A general heavy-flavor mass scheme for charge-current DIS at NNLO and beyond

& implications for EW phenomenology

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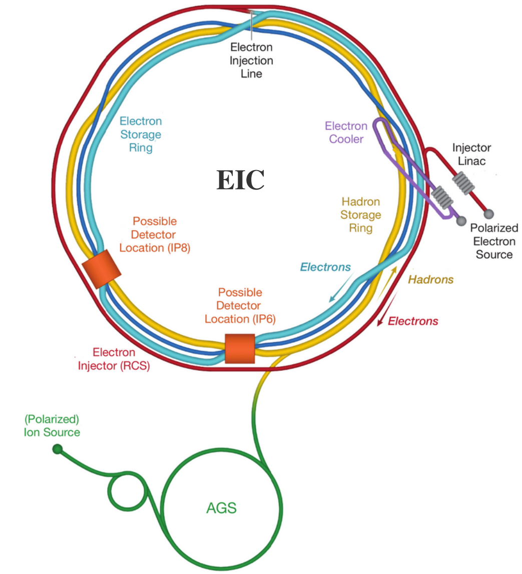
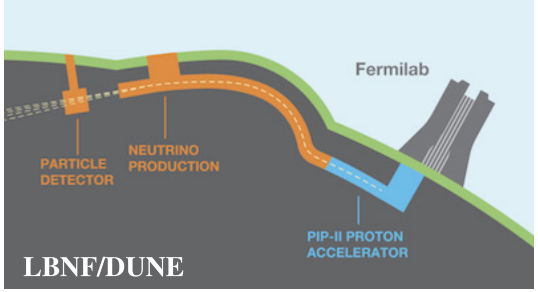
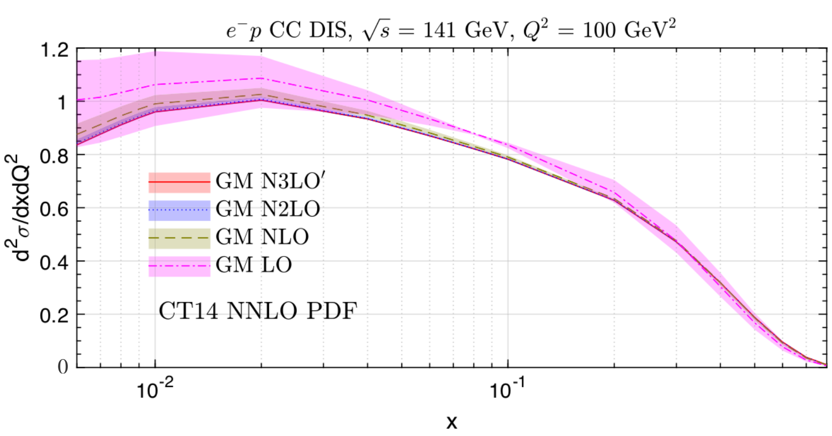
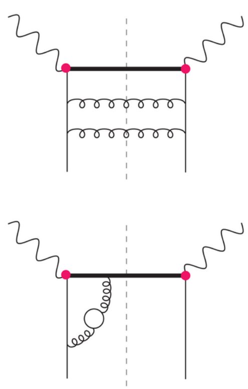
...with Jun Gao, Pavel Nadolsky, ChuanLe Sun and C.-P. Yuan



Based on: Phys. Rev. D**105** (2022) 1, **L**011503 [arXiv: 2107.00460]







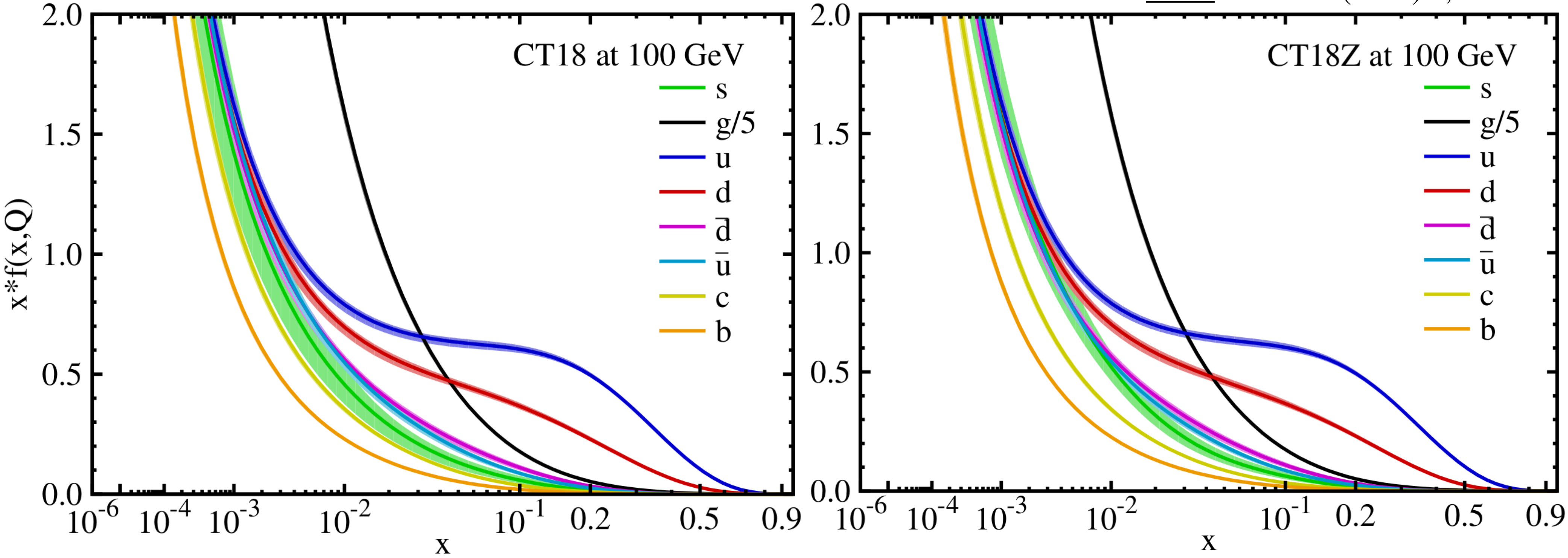
pQCD at NNLO → next-generation PDF extractions

