

## 1 Introduction

This work is mainly based on the paper “Complete  $O(\alpha_S)$  corrections to heavy-flavour structure functions in electroproduction” by Laenen et. al.[1] - that is, it recalculates all properties and formulas. It extends then the application to the equivalent *polarized* processes. The treating of the polarized processes can for example be found in [2] and we will use many ideas and technics from there. **FiXme Error: more**

FiXme  
Error!

### 1.1 Motivation

FiXme  
Error!

**FiXme Error: why do we do this**

### 1.2 Notation

To collect all soft and collinear poles we have to calculate in  $n = 4 + \epsilon$  dimension. Unfortunaly the extension for *polarized* processes is nontrivial, because the occuring Levi-Civita tensors  $\varepsilon_{\mu\nu\rho\sigma}$  and  $\gamma_5$ . A common choice to deal with these objects is the HVBM prescription[3] that keeps those two objects four dimensional at the price for splitting the full  $n$ -dimensional space into a  $(n - 4)$ -dimensional space, called “hat-space”, and a four-dimensional space (that is actually never used).

In leading order (LO) we have to consider the following processes

$$\gamma^*(q; \sigma_q) + g(k_1; \sigma_{k_1}) \rightarrow Q(p_1) + \bar{Q}(p_2) \quad (1)$$

The corresponding parton structure tensor  $W_{\mu\mu'}^{(0)}$ , can then be written as **FiXme Error: avoid all order expr?**

FiXme  
Error!

$$\begin{aligned} & W_{\mu\mu'}^{(0)}(k_1, q; s, t_1, u_1, q^2; \sigma_{k_1} \sigma_q) \\ &= \frac{1}{2} E_k(\epsilon) K_{g\gamma} \int \frac{d^{n-1} p_1}{2E_1 (2\pi)^{n-1}} \int \frac{d^{n-1} p_2}{2E_2 (2\pi)^{n-1}} \delta(p_1^2 - m^2) \delta(p_2^2 - m^2) \\ & \quad (2\pi)^n \delta^{(n)}(k_1 + q - p_1 - p_2) \mathcal{M}_{\mu}^{(0)}(\sigma_{k_1}, \sigma_q) \mathcal{M}_{\mu'}^{(0)}(\sigma_{k_1}, \sigma_q) \end{aligned} \quad (2)$$

where the initial  $1/2$  is the initial state spin average,  $K_{g\gamma}$  is the color average,

$$E_\epsilon := \begin{cases} 1/(1 + \epsilon/2) & \text{unpolarized} \\ 1 & \text{polarized} \end{cases} \quad (3)$$

accounts for initial freedom in  $n$  dimensions for bosons and we defined the following Mandelstam variables:

$$s = (q + k_1)^2, \quad t_1 = t - m^2 = (k_1 - p_2)^2 - m^2, \quad u_1 = u - m^2 = (q - p_2)^2 - m^2 \quad (4)$$

$$s' = s - q^2, \quad u'_1 = u_1 - q^2 \quad (5)$$

**FiXme Error: move to LO?** The Lorentz indices  $\mu$  and  $\mu'$  refer to the virtual photon that is exchanged with the scattering lepton.

FiXme  
Error!

By using Lorentz covariance, hermiticity, parity invariance and current conservation the parton structure tensor can be decomposed into several parts:

$$\begin{aligned} W_{\mu\mu'}(k_1, q; s, t_1, u_1, q^2; \sigma_{k_1}, \sigma_q) = & \left( -g_{\mu\mu'} + \frac{q_\mu q_{\mu'}}{q^2} \right) \frac{d^2 \sigma_T(s, t_1, u_1, q^2)}{dt_1 du_1} \\ & + \left( k_{1,\mu} - \frac{k_1 \cdot q}{q^2} q_\mu \right) \left( k_{1,\mu'} - \frac{k_1 \cdot q}{q^2} q_{\mu'} \right) \left( \frac{-4q^2}{s'^2} \right) \\ & \cdot \left( \frac{d^2 \sigma_T(s, t_1, u_1, q^2)}{dt_1 du_1} + \frac{d^2 \sigma_L(s, t_1, u_1, q^2)}{dt_1 du_1} \right) \end{aligned} \quad (6)$$

**FiXme Error: extend** We can then define appropriate projection operators[1, 4]:

FiXme  
Error!

$$\mathcal{P}_{G,\mu\mu'} = -g_{\mu\mu'} \quad b_G(\epsilon) = \frac{1}{2(1 + \epsilon/2)} \quad (7)$$

$$\mathcal{P}_{L,\mu\mu'} = -\frac{4q^2}{s'^2} k_{1,\mu} k_{1,\mu'} \quad b_L(\epsilon) = 1 \quad (8)$$

$$\mathcal{P}_{P,\mu\mu'} = i\varepsilon_{\mu\mu'\rho\rho'} \frac{q^\rho k_1^{\rho'}}{s'} \quad b_P(\epsilon) = 1 \quad (9)$$

**FiXme Error: justify avoidance of  $\Delta$ ?**

FiXme  
Error!

