Gamma ray backgrounds for the diffuse SN neutrino search with water-Cherenkov detectors

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Outline

- Why the O(ν, ν') and O($\bar{\nu}$, $\bar{\nu}'$) cross sections in the ~1 GeV region are important for the DSN search
- Spectral function results for primary gammas and nucleon knockout
- Comparisons to other theoretical approaches
- Summary

Core-collapse supernovae

In our Galaxy, SN happens every 30-50 years, with the last visible one in 1604.

High statistics of supernova explosions is **impossible to observe over our lifetime**, but relevant for the understanding of the abundances of the chemical elements, high energy cosmic rays, etc.

Diffuse supernova neutrinos (DSN)

In the Universe, a supernova explodes every second, contributing to a tiny flux of neutrinos, constant in time and isotropic in space: **window on the bulk properties of the entire supernova population**.

The expected signal (energy ~10-40 MeV) is

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

a few events ***per year*** in Super-Kamiokande, compared to ~25 solar and atmospheric events ***per day***.

Backgrounds for the DSN search

In Cherenkov detectors, the signal

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

cannot be distinguished from processes yielding

$$\gamma + n$$ or $$e^- + n$$

in the final state.

Gamma + neutron

Primary gamma rays:

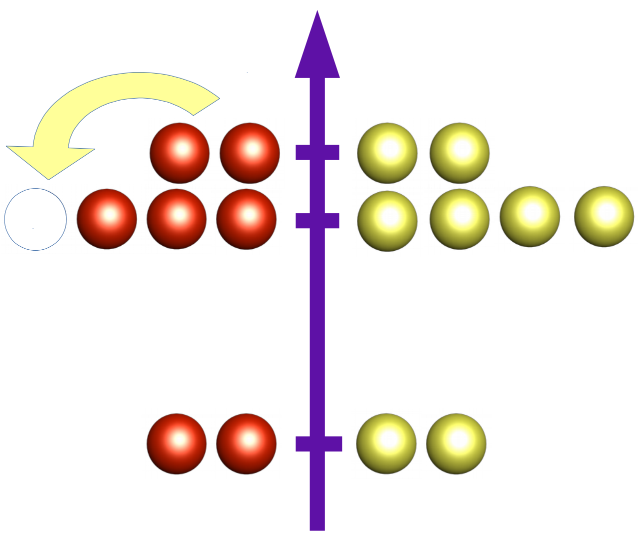
$$\nu + {}^{16}_{8}\mathrm{O} \to \nu + X^* + N$$
$$\hookrightarrow X^* \to Y + \gamma$$

nuclear deexcitation following a NC event,
e.g. atmospheric neutrino interaction (~1 GeV).

Secondary gamma rays: nucleon propagation in water may produce gamma rays.

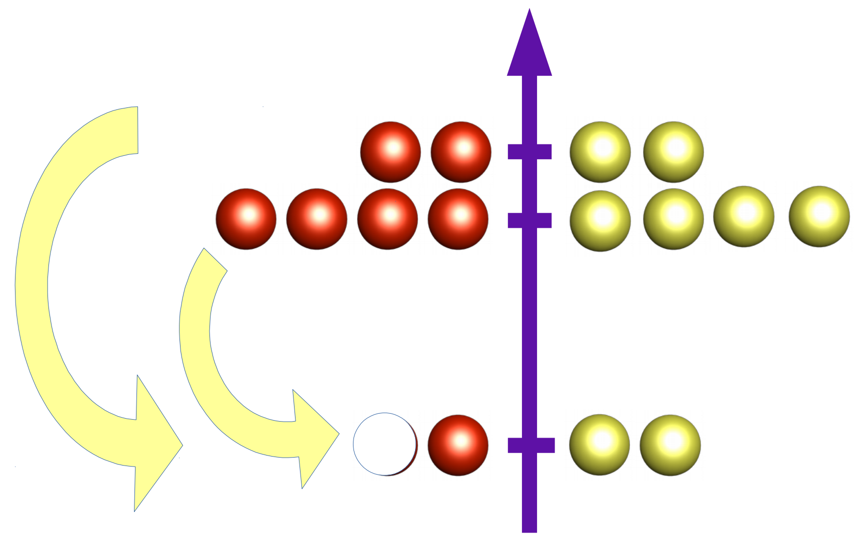
Primary gammas

6-MeV
gamma



p3/2 KO

Many channels,
Br = 16% for Eγ > 4 MeV



s1/2 KO

Ejiri, PRC **48**, 1442 (1993);
Kobayashi *et al.*, nucl-ex/0604006

Primary gammas

The corresponding cross section can be calculated as a product of **the cross section for a given shell** and **its branching ratio** for gamma ray emission, summed over all contributions

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

Spectral function approach

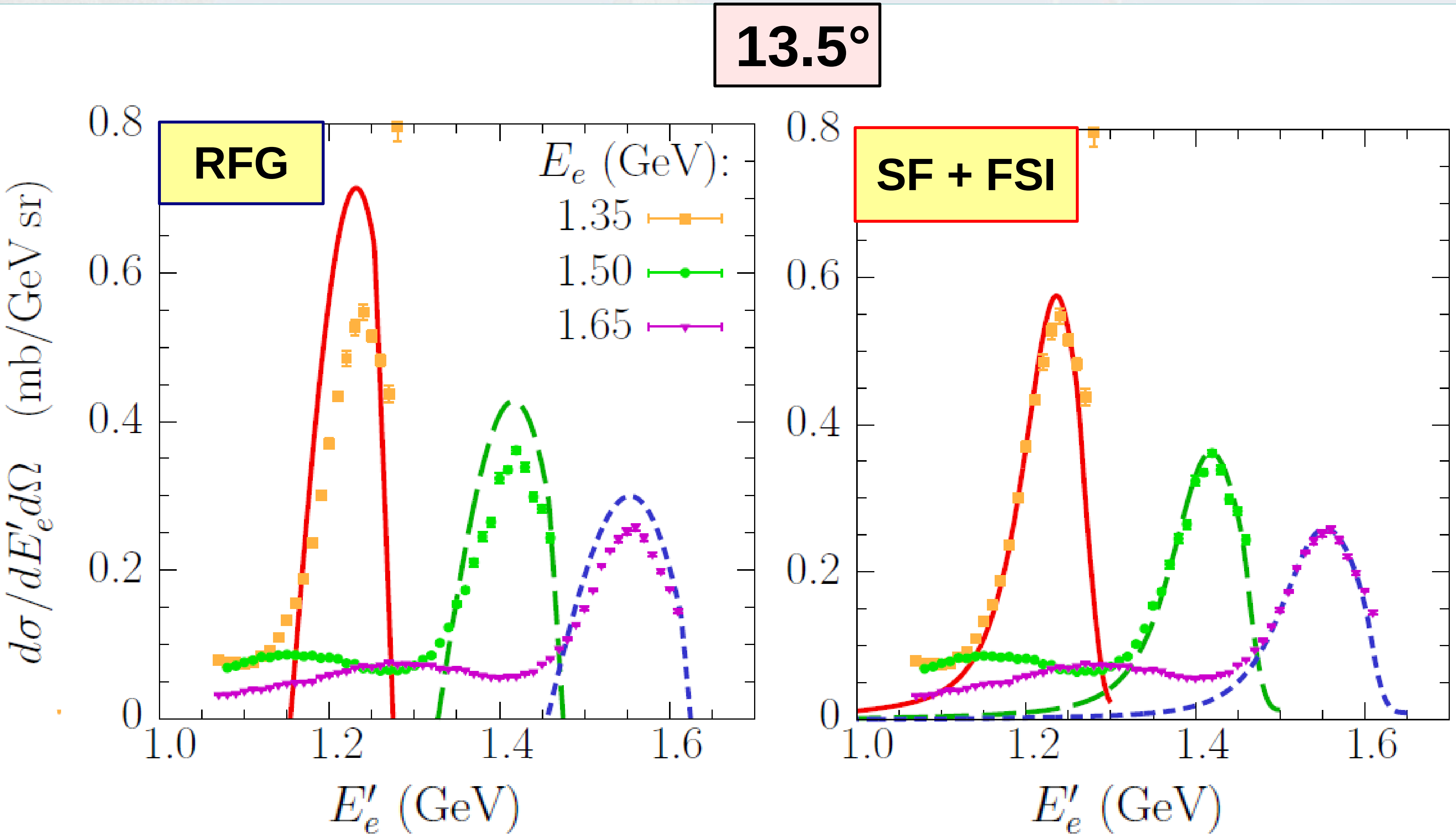
Nucleon-nucleon correlations in nuclei depend on the density but not on the shell or surface effects.

The ground-state nuclear properties can be described combining

- **the shell structure** extracted from (*e*, *e′p*) data
- **the correlation contribution** obtained from theoretical calculations for nuclear matter at different densities, including two- and three-nucleon interactions

Benhar *et al.*, NPA **579**, 493 (1994)
PRD **72**, 053005 (2005).

