Neutrino-Nucleus scattering:
structure and connections to fundamental symmetries

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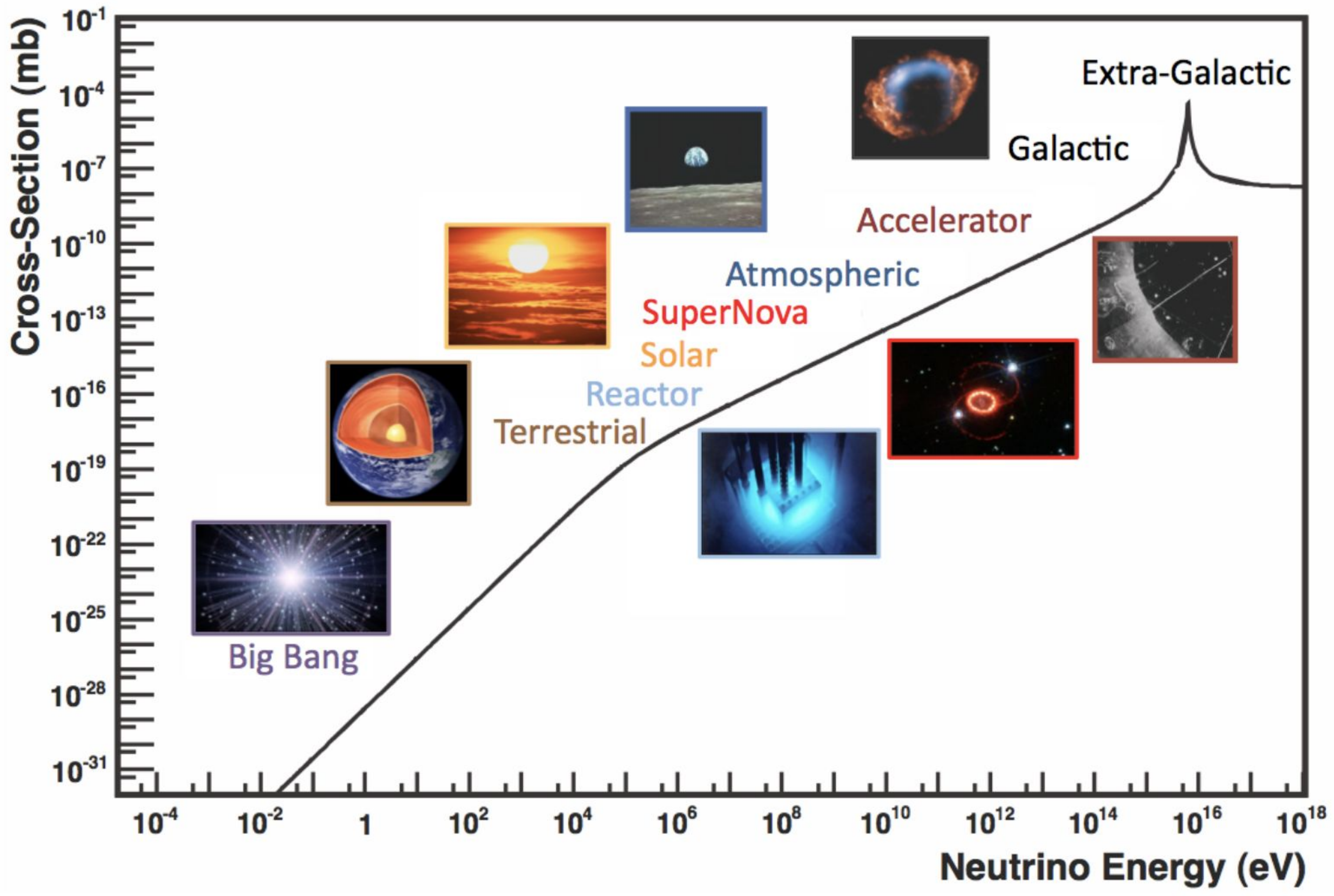
with input from K Mahn, K. Scholberg, S. Pastore, A. Lovato, N. Rocco, Bill Louis, …

Outline

- Introduction
- COHERENT and stopped pion energy experiments
- Inelastic scattering at astrophysical energies ($\leq$ 50 MeV)
- Quasielastic scattering and beyond (pion production)
- Theory and computation
- Relation to other processes:
    - Electron scattering
    - Beta Decay for fundamental symmetries - radiative corrections
    - Low-energy neutrinos in dense neutron-rich matter
    - Double Beta Decay

Neutrino Spectra and cross-sections



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Neutrinos in Astrophysics and Fundamental Symmetries

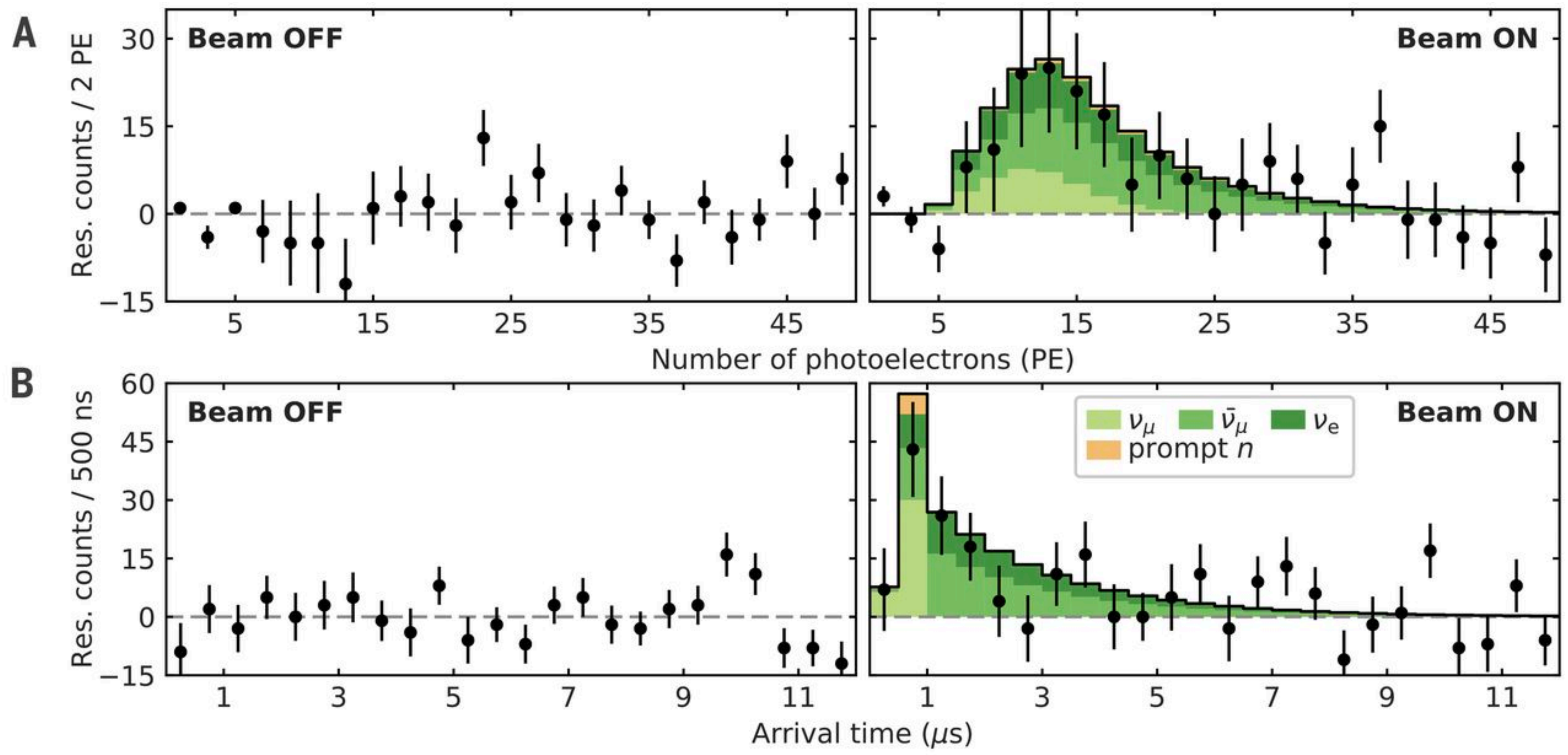
- Double Beta Decay (Majorana neutrinos)
- Accelerator: Neutrino Mass Hierarchy, CP violation
- BSM in beta decay

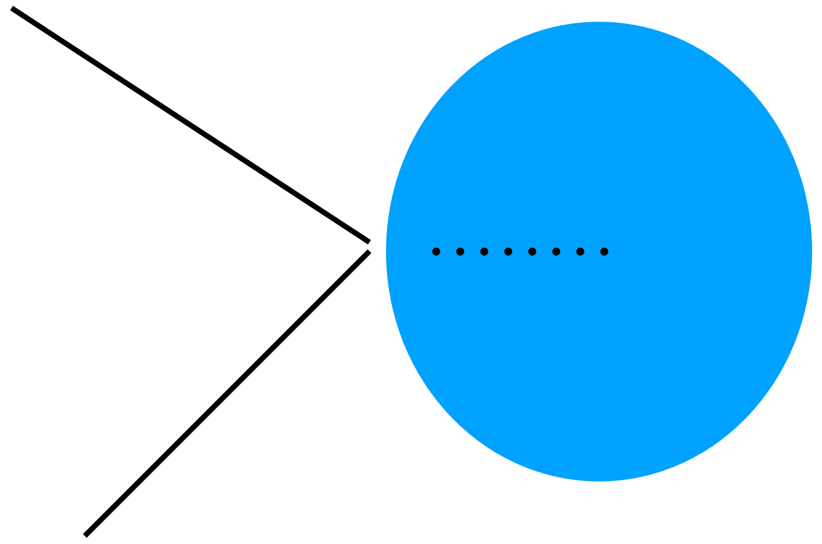
- Nucleosynthesis in NS mergers, Supernovae
- Neutron Star cooling

Neutrino-Nucleus Interactions

- COHERENT: nuclear form factor
- Astrophysical energies (~50 MeV)
- Accelerator energies
  quasi elastic, pion and delta, …, DIS

COHERENT Experiment at SNS
Low-energy neutrinos

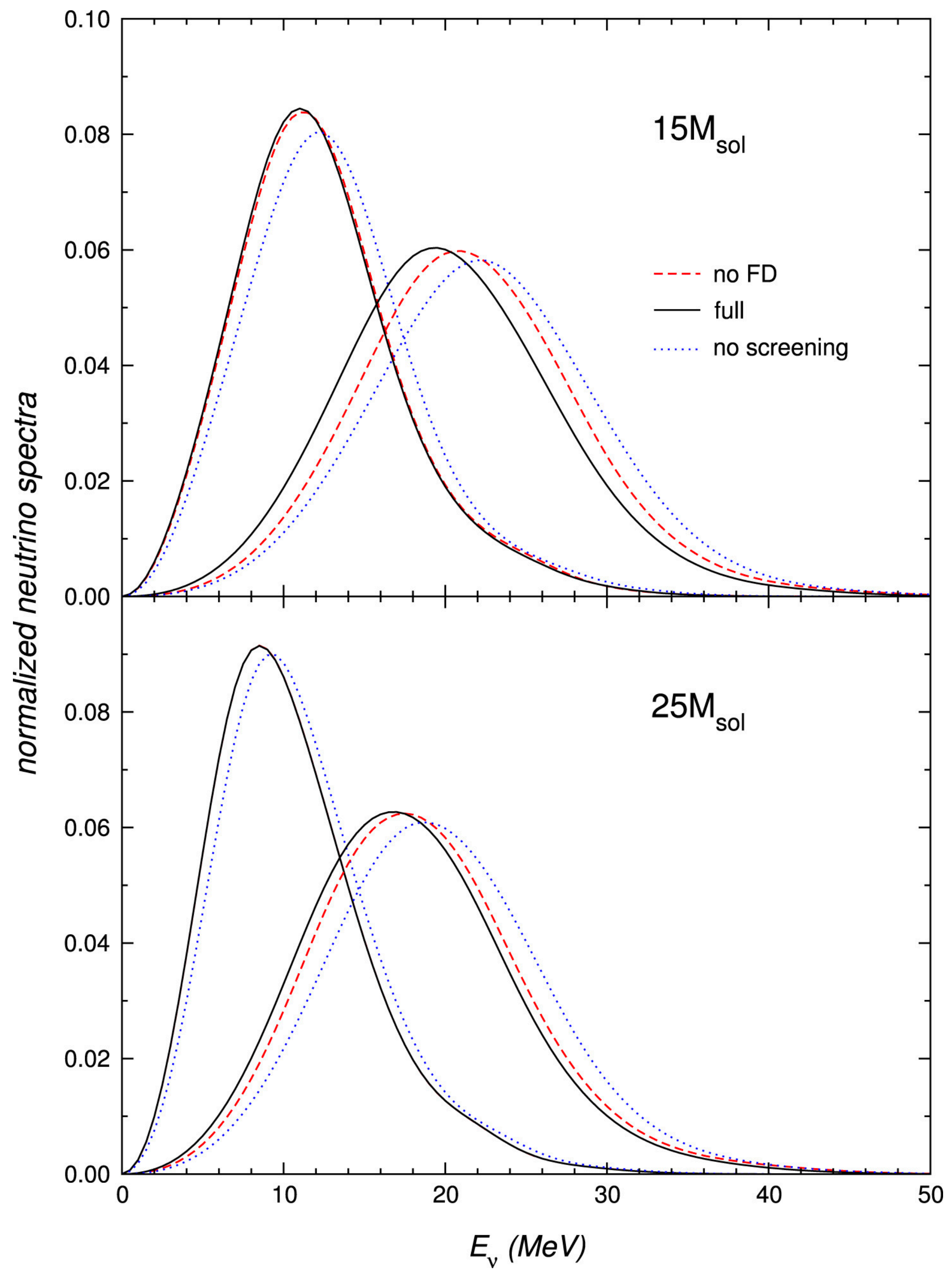




- Observation of neutrino elastic scattering from entire nucleus
- Sensitive to the neutron distribution in the nucleus
  Similar to parity-violating electron scattering (PREX, CREX, …)
- Also sensitive to Dark Matter and non-standard BSM neutrino-nucleus interactions
- Stopped pion source can also do inelastic measurements
  neutrino-Ar scattering for detecting supernovae neutrinos from DUNE
- Astrophysical neutrinos more generally (neutrinos impact number of neutrons available for nucleosynthesis)

