Test of the GENIE neutrino event generator against reduced cross sections extracted from $^{16}O(e, e'p)$ data

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Importance of neutrino scattering models accuracy

- GENIE - neutrino event generator, employed by all Femilab-based neutrino experiments
- Goal of accelerator-based neutrino experiments - measuring the lepton CP violation phase, determining neutrino mass ordering, and testing the three-flavor paradigm
- To evaluate the oscillation parameters, the probabilities of neutrino oscillations as functions of neutrino energy are measured
- The accuracy to which neutrino oscillation parameters can be extracted depends on the ability of experiments to determine the individual energy of detected neutrino
- The neutrino beams are not monoenergetic - broad distributions from tens of MeVs to a few GeVs

- At the GeV-scale neutrino interacts with a nucleus through a wide range of reaction channels: the charged-current (CC) quasielastic (QE) scattering, two-body meson exchange current (MEC) channels, resonance production and deep inelastic scattering
- The incident neutrino energy is reconstructed using kinematic or calorimetric methods. At energy about 1 GeV, where the CCQE scattering is dominant, the incoming neutrino energy can be derived from lepton kinematics alone
- Calorimetric method: $\varepsilon_\nu = \varepsilon_l + \varepsilon_h$, where ε_ν, ε_l, and ε_h are neutrino, leptonic, and hadronic energies, respectively. All visible energy in detector not associated with lepton are measured. A model dependent fit $\varepsilon_h = f(E_{vis})$ obtained from simulation is used to relate the visible energy E_{vis} to the estimated total hadronic energy ε_h.
- Calorimetric method relies on the models of the neutrino-nucleus interactions that are implemented in neutrino event generators
- Uncertanties in these models come from nuclear medium effects such as the nuclear ground state and interaction of the outgoing nucleon with the residual nucleus

- Electron and neutrino interactions are different at the primary vertex, but nuclear medium effects such as the nuclear ground state and interaction of the outgoing nucleon with the residual nucleus are largely the same
- Electron and neutrino scattering are strongly linked in theory, any model of neutrino interactions (vector+axial) should also be able to reproduce electron (vector) interactions
- Electron scattering data has precise kinematics and large statistics, incident electron energy is known
- Use electron scattering data to test the neutrino energy reconstruction methods and interaction models

- Reduced cross section: $\sigma_{red} = \frac{d^5\sigma^{(el)(cc)}}{d\varepsilon_f d\Omega_f d\Omega_x} / K^{(el)(cc)} \sigma_{lN}^{(el)(cc)}$,

  $\frac{d^5\sigma^{(el)(cc)}}{d\varepsilon_f d\Omega_f d\Omega_x} = \frac{N_{1\mu 1p}}{N_{tot}} \frac{\sigma_{tot}(\varepsilon_\nu)}{\Delta\varepsilon_f \Delta\Omega_f \Delta\Omega_x}$ - differential cross-section,

  $K^{(el)(cc)}$ are phase-space factors for electron and neutrino scattering and $\sigma_{lN}^{(el)(cc)}$ are elementary cross sections for the electron and neutrino scattering on the moving free nucleon

- Reduced cross section is irrespective of the type of interaction (electromagnetic or weak)

- Reduced cross section determined mainly: by the intrinsic properties of the target, the ejected nucleon interaction with residual nucleus

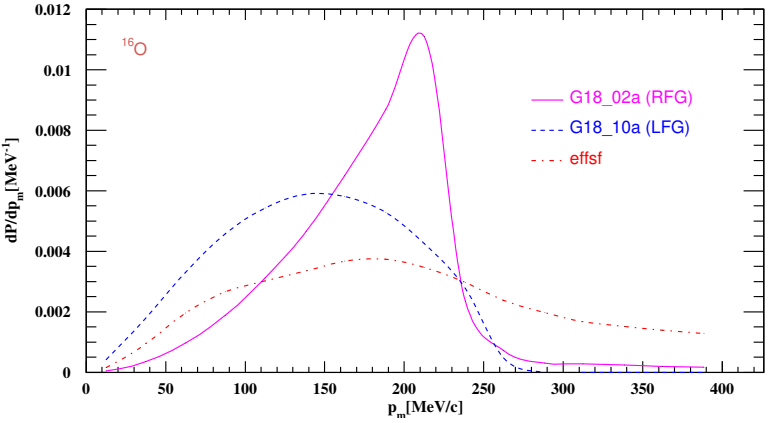
- G18_02a - relativistic Fermi gas model (RFG), uses Llewellyn-Smith model for CCQE, incorporates short-range NN-correlations and Pauli blocking
- G18_10a - full Valencia model for the local Fermi gas (LFG), uses long-range (RPA) and short-range NN correlations
- The G21_11 - superscaling model SuSAv2, uses phenomenological superscaling function
- EffectiveSF - the effective spectral function (effsf) model with or without transverse enhancement contribution

