

# THESIS

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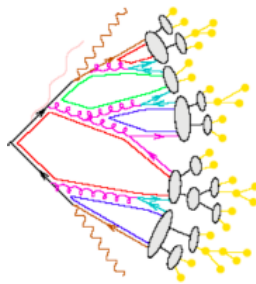
TIGRAN SAIDNIA

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## Emission kernels of parton shower in NLO

Emission kernel of parton shower in NLO

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statement of originality

I hereby confirm that I have written the accompanying thesis by myself, without contributions from any sources other than those cited in the text and acknowledgements. This applies also to all graphics, drawings, maps and images included in the thesis.

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# Abstract

Infra red divergences come in two flavours: soft, due to the massless nature of the radiation (e.g. the massless photon in QED), and collinear, which comes from treating the radiating particle as massless. By the Catani-Seymour dipole factorization a  $m+1$ -parton matrix element can be written as product of  $m$ -parton matrix element and an universal singular splitting function. In this work a mapping for  $3 \rightarrow 2$  will be outlined and following along those lines one for  $m+1 \rightarrow m$  is proposed, which is explicitly evaluated for the quadratic matrix elements in terms of the four possible parton splitting in the soft and collinear regions. Furthermore, a general prescription for the simplification of the usage of this algorithm in the next-to-leading order (NLO) level will also be given. For comparison, the known result from the  $e^+e^- \rightarrow q\bar{q}g$  process is compared with the result of the gluon radiation from a parton quark in the first part of chapter 4. The algorithm is straightforwardly implementable in general purpose Mathematica or Herwig++ [1].

# Zusammenfassung

Infrarot-Divergenzen gibt es in zwei Varianten: soft, aufgrund der masselosen Natur der Emission (z.B. das masselose Photon in QED), und kollinear, das von der Behandlung des strahlenden Partikels als masselos verursacht wird. Durch die Catani-Seymour Dipolfaktorisierung kann ein  $m+1$ -Partonmatrixelement als Produkt aus einem  $m$ -Parton Matrixelement und einer universellen singulären Splittingfunktion geschrieben werden. In dieser Arbeit wird eine Mapping für  $3 \rightarrow 2$  und ebenso für eine  $m+1 \rightarrow m$  präsentiert, die dann explizit bei der Auswertung der Matrixelemente der vier möglichen Partonsplittings in den soft und kollinearen Bereichen eingesetzt wird. Vielmehr wird eine allgemeine Prozedur für die Vereinfachung dieses Algorithmusses in der Next-to-Leading Order (NLO) Ebene vorgeschlagen. Zum Vergleich wird das bekannte Ergebnis aus  $e^+e^- \rightarrow q\bar{q}g$  Prozess mit dem Ergebnis der Gluonenabstrahlung eines Parent-Quarks aus dem ersten Teil vom Kapitel 4 verglichen. Der Algorithmus kann in Mathematica oder Herwig++ [1] implementiert werden.



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# 1 Introduction

Knowledge is a human need. For thousands of years we have been trying to understand the secrets of the universe. Such riddles fascinated even Johann Wolfgang von Goethe, as he wrote in his book *Faust* [15]; eine Tragedie, "What holds the world together in its innermost." Almost 400 years before Christ, an ancient Greek philosopher, Democritus, and his teacher Leukipp claimed matter can not be divided at will. Rather, there must be an Atomos (Greek: indivisible) that could no longer be subdivided. Democritus was of the opinion that there were infinitely many atoms with different geometric forms that were in contact in a certain way. He pointed out that a thing has a color, taste or even soul, based on the apparent effect of the composition of these small grains. [4]

This statement of Democritus was first laughed at by the renowned philosopher Aristotiles. It took about 2000 years for a chemist named John Dalton to deal with the subject. Based on various test series, he summarized his conclusion in his book *A New System of Chemical Philosophy*, that all substances consist of spherical indivisible atoms. The atoms of different elements have different masses and volumes. This was exactly the most striking difference to Democritus's atomic world.[7]

The discovery of the periodic system by D. Mendeleev and P. Meyer enabled us to arrange the atoms according to their mass in such a way that their properties occur in a certain order.[18]

In 1897 Joseph Thompson was able to obtain a stream of particles by heating metals and deflecting them by a magnetic field. This electron beam was 200 times lighter than the lightest atom, hydrogen. His conclusion was that atoms cannot be indivisible. He suggested that each atom consists of an electrically positively charged sphere in which electrically negatively charged electrons are stored - like raisins in a cake.

furthermore, renowned scientists as well as Marie and Pierre Curie have contributed much to the development of atomic theory by discovering radioactivity, Boltzmann by kinetic gas theory and Plank, the founder of quantum physics. However, one of the most important steps in the atomic model was taken by the British physicist Rutherford. He bombarded a thin aluminium foil with a radioactive sample. If Thompson's cake model were correct, only a few alpha particles would be detected behind the aluminium foil. Surprisingly, many particles were visible, which could only be explained by the assumption that the majority of atoms consisted of empty spaces. Another miracle was that some particles could be seen above or below the target sample. Since it is known, the alpha particles are positively charged, it could be assumed the electric repulsive force of two positive charges. From the ideas of Planck and Rutherford, the Danish physicist Bohr (1885-1962) developed a planetary atomic model. The electrons then move around the nucleus in certain orbits, like planets orbit the sun. The orbits are also called shells. The special

thing about it was that the distances of the electron orbits follow strict mathematical laws.

At first, however, it remained unclear what this core should consist of. [8, 18] In 1912, the Austrian physicist Victor Hess discovered during his balloon flights that the ionization rate of the Earth's atmosphere increases with altitude. This result was not expected because until then the Earth's radioactivity was known as the only source of air ionization. Therefore, he postulated this new type of radiation as cosmic radiation, which must originate outside the Earth's atmosphere [11].

Further investigations two years later confirmed the thesis of a cosmic background of such radiation. After this new discovery, it was discovered that the radiation consists of charged particles. In 1932, the American physicist Carl David Anderson was able to prove the postulated particle of Dirac, the positron, as a component of an air shower through his cloud chamber. For a long time, cosmic rays were the only way to analyse such exotic particles.[2] This changed when particle accelerators were able to generate particles in collisions. But even today, cosmic rays are the only way to study particles of the highest energies, since these energies cannot be reached by today's particle accelerators, such as the LHC. The LHC, the world's largest accelerator at CERN, produces particles with centre-of-mass energy equivalent to a cosmic particle of nearly  $10^{17}eV$ , with the energy spectrum of cosmic particles reaching up to  $10^{20}eV$ . However, we can only analyse such exotic particles in detail by increasing the luminosity and proccession of the particle accelerators at the nucleus. The discovery of the neutron by Chadwick (1932) showed that atomic nuclei are made up of protons and neutrons. It was also clear that, in addition to gravitation and the electromagnetic force, there should exist two short-range forces in nature; a strong force which binds the nucleons together and a weak force which is responsible for radioactive. In the meantime it was agreed that a new theory was needed for the classification and grouping of this particle zoo. This is how the current standard model came into being.

The SLAC experiments indicate that the electrons can be scattered as quasi-free point-like constituents within the proton structure, which actually meant that the protons or neutrons are not point-like and must consist of other constituents. Through the bubble chamber a huge number of previously invisible particles (Gell-Mann's eightfold path) could suddenly be made visible, which represented contradictions to the previous physics. To explain this, the physicist Gell-Mann found basic building blocks from which all previously known atomic particles should be built. The components are later identified with quarks. For the results of particle physics experiments in connection with the strong interaction the perturbation theory is used. In order to make useful and more accurate predictions, the calculations must be carried out at least in next-to-leading order, in order to avoid large uncertainties arising from the non-physical scale dependencies. In this work, the dipole subtraction method will be used for calculating next-to-leading order splitting functions of parton shower in QCD.

The thesis begins with the Feynmann Rules and Colour Algebra in chapter 2 which are later used for the evaluation of the matrix elements. Chapter 3 provides a brief overview of the general method, describing the subtraction procedure and presenting the dipole formulae. Thereafter, the kinematics for the case of massless partons with the useful prescriptions for the matrix elements evaluation are discussed. The factorization properties of QCD matrix elements in the soft and collinear limits for four possible parton

shower due to parametrisations is outlined in 4. The known result from the  $e^+e^- \rightarrow q\bar{q}g$  process is compared with the result of the gluon radiation from a parton quark in the first part of chapter 4 in chapter 5. Chapter 6 represents a summary of the previous final results that were obtained. MATHEMATICAL TOOLS 6 gives more details, and some examples, of the necessary mathematical formulae for the handling of parametrisations. All detailed steps of the calculations can be found in the appendix 6.



## 2 Prerequisites

The Standard Model in particle physics encompasses all of the Elementary particles and their interactions. It is a gauge theory spontaneously broken by the Higgs mechanism with the gauge group  $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ .

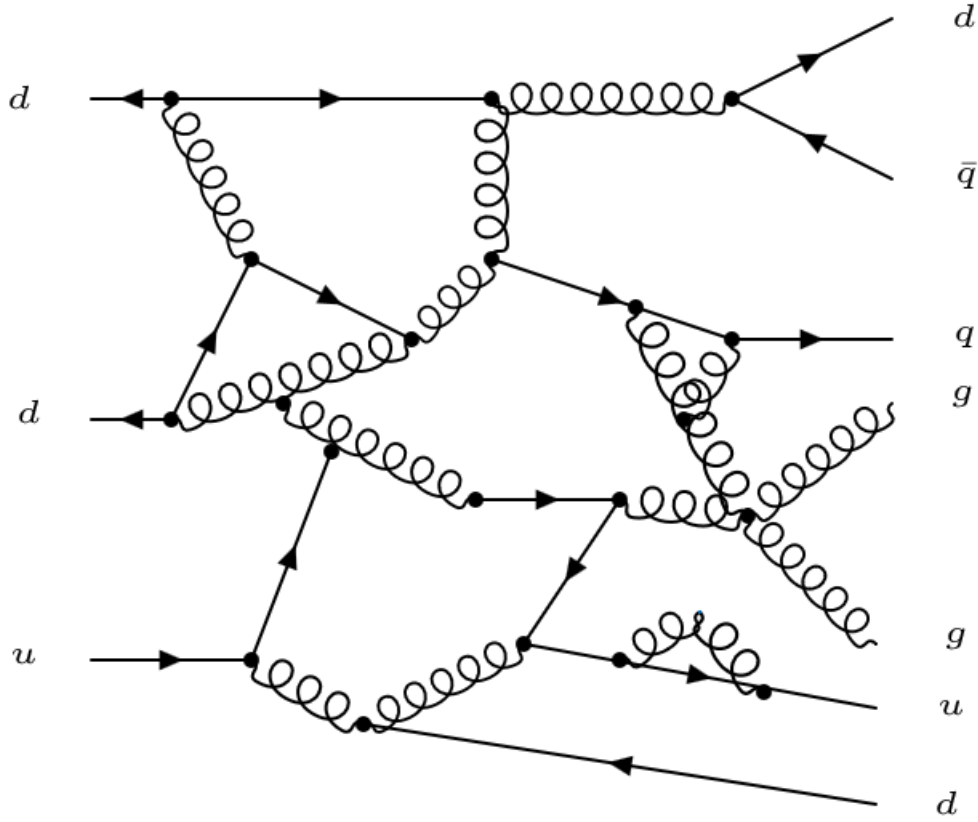
From a theoretical point of view, the Standard Model is a quantum field theory based on local gauge invariance and consists of two rough parts. The electroweak sector  $SU(2)_L \otimes U(1)_Y$  is called GWS (Glashow-Weinberg-Salam) theory and describes the gauge bosons  $W^\pm, Z^0, \gamma$ , the Higgs sector and its interaction with the leptons and quarks. In contrast to the other gauge bosons, the exchange particles of the weak interaction carry mass, which also affects the properties of the interactions. The color-charged sector  $SU(3)_C$ , the chromodynamics, deals with quarks and contains the eight massless, electrically neutral gluons as gauge bosons. The gauge groups  $SU(3)_C$  and  $SU(2)_L$  are non-abel gauge theories, more precisely Yang Mills theories. The massive particles, fermions, will be divided into two groups, leptons and quarks. Each group is arranged in 3 generations. Within the leptons there are three electrically neutral neutrinos. The mass of the particles increases from generation to generation. Neutrinos only interact weakly, whereas the charged leptons interact both weakly and electromagnetically. Quarks are characterized by the fact that they can also interact strongly [9].

### 2.1 Quantum chromo dynamics

Overall, there are four types of interactions.

Interaction	Energy scale	Range [m]	Mediators
Strong	$\sim 1$	$10^{-15}$	$g$
Electromagnetic	$\sim 10^{-2}$	$\infty$	$\gamma$
Weak	$\sim 10^{-6}$	$10^{-18}$	$W^\pm, Z$
Gravity	$\sim 10^{-38}$	$\infty$	maybe graviton

Nucleons are made up of quark and gluons called partons. Whereby, the gluons are the exchange bosons for this short ranged interaction. To explain the short range of the strong interaction Yukawa (1934) postulated mesons as a mediator for the nuclear force by the exchange of this massive field quanta. Three years later a candidate ( $\pi$  meson) was found in cosmic rays. Later on it was shown massive field quanta break the gauge symmetry so that the mediator must be massless. If it is based on the  $SU(3)$  gauge symmetry of the



**Figure 2.1:** A schematic picture of neutron structure. at the left side of the resolution is too low to see. The 3 quarks picture allows us to interpretate the quantum numbers of the neutron in the valence band. In high-resolution picture for a large  $Q^2$  can be obtained a gluon sea and a lot of quarks pairs[3]. The quantum number of a neutron is for each energy scale the same

QCD massless Lagrangian how can the strong sector be short range? Another question came from a series of experiments at SLAC. Through high-energy electron-proton scattering there was a search for evidence of the existence of quarks and their behaviour like free particles despite the energetically bound inner proton. The solution to these question was explained by Gross, Politzer and Wilczek through asymptotic freedom. This effect can be proved by the running coupling and anti screening in QCD. For the calculation of the propagator loop correction in QCD both quark loops (negative contribution  $\rightarrow$  screening) and gluon loops (positive contribution  $\rightarrow$  anti screening) have to be taken into account. The one loop running coupling in QCD is:

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \beta_0 \alpha_s(\mu^2) \ln(\frac{Q^2}{\mu^2})} \quad (2.1)$$

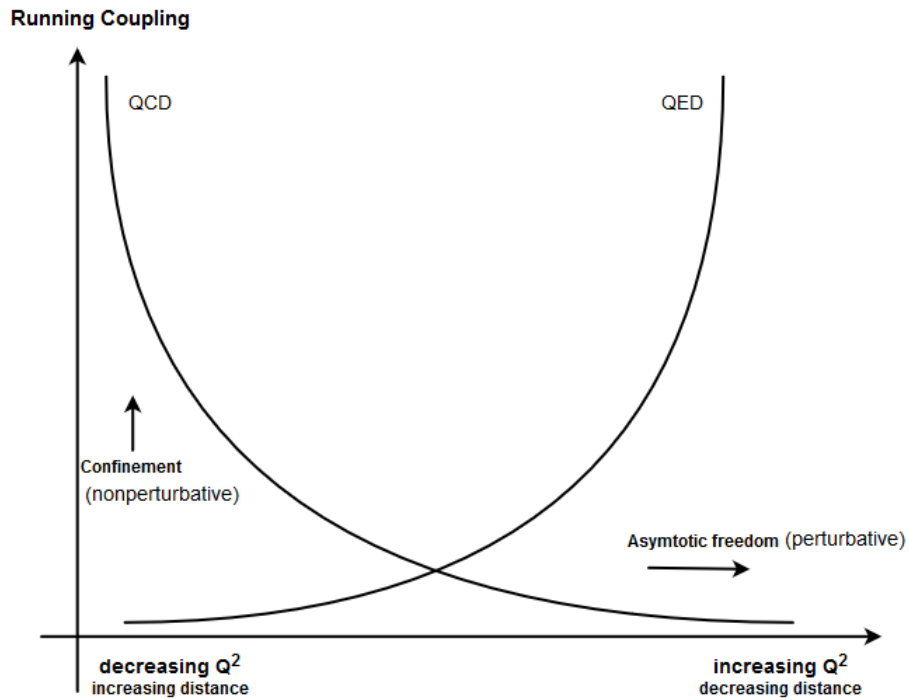


**Figure 2.2:** Running coupling compared for QED, with a positive and QCD with a negative beta function. The quark loop vacuum polarization diagram gives a negative contribution to  $\beta_0 \sim n_f$  and the gluon loop gives a positive contribution to  $\beta_0 \sim N_c$ . The second contribution is bigger than the first, so that  $\beta_0 > 0$  in QCD. The beta function in QED is negative since the second contribution does not exist  $N_C = 0$ .

Where  $\beta_0 = \frac{11N_c - 2n_f}{12\pi}$ ,  $n_f$  the number of quarks comes from the first diagram and causes screening.  $N_c$  the number of colours is due to anti screening. Obviously, with  $n_f = 6$  and  $N_c = 3$  in standard model we will get  $\beta_0 > 0$ . The Beta function is defined as:

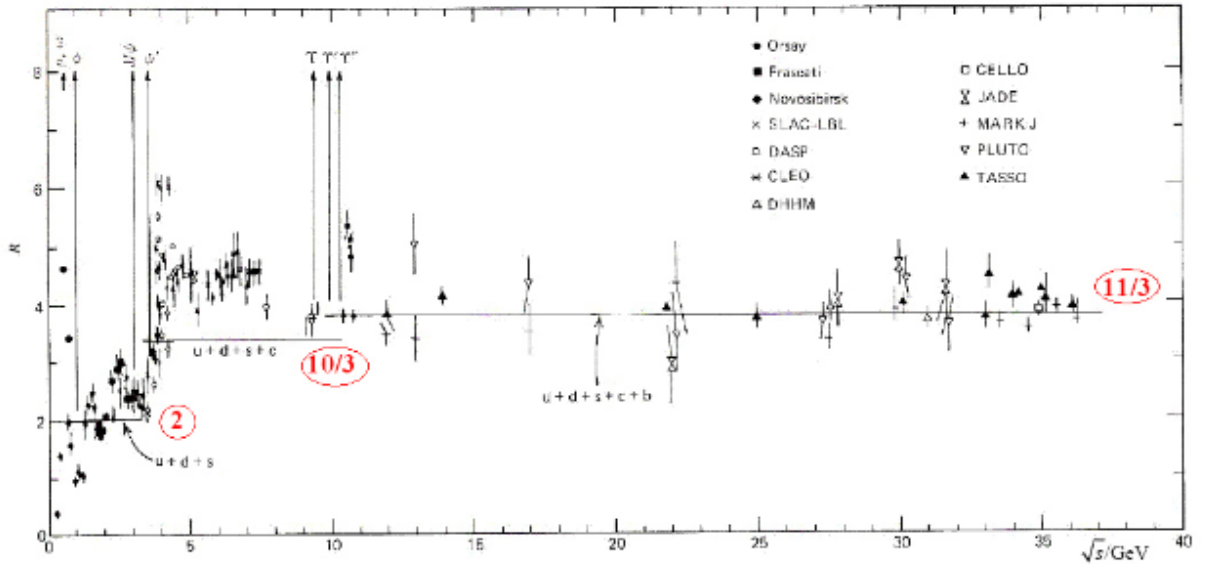
$$\beta(\alpha) = -(\beta_0\alpha^2 + \beta_1\alpha^3 + \beta_2\alpha^4 + \dots) = \frac{d\alpha(Q^2)}{d\ln(Q^2)} \quad (2.2)$$

e.g. the first term of beta-function is negative in contrast to QED with  $\beta_0 = -\frac{\pi}{3} \rightarrow -(\beta_0\alpha^2) > 0$ . The coupling constant in QCD will be increased with reduction of  $Q^2$  (increasing distance), in QED vice versa.





Asymptotic freedom allows us to use perturbation theory. Actually there is need of two more things to make the connection between theory and experiment: either infrared safety or factorisation. That is clarified in the next chapter 3.2. Quarks have not yet been observed as free particles. With increasing separation it will be easier to produce a quark-antiquark pair than to isolate a quark because the coupling between them is too strong. This mechanism is called confinement. Confinement as a non-perturbative theory has been confirmed in Lattice QCD, but not yet mathematically. Quarks prefer to bind into hadrons which can be classified into baryons with three quarks state and mesons with a quark-antiquark state. The wave function of fermions must be antisymmetric according to the Pauli exclusion principle under exchange of two quarks. Interestingly, there are resonance states with spin  $\frac{3}{2}$  like  $\Delta^{++}$ . The spins of the three up quarks are parallel to each other, have the same flavour and orbital angular momentum  $L=0$ . This means that an exchange of flavour, spin and space (orbital angular momentum) does not lead to any change. This problem was explained with the additional degree of freedom, the so-called color charge. This additional factor  $N_C$  could be determined experimentally in the electron-positron annihilation into hadrons schematically in figure 2.3.



**Figure 2.3:** Key measurement at lepton collider,  $R = \frac{\sigma(e^+e^- \rightarrow \text{Hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = N_C \sum_q e_q^2$ , evidence for  $N_C = 3$  colours of quarks. Without this factor the ratio is for  $u, d, s$ ,  $u, d, s, c$  and  $u, d, s, c, b$  respectively  $\frac{2}{3}, \frac{10}{9}, \frac{11}{10}$ . The experiment showed a third of the expected results [27].

Each quark comes in one of three colours red, green or blue and also anti-colour  $\bar{r}, \bar{b}, \bar{g}$  for anti-quarks. The hadrons are colour singlets with regard to the hypothesis and so are invariant under rotations in colour space. The colour hypothesis describes the existence of mesons with  $q\bar{q}$  and baryons with  $qqq$ .

The total wave function for each particle can be expressed:

$$\Psi_{3q} = \psi_{space} \times \chi_{spin} \times \theta_{colour} \times \phi_{flavour} \quad (2.3)$$

$$O(3) \quad SU(2) \quad SU(3) \quad SU(6)$$

All possible colour states are described with Young Tableaux [16]. The group theory methods are used to decompose products of irreducible representations into sums for instance the Young Tableaux technique.

$$\begin{array}{c}
 \boxed{3} \otimes \boxed{3} \otimes \boxed{3} = \boxed{3/3} \boxed{4/2} \boxed{5/1} \oplus \begin{array}{|c|c|} \hline 3/3 & 4/1 \\ \hline 2/1 & \\ \hline \end{array} \oplus \begin{array}{|c|c|} \hline 3/3 & 4/1 \\ \hline 2/1 & \\ \hline \end{array} \oplus \begin{array}{|c|} \hline 3/3 \\ \hline 2/2 \\ \hline 1/1 \\ \hline \end{array} \\
 \text{Totally} \quad \text{Mixed} \quad \text{Mixed} \quad \text{Totally} \\
 \text{symmetric} \quad \text{symmetric} \quad \text{symmetric} \quad \text{antisymmetric} \\
 \\
 = 10 \oplus 8 \oplus 8 \oplus 1
 \end{array}$$

The same procedure for SU(2) and SU(6) for spins and flavours of the three quarks turns out:

$$\begin{aligned}
 2 \otimes 2 \otimes 2 &= 4 \oplus 2 \oplus 2 \oplus 0 \\
 6 \otimes 6 \otimes 6 &= 56 \oplus 70 \oplus 70 \oplus 20
 \end{aligned} \quad (2.4)$$

## 2.2 QCD Lagrangian

QCD like QED and the weak interaction theory is described by representations of a symmetry group. From the condition that the Lagrangian must be invariant under arbitrary global and local symmetry transformations (Noether's theorem) follows the interaction terms. The Lagrangian of QCD is invariant under  $U(1) \times SU(3)$  global transformation. The three Pauli matrices from  $SU(2)$  can be replaced by the eight Gell-Mann  $\lambda^a$  with the following Lie algebra:

$$\begin{aligned} T^a &= \frac{1}{2}\lambda^a \\ [T^a, T^b] &= if^{abc}T^c && \text{fundamental representation} \\ (T^a_{adj})_{bc} &= -if^{abc} && \text{adjoint representation} \end{aligned} \quad (2.5)$$

To quantize QCD theory, the Faddeev-Popov method [12] is usually used in the path integral to fix a gauge and define a gluon propagator. The Lagrangian is given:

$$\begin{aligned} \mathcal{L} = \sum_f \bar{\psi}_{if}(i\gamma^\mu\partial_\mu - m_f)\psi^{jf} &- \frac{1}{4}F_a^{\mu\nu}F_{\mu\nu}^a - \frac{1}{2\xi}(\partial^\mu A_\mu^a)(\partial^\nu A_\nu^a) + (\partial^\mu \chi^{a*})(\partial_\mu \chi^a) \\ &- g_s \bar{\psi}_i T^a_{ij} \psi_j \gamma^\mu A_\mu^a - \frac{g_s}{2} f^{abc} (\partial_\mu A_\nu^a - \partial_\nu A_\mu^a) A_b^\mu A_c^\nu - \frac{g_s^2}{4} f^{abc} (A_b^\mu A_c^\nu) f^{ade} (A_\mu^d A_\nu^e) \\ &- g_s f^{abc} (\partial^\mu \chi^{a*}) \chi^b A_\mu^c \end{aligned} \quad (2.6)$$

The red marked part gives the Lagrangian of free particles and the black part takes care of the interactions.  $F_{\mu\nu}^a$  is field strength tensor for spin-1 gluon field  $A_\mu^a$  corresponded to a non-Abelian gauge theory with the structure constants  $f^{abc}$ .

$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - g_s f_{abc} A_\mu^b A_\nu^c \quad (2.7)$$

The third term distinguishes QCD from QED, giving rise to triplet and quartic gluon self-interaction. Here  $i, j$  are color indices in the fundamental representation,  $a, b, c$  run over 8 colour degrees of freedom of the gluon fields in the adjoint representation of  $SU(3)$ .  $f$  labels the six flavours of the quarks.  $g_s$  describes the strong coupling constant. Due to gauge fixing the Lagrangian in the non-Abelian case requires the introduction of additional fields. These anti commuting complex scalar fields  $\chi^a$  are called Faddeev Popov ghosts [23, 29]. Feynman rules follows the Lagrangian. A list of the respective Feynman rules regarding the terms can be found in 6 which will be used for the aims of this work later.

## 2.3 Colour factor calculation

In this section the calculation of the Casimir operators of the respective diagrams is motivated, which occur later with the evaluation of the matrix elements. The generalization of the Pauli matrices are the so-called Gell-Mann matrices  $\lambda^a$  which is given by [26, 29]

$$T^a = \vartheta^a \equiv \frac{\lambda^2}{2} \quad (2.8)$$

$$\begin{aligned} \lambda^1 &= \begin{pmatrix} 0 & 1 & \\ 1 & 0 & \\ & & 0 \end{pmatrix}, \quad \lambda^2 = \begin{pmatrix} 0 & -i & \\ i & 0 & \\ & & 0 \end{pmatrix}, \quad \lambda^3 = \begin{pmatrix} 1 & & \\ & -1 & \\ & & 0 \end{pmatrix}, \quad \lambda^4 = \begin{pmatrix} & & 1 \\ & 0 & \\ 1 & & \end{pmatrix} \\ \lambda^5 &= \begin{pmatrix} & & -i \\ & 0 & \\ i & & \end{pmatrix}, \quad \lambda^6 = \begin{pmatrix} 0 & & \\ & 0 & 1 \\ & 1 & 0 \end{pmatrix}, \quad \lambda^7 = \begin{pmatrix} 0 & & \\ & 0 & -i \\ & i & 0 \end{pmatrix}, \quad \lambda^8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & & \\ & 1 & \\ & & -2 \end{pmatrix} \end{aligned} \quad (2.9)$$

$\lambda^3$  and  $\lambda^8$  are diagonal. These generators satisfy schematically:

- in the fundamental representation

$$[T^a, T^b] = if^{abc} T^c \Rightarrow \quad \begin{array}{c} \text{Diagram 1} \\ T^a T^b \end{array} - \begin{array}{c} \text{Diagram 2} \\ T^b T^a \end{array} = \begin{array}{c} \text{Diagram 3} \\ if^{abc} T^c \end{array}$$

- in the adjoint representation

$$[F^a, F^b] = if^{abc} F^c \Rightarrow \quad \begin{array}{c} \text{Diagram 1} \\ F^a F^b \end{array} - \begin{array}{c} \text{Diagram 2} \\ F^b F^a \end{array} = \begin{array}{c} \text{Diagram 3} \\ if^{abc} F^c \end{array}$$

The most common convention for the normalization of the generators in physics is:

$$\sum_{c,d} f^{acd} f^{bcd} = N \delta^{ab} \quad (2.10)$$

One of the most important equations for the colour factor calculation is the Jaccobi-Identity:

$$[T^a, [T^b, T^c]] + [T^c, [T^a, T^b]] + [T^b, [T^c, T^a]] = 0 \quad (2.11)$$

In terms of the structure constant:

$$f^{axd} f^{bcx} + f^{cxd} f^{abx} + f^{bxd} f^{cax} = 0 \quad (2.12)$$

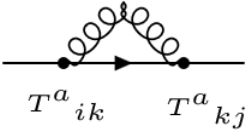
$$f^{abc} = -2i \operatorname{tr}(T^a [T^b, T^c]) \quad (2.13)$$

Which generalises to:

$$f^{abc} f^{xcd} = 4i \operatorname{tr}(T^a [T^b, [T^c, T^d]]) \quad (2.14)$$


With these relations all Casimir operators can be calculated:

- Fundamental representation Casimir operator

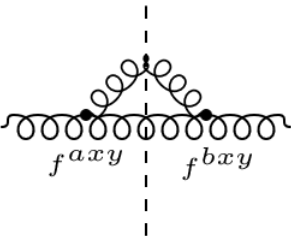


$$\sum_a (T^a T^a)_{ij} = C_F \delta_{ij}$$

$$C_F = \frac{N_c^2 - 1}{2N_c} = C_F \sim \frac{N_c}{2}$$


$\Rightarrow C_F \rightarrow$ 


- Adjoint representation Casimir operator



$$\sum_{xy} f^{axy} f^{bxy} = C_A \delta^{ab}$$

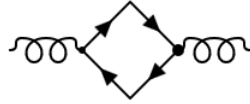
$$C_A = N_C$$

$\Rightarrow C_A$ 


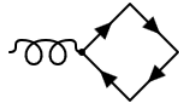
Which means the charge of the gluon is twice that of the quark because:

$$C_A = N_c = 2C_F \sim 2\left(\frac{N_C}{2}\right) \quad (2.15)$$

- Trace identities:



$$T_f \delta^{ab}$$

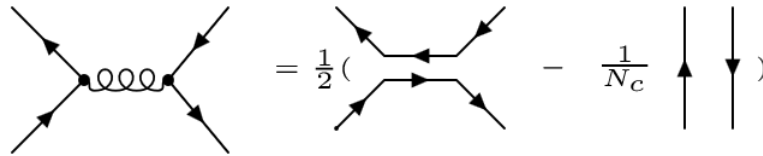


$$tr(T^a) = 0$$

- Fierz identity

$$\sum_a T_{ij}^a T_{kl}^a = \frac{1}{2}(\delta_{il}\delta_{kj} - \frac{1}{N}\delta_{ij}\delta_{kl}) \quad (2.16)$$

With this identity is clarified the difference between QED and QCD. The charge transfer in QED takes place along the Fermion line because photons cannot transport charges. On the other hand, the gluons transfer color charges.