Astrophysical Energy Neutrinos (< 50 MeV)

Neutrino Spectra from core-collapse SN



- **Nucleosynthesis in core-collapse supernovae and neutron star mergers depend upon neutrino cross sections (e.g. neutron to seed ratio, ….)**
- **Cross sections on detector materials also very important**

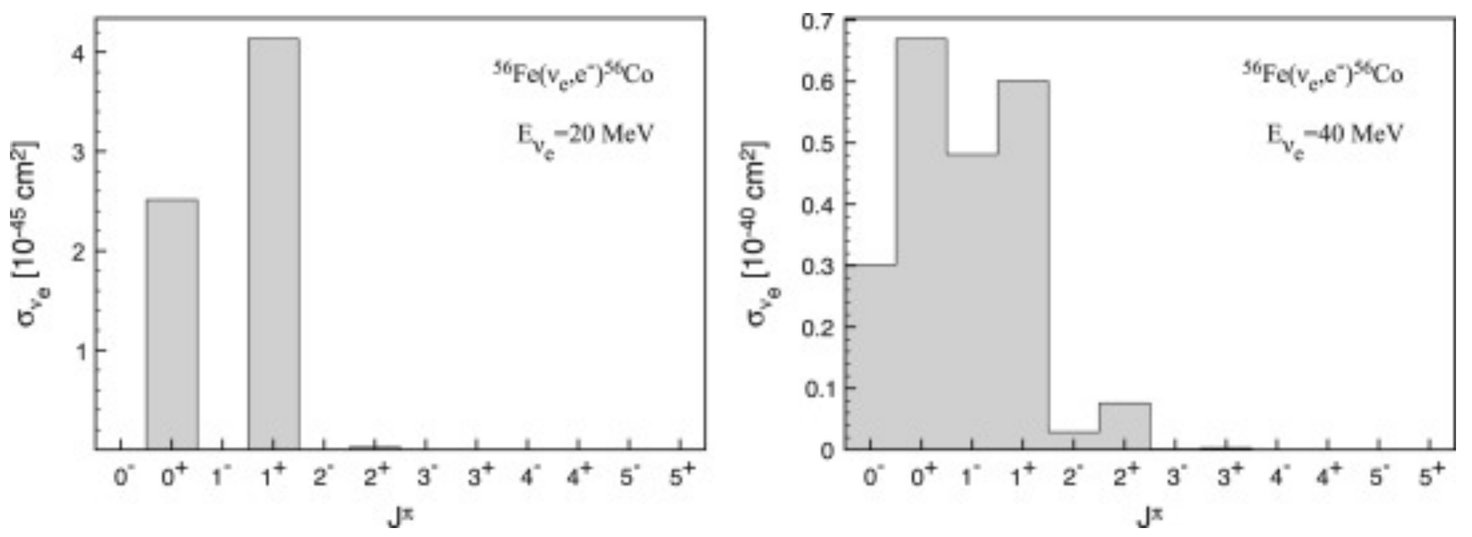
Limited data to date:

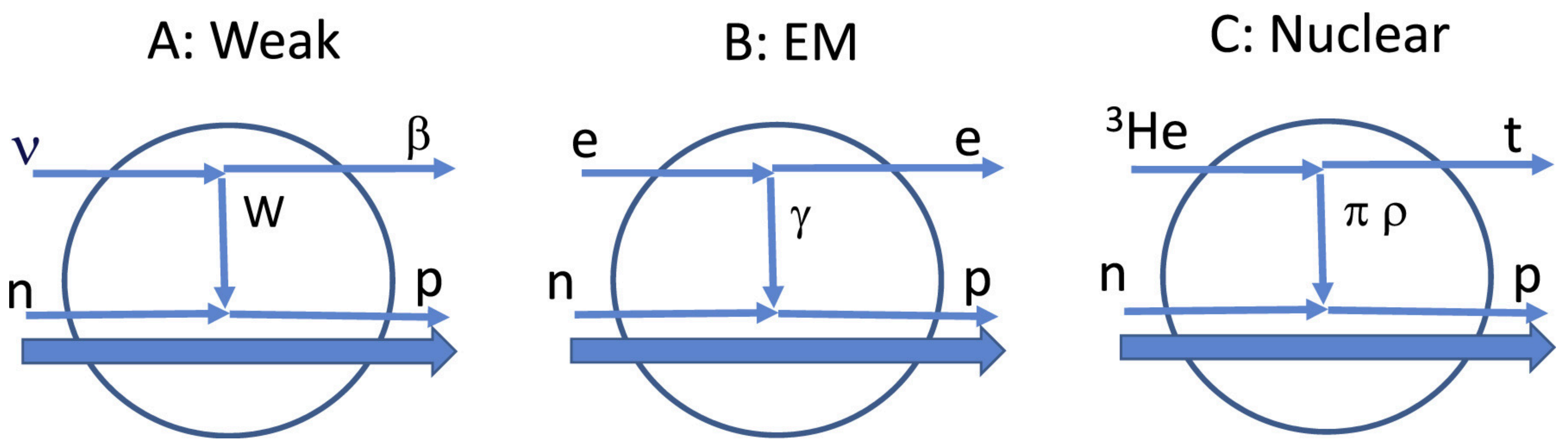
Data on ^{12}C from LSND, KARMEN on nu-μ scattering to specific states
LSND used muon decay at rest (40 MeV)
Best experiment uses electron capture (<3 MeV)
Projects on Ar cross sections underway for DUNE detectors
Vector currents can be constrained by electron scattering data

Much more data to come: 12C, 40Ar

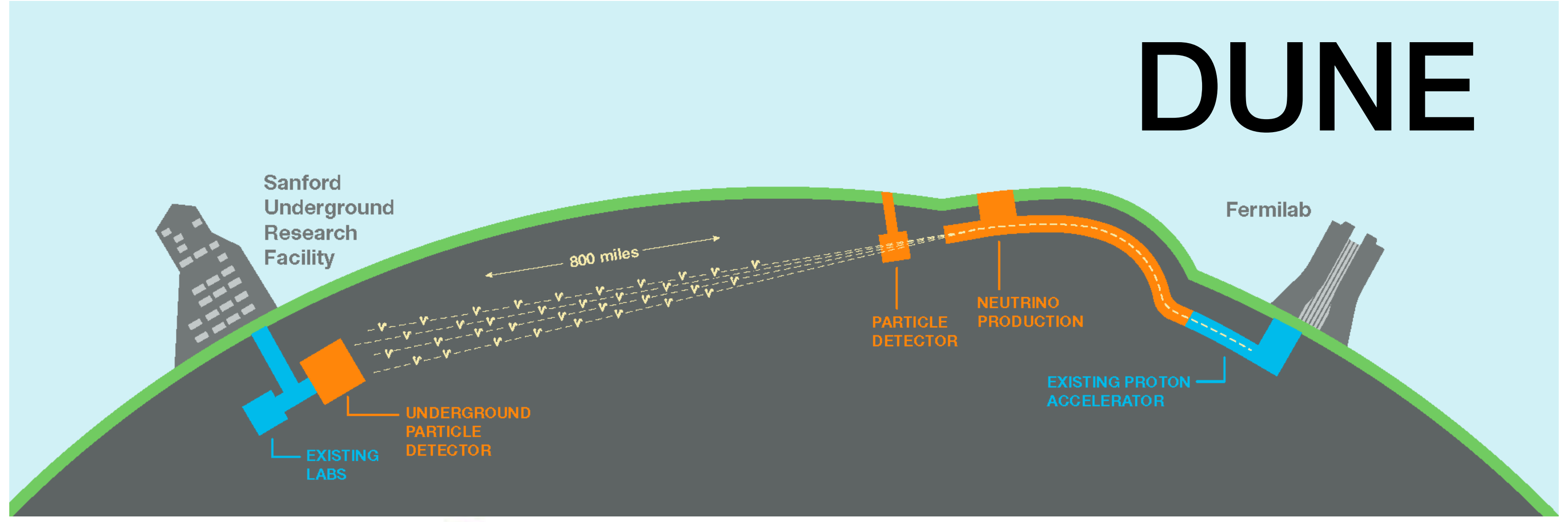
JSNS^2 experiment uses proton target w/ Gd doping, prompt/delayed candidate sensitive to energies up to ~50 MeV
12C K decay at rest produces mono energetic neutrinos (236 MeV)
~5% backgrounds

