Deep inelastic neutrino scatterings at high and ultra-high energies

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Outline

- 1. Introduction

- 2. NNLO calculations for Deep inelastic neutrino scatterings

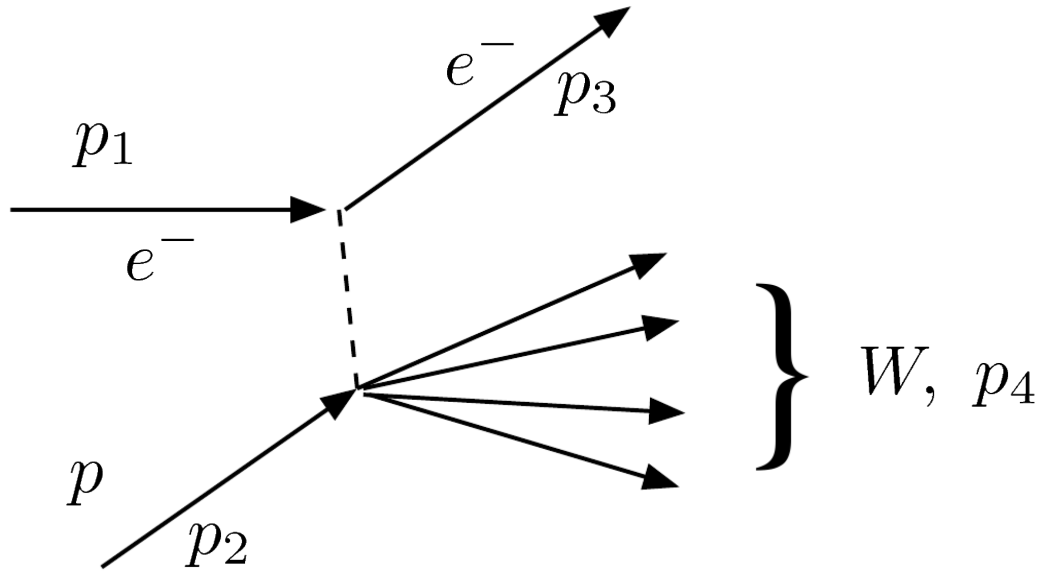
- 3. Predictions for ultra-high energy neutrino scatterings

- 4. Summary

Deep inelastic neutrino scattering

- Deep inelastic lepton/neutrino scatterings on fixed-target reveal the internal structure of nucleons, consisting of quarks and gluons (QPM), and lead to the establishment of QCD

DIS kinematics



$$W^2 = M^2 + 2M\nu + q^2 = M^2 + Q^2(1/x - 1)$$

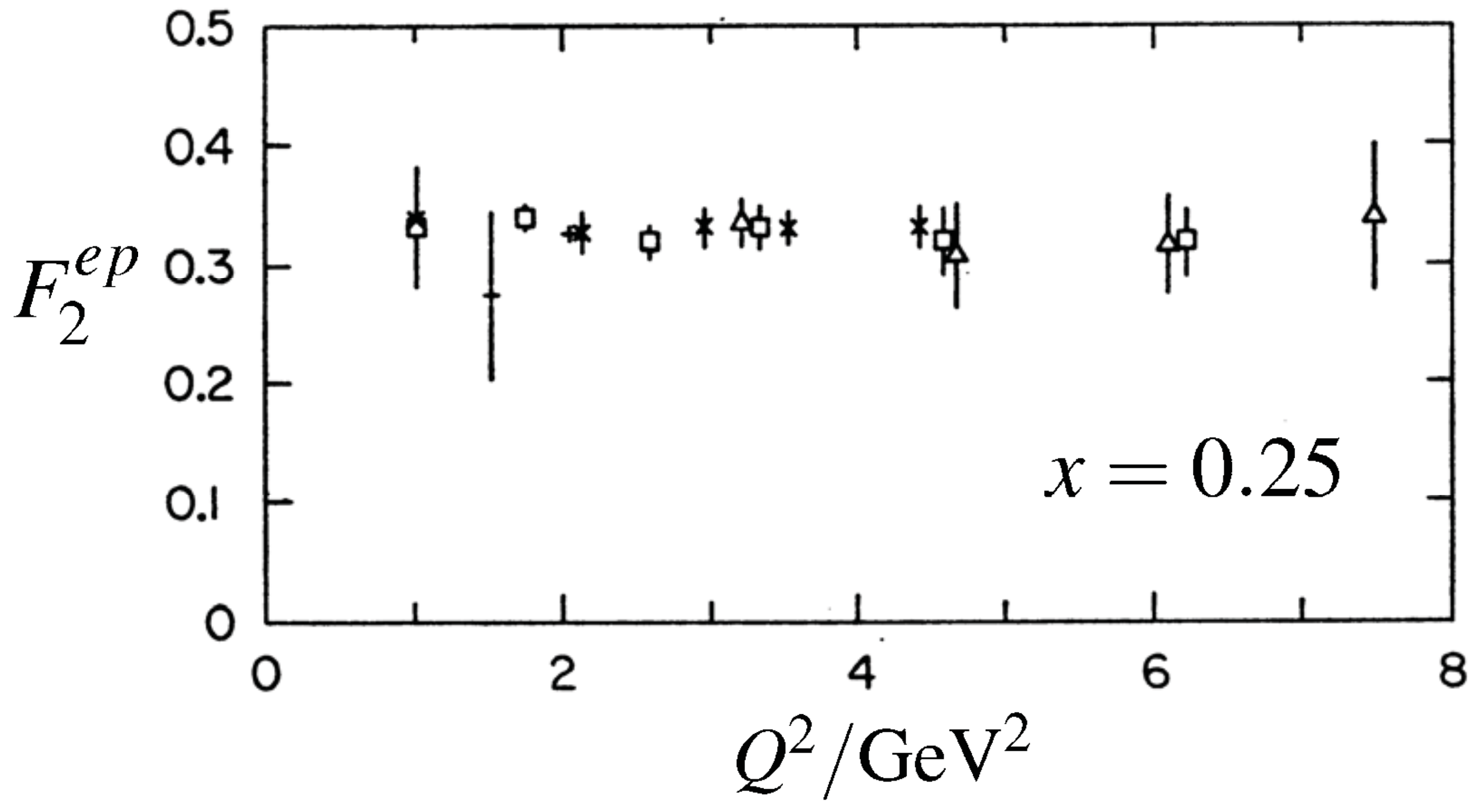
W=M → elastic scattering

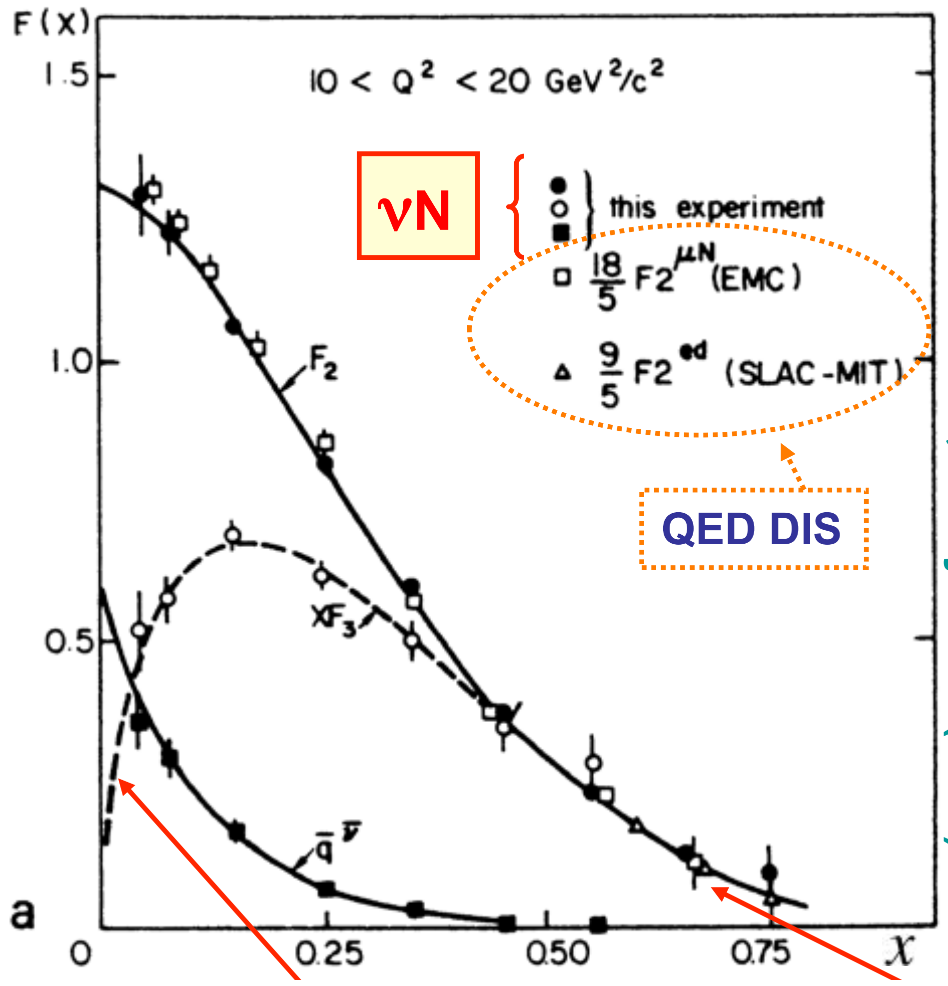
1 < W < 2 GeV → inelastic scattering (exitation of resonances)

W > 2 GeV → deep inelastic scattering

	lab frame - proton at rest before collision: $p_2 = (M, 0, 0, 0)$		lorentz invariant form
energy loss of incoming particle	$\nu = E_1 - E_3$		$\nu = \dfrac{p_2 q}{M}$
Bjorken x	$x = \dfrac{Q^2}{2M\nu}$	x in [0,1]	$x = \dfrac{Q^2}{2p_2 q}$
fractional energy loss of incoming particle	$y = 1 - \dfrac{E_3}{E_1}$	y in [0,1]	$y = \dfrac{p_2 q}{p_2 p_1}$
4-momentum transver	$q^2 = (p_1 - p_3)^2$	$Q^2 = -q^2$	$q^2 = (p_1 - p_3)^2$

Bjorken scaling and QPM





H. Abramowicz et al., Z.Phys. C17 (1983) 283

quark number sum rules

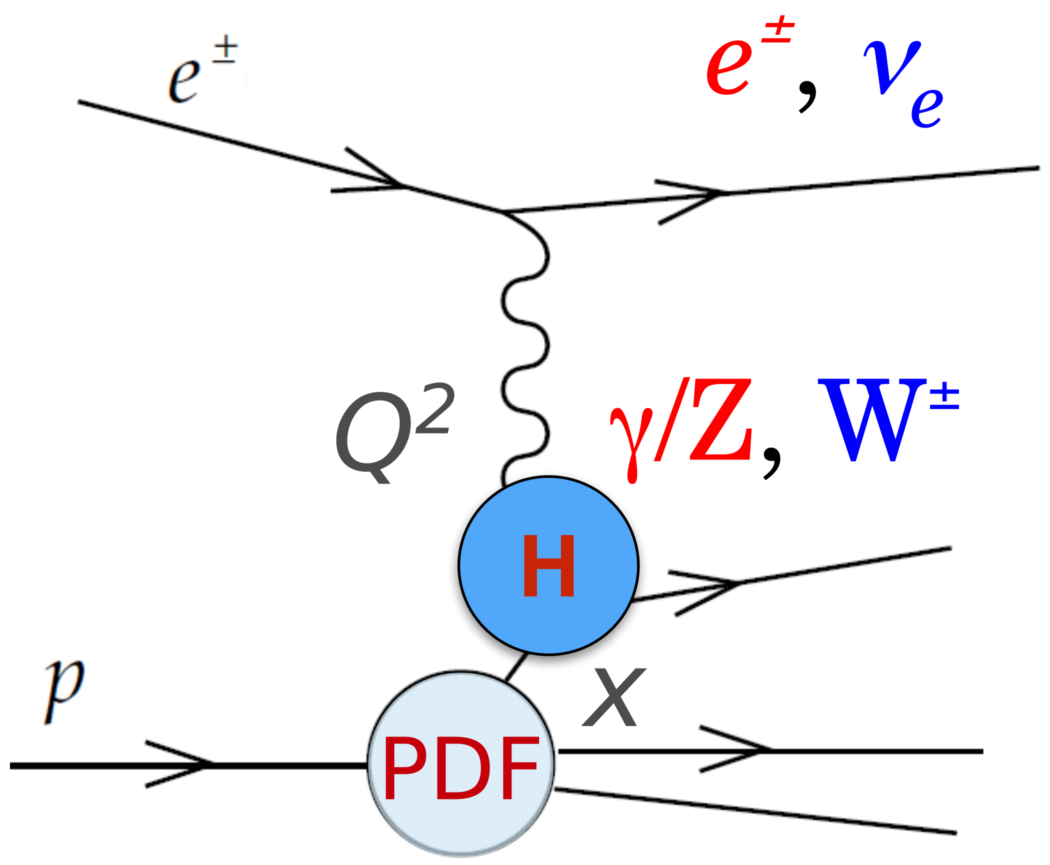
expect $\int_0^1 F_3^{\nu N}(x)\mathrm{d}x = 3$

Experiment: **3.0±0.2**

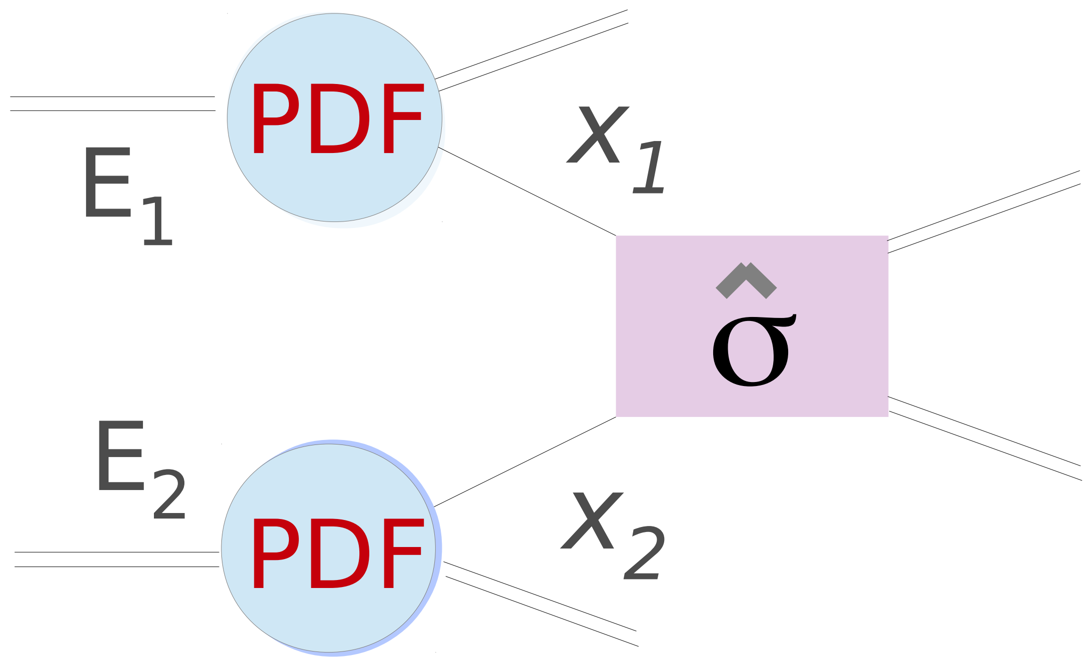
QCD collinear factorization

- QCD collinear factorization ensures universal separation of long-distance and short-distance contributions in high energy scatterings involving initial/final state hadrons, and enables predictions on DIS cross sections

DIS structure functions



hadron-hadron collision



$$\sigma = \hat{\sigma} \otimes f_1 \otimes f_2$$

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dx dQ^2} = \frac{G_F^2}{4\pi x(1+Q^2/M_{W,Z}^2)^2}\left[Y_+ F_2 - y^2 F_L \pm Y_- x F_3\right], \quad Y_\pm = 1 \pm (1-y)^2$$

$$F_2(x,Q^2) = \sum_{i=q,\bar{q},g} \int_0^1 d\xi\, C_2^i(x/\xi, Q^2/\mu_r^2, {\mu_f}^2/\mu_r^2, \alpha_s(\mu_r^2)) \times f_{i/h}(\xi, \mu_f)$$

