Nu-Tau Cross Sections with Ar40

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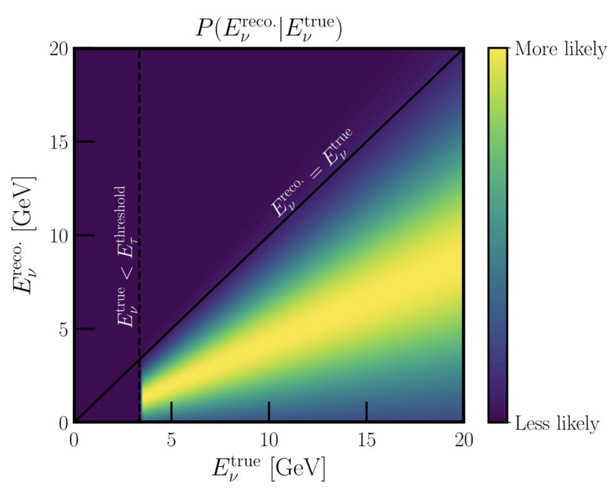
CC-ν_τ scattering in DUNE

- The production of τ leptons by CC(ν_τ) - nucleus scattering requires neutrino energies $E_\nu \gtrsim 3.4$ GeV.
- Hadronic τ decays make up the largest branching fraction for the τ (~ 65%)



arXiv:1904.07265

- **To test the Standard Model predictions and check the validity of the lepton universality hypothesis,** the interaction cross sections for all three flavors of neutrinos should be known to high accuracy requiring better measurements of the $\nu_\tau/\bar{\nu}_\tau$ XSec.
- **Interaction studies** are also required to better determine the properties of the **third neutrino weak eigenstate to have precise understanding of the neutrino oscillation parameters (SHiP, DsTau experiments).**
- **DUNE** would also have the ability to **test the validity of three neutrino hypotheses** and if possible some new physics associated with neutrinos.
- The importance of the kinematic cuts on Q^2 and W

Differential Cross-Section

arXiv:2008.03527

$$\frac{d\sigma}{dQ^2}(Q^2, E_\nu) = \frac{c_{qq'}^2}{16\pi}\frac{M^2}{E_\nu^2}\left[\left(\tau + r^2\right) A(Q^2) - \nu B(Q^2) + \frac{\nu^2}{1+\tau} C(Q^2)\right], \tag{5}$$

where $r = m_\ell/(2M)$ with the lepton mass m_ℓ, incoming neutrino energy E_ν and variable $\nu = E_\nu/M - \tau - r^2$. The structure-dependent factors A, B, and C are given by

$$A = \tau\left(G_M^V\right)^2 - \left(G_E^V\right)^2 + (1+\tau)F_A^2 - r^2\left(\left(G_M^V\right)^2 + F_A^2 - 4\tau F_P^2 + 4F_A F_P\right), \tag{6}$$

$$B = 4\eta\tau F_A G_M^V, \tag{7}$$

$$C = \tau\left(G_M^V\right)^2 + \left(G_E^V\right)^2 + (1+\tau)F_A^2, \tag{8}$$

- The structure functions **F4 and F5**, are pointed out by Albright and Jarlskog **are neglected in muon neutrino interactions** because of a suppression factor depending on the square of the charged lepton mass divided by the nucleon mass times neutrino energy.

Structure Functions F4 and F5

- Given the higher mass value of the τ lepton, **F_4 and F_5 contribute**, instead, to the **tau neutrino cross-section.**

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\Bigg((y^2x + \frac{m_\tau^2 y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau^2}{4E_\nu^2}) - (1+\frac{Mx}{2E_\nu})\right]F_2 \pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M}\right]F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x}F_4 - \frac{m_\tau^2}{E_\nu M}F_5\Bigg),$$

