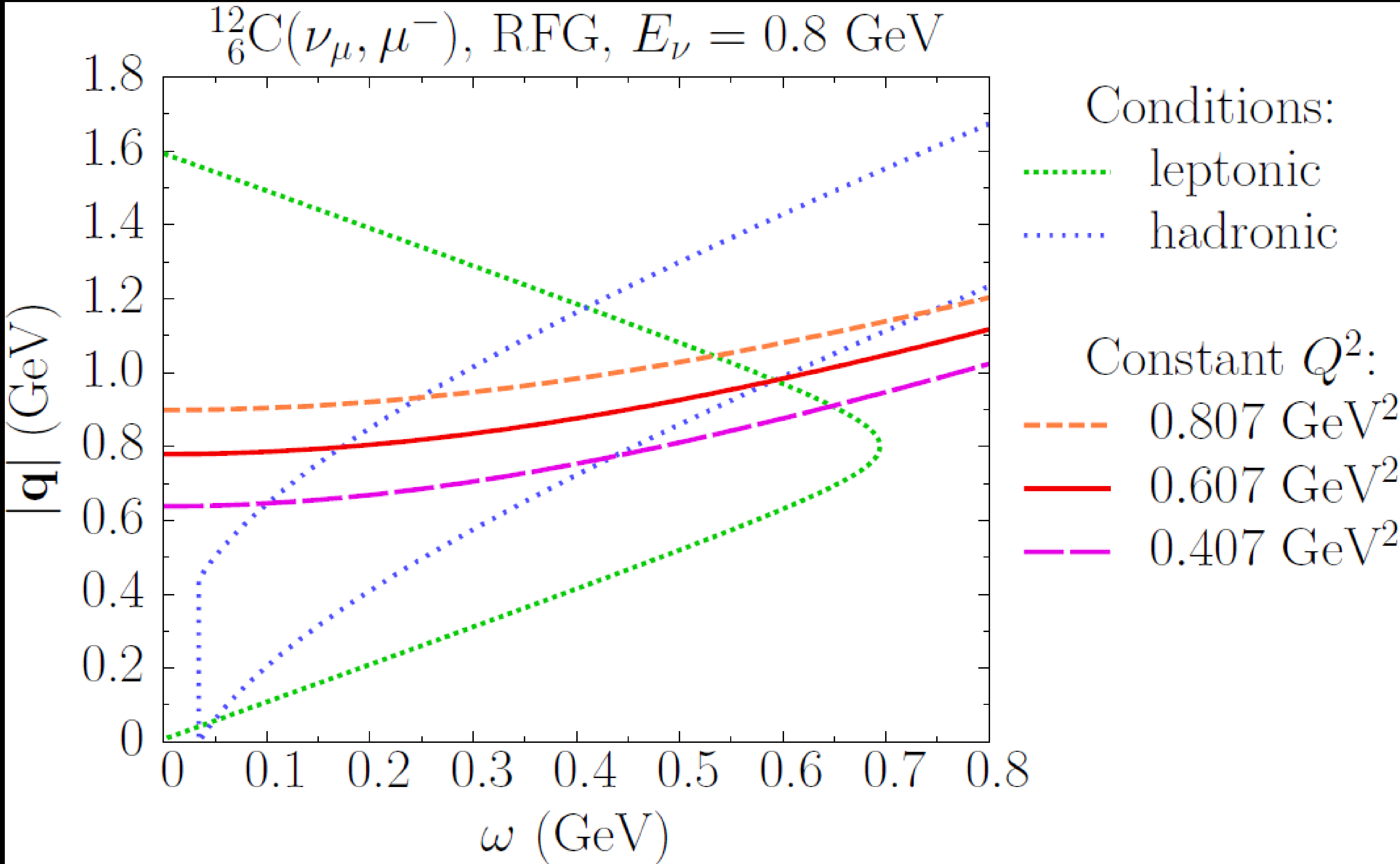
Q^2 vs. Q^2_{rec} for fixed energy



Q^2_{rec} at the (ω, |q|) plane



Q^2 at the (ω, |q|) plane



Why 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.

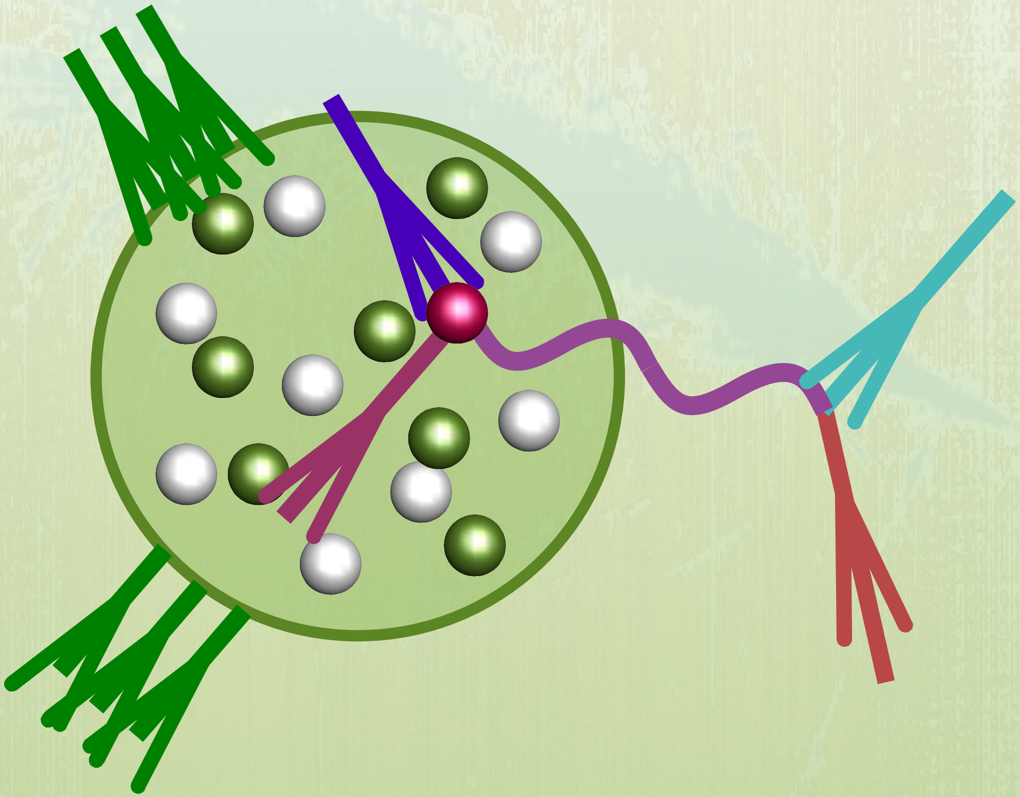
The Physics is relatively simple in terms of **|q|.**

