Universität Münster

Heavy-quark contributions to the DIS structure functions F_4 and F_5 at NLO in ACOT

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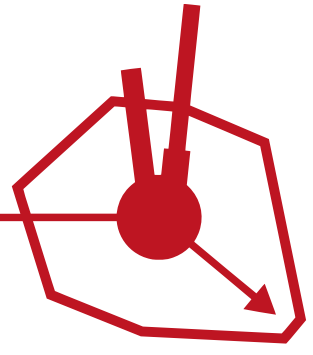
In collaboration with E. Spezzano, M. Klasen, P. Risse and I. Schienbein

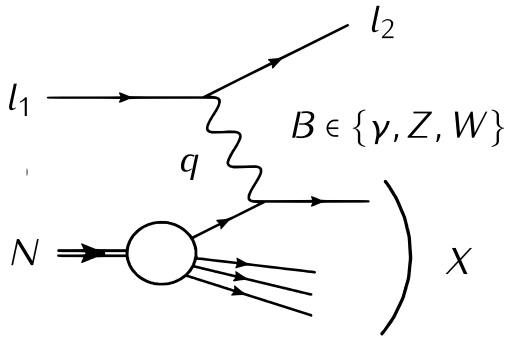
DIS2026



living.knowledge

Deep Inelastic Scattering with massive leptons

- Consider DIS



- With general lepton masses we get

$$\frac{d^2\sigma^{BB'}}{dx\,dy}(\lambda_1) = \frac{8S^2}{F^2}\frac{2\pi\alpha^2 y}{Q^4}\,\eta_{BB'}\,C^{BB'}\Bigg[(m_{l_1}^2 + m_{l_2}^2 + Q^2)\,F_1^{BB'} + \frac{Q^4(1-y) - x^2y^2M^2(m_{l_1}^2 + m_{l_2}^2 + Q^2)}{Q^2xy^2}\,F_2^{BB'}$$
$$-\lambda_1\,\frac{Q^2(2-y) + y(m_{l_1}^2 - m_{l_2}^2)}{2y}\,F_3^{BB'} + \frac{(m_{l_1}^2 - m_{l_2}^2)^2 + Q^2(m_{l_1}^2 + m_{l_2}^2)}{2Q^2}\,F_4^{BB'} - \frac{m_{l_1}^2(y-1) + m_{l_2}^2}{y}\,F_5^{BB'}\Bigg]$$

  - Note the appearance of new "mass-suppressed" structure functions F_4 and F_5
  - Relevance for future experiments involving the τ lepton

Deep Inelastic Scattering with massive leptons

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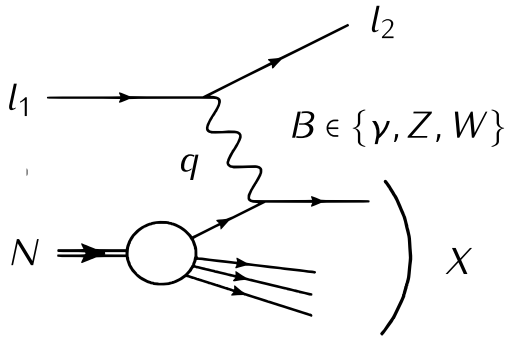

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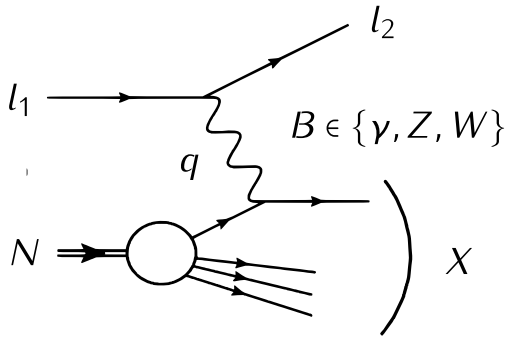
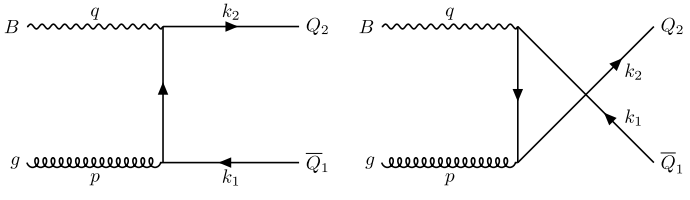
Deep Inelastic Scattering at NLO