Other useful relation for the calculation of casimir operators in SU(N):

$$tr(T^a T^b) = T_{ij}^a T_{ji}^b = T_F \delta^{ab} \quad (2.17)$$

$$\sum_a (T^a T^a) = C_F \delta^{ij} \quad (2.18)$$

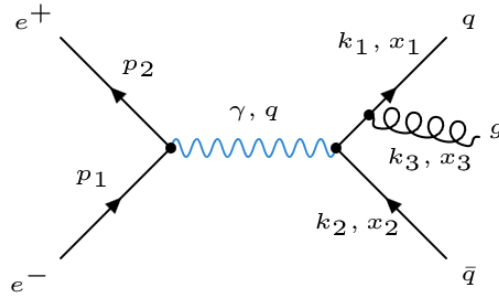
$$f^{acd} f^{bcd} = C_A \delta^{ab} \quad (2.19)$$

With  $T_F = \frac{1}{2}$ ,  $C_A = N$  and  $C_F = \frac{N^2-1}{2N}$

# 3 Parton showers based on subtraction method

## 3.1 IR and Collinear Divergences

Beyond the LO (Leading order) diagrams can occur singularities. Consider first the process  $e^-e^+ \rightarrow q\bar{q}g$



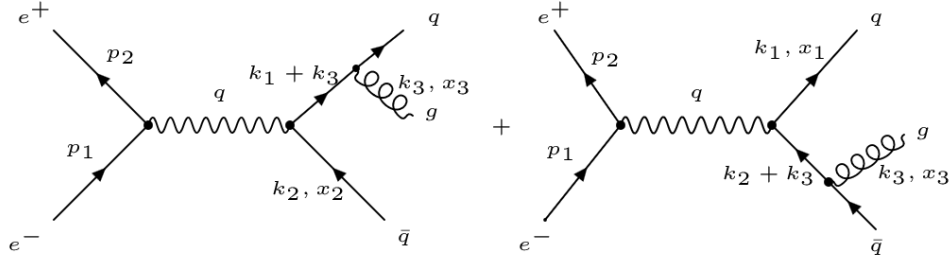
In order to calculate the cross section of electron-positron annihilation, contemplate the gluon emission from a parent (anti)quark. The amplitude of this process fig. 3.1 is:

$$\begin{aligned}
 A &= \frac{\bar{u}(k_1)(-ig_s\gamma^\nu \times T^a)[-i(\not{k}_1 + \not{k}_3)](-iee_q\gamma^\mu)v(k_2)\epsilon_\mu^{\lambda_1}\epsilon_\nu^{\lambda_2*}}{(k_1 + k_3)^2} \\
 &\quad - \frac{\bar{u}(k_1)(-iee_q\gamma^\mu)[i(\not{k}_2 + \not{k}_3)](-ig_s\gamma^\nu \times T^a)v(k_2)\epsilon_\mu^{\lambda_1}\epsilon_\nu^{\lambda_2*}}{(k_1 + k_3)^2} \\
 \Rightarrow A &= -g_s T^a \left[ \frac{\bar{u} \not{\epsilon} (\not{k}_1 + \not{k}_3) \Gamma v}{(k_1 + k_3)^2} - \frac{\bar{u} \Gamma (\not{k}_2 + \not{k}_3) \not{\epsilon} v}{(k_2 + k_3)^2} \right]
 \end{aligned} \tag{3.1}$$

With  $\Gamma = (-iee_q\gamma^\mu)\epsilon_\mu^{\lambda_1}$ .

Under considering that the partons are on-shell, the amplitude can be written:

$$A = -g_s T^a \left[ \frac{\bar{u} \not{\epsilon} (\not{k}_1 + \not{k}_3) \Gamma v}{2k_1 \cdot k_3} - \frac{\bar{u} \Gamma (\not{k}_2 + \not{k}_3) \not{\epsilon} v}{2k_2 \cdot k_3} \right] \tag{3.2}$$



**Figure 3.1:** Left diagram  $e^-e^+ \rightarrow qq\bar{q}$  and right  $e^-e^+ \rightarrow q\bar{q}g$

In the soft limit with  $k_0 \rightarrow 0$ , the amplitude can be factorized in two parts:

$$A = -g_s T^a \left[ \frac{k_1 \cdot \epsilon}{k_1 \cdot k_3} - \frac{k_2 \cdot \epsilon}{k_2 \cdot k_3} \right] A_{born} \quad \text{with } A_{born} = \bar{u} \Gamma v \quad (3.3)$$

Where the left side contains all information about colour and momenta and the other one involves all spin information. The calculation of the cross section results in:

$$A = -C_F g_s^2 \sigma^{born} \int \frac{d^3 k}{2k_0 (2\pi)^3} 2 \left( \frac{k_1 \cdot k_2}{(k_1 \cdot k_3)(k_2 \cdot k_3)} \right) - C_F g_s^2 \sigma^{born} \int d\cos \theta \frac{dk_0}{k_0} \frac{4}{(1 - \cos \theta)(1 + \cos \theta)} \quad (3.4)$$

The energy fraction is defined as:

$$x_i = \frac{2E_i}{\sqrt{s}} = \frac{2q \cdot k_i}{s} \quad (3.5)$$

It can be shown that  $\sum x_i = 2$  and thus, that only two of momenta are independent.

The partonic differential cross section with respect to the quark and anti-quark momentum fractions is given by:

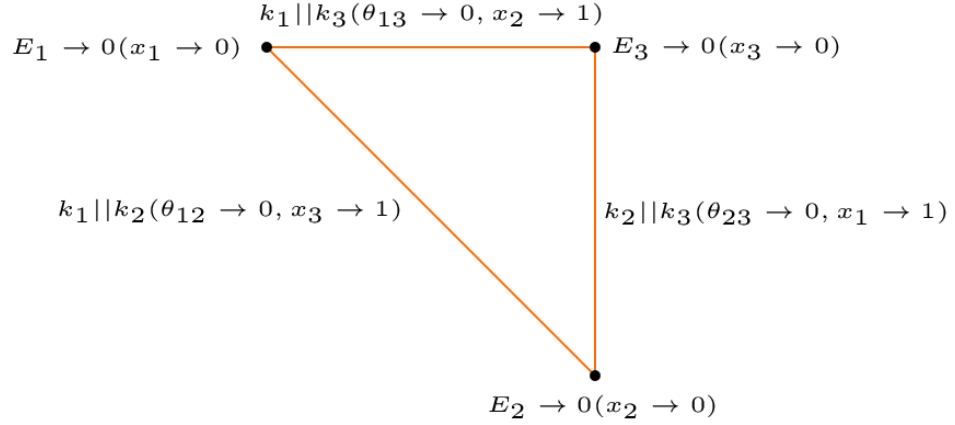
$$\frac{d^2 \sigma}{dx_1 dx_2} = \left( \frac{4\pi\alpha}{s} \right) \sum e_i^2 \frac{2\alpha_s}{3\pi} \frac{x_1^2 + x_2^2}{(1 - x_1)(1 - x_2)} \quad (3.6)$$

There are three singularities within the final result. If the emitted photon is collinear to the outgoing quark or anti-quark ( $x_1 \rightarrow 1$  or  $x_2 \rightarrow 1$ ) and when the emitted gluon is soft ( $x_1 \rightarrow 1$  and  $x_2 \rightarrow 1$ ) 3.2. The singularities come from the quark propagator in each diagram. The denominators contain terms proportional to  $\frac{1}{(k_i + k_j)^2}$ . With the eliminating the quark mass follows:

$$\frac{1}{(k_i + k_j)^2} = \frac{1}{2k_i \cdot k_j} = \frac{1}{2E_i E_j (1 - \cos \theta_{ij})} = \frac{1}{s(1 - x_k)} \quad (3.7)$$

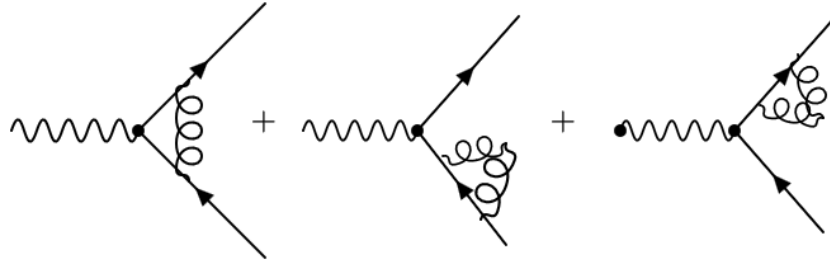
can show all possibilities for three partons through a triangle:





**Figure 3.2:** three-parton configurations at the boundaries of phase space

The Kinoshita-Lee-Nauenberg (KLN) Theorem assures that a summation over degenerate initial and final states removes all infra red (IR) divergences. The sum of the integrals  $\int_R$  and  $\int_V$  over the phase space is finite. However, this is not true for the individual contributions. In the next section it is seen how the infra red singularities are absorbed



**Figure 3.3:** Virtual corrections: one-loop corrections to  $e^- e^+ \rightarrow q \bar{q}$

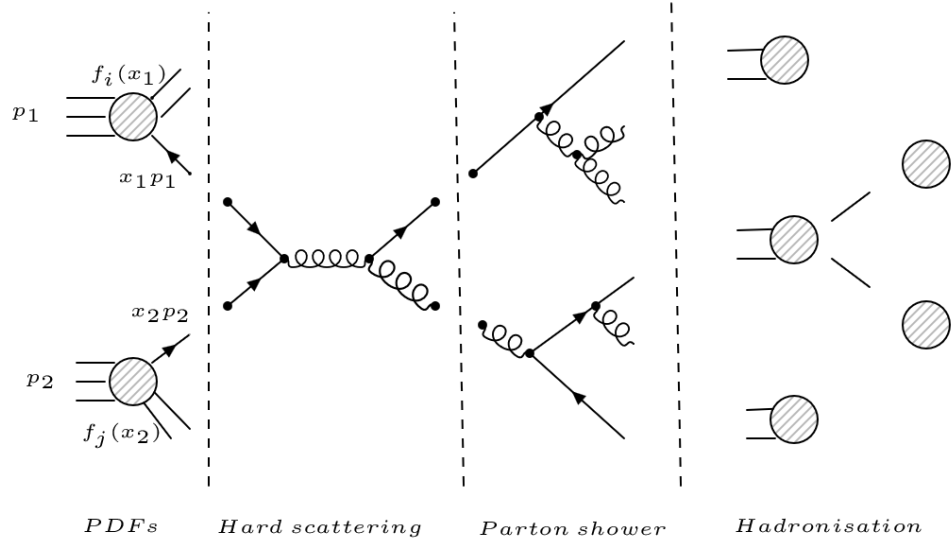
in the parton distributions in connection with the deep inelastic scattering (DIS) [3].

## 3.2 Hard scattering

In the last section it was seen that IR singularities occur in QCD due to the collinearity of two partons or the soft energy of a parton. These divergences happen long time after the initial hard scattering (long distance physics). Fortunately, the infrared-safe observables are calculable in perturbative QCD. But this is not the best way to solve this problem. An interesting way for this aim is the factorization theorem. By this theorem the singularities of long-distance physics are removed from the partonic cross section and absorbed into the parton distribution of the hadrons. This is even feasible for all orders of calculation. The background idea is that the partonic cross section is calculable in perturbation theory. Consider the hadron hadron scattering:

$$\sigma = \sum_{ij} \int dx_1 dx_2 f_i(x_1, \mu^2) f_j(x_2, \mu^2) \sigma_{ij}(x_1, x_2, Q^2/\mu^2 \dots) \quad (3.8)$$

With a factorisation scale  $\mu$  the long and short-distance physics could be separated.



Partons with a greater momentum than  $\mu$  participate in the hard-scattering and those with less momentum are considered as components of the hadron structure and accordingly absorbed in the parton distribution [22].

The factorisation theorem also applies to deep inelastic scattering, with one of the parton distributions replaced by an  $e^+e^-\gamma$  vertex. The DIS cross section can be written as [10]

$$\frac{d^2\sigma}{dx dQ^2} = \frac{4\pi\alpha^2}{xQ^4} [(1-y)F_2(x, Q^2) + xy^2 F_1(x, Q^2)] \quad (3.9)$$

In this case, the structure function need to be introduced:

$$F_2^{exp}(x) = \sum_i e_i^2 x f_i(x) \quad (3.10)$$

It is defined as the charge weighted sum of the parton momentum densities which describe

the probability that the parton carries a momentum fraction between  $x$  and  $\partial x$  of the proton momentum. The index  $i$  denotes the quark flavour. Parton distributions are non-perturbative. fortunately, they are universal and it is obtained from fit to the data for a particular factorization scheme and use them for other processes.

The perturbative evolution kernel of a parton distribution due to splitting can be described by the solution of DGLAP evolution equation [31]. It is based on the collinear factorization property of QCD. Fixing the accuracy of the calculation and the factorization scheme the evolution kernel is well defined.

$$\frac{\partial f(x, \mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s}{2\pi} \int_x^1 \frac{dy}{y} f_j(y, \mu^2) P_{ij}\left(\frac{x}{y}\right) + O(\alpha_s^2) \quad (3.11)$$

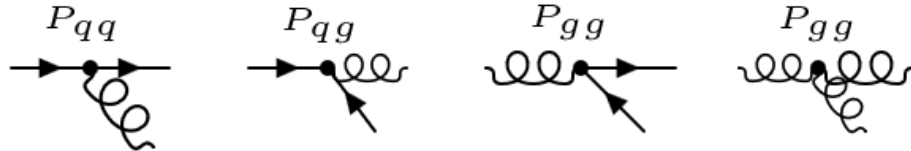
This is a system of coupled integral or differential equations.  $P_{ij}(\frac{x}{y})$  represents the probability, a daughter parton  $i$  with momentum fraction  $\frac{x}{y}$  is splits from a parent parton  $j$ . The above convolution in compact notation (Mellin Convolution) in the general case:

$$\frac{\partial f_i(x, \mu^2)}{\partial \ln \mu^2} = \sum_{j=-n_f}^{n_f} P_{ij} \otimes f_j(\mu^2) \quad (3.12)$$

The four splitting probabilities are illustrated in the diagram 3.4 and the qq, qg, gg and gq transitions lead to a set of  $2n_f + 1$  coupled evolution equations.

$$\frac{\partial}{\partial \ln \mu^2} \begin{pmatrix} q_s \\ g \end{pmatrix} = \frac{\alpha_s}{2\pi} \begin{bmatrix} P_{qq} & 2n_f P_{qg} \\ P_{gq} & P_{gg} \end{bmatrix} \otimes \begin{pmatrix} q_s \\ g \end{pmatrix} \quad (3.13)$$

A parton distribution changes when a different parton splits or the parton itself splits. Parton densities can not be analytically determined, but it is possible to predict how they evolve from one scale to another. PDFs are measured in one process and use them as an input for another process.



**Figure 3.4:** The four splitting probabilities

Here are the leading order splitting functions which is going to be verified with the both old and new kinematic in the 3.4 section.

$$\left. \begin{aligned} \langle \hat{P}_{qq} \rangle &= C_F \left[ \frac{1+z^2}{1-z} - \varepsilon(1-z) \right] \\ \langle \hat{P}_{gq} \rangle &= T_R \left[ 1 - \frac{2z(1-z)}{1-\varepsilon} \right] \\ \langle \hat{P}_{qg} \rangle &= C_F \left[ \frac{1+(1-z)^2}{z} - \varepsilon z \right] \\ \langle \hat{P}_{gg} \rangle &= 2C_A \left[ \frac{z}{1-z} + \frac{1-z}{z} + z(1-z) \right] \end{aligned} \right\} \text{Altarelli-Parisi} \quad (3.14)$$

### 3.3 Subtraction method

The subtraction term is constructed as a sum over all possible dipole configurations, i.e. all possible combinations of two partons are formed to build an emitter while every single one of the remaining partons is considered a spectator. The general quadratic matrix element is defined:

$$|A|^2 = |A^{(0)}_m|^2 + |A^{(0)}_{m+1}|^2 + 2\text{Re}(A^{(0)*}_n A^{(1)}_m) \quad (3.15)$$

Where  $|A^{(0)}_m|^2$  is the tree level contribution (Born sector) from LO and has no divergences,  $|A^{(0)}_{m+1}|^2 + 2\text{Re}(A^{(0)*}_n A^{(1)}_m)$  comes from NLO and each of them is divergent. The problem in this case is the Integrals which can not be combined due to different phase space dimensions:

$$\sigma^{NLO} = \int_{m+1} \partial\sigma^R + \int_m \partial\sigma^V \quad (3.16)$$

The real and virtual contributions are both IR divergent and need to be regularised in  $d = 4 - 2\epsilon$  dim. To tackle this problem one can use the subtraction method with adding and subtracting a local counter term  $\partial\sigma^A$  with the same singularity structure as term  $\partial\sigma^R$  to the integral.  $\partial\sigma^A$  approximates the soft and collinear singularities of  $\partial\sigma^R$ .

$$\sigma^{NLO} = \int_{m+1} [\partial\sigma^R - \partial\sigma^A] + \int_m [\partial\sigma^V + \int_1 \partial\sigma^A] \quad (3.17)$$

In this case, one can safely set  $\epsilon \rightarrow 0$  for  $\partial\sigma^R|_{\epsilon \rightarrow 0} - \partial\sigma^A|_{\epsilon \rightarrow 0}$  under the integral sign in the first term and calculate the integral numerically in 4-dimensions. All the singularities are now associated to the last two terms on the right-hand side. If one is able to carry out analytically the integration of  $\partial\sigma^A$  over the one parton subspace leading to the  $\epsilon$  poles, one can combine these poles with those in  $\partial\sigma^V$ , thus cancelling all the divergences, performing the limit  $\epsilon \rightarrow 0$  and carrying out numerically the remaining integration over the  $m$ -parton phase space [6].

$$\sigma^{NLO} = \int_{m+1} [\partial\sigma^R|_{\epsilon \rightarrow 0} - \partial\sigma^A|_{\epsilon \rightarrow 0}] + \int_m [\partial\sigma^V + \int_1 \partial\sigma^A]_{\epsilon \rightarrow 0} \quad (3.18)$$

The virtual contribution must be UV-finite:

$$\int_m \partial\sigma^V = \int_m [\int_{loop} \partial\sigma^V_{bare} + \sigma^V_{Counter term}] \quad (3.19)$$

The addition of  $\int_1 \partial\sigma^A$  to the  $\int_m \partial\sigma^V$  ensures that IR poles are cancelled. The bare and counter contribution are separately divergent and have also different integral dimensions. One can use the same idea with the subtraction method to solve this problem [5]

$$\int_m \partial\sigma^V + \int_{loop} \partial\sigma^L - \int_{loop} \partial\sigma^L = \int_m \int_{loop} [\partial\sigma^V_{bare} - \partial\sigma^L] + \int_m [\sigma^V_{Counter term} + \int_{loop} \partial\sigma^L] \quad (3.20)$$

together one receives:

$$\sigma^{NLO} = \int_{m+1} [\partial\sigma^R - \partial\sigma^A] + \int_m \int_{loop} [\partial\sigma^V_{bare} - \partial\sigma^L] + \int_m [\sigma^V_{Counter term} + \int_{loop} \partial\sigma^L + \partial\sigma^A] \quad (3.21)$$

## Determination of emission kernels

Now we want to introduce the properties of the counter term  $\partial\sigma_A$ . This term needs to have the same behaviour as  $\partial\sigma_R$  in  $d$  dimensions. This process and specific observable has to be obtained in a way that is independent of the particular jet observable considered. It must be exactly integrable analytically over one-parton phase space in  $d$  and  $\partial\sigma_R - \partial\sigma_A$  has to be integrable via Monte Carlo methods.  $\partial\sigma_A$  acts as a local counter-term for  $\partial\sigma_B$  at this point. One derives improved factorization formulae which are called dipole or antenna formulae which is symbolic:

$$\partial\sigma_A = \sum_{dipoles} \partial\sigma_B \otimes \partial V_{dipoles} \quad (3.22)$$

Where the sum is over dipoles for all  $m + 1$  configurations with consideration to a given  $m$ -parton state.  $\partial\sigma_B$  describes the color/spin projection of the Born-level exclusive cross section. The symbol  $\otimes$  describes phase space convolutions and sums over colour and spin indices.  $\partial V_{dipoles}$  will be computed and its singular properties matched to the real part. The Dipoles are universal in the sense that they do not depend on the hard scattering. This allows the use of a factorisable mapping from the  $m + 1$ -parton phase space to an  $m$ -parton subspace. That will be clearer when the parametrisation is used in the next chapter. The integral over all  $m + 1$  configuration can be written:

$$\int_{m+1} \partial\sigma_A = \int_m \partial\sigma_B \otimes \sum_{dipoles} \int_1 \partial V_{dipoles} \quad (3.23)$$

This is the important result because this can now be written in terms of the known  $m$ -sector from LO and the other universal factor which contains all  $\epsilon$ -poles [6].

## Singularity Structure

Before beginning with the collinear limit or soft limit respectively the structure of matrix element from LO has to be introduced:

$$\mathcal{M}_m^{c_1, \dots, c_m; s_1, \dots, s_m}(p_1, \dots, p_m) \quad (3.24)$$

$c_i$ ,  $s_i$  and  $p_i$  denote respectively the colour, spin indices and the momenta for each  $m$ -parton in the tree level matrix element in the initial/final-state. A common used method here is to define a basis in colour+helicity space.

$$\mathcal{M}_m^{c_1, \dots, c_m; s_1, \dots, s_m}(p_1, \dots, p_m) \equiv (\langle c_i, \dots, c_m | \otimes \langle s_1, \dots, s_m |) | 1, \dots, m \rangle_m \quad (3.25)$$

With  $\langle c_i, \dots, c_m | \otimes \langle s_1, \dots, s_m |$  as the basis and  $| 1, \dots, m \rangle_m$  as a vector in this space. Thus, for the matrix element squared:

$$\begin{aligned} |\mathcal{M}_m|^2 &= (\langle c_i, \dots, c_m | \otimes \langle s_1, \dots, s_m |) (| c_i, \dots, c_m \rangle \otimes | s_1, \dots, s_m \rangle) \langle 1, \dots, m | 1, \dots, m \rangle \\ &= \delta_{c_1 c_1} \dots \delta_{c_m c_m} \otimes \delta_{s_1 s_1} \dots \delta_{s_m s_m} \langle 1, \dots, m | 1, \dots, m \rangle \end{aligned} \quad (3.26)$$

Define a colour-charge operator  $T_i$  with the emission of a gluon from each parton i:

$$T_i = T_i^c |c \rangle \quad (3.27)$$

Its action onto the colour space is defined by:

$$\langle c_1, \dots, c_i, \dots, c_m, c | T_i | b_1, \dots, b_i, \dots, b_m \rangle = \delta_{c_1 b_1} \dots T_{c_i b_i}^c \dots \delta_{c_m b_m} \quad (3.28)$$

Where  $T_{c_i b_i}^c$  is the colour-charge matrix in the adjoint representation for the gluon emission or colour-charge matrix in the fundamental representation for the quark/anti-quark emission case. The following properties must be taken into account:

$$\begin{aligned} T_i \cdot T_j &= T_j \cdot T_i && \text{if } i \neq j, \text{ commutative property} \\ T_i^2 &= C_i && C_i = C_A \text{ for gluon and } C_i = C_F \text{ for (anti)quark} \\ \sum_{i=1}^m T_i |1, \dots, m \rangle_m &= 0 && \text{for single state} \end{aligned} \quad (3.29)$$

Thus, the square of colour-correlated tree-amplitudes for the indices  $I, J$  referring either to final-state or initial-state partons will be [5, 6]

$$|\mathcal{M}_{m,a\dots}^{I,J}|^2 = \langle 1, \dots, m; a, \dots | T_I \cdot T_J | 1, \dots, m; a, \dots \rangle_{m,a\dots} \quad (3.30)$$

## Dipole factorisation

depending on the investigated region, there is a total of three factorisation possibilities, see figures 3.5, 3.6 and 3.7.

$$\left| \text{Diagram 1} + \text{Diagram 2} \right|^2 \approx \left| \text{Diagram 1} \right|^2 \left( \text{Soft Emission 1} + \text{Soft Emission 2} \right)$$

**Figure 3.5:** Soft factorisation

$$\left| \text{Diagram 1} + \text{Diagram 2} \right|^2 \approx \left| \text{Diagram 1} \right|^2 \left( \left| \text{Collinear Emission 1} \right|^2 + \left| \text{Collinear Emission 2} \right|^2 \right)$$

**Figure 3.6:** Collinear factorisation

$$\left| \text{Diagram 1} + \text{Diagram 2} \right|^2 \approx \left| \text{Diagram 1} \right|^2 \left( \text{Dipole/Antenna Emission 1} + \text{Dipole/Antenna Emission 2} \right)$$

**Figure 3.7:** Dipole/Antenna factorisation

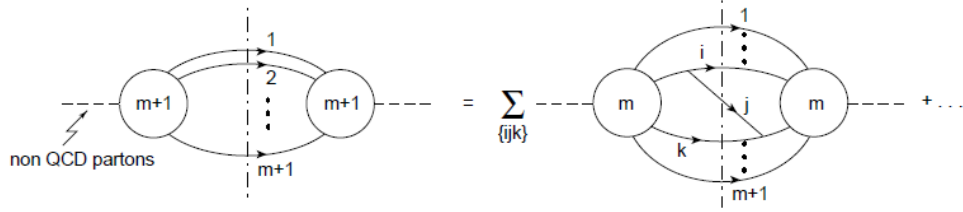
To explain the meaning of the factorisation consider  $(m + 1)$ -partons with the general matrix element [6, 30]

$$|\mathcal{M}_{m+1}(Q; p_1, \dots, p_i, \dots, p_j, \dots, p_{m+1})|^2 \quad (3.31)$$

In the soft region the momentum  $p_j$  can be parametrised with  $p_j \rightarrow \lambda q, \lambda \rightarrow 0$ , where  $q$  is an arbitrary four vector and  $\lambda$  a scale parameter. The squared matrix element is characterised by  $|\mathcal{M}|^2 \sim \frac{1}{\lambda^2}$ . and if  $p_i$  and  $p_j$  become collinear,  $p_j = \frac{z}{1-z} p_i$  is parametrise. So the matrix element will be  $|\mathcal{M}|^2 \sim \frac{1}{p_i \cdot p_j}$ . This get covered in more detail in the next chapter. Here is given a summery of the behaviour of the matrix elements in different regions. Based on the Catani-Seymour method for  $(m + 1)$ -partons.

$$|\mathcal{M}_{m+1}|^2 \rightarrow \sum |\mathcal{M}_m|^2 \otimes V_{ij,k} \Rightarrow |\mathcal{M}_{m+1}|^2 \rightarrow \sum |\mathcal{M}_m|^2 \otimes V_{ij,k} \quad (3.32)$$

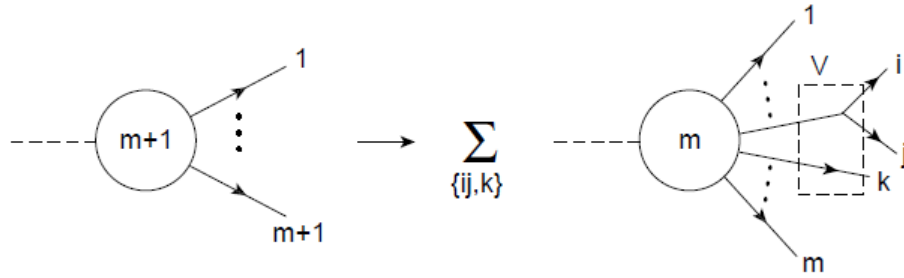
$V_{ij,k}$  a singular factor including parton  $k$  and its interaction with partons  $i$  and  $j$  from the  $m$ -parton amplitude. This situation can be represented by the diagram 3.8.



**Figure 3.8:** Factorisation in dipole formalism

[5]

Here  $i$  and  $j$  are the emitters and  $k$  plays the role of a spectator. The spectator absorbs a longitudinal recoil that arises when a splitting is performed with all participating partons remaining on their mass shells. The blobs denote the tree-level matrix elements and their complex conjugate. The dots on the right-hand side stand for non-singular terms both in the soft and collinear limits. When the partons  $i$  and  $j$  become soft and/or collinear, the singularities are factorized into the term  $V_{ij,k}$  (the dashed box on the right-hand side) which embodies correlations with a single additional parton  $k$ .



**Figure 3.9:** Effective diagrams for the different emitter-spectator cases.

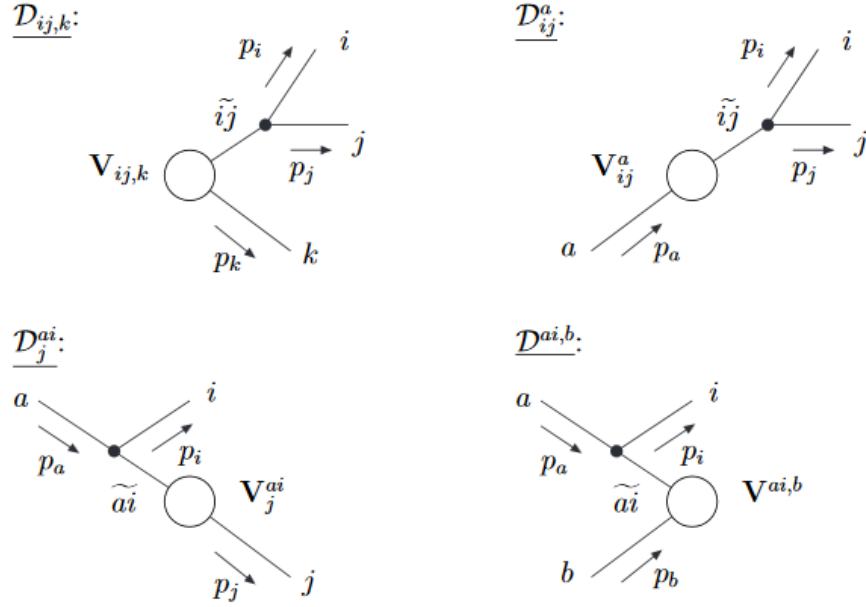
[6]

In this context the different dipole factorisation for both initial states and final states shall be presented. All these different possibilities can be seen in the diagram 3.9.  $\mathcal{D}_{ij,k}$  describes the final state emitter and final-state spectator (FF),  $\mathcal{D}_{ij}^a$  the final-state emitter and initial-state spectator (FI),  $\mathcal{D}_{ik}^{ai}$  the initial-state emitter and final-state spectator (IF) and  $\mathcal{D}_{aj,b}^{aj}$  the initial-state emitter and initial-state spectator (II). The dipole factorisation formula for all these possibilities is [28]

$$|\mathcal{M}_{m+1}|^2 = \sum_{i,j} \sum_{k \neq i,j} \mathcal{D}_{ij,k} + \sum_{i,j} \sum_a \mathcal{D}_{ij}^a + \sum_{a,i} \sum_{k \neq i} \mathcal{D}_{ik}^{ai} + \sum_{a,i} \sum_{b \neq a} \mathcal{D}_{aj,b}^{aj} + \dots \quad (3.33)$$

In each term  $i, j$  and  $k$  denote final-state partons and  $a$  and  $b$  stand for initial-state partons. Note that there are many not-divergent contributions or diagrams, which are marked here with the dots. In this Work the first contribution final-state emitter and final-state spectator (FF) is used. Later it becomes clear how to deal with the formula.