Using Q^2 makes the situation more difficult and Q^2_{rec} produces further complications.

The impulse approximation

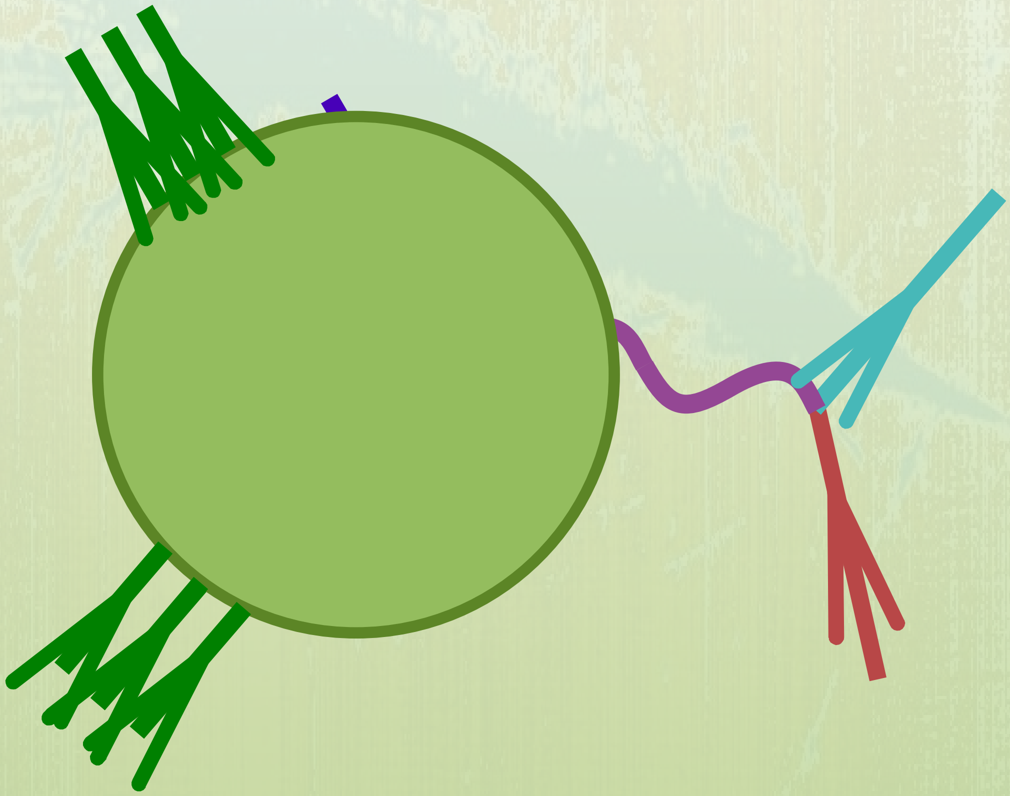
The impulse approximation

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



The impulse approximation

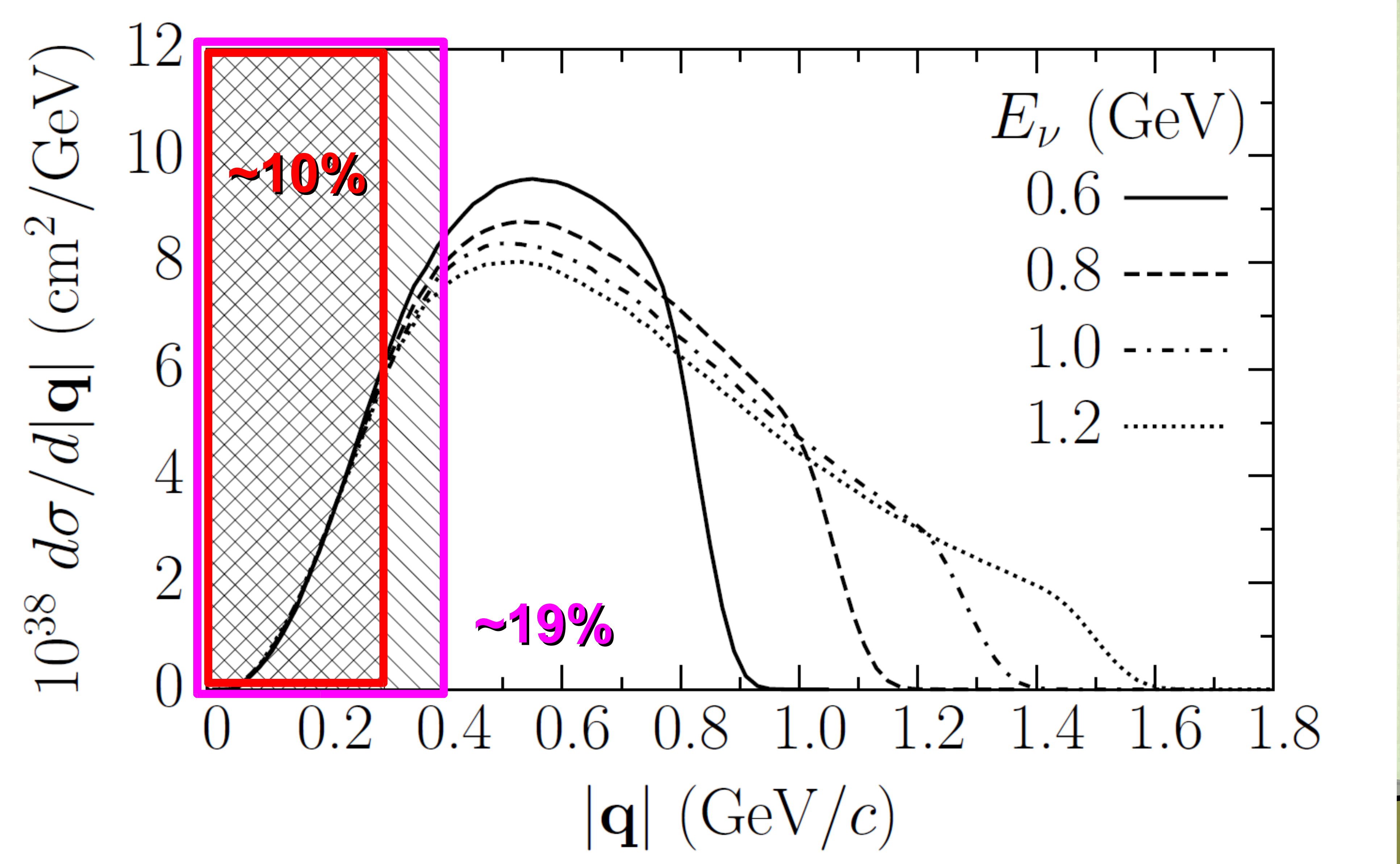
The probe **transferring momentum |q|** sees the structures of the size ~ 1/|**q**|



