Spectral function in NEUT (NuWro)

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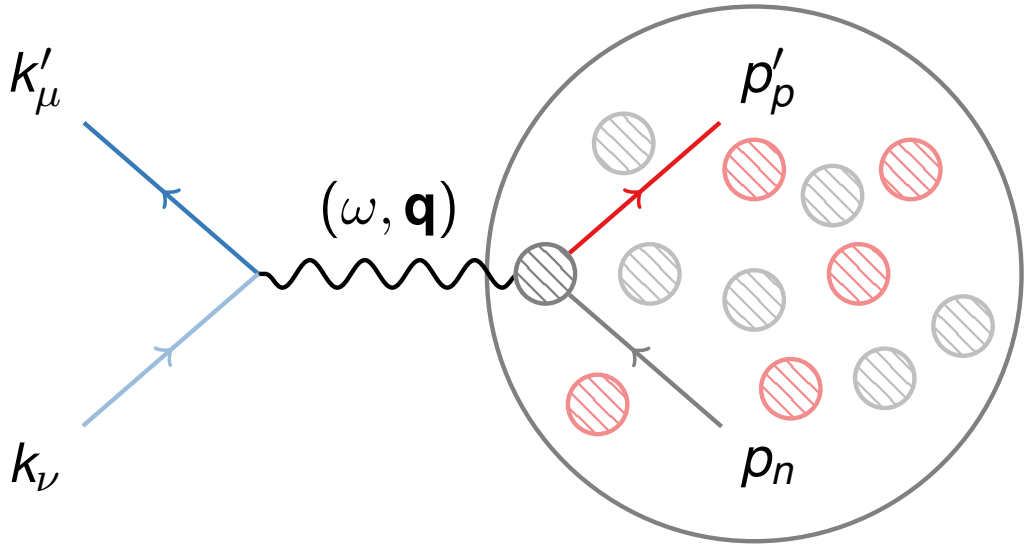
Plane-wave impulse approximation



Factorization of the cross section in the **absence of FSI**:

$$\frac{\mathrm{d}^6\sigma^{\mathrm{PWIA}}}{\mathrm{d}\omega \mathrm{d}|\mathbf{q}|\mathrm{d}E_m\mathrm{d}\mathbf{p}_m} = \frac{G_F^2\cos^2\theta_C|\mathbf{q}|}{4\pi E_{\mathbf{k}}^2 E_{\mathbf{p}} E_{\mathbf{p}'}} P_{(n)}(E_m, \mathbf{p}_m) L_{\mu\nu}\widetilde{H}^{\mu\nu}\delta(\omega + M - E_m - E_{\mathbf{p}'})$$

$P_{(n)}(E_m, \mathbf{p}_m)$ - probability density of initial nucleons

$L_{\mu\nu}\widetilde{H}^{\mu\nu}\delta(\omega + M - E_m - E_{\mathbf{p}'})$ - interaction dynamics for a given nucleon

Hole spectral function

$$S(E_m, \mathrm{p}_m) = \sum_n \left| \left\langle \Psi_n^{A-1} \right| a_{p_m} \left| \Psi_0^A \right\rangle \right|^2 \delta(E_m + E_0 - E_n)$$

*The **probability** distribution of removing a **nucleon** with **momentum** $\vec{p}$ and leaving the residual **nucleus** with the **excitation energy** E.*

(shell model + nucleon correlations)

