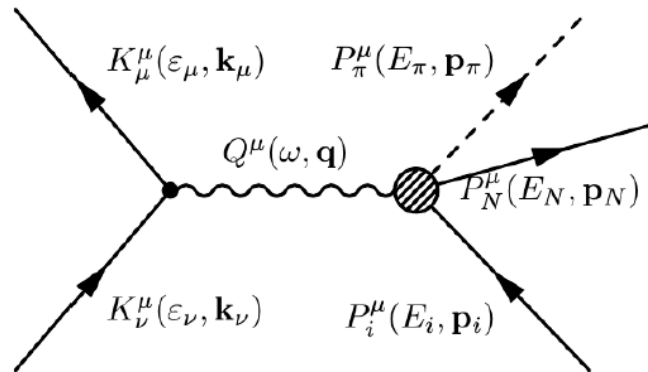


# Microscopic cross-sections for ESS $\nu$ SB+

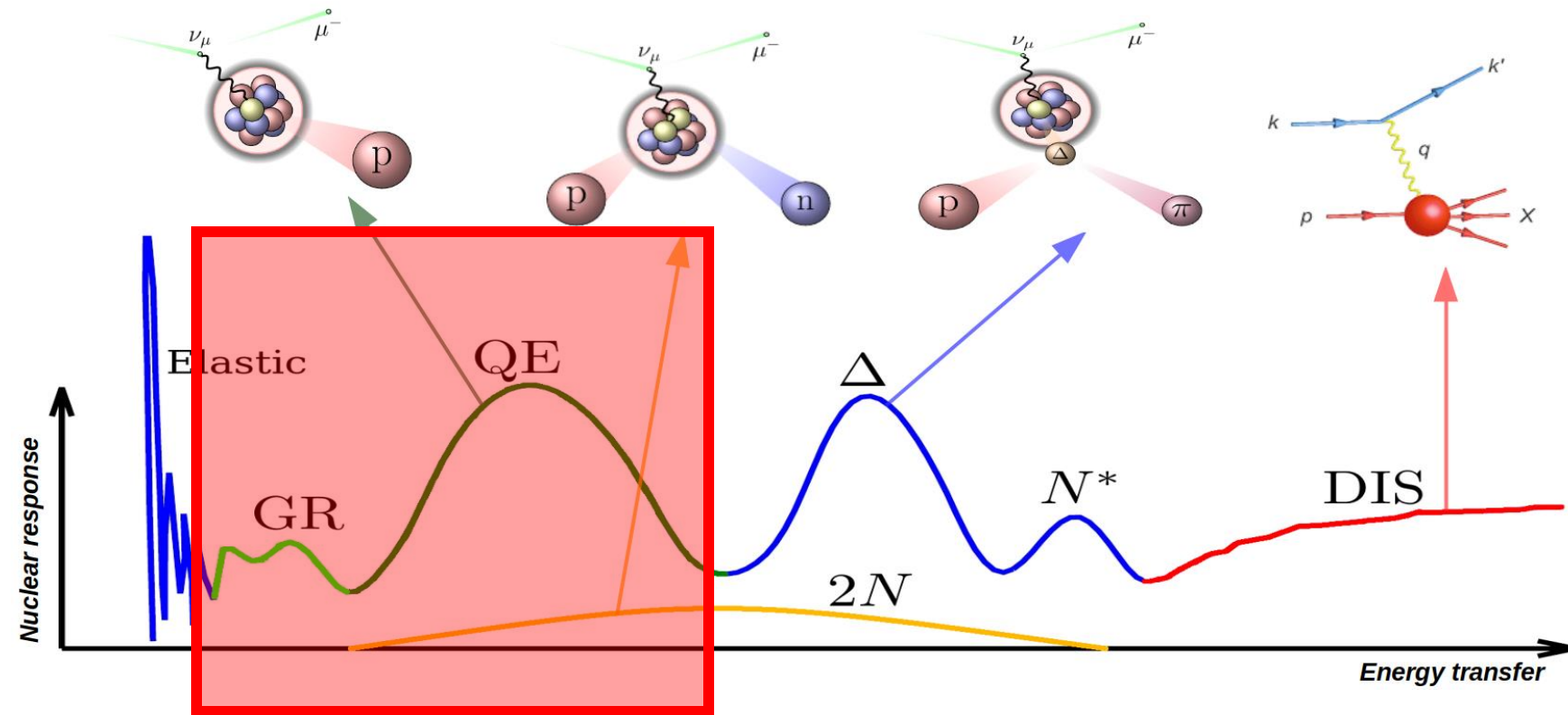
Marco Vanderpoorten, Natalie Jachowicz

# Overview



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ESS  $\nu$ SB+'s energy regime

# Overview

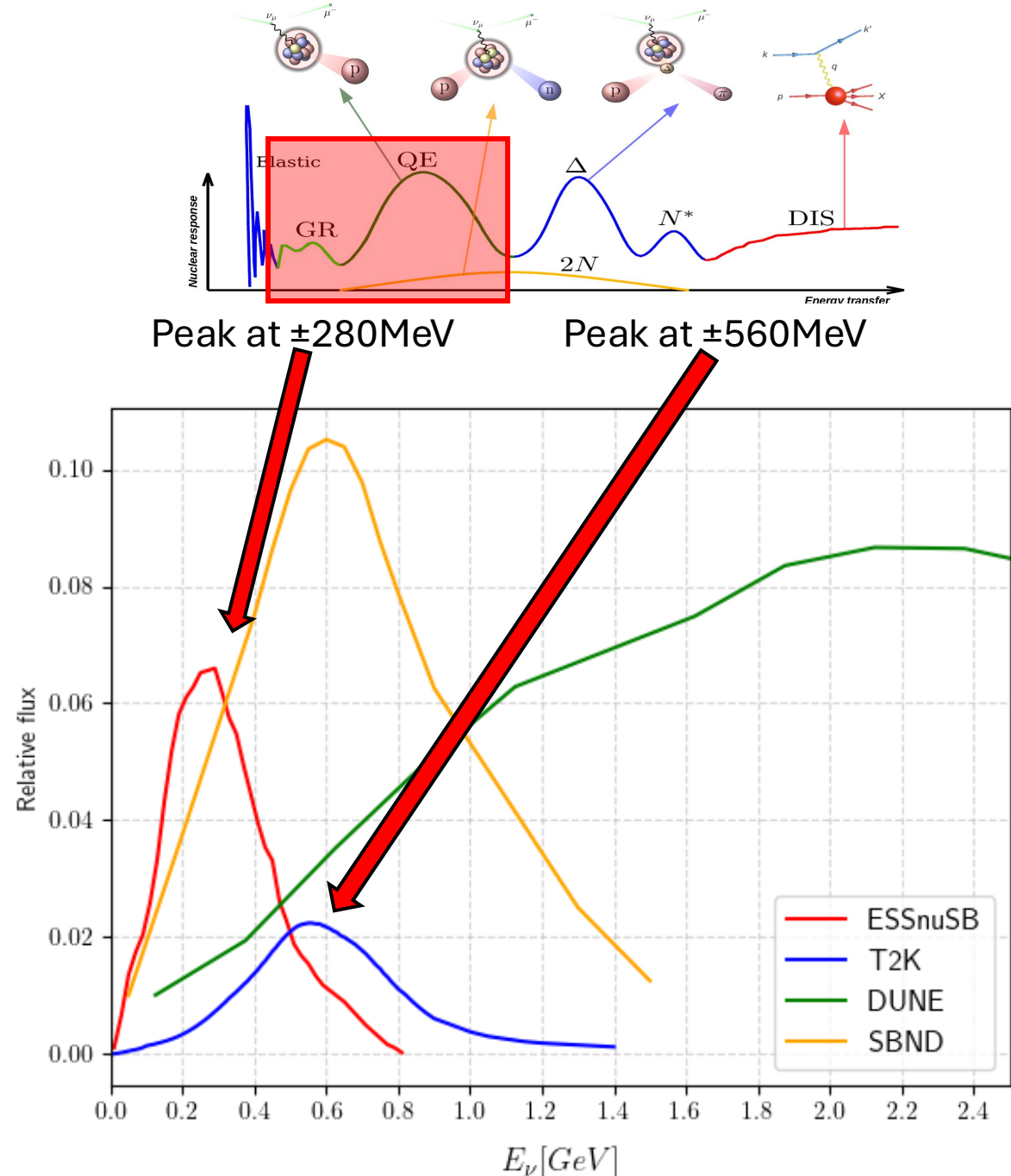
- Flux ESS  $\nu$ SB peaked at low energies
- Flux has a small high-energy tail
- Different interaction mechanisms important
- ESS  $\nu$ SB:
  - Quasi-elastic
  - Giant-resonances
- Precise cross-sections important
  - Estimation amount of events
  - Energy reconstruction
  - Oscillation parameters



