Theoretical uncertainty of the O(ν, ν'N) and O($\bar{\nu}$, $\bar{\nu}$'N) cross sections

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

NuInt15, Osaka, November 16–21, 2015

Outline

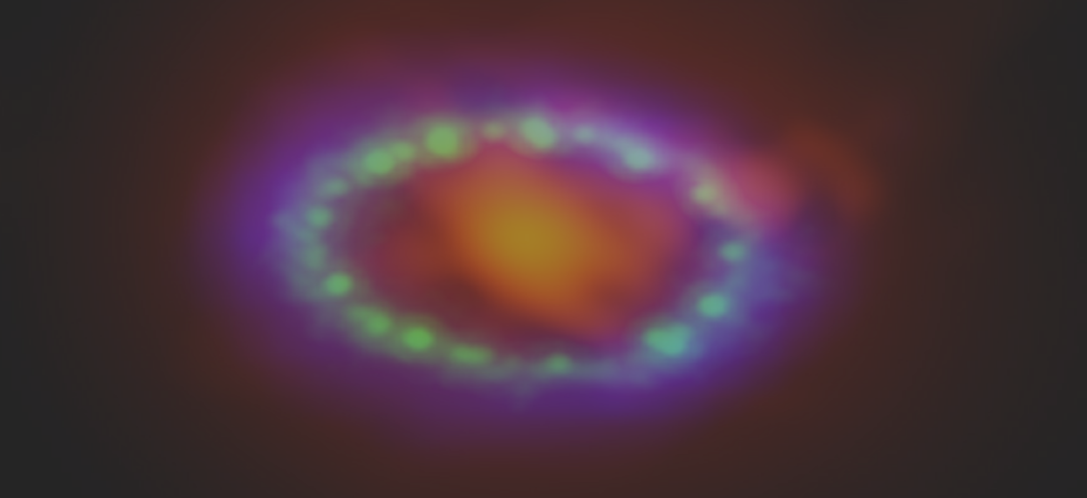
- Why NC cross sections for oxygen are important
- Available results
- Considered theoretical approaches
- Comparisons of the cross sections
- Summary

Why NC cross sections for oxygen are important

Supernova 1987A
in the Large Magellanic Cloud

First detection of extra-galactic neutrinos:

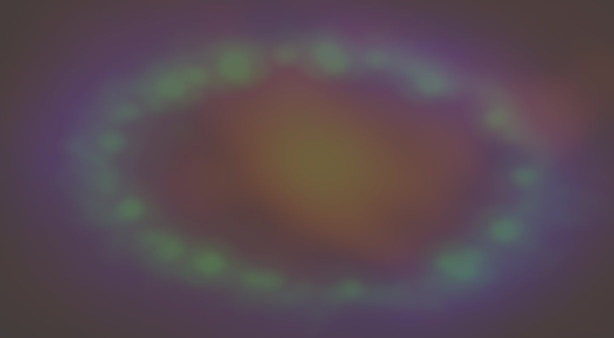
dawn of a new era in observational astronomy



- 24 events in total (Kamiokande-II, IMB, Baksan)
- 1274 (1110) citations of the Kamiokande-II (IMB) paper
- 2002 Nobel prize for Prof. Masatoshi Koshiba

Core-collapse supernovae

In our Galaxy, SN happens every 30-50 years, with the last 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

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

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

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

cannot be distinguished from processes yielding

$$\boxed{\gamma + n} \quad \text{or} \quad \boxed{e^- + n}$$

in the final state.

Gamma + neutron

Primary gamma rays:

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

nuclear deexcitation following a NC event.

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

Search for sterile neutrinos

All active neutrinos undergo NC scattering: a deficit of NC events would indicate oscillations into steriles.

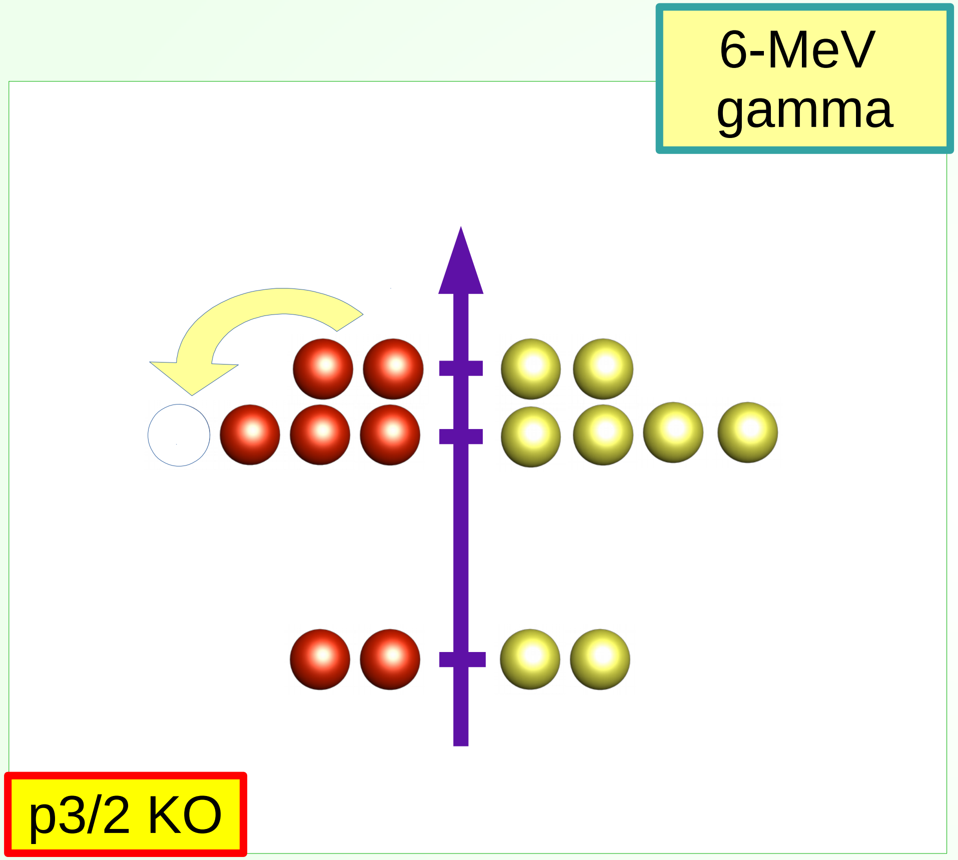
NC event detection in water is challenging

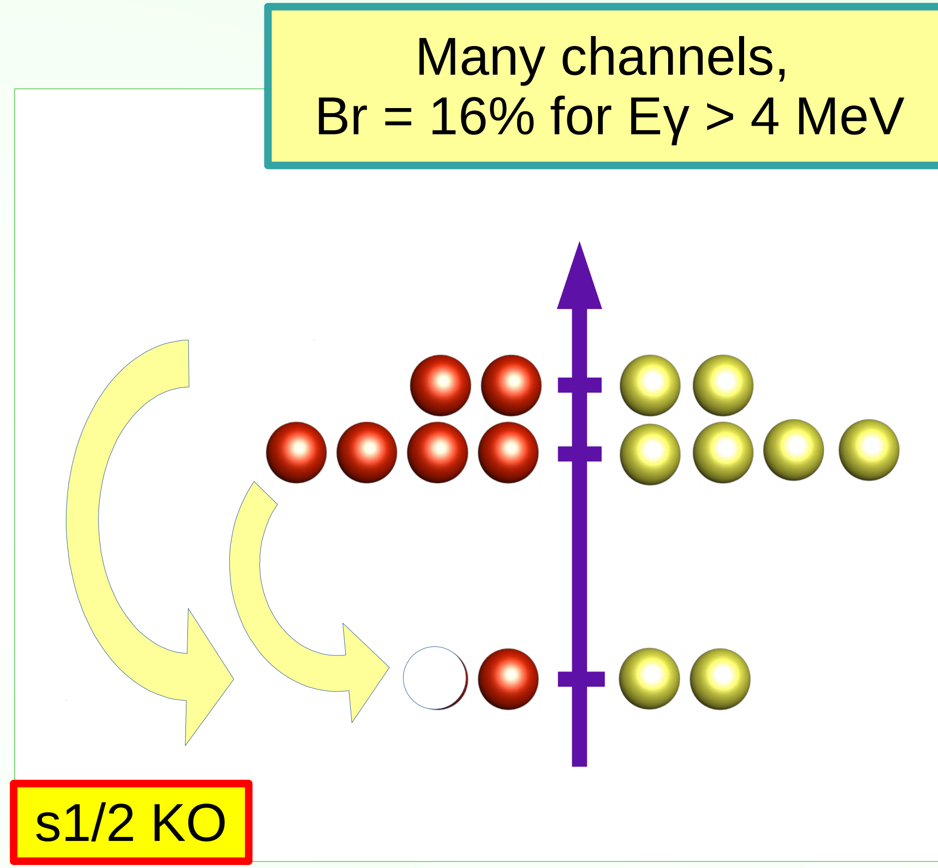
- knocked out neutrons (~50% of NC events for oxygen) don't emit Cherenkov light
- for protons, the threshold is $|\mathbf{p}| = 1.07$ GeV/c [at $E = 0.6$ (0.9) GeV, 100% (93.7%) of proton events is below the threshold]

Therefore, **the gamma rays are an important signature of NC events**.