$$\frac{d^2 \sigma_k(s, t_1, u_1, q^2)}{dt_1 tu_1} = b_k(\epsilon) \mathcal{P}_{k,\mu\mu'} W^{\mu\mu'} \quad (10)$$

with  $k \in \{G, L, P\}$  denoting (here and mostly ever after) the projection type. The transverse partonic cross section  $d\sigma_T$  can be reconstructed from the above definitions by using

$$d\sigma_T = d\sigma_G + b_G(\epsilon) d\sigma_L \quad (11)$$

We also define accordingly

$$E_G(\epsilon) = E_L(\epsilon) = \frac{1}{1 + \epsilon/2} \quad E_P(\epsilon) = 1 \quad (12)$$

The final state spins are always summed over, but the initial spins have to be treated seperately: for unpolarized projections  $k \in \{G, L\}$  they are also summed over, but for polarized  $k = P$  they are combined as follows

$$\sum_{G,\sigma} f(\sigma_{k_1}, \sigma_q) = \sum_{L,\sigma} f(\sigma_{k_1}, \sigma_q) = f(+, +) + f(-, -) + f(+, -) + f(-, +) \quad (13)$$

$$\sum_{P,\sigma} f(\sigma_{k_1}, \sigma_q) = f(+, +) + f(-, -) - f(+, -) - f(-, +) \quad (14)$$

which keeps spin asymmetries well behaving.

When computing total partonic cross sections we define a set of partonic variables:

$$0 \leq \rho = \frac{4m^2}{s} \leq 1 \quad 0 \leq \beta = \sqrt{1 - \rho} \leq 1 \quad 0 \leq \chi = \frac{1 - \beta}{1 + \beta} \leq 1 \quad (15)$$

$$\rho_q = \frac{4m^2}{q^2} \leq 0 \quad 1 \leq \beta_q = \sqrt{1 - \rho_q} \quad 0 \leq \chi_q = -\frac{1 - \beta_q}{1 + \beta_q} \leq 1 \quad (16)$$

When computing Feynman diagrams a computer algebra system (CAS) is almost obligatory: common choices are **FORM**[5] or **Mathematica**[6] - for the later the most common choice is **TRACER**[7], but we have chosen **HEPMath**[8]. We used the Feynman rules given by [9]. **FiXme Error: explain ghosts?**

FiXme  
Error!

## 2 Leading Order Calculations

In leading order we have to consider photon-gluon-fusion (PGF), that is

$$\gamma^*(q; \sigma_q) + g(k_1; \sigma_{k_1}) \rightarrow Q(p_1) + \bar{Q}(p_2) \quad (17)$$

with two contributing diagrams depicted in figure **FiXme Error: todo**. The result can then be written as

FiXme  
Error!

$$\sum_{k, \sigma} \hat{\mathcal{P}}_k^{\mu\mu'} \sum_{j=1}^2 \mathcal{M}_{j, \mu}^{(0)}(\sigma_{k_1}, \sigma_q) \mathcal{M}_{j, \mu'}^{(0)*}(\sigma_{k_1}, \sigma_q) = 8g^2 e^2 e_H^2 N_C C_F B_{k, QED} \quad (18)$$

where  $g$  and  $e$  are the strong and electromagnetic coupling constants respectively and  $e_H$  is the magnitude of the heavy quark in units  $e$ . Further  $N_C$  corresponds to the gauge group  $SU(N_C)$  and the color factor  $C_F = (N_C^2 - 1)/(2N_C)$  refers to the second Casimir constant of the fundamental representation for the quarks. We then find:

$$B_{G, QED} = \frac{t_1}{u_1} + \frac{u_1}{t_1} + \frac{4m^2 s'}{t_1 u_1} \left( 1 - \frac{m^2 s'}{t_1 u_1} \right) + \frac{2s' q^2}{t_1 u_1} + \frac{2q^4}{t_1 u_1} + \frac{2m^2 q^2}{t_1 u_1} \left( 2 - \frac{s'^2}{t_1 u_1} \right) + \epsilon \left\{ -1 + \frac{s'^2}{t_1 u_1} + \frac{s' q^2}{t_1 u_1} - \frac{q^4}{t_1 u_1} - \frac{m^2 q^2 s'^2}{t_1^2 u_1^2} \right\} + \epsilon^2 \frac{s'^2}{4t_1 u_1} \quad (19)$$

$$B_{L, QED} = -\frac{4q^2}{s'} \left( \frac{s}{s'} - \frac{m^2 s'}{t_1 u_1} \right) \quad (20)$$

$$B_{P, QED} = \frac{1}{2} \left( \frac{t_1}{u_1} + \frac{u_1}{t_1} \right) \left( \frac{2m^2 s'}{t_1 u_1} - 1 - \frac{2q^2}{s'} \right) \quad (21)$$

