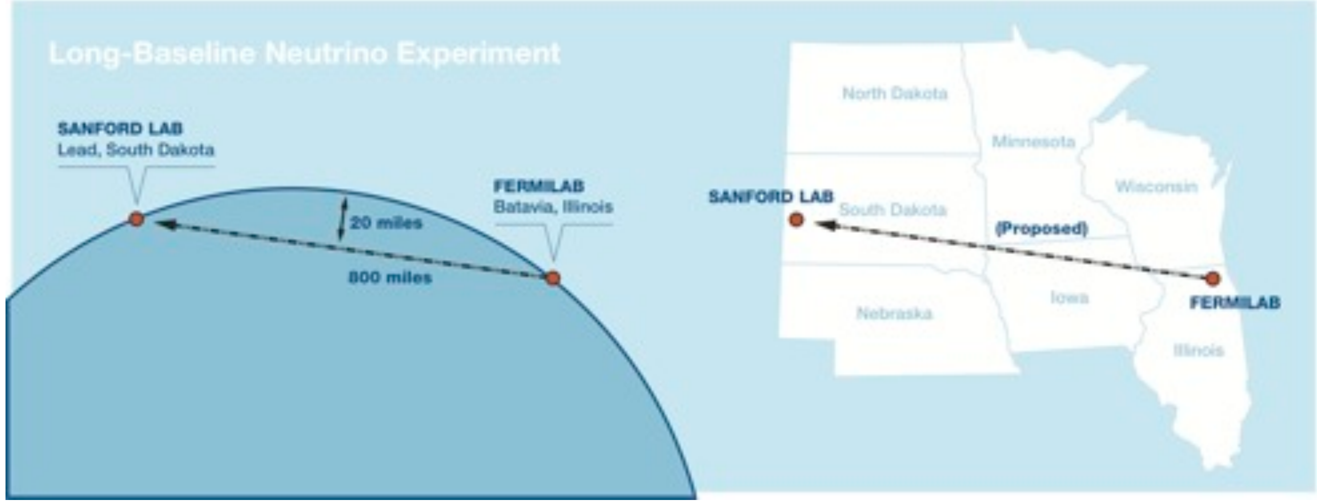


Spectral Functions in Generators (GENIE)

Omar Benhar, Chun-Min Jen, Camillo Mariani

Virginia Tech, Dec. 3rd, 2013

INT Workshop INT-13-54W
Neutrino-Nucleus Interactions for Current and Next Generation
Neutrino Oscillation Experiments
December 3-13, 2013

Outline

- Difficulties in neutrino scattering experiments
- Why QE (Quasi-Elastic) first?
- RFG (Relativistic Fermi Gas) vs. SF (Spectral Function)
- Motivation - Why SF?
- Why electron scattering data? SF for Oxygen and Carbon - validation with electron data
- SF for Argon - from Oxygen to Argon (MicroBooNE (short-baseline)/LBNE (long-baseline))
- Conclusions & Future Plans

Neutrino Oscillation Experiment
- difficult but not impossible

- **Neutrino beam properties are poorly understood and hardly controlled (beam source/beam transportation/beam flux)**

- **Neutrino-nucleus interaction's four-momentum transfer Q=(iw,q) is not as accurate as that as determined in the electron-nucleus interaction (at target nucleus)**

- **Neutrino-nucleus interaction's cross-section is smaller than electron-nucleus interaction's by a factor of 8-9 (at target nucleus)**

- **Neutrino energy reconstruction is imprecise due to the insufficient information of final-state productions (event identification/energy reconstruction)/final-state interactions (numerous nuclear effects) (at detector)**

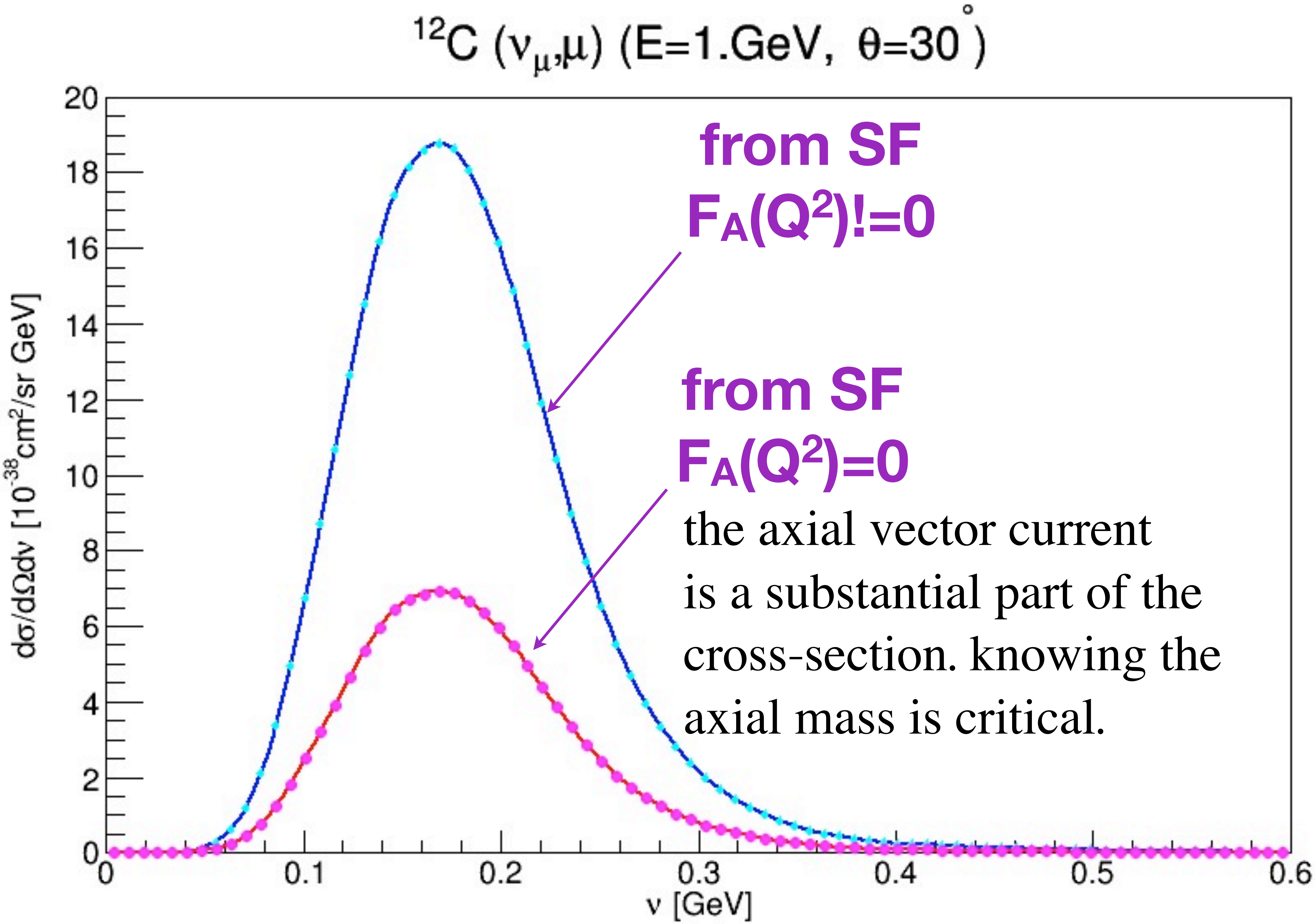
Unsolved issues in quasi-elastic neutrino scattering

- **At neutrino beam energy ~ 1GeV. Q^2 is high enough to regard the target nucleus as composed of a group of quasi-free nucleons. Impulse approximation (IA) hypothesis is valid.**

- **At lower Q^2 (<0.1 GeV^2, $q<=350-400$ MeV/c), random phase approximation (RPA - long-range nucleon nucleon correlation) may be more reliable than IA to account for (15-20)% CCQE cross-section.**

- **At lower Q^2 (<0.4 GeV^2), the Pauli-blocking effect becomes non-negligible, and thus affects the kinematically allowed phase space in the integrand of the double-differential CCQE cross-section.**

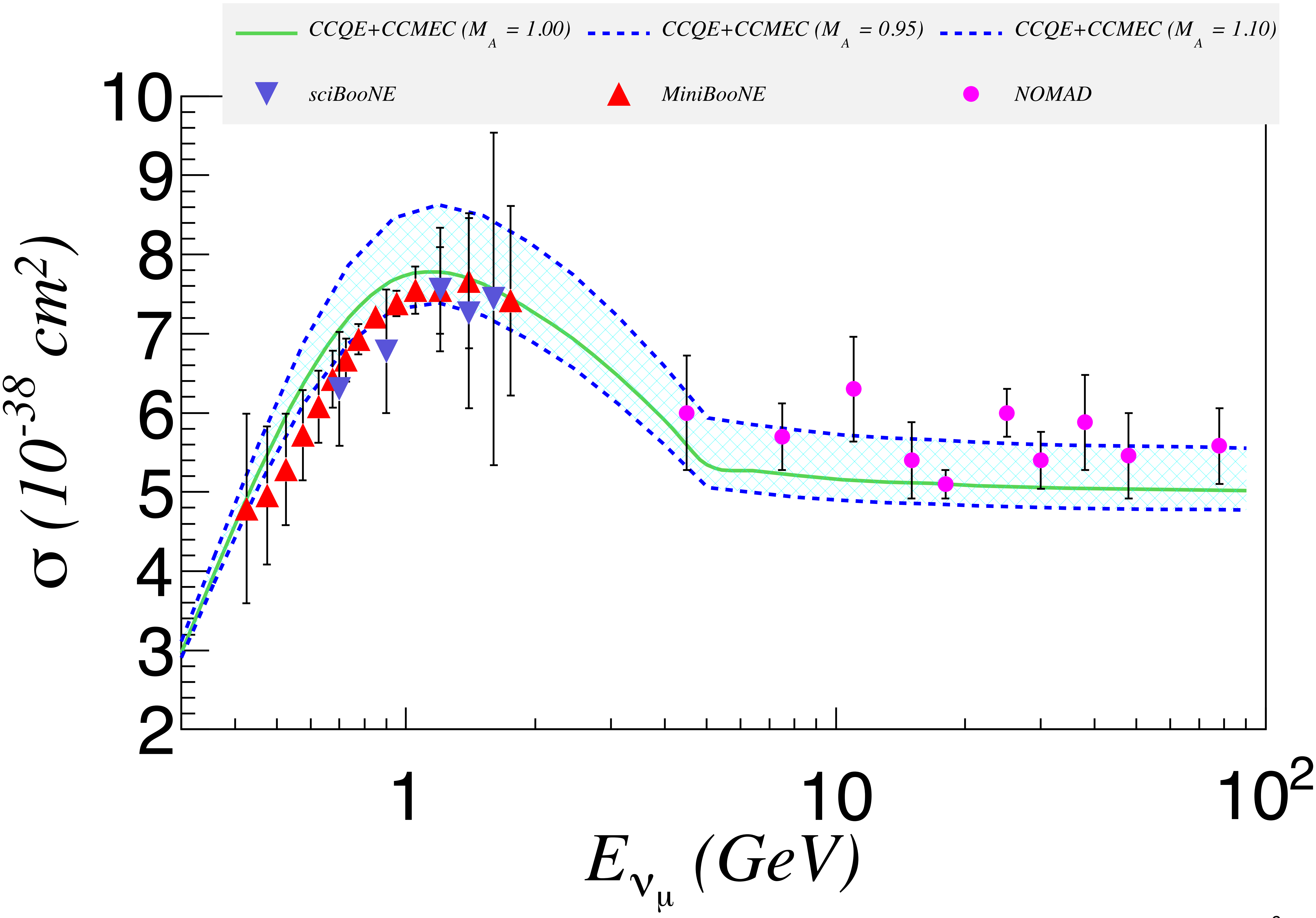
- **Axial mass as appeared in the axial form factor is treated by neutrino oscillation experiment as a free parameter but measured in Deuterium and should be regarded as an input for the form factor calculation**



