Neutrino cross section at the transition region between shallow- and deep-inelastic scattering

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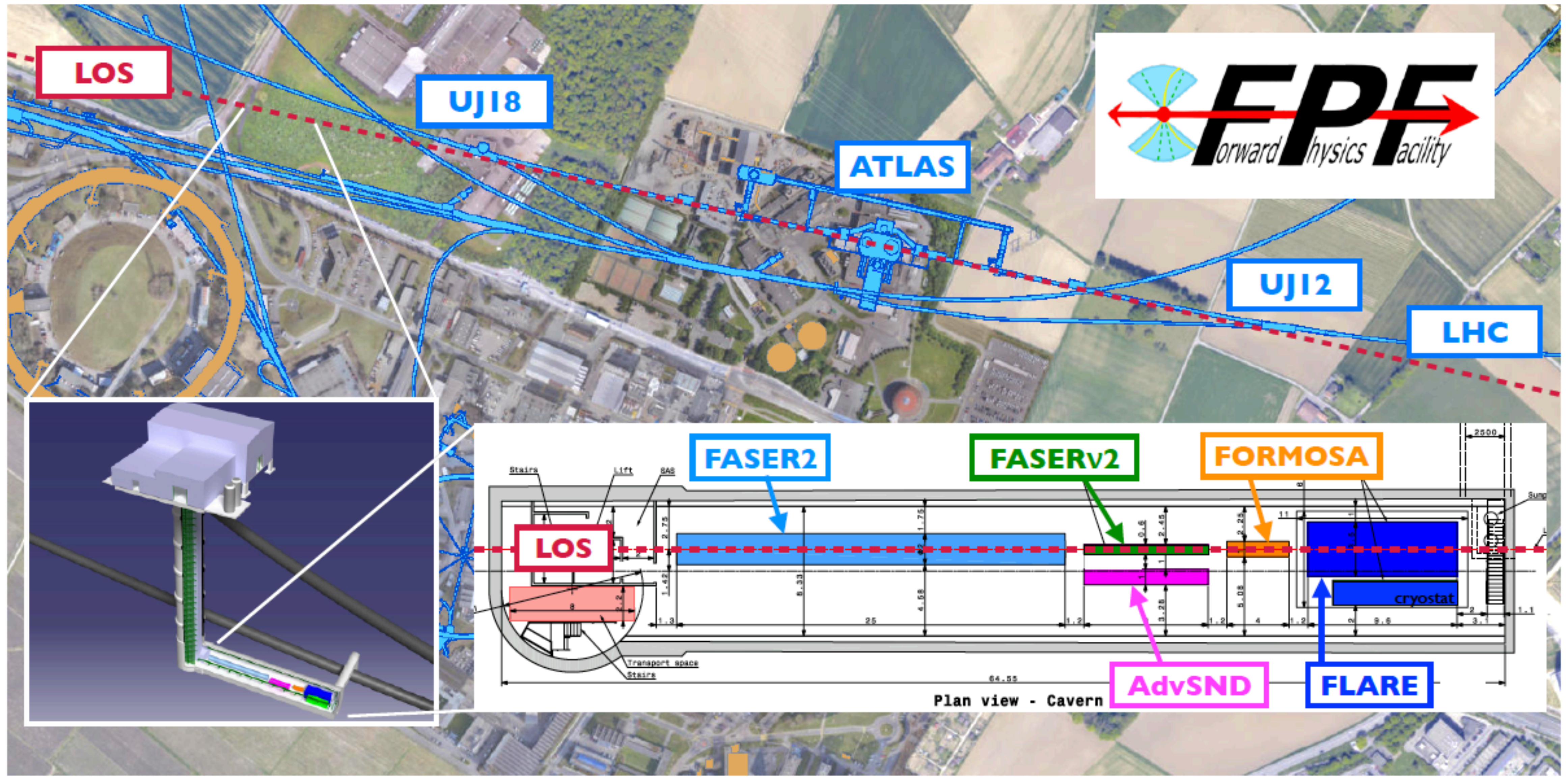
Based on the contribution to the FPF white paper (arXiv: 2203.05090)
and work in progress with M. H. Reno (Univ. of Iowa),