- theory accuracy now/approaching (N)NNLO in α_s for typical processes

→ NLO EW corrections, especially for LHC data WG3, K. Xie

see plenary, J. Gao; WG1, P. Nadolsky

<u>CT18</u>: PRD**103** (2021) 1, 014013



- fit a wide assortment of data from various underlying processes; scales

→ CC DIS (*e.g.*, HERA) important complement in CT; needs NNLO treatment

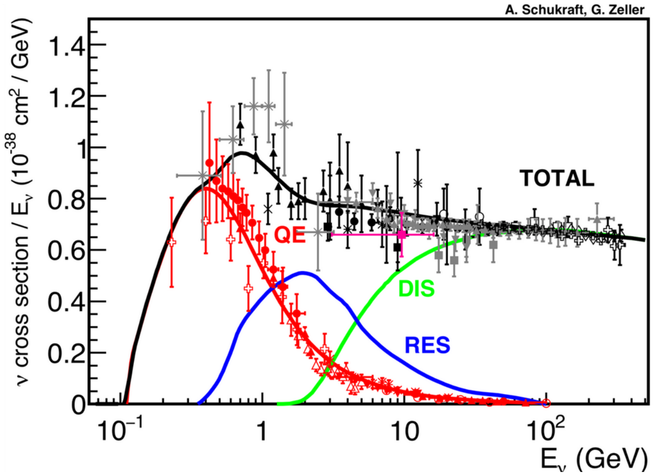
CC DIS: **motivation**

- charged-current DIS: central component in several next-generation QCD expt. programs

  → νA, forward physics: DUNE, FASERν

  → precision QCD: EIC, LHeC

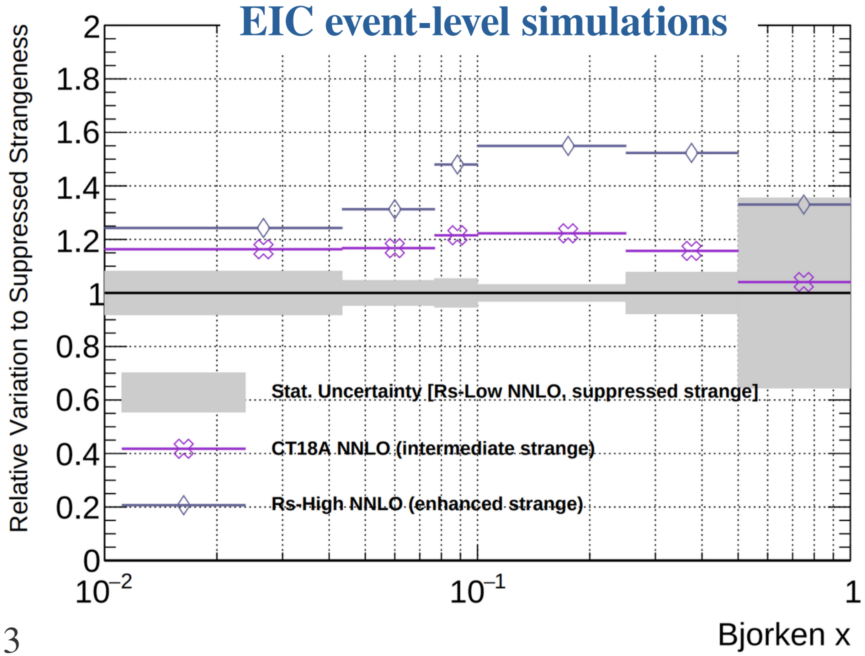
<u>example</u>: DUNE target sensitivity to δ_{CP} → control over CC DIS for $E_\nu \sim$ few GeV

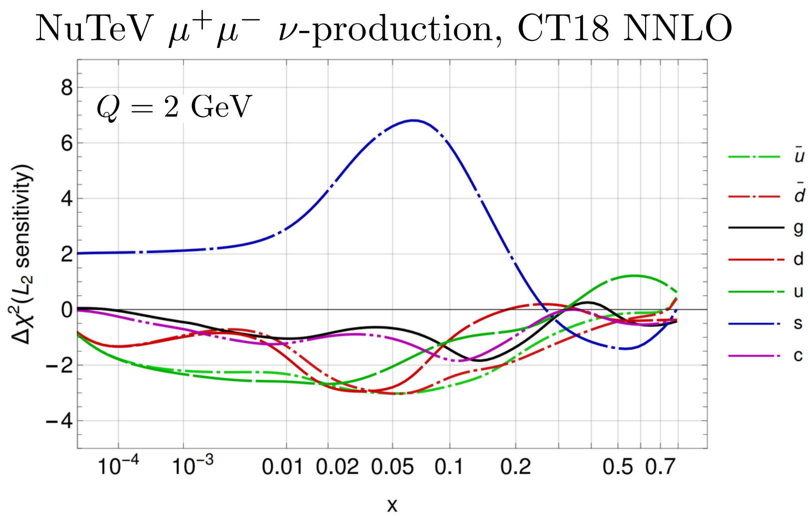


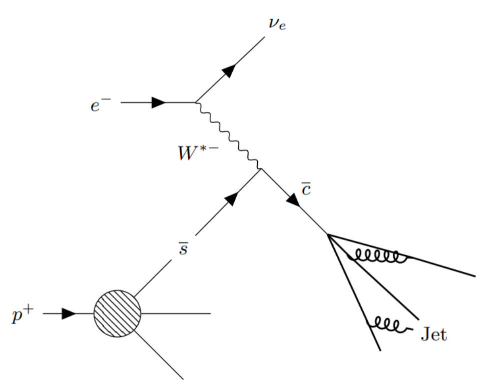
- *W*-exchange processes probe unique combinations of in-nucleon flavor currents; *e.g.*, nucleon $s(x,Q)$