Available results

Primary gammas





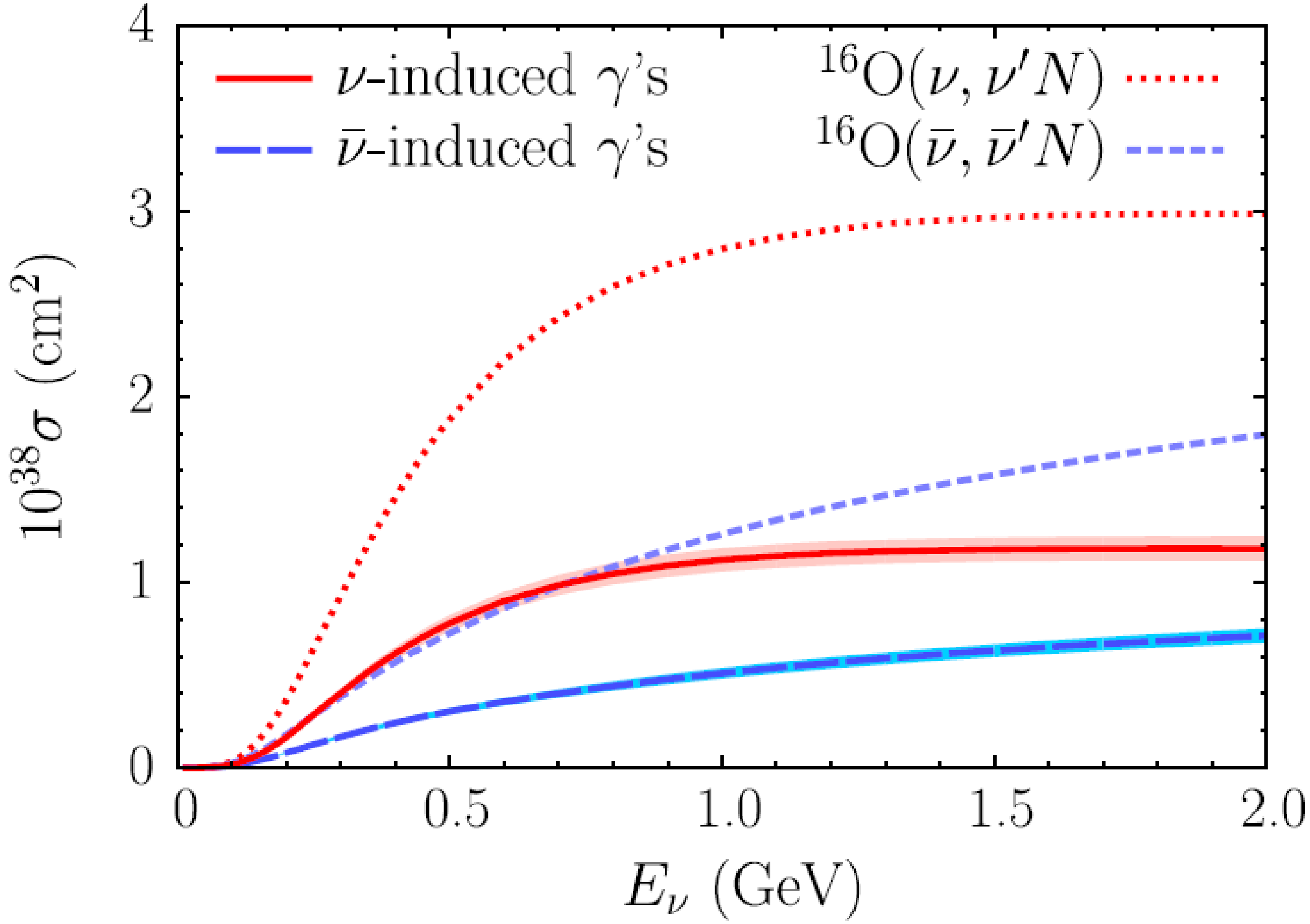
Ejiri, PRC 48, 1442 (1993);
Kobayashi *et al.*, nucl-ex/0604006

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

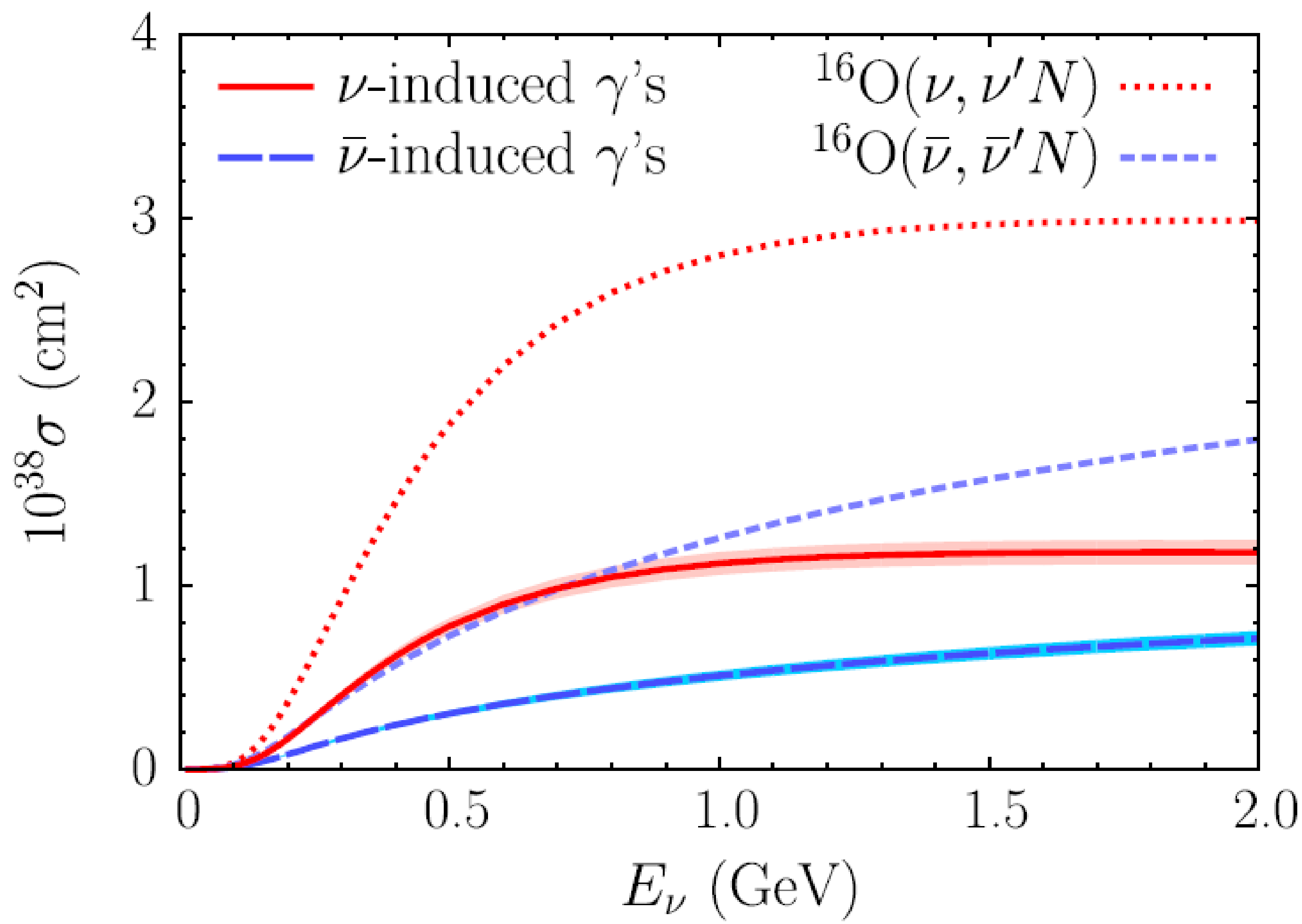
$$\sigma_\gamma = \sum_\alpha \boxed{\sigma(\nu + {}^{16}_{8}\mathrm{O} \rightarrow \nu + X_\alpha + N)}\ \boxed{\mathrm{Br}(X_\alpha \rightarrow \gamma + Y)},$$

