

High-energy neutrino-nucleon deep inelastic scattering

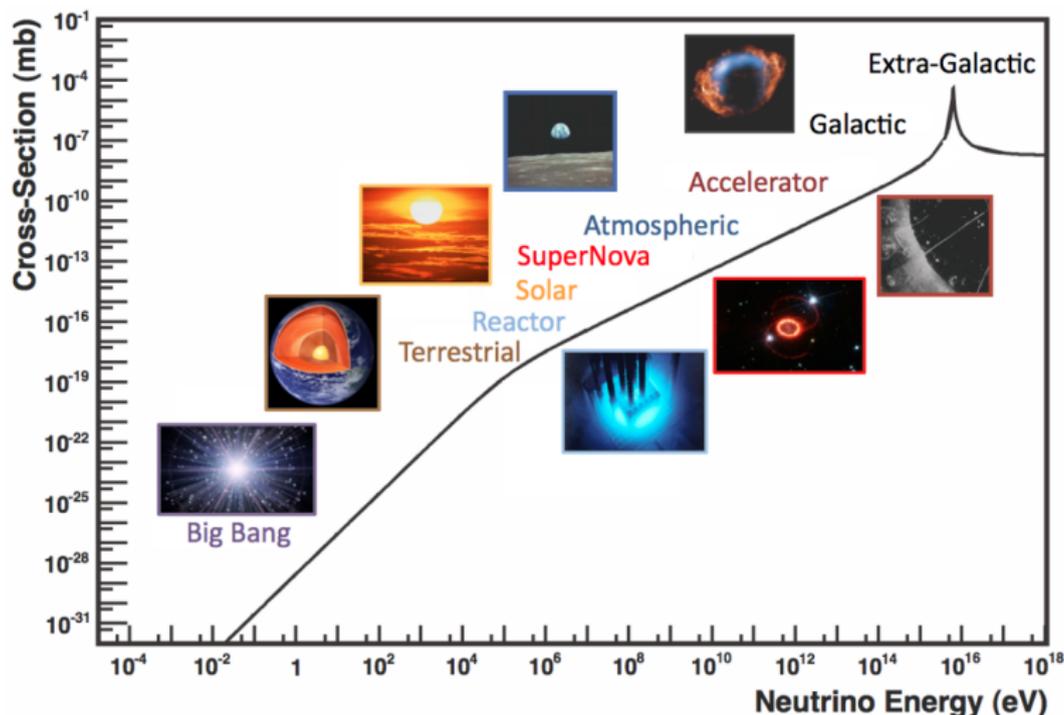
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In collaboration with Jun Gao (SJTU), Tim Hobbs (Argonne),
Daniel Stump and C.-P. Yuan (MSU)
[\[arXiv:2303.13607\]](https://arxiv.org/abs/2303.13607)

Neutrino Sources

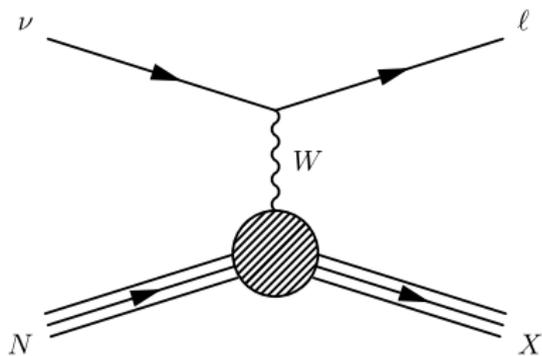


[J. A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)]

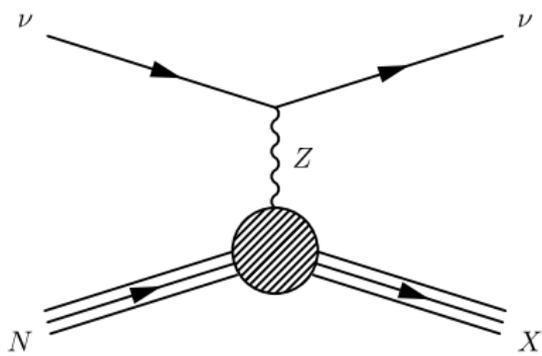
- We focus on ultra-high-energy neutrinos, mainly from Galactic plane.
- Some accelerator neutrinos can reach intermediate high energies ($\gtrsim 10$ GeV)

