Heavy Quark Production in the ACOT Scheme beyond NLO

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Outline

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  - extension beyond NLO
- Results for F_2 and F_L structure functions
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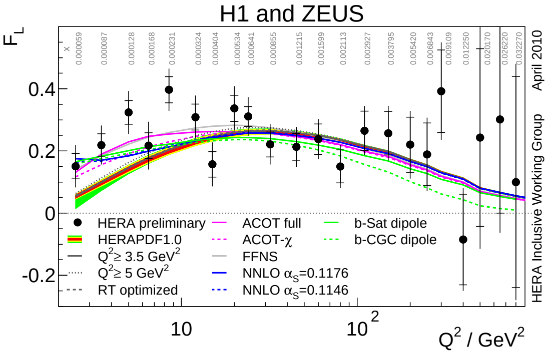
Motivations

- Increasing precision of experimental data requires also the progression in precision of theoretical calculations. One of the important theoretical aspects is the implementation of heavy quark schemes beyond NLO.
- Probably the most important cases for which it should be done is heavy quark production in inclusive DIS, as the very precise DIS HERA data form the backbone of any modern global analysis of PDFs.
- Extending the heavy quark schemes to higher orders is relevant for extracting precise PDFs, and hence for accurate predictions of observables at the LHC.

Motivations

An example where higher order corrections are particularly important is the longitudinal structure function F_L in DIS.



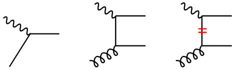
For massless quarks F_L vanishes in LO $\rightarrow$ first unsuppressed contribution is at NLO $\rightarrow$ the NNLO and N^{3}LO corrections are more important than for F_2.

ACOT scheme

ACOT scheme provides a mechanism to incorporate the heavy quark mass into the calculation of heavy quark production. It is based on heavy quarks factorization theorem of Collins.

The key ingredient of ACOT scheme is subtraction term (SUB), at NLO we have

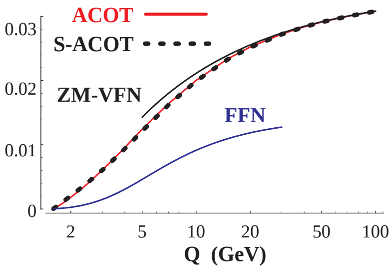
$$\sigma_{TOT} = \sigma_{LO} + \{\sigma_{NLO} - \sigma_{SUB}\}$$

for gluon-initiated processes: 

$$\sigma_{SUB} = f_g \otimes \tilde{P}_{g\to Q} \otimes \sigma_{QV\to Q}$$

$\tilde{P}_{g\to Q}$ is the $\overline{MS}$ splitting times the logarithm $\ln(\mu^2/m_Q^2)$

Limits of ACOT scheme



F_2^c at $x = 0.1$ for NLO DIS heavy quark production for different schemes:

- ACOT, S-ACOT,
- Fixed-Flavor-Number-Scheme (FFNS),
- Zero-Mass Variable-Flavor-Number-Scheme (ZM-VFNS)

- $\mu \lesssim m_Q$: ACOT $\rightarrow$ FFNS
  heavy quark is treated as extrinsic to hadron, $f_Q(x, \mu) = 0$
- $\mu \gtrsim m_Q$: ACOT $\rightarrow$ $\overline{MS}$ ZM-VFNS (exactly–**without** any finite renormalizations) quark mass m serves purely as a regulator – no dynamical role

ACOT scheme beyond NLO

ACOT is a factorization scheme valid to all orders so we can use it beyond NLO but we need massive Wilson coefficients.

Problem: they haven't been calculated.

The massless Wilson coefficients for F_2 and F_L structure functions are known at NNLO and even N^{3}LO.

Question: can we use these results, and the knowledge that ACOT reduces to the massless $\overline{MS}$ (ZM-VFNS) for $m_Q \to 0$, to estimate mass effects at NNLO and N^{3}LO?

Mass dependence in ACOT scheme

There are two ways heavy quark mass enters calculation of a cross section in ACOT scheme

- **dynamically** – through the mass dependent Wilson coefficients
- **kinematically** – restricting available phase space

$$\sigma = f\left(\xi(x, m_{kin}), Q\right) \otimes \hat{\sigma}_{QV}(m_{dyn})$$

We investigated numerically using full ACOT at NLO that the dominant contribution is given by the **kinematical** dependence.