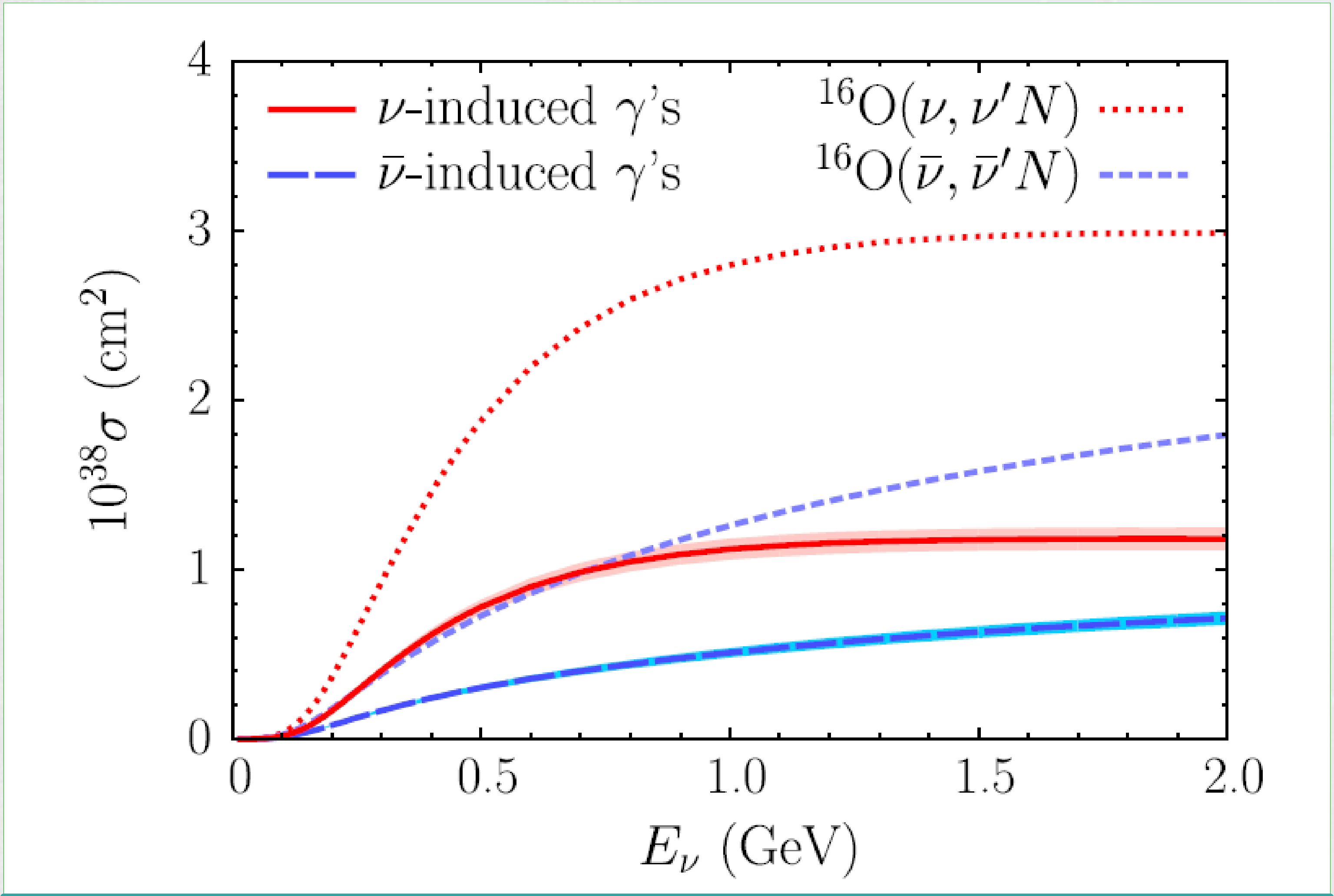
Comparison to C(*e*,*e'*) data



data: Baran *et al.*, PRL 61, 400 (1988)

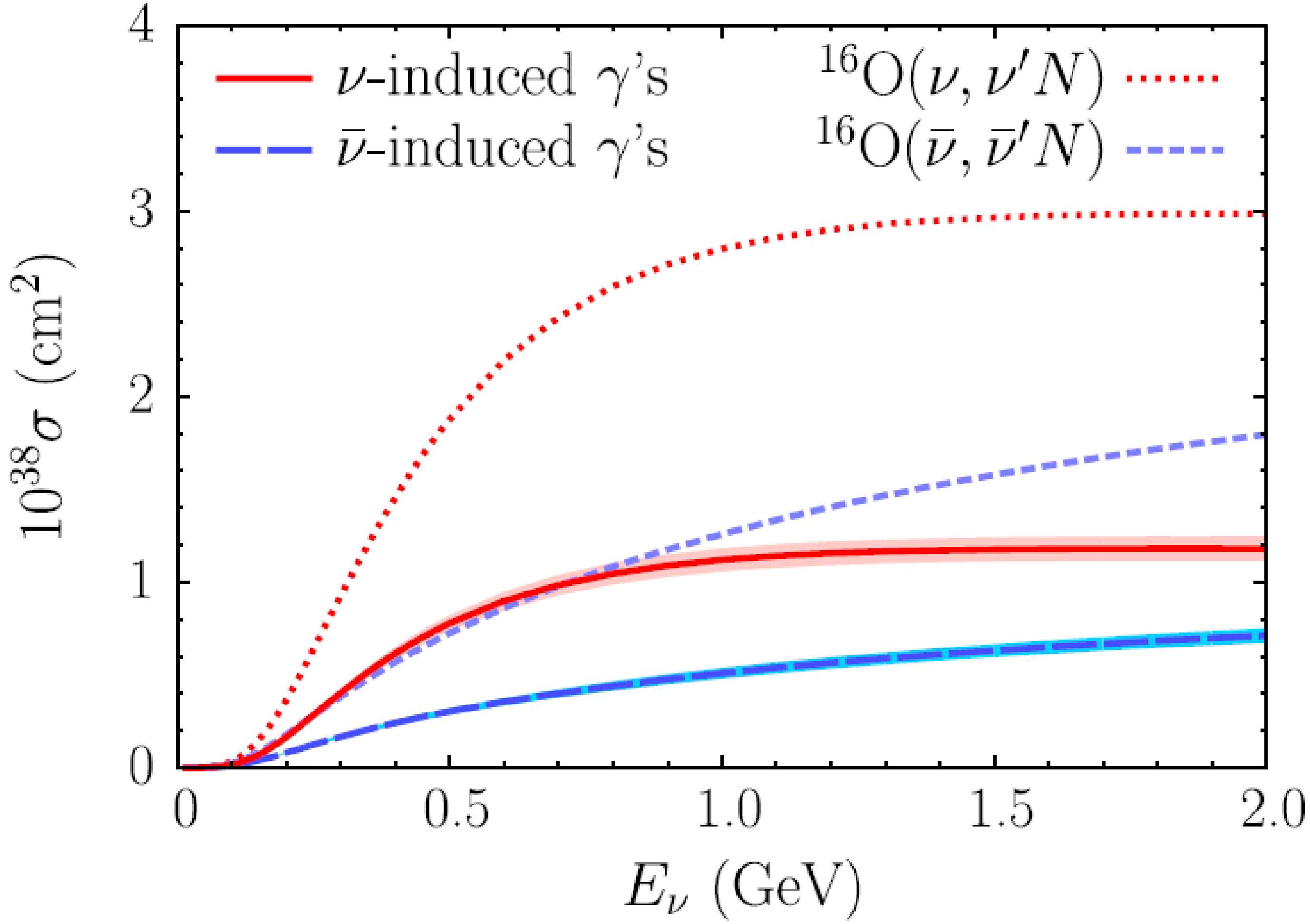
A.M.A., O. Benhar & M. Sakuda, PRD 91, 033005 (2015)

Primary gammas



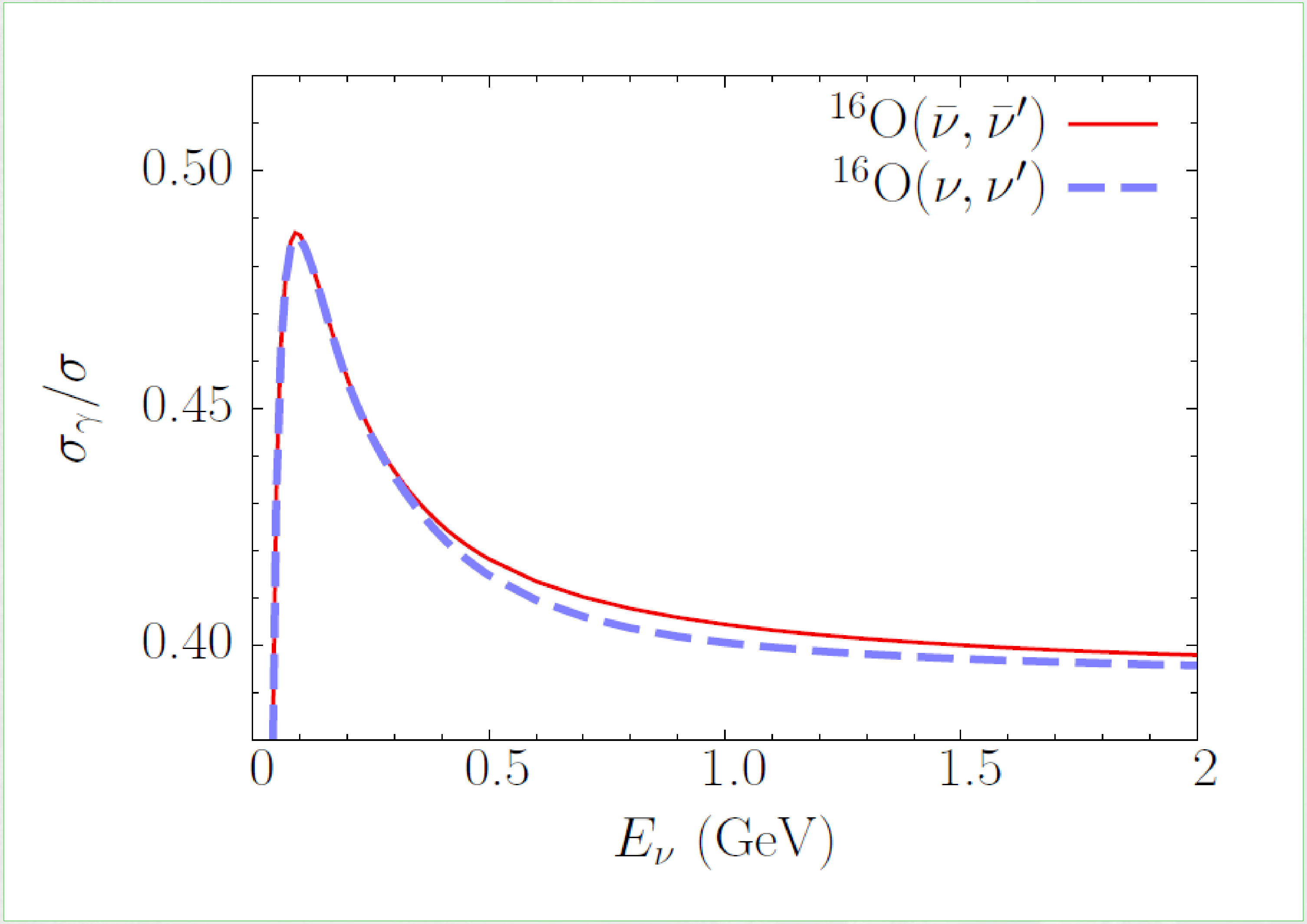
A.M.A., O. Benhar, T. Mori, R. Yamaguchi, and M. Sakuda
PRL **108**, 052505 (2012)