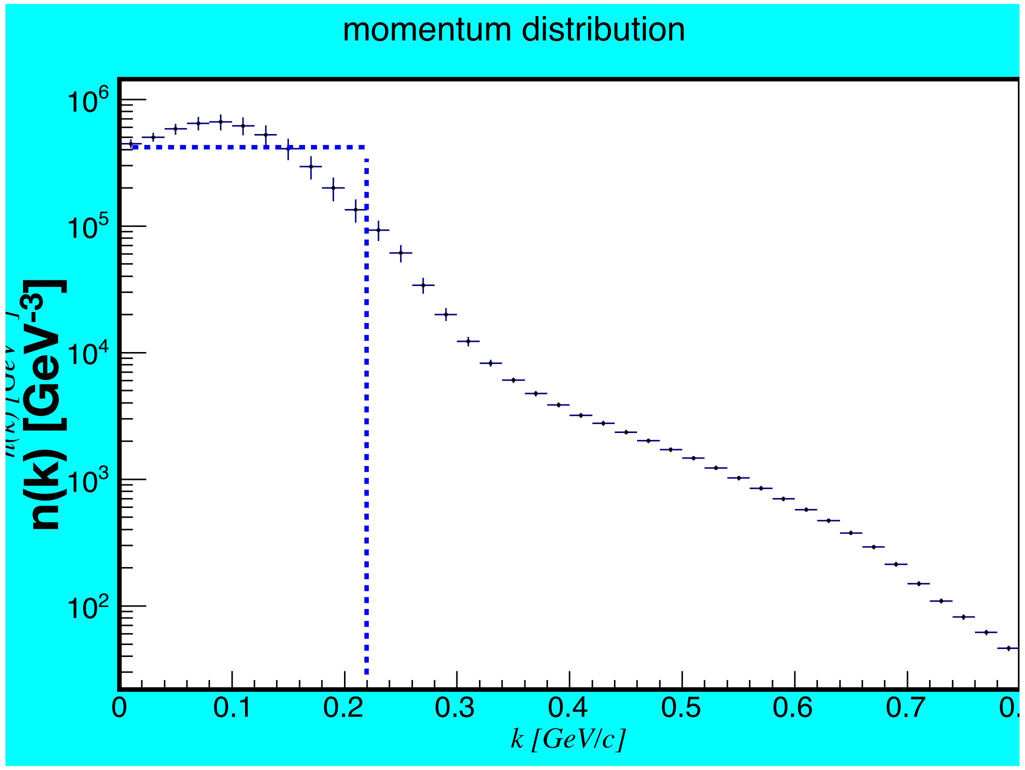
from SF
$F_A(Q^2)$!=0

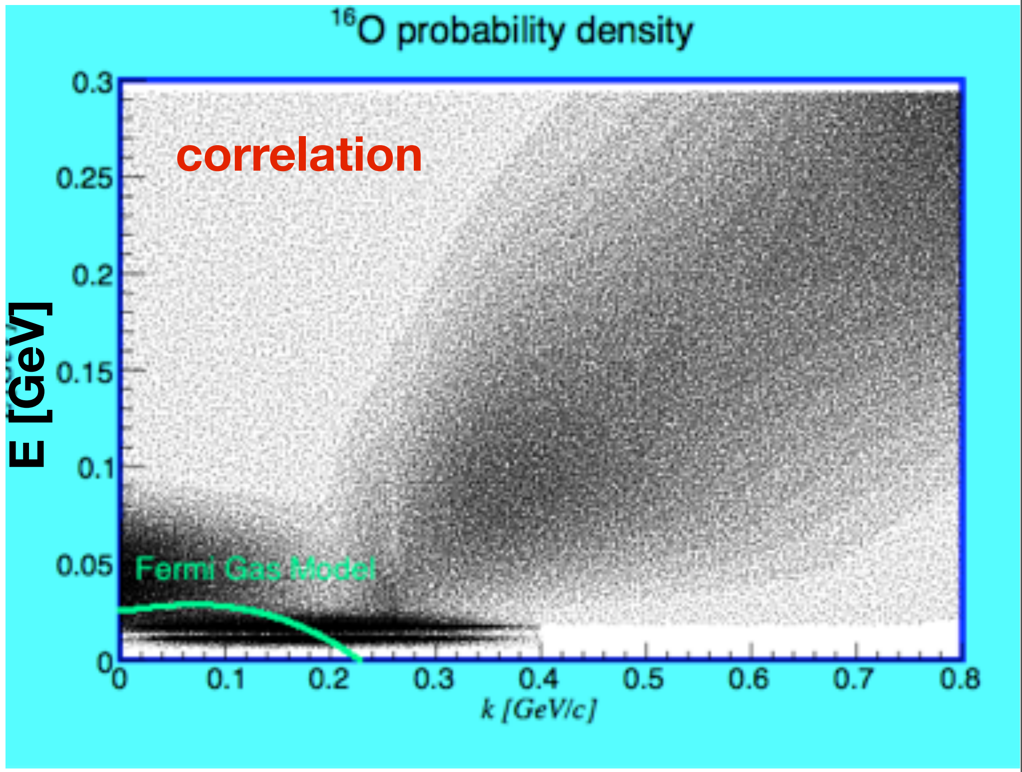
from SF
$F_A(Q^2)$=0

the axial vector current is a substantial part of the cross-section. knowing the axial mass is critical.


CCQE+CCMEC (M_A = 1.00)
CCQE+CCMEC (M_A = 0.95)
CCQE+CCMEC (M_A = 1.10)
sciBooNE
MiniBooNE
NOMAD
$\sigma\ (10^{-38}\ cm^2)$
2
3
4
5
6
7
8
9
10
1
10
10^2
E_{ν_μ} (GeV)

RFG vs. SF (I)





- **RFG model:**

$$P(\vec{k},E) = \frac{3}{4\pi p_F^3}\boxed{\theta(p_F - \vec{k})}\,\delta\left(\sqrt{m^2+|\vec{k}|^2} - m - \epsilon_0 + E\right)$$

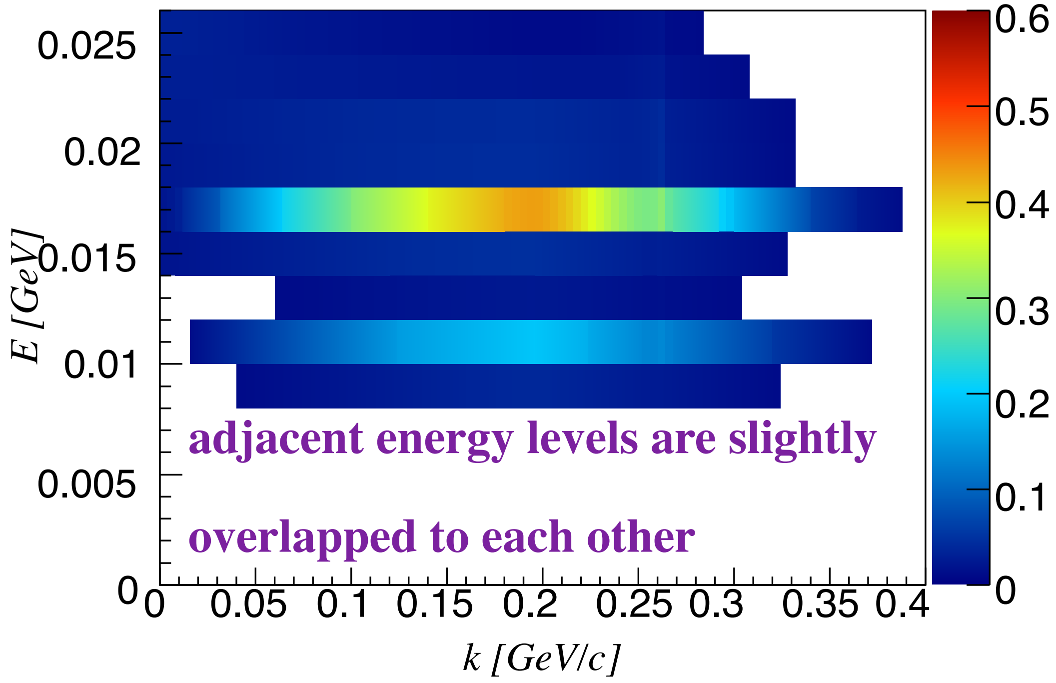
no correlation between energy and momentum

- **SF model:**
  - **one-particle one-hole** **(assume each energy level is a delta function):**

$$\mathbf{P}(\vec{k},E) = \sum_{N=p,n} \boxed{|<^{40}Ar|^{39}Ar,p>|^2}\, e^{i\vec{k}\cdot\vec{x}}\,\delta(E_{^{40}Ar} - E_{^{39}Ar} + E)$$

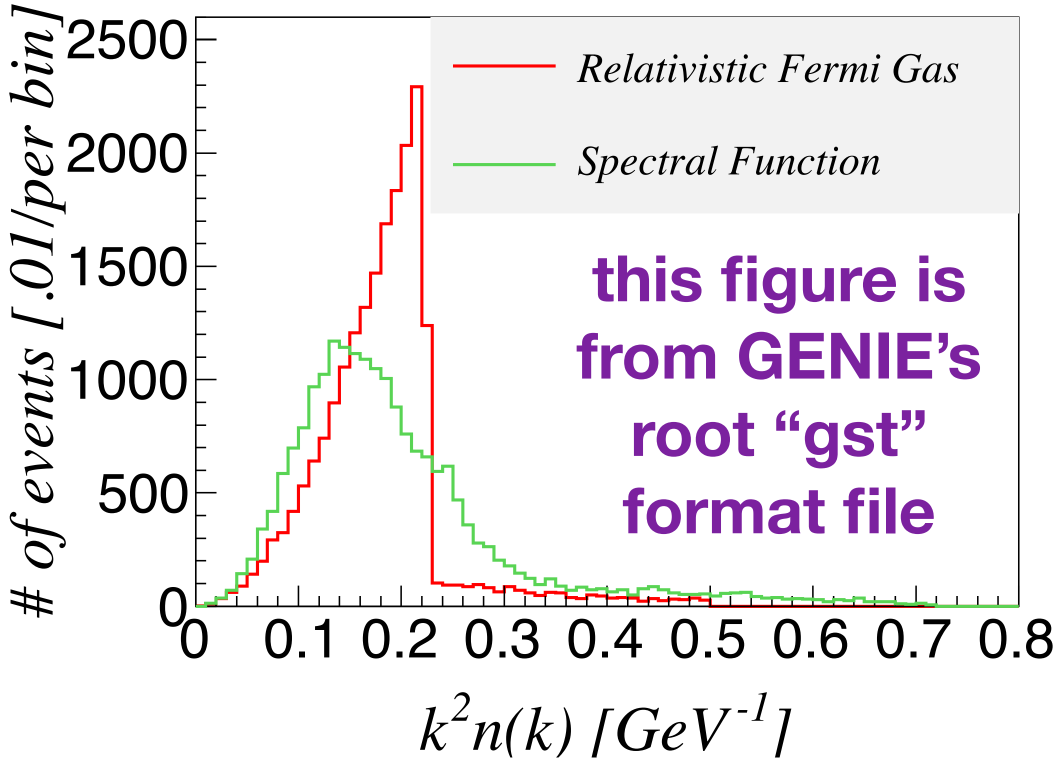
RFG vs. SF (II)