Primary gammas



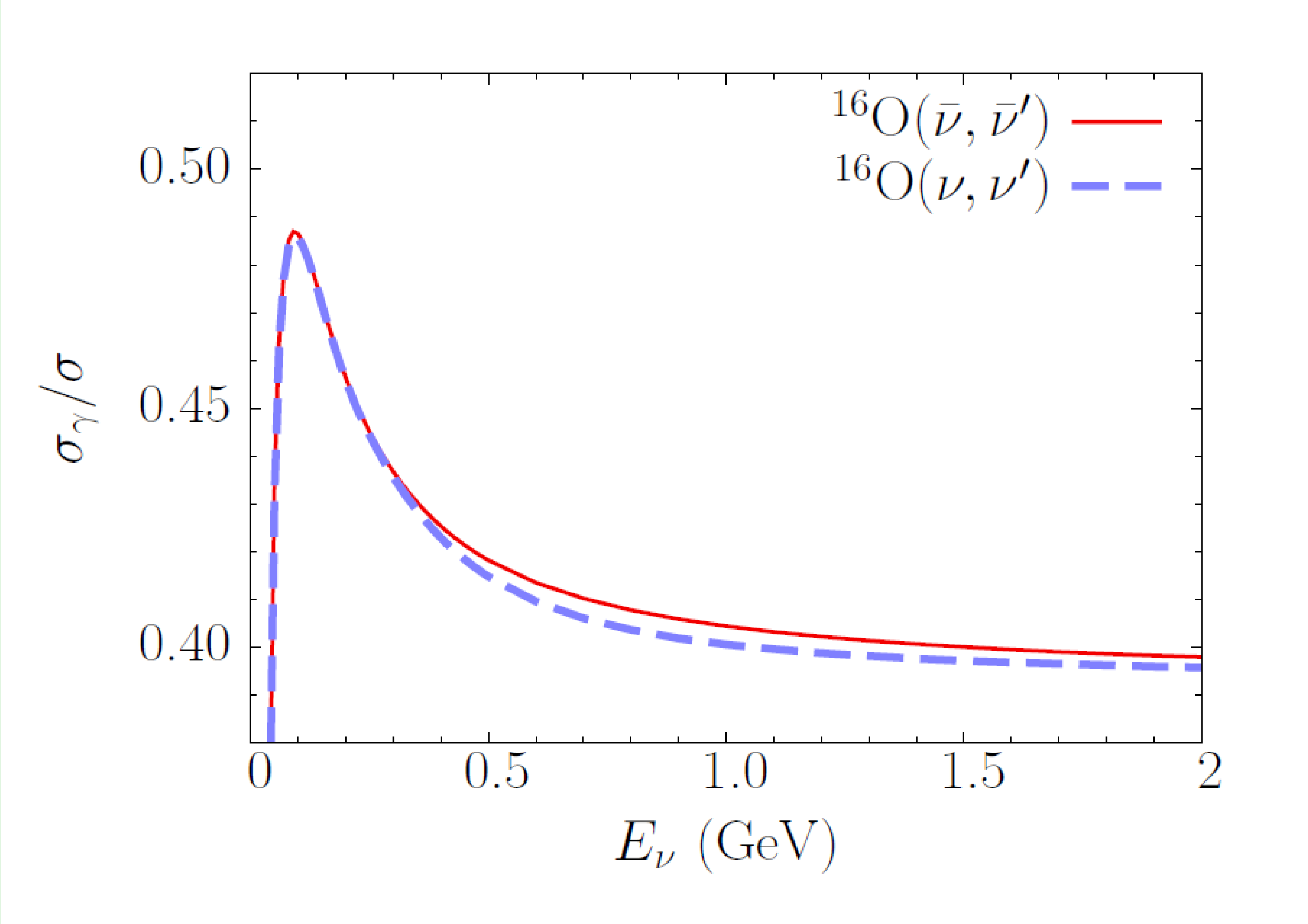
A.M.A., O. Benhar, T. Mori, R. Yamaguchi, and M. Sakuda
PRL 108, 052505 (2012)

Primary gammas

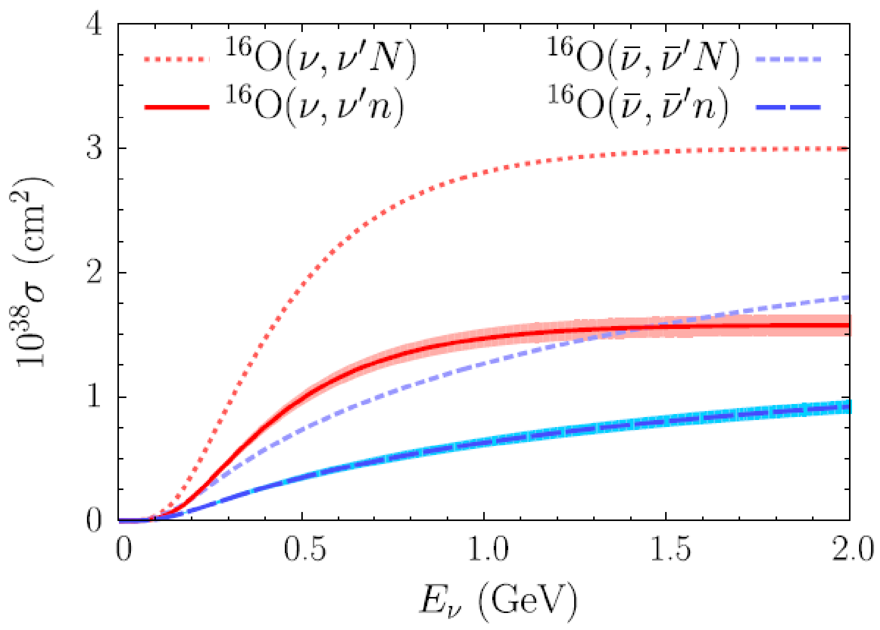


At 0.5 (1.0) GeV, **~10 (15) x** σ(ν+O → ν'+O*)
Kolbe et al., PRD 66, 013007 (2002)

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

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

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

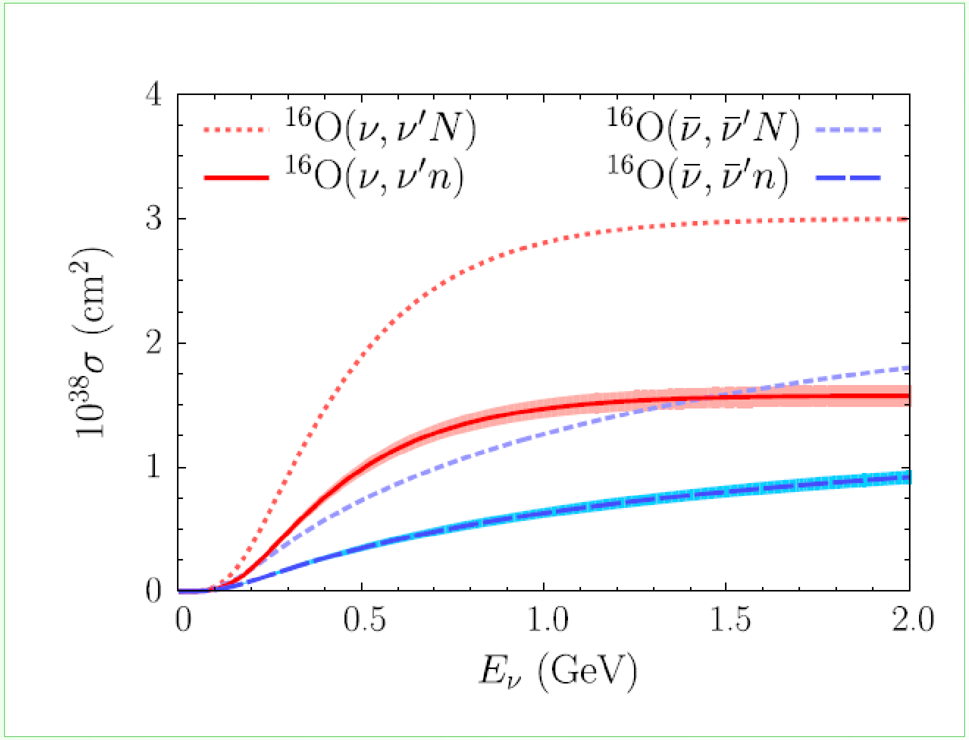
Excellent agreement with HERMES,
positron scattering off deuteron
Airapetian et al., PRD 75, 012007 (2007)

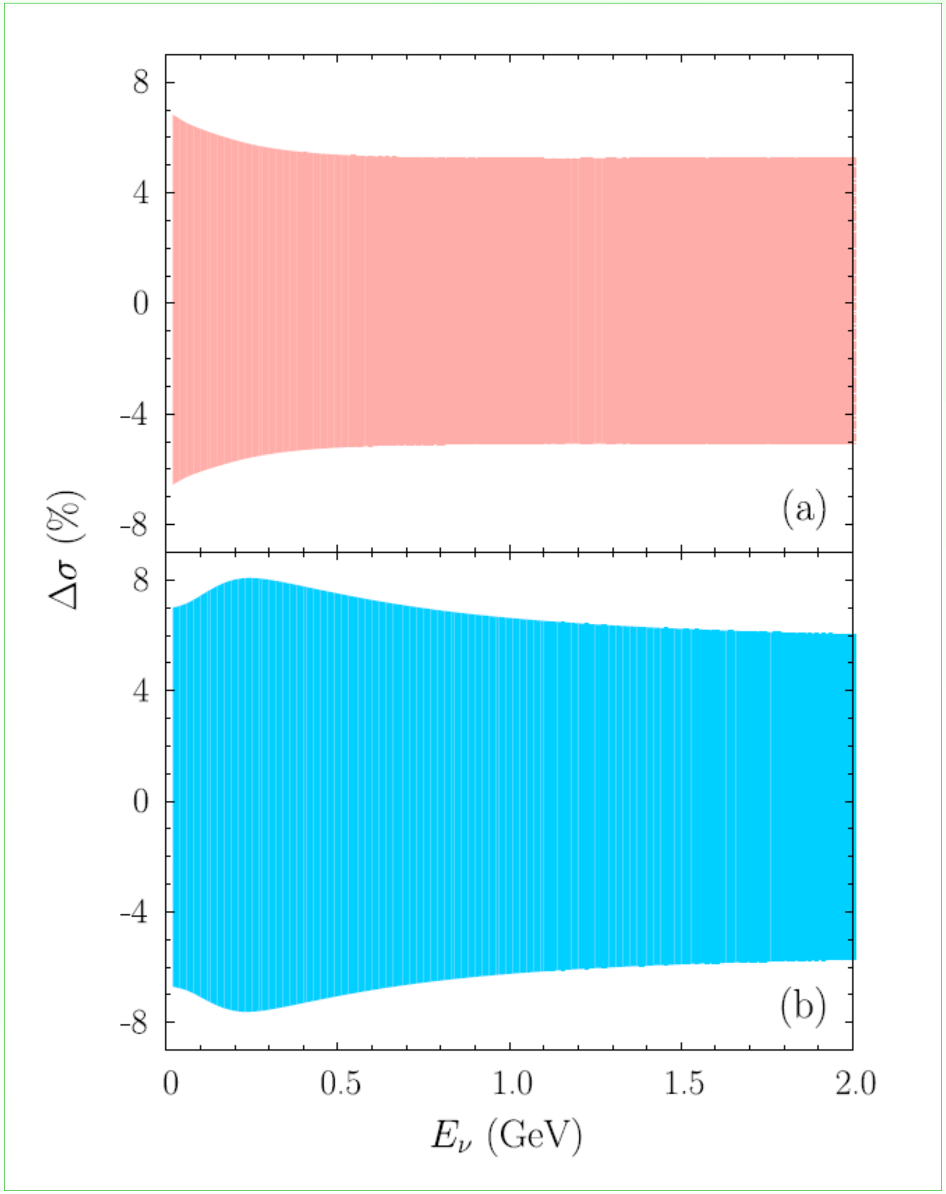
If SU(3)$_f$ violated in hyperon beta decays,
[< 20% from the KTeV experiment]
Δs may shift by ± 0.04.