Multipole decomposition of Fe cross sections at 20 and 40 MeV



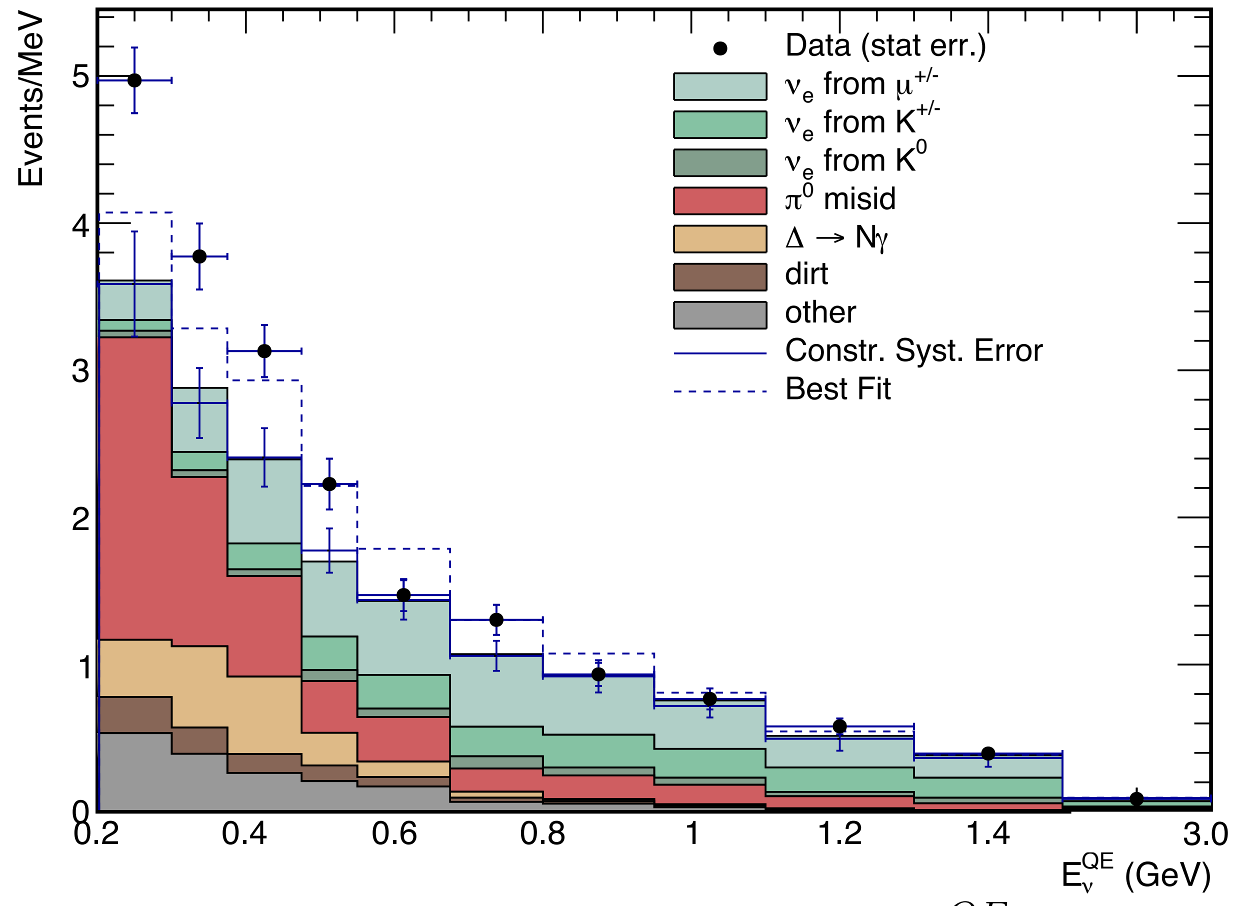


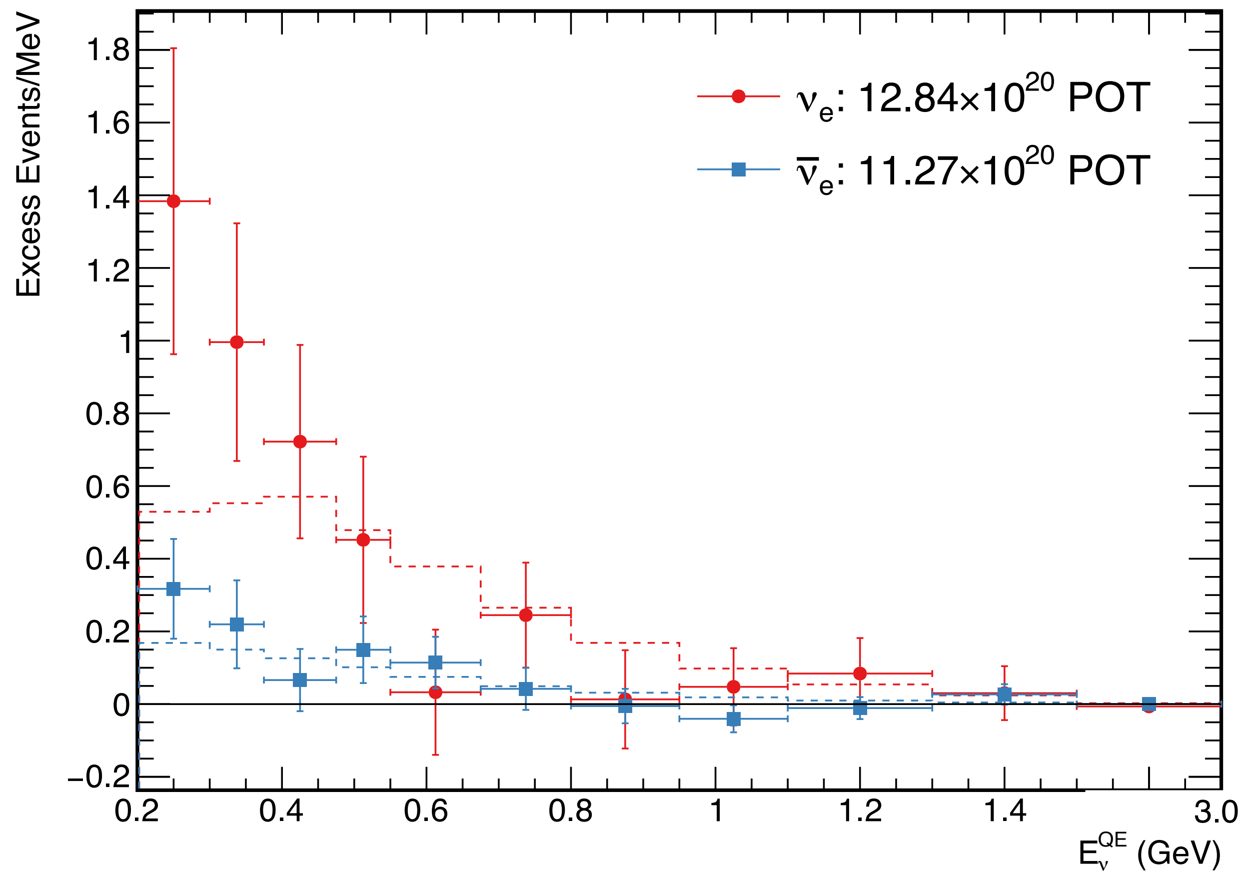
Accelerator Neutrino Scattering



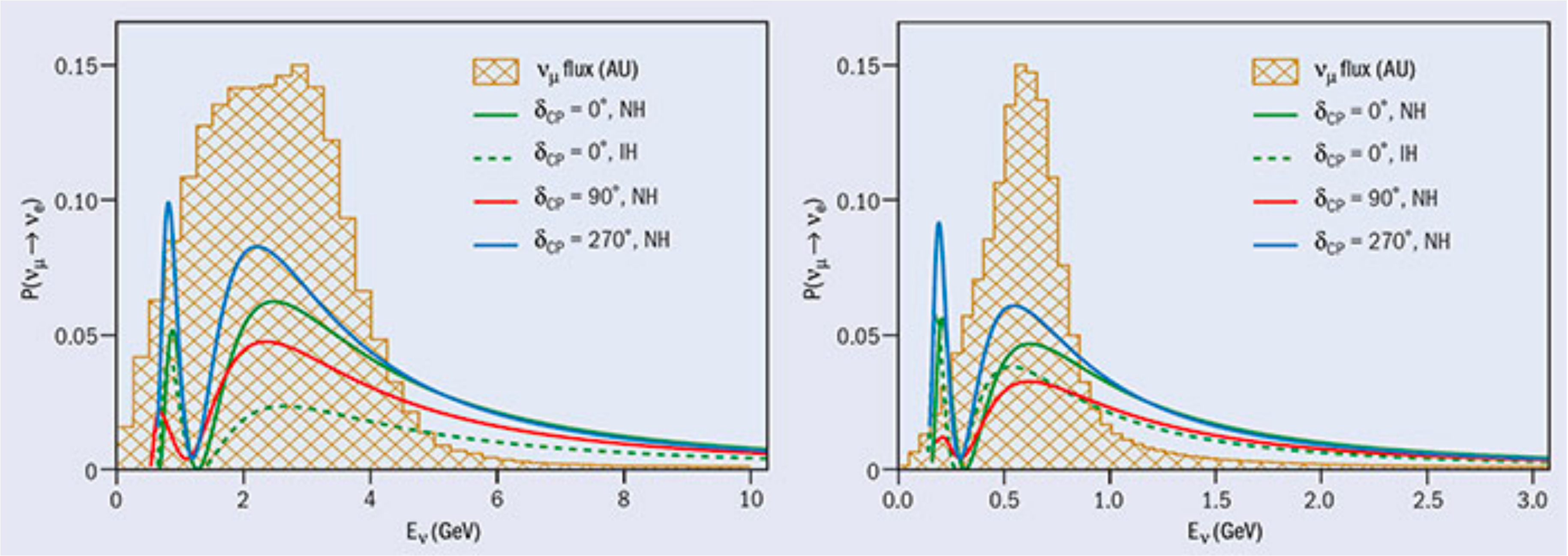
T2K

MiniBoone (2018)





Need L/E for oscillation analysis



Quasi-elastic scattering: neutrinos (and electrons)

- DUNE neutrino experiment
  to measure neutrino mass hierarchy, CP violation

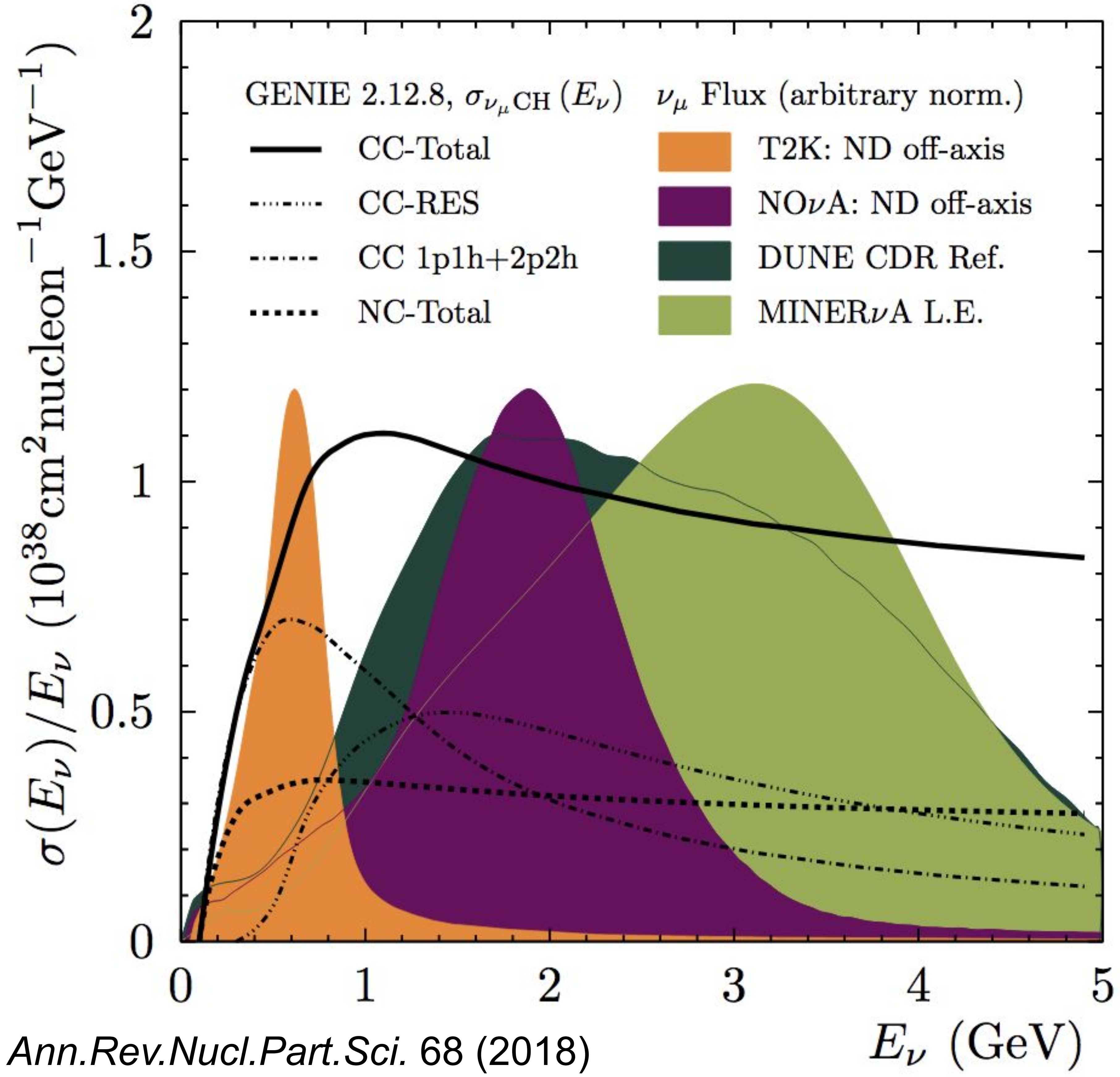
- A great deal of new data expected, near detector at FNAL (Ar)

- Electron scattering experiments (JLAB, …) help understand nuclear physics at scale of nucleon-nucleon separation and below
  (back-to-back final states, EMC effect,…)

- Nuclear theory / computation to help constrain nuclear electroweak
  response at QE energies

Accelerator Neutrino Experiments

Flux versus Energy



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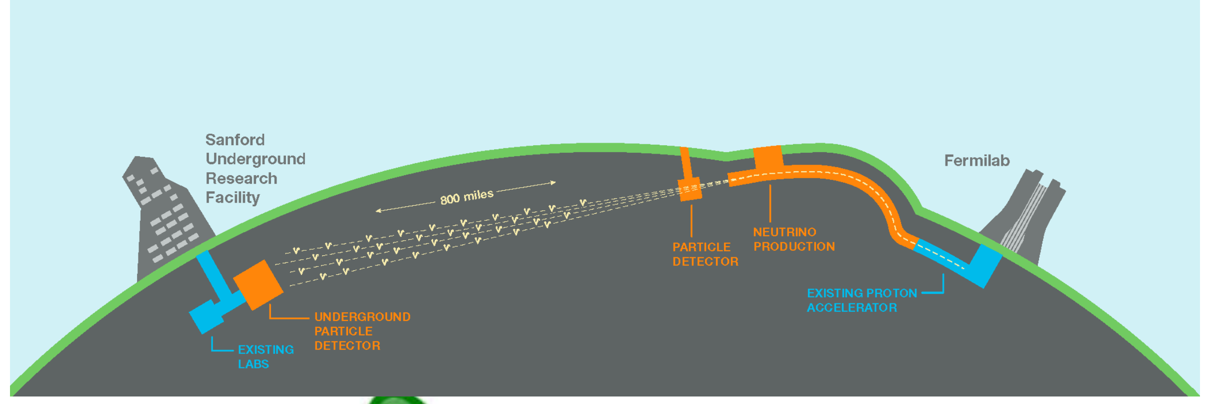
DUNE



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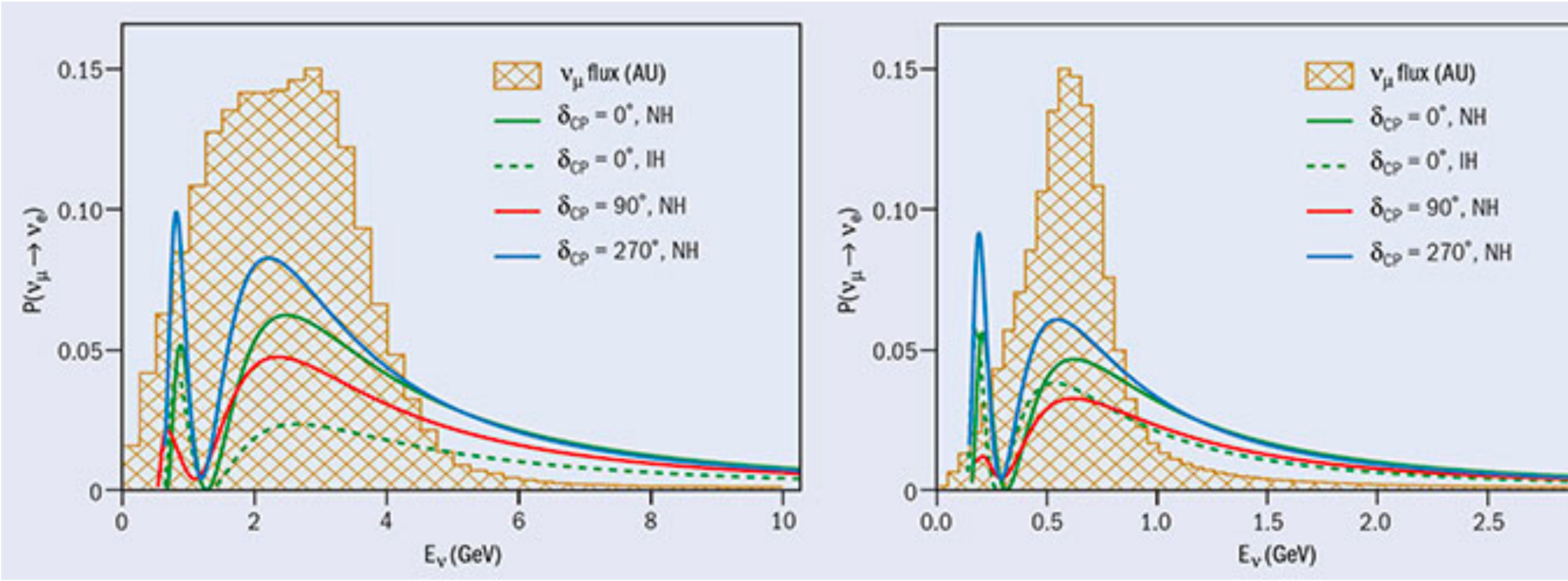
CP violation sensitivity (DUNE)