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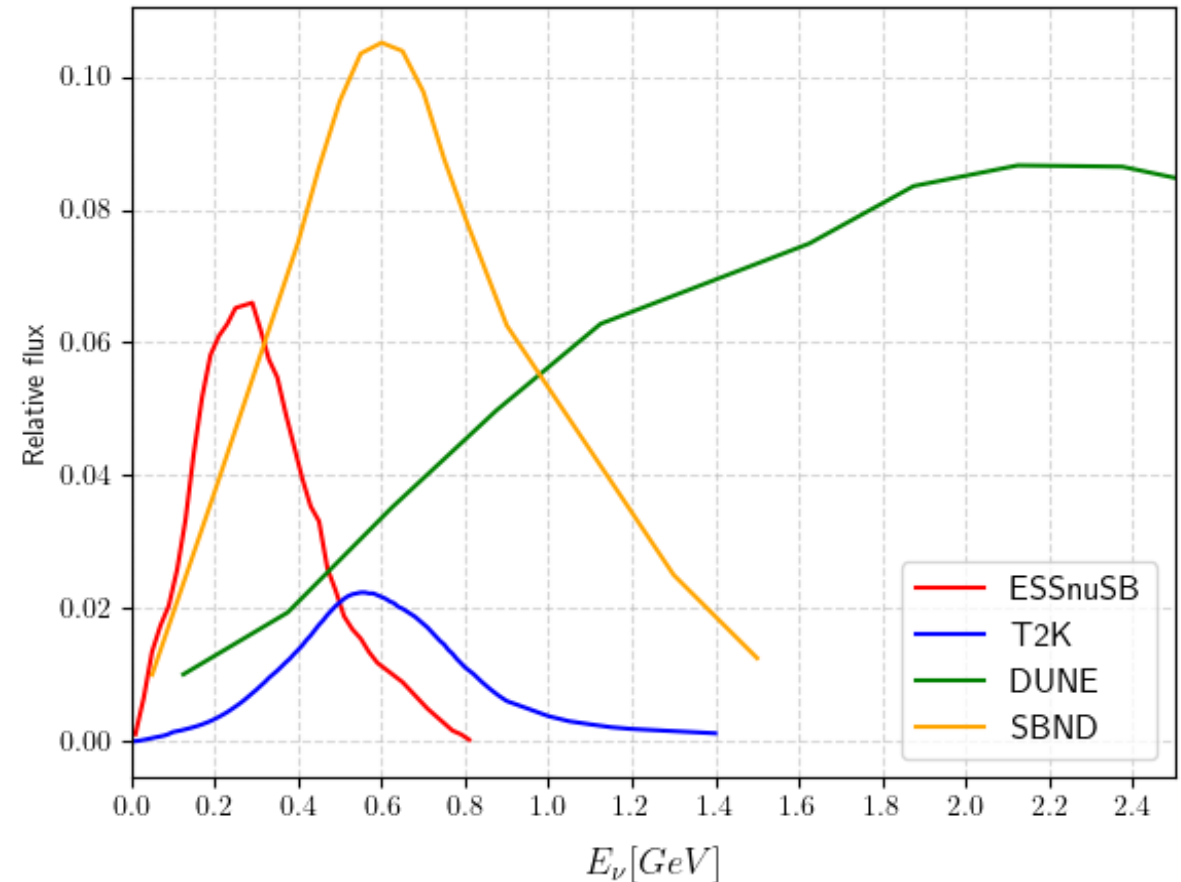
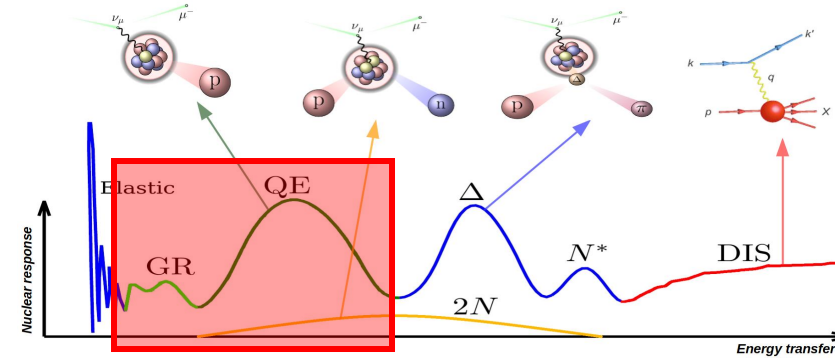


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# Overview

- Majority of current MC event generators are based on a fermi gas, a non-microscopic description of the nucleus
- Majority of current MC event generators don't have a model to calculate the Giant Resonances-region
- A basic description of the nucleus is not sufficient to capture the nuclear effects important in ESS  $\nu$ SB's energy range
- In this work, we compared a detailed microscopic model against event generator predictions by GENIE and NuWro and investigated the impact on the sensitivities of oscillation parameters

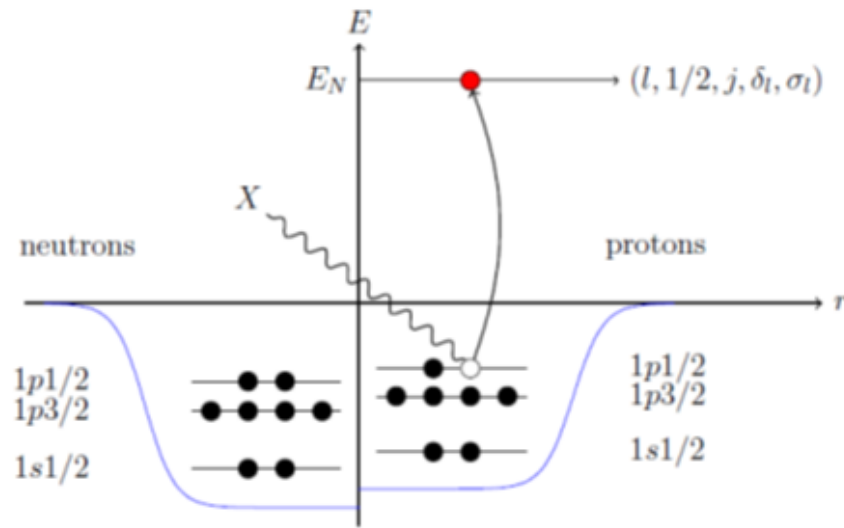


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# Ghent model for the nucleus



- Starting point : mean-field nucleus with Hartree-Fock single-particle wave functions
- Skyrme SkE2 force used to build the potential
- Distortion of the final nucleon
- Pauli blocking
- Single-particle energy shells
- Long-range correlations included in a Continuum Random Phase Approximation (CRPA) approach



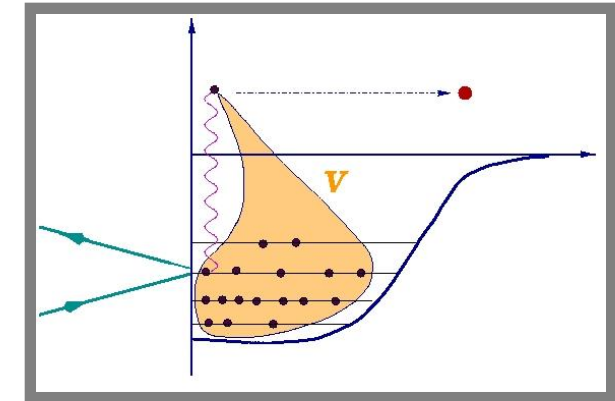
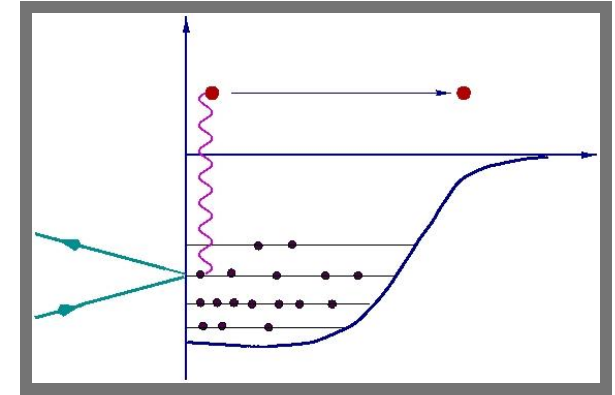
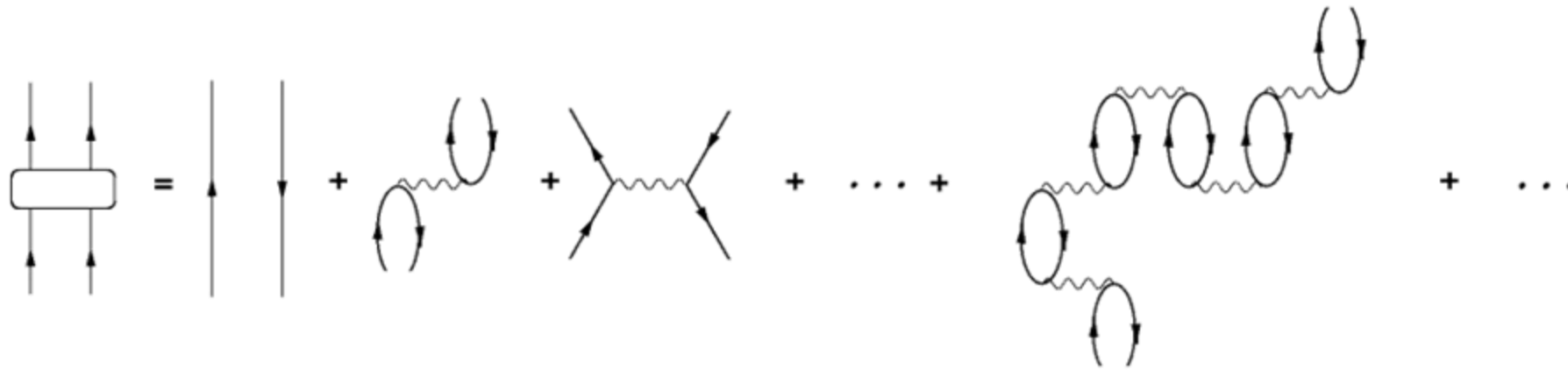
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# Continuum Random Phase Approximation

- Skyrme SkE2 residual interaction
- Green's function approach
- self-consistent calculations