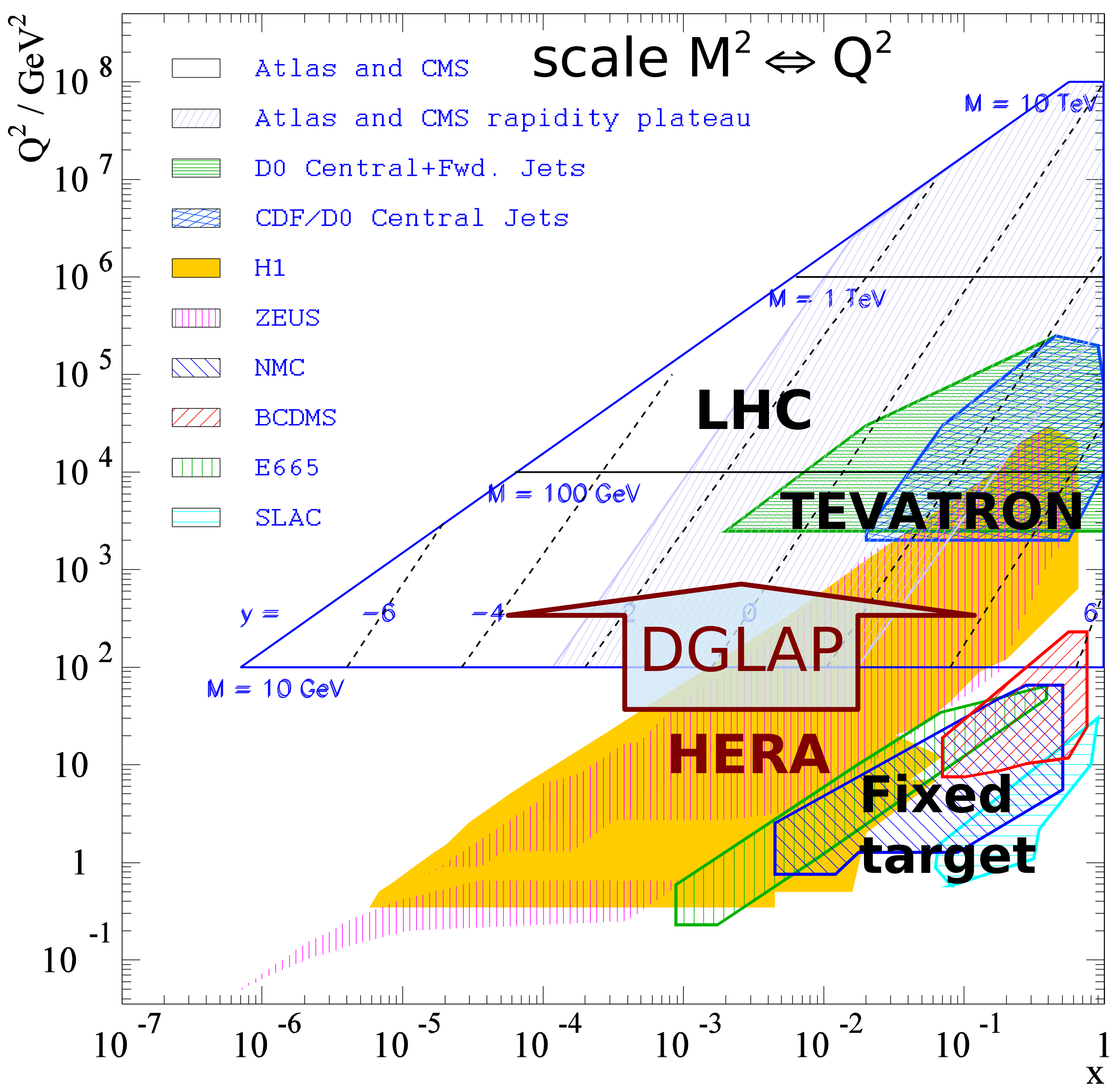
[Collins, Soper, Sterman, 1989]

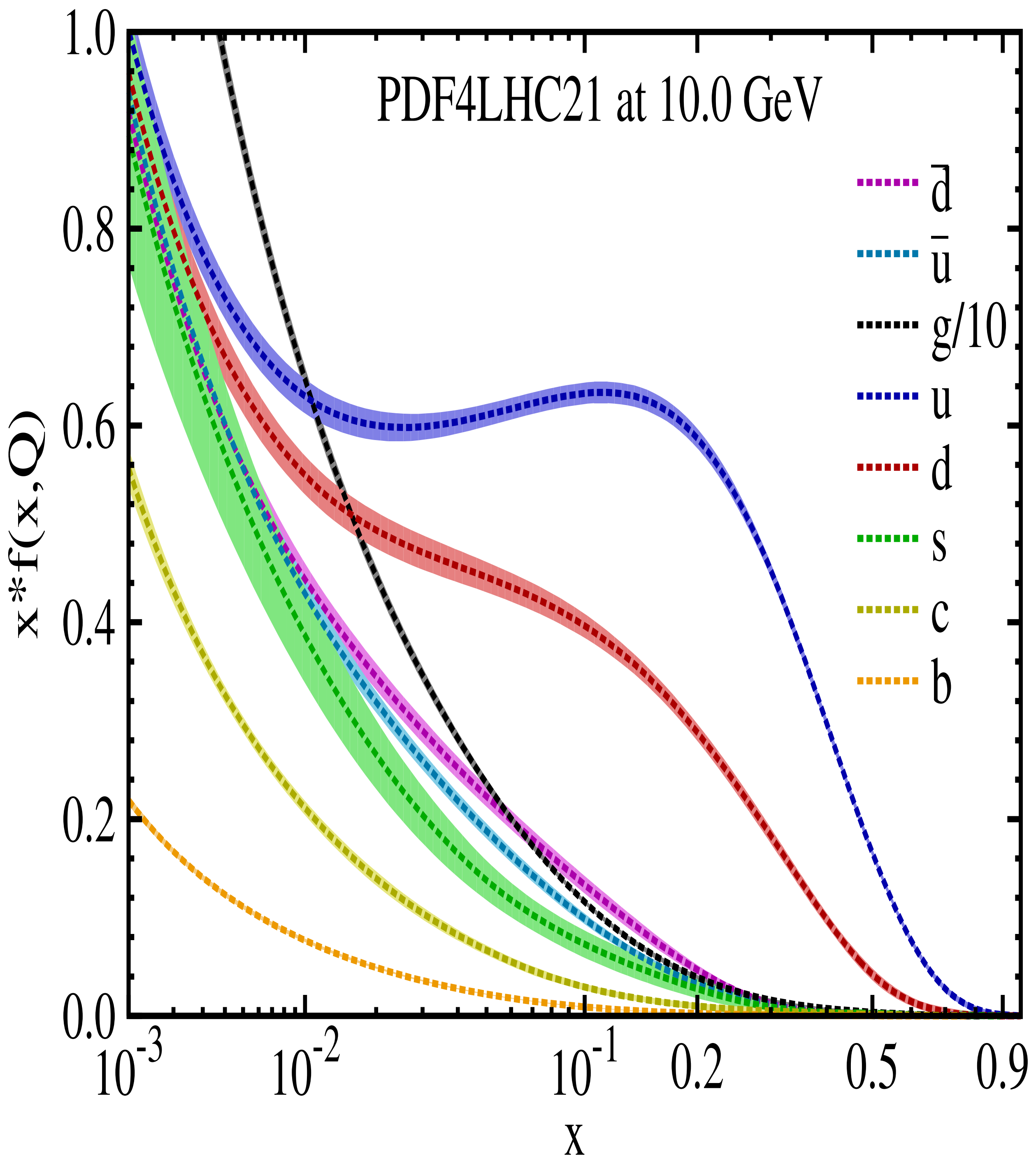
- coefficient functions, represent hard scattering; infrared (IR) safe, calculable in perturbative QCD, independent of the hadron
- parton distributions (PDFs), reveal inner structure of hadrons; non-perturbative (NP) origin, universality, e.g. DIS vs. pp collisions
- runnings of PDFs with respect to factorization scale μ_f are governed by the DGLAP equation

Global analysis of PDFs

- PDFs are usually extracted from global analysis on variety of data, e.g., DIS, Drell-Yan, jets and top quark productions at fixed-target and collider experiments, with increasing weight from LHC

[JG, Harland-Lang, Rojo, 1709.04922; 1905.06957 for recent review articles]





parameter variations

α_S(Mz)

Mc, Mb, Mt

QCD/EW corrections

nuclear corrections

EW parameters

New Physics

- diversity of the analysed data are important to ensure flavor separation and to avoid theoretical/experimental bias; possible extensions to include EW parameters and possible new physics for a self-consistent determination

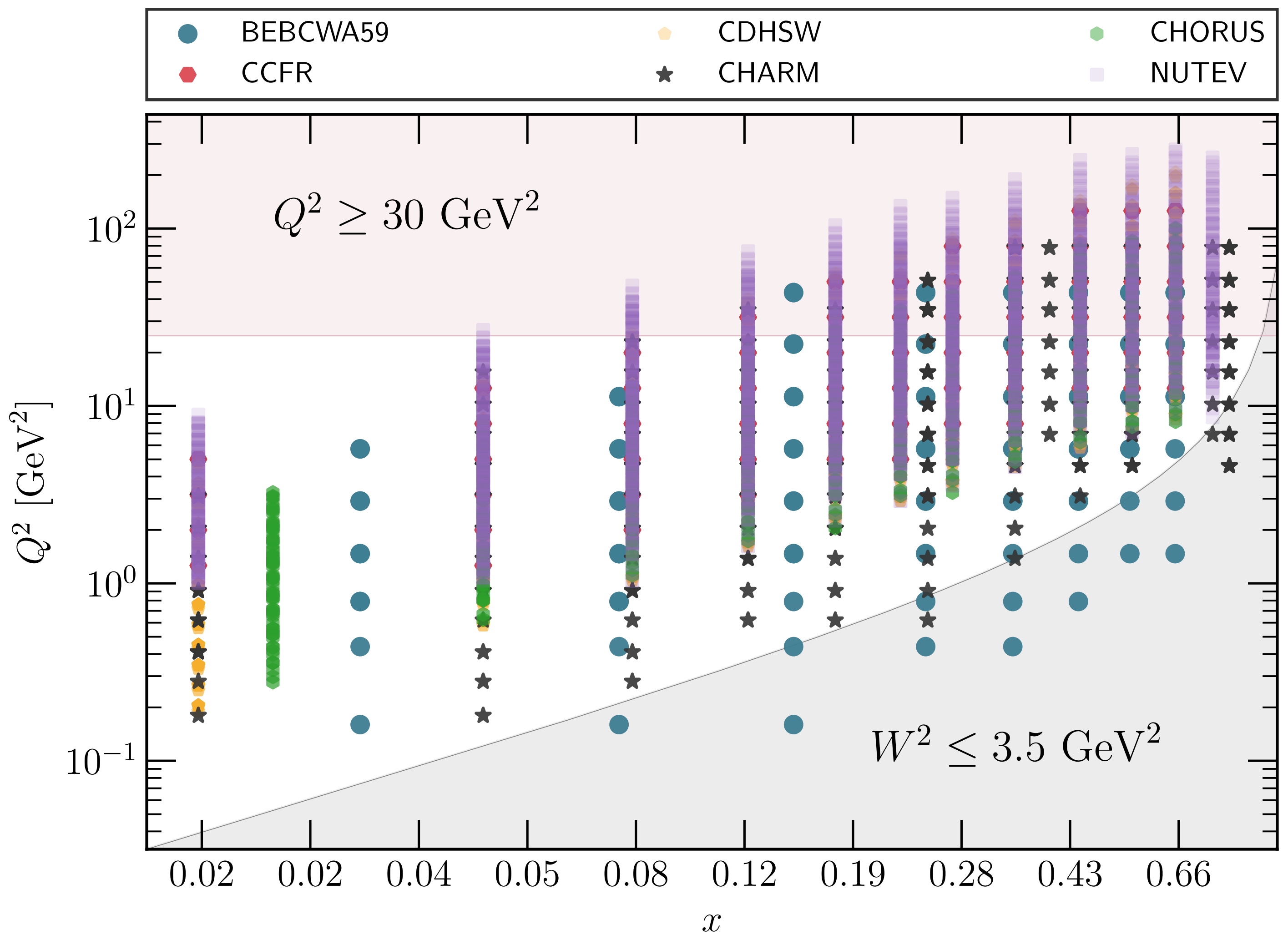
- alternative approach from lattice QCD simulations, for various PDF moments or PDFs directly calculated in x-space with large momentum effective theory or pseudo-PDFs [2004.03543]

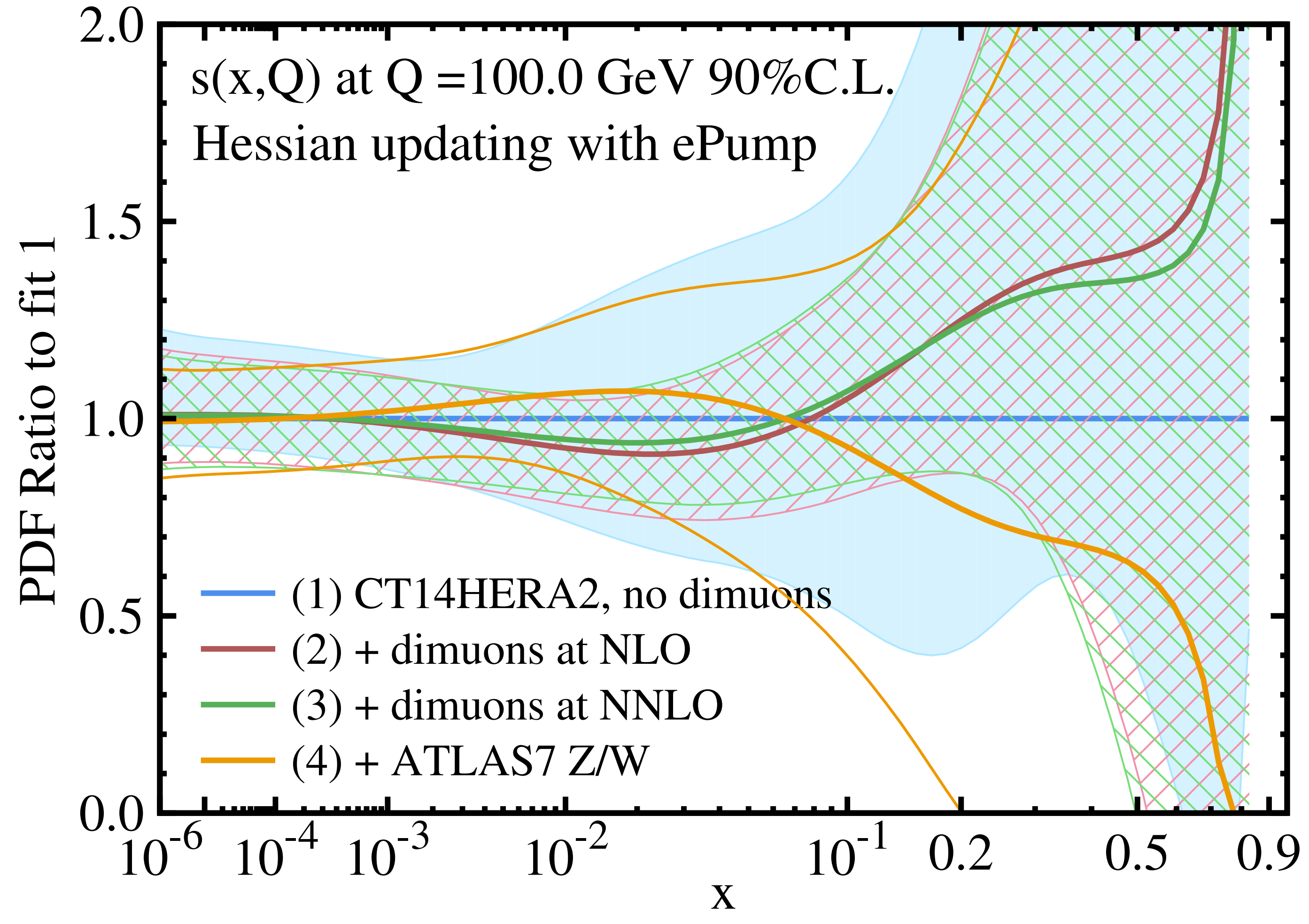
Impact of neutrino DIS data

- In probing partonic structure of nucleons, neutrino CC DIS are complementary to the neutral current DIS for separations of quark and anti-quarks and also quark flavors, especially strange quark PDF

representative neutrino DIS data

Data set	Nucleus	$E_{\nu/\bar{\nu}}$(GeV)	#pts	Corr.sys.	Ref.
CDHSW ν	Fe	23 - 188	465	No	[48]
CDHSW $\bar{\nu}$			464		
CCFR ν	Fe	35 - 340	1109	No	[50]
CCFR $\bar{\nu}$			1098		
NuTeV ν	Fe	35 - 340	1170	Yes	[23]
NuTeV $\bar{\nu}$			966		
Chorus ν	Pb	25 - 170	412	Yes	[27]
Chorus $\bar{\nu}$			412		
CCFR dimuon ν	Fe	110 - 333	40	No	[19]
CCFR dimuon $\bar{\nu}$		87 - 266	38		
NuTeV dimuon ν	Fe	90 - 245	38	No	[19]
NuTeV dimuon $\bar{\nu}$		79 - 222	34		