The circle in the center of each sub diagram presents the  $m$ -partons matrix element and the tilde labels the collinear splitting process for the initial or final states. For this work, the first upper diagram with final-state singularities without initial-state partons, is completely sufficient and is discussed here in detail with its formula. The matrix element for this is written:

$$|\mathcal{M}_{m+1}|^2 = \langle 1, \dots, m+1 | 1, \dots, m+1 \rangle = \sum_{k \neq i, j} \mathcal{D}_{ij,k}(p_1, \dots, p_{m+1}) + \text{finite terms} \quad (3.34)$$

The first term with the sum over dipoles is divergent as  $p_i \cdot p_j \rightarrow 0$ . For the case of final-state emitters with a final-state spectator, for instance, the individual dipole contributions:

$$\mathcal{D}_{ij,k}(p_1, \dots, p_{m+1}) = \frac{-1}{2p_i \cdot p_j} {}_m \langle 1, \dots, \tilde{i}\tilde{j}, \dots, k, \dots, m+1 | \frac{T_k \cdot T_{ij}}{T_{ij}^2} V_{ij,k} | 1, \dots, \tilde{i}\tilde{j}, \dots, k, \dots, m+1 \rangle_m \quad (3.35)$$

Where  $T_k \cdot T_{ij}$  are the color charges of spectator and emitter,  $V_{ij,k}$  splitting kernel in helicity space of emitter explicit form depends on parton type become proportional to Altarelli-Parisi splitting functions 3.14 and eikonal factors in collinear and soft limits.

The occurring  $m$ -parton states are constructed from the original  $(m+1)$ -particle matrix element by replacing the partons  $i$  and  $j$  with the new parton  $\tilde{i}\tilde{j}$ , and the original parton

$k$  with the  $\tilde{k}$  spectator. In the massless case, their momenta are given by:

$$\begin{aligned}\tilde{p}_{ij}^\mu &= p_i^\mu + p_j^\mu - \frac{y_{ij,k}}{1 - y_{ij,k}} p_k^\mu \\ \tilde{p}_k^\mu &= \frac{1}{1 - y_{ij,k}} p_k^\mu \\ y_{ij,k} &= \frac{p_i \cdot p_j}{p_i \cdot p_j + p_j \cdot p_k + p_k \cdot p_i}\end{aligned}\tag{3.36}$$

Note, that momenta are on-shell. Due to momentum conservation  $p_i^\mu + p_j^\mu + p_k^\mu = \tilde{p}_k^\mu + \tilde{p}_{ij}^\mu$ .

### 3.4 Mapping 3 partons to 2 for single emission

As we have already seen in the last section, the dipole factorization is obtained from the square matrix element. Now we want to take a closer look at the four possible parton showers from the previous section. For this goal we first calculate the respective matrix elements and the complex-conjugated one of them in the known 3 parton evaluation. This results in the dipole-term, which contains the soft- and collinear singularities. Then this is parametrized with a certain kinematics in order to separate the finite terms from infinities. First of all, the Emmitter and the spectator are defined. After the substitution of the new momenta we get splitting kernel in helicity space and color charges of spectator and emitter. Then we ignore the finite terms because we are looking for the singular terms. It should be noted that at the beginning of this thesis a parametrisation was used, which unfortunately only works for LO. This was recognized later and therefore a new kinematics was used. This theoretical description will become clearer as we begin to implement the mappings. First of all the kinematics have to be introduced [14, 24, 25, 26].

### 3.5 Old mapping

The old parametrisation is defined as follows:

$$\left. \begin{aligned} q_i^\mu &= z p_i^\mu + y(1 - z) p_j^\mu + \sqrt{zy(1 - z)} m_\perp^\mu \\ q^\mu &= (1 - z) p_i^\mu + y z p_j^\mu - \sqrt{zy(1 - z)} m_\perp^\mu \\ q_j^\mu &= (1 - y) p_j^\mu \end{aligned} \right\} \text{parametrisation} \tag{3.37}$$

Where  $q$  is the radiated soft momentum,  $q_i$  the momenta of the emitter and  $q_j$  the momentum of the spectator is. The variable  $y_{ij,k} = \frac{q_i \cdot q}{p_i \cdot p_j}$  need to be introduced, that is zero in the soft and collinear limit. Note that both the emitter and the spectator are on-shell. momentum conservation is implemented exactly:

$$q_i^\mu + q^\mu + q_k^\mu = p_i^\mu + p_j^\mu + m_\perp^\mu \tag{3.38}$$

For this mapping it is useful to calculate some common relations which are computed as follow:

$$\begin{aligned}
 q_i^\mu + q^\mu &= p_i^\mu + y p_j^\mu \\
 q_j^\mu + q^\mu &= (1 - z) p_i^\mu + (1 + yz - y) p_j^\mu - \sqrt{zy(1 - z)} m_{\perp}^\mu \\
 q_i \cdot q &= y(p_i \cdot p_j) \\
 q_i \cdot q_j &= z(1 - y)(p_i \cdot p_j) \\
 q_j \cdot q &= (1 - z)(1 - y)(p_i \cdot p_j)
 \end{aligned} \tag{3.39}$$

### 3.6 Mapping $m + 1$ partons to $m$ for multi-emissions

For the general  $m$  emission case it must be defined a new mapping. The parametrisation of the splitting momenta is formalized as:

$$\begin{aligned}
 k_l^\mu &= \alpha_l \Lambda^\mu{}_\nu p_i^\nu + y \beta_l n^\mu + \sqrt{y \alpha_l \beta_l} n_{\perp, l}^\mu \quad l = 1, \dots, m \\
 q_i^\mu &= (1 - \sum_{l=1}^m \alpha_l) \Lambda^\mu{}_\nu p_i^\nu + y(1 - \sum_{l=1}^m \beta_l) n^\mu - \sqrt{y \alpha_l \beta_l} n_{\perp, l}^\mu \\
 q_k^\mu &= \alpha \Lambda^\mu{}_\nu p_k^\nu \quad k = 1, \dots, n \quad k \neq i
 \end{aligned} \tag{3.40}$$

$k = 1, \dots, n$  labels the emission momenta and is taken to be massless  $k_l^2 = 0$ . Where the label  $l$  denotes the count of emissions. In this work the one-emission kernels is just considered. All hard momenta in this mapping are also on-shell,  $p_k^2 = q_k^2 = 0$ .  $n^\mu$  is an auxiliary light-like vector which is necessary to specify the transverse component of  $n_{\perp, l}^\mu$ . To absorb the recoil  $n^\mu$  is defined as:

$$n^\mu = Q^\mu - \frac{Q^2}{2p_i \cdot Q} p_i^\mu \tag{3.41}$$

Whereby  $Q$  is the total momentum with:

$$Q^\mu = q_i^\mu + \sum_{l=1}^m k_l^\mu + \sum_{k=1}^m q_k^\mu = p_i^\mu + \sum_{k=1}^m p_k^\mu \tag{3.42}$$

To fulfil the condition that the emission momenta are massless, the following condition must be taken into account:

$$\begin{aligned}
 n_{\perp, l}^\mu \Lambda^\mu{}_\nu p_i^\nu &= n_{\perp, l} \cdot n = n_{\perp, l} \cdot Q = 0 \\
 n_{\perp, l}^\mu \cdot p_k &\neq 0
 \end{aligned} \tag{3.43}$$

$n_{\perp, l}^2 = -2\alpha \Lambda^\mu{}_\nu p_i^\nu n_\mu$  is not on-shell and in terms of single emission case it follows  $n_{\perp, 1}^2 = -2p_i \cdot Q$ . The parameter  $y$  is related to the virtuality of the splitting parton:

$$q_i^\mu + \sum_{l=1}^m k_l^\mu = \alpha \Lambda^\mu{}_\nu p_i^\nu + y n^\mu \tag{3.44}$$

With  $\alpha = \sqrt{1 - y}$ .

### Lorentz transformation of momenta

From the parametrisation it is immediately to calculate the respective Lorentz transformation for the Emitters, Spectator and total momentum first. The general definition of the transformation is given by:

$$\begin{aligned} \alpha \Lambda^\mu{}_\nu &= p_i^\mu p_{i\nu} \frac{-y^2 Q^2}{4(p_i \cdot Q)^2 (1 + \sqrt{1-y} - \frac{y}{2})} + p_i^\mu Q_\nu \frac{y(1 + \sqrt{1-y})}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} \\ &+ Q^\mu p_{i\nu} \frac{(y^2 - y - y\sqrt{1-y})}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} + \sqrt{1-y} \eta^\mu{}_\nu \end{aligned} \quad (3.45)$$

In the collinear limit with  $y \rightarrow 0, \alpha \rightarrow 1$  this transformation reduces to trivial  $\eta^\mu{}_\nu$ . Finally we are going to compute the Lorentz transformation of the Momenta. The detailed calculation of Lorentz transformation for the Emitters, Spectator and total momentum can be found in the appendix section 6.

$$\boxed{\hat{p}_i^\mu = \alpha \Lambda^\mu{}_\nu p_i^\nu = p_i^\mu} \quad (3.46)$$

$$\boxed{\hat{Q}^\mu = \frac{Q^2}{2p_i \cdot Q} y p_i^\mu + (1-y) Q^\mu} \quad (3.47)$$

$$\boxed{\hat{p}_k^\mu = A_1 p_i^\mu + A_2 Q^\mu + \sqrt{1-y} p_k^\mu} \quad (3.48)$$

with

$$\begin{aligned} A_1 &\equiv \frac{-y^2 Q^2 (p_i \cdot p_k)}{4(p_i \cdot Q)^2 (1 + \sqrt{1-y} - \frac{y}{2})} + \frac{y(1 + \sqrt{1-y})(Q \cdot p_k)}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} \\ A_2 &\equiv \frac{(y^2 - y - y\sqrt{1-y})(p_i \cdot p_k)}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} \end{aligned}$$

### 3.7 Single emission part

In terms of one emission where  $l = 1$  the mapping will be simplified to:

$$\begin{aligned} k_1^\mu &= (\alpha_1 - y\beta_1(\frac{Q^2}{2p_i \cdot Q}))p_i^\mu + y\beta_1 Q^\mu + \sqrt{y\alpha_1\beta_1}n_{\perp,1}^\mu \\ q_i^\mu &= (\beta_1 - \alpha_1 y(\frac{Q^2}{2p_i \cdot Q}))p_i^\mu + y\alpha_1 Q^\mu - \sqrt{y\alpha_1\beta_1}n_{\perp,1}^\mu \\ q_k^\mu &= \alpha\Lambda^\mu{}_\nu p_k^\nu \quad k = 1, \dots, n \quad k \neq i \end{aligned} \quad (3.49)$$

Short form:

$$\begin{aligned} k_1^\mu &= \zeta_1 p_i^\mu + \lambda_1 Q^\mu + \sqrt{y\alpha_1\beta_1}n_{\perp,1}^\mu \\ q_i^\mu &= \zeta_q p_i^\mu + \lambda_q Q^\mu - \sqrt{y\alpha_1\beta_1}n_{\perp,1}^\mu \\ q_k^\mu &= A_1 p_i^\mu + A_2 Q^\mu + \sqrt{1-y}p_k^\mu \end{aligned}$$

### 3.8 Common scalar products

For the investigating of the mapping it is useful to determine first the dot products between these four vectors. The often occurring pre-factor products are given in 6.

$$\boxed{k_1 \cdot q_i = y(\alpha_1 + \beta_1)^2 p_i \cdot Q = y p_i \cdot Q} \quad (3.50)$$

$$\boxed{k_1 \cdot q_k = [\alpha_1(1-y) + y\beta_1(\frac{Q^2}{2p_i \cdot Q})] p_i \cdot p_k + y\beta_1 Q \cdot p_k + \sqrt{\alpha_1\beta_1}y(1-y)p_k \cdot n_{\perp,1}} \quad (3.51)$$

$$\boxed{q_i \cdot q_k = [\beta_1(1-y) + y\alpha_1(\frac{Q^2}{2p_i \cdot Q})] p_i \cdot p_k + y\alpha_1 Q \cdot p_k - \sqrt{\alpha_1\beta_1}y(1-y)p_k \cdot n_{\perp,1}} \quad (3.52)$$

### 3.9 Recipe for the usage of the new parametrisation

As in the last chapter mentioned the singularities come from the propagators in each diagram since the denominators contain according Feynmann rules terms with  $\sim \frac{1}{2q_a \cdot q_b}$ . Whereby a and b label the respective momenta. Since the calculations are sometimes very complicated and confusing, the procedure for eliminating the finite terms is as follows: In the calculating of the square matrix elements always appear products in the form of  $p_a \cdot p_b$  both in the numerator and denominator. The denominator shows which pre-factor causes the singularity. These terms from the numerator with the same prefix can be omitted from the beginning because they appear in both the denominator and the numerator and are therefore finite. This is explicitly shown below for a common denominators. This operation can be performed for the other types of the denominator.

### 3.9.1 Parametrization in terms of $(k_1 \cdot q_i)(k_1 \cdot q_k)$

$$\boxed{(k_1 \cdot q_i)(k_1 \cdot q_k) \approx y(1 - \beta_1)(1 - y)(p_i \cdot p_k)(p_i \cdot Q)} \quad (3.53)$$

Here you can quickly see that this term converges for  $y \rightarrow 0$  and  $\beta_1 \rightarrow 1$  towards zero. That means, you could ignore all terms with  $y(1 - \beta_1)$ . However, since the equation becomes rather large quickly if we first use all the momenta products and then drop the terms with the pre-factor out of the denominator, this is already done for the scalar products. And this is exactly the biggest simplification in the calculation. The result looks like this:

$$\begin{aligned} k_1^\eta k_1^{\eta'} &= [(1 - \beta_1)^2 - y^2 \beta_1^2 (\frac{Q^2}{2p_i \cdot Q})^2] p_i^\eta p_i^{\eta'} - y^2 \beta_1^2 (\frac{Q^2}{2p_i \cdot Q}) p_i^\eta Q^{\eta'} - y^2 \beta_1^2 (\frac{Q^2}{2p_i \cdot Q}) Q^\eta p_i^{\eta'} \\ k_1^\eta q_i^{\eta'} &= [\beta_1(1 - \beta_1) - y \beta_1^2 (\frac{Q^2}{2p_i \cdot Q})] p_i^\eta p_i^{\eta'} + y \beta_1^2 Q^\eta p_i^{\eta'} \\ q_i^\eta k_1^{\eta'} &= [\beta_1(1 - \beta_1) - y \beta_1^2 (\frac{Q^2}{2p_i \cdot Q})] p_i^\eta p_i^{\eta'} + y \beta_1^2 p_i^\eta Q^{\eta'} \\ q_i^\eta q_i^{\eta'} &= \beta_1^2 p_i^\eta p_i^{\eta'} \\ k_1^\eta q_k^{\eta'} &= [(1 - \beta_1) - y \beta_1 (\frac{Q^2}{2p_i \cdot Q})] \sqrt{1 - y} p_i^\eta p_k^{\eta'} - y \beta_1 (\frac{Q^2}{2p_i \cdot Q}) A_1 p_i^\eta p_i^{\eta'} \\ &\quad - y \beta_1 (\frac{Q^2}{2p_i \cdot Q}) A_2 p_i^\eta Q^{\eta'} + y \beta_1 A_1 Q^\eta p_i^{\eta'} + y \beta_1 A_2 Q^\eta Q^{\eta'} + y \beta_1 \sqrt{1 - y} Q^\eta p_k^{\eta'} \\ q_i^\eta q_k^{\eta'} &= A_1 \beta_1 p_i^\eta p_i^{\eta'} + A_2 \beta_1 p_i^\eta Q^{\eta'} + \beta_1 \sqrt{1 - y} p_i^\eta p_k^{\eta'} \\ q_k^\eta k_1^{\eta'} &= [(1 - \beta_1) - y \beta_1 (\frac{Q^2}{2p_i \cdot Q})] \sqrt{1 - y} p_k^\eta p_i^{\eta'} - y \beta_1 (\frac{Q^2}{2p_i \cdot Q}) A_1 p_i^\eta p_i^{\eta'} \\ &\quad - y \beta_1 (\frac{Q^2}{2p_i \cdot Q}) A_2 Q^\eta p_i^{\eta'} + y \beta_1 A_1 p_i^\eta Q^{\eta'} + y \beta_1 A_2 Q^\eta Q^{\eta'} + y \beta_1 \sqrt{1 - y} p_k^\eta Q^{\eta'} \\ q_k^\eta q_i^{\eta'} &= A_1 \beta_1 p_i^\eta p_i^{\eta'} + A_2 \beta_1 Q^\eta p_i^{\eta'} + \beta_1 \sqrt{1 - y} p_k^\eta p_i^{\eta'} \end{aligned} \quad (3.54)$$

## Concept

Before the procedure is explained, at this point it should be mentioned that the steps are gradually explained in more detail in the next steps. This only provides a rough overview and can be used as a reference for the other sections.

- i) First of all, look at a possible splitting. For this one has to make sure that all possible meaningful diagrams have been considered. All  $M_1$ ,  $M_2$ ,  $M_1^\dagger M_2$  and  $M_1 M_2^\dagger$  diagrams need to be indexed independently of each other. To determine the matrix elements, the Feynmann rules will be used which is explained in detail in section 2.2. Before the kinematics is used, the obtained matrix element should be simplified by matrix algebra, which is completely explained in the appendix Mathematical Tool, otherwise the calculation of the parametrisation becomes clearly more complicated.
- ii) Each diagram consists of an emitter and a spactator part. The emitter part itself contains an emitter parent with the momentum  $q_i + q$  in the old kinematic, of which a patron is split with  $q$ . A daughter-patron with  $q_i$  remains of the parent patron. One should select the spectator  $q_j$  skilfully, so that the diagrams are meaningful and calculable in the case of the interference terms, otherwise one must manipulate with the final results because of the unanimity of the indices. Thus a structure is achieved and the diagrams can be replaced from  $M_1, M_1^\dagger, M_2^\dagger$  and  $M_2$  side by side and even use their probability amplitude for the interference terms without having to recalculate them every time.
- iii) Before starting to calculate, it will be firs tried to predict the expected result based on the contracting indices. Usually the non-contracting indices that remain form the final result as one or more tensors. This is relatively helpful when a calculation for a certain limit is performed, because it can be quickly seen from the square matrix element which terms must be calculated for the final result.
- iv) When using parametrisation, it is recommended to use the concepts from the previous section. This is paractic, because when evaluating matrix elements, the multiplication of two tensors often occurs. To see which case to use for which matrix element, first look at the scalar products in the denominator that come from the propagators. Basically, there are four common scalar products listed here for this thesis:

- $(q \cdot q_i)(q \cdot q_i)$
- $(q \cdot q_j)(k_1 \cdot q_j)$
- $(q \cdot q_i)(q \cdot q_j)$
- $(q \cdot q_i)(q_i \cdot q_i)$

With the concept from the last section it was recognized exactly, which terms are finite, so that they can be omitted with the multiplication of the tensors in the apron. In other words, it is first recognized which pre-factors in the denominator cause singularities and then those terms with the same pre-factors are eliminated as finite terms. This considerably reduces the evaluation. This will become clearer later if the splitting functions are determined in the collinear limit from the respective diagram. For the new parametrisation, the following substitution is used:

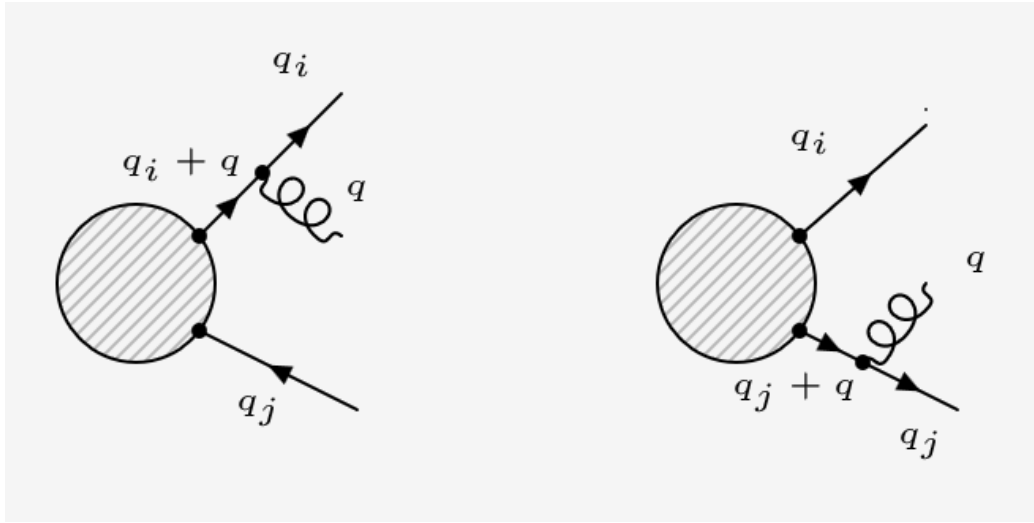
$$\begin{aligned} q_i &\rightarrow q_i \\ q &\rightarrow k_1 \\ q_j &\rightarrow q_k \end{aligned} \tag{3.55}$$

- v) finally, to find out whether everything was calculated correctly, the collinear limits will be used because it is known that in this case the well known Alterali-Parisi 3.14 splitting function have to be output.
- vi) In the case of indistinguishable particles in relation to the calculation of the interferometer, the momentum of the particles for the same diagram must be exchanged once in order to obtain the full result.



## 4 The LO splitting functions

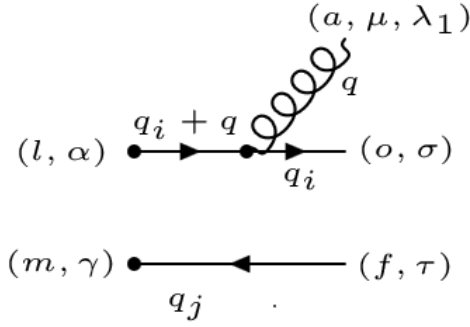
### 4.1 Gluon emission from a parent quark



First we are going to consider a daughter quark from the splitting of a parent quark into a quark and a gluon with an arbitrary spectator like an anti-quark, see the left picture above. where  $q_j + q$  is the momentum of the quark before splitting,  $q$  the momentum of the gluon and  $q_j$  of daughter quark respectively. The momentum of the spectator is  $q_i$ . The distinction between daughter and parent vanishes, when the gluon becomes soft, and a singularity develops. The other possibility to get a singularity is surely if the gluon will be collinear to quark. The splitting functions are flavour independent since the strong interaction is flavour independent. Furthermore, leading order splitting cannot change the flavour of a quark, thus we can write for the splitting functions In leading order QCD:

$$P_{\bar{q}_i \bar{q}_j} = P_{q_i q_j} = P_{qq} \delta_{ij} \quad (4.1)$$

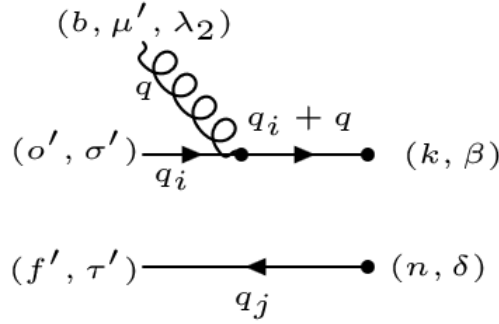
For this aim we have to take any diagram to the account which can have the same splitting. Since there is no distinction between quark and anti-quark, one can imagine exact the same splitting variation for anti-quark with a quark as a spectator, see the right picture above.

4.1.1 Matrix element of a quark with a gluon radiation  $|M_1|^2$ 

If one simply calculates the amplitude of this diagram, one gets:

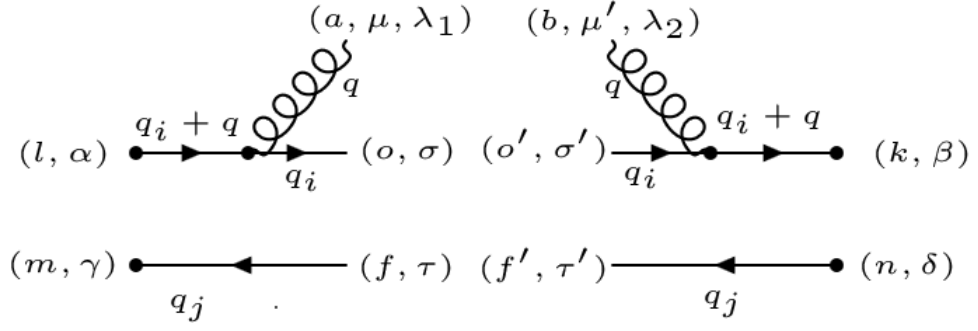
$$M_1 = [\bar{u}_\sigma(q_i)(-ig_s\gamma^\mu \times [T^a]_o^l) \frac{i(\not{q}_i + \not{q})}{(q_i + q)^2} \varepsilon^{\lambda_1}_\mu(q)] [v_\tau(q_j)] \quad (4.2)$$

For the quadratic matrix element we need the dagger of  $M_1$  as well.



$$M_1^\dagger = [\frac{-i(\not{q}_i + \not{q})}{(q_i + q)^2} (ig_s\gamma^{\mu'} \times [T^b]_{o'}^k) u_{\sigma'}(q_i) \varepsilon^{\lambda_2}_{\mu'}(q)] [\bar{v}_{\tau'}(q_j)] \quad (4.3)$$

After multiplying  $M_1^\dagger$  and  $M_1$  we get the desired result.



$$|M_1|^2 = M_1 M_1^\dagger = [\bar{u}_\sigma(q_i) (-ig_s \gamma^\mu \times [T^a]_{o^l}^l) \frac{i(\not{q}_i + \not{q})}{(q_i + q)^2} \varepsilon^{\lambda_1}_\mu(q)] [v_\tau(q_j)]$$

$$[\frac{-i(\not{q}_i + \not{q})}{(q_i + q)^2} (ig_s \gamma^{\mu'} \times [T^b]_{o'^k}^k) u_{\sigma'}(q_i) \varepsilon^{\lambda_2}_{\mu'}^*(q)] [\bar{v}_{\tau'}(q_j)]$$
(4.4)

Now it's time to connect those terms which are related to each other.

$$|M_1|^2 = [\frac{-i(\not{q}_i + \not{q})}{(q_i + q)^2} (ig_s \gamma^{\mu'} \times [T^b]_{o'^k}^k) \bar{u}_\sigma(q_i) u_{\sigma'}(q_i) \varepsilon^{\lambda_2*}_{\mu'}(q) \varepsilon^{\lambda_1}_\mu(q)$$

$$\times (-ig_s \gamma^\mu \times [T^a]_{o^l}^l) \frac{i(\not{q}_i + \not{q})}{(q_i + q)^2}] [\bar{v}_{\tau'}(q_j) v_\tau(q_j)]$$
(4.5)

Sum over the lorenz index  $(\sigma, \sigma')$  and  $(\tau, \tau')$  and spin addition relation leads to:

$$\sum_{\sigma, \sigma'} \bar{u}_\sigma(q_i) u_{\sigma'}(q_i) = \not{q}_i \delta^{\sigma\sigma'},$$

$$\sum_{\tau, \tau'} \bar{v}_\tau(q_j) v_{\tau'}(q_j) = \not{q}_j \delta^{\tau\tau'}$$
(4.6)

Sum over polarization index  $(\lambda_1, \lambda_2)$  :

$$\sum_{\mu, \mu'} \varepsilon^{\lambda_2*}_{\mu'}(q) \varepsilon^{\lambda_1}_\mu(q) = -g_{\mu\mu'} \delta^{ab}$$
(4.7)

The matrix element will be simplified with:

$$|M_1|^2 = \frac{-g_s^2 [T^a]_{o^k}^k [T^a]_{o^l}^l}{(q_i + q)^2 (q_i + q)^2} [(\not{q}_i + \not{q}) \gamma^{\mu'} \not{q}_i g_{\mu'\mu} \gamma^\mu (\not{q}_i + q)] [\not{q}_j]$$
(4.8)

When we contract all related indices we will be actually able to make a statements about the last result.

$$|M_1|^2 = \frac{-g_s^2 [T^a]_{o^k}^k [T^a]_{o^l}^l}{(q_i + q)^2 (q_i + q)^2} [(\not{q}_i + \not{q}) \gamma^{\mu'} \not{q}_i \gamma_{\mu'} (\not{q}_i + q)] [\not{q}_j]$$
(4.9)

In other words we expect the tree level diagram from LO and a number:

Which graphically means:

$$|M^2| = \left| \begin{array}{c} \text{diagram with two shaded circles and arrows } P_i, P_j \\ \text{contribution from LO} \end{array} \right|^2 \otimes \left| \begin{array}{c} \text{diagram with a loop and external lines } q_i, q, q_i+q \\ \text{a complex number} \end{array} \right|^2$$

$$|M_1|^2 = \frac{-g_s^2 [T^a]_o^k [T^a]_o^l}{(q_i + q)^2 (q_i + q)^2} [P_i][P_j] \otimes (\text{a complex number}) \quad (4.10)$$

Let's calculate the contribution and compare the final result with this expectation:

$$\begin{aligned} N &= : \gamma^{\mu'} \not{A}_i \gamma_{\mu'} = q_{i\sigma} \gamma^{\mu'} \gamma^\sigma \gamma_{\mu'} \\ &= q_{i\sigma} (\{\gamma^{\mu'}, \gamma^\sigma\} - \gamma^\sigma \gamma^{\mu'}) \gamma_{\mu'} \\ &= q_{i\sigma} 2g^{\mu'\sigma} \gamma_{\mu'} - d \gamma^\sigma \\ &= (2 - d) \not{A}_i \end{aligned} \quad (4.11)$$

