Massive charged-current DIS at NNLO and impact on strange-quark distributions

Jun Gao

Shanghai Jiao Tong University

based on arXiv: 1601.05430 and 1710.04258

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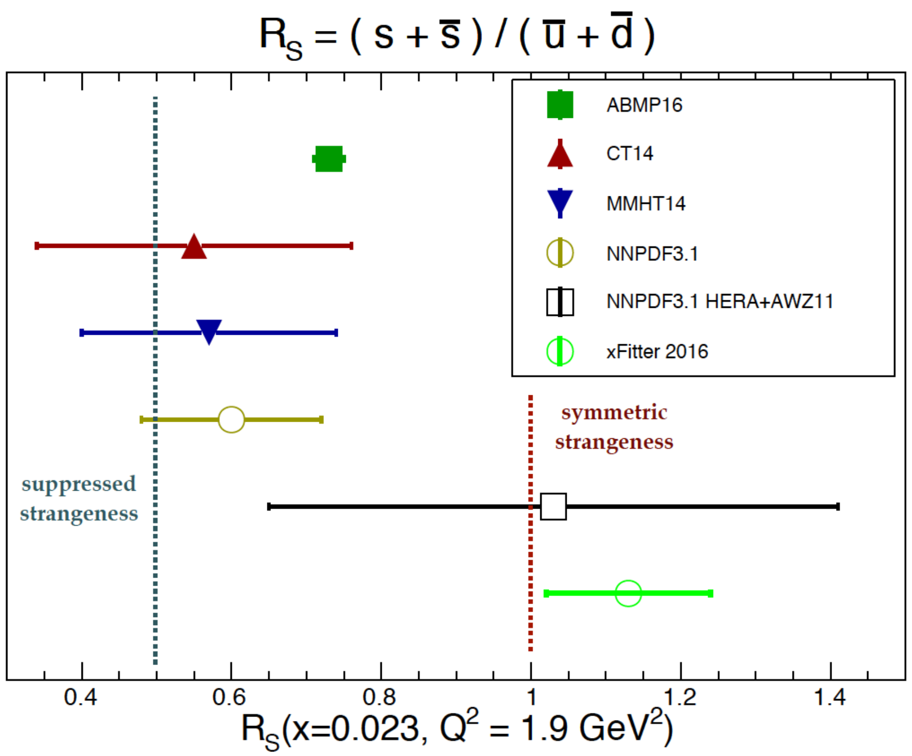
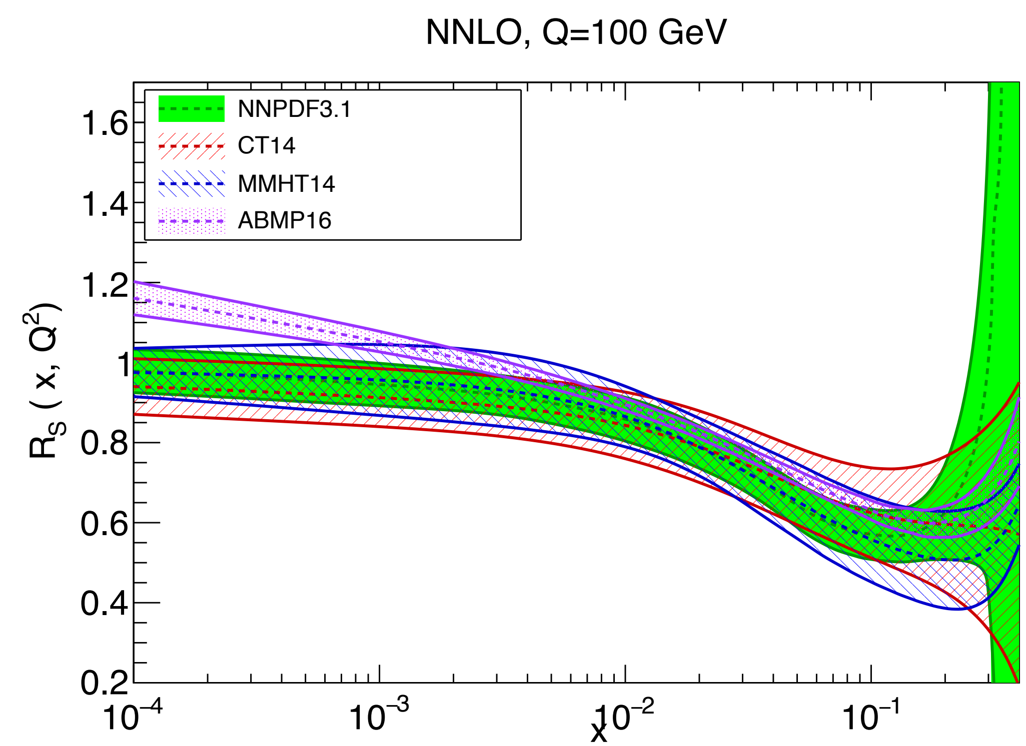
上海交通大學 Shanghai Jiao Tong University | SHANGHAI JIAO TONG UNIVERSITY Department of Physics | INPAC INSTITUTE OF NUCLEAR AND PARTICLE PHYSICS

Strangeness distributions

- Distributions of the strange quark remain poorly known; even not conclusive if the strangeness are suppressed as comparing to u/d sea-quarks or not

[JG, Harland-Lang, Rojo, 2017]





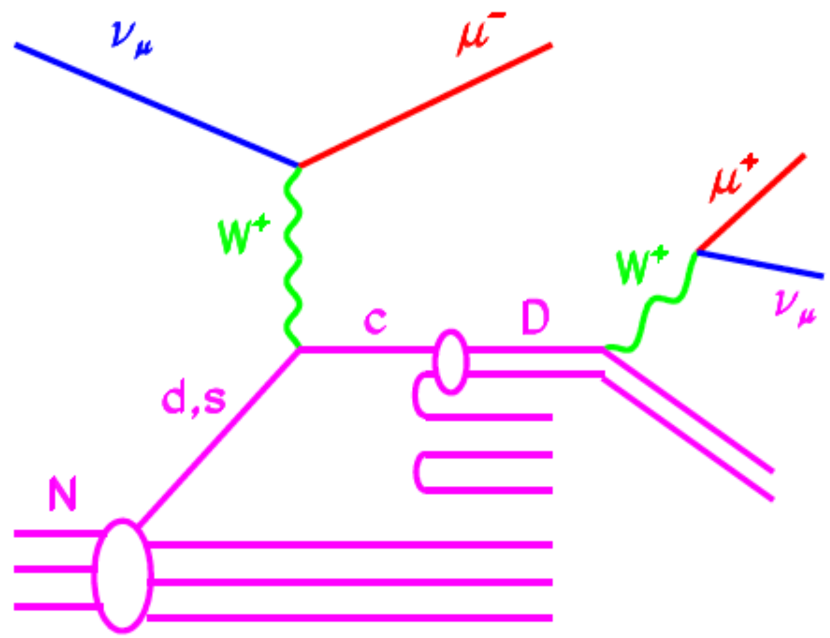
Fixed-target exp.: dimuon production in CCFR, NuTeV, CHORUS, NOMAD

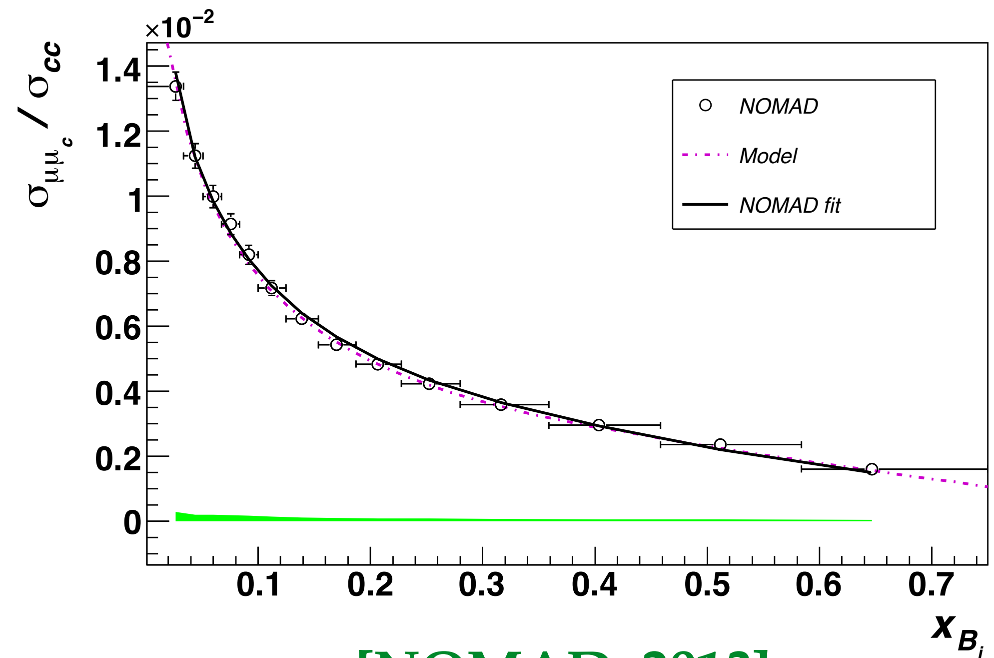
LHC exp.: inclusive W/Z production, W+charm production

different preferences observed though might not be so significant due to possible large uncertainties, e.g., Alekhin+ 2017

Dimuon production

- Charm-quark production in charged-current neutrino DIS on iron target with subsequent inclusive decays of charm to muon





