S-ACOT Heavy flavor contributions at NNLO in CTEQ-TEA analysis

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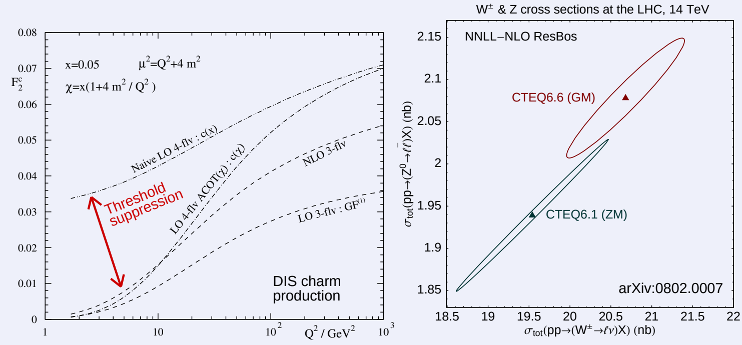
In collaboration with P. Nadolsky, C.-P. Yuan and H.L. Lai

Heavy-quark DIS and LHC observables

Motivation:

General-mass (and not zero-mass of fixed-flavor number) treatment of c, b mass terms in DIS is essential for predicting precision W, Z cross sections at the LHC *(Tung et al., hep-ph/0611254)*

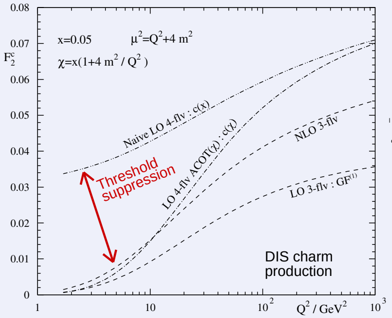
Several quark mass effects are comparable to NNLO radiative contributions, must be included in a consistent way

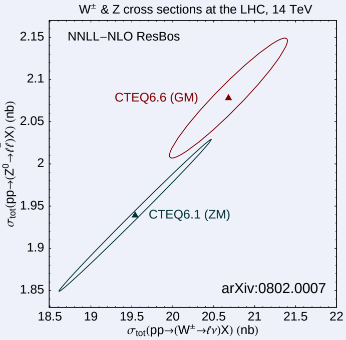


Heavy-quark DIS and LHC observables

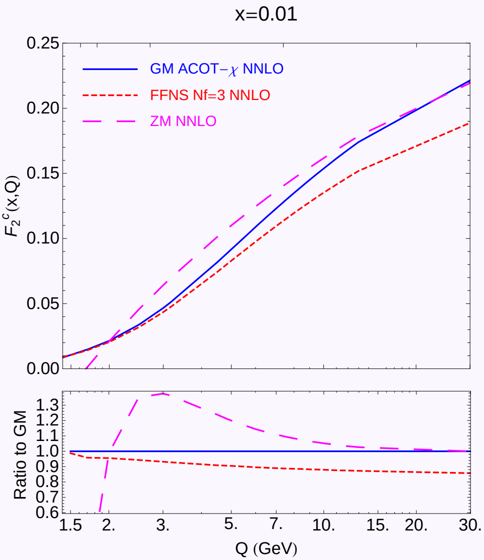
This talk:

- an NNLO computation for heavy-quark DIS structure functions, $F_i^{c,b}(x,Q)$, in a general-mass scheme (S-ACOT)
- focus on consistent treatment of all relevant factors in $F_i^{c,b}(x,Q)$ affecting CTEQ-TEA PDFs at NNLO accuracy





$F_2^c(x, Q^2)$ at NNLO - Preliminary

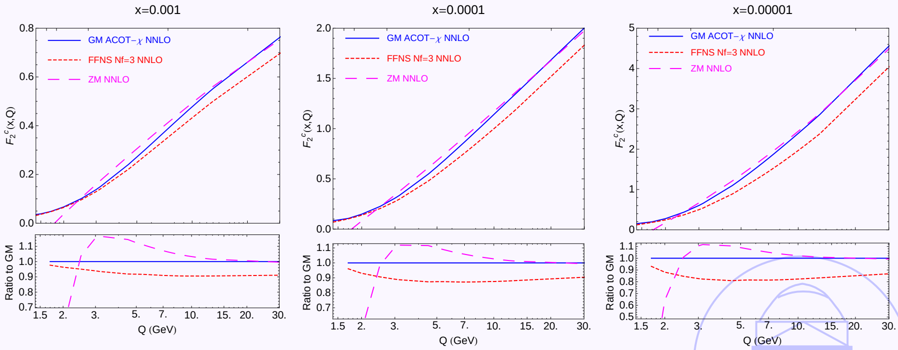


S-ACOT reduces to FFNS at $Q \approx m_c$ and to ZM at $Q \gg m_c$

Les Houches toy PDFs, evolved at NNLO with threshold matching terms

NNLO predictions for F_L^c are in the backup slides

$F_2^c(x, Q^2)$ at NNLO, other x bins - Preliminary



Simplified Aivazis-Collins-Olness-Tung scheme

ACOT, PRD 50 3102 (1994); Collins, PRD 58 (1998) 094002; Kramer, Olness, Soper, PRD (2000) 096007