By using eq. (2) we can derive the  $n$ -dimensional  $2 \rightarrow 2$  phase space

$$dPS_2 = \int \frac{d^n p_1}{(2\pi)^{n-1}} \frac{d^n p_2}{(2\pi)^{n-1}} \Theta(p_{1,0}) \delta(p_1^2 - m^2) \Theta(p_{2,0}) \delta(p_2^2 - m^2) (2\pi)^n \delta^{(n)}(k_1 + q - p_1 - p_2) \quad (22)$$

that can be solved by using the center-of-mass system (CMS) of the incoming particles[2]

$$q = \left( \frac{s+q^2}{2\sqrt{s}}, 0, 0, -\frac{s-q^2}{2\sqrt{s}}, \hat{0} \right) \quad k_1 = \frac{s-q^2}{2\sqrt{s}} (1, 0, 0, 1, \hat{0}) \quad (23)$$

such that  $q + k_1 = (\sqrt{s}, \vec{0})$  and  $k_1^2 = 0$ . For the outgoing particles it follows

$$p_1 = \frac{\sqrt{s}}{2} (1, 0, \beta \sin \theta, \beta \cos \theta, \hat{0}) \quad p_2 = \frac{\sqrt{s}}{2} (1, 0, -\beta \sin \theta, -\beta \cos \theta, \hat{0}) \quad (24)$$

such that  $p_1 + p_2 = (\sqrt{s}, \vec{0})$  and  $p_1^2 = p_2^2 = m^2$ . Finally we have to use the  $n$ -sphere

$$d^n x = \frac{2\pi^{n/2}}{\Gamma(n/2)} x^{n-1} dx = \frac{\pi^{n/2}}{\Gamma(n/2)} (x^2)^{(n-2)/2} dx^2 \quad (25)$$

and arrive at the well known result[1]

$$dPS_2 = \frac{\delta(s' + t_1 + u_1)}{2s'\Gamma((n-2)/2)(4\pi)^{(n-2)/2}} \left( \frac{(t_1 u'_1 - s' m^2)s' - q^2 t_1^2}{s'^2} \right)^{(n-4)/2} dt_1 du_1 \quad (26)$$

$$= \delta(s' + t_1 + u_1) h_2(n) dt_1 du_1 \quad (27)$$

$$h_2(4 + \epsilon) = \frac{2\pi S_\epsilon}{s'\Gamma(1 + \epsilon/2)} \left( \frac{(t_1 u'_1 - s' m^2)s' - q^2 t_1^2}{s'^2} \right)^{\epsilon/2} \quad (28)$$

with  $S_\epsilon = (4\pi)^{(-2-\epsilon/2)}$ .

The final double differential LO partonic cross section can then be written as

$$\begin{aligned} s'^2 \frac{d^2 \sigma_k^{(0)}(s', t_1, u_1, q^2)}{dt_1 du_1} &= 2^6 \alpha \alpha_s e_H^2 K_{g\gamma} N_C C_F E_k(\epsilon) b_k(\epsilon) \delta(s' + t_1 + u_1) \frac{\pi^3 S_\epsilon}{\Gamma(1 + \epsilon/2)} \\ &\quad \left( \frac{(t_1 u'_1 - s' m^2)s' - q^2 t_1^2}{m^2 s'^2} \right)^{\epsilon/2} \left( \frac{\mu_D^2}{m^2} \right)^{-\epsilon/2} B_{k,QED} \end{aligned} \quad (29)$$

where we used  $e^2 = 4\pi\alpha$  and  $g^2 = 4\pi\alpha_s$  and introduced the arbitrary mass parameter  $\mu_D$  to keep the strong coupling dimensionless. The color average is given by  $K_{g\gamma} = 1/(N_C^2 - 1)$ .

From the results above we can easily obtain the total LO partonic cross sections

$$\sigma_G^{(0)}(s', q^2) = -4\pi\alpha\alpha_s e_H^2 K_{g\gamma} N_C C_F \frac{1}{s'^3} \left( (s^2 + q^4 + 4m^2 s)\beta + (s^2 + q^4 - 4m^2(2m^2 - s')) \ln(\chi) \right) \quad (30)$$

$$\sigma_L^{(0)}(s', q^2) = 16\pi\alpha\alpha_s e_H^2 K_{g\gamma} N_C C_F \left( \frac{-q^2 s}{s'^3} \right) \left( \beta + \frac{2m^2}{s} \ln(\chi) \right) \quad (31)$$

$$\sigma_P^{(0)}(s', q^2) = 4\pi\alpha\alpha_s e_H^2 K_{g\gamma} N_C C_F \frac{1}{s'^2} \left( (3s + q^2)\beta + (s + q^2) \ln(\chi) \right) \quad (32)$$

from which we also see

$$\lim_{s \rightarrow 4m^2} \sigma_T^{(0)}(s', q^2) = 4\pi\alpha\alpha_s e_H^2 K_{g\gamma} N_C C_F \frac{\beta}{4m^2 - q^2} + O(\beta^3) = \lim_{s \rightarrow 4m^2} \sigma_P^{(0)}(s', q^2) \quad (33)$$

### 3 Next-To-Leading Order Calculations

Next-to-leading order contributions can be split into three parts: one loop virtual contributions, one gluon radiation and light quark processes. **FiXme Error: more?**

FiXme  
Error!