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| > 2k_F**

Contribution of low-|q|'s to the QE x-section



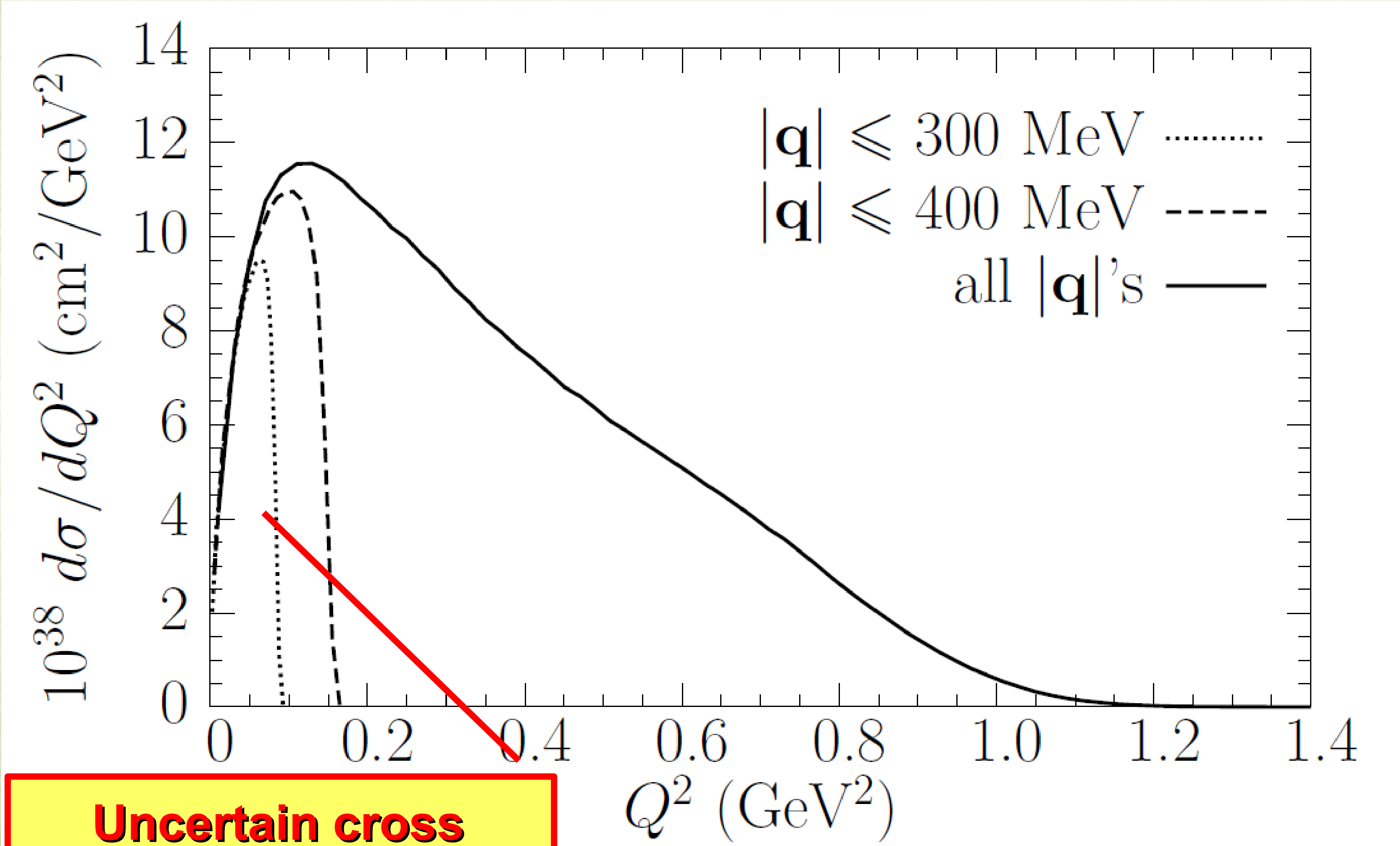
Contribution of low-|q|'s to the QE x-section