[NOMAD, 2013]

theoretically charm-quark production has been calculated to NLO in QCD by T. Gottschalk (1981) and M. Gluck+(1997) in a closed analytic form

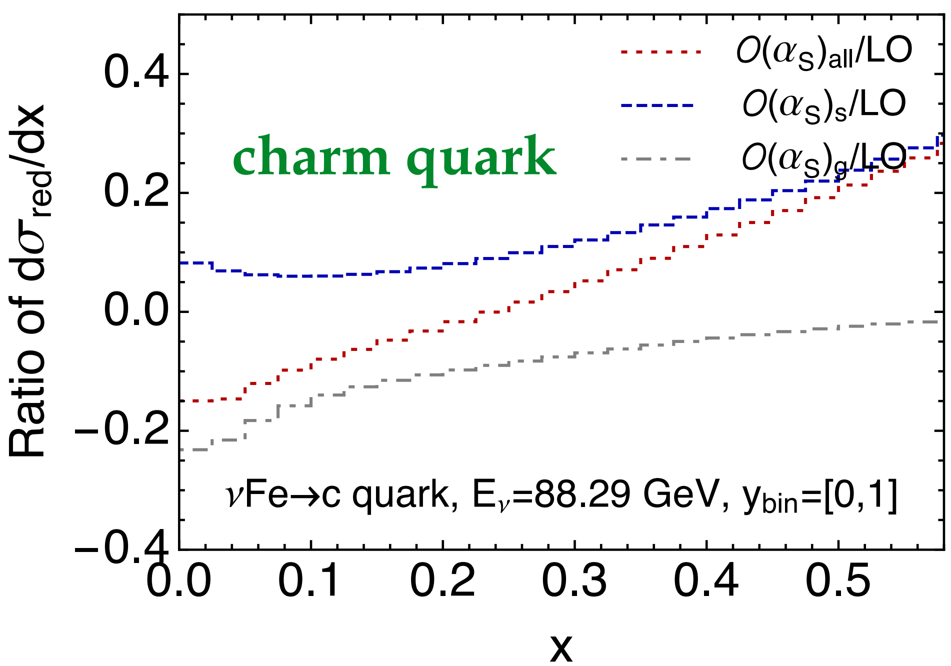
$$\frac{d\sigma_c^\nu}{dxdy} = \frac{G_F^2 ME}{\pi(1+Q^2/M_W^2)^2}\left[\left(1-y-\frac{Mxy}{2E}\right)F_{2,c}^\nu(x,Q^2)+ \right.$$
$$\left. +\frac{y^2}{2}F_{T,c}^\nu(x,Q^2)+y\left(1-\frac{y}{2}\right)xF_{3,c}^\nu(x,Q^2)\right]$$

data has to be corrected for acceptance and unfolded to quark level with MCs and model of fragmentations

Charm-quark production at NLO

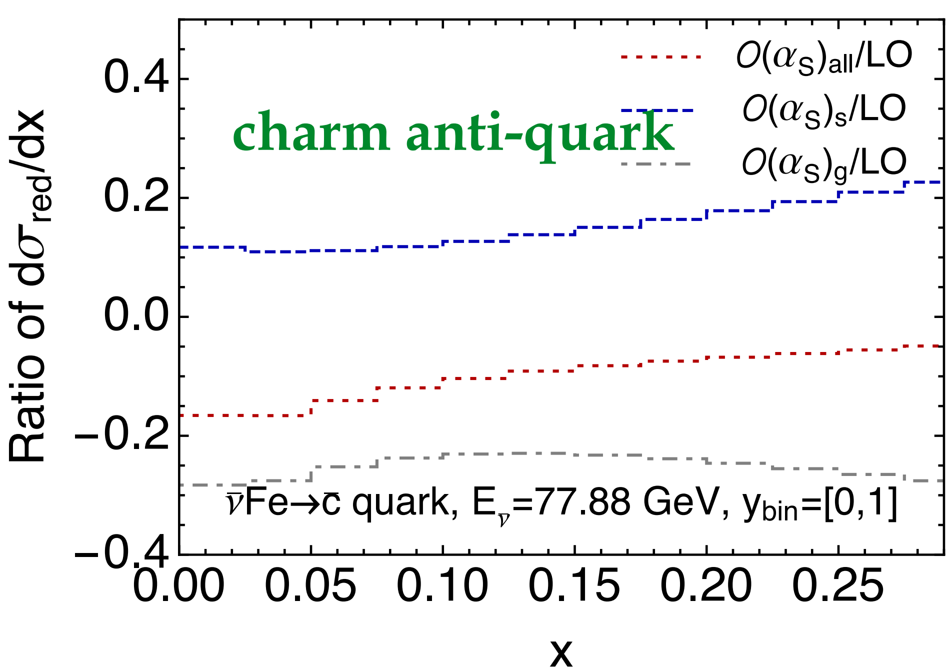
- Calculations beyond next-to-leading order are needed for charm-quark production in charged-current neutrino DIS to control the perturbative uncertainties

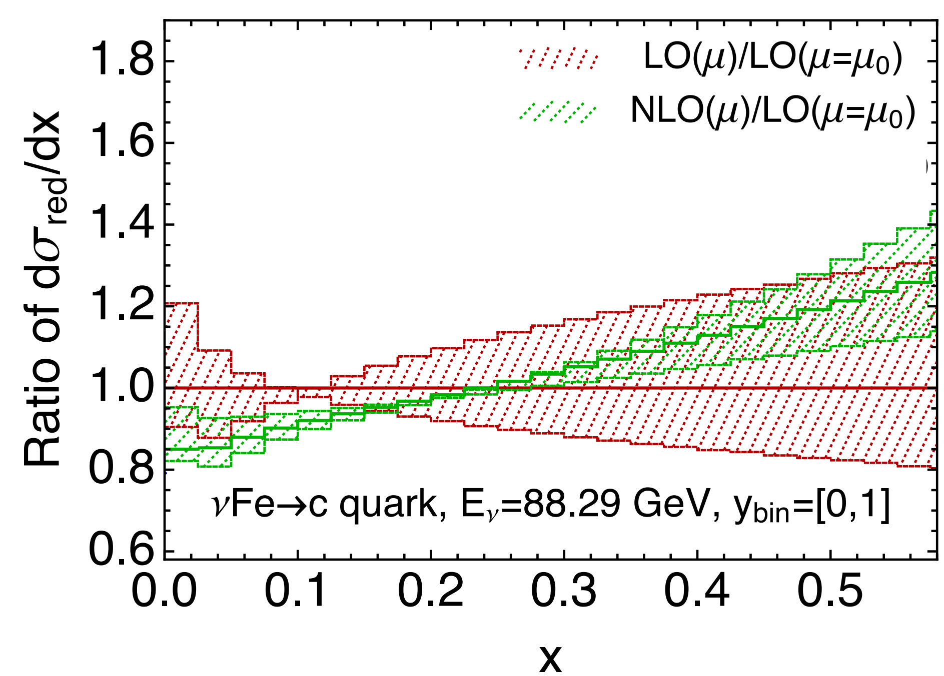
single differential



NNLO are required due to:

- small Q2, α_s large
- large gluon contributions at low-x
- accidental cancellations at NLO

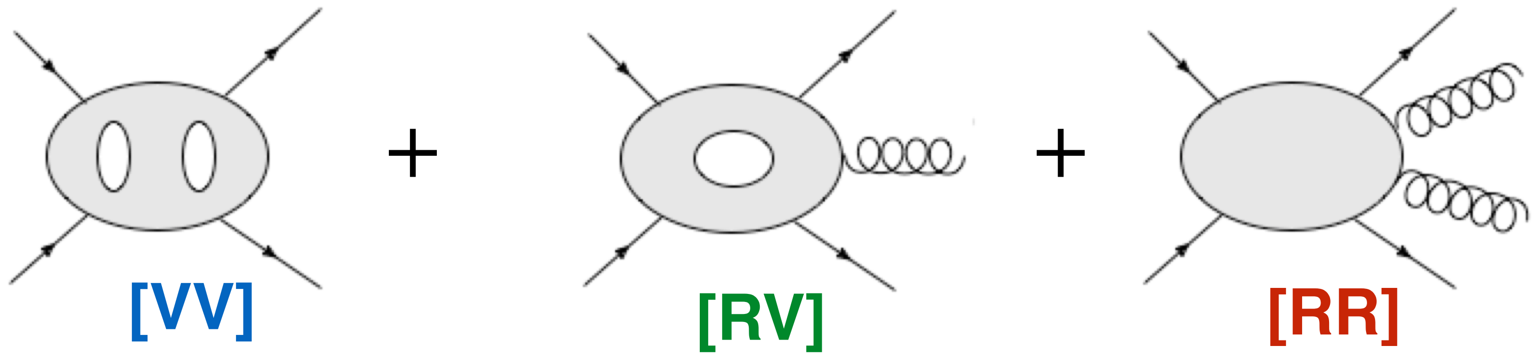


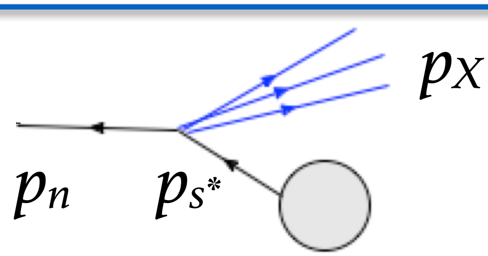


Framework of the NNLO calculation

- A generalization of phase-space slicing method to NNLO is utilized with fully differential Monte Carlo integrations