#### 3.1 One Loop Virtual Contributions

Virtual contributions have the same initial and final state as the Born process, but have a looping particle. All contributing Feynman diagrams are depicted in figure **FiXme Error: do**. The result can then be written as

FiXme  
Error!

$$\begin{aligned} & \sum_{k,\sigma} \hat{\mathcal{P}}_k^{\mu\mu'} \sum_j \left[ \mathcal{M}_{j,\mu}^{(1),V} \left( \mathcal{M}_{1,\mu'}^{(0)} + \mathcal{M}_{2,\mu'}^{(0)} \right)^* + c.c. \right] \\ & = 8g^4 \mu_D^{-\epsilon} e^2 e_H^2 N_C C_F C_\epsilon \left( C_A V_{k,OK} + 2C_F V_{k,QED} \right) \end{aligned} \quad (34)$$

where  $C_\epsilon = \exp(\epsilon/2(\gamma_E - \ln(4\pi)))/(16\pi^2)$  and  $C_A$  is the second Casimir constant of the adjoint representation for the gluon (that introduces a non-abelian part).

For the computation of the loops the Passarino-Veltman-decomposition[10] in  $n = 4 + \epsilon$  dimension is used as far as possible. The decomposition is based on Lorentz invariance and a good explanation is for example given in [2]. The needed scalar integrals are given in [11] and [1], but there is also one wrong integral: we find with [12, Box 16]:

$$\begin{aligned} & D_0(m^2, 0, q^2, m^2, t, s, 0, m^2, m^2, m^2) \\ & = \frac{iC_\epsilon}{\beta s t_1} \left[ -\frac{2\ln(\chi)}{\epsilon} - 2\ln(\chi) \ln(-t_1/m^2) + \text{Li}_2(1 - \chi^2) - 4\zeta(2) + \ln^2(\chi_q) + 2\text{Li}_2(-\chi\chi_q) \right. \\ & \quad \left. + 2\text{Li}_2(-\chi/\chi_q) + 2\ln(\chi\chi_q) \ln(1 + \chi\chi_q) + 2\ln(\chi/\chi_q) \ln(1 + \chi/\chi_q) \right] \end{aligned} \quad (35)$$

where we used the argument ordering of `LoopTools`[13, 14] (and also checked it against `LoopTools`).

As the short example above shows are the full expressions for the  $V_{k,OK}, V_{k,QED}$  quite complicated and too long to be presented here, nevertheless are the arising poles quite compact:

$$V_{k,OK} = -2B_{k,QED} \left( \frac{4}{\epsilon^2} + \left( \ln(-t_1/m^2) + \ln(-u_1/m^2) - \frac{2m^2 - s}{s} \ln(\chi) \right) \frac{2}{\epsilon} \right) + O(\epsilon^0) \quad (36)$$

$$V_{k,QED} = -2B_{k,QED} \left( 1 - \frac{2m^2 - s}{s} \ln(\chi) \right) \frac{2}{\epsilon} + O(\epsilon^0) \quad (37)$$

The above results already include the mass renormalization that we have performed *on-shell*, so all ultra-violet poles have been removed. For the renormalization of the strong

coupling we use the  $\overline{\text{MS}}_m$  scheme defined in [2] and so the full renormalization can be achieved by

$$\frac{d^2 \sigma_k^{(1),V,ren.}}{dt_1 du_1} = \frac{d^2 \sigma_k^{(1),V}}{dt_1 du_1} + \frac{\alpha_s(\mu_R^2)}{4\pi} \left[ \left( \frac{2}{\epsilon} + \gamma_E - \ln(4\pi) + \ln(\mu_R^2/m^2) - \ln(\mu_D^2/m^2) \right) \beta_0 + \frac{2}{3} \ln(\mu_R^2/m^2) \right] \frac{d^2 \sigma_k^{(0)}}{dt_1 du_1} \quad (38)$$

with  $\mu_R$  the renormalization scale introduced by the RGE,  $\beta_0 = (11C_A - 2n_f)/3$  the first coefficient of the beta function and  $n_f$  the number of *total* flavours (i.e.  $n_{lf} = n_f - 1$  active (light) flavours and one heavy flavour). The double poles occuring in  $V_{k,OK}$  are introduced by the diagrams **FiXme Error: do** when the soft and collinear singularities coincide.

FiXme  
Error!