	Neutrino energy (GeV)						
	0.2	0.4	0.6	0.8	1.0	1.2	1.4
$\|\mathbf{q}\| \leq 300$ MeV$/c$	97.2%	18.9%	11.9%	10.1%	9.4%	9.1%	9.0%
$\|\mathbf{q}\| \leq 400$ 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
$\|\mathbf{q}\| \leq 300$ MeV$/c$	9.1%	9.2%	9.3%	9.3%	9.4%	9.4%	9.5%
$\|\mathbf{q}\| \leq 400$ MeV$/c$	18.8%	18.9%	19.1%	19.1%	19.3%	19.3%	19.4%

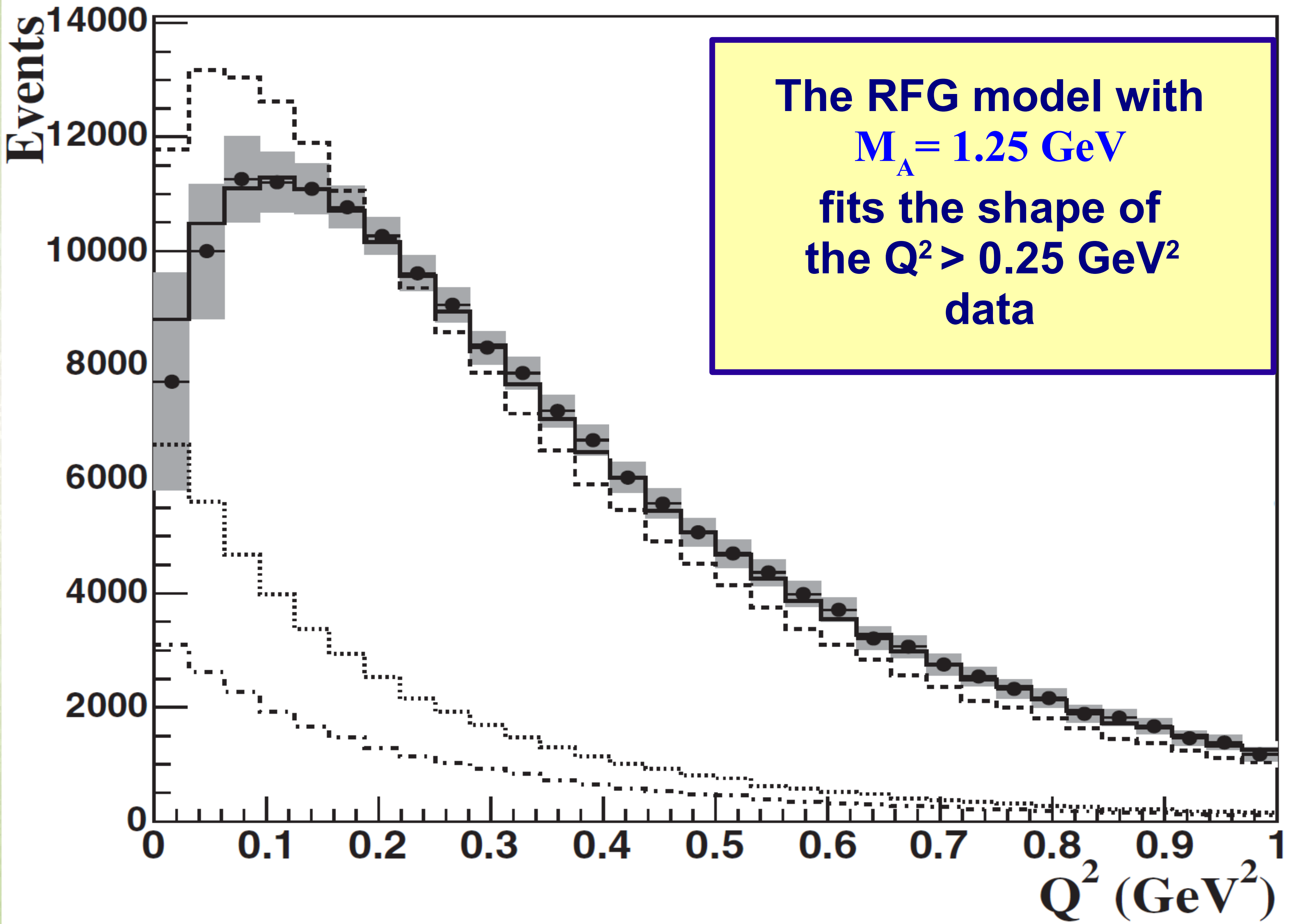
Contribution of low-|q|'s to the QE x-section