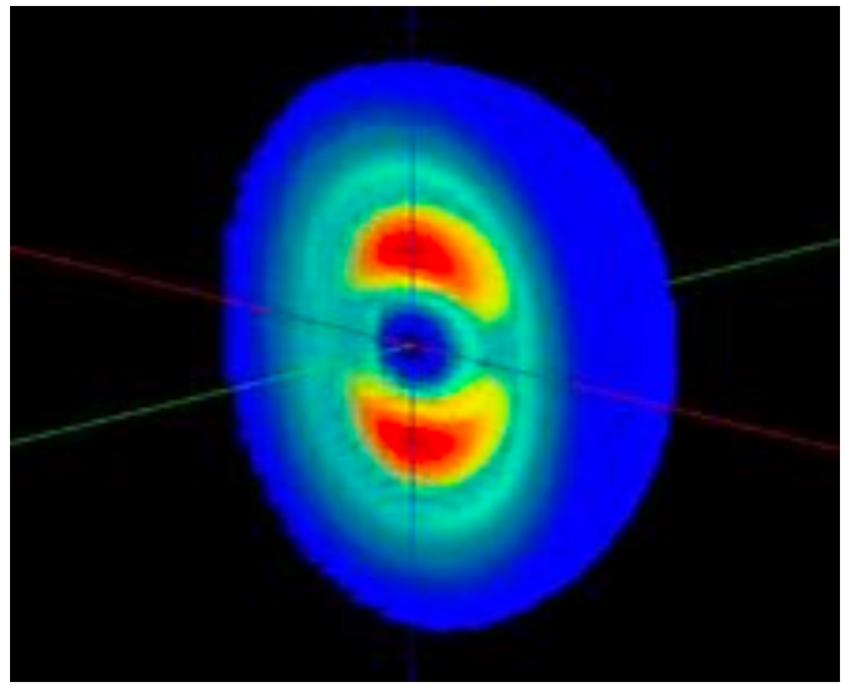
Compare to Electron Scattering

Quasi-elastic scattering: q ~ k_F

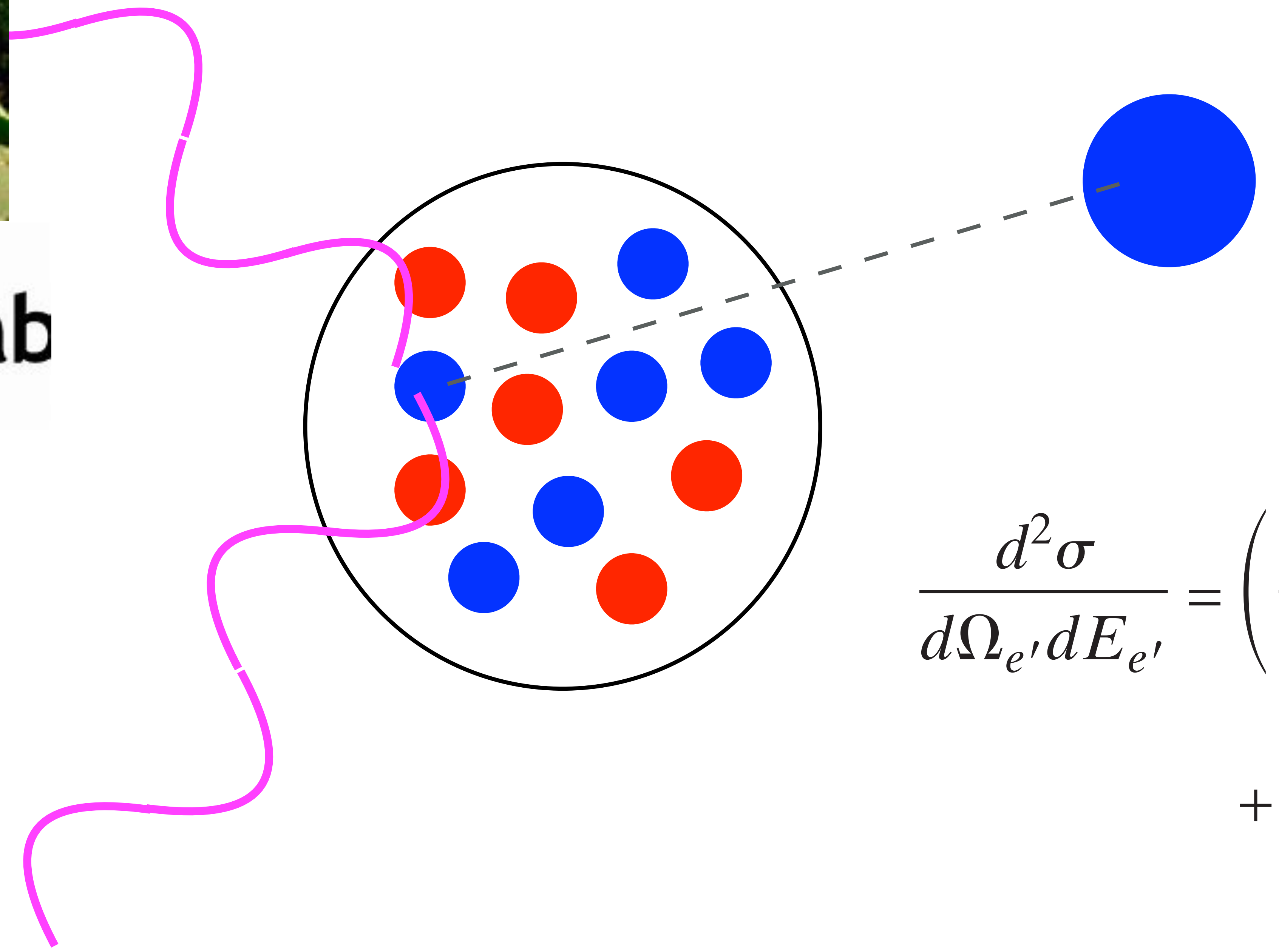
Electron Scattering: 2 response functions

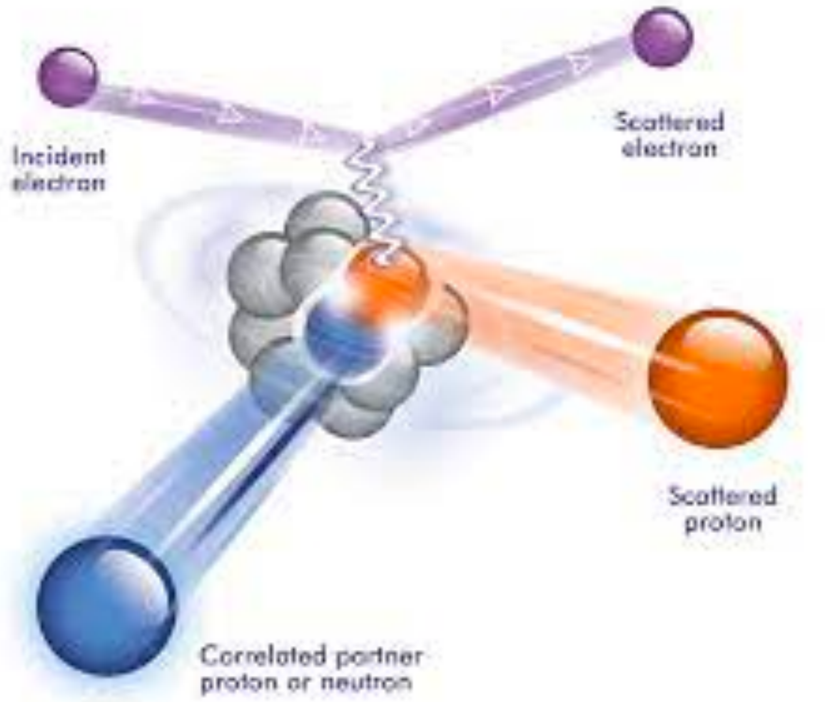
Neutrino/Antineutrinos: 5 response functions

vector and axial vector components



Jefferson Lab

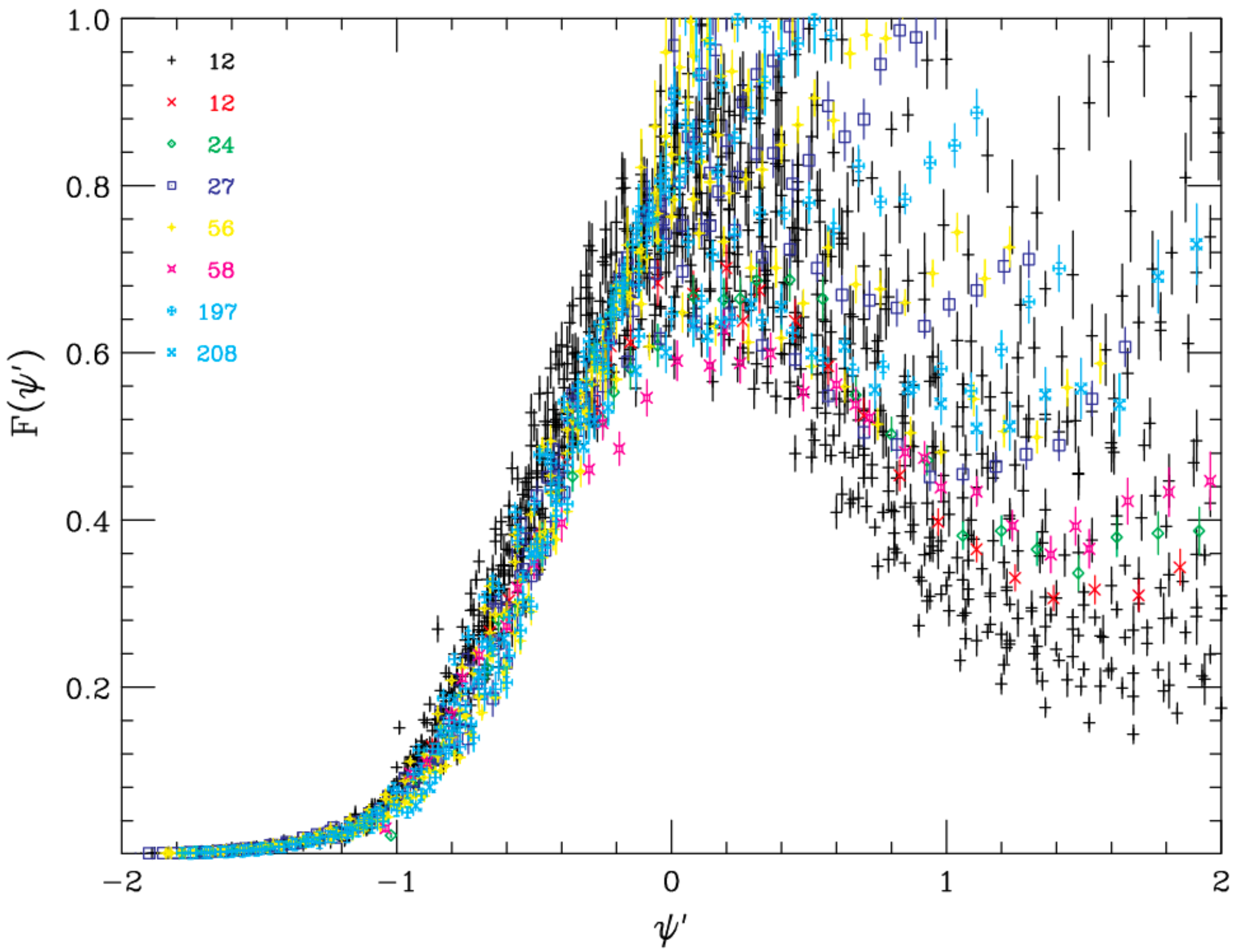




$$\frac{d^2\sigma}{d\Omega_{e'}dE_{e'}} = \left(\frac{d\sigma}{d\Omega_{e'}}\right)_M \left[\frac{Q^4}{|\mathbf{q}|^4} R_L(|\mathbf{q}|,\omega) + \left(\frac{1}{2}\frac{Q^2}{|\mathbf{q}|^2} + \tan^2\frac{\theta}{2}\right) R_T(|\mathbf{q}|,\omega)\right]$$

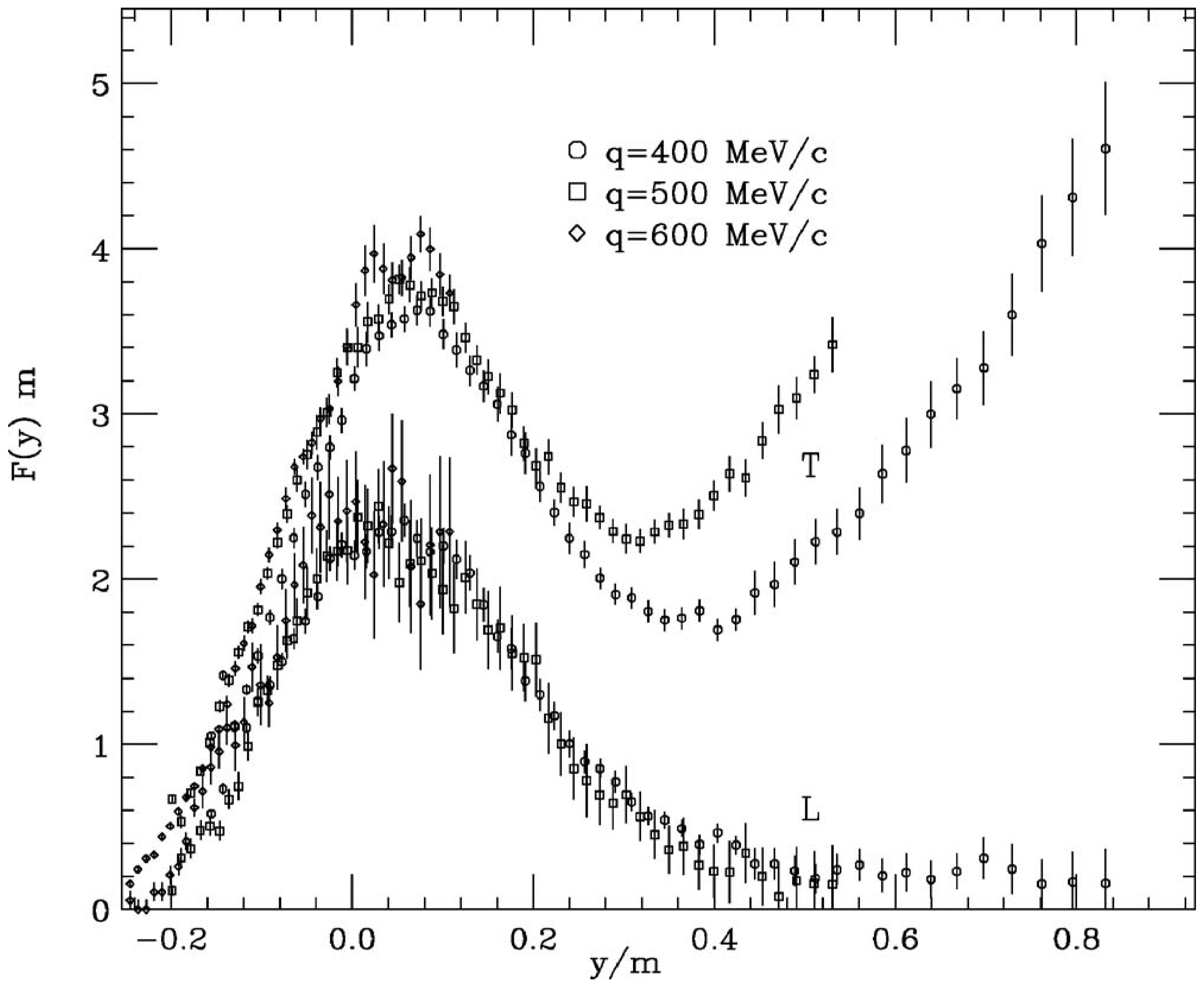
Some basic Observations from Electron Scattering

Superscaling: for the same kinematics, response looks similar for different nuclei ($q > k_F$)



Superscaling in inclusive e-nucleus scattering
Different nuclei at the same kinematics

