Neutrino cross sections for shallow- and deep-inelastic scattering

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Work with M. H. Reno (Univ. of Iowa) (arXiv: 2307.09241)

CHUNG-ANG UNIVERSITY
HIGH ENERGY PHYSICS

Forward Physics Facility theory workshop

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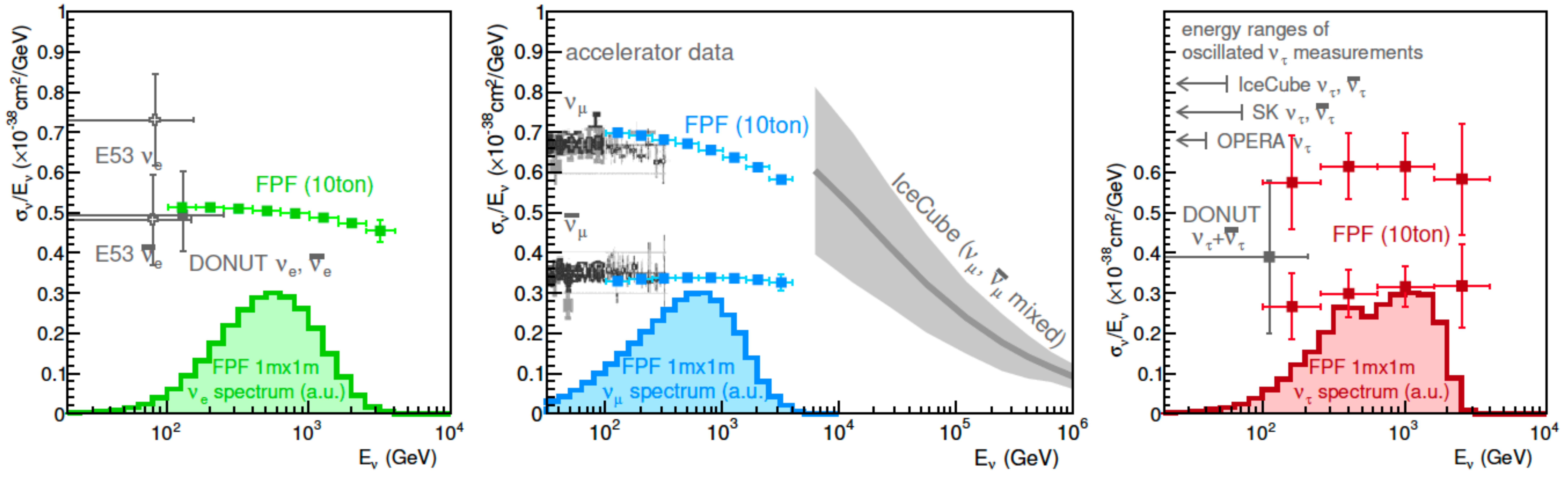
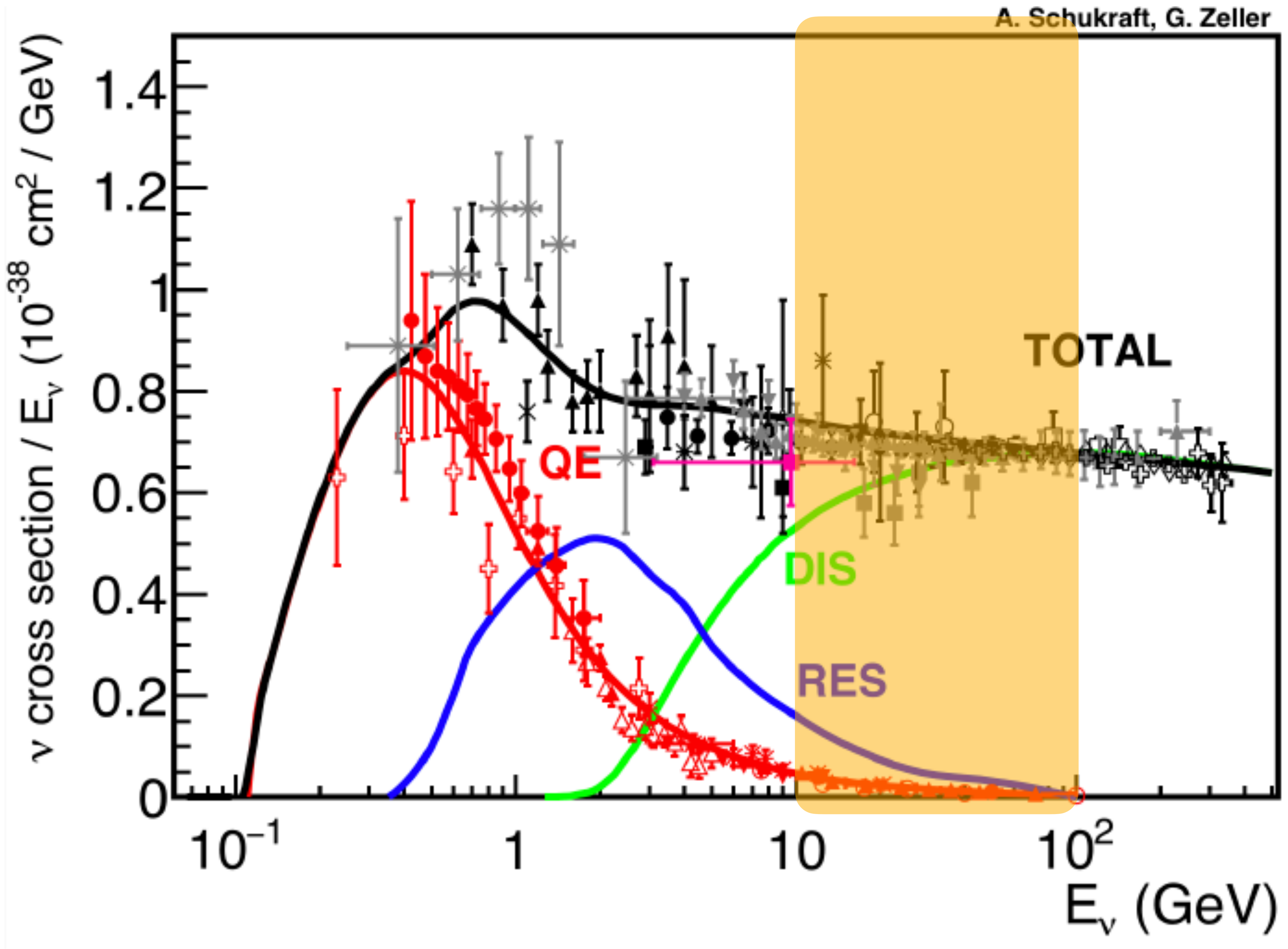
Neutrinos at the FPF



- The LHC produces a large number of neutrinos in the forward direction for all three flavors.
- The neutrinos that reach to the FPF can have energies up to a few TeV.
  - mainly distributed above 100 GeV, but there are considerable amount in 10s GeV region.

