Nucleon structure functions at low momentum transfer and neutrino cross sections

Yu Seon Jeong (Sungkyunkwan University)

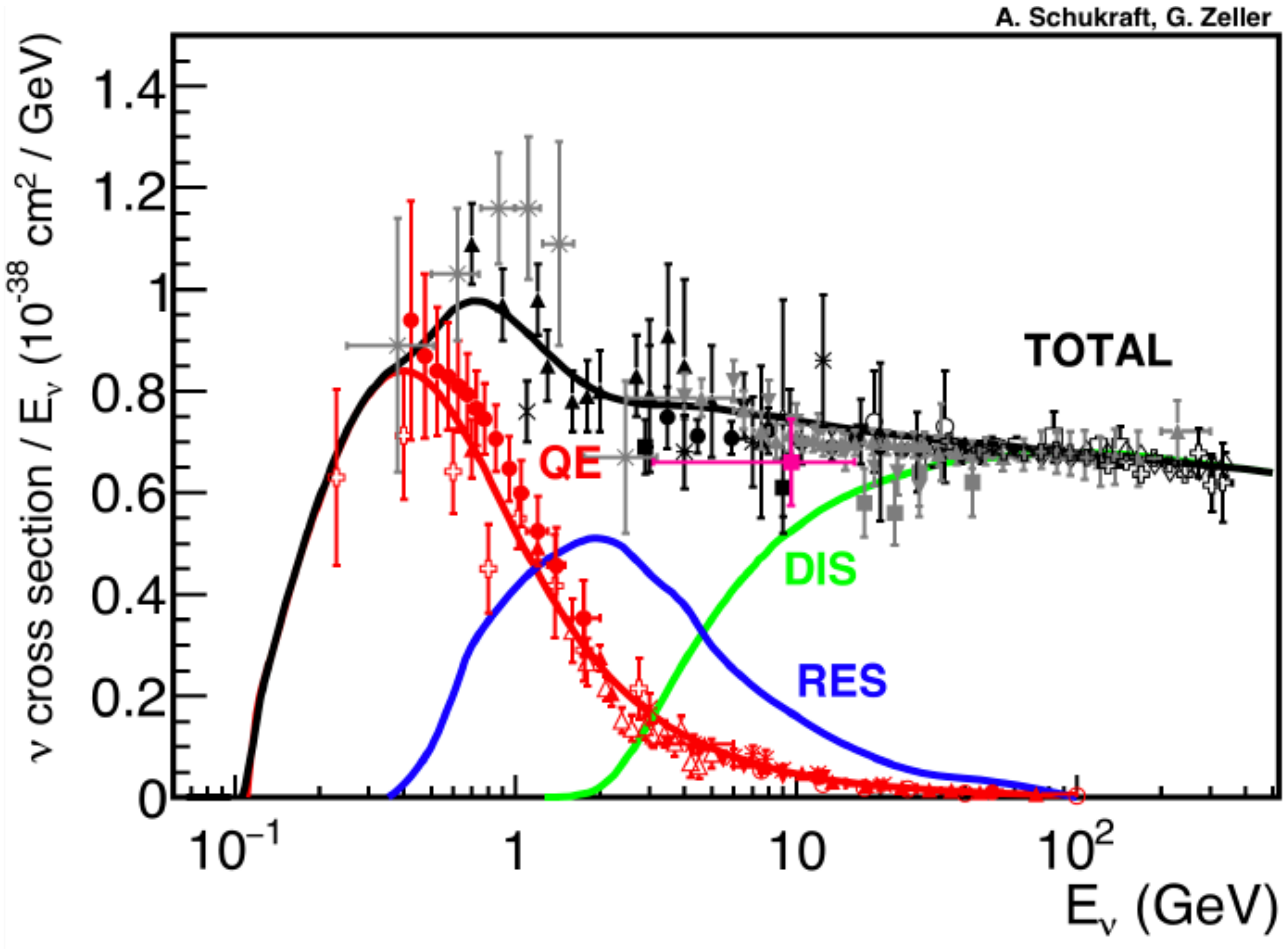
Based on the work with Sudipta Das, Diksha Garg and Mary Hall Reno (University of Iowa)