Kinematic mass dependence

Restriction of the final state phase space is done by rescaling of Bjorken x variable.

For gluon initiated processes at NLO we have (for $c\bar{c}$ pair production)

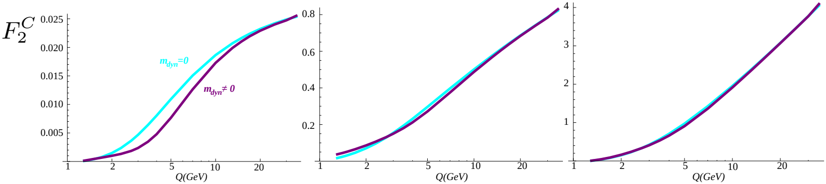
$$x \to x \left[1 + \left(\frac{2m_c}{Q}\right)^2\right]$$

It ensures that phase space is suppressed by twice the charm mass $(2m_c/Q)^2$

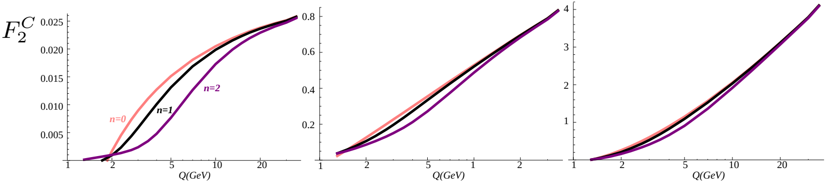
Dynamic vs. kinematic mass dependence

Comparison of F_2^c for NLO ACOT

dynamic: $\hat{\sigma}_{QV}(m_{dyn} = 0)$ vs. $\hat{\sigma}_{QV}(m_{dyn} \neq 0)$ (for $n = 2$)



kinematic: (for $m_{dyn} = 0$)



$x = 10^{-1}$ $x = 10^{-3}$ $x = 10^{-5}$

ACOT scheme beyond NLO

Partial solution is to incorporate kinematical effects in the massless calculations.

Obviously we cannot restore the fully massive ACOT result, but we can extract the dominant higher order contributions.

We introduce a generalized rescaling

$$x \to x \left[1 + \left(\frac{nm}{Q} \right)^2 \right]$$

where $n = 0$ is the massless result, $n = 1$ is the original Barnett rescaling, and $n = 2$ is the χ-rescaling – which we use.

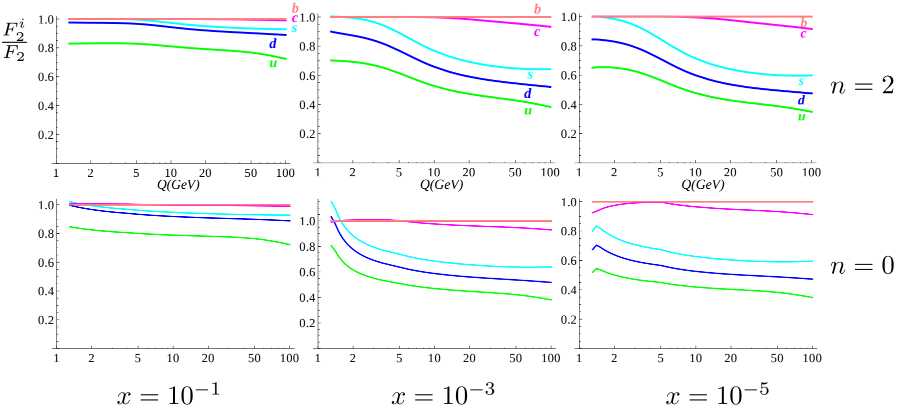
ACOT scheme beyond NLO

Our strategy:

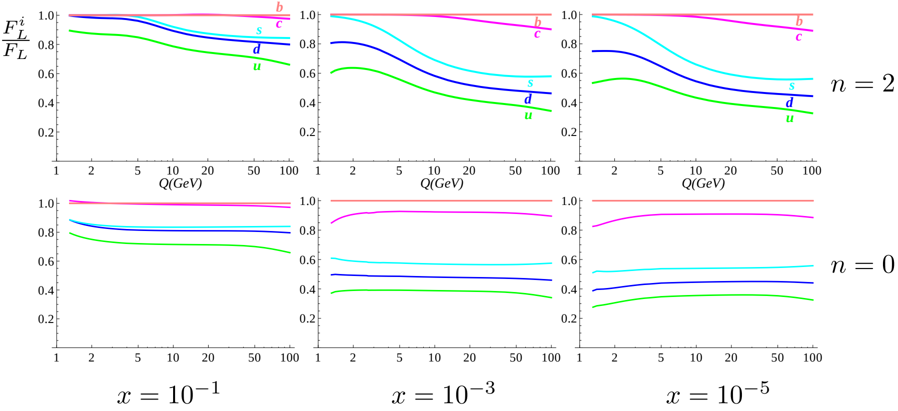
- use fully massive ACOT result to NLO,
- and add massless NNLO and N^3LO contributions with χ-rescaling.

Based on NLO study using full ACOT result the above prescription provides a good approximation of the exact result. At worst, the error is of order $\alpha\,\alpha_S^2 \times [m^2/Q^2]$.

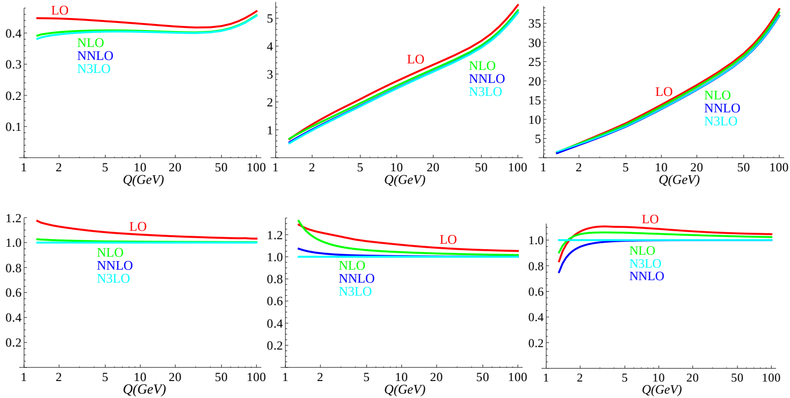
Fractional F_2^i contributions $i = \{u, d, s, c, b\}$ at N^{3}LO



Fractional F_L^i contributions $i = \{u, d, s, c, b\}$ at N^{3}LO

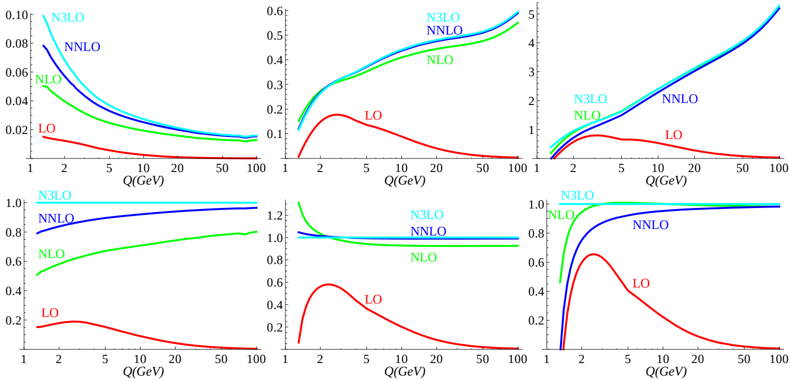


F_2 vs. Q at {LO, NLO, NNLO, N^{3}LO}



$x = 10^{-1}$ $\quad$ $x = 10^{-3}$ $\quad$ $x = 10^{-5}$

F_L vs. Q at {LO, NLO, NNLO, N^{3}LO}



$x = 10^{-1}$ $x = 10^{-3}$ $x = 10^{-5}$

Results

Perturbative calculations are stable and well behaved, uncertainties of the mass implementation seem to be under control.

The presented results suggests that our approximation is useful to include the dominant contributions from the higher orders.

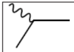
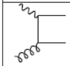
Of course when the full massive Wilson coefficients will be calculated including them in our approach is straightforward.