Primary gammas

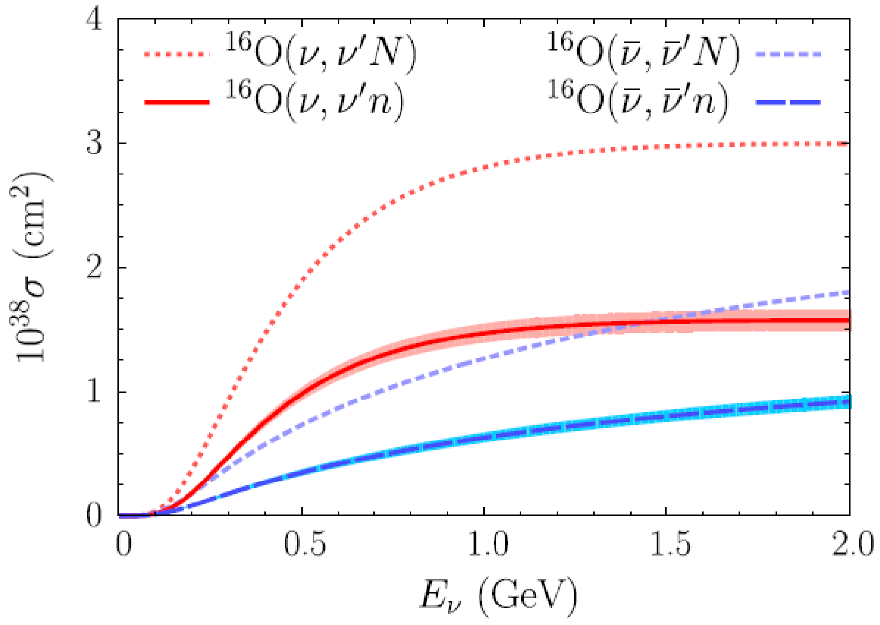


At 0.5 (1.0) GeV, **~10 (15) x** σ(ν+O → ν'+O*)
Kolbe et al., PRD **66**, 013007 (2002)

Fraction of gammas in NC events



Neutron and proton knockout



A.M.A and O. Benhar,
PRD 88, 093004 (2013)

COMPASS experiment
polarized DIS, muon beam, ^{6}LiD target

$$\Delta s = -0.08 \pm 0.01(\text{stat}) \pm 0.02(\text{syst}),$$

Alexakhin *et al.*, PLB 647, 8 (2007)

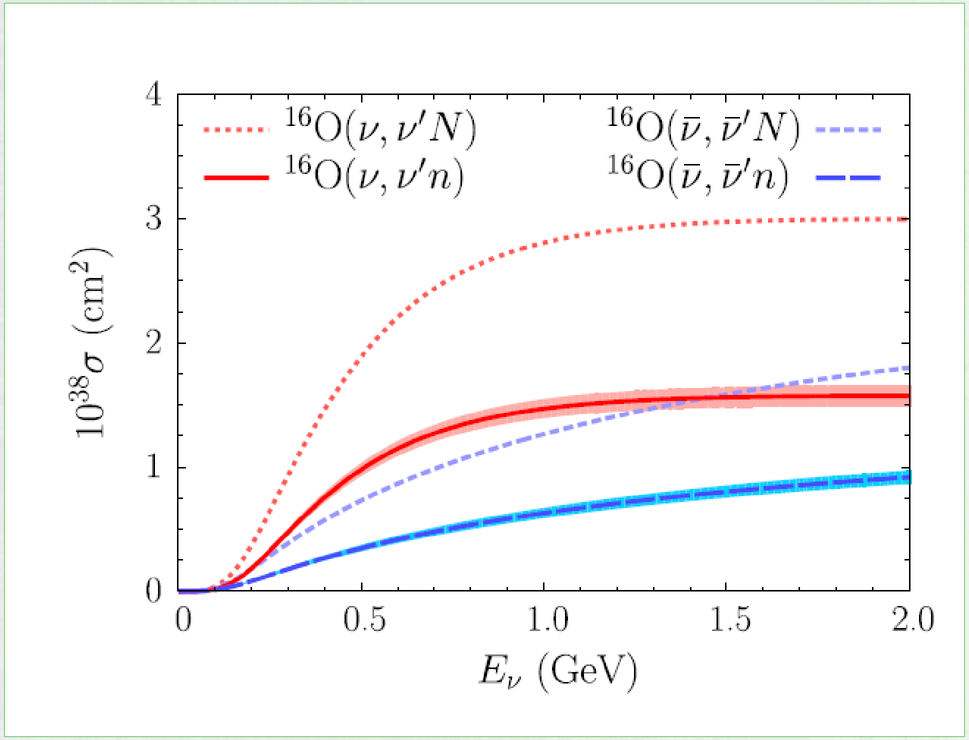
Excellent agreement with HERMES,
positron scattering off deuteron
Airapetian et al., PRD 75, 012007 (2007)

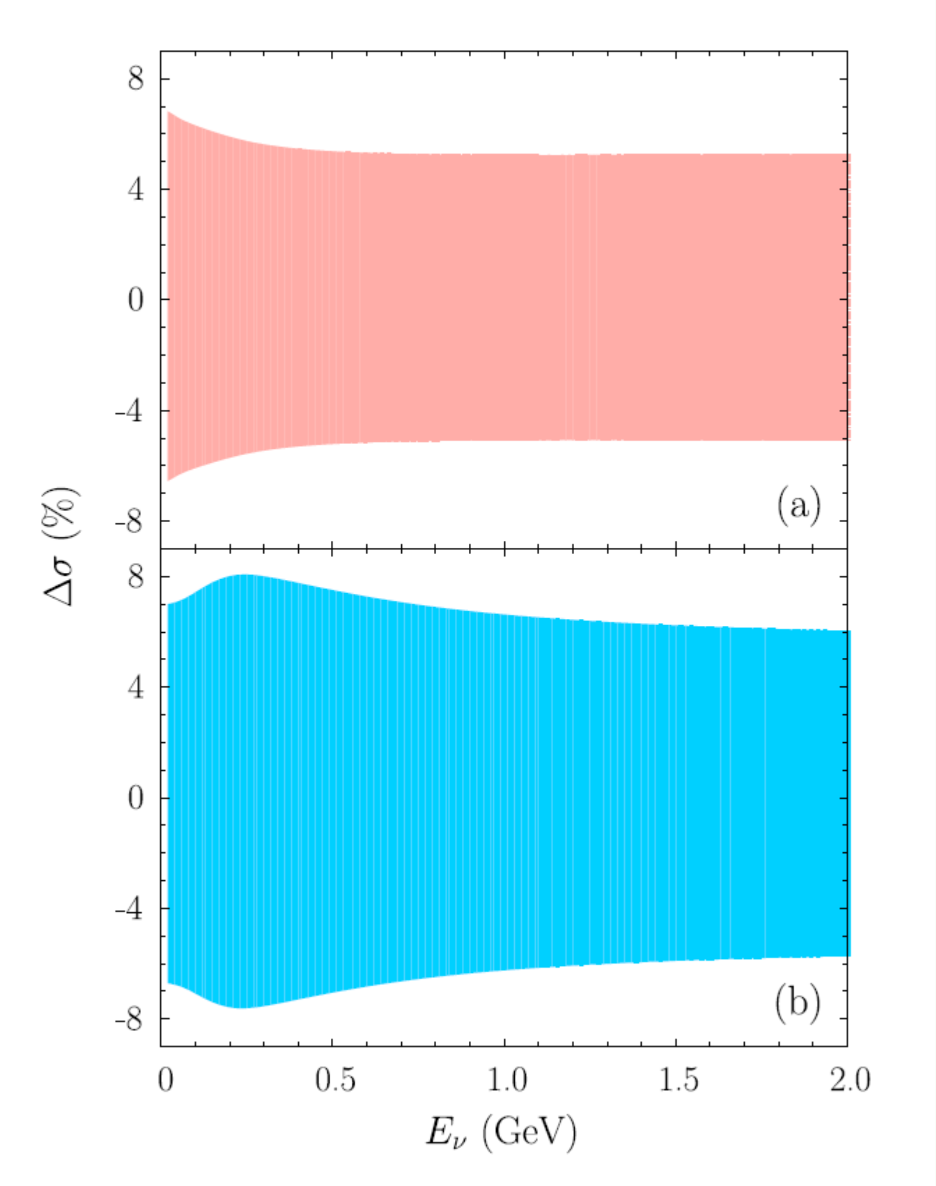
If SU(3)$_f$ violated in hyperon beta decays,
[< 20% from the KTeV experiment]
Δs may shift by ± 0.04.

