Structure functions at low momentum transfer and neutrino cross sections

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Introduction

Motivation

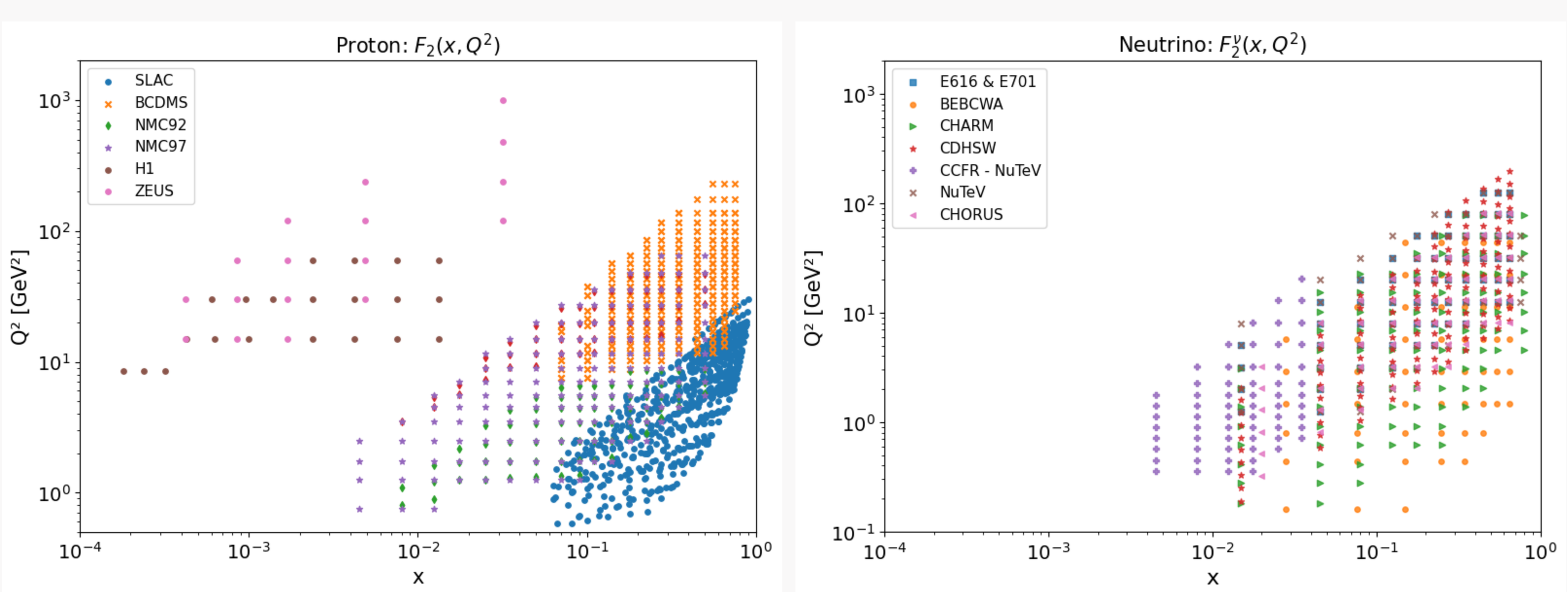
- Reliable neutrino cross section predictions are required for current and future neutrino experiments over the GeV to TeV energy range.
- Deep inelastic scattering (DIS) cross sections below a few tens of GeV include non-negligible contributions from the low-Q^2 region, where PDF based structure functions become unreliable.
- Different models of low-Q^2 structure functions can produce noticeable differences in neutrino cross section predictions.