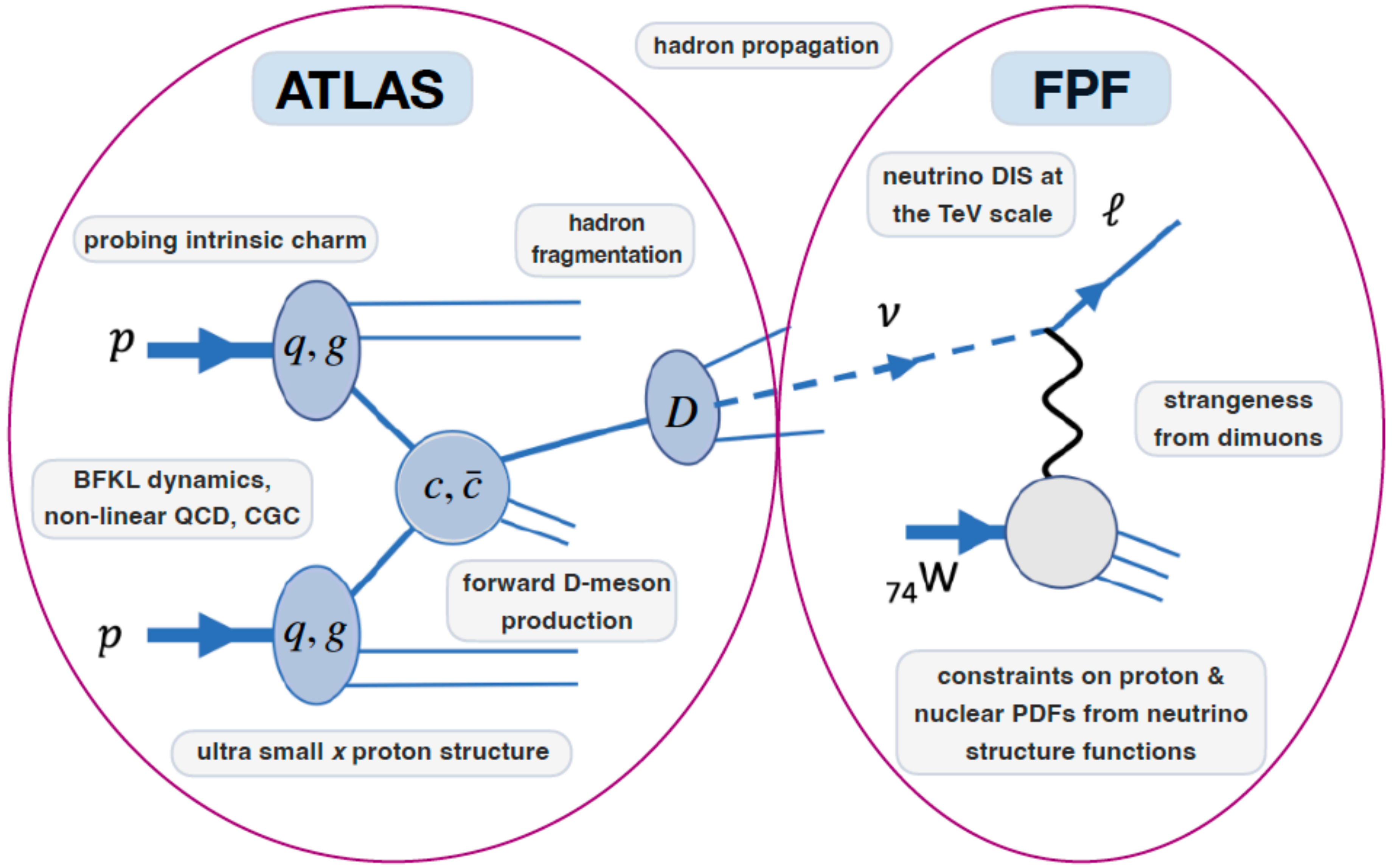
CHUNG-ANG UNIVERSITY
HIGH ENERGY PHYSICS

NuInt 2022

October 24-29, 2022

Forward experiments at the LHC

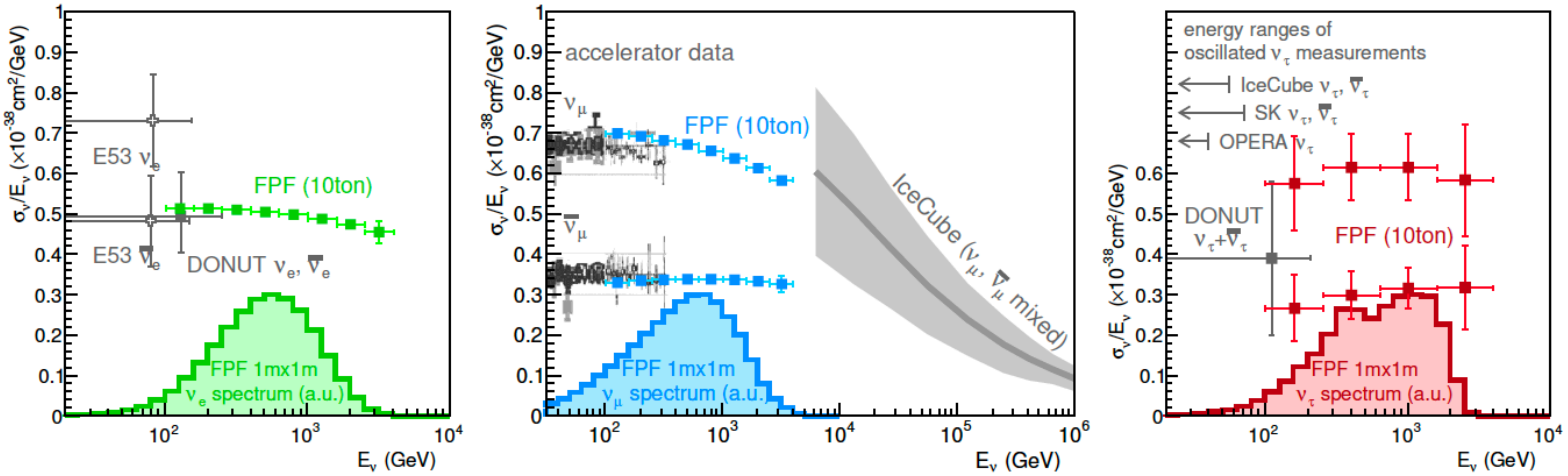




Detector				Number of CC Interactions		
Name	Mass	Coverage	Luminosity	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
FASERν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}	901 / 3.4k	4.7k / 7.1k	15 / 97
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}	137 / 395	790 / 1.0k	7.6 / 18.6
FASERν2	20 tons	$\eta \gtrsim 8.5$	3 ab^{-1}	178k / 668k	943k / 1.4M	2.3k / 20k
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}	36k / 113k	203k / 268k	1.5k / 4k
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	3 ab^{-1}	6.5k / 20k	41k / 53k	190 / 754

Ref: arXiv: 2203.05090

Neutrino energy spectrum at the FPF



- The neutrinos that reach to the FPF are largely distributed from at the energies of hundreds GeV to a few TeV.

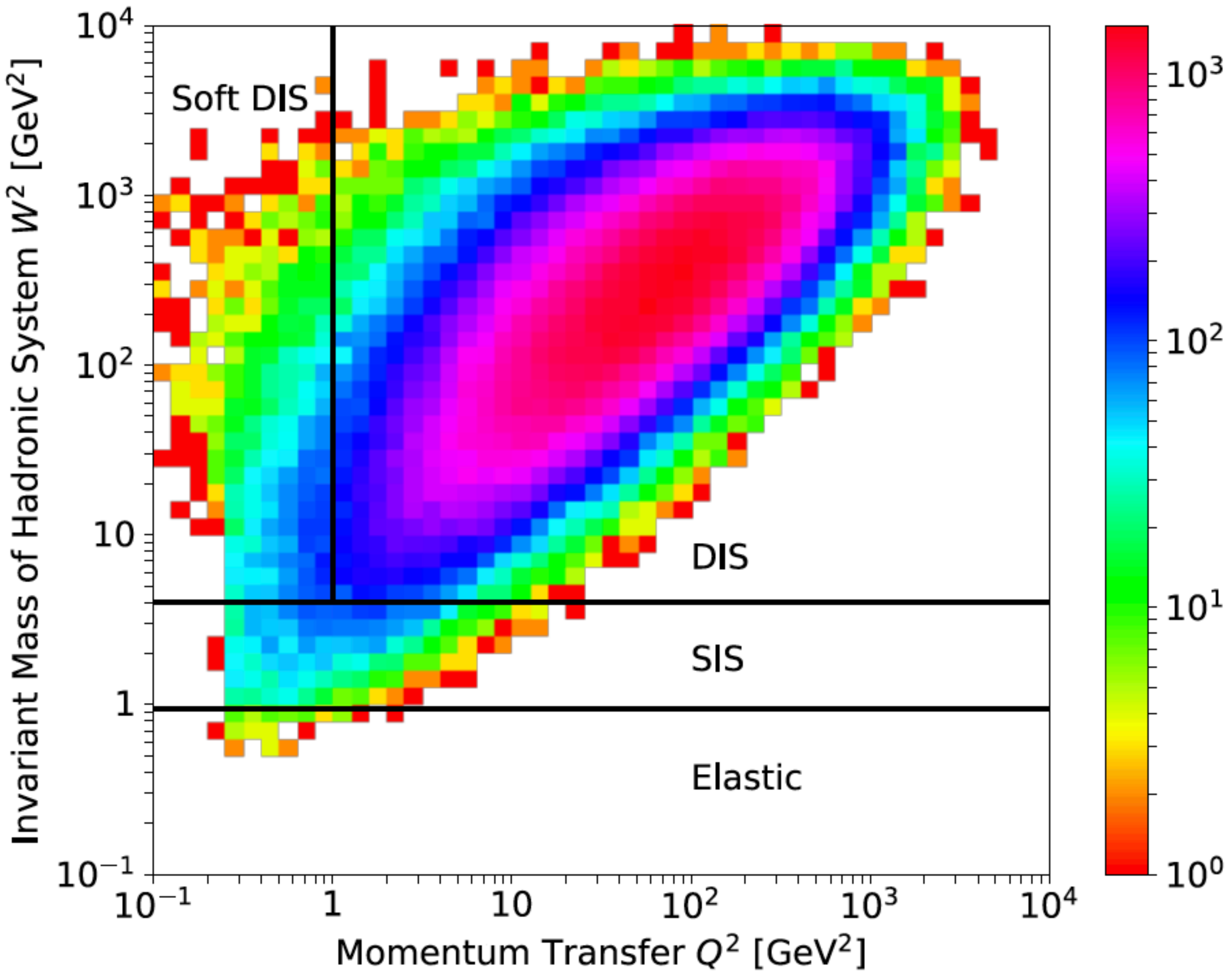
  → unprecedented opportunity to study the neutrino interaction at unexplored energy regime