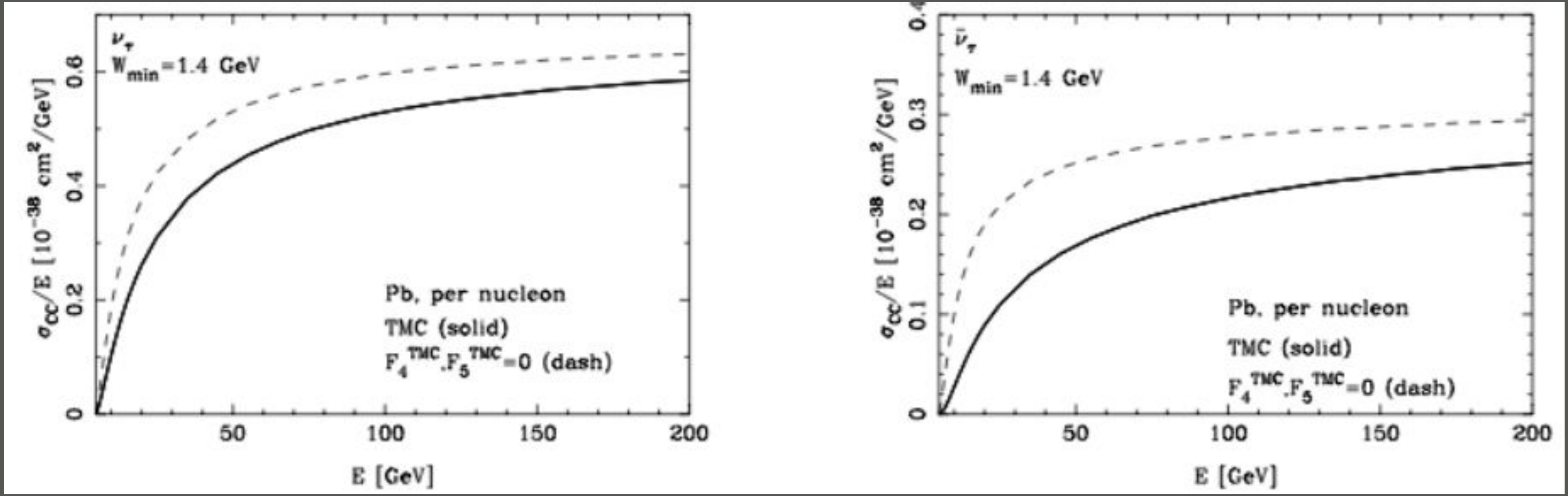
Where x, y and Q^2 are the standard DIS kinematic variables related through $Q^2 = 2M_N E_\nu xy$

- At leading order, in the limit of massless quarks and target hadrons, $F4 = 0$ and $2xF5 = F2$, where x is the Bjorken-x variable. NLO show that $F_4 \sim 1\%$ of F_5 arXiv:hep-ph/0605295

- The SHip Proposal showed the hypothesis of $F_4 = F_5 = 0$ would result in an increase of the ν_τ and $\bar{\nu}_\tau$ charged-current DIS cross-sections and consequently, of the number of expected ν_τ and $\bar{\nu}_\tau$ interactions.

SM prediction (solid)
F4=F5=0 hypothesis (dashed)

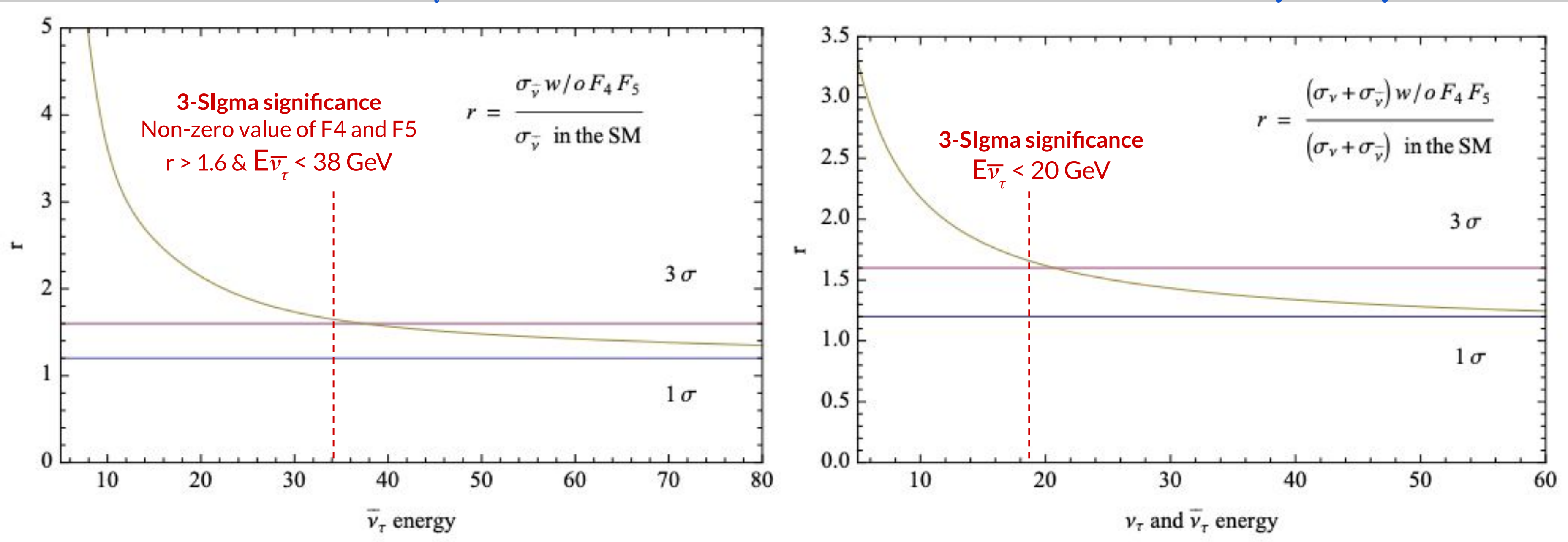
$\bar{\nu}_\tau$ ν_τ



Notice **the difference** between the cross-sections in the **$F_4 = F_5 = 0$ hypothesis** and the **SM prediction** **is larger for lower neutrino energies.**