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



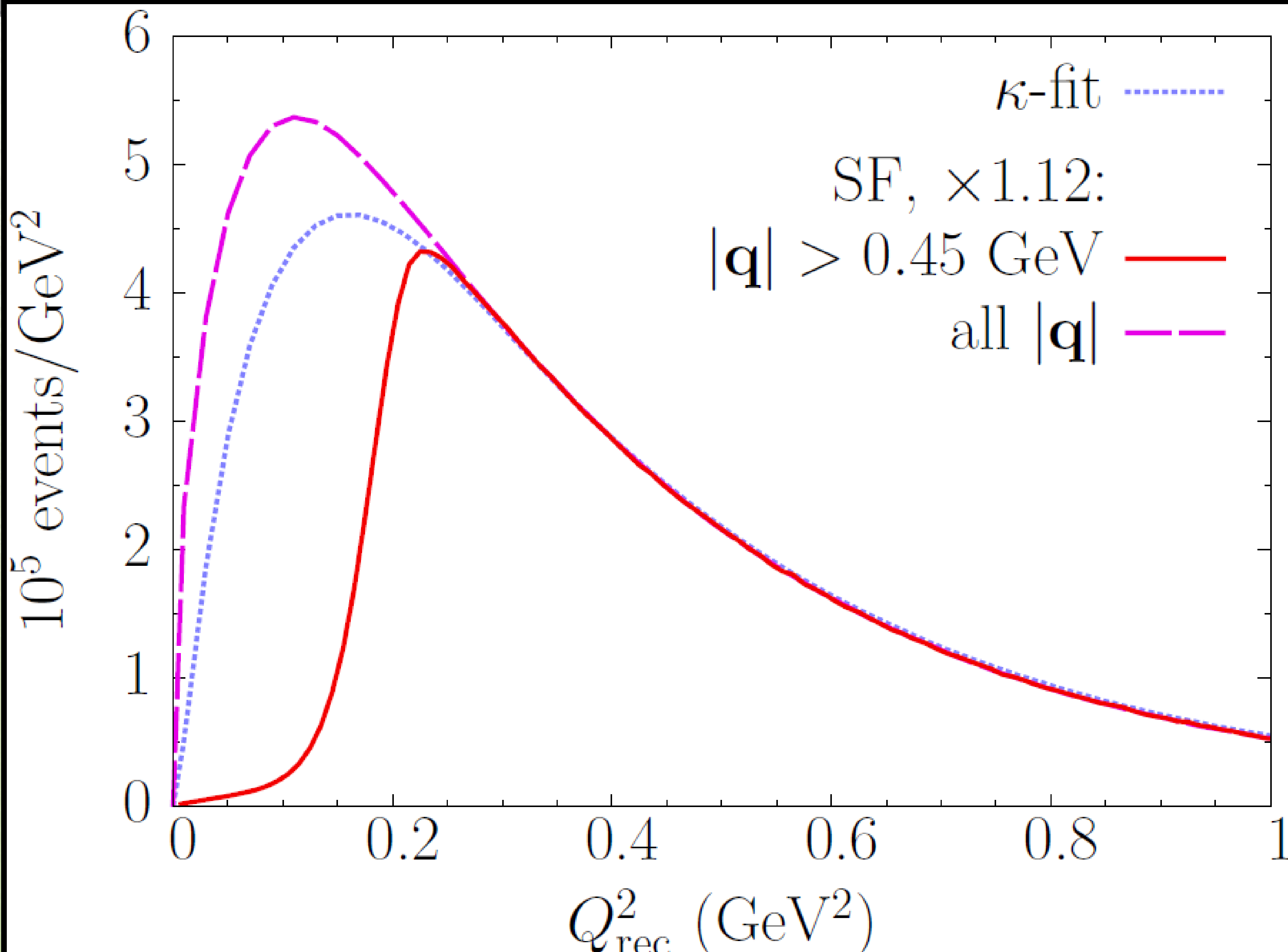
Uncertain cross section

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 data 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 changed by these effects **almost independently of energy**.