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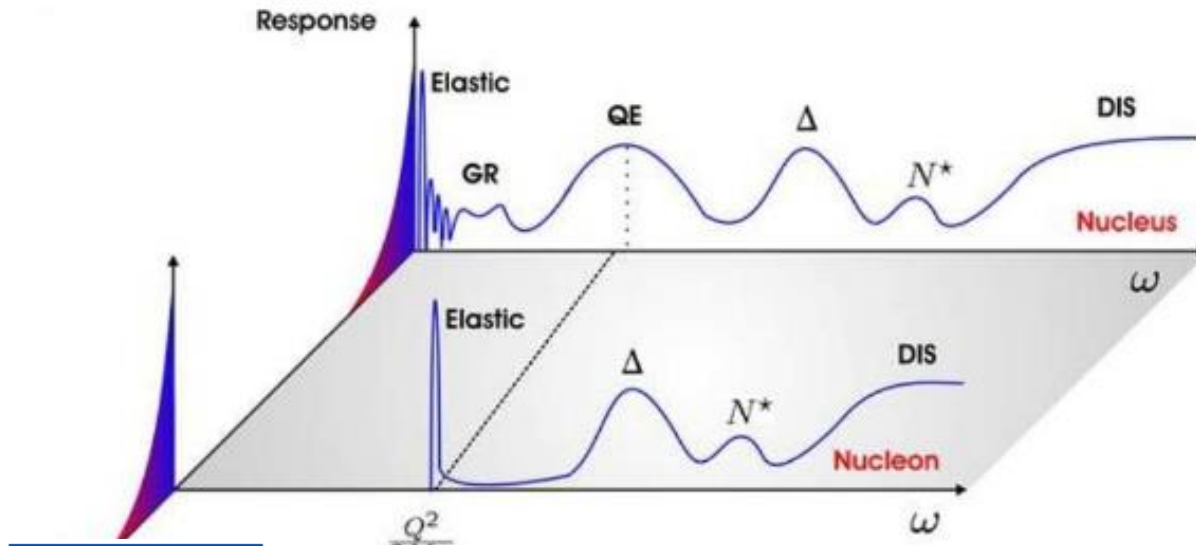


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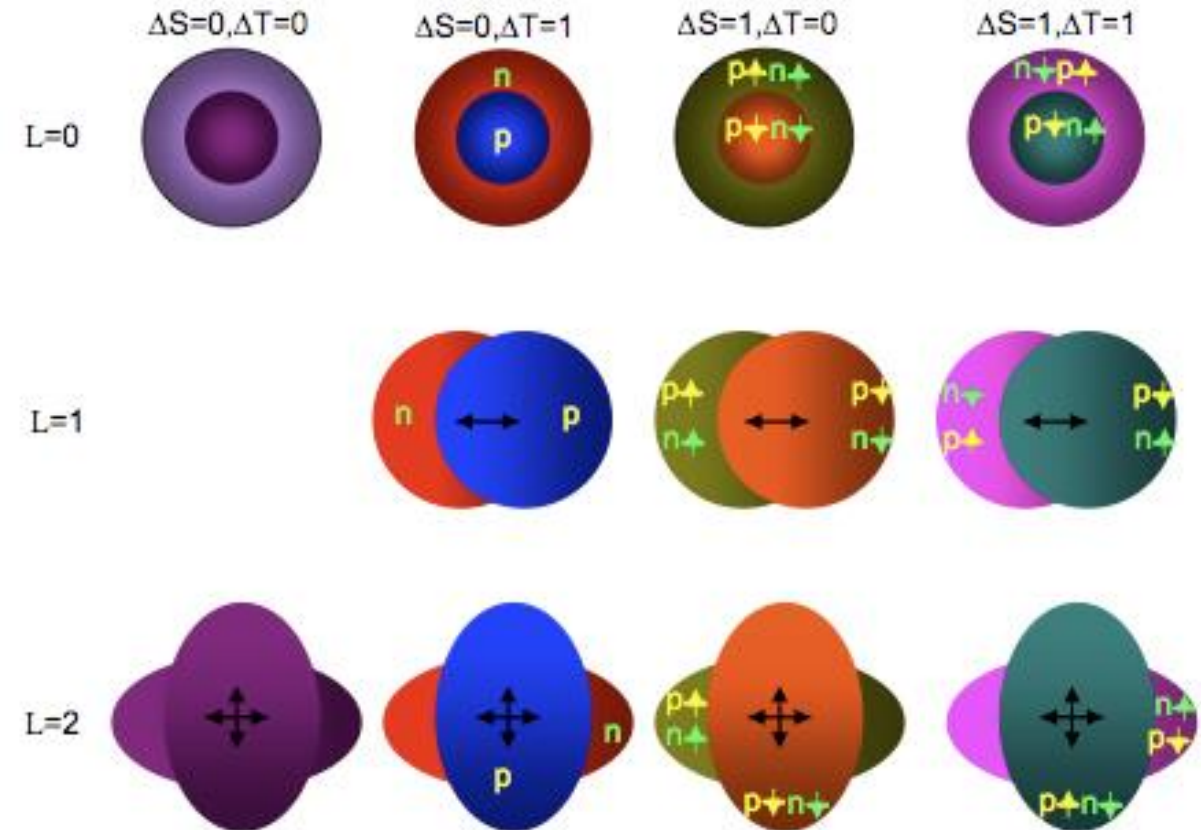
$$|\Psi_{RPA}\rangle = \sum_c \{X_{(\Psi,C)} |ph^{-1}\rangle - Y_{(\Psi,C)} |hp^{-1}\rangle\}$$

# CRPA correlations

- Correlations over the whole size of the nucleus
- Redistribute the incoming energy transfer to the nucleus over all the nuclear constituents.
- They manifest themselves in collective excitations such as giant resonances at  $\sim 10$ s of MeVs excitation energy
- They reduce strength at higher energies

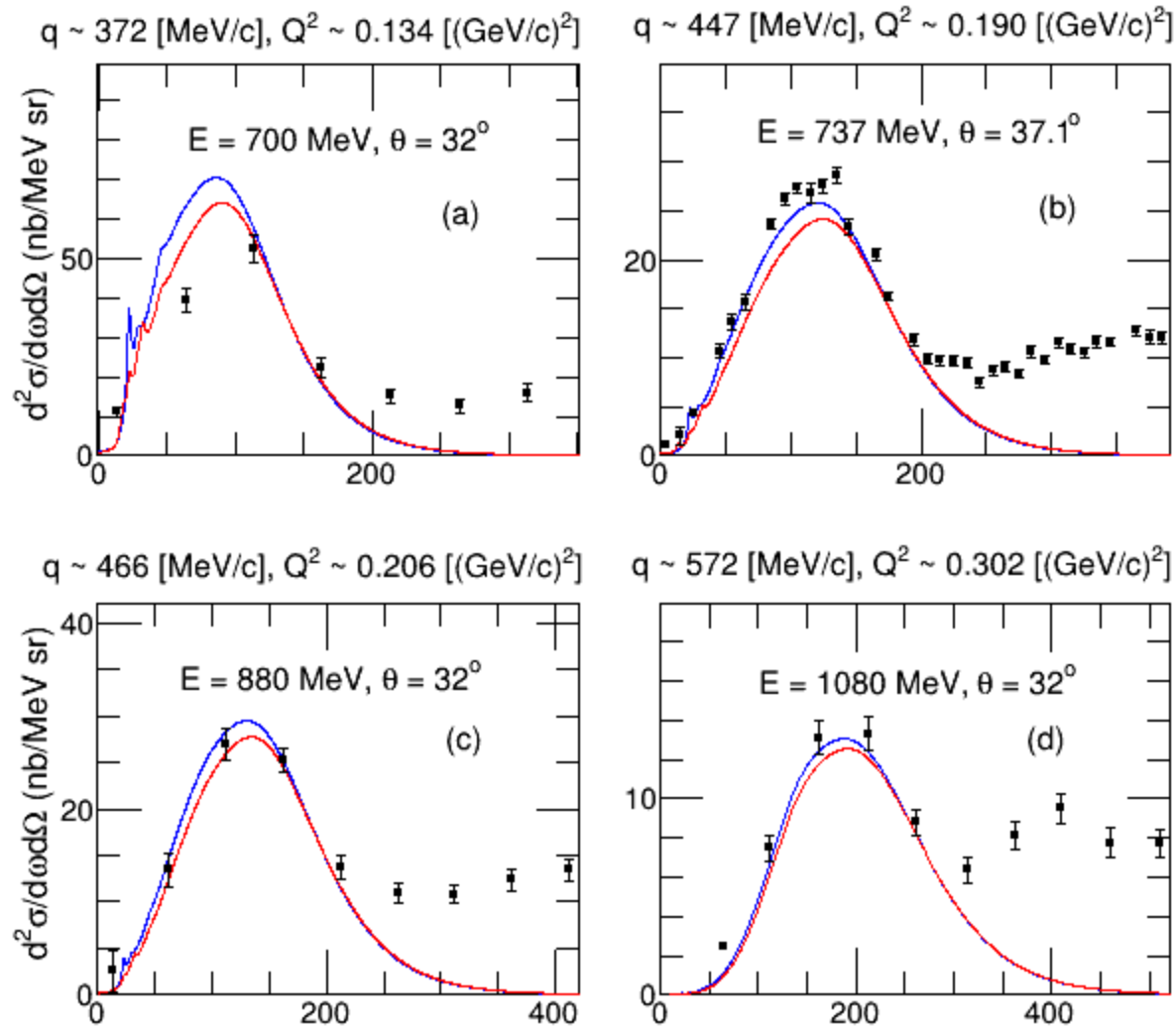


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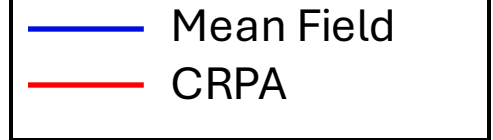


<https://cyclotron.tamu.edu/research/nuclear-structure/>

# Comparison with electron scattering data



$^{16}\text{O}(e, e')$



- Good overall agreement with e-scattering data

Data : P. Barreau et al., [Nucl. Phys. A402, 515](#) (1983), J. S. O'Connell et al., [Phys. Rev. C35, 1063](#) (1987), R. M. Sealock et al., [Phys. Rev. Lett.62, 1350](#) (1989), D. S. Bagdasaryan et al., [YERPHI-1077-40-88](#) (1988), D. B. Day et al., [Phys. Rev. C 48, 1849](#) (1993), D. Zeller, [DESY-F23-73-2](#) (1973).