FLASY 2026

August 17-22, 2026

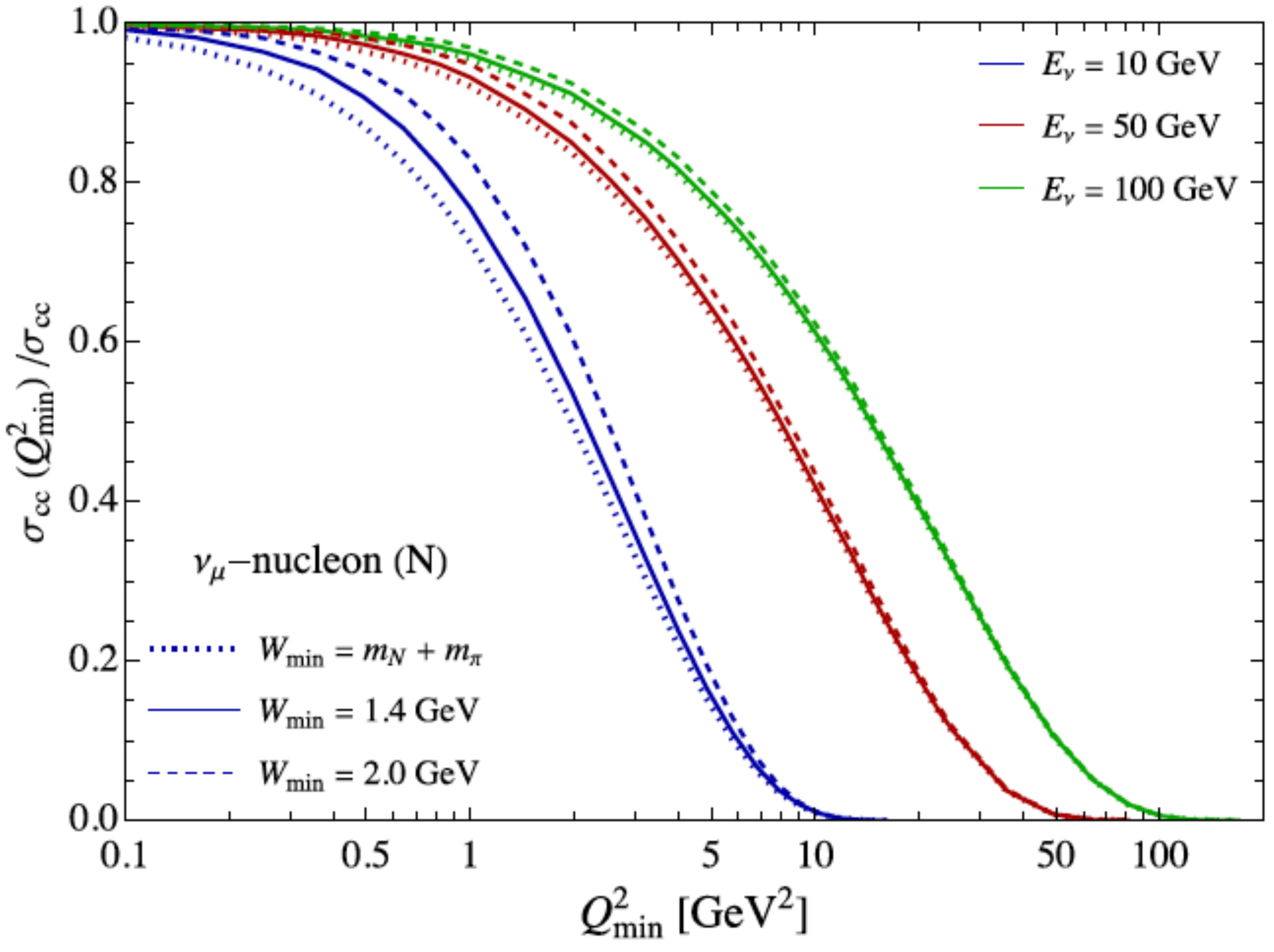
Commodore Hotel, Gyeongju

Why low momentum transfer (Q^2)?



- High energy: deep-inelastic scattering (DIS) dominates
- Intermediate energy: quasi-elastic (QE), RES and DIS overlap
- Shallow inelastic scattering (SIS) region
  - Transition region between RES and DIS
  - No clear boundary between the two regimes -> careful treatment is needed to avoid double counting.

Low-Q^2 contribution to neutrino cross sections



- The low-Q2 contribution to the cross section is non-negligible.
  - (e.g.) at E=10 GeV, about 20-30% of the cross section comes from Q2 < 1GeV2.
  - The contribution becomes more important at lower energies.
- Reliable modeling of the low Q2 region is important for neutrino cross section predictions.

Neutrino DIS and structure functions

- Neutrino-nucleon charged-current (CC) cross section for deep inelastic scattering (DIS)

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

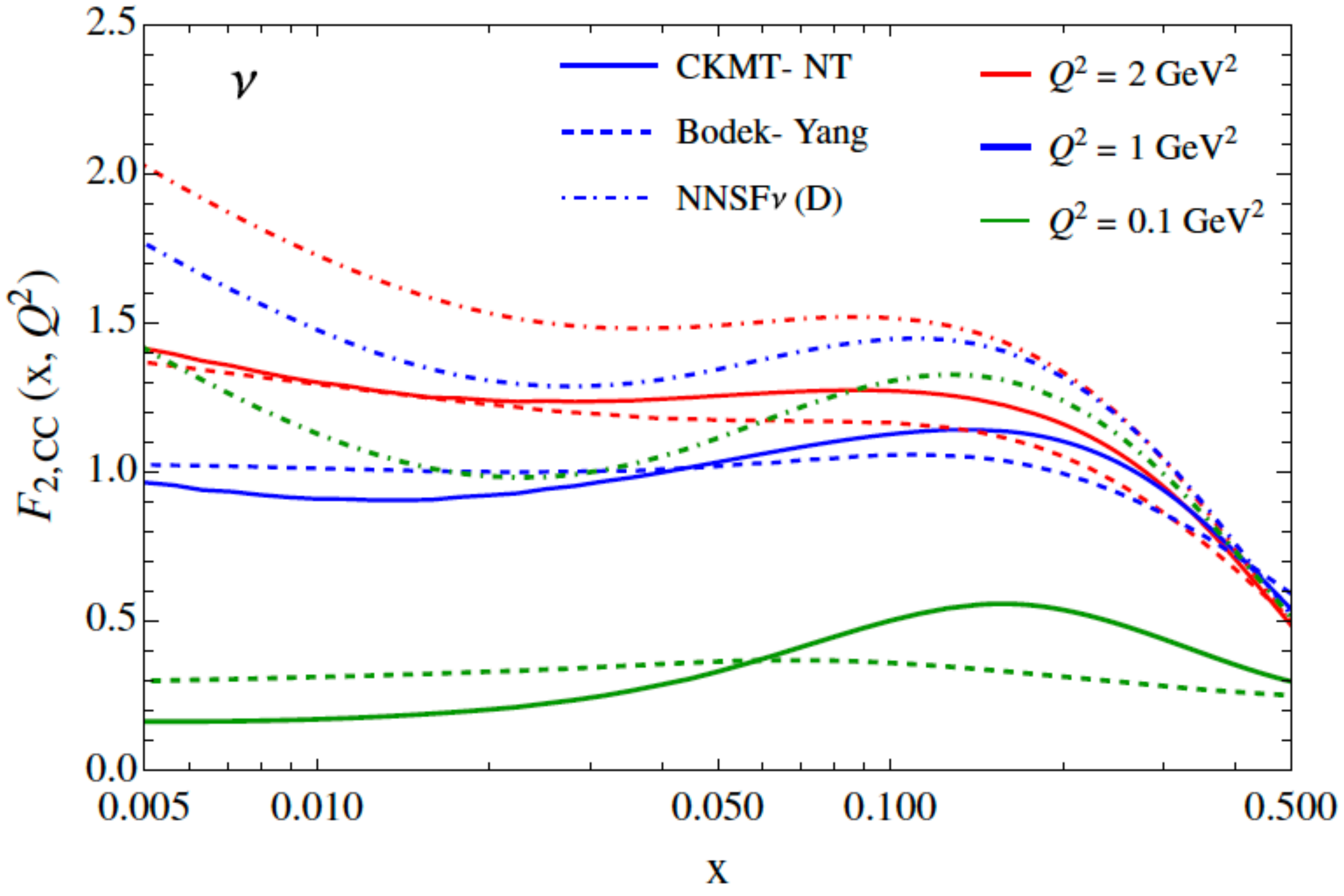
$$\pm \left[xy\left(1-\frac{y}{2}\right) - \frac{m_\ell^2 y}{4E_\nu m_N}\right] F_{3,\mathrm{CC}}(x,Q^2) + \frac{m_\ell^2(m_\ell^2+Q^2)}{4E_\nu^2 m_N^2 x} F_{4,\mathrm{CC}}(x,Q^2) - \frac{m_\ell^2}{E_\nu m_N} F_{5,\mathrm{CC}}(x,Q^2)\Bigg)$$