Simplification of the bracket:

$$|M_1|^2 = -(2 - d) \frac{g_s^2 [T^a]_o^k [T^a]_o^l}{(q_i + q)^2 (q_i + q)^2} [(\not{A}_i + \not{A}) \not{A}_i (\not{A}_i + q)] [\not{A}_j] \quad (4.12)$$

$$|M_1|^2 = -(2 - d) \frac{g_s^2 [T^a]_o^k [T^a]_o^l}{(q_i + q)^2 (q_i + q)^2} [\not{A}_i \not{A}_i \not{A}_i + \not{A}_i \not{A}_i \not{A} + \not{A} \not{A}_i \not{A}_i + \not{A} \not{A}_i \not{A}] [\not{A}_j] \quad (4.13)$$

Momenta are on-shell, so:

$$\begin{aligned} \not{A}_i \not{A}_i &= q_i^2 = m_i^2 \\ \not{A} \not{A} &= q^2 = m^2 \\ \not{A}_j \not{A}_j &= q_j^2 = m_j^2 \end{aligned} \quad (4.14)$$

we can first neglect the mass of patrons:

$$|M_1|^2 = -(2 - d) \frac{g_s^2 [T^a]_o^k [T^a]_o^l}{(2q_i q)(2q_i q)} [\not{A} \not{A}_i \not{A}] [\not{A}_j] \quad (4.15)$$

Here we need to make the terms in the brackets simpler and:

$$\begin{aligned}
L &= \not{q}_i \not{q}_i \not{q} = \not{q}[q_{i\sigma}q_\mu (\{\gamma^\mu, \gamma^\sigma\} - \gamma^\sigma \gamma^\mu)] \\
&= \not{q}[2q_i^\mu q_\mu - q_{i\sigma}q_\mu \gamma^\mu \gamma^\sigma] \\
&= \not{q}(2q_i q) - q_\mu q_{i\sigma}q_\mu [\gamma^\mu \gamma^\mu \gamma^\sigma] \\
&= \not{q}(2q_i q) - q_\mu q_{i\sigma}q_\mu [\frac{\gamma^\mu \gamma^\mu}{2} + \frac{\gamma^\mu \gamma^\mu}{2}] \gamma^\sigma \\
&= \not{q}(2q_i q) - q_\mu q_{i\sigma}q_\mu [g^{\mu\mu}] \gamma^\sigma \\
&= \not{q}(2q_i q) - q_\mu q_{i\sigma}q^\mu \gamma^\sigma = \not{q}(2q_i q) - q^2 \not{q}_i \\
&= \not{q}(2q_i q)
\end{aligned} \tag{4.16}$$

After inserting the last result of  $L$  and simplify the term  $(2q_i q)$  from the denominator and nominator, we get:

$$|M_1|^2 = -(2-d) \frac{g_s^2 [T^a]_o^k [T^a]_o^l}{2y(p_i \cdot p_j)} [\not{q}] [\not{q}_j] \tag{4.17}$$

Now we are going to use the parametrisation from equation (1) to reduce the 3-member matrix element to 2-member and take out the singularity term from the amplitude.

$$|M_1|^2 = (d-2) \frac{g_s^2 [T^a]_o^k [T^a]_o^l}{2y(p_i \cdot p_j)} [(1-z) \not{p}_i + zy \not{p}_j - \sqrt{zy(1-z)} \not{m}_\perp] [(1-y) \not{p}_j] \tag{4.18}$$

Multiplying the both sides

$$\begin{aligned}
|M_1|^2 &= (d-2) \frac{g_s^2 [T^a]_o^k [T^a]_o^l}{2y(p_i \cdot p_j)} [(1-z)(1-y) \not{p}_i \not{p}_j \\
&\quad + zy(1-y) \not{p}_j \not{p}_j - (1-y)\sqrt{zy(1-z)} \not{m}_\perp \not{p}_j]
\end{aligned} \tag{4.19}$$

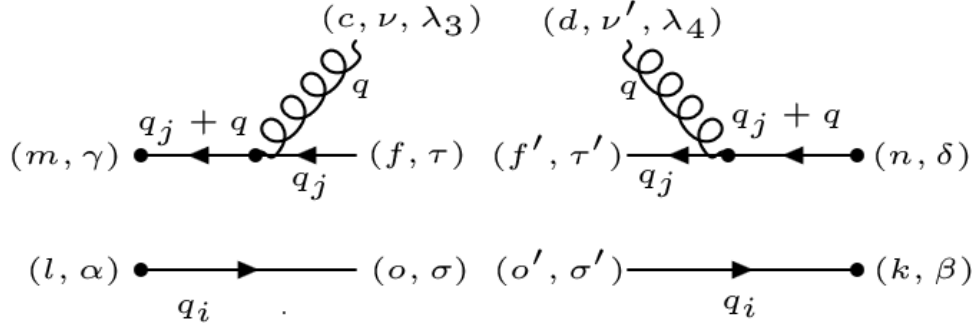
Under consideration of the fact that  $p_i$  and  $p_j$  are the on-shell momenta of the emitter and spectator partons, we can ignore the terms with  $\not{p}_i \not{p}_i$  and  $\not{p}_j \not{p}_j$ . The  $p_i \cdot m_\perp$  and  $p_j \cdot m_\perp$  are always 0 because the  $p_i$  and  $p_j$  are lightlike, i.e. zero transverse component. So those terms can be neglected.

$$|M_1|^2 = \frac{g_s^2 [T^a]_o^k [T^a]_o^l}{2y(p_i \cdot p_j)} [\not{p}_i] [\not{p}_j] \otimes (d-2)(1-z)(1-y) \tag{4.20}$$

As discussed, we get a contribution from the LO a complex number. As you can see, the number is just for  $y \rightarrow 0$  singular and not for  $z \rightarrow 1$ .

### 4.1.2 Matrix element of an anti-quark with a gluon radiation $|M_2|^2$

the same procedure is used to obtain the matrix element for an anti-quark with a single gluon emission.



$$|M_2|^2 = M_2 M_2^\dagger = \left[ \frac{i(\not{q}_j + \not{q})}{(q_j + q)^2} (-ig_s \gamma^\nu \times [T^c]_f^m) v_\tau(q_j) \varepsilon^{\lambda_3}_\nu(q) [u_\sigma(q_i)] \right. \\ \left. [\bar{v}_{\tau'}(q_j) (ig_s \gamma^{\nu'} \times [T^d]_{f'}^n) \frac{-i(\not{q}_j + \not{q})}{(q_j + q)^2} \varepsilon^{\lambda_4}_{\nu'}(q) [\bar{u}_{\sigma'}(q_i)] \right] \quad (4.21)$$

$$|M_2|^2 = \frac{g_s^2 [T^c]_f^m [T^d]_{f'}^n}{(q_j + q)^2 (q_j + q)^2} [(\not{q}_j + \not{q}) \gamma^\nu v_\tau(q_j) \bar{v}_{\tau'}(q_j) \varepsilon^{\lambda_3}_\nu(q) \varepsilon^{\lambda_4}_{\nu'}(q) \gamma^{\nu'} (\not{q}_j + \not{q})] \\ [u_\sigma(q_i)] [\bar{u}_{\sigma'}(q_i)] \quad (4.22)$$

and after sum over the lorenz and polarization indexes like  $(\sigma, \sigma')$ ,  $(\tau, \tau')$  and  $(\lambda_3, \lambda_4)$  as well and using the spin addition relation:

$$|M_2|^2 = \frac{g_s^2 [T^c]_f^m [T^c]_{f'}^n}{(q_j + q)^2 (q_j + q)^2} [(\not{q}_j + \not{q}) \gamma^\nu \not{q}_j (-g_{\nu\nu'}) \gamma^{\nu'} (\not{q}_j + \not{q})] [\not{q}_i] \quad (4.23)$$

Analogous to the last calculation from the previous section:

$$|M_2|^2 = (d-2) \frac{g_s^2 [T^c]_f^m [T^c]_{f'}^n}{(2qq_j)} [\not{q}] [\not{q}_i] \quad (4.24)$$

$$|M_2|^2 = (d-2) \frac{g_s^2 [T^c]_f^m [T^c]_{f'}^n}{(2qq_j)} [(1-z) \not{p}_i + yz \not{p}_j - \sqrt{zy(1-z)} \not{n}_\perp] \\ [z \not{p}_i + y(1-z) \not{p}_j + \sqrt{zy(1-z)} \not{n}_\perp] \quad (4.25)$$

$$\begin{aligned}
|M_2|^2 = & (d-2) \frac{g_s^2 [T^c]_f^m [T^c]_f^n}{(2qq_j)} [y(1-z)^2 \not{p}_i \not{p}_j + (1-z) \sqrt{zy(1-z)} \not{p}_i \not{n}_\perp \\
& + yz^2 \not{p}_j \not{p}_i + yz \sqrt{zy(1-z)} \not{p}_j \not{n}_\perp - z \sqrt{zy(1-z)} \not{n}_\perp \not{p}_i \\
& - y(1-z) \sqrt{zy(1-z)} \not{n}_\perp \not{p}_j - zy(1-z) \not{n}_\perp \not{n}_\perp]
\end{aligned} \tag{4.26}$$

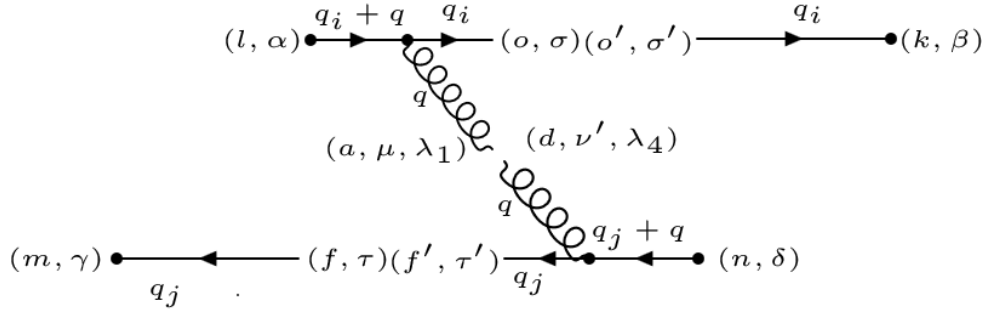
$$\begin{aligned}
|M_2|^2 = & (d-2) \frac{g_s^2 [T^c]_f^m [T^c]_f^n}{(2qq_j)} [y(1-z)^2 \not{p}_i \not{p}_j + (1-z) \sqrt{zy(1-z)} \not{p}_i \not{n}_\perp \\
& + 2yz^2(p_i \cdot p_j) - yz^2 \not{p}_i \not{p}_j + yz \sqrt{zy(1-z)} \not{p}_j \not{n}_\perp + z \sqrt{zy(1-z)} \not{p}_i \not{n}_\perp \\
& + y(1-z) \sqrt{zy(1-z)} \not{p}_j \not{n}_\perp + 2zy(1-z)(p_i \cdot p_j)]
\end{aligned} \tag{4.27}$$

$$\begin{aligned}
|M_2|^2 = & (d-2) \frac{g_s^2 C_F}{2(1-z)(1-y)(p_i \cdot p_j)} [y(1-2z) \not{p}_i \not{p}_j + \sqrt{zy(1-z)} \not{p}_i \not{n}_\perp \\
& + y \sqrt{zy(1-z)} \not{p}_j \not{n}_\perp + 2zy(p_i \cdot p_j)]
\end{aligned} \tag{4.28}$$

Interestingly, here is a term with  $y$  concerning the gluon radiation from an anti-quark. This means that this result cannot contribute to the collinear limit for soft gluon  $y \rightarrow 0$ .

### 4.1.3 Interference contribution

So far most of the work is done and we just have to put the results of  $M_1$  and  $M_2^\dagger$  next to each other, as we can see in the diagram. So we still get the interference contribution. Using the results from the previous section and we received:



$$M_1 M_2^\dagger = [\bar{u}_\sigma(q_i) (-ig_s \gamma^\mu \times [T^a]_o^l) \frac{i(\not{q}_i + \not{q})}{(q_i + q)^2} \varepsilon^{\lambda_1}_\mu(q)] [v_\tau(q_j)]$$

$$[\bar{v}_{\tau'}(q_j) (ig_s \gamma^{\nu'} \times [T^d]_{f'}^n) \frac{-i(\not{q}_j + \not{q})}{(q_j + q)^2} \varepsilon^{\lambda_4}_{\nu'}(q)] [u_{\sigma'}(q_i)] \quad (4.29)$$

$$M_1 M_2^\dagger = \frac{g_s^2 [T^a]_o^l [T^d]_{f'}^n}{(2q_i q)(2q_j q)} [\not{q}_i \gamma^\mu (\not{q}_i + \not{q})] \varepsilon^{\lambda_1}_\mu(q) \varepsilon^{\lambda_4}_{\nu'}(q) [\not{q}_j \gamma^{\nu'} (\not{q}_j + \not{q})] \quad (4.30)$$

$$M_1 M_2^\dagger = \frac{g_s^2 [T^a]_o^l [T^a]_{f'}^n}{(2q_i q)(2q_j q)} [\not{q}_i \gamma^\mu (\not{q}_i + \not{q})] (-g_{\mu\nu'}) [\not{q}_j \gamma^{\nu'} (\not{q}_j + \not{q})] \quad (4.31)$$

$$M_1 M_2^\dagger = \frac{-g_s^2 [T^a]_o^l [T^a]_{f'}^n}{(2q_i q)(2q_j q)} [\not{q}_i \gamma^\mu (\not{q}_i + \not{q})] [\not{q}_j \gamma_\mu (\not{q}_j + \not{q})] \quad (4.32)$$

Expectation:

$$|M^2| = \left| \begin{array}{c} \text{Diagram with two shaded circles connected by two horizontal lines labeled } P_i \text{ and } P_j \\ \text{contribution from LO} \end{array} \right|^2 \otimes \left| \begin{array}{c} \text{Diagram with a shaded circle and a wavy line} \\ \text{a complex number} \end{array} \right|^2$$



$$M_1 M_2^\dagger = \frac{-g_s^2 [T^a]_o^l [T^a]_{f'}^n}{(2q_i q)(2q_j q)} [(z \not{p}_i + y(1-z) \not{p}_j + \sqrt{zy(1-z)} \not{n}_\perp) \gamma^\mu (\not{p}_i + y \not{p}_j)] \\ [(1-y) \not{p}_j \gamma_\mu ((1-z) \not{p}_i + (1+yz-y) \not{p}_j - \sqrt{zy(1-z)} \not{n}_\perp)] \quad (4.33)$$

$$M_1 M_2^\dagger = \frac{-g_s^2 [T^a]_o^l [T^a]_{f'}^n}{4(1-z)y(p_i \cdot p_j)(p_i \cdot p_j)} [z \not{p}_i \gamma^\mu \not{p}_i + zy \not{p}_i \gamma^\mu \not{p}_j \\ + y(1-z) \not{p}_j \gamma^\mu \not{p}_i + y^2(1-z) \not{p}_j \gamma^\mu \not{p}_j + \sqrt{zy(1-z)} \not{n}_\perp \gamma^\mu \not{p}_i \\ + y\sqrt{zy(1-z)} \not{n}_\perp \gamma^\mu \not{p}_j] [(1-z) \not{p}_j \gamma_\mu \not{p}_i + (1+yz-y) \not{p}_j \gamma_\mu \not{p}_j \\ - (1-z)\sqrt{zy(1-z)} \not{p}_j \gamma_\mu \not{n}_\perp] \quad (4.34)$$

$$M_1 M_2^\dagger = \frac{-g_s^2 [T^a]_o^l [T^a]_{f'}^n}{4(1-z)y(p_i \cdot p_j)(p_i \cdot p_j)} [2zp_i^\mu \not{p}_i + 2zyp_i^\mu \not{p}_j - zy \not{p}_i \not{p}_j \\ + 2y(1-z)p_j^\mu \not{p}_i - y(1-z) \not{p}_j \not{p}_i + 2y^2(1-z)p_j^\mu \not{p}_j + 2\sqrt{zy(1-z)}m_\perp^\mu \not{p}_i \\ - \sqrt{zy(1-z)} \not{n}_\perp \not{p}_i + 2y\sqrt{zy(1-z)}m_\perp^\mu \not{p}_j - y\sqrt{zy(1-z)} \not{n}_\perp \not{p}_j] \\ [2(1-z)p_{j\mu} \not{p}_i - (1-z) \not{p}_j \not{p}_i + 2(1+yz-y)p_{j\mu} \not{p}_j \\ - 2(1-z)\sqrt{zy(1-z)}p_{j\mu} \not{n}_\perp + (1-z)\sqrt{zy(1-z)} \not{p}_j \not{n}_\perp] \quad (4.35)$$

$$M_1 M_2^\dagger = \frac{-g_s^2 [T^a]_o^l [T^a]_{f'}^n}{4(1-z)y(p_i \cdot p_j)(p_i \cdot p_j)} [4z(1+yz-y)(p_i \cdot p_j) \not{p}_i \not{p}_j \\ + 4zy(1-z)(p_i \cdot p_j) \not{p}_j \not{p}_i + 4y(1-z)^2(p_i \cdot p_j) \not{p}_j \not{p}_i] \quad (4.36)$$

$$M_1 M_2^\dagger = \frac{-g_s^2 [T^a]_o^l [T^a]_{f'}^n}{y(p_i \cdot p_j)} [\not{p}_i \not{p}_j] \otimes \frac{z}{1-z} \quad (4.37)$$

Now we use the old parametrization to collect the singularities.

Here we can use the singular term in the denominator  $y(1-z)$  to drop the term with the same pre-factor and thus obtain:

#### 4.1.4 Final result

One could assume that for a complete result the contribution  $M_1^\dagger M_2$  is still missing.

$$|M|^2 = |M_1|^2 + |M_2|^2 + M_1 M_2^\dagger + M_1^\dagger M_2 \quad (4.38)$$

It should be noted that it is completely sufficient to calculate  $M_1 M_2^\dagger$ , because we know

$$|M^2| = \left| \begin{array}{c} q_i \quad q_i \\ \text{diagram 1} \end{array} \right|^2 + \left| \begin{array}{c} q_i \quad q_i \\ \text{diagram 2} \end{array} \right|^2 + 2 \operatorname{RE} \left( \begin{array}{c} q_i \quad q_i \\ \text{diagram 3} \end{array} \right)$$

it from the quadratic amount of the complex numbers, we can calculate double of real part of  $2\operatorname{RE}(M_1 M_2^\dagger)$  instead of  $M_1 M_2^\dagger + M_1^\dagger M_2$  and that is exactly what is preferred here.

$$|M|^2 = |M_1|^2 + |M_2|^2 + 2\operatorname{RE}(M_1 M_2^\dagger) \quad (4.39)$$

Let's just add up the results from the previous sections and get:

$$|M|^2 = \left| \begin{array}{c} q_i \quad q_i \\ \text{diagram 1} \end{array} \right|^2 + \left| \begin{array}{c} q_i \quad q_i \\ \text{diagram 2} \end{array} \right|^2 + 2 \operatorname{RE} \left( \begin{array}{c} q_i \quad q_i \\ \text{diagram 3} \end{array} \right)$$

$$\begin{aligned} |M|^2 &= (d-2)(1-z)(1-y) \frac{g_s^2 [T^a]_o^k [T^a]_o^l}{2y(p_i \cdot p_j)} [\not{p}_i][\not{p}_j] \\ &\quad - (d-2)yz^2 \frac{g_s^2 [T^c]_f^m [T^c]_f^n}{2(1-z)(1-y)(p_i \cdot p_j)} [\not{p}_i][\not{p}_j] \\ &\quad + 2\operatorname{RE} \left( \left( \frac{-2z}{z-1} \right) \frac{g_s^2 [T^a]_o^l [T^a]_f^n}{2y(p_i \cdot p_j)} [\not{p}_i][\not{p}_j] \right) \end{aligned} \quad (4.40)$$

Now we use the knowledge from the introduction about the calculation of the Colour factor. With Fritz equation:

$$T^a_{ok} T^a_{lo} = \frac{1}{2}(\delta_{oo}\delta_{lk} - \frac{1}{N}\delta_{ok}\delta_{lo}) = \frac{1}{2}(N\delta_{lk} - \frac{1}{N}\delta_{lk}) = C_F\delta_{lk} \quad (4.41)$$

After summation over the final colour states and averaging over initial colour states we get:

$$T^a_{ok} T^a_{lo} = C_F\delta_{lk} = \frac{1}{N} \sum_{l=1}^N \delta_{lk} C_F = C_F \quad (4.42)$$

The same calculation for  $T^c_{mf} T^c_{fn}$  and  $T^a_{ol} T^a_{fn}$  turns  $C_F$  out as the colour factor. Now we are going to compute the splitting function in the case of the colinearity, wich means, if:

$$y \longrightarrow 0 \quad (4.43)$$

$$|M|^2 = \frac{g_s^2 C_F}{2y(1-2z+2z^2)(p_i \cdot p_j)} [\not{p}_i][\not{p}_j] \otimes ((d-2)(1-z) - \frac{4z}{z-1}) \quad (4.44)$$

for  $d = 4 - 2\epsilon$

$$\begin{aligned} |M|^2 &= \frac{g_s^2}{y(p_i \cdot p_j)} [\not{p}_i][\not{p}_j] \otimes C_F \left( \frac{(1+z^2)}{1-z} - \epsilon(1-z) \right) \\ &= \frac{g_s^2}{q_i \cdot q} [\not{p}_i][\not{p}_j] \otimes \langle \hat{P}_{qq} \rangle \end{aligned} \quad (4.45)$$

With Alterali-Parisi splitting function  $\langle \hat{P}_{qq} \rangle$  in the collinear limes, which was mentioned in the previous chapter. This is exactly the confirmation of our calculation that our calculation was actually performed correctly, otherwise we would not have received the same splitting function for soft gluons.

### 4.1.5 Double-check the results with the new kinematic

One could do exactly the same calculation for the new kinematics to see if you get the same result in the collinear limit. From the next chapter we will explicitly work with the new parametrisation, because we found that the old kinematics only work in NLO and one-single emission.

$$|M_1|^2$$

$$|M_1|^2 = (d-2) \frac{g_s^2 C_F}{(2k_1 \cdot q_i)} [k_1] [\not{q}_k] \quad (4.46)$$

$$|M_1|^2 = (d-2) \frac{g_s^2 C_F}{2y p_i \cdot Q} [(\alpha_1 - y\beta_1 (\frac{Q^2}{2p_i \cdot Q})) \not{p}_i + y\beta_1 \not{Q} + \sqrt{y\alpha_1\beta_1} \not{h}_{\perp,1}] \quad (4.47)$$

$$[A_1 \not{p}_i + A_2 \not{Q} + \sqrt{1-y} \not{p}_k]$$

$$|M_1|^2 = (d-2) \frac{g_s^2 C_F}{2y p_i \cdot Q} [(A_2(\alpha_1 - y\beta_1 (\frac{Q^2}{2p_i \cdot Q})) + A_1 y\beta_1) \not{p}_i \not{Q} \quad (4.48)$$

$$+ (\alpha_1 - y\beta_1 (\frac{Q^2}{2p_i \cdot Q})) \sqrt{1-y} p_i \cdot p_k + A_2 y\beta_1 Q^2 + \sqrt{1-y} \sqrt{y\alpha_1\beta_1} n_{\perp,1} \cdot p_k]$$

For the collinearity  $y \rightarrow 0$  we'll get:

$$|M_1|^2 = (d-2) \frac{g_s^2 C_F}{2y p_i \cdot Q} [(A_2(\alpha_1 - y\beta_1 (\frac{Q^2}{2p_i \cdot Q})) + A_1 y\beta_1) \not{p}_i \not{Q} \quad (4.49)$$

$$+ (\alpha_1 - y\beta_1 (\frac{Q^2}{2p_i \cdot Q})) \sqrt{1-y} \not{p}_i \not{p}_k + A_2 y\beta_1 Q^2 + \sqrt{1-y} \sqrt{y\alpha_1\beta_1} \not{h}_{\perp,1} \not{p}_k]$$

$$|M_1|^2 = (d-2)(1-\beta_1) \sqrt{1-y} \frac{g_s^2 C_F}{2y p_i \cdot Q} [\not{p}_i \not{p}_k] \quad (4.50)$$

$$|M_2|^2$$

$$|M_2|^2 = (d-2) \frac{g_s^2 C_F}{2k_1 \cdot q_k} [k_1] [\not{q}_i] \quad (4.51)$$

$$|M_2|^2 = (d-2) \frac{g_s^2 C_F}{2k_1 \cdot q_k} [(\alpha_1 - y\beta_1 (\frac{Q^2}{2p_i \cdot Q})) \not{p}_i + y\beta_1 \not{Q} + \sqrt{y\alpha_1\beta_1} \not{h}_{\perp,1}] \quad (4.52)$$

$$[(\beta_1 - \alpha_1 y (\frac{Q^2}{2p_i \cdot Q})) \not{p}_i + y\alpha_1 \not{Q} - \sqrt{y\alpha_1\beta_1} \not{h}_{\perp,1}]$$

Which means:

$$|M_2|^2 \sim (d-2) \frac{g_s^2 C_F}{2k_1 \cdot q_k} y [\dots] \quad (4.53)$$

$$|M_2|^2 \rightarrow 0 \quad \text{for } y \rightarrow 0$$

$M_1 M_2^\dagger$ 

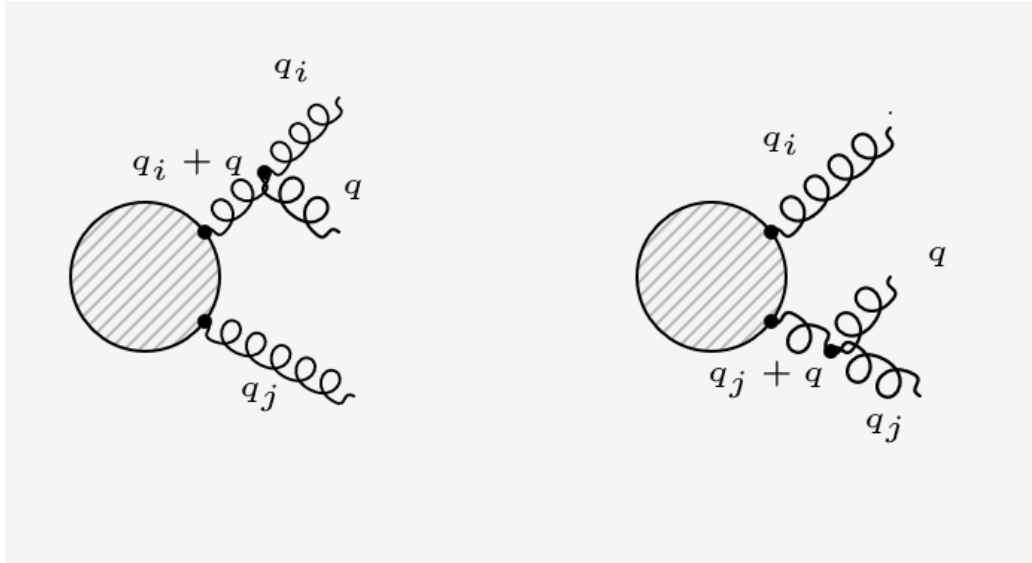
$$M_1 M_2^\dagger = \frac{-g_s^2 C_F}{4y(1-\beta_1)(1-y) (p_i \cdot p_k)(p_i \cdot Q)} \quad (4.54)$$

$$4(\beta_1\sqrt{1-y}p_i \cdot p_k)[\beta_1\sqrt{1-y} \not{p}_i \not{p}_k + (1-\beta_1)\sqrt{1-y} \not{p}_i \not{p}_k]$$

$$M_1 M_2^\dagger = \frac{-g_s^2 C_F}{y(1-\beta_1) (p_i \cdot p_k)(p_i \cdot Q)} \beta_1(p_i \cdot p_k)[\beta_1 \not{p}_i \not{p}_k + (1-\beta_1) \not{p}_i \not{p}_k] \quad (4.55)$$

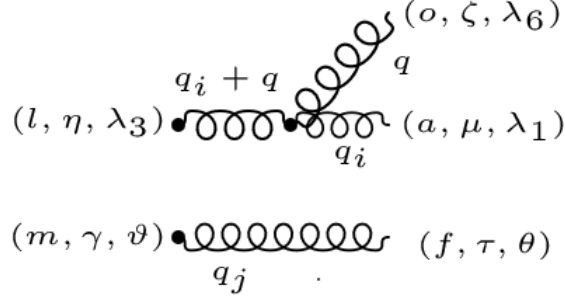
$$M_1 M_2^\dagger = \frac{\beta_1}{(1-\beta_1)} \frac{-g_s^2 C_F}{y (p_i \cdot Q)} [\not{p}_i \not{p}_k] \quad (4.56)$$

## 4.2 Gluon radiation from a parent gluon



Now consider a daughter gluon from the splitting of a parent gluon with radiation an another gluon. When the gluon becomes soft, the distinction between daughter and parent vanishes, and a singularity develops. In this chapter we are going to keep the same procedure with a difference that we won't use the old parametrisation since it only works in LO. One of the mainly challenges about this emission kernel is that the calculations are long and complicated. Before we get started, it must be mentioned that we will work here with the recipe from section 3.6, in which the respective mathematical tools were calculated in detail.