V. Pandey, NJ, M. Martini, [PRC94, 054609](#) (2016)



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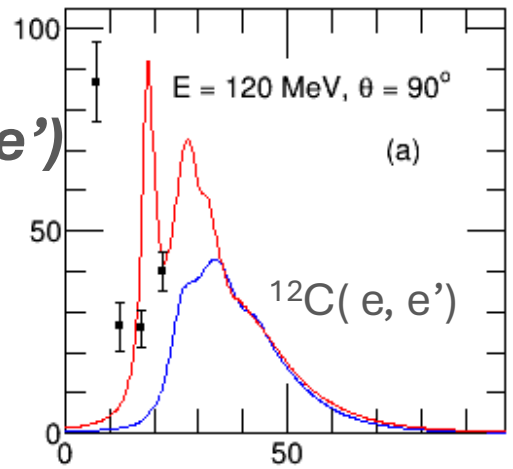
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# Comparison with electron scattering data

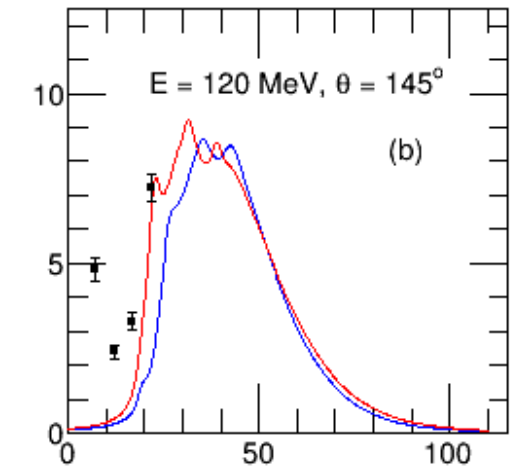
$^{12}\text{C}(e, e')$   
 $d^2\sigma/d\omega d\Omega(\text{nb/MeV sr})$

— Mean Field  
— CRPA

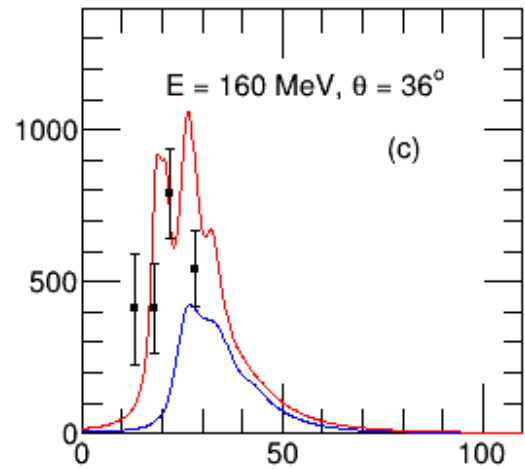
$q \sim 160 \text{ [MeV/c]}, Q^2 \sim 0.026 \text{ [(GeV/c)}^2\text{]}$



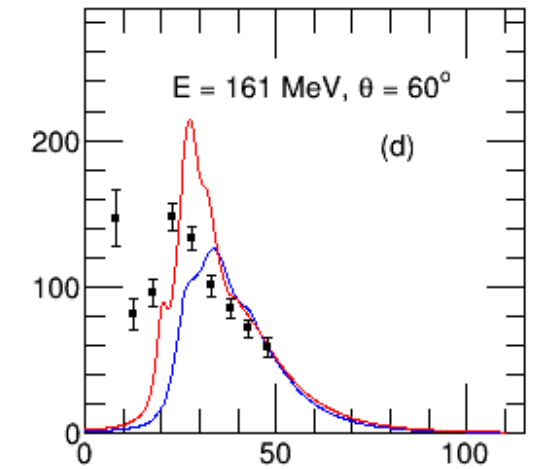
$q \sim 207 \text{ [MeV/c]}, Q^2 \sim 0.042 \text{ [(GeV/c)}^2\text{]}$



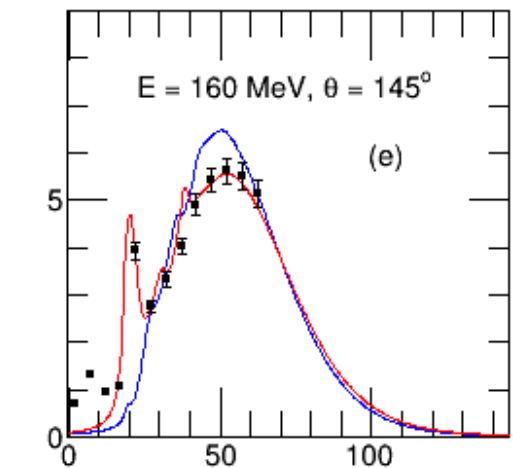
$q \sim 95 \text{ [MeV/c]}, Q^2 \sim 0.009 \text{ [(GeV/c)}^2\text{]}$



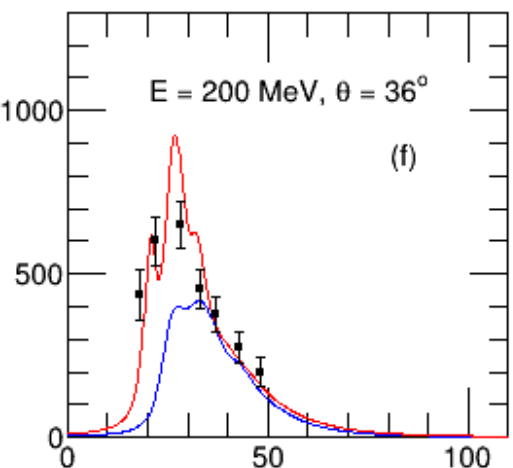
$q \sim 155 \text{ [MeV/c]}, Q^2 \sim 0.024 \text{ [(GeV/c)}^2\text{]}$



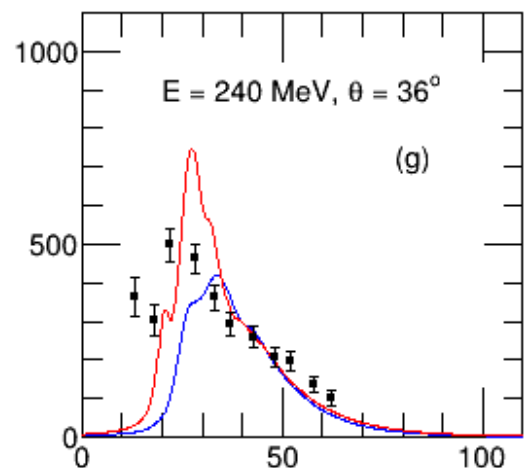
$q \sim 269 \text{ [MeV/c]}, Q^2 \sim 0.071 \text{ [(GeV/c)}^2\text{]}$



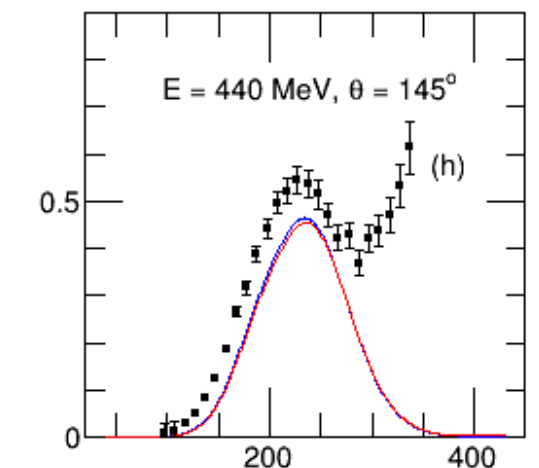
$q \sim 121 \text{ [MeV/c]}, Q^2 \sim 0.015 \text{ [(GeV/c)}^2\text{]}$



$q \sim 145 \text{ [MeV/c]}, Q^2 \sim 0.021 \text{ [(GeV/c)}^2\text{]}$



$q \sim 650 \text{ [MeV/c]}, Q^2 \sim 0.381 \text{ [(GeV/c)}^2\text{]}$



$\omega \text{ (MeV)}$

V. Pandey, N.J., J. Ryckebusch, T. Van Cuyck, M. Martini, [Phys. Rev. C 92, 024606](#) (2015)



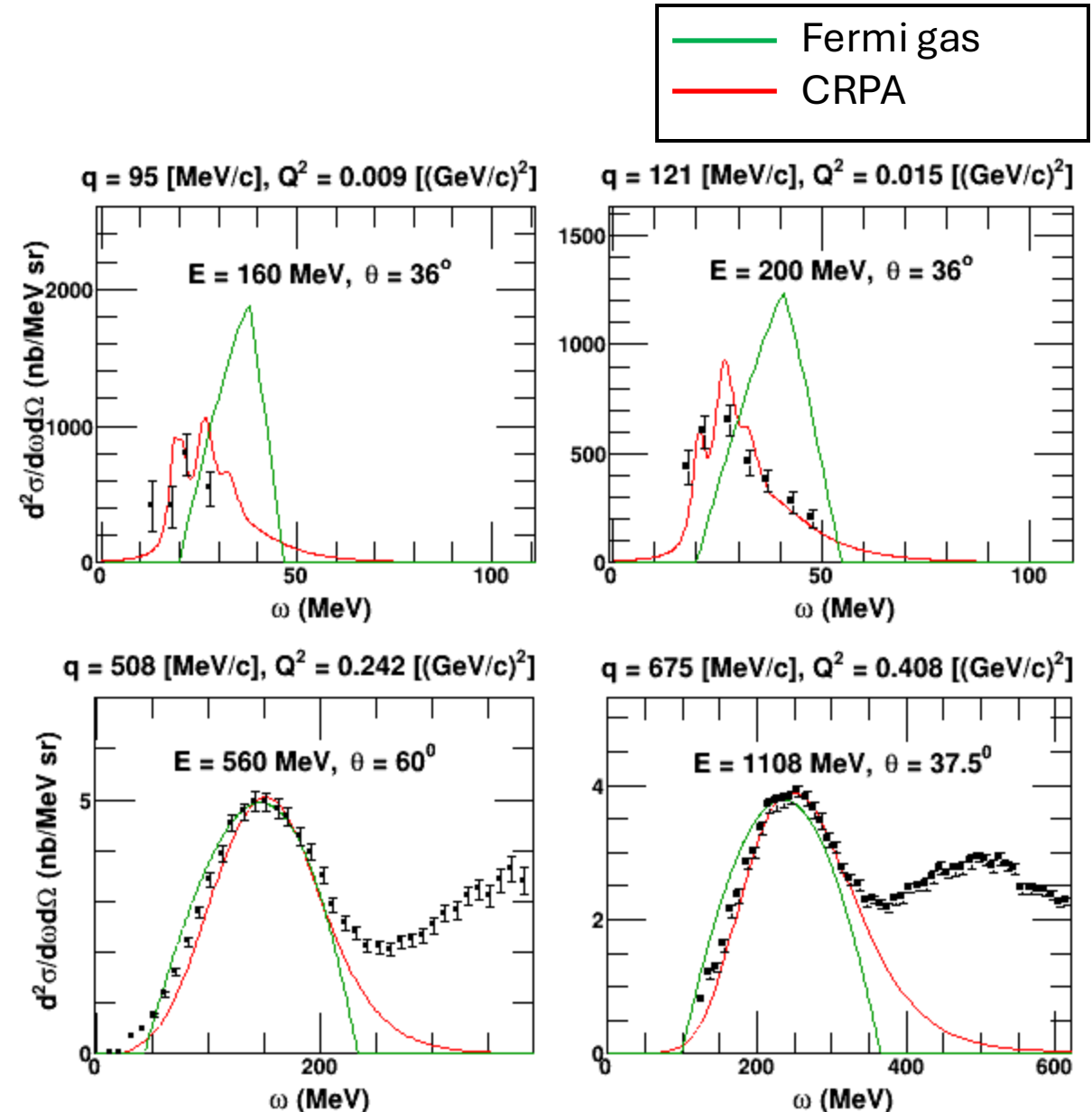
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# Comparison with Fermi gas