Phys. Rev. D**103** (2021) 7, 074023
Arratia, Furletova, TJH, Olness, Sekula

[arXiv: 2006.12520]



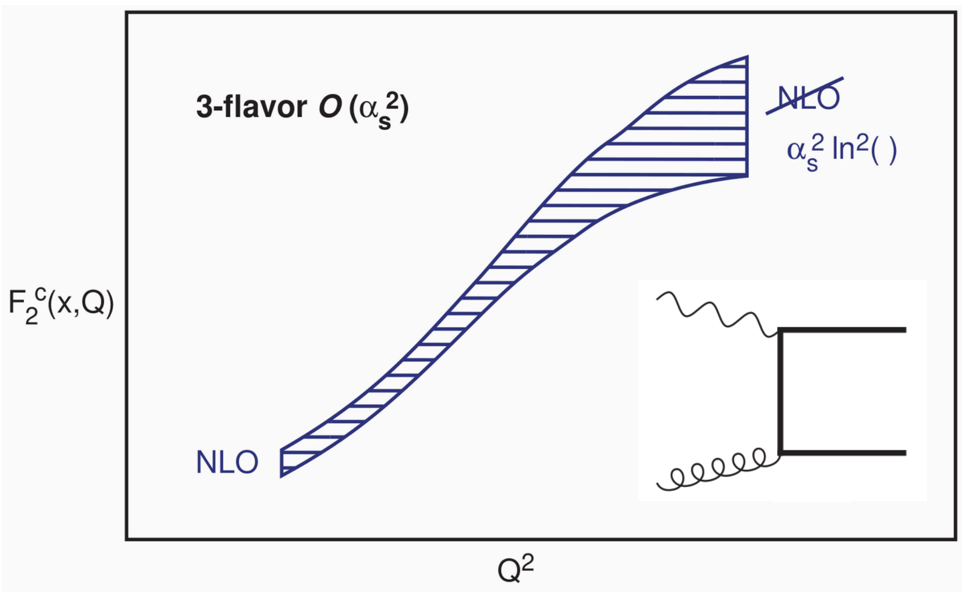


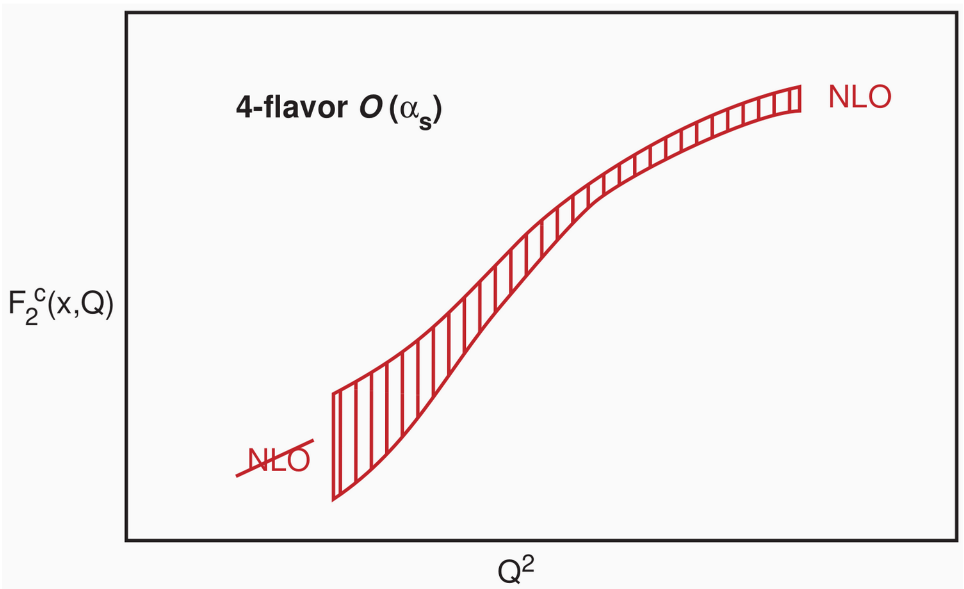


- CC DIS data cover **wide range in *Q***; **<u>higher pQCD accuracy needed</u>** for perturbative stability, PDF extractions

evolution schemes as general problem in QCD

- higher order(s) in pQCD: improved accuracy in Wilson coeff., control over scale dependence
- at given fixed order, nontrivial relationship with chosen heavy-quark (HQ) scheme





→ fixed flavor-number (FFN): $Q \gtrsim M_Q$; flavor-creation (FC) processes with $n_f = 3$

→ zero-mass (ZM) variable flavor-number: $Q \gg M_Q$; flavor-excitation (FE) processes with $n_f = 4$

- 2 paradigms adapted to different regimes w.r.t. HQ mass scale; ∃ **interpolation scheme**?

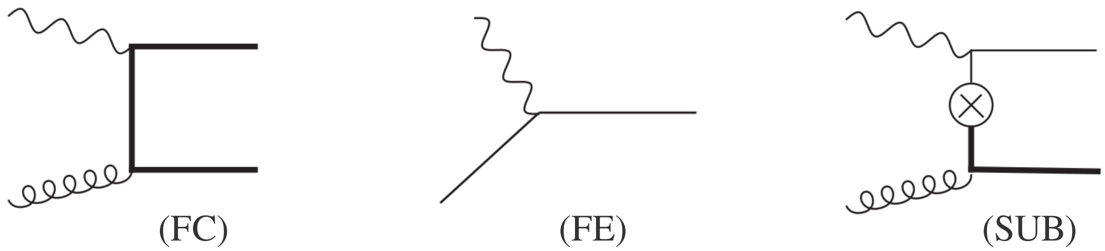
general-mass schemes: S-ACOT-χ

- variable flavor-number scheme to interpolate between ZM and FFN regimes: **ACOT**