[Berger, JG, Li, Liu, Zhu, 2016]





phase space slicing (in heavy-quark vertex)

$$\tau = \frac{2\, p_X \cdot p_n}{Q^2 + m_c^2}$$ slicing variable

- for $\tau > \tau_{cut}$, at most singly-unresolved, can be dealt with NLO techniques

  [RV] + [RR]

- for $\tau < \tau_{cut}$, QCD radiations are unresolved, $\sigma\big|_{\text{unres.}}$

  [VV] + [RV] + [RR]

Hard function | Beam function | Soft function

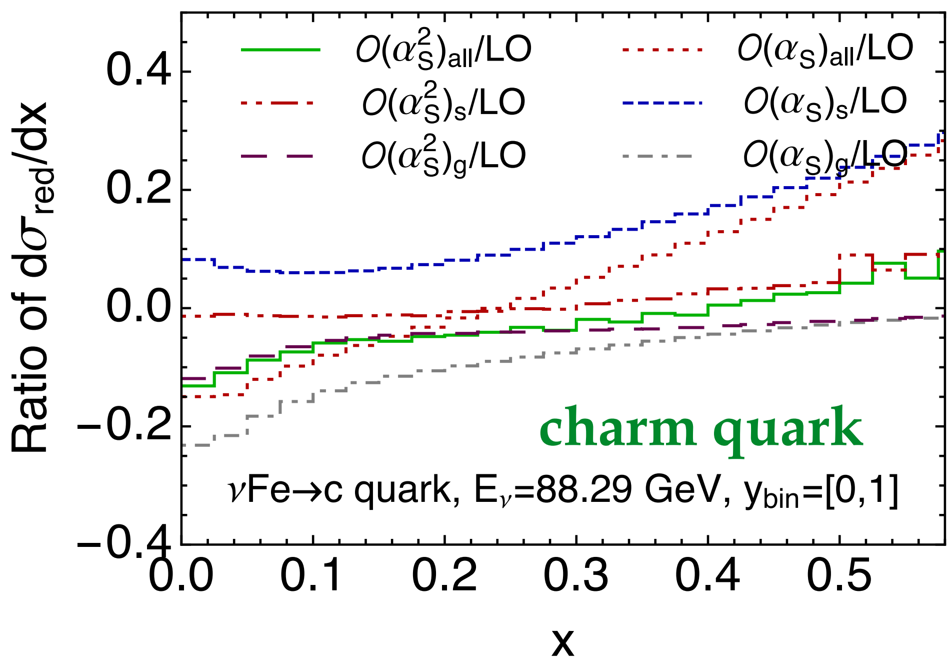
$$\sigma\big|_{\text{unres.}} = \int_0^{\tau_{\text{cut}}} d\tau \int_0^1 dz\, \hat{\sigma}_0(z) H(Q, m_t, \mu) \int d\tau_c\, d\tau_s B_q(\tau_c, z, \mu) S(\tau_s, \mu) \delta(\tau - \tau_c - \tau_s)$$

$$+\mathcal{O}(\tau_{\text{cut}} \ln^k \tau_{\text{cut}})$$ factorization in soft-collinear effective theory

Charm-quark production at NNLO

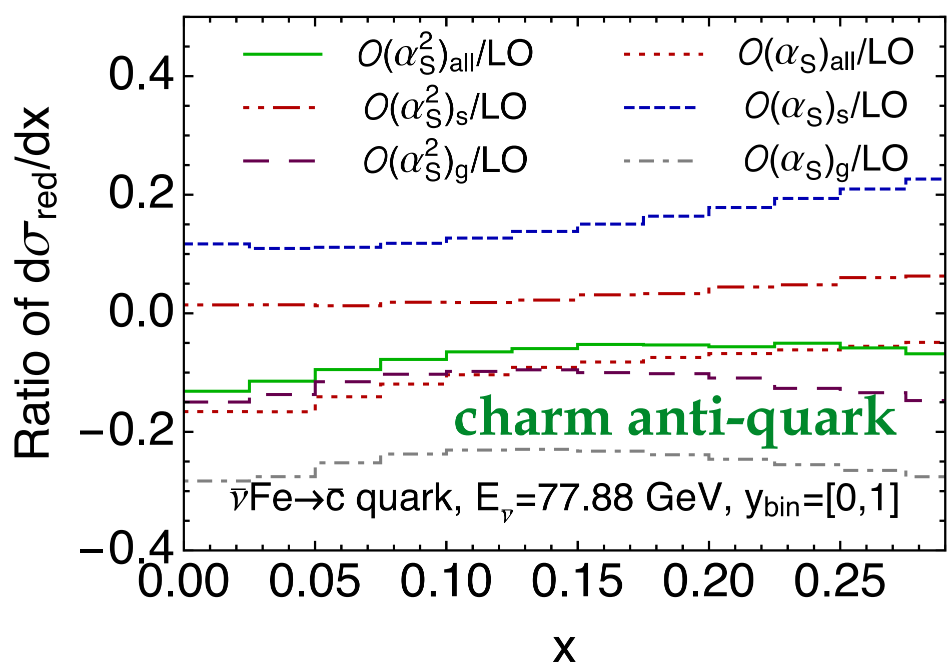
✦ Good convergence of the perturbative expansions are found for individual channels; net corrections at NNLO are comparable to NLO corrections **[Berger, JG, Li, Liu, Zhu, 2016]**

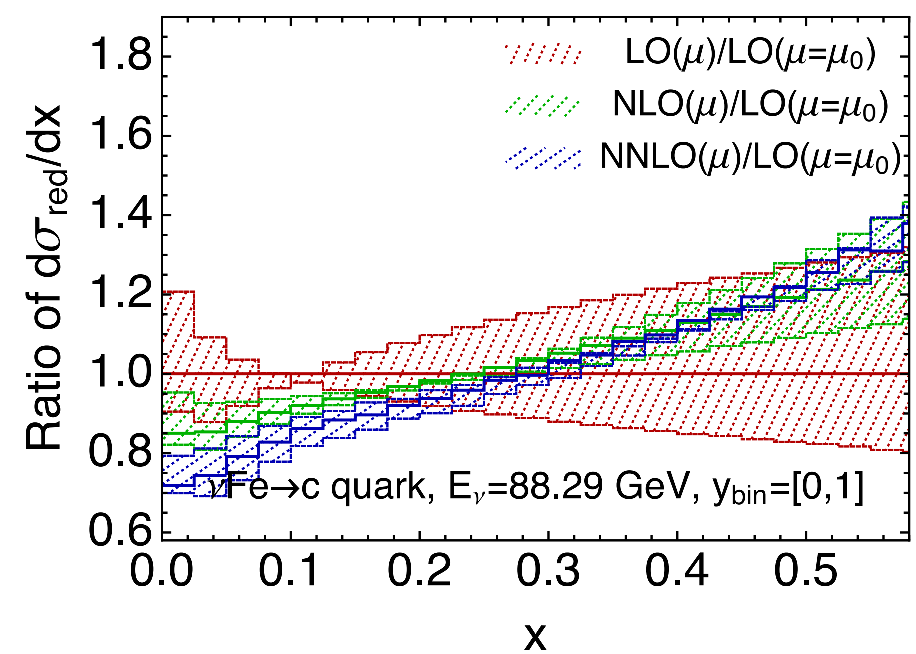
single differential



NNLO are found to be:

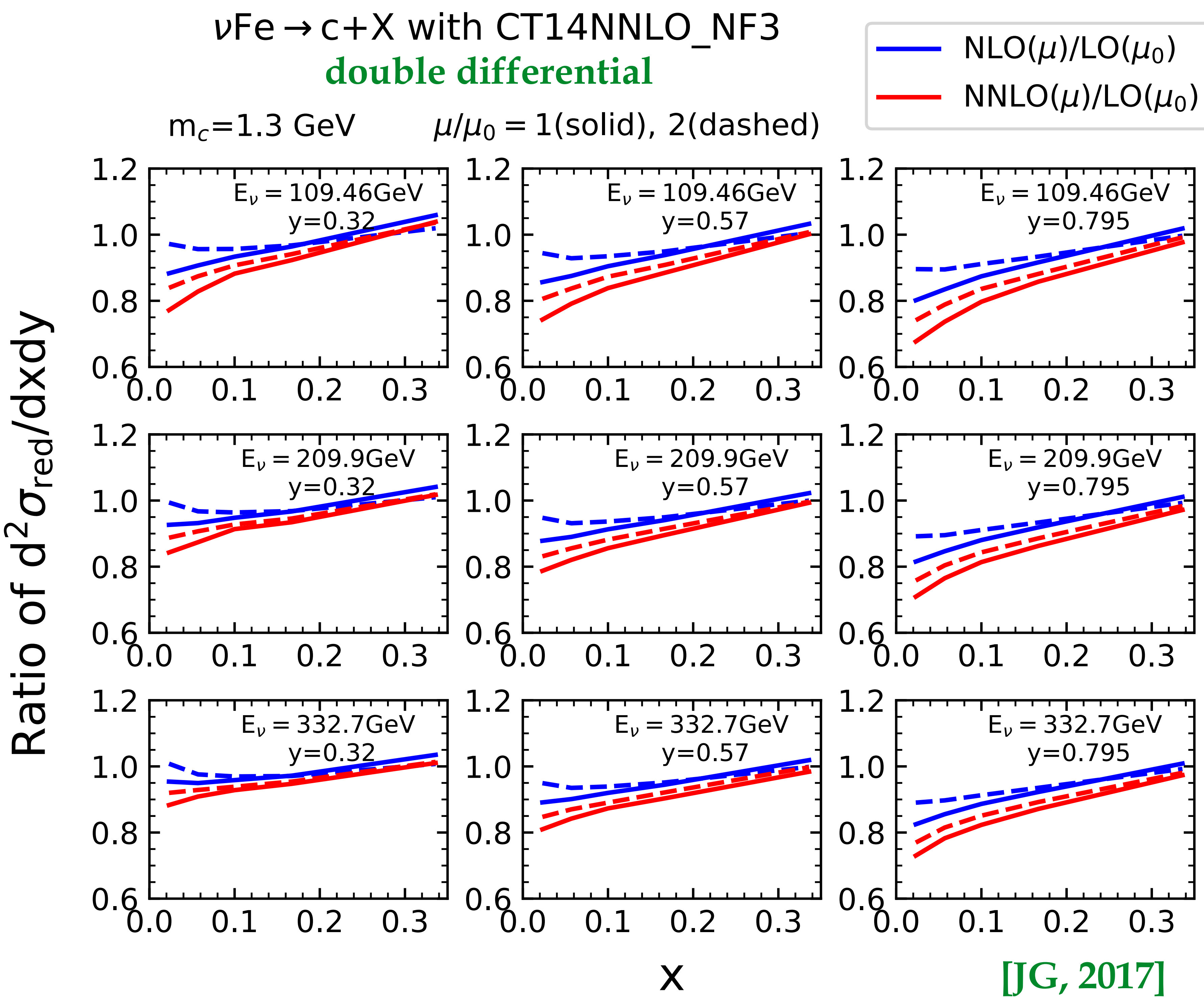
- ☆ dominated by gluon channel
- ☆ large at low-x region, ~ -10%
- ☆ scale variation only improved at large-x