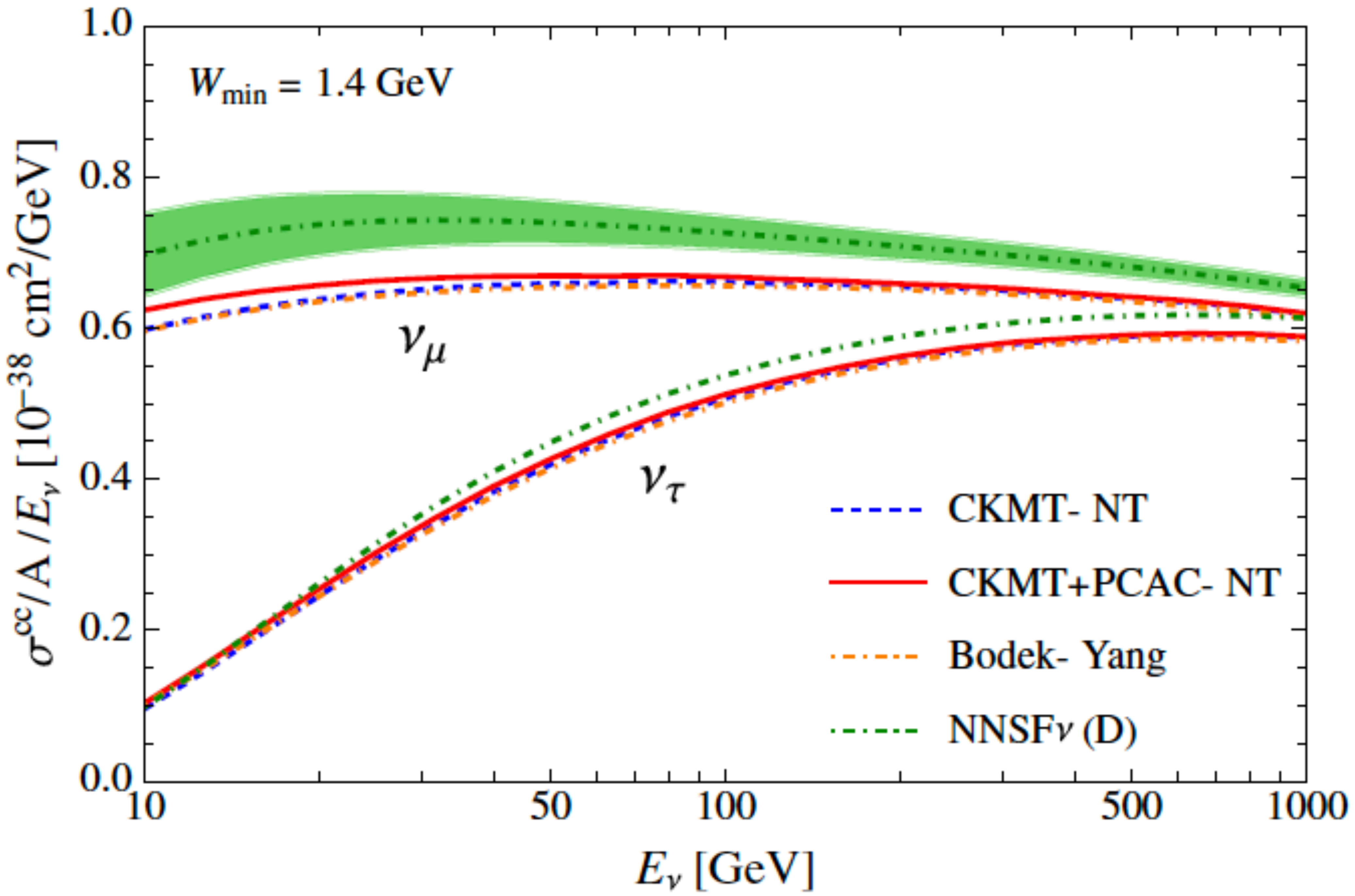
Y. S. Jeong and M. H. Reno, *Phys. Rev. D 81 (2010) 114012*

- Structure functions:
  - Large Q2: perturbative QCD & PDFs -> relatively well understood
  - Low Q2: pQCD is less reliable -> need modeling

- Low Q2 structure function modeling directly affects neutrino cross section predictions.