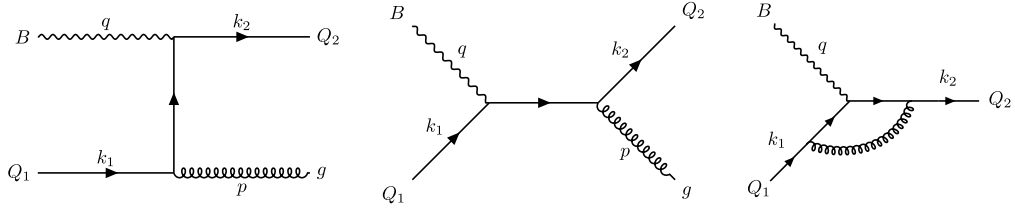
- Consider DIS at $\mathcal{O}(\alpha_S)$



- Contributions from Boson Gluon Fusion (GF) and Quark Gluon Scattering (QS)

$B(q) + g(p) \to \bar{Q}_1(k_1) + Q_2(k_2)$ $\qquad$ $B(q) + Q_1(k_1) \to Q_2(k_2)[+g(p)]$





- Light quark contributions are known, we consider massive contributions
  - Light → heavy, heavy → heavy, heavy → light with explicit mass dependence

Deep Inelastic Scattering at NLO

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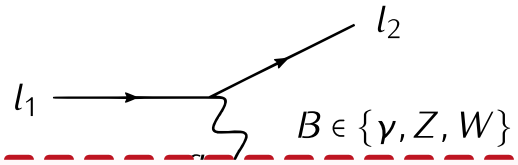
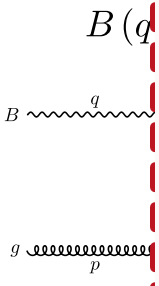
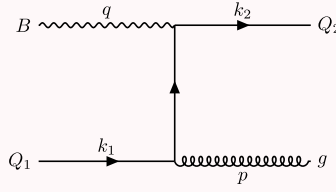


- Cont (QS)

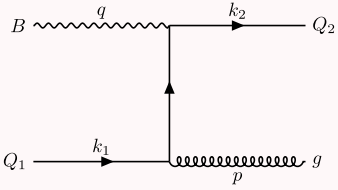


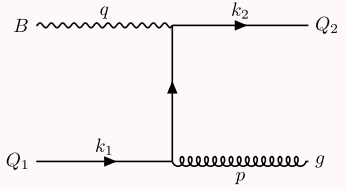
- Light

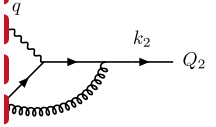
NC



CC





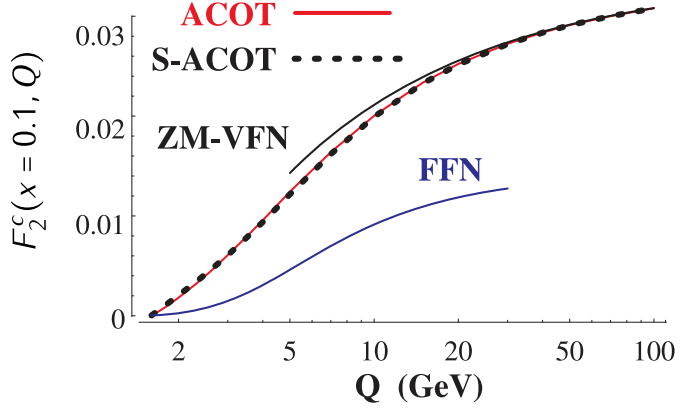


- ▹ Yes, that means massive partons in the initial state!