- There are also considerable number of neutrinos at 10s GeV energies.

Ref: arXiv: 2203.05090

Neutrino interaction regime at the FPF

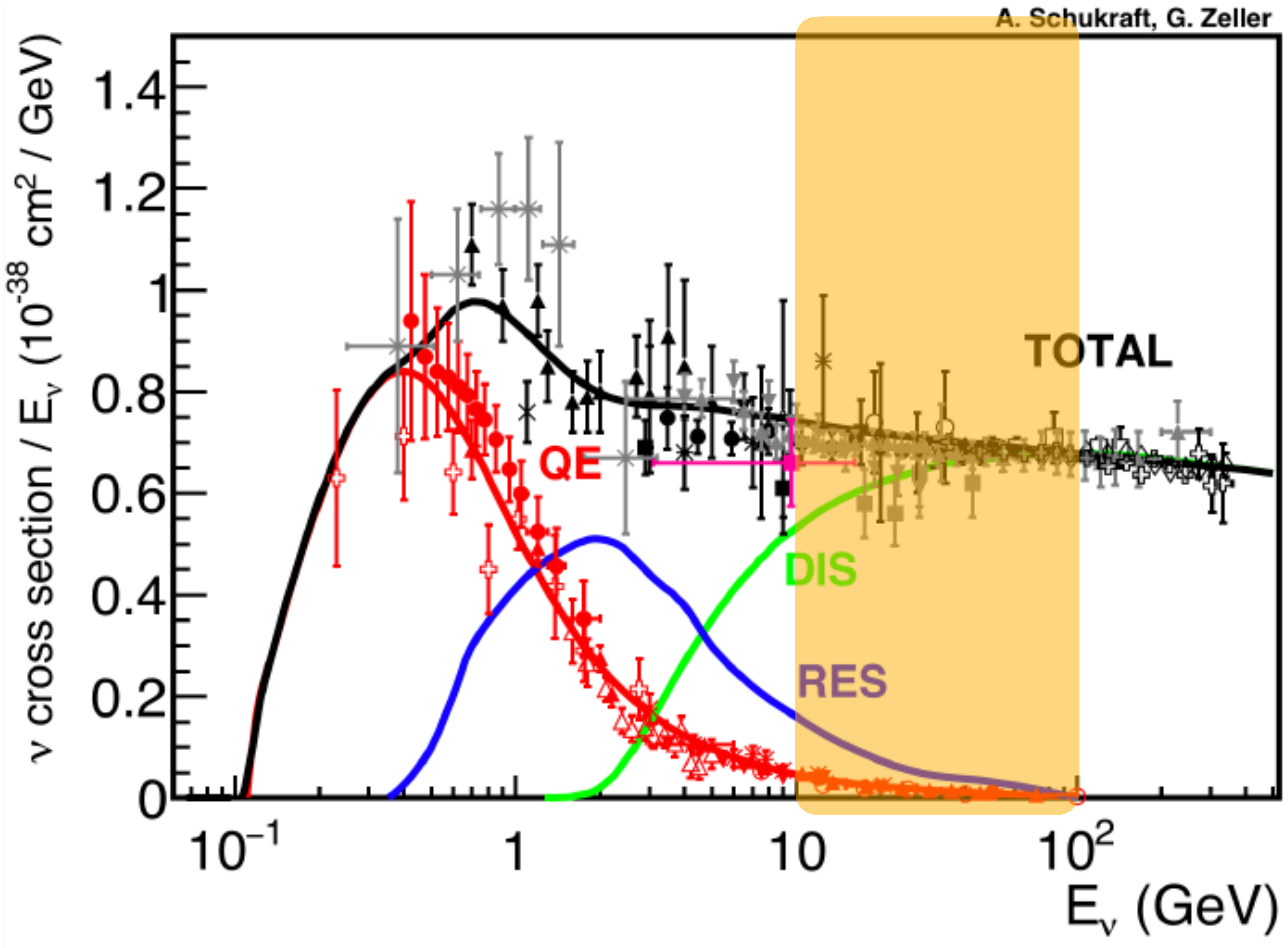
Ref: arXiv: 2203.05090



- Neutrino interactions at the FPF are mainly through deep inelastic scattering (DIS).
- Interactions via shallow inelastic scattering (SIS) are also considerable.
- Kinematic region
  - DIS: $W > 2$ GeV and $Q^2 > 1$ GeV^2
  - SIS: $m_N + m_\pi$ (or 1.4 GeV) $\lesssim W \lesssim 2$ GeV, all Q^2

Ref.: M. S. Athar and J. G. Morfín, J.Phys.G 48 (2021) 3, 034001

Neutrino interaction cross sections



- For E > 100 GeV, neutrino cross sections are from the interactions of deep inelastic scattering.
- In intermediate energies of O(10) GeV — 100 GeV, there exist different types of interactions, so do the transition regions.
- It is important to understand the cross sections in the transition regions to avoid double counting.