^{16}O probability density (zoom in)



adjacent energy levels are slightly overlapped to each other

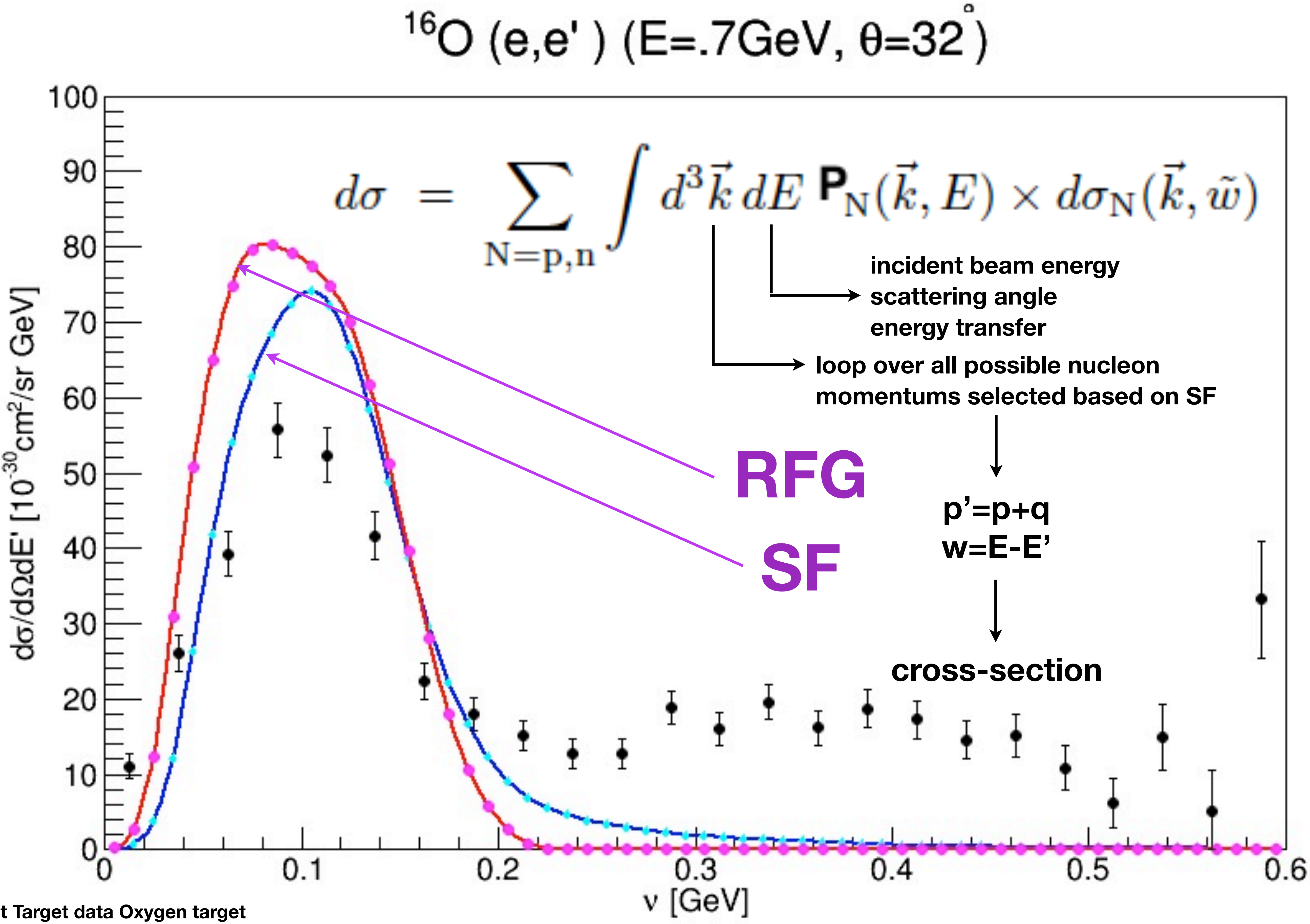
^{16}O $k^2n(k)$ (E_{ν_μ} =1.GeV, axial current off, FSI off)



this figure is from GENIE's root "gst" format file

- **SF model:**
  - **n-particle n-hole (continuous states):**

$$
\begin{aligned}
P_N(\vec{k}, E) = \sum_{N=p,n} \Big(& |<^{40}Ar|^{39}Ar,p>|^2\,\delta(E_{^{40}Ar} - E_{^{39}Ar} + E_1) \\
+ & |<^{40}Ar|^{38}Ar,p,n>|^2\,\delta(E_{^{40}Ar} - E_{^{38}Ar} + E_2) \\
+ & |<^{40}Ar|^{38}K,p,p>|^2\,\delta(E_{^{40}Ar} - E_{^{38}K} + E_3) + ...\Big)\, e^{i\vec{k}\cdot\vec{x}}
\end{aligned}
$$



$$d\sigma = \sum_{N=p,n} \int d^3\vec{k}\, dE\, \mathbf{P}_{\mathrm{N}}(\vec{k},E) \times d\sigma_{\mathrm{N}}(\vec{k},\tilde{w})$$

incident beam energy
scattering angle
energy transfer

loop over all possible nucleon momentums selected based on SF

p'=p+q
w=E-E'

cross-section

Jet Target data Oxygen target
References:
M. Anghinolfi et al.: Journal of Physics G: Nucl. Part. Phys. 21 (1995) L9;
M. Anghinolfi et al.: Nucl. Phys. A602 (1996) 405.

courtesy to
http://faculty.virginia.edu/qes-archive/index.html.

Motivation - Why SF? (I)

various nuclear models have different ways to describe how numerous nuclear effects alter the kinematics of final-state particles. therefore, the extraction of the total flux-unfolded cross-section per proton on target is influenced by the reconstructed neutrino energy

$$\boxed{N_\nu^{\alpha\rightarrow\beta}(L,E)} \sim \epsilon(E) \times \sigma(E) \times \phi(E) \times P_{\alpha\beta}(L,E)$$

experimental measuments

detector effects, nuclear effects

$$\frac{N^{\mu e}_{far}}{N^{\mu e}_{near}} \sim \boxed{\frac{\epsilon_e \sigma_e \phi_\mu}{\epsilon_\mu \sigma_\mu \phi_\mu}} P_{\mu e}$$

how we extract
oscillating parameters?

oscillation frequency

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2\left(\frac{1.27\Delta m^2 L}{\boxed{E}}\right)$$