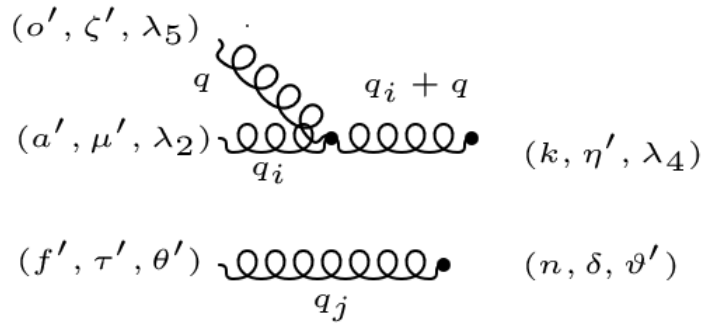
## 4.2.1 Gluon-Emitter Bubble



If we start with the first diagram and use the necessary Feynmann rules, we get:

$$M_1 = \left[ \frac{-i}{(q_i + q)^2} (-g_s f^{a o l} (g^{\mu \zeta} (q - q_i)^\eta - g^{\zeta \eta} (2q + q_i)^\mu + g^{\eta \mu} (2q_i + q)^\zeta) \right. \\ \left. \varepsilon^{\lambda_1}_\mu(q_i) \varepsilon^{\lambda_6}_\zeta(q) \right] [\varepsilon^{\theta}_{\tau'}(q_j)] \quad (4.57)$$

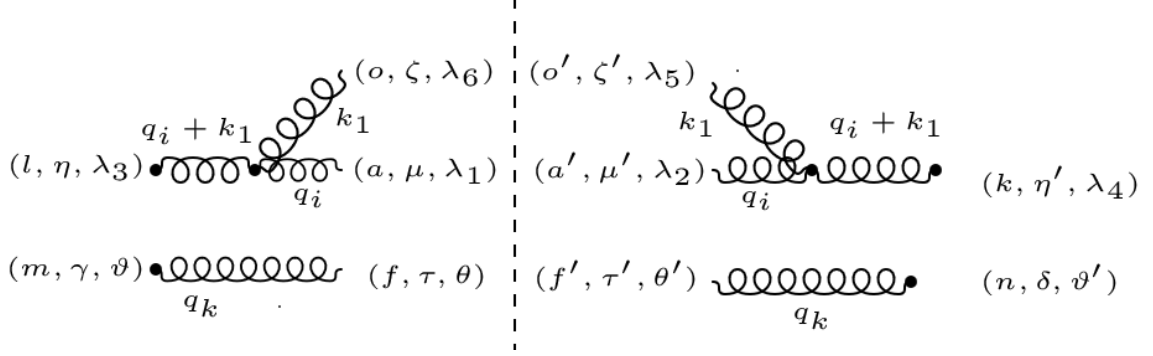
It has to be emphasized that here only the impulse from the parent gluon is incoming and the two further impulses from the vertex are pointing out. This is why the minus signs appear in the equation. If the upper equation is daggered, you get the following diagram and the corresponding following amplitude:



$$M_1^\dagger = \left[ \frac{i}{(q_i + q)^2} (-g_s f^{a' k o'} (-g^{\mu' \eta'} (2q_i + q)^{\zeta'} + g^{\eta' \zeta'} (2q + q_i)^{\mu'} + g^{\zeta' \mu'} (q_i - q)^{\eta'}) \right. \\ \left. \varepsilon^{\lambda_2}_{\mu'}(q_i) \varepsilon^{\lambda_5}_{\zeta'}(q) \right] [\varepsilon^{\theta'}_{\tau'}(q_j)] \quad (4.58)$$

Let us now calculate the matrix element, in which we place the results from above next

to each other, it turns out:



$$\begin{aligned}
 |M_1|^2 = & \left[ \frac{-i}{(q_i + q)^2} (-g_s f^{a o l} (g^{\mu \zeta} (q - q_i)^\eta - g^{\zeta \eta} (2q + q_i)^\mu + g^{\eta \mu} (2q_i + q)^\zeta) \right. \\
 & \varepsilon^{\lambda_1}_\mu(q_i) \varepsilon^{\lambda_2}_{\mu'}(q_i) \varepsilon^{\lambda_6}_\zeta(q) \varepsilon^{\lambda_5}_{\zeta'}(q) (-g_s f^{a' k o'} (-g^{\mu' \eta'} (2q_i + q)^{\zeta'} + g^{\eta' \zeta'} (2q + q_i)^{\mu'}) \\
 & \left. + g^{\zeta' \mu'} (q_i - q)^{\eta'}) \frac{i}{(q_i + q)^2} \right] [g^{\gamma \delta}] \quad (4.59)
 \end{aligned}$$

After the summation over the spin- just as well polarization indices can be obtained:

$$|M_1|^2 = \frac{g_s^2 f^{a o l} f^{a k o}}{(q_i + q)^2 (q_i + q)^2} [N^{\eta \eta'}] [g^{\gamma \delta}] \quad (4.60)$$

The tensor  $N^{\eta \eta'}$  appears exactly when you contract across all possible indices.

The goal of the next step is to evaluate this tensor, which is avoided here and instead of that, it only presents the final result. The more detailed calculation can be found in Appendix A.

$$\begin{aligned}
 N^{\eta \eta'} \equiv & [(6 - d) q^\eta q^{\eta'} + (d + 3) q^\eta q_i^{\eta'} + (d + 3) q_i^\eta q^{\eta'} + (6 - d) q_i^\eta q_i^{\eta'} \\
 & - g^{\eta \eta'} (5q^2 + 5q_i^2 + 8qq_i)] [g^{\gamma \delta}] \quad (4.61)
 \end{aligned}$$

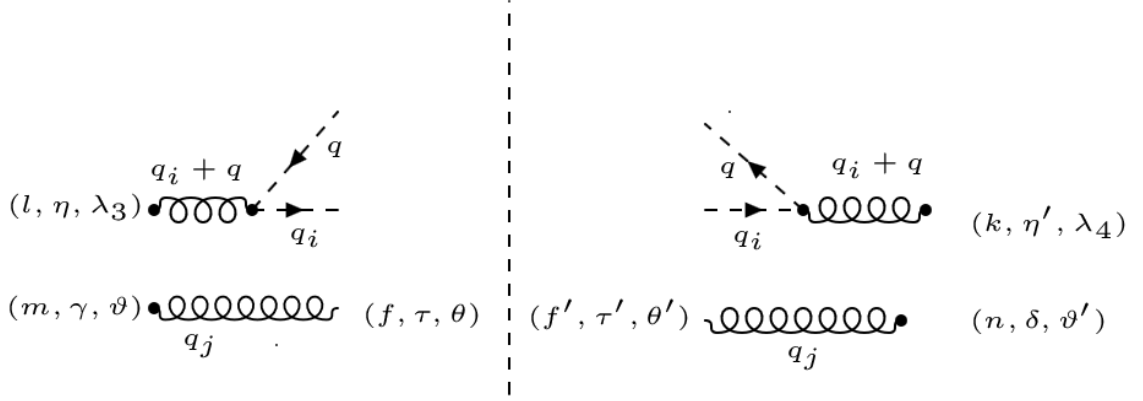
Replace this result in the equation

$$\begin{aligned}
 |M_1|^2 = & \frac{g_s^2 f^{a o l} f^{a k o}}{(q_i + q)^2 (q_i + q)^2} [(6 - d) q^\eta q^{\eta'} + (d + 3) q^\eta q_i^{\eta'} + (d + 3) q_i^\eta q^{\eta'} + (6 - d) q_i^\eta q_i^{\eta'} \\
 & - g^{\eta \eta'} (5q^2 + 5q_i^2 + 8qq_i)] [g^{\gamma \delta}] \quad (4.62)
 \end{aligned}$$

This Gluon self-energy diagram has to be corrected by Ghost Loop to get the complete result. That is exactly what we are going to do in the next section.



## 4.2.1.1 One-loop corrections to the gluon self-energy diagram(Gluon-Emitter Bubble)



In order to get a meaningful result and correct the gluon loop, the same indices must be used. For this the same diagram with a fine difference is used, in which you replace the cut off gluon propagators with ghost propagators and the rest remain as in the previous diagram.

$$|M_1|_{Ghost\ loop}^2 = \frac{g_s^2 f^{aol} f^{ako}}{(q_i + q)^2 (q_i + q)^2} [-q_i^\eta q^{\eta'} - q^\eta q_i^{\eta'}] [g^{\gamma\delta}] \quad (4.63)$$

$$|M_1'|^2 = |M_1|^2 + |M_1|_{Ghost\ loop}^2 = \frac{g_s^2 f^{aol} f^{ako}}{(q_i + q)^2 (q_i + q)^2} [(6 - d)q^\eta q^{\eta'} + (d + 3)q^\eta q_i^{\eta'} + (d + 3)q_i^\eta q^{\eta'} + (6 - d)q_i^\eta q_i^{\eta'} - g^{\eta\eta'} (5q^2 + 5q_i^2 + 8qq_i) - q_i^\eta q^{\eta'} - q^\eta q_i^{\eta'}] [g^{\gamma\delta}] \quad (4.64)$$

After simplification and addition over the same terms:

$$|M_1'|^2 = \frac{g_s^2 f^{aol} f^{ako}}{(q_i + q)^2 (q_i + q)^2} [(6 - d)q^\eta q^{\eta'} + (d + 2)q^\eta q_i^{\eta'} + (d + 2)q_i^\eta q^{\eta'} + (6 - d)q_i^\eta q_i^{\eta'} - g^{\eta\eta'} (8qq_i)] [g^{\gamma\delta}] \quad (4.65)$$

Implementation the new parametrisation:

$$|M_1'|^2 = \frac{g_s^2 f^{aol} f^{ako}}{4y^2(\alpha_1 + \beta_1)^2 (p_i \cdot Q) (p_i \cdot Q)} [(6 - d)(\zeta_1 p_i^\eta + \lambda_1 Q^\eta + \sqrt{y\alpha_1\beta_1} n_{\perp,1}^\eta)(\zeta_1 p_i^{\eta'} + \lambda_1 Q^{\eta'} + \sqrt{y\alpha_1\beta_1} n_{\perp,1}^{\eta'}) + (d + 2)(\zeta_1 p_i^\eta + \lambda_1 Q^\eta + \sqrt{y\alpha_1\beta_1} n_{\perp,1}^\eta)(\zeta_q p_i^{\eta'} + \lambda_q Q^{\eta'} - \sqrt{y\alpha_1\beta_1} n_{\perp,1}^{\eta'}) + (d + 2)(\zeta_q p_i^\eta + \lambda_q Q^\eta - \sqrt{y\alpha_1\beta_1} n_{\perp,1}^\eta)(\zeta_1 p_i^{\eta'} + \lambda_1 Q^{\eta'} + \sqrt{y\alpha_1\beta_1} n_{\perp,1}^{\eta'}) + (6 - d)(\zeta_q p_i^\eta + \lambda_q Q^\eta - \sqrt{y\alpha_1\beta_1} n_{\perp,1}^\eta)(\zeta_q p_i^{\eta'} + \lambda_q Q^{\eta'} - \sqrt{y\alpha_1\beta_1} n_{\perp,1}^{\eta'}) - 8g^{\eta\eta'} [(\alpha_1^2 + \beta_1^2)p_i \cdot Q - (\beta_1(1 - \beta_1))n_{\perp,1} \cdot n_{\perp,1}] [g^{\gamma\delta}] \quad (4.66)$$

Note that here the short version of the kinematics was used to increase the overview. Now you have to multiply the terms in brackets and simplify the matrix element.

$$\begin{aligned}
|M'_1|^2 = & \frac{g_s^2 f^{aol} f^{ako}}{y^2 (p_i \cdot Q) (p_i \cdot Q)} [(6-d) [\zeta_1 \zeta_1 p_i^\eta p_i^{\eta'} + \zeta_1 \lambda_1 p_i^\eta Q^{\eta'} + \zeta_1 \sqrt{y\alpha_1\beta_1} p_i^\eta n^{\eta'}_{\perp,1} \\
& + \lambda_1 \zeta_1 Q^\eta p_i^{\eta'} + \lambda_1 \lambda_1 Q^\eta Q^{\eta'} + \lambda_1 \sqrt{y\alpha_1\beta_1} Q^\eta n^{\eta'}_{\perp,1} + \zeta_1 \sqrt{y\alpha_1\beta_1} n^\eta_{\perp,1} p_i^{\eta'} + \lambda_1 \sqrt{y\alpha_1\beta_1} n^\eta_{\perp,1} Q^{\eta'} \\
& + \sqrt{y\alpha_1\beta_1} \sqrt{y\alpha_1\beta_1} n^\eta_{\perp,1} n^{\eta'}_{\perp,1}] [(d+2) [\zeta_1 \zeta_q p_i^\eta p_i^{\eta'} + \zeta_1 \lambda_q p_i^\eta Q^{\eta'} - \zeta_1 \sqrt{y\alpha_1\beta_1} p_i^\eta n^{\eta'}_{\perp,1} \\
& + \lambda_1 \zeta_q Q^\eta p_i^{\eta'} + \lambda_1 \lambda_q Q^\eta Q^{\eta'} - \lambda_1 \sqrt{y\alpha_1\beta_1} Q^\eta n^{\eta'}_{\perp,1} + \zeta_q \sqrt{y\alpha_1\beta_1} n^\eta_{\perp,1} p_i^{\eta'} + \lambda_q \sqrt{y\alpha_1\beta_1} n^\eta_{\perp,1} Q^{\eta'} \\
& - \sqrt{y\alpha_1\beta_1} \sqrt{y\alpha_1\beta_1} n^\eta_{\perp,1} n^{\eta'}_{\perp,1}] [(d+2) [\zeta_q \zeta_1 p_i^\eta p_i^{\eta'} + \zeta_q \lambda_1 p_i^\eta Q^{\eta'} + \zeta_q \sqrt{y\alpha_1\beta_1} p_i^\eta n^{\eta'}_{\perp,1} \\
& + \lambda_q \zeta_1 Q^\eta p_i^{\eta'} + \lambda_q \lambda_1 Q^\eta Q^{\eta'} + \lambda_q \sqrt{y\alpha_1\beta_1} Q^\eta n^{\eta'}_{\perp,1} - \zeta_1 \sqrt{y\alpha_1\beta_1} n^\eta_{\perp,1} p_i^{\eta'} - \lambda_1 \sqrt{y\alpha_1\beta_1} n^\eta_{\perp,1} Q^{\eta'} \\
& - \sqrt{y\alpha_1\beta_1} \sqrt{y\alpha_1\beta_1} n^\eta_{\perp,1} n^{\eta'}_{\perp,1}] [(6-d) [\zeta_q \zeta_q p_i^\eta p_i^{\eta'} + \zeta_q \lambda_q p_i^\eta Q^{\eta'} - \zeta_q \sqrt{y\alpha_1\beta_1} p_i^\eta n^{\eta'}_{\perp,1} \\
& + \lambda_q \zeta_q Q^\eta p_i^{\eta'} + \lambda_q \lambda_q Q^\eta Q^{\eta'} - \lambda_q \sqrt{y\alpha_1\beta_1} Q^\eta n^{\eta'}_{\perp,1} - \zeta_q \sqrt{y\alpha_1\beta_1} n^\eta_{\perp,1} p_i^{\eta'} - \lambda_q \sqrt{y\alpha_1\beta_1} n^\eta_{\perp,1} Q^{\eta'} \\
& + \sqrt{y\alpha_1\beta_1} \sqrt{y\alpha_1\beta_1} n^\eta_{\perp,1} n^{\eta'}_{\perp,1} - 8g^{\eta\eta'} [(\alpha_1^2 + \beta_1^2) p_i \cdot Q - (\beta_1(1 - \beta_1)) n_{\perp,1} \cdot n_{\perp,1}] [g^{\gamma\delta}]
\end{aligned} \tag{4.67}$$

One replaces now the relations for the often occurring pre-factor products from appendix A and get:

$$\begin{aligned}
|M'_1|^2 = & \frac{g_s^2 f^{aol} f^{ako}}{4y^2 (p_i \cdot Q) (p_i \cdot Q)} [(6-d) \{(\alpha_1^2 - 2y\alpha_1\beta_1 (\frac{Q^2}{2p_i \cdot Q})) p_i^\eta p_i^{\eta'} + y\alpha_1\beta_1 p_i^\eta Q^{\eta'} \\
& + \zeta_1 \sqrt{y\alpha_1\beta_1} p_i^\eta n^{\eta'}_{\perp,1} + y\beta_1\alpha_1 Q^\eta p_i^{\eta'} + \lambda_1 \sqrt{y\alpha_1\beta_1} Q^\eta n^{\eta'}_{\perp,1} + \zeta_1 \sqrt{y\alpha_1\beta_1} n^\eta_{\perp,1} p_i^{\eta'} \\
& + \lambda_1 \sqrt{y\alpha_1\beta_1} n^\eta_{\perp,1} Q^{\eta'} + y\alpha_1\beta_1 n^\eta_{\perp,1} n^{\eta'}_{\perp,1}\} + (d+2) \{(\alpha_1\beta_1 - y(\alpha_1^2 + \beta_1^2)) (\frac{Q^2}{2p_i \cdot Q}) p_i^\eta p_i^{\eta'} \\
& + y\alpha_1^2 p_i^\eta Q^{\eta'} - \zeta_1 \sqrt{y\alpha_1\beta_1} p_i^\eta n^{\eta'}_{\perp,1} + y\beta_1^2 Q^\eta p_i^{\eta'} - \lambda_1 \sqrt{y\alpha_1\beta_1} Q^\eta n^{\eta'}_{\perp,1} + \zeta_q \sqrt{y\alpha_1\beta_1} n^\eta_{\perp,1} p_i^{\eta'} \\
& + \lambda_q \sqrt{y\alpha_1\beta_1} n^\eta_{\perp,1} Q^{\eta'} - y\alpha_1\beta_1 n^\eta_{\perp,1} n^{\eta'}_{\perp,1}\} \\
& + (d+2) \{(\beta_1\alpha_1 - y(\beta_1^2 + \alpha_1^2)) (\frac{Q^2}{2p_i \cdot Q}) p_i^\eta p_i^{\eta'} + y\beta_1^2 p_i^\eta Q^{\eta'} + \zeta_q \sqrt{y\alpha_1\beta_1} p_i^\eta n^{\eta'}_{\perp,1} \\
& + y\alpha_1^2 Q^\eta p_i^{\eta'} + \lambda_q \sqrt{y\alpha_1\beta_1} Q^\eta n^{\eta'}_{\perp,1} - \zeta_1 \sqrt{y\alpha_1\beta_1} n^\eta_{\perp,1} p_i^{\eta'} - \lambda_1 \sqrt{y\alpha_1\beta_1} n^\eta_{\perp,1} Q^{\eta'} \\
& - y\alpha_1\beta_1 n^\eta_{\perp,1} n^{\eta'}_{\perp,1}\} + (6-d) \{(\beta_1^2 - 2y\alpha_1\beta_1 (\frac{Q^2}{2p_i \cdot Q})) p_i^\eta p_i^{\eta'} + y\beta_1\alpha_1 p_i^\eta Q^{\eta'} \\
& - \zeta_q \sqrt{y\alpha_1\beta_1} p_i^\eta n^{\eta'}_{\perp,1} + y\alpha_1\beta_1 Q^\eta p_i^{\eta'} - \lambda_q \sqrt{y\alpha_1\beta_1} Q^\eta n^{\eta'}_{\perp,1} - \zeta_q \sqrt{y\alpha_1\beta_1} n^\eta_{\perp,1} p_i^{\eta'} \\
& - \lambda_q \sqrt{y\alpha_1\beta_1} n^\eta_{\perp,1} Q^{\eta'} + y\alpha_1\beta_1 n^\eta_{\perp,1} n^{\eta'}_{\perp,1}\} - 8g^{\eta\eta'} [(\alpha_1^2 + \beta_1^2) p_i \cdot Q - (\beta_1(1 - \beta_1)) n_{\perp,1} \cdot n_{\perp,1}] [g^{\gamma\delta}]
\end{aligned} \tag{4.68}$$

$$\begin{aligned}
|M'_1|^2 = & \frac{g_s^2 f^{aol} f^{ako}}{4y^2 (p_i \cdot Q) (p_i \cdot Q)} [(6-d) \{ (\alpha_1^2 - 2y\alpha_1\beta_1 (\frac{Q^2}{2p_i \cdot Q})) p_i^\eta p_i^{\eta'} \\
& + y\alpha_1\beta_1 p_i^\eta Q^{\eta'} + y\beta_1\alpha_1 Q^\eta p_i^{\eta'} + y\alpha_1\beta_1 n_{\perp,1}^\eta n_{\perp,1}^{\eta'} \} \\
& + (d+2) \{ (\alpha_1\beta_1 - y(\alpha_1^2 + \beta_1^2) (\frac{Q^2}{2p_i \cdot Q})) p_i^\eta p_i^{\eta'} + y\alpha_1^2 p_i^\eta Q^{\eta'} + y\beta_1^2 Q^\eta p_i^{\eta'} \\
& - y\alpha_1\beta_1 n_{\perp,1}^\eta n_{\perp,1}^{\eta'} \} + (d+2) \{ (\beta_1\alpha_1 - y(\beta_1^2 + \alpha_1^2) (\frac{Q^2}{2p_i \cdot Q})) p_i^\eta p_i^{\eta'} \\
& + y\beta_1^2 p_i^\eta Q^{\eta'} + y\alpha_1^2 Q^\eta p_i^{\eta'} - y\alpha_1\beta_1 n_{\perp,1}^\eta n_{\perp,1}^{\eta'} \} \\
& + (6-d) \{ (\beta_1^2 - 2y\alpha_1\beta_1 (\frac{Q^2}{2p_i \cdot Q})) p_i^\eta p_i^{\eta'} + y\beta_1\alpha_1 p_i^\eta Q^{\eta'} + y\alpha_1\beta_1 Q^\eta p_i^{\eta'} \\
& + y\alpha_1\beta_1 n_{\perp,1}^\eta n_{\perp,1}^{\eta'} \} - 8g^{\eta\eta'} [(\alpha_1^2 + \beta_1^2) p_i \cdot Q - (\beta_1(1 - \beta_1)) n_{\perp,1} \cdot n_{\perp,1}] [g^{\gamma\delta}]
\end{aligned} \tag{4.69}$$

$$\begin{aligned}
|M'_1|^2 = & \frac{g_s^2 f^{aol} f^{ako}}{4y (p_i \cdot Q) (p_i \cdot Q)} [[8 - 4d] \beta_1(1 - \beta_1) n_{\perp,1}^\eta n_{\perp,1}^{\eta'} - 8g^{\eta\eta'} [(\alpha_1^2 + \beta_1^2) p_i \cdot Q \\
& - (\beta_1(1 - \beta_1)) n_{\perp,1} \cdot n_{\perp,1}] [g^{\gamma\delta}]
\end{aligned} \tag{4.70}$$

In this step the equation for  $d = 4 - 2\epsilon$  was calculated and the value of  $(\alpha_1 + \beta_1)^2 p_i \cdot Q$  from equation (3.50) was replaced. What here noticeable is at this point that one  $y$  from the denominator is abbreviated with one from the nominator. The final result looks like this:

$$|M'_1|^2 = \frac{g_s^2 f^{aol} f^{ako}}{y (p_i \cdot Q)} [2[\epsilon - 1] \beta_1(1 - \beta_1) n_{\perp,1}^\eta n_{\perp,1}^{\eta'} - 2g^{\eta\eta'}] [g^{\gamma\delta}] \tag{4.71}$$

### 4.2.2 A simplified way within the concept 3.9.1

During the analysis of the evaluation it turned out that the particularly complicated and extensive calculation can be handled with the substitutions conceived below:

The first consideration is to look in the denominators for the pre-factors that cause a singularity.

In the second step, care must be taken to ensure that the numerator consists of the addition of several terms, which mostly consist of scalar products with two four-vectors. This is the reason why these scalar products have to be considered separately, provided that the terms with the same pre-factor are eliminated from the nominator beforehand, since they are finite anyway. In the last chapter, this has already been deduced with regard to the factors in the denominator. For illustration this is calculated once for  $|M'_1|^2$  with the denominator  $4y^2 (p_i \cdot Q) (p_i \cdot Q)$ .

If one looks at this corrected matrix element, with the pre-factor  $y^2$  in the denominator, it can be seen that in the counter the respective terms with  $y^2$  by the multiplication of two four-vectors can be neglected instead of calculating these, since exactly these form the finite terms. This simplifies the results of the scalar products. Under this assumption, the result looks as follows:

$$\begin{aligned}
 k_1^\eta k_1^{\eta'} &= (\alpha_1^2 - 2\alpha_1\beta_1 y(\frac{Q^2}{2p_i \cdot Q}))p_i^\eta p_i^{\eta'} + y\alpha_1\beta_1 p_i^\eta Q^{\eta'} + y\alpha_1\beta_1 Q^\eta p_i^{\eta'} + y\alpha_1\beta_1 n_{\perp,1}^\eta n_{\perp,1}^{\eta'} \\
 k_1^\eta q_i^{\eta'} &= (\alpha_1\beta_1 - y(\alpha_1^2 + \beta_1^2)(\frac{Q^2}{2p_i \cdot Q}))p_i^\eta p_i^{\eta'} + y\alpha_1^2 p_i^\eta Q^{\eta'} + y\beta_1^2 Q^\eta p_i^{\eta'} - y\alpha_1\beta_1 n_{\perp,1}^\eta n_{\perp,1}^{\eta'} \\
 q_i^\eta k_1^{\eta'} &= (\alpha_1\beta_1 - y(\alpha_1^2 + \beta_1^2)(\frac{Q^2}{2p_i \cdot Q}))p_i^\eta p_i^{\eta'} + y\beta_1^2 p_i^\eta Q^{\eta'} + y\alpha_1^2 Q^\eta p_i^{\eta'} - y\alpha_1\beta_1 n_{\perp,1}^\eta n_{\perp,1}^{\eta'} \\
 q_i^\eta q_i^{\eta'} &= (\beta_1^2 - 2\alpha_1\beta_1 y(\frac{Q^2}{2p_i \cdot Q}))p_i^\eta p_i^{\eta'} + y\alpha_1\beta_1 p_i^\eta Q^{\eta'} + y\alpha_1\beta_1 Q^\eta p_i^{\eta'} + y\alpha_1\beta_1 n_{\perp,1}^\eta n_{\perp,1}^{\eta'}
 \end{aligned} \tag{4.72}$$

Now we insert these results into  $N$  which was an element of the square matrix element.

$$\begin{aligned}
 N &\equiv (6-d)(\alpha_1^2 - 2\alpha_1\beta_1 y(\frac{Q^2}{2p_i \cdot Q}))p_i^\eta p_i^{\eta'} + y\alpha_1\beta_1 p_i^\eta Q^{\eta'} + y\alpha_1\beta_1 Q^\eta p_i^{\eta'} + y\alpha_1\beta_1 n_{\perp,1}^\eta n_{\perp,1}^{\eta'} \\
 &+ (d+2)(\alpha_1\beta_1 - y(\alpha_1^2 + \beta_1^2)(\frac{Q^2}{2p_i \cdot Q}))p_i^\eta p_i^{\eta'} + y\alpha_1^2 p_i^\eta Q^{\eta'} + y\beta_1^2 Q^\eta p_i^{\eta'} - y\alpha_1\beta_1 n_{\perp,1}^\eta n_{\perp,1}^{\eta'} \\
 &+ (d+2)(\alpha_1\beta_1 - y(\alpha_1^2 + \beta_1^2)(\frac{Q^2}{2p_i \cdot Q}))p_i^\eta p_i^{\eta'} + y\beta_1^2 p_i^\eta Q^{\eta'} + y\alpha_1^2 Q^\eta p_i^{\eta'} - y\alpha_1\beta_1 n_{\perp,1}^\eta n_{\perp,1}^{\eta'} \\
 &+ (6-d)(\beta_1^2 - 2\alpha_1\beta_1 y(\frac{Q^2}{2p_i \cdot Q}))p_i^\eta p_i^{\eta'} + y\alpha_1\beta_1 p_i^\eta Q^{\eta'} + y\alpha_1\beta_1 Q^\eta p_i^{\eta'} + y\alpha_1\beta_1 n_{\perp,1}^\eta n_{\perp,1}^{\eta'} \\
 &- 8g^{\eta\eta'} [(\alpha_1^2 + \beta_1^2)p_i \cdot Q - (\beta_1(1 - \beta_1))n_{\perp,1} \cdot n_{\perp,1}]
 \end{aligned} \tag{4.73}$$

Summary of the equation provides:

$$\begin{aligned}
N \equiv & [(6-d)(\alpha_1^2 - 2\alpha_1\beta_1 y(\frac{Q^2}{2p_i \cdot Q})) + (d+2)(\alpha_1\beta_1 - y(\alpha_1^2 + \beta_1^2)(\frac{Q^2}{2p_i \cdot Q}))] \\
& + (d+2)(\alpha_1\beta_1 - y(\alpha_1^2 + \beta_1^2)(\frac{Q^2}{2p_i \cdot Q})) + (6-d)(\beta_1^2 - 2\alpha_1\beta_1 y(\frac{Q^2}{2p_i \cdot Q})) p_i^\eta p_i^{\eta'} \\
& + [(6-d)y\alpha_1\beta_1 + (d+2)y\alpha_1^2 + (d+2)y\beta_1^2 + (6-d)y\alpha_1\beta_1] p_i^\eta Q^{\eta'} \\
& + [(6-d)y\alpha_1\beta_1 + (d+2)y\beta_1^2 + (d+2)y\alpha_1^2 + (6-d)y\alpha_1\beta_1] Q^\eta p_i^{\eta'} \\
& + [(6-d)y\alpha_1\beta_1 - (d+2)y\alpha_1\beta_1 - (d+2)y\alpha_1\beta_1 + (6-d)y\alpha_1\beta_1] n_{\perp,1}^\eta n_{\perp,1}^{\eta'} \\
& - 8g^{\eta'} [(\alpha_1^2 + \beta_1^2)p_i \cdot Q - (\beta_1(1 - \beta_1))n_{\perp,1} \cdot n_{\perp,1}]
\end{aligned} \tag{4.74}$$

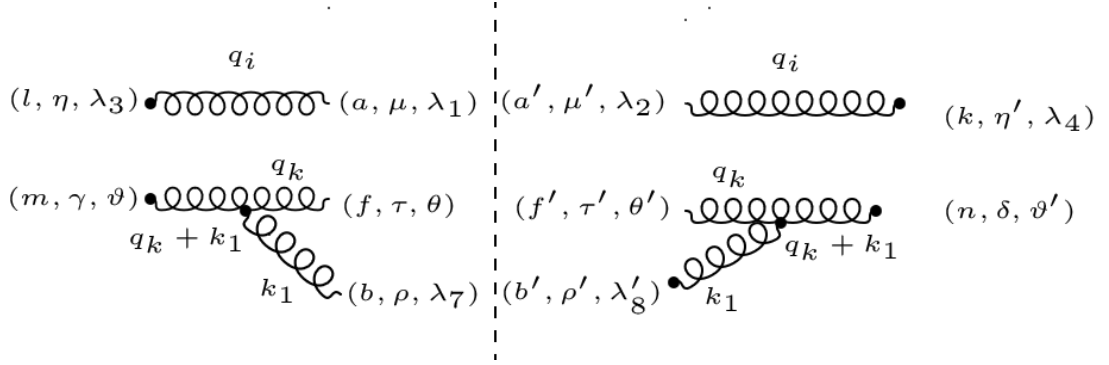
If you now insert the result into the matrix element and simplify it:

$$|M'_1|^2 = \frac{g_s^2 f^{a o l} f^{a k o}}{y(p_i \cdot Q)} [2[\epsilon - 1]\beta_1(1 - \beta_1)n_{\perp,1}^\eta n_{\perp,1}^{\eta'} - 2g^{\eta'}][g^{\gamma\delta}] \tag{4.75}$$

### conclusion

This concept allows to achieve the same result in just a few steps. This can also be done for further calculations. In the following it is imperative to orient oneself to the denominator of the matrix element.