The double differential partonic cross section is given by

$$s'^2 \frac{d^2 \sigma_k^{(1),V}(s', t_1, u_1, q^2)}{dt_1 du_1} = 2^8 \alpha_s^2 e_H^2 K_{g\gamma} N_C C_F E_k(\epsilon) b_k(\epsilon) \delta(s' + t_1 + u_1) \frac{\pi^4 S_\epsilon}{\Gamma(1 + \epsilon/2)} \left( \frac{(t_1 u'_1 - s' m^2) s' - q^2 t_1^2}{m^2 s'^2} \right)^{\epsilon/2} C_\epsilon \left( \frac{\mu_D^2}{m^2} \right)^{-\epsilon/2} (C_A V_{k,OK} + 2C_F V_{k,QED}) \quad (39)$$

### 3.2 Single Gluon Radiation

In next-to-leading order we have to consider the following process:

$$\gamma^*(q; \sigma_q) + g(k_1; \sigma_{k_1}) \rightarrow Q(p_1) + \bar{Q}(p_2) + g(k_2) \quad (40)$$

All contributing diagrams are depicted in figure **FiXme Error: do** and the result can be written as

FiXme  
Error!

$$\sum_{k,\sigma} \hat{\mathcal{P}}_k^{\mu\mu'} \sum_{j,j'} \mathcal{M}_{j,\mu}^{(1),g} \mathcal{M}_{j',\mu'}^{(1),g*} = 8g^4 \mu_D^{-2\epsilon} e^2 e_H^2 N_C C_F (C_A R_{k,OK} + 2C_F R_{k,QED}) \quad (41)$$

and it will depend on ten kinematical invariants:

$$s = (q + k_1)^2 \quad t_1 = (k_1 - p_2)^2 - m^2 \quad u_1 = (q - p_2)^2 - m^2 \quad (42)$$

$$s_3 = (k_2 + p_2)^2 - m^2 \quad s_4 = (k_2 + p_1)^2 - m^2 \quad s_5 = (p_1 + p_2)^2 = -u_5 \quad (43)$$

$$t' = (k_1 - k_2)^2 \quad (44)$$

$$u' = (q - k_2)^2 \quad u_6 = (k_1 - p_1)^2 - m^2 \quad u_7 = (q - p_1)^2 - m^2 \quad (45)$$

from which only five are independent as can be seen from momentum conservation  $k_1 + q = p_1 + p_2 + k_2$  and  $s, t_1, u_1$  match to their leading order definition.

The  $2 \rightarrow 3$   $n$ -dimensional phase space is given by

$$dPS_3 = \int \frac{d^n p_1}{(2\pi)^{n-1}} \frac{d^n p_2}{(2\pi)^{n-1}} \frac{d^n k_2}{(2\pi)^{n-1}} (2\pi)^n \delta^{(n)}(k_1 + q - p_1 - p_2 - k_2) \Theta(p_{1,0}) \delta(p_1^2 - m^2) \Theta(p_{2,0}) \delta(p_2^2 - m^2) \Theta(k_{2,0}) \delta(k_2^2) \quad (46)$$

This can be solved by writing eq. (46) as product of a  $2 \rightarrow 2$  decay and a subsequent  $1 \rightarrow 2$  decay [11]. We find

$$dPS_3 = \frac{1}{(4\pi)^n \Gamma(n-3) s'^1} \frac{s_4^{n-3}}{(s_4 + m^2)^{n/2-1}} \left( \frac{(t_1 u'_1 - s' m^2) s' - q^2 t_1^2}{s'^2} \right)^{(n-4)/2} dt_1 du_1 d\Omega_n d\hat{\mathcal{I}} \quad (47)$$

$$= h_3(n) dt_1 du_1 d\Omega_n d\hat{\mathcal{I}} \quad (48)$$

with  $d\Omega_n = \sin^{n-3}(\theta_1) d\theta_1 \sin^{n-4}(\theta_2) d\theta_2$  and  $d\hat{\mathcal{I}}$  taking care of all occuring hat momenta:

$$d\hat{\mathcal{I}} = \frac{1}{B(1/2, (n-4)/2)} \frac{x^{(n-6)/2}}{\sqrt{1-x}} dx \quad \text{with } x = \hat{p}_1^2 / \hat{p}_{1,max} \quad (49)$$

$$\hat{p}_{1,max} = \frac{s_4^2}{4(s_4 + m^2)} \sin^2(\theta_1) \sin^2(\theta_2) \quad (50)$$

$$\Rightarrow \int d\hat{\mathcal{I}} = 1 \quad \int d\hat{\mathcal{I}} \hat{p}_1^2 = \epsilon \hat{p}_{1,max} + O(\epsilon^2) \quad (51)$$

The needed phase space integrals for  $\theta_1$  and  $\theta_2$  can be found in [11] and [2]. We find for the difference to the  $2 \rightarrow 2$  phase space

$$\frac{h_3(4+\epsilon)}{h_2(4+\epsilon)} = \frac{S_\epsilon}{2\pi} \frac{\Gamma(1+\epsilon/2)}{\Gamma(1+\epsilon)} \frac{s_4^{1+\epsilon}}{(s_4 + m^2)^{1+\epsilon/2}} \quad (52)$$

$$= \frac{C_\epsilon}{2\pi} \left( 1 - \frac{3}{8} \zeta(2) \epsilon^2 \right) \frac{s_4^{1+\epsilon}}{(s_4 + m^2)^{1+\epsilon/2}} + O(\epsilon^3) \quad (53)$$

where  $\zeta$  is Riemanns zeta function. **FiXme Error: introduce psLogs? in appendix?** FiXme Error!

