Realistic spectral function model for charged-current quasielastic-like (anti)neutrino scattering cross sections on <sup>12</sup>C

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## Theoretical scheme

In this work [1] we present a detailed study of charged current quasielastic neutrino and antineutrino scattering cross sections on a  $^{12}\mathrm{C}$  target with no pions in the final state.

The initial nucleus is described by means of a realistic spectral function  $S(p, \mathcal{E})$  [2]:

$$S(p, \mathcal{E}) = \sum_{i} 2(2j_i + 1)n_i(p)L_{\Gamma_i}(\mathcal{E} - \mathcal{E}_i)$$

in which nucleon-nucleon (*NN*) correlations are implemented in  $n_i(p)$  by using natural orbitals [3] through the Jastrow method [4].

[1] M.V. Ivanov et al., Phys. Rev. C 99, 014610 (2019); arXiv:1812.09435 [nucl-th].

- M.V. Ivanov et al., Phys. Rev. C 89, 014607 (2014); Phys. Rev. C 91, 034607 (2015); A.N. Antonov et al., Phys. Rev. C 83, 045504 (2011).
- [3] P.-O. Löwdin, Phys. Rev. 97, 1474 (1955).
- [4] M.V. Stoitsov et al., Phys. Rev. C 48, 74 (1993).

# Theoretical scheme



Figure: The <sup>12</sup>C realistic  $S(p, \mathcal{E})$  using natural orbitals single-particle  $n_i(p)$  from the Jastrow correlation method and Lorentzian function for the energy dependence. Two shells 1*p* and 1*s* are clearly visible.

The model also includes the contribution of the weak two-body currents in the 2p-2h sector, evaluated within a fully relativistic Fermi gas [1]. The theoretical predictions are compared with a large set of experimental data measured by the MiniBooNE [2], MINER $\nu$ A [3] and T2K [4] experiments.

Good agreement with the experimental data is found.

- I. Ruiz Šimo et al., Phys. Rev. D 90, 033012 (2014); J. Phys. G 44, 065105 (2017); Phys. Rev. C 94, 054610 (2016).
- [2] A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), Phys. Rev. D 81, 092005 (2010); Phys. Rev. D 88, 032001 (2013).
- [3] C. Patrick, "Measurement of the Antineutrino Double-Differential Charged-Current Quasi-Elastic Scattering Cross Section at MINERvA", Ph.D. thesis, Northwestern University 2016.
  - [4] K. Abe et al. (T2K Collaboration), Phys. Rev. D 93, 112012 (2016).



# Neutrino scattering



Figure: Flux-integrated double-differential cross section  $\nu_{\mu} + {}^{12}\text{C}$  versus muon kinetic energy  $\hat{T}_{\mu}$  for various bins of  $\cos \theta_{\mu}$ ; data (Aguilar-Arevalo *et al.*, MiniBooNE, 2010).

# Neutrino scattering



Figure: Flux-integrated double-differential cross section  $\nu_{\mu}$ +<sup>12</sup>C versus muon momentum  $p_{\mu}$  for various bins of  $\cos \theta_{\mu}$ ; data (T2K Collaboration, 2016).



## Poster

### Realistic spectral function model for charged-current quasielastic-like (anti)neutrino cross sections on 12C



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> where  $L_{L_{1}}(L - L) = \frac{1}{2} \frac{\Gamma_{1}/2}{(L - L)^{2} + (L - L)^{2}}$ .  $\Gamma_{1,0} = 6$  MeV, Γ<sub>1a</sub> = 20 MeV are fixed to the experimental widths.

> The single-particle (L.p.) momentum distributions

or to natural orbitals (NO) wave functions. The latter are

 $\rho(\mathbf{r}, \mathbf{r}') = \sum_{\alpha} N_{\alpha} \varphi^{*}_{\alpha}(\mathbf{r}) \varphi_{\alpha}(\mathbf{r}'),$ 

where the eigenvalues  $N_{-} (0 \le N_{-} \le 1, \sum_{i} N_{-} = A_{i})$ are the natural occupation numbers [3]. We use  $dx \in C$ 

Fill is accounted for by replacing the il-function in

the PINIA expression for the indusive e<sup>-12</sup>C cross section

by W/r with V and W obtained from the

 $\frac{dx_1}{d-d|a|} = 2\pi a^2 \frac{|\mathbf{q}|}{c^2} \int d\mathbf{E} d^3 \rho \frac{S_1(\mathbf{p}, \mathbf{E})}{E_1 E_2}$  $\times \delta(\omega + M - E - E_{F})L_{\mu\nu}^{\mu\nu}H_{\mu\nu}^{\mu\nu}$ 

101.12

MiniBooNE (12

(4)

### Abstract

(AN) correlations are implemented by using natural orby these correlations and by final-state interactions (FSI) are analyzed. The model also includes the contrievaluated within a fully relativistic Fermi gas (RFG). The MINER-A and T2X experiments. Good agreement with

#### SuSA & SuSAv2

The SuperScaling Approximation (SuSA) method [5] reinclusive differential (e, e') cross sections, divided by a nucleon content of the problem



depend only upon one kinematical variable:  $\psi~=$  $\pm \sqrt{\frac{1}{2T_{F}}} \left(q\sqrt{1+\frac{2}{r}}-\omega-1\right)$ , the scaling variable (this behavior is called scaling of first kind) and the resulting function is roughly the same for all nuclei (scalfilled the cross section is said to superscale. Recently, called Su6Av2 161, has been developed by incorporating relativistic mean field (RMF) effects in the longituisovector and isoscalar channels.









B The spectral function (SF) is constructed in the form 
$$\begin{split} S(\rho,\mathcal{E}) = \sum_i 2(2i+1) a_i(\rho) L_{\mathcal{E}_i}(\mathcal{E}-\mathcal{E}_i), \end{split}$$



n(p) correspond to harmonic-oscillator (HG) shell-model Rever 3(p, 2) of "C using HD s.p. Rever 7(p) for "C sinules defined as the complete orthonormal set of Lo. wave method and isension function for with and without PG are comfunctions that diagonalize the one-body density matrix the energy dependence.



 $\left[\frac{d^2 x}{d x d x^2}\right]_{\mu} = \sigma_0 \mathcal{F}_{\chi}^0$ 

obtained within the lowest-order approximation of the where  $\chi = \pm \operatorname{for}_{2}(\overline{P})$  induced reactions.  $\mathcal{F}_{2}^{2}$  depends on the nuclear structure and can be written as a generalized Rosenbluth decomposition:  $\mathcal{F}_{L}^{2} = [\hat{\mathcal{H}}_{L}\mathcal{R}_{L} + 2\hat{\mathcal{H}}_{L}\mathcal{R}_{L} +$  $\hat{V}_{ii}R_{ii} + \hat{V}_{ii}R_{ij} + \chi[2\hat{V}_{ji}R_{ji}]$ , having charge-charge terms of the nuclear tensor W<sup>44</sup> times the single-nucleor

MiniBooNE (77.-12C)

#### Conclusions

work. The recall can this work can be seen as a test of the reliability of the oresent spectral function based models. They consider