## 4.2.3 Gluon-Spectator Bubble



This concept can also be applied to the gluon spectator. The only difference is that a gluon is emitted by a spectator and other indices are used here.

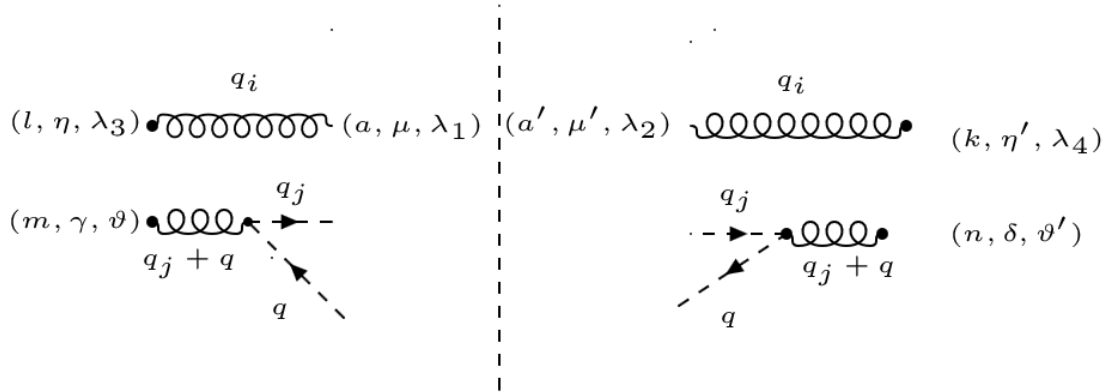
Using the Feynmann rules, the matrix element is evaluated:

$$\begin{aligned}
 |M_2|^2 = & \frac{g_s^2 f^{bfm} f^{bnf}}{(q_j + q)^2 (q_j + q)^2} [(2q + q_j)^\gamma (2q_j + q)^\delta - g^{\delta\gamma} (2q_j + q)^\rho (2q_j + q)_\rho \\
 & - (2q_j + q)^\gamma (q - q_j)^\delta - g^{\delta\gamma} (2q + q_j)^\tau (2q + q_j)_\tau + (2q_j + q)^\gamma (2q + q_j)^\delta \\
 & + (2q + q_j)^\gamma (q - q_j)^\delta - (q_j - q)^\gamma (2q + q_j)^\delta + (q_j - q)^\gamma (2q_j + q)^\delta \\
 & + d(q_j - q)^\gamma (q - q_j)^\delta] [g^{\eta\eta'}]
 \end{aligned} \tag{4.76}$$

It follows:

$$\begin{aligned}
 |M_2|^2 = & \frac{g_s^2 f^{bfm} f^{bnf}}{(q_j + q)^2 (q_j + q)^2} [(3 + d)q^\gamma q_j^\delta + (6 - d)q^\gamma q^\delta + (6 - d)q_j^\gamma q_j^\delta \\
 & + (3 + d)q_j^\gamma q^\delta - g^{\delta\gamma} (5q_j^2 + 5q^2 + 8qq_j)] [g^{\eta\eta'}]
 \end{aligned} \tag{4.77}$$

## 4.2.3.1 One-loop corrections to the gluon self-energy diagram (Gluon-Spectator Bubble)



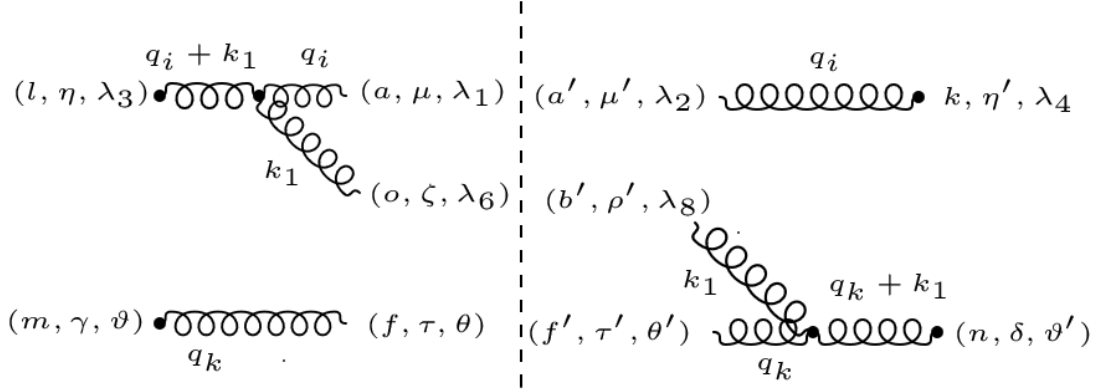
Here not all steps are shown in detail, but only the final result is presented. The reason for this is that all steps can be followed analogously to the last section.

$$|M_2|_{Ghost\ loop}^2 = \frac{g_s^2 f^{b f m} f^{b n f}}{(q_j + q)^2 (q_j + q)^2} [-q_j^\gamma q^\delta - q^\delta q_j^\gamma] [g^{\eta\eta'}] \quad (4.78)$$

$$|M_2'|^2 = \frac{g_s^2 f^{b f m} f^{b n f}}{(q_j + q)^2 (q_j + q)^2} [(2 + d)q^\gamma q_j^\delta + (6 - d)q^\gamma q^\delta + (6 - d)q_j^\gamma q_j^\delta + (2 + d)q_j^\gamma q^\delta - g^{\delta\gamma}(8qq_j)] [g^{\eta\eta'}] \quad (4.79)$$

$$|M_2'|^2 = \frac{g_s^2 f^{b f m} f^{b n f}}{(1 - \beta_1)(1 - y) (p_i \cdot p_k)} [-2g^{\delta\gamma}] [g^{\eta\eta'}] \quad (4.80)$$

## 4.2.4 Joining the emitter and spectator diagrams together



Analogous to the last two sections, we calculate the quadratic matrix element in the case of the interference term.

$$M_1 M_2^\dagger = \frac{g_s^2 f^{l a o} f^{f' b' n} \delta^{a a'} \delta^{o b'} \delta^{f f'}}{(q_i + q)^2 (q_j + q)^2} [g_{\mu'}^{\eta'} g_{\tau \tau'} (g^{\eta \mu} (2q_i + q)^\zeta + g^{\mu \zeta} (q - q_i)^\eta - g^{\zeta \eta} (2q + q_i)^\mu) \\ g_{\zeta \rho'} (g^{\tau' \rho'} (q_j - q)^\delta + g^{\rho' \delta} (2q + q_j)^{\tau'} - g^{\delta \tau'} (2q_j + q)^{\rho'})] \quad (4.81)$$

Multiply the available tensors and summarize all results:

$$M_1 M_2^\dagger = \frac{g_s^2 f^{l a o} f^{f o n}}{4(q \cdot q_i)(q \cdot q_j)} \{ g^{\eta \eta'} [2q_i^\gamma q_j^\delta + 2q_i^\gamma q^\delta + q^\gamma q_j^\delta + q^\gamma q^\delta + 4q^\gamma q_i^\delta \\ + 2q^\gamma q^\delta + 2q_j^\gamma q_i^\delta + q_j^\gamma q^\delta] - g^{\eta \eta'} g^{\gamma \delta} (2q \cdot q_j + q \cdot q + 4q_i \cdot q_j + 2q_i \cdot q) \\ + g^{\gamma \eta'} [q^\eta q_j^\delta - q^\eta q^\delta - q_i^\eta q_j^\delta + q_i^\eta q^\delta] + g^{\eta' \delta} [2q^\eta q^\gamma + q^\eta q_j^\gamma + q_i^\eta q^\gamma + q_i^\eta q_j^\gamma] \\ - g^{\gamma \delta} [2q^\eta q_j^{\eta'} + q^\eta q^{\eta'} - 2q_i^\eta q_j^{\eta'} - q_i^\eta q^{\eta'}] - g^{\gamma \eta} [2q^{\eta'} q_j^\delta - 2q^{\eta'} q^\delta + q_i^{\eta'} q_j^\delta - q_i^{\eta'} q^\delta] \\ - g^{\eta \delta} [4q^{\eta'} q^\gamma + 2q^{\eta'} q_j^\gamma + 2q_i^{\eta'} q^\gamma + q_i^{\eta'} q_j^\gamma] + g^{\gamma \delta} [4q_j^\eta q^{\eta'} + 2q_j^\eta q_i^{\eta'} + q^\eta q^{\eta'} + q^\eta q_i^{\eta'}] \} \quad (4.82)$$

As can be seen here from the term in the denominator, this is the parametrisation in the



case of (3.53)

$$\begin{aligned}
k_1^\eta k_1^{\eta'} &= [(1 - \beta_1)^2 - y^2 \beta_1^2 (\frac{Q^2}{2p_i \cdot Q})^2] p_i^\eta p_i^{\eta'} - y^2 \beta_1^2 (\frac{Q^2}{2p_i \cdot Q}) p_i^\eta Q^{\eta'} - y^2 \beta_1^2 (\frac{Q^2}{2p_i \cdot Q}) Q^\eta p_i^{\eta'} \\
k_1^\eta q_i^{\eta'} &= [\beta_1(1 - \beta_1) - y \beta_1^2 (\frac{Q^2}{2p_i \cdot Q})] p_i^\eta p_i^{\eta'} + y \beta_1^2 Q^\eta p_i^{\eta'} \\
q_i^\eta k_1^{\eta'} &= [\beta_1(1 - \beta_1) - y \beta_1^2 (\frac{Q^2}{2p_i \cdot Q})] p_i^\eta p_i^{\eta'} + y \beta_1^2 p_i^\eta Q^{\eta'} \\
q_i^\eta q_i^{\eta'} &= \beta_1^2 p_i^\eta p_i^{\eta'} \\
k_1^\eta q_k^{\eta'} &= [(1 - \beta_1) - y \beta_1 (\frac{Q^2}{2p_i \cdot Q})] \sqrt{1 - y} p_i^\eta p_k^{\eta'} - y \beta_1 (\frac{Q^2}{2p_i \cdot Q}) A_1 p_i^\eta p_i^{\eta'} - y \beta_1 (\frac{Q^2}{2p_i \cdot Q}) A_2 p_i^\eta Q^{\eta'} \\
&\quad + y \beta_1 A_1 Q^\eta p_i^{\eta'} + y \beta_1 A_2 Q^\eta Q^{\eta'} + y \beta_1 \sqrt{1 - y} Q^\eta p_k^{\eta'} \\
q_i^\eta q_k^{\eta'} &= A_1 \beta_1 p_i^\eta p_i^{\eta'} + A_2 \beta_1 p_i^\eta Q^{\eta'} + \beta_1 \sqrt{1 - y} p_i^\eta p_k^{\eta'} \\
q_k^\eta k_1^{\eta'} &= [(1 - \beta_1) - y \beta_1 (\frac{Q^2}{2p_i \cdot Q})] \sqrt{1 - y} p_k^\eta p_i^{\eta'} - y \beta_1 (\frac{Q^2}{2p_i \cdot Q}) A_1 p_i^\eta p_i^{\eta'} - y \beta_1 (\frac{Q^2}{2p_i \cdot Q}) A_2 Q^\eta p_i^{\eta'} \\
&\quad + y \beta_1 A_1 p_i^\eta Q^{\eta'} + y \beta_1 A_2 Q^\eta Q^{\eta'} + y \beta_1 \sqrt{1 - y} p_k^\eta Q^{\eta'} \\
q_k^\eta q_i^{\eta'} &= A_1 \beta_1 p_i^\eta p_i^{\eta'} + A_2 \beta_1 Q^\eta p_i^{\eta'} + \beta_1 \sqrt{1 - y} p_k^\eta p_i^{\eta'}
\end{aligned} \tag{4.83}$$

It should be noted that we have not opted for the standard way with the replacement of parametrisation and elimination of limited terms, because otherwise the calculation becomes rather confusing and long. It should be mentioned here that the standard way was still used as a comparison to determine whether the two approaches would lead to the same goal. Let's start with the evaluation of the respective terms. a summarized calculation can be found in the appendix 6. If you are interested in the complete solution which contains both cases, i.e. the collinear and soft region, you simply have to add the terms. Since the calculation becomes quite long and confusing, we focus on the second term, which is important for the collinear case and presents the full result, which is used for the calculation of the splitting function.

The starting point is the second term of the quadratic matrix element:

$$-g^{\eta\eta'} g^{\gamma\delta} (2q \cdot q_j + q \cdot q + 4q_i \cdot q_j + 2q_i \cdot q) \tag{4.84}$$

After the replacement of the corresponding Skalar products from 4.83 it results in:

$$\begin{aligned}
M_1 M_2^\dagger &= g_s^2 C_A g^{\eta\eta'} g^{\gamma\delta} \left[ \frac{1}{2y(p_i \cdot Q)} + \frac{\beta_1 (\frac{Q^2}{2p_i \cdot Q})}{2y(1 - \beta_1)(1 - y)(p_i \cdot Q)} \right. \\
&\quad \left. + \frac{\beta_1 Q \cdot p_k}{2y(1 - \beta_1)(1 - y)(p_i \cdot p_k)(p_i \cdot Q)} + \frac{\beta_1}{y(1 - \beta_1)(p_i \cdot Q)} + \frac{1}{2(1 - \beta_1)(1 - y)(p_i \cdot p_k)} \right]
\end{aligned} \tag{4.85}$$

#### 4.2.4.1 Swapping for indistinguishable partons

If now the results from the previous sections are added together, it is noticeable that a part of the final solution falls, which is not demonstrated here. The problem is that the gluons are indistinguishable with respect to the interference term. In fact, it could not be determined which gluon has which momentum. Here exactly the sixth point from the procedure 3.9.1 appears. This problem is solved by exchanging the impulses for the same diagram once and repeating the steps. Here only the final result is presented and the detailed steps can be looked up in the appendix 6.

$$M_1 M_2^{\dagger'} = g_s^2 C_A g^{\eta\eta'} g^{\gamma\delta} \left[ \frac{1 - \beta_1}{y \beta_1 (p_i \cdot Q)} + \frac{1}{2y(p_i \cdot Q)} + \frac{(1 - \beta_1)(\frac{Q^2}{2p_i \cdot Q})}{2y \beta_1 (1 - y) (p_i \cdot Q)} \right. \\ \left. + \frac{(1 - \beta_1) Q \cdot p_k}{2y \beta_1 (1 - y) (p_i \cdot p_k)(p_i \cdot Q)} + \frac{1}{2(1 - \beta_1)(1 - y)(p_i \cdot p_k)} \right] \quad (4.86)$$

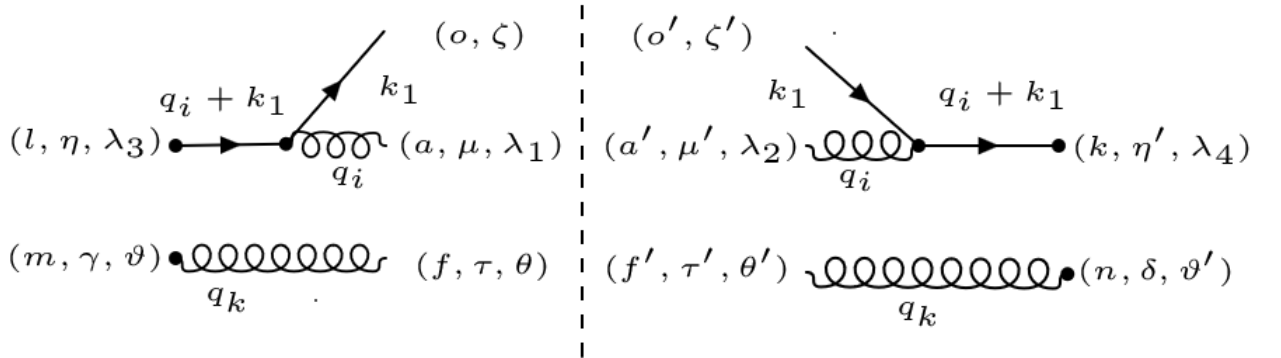
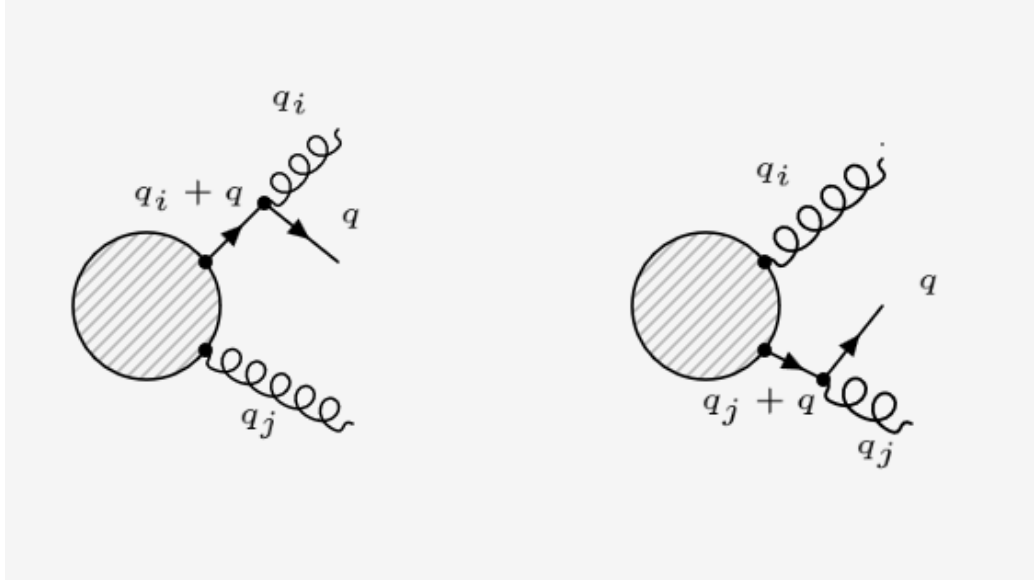
#### 4.2.5 Summary of the results

$$|M|^2 = |M'_2|^2 + |M'_1|^2 + 2RE(M_1 M_2^{\dagger} + M_1 M_2^{\dagger'}) \\ |M|^2 = \frac{g_s^2 C_A}{y (p_i \cdot Q)} [2[\epsilon - 1] \beta_1 (1 - \beta_1) n_{\perp,1}^{\eta} n_{\perp,1}^{\eta'} - 2g^{\eta\eta'}] [g^{\gamma\delta}] \\ + \frac{g_s^2 C_A}{(1 - \beta_1)(1 - y) (p_i \cdot p_k)} [-2g^{\delta\gamma}] [g^{\eta\eta'}] \\ + 2Re(g_s^2 C_A g^{\eta\eta'} g^{\gamma\delta} \left[ \frac{1}{2y(p_i \cdot Q)} + \frac{\beta_1(\frac{Q^2}{2p_i \cdot Q})}{2y(1 - \beta_1)(1 - y) (p_i \cdot Q)} \right. \\ \left. + \frac{\beta_1 Q \cdot p_k}{2y(1 - \beta_1)(1 - y) (p_i \cdot p_k)(p_i \cdot Q)} + \frac{\beta_1}{y(1 - \beta_1)(p_i \cdot Q)} + \frac{1}{2(1 - \beta_1)(1 - y)(p_i \cdot p_k)} \right] \\ + g_s^2 C_A g^{\eta\eta'} g^{\gamma\delta} \left[ \frac{1 - \beta_1}{y \beta_1 (p_i \cdot Q)} + \frac{1}{2y(p_i \cdot Q)} + \frac{(1 - \beta_1)(\frac{Q^2}{2p_i \cdot Q})}{2y \beta_1 (1 - y) (p_i \cdot Q)} \right. \\ \left. + \frac{(1 - \beta_1) Q \cdot p_k}{2y \beta_1 (1 - y) (p_i \cdot p_k)(p_i \cdot Q)} + \frac{1}{2(1 - \beta_1)(1 - y)(p_i \cdot p_k)} \right]) \quad (4.87)$$

$$|M|^2 = g_s^2 C_A g^{\gamma\delta} [-2[1 - \epsilon] \beta_1 (1 - \beta_1) n_{\perp,1}^{\eta} n_{\perp,1}^{\eta'} + \frac{\beta_1(\frac{Q^2}{2p_i \cdot Q})}{y(1 - \beta_1)(1 - y) (p_i \cdot Q)} g^{\eta\eta'} \\ + \frac{\beta_1 Q \cdot p_k}{y(1 - \beta_1)(1 - y) (p_i \cdot p_k)(p_i \cdot Q)} g^{\eta\eta'} + \frac{2\beta_1}{y(1 - \beta_1)(p_i \cdot Q)} g^{\eta\eta'} + \frac{2(1 - \beta_1)}{y \beta_1 (p_i \cdot Q)} g^{\eta\eta'} \quad (4.88) \\ + \frac{(1 - \beta_1)(\frac{Q^2}{2p_i \cdot Q})}{y \beta_1 (1 - y) (p_i \cdot Q)} g^{\eta\eta'} + \frac{(1 - \beta_1) Q \cdot p_k}{y \beta_1 (1 - y) (p_i \cdot p_k)(p_i \cdot Q)} g^{\eta\eta'}]$$

$$\begin{aligned}
|M|^2 = & g_s^2 C_A g^{\gamma\delta} [-2(1-\epsilon)\beta_1(1-\beta_1)n_{\perp,1}^\eta n_{\perp,1}^{\eta'} + \frac{2\beta_1}{y(1-\beta_1)(p_i \cdot Q)} g^{\eta\eta'} + \frac{2(1-\beta_1)}{y\beta_1(p_i \cdot Q)} g^{\eta\eta'} \\
& + \frac{Q^2}{2y\beta_1(1-y)(p_i \cdot Q)(p_i \cdot Q)} g^{\eta\eta'} + \frac{Q \cdot p_k}{y\beta_1(1-y)(p_i \cdot p_k)(p_i \cdot Q)} g^{\eta\eta'}]
\end{aligned}
\tag{4.89}$$

### 4.3 A daughter gluon from a parent quark



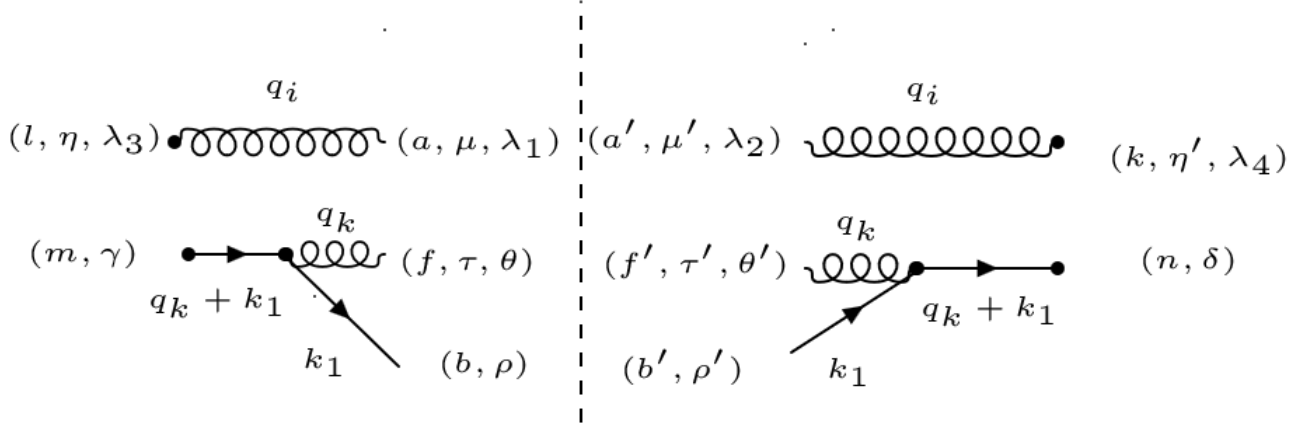
$$|M_1|^2 = -\frac{g_s^2 [T^{a'}]_k^{o'} [T^a]_o^l}{4(k_1 \cdot q_i)(k_1 \cdot q_i)} [(\not{q}_i + \not{k}_1) \gamma_\mu \not{k}_1 \gamma^\mu (\not{q}_i + \not{k}_1)] [-g^\delta_\gamma] \quad (4.90)$$

$$|M_1|^2 = -(2-d) \frac{g_s^2 [T^{a'}]_k^{o'} [T^a]_o^l}{4(k_1 \cdot q_i)(k_1 \cdot q_i)} [(\not{q}_i + \not{k}_1) \not{k}_1 (\not{q}_i + \not{k}_1)] [-g^\delta_\gamma] \quad (4.91)$$

$$|M_1|^2 = -(2-d) \frac{g_s^2 [T^{a'}]_k^{o'} [T^a]_o^l}{2(k_1 \cdot q_i)} [\not{q}_i] [-g^\delta_\gamma] \quad (4.92)$$

$$|M_1|^2 = -(2-d) \frac{g_s^2 C_F}{2y p_i \cdot Q} [(\alpha_1 - y\beta_1 (\frac{Q^2}{2p_i \cdot Q})) \not{p}_i + y\beta_1 \not{Q} + \sqrt{y\alpha_1\beta_1} \not{h}_{\perp,1}] [-g^\delta_\gamma] \quad (4.93)$$

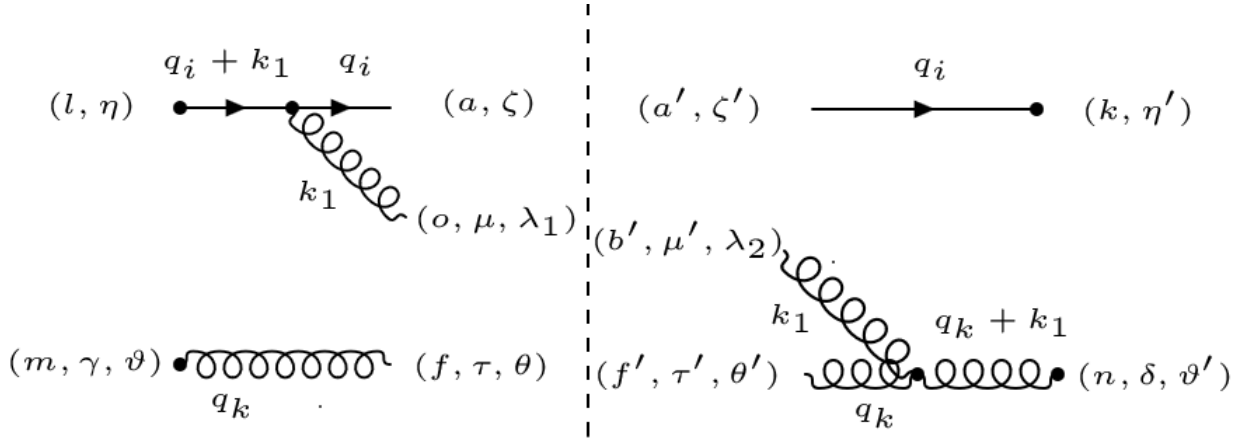
$$|M_1|^2 = (d-2)(1-\beta_1) \frac{g_s^2 C_F}{2y p_i \cdot Q} [\not{p}_i] [-g^\delta_\gamma] \quad (4.94)$$



$$|M_2|^2 = -\frac{g_s^2 C_F}{4(k_1 \cdot q_k)(k_1 \cdot q_k)} [(\not{k}_k + \not{k}_1) \gamma_{\tau'} \not{k}_1 \gamma^{\tau} (\not{k}_k + \not{k}_1)] [-g^{\eta\eta'}] \quad (4.95)$$

$$|M_2|^2 = (d-2) \frac{g_s^2 C_F}{4(k_1 \cdot q_k)} [\not{k}_k] [-g^{\eta\eta'}] \quad (4.96)$$

It doesn't contribute to the final result!!



$$M_1 M_2^\dagger = \frac{-g_s^2 [T^o]_a^l f^{f' b' n}}{4(k_1 \cdot q_i)(k_1 \cdot q_k)} [\not{k}_i \gamma_\mu (\not{k}_1 + \not{k}_i)] \quad (4.97)$$

$$[(g^{\gamma\mu}(q_k - k_1)^\delta + g^{\mu\delta}(2k_1 + q_k)^\gamma - g^{\delta\gamma}(2q_k + k_1)^\mu)]$$

$$M_1 M_2^\dagger = \frac{-g_s^2 [T^o]_a^l f^{f' b' n}}{4(k_1 \cdot q_i)(k_1 \cdot q_k)} [-\gamma_\mu \not{k}_i \not{k}_1 + 2(\not{k}_1 + \not{k}_i) q_{i\mu}] \quad (4.98)$$

$$[g^{\gamma\mu}(q_k - k_1)^\delta + g^{\mu\delta}(2k_1 + q_k)^\gamma - g^{\delta\gamma}(2q_k + k_1)^\mu]$$

$$\begin{aligned}
M1M2^\dagger &= \frac{-g_s^2 [T^a]_c^l f^{f' b' n}}{4y(1-\beta_1)(1-y)(p_i \cdot p_k)(p_i \cdot Q)} \\
&[-\gamma_\mu((\beta_1 - \alpha_1 y(\frac{Q^2}{2p_i \cdot Q})) \not{p}_i + y\alpha_1 \not{Q})((\alpha_1 - y\beta_1(\frac{Q^2}{2p_i \cdot Q})) \not{p}_i + y\beta_1 \not{Q}) \\
&+ (2((\alpha_1 - y\beta_1(\frac{Q^2}{2p_i \cdot Q})) \not{p}_i + 2y\beta_1 \not{Q} + 2(\beta_1 - \alpha_1 y(\frac{Q^2}{2p_i \cdot Q})) \not{p}_i + 2y\alpha_1 \not{Q})(\beta_1 q_{i\mu})] \\
&[g^{\gamma\mu}(-\alpha_1 p_i)^\delta + g^{\mu\delta}(2\alpha_1 p_i)^\gamma - g^{\delta\gamma}(\alpha_1 p_i + (2-y)Q)^\mu]
\end{aligned} \tag{4.99}$$

$$\begin{aligned}
M1M2^\dagger &= \frac{-g_s^2 C_F}{4y(1-\beta_1)(1-y)(p_i \cdot p_k)(p_i \cdot Q)} \\
&[-\gamma_\mu(y\beta_1^2) \not{p}_i \not{Q} + 2(\not{p}_i + y \not{Q})(\beta_1 p_{i\mu})] \\
&[g^{\gamma\mu}(-\alpha_1 p_i + \sqrt{1-y}p_k)^\delta + g^{\mu\delta}(2\alpha_1 p_i + \sqrt{1-y}p_k)^\gamma - g^{\delta\gamma}(\alpha_1 p_i + 2\sqrt{1-y}p_k)^\mu]
\end{aligned} \tag{4.100}$$

$$\begin{aligned}
M1M2^\dagger &= \frac{-g_s^2 C_F}{4y(1-\beta_1)(1-y)(p_i \cdot p_k)(p_i \cdot Q)} \\
&[-\gamma_\mu(y\beta_1^2) \not{p}_i \not{Q}][g^{\gamma\mu}(-\alpha_1 p_i + \sqrt{1-y}p_k)^\delta + g^{\mu\delta}(2\alpha_1 p_i + \sqrt{1-y}p_k)^\gamma - g^{\delta\gamma}(\alpha_1 p_i + 2\sqrt{1-y}p_k)^\mu] \\
&+ [2(\not{p}_i + y \not{Q})(\beta_1 p_{i\mu})][g^{\gamma\mu}(-\alpha_1 p_i + \sqrt{1-y}p_k)^\delta + g^{\mu\delta}(2\alpha_1 p_i + \sqrt{1-y}p_k)^\gamma - g^{\delta\gamma}(\alpha_1 p_i + 2\sqrt{1-y}p_k)^\mu]
\end{aligned} \tag{4.101}$$

$$\begin{aligned}
M1M2^\dagger &= \frac{-g_s^2 C_F}{4y(1-\beta_1)(1-y)(p_i \cdot p_k)(p_i \cdot Q)} \\
&[-\gamma_\mu(y\beta_1^2) \not{p}_i \not{Q}][g^{\gamma\mu}(-\alpha_1 p_i)^\delta + g^{\mu\delta}(\alpha_1 p_i)^\gamma - g^{\delta\gamma}((2-y)Q)^\mu][g^\delta_\gamma] \\
&+ [2\beta_1(\not{p}_i + y \not{Q})][p_i^\gamma(-\alpha_1 p_i)^\delta + p_i^\delta(2\alpha_1 p_i)^\gamma - g^{\delta\gamma}(\alpha_1 p_i + (2-y)Q)^\gamma Q \cdot p_i]
\end{aligned} \tag{4.102}$$

$$\begin{aligned}
M1M2^\dagger &= \frac{-g_s^2 C_F}{4y(1-\beta_1)(1-y)(p_i \cdot p_k)(p_i \cdot Q)} \\
&[-\gamma_\mu(y\beta_1^2) \not{p}_i \not{Q}][-g^{\delta\gamma}(\alpha_1 p_i + 2\sqrt{1-y}p_k)^\mu] \\
&+ [2\beta_1(\not{p}_i + y \not{Q})][-g^{\delta\gamma}(\alpha_1 p_i + 2\sqrt{1-y}p_k)^\gamma p_i \cdot p_k]
\end{aligned} \tag{4.103}$$

$$\begin{aligned}
M1M2^\dagger &= \frac{-g_s^2 C_F}{4y(1-\beta_1)(1-y)(p_i \cdot p_k)(p_i \cdot Q)} \\
&[-2y\beta_1^2 \sqrt{1-y} \not{p}_k \not{p}_i \not{Q} + 4\sqrt{1-y}\beta_1(\not{p}_i + y \not{Q})p_i \cdot p_k][g^{\delta\gamma}]
\end{aligned} \tag{4.104}$$