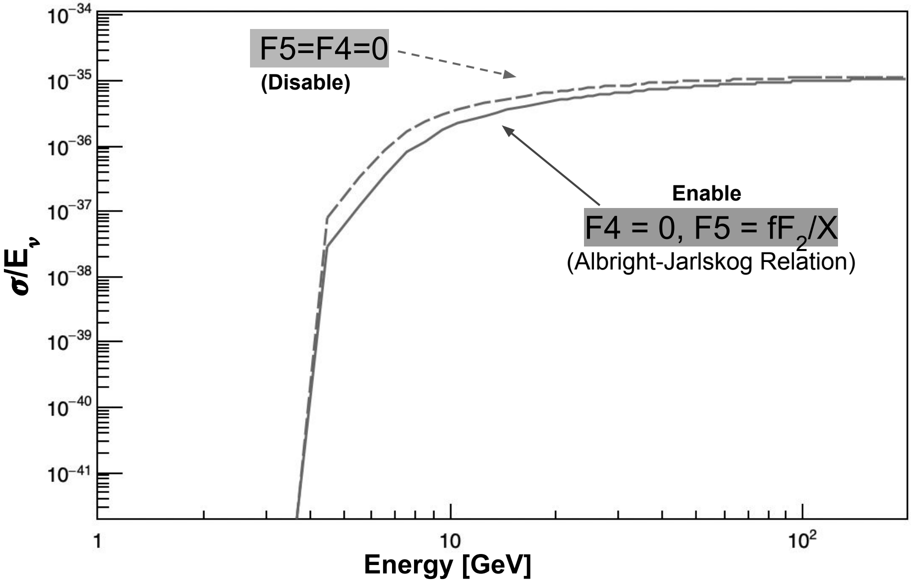
Ratio “r” between F4 = F5 = 0 hypothesis and the SM prediction
SHip Proposal

Ratio for $\bar{\nu}_\tau$ | Ratio for the sum of $\bar{\nu}_\tau$ and ν_τ

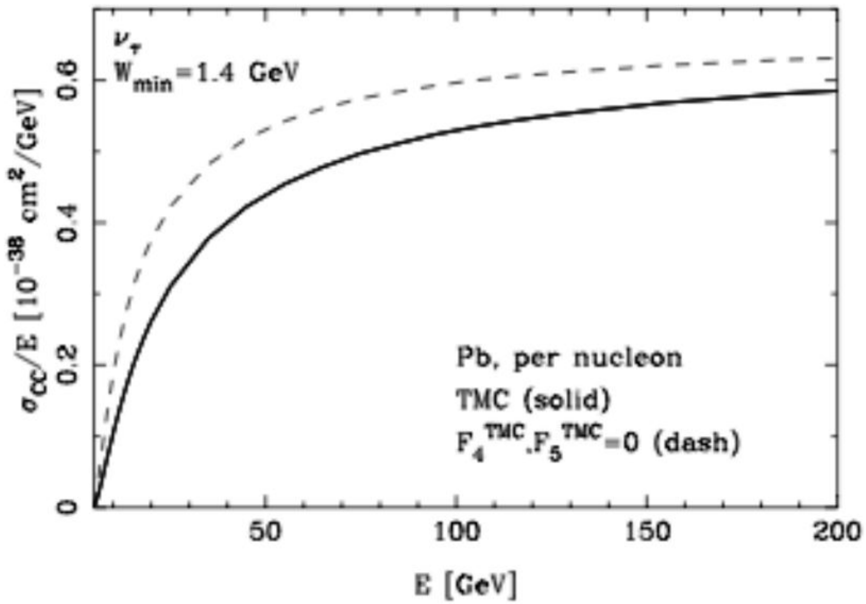


Notice that **r is higher for lower neutrino energies,** where the discrepancy of the two curves is larger, and decreases, **tending to one, for higher energies,** where the contribution of **F_4 and F_5 becomes negligible.**