Charm-quark production at NNLO

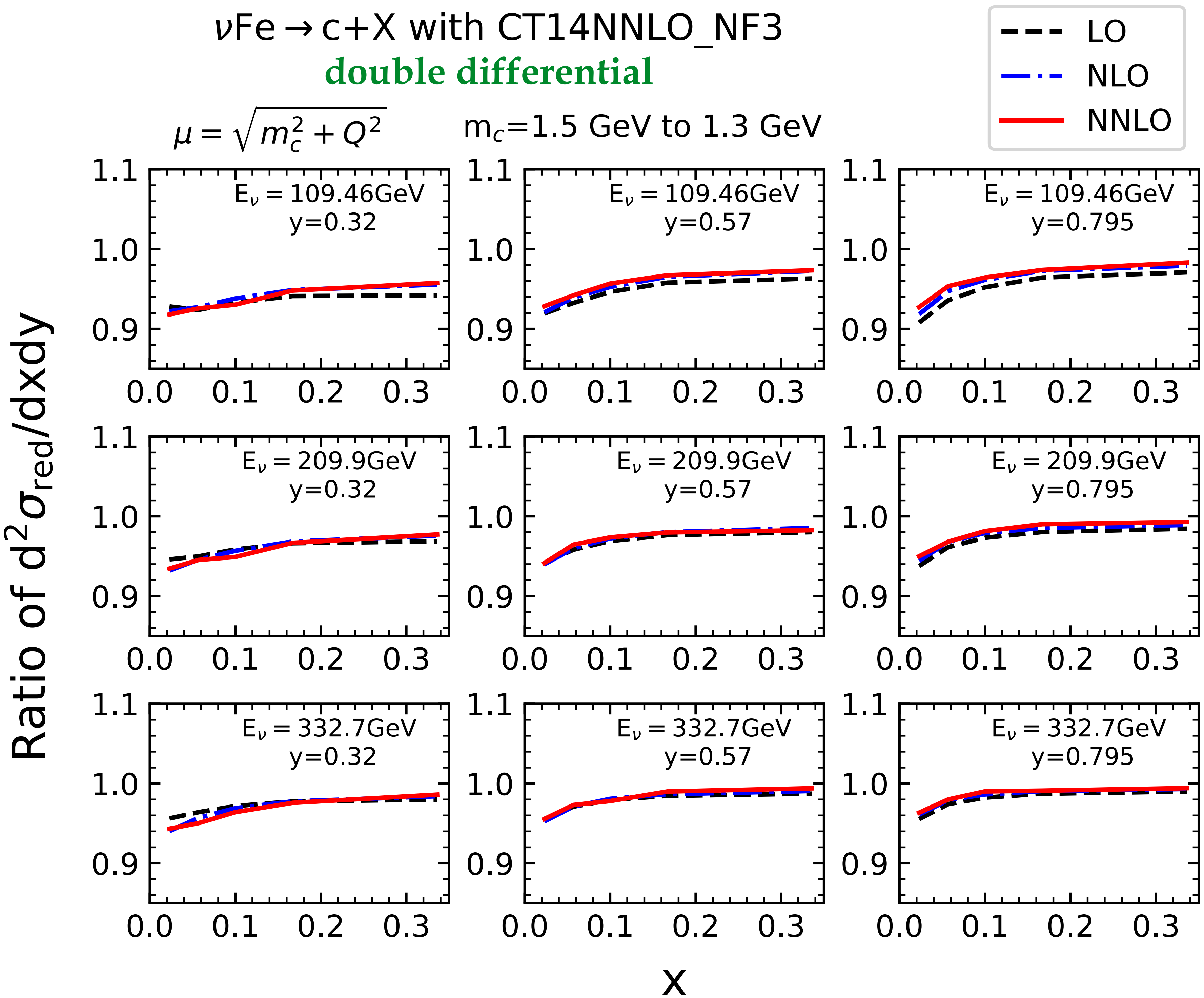
- Results are similar for double differential cross sections; shown here for charm-quark case with CCFR energy and kinematics



[JG, 2017]

Charm-quark production at NNLO

- Charm-quark mass dependence of the cross sections at various orders; almost identical at NLO and NNLO

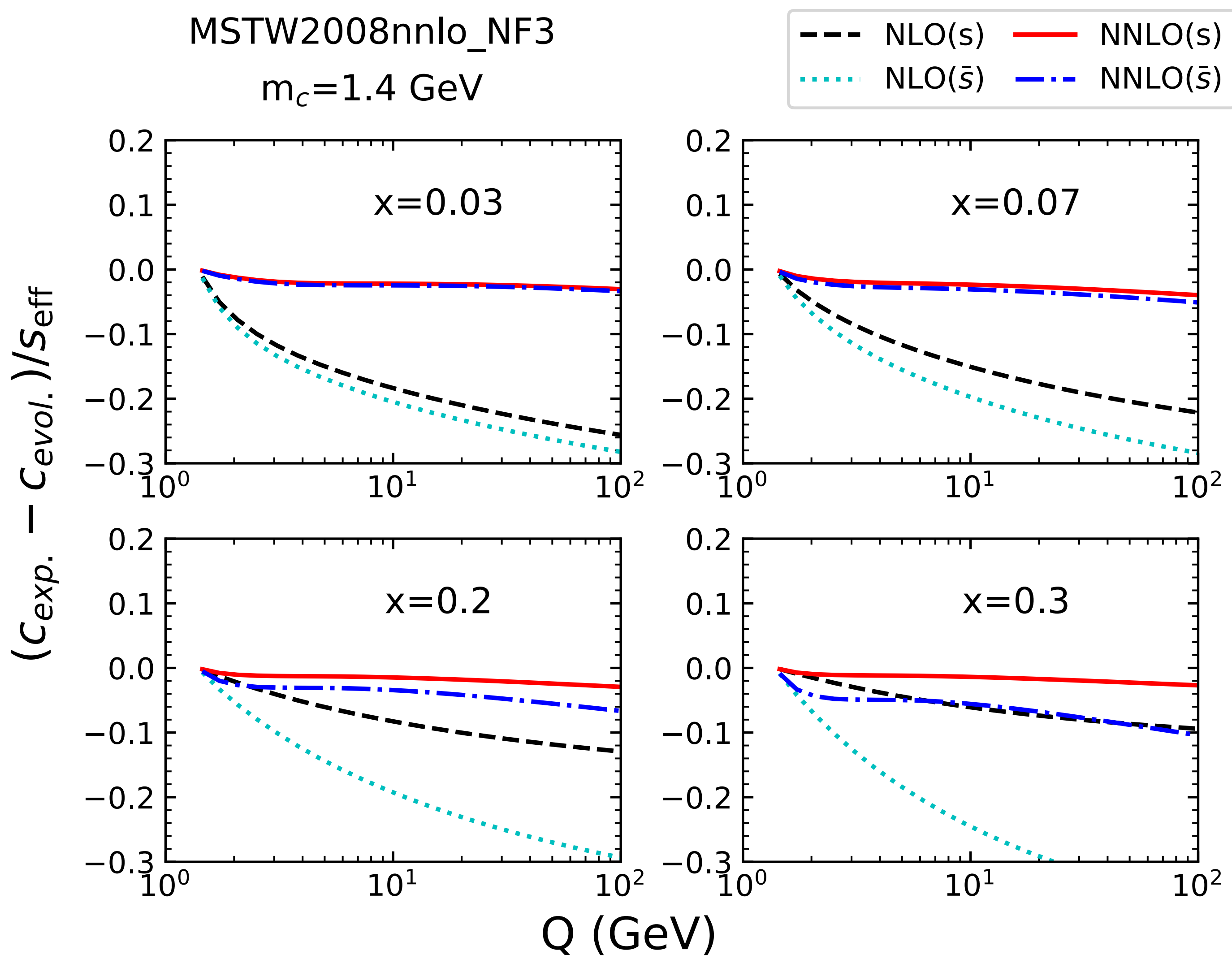


Heavy-quark scheme

- NNLO calculations are done for FFN scheme with $n_F=3$; contributions for initial gluon splitting into charm-quark pair can be resumed with GM-VFN scheme

