Plan to implement SuSAM* model into GENIEv3

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25th of February 2019

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Introduction to the SuSAM* model

- The SuSAM* model is theoretically inspired in the Walecka relativistic mean field model of nuclear matter. This model is a mean field model with σ and ω exchanges which is fully relativistic, does not break gauge invariance and reproduces saturation property of nuclear matter.

Introduction to the SuSAM* model

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- When this model is applied to nuclear matter, the σ and ω exchanges give rise to constant scalar and vector potentials that modify the dispersion relation of the nucleons. These obey the Dirac equation with scalar and vector sources.

$$[\vec{\alpha} \cdot \vec{p} + \beta \left(m_N - g_\sigma \langle \sigma \rangle \right)] u(\vec{p}) = \left(E - g_\omega \left\langle \omega^0 \right\rangle \right) u(\vec{p}), \quad (1)$$

where $\langle \sigma \rangle$ and $\left\langle \omega^0 \right\rangle$ are the ground state expectation values of the scalar and vector mesons giving rise to the constant scalar and vector potentials.

- Equation (1) is the same as the free Dirac equation for a nucleon with shifted (effective) mass and energy, respectively,

$$m_N^* = m_N - g_\sigma \langle \sigma \rangle \qquad E^* = E - g_\omega \left\langle \omega^0 \right\rangle \tag{2}$$

- In the Walecka model, m_N^* and k_F can be theoretically calculated by means of coupled self-consistent Hartree equations to minimize the binding energy per particle (saturation of nuclear matter).
- However, in the SuSAM* approach, m_N^* and k_F are tunable parameters of the model that we fix, with a suitable scaling function, to reliable reproduce QE electron scattering data from the world database[3]. Afterwards the fitting of the parameters of the model from electron scattering data, we apply the model without any re-fit to CCQE or CCQE-like neutrino scattering.

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[3] O. Benhar, D. Day and I. Sick, http://faculty.virginia.edu/qes-archive/

Theoretical formalism of the SuSAM* model

The model is based on the factorization property of the nuclear response functions in the RFG, namely,

$$R_K(\omega, q) = r_k f^*(\psi^*), \qquad \text{with} \quad K = CC, CL, LL, T, T' \tag{3}$$

r_k are the five single-nucleon weak response functions obtained with the bare weak CC one-body current operator[4]

$$J^{\mu}_{s'\,s}(\vec{p}', \vec{p}) = V^{\mu}_{s'\,s}(\vec{p}', \vec{p}) - A^{\mu}_{s'\,s}(\vec{p}', \vec{p}) \tag{4}$$

$$V^{\mu}_{s'\,s}(\vec{p}', \vec{p}) = \bar{u}_{s'}(\vec{p}') \left[2F_1^V \gamma^\mu + \frac{2iF_2^V}{2m_N} \sigma^{\mu\nu} q_\nu \right] u_s(\vec{p}) \tag{5}$$

$$A^{\mu}_{s'\,s}(\vec{p}', \vec{p}) = \bar{u}_{s'}(\vec{p}') \left[G_A \gamma^\mu \gamma_5 + \frac{G_P}{2m_N} q^\mu \gamma_5 \right] u_s(\vec{p}) \tag{6}$$

Notice that the current operators have the bare nucleon mass m_N, while the nucleon spinors carry the effective mass m_N^*. And when calculating spin traces, the sum over nucleon polarizations will give

$$\sum_s u_s(\vec{p})\, \bar{u}_s(\vec{p}) = \frac{(\not{p} + m_N^*)}{2m_N^*} \tag{7}$$

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[4] I. Ruiz Simo, V.L. Martinez-Consentino, J.E. Amaro and E. Ruiz Arriola, PRD 97, 116006 (2018).

Theoretical formalism of the SuSAM* model

In equation (3) of previous slide, $f^*(\psi^*)$ is a phenomenological scaling function with a suitable form (the sum of two Gaussians), which is fitted (within an error band) to the world QE electron scattering data. The different kind of fits performed (and these were returning similar values for m_N^* and k_F for each nuclear species) are thoroughly explained in *J.E. Amaro, V.L. Martinez-Consentino, E. Ruiz Arriola and I. Ruiz Simo, PRC 98, 024627 (2018).*

$$f^*(\psi^*) = a_3\, e^{-\frac{(\psi^*-a_1)^2}{2\,a_2^2}} + b_3\, e^{-\frac{(\psi^*-b_1)^2}{2\,b_2^2}} \tag{8}$$

This form of the phenomenological scaling function provides the characteristic tail of the Relativistic Mean Field model in finite nuclei[5].