FPF White paper: *J.Phys.G 50 (2023) 3, 030501*

Neutrino interactions



- For E > 100 GeV, neutrinos interact through deep inelastic scattering.
- In the energies of 10 – 100 GeV, there exist different types of interactions, so there should be the transition regions.
- It is important to understand the cross sections in the transition regions to avoid double counting.

Detector	CCQE					CCRES					NCEL	NCRES
	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$	all	all
FASERν2	60	50	570	350	3.5	170	180	1.6k	1.1k	10	170	1.3k
FLArE	40	40	420	260	3.5	120	140	1.2k	860	10	130	940

Table from FPF White paper: *J.Phys.G 50 (2023) 3, 030501*

Deep inelastic scattering cross sections

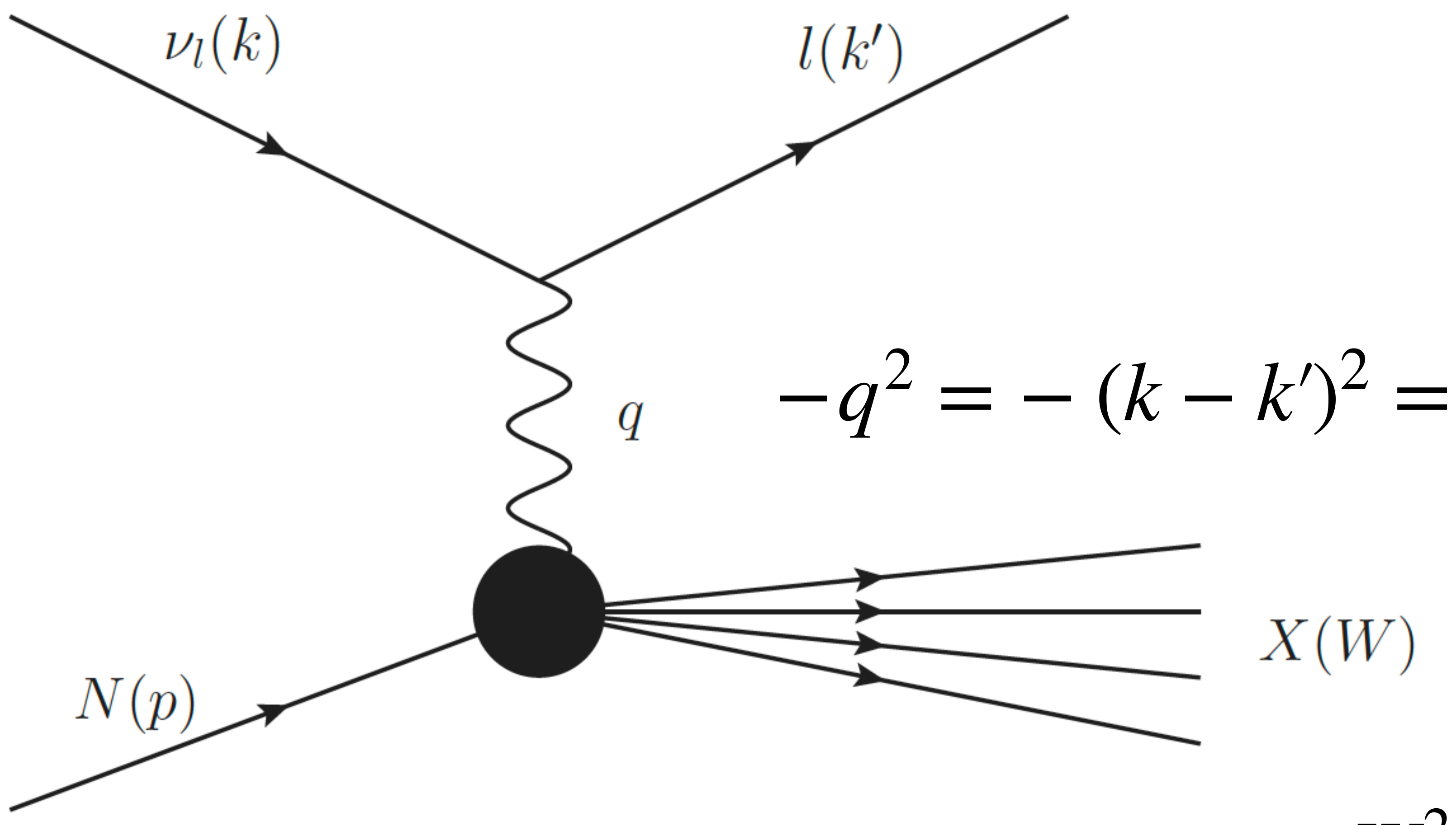
■ Neutrino-nucleon charged-current (CC) cross section for deep inelastic scattering

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

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

$y = (E - E')/E$

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



$$-q^2 = -(k-k')^2 = Q^2$$

$$W^2 = Q^2\left(\frac{1}{x}-1\right)+m_N^2$$

■ Kinematic region

- DIS: $W > 2$ GeV and $Q^2 > 1$ GeV^2
- SIS: $m_N + m_\pi < W \lesssim 2$ GeV, all Q^2

Structure functions $F_i(x, Q^2)$

- Structure functions are:
  - essential components in evaluating the DIS cross section.
  - expressed in terms of Bjorken-x and the parton distribution functions (PDF) $q(x, Q^2)$

    e.g. $F_{2,\mathrm{CC}}(x, Q^2) = \sum_{q,q'} 2x\left(q(x, Q^2) + \bar{q}'(x, Q^2)\right)$ (at LO in pQCD)
  - not reliable for $Q^2 < 1\ \mathrm{GeV}^2$, where the perturbative QCD is not applicable.

- Non-perturbative structure functions at low Q ($Q^2 < 1\ \mathrm{GeV}^2$)
  - phenomenologically constructed by fitting to the data.
  - (e.g.) Bodek-Yang, CKMT, NNSFν

CKMT

A. Capella, A. Kaidalov, C. Merino and J. Tran Thanh Van, Phys. Lett. B 337, 358 (1994)

- Parameterization from fits to the electromagnetic structure function data.

$$F_2^{\mathrm{CKMT}}(x,Q^2) = Ax^{-\Delta(Q^2)}(1-x)^{n(Q^2)+4}\left(\frac{Q^2}{Q^2+a}\right)^{1+\Delta(Q^2)} + Bx^{1-\alpha_R}(1-x)^{n(Q^2)}\left(\frac{Q^2}{Q^2+b}\right)^{\alpha_R}\left(1+f(1-x)\right)$$

$$n(Q^2) = \frac{3}{2}\left(1+\frac{Q^2}{Q^2+c}\right)$$

$$\Delta(Q^2) = \Delta_0\left(1+\frac{2Q^2}{Q^2+d}\right)$$

- Using the same functional form, normalization parameters are modified for neutrino-nucleon charged-current scattering.