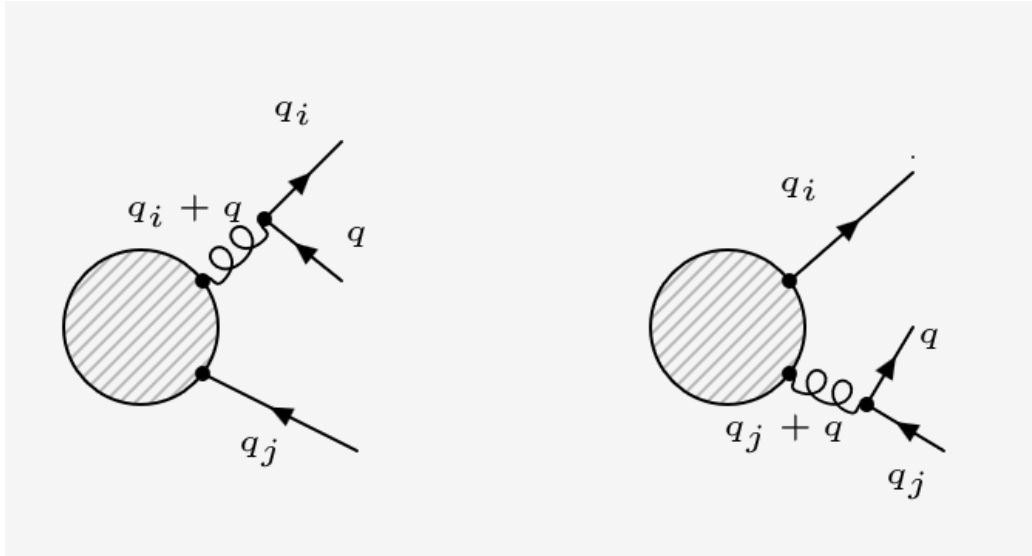
$$M1M2^\dagger = \frac{-g_s^2 C_F}{y(1-\beta_1)(1-y)(p_i \cdot Q)} \sqrt{1-y}\beta_1[\not{p}_i][g^{\delta\gamma}] \tag{4.105}$$

### 4.3.1 Interpretation of the result

$$|M|^2 = \frac{-g_s^2 C_F}{2y(1-y)(p_i \cdot Q)} [\not{p}_i][g^{\delta\gamma}] \otimes [2RE(\frac{2\beta_1}{1-\beta_1}) + (d-2)(1-\beta_1)] \tag{4.106}$$



#### 4.4 A daughter quark from a parent gluon



This case concerns a daughter quark from a parent gluon which splits into a quark-anti-quark pair. Here no singularity develops since daughter and parent can always be distinguished.

This is the reason why the calculation is not mentioned here, because the evaluation is analogous to the other parts considered so far.

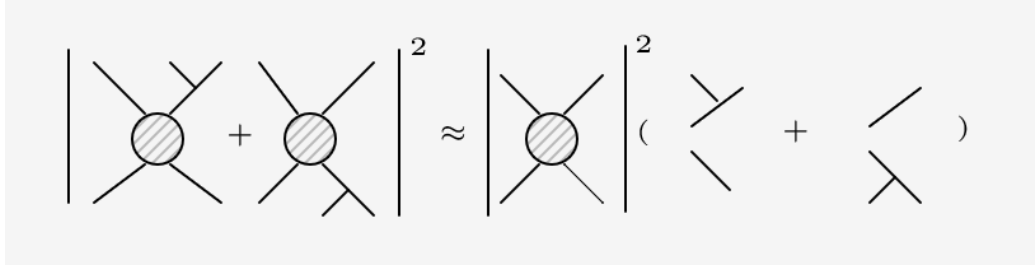


## 5 Example Applications

Our method has to be illustrated with a simplest examples, namely Two-jet production at lepton-colliders  $e^+e^- \rightarrow q + \bar{q} + g$ . As in section shown, At first perturbative order, two Feynman diagrams contribute to the matrix element corresponding to the emission of a gluon from either the final-state quark or the anti-quark. The partonic differential cross section with respect to the quark and anti-quark momentum fractions was given by:

$$\frac{d^2\sigma}{dx_1 dx_2} = \hat{\sigma}_0 \frac{\alpha_s}{2\pi} C_F \frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)} \quad (5.1)$$

In the parton shower approach, two contributions occur as well. For the final result, those two contributions have to be summed.



**Figure 5.1:** Dipole/Antenna factorisation

The calculation of the subtracted cross section involves the evaluation of two dipole contributions:  $D_{13,2}$  and  $D_{23,1}$ .

$$|\mathcal{M}_m + 1|^2 = \sum_{i,j} \sum_{k \neq i,j} \mathcal{D}_{ij,k} + \sum_{i,j} \sum_a \mathcal{D}^a_{ij} + \sum_{a,i} \sum_{k \neq i} \mathcal{D}^{ai}_k + \sum_{a,i} \sum_{b \neq a} \mathcal{D}^{aj,b} + \dots \quad (5.2)$$

$$\begin{aligned} \mathcal{D}_{13,2}(q_i, q_j, q) &= \frac{-1}{2q_i \cdot q} \left[ \frac{T_2 \cdot T_{13}}{T_{13}^2} V_{13,2} |1, \tilde{13}, \tilde{2} \rangle \right] \\ \mathcal{D}_{13,2}(q_i, q_j, q) &= \frac{1}{2p_i \cdot p_j} V_{13,2} |\mathcal{M}_2|^2 \end{aligned} \quad (5.3)$$

$$\begin{aligned} \mathcal{D}_{13,2}(q_i, q_j, q) &= \frac{-1}{2p_i \cdot p_j} \left[ \frac{-(d-2)(1-z)(1-y)}{y(1-2z+2z^2)} + \frac{(d-2)yz^2}{(1-z)(1-y)} \right. \\ &\quad \left. - \left( \frac{-2z}{z-1} \right) \frac{1}{y(1-2z+2z^2)} \right] |\mathcal{M}_2|^2 \end{aligned} \quad (5.4)$$

For convenience, the shower variables are introduced expressed in terms of the  $x_i$ :

$$\begin{aligned}\tilde{z}_1 &= \frac{x_1 + x_2 - 1}{x_2} \\ y_{13,2} &= 1 - x_2\end{aligned}\tag{5.5}$$

For the gluon emission from the quark, after using the expressions it can be obtained [28]

$$\frac{d^2\sigma}{dx_1 dx_2}_{PS_q} = \hat{\sigma}_0 \frac{\alpha_s}{2\pi} C_F \left[ \frac{1}{1-x_2} \left( \frac{2}{2-x_1-x_2} - (1+x_1) \right) + \frac{1-x_1}{x_2} \right]\tag{5.6}$$

For exactly the same calculating for a gluon emission of an anti-quark, it is enough to swap  $x_1$  with  $x_2$ :

$$\frac{d^2\sigma}{dx_1 dx_2}_{PS_{\bar{q}}} = \hat{\sigma}_0 \frac{\alpha_s}{2\pi} C_F \left[ \frac{1}{1-x_1} \left( \frac{2}{2-x_2-x_1} - (1+x_2) \right) + \frac{1-x_2}{x_1} \right]\tag{5.7}$$

Thus, the total parton shower cross section will be:

$$\frac{d^2\sigma}{dx_1 dx_2}|_{PS} = \frac{d^2\sigma}{dx_1 dx_2}|_{PS_q} + \frac{d^2\sigma}{dx_1 dx_2}|_{PS_{\bar{q}}} = \hat{\sigma}_0 \frac{\alpha_s}{2\pi} C_F \left[ \frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)} + \frac{1-x_1}{x_2} + \frac{1-x_2}{x_1} \right]\tag{5.8}$$

Obviously, the parton shower exactly reproduces the soft and collinear singular structure of the matrix element as  $x_{1,2} \rightarrow 1$ .

## 6 Summary and conclusions





# Appendix A

## DETAILED CALCULATIONS

Detailed calculation of the gluon radiation of a quark

$$|M_1|^2$$

$$|M_1|^2 = (d-2) \frac{g_s^2 C_F}{(2k_1 \cdot q_i)} [k_1][\not{q}_k] \quad (1)$$

$$|M_1|^2 = (d-2) \frac{g_s^2 C_F}{2y p_i \cdot Q} [(\alpha_1 - y\beta_1(\frac{Q^2}{2p_i \cdot Q})) \not{p}_i + y\beta_1 \not{Q} + \sqrt{y\alpha_1\beta_1} \not{n}_{\perp,1}] [A_1 \not{p}_i + A_2 \not{Q} + \sqrt{1-y} \not{p}_k] \quad (2)$$

$$|M_1|^2 = (d-2) \frac{g_s^2 C_F}{2y p_i \cdot Q} [(A_2(\alpha_1 - y\beta_1(\frac{Q^2}{2p_i \cdot Q})) + A_1 y\beta_1) p_i \cdot Q + (\alpha_1 - y\beta_1(\frac{Q^2}{2p_i \cdot Q})) \sqrt{1-y} p_i \cdot p_k + A_2 y\beta_1 Q^2 + \sqrt{1-y} \sqrt{y\alpha_1\beta_1} n_{\perp,1} \cdot p_k] \quad (3)$$

For the collinearity  $y \rightarrow 0$  we'll get:

$$|M_1|^2 = (d-2) \frac{g_s^2 C_F}{2y p_i \cdot Q} [(A_2(\alpha_1 - y\beta_1(\frac{Q^2}{2p_i \cdot Q})) + A_1 y\beta_1) \not{p}_i \not{Q} + (\alpha_1 - y\beta_1(\frac{Q^2}{2p_i \cdot Q})) \sqrt{1-y} \not{p}_i \not{p}_k + A_2 y\beta_1 Q^2 + \sqrt{1-y} \sqrt{y\alpha_1\beta_1} \not{n}_{\perp,1} \not{p}_k] \quad (4)$$

$$|M_1|^2 = (d-2)(1-\beta_1)\sqrt{1-y} \frac{g_s^2 C_F}{2y p_i \cdot Q} [\not{p}_i \not{p}_k] \quad (5)$$



$$|M_2|^2$$

$$|M_2|^2 = (d-2) \frac{g_s^2 [T^c]_f^m [T^c]_f^n}{2k_1 \cdot q_k} [\not{k}_1] [\not{q}_i] \quad (6)$$

$$|M_2|^2 = (d-2) \frac{g_s^2 C_F}{2k_1 \cdot q_k} [(\alpha_1 - y\beta_1(\frac{Q^2}{2p_i \cdot Q})) \not{p}_i + y\beta_1 \not{Q} + \sqrt{y\alpha_1\beta_1} \not{n}_{\perp,1}]$$

$$[(\beta_1 - \alpha_1 y(\frac{Q^2}{2p_i \cdot Q})) \not{p}_i + y\alpha_1 \not{Q} - \sqrt{y\alpha_1\beta_1} \not{n}_{\perp,1}] \quad (7)$$

$$|M_2|^2 = (d-2) \frac{g_s^2 C_F}{2k_1 \cdot q_k} [y\alpha_1(\alpha_1 - y\beta_1(\frac{Q^2}{2p_i \cdot Q})) \not{p}_i \not{Q} + y\beta_1(\beta_1 - \alpha_1 y(\frac{Q^2}{2p_i \cdot Q})) \not{Q} \not{p}_i$$

$$+ y^2\alpha_1\beta_1 Q^2 - y\beta_1 \sqrt{y\alpha_1\beta_1} \not{Q} \not{n}_{\perp,1} + y\beta_1 \sqrt{y\alpha_1\beta_1} \not{n}_{\perp,1} \not{Q} - y\alpha_1\beta_1 n_{\perp,1}^2$$

$$+ (\beta_1 - \alpha_1 y(\frac{Q^2}{2p_i \cdot Q})) \sqrt{y\alpha_1\beta_1} \not{n}_{\perp,1} \not{p}_i - (\alpha_1 - \alpha_1 y(\frac{Q^2}{2p_i \cdot Q})) \sqrt{y\alpha_1\beta_1} \not{p}_i \not{n}_{\perp,1}] \quad (8)$$

Which means:

$$|M_2|^2 \sim (d-2) \frac{g_s^2 C_F}{2k_1 \cdot q_k} y[...]$$

$$|M_2|^2 \rightarrow 0 \quad \text{for } y \rightarrow 0 \quad (9)$$

$$M_1 M_2^\dagger$$

$$M_1 M_2^\dagger = \frac{-g_s^2 [T^a]_o^l [T^a]_{f'}^n}{(2q_i k_1)(2q_k k_1)} [(\not{q}_i + \not{k}_1) \not{q}_i \gamma^\mu] [(\not{q}_k + \not{k}_1) \not{q}_k \gamma_\mu]$$

$$+ 4[(\not{q}_i + \not{k}_1) q_i^\mu] [(\not{q}_k + \not{k}_1) q_{k\mu}] \quad (10)$$

$$M_1 M_2^\dagger = \frac{-g_s^2 C_F}{4y(1-\beta_1)(1-y)(p_i \cdot p_k)(p_i \cdot Q)}$$

$$[(\not{q}_i \not{q}_i + \not{k}_1 \not{q}_i) \gamma^\mu] [(\not{q}_k \not{q}_k + \not{k}_1 \not{q}_k) \gamma_\mu] + 4(q_i^\mu q_{k\mu}) [\not{q}_i + \not{k}_1] [\not{q}_k + \not{k}_1] \quad (11)$$

$$M_1 M_2^\dagger = \frac{-g_s^2 C_F}{4y(1-\beta_1)(1-y)(p_i \cdot p_k)(p_i \cdot Q)}$$

$$[\not{k}_1 \not{q}_i \gamma^\mu] [\not{k}_1 \not{q}_k \gamma_\mu] + 4(q_i \cdot q_k) [\not{q}_i \not{q}_k + \not{k}_1 \not{q}_k + \not{q}_i \not{k}_1] \quad (12)$$

$$\begin{aligned}
M_1 M_2^\dagger &= \frac{-g_s^2 C_F}{4y(1-\beta_1)(1-y)(p_i \cdot p_k)(p_i \cdot Q)} \\
&4(A_1\beta_1 p_i \cdot p_i + A_2\beta_1 p_i \cdot Q + \beta_1\sqrt{1-y} p_i \cdot p_k) \\
&[A_1\beta_1 \not{p}_i \not{p}_i + A_2\beta_1 \not{p}_i \not{Q} + \beta_1\sqrt{1-y} \not{p}_i \not{p}_k \\
&+ [(1-\beta_1) - y\beta_1(\frac{Q^2}{2p_i \cdot Q})]\sqrt{1-y} \not{p}_i \not{p}_k - y\beta_1(\frac{Q^2}{2p_i \cdot Q})A_1 \not{p}_i \not{p}_i \\
&- y\beta_1(\frac{Q^2}{2p_i \cdot Q})A_2 \not{p}_i \not{Q} + y\beta_1 A_1 \not{Q} \not{p}_i + y\beta_1 A_2 \not{Q} \not{Q} + y\beta_1\sqrt{1-y} \not{Q} \not{p}_k \\
&+ [\beta_1(1-\beta_1) - y\beta_1^2(\frac{Q^2}{2p_i \cdot Q})] \not{p}_i \not{p}_i + y\beta_1^2 \not{p}_i \not{Q}]
\end{aligned} \tag{13}$$

$$\begin{aligned}
M_1 M_2^\dagger &= \frac{-g_s^2 C_F}{4y(1-\beta_1)(1-y)(p_i \cdot p_k)(p_i \cdot Q)} \\
&4(A_2\beta_1 p_i \cdot Q + \beta_1\sqrt{1-y} p_i \cdot p_k)[A_2\beta_1 \not{p}_i \not{Q} + \beta_1\sqrt{1-y} \not{p}_i \not{p}_k \\
&+ [(1-\beta_1) - y\beta_1(\frac{Q^2}{2p_i \cdot Q})]\sqrt{1-y} \not{p}_i \not{p}_k - y\beta_1(\frac{Q^2}{2p_i \cdot Q})A_2 \not{p}_i \not{Q} \\
&+ y\beta_1 A_1 \not{Q} \not{p}_i + y\beta_1 A_2 \not{Q} \not{Q} + y\beta_1\sqrt{1-y} \not{Q} \not{p}_k + y\beta_1^2 \not{p}_i \not{Q}]
\end{aligned} \tag{14}$$

$$\begin{aligned}
M_1 M_2^\dagger &= \frac{-g_s^2 C_F}{4y(1-\beta_1)(1-y)(p_i \cdot p_k)(p_i \cdot Q)} \\
&4(\beta_1\sqrt{1-y} p_i \cdot p_k)[\beta_1\sqrt{1-y} \not{p}_i \not{p}_k + (1-\beta_1)\sqrt{1-y} \not{p}_i \not{p}_k]
\end{aligned} \tag{15}$$

$$M_1 M_2^\dagger = \frac{-g_s^2 C_F}{y(1-\beta_1)(p_i \cdot p_k)(p_i \cdot Q)} \beta_1(p_i \cdot p_k)[\beta_1 \not{p}_i \not{p}_k + (1-\beta_1) \not{p}_i \not{p}_k] \tag{16}$$

$$M_1 M_2^\dagger = \frac{\beta_1}{(1-\beta_1)} \frac{-g_s^2 C_F}{y(p_i \cdot Q)} [\not{p}_i \not{p}_k] \tag{17}$$

Evaluation of the tensor  $N^{\eta\eta'}$

$$\begin{aligned}
N^{\eta\eta'} &\equiv g_{\mu\mu'} g_{\zeta\zeta'} [-g^{\mu\zeta} g^{\mu'\eta'} (q - q_i)^\eta (2q_i + q)^{\zeta'} + g^{\mu\zeta} g^{\eta'\zeta'} (q - q_i)^\eta (2q + q_i)^{\mu'} \\
&+ g^{\mu\zeta} g^{\zeta'\mu'} (q - q_i)^\eta (q_i - q)^{\eta'} + g^{\zeta\eta} g^{\mu'\zeta'} (2q + q_i)^\mu (2q_i + q)^{\zeta'} \\
&- g^{\zeta\eta} g^{\eta'\zeta'} (2q + q_i)^\mu (2q + q_i)^{\mu'} - g^{\zeta\eta} g^{\zeta'\mu'} (2q + q_i)^\mu (q_i - q)^{\eta'} \\
&- g^{\eta\mu} g^{\mu'\eta'} (2q_i + q)^\zeta (2q_i + q)^{\zeta'} + g^{\eta\mu} g^{\eta'\zeta'} (2q_i + q)^\zeta (2q + q_i)^{\mu'} \\
&+ g^{\eta\mu} g^{\zeta'\mu'} (2q_i + q)^\zeta (q_i - q)^{\eta'}] [g^{\gamma\delta}]
\end{aligned} \tag{18}$$

$$\begin{aligned}
N^{\eta\eta'} &\equiv [-(q - q_i)^\eta (2q_i + q)^{\eta'} + (q - q_i)^\eta (2q + q_i)^{\eta'} + d(q - q_i)^\eta (q_i - q)^{\eta'} \\
&+ (2q + q_i)^{\eta'} (2q_i + q)^\eta - g^{\eta\eta'} (2q + q_i)^\mu (2q + q_i)_\mu - (2q + q_i)^\eta (q_i - q)^{\eta'} \\
&- g^{\eta\eta'} (2q_i + q)^\zeta (2q_i + q)_\zeta + (2q_i + q)^{\eta'} (2q + q_i)^\eta + (2q_i + q)^\eta (q_i - q)^{\eta'}] [g^{\gamma\delta}]
\end{aligned} \tag{19}$$



$$\begin{aligned}
N^{\eta\eta'} \equiv & [-(q^\eta q^{\eta'} + 2q^\eta q_i^{\eta'} - q_i^\eta q^{\eta'} - 2q_i^\eta q_i^{\eta'}) + (2q^\eta q^{\eta'} + q^\eta q_i^{\eta'} - 2q_i^\eta q^{\eta'} - q_i^\eta q_i^{\eta'}) \\
& + (dq^\eta q_i^{\eta'} - dq^\eta q^{\eta'} - dq_i^\eta q_i^{\eta'} + dq_i^\eta q^{\eta'}) + (4q^{\eta'} q_i^\eta + 2q^{\eta'} q^\eta + 2q_i^{\eta'} q_i^\eta + q_i^{\eta'} q^\eta) \\
& - (-2q^\eta q^{\eta'} + 2q^\eta q_i^{\eta'} - q_i^\eta q^{\eta'} + q_i^\eta q_i^{\eta'}) + (2q^{\eta'} q^\eta + q^{\eta'} q_i^\eta + 4q_i^{\eta'} q^\eta + 2q_i^{\eta'} q_i^\eta) \\
& + (-q^\eta q^{\eta'} + q^\eta q_i^{\eta'} - 2q_i^\eta q^{\eta'} + 2q_i^\eta q_i^{\eta'}) - g^{\eta\eta'} (5q^2 + 5q_i^2 + 8qq_i)] [g^{\gamma\delta}]
\end{aligned} \quad (20)$$

## Evaluation of the interference term $M_1 M_2^\dagger$

### Calculation of the first Term

$$\begin{aligned}
& g^{\eta\eta'} [2\{A_1 \beta_1 p_i^\gamma p_i^\delta + A_2 \beta_1 p_i^\gamma Q^\delta + \beta_1 \sqrt{1-y} p_i^\gamma p_k^\delta\} \\
& + 2\{[\beta_1(1-\beta_1) - y\beta_1^2 (\frac{Q^2}{2p_i \cdot Q})] p_i^\gamma p_i^\delta + y\beta_1^2 p_i^\gamma Q^\delta\} \\
& + \{[(1-\beta_1) - y\beta_1 (\frac{Q^2}{2p_i \cdot Q})] \sqrt{1-y} p_i^\gamma p_k^\delta - y\beta_1 (\frac{Q^2}{2p_i \cdot Q}) A_1 p_i^\gamma p_i^\delta - y\beta_1 (\frac{Q^2}{2p_i \cdot Q}) A_2 p_i^\gamma Q^\delta \\
& + y\beta_1 A_1 Q^\gamma p_i^\delta + y\beta_1 A_2 Q^\gamma Q^\delta + y\beta_1 \sqrt{1-y} Q^\gamma p_k^\delta\} \\
& + 3\{[(1-\beta_1)^2 - y^2 \beta_1^2 (\frac{Q^2}{2p_i \cdot Q})^2] p_i^\gamma p_i^\delta - y^2 \beta_1^2 (\frac{Q^2}{2p_i \cdot Q}) p_i^\gamma Q^\delta - y^2 \beta_1^2 (\frac{Q^2}{2p_i \cdot Q}) Q^\gamma p_i^\delta\} \\
& + 4\{[\beta_1(1-\beta_1) - y\beta_1^2 (\frac{Q^2}{2p_i \cdot Q})] p_i^\gamma p_i^\delta + y\beta_1^2 Q^\gamma p_i^\delta\} \\
& + 2\{A_1 \beta_1 p_i^\gamma p_i^\delta + A_2 \beta_1 Q^\gamma p_i^\delta + \beta_1 \sqrt{1-y} p_k^\gamma p_i^\delta\} \\
& + \{[(1-\beta_1) - y\beta_1 (\frac{Q^2}{2p_i \cdot Q})] \sqrt{1-y} p_k^\gamma p_i^\delta - y\beta_1 (\frac{Q^2}{2p_i \cdot Q}) A_1 p_i^\gamma p_i^\delta - y\beta_1 (\frac{Q^2}{2p_i \cdot Q}) A_2 Q^\gamma p_i^\delta \\
& + y\beta_1 A_1 p_i^\gamma Q^\delta + y\beta_1 A_2 Q^\gamma Q^\delta + y\beta_1 \sqrt{1-y} p_k^\gamma Q^\delta\}]
\end{aligned} \quad (21)$$

### Calculation of the second term

$$-g^{\eta\eta'} g^{\gamma\delta} (2q \cdot q_j + q \cdot q + 4q_i \cdot q_j + 2q_i \cdot q) \quad (22)$$

$$\begin{aligned}
& -g^{\eta\eta'} g^{\gamma\delta} [2([\alpha_1(1-y) + y\beta_1 (\frac{Q^2}{2p_i \cdot Q})] p_i \cdot p_k + y\beta_1 Q \cdot p_k + \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1}) \\
& 4([\beta_1(1-y) + y\alpha_1 (\frac{Q^2}{2p_i \cdot Q})] p_i \cdot p_k + y\alpha_1 Q \cdot p_k - \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1}) \\
& + 2(y p_i \cdot Q)]
\end{aligned} \quad (23)$$



## Calculation of the third term

$$\begin{aligned}
& + g^{\gamma\eta'} \{ [(1 - \beta_1) - y\beta_1(\frac{Q^2}{2p_i \cdot Q})] \sqrt{1 - y} p_i^\eta p_k^\delta - y\beta_1(\frac{Q^2}{2p_i \cdot Q}) A_1 p_i^\eta p_i^\delta - y\beta_1(\frac{Q^2}{2p_i \cdot Q}) A_2 p_i^\eta Q^{\eta'} \\
& + y\beta_1 A_1 Q^\eta p_i^\delta + y\beta_1 A_2 Q^\eta Q^\delta + y\beta_1 \sqrt{1 - y} Q^\eta p_k^\delta \\
& - [ [(1 - \beta_1)^2 - y^2 \beta_1^2 (\frac{Q^2}{2p_i \cdot Q})^2] p_i^\eta p_i^\delta - y^2 \beta_1^2 (\frac{Q^2}{2p_i \cdot Q}) p_i^\eta Q^\delta - y^2 \beta_1^2 (\frac{Q^2}{2p_i \cdot Q}) Q^\eta p_i^\delta ] \\
& - [ A_1 \beta_1 p_i^\eta p_i^\delta + A_2 \beta_1 p_i^\eta Q^\delta + \beta_1 \sqrt{1 - y} p_i^\eta p_k^\delta ] \\
& + [\beta_1(1 - \beta_1) - y\beta_1^2 (\frac{Q^2}{2p_i \cdot Q})] p_i^\eta p_i^{\eta'} + y\beta_1^2 p_i^\eta Q^{\eta'} \}
\end{aligned} \tag{24}$$

## Calculation of the fourth term

$$\begin{aligned}
& + g^{\eta'\delta} \{ [(1 - \beta_1) - y\beta_1(\frac{Q^2}{2p_i \cdot Q}) - \beta_1] \sqrt{1 - y} p_i^\eta p_k^\gamma \\
& + [2[(1 - \beta_1)^2 - y^2 \beta_1^2 (\frac{Q^2}{2p_i \cdot Q})^2] - y\beta_1(\frac{Q^2}{2p_i \cdot Q}) A_1 + A_1 \beta_1 + \\
& [\beta_1(1 - \beta_1) - y\beta_1^2 (\frac{Q^2}{2p_i \cdot Q})] p_i^\eta p_i^\gamma \\
& + [-2y^2 \beta_1^2 (\frac{Q^2}{2p_i \cdot Q}) - y\beta_1(\frac{Q^2}{2p_i \cdot Q}) A_2 + A_2 \beta_1 + y\beta_1^2] p_i^\eta Q^\gamma \\
& + [y\beta_1 A_1 + 2y^2 \beta_1^2 (\frac{Q^2}{2p_i \cdot Q})] Q^\eta p_i^\gamma + y\beta_1 A_2 Q^\eta Q^\gamma + y\beta_1 \sqrt{1 - y} Q^\eta p_k^\gamma \}
\end{aligned} \tag{25}$$