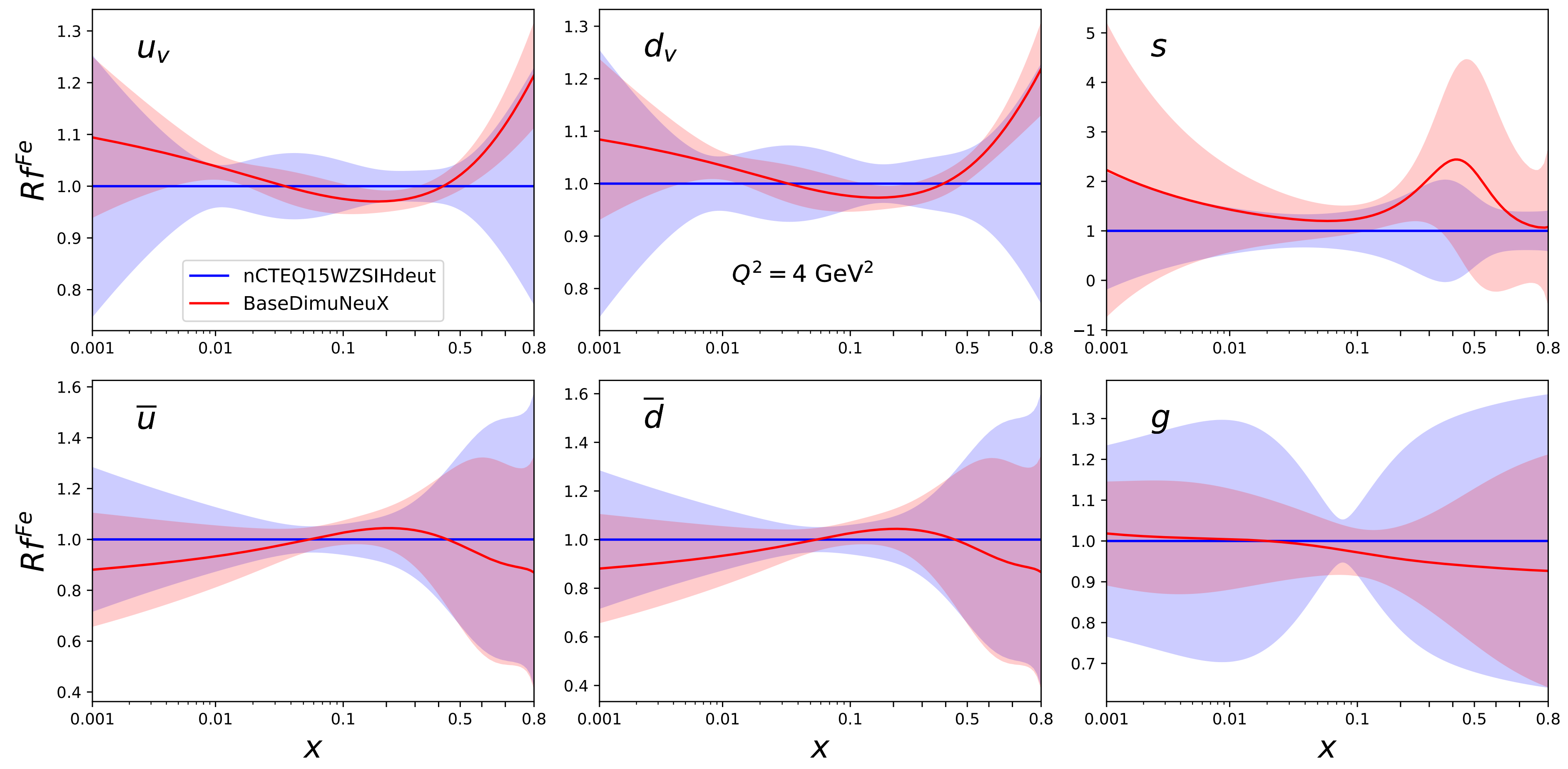


CT18 proton PDF fit

W>3.5 GeV, Q>2 GeV

dimuon data on strange PDFs

[Hou, JG+, 1912.10053]



nCTEQ nuclear PDF fit

Inclusive and dimuon data on PDFs of Pb

[2204.13157]

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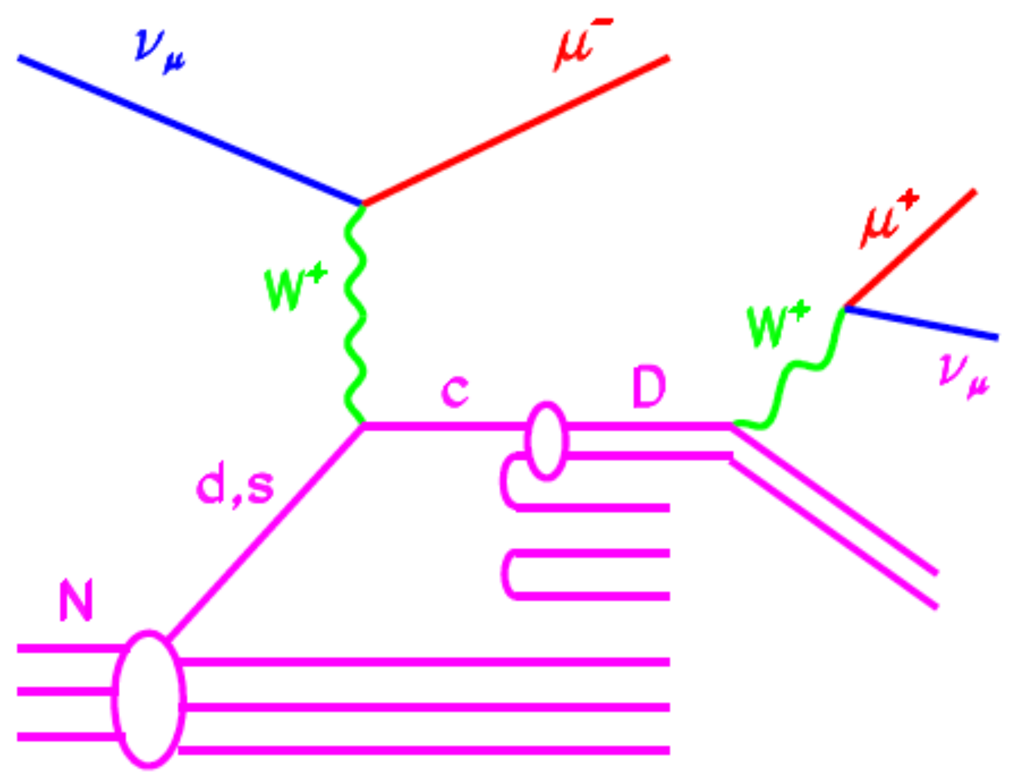
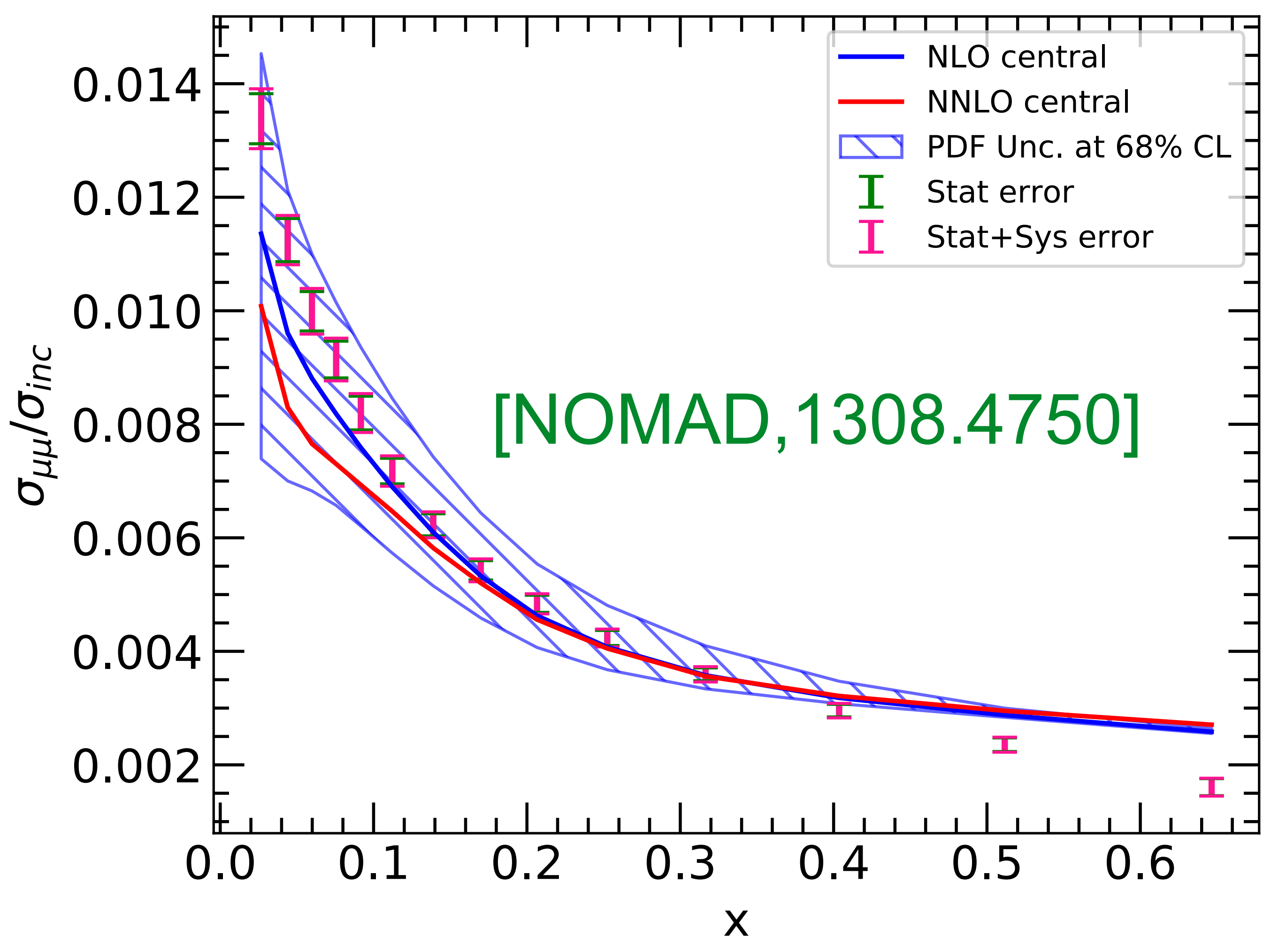
Charm quark production in CC DIS

- In semi-inclusive CC DIS, charm-quark production with subsequent leptonic decays (so-called dimuon events) can serve as a direct probe of the strange-quark parton distribution, e.g., as from NuTeV, CCFR, and NOMAD; especially the NOMAD dimuon data have a high quality

Dimuon production from SIDIS





Differential cross sections

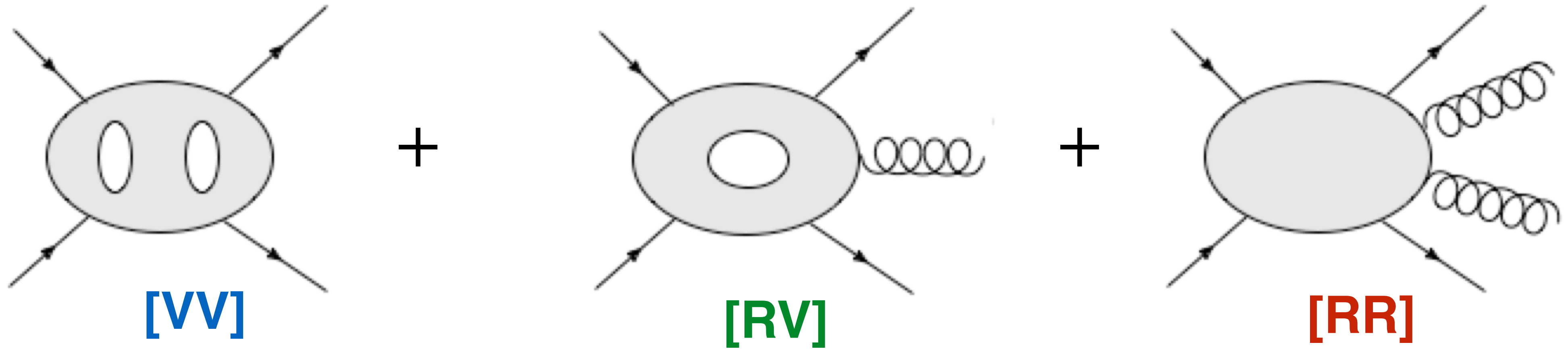
$$\frac{d\sigma_c^\nu}{dxdy} = \frac{G_F^2 ME}{\pi(1+Q^2/M_W^2)^2}\left[\left(1-y-\frac{Mxy}{2E}\right)F_{2,c}^\nu(x,Q^2)+ \right.$$
$$\left. +\frac{y^2}{2}F_{T,c}^\nu(x,Q^2)+y\left(1-\frac{y}{2}\right)xF_{3,c}^\nu(x,Q^2)\right]$$

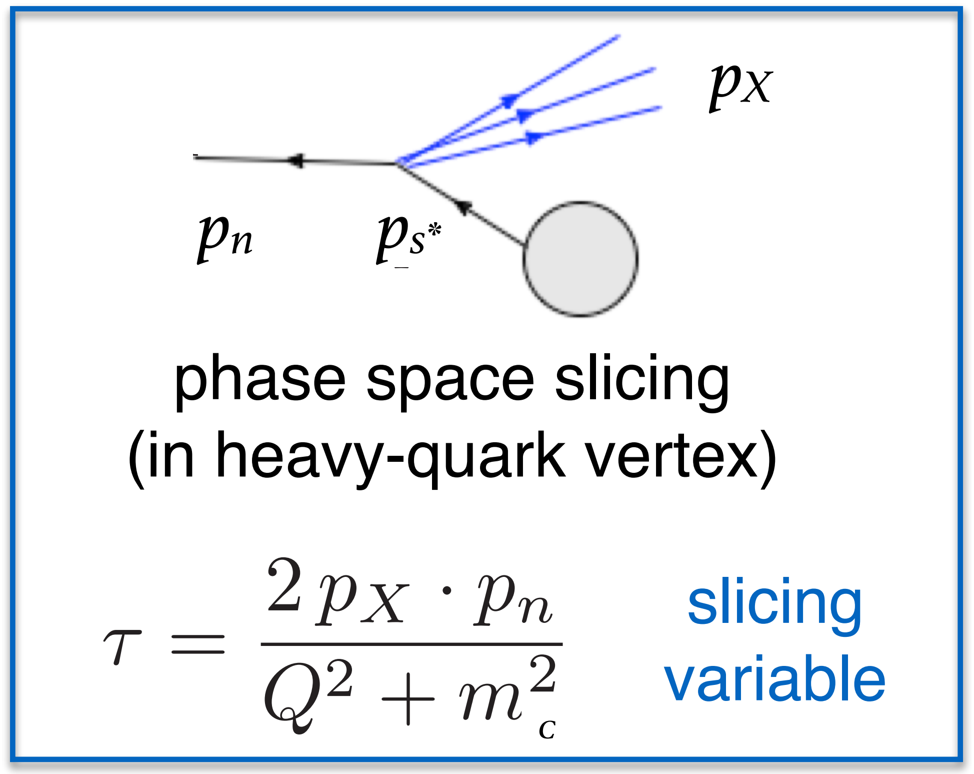
- Finite charm-quark mass corrections are important for kinematic region of neutrino DIS (Eν ≲ hundreds GeV), known at LO via the slow scaling variable $\chi \sim x_B(1+m_h^2/Q^2)$
- Charm-quark production has been calculated to NLO in QCD by T. Gottschalk (1981) and M. Gluck+(1997) in a closed analytic form
- No one bother to calculate the NNLO corrections for more than 30 years since the first NLO result