evolved charm PDFs in $n_F=4$

$$\frac{df_c^{(n_f=4)}(x,\mu^2)}{d\ln\mu^2} = \sum_{i=q,\bar{q},c,\bar{c},g} P_{ci}(x,\alpha_S(\mu^2)) \otimes f_i^{(n_f=4)}(x,\mu^2)$$



expanded charm PDFs

$$f_c^{(n_f=4)}(x,\mu^2) = \Delta^{(2)} + \left(\frac{\alpha_S(\mu^2)}{2\pi}\right)\left\{L(P_{cg}^{(0)} \otimes f_g^{(n_f=3)}(x,\mu^2))\right\}$$
$$+ \left(\frac{\alpha_S(\mu^2)}{2\pi}\right)^2 \Big\{L(\sum_i P_{ci}^{(1)} \otimes f_i^{(n_f=3)}(x,\mu^2))$$
$$- \frac{L^2}{2}(\sum_i P_{cg}^{(0)} \otimes P_{gi}^{(0)} \otimes f_i^{(n_f=3)}(x,\mu^2)$$
$$- \beta_0 P_{cg}^{(0)} \otimes f_g^{(n_f=3)}(x,\mu^2))\Big\} + \mathcal{O}(\alpha_S^3)$$

differences of the two serve as an estimate of those contributions beyond FO

NNLO (FFN) calculation captures most of those large logarithms (g->cc) for NuTeV & CCFR kinematics

Fast grid interpolation

- PDFs at arbitrary scales can be approximated by an interpolation on a one-dimensional grid of x, thus the DIS cross sections; fast interface similar to APPLgrid and FastNLO approaches

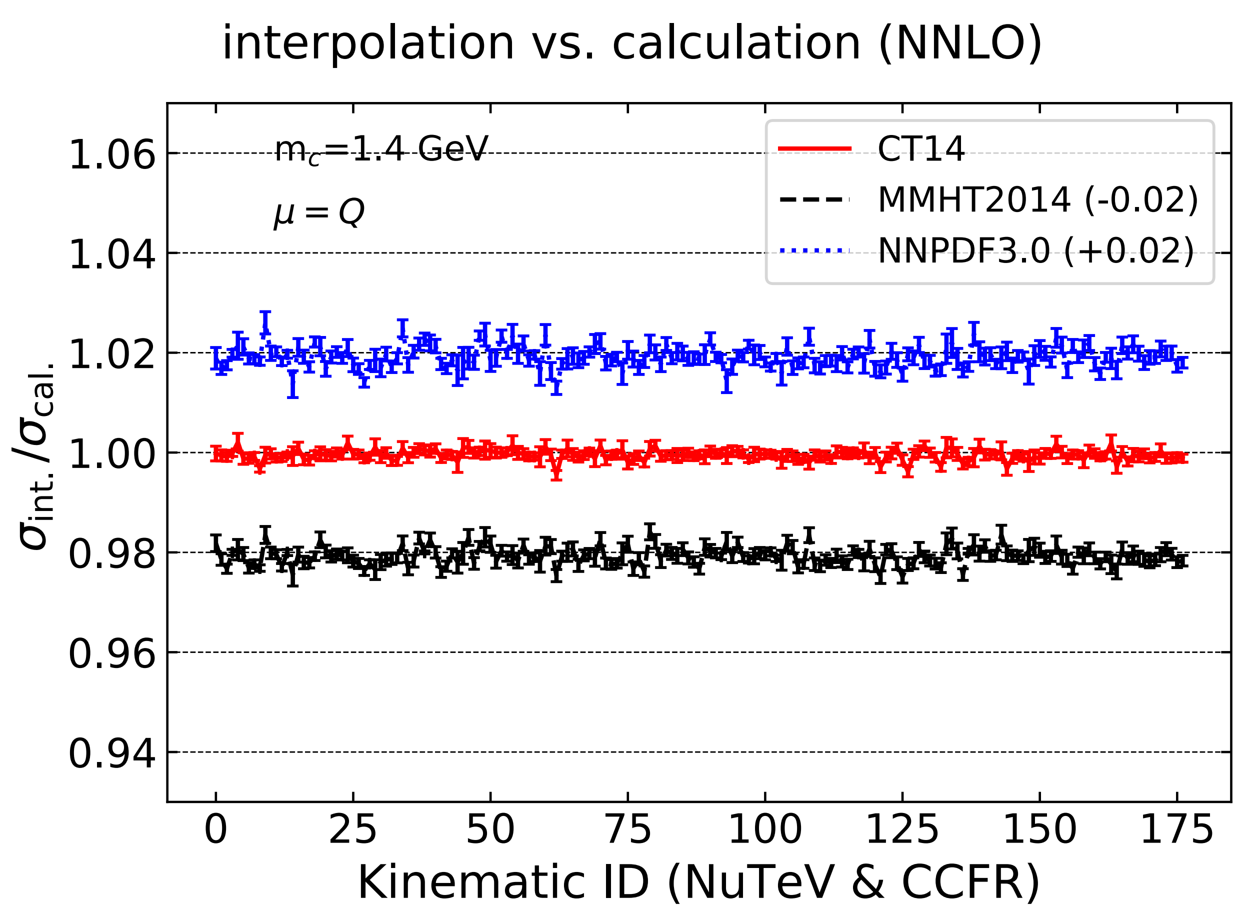
$$f(x,\mu) = \sum_{i=0}^{n} f_{k+i} I_i^{(n)} \left(\frac{y(x)}{\delta y} - k \right)$$

$$d\sigma_{bin} = \sum_{p} \sum_{m} \sum_{i} \left(\frac{\alpha_s(\mu)}{2\pi} \right)^m \mathcal{B}(p,m,i) f_i$$

	CPU core-hours (NNLO)
direct calculation	60
grid generation	280
interpolation	10^{-7}

with pre-generated grid the NNLO calculations take less than a millisecond

accuracy of the interpolation is a few per mille; MC errors are at similar level



Theory vs. data

- Fit to NuTeV and CCFR dimuon data (Q>2 GeV, 149 points) with various recent NNLO PDFs, NLO and NNLO cross sections

Chi2 for $m_c = 1.3$ GeV $\mu = \sqrt{Q^2 + m_c^2}$

$N_{pt} = 149$	NLO		NNLO	
CT14	167.3(-1.0)	**130.2(1.1)**	154.2(-0.4)	**132.9(1.3)**
MMHT14	132.2(-1.0)	**118.6(0.1)**	127.7(-0.3)	**118.8(0.1)**
NNPDF3.1	157.8(-1.2)	**115.8(-1.0)**	161.3(-0.5)	**115.1(-0.6)**
ABMP16	189.3(-1.6)	**170.8(-0.8)**	170.2(-1.0)	**157.6(-0.3)**
HERAPDF2.0	258.4(-0.8)	**130.3(0.3)**	221.6(-0.1)	**132.0(0.5)**
ATLAS-epWZ16	352.8(-4.0)	**246.6(-2.1)**	321.5(-3.7)	**228.7(-1.6)**
NNPDF3.1 (collider)	513.4(-5.1)	**118.5(-2.3)**	537.8(-4.8)	**114.0(-1.9)**

Chi2 for $m_c = 1.4$ GeV $\mu = Q$

$N_{pt} = 149$	NLO		NNLO	
CT14	158.2(-0.8)	**131.1(1.0)**	150.5(-0.1)	**134.1(1.3)**
MMHT14	128.2(-0.8)	**118.9(0.0)**	129.4(-0.1)	**119.6(0.1)**
NNPDF3.1	156.6(-1.0)	**115.9(-0.9)**	166.4(-0.3)	**115.5(-0.5)**
ABMP16	177.1(-1.4)	**162.6(-0.7)**	163.2(-0.8)	**153.2(-0.1)**
HERAPDF2.0	240.9(-0.6)	**130.5(0.2)**	209.2(0.2)	**132.6(0.5)**
ATLAS-epWZ16	332.8(-3.9)	**234.4(-2.0)**	303.5(-3.5)	**218.9(-1.5)**
NNPDF3.1 (collider)	527.0(-5.0)	**116.4(-2.2)**	553.7(-4.8)	**110.2(-1.9)**