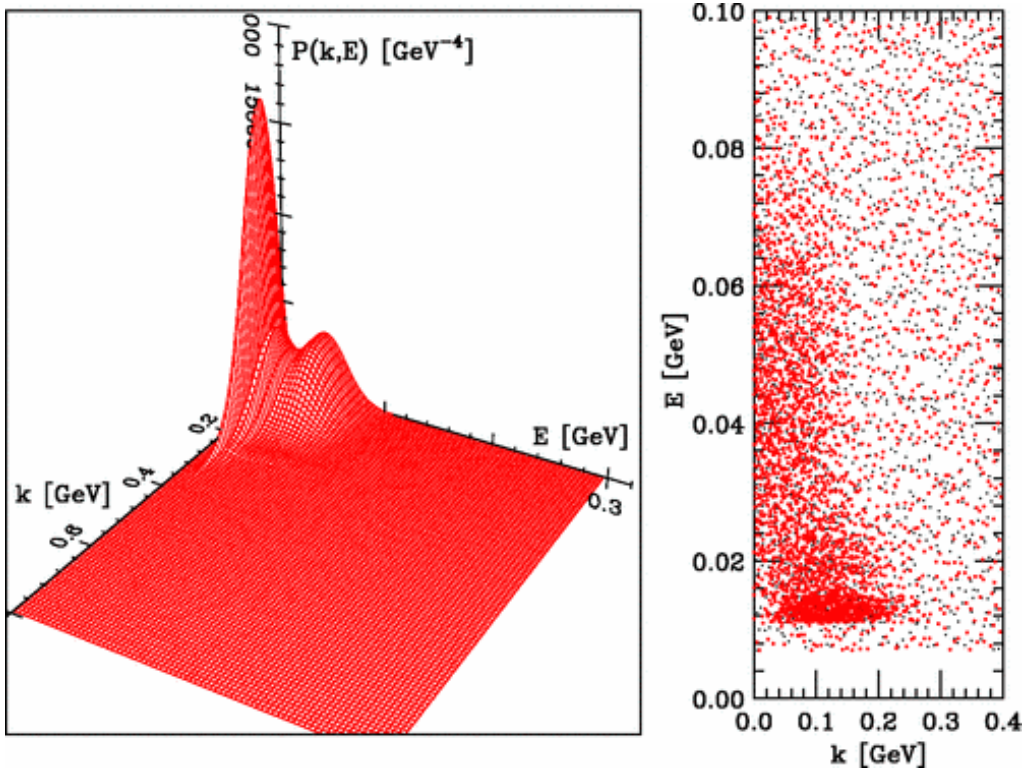
In NuWro available for:

- carbon
- oxygen
- calcium*
- argon*
- iron

*approximation, see

A. Ankowski, J.T. Sobczyk,

Phys.Rev. C77 (2008) 044311



O. Benhar et al., Phys.Rev. D72 (2005) 053005

Neutrino-nucleon interaction

→ nucleon **form factors**:

$$\mathrm{CC1}: \quad \Gamma^{\mu} = \gamma^{\mu} F_1 + i\sigma^{\mu\nu} q_k F_2/2M + \gamma^{\mu}\gamma_5 F_A + \gamma_5 q^{\mu} F_P/M$$

$$\rightarrow \mathrm{CC2}: \quad \Gamma^{\mu} = \gamma^{\mu}(F_1 + F_2) - (p + p')F_2/2M + \gamma^{\mu}\gamma_5 F_A + \gamma_5 q^{\mu} F_P/M$$

→ **de Forest** prescription:

we use $\tilde{q} = (\omega - E_B, \mathbf{q})$, where $E_B = E_{\mathbf{p}} - M + E_m$

→ tensor **contraction**:

$$\begin{aligned}
\frac{1}{2} L_{\mu\nu} \widetilde{H}^{\mu\nu} = {} & 2M^2 k \cdot k' \left[{F_A}^2 (1 - \frac{\tilde{q}^2}{4M^2}) - \frac{\tilde{q}^2}{4M^2} (F_1 + F_2)^2 \right] \\
& + (2p \cdot k \; p \cdot k' - M^2 \; k \cdot k') \left[{F_A}^2 + {F_1}^2 - \frac{\tilde{q}^2}{4M^2} {F_2}^2 \right] \\
& + (p \cdot k' \; k \cdot \tilde{q} - p \cdot k \; k' \cdot \tilde{q}) \left[2F_A (F_1 + F_2) \right] \\
& + (k \cdot k' \; \tilde{q}^2 - 2k \cdot \tilde{q} \; k' \cdot \tilde{q}) \left[\frac{1}{4} {F_2}^2 (1 + \frac{\tilde{q}^2}{4M^2}) + \frac{1}{2} F_1 F_2 + F_A F_P + \frac{\tilde{q}^2}{4M^2} {F_P}^2 \right] \\
& + (p \cdot k \; k' \cdot \tilde{q} + p \cdot k' \; k \cdot \tilde{q} - k \cdot k' \; p \cdot \tilde{q}) \left[{F_A}^2 + {F_1}^2 - \frac{\tilde{q}^2}{4M^2} {F_2}^2 \right]
\end{aligned}$$

Algorithm

1.

Choose k_ν

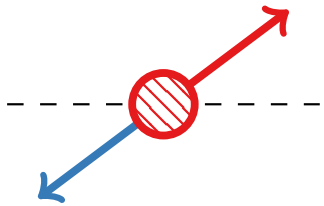
2.

Choose p_n

3.

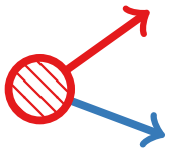
Boost to the CMS frame

4.