## Calculation of the fifth term

$$\begin{aligned}
& - g^{\gamma\delta} \{ [2[(1 - \beta_1) - y\beta_1(\frac{Q^2}{2p_i \cdot Q})] - 2\beta_1] \sqrt{1 - y} p_i^\eta p_k^{\eta'} \\
& [-2y\beta_1(\frac{Q^2}{2p_i \cdot Q}) A_1 + [(1 - \beta_1)^2 - y^2 \beta_1^2 (\frac{Q^2}{2p_i \cdot Q})^2] - 2A_1 \beta_1 \\
& - [\beta_1(1 - \beta_1) - y\beta_1^2 (\frac{Q^2}{2p_i \cdot Q})] p_i^\eta p_i^{\eta'} \\
& [-2y\beta_1(\frac{Q^2}{2p_i \cdot Q}) A_2 - y^2 \beta_1^2 (\frac{Q^2}{2p_i \cdot Q}) - y\beta_1^2 - 2A_2 \beta_1] p_i^\eta Q^{\eta'} \\
& + [2y\beta_1 A_1 - y^2 \beta_1^2 (\frac{Q^2}{2p_i \cdot Q})] Q^\eta p_i^{\eta'} + 2y\beta_1 A_2 Q^\eta Q^{\eta'} + 2y\beta_1 \sqrt{1 - y} Q^\eta p_k^{\eta'} \}
\end{aligned} \tag{26}$$

## Calculation of the sixth term

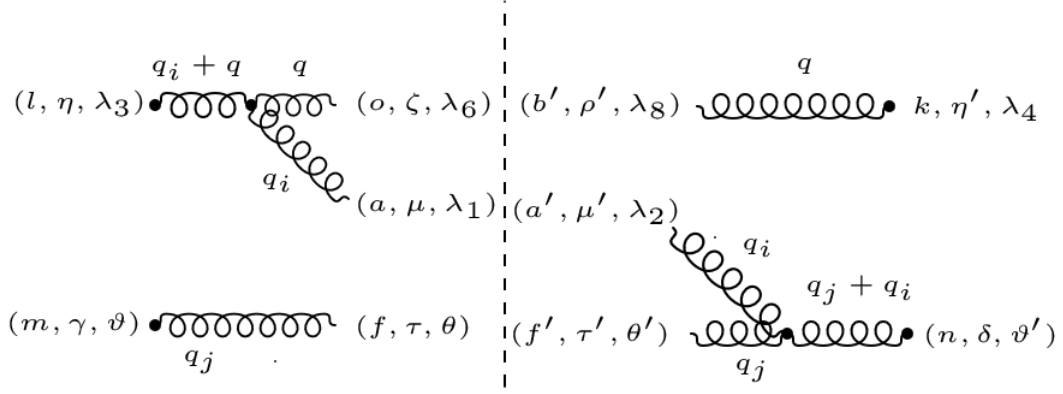
$$\begin{aligned}
& -g^{\eta\eta}\{[2[(1-\beta_1)-y\beta_1(\frac{Q^2}{2p_i \cdot Q})] + \beta_1]\sqrt{1-y}p_i^{\eta'}p_k^\delta \\
& [-2y\beta_1(\frac{Q^2}{2p_i \cdot Q})A_1 - 2[(1-\beta_1)^2 - y^2\beta_1^2(\frac{Q^2}{2p_i \cdot Q})^2] \\
& - [\beta_1(1-\beta_1) - y\beta_1^2(\frac{Q^2}{2p_i \cdot Q})] + A_1\beta_1] p_i^{\eta'}p_i^\delta \\
& [-2y\beta_1(\frac{Q^2}{2p_i \cdot Q})A_2 + 2y^2\beta_1^2(\frac{Q^2}{2p_i \cdot Q}) + A_2\beta_1 - y\beta_1^2] p_i^{\eta'}Q^\delta \\
& + [2y\beta_1A_1 + 2y^2\beta_1^2(\frac{Q^2}{2p_i \cdot Q})] Q^{\eta'}p_i^\delta + 2y\beta_1A_2 Q^{\eta'}Q^\delta + 2y\beta_1\sqrt{1-y}Q^{\eta'}p_k^\delta\}
\end{aligned} \tag{27}$$

## Calculation of the seventh term

$$\begin{aligned}
& -g^{\eta\delta}\{[2[(1-\beta_1)-y\beta_1(\frac{Q^2}{2p_i \cdot Q})] + \beta_1]\sqrt{1-y}p_i^{\eta'}p_k^\gamma \\
& [4[(1-\beta_1)^2 - y^2\beta_1^2(\frac{Q^2}{2p_i \cdot Q})^2] - 2y\beta_1(\frac{Q^2}{2p_i \cdot Q})A_1 + A_1\beta_1 \\
& + 2[\beta_1(1-\beta_1) - y\beta_1^2(\frac{Q^2}{2p_i \cdot Q})]] p_i^{\eta'}p_i^\gamma \\
& + [-4y^2\beta_1^2(\frac{Q^2}{2p_i \cdot Q}) - 2y\beta_1(\frac{Q^2}{2p_i \cdot Q})A_2 + 2y\beta_1^2 + A_2\beta_1] p_i^{\eta'}Q^\gamma \\
& + [-4y^2\beta_1^2(\frac{Q^2}{2p_i \cdot Q}) + 2y\beta_1A_1] Q^\eta p_i^{\eta'} + 2y\beta_1A_2 Q^\eta Q^{\eta'} + 2y\beta_1\sqrt{1-y}Q^{\eta'}p_k^\gamma\}
\end{aligned} \tag{28}$$

## Calculation of the eighth term

$$\begin{aligned}
& +g^{\gamma\delta}\{[4[(1-\beta_1)-y\beta_1(\frac{Q^2}{2p_i \cdot Q})] + 2\beta_1]\sqrt{1-y}p_k^\eta p_i^{\eta'} \\
& + [-4y\beta_1(\frac{Q^2}{2p_i \cdot Q})A_1 + 2A_1\beta_1 + [\beta_1(1-\beta_1) - y\beta_1^2(\frac{Q^2}{2p_i \cdot Q})] \\
& + [(1-\beta_1)^2 - y^2\beta_1^2(\frac{Q^2}{2p_i \cdot Q})^2]] p_i^\eta p_i^{\eta'} \\
& + [4y\beta_1A_1 - y^2\beta_1^2(\frac{Q^2}{2p_i \cdot Q})] p_i^\eta Q^{\eta'} + 4y\beta_1A_2 Q^\eta Q^{\eta'} + 4y\beta_1\sqrt{1-y}p_k^\eta Q^{\eta'} \\
& + [2A_2\beta_1 - 4y\beta_1(\frac{Q^2}{2p_i \cdot Q})A_2 - y^2\beta_1^2(\frac{Q^2}{2p_i \cdot Q}) + y\beta_1^2] Q^\eta p_i^{\eta'}\}
\end{aligned} \tag{29}$$



Evaluation of the interference term of inverse  $M_1 M_2^{\dagger'}$

$$M_1 M_2^{\dagger} = \frac{g_s^2 f^{l o a} f^{f' a' n} \delta^{a a'} \delta^{o b'} \delta^{f f'}}{(q_i + q)^2 (q_j + q_i)^2} [g_{\zeta}^{\eta'} g^{\gamma}_{\tau'} (g^{\eta \zeta} (2q + q_i)^{\mu} + g^{\zeta \mu} (q_i - q)^{\eta} - g^{\mu \eta} (2q_i + q)^{\zeta}) \\ g_{\mu \mu'} (g^{\tau' \mu'} (q_j - q_i)^{\delta} + g^{\mu' \delta} (2q_i + q_j)^{\tau'} - g^{\delta \tau'} (2q_j + q_i)^{\mu'})] \quad (30)$$

$$M_1 M_2^{\dagger} = \frac{g_s^2 f^{l o a} f^{f a n}}{4(q \cdot q_i)(q_i \cdot q_j)} [g^{\eta \eta'} (2q + q_i)^{\gamma} (q_j - q_i)^{\delta} + g^{\eta \eta'} (2q_i + q_j)^{\gamma} (2q + q_i)^{\delta} - g^{\eta \eta'} g^{\gamma \delta} (2q + q_i) \cdot (2q_j + q_i) \\ + g^{\gamma \eta'} (q_i - q)^{\eta} (q_j + q_i)^{\delta} + g^{\eta' \delta} (q_i - q)^{\eta} (2q_i + q_j)^{\gamma} - g^{\gamma \delta} (q_i - q)^{\eta} (2q_j + q_i)^{\eta'} \\ - g^{\gamma \eta} (2q_i + q)^{\eta'} (q_j - q_i)^{\delta} - g^{\eta \delta} (2q_i + q)^{\eta'} (2q_i + q_j)^{\gamma} + g^{\gamma \delta} (2q_j + q_i)^{\eta} (2q_i + q)^{\eta'}] \quad (31)$$

Parametrization in terms of  $(k_1 \cdot q_i)(q_i \cdot q_k)$

$$(k_1 \cdot q_i)(q_i \cdot q_k) \approx y \beta_1 (1 - y) (p_i \cdot Q)(p_i \cdot p_k) \quad (32)$$

Calculation of the third term

$$-g^{\eta \eta'} g^{\gamma \delta} \{4k_1 \cdot q_j + 2k_1 \cdot q_i + 2q_i \cdot q_k\} \quad (33)$$

$$M_1 M_2^{\dagger} = \frac{g_s^2 C_A}{4y \beta_1 (1 - y) (p_i \cdot p_k) (p_i \cdot Q)} g^{\eta \eta'} g^{\gamma \delta} \\ [4([\alpha_1 (1 - y) + y \beta_1 (\frac{Q^2}{2p_i \cdot Q})] p_i \cdot p_k + y \beta_1 Q \cdot p_k + \sqrt{\alpha_1 \beta_1 y (1 - y)} p_k \cdot n_{\perp, 1}) \\ 2([\beta_1 (1 - y) + y \alpha_1 (\frac{Q^2}{2p_i \cdot Q})] p_i \cdot p_k + y \alpha_1 Q \cdot p_k - \sqrt{\alpha_1 \beta_1 y (1 - y)} p_k \cdot n_{\perp, 1}) \\ + 2(y p_i \cdot Q)] \quad (34)$$

$$\begin{aligned}
& -g^{\eta\eta'} g^{\gamma\delta} [4([\alpha_1(1-y) + y\beta_1(\frac{Q^2}{2p_i \cdot Q})] p_i \cdot p_k + y\beta_1 Q \cdot p_k + \sqrt{\alpha_1\beta_1 y(1-y)} p_k \cdot n_{\perp,1}) \\
& 2([\beta_1(1-y) + y\alpha_1(\frac{Q^2}{2p_i \cdot Q})] p_i \cdot p_k + y\alpha_1 Q \cdot p_k - \sqrt{\alpha_1\beta_1 y(1-y)} p_k \cdot n_{\perp,1}) \\
& + 2(y p_i \cdot Q)]
\end{aligned} \tag{35}$$

$$\begin{aligned}
M_1 M_2^\dagger = & g_s^2 C_A g^{\eta\eta'} g^{\gamma\delta} [\frac{1-\beta_1}{y\beta_1(p_i \cdot Q)} + \frac{1}{2y(p_i \cdot Q)} + \frac{(1-\beta_1)(\frac{Q^2}{2p_i \cdot Q})}{2y\beta_1(1-y)(p_i \cdot Q)} \\
& + \frac{(1-\beta_1) Q \cdot p_k}{2y\beta_1(1-y)(p_i \cdot p_k)(p_i \cdot Q)} + \frac{1}{2(1-\beta_1)(1-y)(p_i \cdot p_k)}]
\end{aligned} \tag{36}$$



# MATHEMATICAL TOOLS

## Feynman rules in QCD

$$L_{q,free} = \sum_f \bar{\psi}_{if}(i\gamma^\mu \partial_\mu - m_f)\delta_{ij}\psi^j_f$$

$$\begin{array}{c} i, \alpha \qquad \qquad \qquad j, \beta \\ \bullet \longrightarrow \bullet \\ k, m_f \end{array} = (\frac{i}{\not{k} - m_f})_{\alpha\beta} \delta_{ij}$$

$$L_{g,free} = -\frac{1}{4}F_a^{\mu\nu}F^a_{\mu\nu} - \frac{1}{2\xi}(\partial^\mu A^a_\mu)(\partial^\nu A^a_\nu)$$

$$\begin{array}{c} a, \mu \qquad \qquad \qquad b, \nu \\ \bullet \text{-----} \bullet \\ k \end{array} = \frac{-i}{k^2}(-g_{\mu\nu} - (1 - \zeta)\frac{k_\mu k_\nu}{k^2})\delta^{ab}$$

$$L_{ghost,free} = (\partial^\mu \chi^{a*})(\partial_\mu \chi^a)$$

$$\begin{array}{c} \bar{u}^a \qquad \qquad \qquad u^b \\ \bullet \text{-----} \bullet \\ k \end{array} = \frac{i}{k^2} \delta^{ab}$$

$$L_{qg\bar{q},int} = g_s \bar{\psi}_i T^a_{ij} \psi_j \gamma^\mu A^a_\mu$$

$$= i g_s \gamma^\mu \otimes T^a_{ij}$$

$$L_{ggg,int} = -\frac{g_s}{2} f^{abc} (\partial_\mu A^a_\nu - \partial_\nu A^a_\mu) A_b^\mu A_c^\nu$$

$$= -g_s f^{bca} [(k_1 - k_2)^\rho g^{\mu\nu} + (k_2 - k_3)^\mu g^{\nu\rho} + (k_3 - k_1)^\nu g^{\rho\mu}]$$

(all Momenta are incoming!)

$$L_{gggg,int} = -\frac{g_s^2}{4} f^{abc} (A_b^\mu A_c^\nu) f^{ade} (A^d_\mu A^e_\nu)$$

$$= -i g_s^2 [f^{abe} f^{cde} (g^{\mu\rho} g^{\nu\sigma} - g^{\mu\sigma} g^{\nu\rho}) + f^{ade} f^{bce} (g^{\mu\nu} g^{\rho\sigma} - g^{\mu\sigma} g^{\nu\rho}) + f^{ade} f^{bce} (g^{\mu\nu} g^{\rho\sigma} - g^{\mu\rho} g^{\nu\sigma})]$$

$$L_{\chi g \bar{\chi}} = -g_s f^{abc} (\partial^\mu \chi^{a*}) \chi^b A^c_\mu$$

$$= g_s f^{abc} k^\mu$$

### Lorentz transformation of momenta $\hat{p}_i^\mu$ , $\hat{p}_k^\mu$ and $\hat{Q}^\mu$

$$\begin{aligned}
\hat{p}_i^\mu &= \alpha \Lambda^\mu{}_\nu p_i^\nu = p_i^\mu p_{i\nu} p_i^\nu \frac{-y^2 Q^2}{4(p_i \cdot Q)^2 (1 + \sqrt{1-y} - \frac{y}{2})} + p_i^\mu Q_\nu p_i^\nu \frac{y(1 + \sqrt{1-y})}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} \\
&+ Q^\mu p_{i\nu} p_i^\nu \frac{(y^2 - y - y\sqrt{1-y})}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} + \sqrt{1-y} \eta^\mu{}_\nu p_i^\nu \\
\hat{p}_i^\mu &= p_i^\mu (Q \cdot p_i) \frac{y(1 + \sqrt{1-y})}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} + \sqrt{1-y} p_i^\mu \\
&= p_i^\mu \left[ \frac{y(1 + \sqrt{1-y})}{(2 + 2\sqrt{1-y} - y)} + \sqrt{1-y} \right] = p_i^\mu \\
\boxed{\hat{p}_i^\mu &= \alpha \Lambda^\mu{}_\nu p_i^\nu = p_i^\mu} \tag{6.37}
\end{aligned}$$

$$\begin{aligned}
\hat{p}_k^\mu &= \alpha \Lambda^\mu{}_\nu p_k^\nu = p_i^\mu \left[ \frac{-y^2 Q^2 (p_i \cdot p_k)}{4(p_i \cdot Q)^2 (1 + \sqrt{1-y} - \frac{y}{2})} + \frac{y(1 + \sqrt{1-y})(Q \cdot p_k)}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} \right] \\
&+ Q^\mu \left[ \frac{(y^2 - y - y\sqrt{1-y})(p_i \cdot p_k)}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} \right] + \sqrt{1-y} p_k^\mu \\
\hat{p}_k^\mu &= \alpha \Lambda^\mu{}_\nu p_k^\nu = p_i^\mu \left[ \frac{-y^2 Q^2 (p_i \cdot p_k)}{4(p_i \cdot Q)^2 (1 + \sqrt{1-y} - \frac{y}{2})} + \frac{y(1 + \sqrt{1-y})(Q \cdot p_k)}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} \right] \\
&+ Q^\mu \left[ \frac{(y^2 - y - y\sqrt{1-y})(p_i \cdot p_k)}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} \right] + \sqrt{1-y} p_k^\mu
\end{aligned}$$

with

$$\begin{aligned}
A_1 &\equiv \frac{-y^2 Q^2 (p_i \cdot p_k)}{4(p_i \cdot Q)^2 (1 + \sqrt{1-y} - \frac{y}{2})} + \frac{y(1 + \sqrt{1-y})(Q \cdot p_k)}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} \\
A_2 &\equiv \frac{(y^2 - y - y\sqrt{1-y})(p_i \cdot p_k)}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})}
\end{aligned}$$

$$\boxed{\hat{p}_k^\mu = A_1 p_i^\mu + A_2 Q^\mu + \sqrt{1-y} p_k^\mu} \tag{6.38}$$

$$\begin{aligned}
\hat{Q}^\mu &= \alpha \Lambda^\mu{}_\nu Q^\nu = p_i^\mu \left[ \frac{-y^2 Q^2 (p_i \cdot Q)}{4(p_i \cdot Q)^2 (1 + \sqrt{1-y} - \frac{y}{2})} + \frac{y(1 + \sqrt{1-y})Q^2}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} \right] \\
&+ Q^\mu \left[ \frac{(y^2 - y - y\sqrt{1-y})(p_i \cdot Q)}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} \right] + \sqrt{1-y} Q^\mu
\end{aligned}$$

with

$$\begin{aligned}
S_1 &\equiv \frac{Q^2}{2p_i \cdot Q} \left[ \frac{-y^2}{2(1 + \sqrt{1-y} - \frac{y}{2})} + \frac{y(1 + \sqrt{1-y})}{(1 + \sqrt{1-y} - \frac{y}{2})} \right] = \frac{Q^2}{2p_i \cdot Q} y \\
S_2 &\equiv \frac{(y^2 - y - y\sqrt{1-y})}{2(1 + \sqrt{1-y} - \frac{y}{2})} + \sqrt{1-y} = 1 - y
\end{aligned}$$



$$\hat{Q}^\mu = \frac{Q^2}{2p_i \cdot Q} y p_i^\mu + (1 - y) Q^\mu \quad (6.39)$$

The often occurring pre-factor products

$$\begin{aligned} \zeta_1 \zeta_1 &= (\alpha_1^2 - 2y\alpha_1\beta_1(\frac{Q^2}{2p_i \cdot Q}) + y^2\beta_1^2(\frac{Q^2}{2p_i \cdot Q})^2) \\ \zeta_1 \lambda_1 &= (y\alpha_1\beta_1 - y^2\beta_1^2(\frac{Q^2}{2p_i \cdot Q})) \\ \zeta_1 \zeta_q &= (\alpha_1\beta_1 - y(\alpha_1^2 + \beta_1^2)(\frac{Q^2}{2p_i \cdot Q}) + y^2\alpha_1\beta_1(\frac{Q^2}{2p_i \cdot Q})^2) \\ \zeta_1 \lambda_q &= (y\alpha_1^2 - y^2\beta_1\alpha_1(\frac{Q^2}{2p_i \cdot Q})) \\ \zeta_q \zeta_q &= (\beta_1^2 - 2y\alpha_1\beta_1(\frac{Q^2}{2p_i \cdot Q}) + y^2\alpha_1^2(\frac{Q^2}{2p_i \cdot Q})^2) \\ \zeta_q \lambda_1 &= (y\beta_1^2 - y^2\alpha_1\beta_1(\frac{Q^2}{2p_i \cdot Q})) \\ \zeta_q \lambda_q &= (y\beta_1\alpha_1 - y^2\alpha_1^2(\frac{Q^2}{2p_i \cdot Q})) \\ \lambda_1 \lambda_1 &= y^2\beta_1^2 \quad \lambda_1 \lambda_q = y^2\beta_1\alpha_1 \quad \lambda_q \lambda_q = y^2\alpha_1^2 \end{aligned} \quad (6.40)$$

Common scalar products

$$\begin{aligned} k_1 \cdot q_i &= (\zeta_1 \lambda_q + \lambda_1 \zeta_q) p_i \cdot Q + \lambda_1 \lambda_q Q^2 - y\alpha_1\beta_1 n_{\perp,1}^2 \\ &= [(\alpha_1 - y\beta_1(\frac{Q^2}{2p_i \cdot Q}))y\alpha_1 + y\beta_1(\beta_1 - \alpha_1 y(\frac{Q^2}{2p_i \cdot Q}))] p_i \cdot Q \\ &\quad y^2\beta_1\alpha_1 Q^2 + 2y\alpha_1\beta_1 p_i Q \\ \Rightarrow k_1 \cdot q_i &= [y\alpha_1^2 - y^2\alpha_1\beta_1(\frac{Q^2}{2p_i \cdot Q}) + y\beta_1^2 - y^2\alpha_1\beta_1(\frac{Q^2}{2p_i \cdot Q})] p_i \cdot Q \\ &\quad y^2\beta_1\alpha_1 Q^2 + 2y\alpha_1\beta_1 p_i Q \end{aligned} \quad (6.41)$$

$$k_1 \cdot q_i = y(\alpha_1 + \beta_1)^2 p_i \cdot Q = y p_i \cdot Q \quad (6.42)$$

$$\begin{aligned}
k_1 \cdot q_k &= (\zeta_1 A_2 + \lambda_1 A_1) p_i \cdot Q + \zeta_1 \sqrt{1-y} p_i \cdot p_k + \lambda_1 A_2 Q^2 + \lambda_1 \sqrt{1-y} Q \cdot p_k \\
&+ \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1} \\
&= \left\{ \left[ \left( \alpha_1 - y\beta_1 \left( \frac{Q^2}{2p_i \cdot Q} \right) \right) \frac{(y^2 - y - y\sqrt{1-y})(p_i \cdot p_k)}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} \right] \right. \\
&+ y\beta_1 \left[ \frac{-y^2 Q^2 (p_i \cdot p_k)}{4(p_i \cdot Q)^2 (1 + \sqrt{1-y} - \frac{y}{2})} + \frac{y(1 + \sqrt{1-y})(Q \cdot p_k)}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} \right] \left. \right\} p_i \cdot Q \\
&+ \left( \alpha_1 - y\beta_1 \left( \frac{Q^2}{2p_i \cdot Q} \right) \right) \sqrt{1-y} p_i \cdot p_k + y\beta_1 \frac{(y^2 - y - y\sqrt{1-y})(p_i \cdot p_k)}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} Q^2 \\
&+ y\beta_1 \sqrt{1-y} Q \cdot p_k + \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1}
\end{aligned} \tag{6.43}$$

$$\begin{aligned}
k_1 \cdot q_k &= \alpha_1 \frac{(y^2 - y - y\sqrt{1-y})}{2(1 + \sqrt{1-y} - \frac{y}{2})} (p_i \cdot p_k) - y\beta_1 \left( \frac{Q^2}{2p_i \cdot Q} \right) \frac{(y^2 - y - y\sqrt{1-y})}{2(1 + \sqrt{1-y} - \frac{y}{2})} (p_i \cdot p_k) \\
&+ y\beta_1 \frac{-y^2 Q^2}{4(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} (p_i \cdot p_k) + y\beta_1 \frac{y(1 + \sqrt{1-y})}{2(1 + \sqrt{1-y} - \frac{y}{2})} Q \cdot p_k \\
&+ \alpha_1 \sqrt{1-y} p_i \cdot p_k - y\beta_1 \left( \frac{Q^2}{2p_i \cdot Q} \right) \sqrt{1-y} p_i \cdot p_k \\
&+ y\beta_1 \left( \frac{Q^2}{2p_i \cdot Q} \right) \frac{(y^2 - y - y\sqrt{1-y})}{2(1 + \sqrt{1-y} - \frac{y}{2})} (p_i \cdot p_k) + y\beta_1 \sqrt{1-y} (Q \cdot p_k) \\
&+ \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1}
\end{aligned} \tag{6.44}$$

$$\begin{aligned}
k_1 \cdot q_k &= \left[ \alpha_1 \frac{(y^2 - y - y\sqrt{1-y})}{2(1 + \sqrt{1-y} - \frac{y}{2})} + y\beta_1 \frac{-y^2 Q^2}{4(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} + \alpha_1 \sqrt{1-y} \right. \\
&- y\beta_1 \left( \frac{Q^2}{2p_i \cdot Q} \right) \sqrt{1-y} \left. \right] p_i \cdot p_k + \left[ y\beta_1 \frac{y(1 + \sqrt{1-y})}{2(1 + \sqrt{1-y} - \frac{y}{2})} + y\beta_1 \sqrt{1-y} \right] (Q \cdot p_k) \\
&+ \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1}
\end{aligned} \tag{6.45}$$

$$\begin{aligned}
k_1 \cdot q_k &= \left\{ \alpha_1 \left[ \frac{(y^2 - y - y\sqrt{1-y})}{2(1 + \sqrt{1-y} - \frac{y}{2})} + \sqrt{1-y} \right] \right. \\
&+ y\beta_1 \left( \frac{Q^2}{p_i \cdot Q} \right) \left[ \frac{-y^2}{4(1 + \sqrt{1-y} - \frac{y}{2})} - \sqrt{1-y} \right] \left. \right\} p_i \cdot p_k \\
&+ y\beta_1 \left[ \frac{y(1 + \sqrt{1-y})}{2(1 + \sqrt{1-y} - \frac{y}{2})} + \sqrt{1-y} \right] (Q \cdot p_k) \\
&+ \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1}
\end{aligned} \tag{6.46}$$

$$\boxed{k_1 \cdot q_k = [\alpha_1(1-y) + y\beta_1 \left( \frac{Q^2}{2p_i \cdot Q} \right)] p_i \cdot p_k + y\beta_1 Q \cdot p_k + \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1}} \tag{6.47}$$

$$\begin{aligned}
q_i \cdot q_k &= (\zeta_q A_2 + \lambda_q A_1) p_i \cdot Q + \zeta_q \sqrt{1-y} p_i \cdot p_k + \lambda_q A_2 Q^2 + \lambda_q \sqrt{1-y} Q \cdot p_k \\
&\quad - \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1} \\
&= \left\{ \left[ \left( \beta_1 - y \alpha_1 \left( \frac{Q^2}{2 p_i \cdot Q} \right) \right) \frac{(y^2 - y - y \sqrt{1-y})(p_i \cdot p_k)}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} \right] \right. \\
&\quad \left. + y \alpha_1 \left[ \frac{-y^2 Q^2 (p_i \cdot p_k)}{4(p_i \cdot Q)^2 (1 + \sqrt{1-y} - \frac{y}{2})} + \frac{y(1 + \sqrt{1-y})(Q \cdot p_k)}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} \right] \right\} p_i \cdot Q \\
&\quad + (\beta_1 - y \alpha_1 \left( \frac{Q^2}{2 p_i \cdot Q} \right)) \sqrt{1-y} p_i \cdot p_k + y \alpha_1 \frac{(y^2 - y - y \sqrt{1-y})(p_i \cdot p_k)}{2(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} Q^2 \\
&\quad + y \alpha_1 \sqrt{1-y} Q \cdot p_k - \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1}
\end{aligned} \tag{6.48}$$

$$\begin{aligned}
q_i \cdot q_k &= \beta_1 \frac{(y^2 - y - y \sqrt{1-y})}{2(1 + \sqrt{1-y} - \frac{y}{2})} (p_i \cdot p_k) - y \alpha_1 \left( \frac{Q^2}{2 p_i \cdot Q} \right) \frac{(y^2 - y - y \sqrt{1-y})}{2(1 + \sqrt{1-y} - \frac{y}{2})} (p_i \cdot p_k) \\
&\quad + y \alpha_1 \frac{-y^2 Q^2}{4(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} (p_i \cdot p_k) + y \alpha_1 \frac{y(1 + \sqrt{1-y})}{2(1 + \sqrt{1-y} - \frac{y}{2})} Q \cdot p_k \\
&\quad + \beta_1 \sqrt{1-y} p_i \cdot p_k - y \alpha_1 \left( \frac{Q^2}{2 p_i \cdot Q} \right) \sqrt{1-y} p_i \cdot p_k \\
&\quad + y \alpha_1 \left( \frac{Q^2}{2 p_i \cdot Q} \right) \frac{(y^2 - y - y \sqrt{1-y})}{2(1 + \sqrt{1-y} - \frac{y}{2})} (p_i \cdot p_k) + y \alpha_1 \sqrt{1-y} (Q \cdot p_k) \\
&\quad - \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1}
\end{aligned} \tag{6.49}$$

$$\begin{aligned}
q_i \cdot q_k &= \left[ \beta_1 \frac{(y^2 - y - y \sqrt{1-y})}{2(1 + \sqrt{1-y} - \frac{y}{2})} + y \alpha_1 \frac{-y^2 Q^2}{4(p_i \cdot Q)(1 + \sqrt{1-y} - \frac{y}{2})} + \beta_1 \sqrt{1-y} \right. \\
&\quad \left. - y \alpha_1 \left( \frac{Q^2}{2 p_i \cdot Q} \right) \sqrt{1-y} \right] p_i \cdot p_k + \left[ y \alpha_1 \frac{y(1 + \sqrt{1-y})}{2(1 + \sqrt{1-y} - \frac{y}{2})} + y \alpha_1 \sqrt{1-y} \right] (Q \cdot p_k) \\
&\quad - \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1}
\end{aligned} \tag{6.50}$$

$$\begin{aligned}
k_1 \cdot q_k &= \left\{ \beta_1 \left[ \frac{(y^2 - y - y \sqrt{1-y})}{2(1 + \sqrt{1-y} - \frac{y}{2})} + \sqrt{1-y} \right] \right. \\
&\quad \left. + y \alpha_1 \left( \frac{Q^2}{p_i \cdot Q} \right) \left[ \frac{-y^2}{4(1 + \sqrt{1-y} - \frac{y}{2})} - \sqrt{1-y} \right] \right\} p_i \cdot p_k \\
&\quad + y \alpha_1 \left[ \frac{y(1 + \sqrt{1-y})}{2(1 + \sqrt{1-y} - \frac{y}{2})} + \sqrt{1-y} \right] (Q \cdot p_k) \\
&\quad - \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1}
\end{aligned} \tag{6.51}$$

$$\boxed{q_i \cdot q_k = [\beta_1(1-y) + y \alpha_1 \left( \frac{Q^2}{2 p_i \cdot Q} \right)] p_i \cdot p_k + y \alpha_1 Q \cdot p_k - \sqrt{\alpha_1 \beta_1 y(1-y)} p_k \cdot n_{\perp,1}} \tag{6.52}$$



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