DIS cross section and structure functions at low Q^2

- Neutrino-nucleon cross section for deep inelastic scattering

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

- Structure function $F_i(x, Q^2)$
  - essential component in evaluating the DIS cross section.
  - expressed in terms of the parton distribution function (PDF) → Not reliable for $Q^2 < 1\ \mathrm{GeV}^2$.
  - phenomenologically constructed by fitting to the data. (e.g) Bodek-Yang Model

The Bodek-Yang parameterization

- Parameterizations for effective PDFs at low Q^2
- GRV98 LO PDFs + Fits to ep electromagnetic scattering data.

$$\xi \to \xi_\omega = \frac{2x\left[1 + \left(M_f^2 + B\right)/Q^2\right]}{\left[1 + \sqrt{1 + (2Mx)^2/Q^2}\right] + 2Ax/Q^2}$$

$$K_{sea}(Q^2) = \frac{Q^2}{Q^2 + C_s}$$

$$K_{valence}(Q^2) = [1 - G_D^2(Q^2)]\left(\frac{Q^2 + C_{v2}}{Q^2 + C_{v1}}\right)$$

→

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

Ref.: A. Bodek and I. Park and U. K. Yang,
Nuclear Physics B (Proc. Suppl.) 139 (2005) 113–118

The CKMT parameterization

- Parameterizations of structure function at low Q^2
- Fits to the electromagnetic structure function data.

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

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

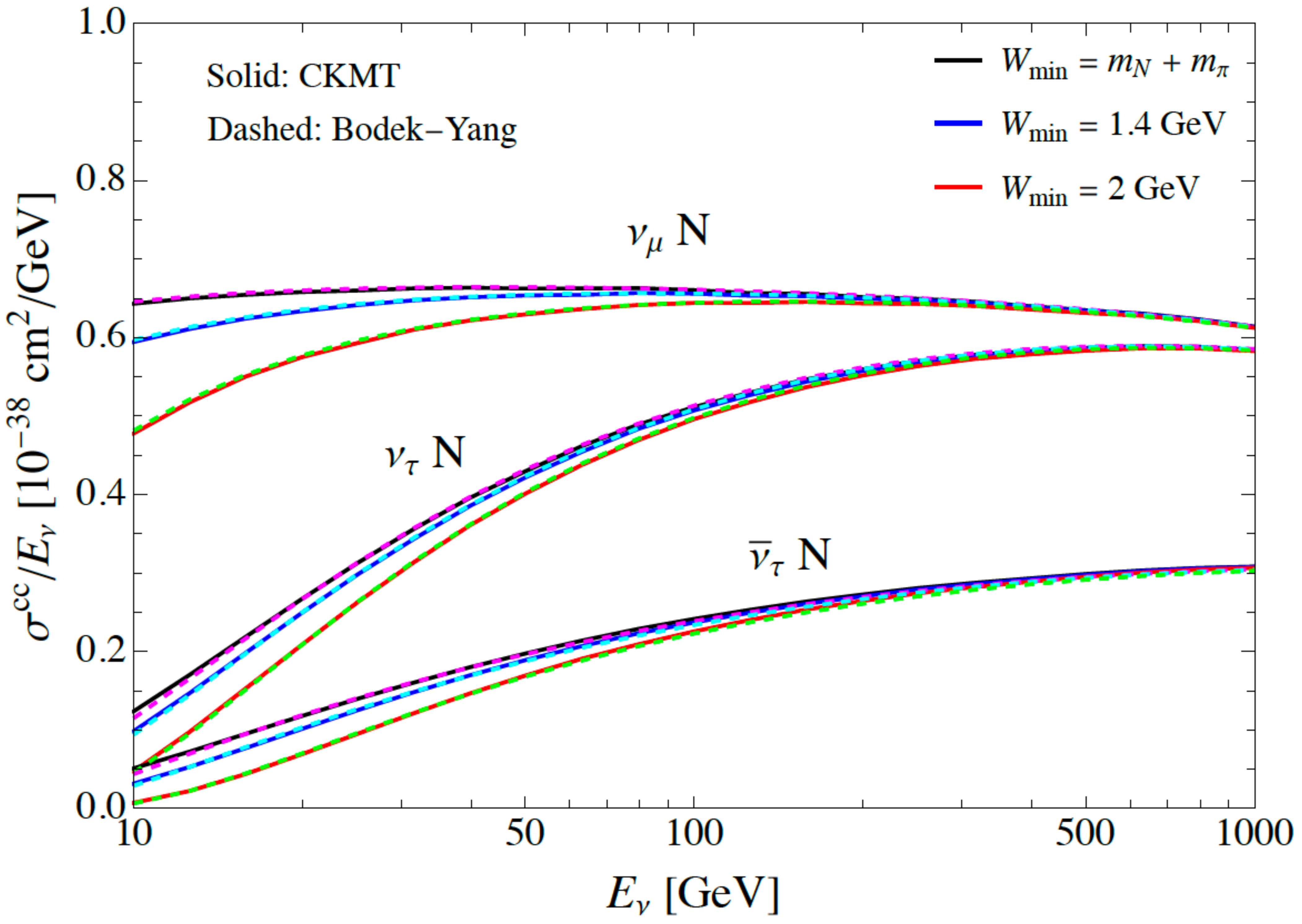
$$\Delta(Q^2) = \Delta_0\left(1+\frac{2Q^2}{Q^2+d}\right)$$