Neutrino Interactions

Charged-Current (CC) interactions
via W boson

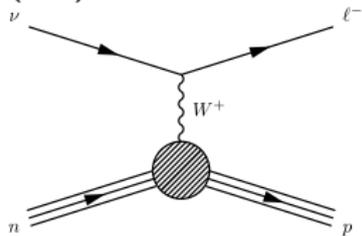


Neutral-Current (NC) interactions
via Z boson

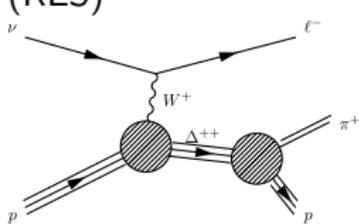


Charged-Current interactions

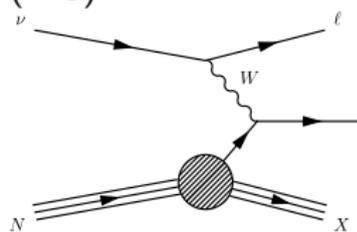
Quasi-elastic scattering (QE)



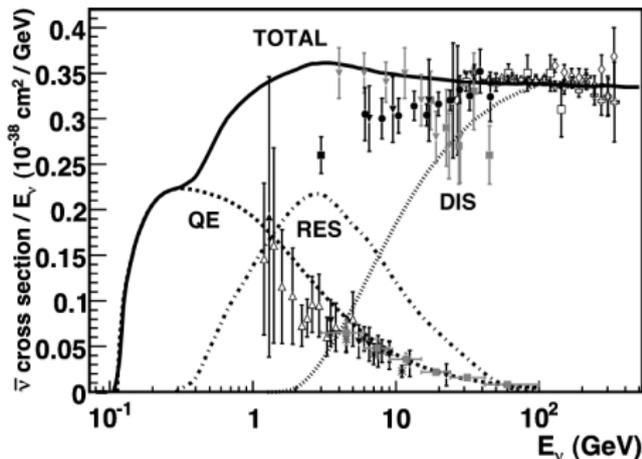
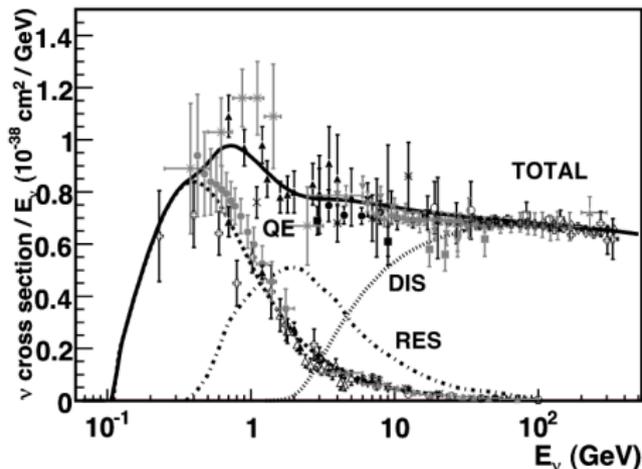
Resonance production (RES)