Model discrepancy at low Q^2



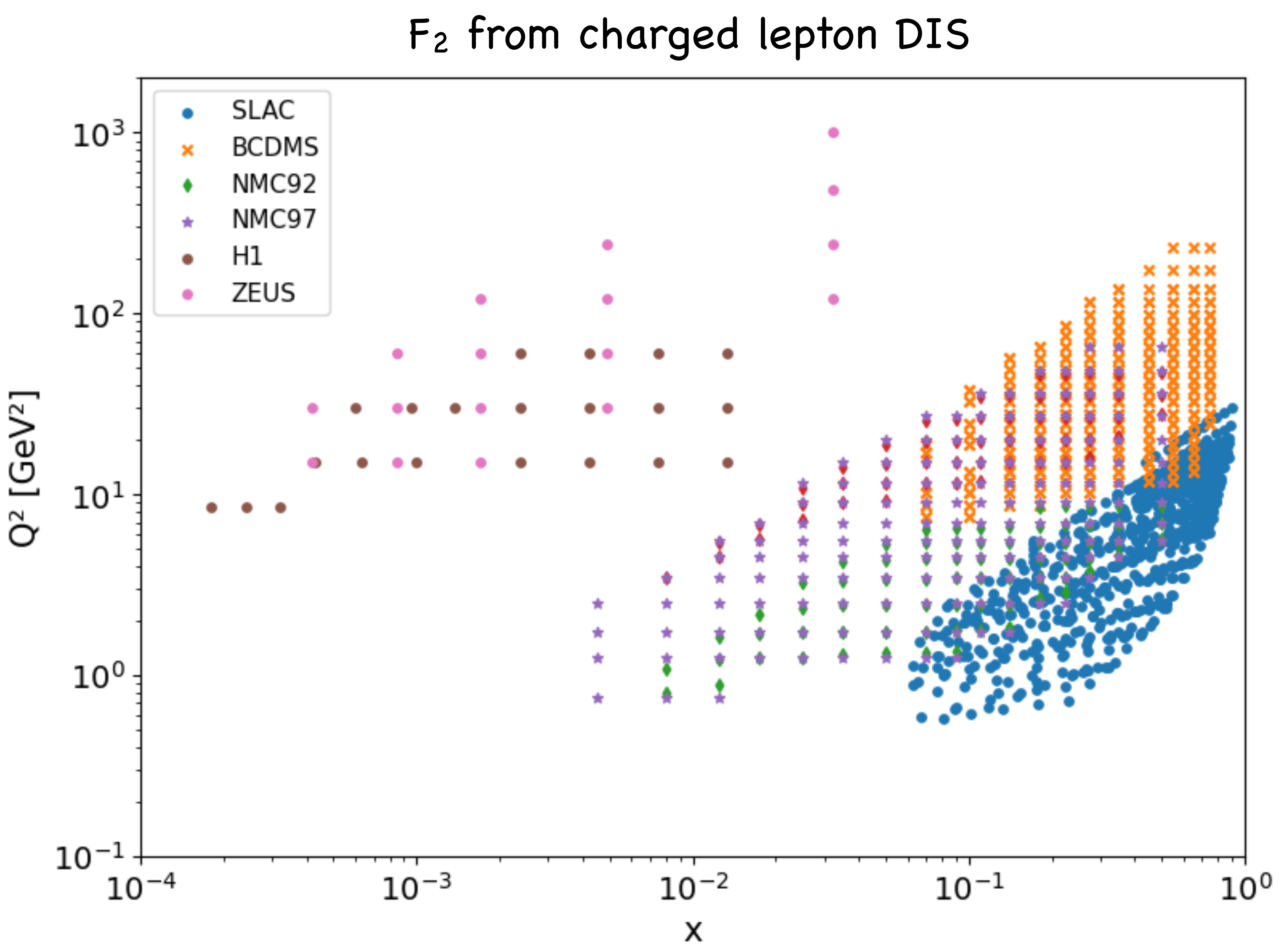


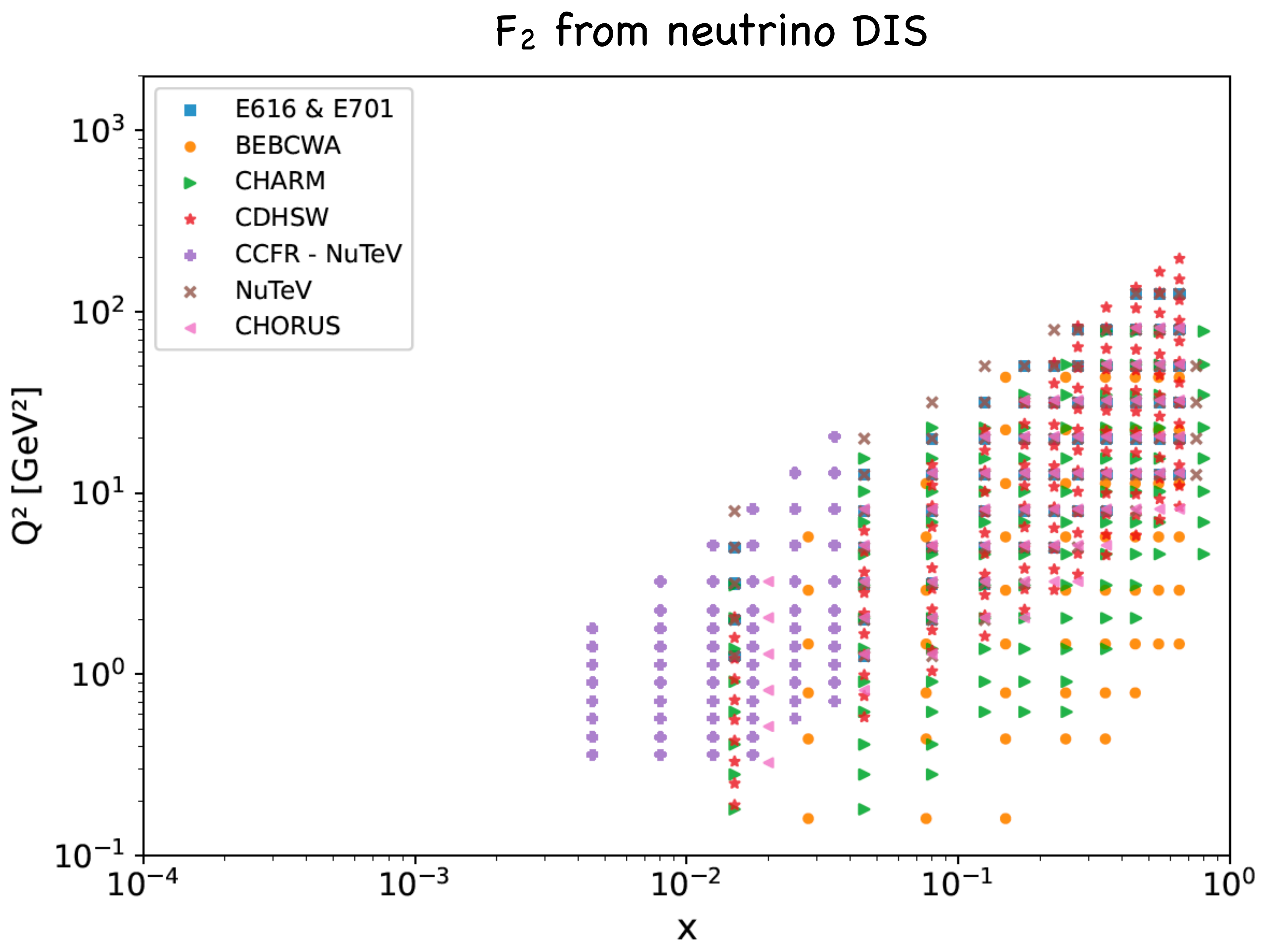
- CKMT-based and Bodek-Yang results are relatively close.
- NNSFnu, based on a neural