- Fermi gas struggles to predict inclusive cross-sections at lower incoming energies
- Most important energy regime for ESS  $\nu$ SB!



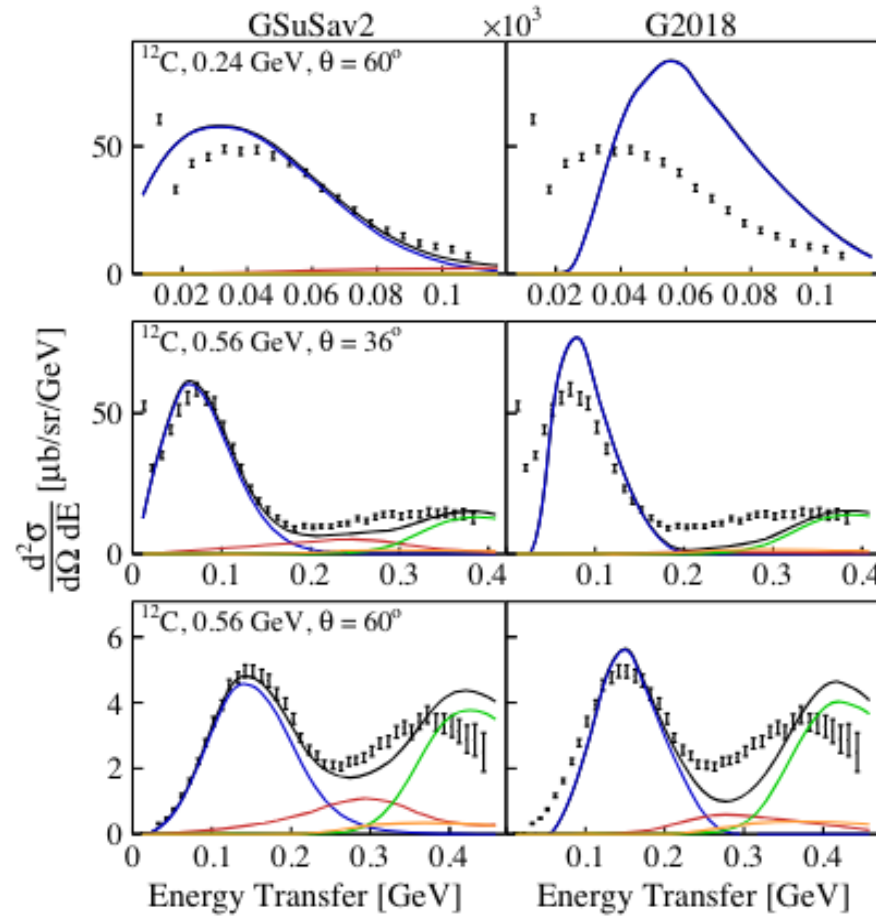
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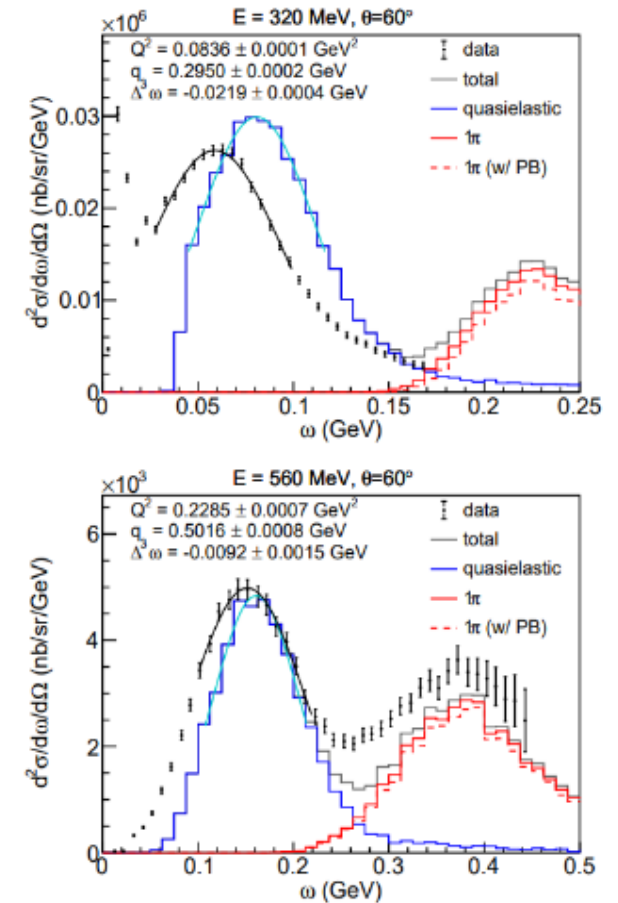
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# What about event generators?

- Event generators, based on FG, show similar problems to predict cross-sections for ESS  $\nu$  SB's energy regime
- Peak too high and shifted to high energies due to lack of description of nuclear effects



GENIE: [Phys. Rev. D \*\*103\*\*, 113003](#)



NEUT: [PhysRevD.111.033006](#)



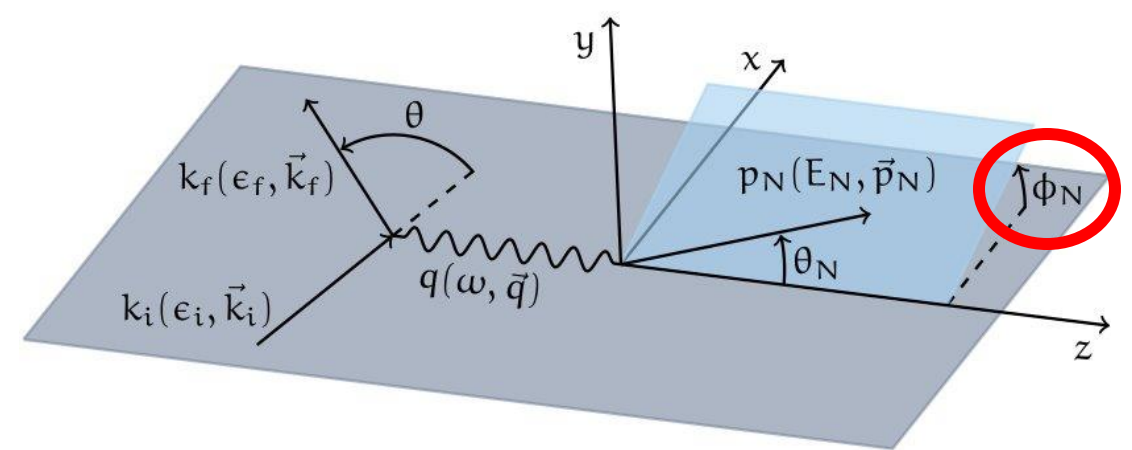
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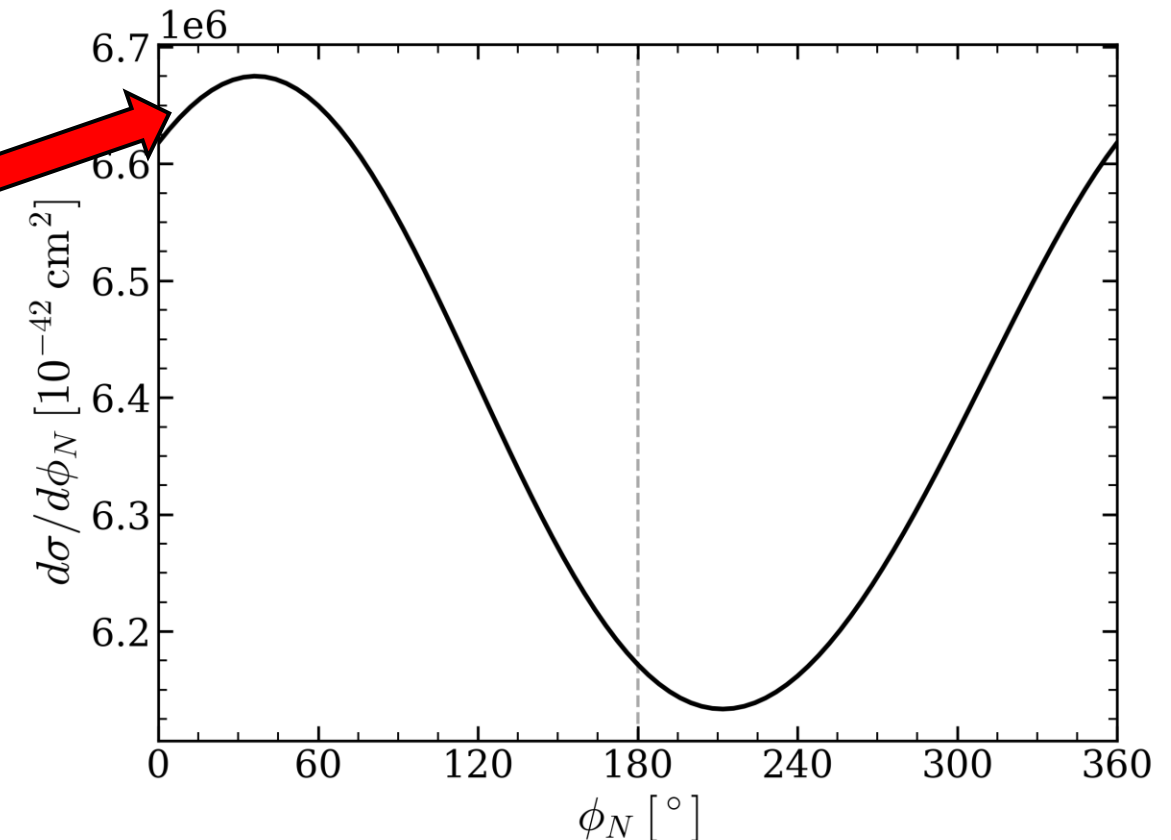
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# Exclusive variables