Δ_0	α_R	a [GeV^2]	b [GeV^2]	c [GeV^2]	d [GeV^2]
0.07684	0.4150	0.2631	0.6452	3.5489	1.1170

Process	A	B	f
EM F_2	0.1502	1.2064	0.15
νN F_2	0.5967	2.7145	0.5962
νN xF_3	9.3955×10^{-3}	2.4677	0.5962
$\bar{\nu} N$ xF_3	9.3955×10^{-3}	-2.4677	0.5962

M. H. Reno, *Phys. Rev. D74 (2006) 033001*
Y. S. Jeong and M. H. Reno, *arXiv:2307.09241*

CKMT + PCAC

- Partially conserved axial-vector current (PCAC) gives non-zero structure function at low Q^2 limit through F_L.

- According to Kulagin and Petti for the PCAC corrections to F_L at low Q^2:

S. A. Kulagin, and R. Petti, *Phys. Rev. D 76, 094023 (2007)*

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

$$\sigma_\pi \simeq X(W^2)^\epsilon + Y(W^2)^{-\eta_1}, \quad f_{\mathrm{PCAC}}(Q^2) = \left(1 + \frac{Q^2}{M_{\mathrm{PCAC}}^2}\right)^{-2}$$ with $M_{\mathrm{PCAC}} = 0.8\,\mathrm{GeV}$

- We further implemented PCAC correction approximately to CKMT parameterizations.

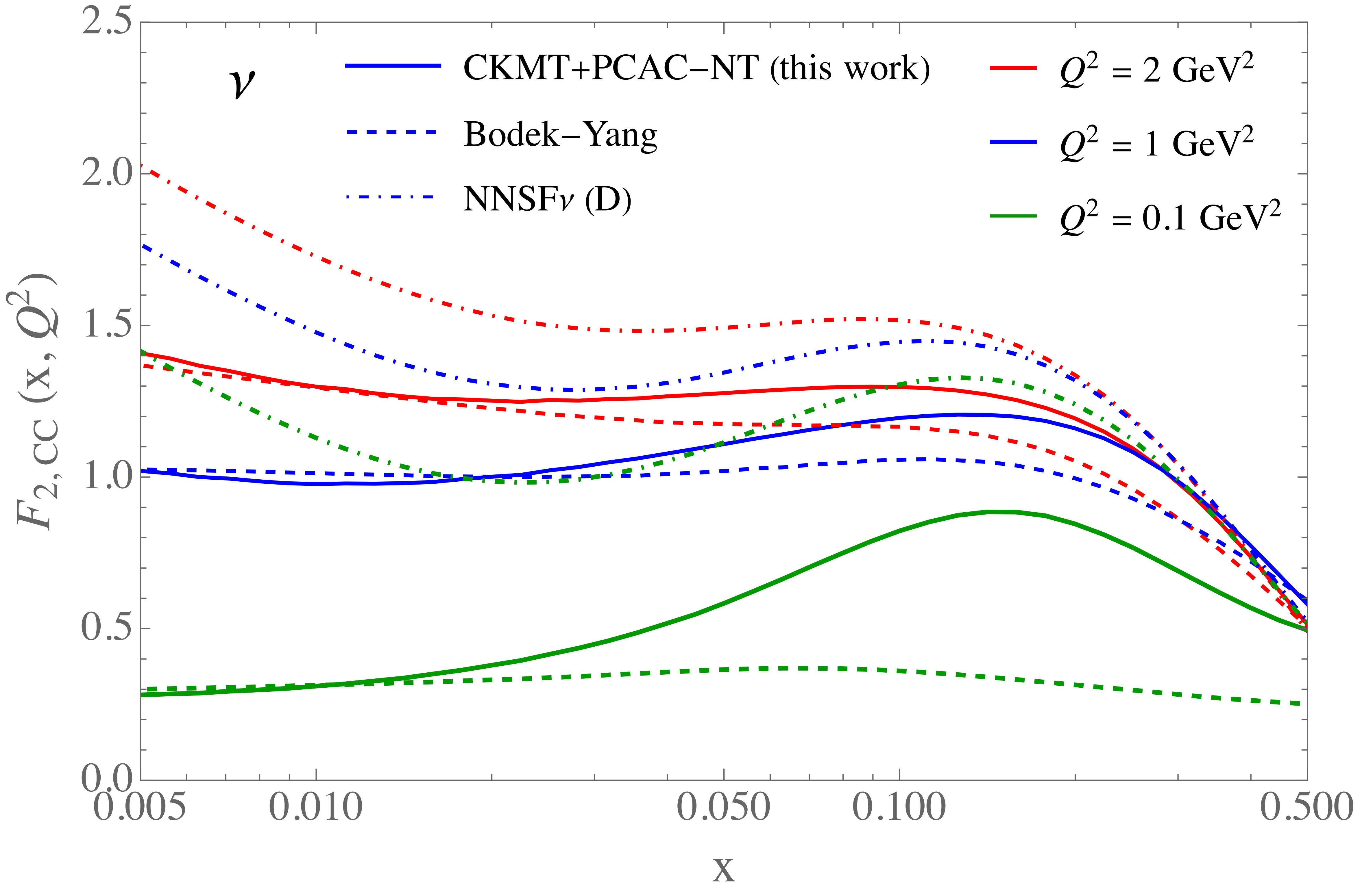
Other structure functions at low Q

- **Bodek-Yang** A. Bodek, I. Park, U. K. Yang, *Nucl. Phys. B Proc. Suppl. 139, 113 (2005)*
  - proivdes the effective PDFs at low Q^2 to construct structure functions.
  - GRV98 LO PDF + charged lepton DIS data

$$F_2(x, Q^2 < 0.8\,\mathrm{GeV}^2) = K(Q^2) \times F_2\left(\xi_\omega, Q^2 = 0.8\,\mathrm{GeV}^2\right)$$