- The default mass scheme of CTEQ6.6 and CT10 PDFs
- Based upon, and closely follows, the proof of QCD factorization for DIS with massive quarks *(Collins, 1998)*
- Relatively simple, compared to BMSN or TR schemes
  - One value of N_f (and one PDF set) in each Q range
  - Straightforward matching based on kinematical rescaling
  - Sets $m_Q = 0$ in ME with incoming c or b
- Reduces to the ZM $\overline{MS}$ scheme at $Q^2 \gg m_Q^2$, without additional renormalization
- Reduces to the FFN scheme at $Q^2 \approx m_Q^2$
  - has reduced dependence on tunable parameters at NNLO

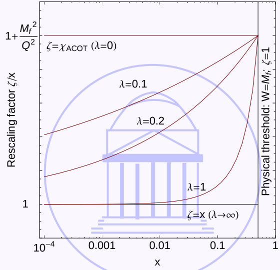
S-ACOT input parameters

At $Q \approx m_c$, F_2^c depends significantly on

1. **Charm mass:** $m_c = 1.3$ GeV in CT10
2. **Factorization scale:** $\mu = \sqrt{Q^2 + \kappa m_c^2}$; $\kappa = 1$ in CT10
3. **Rescaling variable** $\zeta(\lambda)$ for matching in $\gamma^* c$ channels
   (*Tung et al., hep-ph/0110247; Nadolsky, Tung, PRD79, 113014 (2009)*)

$$F_i(x, Q^2) = \sum_{a,b} \int_\zeta^1 \frac{d\xi}{\xi} \, f_a(\xi, \mu) \, C^a_{b,\lambda}\left(\frac{\zeta}{\xi}, \frac{Q}{\mu}, \frac{m_i}{\mu}\right)$$

$$x = \zeta \Big/ \left(1 + \zeta^\lambda \cdot (4m_c^2)/Q^2\right), \text{ with } 0 \leq \lambda \lesssim 1$$



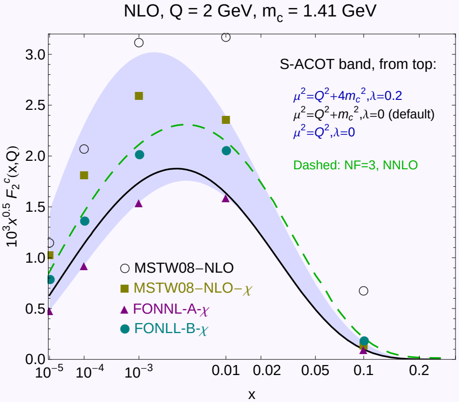
CT10 uses

$$\zeta(0) \equiv \chi \equiv x\left(1 + 4m_c^2/Q^2\right),$$

motivated by momentum conservation

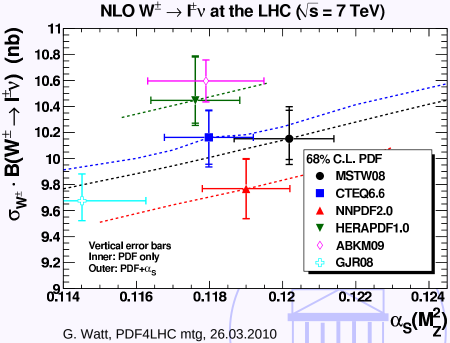
Input parameters of the S-ACOT scheme

At NLO, the m_c, μ, and ζ parameters of CTEQ PDFs are tuned to best describe the DIS data



2009 Les Houches HQ benchmarks with toy PDFs;

$\mu = Q$ in non-CTEQ predictions



G. Watt, PDF4LHC mtg, 26.03.2010

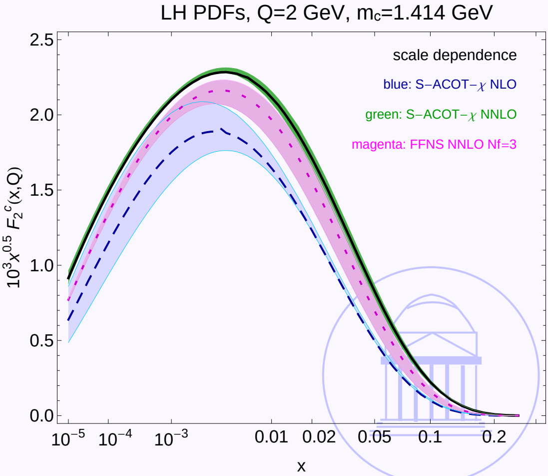
W, Z cross sections;