- Microscopic description necessary to explain azimuthal asymmetry
- Caused by interference nucleon wavefunctions with different phase shifts  
-> Only described in microscopic theories
- Leads to preference of nucleon emittance above lepton plane



For ESS  $\nu$ SB



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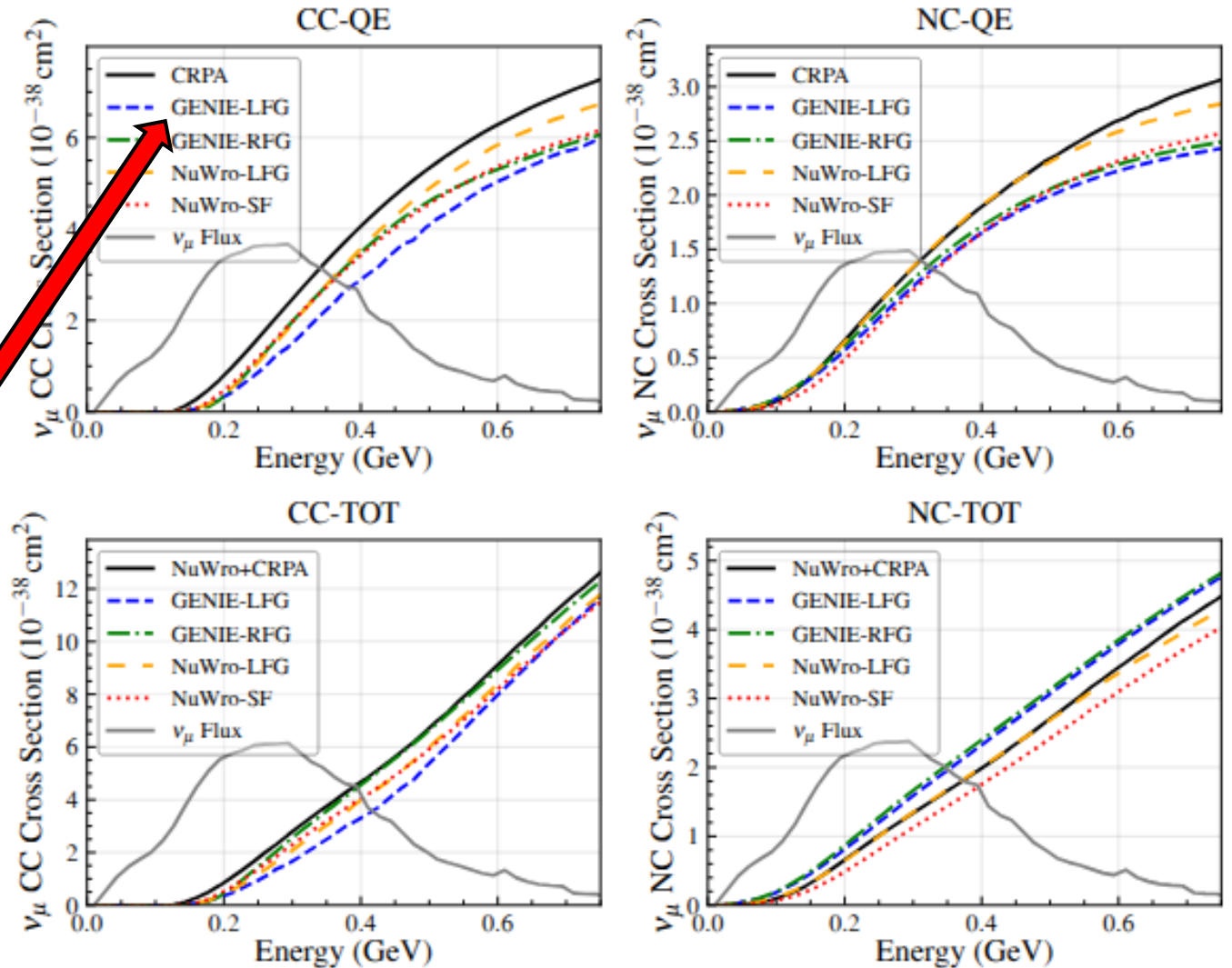


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# Comparison CRPA with Event Generators (CC)

- Event generators fail to describe strength provided by the Giant Resonances region

-> Differences originate from genuine nuclear effects not included in fermi gas!



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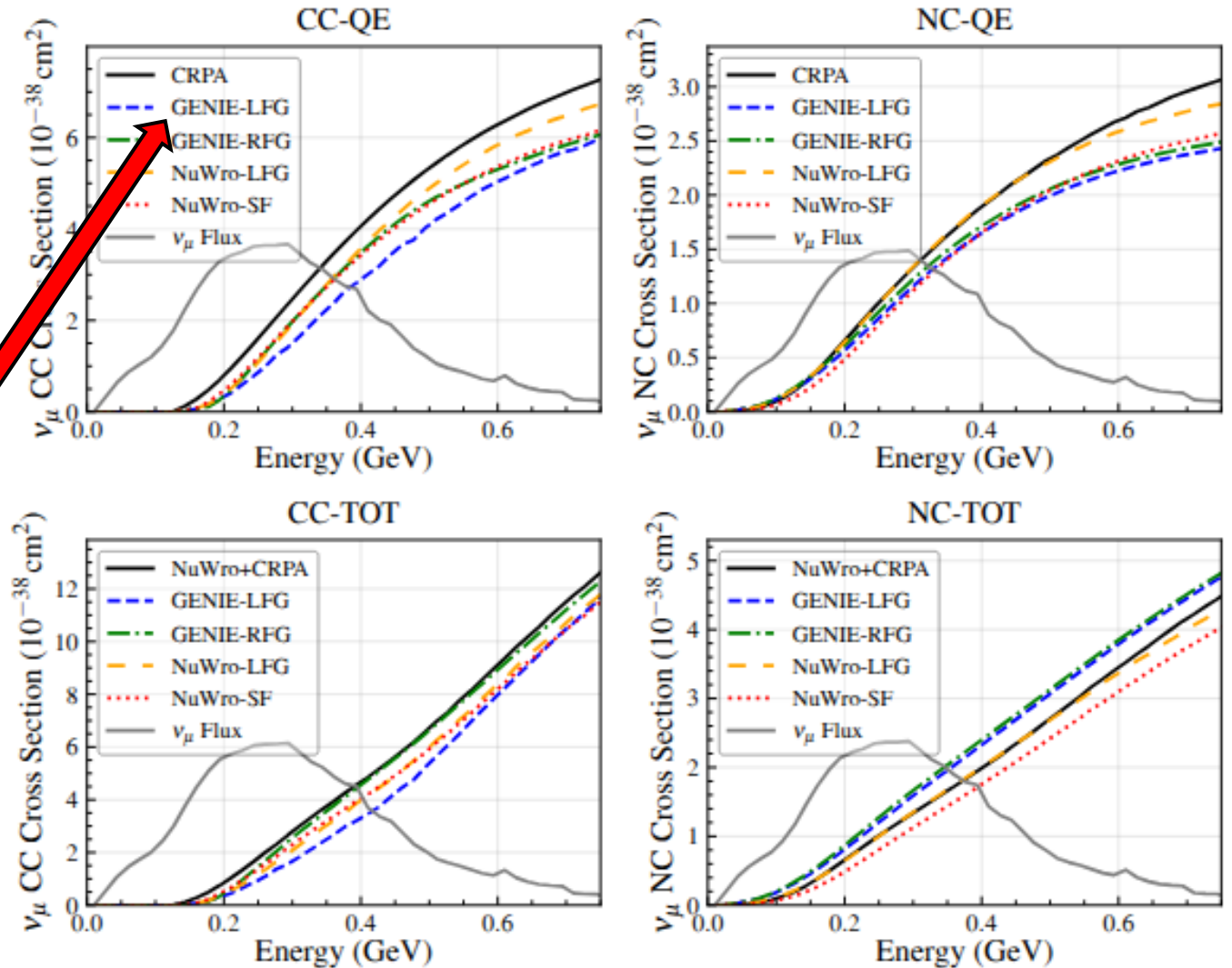
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Tune used in CDR

# Comparison CRPA with Event Generators (NC)

- Non-QE processes from NuWro SF added on top of CRPA
  - GENIE overestimates NC cross-sections, leading to overestimation of background
- > Differences originate from genuine nuclear effects not included in fermi gas!