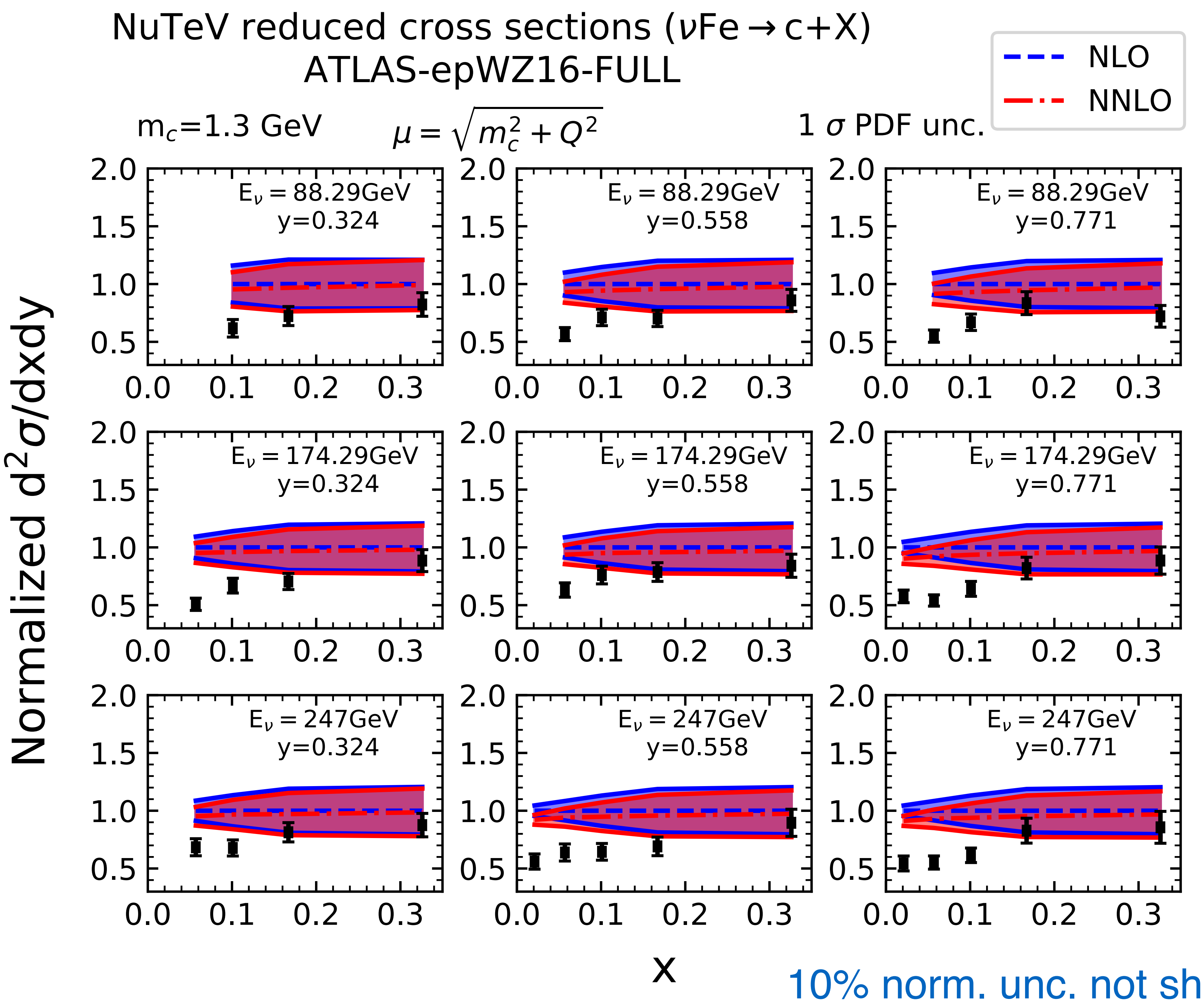
double differential data corrected for nuclear effects; assuming BR=0.099 with a 10% uncertainty

plain (bold) number shows chi2 w/o (with) including PDF uncertainty; in parenthesis are normalization shift

NNLO results show slightly better agreement though all PDFs are fitted with NLO dimuon cross sections; ATLAS PDFs give poor description

Theory vs. data

- Tension between ATLAS-epWZ16 extraction of strange-quark PDFs and the dimuon measurements are seen for low-x region

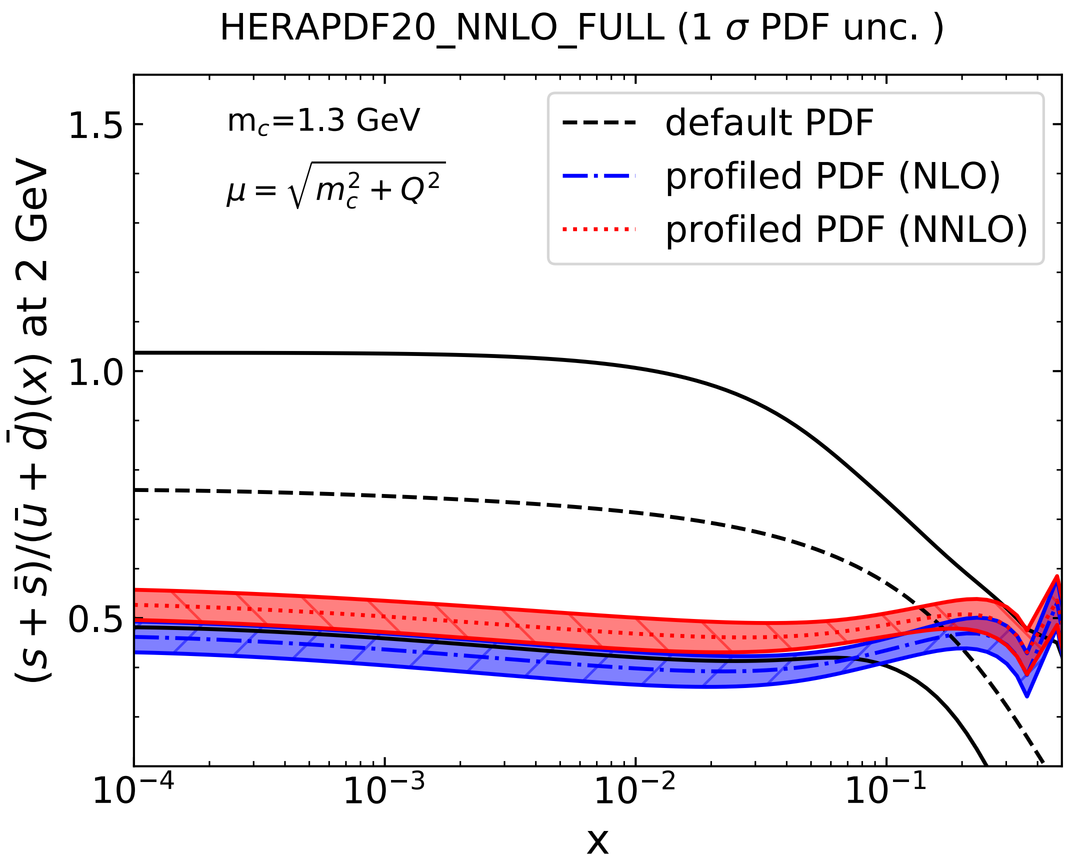


10% norm. unc. not shown

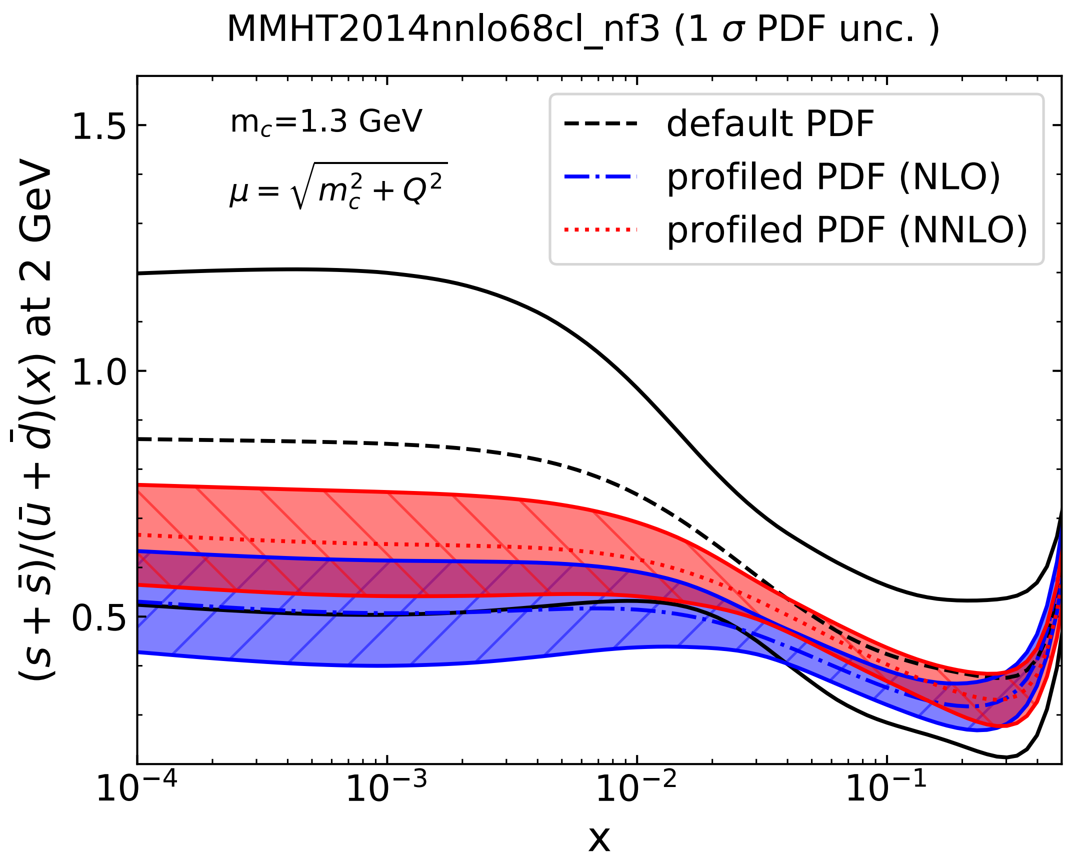
Impact of NNLO corrections

- Impact of the NNLO corrections to the extraction of the strange-quark PDFs are studied with Hessian profiling, see **NNLO** vs. **NLO**