$m_c = 1.3$ GeV in CTEQ6.6

Results for $F_2^c(x, Q^2)$ at NLO/NNLO - Preliminary

At NNLO and $Q \approx m_c$:

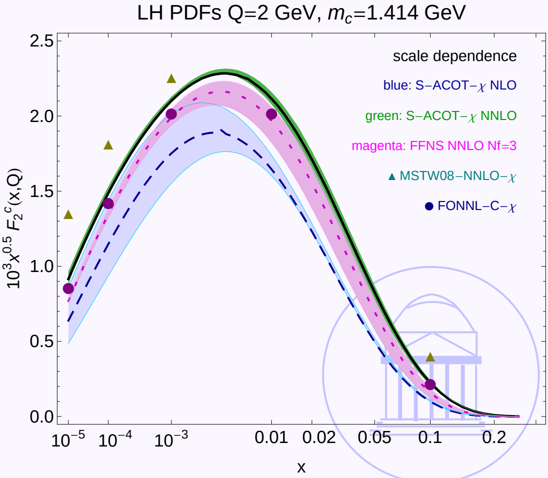
- S-ACOT-$\chi \approx$ FFN($N_f = 3$) without tuning



Results for $F_2^c(x, Q^2)$ at NLO/NNLO - Preliminary

At NNLO and $Q \approx m_c$:

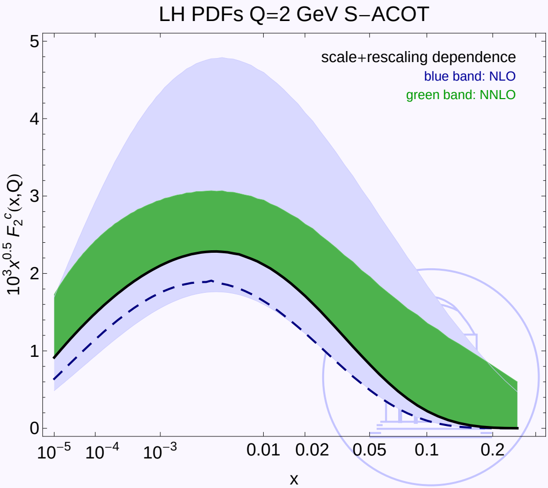
- S-ACOT-$\chi \approx$ FFN($N_f = 3$) without tuning
- It is close to other NNLO schemes



Results for $F_2^c(x, Q^2)$ at NLO/NNLO - Preliminary

At NNLO and $Q \approx m_c$:

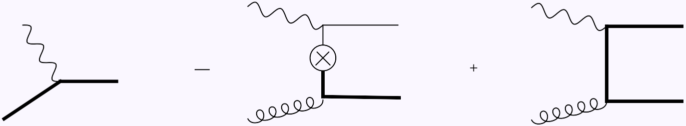
- S-ACOT-χ $\approx$ FFN($N_f = 3$) without tuning
- It is close to other NNLO schemes
- Dependence on rescaling is also reduced



Details of the computation

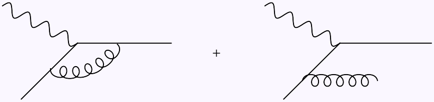
- NNLO evolution for α_s and PDFs (HOPPET)
  - matching coefficients relating the PDFs in N_f and N_{f+1} schemes *(Smith, van Neerven, et al.)*
- NNLO Wilson coefficient functions for $F_2^c(x, Q)$, $F_L^c(x, Q)$
- Work in progress: $\overline{MS}$ masses from PDG as input

Classes of Feynman diagrams I



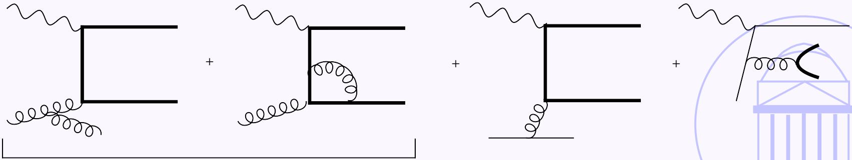
LO γ^* c — NLO Subtraction + NLO γ^* g

ACOT II: Phys.Rev.D50 (1994) 3102



NLO γ^* c

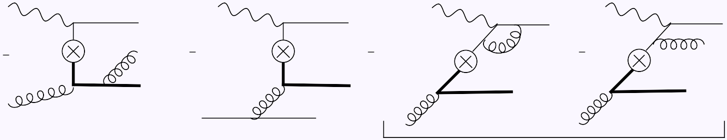
Furmanski, Petronzio, Z.Phys. C11 (1982) 293.
Kramer, Olness, Soper, PR D62 (2000) 096007



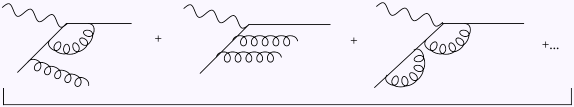
NNLO: γ^* g + NNLO: γ^* Σ + NNLO: γ^* q NS