Tune used in CDR



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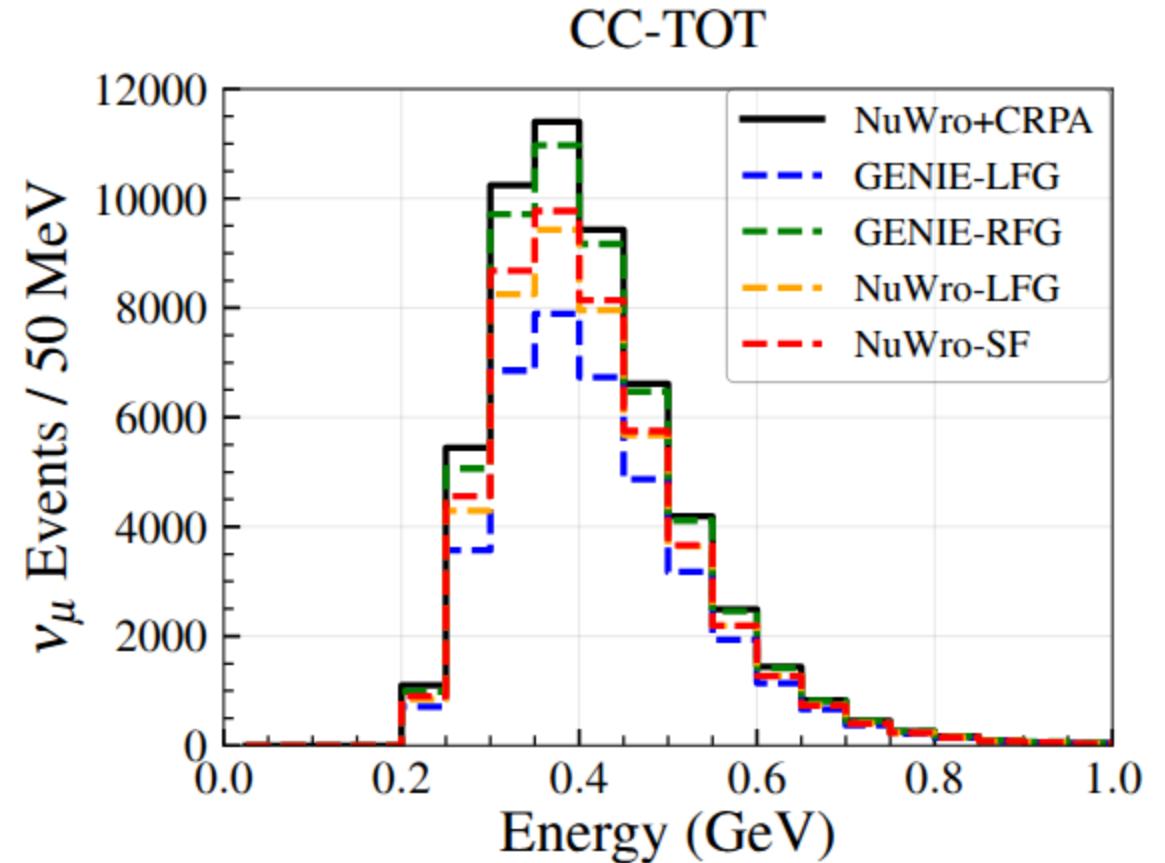


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# Event rate prediction

- Non-QE processes from NuWro SF added on top of CRPA
- 5 year runtime
- Improved description predicts more neutrino events

-> Differences originate from genuine nuclear effects not included in fermi gas!



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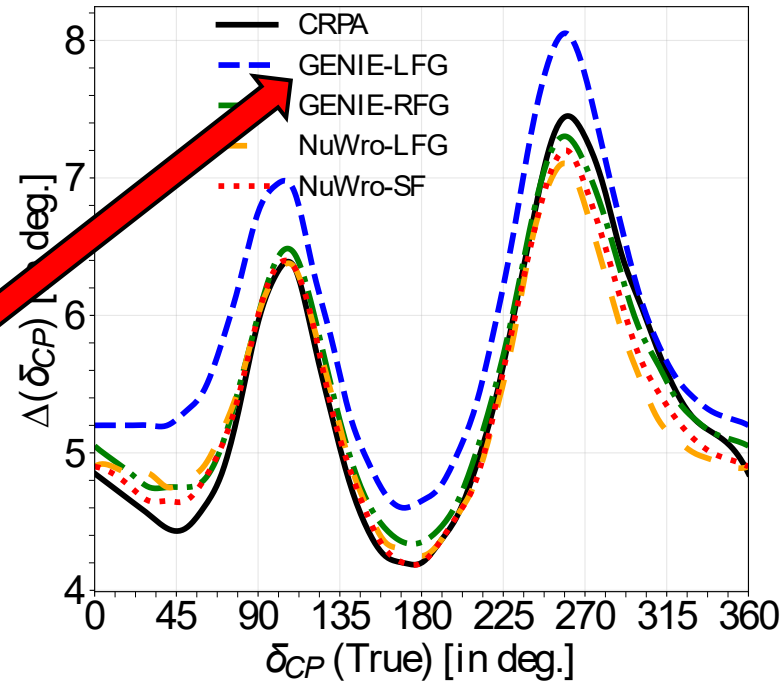
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# Influence on sensitivities ESSvSB

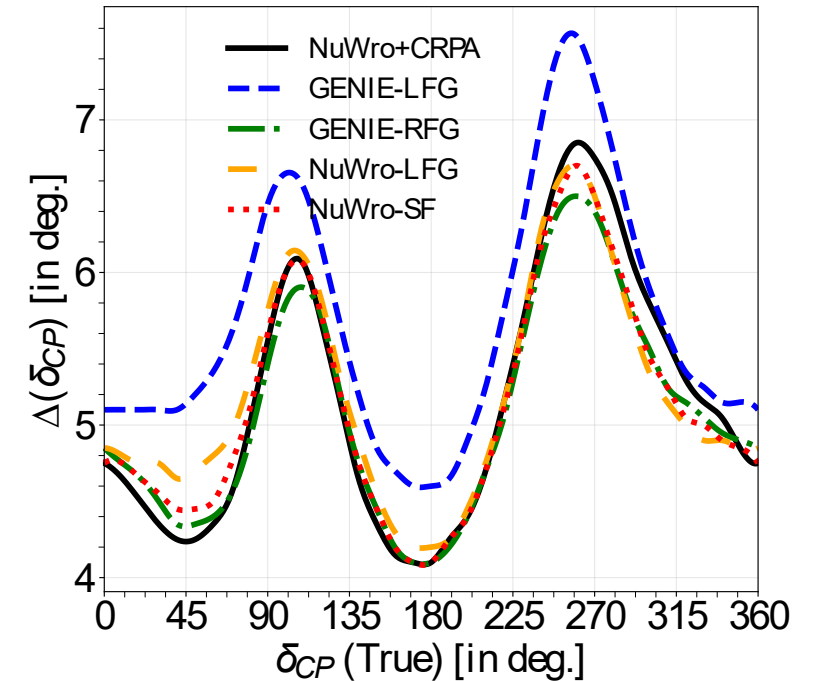
- Overestimation background in GENIE results in reduced sensitivity
- More detailed description improves ESS  $\nu$ SB's sensitivity to  $\delta_{CP}$

Tune used in CDR

CP Precision with : QE



CP Precision with : TOTAL



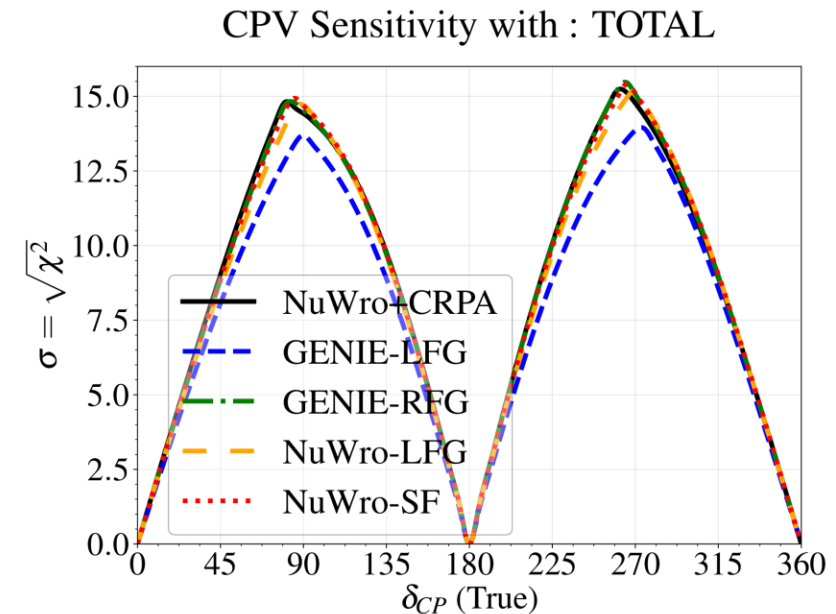
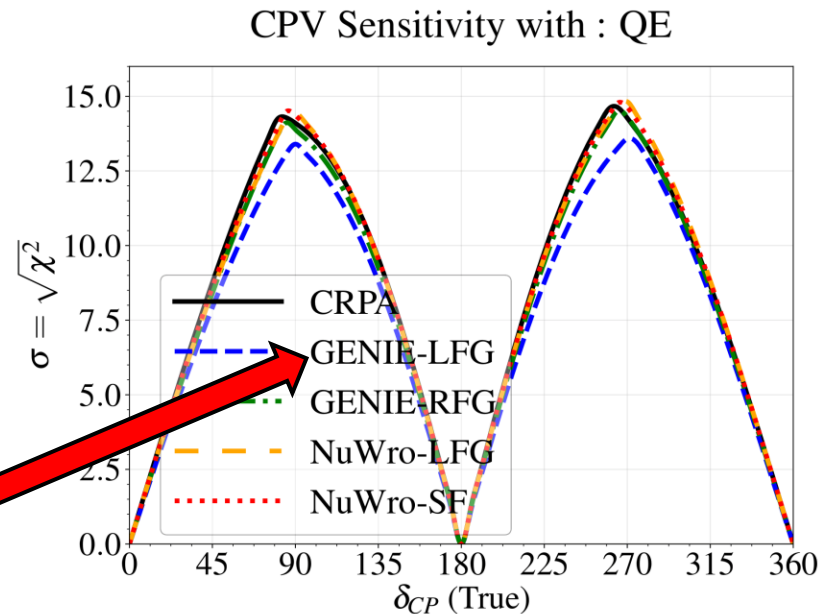
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# Influence on sensitivities ESSvSB