Production cross section at NNLO

- The two-loop production cross sections with exact charm-quark mass dependence are calculated numerically with MC integrations and with a phase-space slicing (on beam thrust) method to render subtractions of infrared/collinear divergences [Berger, JG, Li, Liu, Zhu, 1601.05430; JG, 1710.04258]

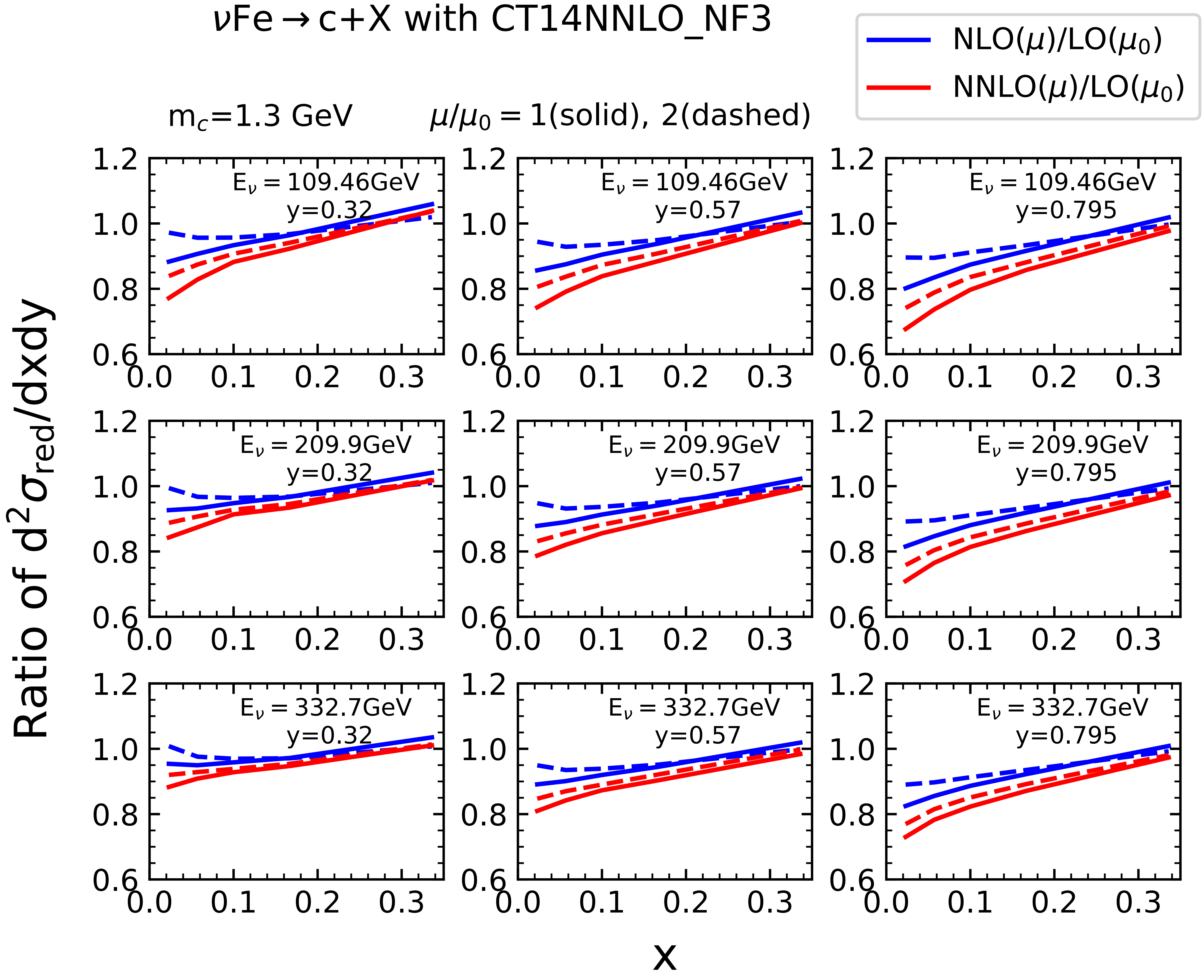
Slicing method





- unresolved region: factorization derived in soft-collinear effective theory with all perturbative ingredients available at two-loops

Corrections with CCFR data kinematics

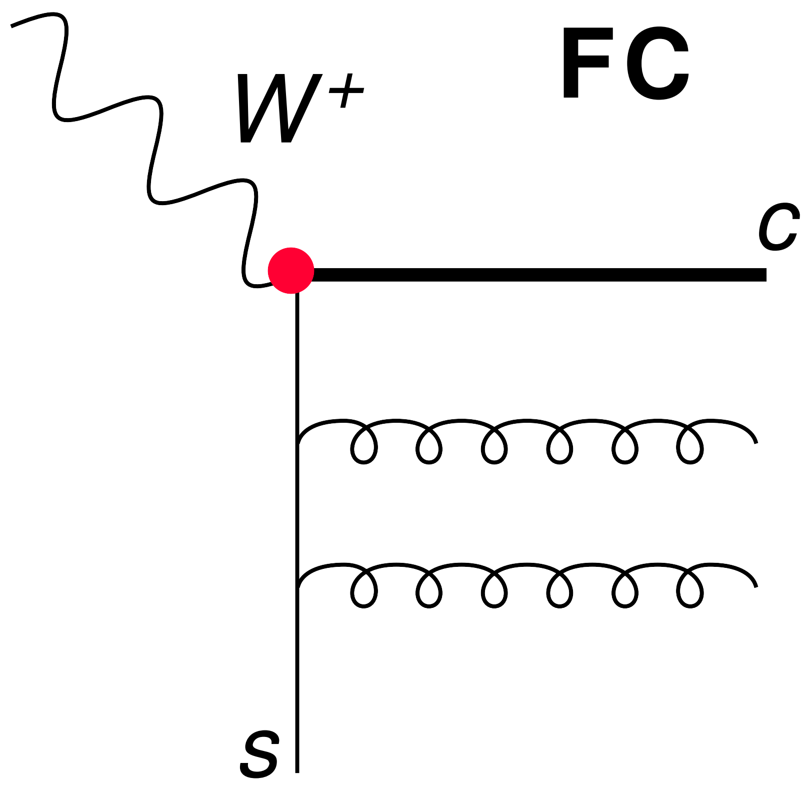


GM-VFNs at NNLO for inclusive CC DIS

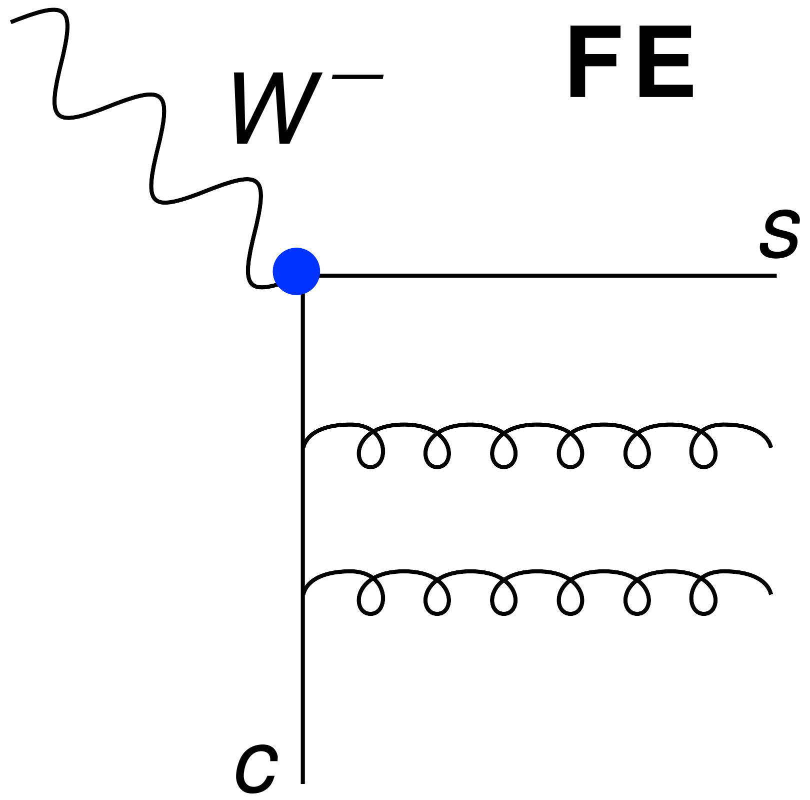
- General-mass(GM) VFN schemes are frameworks to predict full heavy-mass dependence, interpolating between FFNs and ZM-VFNs, have been widely used in PDF fits, e.g., ACOT-like, FONLL, RT schemes

[JG, Hobbs, Nadolsky, Sun, Yuan, 2107.00460]

power term of mc

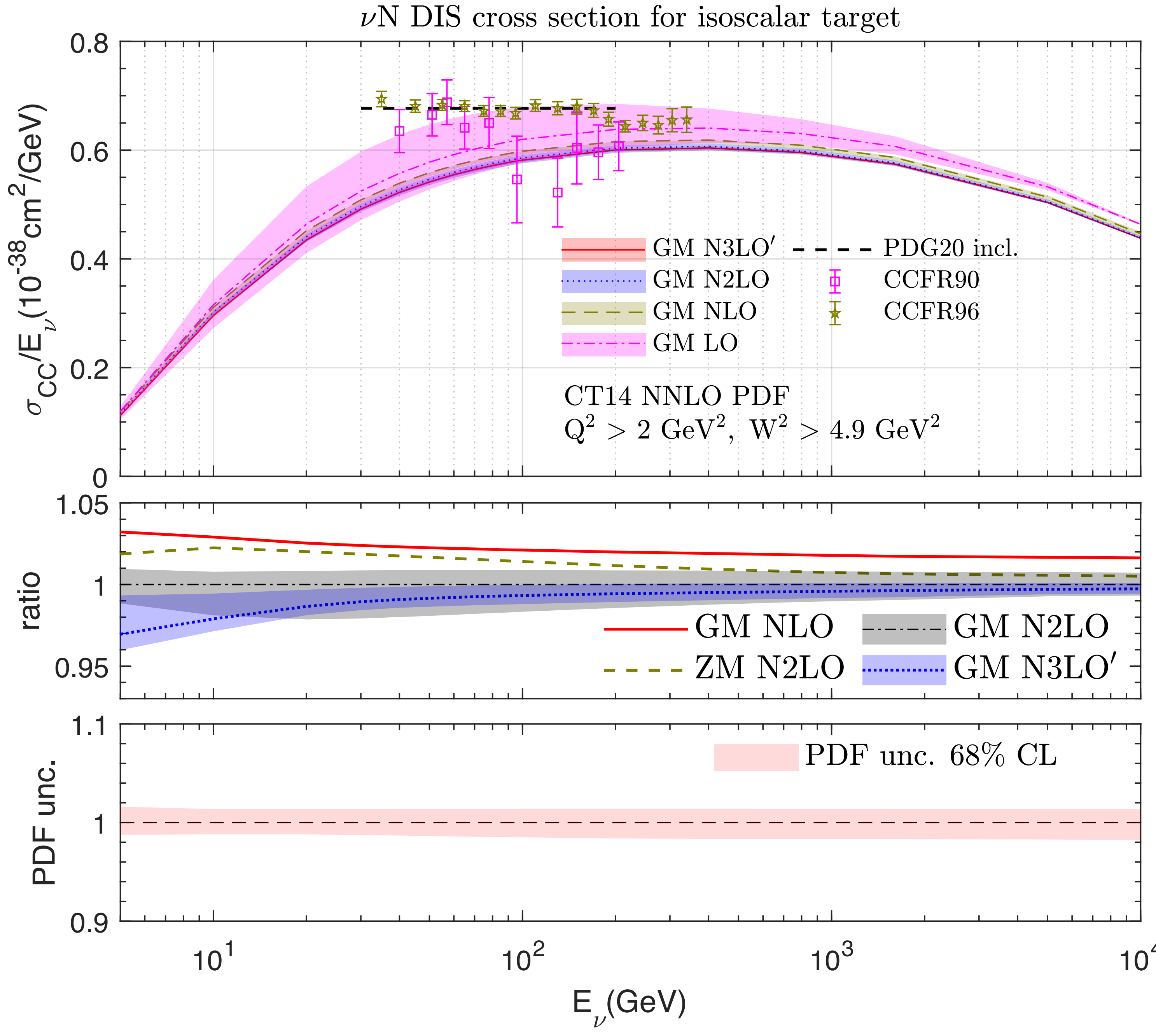


logarithms of mc



- factorization on heavy-quark contribution to DIS was proved by Collins and result in ACOT-like HQ schemes
- the coefficient functions for CC DIS in simplified ACOT-χ, a GM-VFN, scheme have been calculated to NNLO with full mass dependence

application to total cross sections of neutrino CC DIS on iso-scalar target



- finite mass corrections are about 2% at low Ev comparing GM and ZM both at N2LO; scale variations are 1~3% for GM N2LO, and <1% for N3LO′ at large Ev