network approach, shows a sizable difference.

Physics guided neural network approach

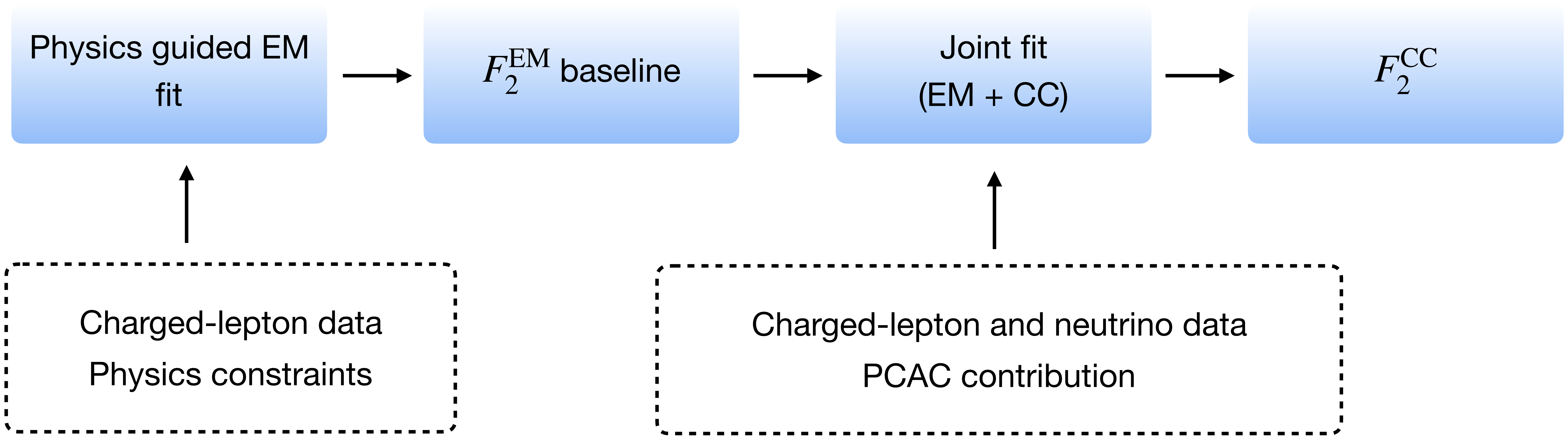
- Physics constraints
- Charged lepton scattering and neutrino scattering data