Goal of this work

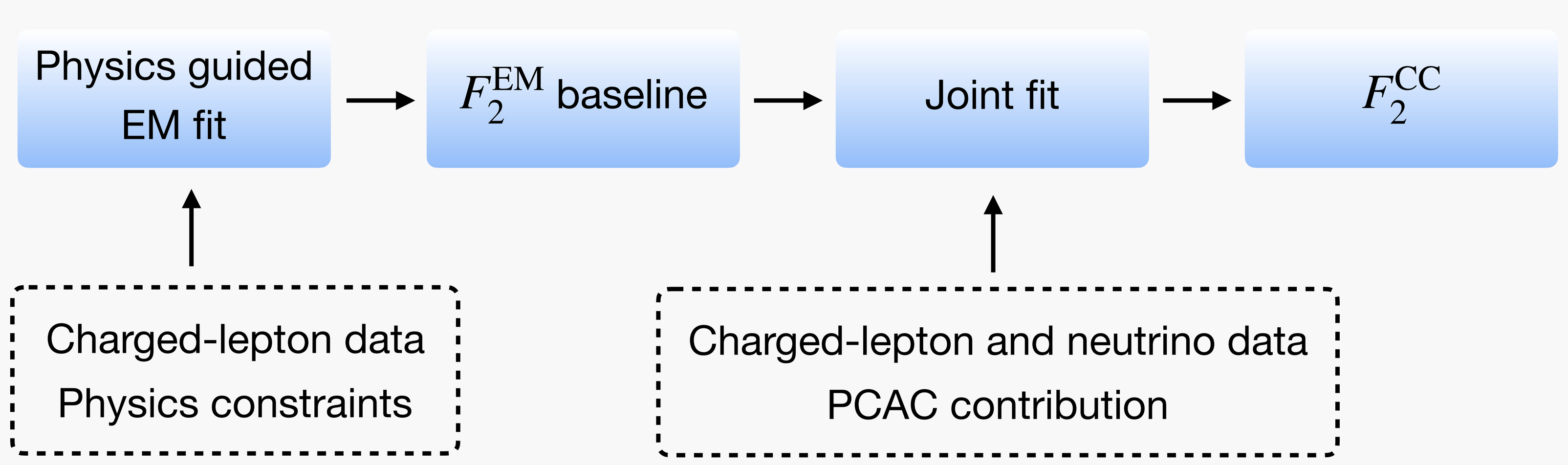
- Construct charged current structure functions at low Q2 using neural networks with physics guidance.
- Improve predictions for neutrino DIS cross sections.

Input data and fitting strategy

Charged lepton scattering   Neutrino scattering



Kinematic coverage of the charged lepton and neutrino scattering data used in the fit.



Physics inputs

Baseline constraints

- **Small-x**: rise based on Regge theory, implemented through $x^{-a(Q^2)}$.
- **Large-x**: suppression as $x \to 1$, implemented through $(1-x)^{b(Q^2)}$.
- **Low-Q^2**: real photon limit $(F_2^{EM} \propto Q^2$ as $Q^2 \to 0)$, implemented through $Q^2/(Q^2+C)$.

PCAC contribution

- **Kulagin—Petti (KP) model:** relates the PCAC contribution to the longitudinal structure function with the pion-nucleon cross section,

$$F_L^{PCAC}(x,Q^2) = \frac{f_\pi^2}{\pi}\sigma_\pi(W^2) f_{PCAC}(Q^2)$$

with a dipole form factor $f_{PCAC}(Q^2) = \left(1+Q^2/M_{PCAC}^2\right)^{-2}$.