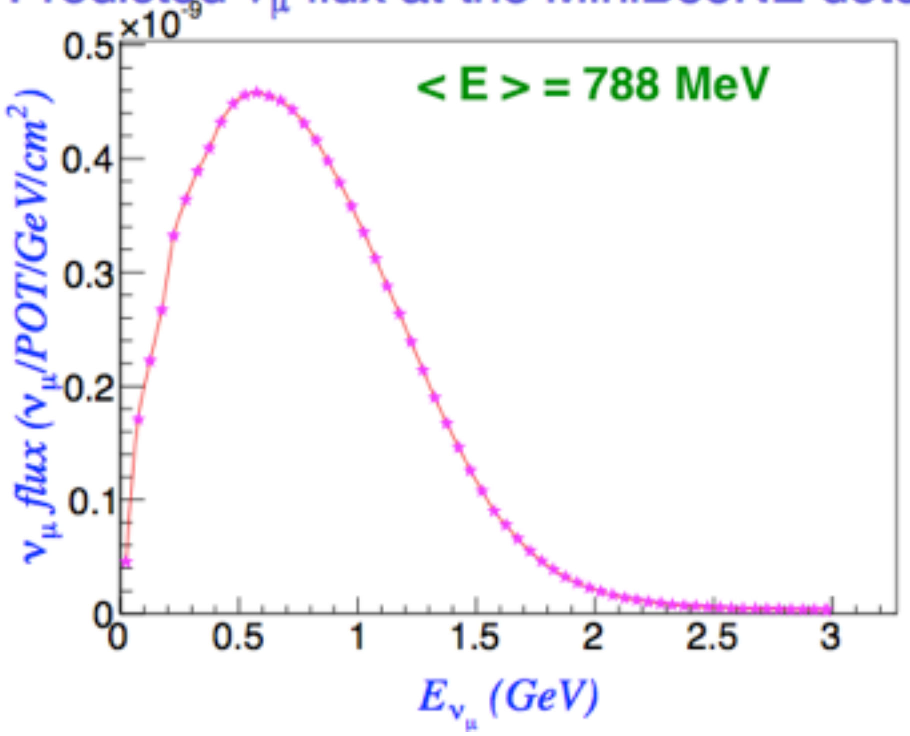
oscillation amplitude

reconstructed E_{beam}

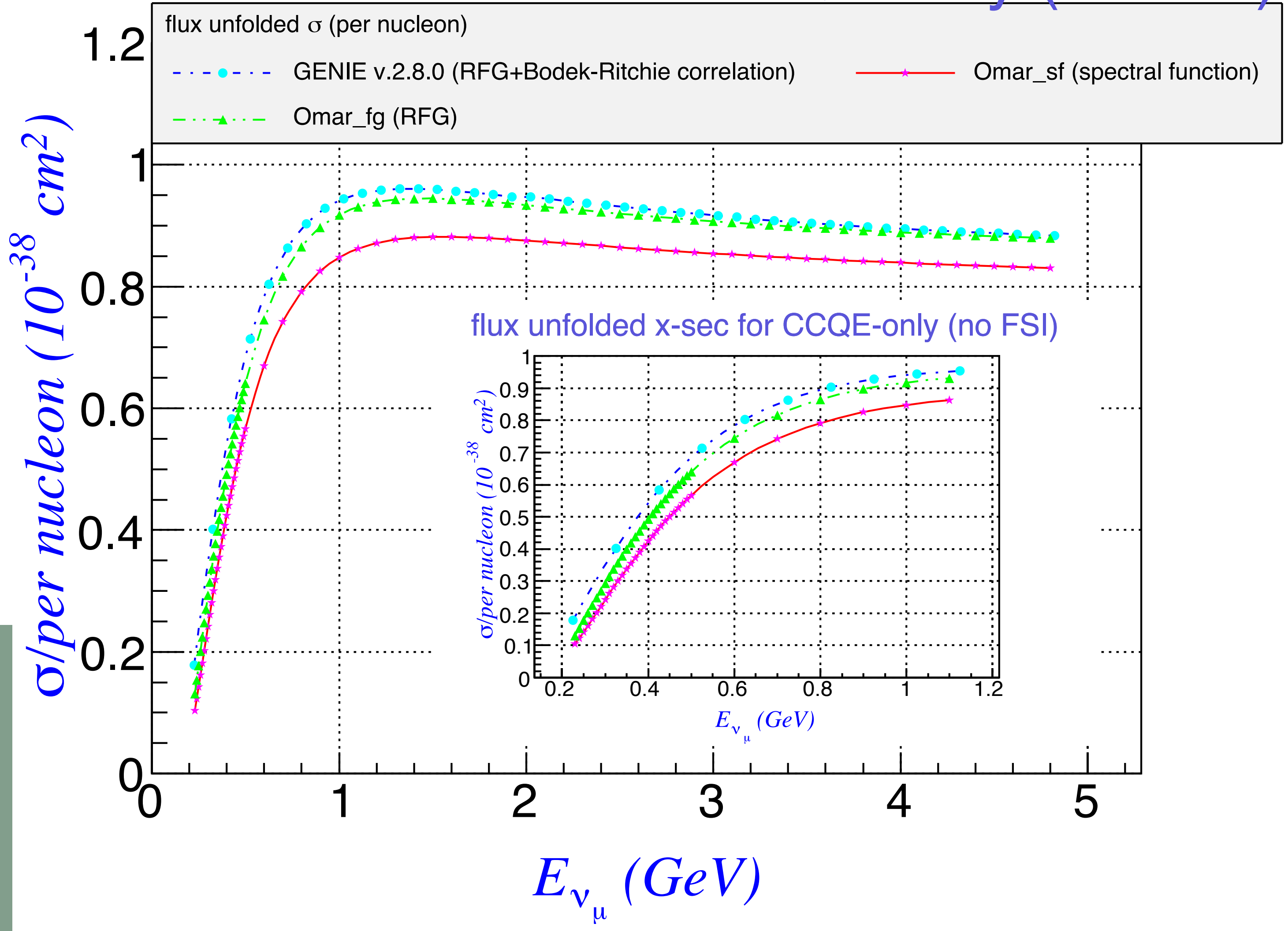
courtesy to Dr. Pilar Coloma

Motivation - Why SF? (II)

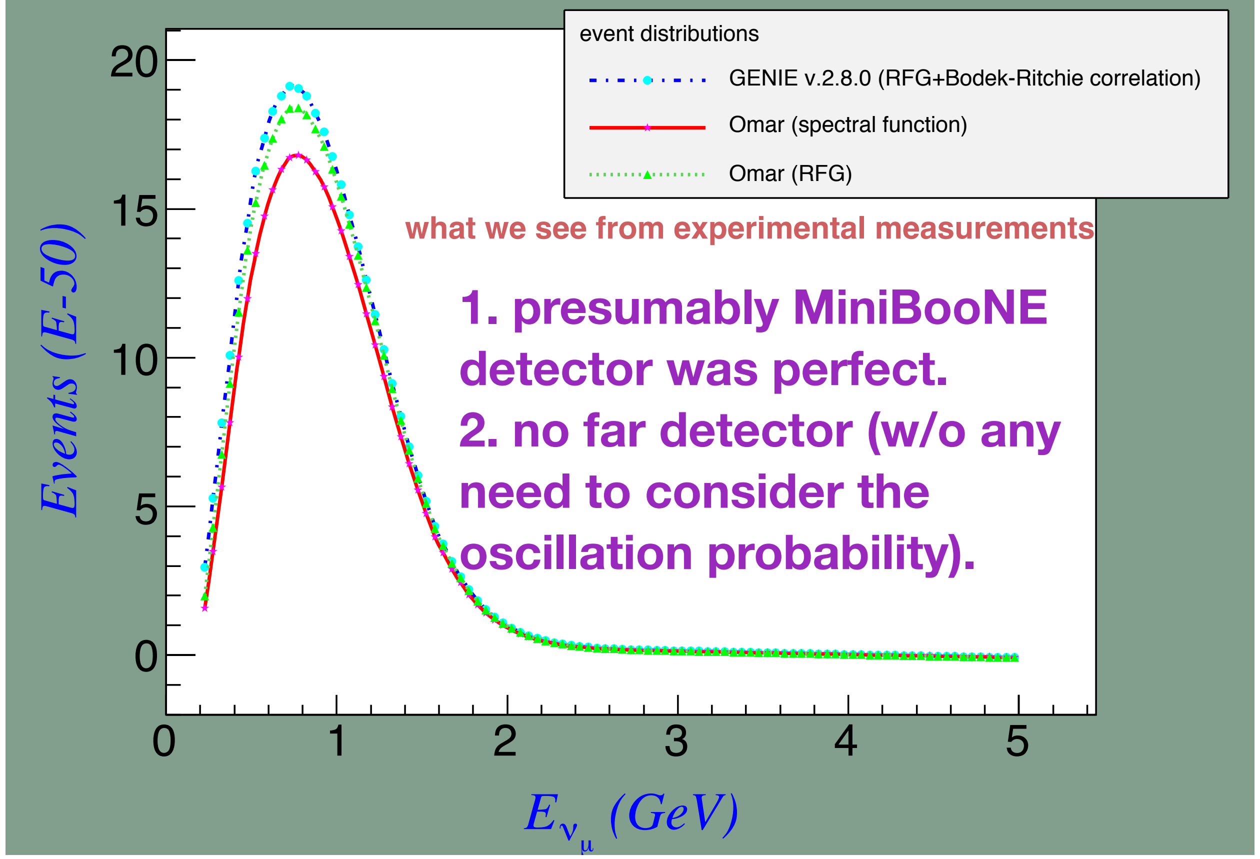
Predicted ν_μ flux at the MiniBooNE detector



flux unfolded x-sec for CCQE-only (no FSI)



event distributions for CCQE-only (no FSI)



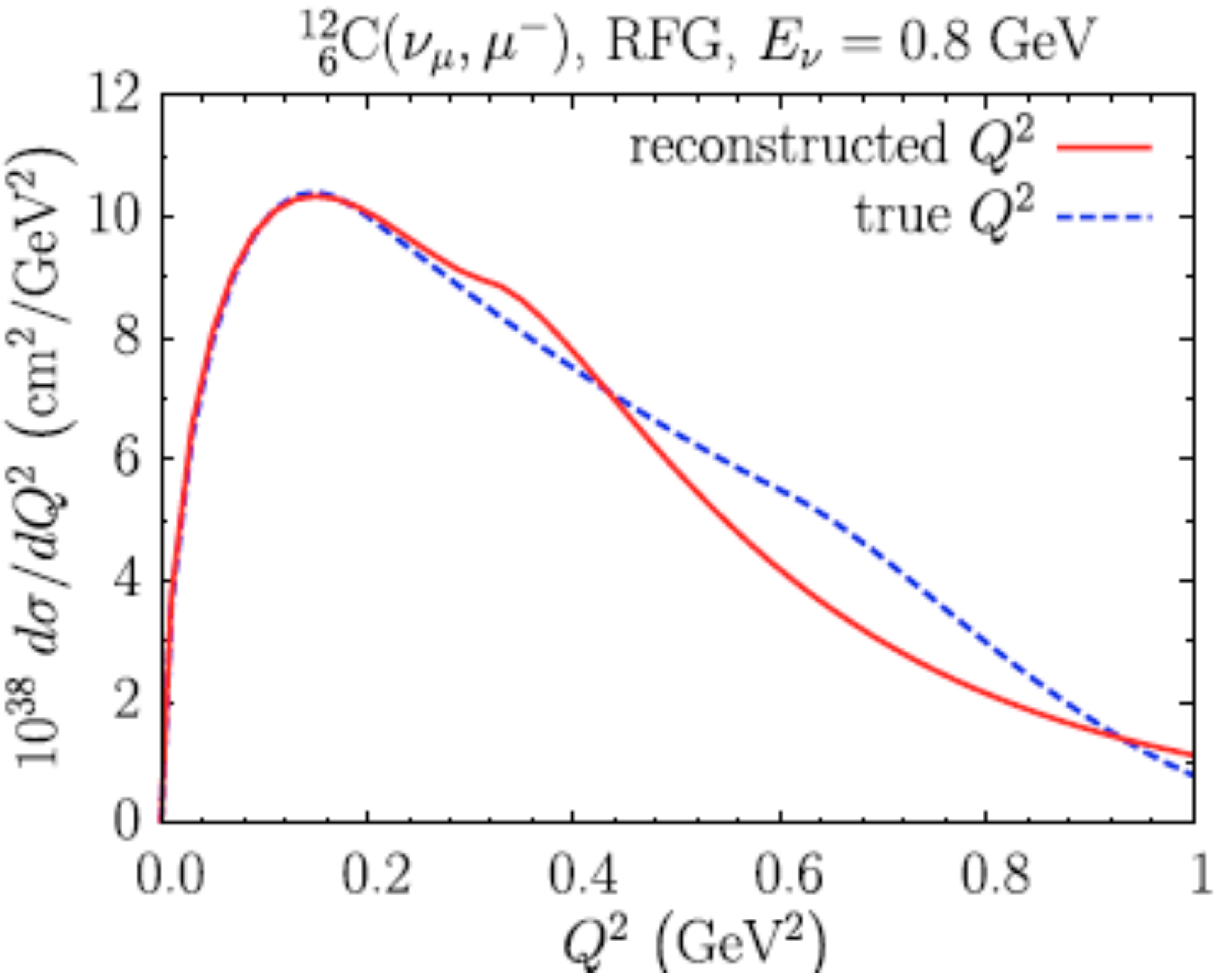
what we see from experimental measurements

1. presumably MiniBooNE detector was perfect.
2. no far detector (w/o any need to consider the oscillation probability).

10% difference in total flux-unfolded cross-section between RFG and SF

Motivation - Why SF? (III)

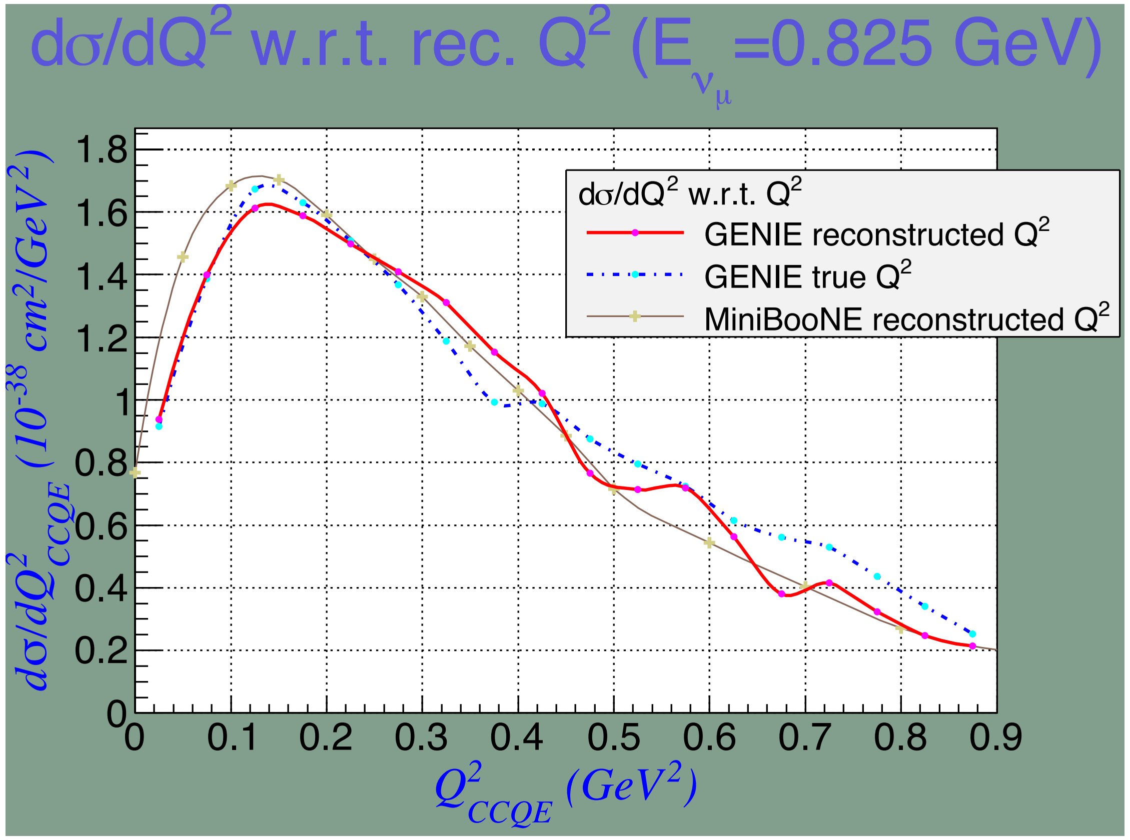
reconstructed Q² is determined by not only the target's intrinsic responses and properties but the coupling strength at the interaction vertex.