Choose scattering angles

5.



Boost back to the LAB frame

6.

$$\frac{\mathrm{d}^6\sigma}{\mathrm{d}\omega \mathrm{d}|\mathbf{q}|\mathrm{d}E_m\mathrm{d}\mathbf{p}_m}$$

Calculate the cross section

Algorithm

Spectral function formalism yields:

$$\sigma^{\mathrm{PWIA}} = \int_V \frac{\mathrm{d}^6\sigma^{\mathrm{PWIA}}}{\mathrm{d}\omega \mathrm{d}|\mathbf{q}|\mathrm{d}E_m\mathrm{d}\mathbf{p}_m}\left[\mathrm{d}\omega \mathrm{d}|\mathbf{q}|\mathrm{d}E_m\mathrm{d}\mathbf{p}_m\right]$$

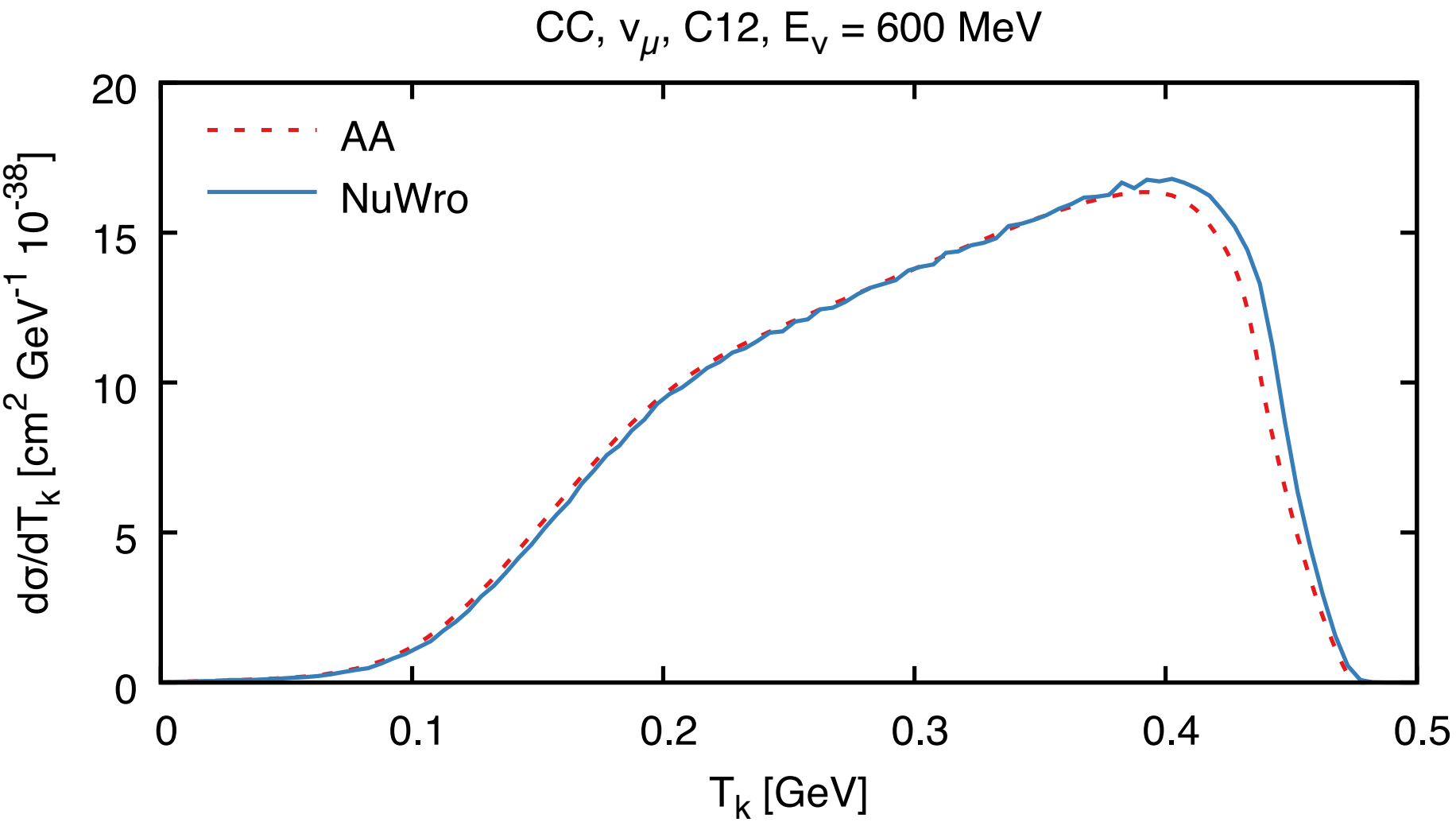
In **NuWro**, the **invariant variables** are: Ω^*_μ, E_m, $\mathbf{p}_m$.