In our calculations,

$$\boxed{\Delta s = -0.08 \pm 0.05}$$

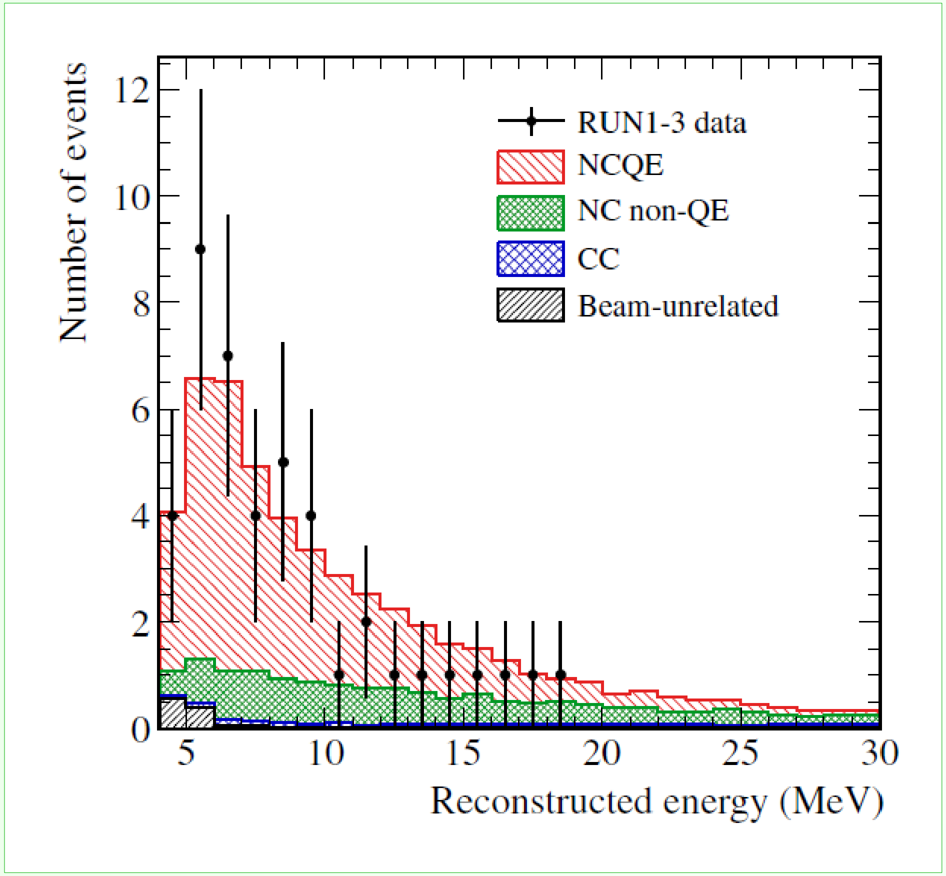
Neutron and proton knockout

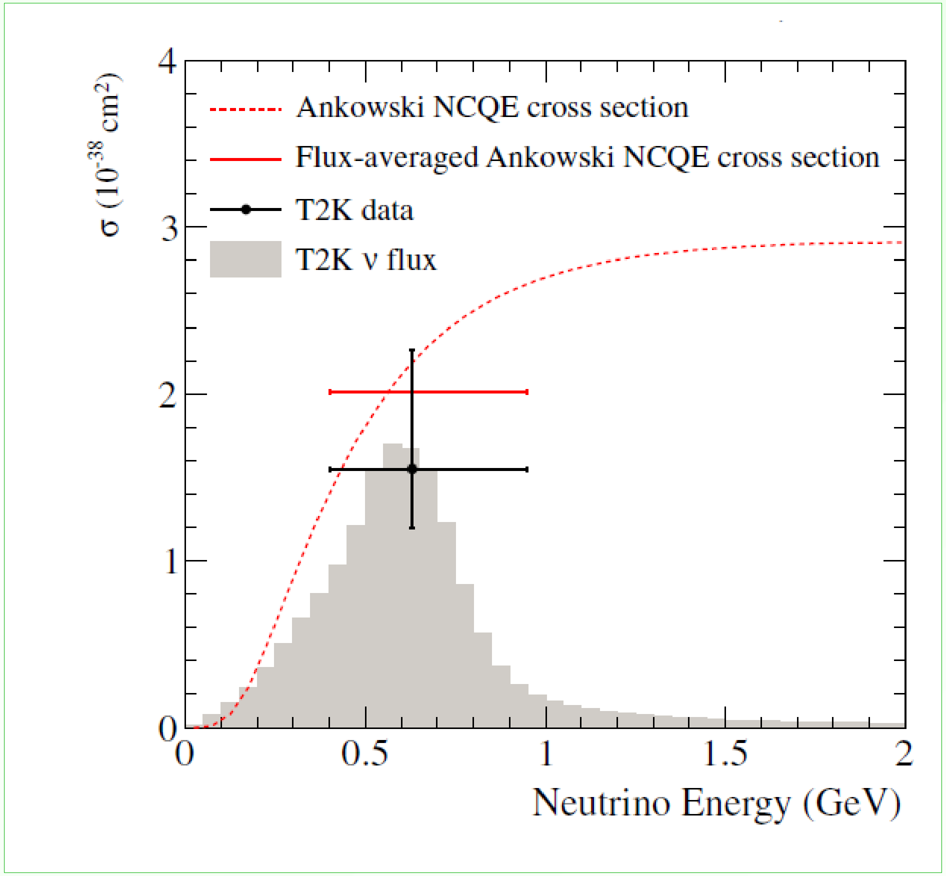




A.M.A and O. Benhar,
PRD 88, 093004 (2013)

T2K neutrino measurement





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

Considered theoretical approaches

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)
Phys. Rev. D 72, 053005 (2005).

Superscaling approach

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

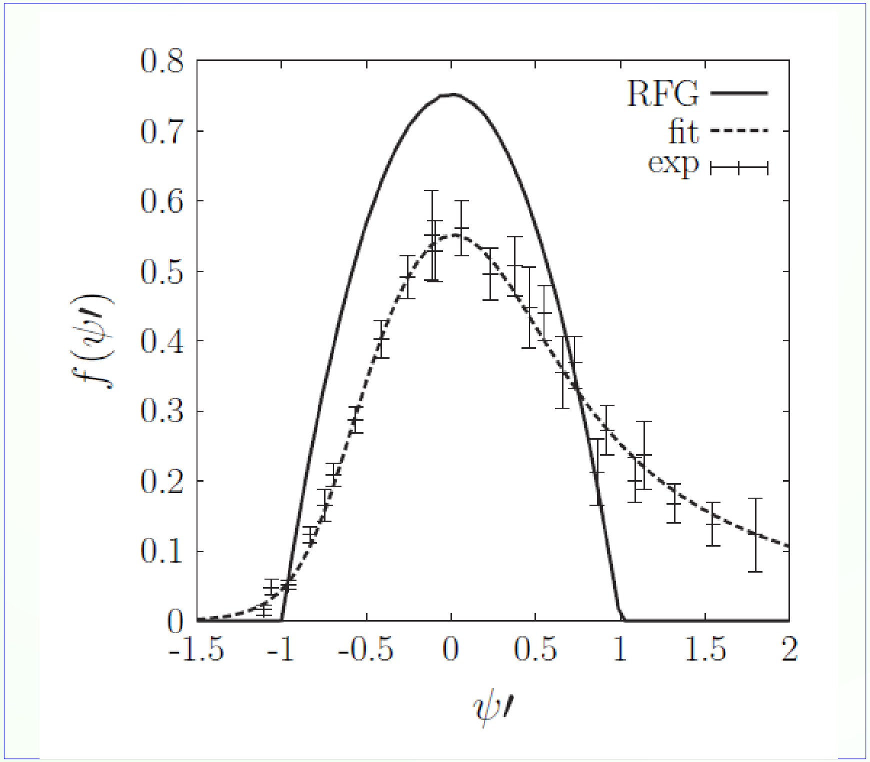
$$\boxed{f(\psi', |\mathbf{q}|) = \frac{k_F}{Z\overline{\sigma}_{\ell p} + N\overline{\sigma}_{\ell n}} \frac{d\sigma_{\ell A}}{d\omega d\Omega}}$$

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).