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[5] J.A. Caballero, J.E. Amaro, M.B. Barbaro, T.W. Donnelly, C. Maieron and J.M. Udias, PRL 95, 252502 (2005)

Differences with other scaling approaches

- In the other scaling approach being included in GENIE, SuSAv2-MEC[6] [7], there are several different scaling functions, while in the SuSAM* model there is an unique scaling function $f^*(\psi^*)$ multiplying all the single-nucleon responses.
- Additionally, in the SuSAv2-MEC model the final scaling function to be used is an admixture of scaling functions from different models, namely the RMF and the Relativistic Plane Wave Impulse Approximation (RPWIA), as

  $$\mathcal{F}_{L,T} = \cos^2\chi(q)\tilde{f}_{L,T}^{\mathrm{RMF}} + \sin^2\chi(q)\tilde{f}_{L,T}^{\mathrm{RPWIA}}, \tag{9}$$

  where while the $\tilde{f}_{L,T}$ depend only upon the scaling variable ψ', the mixing angle $\chi(q)$ explicitly depends on the momentum transfer, thus explicitly breaking scaling in $\mathcal{F}_{L,T}$.
- Finally, the SuSAv2-MEC approach includes MEC, which are essential to reproduce the data, while the SuSAM* model does not include MEC.

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[6] G.D. Megias, J.E. Amaro, M.B. Barbaro, J.A. Caballero and T.W. Donnelly, PRD 94, 013012 (2016)

[7] G.D. Megias, J.E. Amaro, M.B. Barbaro, J.A. Caballero, T.W. Donnelly and I. Ruiz Simo, PRD 94, 093004 (2016)

Comparisons of the model with CCQE data

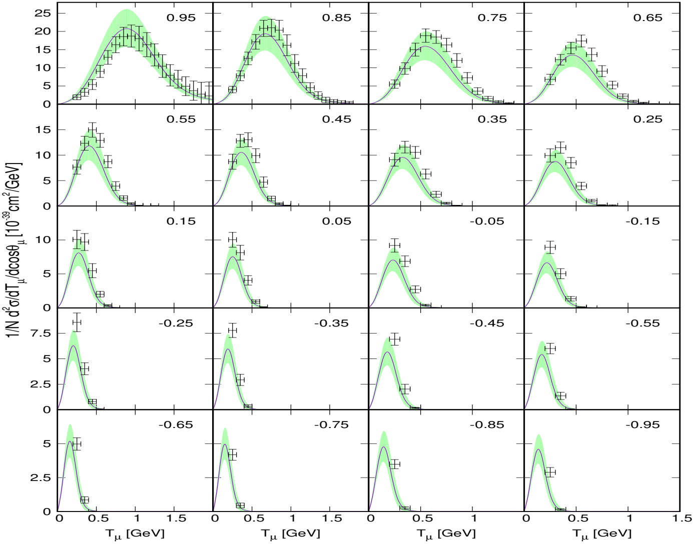
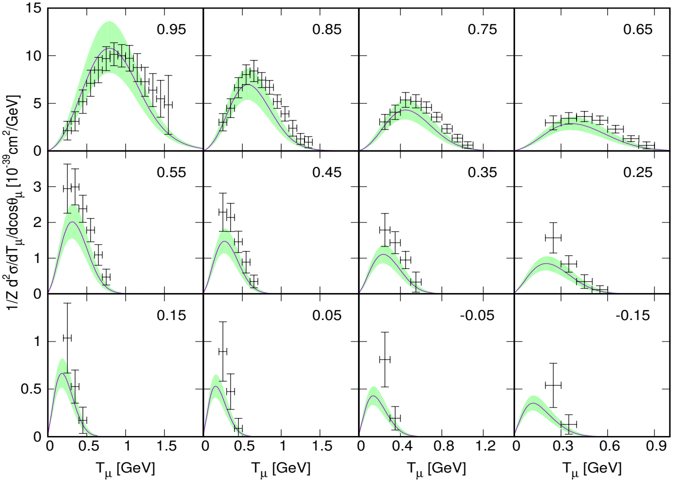


Figure: Comparison of SuSAM* model with MiniBooNE flux-folded double differential (ν_μ, μ^-) CCQE cross section. Each panel is labelled by the average value of the cosine in the experimental bin.