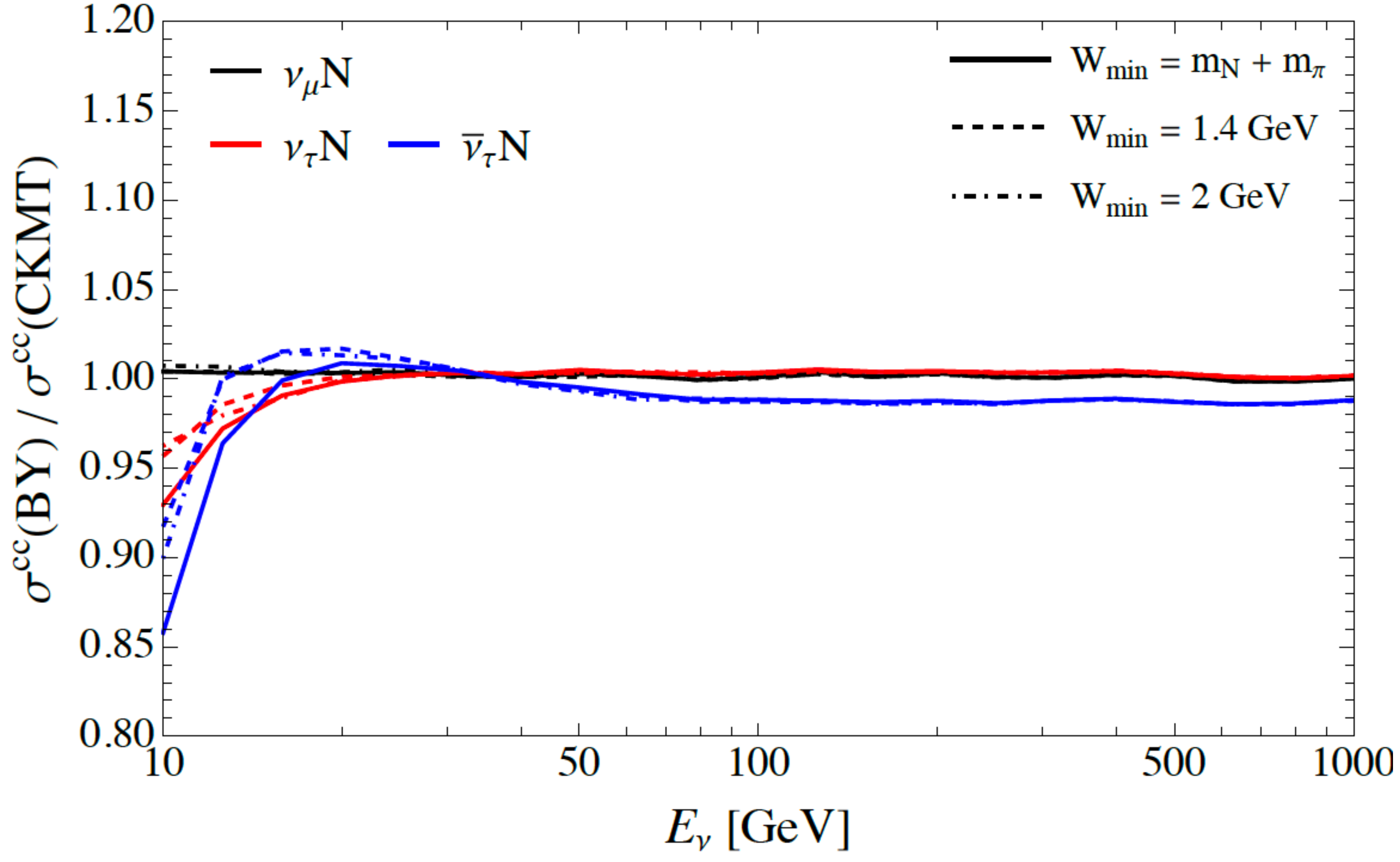
- Further modified with normalization to be adopted to νN charged-current scattering.
  (M. H. Reno, Phys. Rev. D74 (2006) 033001)