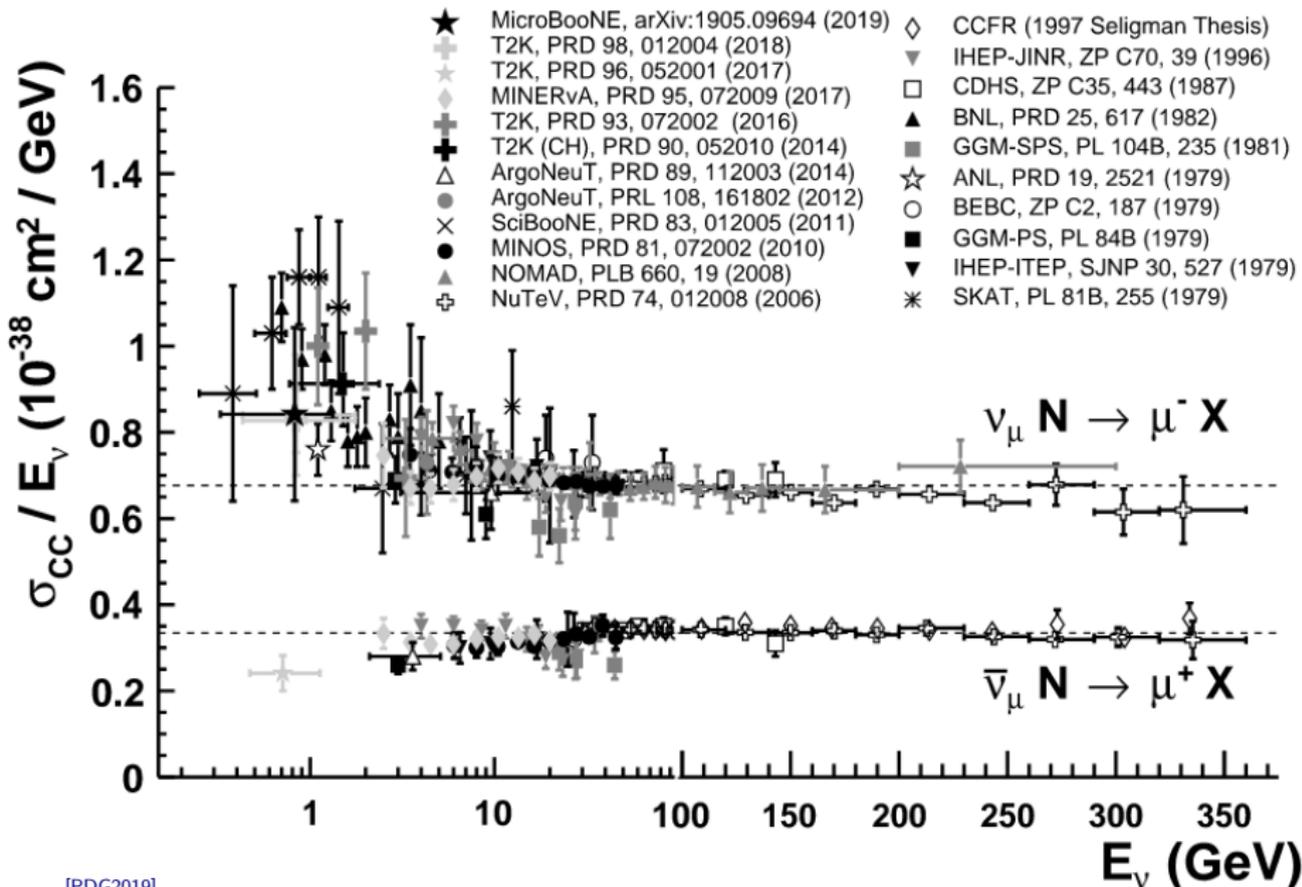
Deeply inelastic scattering (DIS)



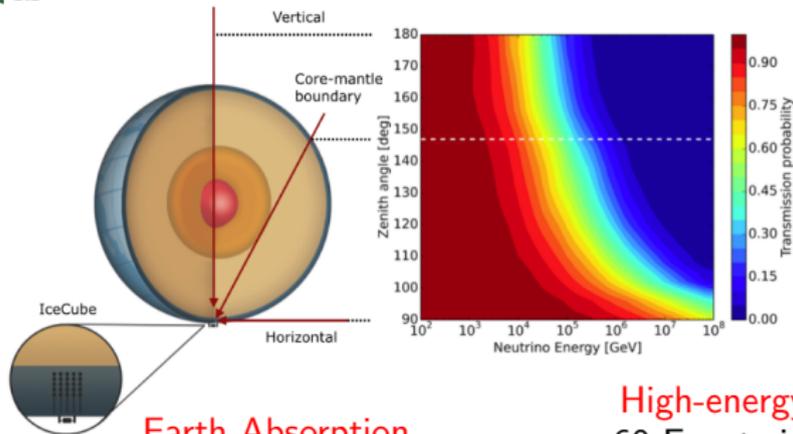
Total neutrino and antineutrino per nucleon CC cross sections