GENIE DIS Total CC-XSec. ν_τ + Ar40



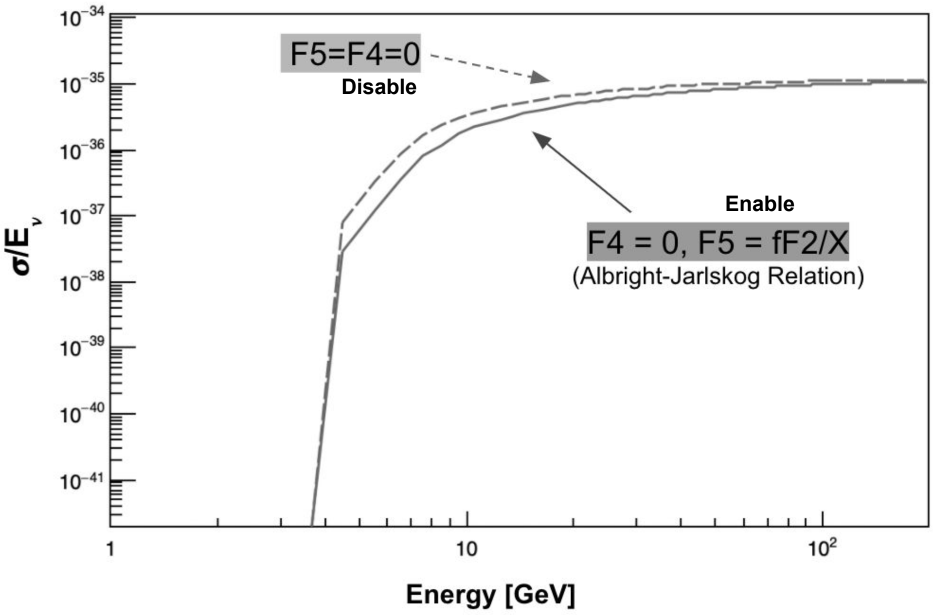
GENIE DIS Total CC-XSec. ν_τ + Pb

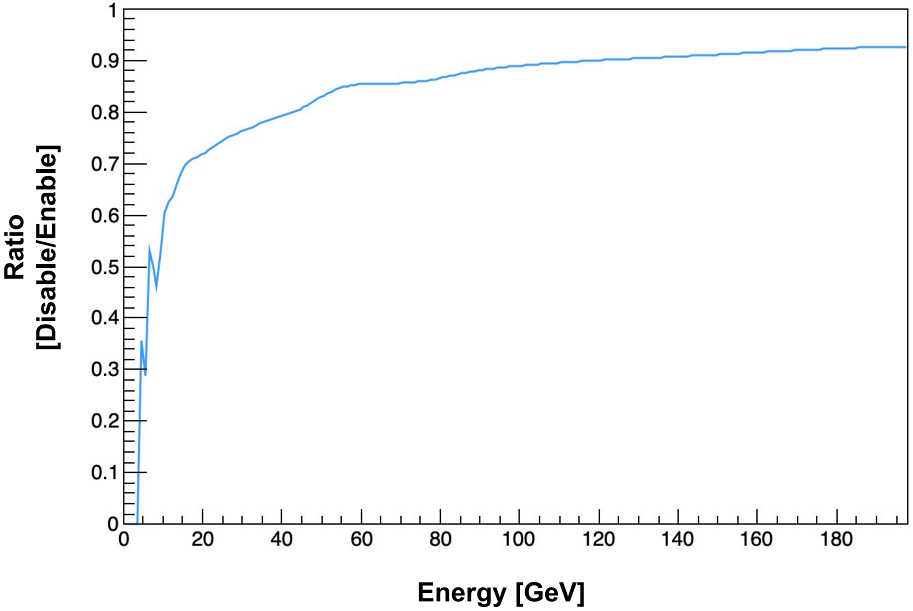


This are GENIE (v2.12.6) splines in the DIS region

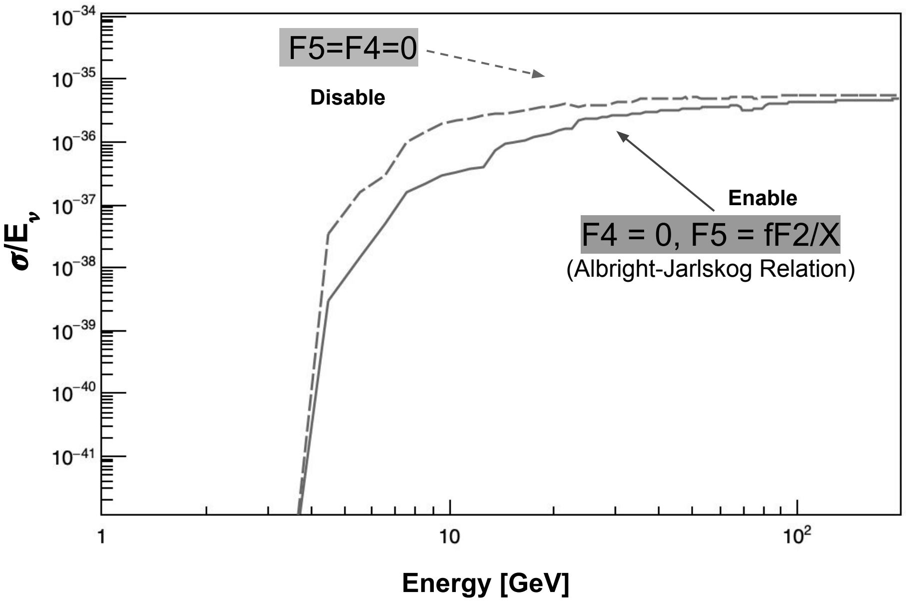
- These are files that **store the total cross section** as a function of channel and neutrino energy on different targets.
- Computing the total cross-section is computationally expensive, but it doesn't change event to event, so do it once for all the materials in your experiment and store the results.