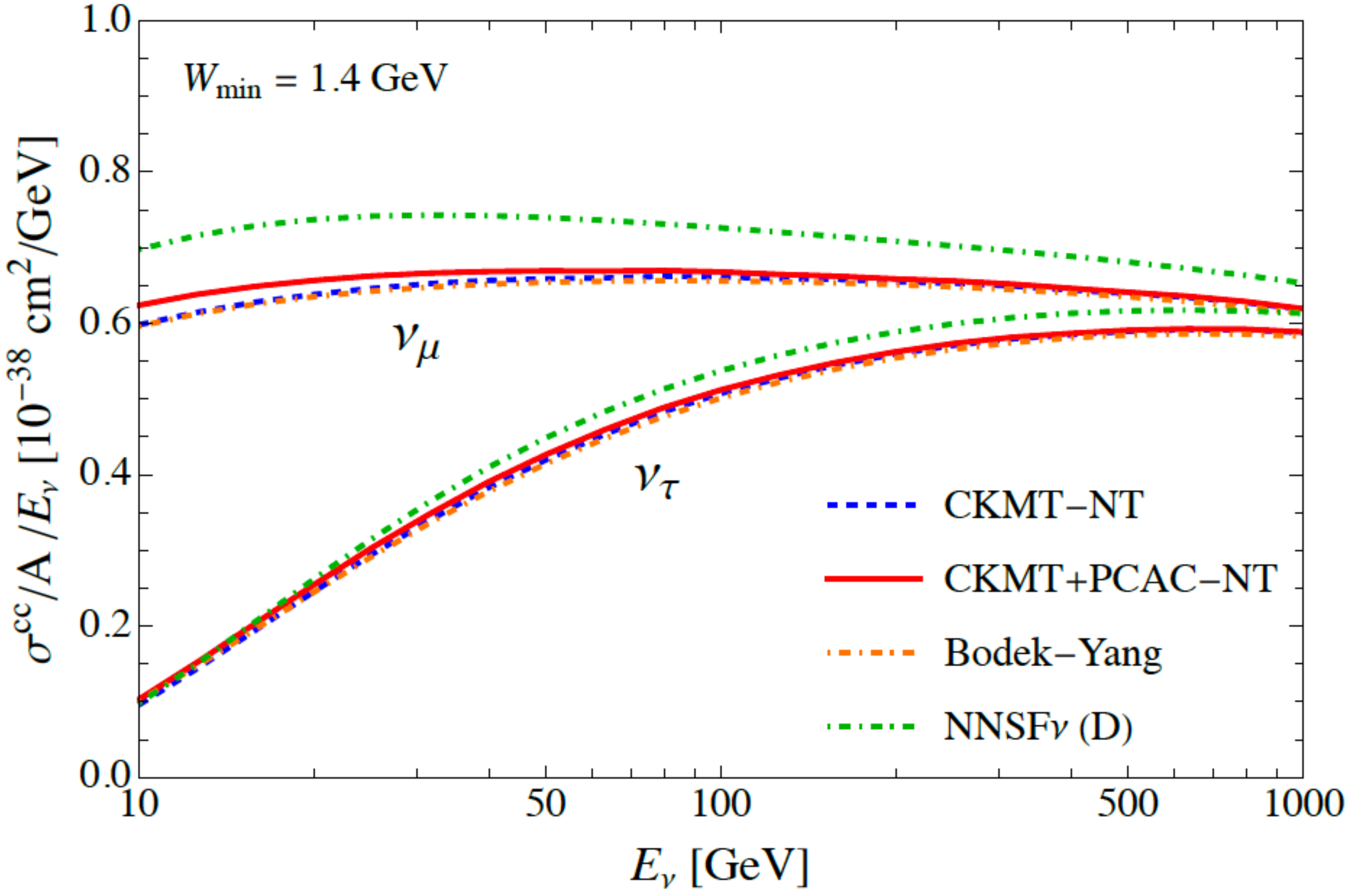
- **NNSFν** A. Candido, A. Garcia, G. Magni, T. Rabemananjara, J. Rojo, and R. Stegeman, *JHEP 05 (2023) 149*
  - machine learning parameterization fitted to neutrino scattering data.