Again when integrating the phase space angles the expressions become quite lengthy, but the (collinear) pole parts are compact:

$$\frac{s_4}{4\pi(s_4 + m^2)} \int d\Omega_n d\hat{\mathcal{I}} C_A R_{k,OK} = -\frac{1}{u_1} B_{k,QED} \left( \begin{matrix} s' \rightarrow x_1 s' \\ t_1 \rightarrow x_1 t_1 \end{matrix} \right) P_{k,gg}^H(x_1) \frac{2}{\epsilon} + O(\epsilon^0) \quad (54)$$

with  $x_1 = -u_1/(s' + t_1)$  and the hard part of the Altarelli-Parisi splitting functions  $P_{k,gg}^H$  [15, 16]:

$$P_{G,gg}^H(x) = P_{L,gg}^H(x) = C_A \left( \frac{2}{1-x} + \frac{2}{x} - 4 + 2x - 2x^2 \right) \quad (55)$$

$$P_{P,gg}^H(x) = C_A \left( \frac{2}{1-x} - 4x + 2 \right) \quad (56)$$

The  $R_{k,QED}$  do not contain poles.

The double differential partonic cross section is given by

$$s'^2 \frac{d^2 \sigma_k^{(1),R}(s', t_1, u_1, q^2)}{dt_1 du_1} = 2^7 \alpha \alpha_s^2 e_H^2 K_{g\gamma} N_C C_F E_k(\epsilon) b_k(\epsilon) \frac{\pi^3 S_\epsilon^2}{\Gamma(1+\epsilon)} \frac{s_4}{s_4 + m^2} \left( \frac{(t_1 u'_1 - s' m^2) s' - q^2 t_1^2}{m^2 s'^2} \right)^{\epsilon/2} \left( \frac{s_4^2}{m^2 (s_4 + m^2)} \right)^{\epsilon/2} \left( \frac{\mu_D^2}{m^2} \right)^{-\epsilon} \int d\Omega_n d\hat{\mathcal{I}} (C_A R_{k,OK} + 2 C_F R_{k,QED}) \quad (57)$$

From the above expression we can obtain the soft limit  $k_2 \rightarrow 0$  and separate their calculations:

$$\lim_{k_2 \rightarrow 0} (C_A R_{k,OK} + 2 C_F R_{k,QED}) = (C_A S_{k,OK} + 2 C_F S_{k,QED}) + O(1/s_4, 1/s_3, 1/t') \quad (58)$$

$$S_{k,OK} = 2 \left( \frac{t_1}{t' s_3} + \frac{u_1}{t' s_4} - \frac{s - 2m^2}{s_3 s_4} \right) B_{k,QED} \quad (59)$$

$$S_{k,QED} = 2 \left( \frac{s - 2m^2}{s_3 s_4} - \frac{m^2}{s_3^2} - \frac{m^2}{s_4^2} \right) B_{k,QED} \quad (60)$$

Note that the einkonal factors multiplying the Born functions  $B_{k,QED}$  neither depend on  $q^2$  nor on the projection  $k$ . We can then split the phase space by introducing an infrared cut-off  $\Delta$  and distinguish then between soft  $s_4 \leq \Delta$  and hard  $s_4 > \Delta$  contributions. Let  $\mathcal{R}(s_4)$  be a function with a soft pole  $s_4^{-1+\epsilon} \mathcal{S}(s_4)$  and a finite part  $\mathcal{F}(s_4)$ , we then find [2]:

$$\int_0^{s_{4,max}} \mathcal{R}(s_4) = \int_0^{s_{4,max}} \left( s_4^{-1+\epsilon} \mathcal{S}(s_4) + \mathcal{F}(s_4) \right) \quad (61)$$

$$\simeq \frac{\Delta^\epsilon}{\epsilon} \mathcal{S}(0) + \int_\Delta^{s_{4,max}} \mathcal{R}(s_4) \quad (62)$$

This expansion is valid for  $\Delta$  being small, i.e. smaller than any leading order scale or  $m^2$ ;



a typical choice is  $\Delta/m^2 \sim 10^{-6}$ . We then find

$$\begin{aligned} & \frac{s_4^2}{4\pi(s_4 + m^2)} \left(1 - \frac{3}{8}\zeta(2)\epsilon^2\right) \int d\Omega_n d\hat{\mathcal{L}} S_{k,QED} \\ &= B_{k,QED} \left[ -\frac{2}{\epsilon} \left(1 + \frac{s - 2m^2}{s\beta} \ln(\chi)\right) + 1 - \frac{s - m^2}{s\beta} \left(\ln(\chi)(1 + \ln(\chi)) + \text{Li}_2(1 - \chi^2)\right) \right] \end{aligned} \quad (63)$$

$$\begin{aligned} & \frac{s_4^2}{4\pi(s_4 + m^2)} \left(1 - \frac{3}{8}\zeta(2)\epsilon^2\right) \int d\Omega_n d\hat{\mathcal{L}} S_{k,OK} \\ &= B_{k,QED} \left[ \frac{4}{\epsilon^2} + \frac{2}{\epsilon} \left(\ln(t_1/u_1) + \frac{s - 2m^2}{s\beta} \ln(\chi)\right) - \ln^2(\chi) - \frac{3}{2}\zeta(2) + \frac{1}{2} \ln^2(t_1/(u_1\chi)) \right. \\ & \quad \left. + \text{Li}_2(1 - t_1/(u_1\chi)) - \text{Li}_2(1 - u_1/(t_1\chi)) + \frac{s - 2m^2}{s\beta} \left(\text{Li}_2(1 - \chi^2) + \ln^2(\chi)\right) \right] \end{aligned} \quad (64)$$