In our calculations,

$$\Delta s = -0.08 \pm 0.05$$

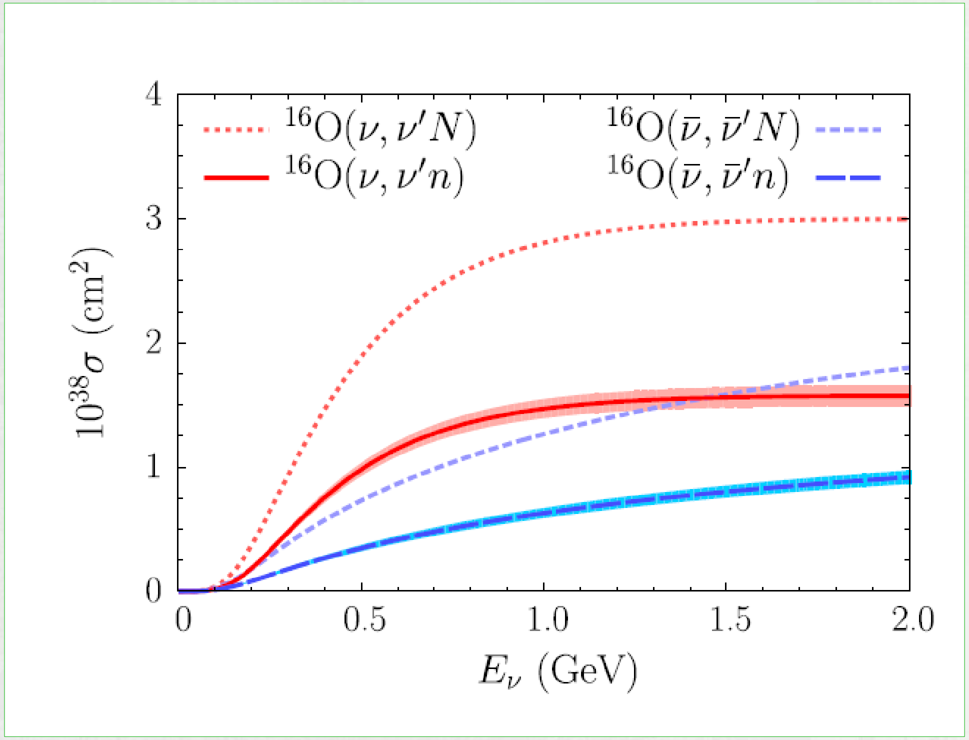
Neutron and proton knockout

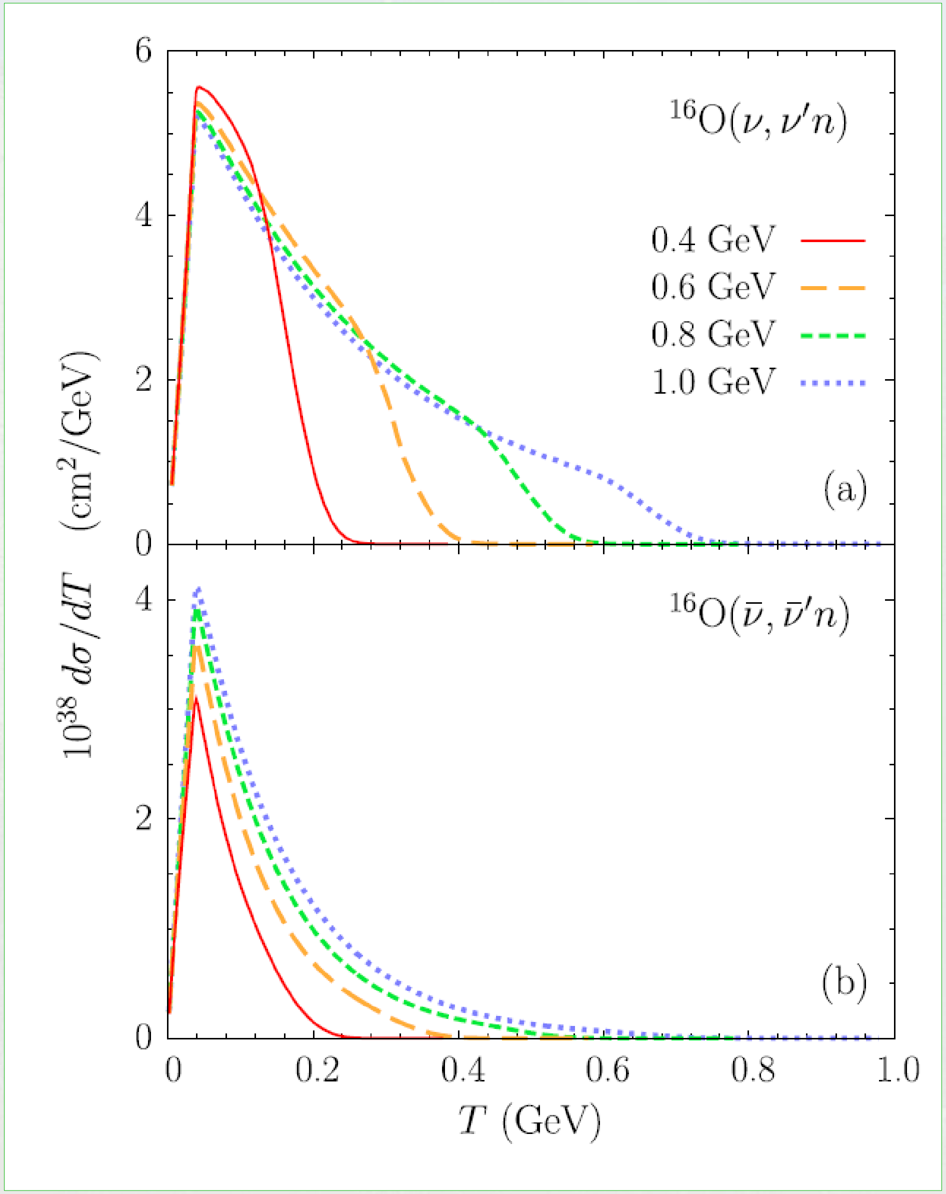




A.M.A and O. Benhar,
PRD 88, 093004 (2013)

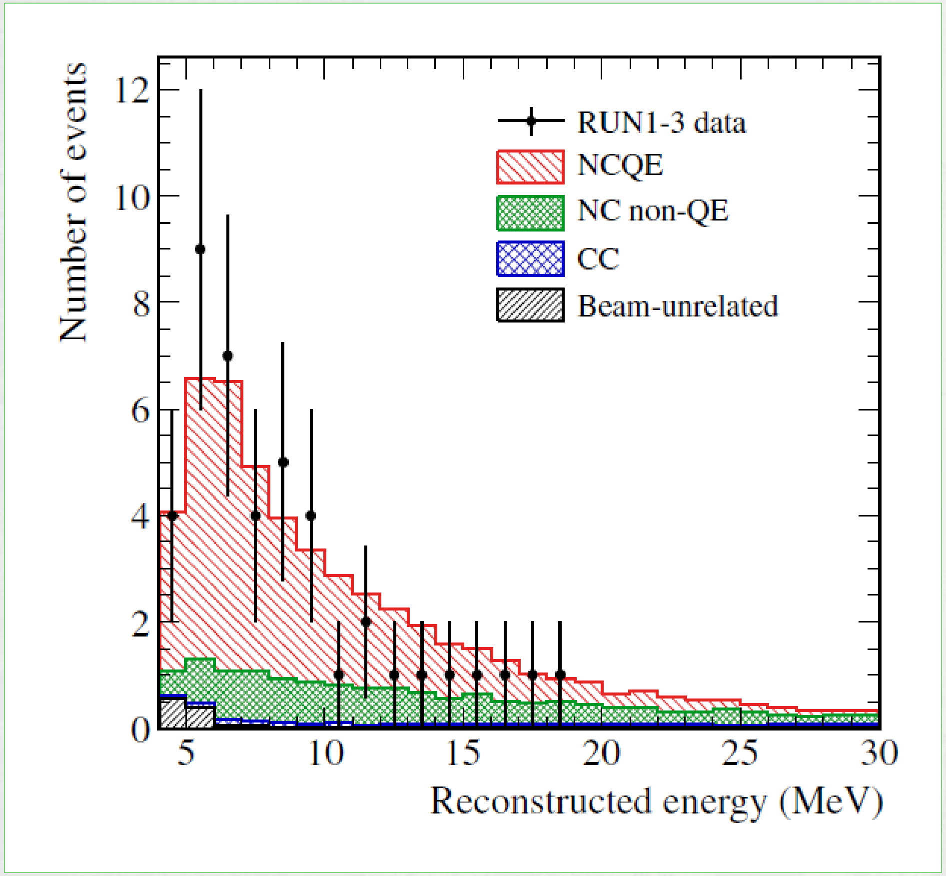
Neutron and proton knockout

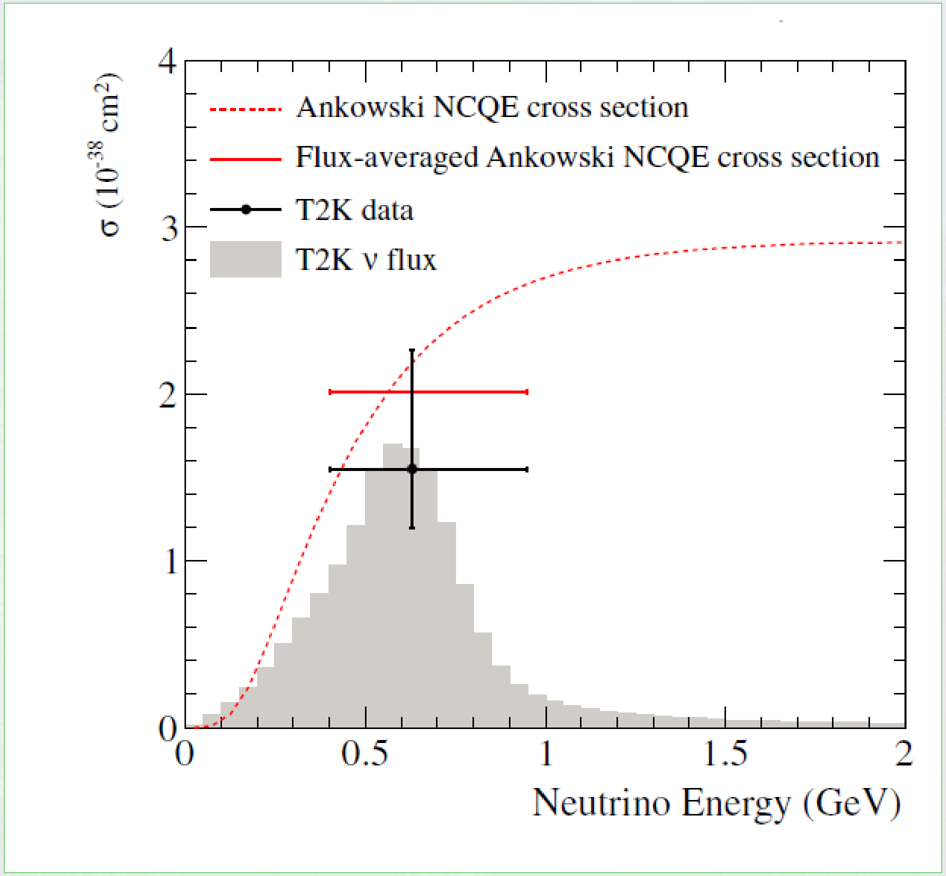




A.M.A and O. Benhar,
PRD 88, 093004 (2013)