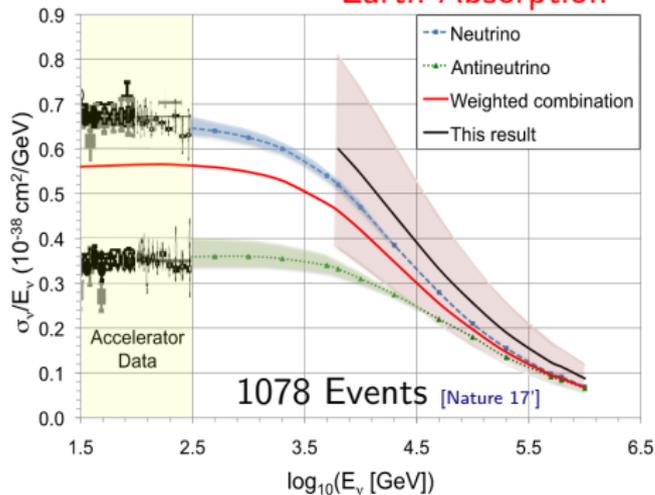
Neutrino-Nucleon CC cross sections



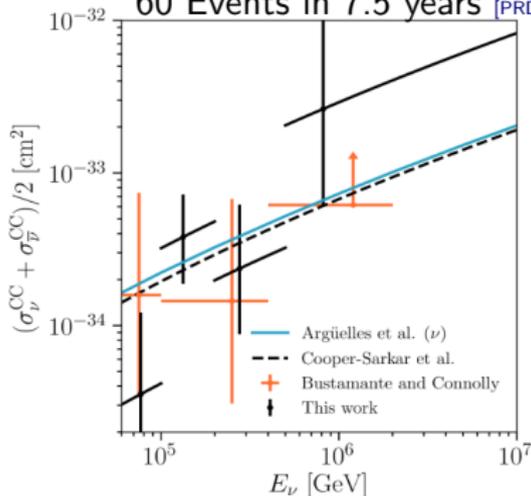
High-energy neutrinos at IceCube



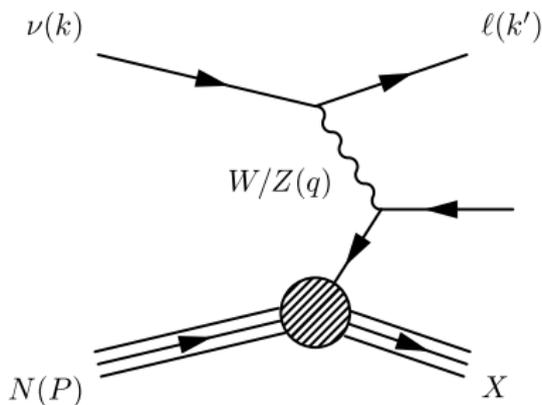
Earth Absorption



High-energy Starting Event 60 Events in 7.5 years [PRD 21]



The neutrino-nucleon DIS cross section



Kinematic variables

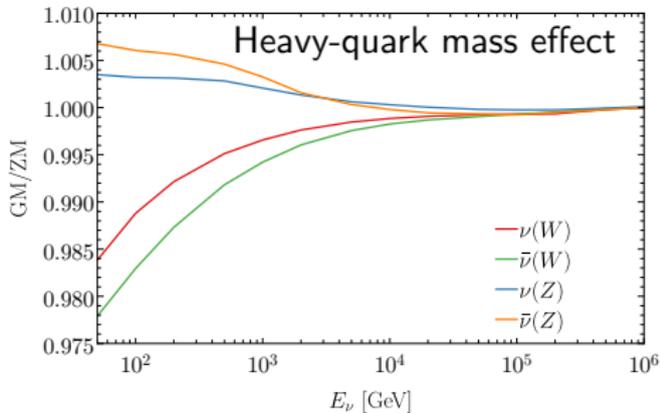
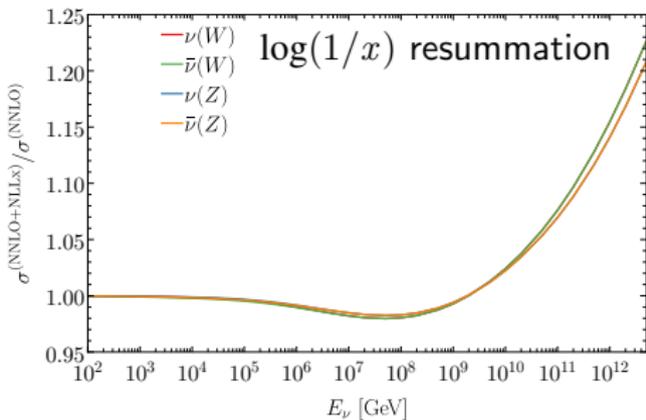
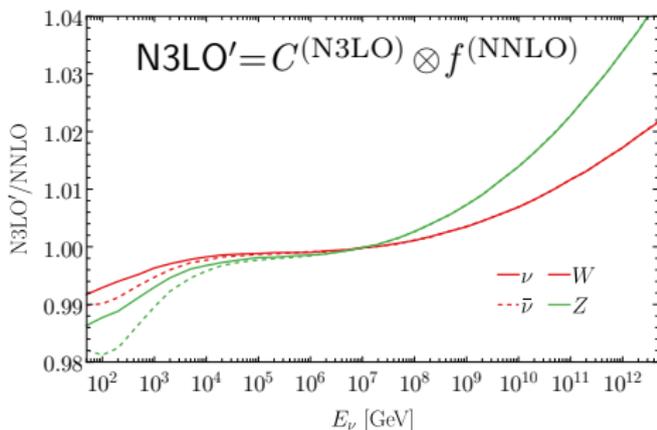
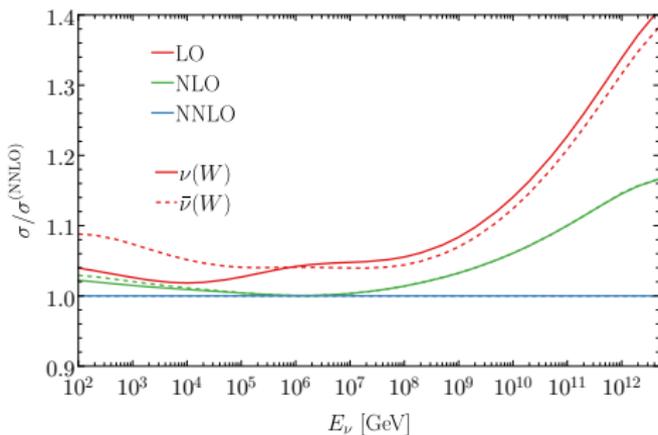
$$Q^2 = -q^2 = -m_\ell^2 + 2E_\nu(E' - k' \cos \theta)$$