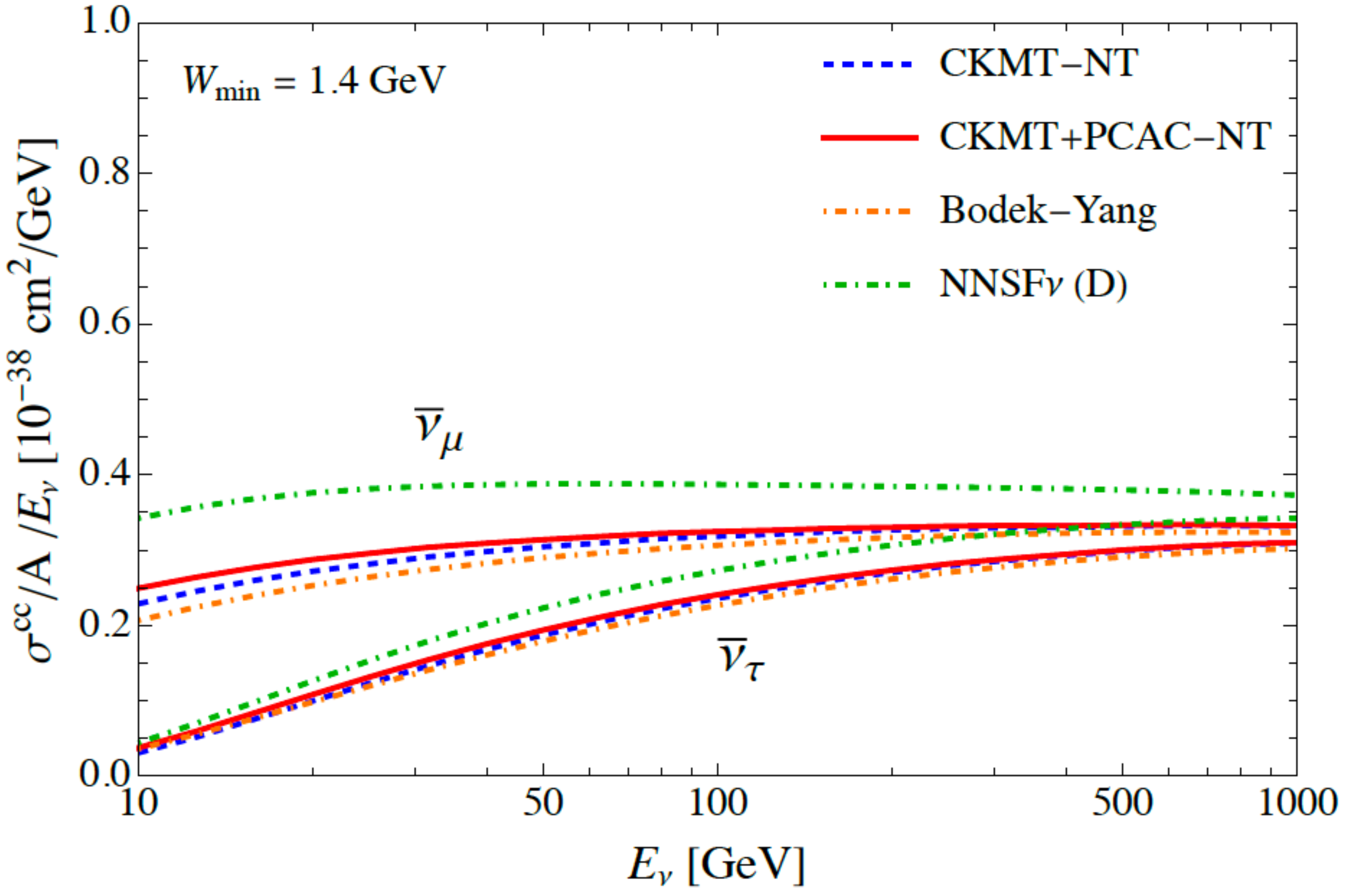
See Tanjona's talk for NNSFν



✳ NT: NLO+TMC

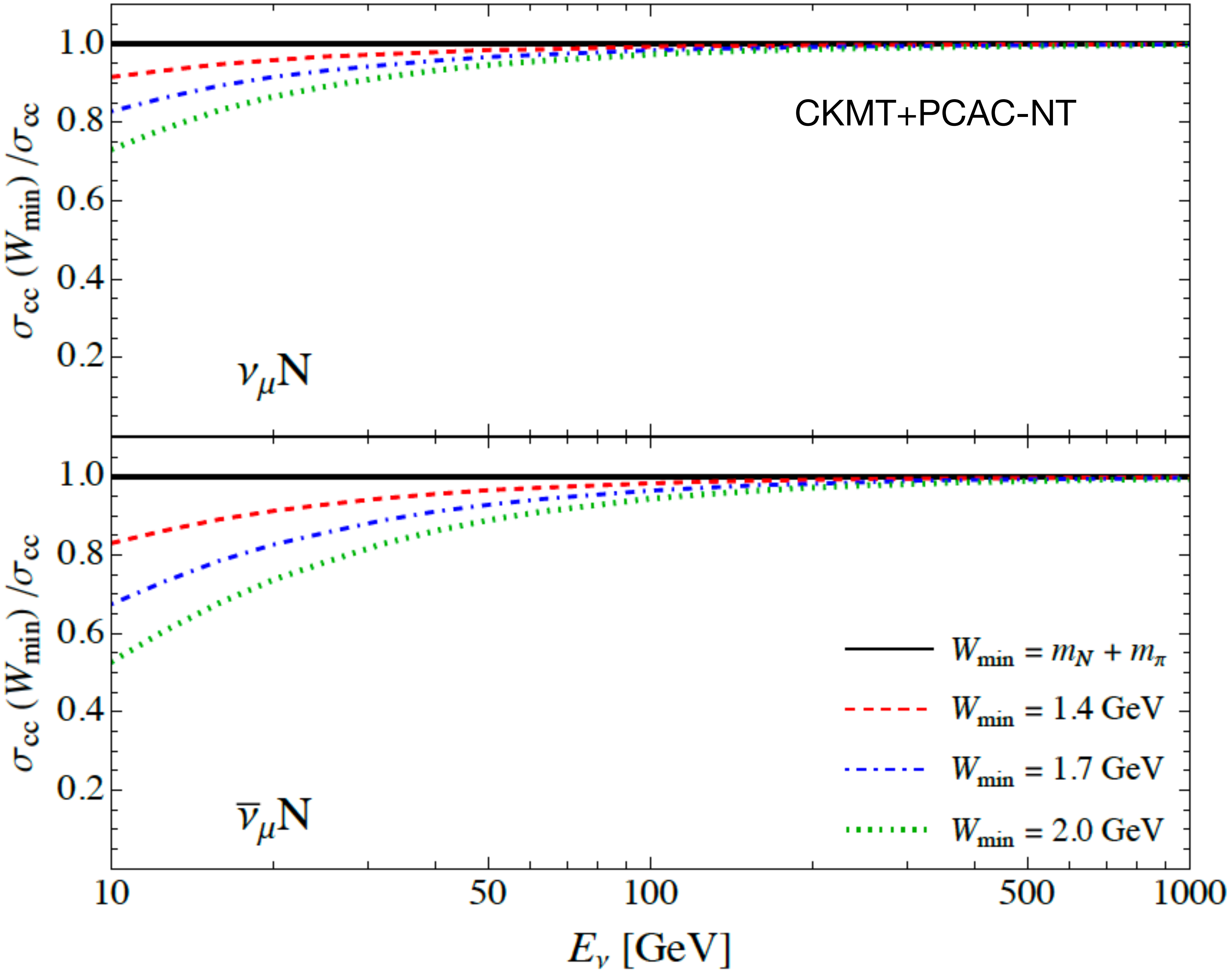
The neutrino-nucleon DIS cross sections





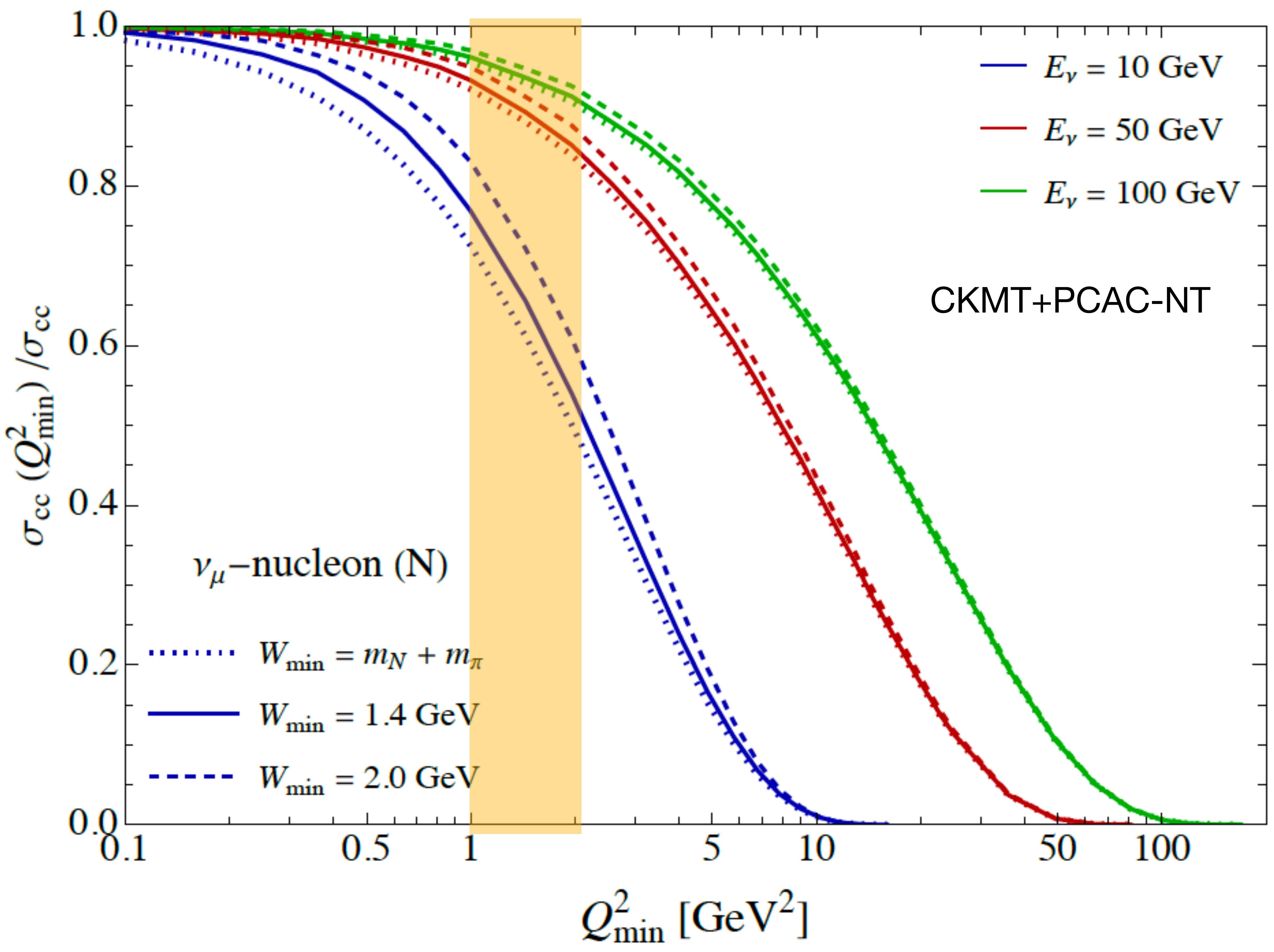
- Cross sections with CKMT+PCAC structure functions are similar to the Bodek-Yang results with about 10% difference at 10 GeV and closer at higher energies.
- NNSFnu results are much larger than the CKMT and BY across the energies.