$$E_\nu^{\rm rec} = \frac{2E_\mu(M_n-\varepsilon) - (\varepsilon^2 - 2M_n\varepsilon + m_\mu^2 + \Delta M^2)}{2(M_n - \varepsilon - E_\mu + |\mathbf{k}'|\cos\theta)}$$

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

$$\frac{d\sigma}{dQ^2} \approx \sigma(E)\,\frac{dN}{dQ^2}$$

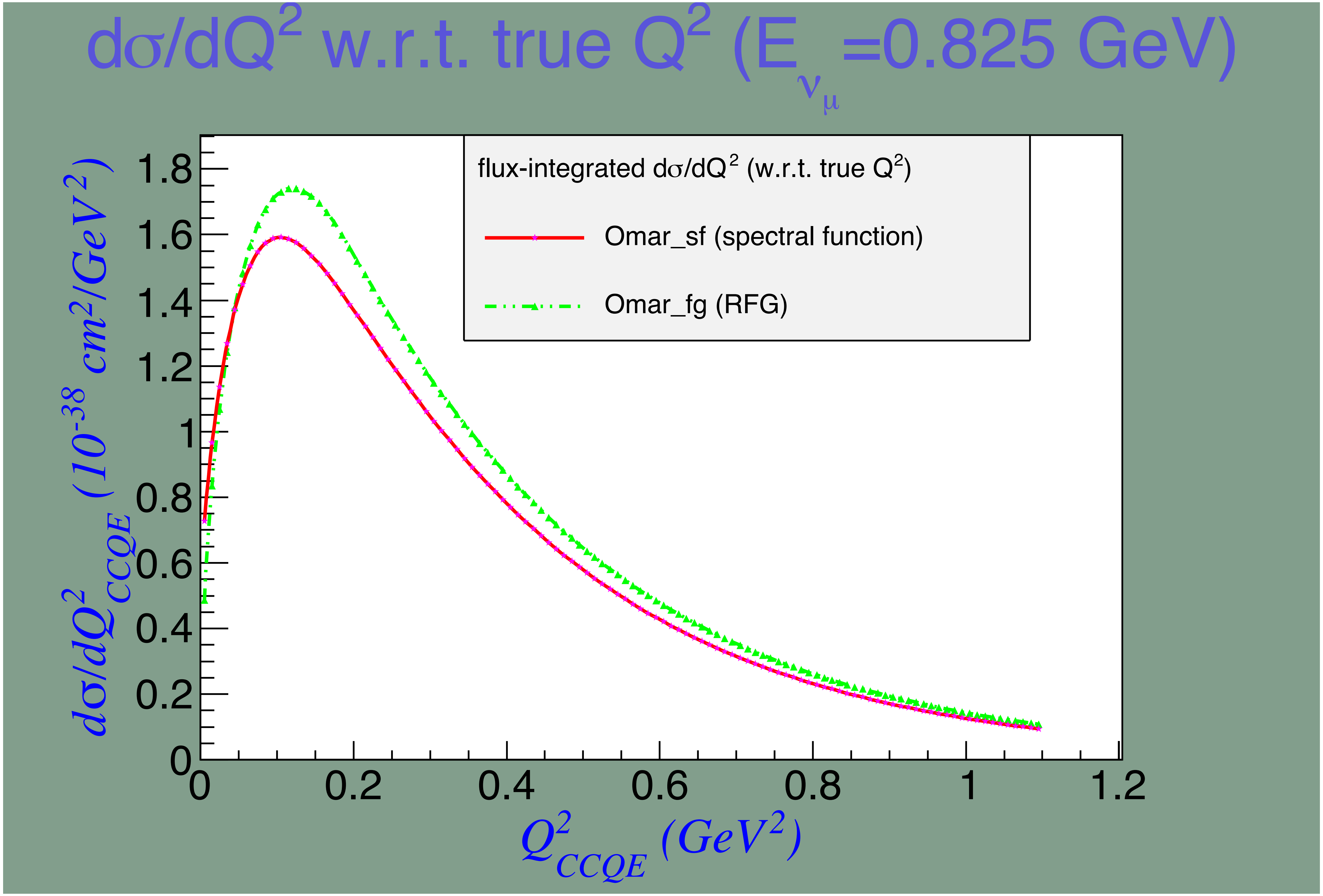


Phys. Rev. D 82, 013002 (2010)

Analysis of the Q² dependence of charged-current quasielastic processes in neutrino-nucleus interactions

Artur M. Ankowski, Omar Benhar, Nicola Farina

Motivation - Why SF? (IV)



Phys. Rev. D 82, 013002 (2010)

Analysis of the Q^2 dependence of charged-current quasielastic processes in neutrino-nucleus interactions

Artur M. Ankowski, Omar Benhar, Nicola Farina

Motivation - Why SF? (V)

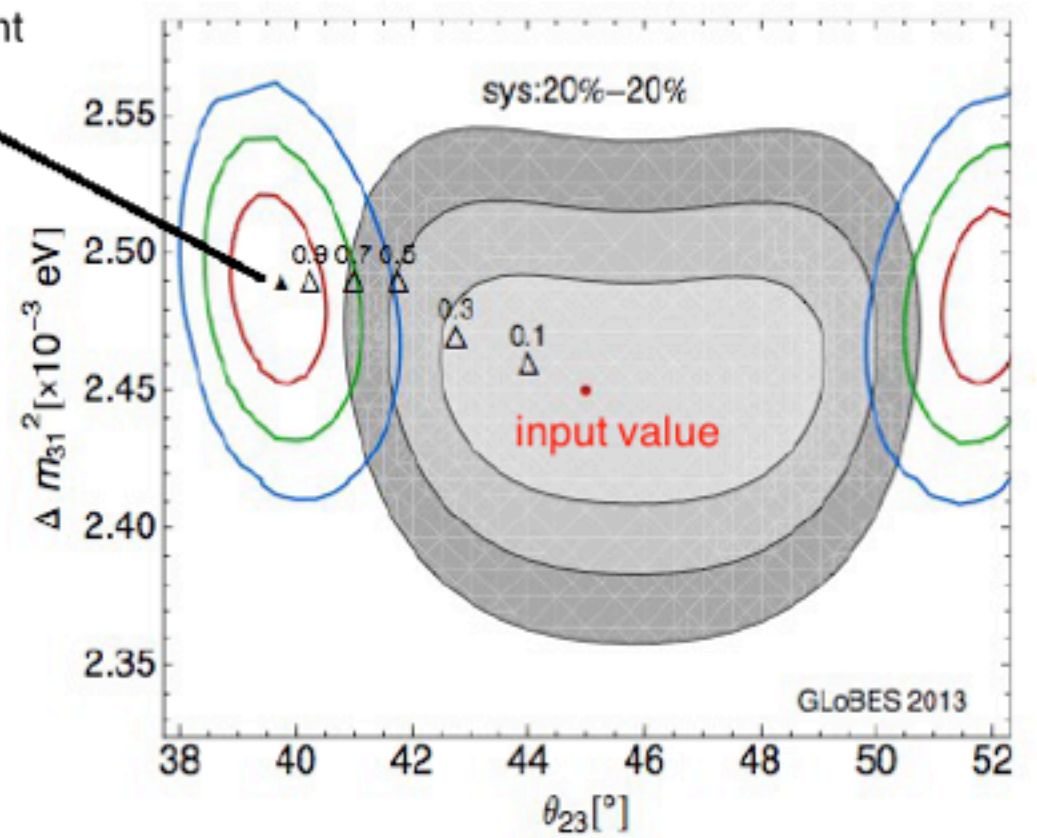
this is case similar to T2K but is not the real T2K case

$$N_i^{QE} = \sigma_{QE}(E_i)\phi(E_i)P_{\mu\mu}(E_i)$$

$$N_i^{QE-like} = \sum_j M_{ij}^{QE} N_j^{QE} + \sum_{non-QE} \sum_j M_{ij}^{non-QE} N_j^{non-QE}$$

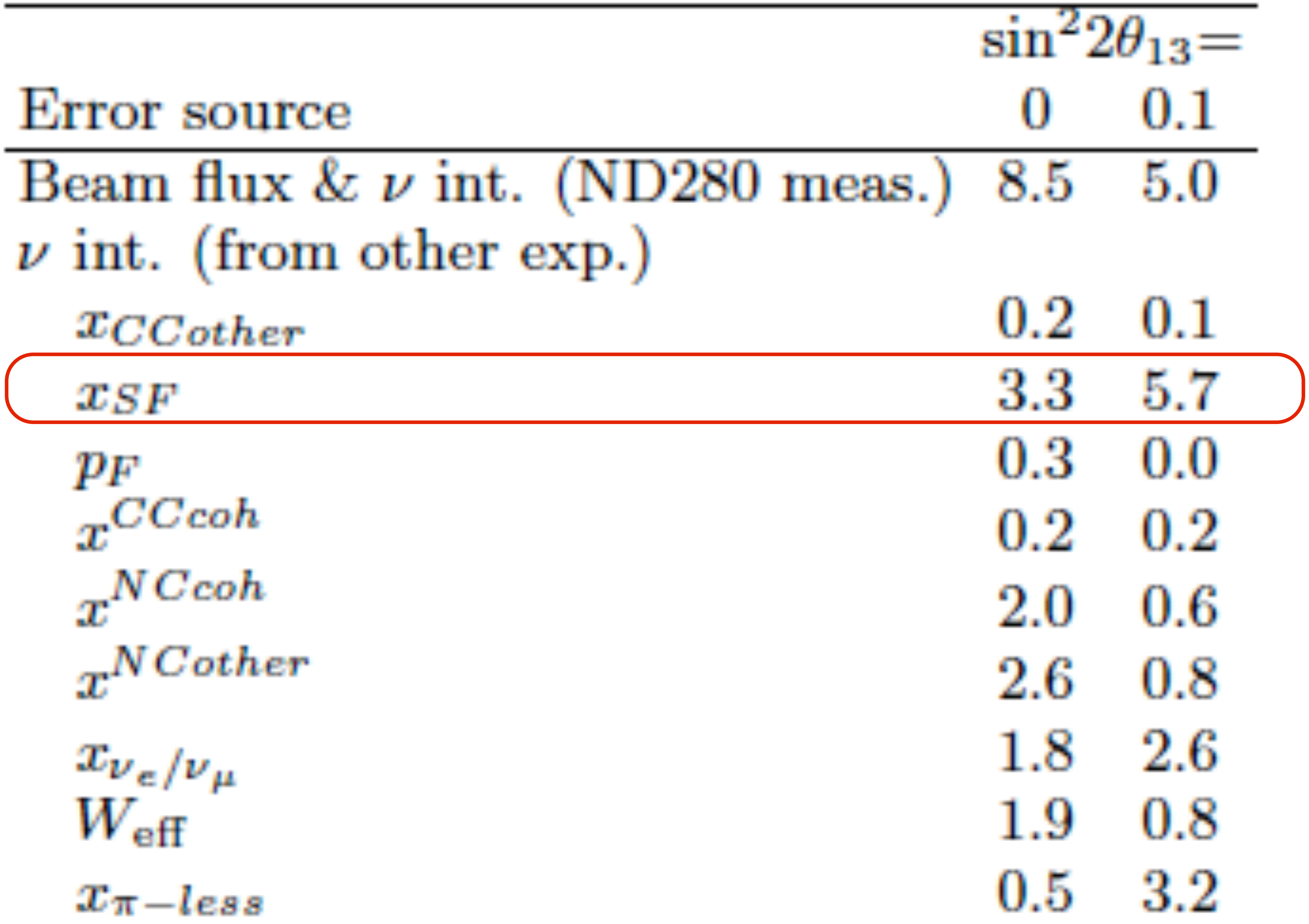
$$N_i^{test}(\alpha) = \alpha N_i^{QE} + (1-\alpha) N_i^{QE-like}$$