Aivazis, Collins, Olness, Tung; PRD**50** (1994) 3085-3118

→ systematic approach to incorporating HQ mass dependence

- introduce subtraction term(s) to eliminate double counting between FC/FE contributions:



$$\begin{cases} Q \gtrsim M_Q \implies \text{(SUB)} \approx \text{(FE) such that } \mathrm{n}_f = 3 \text{ FC dominates} \\ Q \gg M_Q \implies \text{(SUB)} \approx \text{(FC) such that } \mathrm{n}_f = 4 \text{ FE dominates} \end{cases}$$

$$\chi(x, Q, M_Q) = x\left(1 + \frac{1}{Q^2}[\sum_{\mathrm{F.S.}} M_Q]^2\right)$$

  - "simplified" ACOT (S-ACOT): neglect full HQ mass dependence in FE graphs
  - S-ACOT-χ: smooth HQ thresholds, include approx. HQ mass dependence: $C_i(x) \to C_i(\chi)$

- formulation necessitates careful tracking of diagrams to organize calculation correctly

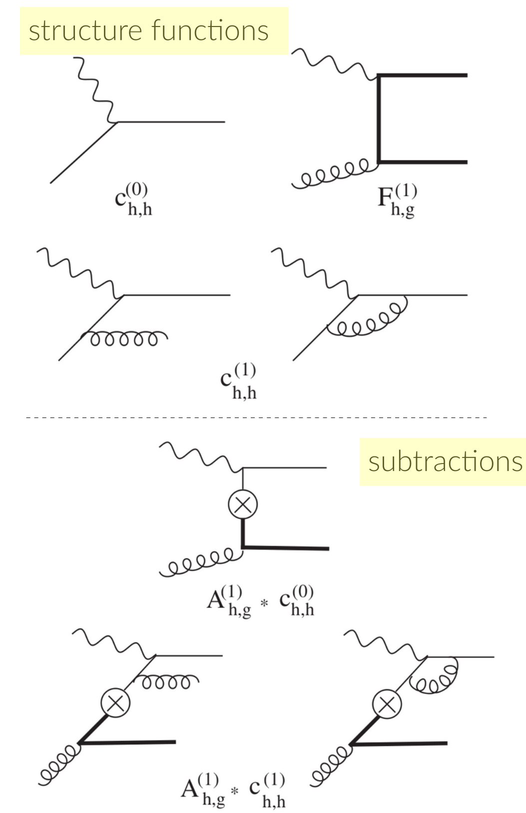
template calculation: NC DIS at NNLO

Guzzi, Nadolsky, Lai, Yuan Phys. Rev. D**86**, 053005 (2012) [arXiv: 1108.5112]

- at structure-function level, factorization allows separation of coeff. functions, PDFs:

$$F(x,Q) = \sum_{i=1}^{N_f^{fs}} e_i^2 \sum_{a=0}^{N_f} \left[C_{i,a} \otimes \Phi_{a/p}\right](x,Q) \qquad (F = F_{2,L})$$

- compute S-ACOT-χ coeff. functions: expand in α_s each term in auxiliary partonic struct. func.:



$$F_{i,b}(\hat{x},Q) = \sum_{a=0}^{N_f} \left[C_{i,a} \otimes \Phi_{a/b}\right](\hat{x},Q)$$

→ matching terms order-by-order,

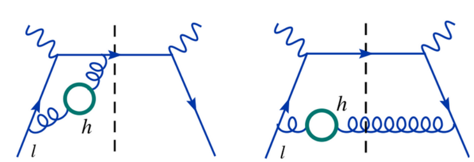
$$\begin{cases} C^{(0)}_{i,b}(\hat{x}) &= F^{(0)}_{i,b}(\hat{x}) \\ C^{(1)}_{i,b}(\hat{x}) &= F^{(1)}_{i,b}(\hat{x}) - \left[C^{(0)}_{i,a} \otimes A^{(1)}_{ab}\right](\hat{x}) \\ C^{(2)}_{i,b}(\hat{x}) &= F^{(2)}_{i,b}(\hat{x}) - \left[C^{(0)}_{i,a} \otimes A^{(2)}_{ab}\right](\hat{x}) - \left[C^{(1)}_{i,a} \otimes A^{(1)}_{ab}\right](\hat{x}) \end{cases}$$

- organize into heavy-, light-quark pieces: $F = \sum_{l=1}^{N_l} F_l + F_h$

$$C^{(2)}_{h,g} = \hat{F}^{(2)}_{h,g} - A^{(2)}_{hg} - c^{(1)}_{h,h} \otimes A^{(1)}_{hg}$$

↳ S-ACOT-χ: massless FE, χ-rescaled

→ light-quark SFs: additional flavor non-sing. (NS) *disconnected* graphs:

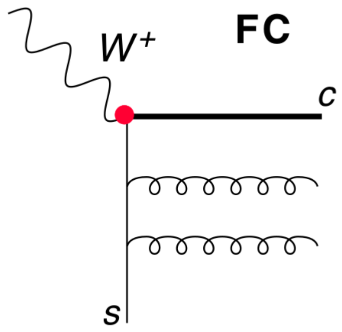


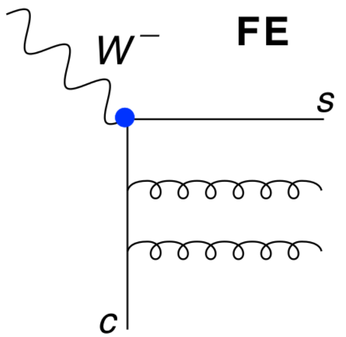
CC DIS at NNLO and beyond (i)

- conceptually, organization of CC DIS calculation resembles NC
- gauge-boson coupling introduces charge/flavor-changing vertices

$$F_l \iff W\bar{q}_l q_l$$

$$F_h \iff W\bar{q}_h q_l \text{ or } W\bar{q}_l q_h$$





→ appearance of heavy flavor occurs at different orders w.r.t. NC

- HQ contributions begin only at NNLO for F_l
- FE and FC diagrams involving HQ start from LO for F_h