Impact of the W_{min}



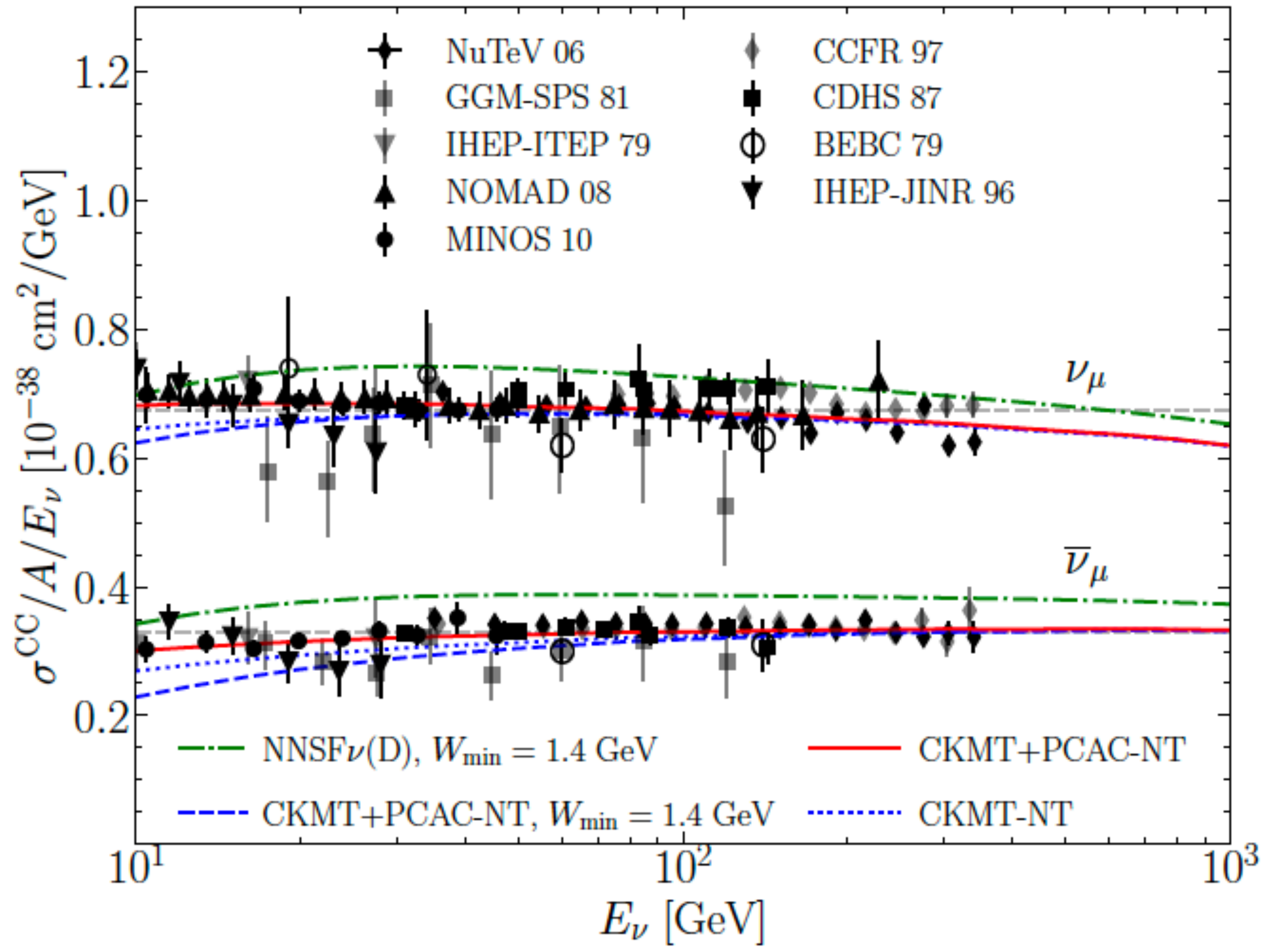
- The impact of $W_{\rm min}$ appears below a few hundred GeV, and more significant at lower energies.
- The hadronic final states between RES and DIS ($m_N + m_\pi < W_{\rm min} < 2\,{\rm GeV}$) can affect the cross sections by a few % at 100 GeV and about 30 % at 10 GeV and have larger impact on antineutrinos.
- These results with σ-ratio are approximately the same for nuclear targets.