- Generate 10^8 CCQE neutrino interactions on oxygen target for each 4 Genie models
- Select one muon and only one proton in the final state
- Select events to match electron scattering experiments kinematics

data set	ε_i (MeV)	ε_f (MeV)	θ_e (deg)	T_p (MeV)	θ_p (deg)
Saclay	500	372	59	102	35 - 88
IKHEF	304 - 521	188 - 406	29 - 81	89 - 99	36 - 49

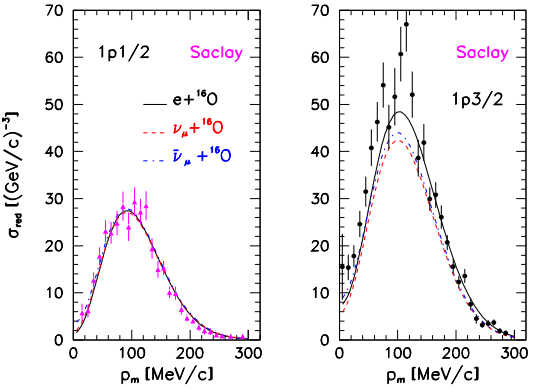
ε_i - beam energy
ε_f - central electron energy
θ_e - central electron angle
T_p - central proton kinetic en.
θ_p - central proton angle

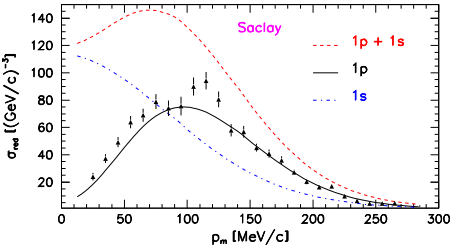
Saclay - M. Bernheim et al., Nucl. Phys. A 375, 461 (1976); IKHEF - C. De Vries et al., Nucl. Instrum. Meth. A 223, 1 (1984); M. Leuschner et al., Phys. Rev. C 49, 955 (1994)

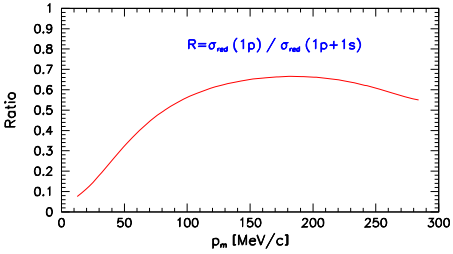


The bound nucleon momentum distribution in oxygen for the genuine CCQE events produced using GENIE and RFG, LFG and effsf representations of the target nucleus

- $\sigma_{red}^{MC}(1p) = R_{1p} \cdot \sigma_{red}^{MC}(1p+1s)$ - contribution of the 1p shell to the reduced cross section calculated with the GENIE models







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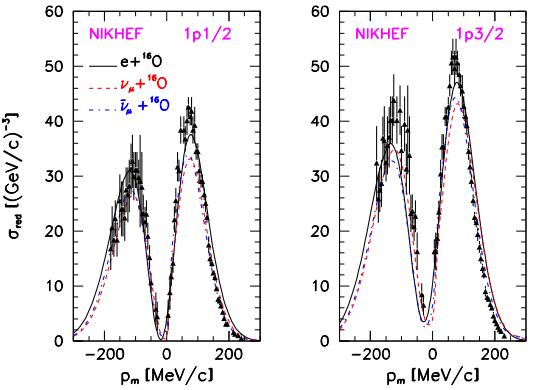
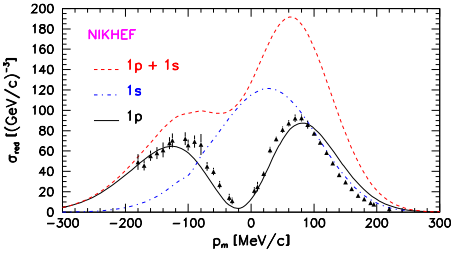
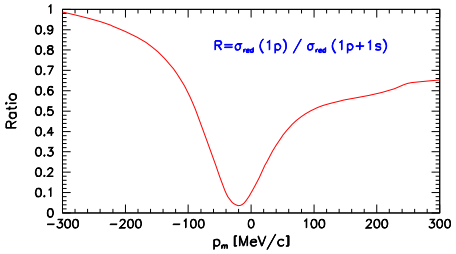
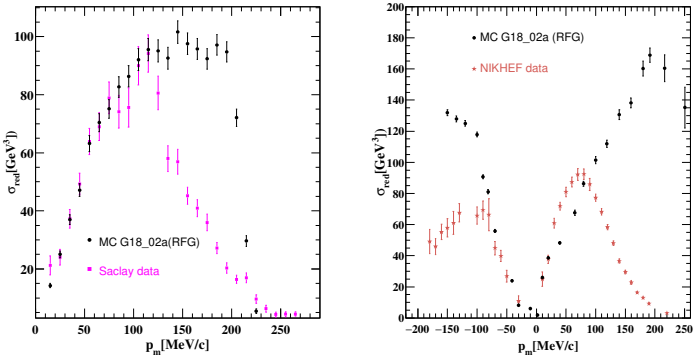