- S-ACOT-χ patterns of subtractions, HQ mass dependence in CC NLO Wilson coeffs.:

$$\begin{cases} C^{(1)}_{l,l} = c^{(1)}_{l,l}(z),\ C^{(1)}_{l,g} = c^{(1)}_{l,g}(z),\ C^{(1)}_{h,h} = c^{(1)}_{l,l}(\chi) \\ C^{(1)}_{h,l} = H^{(1)}_l(z) - C^{(0)}_{h,l} \otimes A^{(1)}_{ll} \\ C^{(1)}_{h,g} = H^{(1)}_g(z) - C^{(0)}_{h,l} \otimes A^{(1)}_{lg} - C^{(0)}_{h,h} \otimes A^{(1)}_{hg} \end{cases}$$

- HQ contributions explicitly appear in light-quark SF at NNLO; subtracted NS coeff.:

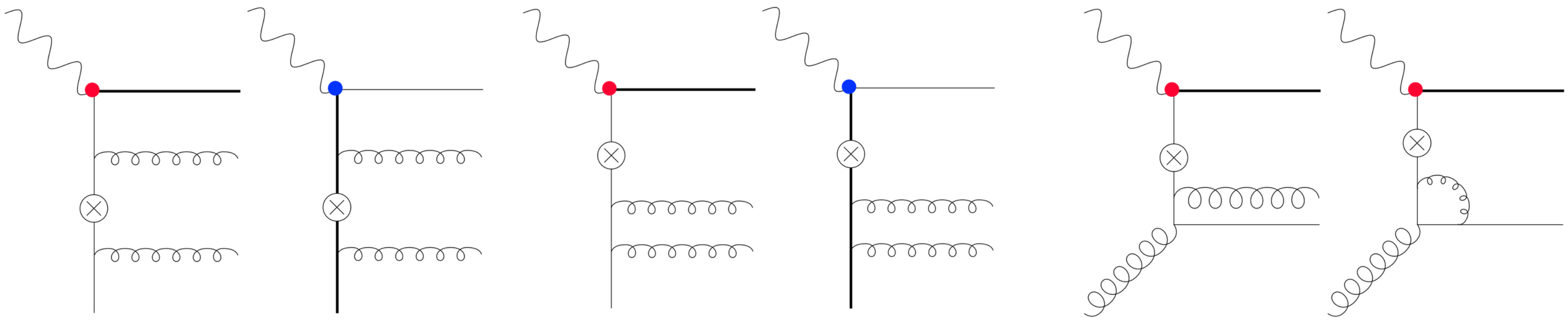
$$C^{(2)}_{l,g} = c^{(2)}_{l,g}(z),\ C^{(2)}_{l,h} = c^{(2)}_{l,h}(\chi)$$

$$C^{(2)}_{l,l} = c^{(2)}_{l,l}(z) + \widetilde{C}^{(NS,2)}_{l,l}(z)$$

- **careful ordering of diagrams by flavor structure, topology is crucial**

CC DIS at NNLO and beyond (ii)

→ representative CC NNLO subtraction diagrams – identifiable with coeff. expressions



$$C^{(2)}_{h,h} = c^{(2)}_{h,h}(\chi)$$
$$C^{(2)}_{h,l} = H^{(2)}_{l}(z) - \Delta C^{(2)}_{h,l}$$
$$C^{(2)}_{h,g} = H^{(2)}_{g}(z) - \Delta C^{(2)}_{h,g}$$

constructed from 2-loop operator matrix elements

- finally, ZM N³LO Wilson coeffs. available!
  → evaluate approximate N³LO (*i.e.*, N³LO′)

- S-ACOT-χ patterns of subtractions, HQ mass dependence in CC NLO Wilson coeffs.:

$$\begin{cases} C^{(1)}_{l,l} = c^{(1)}_{l,l}(z),\ C^{(1)}_{l,g} = c^{(1)}_{l,g}(z),\ C^{(1)}_{h,h} = c^{(1)}_{l,l}(\chi) \\ C^{(1)}_{h,l} = H^{(1)}_{l}(z) - C^{(0)}_{h,l} \otimes A^{(1)}_{ll} \\ C^{(1)}_{h,g} = H^{(1)}_{g}(z) - C^{(0)}_{h,l} \otimes A^{(1)}_{lg} - C^{(0)}_{h,h} \otimes A^{(1)}_{hg} \end{cases}$$