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

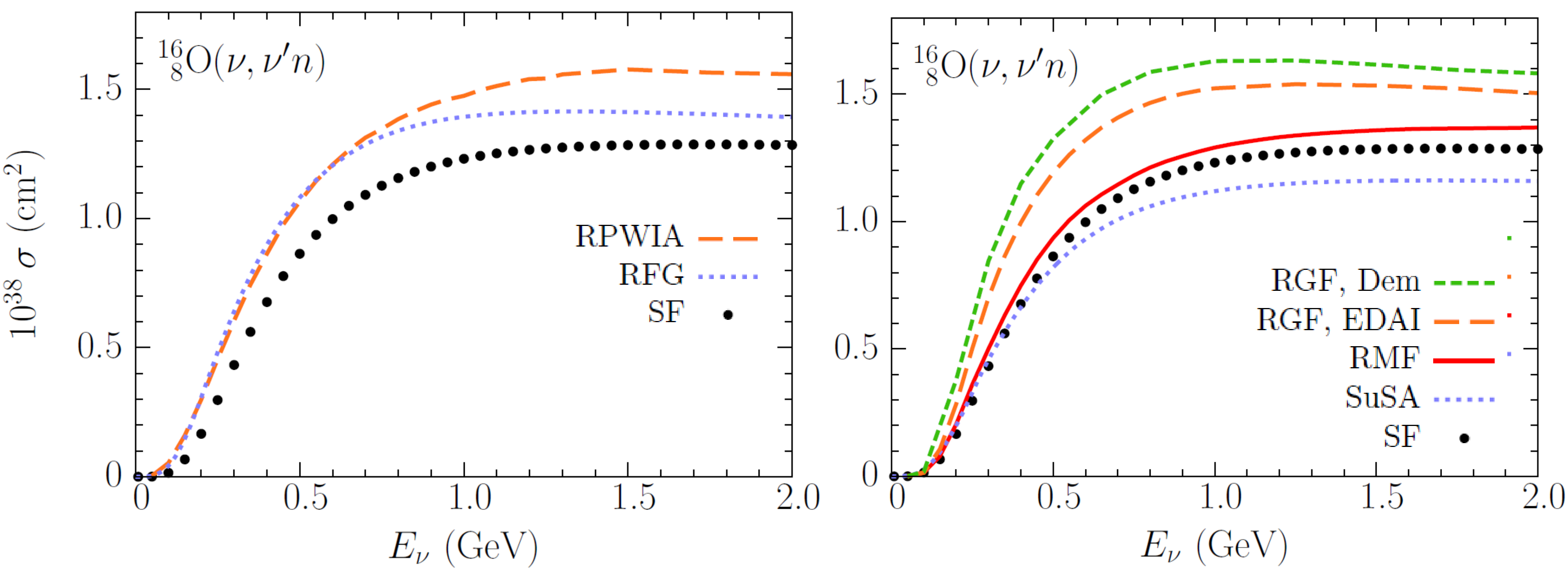
PWIA: no final-state interactions (FSI)

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)

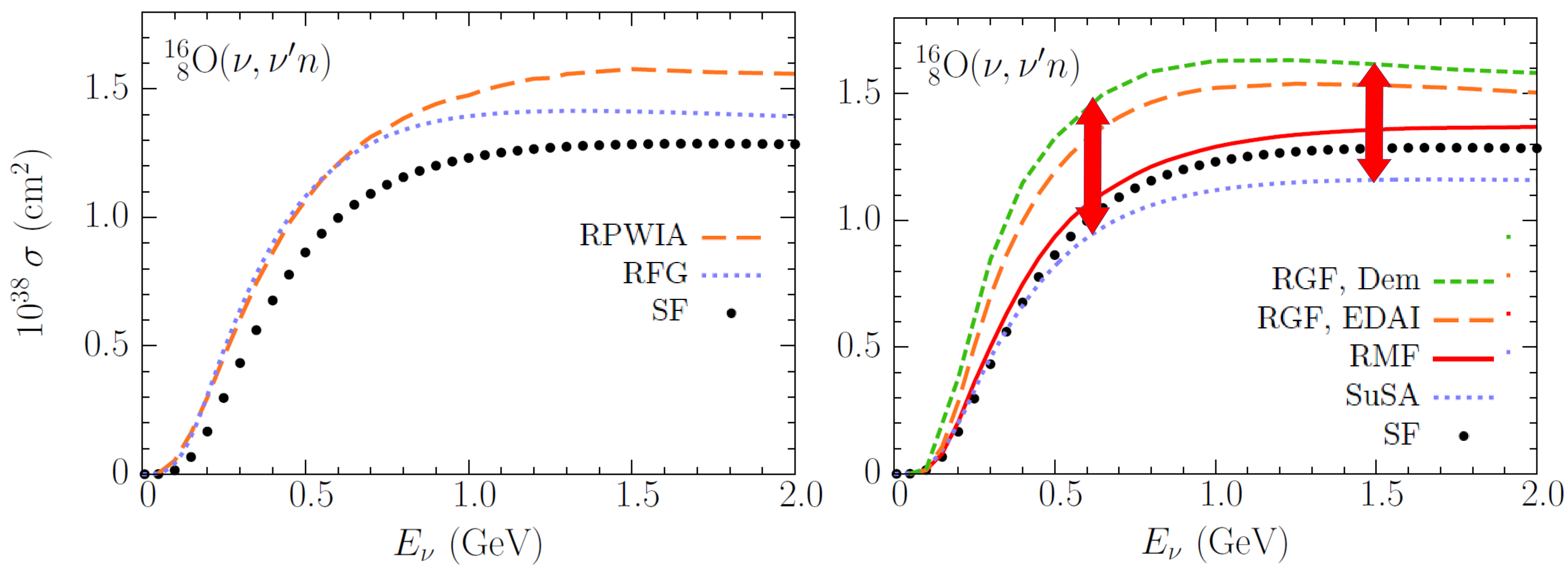
Comparisons of the cross sections

O(*ν*, *ν'n*)



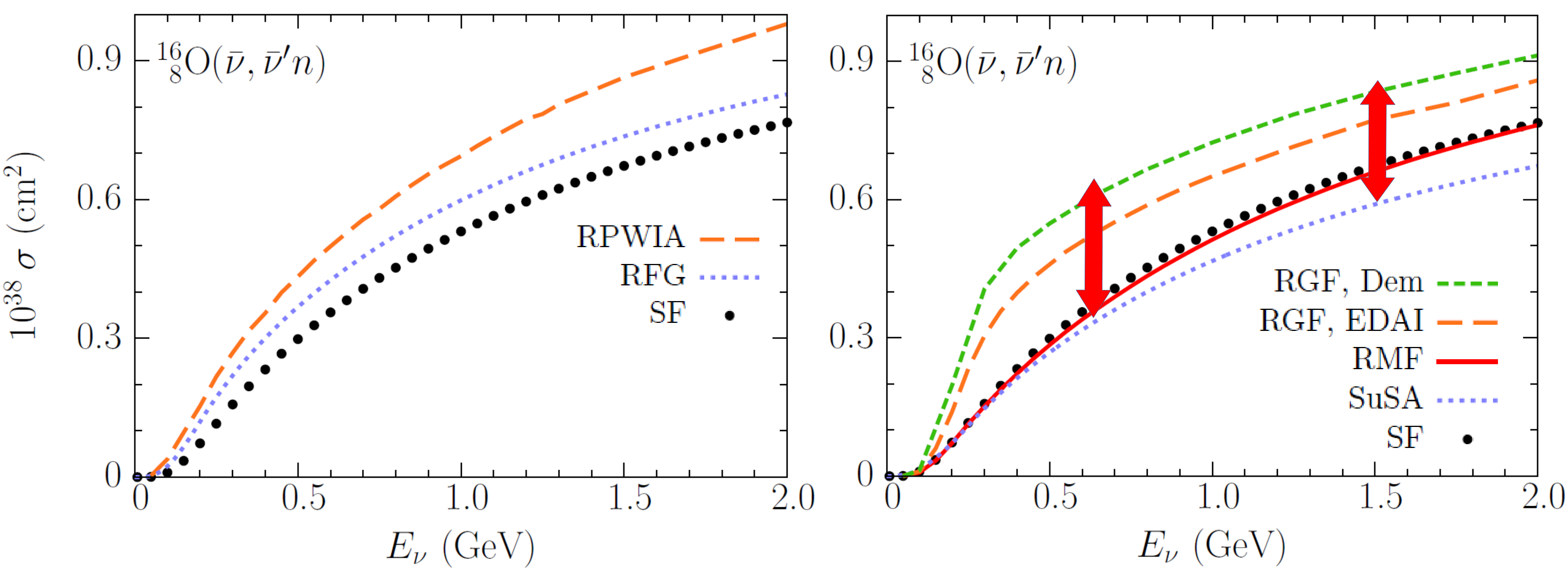
$^{16}_{8}O(\nu,\nu' n)$
RPWIA
RFG
SF
$10^{38}\,\sigma$ (cm^2)
E_ν (GeV)
0
0.5
1.0
1.5
2.0
$^{16}_{8}O(\nu,\nu' n)$
RGF, Dem
RGF, EDAI
RMF
SuSA
SF
E_ν (GeV)

O(ν, ν'n)