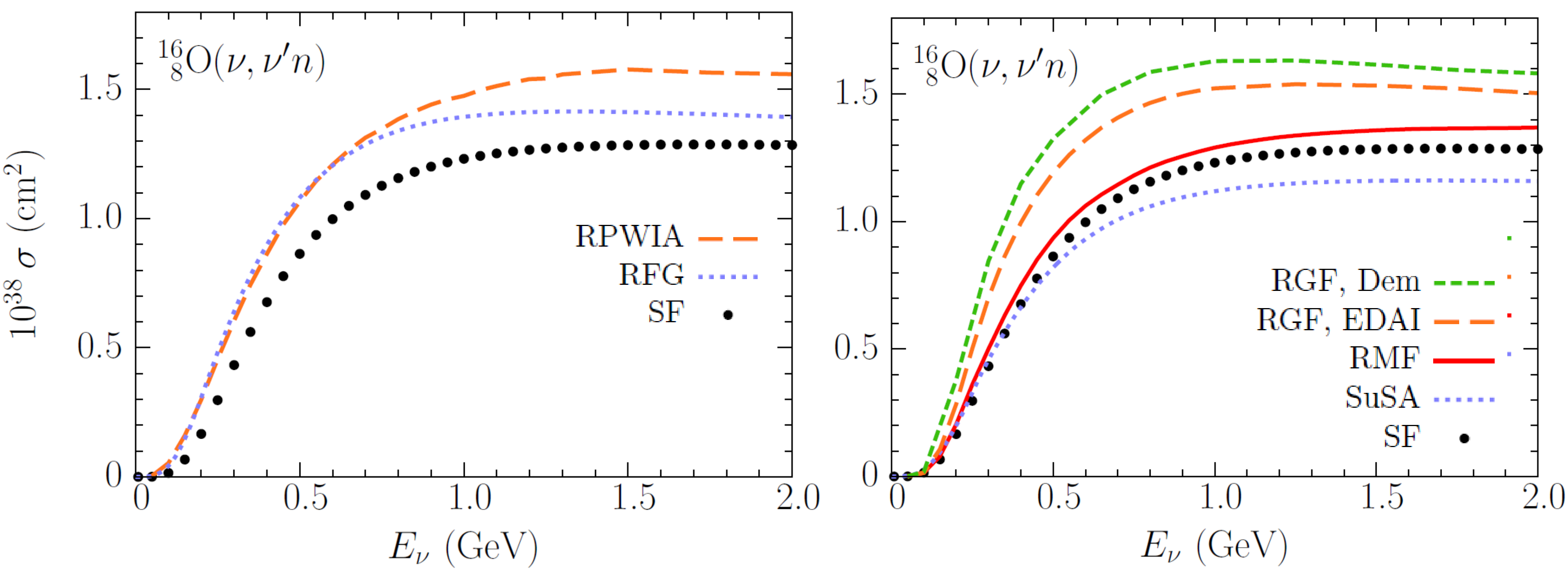
T2K neutrino measurement





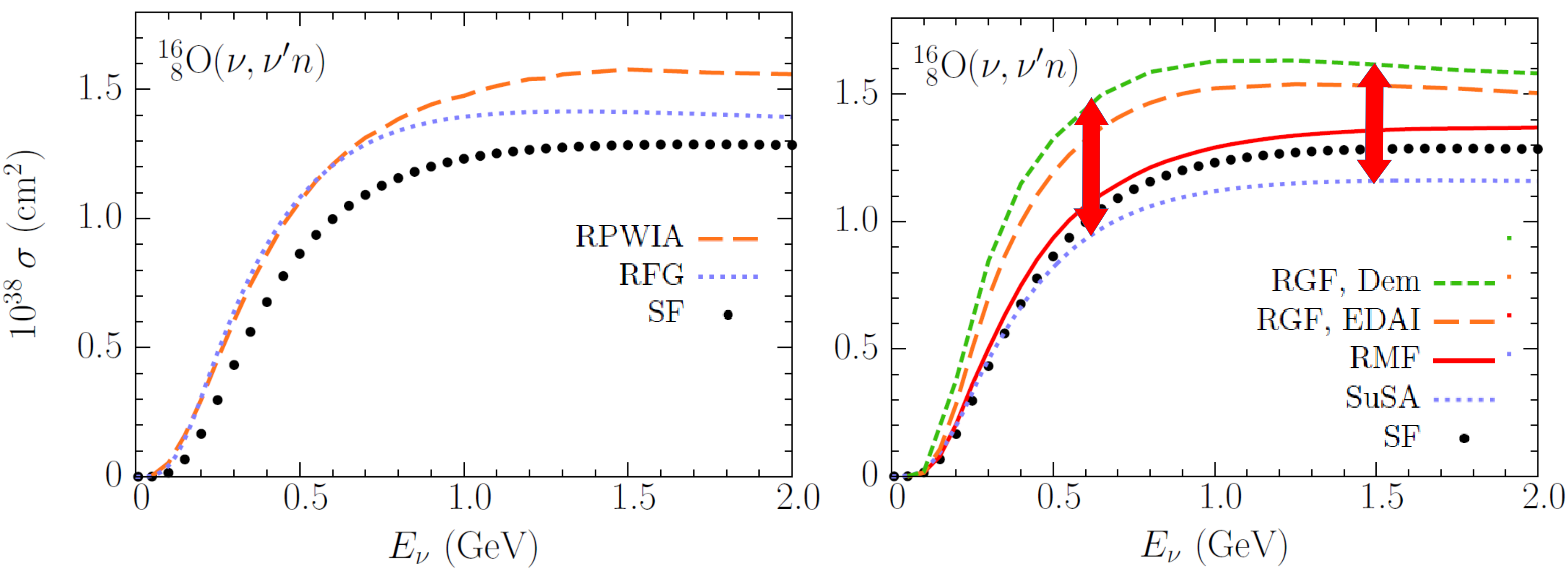
T. Abe *et al.* (T2K Collaboration),
PRD 90, 072012 (2014)

O(*v*, *v'n*)



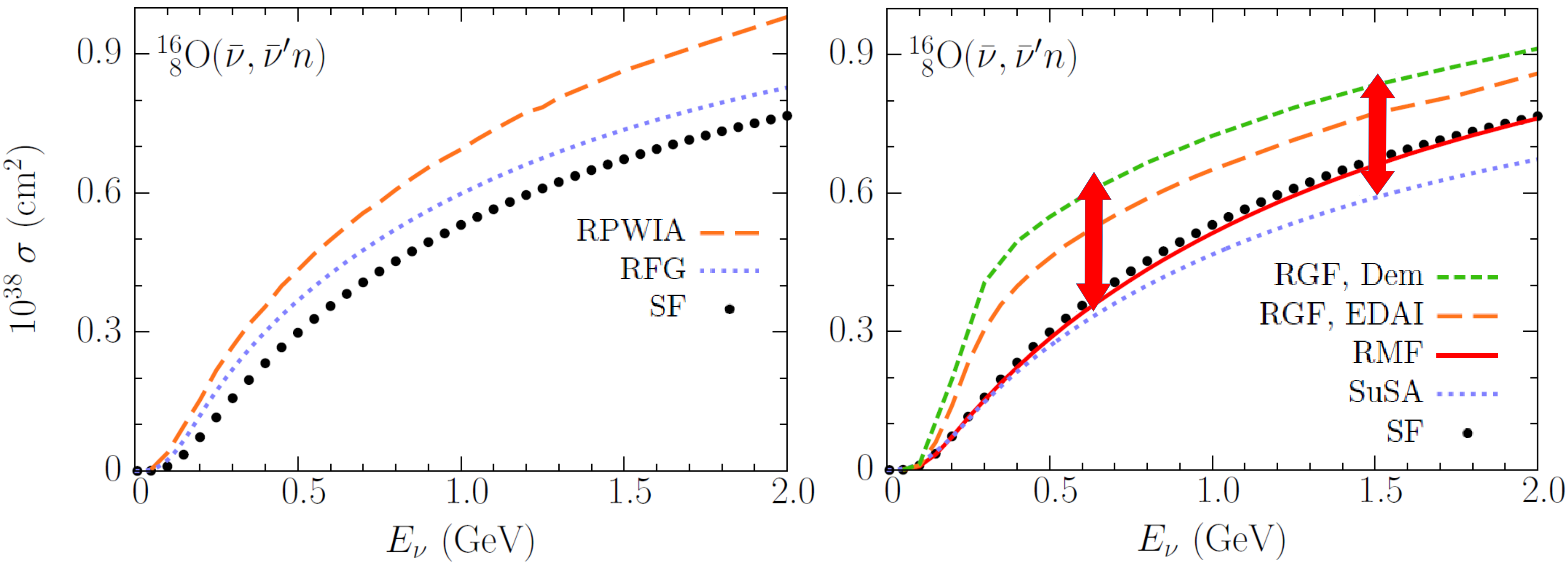
A.M. A, M.B. Barbaro, O. Benhar, J.A. Caballero, C. Giusti,
R. González-Jiménez, G.D. Megias, and A. Meucci,
PRC **92**, 025501 (2015)