Experimental input data and kinematic coverage





Overall fitting strategy



Physics-guided EM structure function

- Physics guided neural-network parameterization

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

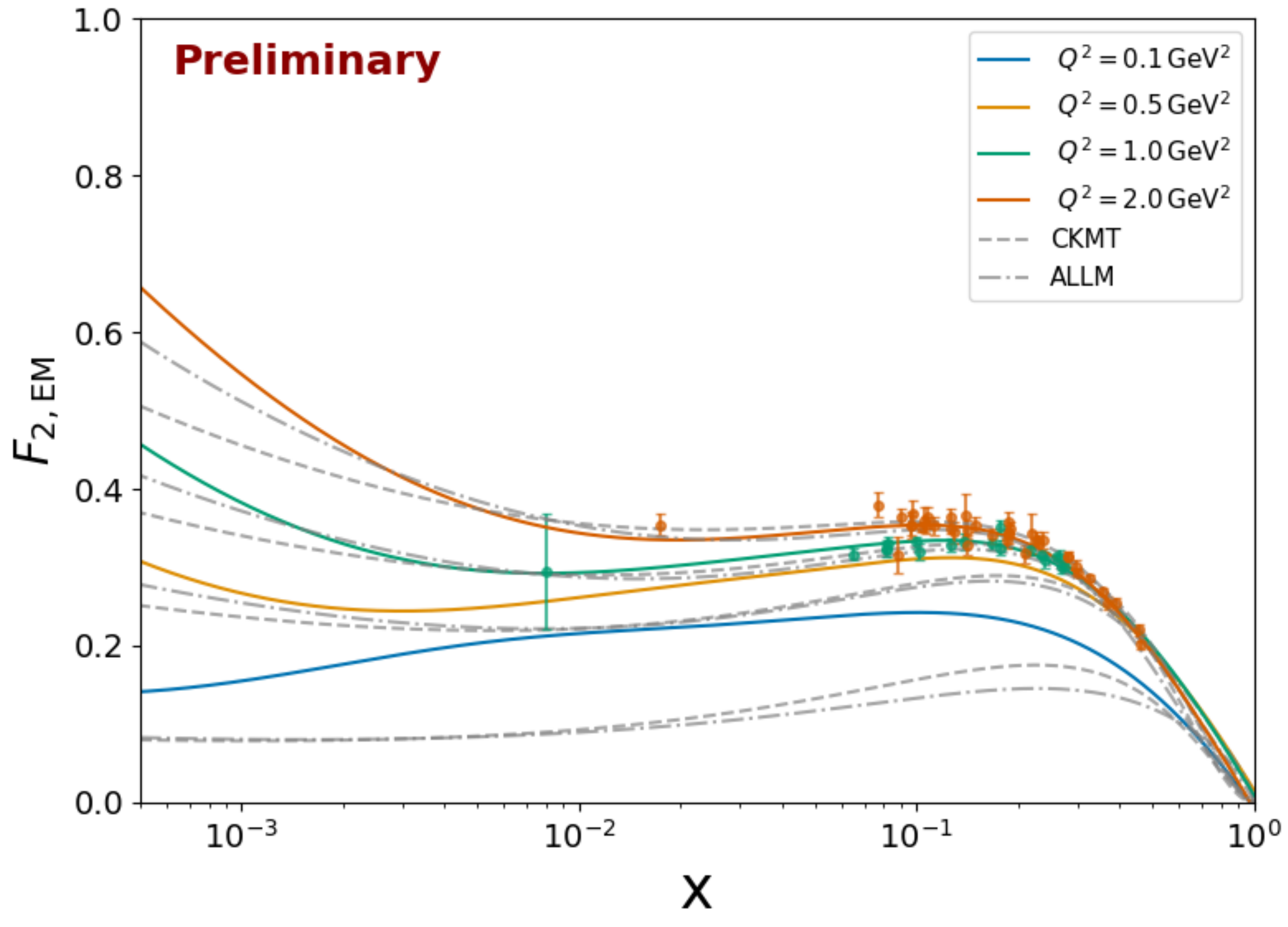
Small-x   Large-x   Low-Q2

- Physics constraints
  - Small-x: rise toward lower x, motivated by Regge theory
  - Large-x: suppression as $x \to 1$
  - Low-Q2: $F_2^{\rm EM} \propto Q^2$ as $Q^2 \to 0$, required by EM current conservation in the real-photon limit.

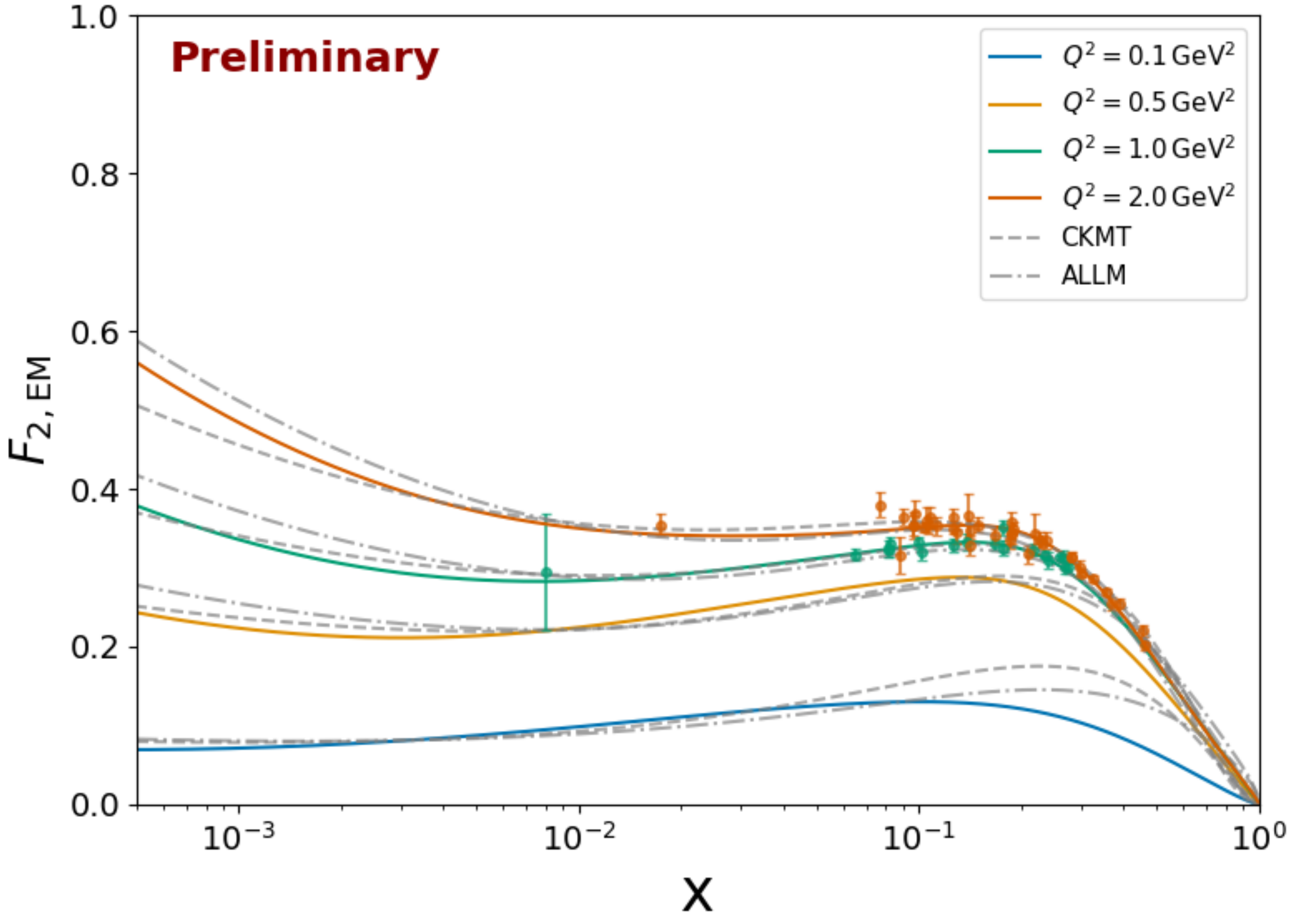
- $f_2^{\rm NN}(x, Q^2)$: learns the remaining x and Q2 dependence from data