Comparison of Reduced cross sections



GENIE G18_02a (RFG model) and data as function of missing momentum

A.V. Butkevich, S.V. Luchuk, Phys.Rev.D 113 (2026) 5, 053006

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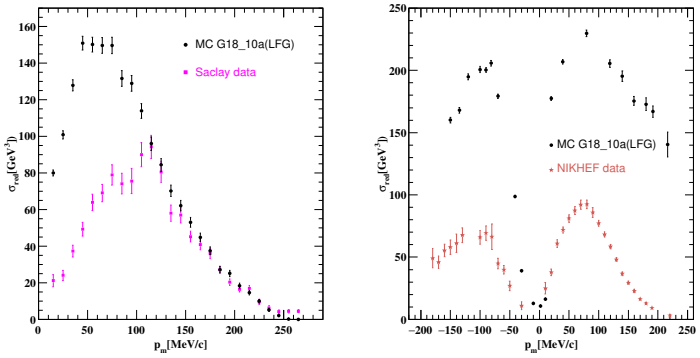
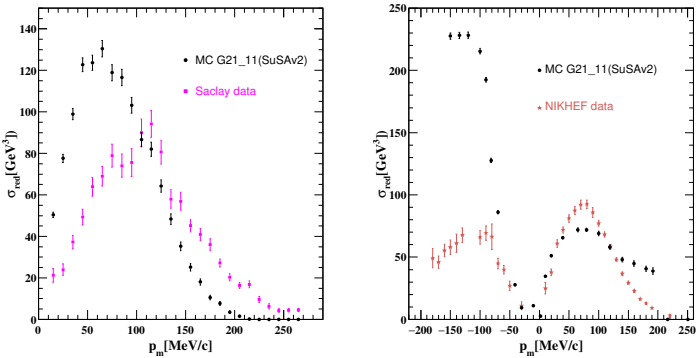


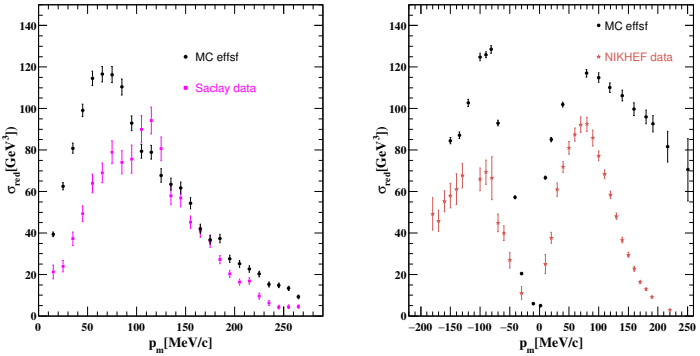
GENIE G18_10a (LFG model) and data as function of missing momentum

Comparison of Reduced cross sections



GENIE G21_11 (SuSAv2 model) and data as function of missing momentum

Comparison of Reduced cross sections



GENIE EffectiveSF model and data as function of missing momentum

Conclusion

- Reduced cross sections measured in QE electron-scattering experiments - the new effective tool for testing neutrino event generators, because electron-experiments features precisely known electron and proton kinematics
- We carried out a comparison of the CCQE reduced cross sections for the removal of protons from 1p shells calculated with models employed in the GENIE simulation framework with the data measured in electron scattering off oxygen target
- We observed persistent disagreements between the GENIE predictions and electron scattering data for reduced cross sections:
  At NIKHEF parallel kinematics GENIE models demonstrates absolutely different behavior than the measured ones
  At Saclay perpendicular kinematics below $p_m \approx 100$ MeV/c GENIE models G18_10a, G21_11 and EffectiveSF overestimates data
- RDWIA model describes the semiexclusive lepton scattering reactions better than the phenomenological models employed in the GENIE generator