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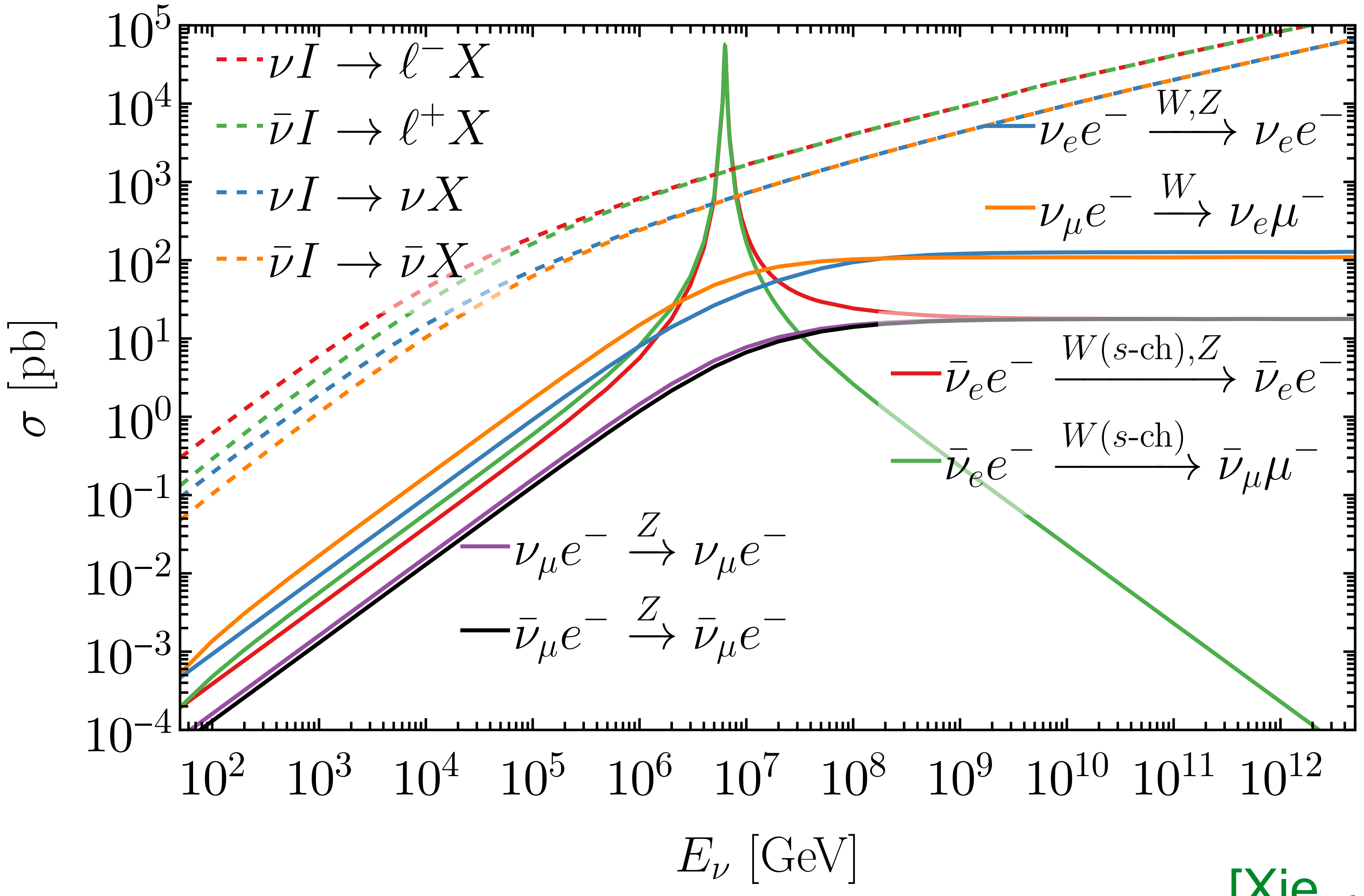
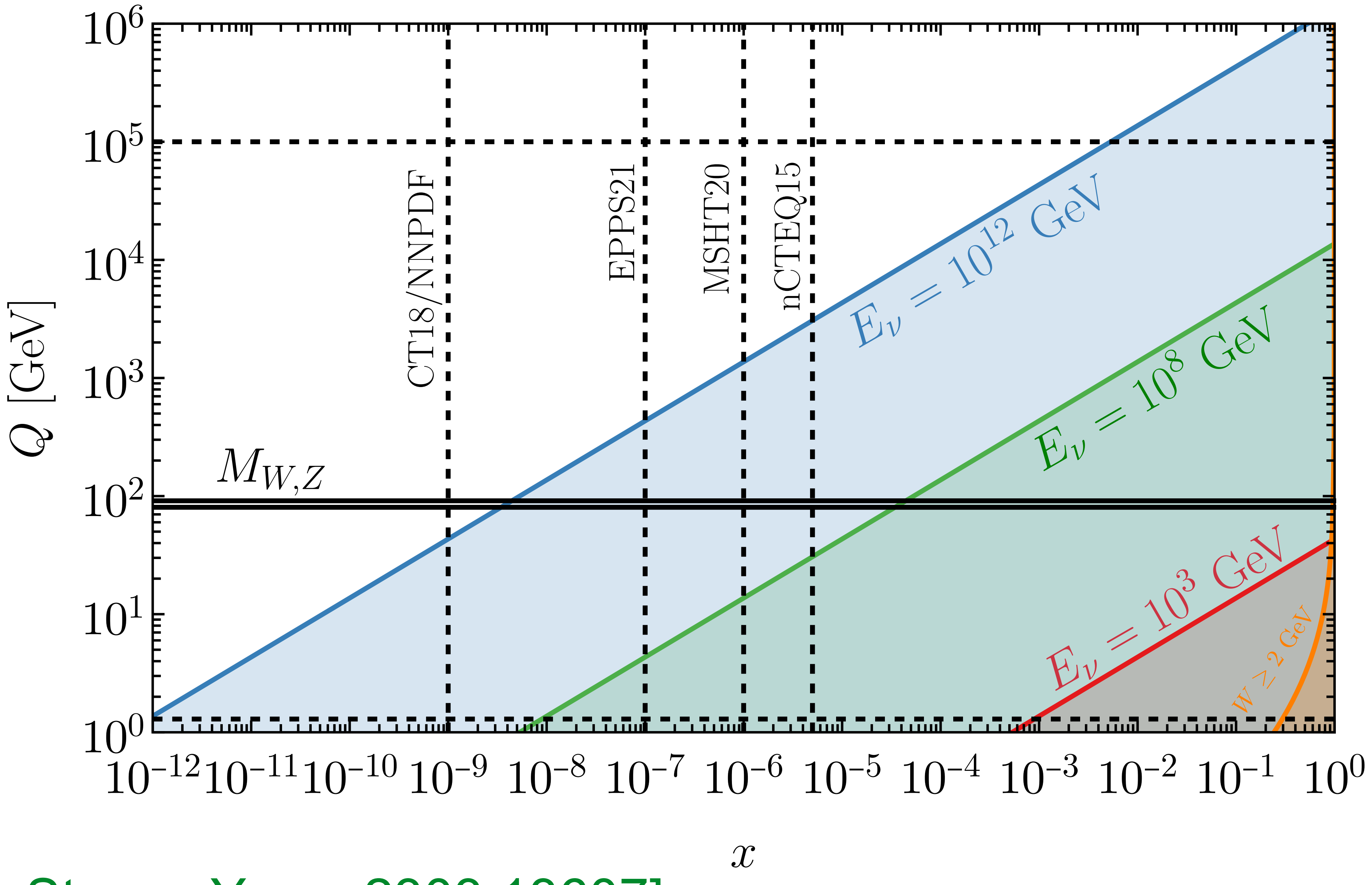
Predictions for ultra-high energy neutrinos

- Neutrino scattering cross sections on nucleus, both charged-current (CC) and neutral-current (CC) are key inputs for calculating absorption rate and detection efficiency of ultra-high energy neutrinos (e.g., IceCUBE) and are dominated by regions of deeply inelastic scatterings (DIS)

total cross sections vs. energy



DIS x-Q² coverage



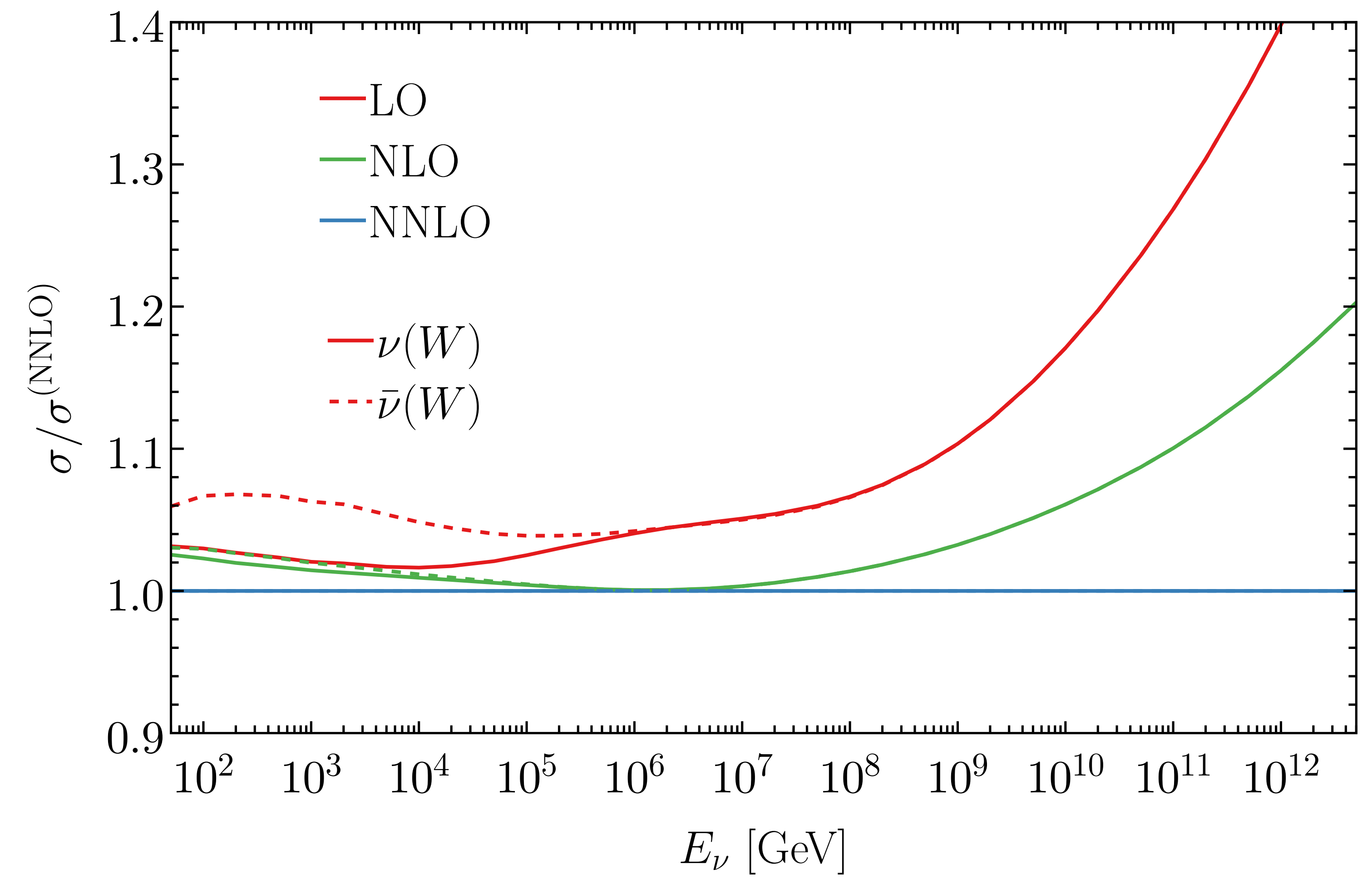
[Xie, JG, Hobbs, Stump, Yuan, 2303.13607]

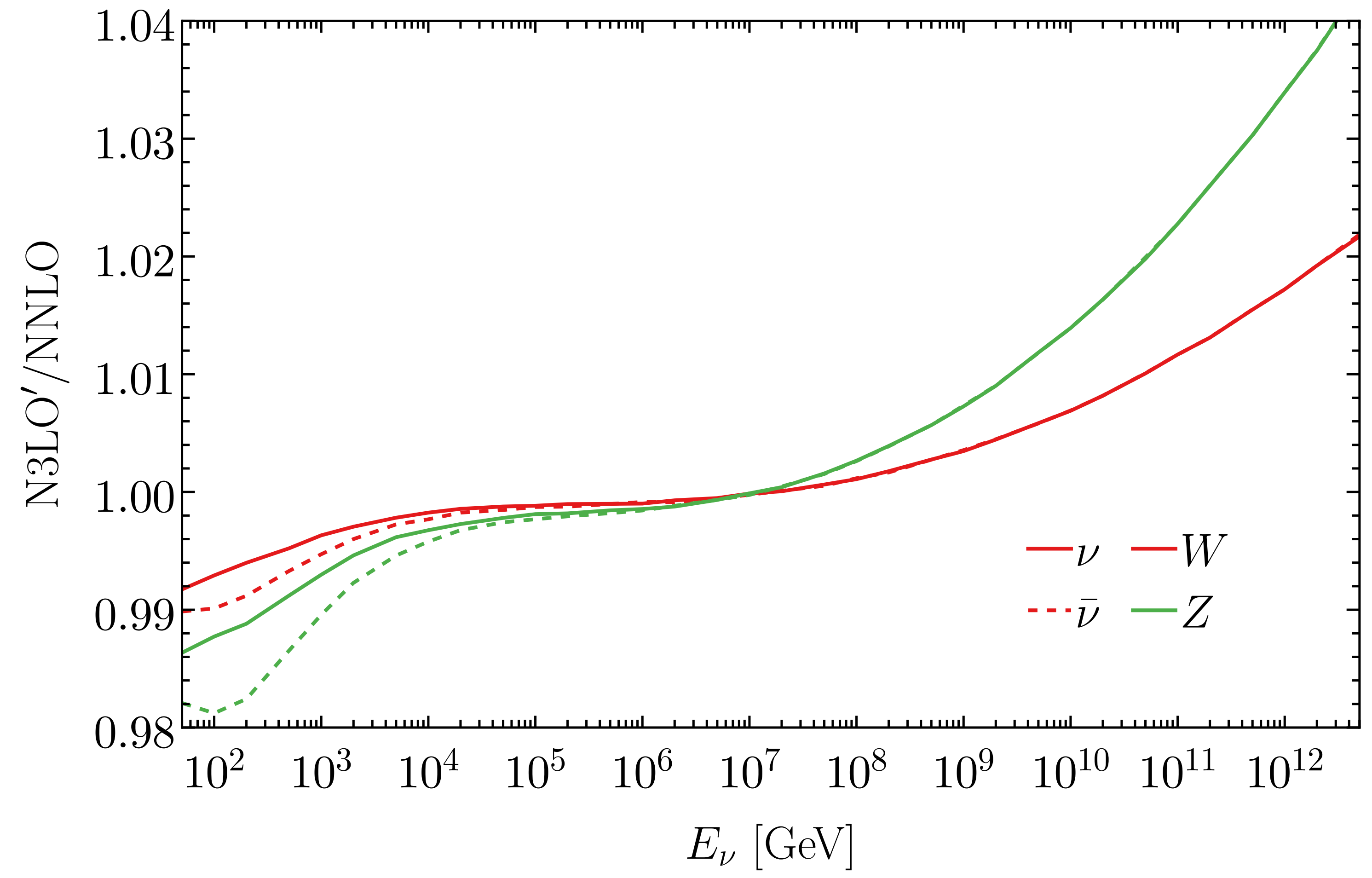
- an important observation is DIS of ultra-high energy (UHE) neutrinos involves kinematic regions with rather small-x (<10^{-5}) that are unexplored by all other experiments; careful examination on small-x extrapolation and various uncertainties are required

Uncertainty: Perturbative QCD calculations

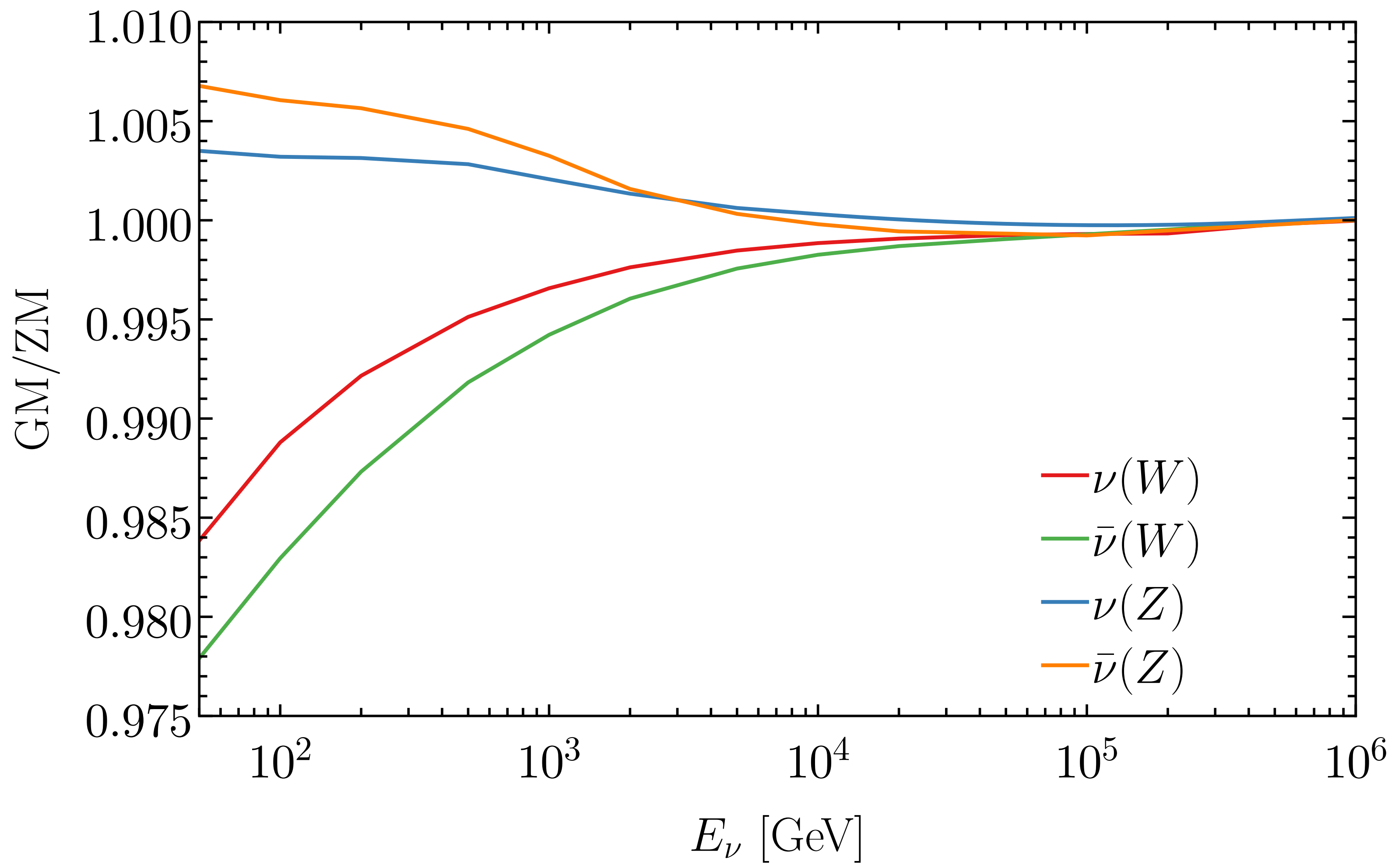
- Perturbative calculations on the coefficient functions can be improved order by order in QCD, with full results available at NNLO and partial results known at N3LO for CC and NC DIS