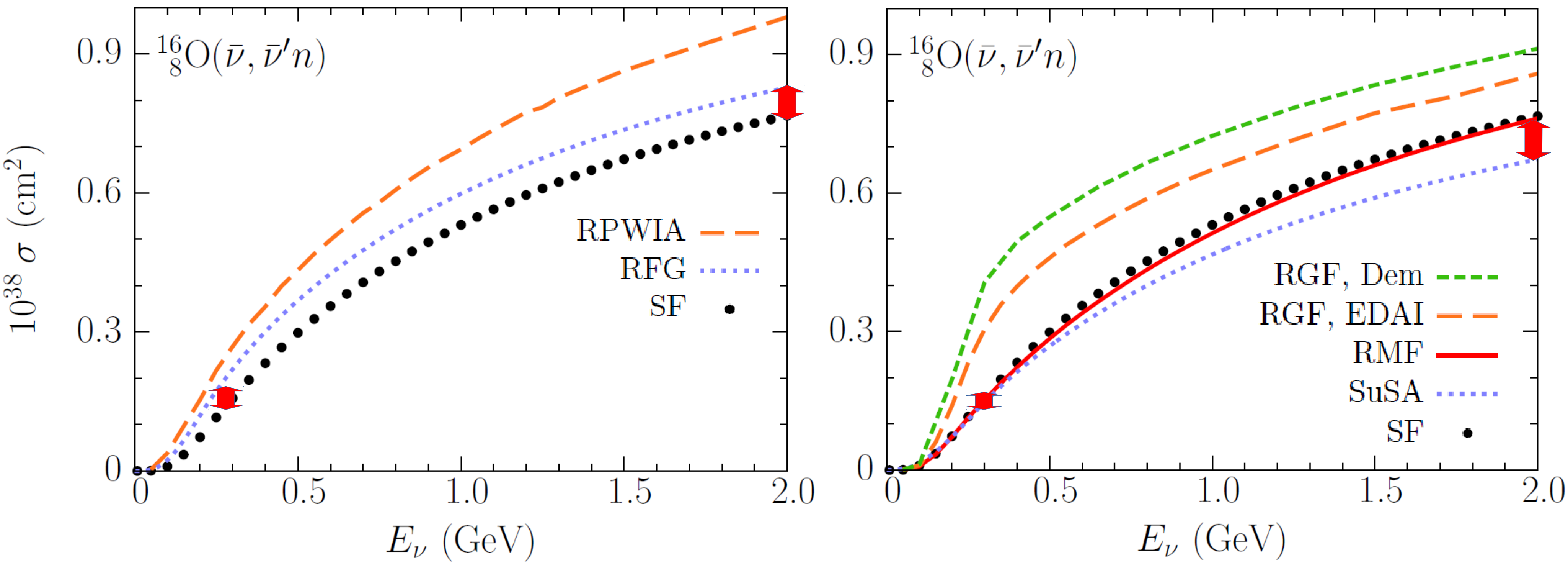
37% (30%) difference at 0.6 GeV (1.5 GeV)

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



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

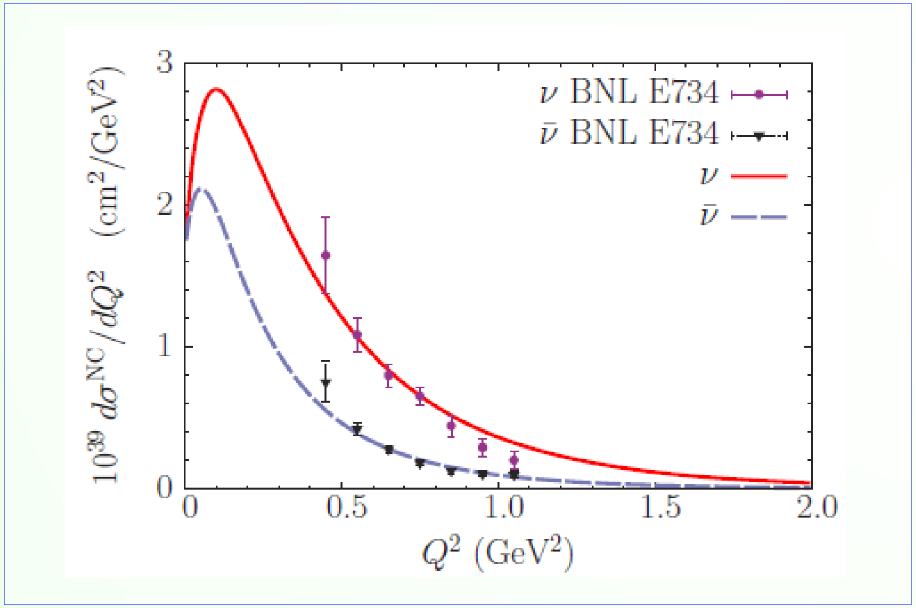
- Precise estimate of the NC QE cross sections is important for **the searches for diffuse supernova neutrinos and sterile neutrinos**

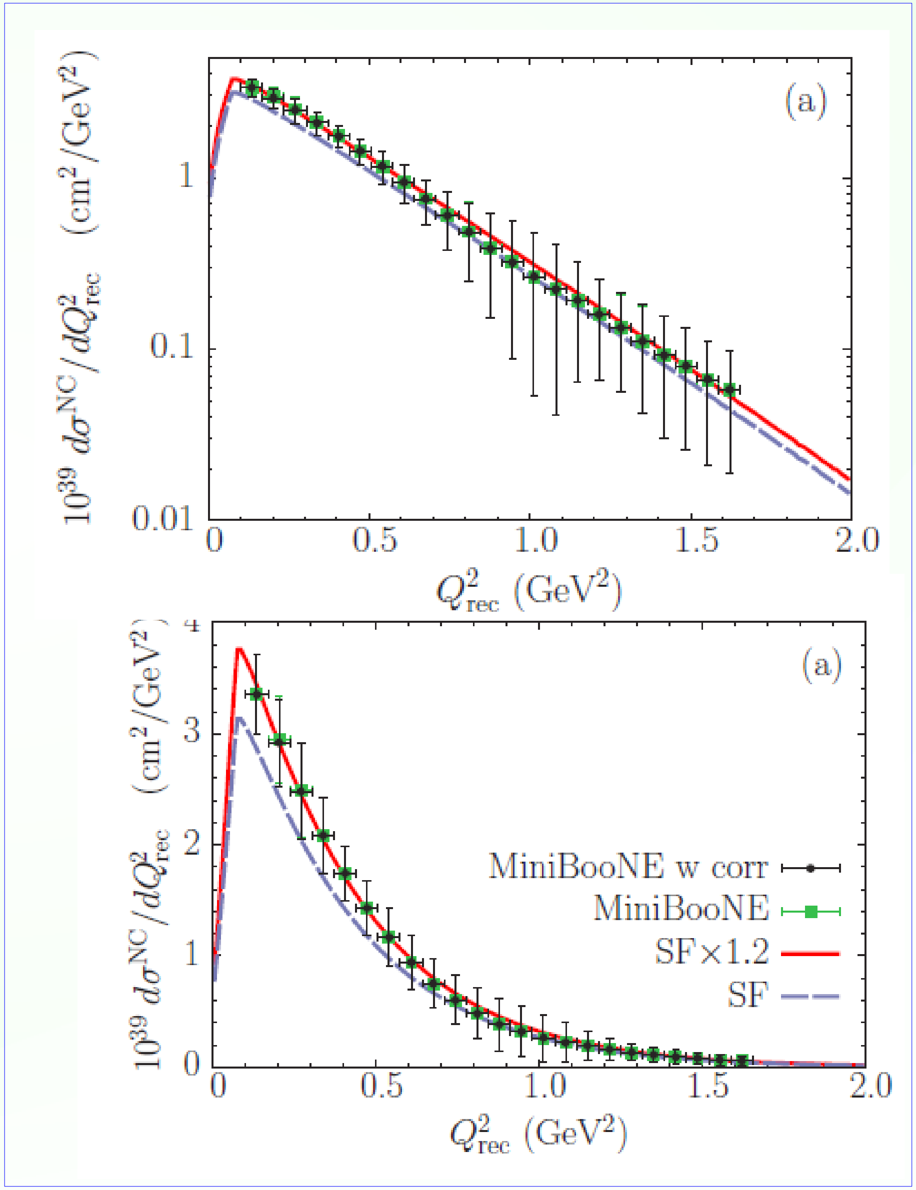
- The spread between the theoretical calculations depends significantly on energy and is **larger for antineutrinos**

- For energies between 0.3 and 2 GeV the theoretical discrepancies can be optimistically estimated at **~15%**