Impact of physics constraints

Without physics constraints



With physics constraints



- Physics constraints affect the results outside the data region.
- With physics constraints, the results become closer to traditional phenomenological models.

CC structure functions: joint fit

$$F_2^{CC}(x,Q^2) = \underbrace{R_{\nu/EM}^{PDF}(x,Q^2)\, F_2^{EM,mod}(x,Q^2)}_{\text{EM-based CC baseline}} + F_2^{PCAC}(x,Q^2) + \Delta F_2^{CC}(x,Q^2)$$

- $R_{\nu/EM}^{PDF}$: EM to CC matching factor, evaluated using CT18 PDFs
- F_2^{PCAC} : low Q^2 axial contribution from the partially conserved axial vector current
- ΔF_2^{CC} : remaining contributions

■ Joint fit:

- Using charged lepton and neutrino data
- The EM component is re-optimized in the joint fit.

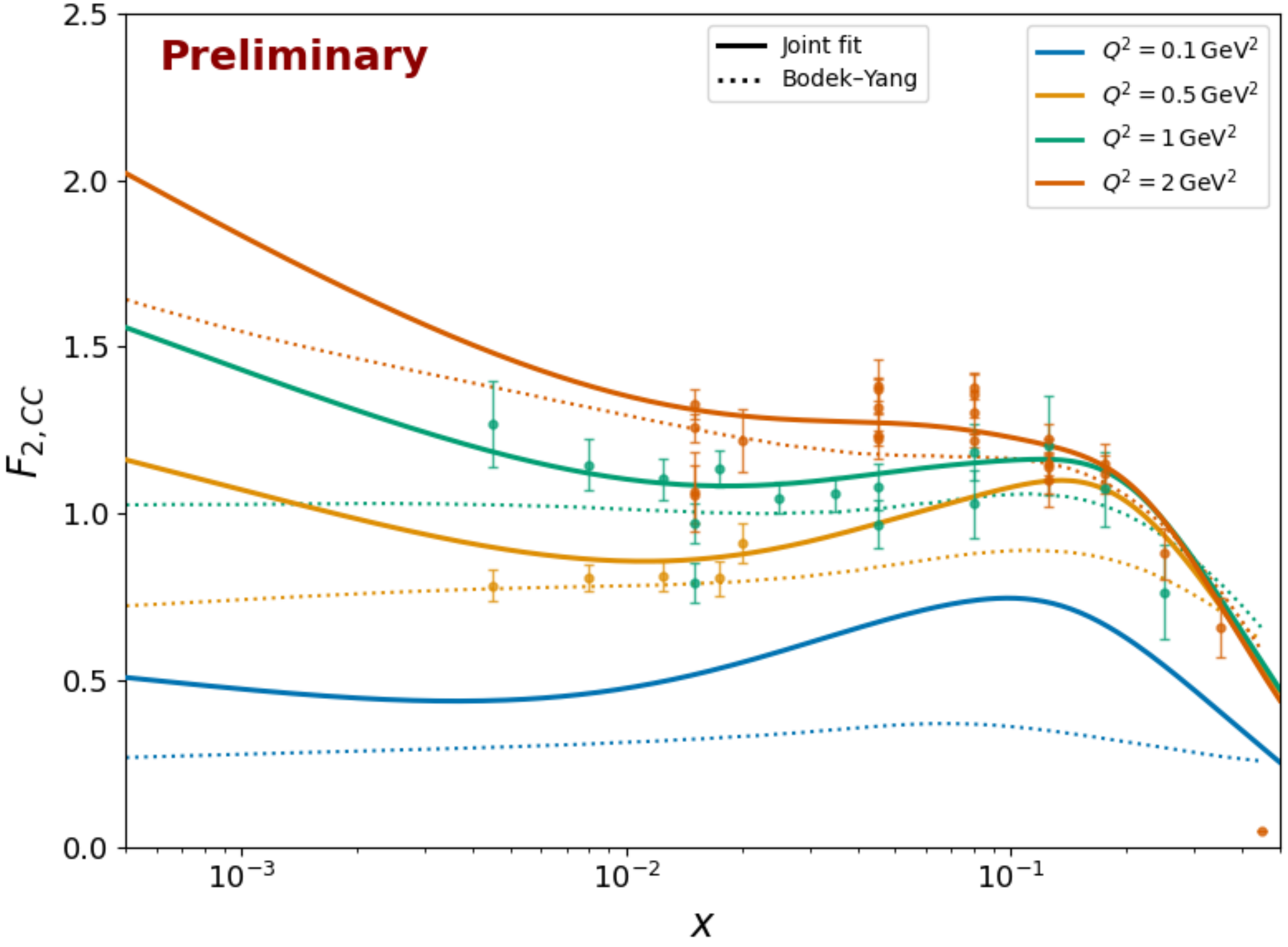
PCAC input

Kulagin—Petti model: PCAC contribution related to the pion-nucleon cross section,