Comparisons of the model with CCQE data



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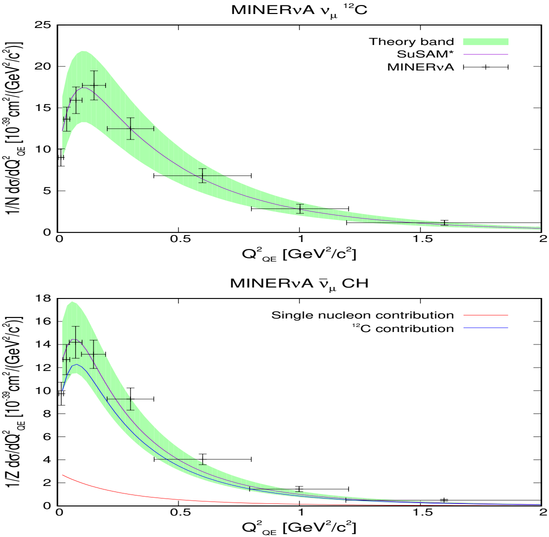

Figure: Comparison of SuSAM* model with MINERvA flux-folded $Q^2_{\rm QE}$ distributions.

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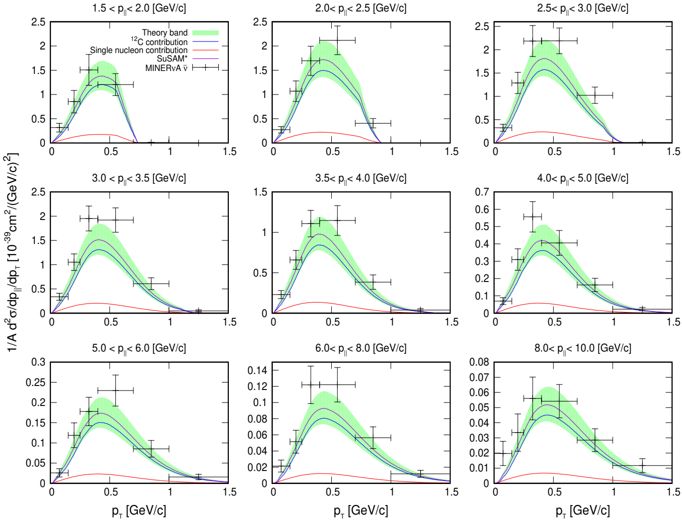

Figure: Comparison of SuSAM* model with CCQE MINERvA flux-folded $\frac{d^2\sigma}{dp_{||}\,dp_\perp}$ antineutrino-CH cross section data. The experimental angular cut $\theta_\mu < 20^\circ$ has also been applied to the theoretical calculation.

Implementation in GENIE

For event generation, we will try to utilize existing class *QELEventGenerator*, but there are some issues with it:

- Maximum search
  Maybe there is a sense to use Afroditi suggestion? In any case we would like to test this option.
- The project is being worked on now
  Steven says that the work mostly leaves the interfaces intact, so we hope that it won't concern us.

If there is a need to leave *QELEventGenerator* unchanged or in contrast we have to modify it significantly then we will create a new class (any suggestion?)

Implementation in GENIE

For dealing with cross section computation we plan:

- Create a new class *SuSAMQELCCPXSec*.
- Use the implicit formula for the double differential xsec (by adopting the original FORTRAN code).
- Calculate all component of the model on-the-fly, since the calculations are sufficiently fast.

Timetable

- Implementation of the model and its testing: about 1.5 months (starting from March 12).
- Work on the event generation: 1 week – 1 month (it depends of the possibility to use the existing code).
- Implement reweighting of SuSAM* predictions: long term (to summer?)