- Light → heavy, heavy → heavy, heavy → light with explicit mass dependence

Massive incoming partons & ACOT

- Keeping masses in the hard scattering is consistent with factorization
  - if the incoming parton is **projected collinear** to the hadron
  - the **collinear overlap** (the $g \to Q\overline{Q}$ contribution already resummed in the PDF) is **subtracted**
- ACOT scheme addresses this issue
  - interpolates between FFNS (massive quarks at low energy scales) and ZM-VFNS (quarks treated as light partons at high energies)



- $F^{\text{ACOT}} = F^{\text{GF}} + F^{\text{QS}} - F^{\text{SUB}}$
- ACOT redistributes the heavy quark effects between PDFs and matrix element

Results

- Calculate all contributions and implement them in `APFEL++`
- For example for CC we obtain:

$$F_i^{W^+} = \sum_U^{u,c,t} \sum_D^{d,s,b} |V_{UD}|^2 \left[C_{i,\mathrm{QS}}^{D\to U} \otimes D + C_{i,\mathrm{QS}}^{U\to D} \otimes \overline{U} + \left(C_{i,\mathrm{GF}}^{D\to U} + C_{i,\mathrm{GF}}^{U\to D} \right) \otimes g \right]$$

$$F_i^{W^-} = \sum_U^{u,c,t} \sum_D^{d,s,b} |V_{UD}|^2 \left[C_{i,\mathrm{QS}}^{D\to U} \otimes \overline{D} + C_{i,\mathrm{QS}}^{U\to D} \otimes U + \left(C_{i,\mathrm{GF}}^{D\to U} + C_{i,\mathrm{GF}}^{U\to D} \right) \otimes g \right]$$

with

$$C_{i,\mathrm{QS}}^{Q_1\to Q_2} = \mathcal{H}_i^{\mathrm{QS,LO}} + \frac{\alpha_s}{2\pi} \left(\mathcal{H}_i^{\mathrm{QS,NLO}} - \mathcal{H}_i^{\mathrm{QS,SUB}} \right)$$

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CKM

PDF

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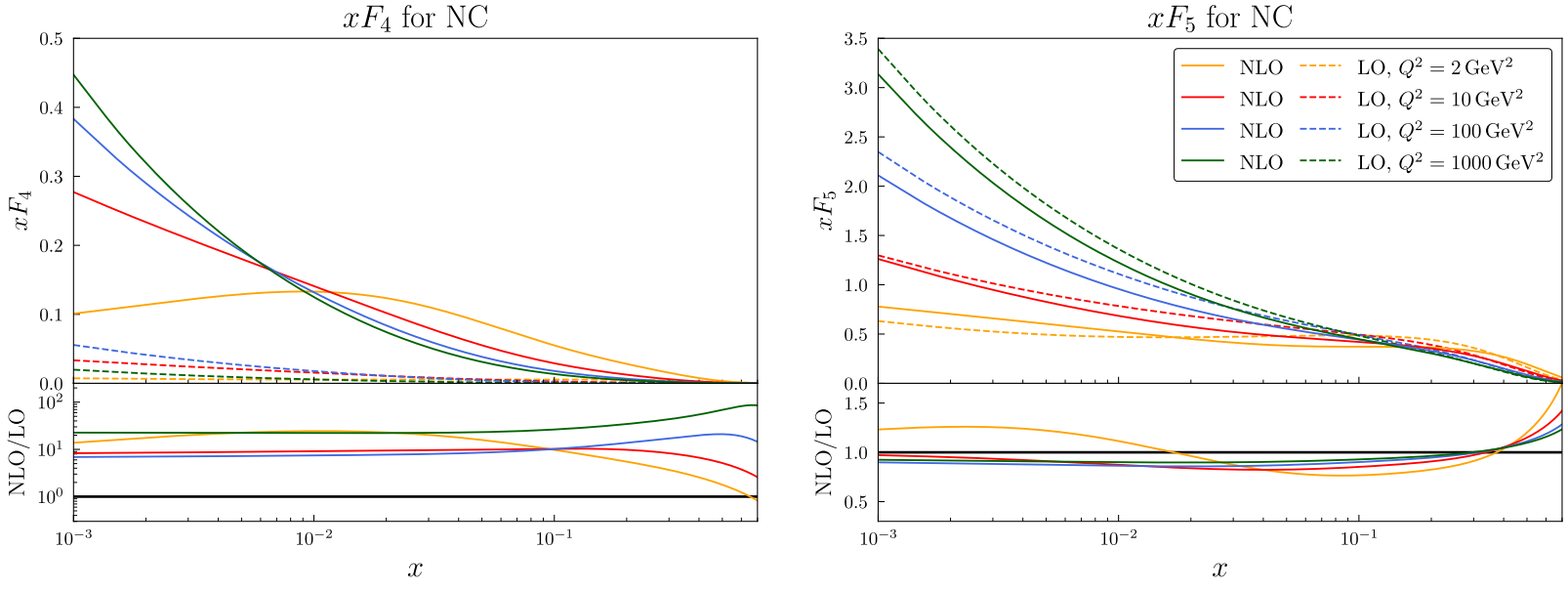
$$C_{i,\mathrm{GF}}^{Q_1\to Q_2} = \frac{\alpha_s}{2\pi} \left(\mathcal{H}_i^{\mathrm{GF,NLO}} - \mathcal{H}_i^{\mathrm{GF,SUB}} \right)$$