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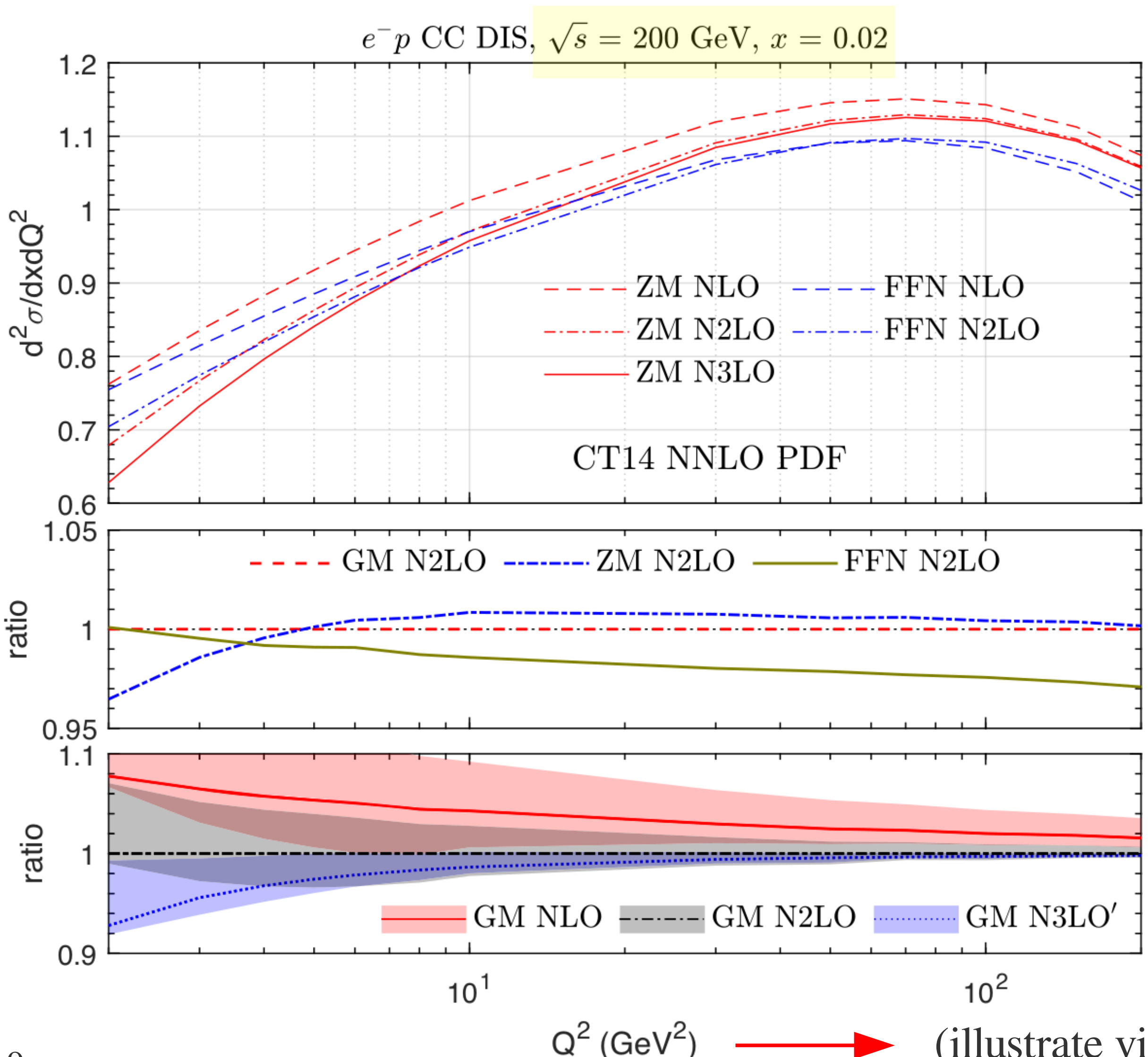
- **careful ordering of diagrams by flavor structure, topology is crucial**

illustration for arbitrary DIS cross sections

- before expt.-specific predictions, compute generic DIS reduced cross section(s)

  → compare calculations of highest available order: FFN vs. ZM vs. GM schemes



NLO: ZM vs FFN, $\lesssim 6\%$

NNLO: ZM vs FFN, $\lesssim 3\%$

GM interpolation between FFN at low Q, ZM at high Q

GM N^{3}LO$'$: GM NNLO + ZM N^{3}LO [NNLO PDFs]

scale variations: shift μ_R, μ_F by $\times 2$

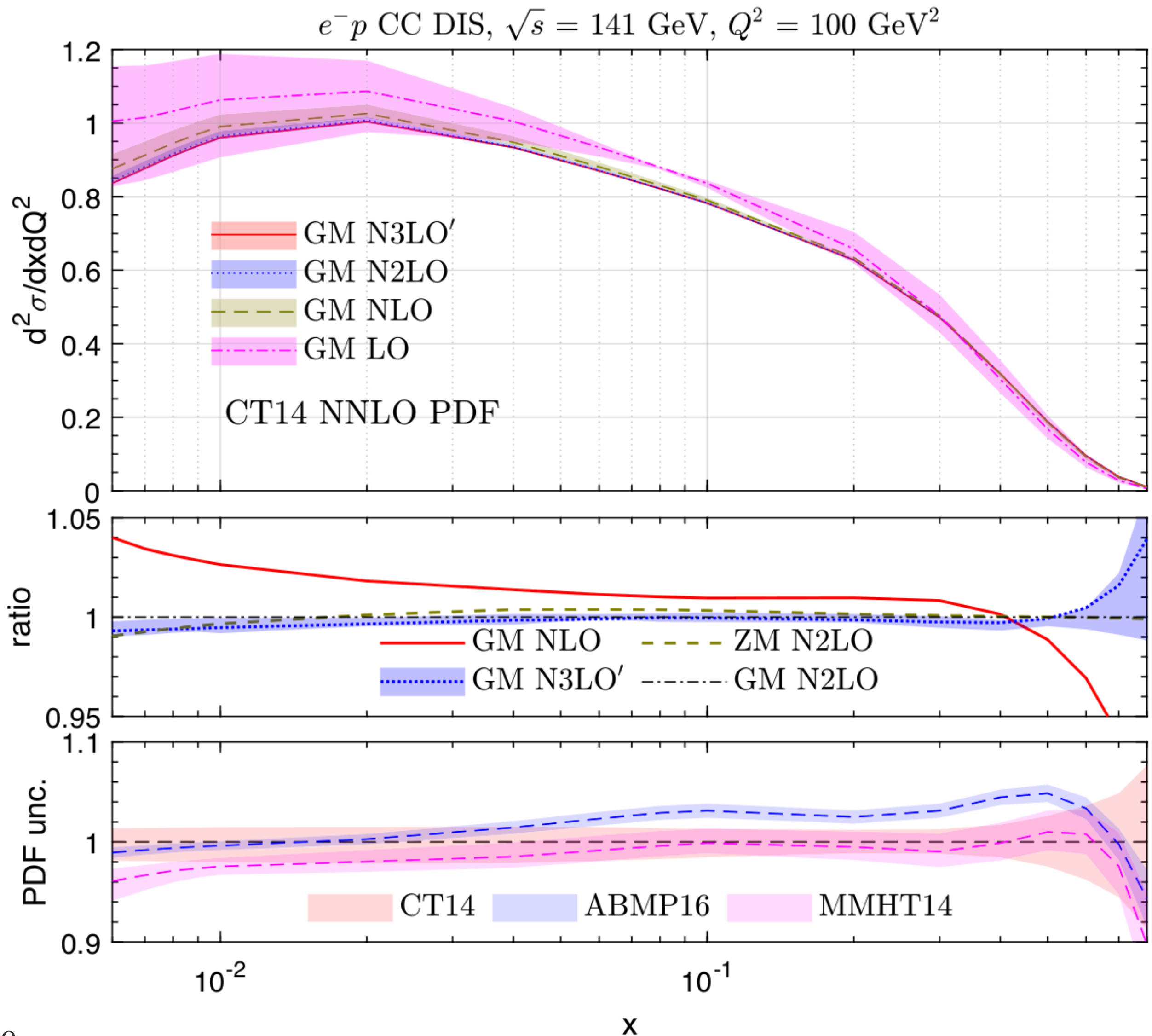
→ improved convergence with order!