Coloma and Huber, 1307.1243 [hep-ph]



due to a variety of nuclear effects, non-CCQE events are more likely to be misidentified as CCQE signals. extraction of oscillating parameters requires the accurate knowledge of reconstructed neutrino energies. take T2K, the fitted oscillating parameters are deviated from the true input value.

Evidence of Electron Neutrino Appearance in a Muon Neutrino Beam **T2K Collaboration**



Error source	$\sin^2 2\theta_{13}=$ 0	0.1
Beam flux & ν int. (ND280 meas.)	8.5	5.0
ν int. (from other exp.)		
$x_{CCother}$	0.2	0.1
x_{SF}	3.3	5.7
p_F	0.3	0.0
x^{CCcoh}	0.2	0.2
x^{NCcoh}	2.0	0.6
$x^{NCother}$	2.6	0.8
x_{ν_e/ν_μ}	1.8	2.6
W_{eff}	1.9	0.8
$x_{\pi-less}$	0.5	3.2

10.1103/PhysRevD.88.032002

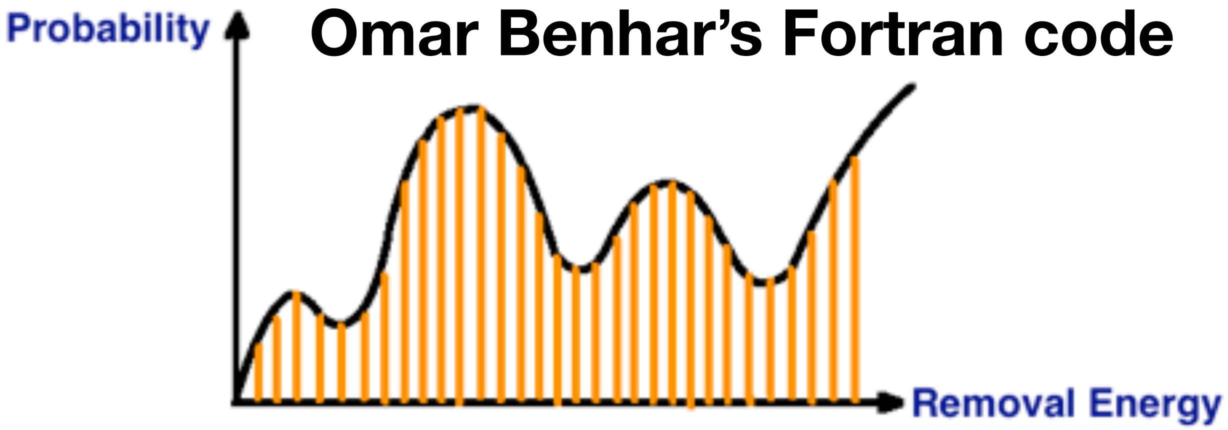
Motivation - Why SF? (VI)

nuclear model option plays an important role in systematics

Alternative SF algorithm implemented in GENIE

- **Sample momentum and energy (both are correlated)**
- **Sum all of the samples**
- **Select one sample randomly**
- **Search for the corresponding momentum and energy to this sample number according to the probability in SF**
- **Smear the returning momentum and energy**
- **Store a pair of nucleon momentum and removal energy in two arrays**

courtesy to
Omar Benhar's Fortran code



$N_{\text{total samples}}$ * Rndm # = N (E_i)

↓

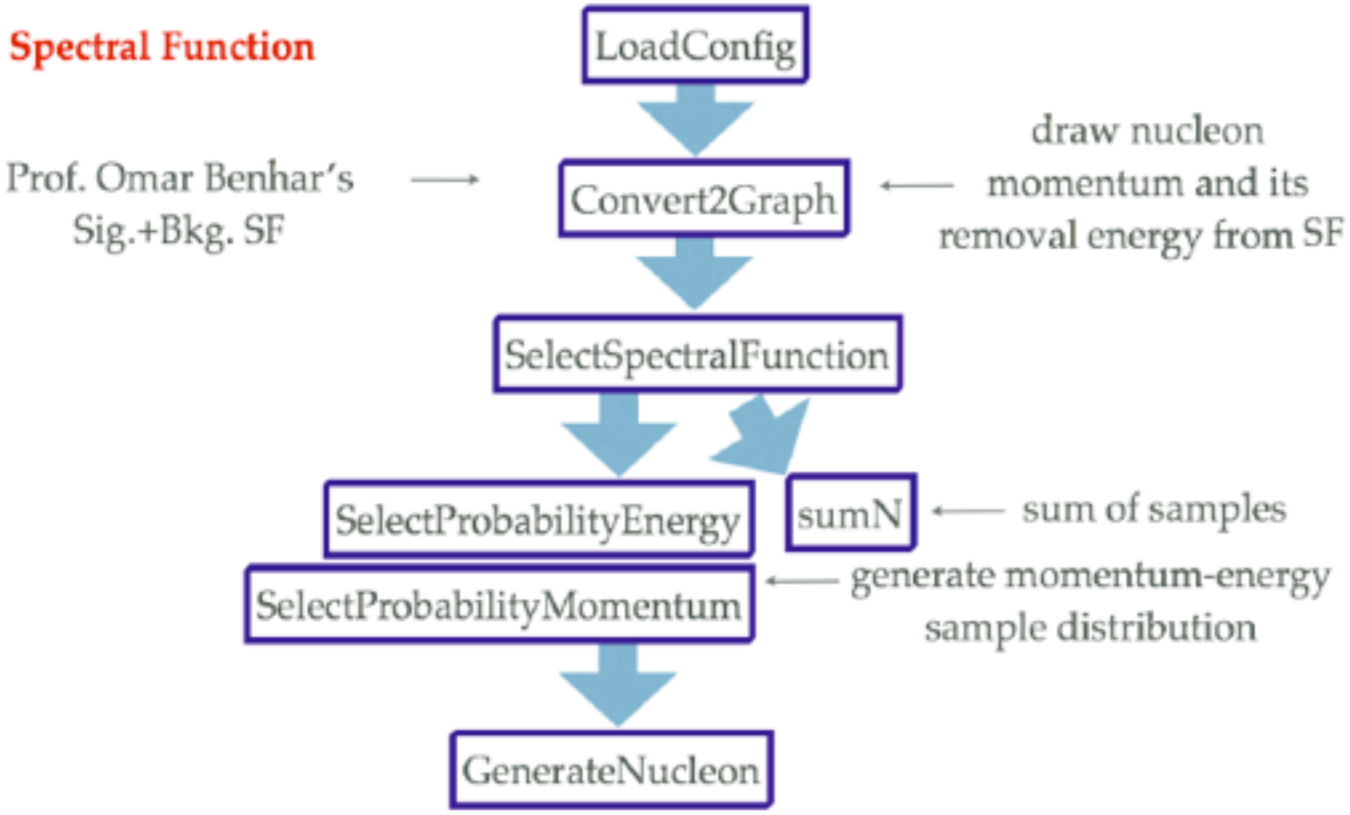
return E_i

↓

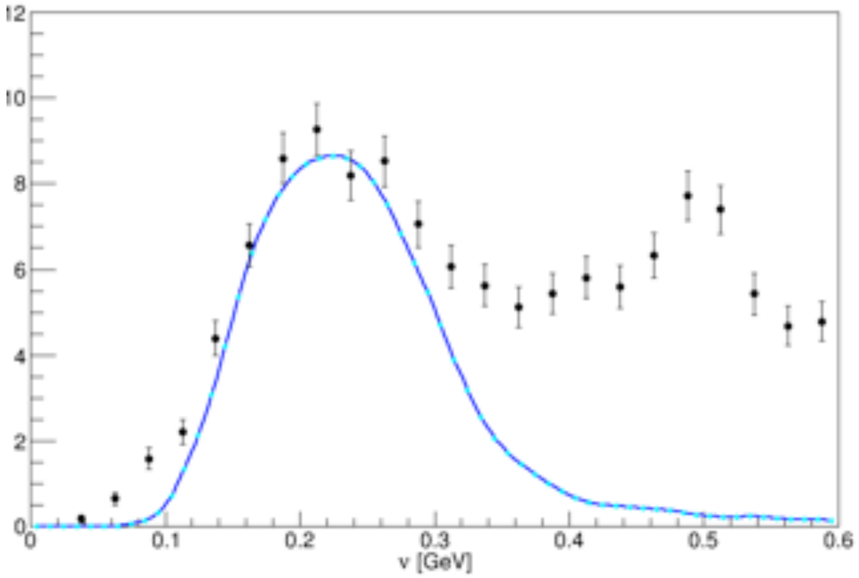
return P (N(E_i))