$O(\nu, \nu' n)$



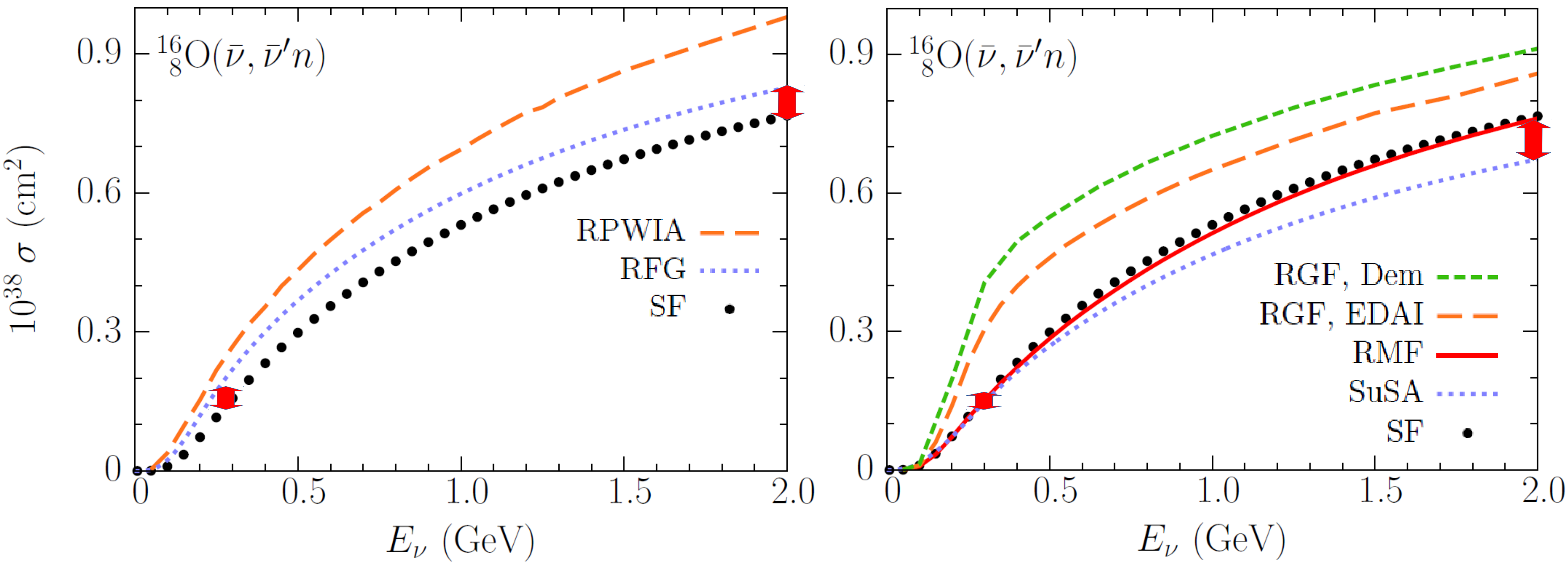
37% (30%) difference at 0.6 GeV (1.5 GeV)

$O(\bar{\nu}, \bar{\nu}'n)$



47% (33%) difference at 0.6 GeV (1.5 GeV)

$O(\bar{\nu}, \bar{\nu}'n)$



Excluding RGF, the differences are below ~15% for 0.3 < E < 2 GeV [all channels]

Summary

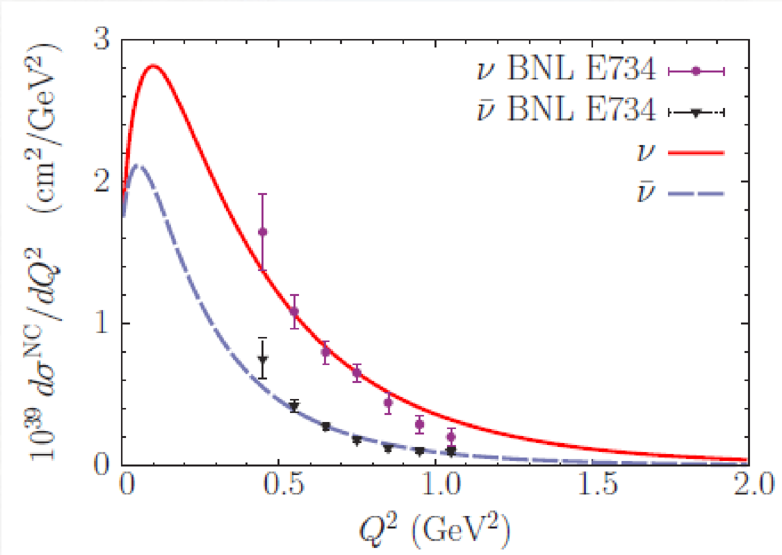
- Precise estimate of the NC QE cross sections for oxygen is important for **the searches for diffuse supernova neutrinos**

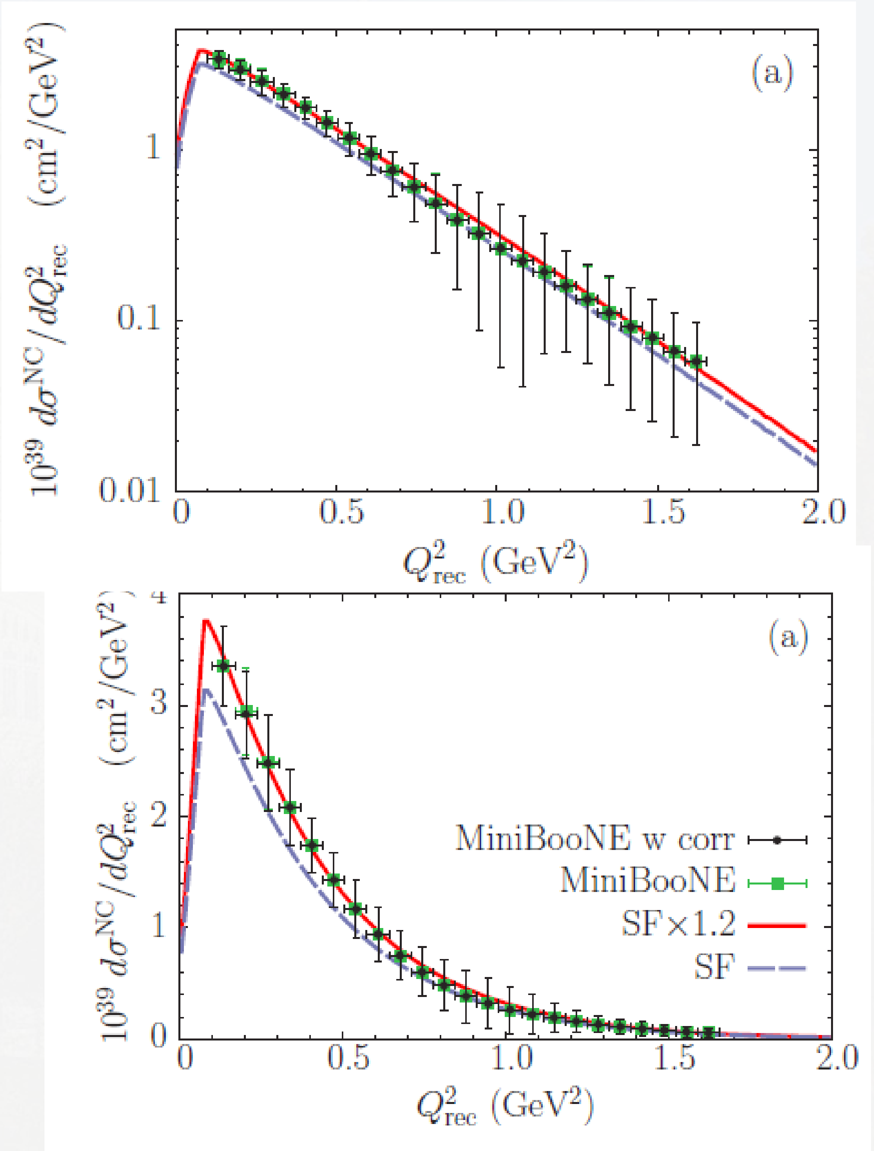
- In the spectral function approach, we have obtained the results for **gamma-ray emission** and **nucleon KO**

- Theoretical models yield the KO cross sections differing by at least **~15%** for energies between 0.3 and 2 GeV

Backup slides

Kinetic energy distributions





Superscaling approach

In QE (e, e') scattering, at sufficiently high momentum transfer $|\mathbf{q}|$, the scaling function

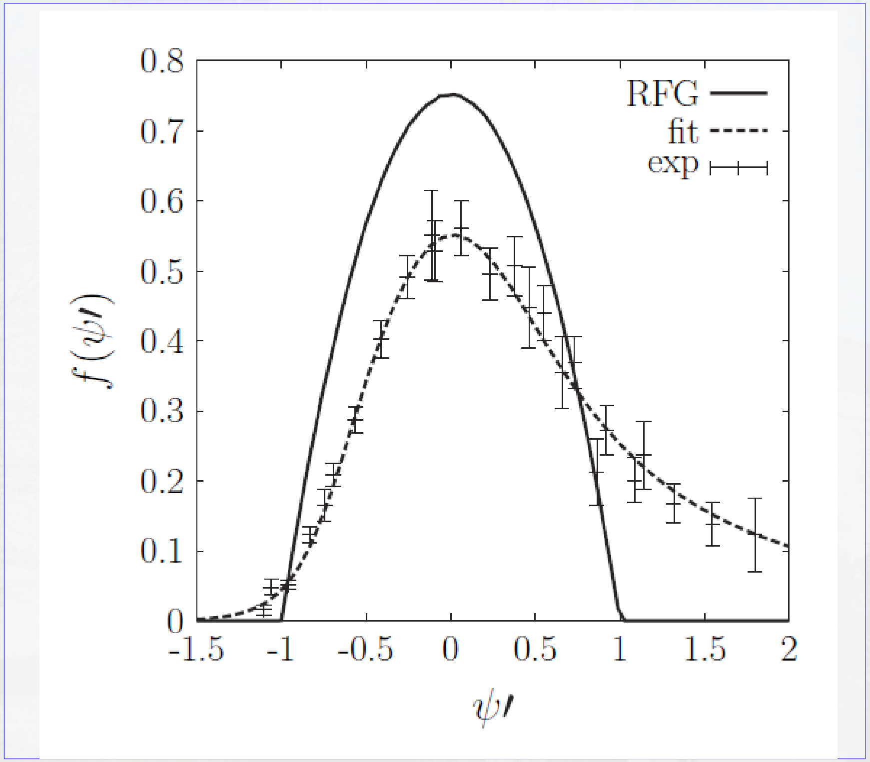
$$f(\psi', |\mathbf{q}|) = \frac{k_F}{Z\overline{\sigma}_{\ell p} + N\overline{\sigma}_{\ell n}} \frac{d\sigma_{\ell A}}{d\omega d\Omega}$$

with $\psi' = \psi'(\omega, |\mathbf{q}|)$ and σ_{lN} being the elementary cross section, becomes independent of $|\mathbf{q}|$ and the nuclear target.