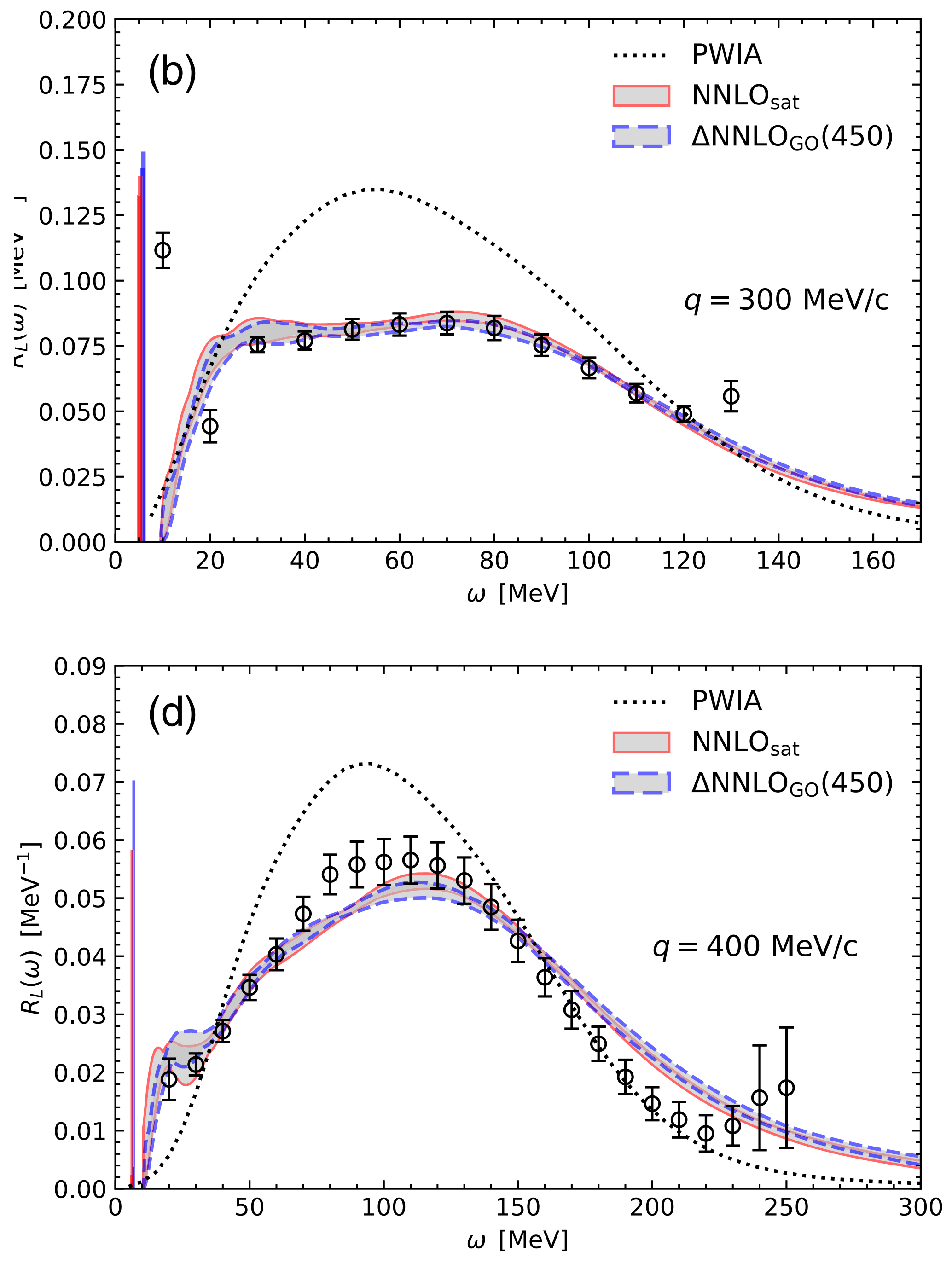
Incoherent Scattering from individual nucleons not the whole picture



Scaled longitudinal vs. transverse scattering from ^{12}C

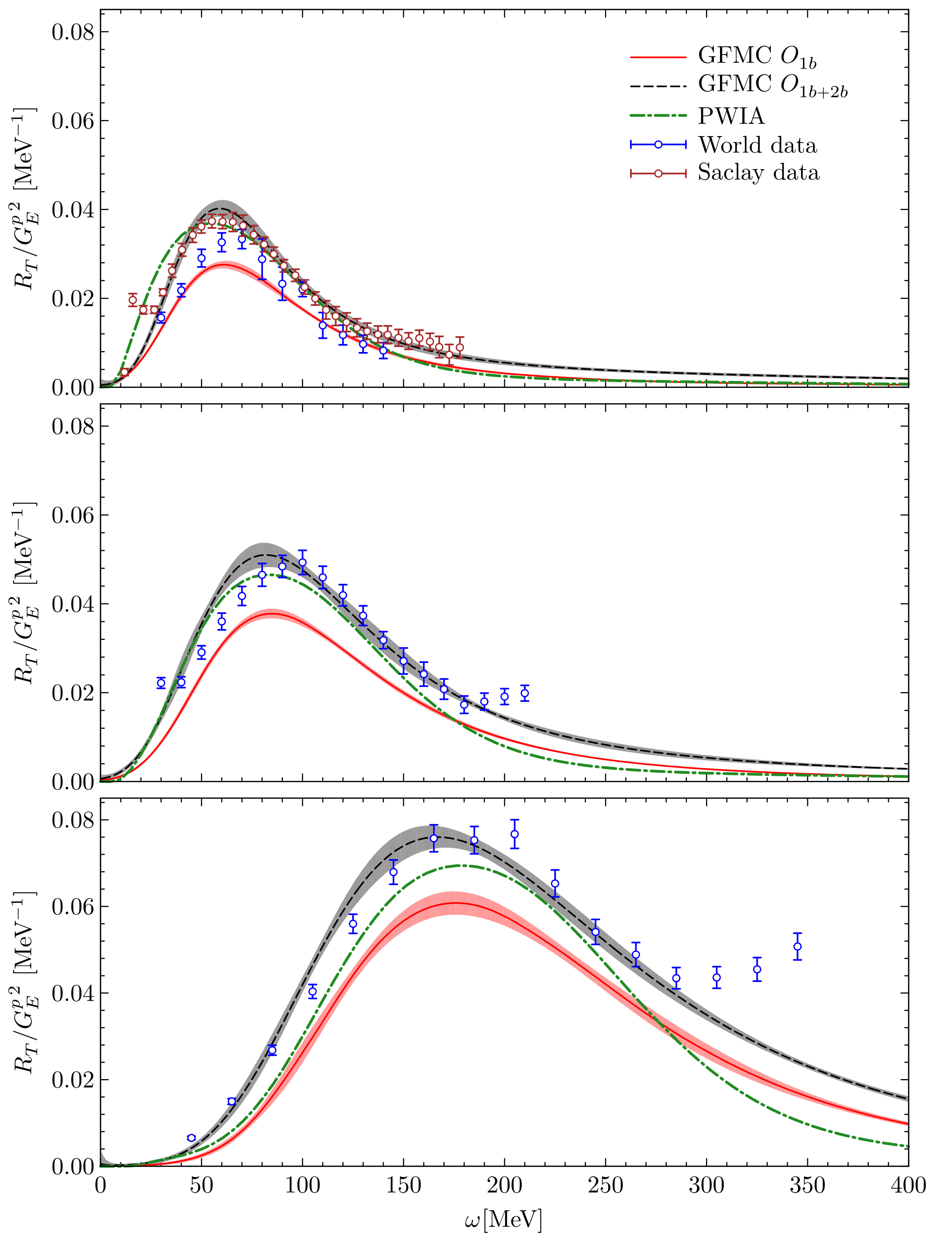
Electron Scattering (q > k_F)

Longitudinal (charge) scattering in ^{40}Ca



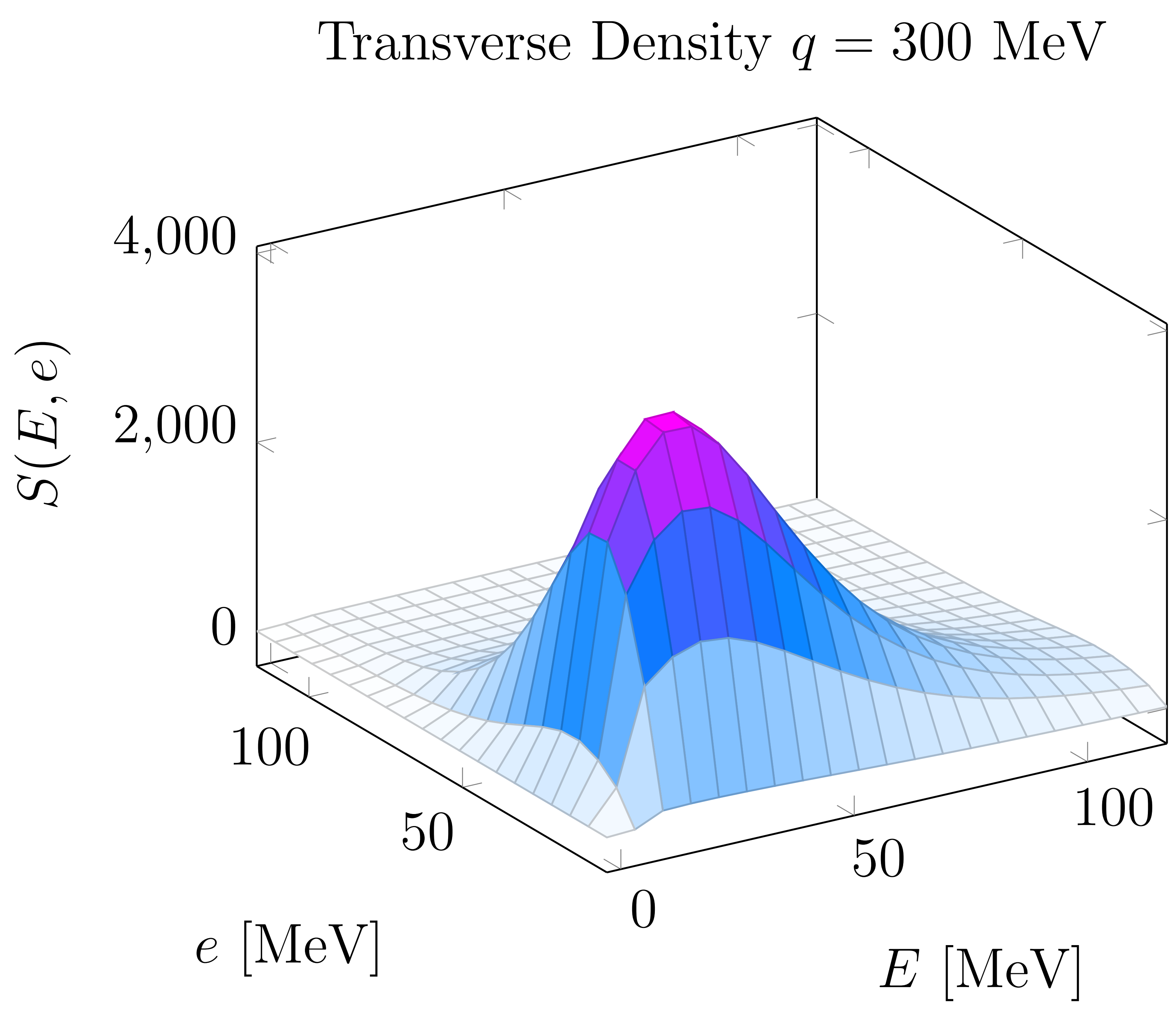
Note: Interaction moves charge

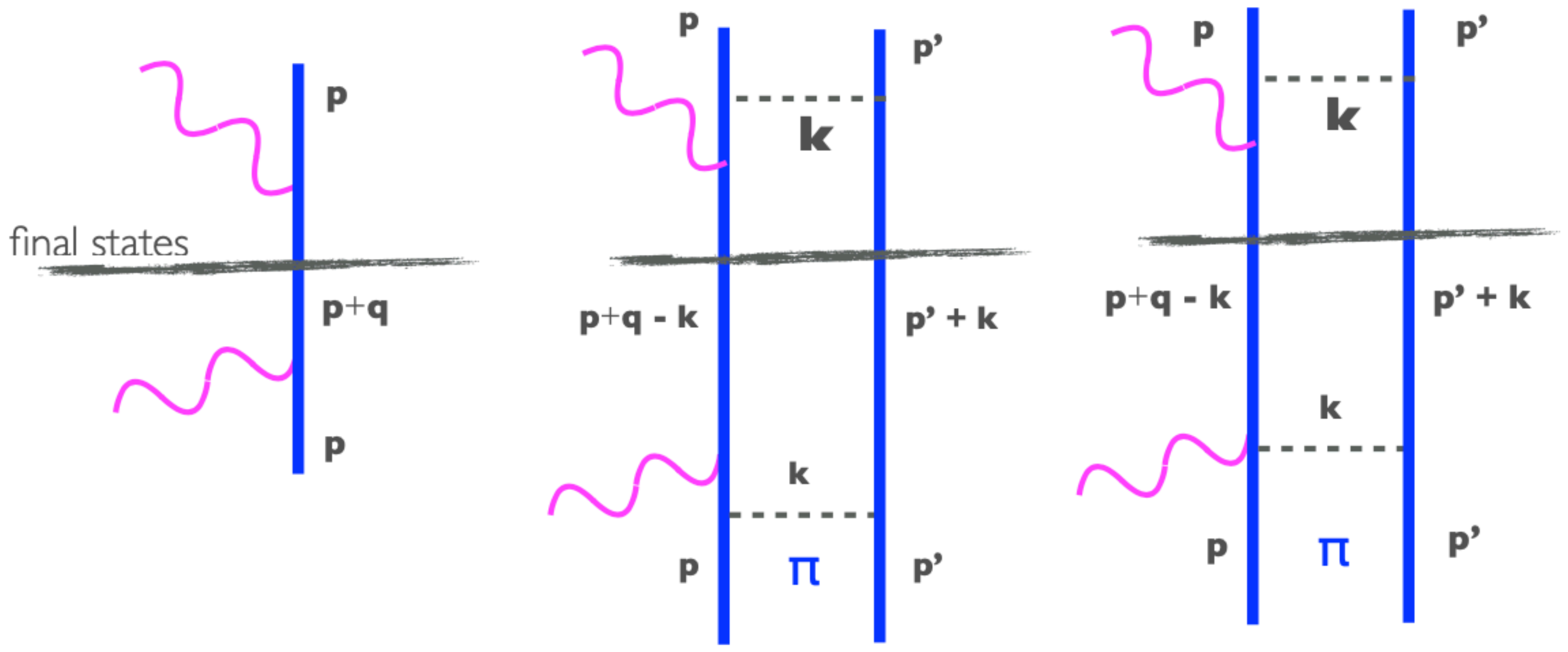
Transverse (current) scattering in ^{12}C