→ (illustrate virtuality dependence)

implications for CC DIS at EIC

- EIC will undertake various precision QCD measurements; EIC Yellow Report arXiv: 2103.05419

  → Inclusive Reactions Study (YR7.1.1): CC – including positron beam – access to *d*, *s* PDFs



- consider high-energy EIC collisions

  → reconstruction challenges: CC events restricted to high Q^2

- strong perturbative convergence

  → for N^{3}LO′, scale variations generally contained to $\lesssim 0.5 - 1\%$

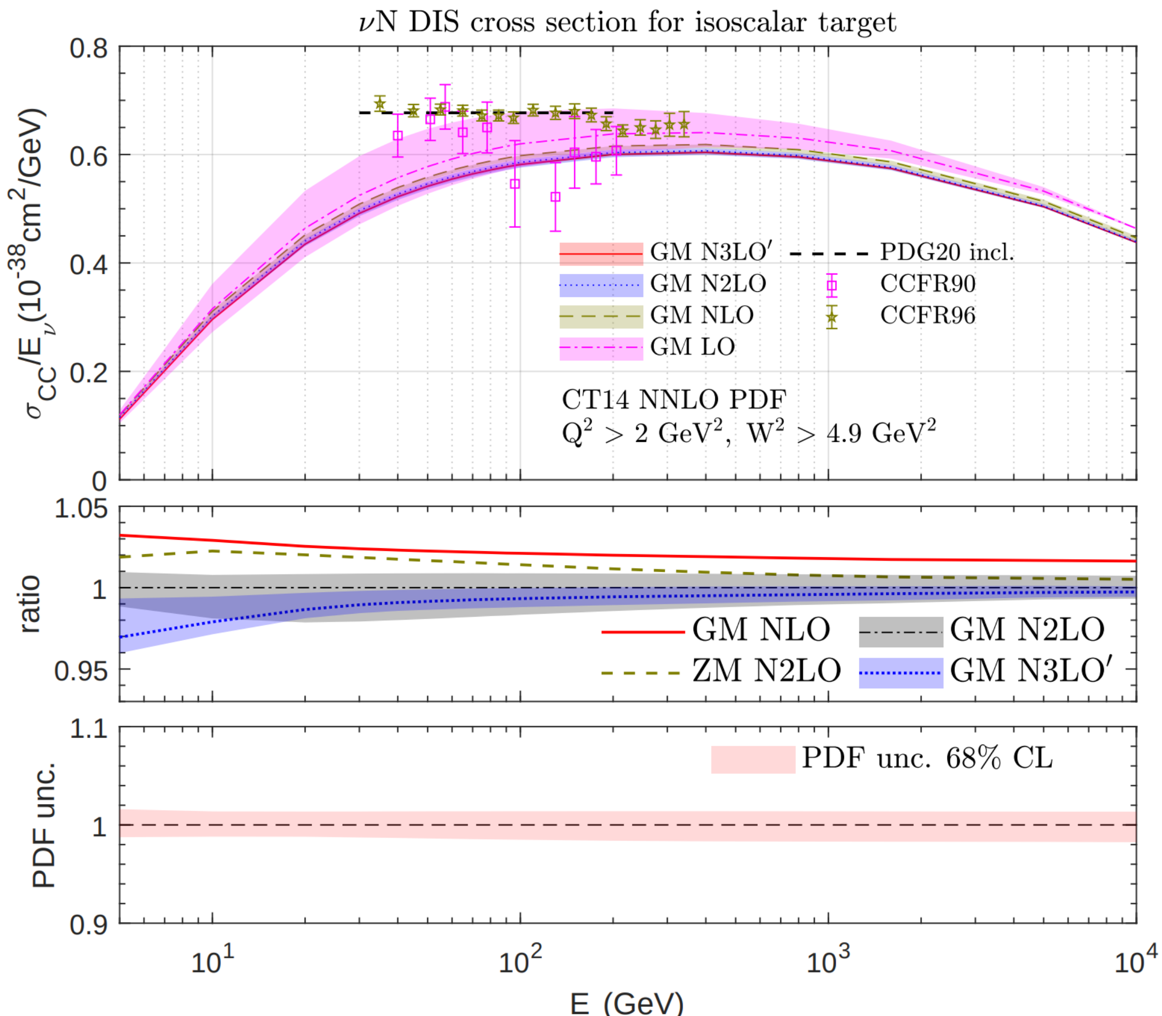
- significantly smaller than PDF-driven uncertainties, which can be as large as $\approx 2\%$

  vital ingredient in EIC PDF program

precision QCD will also be necessary for νA

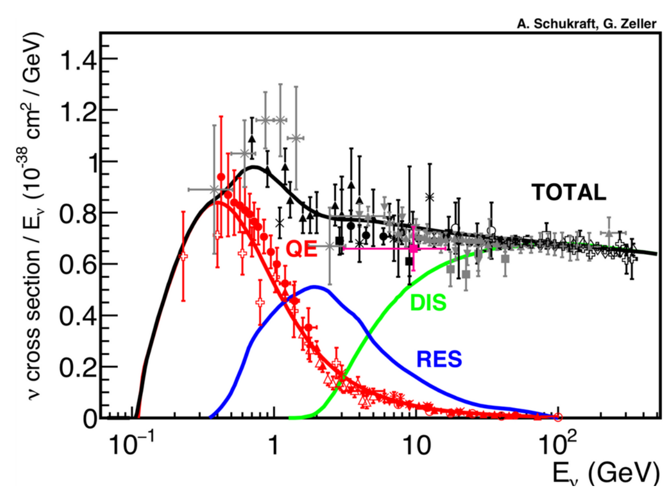
- forthcoming neutrino-nuclear experiments cover wide range of energies, E_ν
- even at DUNE, events coming from DIS represent $\gtrsim 40\%$