(Note the mistyped sign of  $\ln(\chi)^2$  in [1, eq. (3.25)]) The additional factors originate from the difference between the  $2 \rightarrow 3$  phasespace of  $R_k$  and the  $2 \rightarrow 2$  phasespace needed for  $S_k$ .

The double differential partonic cross section is given by

$$\begin{aligned} & s'^2 \frac{d^2 \sigma_k^{(1),S}(s', t_1, u_1, q^2)}{dt_1 du_1} \\ &= 2^8 \alpha_s^2 e_H^2 K_{g\gamma} N_C C_F E_k(\epsilon) b_k(\epsilon) \delta(s' + t_1 + u_1) \frac{\pi^4 S_\epsilon}{\Gamma(1 + \epsilon/2)} \\ & \quad \left( \frac{(t_1 u'_1 - s' m^2) s' - q^2 t_1^2}{m^2 s'^2} \right)^{\epsilon/2} C_\epsilon \left( \frac{\mu_D^2}{m^2} \right)^{-\epsilon} \left( \frac{\Delta}{m^2} \right)^\epsilon \\ & \quad \frac{s_4^2}{4\pi(s_4 + m^2)} \left(1 - \frac{3}{8}\zeta(2)\epsilon^2\right) \int d\Omega_n d\hat{\mathcal{L}} (C_A S_{k,OK} + 2C_F S_{k,QED}) \end{aligned} \quad (65)$$

### 3.3 Light Quark Processes

In next-to-leading order a new production mechanism enters, that is induced by a light quark, so we have to consider the process

$$\gamma^*(q; \sigma_q) + q(k_1; \sigma_{k_1}) \rightarrow Q(p_1) + \bar{Q}(p_2) + q(k_2) \quad (66)$$

All contributing diagrams are depicted in figure **FiXme Error: do** and the result can be written as

FiXme  
Error!

$$\sum_{k,\sigma} \hat{\mathcal{P}}_k^{\mu\mu'} \sum_{j,j'} \mathcal{M}_{j,\mu}^{(1),q} \mathcal{M}_{j',\mu'}^{(1),q*} = 8g^4 \mu_D^{-2\epsilon} e^2 N_C C_F \left( e_H^2 A_{k,1} + e_L^2 A_{k,2} + e_L e_H A_{k,3} \right) \quad (67)$$

where  $e_L$  denotes the charge of the light quark  $q$  in units of  $e$ .

The needed  $2 \rightarrow 3$  phase space has already been calculated in section 3.2, so we can immediately quote the (collinear) poles:

$$\frac{s_4}{2\pi(s_4 + m^2)} \int d\Omega_n d\hat{\mathcal{I}} C_F A_{k,1} = -\frac{1}{u_1} B_{k,QED} \left( \frac{s' \rightarrow x_1 s'}{t_1 \rightarrow x_1 t_1} \right) P_{k,gq}(x_1) \frac{2}{\epsilon} + O(\epsilon^0) \quad (68)$$

with  $x_1 = -u_1/(s' + t_1)$  and the Altarelli-Parisi splitting functions  $P_{k,gq}$  [15, 16]:

$$P_{G,gq}(x) = P_{L,gq}(x) = C_F \left( \frac{1}{x} + \frac{(1-x)^2}{x} \right) \quad (69)$$

$$P_{P,gq}(x) = C_F (2-x) \quad (70)$$

$A_{k,2}$  does not contain poles and we find  $\int d\Omega_n d\hat{\mathcal{I}} A_{k,3} = 0$ . Note that in the limit  $q^2 \rightarrow 0$   $A_{k,2}$  will also get collinear poles.

The double differential partonic cross section is given by

$$\begin{aligned} s'^2 \frac{d^2 \sigma_k^{(1),q}(s', t_1, u_1, q^2)}{dt_1 du_1} &= 2^7 \alpha \alpha_s^2 K_{q\gamma} N_C C_F b_k(\epsilon) \frac{\pi^3 S_\epsilon^2}{\Gamma(1+\epsilon)} \frac{s_4}{s_4 + m^2} \\ &\quad \left( \frac{(t_1 u'_1 - s' m^2) s' - q^2 t_1^2}{m^2 s'^2} \right)^{\epsilon/2} \left( \frac{s_4^2}{m^2 (s_4 + m^2)} \right)^{\epsilon/2} \left( \frac{\mu_D^2}{m^2} \right)^{-\epsilon} \\ &\quad \int d\Omega_n d\hat{\mathcal{I}} \left( e_H^2 A_{k,1} + e_L^2 A_{k,2} + e_H e_L A_{k,3} \right) \end{aligned} \quad (71)$$

with the color average  $K_{q\gamma} = 1/N_C$ .