Two-nucleon currents important in transverse response

Factorization at One (Spectral Fn) or Two-nucleon (STA) level

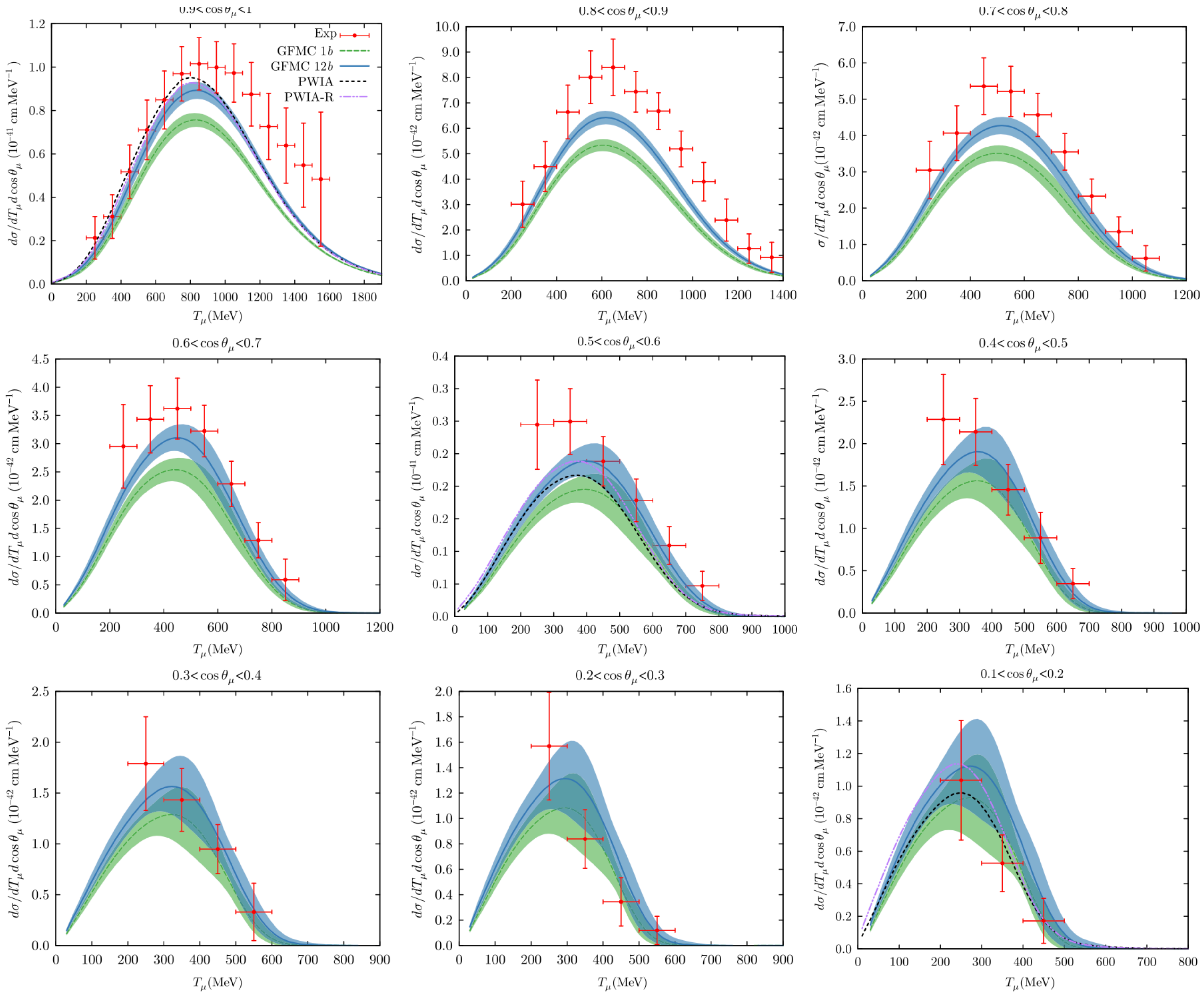




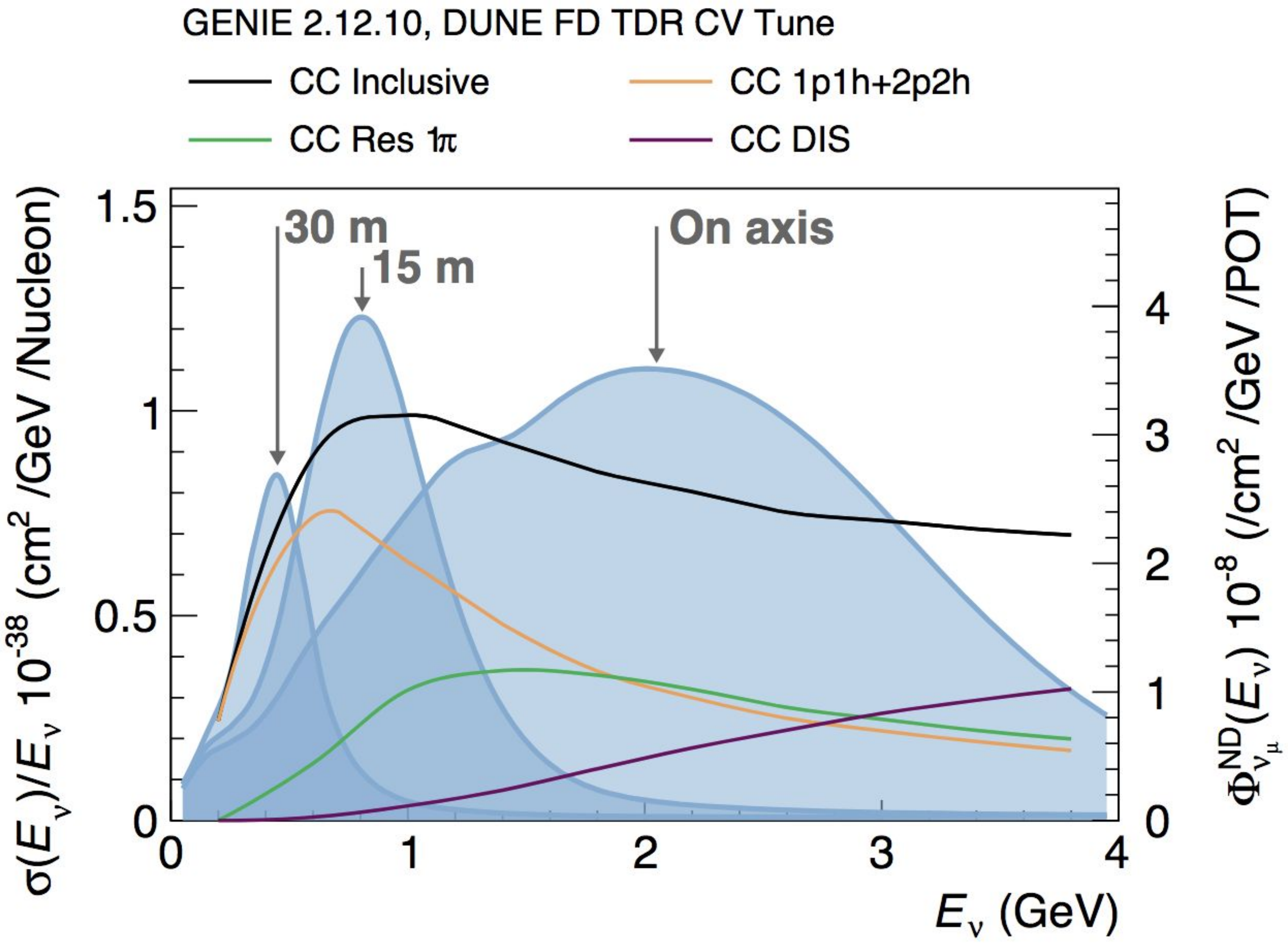
$$R^O(q,\omega) \;=\; \frac{\int d\Omega_q}{4\pi}\int \frac{dt}{2\pi}\exp[i\omega t]\langle\Psi_0|\mathcal{O}^\dagger(\mathbf{q},t')\exp[-iHt]\mathcal{O}(\mathbf{q},t=0)\Psi_0\rangle,$$

Can be used to begin to study exclusive final states: coupling to generators

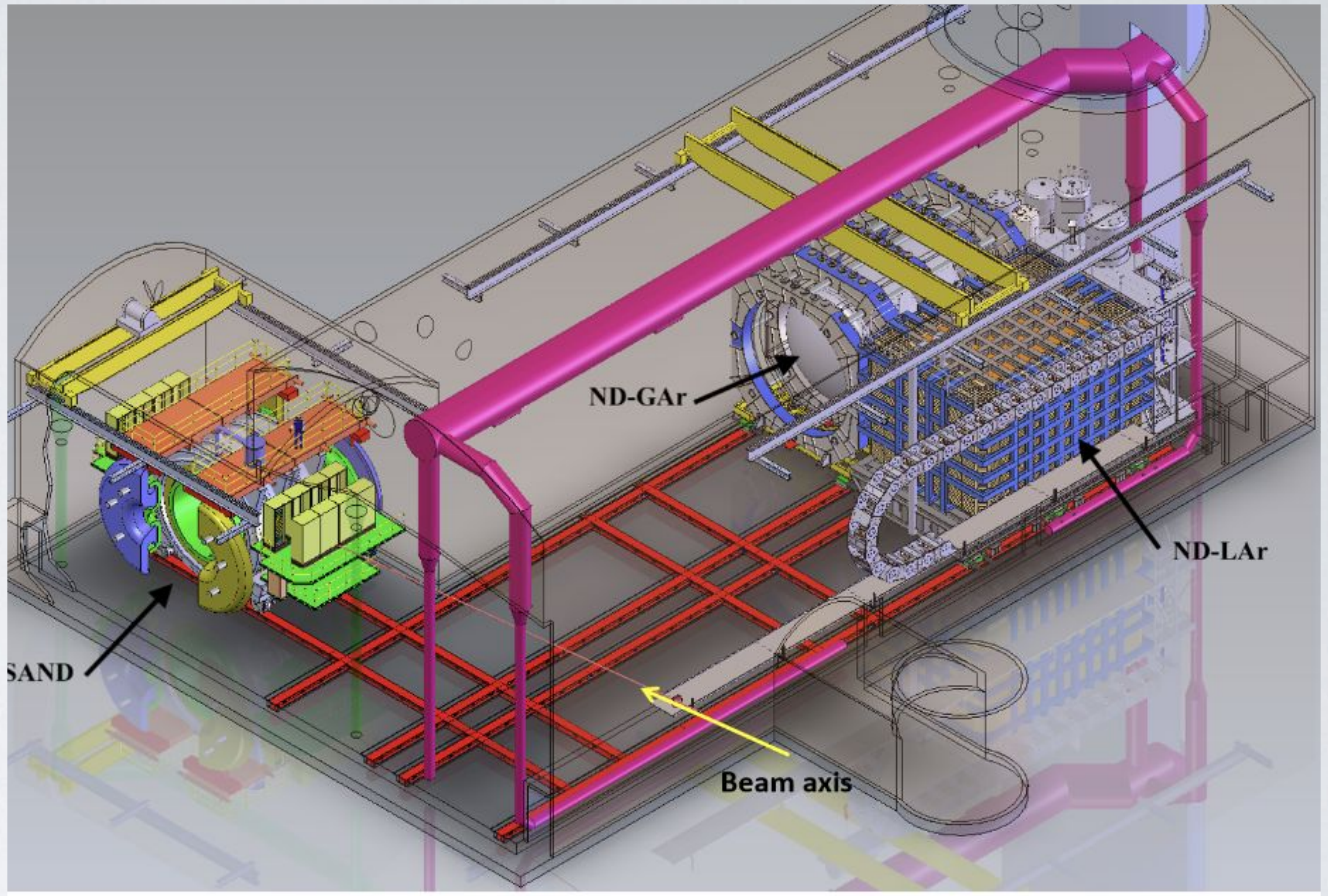
Anti-Neutrino (and neutrino) scattering

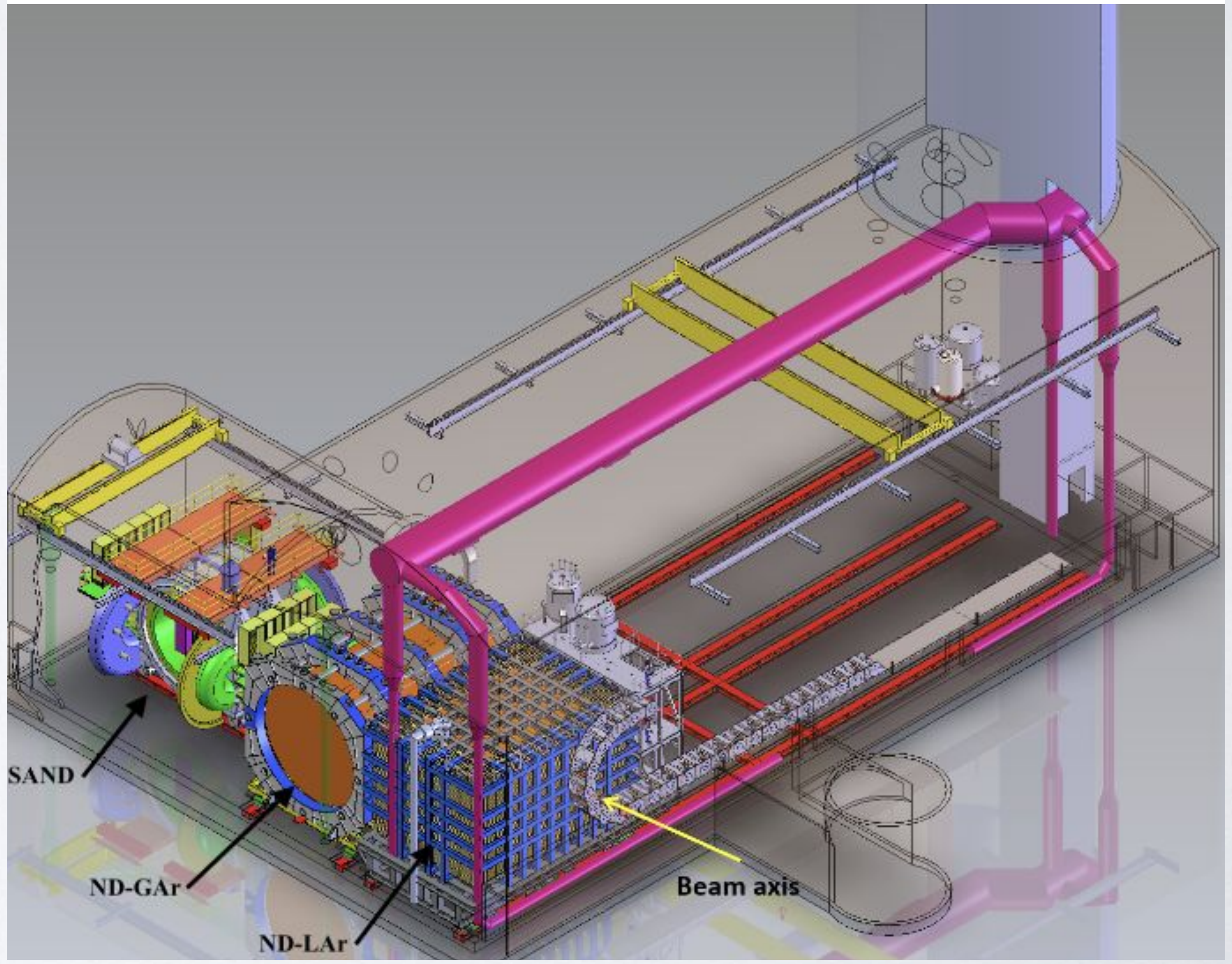


New approach: DUNE PRISM



Place detectors at different positions relative to beam to measure different energy spectra