$$x = \frac{Q^2}{2P \cdot q} = \frac{Q^2}{2M(E_\nu - E')}, \quad y = \frac{P \cdot q}{P \cdot k} = \frac{E_\nu - E'}{E_\nu} = \frac{Q^2}{2xME_\nu},$$

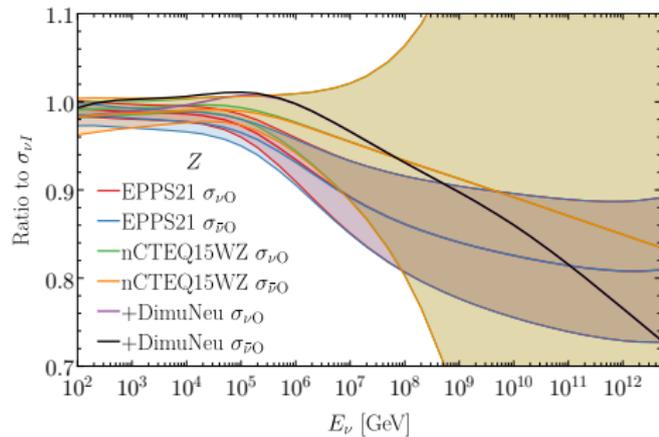
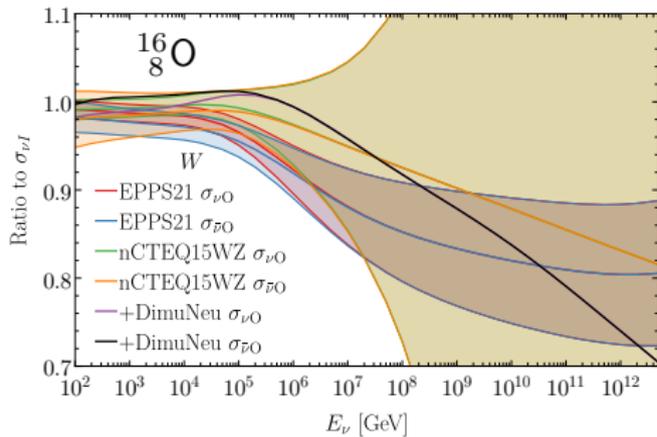
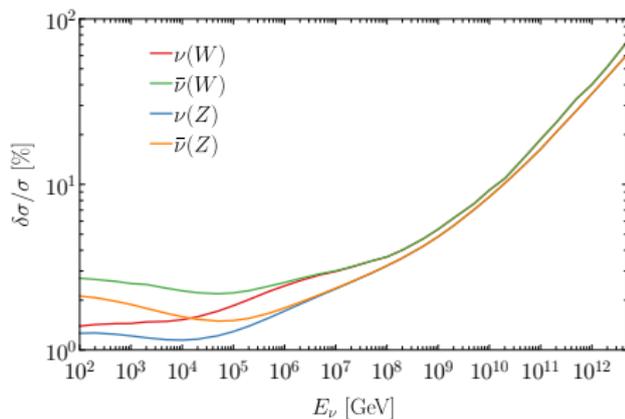
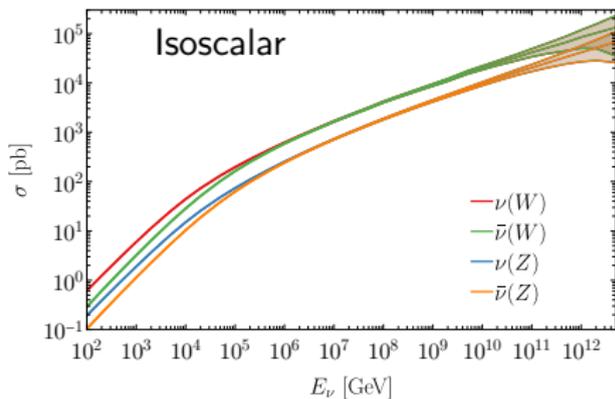
Inclusive cross section