New variables

Proposal of new variables

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

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

or

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

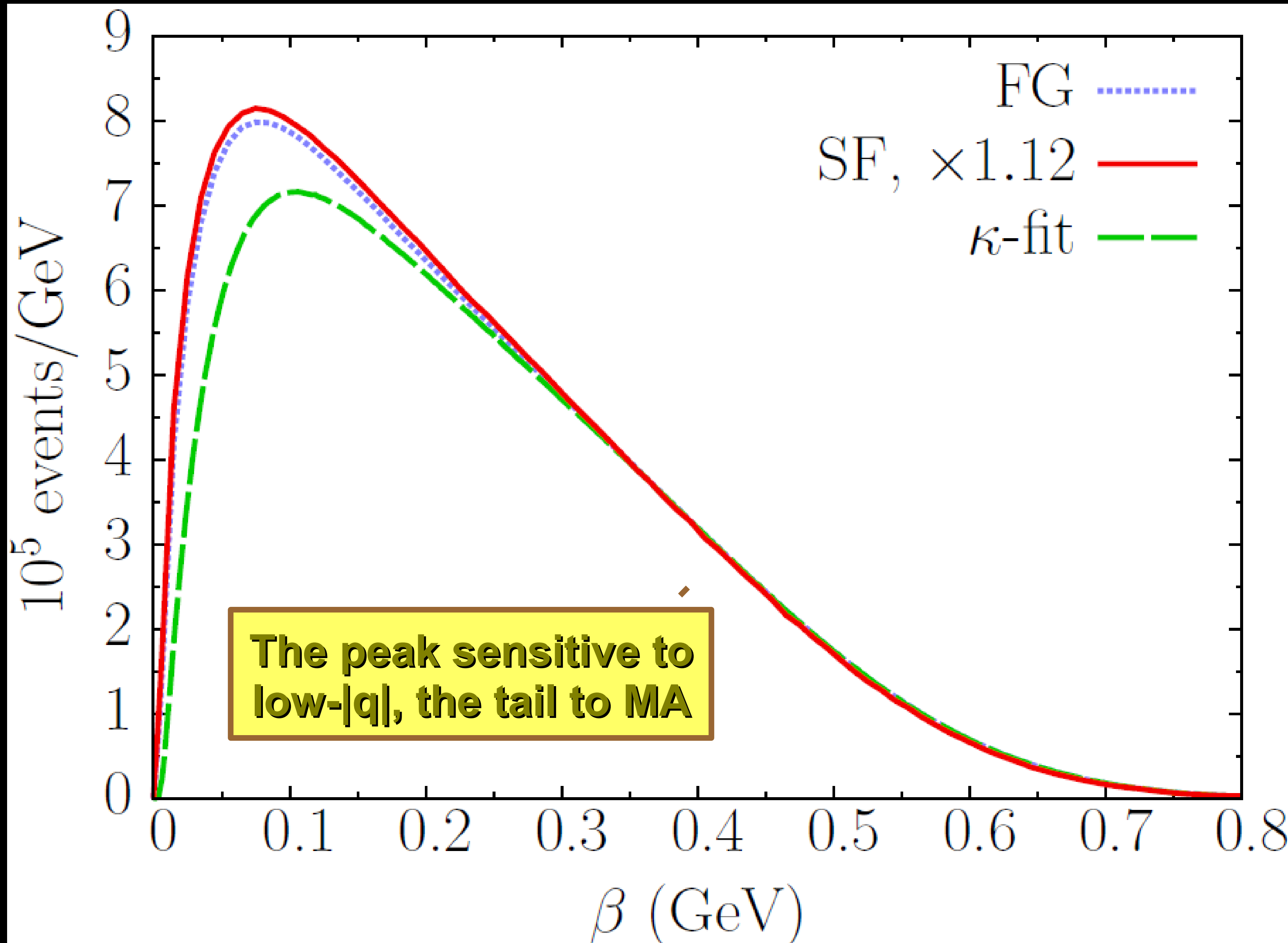
Proposal of new variables

Advantages:

- model independent
- involve only measured quantities
- do not contain any assumptions regarding dynamics, work well even for low energy
- sensitive to the axial mass due to

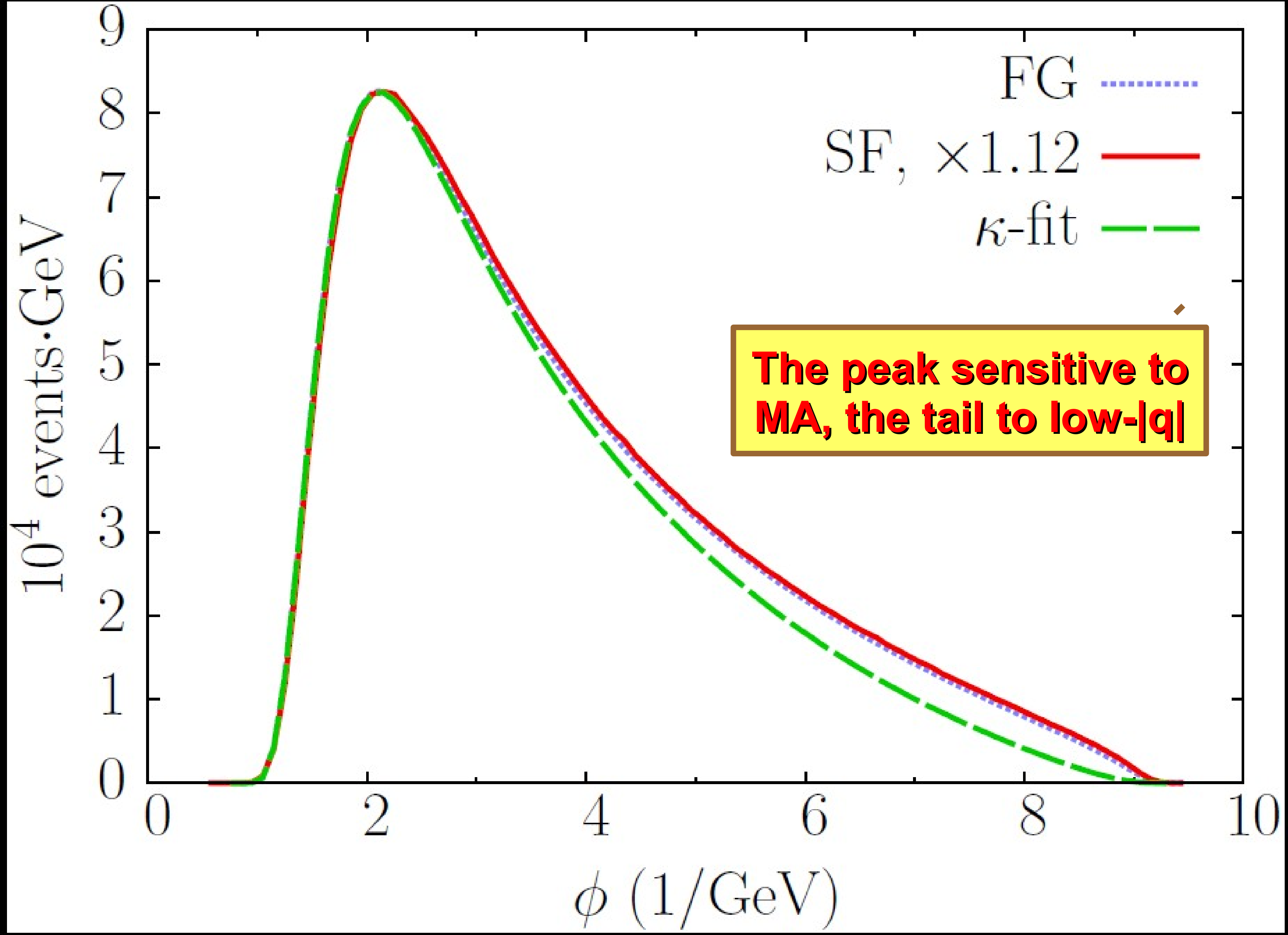
$$\beta = \frac{k \cdot k'}{E_\nu} = \frac{Q^2 + m_\mu^2}{2E_\nu}$$