perturbative convergence





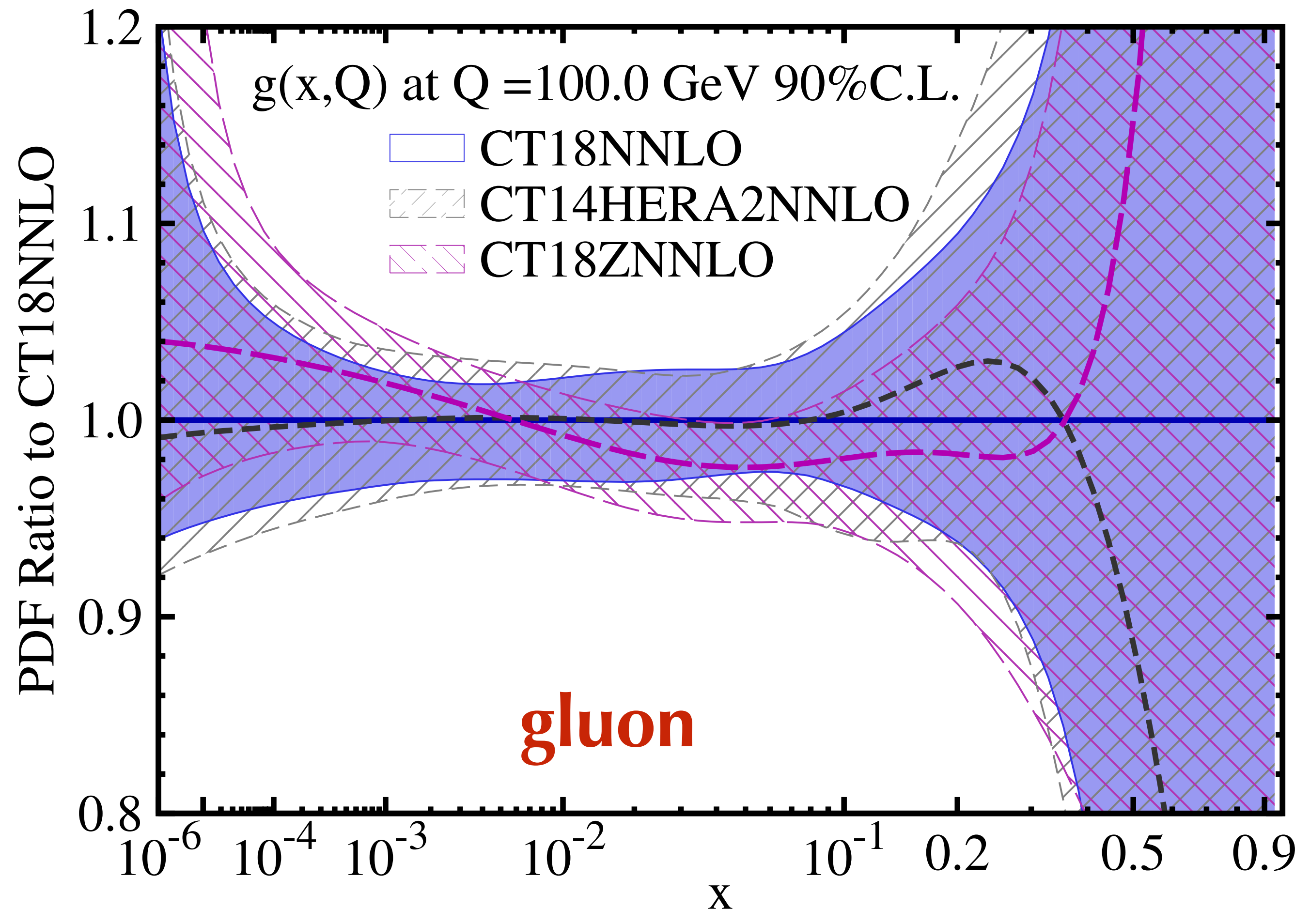
charm mass corrections

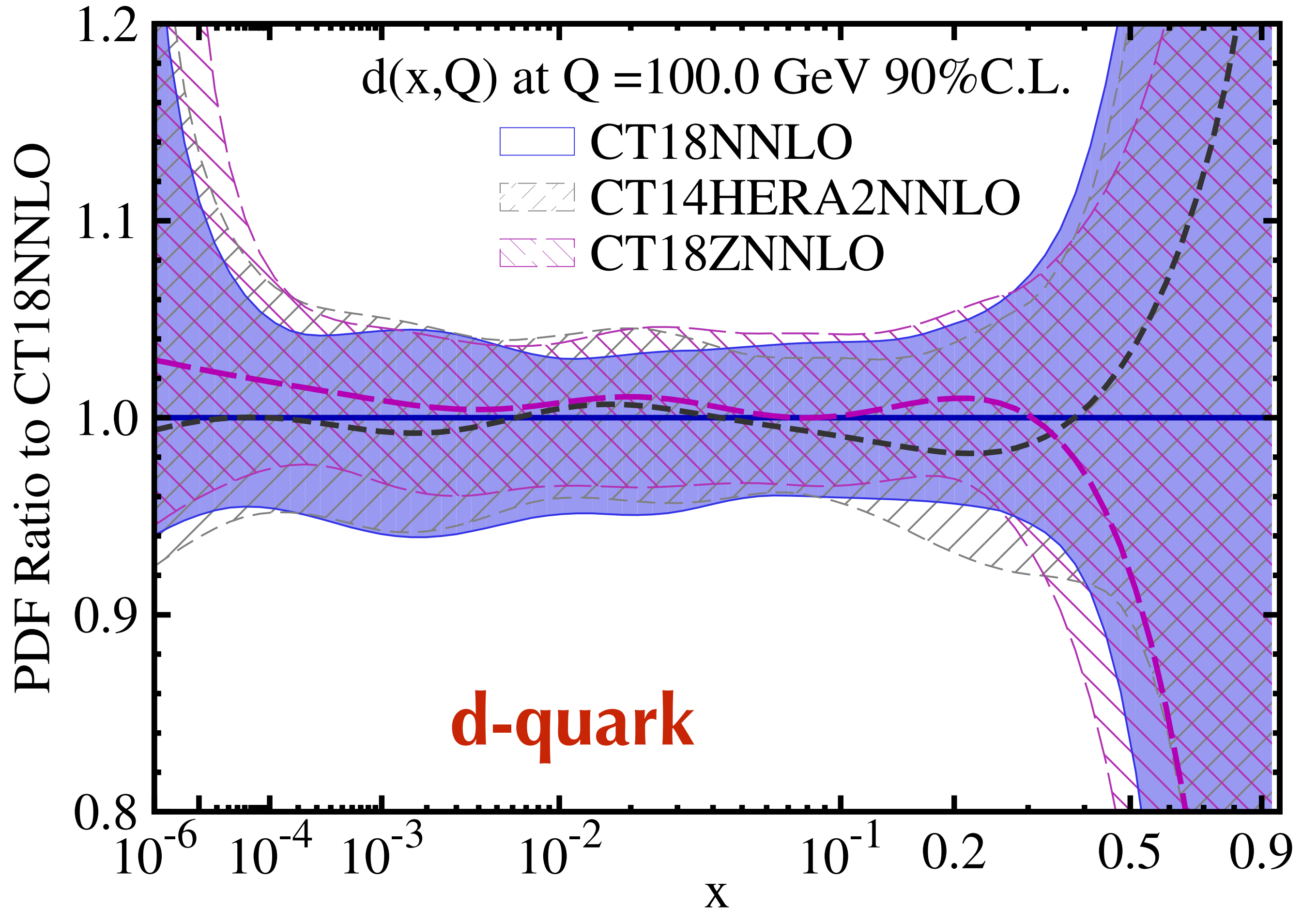


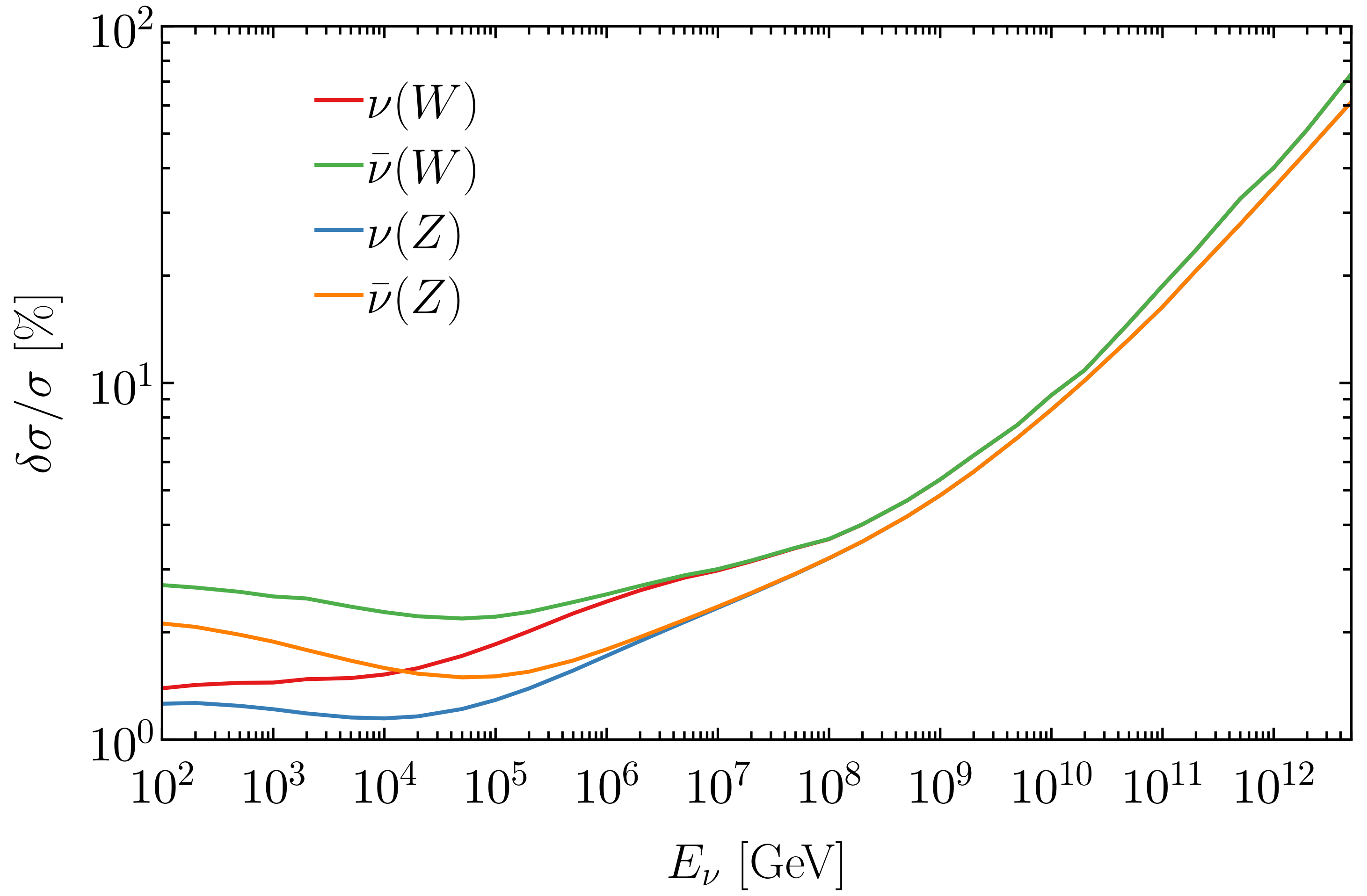
- perturbative calculations show good convergence with remaining unc. at most a few percents

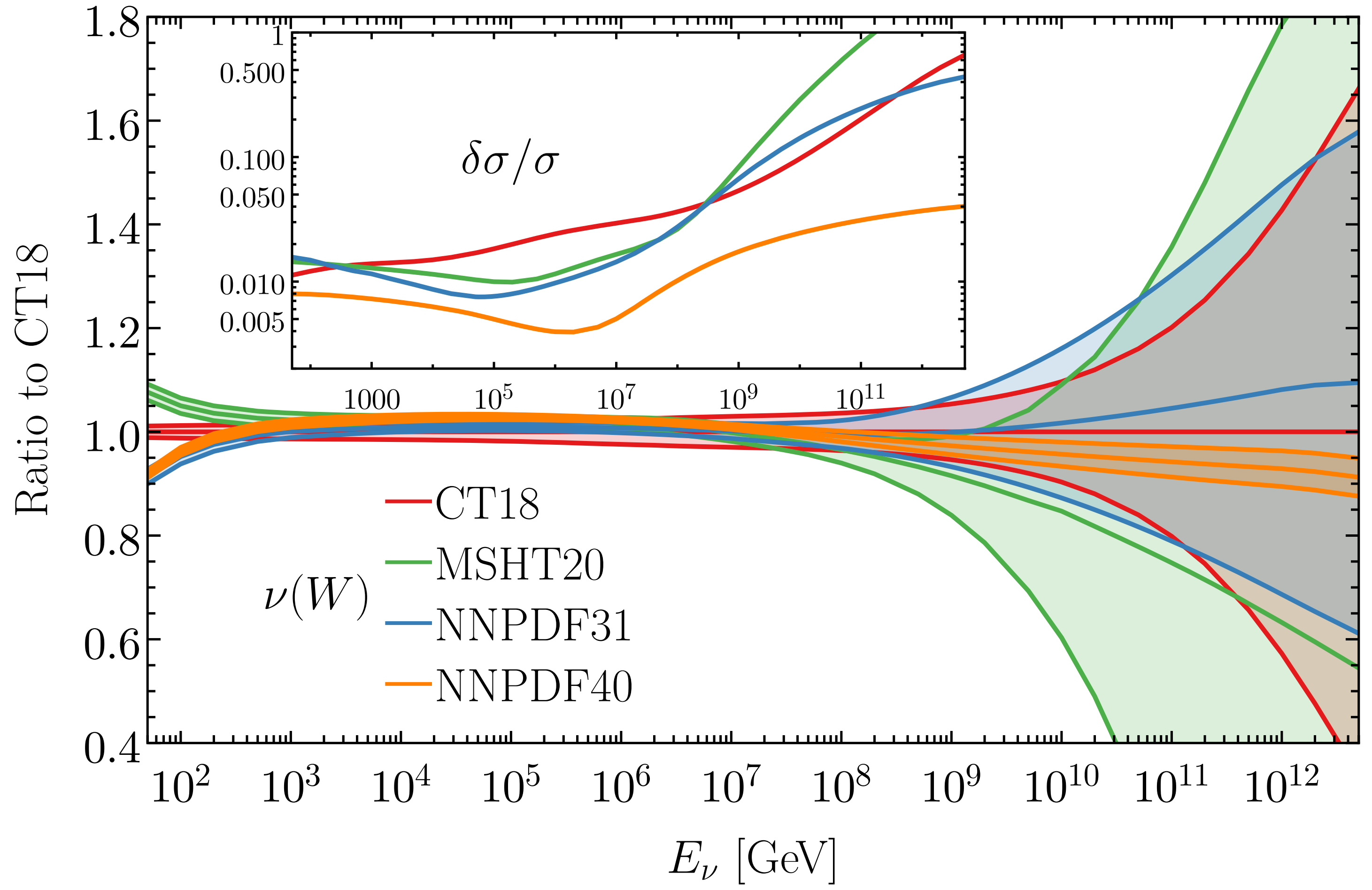
Uncertainty: Parton distribution functions

- Proton PDFs provided by several major analysis groups (CT, MSHT, NNPDF, ABM, HERAPDF, ATLASpdf, CJ, JAM…) using slightly different heavy-quark schemes, selections of data, and methodologies