Riemersma et. al. Phys.Lett. B347 (1995) 143

Classes of Feynman Diagrams II



NNLO Subtractions Buza, Matiounine, Smith, Van Neerven, Eur. Phys. J. C 1998



NNLO γ^* c Moch, Vermaseren and Vogt, Nucl.Phys.B724, 2005

Cancellations between Feynman diagrams

Validity of the S-ACOT calculation was verified by checking for certain cancelations at $Q \approx m_c$ and $Q \gg m_c$

- $Q \approx m_c$:

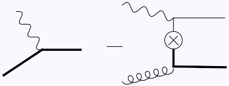
$$D^{(2)}_{C1} \ll D^{(2)}_{C0} \ll D^{(1)}_{C0} \leq F^c_2(x, Q)$$

- $Q \gg m_c$:

$$D^{(2)}_{g} \ll D^{(1)}_{g} < F^c_2(x, Q)$$

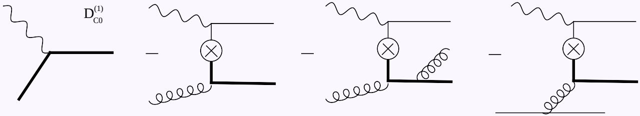
These cancellations are indeed observed in our results

NNLO: Cancellations at $Q^2 \approx m_c^2$



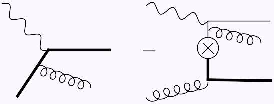
$$D^{(1)}_{C0} = C^{(0)}_Q \otimes c - a_s C^{(0)}_Q \otimes A^{(1)}_{Qg} \otimes g; \qquad a_s = \frac{\alpha_s}{(4\pi)} \qquad (1)$$

$D^{(1)}_{C0}$



$D^{(2)}_{C0}$

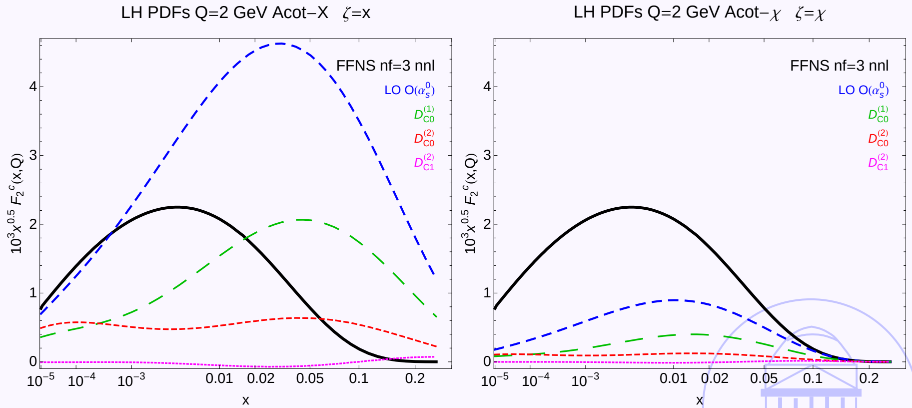
$$D^{(2)}_{C0} = D^{(1)}_{C0} - a_s^2 C^{(0)}_Q \otimes A^{(2),S}_{Qg} \otimes g - a_s^2 C^{(0)}_Q \otimes A^{(2),PS}_{Q\Sigma} \otimes \Sigma \qquad (2)$$



$$D^{(2)}_{C1} = C^{(1)}_Q \otimes c - a_s^2\, C^{(1)}_Q \otimes A^{(1)}_{Qg} \otimes g \qquad (3)$$

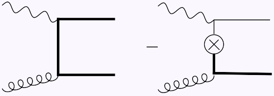
$D^{(2)}_{C1}$

NNLO: Cancellations at $Q^2 \approx m_c^2$



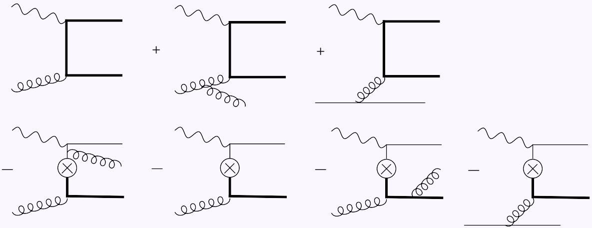
$D_{C1}^{(2)} << D_{C0}^{(2)} << D_{C0}^{(1)} \leq$ FFN at NNLO both for $\zeta = x$ and $\zeta = \chi$.