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dx dy} = \frac{G_F^2 ME_\nu}{\pi \left(1 + Q^2/M_{W,Z}^2\right)^2} \left[\begin{array}{c} \frac{y^2}{2} 2xF_1(x, Q^2) + \left(1 - y - \frac{Mxy}{2E}\right) F_2(x, Q^2) \\ \pm y \left(1 - \frac{y}{2}\right) xF_3(x, Q^2) \end{array} \right]$$

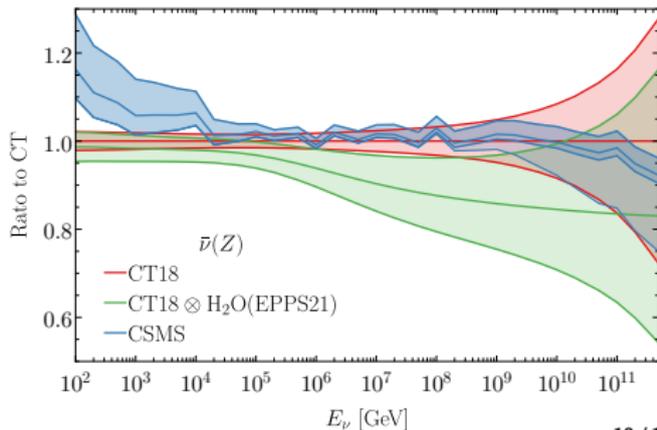
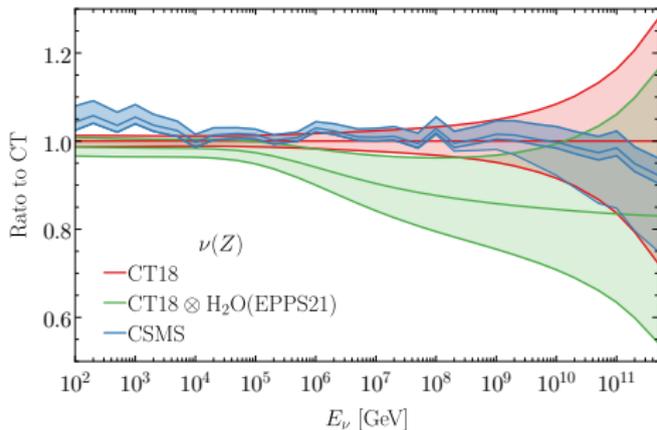
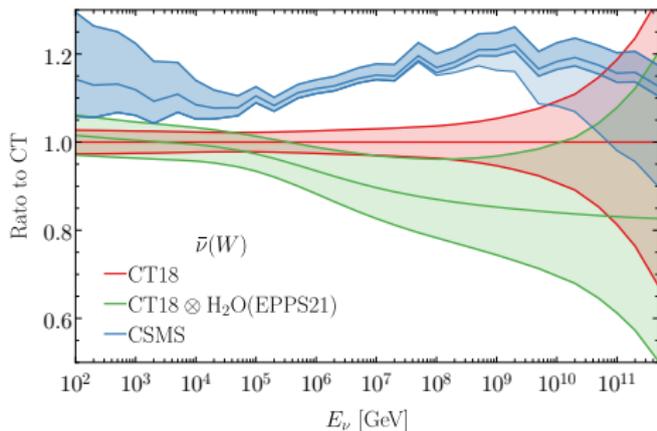
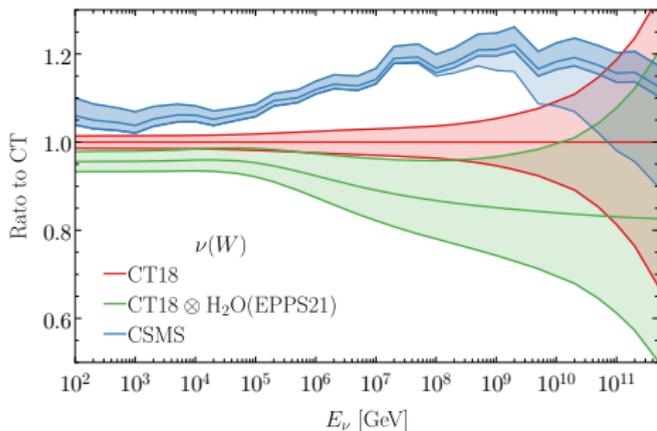
Perturbative calculation