Day *et al.*, Annu. Rev. Nucl. Part. Sci. 40, 357 (1990)

Superscaling approach

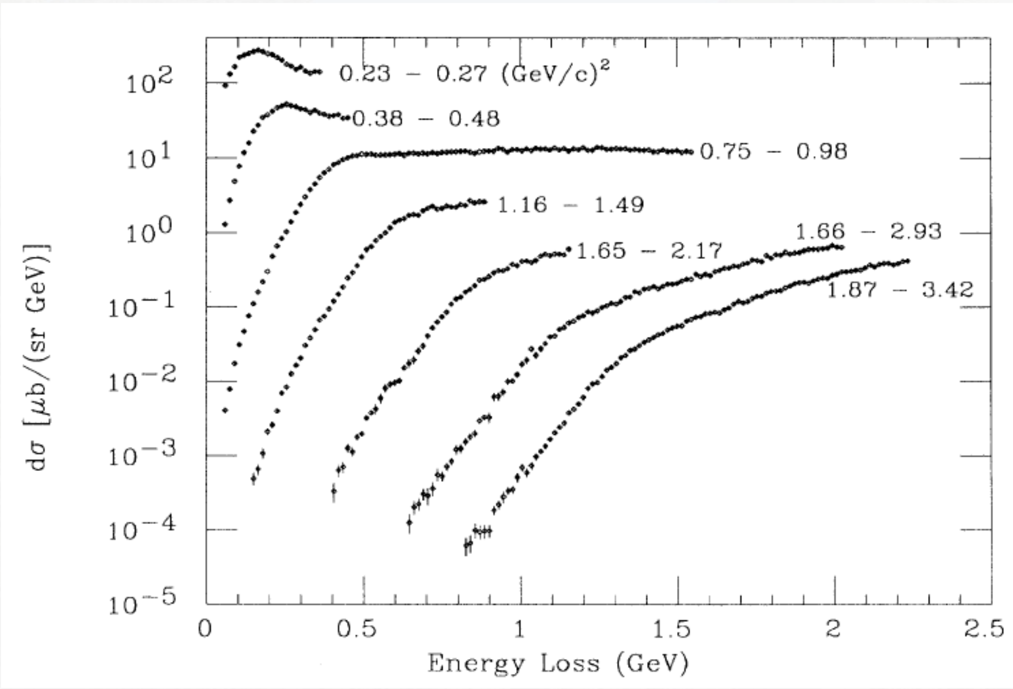
To calculate the QE cross sections, it is sufficient to know the scaling function *f(ψ')* and elementary cross sections.

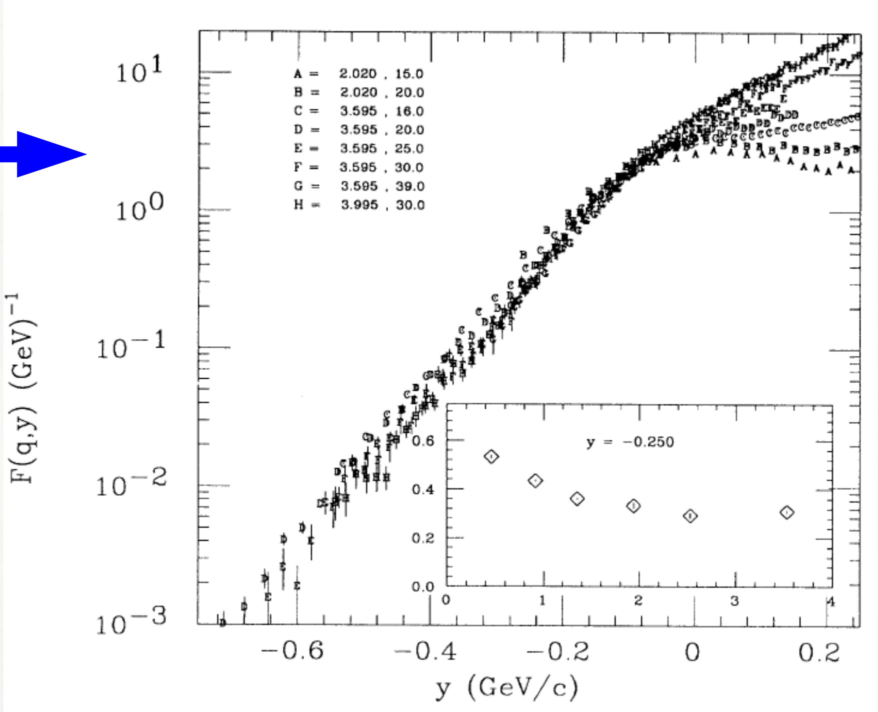


Amaro *et al.*, PRC 71, 015501 (2005); PRC 73, 035503 (2006).

Superscaling approach

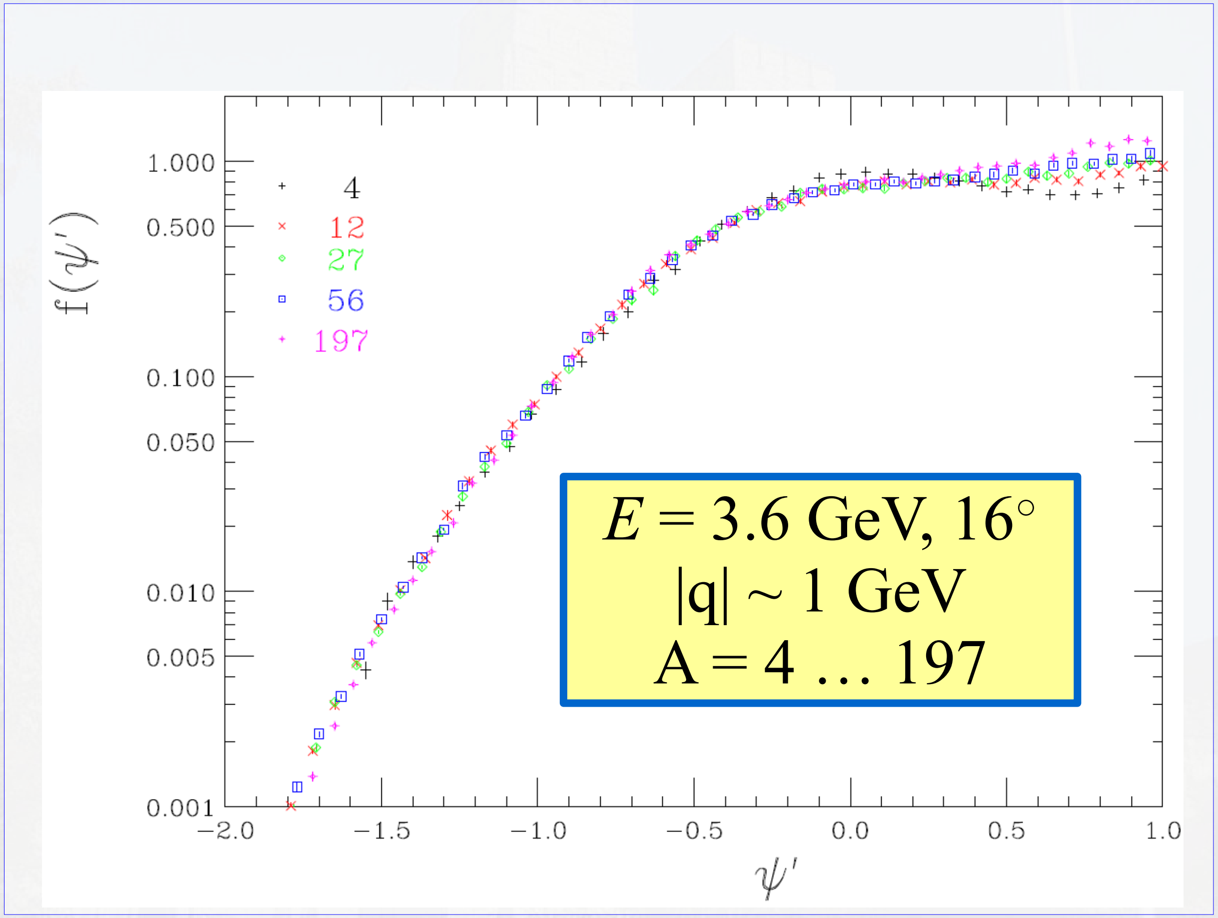
Fe(*e*,*e*′) at different kinematics





Day *et al.*, PRC 48, 1849 (1993)

Superscaling approach



Donnelly & Sick, PRL 82, 3212 (1999)