HERAPDF2.0 base



MMHT2014 base

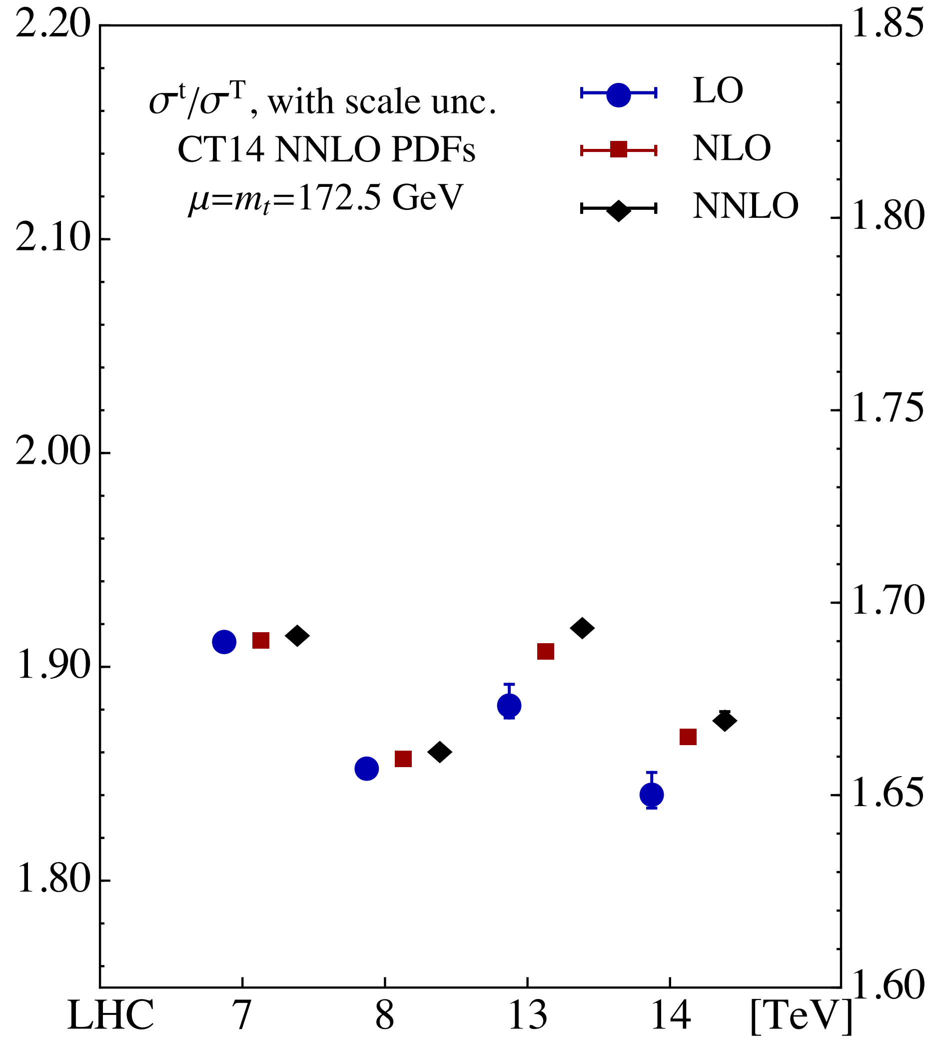


NNLO predictions prefer higher values of strange to non-strange ratio since the NNLO corrections are negative in the bulk of the NuTeV and CCFR data

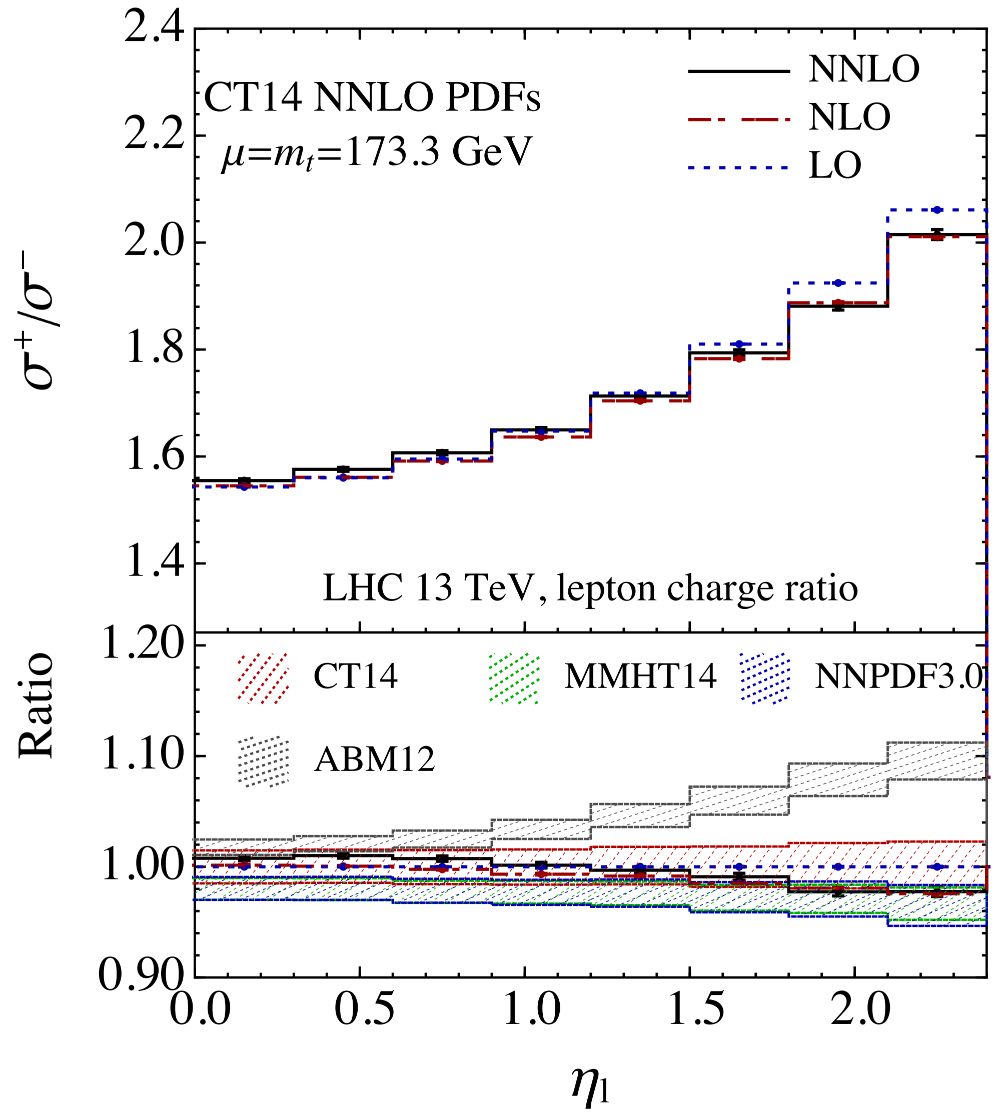
Single top quark production

- The NNLO computation can also be applied to t-channel single top quark production at the LHC; the latter can provide constraints on ratio of u and d quark PDFs **[Berger, JG, Yuan, Zhu, 2016]**

inclusive charge ratio



charge ratio differential on lepton rapidity



NNLO corrections are small, within 1%, for the charge ratio

Summary and outlook

- Heavy quark production in charged-current DIS has been calculated to NNLO in QCD using fully differential MC methods
- The NNLO corrections can be comparable to the NLO ones in low-x region for charm-quark production, reaching -10%
- Comparisons of various theory predictions to CCFR and NuTeV dimuon data are made; good agreements in general
- The NNLO corrections are expected to raise the strange to non-strange sea-quark ratio but not significantly
- The computation are ready to be included in future global analysis with fast interface and grids publicly available

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Thank you for your attention!

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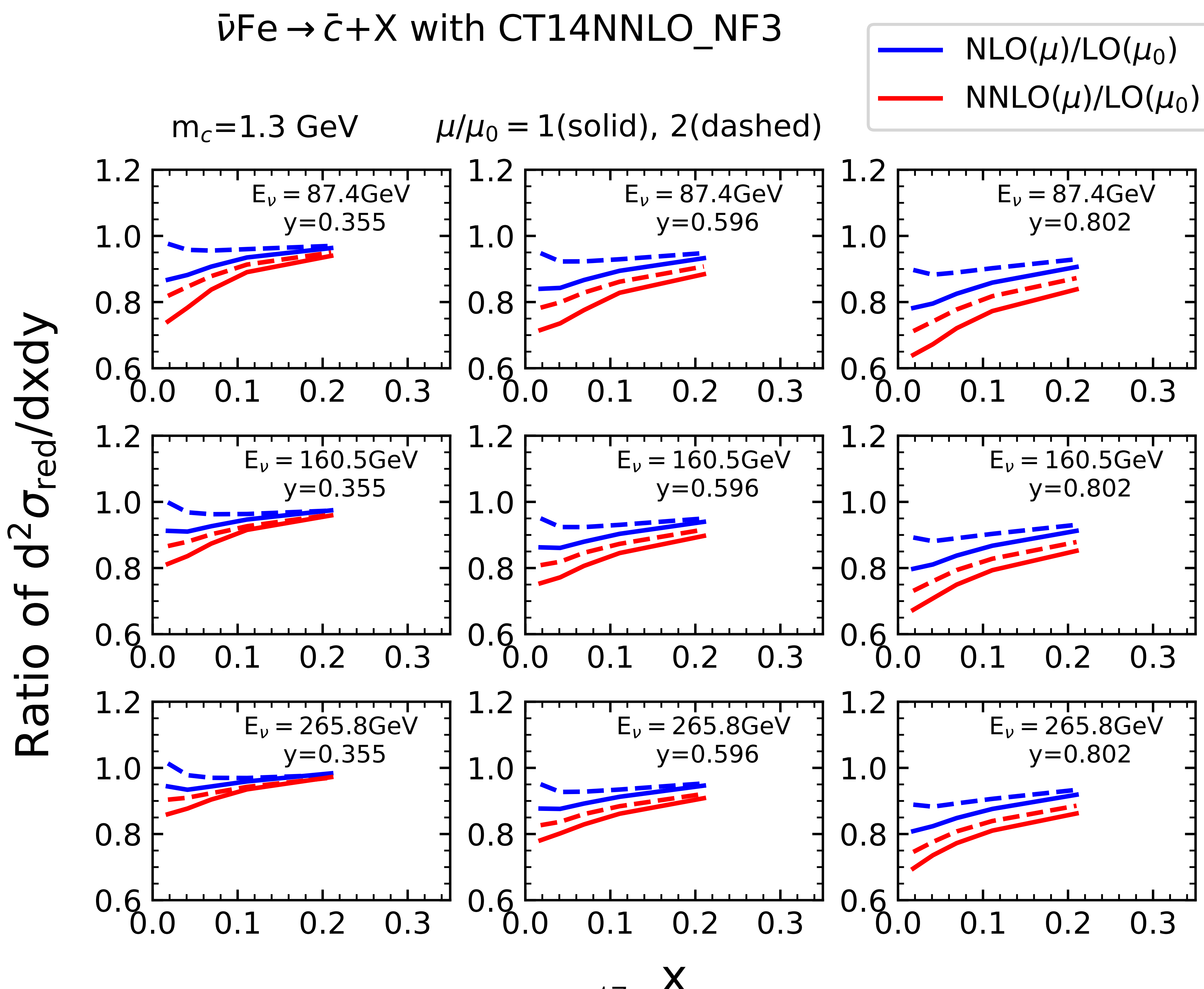
- Results are similar for double differential cross sections; shown here for charm anti-quark case with CCFR energy and kinematics