Additionally, E_m, p_m are **sampled** from the **spectral function**.

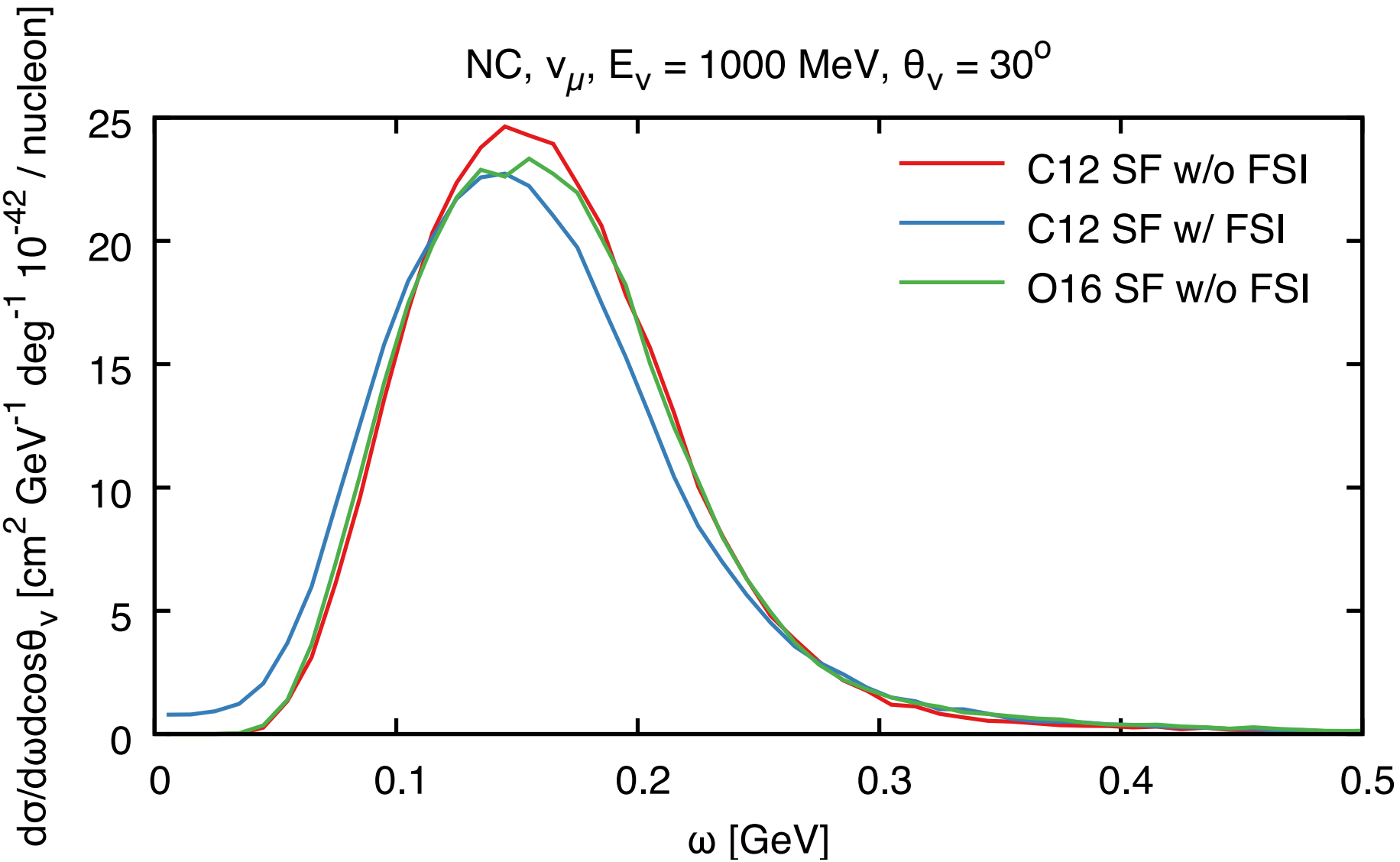
Therefore, **NuWro calculates**

$$\sigma^{\mathrm{PWIA}} = \int_V \frac{\mathrm{d}^6\sigma^{\mathrm{PWIA}}}{\mathrm{d}\omega \mathrm{d}|\mathbf{q}|\mathrm{d}E_m\mathrm{d}\mathbf{p}_m}\frac{1}{S(E_m,|\mathbf{p}_m|)}\left[\mathrm{d}\Omega^*_\mu S(E_m,|\mathbf{p}_m|)\mathrm{d}E_m\mathrm{d}\mathbf{p}_m\right]$$