GENIE DIS Total CC-XSec. ν_τ + Ar40

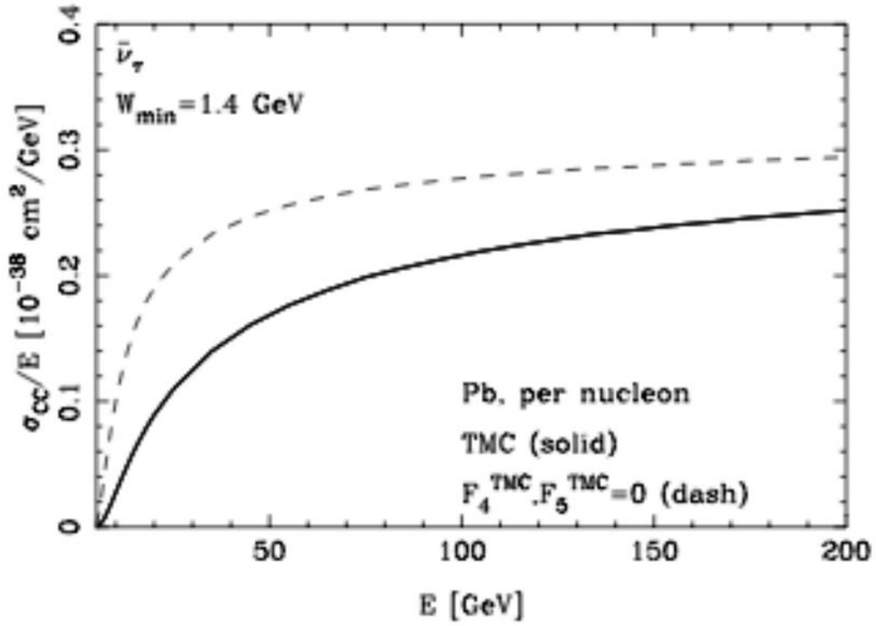




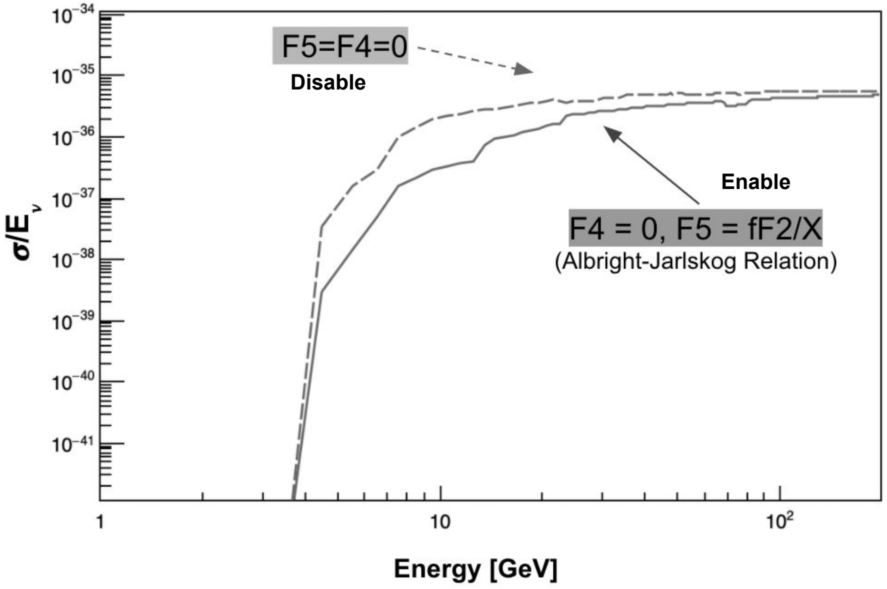
GENIE DIS Total CC-XSec. $\overline{\nu}_\tau$ + Ar40