↓

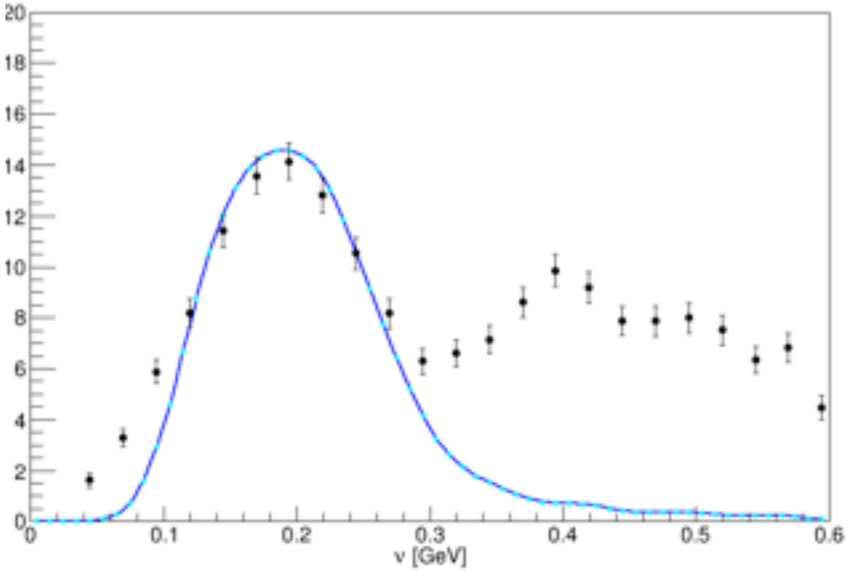
smearing P_i , E_i



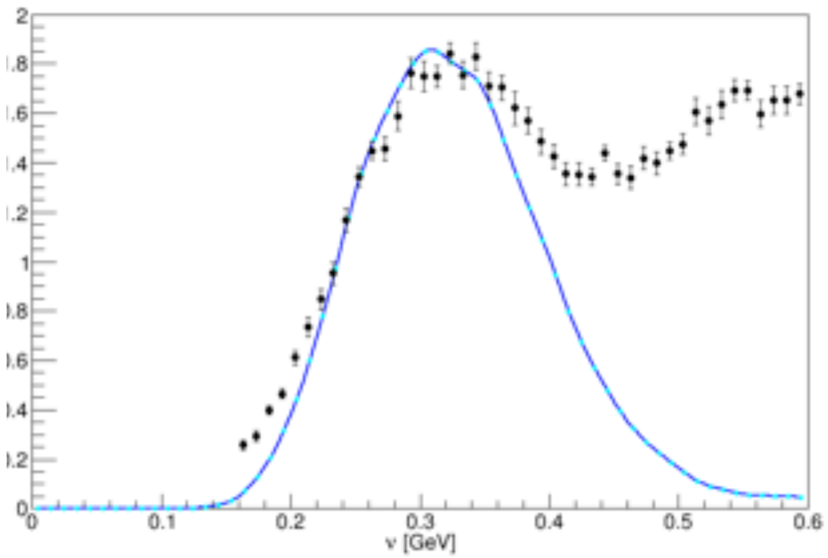
^{16}O (e,e') (E=1.2GeV, θ=32°)



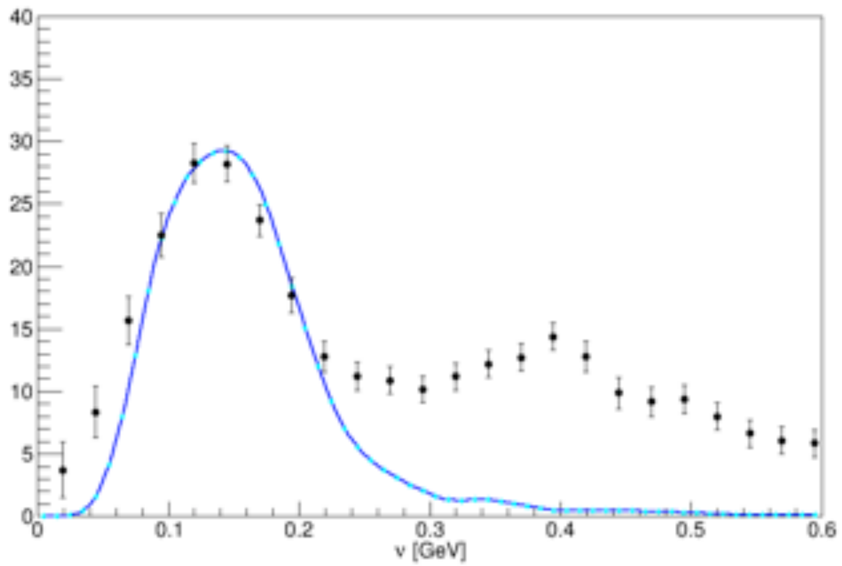
^{16}O (e,e') (E=1.08GeV, θ=32°)



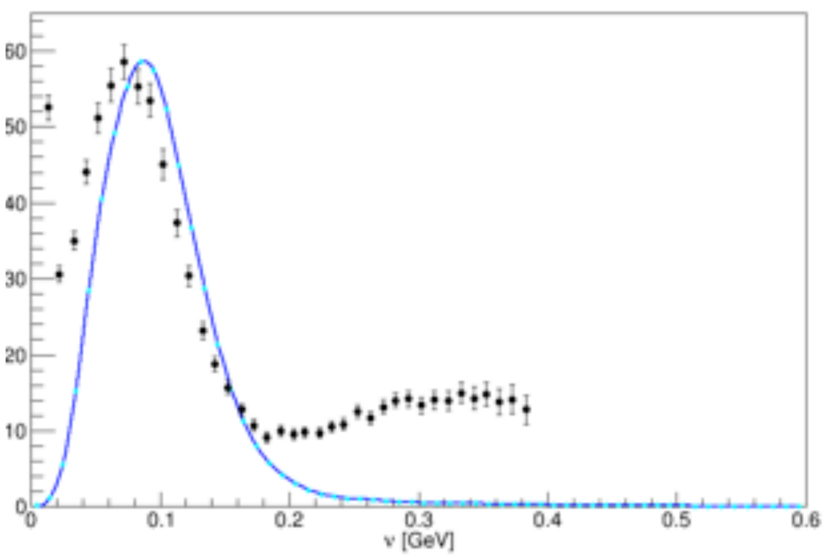
^{12}C (e,e') (E=1.299GeV, θ=37.5°)



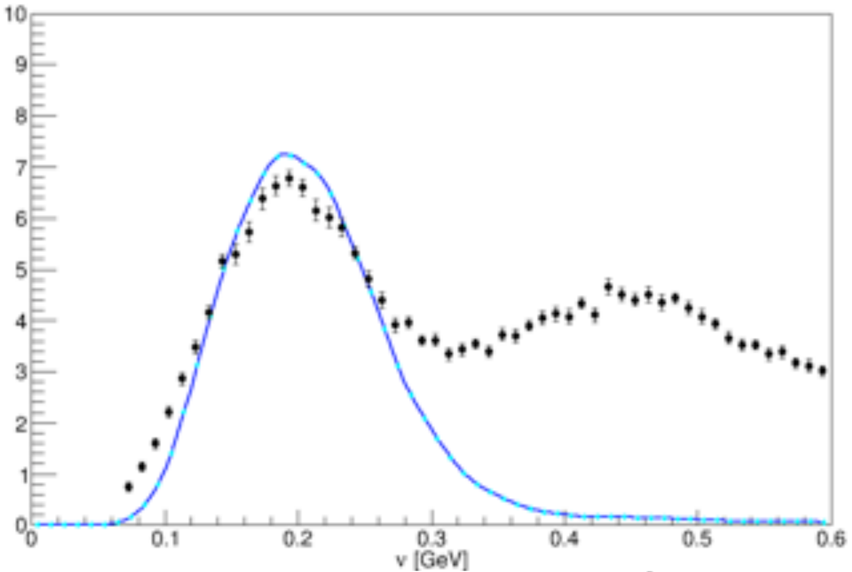
^{16}O (e,e') (E=.88GeV, θ=32°)



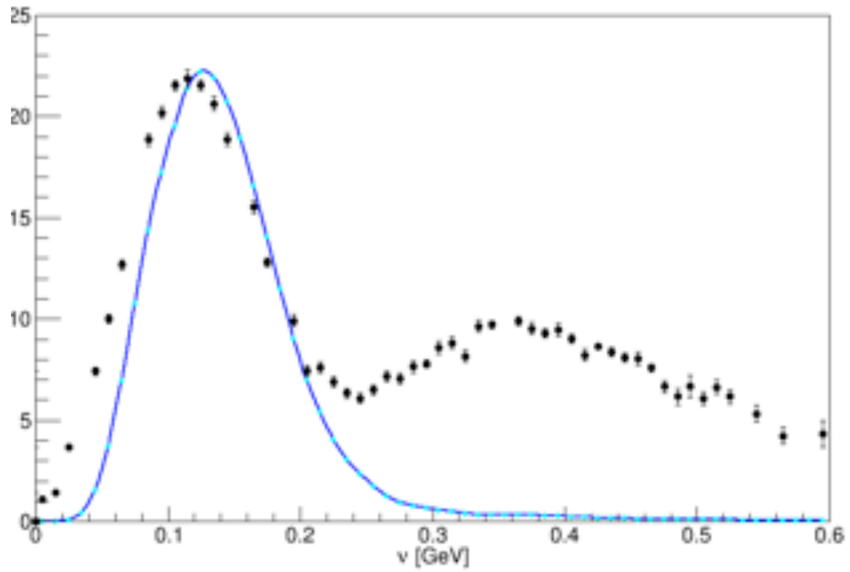
^{12}C (e,e') (E=0.56GeV, θ=36.0°)



^{12}C (e,e') (E=0.961GeV, θ=37.5)



^{12}C (e,e') (E=0.73GeV, θ=37.1°)



why electron data for validation ?

- **fixed incident beam energy**
- **fixed scattering angle**
- **a range of energy transfer**
- **Q^2 is precisely determined**
- **cross-section is bigger and more robust**

Jet Target data Oxygen target
References:
M. Anghinolfi et al.: Journal of Physics G: Nucl. Part. Phys. 21 (1995) L9;
M. Anghinolfi et al.: Nucl. Phys. A602 (1996) 405.

courtesy to
http://faculty.virginia.edu/qes-archive/index.html.