NNLO: Cancellations at $Q >> m_c$



$$D_g^{(1)} \equiv C_g^{(1)} = a_s \left(F_g^{(1)} \otimes g - C_Q^{(0)} \otimes A_{Qg}^{(1),S} \otimes g \right) \qquad (4)$$

$D_g^{(1)}$

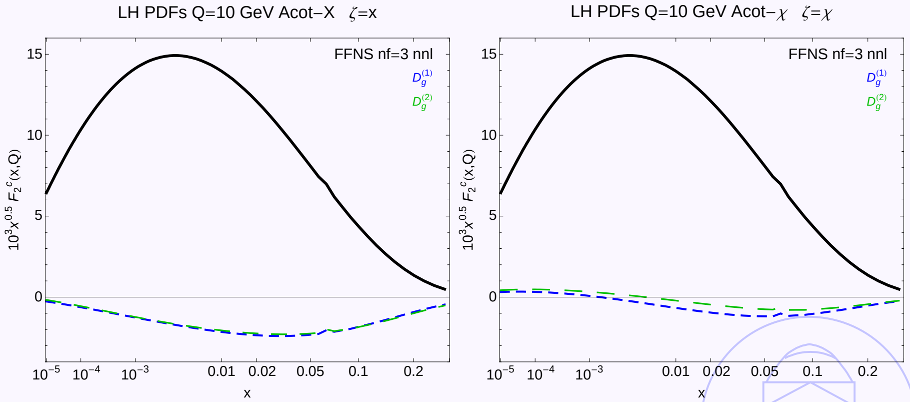


$D_g^{(2)}$

$$D_g^{(2)} = D_g^{(1)} + a_s^2 \Big[\tilde{F}_g^{(2)} \otimes g + \tilde{F}_\Sigma^{(2)} \otimes \Sigma - C_Q^{(1)} \otimes A_{Qg}^{(1),S} \otimes g$$
$$- C_Q^{(0)} \otimes A_{Qg}^{(2),S} \otimes g - C_Q^{(0)} \otimes A_{Q\Sigma}^{(2),PS} \otimes \Sigma \Big] \qquad (5)$$

$D_g^{(1)}$ is of order of α_s^2 while $D_g^{(2)}$ is of order of α_s^3.

F_2^c at NNLO: Cancellations at $Q = 10$ GeV



$D_g^{(2)} << D_g^{(1)} <$ FFN at NNLO $<$ ACOT

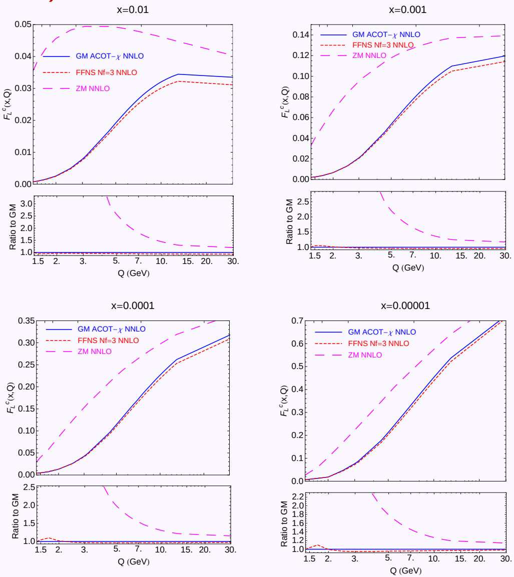
$\log \frac{Q^2}{m_c^2}$ terms in FFN are cancelled well by subtractions.

Main messages

- An NNLO calculation for $F_2^{c,b}$ and $F_L^{c,b}$ in the S-ACOT scheme is proven to be viable
- This is the most challenging component of the NNLO CTEQ PDF analysis, which will be made available soon.
- NNLO predictions are stable and show a remarkable reduction in the dependence on free parameters, compared to NLO.
- They will help us to reduce tuning of m_c and scale parameters, currently used by NLO CT10 PDFs to achieve excellent agreement with the HERA DIS data