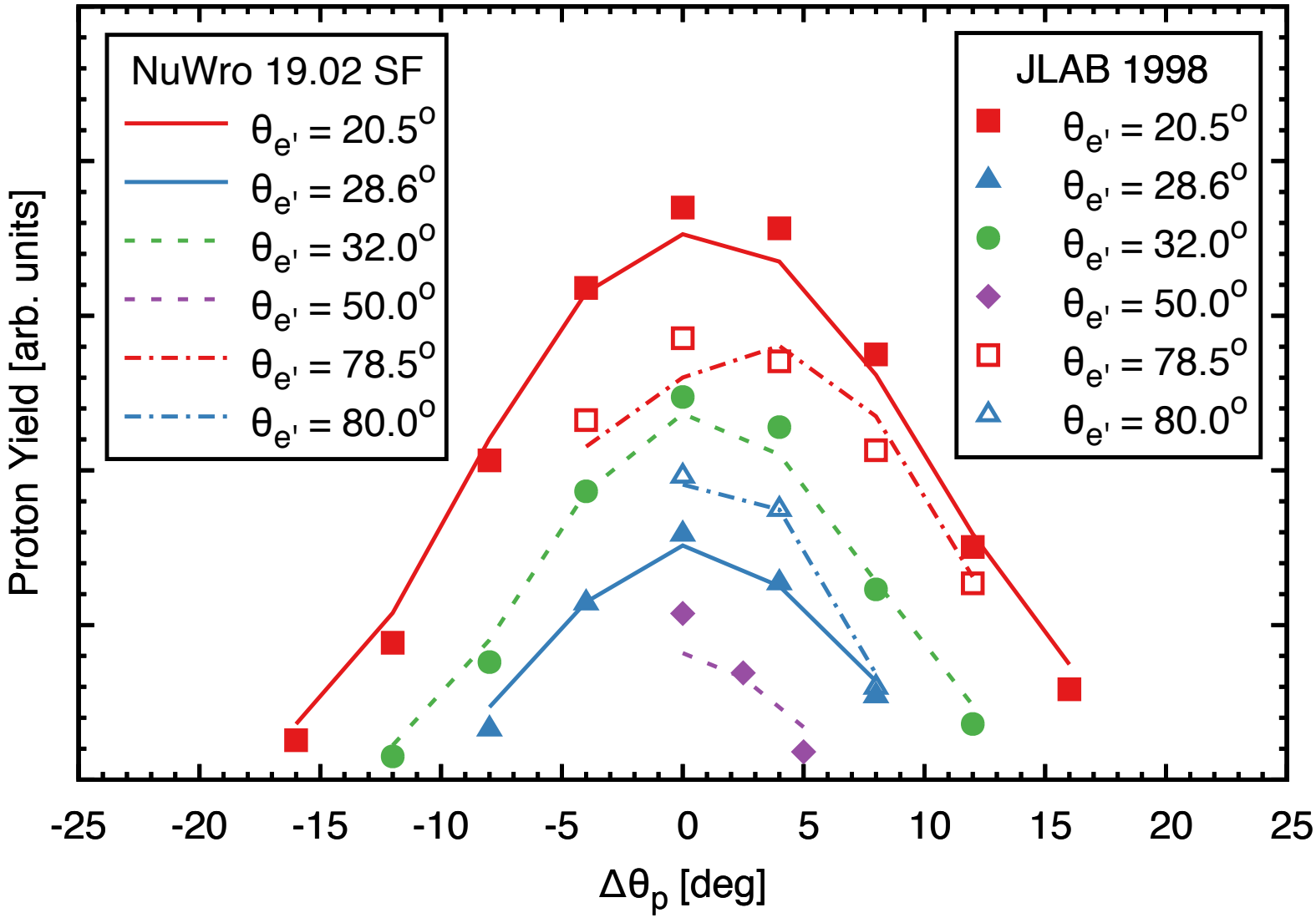
Inclusive results (hot take)



Inclusive results (hot take)



Exclusive results



Neutral current scattering of ν_e on protons, arXiv:1902.05618