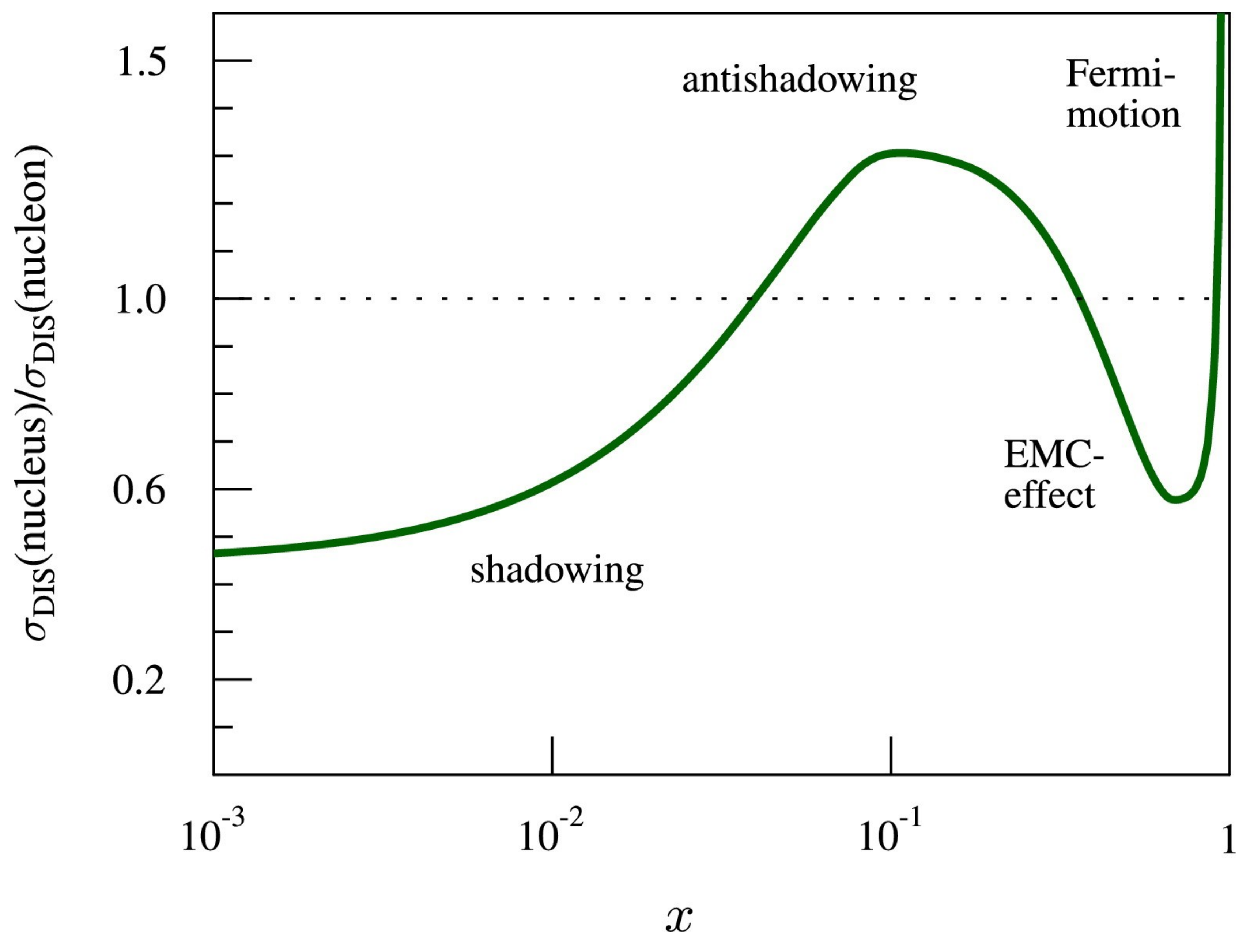
- CT18 represents the state of art PDFs of proton with a faithful/ conservative estimation of uncertainties

- PDF unc propagated into neutrino cross sections at the level of <10% in general for energy upto EeV

Uncertainty: Nuclear modifications

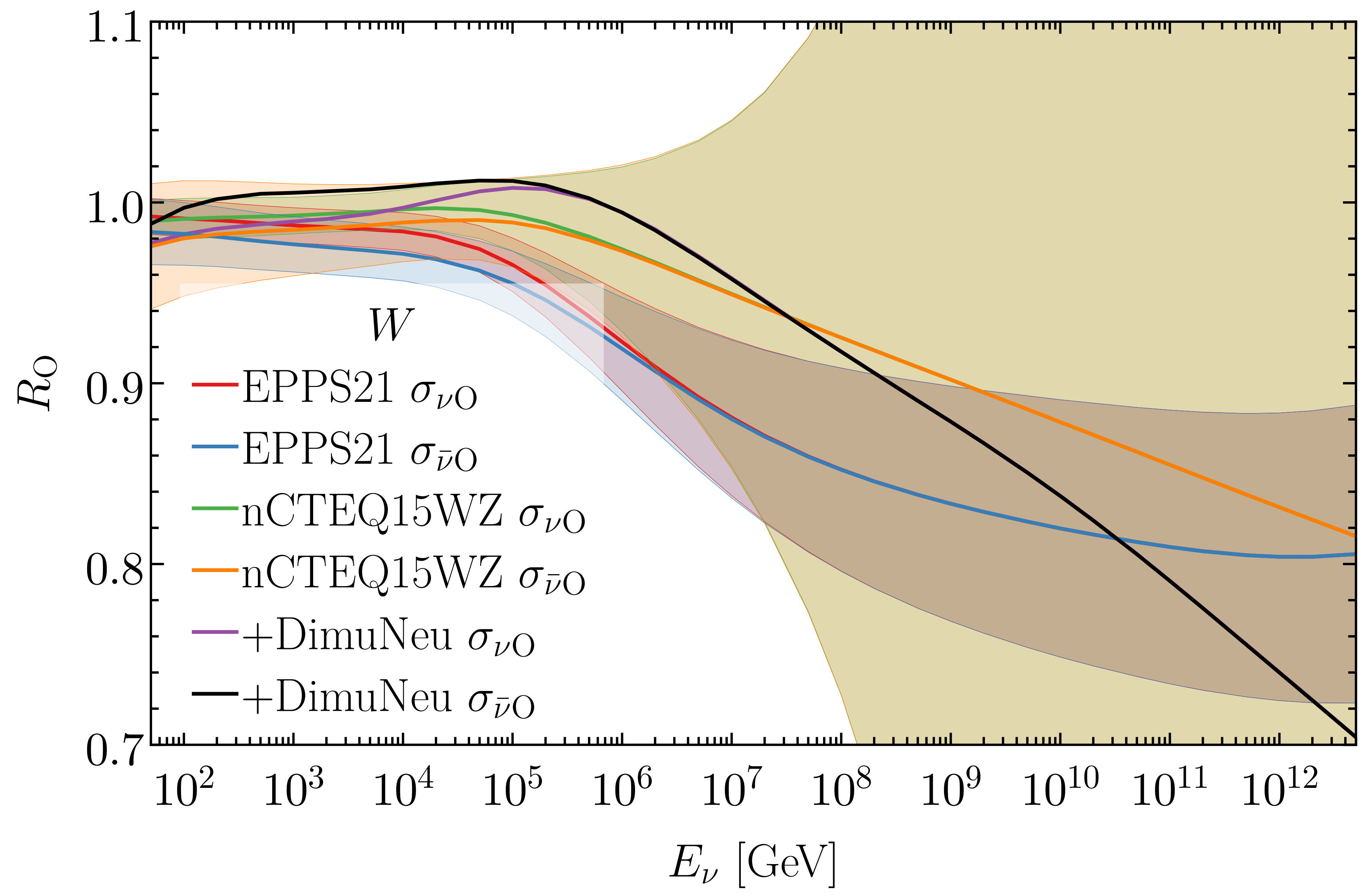
- DIS structure functions or cross sections per nucleon are different for free nucleons and for nucleus, and depends on the kinematic regions (x); those nuclear modifications are especially uncertain at small-x and for charged-current scatterings

general feature of nuclear modifications



[1401.2345]

predictions on nuclear corrections for neutrino scatterings on oxygen

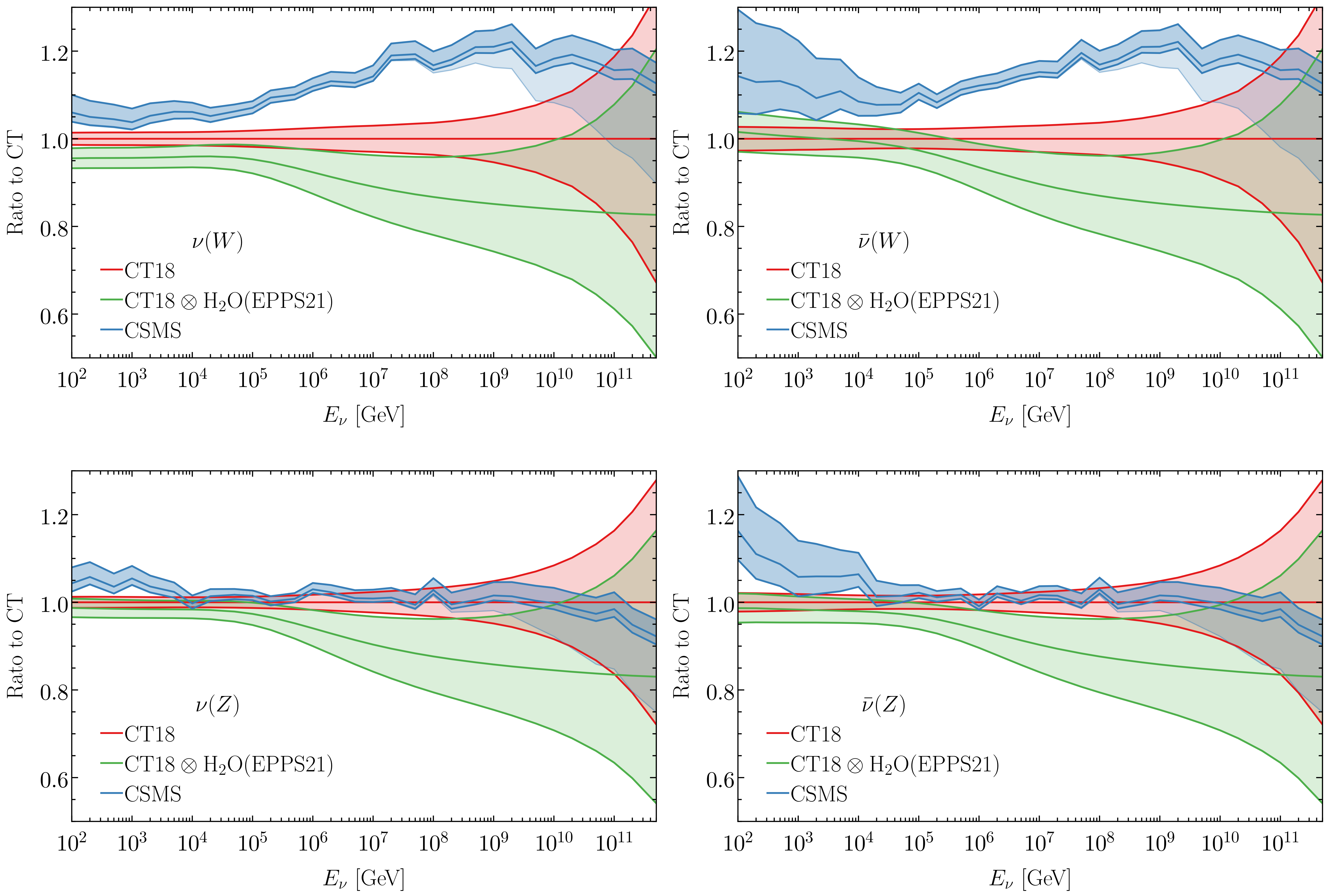


- spread of predictions from different groups can be as large as 20% for tens PeV neutrinos

Comparison to CSMS results

- Our final predictions (from CT18+nuclear corrections) are compared to the CSMS predictions [Cooper-Sarkar, Mertsch, Sarkar 2011] which are the benchmarks of DIS cross sections used by the IceCube collaboration

ratio of DIS total cross sections

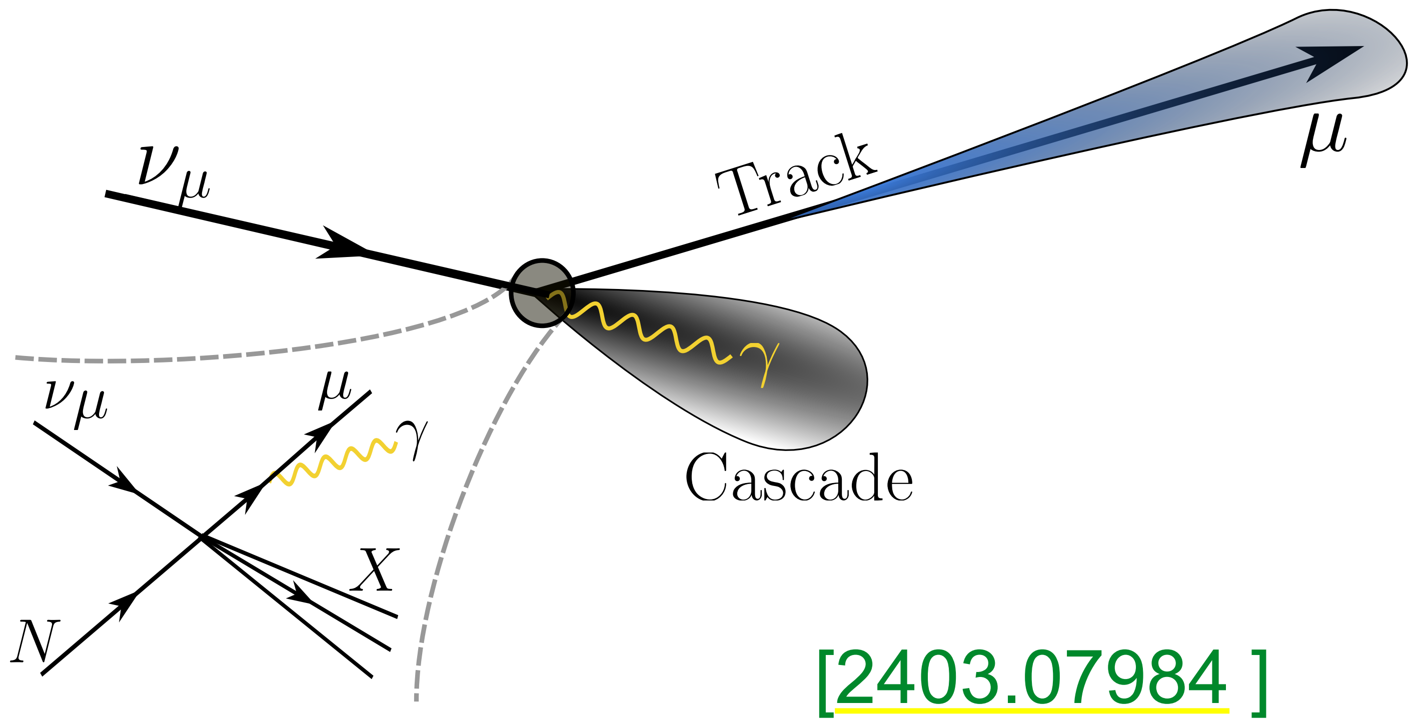


- three results are compared: CT18 with (w/o) nuclear corrections, CSMS
- central predictions differ especially for CC DIS by upto ~20%; can affect neutrino transmission probability and also the measured flux
- larger unc. from PDFs and nuclear corrections especially for UHE neutrinos