- Background overestimation GENIE results in reduced CPV sensitivity
- More detailed description improves ESSvSB's sensitivity to CPV



Tune used in CDR



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Back-up slides



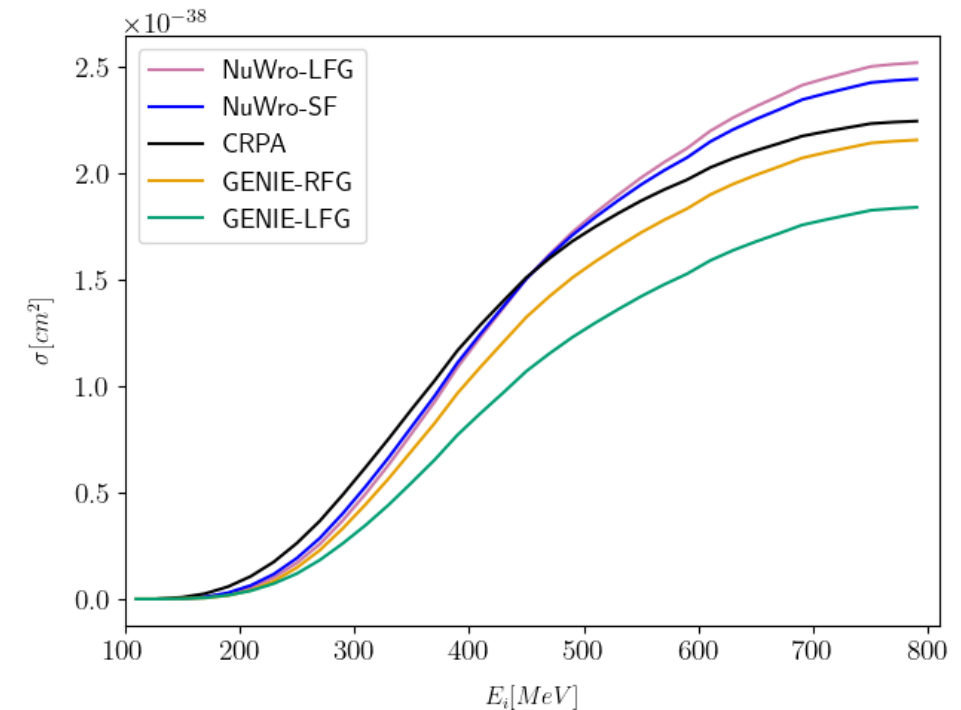
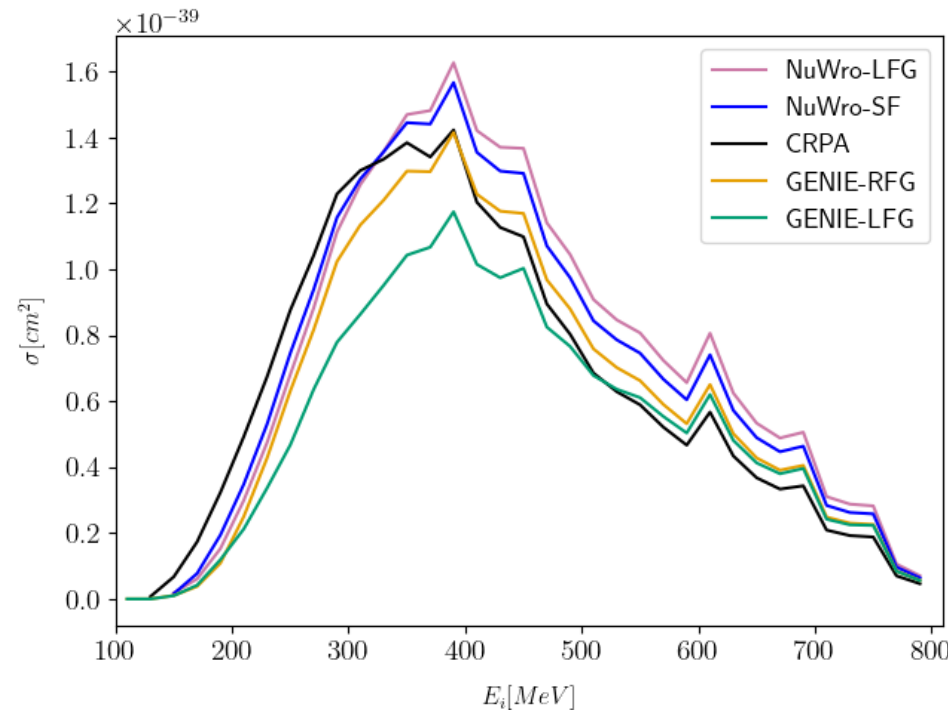
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# Results ESS $\nu$ SB+ at 1km from source

Cumulative distribution:  $\int_0^{E_i} \sigma(E) dE$



- Peak cross-section shifted to lower energies
- Fermi gas/spectral functions misses strength at low energies due to mean-field effects and giant-resonances
- Reduced strength for higher energies due to nuclear correlations

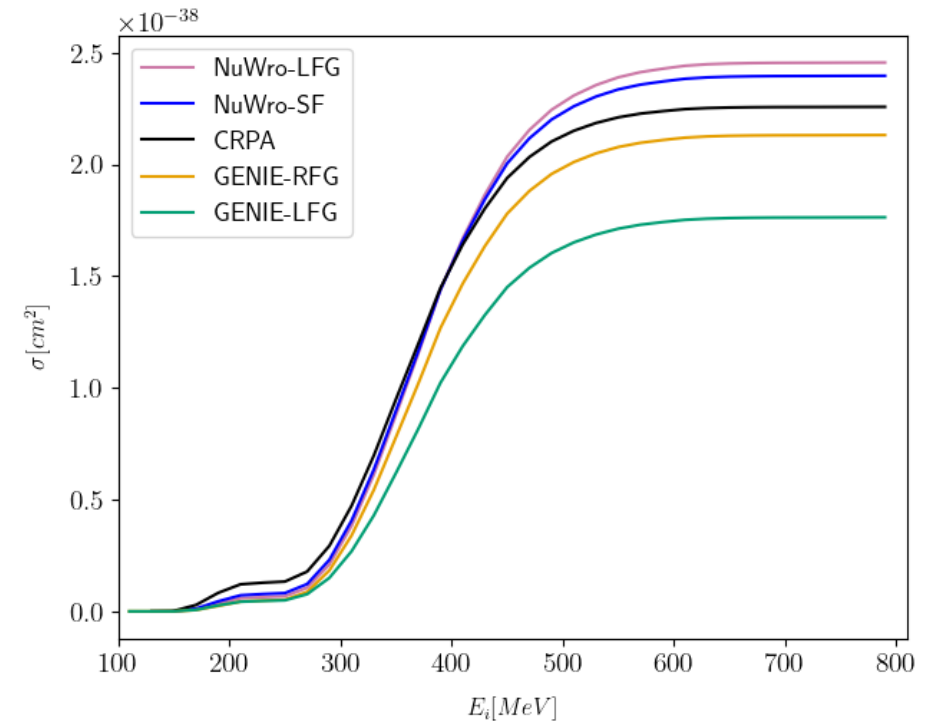
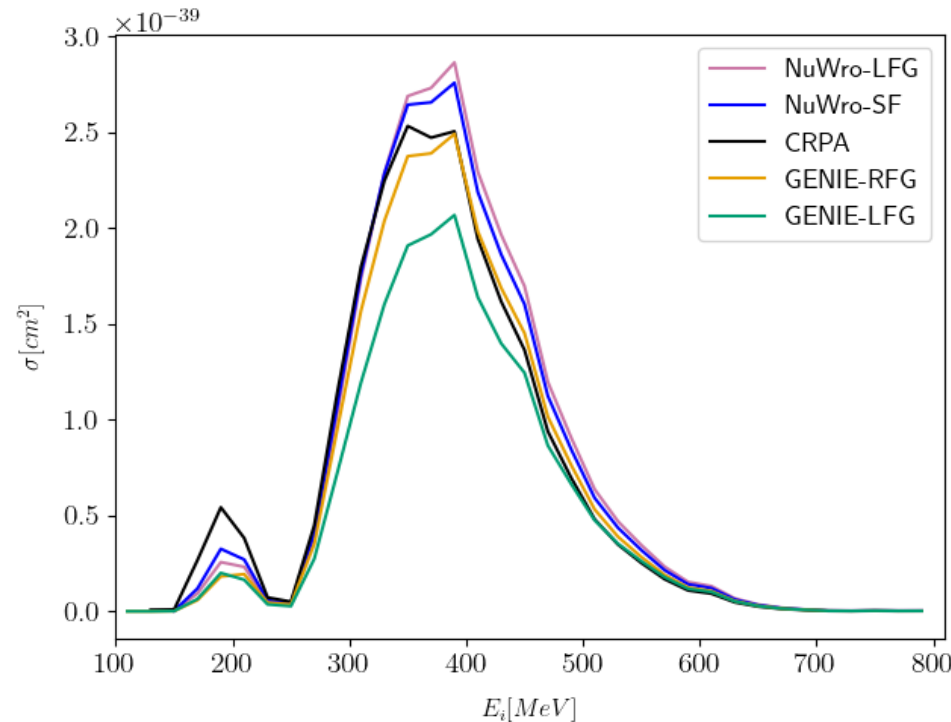


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# Results ESS $\nu$ SB+ at far detector

Cumulative distribution:  $\int_0^{E_i} \sigma(E) dE$



- At Zinkgruvan(360km)
- Fermi gas/spectral functions misses strength at low energies due to mean-field effects and giant-resonances
- Reduced strength for higher energies due to nuclear correlations



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