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

Comparison with the Bodek-Yang

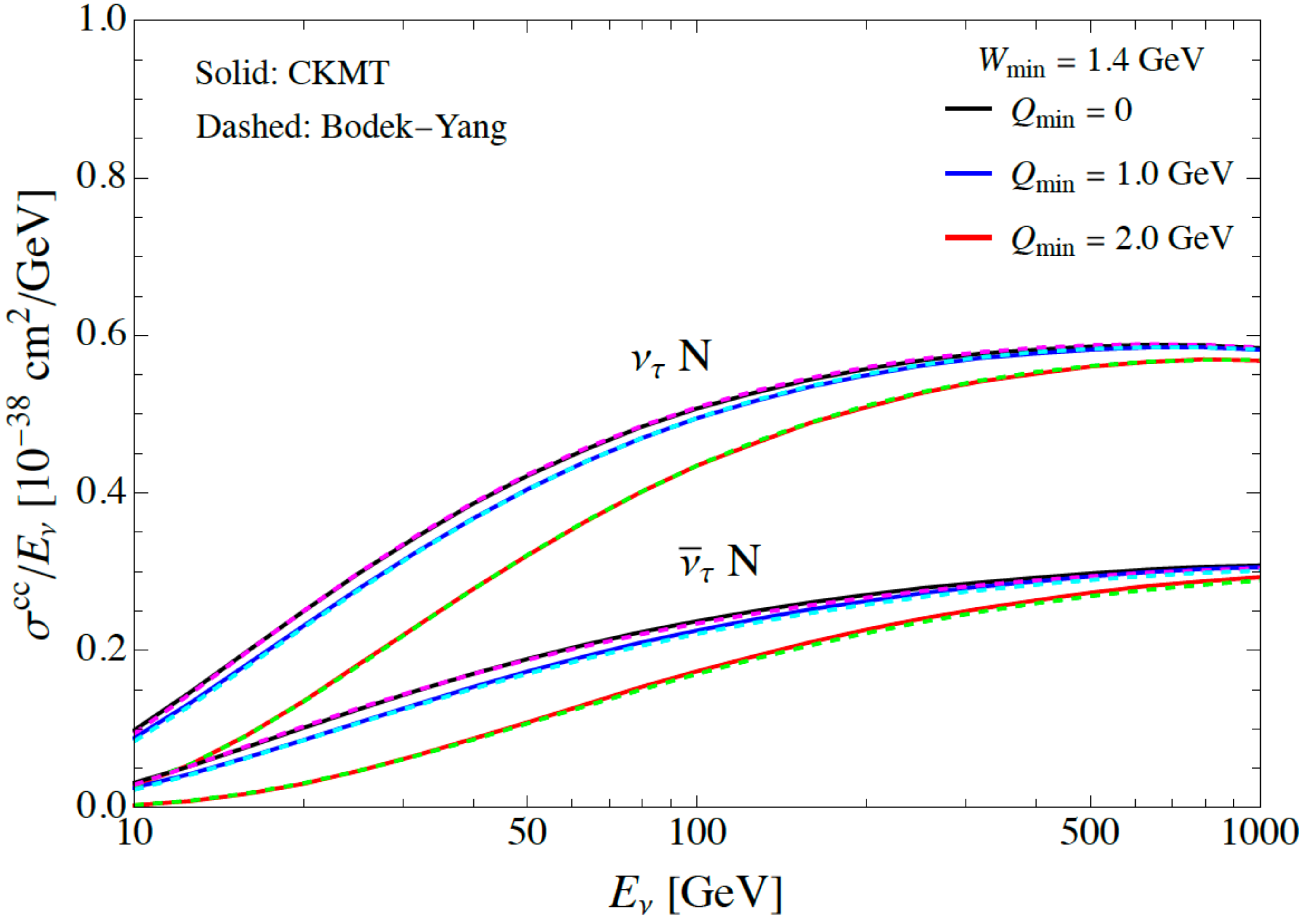
Preliminary

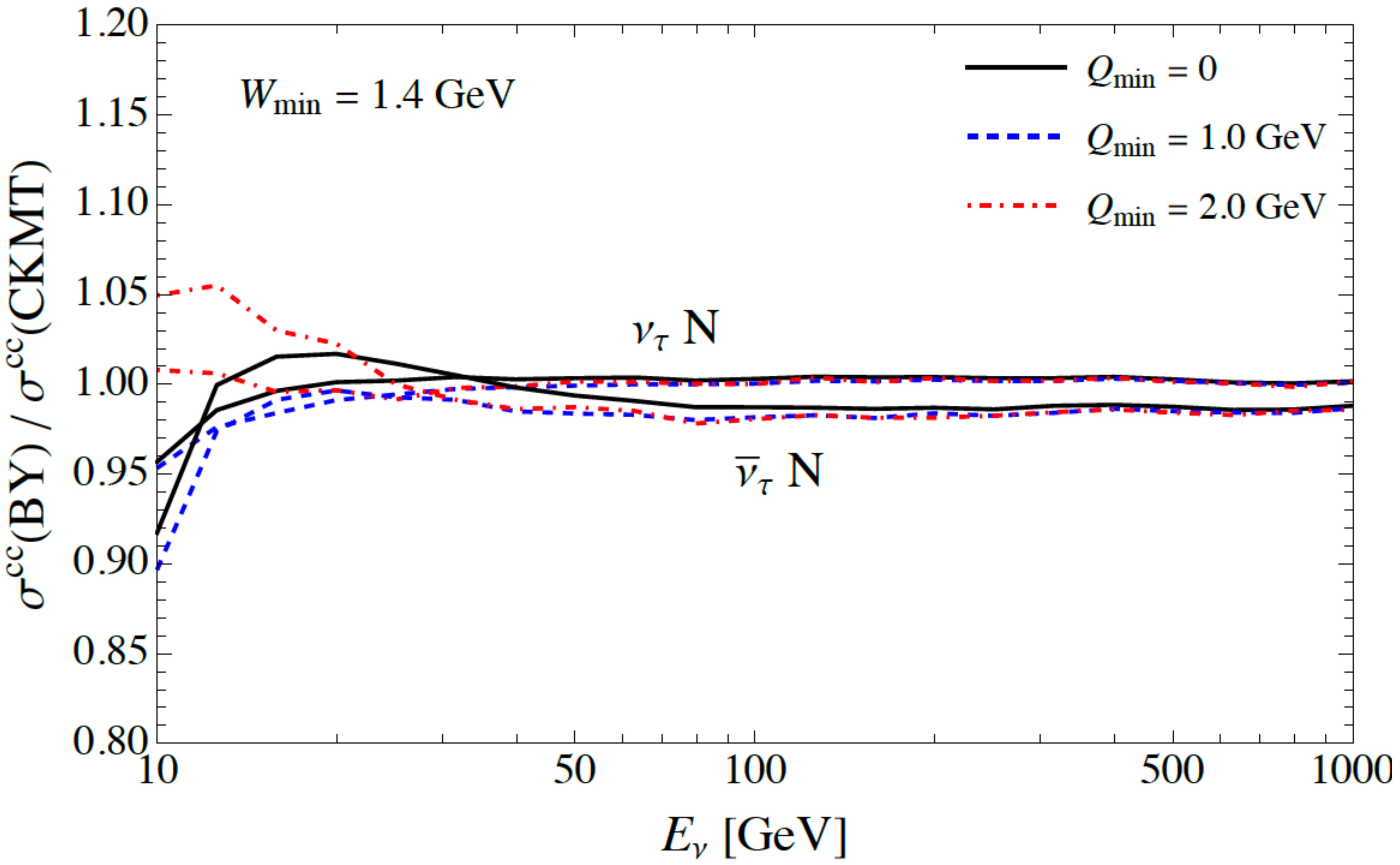




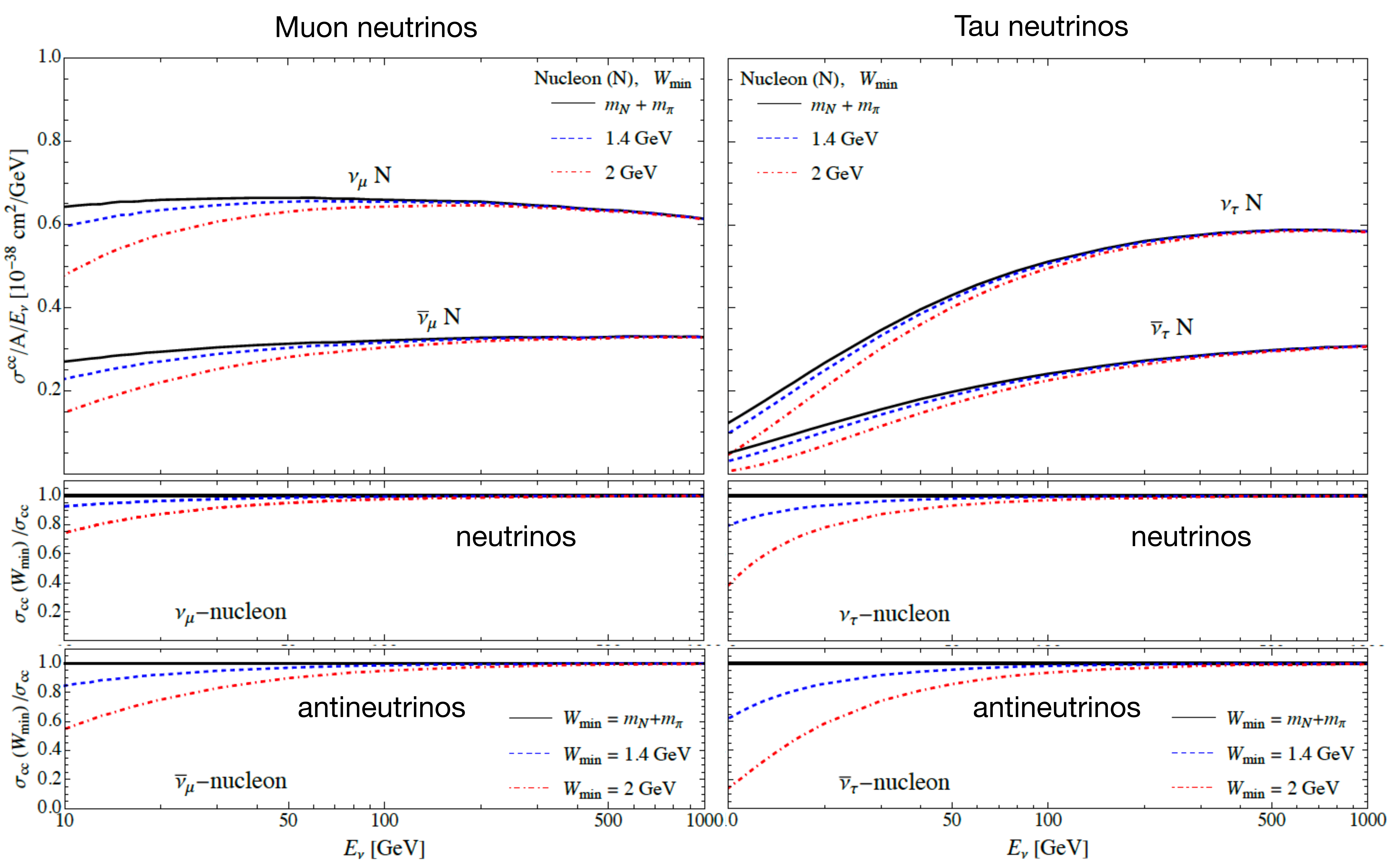
Comparison with the Bodek-Yang

Preliminary





Impact of the W_{min} on $\nu/\bar{\nu}$-nucleon CC cross section



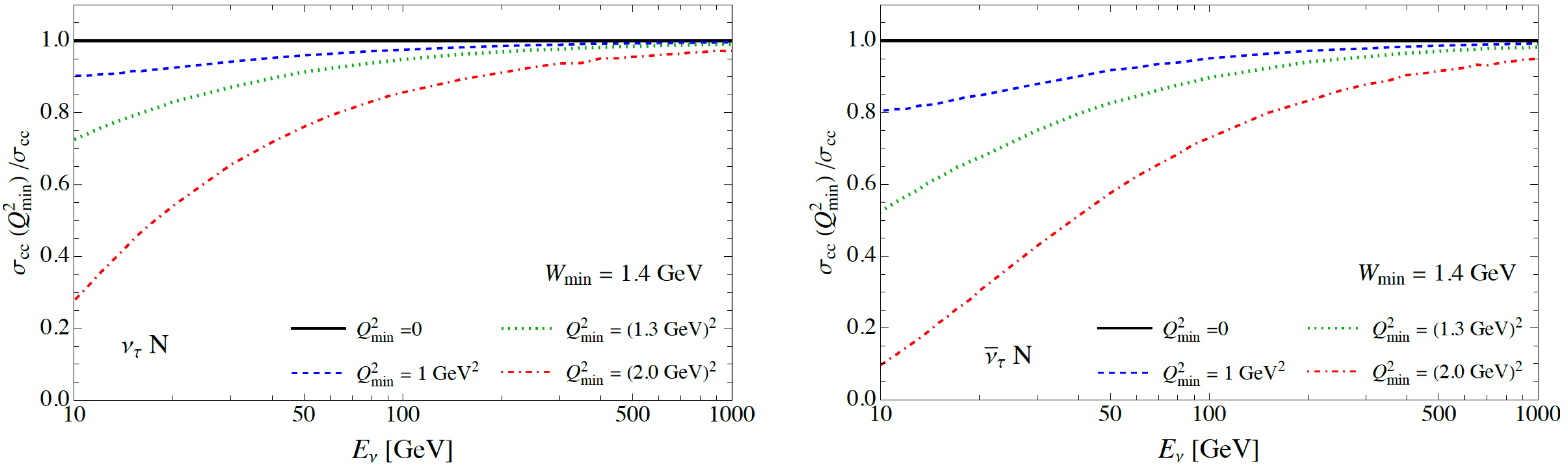