Spectral Function for Calcium & Argon

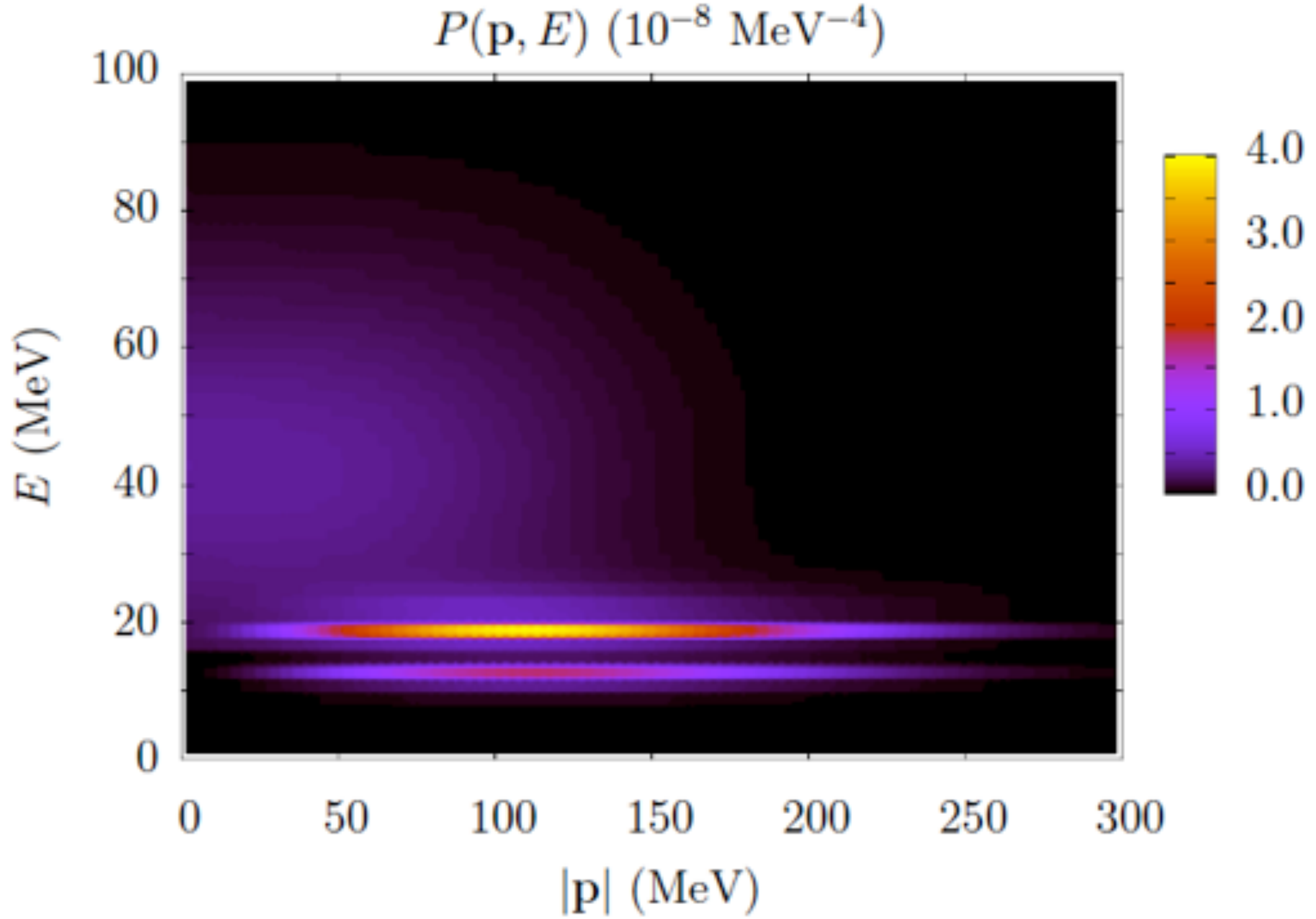
$$\delta(x) = \lim_{\epsilon \to 0} \frac{1}{2\sqrt{\pi\epsilon}}\, \mathrm{e}^{-x^2/4\epsilon}$$

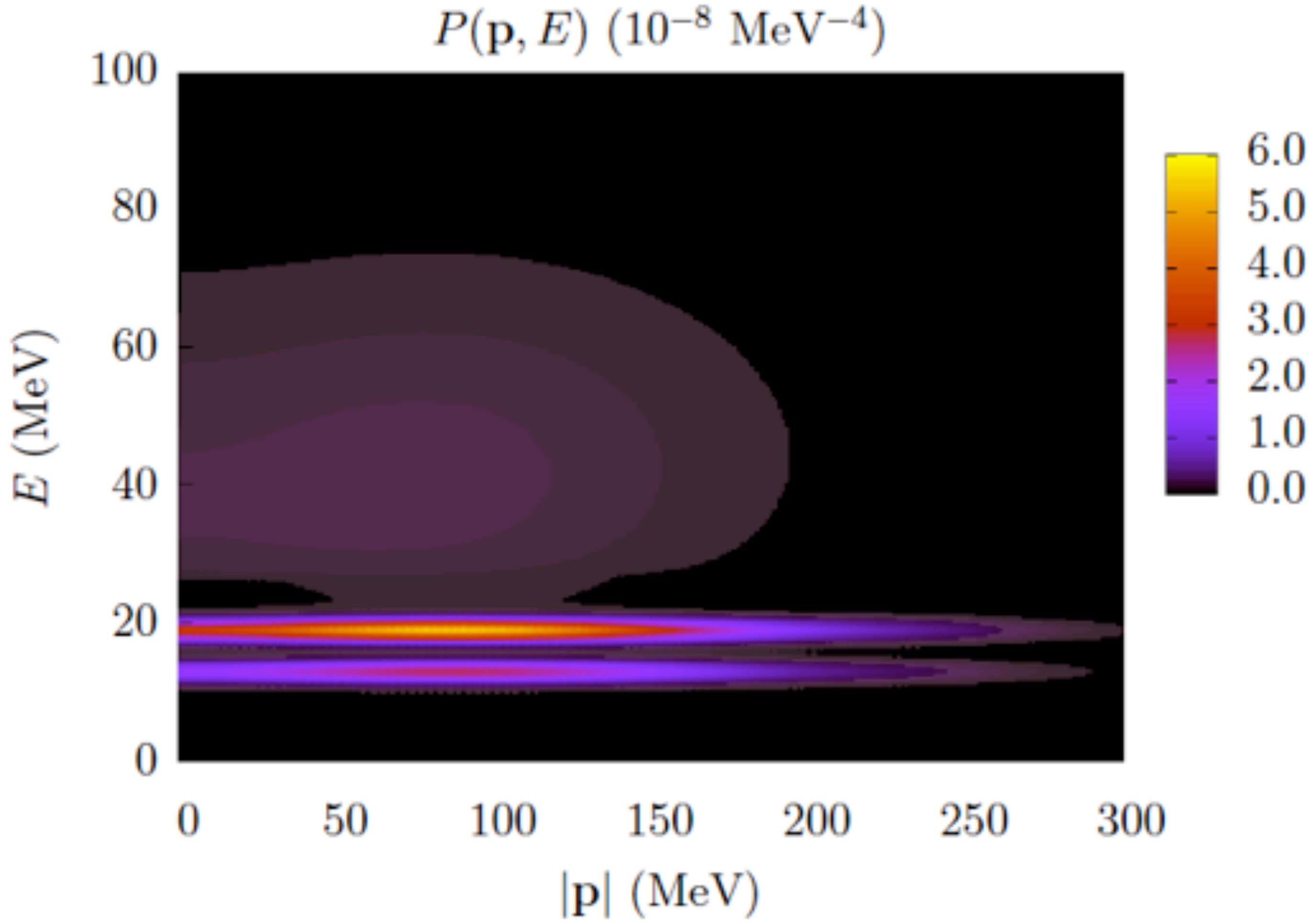
$$\big\downarrow$$

Gaussian function replaces the delta function

$$\delta(x) \to \mathcal{G}(x) = \frac{1}{\sqrt{\pi}\mathcal{D}} e^{-(x/\mathcal{D})^2}$$

courtesy to
Dr. Artur M. Ankowski

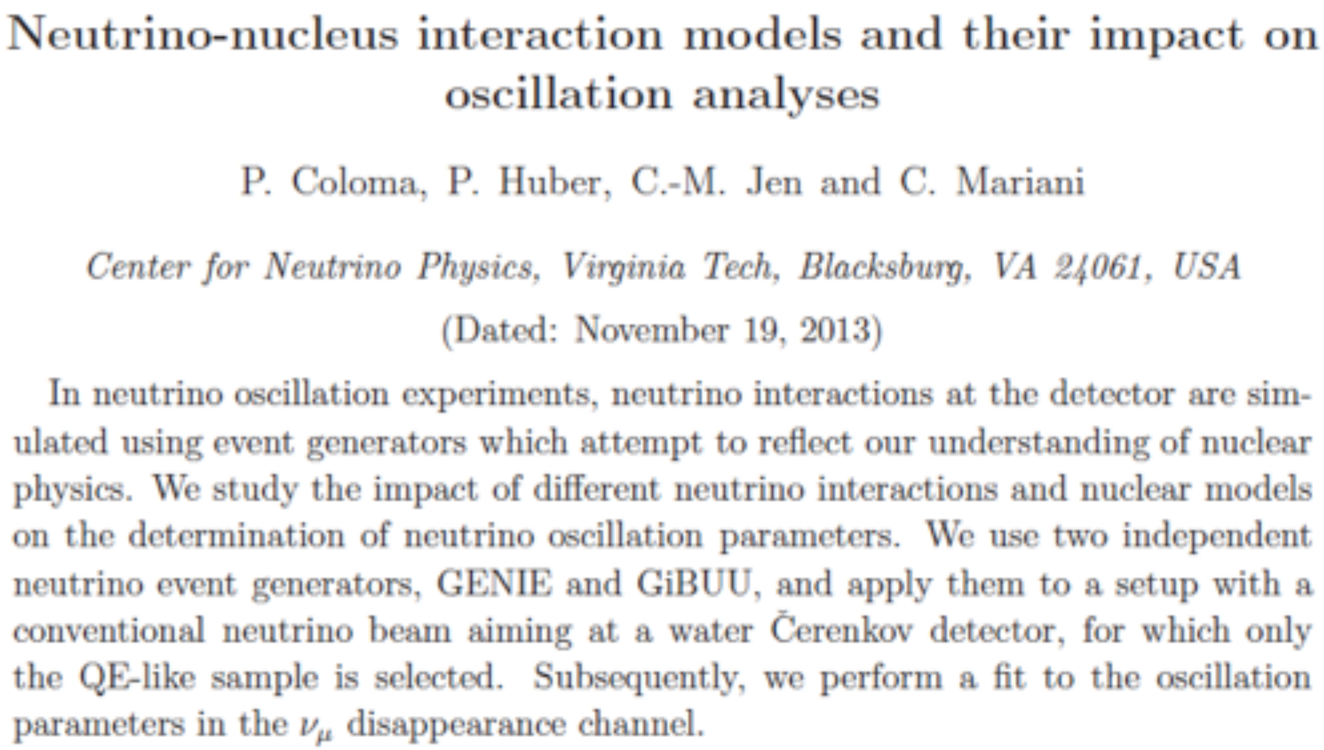




Conclusions

- studies of nuclear effects can help control the bin-by-bin correlation in the uncertainty of the inclusive CCQE cross-section's shape, leading to one of the most significant systematics resources
- implementation of the spectral function can enhance the precision of the inclusive CCQE cross-section at the interaction vertex
- different neutrino event generators can yield different simulation results due to different approaches of implementing the same nuclear model (RFG/SF)

hep-ph/1311.4506



Neutrino-nucleus interaction models and their impact on oscillation analyses

P. Coloma, P. Huber, C.-M. Jen and C. Mariani

Center for Neutrino Physics, Virginia Tech, Blacksburg, VA 24061, USA

(Dated: November 19, 2013)

In neutrino oscillation experiments, neutrino interactions at the detector are simulated using event generators which attempt to reflect our understanding of nuclear physics. We study the impact of different neutrino interactions and nuclear models on the determination of neutrino oscillation parameters. We use two independent neutrino event generators, GENIE and GiBUU, and apply them to a setup with a conventional neutrino beam aiming at a water Čerenkov detector, for which only the QE-like sample is selected. Subsequently, we perform a fit to the oscillation parameters in the ν_μ disappearance channel.

courtesy to
S. Dytman, U. Mosel
O. Lalakulich, O. Benhar

Future Plans

- both spectral functions of Oxygen and Carbon are already implemented in GENIE with the electron validation
- we are going to implement the spectral function of Argon for MicroBooNE and LBNE (with the help from **Dr. Artur M. Ankowski**)
- RPA will follow to be implemented in order to account for the inclusive CCQE cross-section at lower Q^2
- The Pauli-blocking effect (~10%) is small but will be taken into account
- MEC will be implemented by the end of next year (2014 -)

Thank you!

NuTEQ is a collaboration of theorists and experimentalists!