Revisit of QED corrections

- Final state QED corrections are recently revisited; e.g., photon radiation from final state muon, can lead to large impact due to the nature of "infrared unsafe" of the water Cherenkov detectors

radiated photon from muon goes into cascade

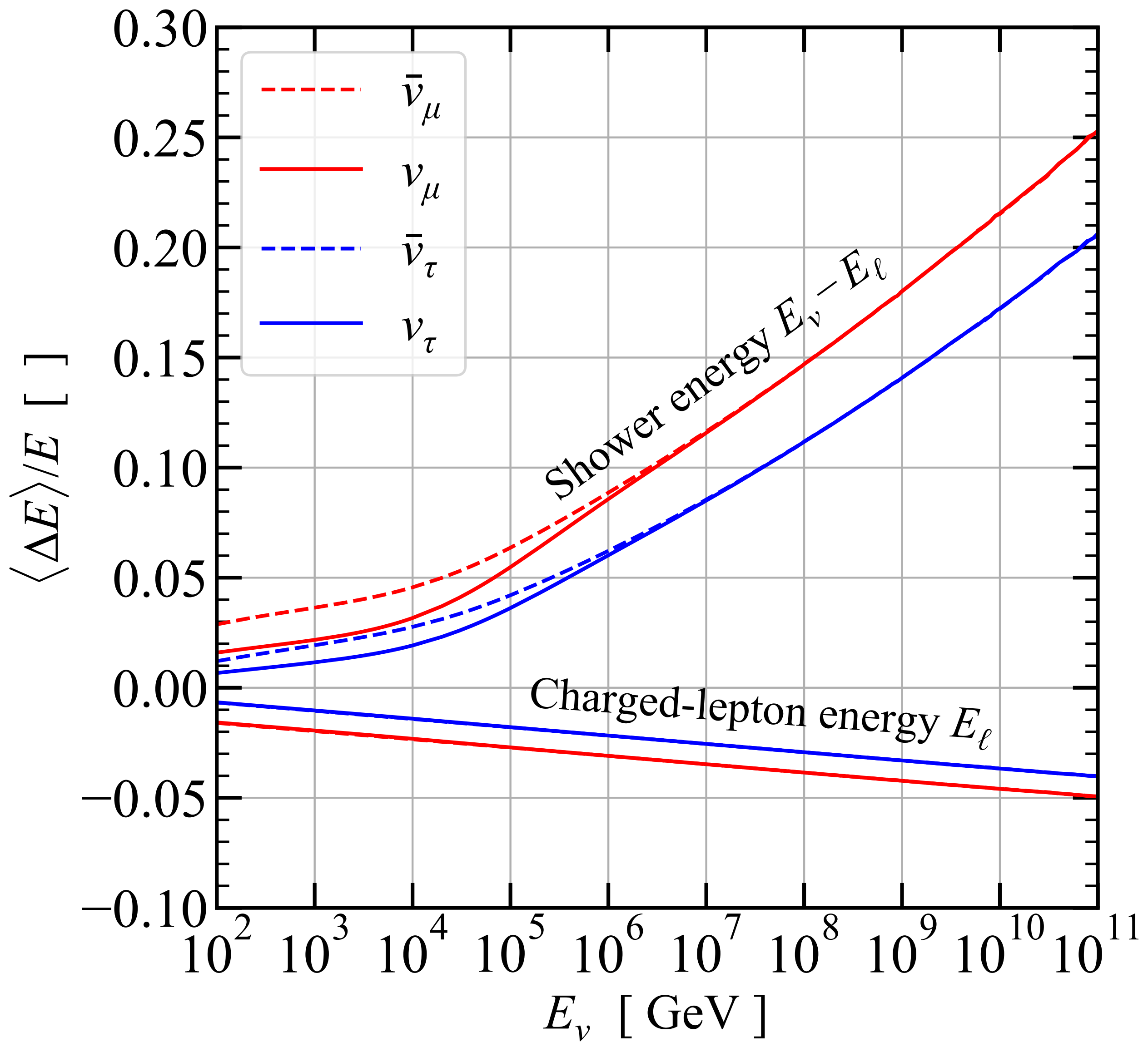


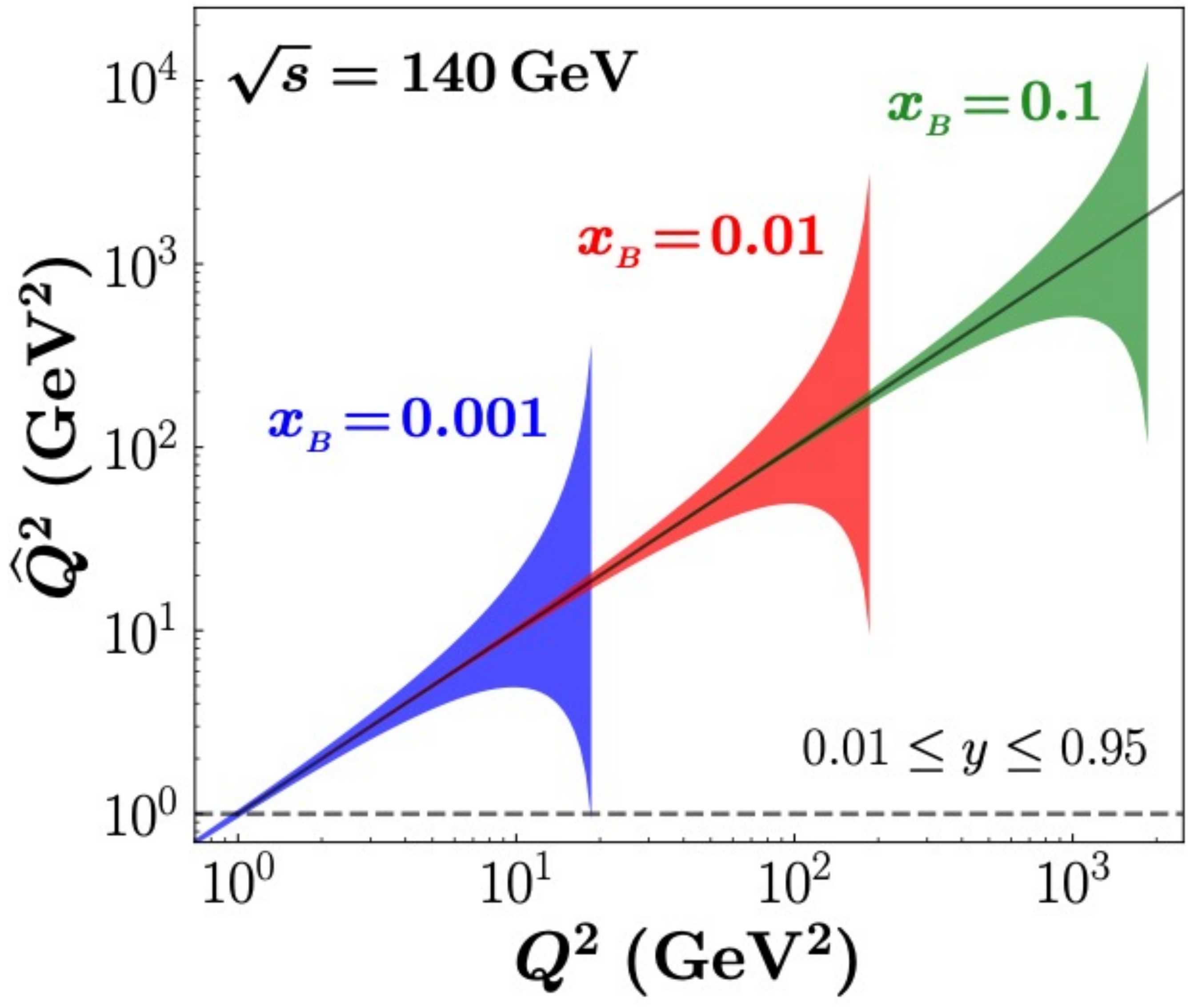
[2403.07984]

QED correction to cross section of bare muon

$$\frac{d\sigma^{(1)}}{dE_\ell} = \frac{\alpha}{2\pi}\int dy \int dz\, \frac{d\sigma^{(0)}}{dy}\delta(E_\ell - (1-y)zE_\nu) \times \log\left(\frac{s}{m_\ell^2}\right)\left[\frac{1+z^2}{[1-z]_+} + \frac{3}{2}\delta(1-z)\right]$$

effective shift of the kinematic variable





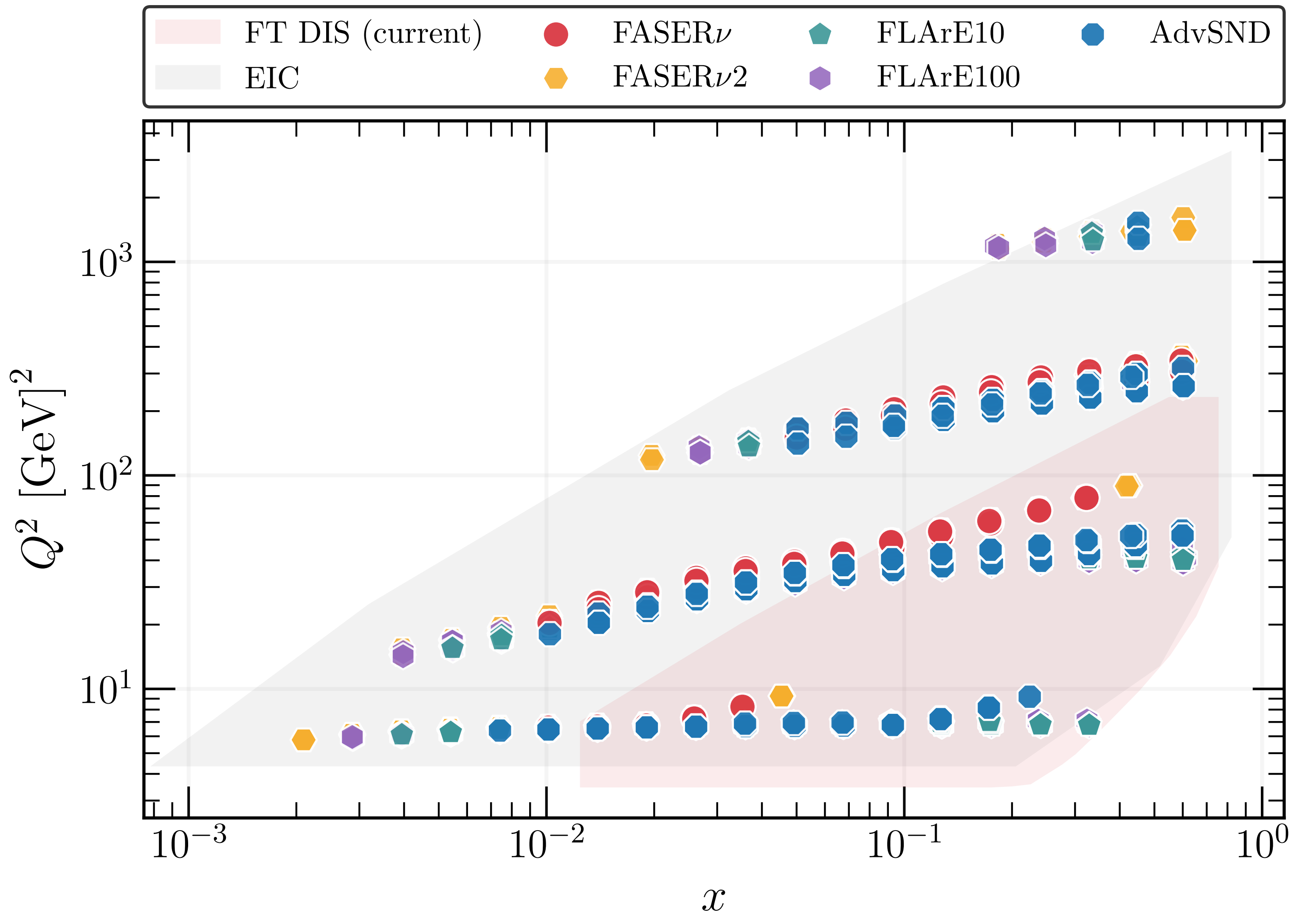
- QED corrections lead to a systematic shift/smearing of kinematic variable if using bare kinematics; similar effects also studied recently in the scenario of EIC using new factorization approach of QED correction in DIS [Qiu, Liu+, 2022]

DIS from collider neutrinos at LHC

✦ New opportunities from forward detectors at the LHC, e.g., FASERν and its upgrade on neutrino CC DIS, probing region of ~ 1 TeV neutrino energies; note EIC/HERA only cover ep CCDIS with Q^2 >100 GeV^2

Expected CC DIS event rates

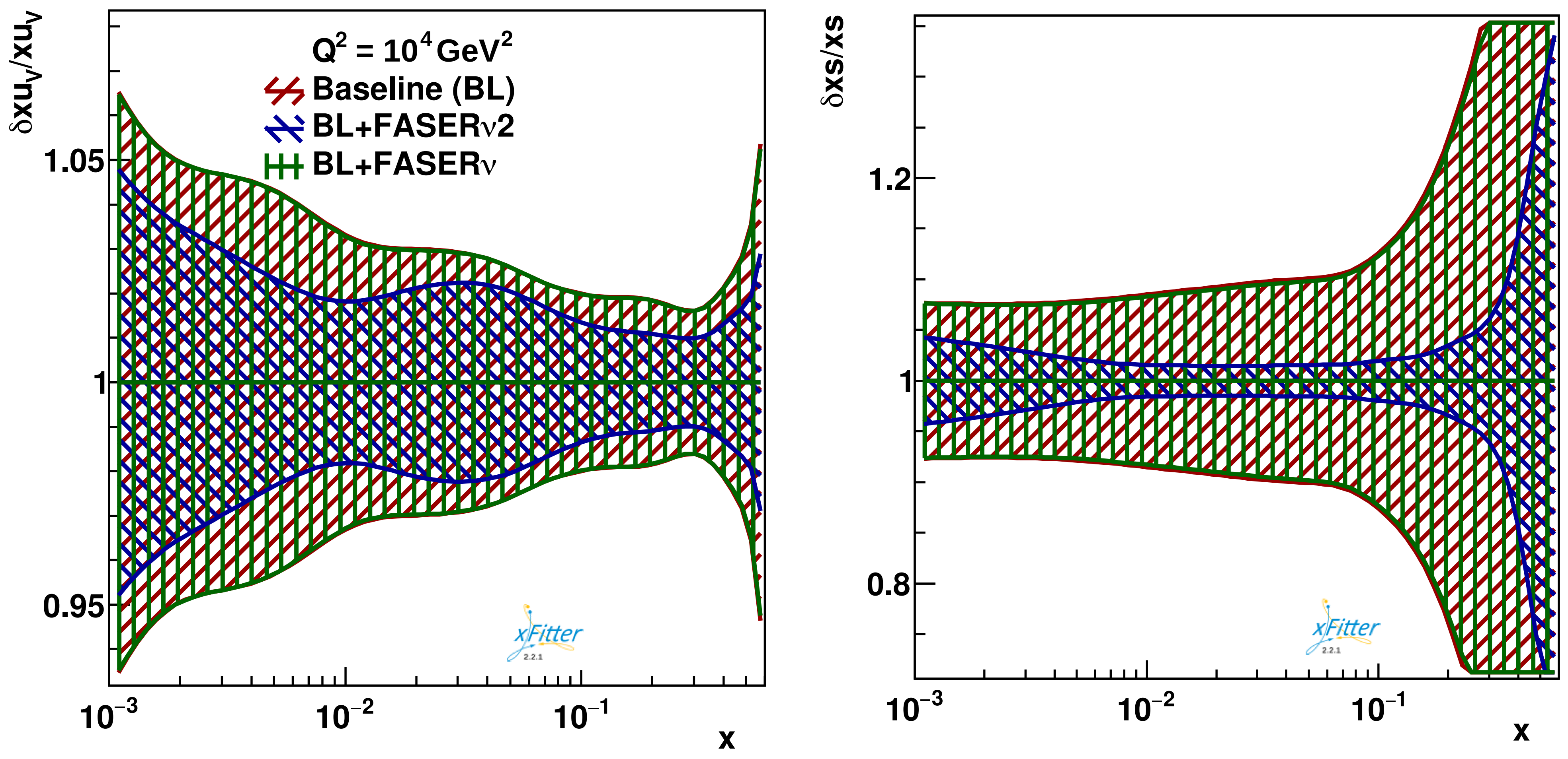
Detector	before cuts $N_{\nu_e}+N_{\bar\nu_e},\ N_{\nu_\mu}+N_{\bar\nu_\mu}$	after DIS and acceptance cuts $N_{\nu_e}+N_{\bar\nu_e},\ N_{\nu_\mu}+N_{\bar\nu_\mu}$	acceptance efficiency $N_{\nu_e}+N_{\bar\nu_e},\ N_{\nu_\mu}+N_{\bar\nu_\mu}$
FASERν	1.2k, 4.1k	610, 1.8k	51%, 44%
SND@LHC	280, 860	260, 700	92%, 81%
FASERν2	270k, 980k	170k, 510k	63%, 52%
AdvSND-far	19k, 66k	18k, 56k	95%, 85%
FLArE10	65k, 202k	64k, 110k	98%, 55%
FLArE100	427k, 1.3M	420k, 670k	98%, 52%



DIS kinematics

[2309.09581]

Projection on proton PDFs (with only stat. unc.)



❖ wide kinematic coverage, but impact of FASERν limited by statistics

❖ next-generation proposals show potential strong constraint on PDFs, especially for strange quark, also possibility on pining down nuclear corrections

Summary

- Neutrino DIS data play important role in development of QCD and still provide key inputs to global analyses of proton and nuclear parton distribution functions

- Neutrino DIS cross sections can be well described by perturbative QCD approach within collinear factorization, with high precisions due to great efforts from loop calculations, fits of proton PDFs and nuclear modifications, even more to expect with future EIC

- However, combining DIS predictions with other low-Q/non-DIS contributions are crucial for neutrino energies of a few tens GeV and below, and much more efforts are needed

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Thank you for your attention!