Results for the MiniBoone flux: beta



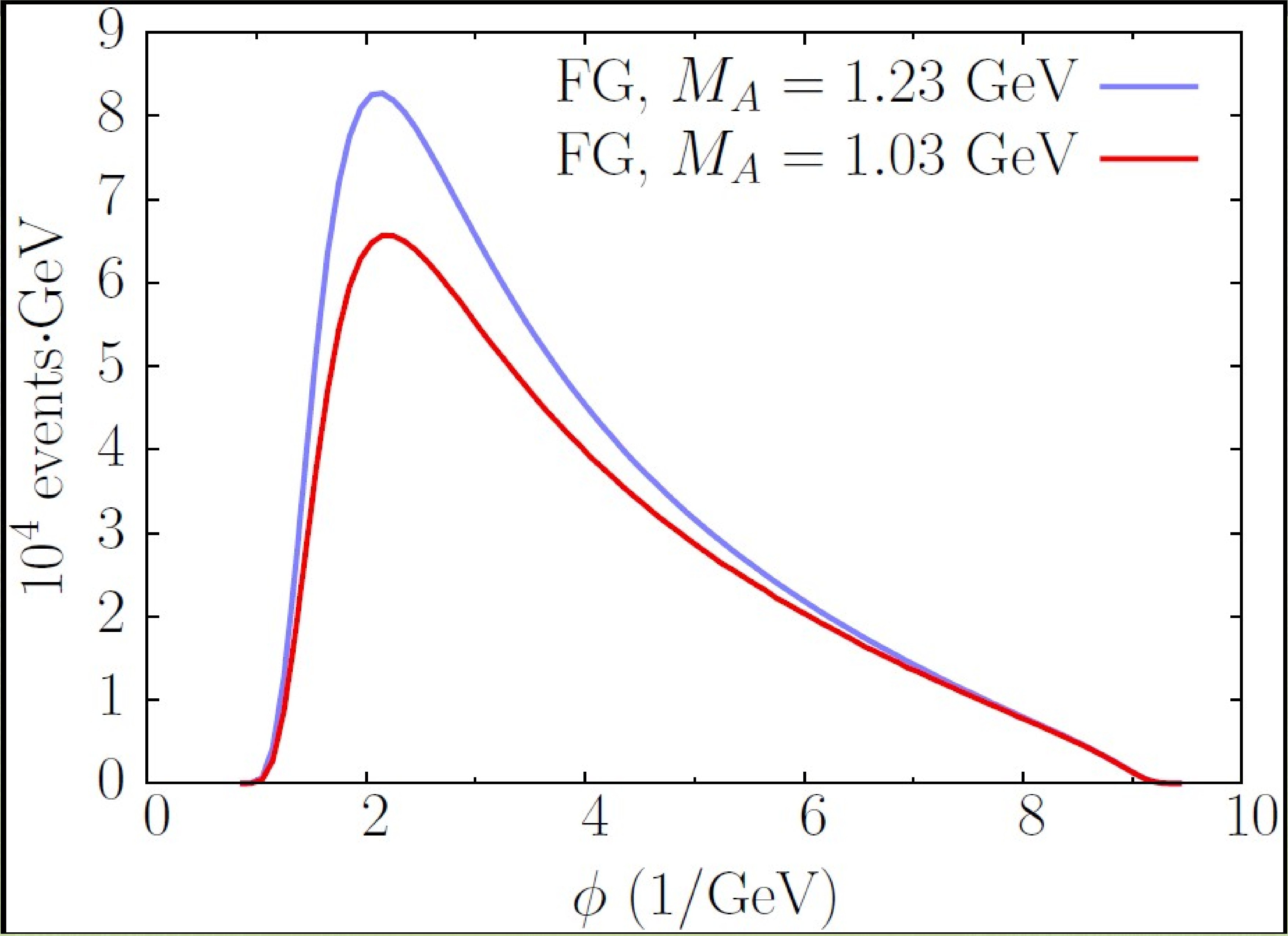
The peak sensitive to low-|q|, the tail to MA