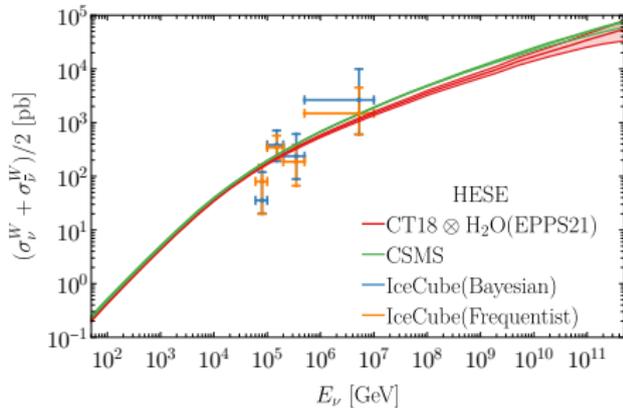
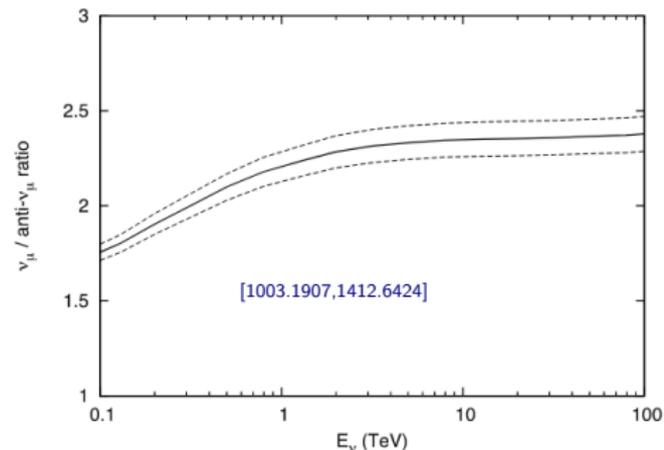
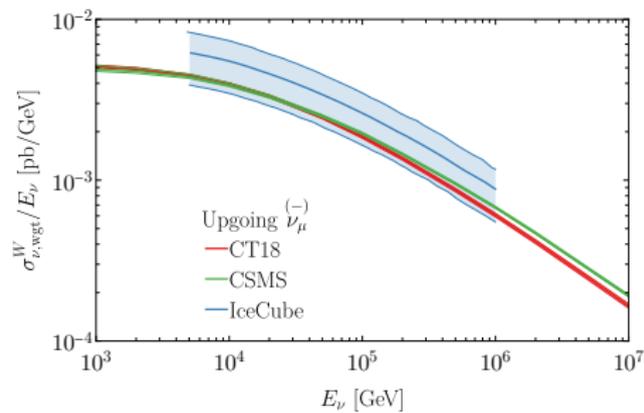
Predictions for neutrino-nuclei cross sections



Comparison with the CSMS (adopted by IceCube)