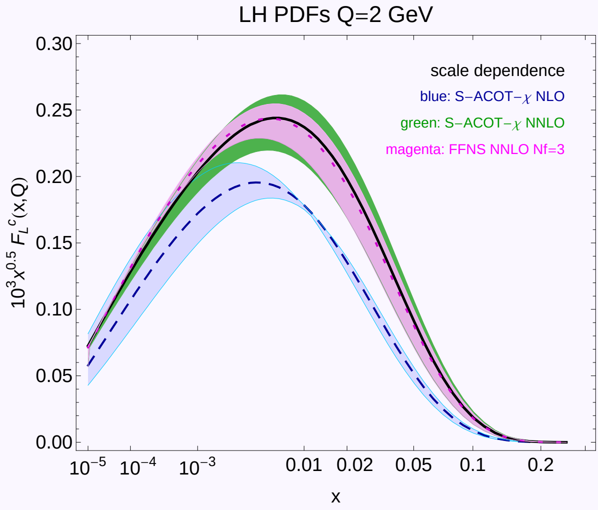
BACK UP SLIDES

$F_L^c(x, Q^2)$ at NNLO - Preliminary



S-ACOT is close to FFNS at all Q. ZM over-estimates S-ACOT everywhere

Results for $F_L^c(x, Q^2)$ at NLO/NNLO - Preliminary



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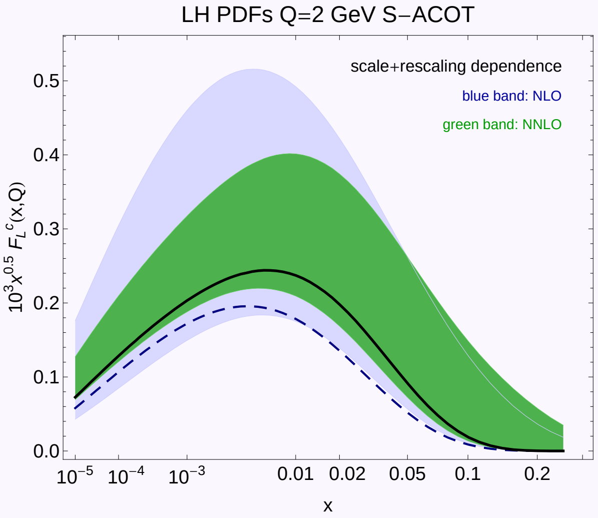
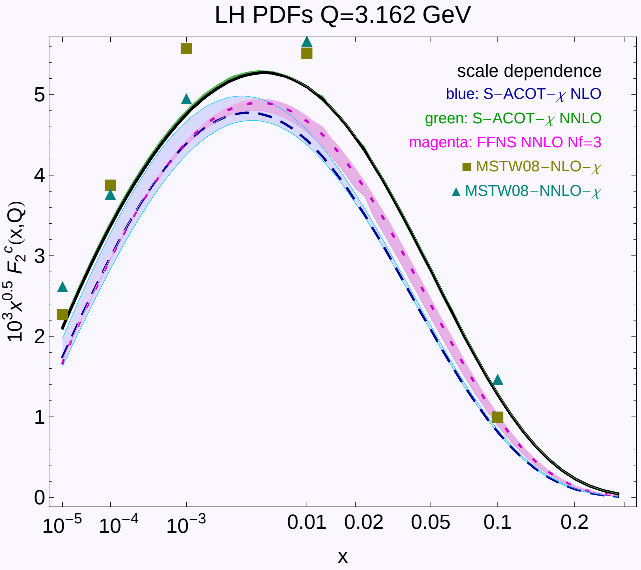


Plots for $Q^2 = 10\ GeV^2$ and $Q^2 = 100\ GeV^2$ are in the backup.

Results for $F_2^c(x, Q^2)$ at NLO/NNLO - Preliminary



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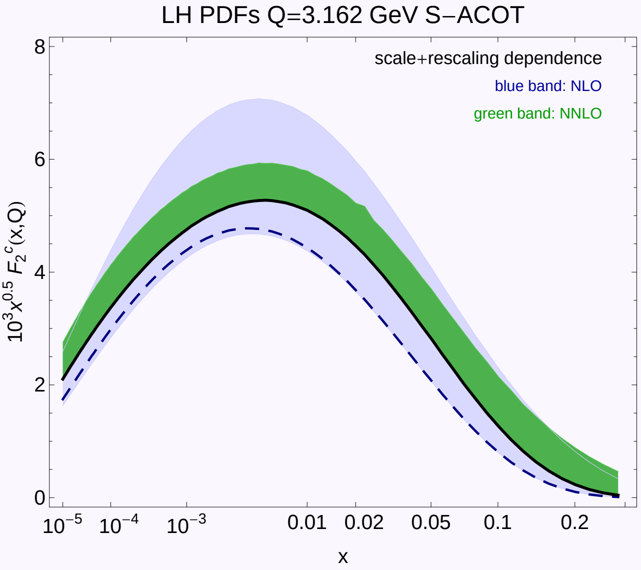