- Tau neutrino cross sections are suppressed for $E_\nu < 1$ TeV → tau lepton mass effect.

- Lower panels: $\dfrac{\sigma\ (W_{min})}{\sigma\ (W_{min} = m_N + m_\pi)}$

- Impact of $W_{\rm min}$
  - appears at $E_\nu \lesssim 100$ GeV
  - larger at lower energies.
  - Larger for antineutrinos

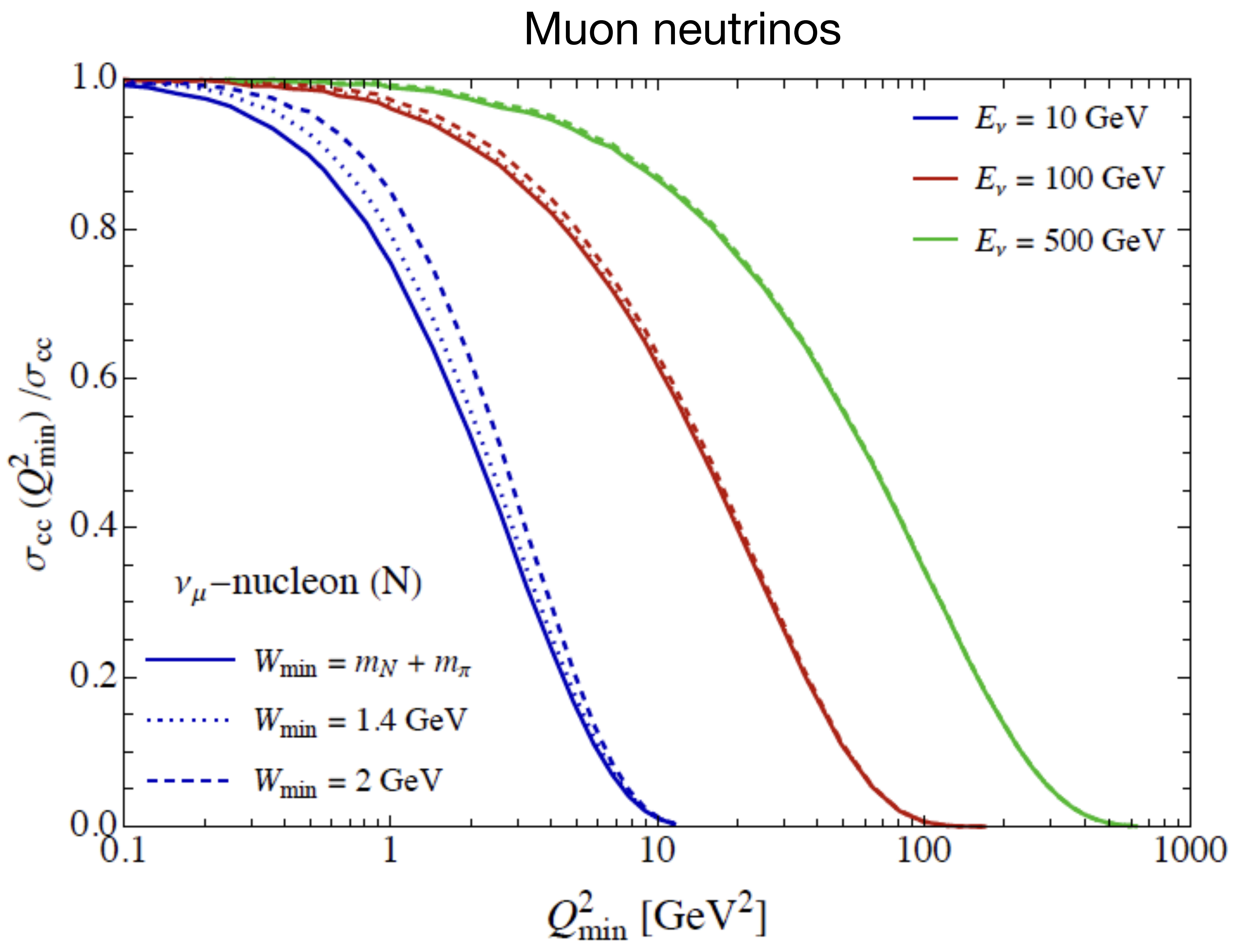
    (e.g.) $E_\nu = 100$ GeV, $W_{min} = 2$ GeV cross section is suppressed by 3% for tau neutrinos, and by 7% for antineutrinos.