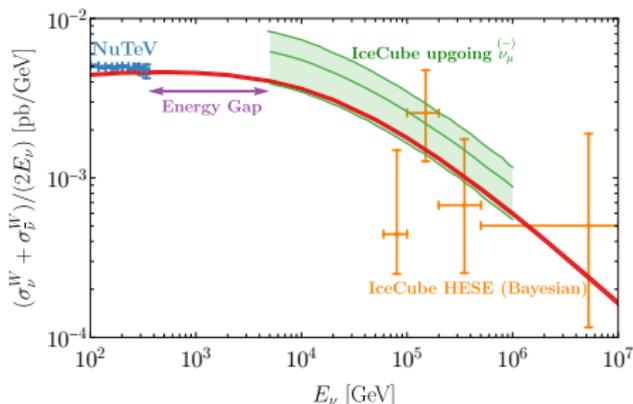
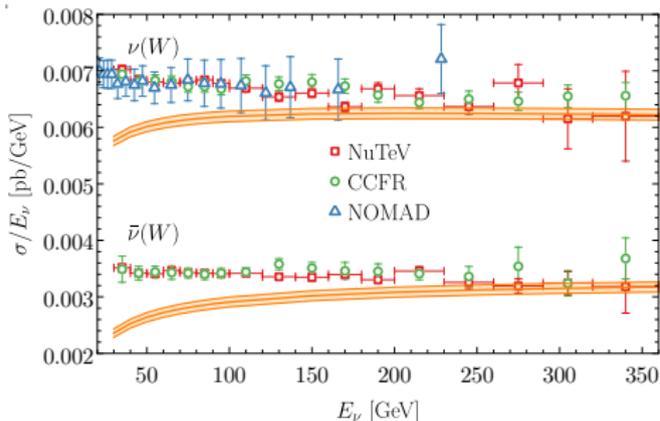


Compare with IceCube data

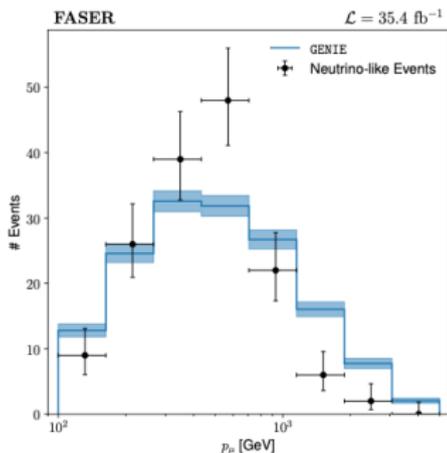


- The absorption cross section is weighted with neutrino flux.
- the HESE cross section is averaged.

Accelerator neutrinos and energy gap



- At low E_ν , the missing Quasi-Elastic (QE) scattering and Resonance (RES) production become important.
- The energy gap can be potentially filled by the FASER (FPF) measurements.
- First FASER measurement comes out [\[2303.14185\]](#).



Conclusion

- We have performed a state-of-art calculation for high-energy neutrino-nucleon scattering.
- Partons have been included up to $n_f = 6$ flavors (4%).
- The perturbative QCD order has been achieved up to exact NNLO (heavy-quark mass effect -2%), and zero-mass N³LO (3%).
- Small- x resummation has been included with the BFKL equation (20%).
- Nuclear effects have been explored with the nuclear PDF approach (20%).
- The PDF uncertainty varies from 1% to 70%.
- Our calculation provides a good description of IceCube data.
- The energy gap between IceCube and accelerator sources can be filled by the FASER (FPF) experiment.

The Earth absorption

- At high E_ν , astrophysical neutrinos dominate.
- Single-power-law astro. flux

$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\text{astro}} \left(\frac{E_\nu}{100 \text{ TeV}} \right)^{-\gamma_{\text{astro}}} \cdot 10^{-18} \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1},$$

- The upward-going events (from northern sky)

$$\frac{dN_{\text{evt}}}{dE_\nu} = \sigma_\nu^W \frac{d\Phi_{6\nu}}{dE_\nu} \mathcal{P}_{\text{trans}}$$

- The transmission probability

$$\mathcal{P}_{\text{trans}} \sim \exp\{-L(\theta)/\lambda(E_\nu)\} = \exp\{-L(\theta)\kappa\sigma(E_\nu)\}$$

- Earth model: isotopic abundance and density