Impact of the Q^2_{min} and W_{min}



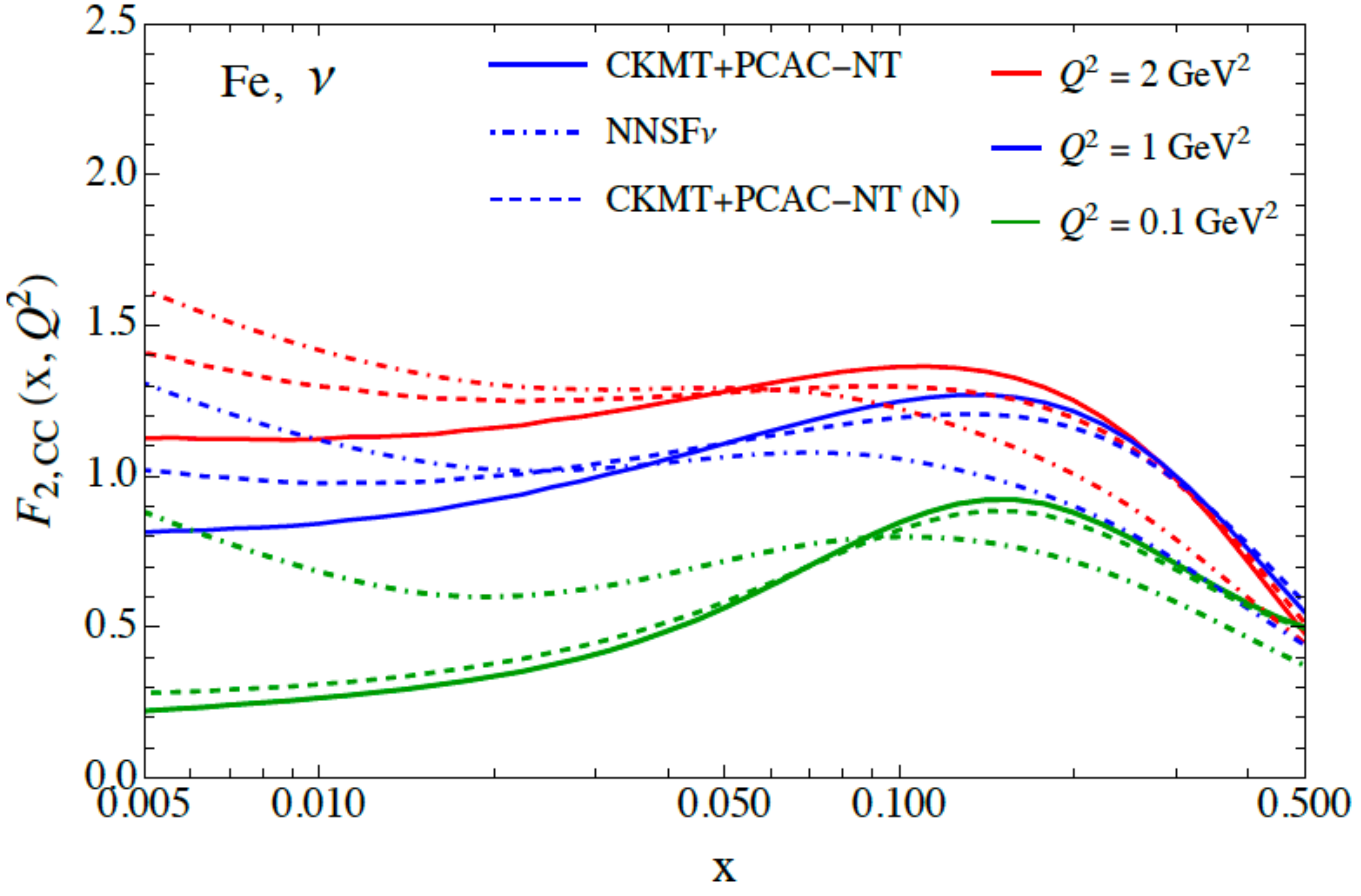
- The impact of Q^2_{min} and W_{min} is more evident at low energies.
- (e.g.) For W_{min} = 1.4 GeV, the contribution from $Q^2_{min} < 1\ \mathrm{GeV}^2$ to the CC cross section for muon neutrino-nucleon scattering:
  - is less than 5 % at $E_\nu = 100$ GeV
  - increases to about 25 % at $E_\nu = 10$ GeV.

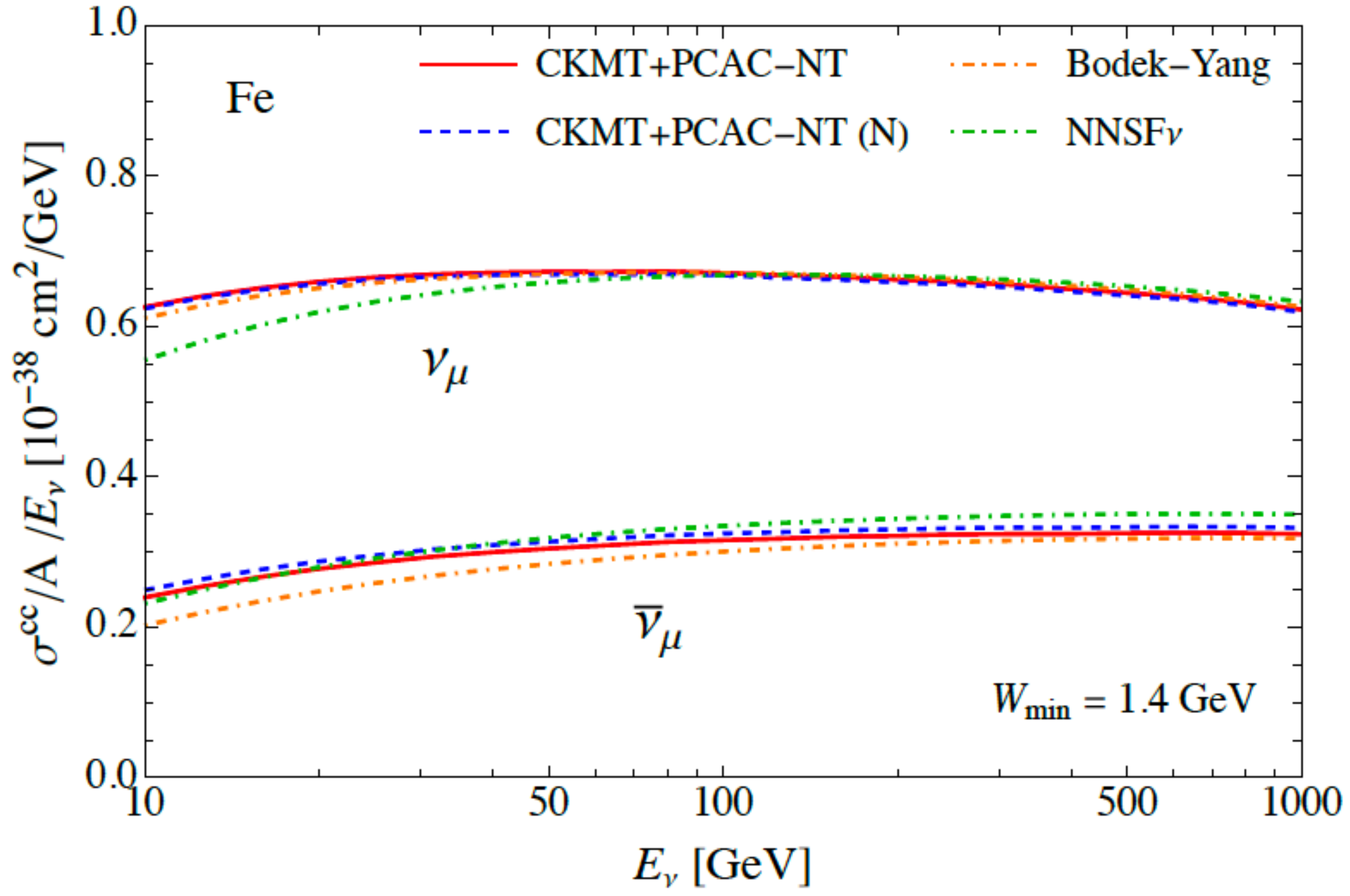
Neutrino cross sections for ν_μ / $\bar{\nu}_\mu$ - nucleon scattering