Neutrinos in dense neutron matter

(Cooling of neutron stars)

$$S_\sigma^{-1} = \frac{\chi_\sigma}{2n},$$

$$S_\sigma^0 = 1 + \lim_{q\to 0} \frac{4}{3N} \sum_{i\neq j}^{N} \langle 0| e^{-i\mathbf{q}\cdot(\mathbf{r}_i - \mathbf{r}_j)} \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j |0\rangle,$$

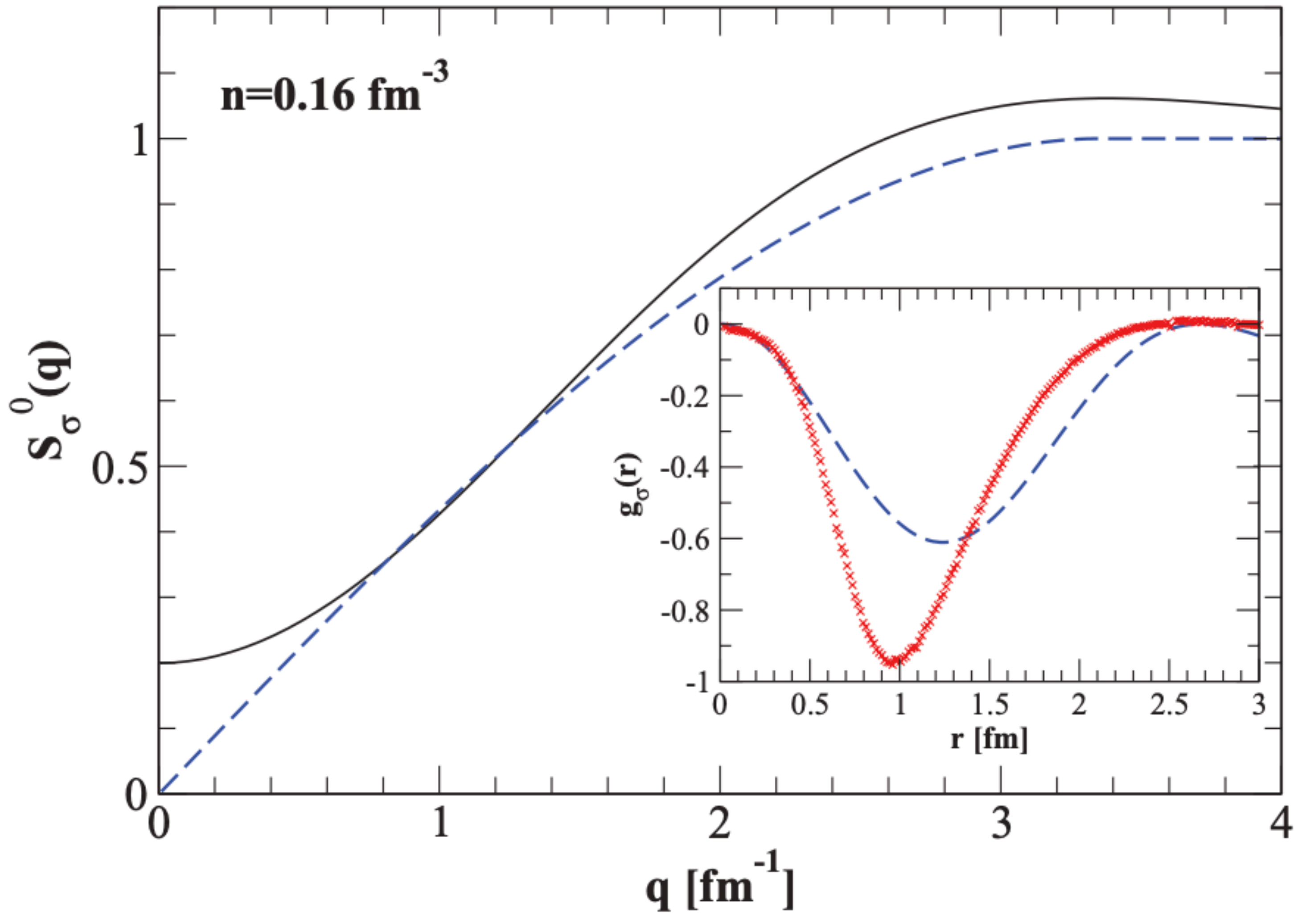
$$S_\sigma^{+1} = -\frac{4}{3N} \lim_{q\to 0} \langle 0| [H_N, \boldsymbol{s}(\mathbf{q})] \cdot \boldsymbol{s}(-\mathbf{q}) |0\rangle,$$

Ignoring superfluid nature (T> Tc),
two-nucleon currents

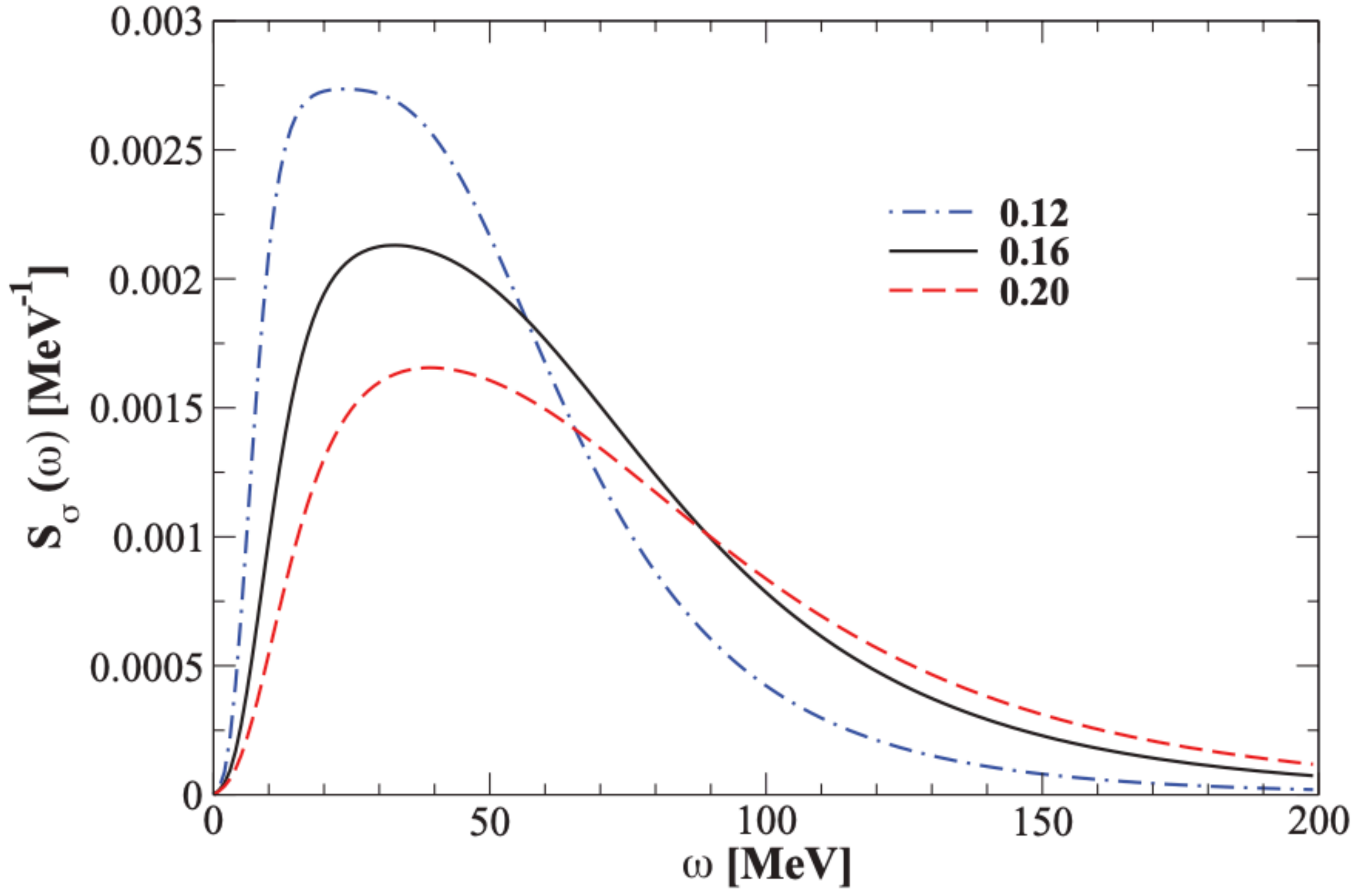
$$Q = \frac{C_A^2 G_F^2 n}{20\pi^3} \int_0^\infty d\omega\, \omega^6 e^{-\omega/T} S_\sigma(\omega),$$

Most of the response at high energies ~ E_F
Even though momentum transfer is low.

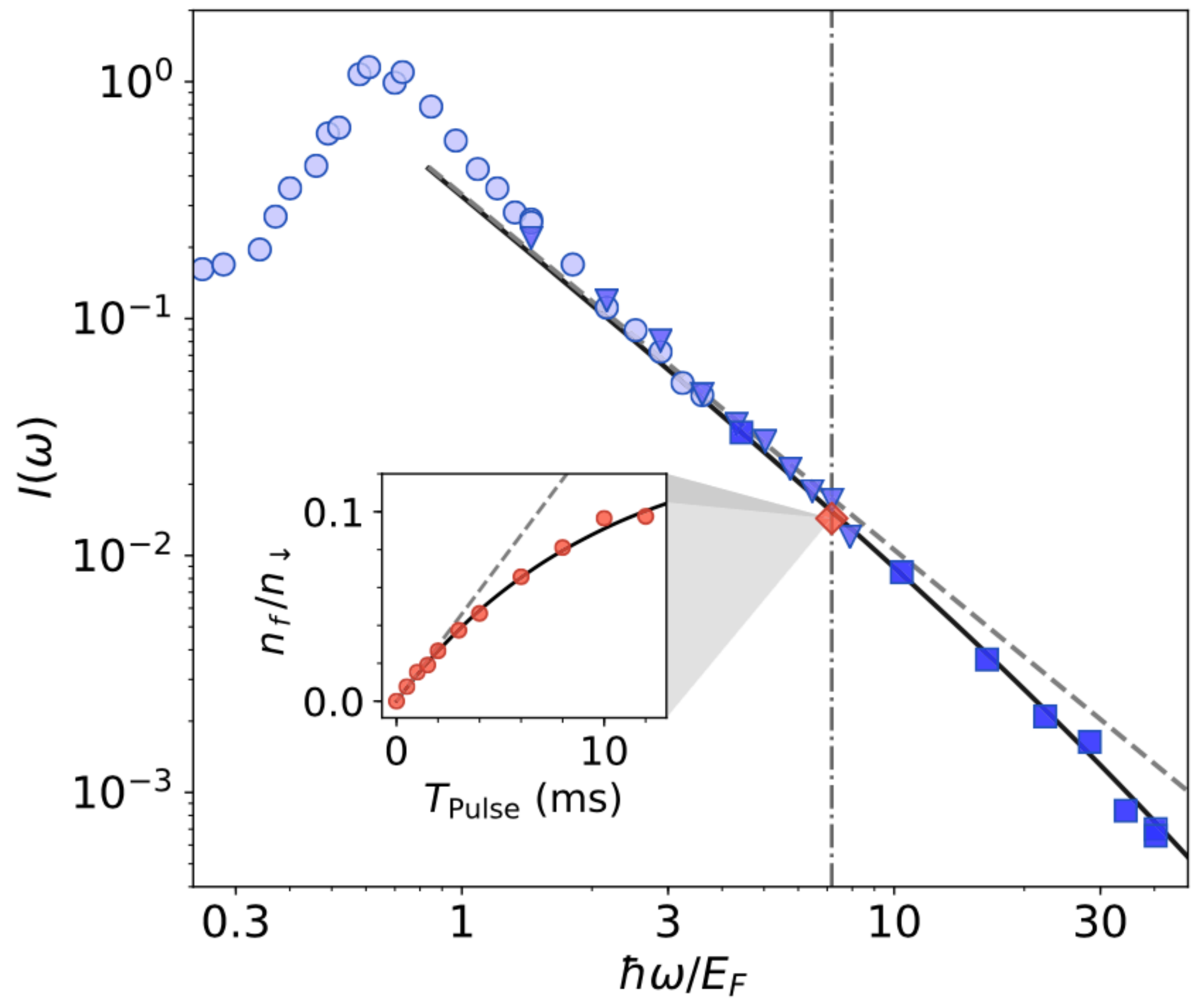
Analogous to RF response in cold atoms
(Spin flip to 3rd unoccupied state)
Used to measure contact



Statics: structure factor S(q) in blue
Pair correlation function (spin-spin)
in red (inset)