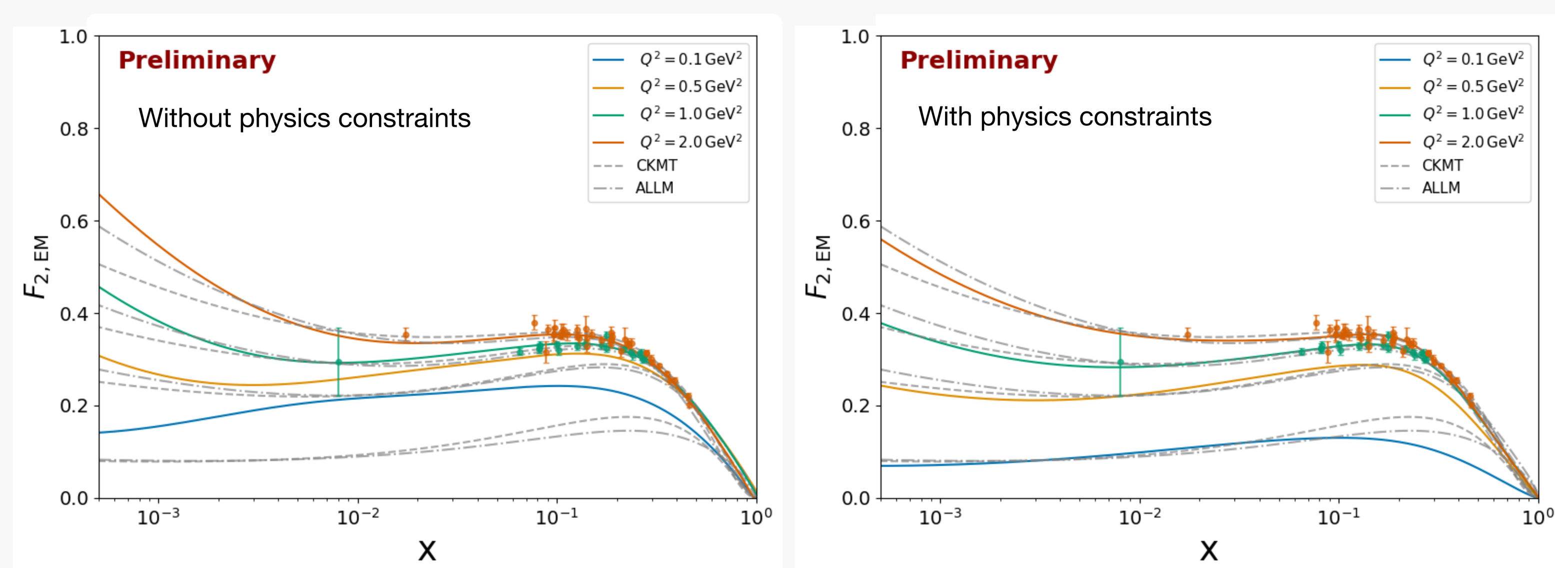
Structure functions

Electromagnetic structure function

- Electromagnetic structure function is first constructed as a baseline using charged lepton scattering data and physics constraints.

$$F_2^{EM}(x,Q^2) = x^{-a(Q^2)}(1-x)^{b(Q^2)}\frac{Q^2}{Q^2+C} f_2^{NN}(x,Q^2)$$

- The exponent $a(Q^2)$ is adopted from a phenomenological fit to low-x HERA data[2], while $b(Q^2)$ and C are optimized through training with the data.



The figures compare the EM structure function fit without and with the physics constraints. The CKMT[1] and ALLM[2] models are also included for comparison.

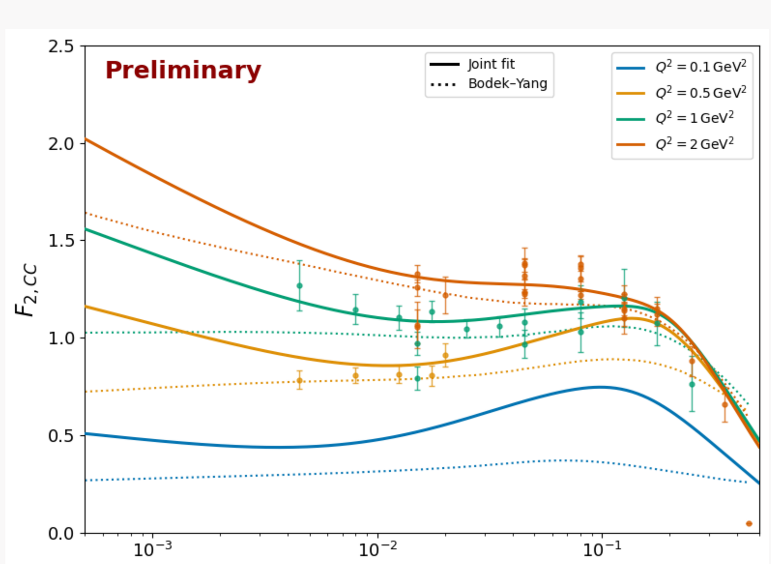
Charged current structure function

- The electromagnetic baseline is extended to the charged current structure function through a joint fit to charged lepton and neutrino data

$$F_2^{CC}(x,Q^2) = R_{\nu/EM}^{PDF}(x,Q^2)\, F_2^{EM,mod}(x,Q^2) + F_2^{PCAC}(x,Q^2) + \Delta F_2^{CC}(x,Q^2)$$

- $R_{\nu/EM}^{PDF}$: EM to CC matching factor evaluated from CT18 PDFs
- F_2^{PCAC} : axial contribution from the partially conserved axial vector current.
- ΔF_2^{CC} : remaining contribution