(important dependence on SF extrapolations, correlations in tunes with low-energy model parameters)



→ small DIS cross section variations influence DUNE sensitivity

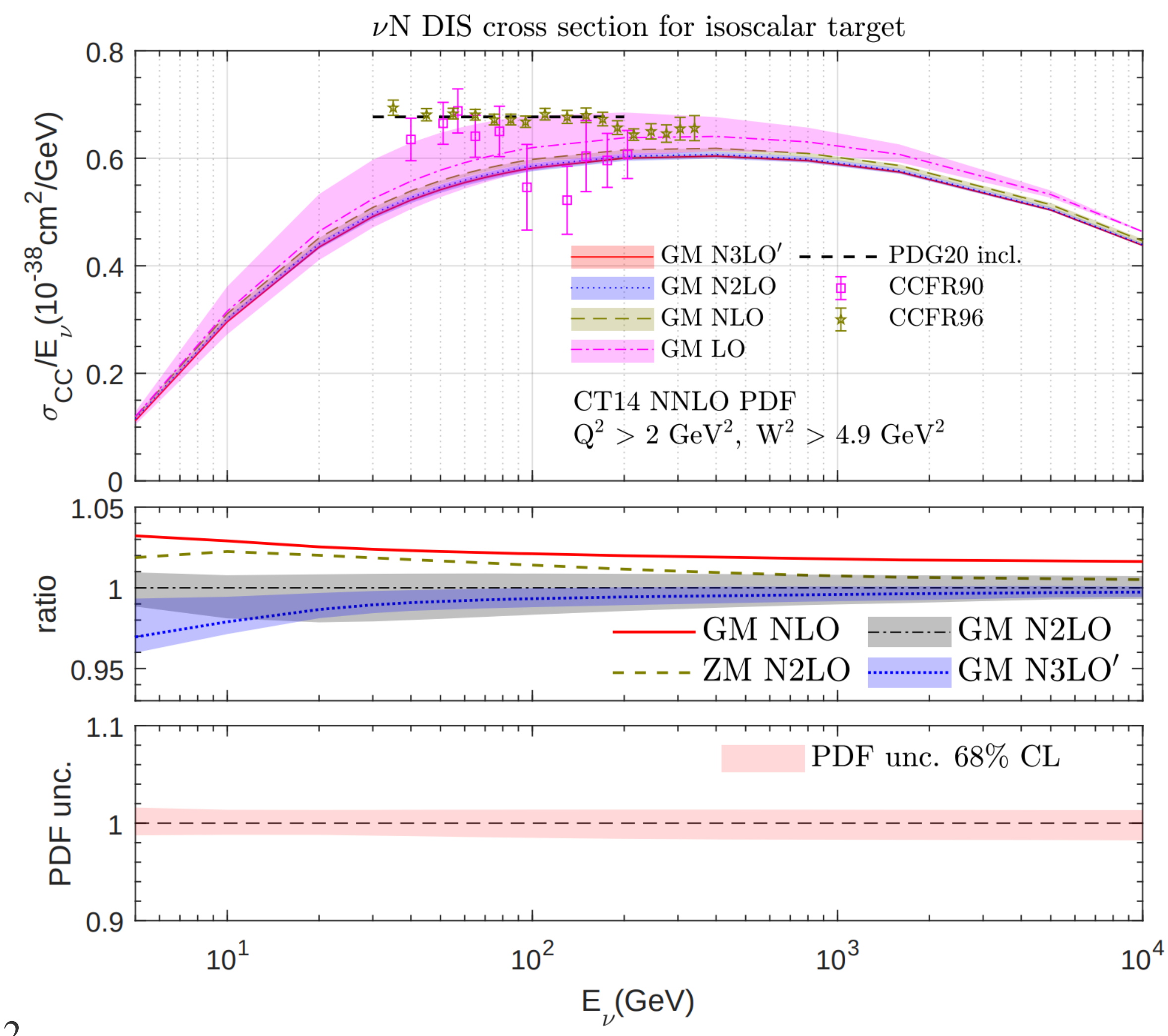
→ at higher energies, significant impact on sensitivity of forward-physics program at FASERν (~100s GeV); neutrino telescopes (>TeV)



precision QCD will also be necessary for νA

- ν cross sections generally diminished by LO → (N)NNLO, by 6% for most E_ν
- as before, NNLO and N³LO´ corrections greatly reduce scale variations

$\begin{cases} E_\nu > 100\,\text{GeV: negligible} \\ \sim 1-3\%\ \text{elsewhere} \end{cases}$



- in contrast, PDF uncertainties are ~1-2%

→ strong pQCD theory for FASERν program

- future analyses will witness an interplay between pQCD and **<u>nuclear effects</u>**

→ assessed nuclear correction using nCTEQ15: $\sim 0.5\%$ effect

conclusions: next steps, PDF implications

- have extended general-mass HQ scheme to CC DIS at NNLO; approximate N^{3}LO
  - → incorporates full HQ threshold dependence; interpolation between FFN, ZM approaches
  - → dramatic reductions to dependence on perturbative QCD scale choices
  - → consistency across broad ranges of $x, Q^2; E_\nu$

- perturbative uncertainties at EIC reduced to sub-percent level for target kinematics
  - → substantially boosts precision of inclusive measurements program; PDF sensitivity

- (N)NNLO accuracy reduces νDIS scale uncertainties to ~1-3%; less at high energies
  - → critical to achieving precision objectives in νA programs at DUNE

- interfaces with PDF global analyses (and perhaps generators) will be valuable
  - → higher pQCD accuracy suggests need for parallel enhancements in, *e.g.*, nuclear modeling, EW corrections, few-GeV nonperturbative theory