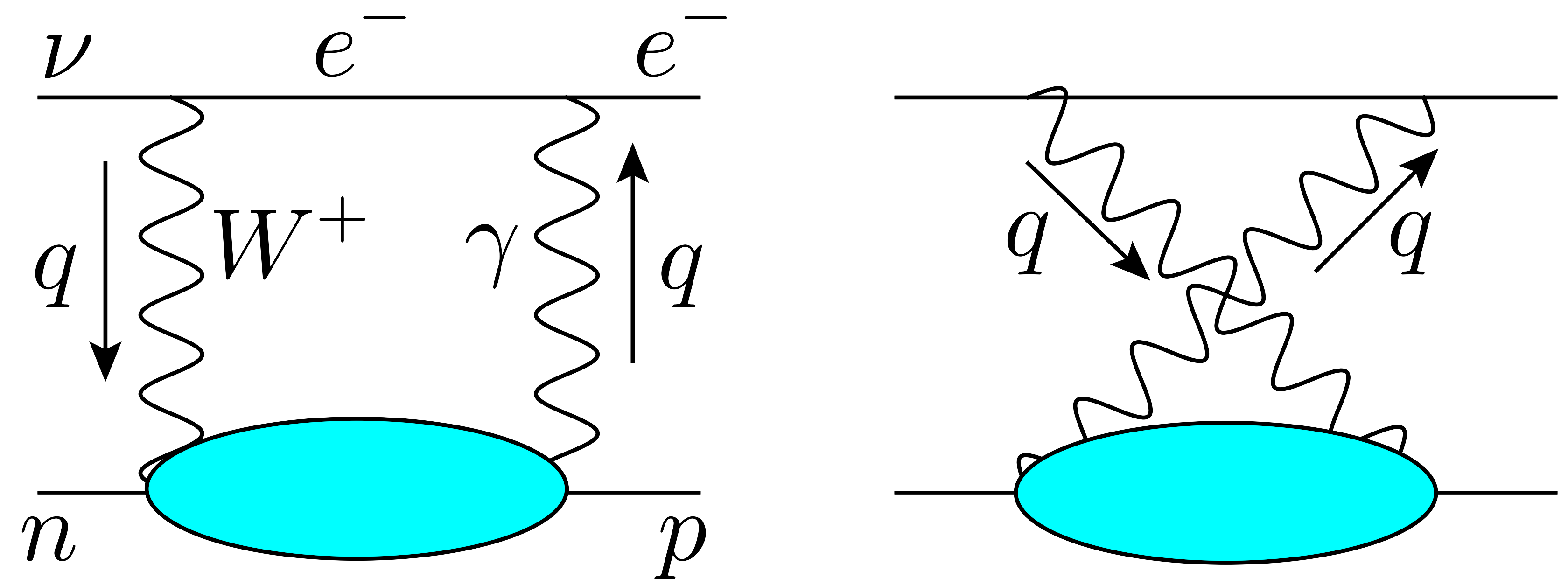


Reconstructed response fns
vs. density (note assuming T > Tc)

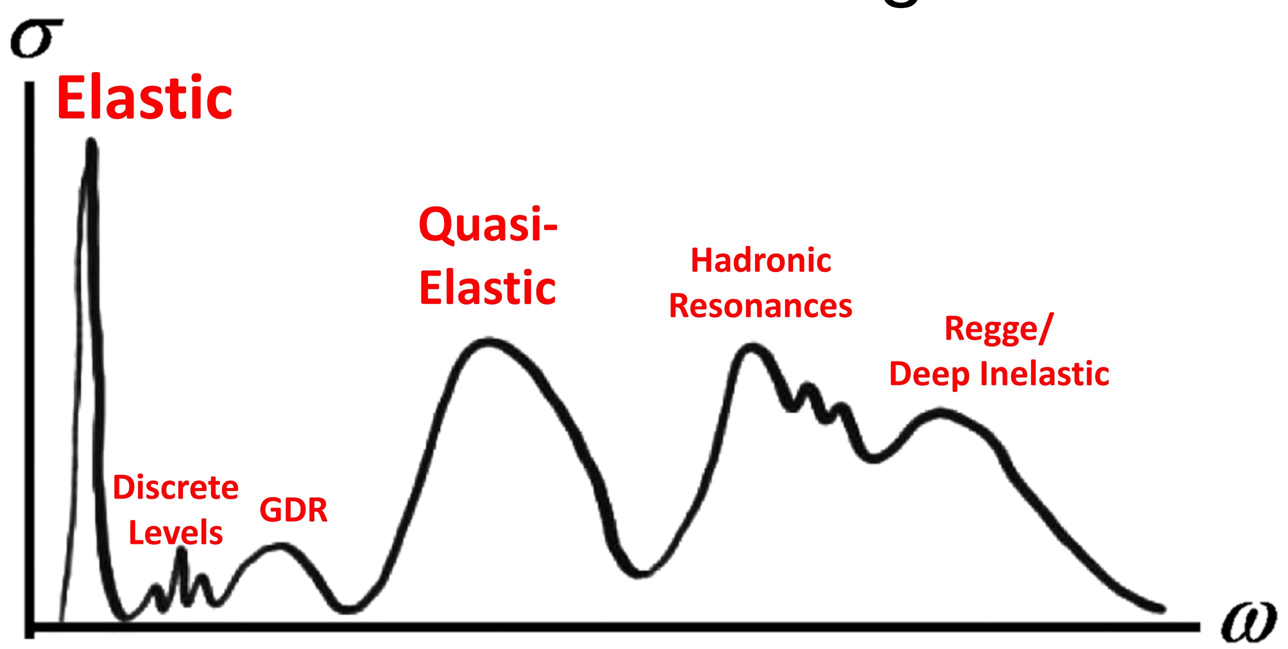


Ties to fundamental symmetries: CKM unitarity
low energy, mixed Q

Superallowed beta decay
Used to test unitarity of the CKM matrix



Inner radiative corrections to nuclear beta decay
Involve connections to inclusive
neutrino scattering



Idealized structure of nuclear
virtual photoabsorption.

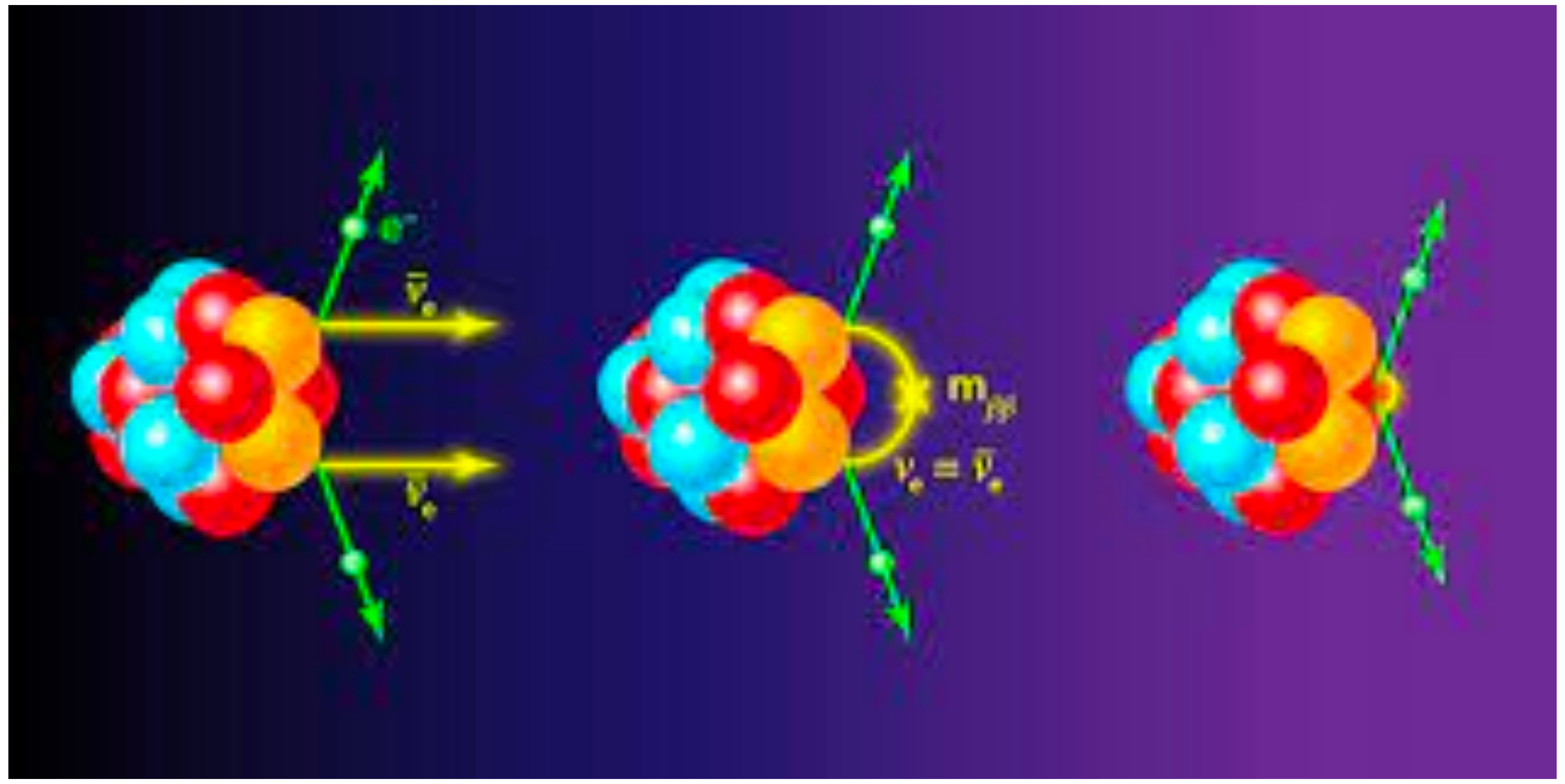
$$|V_{ud}^{\rm new}| = 0.97370(14) \rightarrow |V_{ud}^{{\rm new},QE}| = 0.97395(14)(16).$$

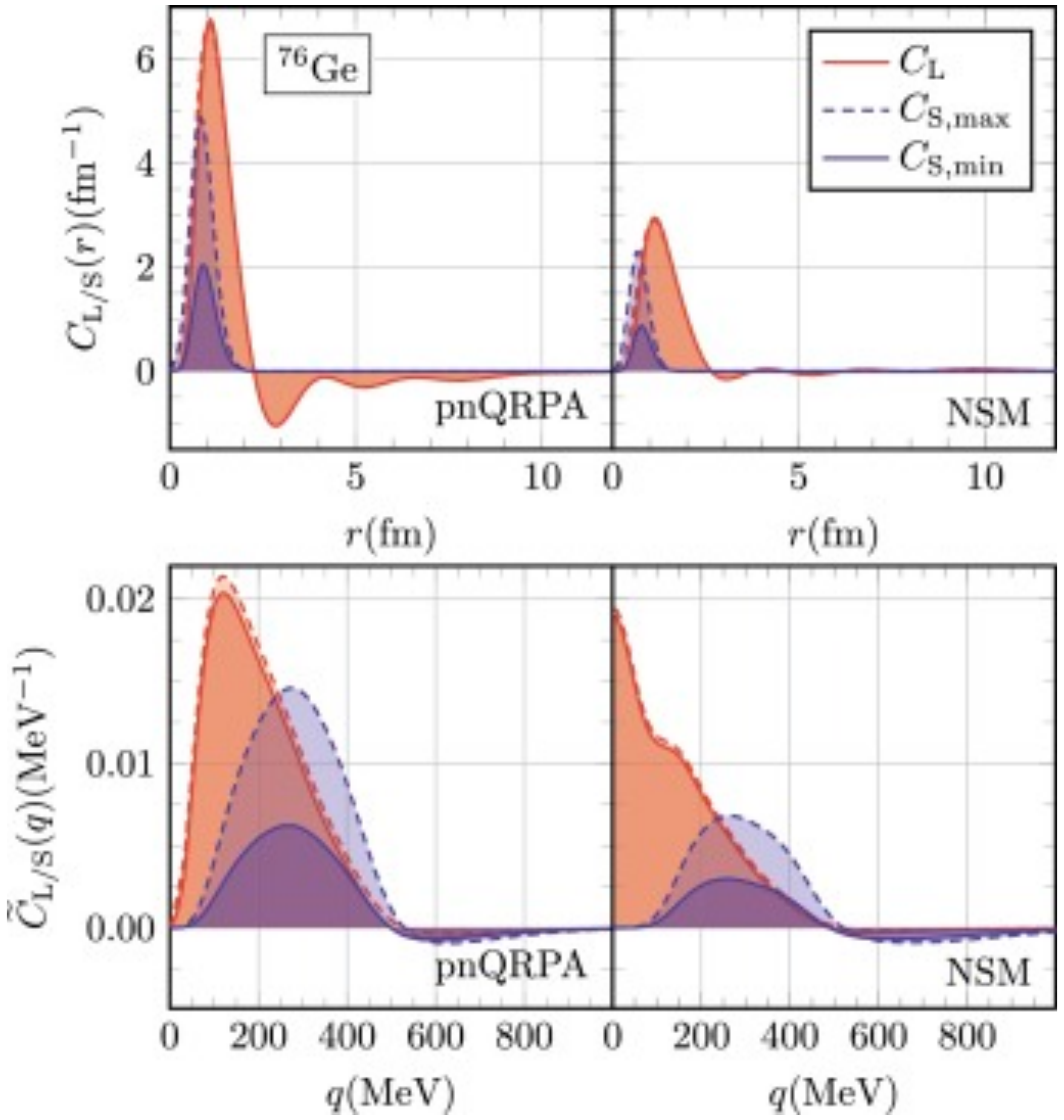
$$\rightarrow |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9989 \pm 0.0005.$$

Quasielastic contrition is significant
Present evaluation is a bit simplified

Double Beta decay
and the search for lepton number violation / Majorana Neutrinos

Low Energy Transition:
Traditional neutrino exchange - long range (1/r) propagator
Two nucleon EW currents
New contact Operator





Neutrino-nucleus interactions and fundamental symmetries

- Nuclear Physics with neutrinos is important in astrophysics
    - Nucleosynthesis and supernovae / neutron star mergers
    - Neutron star cooling
- And in Fundamental Symmetries/ BSM Physics
    - Neutrinoless double beta decay
    - CKM unitarity via super allowed beta decay
    - Accelerator neutrinos : mass hierarchy and CP violation
- Theory/computation can make valuable contributions