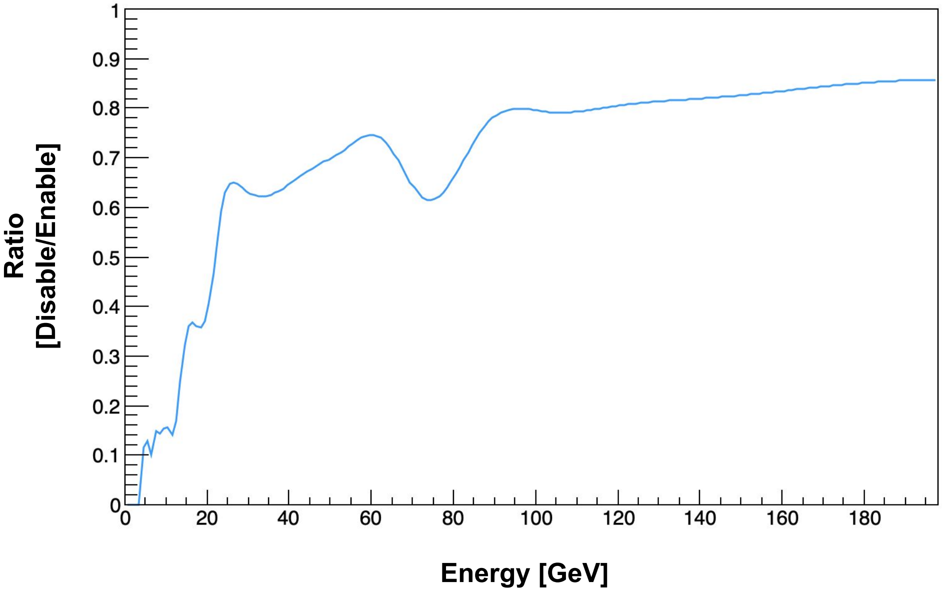


GENIE DIS Total CC-XSec. $\overline{\nu}_\tau$ + Pb



GENIE DIS Total CC-XSec. $\bar{\nu}_\tau$ + Ar40





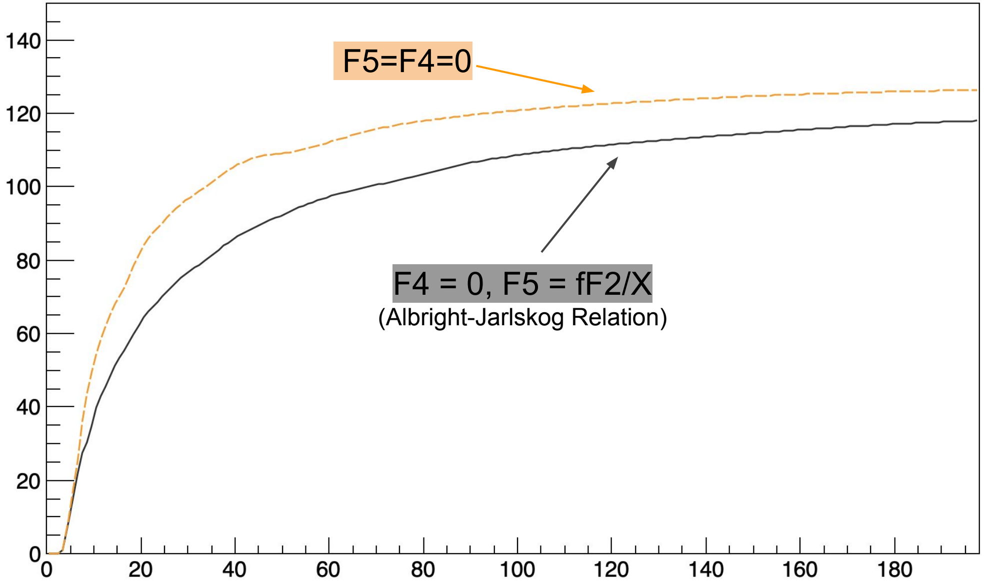
Comments:

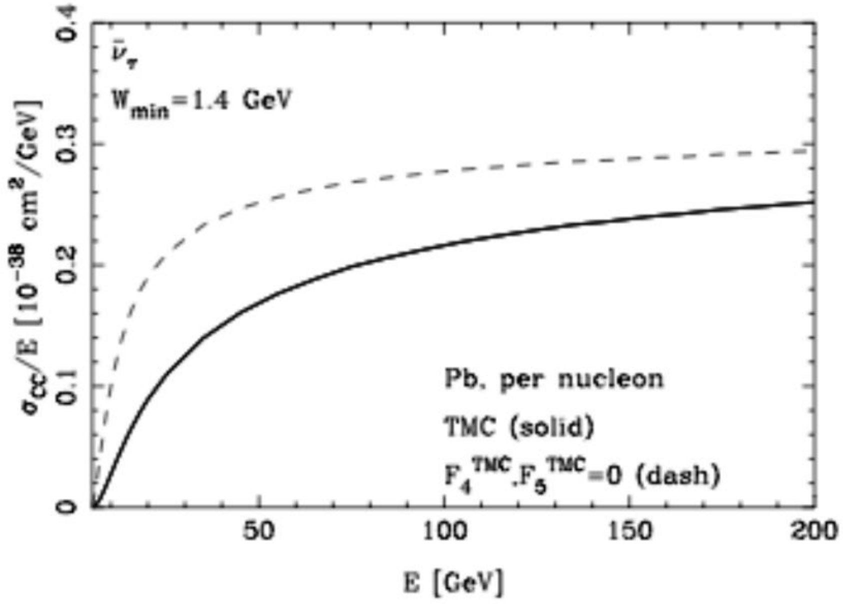
- We are ready to start to generate events and therefore get Nu-Tau cross section ratios.
- Check Nu-Tau efficiency as a function of the energy from the cross section.
- CC-NuTau can be categorized as hadronic or leptonic interactions → here we plan to take a machine learning approach via Graph Neural Networks.