## 4 Mass Factorization

FiXme  
Error!

FiXme Error: do

## 5 Partonic Results

FiXme  
Error!

FiXme Error: do

## 6 Hadronic Results

FiXme  
Error!

FiXme Error: do

## 7 Summary

FiXme Error: do

FiXme  
Error!

## A References

- [1] E. Laenen, S. Riemersma, J. Smith, and W. van Neerven, “Complete  $O(\alpha_S)$  corrections to heavy-flavour structure functions in electroproduction,” Nuclear Physics B **392** no. 1, (1993) 162 – 228.  
<http://www.sciencedirect.com/science/article/pii/055032139390201Y>.
- [2] I. Bojak,  
NLO QCD corrections to the polarized photoproduction and hadroproduction of heavy quarks.  
PhD thesis, Dortmund U., 2000. [arXiv:hep-ph/0005120](https://arxiv.org/abs/hep-ph/0005120) [hep-ph].
- [3] P. Breitenlohner and D. Maison, “Dimensional renormalization and the action principle,” Comm. Math. Phys. **52** no. 1, (1977) 11–38.  
<http://projecteuclid.org/euclid.cmp/1103900439>.
- [4] W. Vogelsang,  
Tests and signatures of spin dependent parton distributions in leading and next-to-leading order o  
PhD thesis, Dortmund U., 1993.  
<http://alice.cern.ch/format/showfull?sysnb=0171841>.
- [5] J. A. M. Vermaseren, “New features of FORM,” [arXiv:math-ph/0010025](https://arxiv.org/abs/math-ph/0010025) [math-ph].
- [6] S. Wolfram, “Mathematica.” Wolfram research, 1997. Ver. 3 or higher.
- [7] M. Jamin and M. E. Lautenbacher, “TRACER version 1.1: A mathematica package for  $\gamma$ -algebra in arbitrary dimensions,” Computer Physics Communications **74** no. 2, (1993) 265 – 288.  
<http://www.sciencedirect.com/science/article/pii/001046559390097V>.
- [8] M. Wiebusch, “HEPMath 1.4: A Mathematica Package for Semi-Automatic Computations in High Energy Physics,” Computer Physics Communications **195** (Oct., 2015) 172–190. <http://arxiv.org/abs/1412.6102>. [arXiv: 1412.6102](https://arxiv.org/abs/1412.6102).
- [9] E. Leader and E. Predazzi, An introduction to Gauge theories and modern particle physics. Univ. Pr., Cambridge.
- [10] G. Passarino and M. J. G. Veltman, “One Loop Corrections for  $e^+ e^-$  Annihilation Into  $\mu^+ \mu^-$  in the Weinberg Model,” Nucl. Phys. **B160** (1979) 151.
- [11] Beenakker, W. and Kuijf, H. and van Neerven, W. L. and Smith, J., “Qcd corrections to heavy-quark production in  $p\bar{p}$  collisions,” Phys. Rev. D **40** (Jul, 1989) 54–82. <http://link.aps.org/doi/10.1103/PhysRevD.40.54>.
- [12] R. K. Ellis and G. Zanderighi, “Scalar one-loop integrals for QCD,” JHEP **02** (2008) 002, [arXiv:0712.1851](https://arxiv.org/abs/0712.1851) [hep-ph].
- [13] T. Hahn and M. Perez-Victoria, “Automatized one loop calculations in four-dimensions and D-dimensions,” Comput. Phys. Commun. **118** (1999) 153–165, [arXiv:hep-ph/9807565](https://arxiv.org/abs/hep-ph/9807565) [hep-ph].

- [14] T. Hahn, “LoopTools 2.12 User’s Guide.” <http://www.feynarts.de/looptools/>, 2014.
- [15] G. Altarelli and G. Parisi, “Asymptotic Freedom in Parton Language,” Nucl. Phys. **B126** (1977) 298–318.
- [16] W. Vogelsang, “A Rederivation of the spin dependent next-to-leading order splitting functions,” Phys. Rev. **D54** (1996) 2023–2029, [arXiv:hep-ph/9512218](#) [hep-ph].

## List of Corrections

Error: more . . . . .	1
Error: why do we do this . . . . .	1
Error: avoid all order expr? . . . . .	1
Error: move to LO? . . . . .	2
Error: extend . . . . .	2
Error: justify avoidance of $\Delta$ ? . . . . .	2
Error: explain ghosts? . . . . .	3
Error: todo . . . . .	3
Error: more? . . . . .	5
Error: do . . . . .	5
Error: do . . . . .	6
Error: do . . . . .	6
Error: introduce psLogs? in appendix? . . . . .	7
Error: do . . . . .	9
Error: do . . . . .	10
Error: do . . . . .	10
Error: do . . . . .	10
Error: do . . . . .	11