- Cross sections per nucleon normalized with E_ν
- Red: CKMT+PCAC-NT with $W_{\rm min} = m_N + m_\pi$
  - Account for all CC cross sections for inelastic collisions beyond quasi-elastic scattering.
  - Very well matched to the experimental data.
- PCAC improves the prediction to have a better agreement with the data.

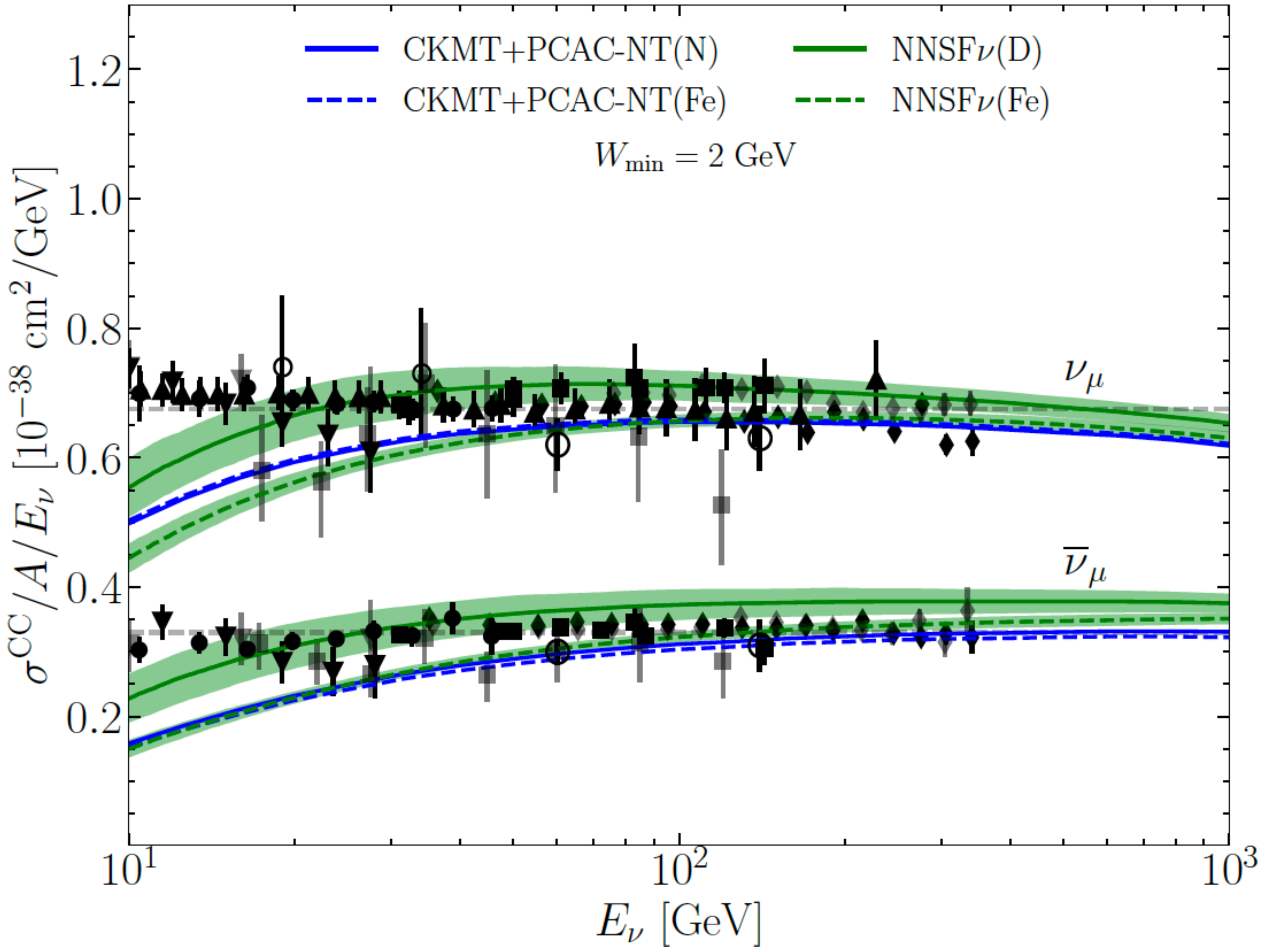
More comparison with NNSFν for Fe target





- For heavier nuclear target, disagreement between NNSFv and CKMT based result is relieved compared to the nucleon target.

More comparison with NNSFν ($W_{\min} = 2\,\mathrm{GeV}$)



- There is still disagreement in the CC cross sections for neutrino scattering with isoscalar nucleon with $W_{\min}$ = 2 GeV.

Summary

- We have evaluated neutrino CC DIS cross sections using the structure functions at low Q^2 and investigated the impact of low Q^2 and low W outside DIS interaction region.
- Although the impact of low W and Q^2 is negligible for the main energy region of the FPF, it appears below 100 GeV, where the FPF could obtain sufficient events for interaction study.
- There is discrepancy between the low Q structure functions and cross sections (esp. NNSFν).
- More theoretical study on structure functions for low Q/cross sections for low E will be helpful. Also, the FPF could provide the useful data for interaction study in the transition region.

Thank you for your attention