$$\frac{dn_\beta^{\mathrm{IT}}}{dE'} = N \int_0^\infty \int_0^\infty dE \, d\hat{E} \underbrace{\Phi_\alpha(E)}_{\text{Production}} \times \underbrace{\frac{1}{L^2} P_{(\alpha\to\beta)}(E, L, \rho; \theta_{12}, \theta_{13}, \theta_{23}, \Delta m_{31}^2, \Delta m_{21}^2, \delta_{\mathrm{CP}}) \times}_{\text{Propagation}} \underbrace{\sigma_f^{\mathrm{IT}}(E) k_f^{\mathrm{IT}}(E - \hat{E})}_{\text{Interaction}} \times \underbrace{T_f(\hat{E}) V_f(\hat{E} - E')}_{\text{Detection}},$$

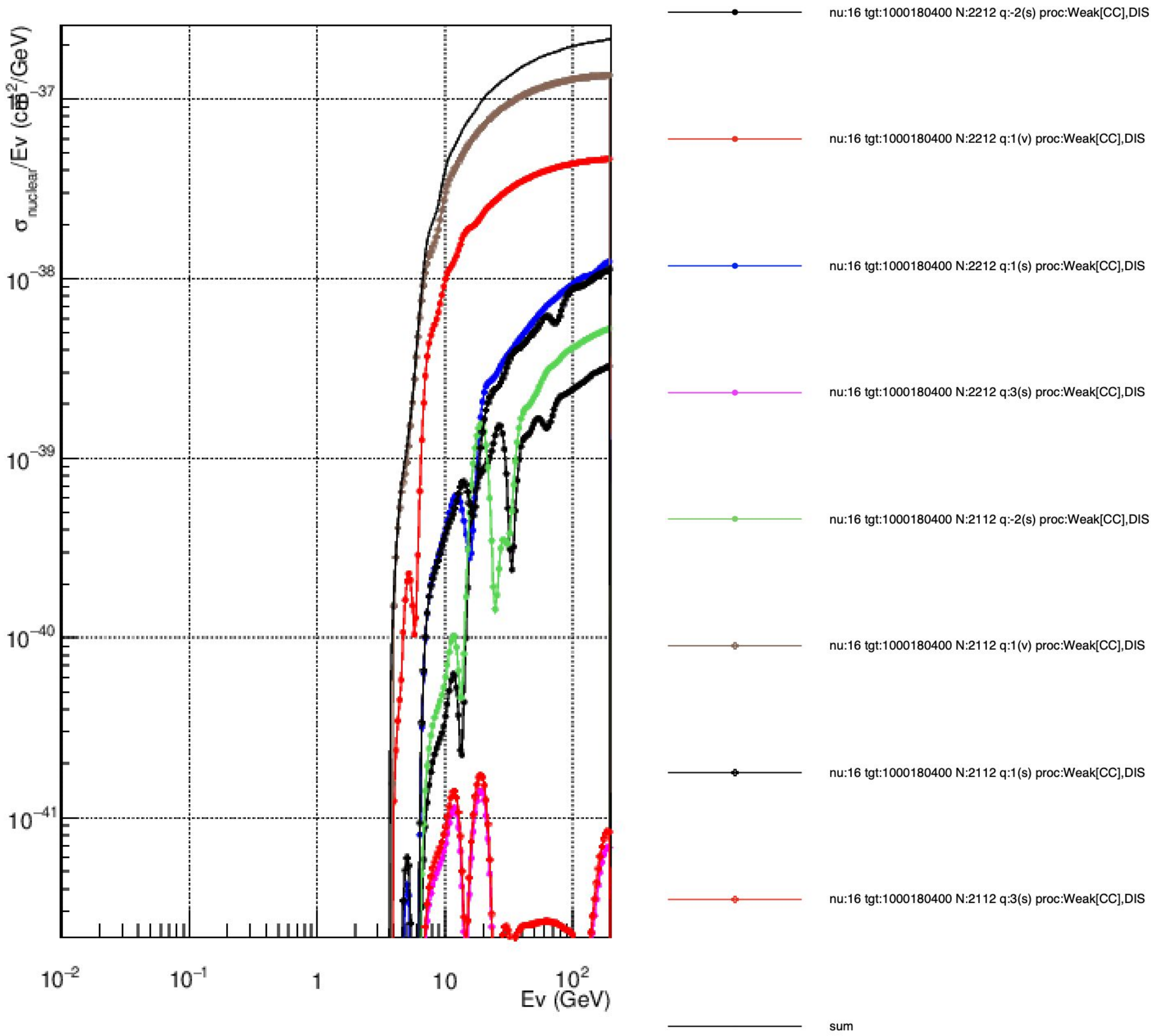
Backup

GENIE Total CC-XSec. ν_τ + Ar40

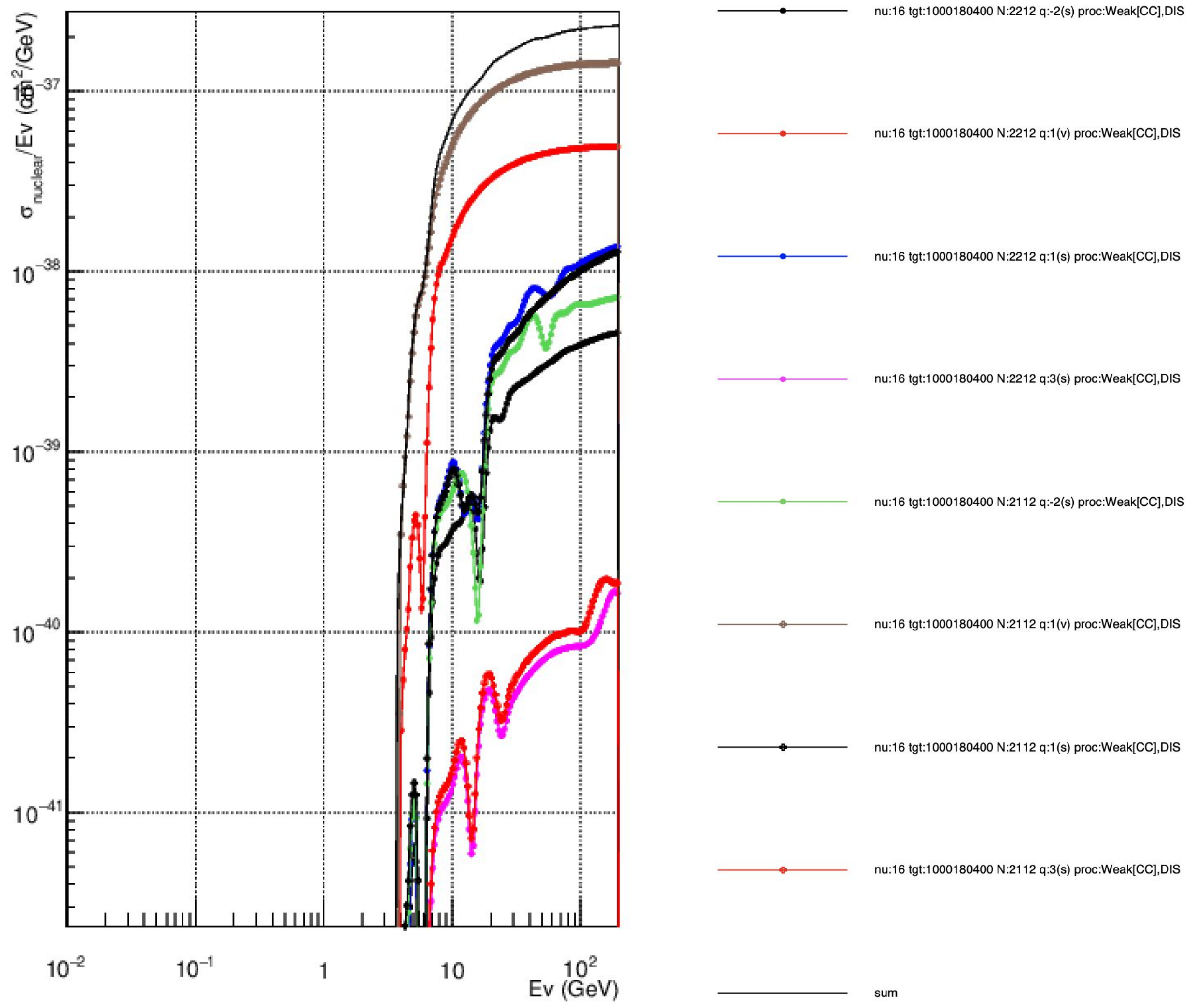




Enable (F4 = 0,
F5 = fF2/X)
NuTau Total XSec. - DIS



Disable (F4=F5=0)
NuTau Total XSec. - DIS



GENIE Total CC-XSec. $\overline{\nu}_\tau$ + Ar40