subtraction terms

Results

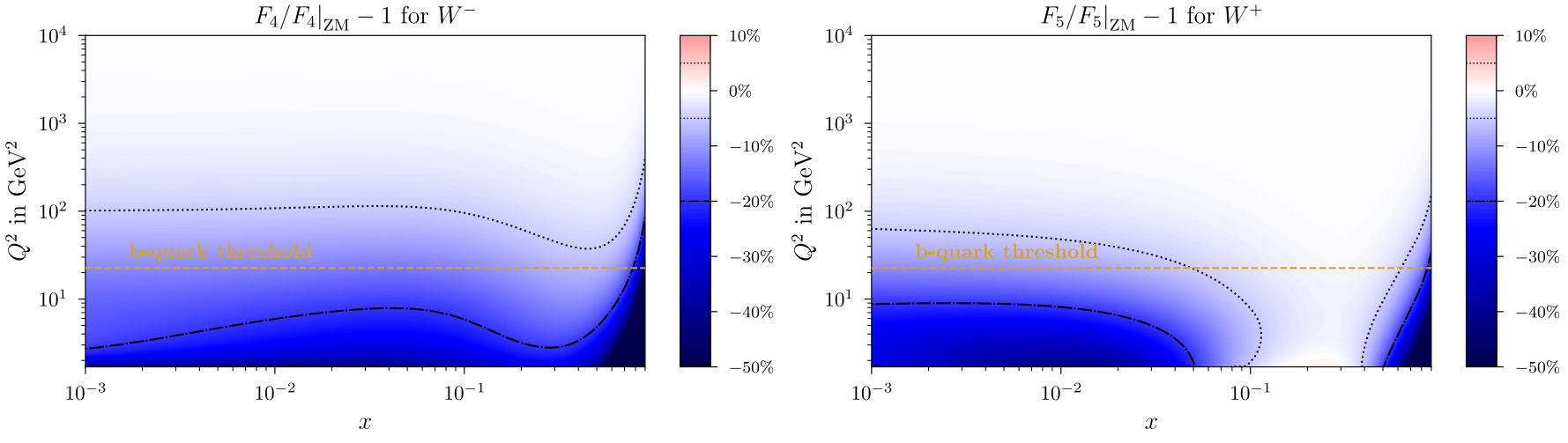
- Impact of higher order corrections



  - F_4 suppressed by quark mass at LO $\Rightarrow$ huge K-factor
  - Corrections to F_5 also substantial

Results

- Impact of heavy quark contribution



  - Mass effects very important at low Q

Summary

- Calculated unpolarised F_4 and F_5 for DIS with massive leptons (NC and CC)
- Included heavy-quark mass effects at NLO via gluon fusion and quark scattering
- Used ACOT scheme: collinear projection of incoming partons and subtraction of PDF overlap
- Implemented in APFEL++ across the full kinematic range
- Found large higher-order corrections for F_4 (suppressed at LO), while F_5 behaves similarly to F_2
- Mass effects significant at low Q^2, diminishing towards the high-energy limit
- Our predictions for polarised structure functions [2603.10593] submitted to JHEP