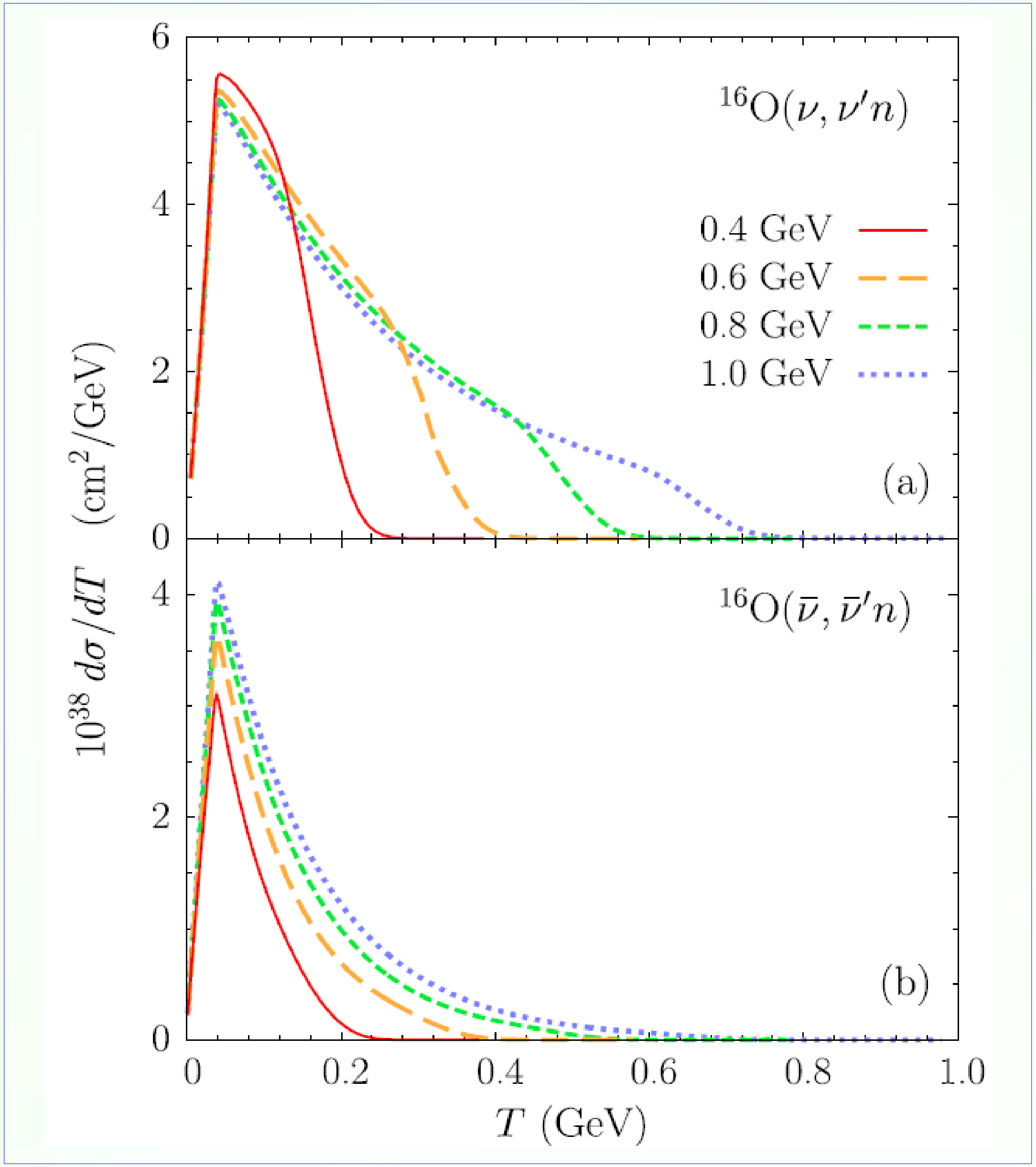
Backup slides

Kinetic energy distributions



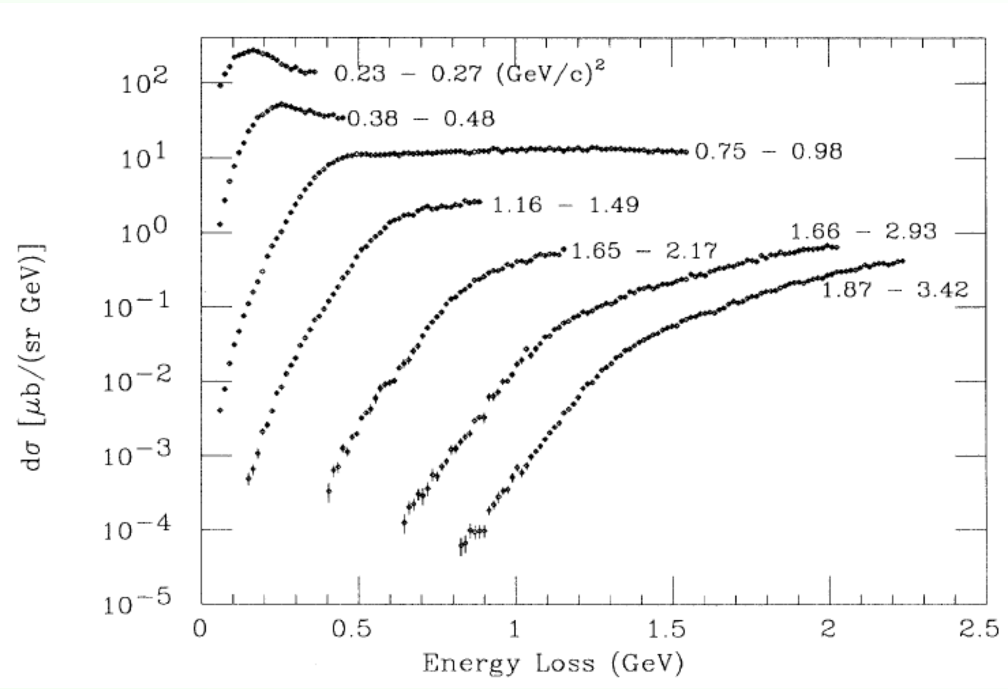


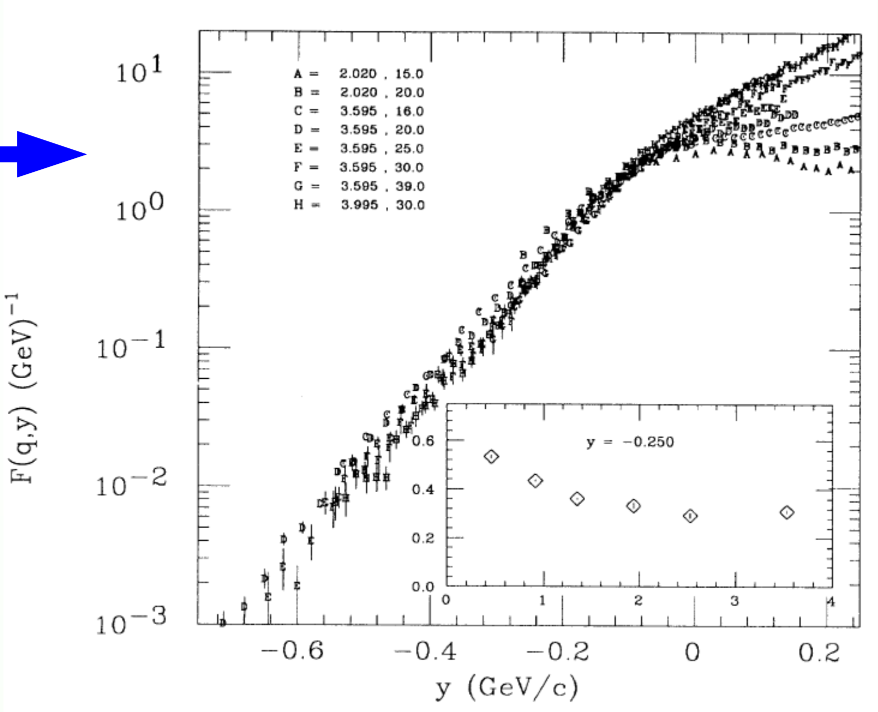
Kinetic energy distributions



Superscaling approach

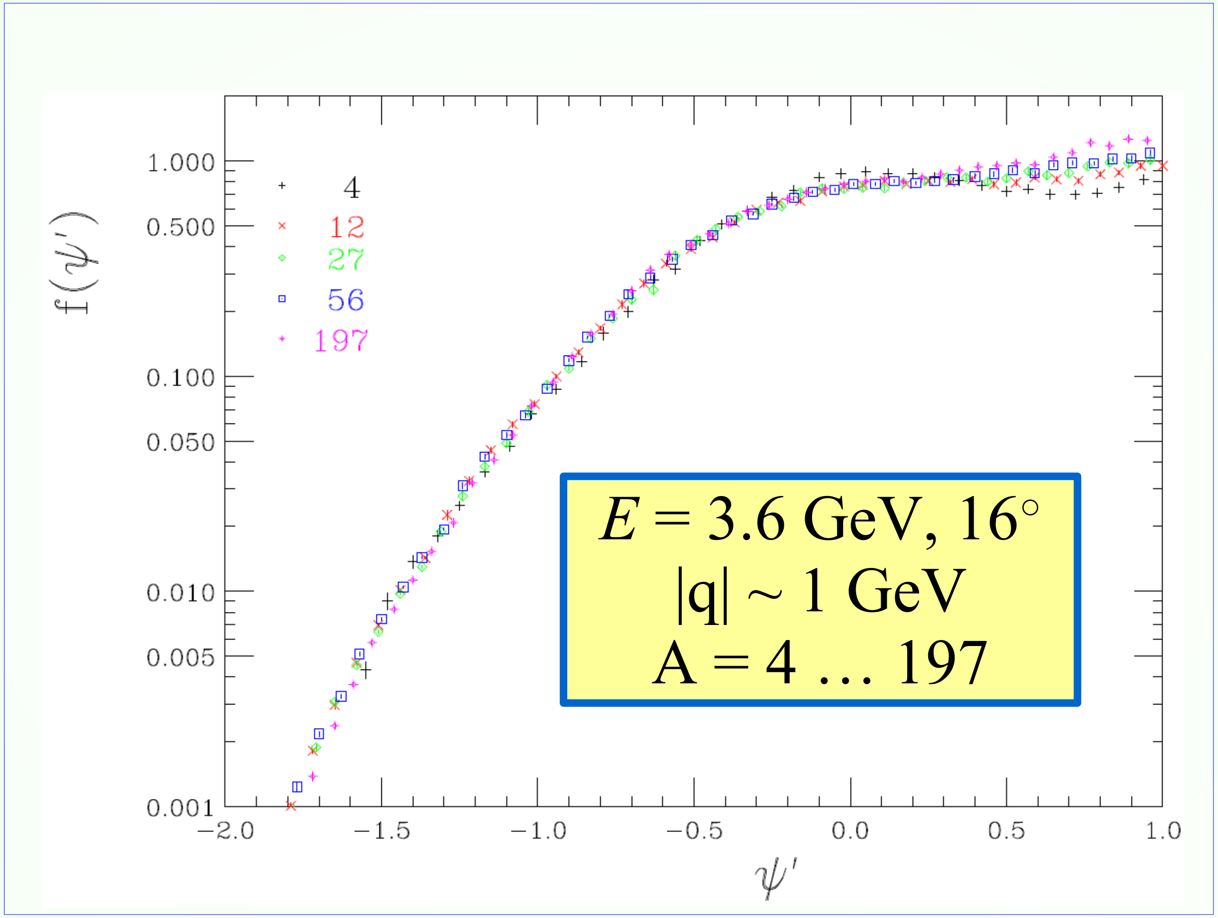
Fe(e,e') at different kinematics





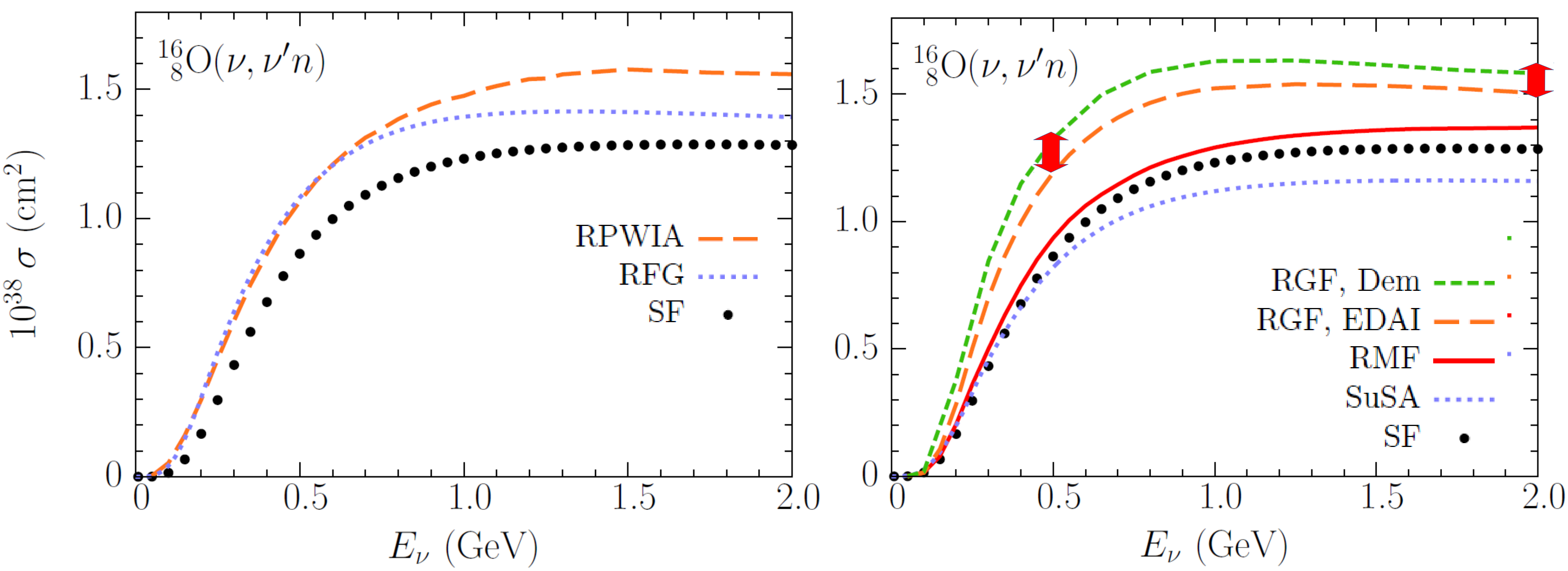