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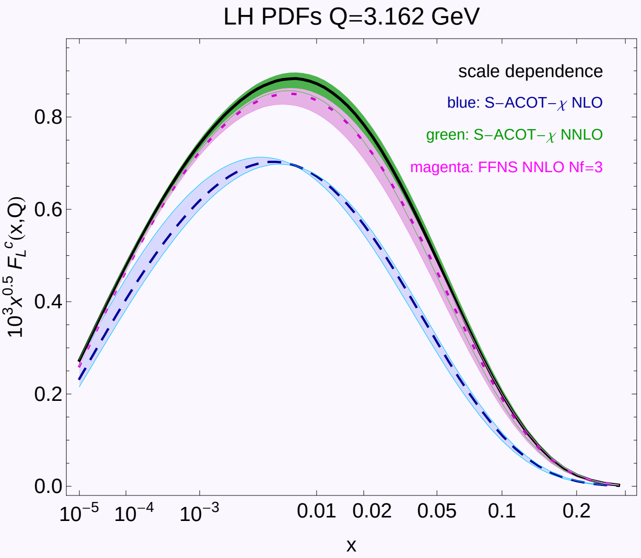
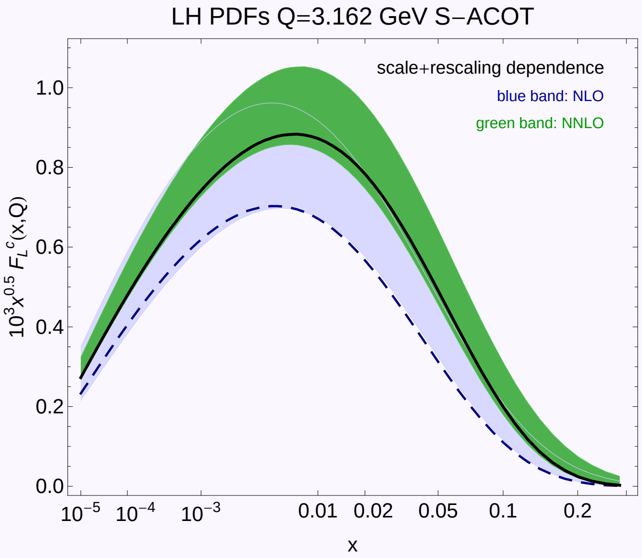
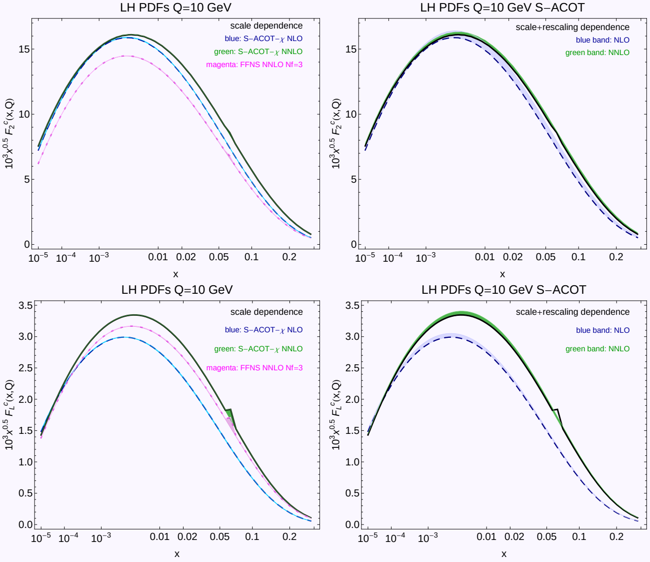


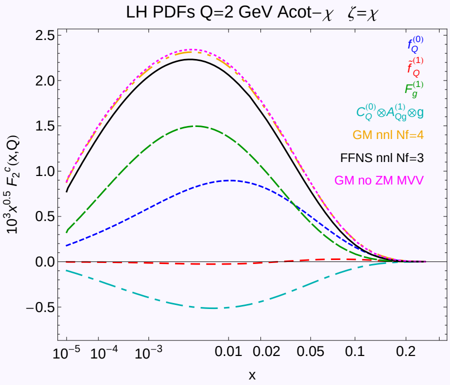
Results for $F_L^c(x, Q^2)$ at NLO/NNLO - Preliminary

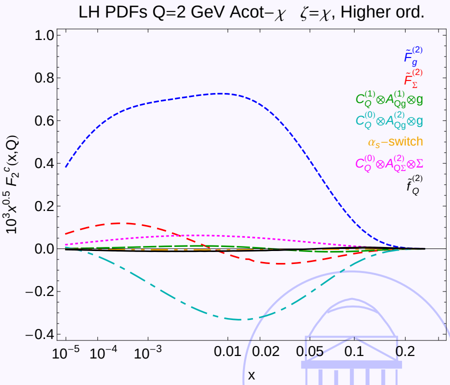


$F^c_{2,L}(x, Q^2)$ at NLO/NNLO $Q = 10$ GeV - Preliminary

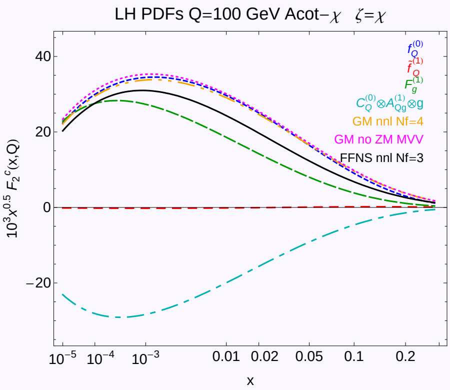


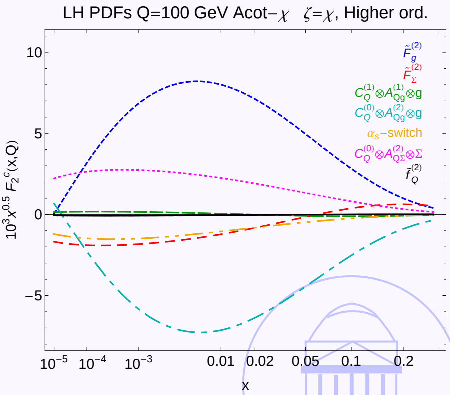
F_2^c: Anatomy of the contributions $Q = 2$ GeV