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

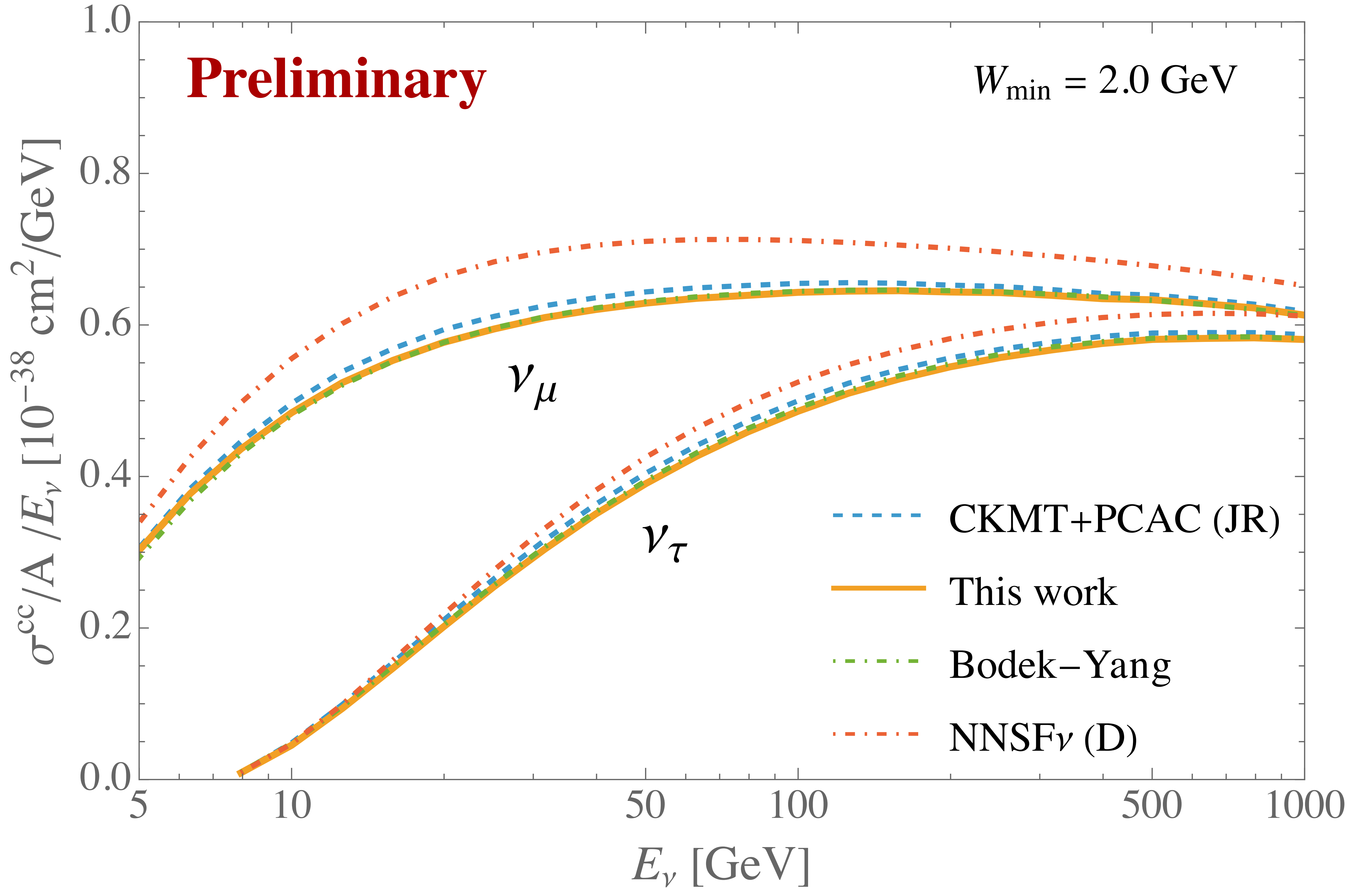
with a dipole form factor $f_{PCAC}(Q^2) = \left(1 + Q^2/M_{PCAC}^2\right)^{-2}$.

Joint fit result for CC structure function



- The results from the joint fit agree reasonably well with the neutrino data
- The physics guided behavior is retained, especially in the poorly constrained low Q^2 region.

Charged current neutrino cross sections



- Physics guided NN predictions are closer to traditional phenomenological models.
- Differences between structure function models are less pronounced in the total cross sections.

Summary and outlook

- Key findings
  - Physics guidance has a significant impact in poorly constrained regions.
  - The resulting structure functions and cross sections are closer to conventional models.
  - Model differences visible in structure functions are less pronounced in total cross sections.

- Ongoing/outlook
  - Differential cross sections to better probe model dependence of structure functions.
  - Low Q^2 modeling is important for precision measurements of neutrino oscillation.
  - Higher-energy neutrino and ν_τ measurements may help test and constrain the structure function models relevant to lower energies.