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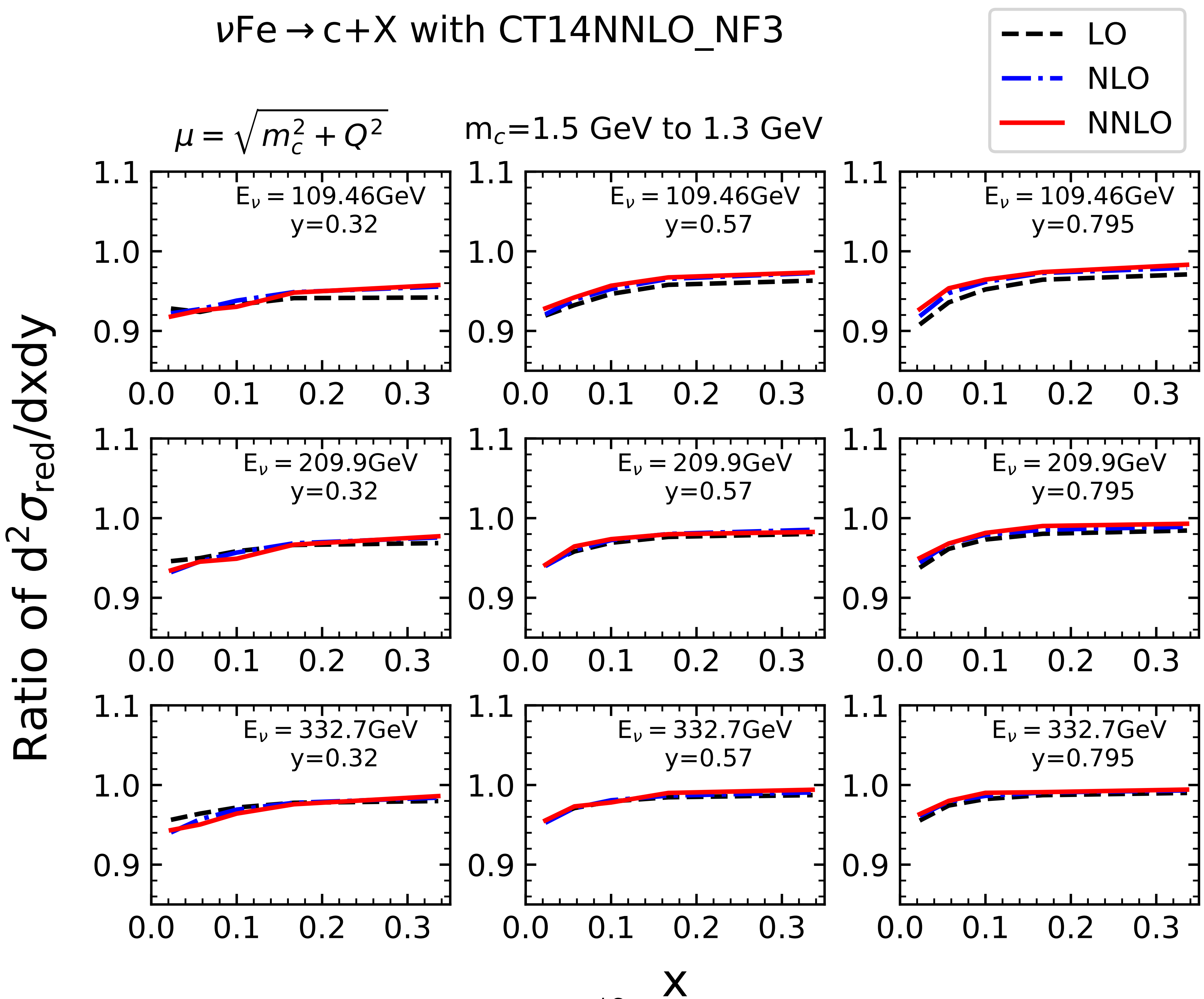
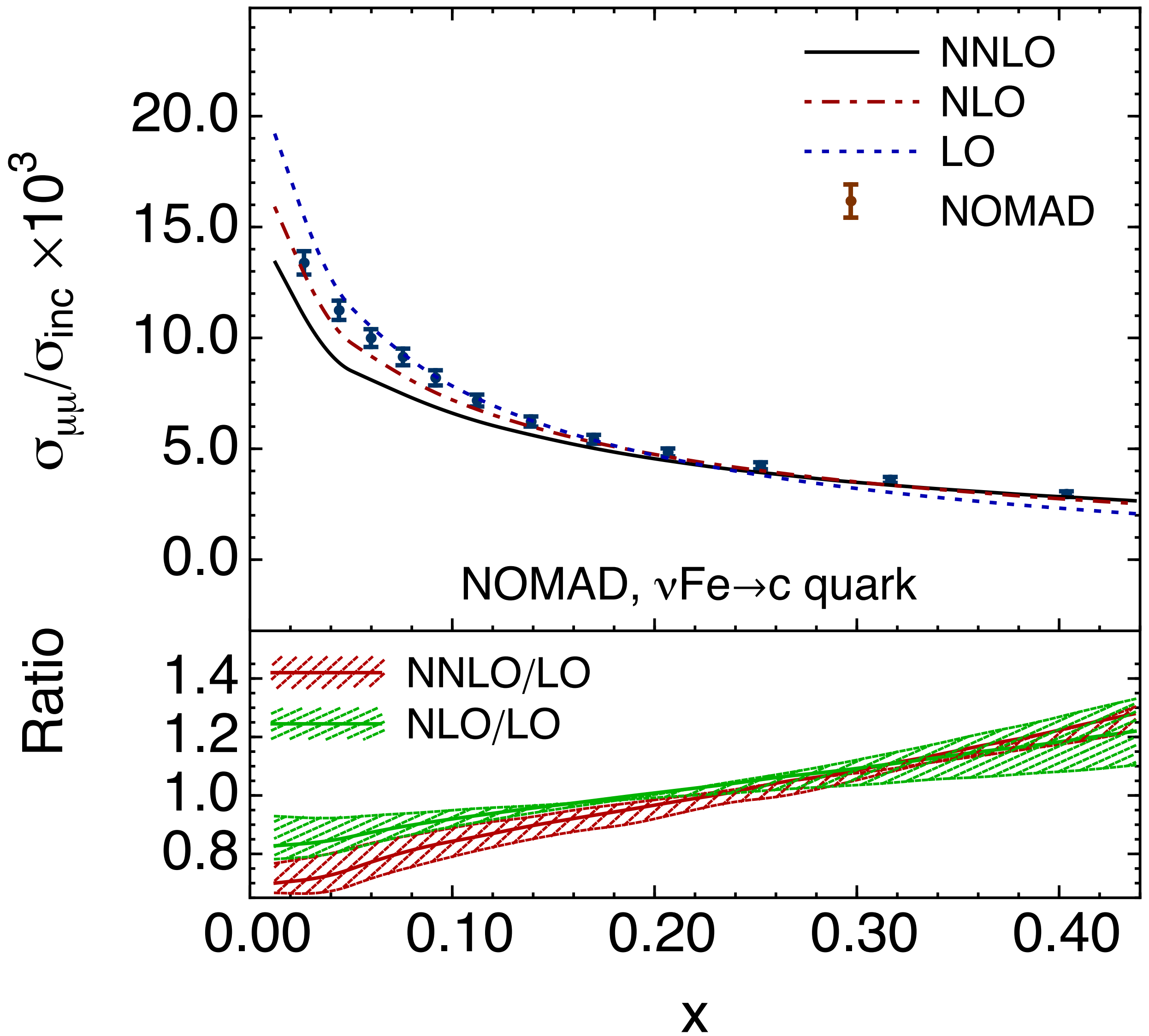


NOMAD **[Backups]**

- Single differential distributions are shown here for charm-quark case with NOMAD neutrino flux and kinematics



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