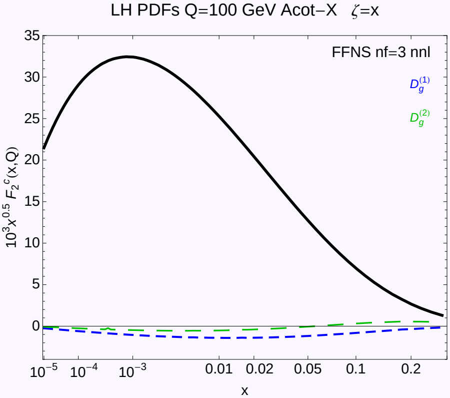


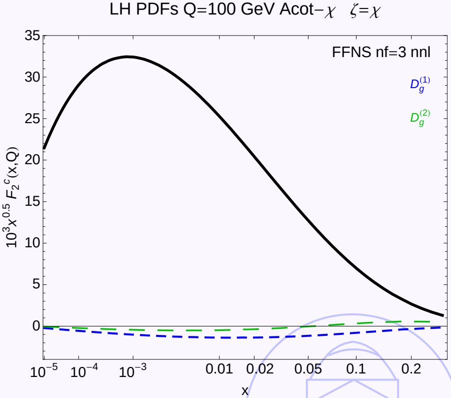
F_2^c: Anatomy of the contributions $Q = 100$ GeV





F_2^c at NNLO: Cancellations at $Q = 100$ GeV





$D_g^{(2)} << D_g^{(1)} <$ FFN at NNLO $<$ Acot

$\log \frac{Q^2}{m_c^2}$ terms in FFN are cancelled well by subtractions.

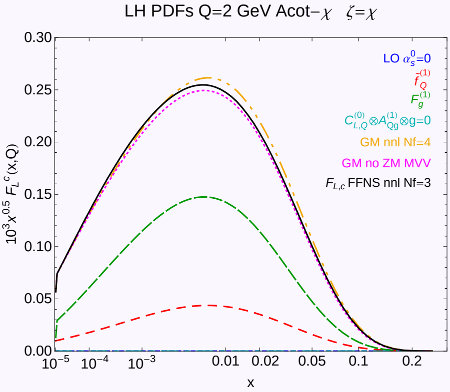
FFNS expression for $F_{2,L}^{c}(x, Q)$

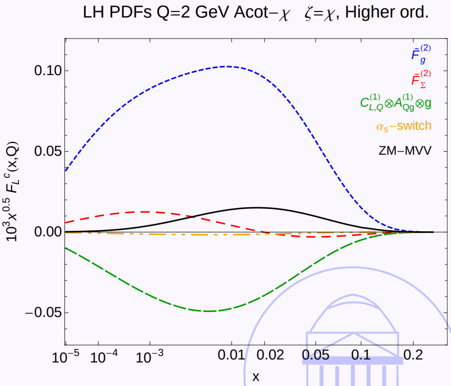
- Riemersma, Smith, Van Neerven, Phys. Lett. B347 (1995) 143-151- The structure functions are given by

$$\begin{aligned} F_k(x,Q) &= \frac{Q^2\alpha_s}{4\pi^2 m^2}\int_x^{z_{max}}\frac{dz}{z}\left[e_H^2\, g\left(\frac{x}{z},\mu^2\right) c_{k,g}^{(0)}\right] \\ &+ \frac{Q^2\alpha_s^2}{\pi m^2}\int_x^{z_{max}}\frac{dz}{z}\left\{e_H^2\, g\left(\frac{x}{z},\mu^2\right)\left(c_{k,g}^{(1)} + \bar{c}_{k,g}^{(1)}\ \ln\frac{\mu^2}{m^2}\right)\right. \\ &+ \sum_{i=q,\bar{q}}\left[e_H^2\, f_i\left(\frac{x}{z},\mu^2\right)\left(c_{k,i}^{(1)} + \bar{c}_{k,i}^{(1)}\ \ln\frac{\mu^2}{m^2}\right)\right. \\ &+ \left.\left. e_{L,i}^2\, f_i\left(\frac{x}{z},\mu^2\right)\left(d_{k,i}^{(1)} + \bar{d}_{k,i}^{(1)}\ \ln\frac{\mu^2}{m^2}\right)\right]\right\}, \end{aligned} \tag{6}$$

Here e_H is the charge of the heavy quark while e_L refers to the light quark. Furthermore $k = 2, L$, $z_{max} = Q^2/(Q^2 + 4m^2)$ and $i = g, q, \bar{q}$.

F_L^c: Anatomy of the contributions $Q = 2$ GeV





F_L^c: Anatomy of the contributions $Q = 100$ GeV