Summary

- We have computed the F_2 and F_L structure functions in the ACOT scheme at NNLO and N^{3}LO.
- The full mass dependence is computed to NLO, and the dominant mass effects for the higher orders are approximated using a generalized rescaling.
- This allows us to make detailed predictions throughout the kinematic range investigated by HERA, and we obtain a reasonable estimate of the uncertainty due to the higher order mass effects.
- Together with the precise HERA data, these calculations facilitate accurate determination of PDFs.

BACKUP SLIDES

General rescaling

ξ	General	$m_1 = 0$	$m_1 = m_2 = m$	χ-scheme:
	$\eta\left[\frac{Q^2 - m_1^2 + m_2^2 + \Delta[-Q^2, m_1^2, m_2^2]}{2Q^2}\right]$	$\eta\left[1 + \frac{m_2^2}{Q^2}\right]$	$\eta\left[1 + \frac{m^2}{Q^2}\right]$	$\eta\left[1 + \frac{(2m)^2}{Q^2}\right]$
	$\eta\left[1 + \left(\frac{m_1 + m_2}{Q}\right)^2\right]$	$\eta\left[1 + \frac{m_2^2}{Q^2}\right]$	$\eta\left[1 + \frac{(2m)^2}{Q^2}\right]$	$\eta\left[1 + \frac{(2m)^2}{Q^2}\right]$

$$\Delta[a, b, c] = \sqrt{a^2 + b^2 + c^2 - 2(ab + bc + ca)}$$

Initial state contributions to F_2

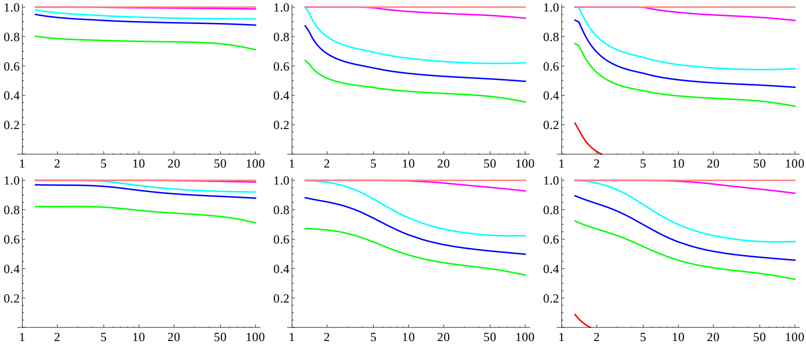


Figure: Fractional flavor decomposition of F_2^i/F_2 vs. Q for a) $x = 10^{-1}$, b) $x = 10^{-3}$ and c) $x = 10^{-5}$ for $n = 0$ (upper raw) and $n = 2$ (lower raw) scaling. Reading from the bottom, we plot the cumulative contributions for $\{g, u, d, s, c, b\}$, (green, blue, cyan, magenta, red).

Initial state contributions to F_L

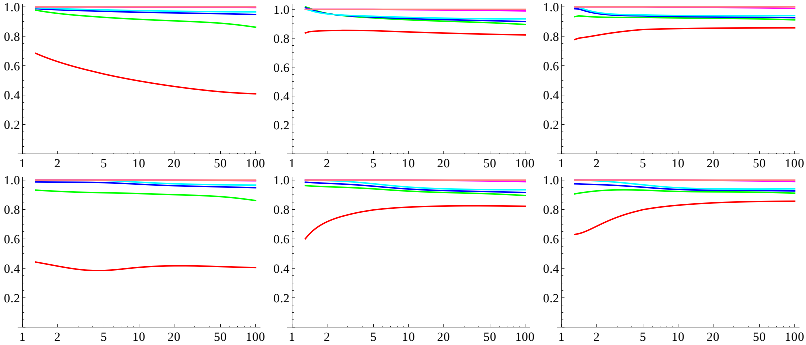


Figure: Fractional flavor decomposition of F_L^i/F_L vs. Q for a) $x = 10^{-1}$, b) $x = 10^{-3}$ and c) $x = 10^{-5}$ for $n = 0$ (upper raw) and $n = 2$ (lower raw) scaling. Reading from the bottom, we plot the cumulative contributions for $\{g, u, d, s, c, b\}$, (green, blue, cyan, magenta, red).