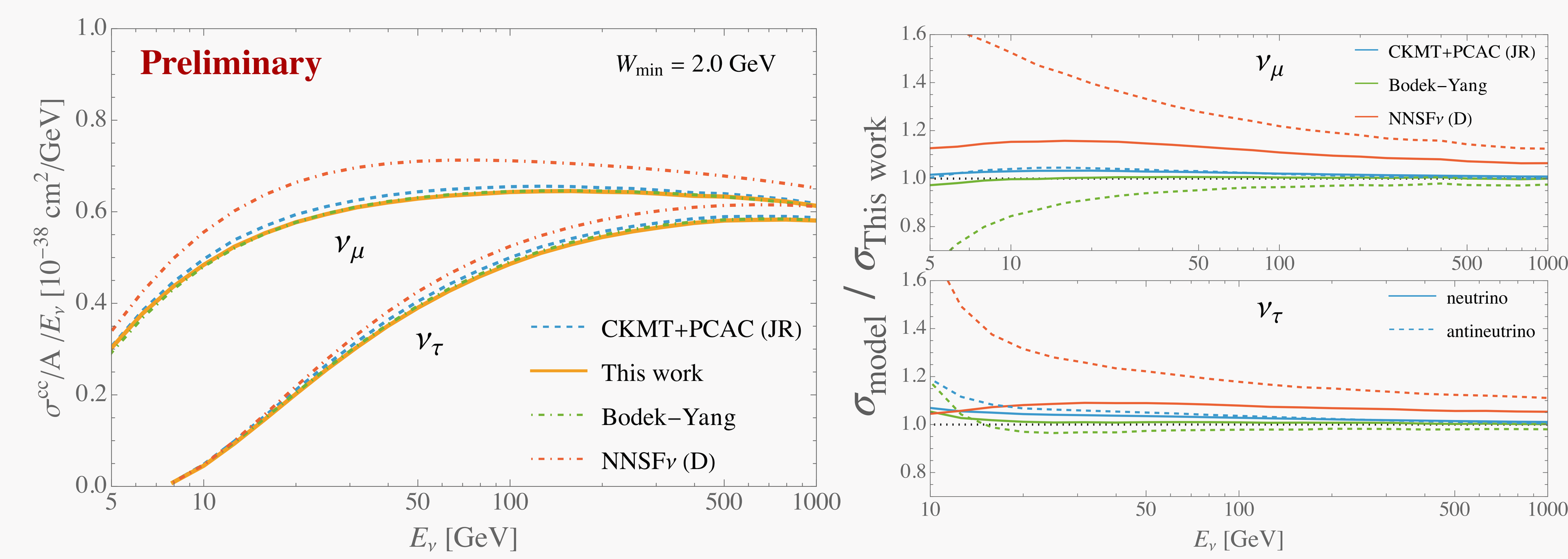
Charged current structure function F_2^{CC} from the joint fit. The Bodek–Yang[3] model is also shown for comparison.



Cross sections

- Using the resulting low-Q^2 structure functions, charged current DIS cross sections are evaluated for neutrinos and antineutrinos. The differential DIS cross section is given by

$$\frac{d^2\sigma^{\nu(\bar\nu)}}{dx\,dy} \simeq \frac{G_F^2 m_N E_\nu}{\pi(1+Q^2/M_W^2)^2}\left(\left(y^2 x + \frac{m_\ell^2 y}{2E_\nu m_N}\right)F_{1,CC} + \left[\left(1-\frac{m_\ell^2}{4E_\nu^2}\right) - \left(1+\frac{m_N x}{2E_\nu}\right)y\right]F_{2,CC}\right.$$
$$\left. \pm \left[xy\left(1-\frac{y}{2}\right) - \frac{m_\ell^2 y}{4E_\nu m_N}\right]F_{3,CC} + \frac{m_\ell^2(m_\ell^2+Q^2)}{4E_\nu^2 m_N^2 x}F_{4,CC} - \frac{m_\ell^2}{E_\nu m_N}F_{5,CC}(x,Q^2)\right)$$



Cross sections for muon and tau neutrinos with different structure function models, JR[5], BY[3], NNSFν[6], and the corresponding ratios. Antineutrino results are also included in the ratio plots.

- The model dependence is generally larger at lower energies, particularly for antineutrinos.
- The physics guided neural network predictions show closer agreement with conventional low-Q^2 models than the unconstrained neural network result.

Key findings and outlook

Key findings

- Low-Q^2 charged current structure functions have been constructed using neural networks with physics constraints.
- Physics constraints reduce discrepancies between data-driven and phenomenological models.
- The model dependence of cross sections is stronger for antineutrinos.

Ongoing/Future works

- Improve the F_3^{CC} and investigate the different model dependence between neutrino and antineutrino cross sections
- Refine the PCAC correction and assess its impact on the cross sections.

References

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[6] NNSFν: A. Candido et al., J. High Energy Phys. 05 (2023) 149

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