Results for the MiniBoone flux: phi



The peak sensitive to MA, the tail to low-|q|

Results for the MiniBoone flux: phi



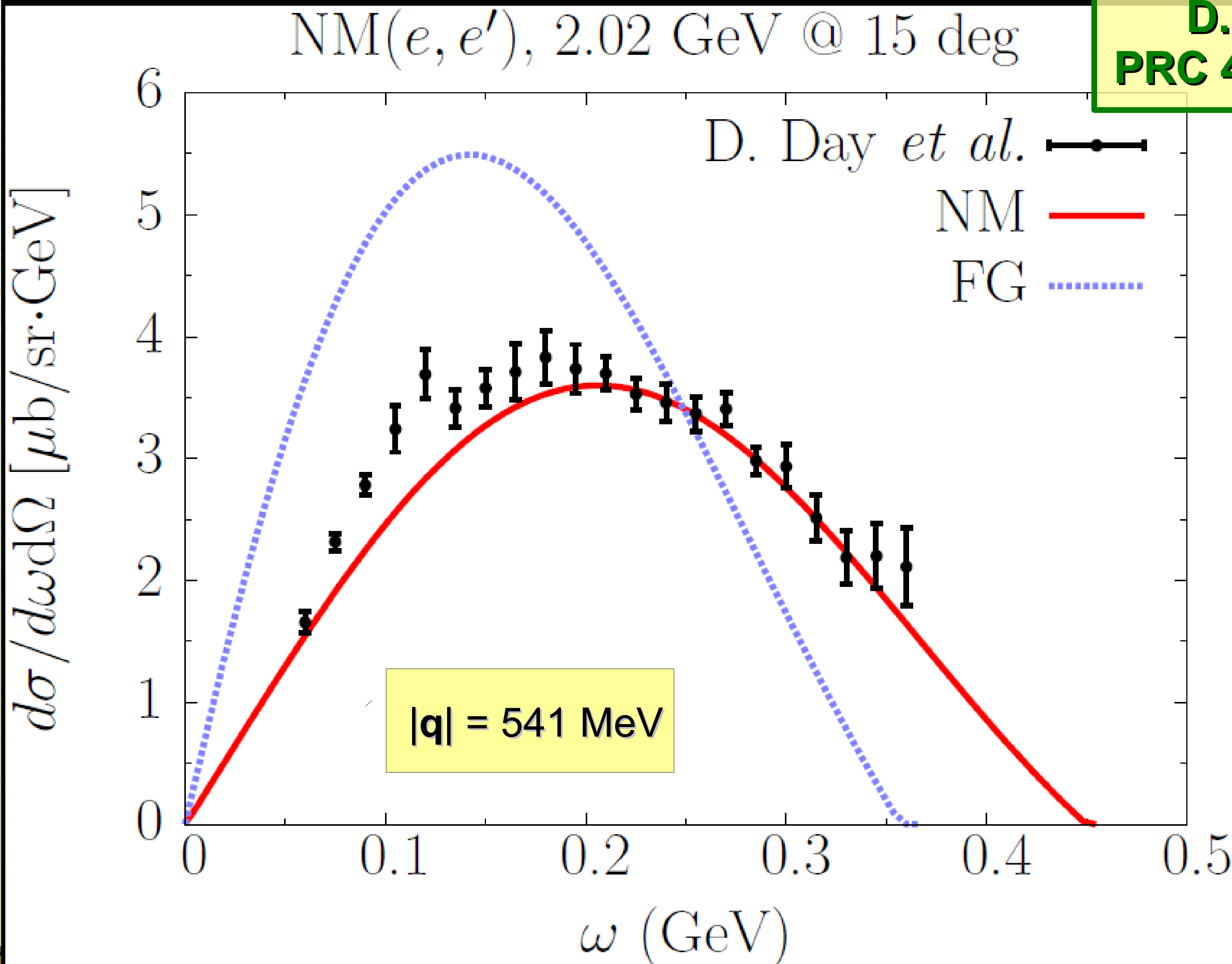
Summary

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

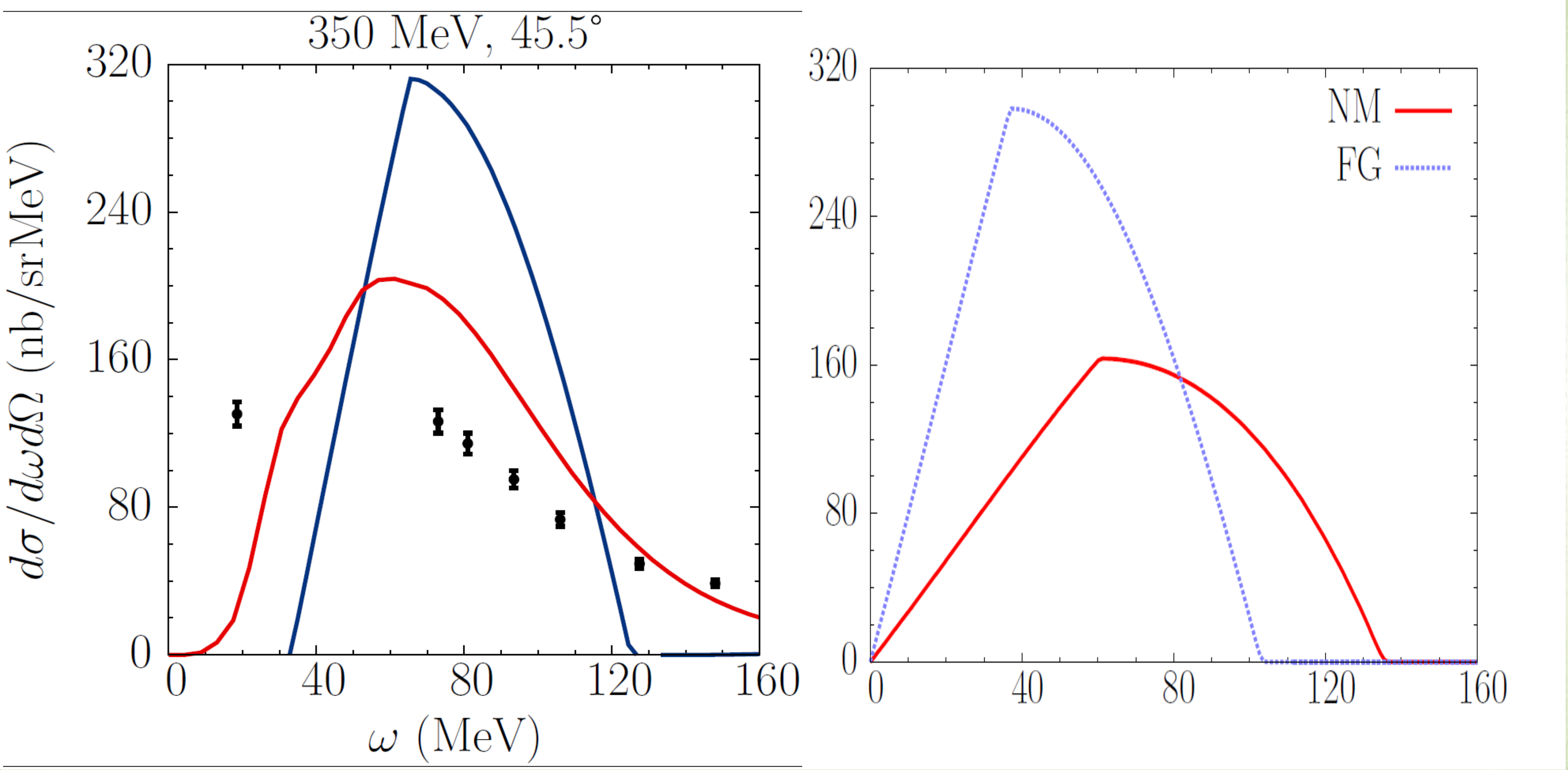
Back-up slides

Electron scattering: nuclear matter

D. Day *et al.*, PRC 40, 1011 (1989)



Electron scattering: calcium and NM



|**q**| = 254 MeV