Day *et al.*, PRC 48, 1849 (1993)

Superscaling approach



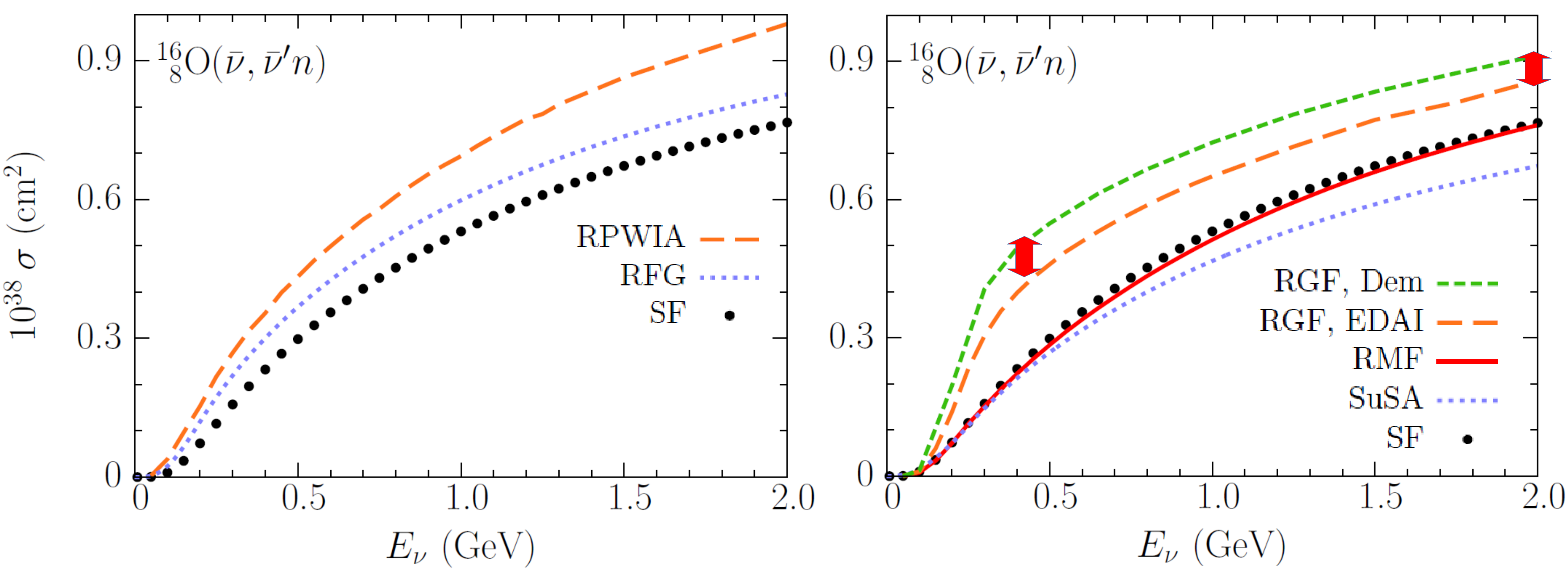
Donnelly & Sick, PRL 82, 3212 (1999)

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)
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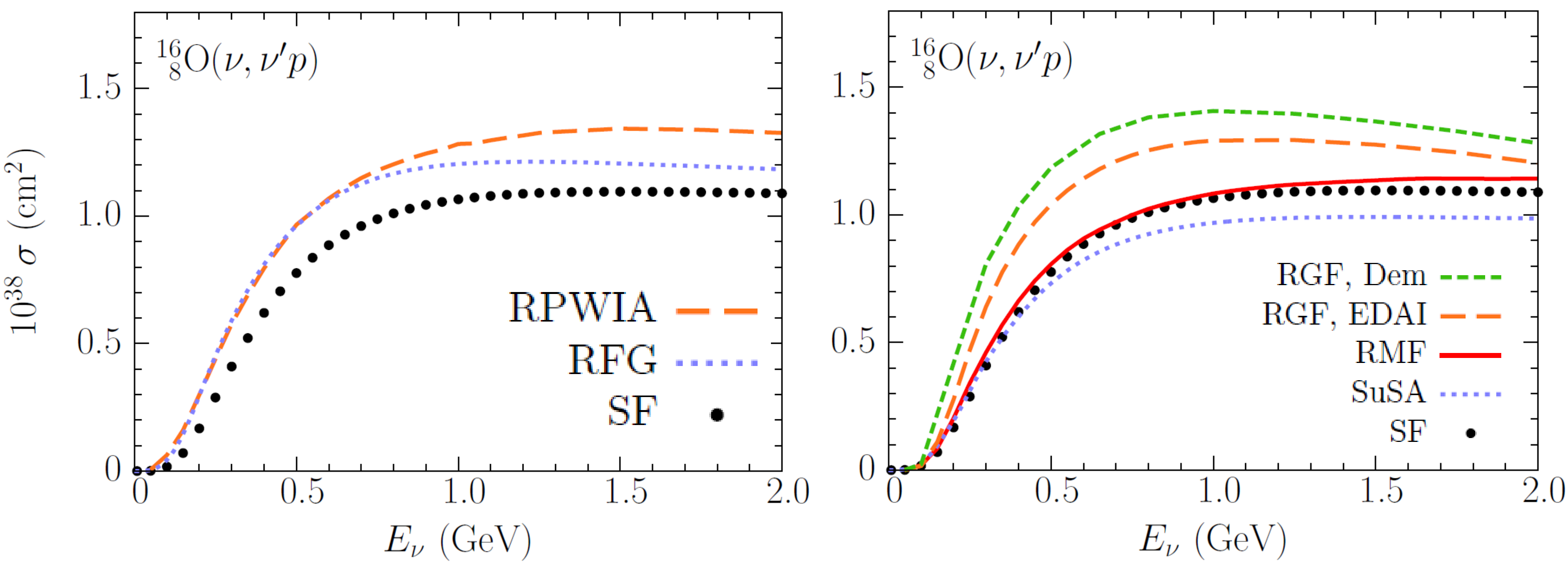
O(*ν*, *ν'p*)



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