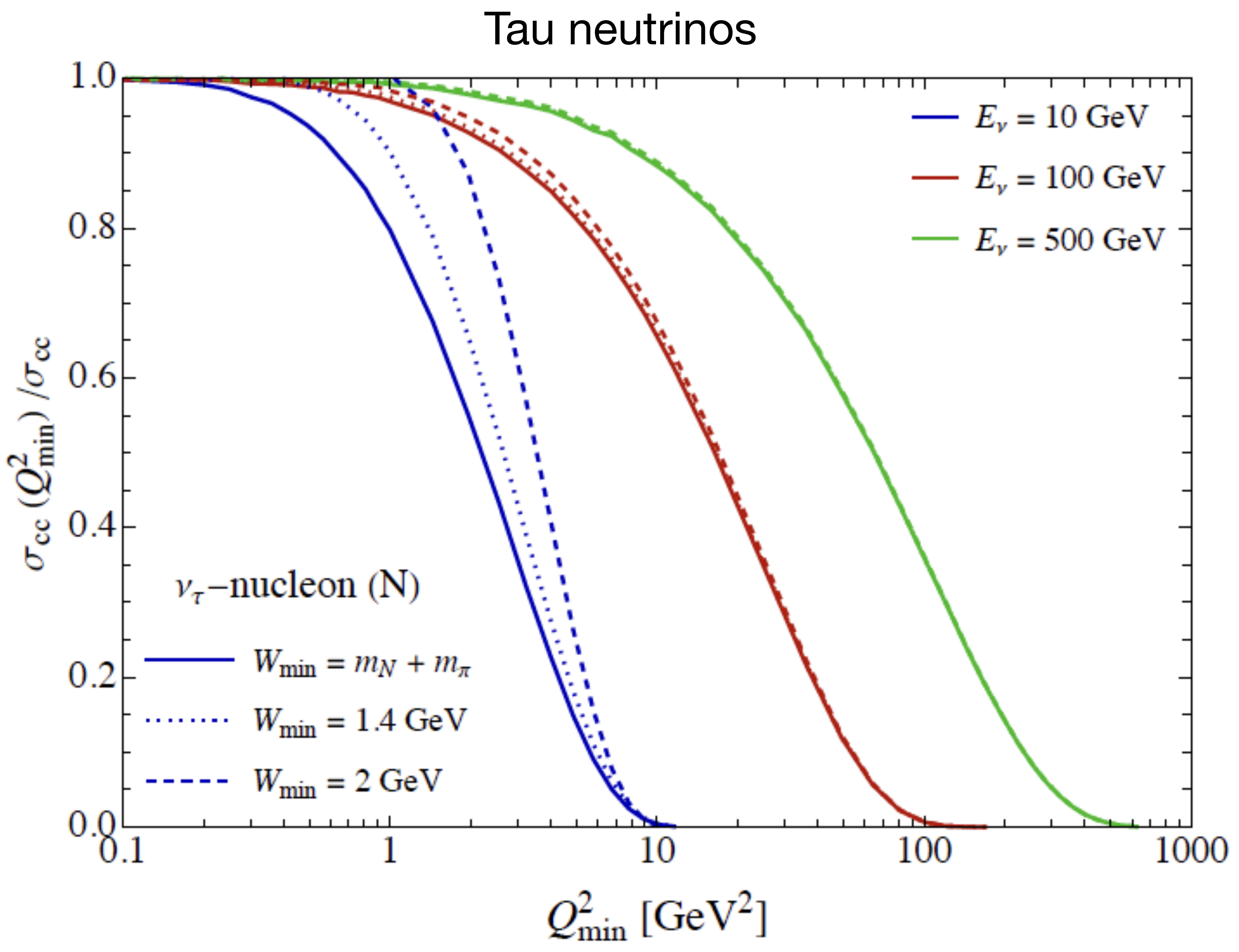
Impact of the Q^2_{min} on $\nu/\bar{\nu}$-nucleon CC cross section



- The impact of cutoff on $Q^2_{\rm min}$ appears on a wider energy and it is more significant than that of W_{min}.
- For W_{min} = 1.4 GeV, the cut on $Q^2_{min} = 1\ \mathrm{GeV}^2$ affect 3% for neutrino and 5% for antineutrinos at 100 GeV.
- The results with tungsten target are approximately the same.

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





- The impact of Q^2_{min} and W_{min} is more evident at low energies.
  - For tau neutrinos results, the kinematic effect for tau production is indicated at lower energies.
- For W_{min} = 1.4 GeV, the contribution from $Q^2_{min} < 1\ \mathrm{GeV}^2$ to the CC cross section:
  - 3% for both muon neutrinos and tau neutrinos at $E_\nu = 100\ \mathrm{GeV}$
  - 21% for muon neutrinos and 10% for tau neutrinos $E_\nu = 10\ \mathrm{GeV}$

Summary

- We have investigated and quantified the impact of low Q^2 and low W, relevant for the transition region between the SIS and DIS interactions, using the neutrino-nucleon CC DIS cross sections.

- Two phenomenological models for the low Q structure functions, the Bodek-Yang and CKMT, yield the consistent cross sections.

- The cutoff on Q^2 and W bring about difference in the predictions at a few percent level for $E_\nu \sim 100$ GeV, and the impact is greater at lower energies.

- Further investigation for structure functions/PDFs for $Q^2_{min} < 1 \text{ GeV}^2$ is important to have reliable neutrino cross sections.
    - e.g.) The treatment of the portion of the axial and vector structure functions
      (ref. Bodek-Yang, arXiv:2108.09240)

Thank you for your attention