Relativistic approaches

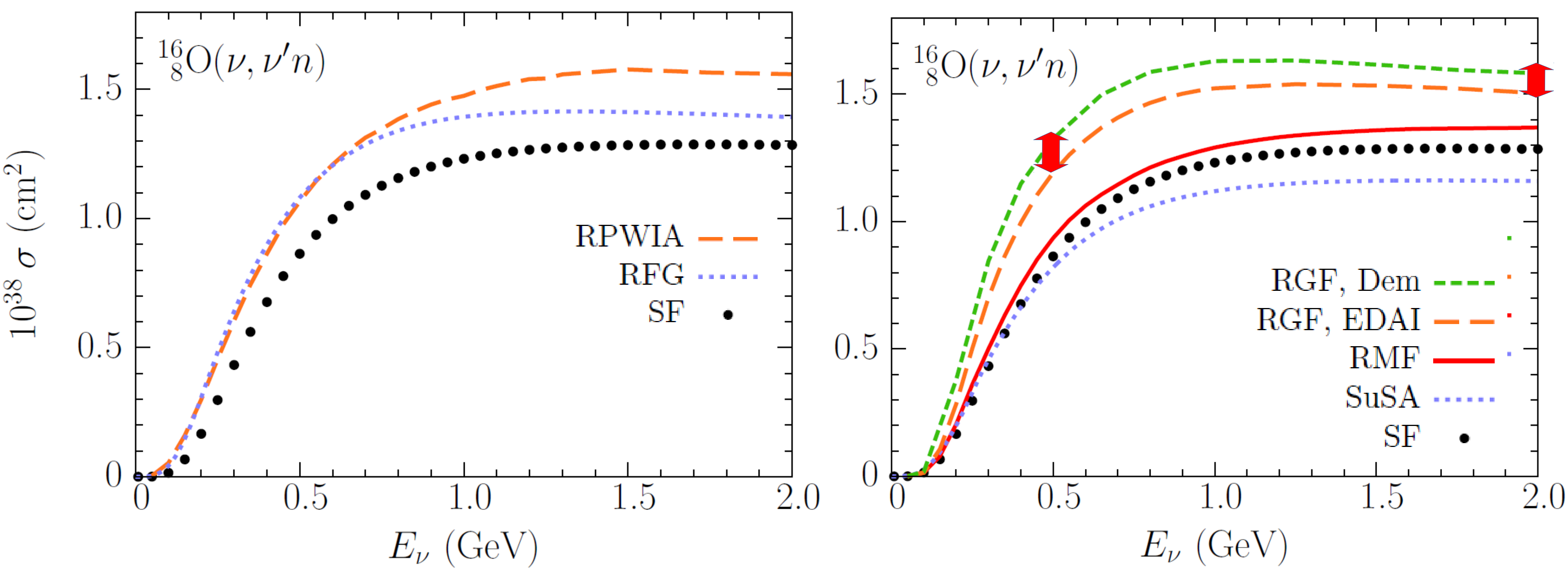
The bound nucleons described by the self-consistent solutions of the Dirac-Hartree equation derived from a Lagrangian including σ, ω, and ρ mesons within the mean-field approximation

PWIA: no final-state interactions (FSI)

RMF: final and initial states obtained using the same (real) energy-independent potentials

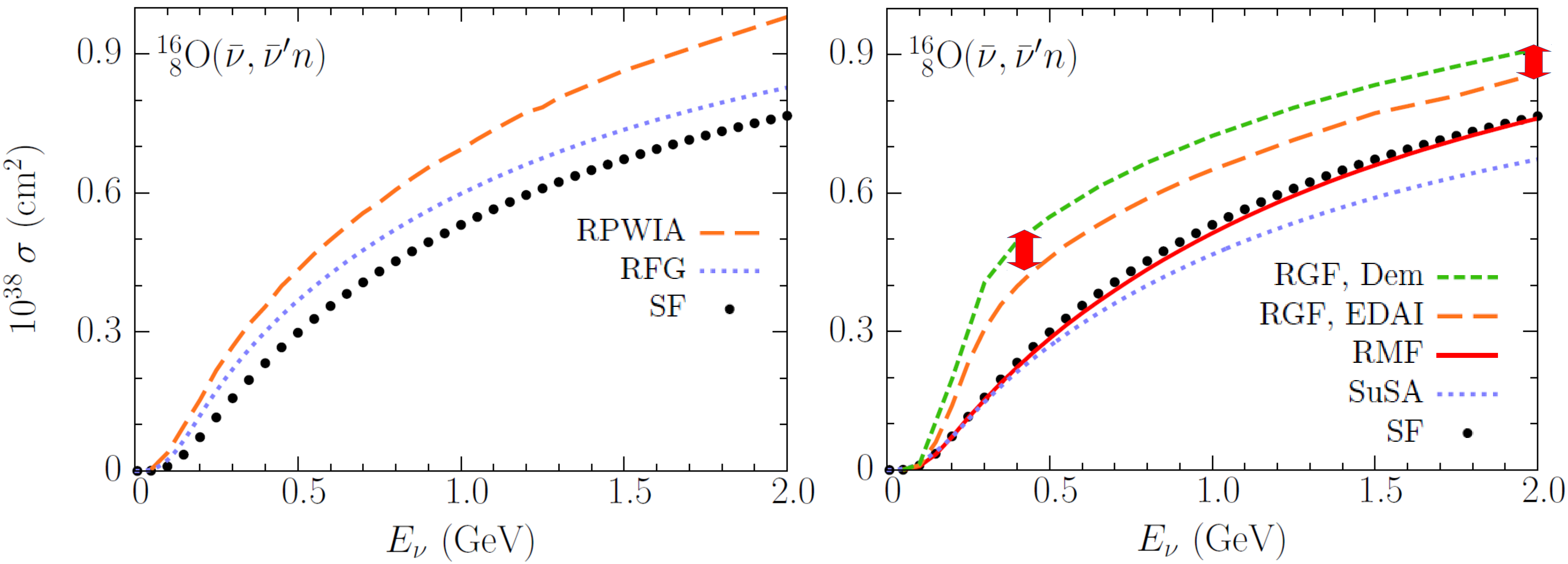
RGF: FSI described using a complex optical potential, the loss of single-particle states leads to multiparticle states (the flux is conserved)

O(ν, ν'n)



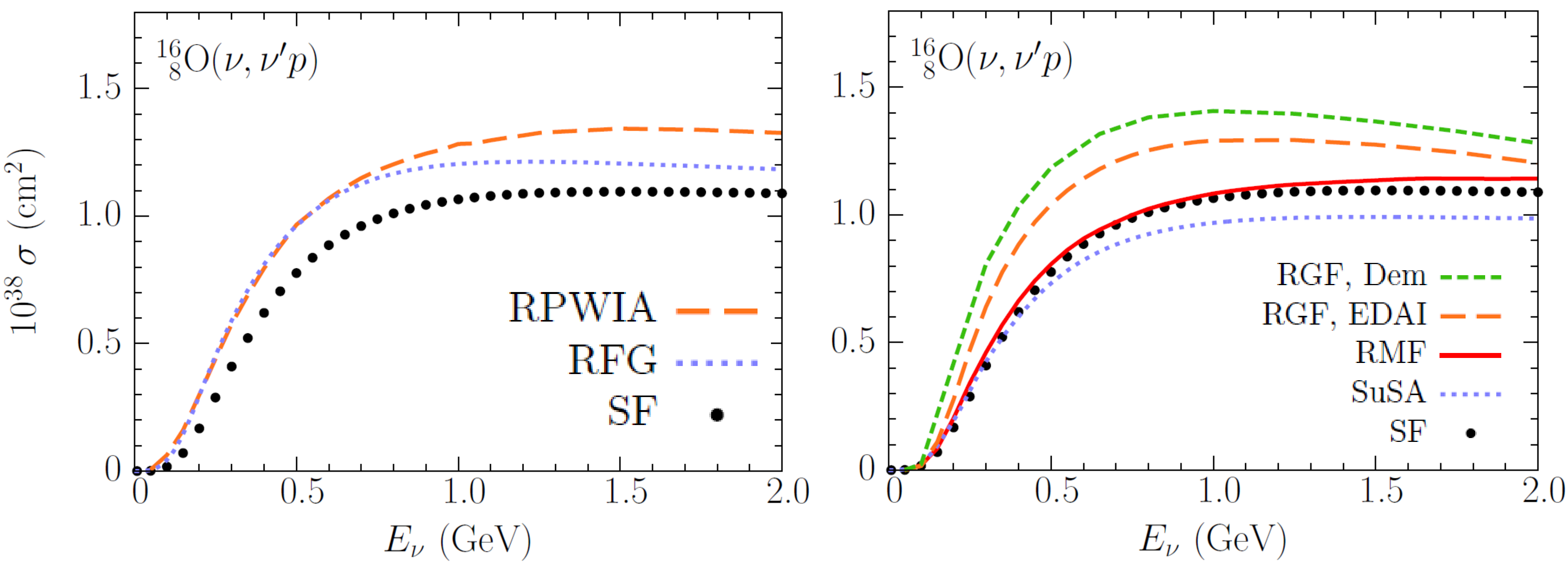
RGF: sensitive to the applied optical potential
10-25% (5-10%) differences at 0.3-0.5 GeV (2 GeV)
[all channels]

$O(\bar{\nu}, \bar{\nu}'n)$



RGF: sensitive to the applied optical potential
10-25% (5-10%) differences at 0.3-0.5 GeV (2 GeV)
[all channels]

$O(\nu, \nu' p)$



$^{16}_{8}O(\nu, \nu' p)$
$10^{38}\,\sigma$ (cm^2)
1.5
1.0
0.5
0
0.5
1.0
1.5
2.0
E_ν (GeV)
RPWIA
RFG
SF
$^{16}_{8}O(\nu, \nu' p)$
RGF, Dem
RGF, EDAI
RMF
SuSA
SF
E_ν (GeV)

$O(\bar{\nu}, \bar{\nu}'p)$